Can the Dark Matter in the Universe be Black Holes?

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Frontier Research Master Seminar, IFCA

31st May 2021

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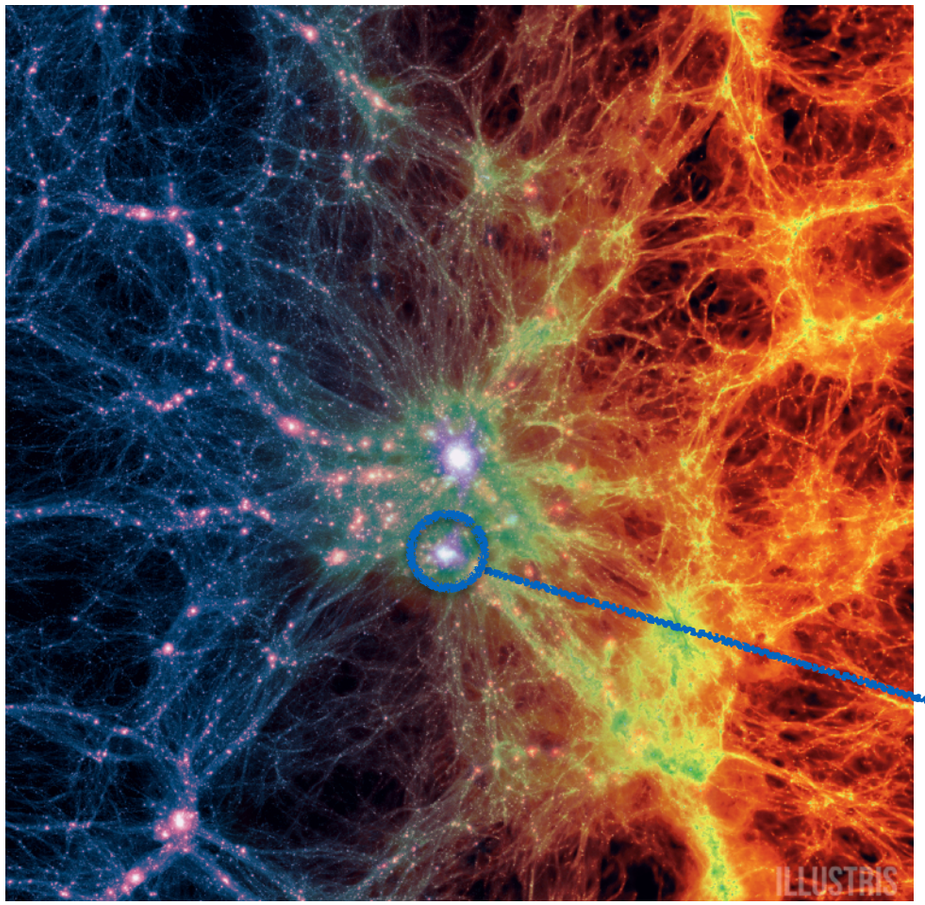
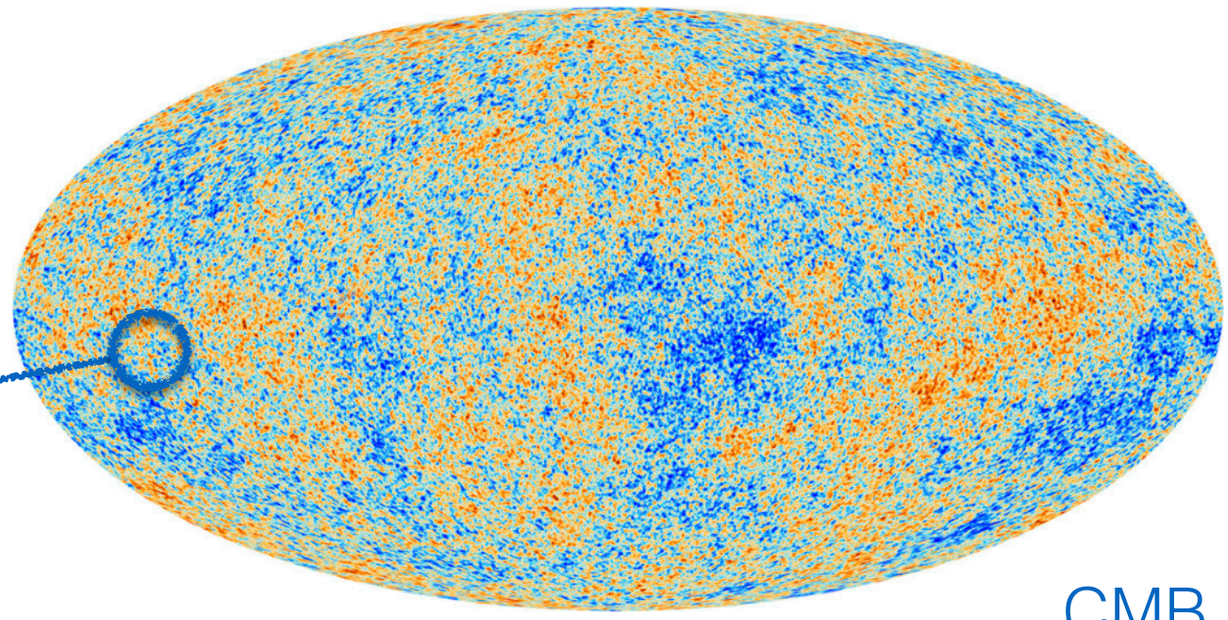
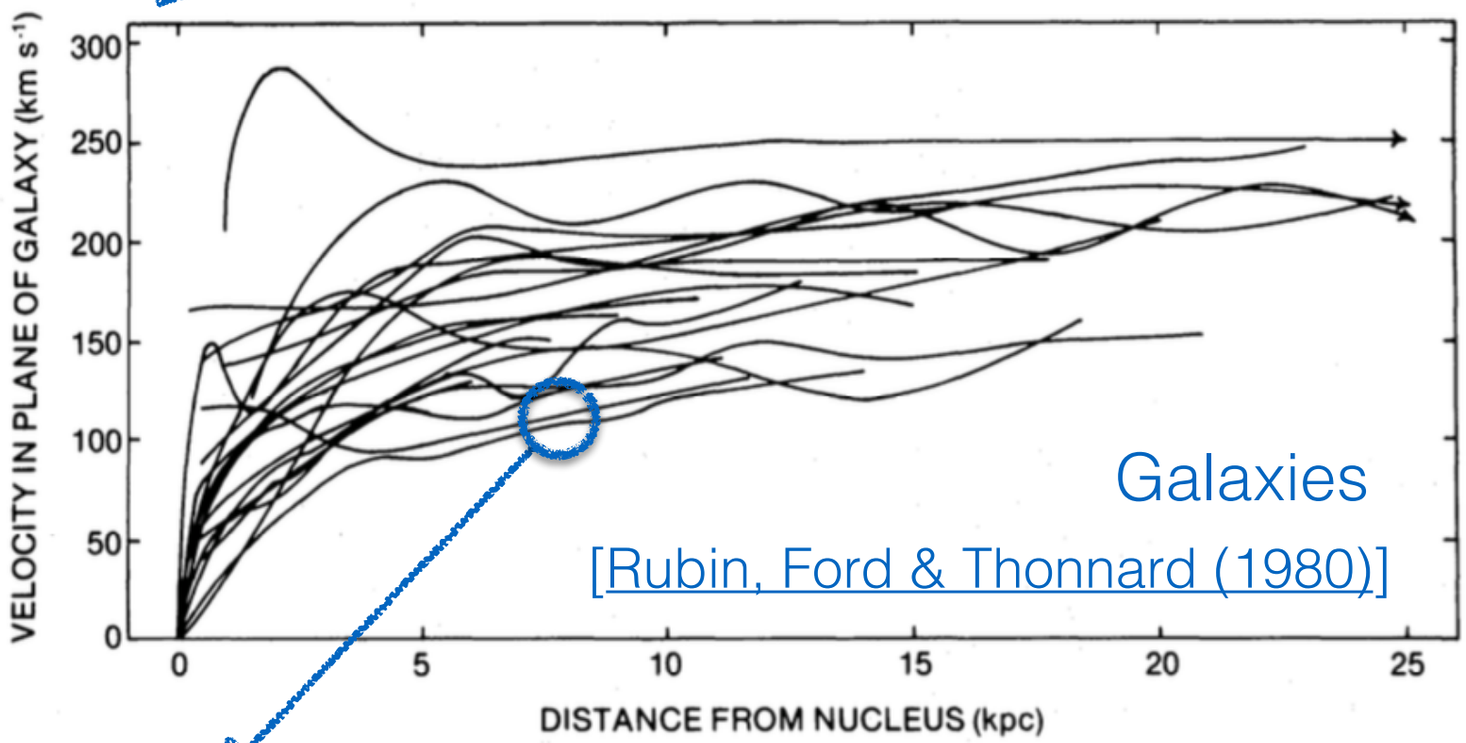
Dark Matter on all scales



Galaxy clusters
[Illustris, 1405.2921]
[astro-ph/0006397]



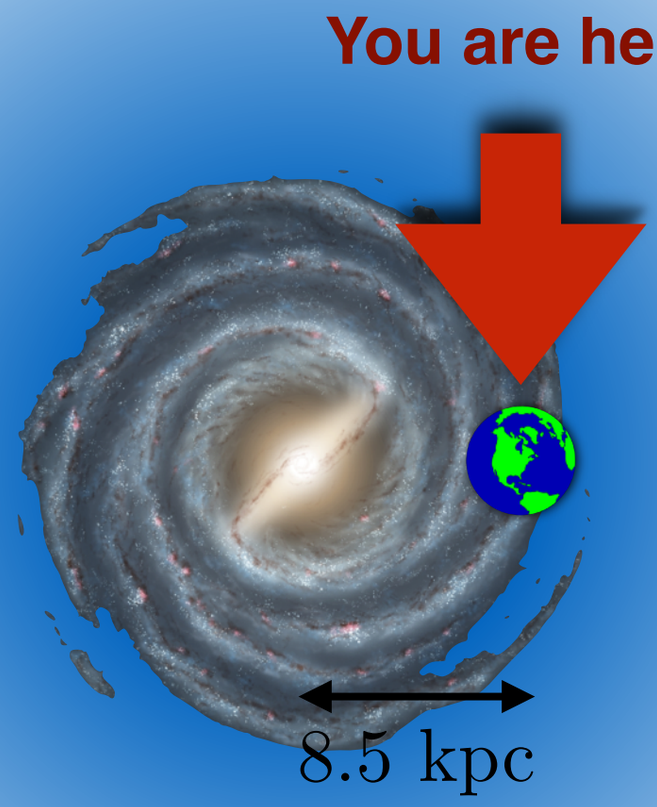
CMB
[Planck, 1502.01589]



Galaxies
[Rubin, Ford & Thonnard (1980)]

Dark Matter at Earth

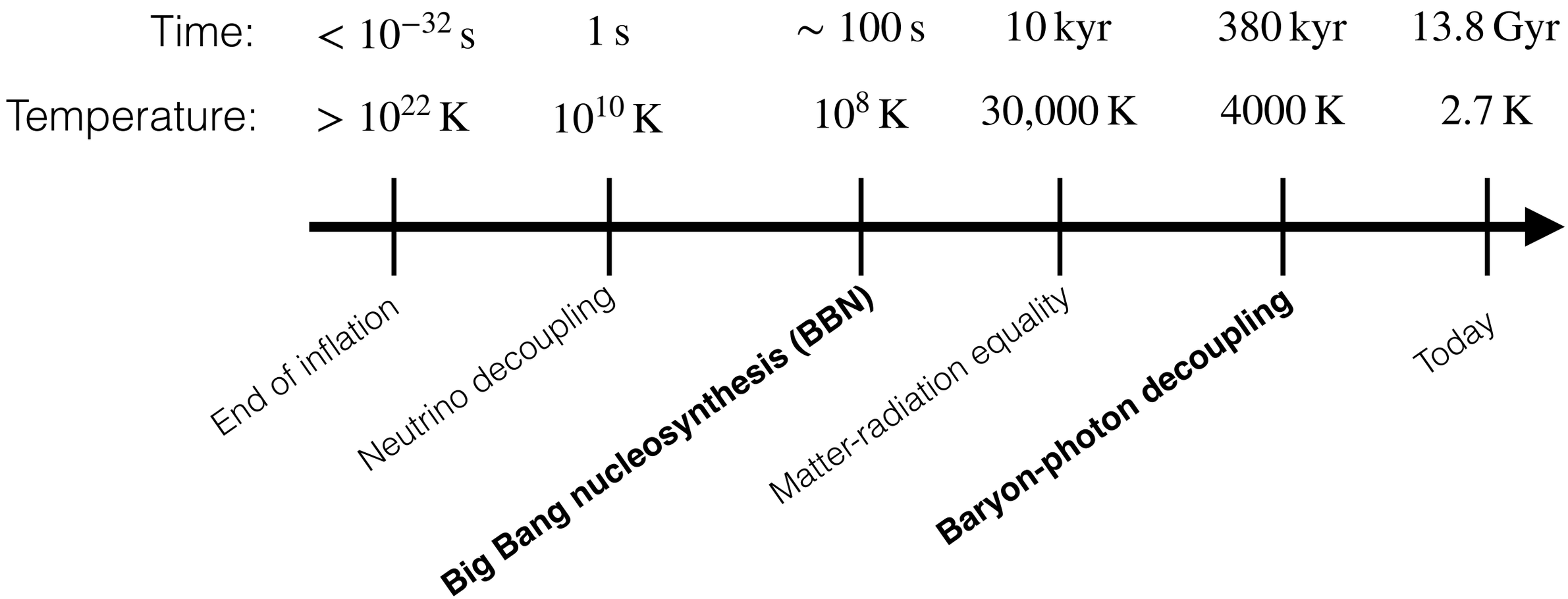
NOT TO SCALE



Global and local estimates of DM at Solar radius give: $\rho_\chi \sim 0.2 - 0.8 \text{ GeV cm}^{-3}$

E.g. Iocco et al. [1502.03821], Garbari et al. [1206.0015], Read [1404.1938]

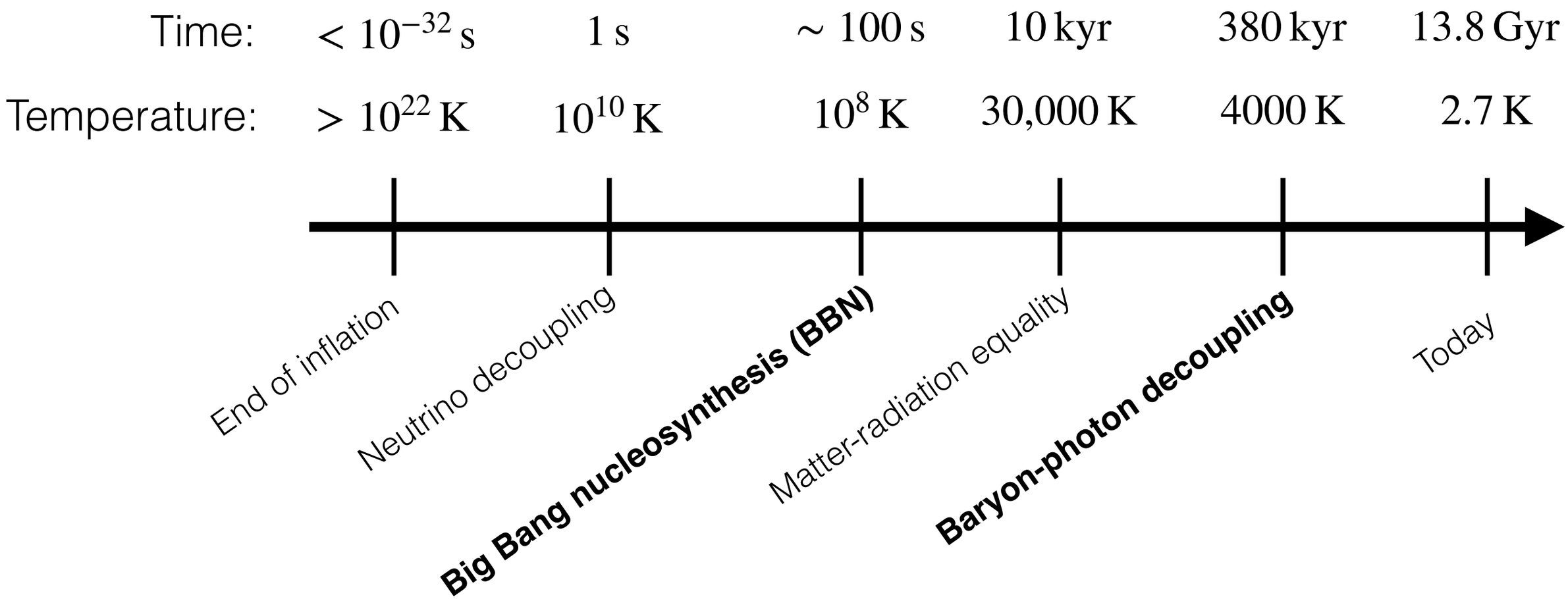
‘Non-baryonic’ DM



Dark Matter must (among other things):

- Not participate in BBN
- Decouple before baryons

‘Non-baryonic’ DM



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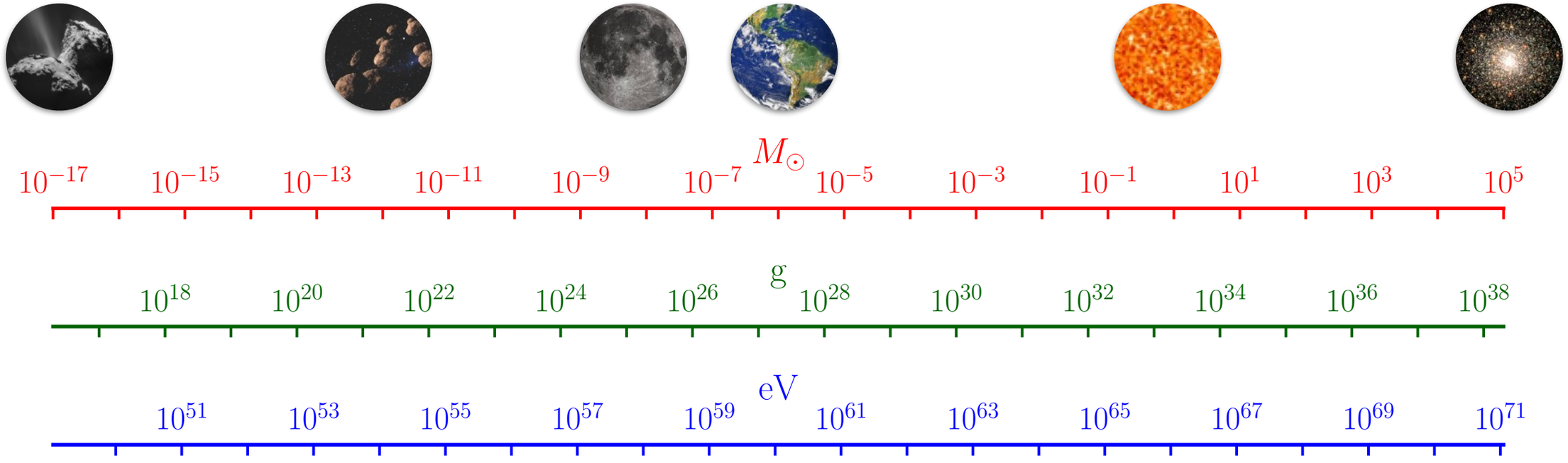
Black Holes?

Primordial Black Holes

Primordial Black Holes (PBHs) could form in the early Universe ($z \gg 10^8$) from large over-densities

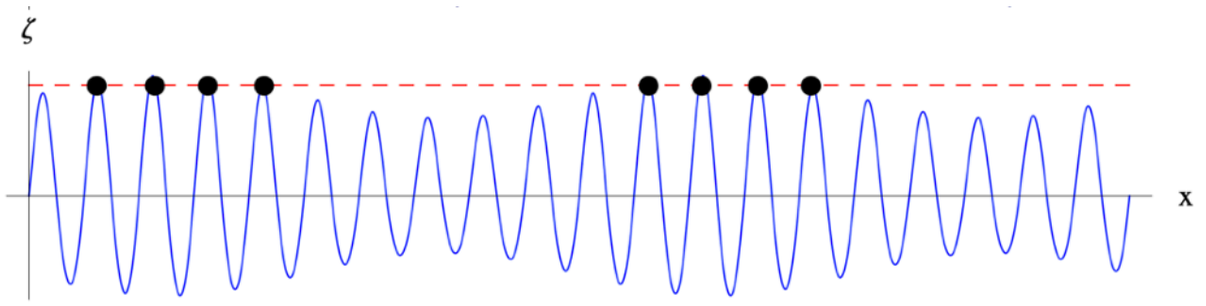
Mass roughly given by mass inside horizon at time of formation:

[Green & Liddle, astro-ph/9901268]

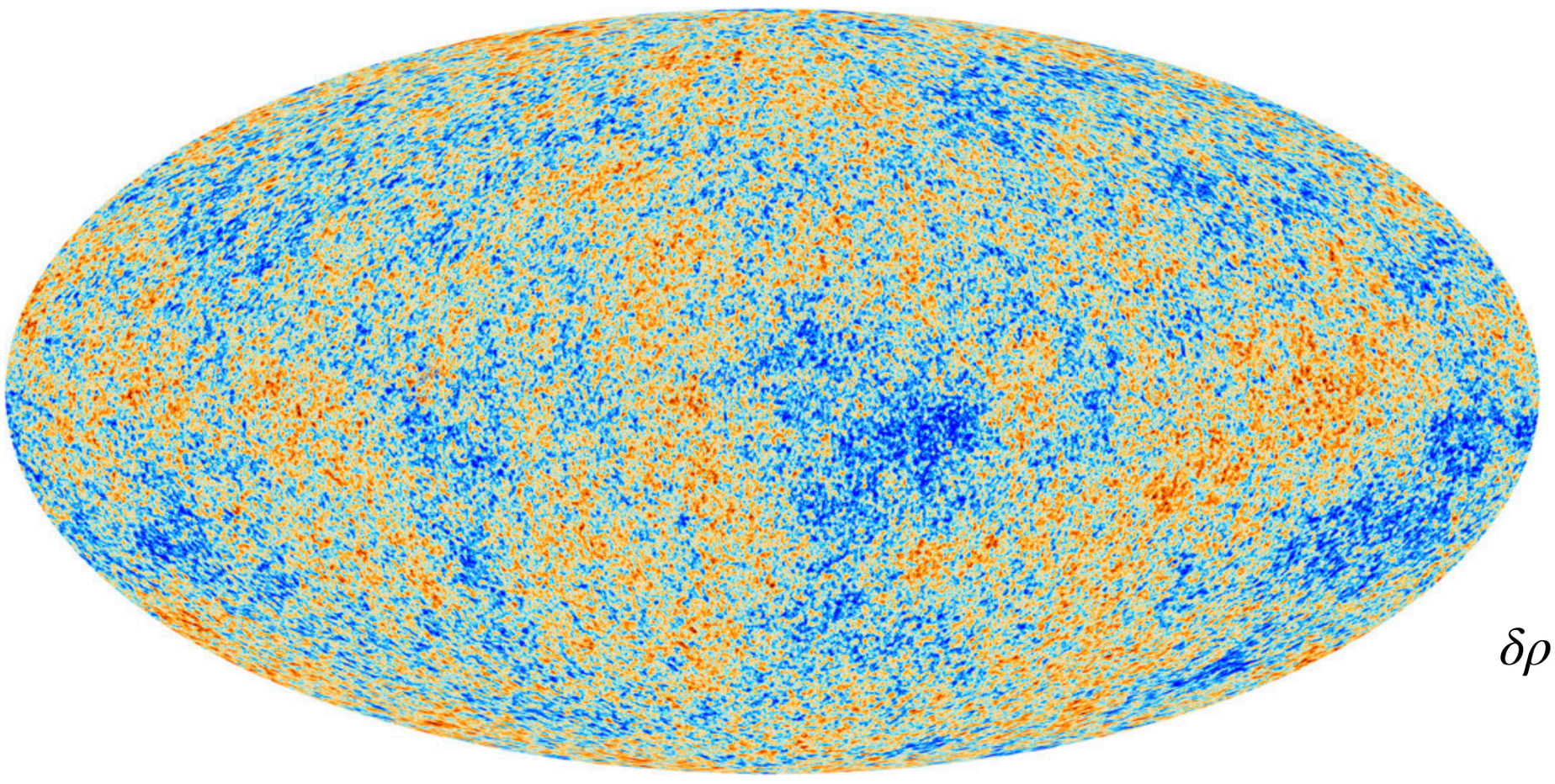


[Zel'dovich & Novikov (1967), Hawking (1971), Carr & Hawking (1974), Carr (1975)]

Primordial fluctuations



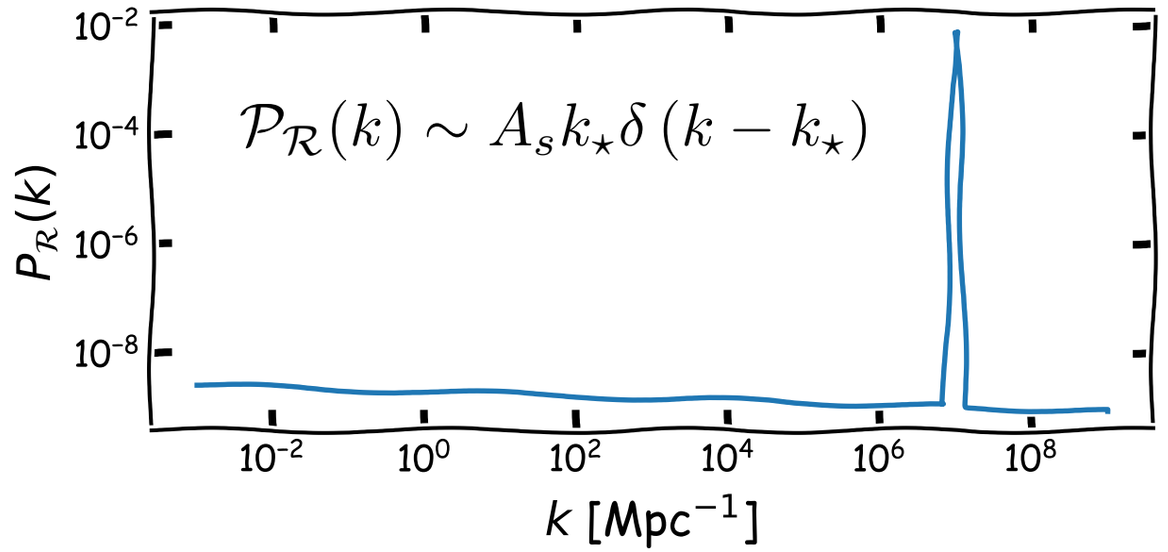
[Young & Byrnes, 1411.4620]

