PRIMORDIAL BLACK HOLES AS THE SOLUTION OF MANY COSMOLOGICAL CONUNDRA

Bernard Carr, Queen Mary University of London

ICTS (13/11/20)

PBH FORMATION AND EVAPORATION

$R_S = 2GM/c^2 = 3(M/M_O)$ km => $\rho_S = 10^{18}(M/M_O)^{-2}$ g/cm^3

Small BHs can only form in early Universe

cf. cosmological density $\rho \sim 1/(Gt^2) \sim 10^6 (t/s)^{-2}$g/cm^3

=> $M_{PBH} \sim c^3 t/G =$
- 10^{-5}g at 10^{-43}s (minimum)
- $1 M_O$ at 10^{-5}s (QCD transition)
- $10^5 M_O$ at 1s (maximum?)

Black holes radiate thermally with temperature

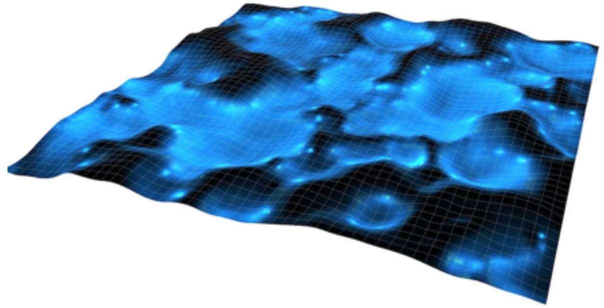
$$T = \frac{hc^3}{8\pi GkM} \sim 10^{-7} \left[\frac{M}{M_0}\right]^{-1} K$$

=> evaporate completely in time $t_{evap} \sim 10^{64} \left[\frac{M}{M_0}\right]^3$ y

$M \sim 10^{15}$g => final explosion phase today (10^{30} ergs)

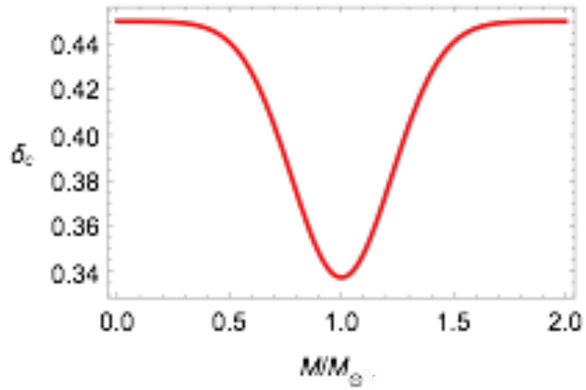
$T > T_{CMB}$=3K for $M < 10^{26}$g => "quantum" black holes

FORMATION MECHANISMS

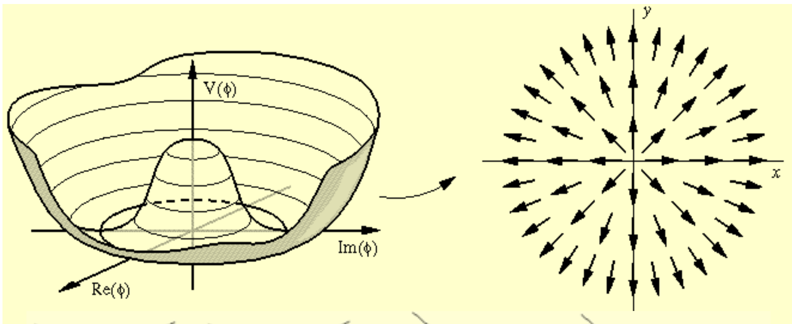


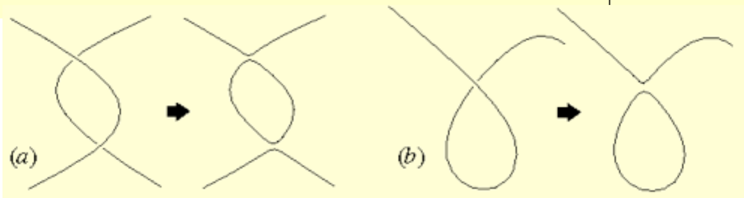
Primordial inhomogeneities Inflation

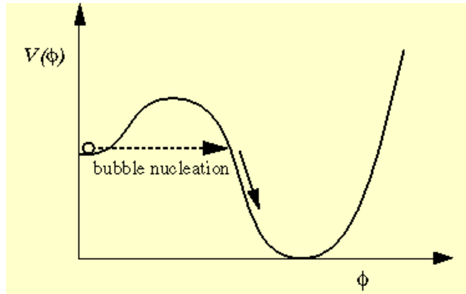
Pressure reduction Form more easily but need spherical symmetry



Cosmic strings PBH constraints => $G\mu < 10^{-6}$

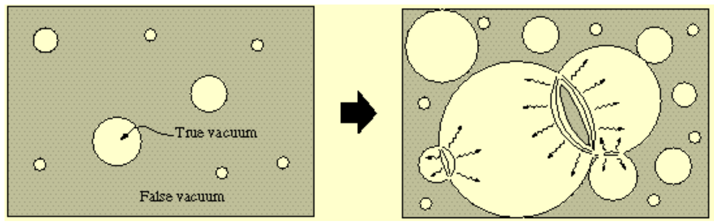






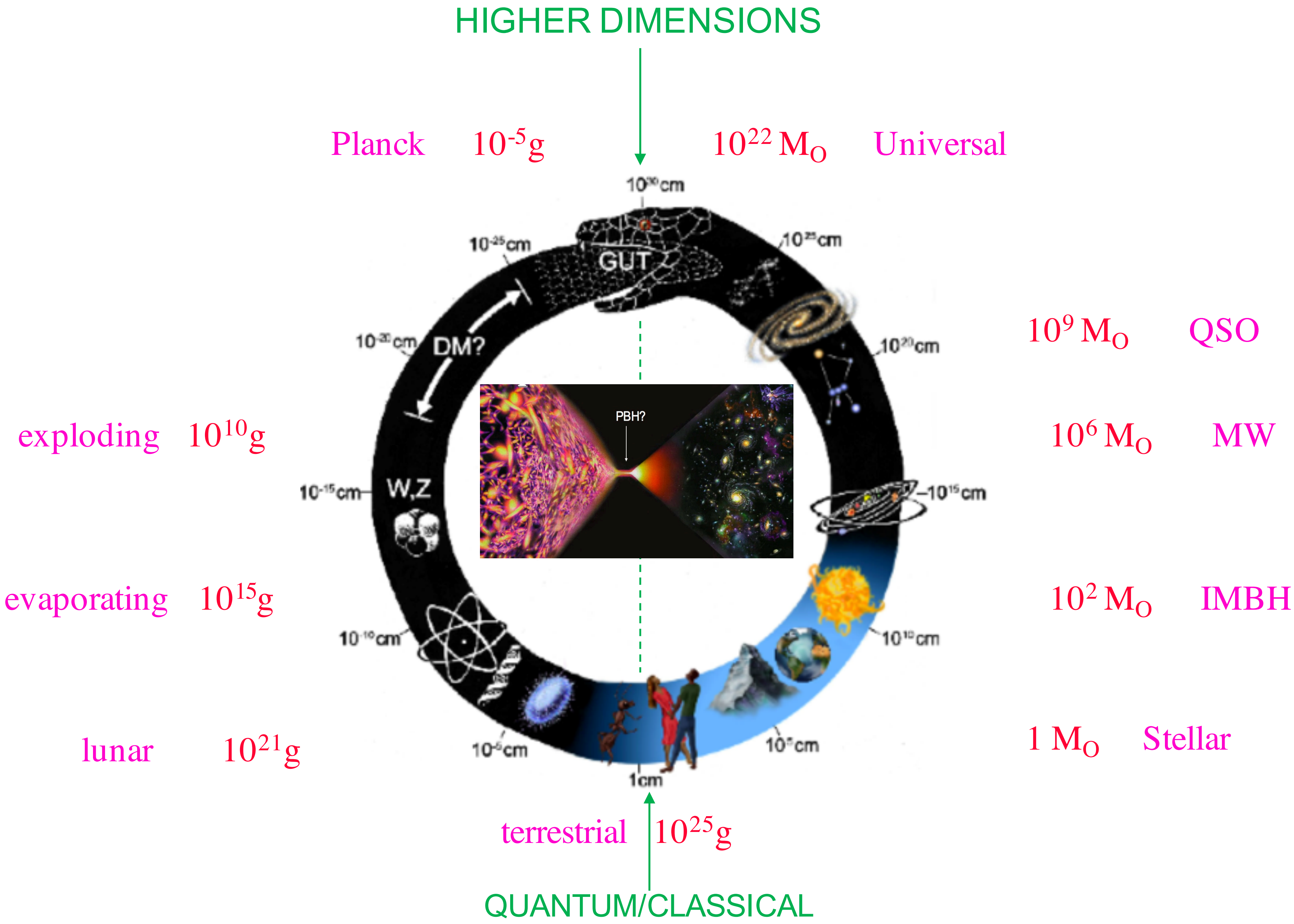
Bubble collisions

Need fine-tuning of bubble formation rate

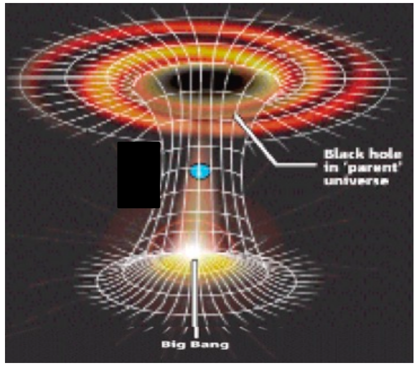


Domain walls PBHs can be very large

BLACK HOLES AS LINK BETWEEN MICRO AND MACRO PHYSICS

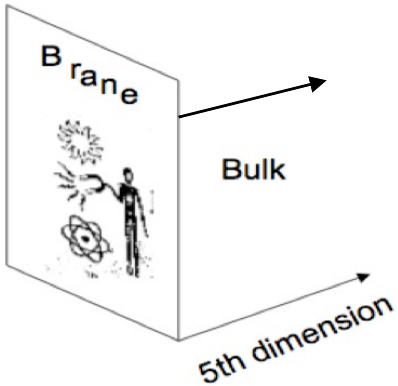


IS THE UNIVERSE A PRIMORDIAL BLACK HOLE?



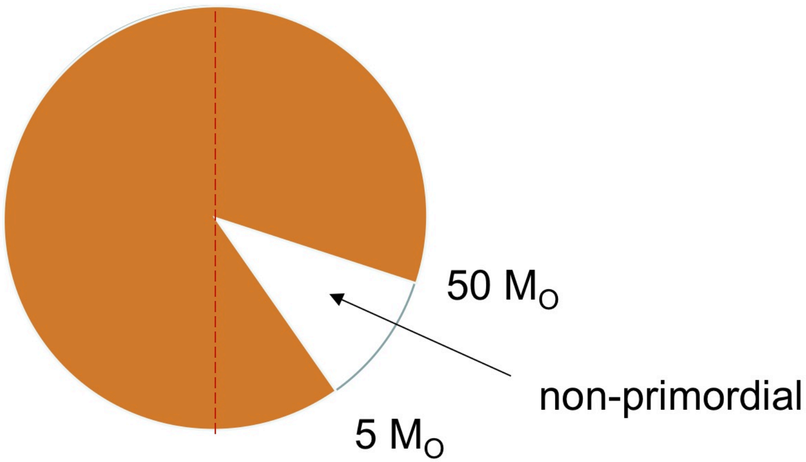
Collapse to black hole generates a baby Universe

Smolin (1997)



Brane cosmology => 5D Schwarzschild de Sitter model
=> Universe emerges out of 5D black hole

Bowcock et al. (2000), Mukhoyama et al. (2000)



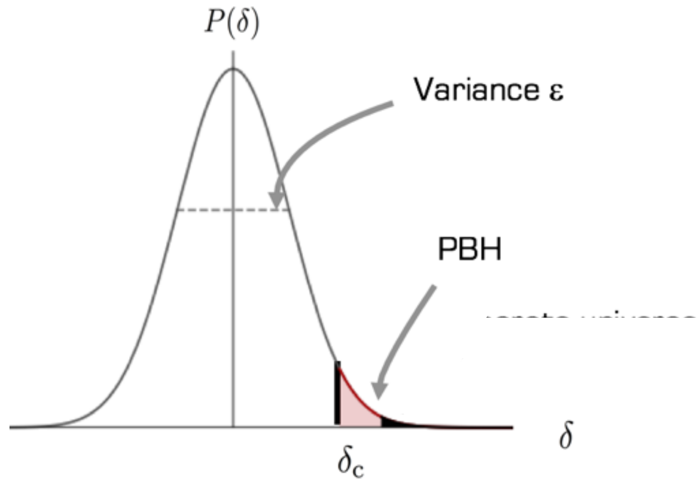
ARE MOST BLACK HOLES PRIMORDIAL?

PBH FORMATION => LARGE INHOMOGENEITIES

To collapse against pressure, need (Carr 1975)

$$R > \sqrt{\alpha}\, ct \quad \text{when } \delta \sim 1 \implies \delta_H > \alpha \qquad (p = \alpha \rho c^2)$$

Gaussian fluctn's with $\langle \delta_H^2 \rangle^{1/2} = \varepsilon(M)$



$\Rightarrow$ fraction of PBHs

$$\beta(M) \sim \varepsilon(M) \exp\left[-\frac{\alpha^2}{2\varepsilon(M)^2} \right]$$

General limit

$$\frac{\rho_{PBH}}{\rho_{CBR}} \approx \frac{\Omega_{PBH}}{10^{-4}} \left[\frac{R}{R_0} \right] \implies \beta \sim 10^{-6}\, \Omega_{PBH} \left[\frac{t}{\sec} \right]^{1/2} \sim 10^{-18}\, \Omega_{PBH} \left[\frac{M}{10^{15} g} \right]^{1/2}$$

So both require and expect $\beta(M)$ to be tiny

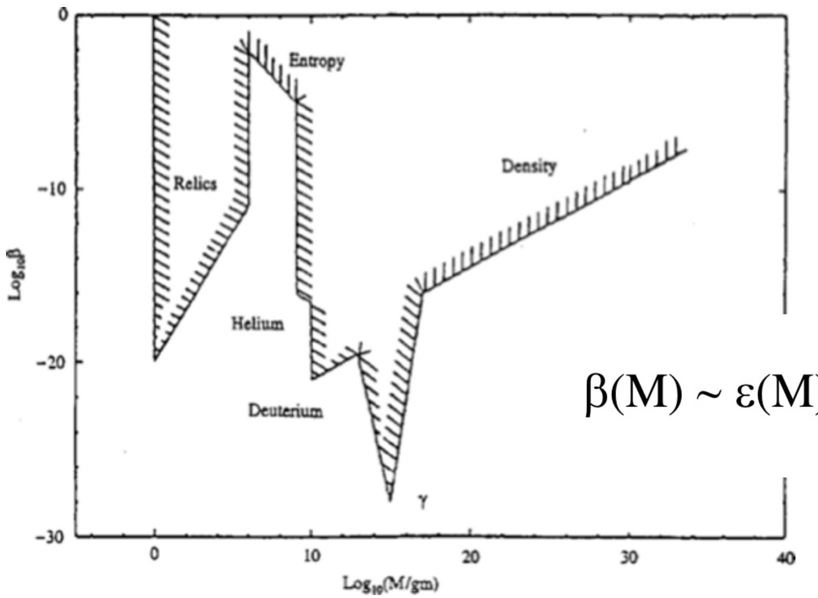
Limit on fraction of Universe collapsing

Unevaporated $M > 10^{15}g \Rightarrow \Omega_{PBH} < 0.25$ (CDM)

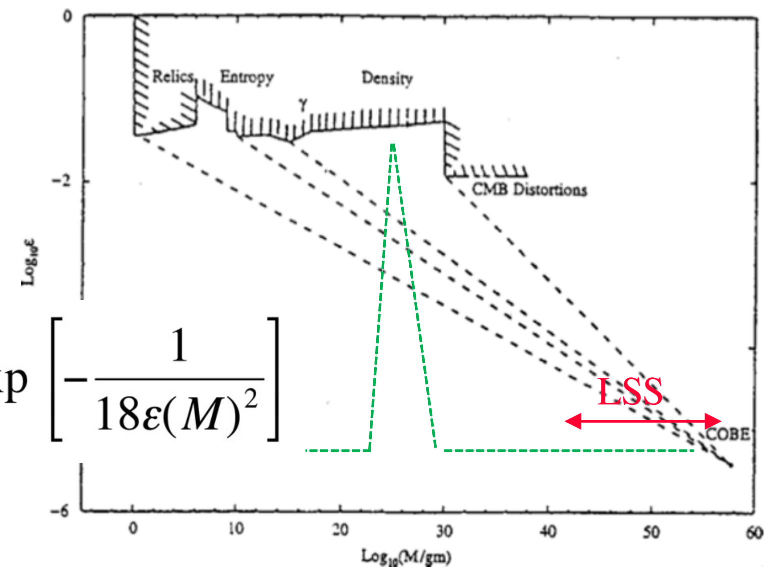
Evaporating now $M \sim 10^{15}g \Rightarrow \Omega_{PBH} < 10^{-8}$ (GRB)

