Current status of Primordial Black Holes

ICTS, Less Travelled Path DM, 11th Nov 2020

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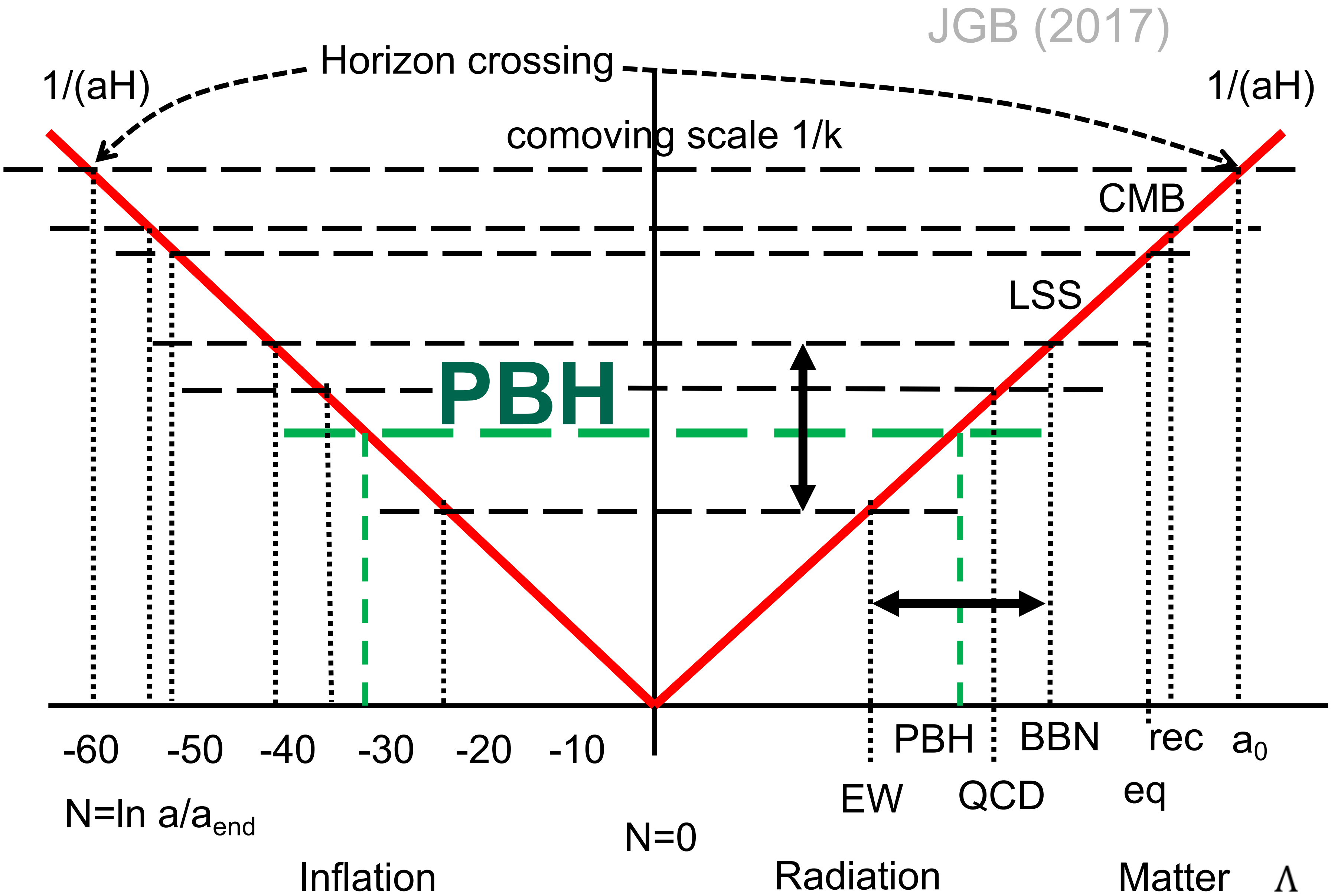
PBH scenario (1996-2020)

- From Quantum Fluctuations during inflation to PBH as all of DM
- Quantum diffusion → NG tails → PBH inevitable @ small scales
- Gravitational collapse during radiation era: Thermal History
- Origin of matter (baryons) and DM at QCD transition: $\Omega_{\rm DM} \sim 5\Omega_{\rm B}$
- Multimodal mass distribution PBH: 10^{-5}, 1, 50, 10^{5} Msun
- PNG → Clustered PBH: 10^{4} Msun evades all “monochromatic”
- Seeds for Large Scale Structure: IMBH and SMBH
- Resolve Small Scale Structure crisis: UFDG, core-cusp, etc.
- Very rich phenomenology: wealth of observational signatures
- Gravitational Lensing probes: strong, weak, micro, etc.
- Gravitational Waves probe: mass, spin, merger rate, clustering
- CMB spectral distortions: mass range, clustering prop. PBH
- Galactic structures: UFDG, rot. curves, MBH(Mhalo), HVS-GAIA
- Bright future: G3 GWO ET & LISA, LSST, Pixie, Theia,

Inflation


JGB (2017)
Horizon crossing
1/(aH)
1/(aH)
comoving scale 1/k
CMB
LSS
PBH
-60
-50
-40
-30
-20
-10
N=ln a/a_end
N=0
EW
PBH
QCD
BBN
eq
rec
a0
Inflation
Radiation
Matter
Λ

Critical Higgs Inflation

Standard Model Lagrangian

Ezquiaga, JGB, Ruiz Morales (2017)

$$
\begin{aligned}
\mathcal{L} = & -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi) \\
& + \xi |\phi|^2 R
\end{aligned}
$$

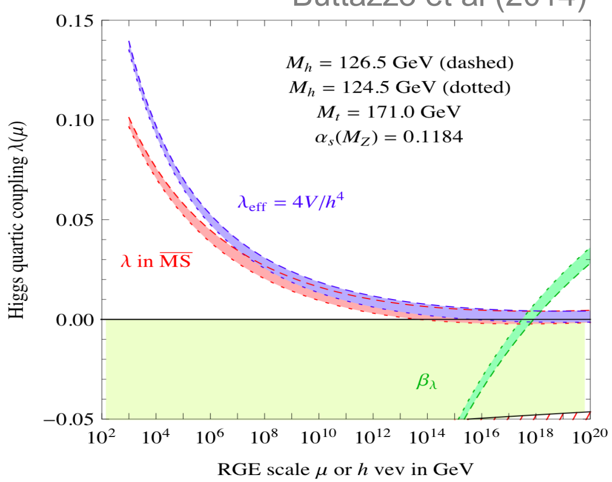
$$S=\int d^4x\sqrt{g}\left[\left(\frac{1}{2\kappa^2}+\frac{\xi(\phi)}{2}\phi^2\right)R-\frac{1}{2}(\partial\phi)^2-\frac{1}{4}\lambda(\phi)\phi^4\right]$$

$$\lambda(\phi) \;=\; \lambda_0 + b_\lambda \ln^2(\phi/\mu)\ ,$$

$$\xi(\phi) \;=\; \xi_0 + b_\xi \ln(\phi/\mu)\ ,$$

$$\frac{d\varphi}{d\phi}=\frac{\sqrt{1+\xi(\phi)\,\phi^2+6\,\phi^2\,(\xi(\phi)+\phi\,\xi'(\phi)/2)^2}}{1+\xi(\phi)\,\phi^2}$$

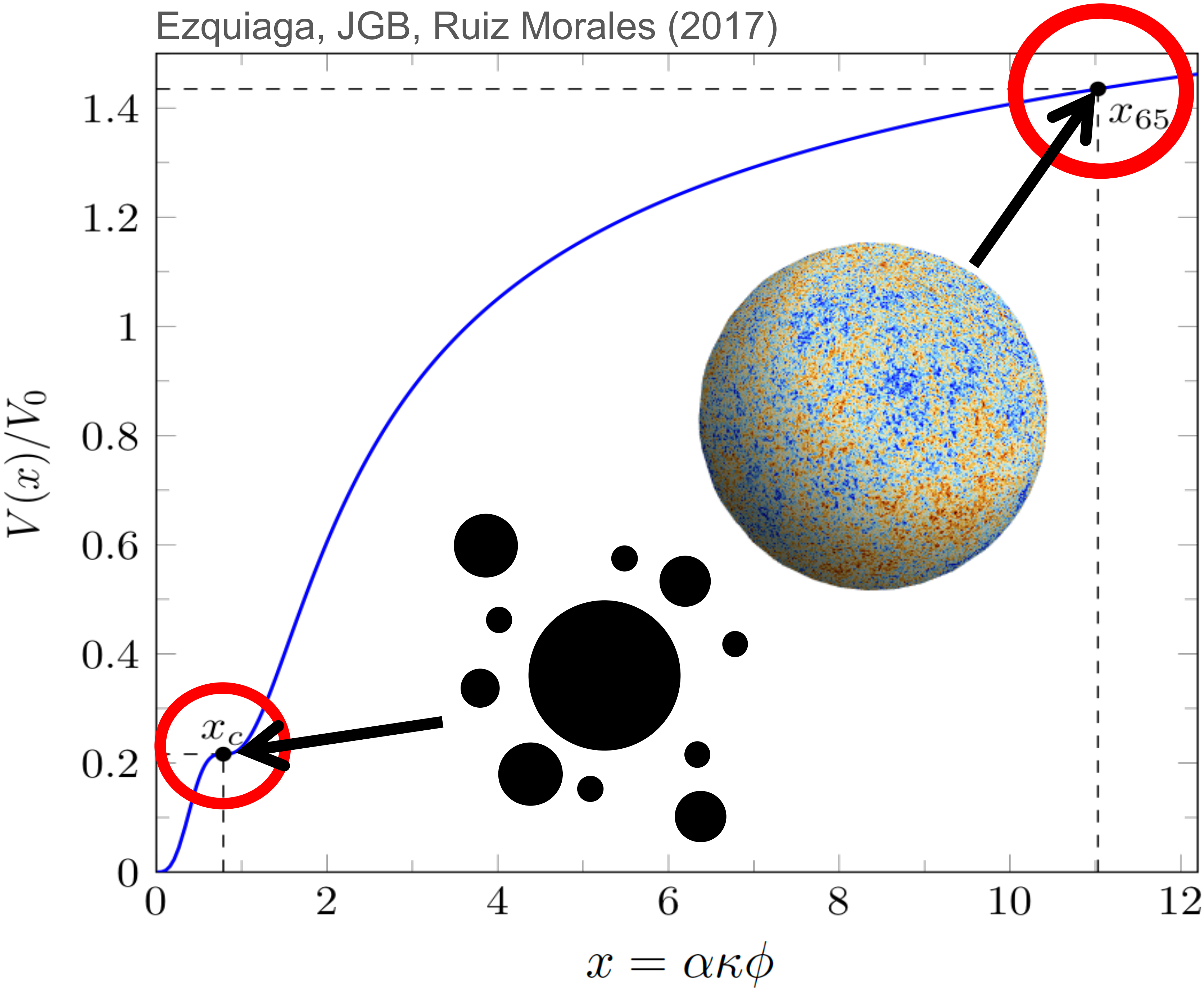
Buttazzo et al (2014)



$$V(x)=\frac{V_0\,(1+a\,\ln^2 x)\,x^4}{(1+c\,(1+b\,\ln x)\,x^2)^2} \qquad x=\phi/\mu$$

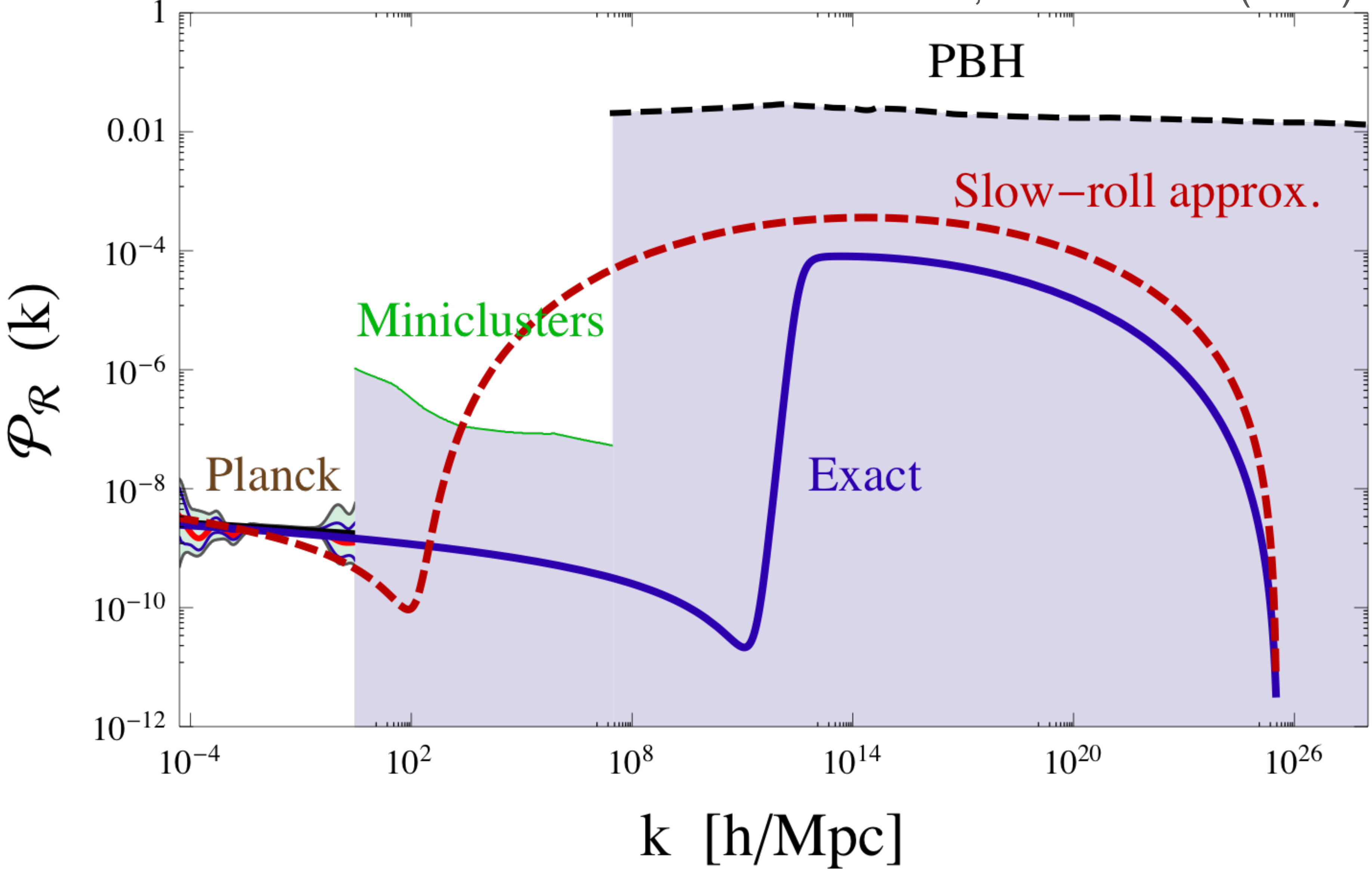
$$V_0=\lambda_0\mu^4/4,\ a=b_\lambda/\lambda_0,\ b=b_\xi/\xi_0 \text{ and } c=\xi_0\,\kappa^2\mu^2$$

Ezquiaga, JGB, Ruiz Morales (2017)



