



Constantly changing constraints on
Primordial Black Hole Dark Matter

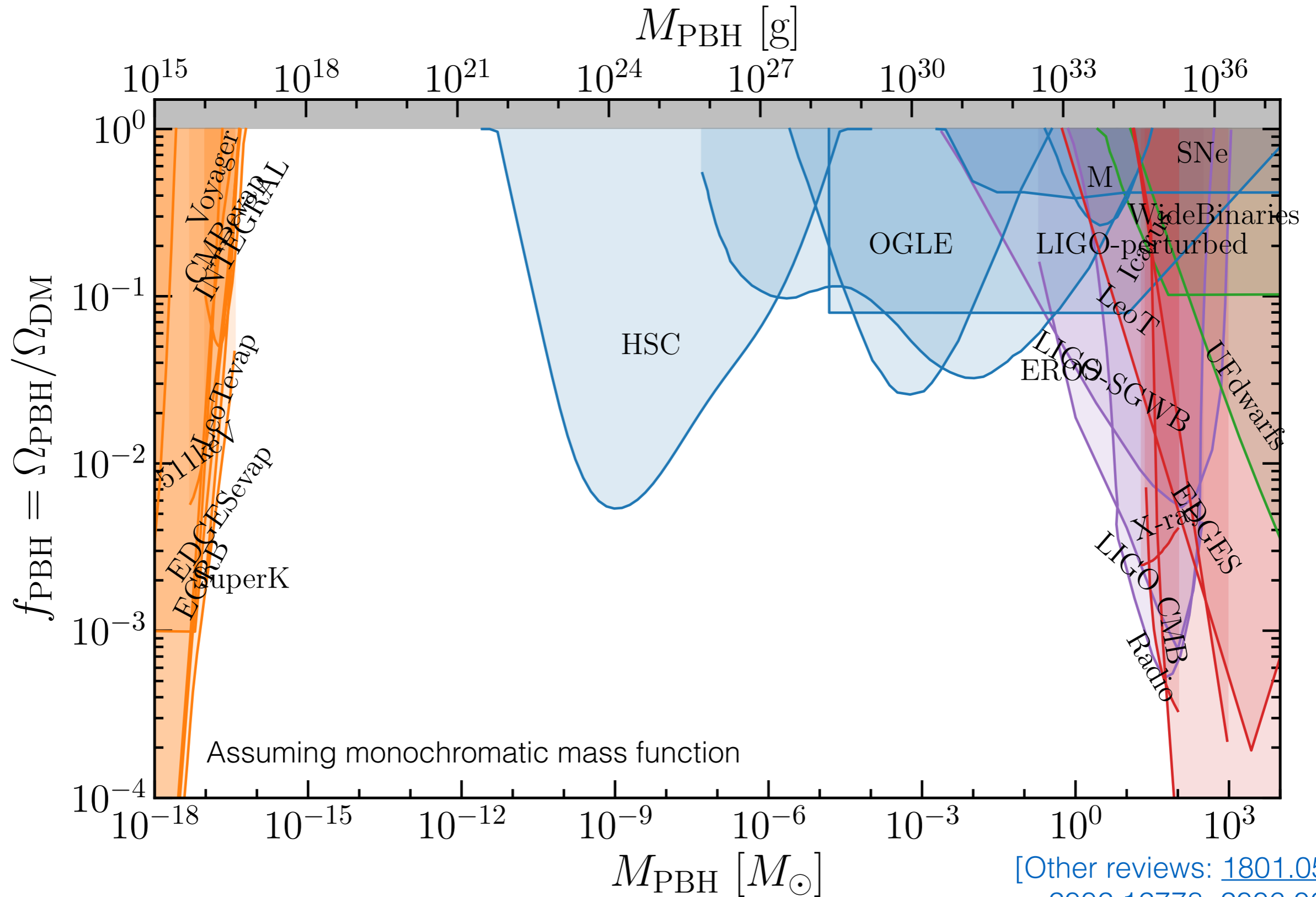
Bradley J Kavanagh
Instituto de Física de Cantabria (IFCA)
CSIC-Universidad de Cantabria, Spain

IRN@Zoom, 5th November 2020

PBH bounds

[Green & **BJK**, [1709.06576](#)]

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

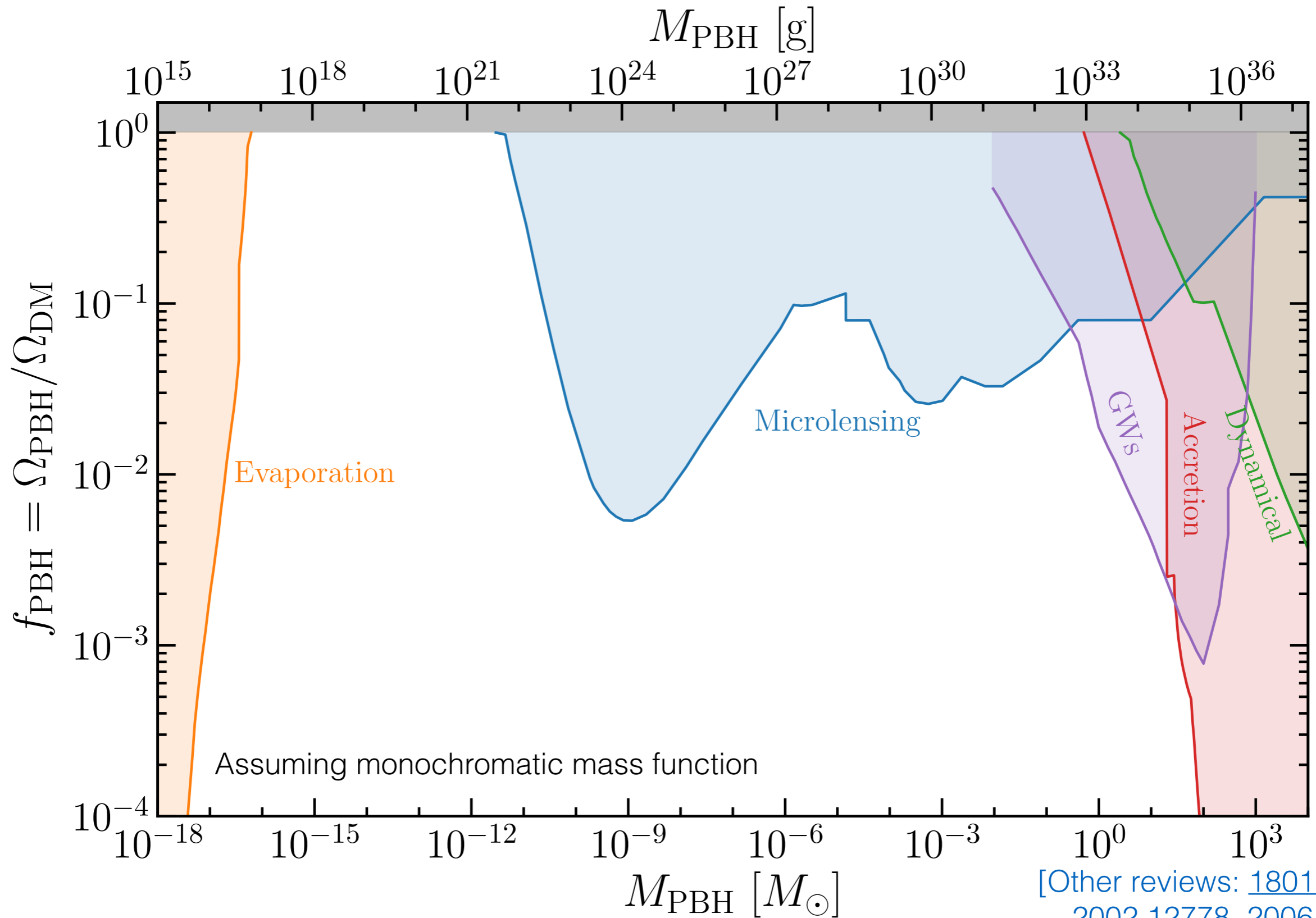


[Other reviews: [1801.05235](#),
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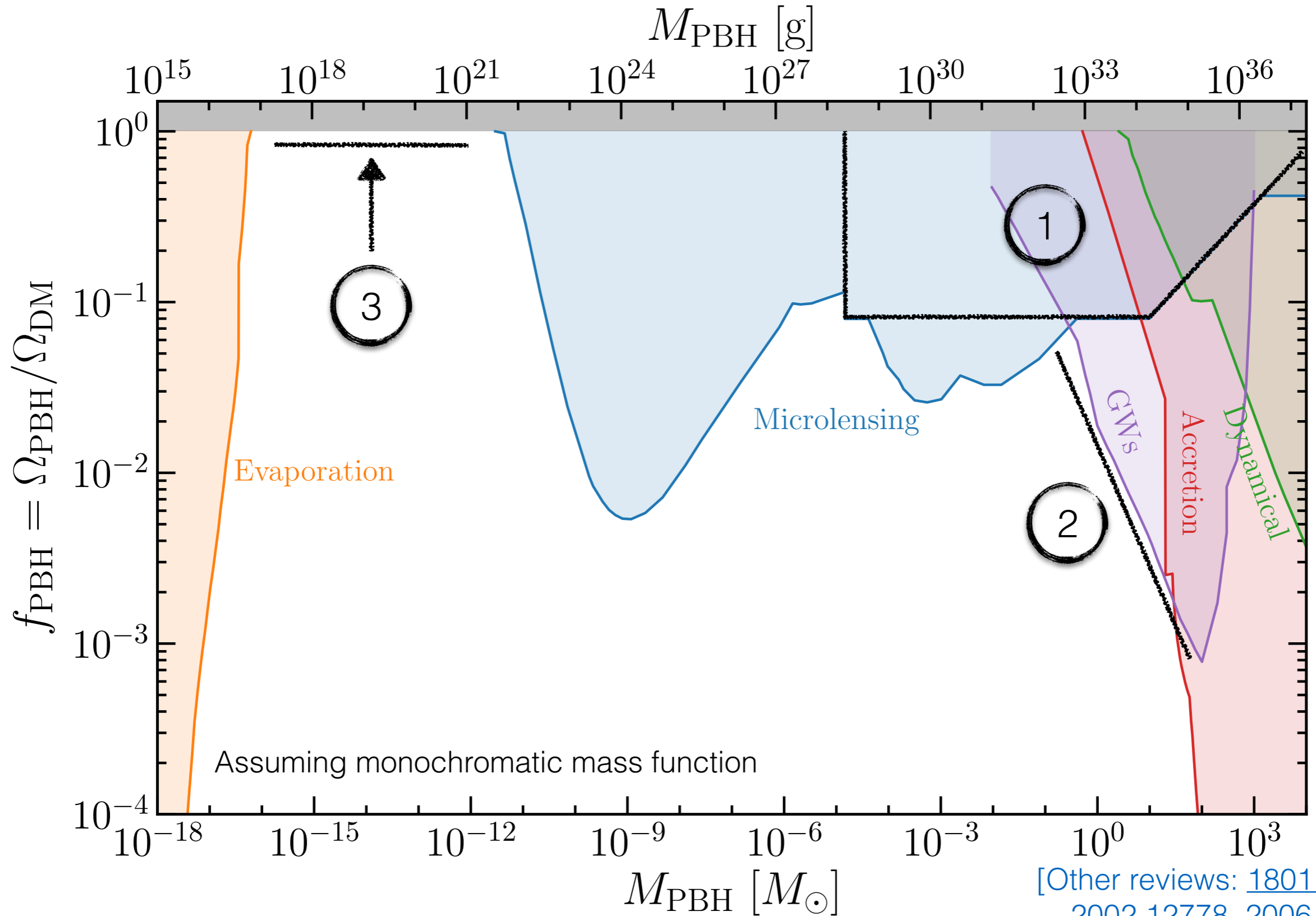