Evaporated in past $M < 10^{15}g$

=> constraints from entropy, γ-background, BBNS

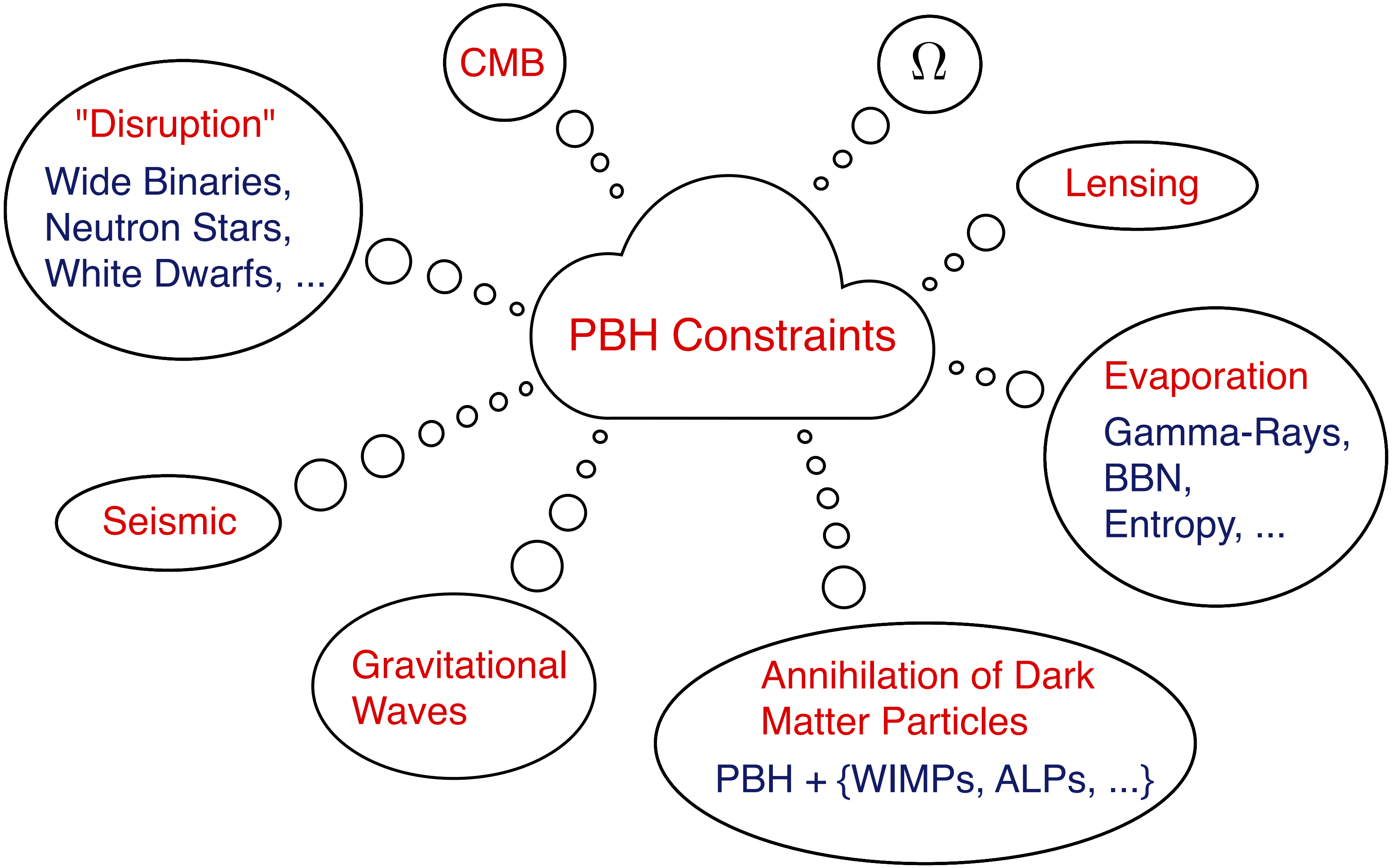


$$\beta(M) \sim \varepsilon(M) \exp\left[-\frac{1}{18\varepsilon(M)^2}\right]$$



PBHs are unique probe of ε on small scales.

Need blue spectrum or spectral feature to produce them.



PBH Constraints
CMB
Ω
Lensing
"Disruption"
Wide Binaries,
Neutron Stars,
White Dwarfs, ...
Evaporation
Gamma-Rays,
BBN,
Entropy, ...
Seismic
Gravitational
Waves
Annihilation of Dark
Matter Particles
PBH + {WIMPs, ALPs, ...}

CONSTRAINTS FOR EVAPORATING PBHS

B. Carr, K. Kohri, Y. Sendouda & J. Yokoyama PRD 81(2010) 104019

Big bang nucleosynthesis

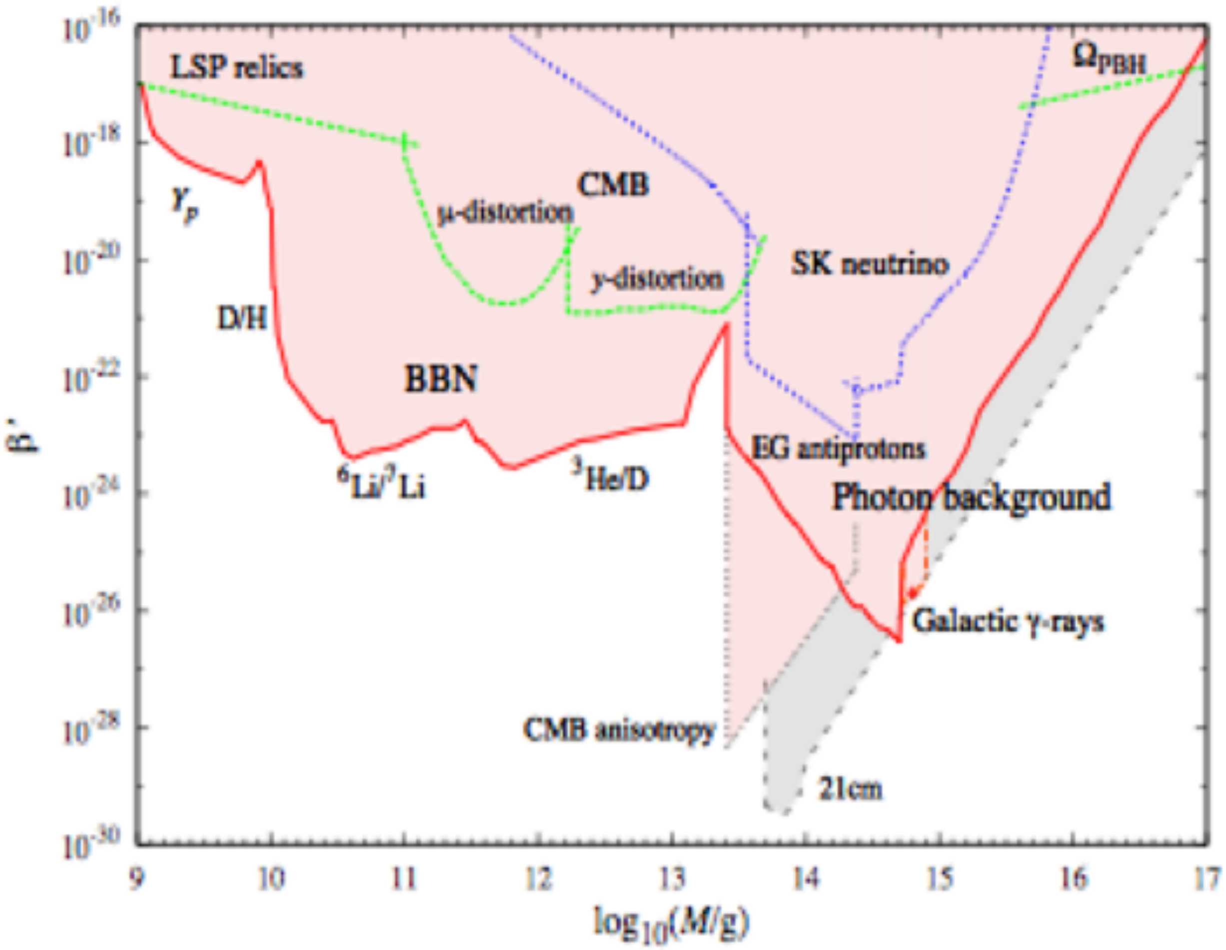
Gamma-ray background

Extragalactic cosmic rays

Neutrino relics

LSP relics

CMB distortions



This assumes monochromatic mass function

VOYAGER-1 $e^{\pm}$ further constrain Primordial Black Holes as Dark Matter

Mathieu Boudaud[1] and Marco Cirelli[1]

arXiv:1807.03075

Direct Detection of Hawking Radiation from Asteroid-Mass Primordial Black Holes

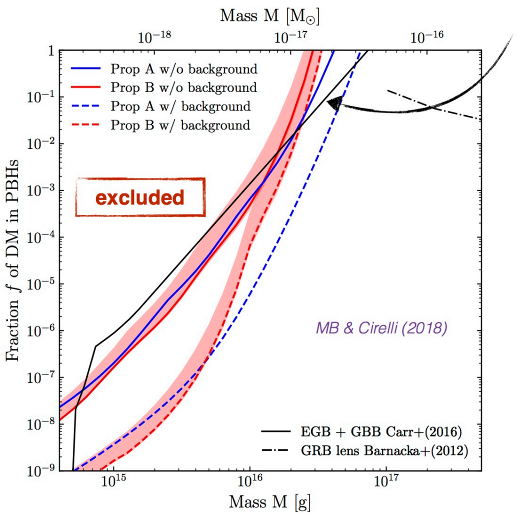
Adam Coogan,[1,*] Logan Morrison,[2,†] and Stefano Profumo[2,‡]

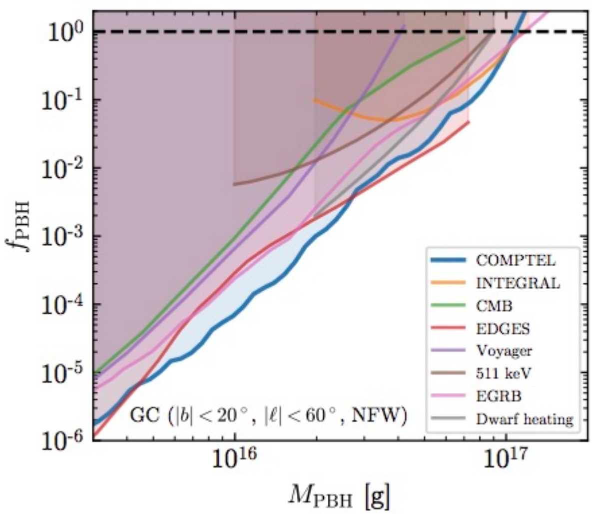
arXiv:2010.04797

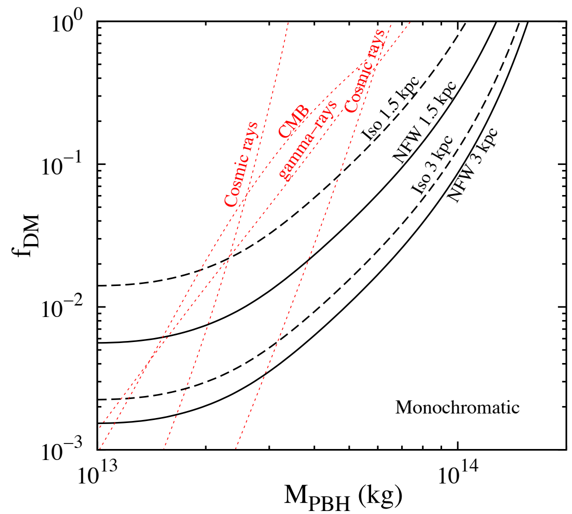
PBHs as DM candidate are severely constrained by the Galactic Center 511 keV γ-ray line

Laha

arXiv:1906.09994





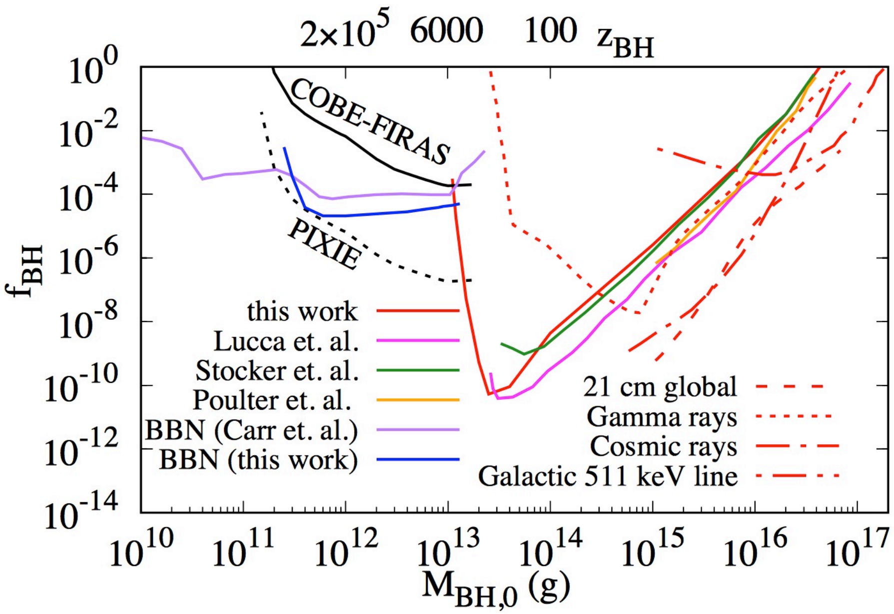


RECENT CONSTRAINTS ON EVAPORATING PBHS

CMB anisotropies

CKSY 2010

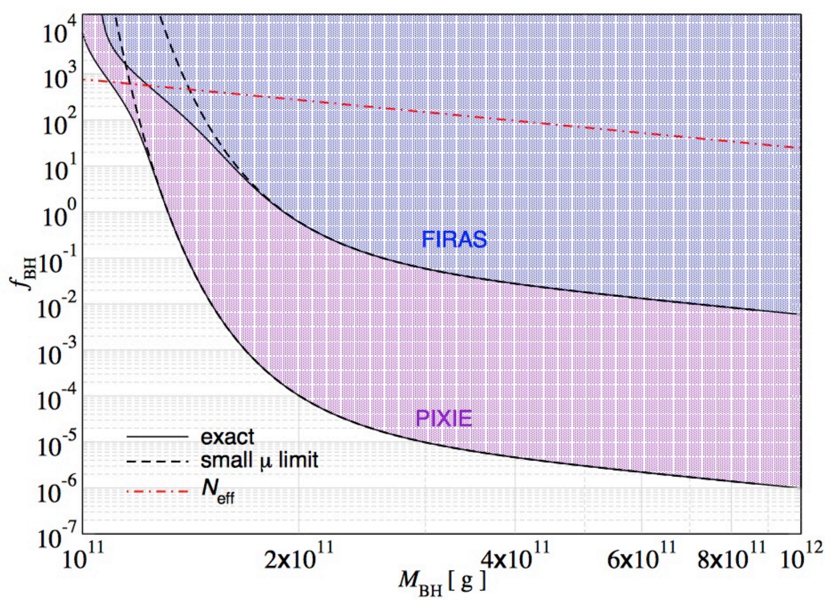
"CMB constraints on evaporating PBHs revisited"
Acharya & Khatri
2002.00898



CMB spectral distortions

Tashiro & Sugiyama (2008)

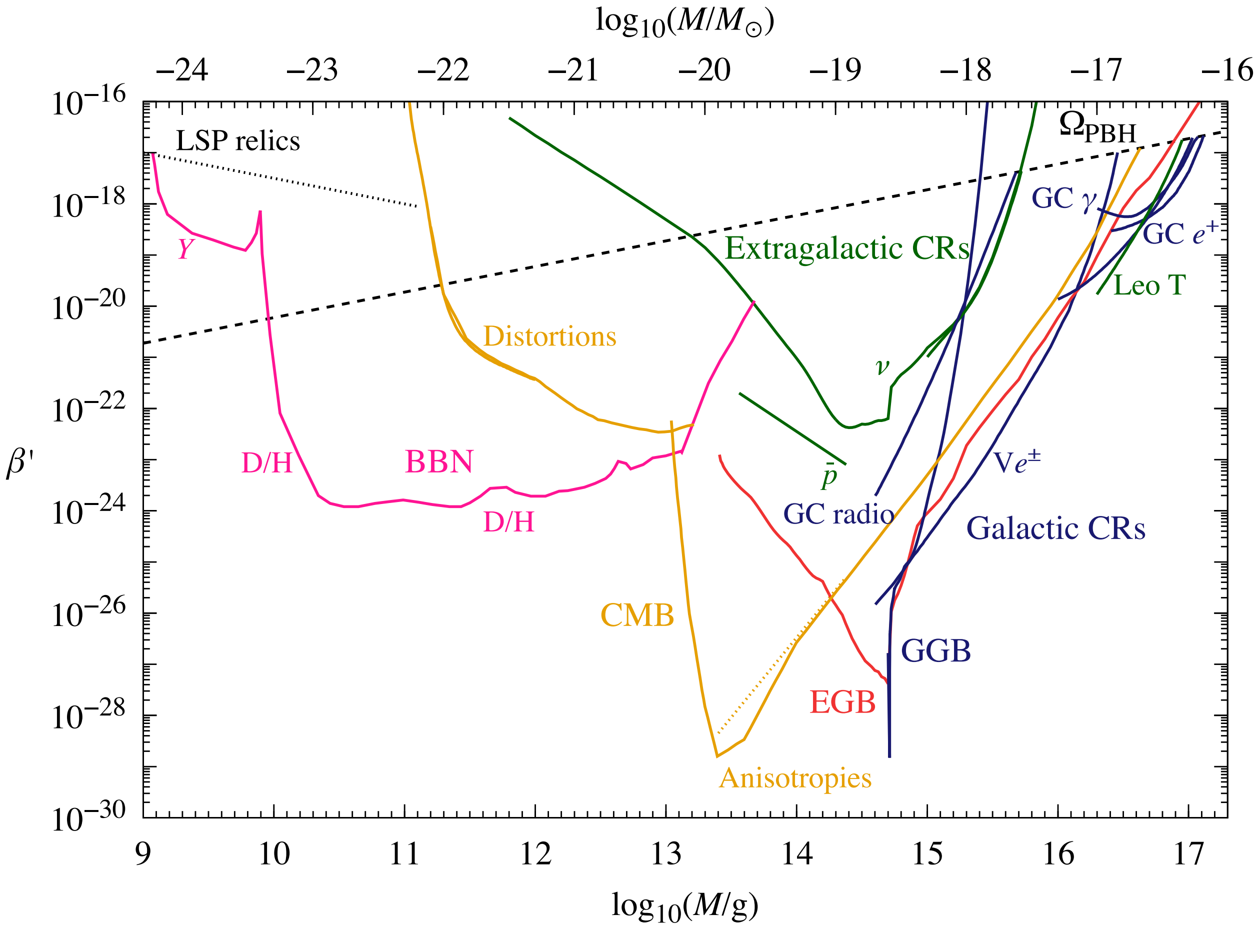
"Thermalization of large energy release in the early Universe"
Chluba, Ravenni & Acharya
2005.11325