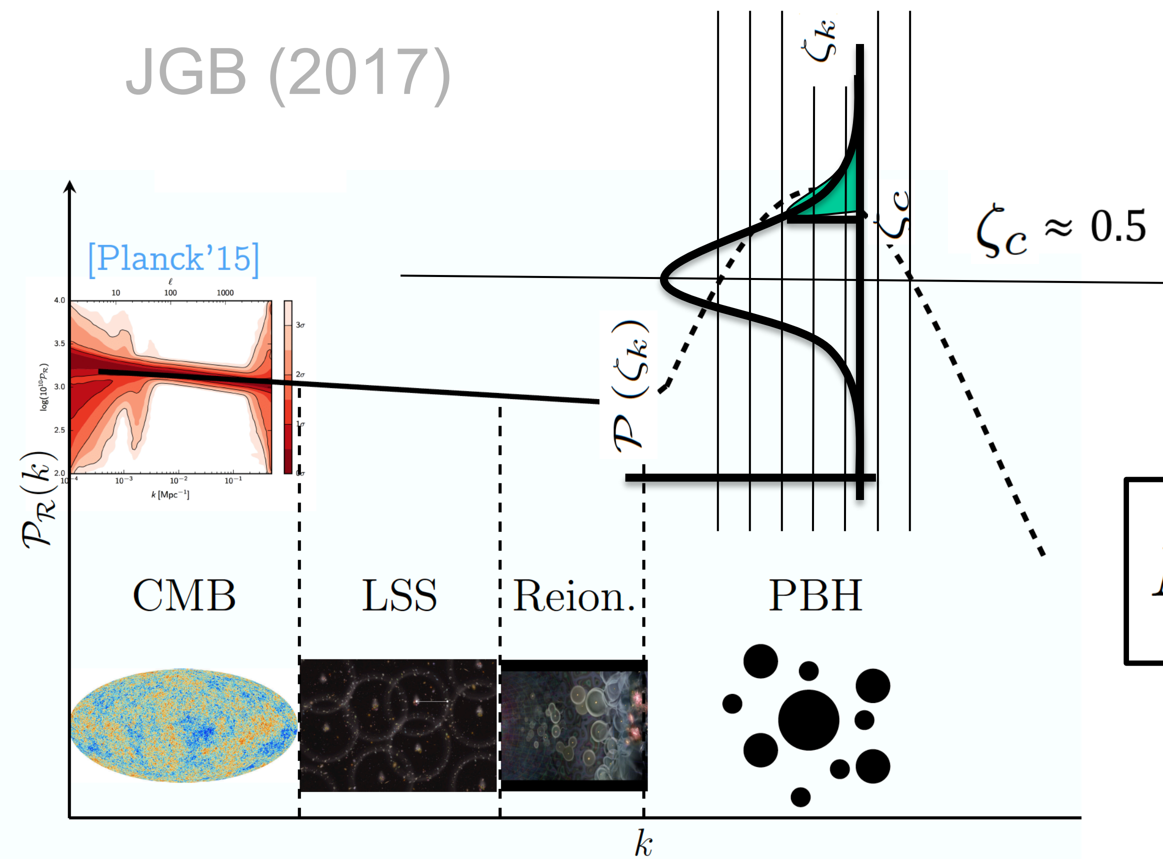
Primordial Spectrum PBH

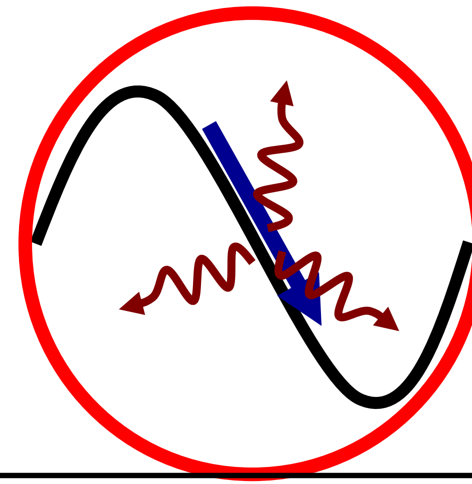
JGB, Ruiz Morales (2017)



Gravitational Collapse of PBH

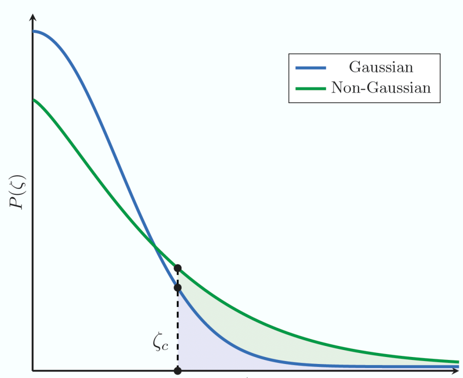
JGB (2017)





$$\boxed{M_{\rm PBH} \simeq 30\, M_\odot\, e^{2(N-36)}}$$

$$\beta^{\rm form}(M_k) = \int_{\zeta_c}^{\infty} \mathcal{P}(\zeta_k)\, d\zeta_k$$



$$\beta(N) = \begin{cases} \mathrm{Erfc}\left(\dfrac{\zeta_c}{\sqrt{2P_\zeta(N)}}\right) , & \text{Gaussian statistics} , \\ \mathrm{Erfc}\left(\sqrt{\dfrac{1}{2} + \dfrac{\zeta_c}{\sqrt{2P_\zeta(N)}}}\right) , & \chi^2 \ \text{ statistics} \end{cases}$$

Stochastic δN - formalism

Coarse-grained curvature perturbation

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)e^{2\zeta(t,\mathbf{x})}\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j \qquad \zeta_{\rm cg}(\mathbf{x}) = \delta N_{\rm cg}(\mathbf{x}) = \mathcal{N}(\mathbf{x}) - \langle\mathcal{N}\rangle$$

$$\frac{1}{M_{\rm pl}^2}\frac{\mathrm{d}}{\mathrm{d}\mathcal{N}}P_{\mathbf{\Phi}}(\mathcal{N}) = \left(-\sum_i \frac{v_{\phi_i}}{v}\frac{\partial}{\partial\phi_i} + v\sum_i\frac{\partial^2}{\partial\phi_i^2}\right)\cdot P_{\mathbf{\Phi}}(\mathcal{N})$$

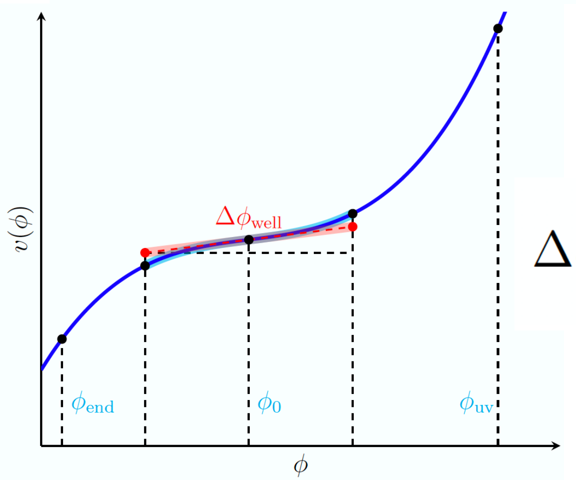
Fokker-Planck Diffusion Eq.

Determined by the poles of the characteristic function

$$P_\phi(\mathcal{N}) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-it\mathcal{N}}\chi_{\mathcal{N}}(t,\phi)dt = \sum_n a_n(\phi)\, e^{-\Lambda_n\mathcal{N}}$$

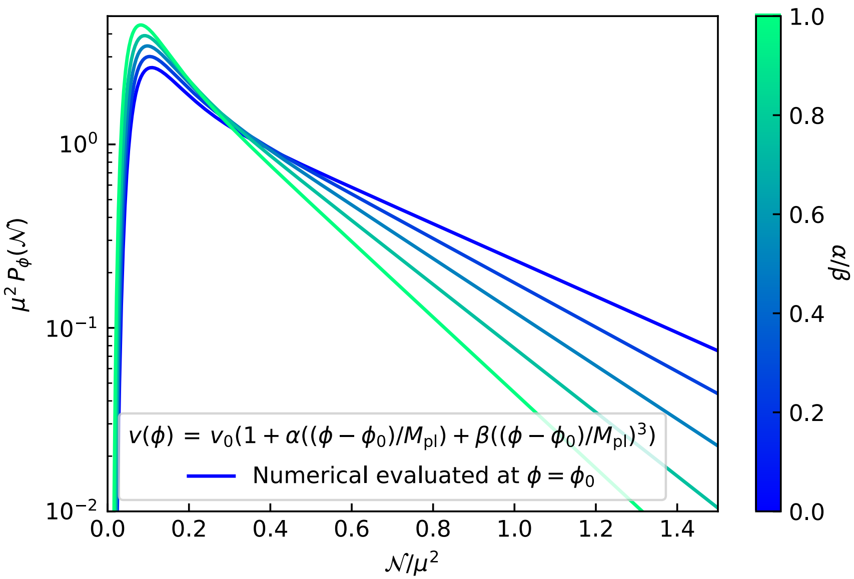
$$\chi_{\mathcal{N}}(t,\phi) = \sum_n \frac{a_n(\phi)}{\Lambda_n - it} + \text{regular func.}$$

Ezquiaga, JGB, Vennin (2019)

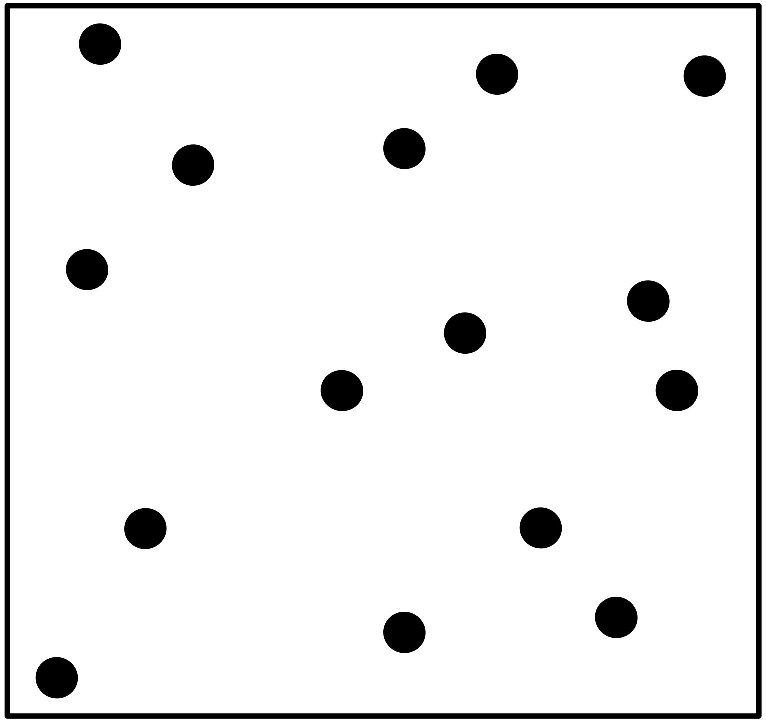


$$\alpha \gg (v_0^2\beta)^{1/3}$$

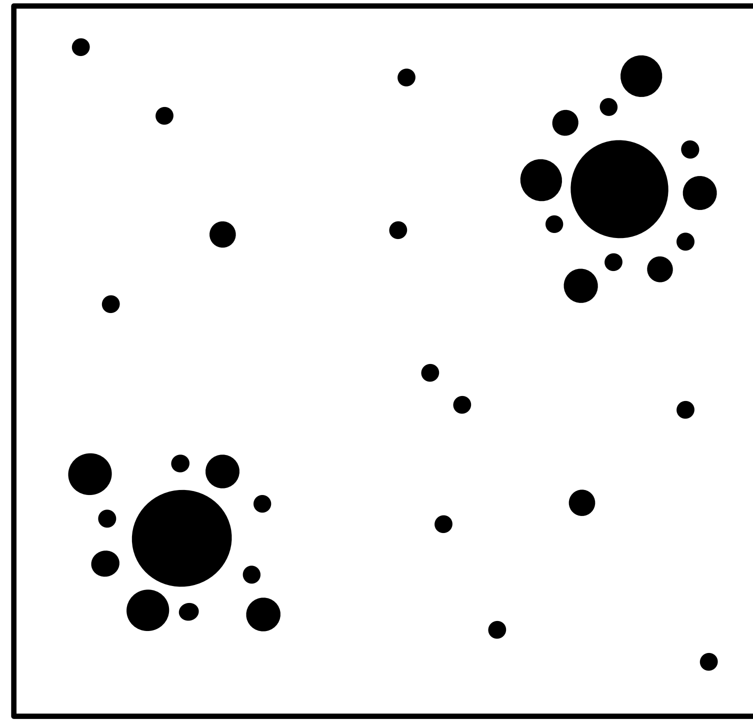
$$\Delta\phi_{\rm well} \simeq 2M_{\rm pl}\sqrt{\frac{\alpha}{3\beta}}$$



Spatial Distribution PBH



- Monochromatic
- Uniformly distributed

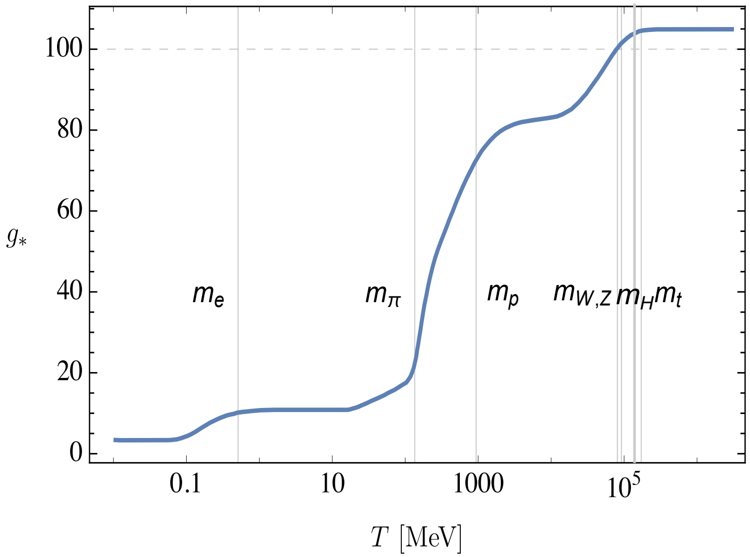


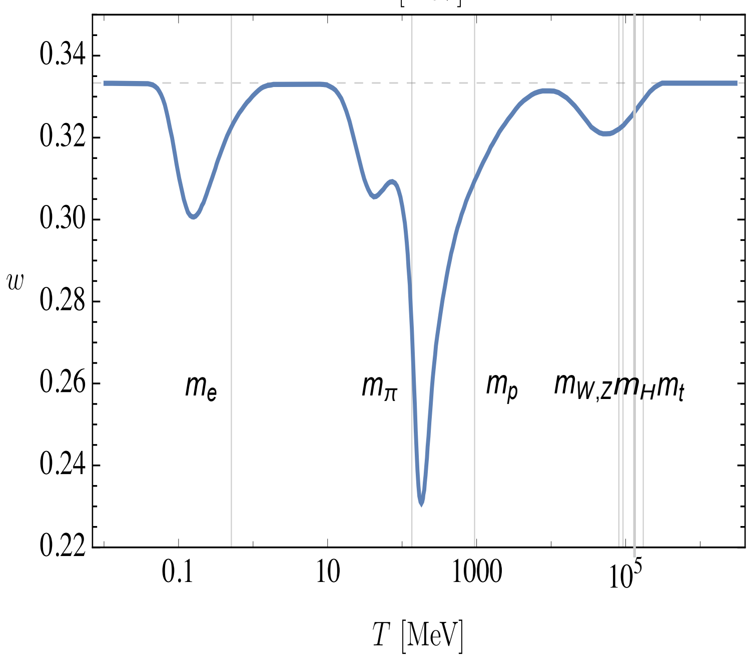
- Broad range masses
- PBH clusters

JGB (2017)

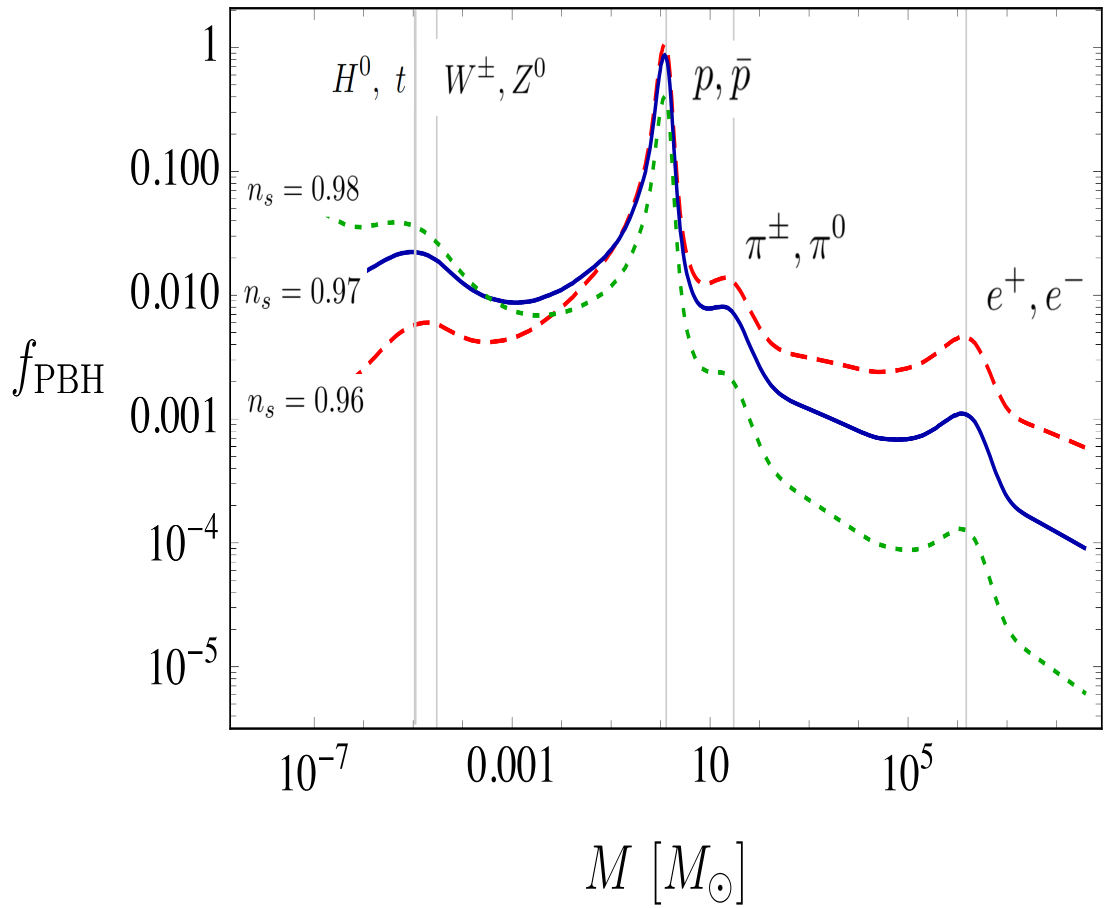
Thermal history of the universe

Carr, Clesse, JGB, Kühnel (2019)