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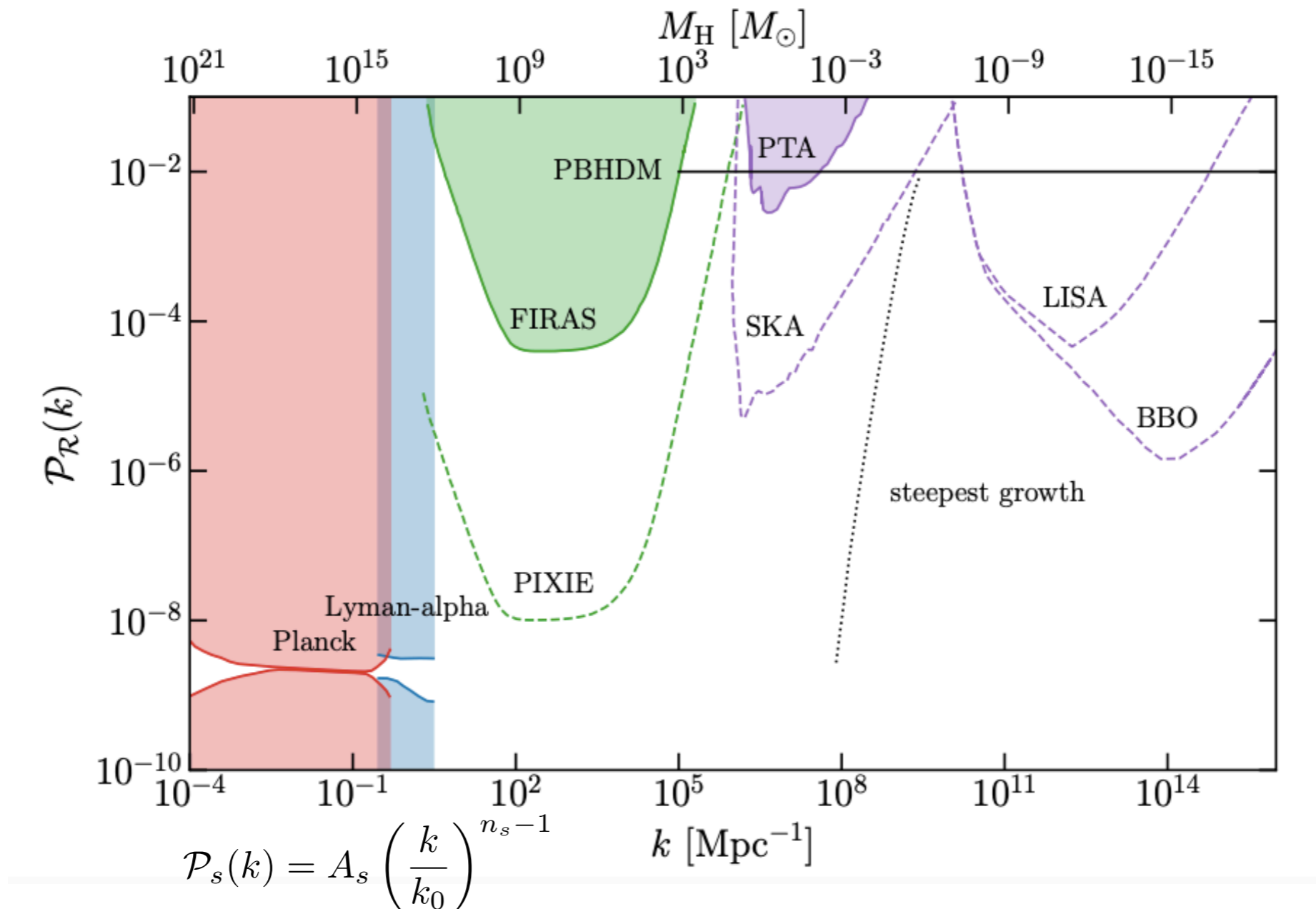
[Green & **BJK**, [1709.06576](#)]

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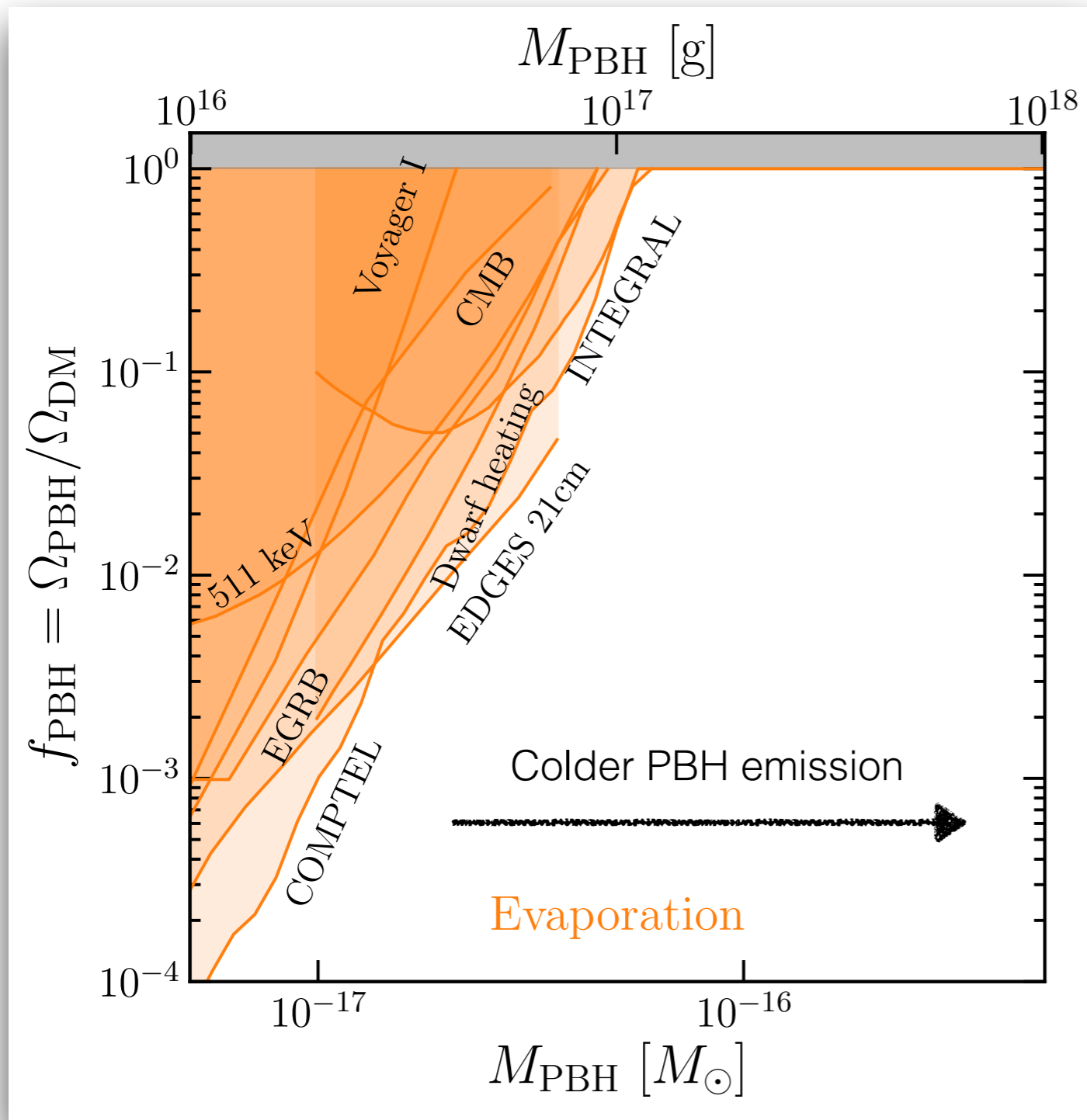
[Other reviews: [1801.05235](#), [2002.12778](#), [2006.02838](#)]

PBHs may form out of large primordial fluctuations on small scales
(among other things)...



...but we'll focus on *direct* observational constraints.

Evaporation



$$T_H = (4\pi G_N M_{\text{PBH}})^{-1}$$

$$\simeq 1 \text{ MeV} \left(\frac{10^{16} \text{ g}}{M_{\text{PBH}}} \right)$$

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

Many interesting constraints from 'old' experiments, e.g.

Voyager I

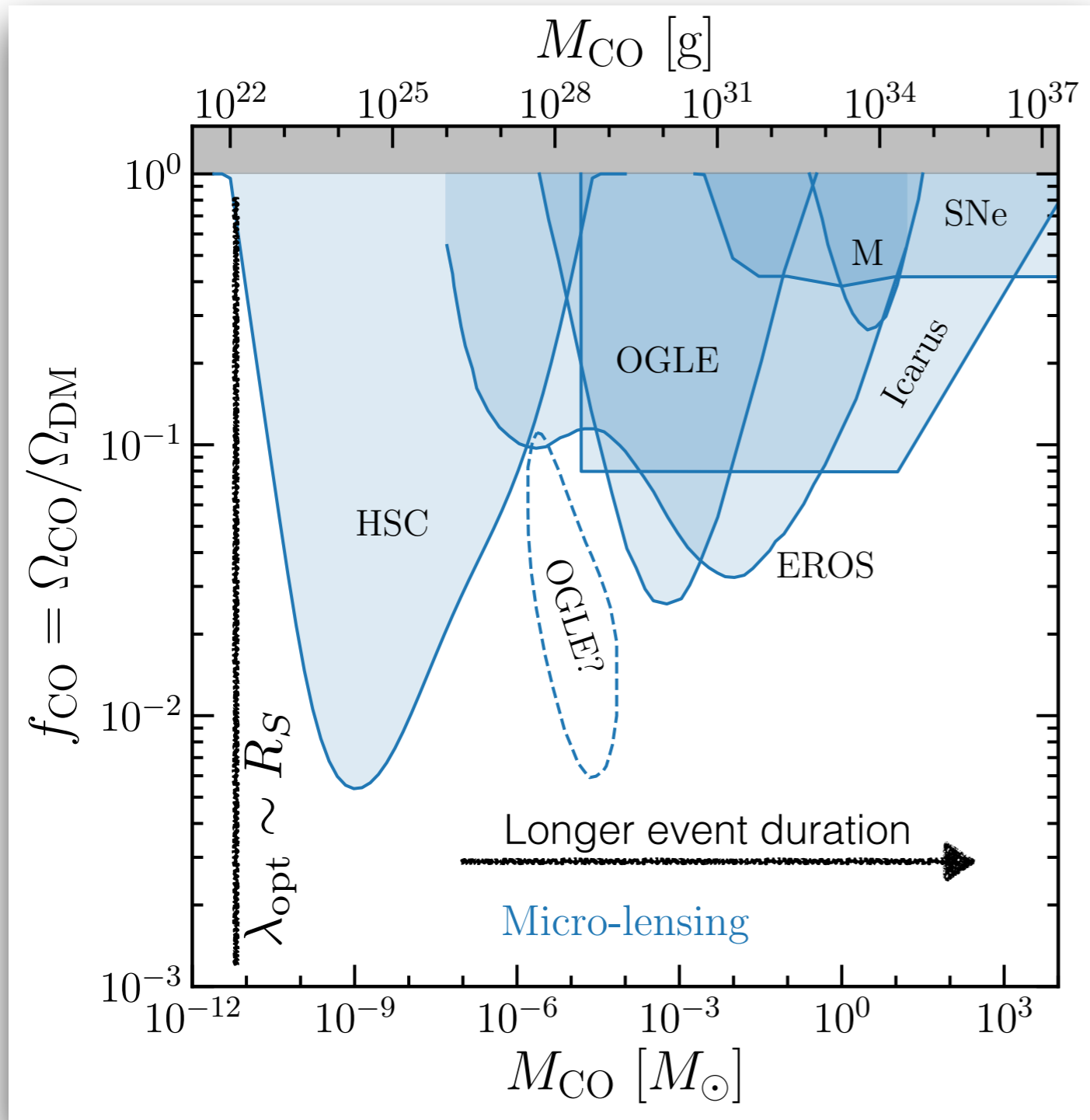
[Boudaud & Cirelli, [1807.03075](#)]

COMPTEL

[Coogan et al., [2010.04797](#)]