CONSTRAINTS FOR EVAPORATING PBHS

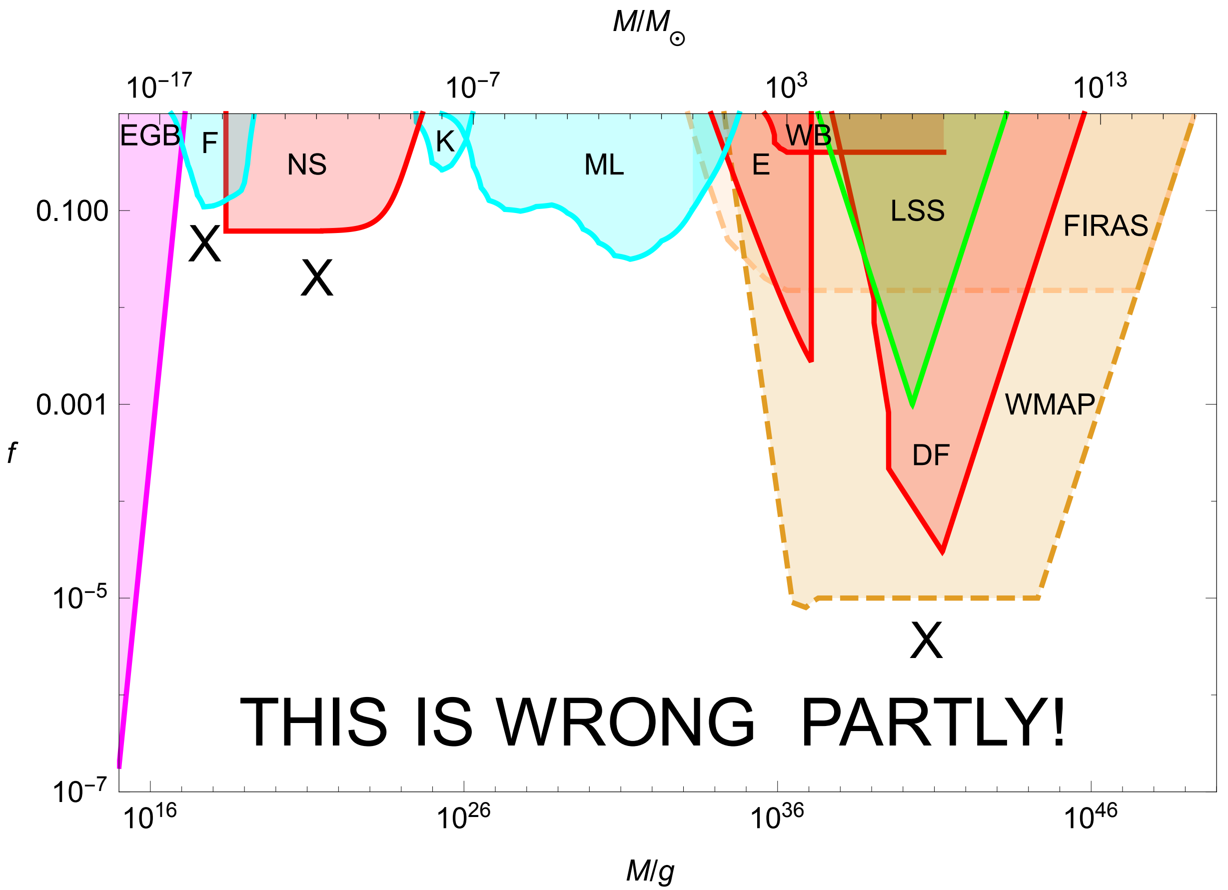
B. Carr, K. Kohri, Y. Sendouda & J. Yokoyama

Progress Theoretical Physics (2020), arXiv:2002.12778



CONSTRAINTS ON NON-EVAPORATED PBHS

Carr, Kuhnel & Sandstad, arXiv:1607.06077



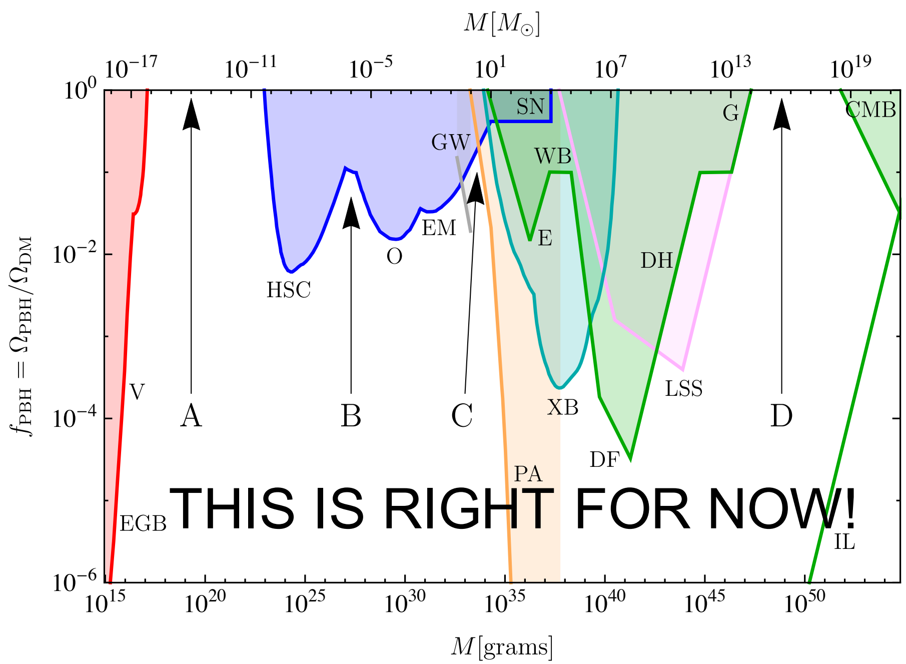
Some of these limits are now thought to be wrong

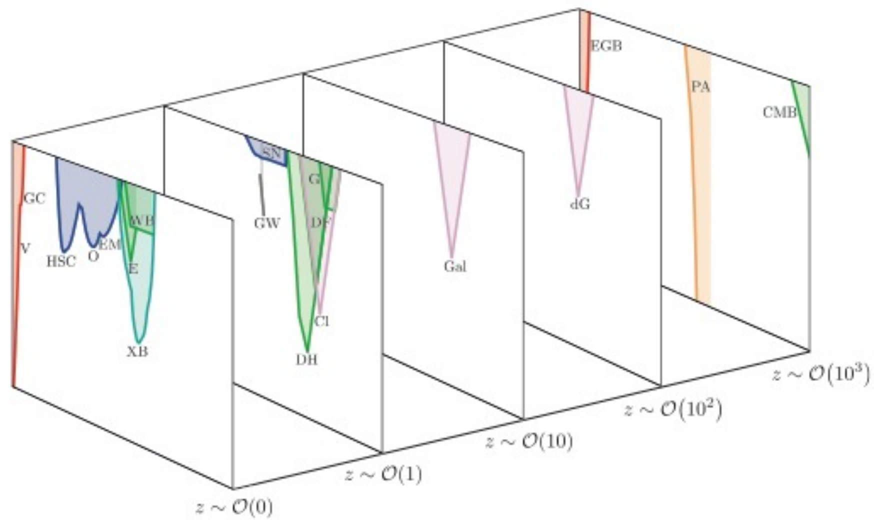
Primordial Black Holes as Dark Matter: Recent Developments

Bernard Carr[1,*] and Florian Kühnel[2,†]

Annu. Rev. Nucl. Part. Sci. 2020. 70:14.1–14.40

arXiv:2006.02838



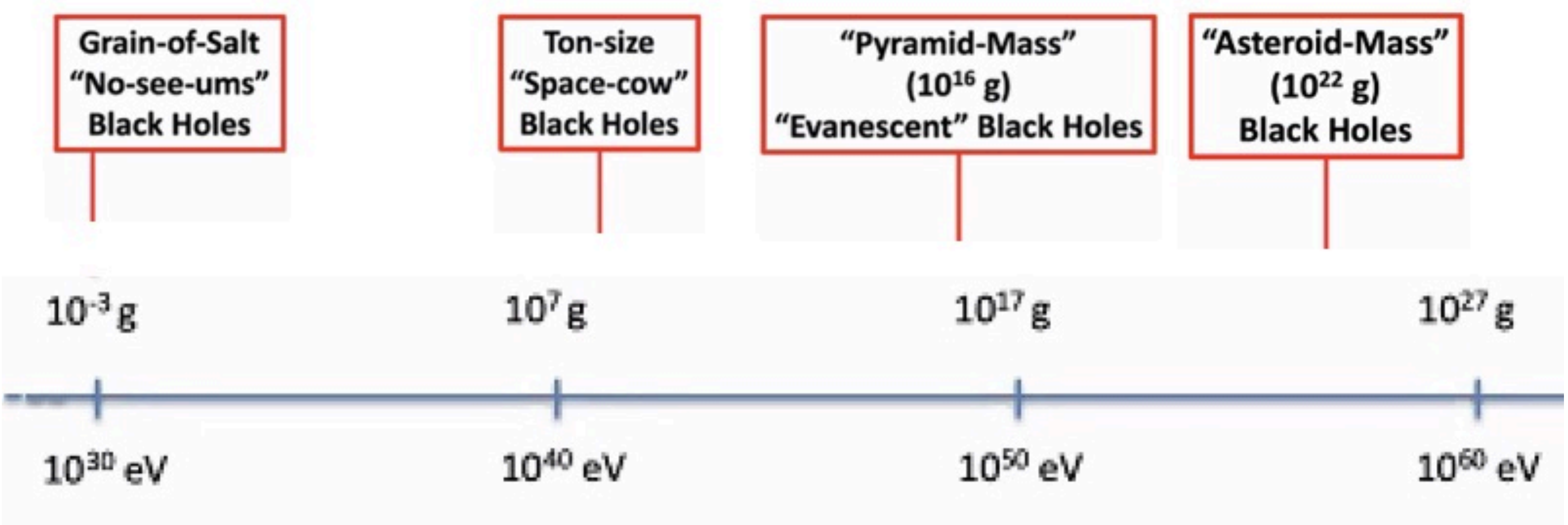


(credit: based on JGB)

Three windows: (A) intermedate mass; (B) sublunar mass; (C) asteroid mass;

(D) stupendously massive; (E) Planck mass relics

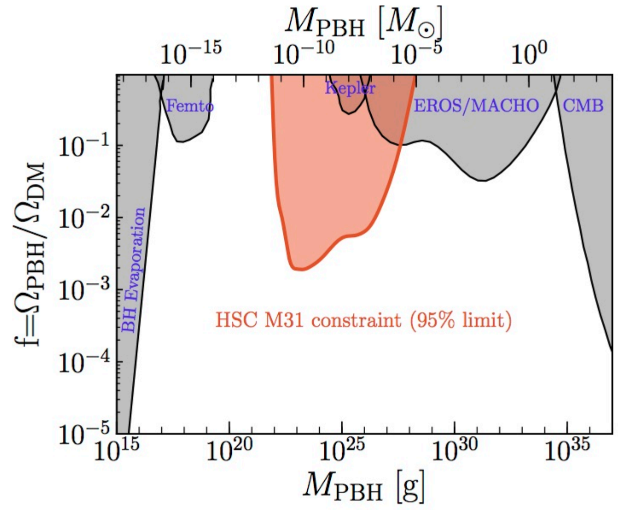
Profumo talk



Microlensing constraints on primordial black holes with the Subaru/HSC Andromeda observation

Hiroko Niikura[1,2], Masahiro Takada[1], Naoki Yasuda[1], Robert H. Lupton[3], Takahiro Sumi[4], Surhud More[1,5], Toshiki Kurita[1,2], Sunao Sugiyama[1,2], Anupreeta More[1], Masamune Oguri[1,2,6], Masashi Chiba[7]

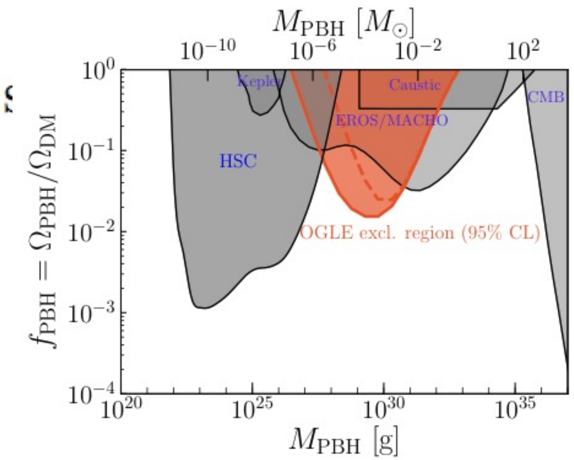
Nature Astronomy 3, 524 (2019),



Earth-mass black holes? – Constraints on primordial black holes with 5-years OGLE microlensing events

Hiroko Niikura,[1,2,*] Masahiro Takada,[2,†] Shuichiro Yokoyama,[3,2] Takahiro S

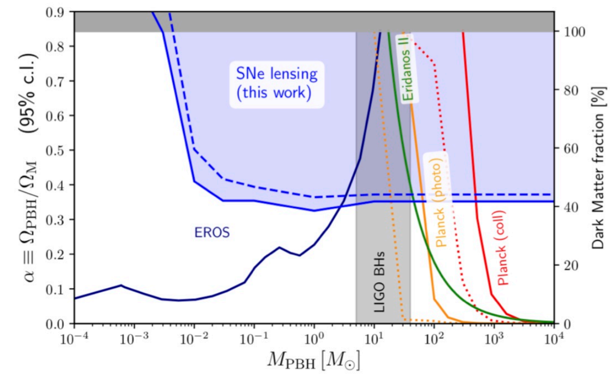
arXiv:1901.07120



Limits on stellar-mass compact objects as dark matter from gravitational lensing of type Ia supernovae

Miguel Zumalacárregui[1,2,3,*] and Uroš Seljak[1,4,†]

arXiv:1712.02240

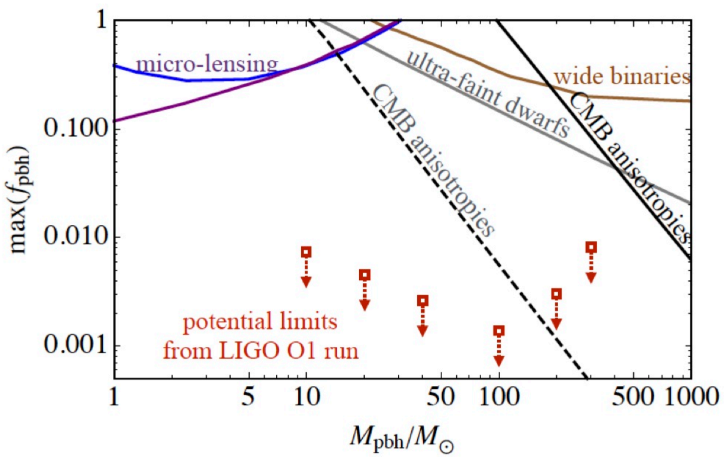


Can PBHs can evade these limits?

