ICTS Lectures, Nov. 9th 2020:

Introduction to Primordial Black Hole Dark Matter

Ely D. Kovetz
Ben-Gurion University

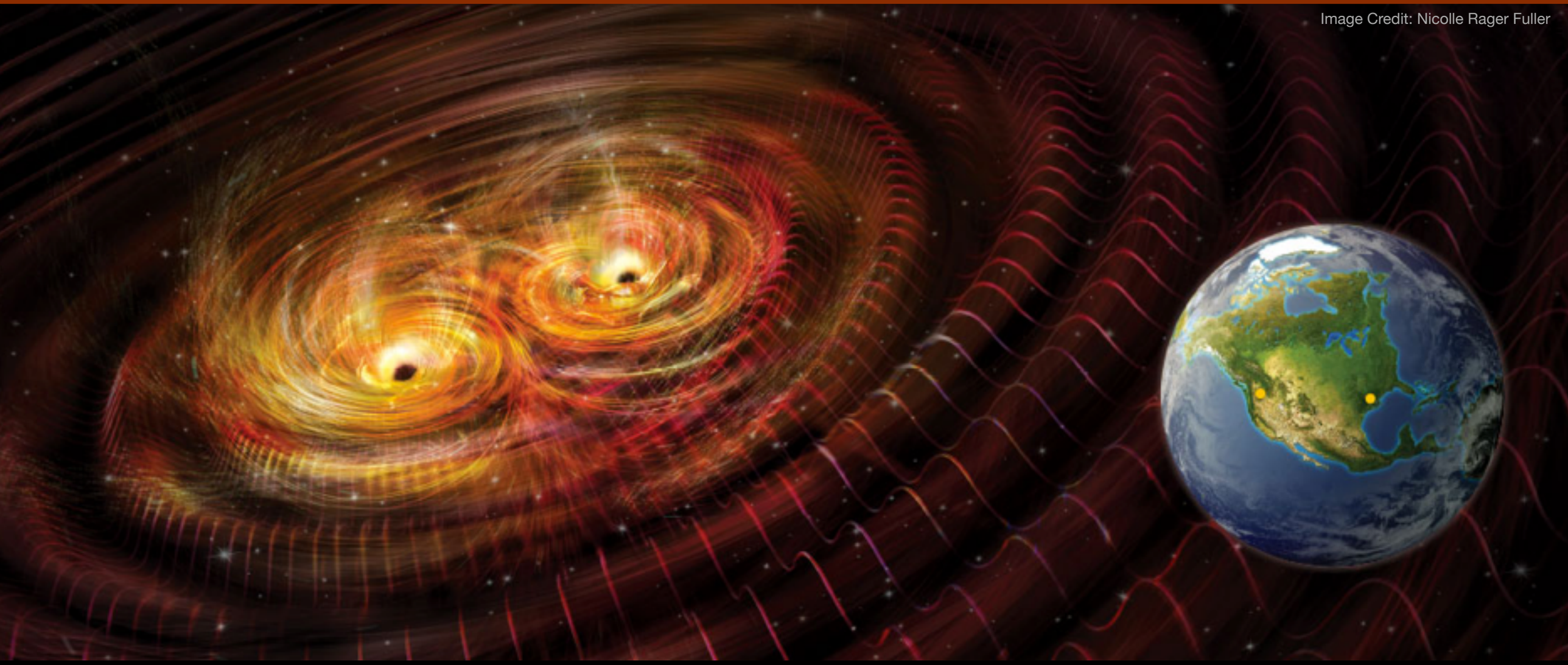
Image Credit: Nicolle Rager Fuller

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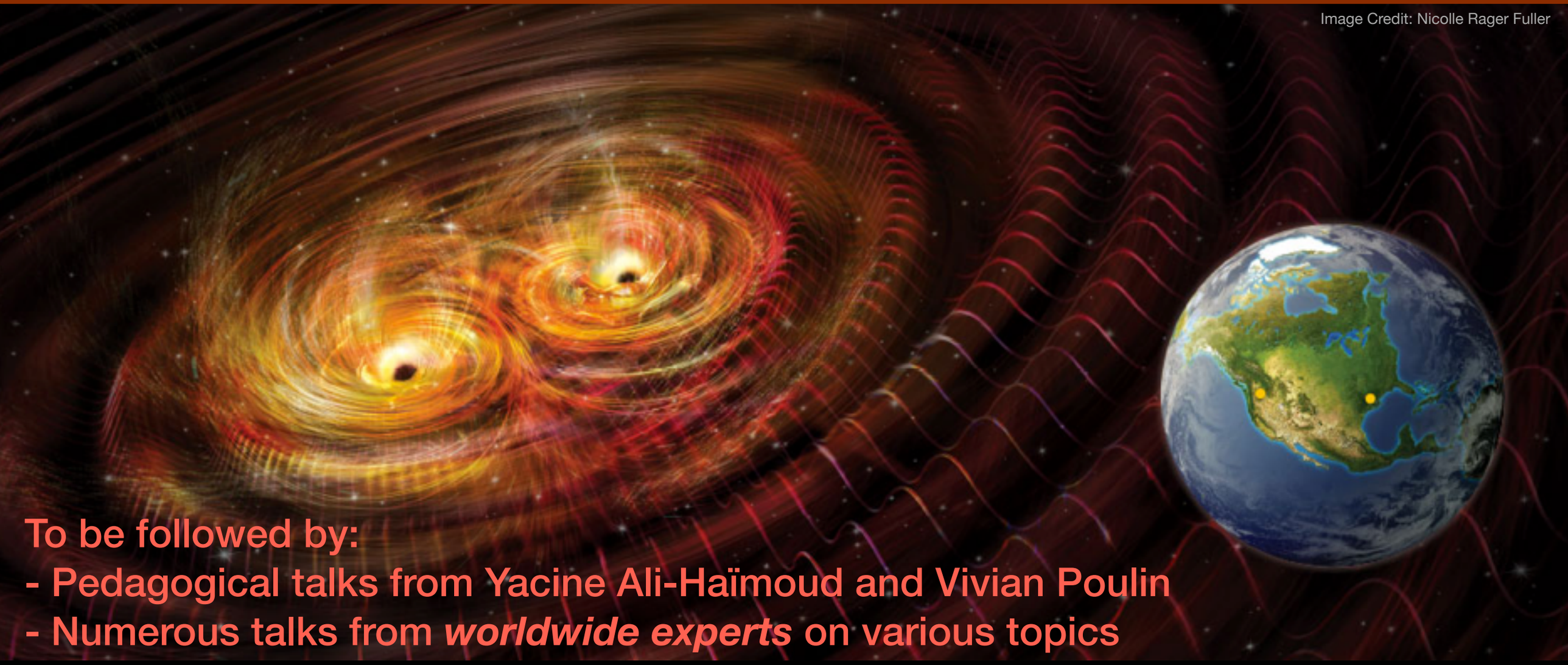
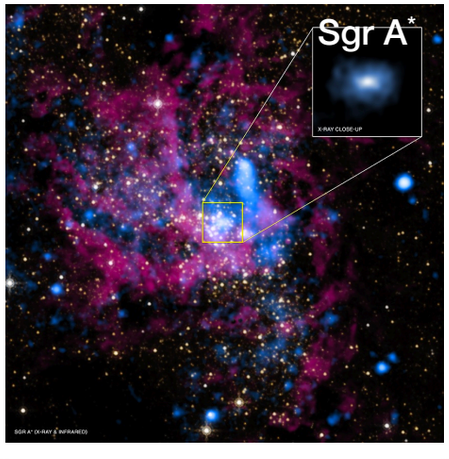


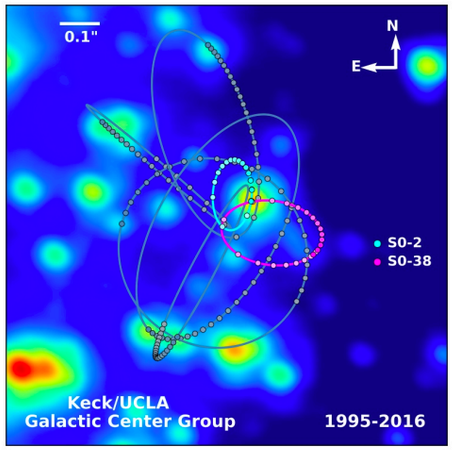
To be followed by:
- Pedagogical talks from Yacine Ali-Haïmoud and Vivian Poulin
- Numerous talks from ***worldwide experts*** on various topics

Very Exciting Times for Black Holes!

Very Exciting Times for Black Holes!

$10^6\ M_\odot$





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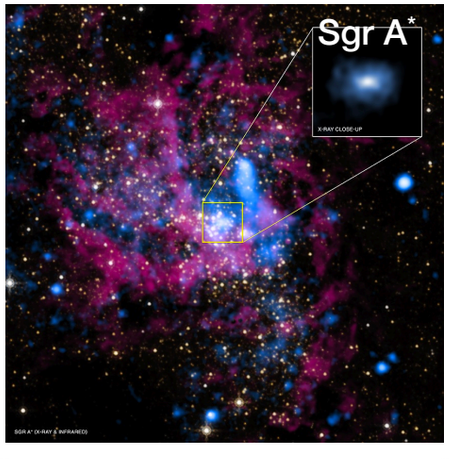

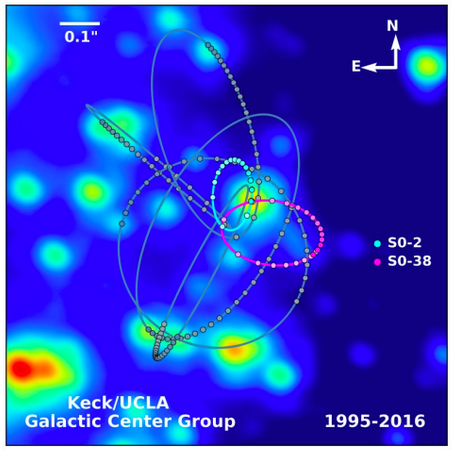

Ill. Niklas Elmehed. © Nobel Media.
Reinhard Genzel
Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media.
Andrea Ghez
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Nobel Prize (2020)

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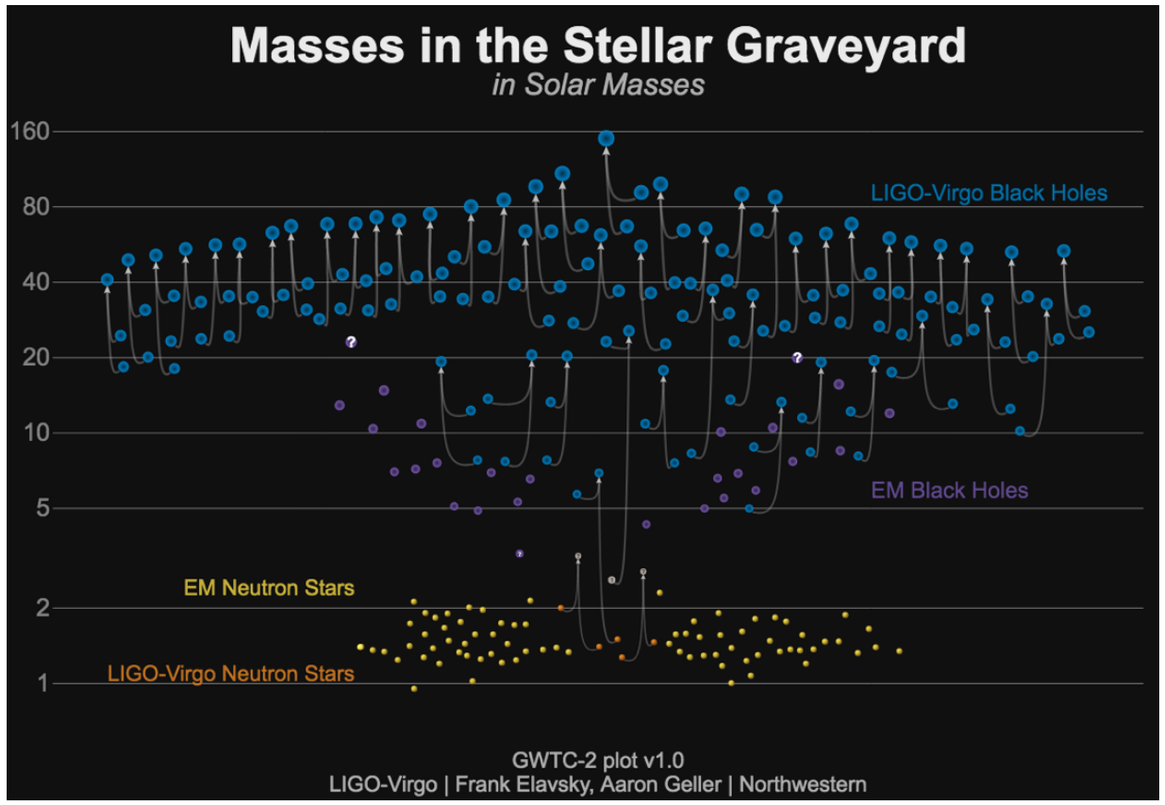
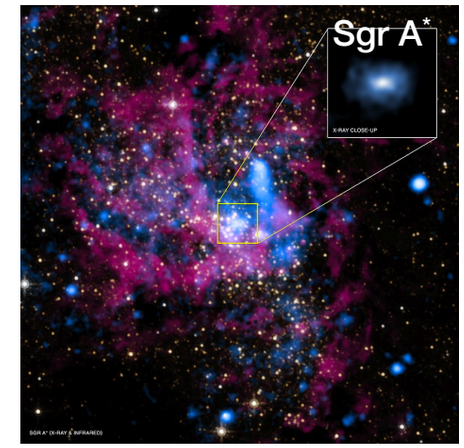
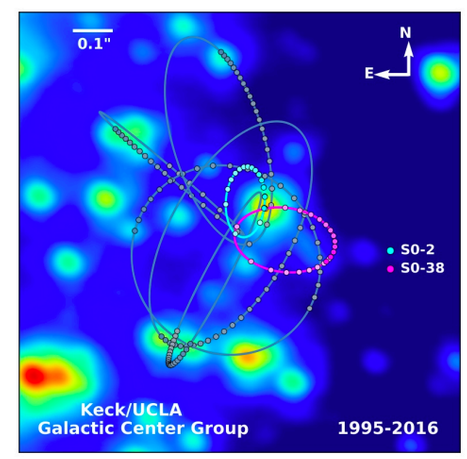
$1\,M_\odot$ $100\,M_\odot$ $10^6\,M_\odot$







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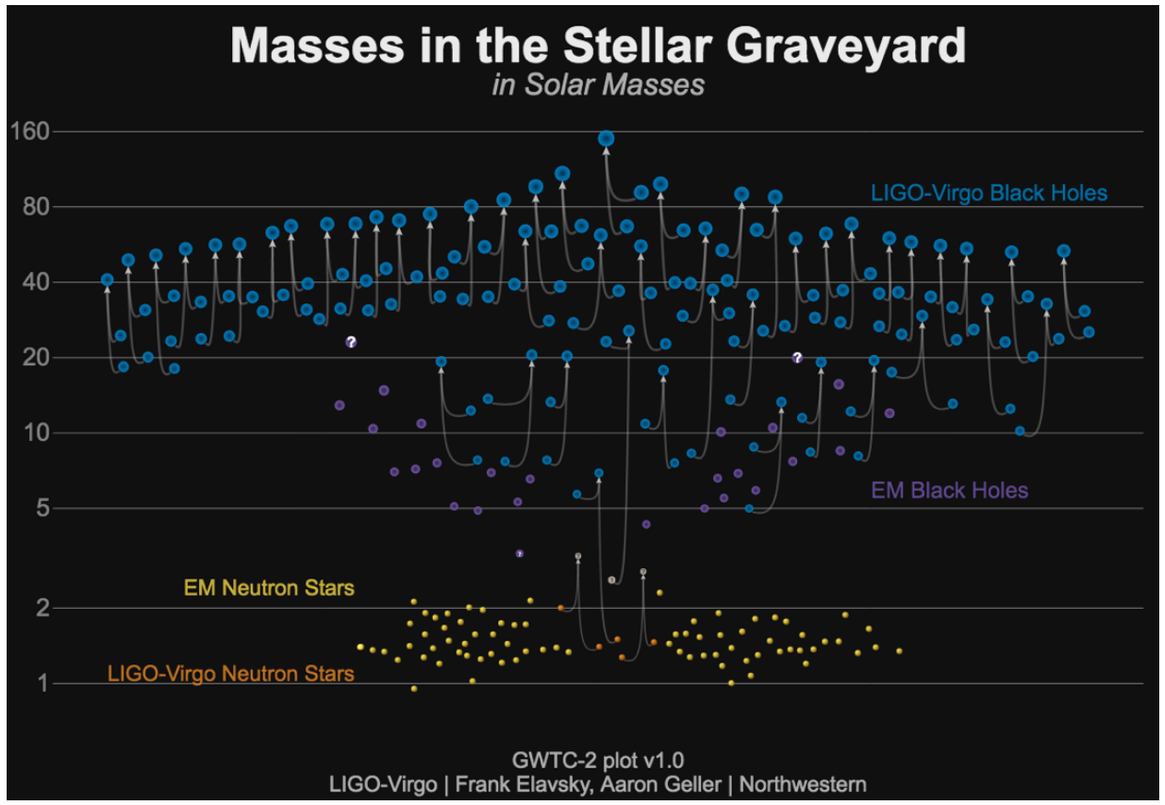

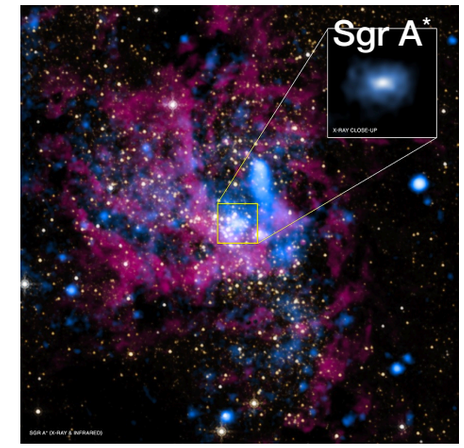

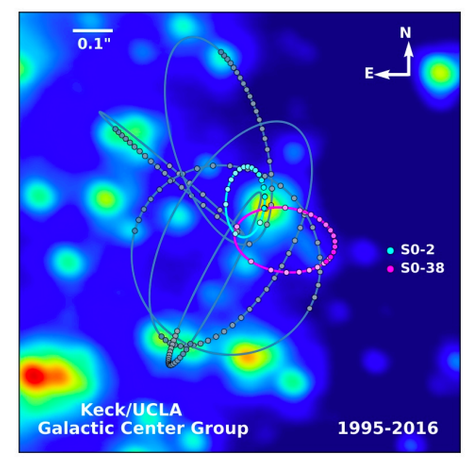

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Nobel Prize (2017)

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Reinhard Genzel
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Ill. Niklas Elmehed. © Nobel Media.
Andrea Ghez
Prize share: 1/4

Nobel Prize (2020)

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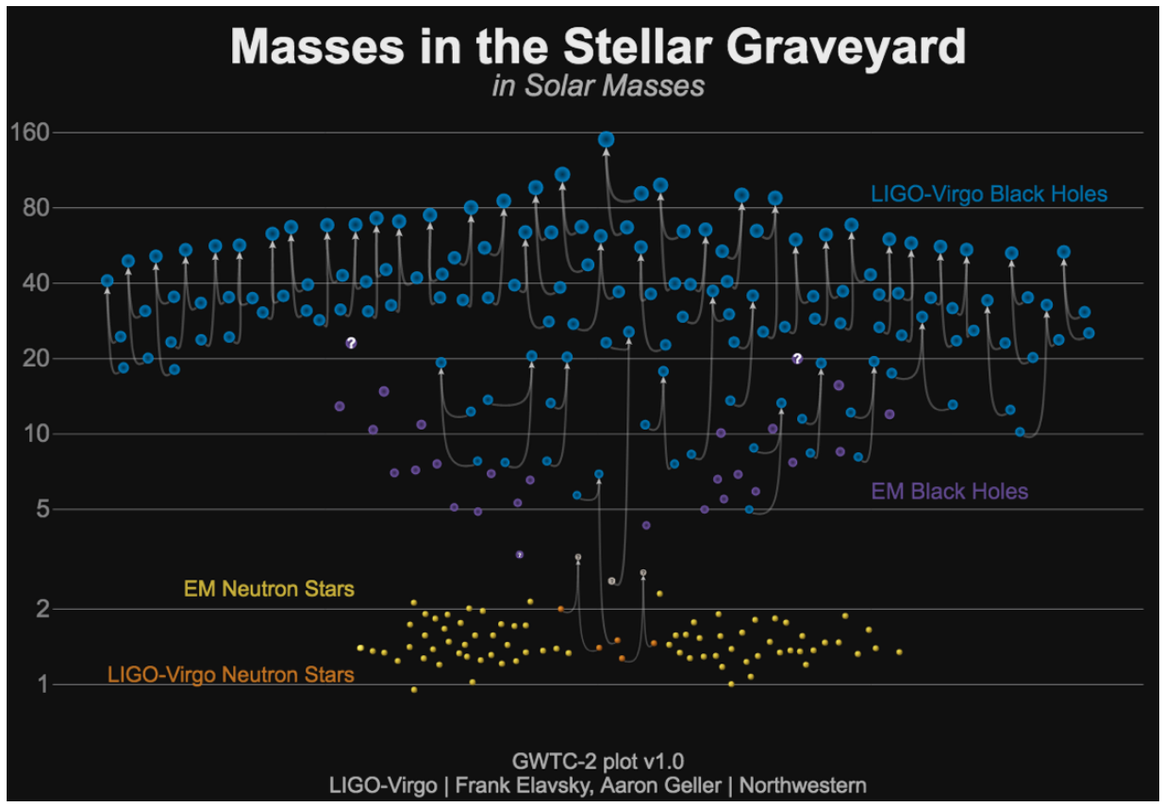

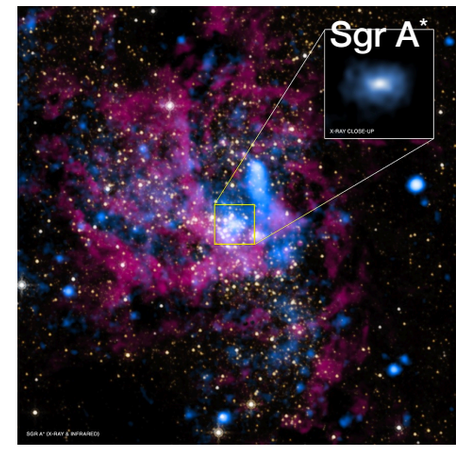

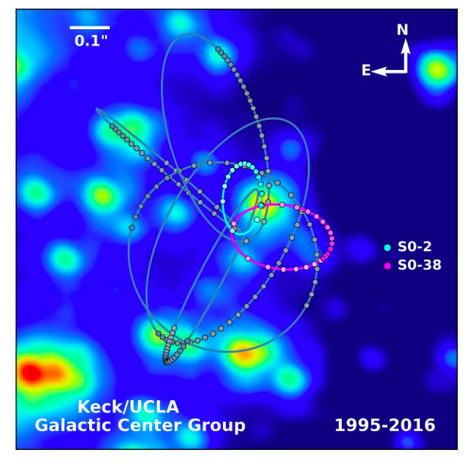

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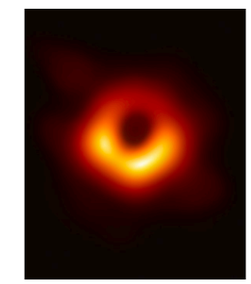

EHT (2019)

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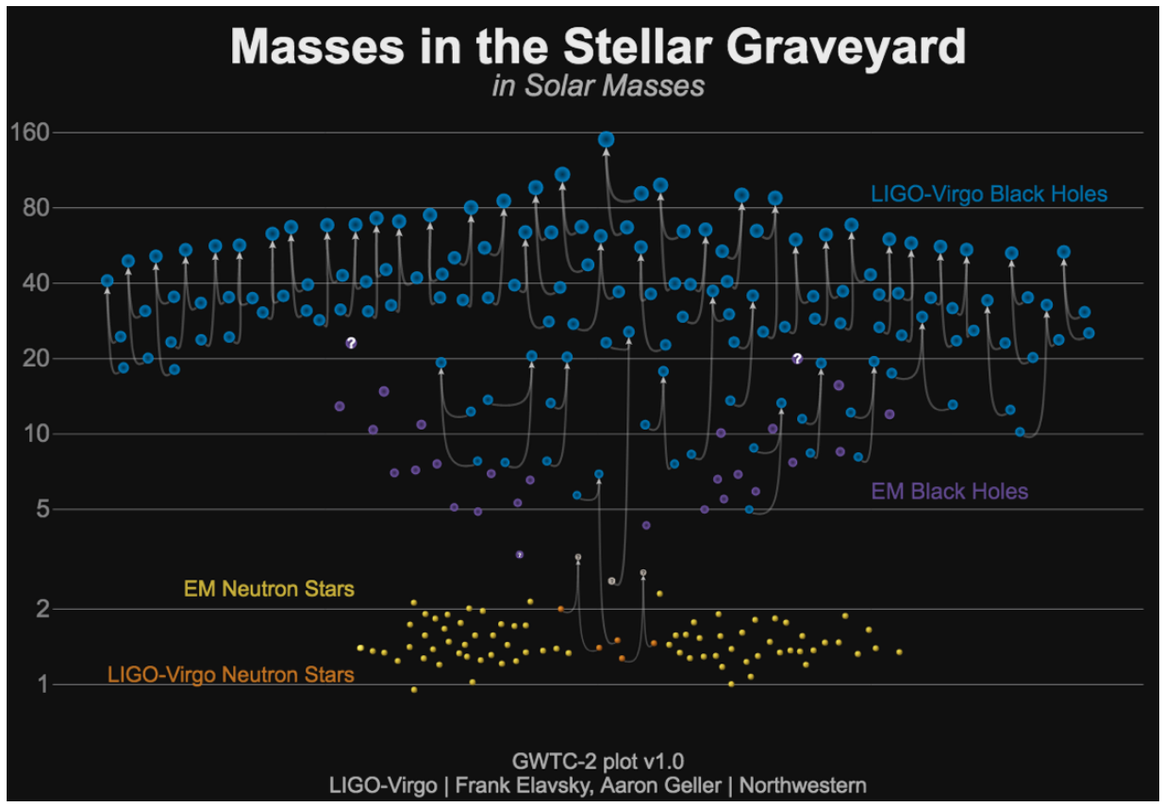

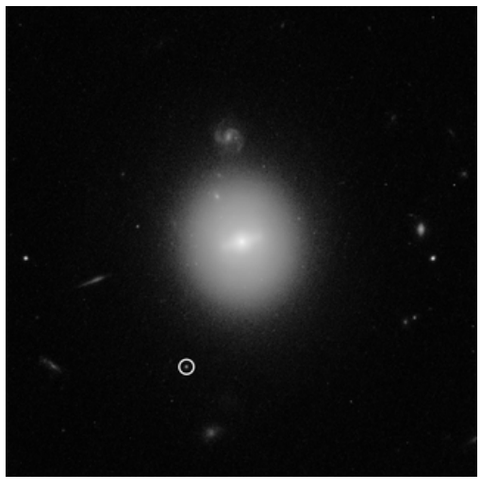

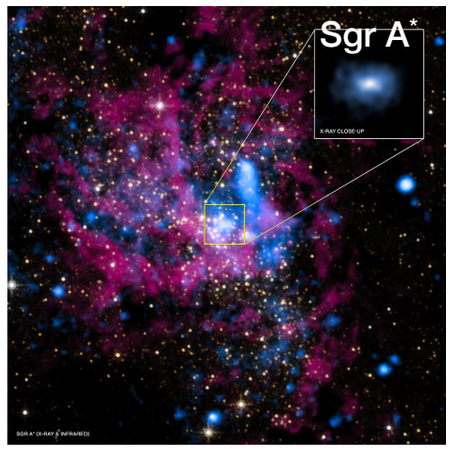

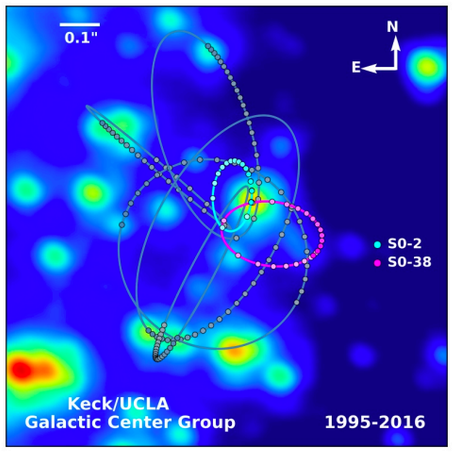

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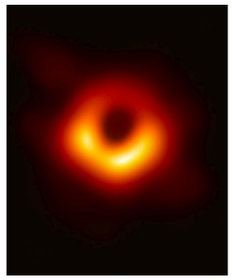

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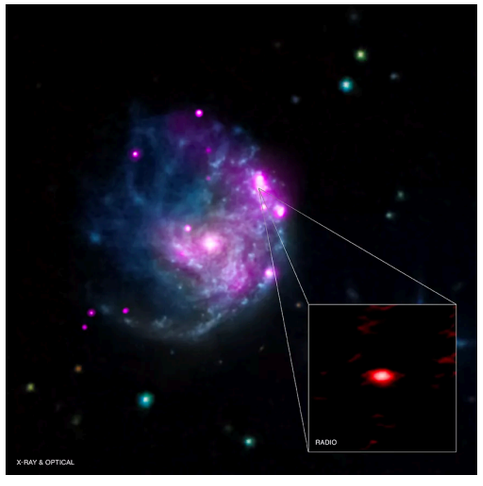

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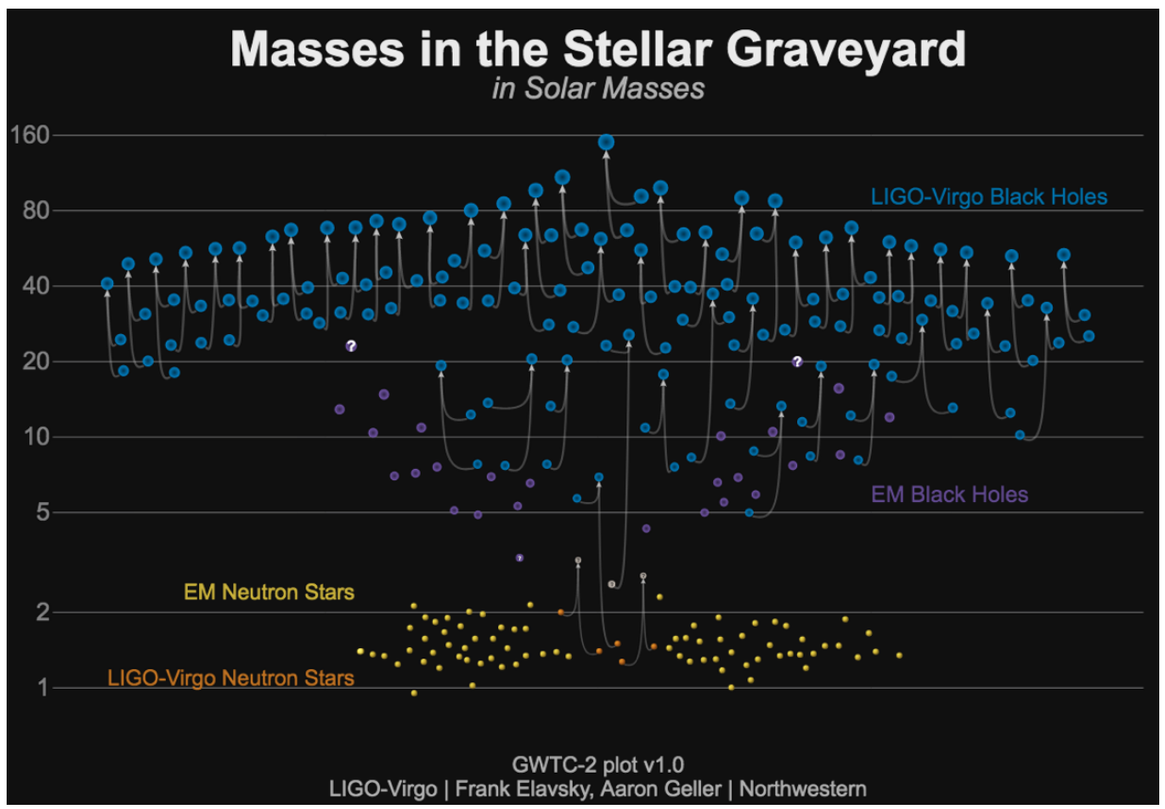

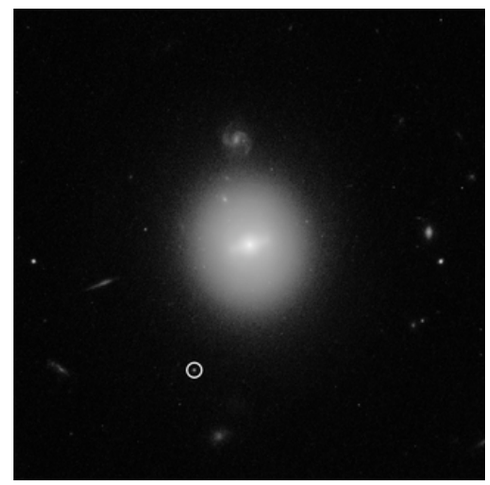

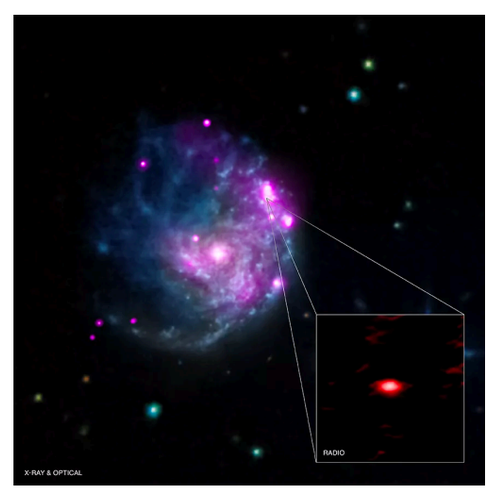

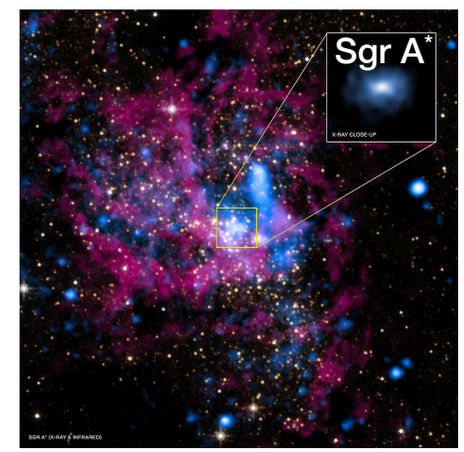

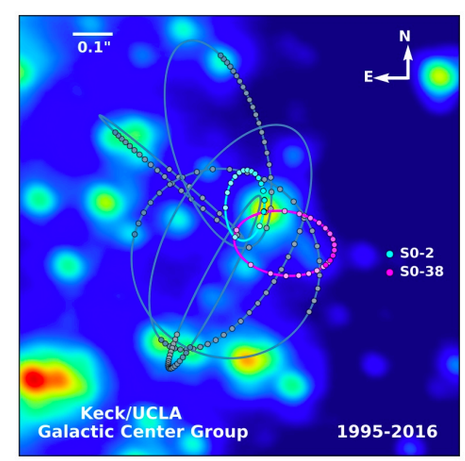

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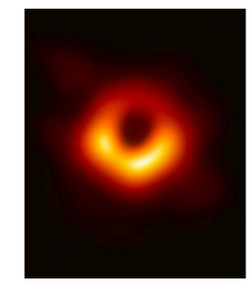

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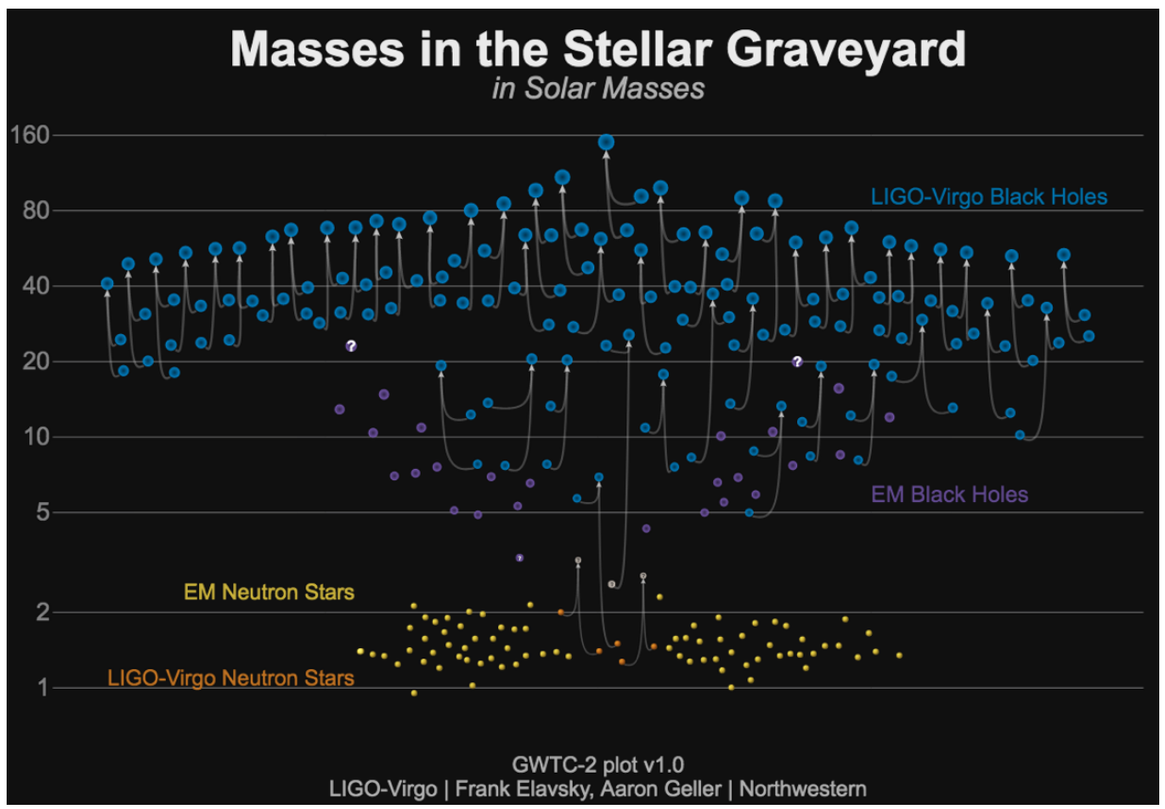
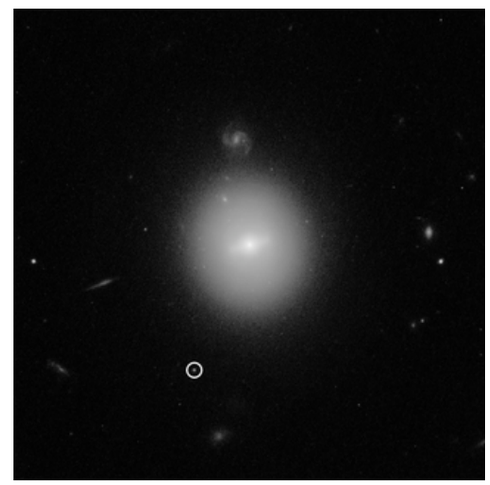
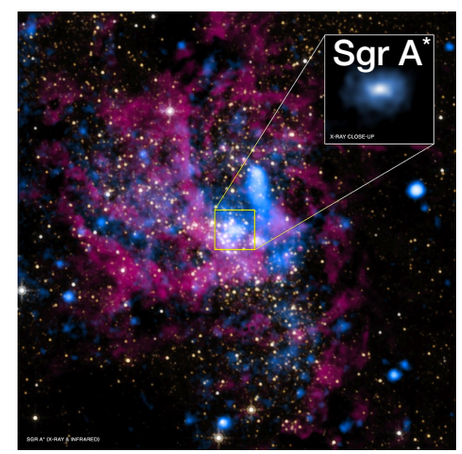
Explain Rate/Outliers?







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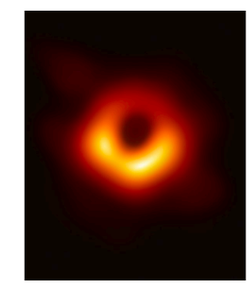

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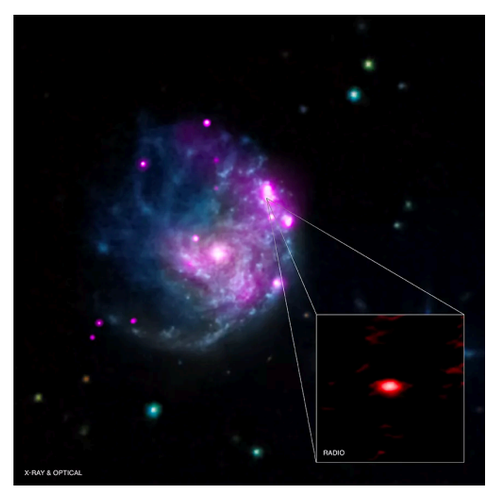

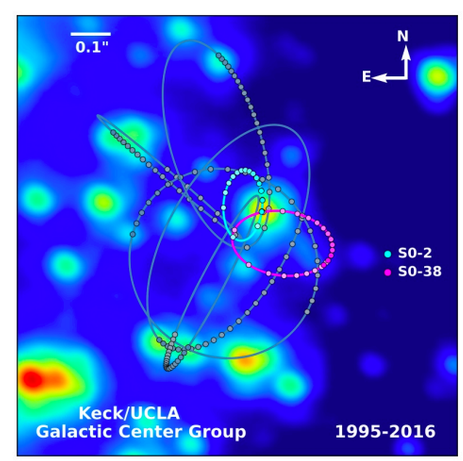

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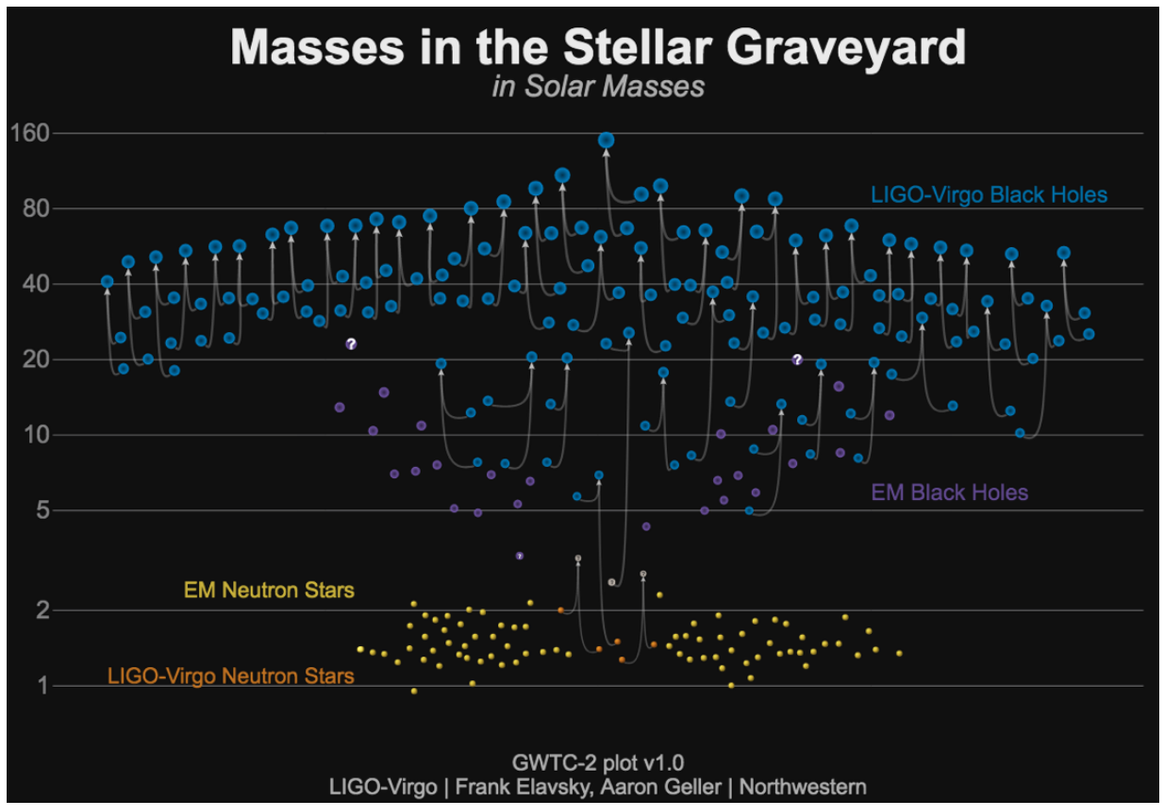

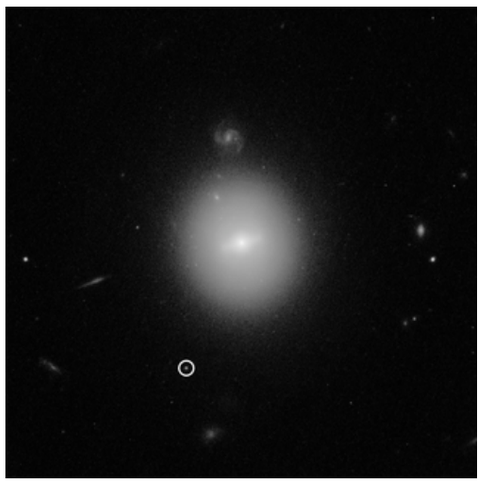

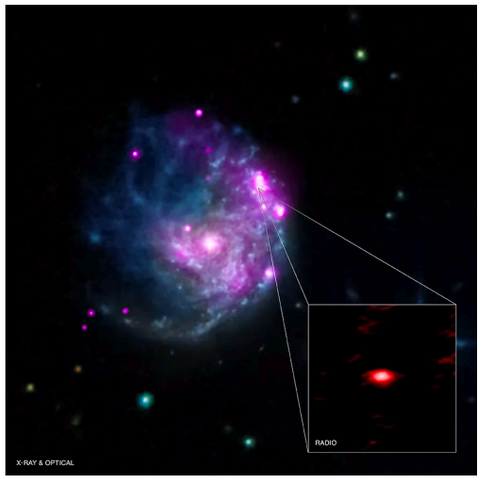

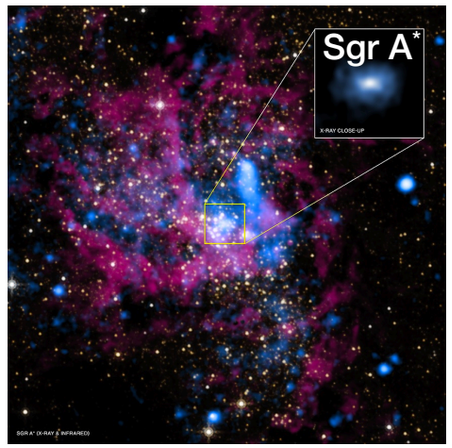

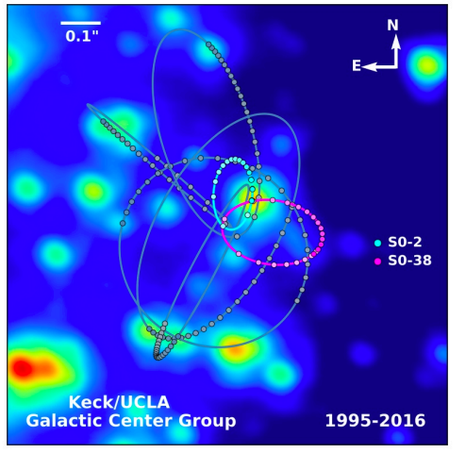

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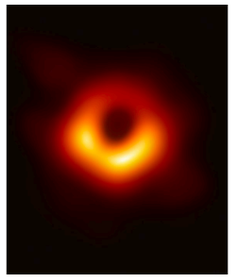

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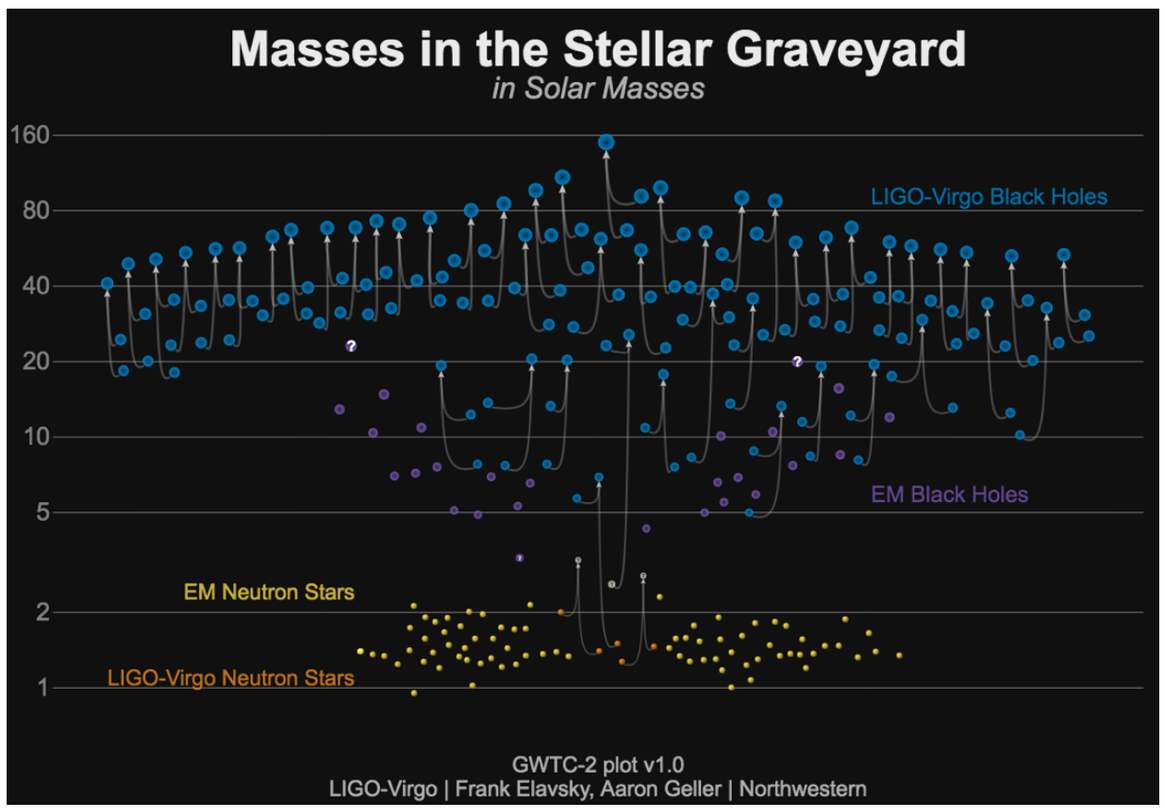

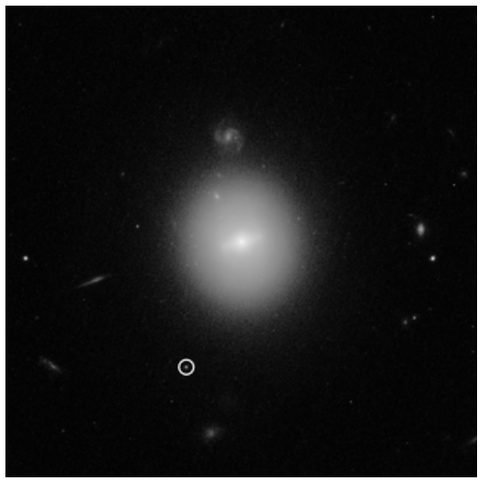

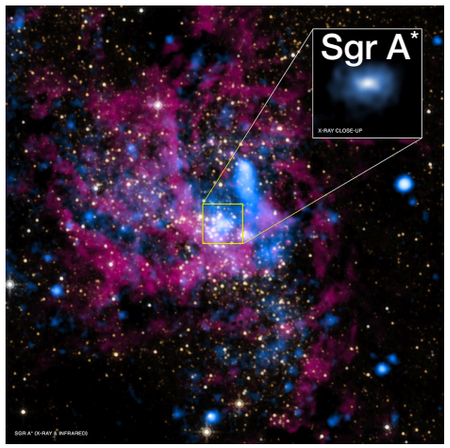

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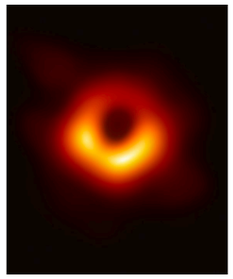

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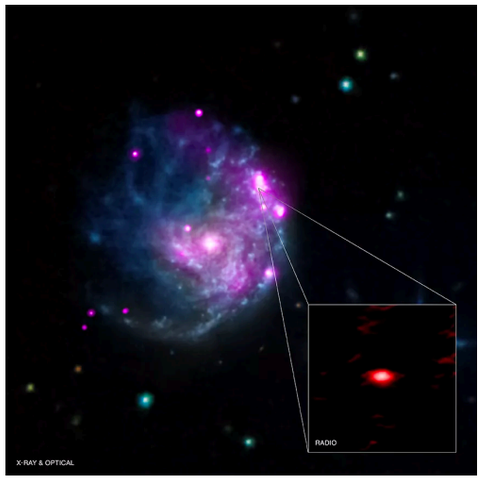

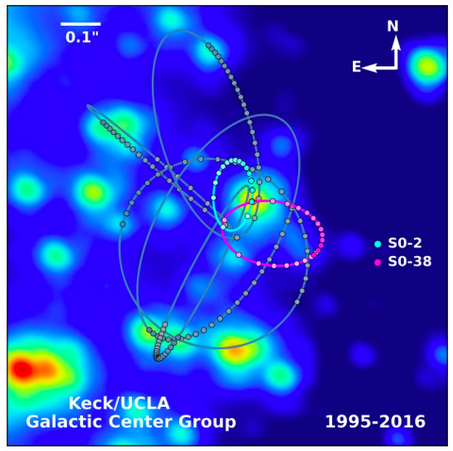

Primordial + Black: Can They Explain *Dark Matter*?

Ingredients of the Standard Model of Cosmology

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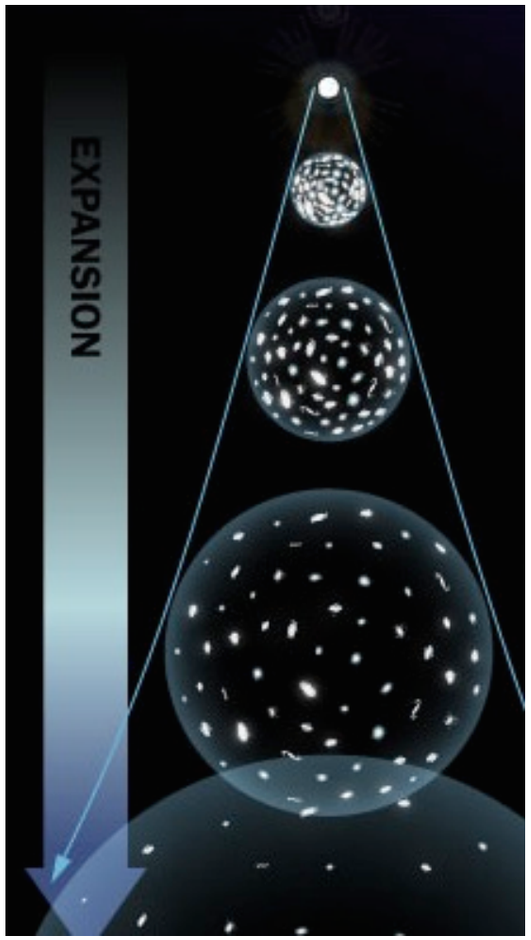
Hot big bang



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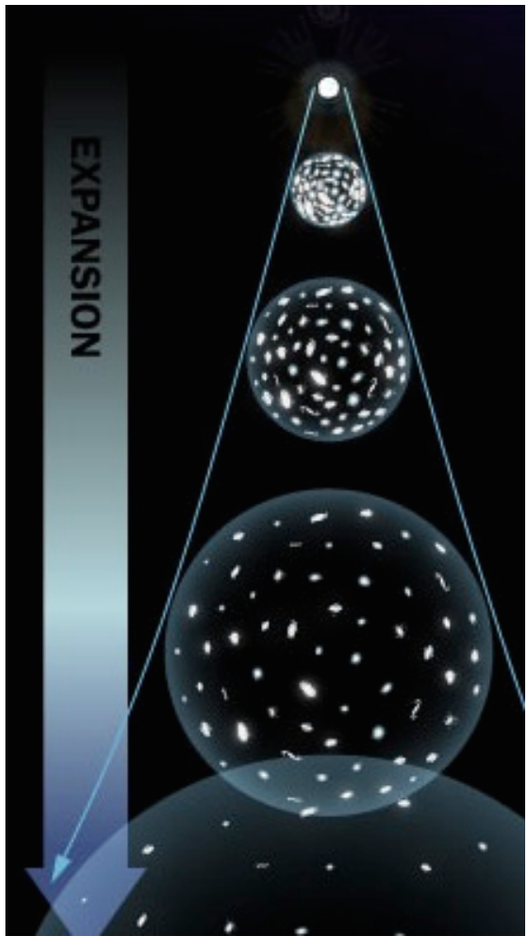

Gravitational instability

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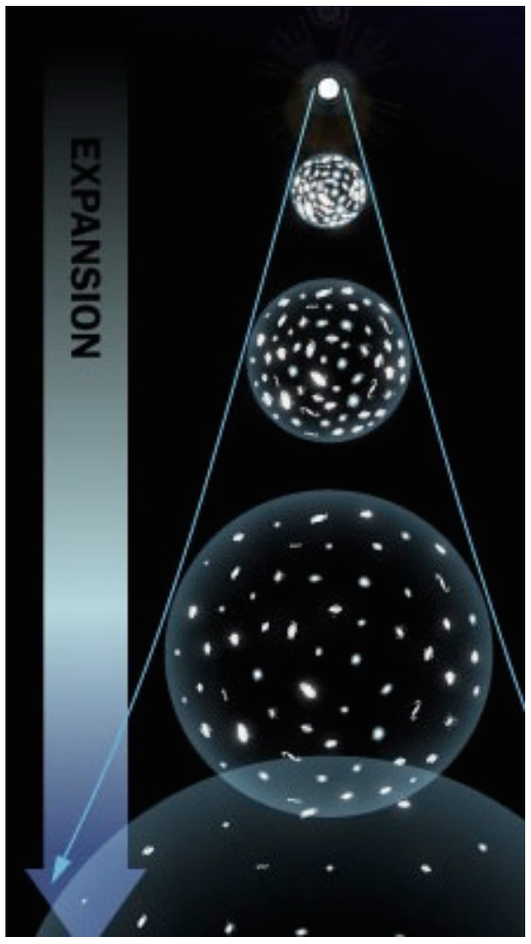
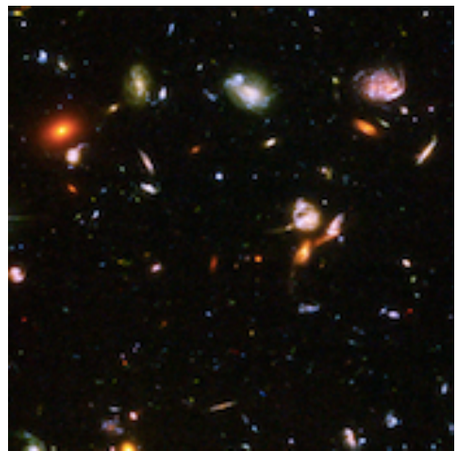
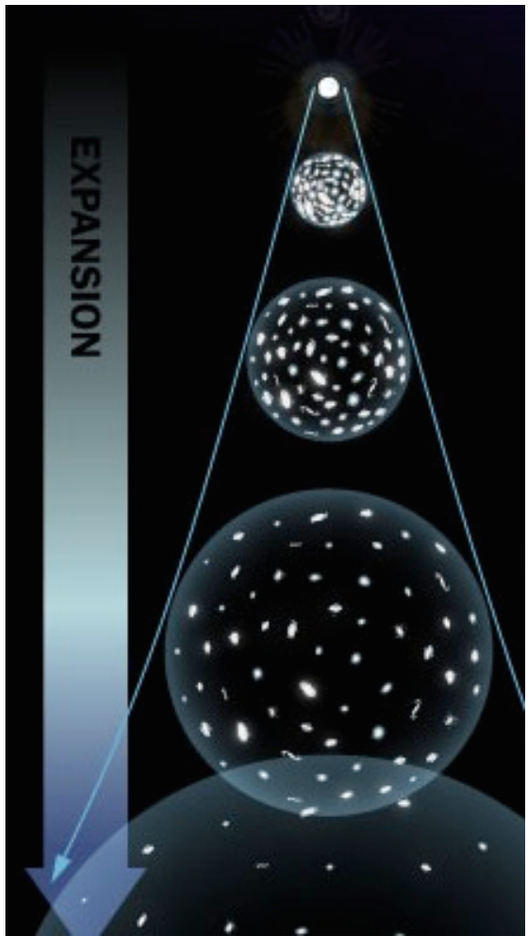


Gravitational instability



Ingredients of the Standard Model of Cosmology

Hot big bang



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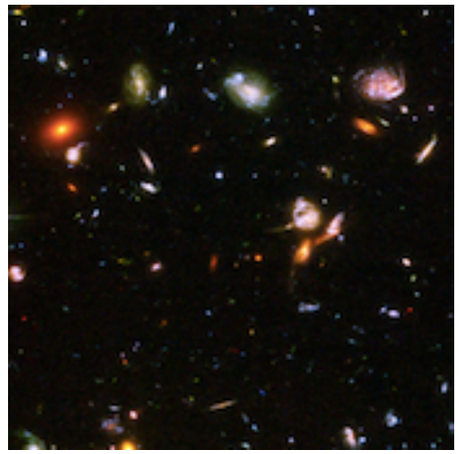

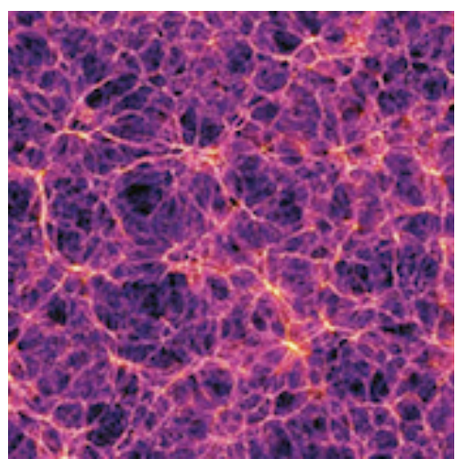

Ingredients of the Standard Model of Cosmology

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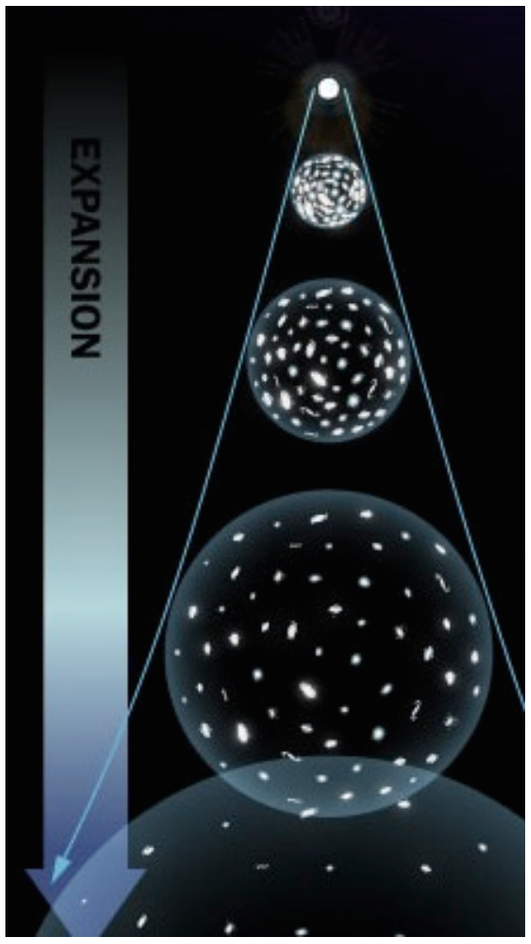

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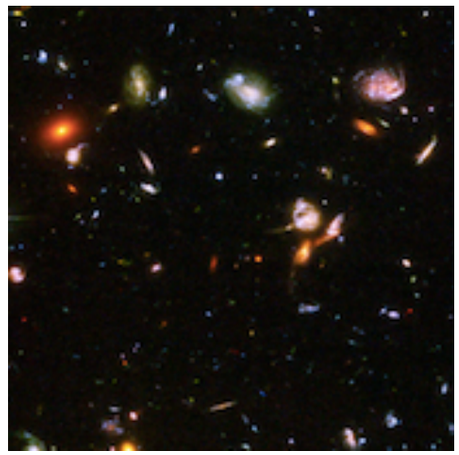
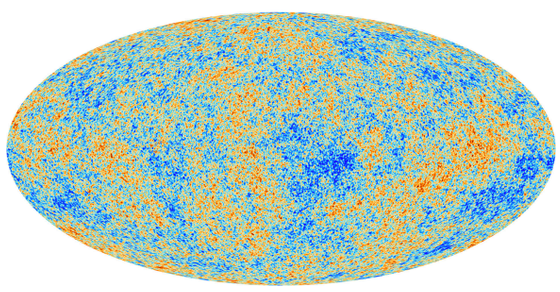
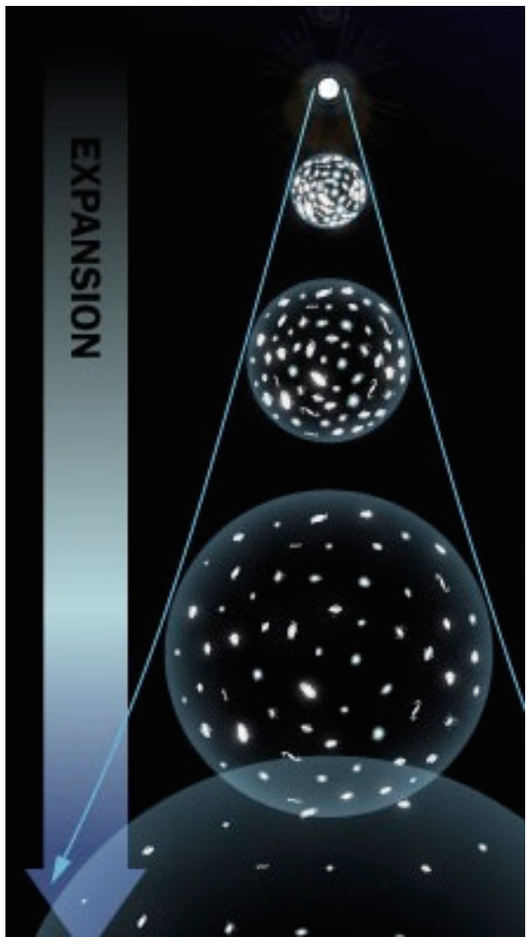




Ingredients of the Standard Model of Cosmology

Hot big bang



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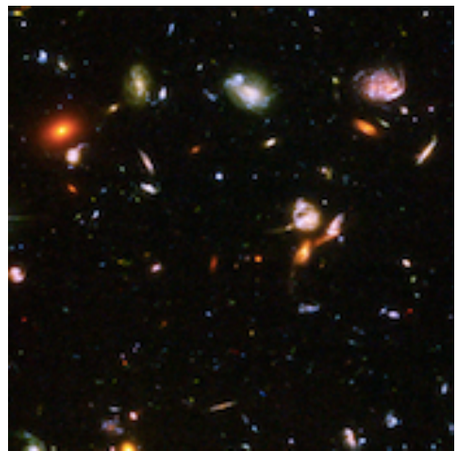
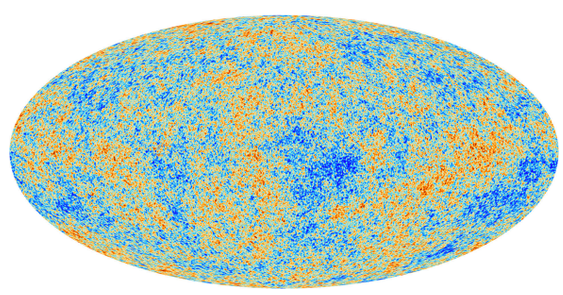
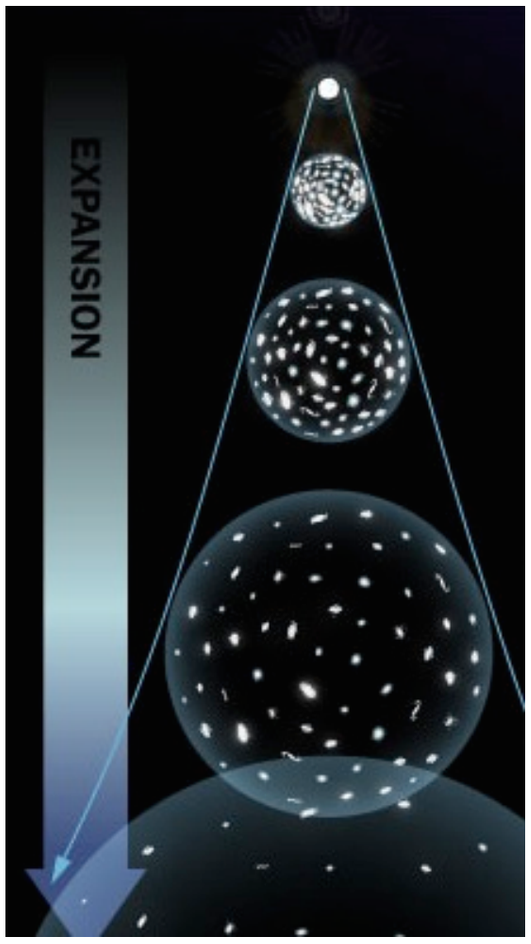




Inflation

Ingredients of the Standard Model of Cosmology

Hot big bang



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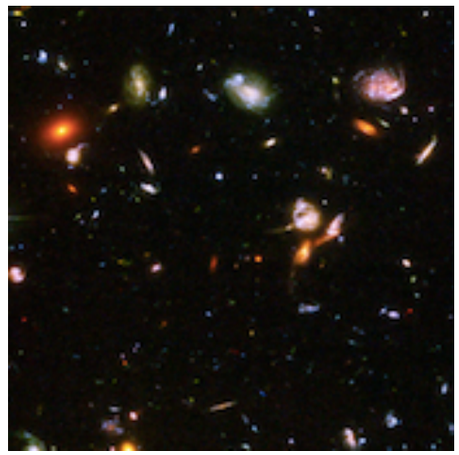

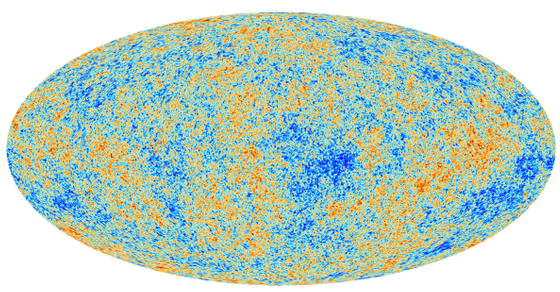

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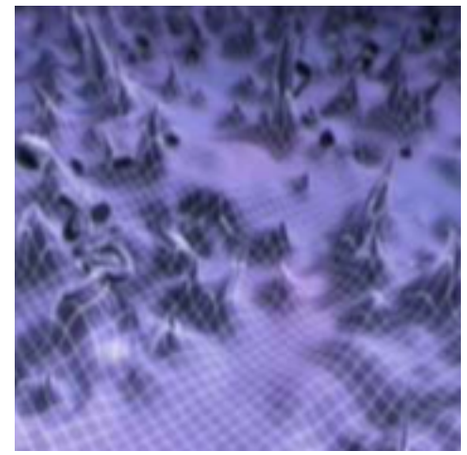

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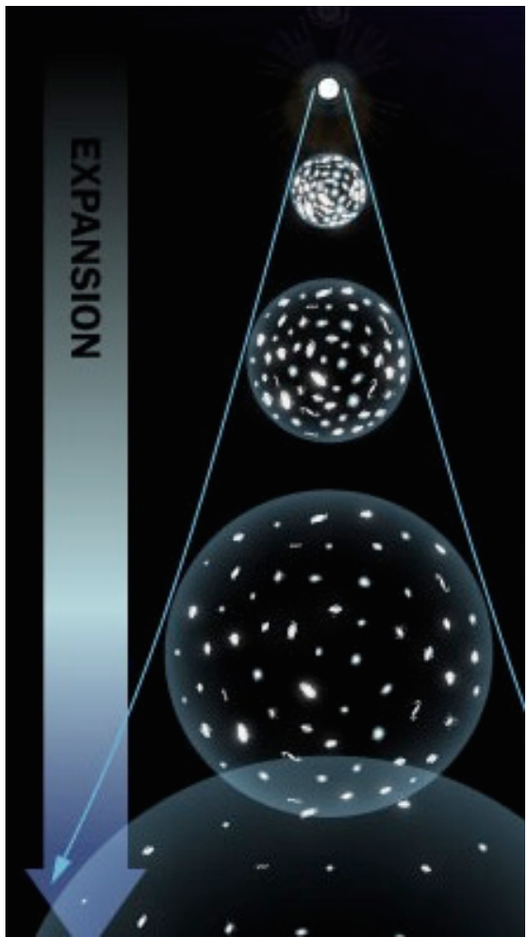
Hot big bang



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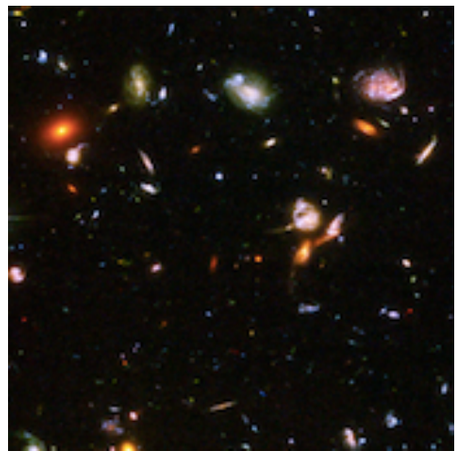

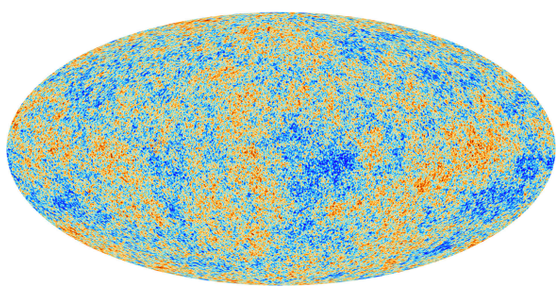

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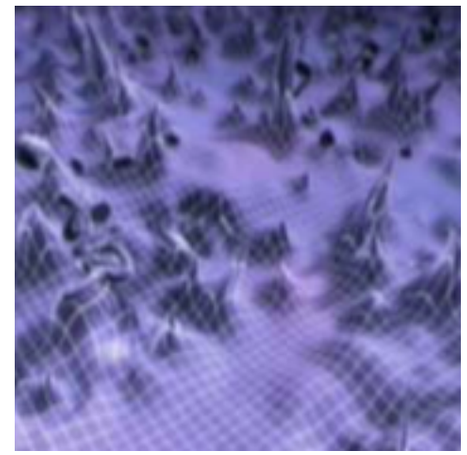

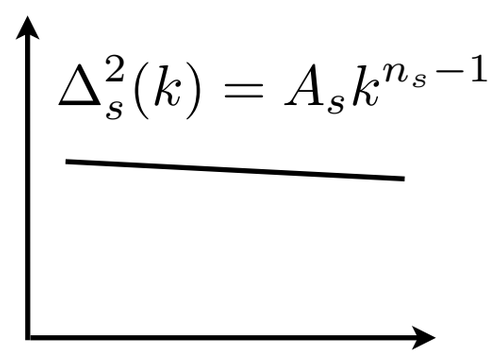

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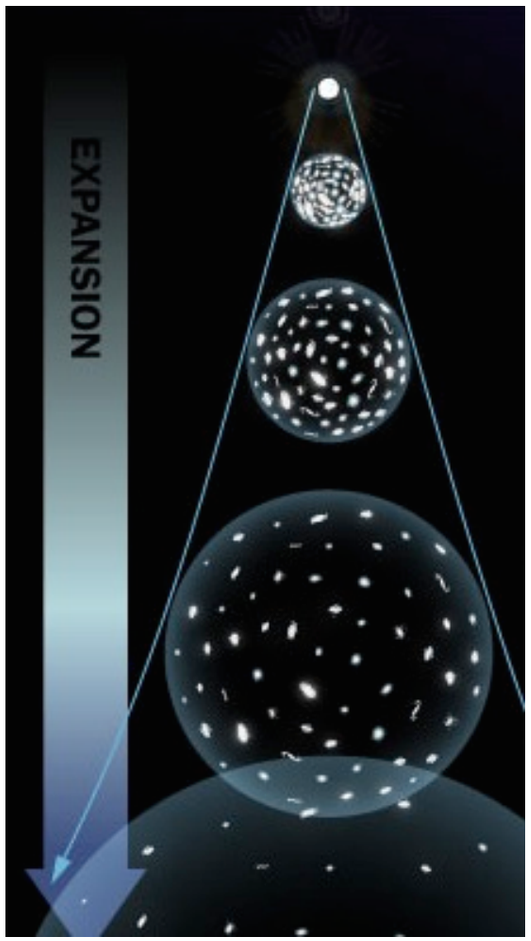

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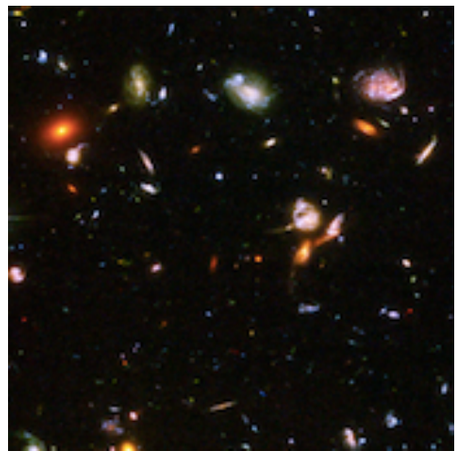

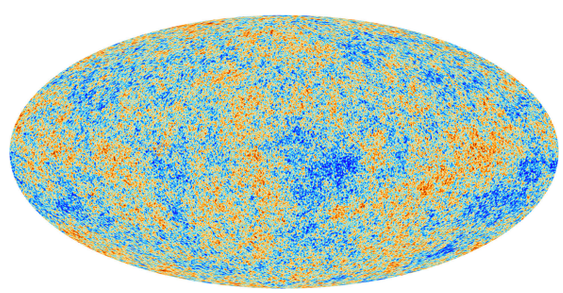

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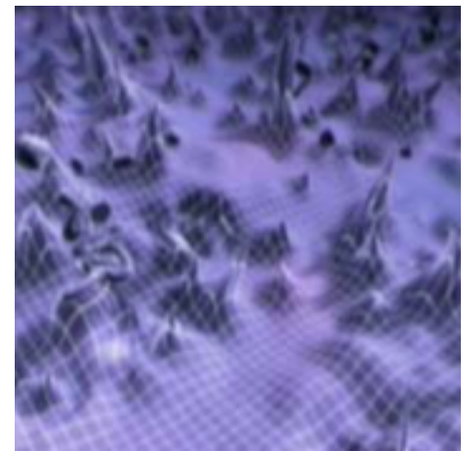
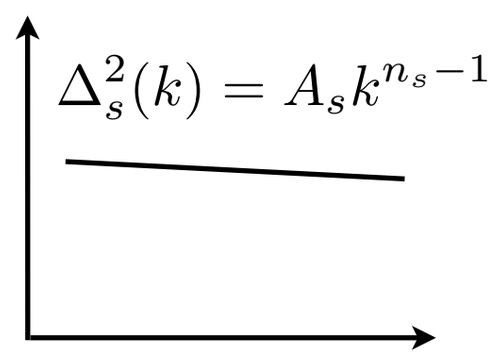
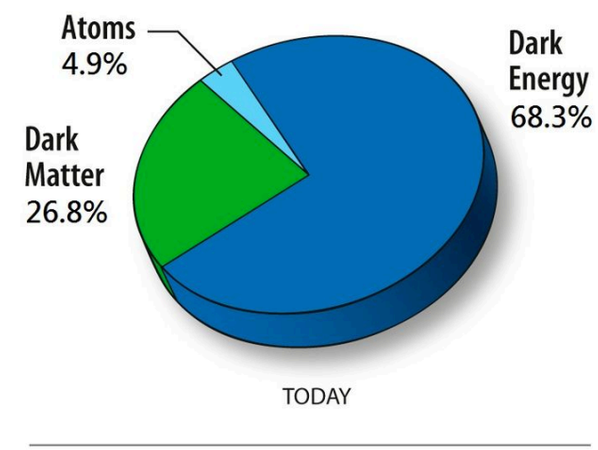
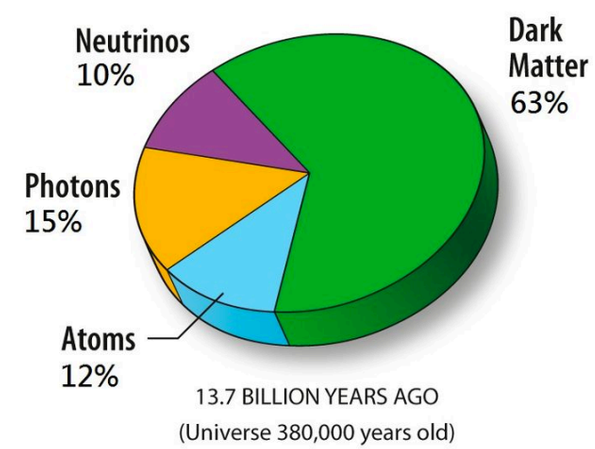




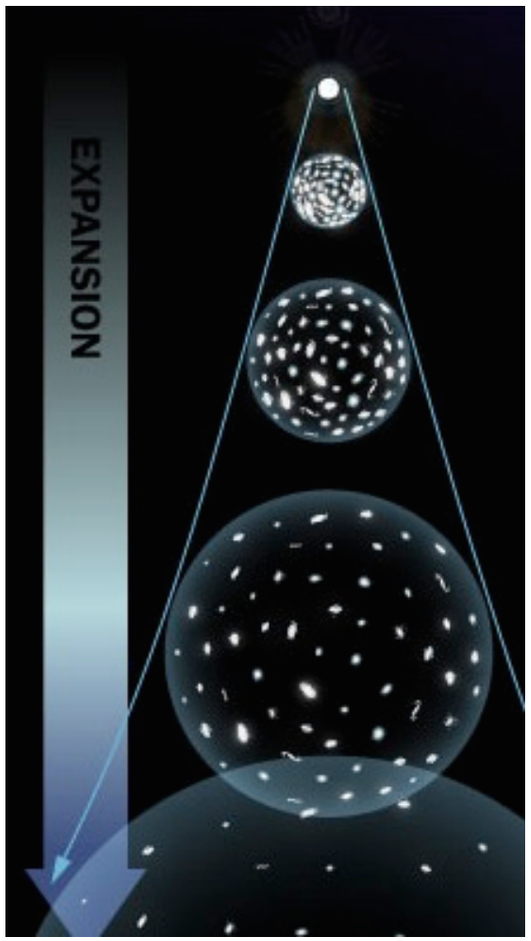
ΛCDM



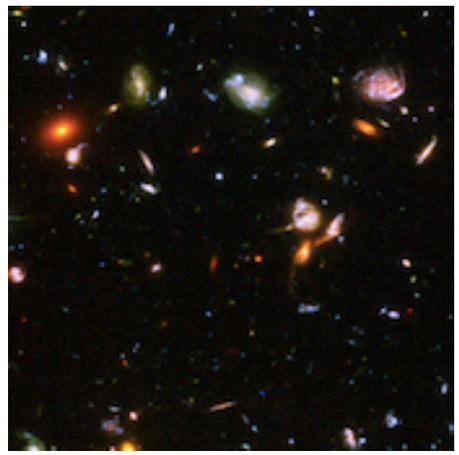


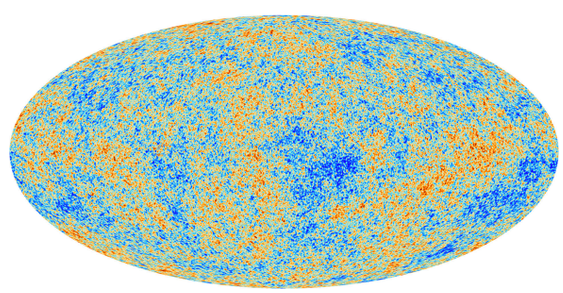
Ingredients of the Standard Model of Cosmology

Hot big bang



Gravitational instability





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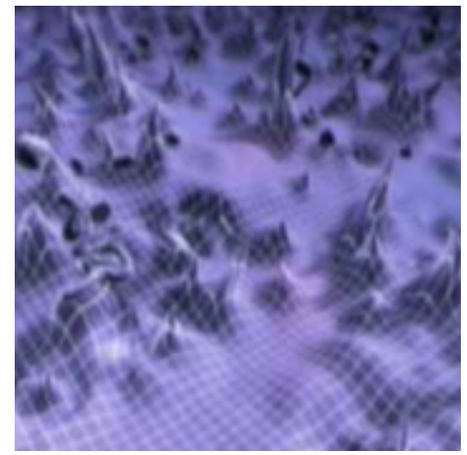
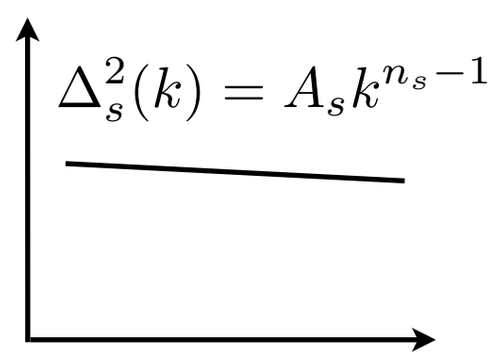
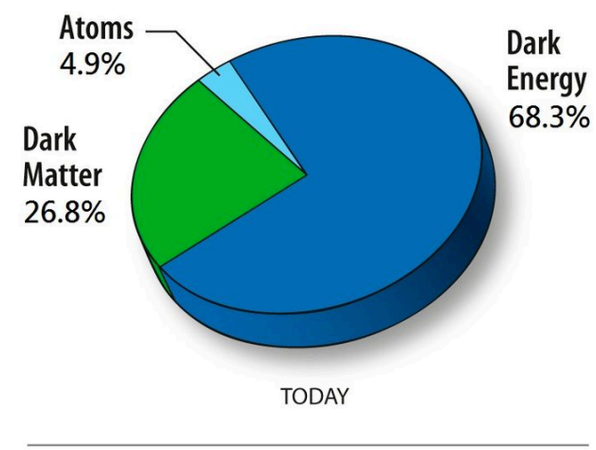
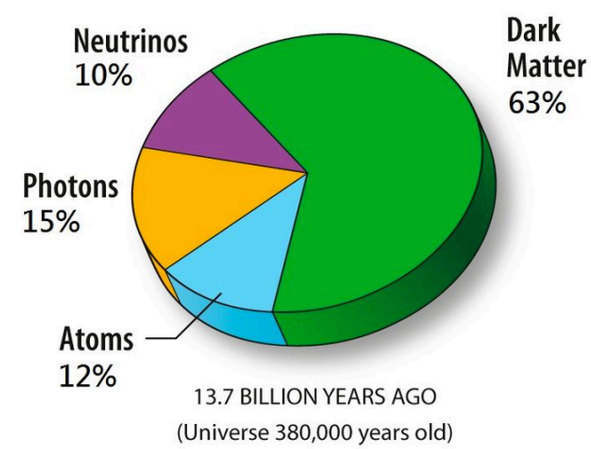




ΛCDM

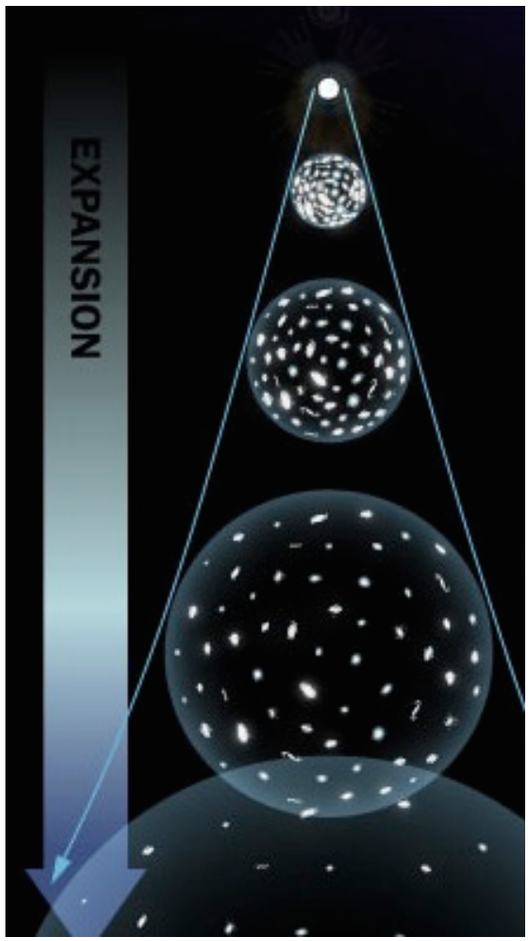




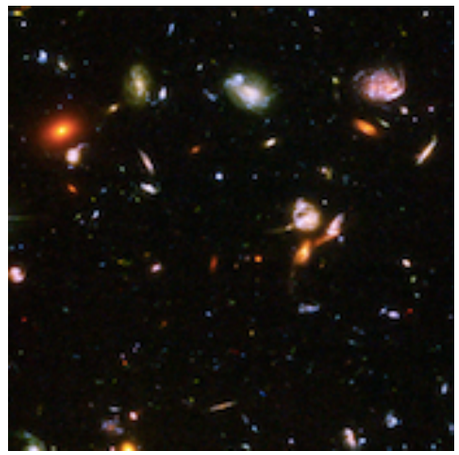
Amazingly: a handful of parameters is enough to fit all existing data.

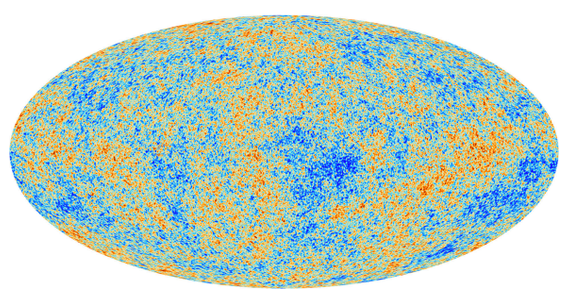
Ingredients of the Standard Model of Cosmology

Hot big bang



Gravitational instability





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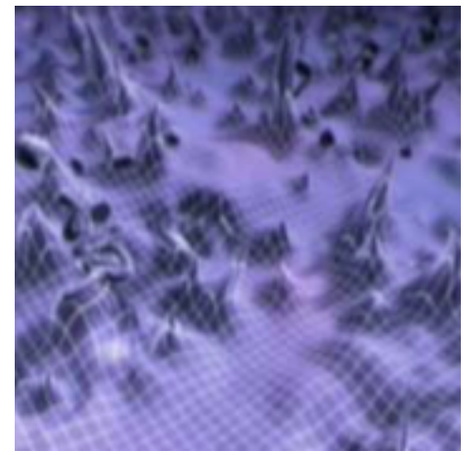
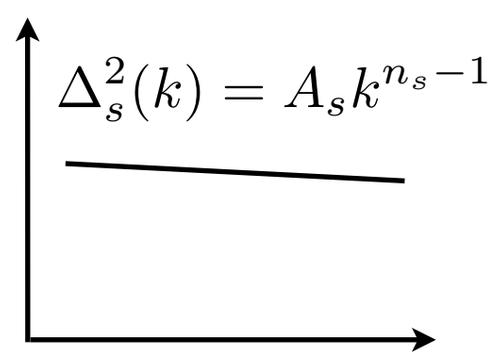
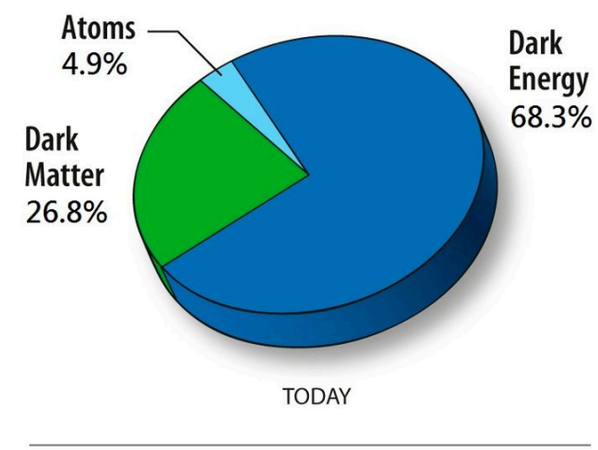
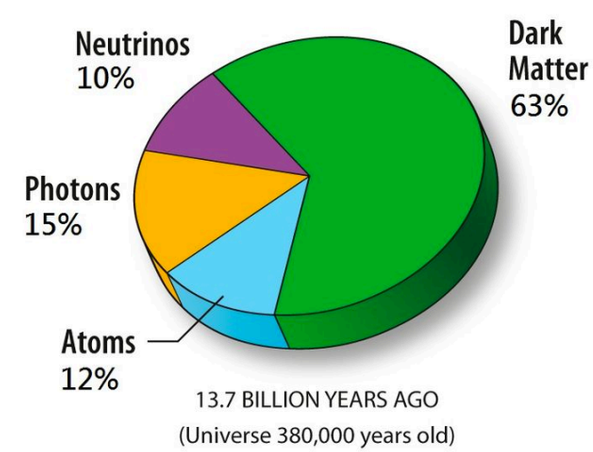




ΛCDM





H_0	τ	A_s	n_s	$\Omega_{\rm M}$	$\Omega_{\rm b}$

Amazingly: a handful of parameters is enough to fit all existing data.

History of the ΛCDM Universe

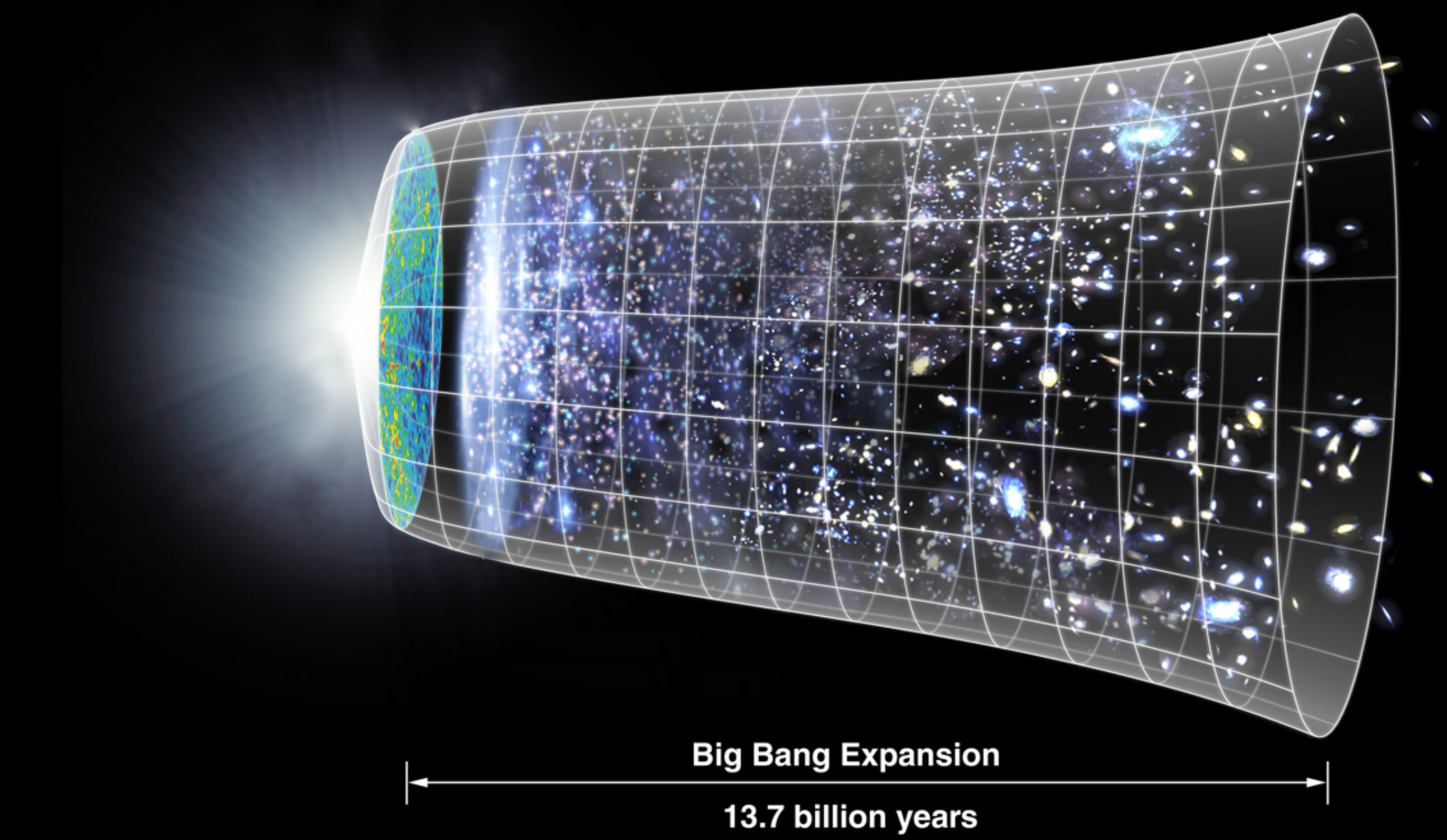
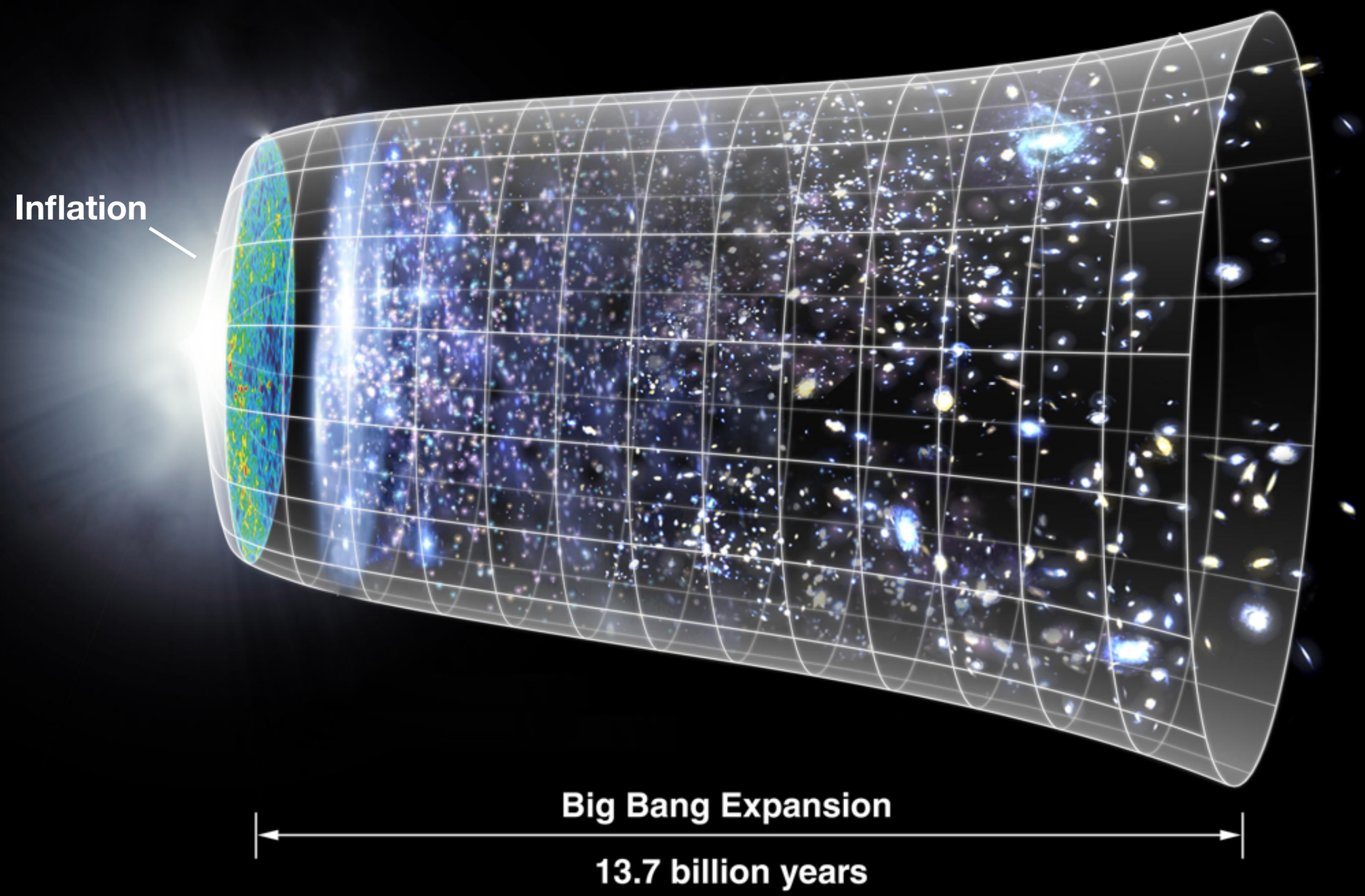


Image Credit: NASA Lambda GSFC

History of the ΛCDM Universe



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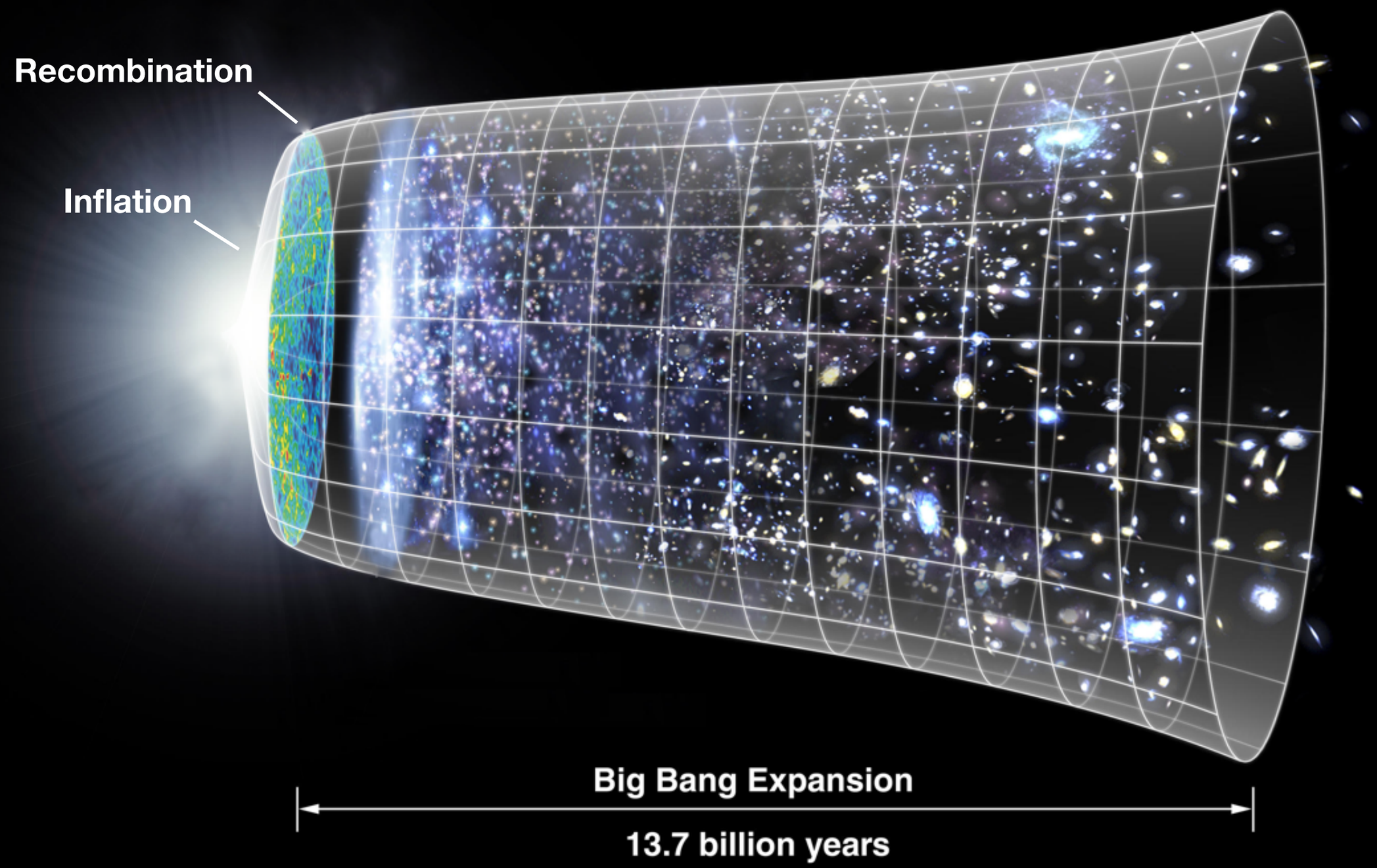

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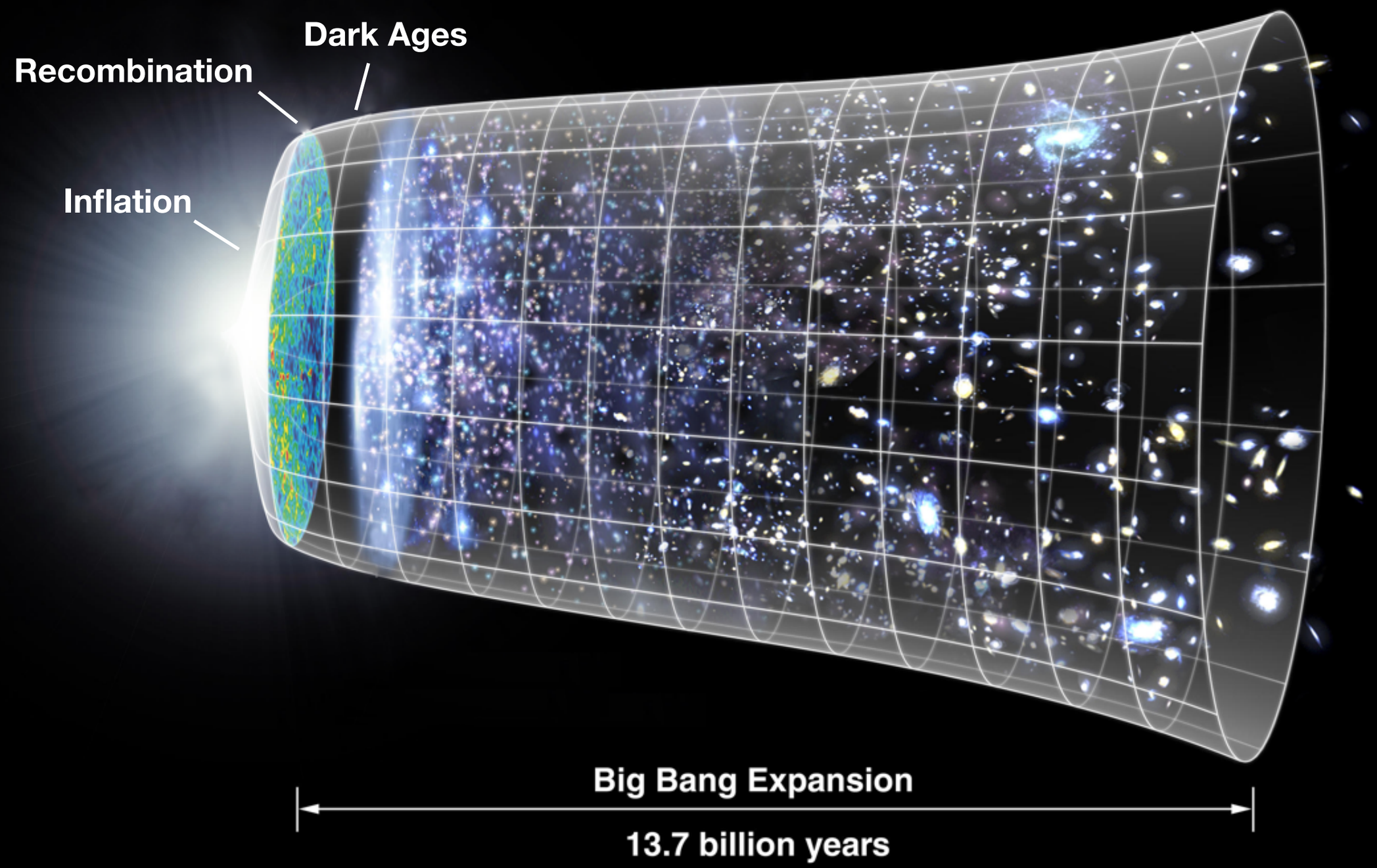

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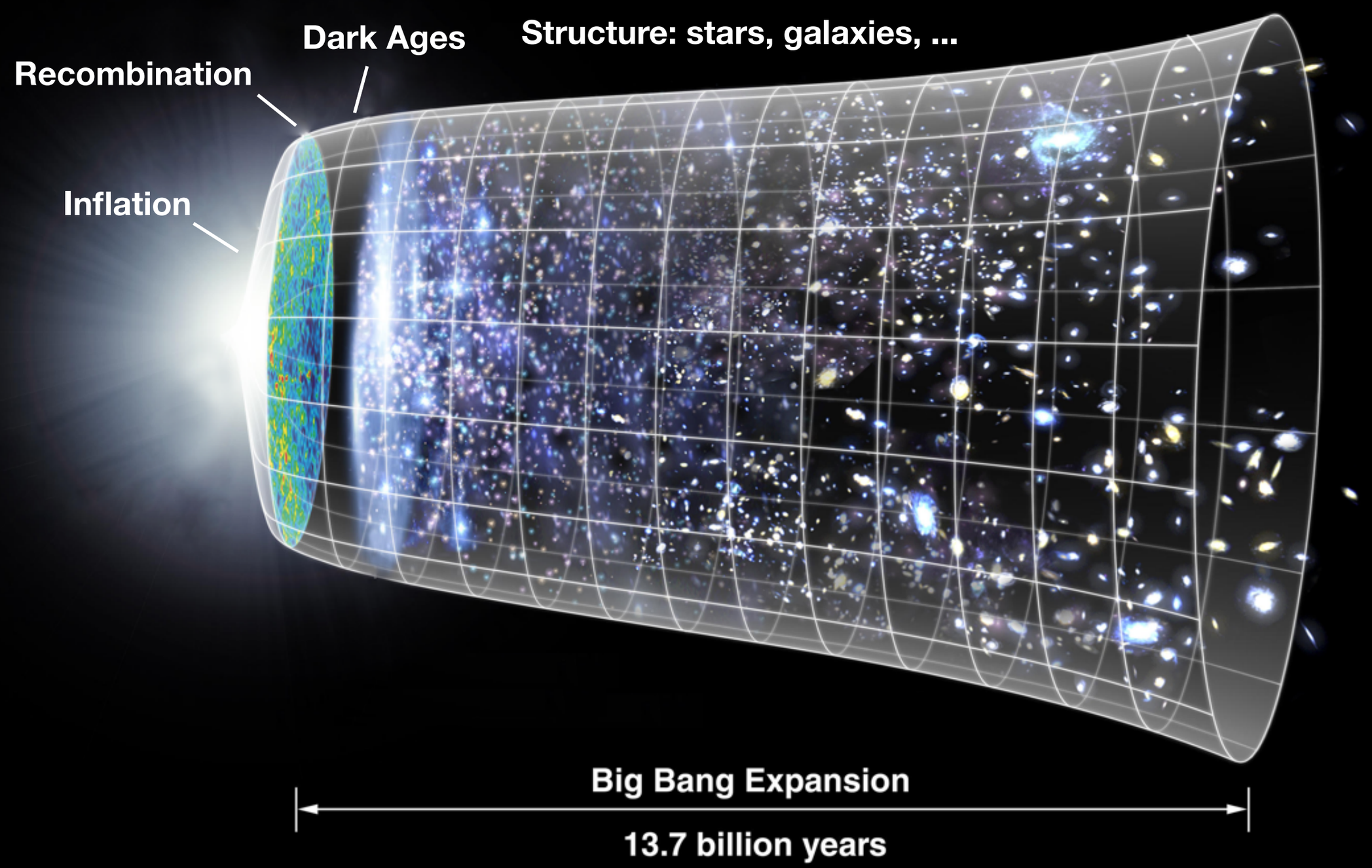

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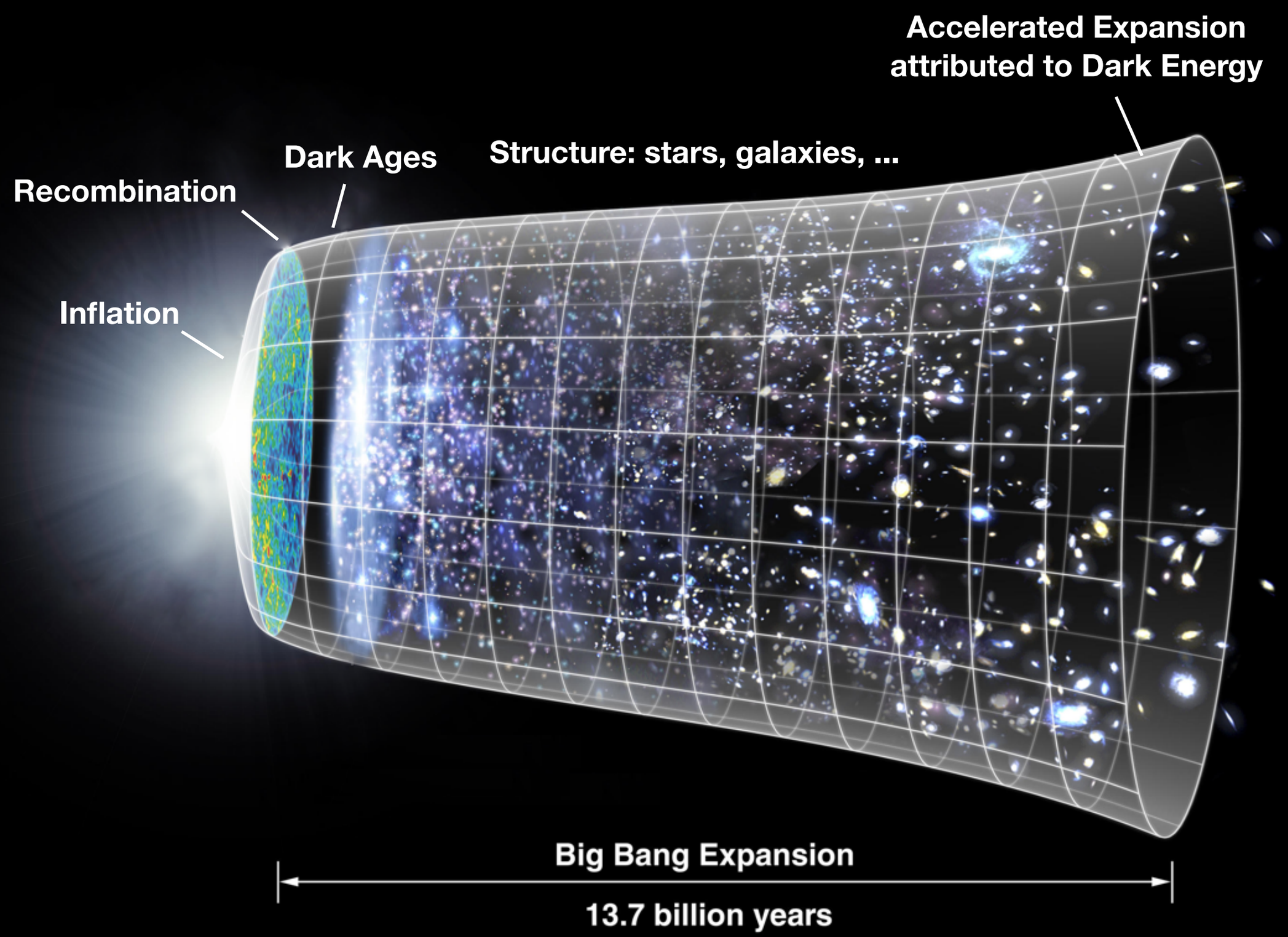

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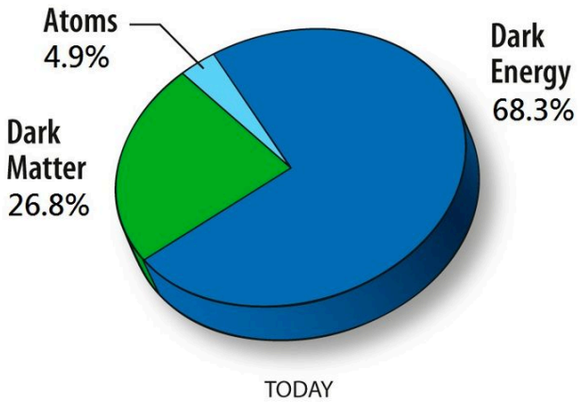
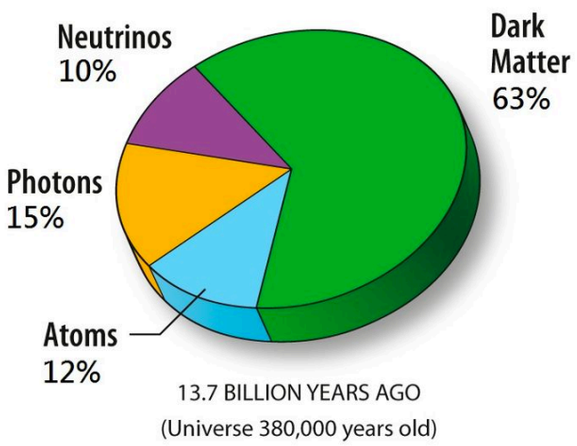
Precision Cosmology

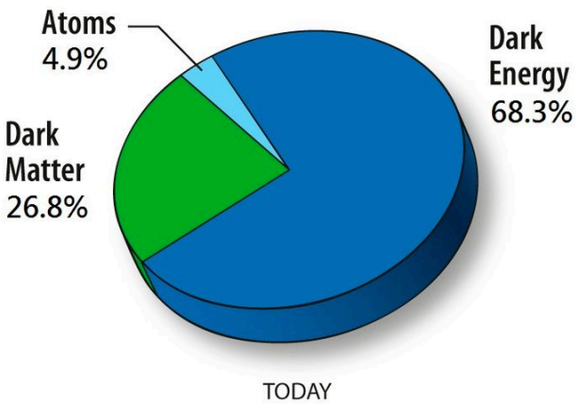
LCDM

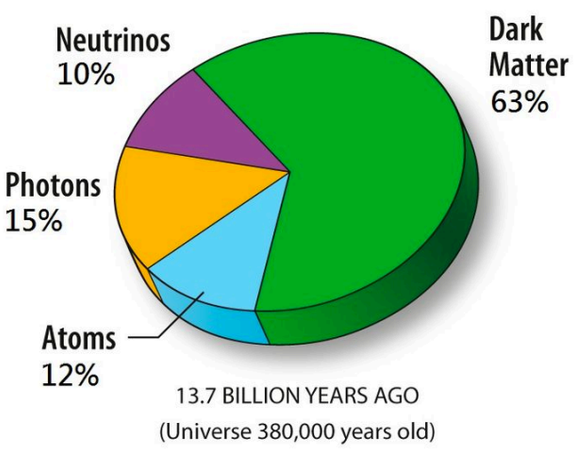




Precision Cosmology

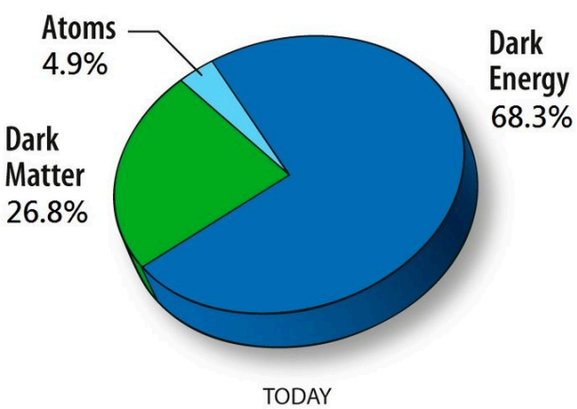
LCDM

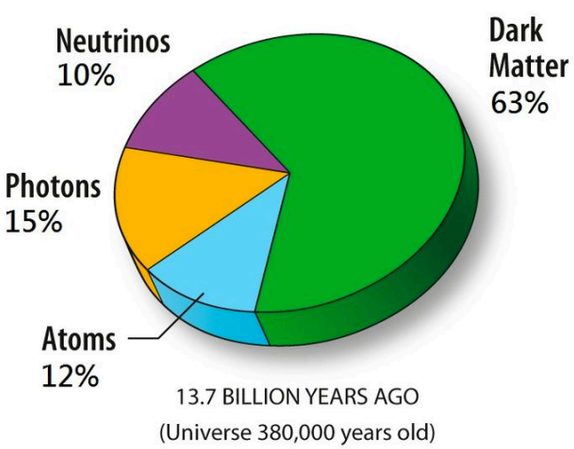


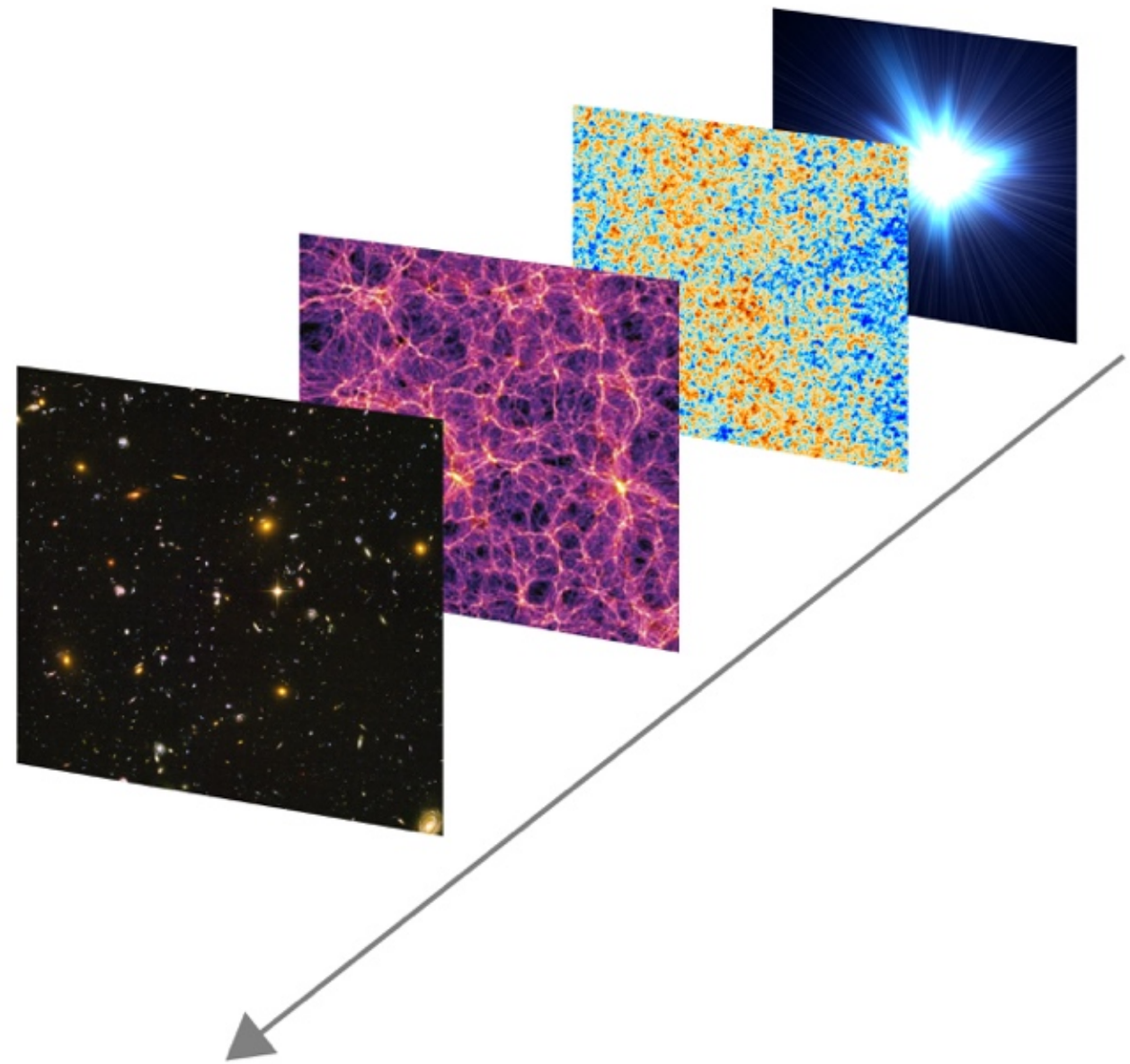


Precision Cosmology

LCDM

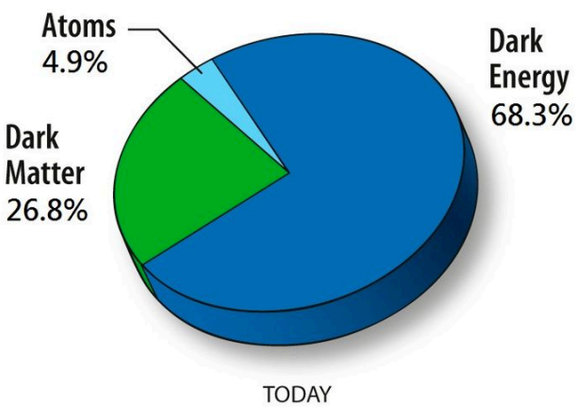


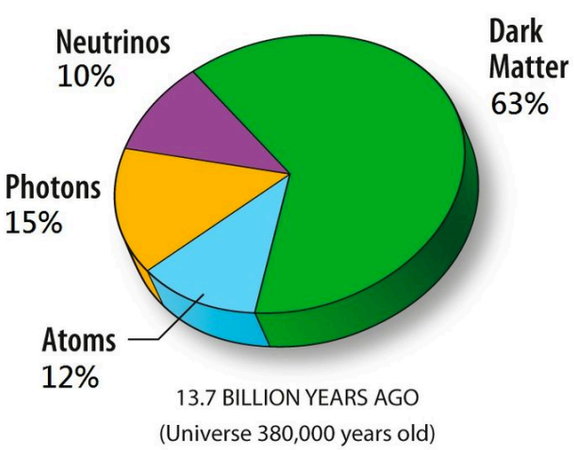


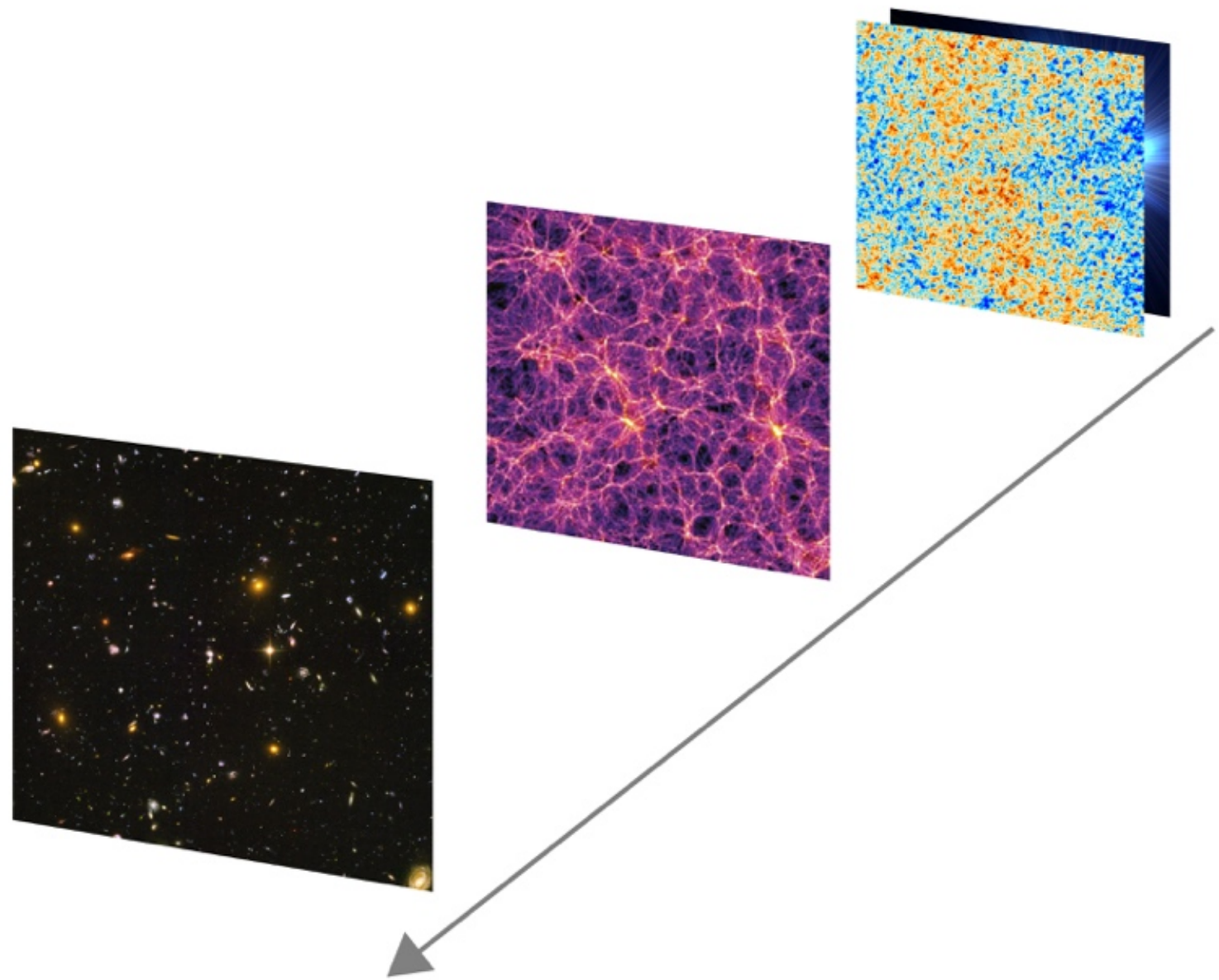


Precision Cosmology

LCDM







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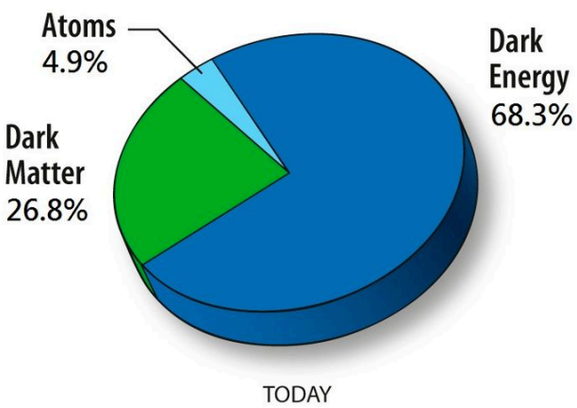
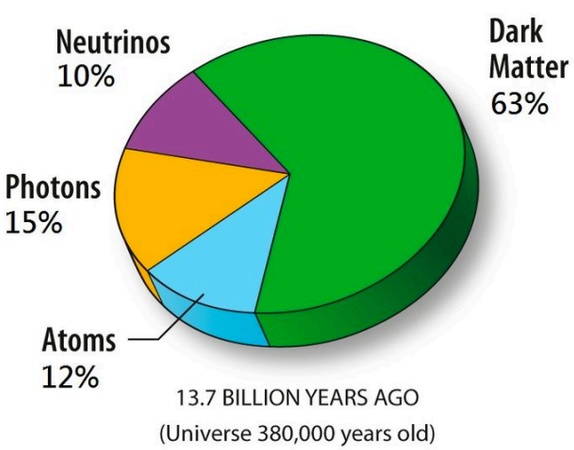
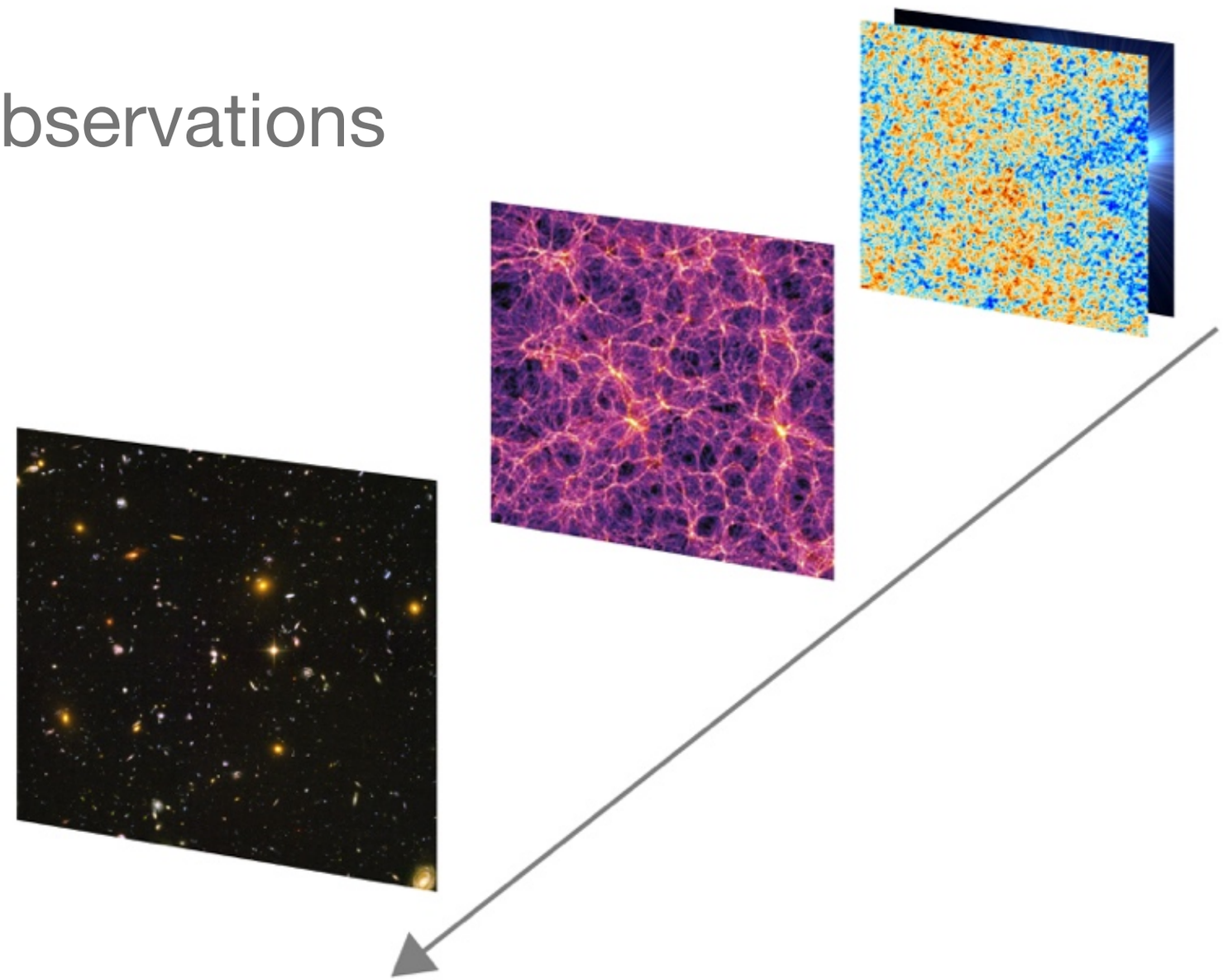




Observations



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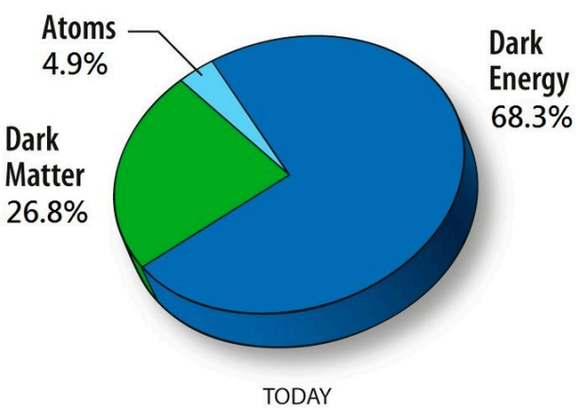
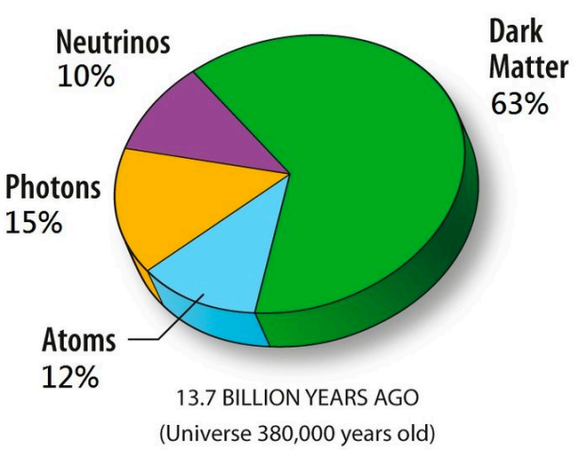
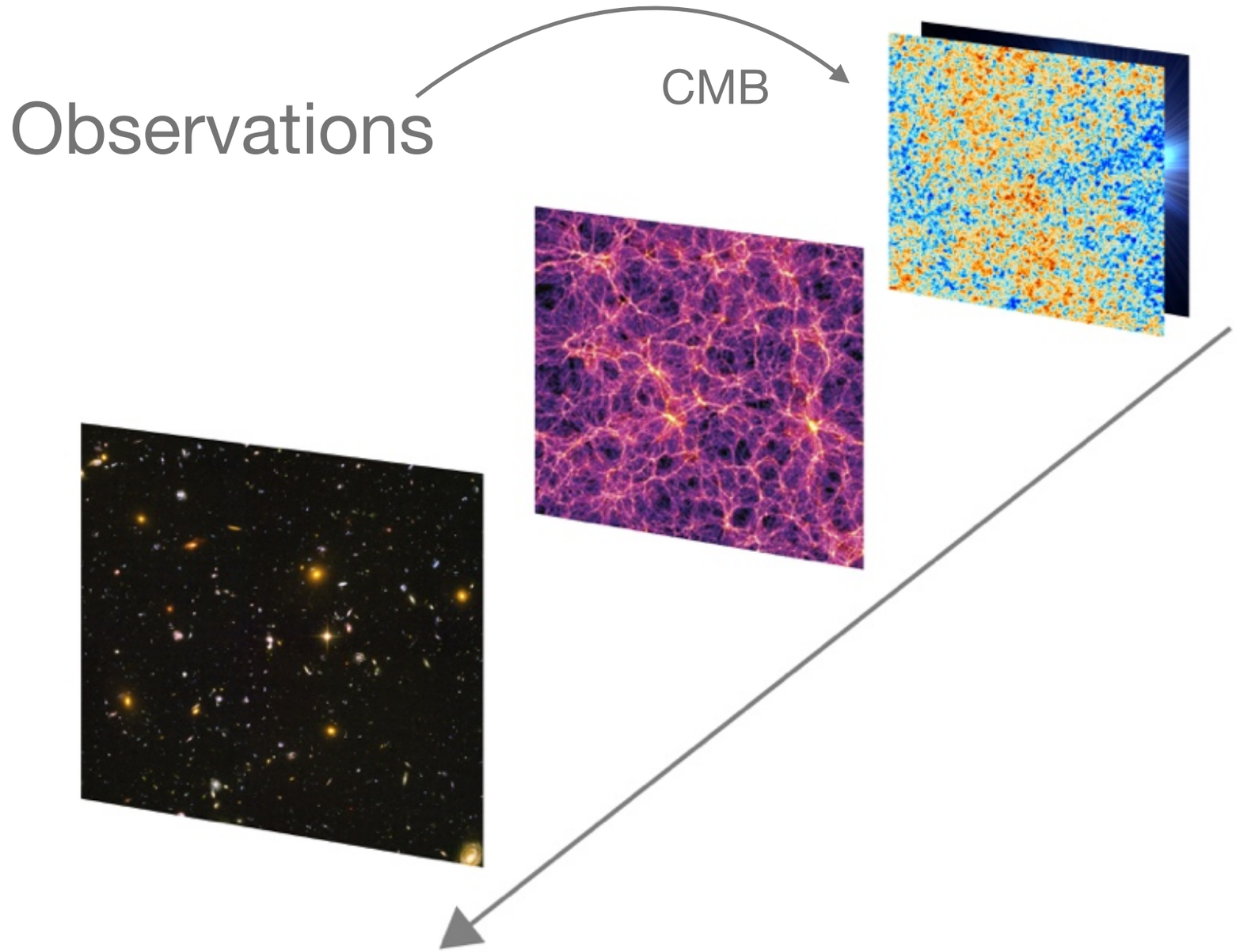
LCDM

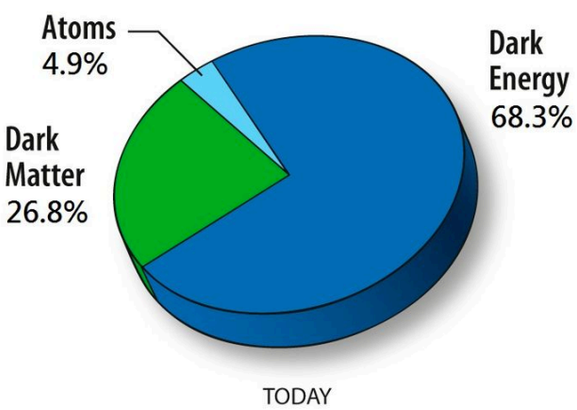


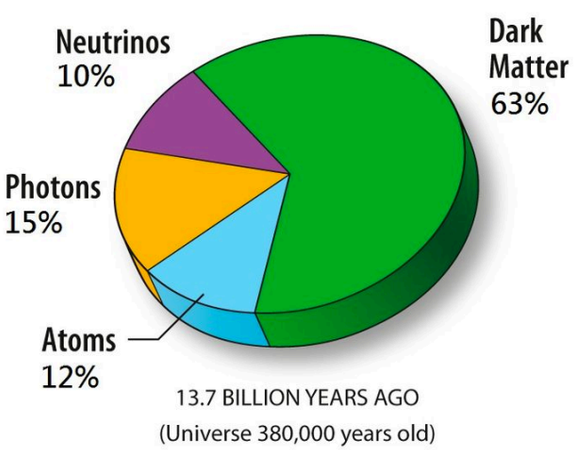


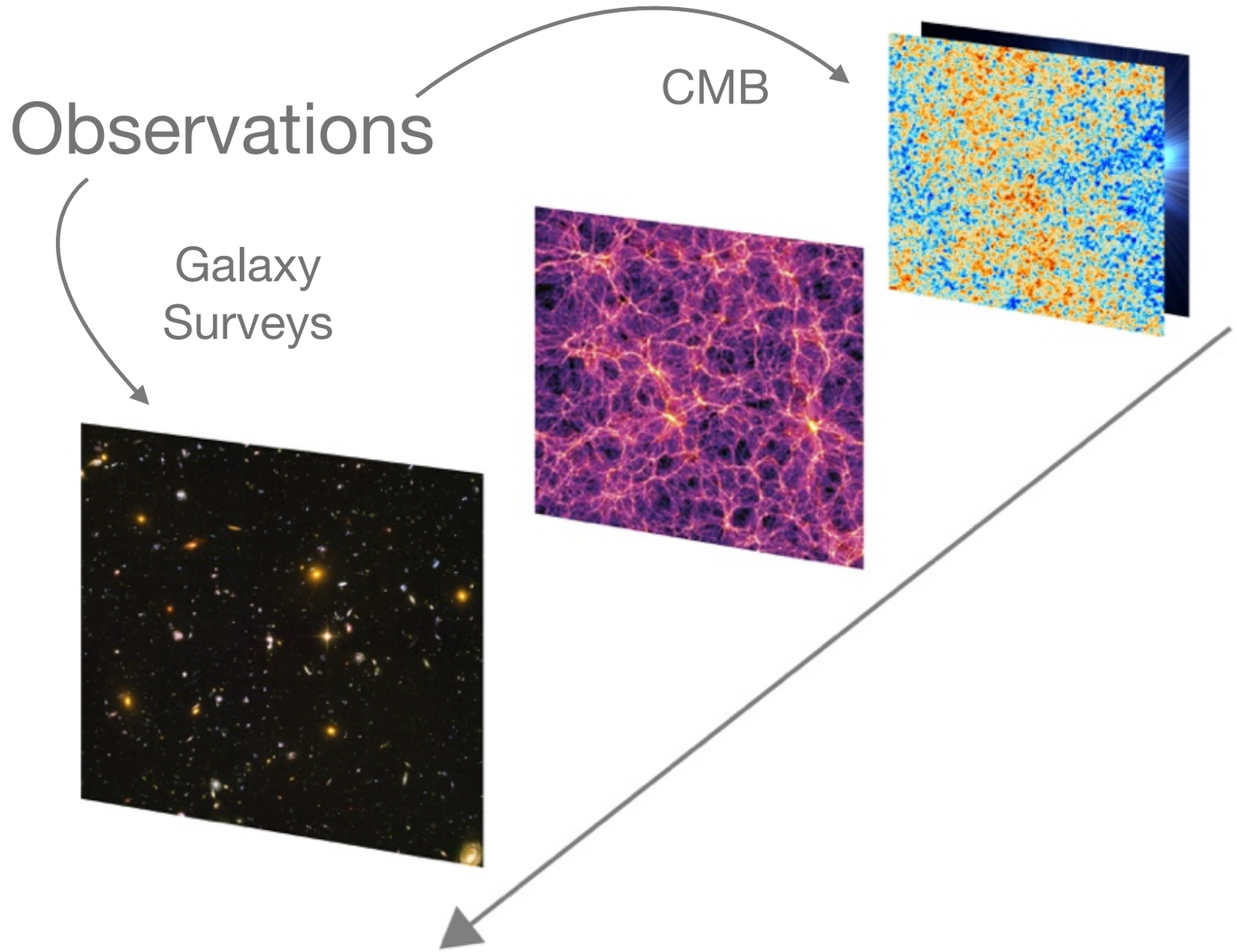


Precision Cosmology

LCDM

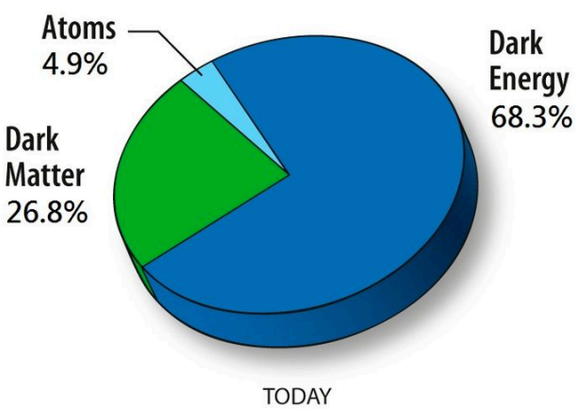


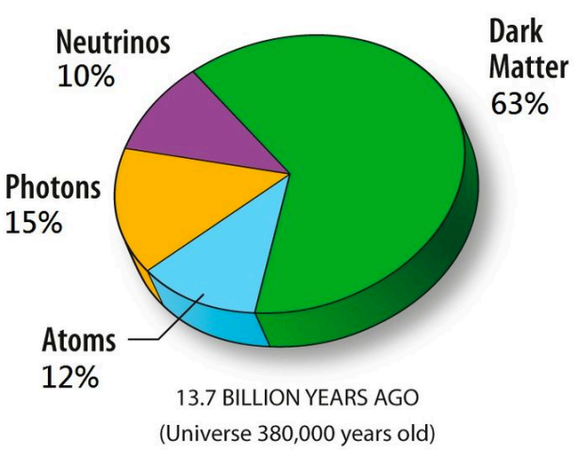




Precision Cosmology

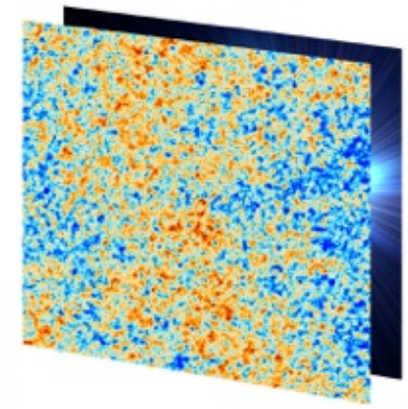
LCDM



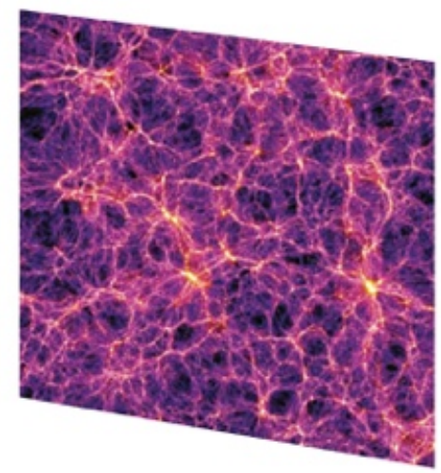


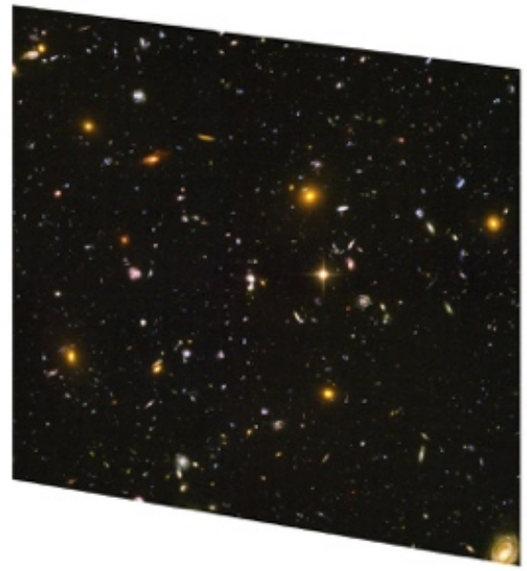
Observations

CMB



Galaxy
Surveys

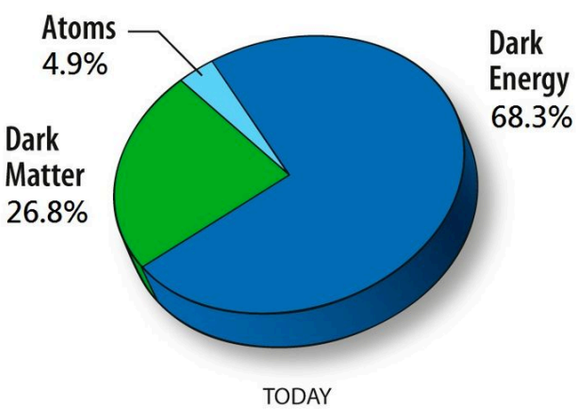


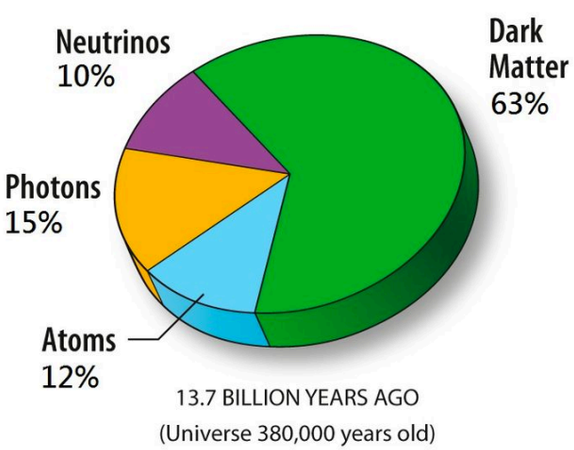


Simulations

Precision Cosmology

LCDM





Observations

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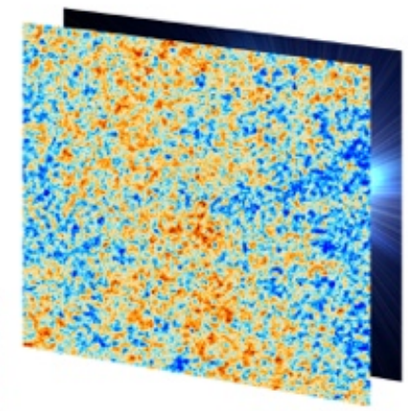
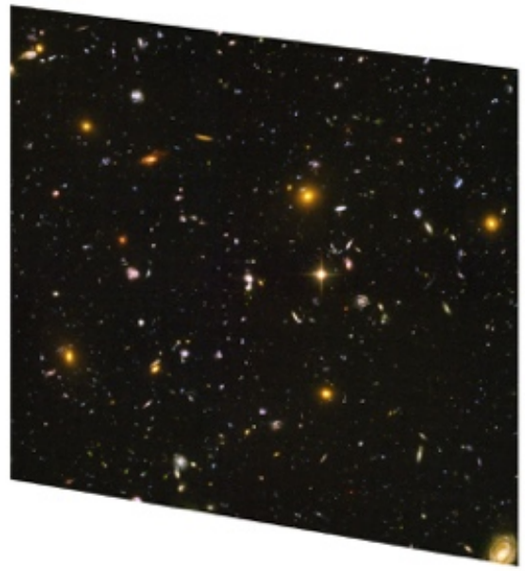
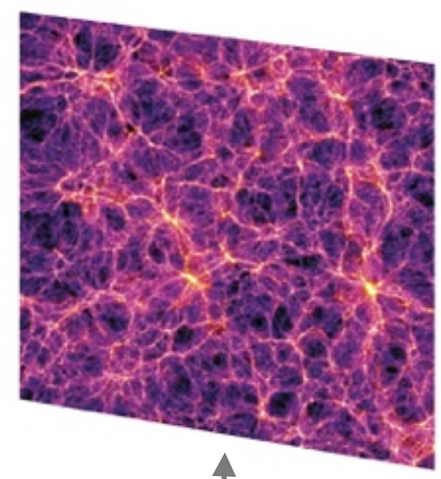


Galaxy
Surveys



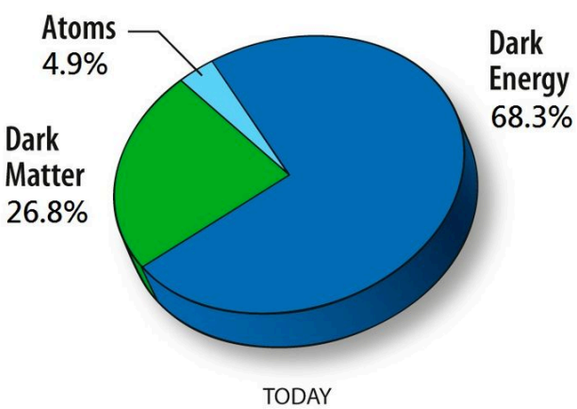


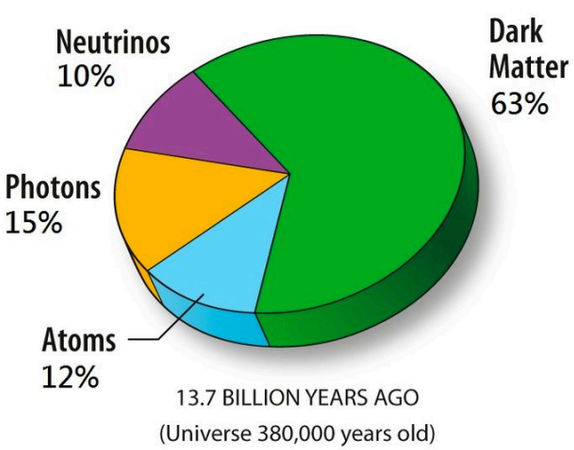
Simulations

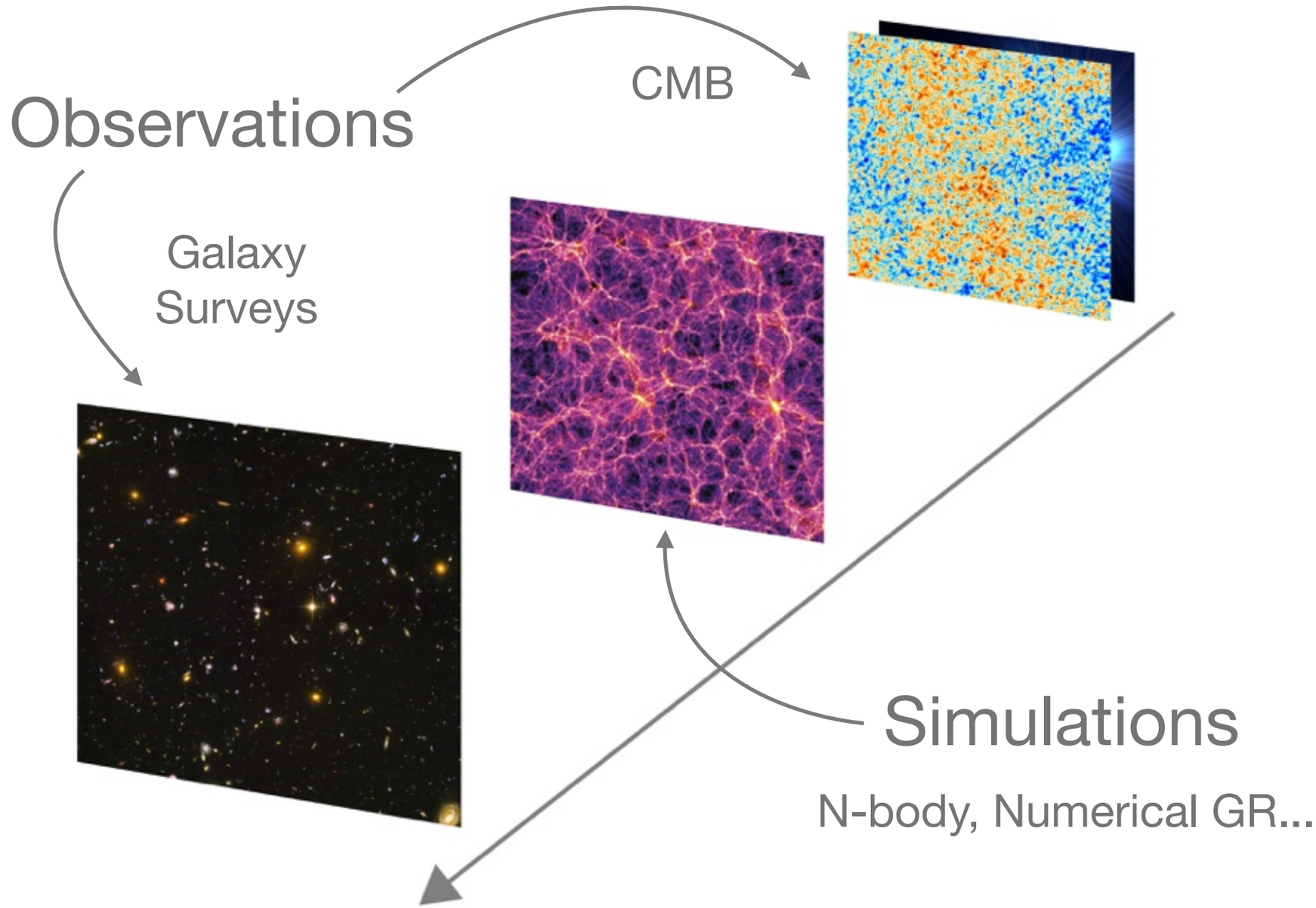
N-body, Numerical GR...