Micro-lensing

$$t_E \simeq 44 \text{ days} \left(\frac{M}{M_\odot} \right)^{1/2} \left(\frac{d_L d_{LS} / d_S}{4 \text{ kpc}} \right)^{1/2}$$



Recently updated at the
low mass end

[Smyth et al., [1910.01285](#),
Croon et al., [2007.12697](#)]

Hint from 6 ultra-short events?
($t \sim 0.1\text{-}0.3$ days)

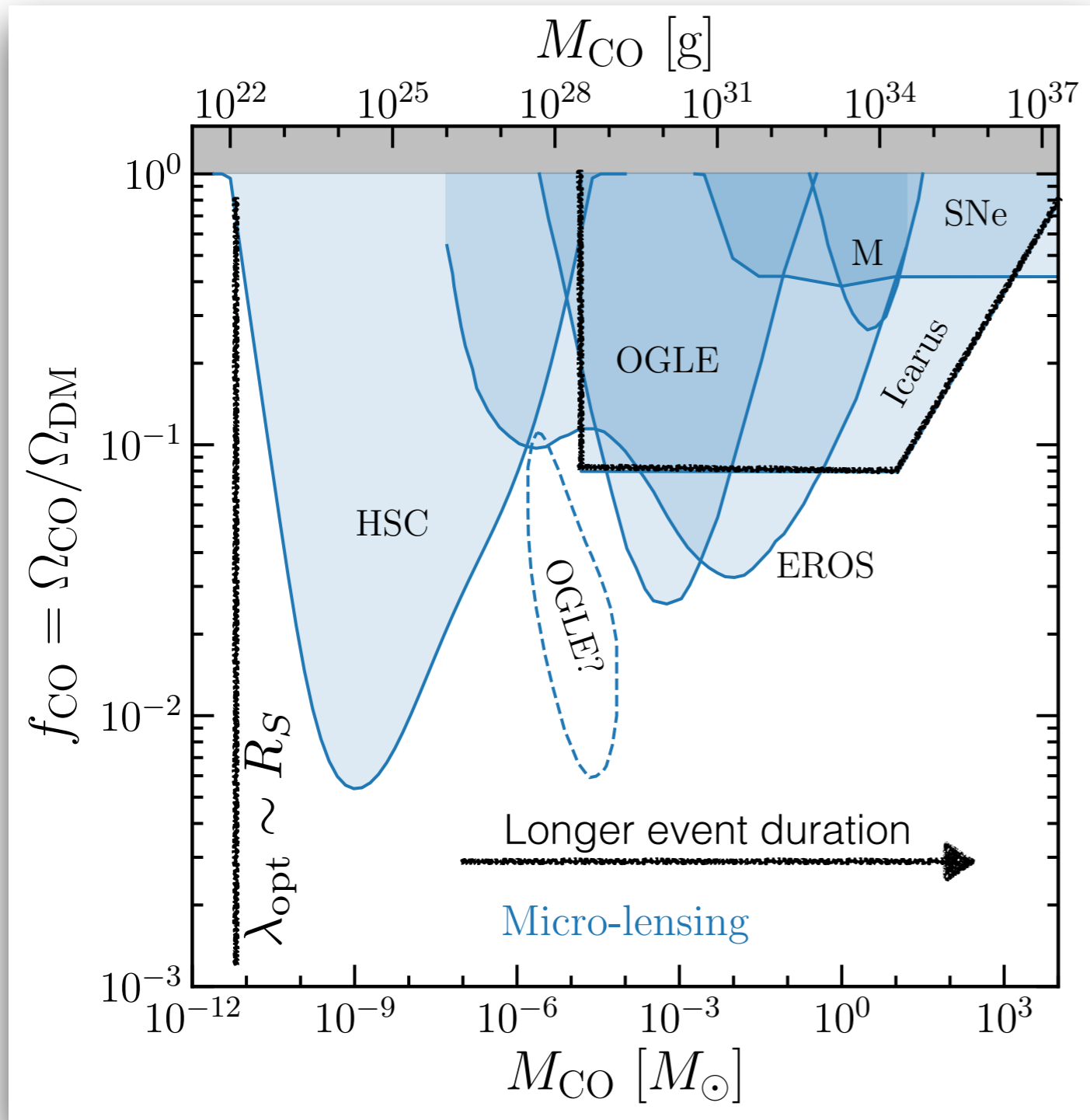
[OGLE, [1901.07120](#)]

ICARUS! A star at $z \sim 1.5$

[Kelly et al., [1706.10279](#),
Oguri et al., [1710.00148](#)]

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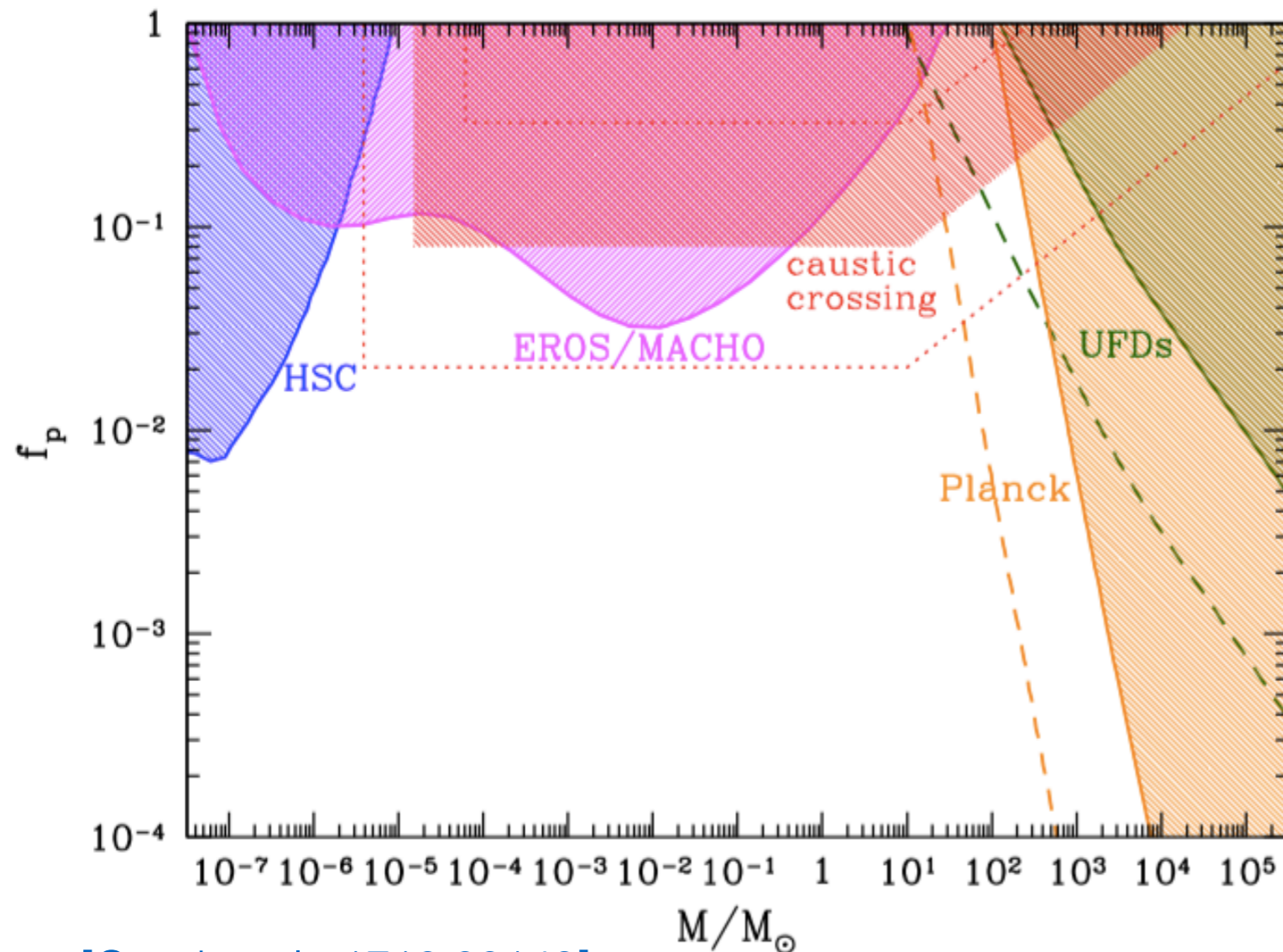
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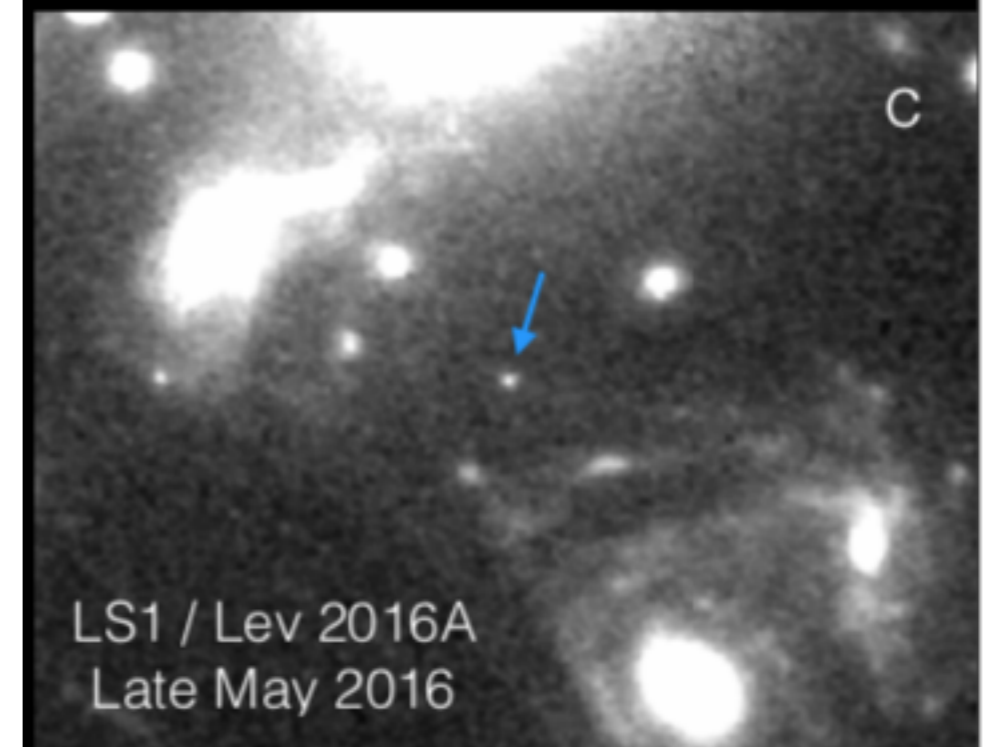
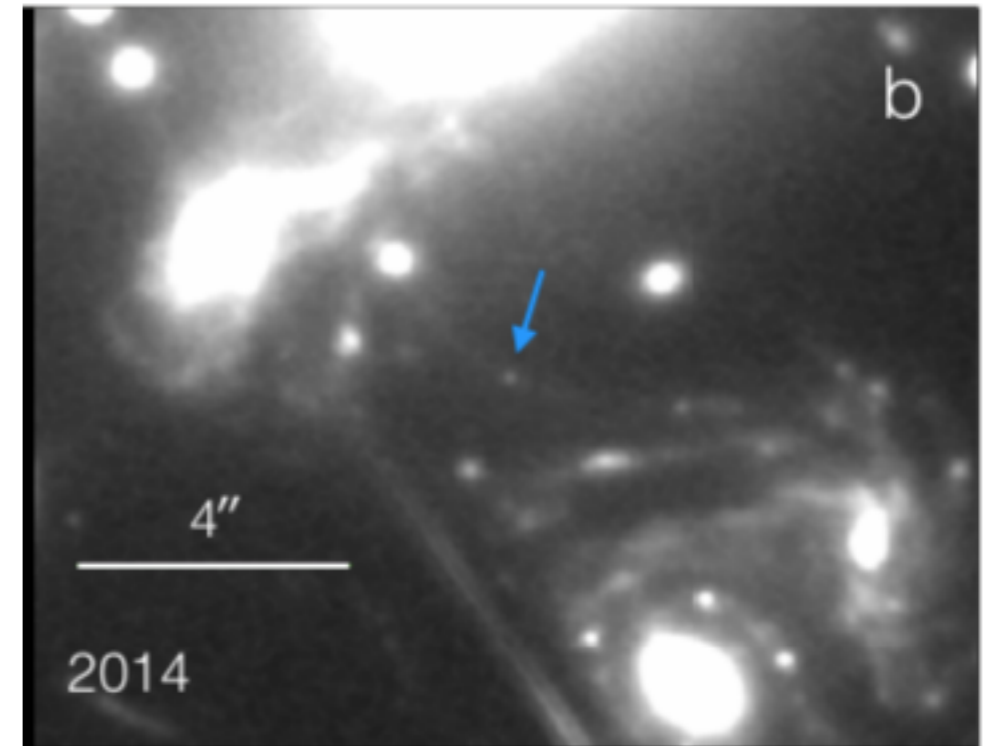
Icarus