PBH mass spectrum



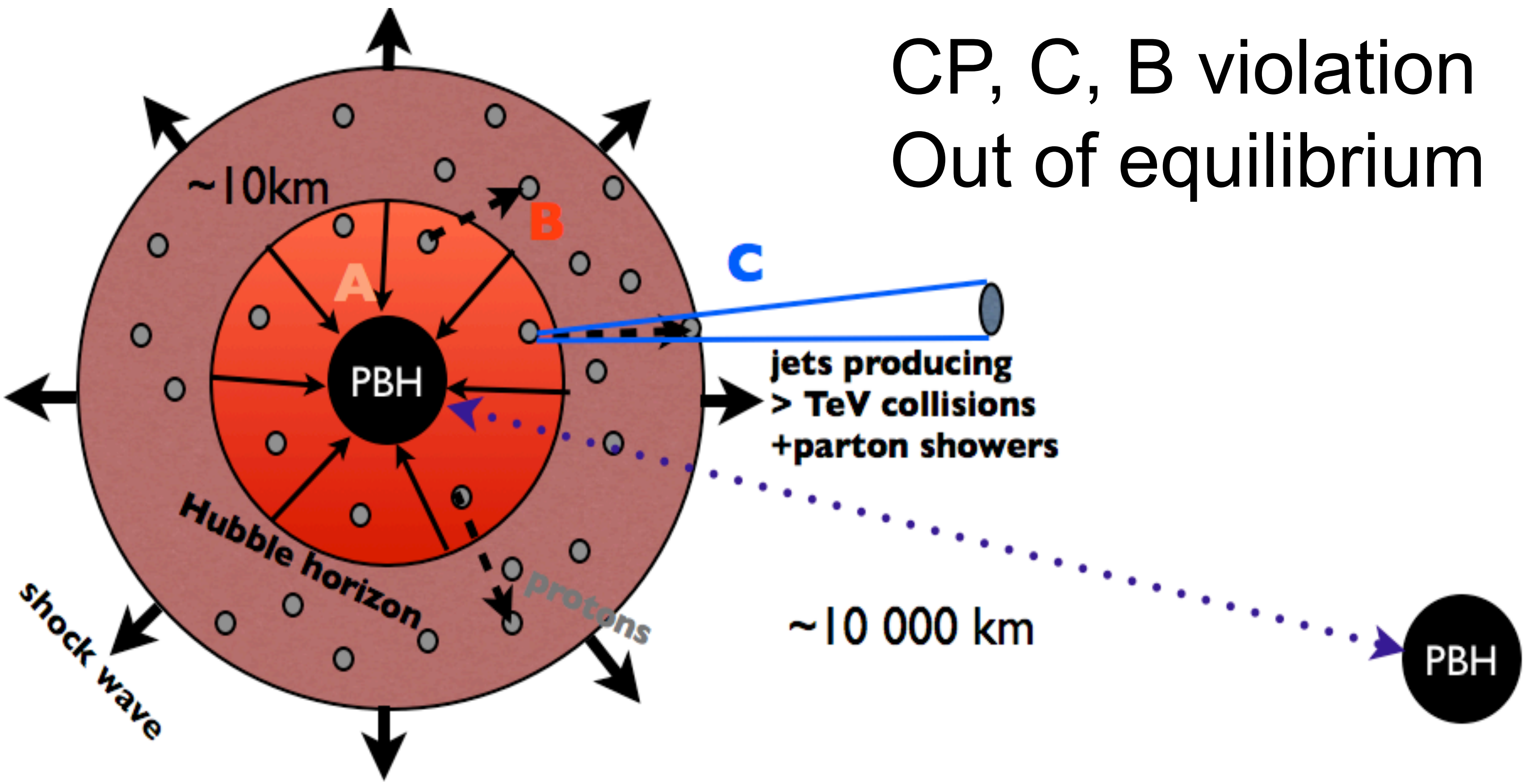
Electroweak baryogenesis @ QCD

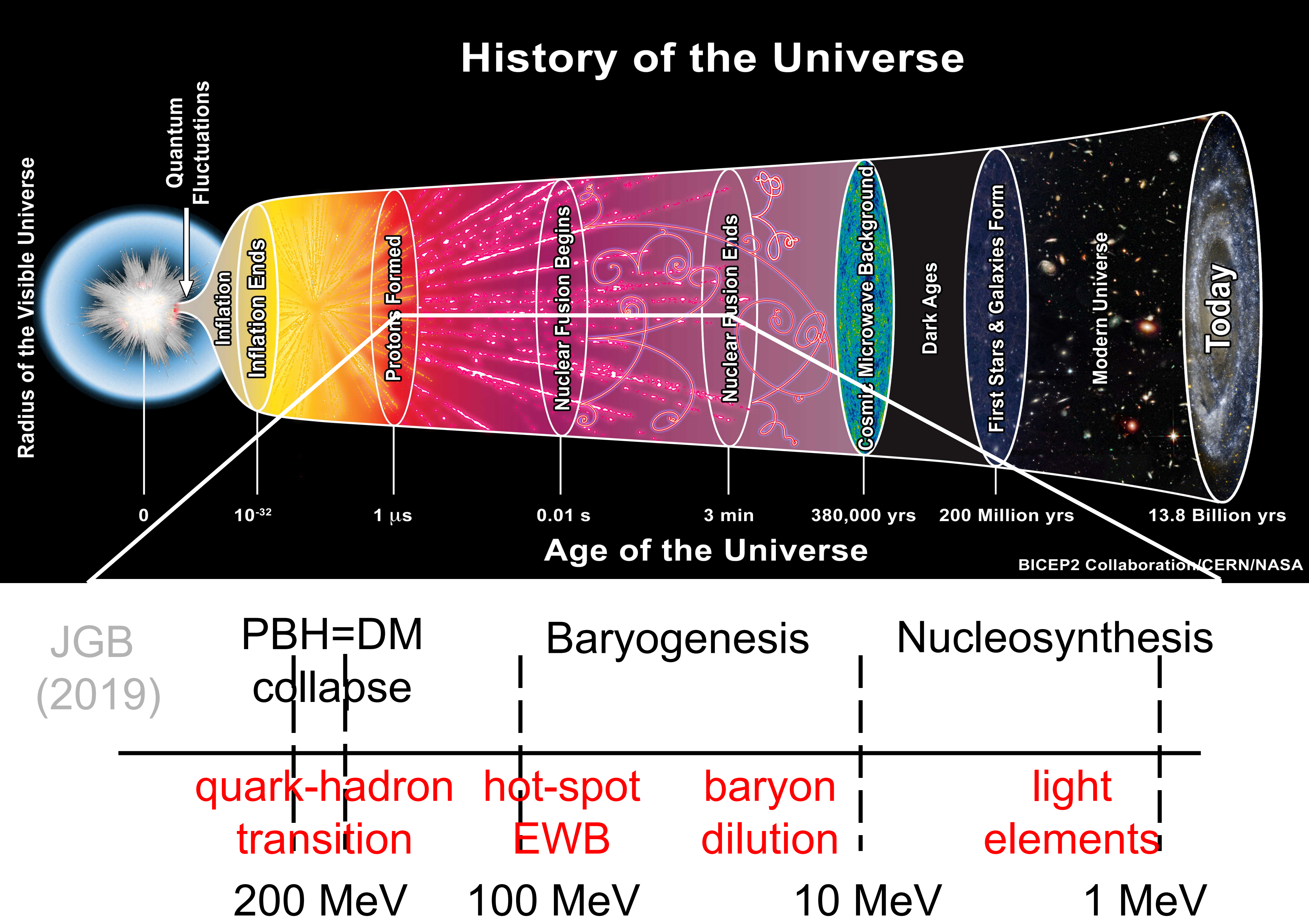
"Primordial supernova"

JGB, Carr, Clesse (2019)

Sakharov conditions:

CP, C, B violation
Out of equilibrium




History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10^{-32}
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA
JGB (2019)
PBH=DM collapse
Baryogenesis
Nucleosynthesis
quark-hadron transition
hot-spot EWB
baryon dilution
light elements
200 MeV
100 MeV
10 MeV
1 MeV

Cosmic Conundra explained

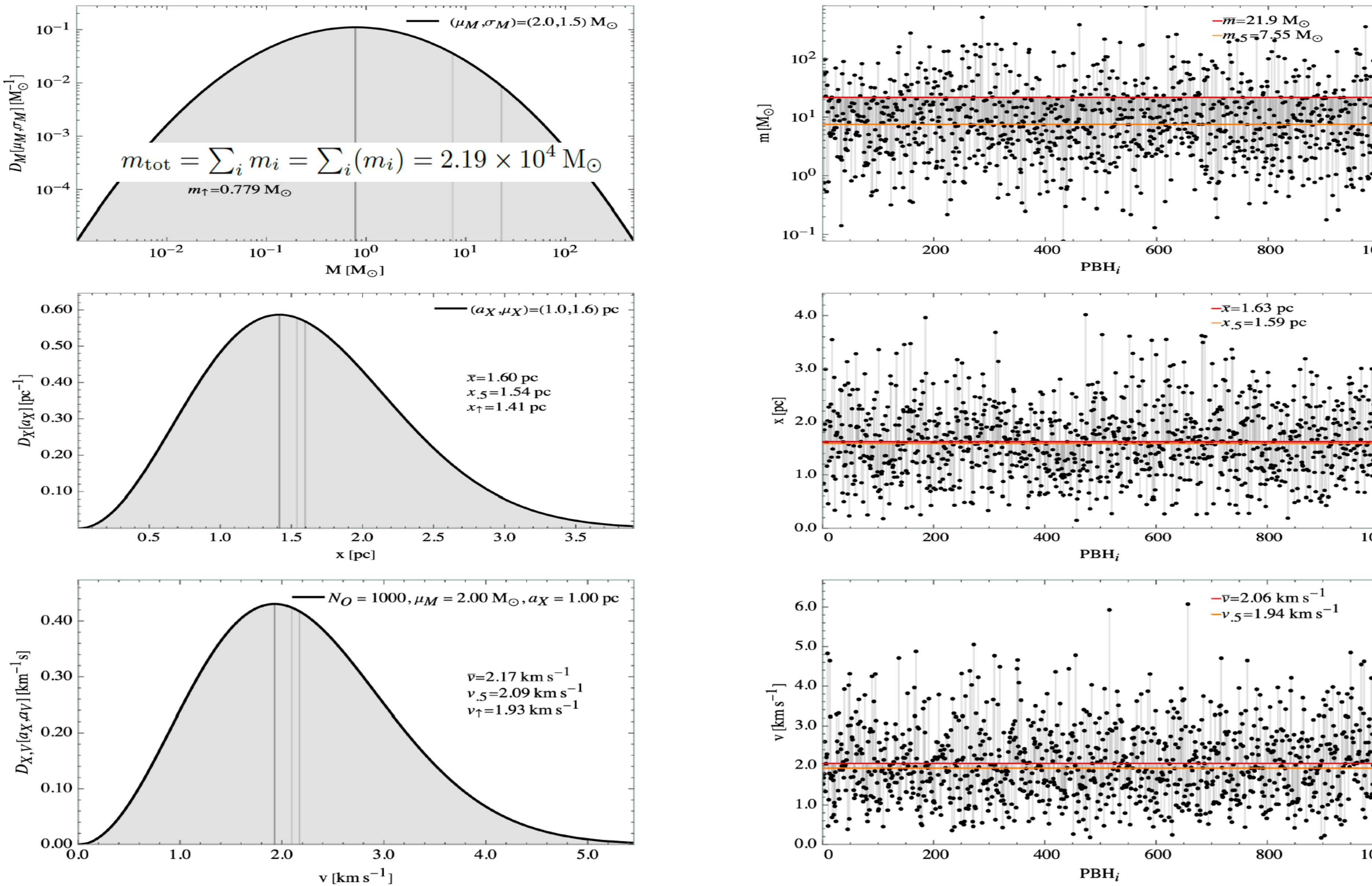
Clesse, JGB (2017)

Carr, Clesse, JGB, Kühnel (2019)

- Planetary-mass microlensing
- Quasar microlensing
- OGLE/GAIA microlensing Gal.Bulge
- CIB/X-ray background
- UFDG substructure large M/L
- IMHB & SMBH seeds for LSS
- Mass, spin & merger rate LVC BBH

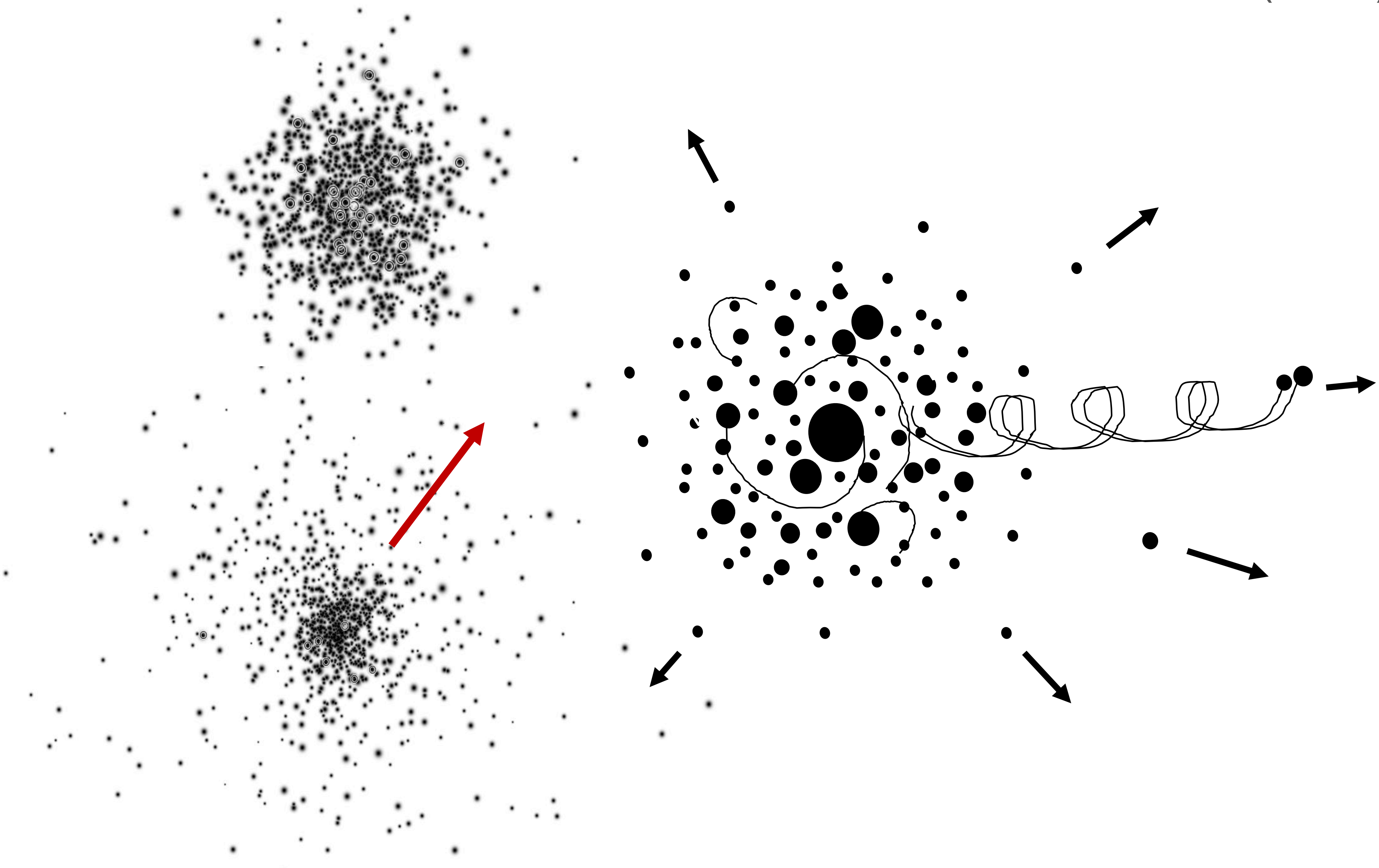
Primordial Black Holes Clusters

Trashorras, JGB, Nesseris (2020)