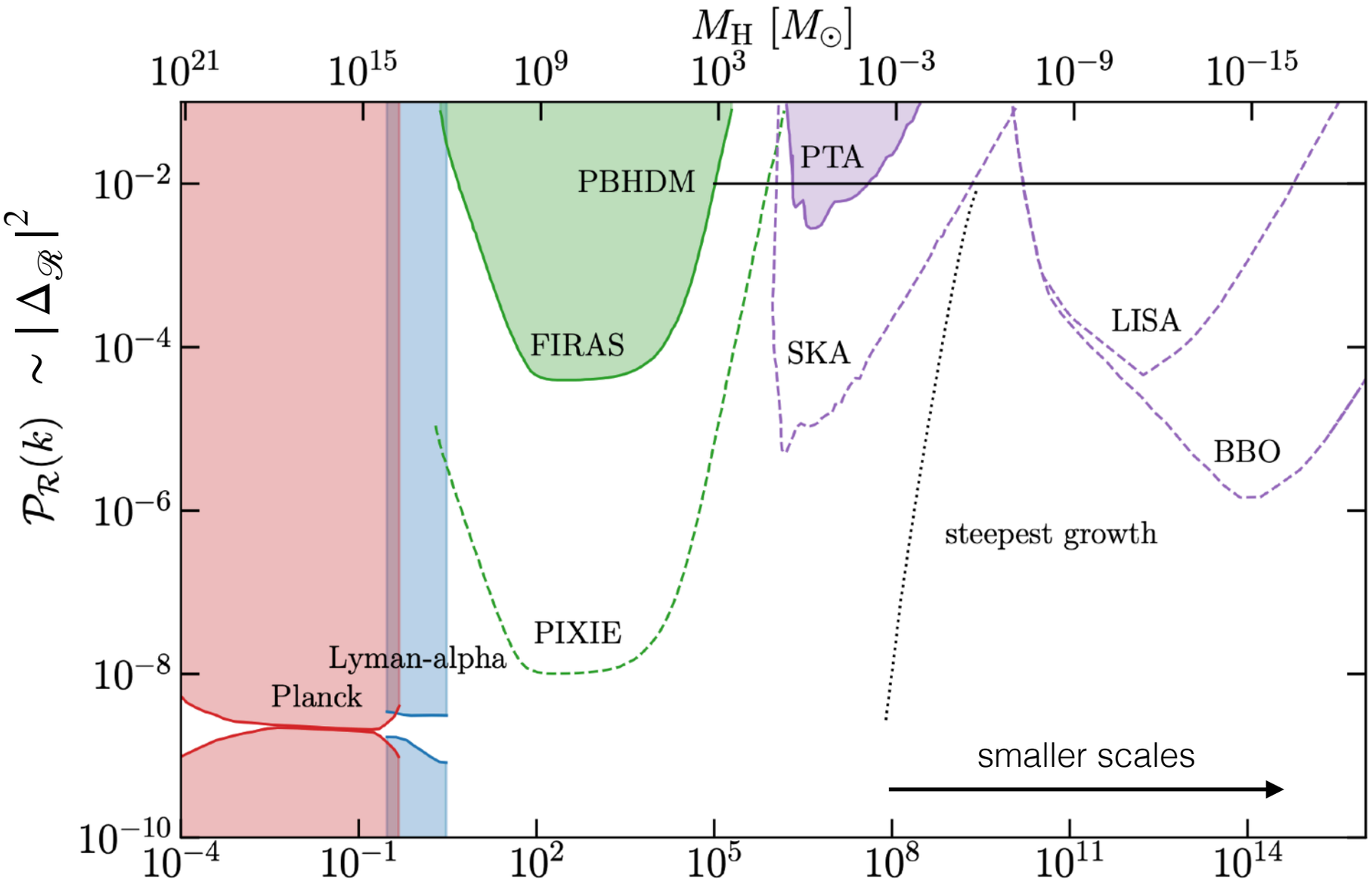


$\delta\rho/\rho \sim 10^{-5}$

$$\lambda \sim 10\,\mathrm{Mpc} \longrightarrow k \sim 0.05\,\mathrm{Mpc}^{-1} \longrightarrow M_H \sim 10^{16}\,M_\odot$$

Making a PBH (1)





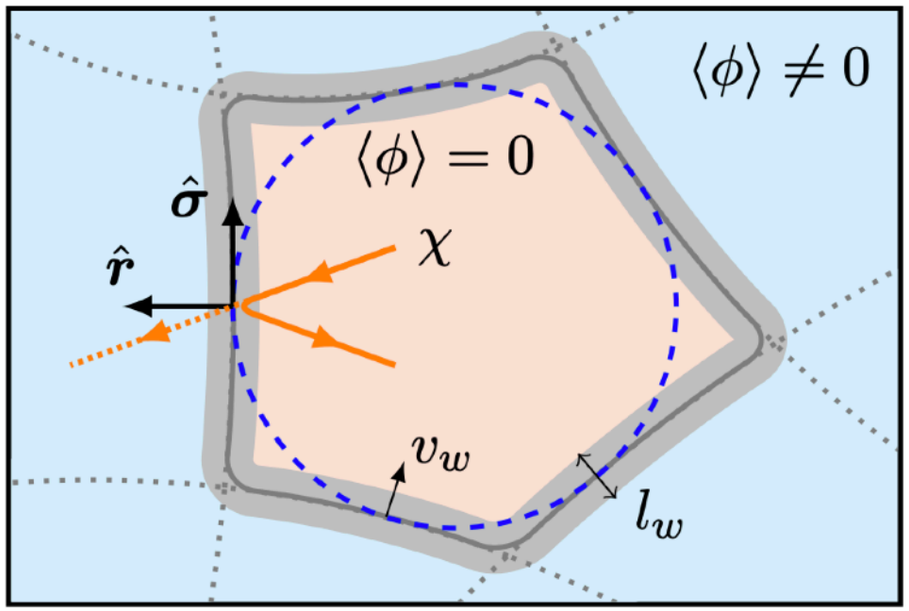
[Green & **BJK**, 2007.10722]

Making a PBH (2)

Early Universe Phase Transitions:

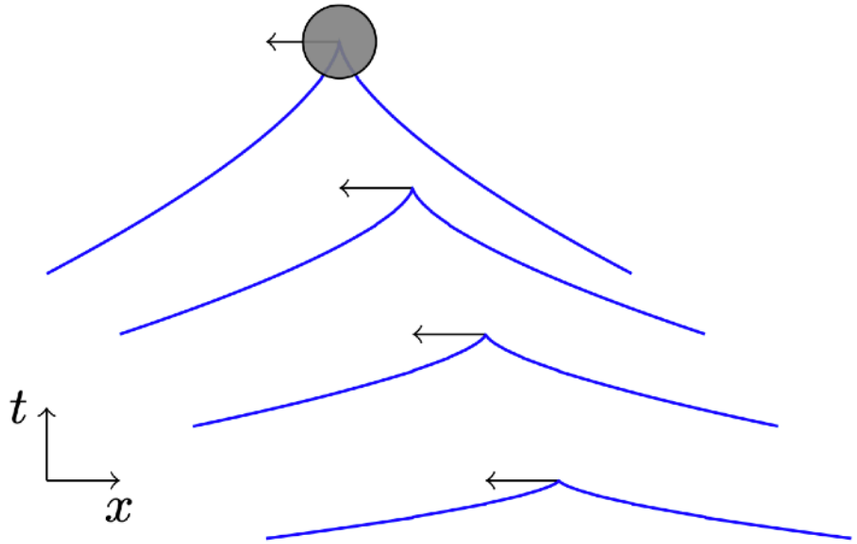
[e.g. Hawking, Moss & Stewart (1982); La & Steinhart (1989)]

[Baker et al., 2105.07481]



Collapse of Cosmic Strings:

[e.g. Hawking (1987), Polnarev & Zembowicz (1991), gr-qc/9509012]



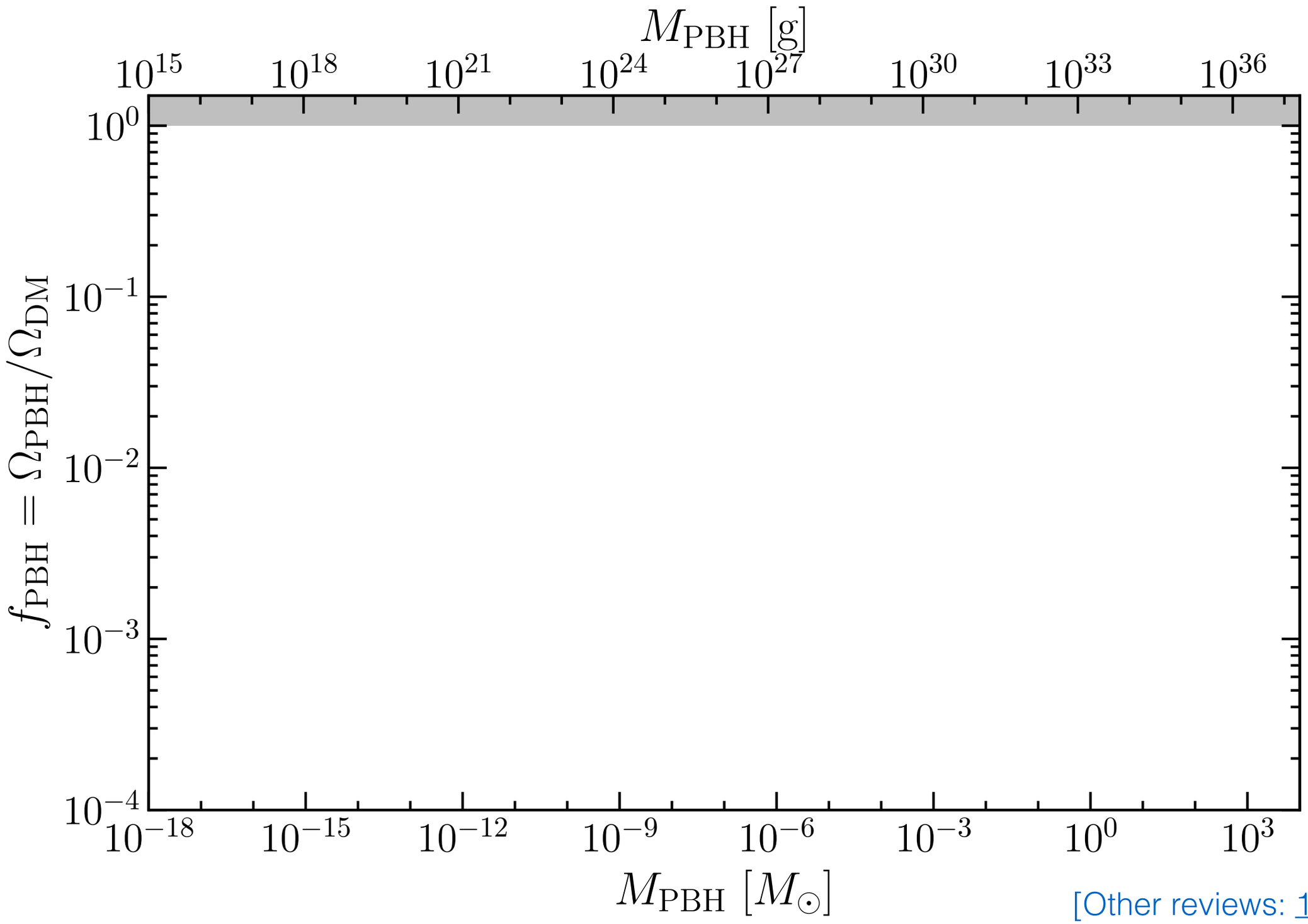
[Jenkins & Sakellariadou, 2006.16249]

PBHs would be a sign of New Physics and a probe of the early universe.

[Green, 1403.1198; Sasaki et al, 1801.05235]

PBH Constraints

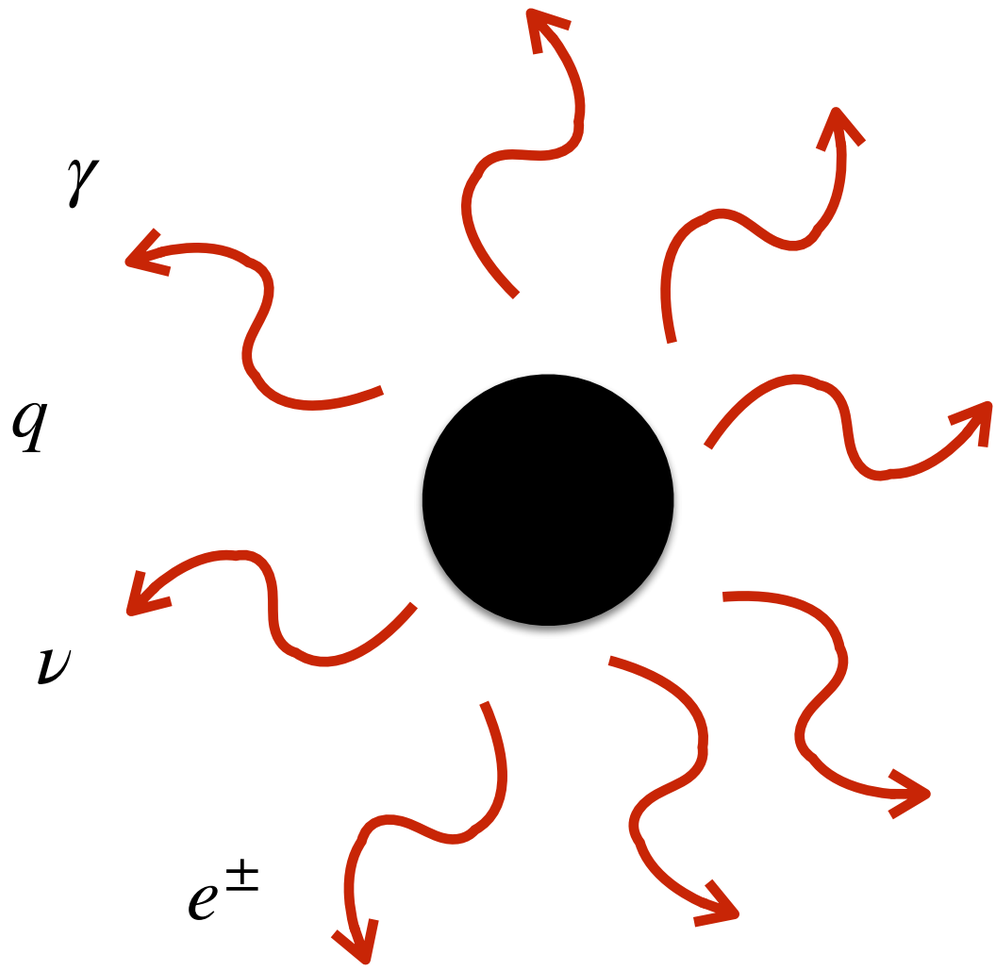
[Green & **BJK**, 2007.10722]
[Code online: github.com/bradkav/PBHbounds]



[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Hawking Radiation

Black holes *radiate* with a temperature depending on the mass:



$$T_{\rm H} = \frac{\hbar c^3}{8\pi G k_{\rm B} M}$$

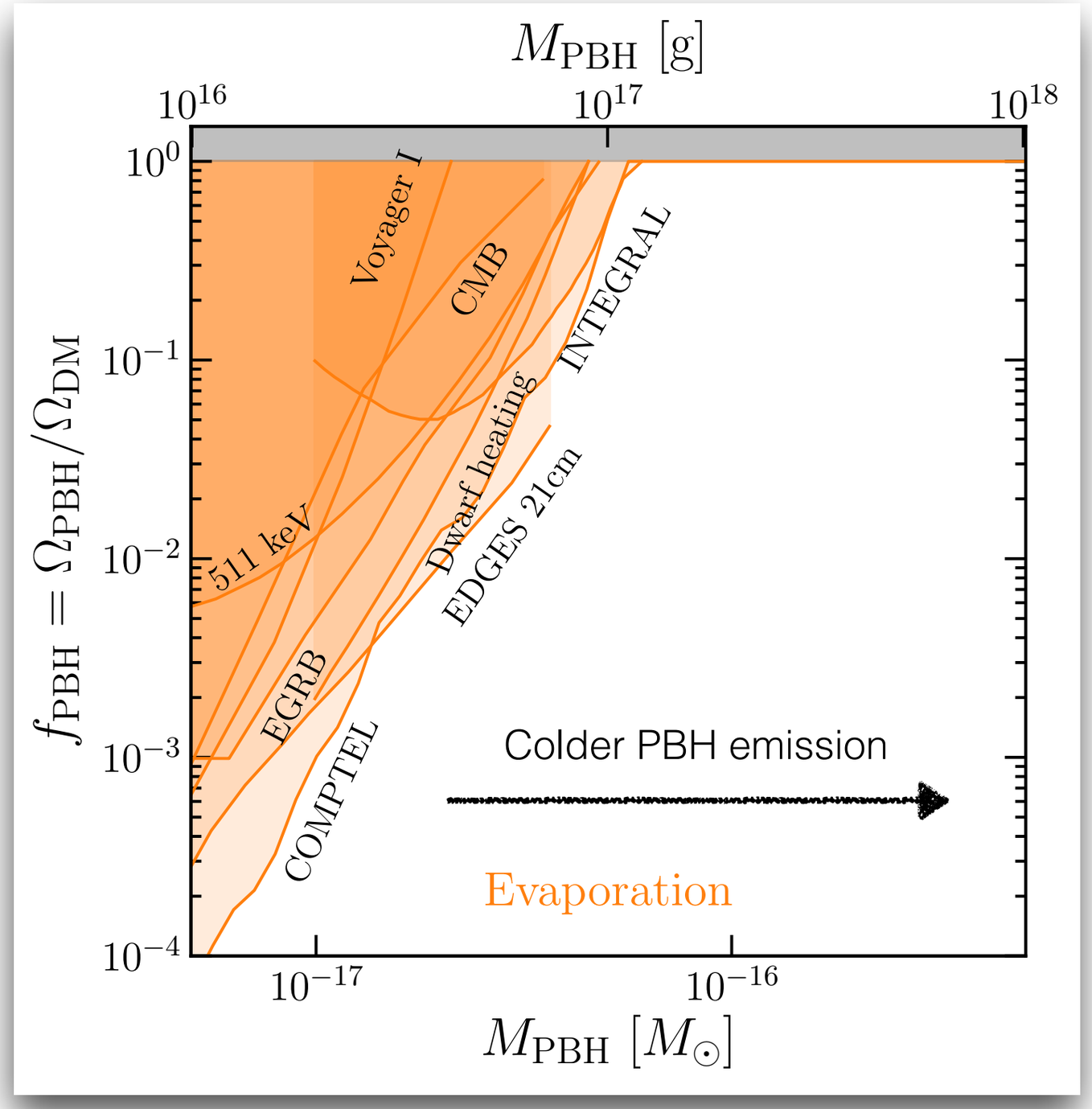
$$\approx 1\,{\rm MeV}\left(\frac{10^{16}\ {\rm g}}{M_{\rm PBH}}\right)$$

[Hawking, Nature (1974);
Carr & Hawking, MNRAS (1974);
Arbey & Auffinger, 1905.04268]

BHs lose mass and eventually evaporate with a lifetime:

$$\tau(M) \simeq 200\,\tau_U \left(\frac{M}{10^{15}{\rm g}}\right)^3$$

PBH Evaporation



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Many interesting constraints from ‘old’ experiments, e.g.

Voyager I

[Boudaud & Cirelli, 1807.03075]

COMPTEL

[Coogan et al., 2010.04797]

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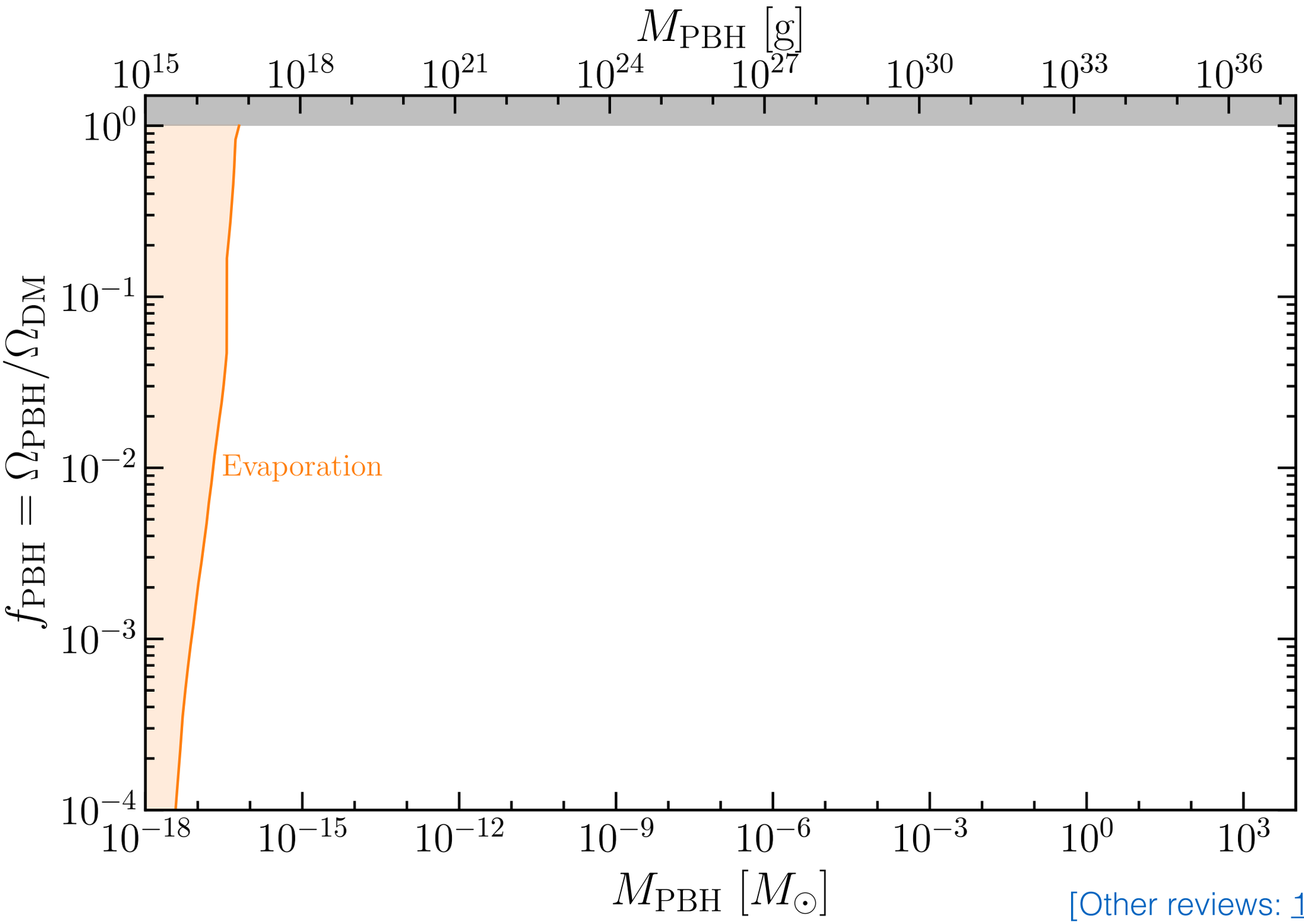
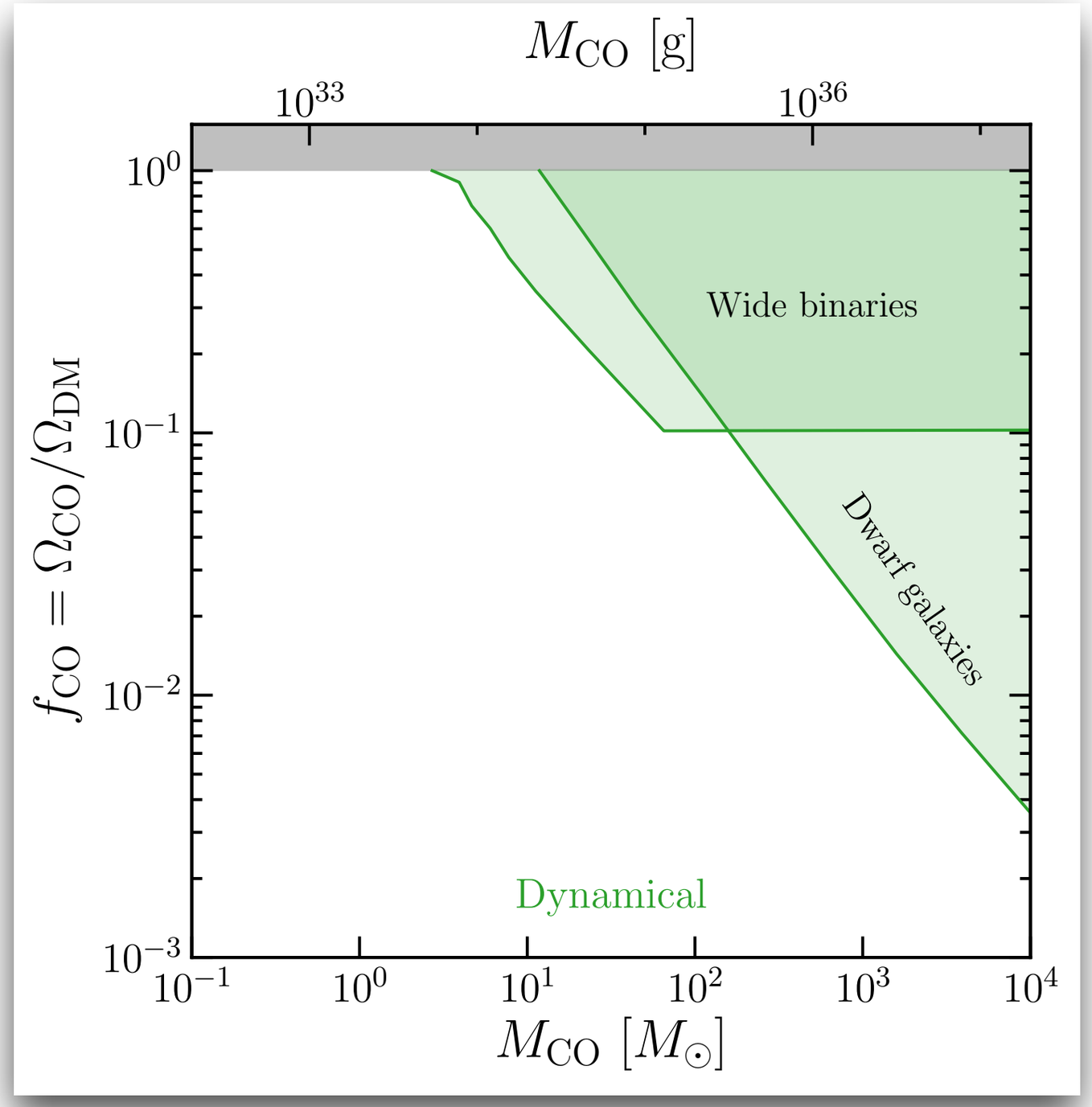


[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Dynamical Constraints



Heavy PBHs can ‘inject’ energy and disrupt bound systems

Wide binary constraints should improve with *Gaia*

[Price-Whelan, Oh & Spergel, 1709.03532]

Dwarf galaxy constraints weakening somewhat with improved analysis (e.g. Fokker-Planck)

[E.g. Zhu et al., 1710.05032, Stegmann et al., 1910.04793]