Star at $z \sim 1.49$, magnified by $>2000\times$

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



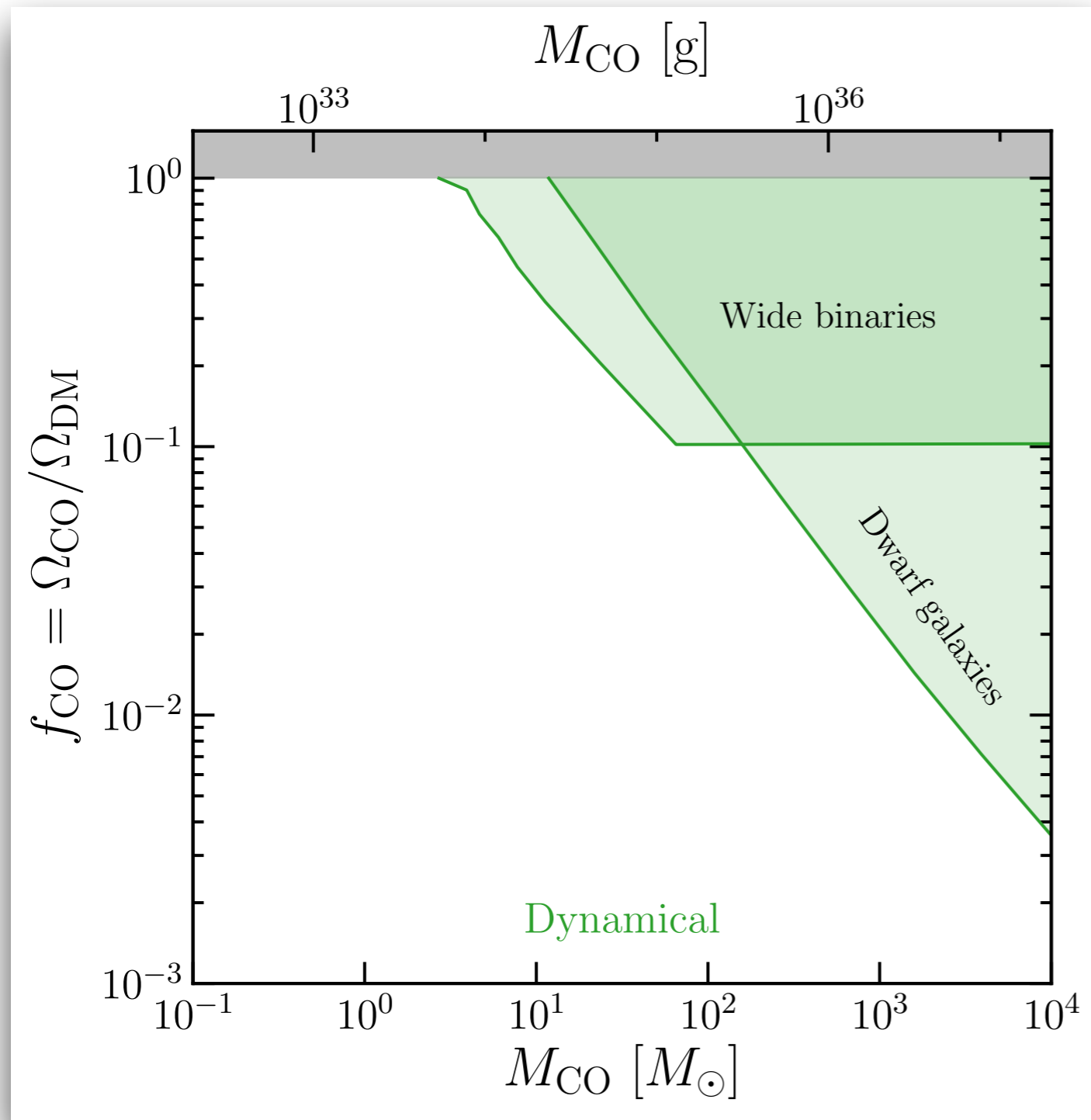
[Oguri et al., [1710.00148](#)]



[Kelly et al., [1706.10279](#)]

Dynamical constraints

Heavy PBHs can ‘inject’ energy and disrupt bound systems



Wide binary constraints should improve with *Gaia*

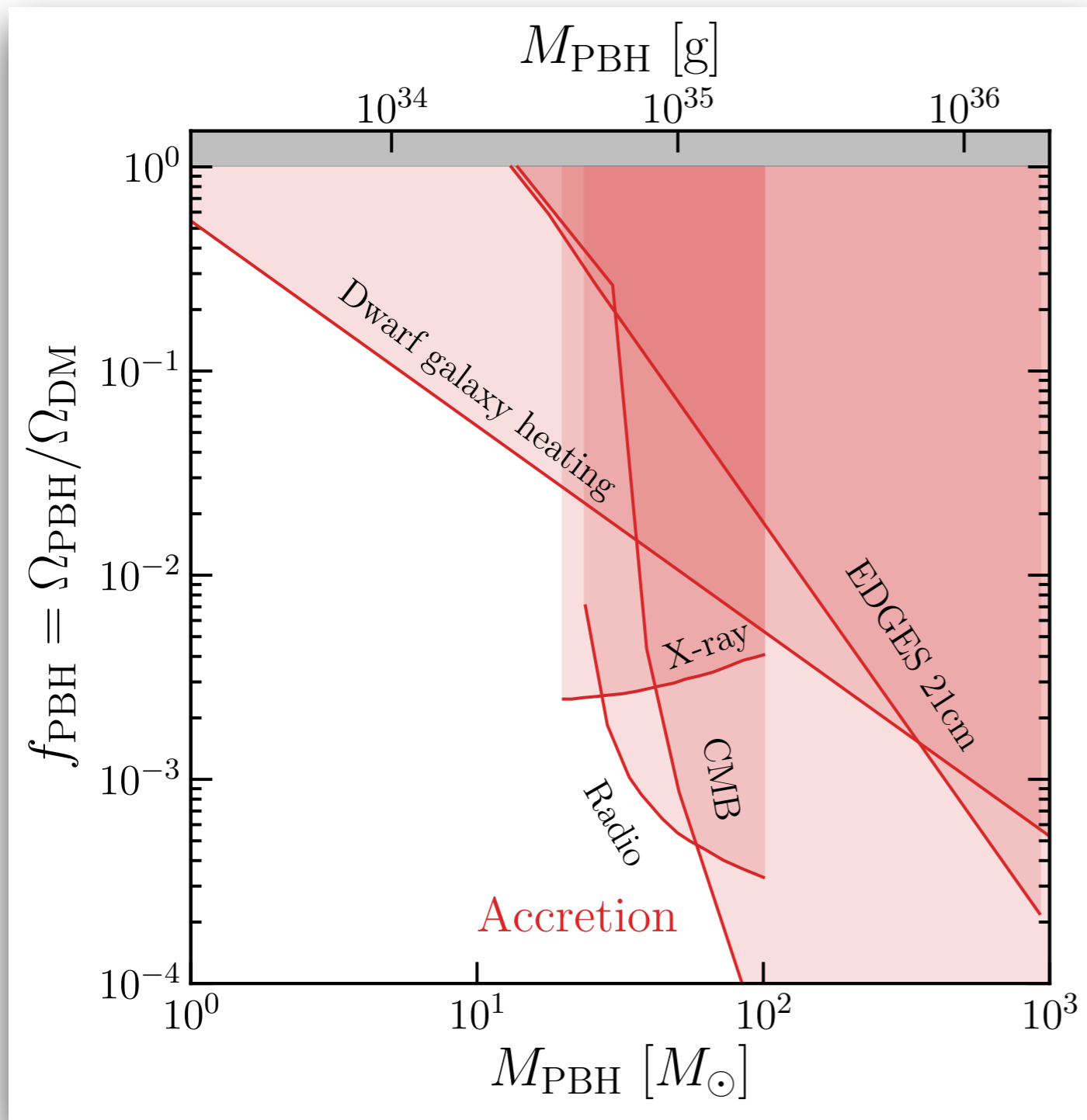
[Price-Whelan, Oh & Spergel, [1709.03532](#)]

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

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

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)

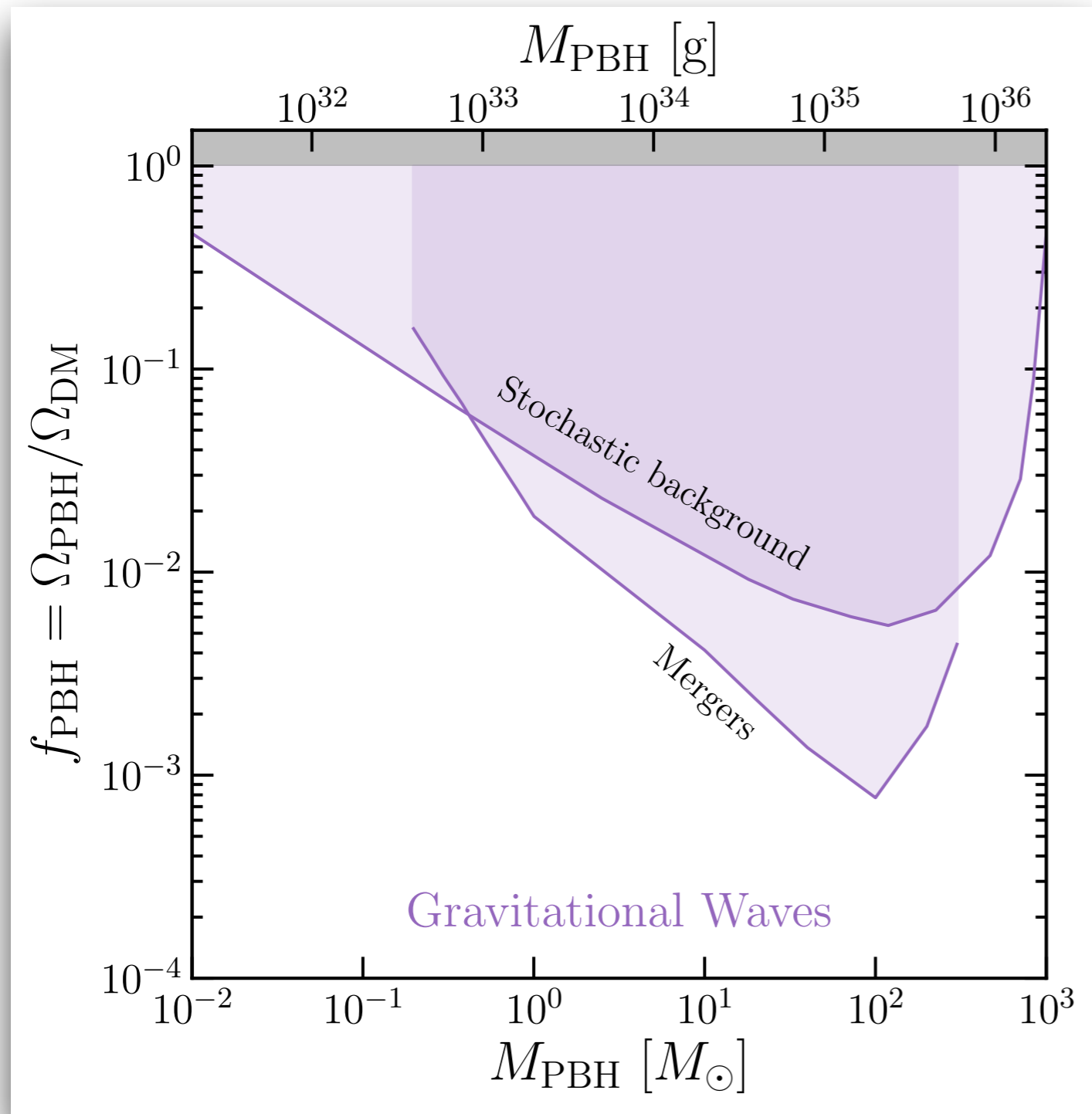
[Serpico et al., [2002.10771](#)]

New bounds from gas heating in Leo T dwarf

[Lu et al., [2007.02213](#)]

Gravitational Waves

Constrain individual PBH mergers
and stochastic background



PBH binaries may form in the
late Universe...