Precision Cosmology

LCDM







Parameters ($H_0 \;\; \tau \;\; A_s \;\; n_s \;\; \Omega_{\rm b} \;\; \Omega_{\rm CDM}$): measured to few percent uncertainty!

Motivation: The Ongoing Search for Dark Matter

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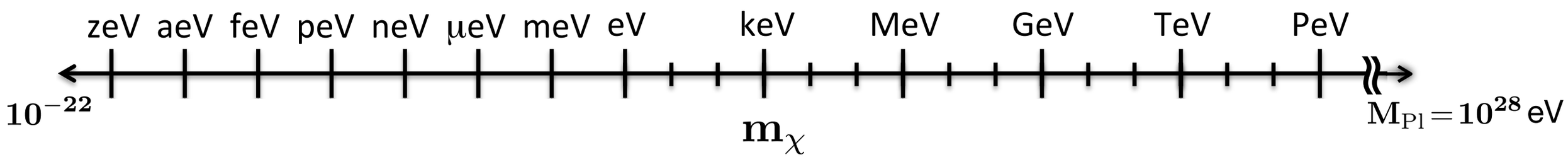
(adapted from Battaglieri et al., arXiv:1707.04591)



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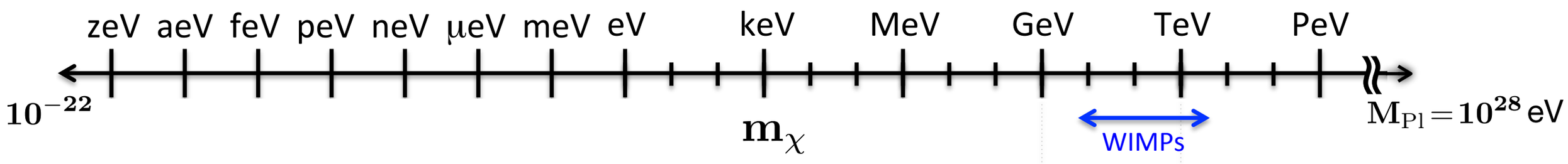

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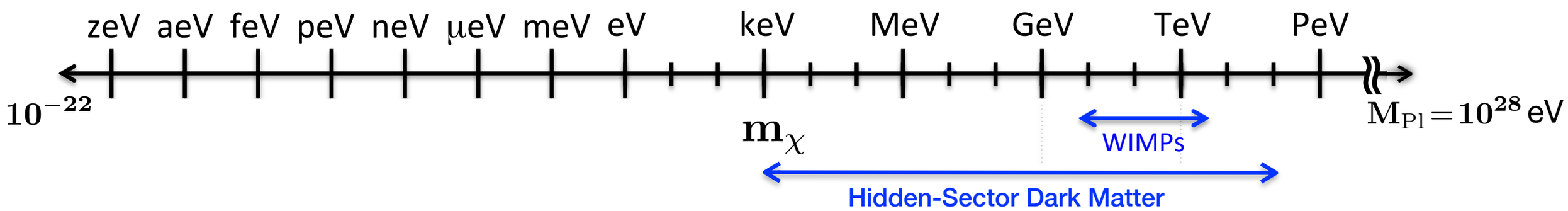

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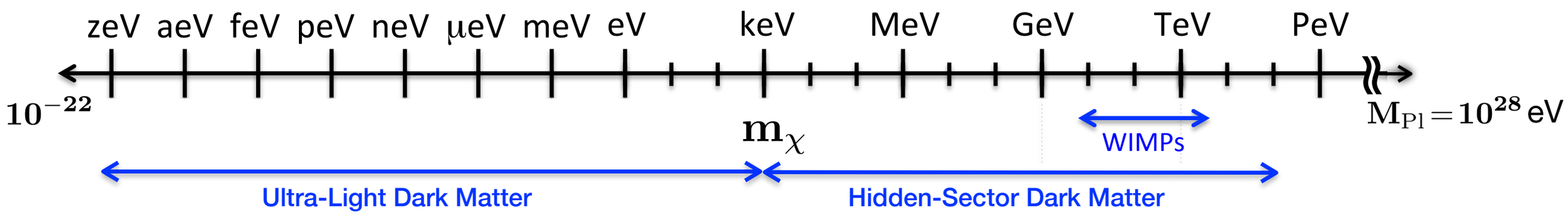

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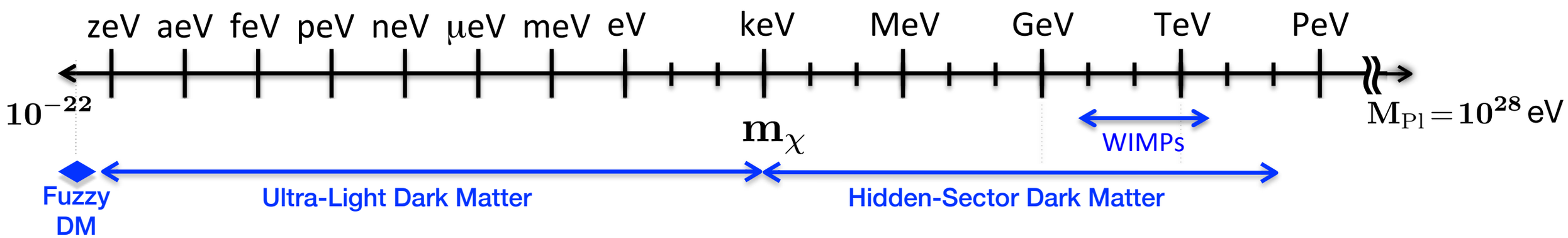

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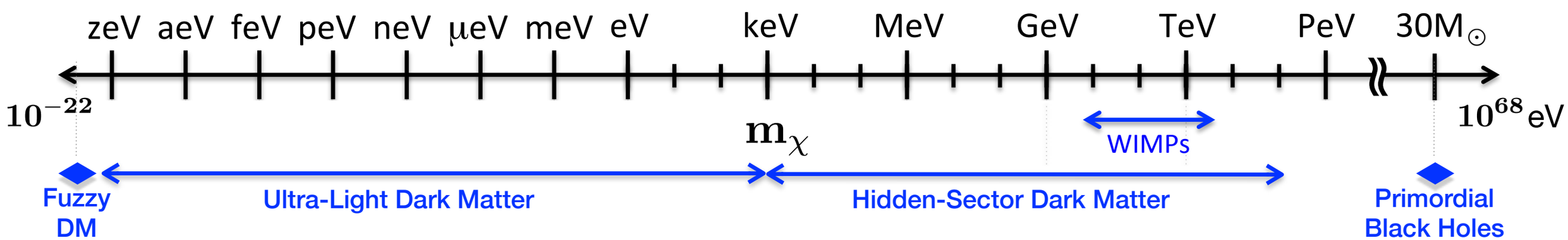

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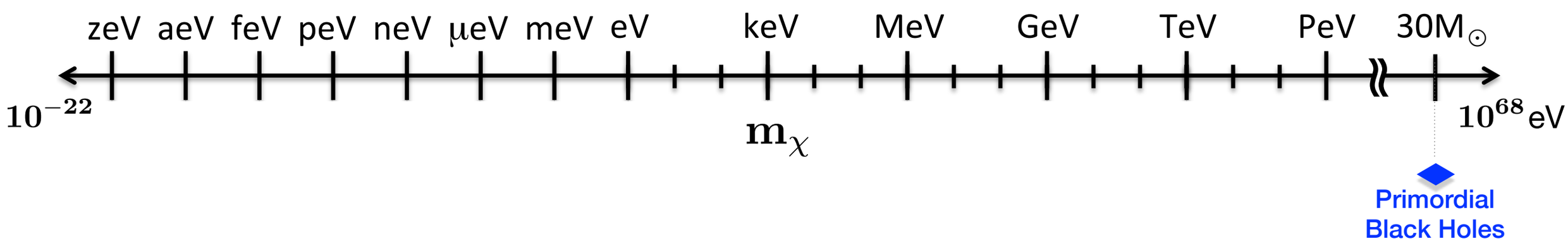

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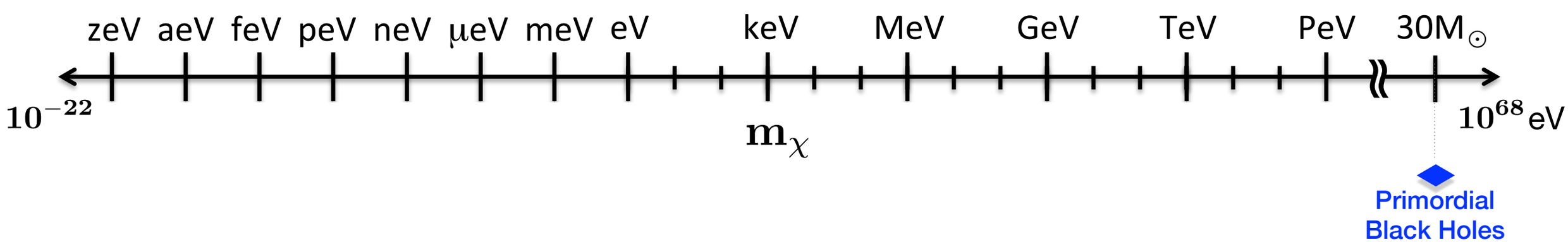

On September 14, 2015:

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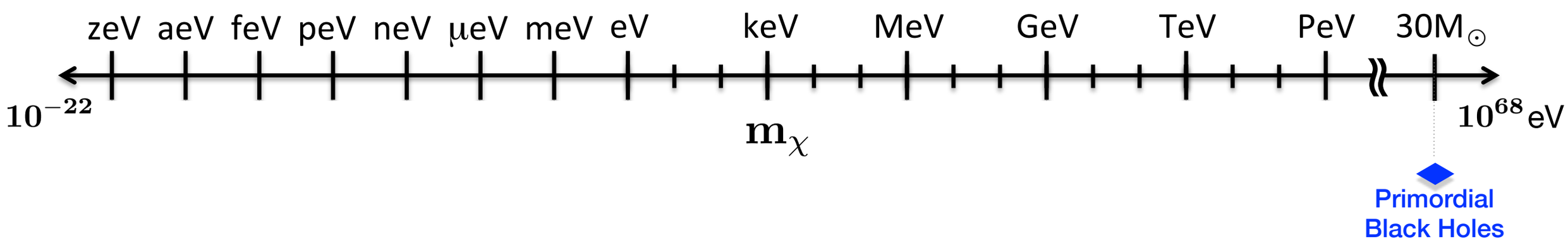

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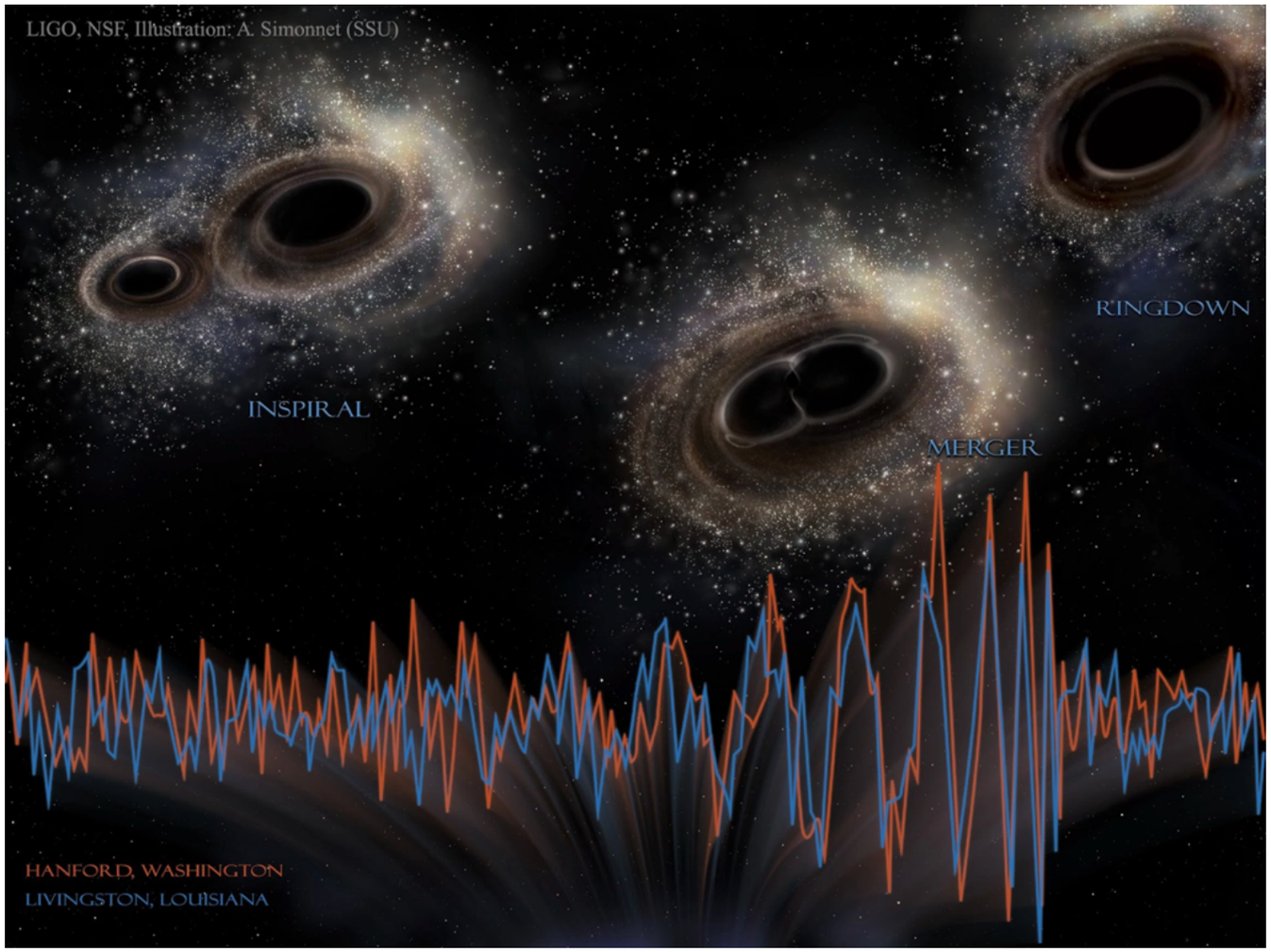

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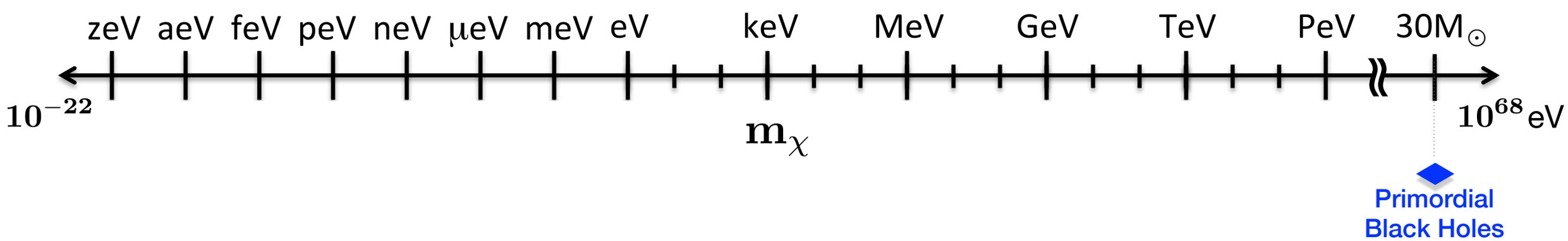

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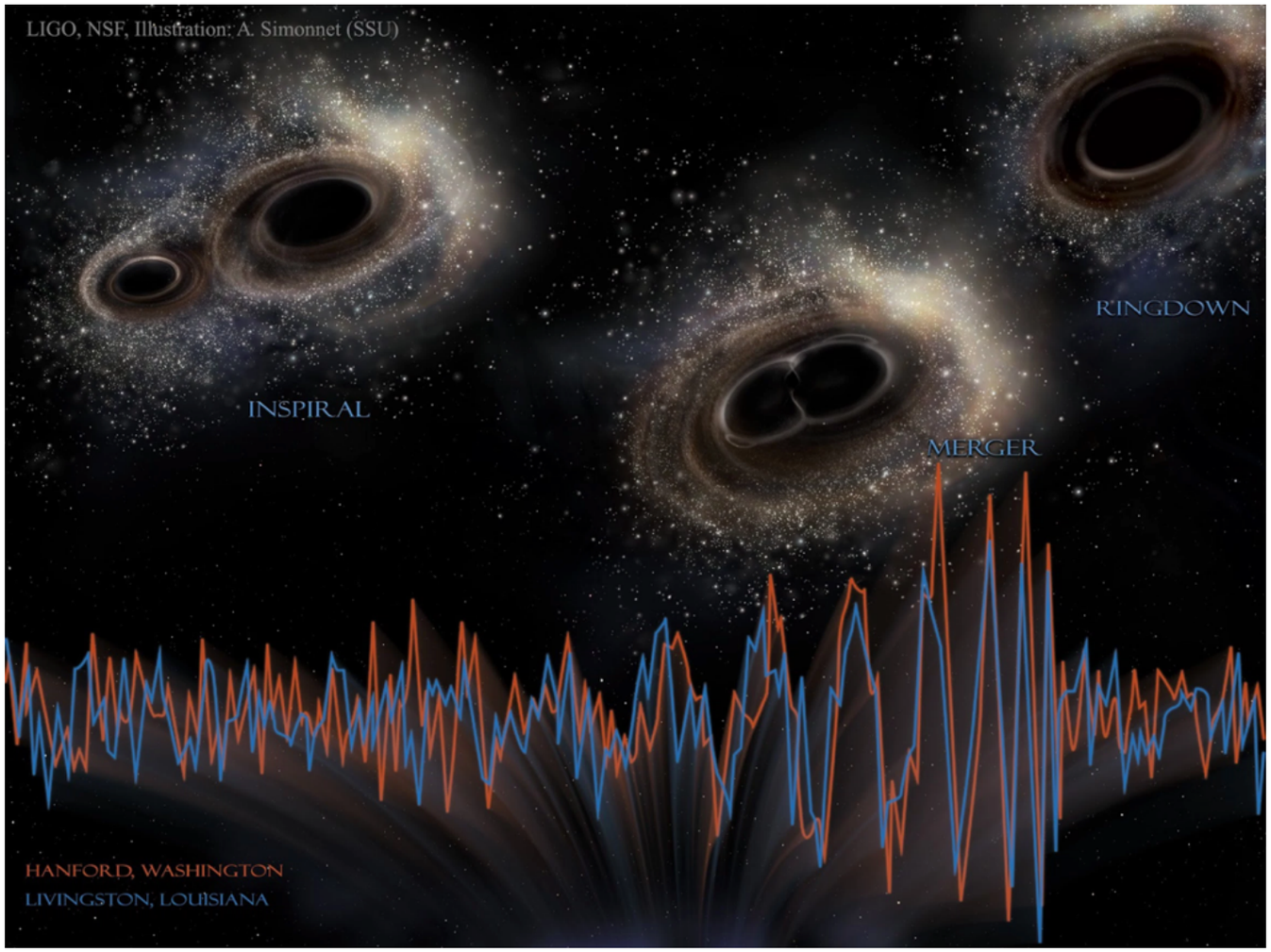
Lots of information....



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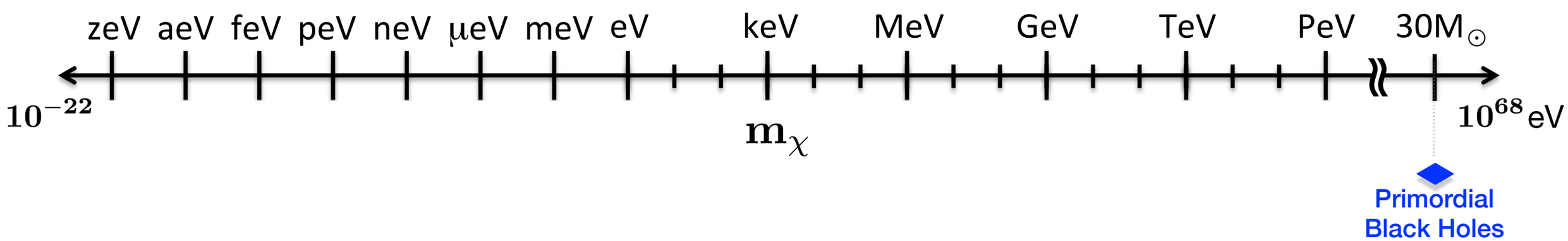

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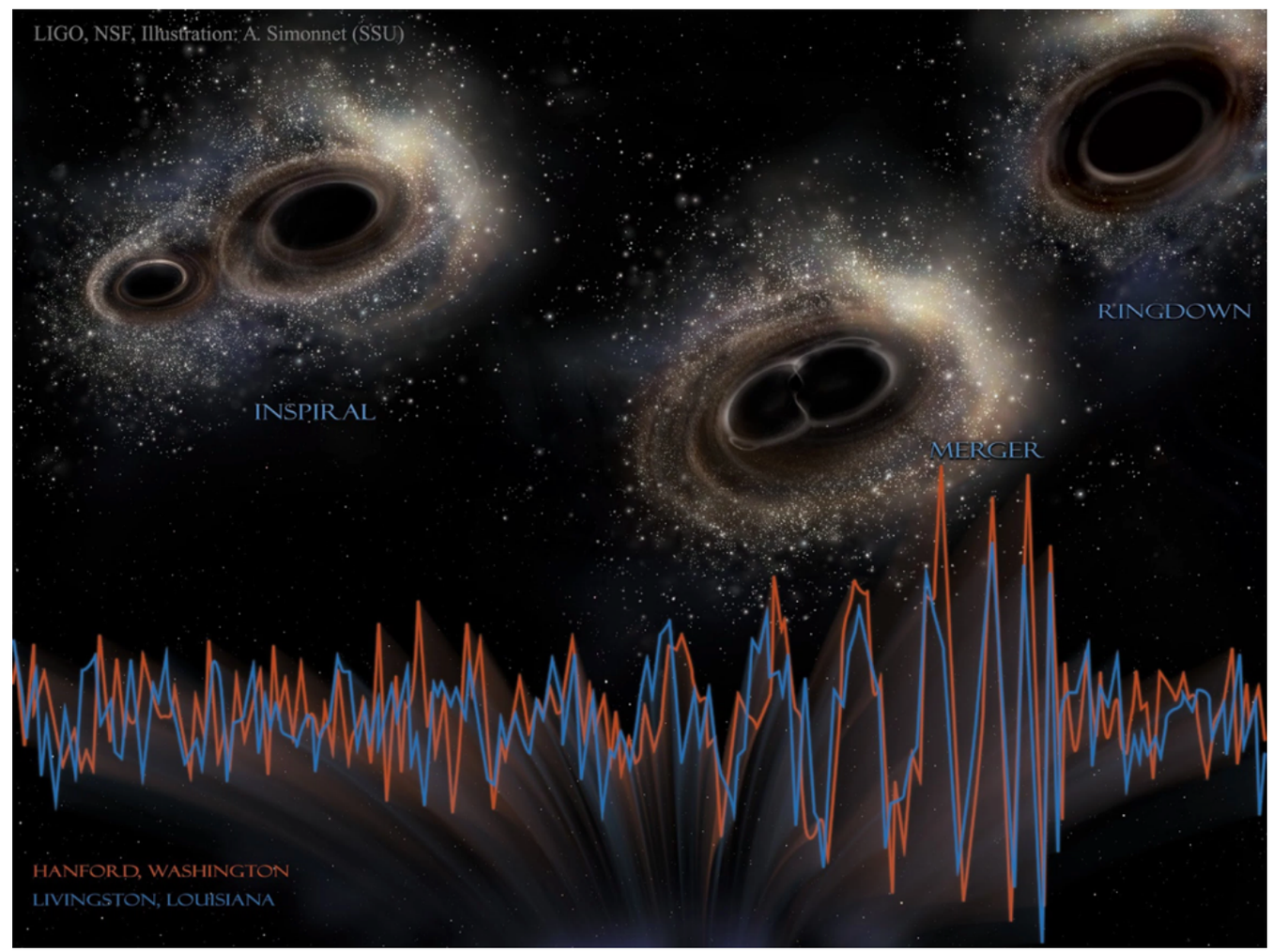
Black hole masses: ~ $29, 36 M_\odot$



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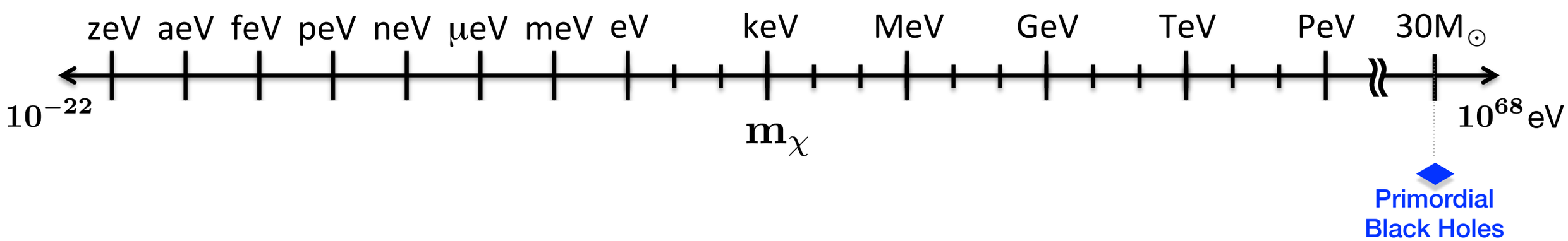

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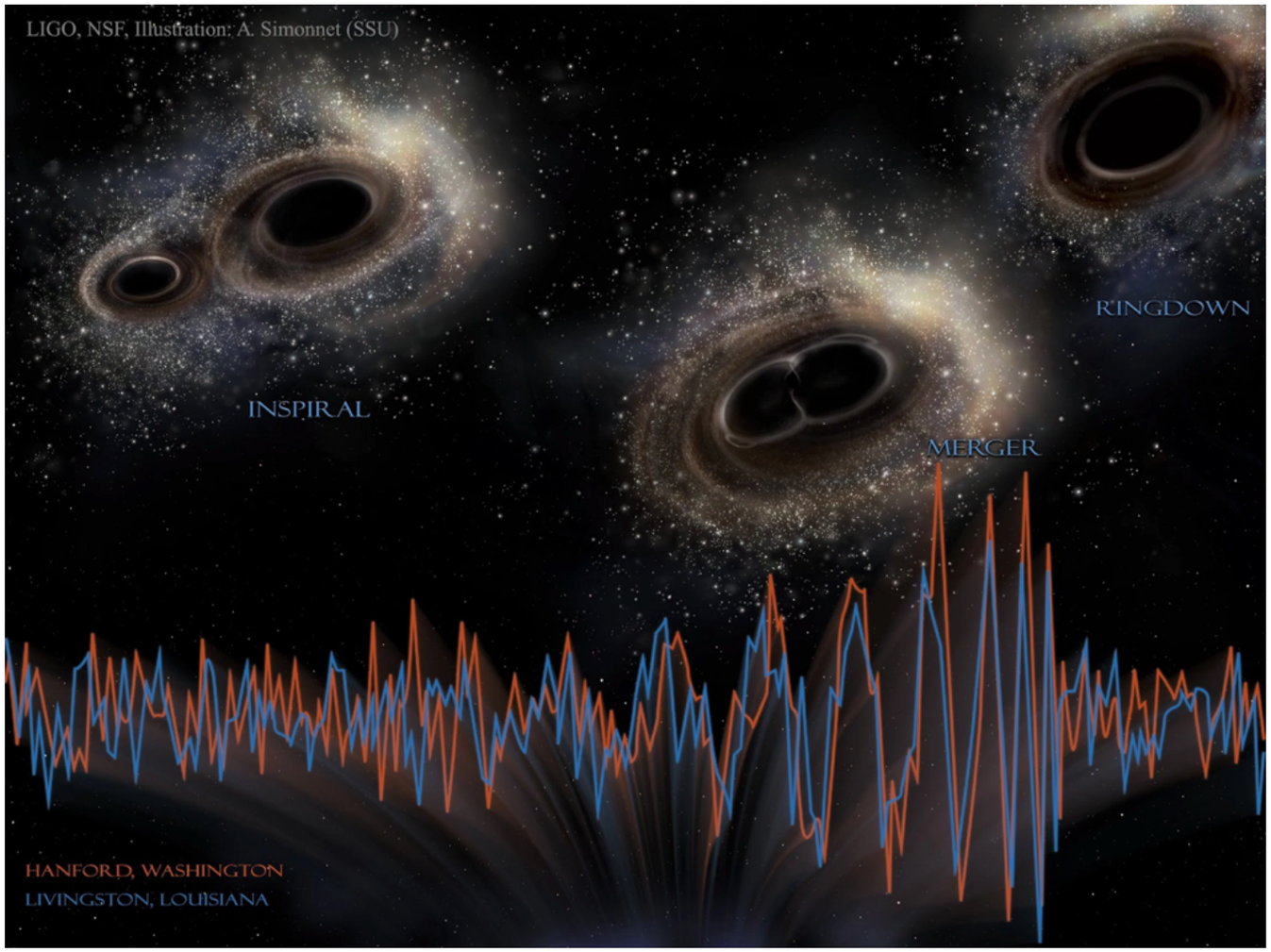
Could these be primordial?

Zel'dovich & Novikov (1967), Hawking (1971), Carr & Hawking (1974)...



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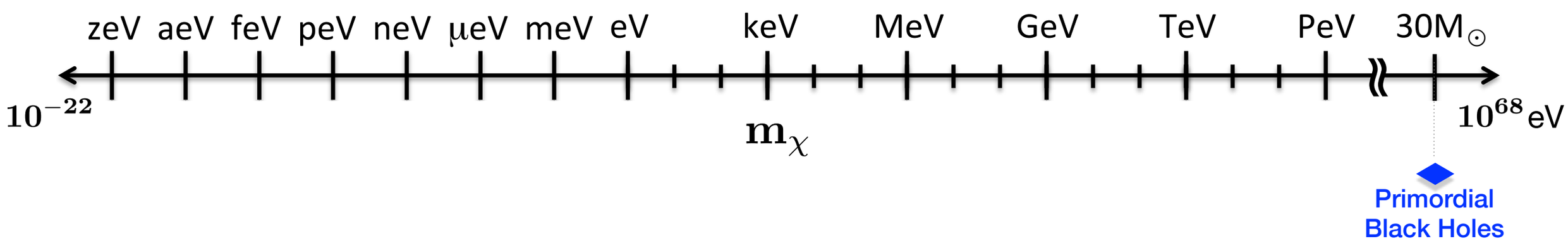

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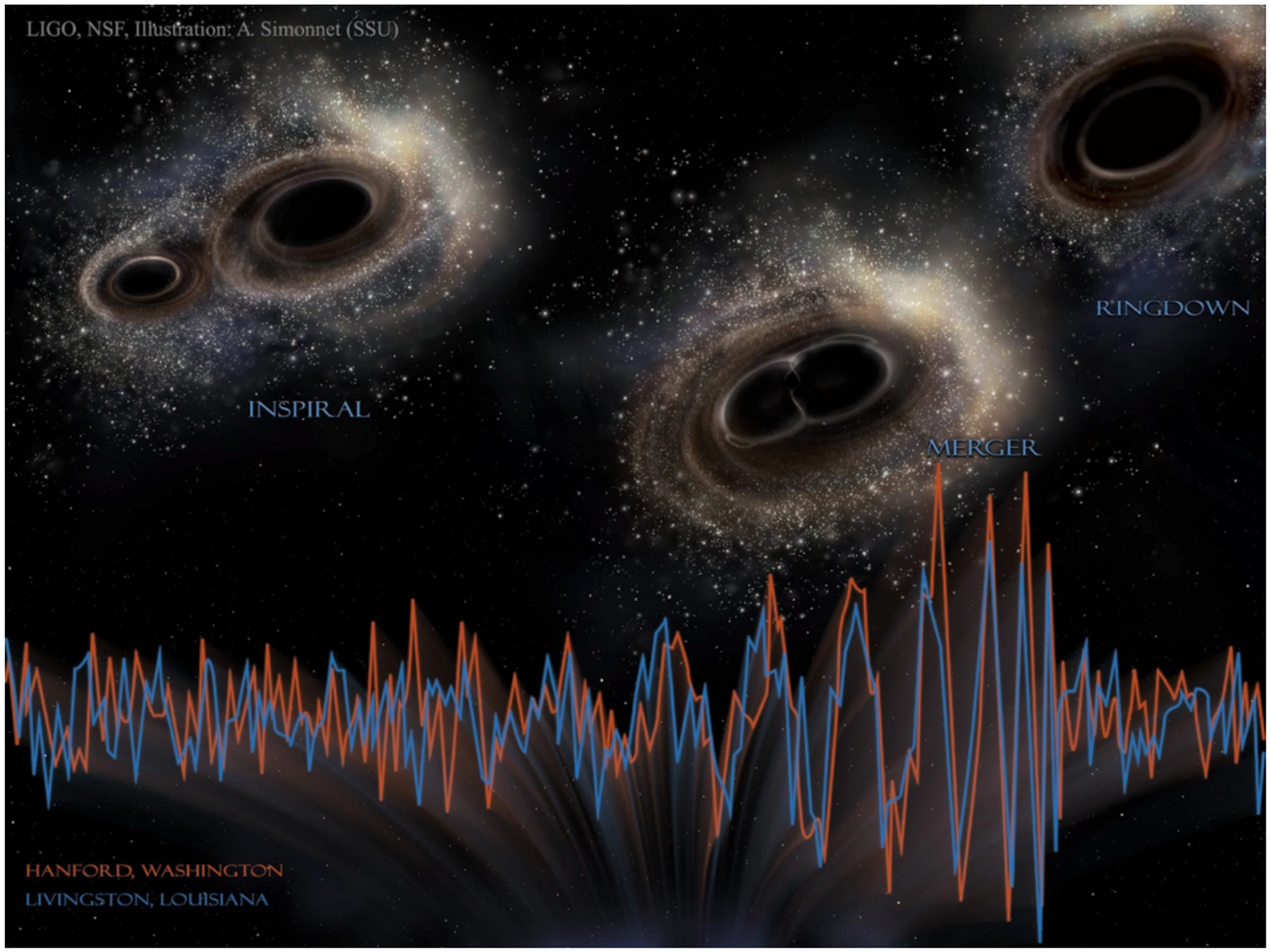
Did LIGO detect Dark Matter?

Bird,..., **EDK**,... et al., Phys. Rev. Lett. 116 (2016)

Sasaki et al., Phys. Rev. Lett. 117 (2016)

Clesse and Garca-Bellido, Phys. Dark Univ. 15, 142 (2017)



What's the Status with Current Observations?

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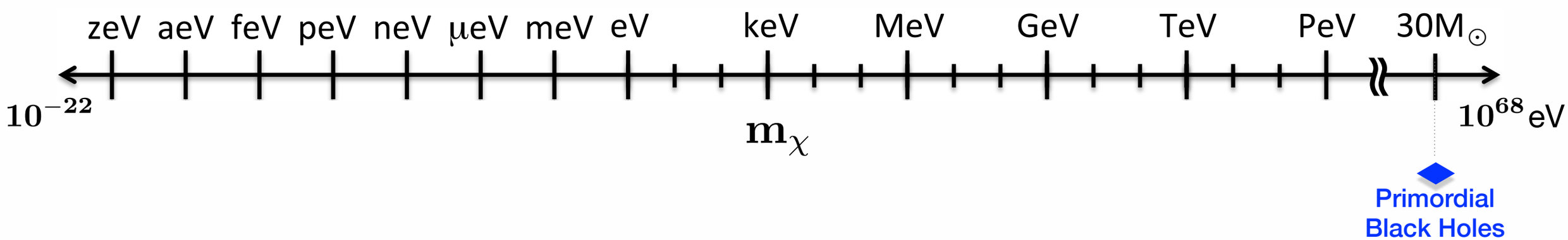

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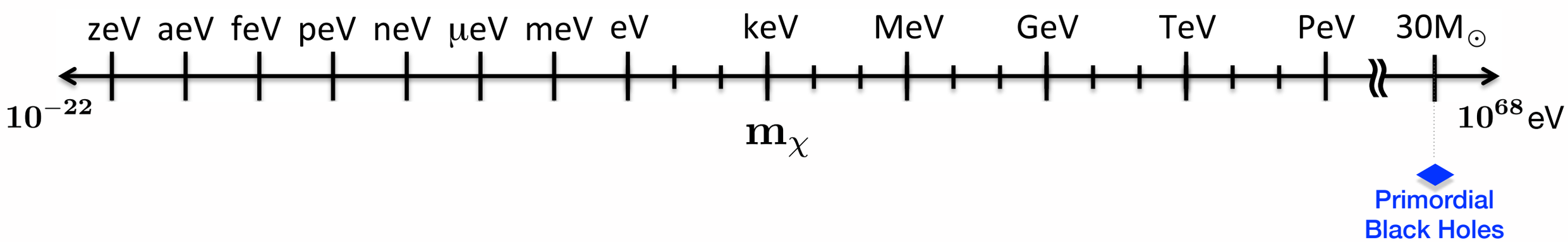

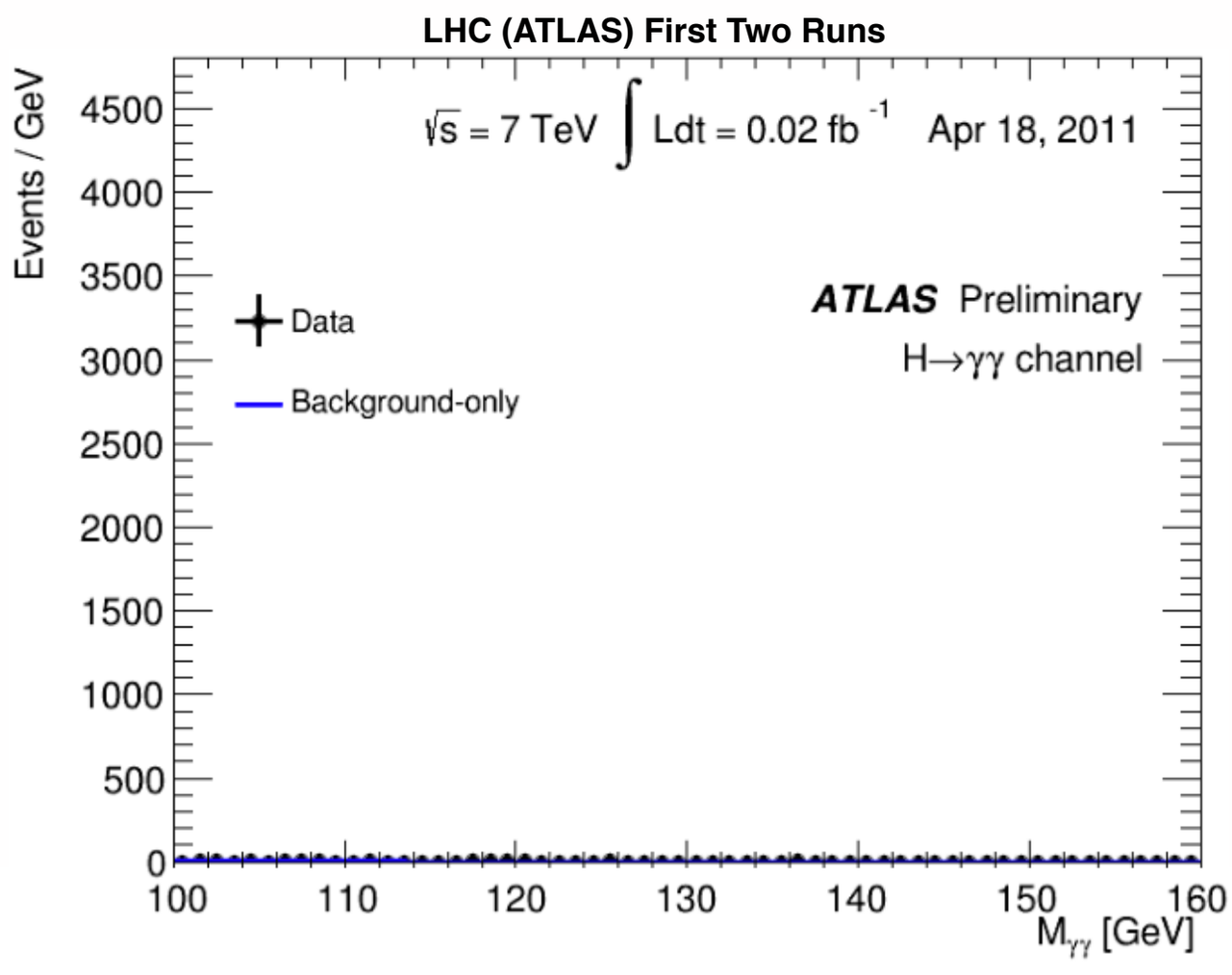

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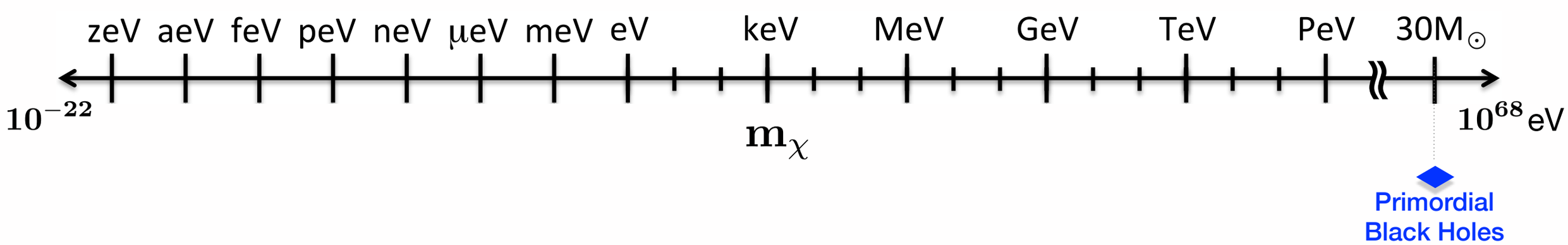

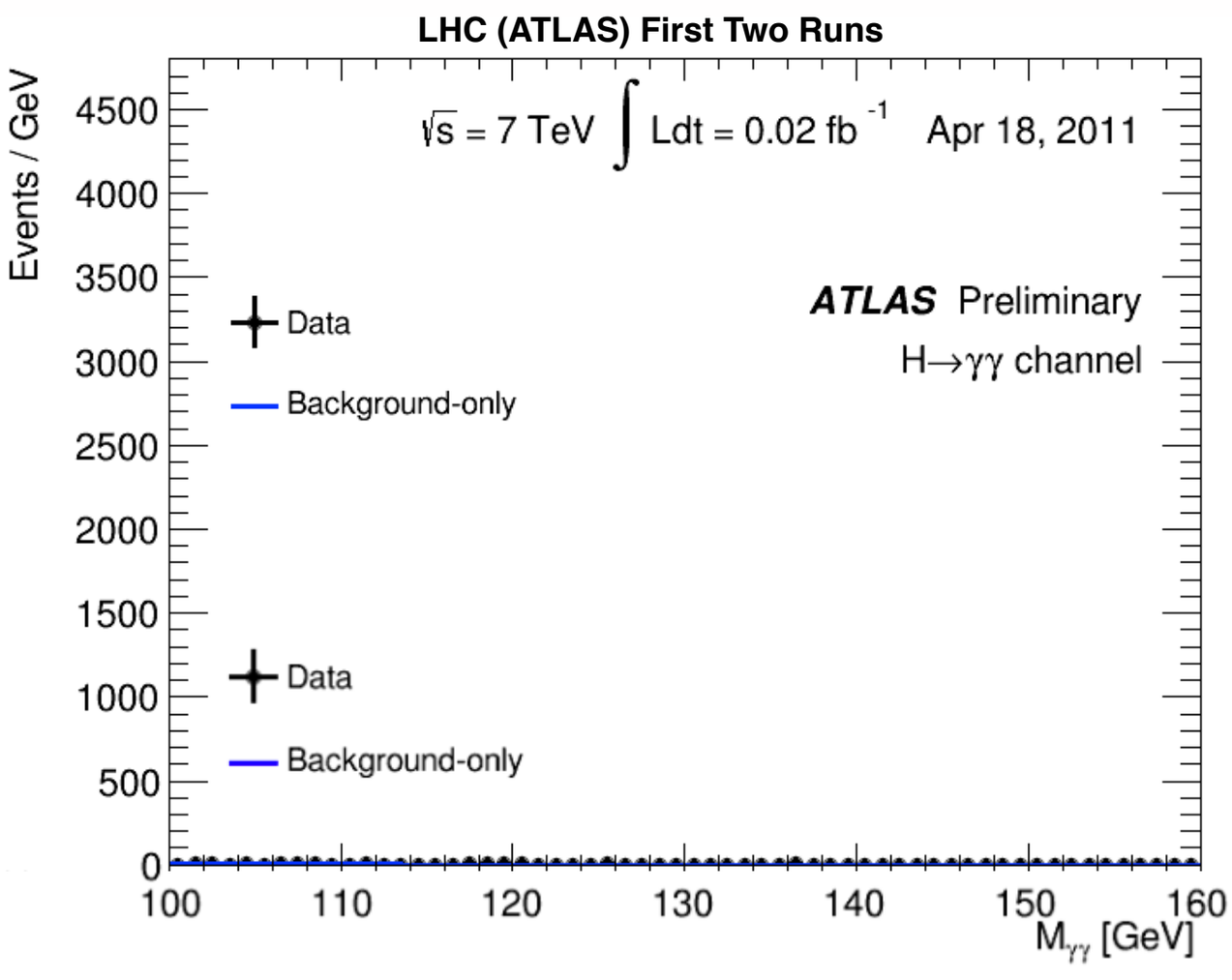

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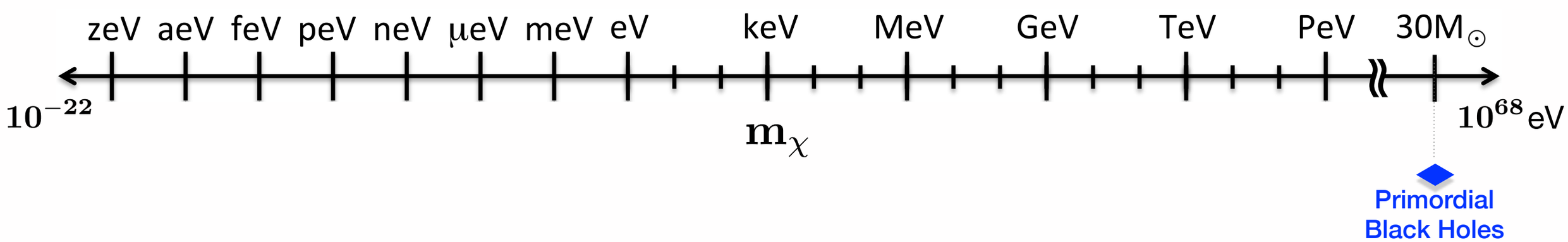
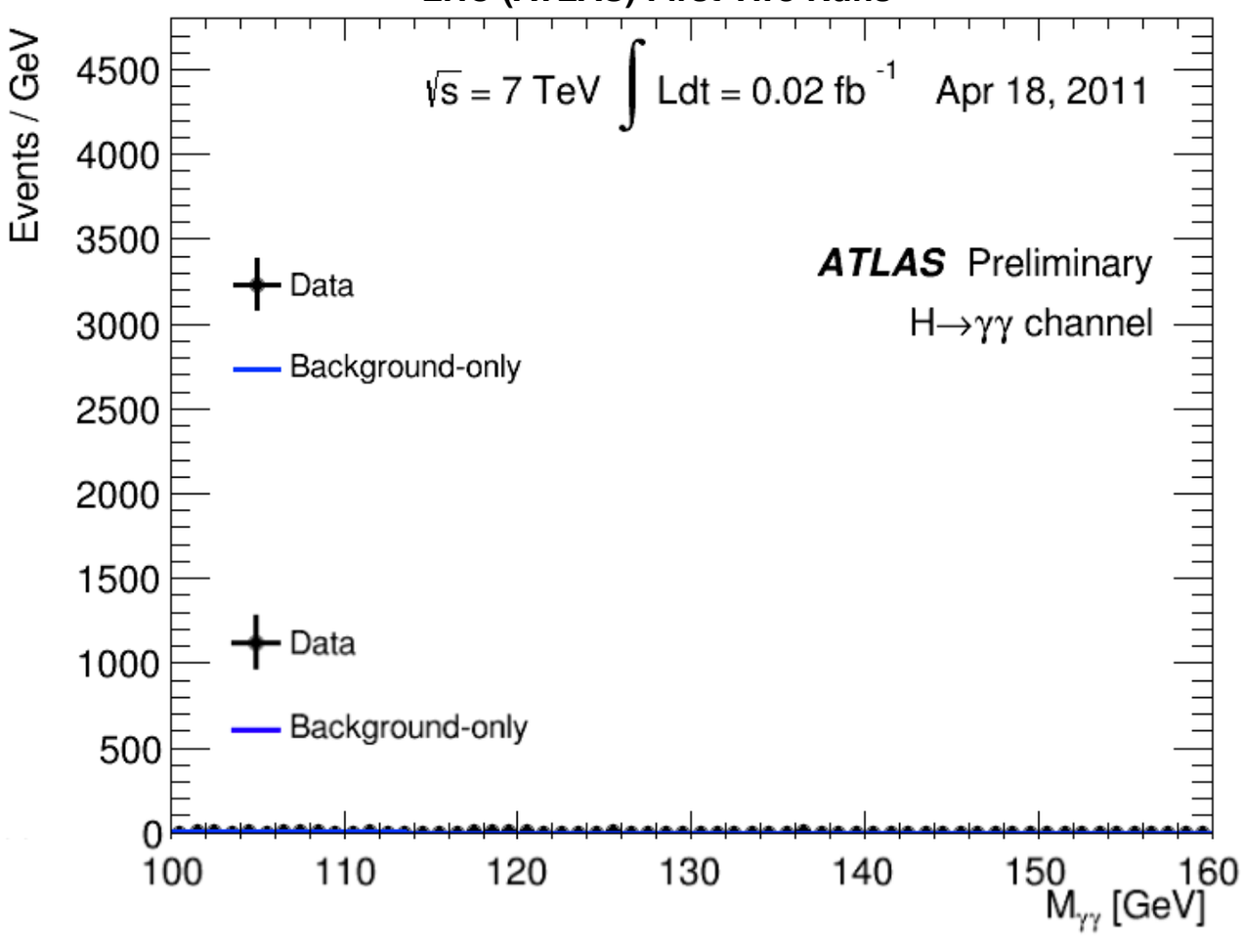
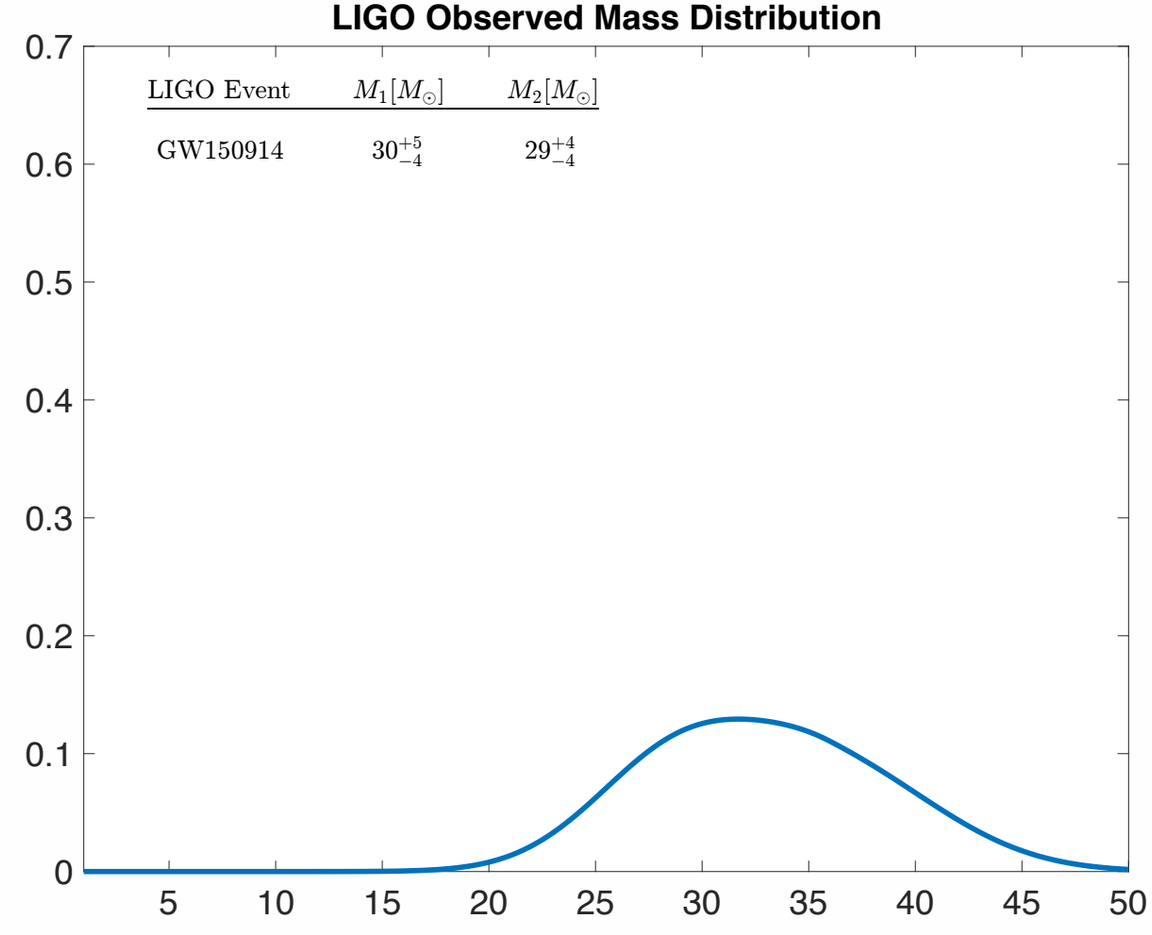


LHC (ATLAS) First Two Runs

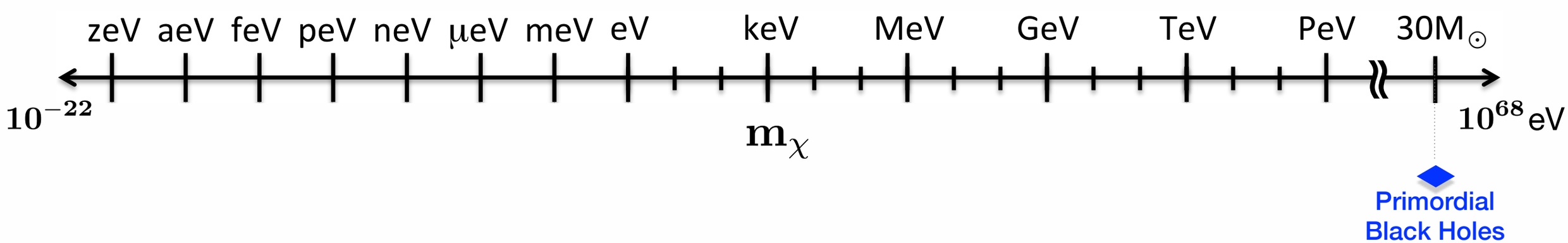


LIGO Observed Mass Distribution

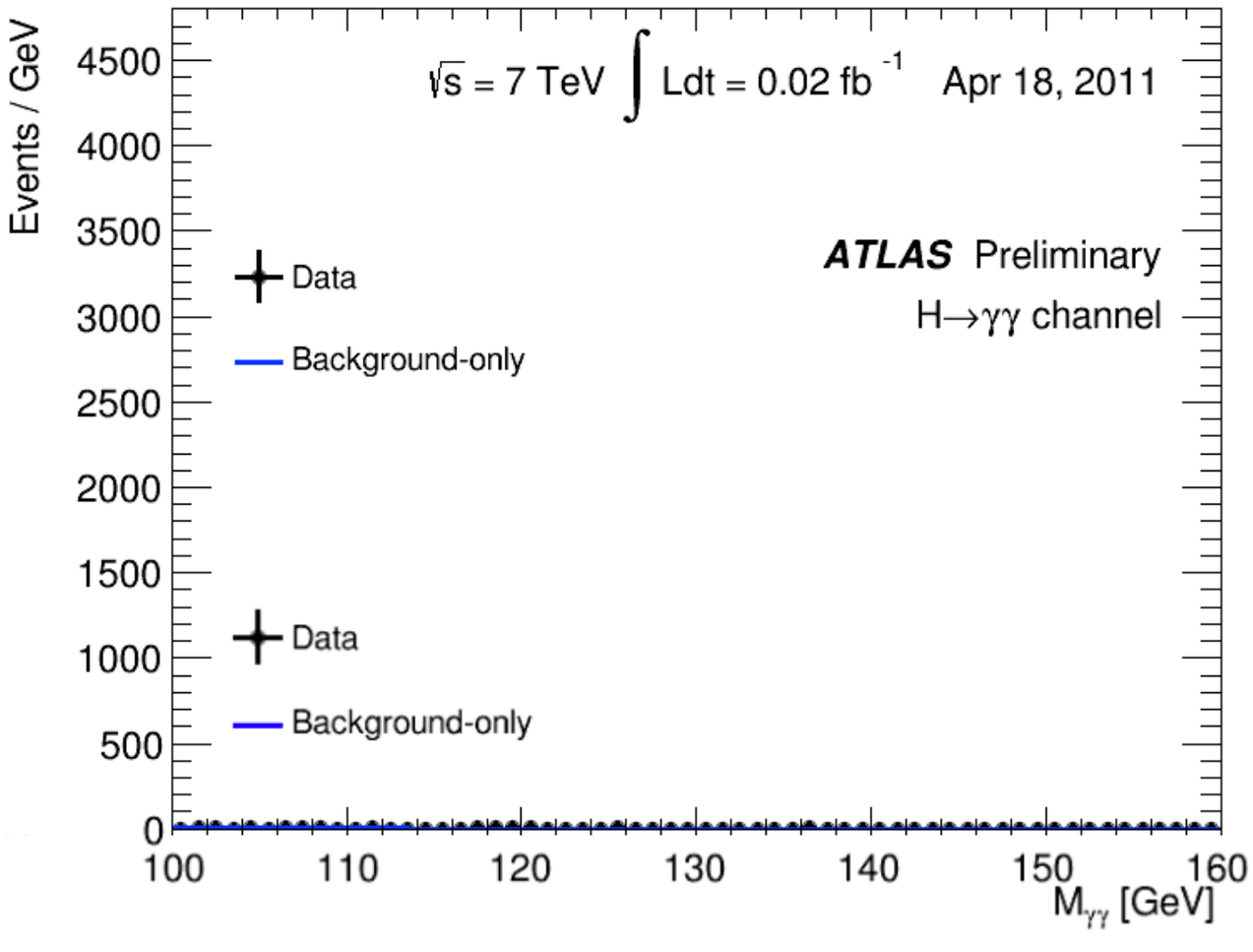


What's the Status with Current Observations?

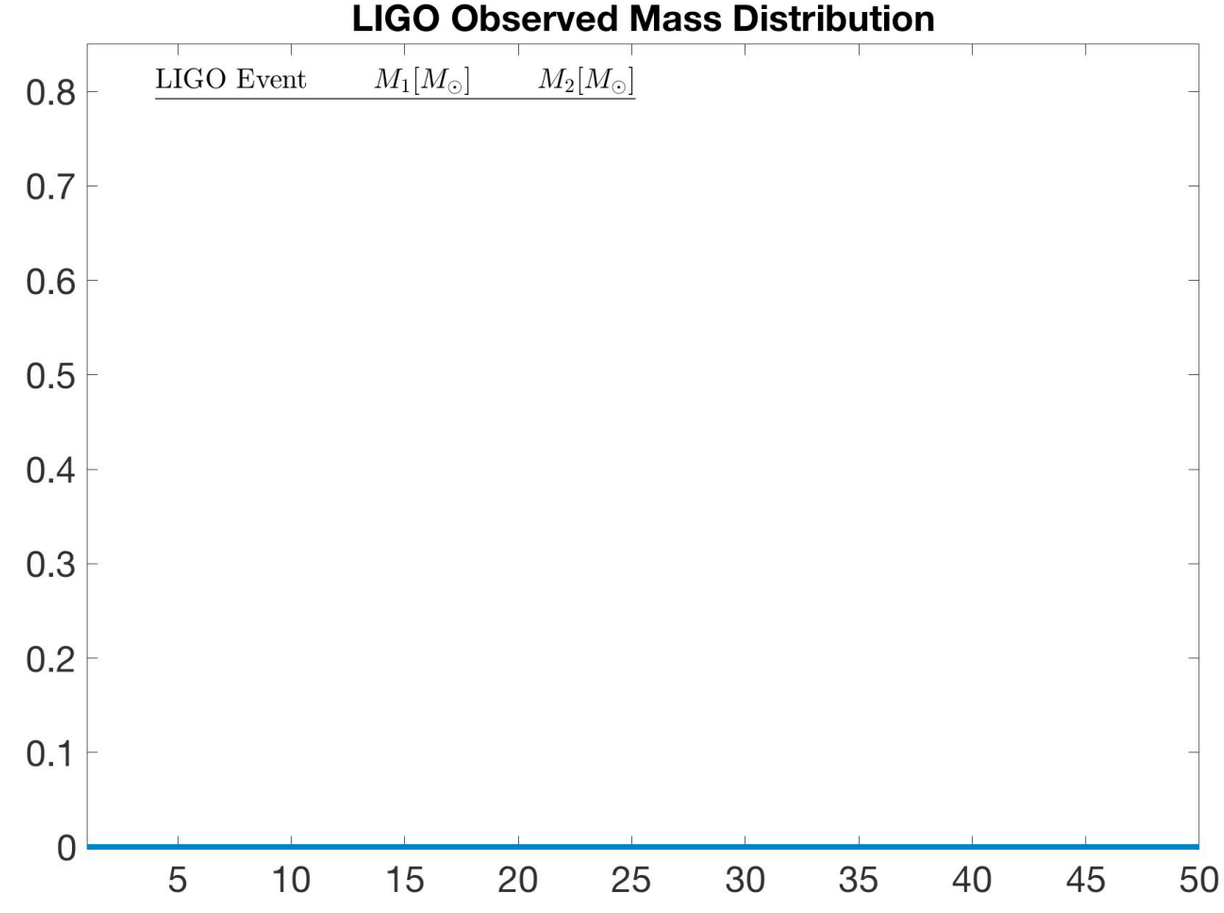
(adapted from Battaglieri et al., arXiv:1707.04591)



LHC (ATLAS) First Two Runs



LIGO Observed Mass Distribution



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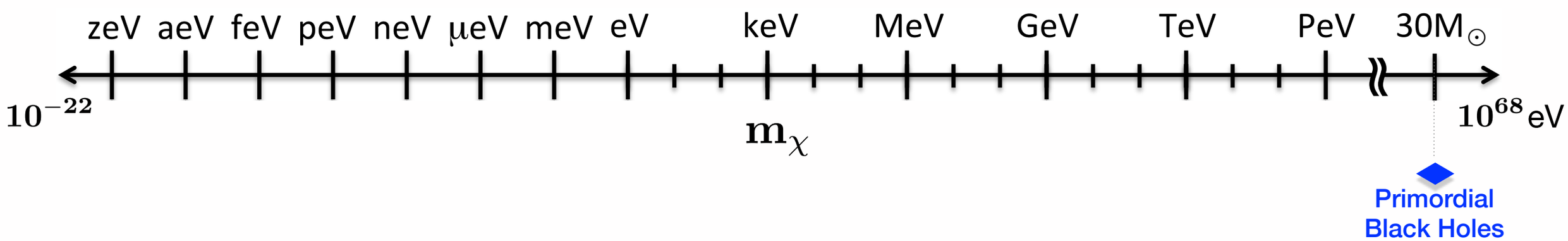

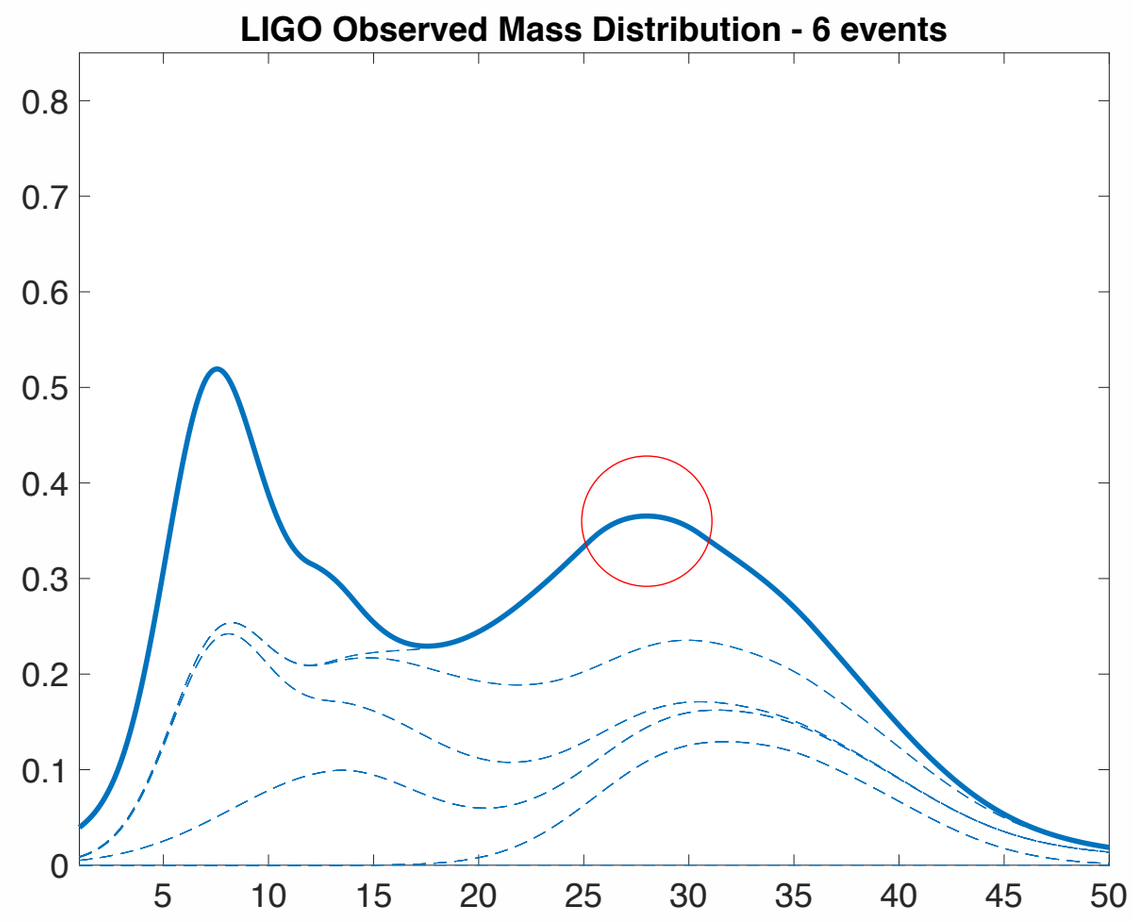

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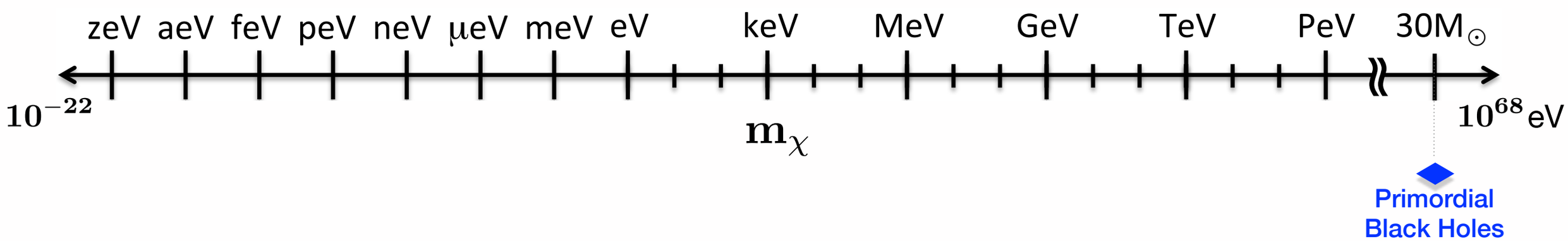
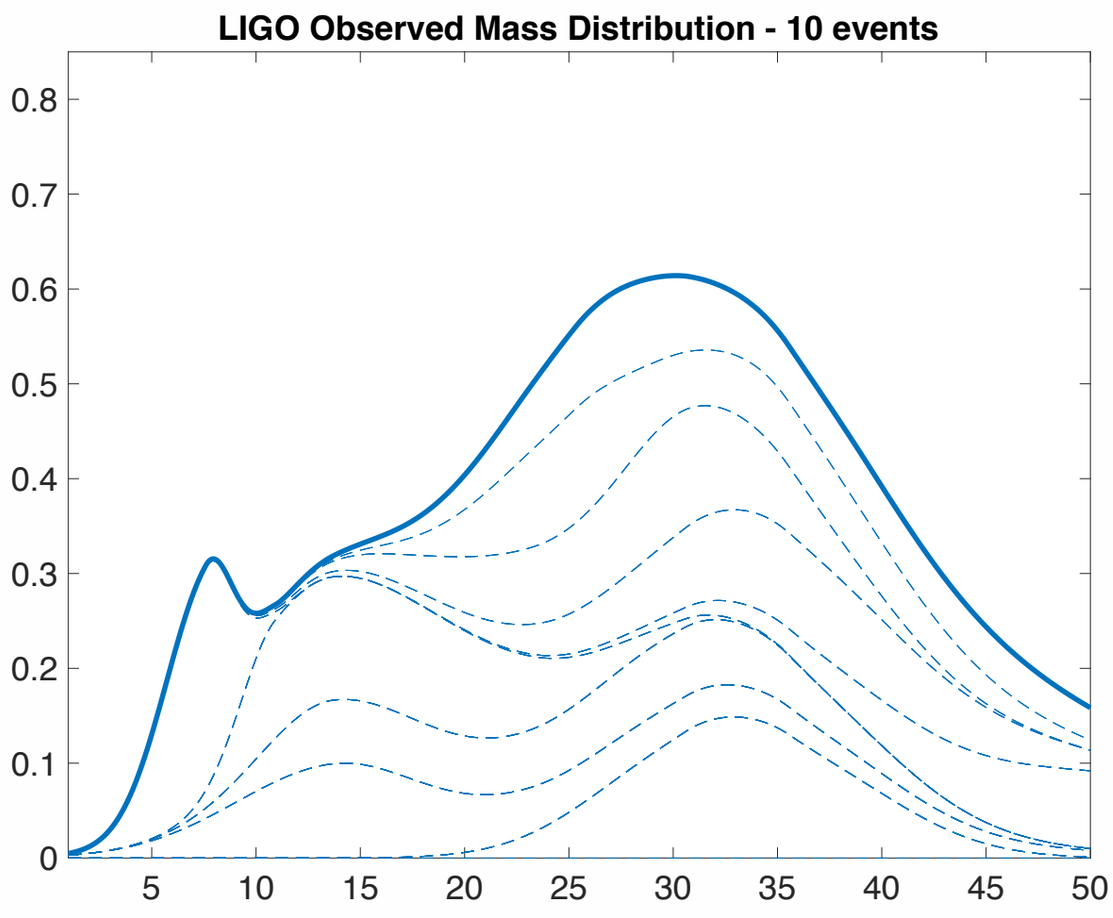
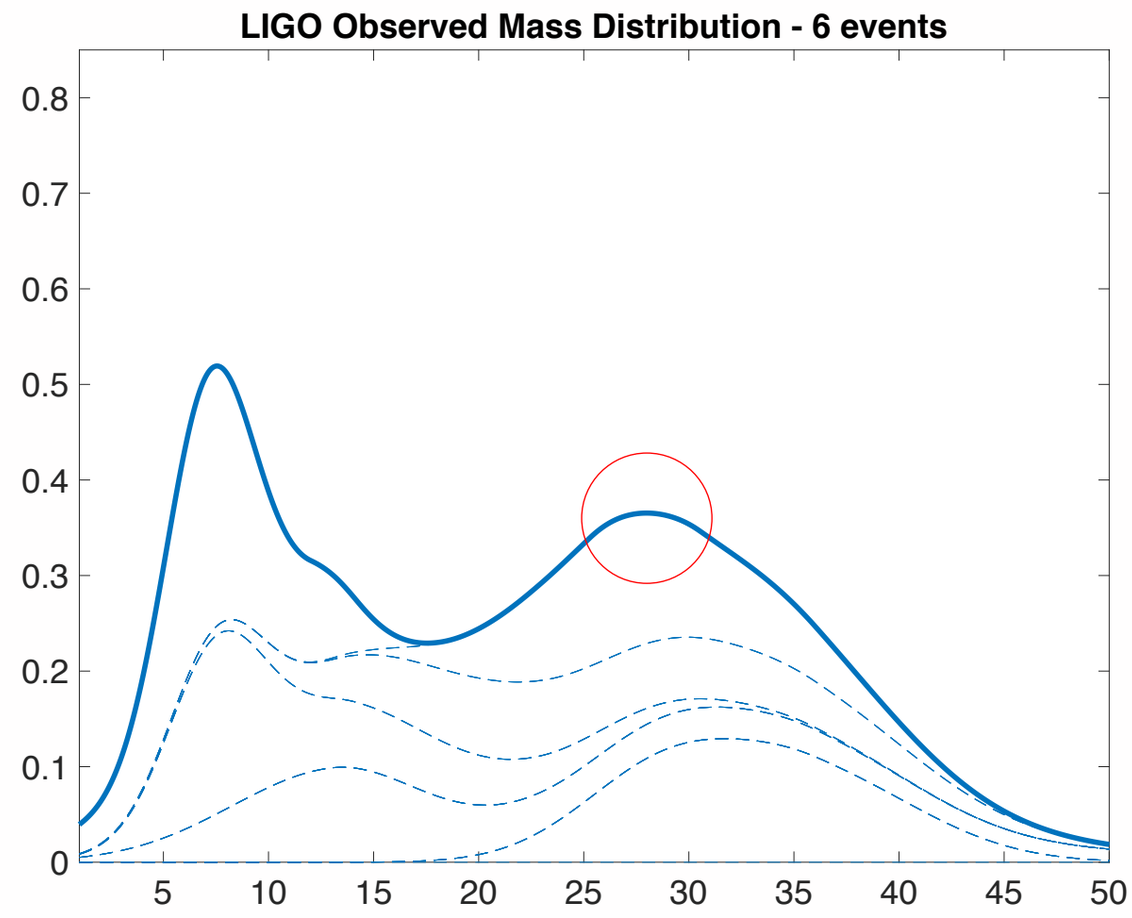
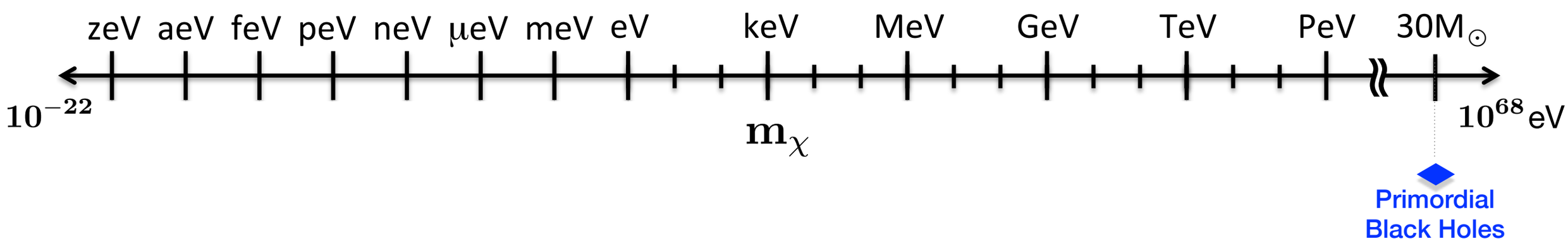






Searching for PBH Dark Matter

(adapted from Battaglieri et al., arXiv:1707.04591)



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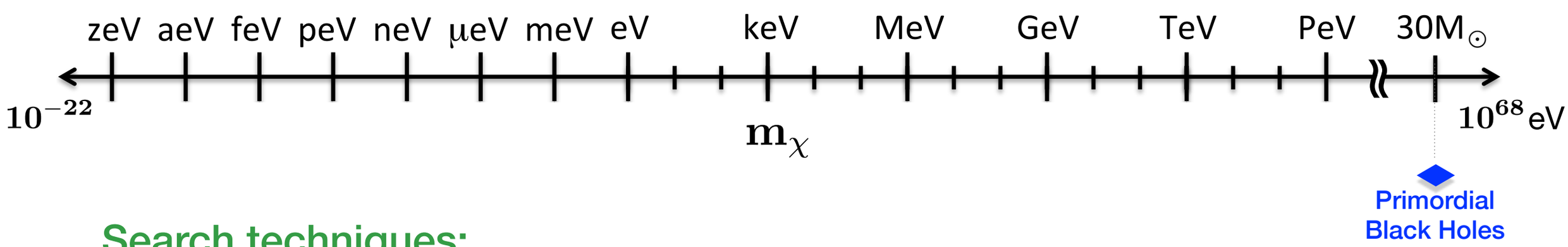

Search techniques:

Searching for PBH Dark Matter

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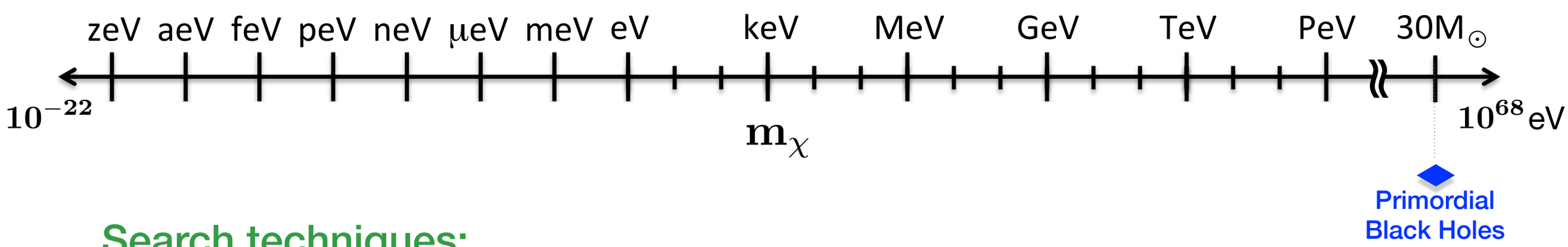

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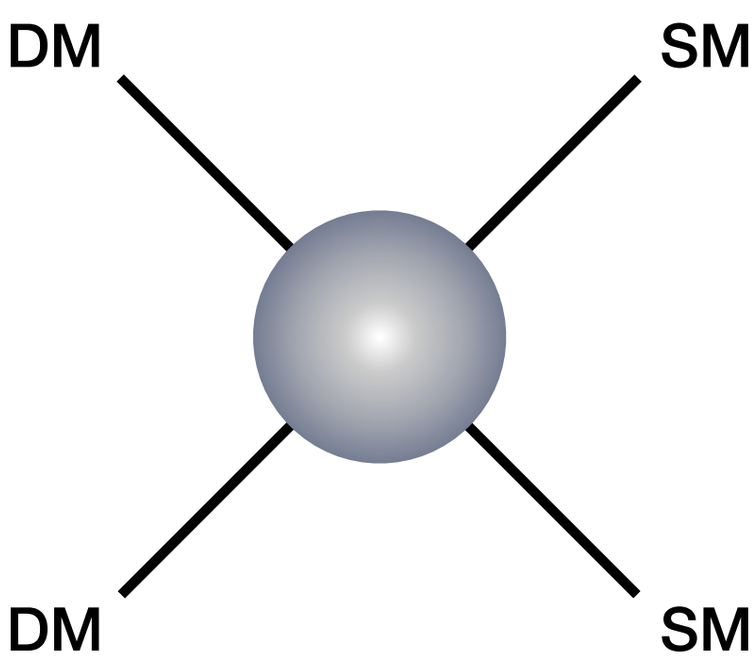

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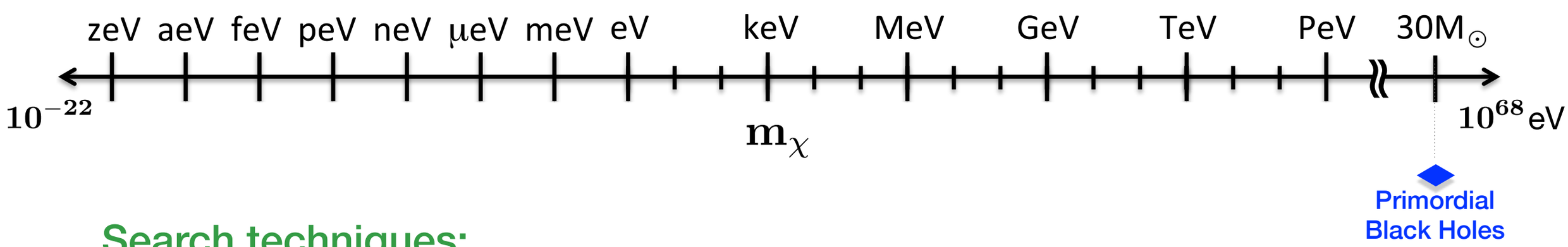

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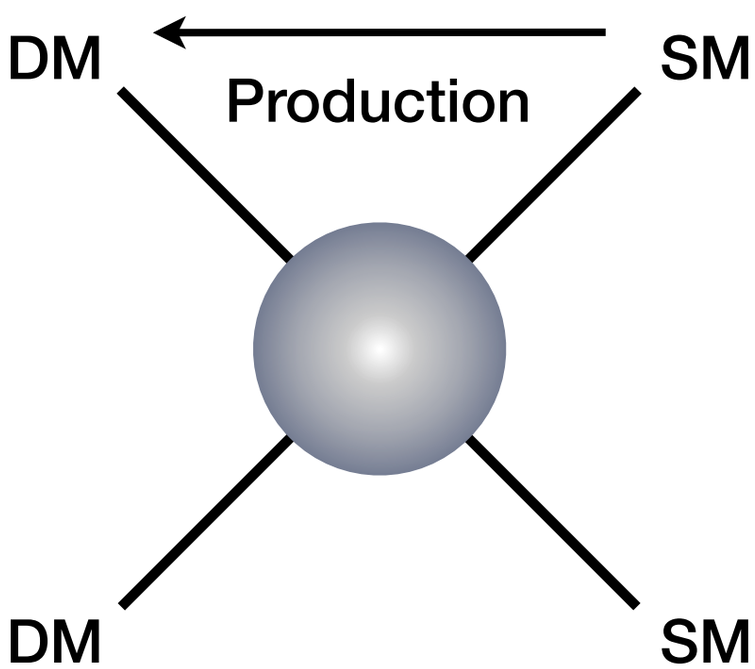

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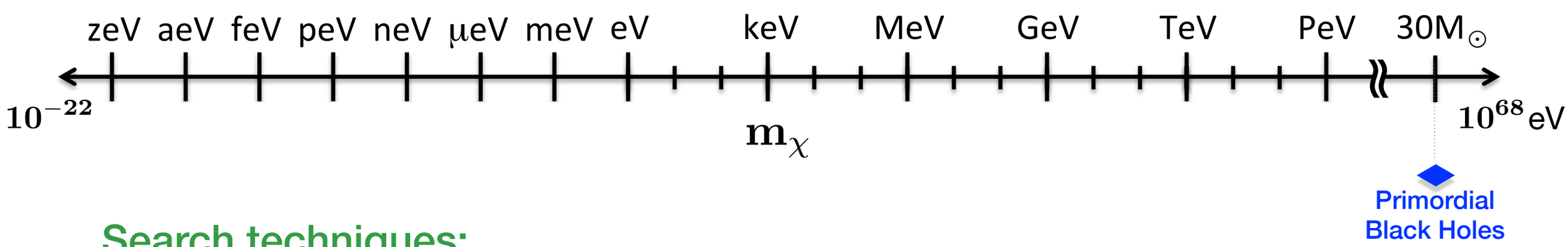

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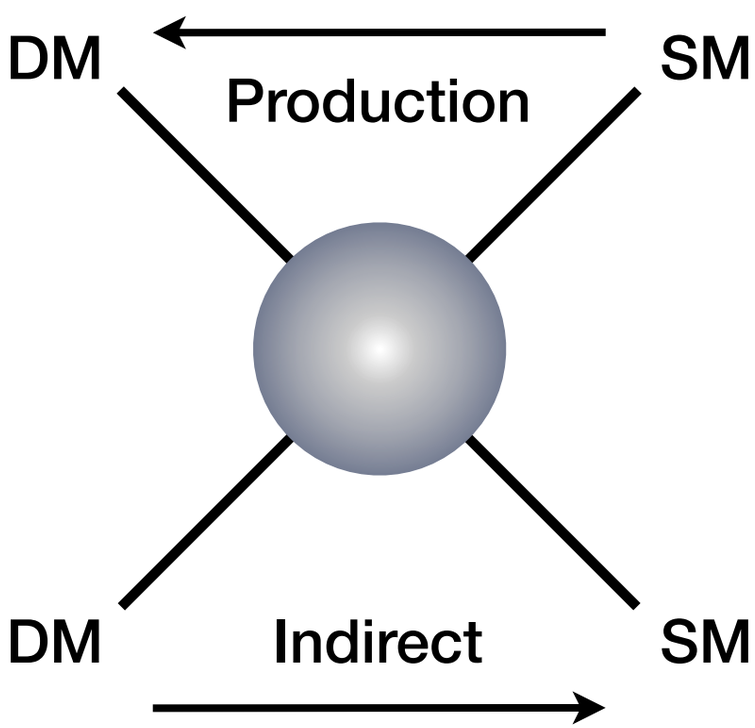

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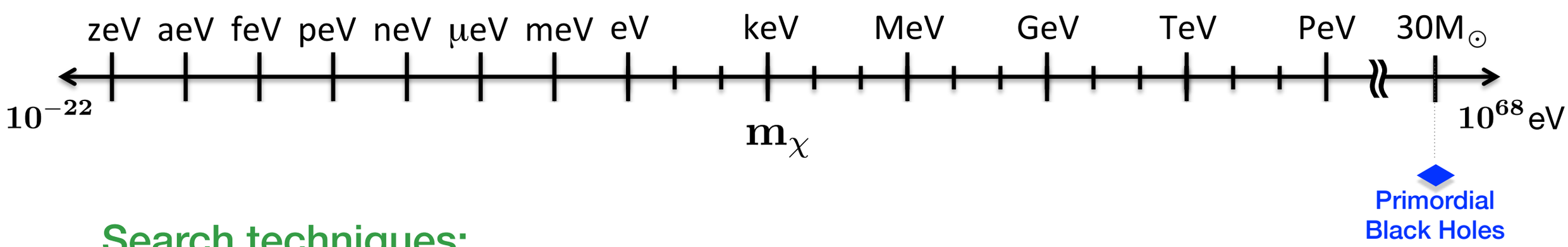

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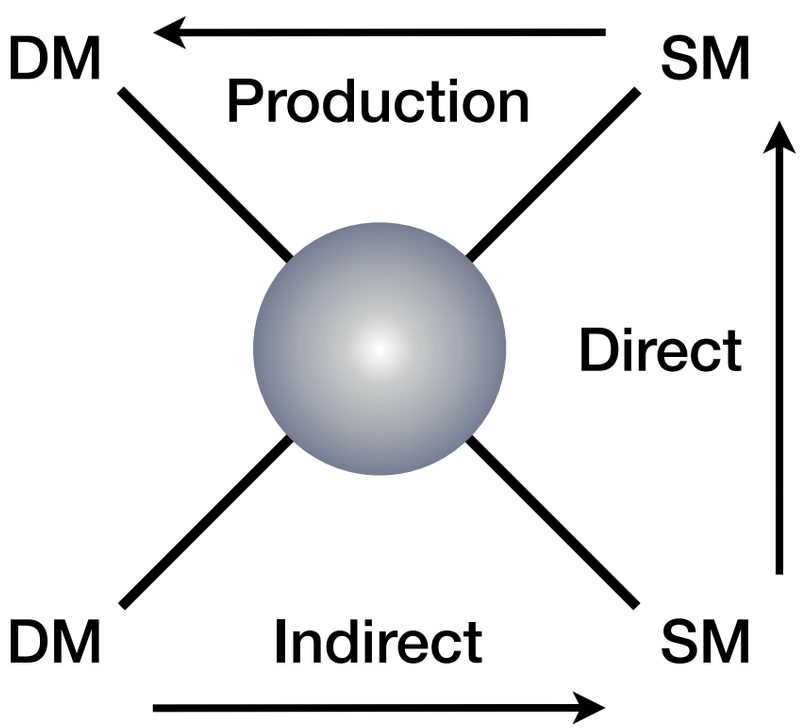

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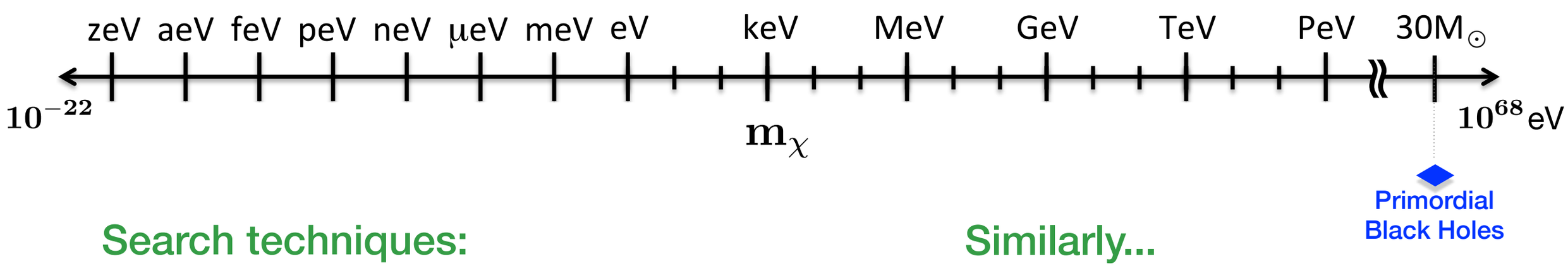

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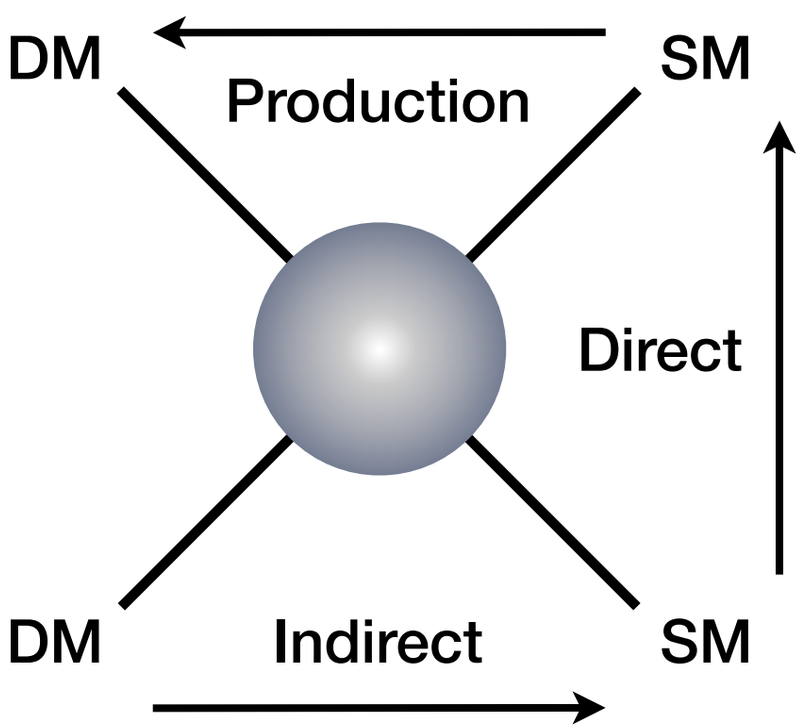

Similarly...

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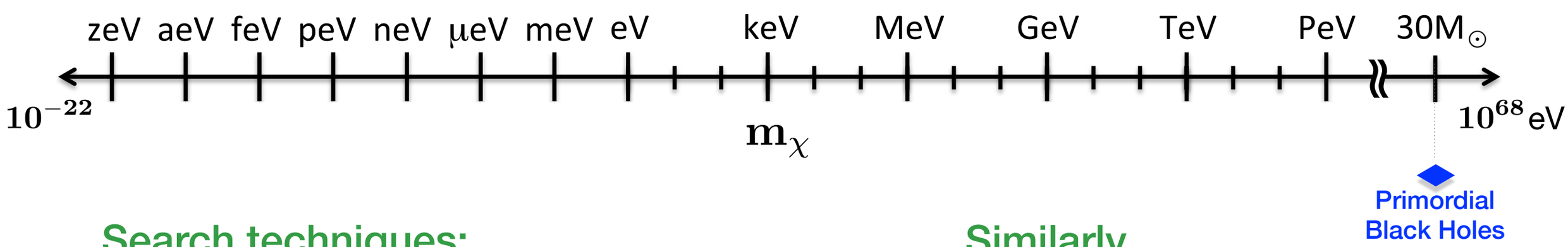

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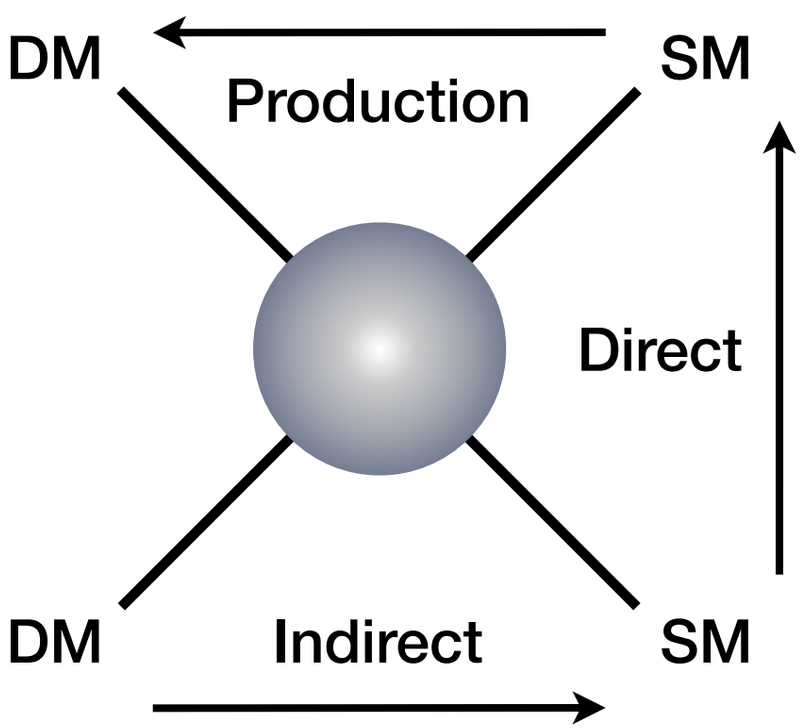
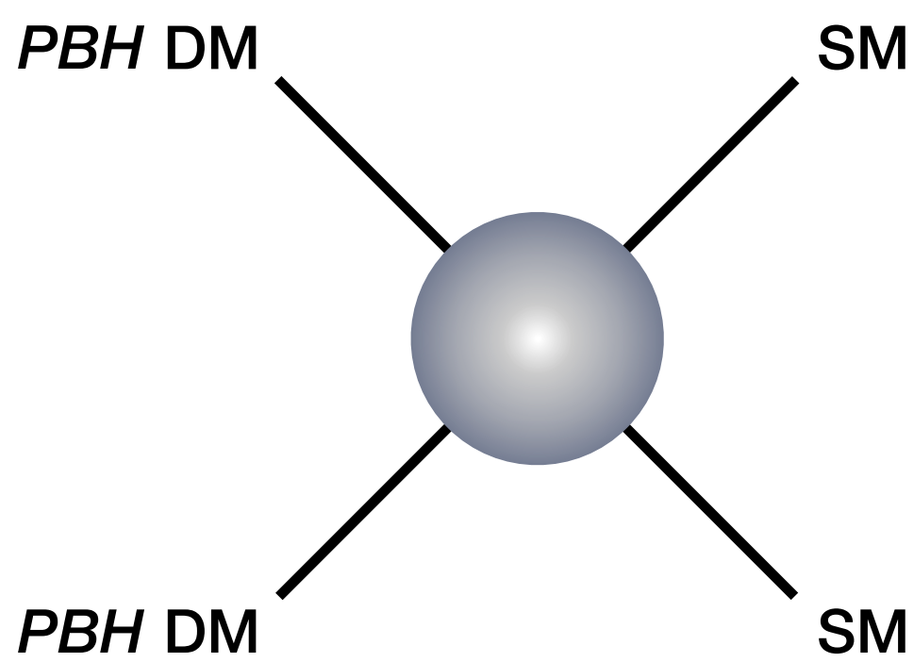


Similarly...

Kovetz, PRL 2017



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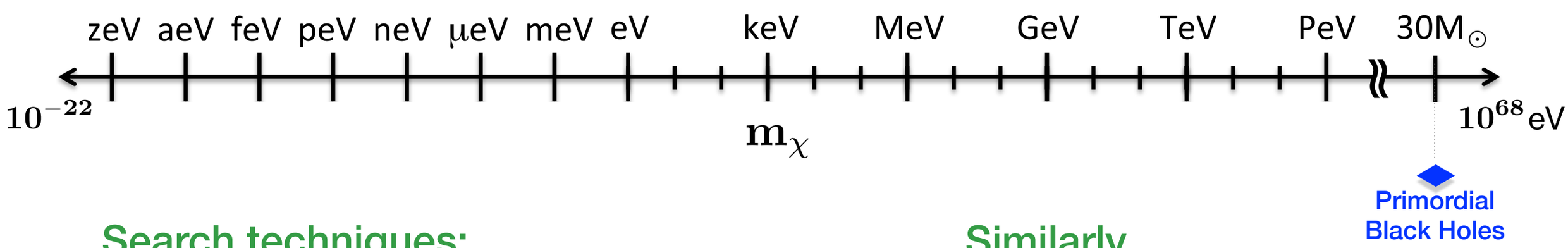

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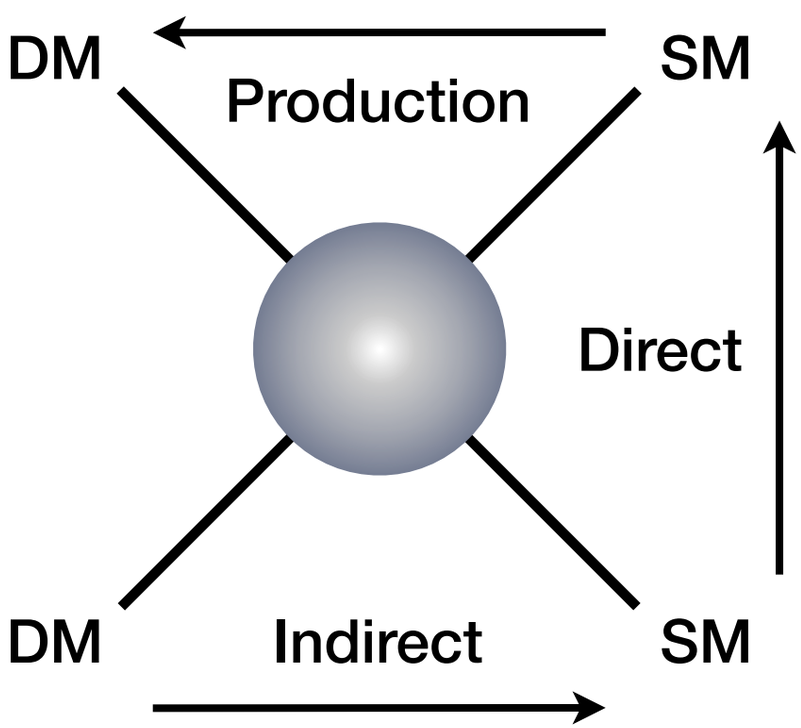

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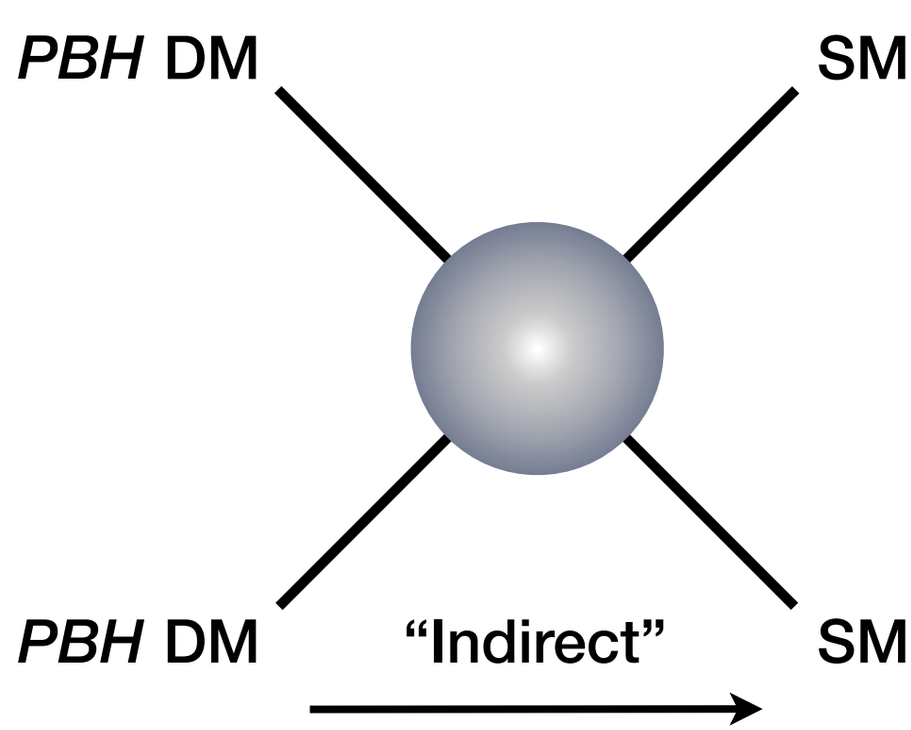

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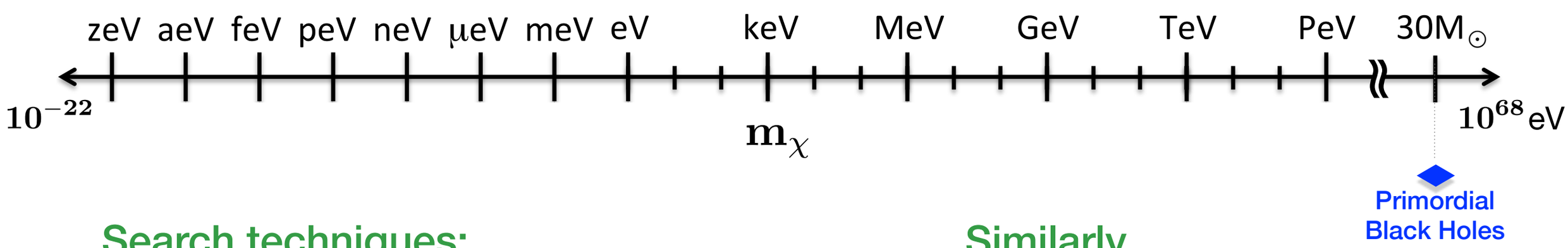

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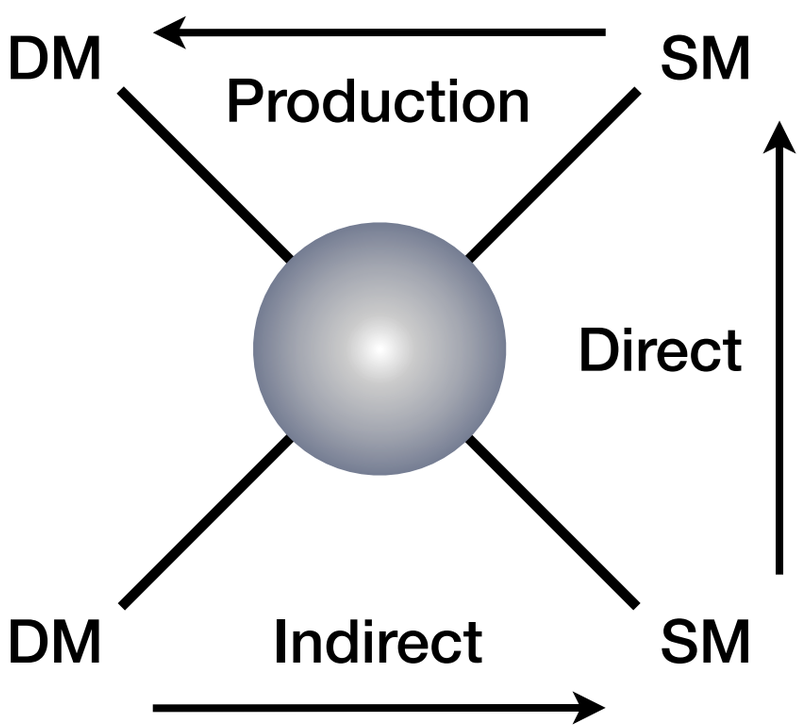

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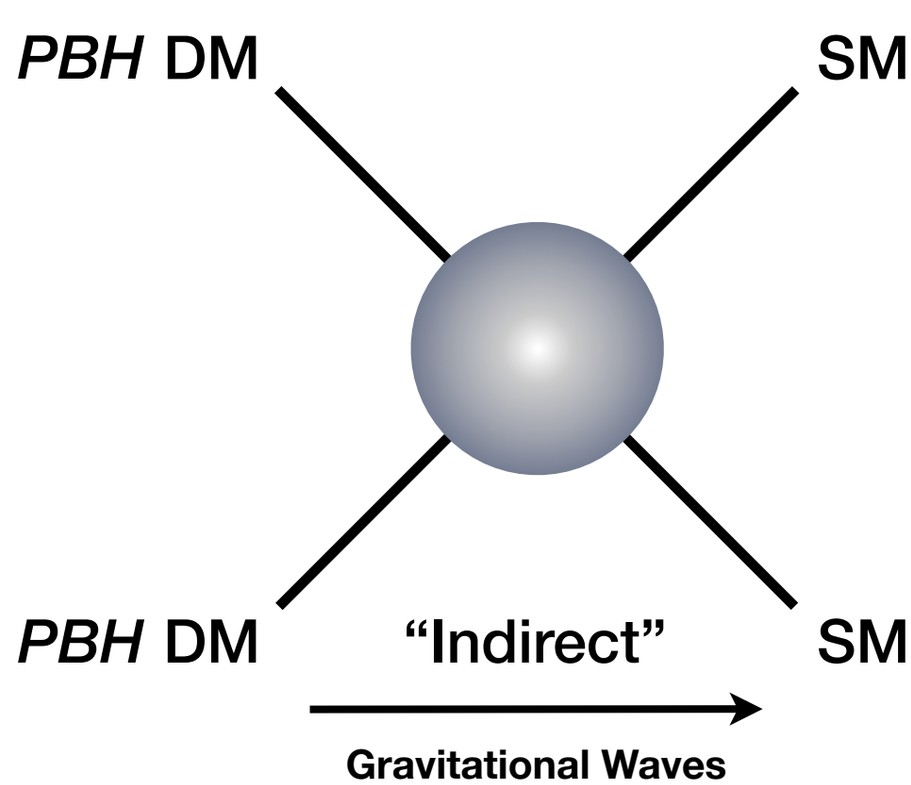

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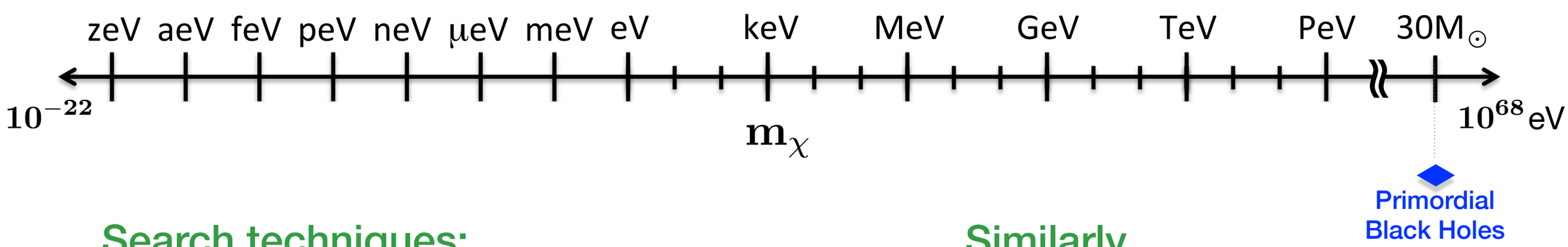

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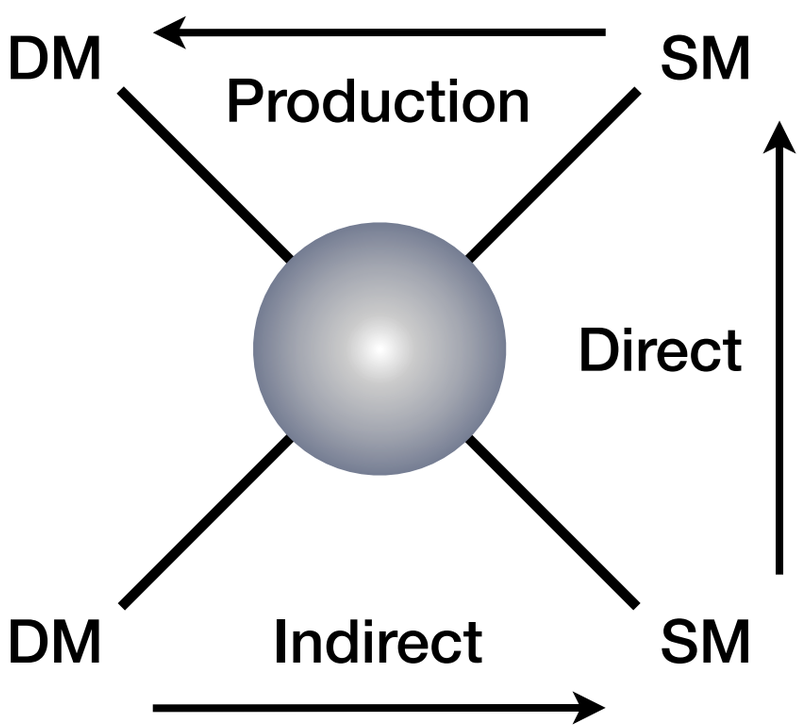

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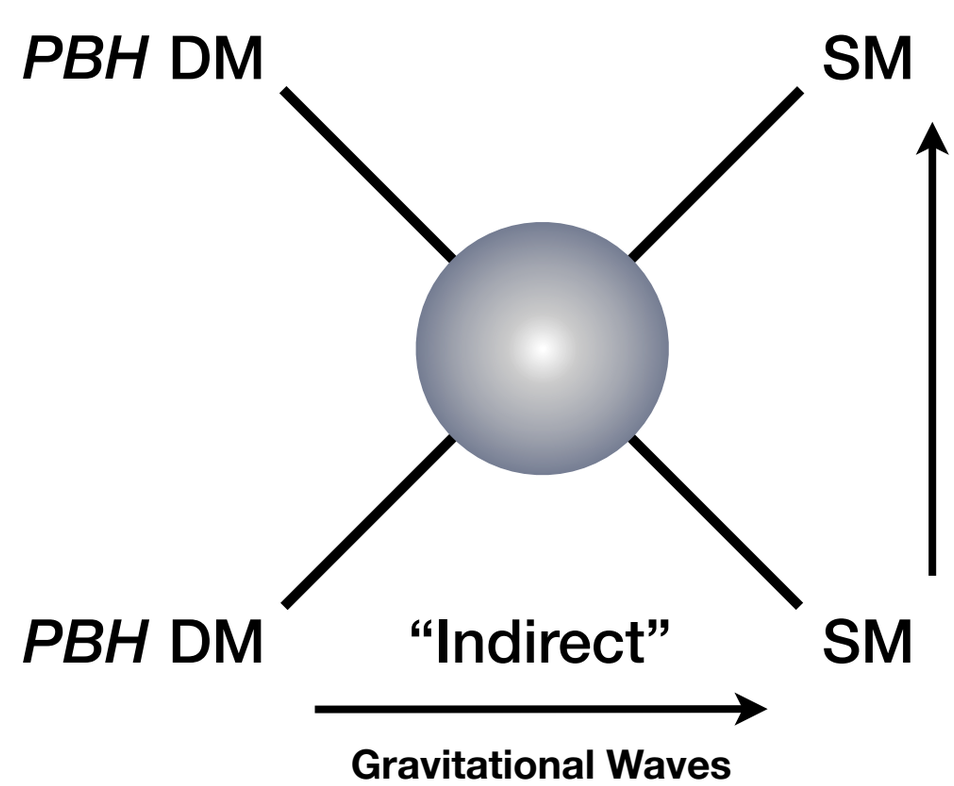
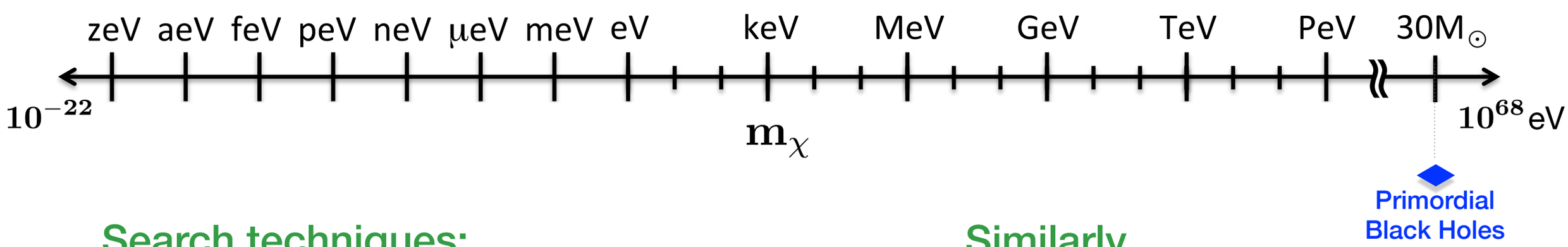


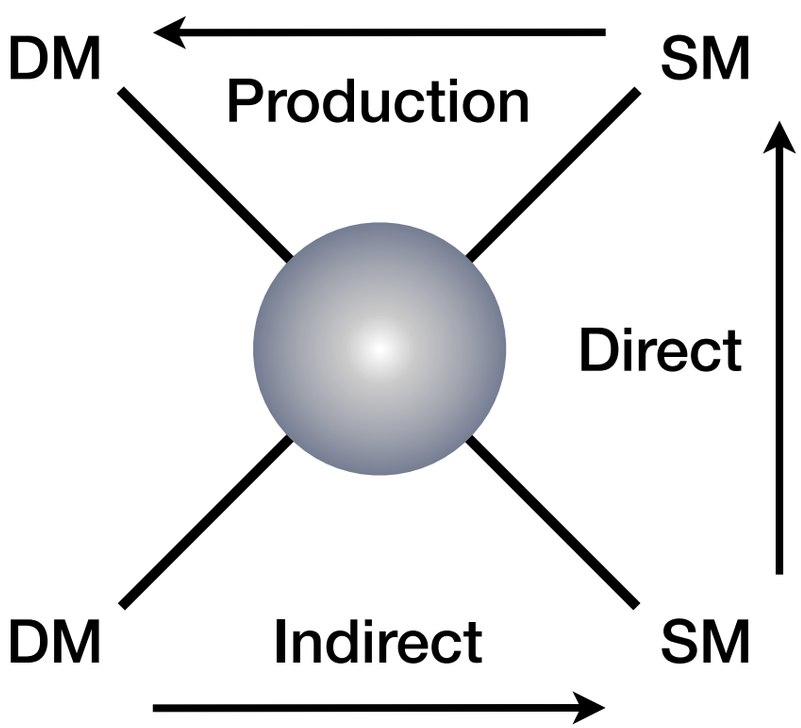
"Direct":

Searching for PBH Dark Matter

(adapted from Battaglieri et al., arXiv:1707.04591)



Search techniques:



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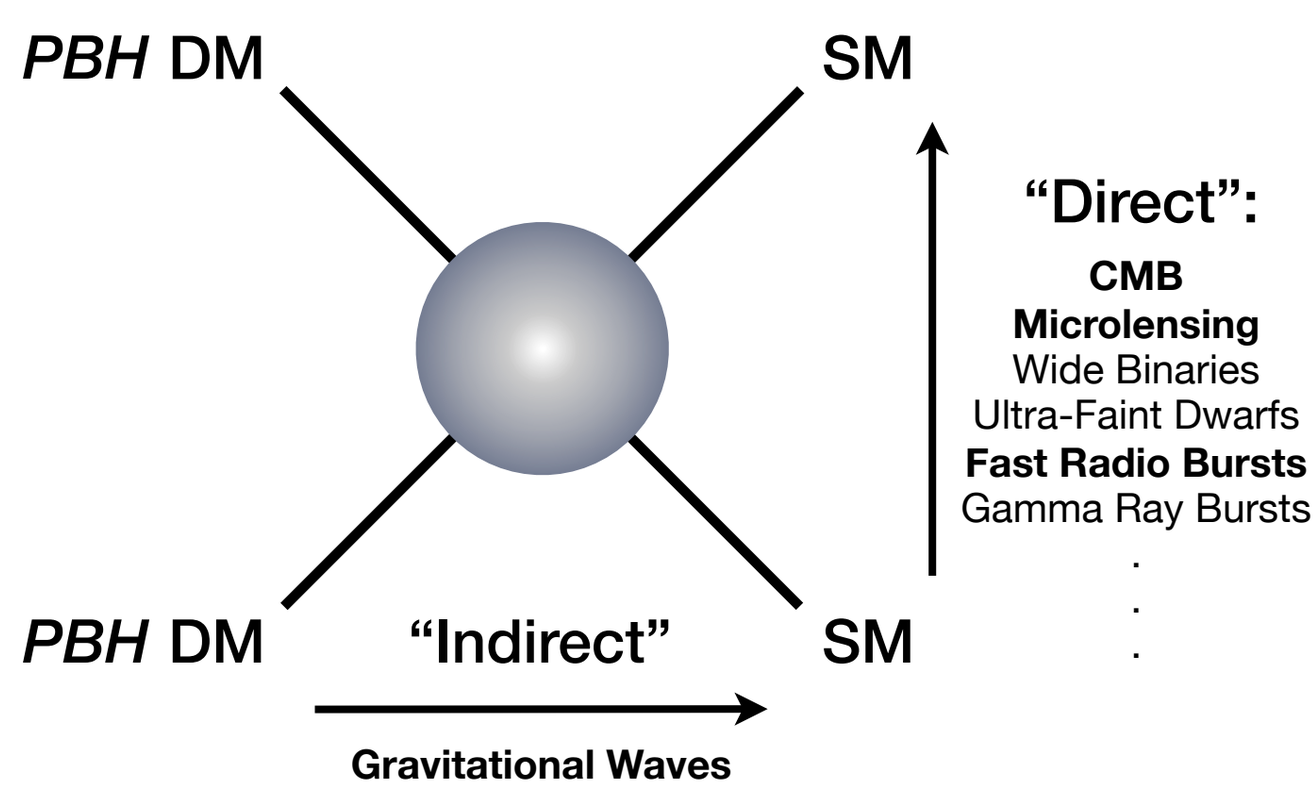

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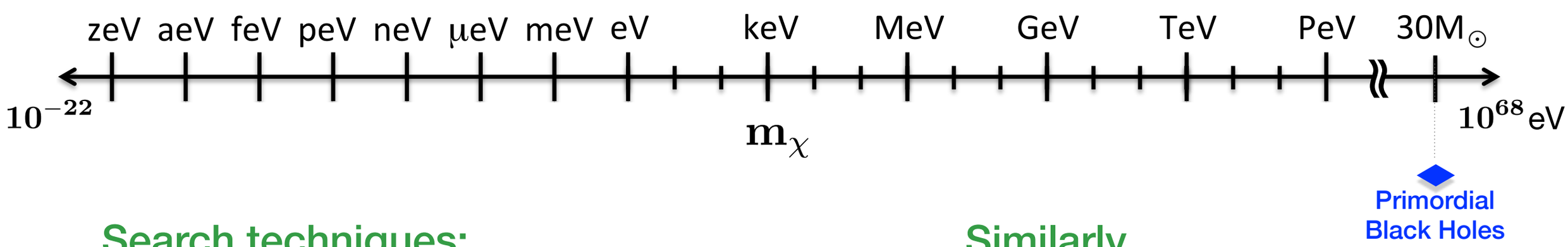

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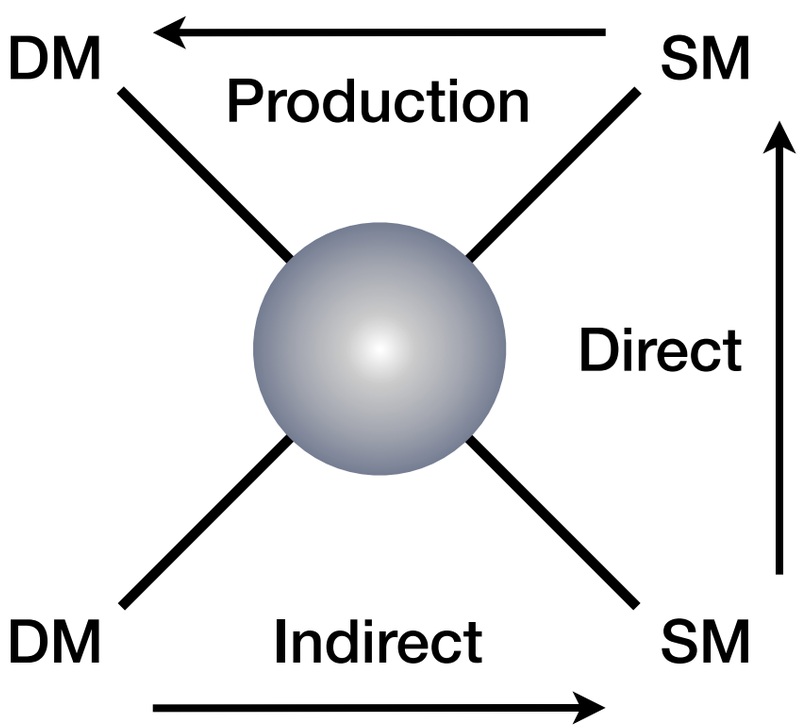

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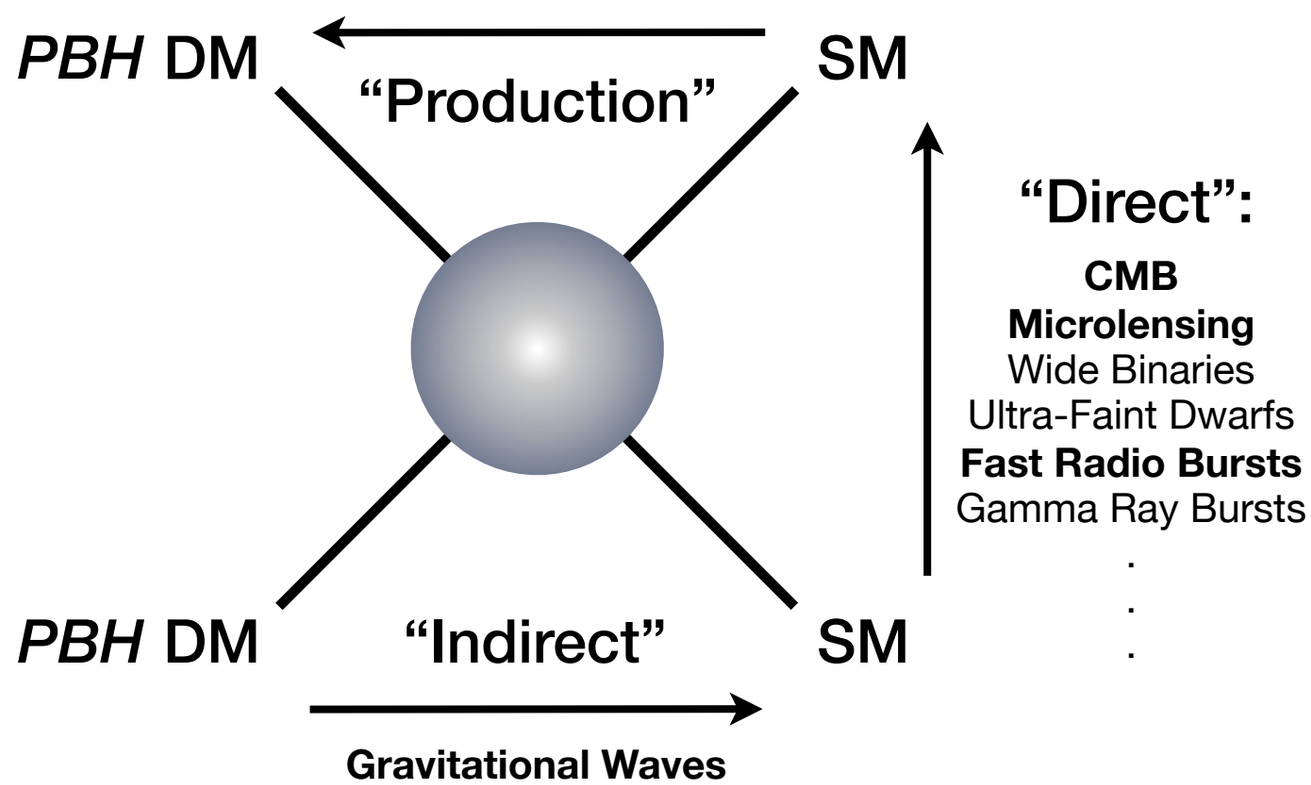
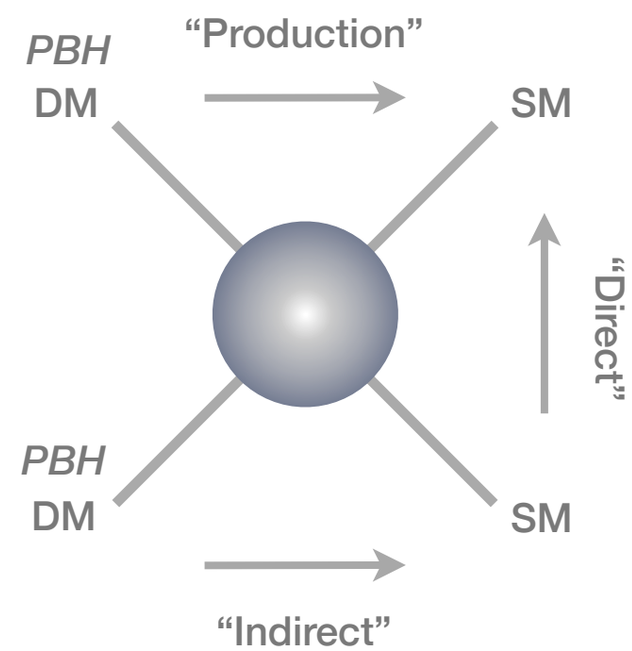
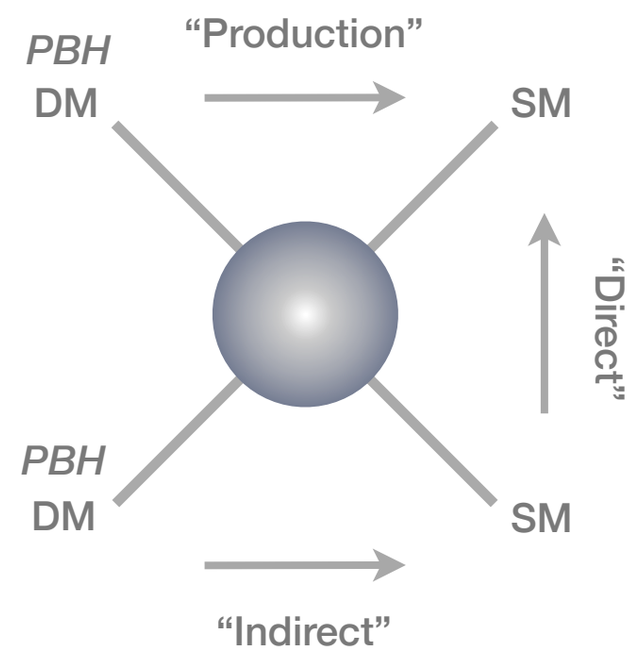


Outline



Outline

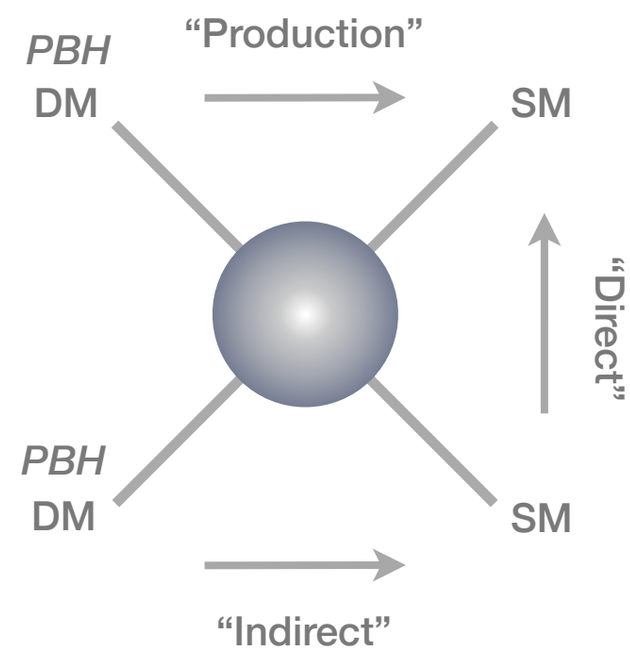
- PBH Production: Early Universe Formation



Outline

- PBH Production: Early Universe Formation

- Indirect Detection: GWs from mergers

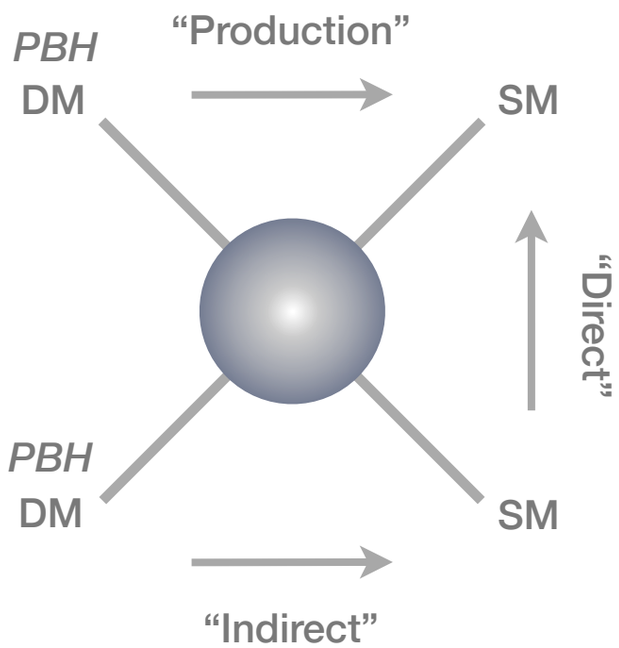


Outline

- PBH Production: Early Universe Formation

- Indirect Detection: GWs from mergers

- Direct Detection: Constraints on PBHs



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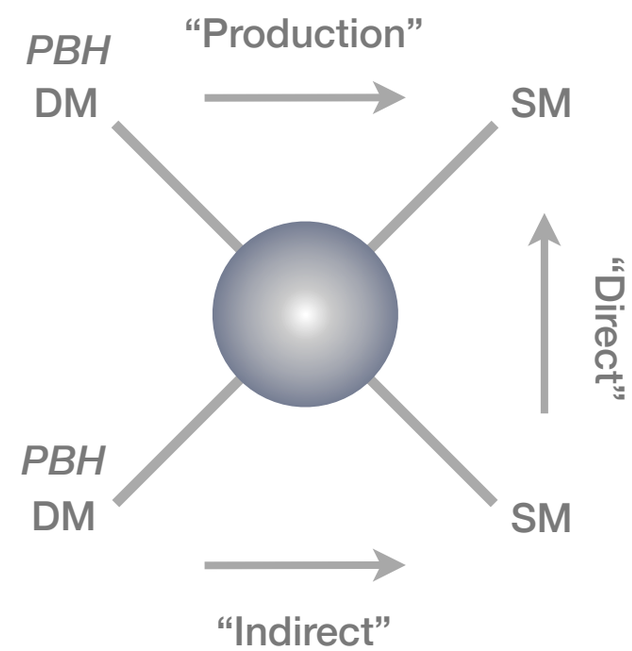

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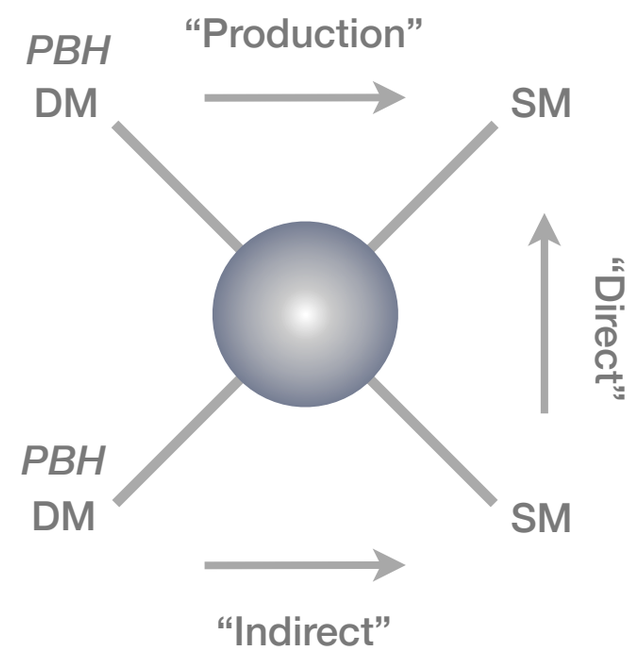
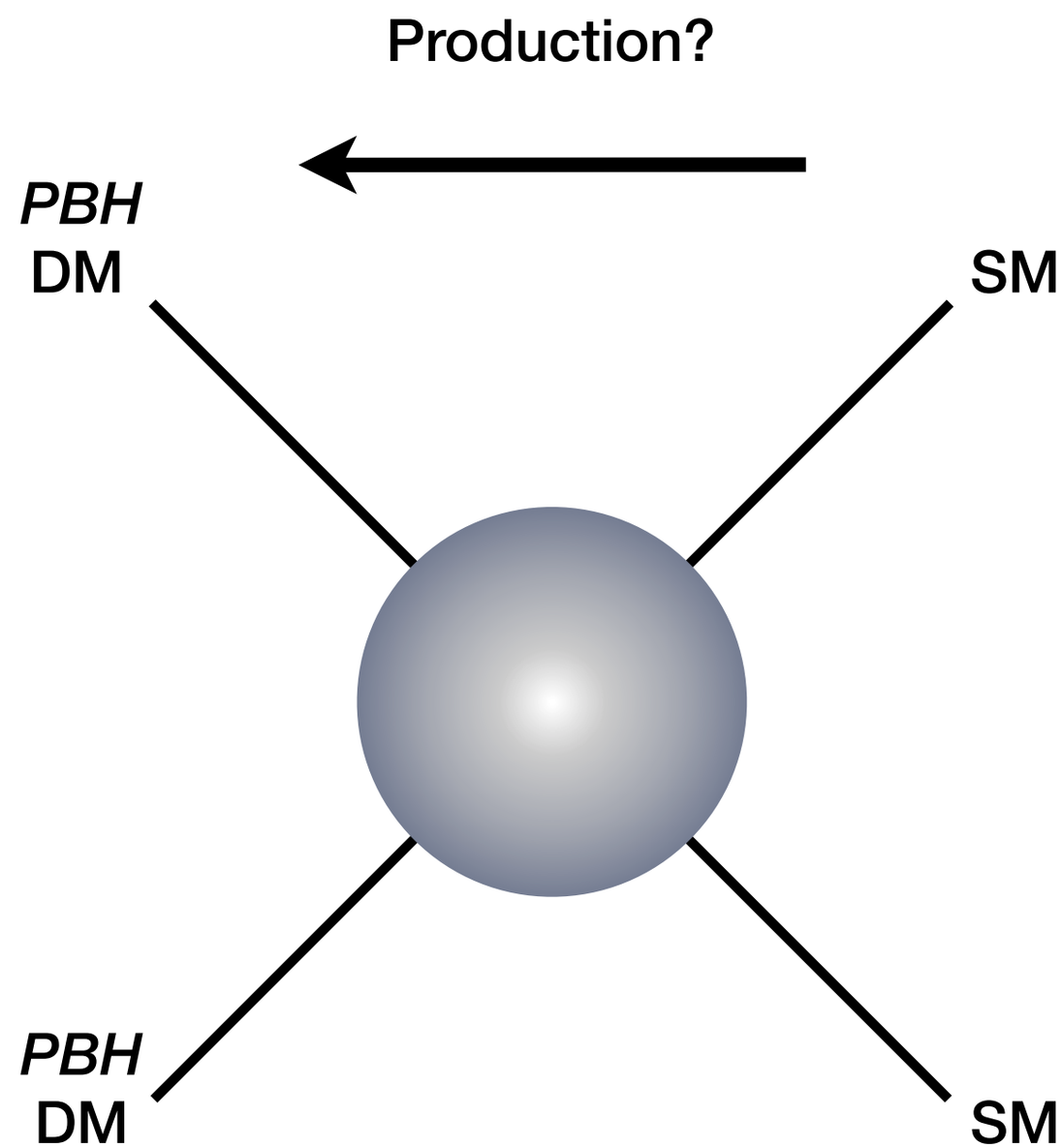


PBH Formation: Rough Numbers

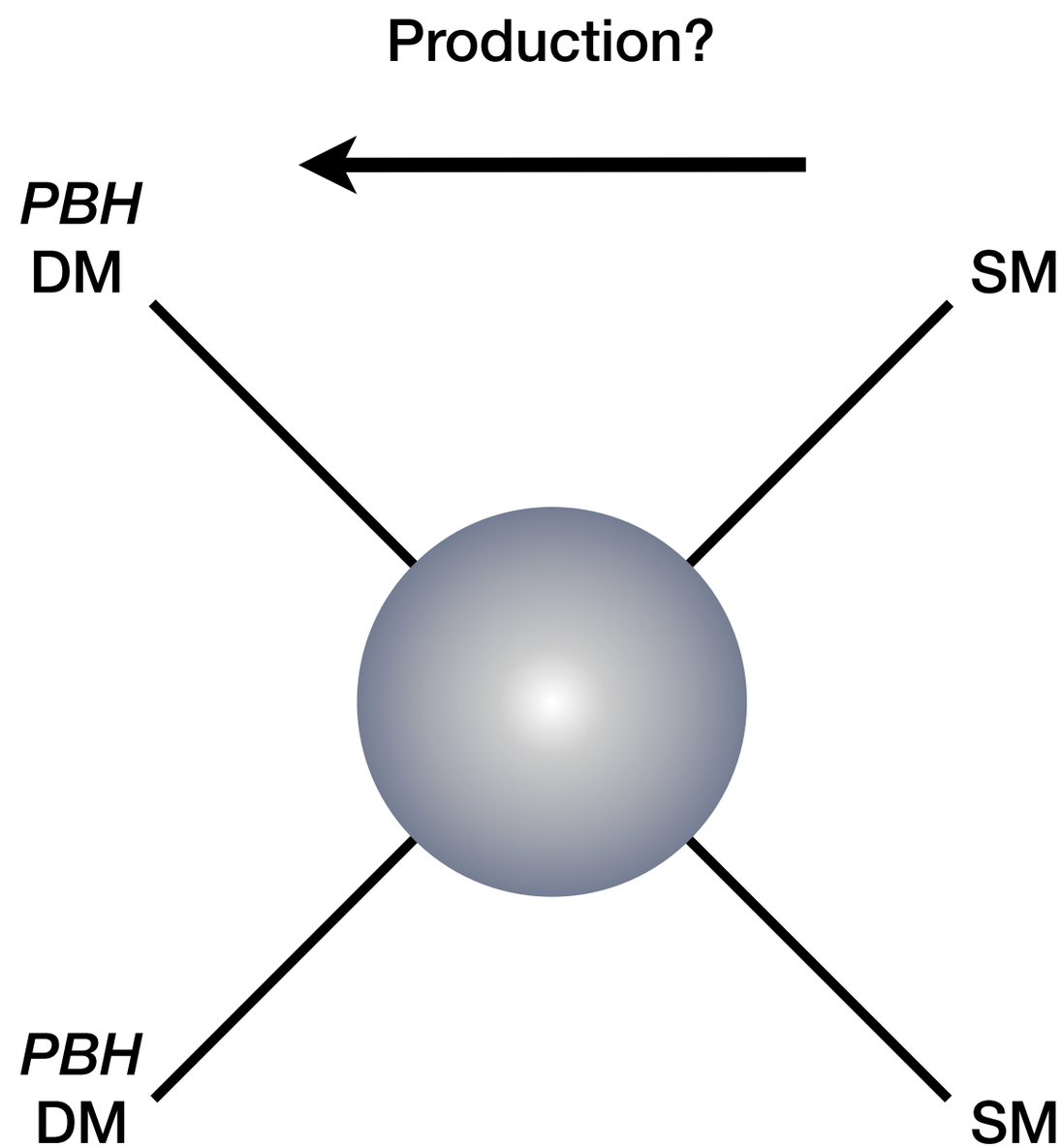


PBH Formation: Rough Numbers

Requires high density:

$$R_s = \frac{2GM}{c^2} = 3\left(\frac{M}{M_\odot}\right)\ \mathrm{km}$$

$$\rho_s = 10^{18}\left(\frac{M}{M_\odot}\right)^{-2}\ \mathrm{g\,cm^{-3}}$$



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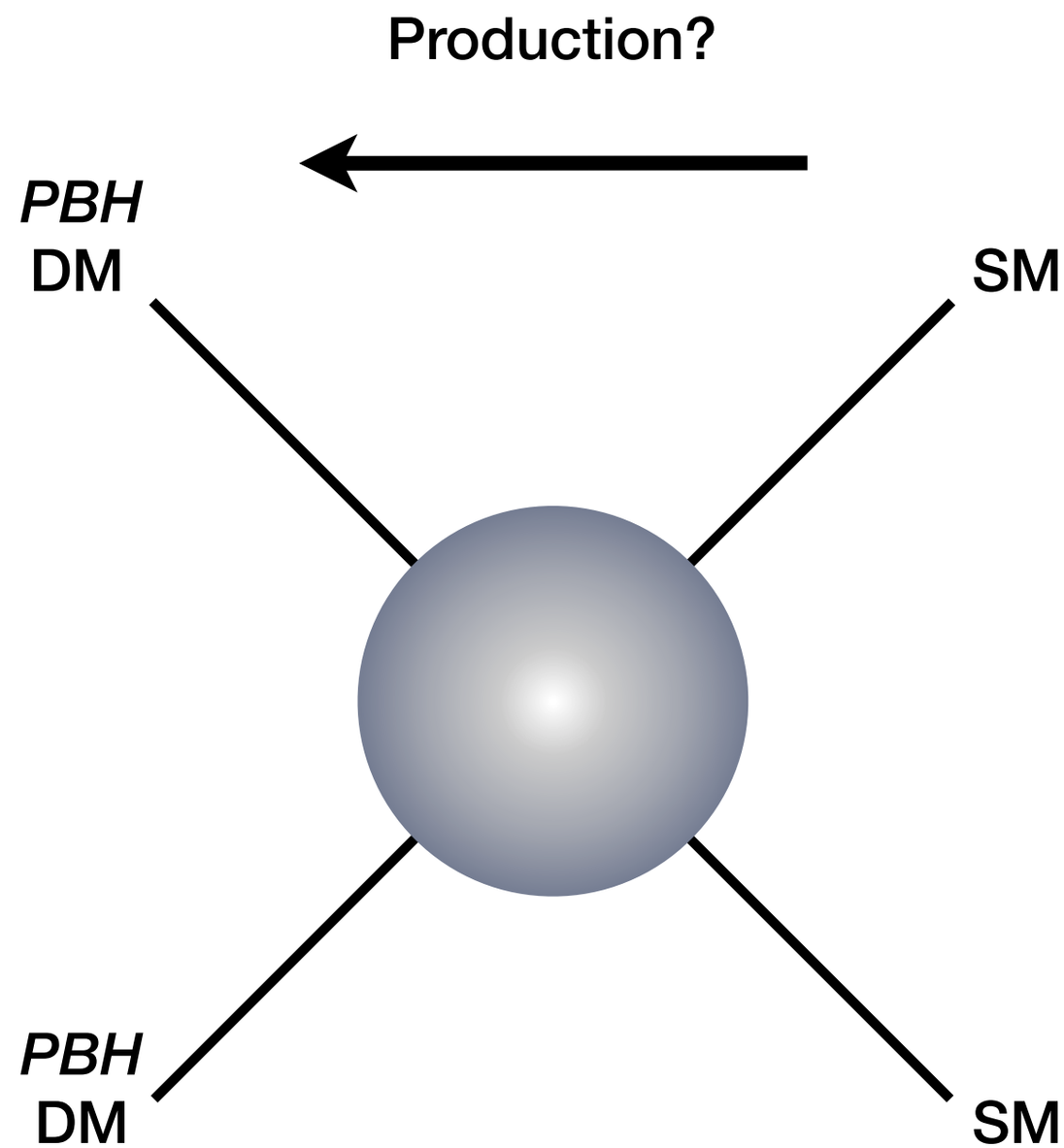
Compare with: $\rho_c = 10^6\left(\frac{t}{s}\right)^{-2}\ \mathrm{g\,cm^{-3}}$



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Compare with: $\rho_c = 10^6\left(\frac{t}{s}\right)^{-2}\,\mathrm{g\,cm^{-3}}$

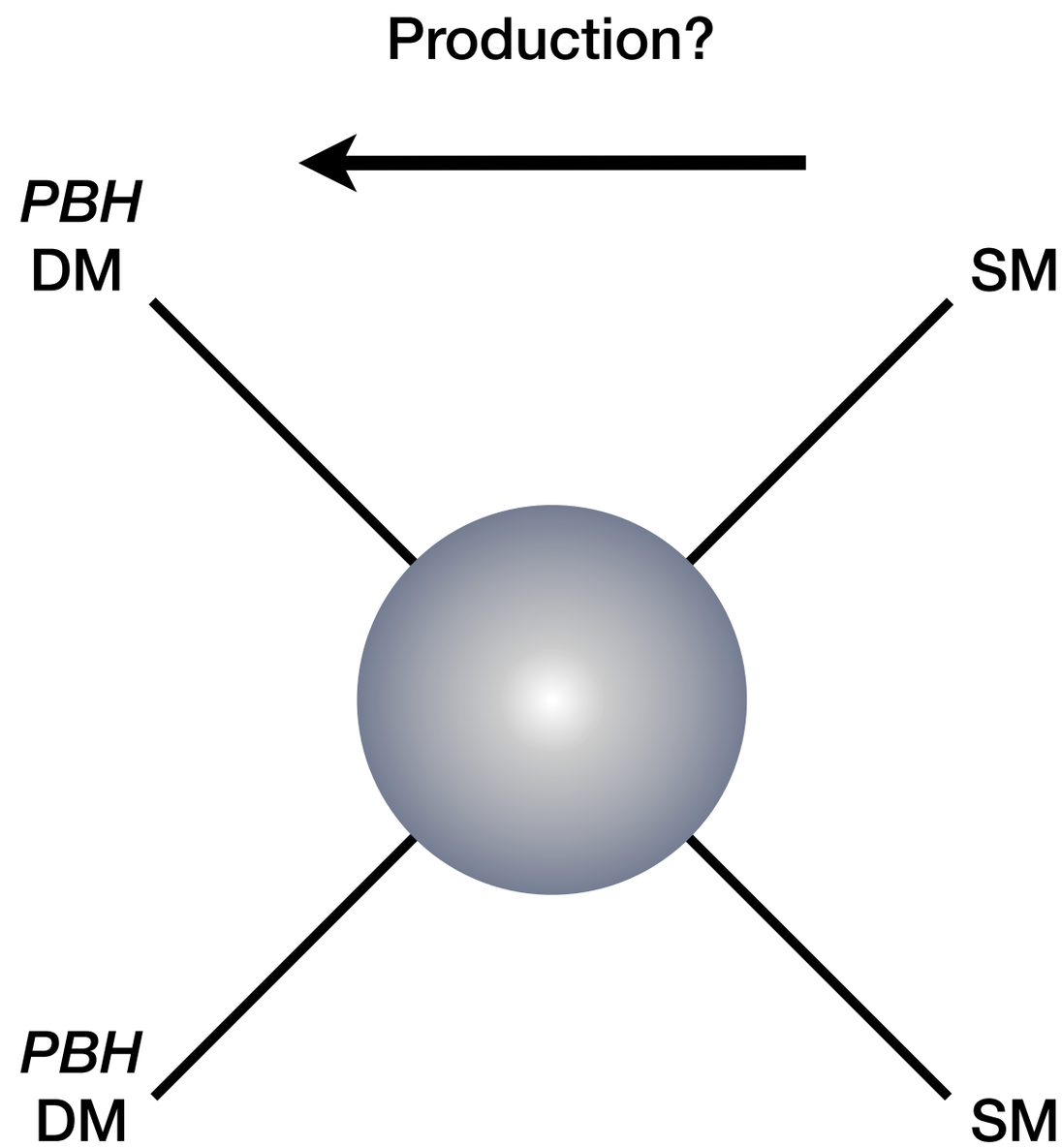
Possibly in the early Universe?

$$M_H \approx \frac{c^3 t}{G} = 10^{15}\,\mathrm{g}\left(\frac{t}{10^{-23}\,\mathrm{s}}\right)$$

(Planck mass) $10^{-5}\,\mathrm{g}:\ t \sim 10^{-43}\,\mathrm{s}$

(post QCD transition) $30\,M_\odot:\ t \sim 1\,\mathrm{ms}$

(Nucleosynthesis) $10^5 M_\odot:\ t \sim 1\,\mathrm{s}$



PBH Formation: Loopy ideas aside...