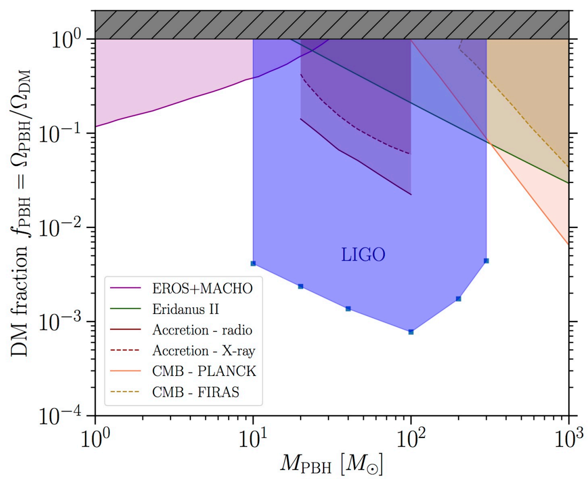
Garcia-Bellido et al, arXiv:1712.06574

CONSTRAINTS ON f(M) FROM LIGO

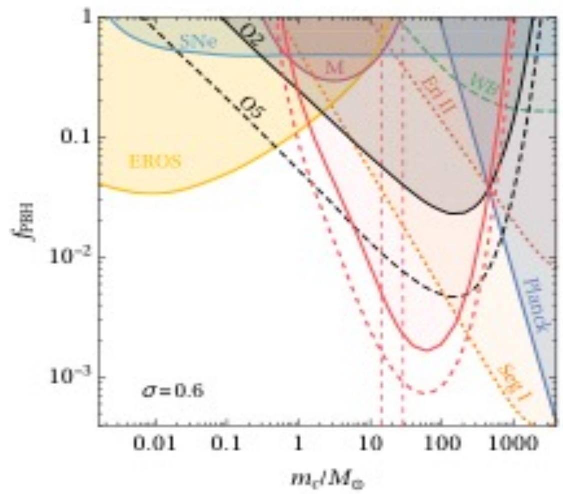
Ali-Haimoud et al. 1709.06576



Kavanagh et al 1805.09034



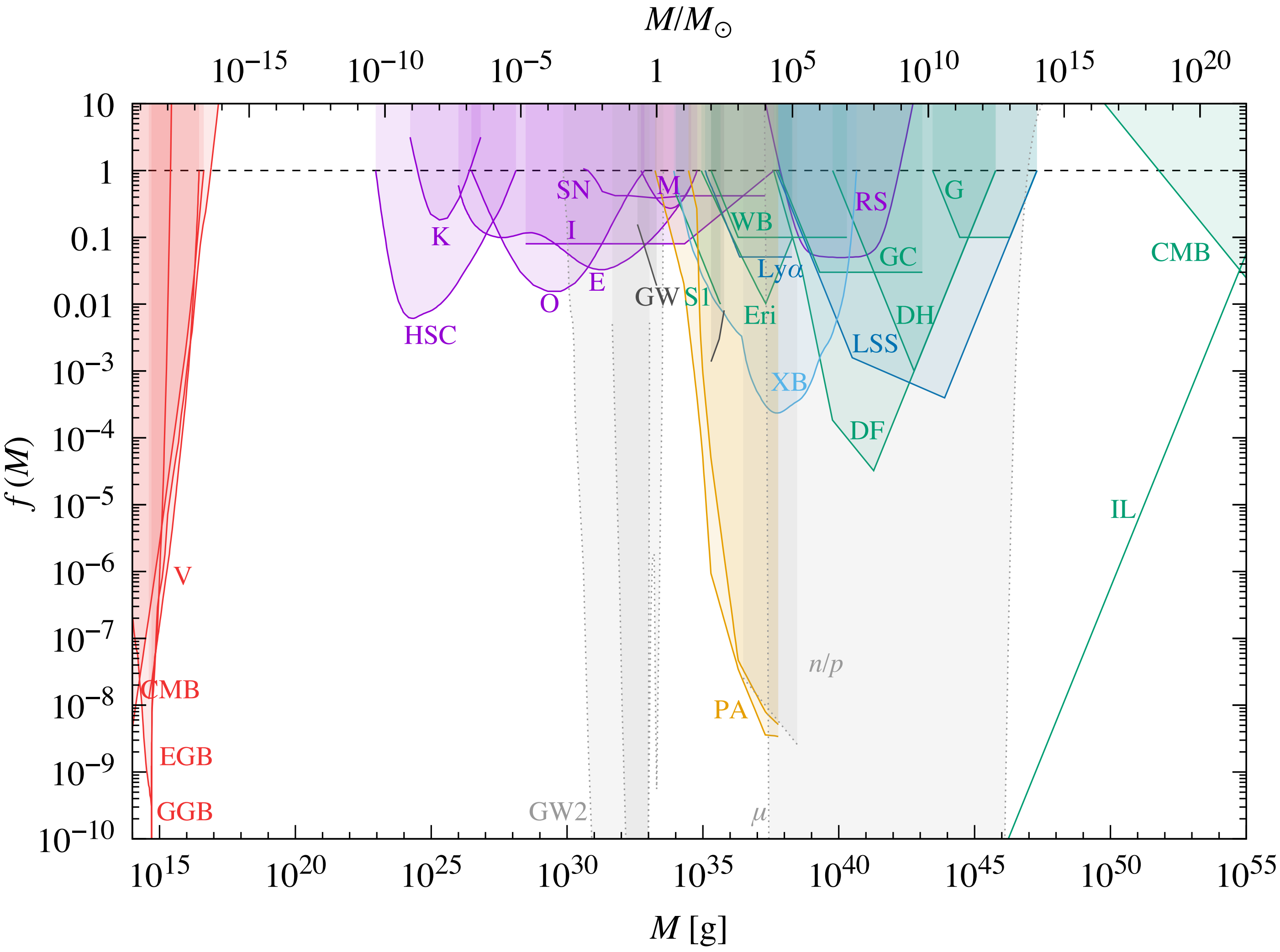
Raidal et al. 1812.01930



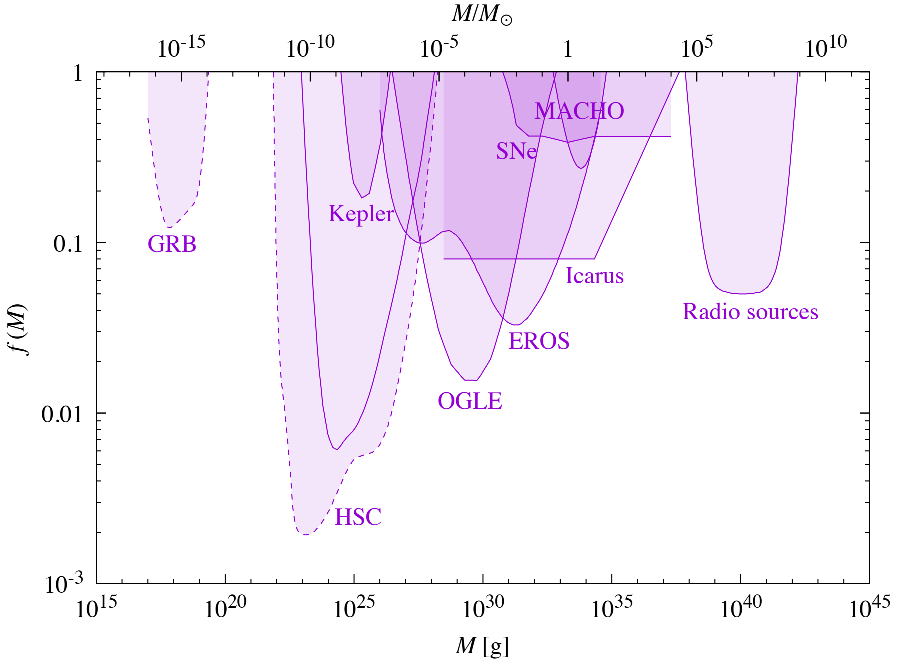
CONSTRAINTS ON PRIMORDIAL BLACK HOLES

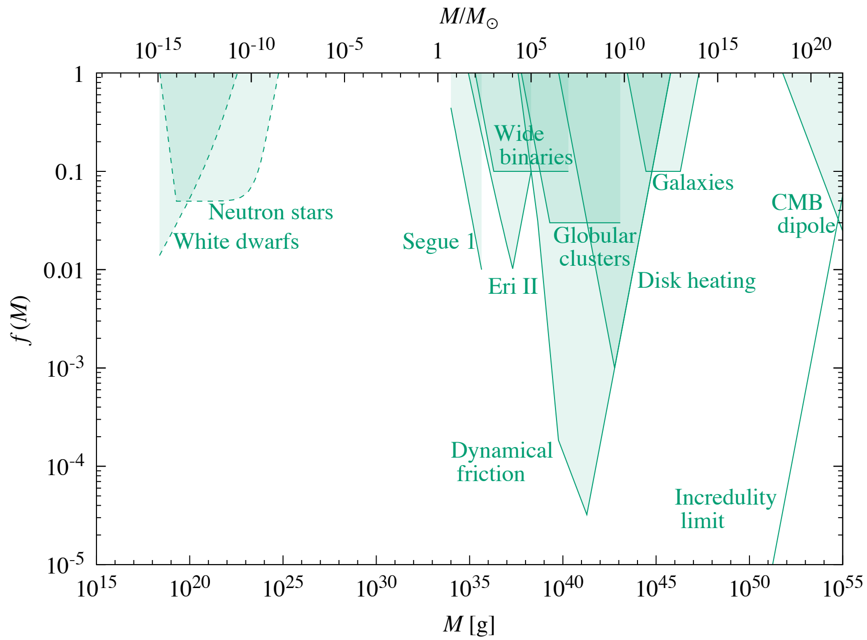
Bernard Carr,[1,2,*] Kazunori Kohri,[3,†] Yuuiti Sendouda,[4,‡] and Jun'ichi Yokoyama[2,5,§]

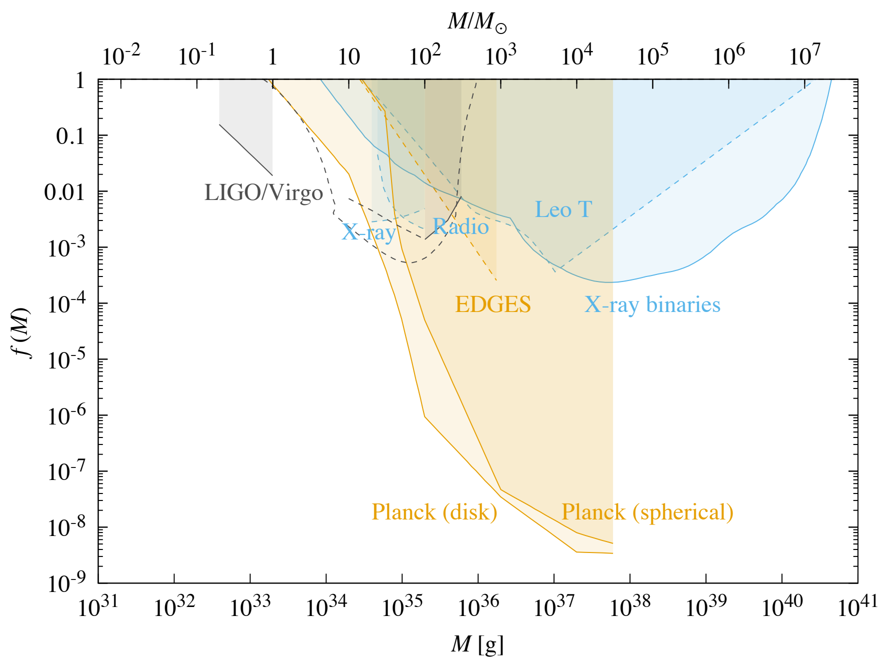
Progress Theoretical Physics (2020), arXiv:2002.12778

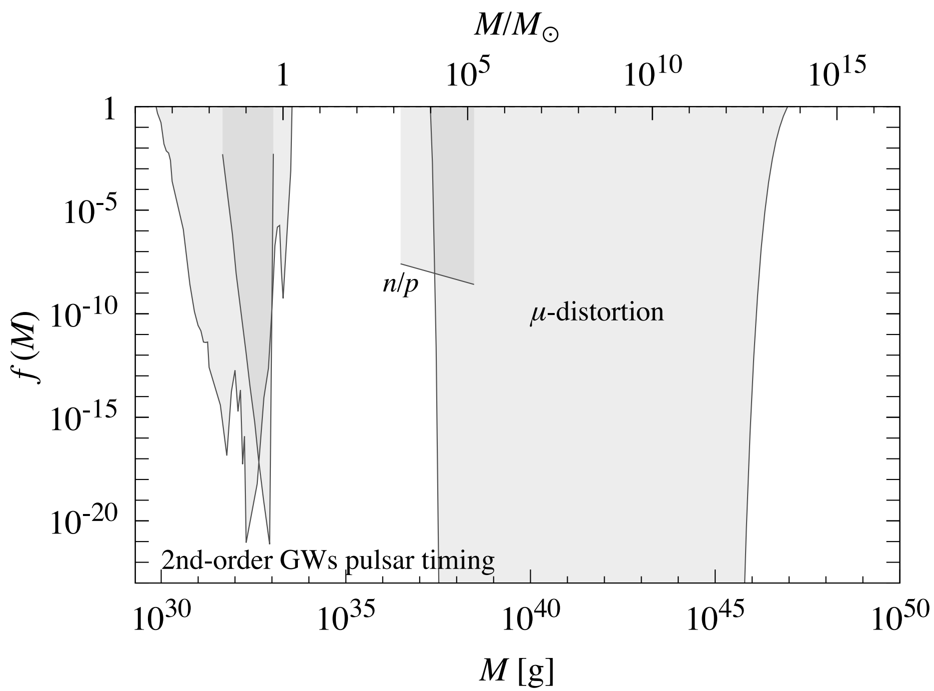


LENSING, DYNAMICAL, ACCRETION AND COSMOLOGICIAL LIMITS

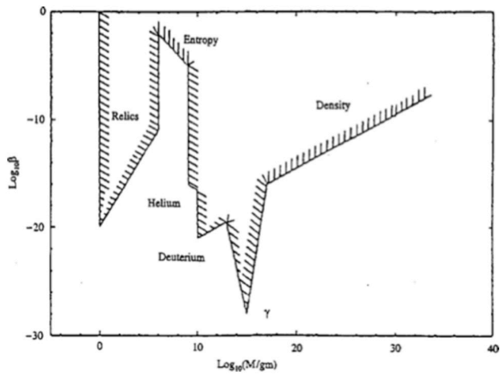


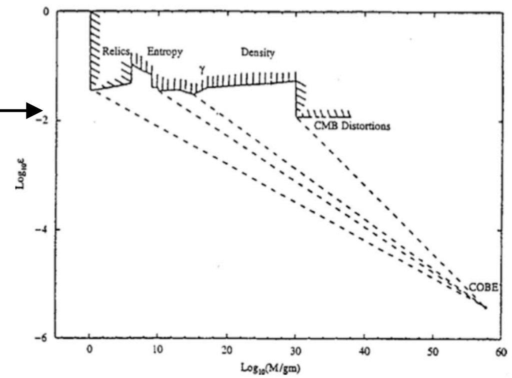


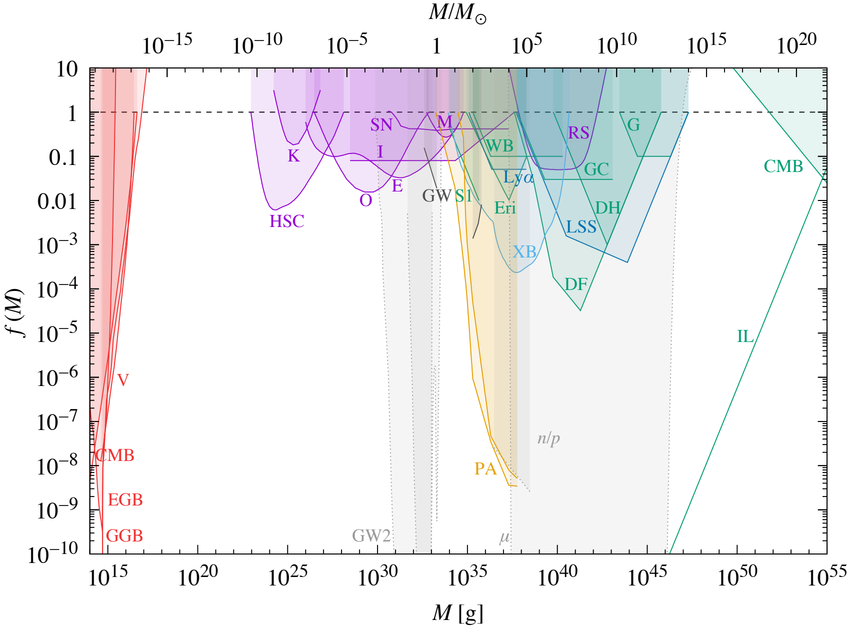


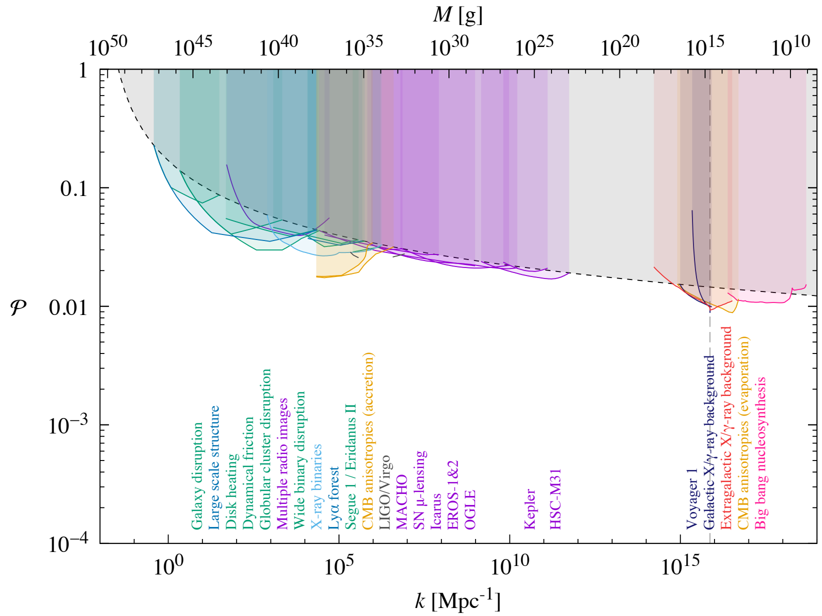


CONSTRAINTS ON POWER SPECTRUM









These constraints are not just nails in a coffin!