[Bird et al., [1603.00464](#)]

...but dominate rate comes from
early Universe binaries...

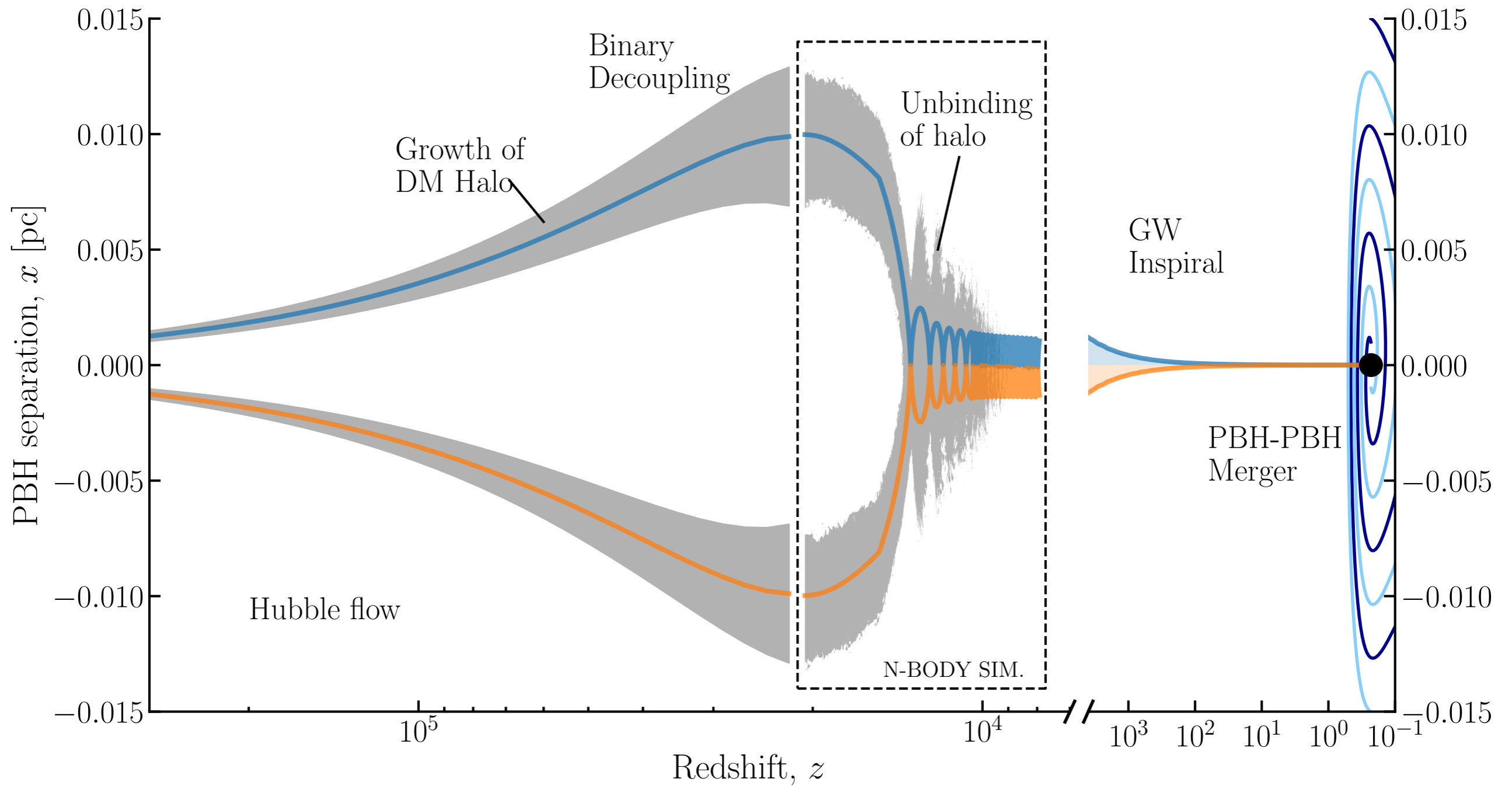
[Nakamura et al, [astro-ph/9708060](#),
Sasaki et al, [1603.08338](#)]

or so we (?) thought...

Life of a PBH binary

$$a_i = 0.01 \text{ pc}$$

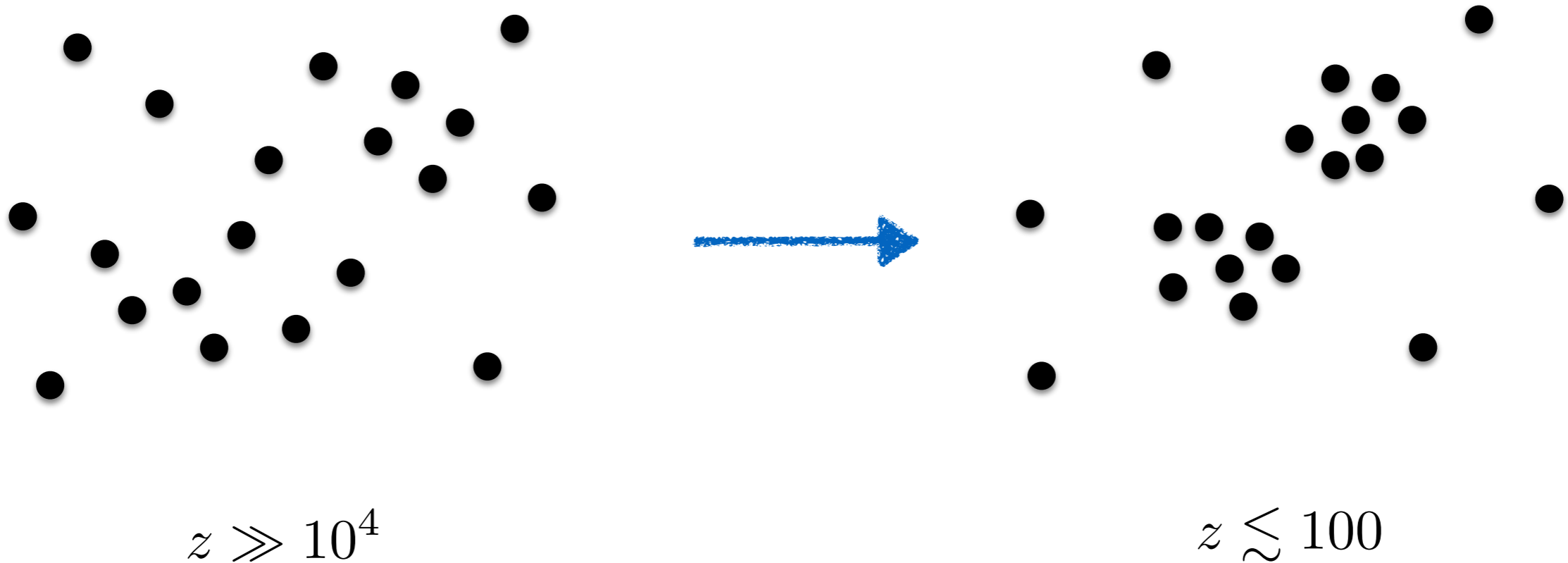
$$e_i = 0.995$$



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

PBH clustering

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

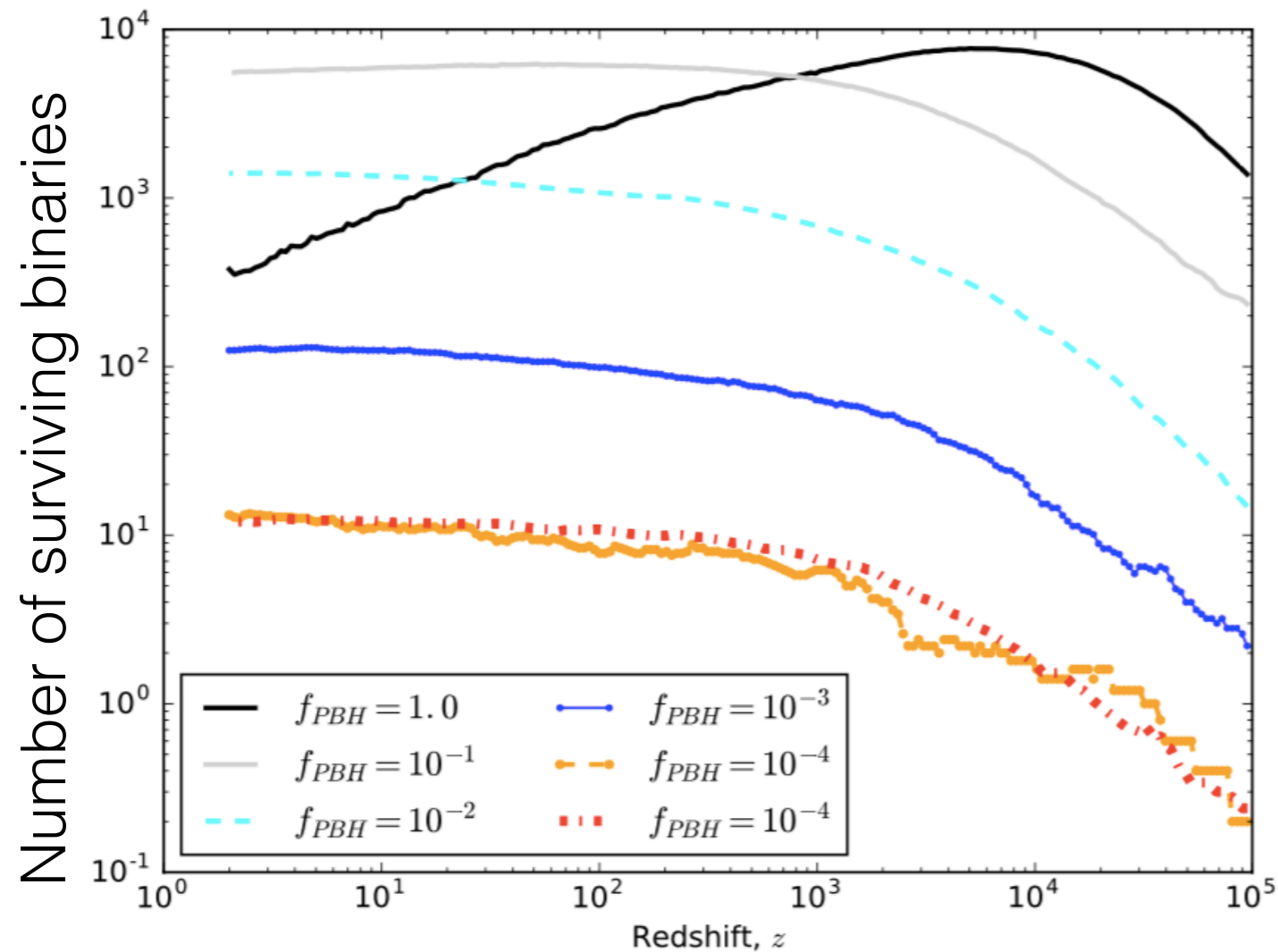


A cluster of N PBHs is expected to form around $z_c \sim z_{\text{eq}} f_{\text{PBH}} / \sqrt{N}$