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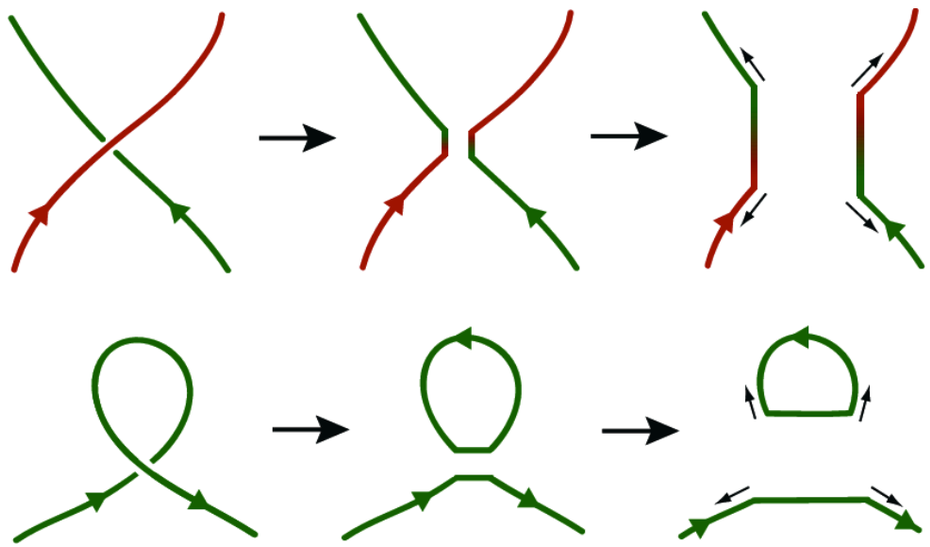
Cosmic Strings:

Figure: J. Rocha (2008)



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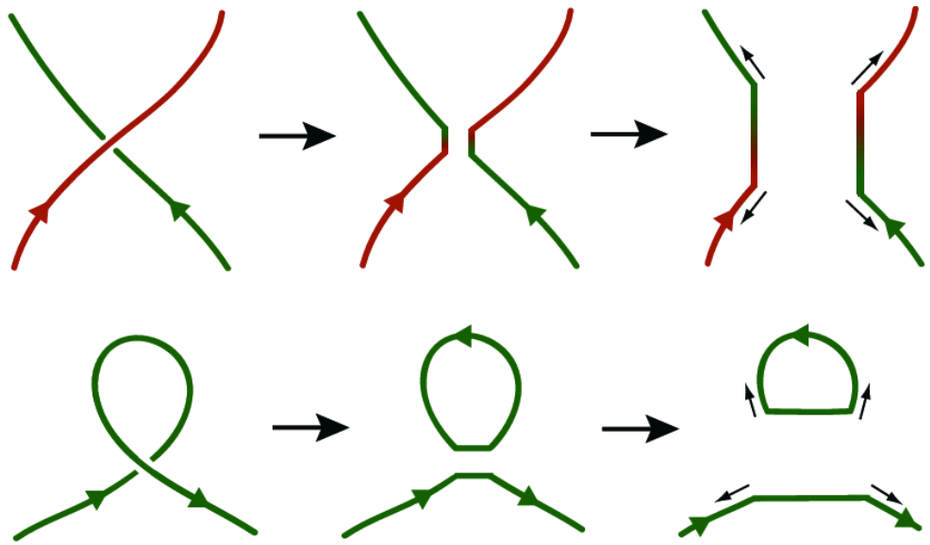

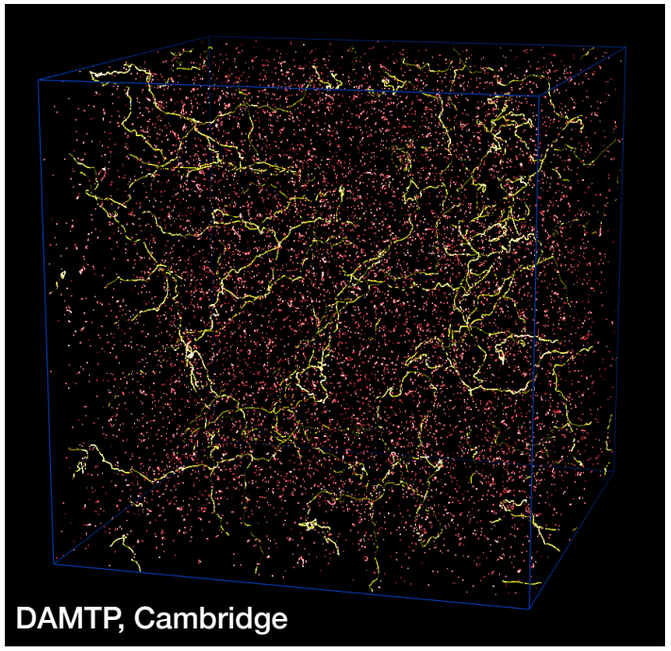

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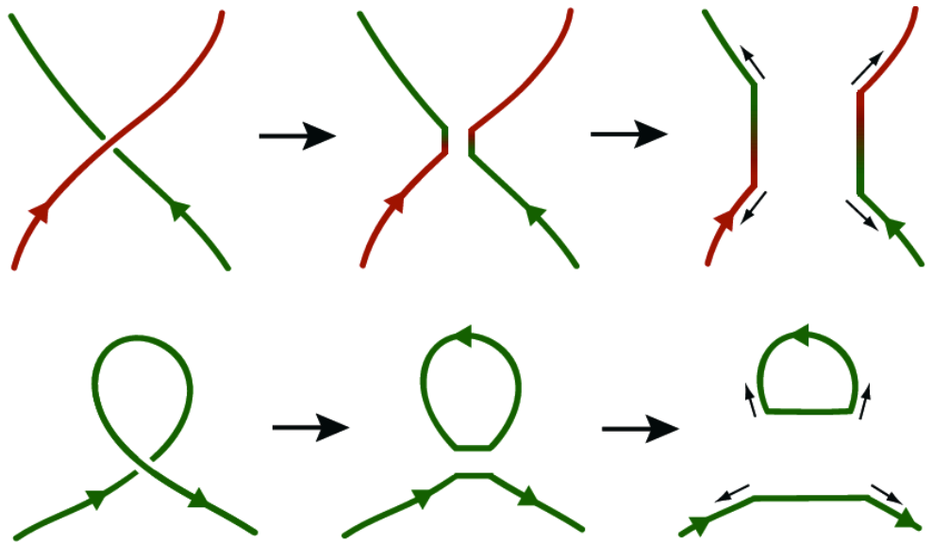

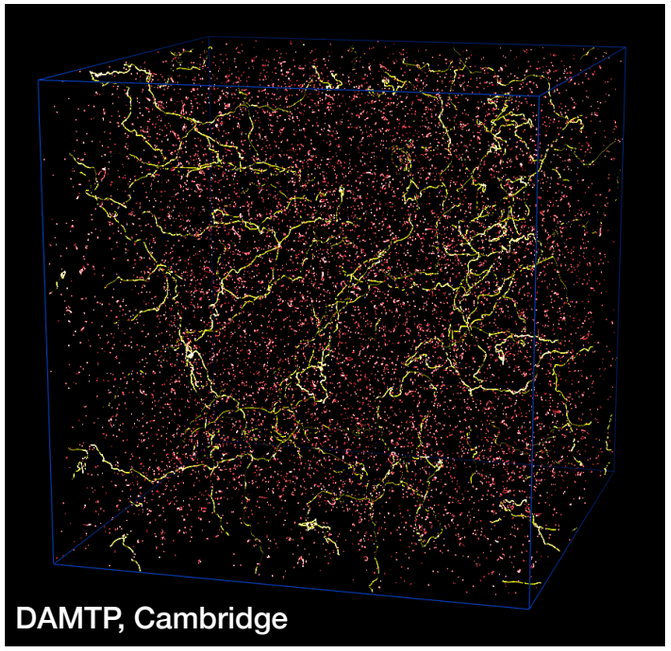

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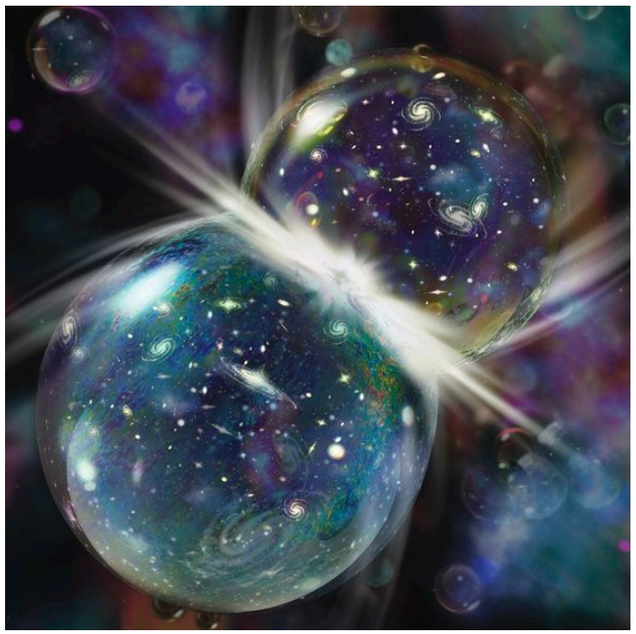

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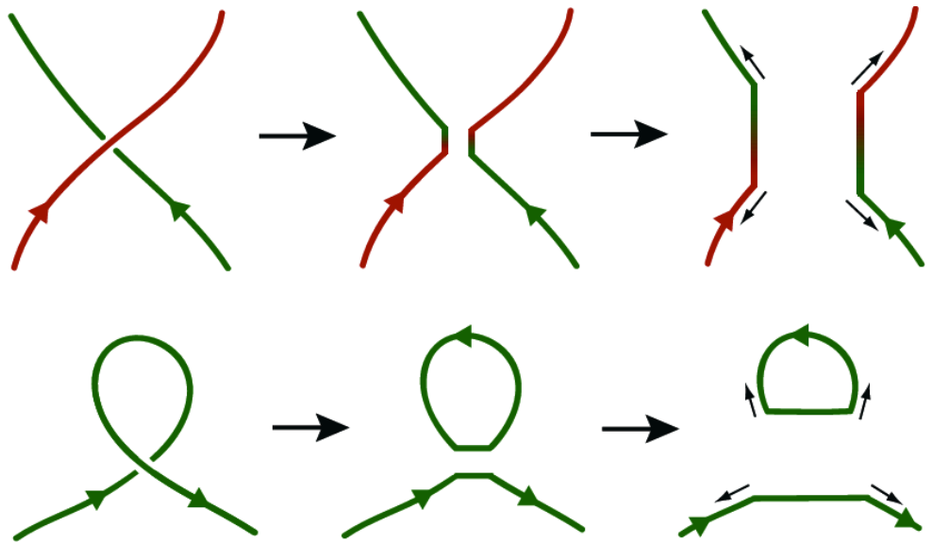

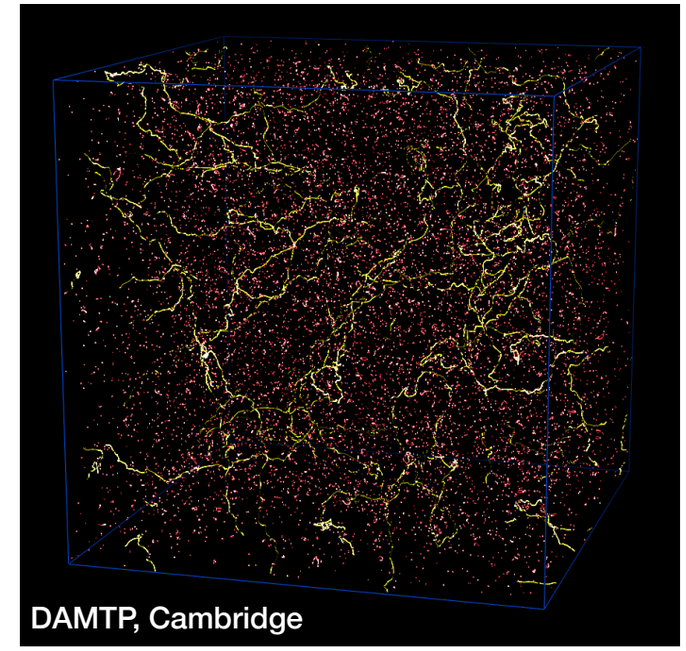

Bubble Collisions:

QCD phase transition: $1\,M_\odot: \;\; t \sim 10\,\mu\mathrm{s}$

(we'll get back to this later...)

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PBH Formation: Collapse of Density Perturbations

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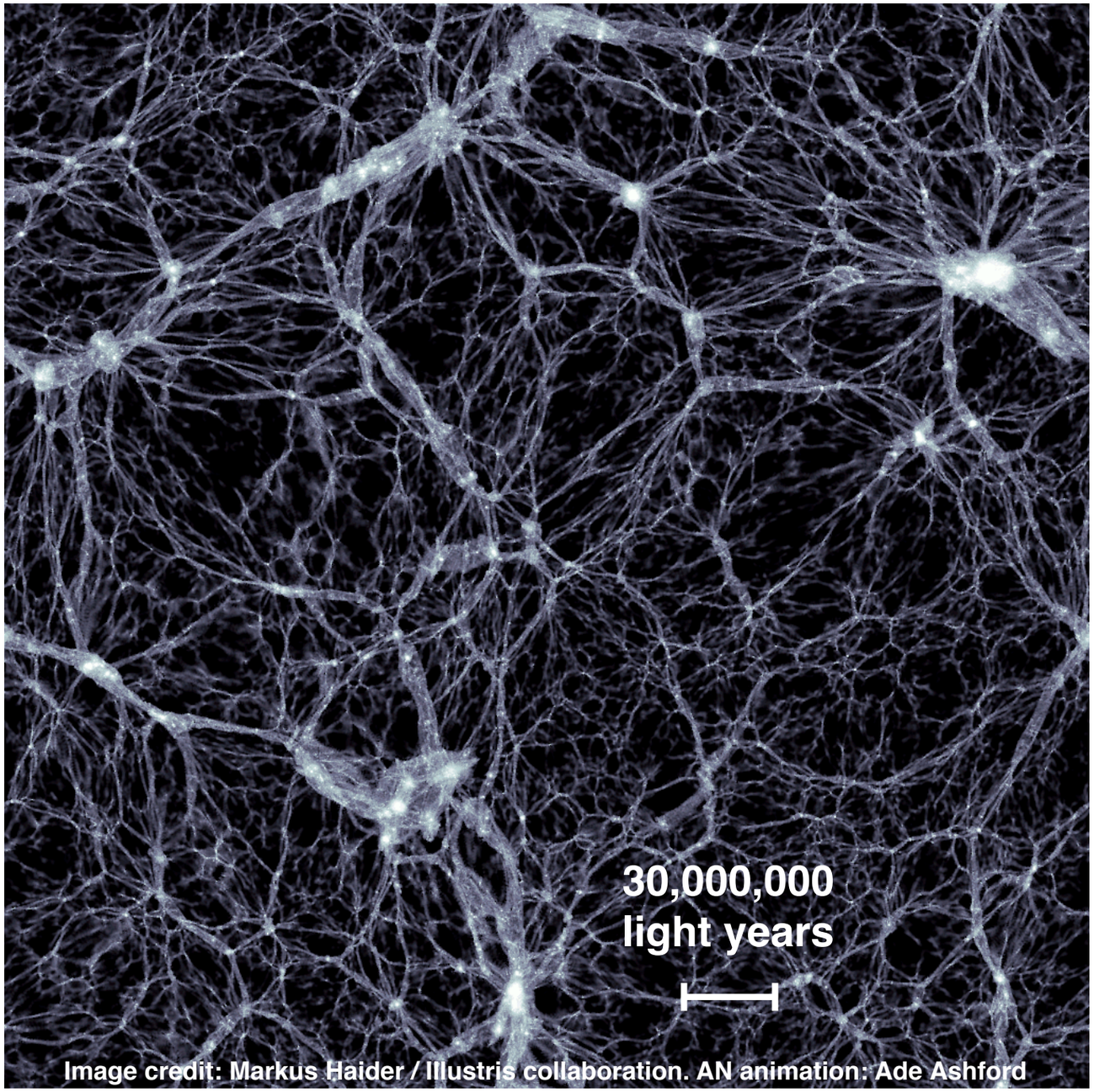

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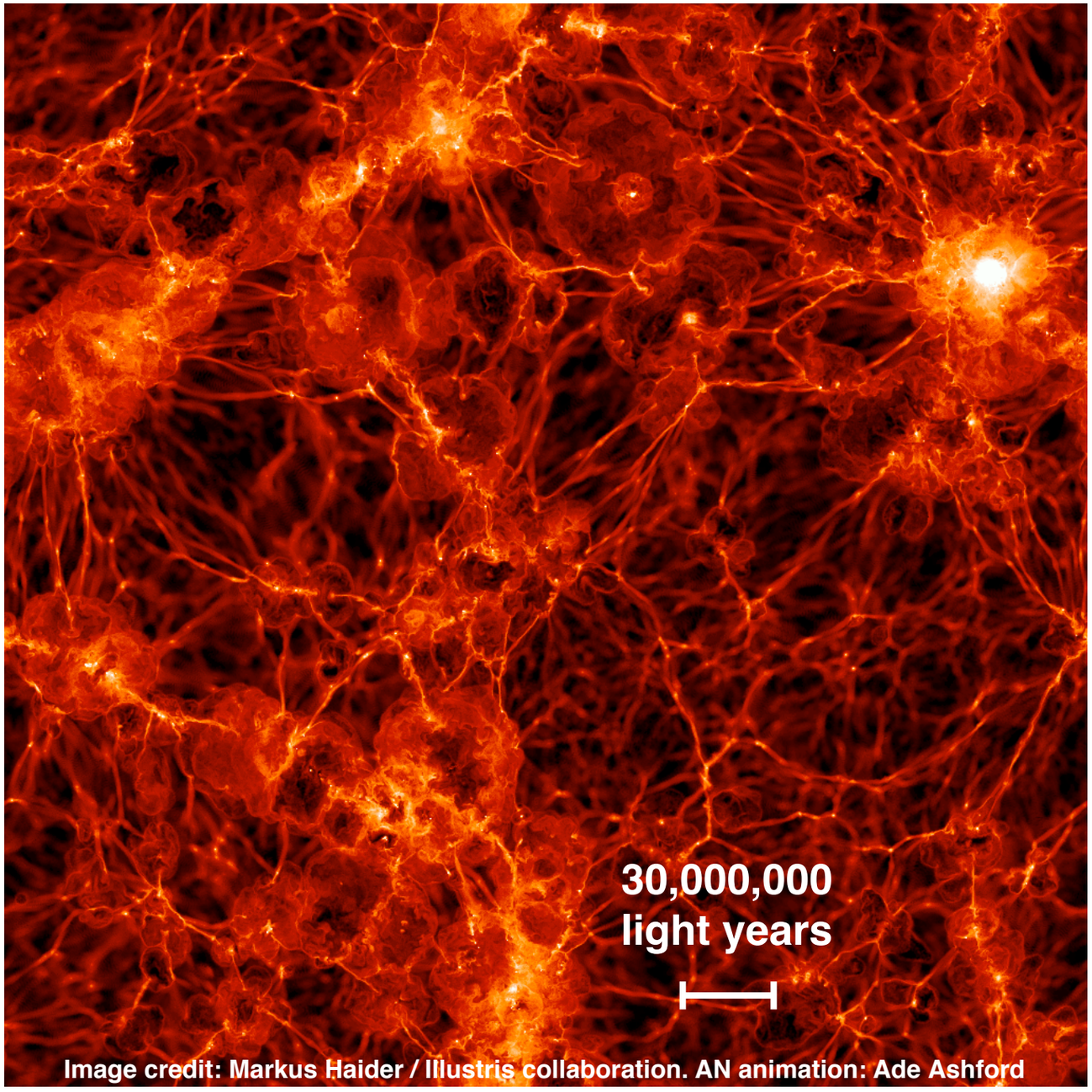
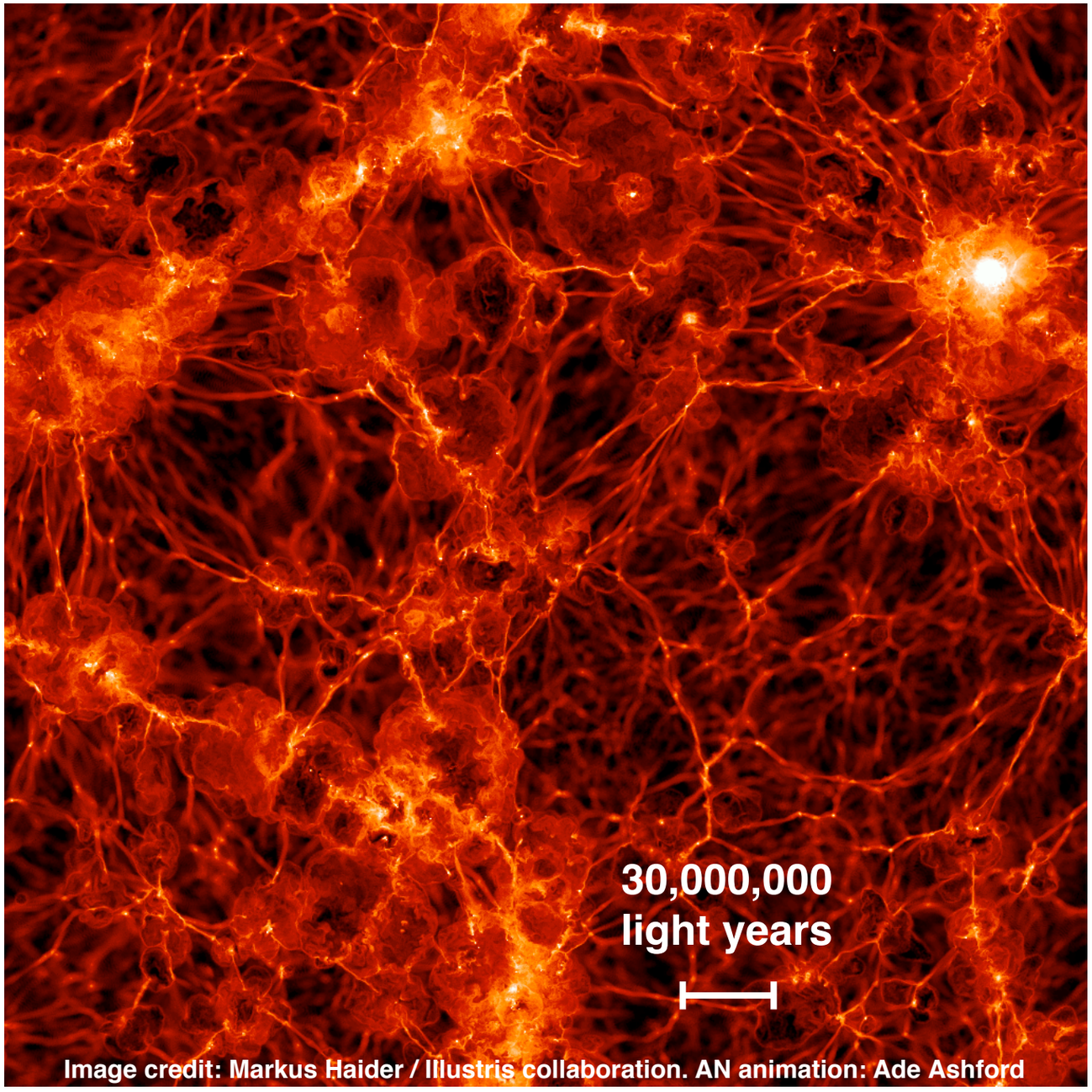


PBH Formation: Collapse of Density Perturbations

Gravitational instability → Growth of structure



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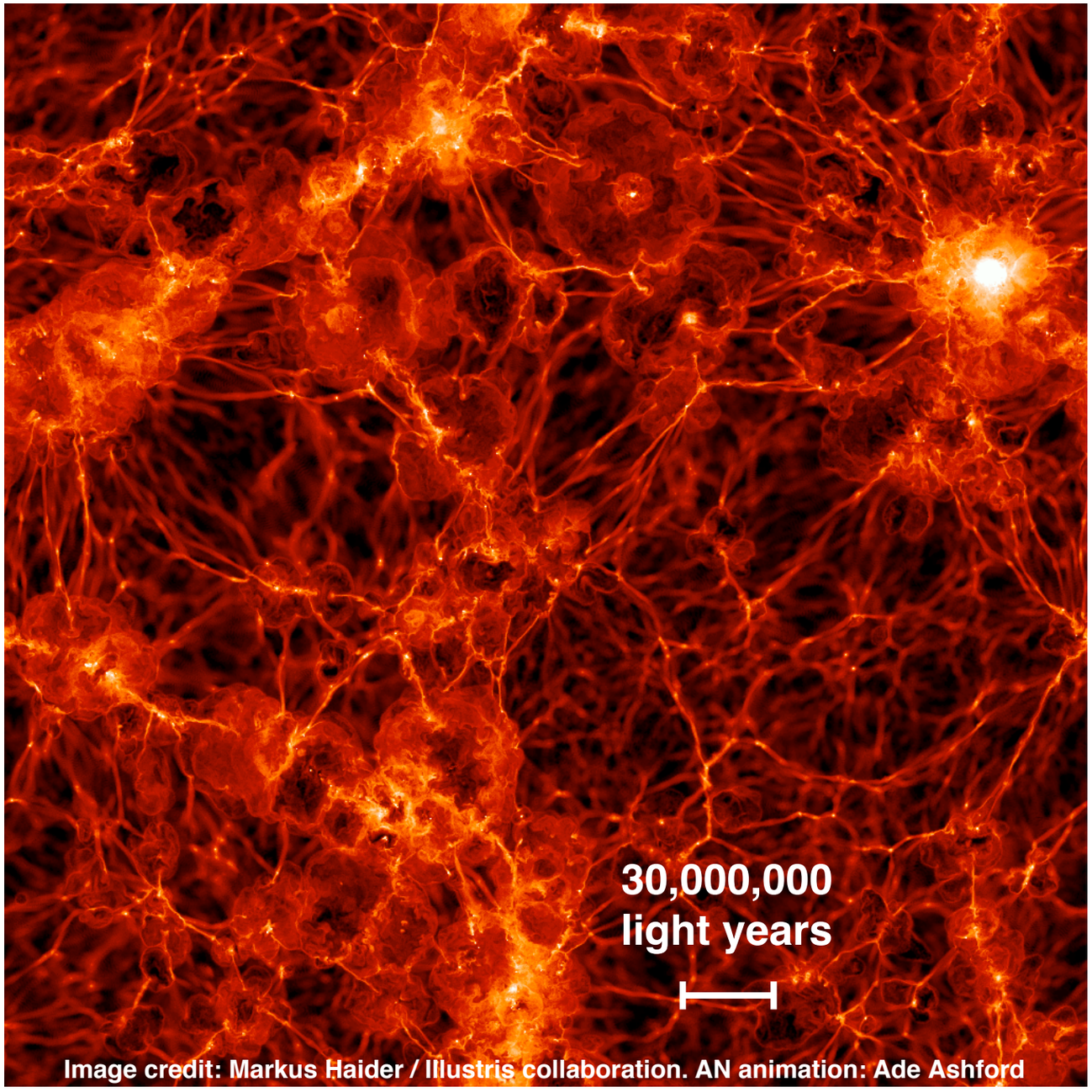
Density contrast:

$$\delta \equiv (\rho - \bar{\rho})/\bar{\rho}$$



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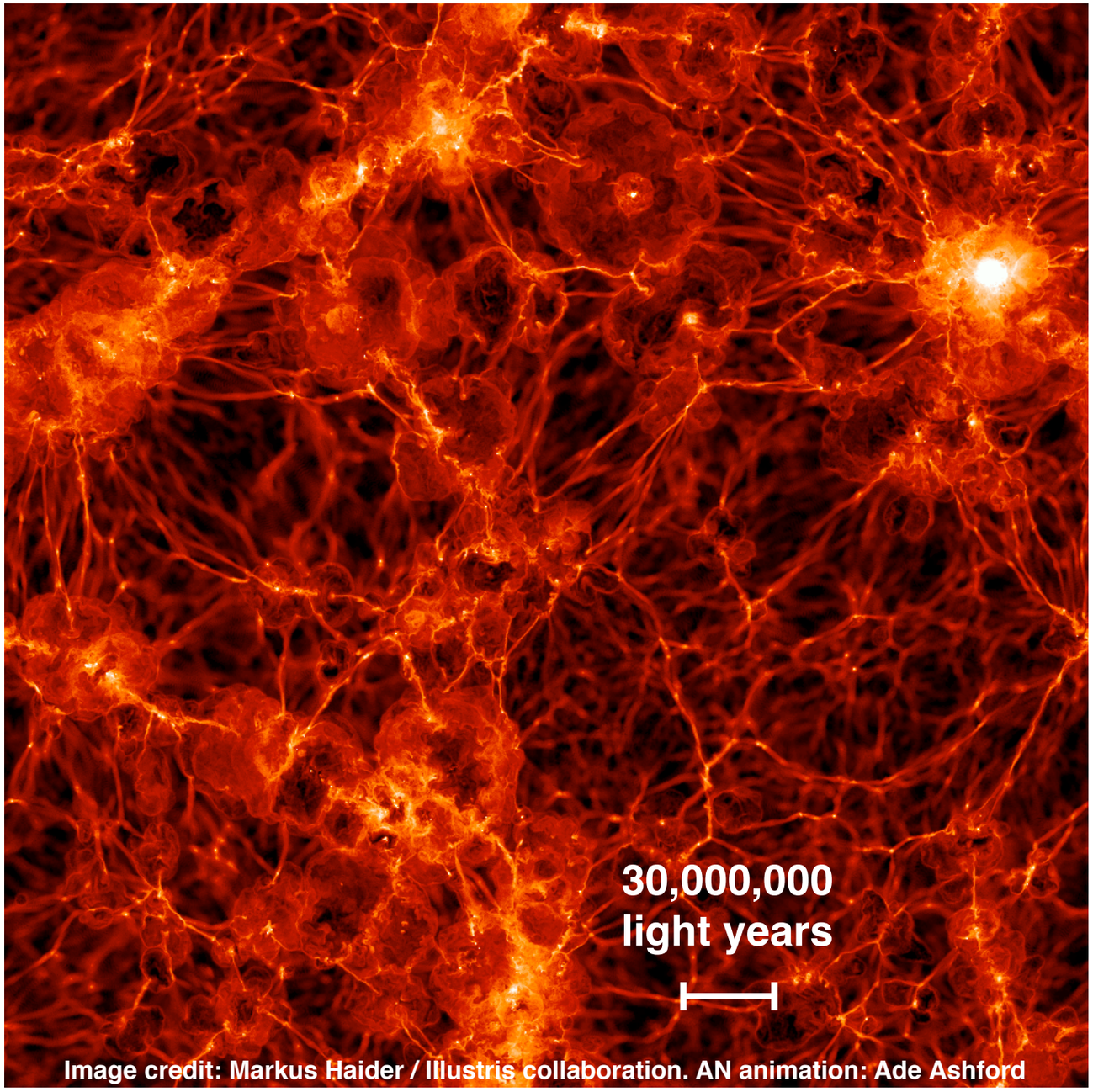

Image credit: Markus Haider / Illustris collaboration. AN animation: Ade Ashford

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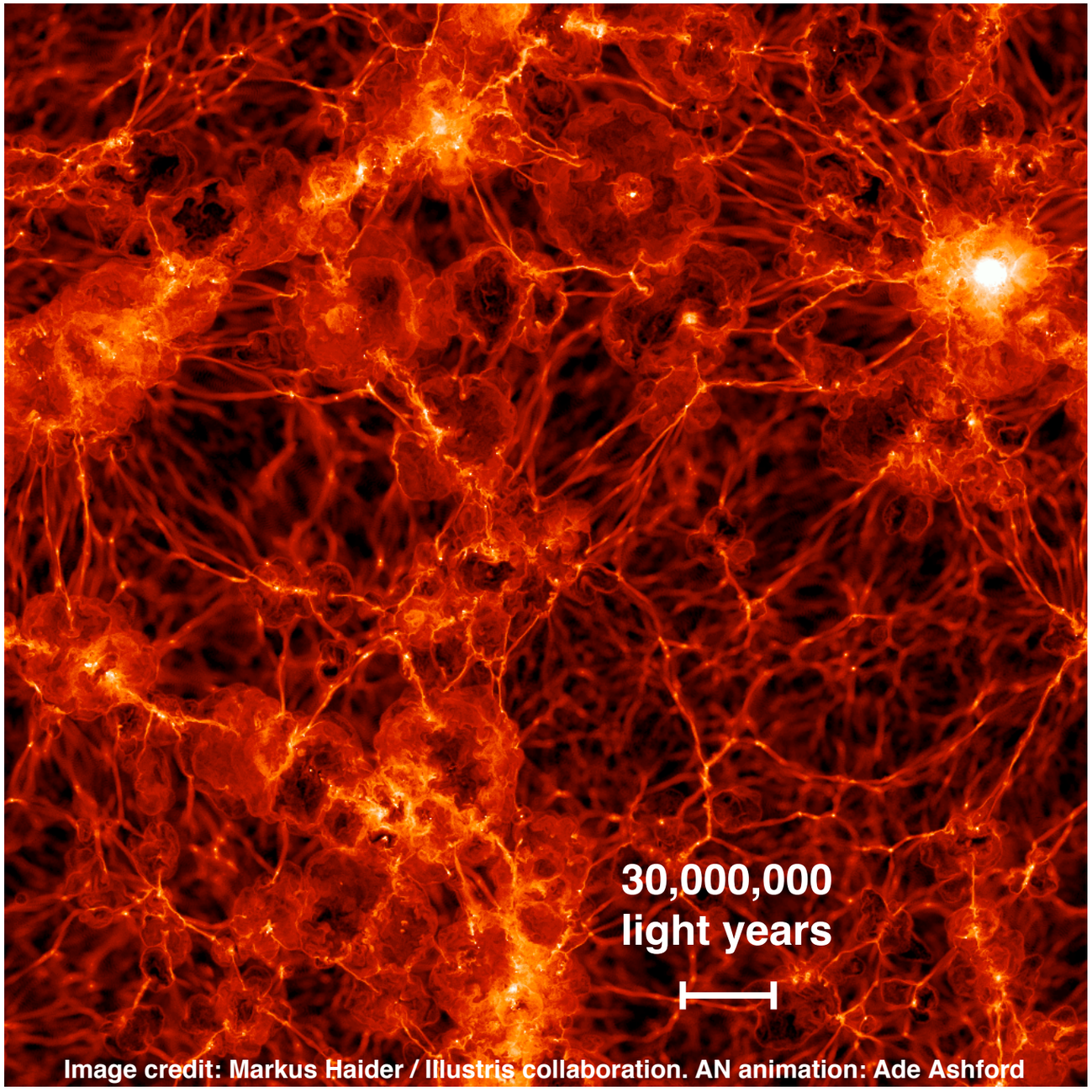

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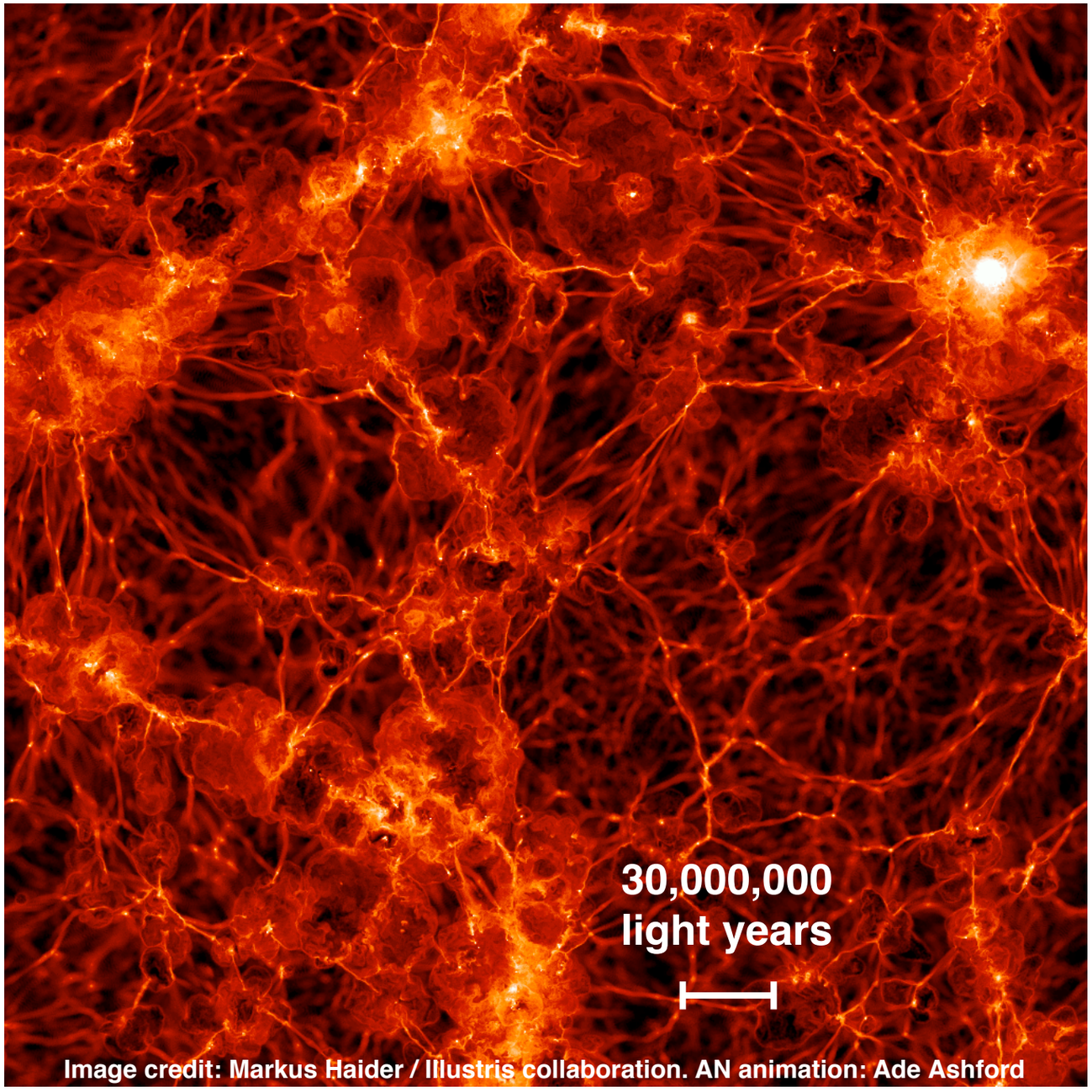

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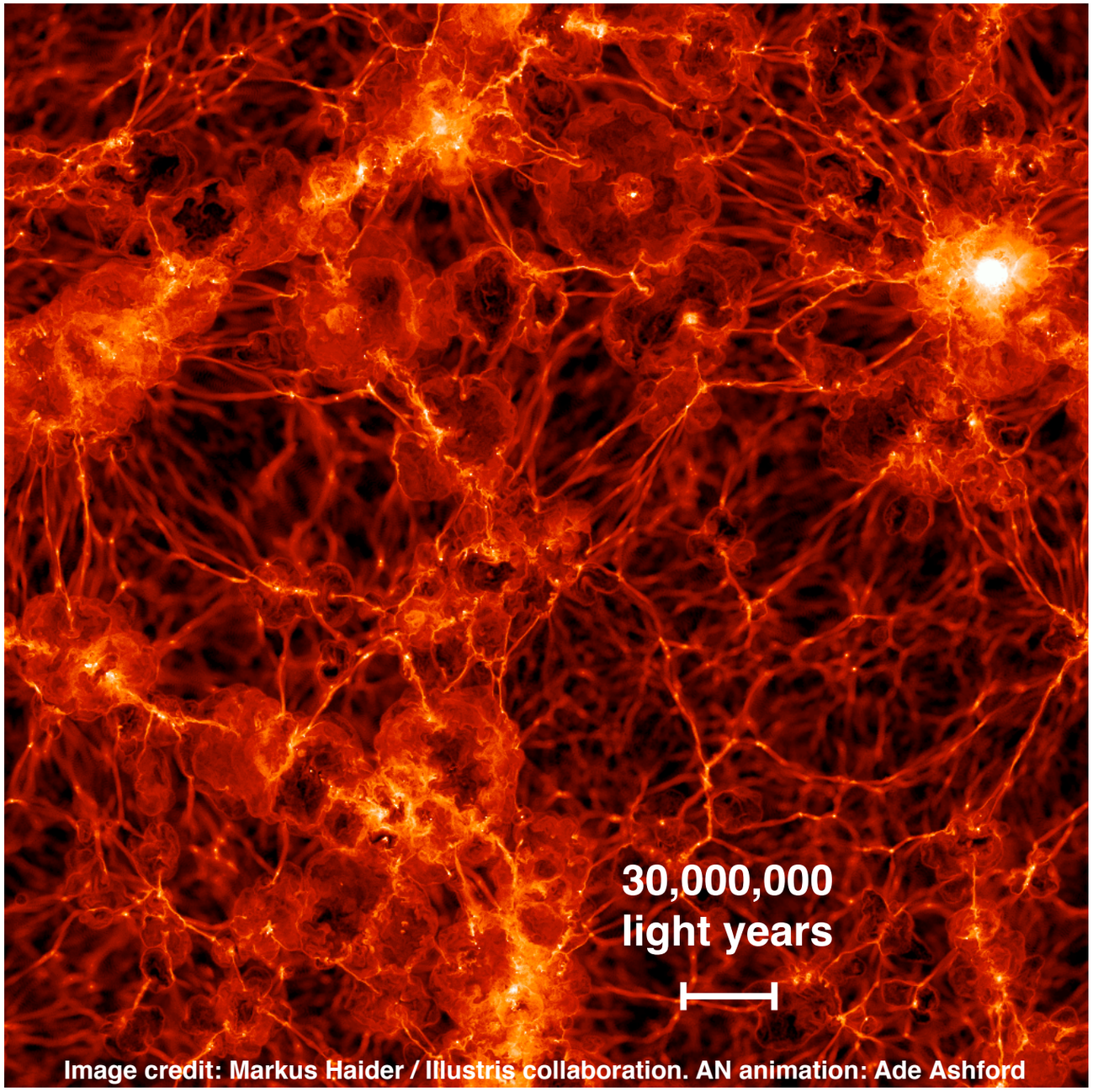

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PBH mass:

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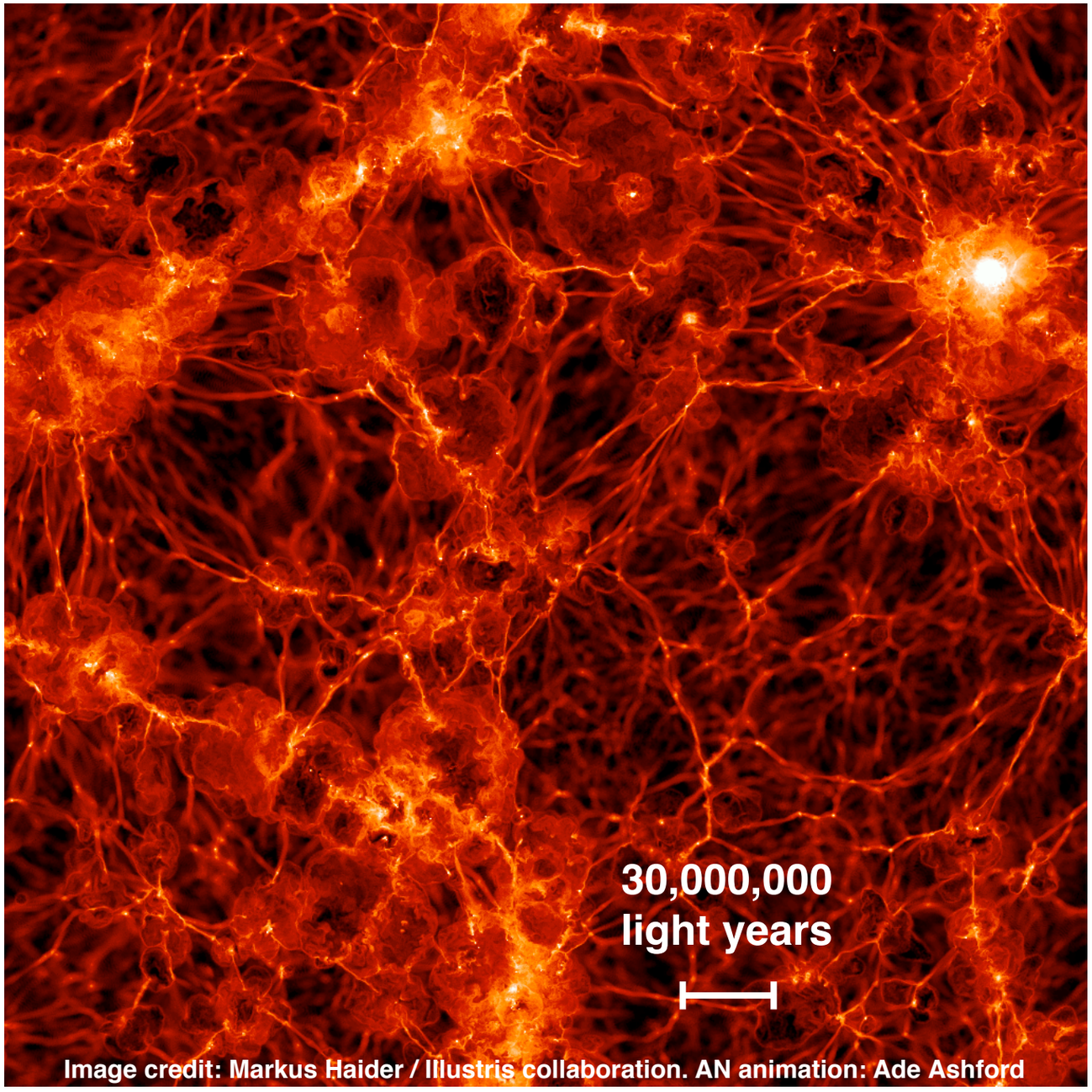

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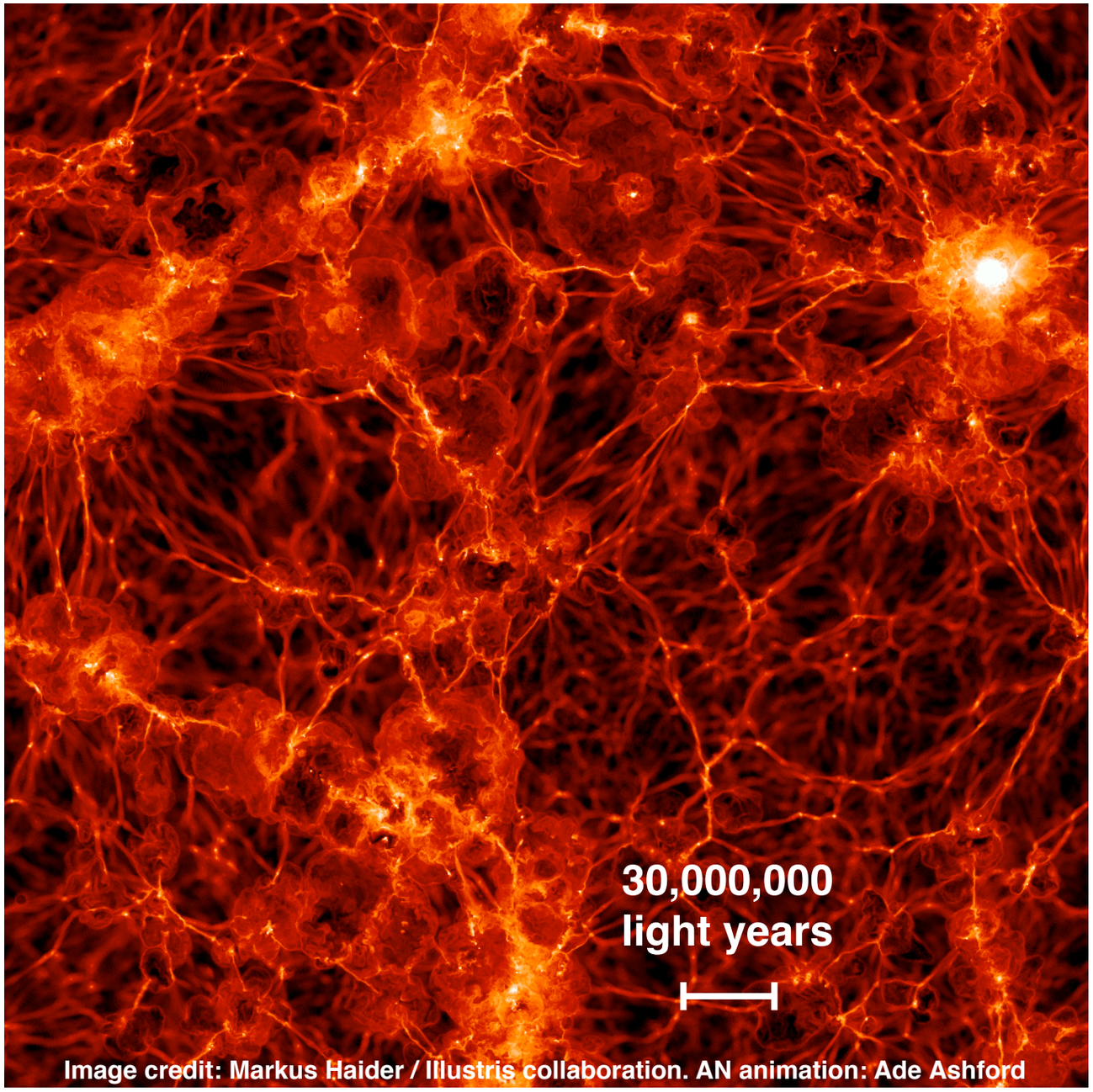

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(For details see Musco et al., arXiv:2011.03014 and Riotto's talk on Wednesday!)

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Collapse of overdensities during radiation domination:

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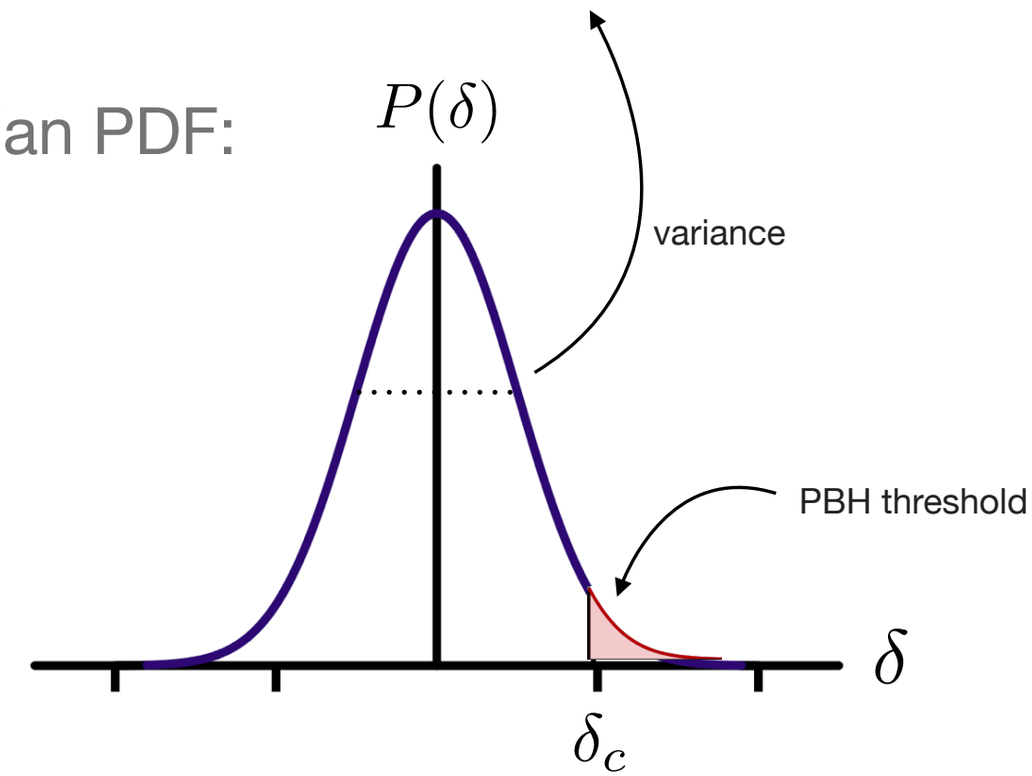
Press-Schechter for a Gaussian PDF:



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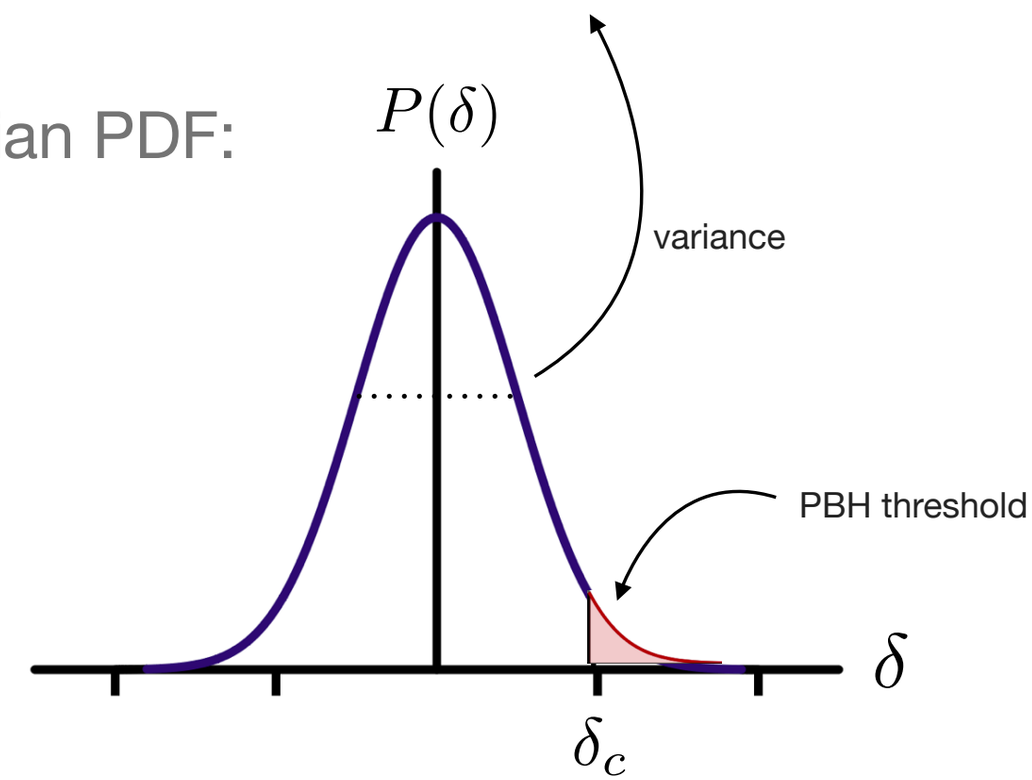

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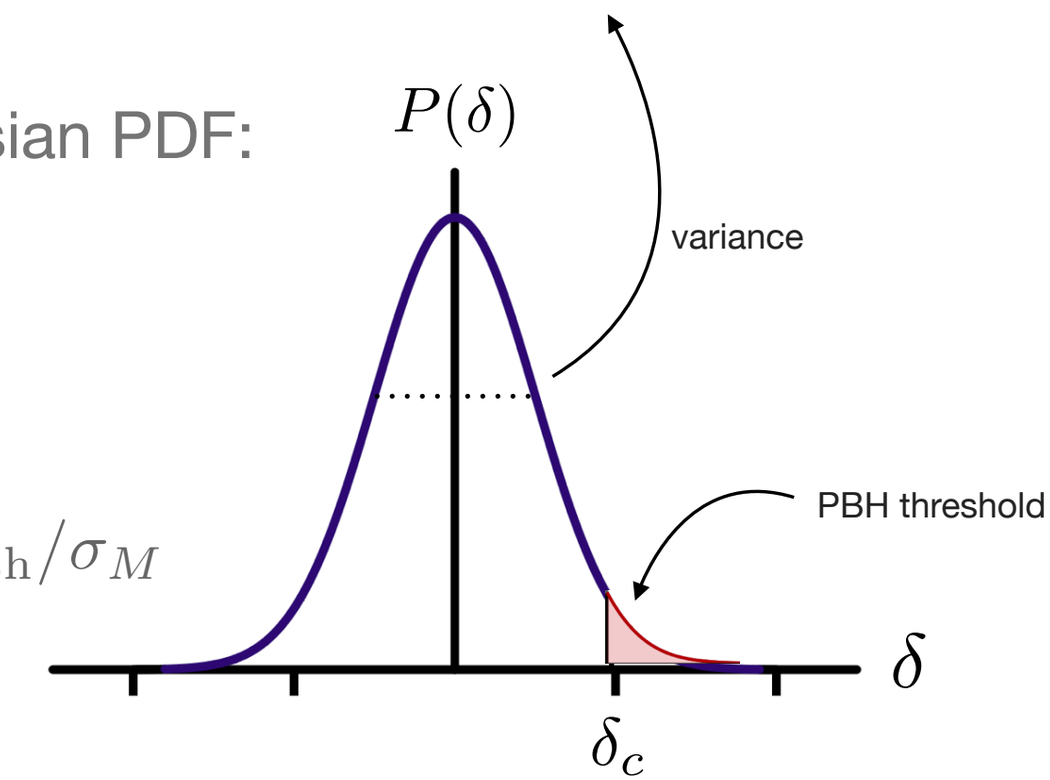

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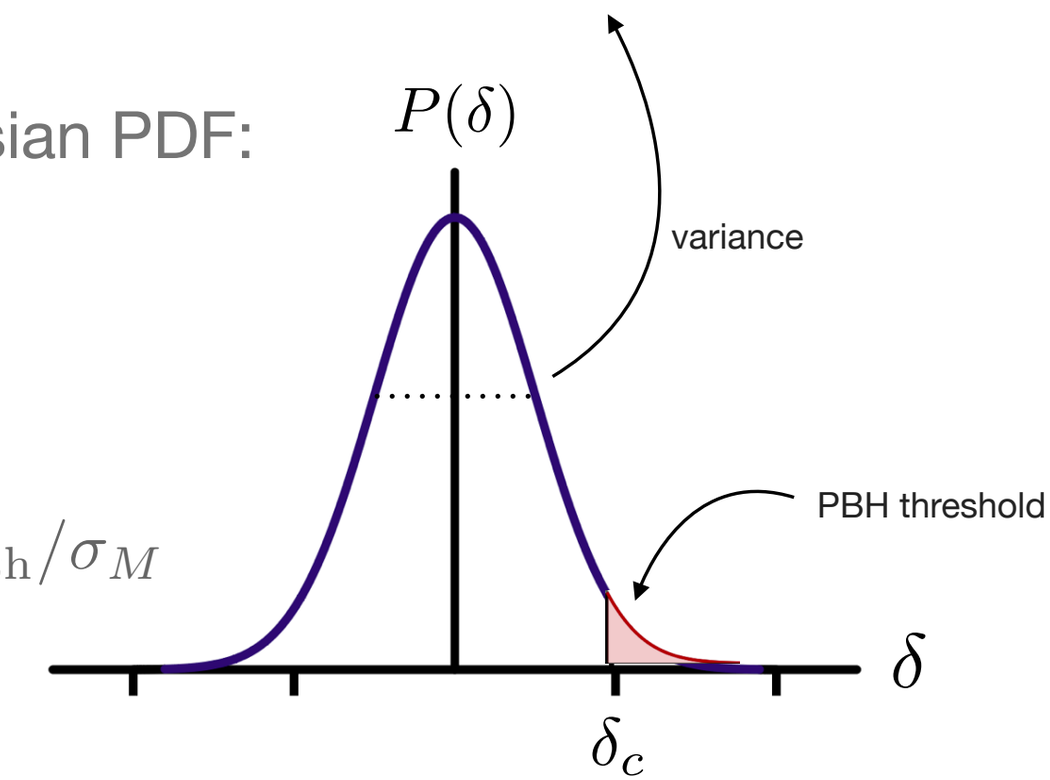

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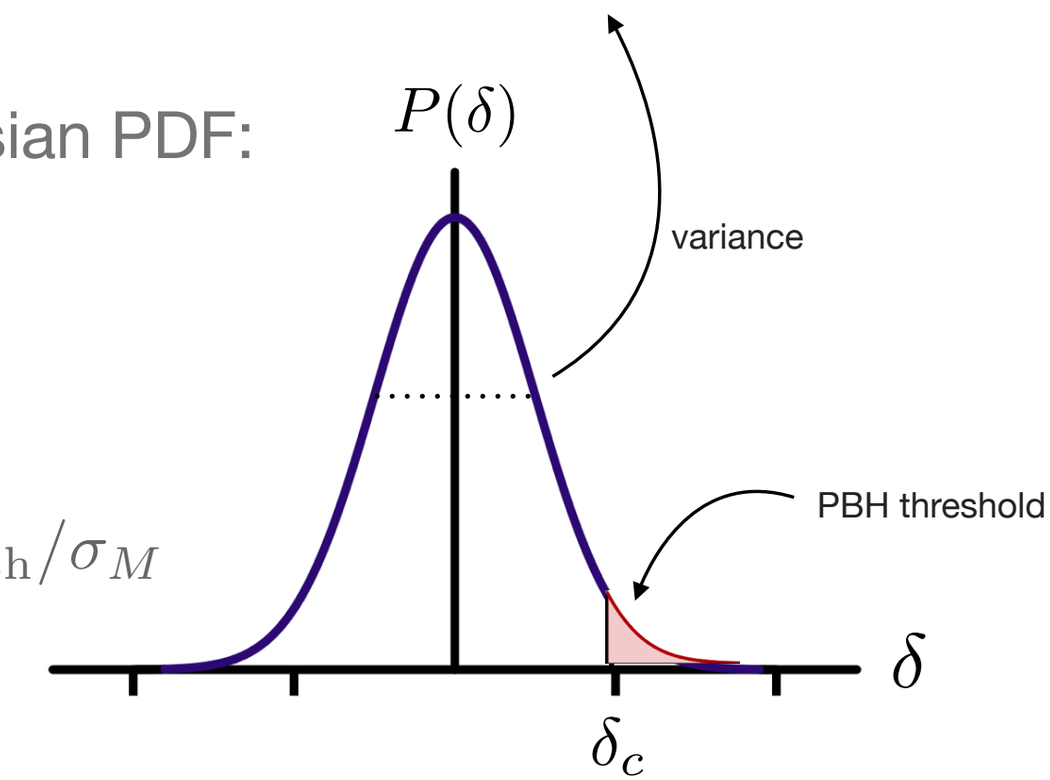

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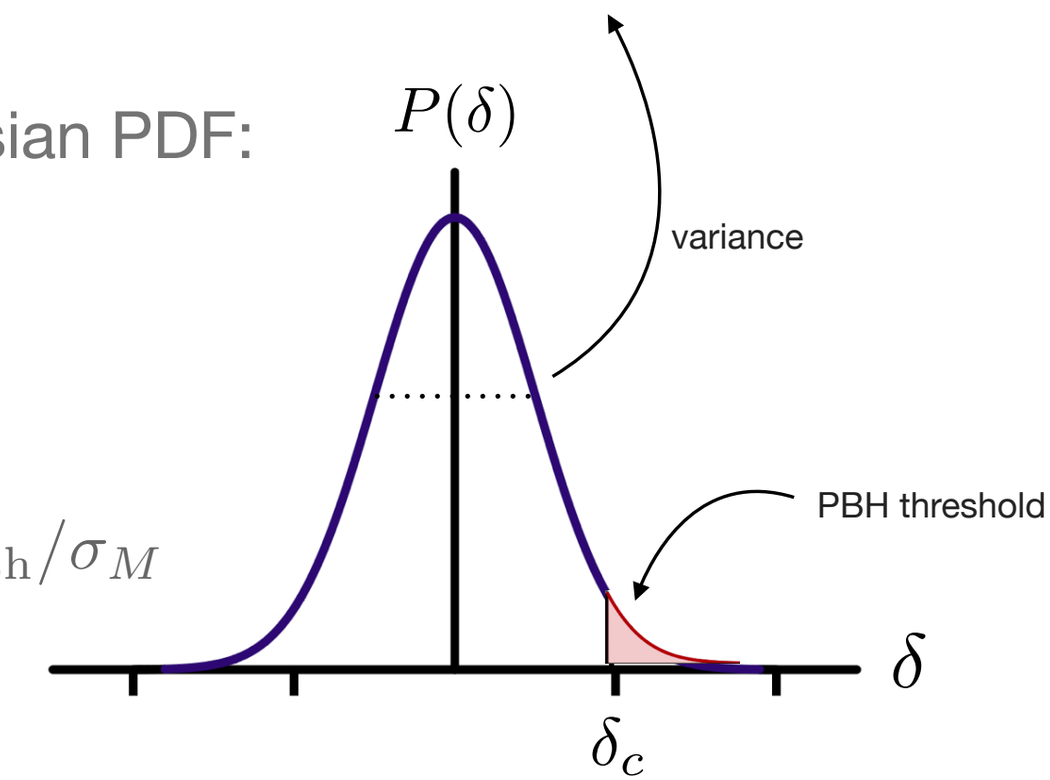

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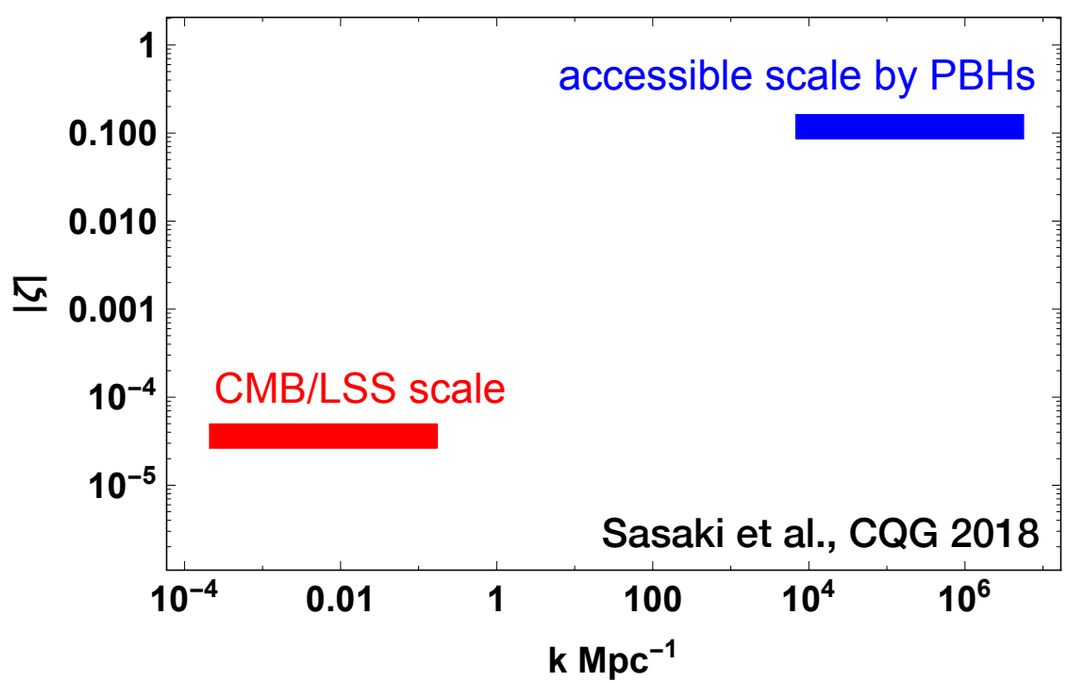

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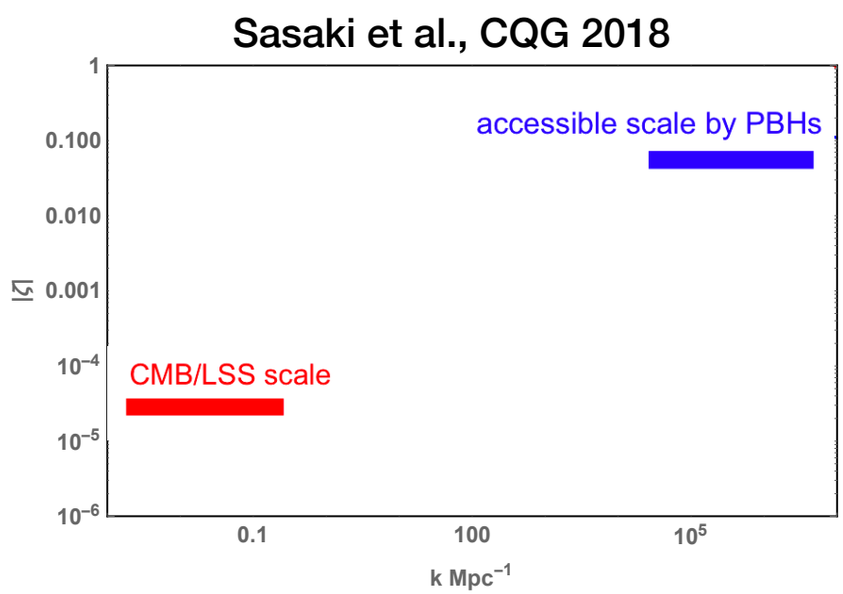

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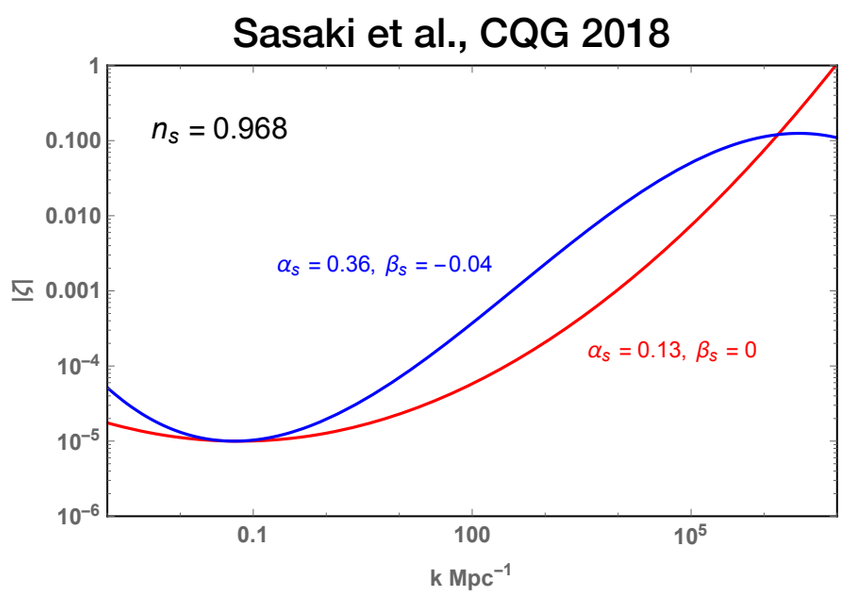

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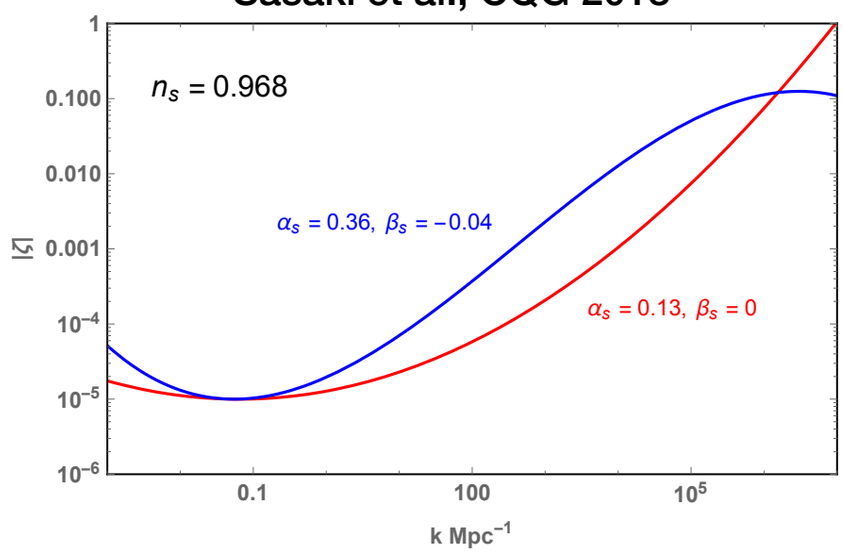
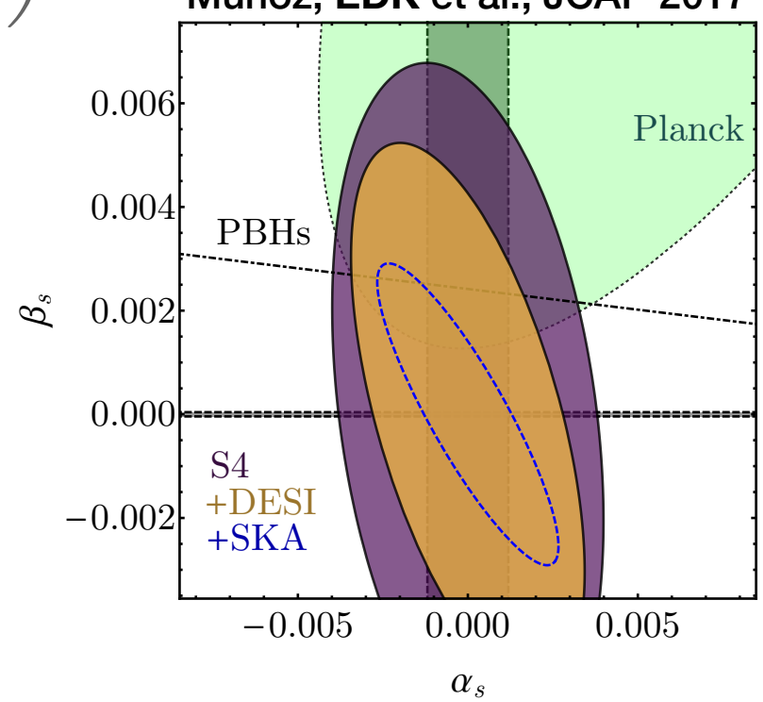
Sasaki et al., CQG 2018



Muñoz, EDK et al., JCAP 2017



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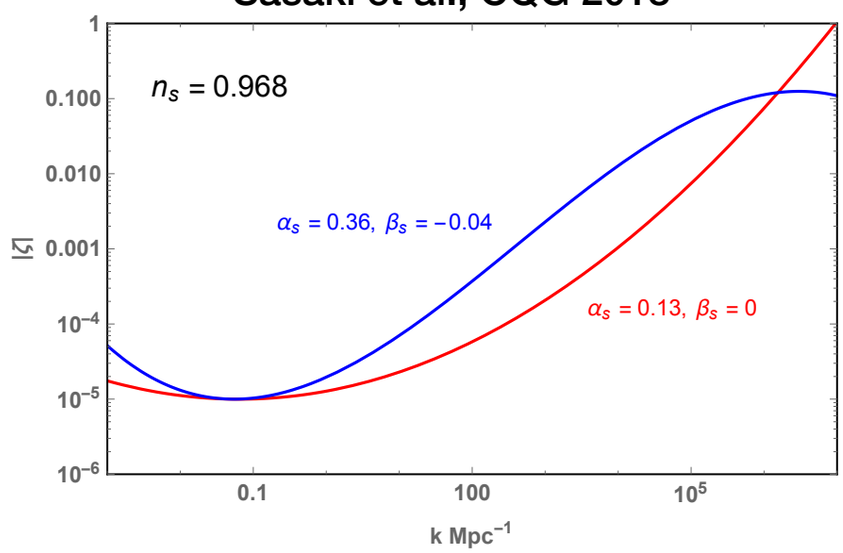

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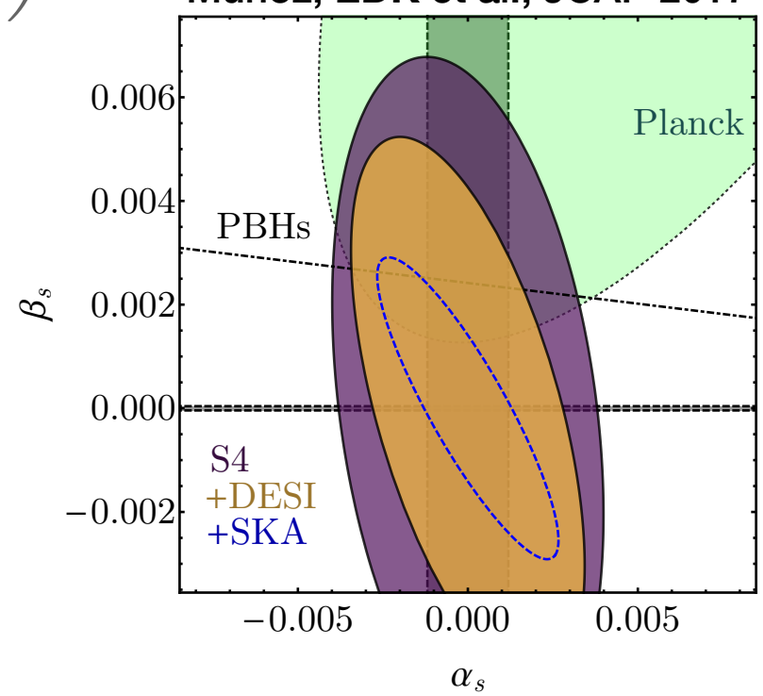

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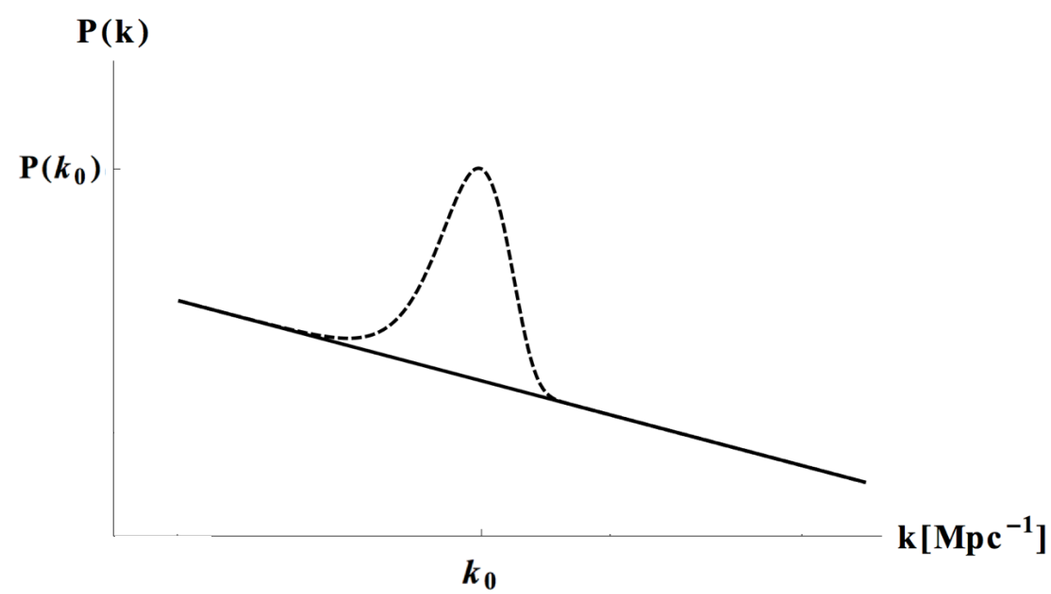

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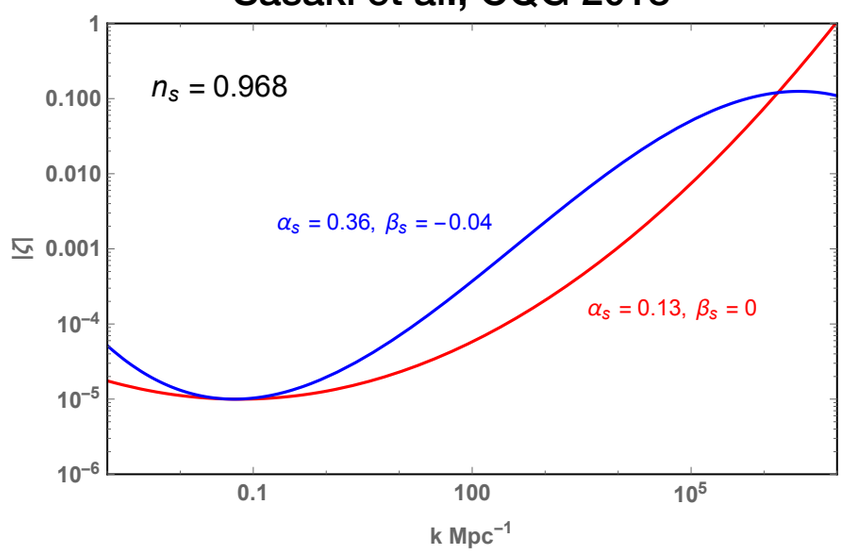

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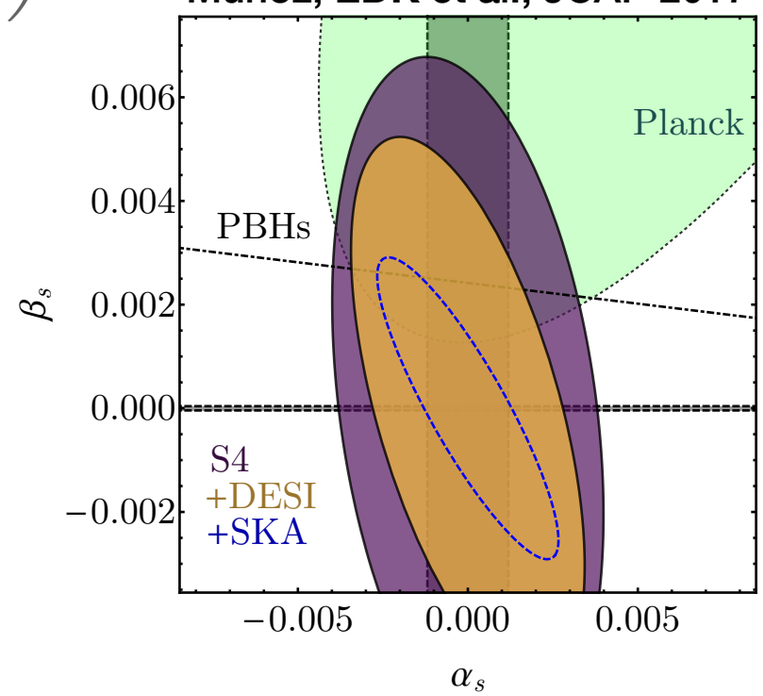

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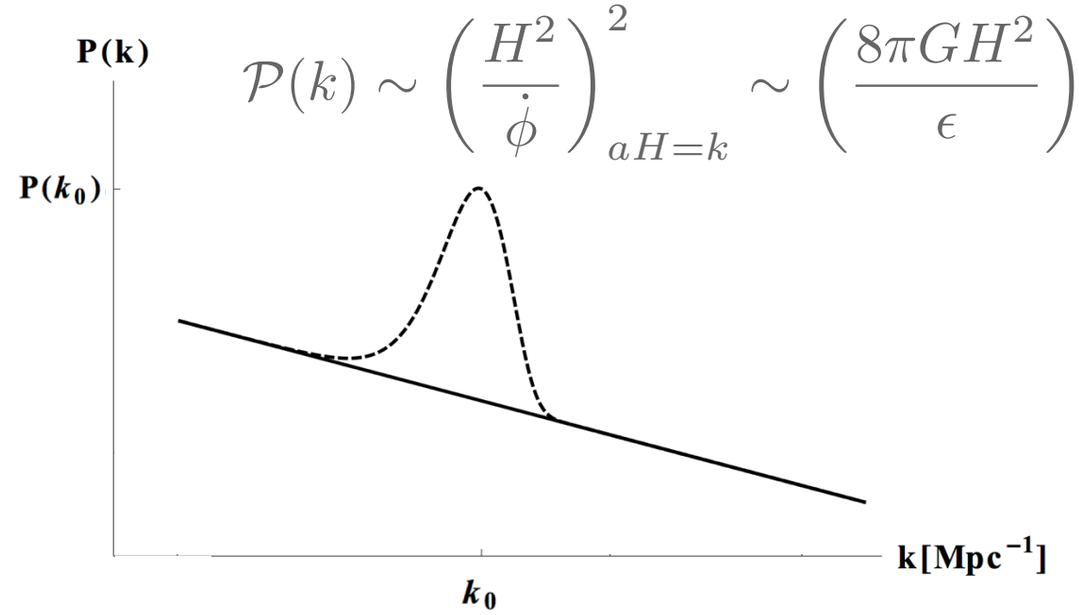

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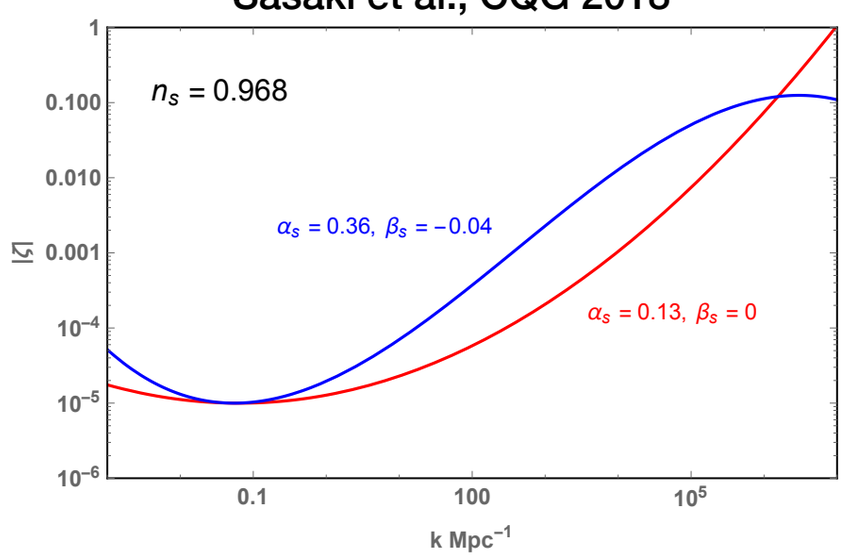

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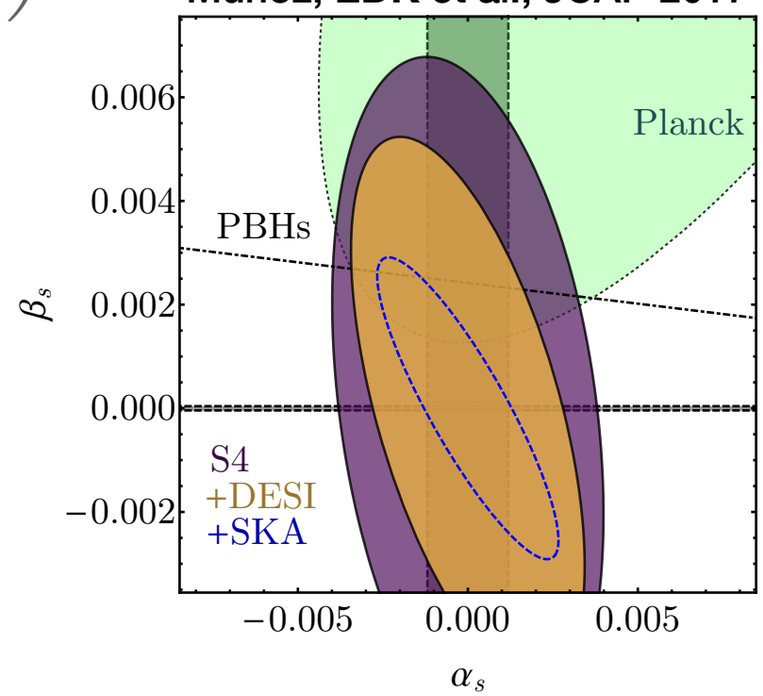

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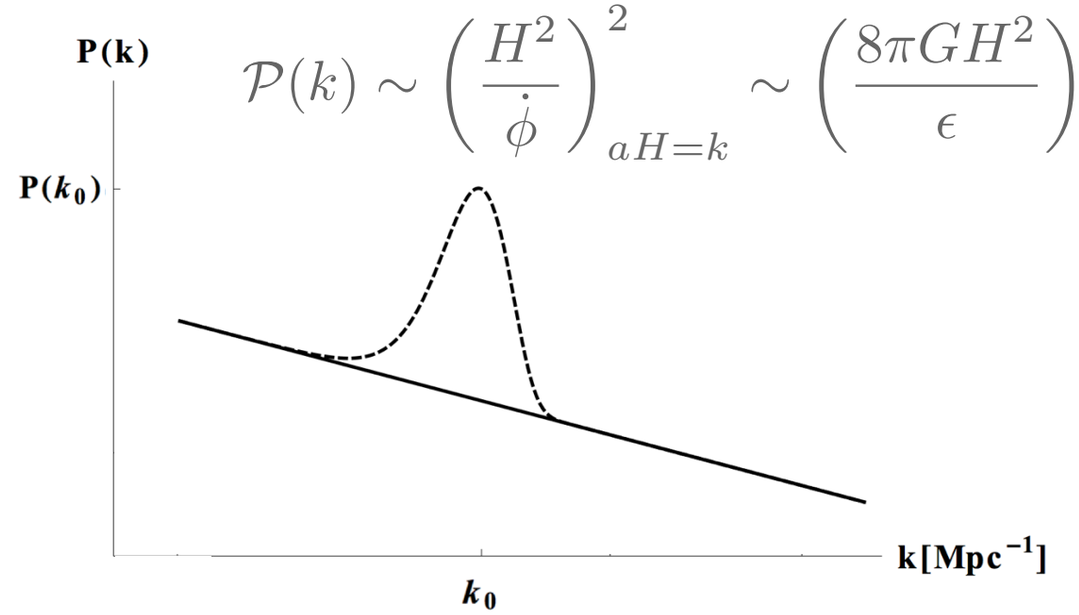

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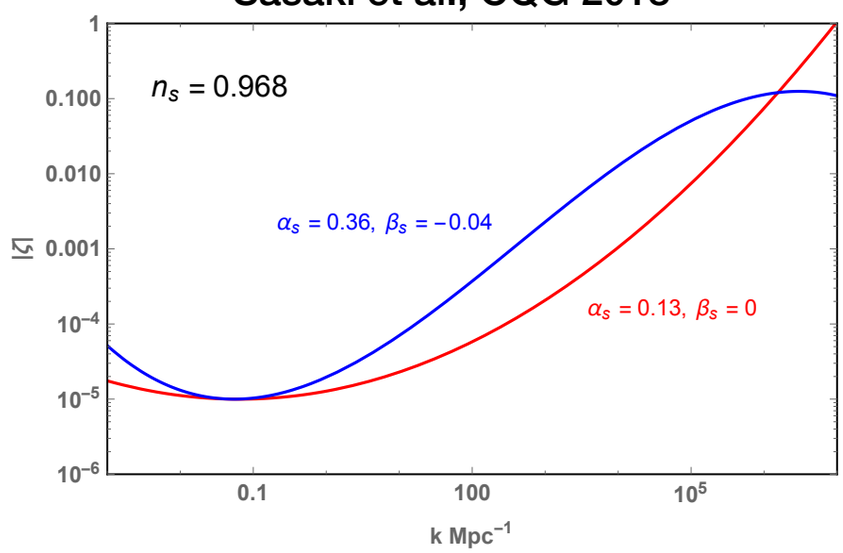

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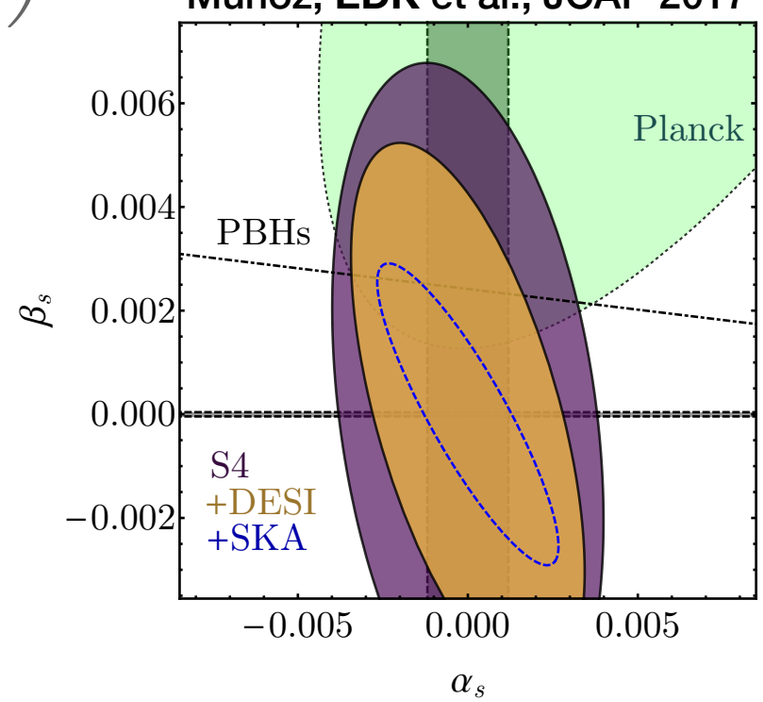

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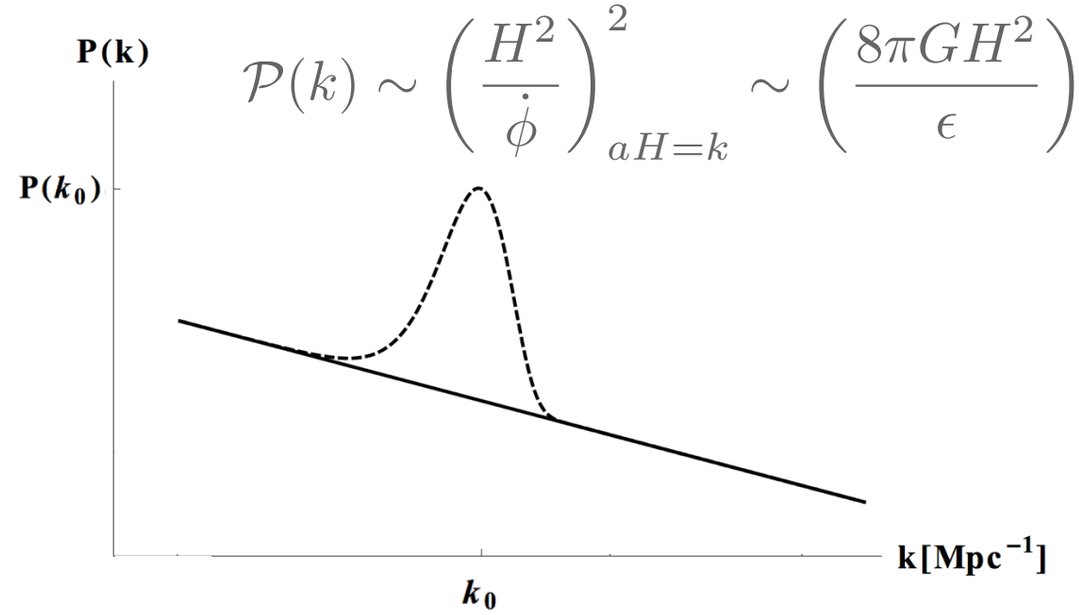

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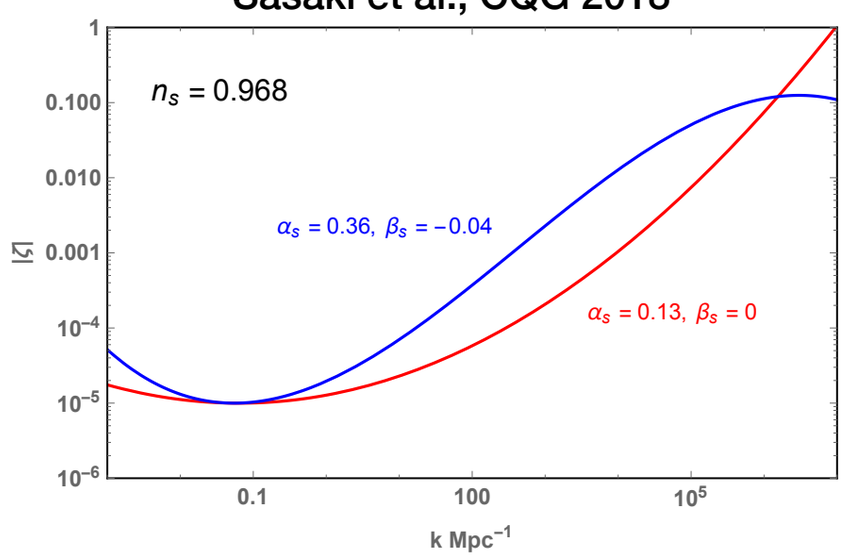

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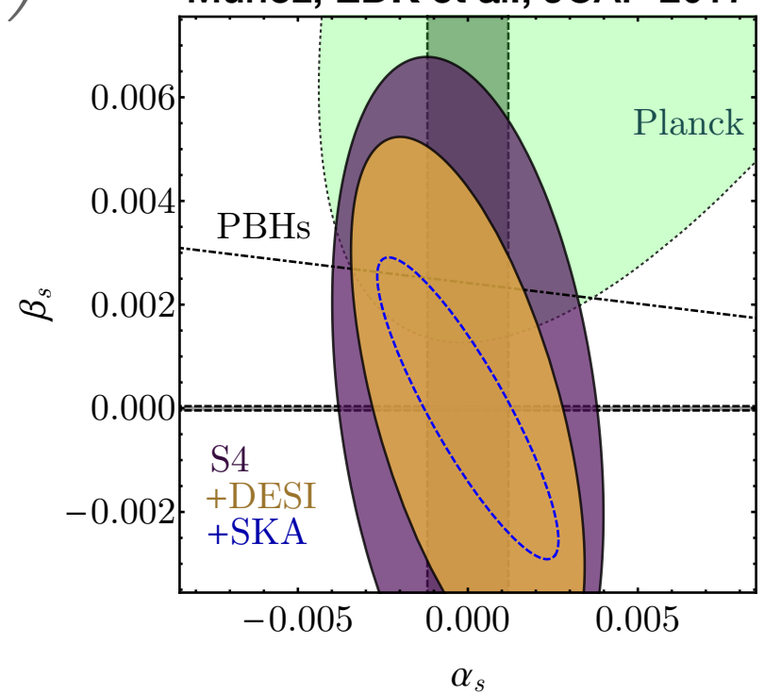

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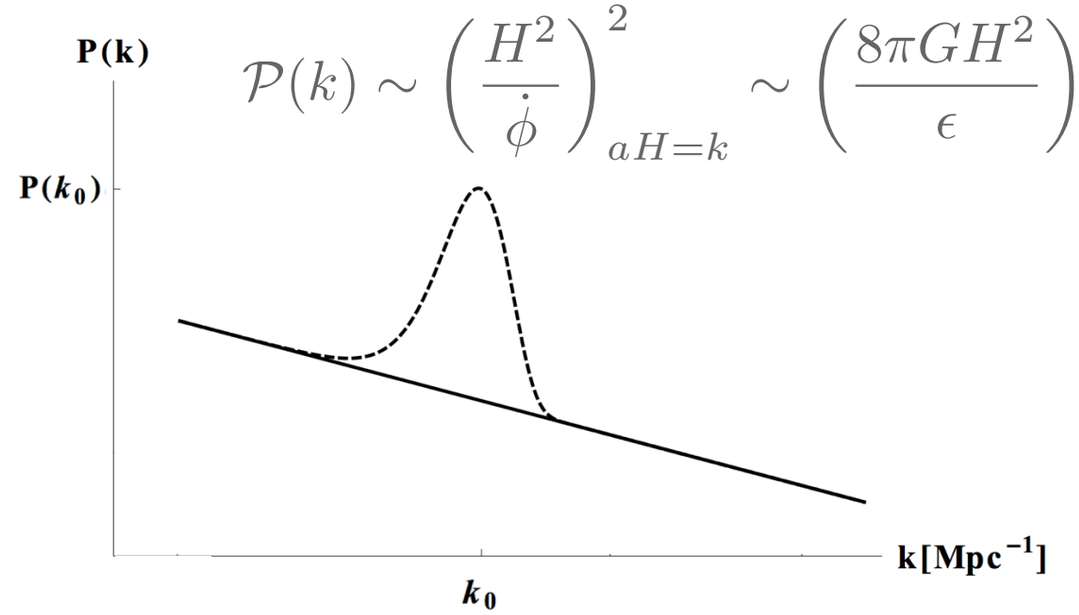

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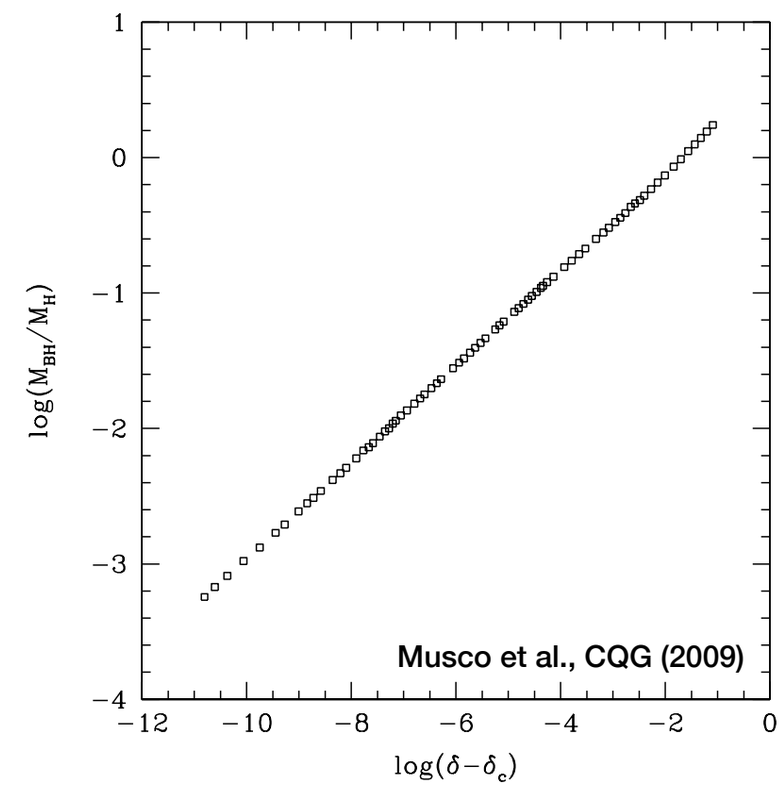

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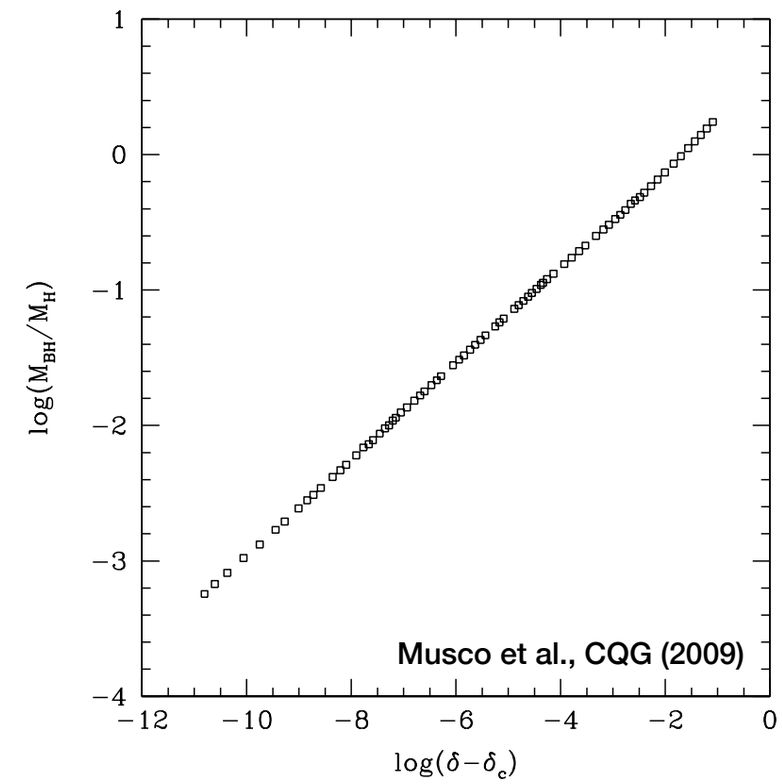

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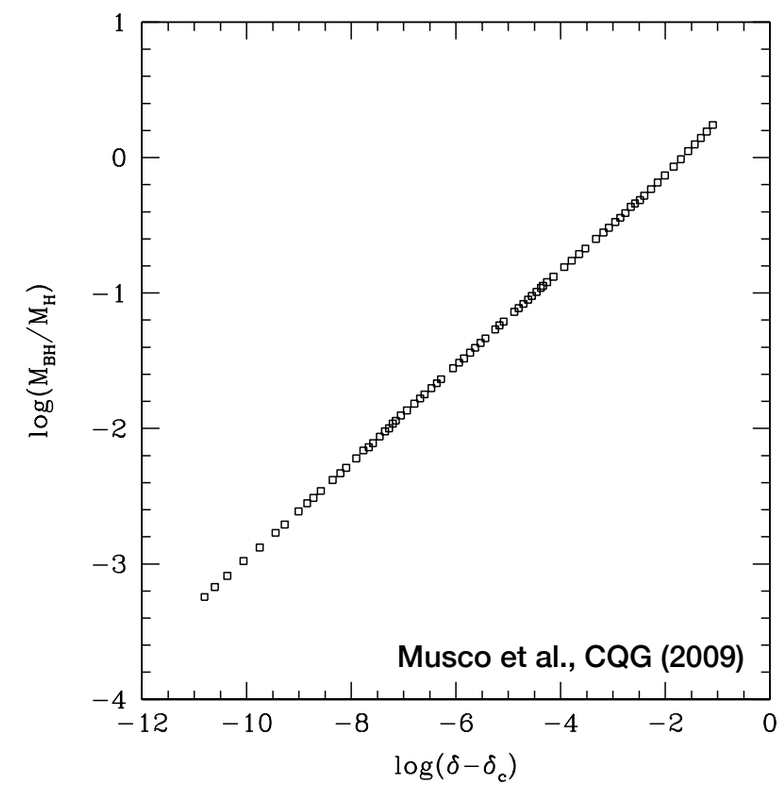

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e.g. Carr et al., PRD (2017)

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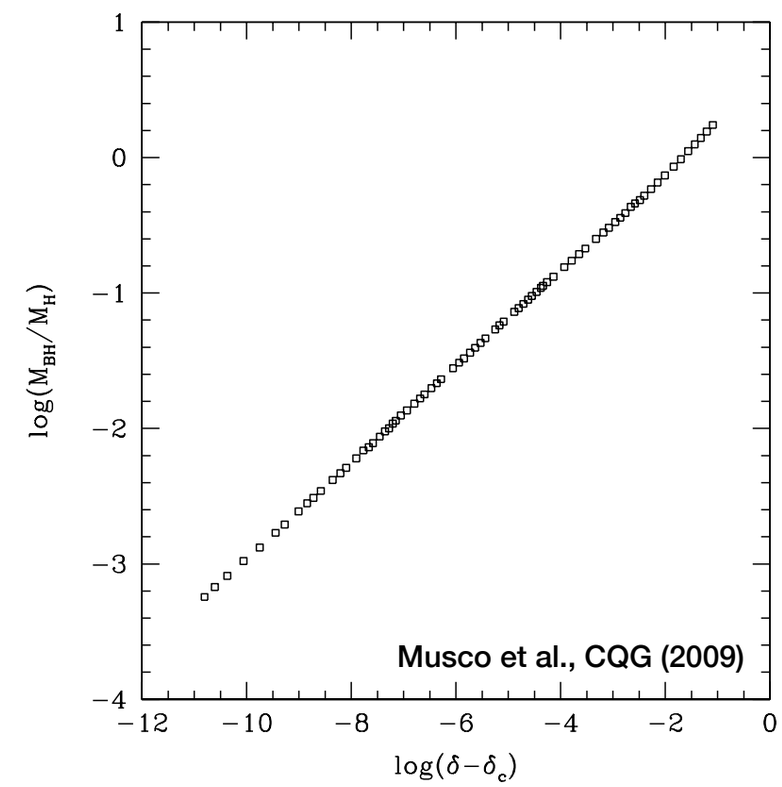

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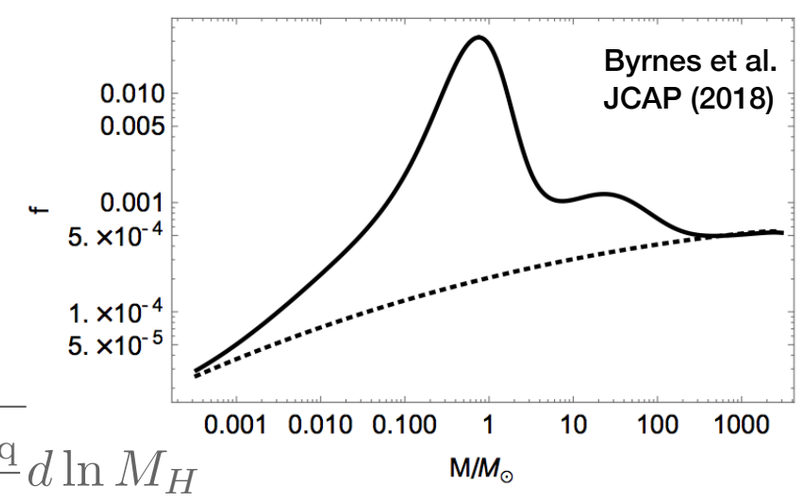

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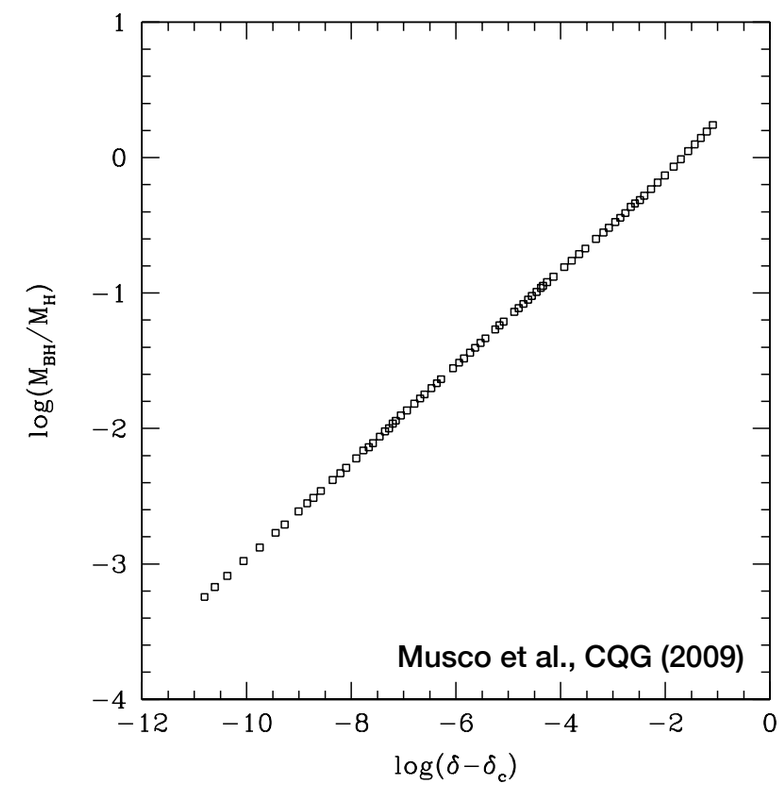

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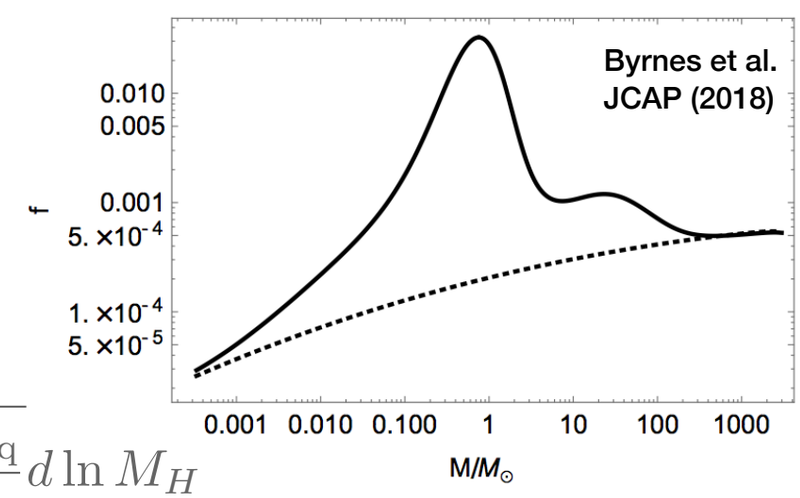

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(See Byrnes' talk on Thursday, Riotto and Sasaki on Wednesday and Dolgov on Friday!)