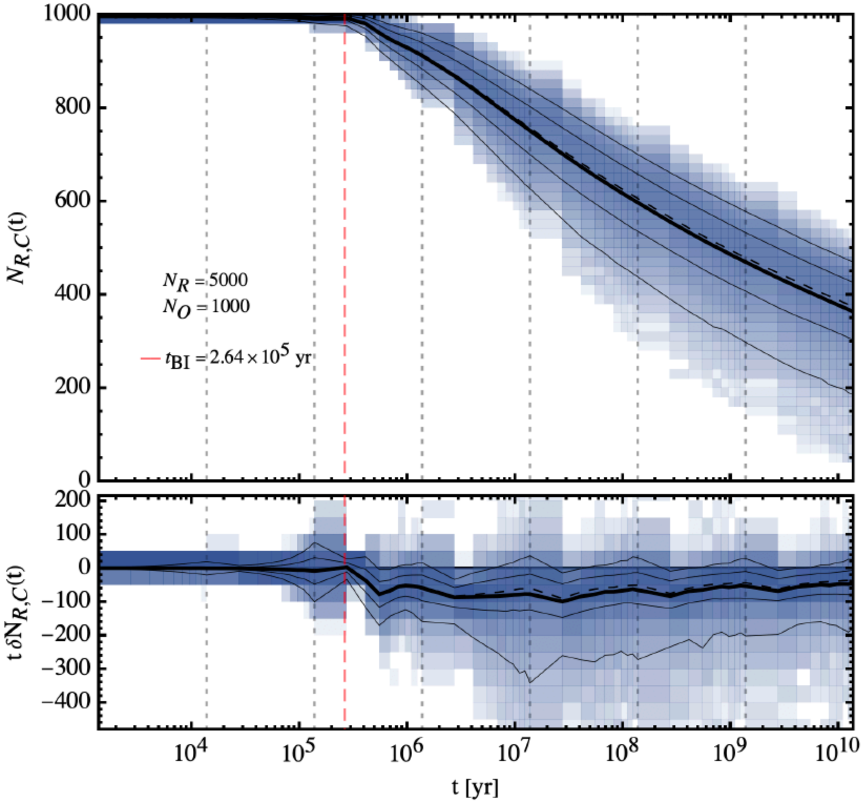
PBH clusters

Trashorras , JGB, Nesseris (2020)

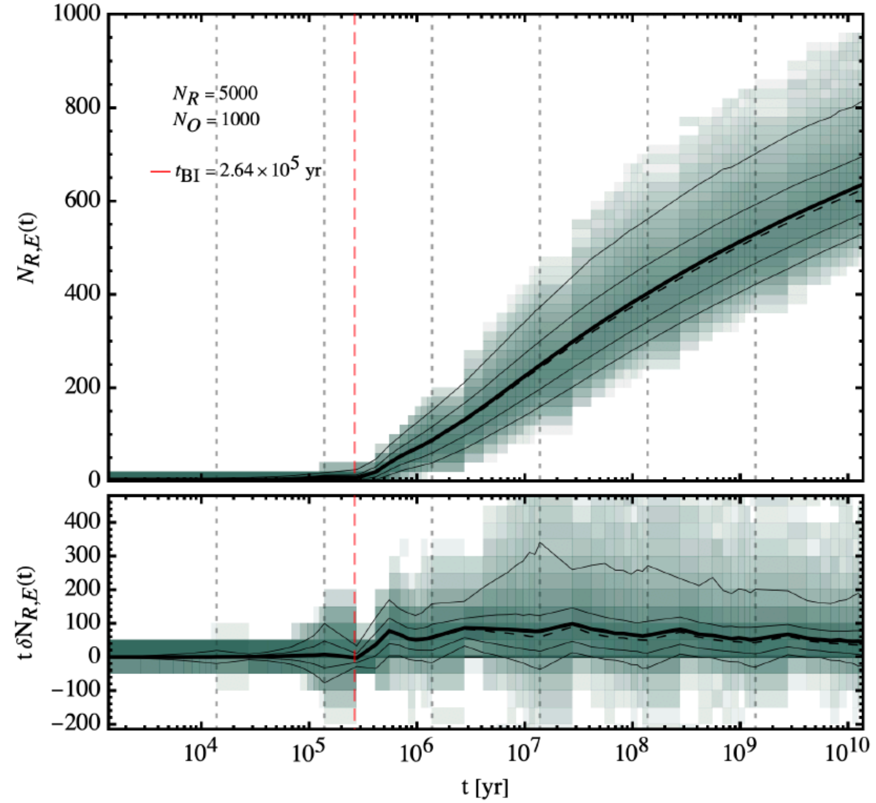


Primordial Black Holes Clusters

Trashorras, JGB, Nesseris (2020)



(a) Remaining cluster population of objects, $N_{R,C}(t)$.

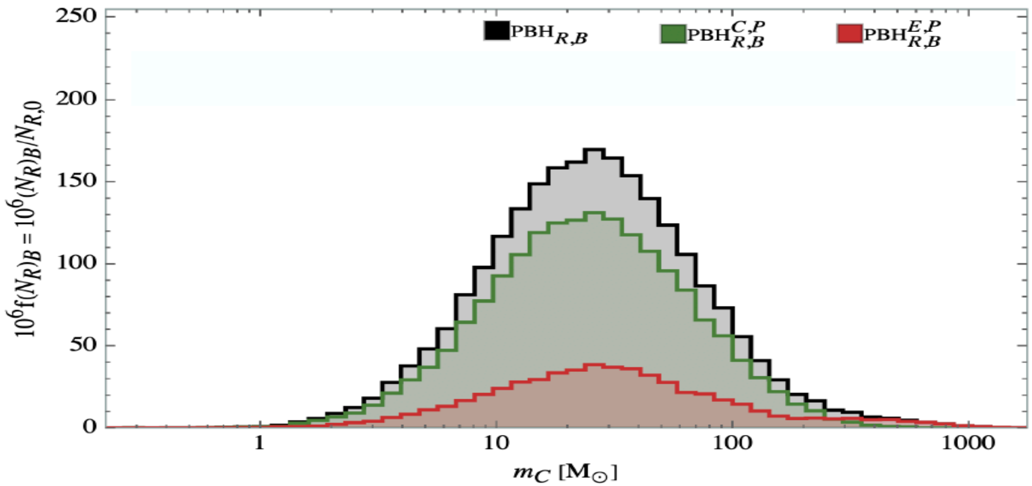


(b) Remaining ejecta population of objects, $N_{R,E}(t)$.

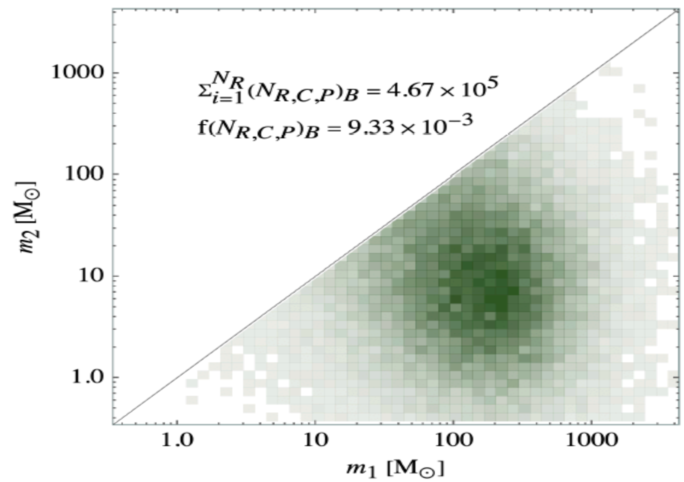
Clusters slingshot light components

PBH binaries in/out of Clusters

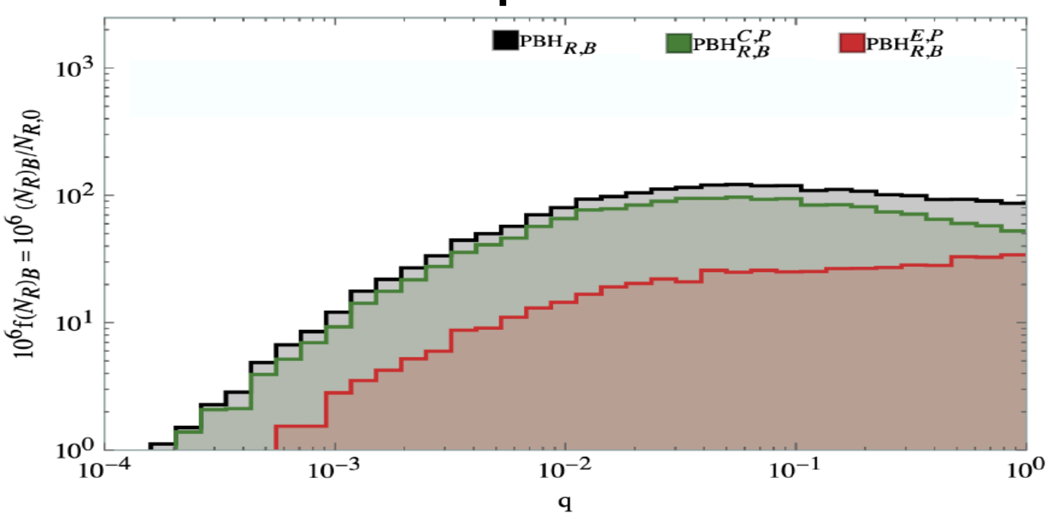
Trashorras, JGB, Nesseris (2020)