All constraints have caveats and may change

Each constraint is a potential signature

PBHs are interesting even if $f << 1$

PRIMORDIAL BLACK HOLES AS DARK MATTER

PRO

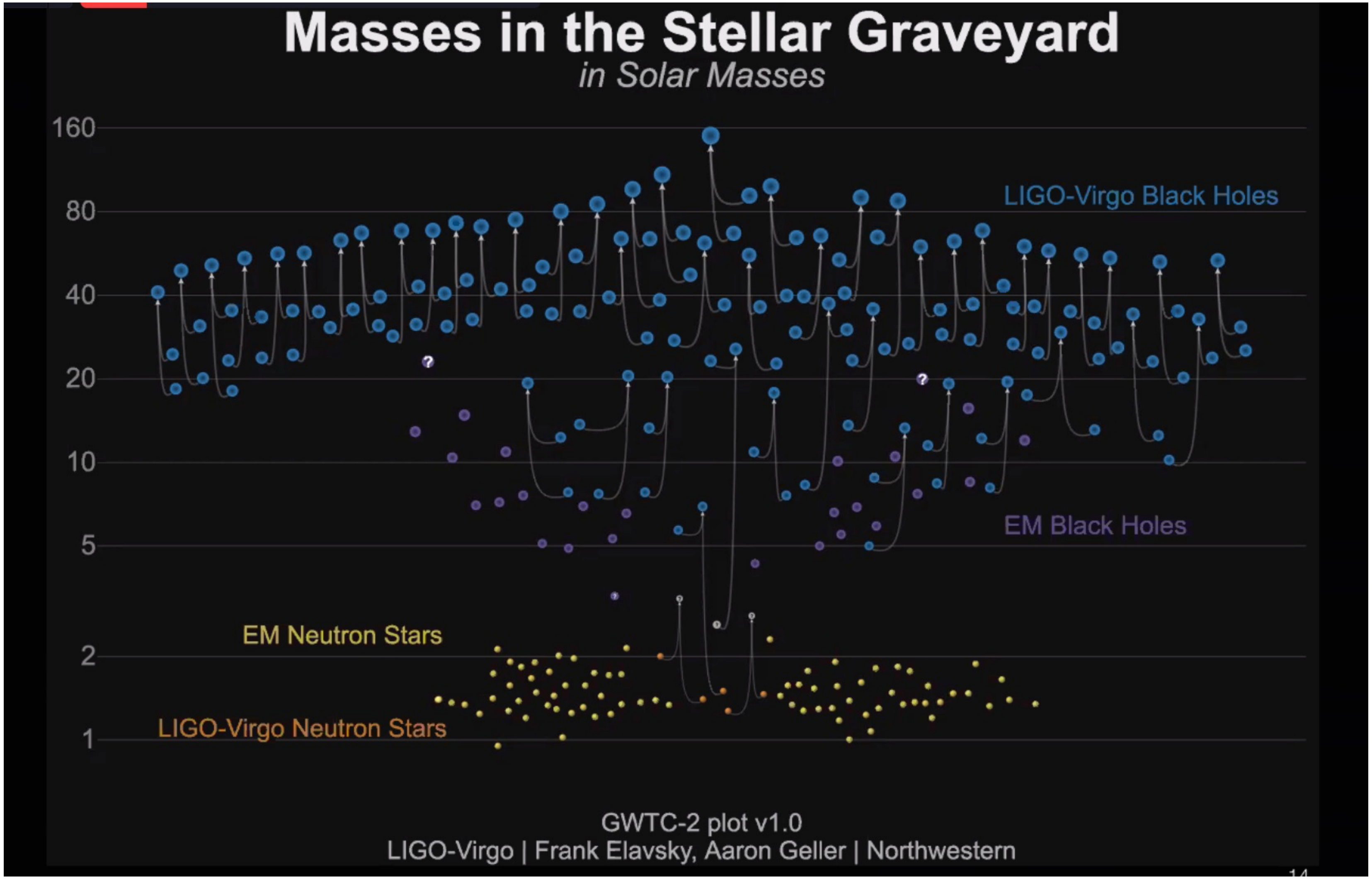
* Black holes exist
* No new physics needed
* LIGO results

CON

* Requires fine-tuning

PBH can do it!

PBHS AND LIGO/Virgo/KAGRA



Do we need Population III or primordial BHs?

RECENT PBH PAPERS

PBHs, dark matter and hot-spot electroweak baryogenesis at the QCD epoch

Bernard Carr,[1*] Sebastien Clesse,[2,3] and Juan García-Bellido[4]

arXiv:1904.02129

A common origin of baryons and dark matter via the gravitational collapse of black holes in the early universe

Juan García-Bellido[a,*] Bernard Carr[b,c,†] and Sébastien Clesse[d,e‡]

arXiv:1904.11482

Cosmic Conundra Explained by Thermal History and Primordial Black Holes

Bernard Carr,[1,2,*] Sébastien Clesse,[3,4,†] Juan García-Bellido,[5,‡] and Florian Kühnel[6,§]

arXiv:1906.08217

Constraints on Stupendously Large Black Holes

Bernard Carr,[1,2,*] Florian Kühnel,[3,†] and Luca Visinelli[4,‡]

arXiv:2008.08077

Black Holes and WIMPs: All or Nothing or Something Else

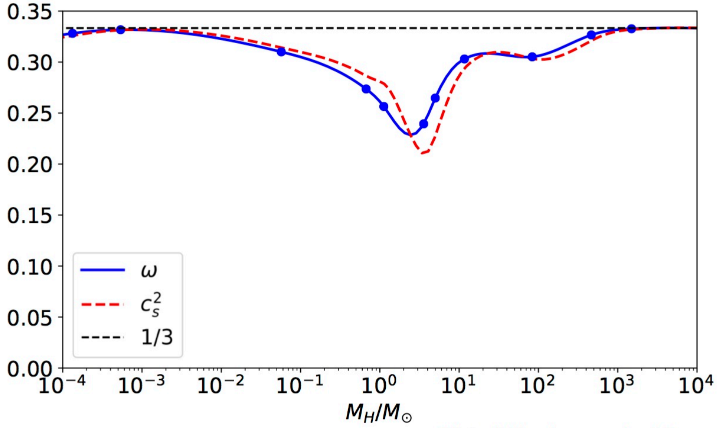
Bernard Carr,[1,2,*] Florian Kühnel,[3,†] and Luca Visinelli[4,5,‡]

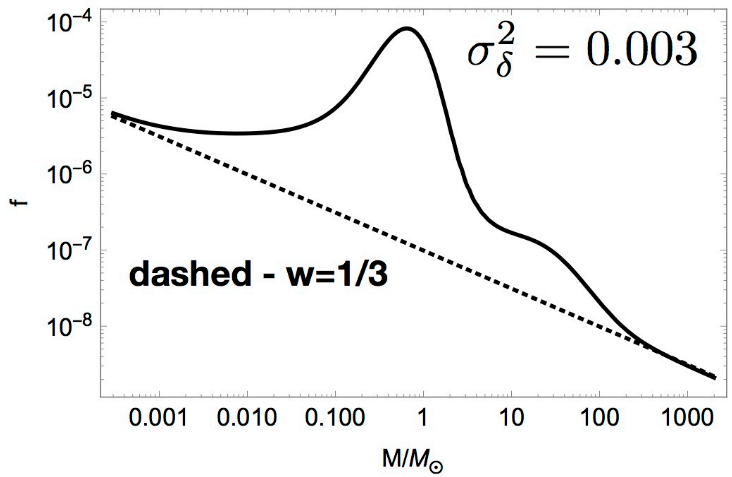
arXiv:2011.01930

Primordial black holes with an accurate QCD equation of state

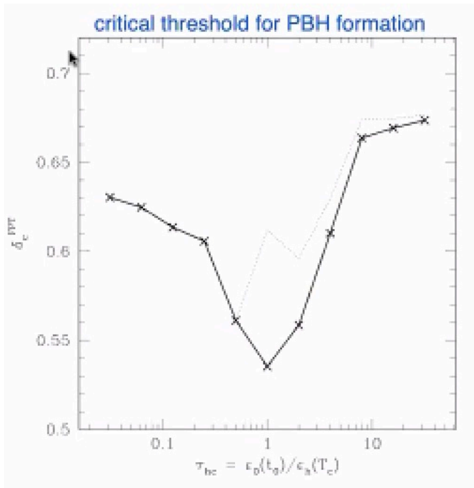
Christian T. Byrnes,[1,*] Mark Hindmarsh,[1,2,†] Sam Young,[1,‡] and Michael R. S. Hawkins[3,§]

arXiv:1801.06138





Jedamzik (1996)

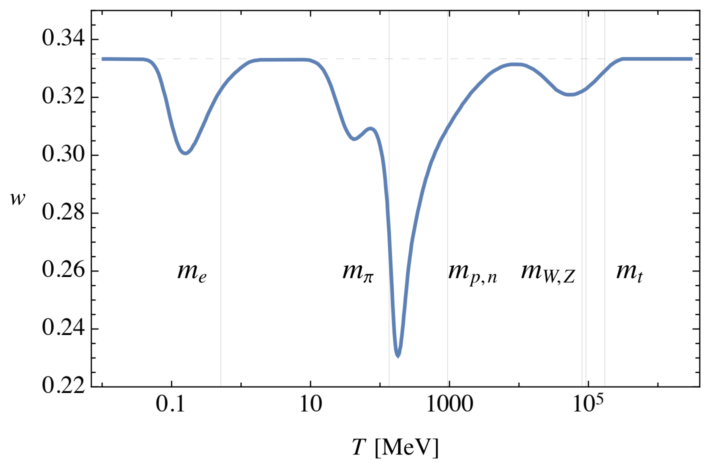


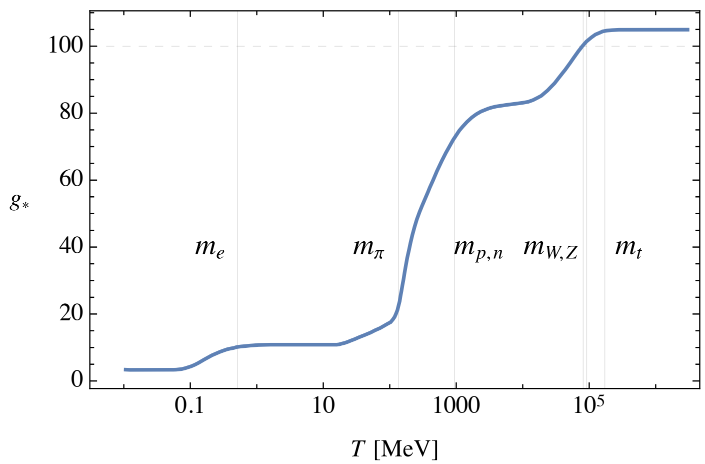
Cosmic Conundra Explained by Thermal History and Primordial Black Holes

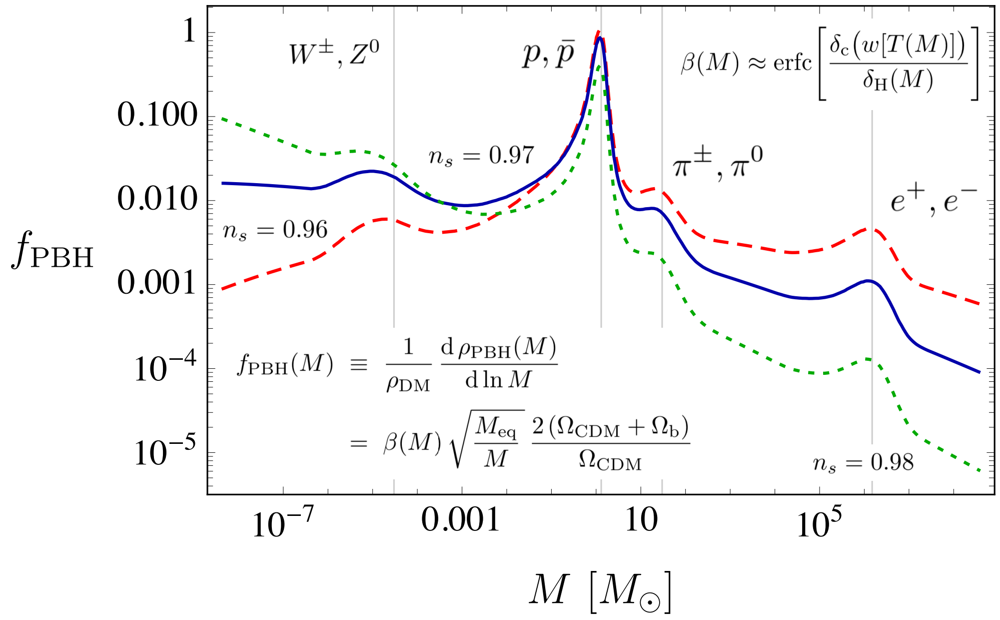
Bernard Carr,[1,2,*] Sébastien Clesse,[3,4,†] Juan García-Bellido,[5,‡] and Florian Kühnel[6,§]

arXiv:1906.08217

Extend this to include other stages in thermal history

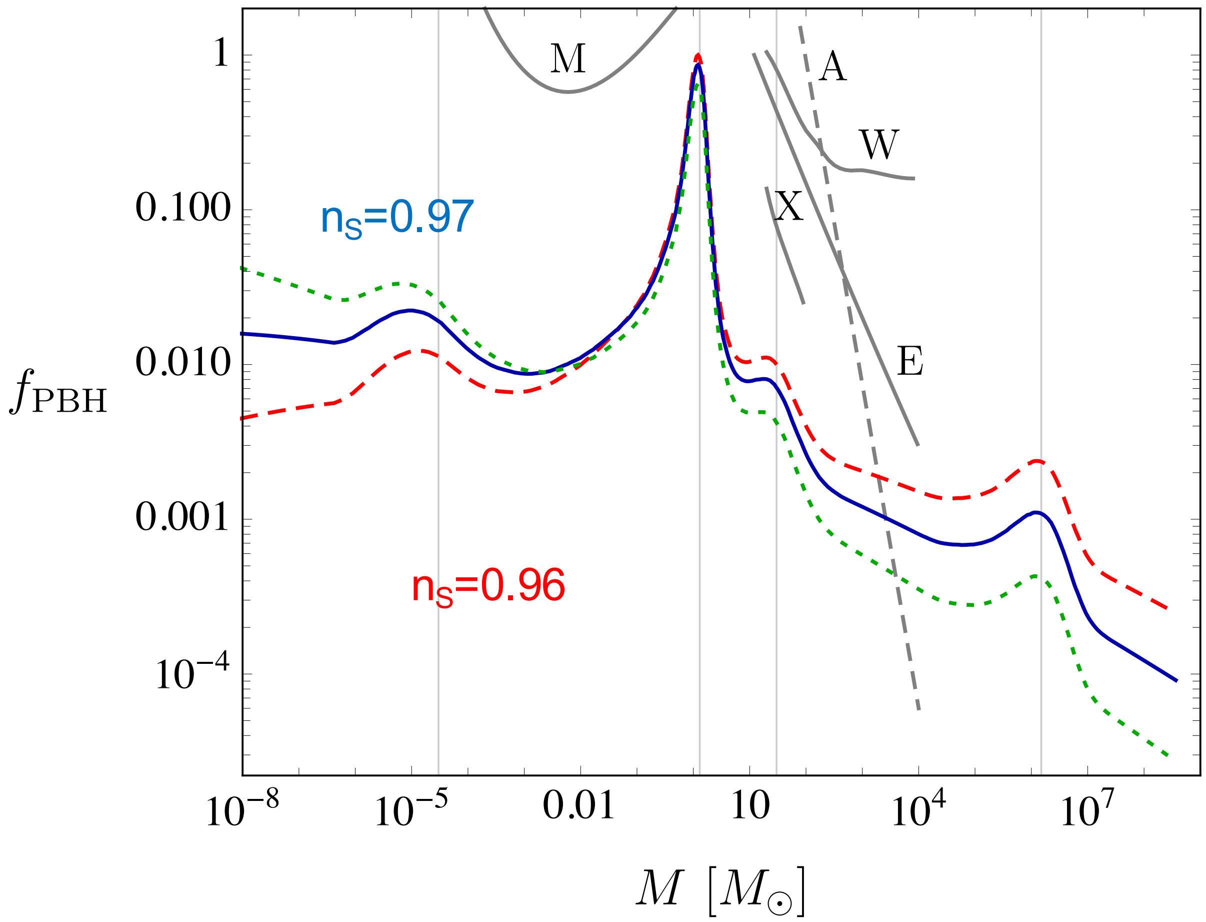






- **Nearly scale-invariant PS**
- **Spectral index: $n_s = 0.97$**
- **Peak at ~2 M⊙**
- **Second peak at ~30 M⊙**
- **Two bumps at 10^{-6} and 10^6 M⊙**

CONSTRAINTS



$$\delta_{\rm rms}(M) = A\left(\frac{M}{M_\odot}\right)^{(1-n_{\rm s})/4}$$

$$f_{\rm PBH}^{\rm max} = \left(\int {\rm d}\ln M\,\frac{f_{\rm PBH}(M)}{f_p^{\rm mon}(M)}\right)^{-1}$$

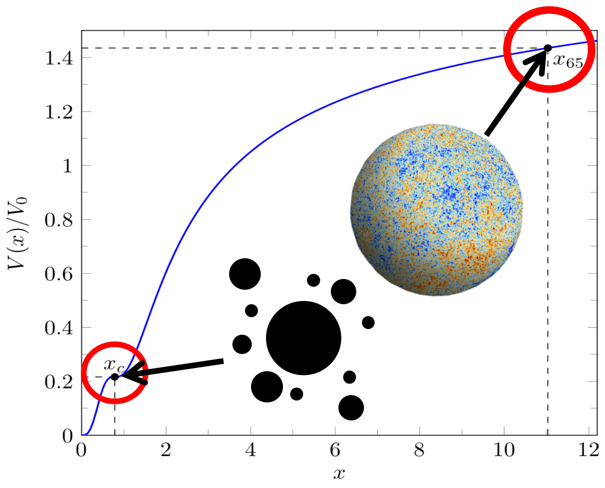
Overproduce light PBHs for $n_S > 0.975$

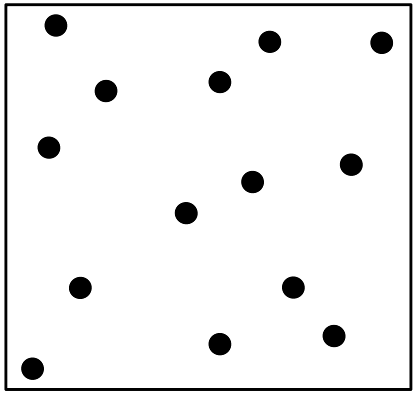
Overproduce heavy PBHs for $n_S < 0.965$

ARE PBHS CLUSTERED?