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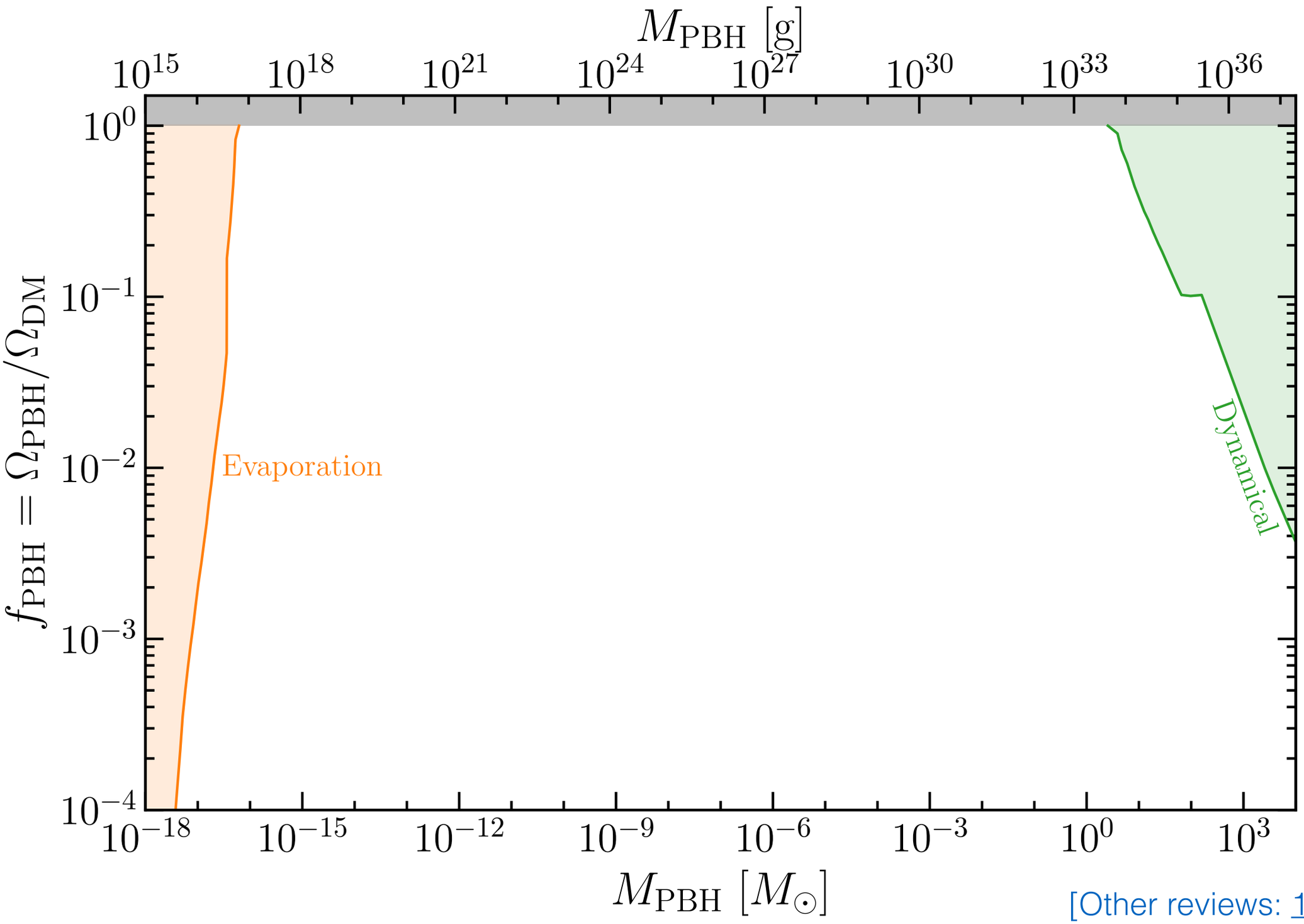

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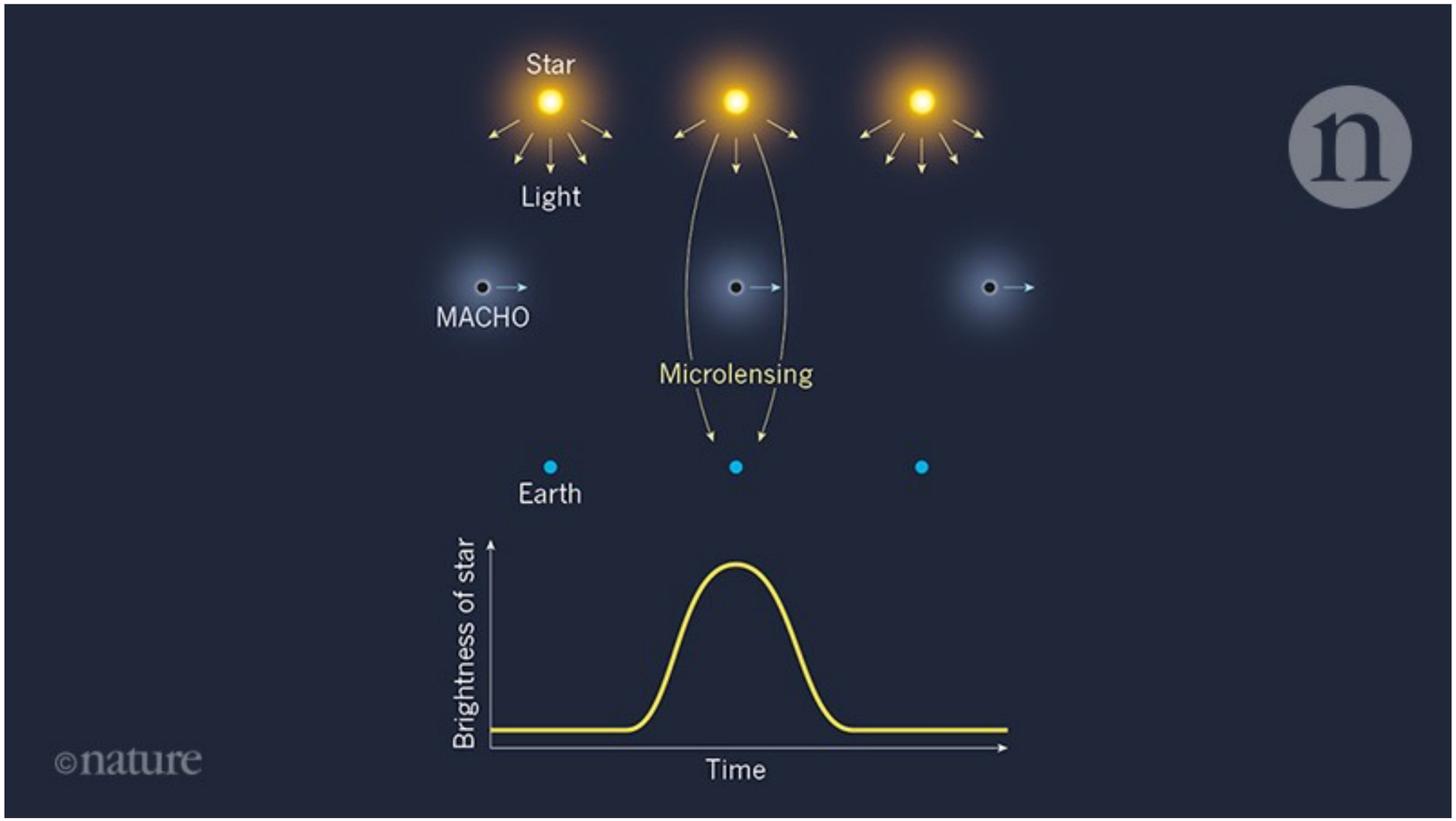
Micro-lensing



$$t_{\rm E} \simeq 44 \text{ days } \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{d_{\rm L} d_{\rm LS}/d_{\rm S}}{4{\rm kpc}}\right)^{1/2}$$

Micro-lensing constraints

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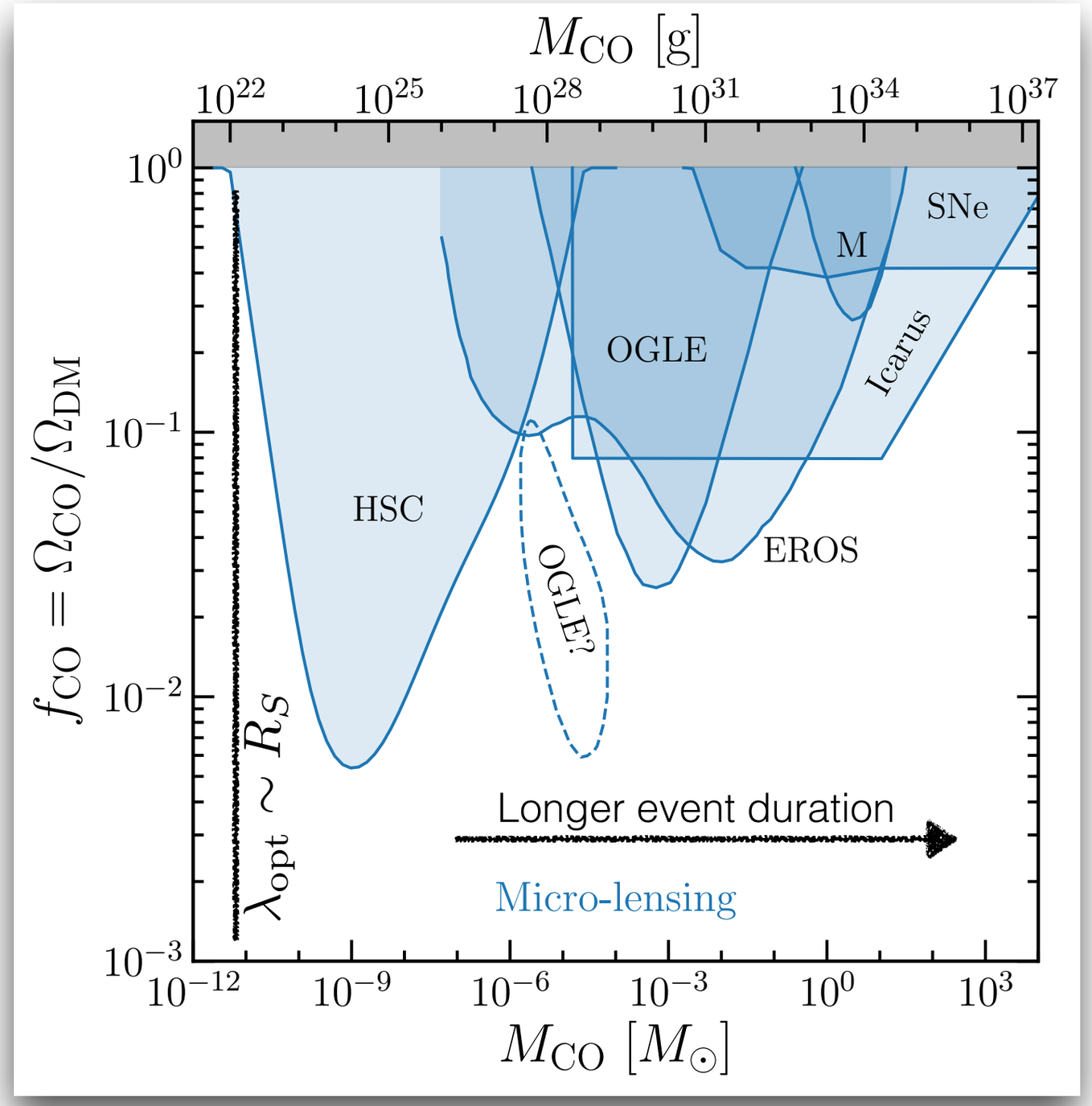

Recently updated at the low mass end

[Smyth et al., 1910.01285, Croon et al., 2007.12697]

Hint from 6 ultra-short events? (t ~ 0.1-0.3 days)

[OGLE, 1901.07120]

ICARUS! A star at z ~ 1.5

[Kelly et al., 1706.10279, Oguri et al., 1710.00148]

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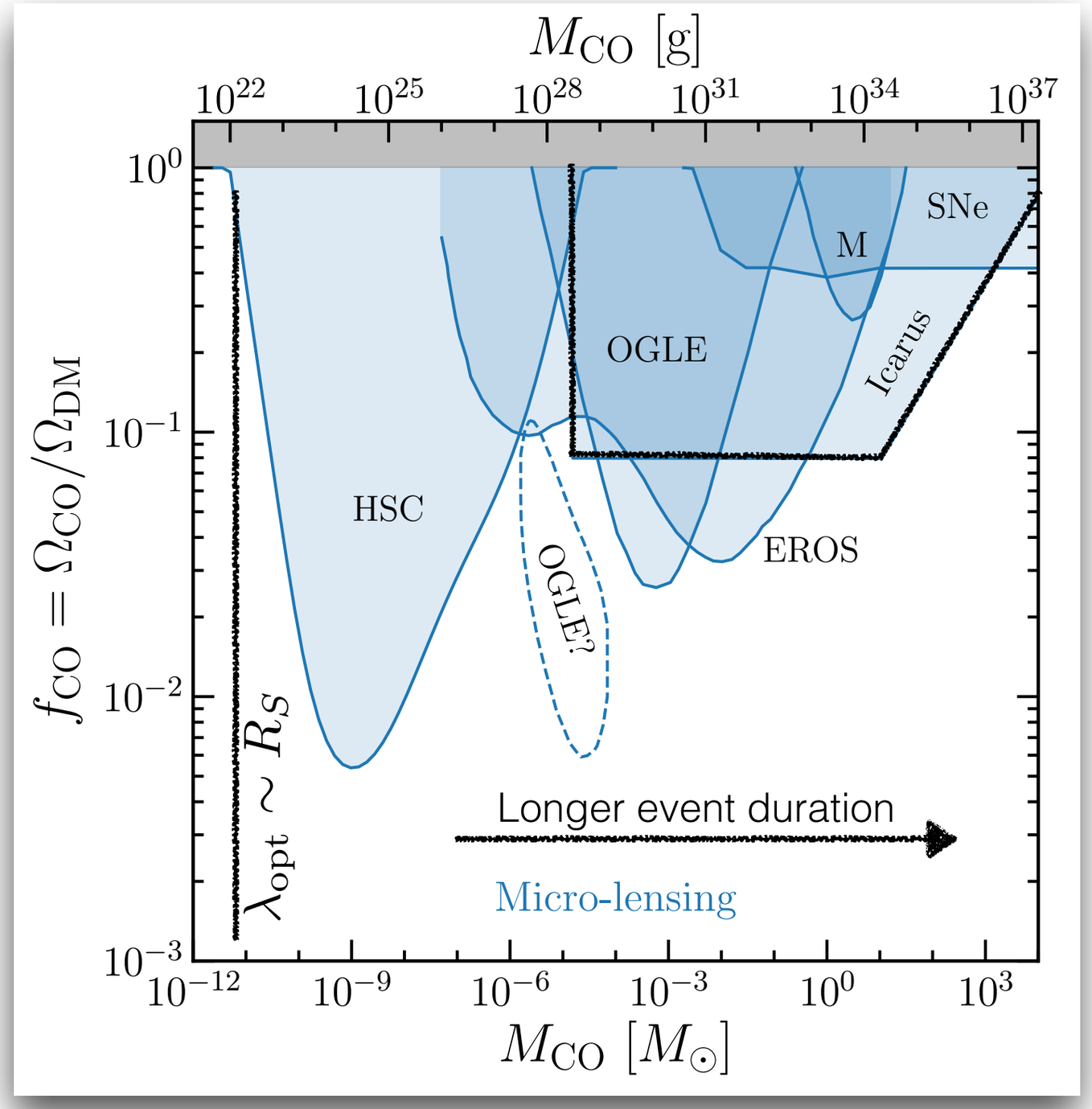

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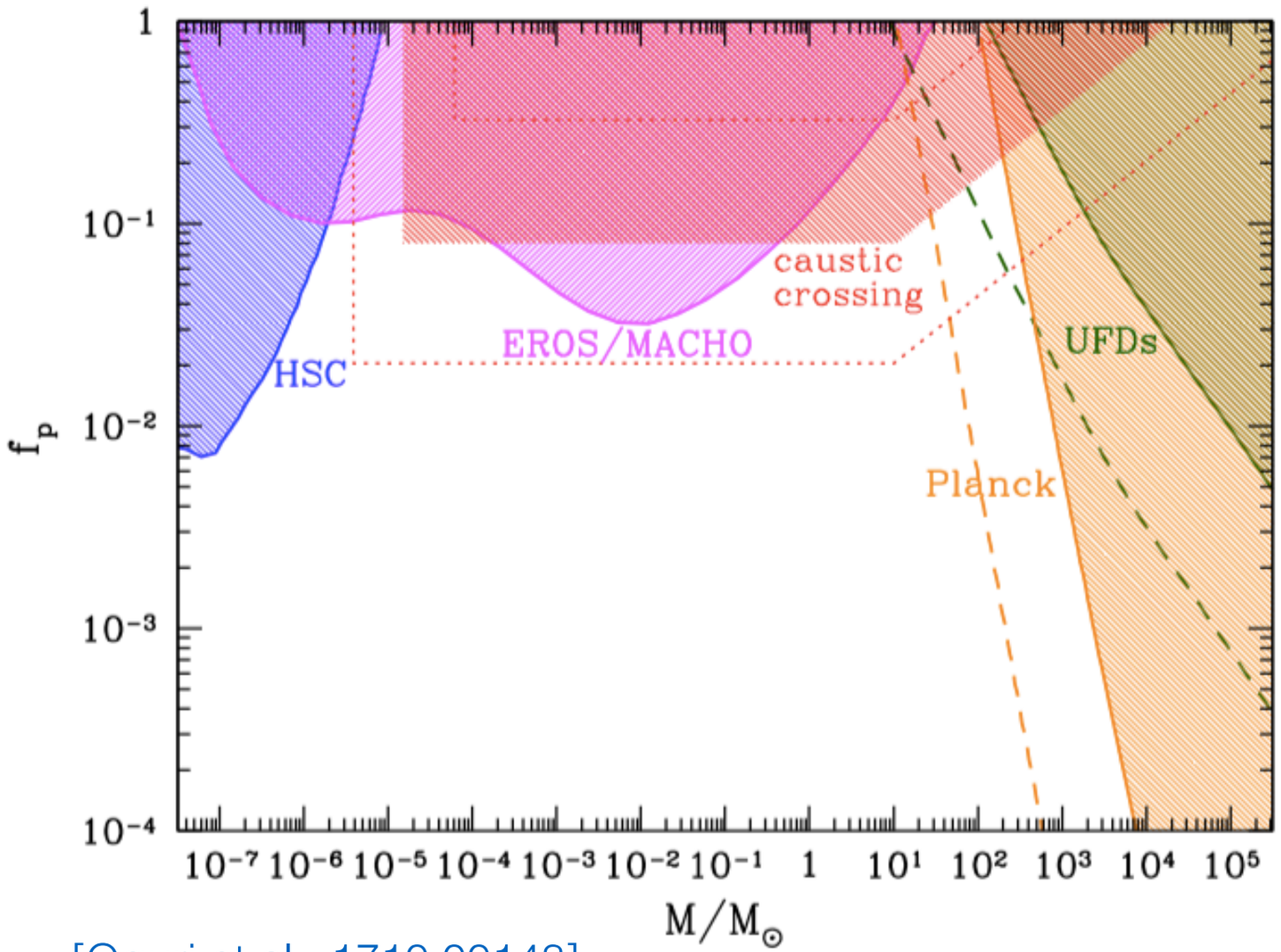
Icarus!

Star at z ~ 1.49, magnified by >2000x

(PBH) substructure in the galaxy-cluster lens would reduce the magnification



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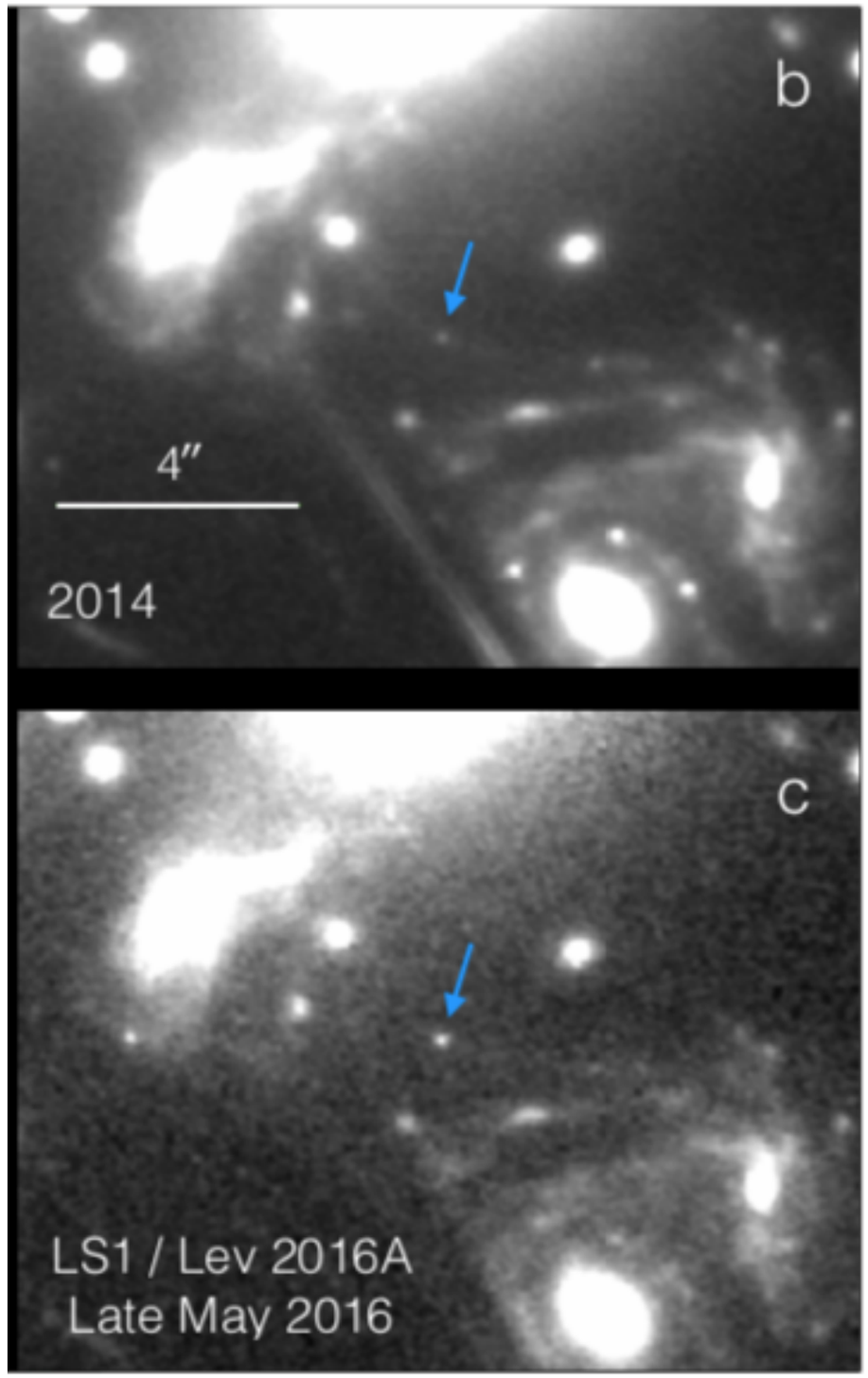

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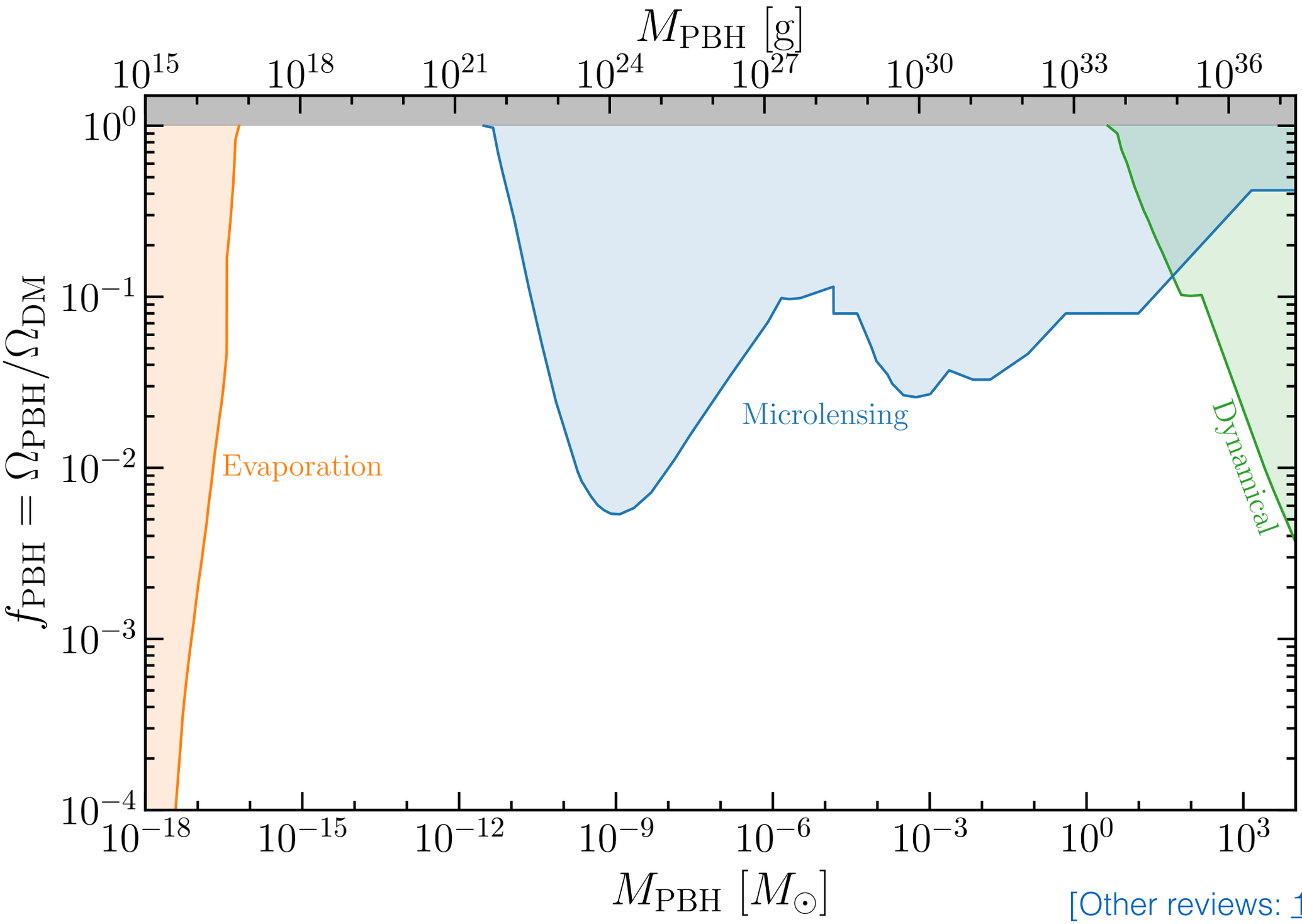
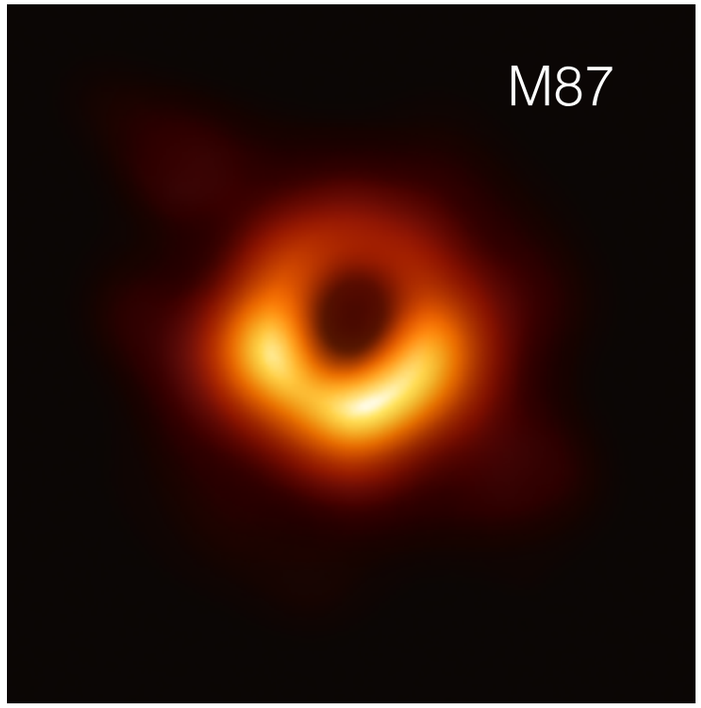