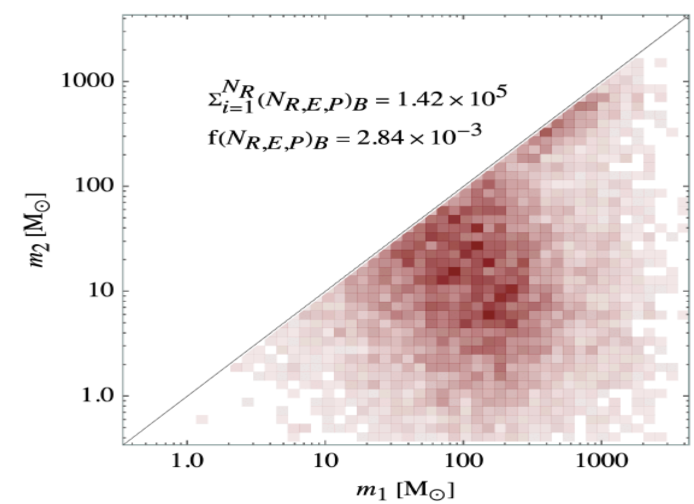
Chirp masses



Cluster binaries

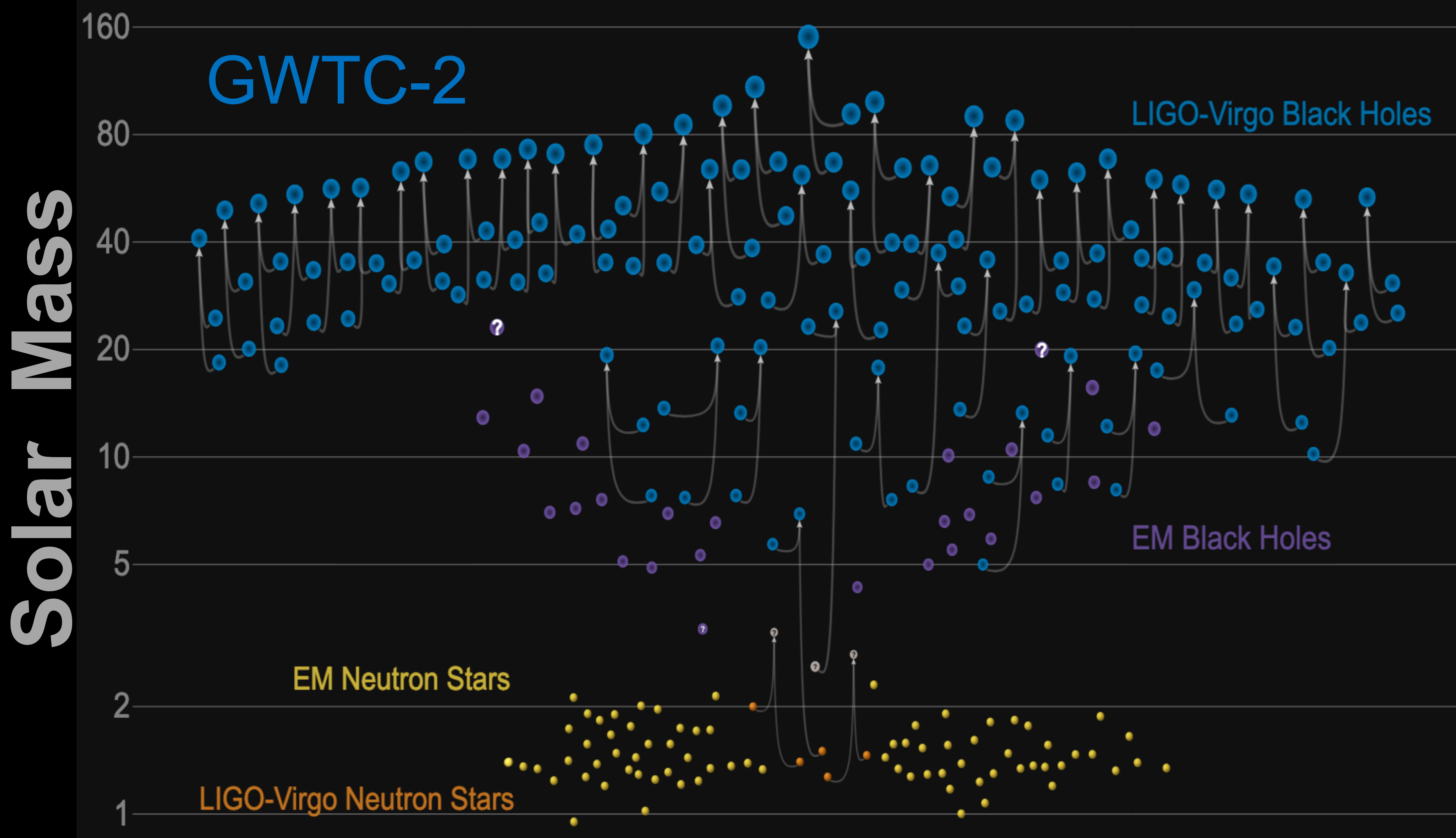


Mass ratios



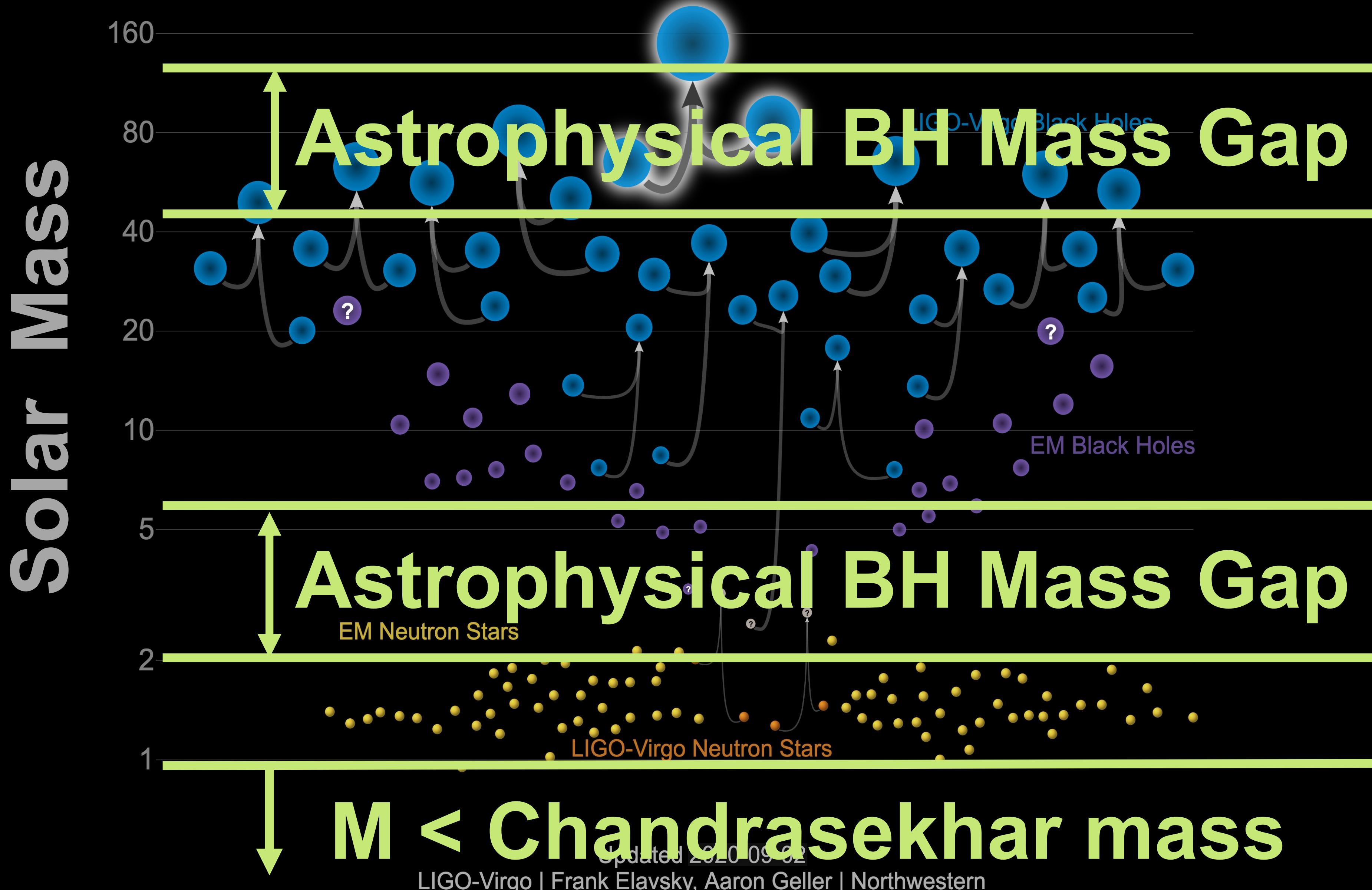
Ejected binaries

Black Holes and Neutron Stars

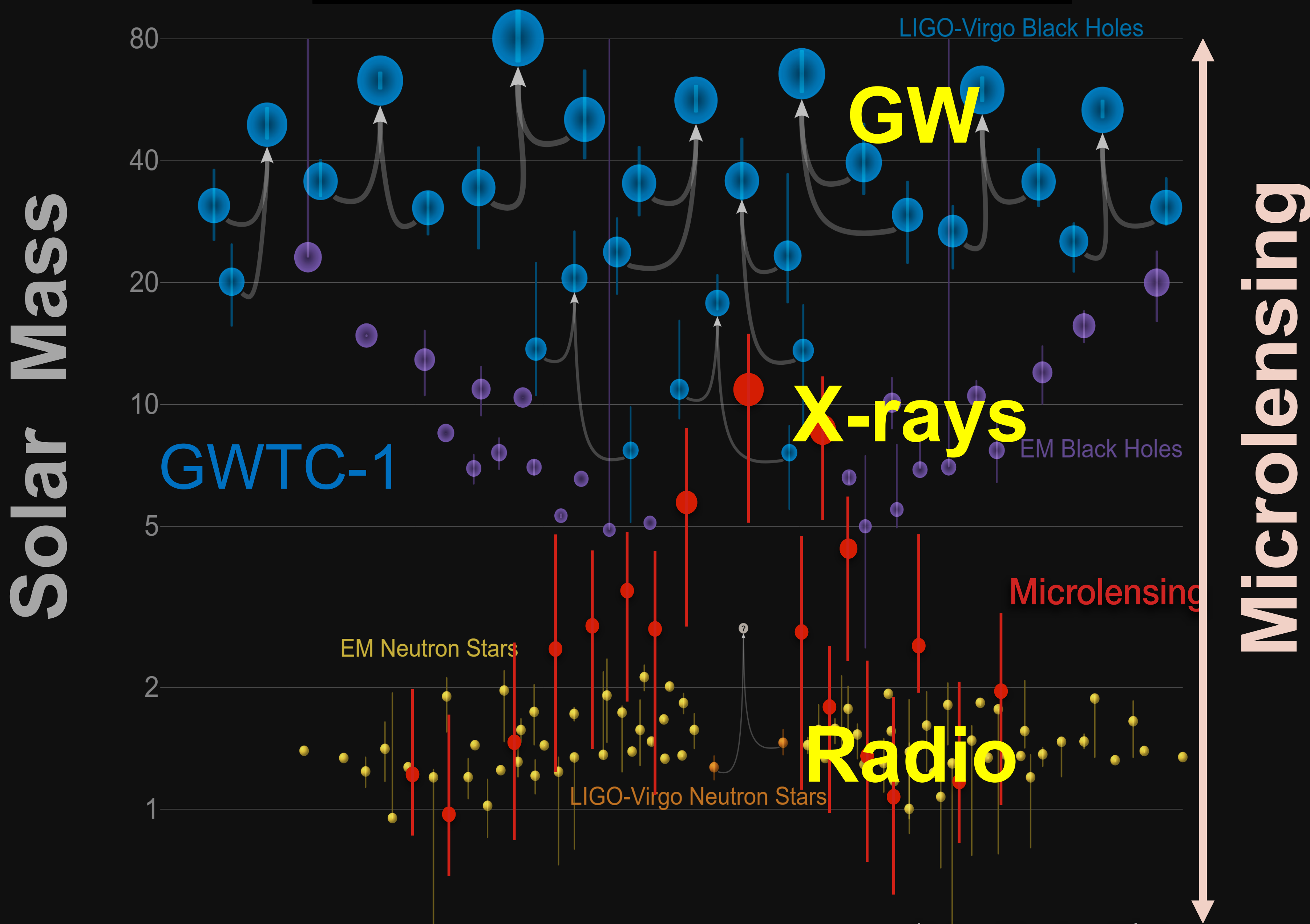


GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Black Holes and Neutron Stars

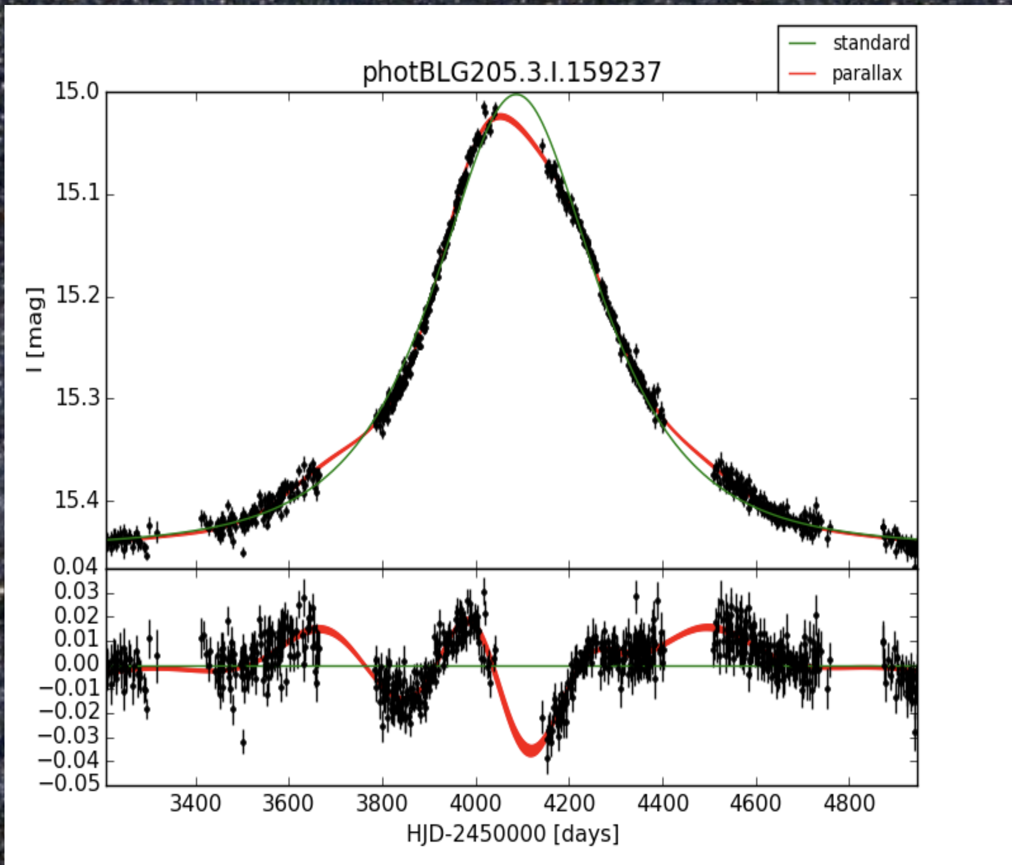


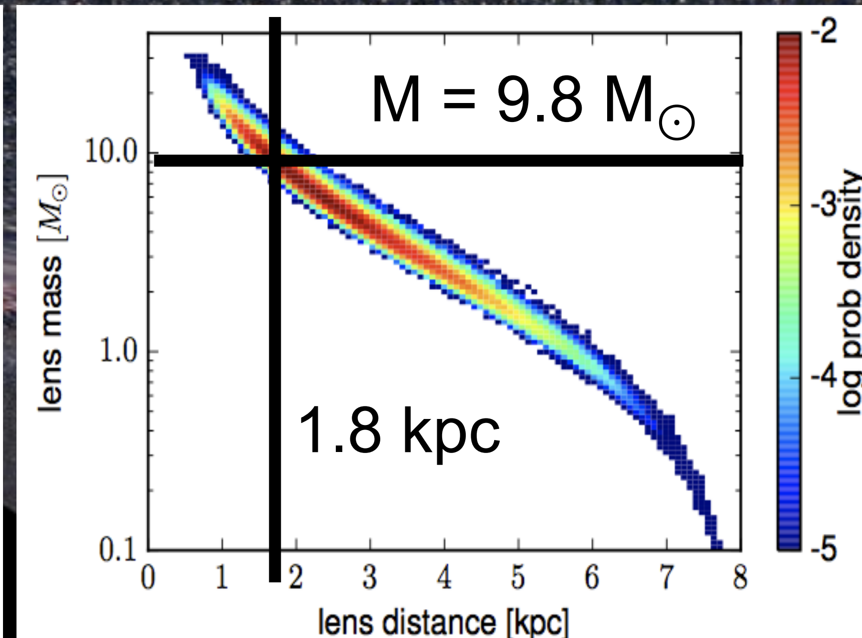
Black Holes and Neutron Stars



OGLE3-UL-PAR-02 - candidate BH

Wyrzykowski (2016)



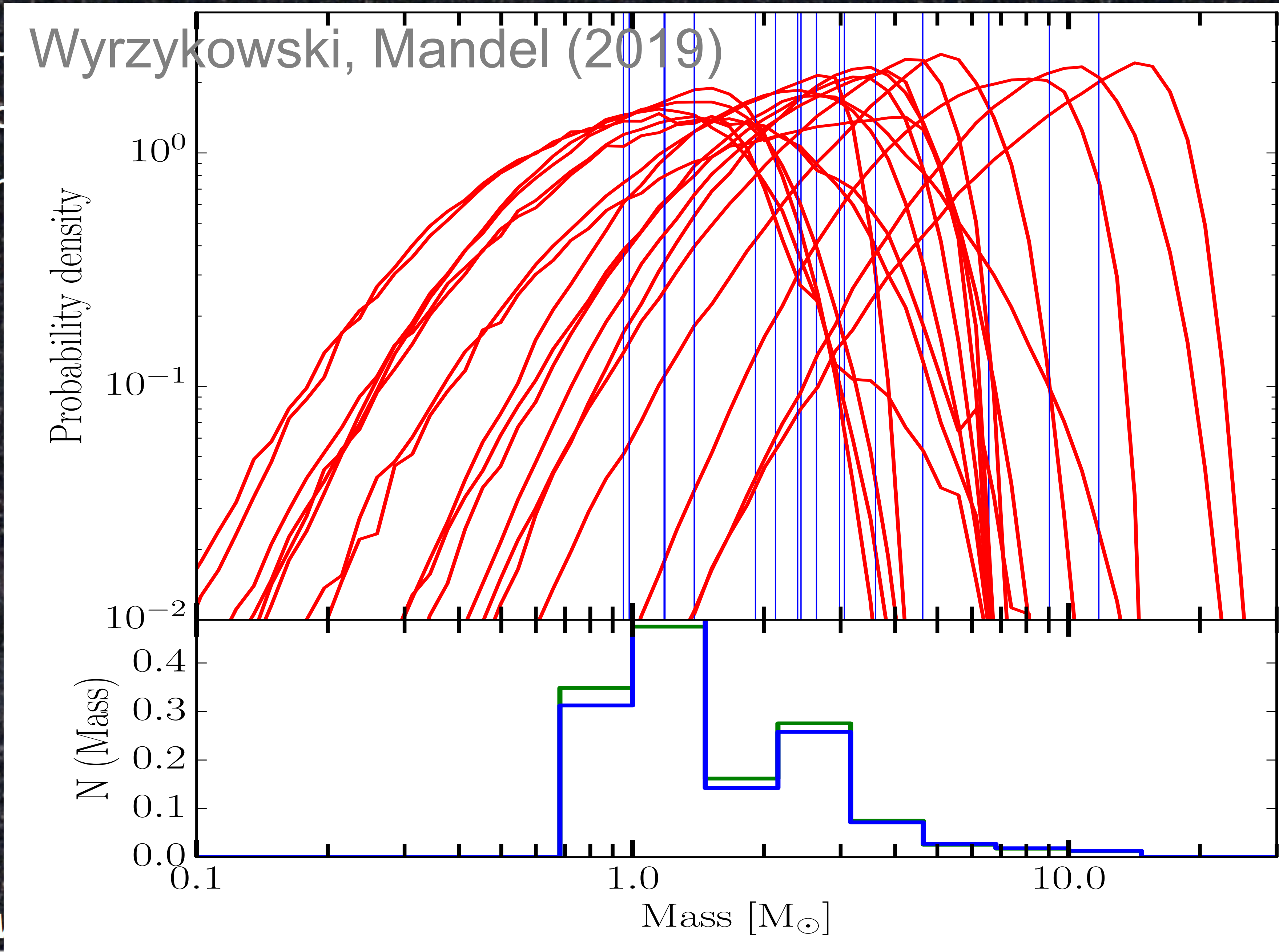


$$\overline{Dt} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v}$$

OGLE photometry from 2001-2008 and microlensing model

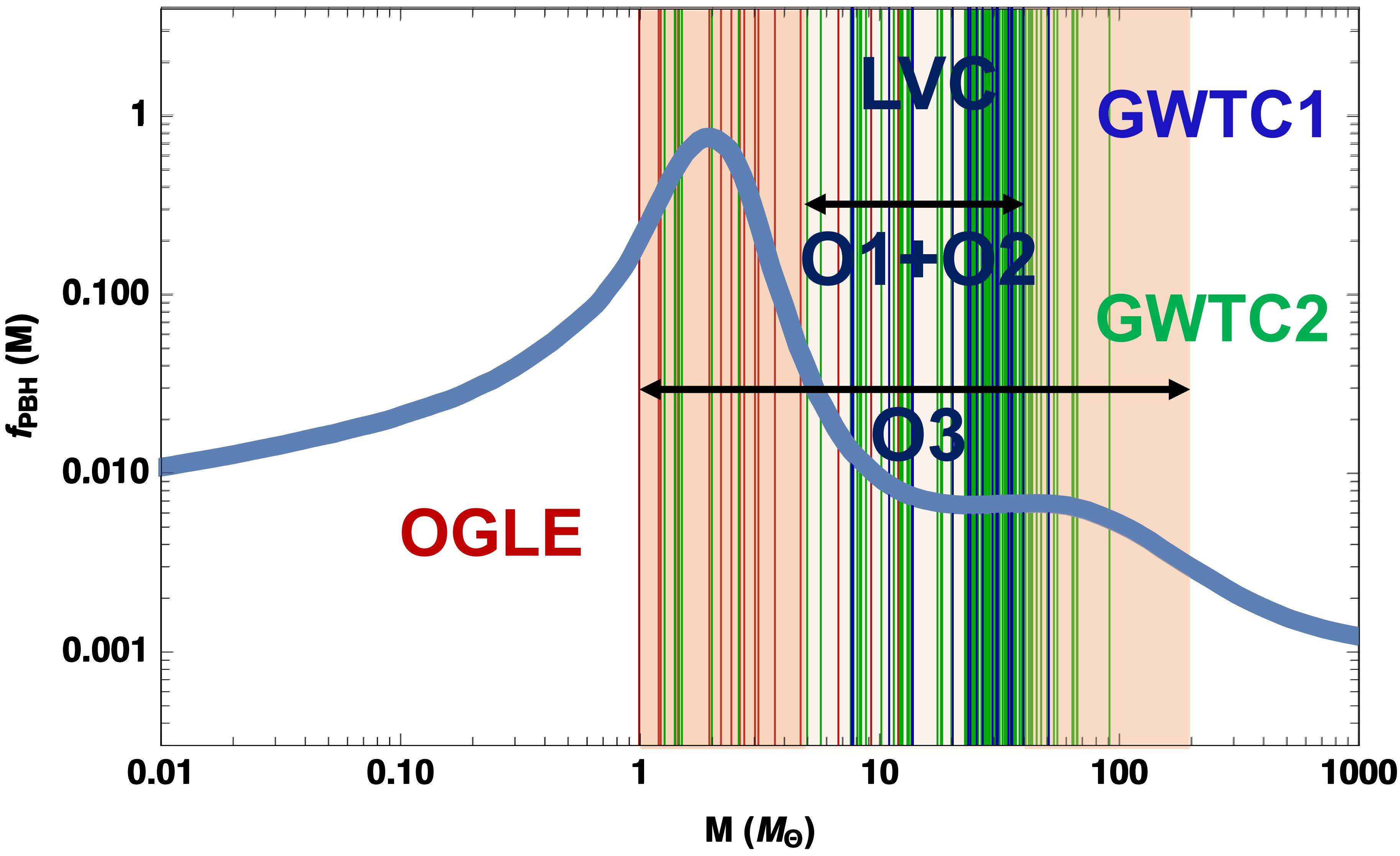
Mass, Distance (degenerated estimate)