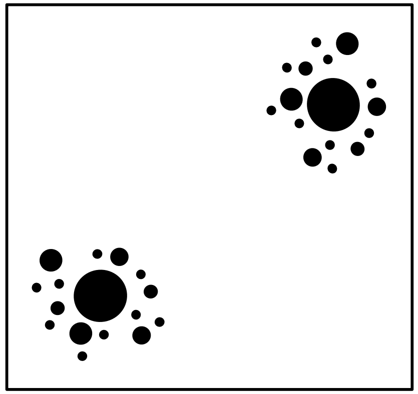
Inflation =>

- Lognormal wide-mass distribution JGB & Clesse (2017)
- Clusters of PBH: N_{cl} ~100-1000 , comoving size ~1mpc





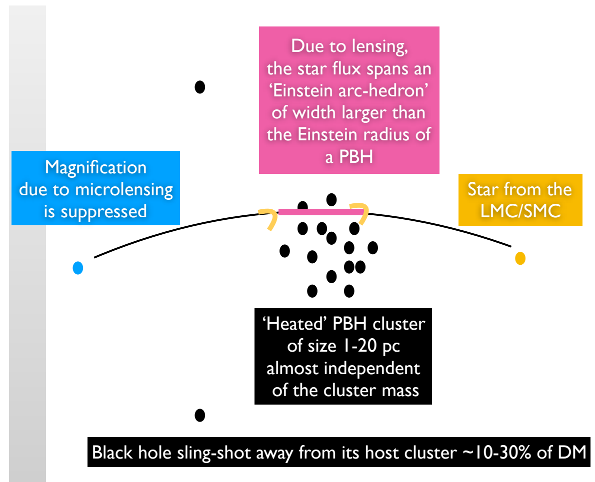
uniform single-mass
is already ruled out



clustered wide-mass
is still viable

[slide credit: JGB]

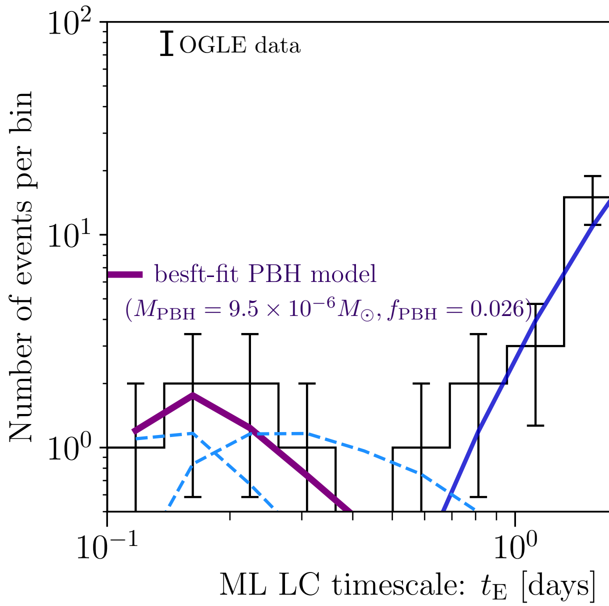
But controversial….



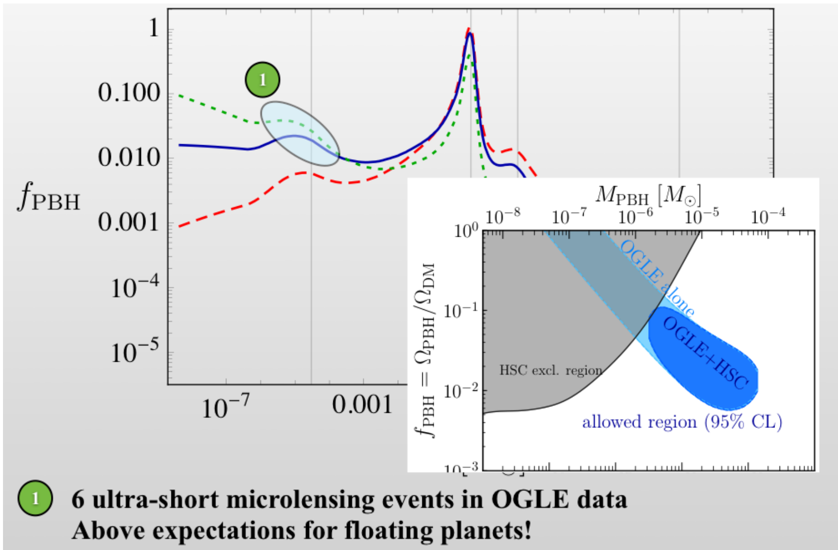
Planetary-mass microlenses

OGLE detected microlenses on 0.1-0.3 day timescale of unknown origin – free-floating planets of PBHs?

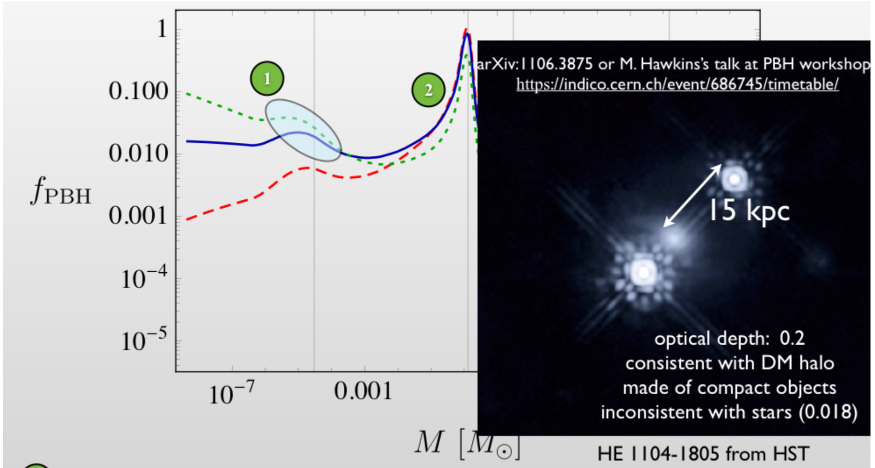
Niikura et al. (2019)



[Niikura *et al.* 2019]



Quasar microlensing



2 Microlensing of quasars (24) with misaligned galaxy (a few)
+ 56 microlensing events in M31

Evidence for dark matter in the form of compact bodies

Michael Hawkins
University of Edinburgh

Evidence for Microlensing

- Lack of time dilation.
- Symmetry of variation.
- Achromatic variation.
- Microlensing in multiply lensed quasars
- Caustic features in light curves
- Slope of structure function

The timescale of variation implies that the mass of the microlensing bodies is around 0.1 $M_\odot$

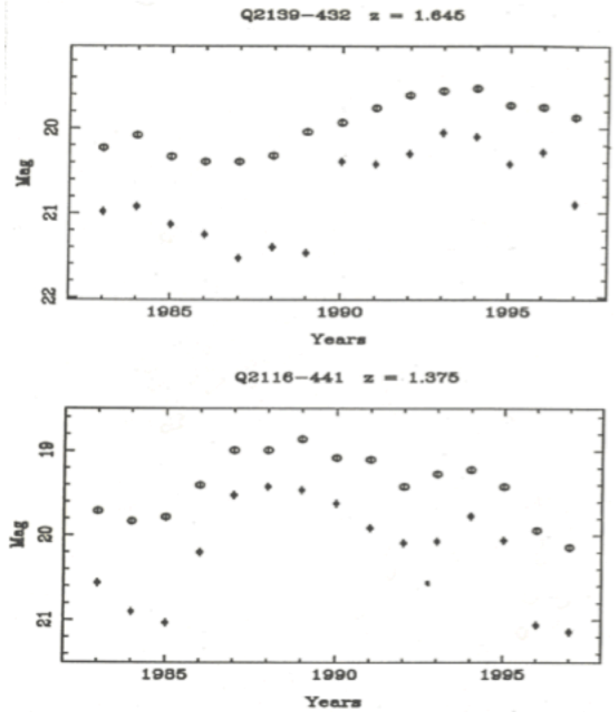
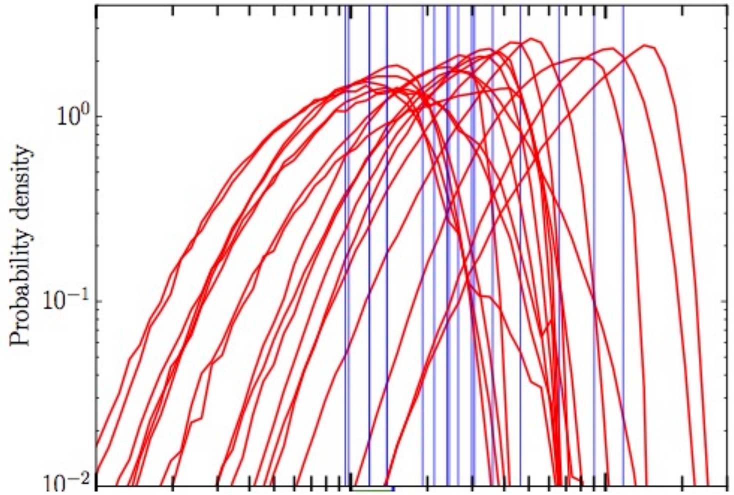
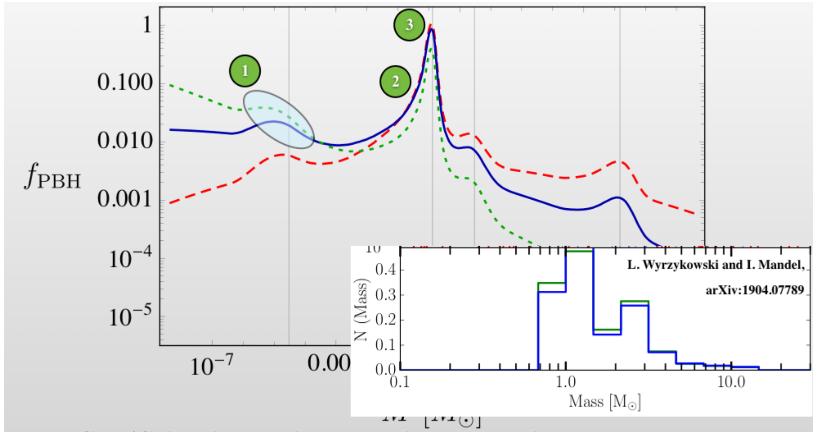


Fig. 3. Light curves for two quasars showing all the characteristics expected of caustic crossing events. Symbols as for Fig. 1.

OGLE/GAIA excess of lenses in Galactic bulge

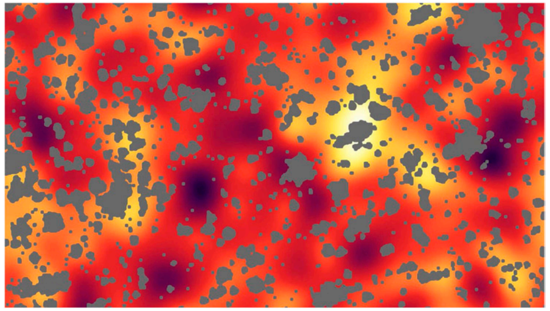




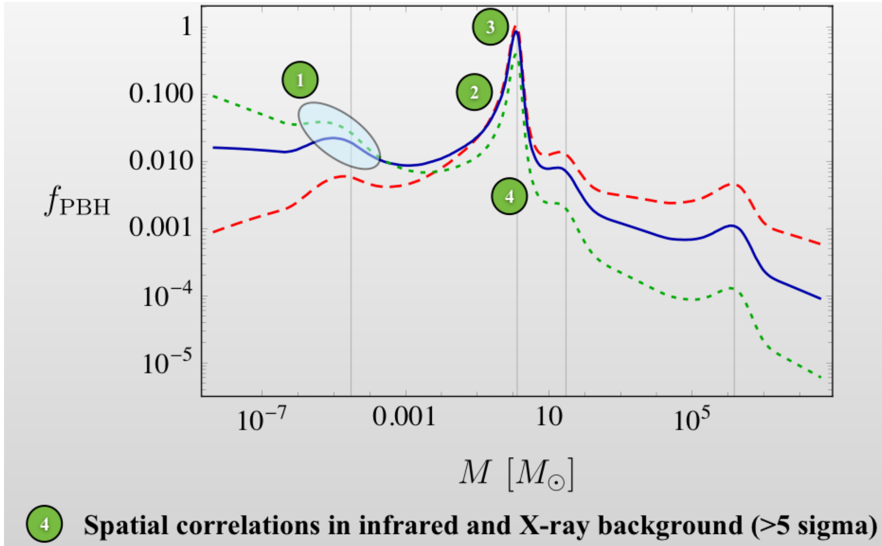
OGLE/Gaia microlensing events in the galactic bulge
Dark lenses: BH in the mass gap ([2-5] $M_\odot$)