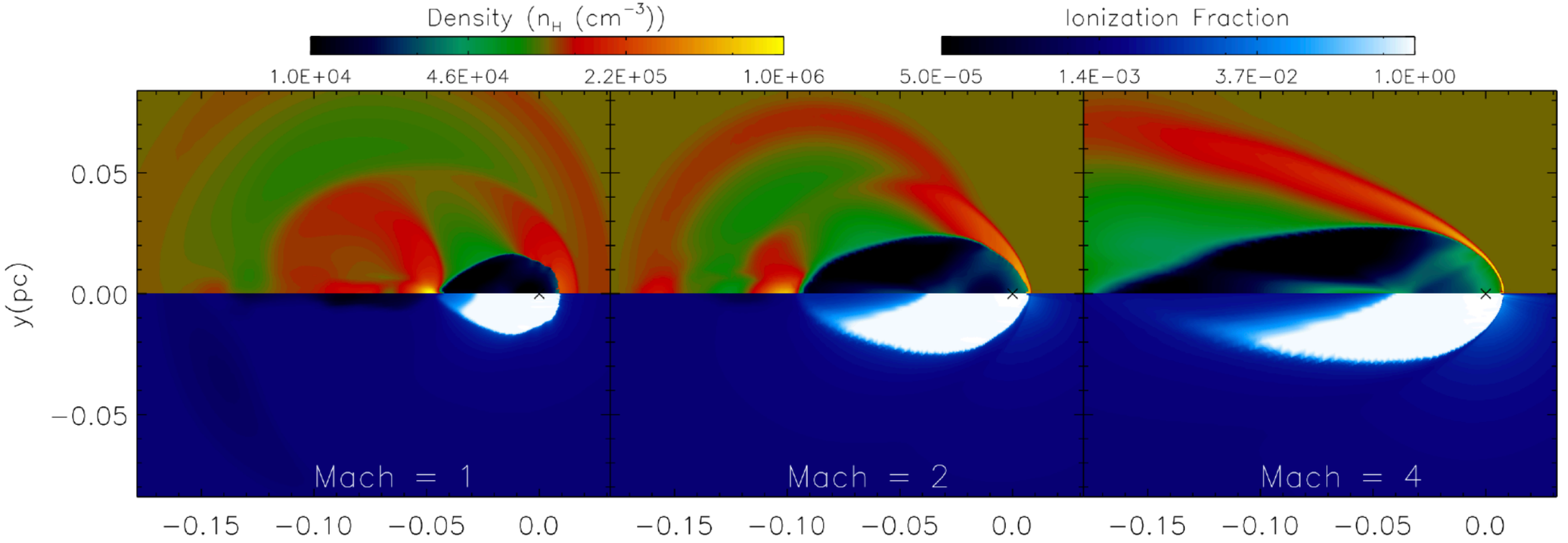
[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Black Hole Accretion

$$\dot{M} \equiv 4\pi \left(G M_{\rm BH}\right)^2 \rho \left(v^2 + c_{\rm s}^2\right)^{-3/2}$$

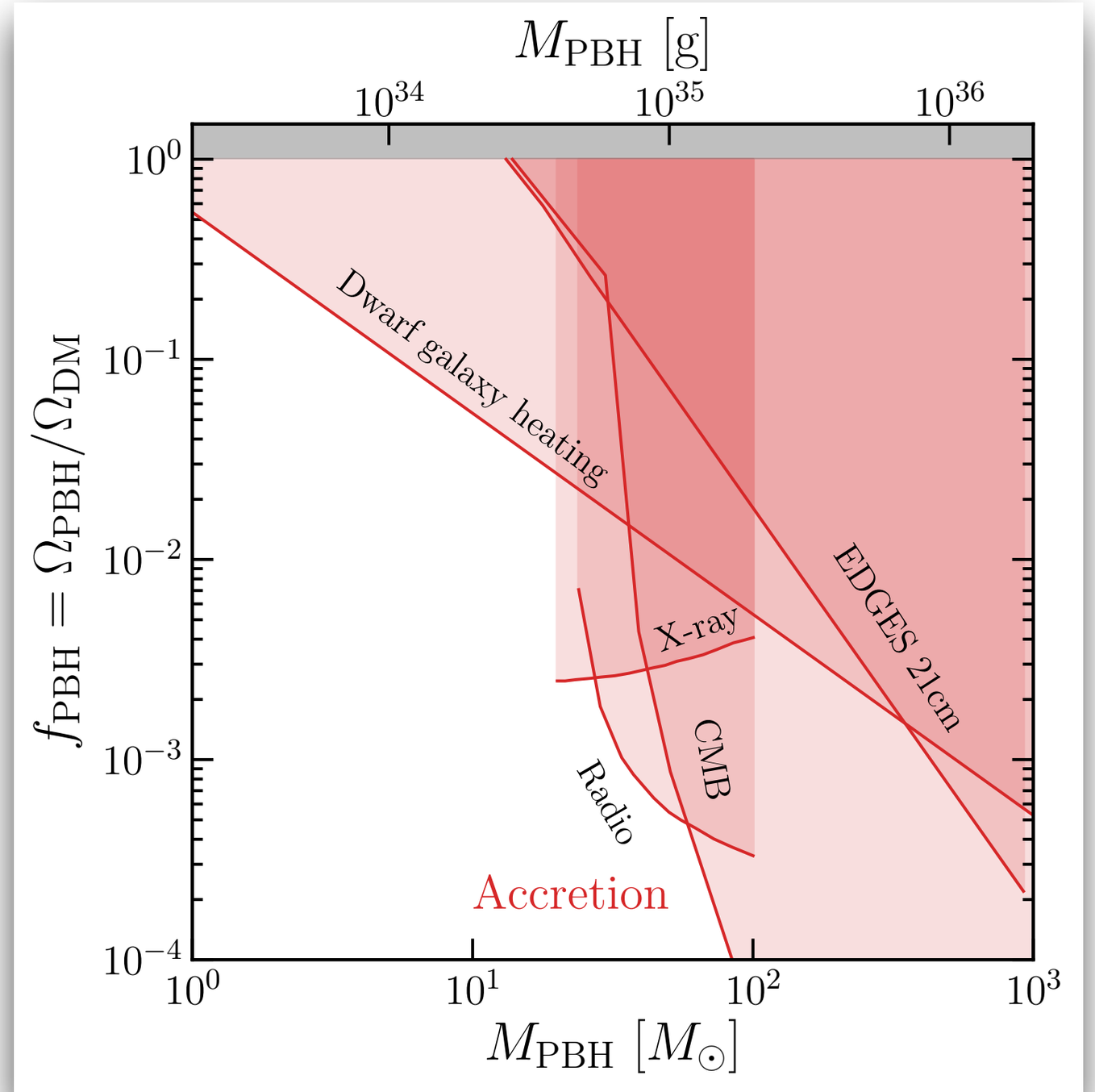


[Event Horizon Telescope, 1906.11241]



[Park & Ricotti, 1211.0542]

PBH Accretion



Emission due to accretion can be relevant at early and late times

Large uncertainties due to accretion model

[E.g. Manshanden et al., 1812.07967]

CMB bounds now on solid ground (and getting stronger)

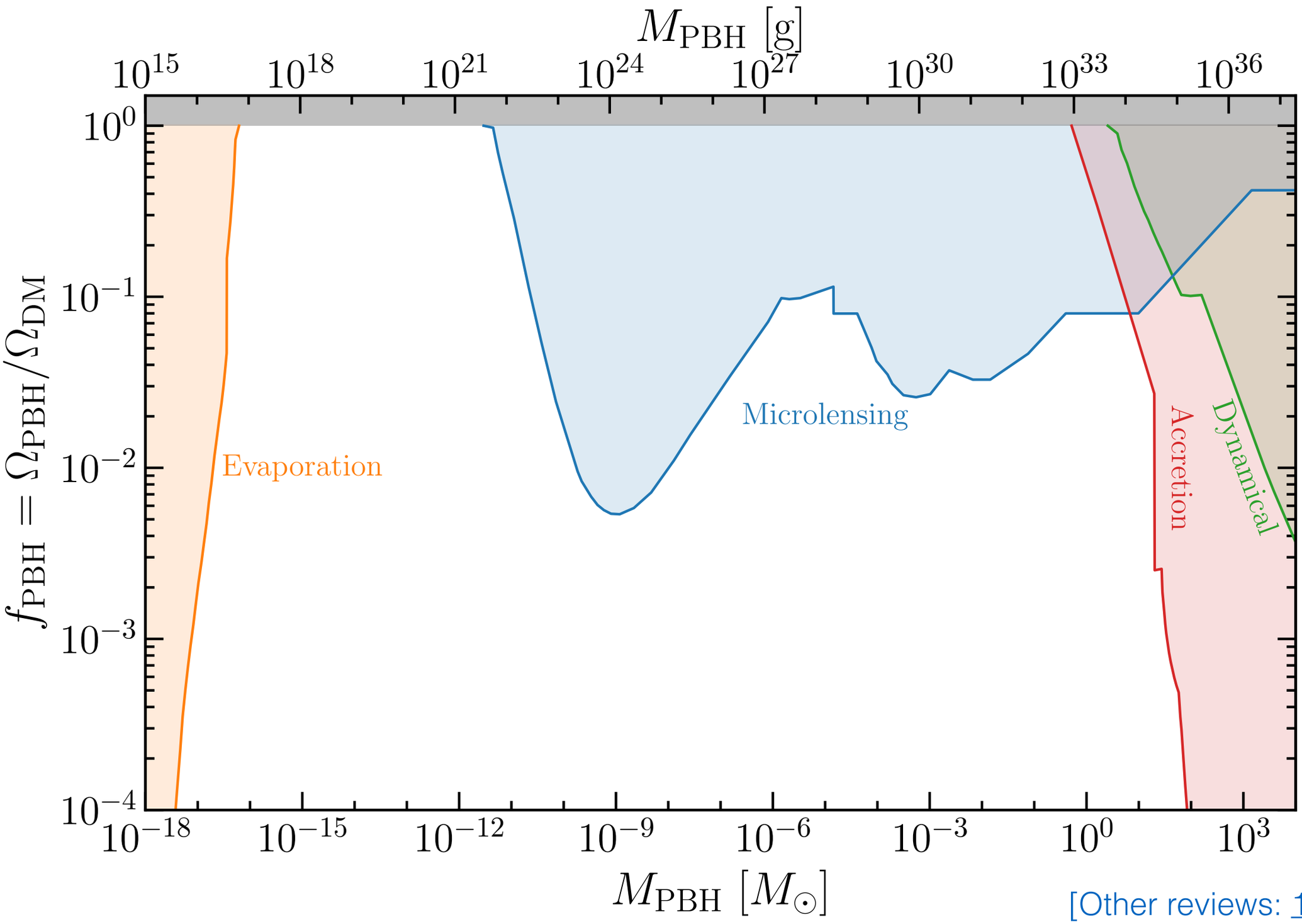
[Serpico et al., 2002.10771]

New bounds from gas heating in Leo T dwarf

[Lu et al., 2007.02213]

PBH Constraints

[Green & **BJK**, 2007.10722]
[Code online: github.com/bradkav/PBHbounds]



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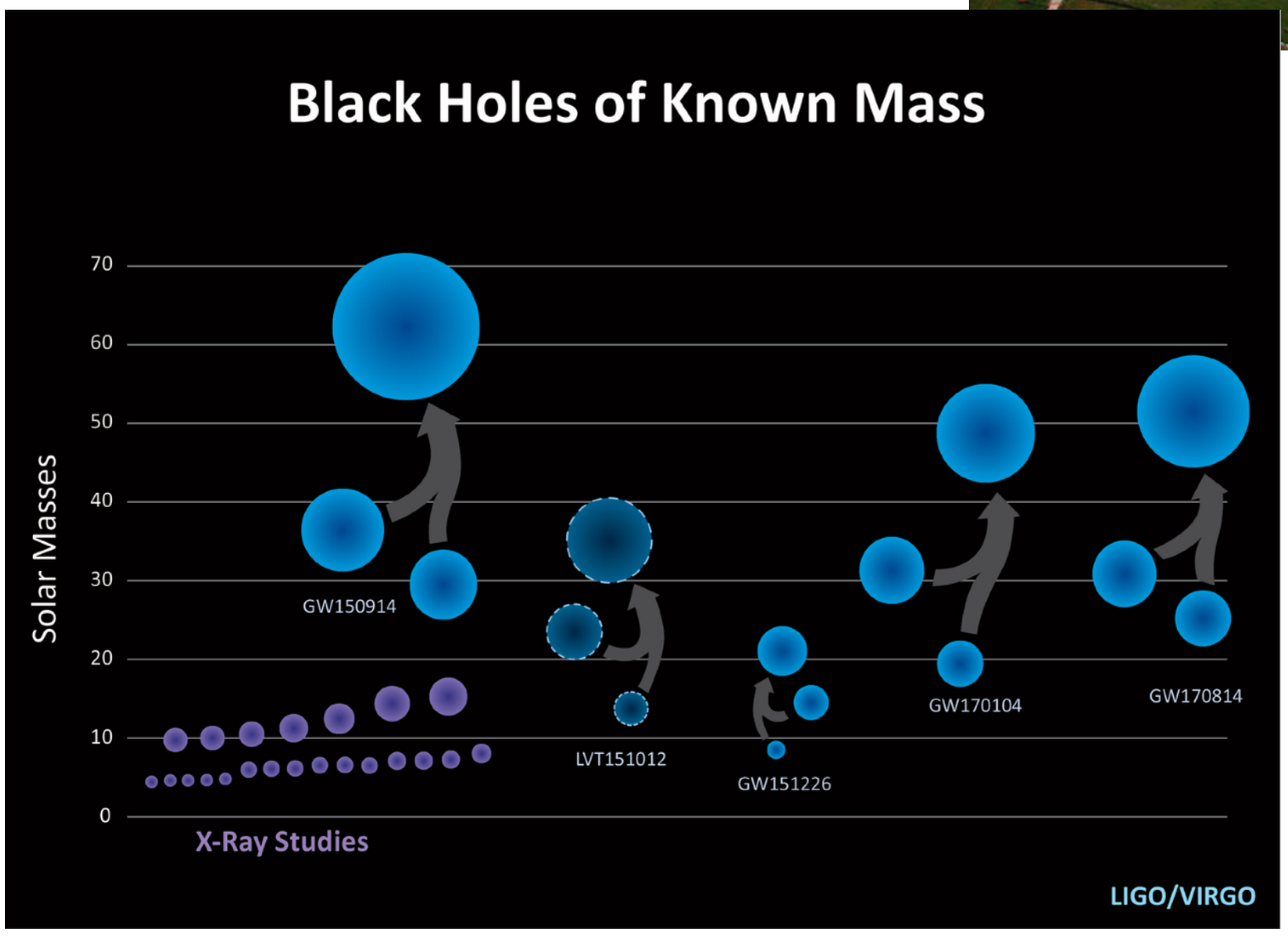
LIGO/Virgo Mergers

The Virgo collaboration/CCO 1.0

LIGO/Caltech/Sonoma State (Aurore Simonnet)



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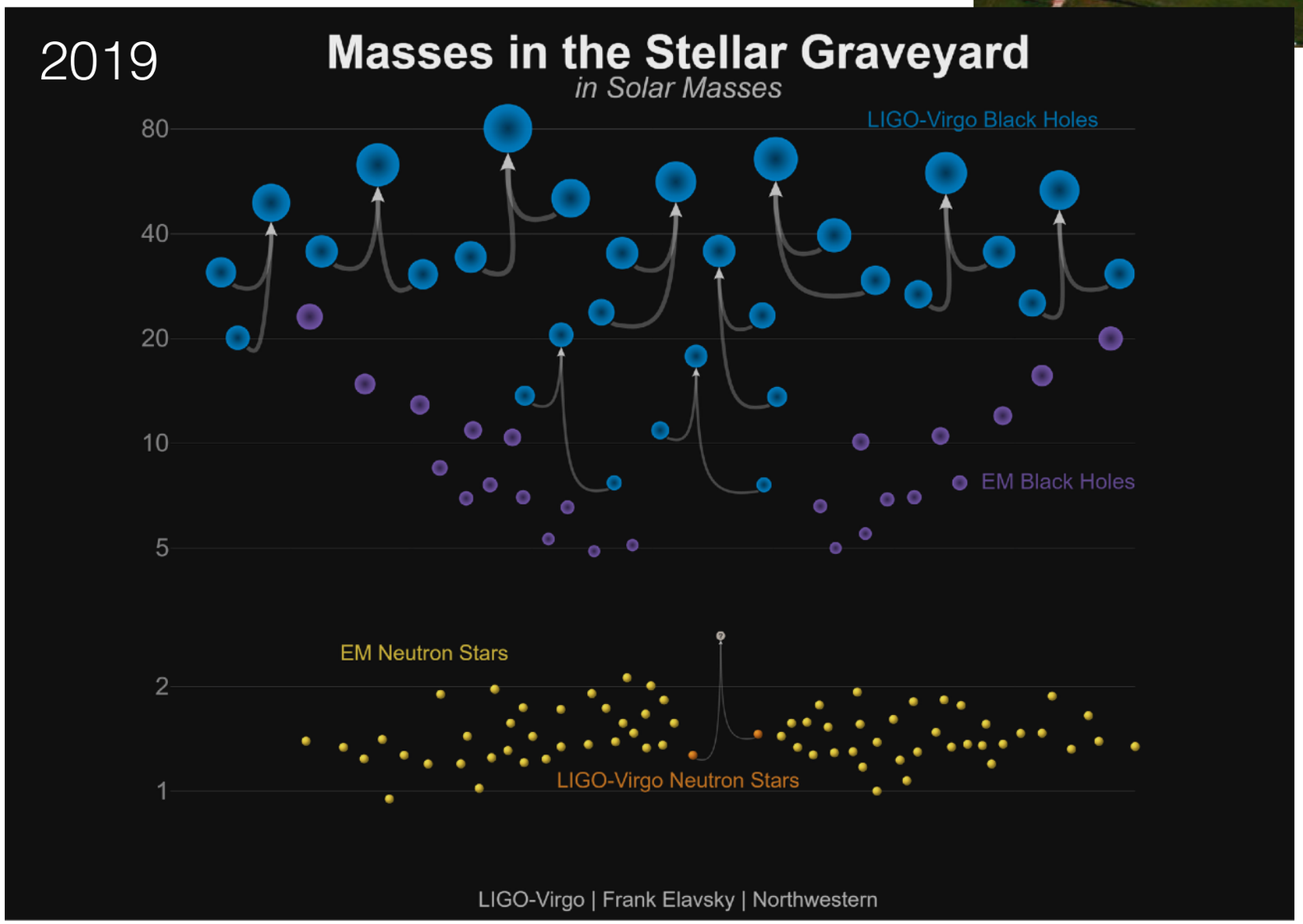

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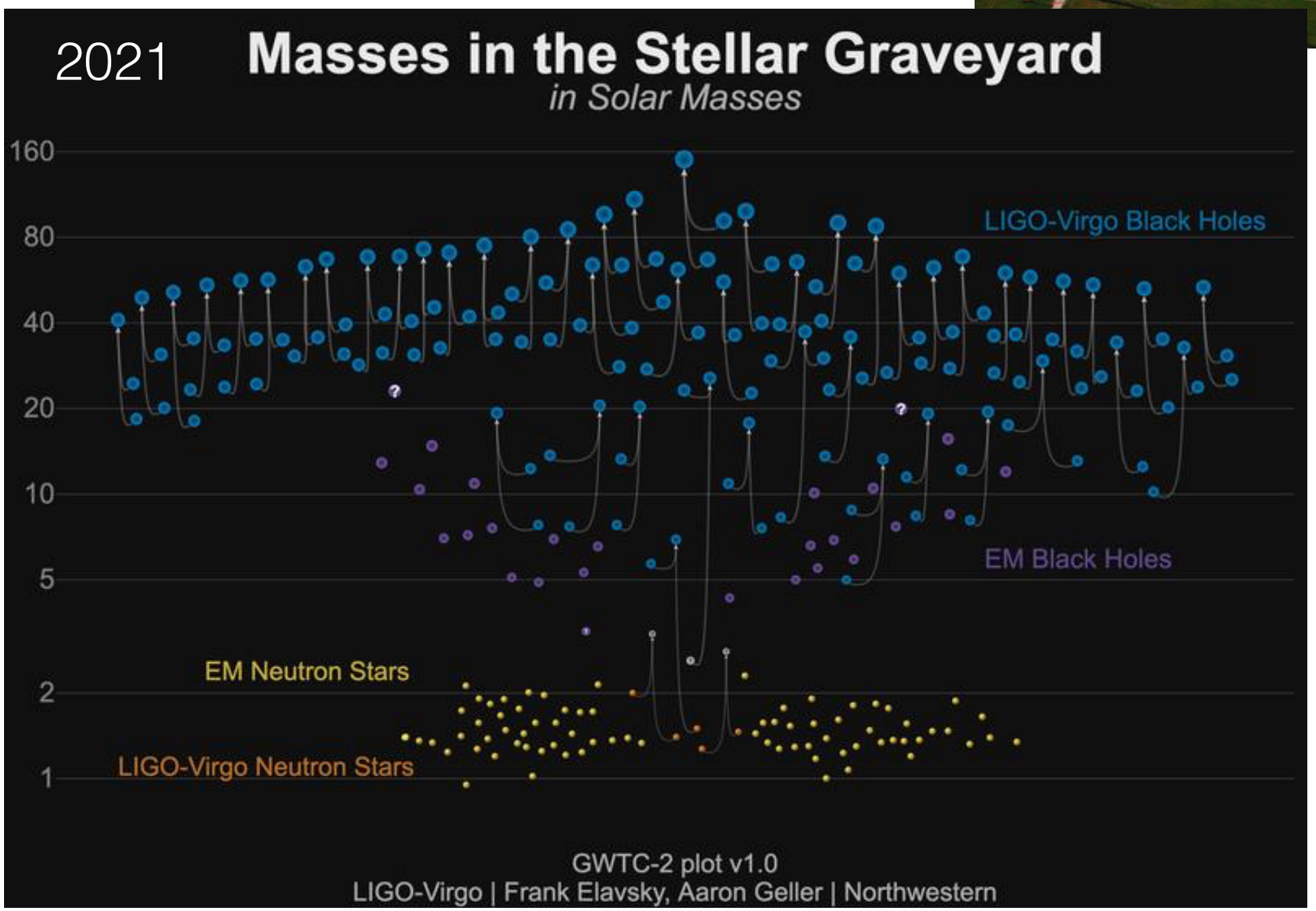
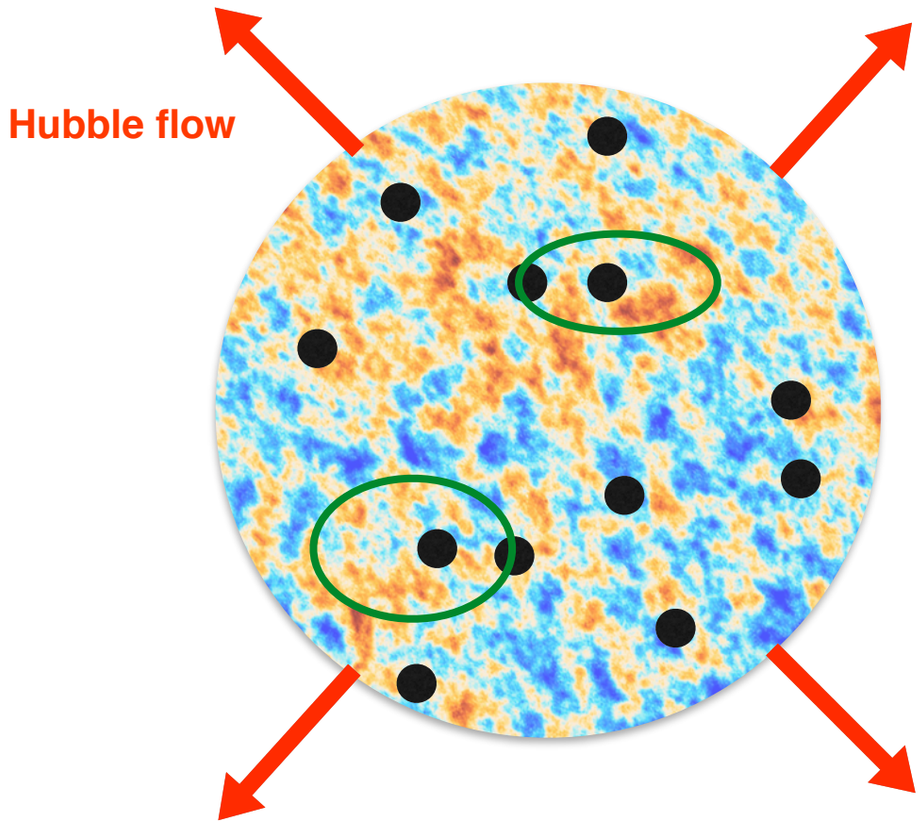


PBH binaries

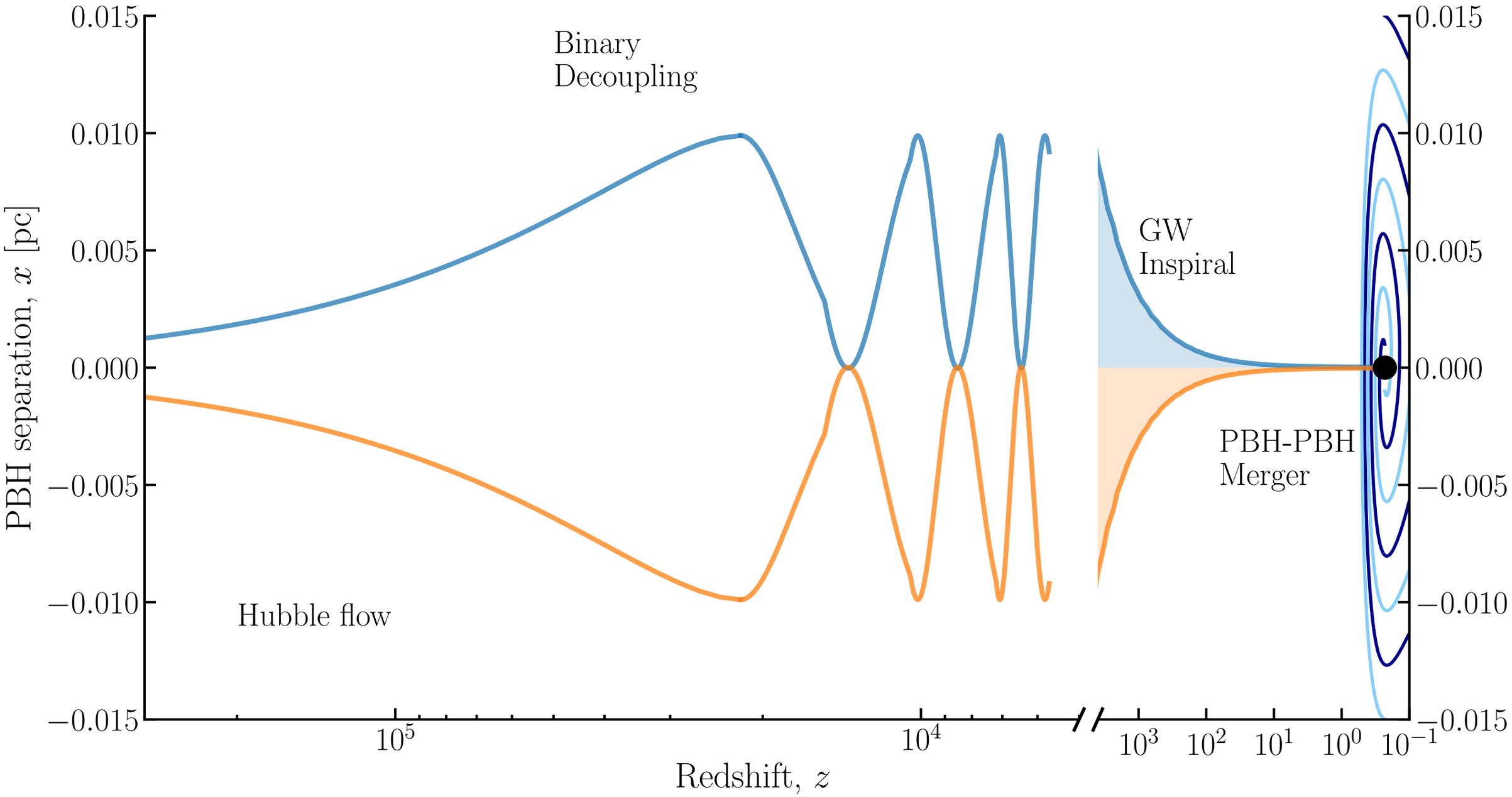
PBHs which are close enough to each other in the early Universe may form binaries!