MASS FUNCTION

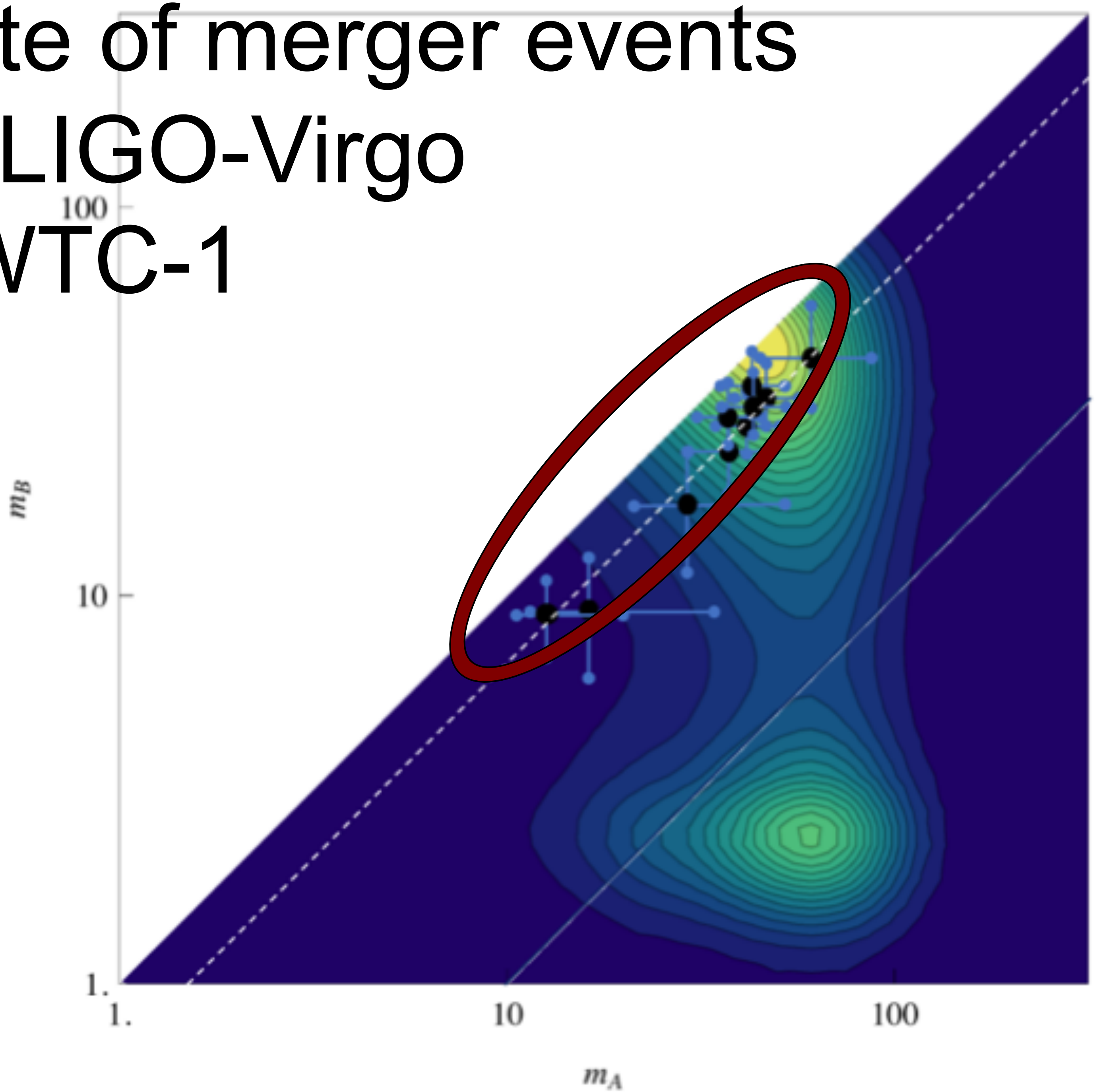


Model prediction: mass spectrum

JGB, Clesse (2020)

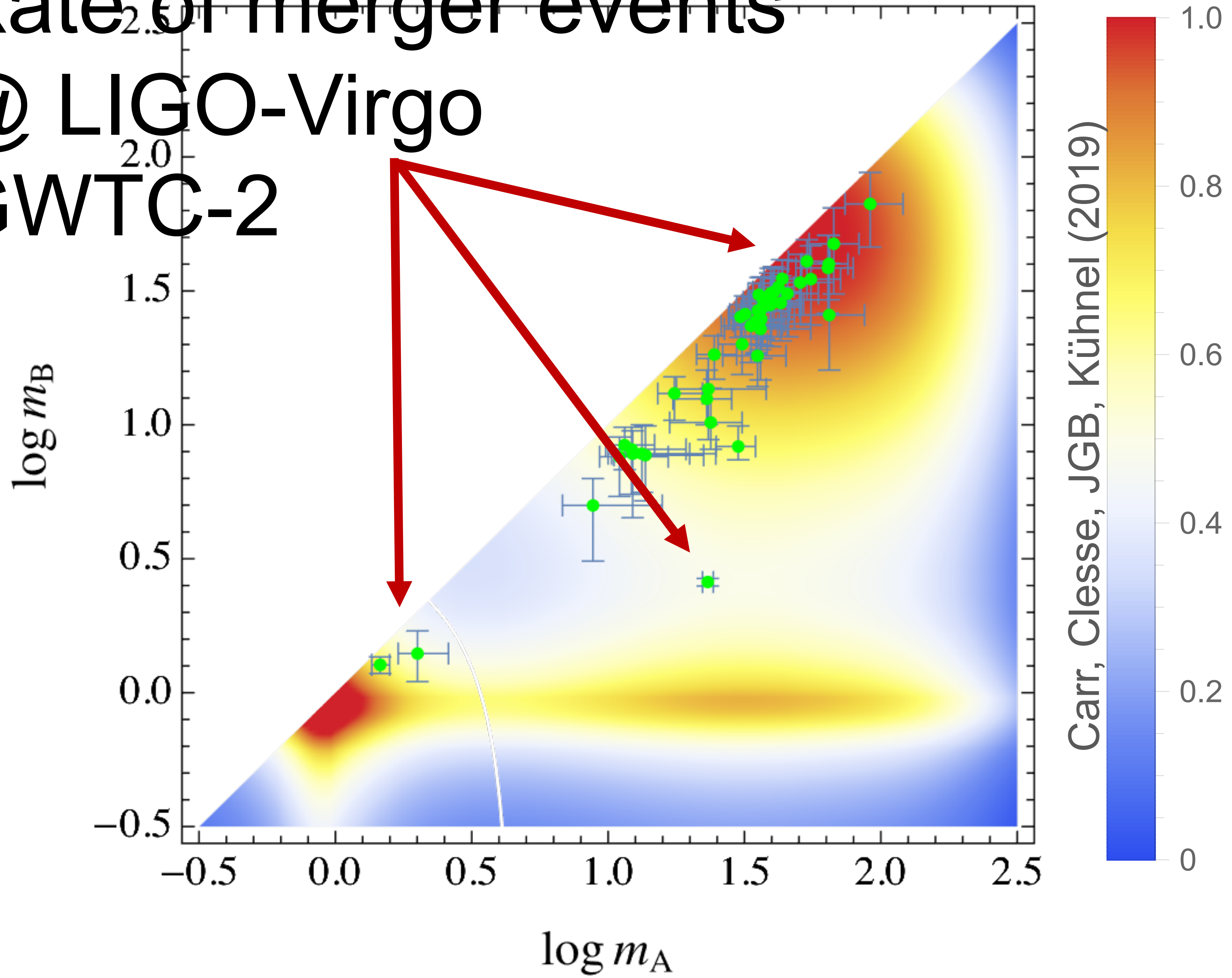


Rate of merger events @ LIGO-Virgo GWTC-1



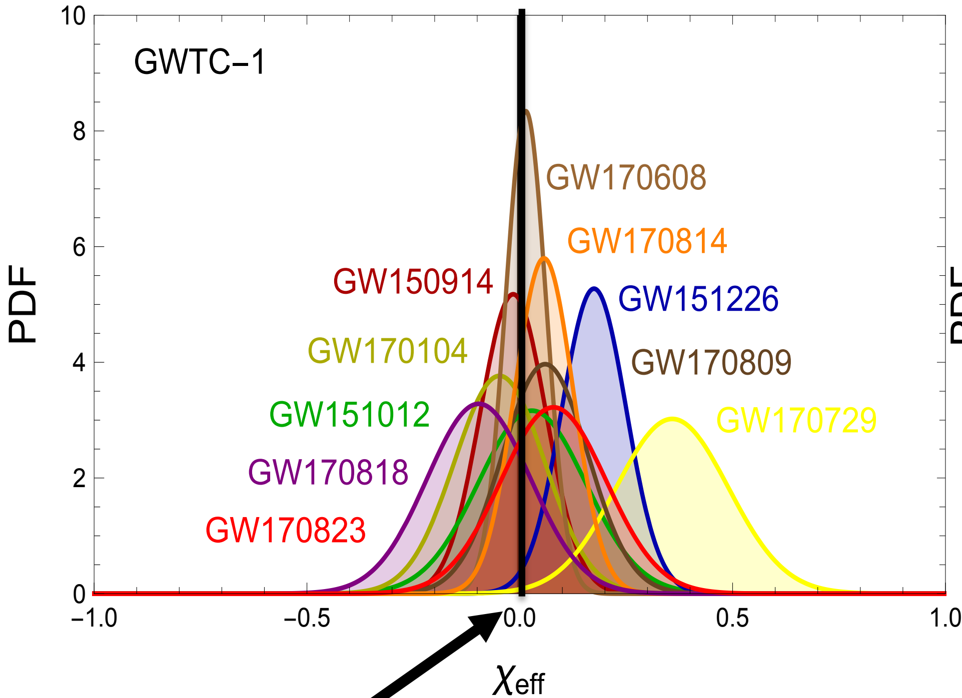
Carr, Clesse, JGB, Kühnel (2019)

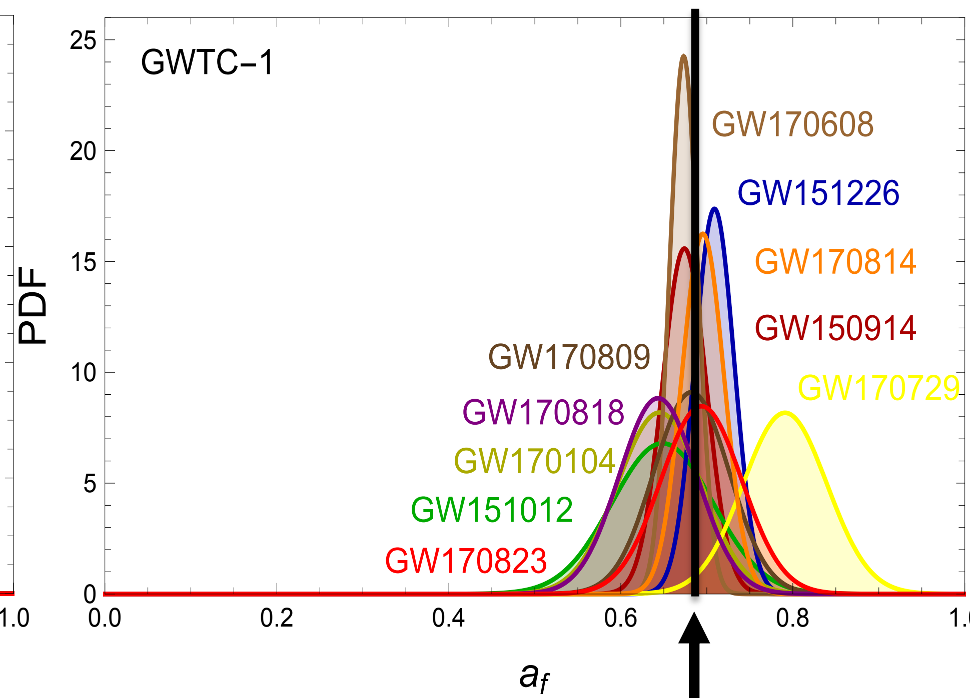
Rate of merger events
@ LIGO-Virgo
GWTC-2



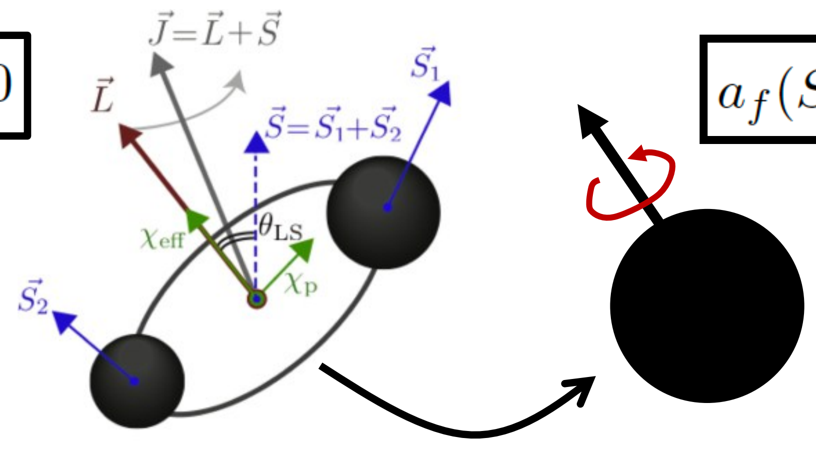
Effective & Final Spin

JGB (2019)