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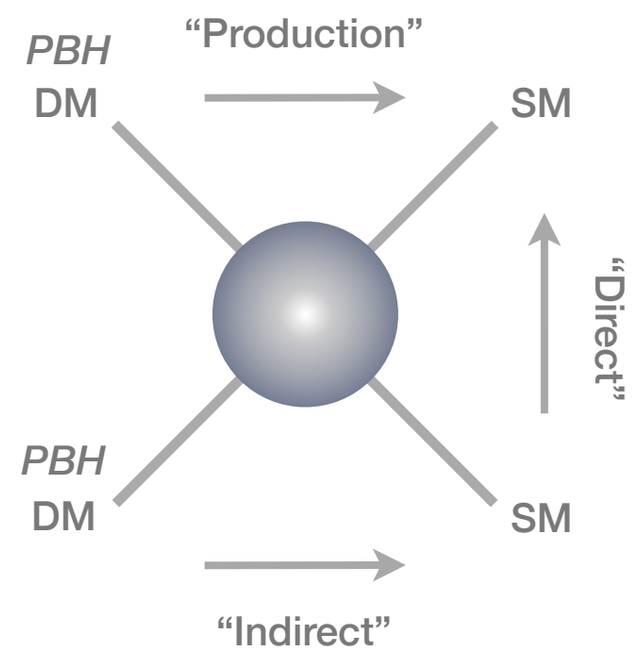

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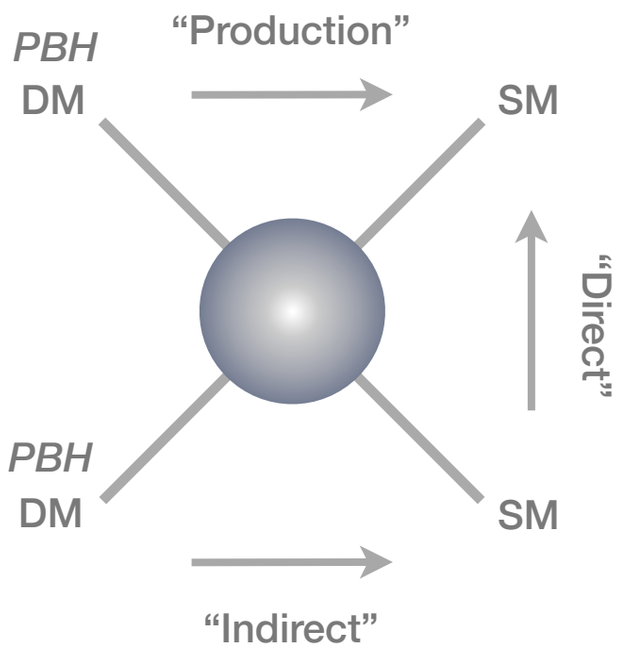

Motivation: 1st Detection of Gravitational Waves

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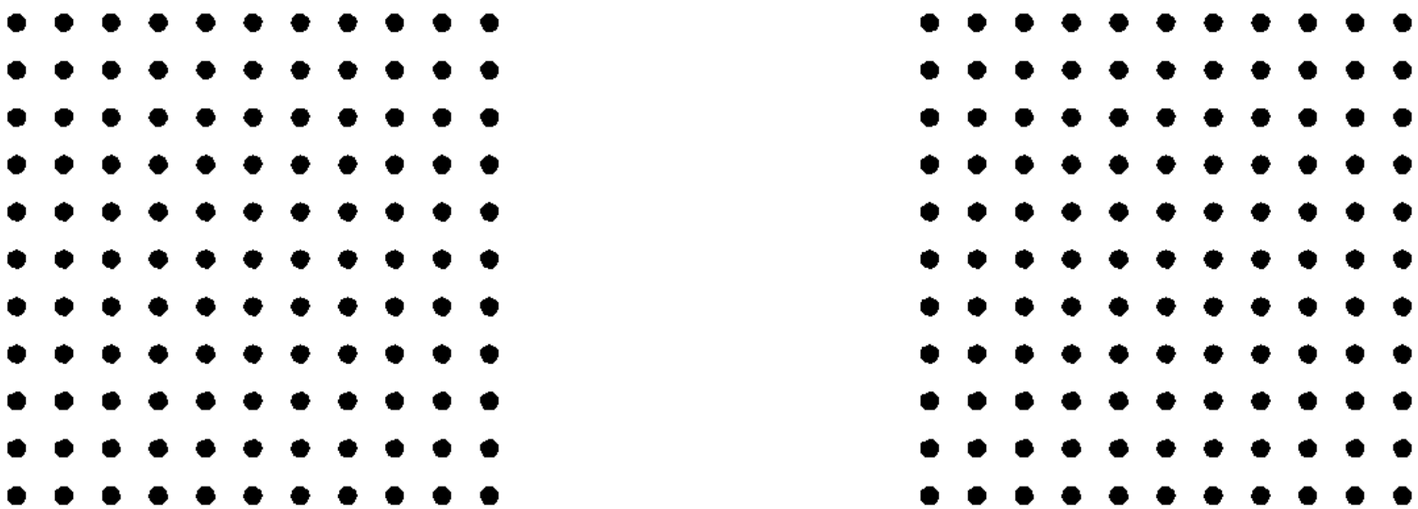

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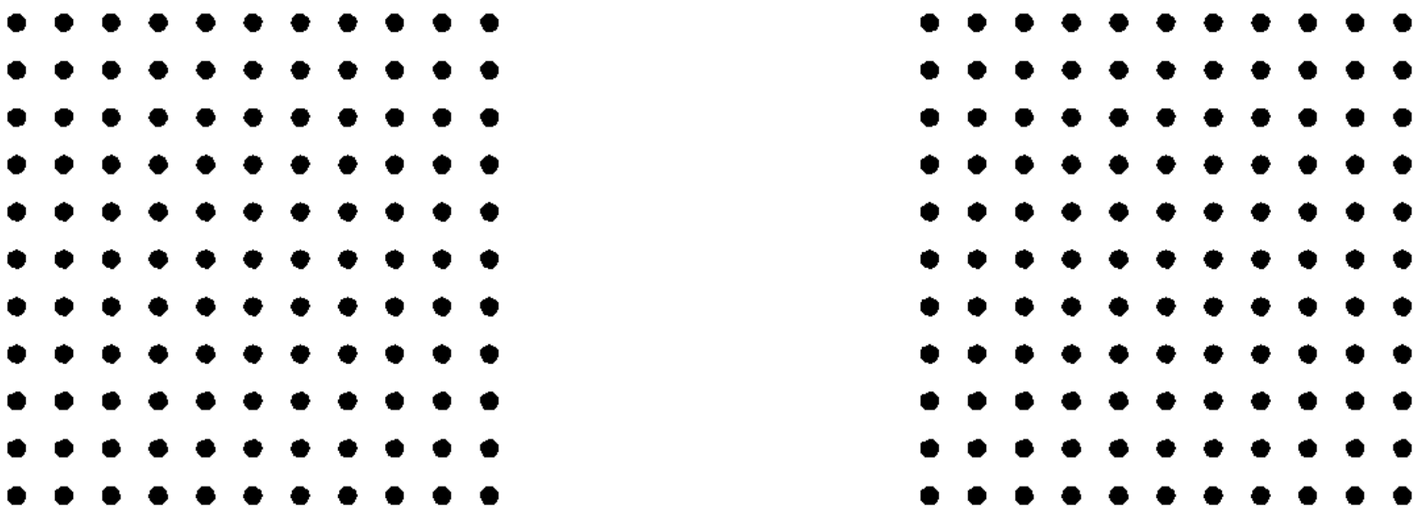

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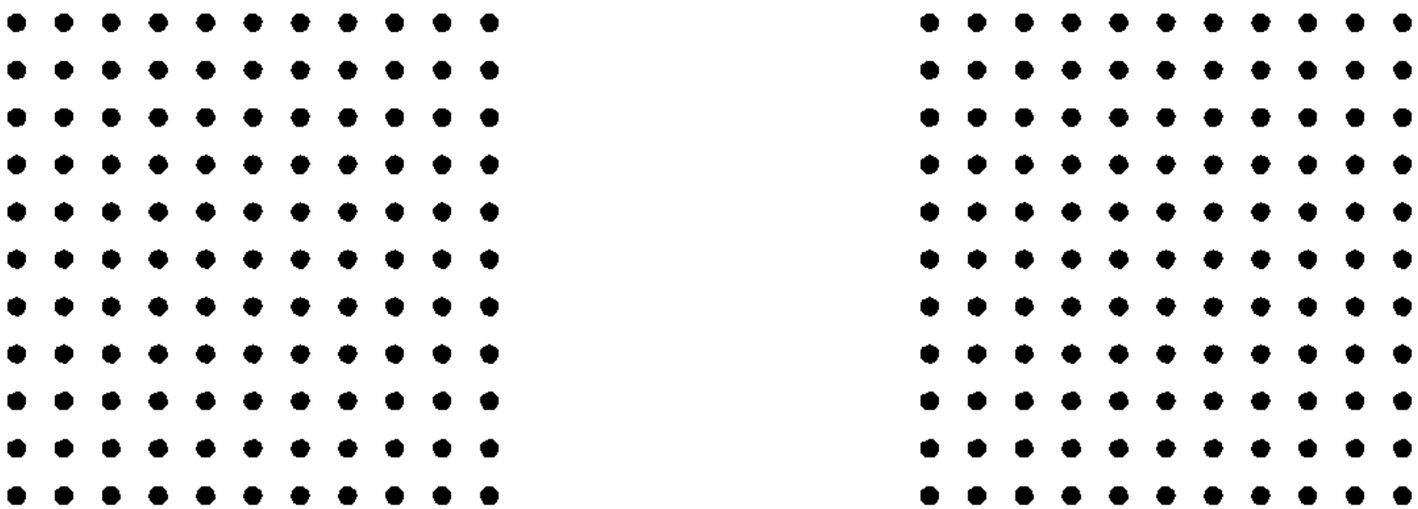

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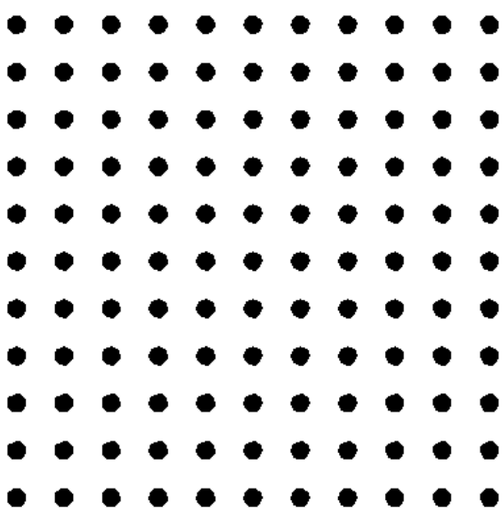

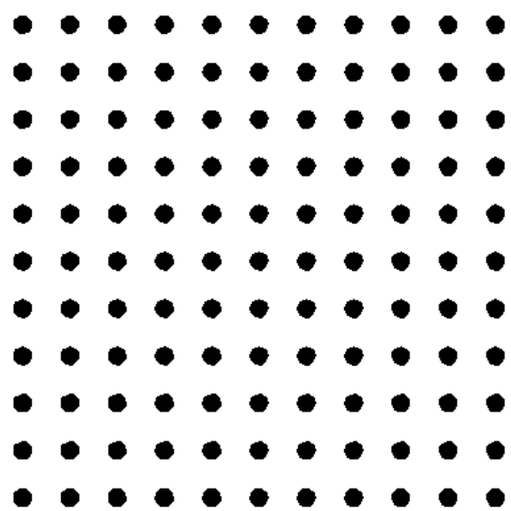

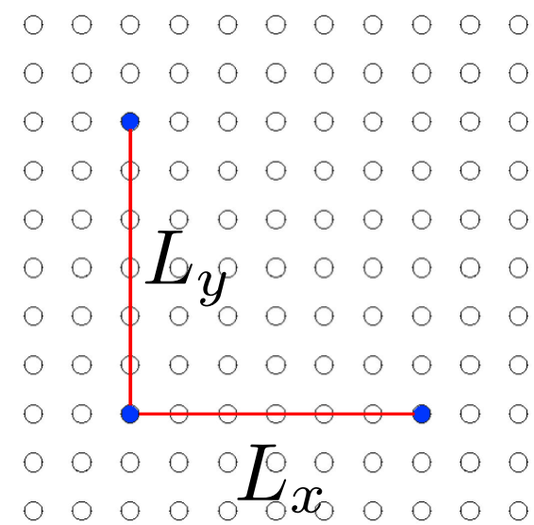

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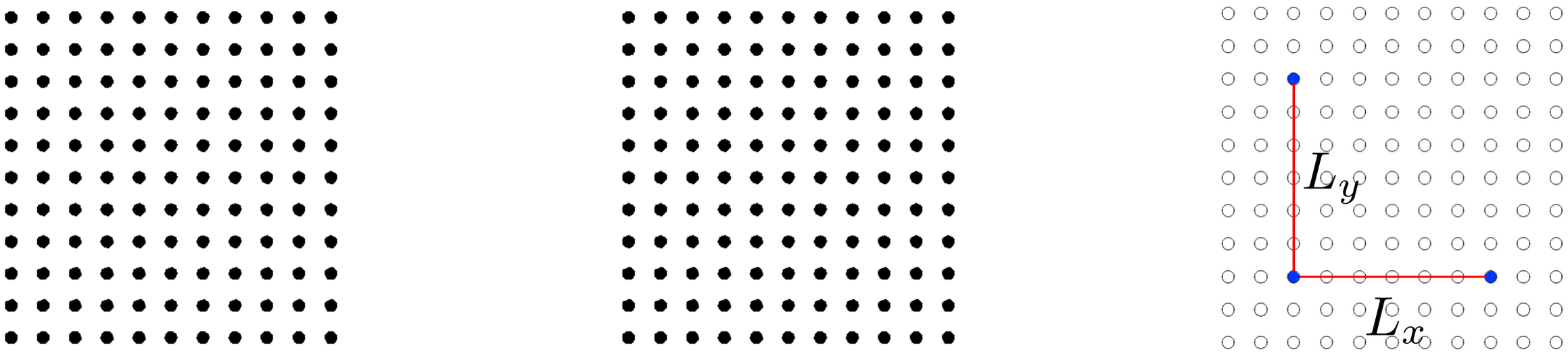

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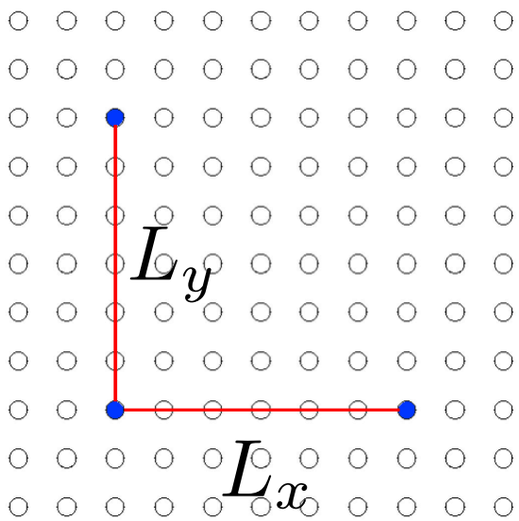

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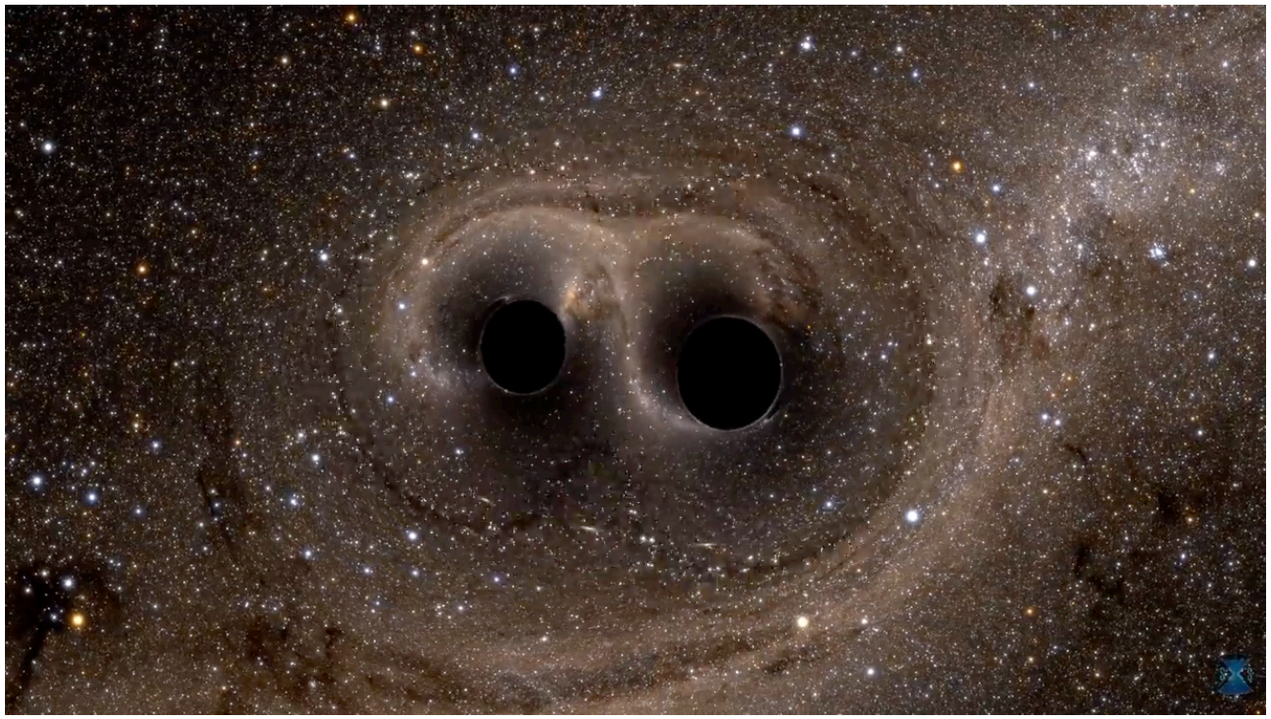

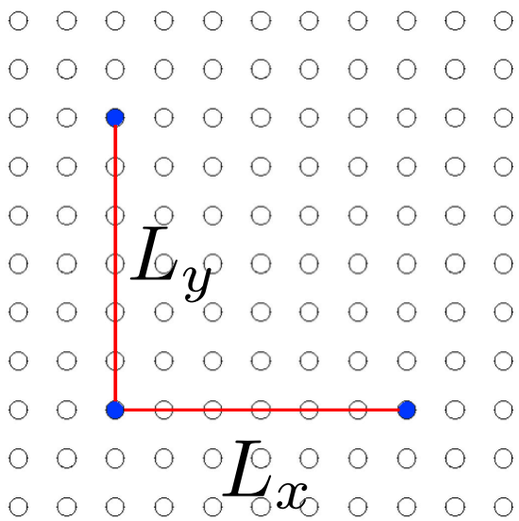

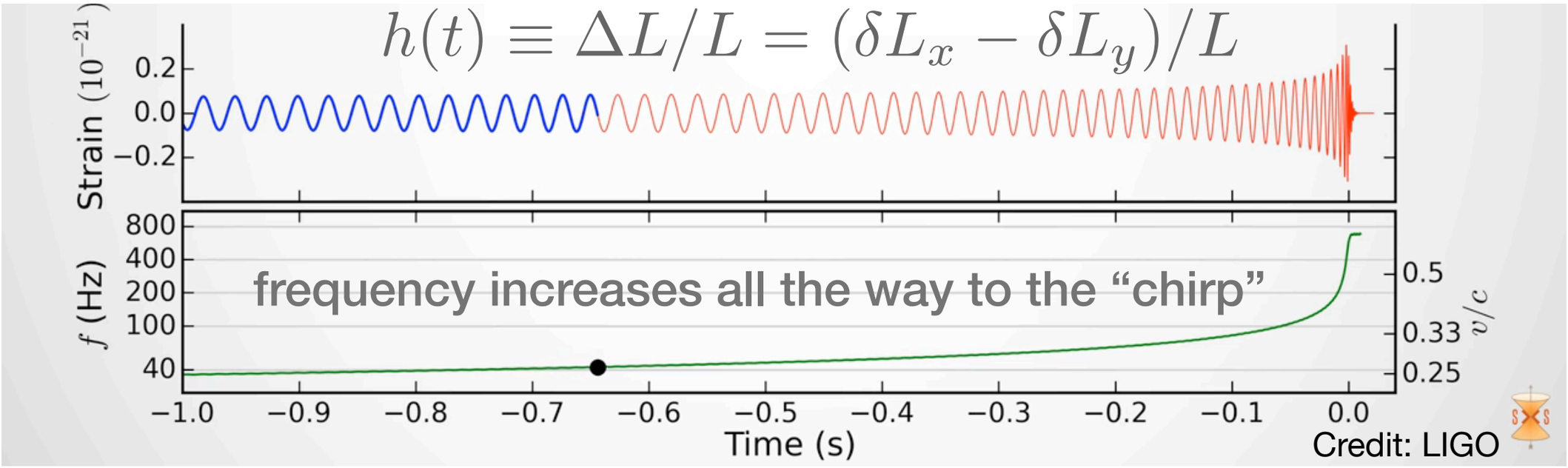

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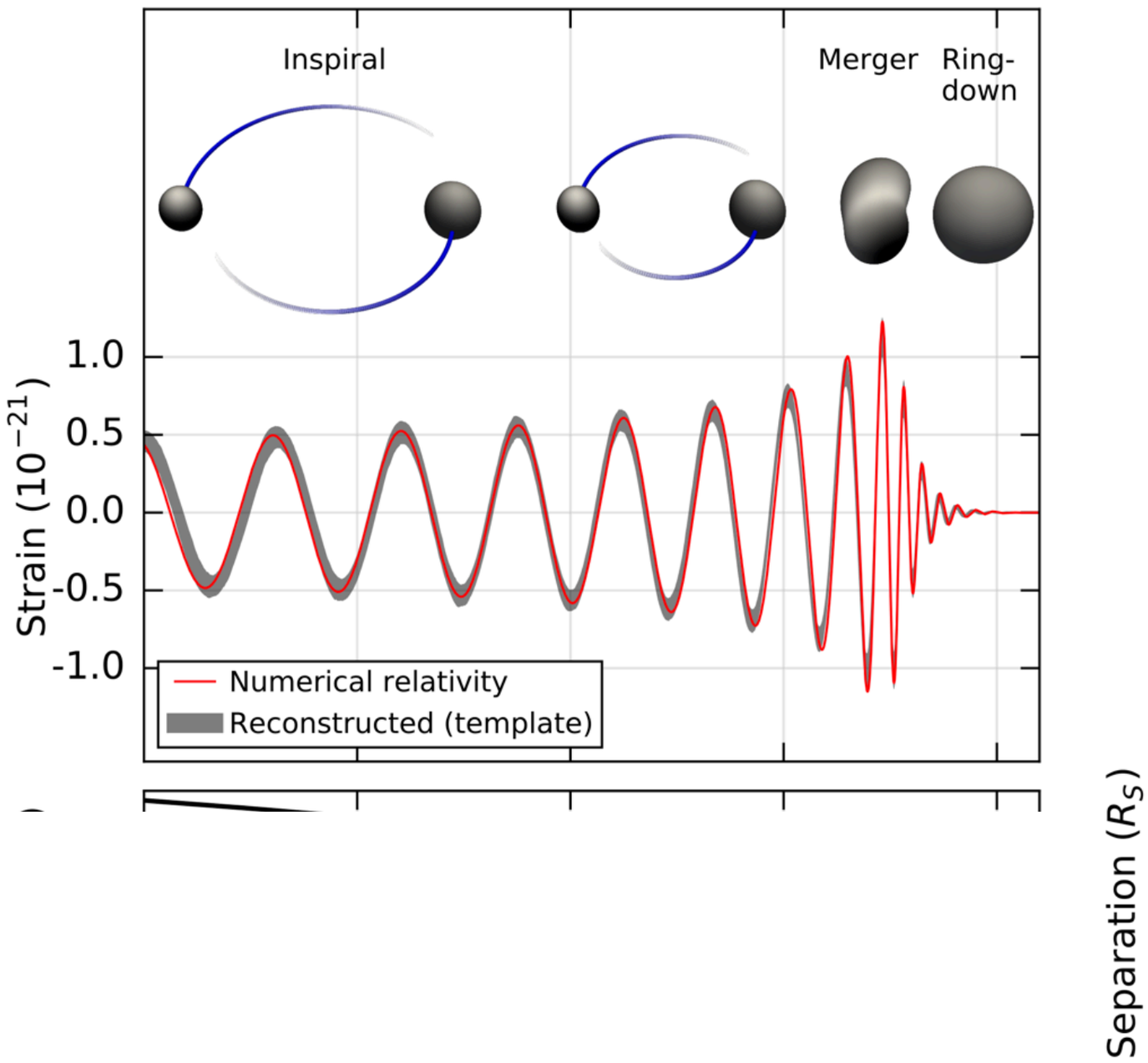

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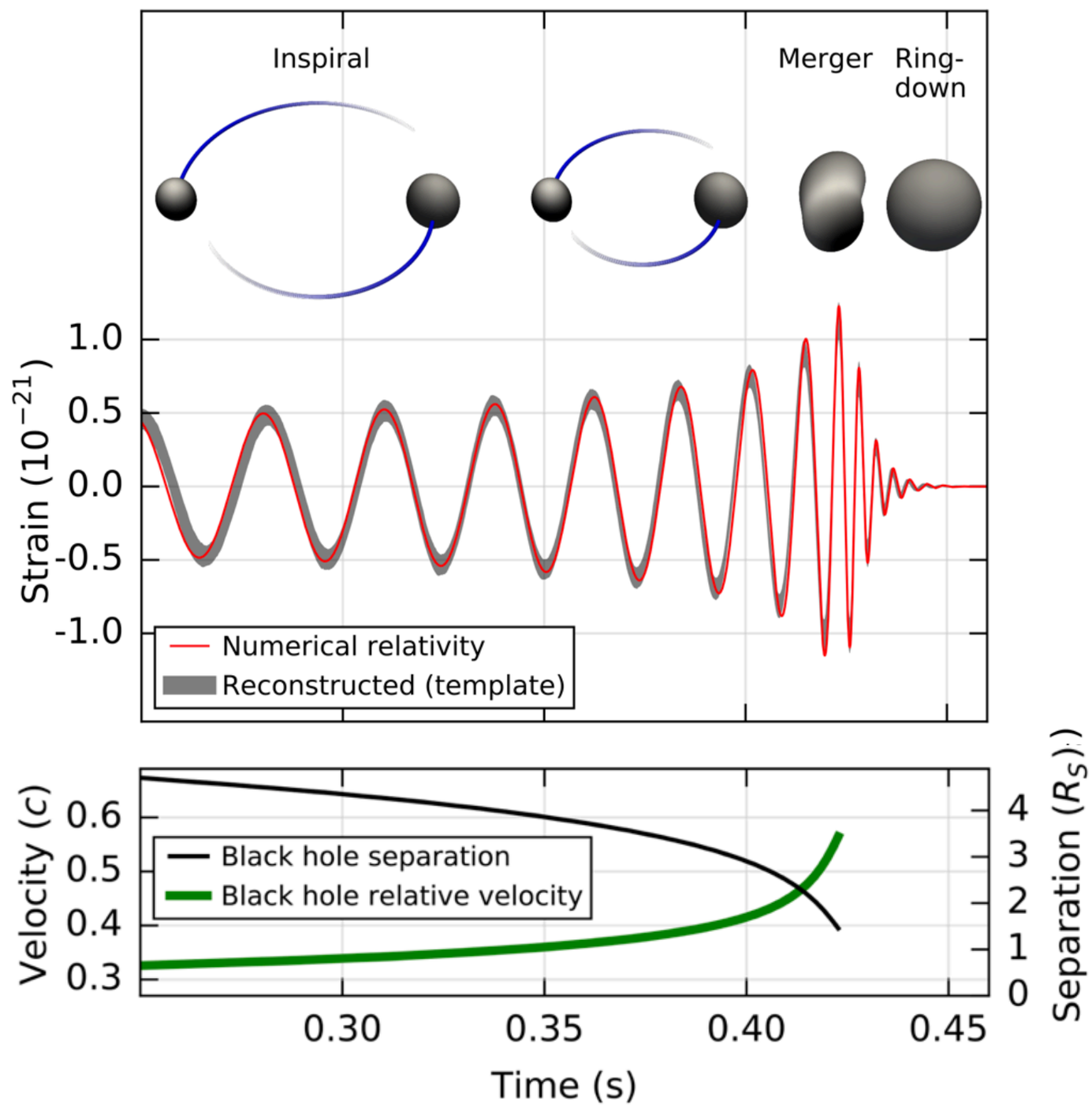

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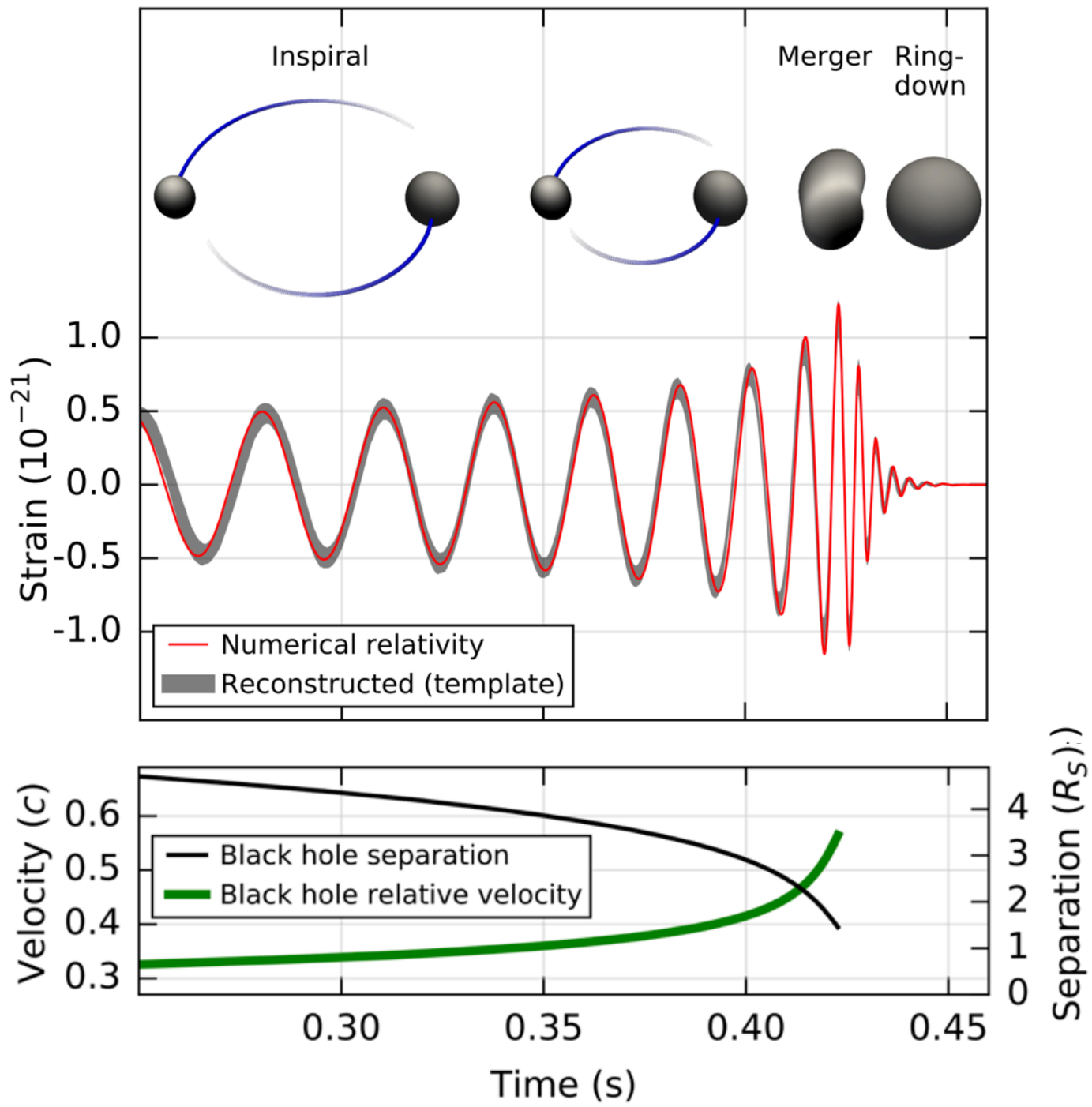

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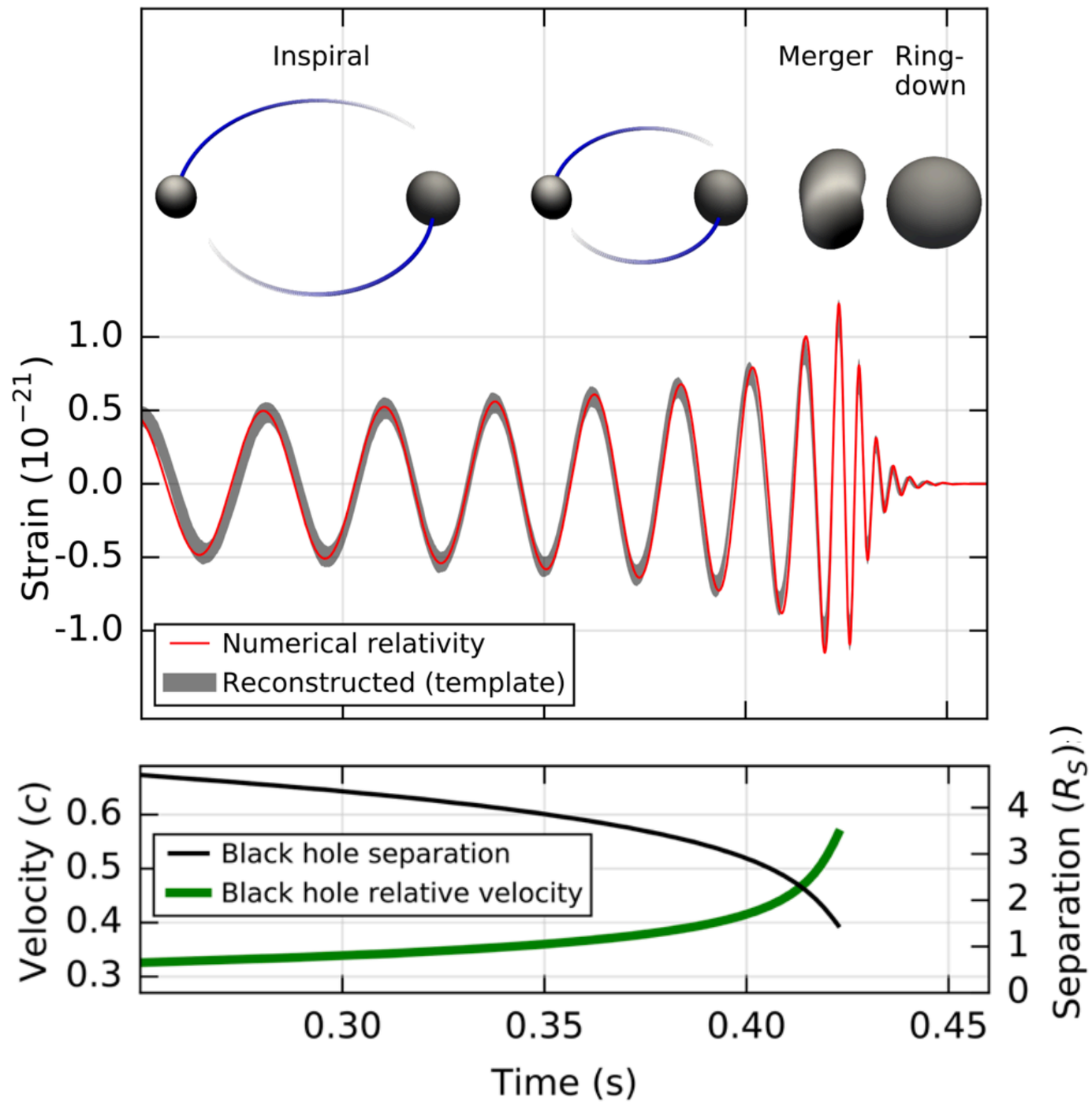

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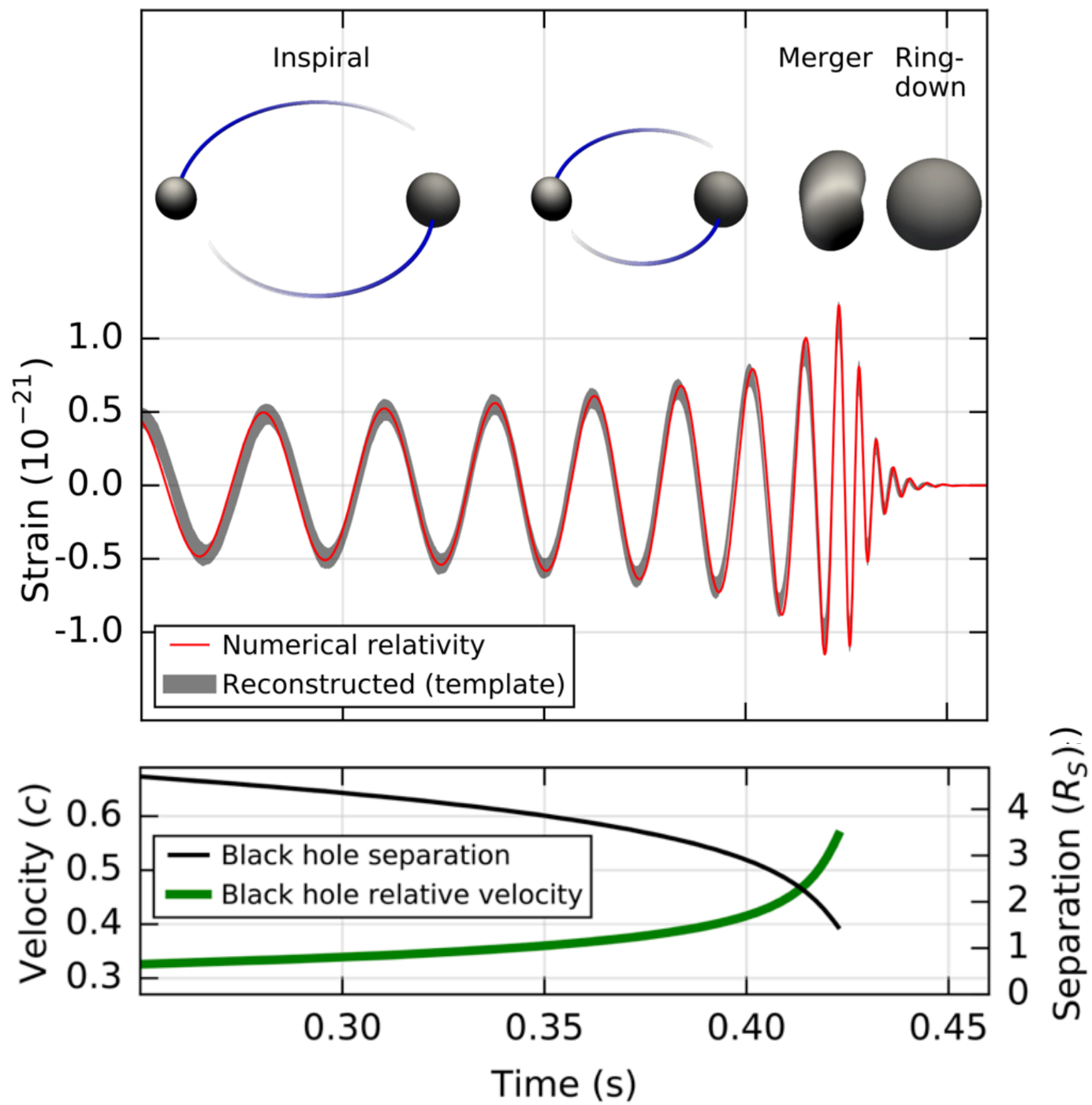

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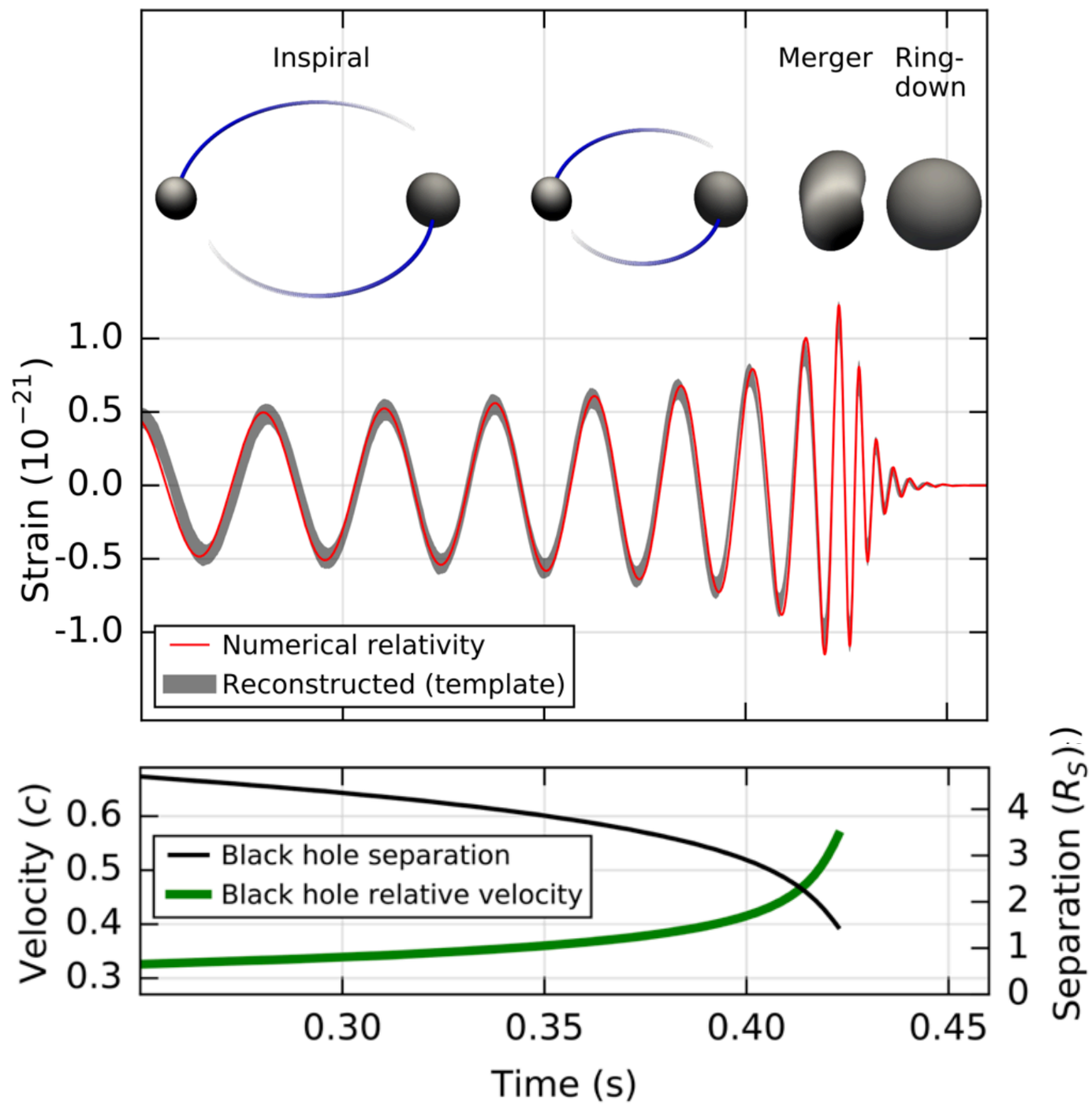

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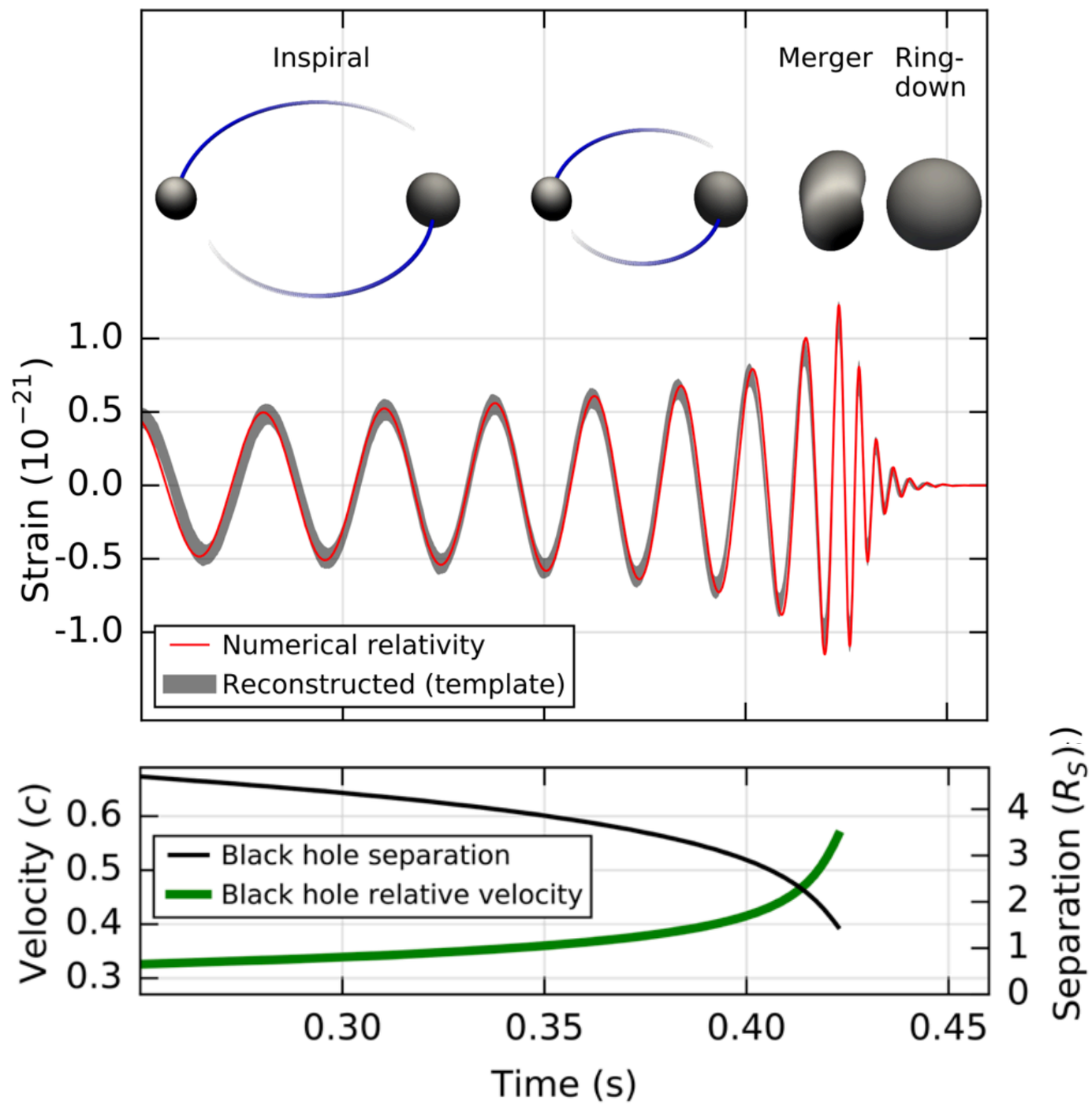

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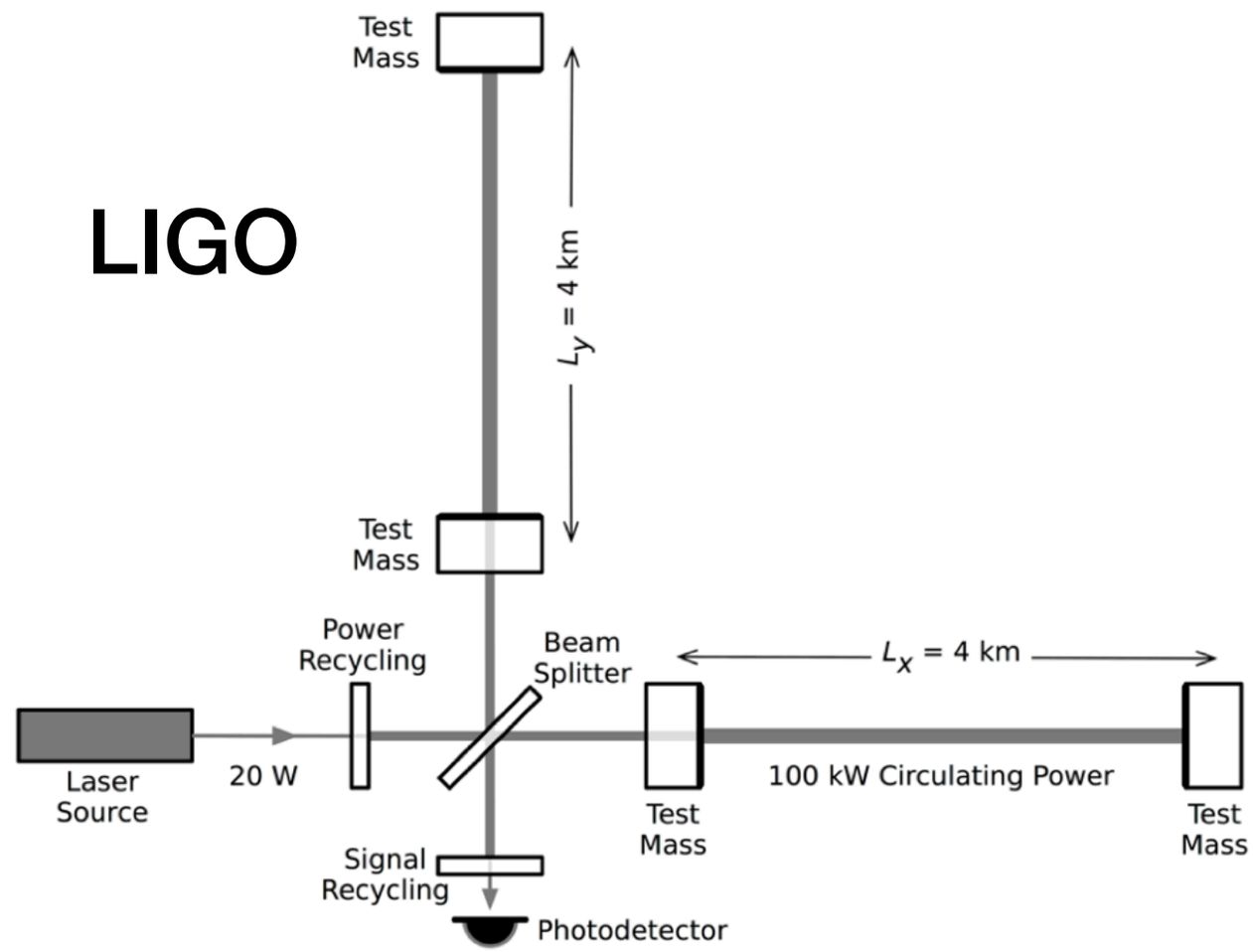

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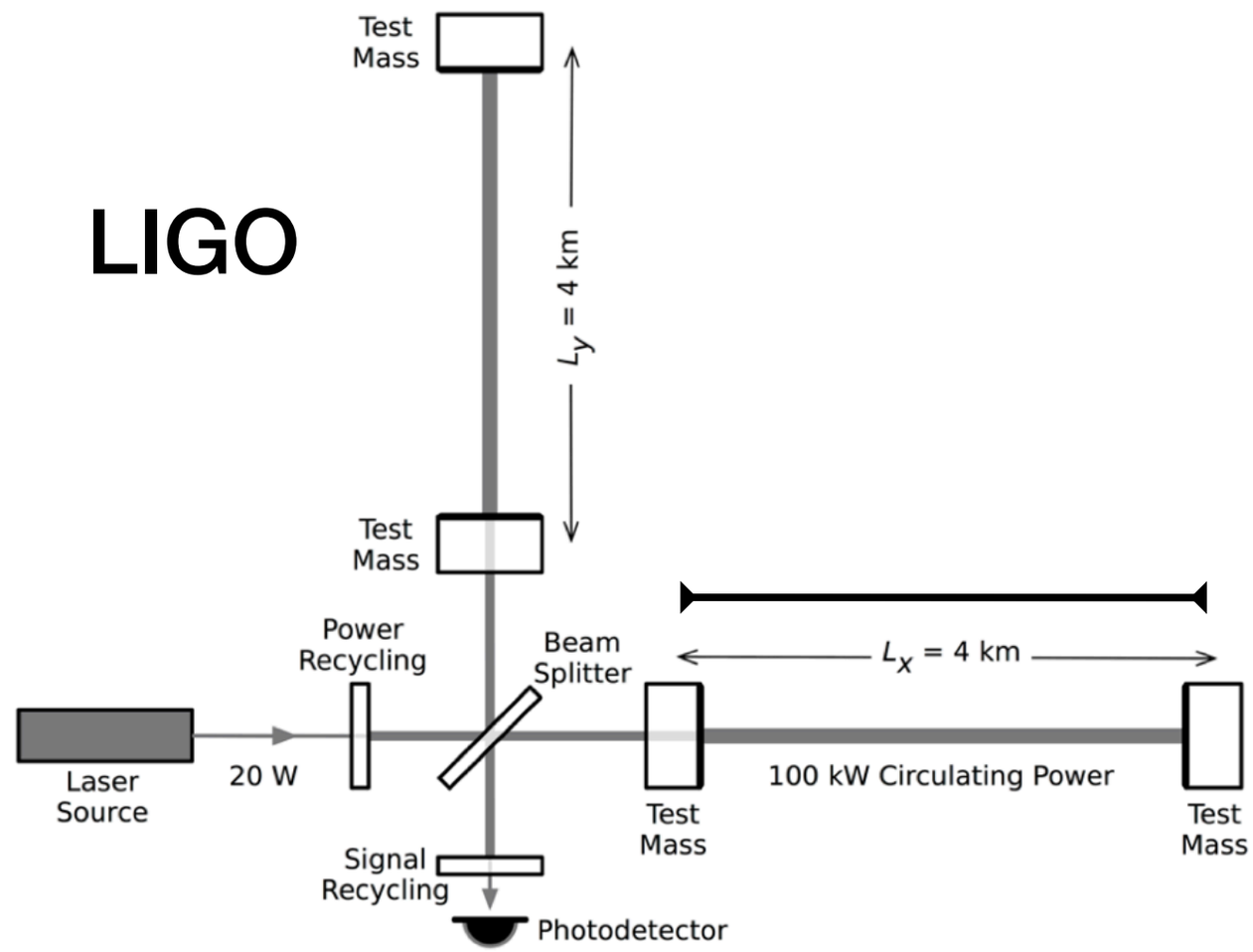

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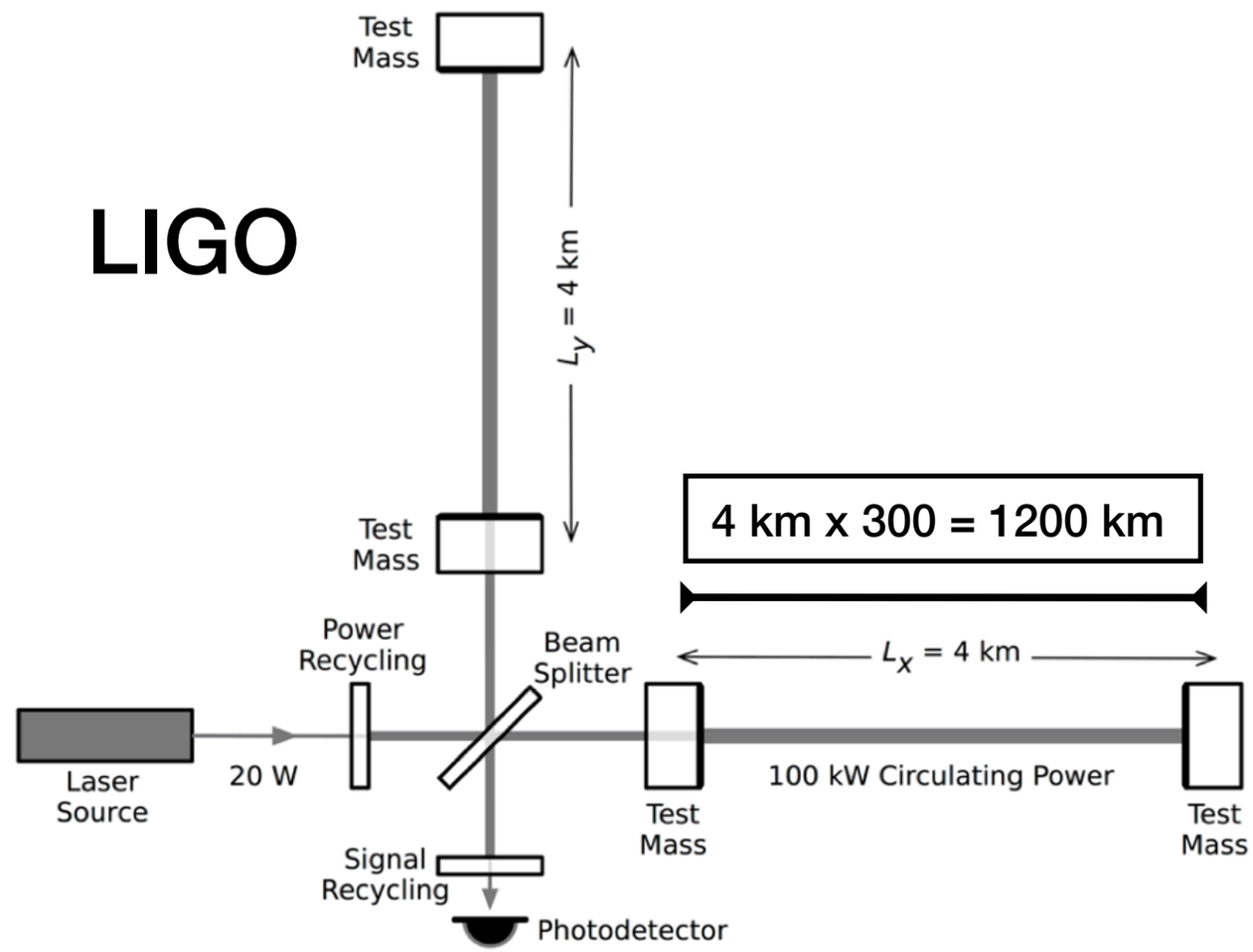

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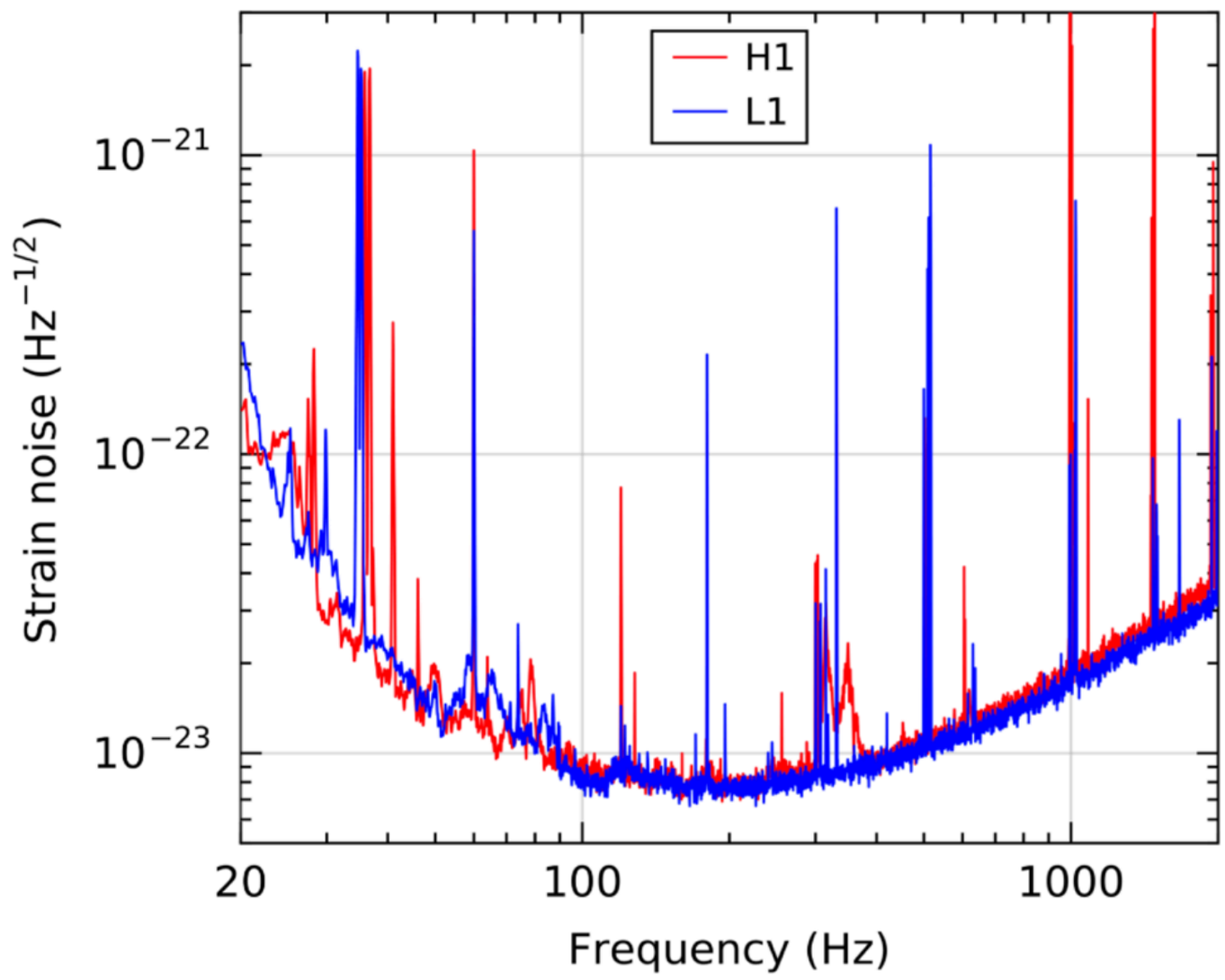

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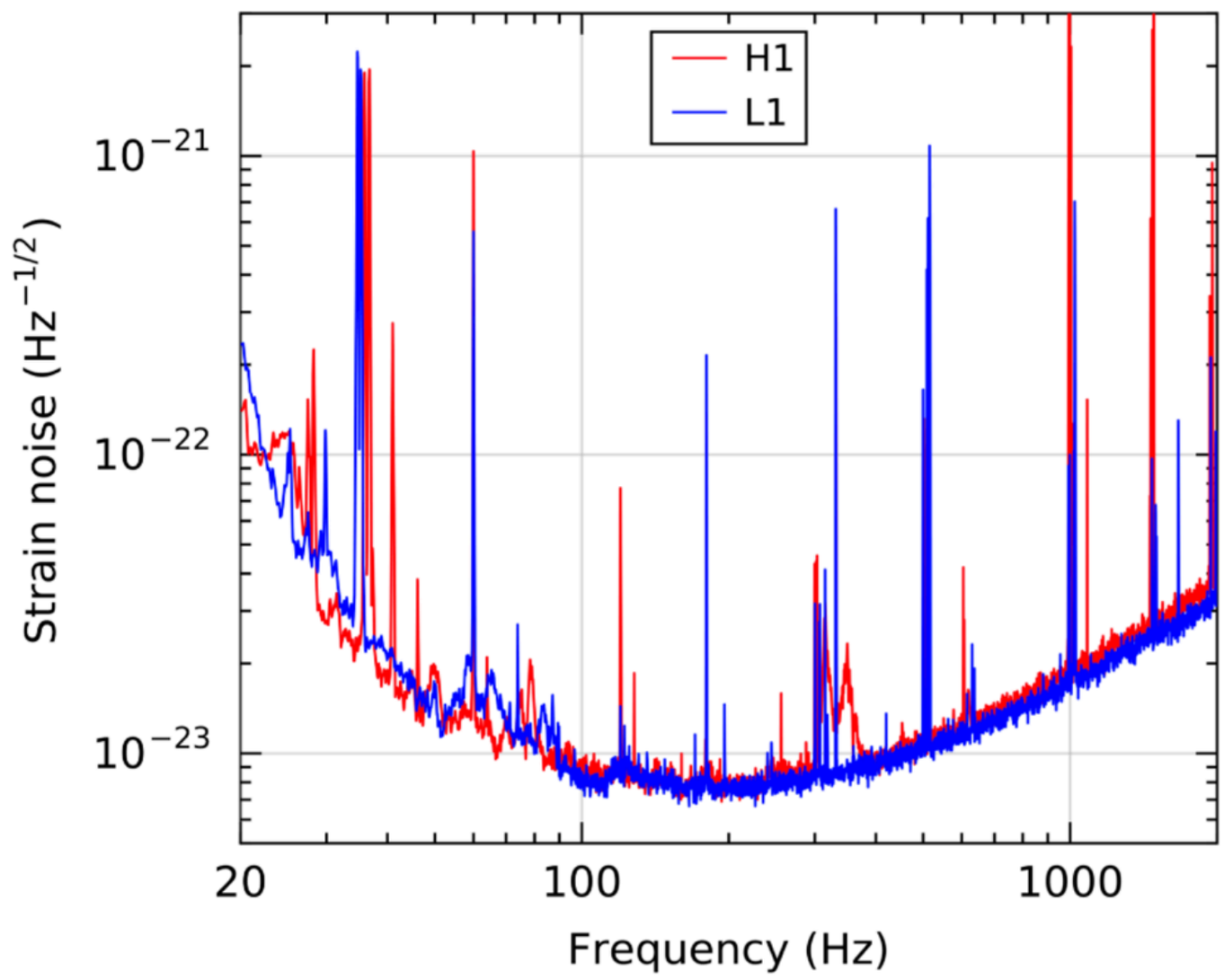
Target strain level: $$h = 10^{-21}\left(\frac{300\,\mathrm{Mpc}}{d_L}\right)\left(\frac{150\,\mathrm{Hz}}{f_{\mathrm{merger}}}\right)$$



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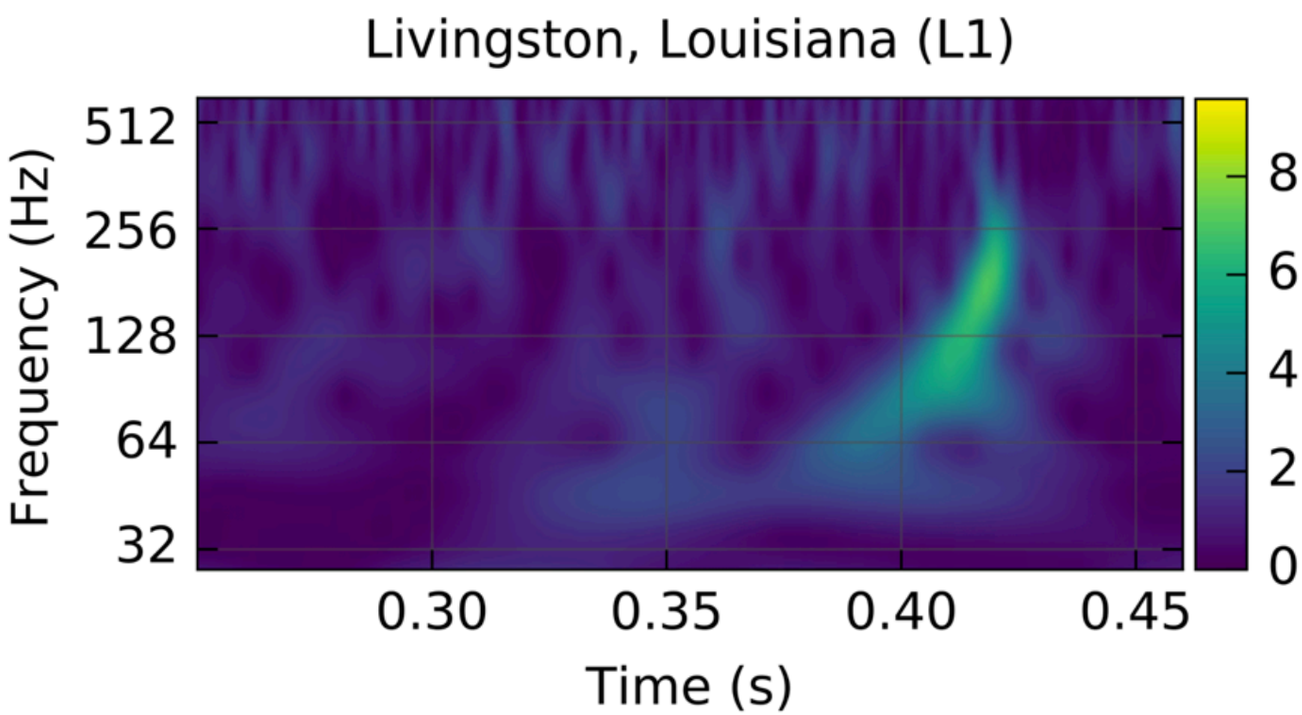

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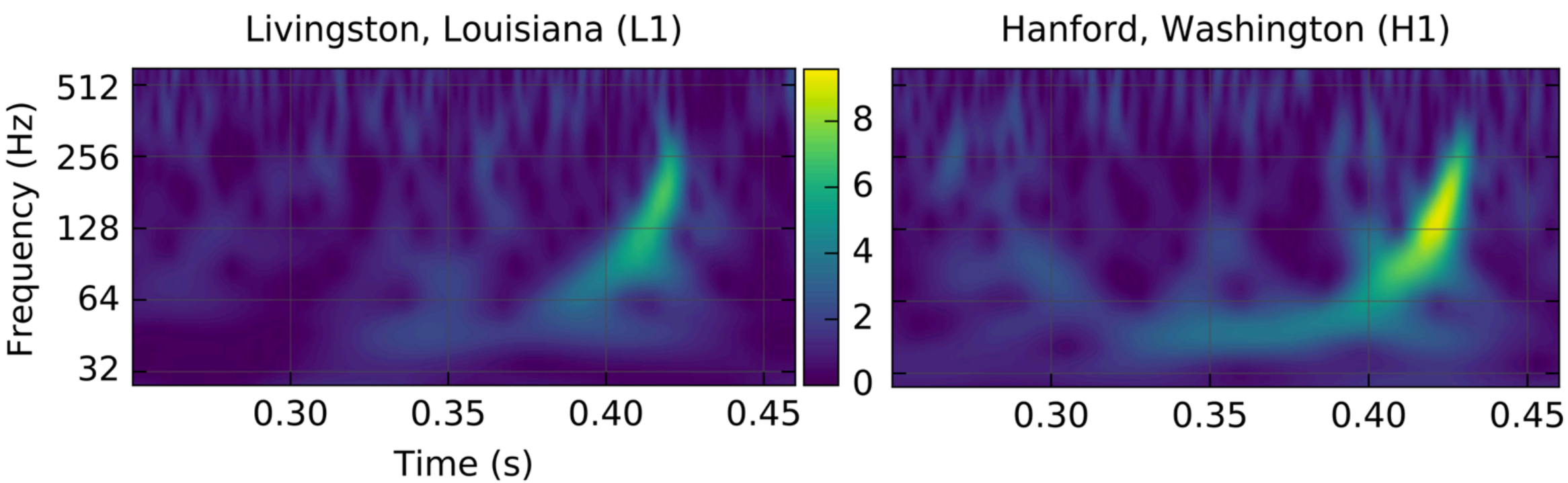

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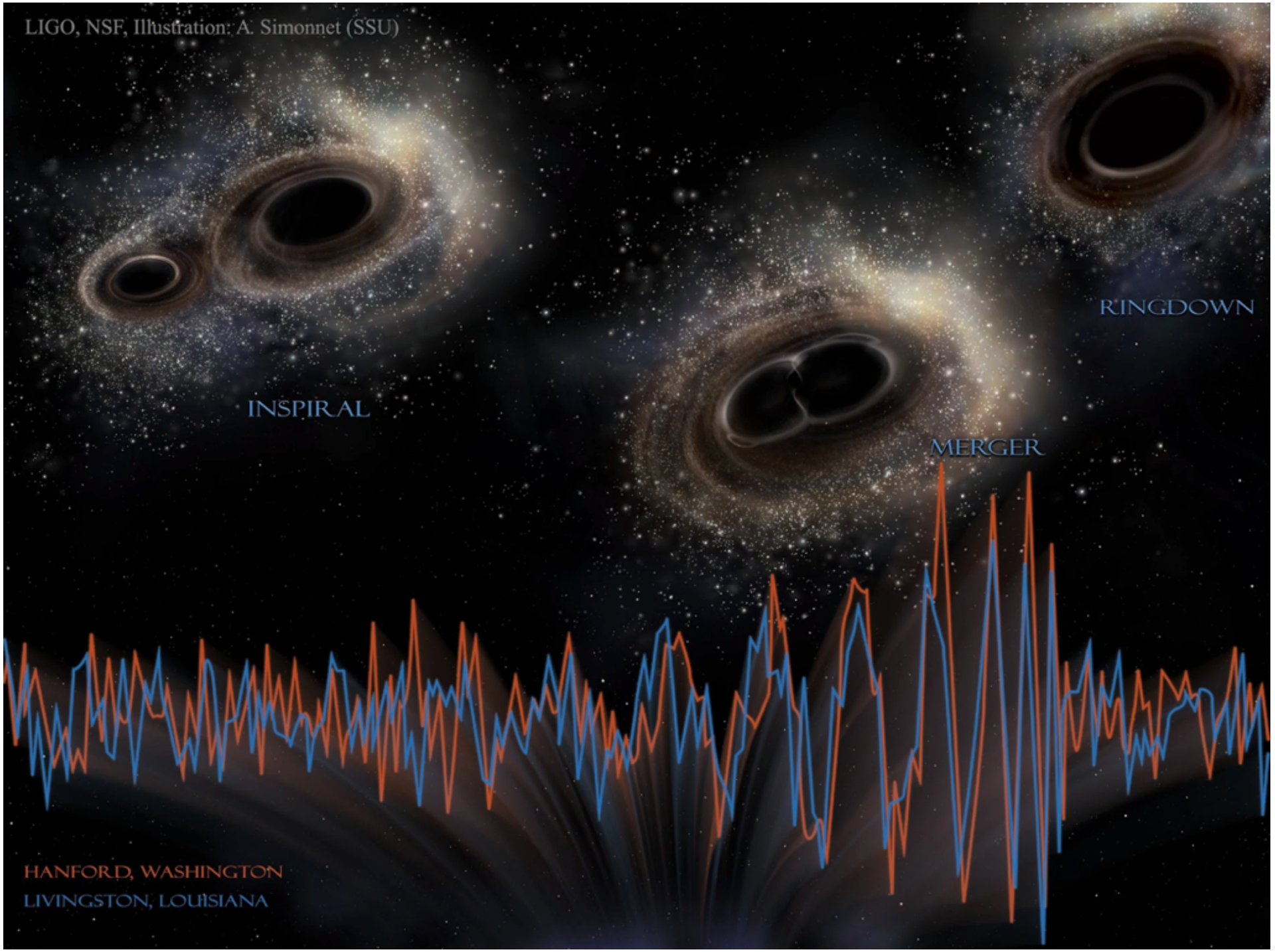

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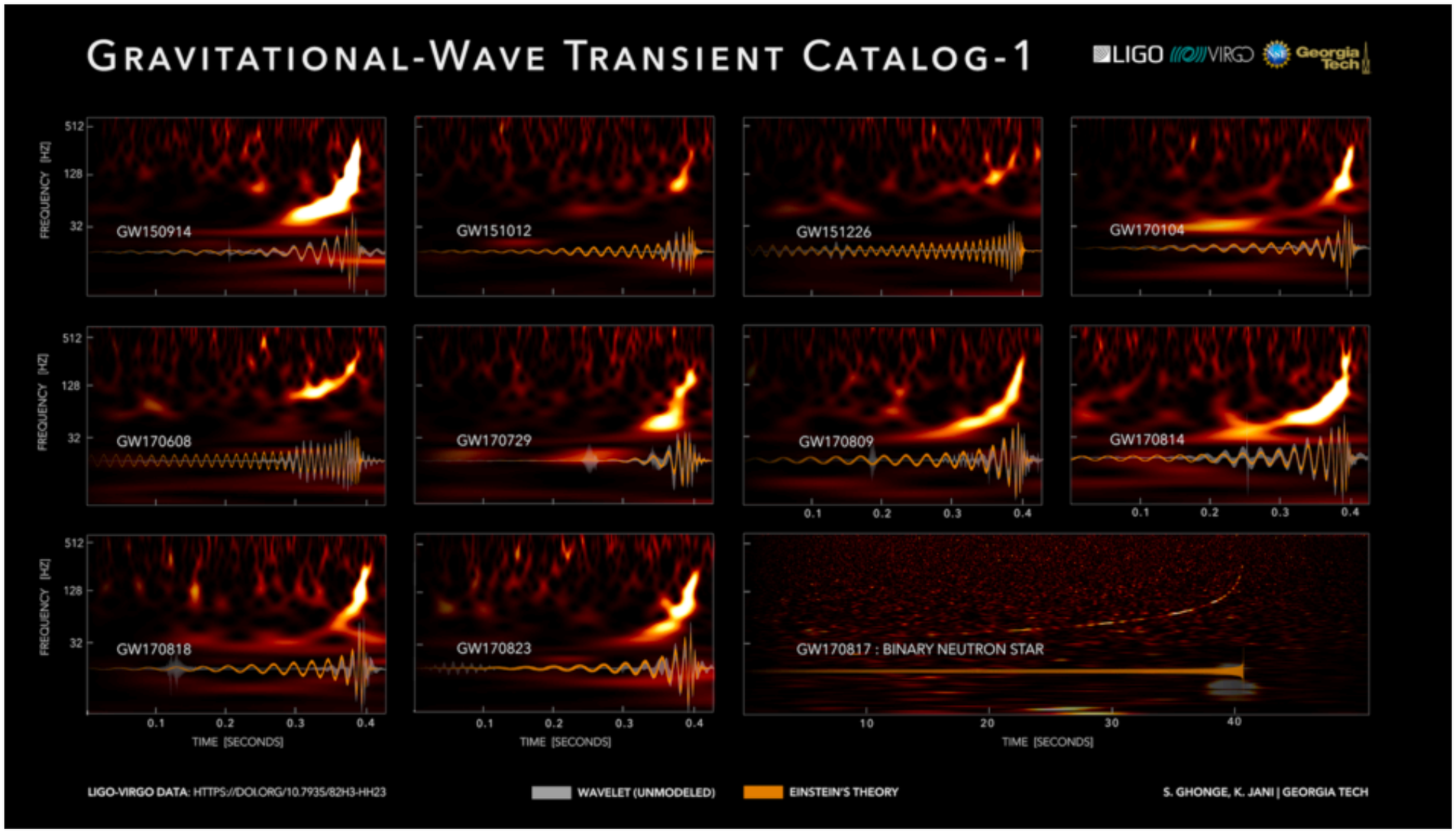

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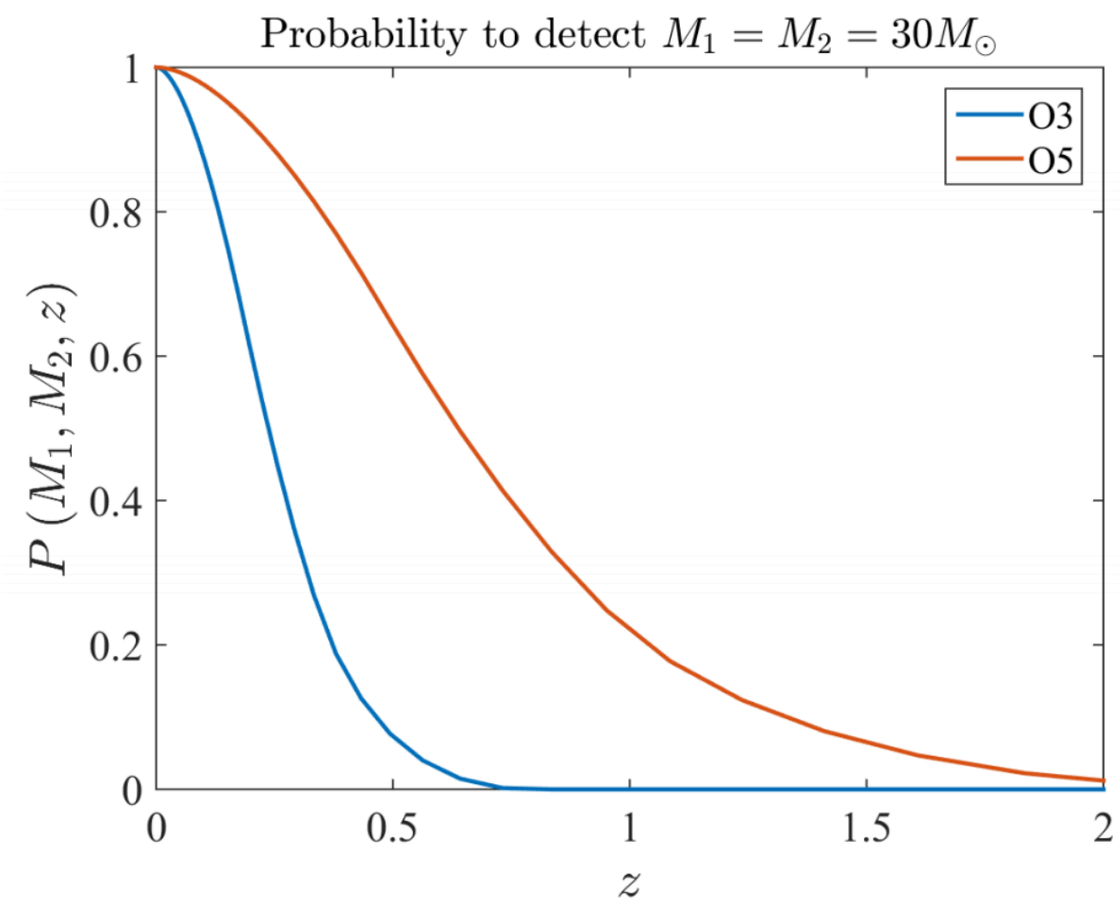

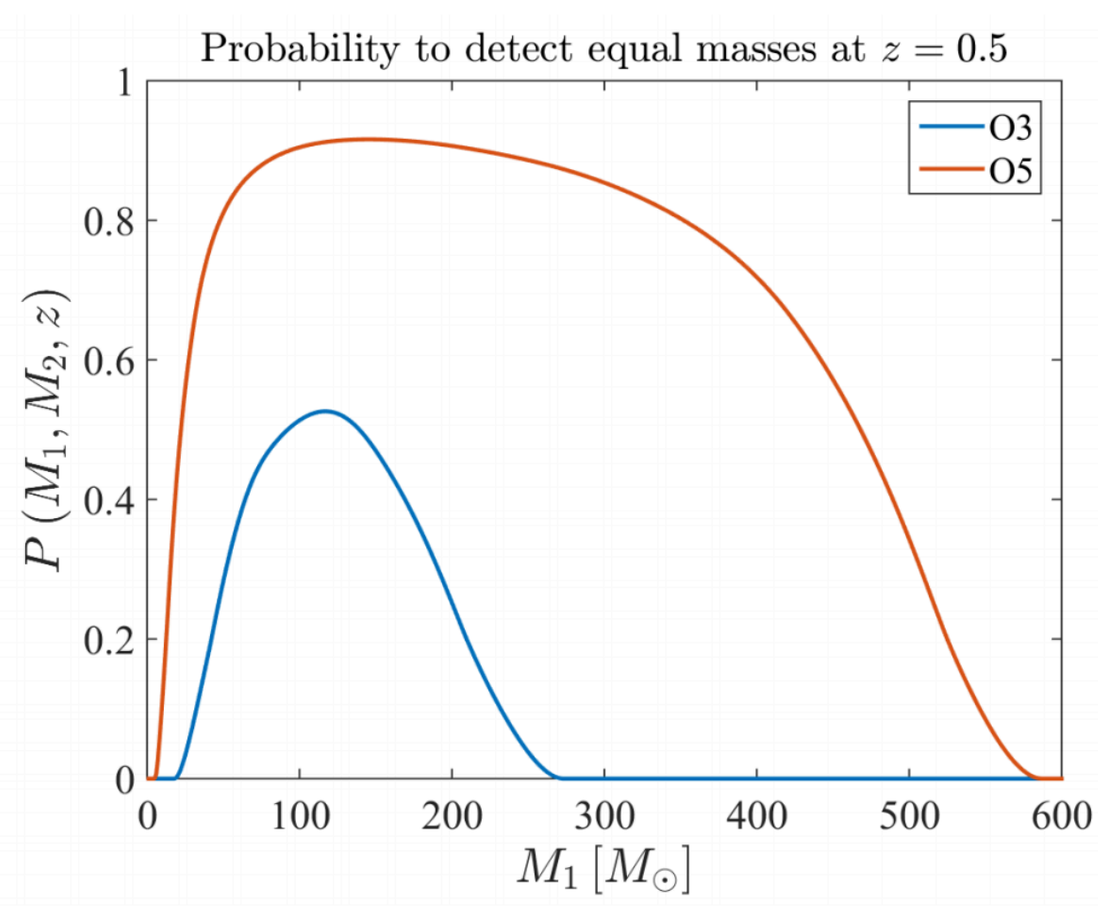

Flitter, Muñoz and **EDK**, arXiv:2008.10389

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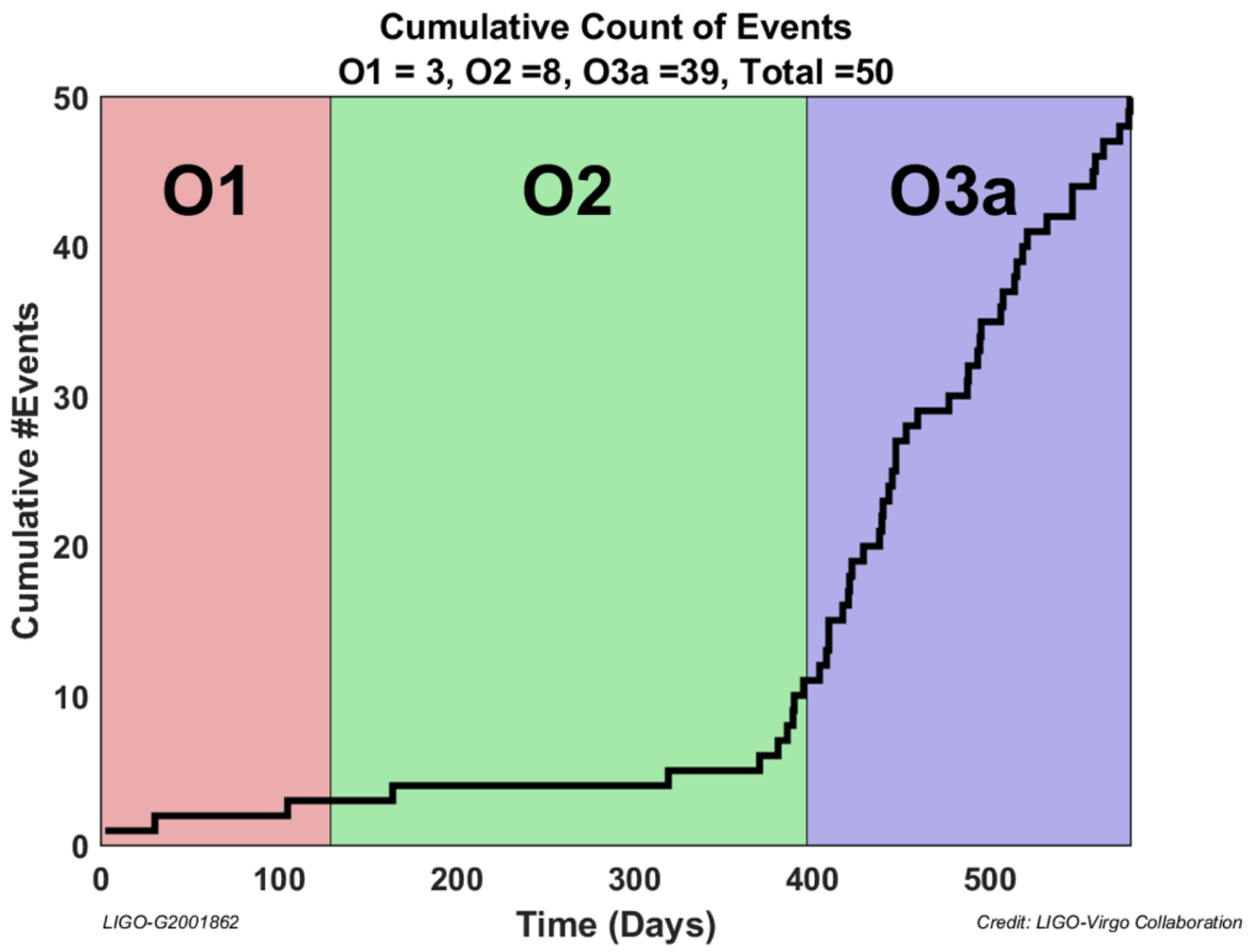
And indeed after O3a:



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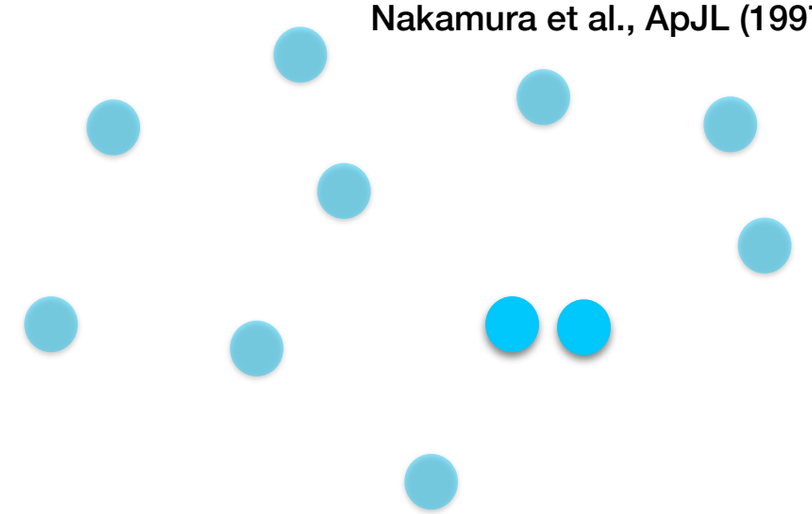

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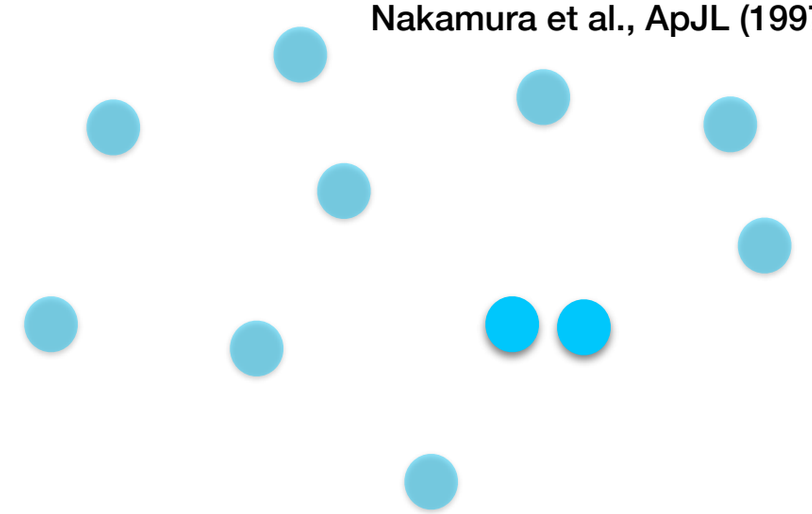

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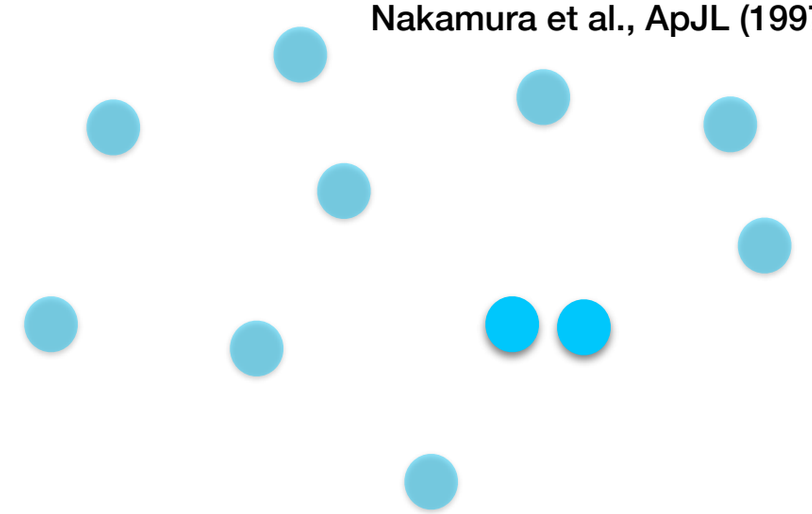

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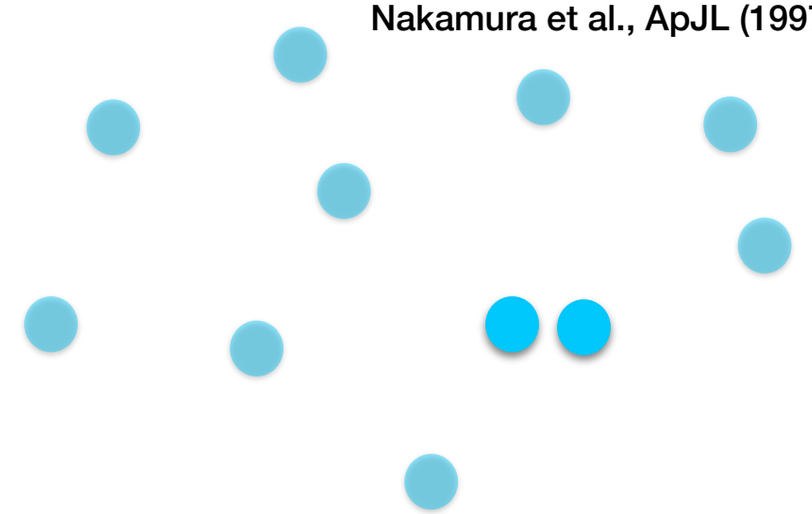

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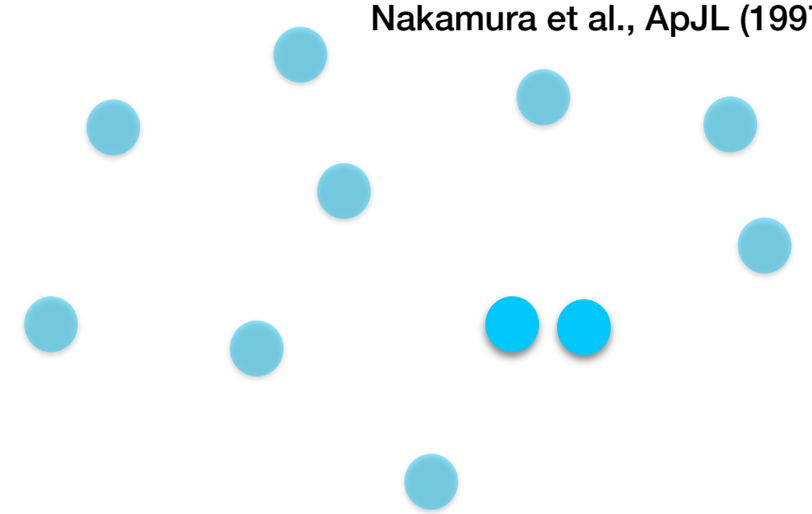

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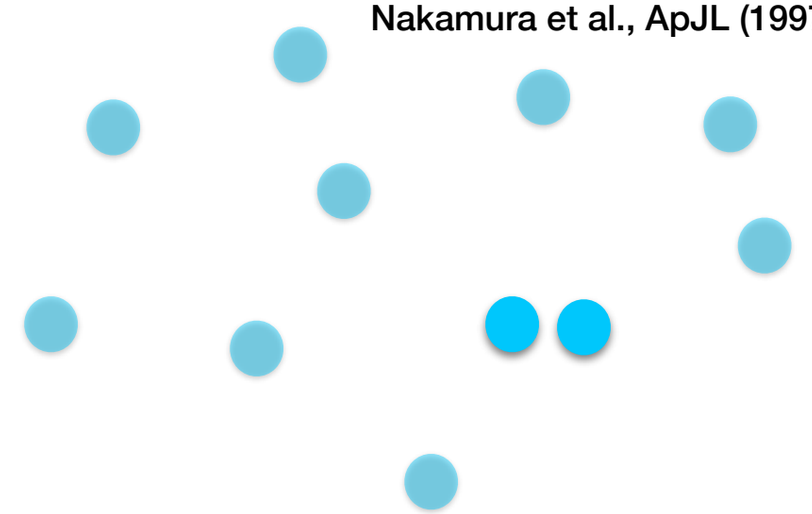

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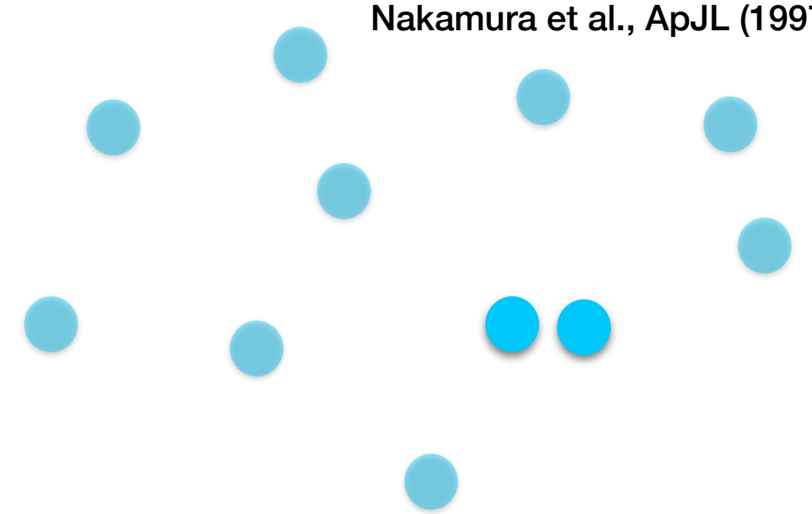

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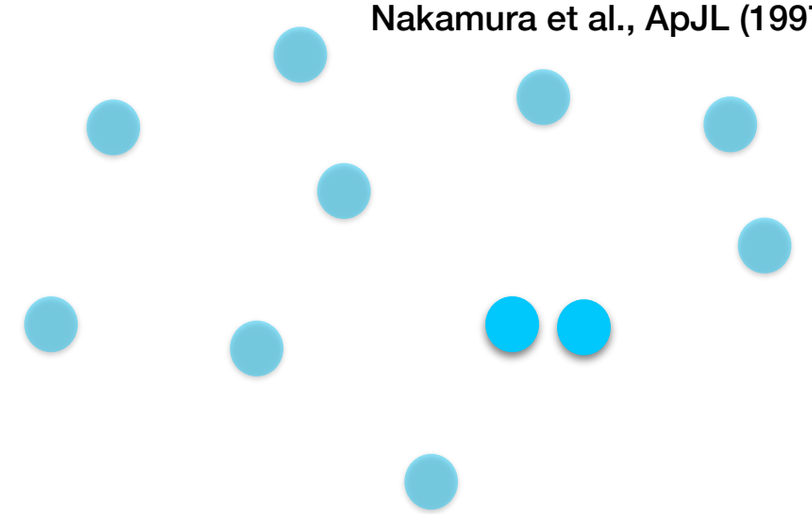

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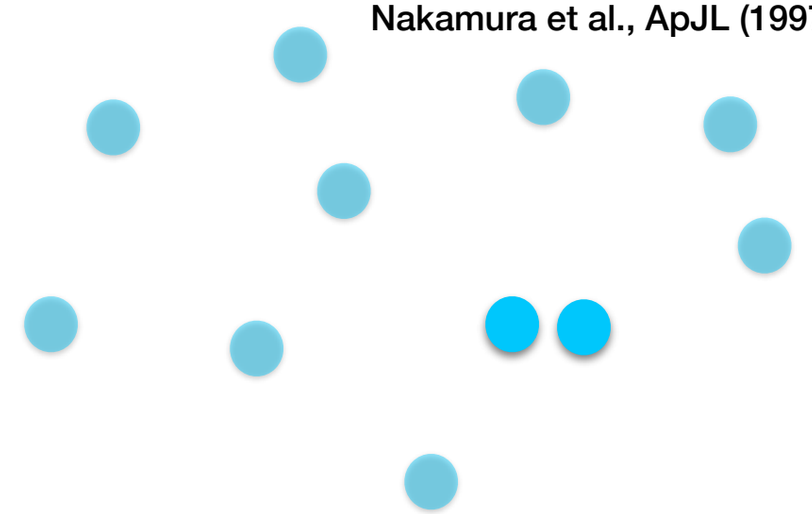

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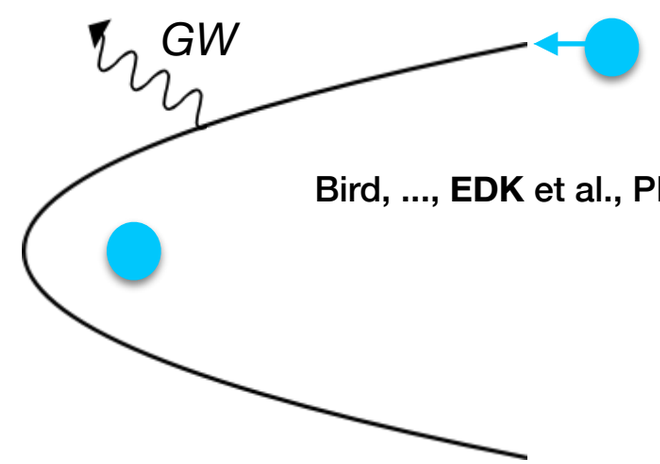

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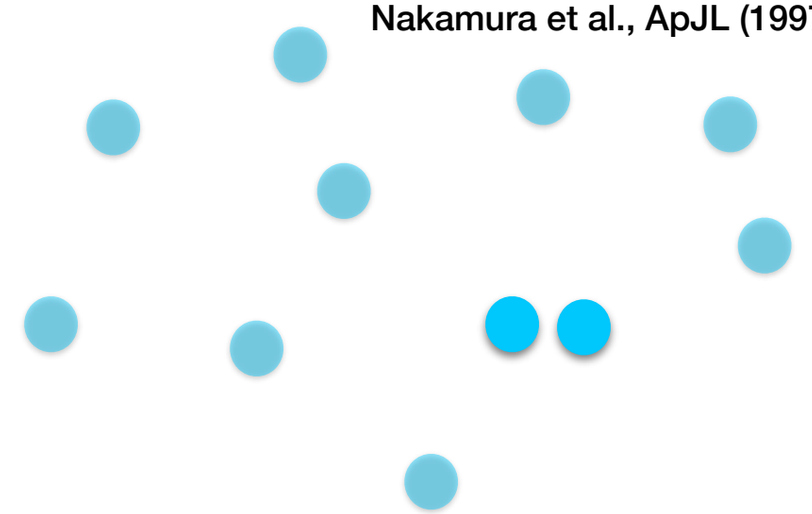

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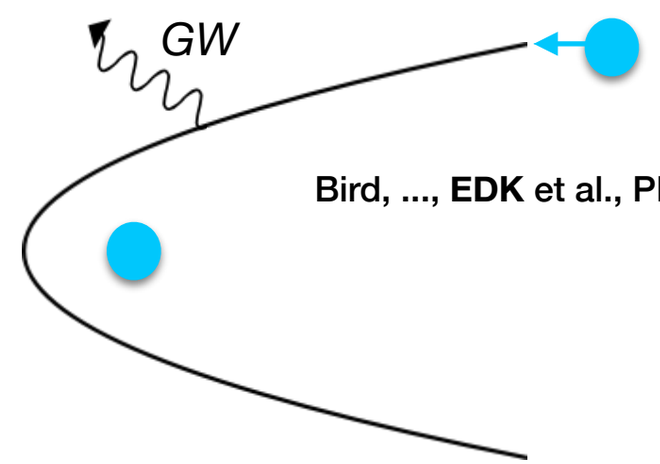

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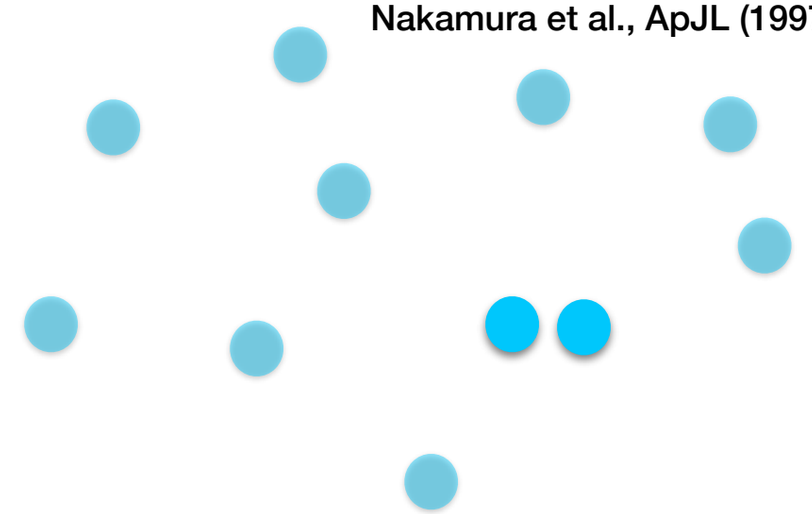

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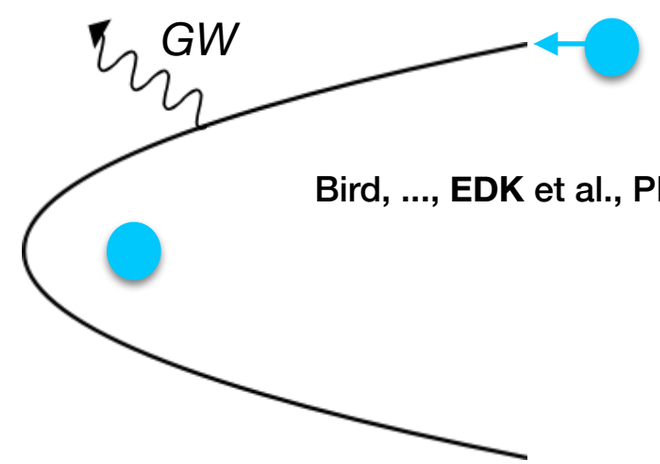

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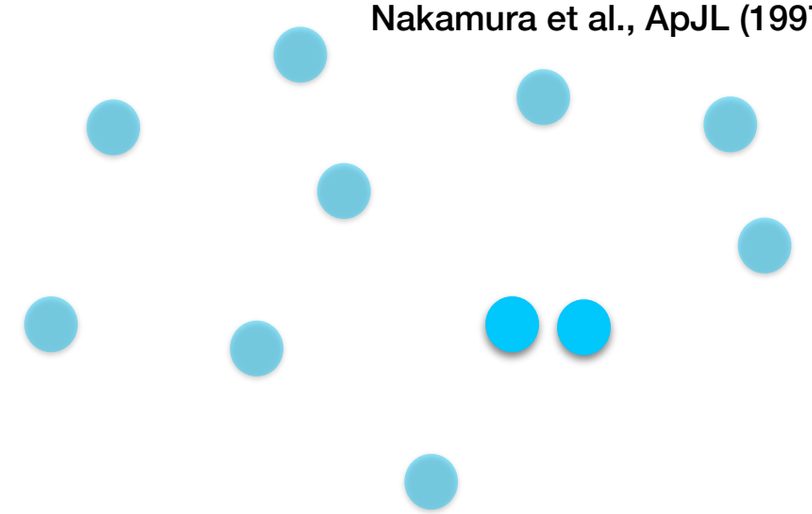

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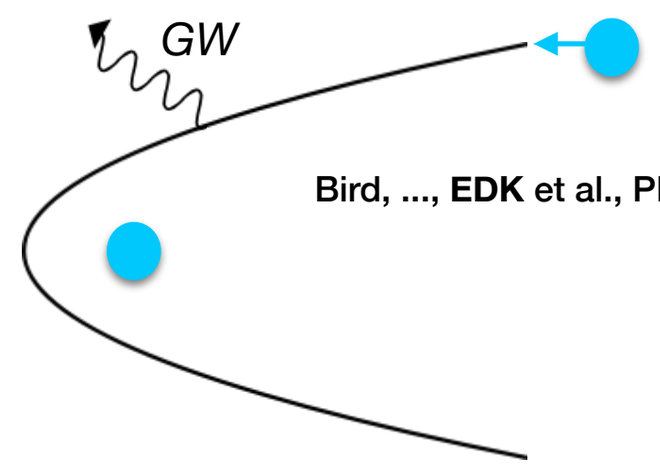

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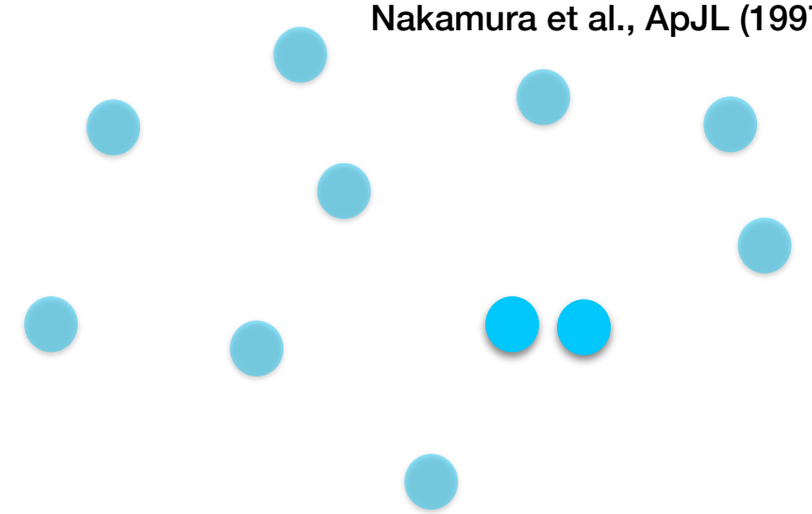

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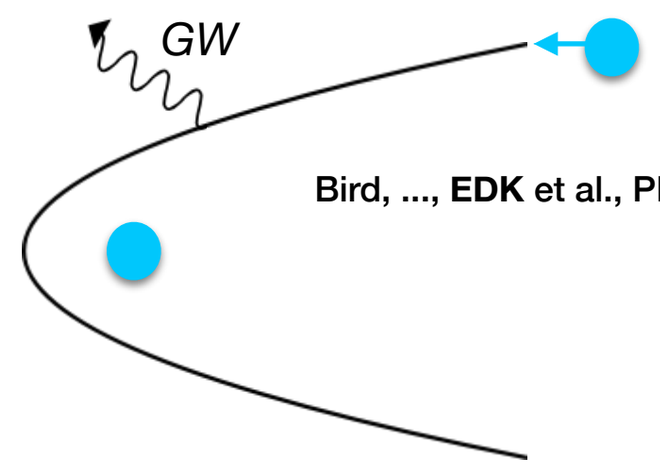

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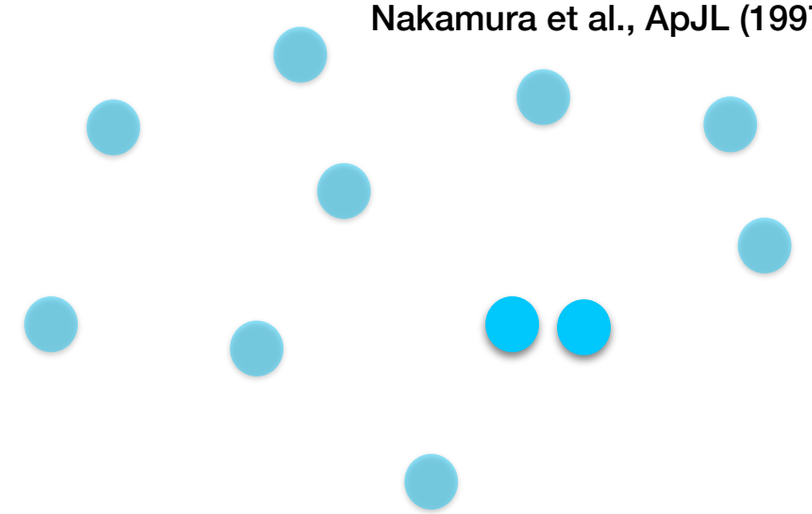

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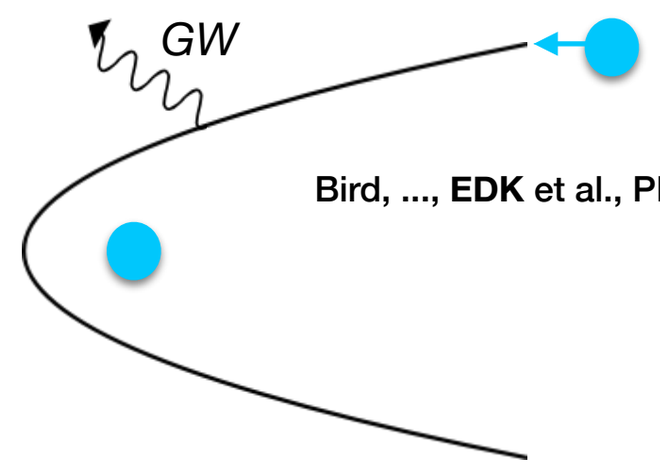

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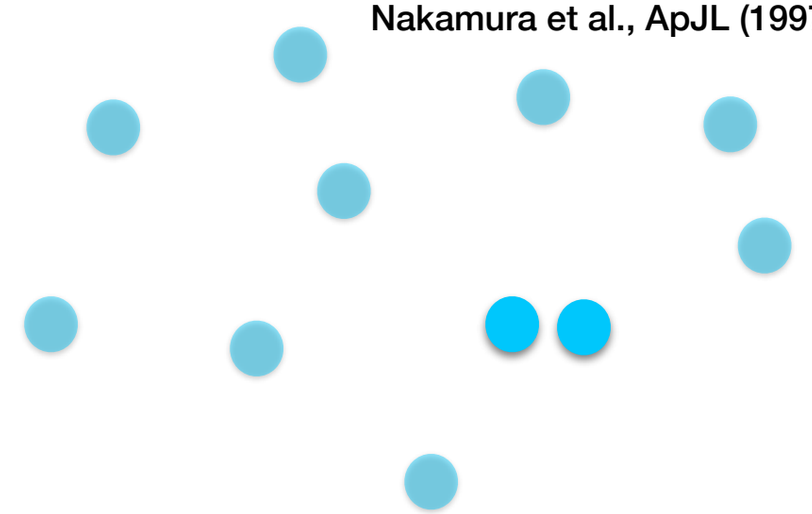

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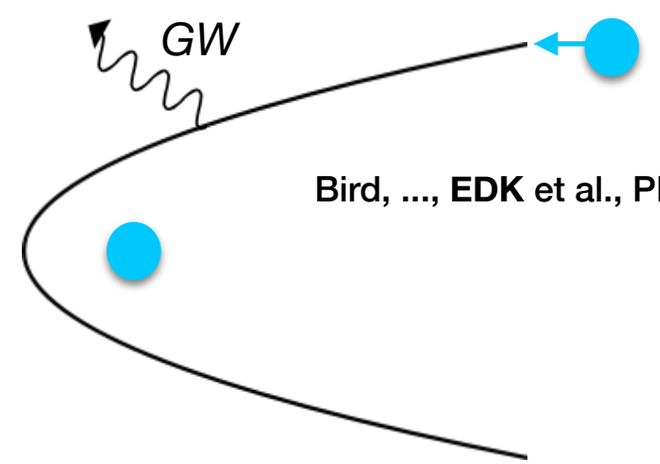

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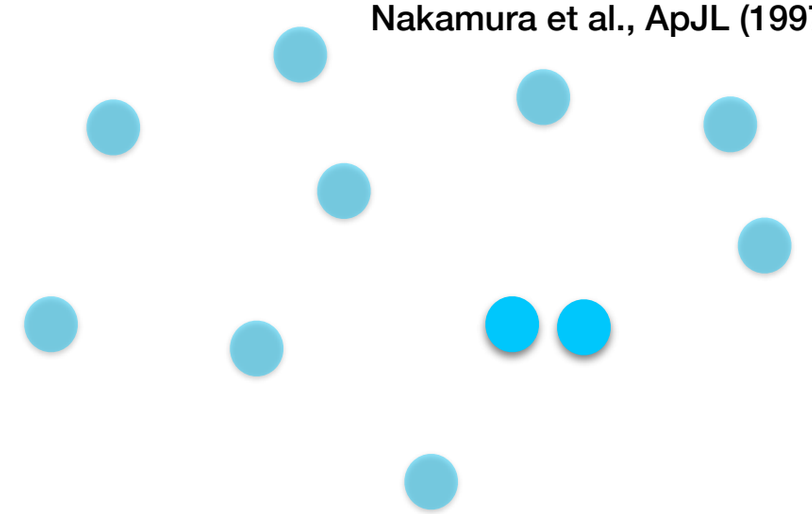

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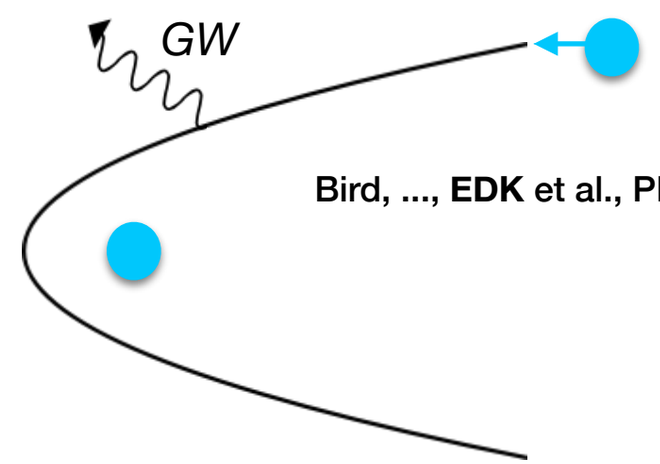

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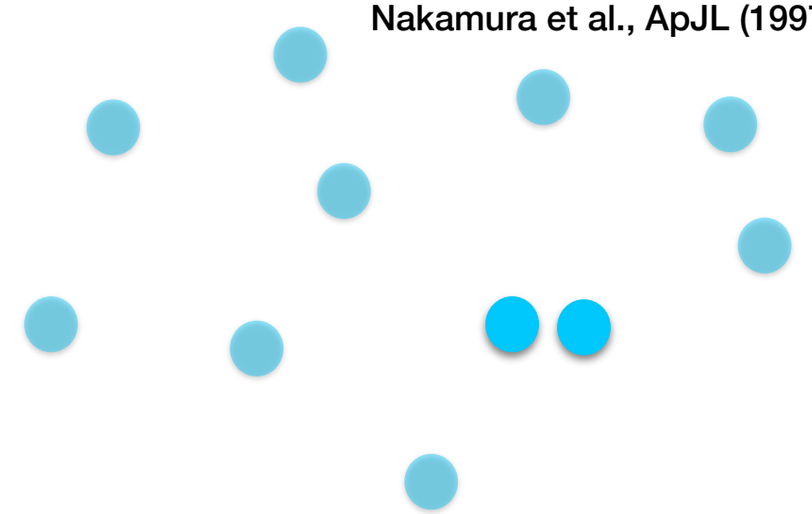

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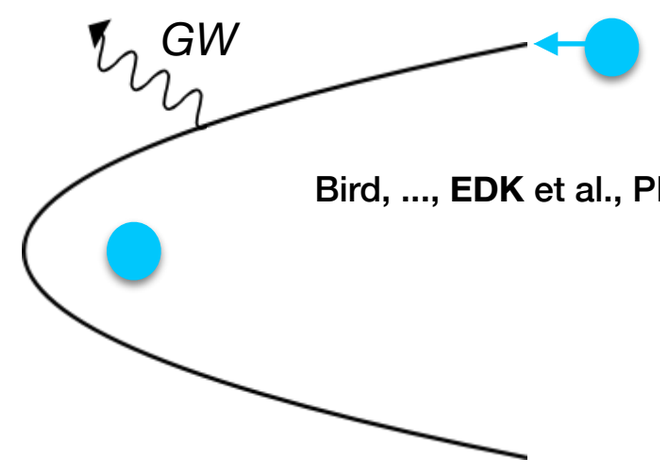

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(See Yacine's talks Tuesday/Wednesday and Jedamzik's talk on Thursday!)

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A: Yes!

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“Simplest” ansatz:

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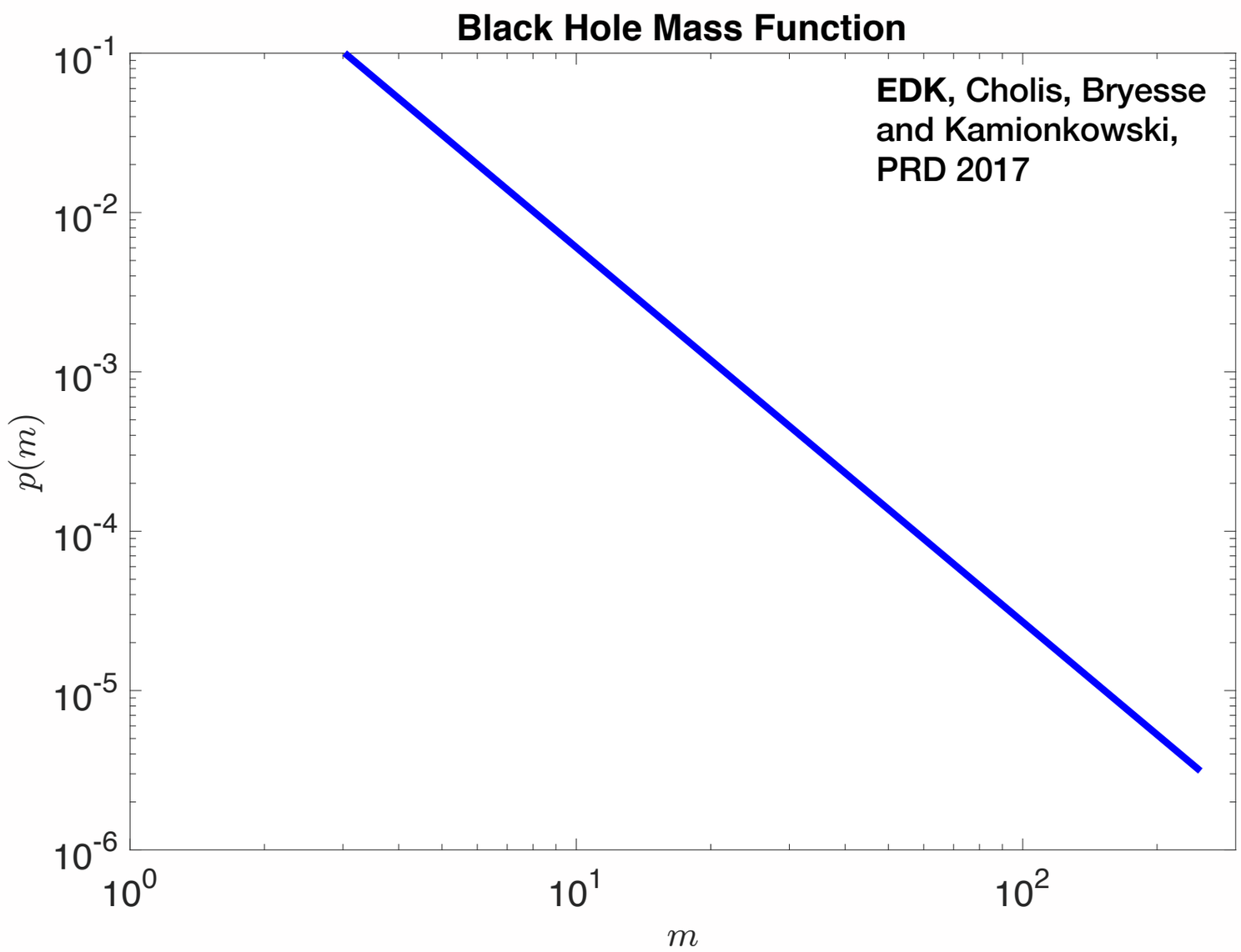
"Simplest" ansatz: $p(m) \propto m^{-\alpha}$



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Stellar IMF
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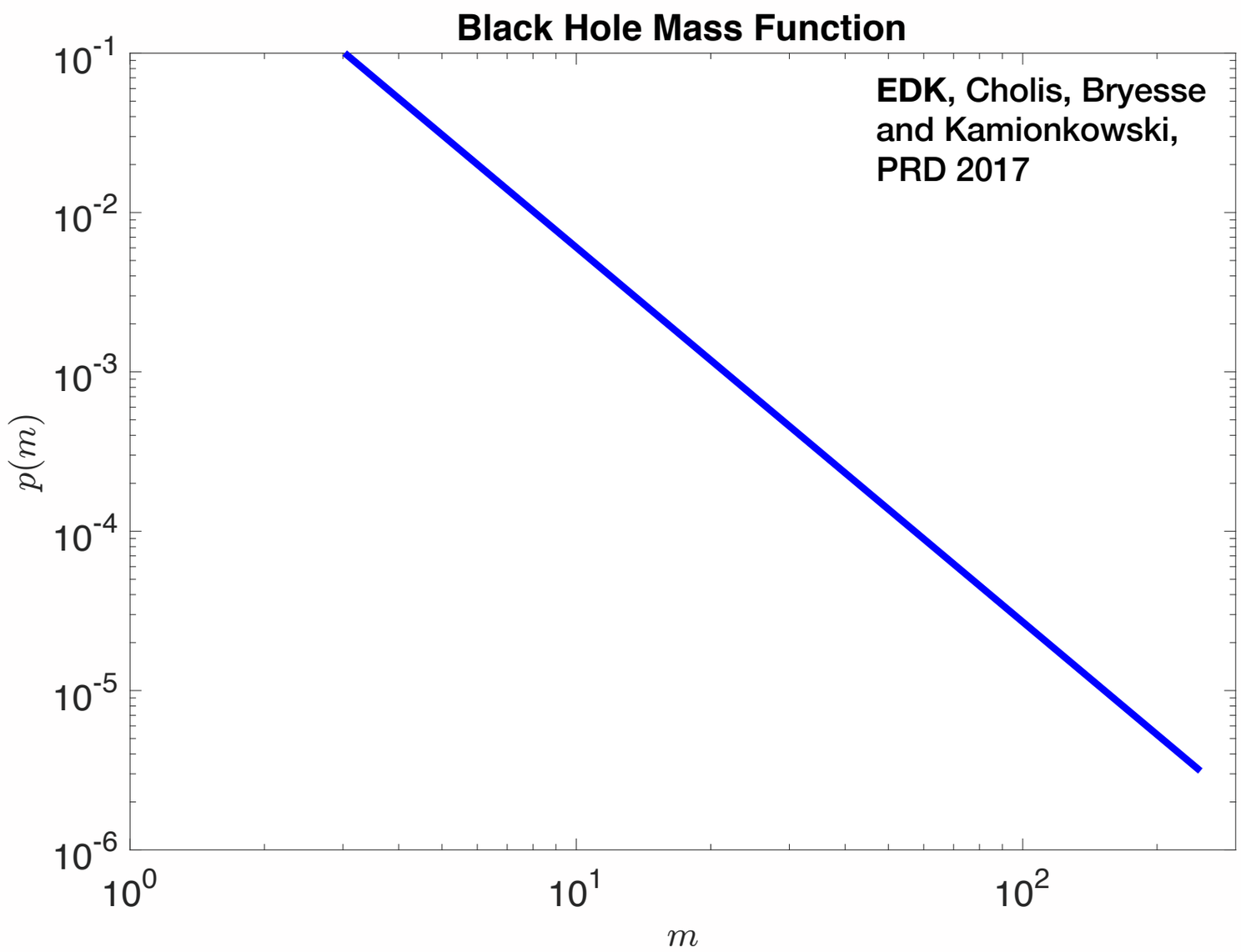

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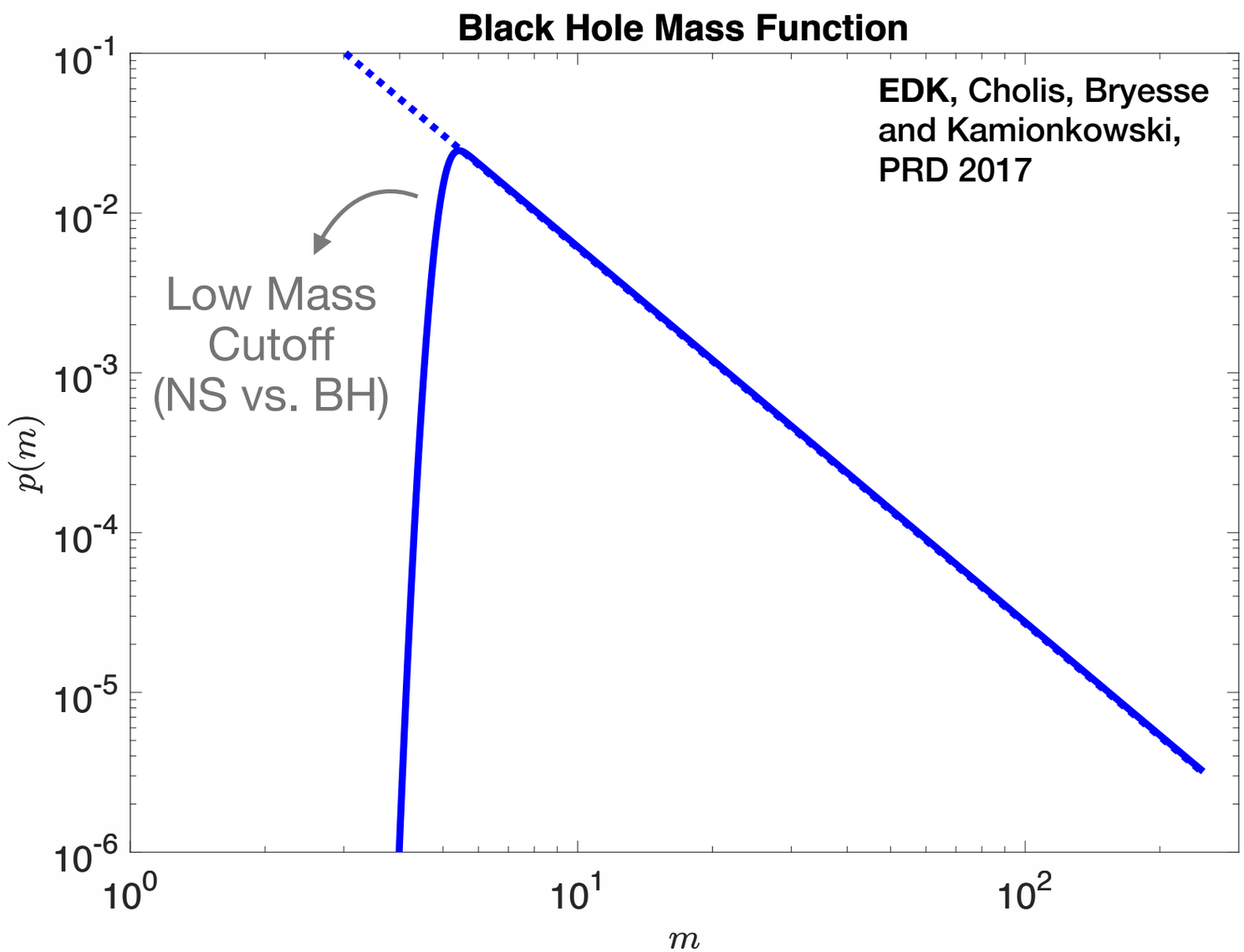

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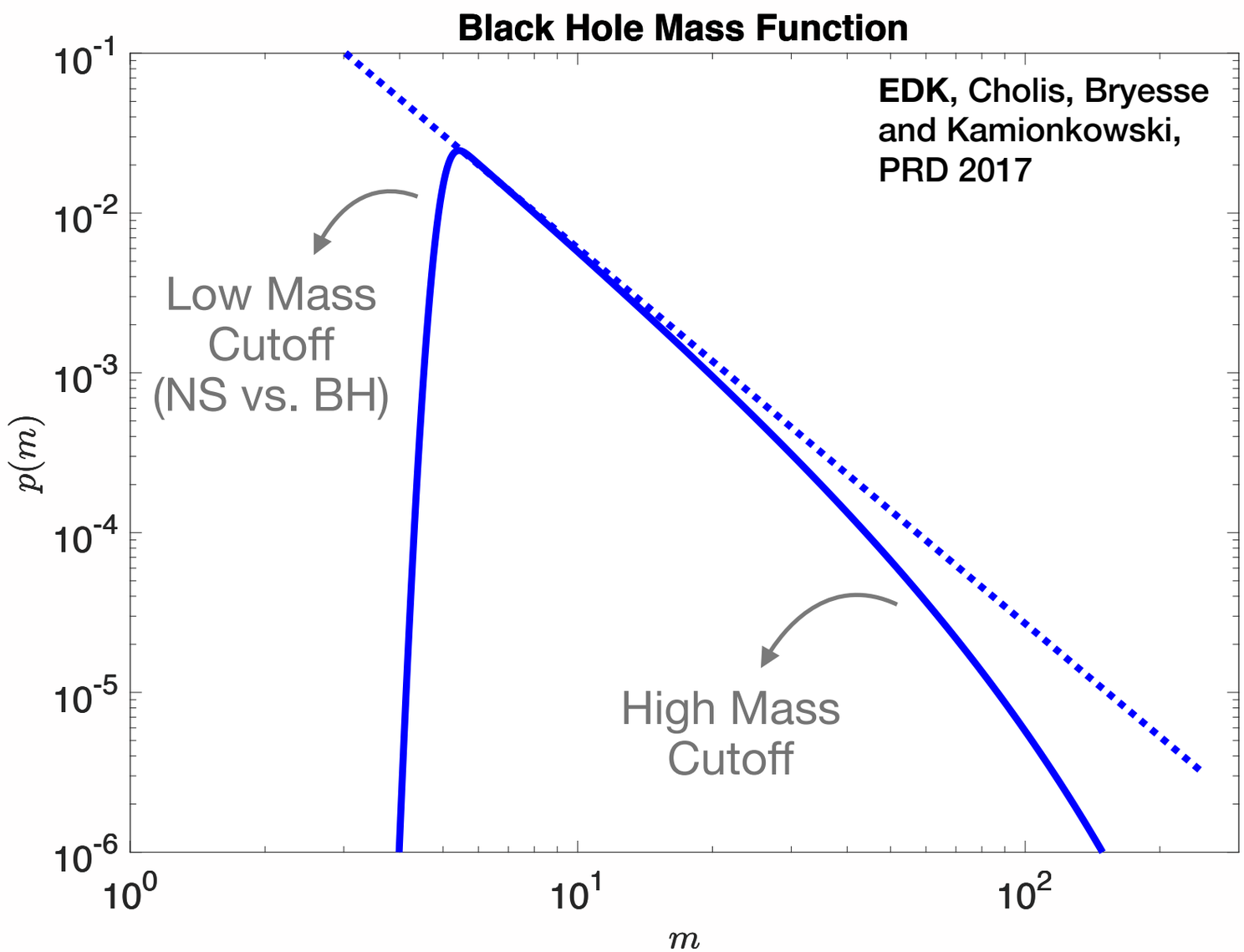

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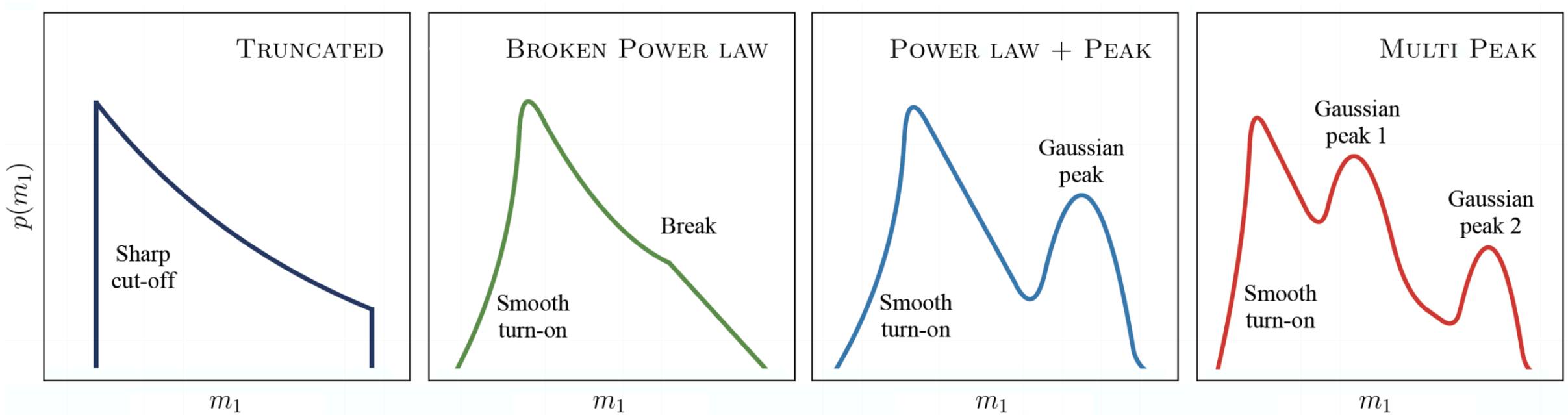

LIGO Collaboration, arXiv:2010.14533

Indirect Detection: The GW Mass Spectrum

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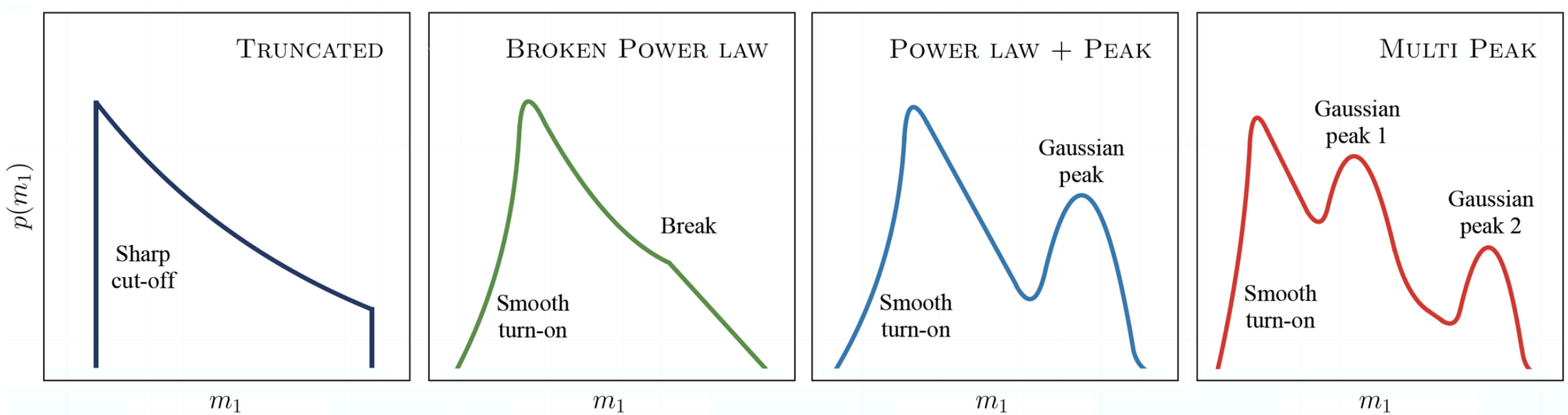

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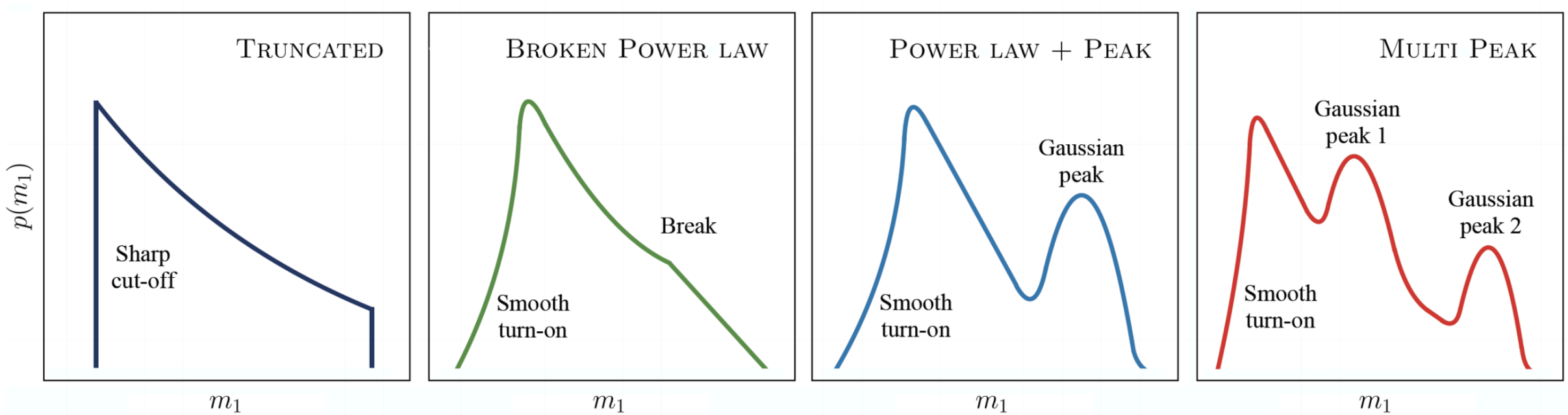

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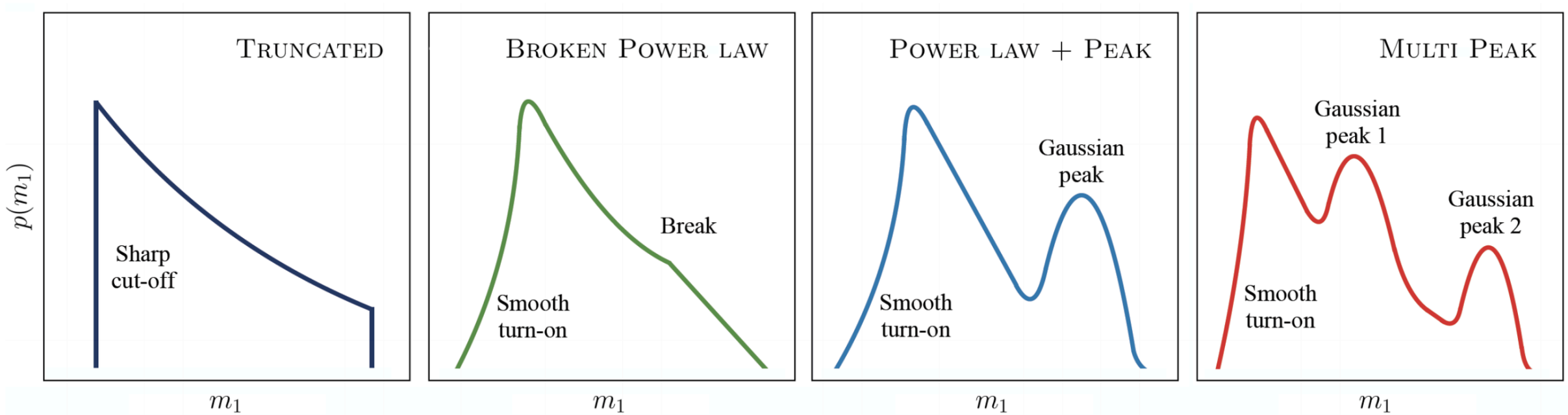

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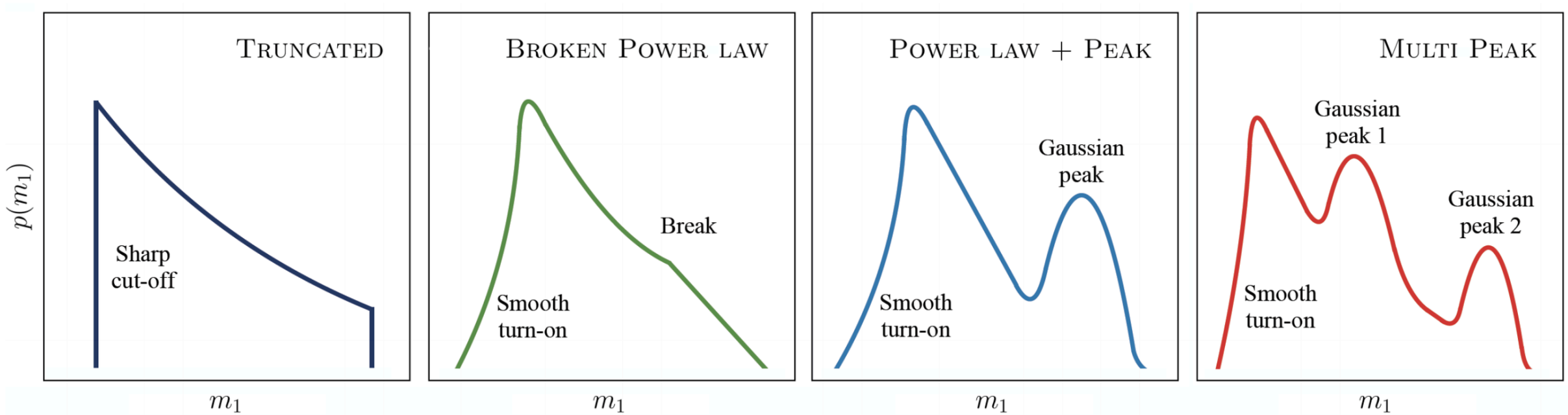

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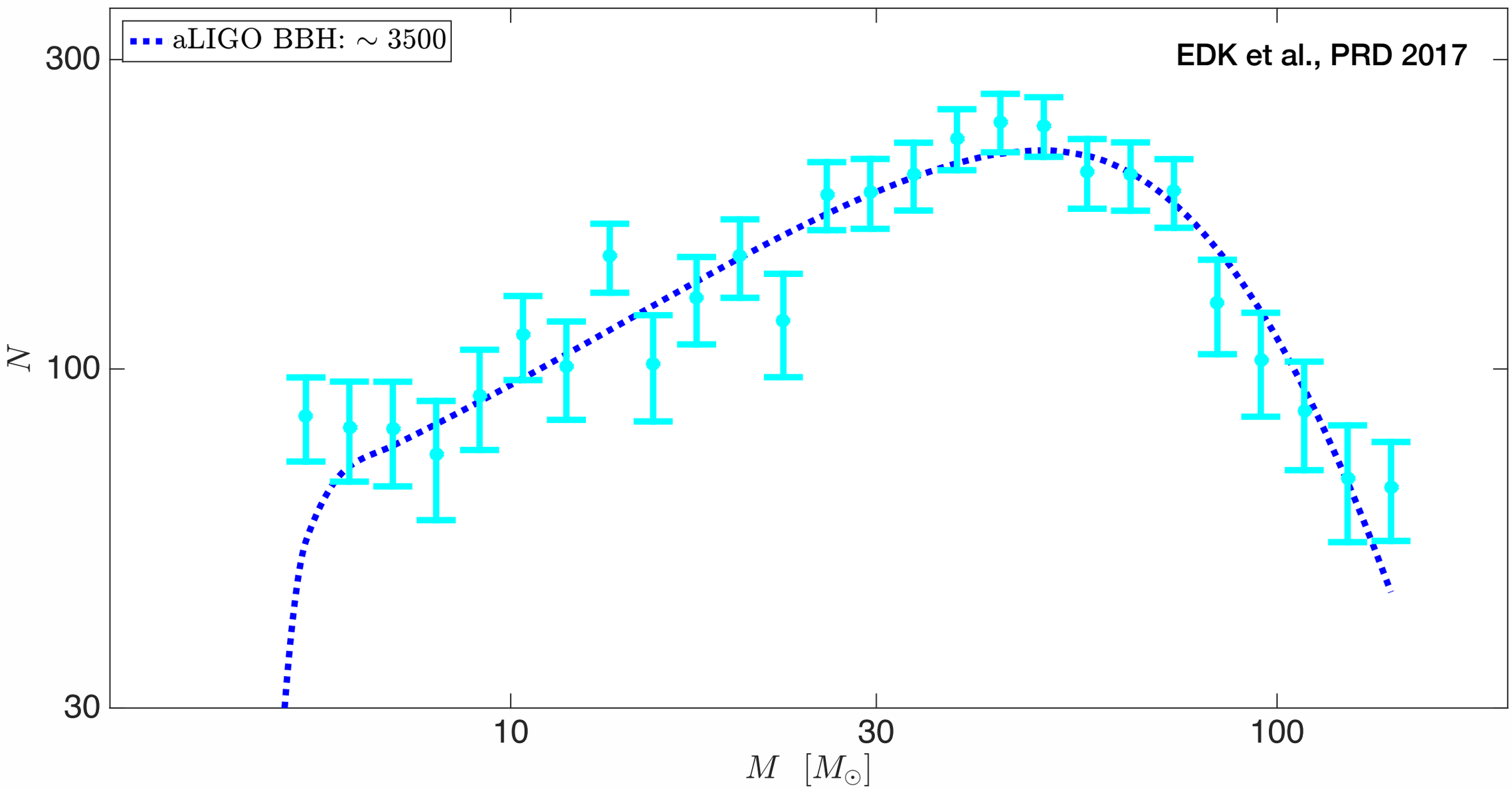
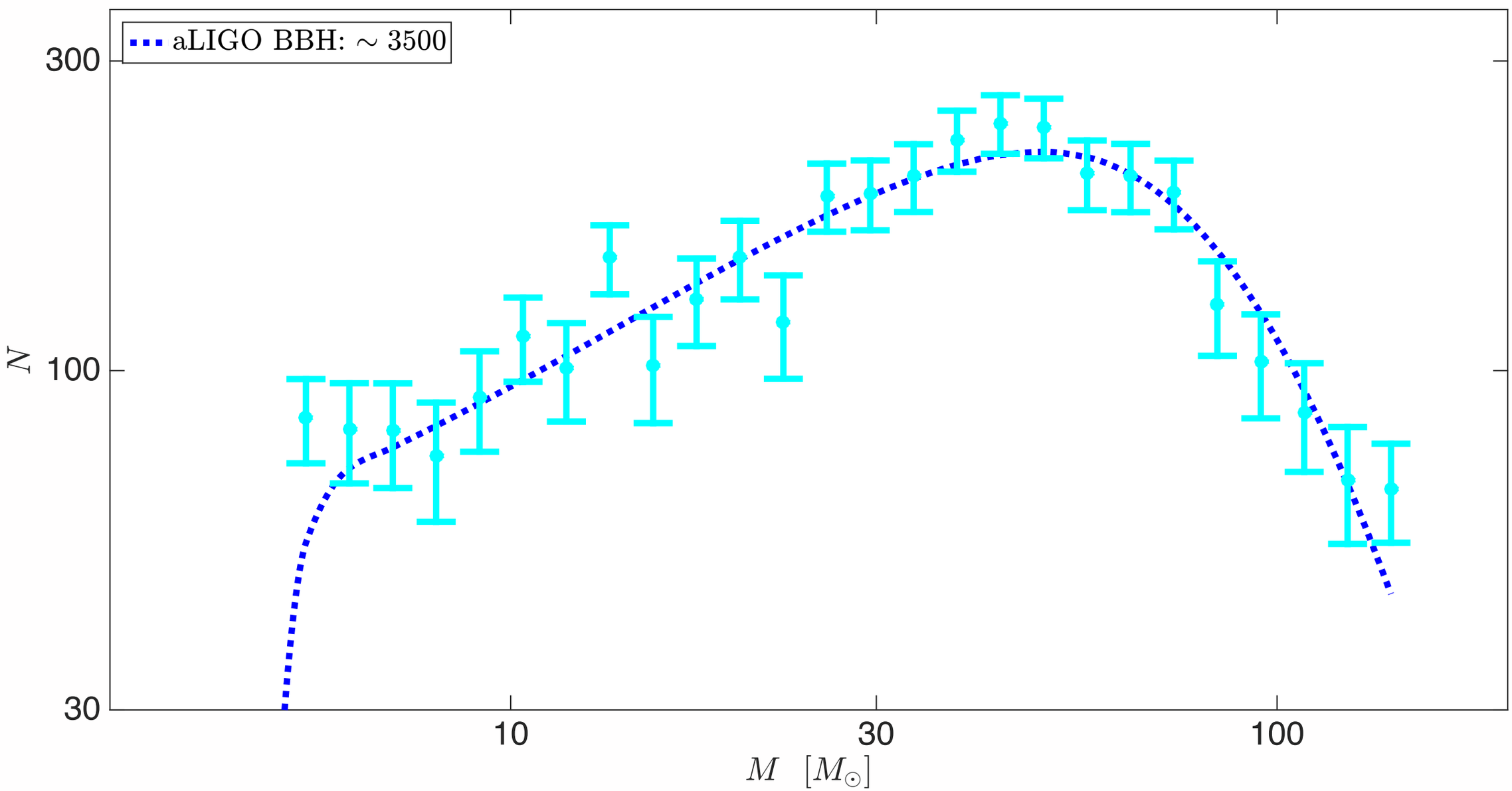
(note logarithmic binning...)