[Nakamura et al, astro-ph/9708060, Sasaki et al, 1603.08338]

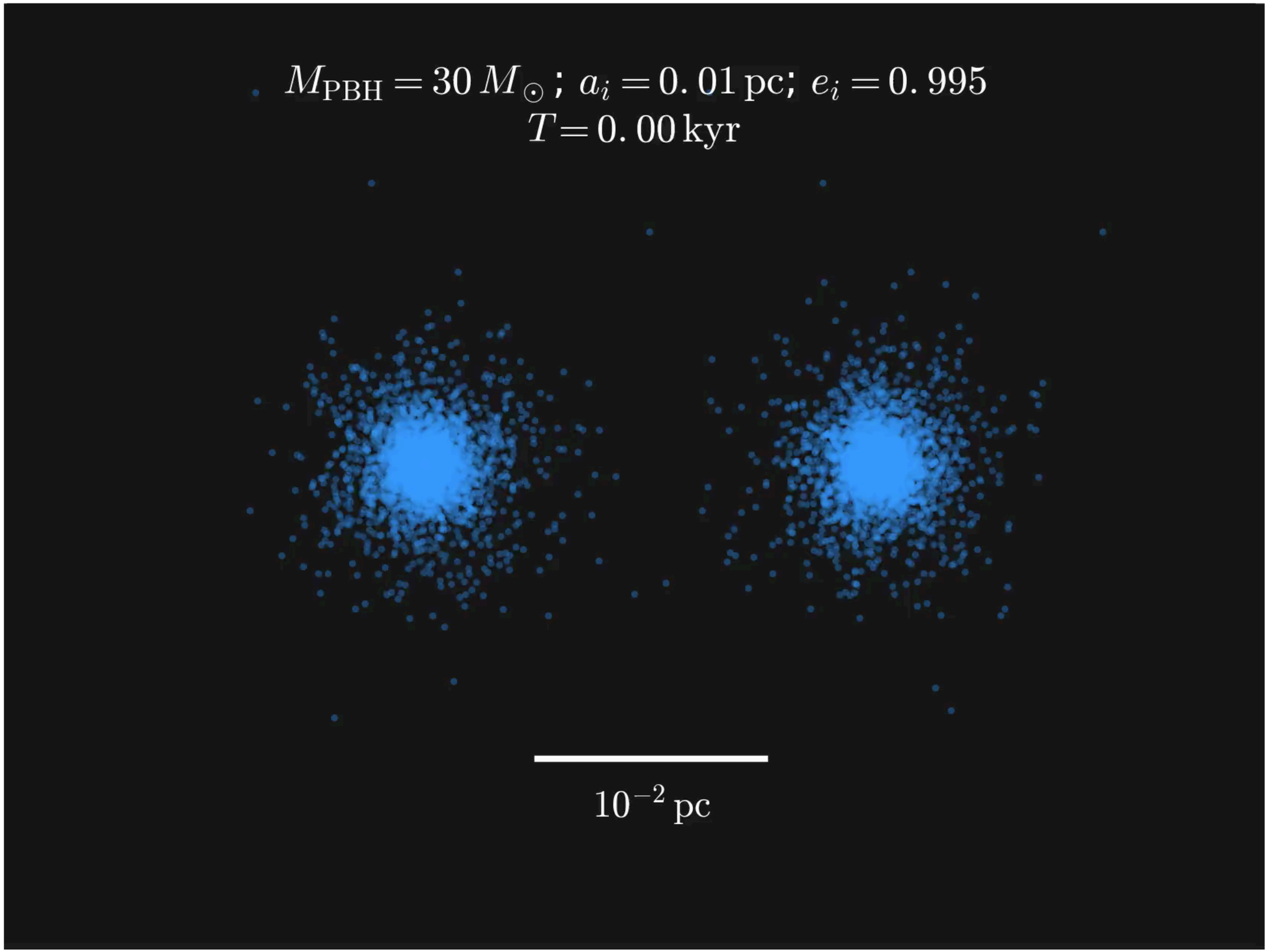
Life of a PBH binary

$$a_i = 0.01\,\mathrm{pc}$$
$$e_i = 0.995$$



[Ali-Haïmoud et al., 1709.06576,
BJK, Gaggero & Bertone, 1805.09034]

Movies at tinyurl.com/BlackHolesDarkDress



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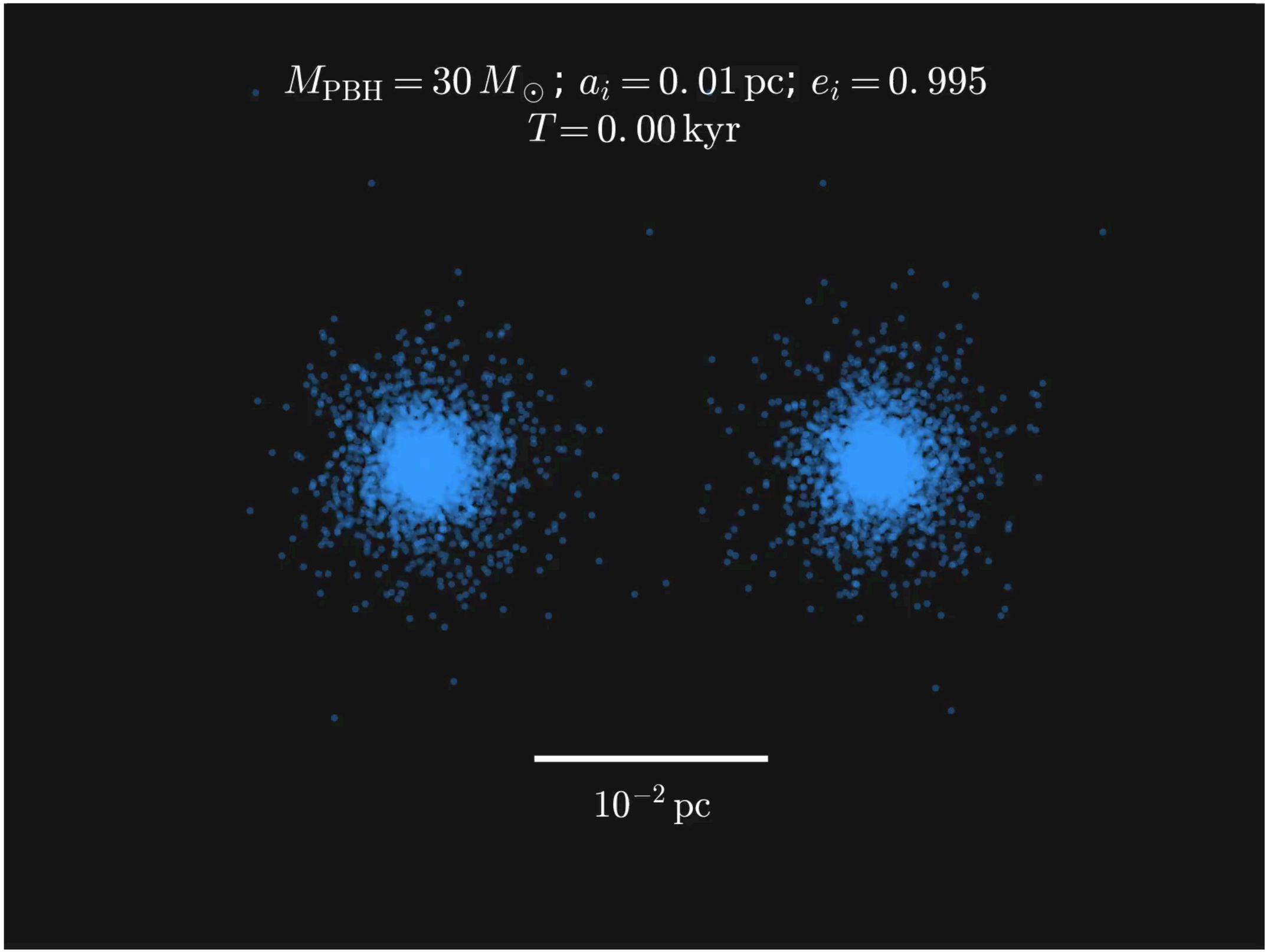

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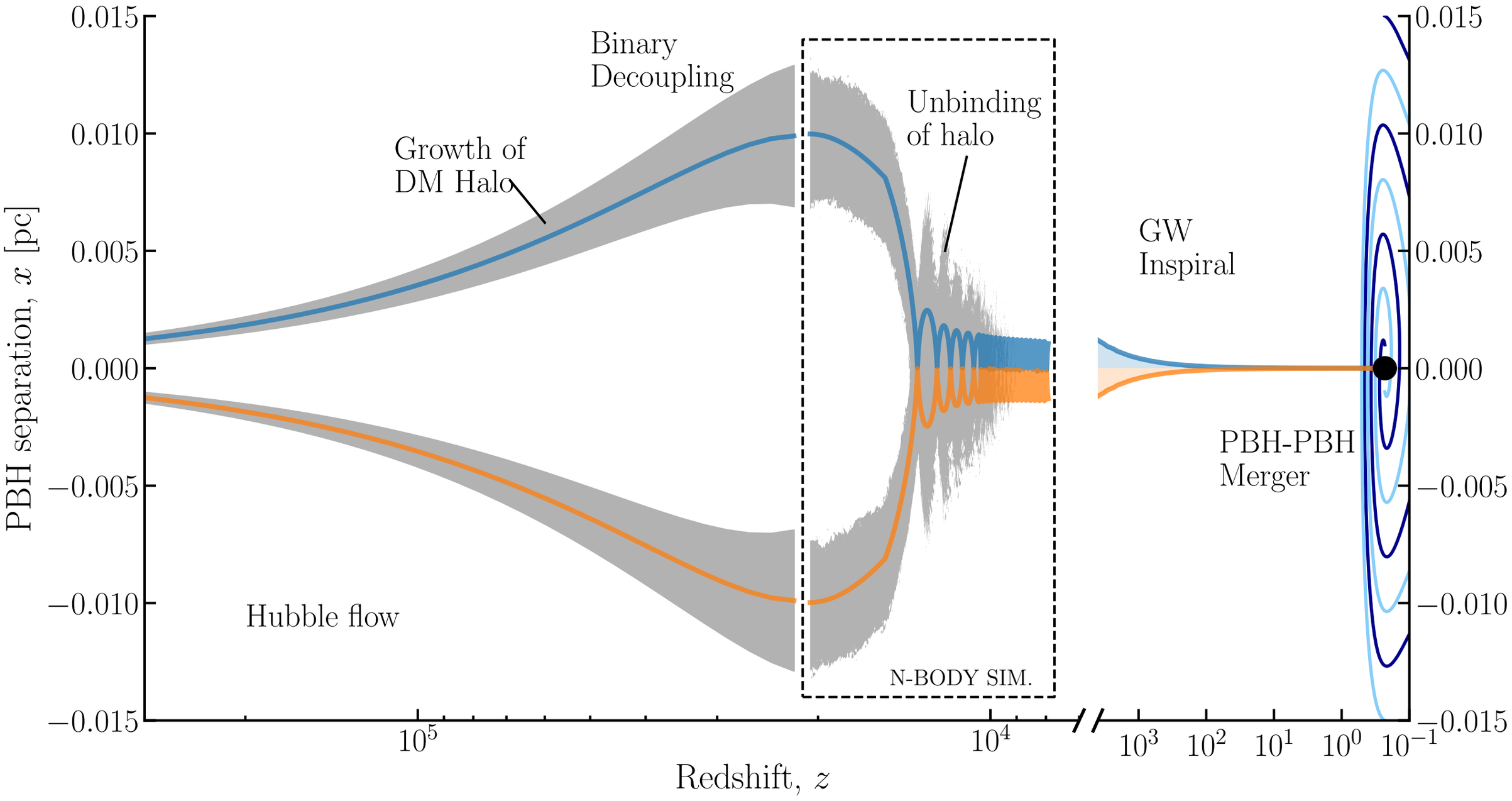

[Ali-Haïmoud et al., 1709.06576,
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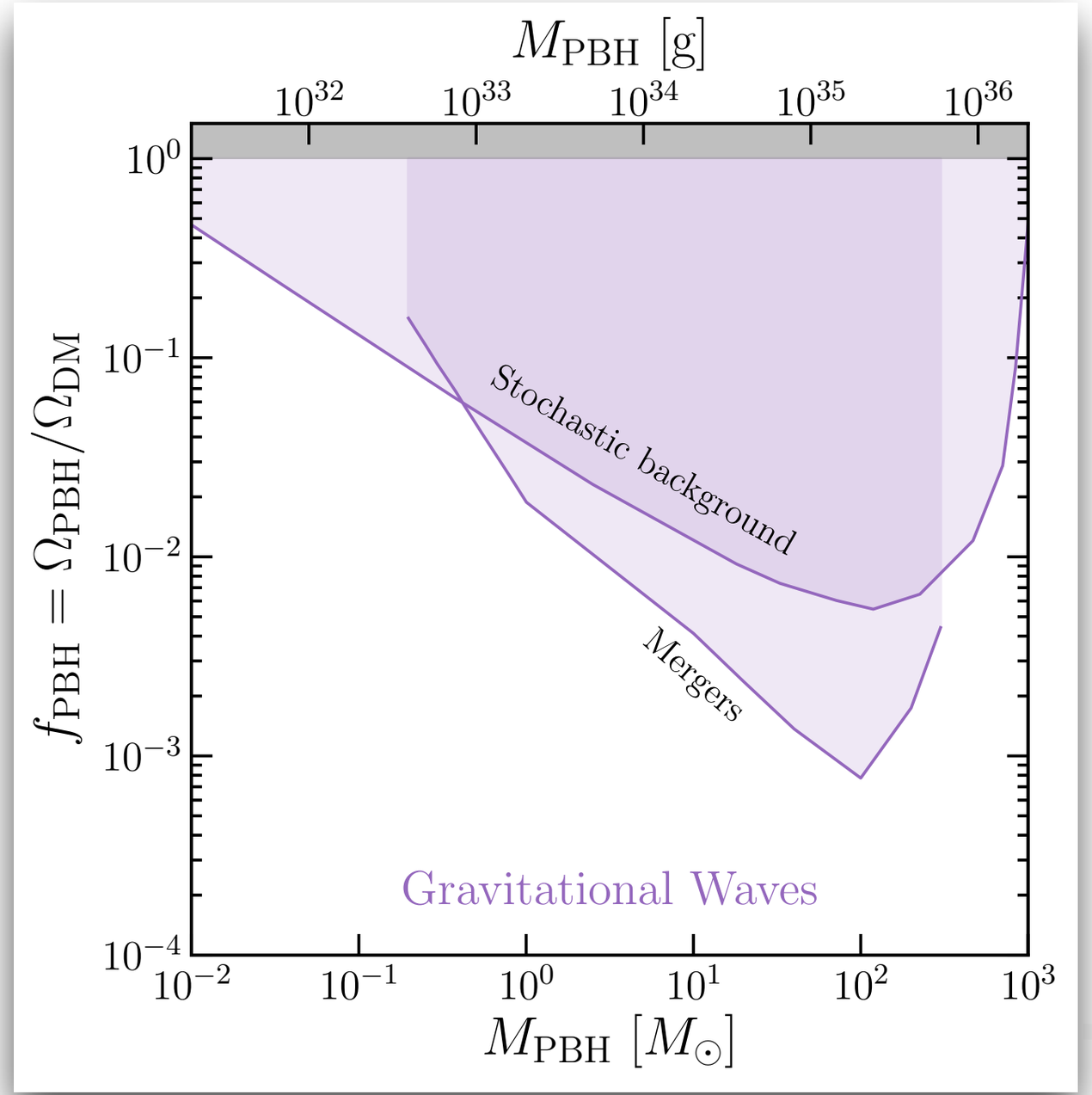
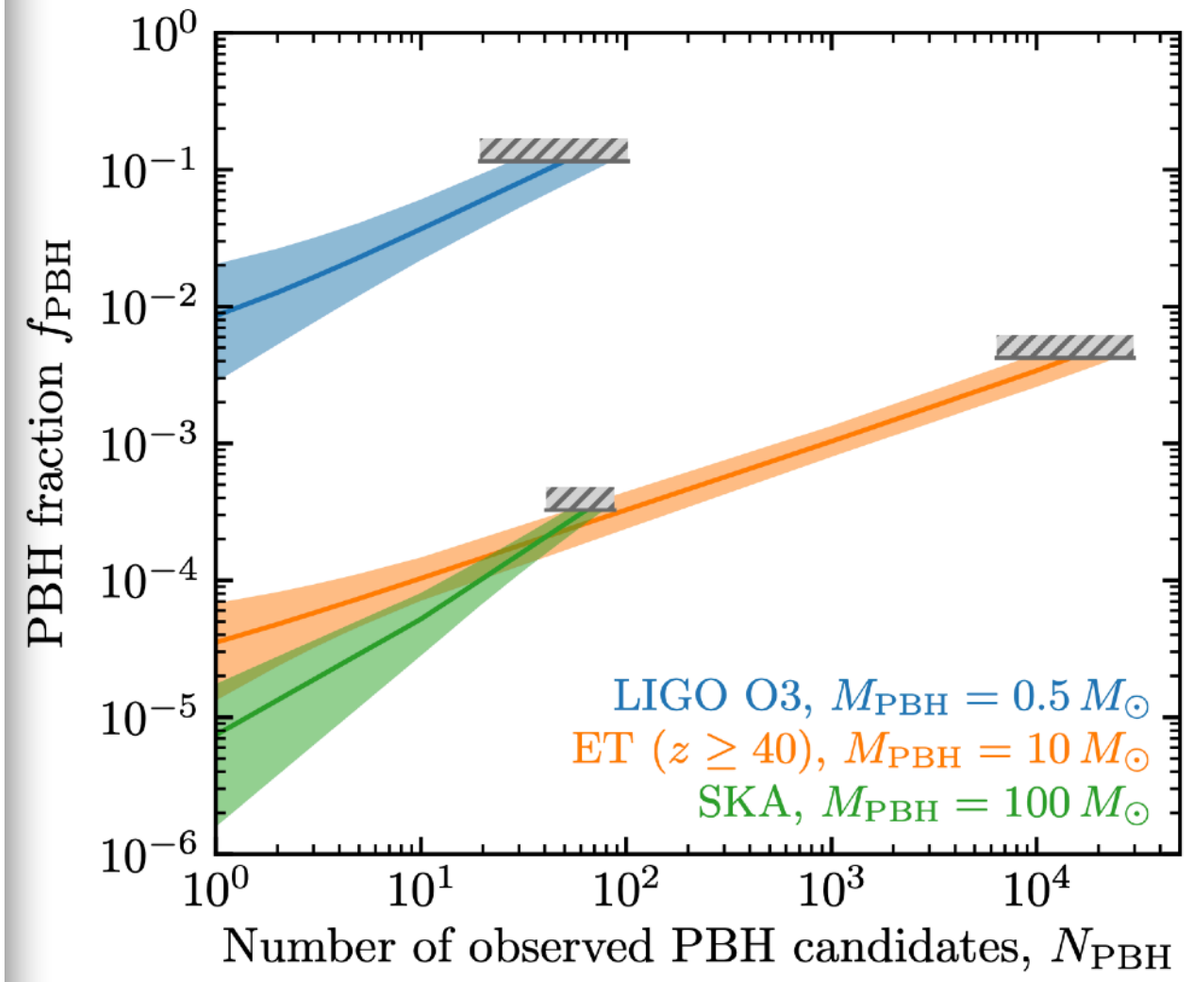
Gravitational Waves



Prospects for detection:

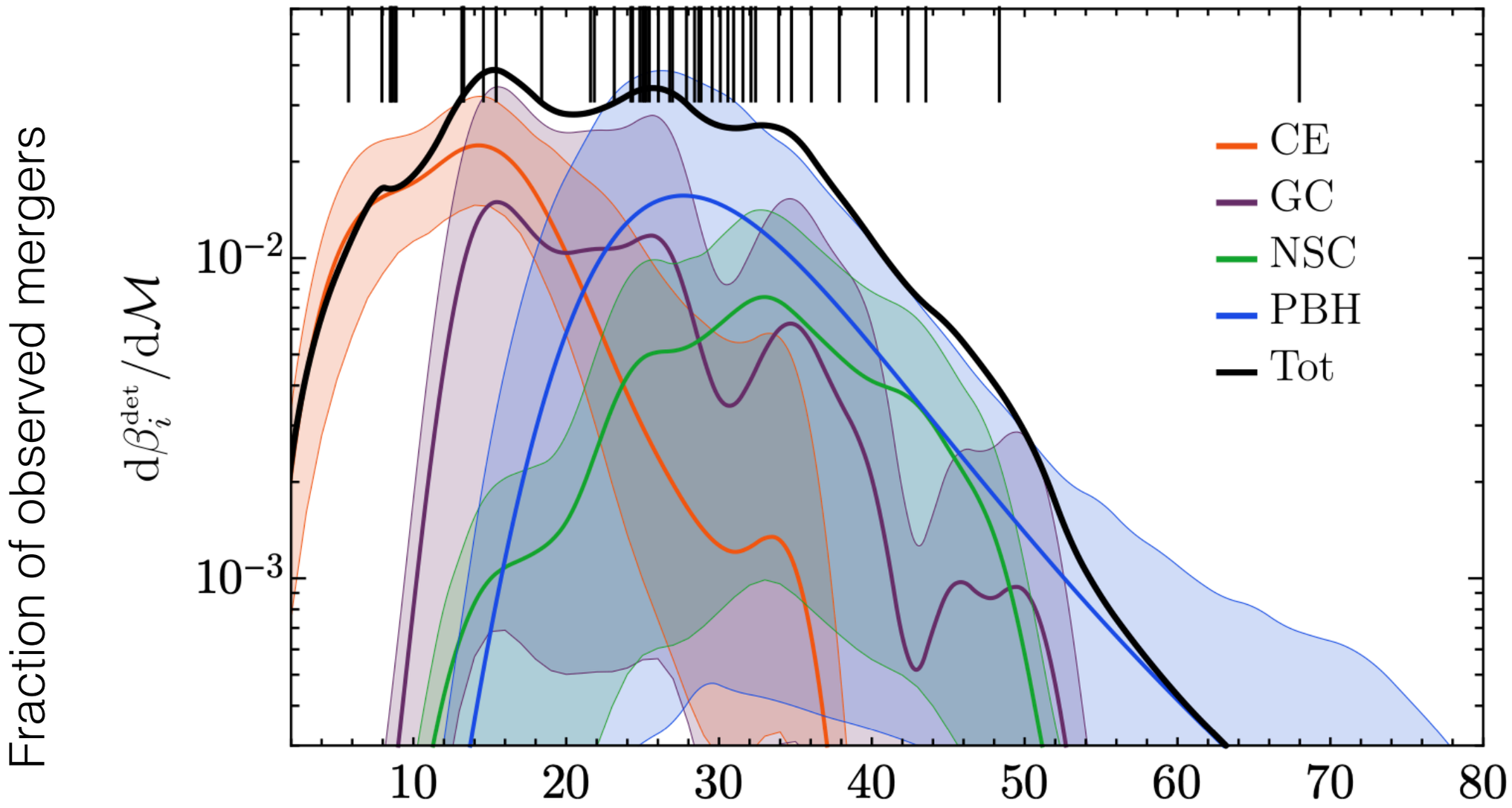


[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

A hint of a signal?