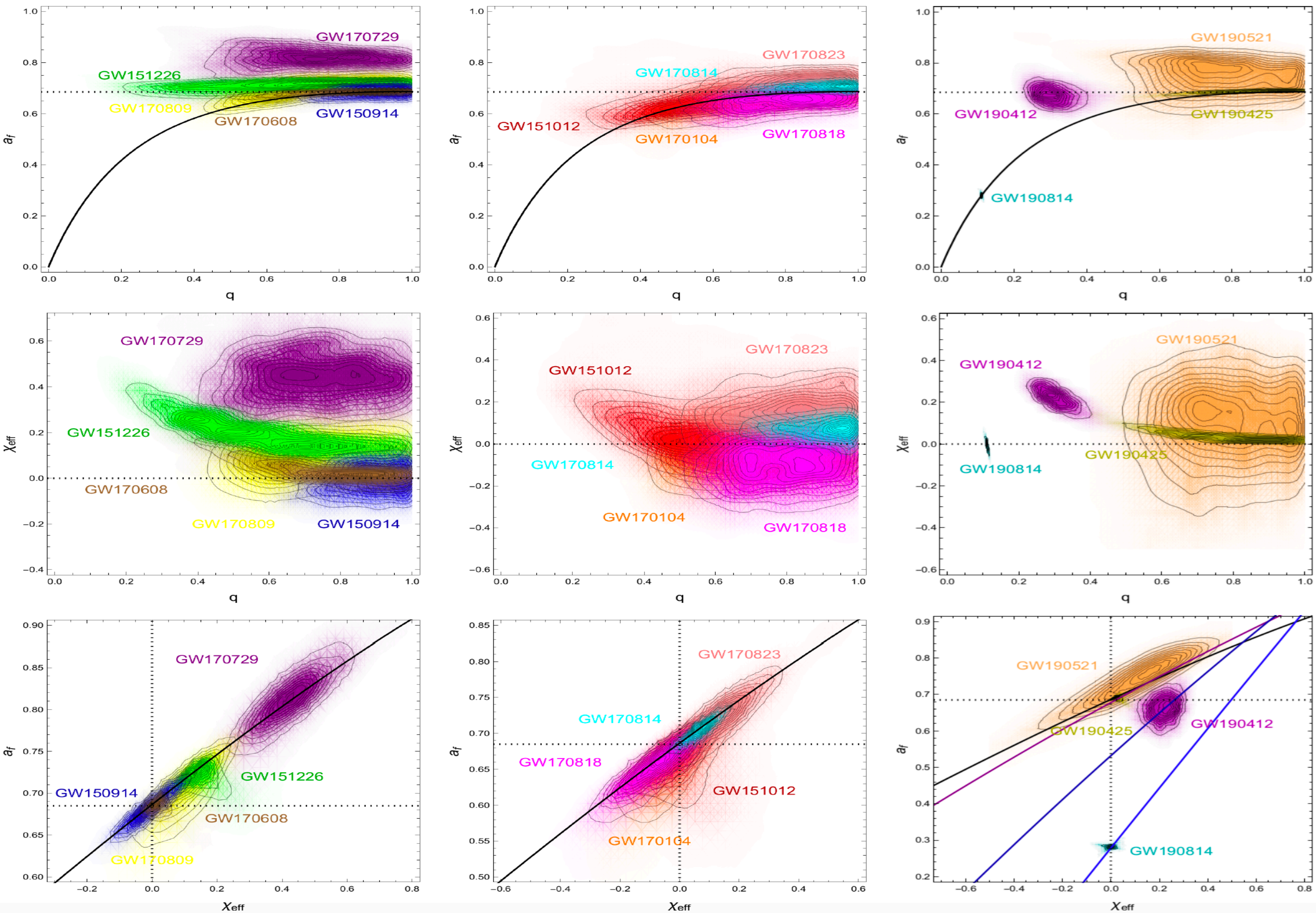
$$\chi_{\rm eff}(S_1 = S_2 = 0) = 0$$



$$a_f(S_1 = S_2 = 0) = 0.686$$

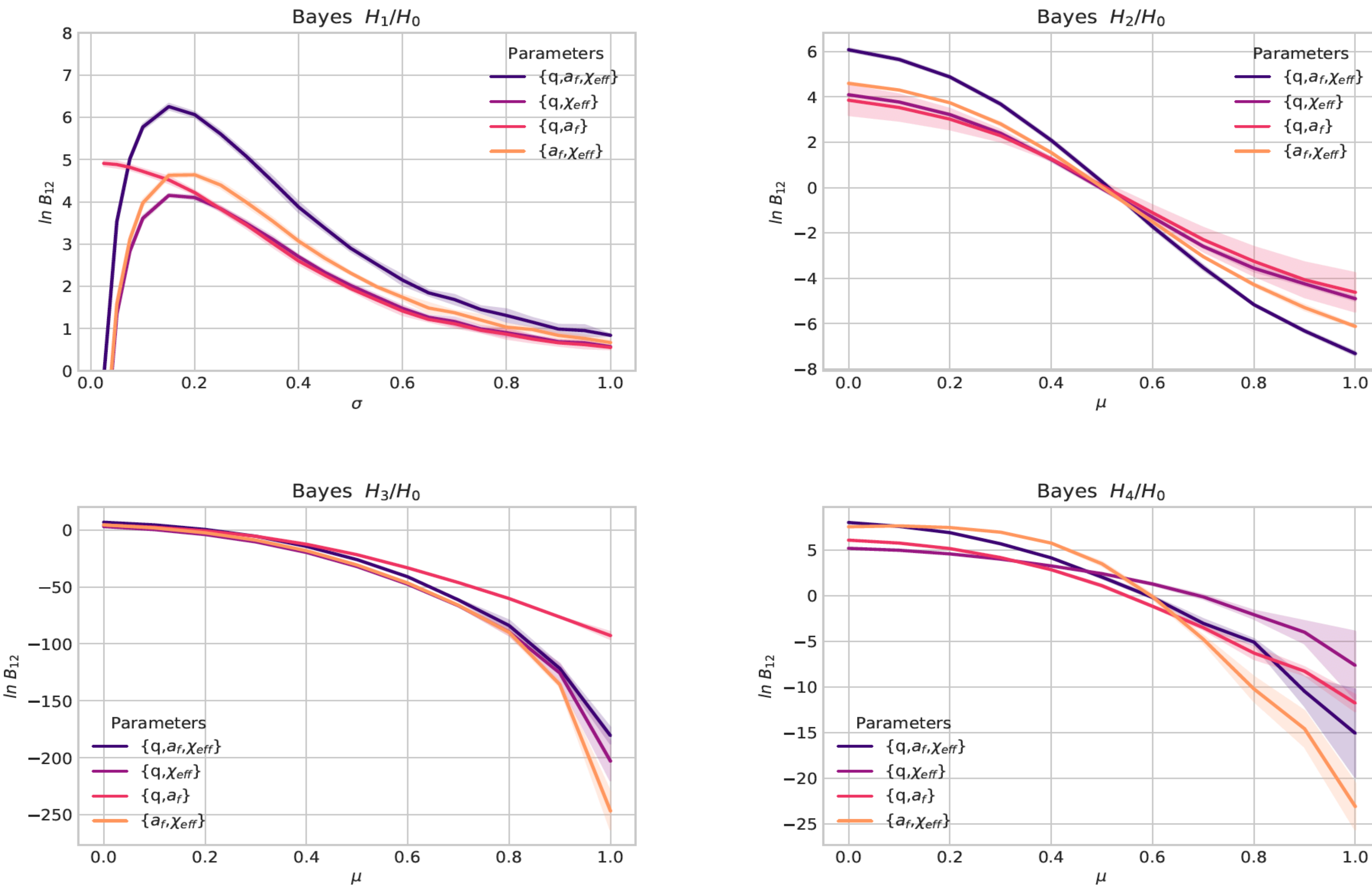
Effective & Final Spin

JGB, Nuño Siles, Ruiz Morales (2020)



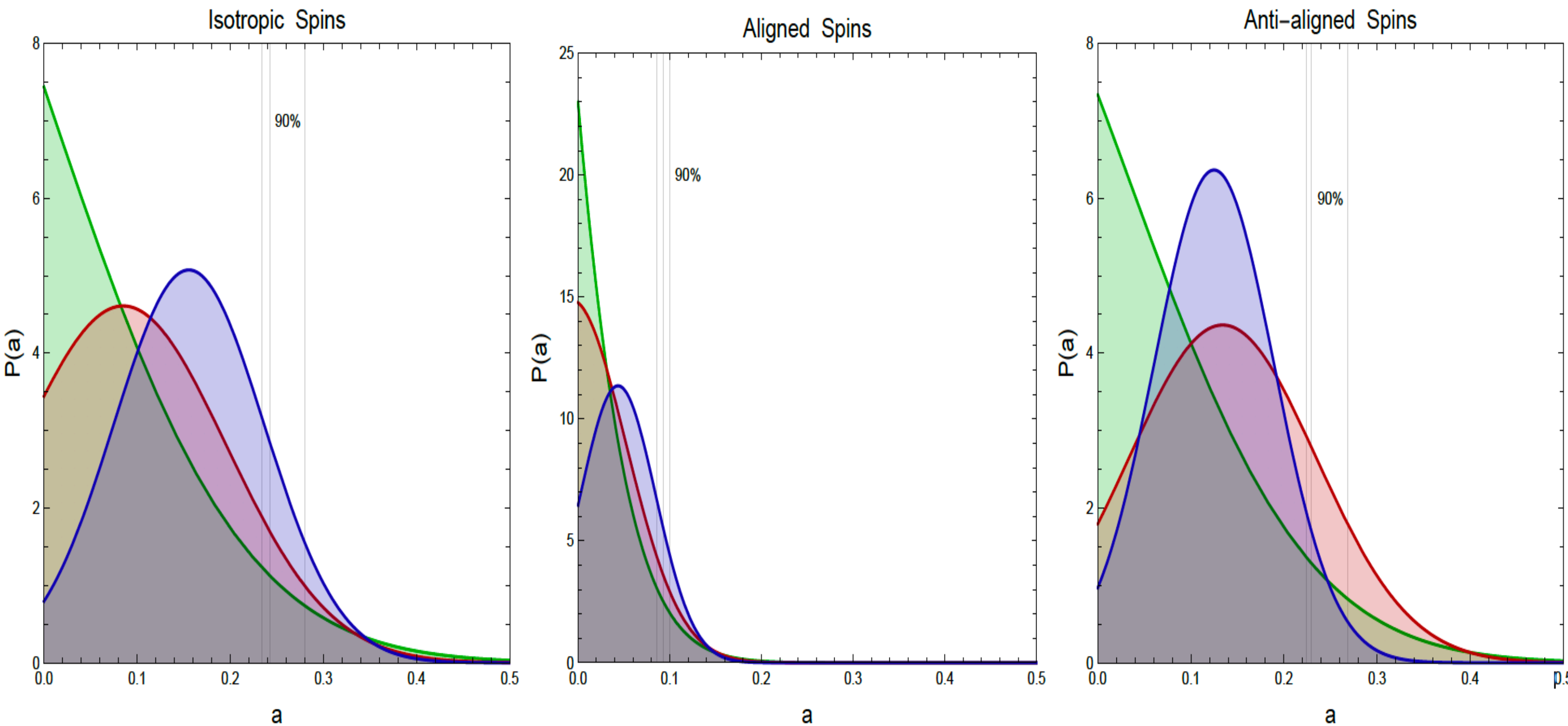
Effective & Final Spin

JGB, Nuño Siles, Ruiz Morales (2020)



Spin magnitude posteriors

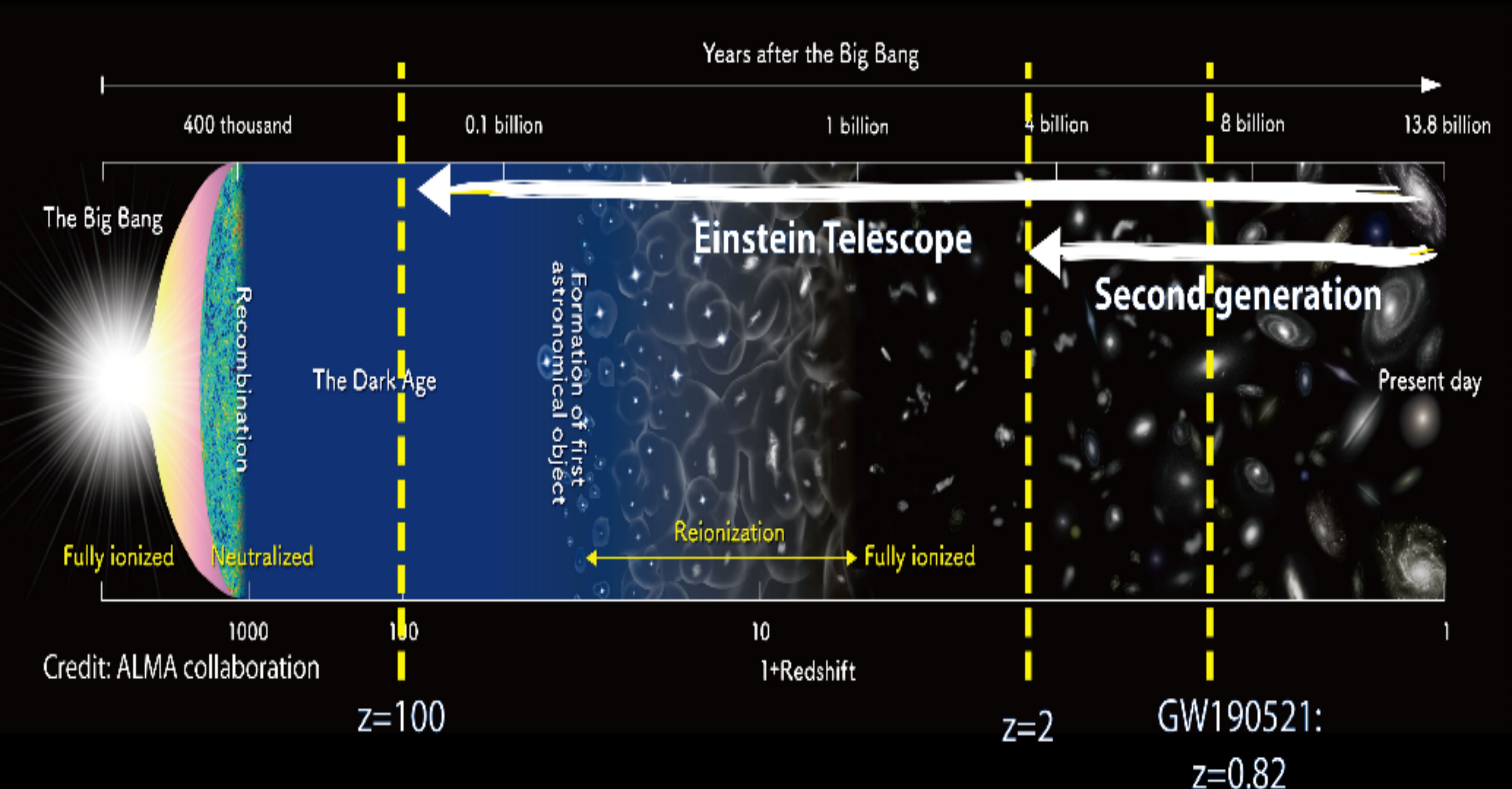
JGB, Nuño Siles, Ruiz Morales (2020)



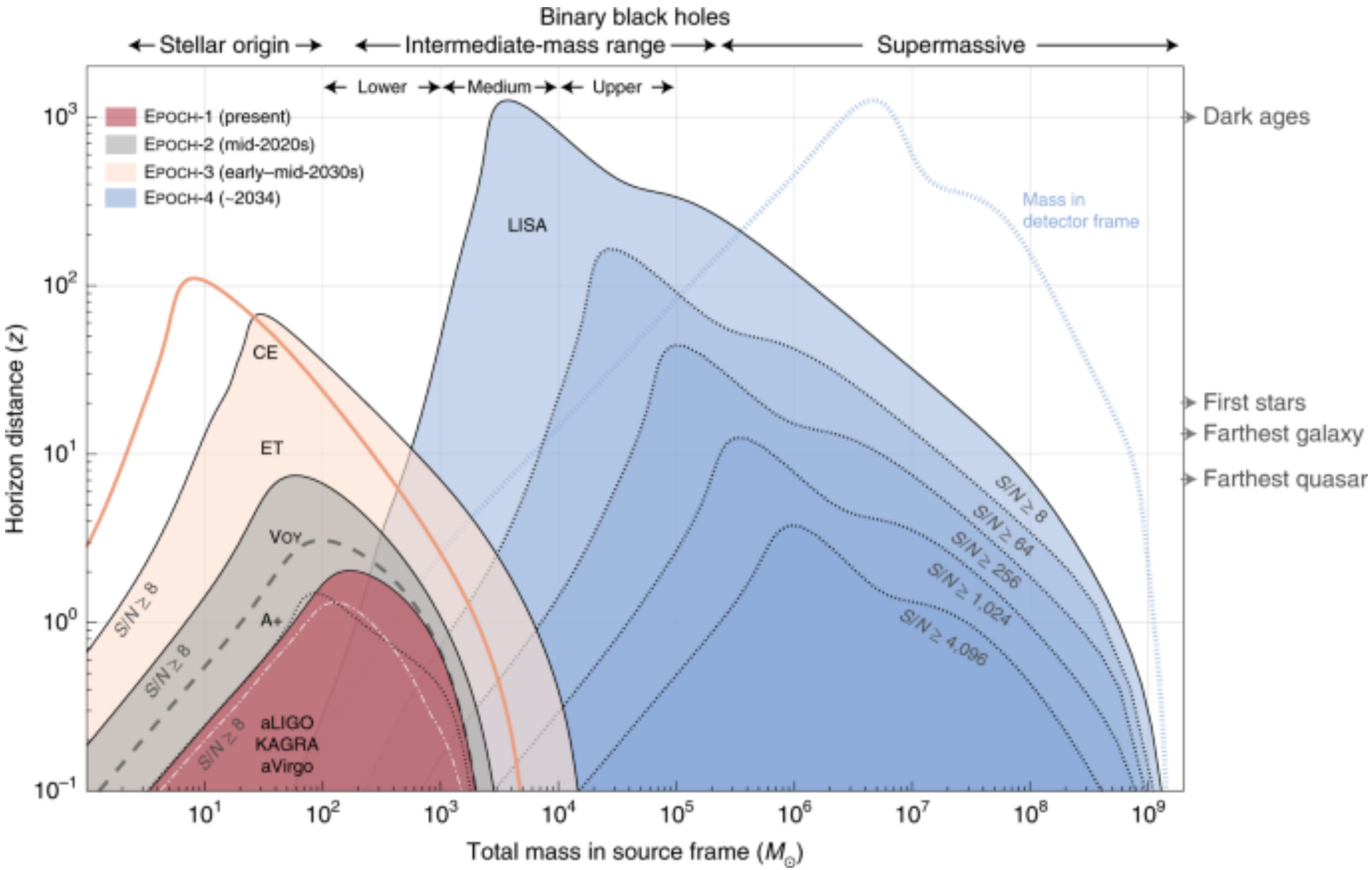
GWTC-1 (2018) + runO3a (2020)