Indirect Detection: Stellar+“mono”-PBH Spectrum



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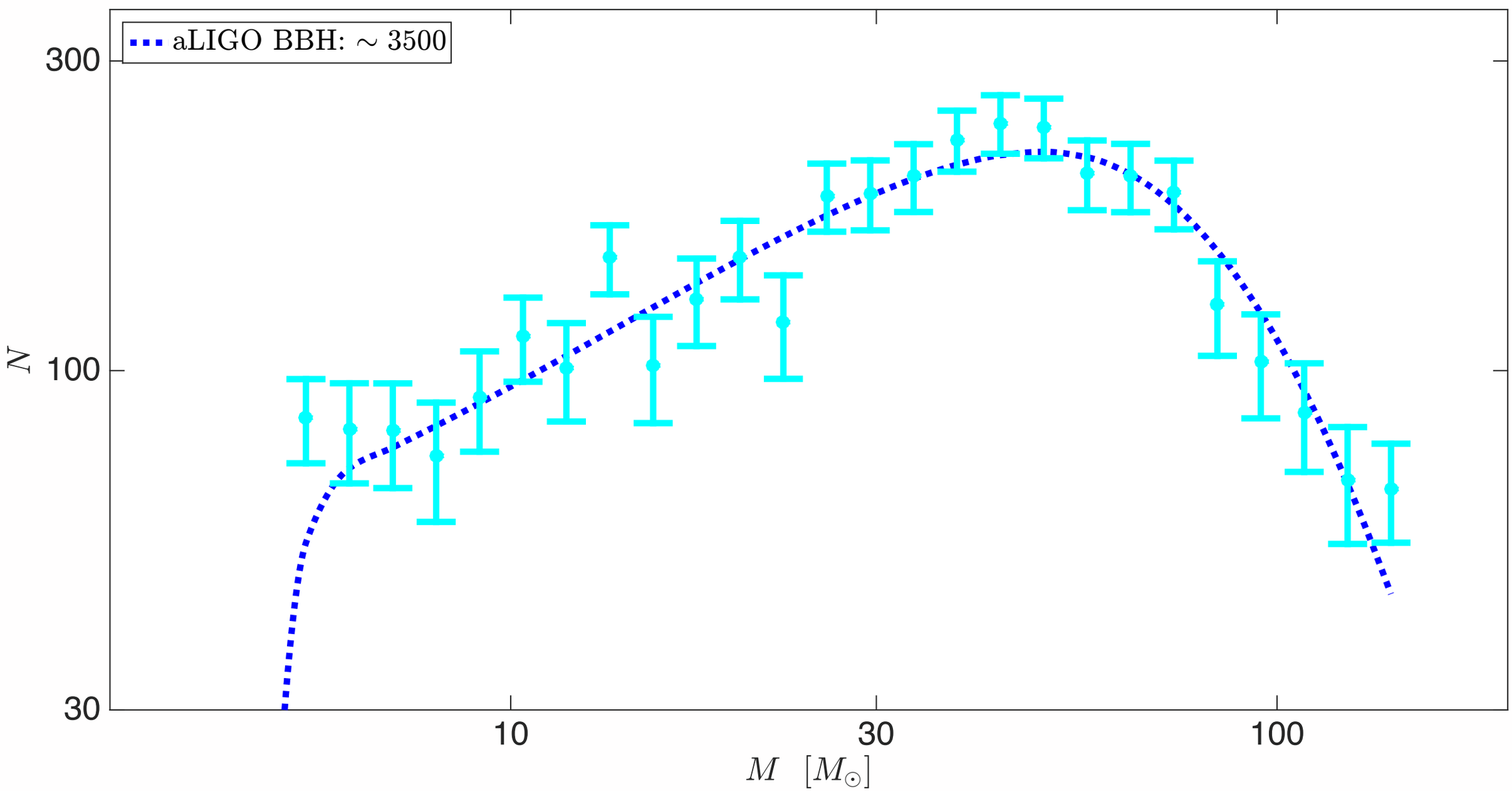

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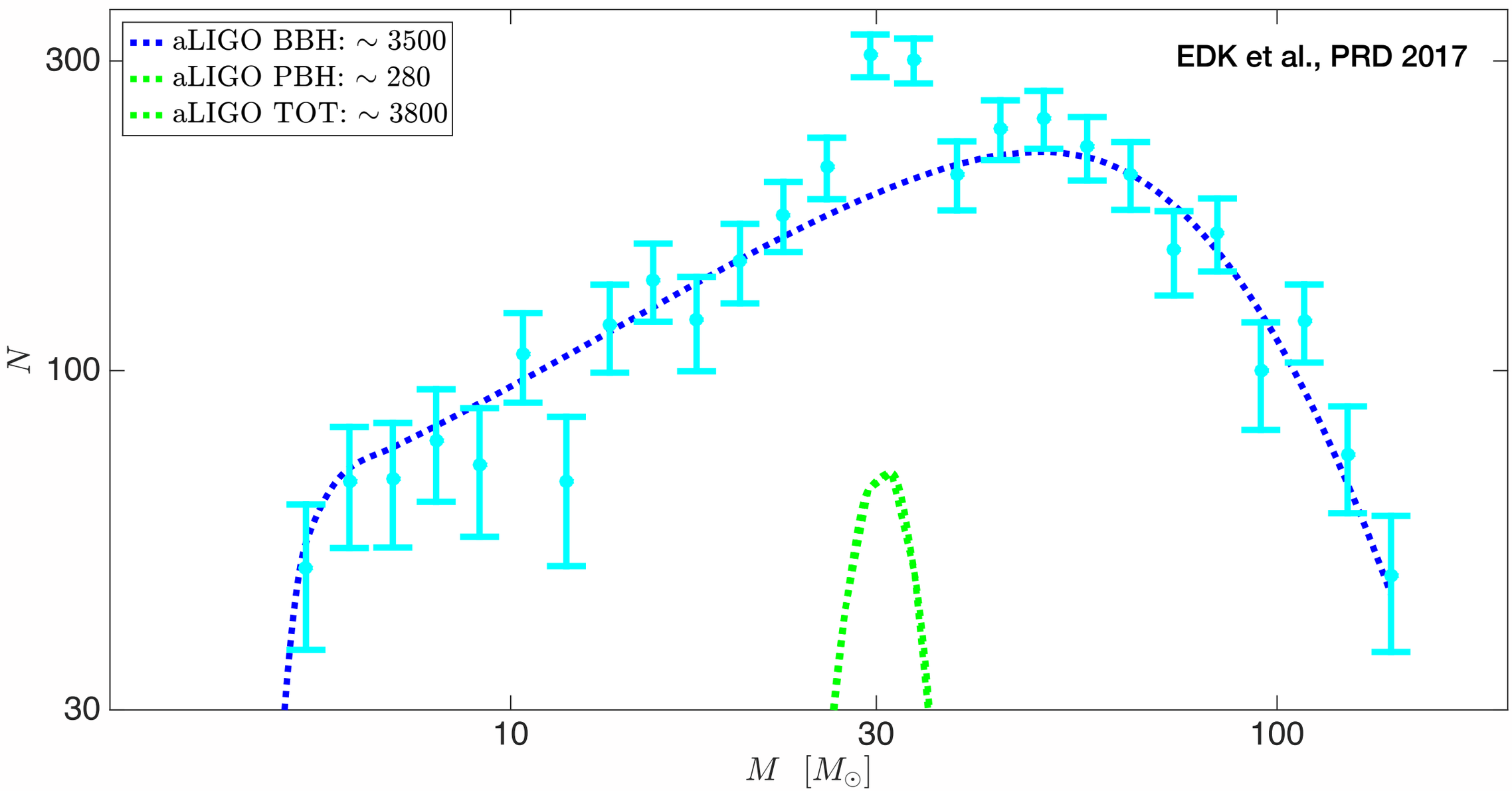

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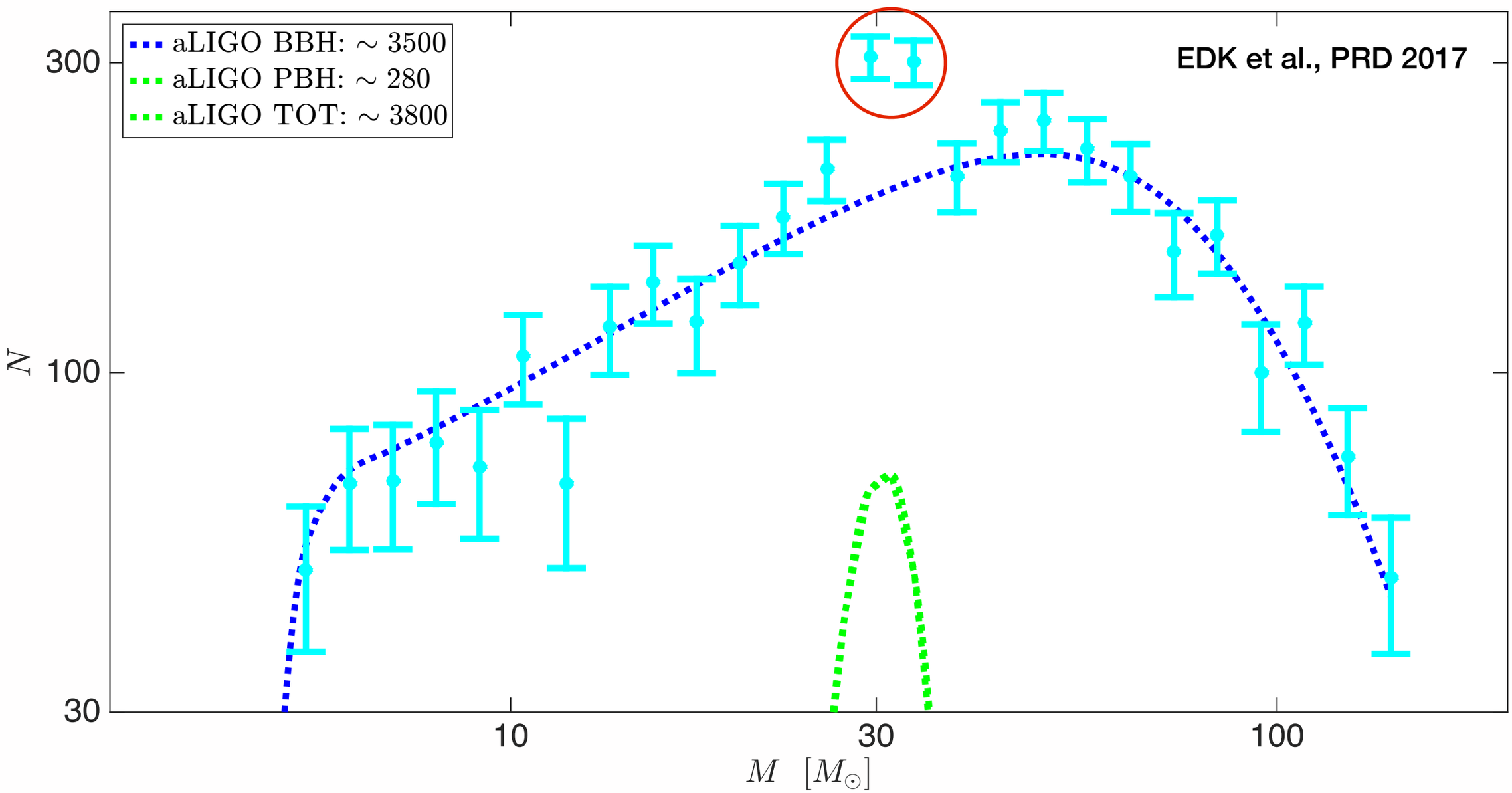

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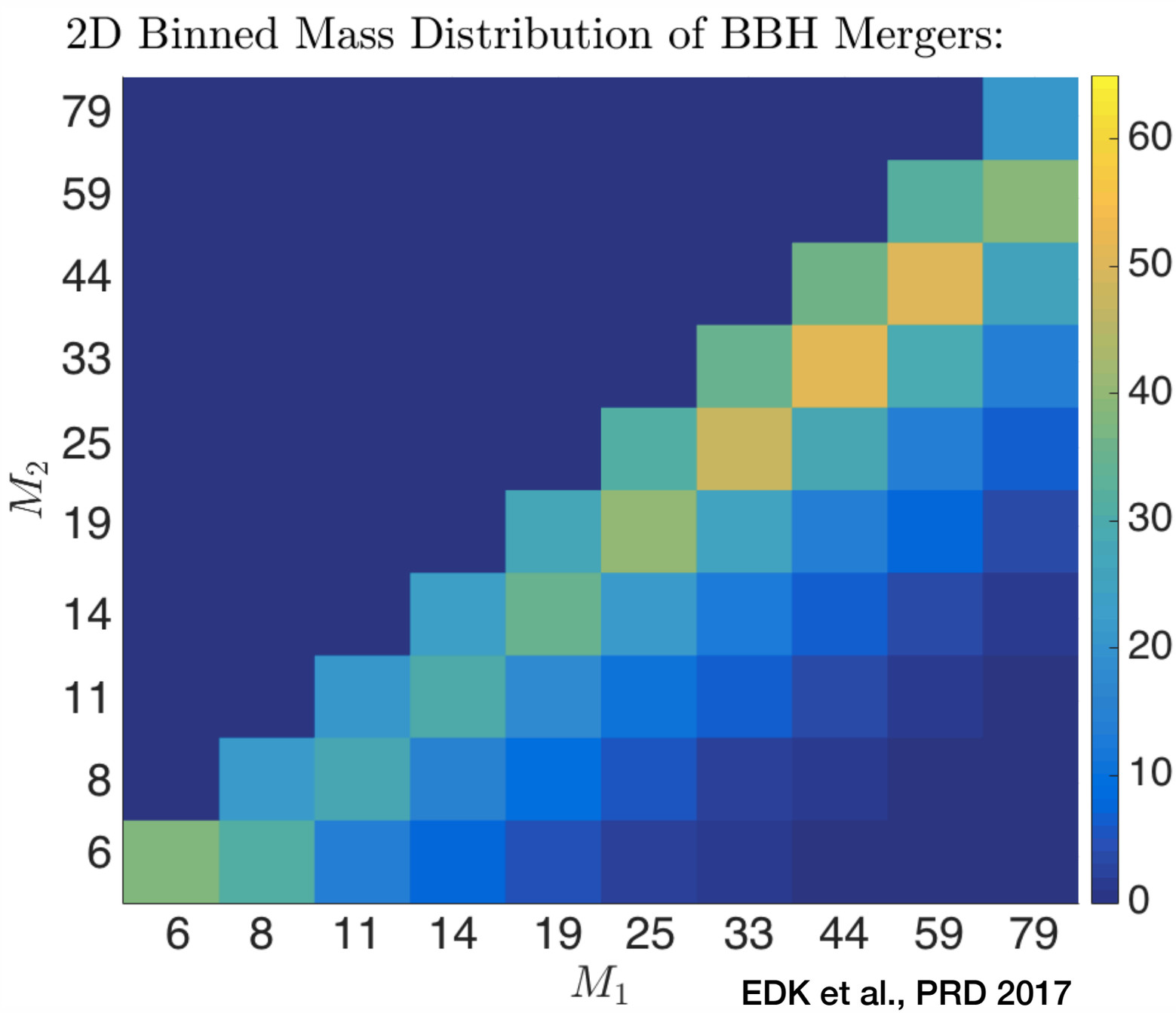

EDK et al., PRD 2017

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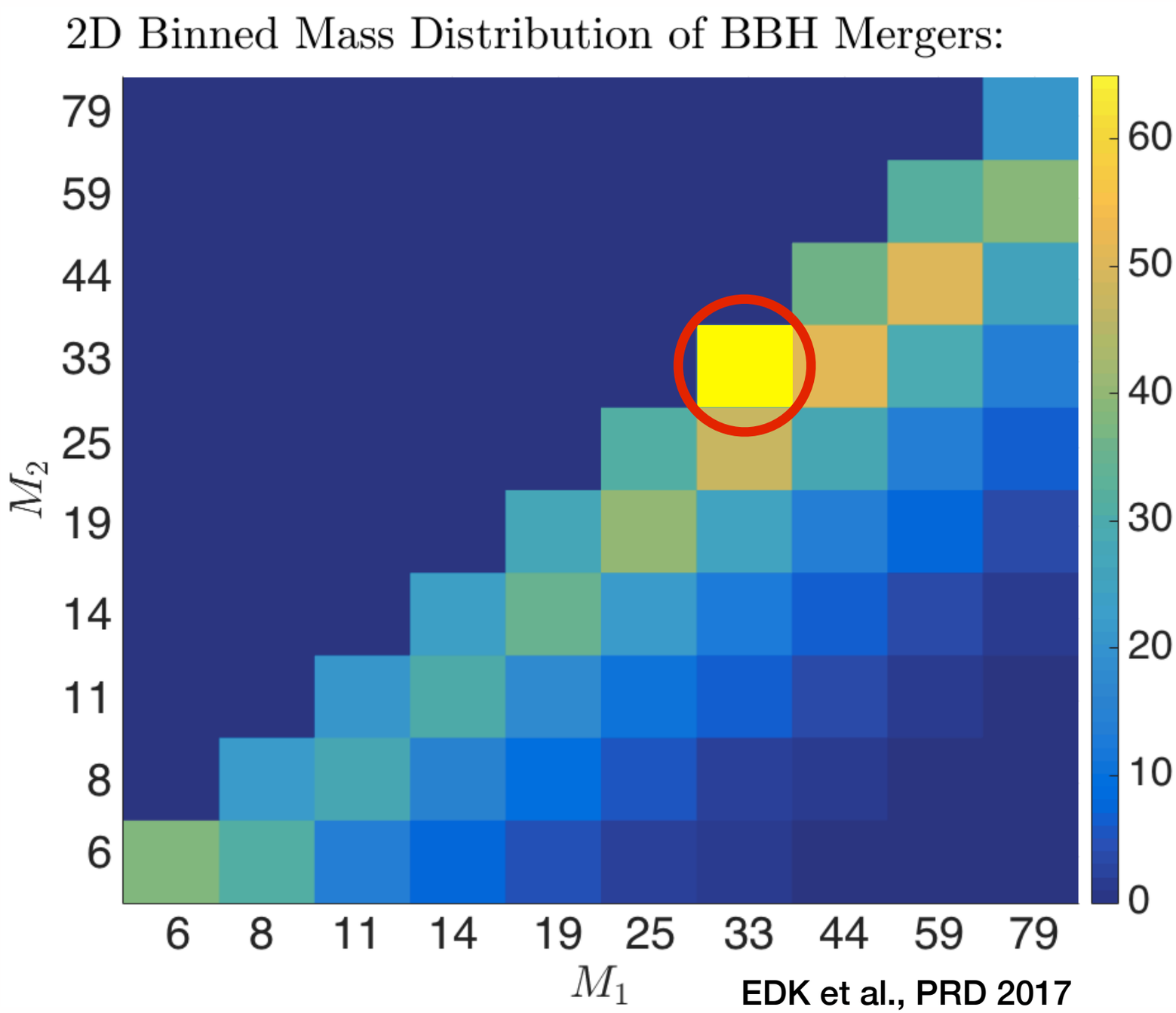

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Indirect Detection: Constraints on PBH fraction

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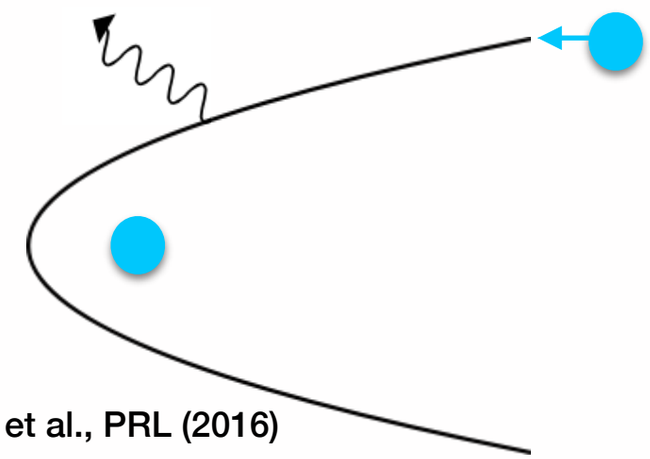

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Indirect Detection: Constraints on PBH fraction

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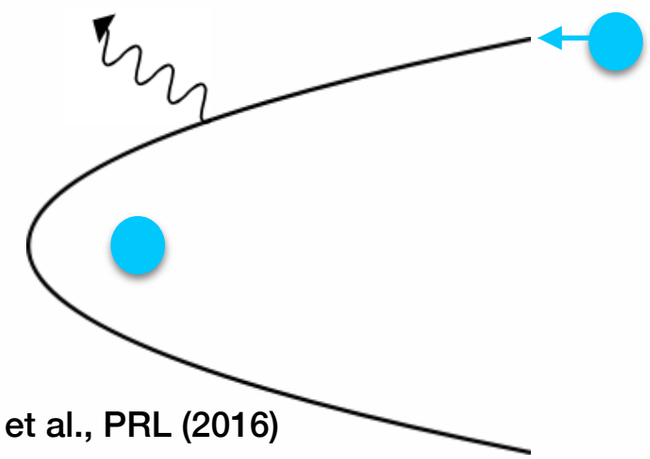
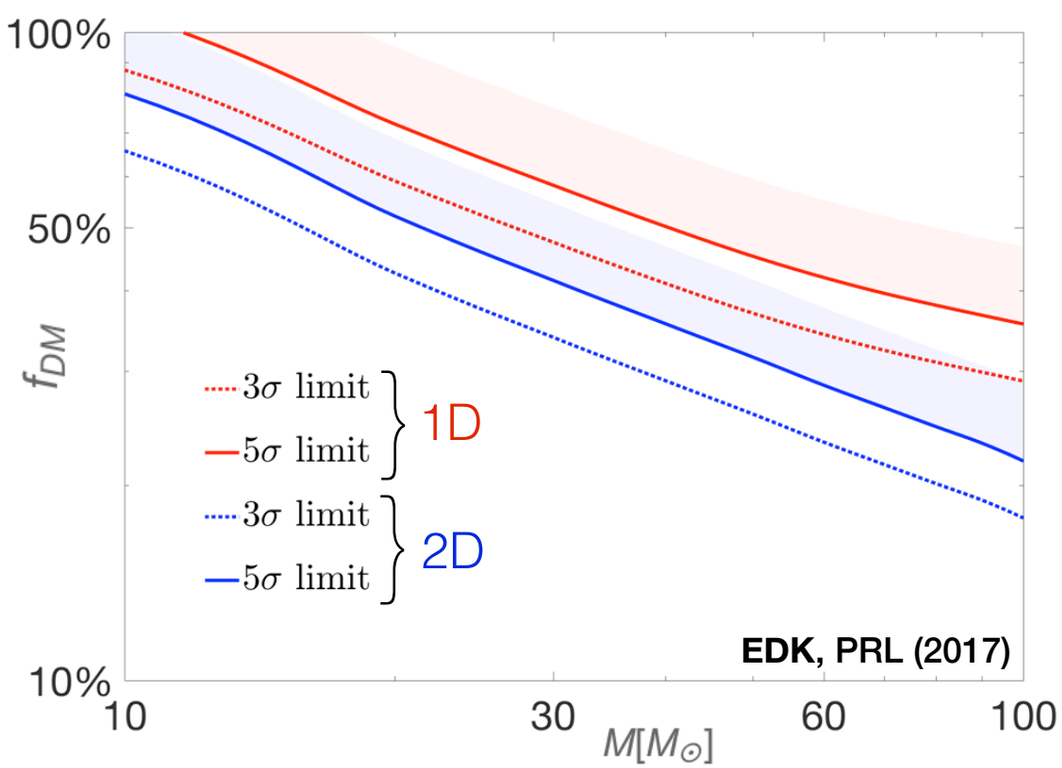


Bird, ..., **EDK** et al., PRL (2016)



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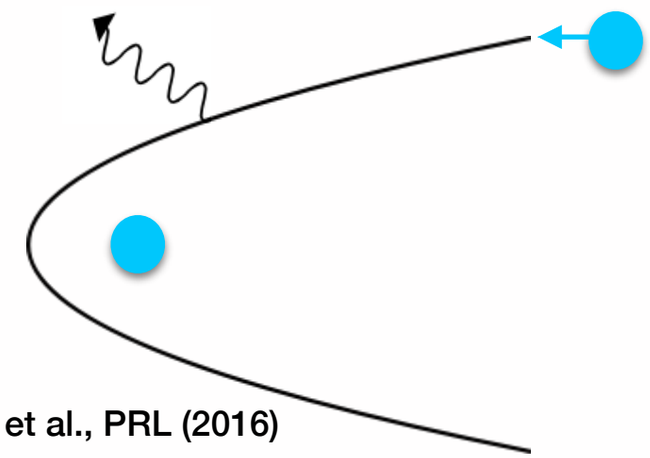

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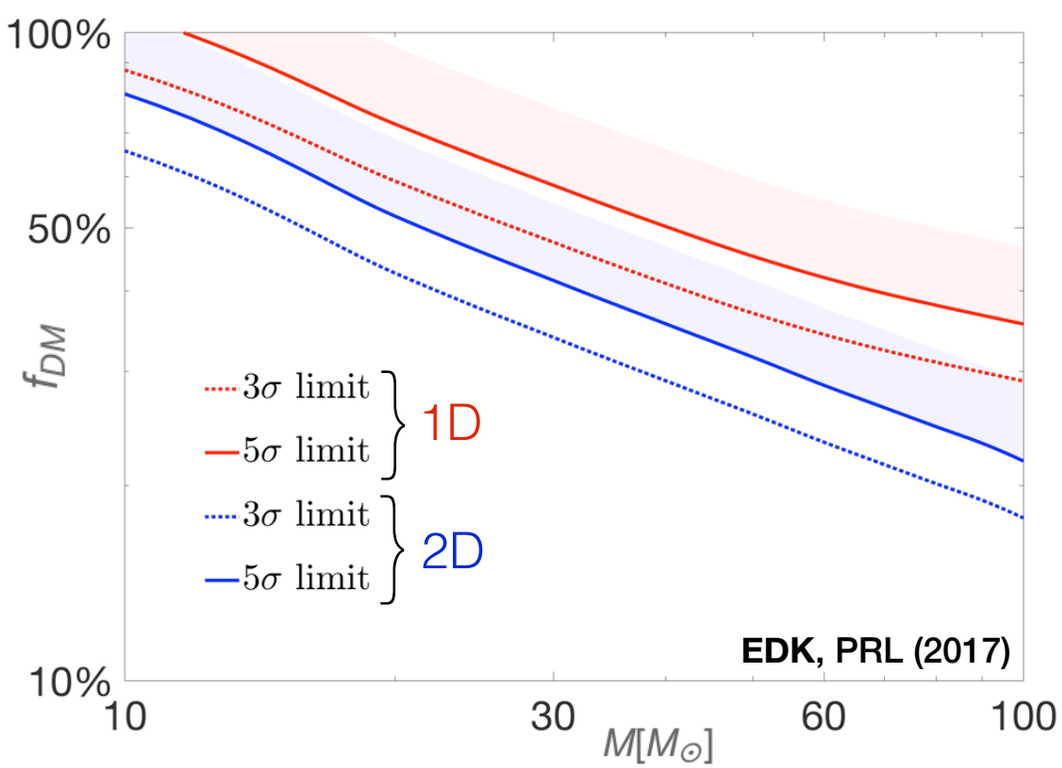

Binaries formed in early-Universe:

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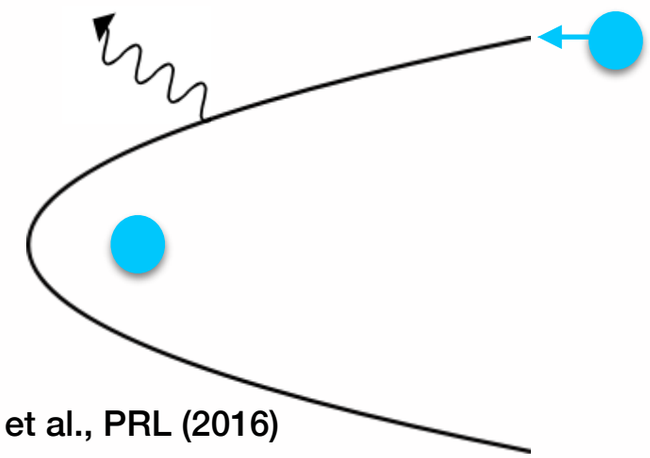

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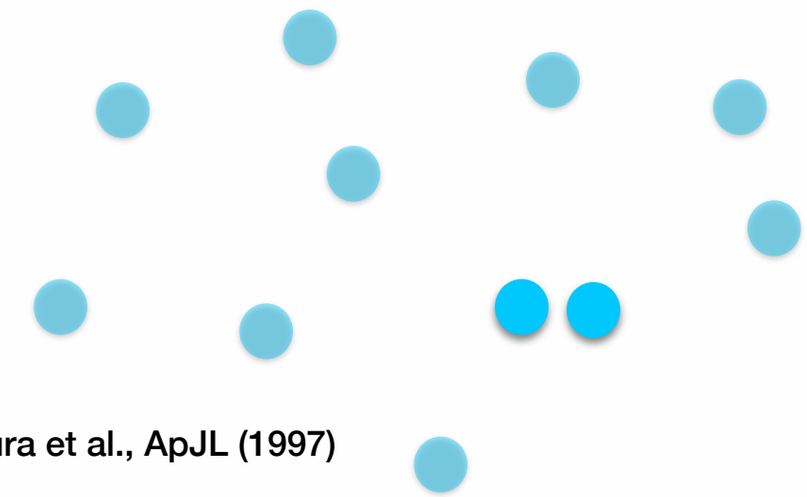

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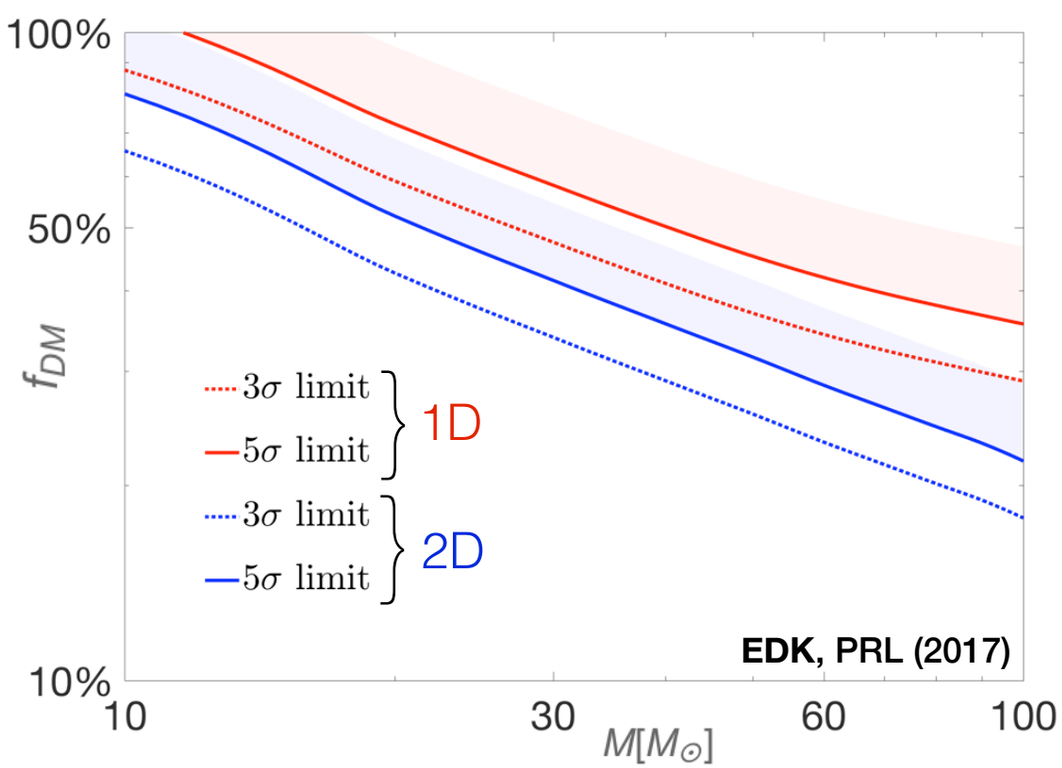

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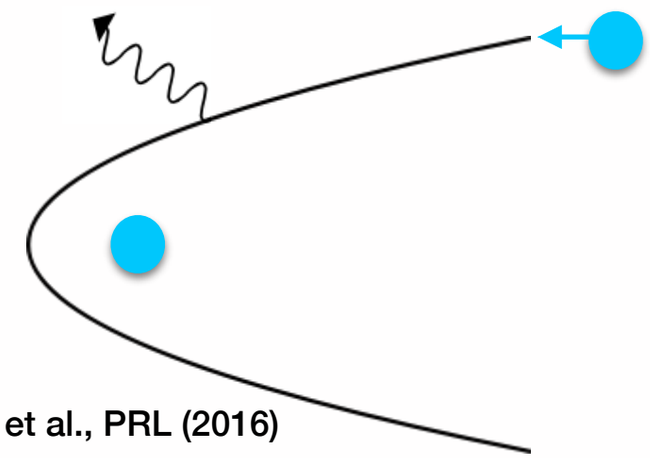

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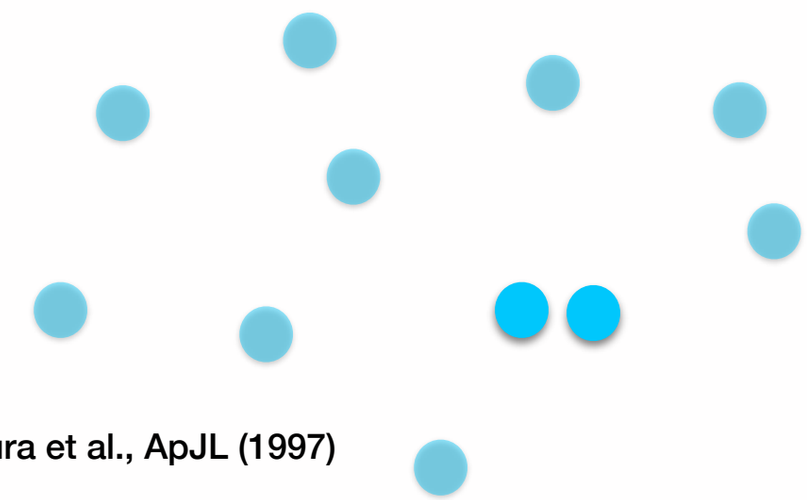

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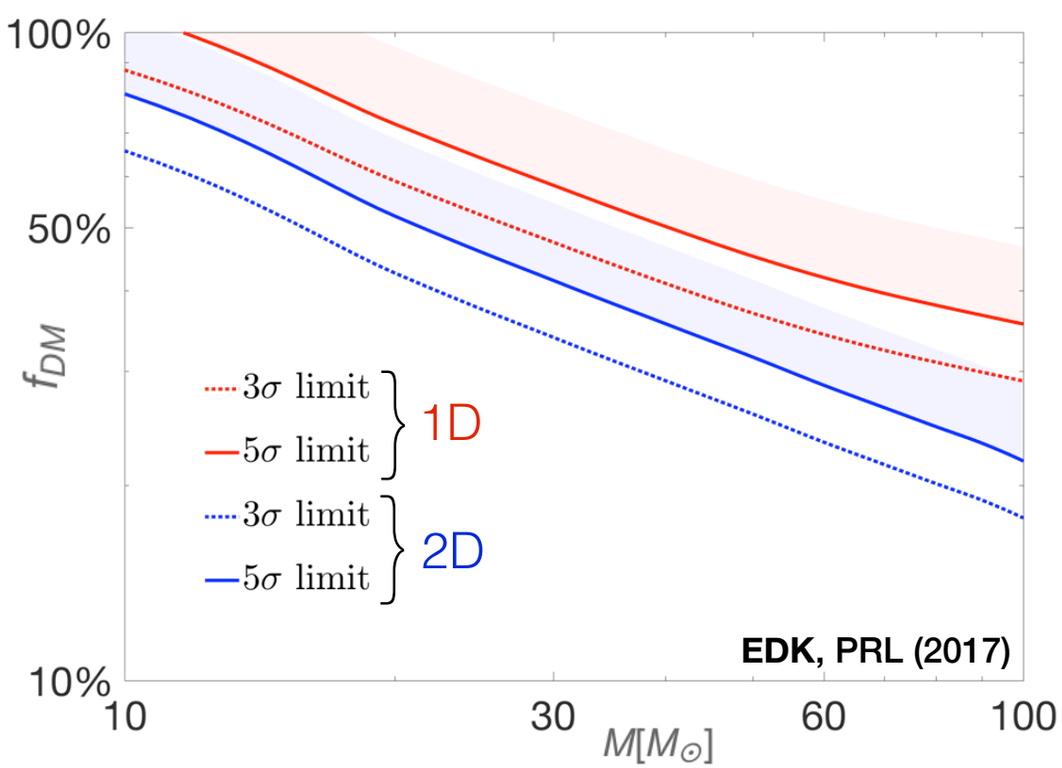

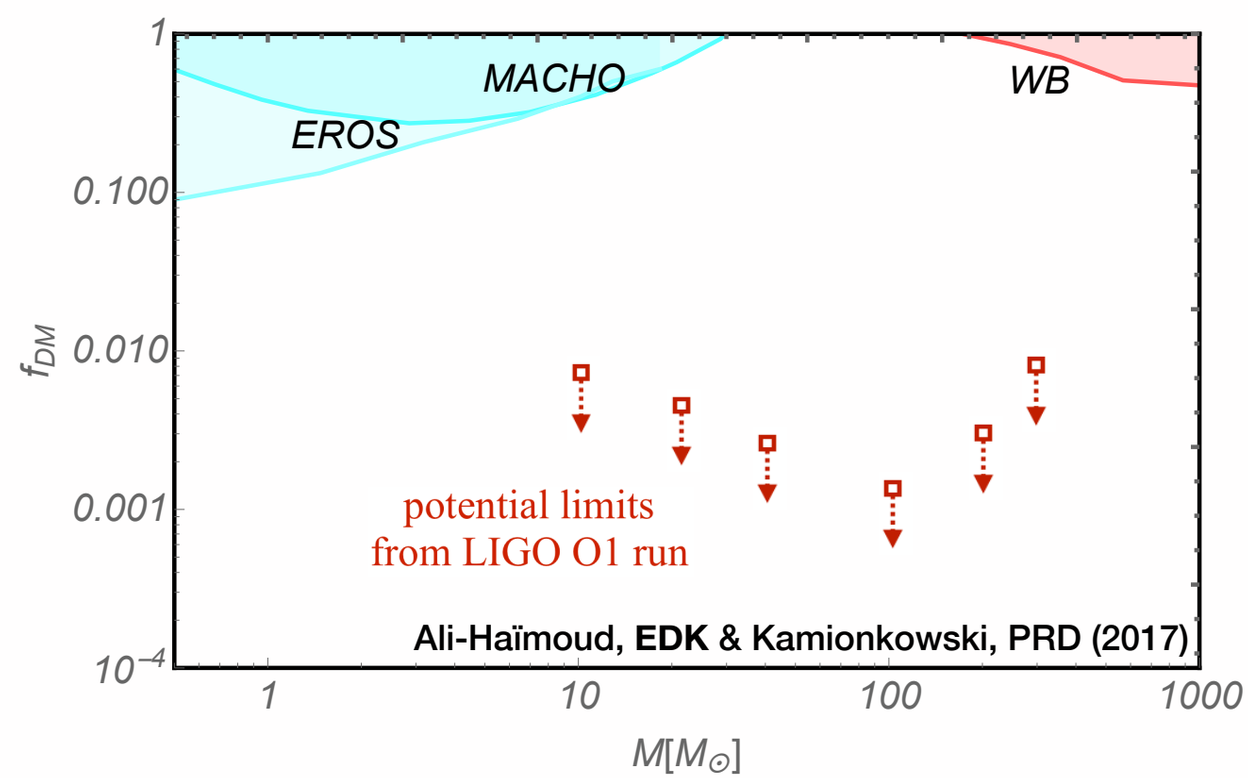

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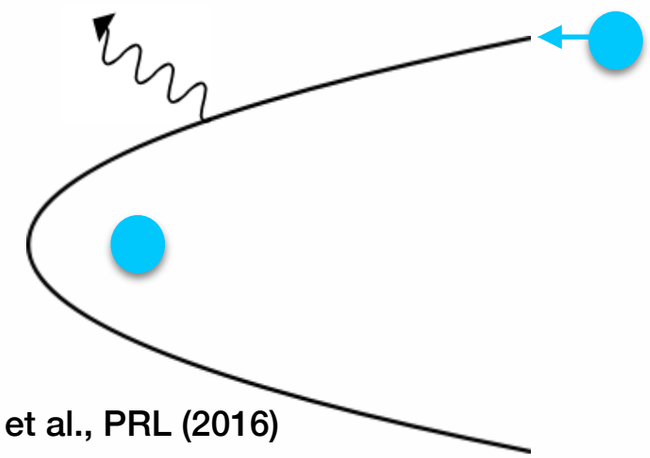

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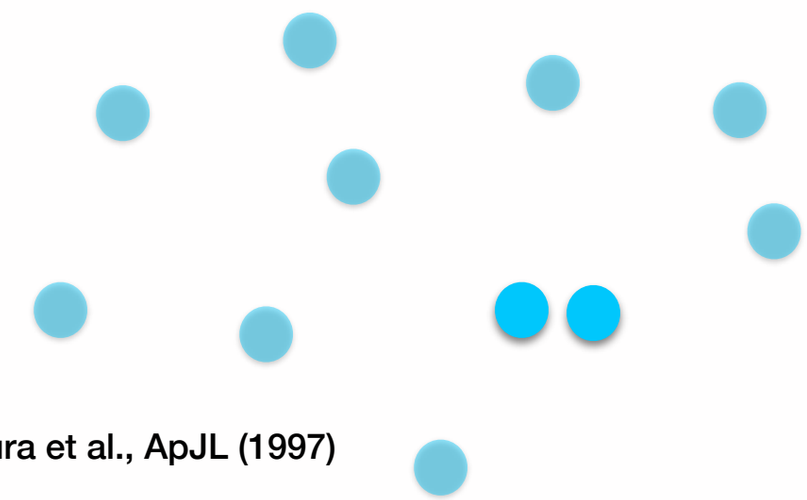

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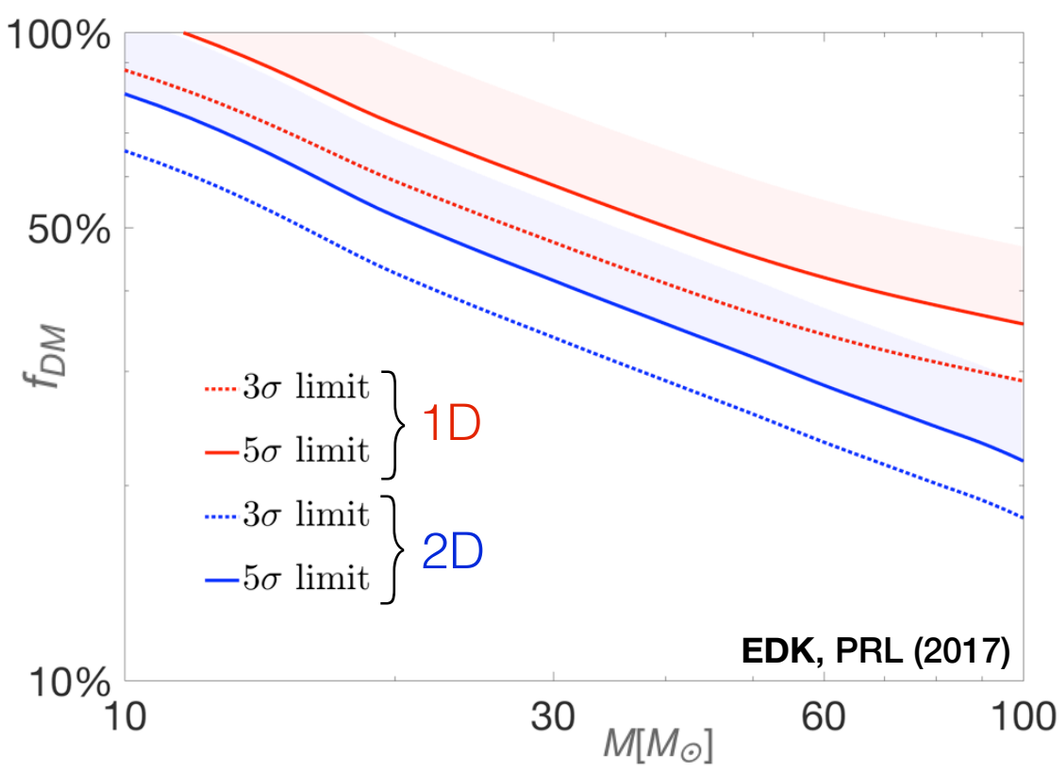

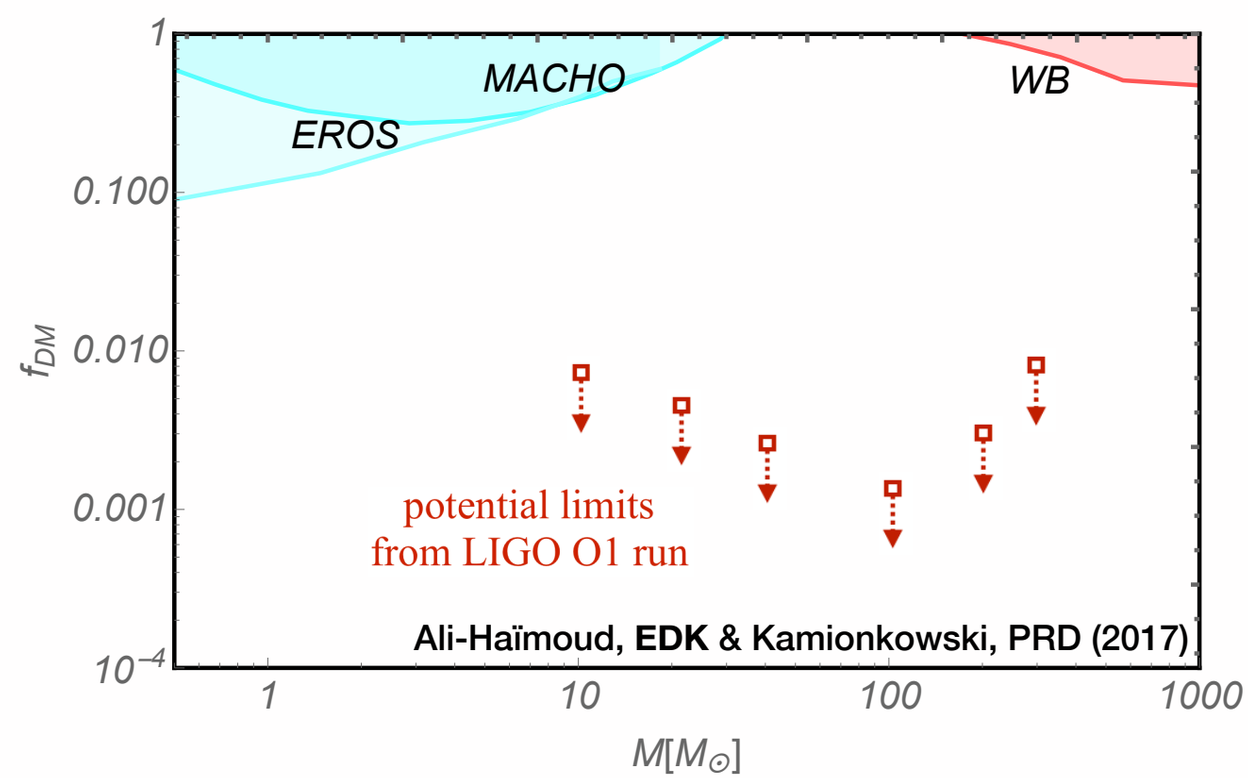

(See Yacine's talks Tuesday/Wednesday)

Indirect Detection: Orbital Eccentricity

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Orbits HIGHLY eccentric at encounter:

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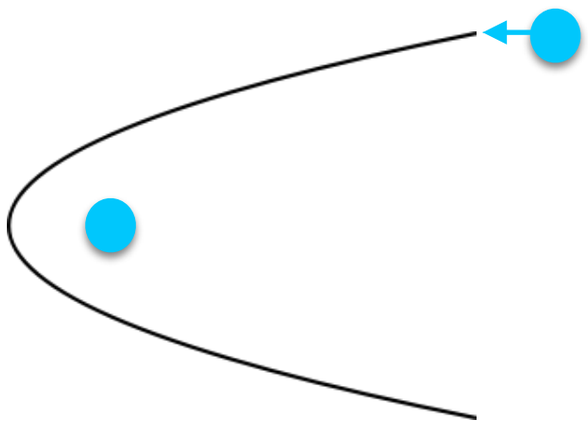

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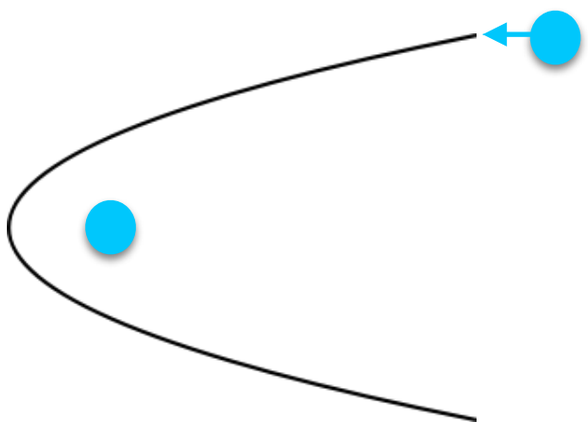

impact factor;
relative velocity

Initial conditions: $(b, v_{\rm pbh})$

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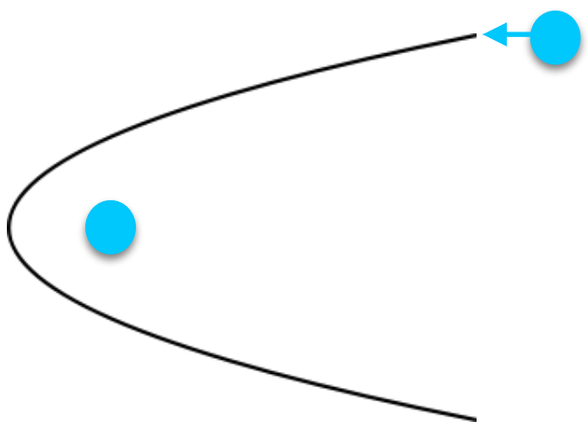

impact factor; *relative velocity* — *semi-major axis*; *eccentricity*

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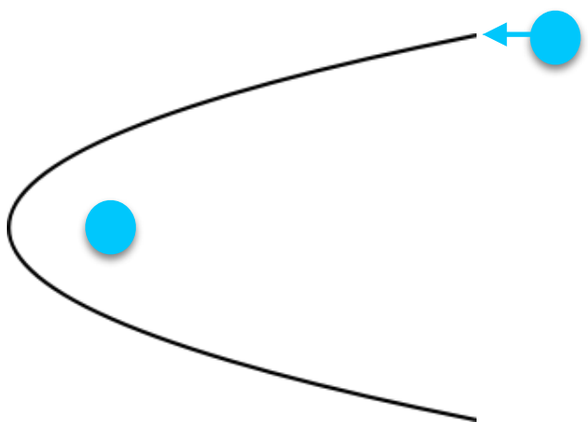

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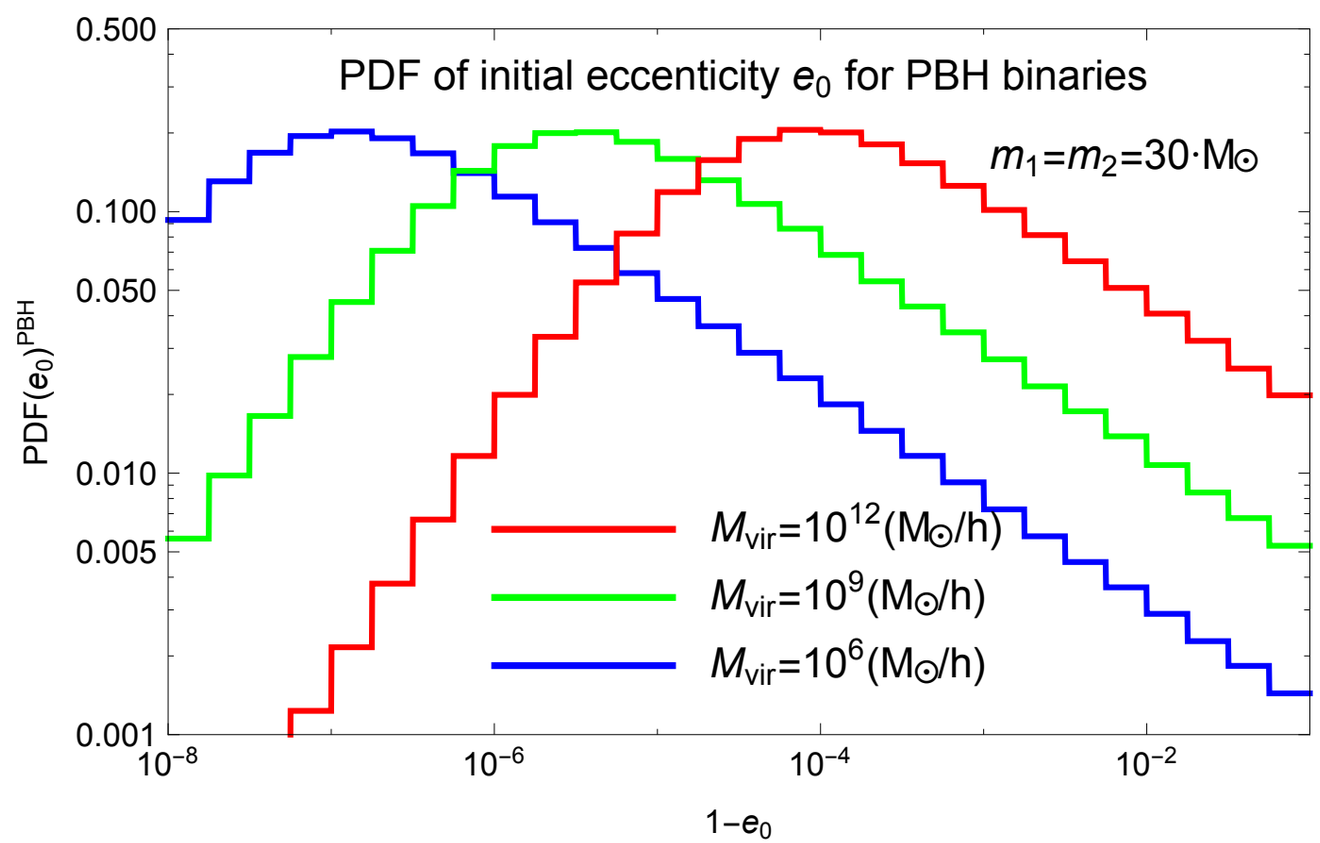

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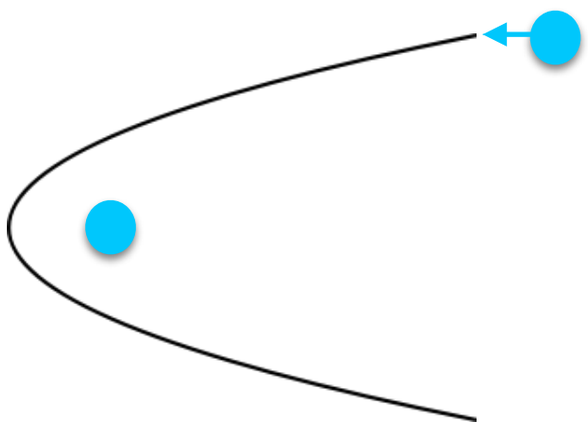

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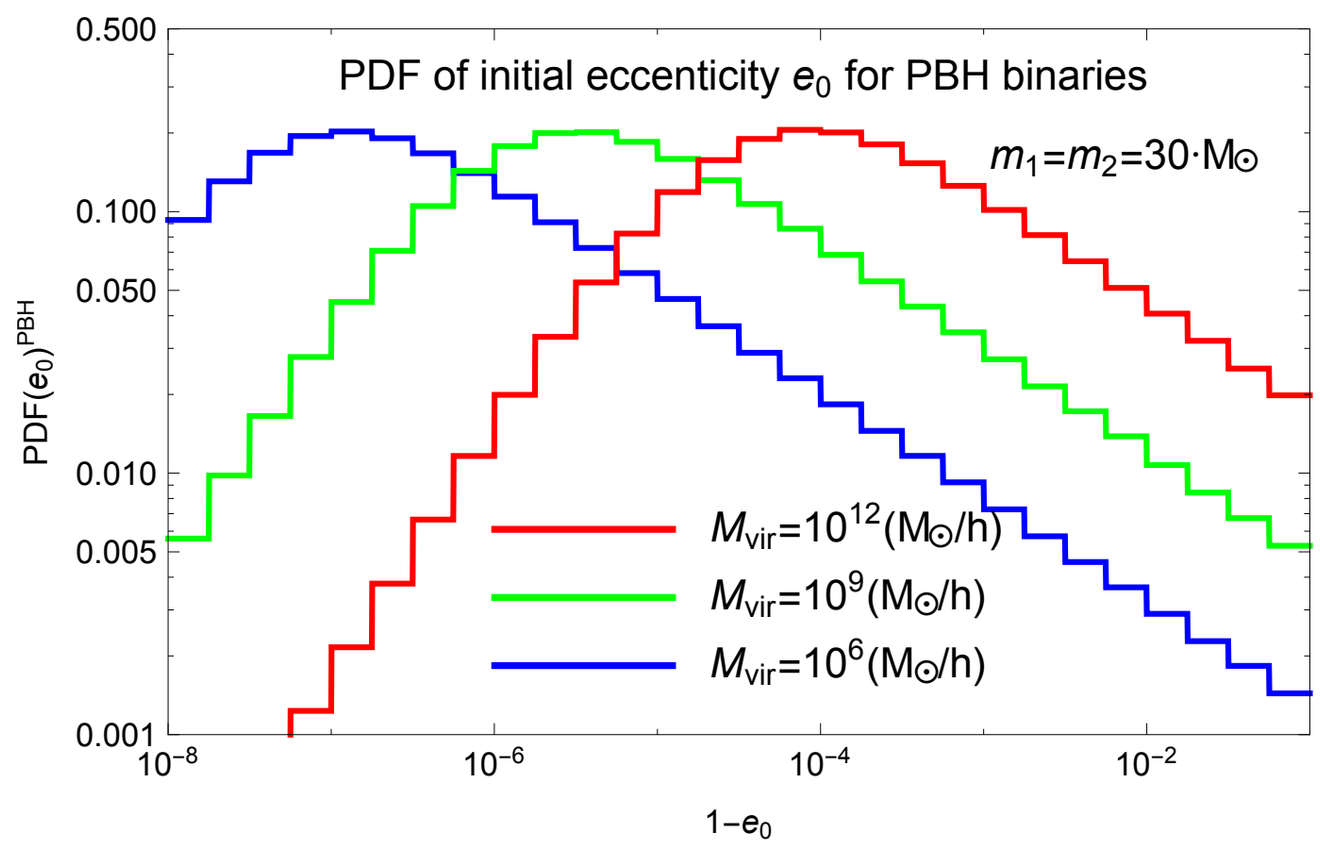

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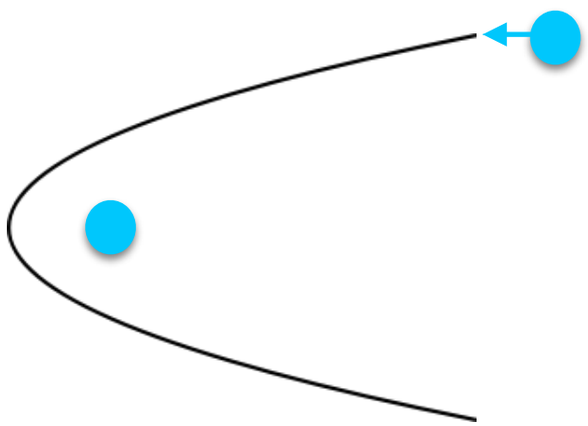

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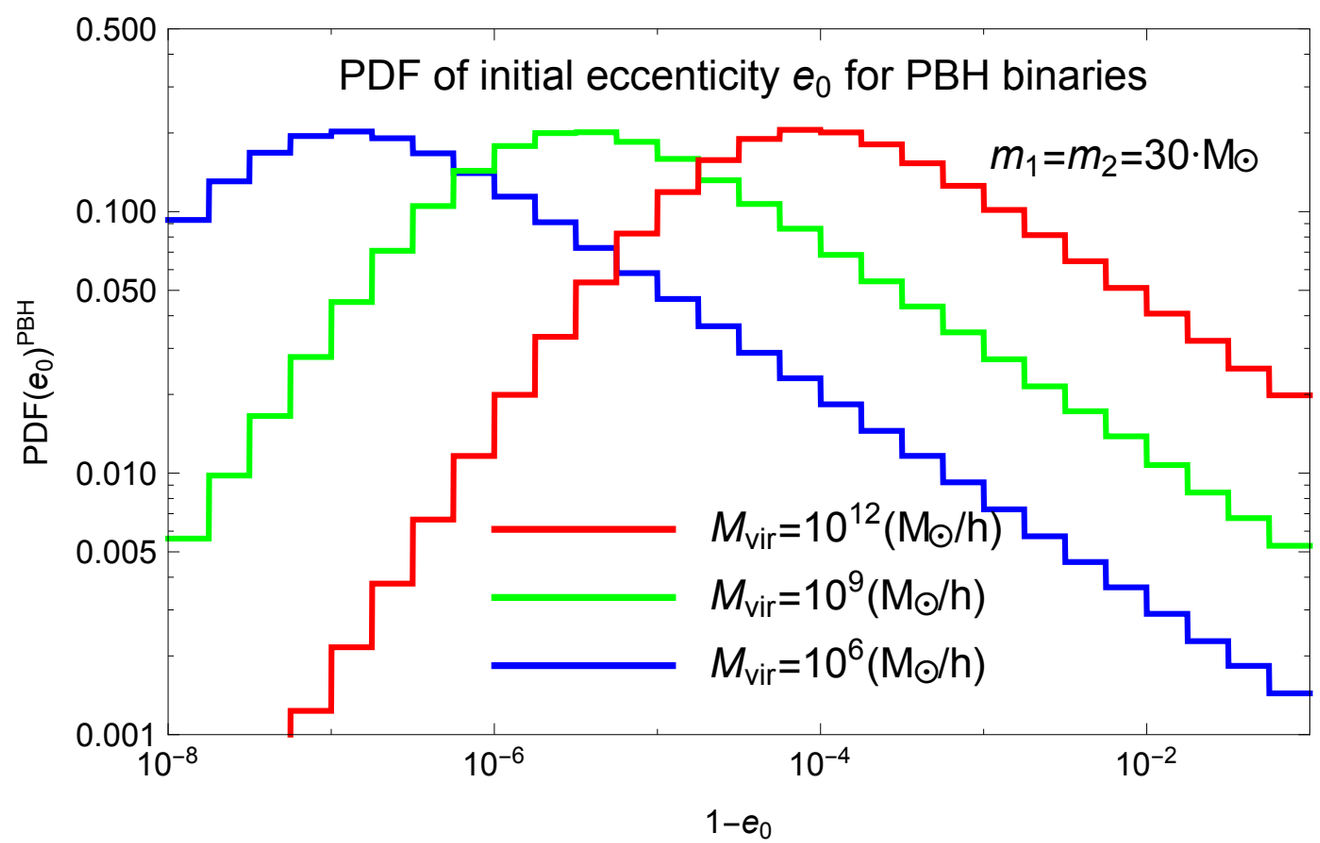

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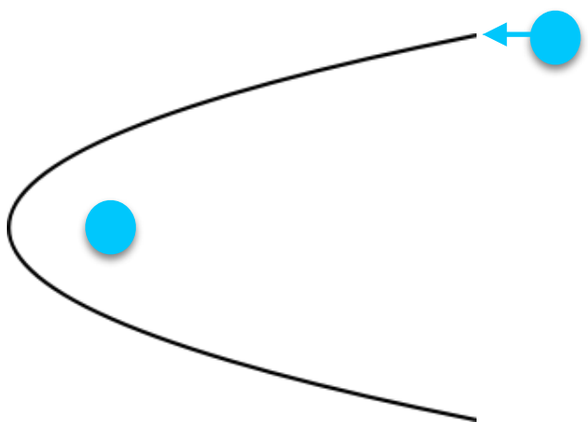

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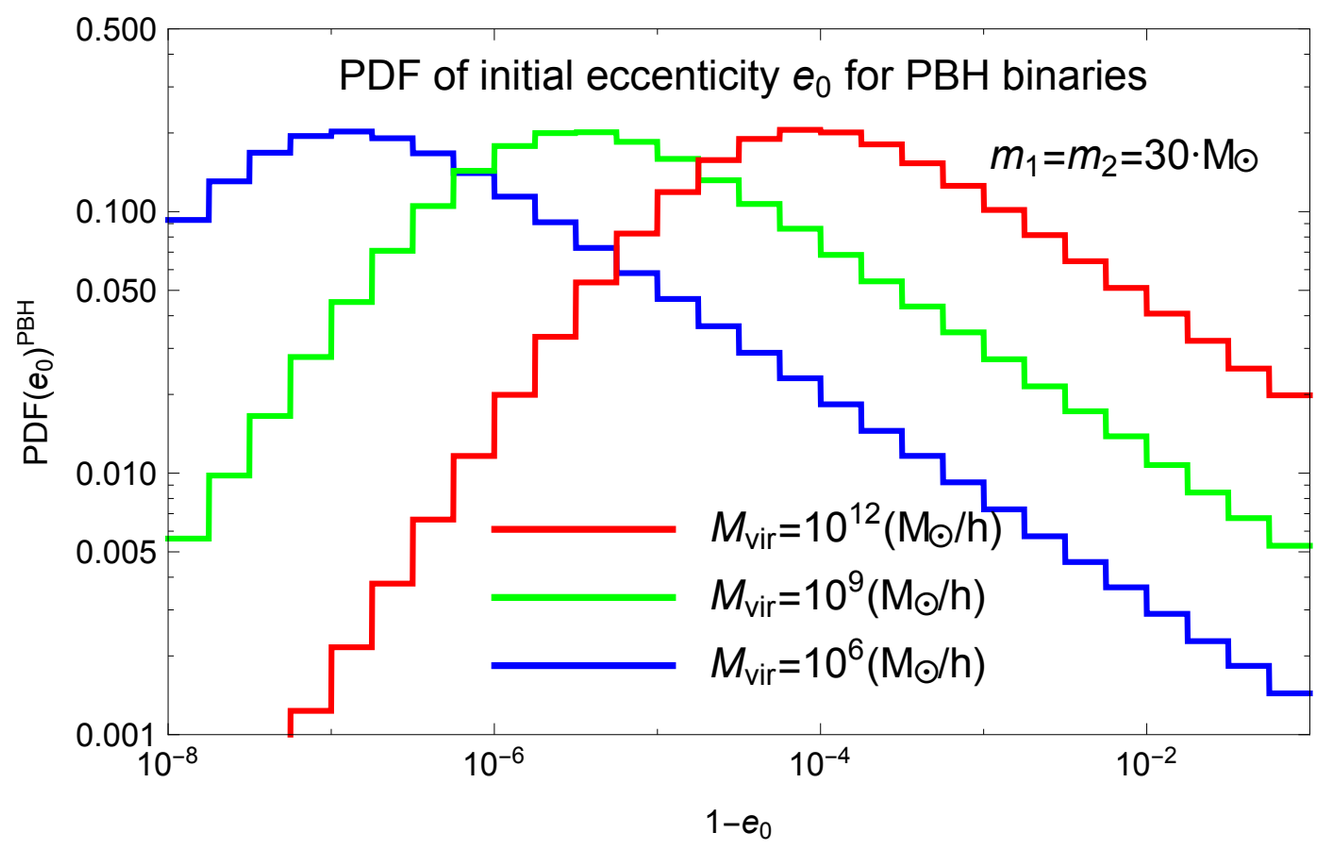

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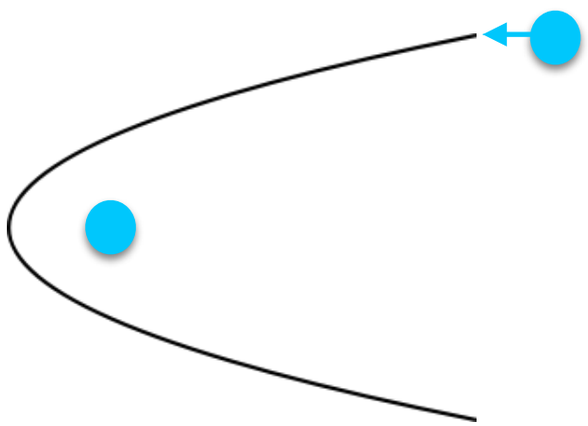

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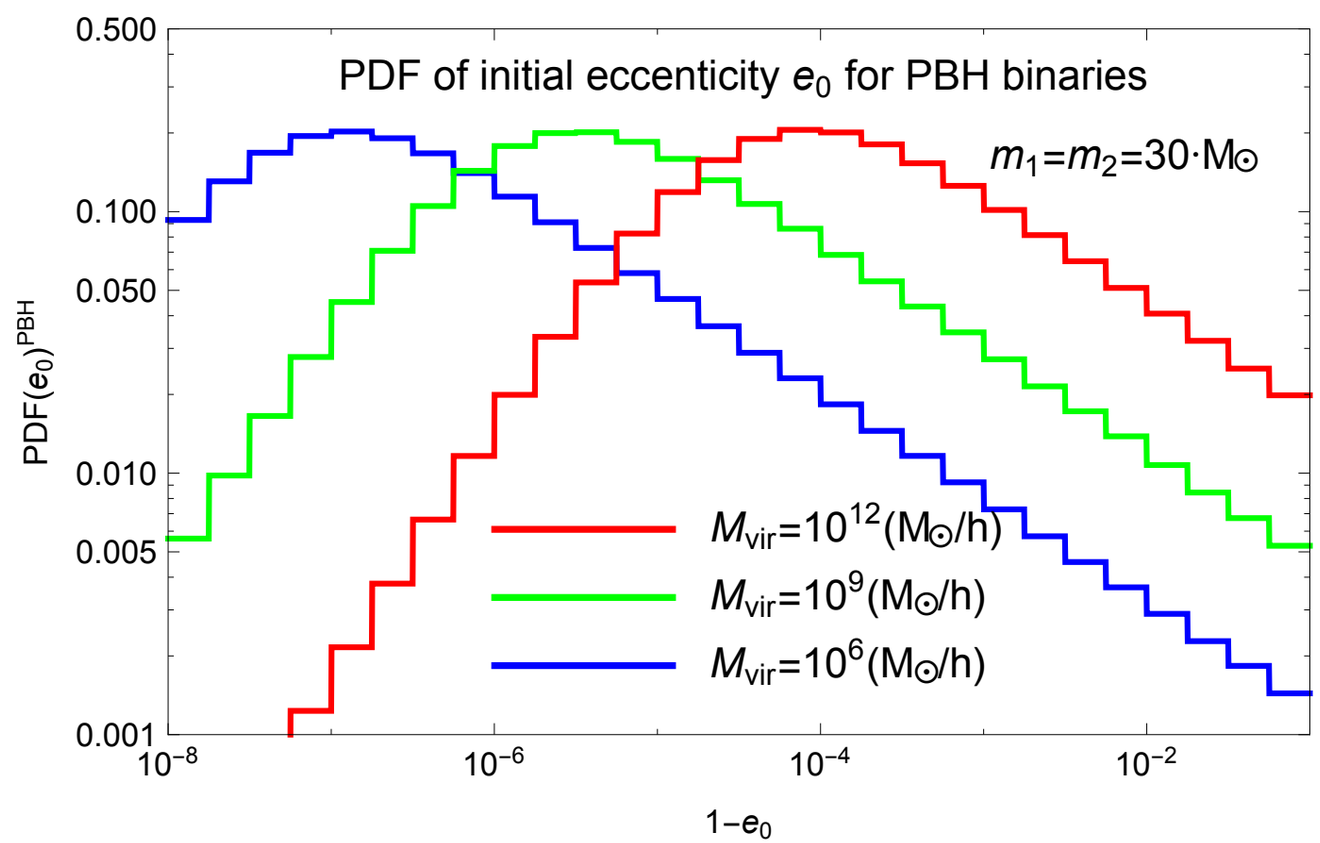

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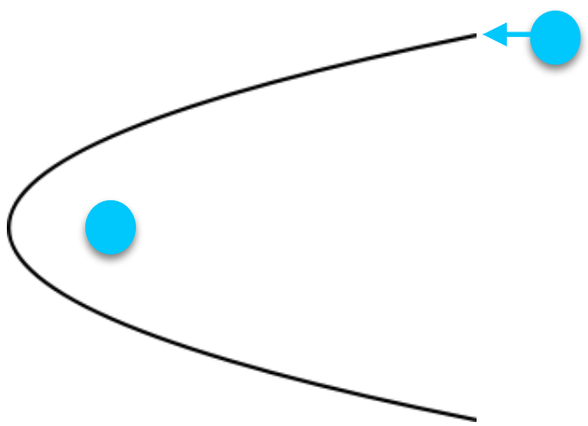

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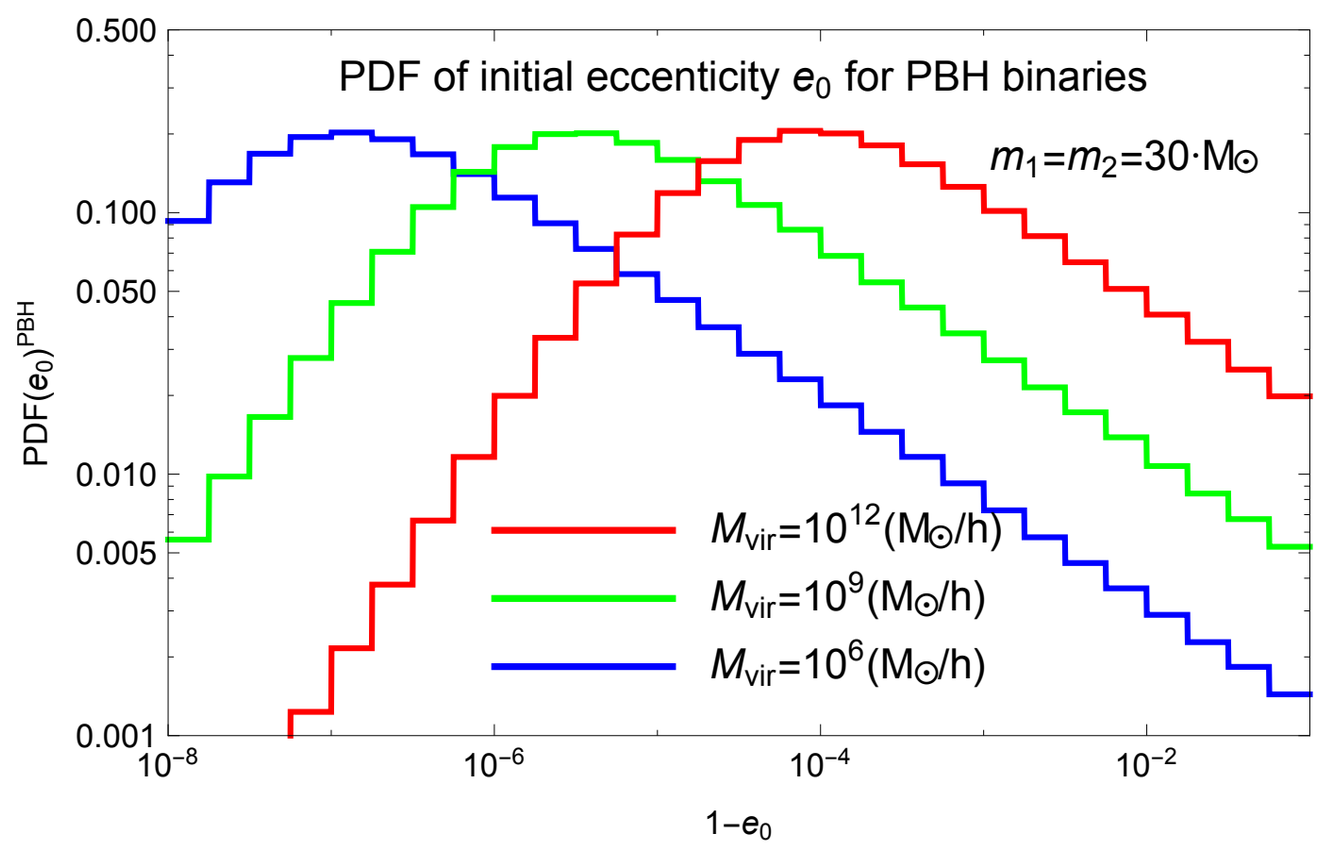

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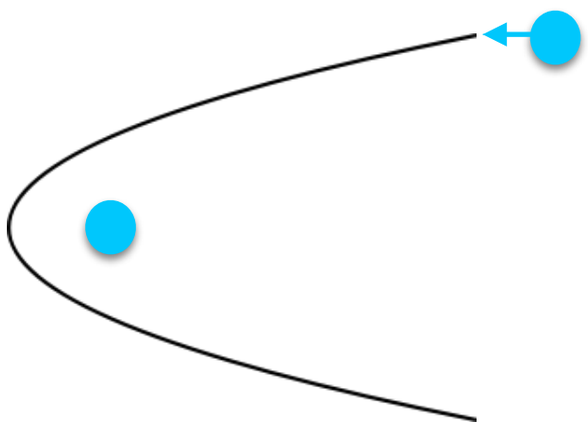

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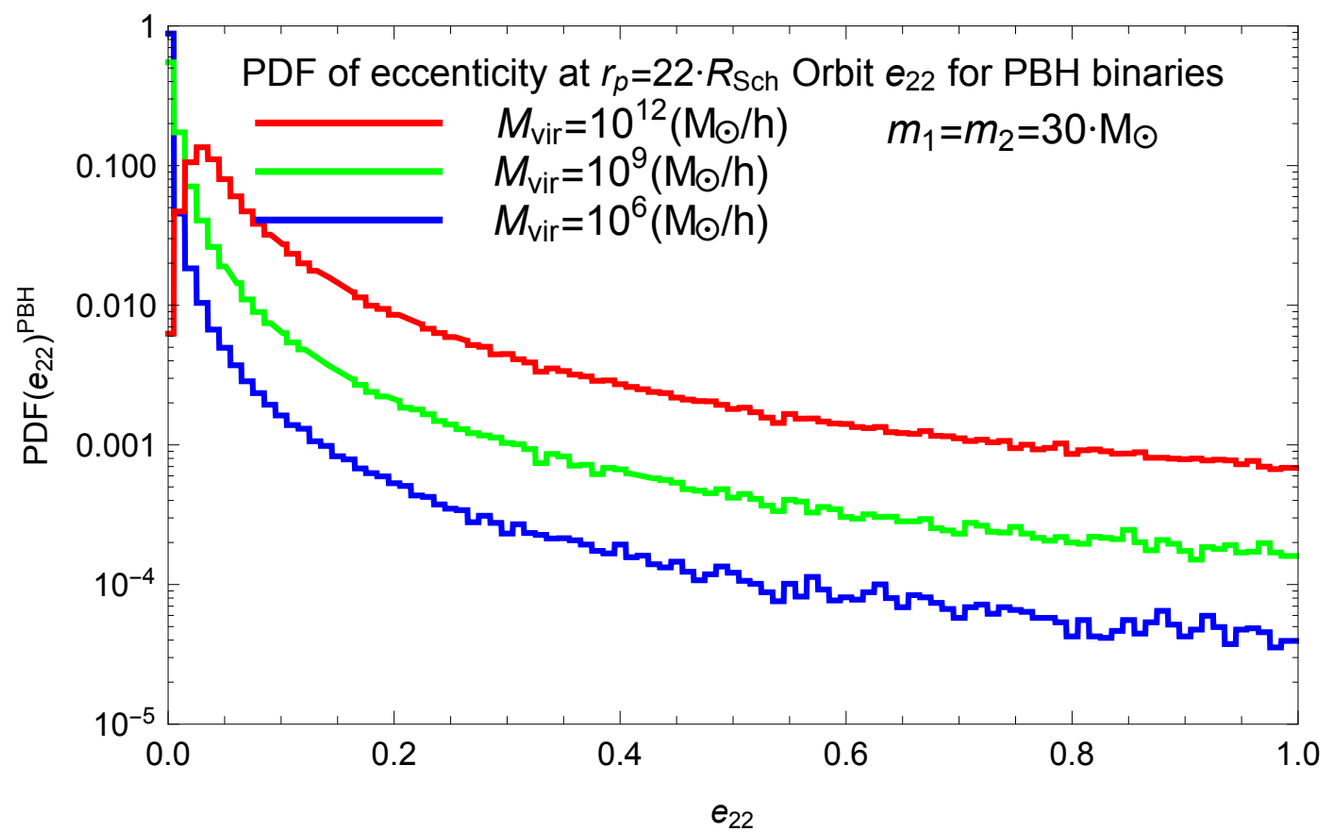

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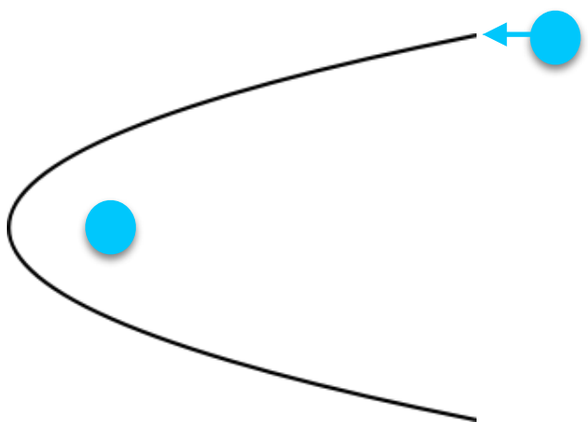

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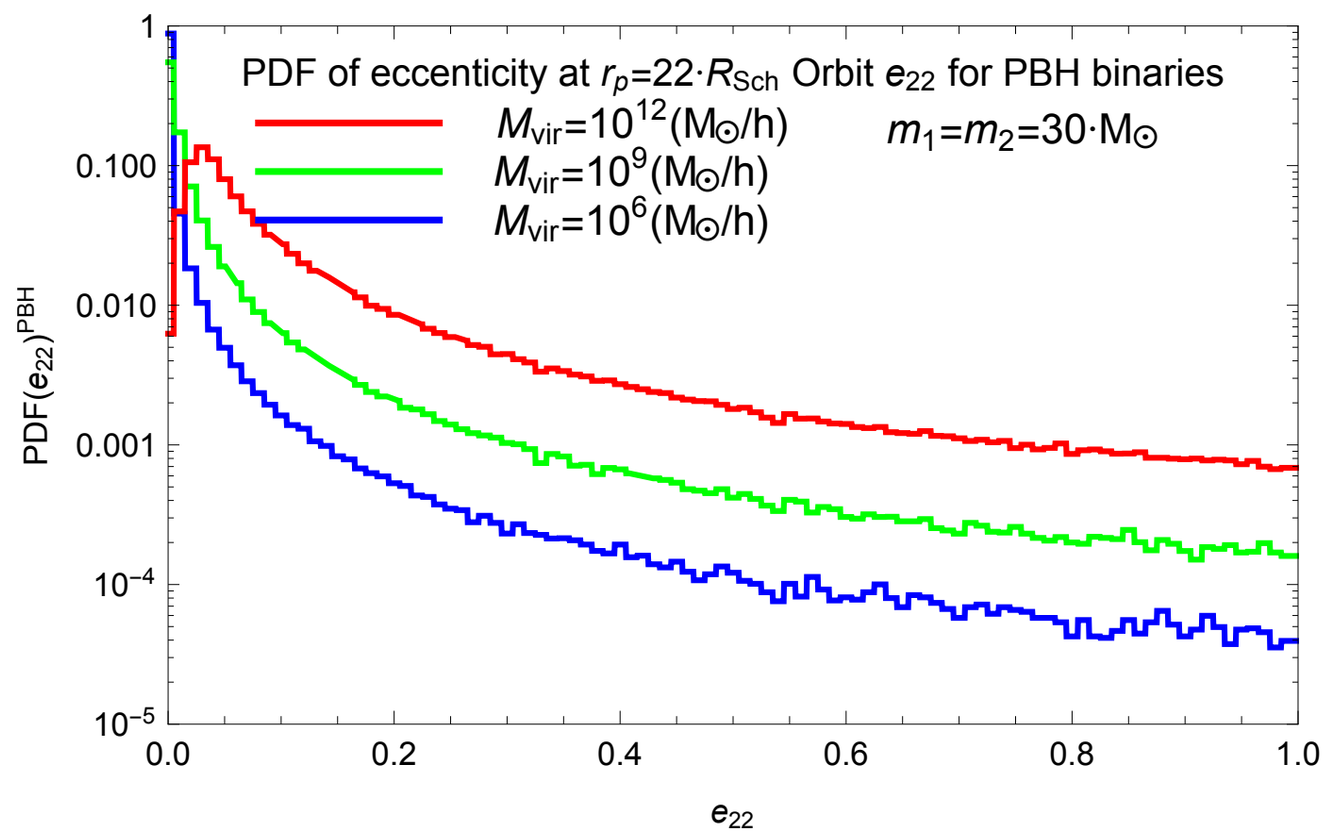

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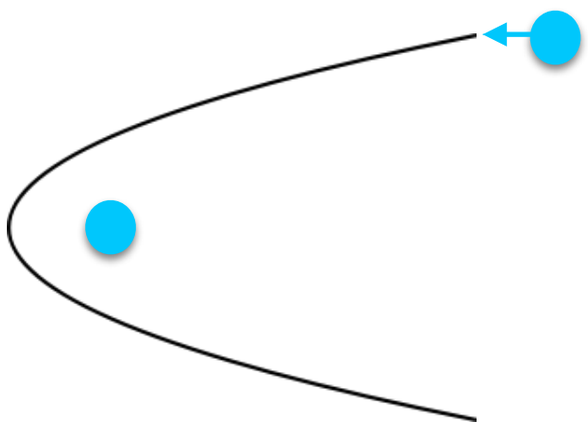

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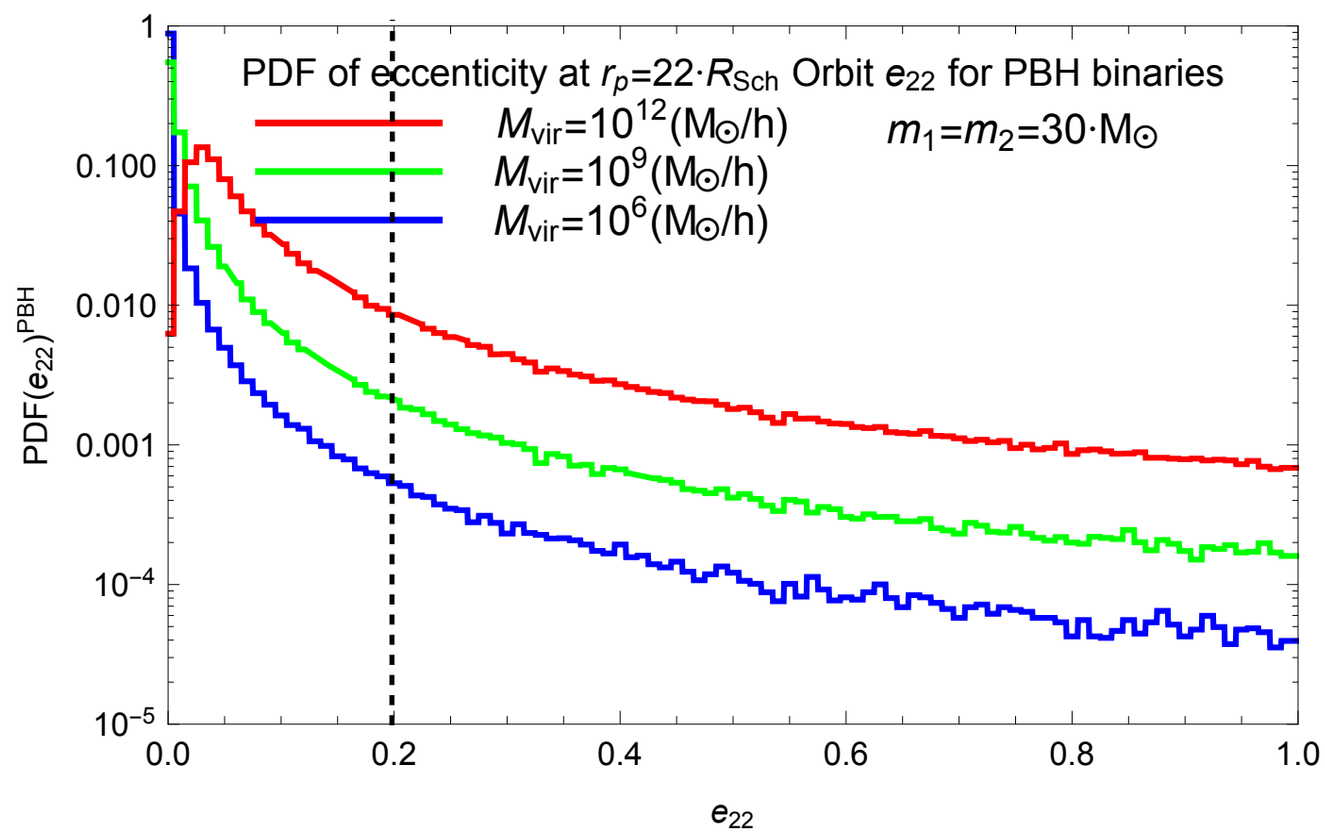
~1% of PBH GW events retain detectable final eccentricity:



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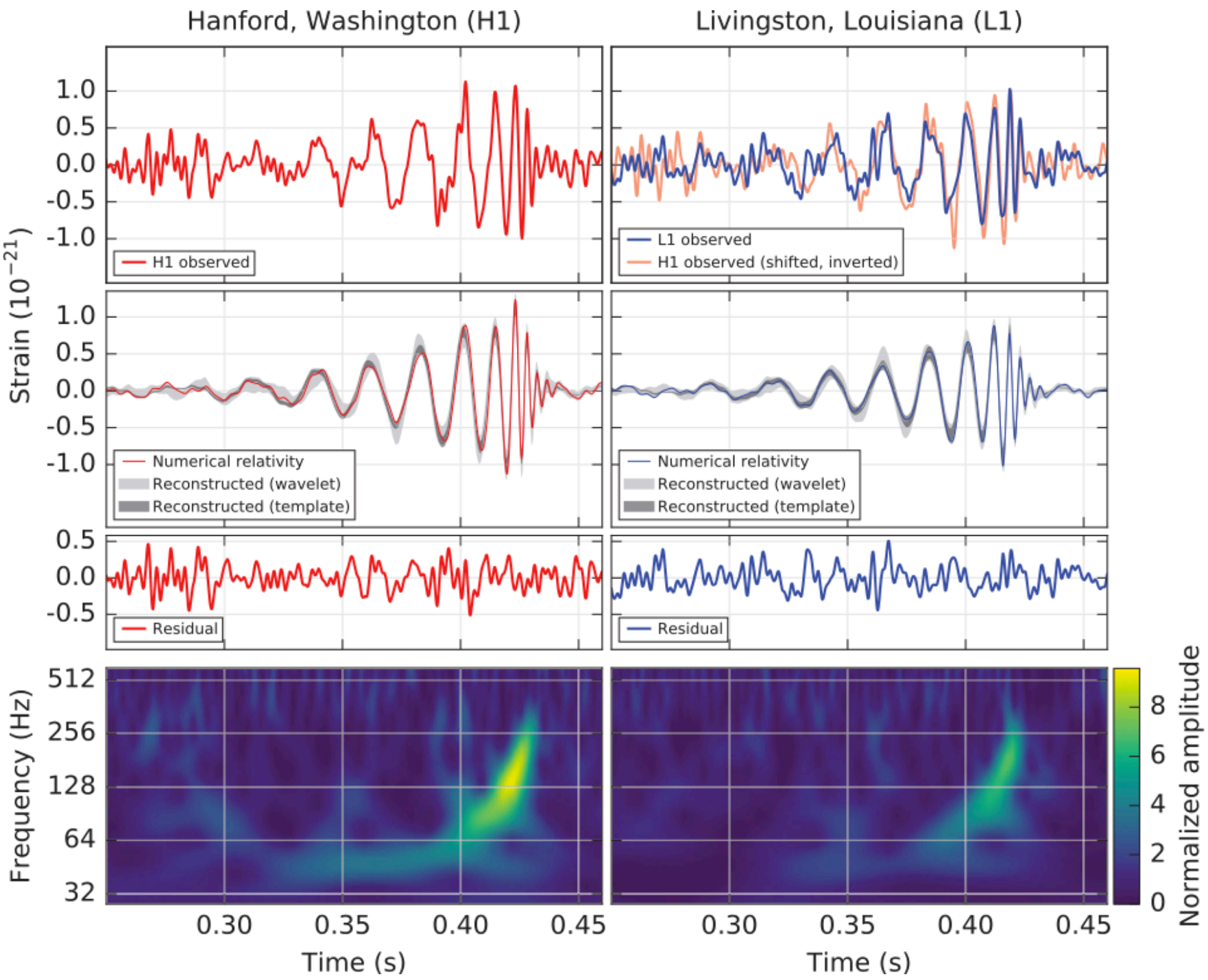

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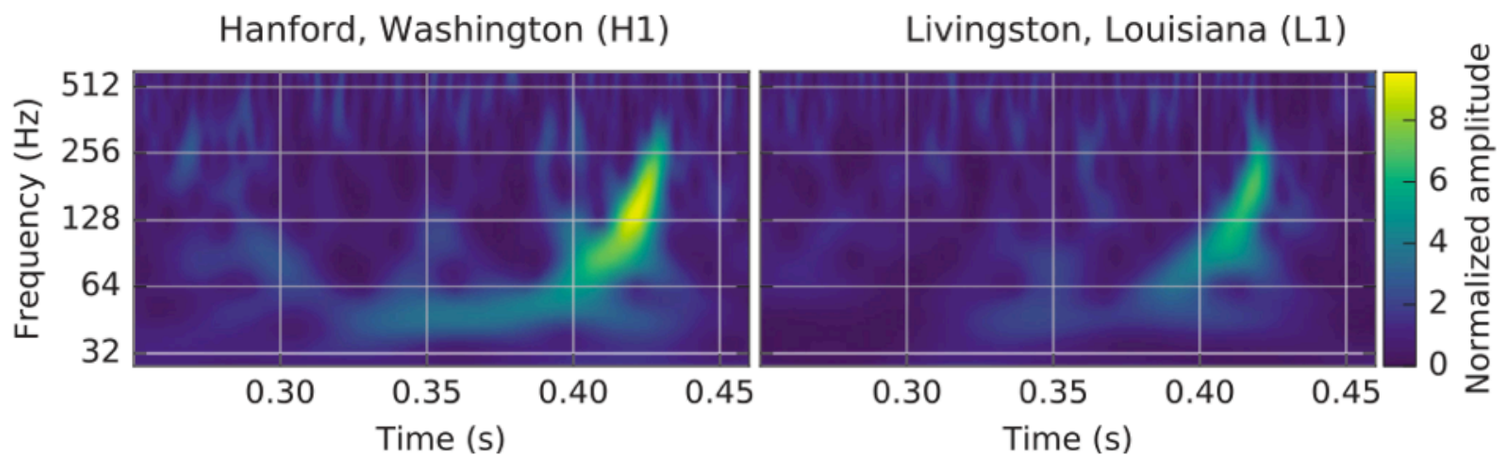

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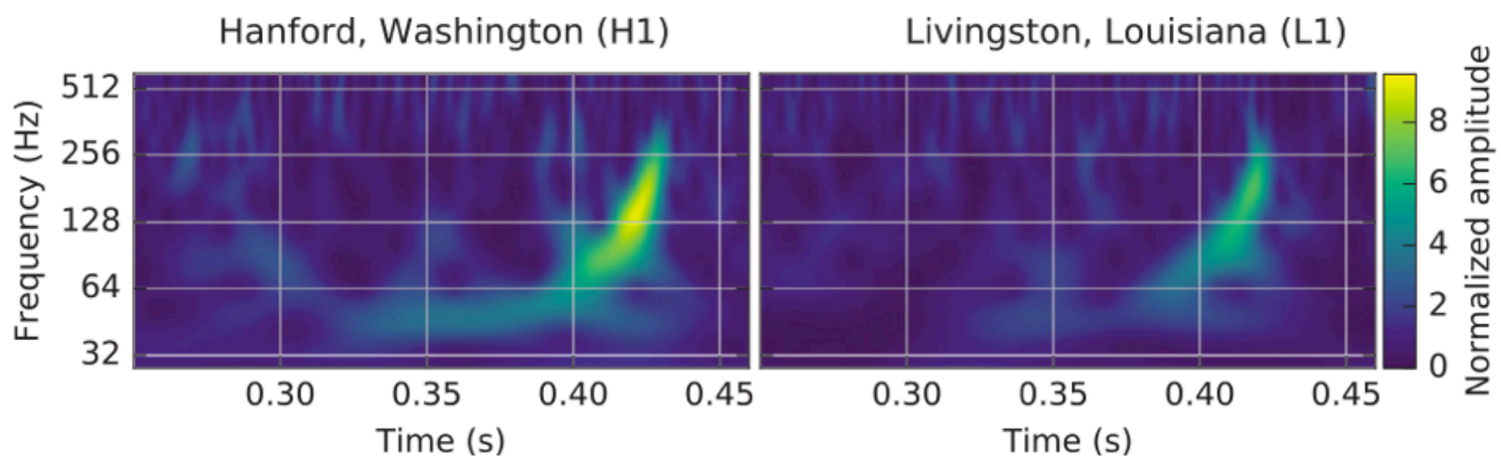

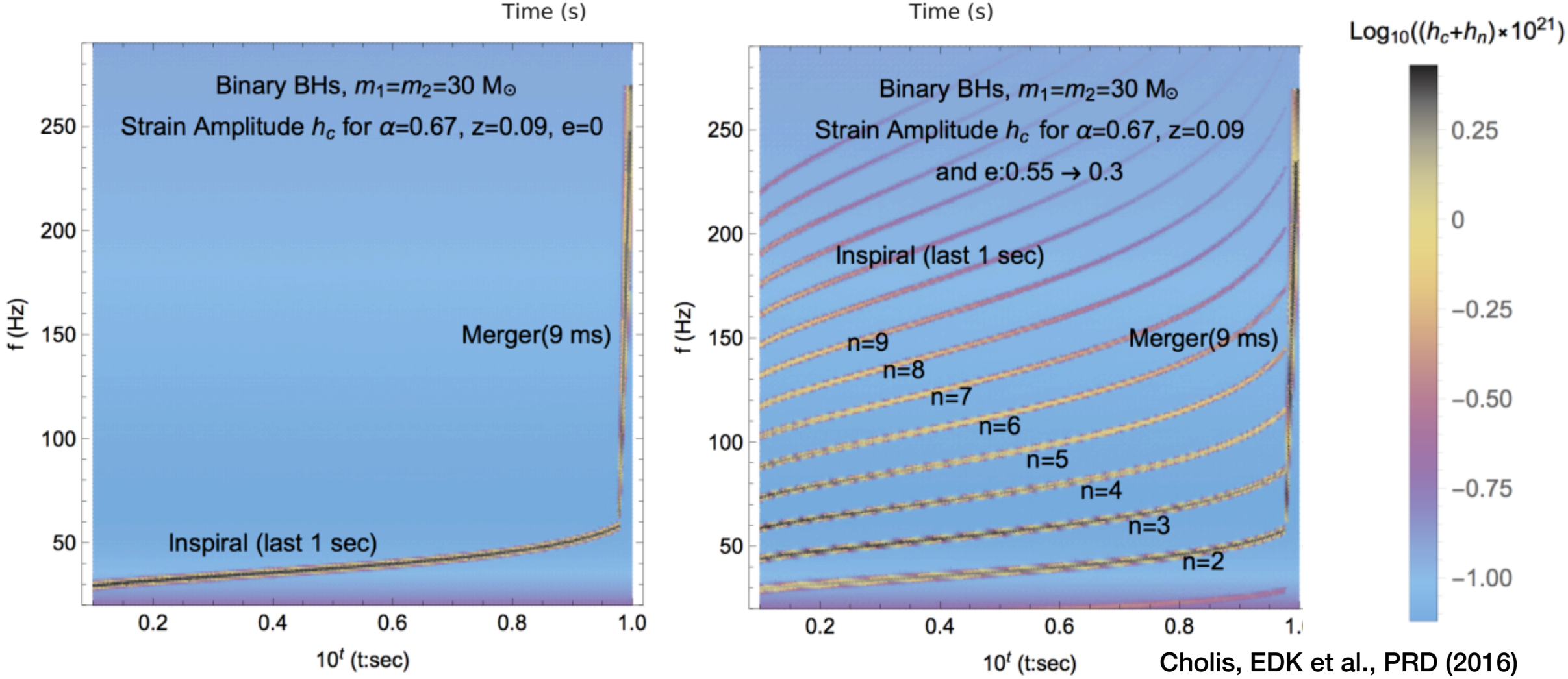

Cholis, EDK et al., PRD (2016)

Indirect Detection: Orbital Eccentricity

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In the ~near future:

Indirect Detection: Orbital Eccentricity

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$$N_{e_f > 0.2} = 0.3 - 5$$

Advanced LIGO (6 yrs)

Indirect Detection: Orbital Eccentricity

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Indirect Detection: Orbital Eccentricity

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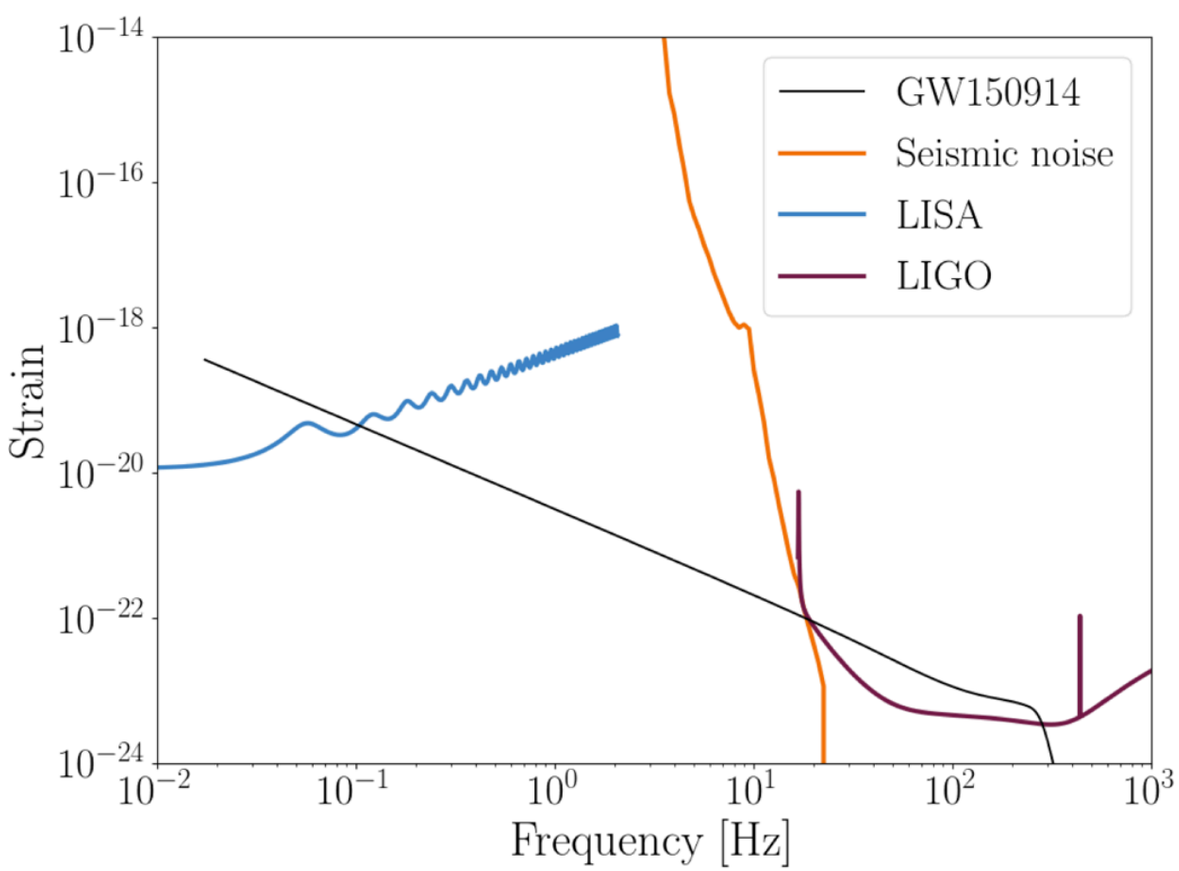

Wong, **EDK**, Cutler and Berti, PRL (2018)

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Advanced LIGO (6 yrs)

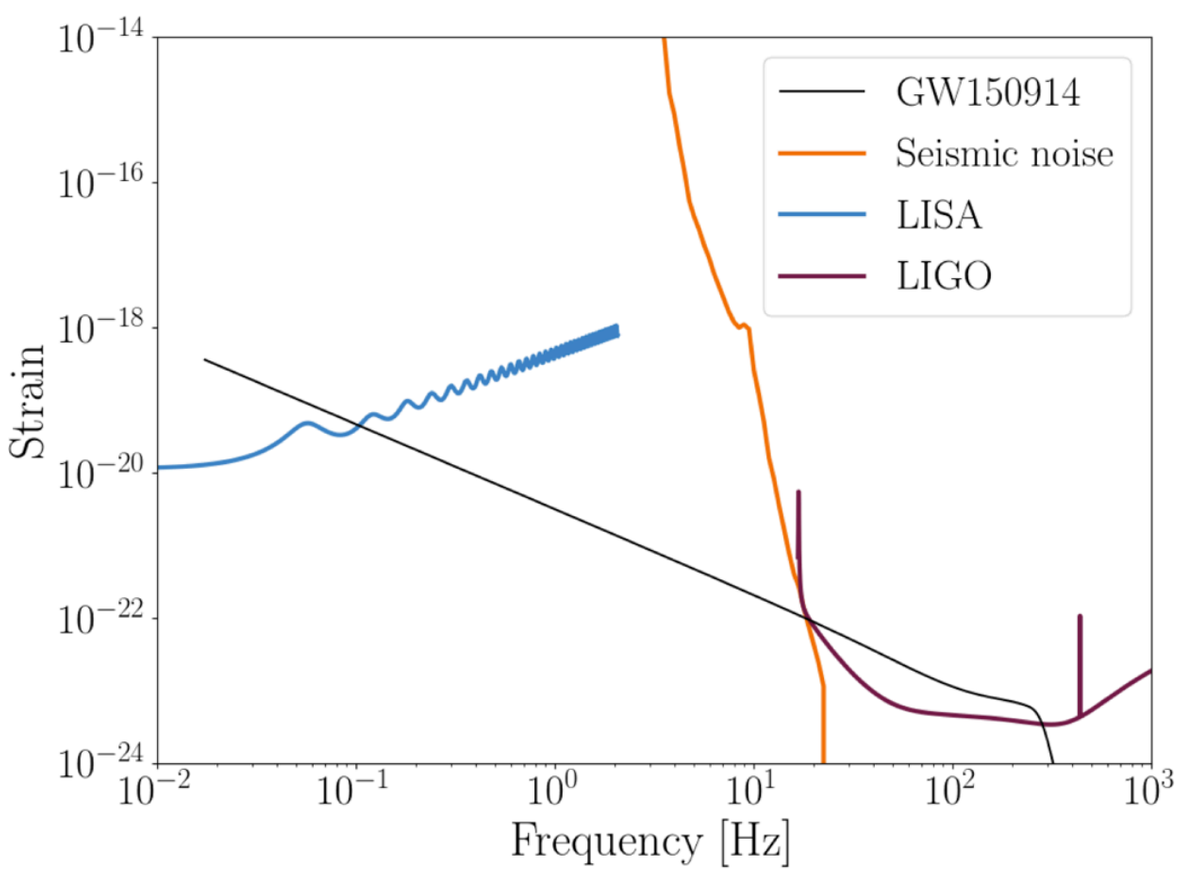
In the distant future:

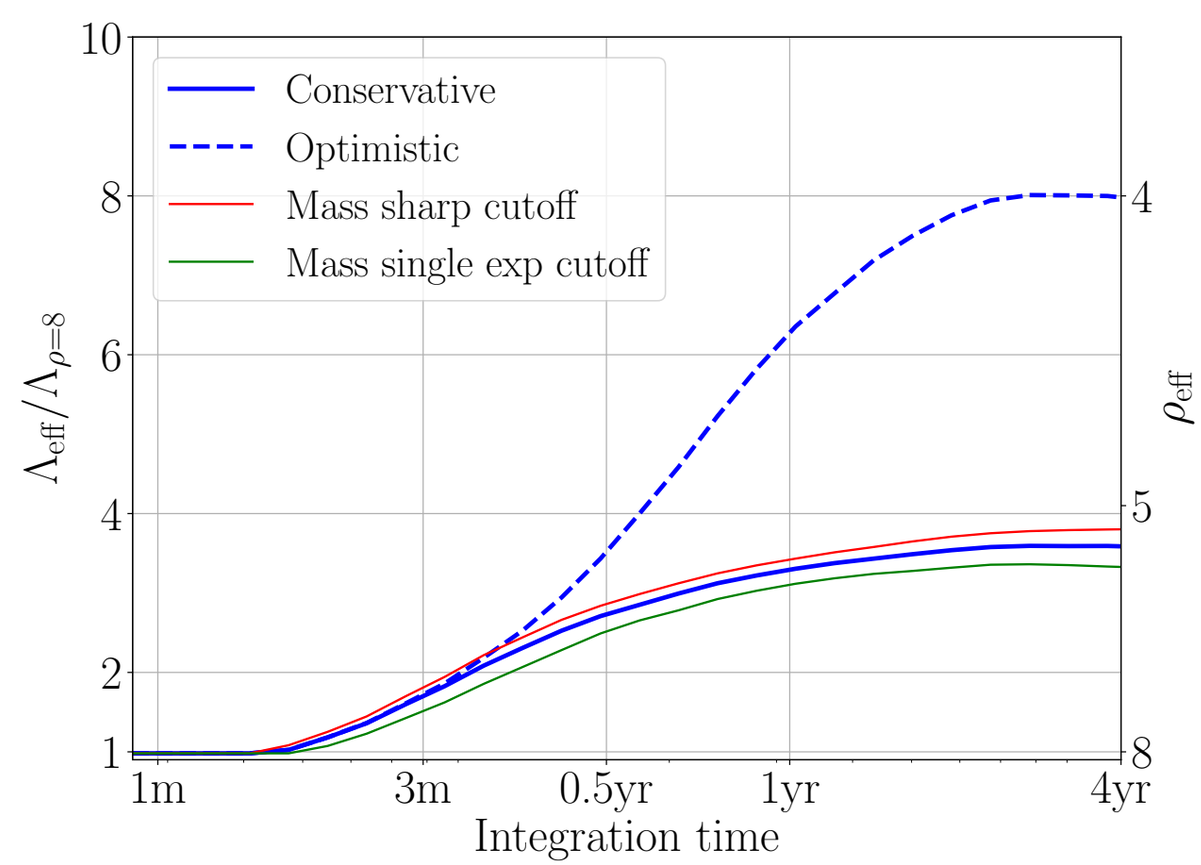
$$N_{e_f>0.1} = 1.5 - 30$$

Einstein Telescope (10 yrs)

In the even more distant future:

O(100) detections in LISA (4 yrs)





Wong, EDK, Cutler and Berti, PRL (2018)

Indirect Detection: Individual and Effective Spin

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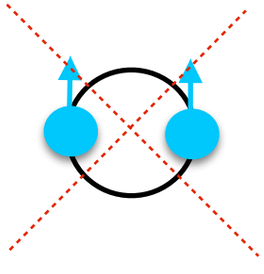

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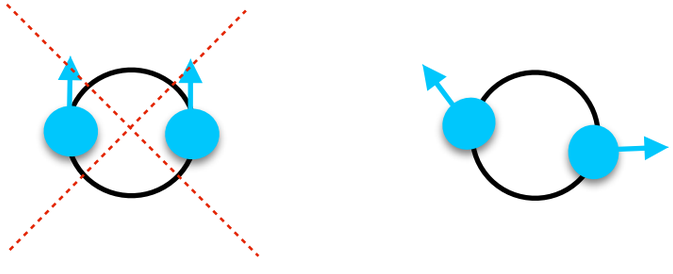

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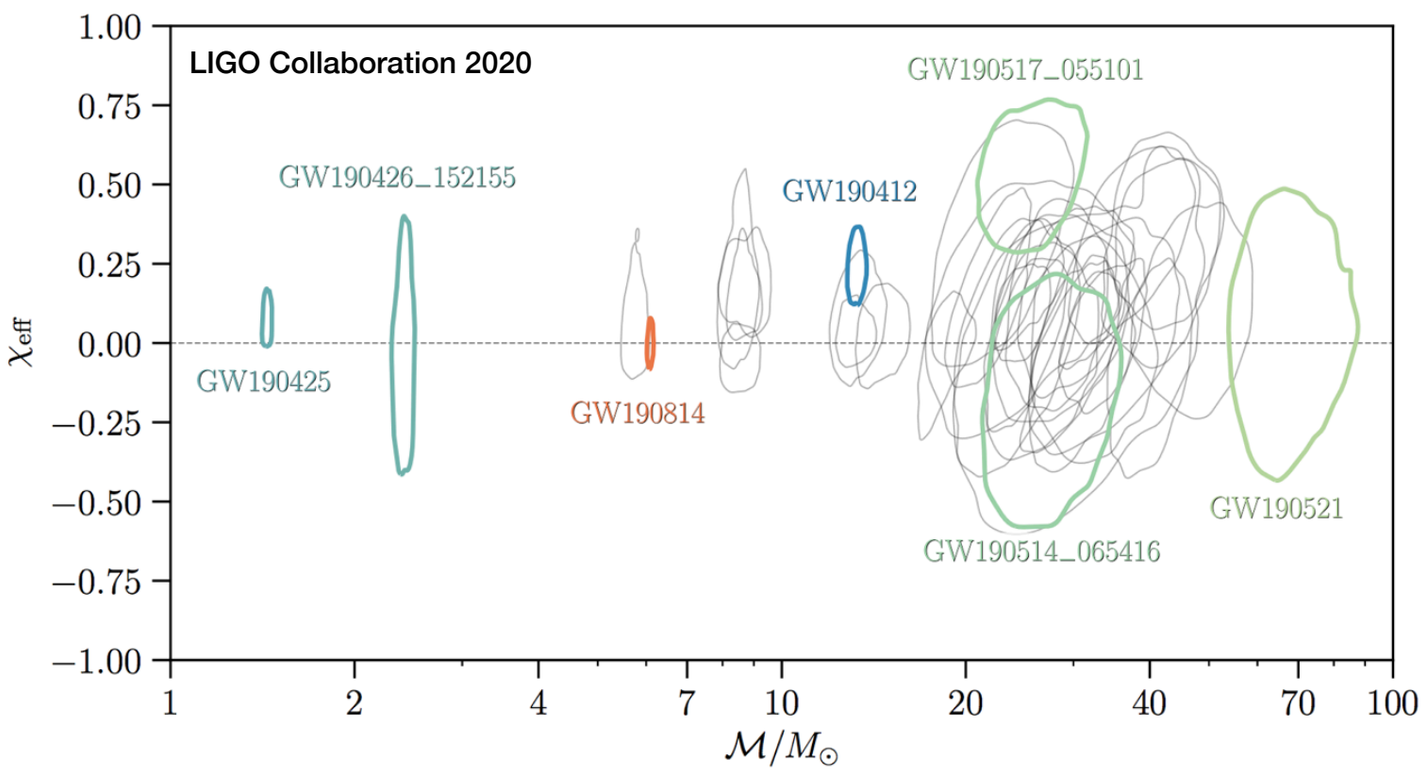

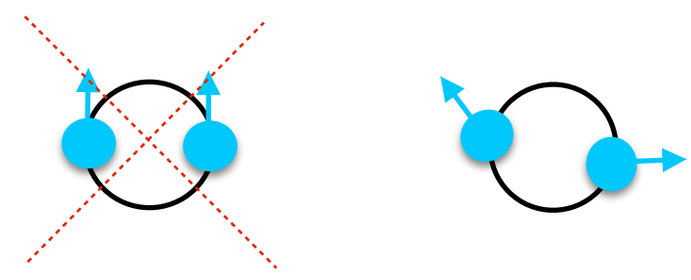

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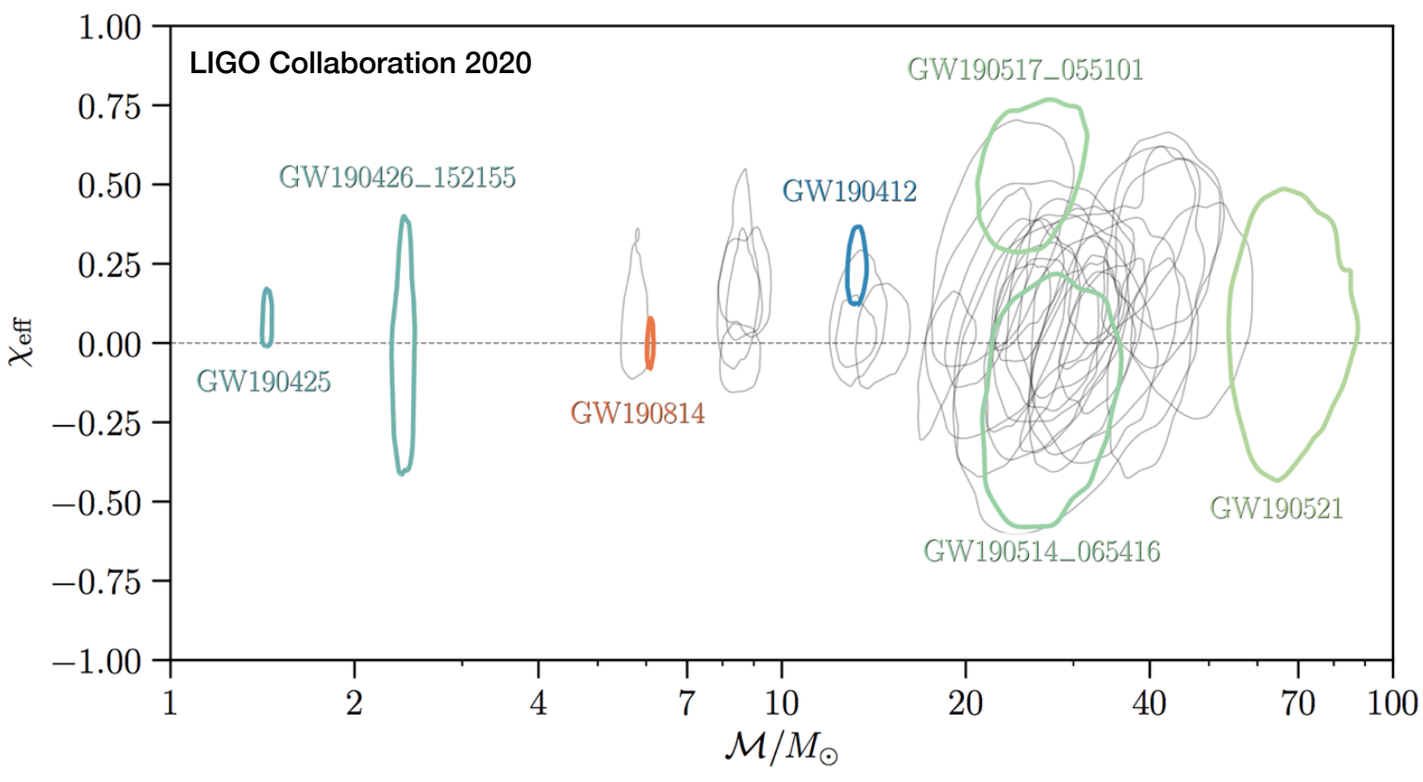

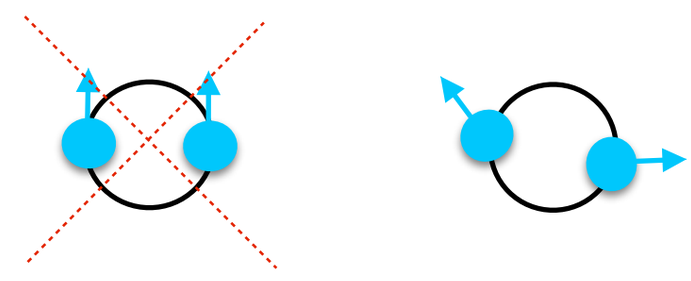

(See Riotto's talk on Wednesday and Profumo's talk on Thursday!)

Indirect Detection: Stochastic GW Background

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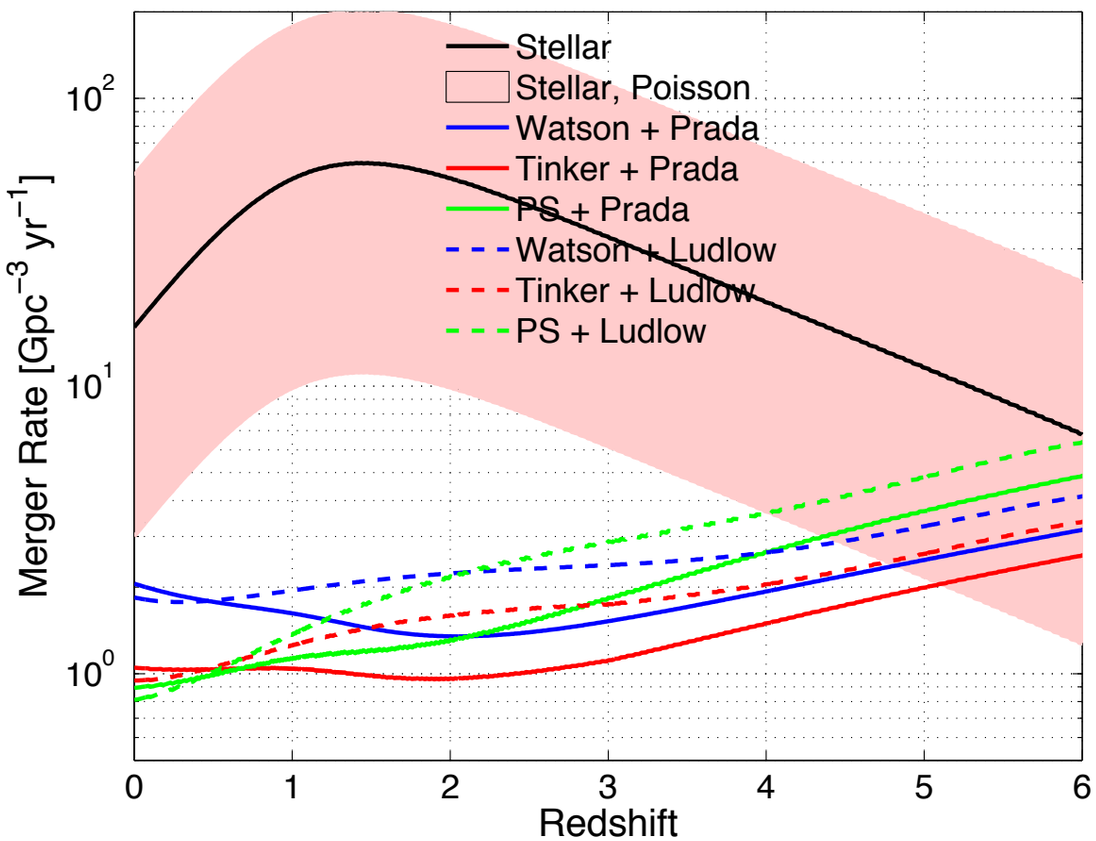

Mandic et al., PRL (2016)

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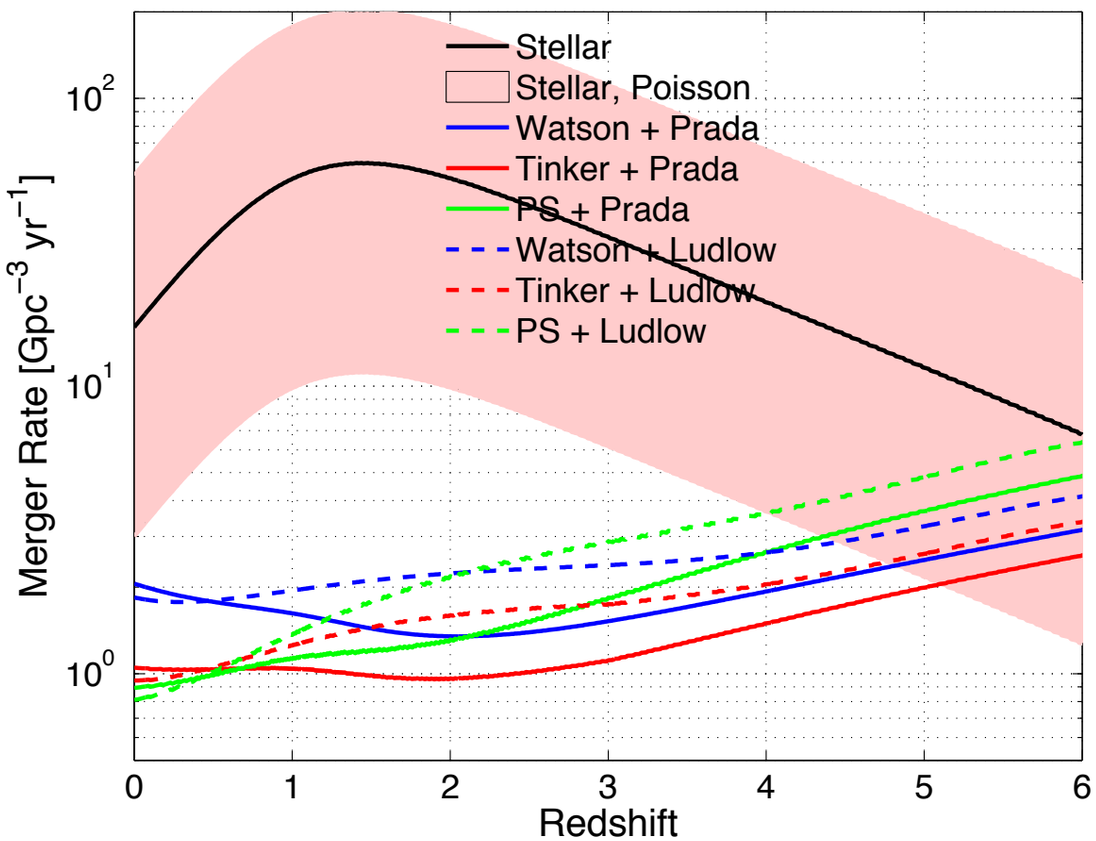

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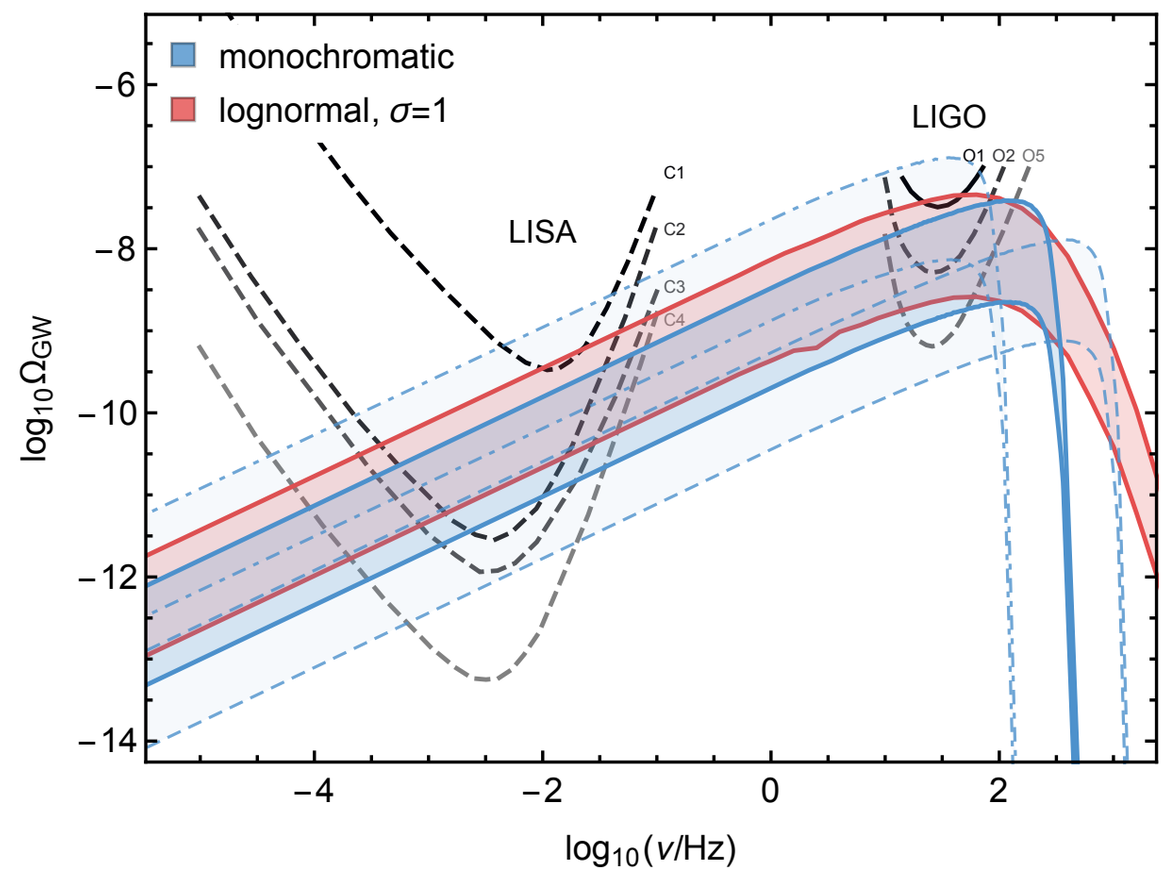

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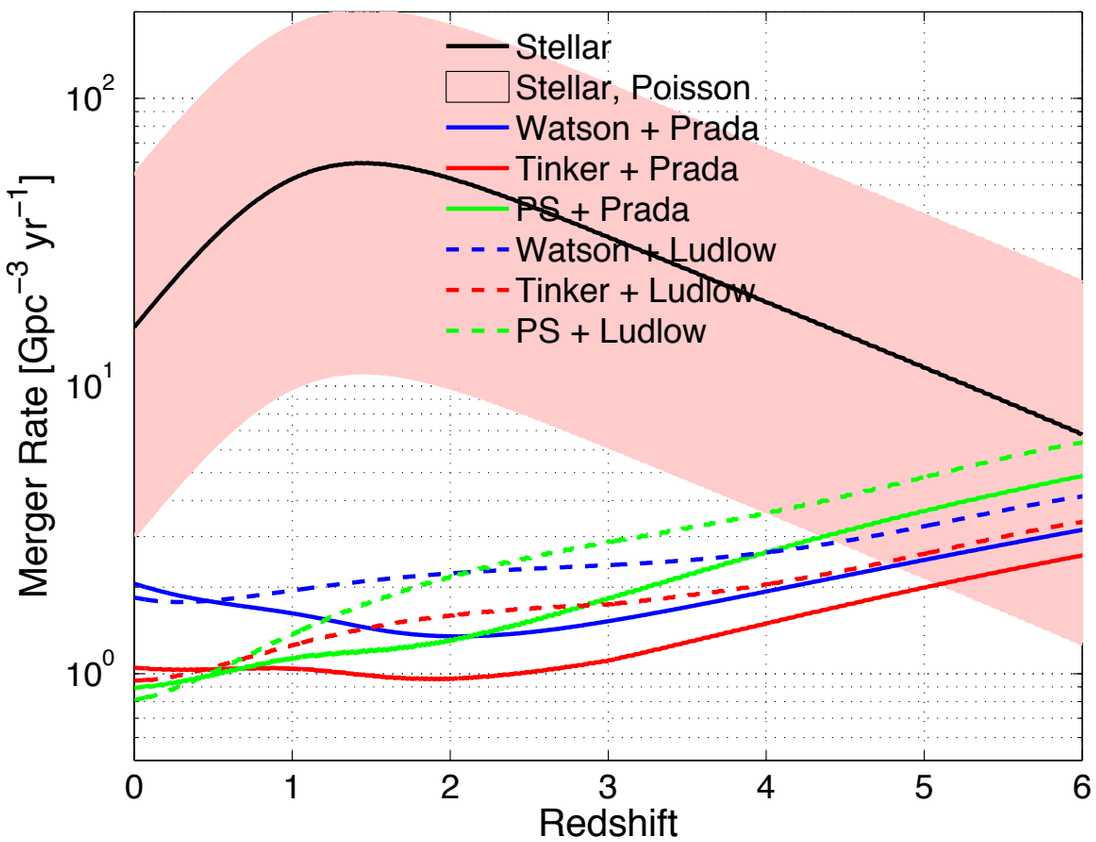

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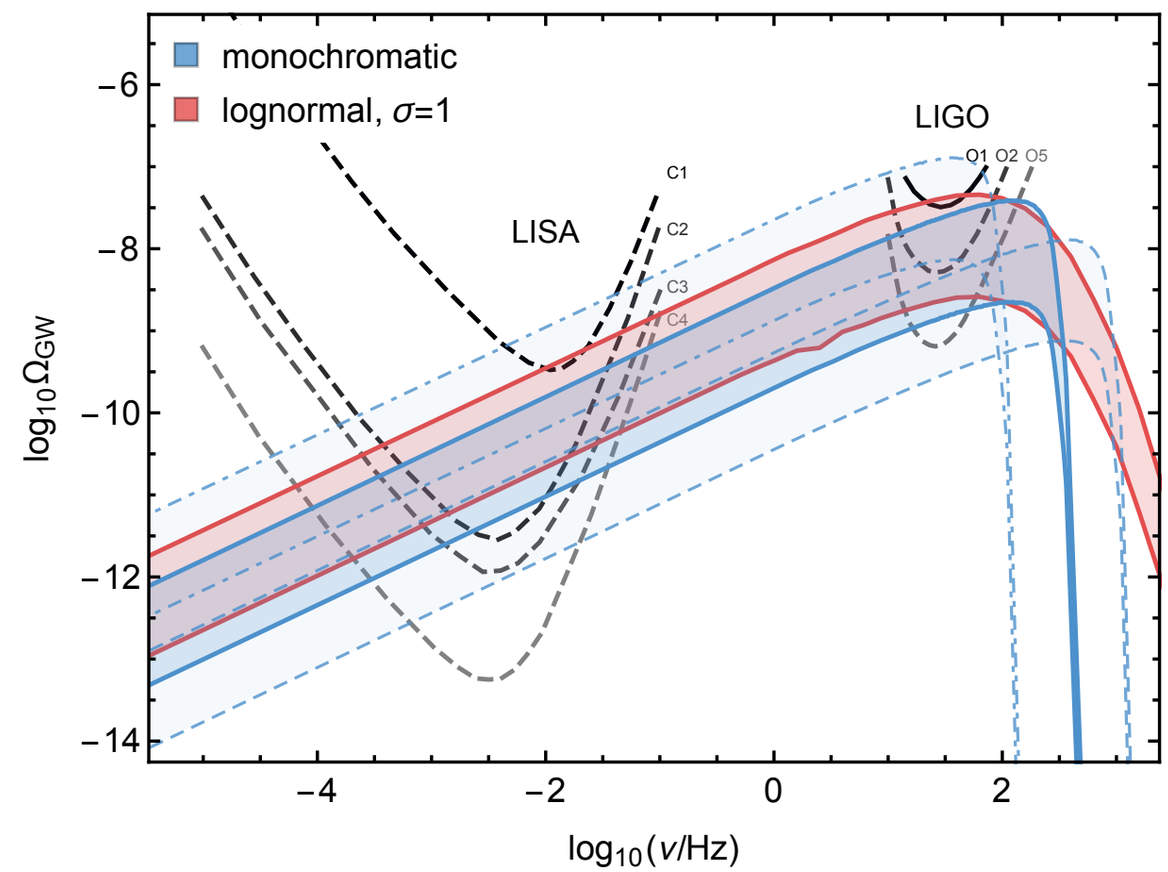

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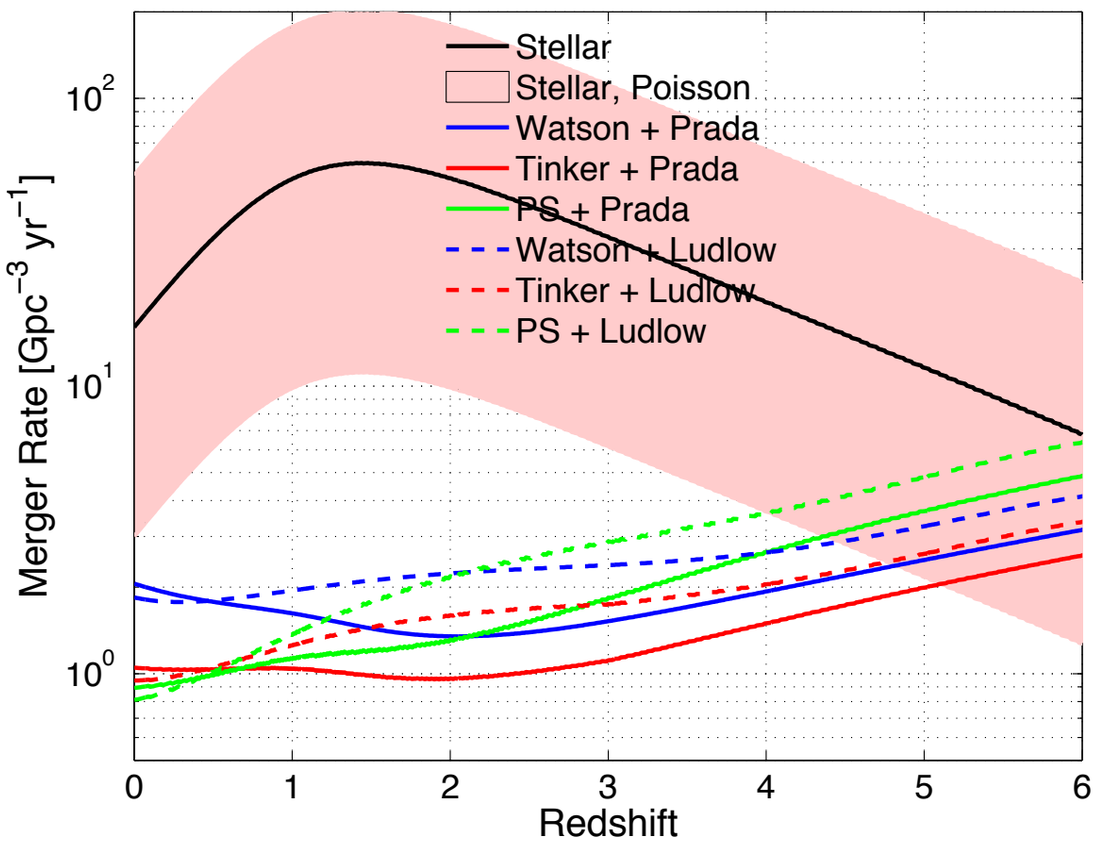

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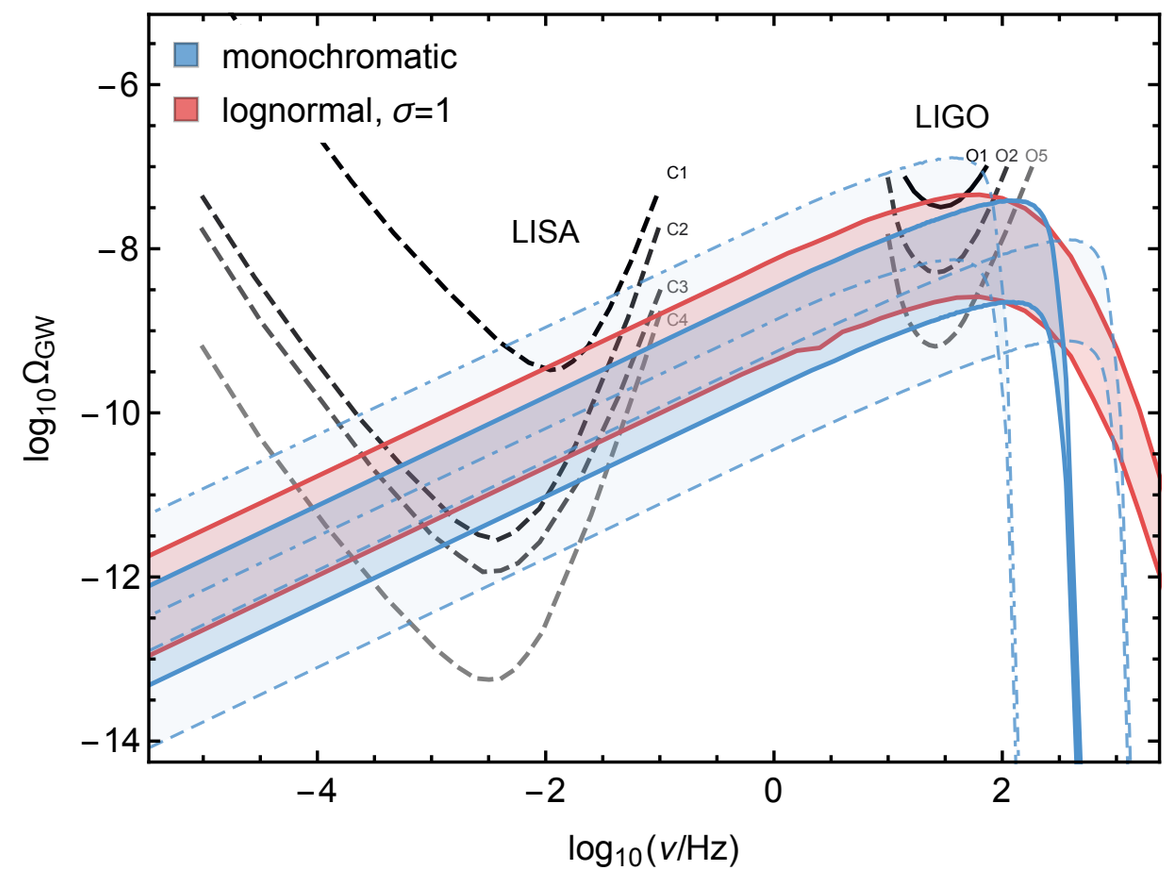

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(see Yacine's talks and Kapadia's talk on Friday!)