Cosmic infrared/X-ray backgrounds

PBHs generate early structure and infrared background

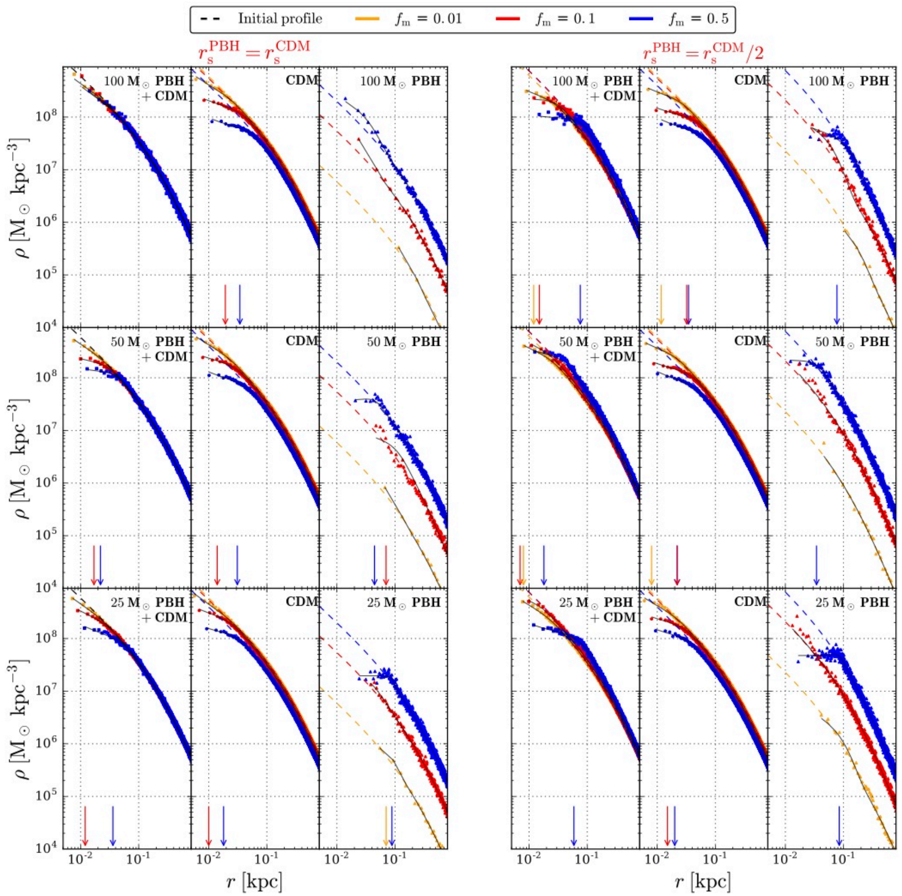


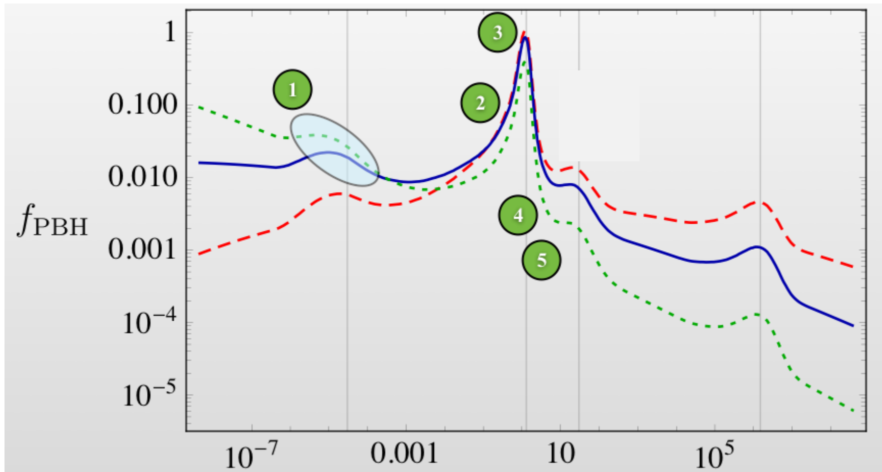
Kashlinsky
arXiv:1605.04023



Ultra-faint dwarf galaxies

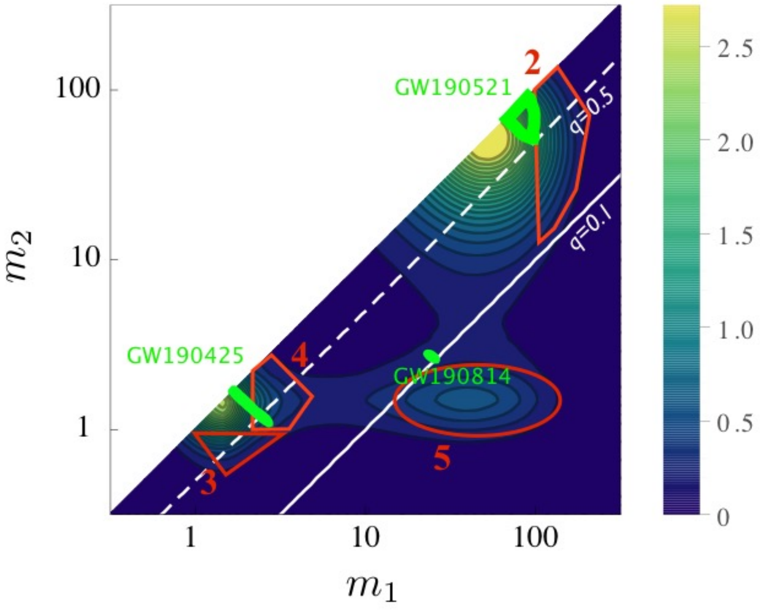
5 Minimum radius of (ultra-faint) dwarf galaxies and cored DM profiles

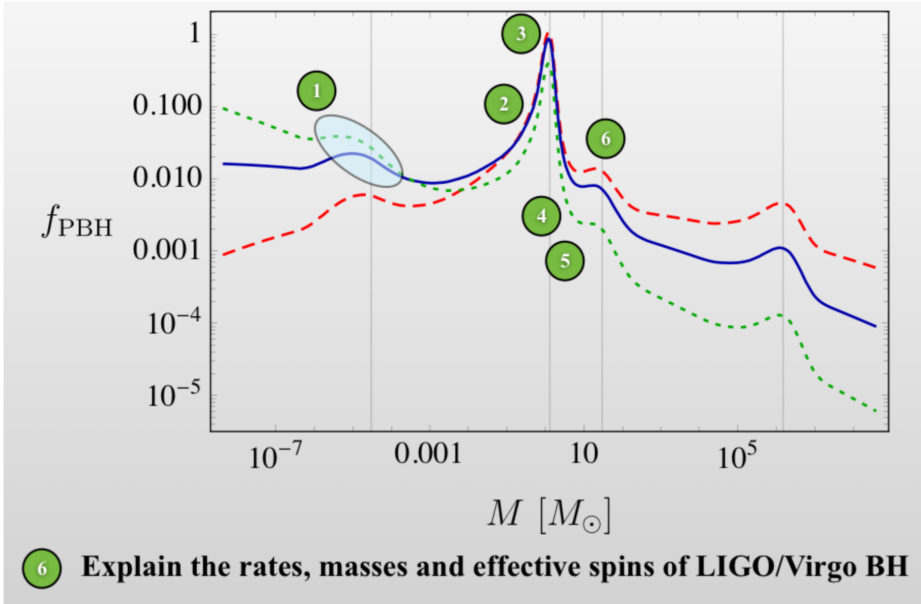


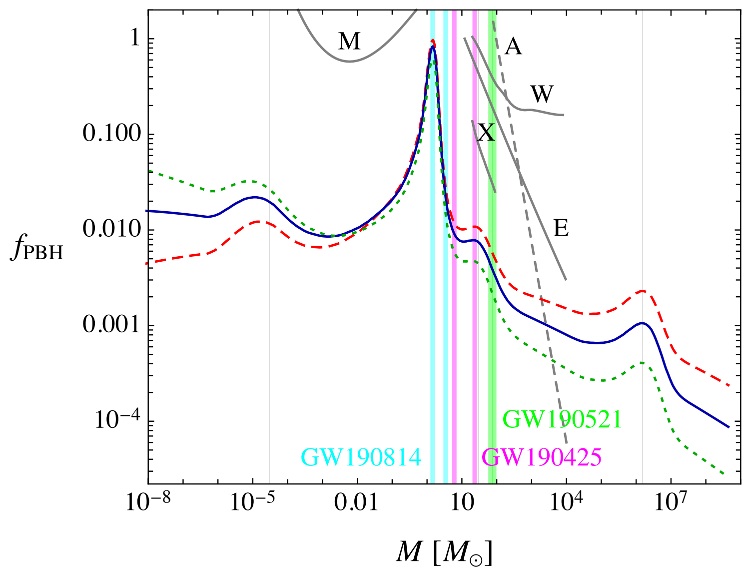


PBHs as dark matter: cusp-to-core transition in low-mass dwarf galaxies
Boldrini et al.
arXiv:1909.07395

LIGO/Virgo black holes

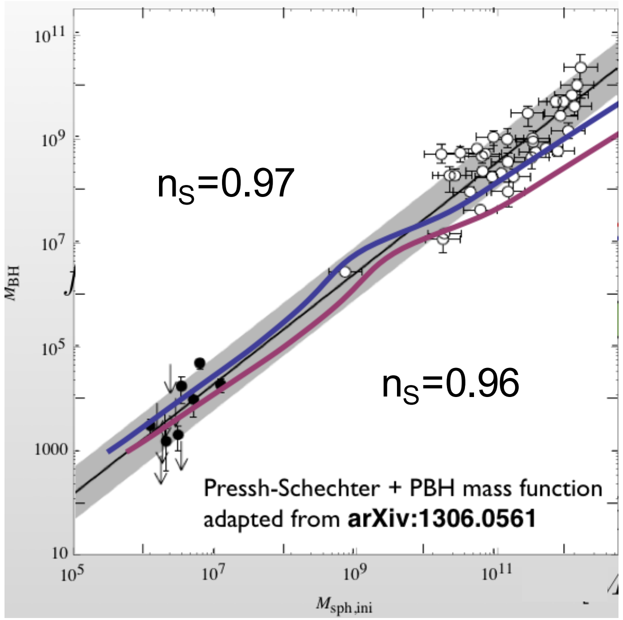


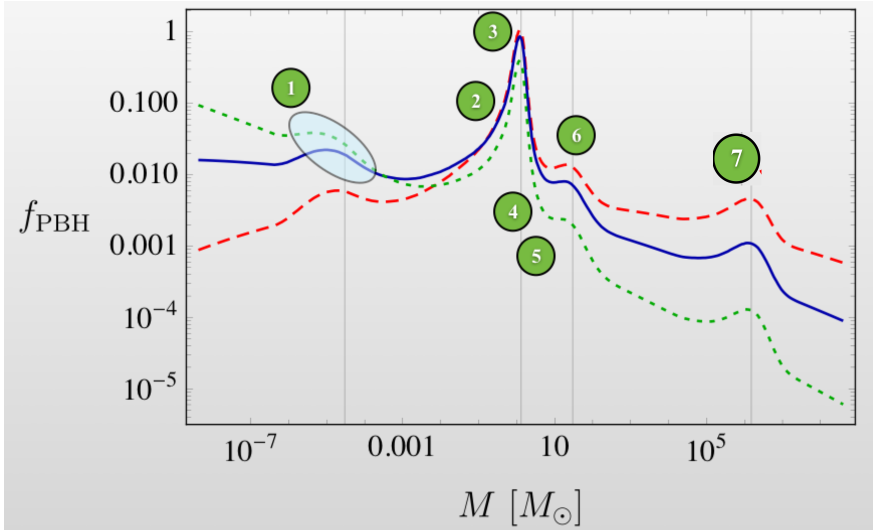




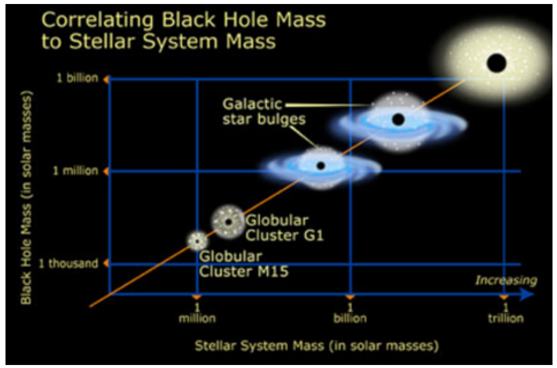
Successful prediction!

Intermediate and supermassive black holes





7 **Right number of intermediate and supermassive black holes**



n_S = 0.97 => observed ratio of BH and halo mass if f_{PBH} ~ 1.

ADDRESSING FINE-TUNING PROBLEM AT QCD EPOCH *

Carr, Clesse & Garcia-Bellido

arXiv:1904.02129

PBHs forming at time t have mass and collapse fraction

$M \sim 10^5 (t/s)\, M_O$, $\beta(M) \sim 10^{-9} f(M) (M/M_O)^{1/2}$

So β appears fine-tuned and we must also explain why

$\chi = \rho_{PBH}/\rho_B = f\, \rho_{DM}/\rho_B = 6 f$ is O(1).

$\chi >> 1$ => $t_{eq} << t_{dec}$ => not enough baryons to make galaxies

$\chi << 1$ => $t_{deq} >> t_{dec}$ => fluctuations too small to make galaxies

QCD epoch => $M \sim M_C \sim 1 M_O$, $\beta(M) \sim \eta = n_B/n_\gamma \sim 10^{-9}$ anthropic selection?

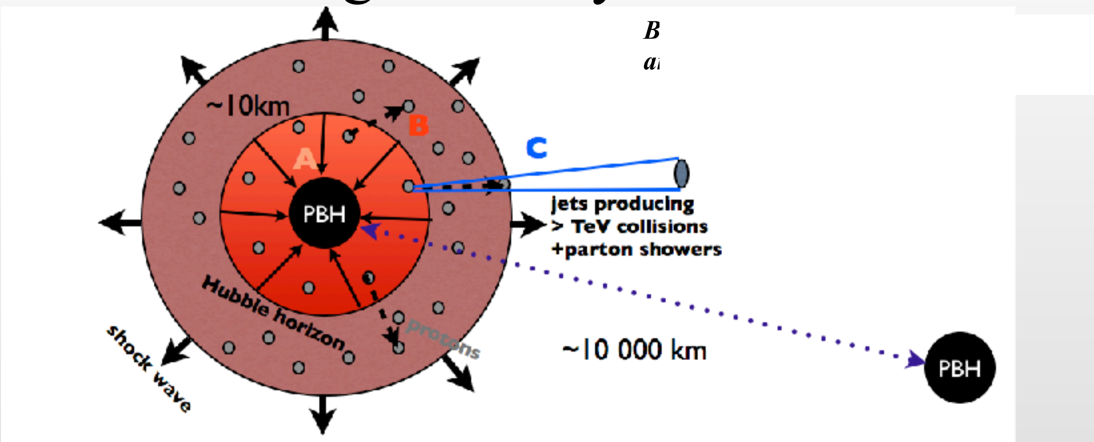
=> dark matter and visible baryons have similar mass

=> PBHs may *generate* baryon asymmetry

* PBHs from the QCD epoch: Linking dark matter, baryogenesis and anthropic selection

Primordial Black Holes

as a common origin of baryons and dark matter



Garcia-Bellido, Carr & Clesse

arXiv:1904.114827

- C and CP violation of the standard model (CKM matrix)
- Baryon number violation: sphaleron transitions from >TeV collisions
- Out of thermal equilibrium (PBH collapse)

$$\Delta K \simeq \left(\frac{1}{\gamma} - 1\right) M_{\rm H} \qquad E_0 = \frac{\Delta K}{n_{\rm p}\, \Delta V} \qquad k_{\rm B} T_{\rm eff} = \frac{2}{3} E_0 \simeq 5\,{\rm TeV}$$

$$\delta_{\rm CP}(T) = 3 \times 10^{-5}\,(20.4\,{\rm GeV}/T)^{12}$$ above sphaleron barrier

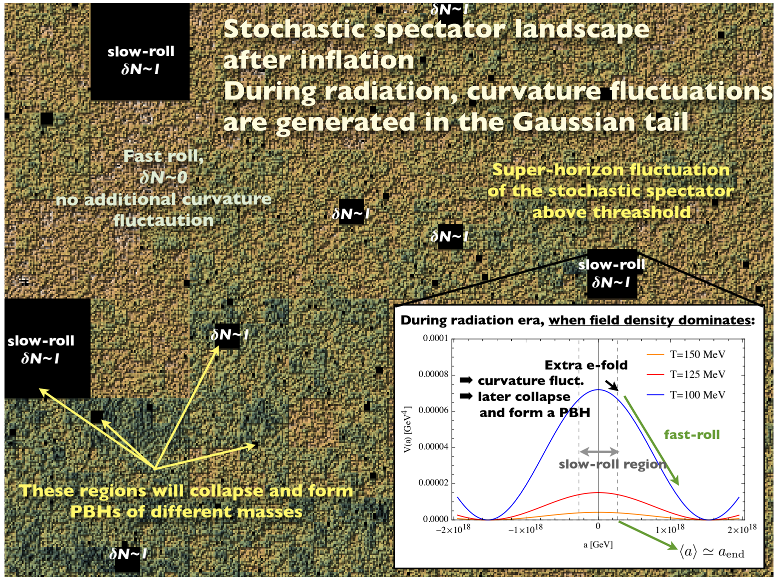
$$\chi \approx \gamma/(1-\gamma) \approx 5 \text{ if } \gamma \approx 0.8$$

η_{loc} ~ 1 => $\eta \sim \beta$ and $\chi \sim 1$ after diffusion of baryon asymmetry

Curvature perturbation scenario

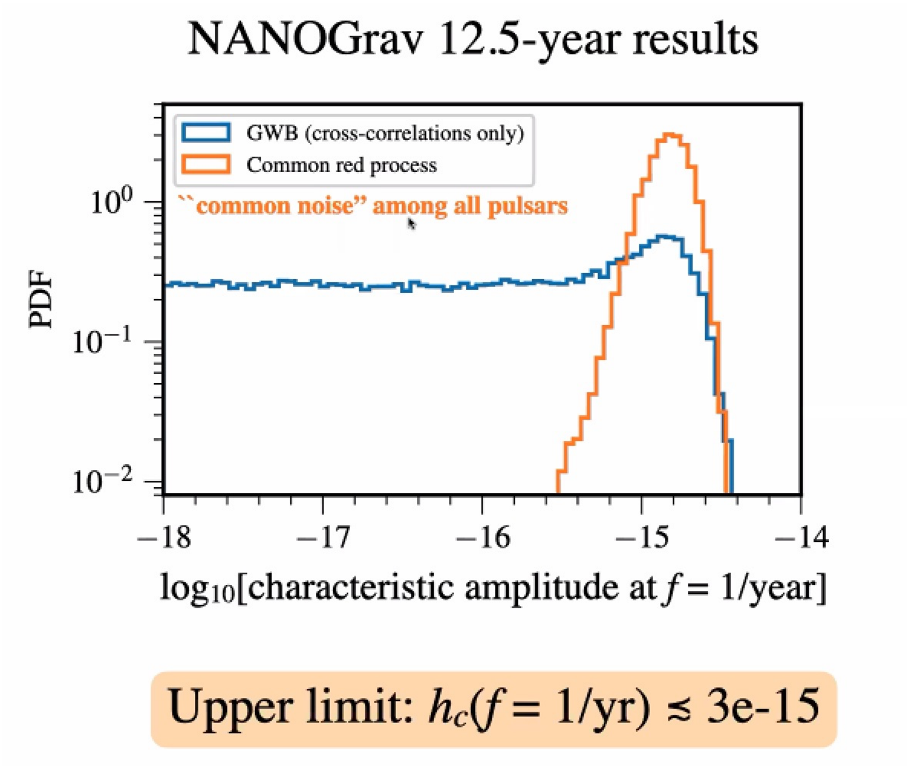
Natural peak in PBH mass function but need to fine-tune pert' amp'

Stochastic fluct'ns in spectator field during inflation
$\Rightarrow$ different values in different patches
$\Rightarrow$ frozen until pot' energy dominates density long after inflation
$\Rightarrow$ 2nd inflation phase within region (few e-folds)
$\Rightarrow$ non-linear perturbations => PBHs.