[Franciolini et al., 2105.03349]

[See also Hütsi et al., 2012.02786]



Fraction of observed mergers due to PBHs (?): $0.27^{+0.28}_{-0.24}$

→ Would imply $f_{\mathrm{PBH}} \sim 6 \times 10^{-4}$…

PBH Clustering

Even a distribution of PBHs which is initially Poisson distributed will cluster at late times

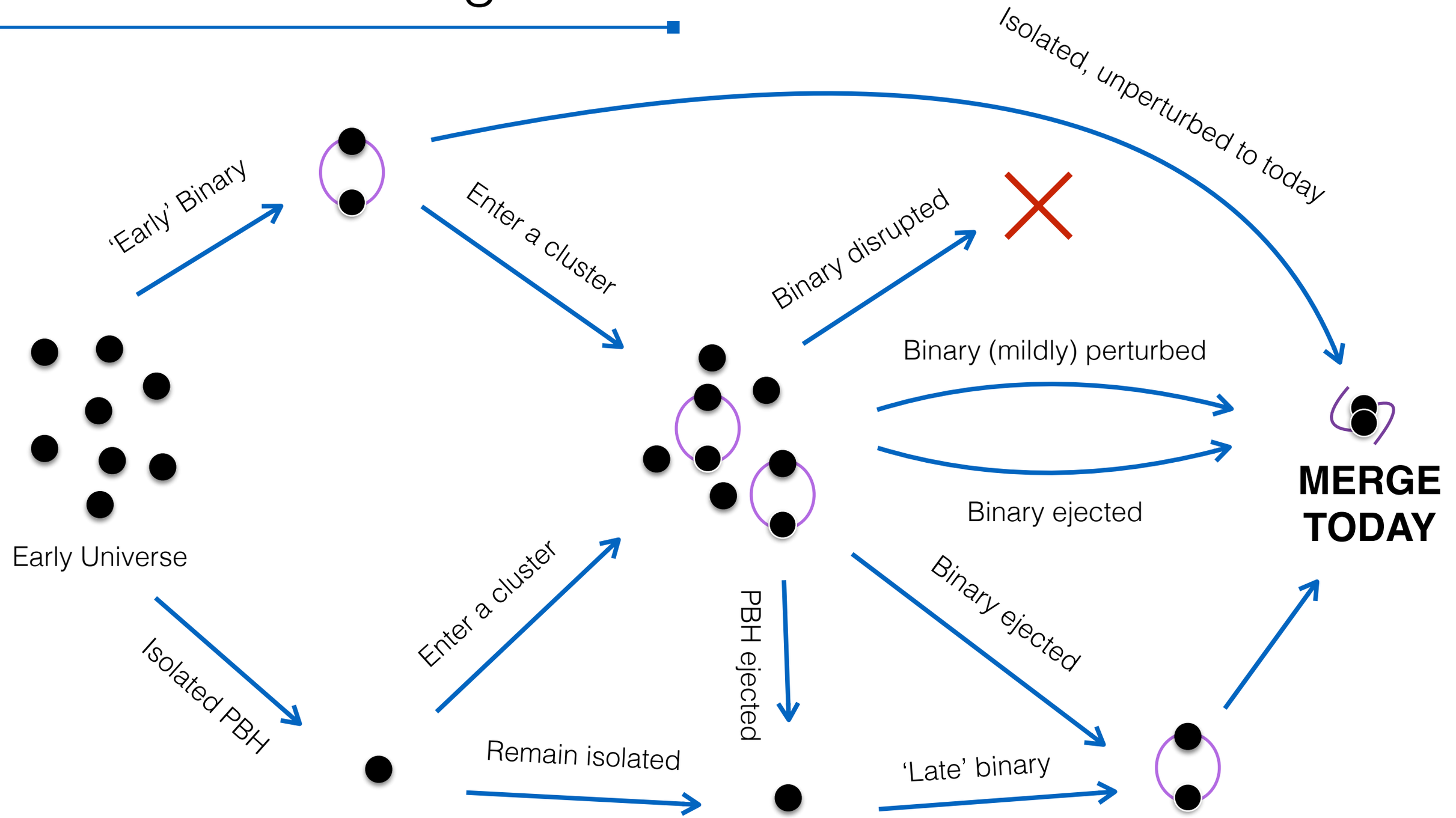
$z \gg 10^4$

$z \lesssim 100$

A cluster of N PBHs is expected to form around $z_c \sim z_{\rm eq} f_{\rm PBH}/\sqrt{N}$

[Chisholm - astro-ph/0509141, 1110.4402; Inman & Ali-Haïmoud, 1907.08129]

Paths to PBH Mergers

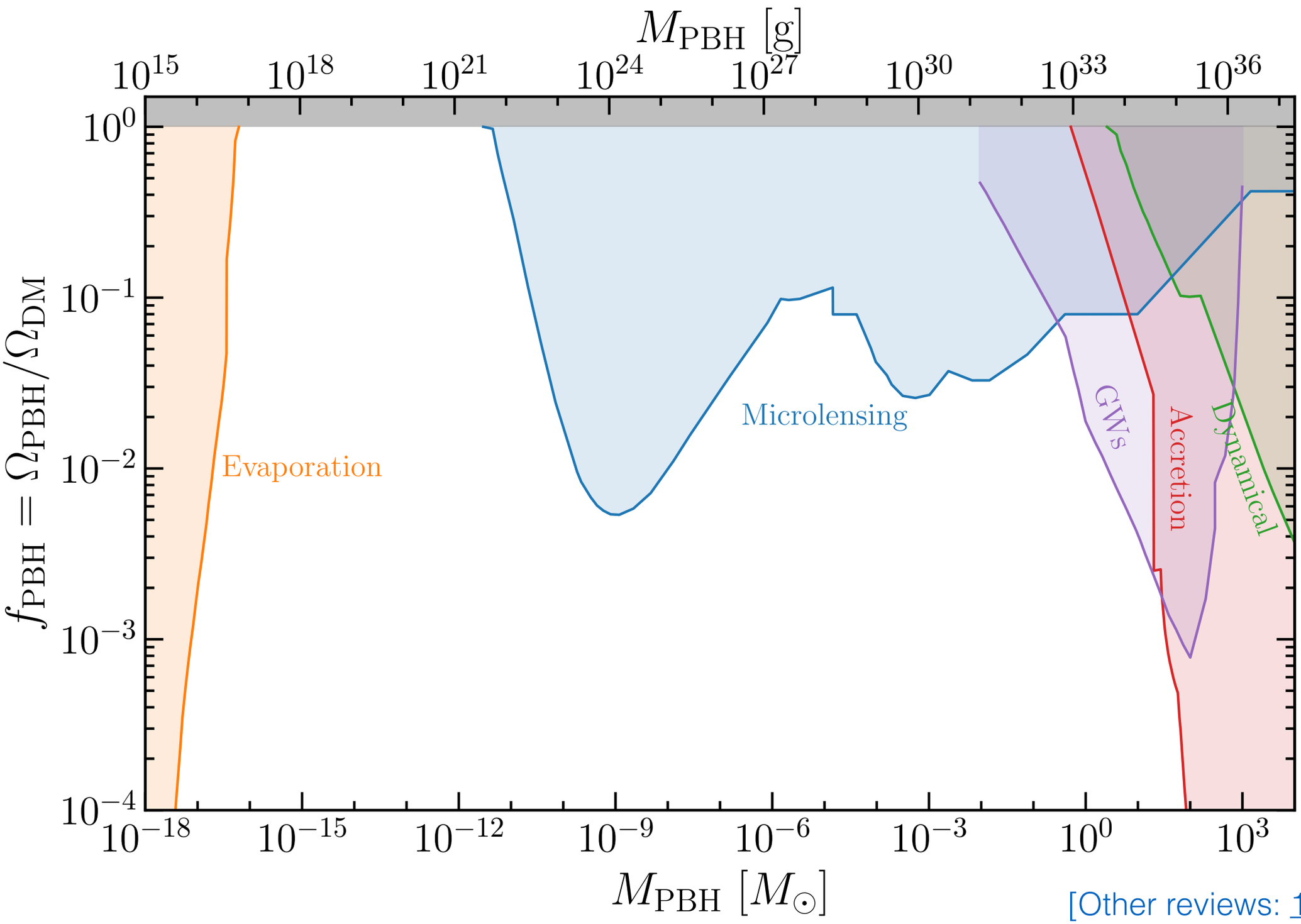


+ particle DM halos?
  [**BJK**, Gaggero & Bertone, 1805.09034]
+ baryonic accretion?
  [De Luca et al., 2003.12589]

[Raidal+, 1812.01930; Vaskonen & Veermäe, 1908.09752; Atal+, 2007.07212; De Luca+, 2009.04731 and others…]

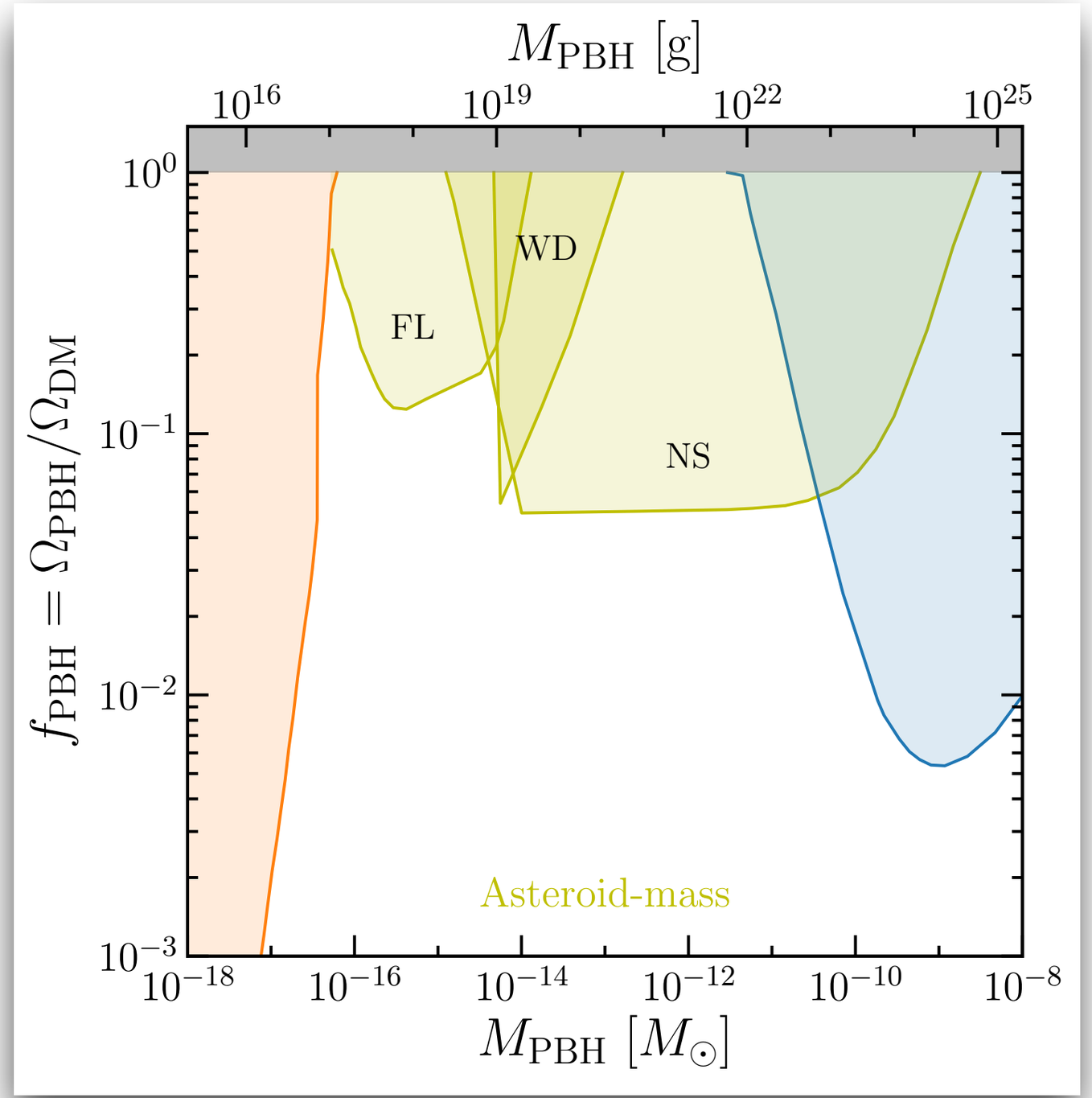
PBH Constraints

[Green & **BJK**, 2007.10722]
[Code online: github.com/bradkav/PBHbounds]



[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Asteroid-mass PBHs



A few years ago this region was well-constrained

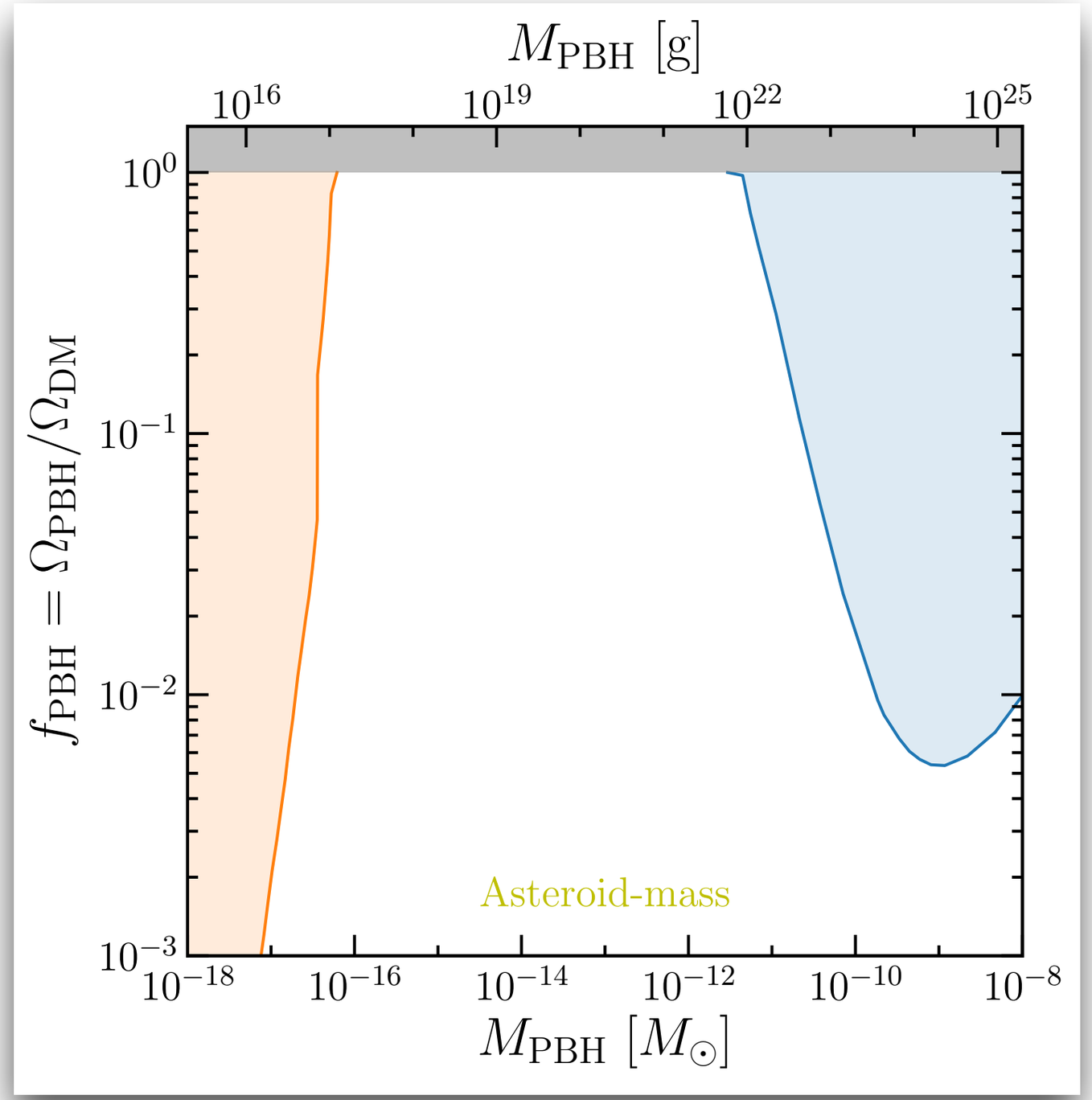
‘Femtolensing’ of Gamma Ray Bursts?

[Barnacka et al., 1204.2056]

PBH capture in compact objects (White Dwarfs/Neutron Stars)

[E.g. Graham et al., 1505.04444, Capela et al., 1301.4984]

Asteroid-mass PBHs



A few years ago this region was well-constrained

‘Femtolensing’ of Gamma Ray Bursts?
[Barnacka et al., 1204.2056]

[Katz et al., 1807.11495]

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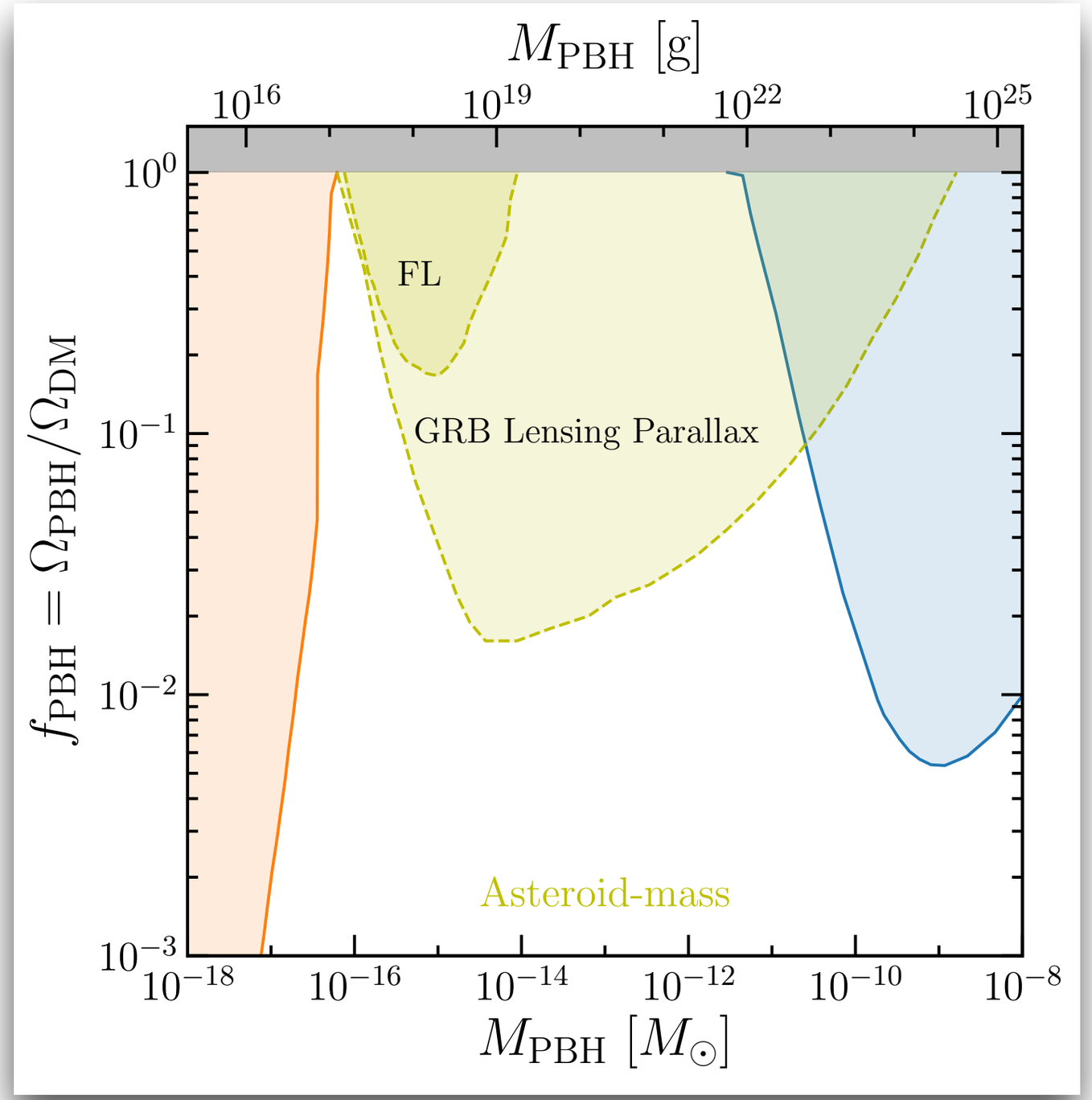
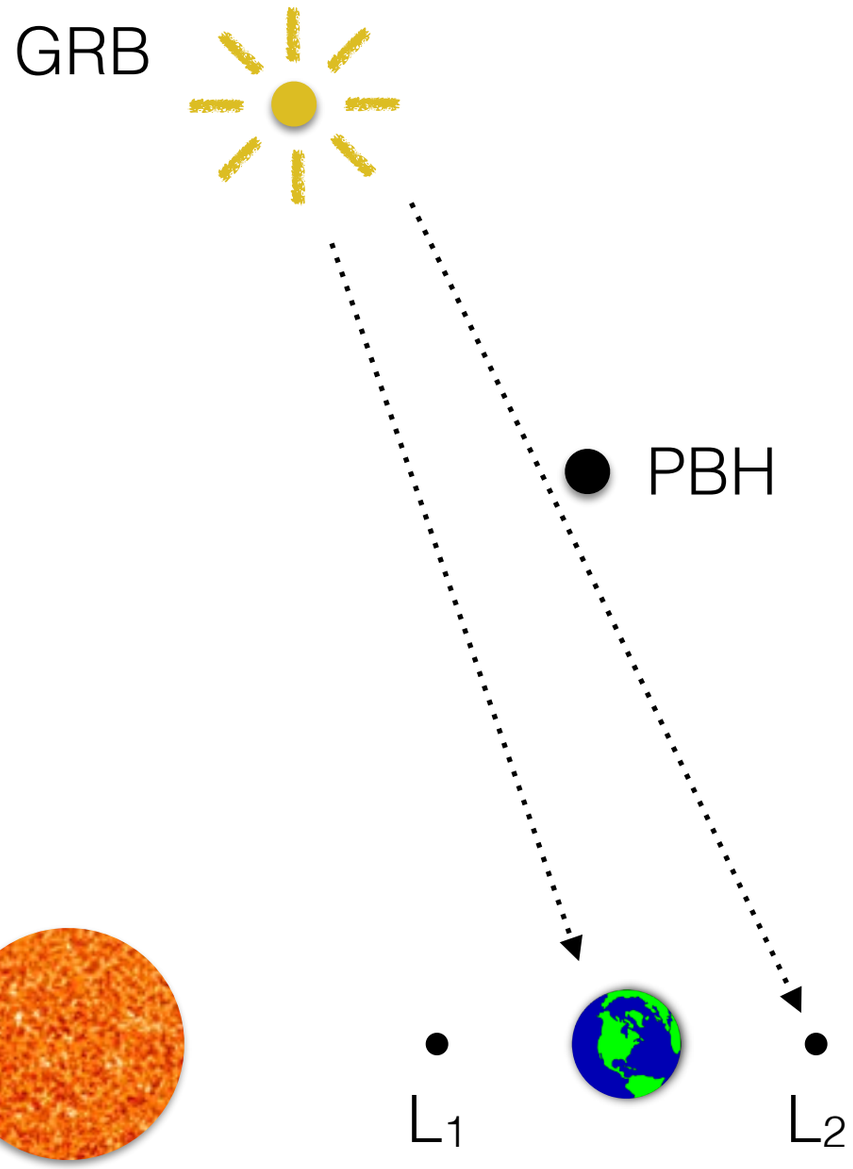
[E.g. Graham et al., 1505.04444, Capela et al., 1301.4984]

[Montero-Camacho et al., 1906.05950]

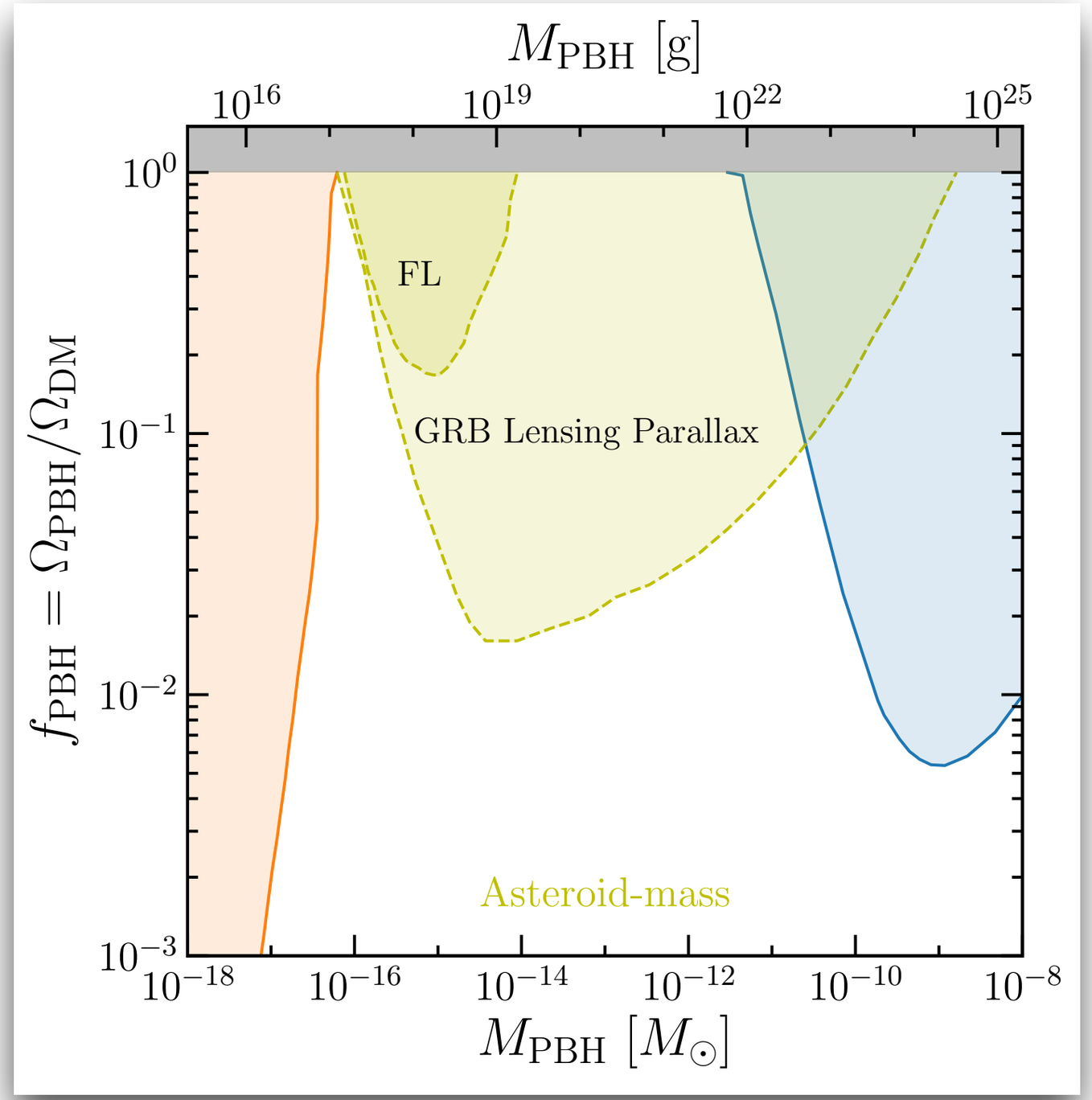
Asteroid-mass PBHs





[Nemiroff & Gould, astro-ph/9505019, Jung & Kim, 1908.00078]

Asteroid-mass PBHs



Craters on the moon?

[Yalinewich & Caplan, 2104.00033]

Disruption of the Kuiper belt?