Indirect Detection: Clustering of GW Events

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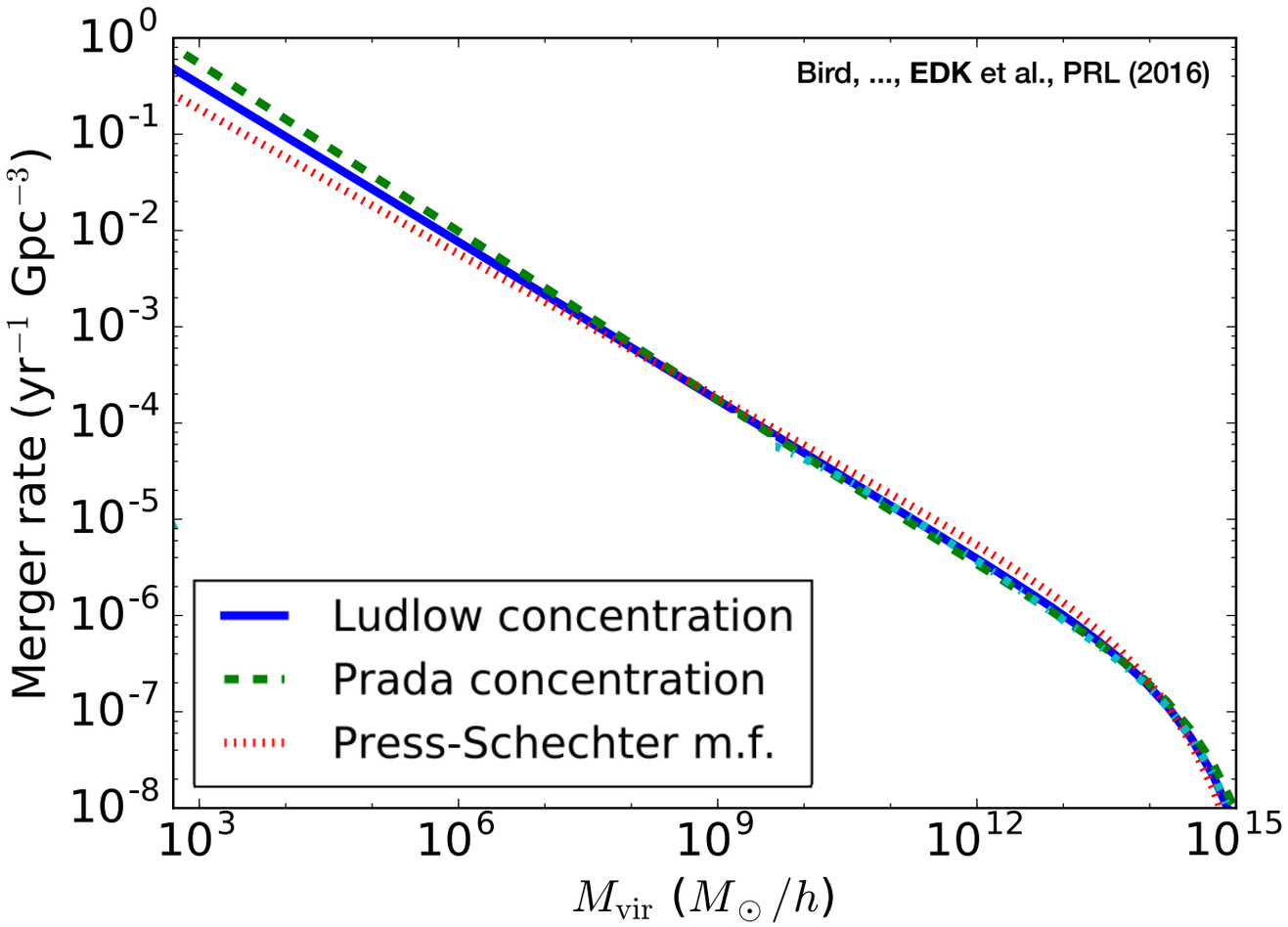

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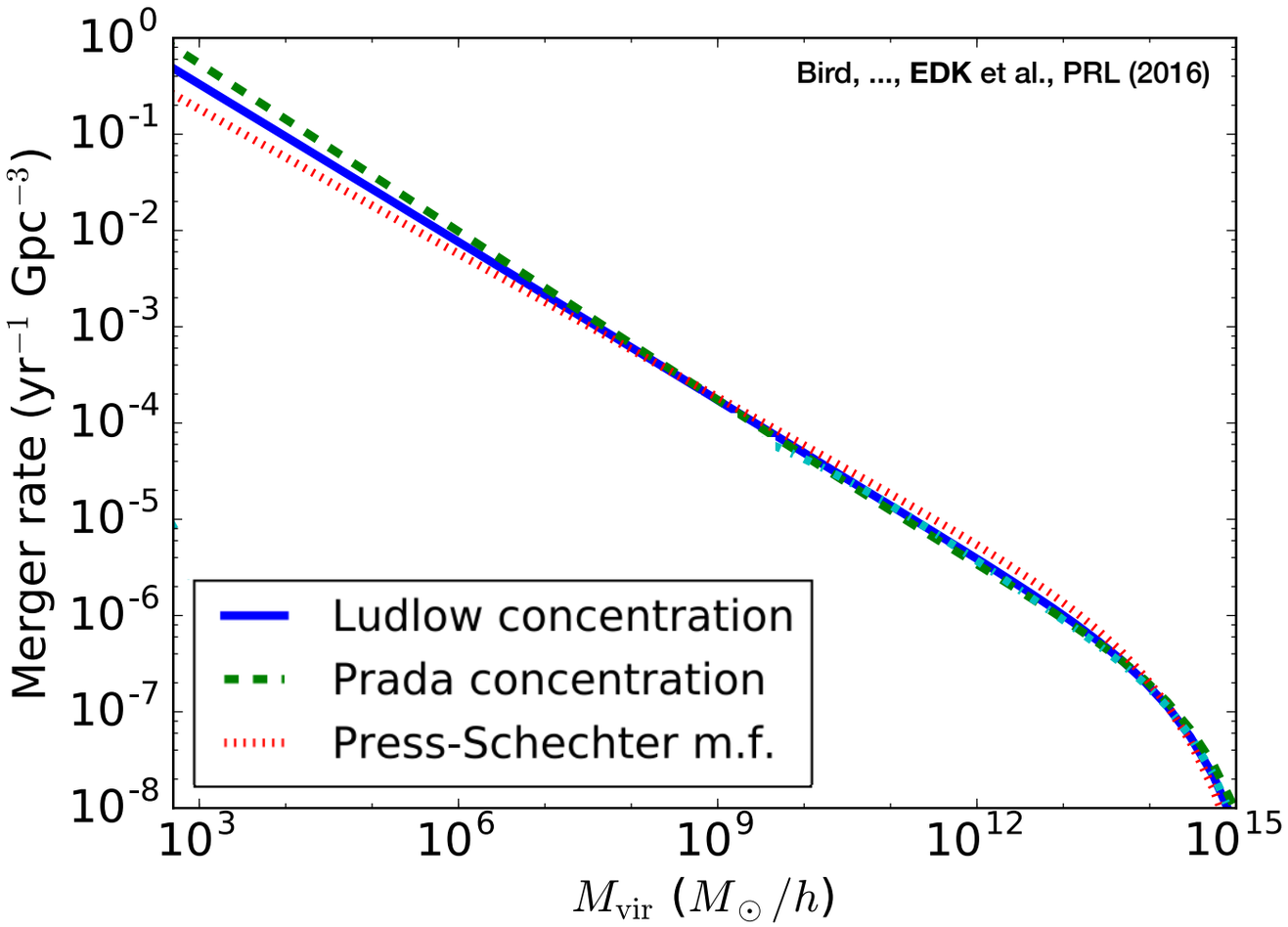

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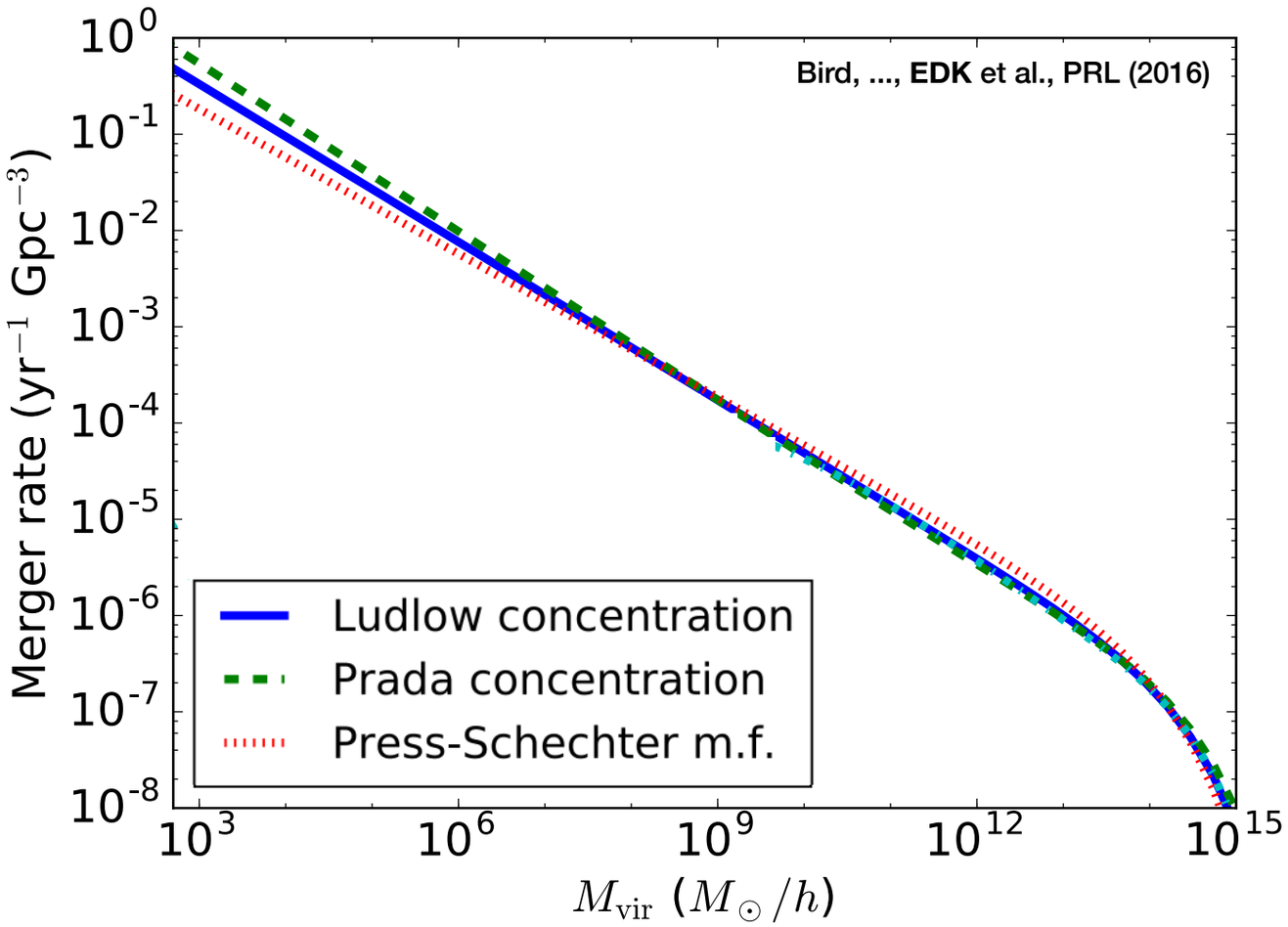

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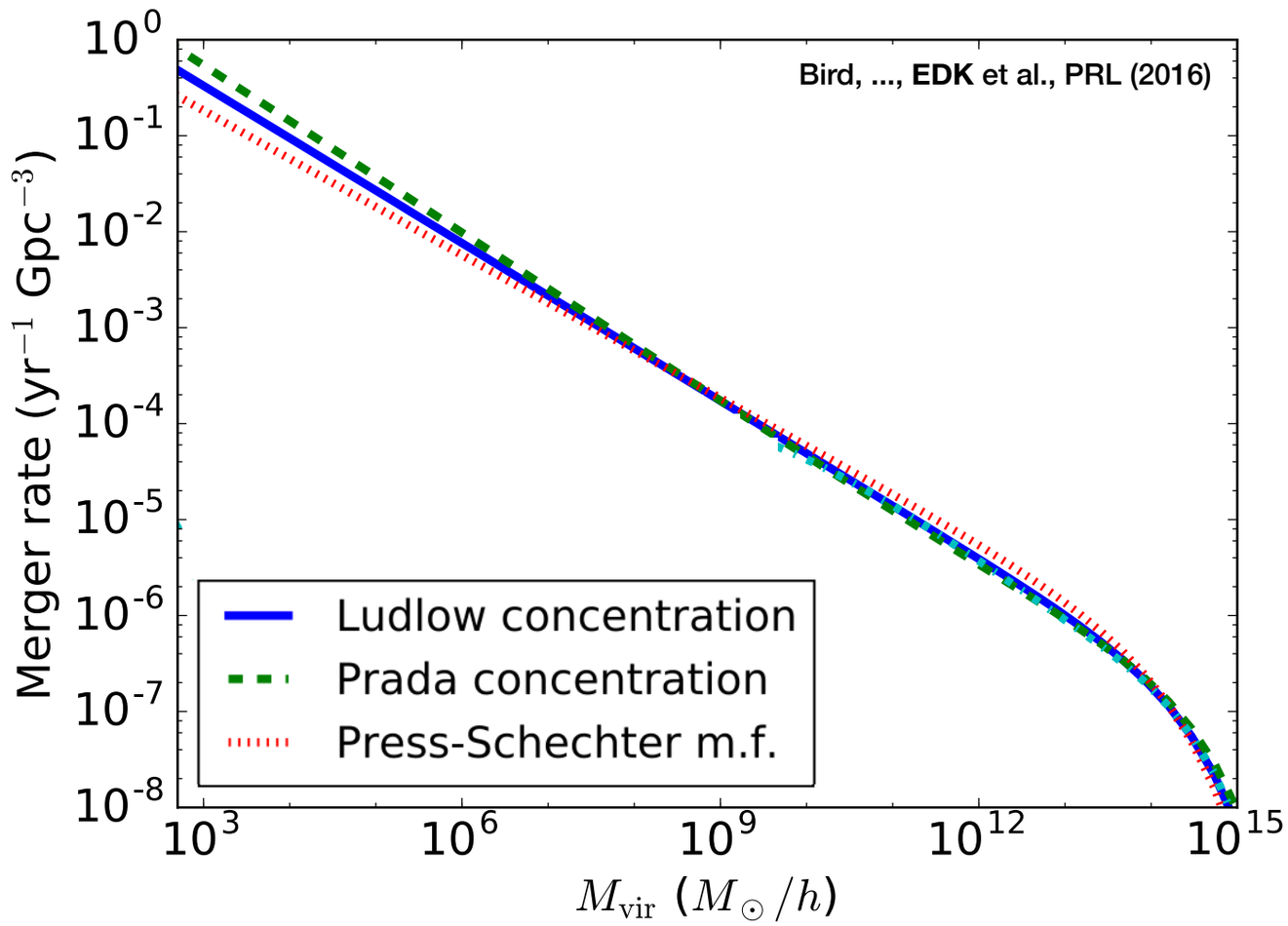

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Distinguish between $b_{\rm Stellar} \sim 1.4$ and $b_{\rm PBH} \sim 0.5$

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Localization:

Indirect Detection: Clustering of GW Events

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GW150914: 230 deg^2
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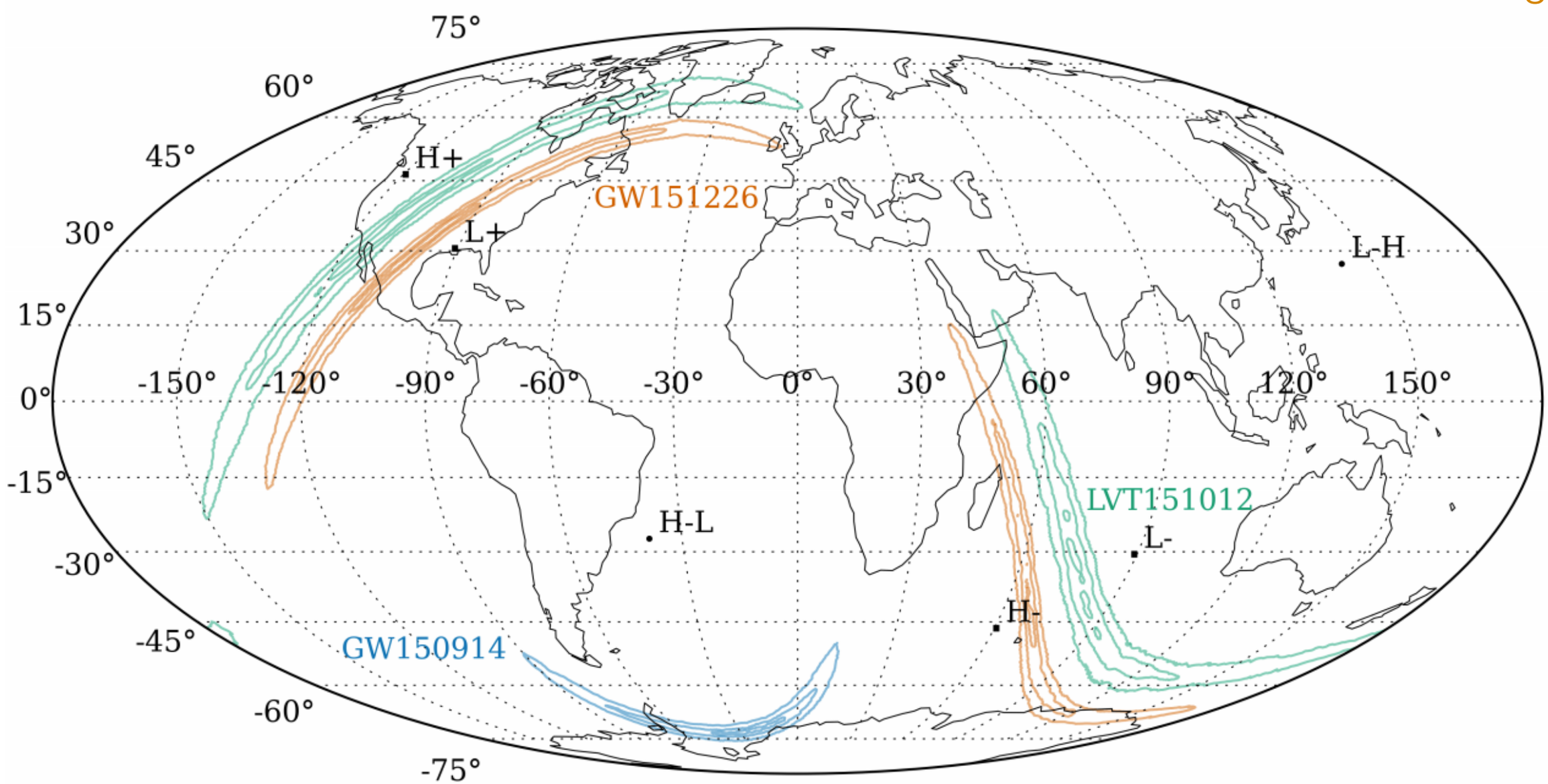

LIGO collaboration, PRX (2016)

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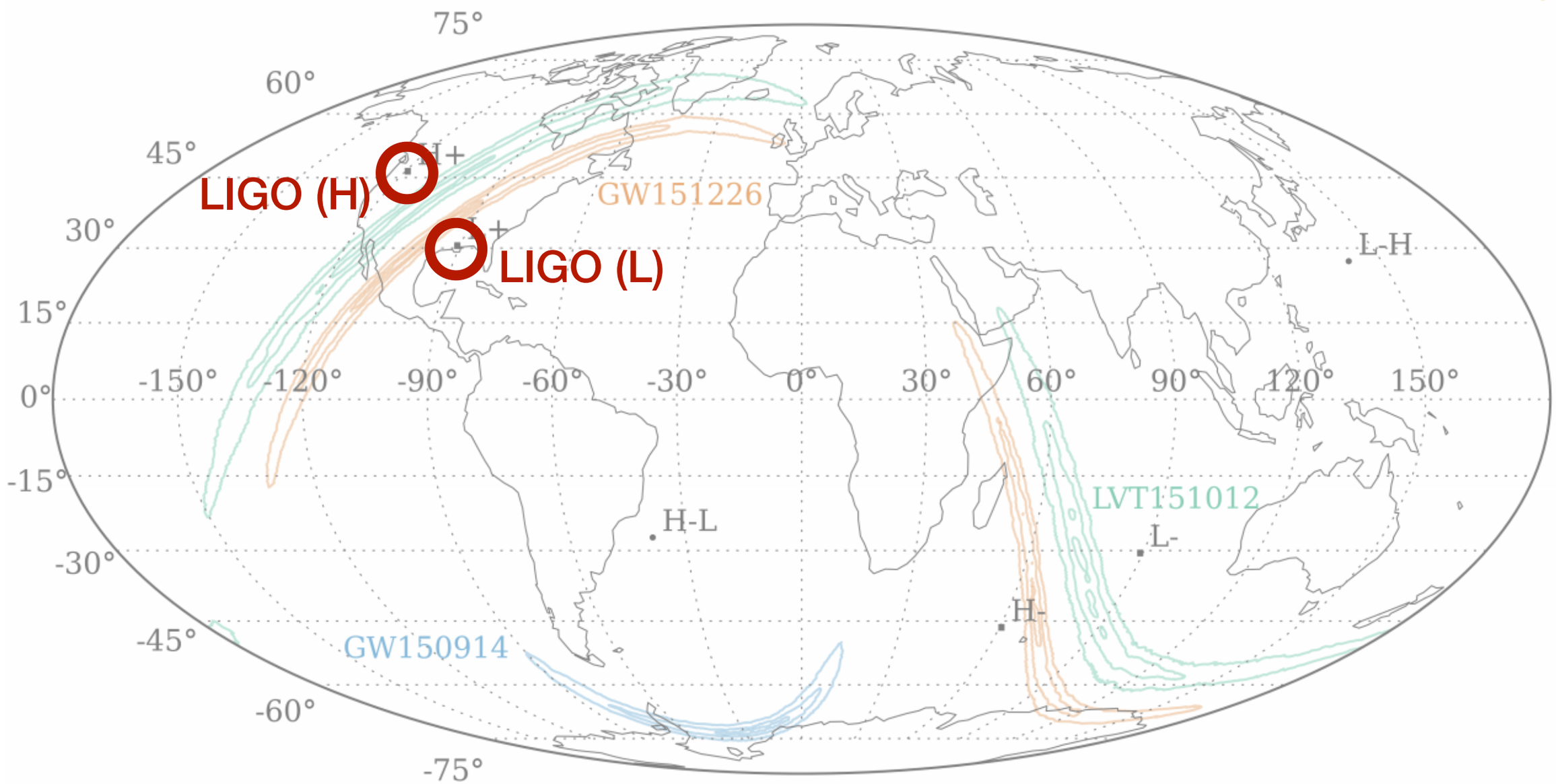

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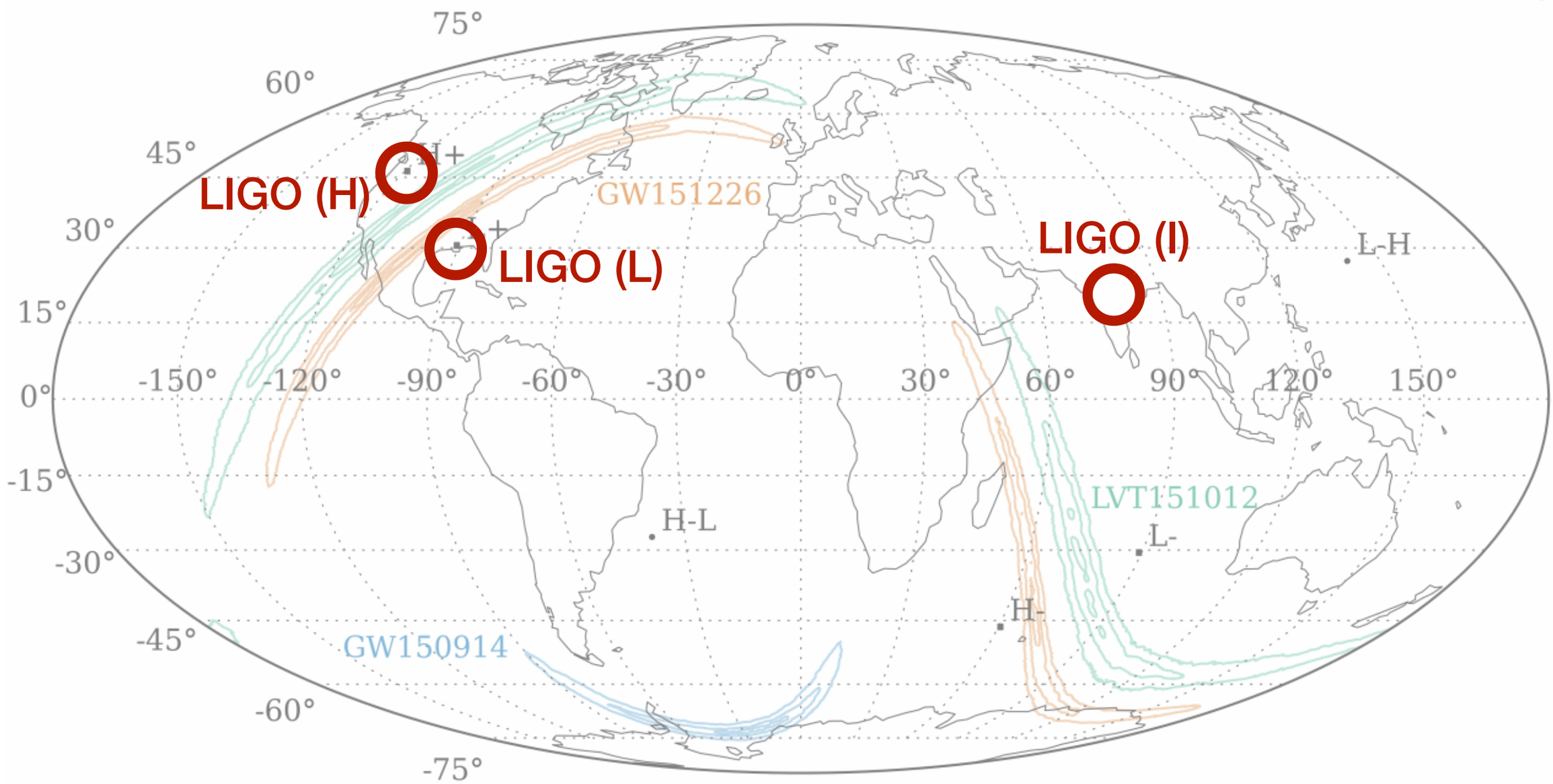

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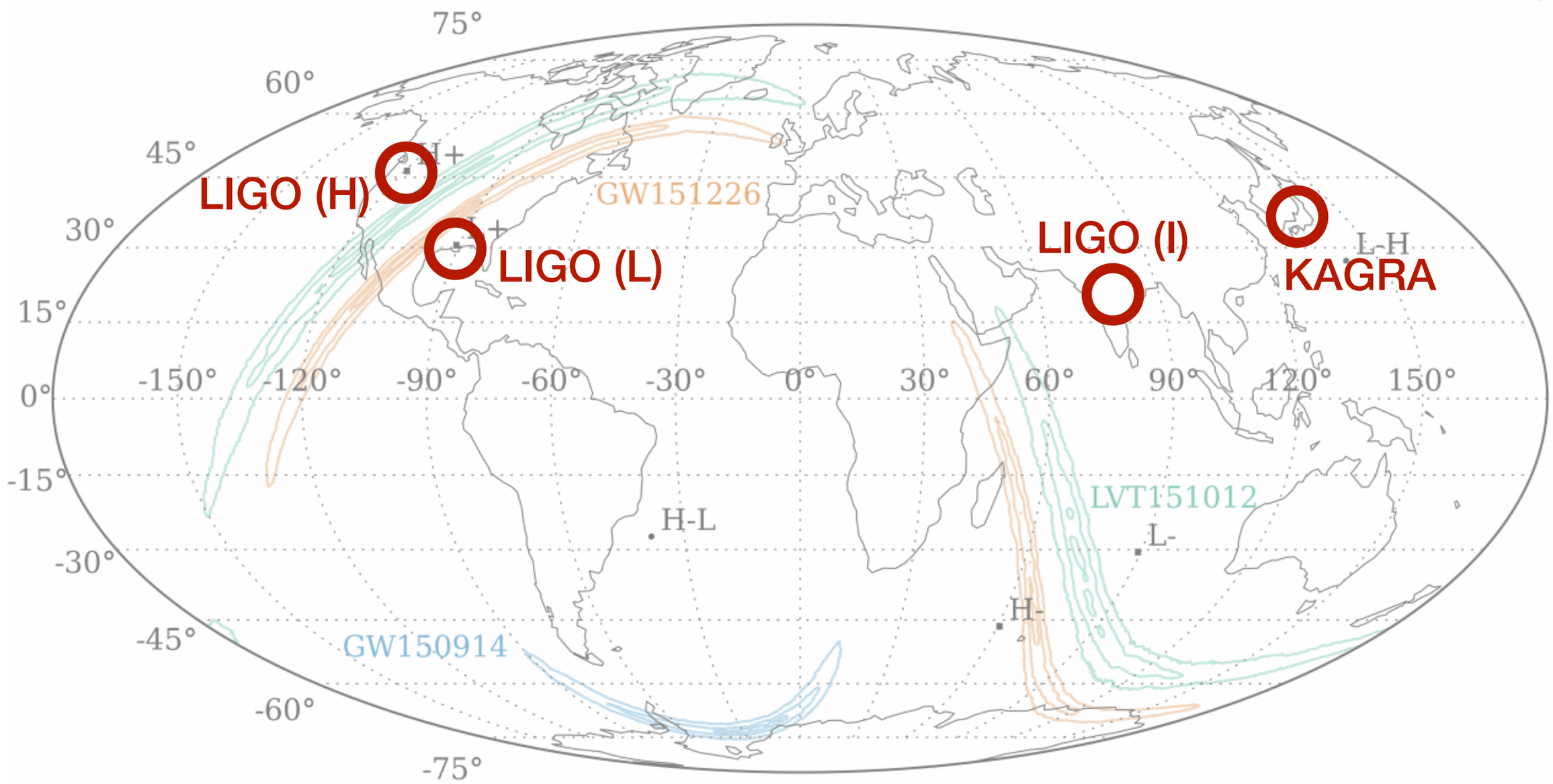

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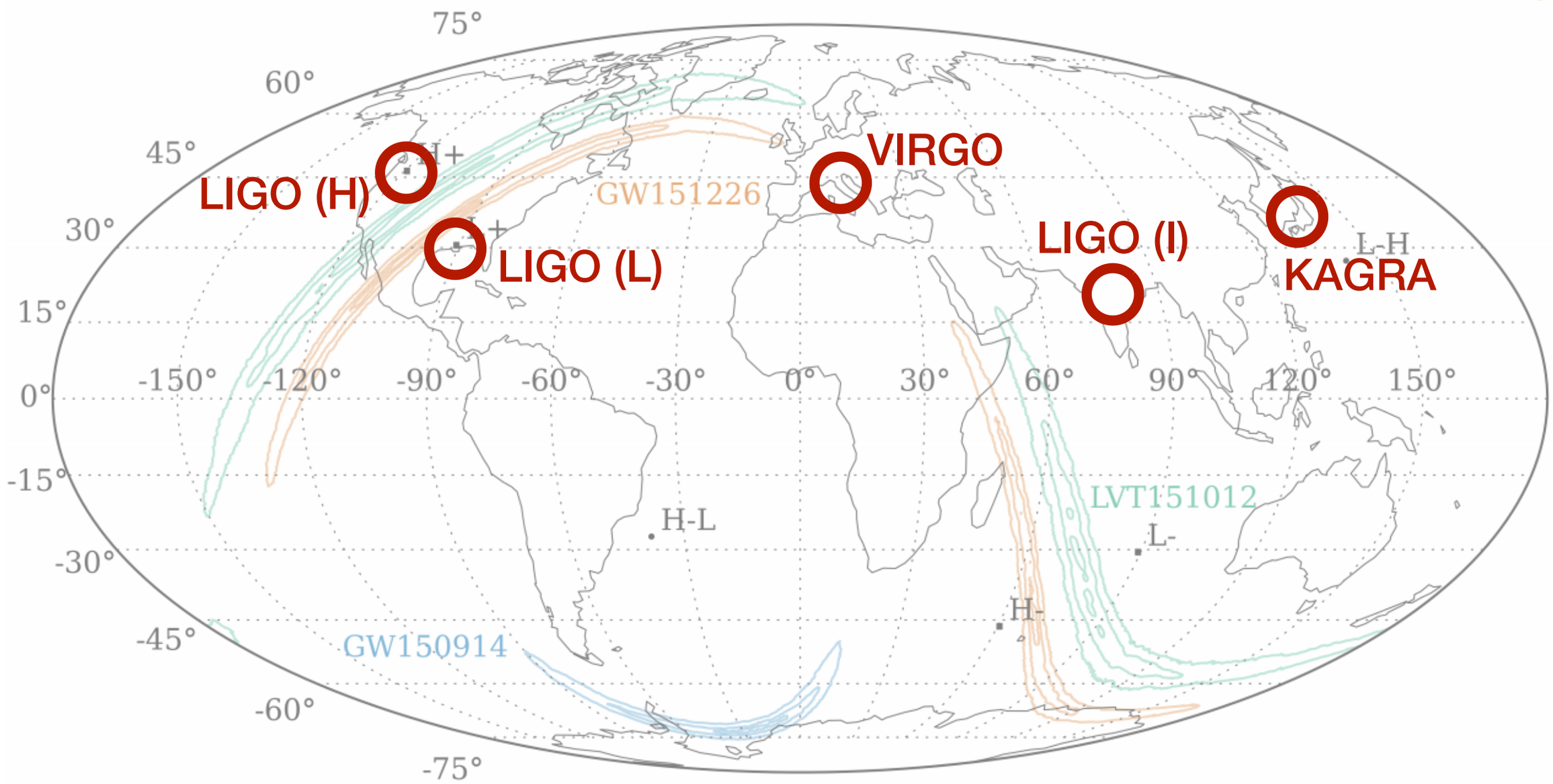

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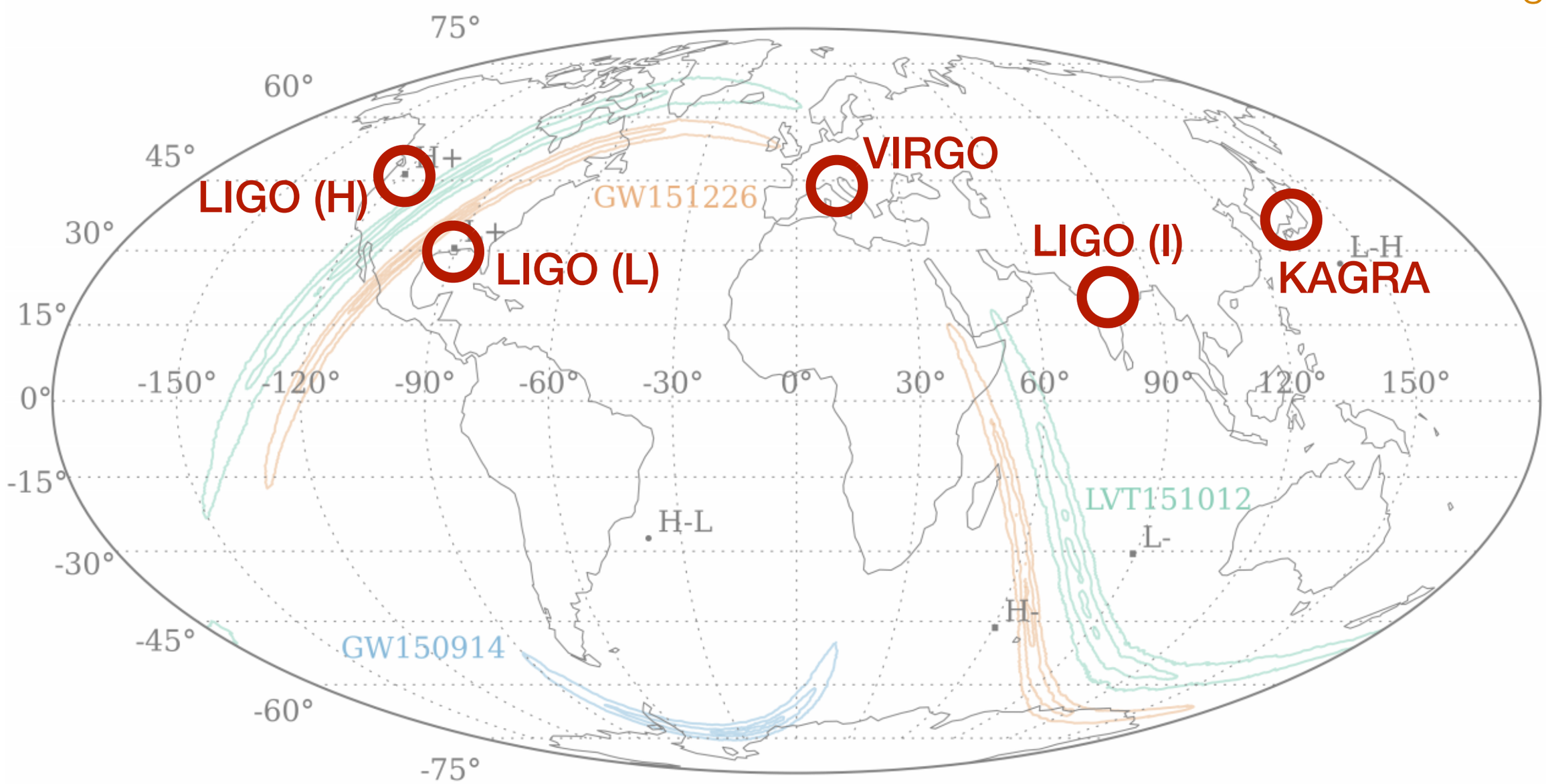

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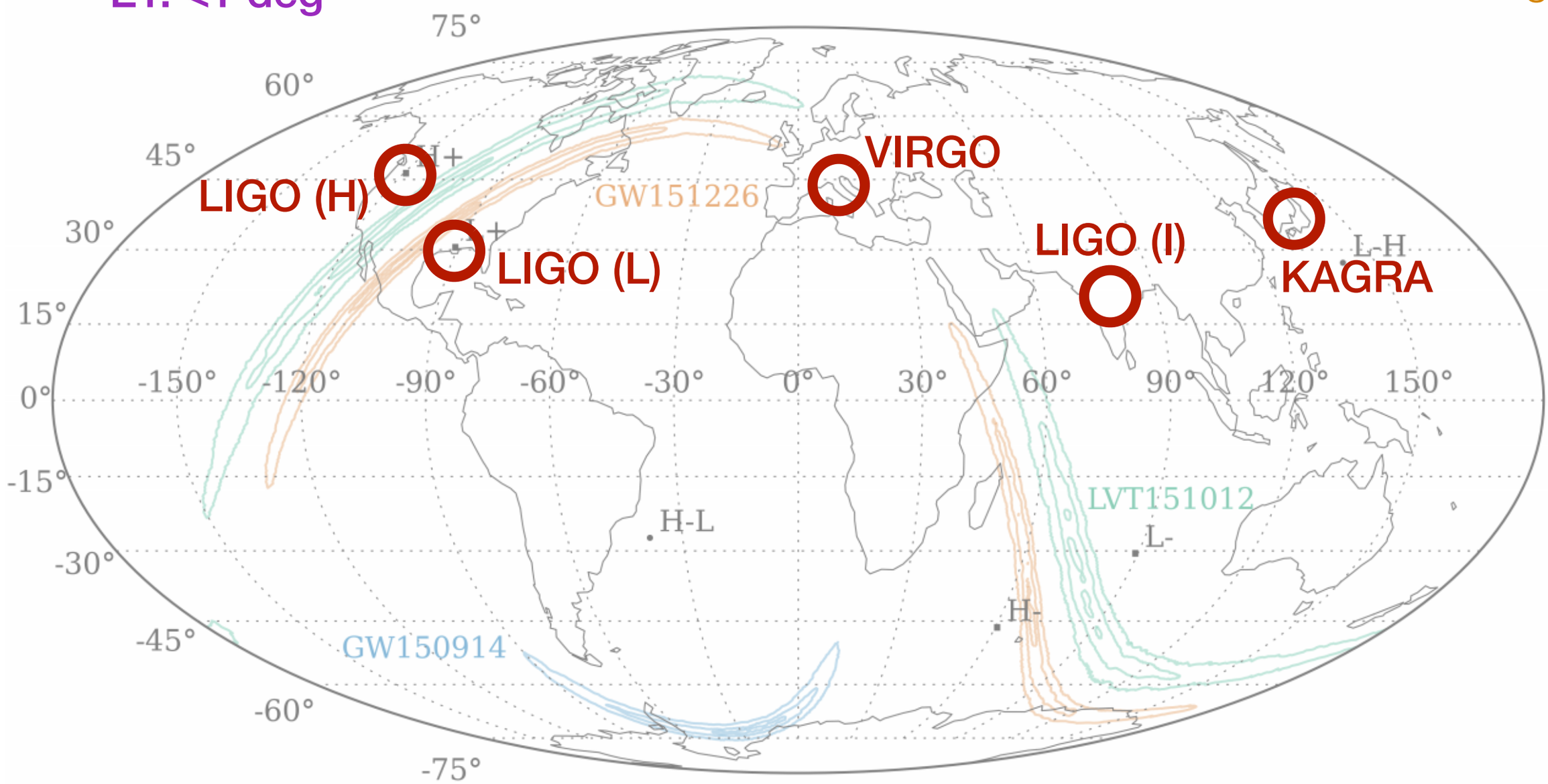

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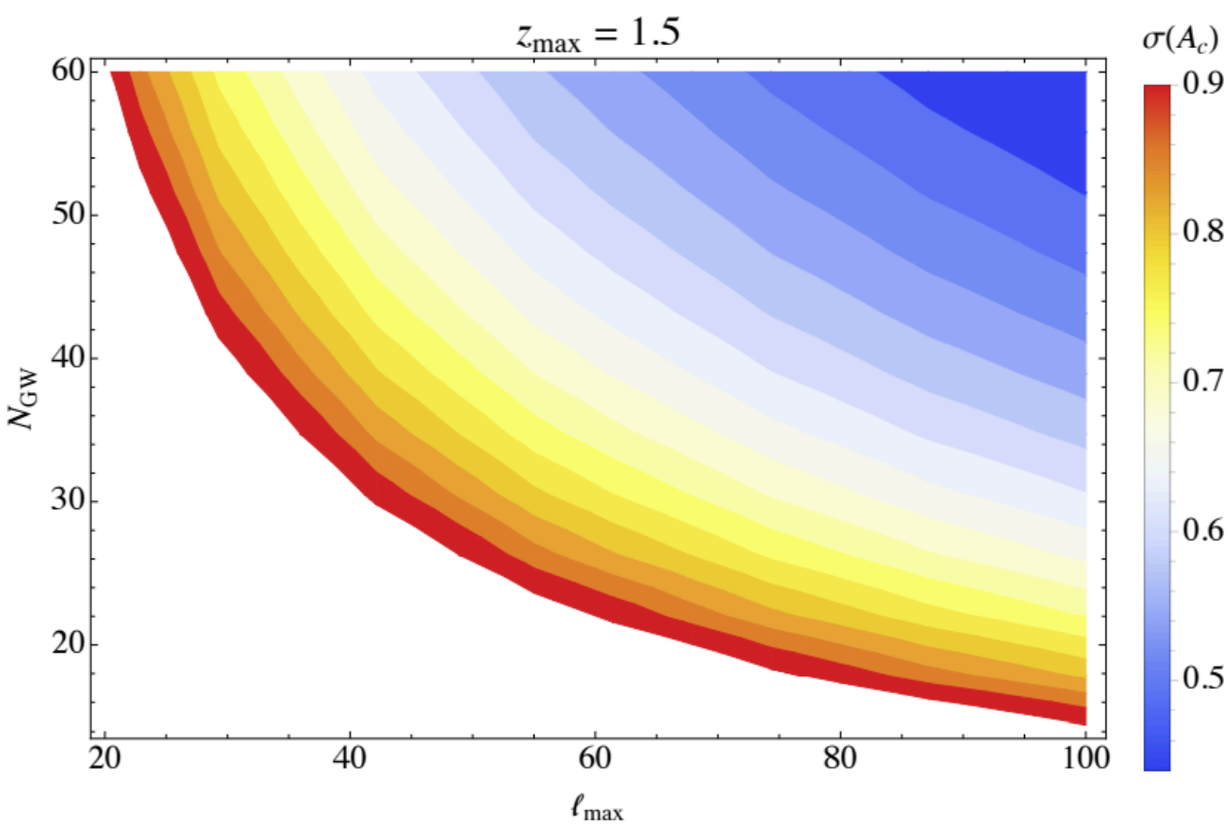

Raccanelli, EDK et al., PRD (2016)

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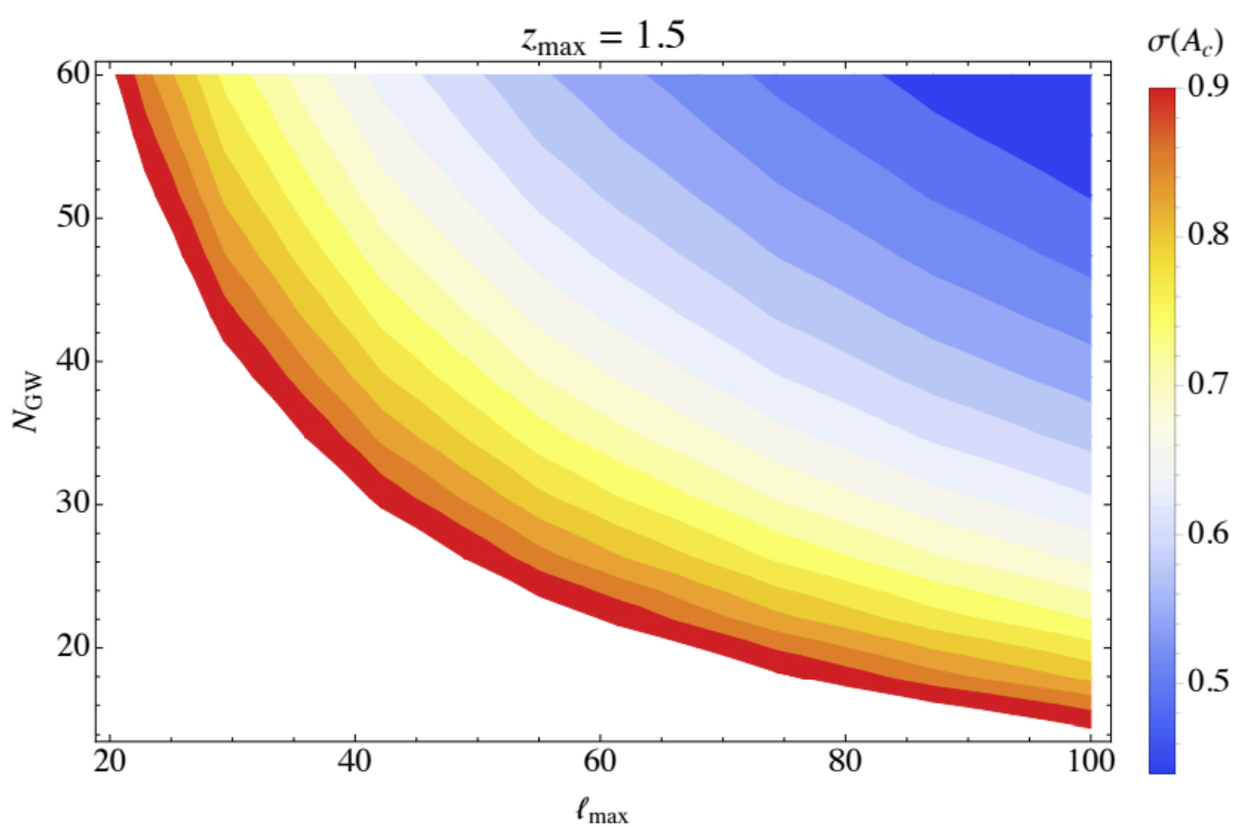

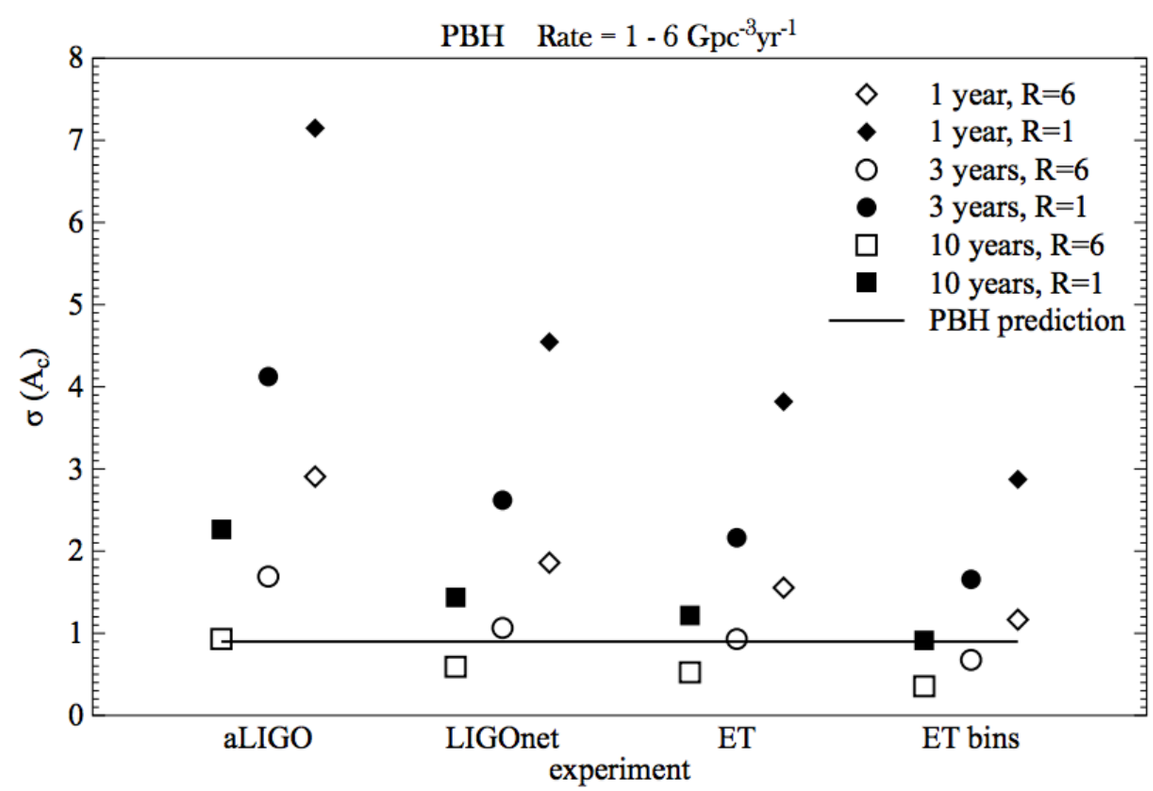

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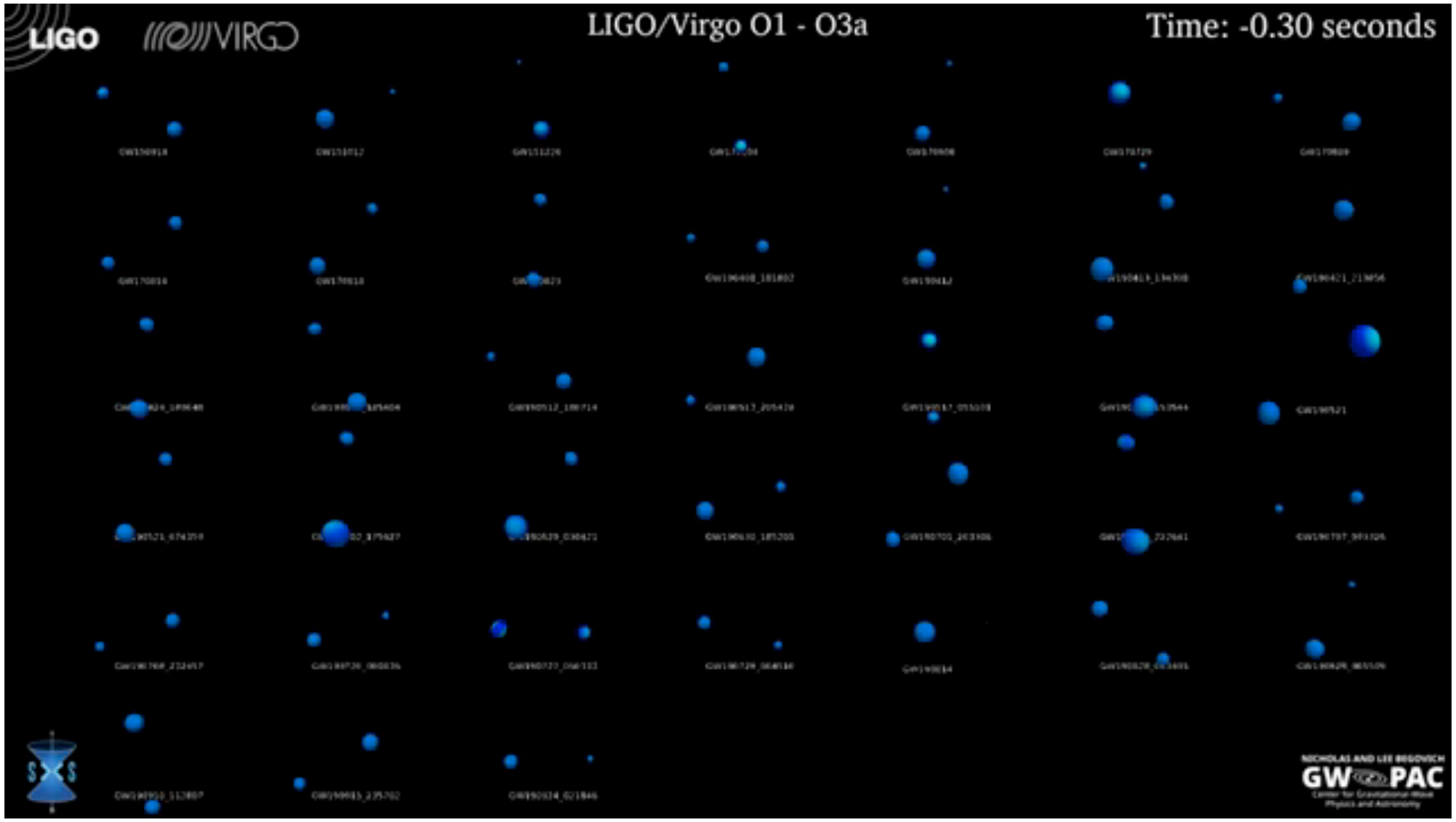
Indirect Detection: O3a Data Hot Off the Press!



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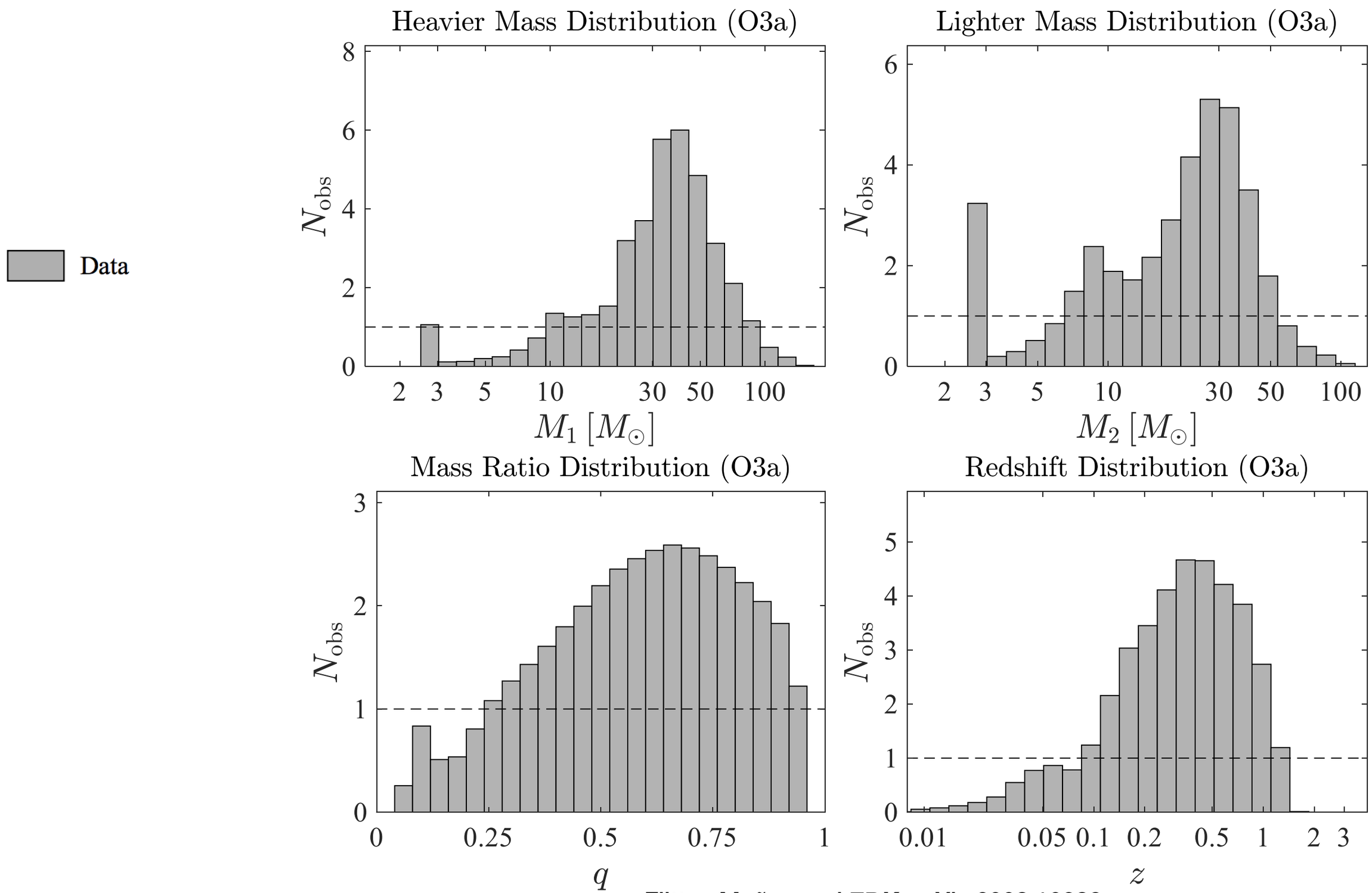
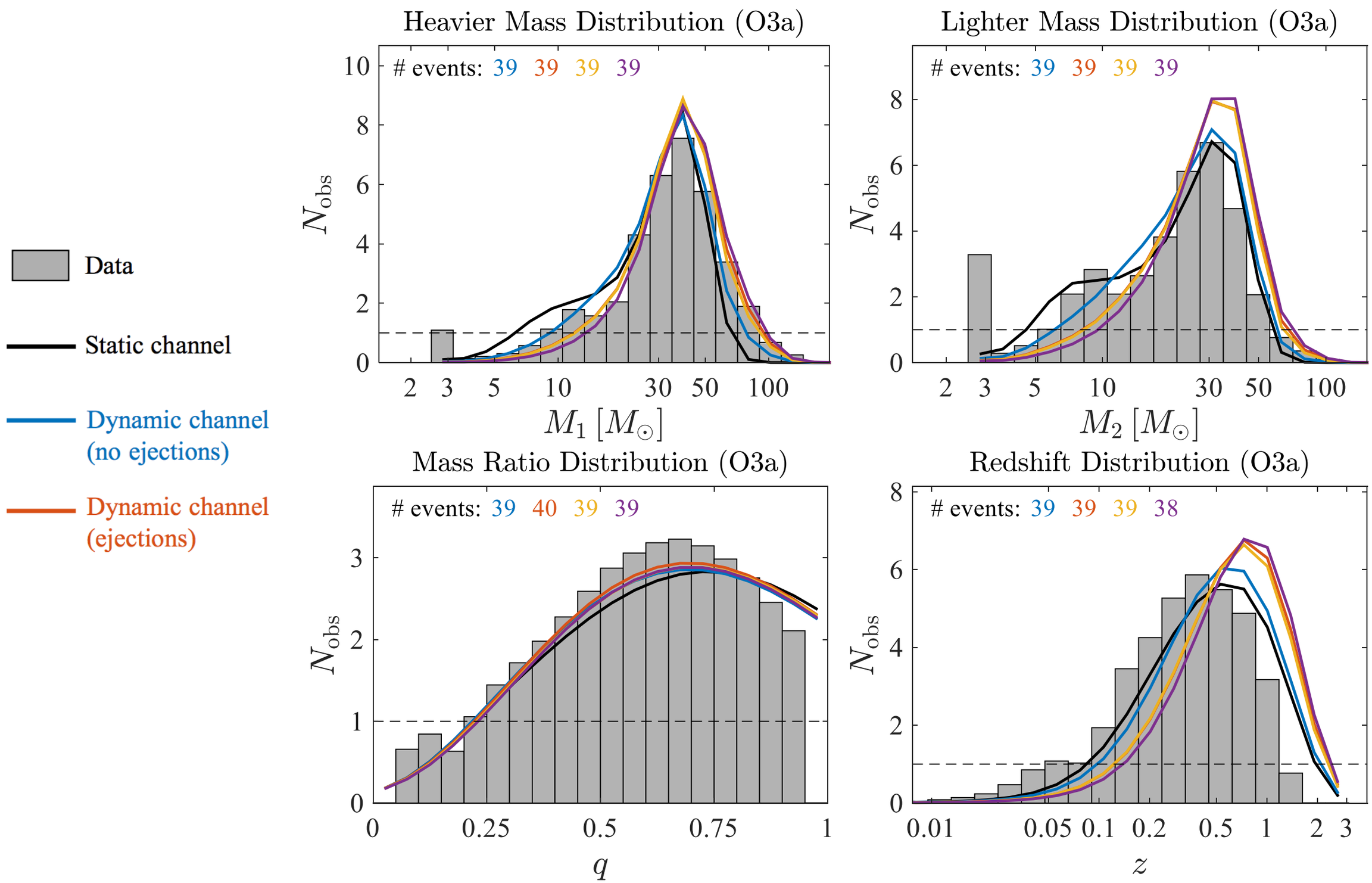


Flitter, Muñoz and **EDK**, arXiv:2008.10389

Indirect Detection: O3a Fit with Astro Channels



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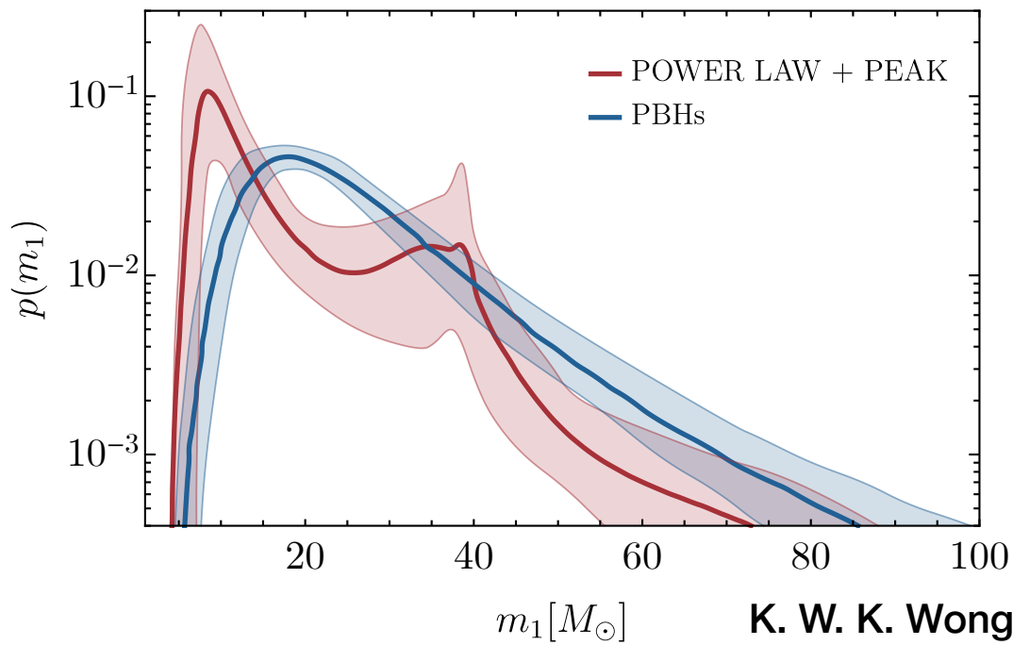

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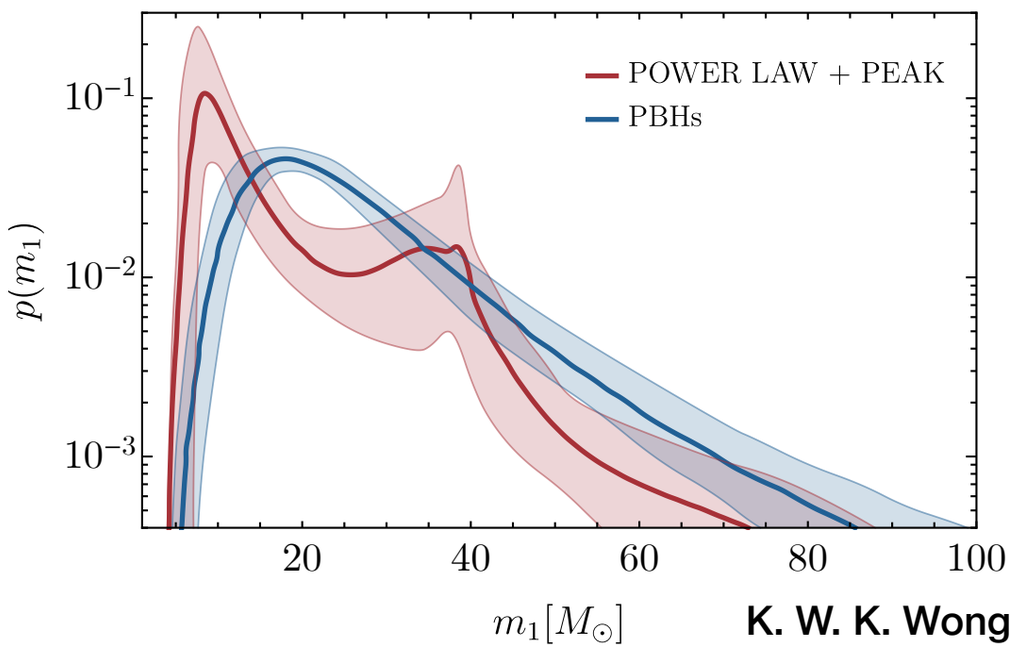

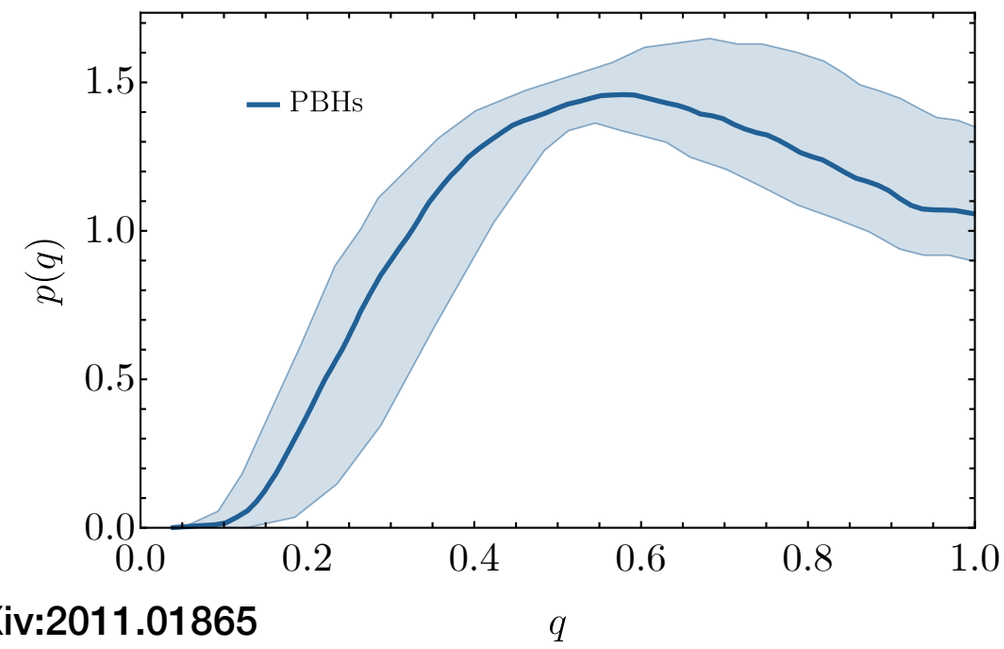

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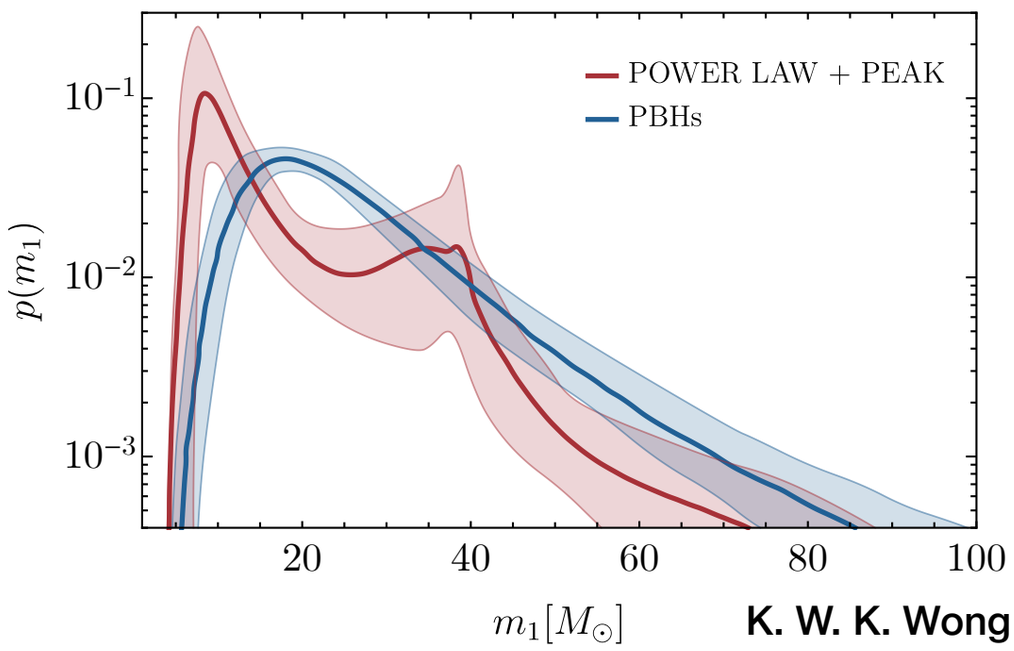

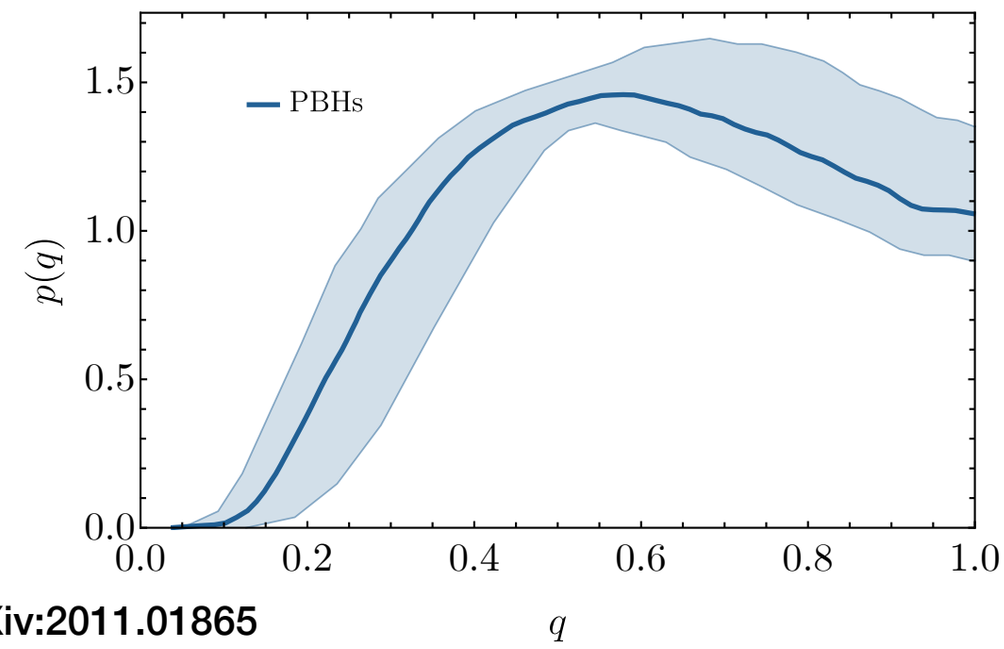

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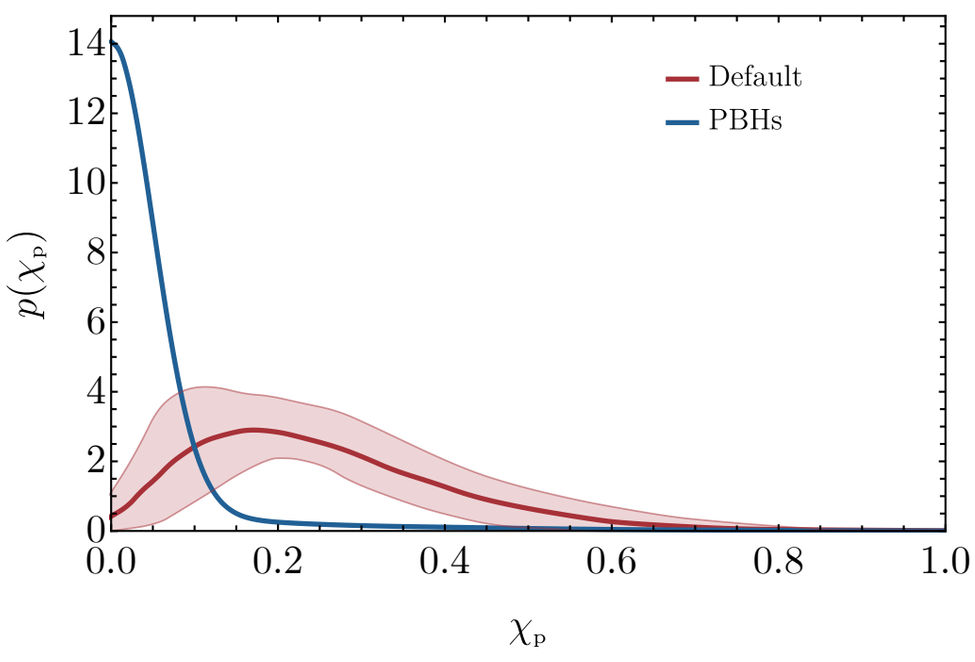

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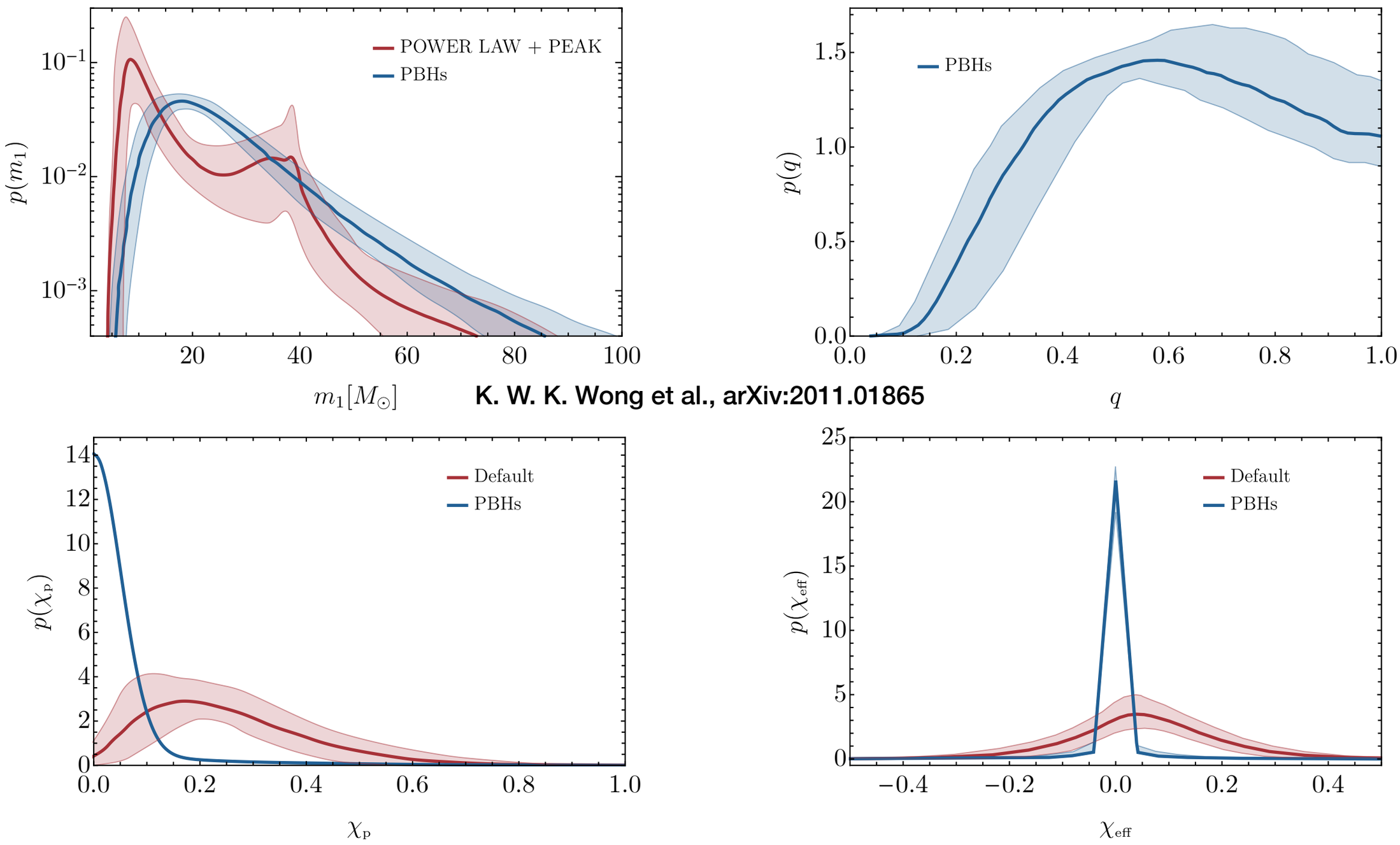

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Outline

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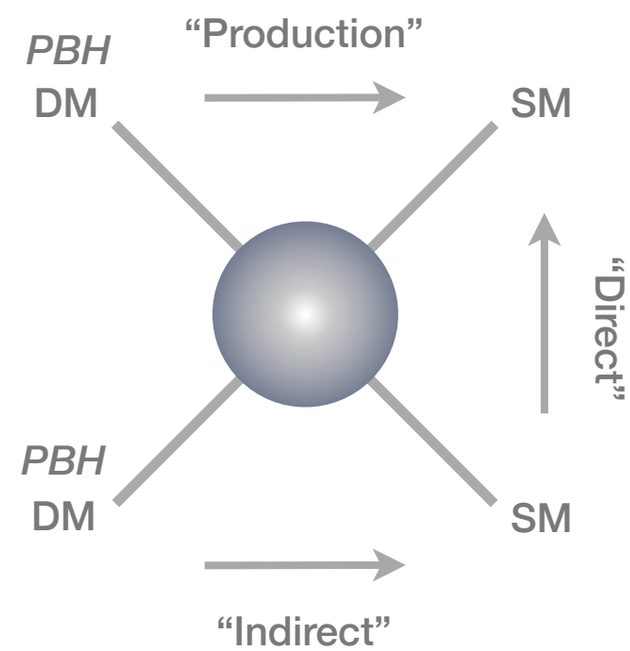

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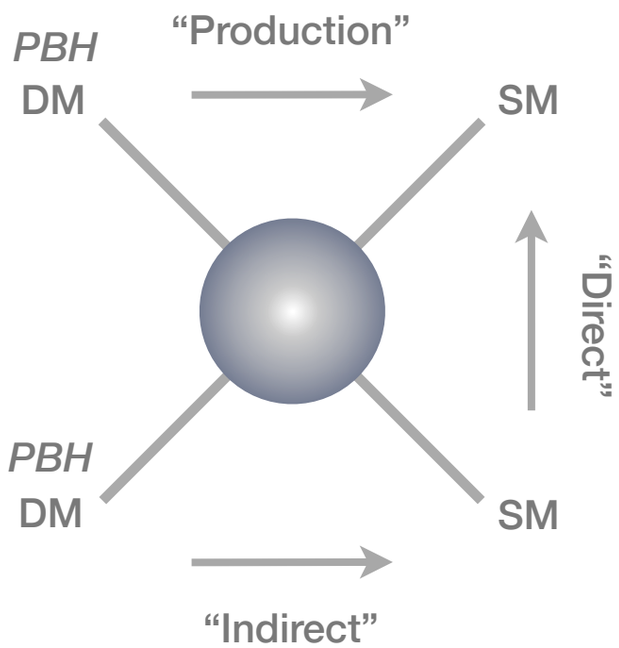

PBH Dark Matter: Constraining the Mass Fraction

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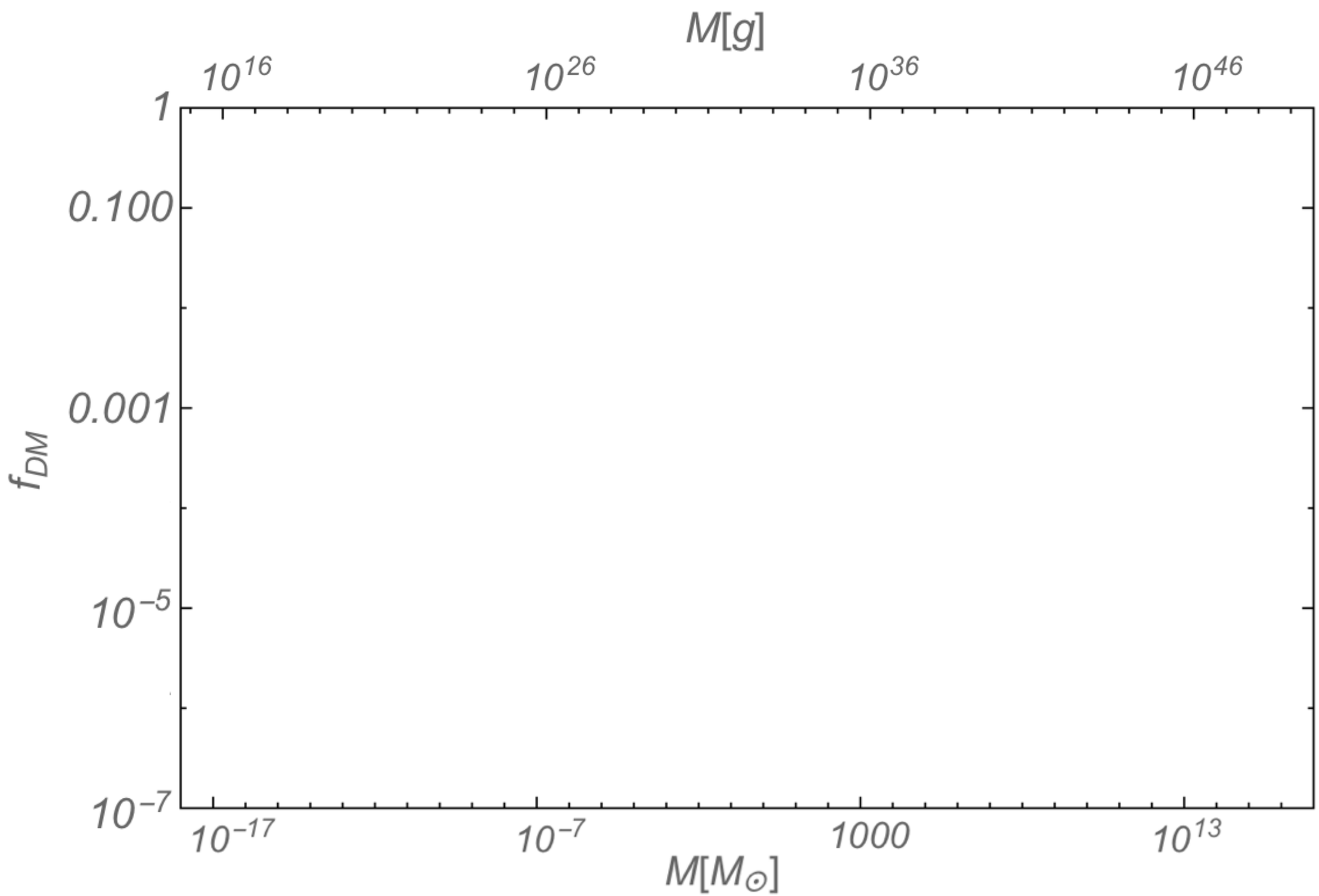

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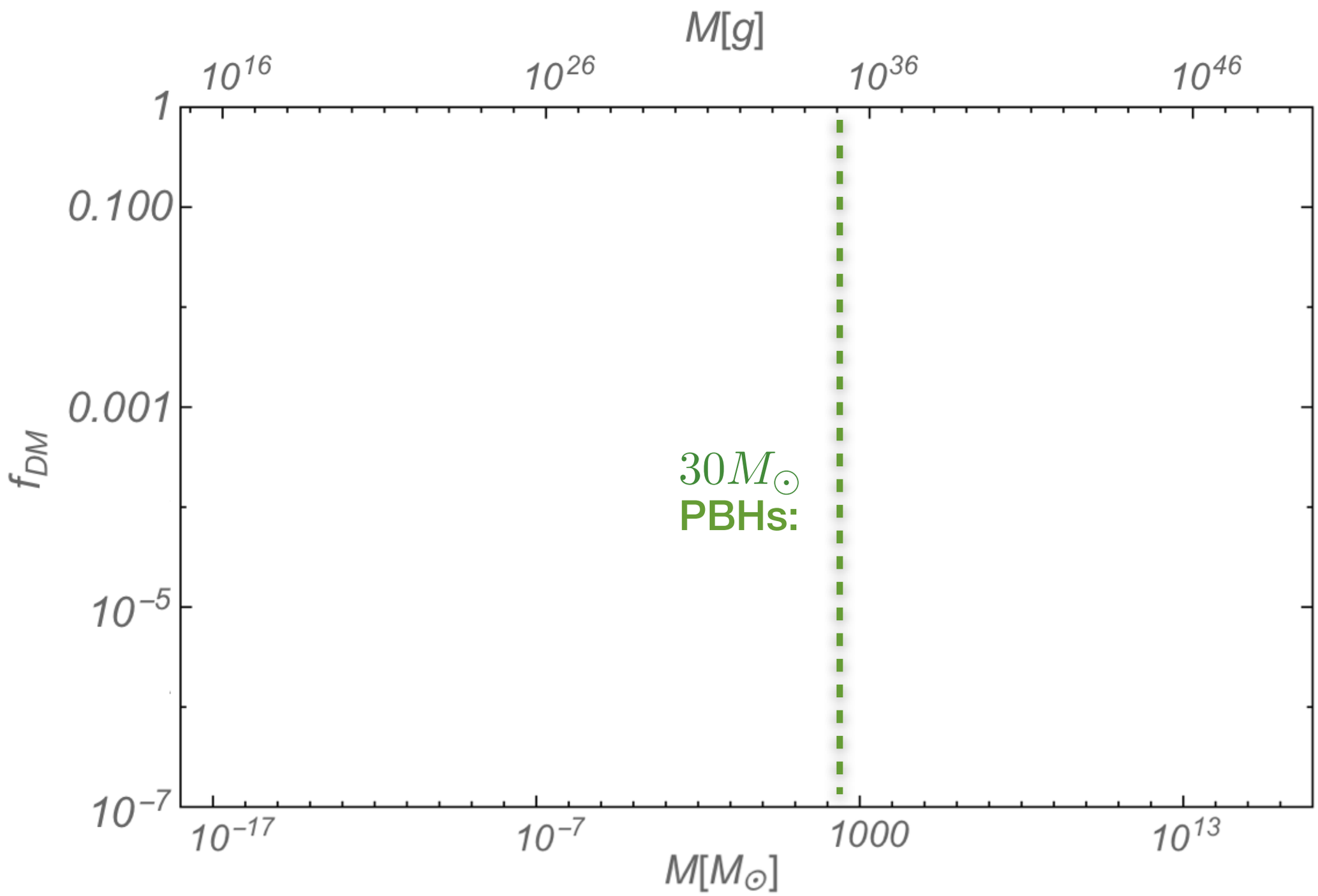

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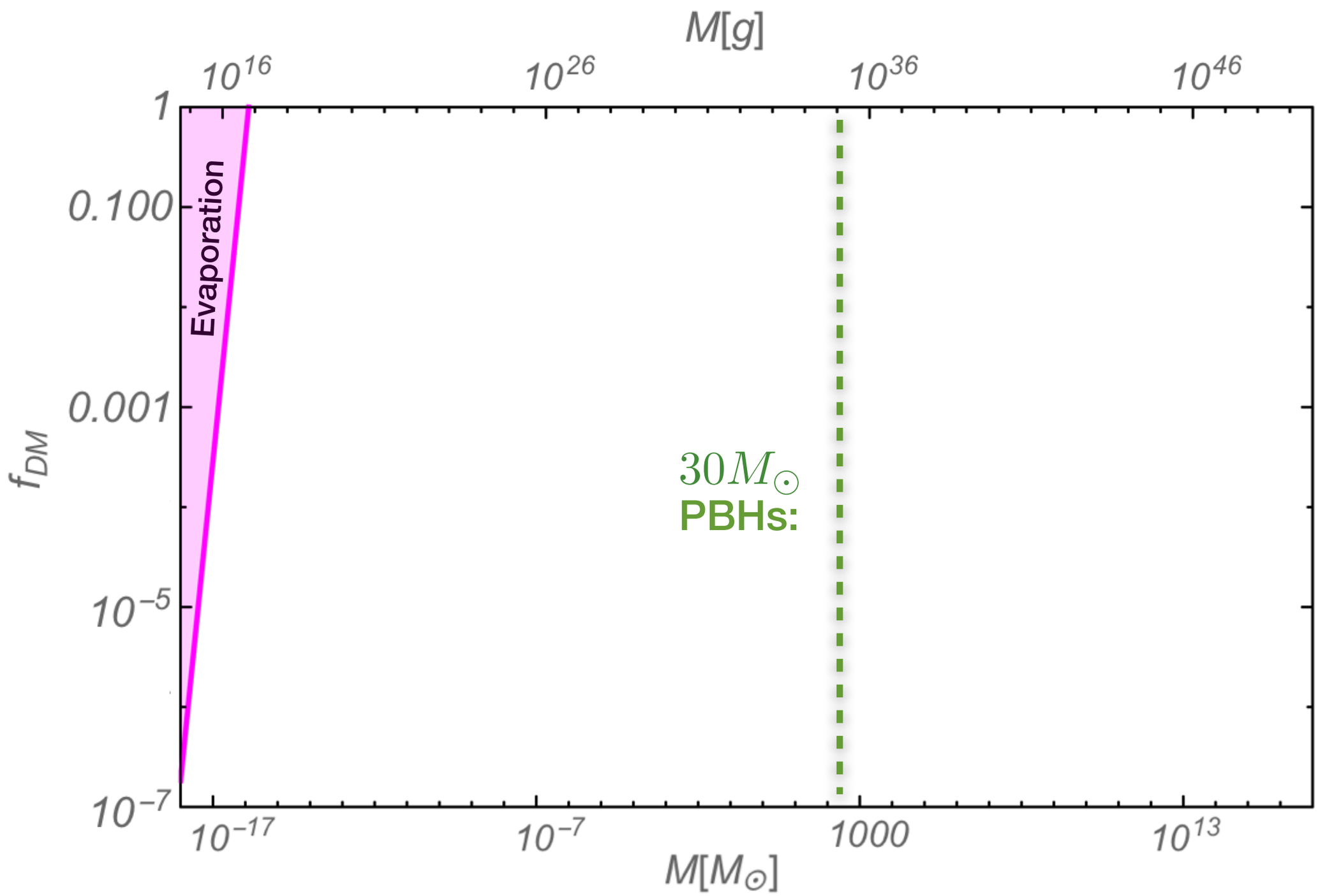

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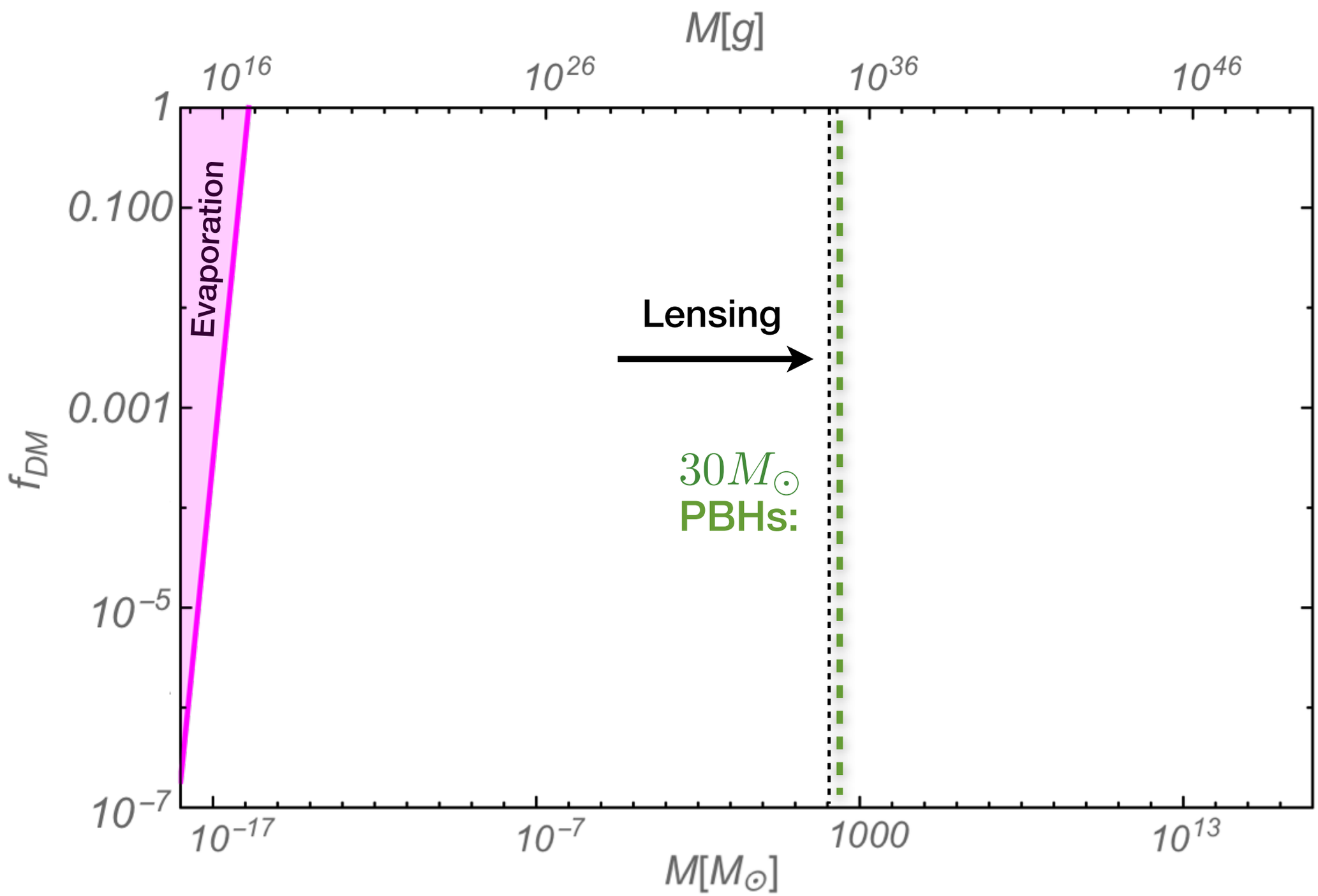

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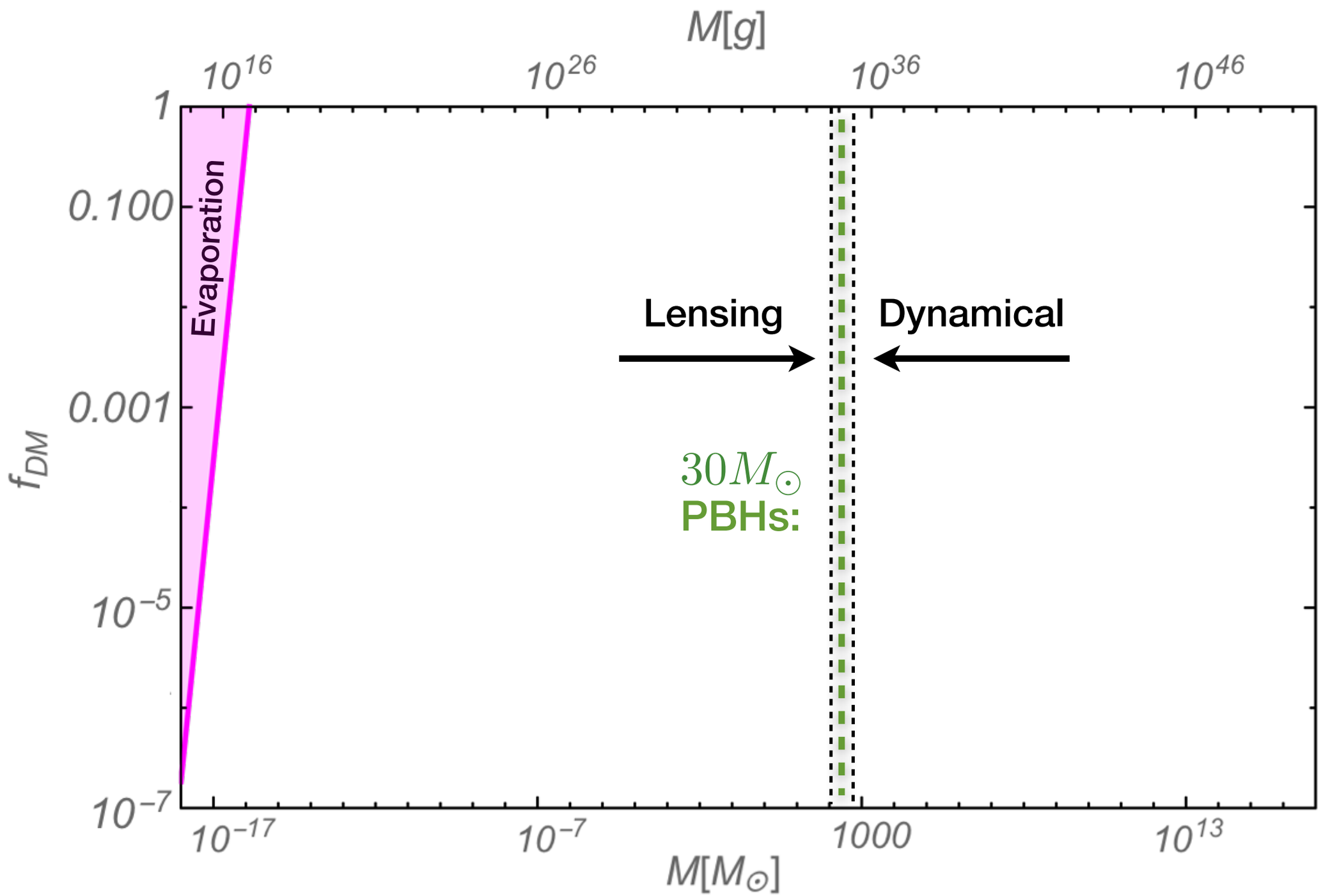

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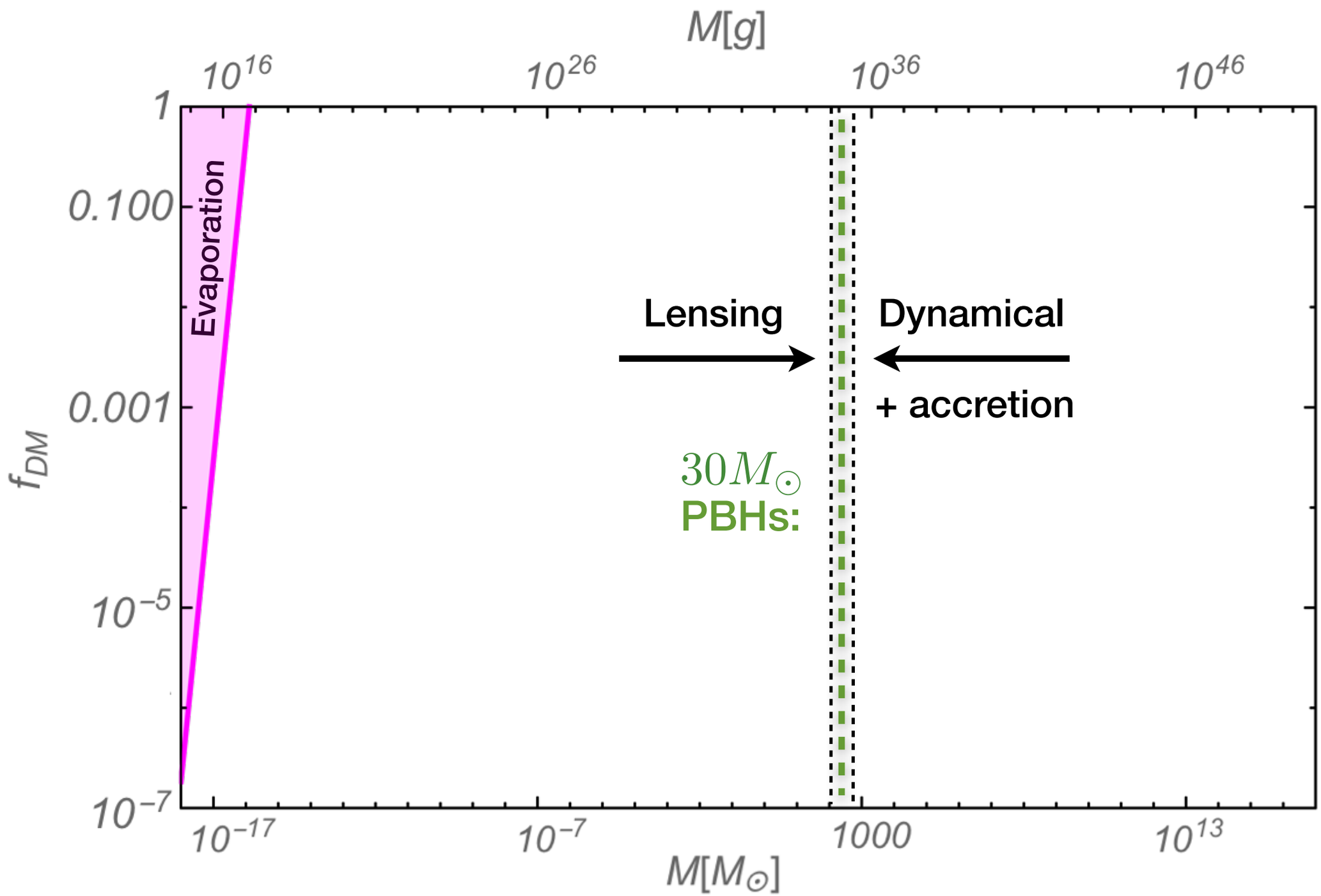

Microlensing: Illustration

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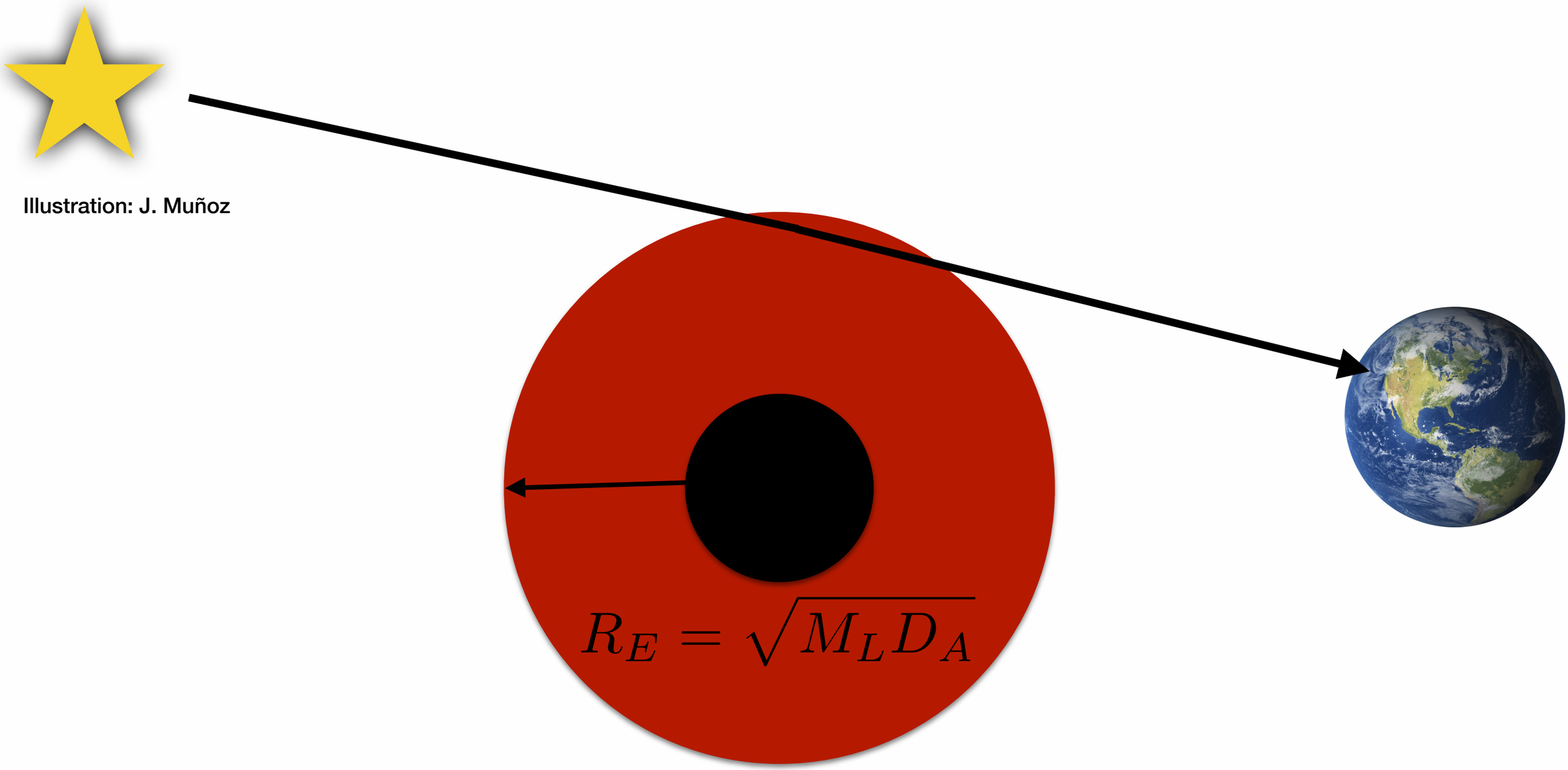

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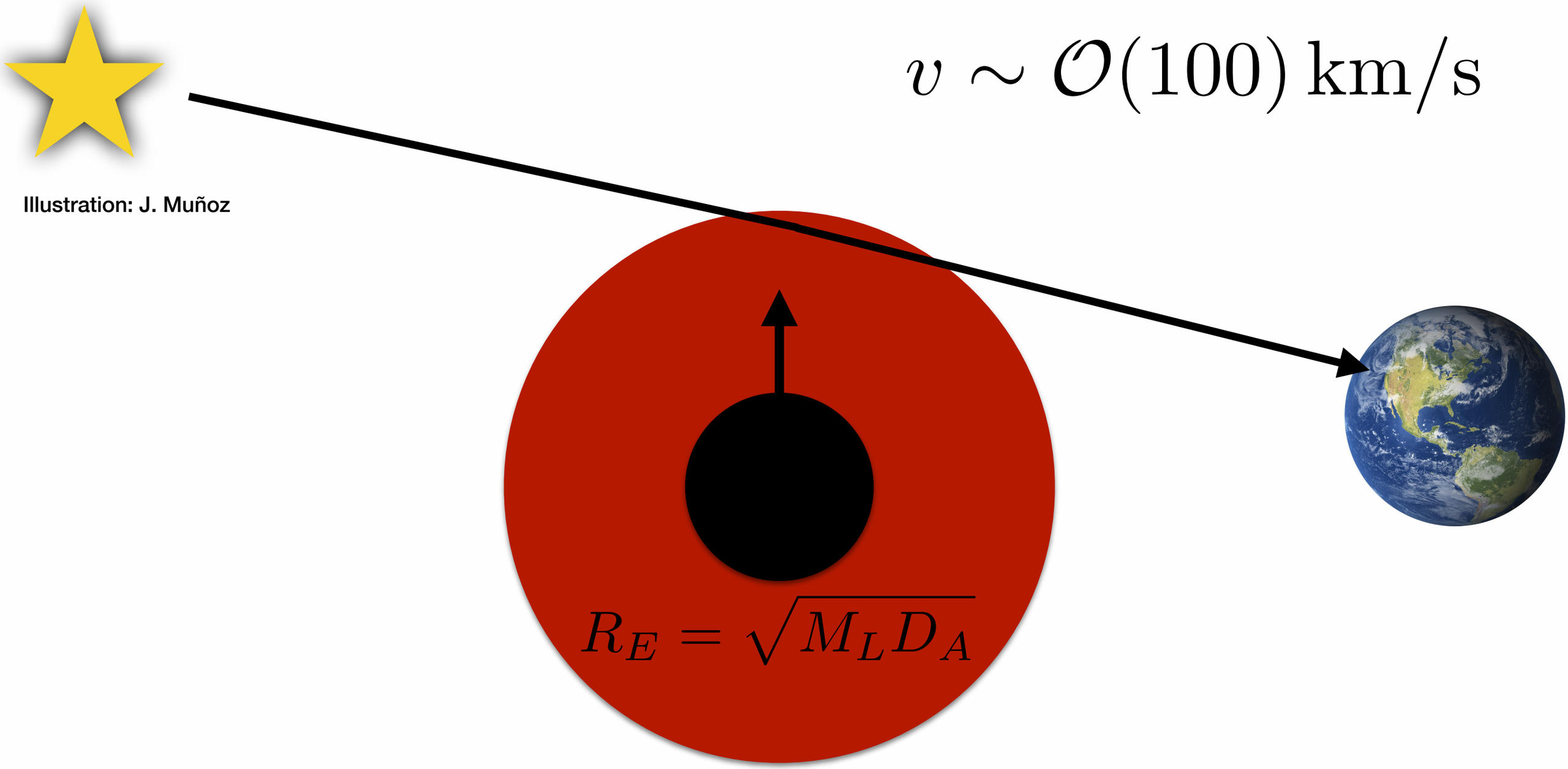

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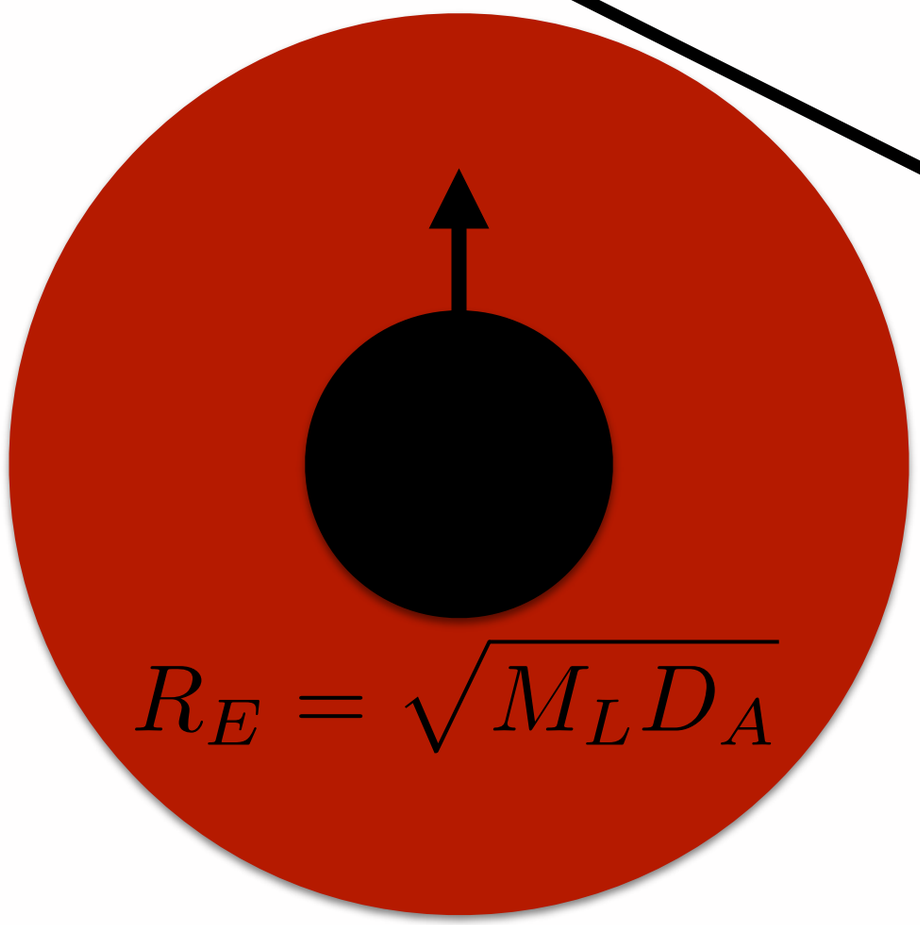

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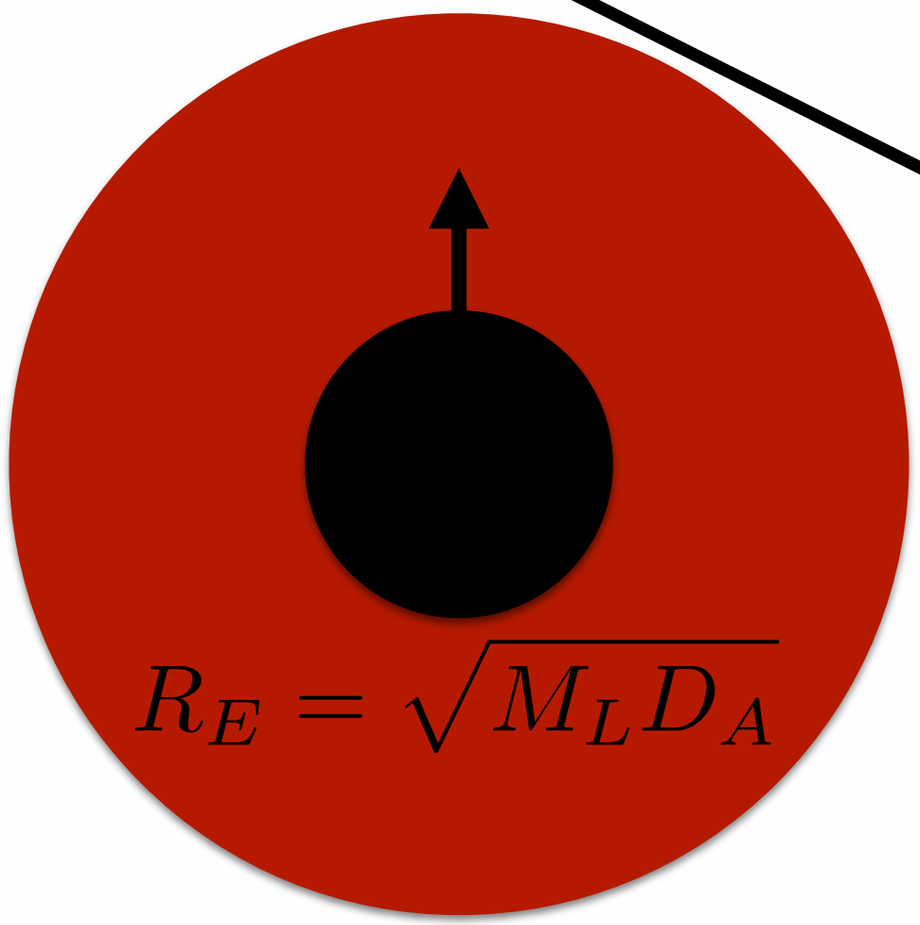

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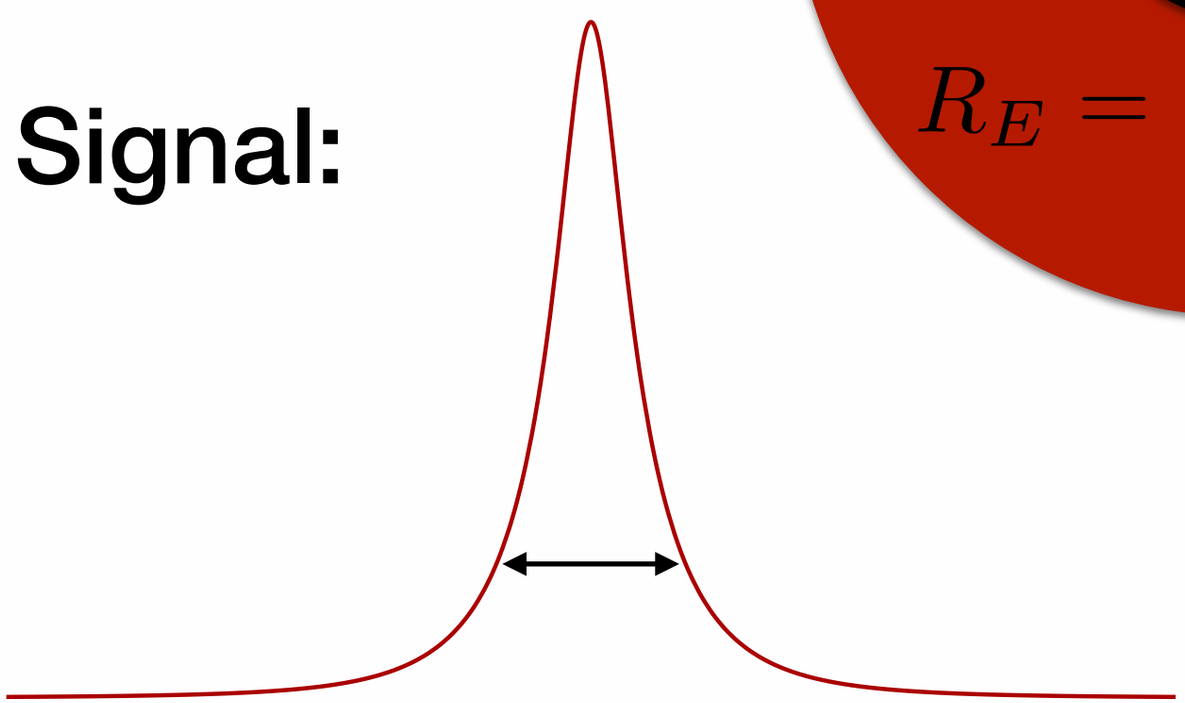

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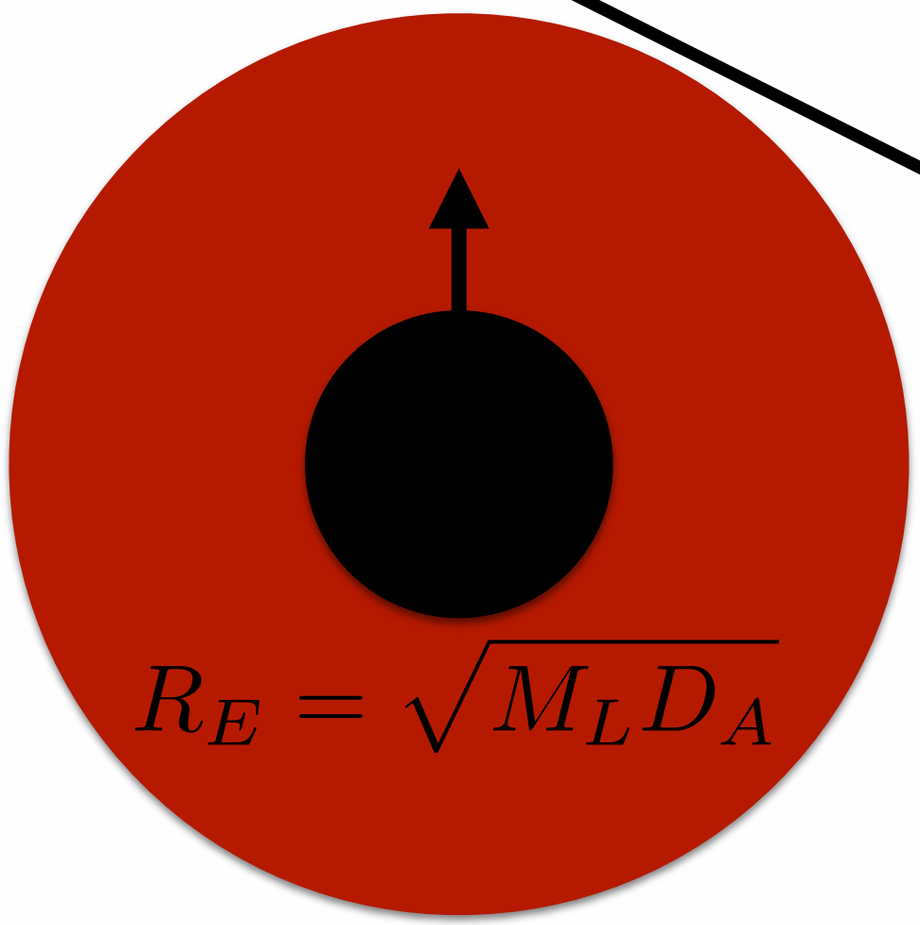

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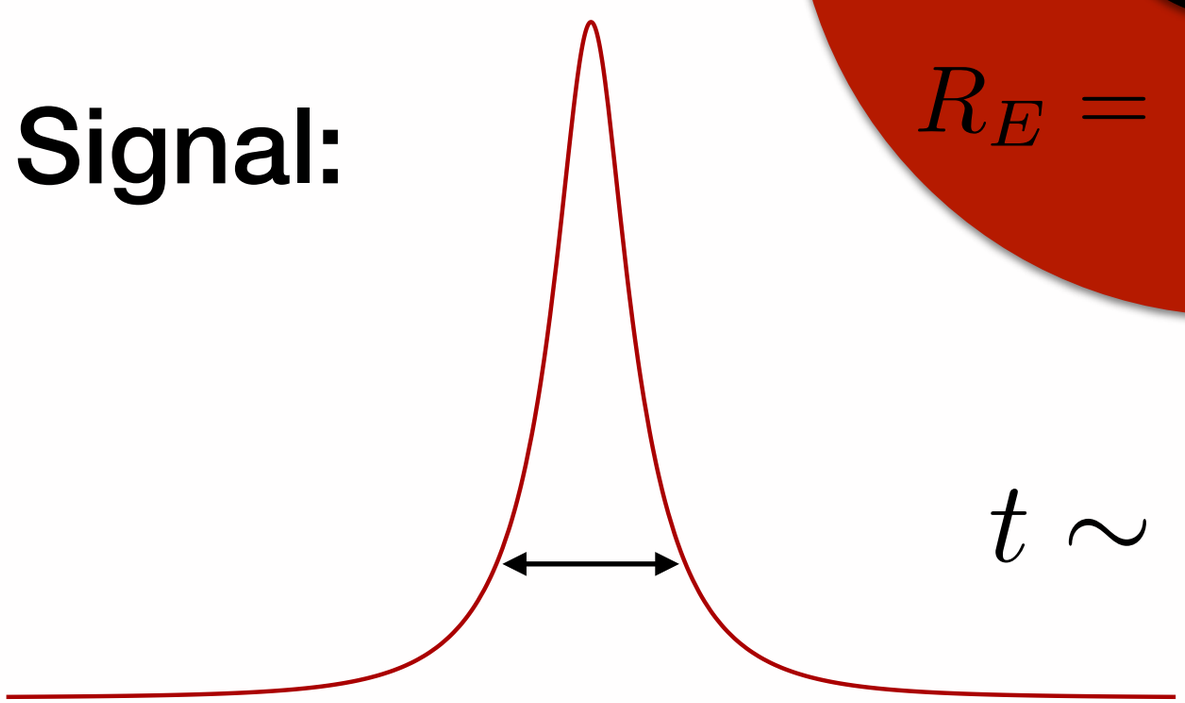
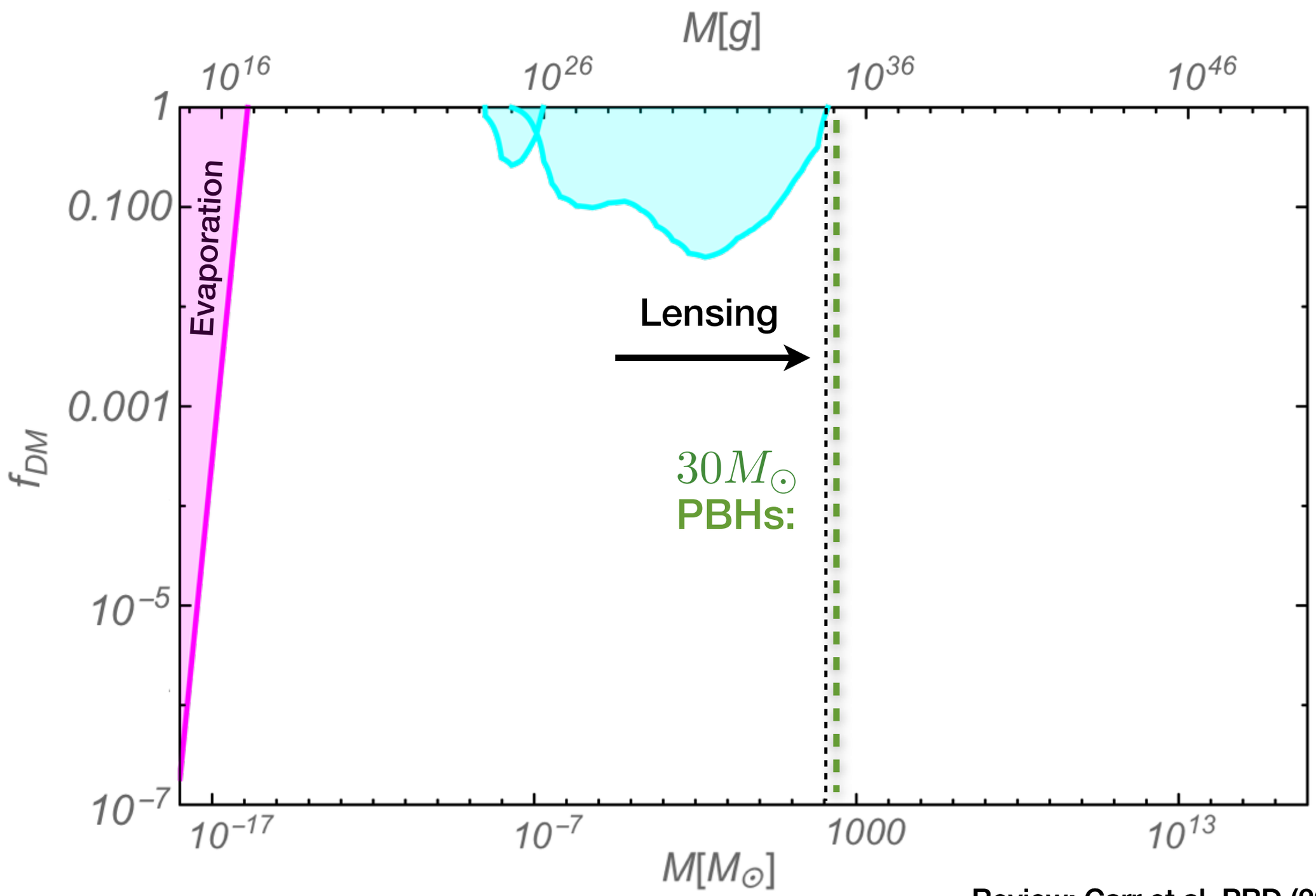


$$t \sim \frac{R_E}{v} \sim \mathrm{yrs} \times \sqrt{\frac{M_L}{10\,M_\odot}}$$

PBH Dark Matter: Existing Constraints



Review: Carr et al. PRD (2016)

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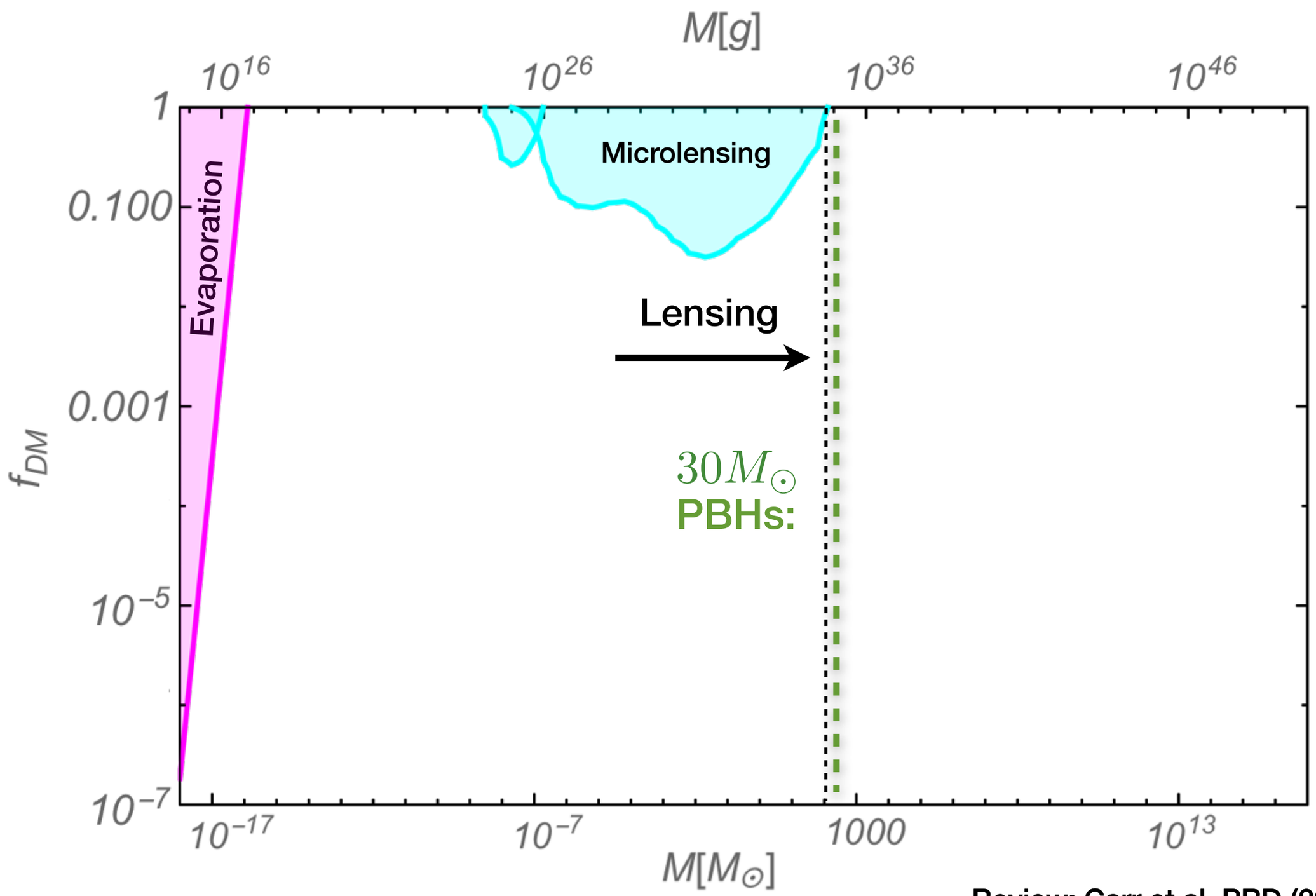

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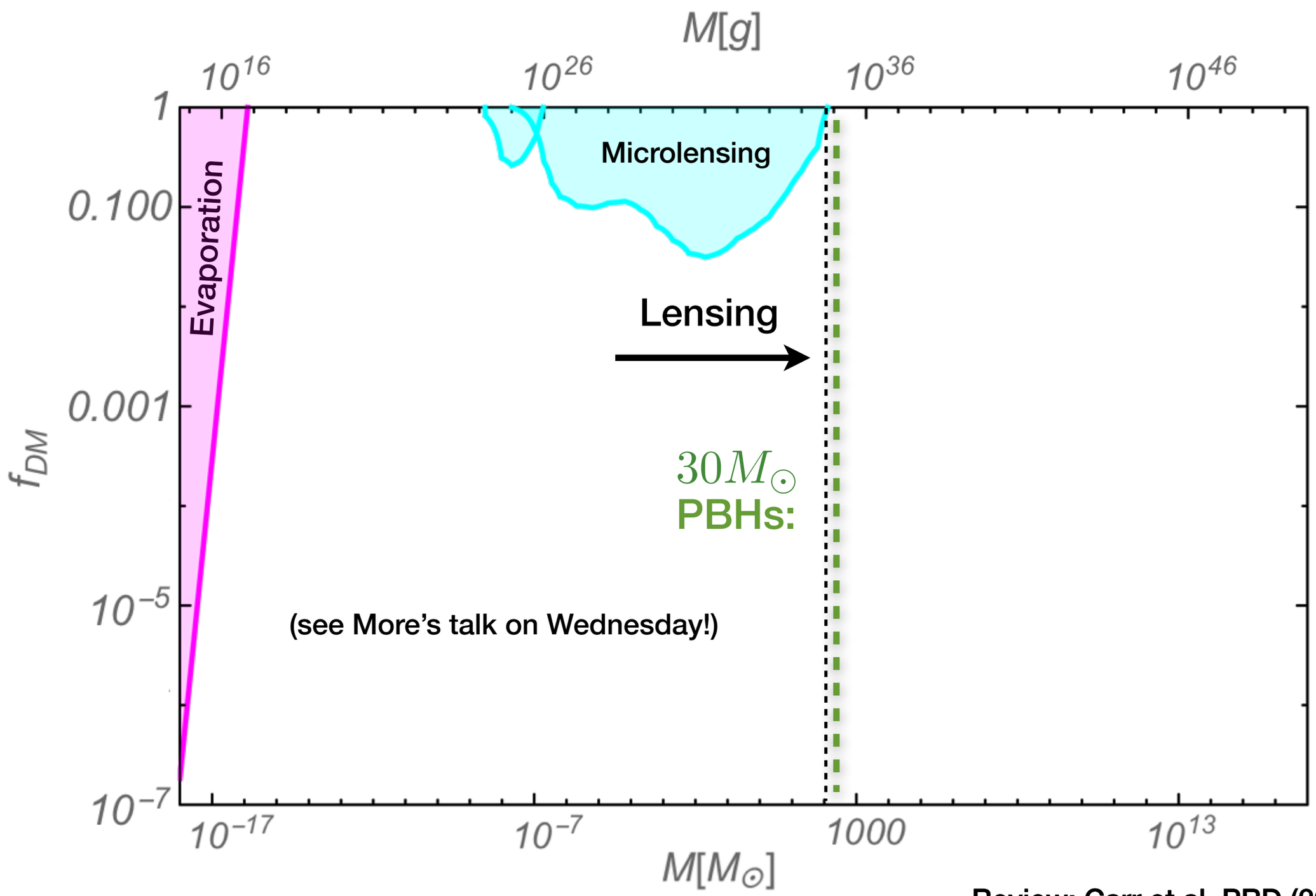

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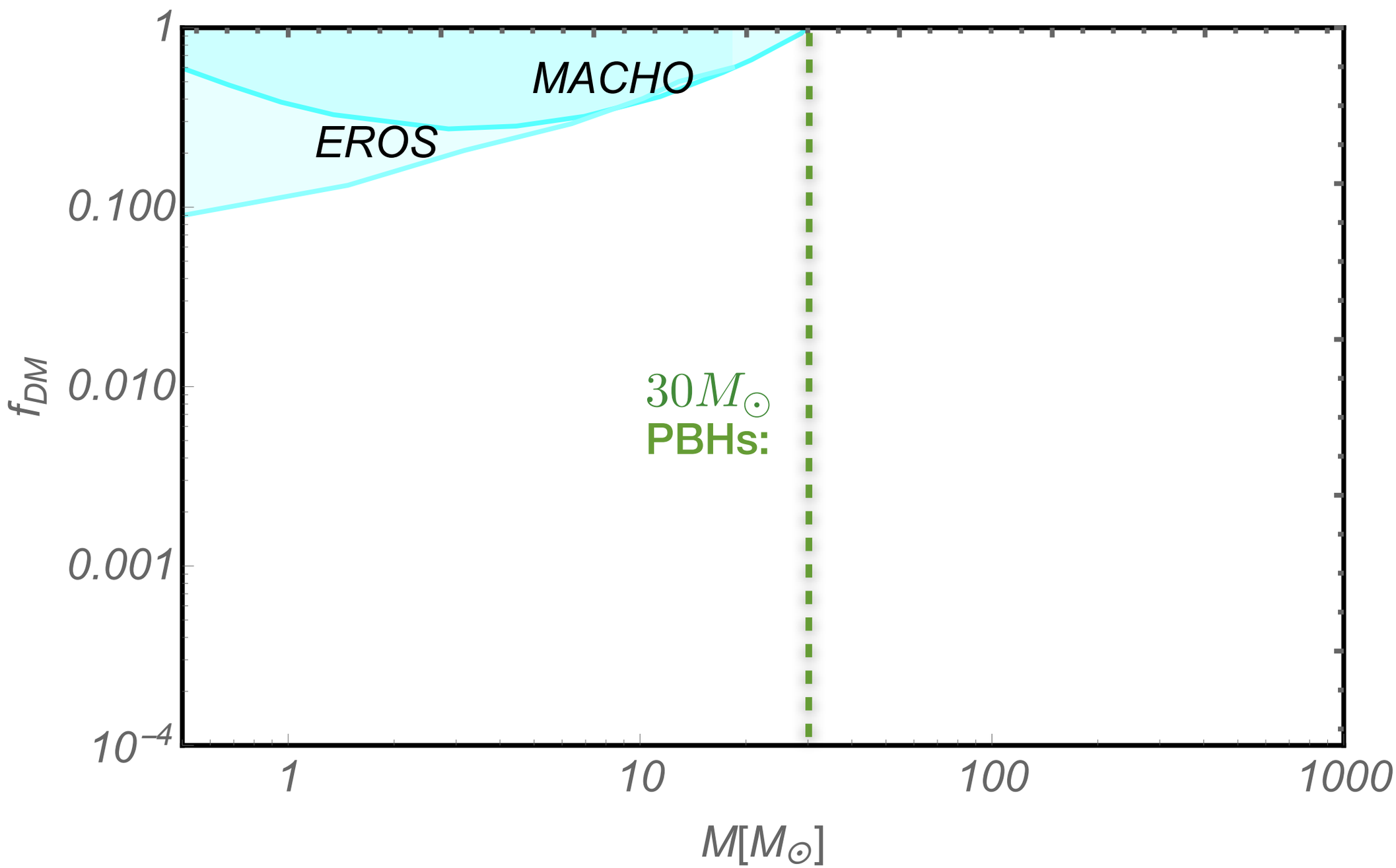

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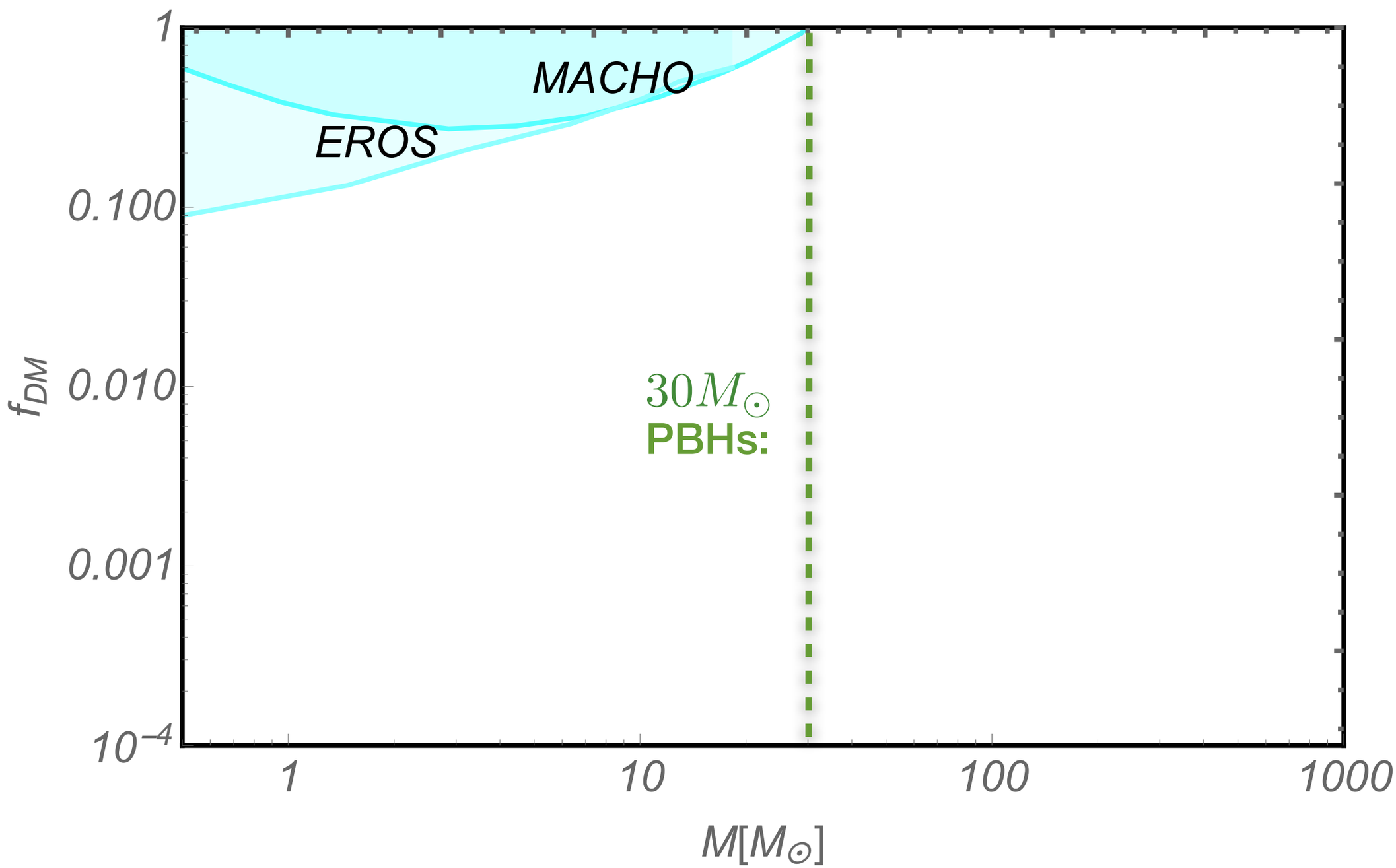
Revisiting wide binary and CMB bounds has opened up a window for PBH DM:



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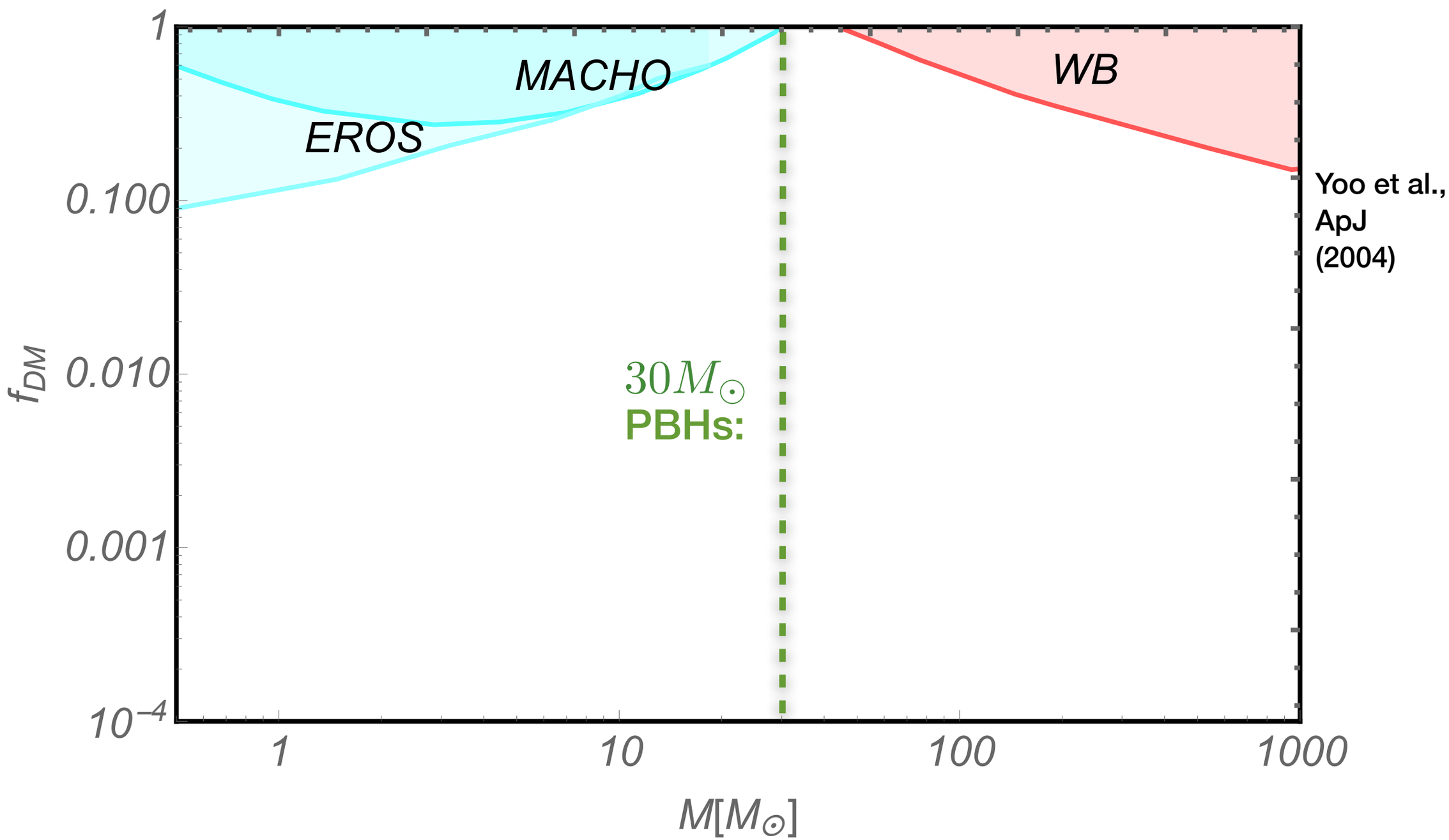

Yoo et al., ApJ (2004)