In the stochastic spectator scenario: no parameter tuning,
but unavoidable **anthropic selection** due to the field **stochasticity**

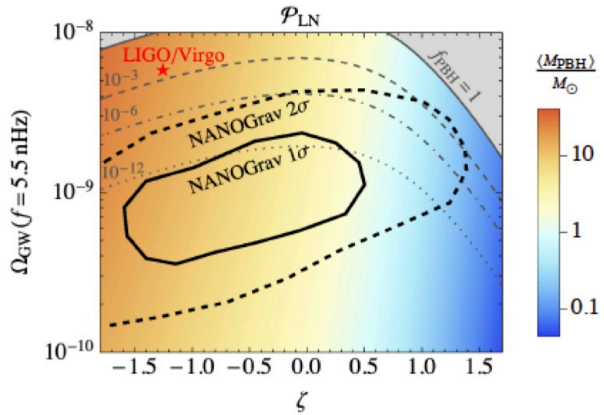
Pulsar Timing Array Constraints on PBHs with NANOGrav



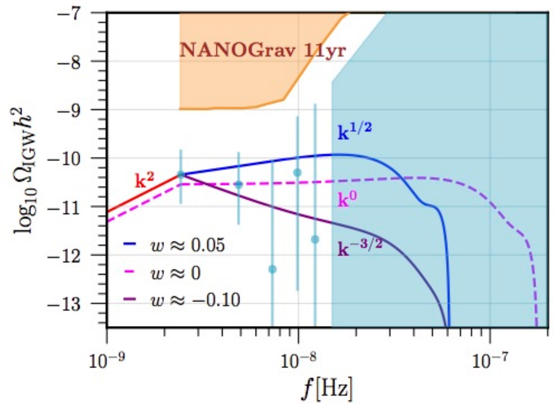
Kapadia et al. arXiv:2009.05514

Four recent claims of positive detection?

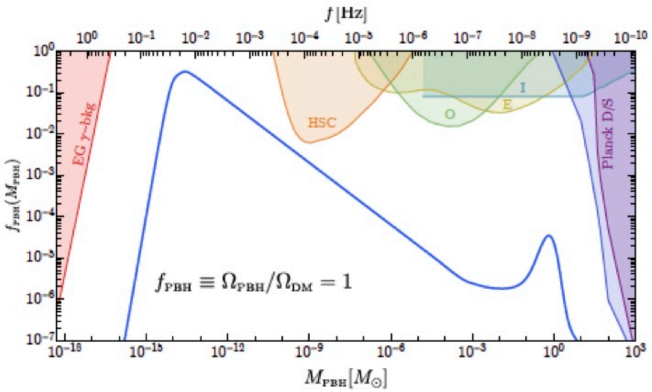
Vaskonen & Veermae
2009.07832
M ~ 10^3–10^6 $M_\odot$, f < 10^{-4}



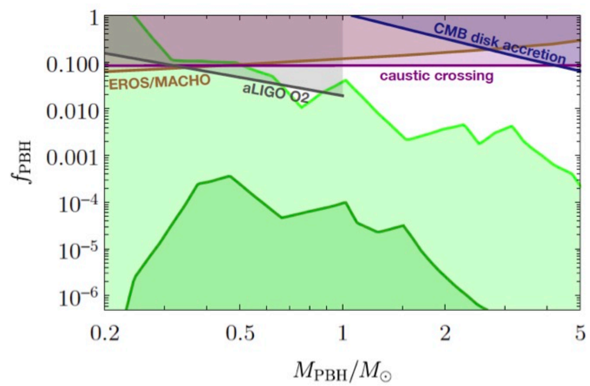
Domenech & Shi Pi
2010.03976
M ~ 10^3–10^6 $M_\odot$, f < 10^{-4}



De Luca et al.
2009.08268
M ~ 10^{-15}–10^{-11} $M_\odot$, f ~ 1



Kohri & Terada
2009.11853
M ~1 $M_\odot$, f = 10^{-3}

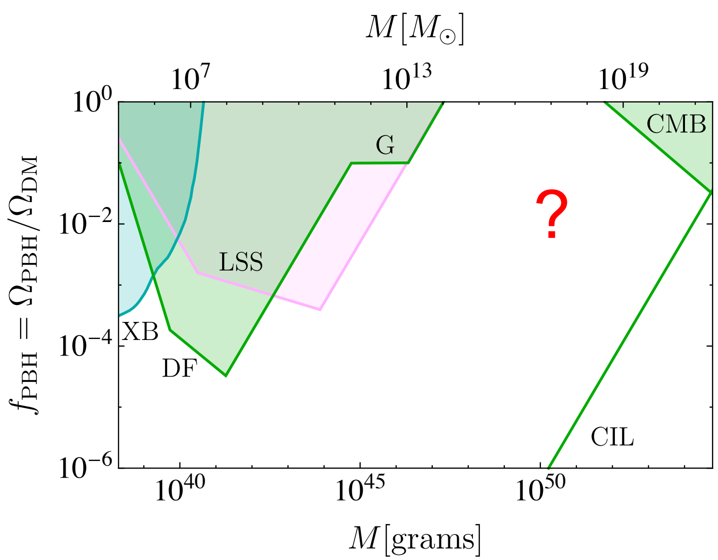


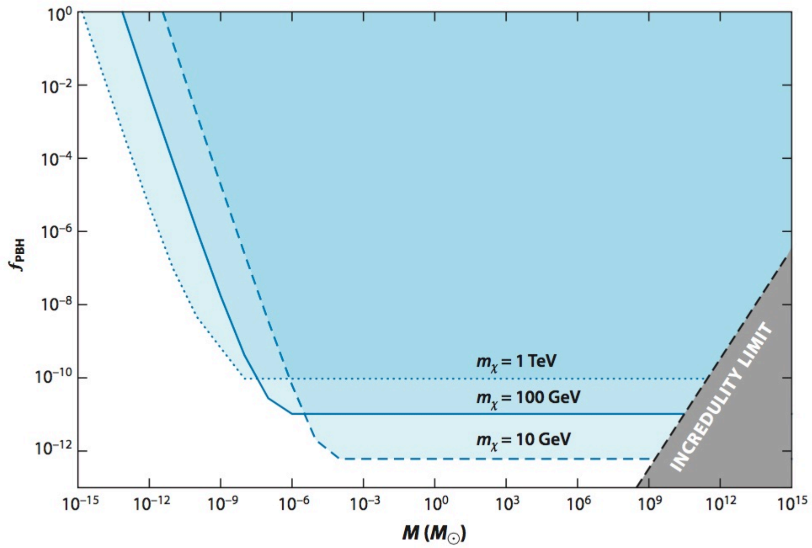
Constraints on Stupendously Large Black Holes

Bernard Carr,[1,2,*] Florian Kühnel,[3,†] and Luca Visinelli[4,‡]

arXiv:2008.08077

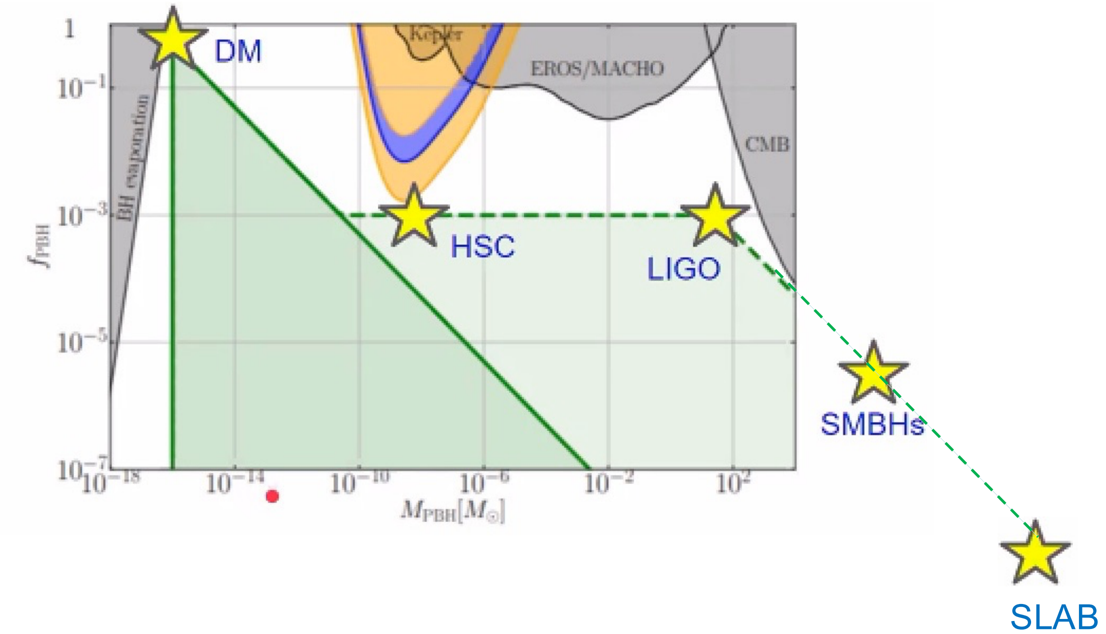
We consider the observational constraints on stupendously large black holes (SLABs) in the mass range $M \gtrsim 10^{11}\,M_\odot$. These have attracted little attention hitherto and we are aware of no published constraints on a SLAB population in the range $(10^{12} - 10^{18})\,M_\odot$. However, there is already evidence for black holes of up to nearly $10^{11}\,M_\odot$ in galactic nuclei, so it is conceivable that SLABs exist and they may even have been seeded by primordial black holes. We focus on limits associated with (i) dynamical and lensing effects, (ii) the generation of background radiation through the accretion of gas during the pregalactic epoch, and (iii) the gamma-ray emission from the annihilation of the halo of weakly interacting massive particles (WIMPs) expected to form around each SLAB if these provide the dark matter. Finally, we comment on the constraints on the mass of ultra-light bosons from future measurements of the mass and spin of SLABs.





Takhistov talk

PBH DM from Bubble Multiverse



Generalized model for everything

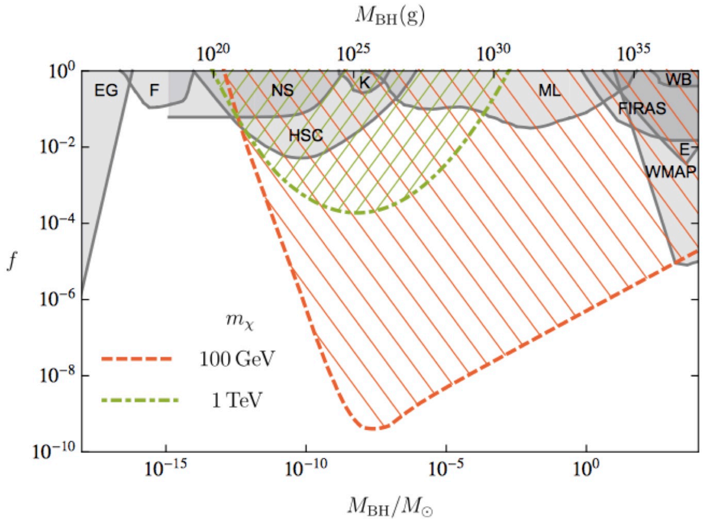
Black Holes and WIMPs: All or Nothing or Something Else

Bernard Carr,[1,2,*] Florian Kühnel,[3,†] and Luca Visinelli[4,5,‡]

arXiv:2011.01930

We consider constraints on primordial black holes (PBHs) in the mass range $(10^{-18}\text{–}10^{15})\,M_\odot$ if the dark matter (DM) comprises weakly interacting massive particles (WIMPs) which form halos around them and generate γ-rays by annihilations. The observed extragalactic γ-ray background then implies that the PBH DM fraction is $f_{\rm PBH} \lesssim 10^{-10}\,(m_\chi/{\rm TeV})^{1.1}$ in the mass range $2 \times 10^{-11}\,M_\odot\,(m_\chi/{\rm TeV})^{-3.2} \lesssim M \lesssim 3 \times 10^{11}\,M_\odot\,(m_\chi/{\rm TeV})^{1.1}$, where m_χ and M are the WIMP and PBH masses, respectively. This limit is independent of M and therefore applies for any PBH mass function. For $M \lesssim 2 \times 10^{-11}\,M_\odot\,(m_\chi/{\rm TeV})^{-3.2}$, the constraint on $f_{\rm PBH}$ is a decreasing function of M and PBHs could still make a significant DM contribution at very low masses. We also consider constraints on WIMPs if the DM is mostly PBHs. If the merging black holes recently discovered by LIGO/Virgo are of primordial origin, this would rule out the standard WIMP DM scenario. More generally, the WIMP DM fraction cannot exceed 10^{-4} for $M > 10^{-9}\,M_\odot$ and $m_\chi > 10\,{\rm GeV}$. There is a region of parameter space, with $M \lesssim 10^{-11}\,M_\odot$ and $m_\chi \lesssim 100\,{\rm GeV}$, in which WIMPs and PBHs can both provide some but not all of the DM, so that one requires a third DM candidate.

WIMPs and PBHs are incompatible



Hybrid models with PBHs and WIMPs
=> clumping of WIMPs around PBHs
⇒ enhanced annihilations
⇒ γ-ray signals which should be seen.

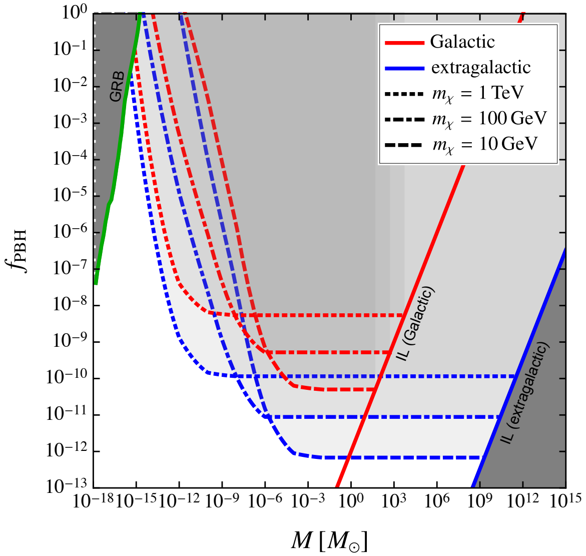
Lacki & Beacom 2010, Eroshenko 2016, Boucenna, Kuhnel & Visinelli 2017; Adamek, Byrnes, Gosenca & Hotchkiss 2019; Cai, Yang & Zhou 2020.

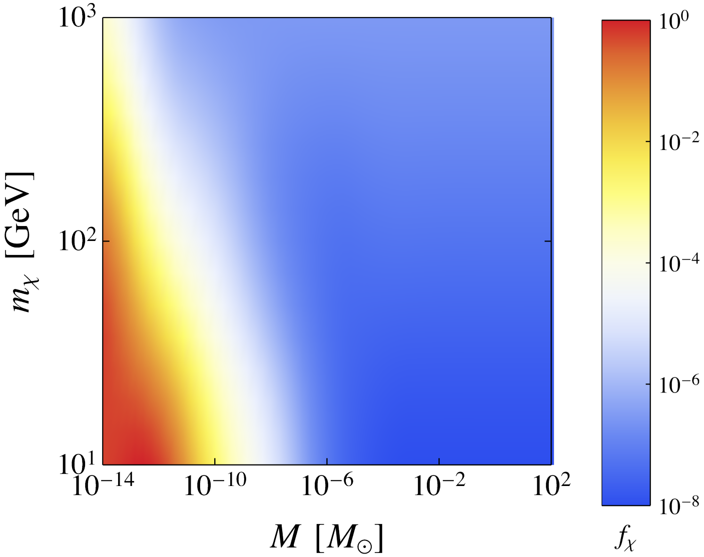
Consider as wide a range of masses for the two components as possible.

PBH mass 10^{-18} - 10^{15} $M_\odot$, WIMP mass 10 GeV - 1 TeV

Distinguish between Galactic and extragalactic γ-ray backgrounds.

m_χ (GeV)	$f_{\rm PBH}^{\rm gal}$	$f_\chi^{\rm gal}$	$f_{\rm PBH}^{\rm eg}$	$f_\chi^{\rm eg}$
10^1	5×10^{-11}	6×10^{-7}	7×10^{-13}	5×10^{-8}
10^2	5×10^{-10}	3×10^{-6}	9×10^{-12}	2×10^{-7}
10^3	5×10^{-9}	1×10^{-5}	1×10^{-10}	1×10^{-6}
10^4	6×10^{-8}	4×10^{-5}	2×10^{-9}	5×10^{-6}





For most of parameter space, one component completely dominates

$f_{\rm PBH}$ > 0.01 above $10^{-9}\,M_\odot$ => canonical WIMP scenario excluded

LIGO/Virgo PBHs => WIMPs and PBHs have $f_{\rm DM} < 1$ => third DM candidate

CONCLUSIONS

PBH studies have already led to profound insights into cosmology and fundamental physics, even if they never formed.

Until recently most work focused on PBH constraints but now they have been invoked for numerous cosmological purposes:

Cosmic rays	Dark matter	LIGO/Virgo	Other conundra

These are distinct roles but PBHs with extended mass function could play all of them with fine-tuning of collapse fraction.

PBHs naturally form at QCD epoch and could explain both dark matter and baryon asymmetry with anthropic fine-tuning.