The future of GW (G3)

Detection horizon for black-hole binaries



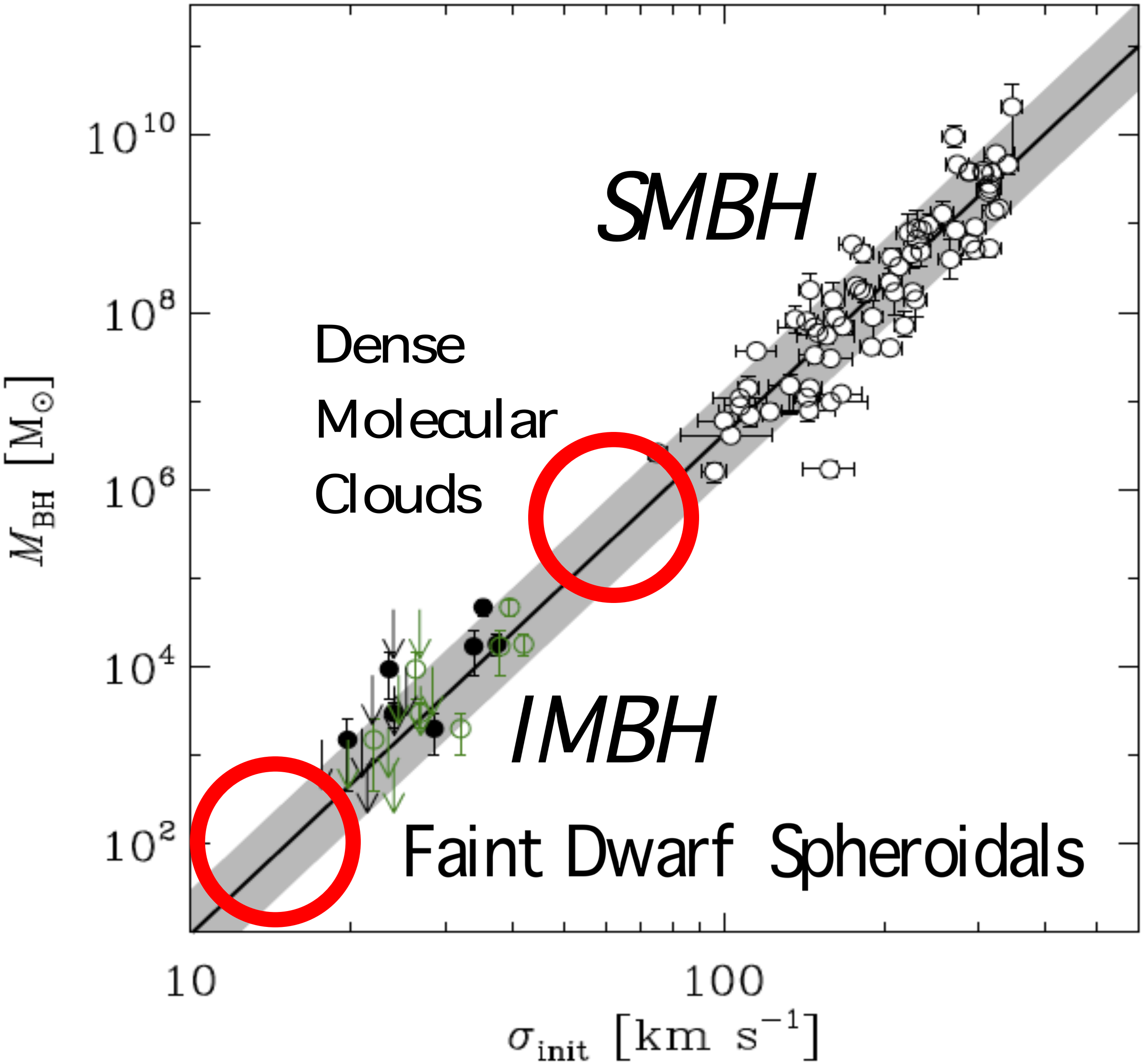
BBH sensitivity in future G3 GW



Conclusions

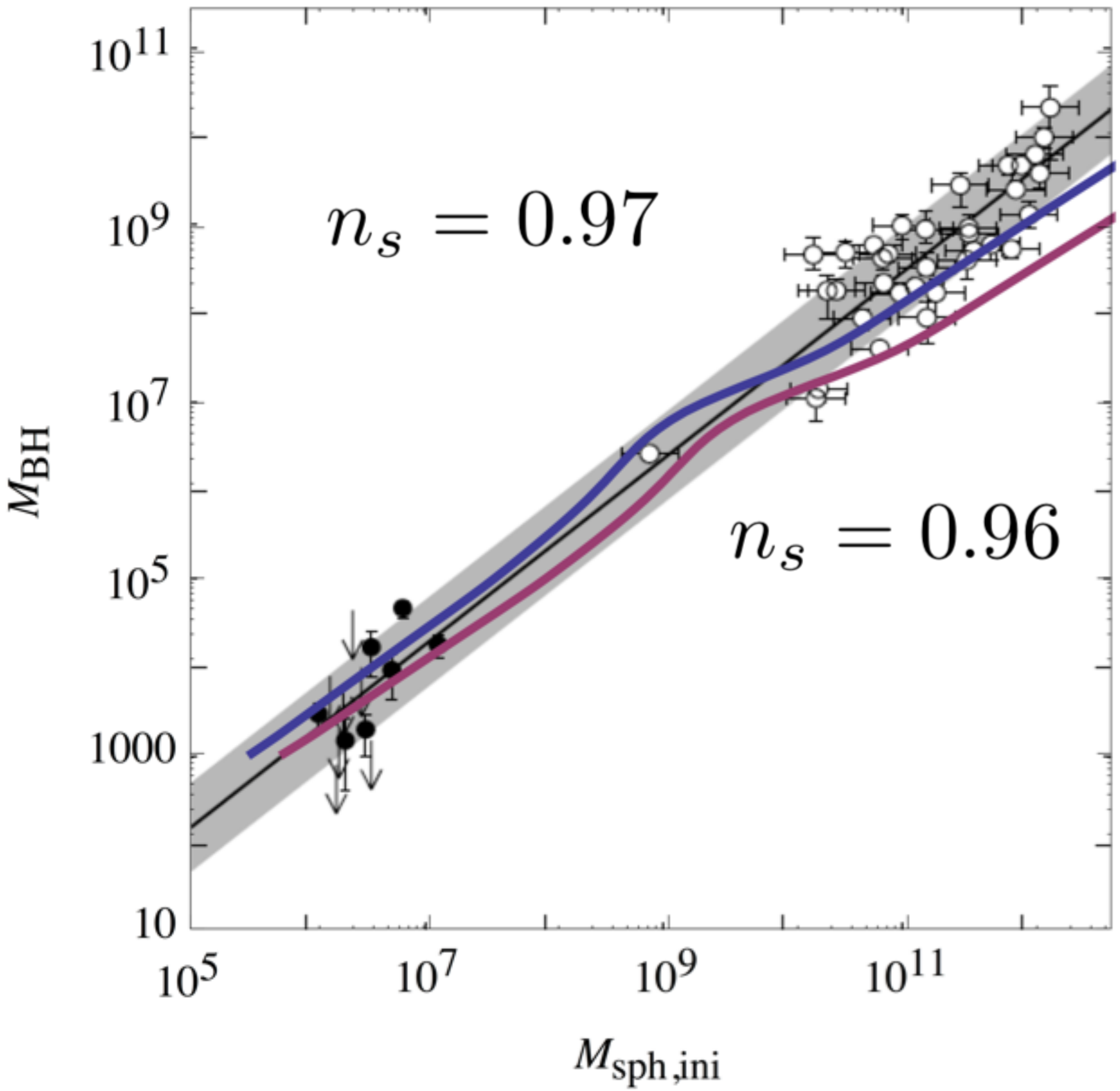
- Quantum diffusion inevitably generates PBH
- Thermal history predicts PBH have multimodal mass distribution ~ 1E-5, 1, 100, 1E5 Msun (1E-10 also?)
- The predicted PBH spin and mass distribution has been measured by LIGO/Virgo + OGLE around 1-100 Msun (features: peak+plateau)
- Other peaks could be explored with microlensing
- PBH scenario can explain various cosmic conundra
- Paradigm shift in Structure Formation of Universe
- Very rich phenomenology: multiscale, multiepoch, multiprobe => Future G3 detectors (ET, LISA, GAIA)

SMBH correlation with Halo Mass



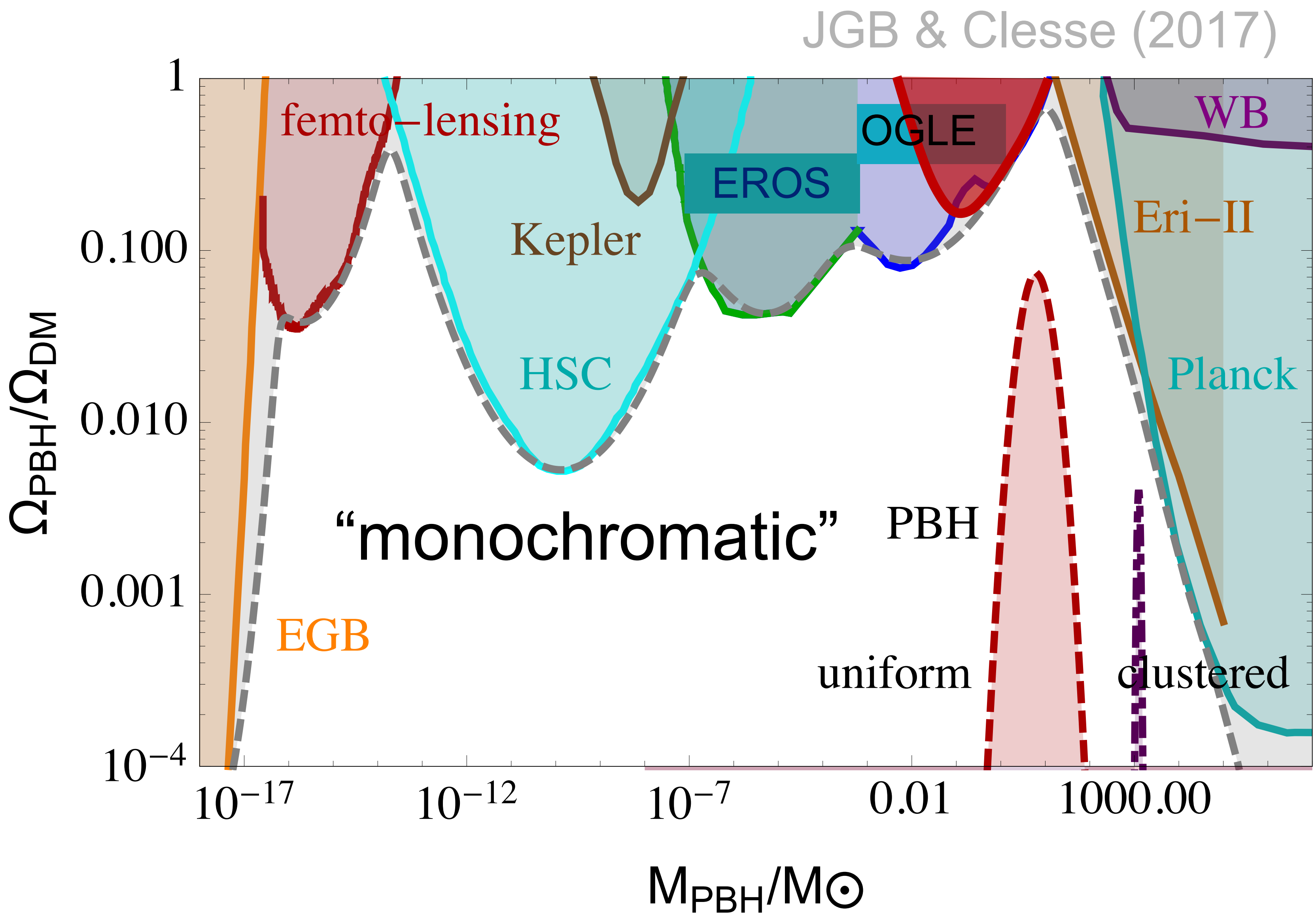
Kruijssen et al. (2013)

SMBH correlation with Halo Mass

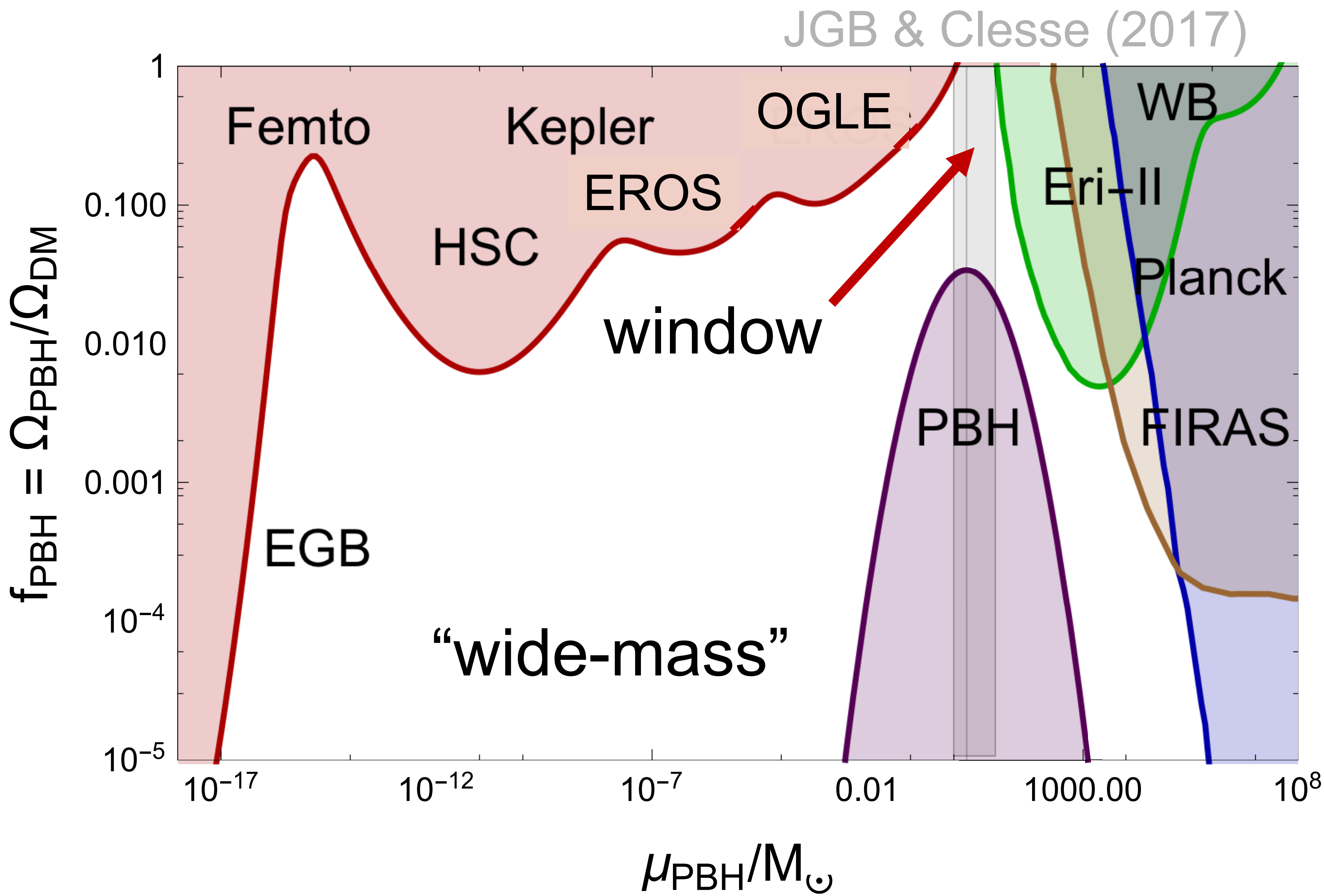


Carr, Clesse, JGB, Kühnel (2019)

PBH constraints



PBH constraints



PBH constraints