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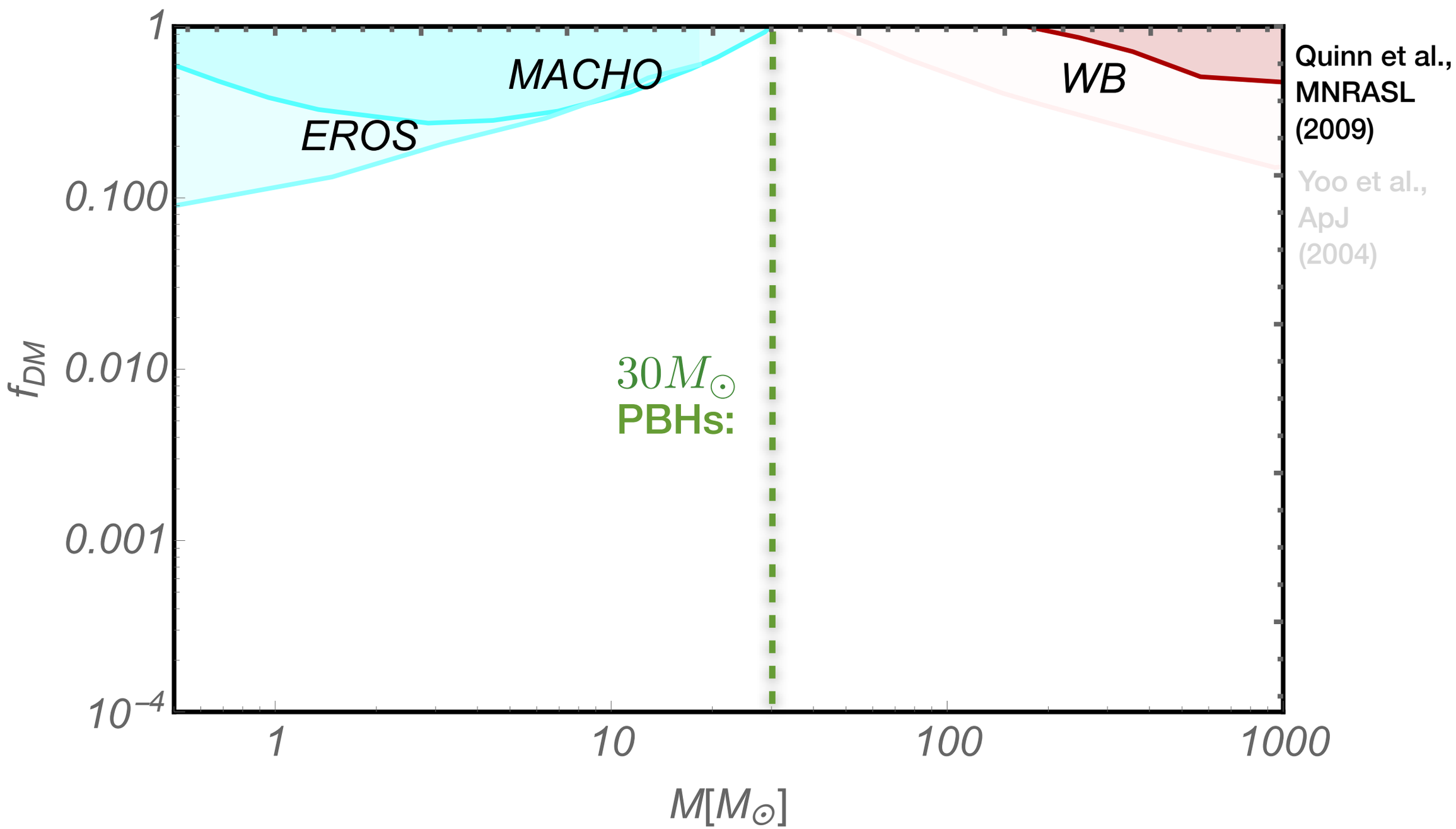

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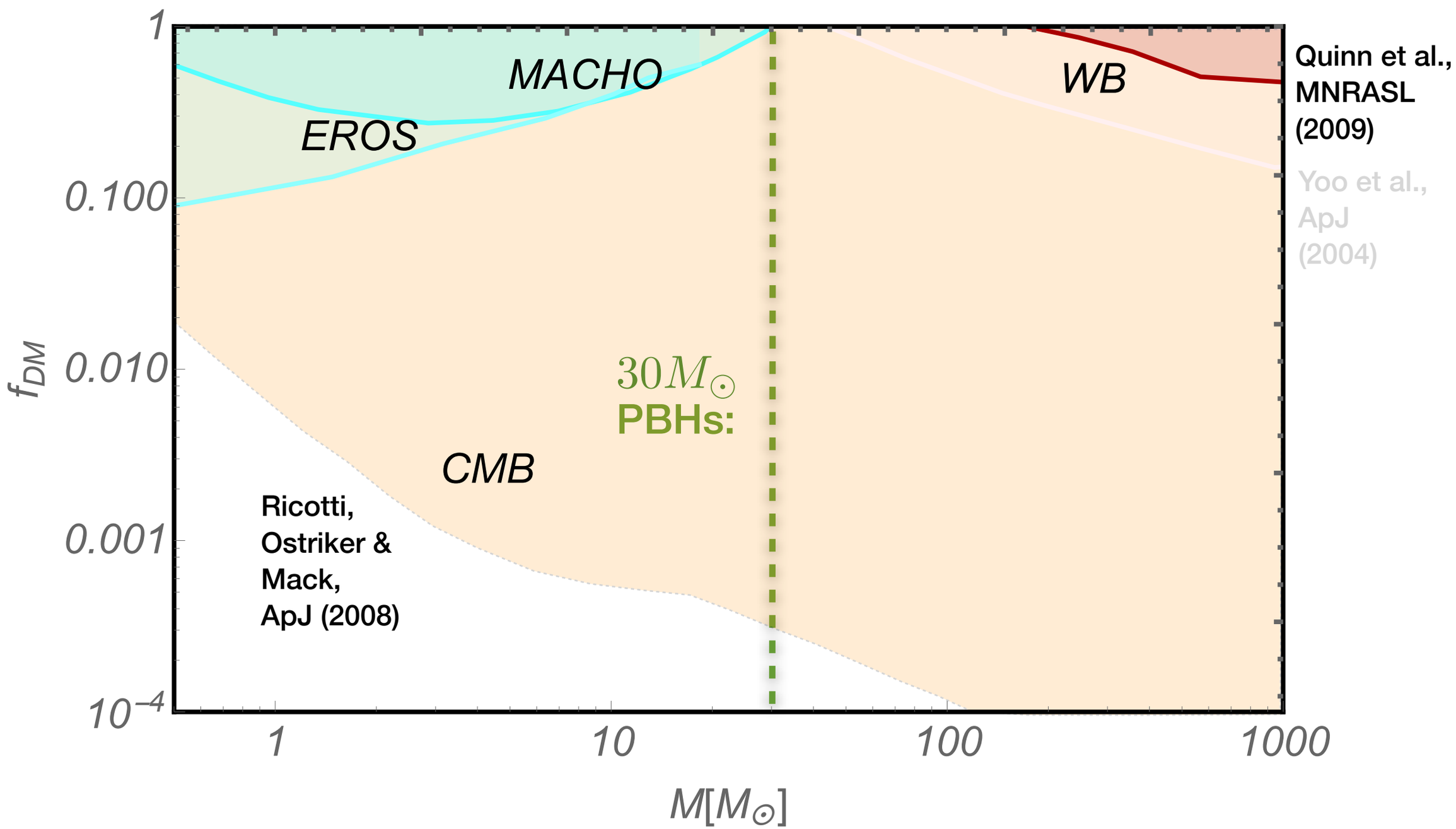

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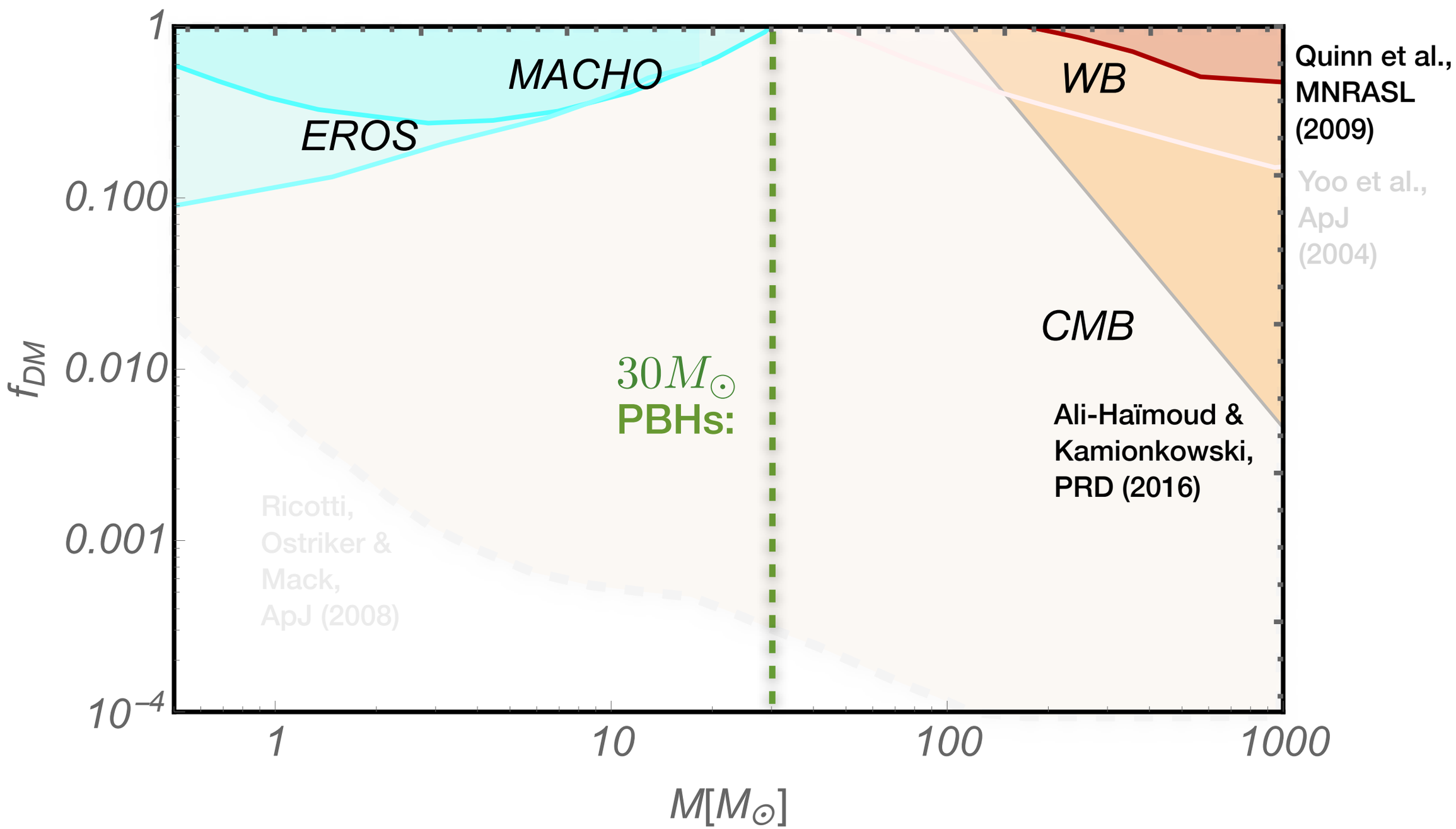

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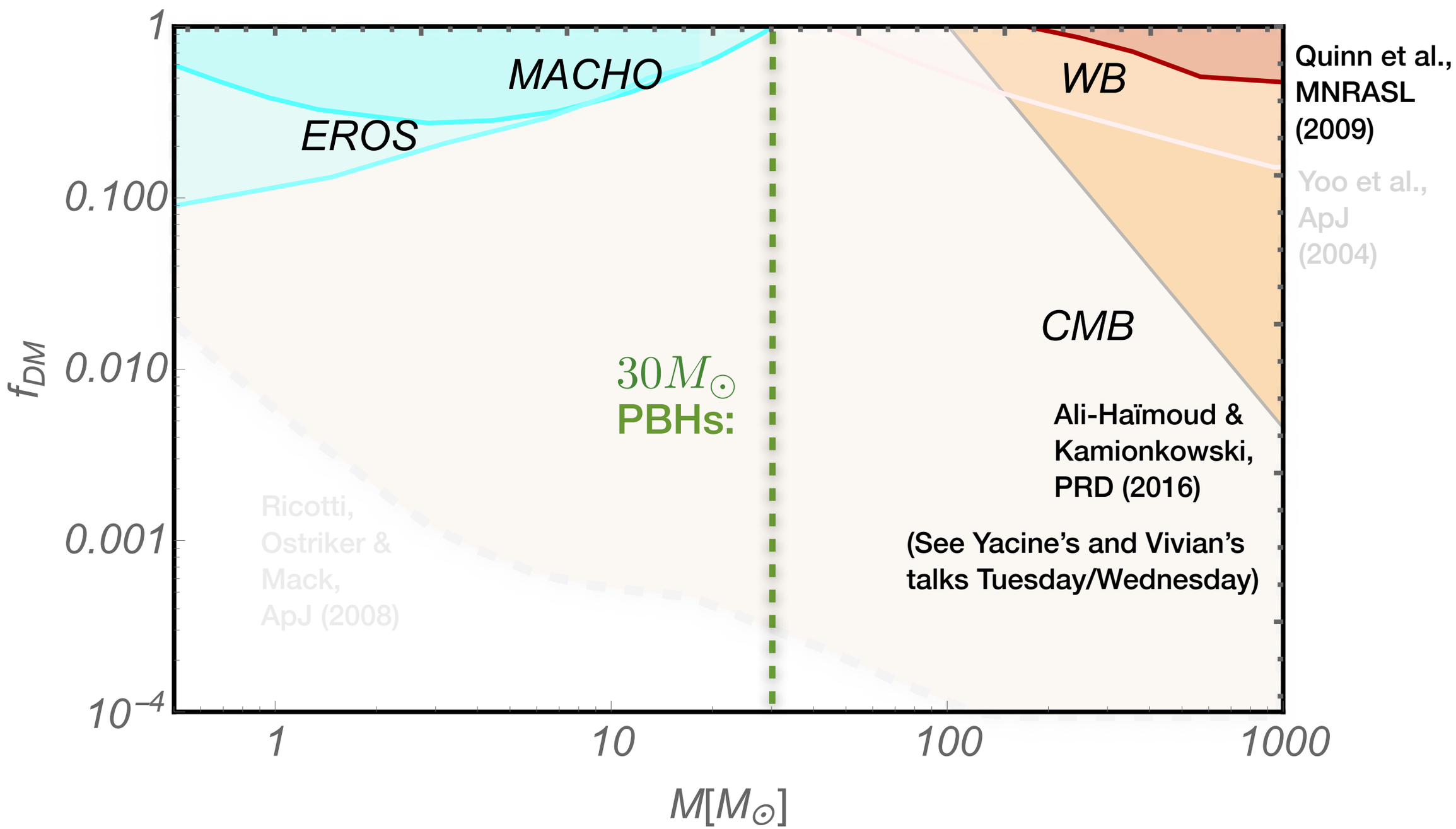

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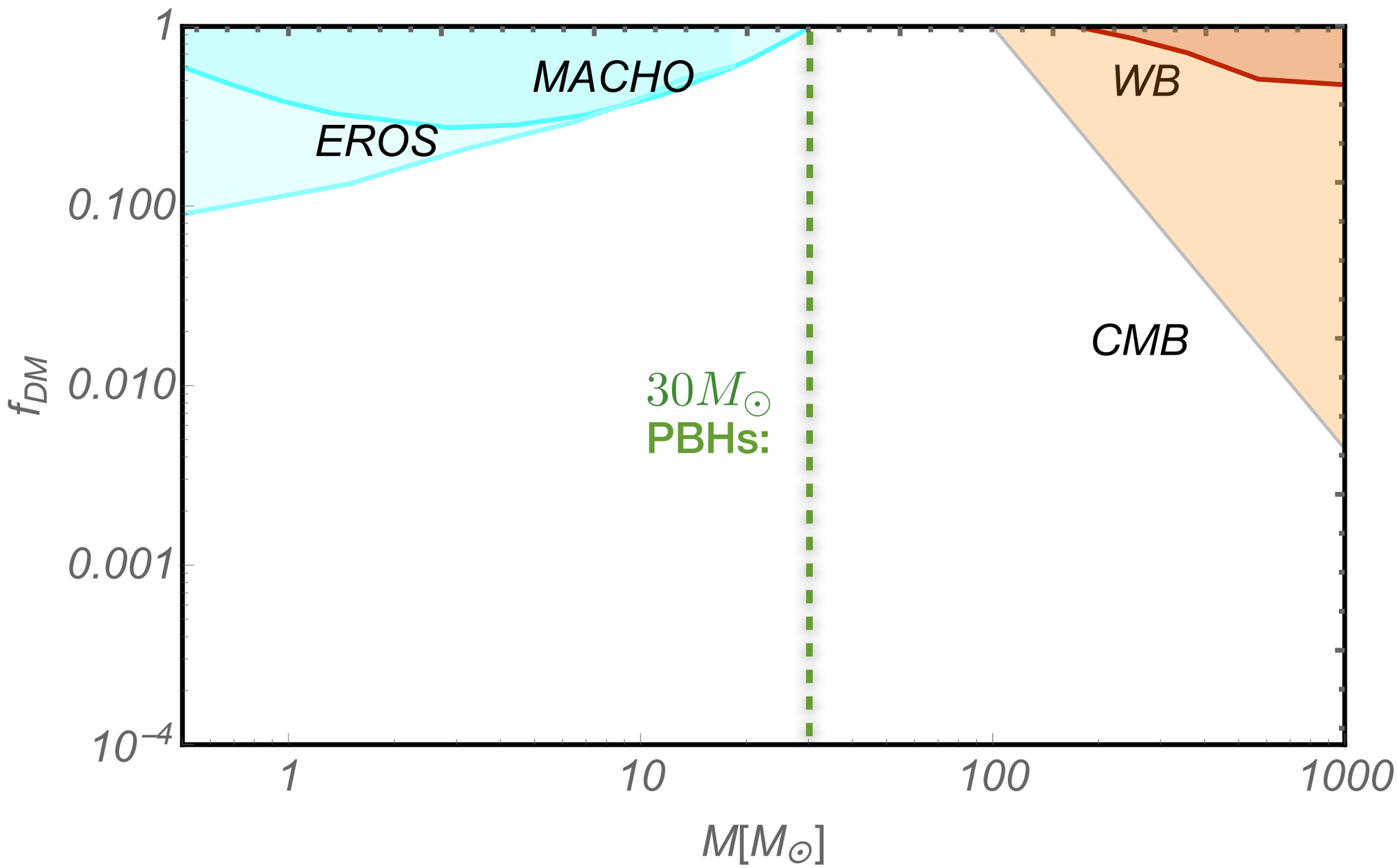

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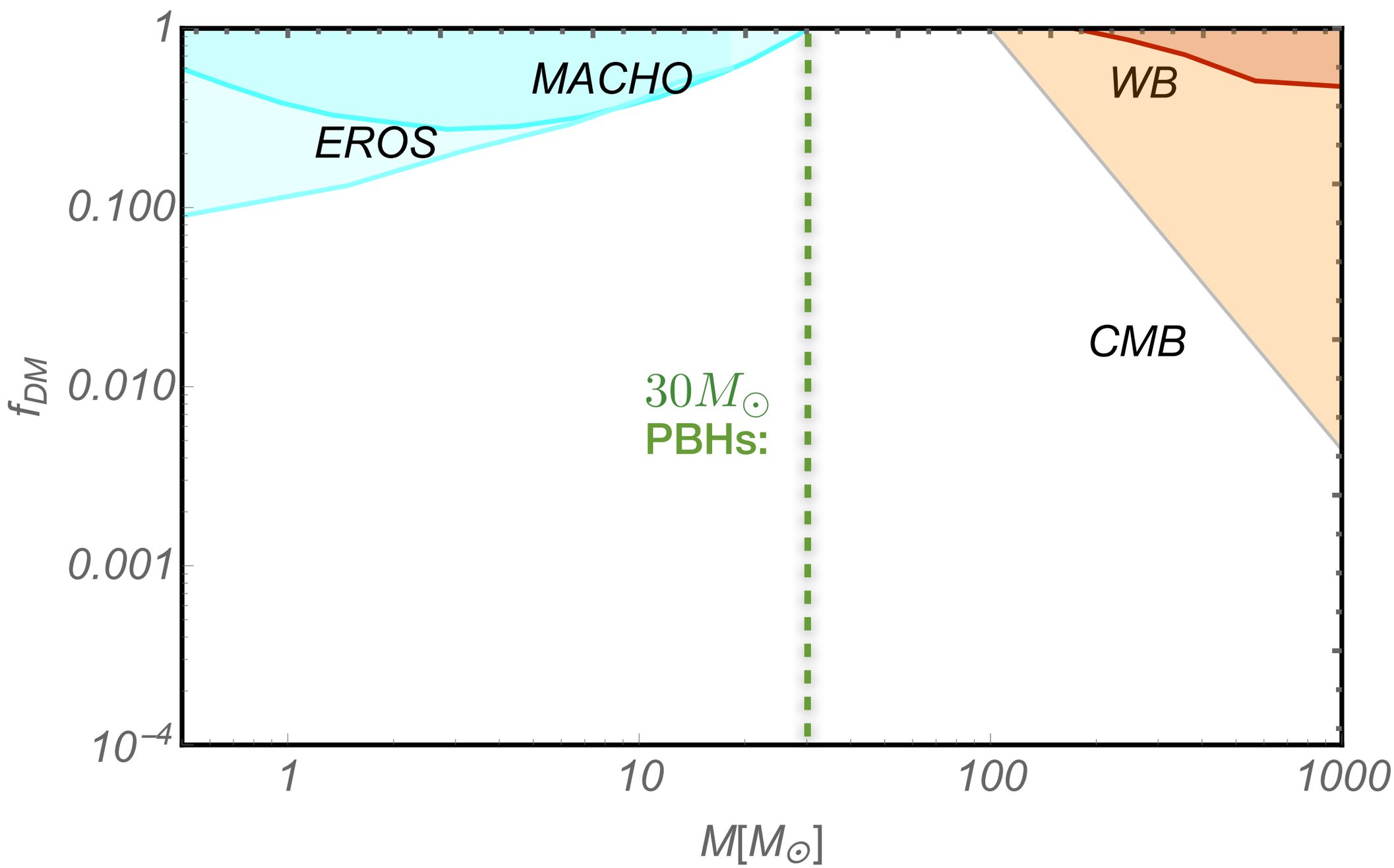
Can we do better than with microlensing of stars?



Fast Radio Bursts!

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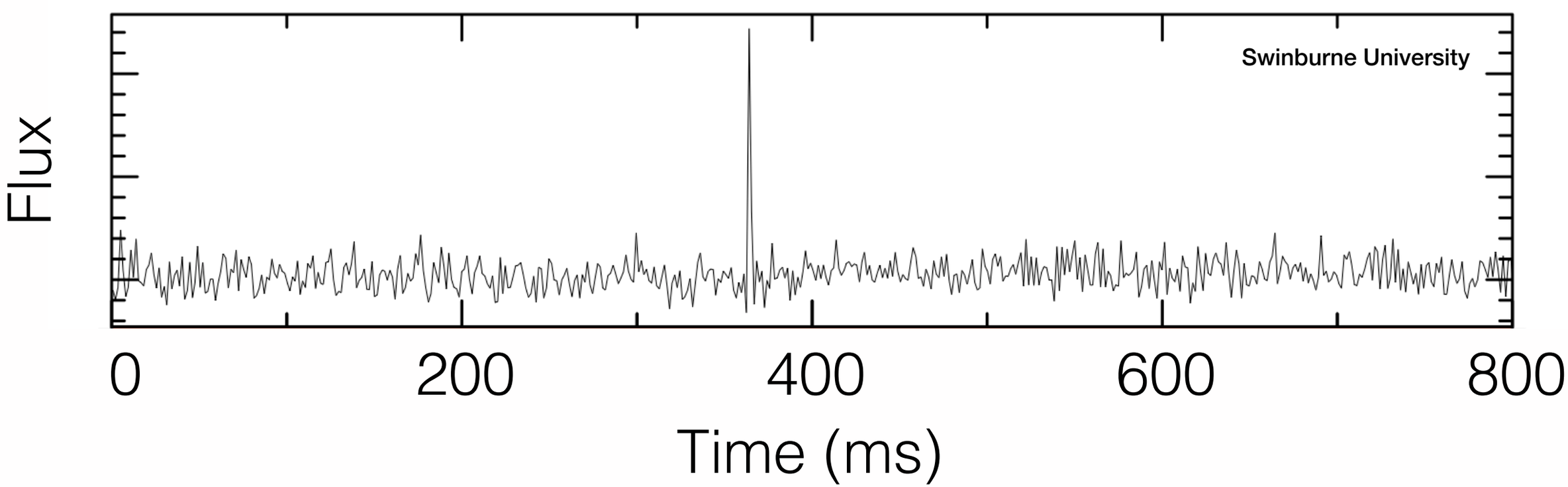

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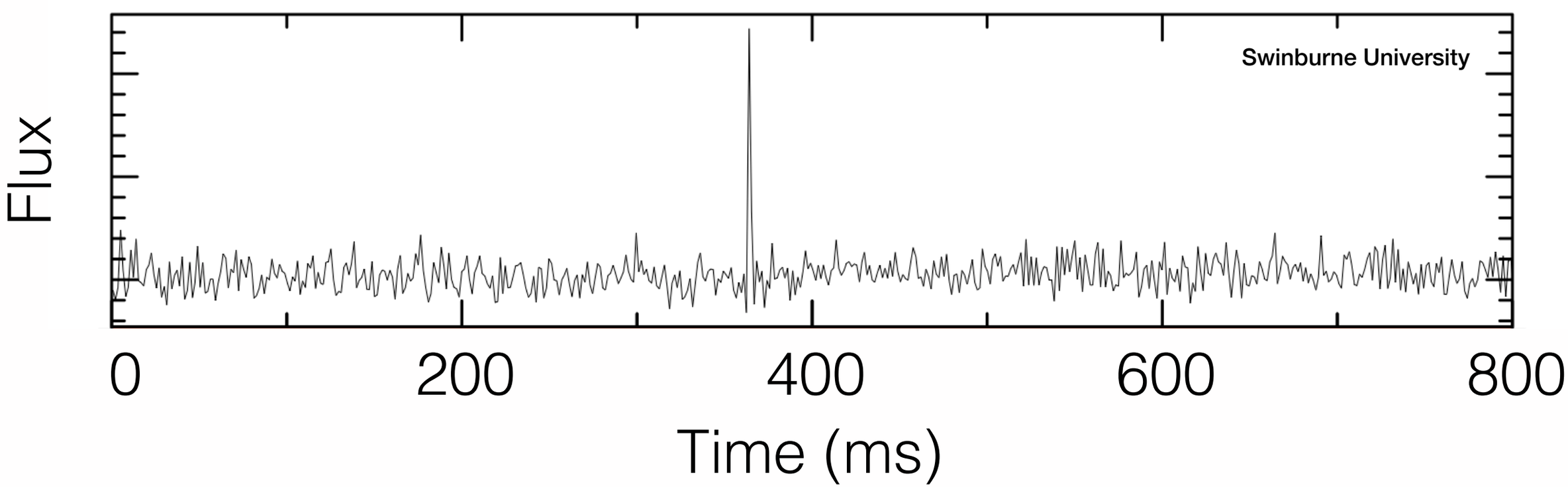

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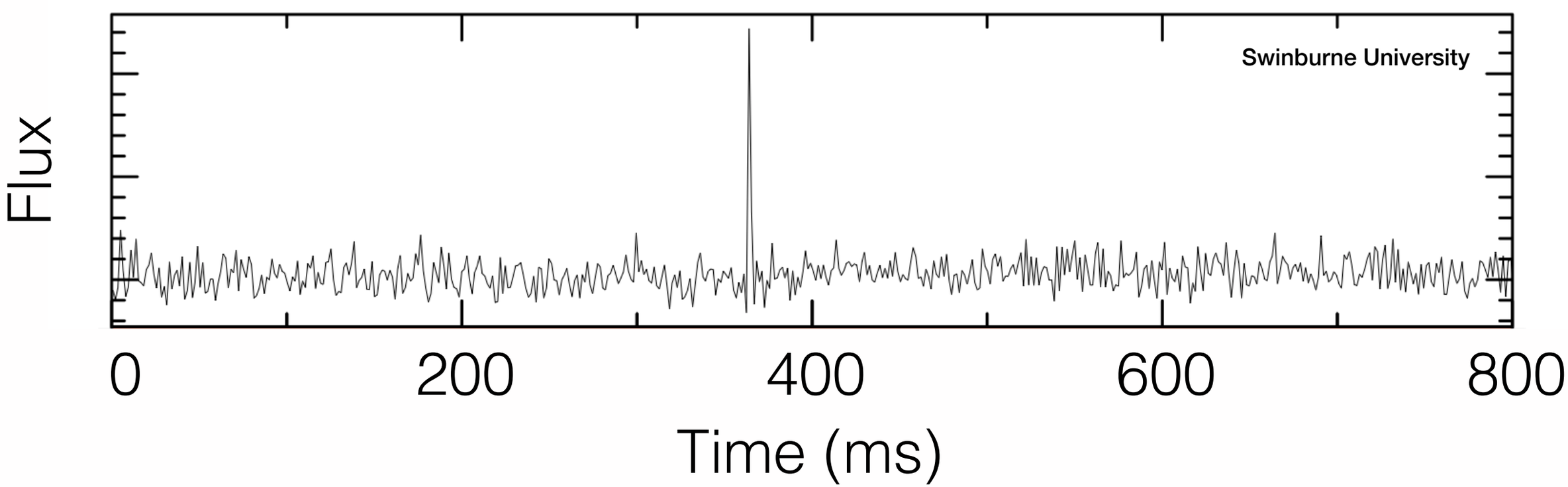

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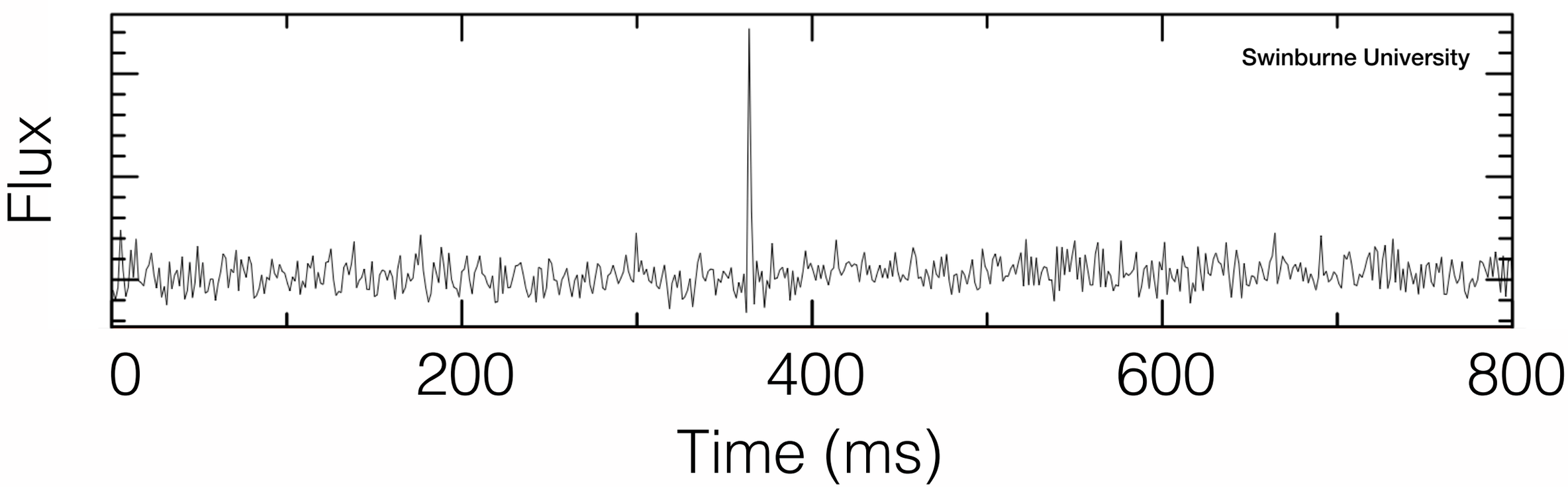

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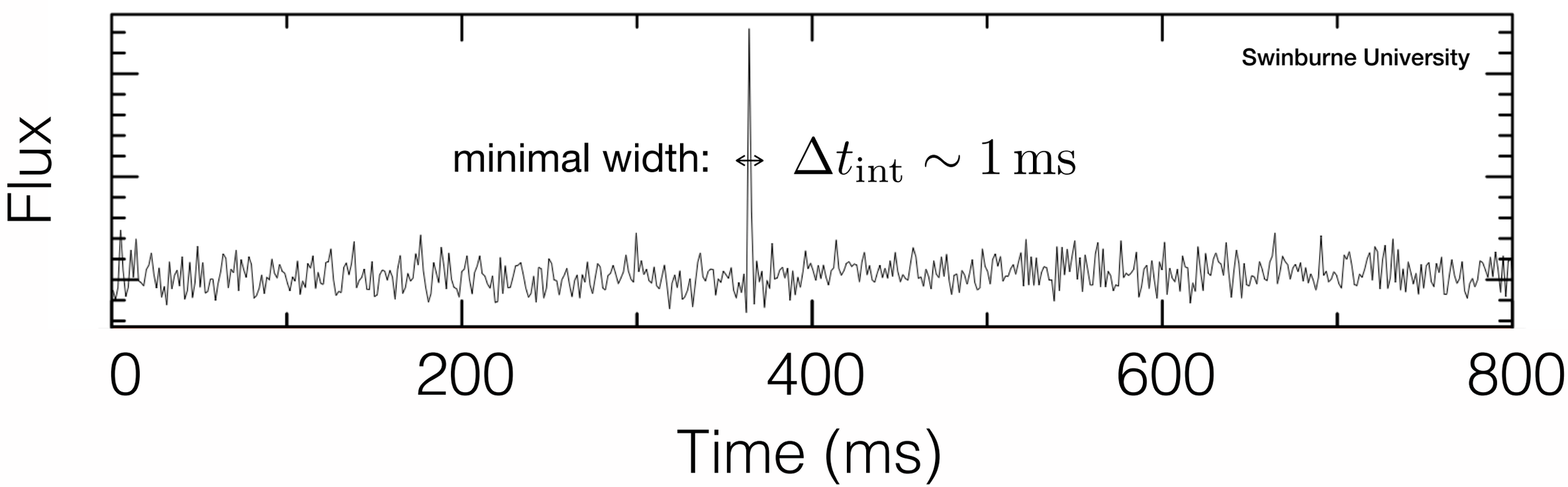

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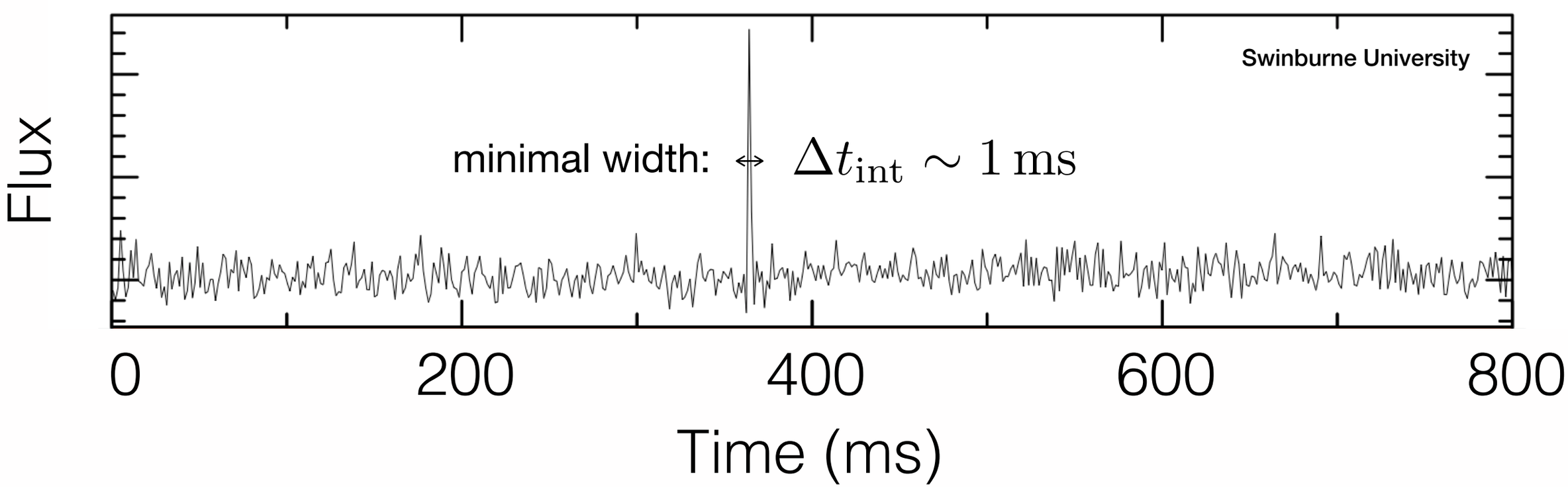

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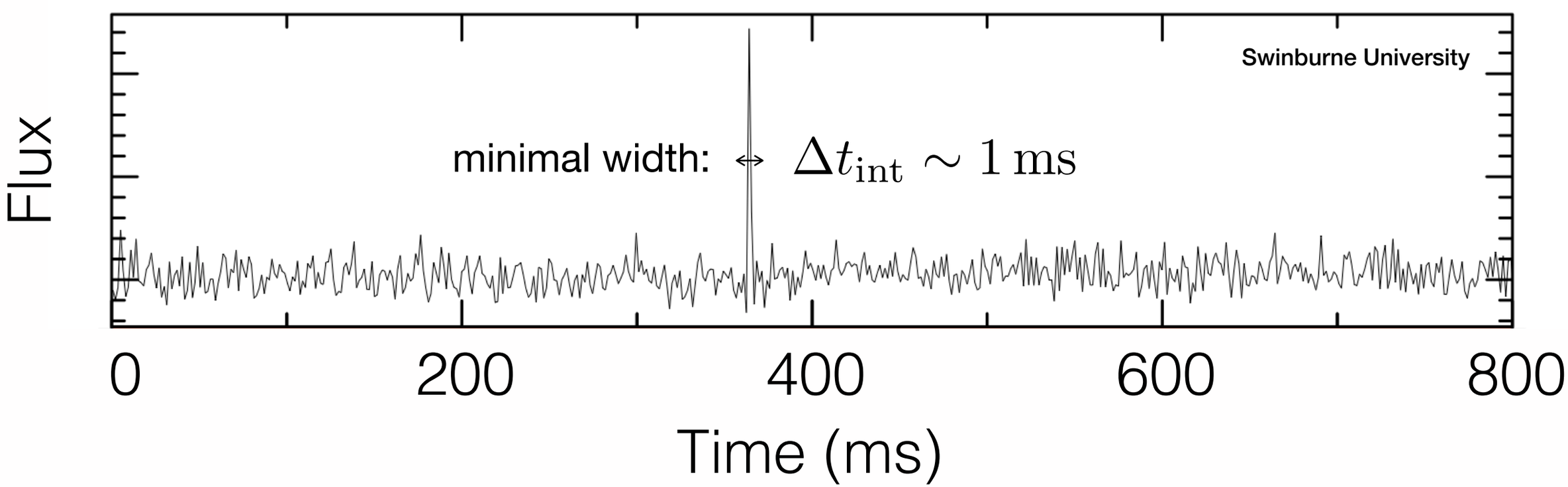

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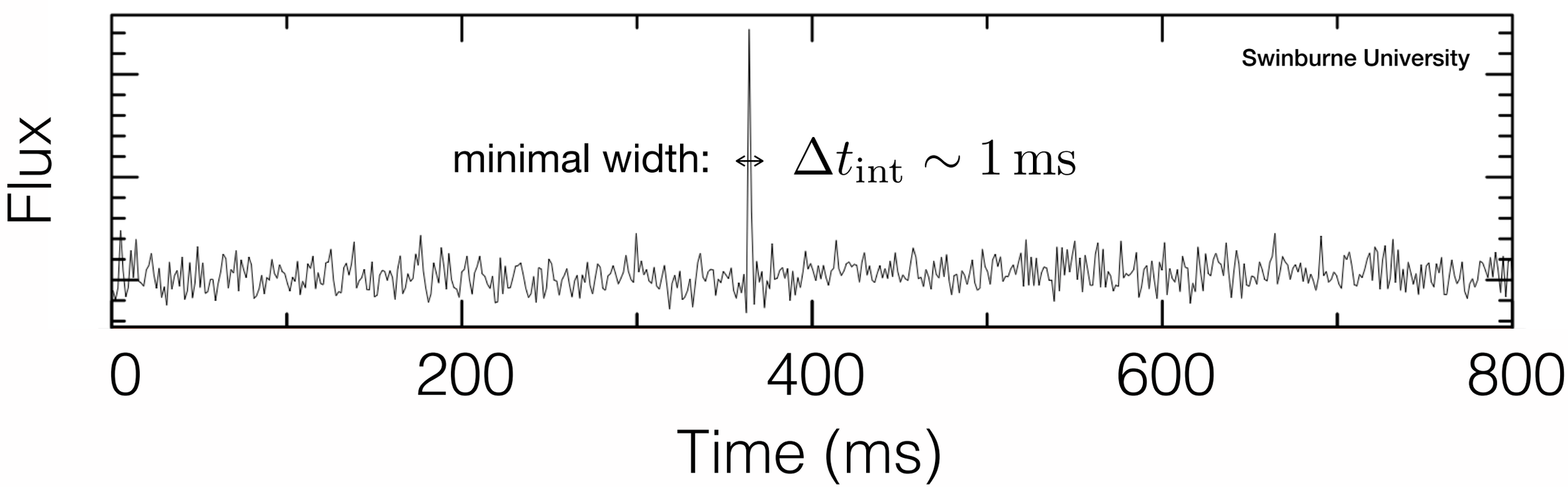

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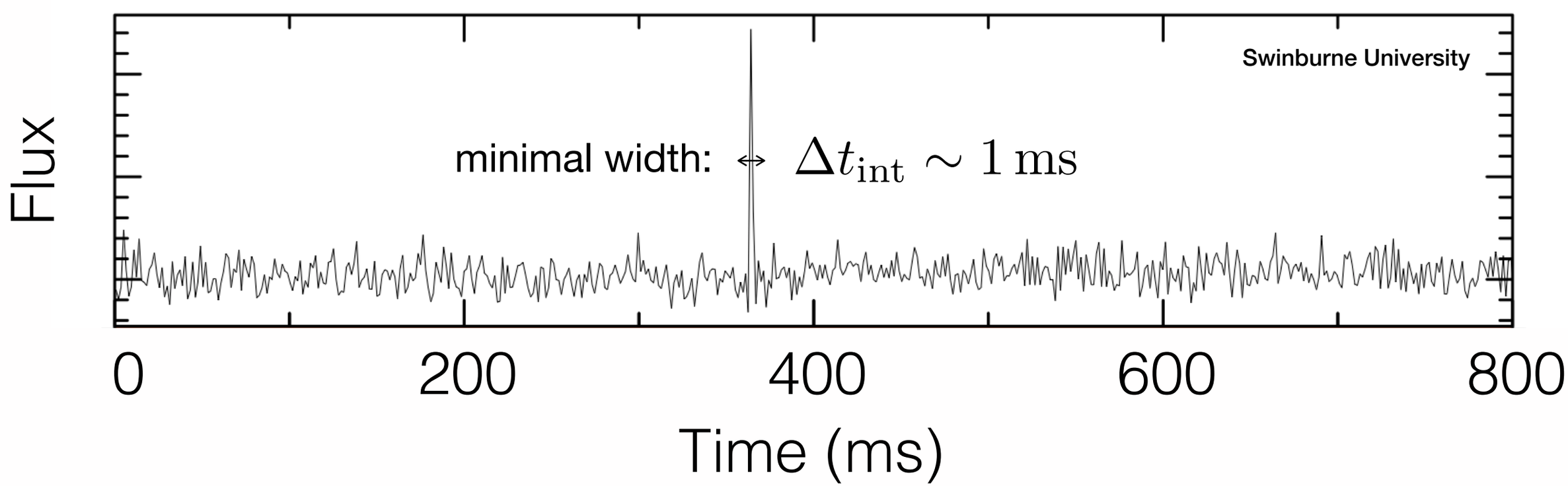

Fast Radio Bursts!

What are they?

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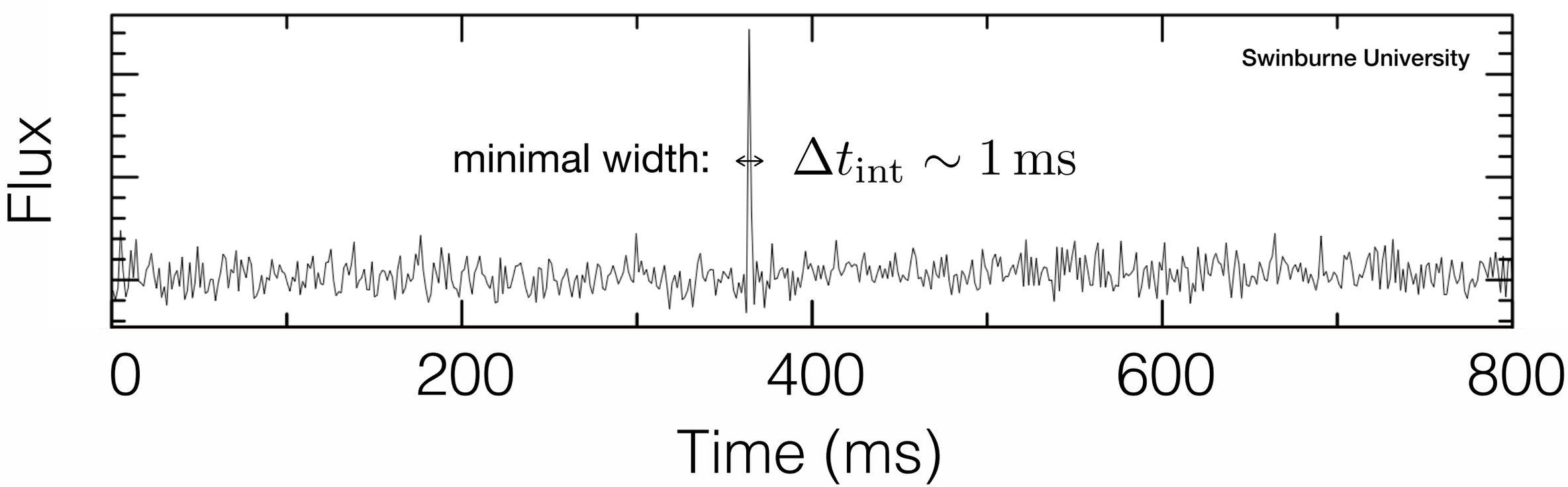

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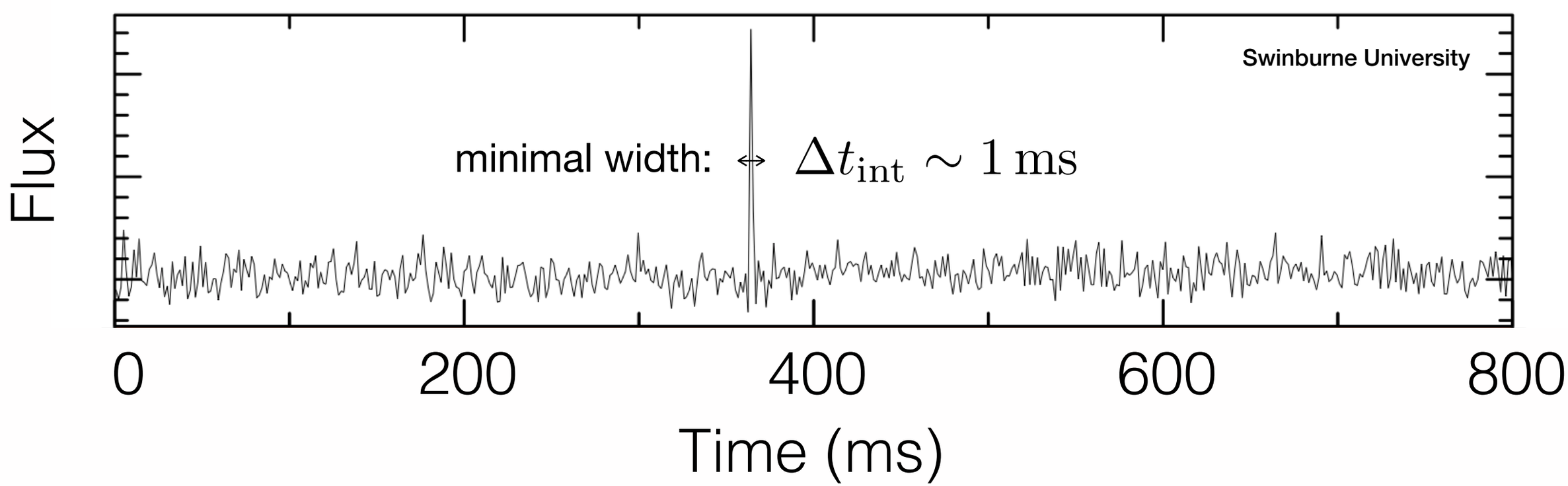
- Estimated rate: $\mathcal{O}(10^4)\ \mathrm{sky}^{-1}\mathrm{day}^{-1}$ (still based on handful observed)



Constraining MACHOs: Fast Radio Burst Lensing

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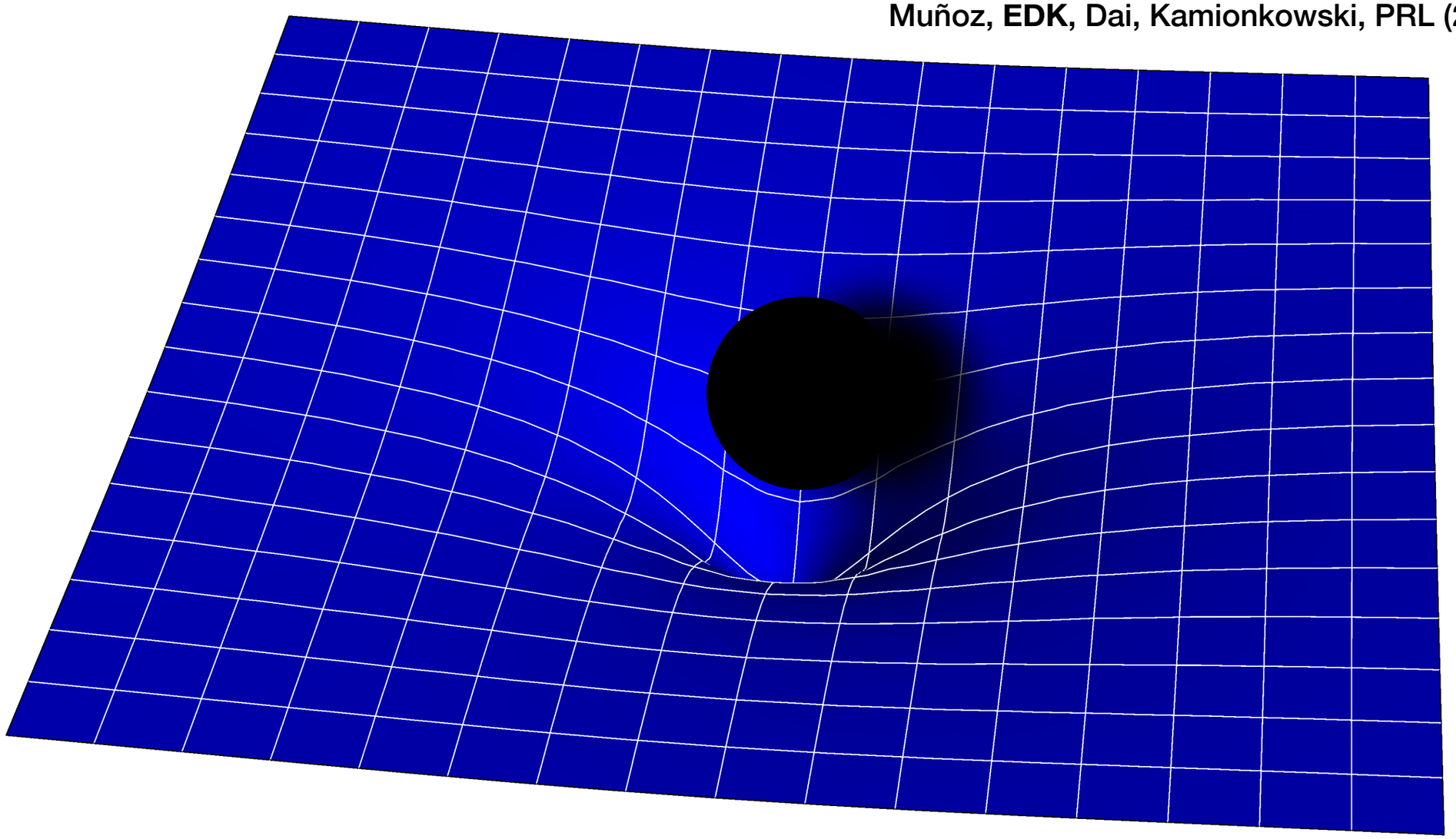
Muñoz, **EDK**, Dai, Kamionkowski, PRL (2016)



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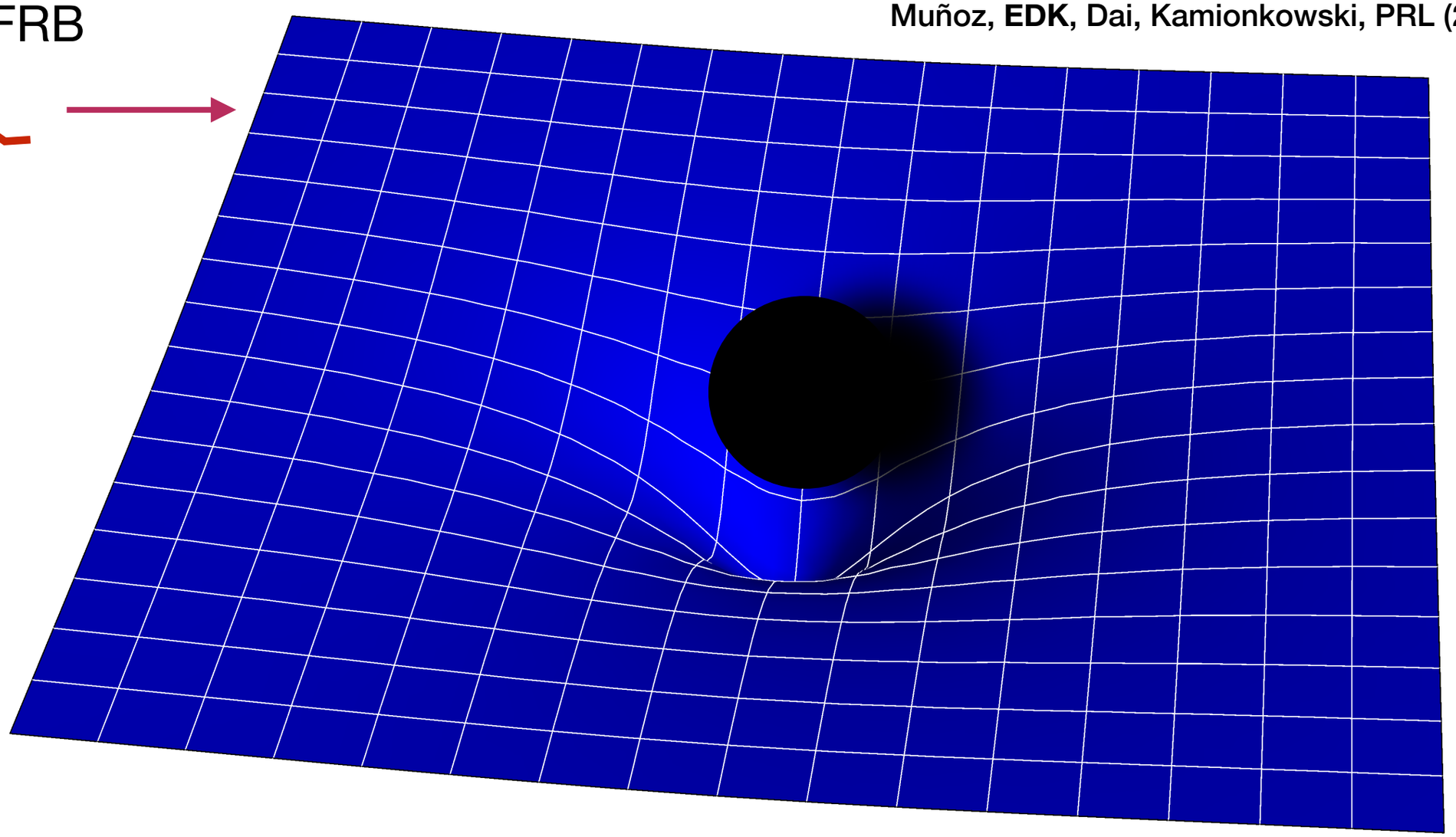
Source FRB

Muñoz, **EDK**, Dai, Kamionkowski, PRL (2016)



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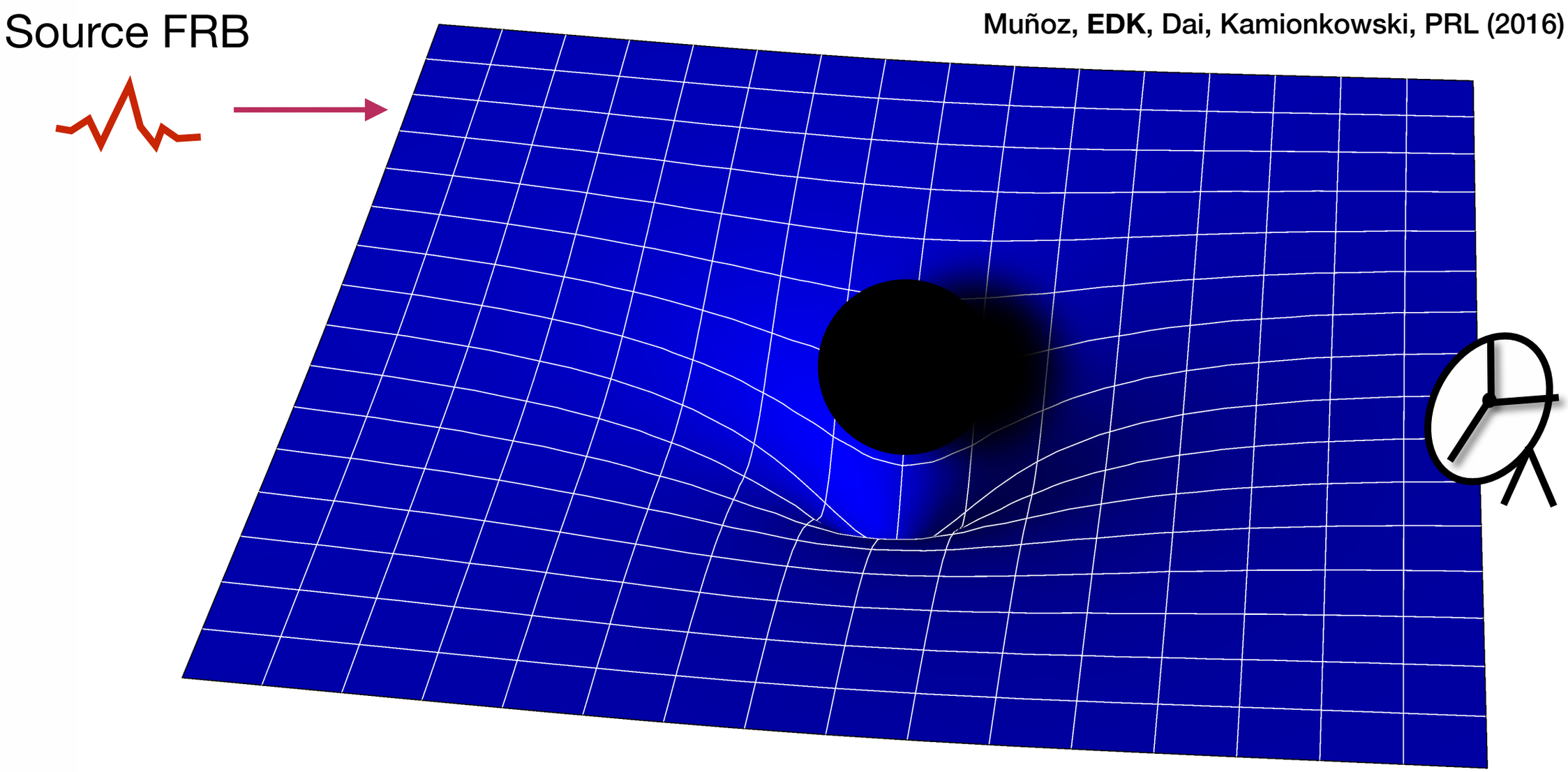

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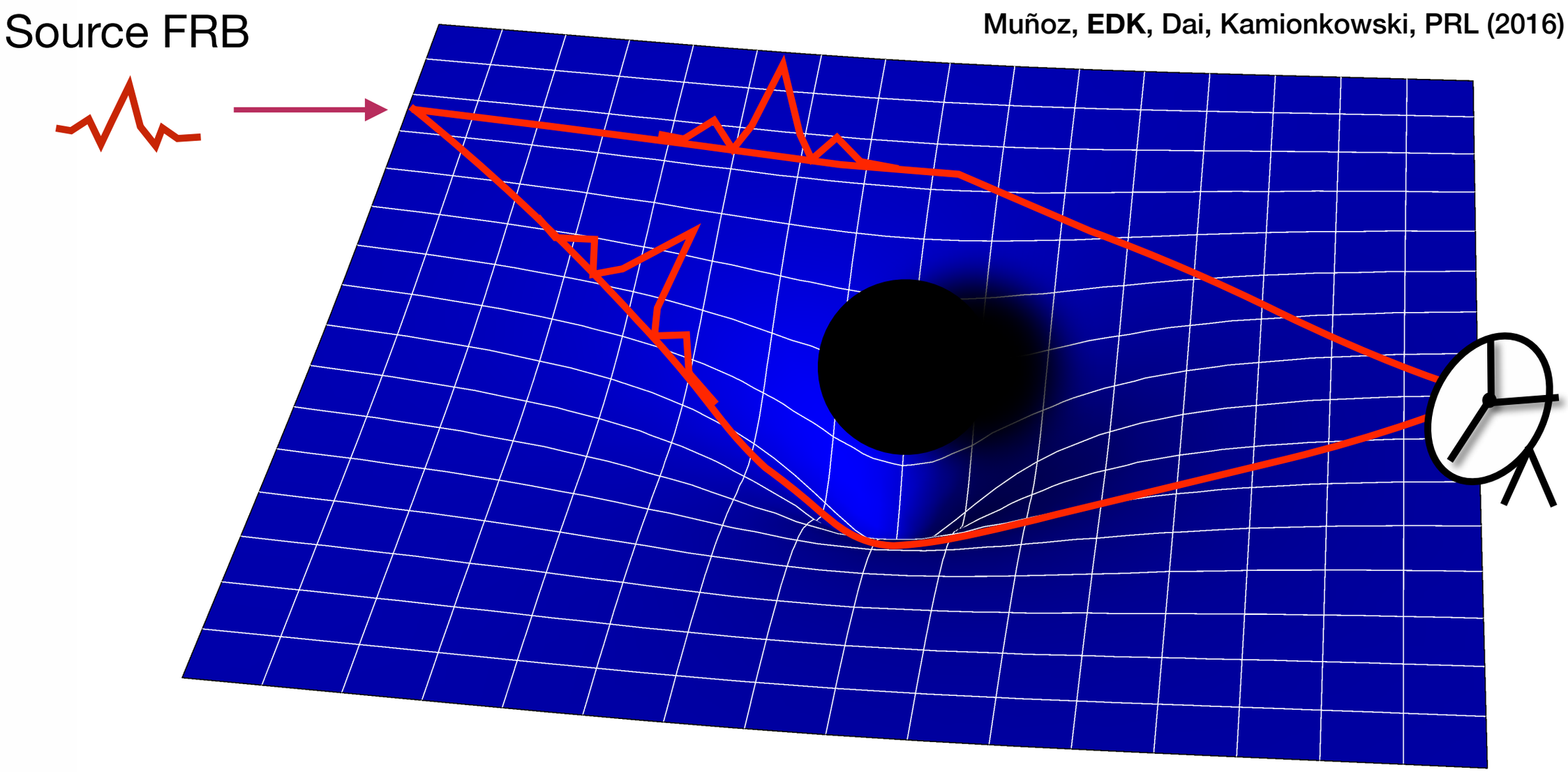

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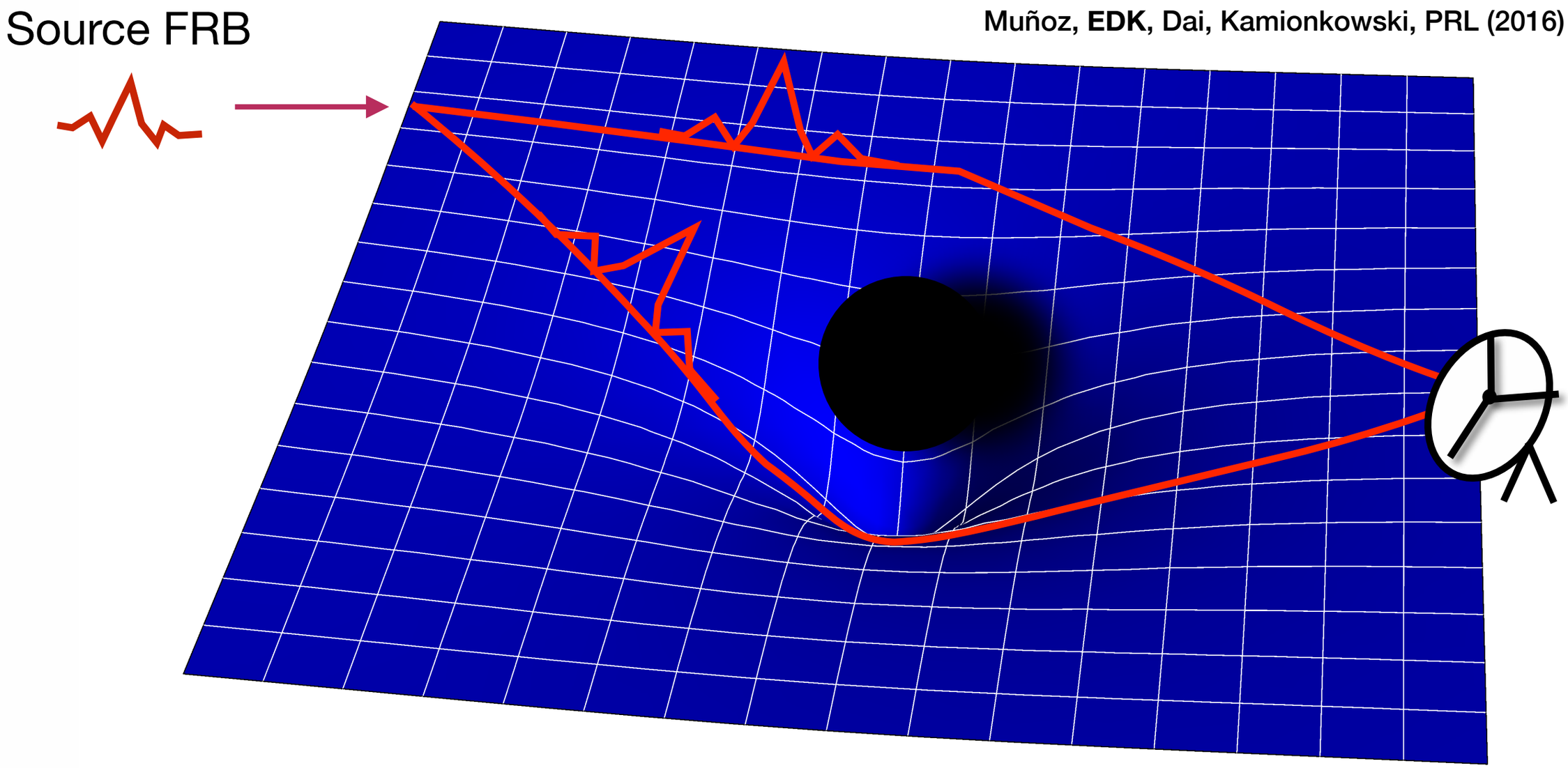

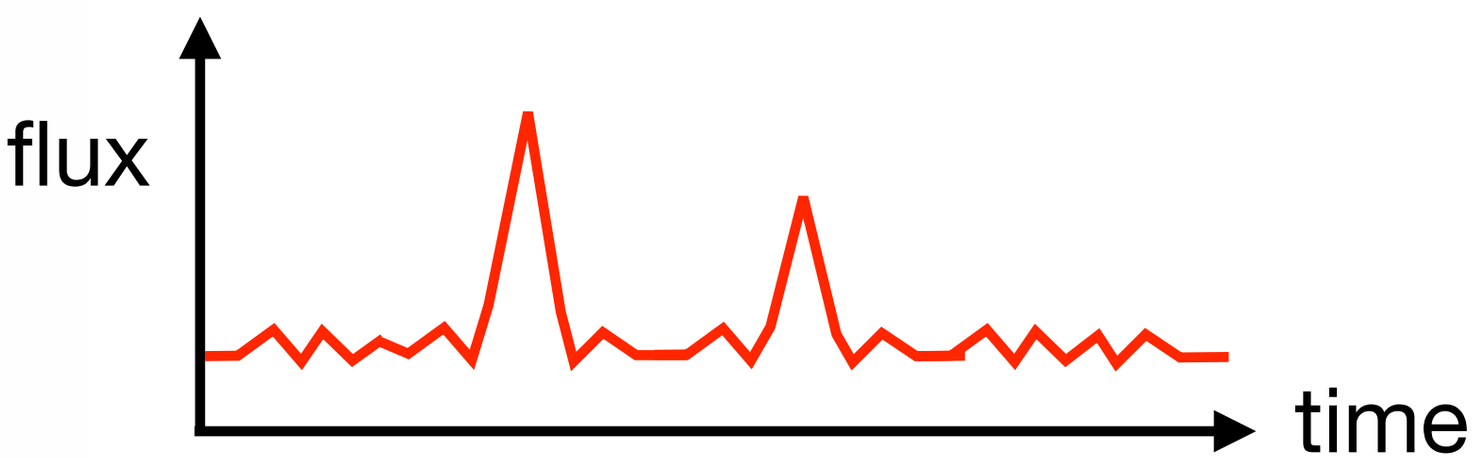

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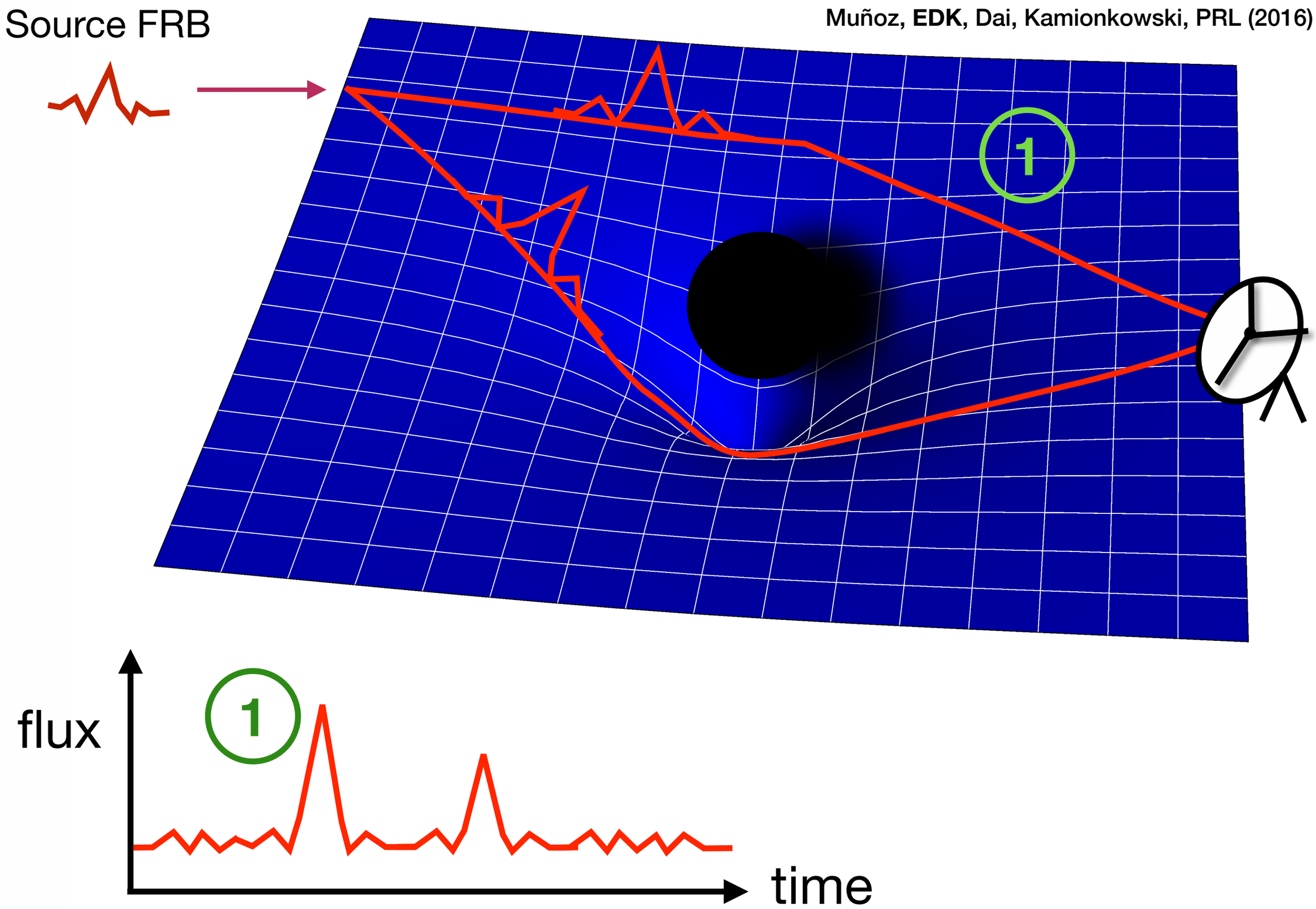

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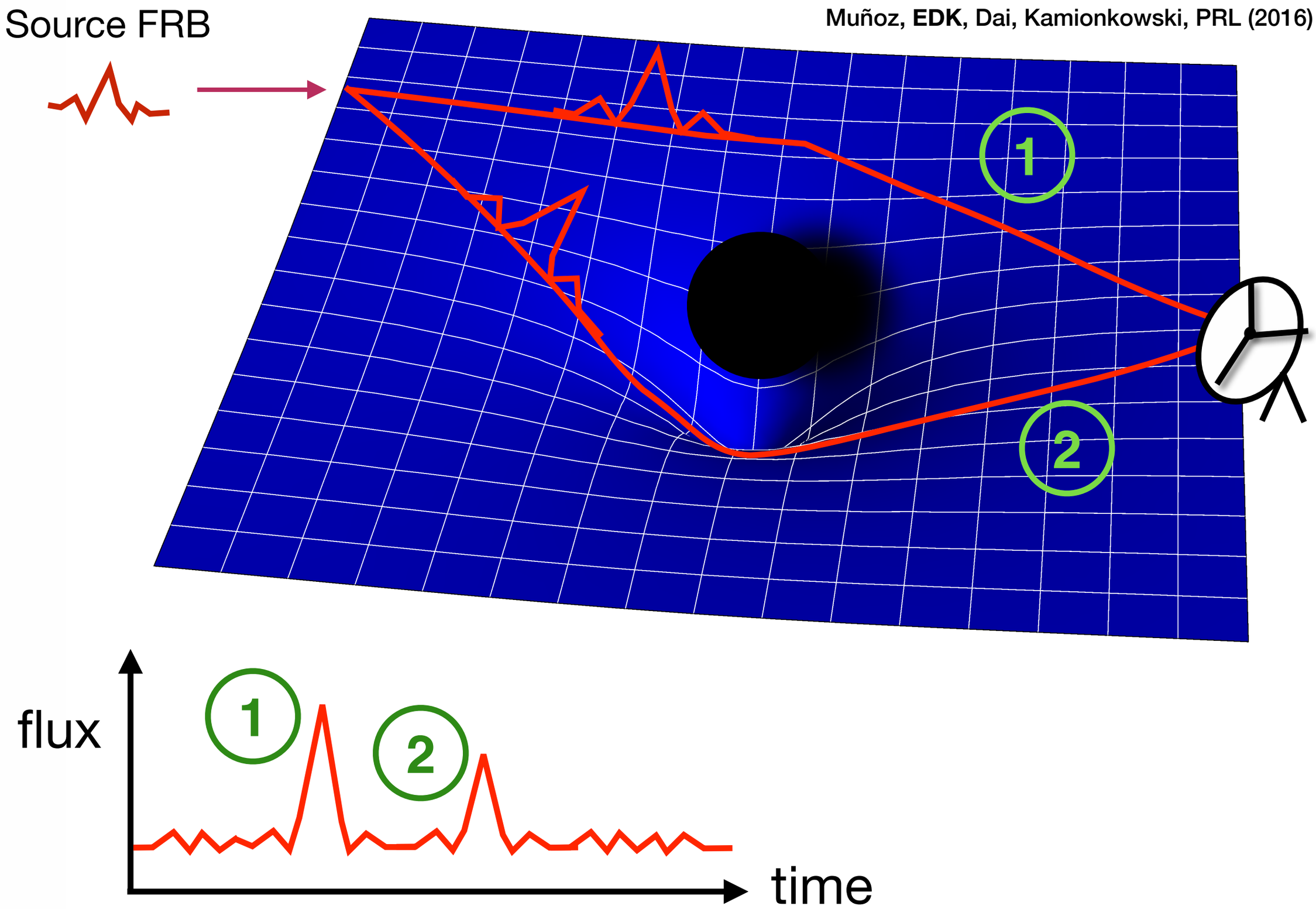

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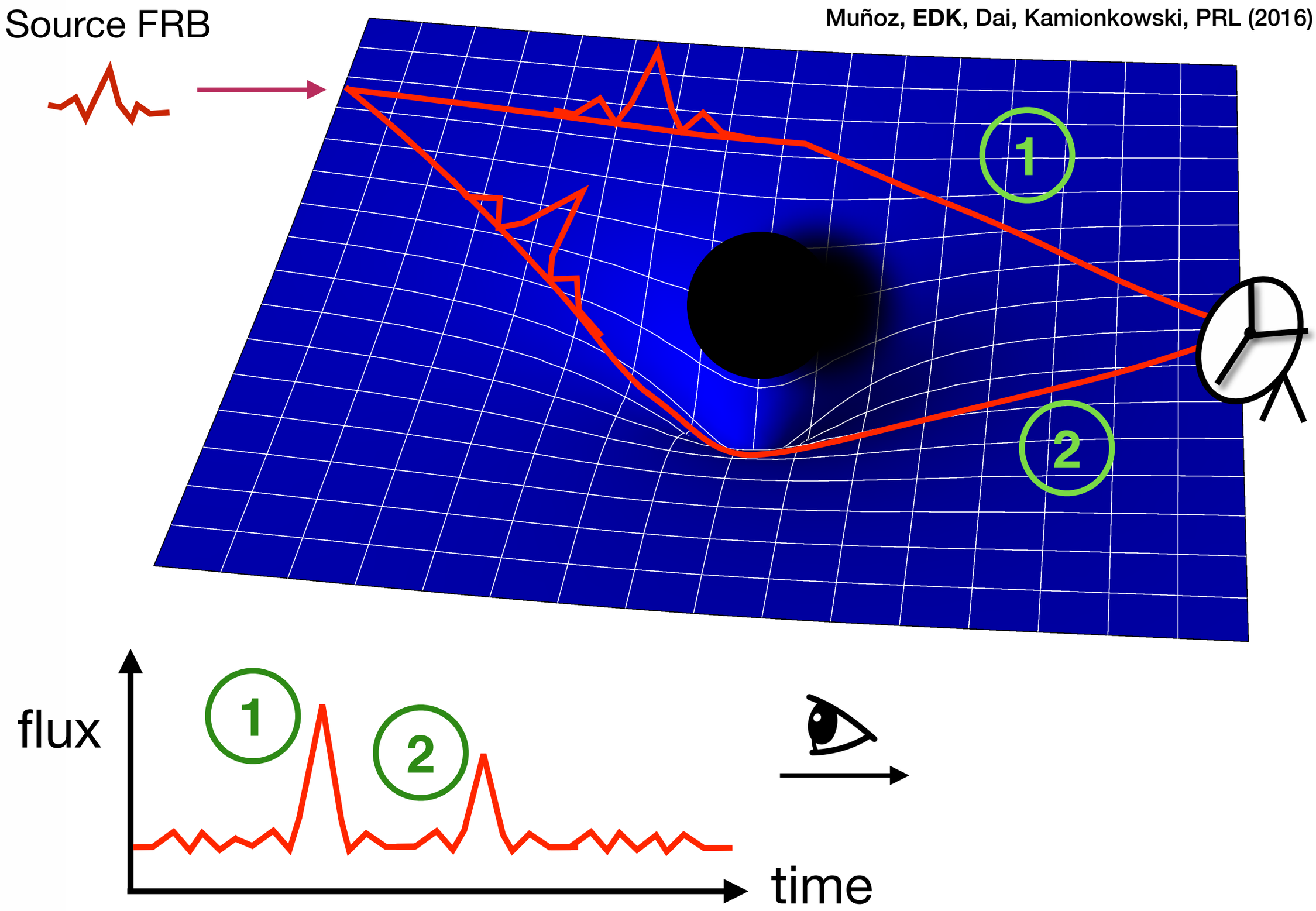

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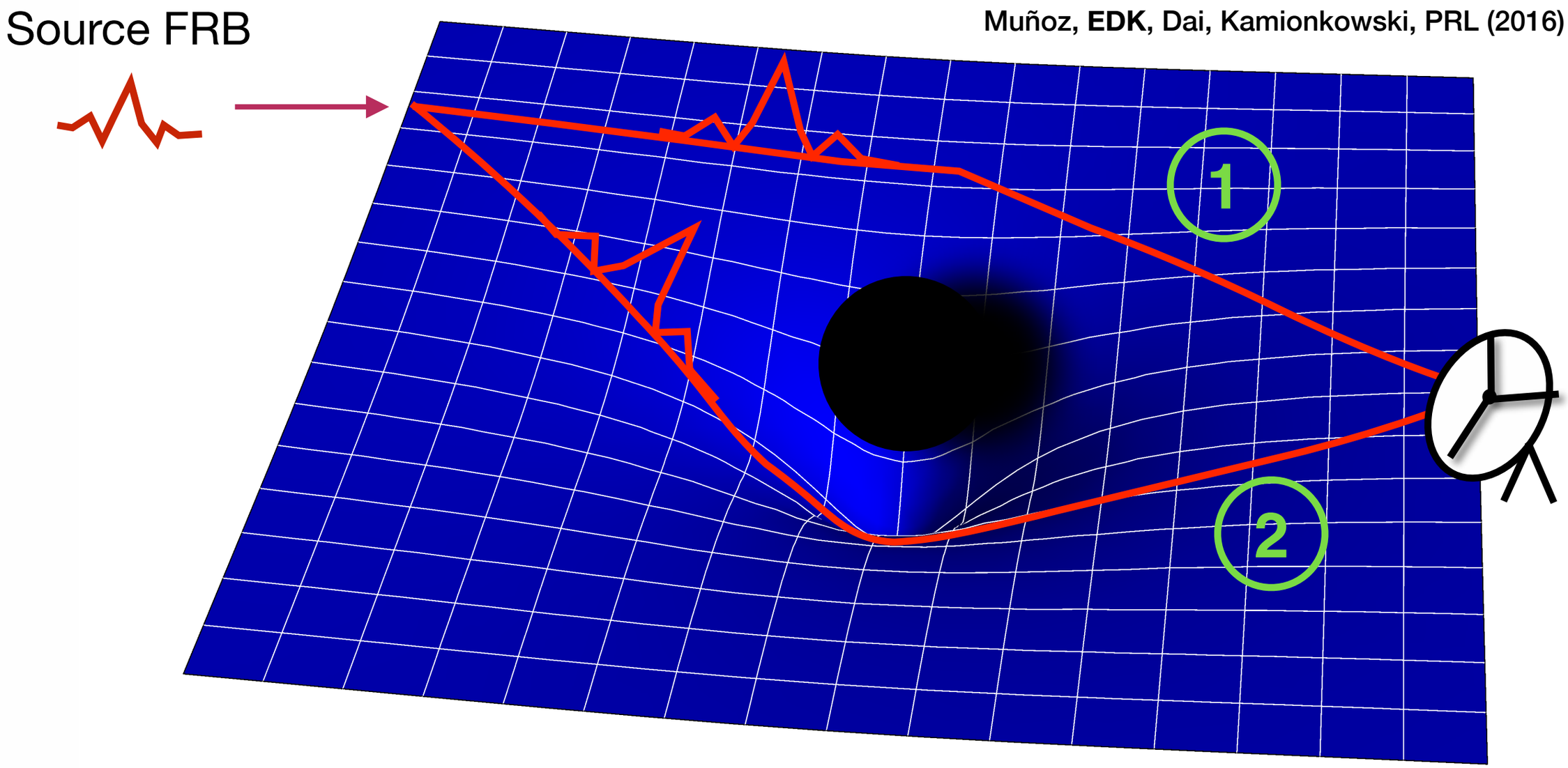

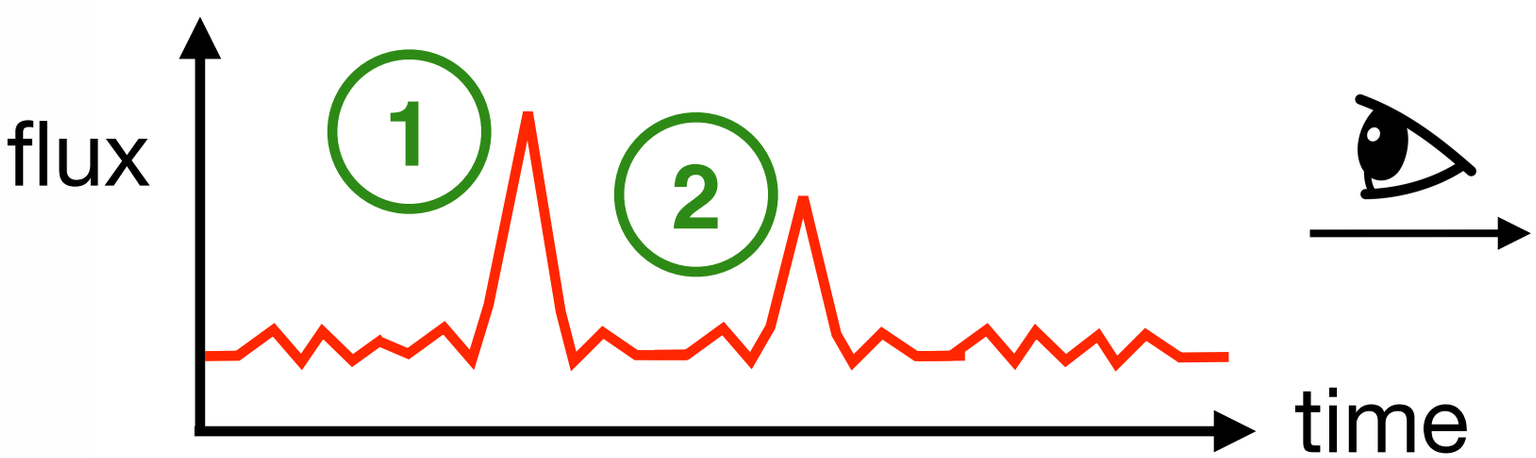

- flux ratio

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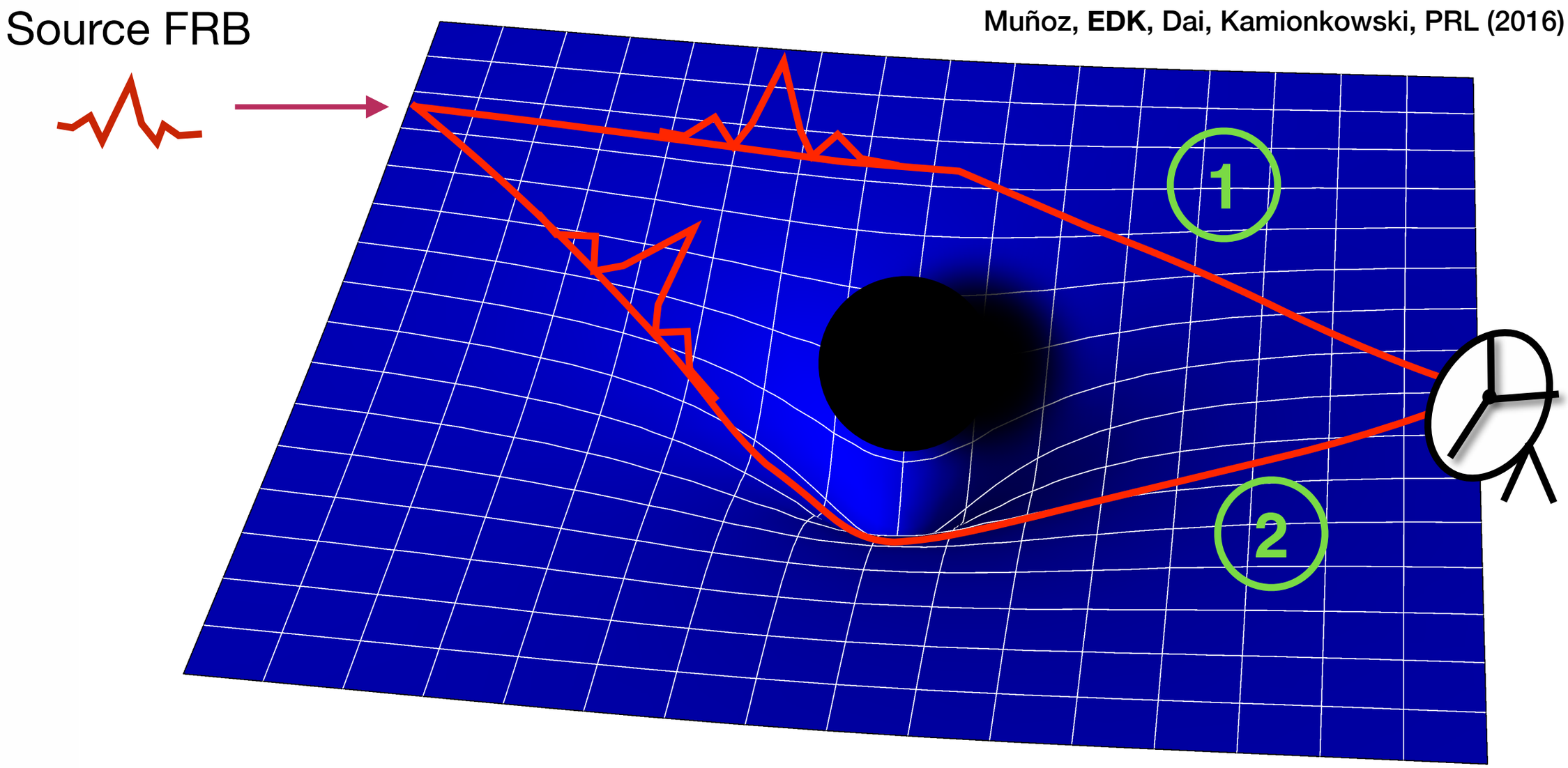

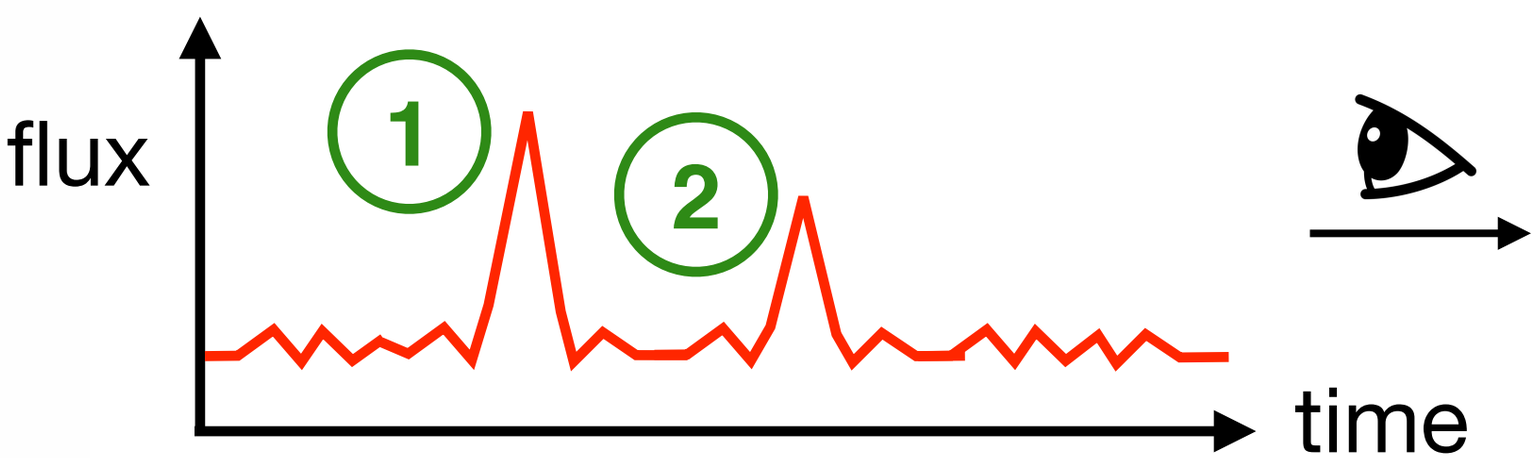

- flux ratio
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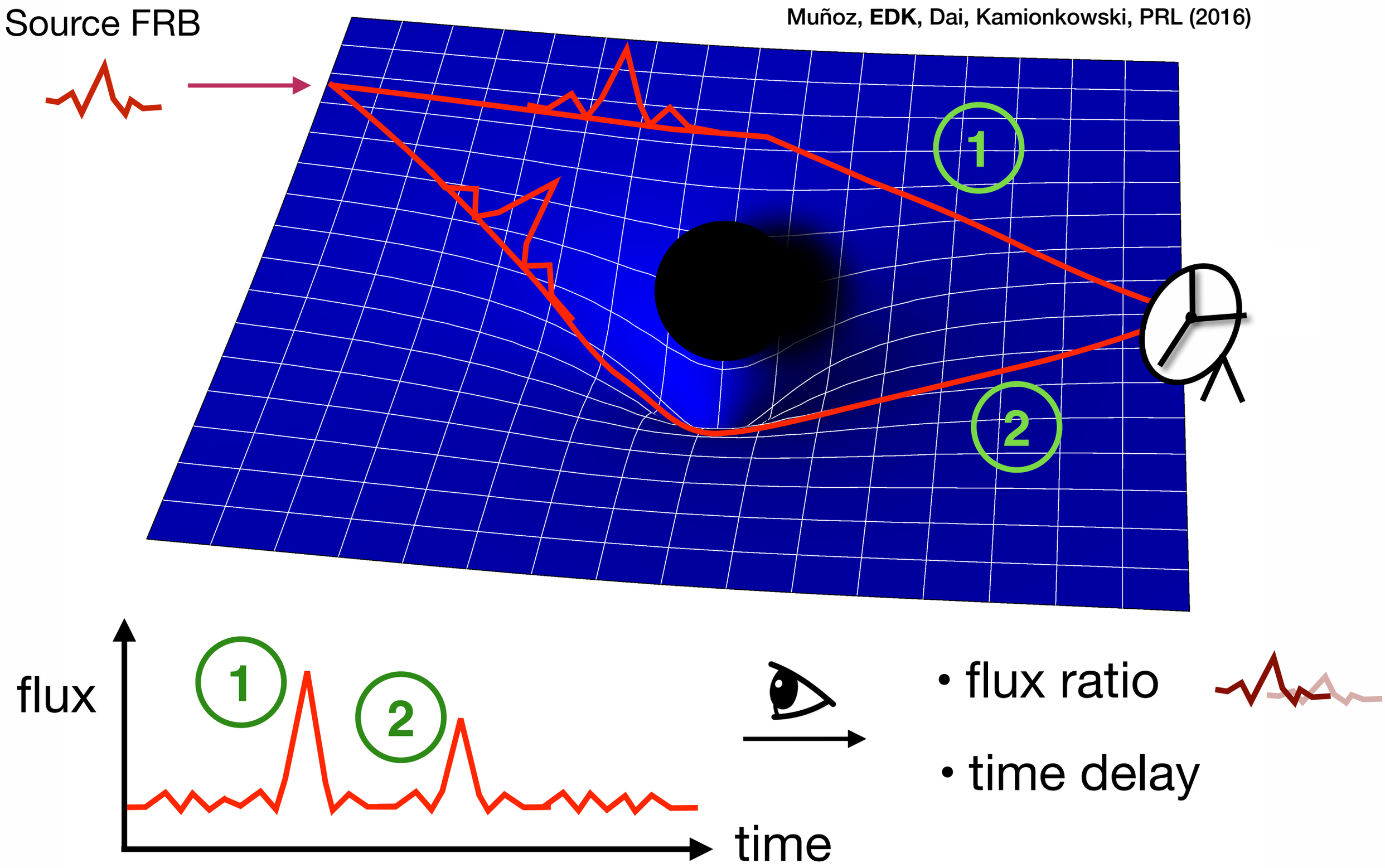

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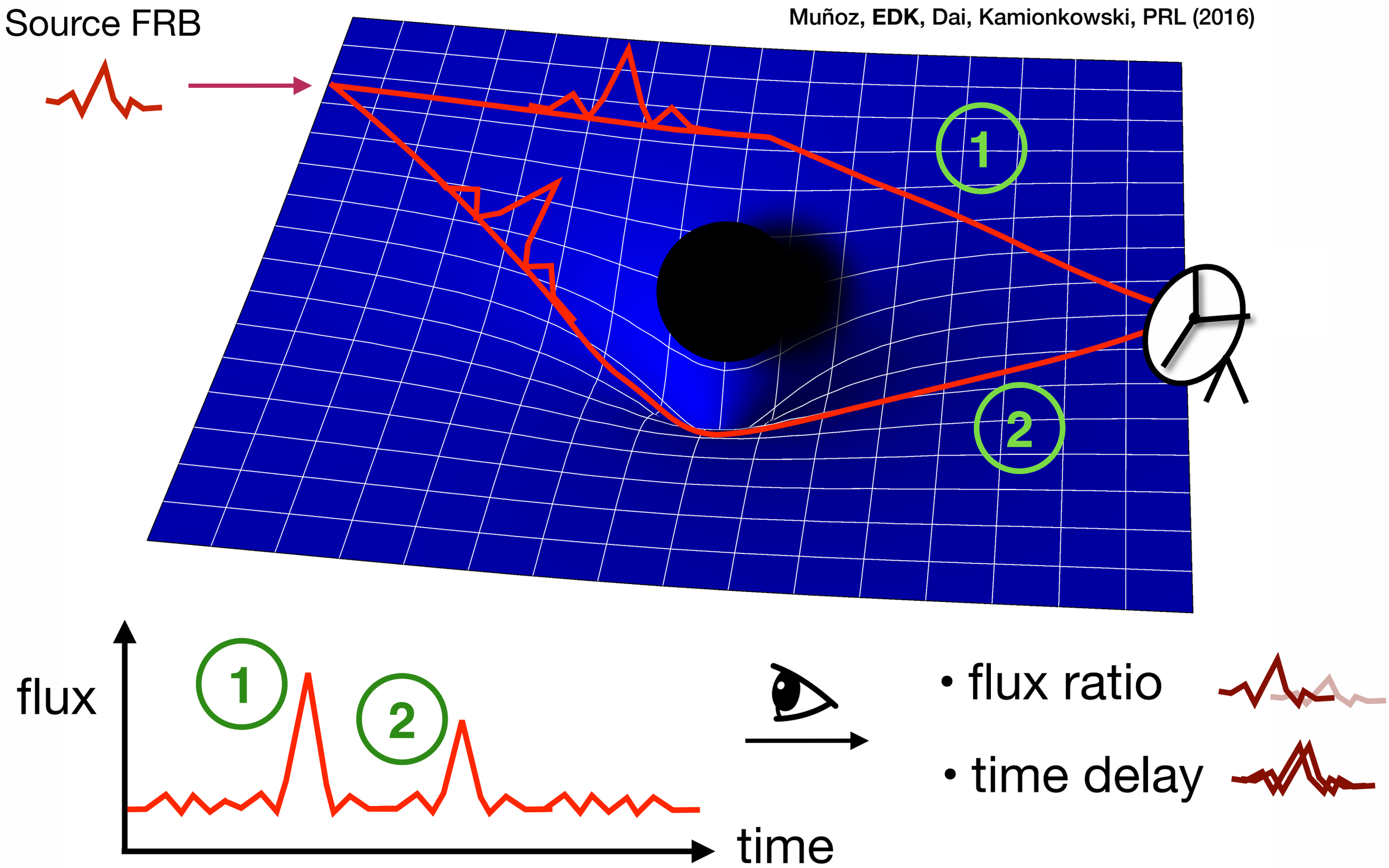

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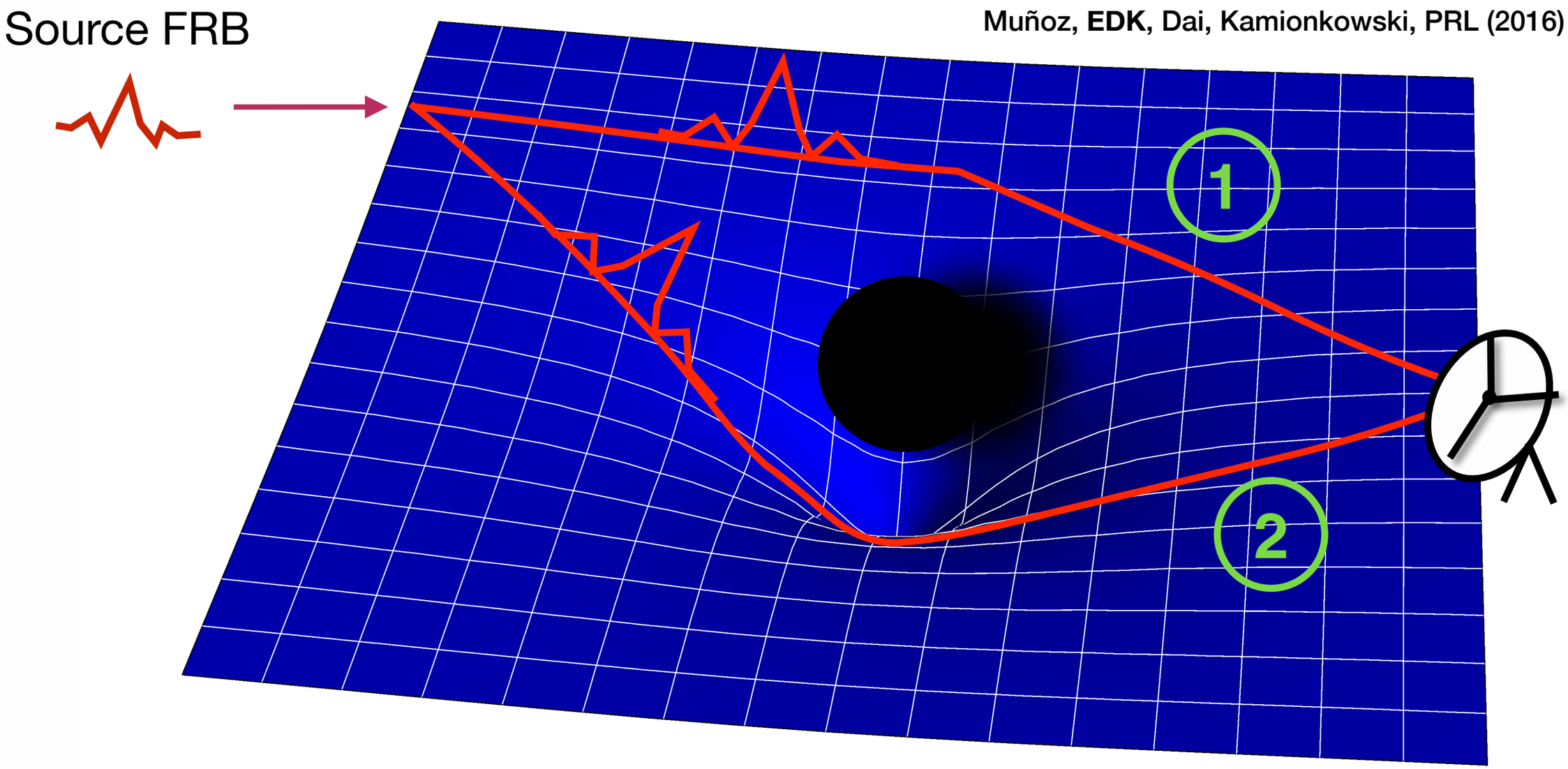

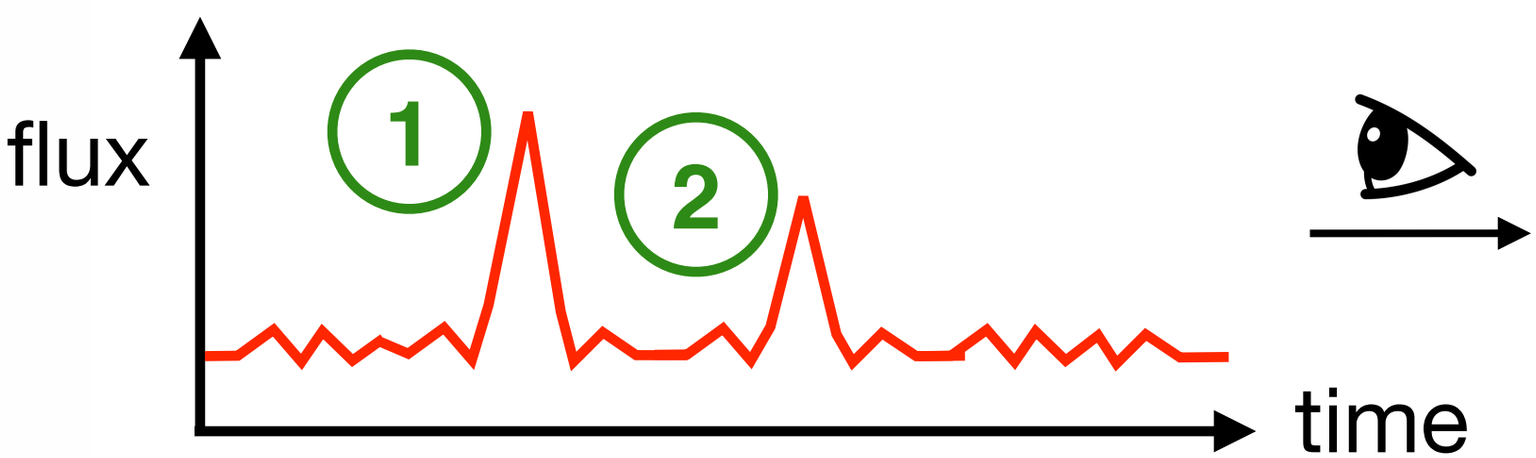

- flux ratio
- time delay

$\Delta t \sim 1\,\mathrm{ms}\,(M_L/30\,M_\odot)$

Constraining MACHOs: Fast Radio Burst Lensing

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CHIME experiment: expected rate of up to $\mathcal{O}(10^4)$ FRBs per year

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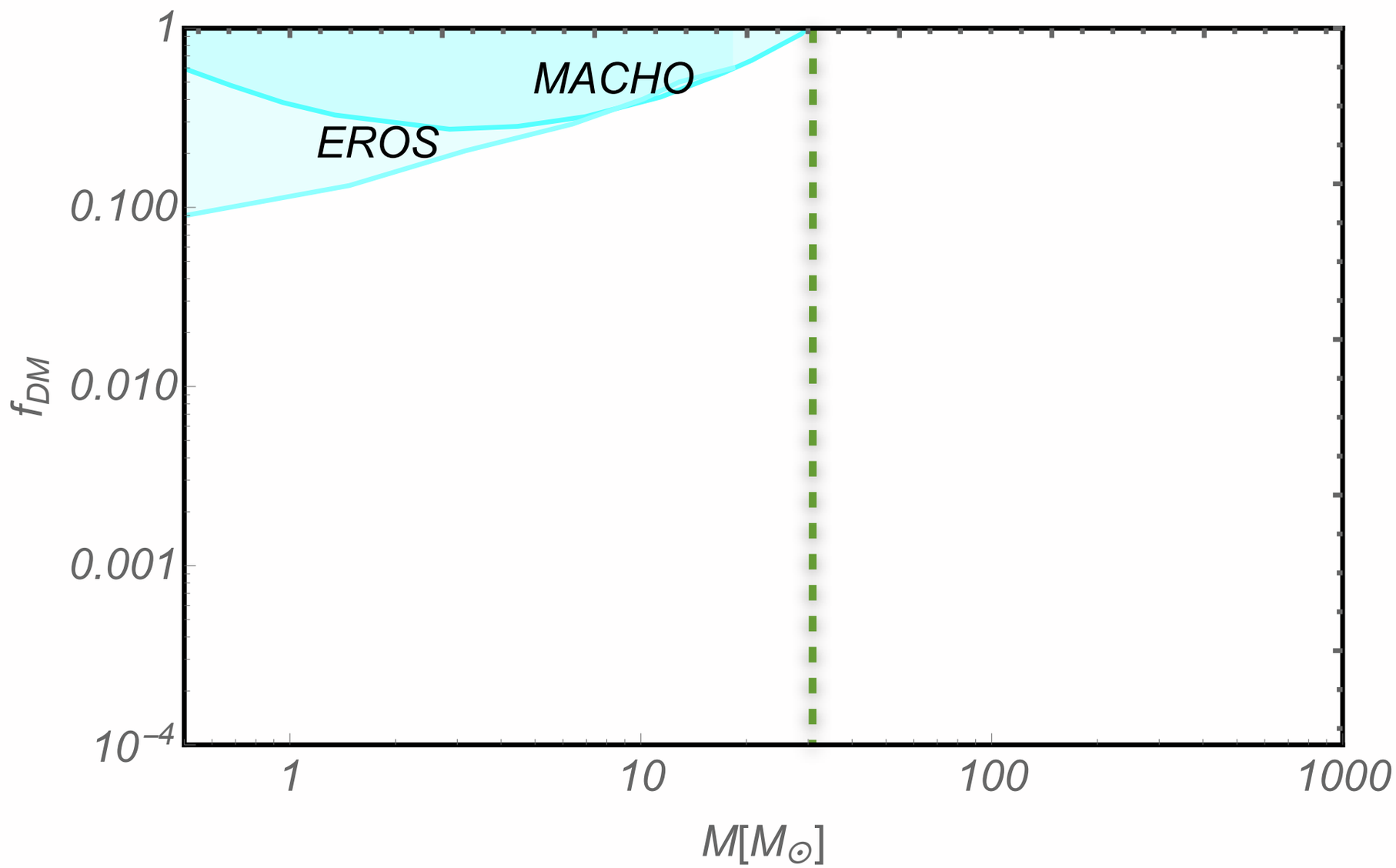

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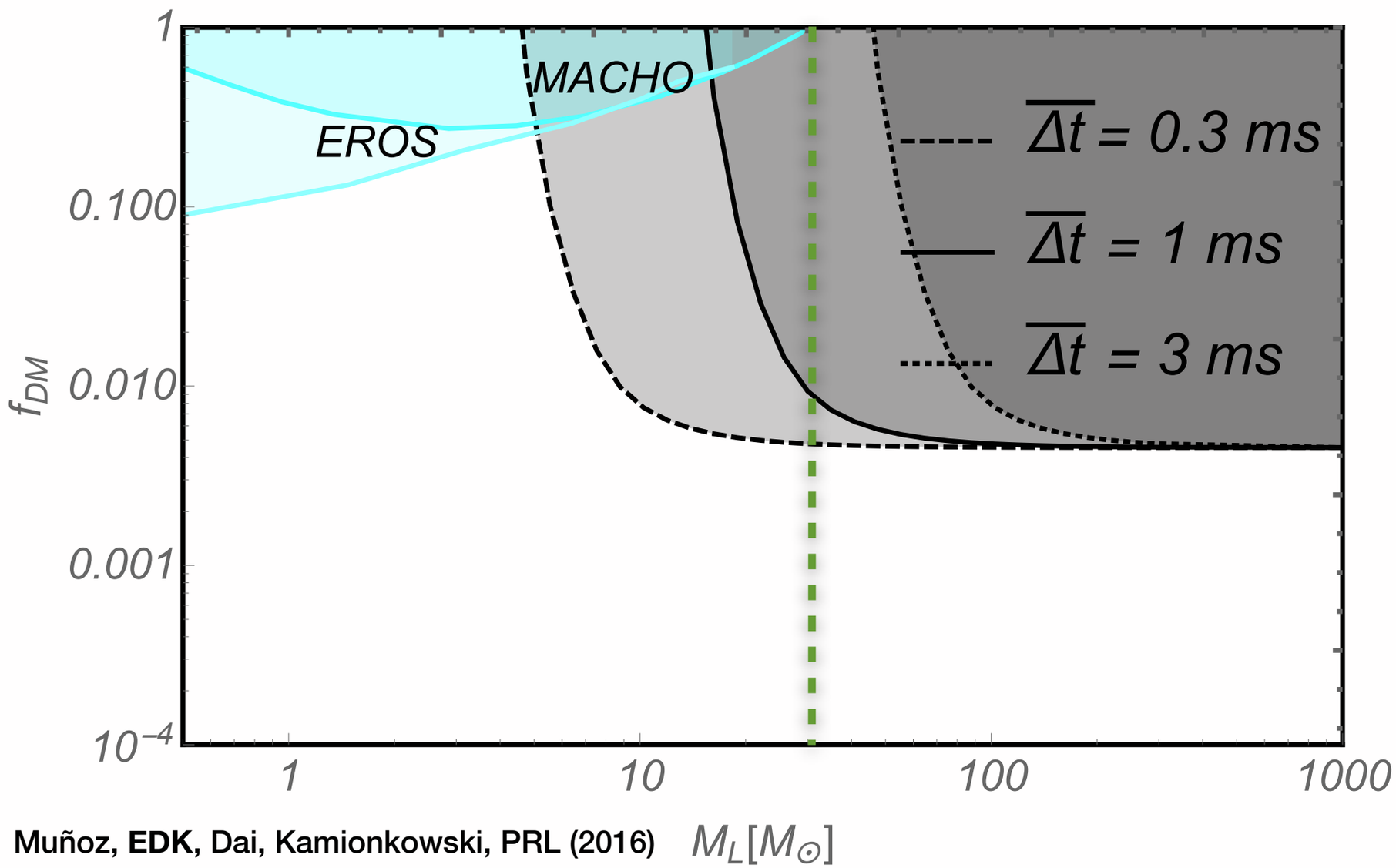

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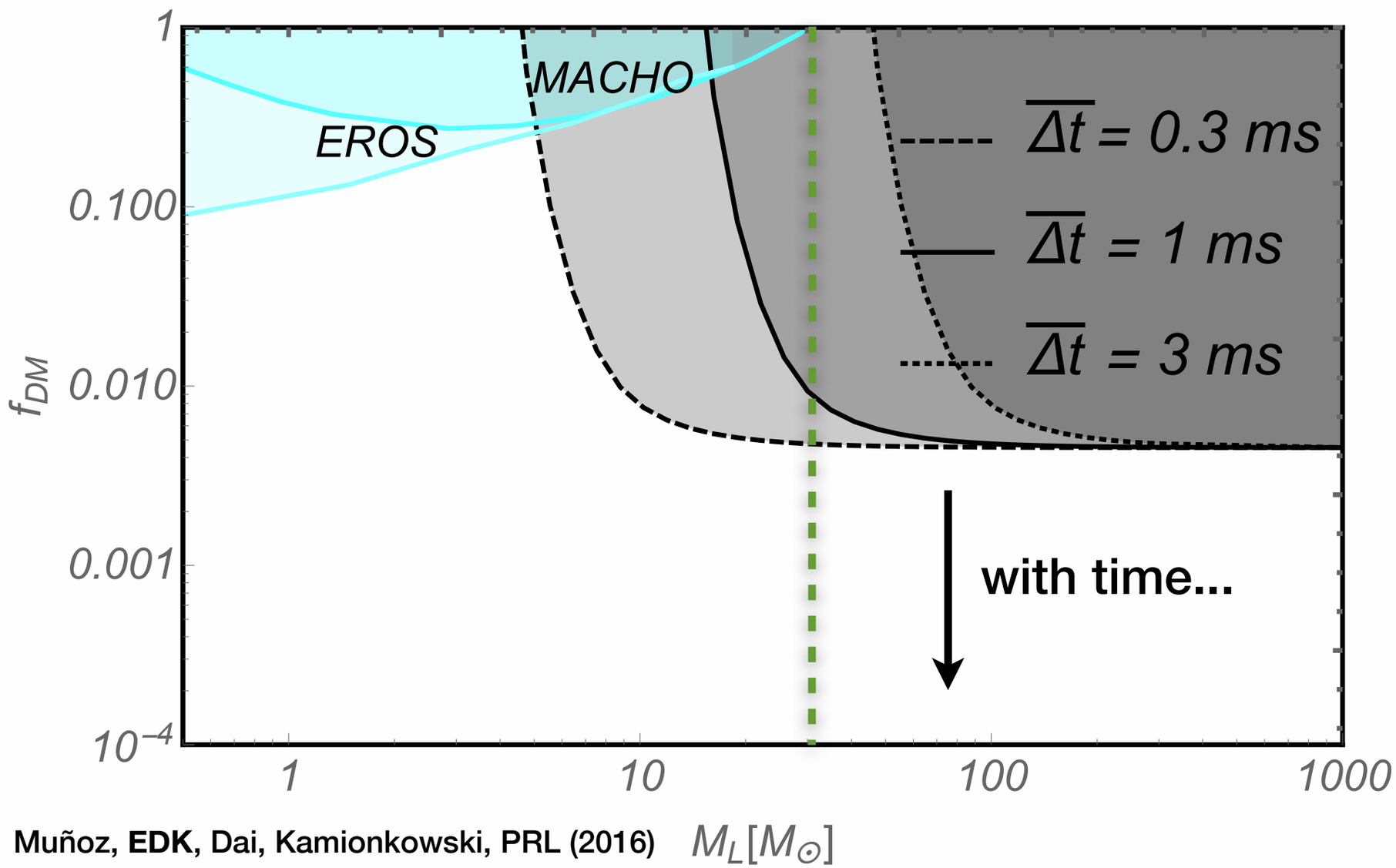

Muñoz, **EDK**, Dai, Kamionkowski, PRL (2016)

Strong Lensing of FRBs: Unique Signature

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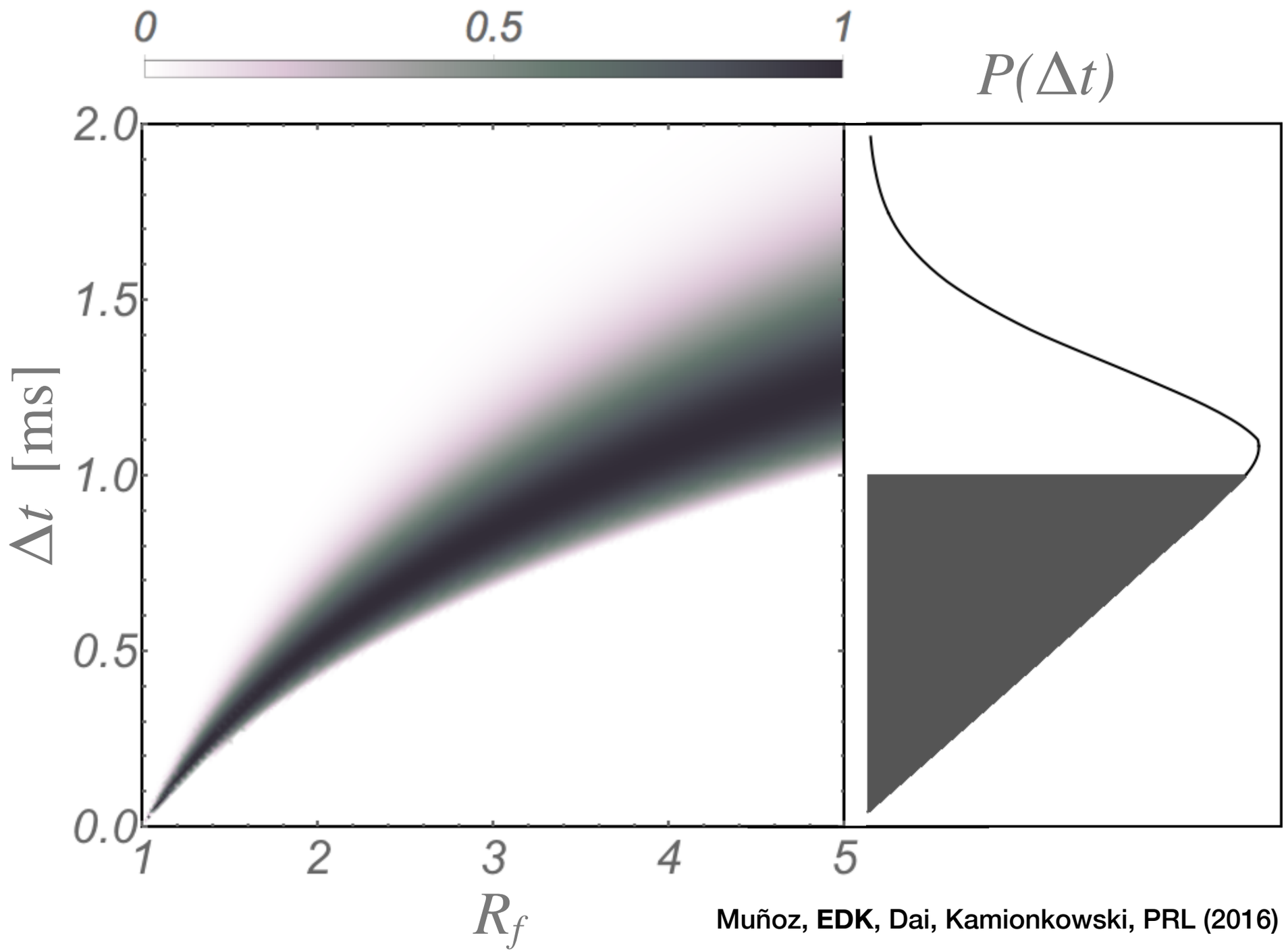
Joint PDF of time delay and flux ratio indicates correlation:



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PBH DM LIGO Window: Constraints Tightening!

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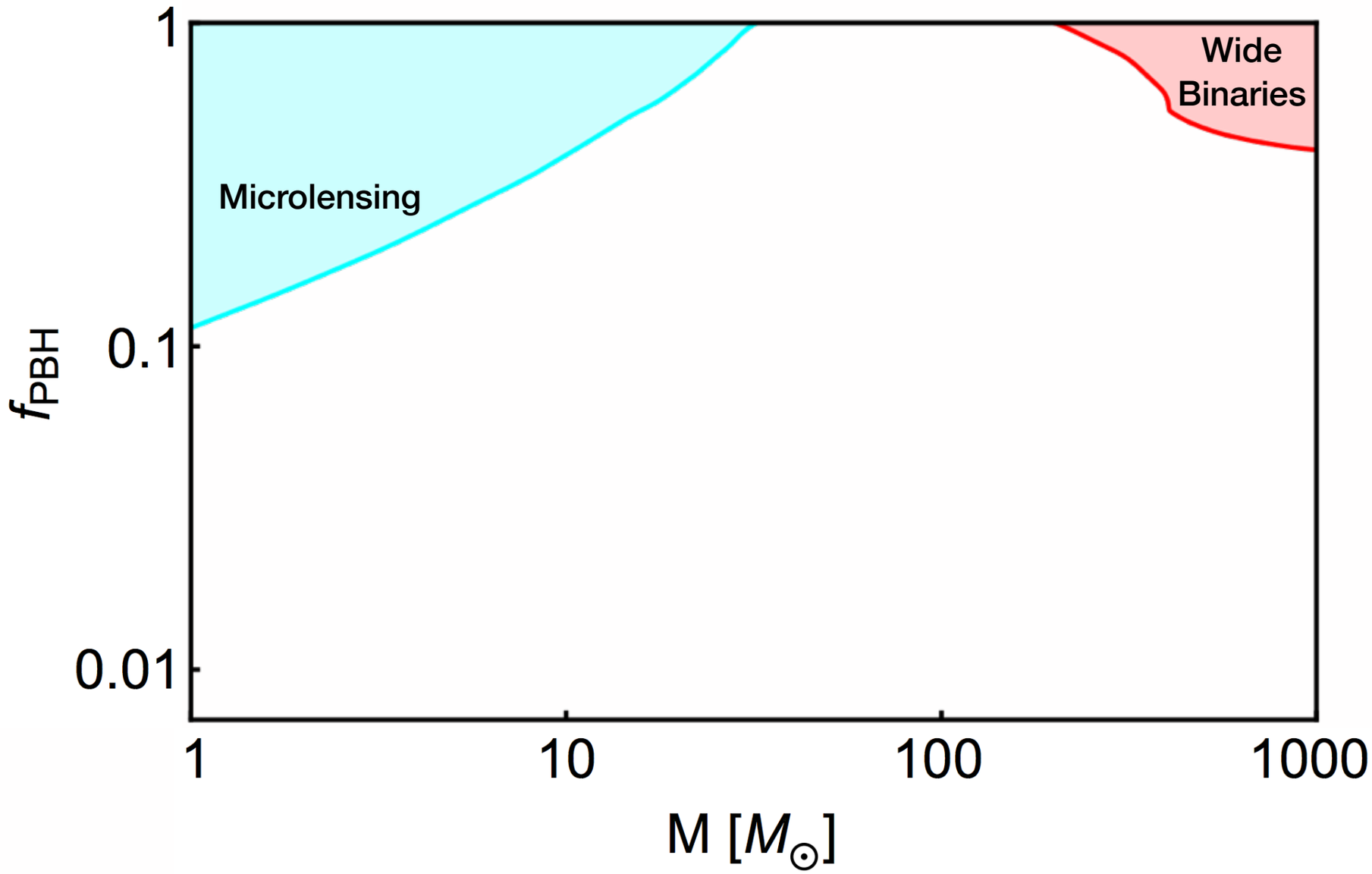

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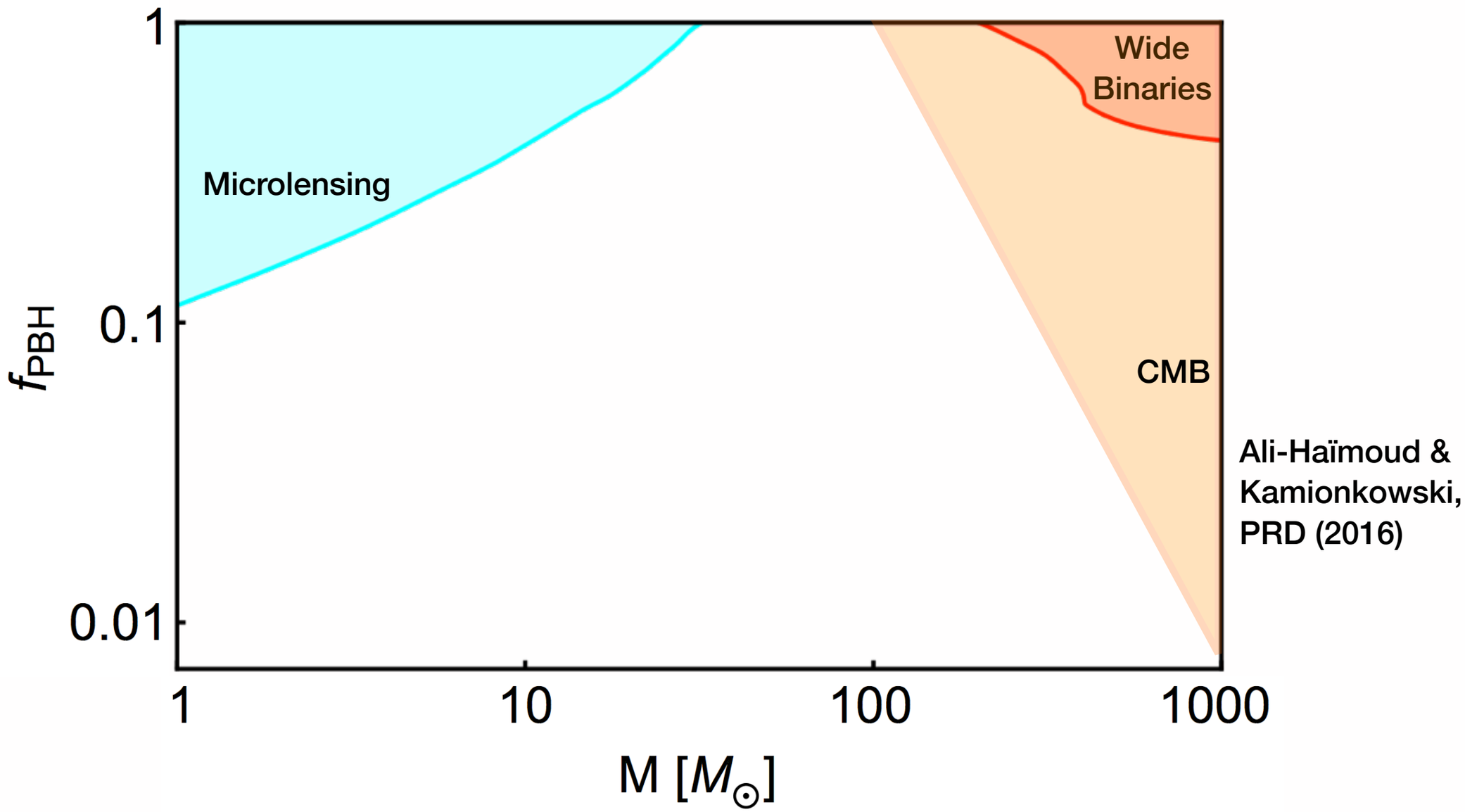

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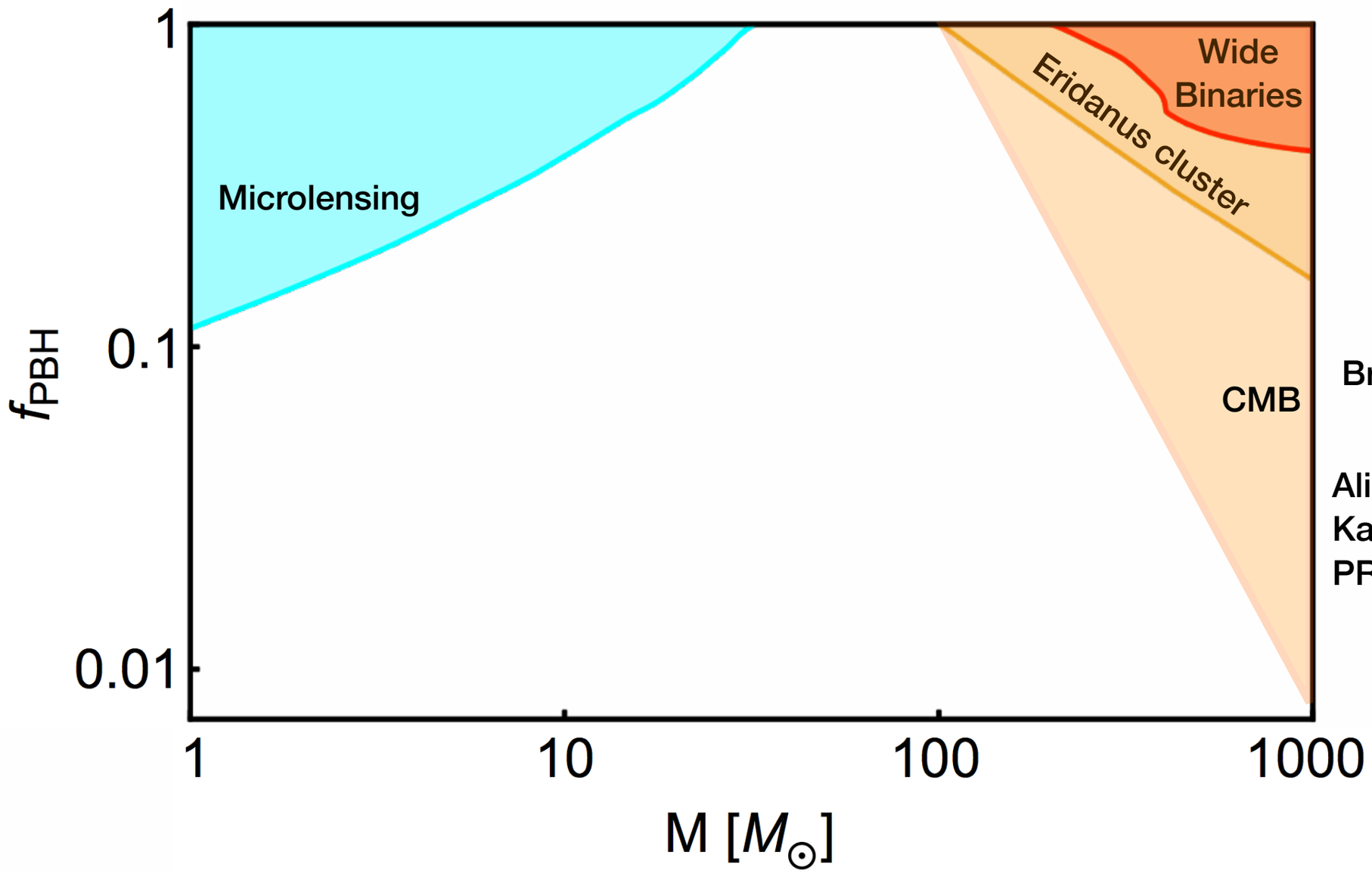

Brandt ApJL (2016)

Ali-Haïmoud & Kamionkowski, PRD (2016)

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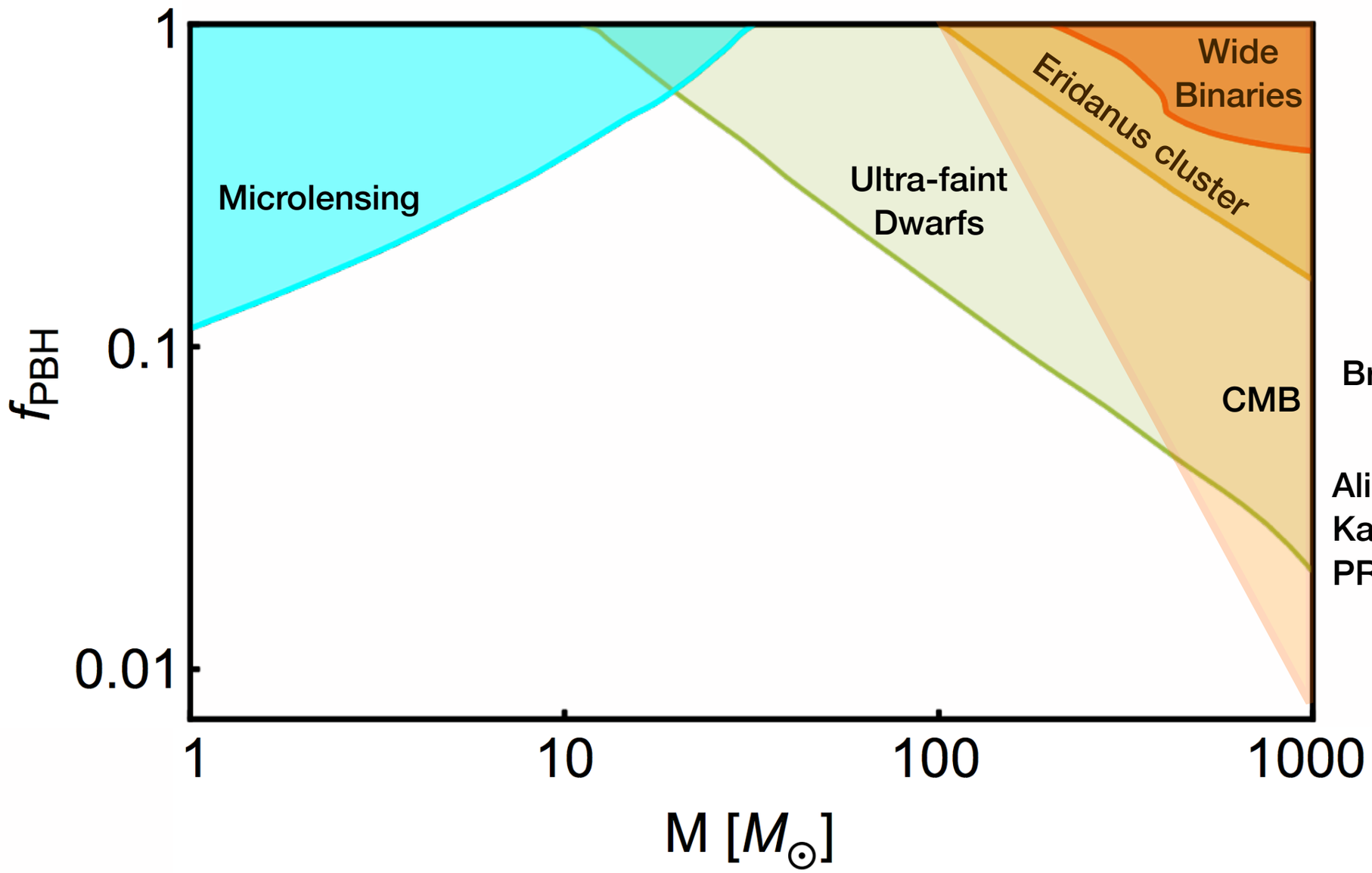

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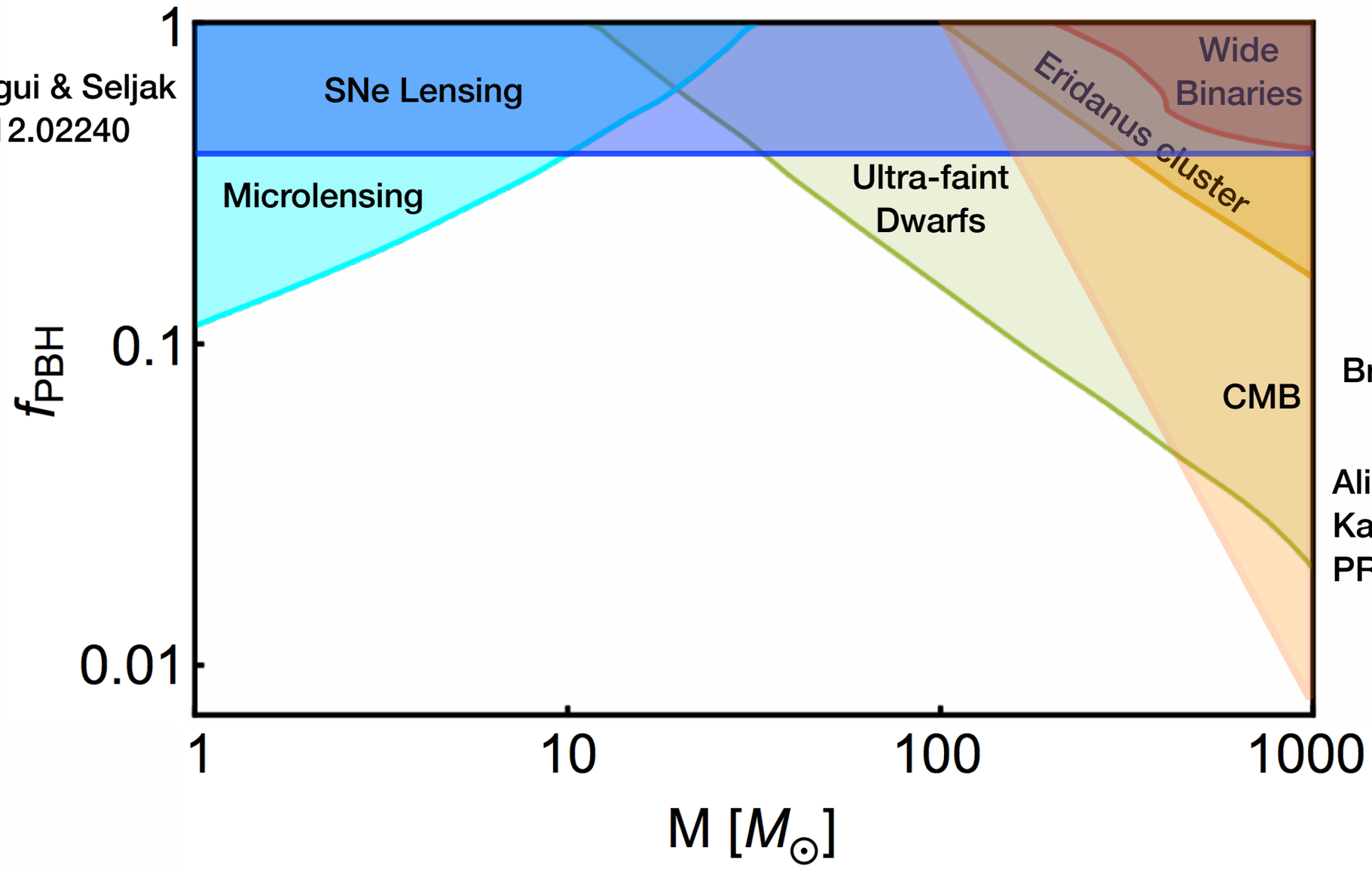
Zumalacarregui & Seljak
arXiv:1712.02240



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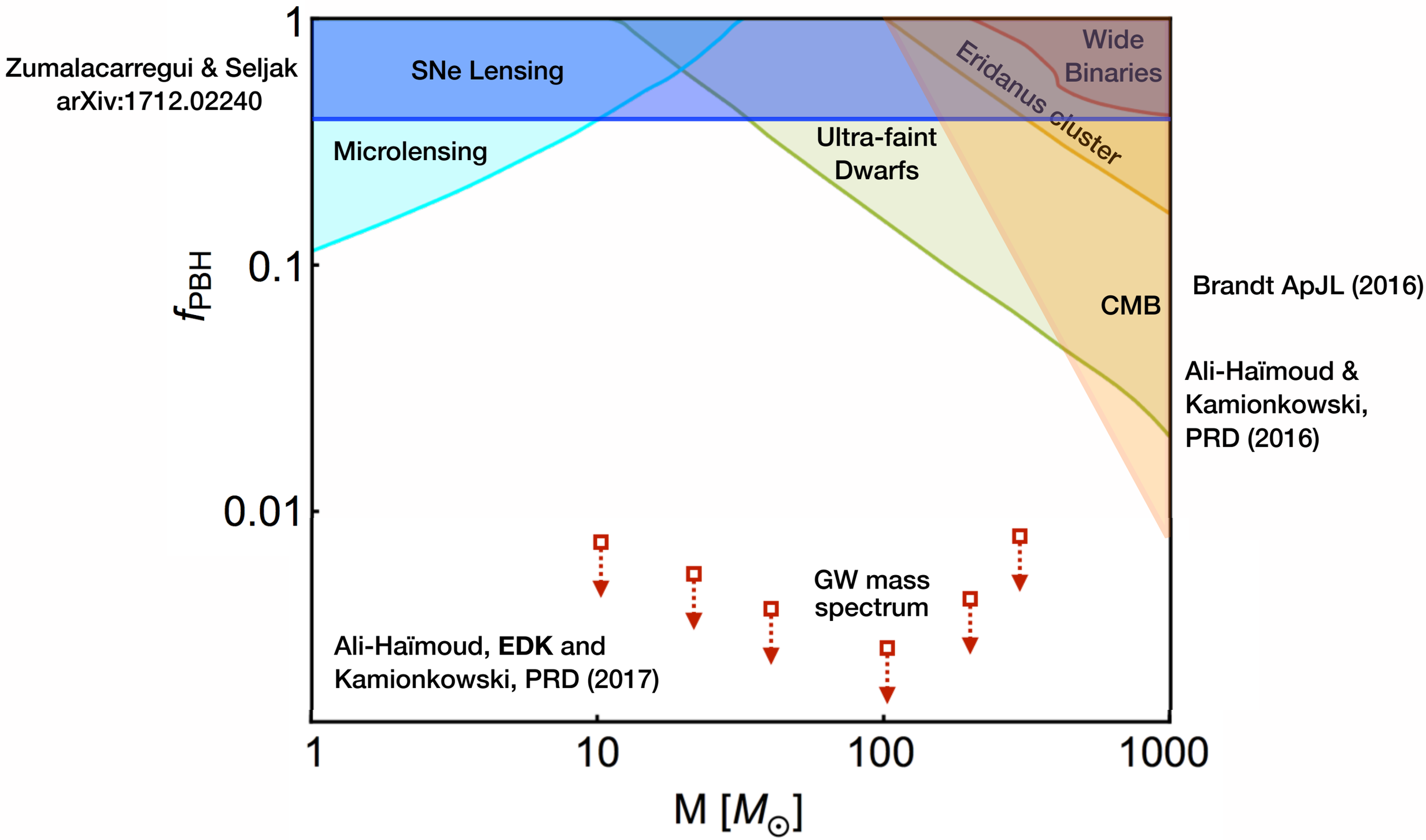