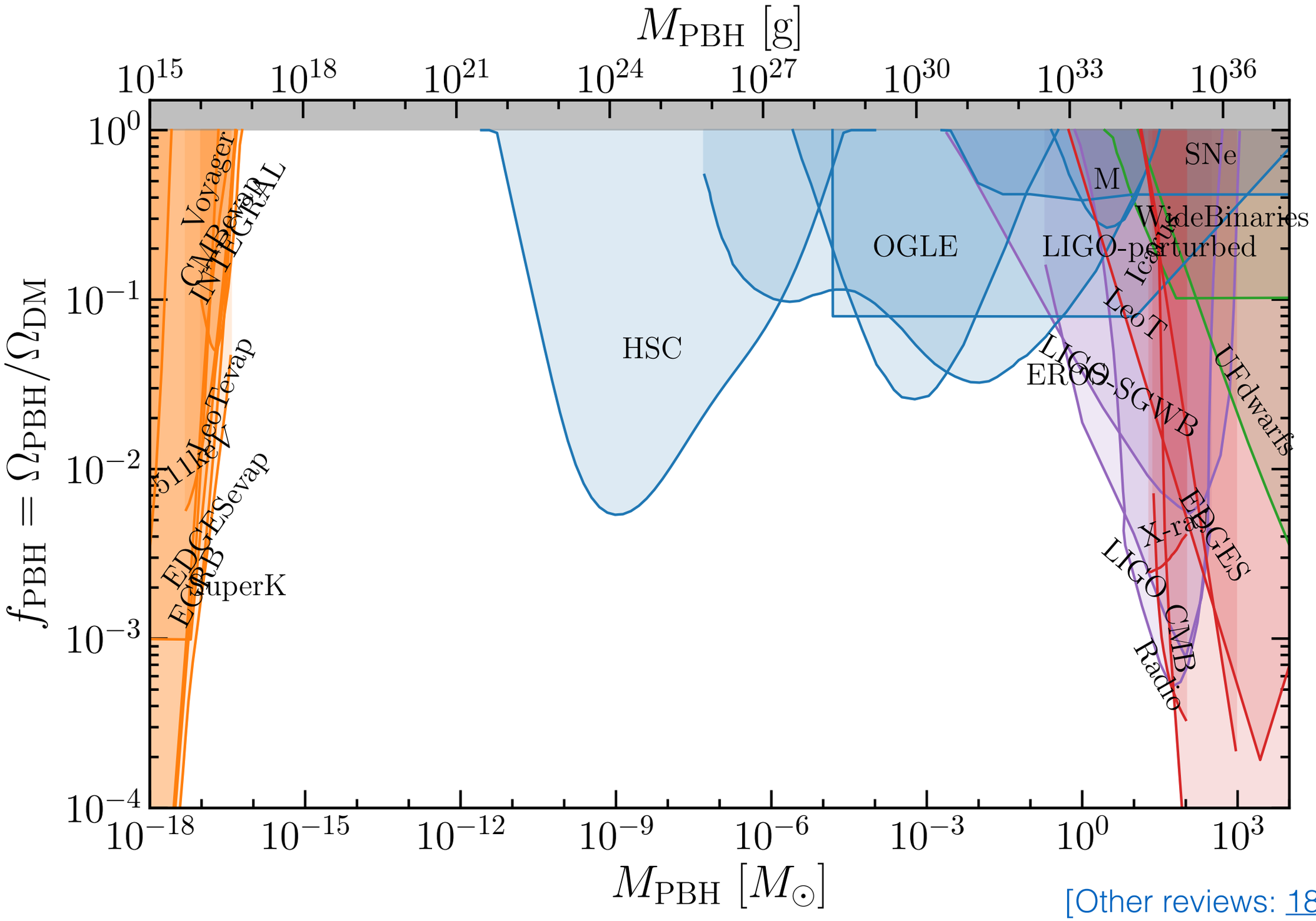
[Siraj & Loeb, 2103.04995]

Time for some new ideas…

PBH Constraints

[Green & **BJK**, 2007.10722]

[Code online: github.com/bradkav/PBHbounds]



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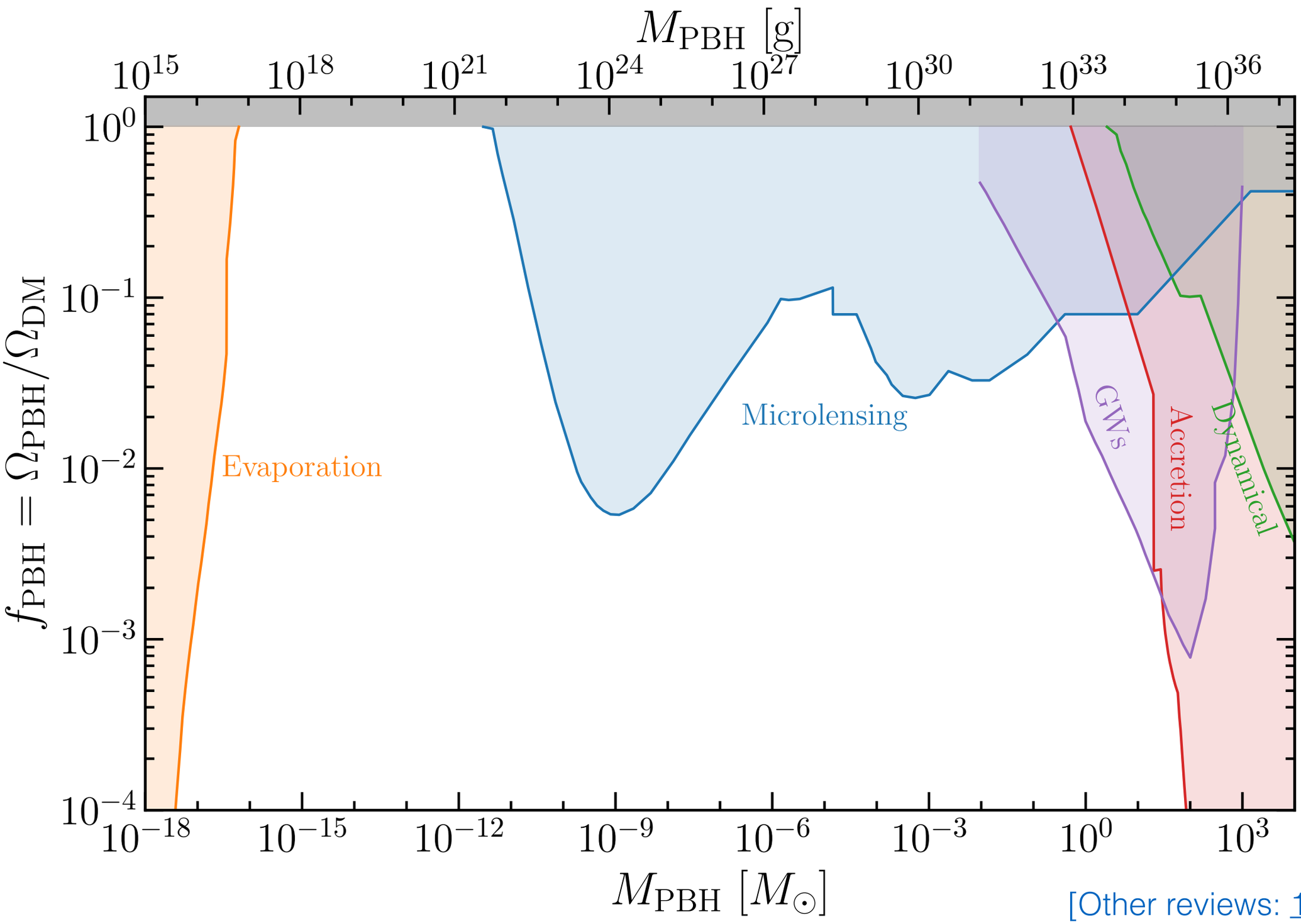

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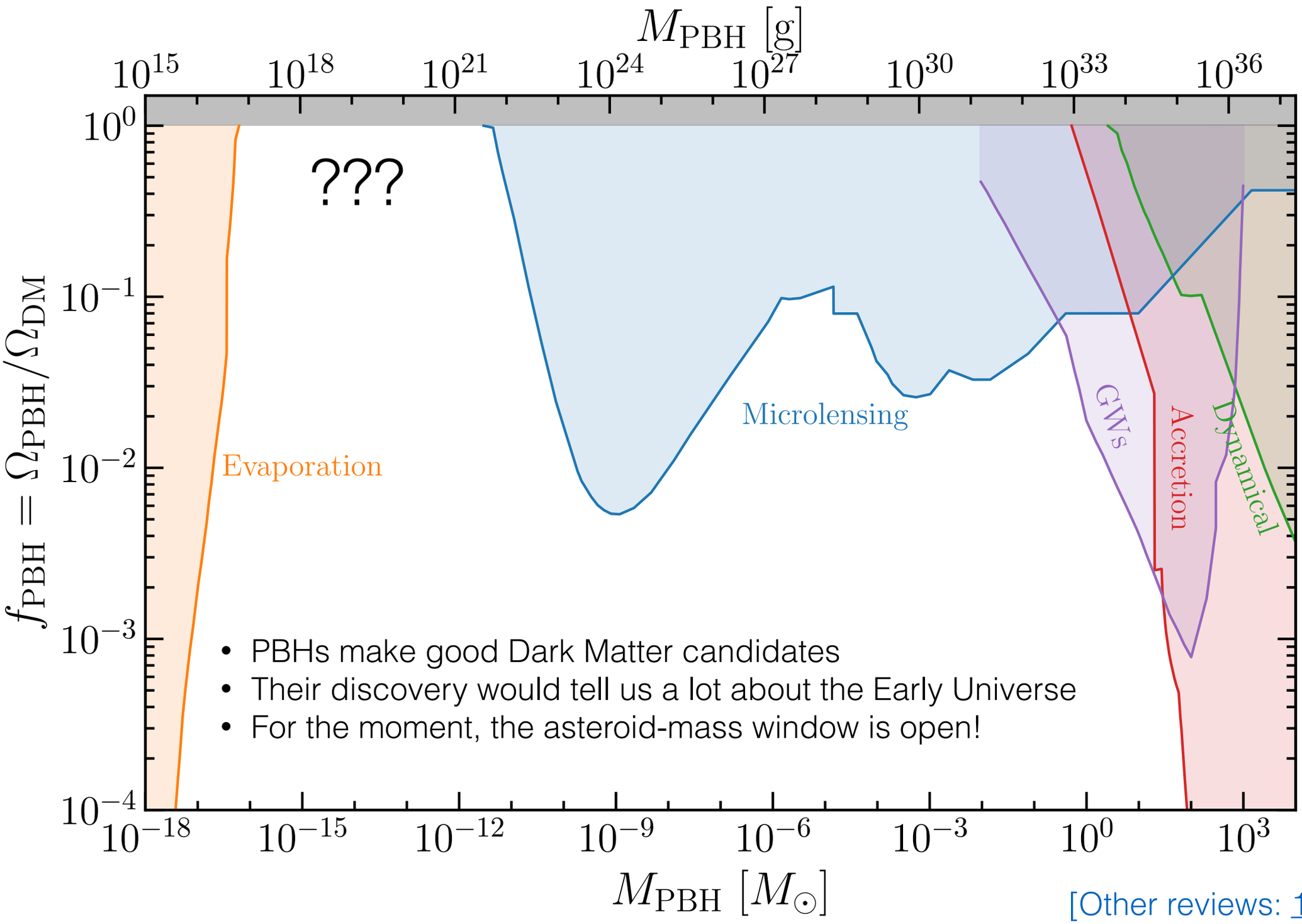

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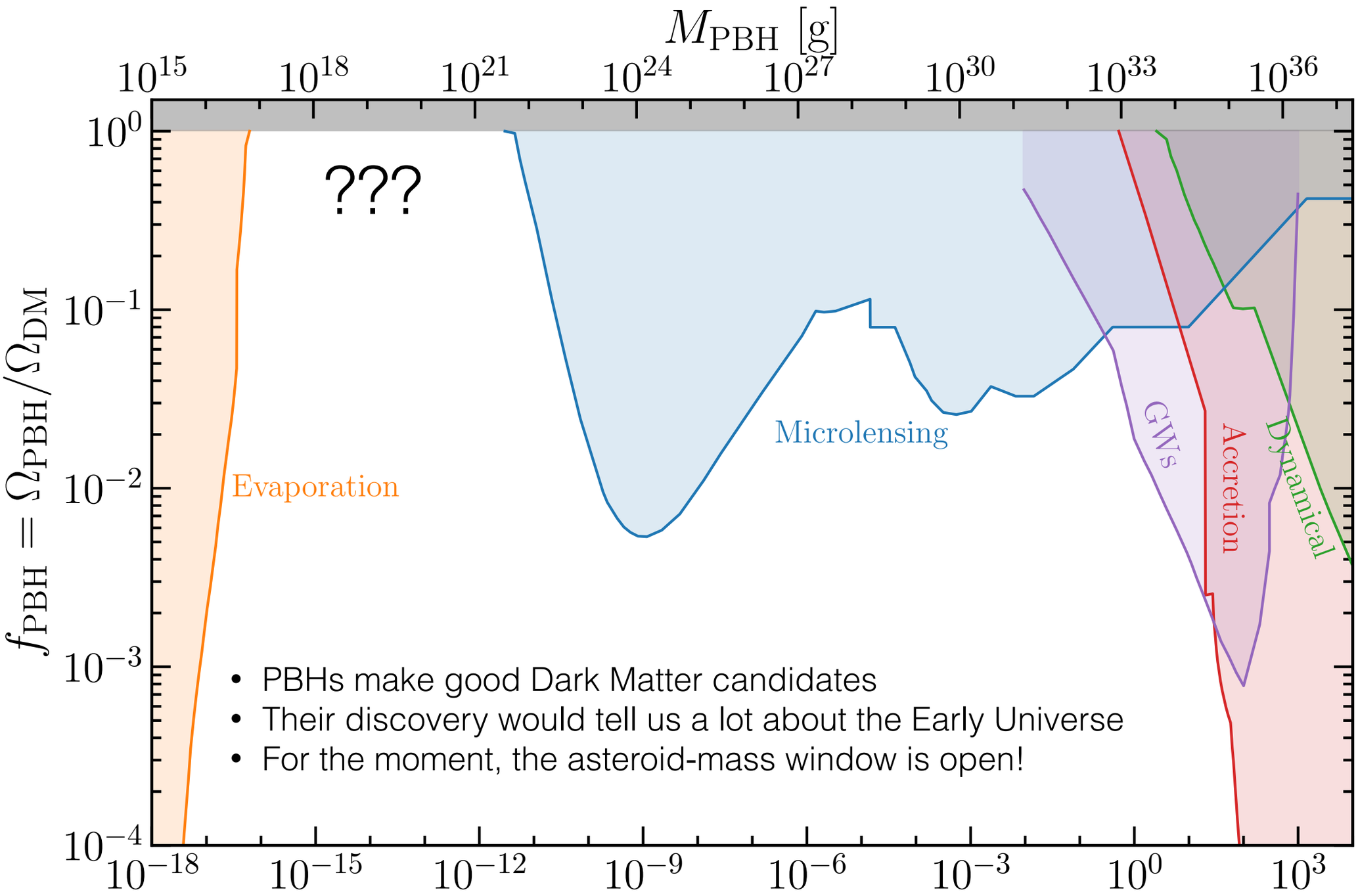


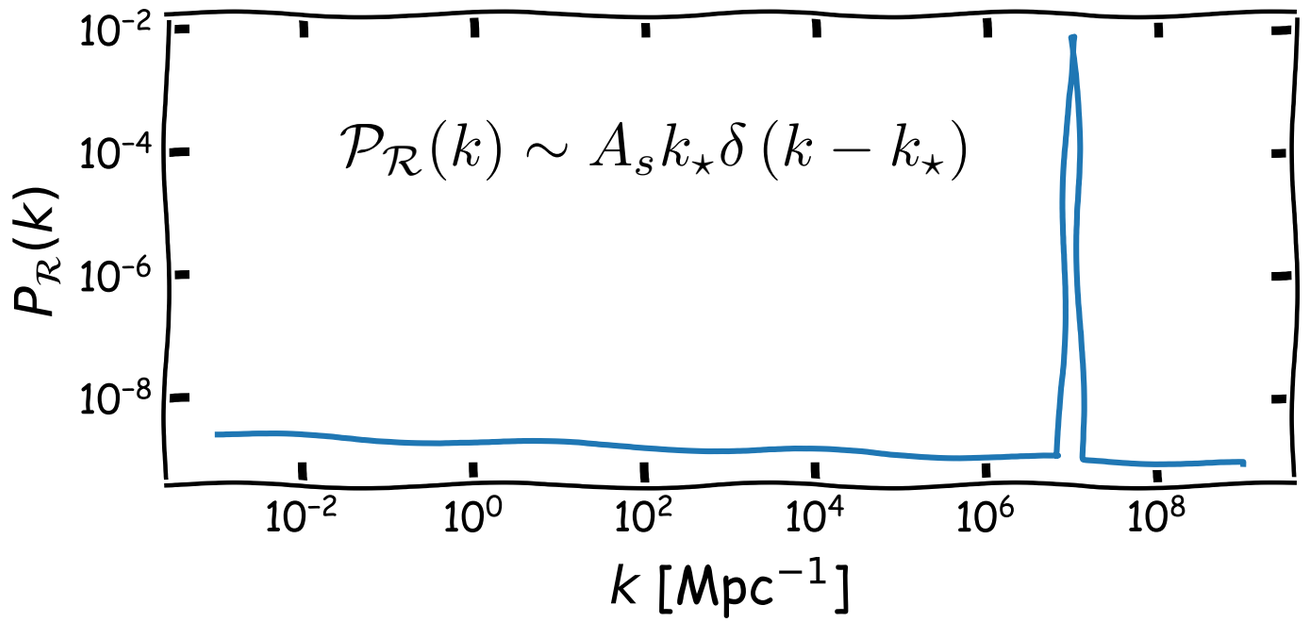
Thank you!

[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Backup Slides

GWs from PBH formation

PBHs may be formed from enhanced primordial scalar perturbations



At second order, these scalar perturbations can source tensor perturbations, leading to stochastic Gravitational waves

↓

Scalar-induced Gravitational Waves (**SIGWs**)

For perturbations on a scale $k_\star$, $\quad M_{\rm PBH} \simeq 1.4 \times 10^{13} M_\odot \left(\frac{k_\star}{\rm Mpc^{-1}}\right)^{-2}$

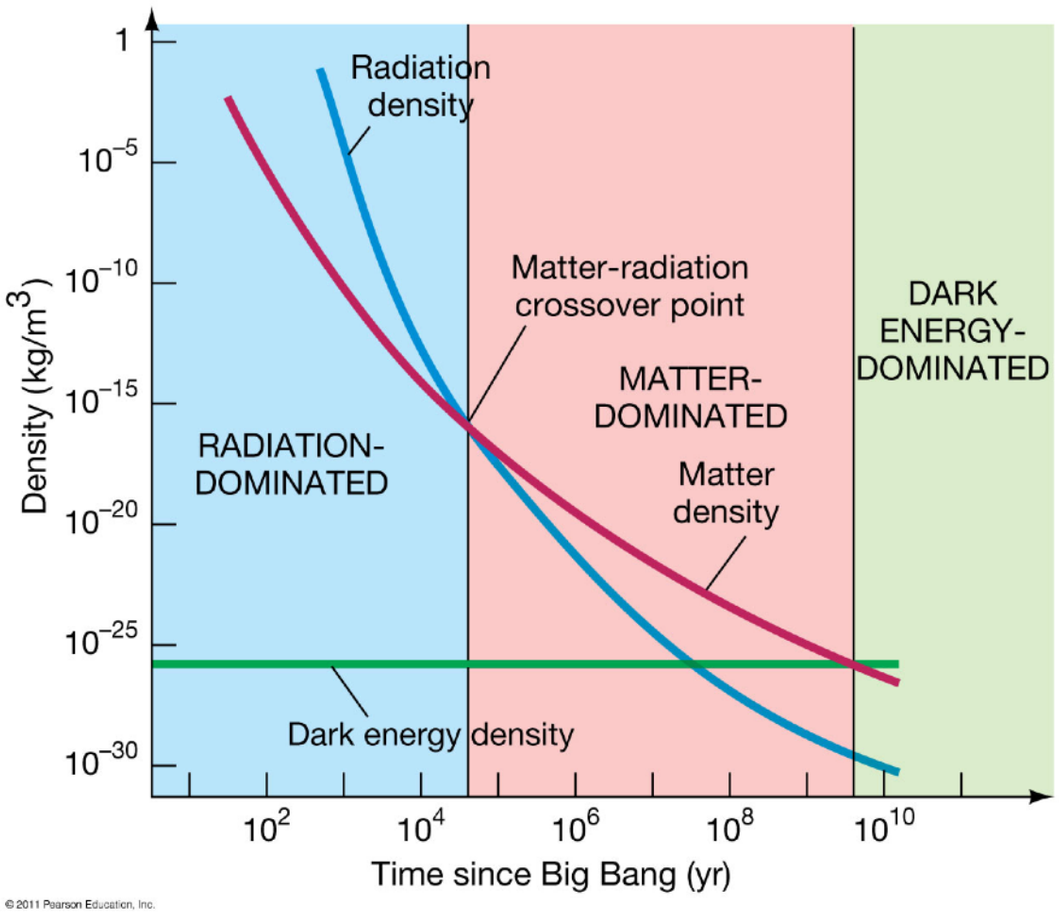
The typical GW frequency scales as $f_{\rm GW}^{\rm peak} \sim k_\star$, giving:

$$f_{\rm GW}^{\rm peak} = 3 \times 10^{-9} \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2} {\rm Hz}$$

[astro-ph/0407611, 0812.4339, 1012.4697] [See recent NanoGRAV results…]

Early Universe Binaries

If f ~ 1, the relative density of PBHs *equals* the background radiation density at matter-radiation equality. All PBHs form binaries…



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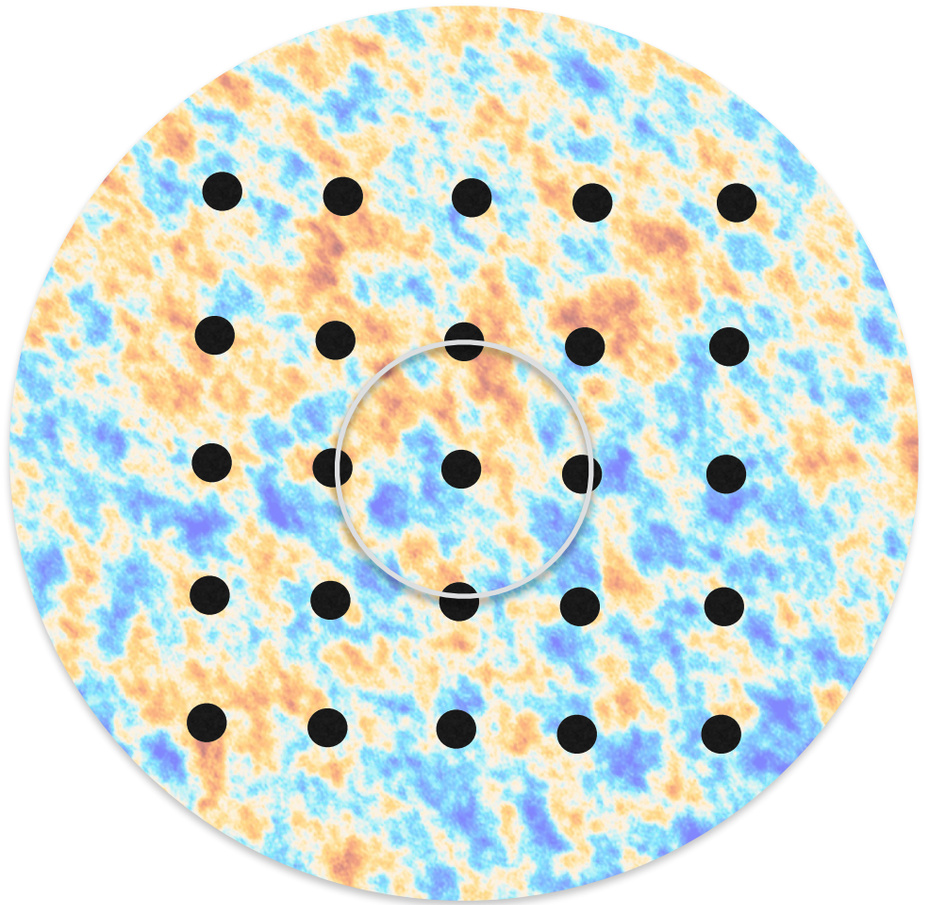

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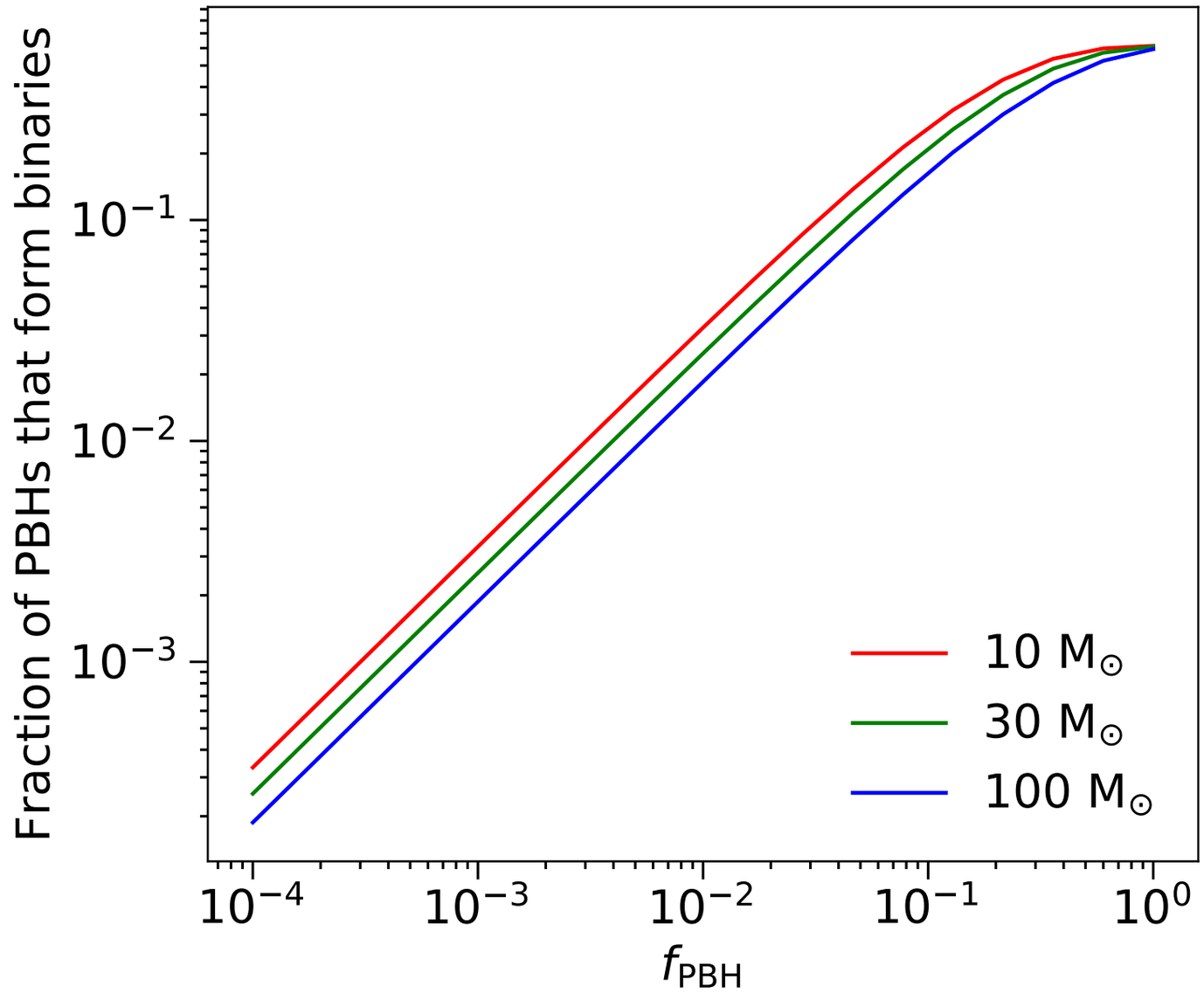


As f decreases, only ‘nearby’ pairs form binaries.