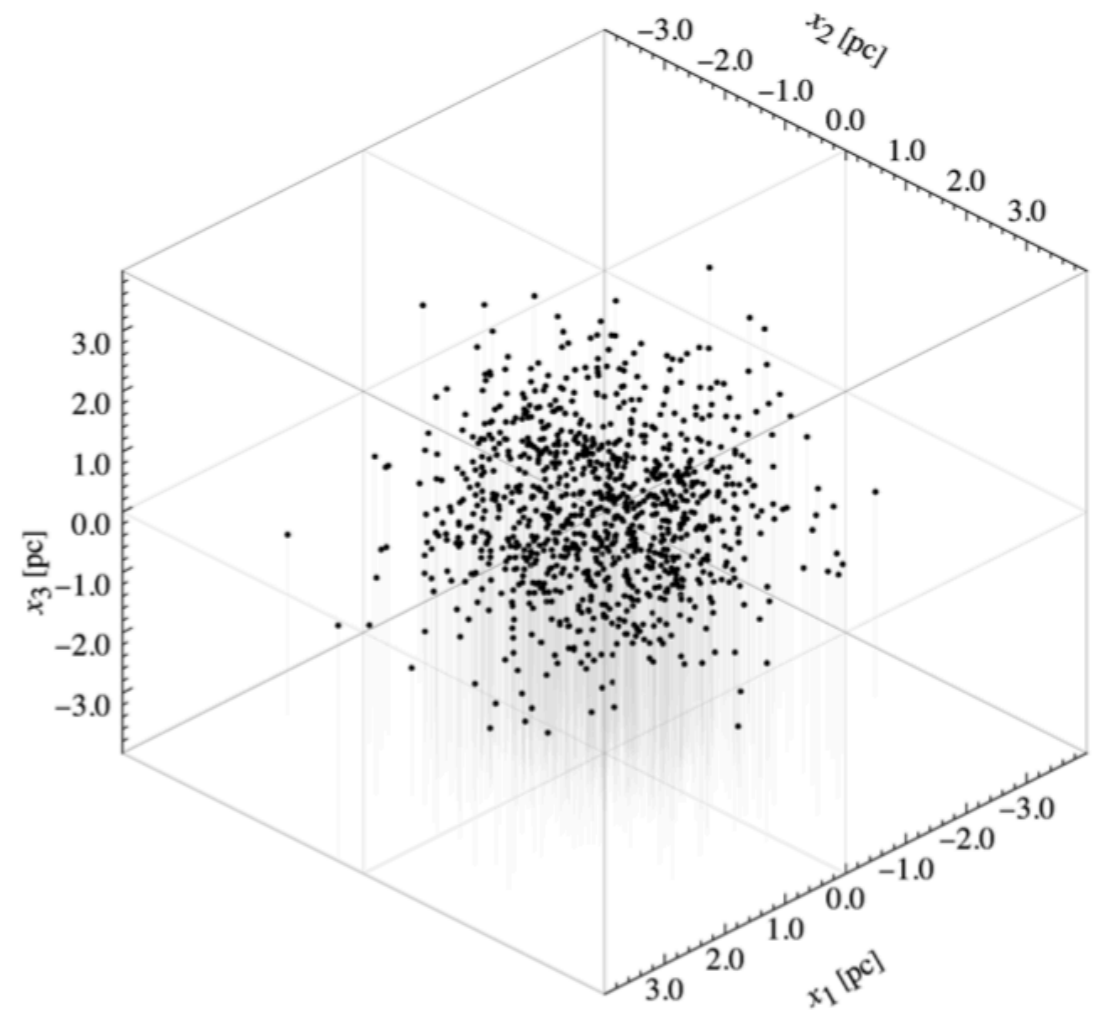
[Chisholm - [astro-ph/0509141](https://arxiv.org/abs/astro-ph/0509141), [1110.4402](https://arxiv.org/abs/1110.4402), Inman & Ali-Haïmoud, [1907.08129](https://arxiv.org/abs/1907.08129)]

Simulations

Simulate isolated clusters or attempt something cosmological:



[Tkachev, Pilipenko & Yepes - [2009.07813](#)]



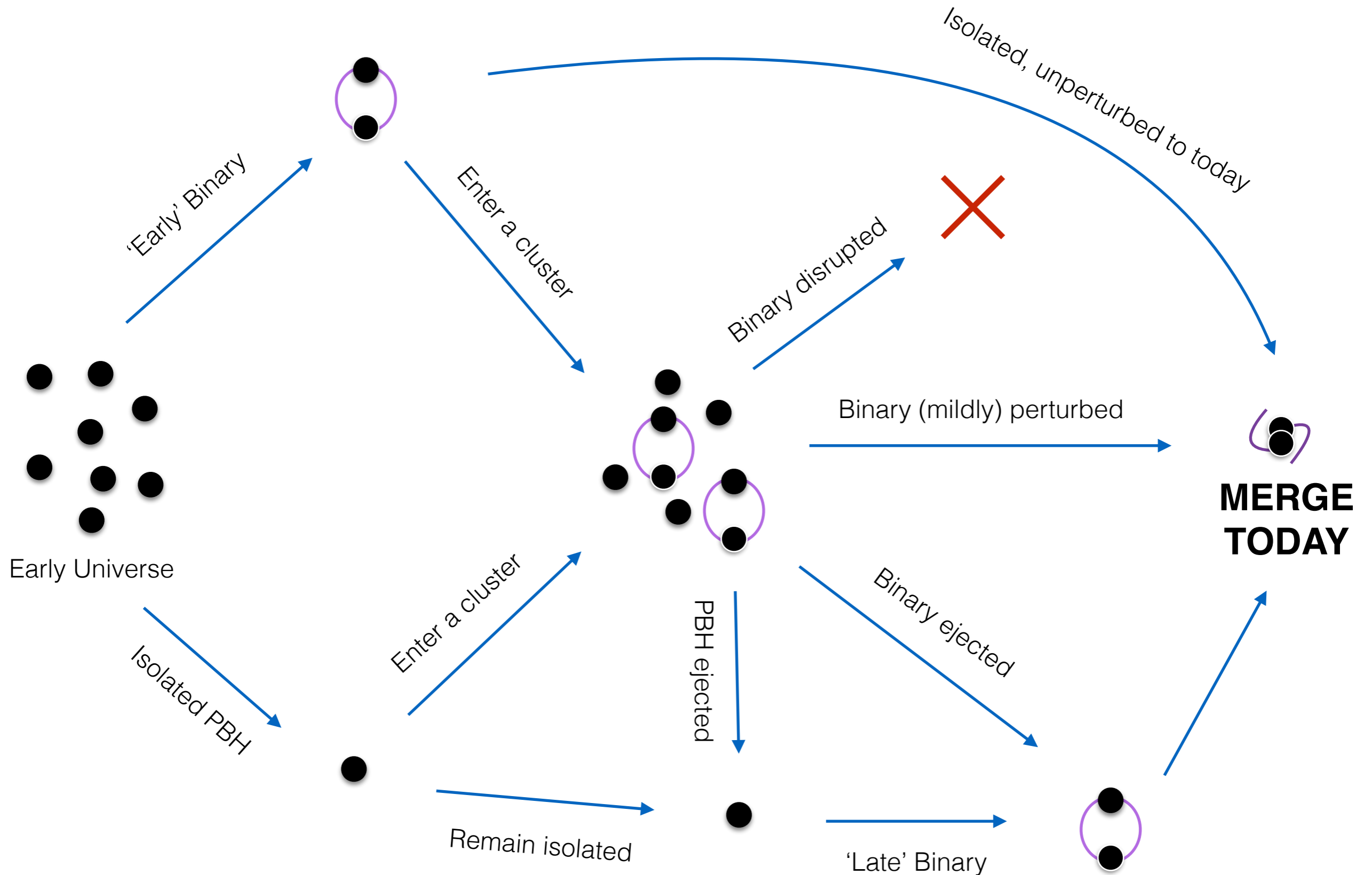
[Trashorras et al., [2006.15018](#)]

Clusters may perturb/disrupt binaries or encourage binary formation...

[Jedamzik - [2006.11172](#), [2007.03565](#)]

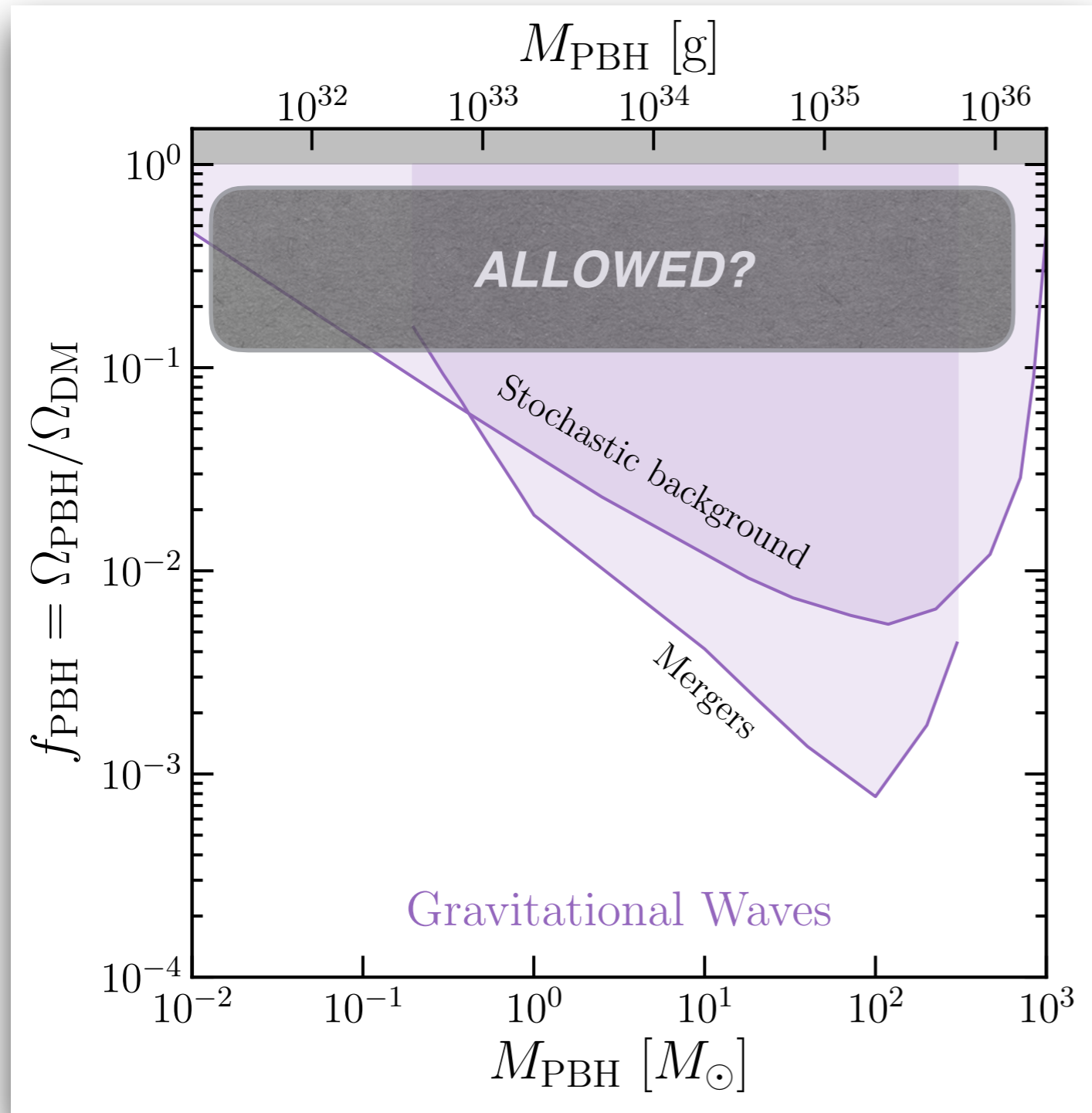
Paths to PBH mergers

[See e.g. [1812.01930](#), [1908.09752](#), [2007.07212](#), [2009.04731](#)]