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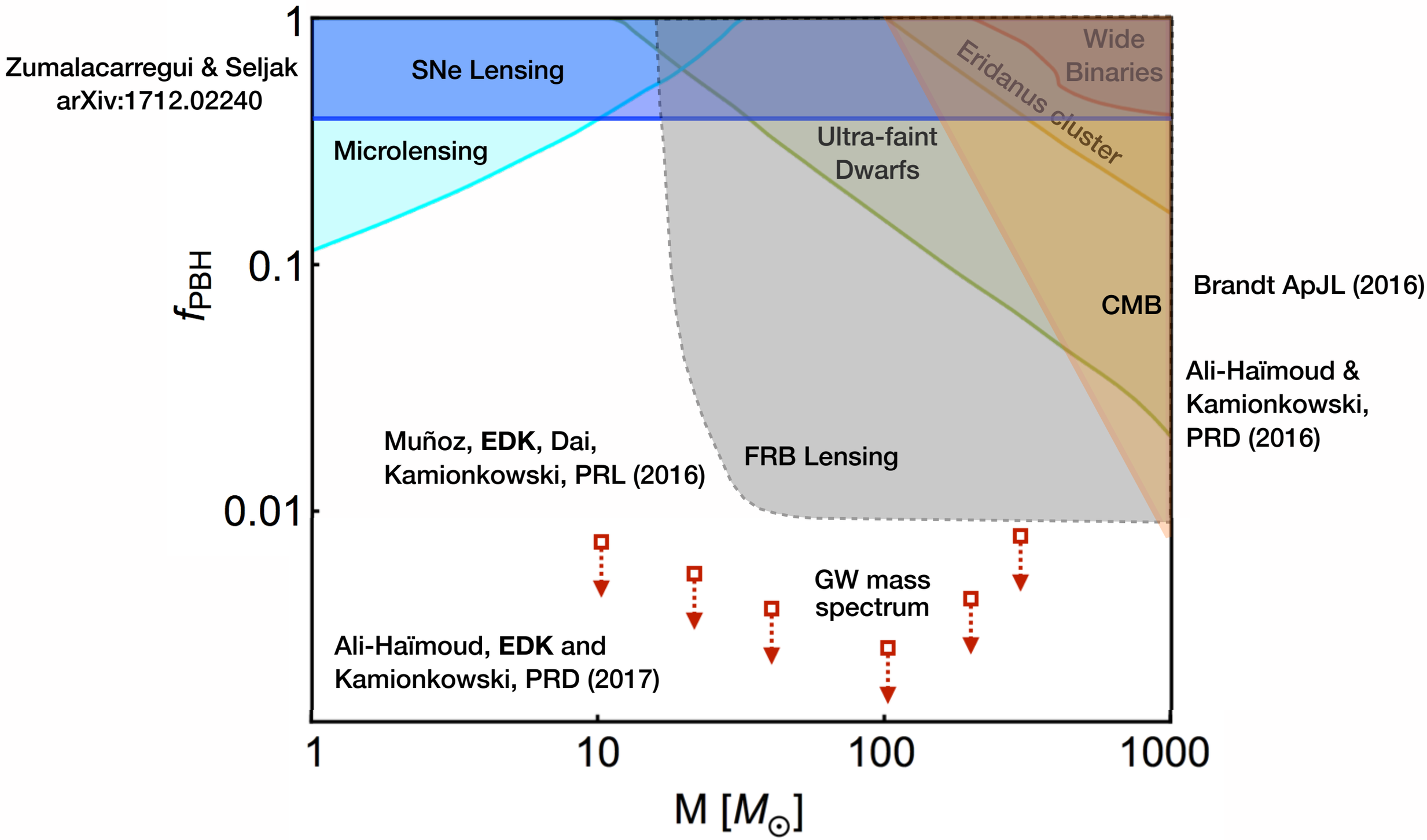

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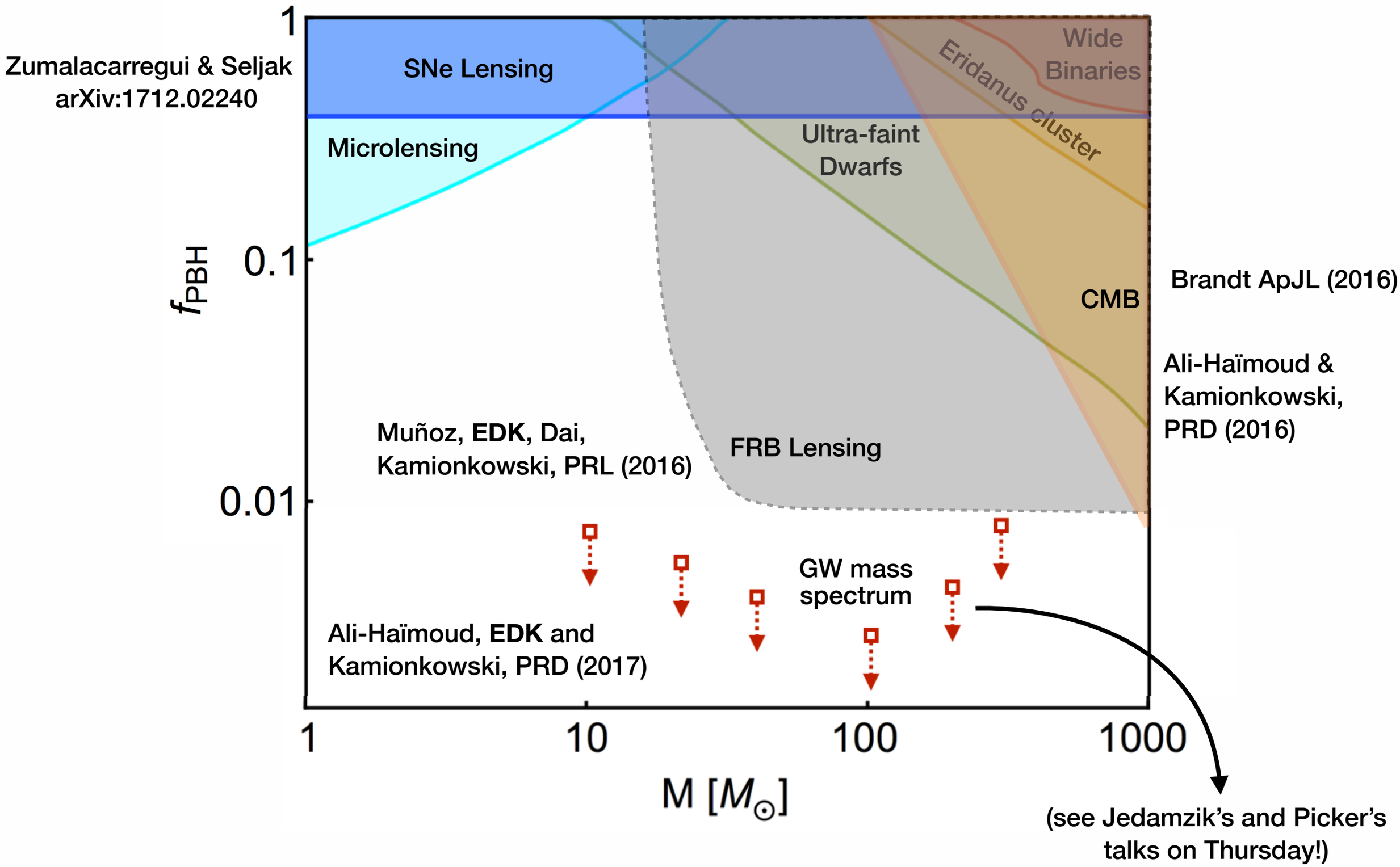

Observational Outlook: Timeline

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Experiment	2015	2020	2025	2030	beyond →

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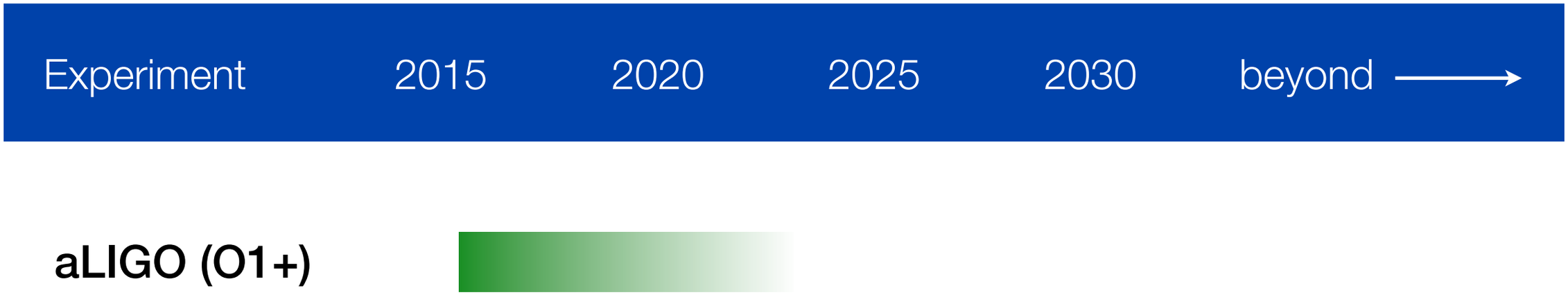

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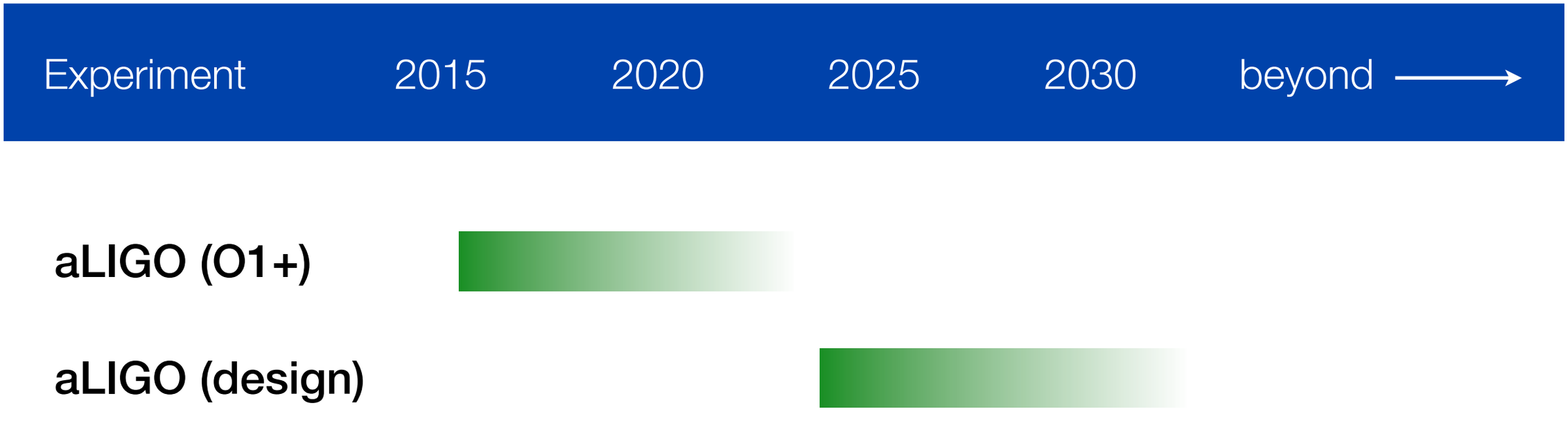

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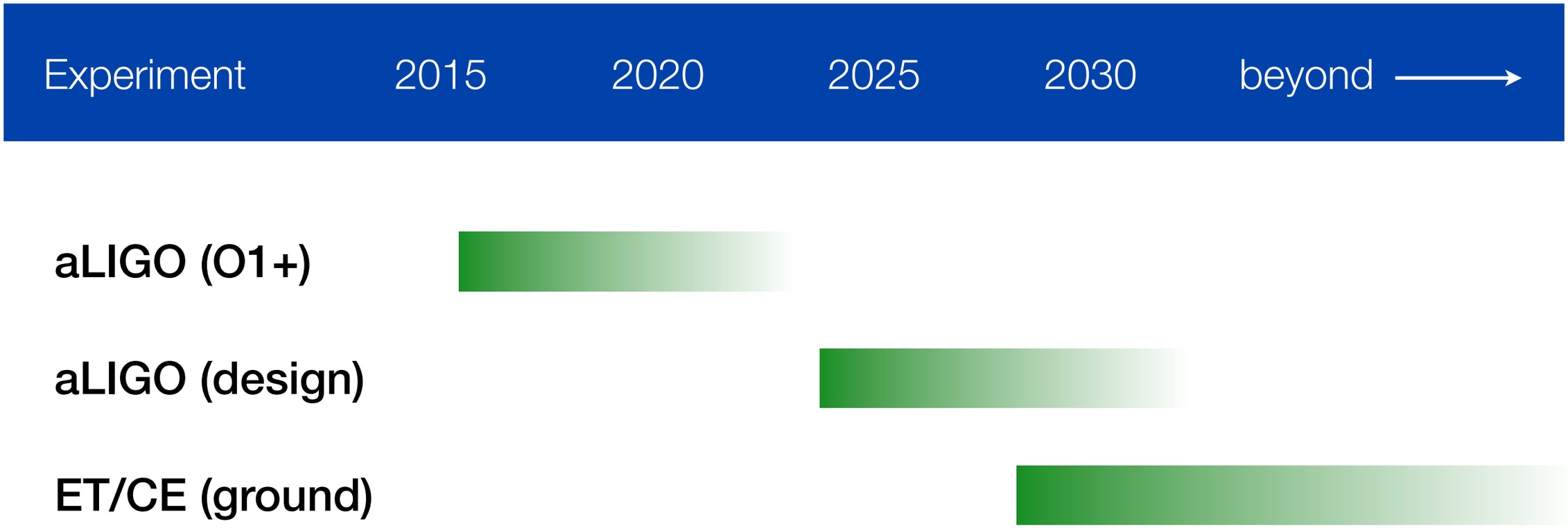

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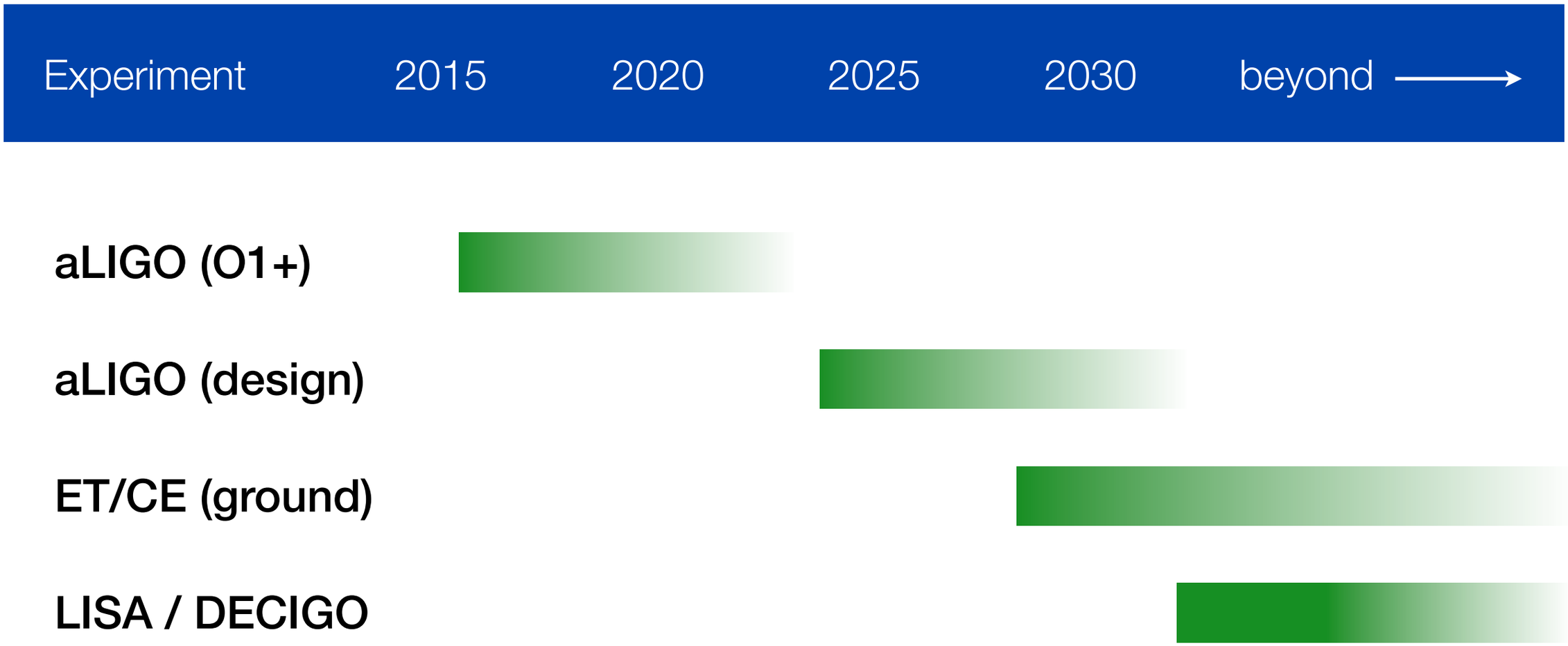

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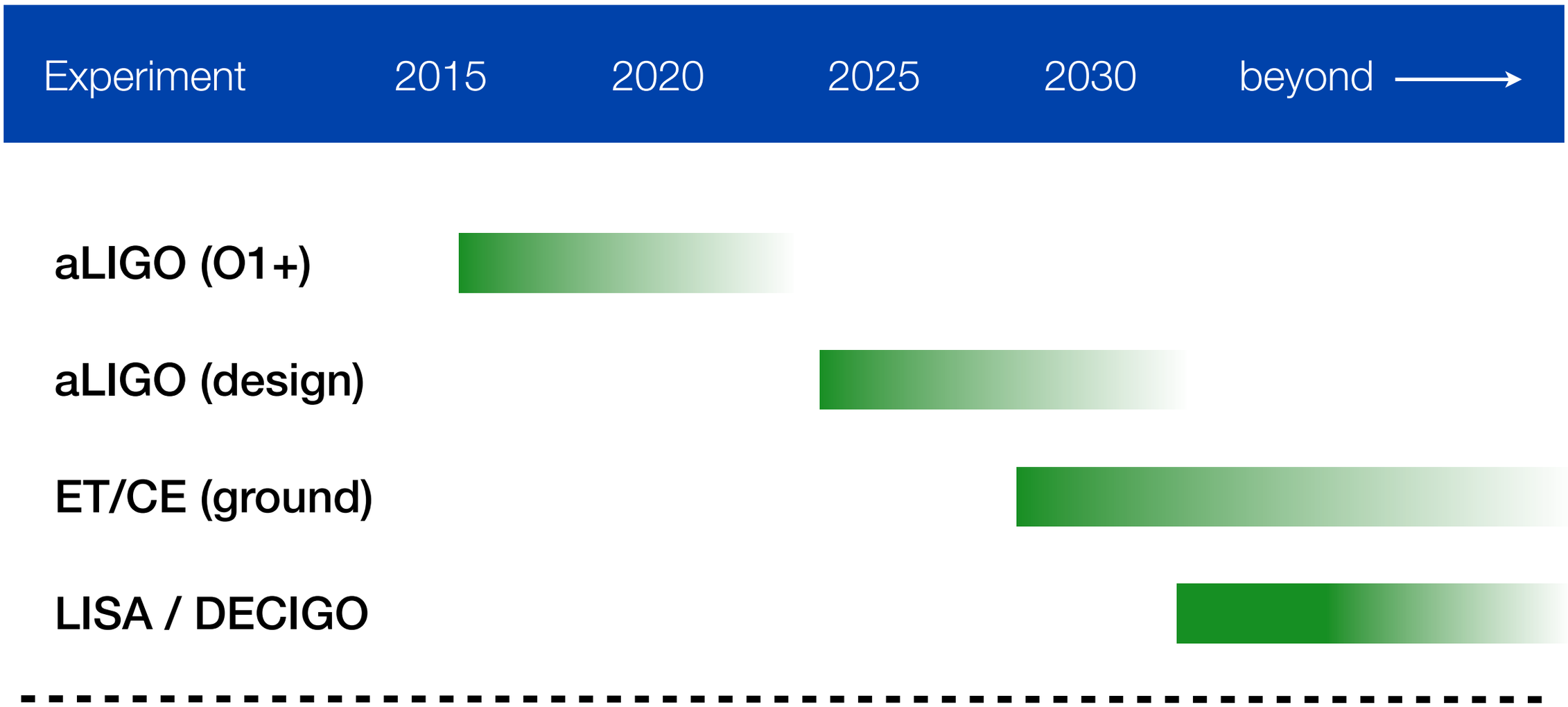

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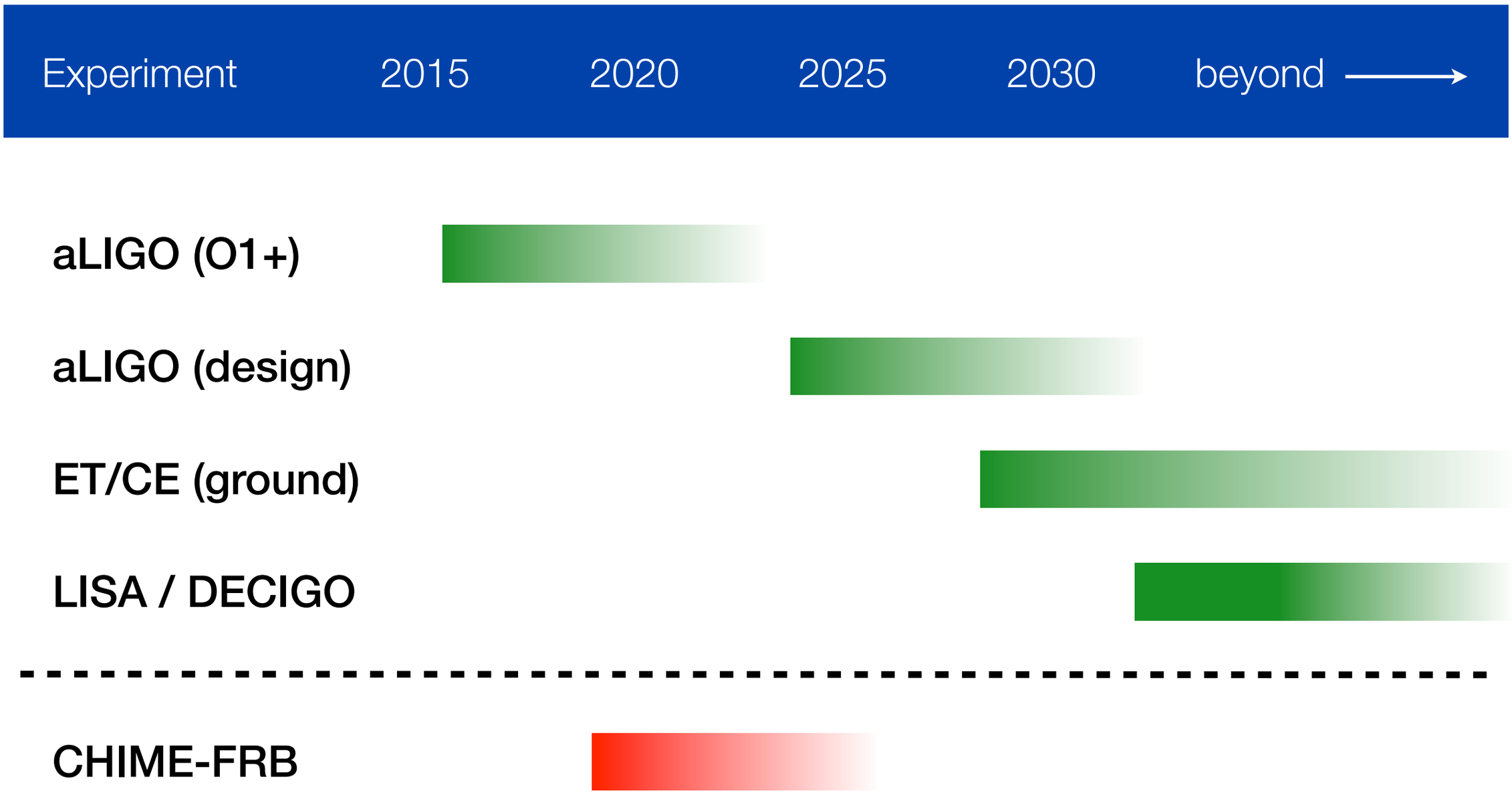

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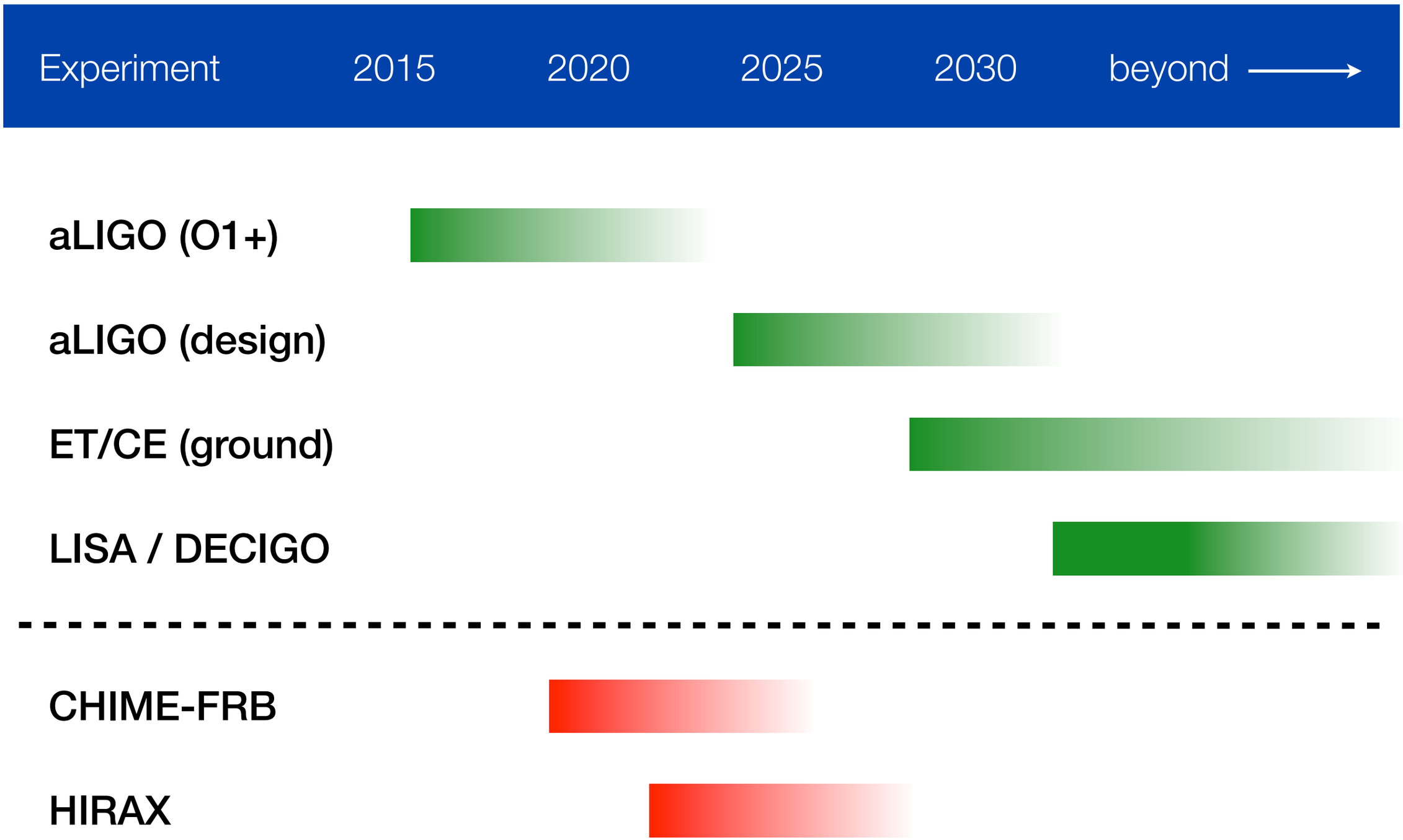

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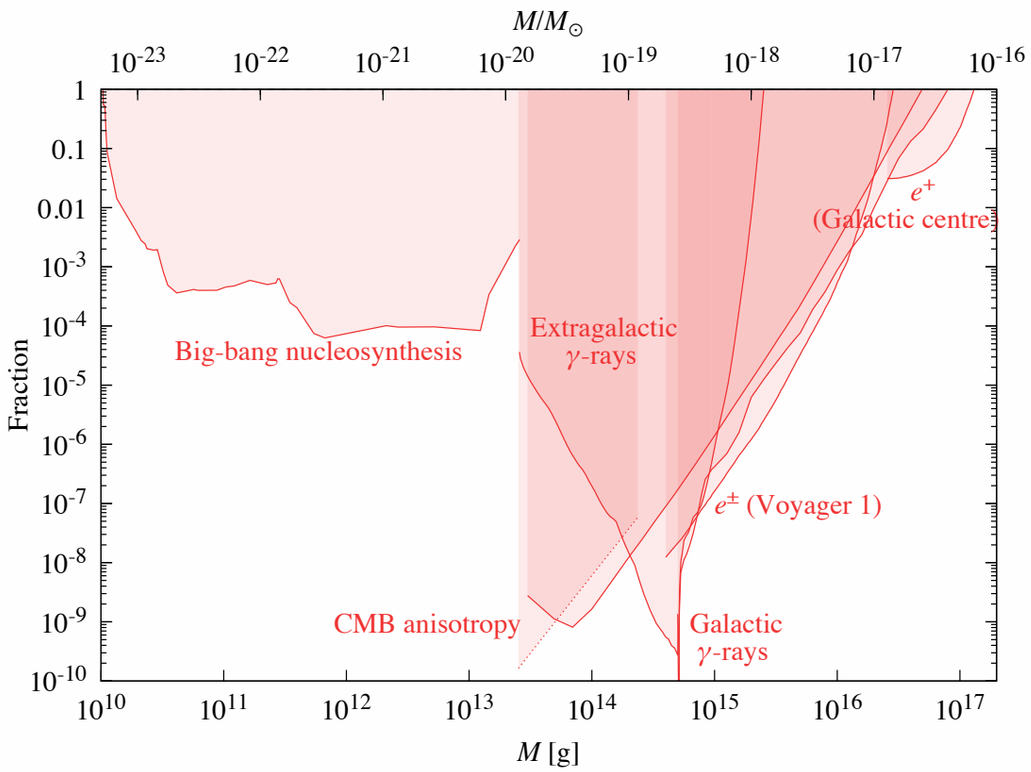

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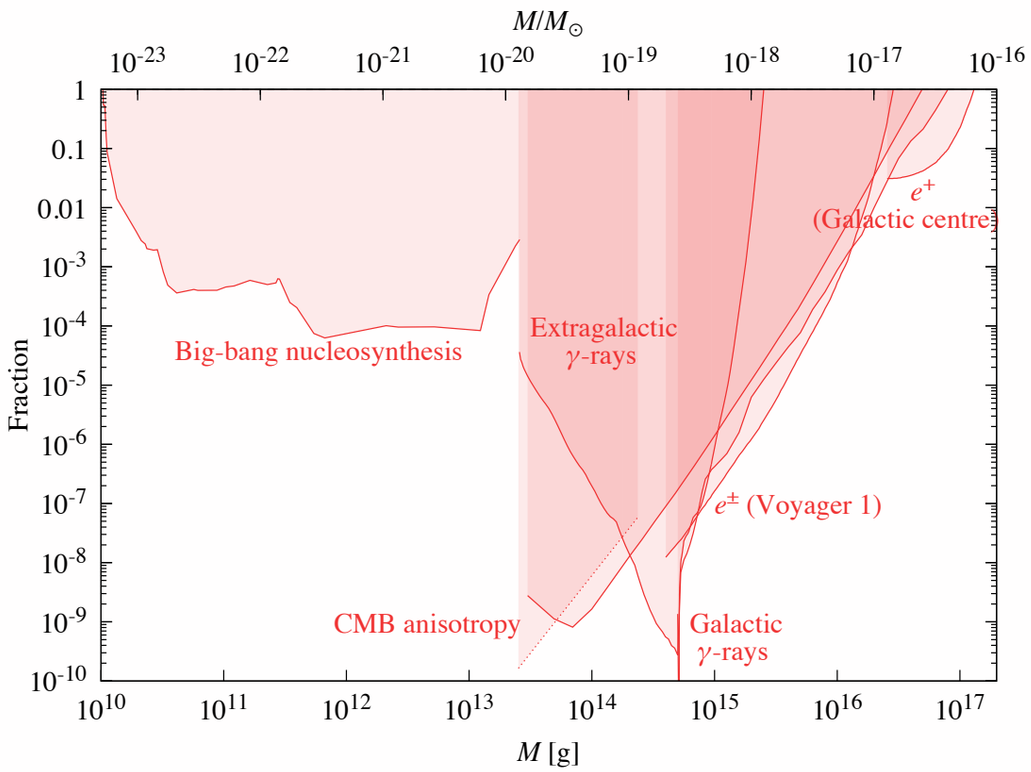

Carr et al., arXiv:2020.12778

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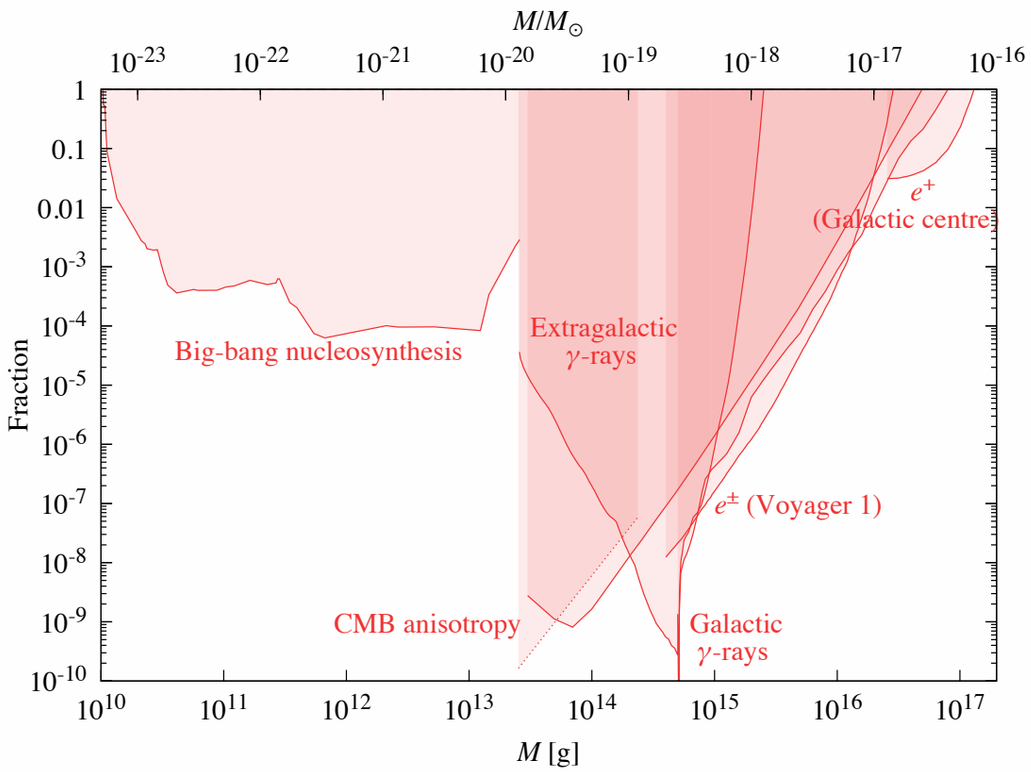

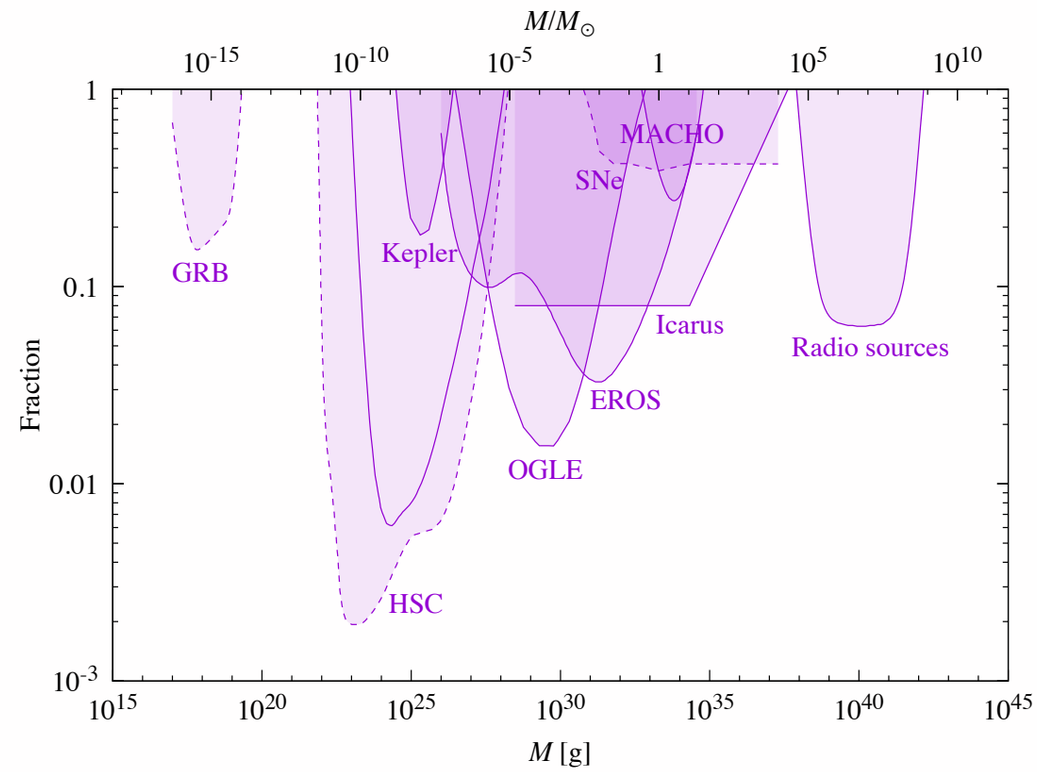

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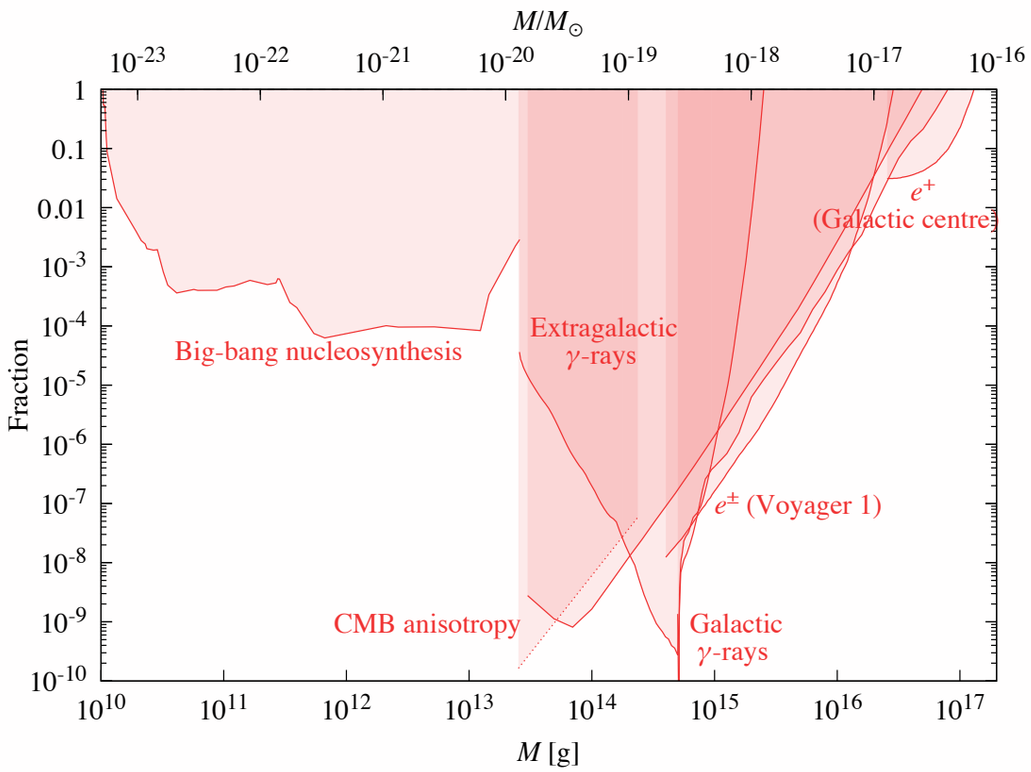

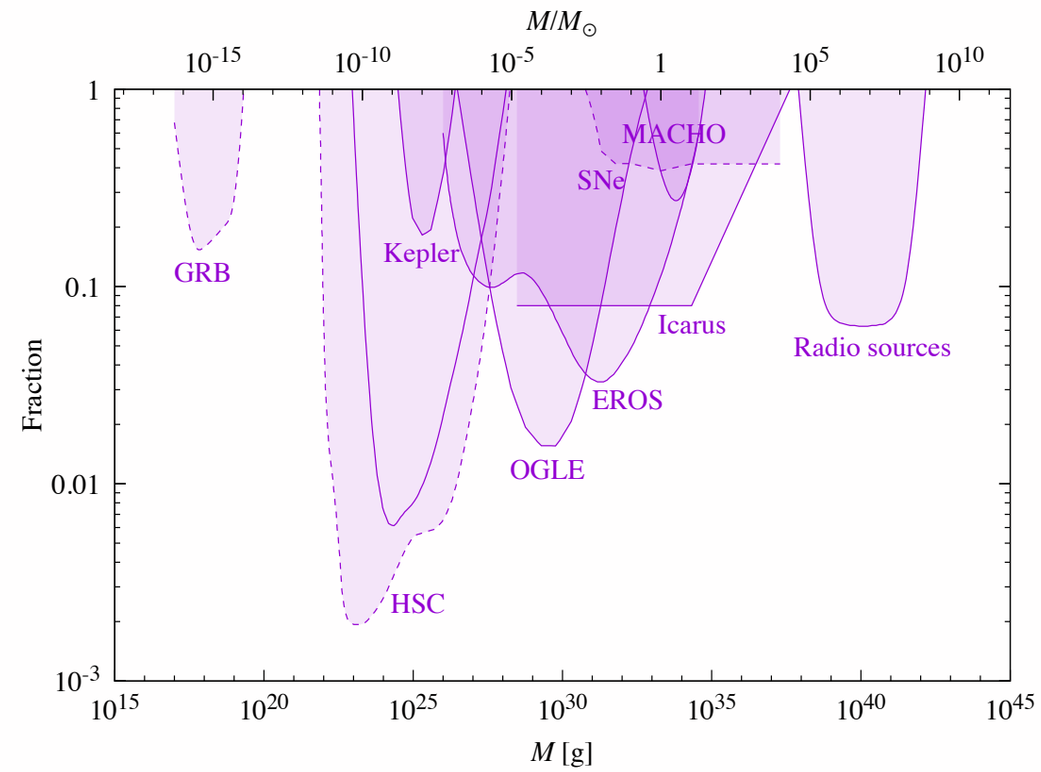

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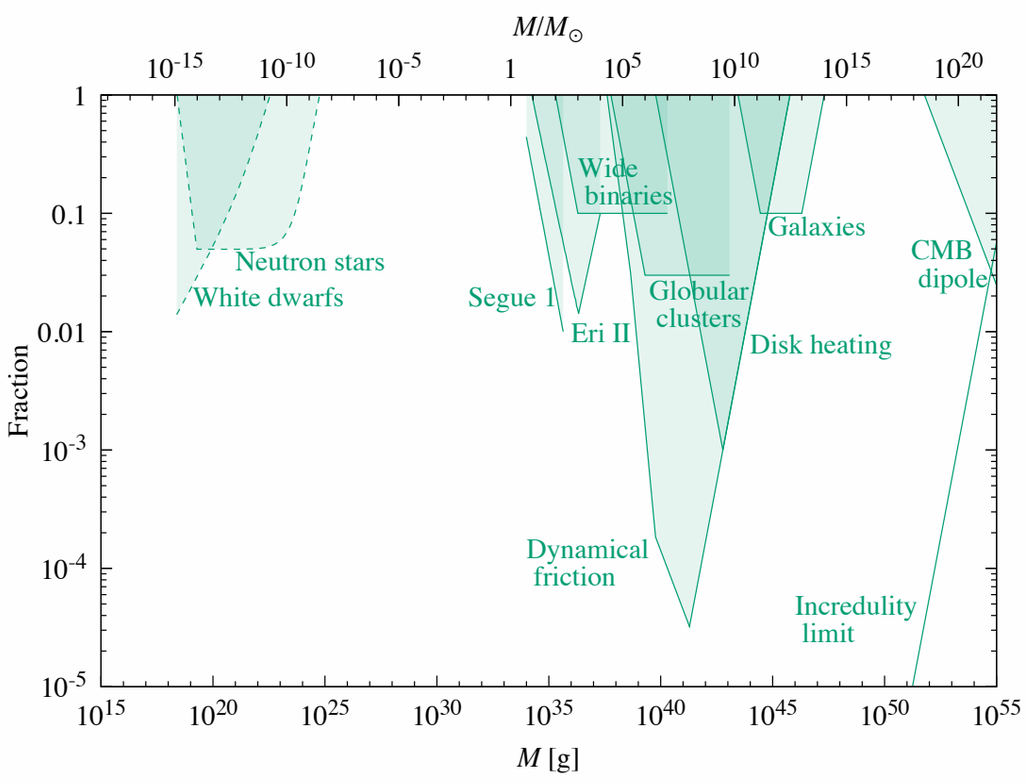

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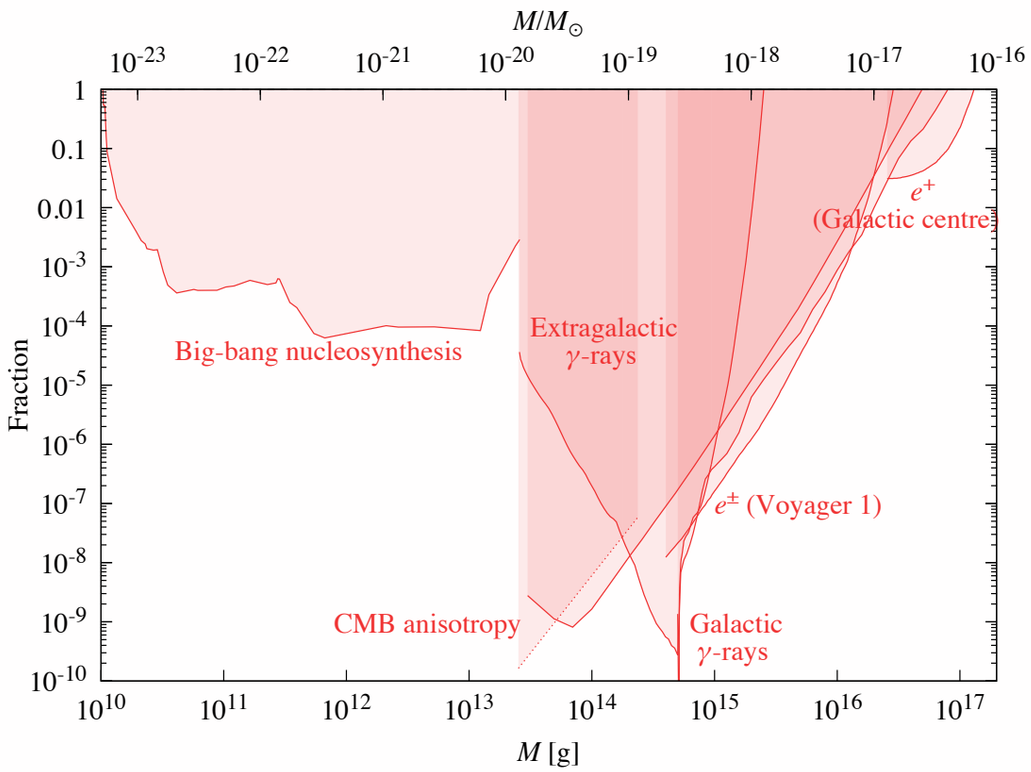

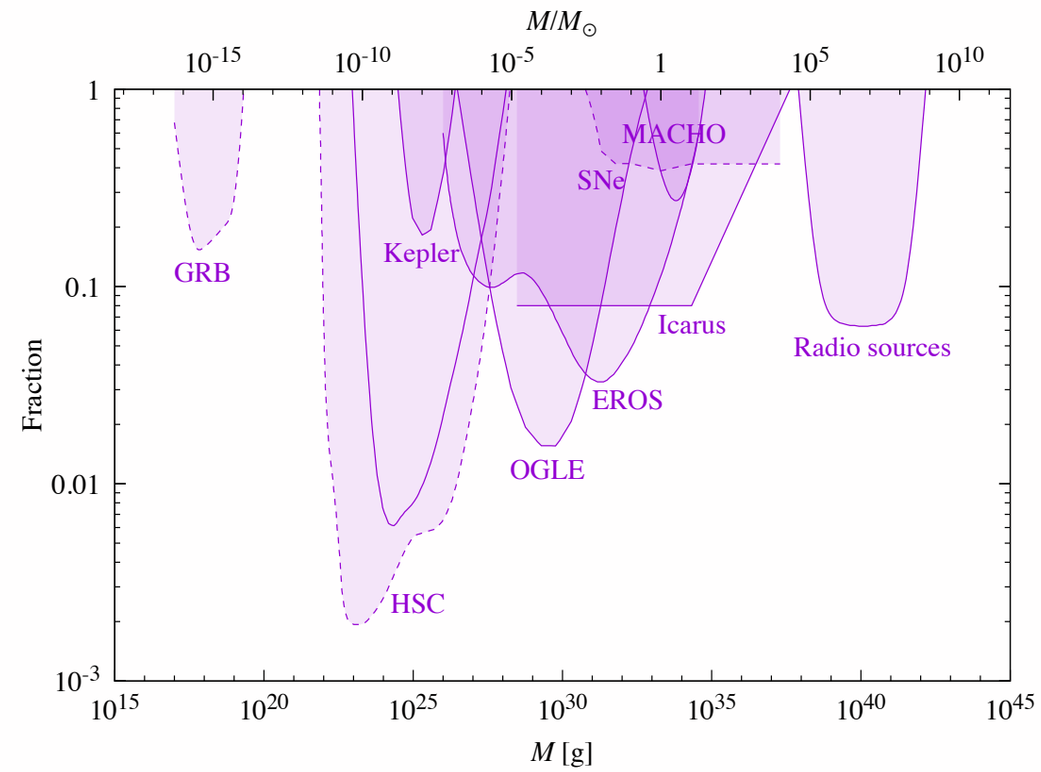

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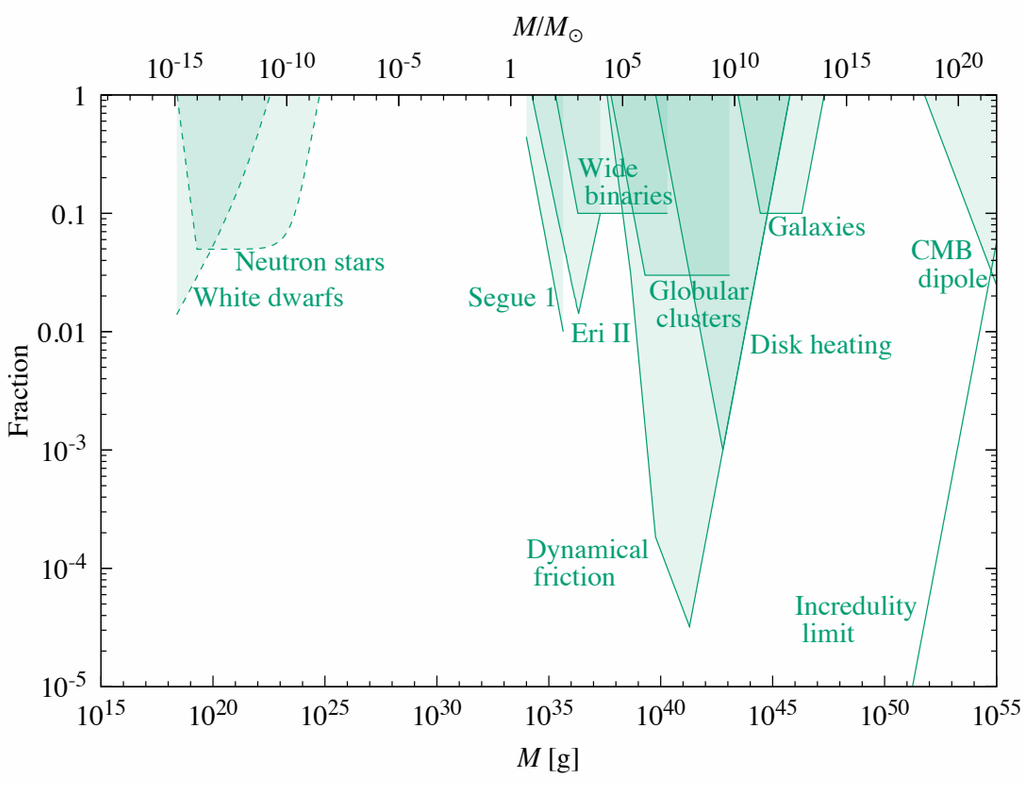

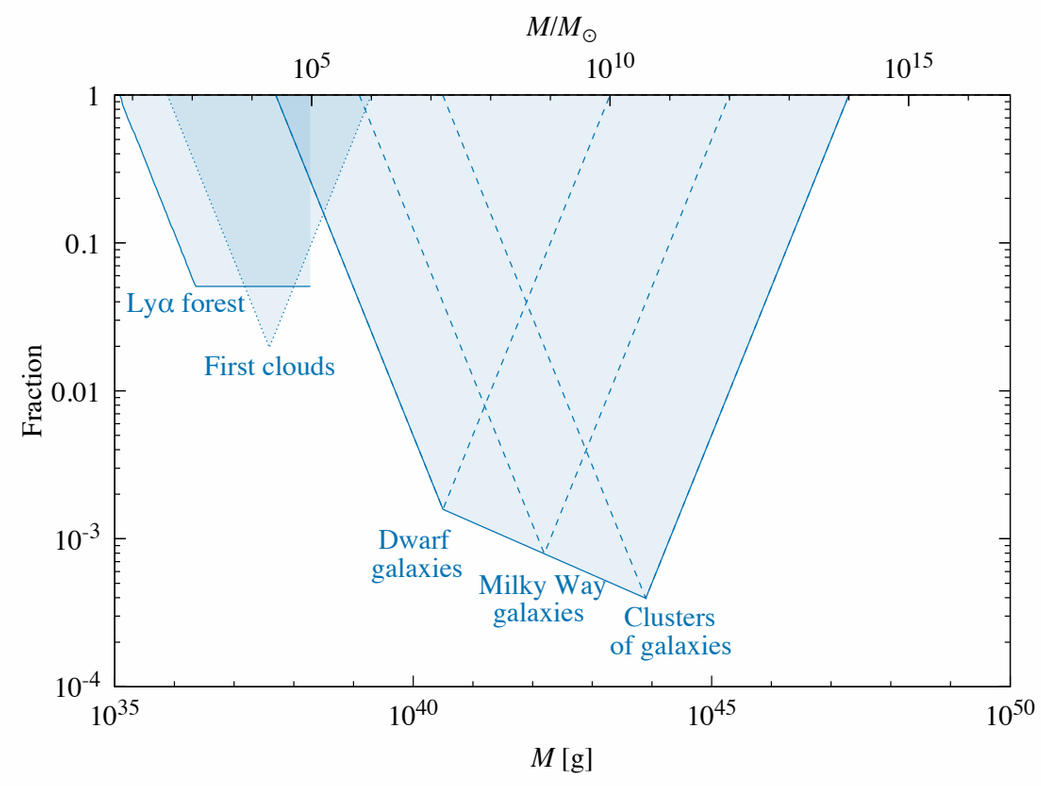

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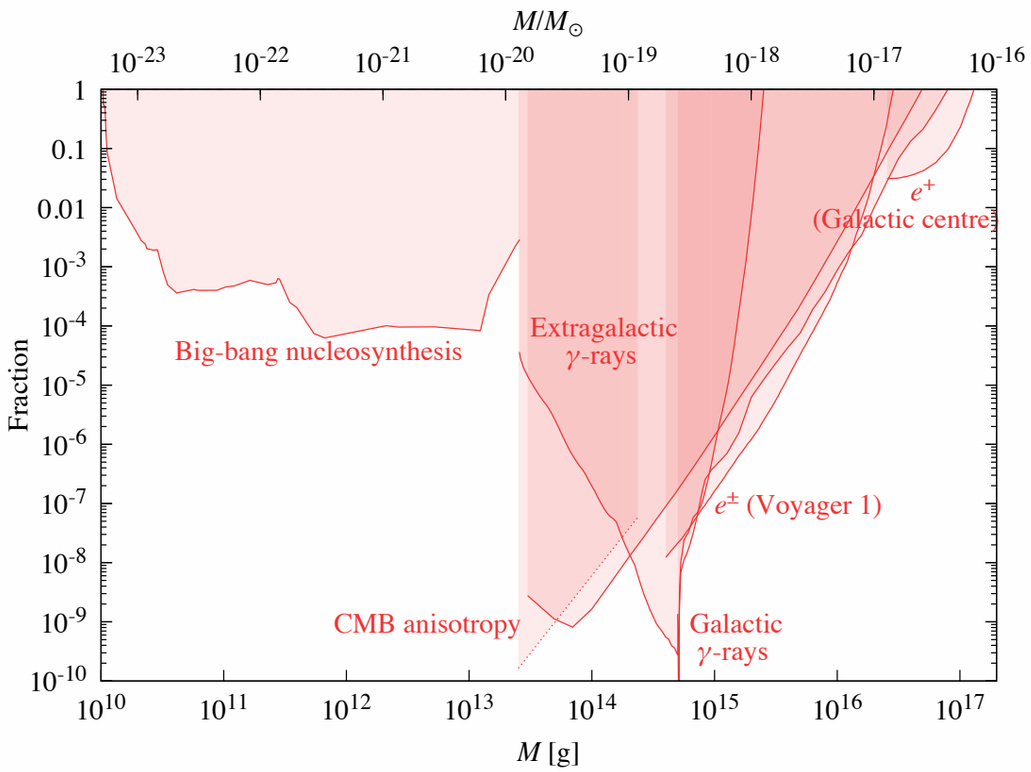
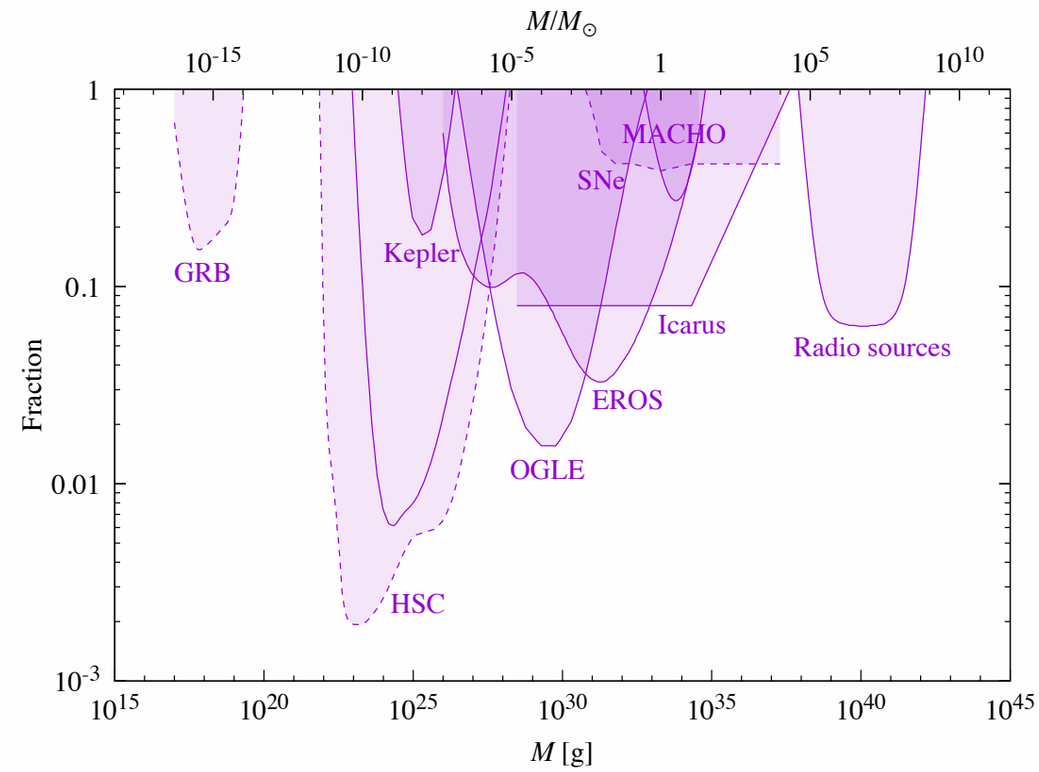
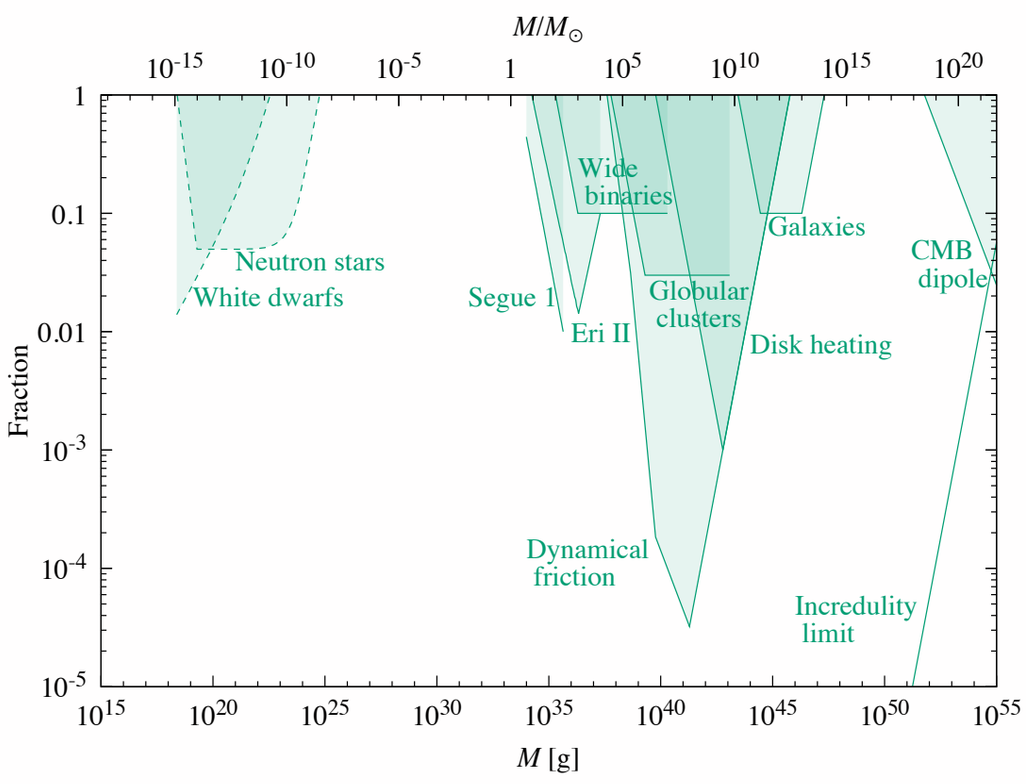
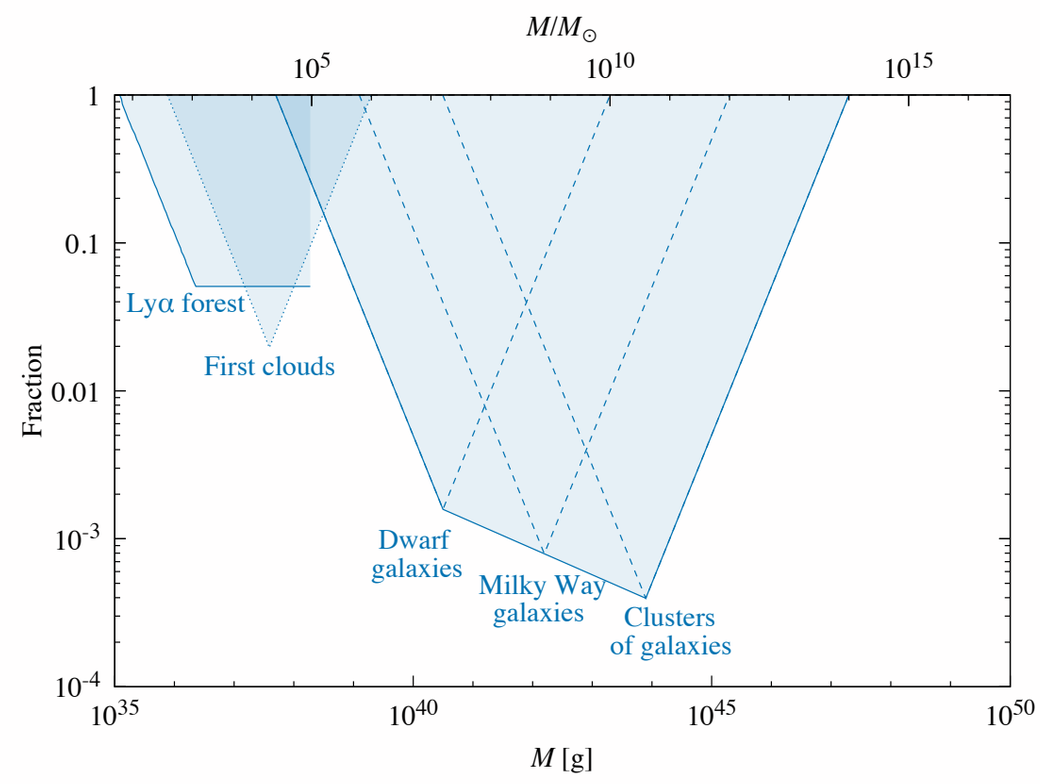




Carr et al., arXiv:2020.12778 (see Carr's and Laha's talks on Friday; Takhistov on Thursday and Garcia-Bellido on Wednesday!)





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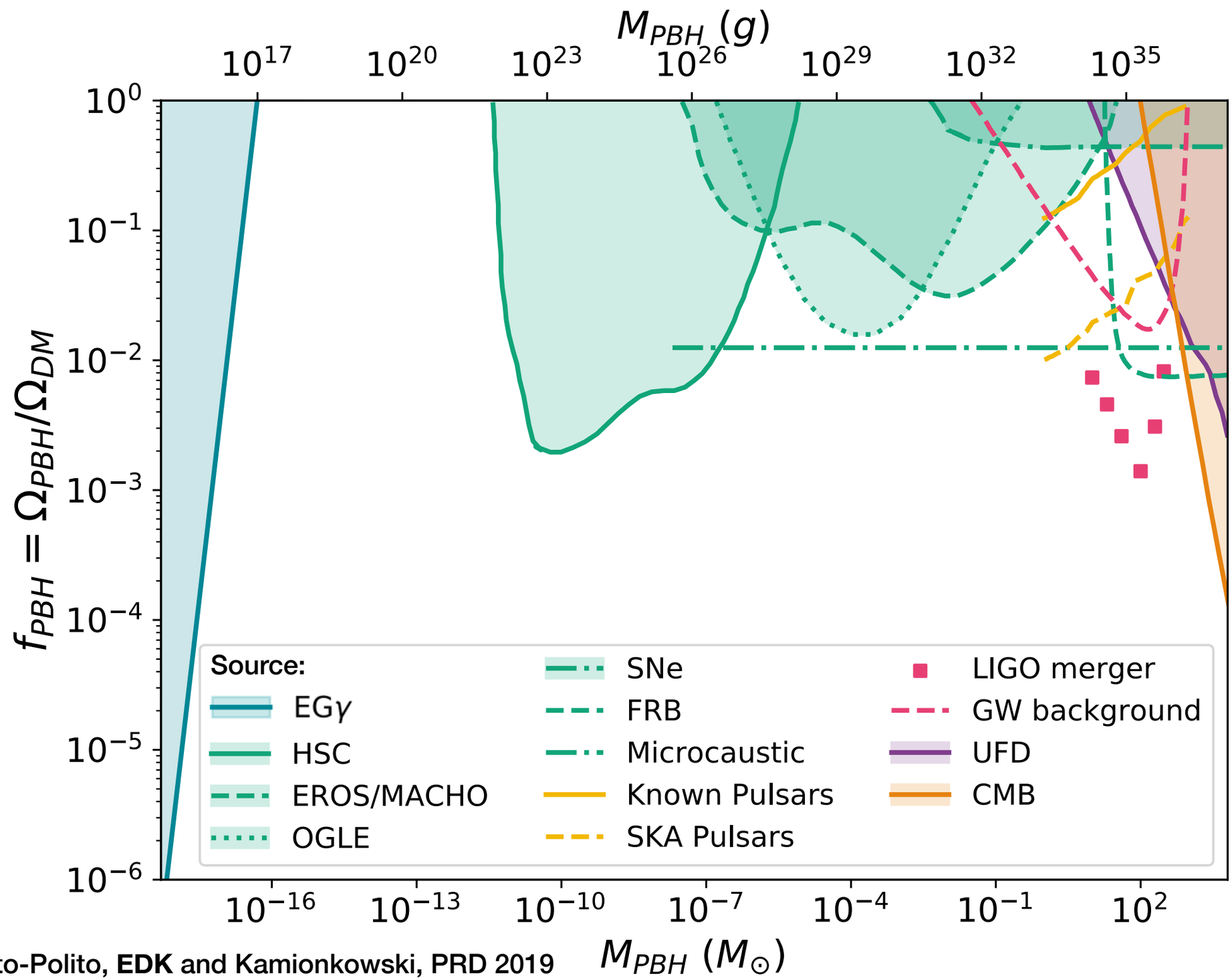

Sato-Polito, **EDK** and Kamionkowski, PRD 2019

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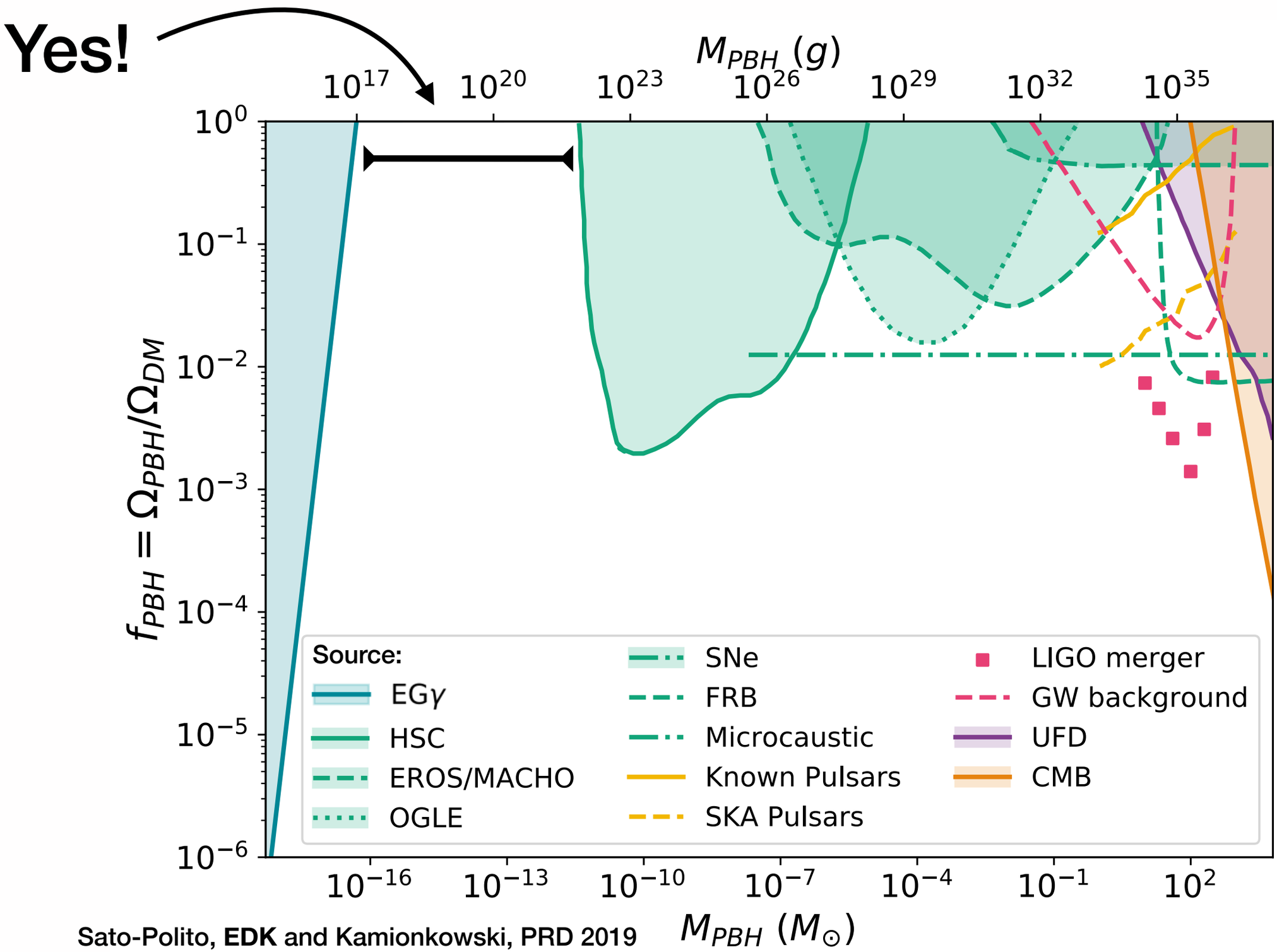

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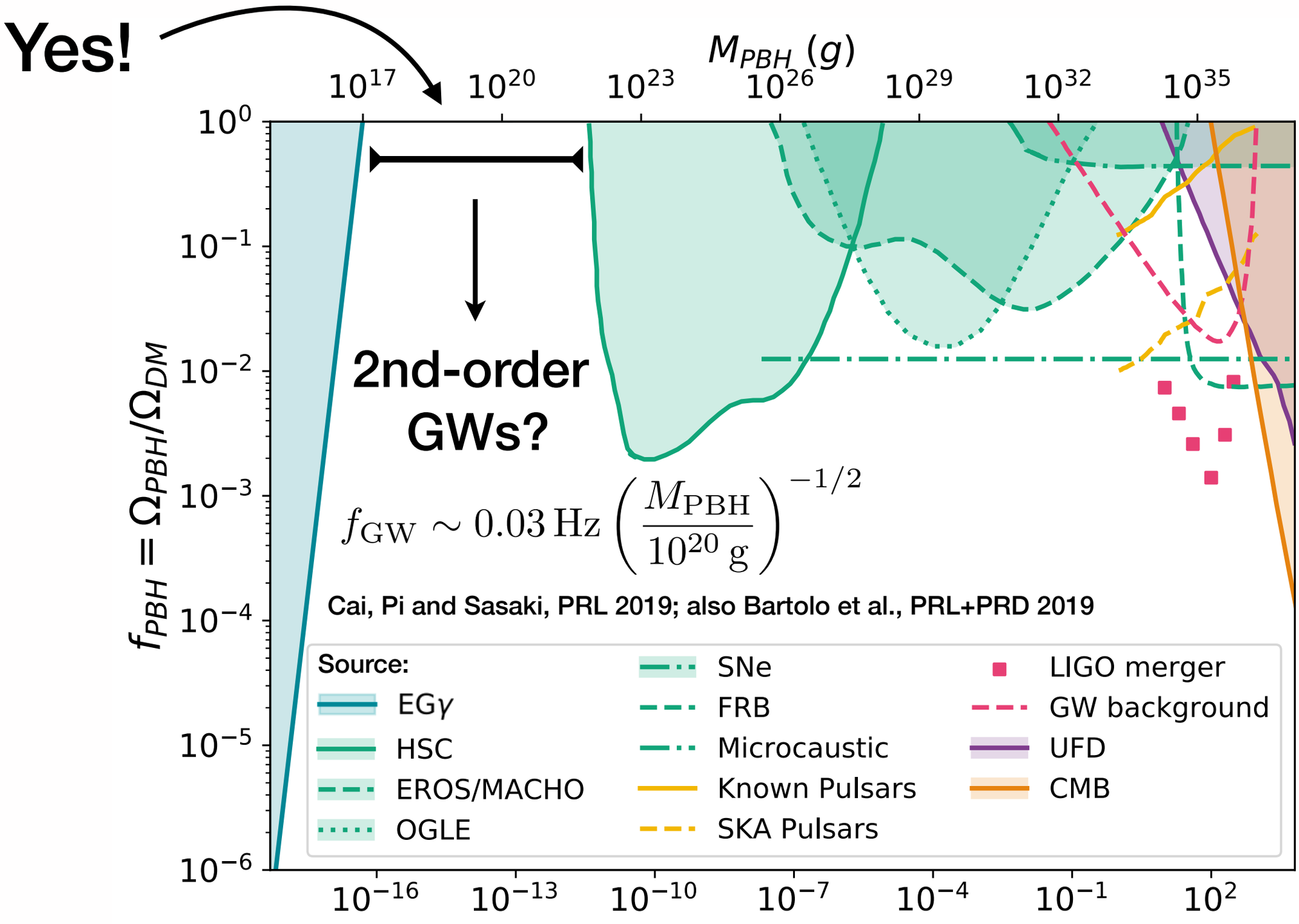

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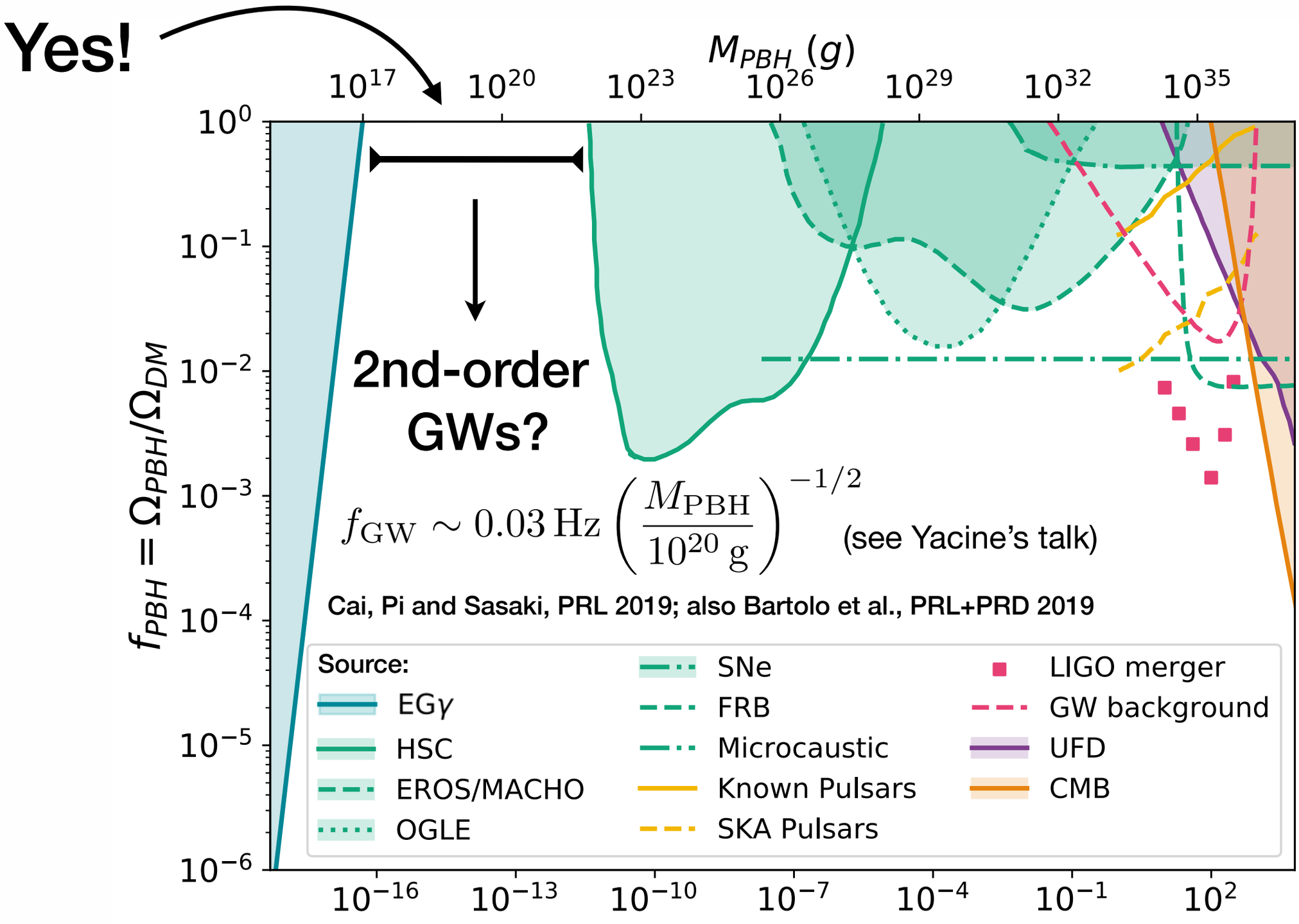

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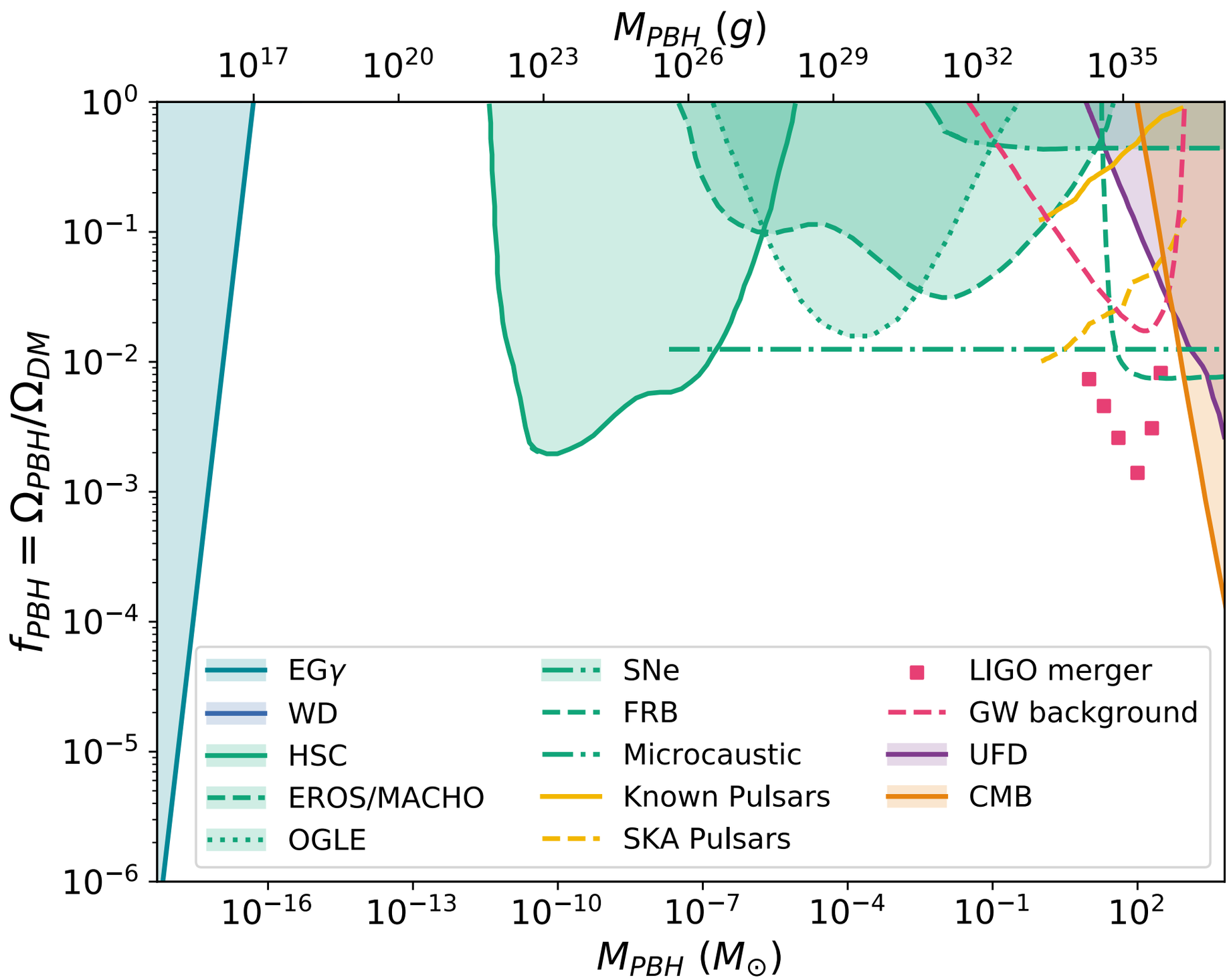
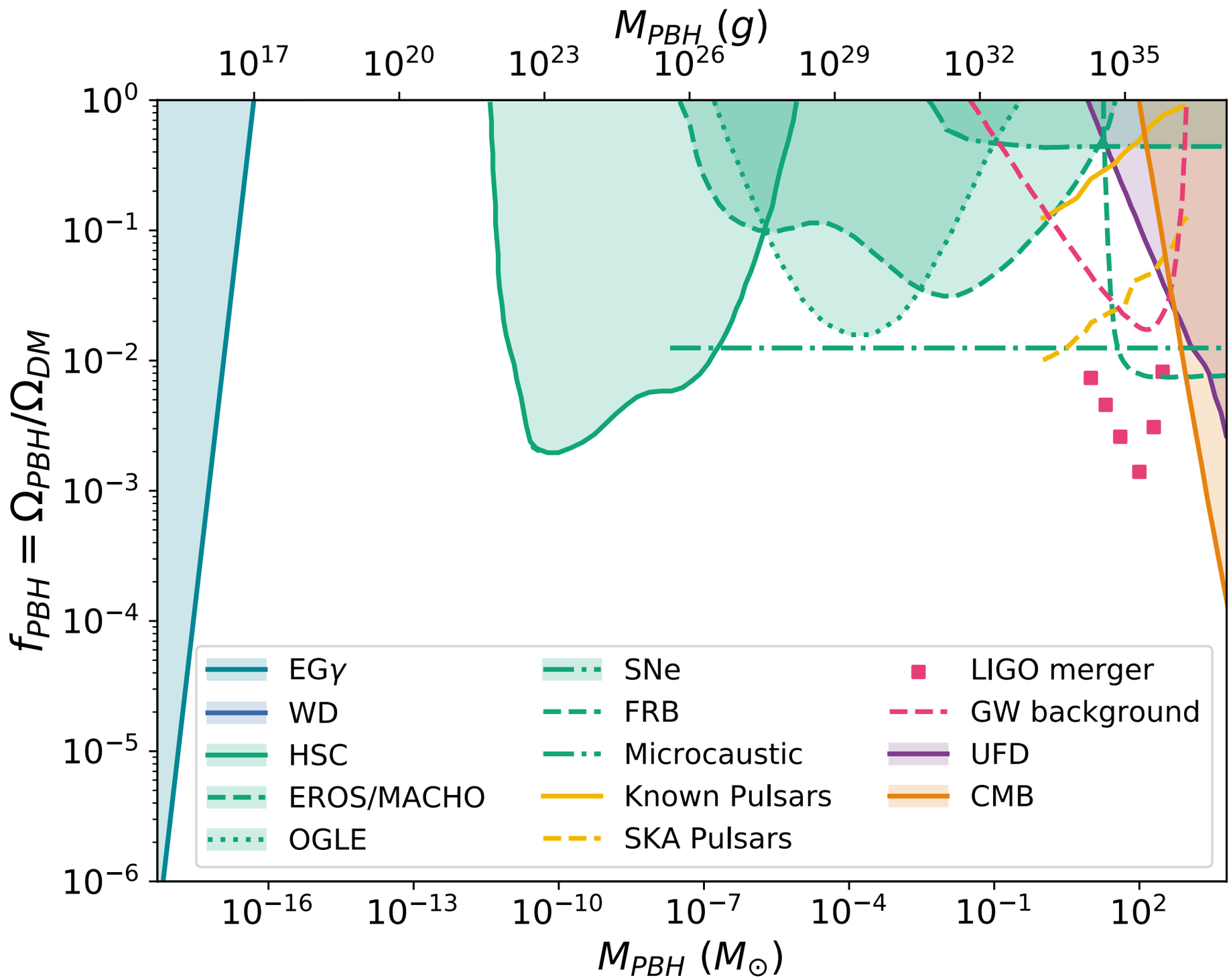
From PBH to Primordial Power Spectrum Limits



From PBH to Primordial Power Spectrum Limits

Convert each limit on PBHs to a limit on the primordial power spectrum amplitude:



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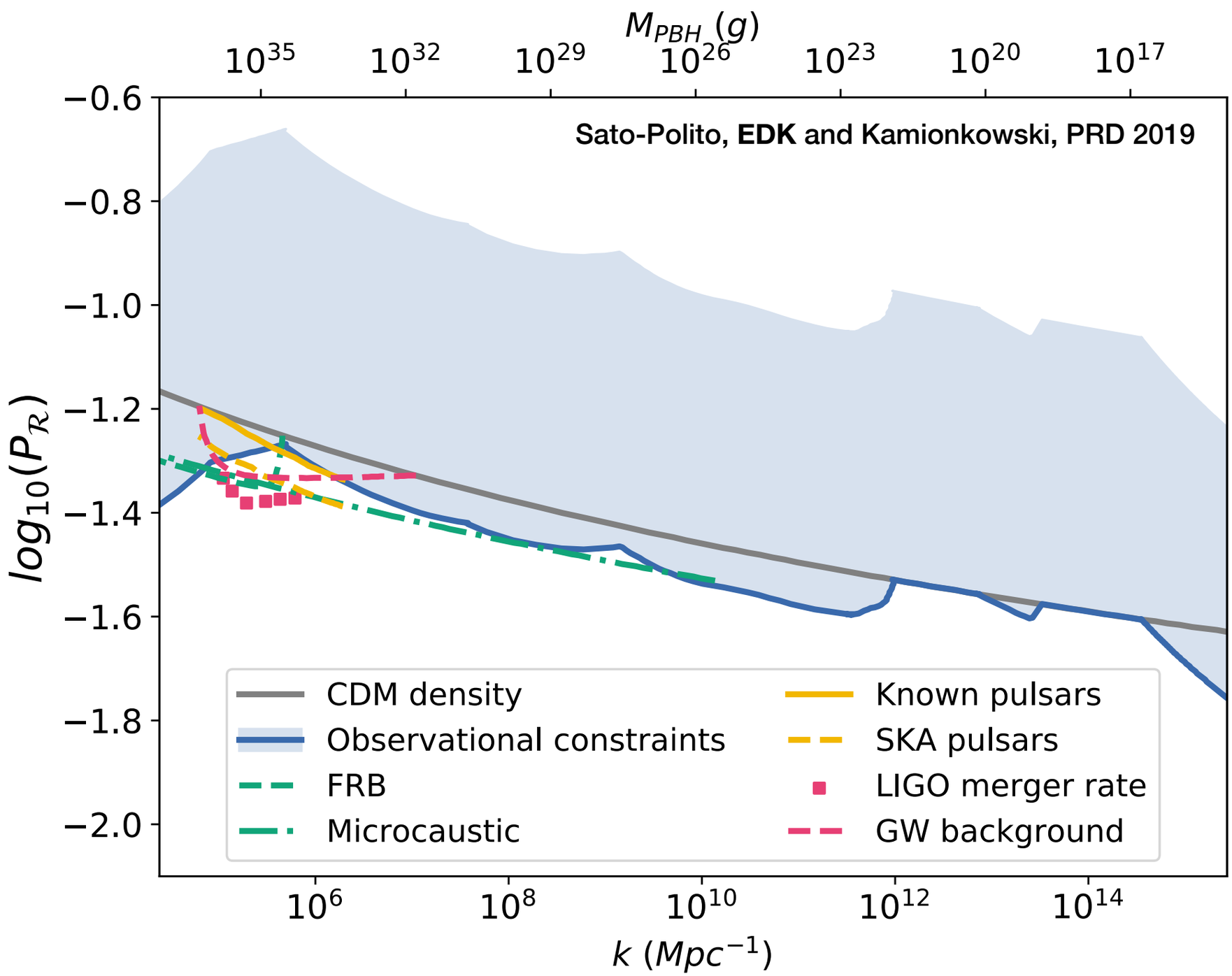

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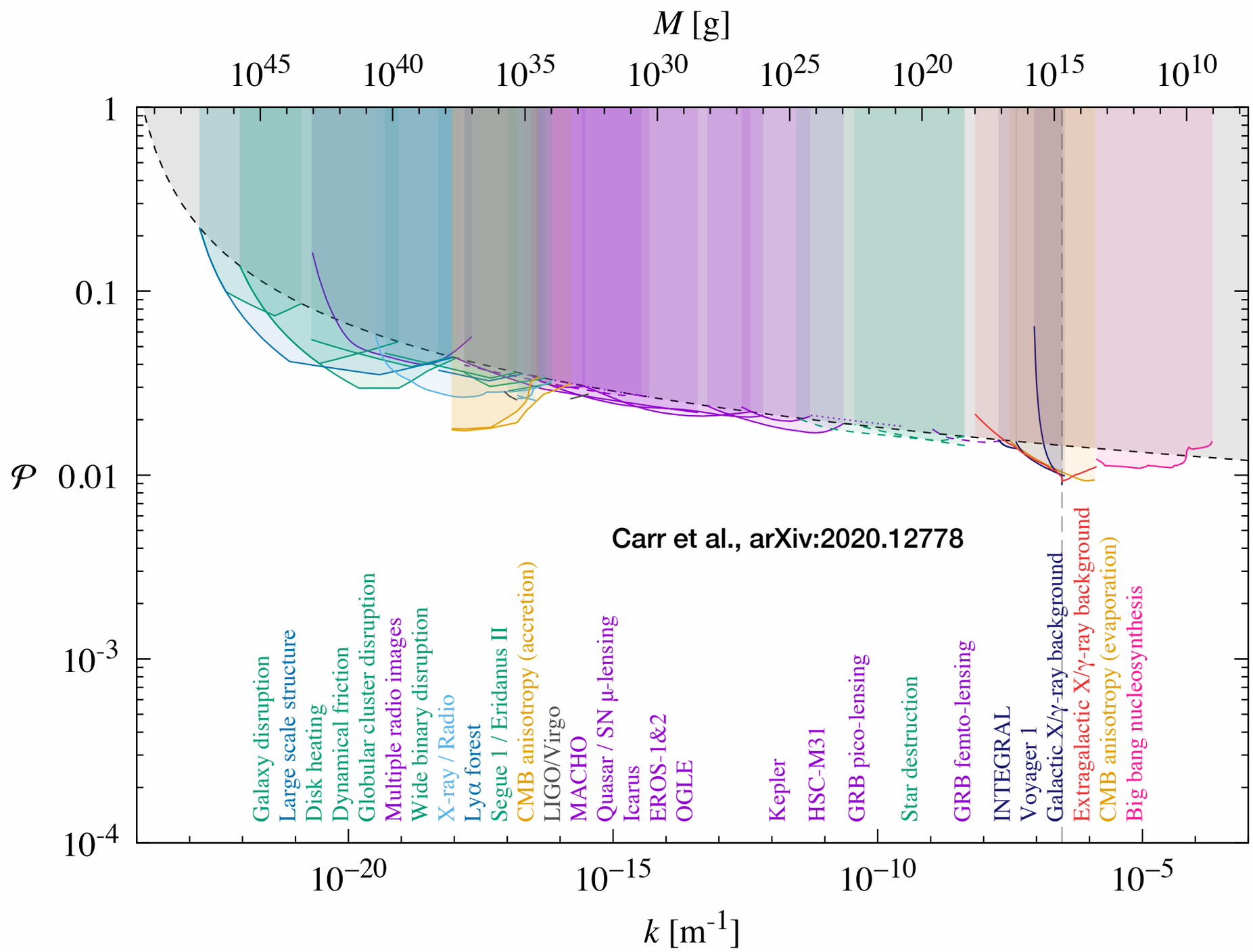
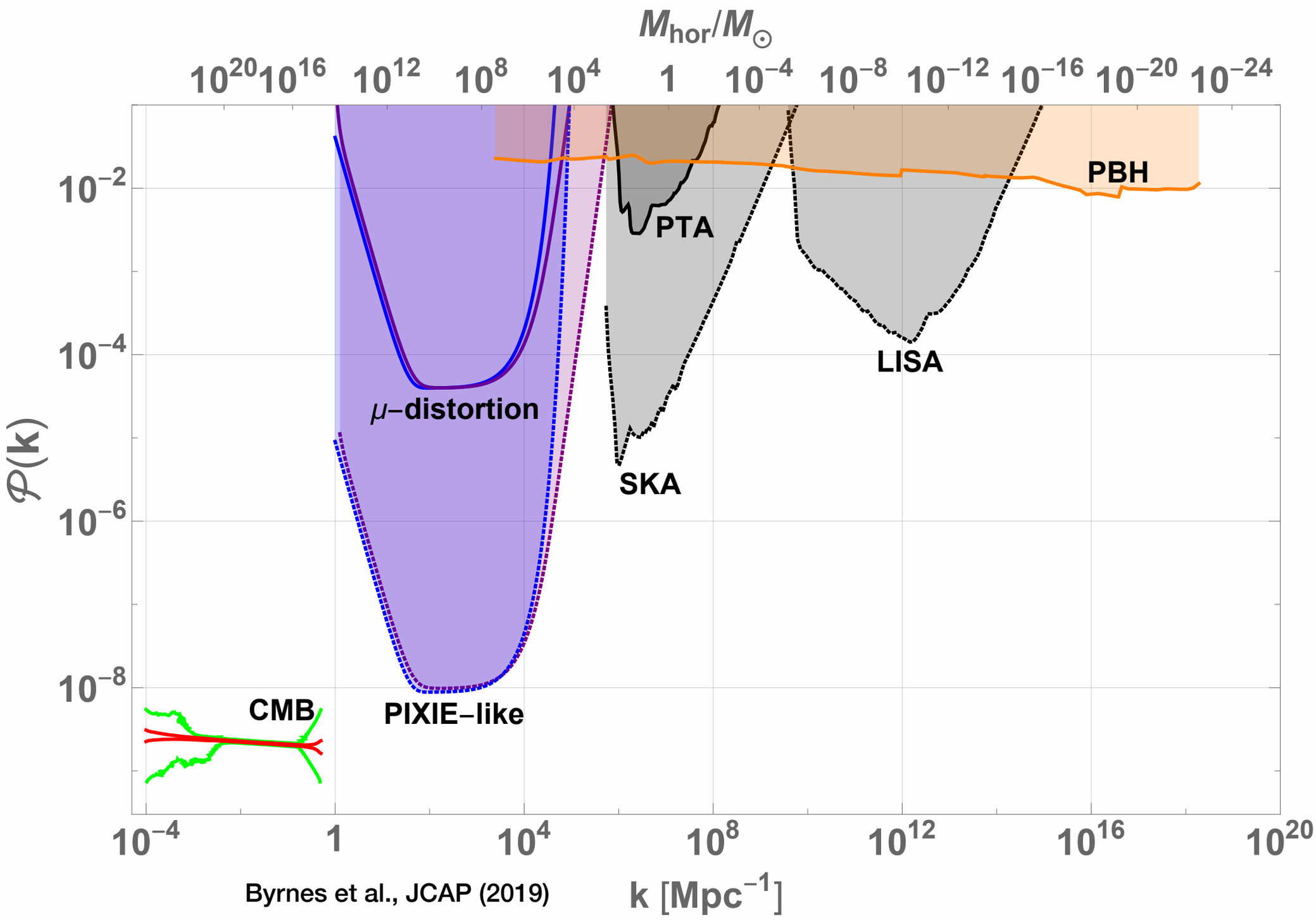


From PBH to Primordial Power Spectrum Limits

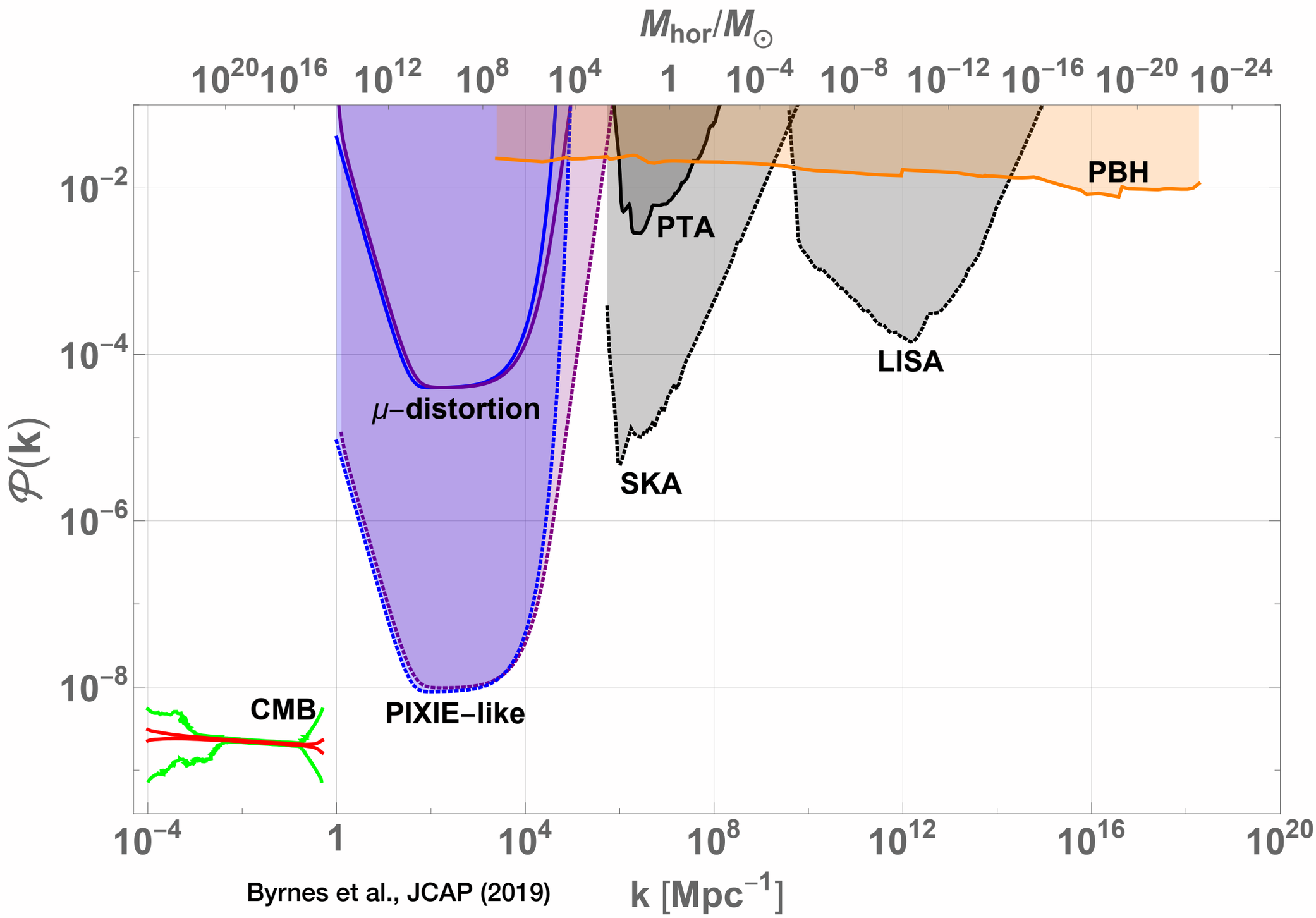
Future constraints:



Byrnes et al., JCAP (2019)

PBHs as SMBH Seeds: Future Tight(!) Constraints

Second-order GW stochastic background can rule out PBH seeds!



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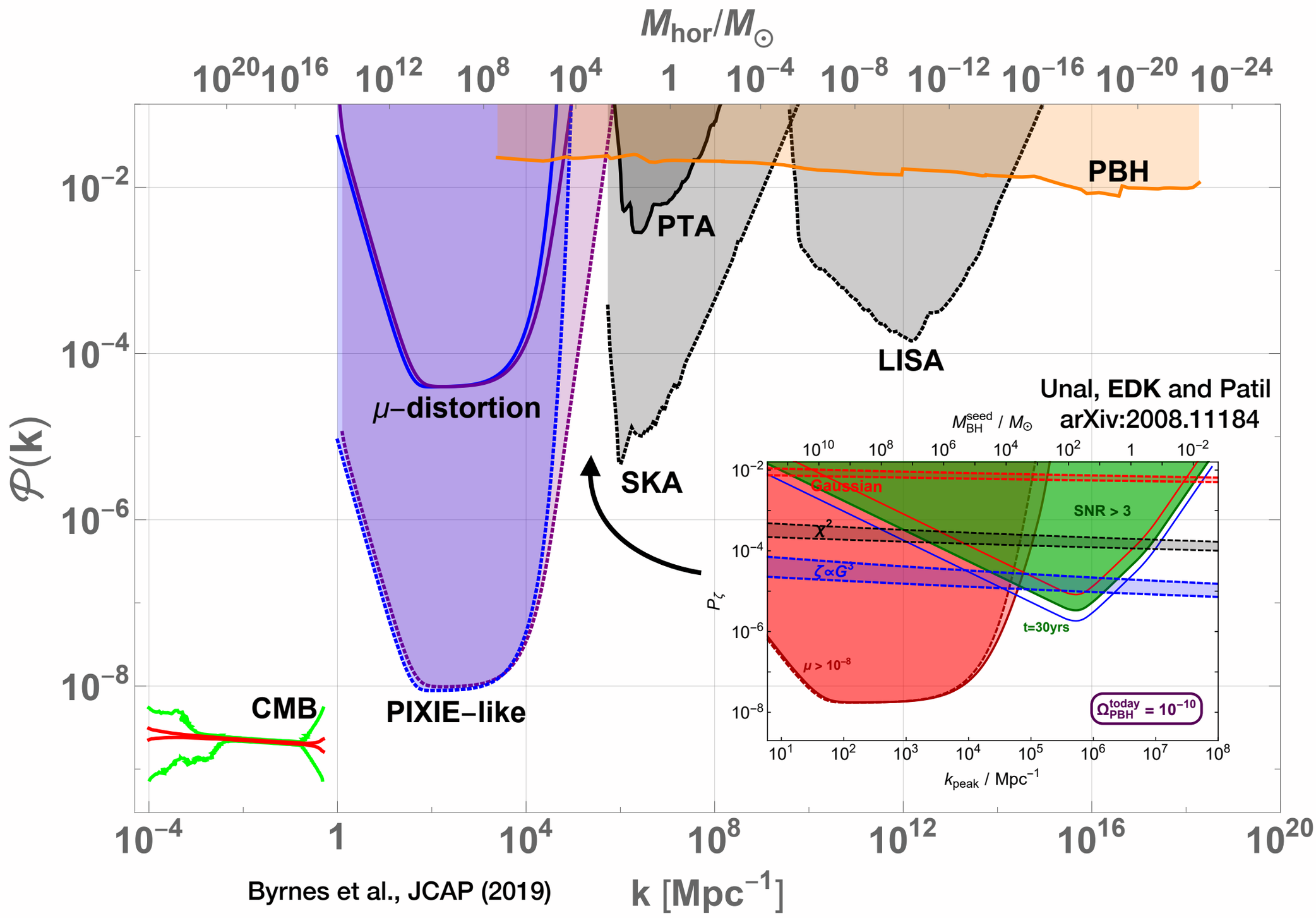

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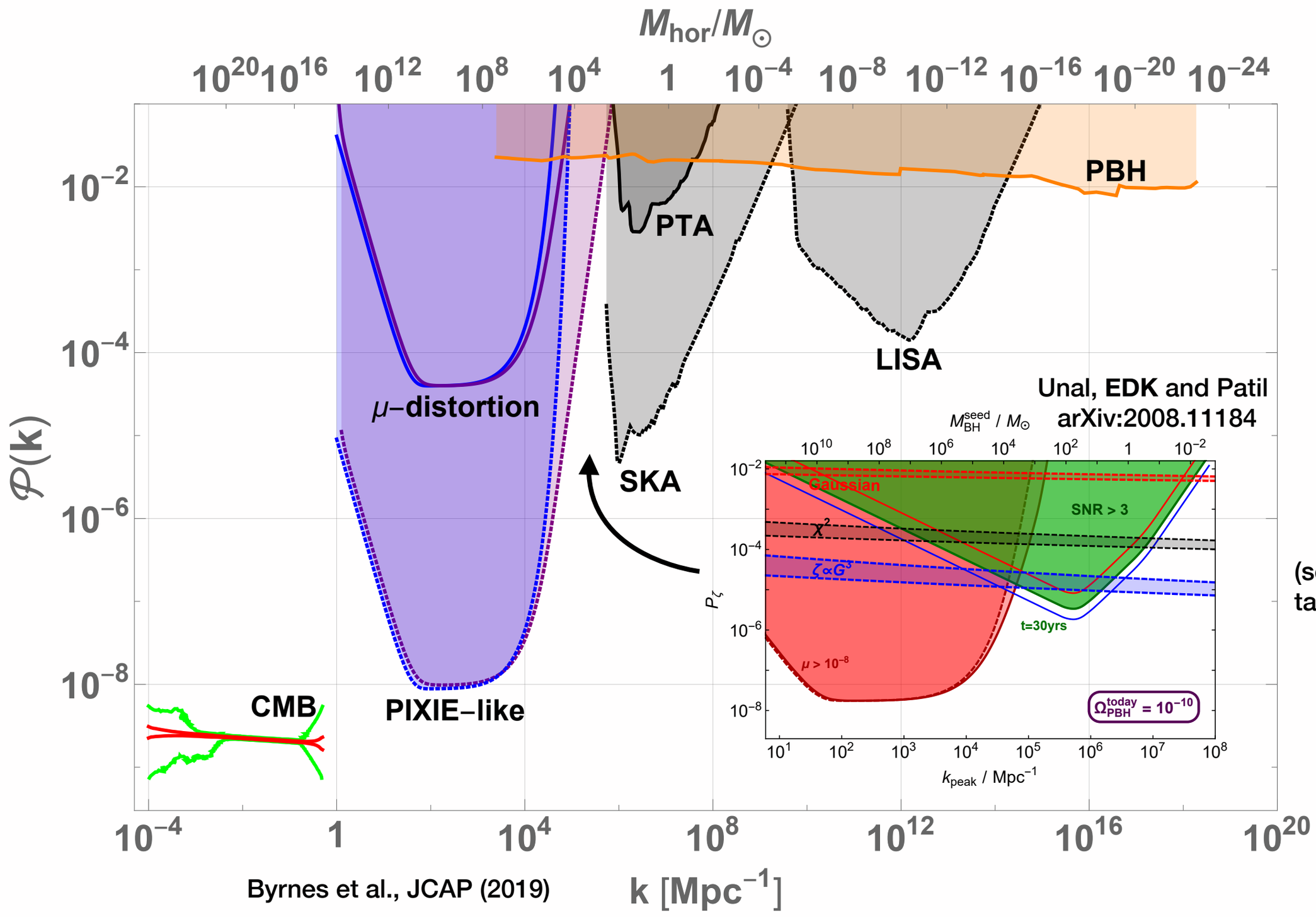


(see Kapadia's talk on Friday!)

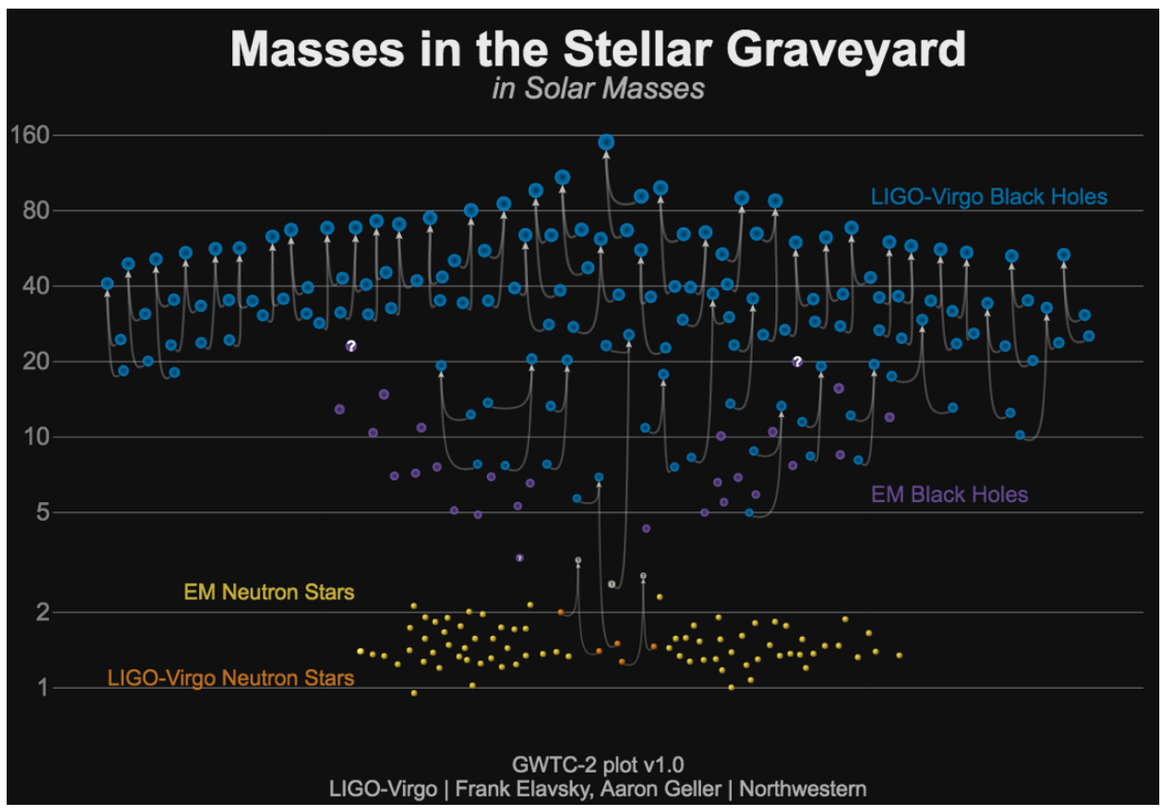
Byrnes et al., JCAP (2019)

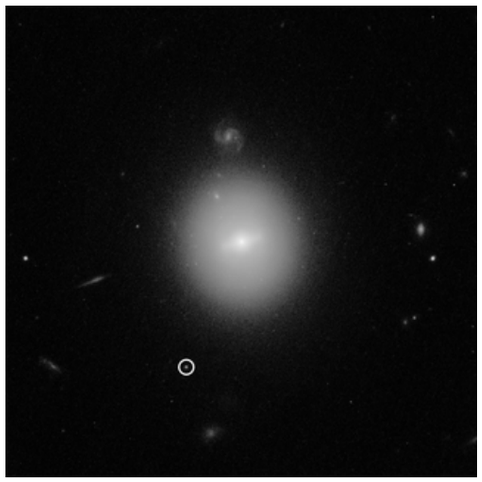
Takeaway:

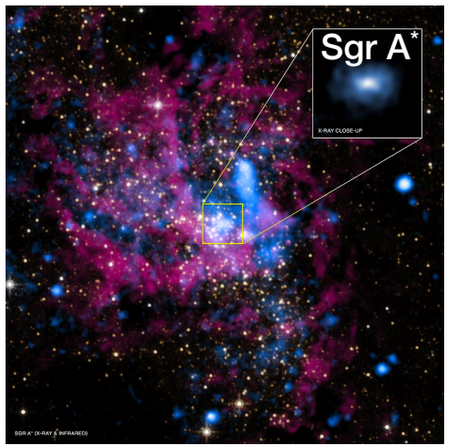
$1\,M_\odot$ — $100\,M_\odot$ — $10^4\,M_\odot$ (?) — $10^6\,M_\odot$ — $10^9\,M_\odot$

Explain Rate/Outliers?

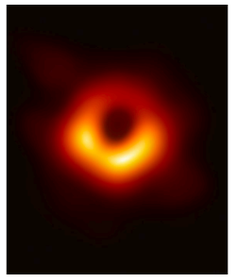
Provide SMBH Seeds?



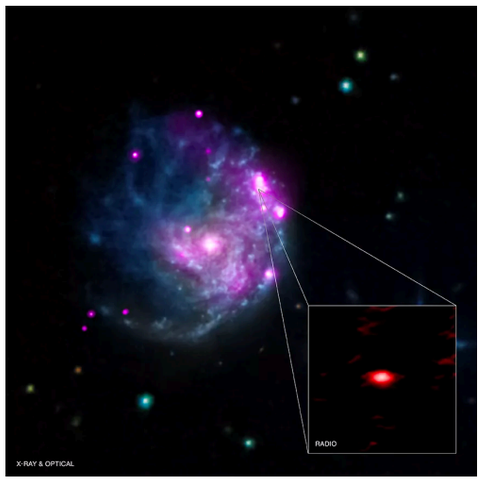


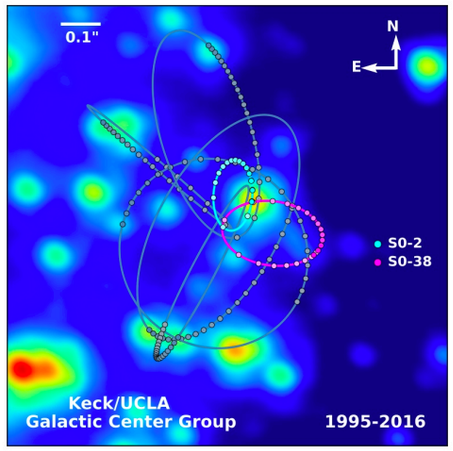


M87 Shadow



EHT (2019)





Primordial + Black: Can They Explain *Dark Matter*?

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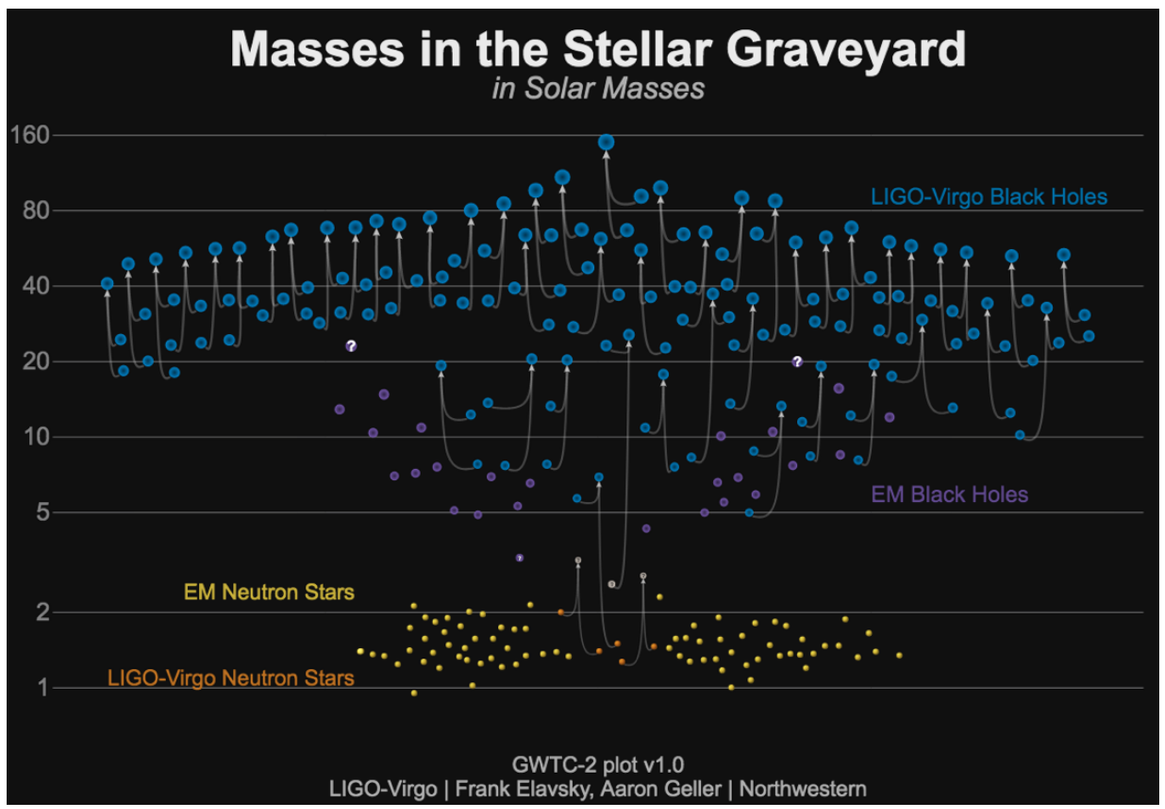

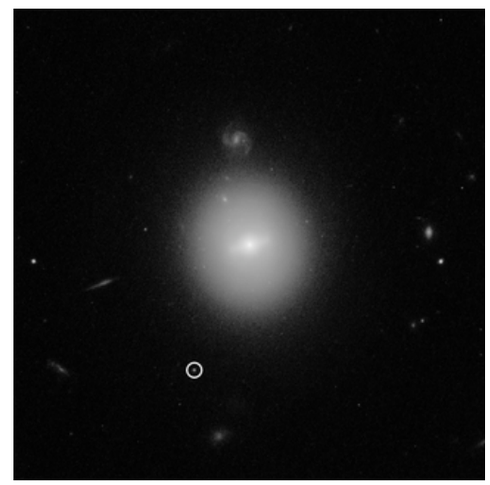

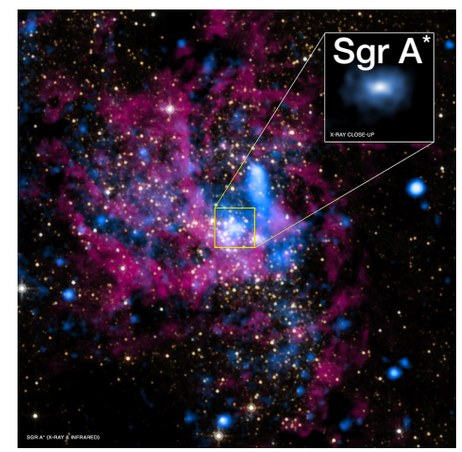

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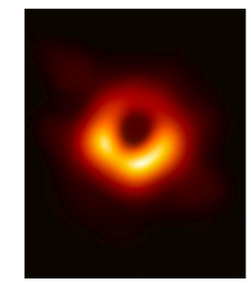

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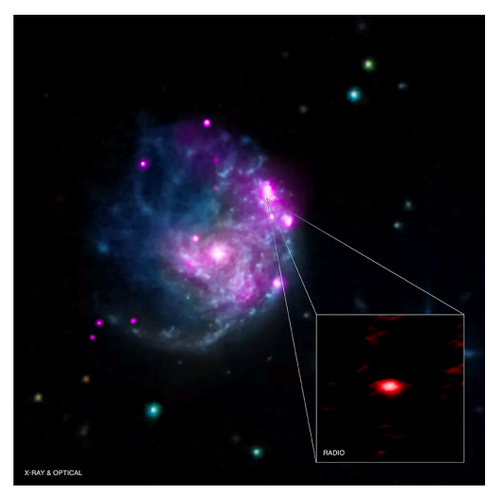

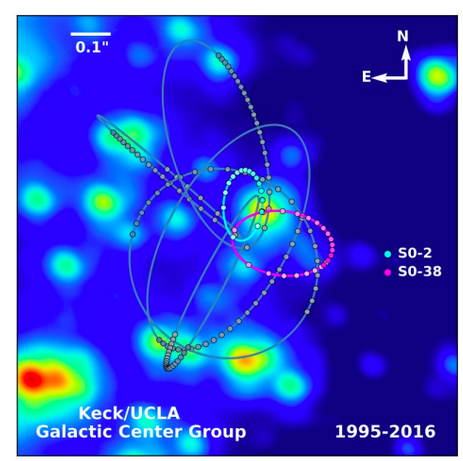

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Takeaway: Lots of Ways to Probe PBH Scenario!

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Theory

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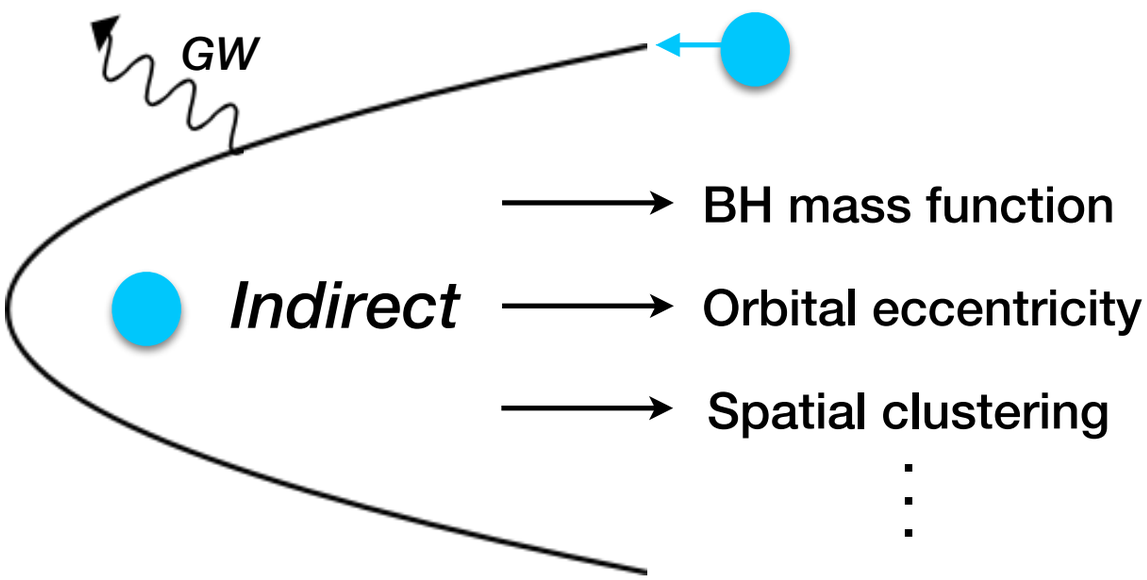

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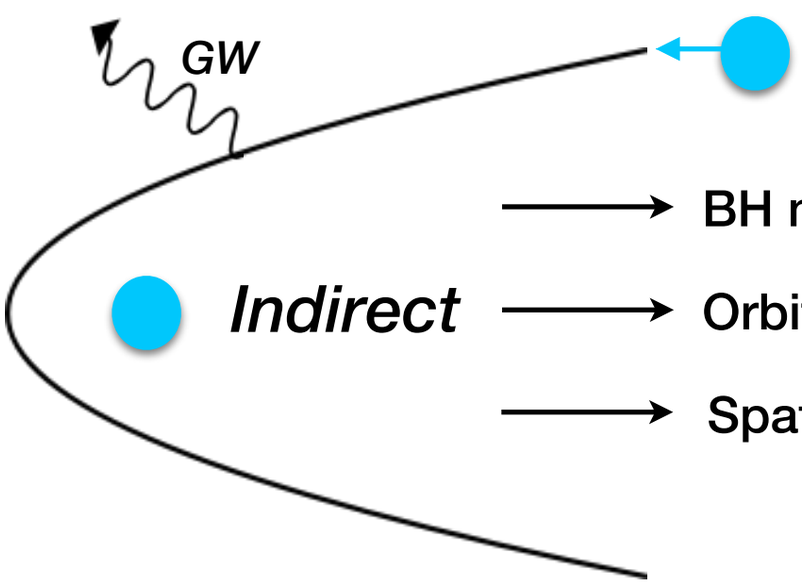


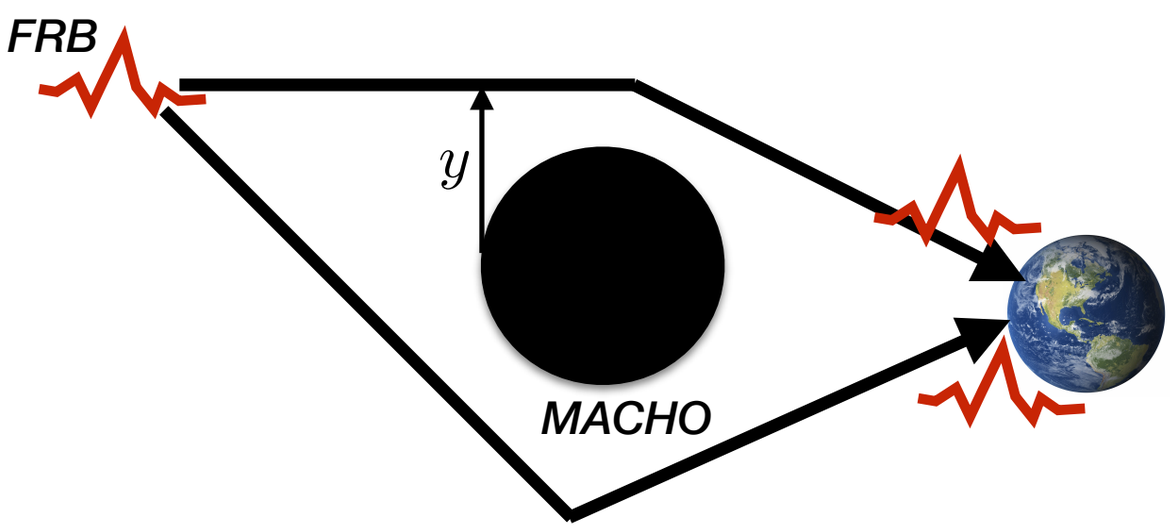
Indirect

→ BH mass function

→ Orbital eccentricity

→ Spatial clustering

⋮



Direct

→ Repeating FRBs

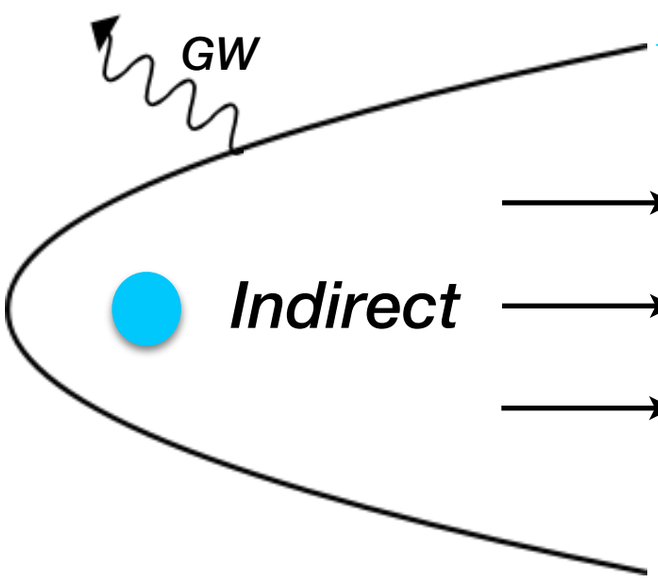
→ SNe Lensing PDF

→ CMB anisotropies

⋮

Takeaway: Lots of Ways to Probe PBH Scenario!

Theory



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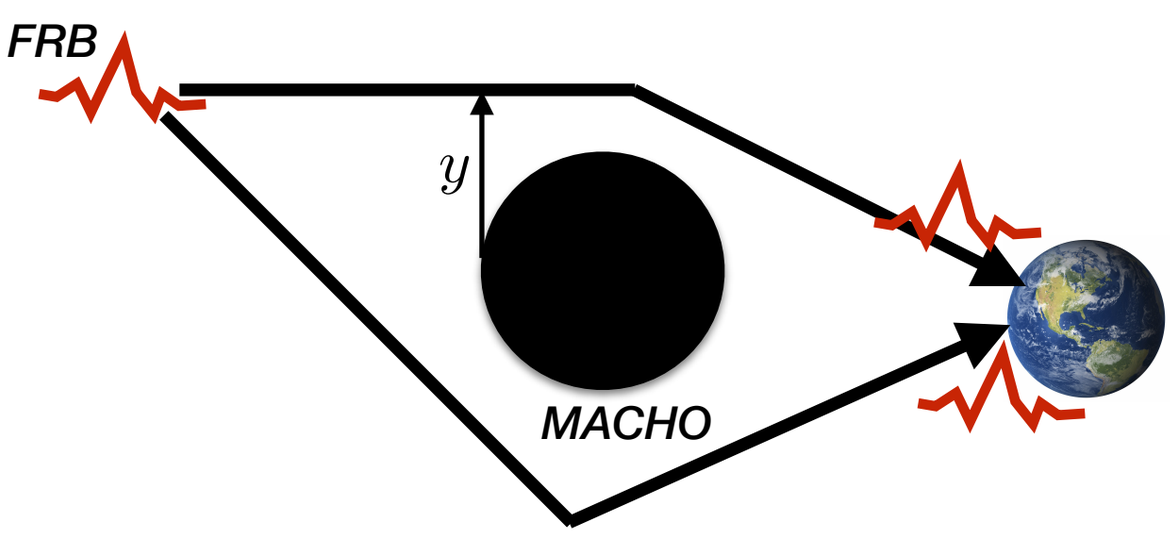

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Experiment

Takeaway: Lots of Ways to Probe PBH Scenario!

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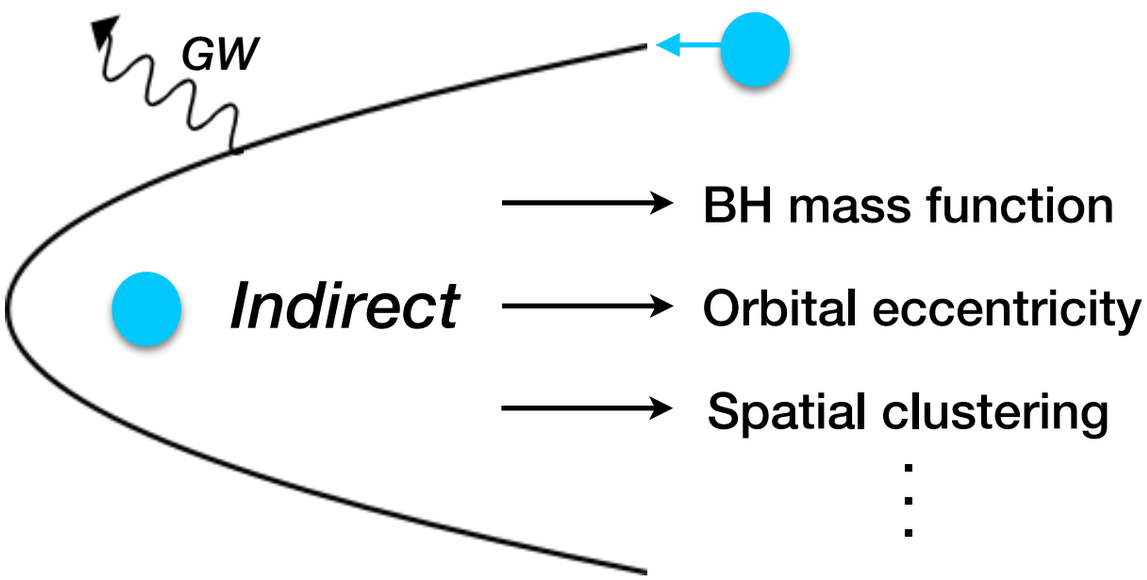

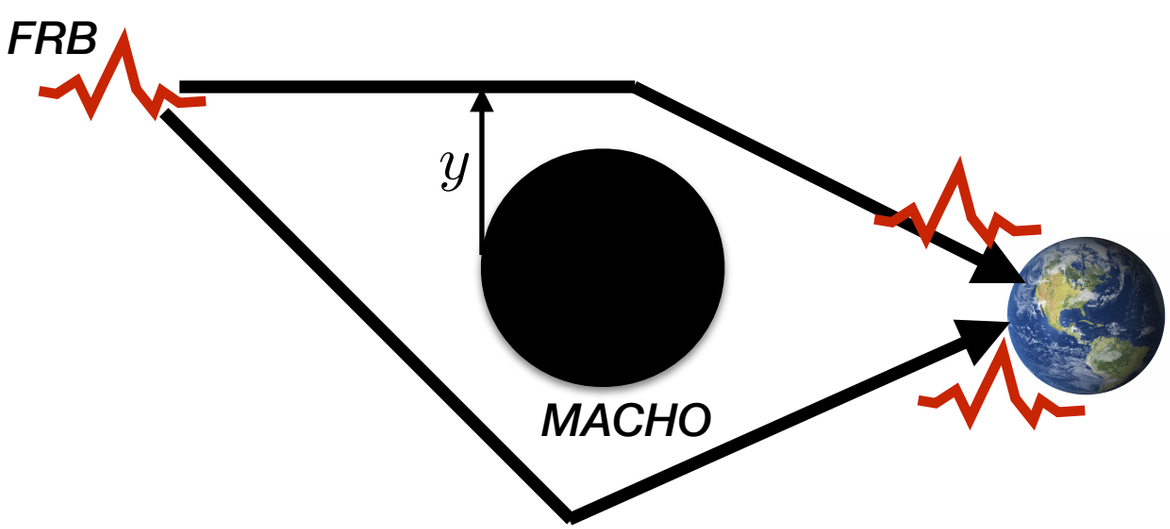

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Experiment

Next Decade is promising!

Thank you!

Ely D. Kovetz
Ben-Gurion University

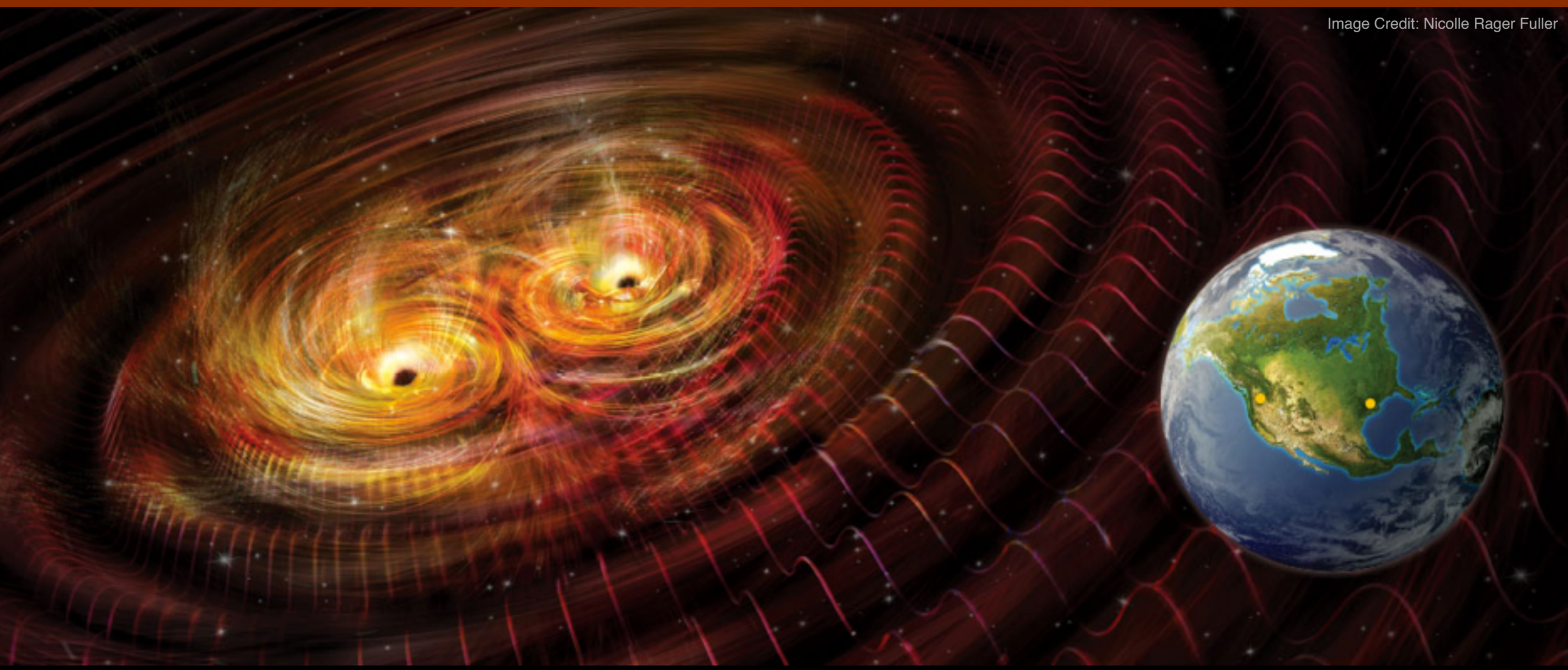

Image Credit: Nicolle Rager Fuller

Thank you!

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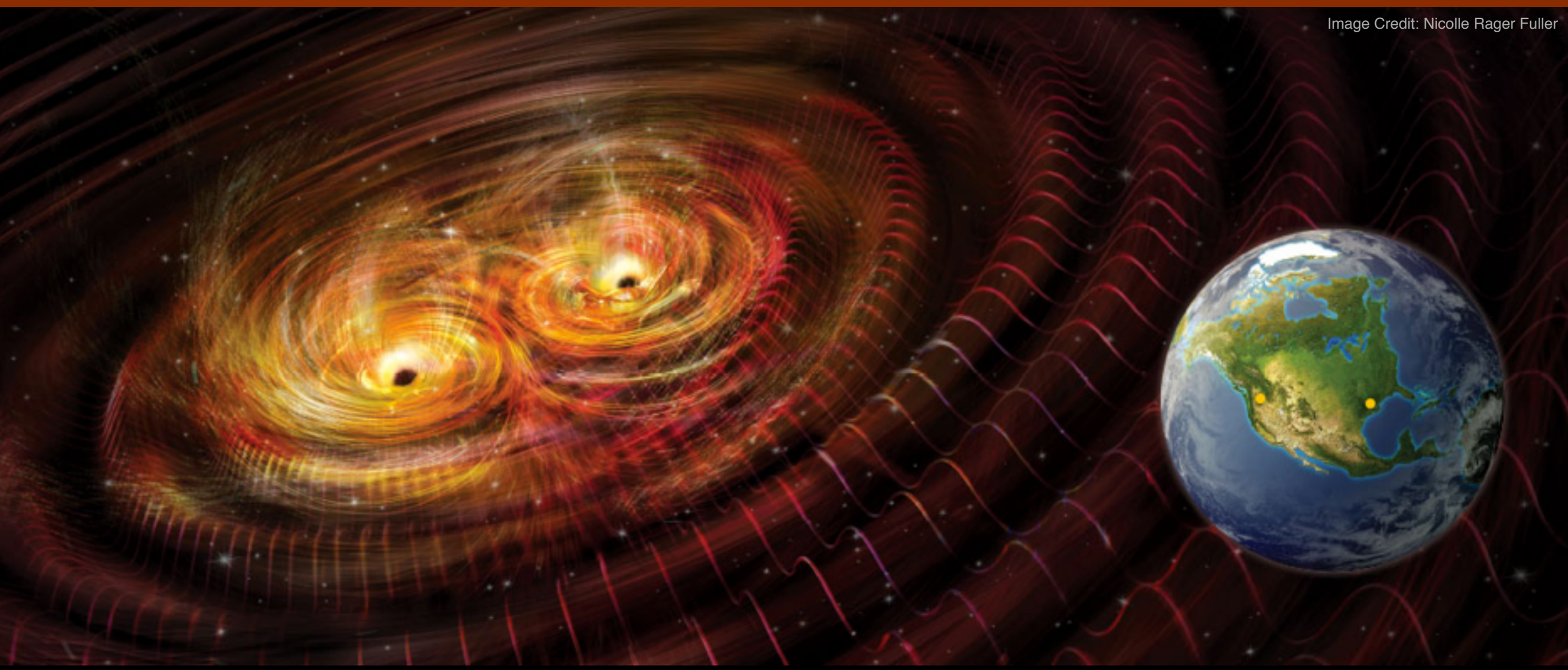

Image Credit: Nicolle Rager Fuller