PBH Binary Population

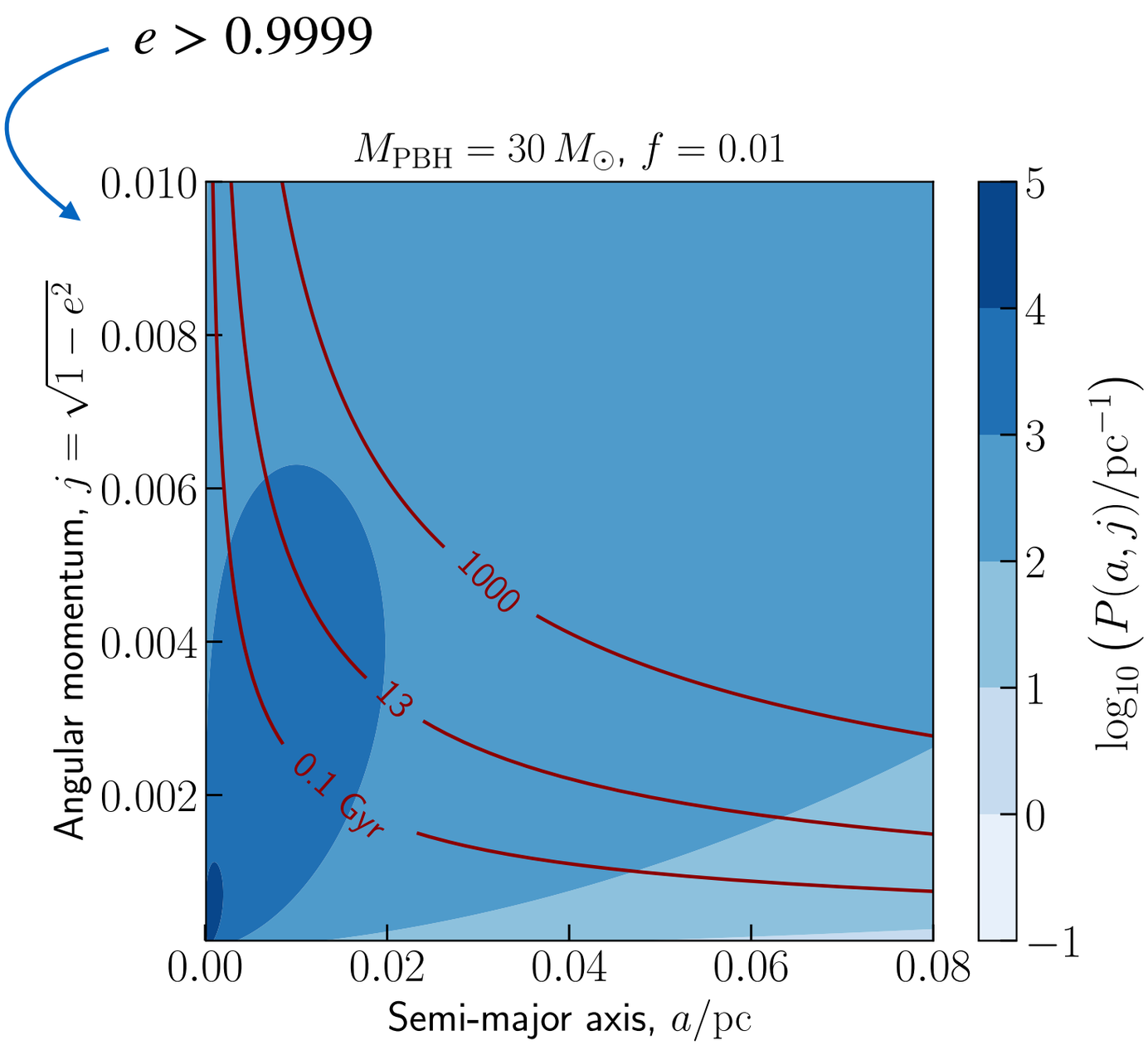
Randomly distributed (unclustered) PBHs

Angular momentum set by torques from smooth density perturbations and *all other PBHs*

Close, eccentric binaries merge today:

$$t_{\rm merge} = \frac{3\,c^5}{170\,G_N^3}\,\frac{a^4 j^7}{M_{\rm PBH}^3}$$

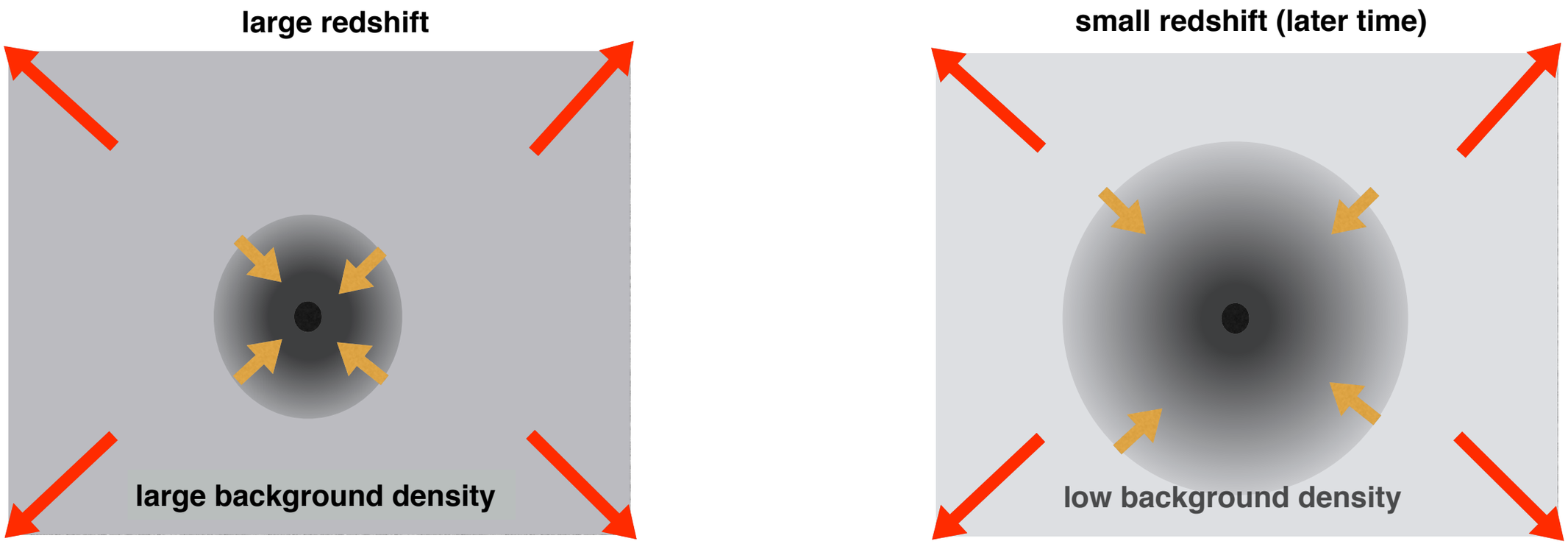
$$j = \sqrt{1-e^2}$$



[Ali-Haïmoud et al., 1709.06576, **BJK**, Gaggero & Bertone, 1805.09034]

Dark Dresses

PBHs seed the formation of `local' DM halos:



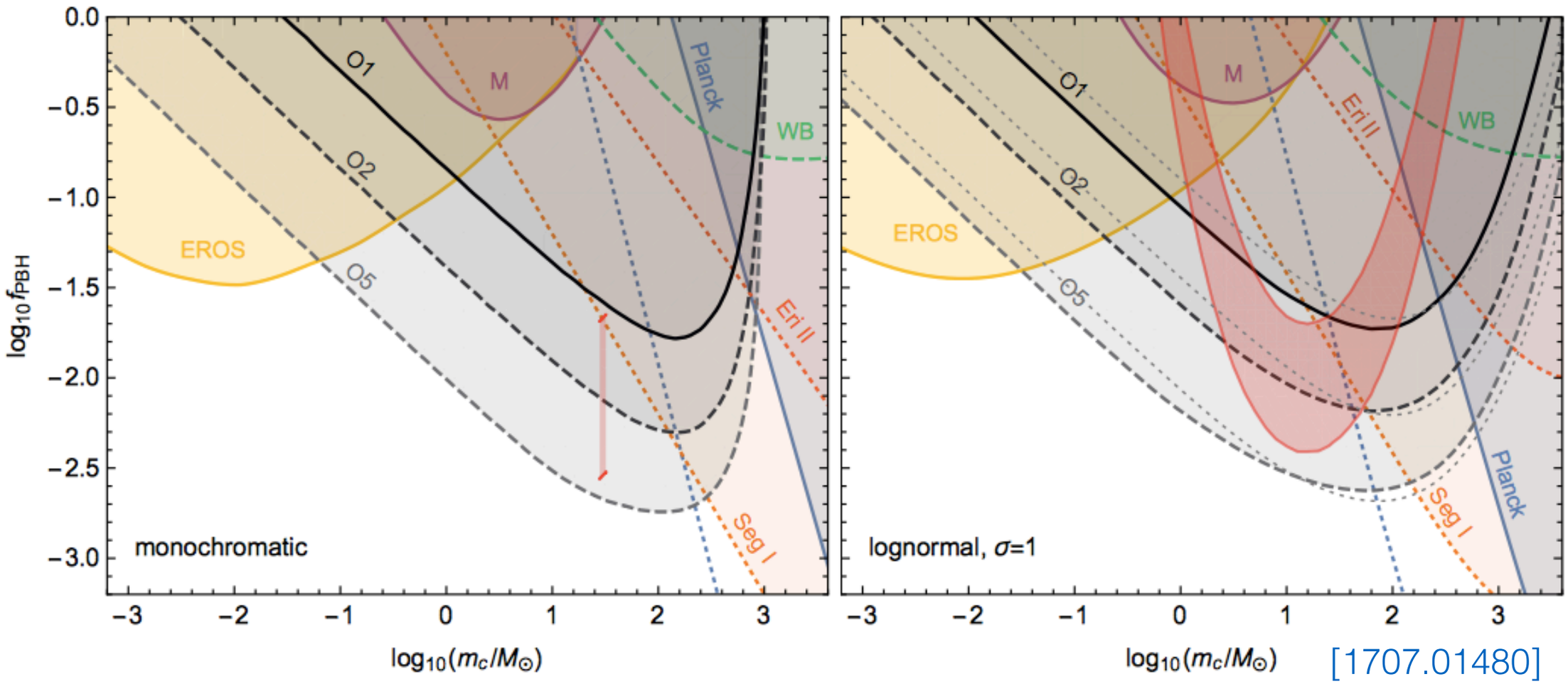
$$R_{\rm tr}(z) \,=\, 0.0063 \left(\frac{M_{\rm PBH}}{M_\odot}\right) \left(\frac{1+z_{\rm eq}}{1+z}\right) {\rm pc} \qquad\qquad \rho(r) \propto r^{-3/2}$$

By matter-radiation equality, $M_{\rm halo} \sim M_{\rm PBH}$

Slide shamelessly ripped off from Daniele Gaggero [astro-ph/0608642, 0706.0864,1712.05421]

Extended mass functions

LIGO O1 Limit



[1707.01480]

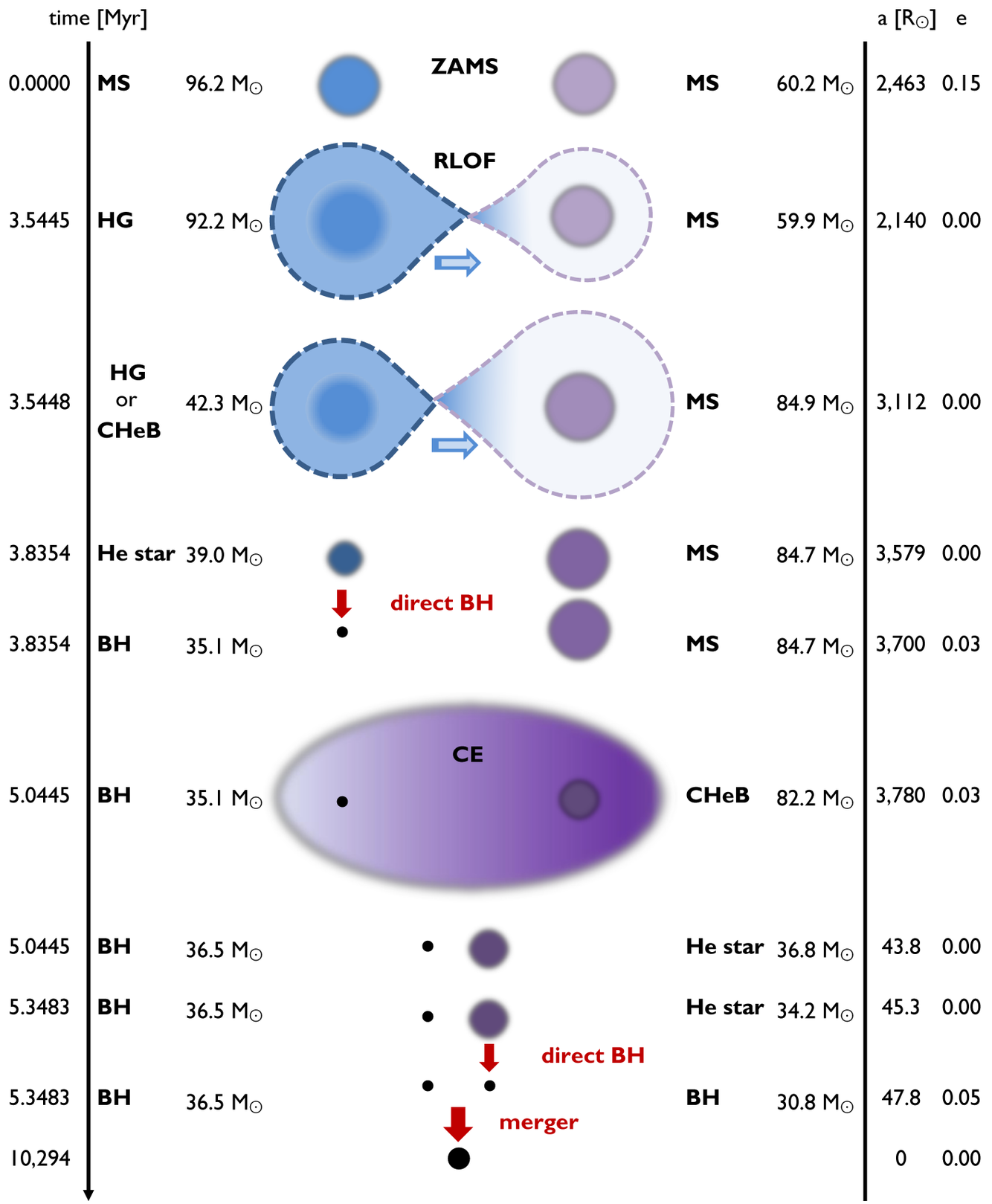
"Old" merger rate calculation *à la* Sasaki et al.,
but picture doesn't change too much…

[See also 1801.10327]

Astrophysical BH binaries

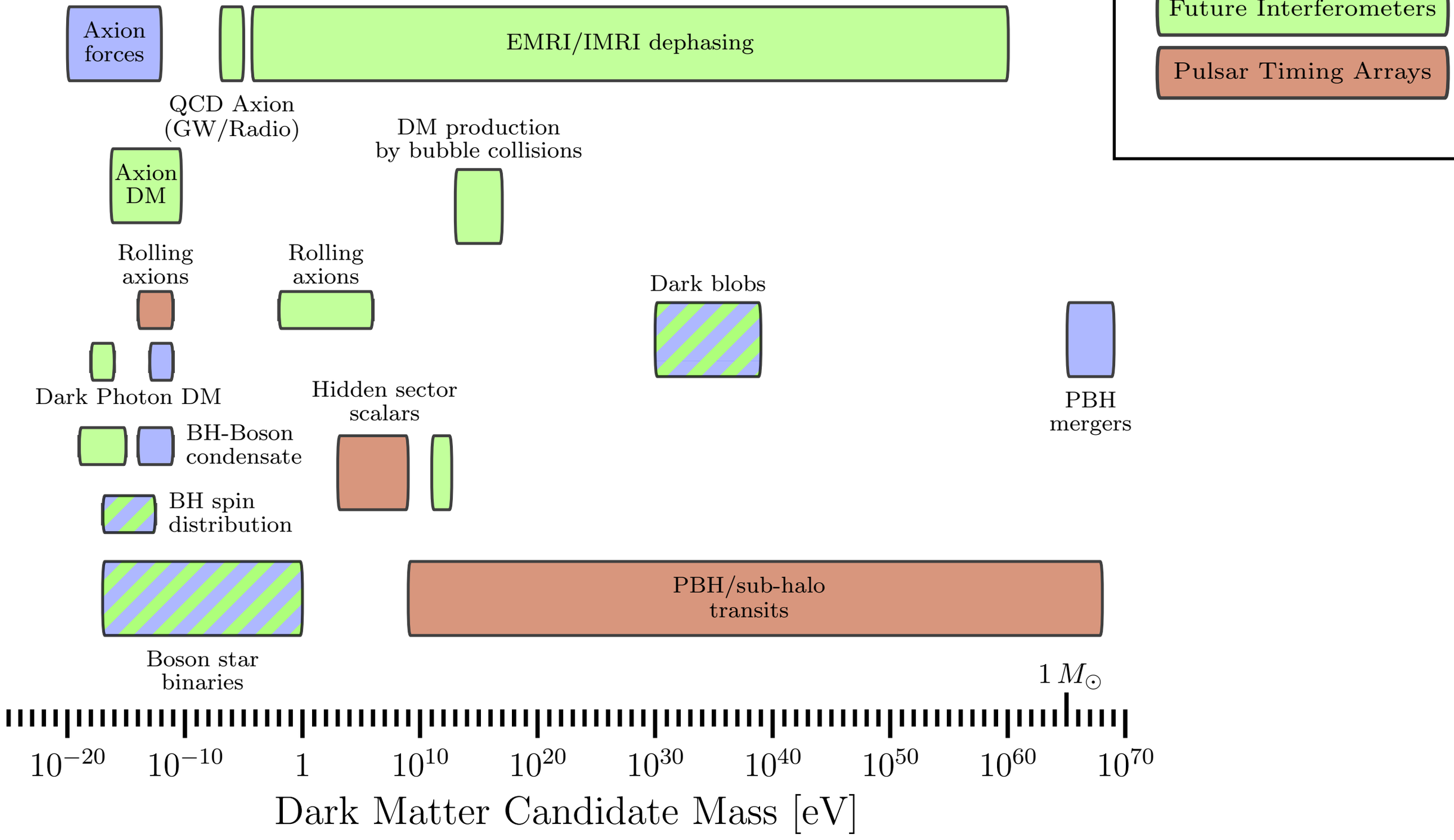
Astrophysical BH binaries could be formed dynamically, or through e.g. common envelope evolution:

[Banerjee, 1611.09357, LIGO-Virgo, 1602.03846, Elbert et al., 1703.02551, Stevenson et al., 1704.01352, and many others…]



[1602.04531]

GW Probes of DM



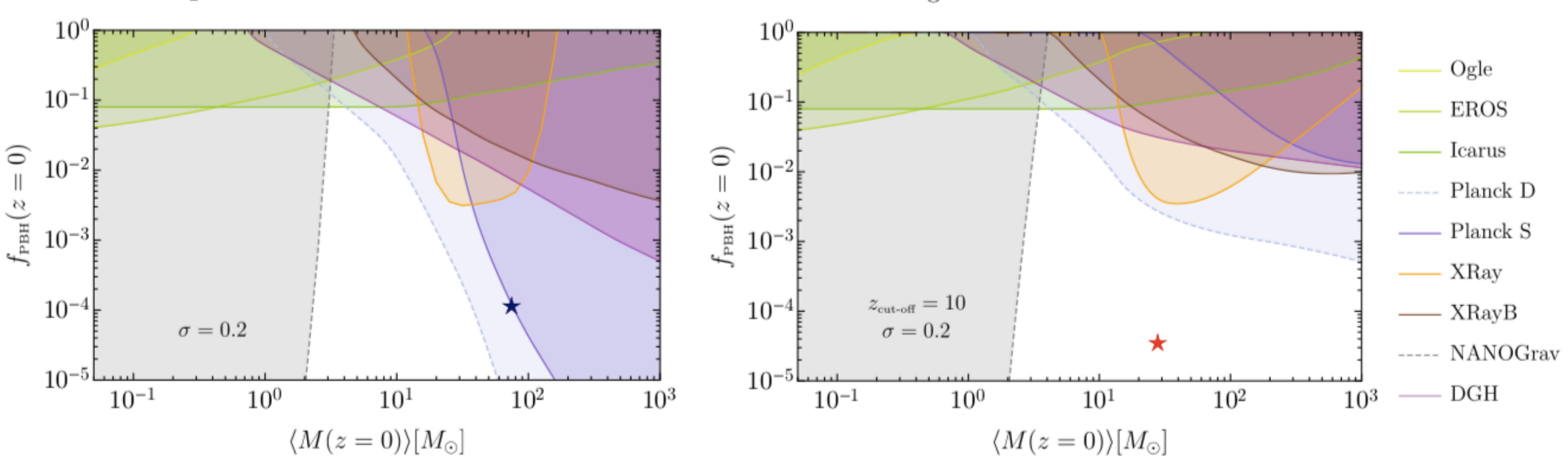
[Bertone, Croon, Amin, Boddy, **BJK**, Mack, Natarajan, Opferkuch, Schutz, Takhistov, Weniger, Yu, SciPost Phys. Core 3, 007 (2020), 1907.10610]

GW190521

TABLE I. Parameters of GW190521 according to the NRSur7dq4 waveform model. We quote median values with 90% credible intervals that include statistical errors.

Parameter	
Primary mass	$85^{+21}_{-14}\ M_\odot$
Secondary mass	$66^{+17}_{-18}\ M_\odot$
Primary spin magnitude	$0.69^{+0.27}_{-0.62}$
Secondary spin magnitude	$0.73^{+0.24}_{-0.64}$
Total mass	$150^{+29}_{-17}\ M_\odot$

[LVC (GW190521), arXiv:2009.01075]

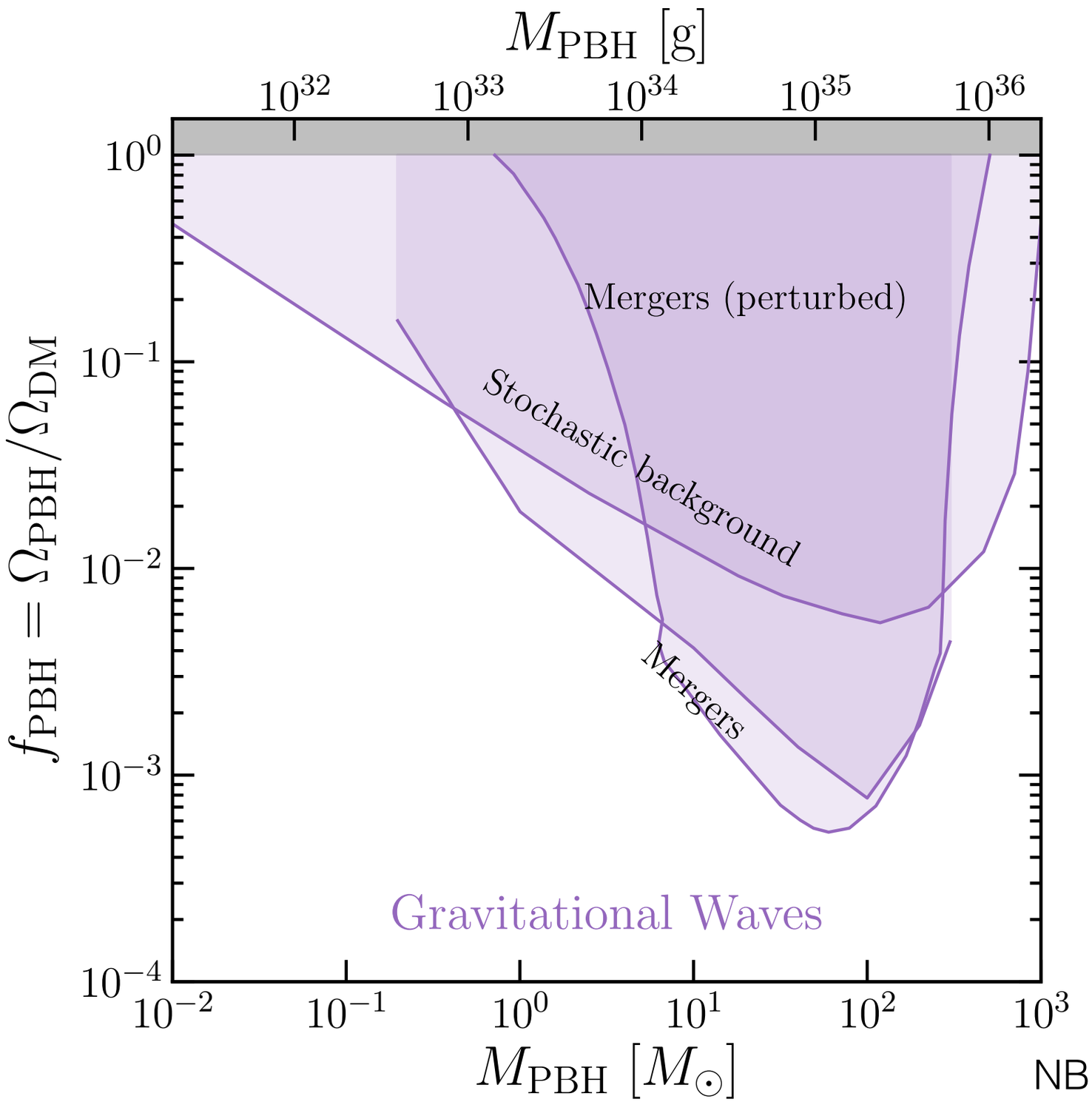


[De Luca et al., arXiv:2009.01728]

GW Bounds

[Green & **BJK**, 2007.10722]

[Code online: github.com/bradkav/PBHbounds]



NB: very conservative and constantly changing!

Inflation and PBHs

A simple model would be a ‘plateau’ in the inflaton potential:

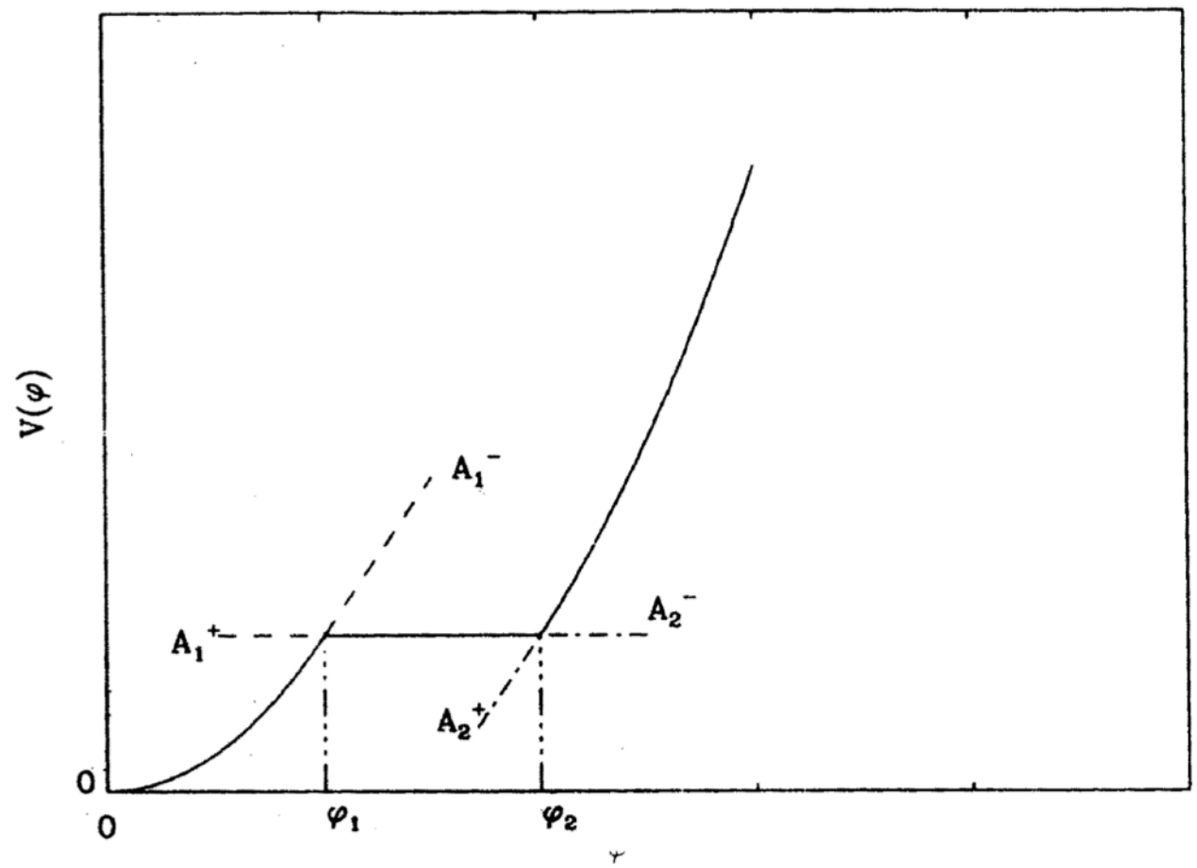


FIG. 1. Schematic representation of the potential $V(\varphi)$ of the scalar field φ (inflaton). The potential has a plateau in the range $\varphi_1 < \varphi < \varphi_2$ and is of the power-law type outside of this range. The breaks of the potential are smoothed out in small ranges $\Delta\varphi_1 \ll \varphi_1$ and $\Delta\varphi_2 \ll \varphi_2$ around φ_1 and φ_2 correspondingly.

[Ivanov et al., PRD (1994)]