Gravitational Waves

Constrain individual PBH mergers
and stochastic background



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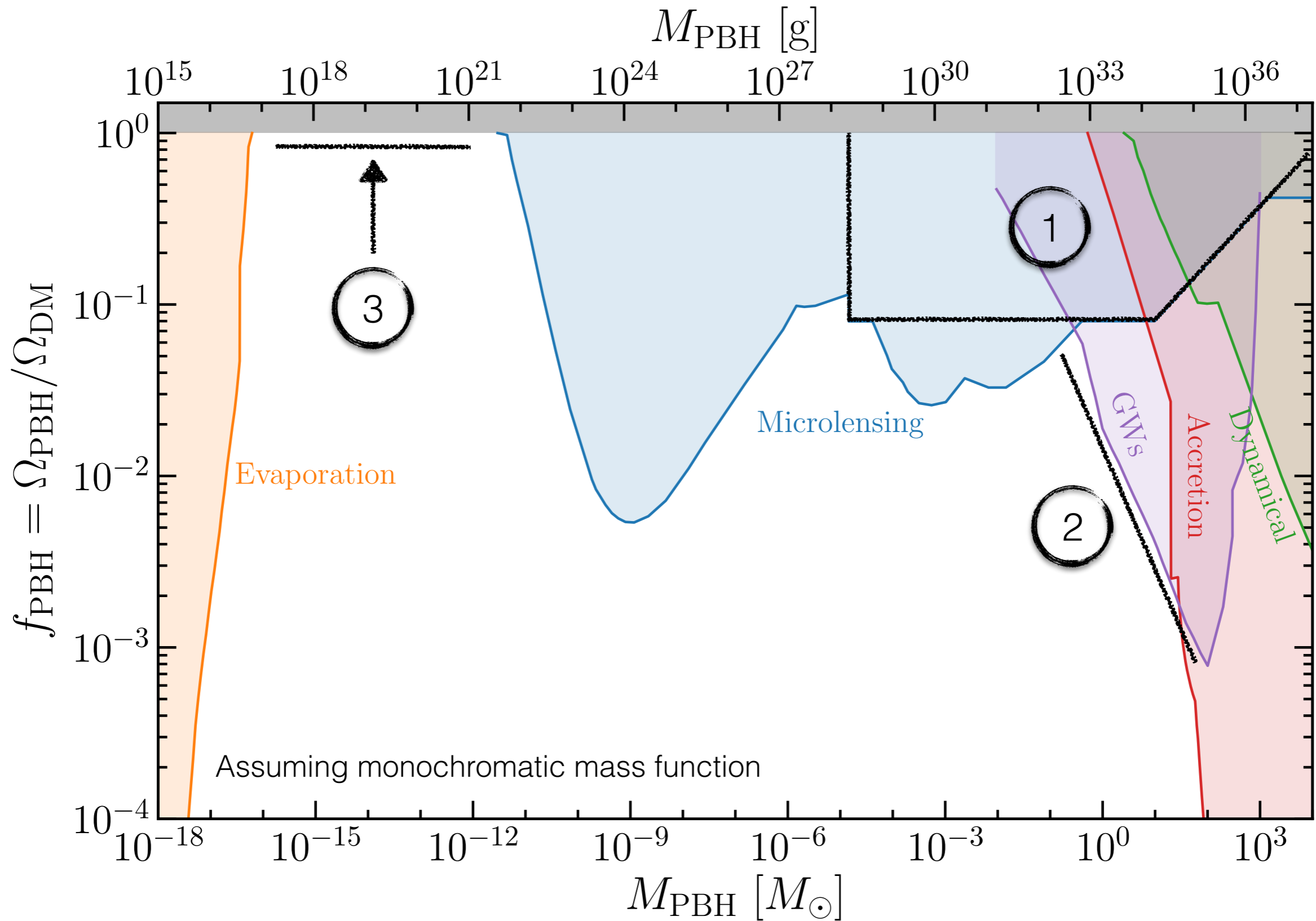
[Nakamura et al, [astro-ph/9708060](#),
Sasaki et al, [1603.08338](#)]

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PBH bounds

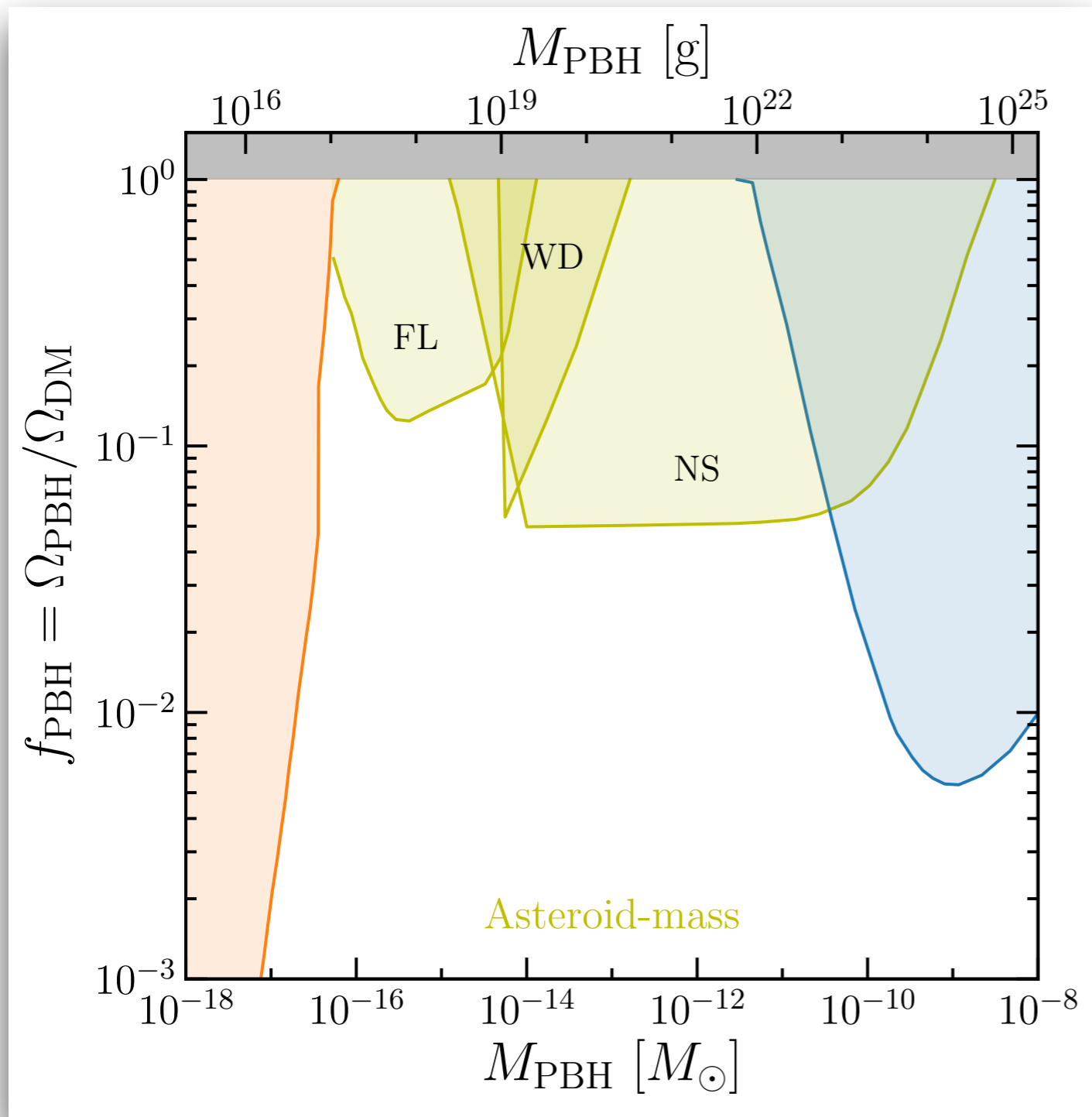
[Green & **BJK**, 1709.06576]

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



Asteroid-mass PBHs

A few years ago this region was well-constrained



‘Femtolensing’ of GRBs?

[Barnacka et al., [1204.2056](#)]

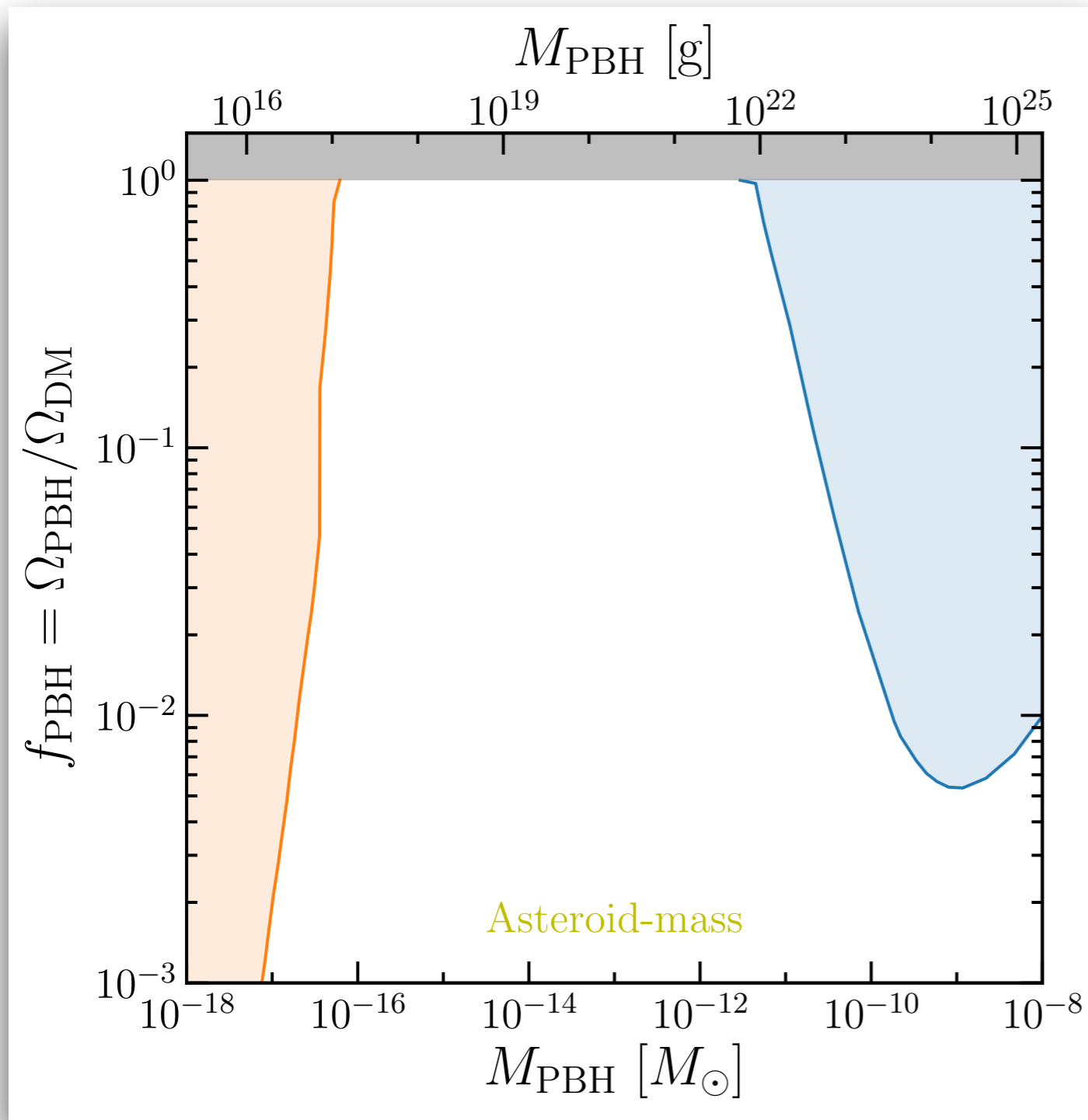
PBH capture in compact objects
(White Dwarfs/Neutron Stars)

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

[Yoann Génolini, [2006.16975](#)
and the next talk]

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[Katz et al., [1807.11495](#)]

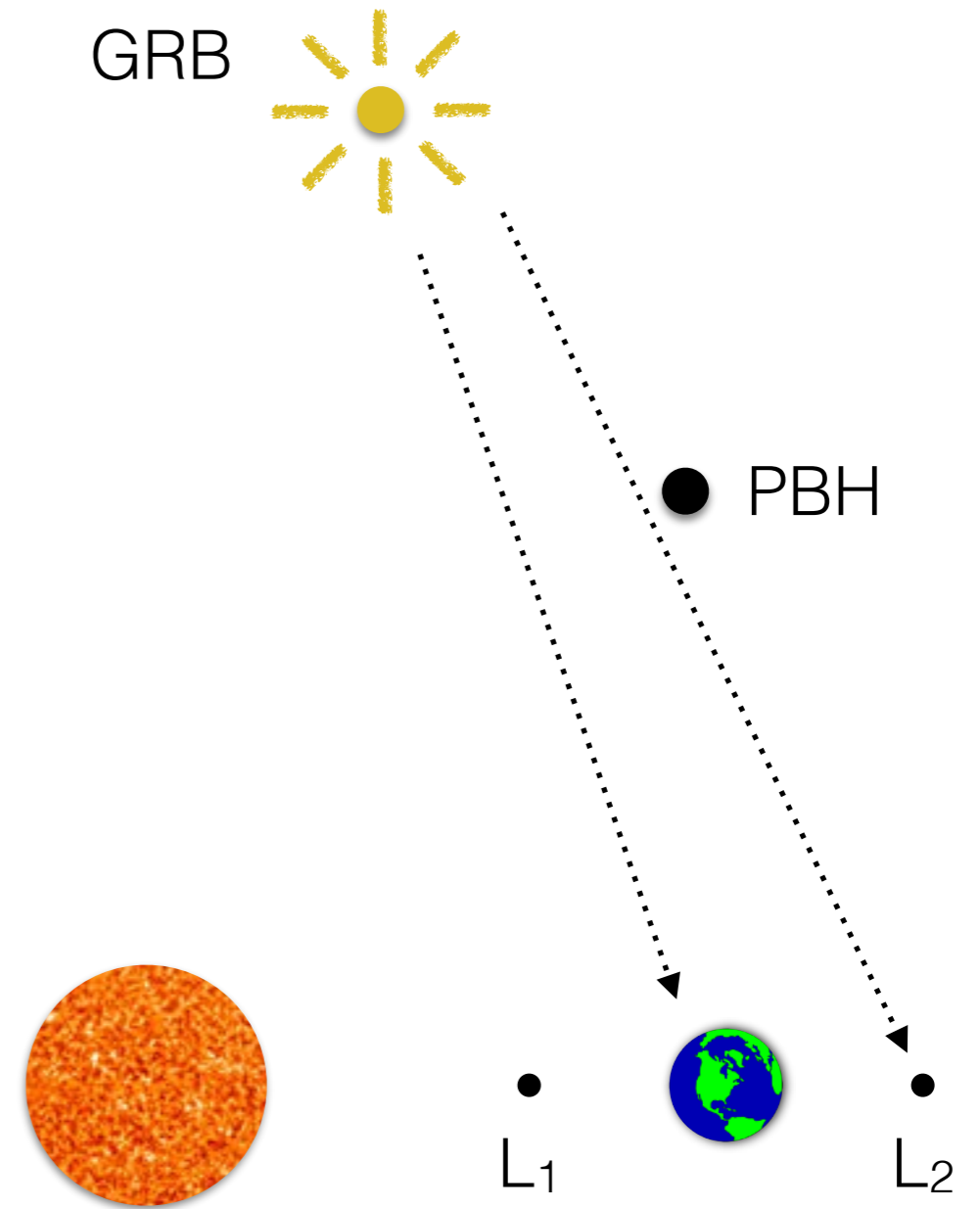
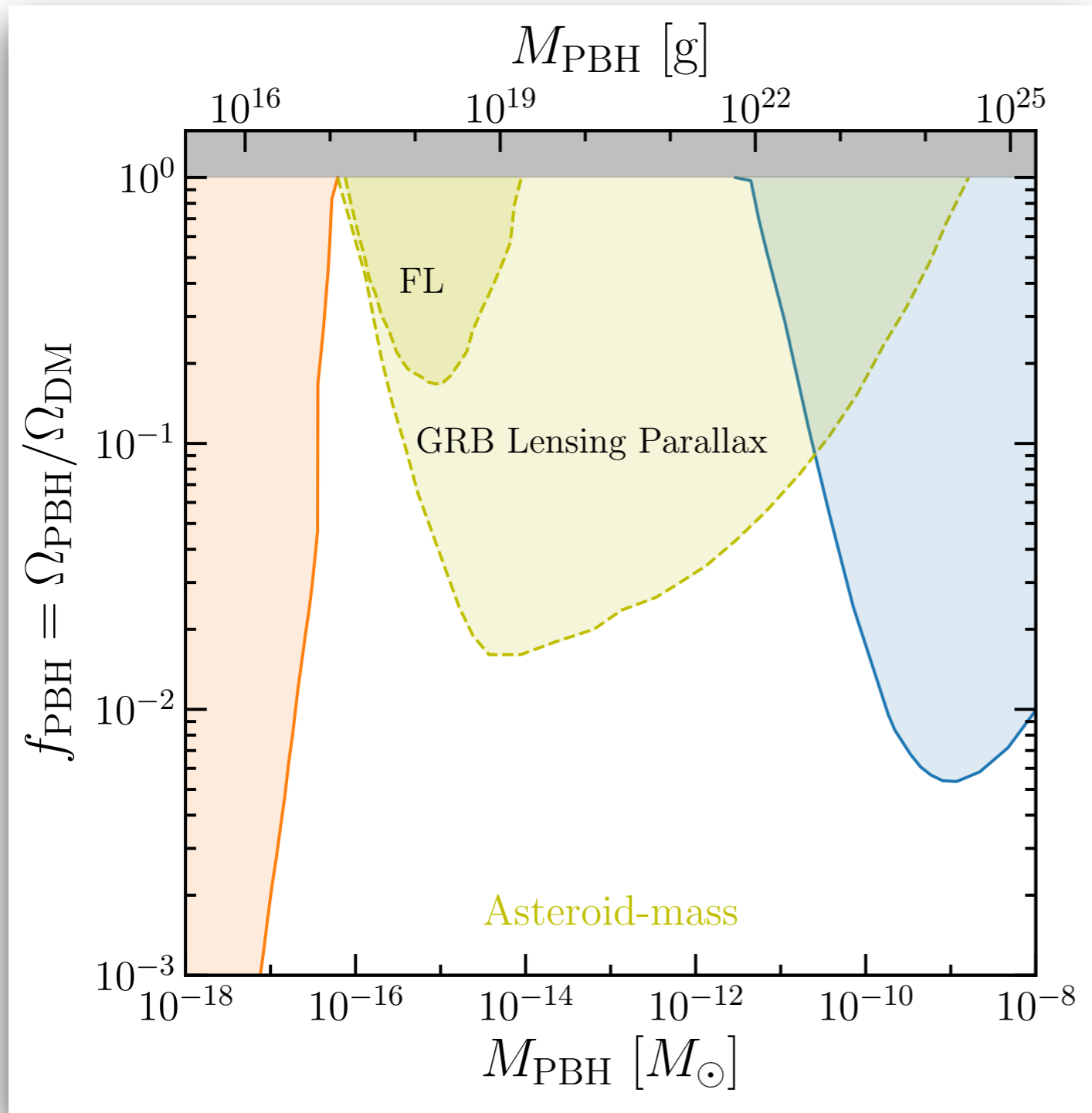
~~PBH capture in compact objects
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[E.g. Graham et al., [1505.04444](#),
Capela et al., [1301.4984](#)]

[Montero-Camacho et al., [1906.05950](#)]

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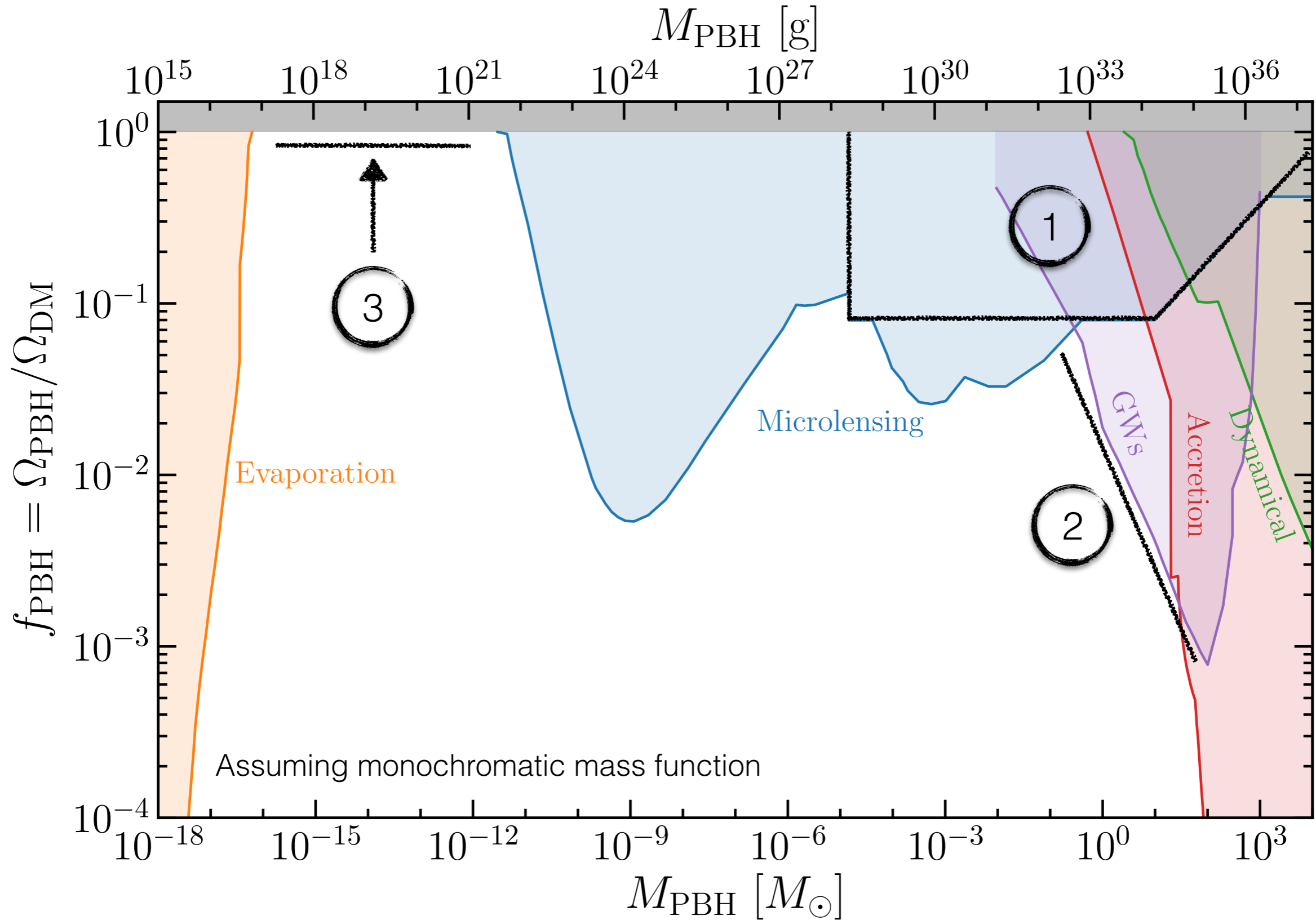


[Nemiroff & Gould, [astro-ph/9505019](https://arxiv.org/abs/astro-ph/9505019),
Jung & Kim, [1908.00078](https://arxiv.org/abs/1908.00078)]

PBH bounds

[Green & **BJK**, 1709.06576]

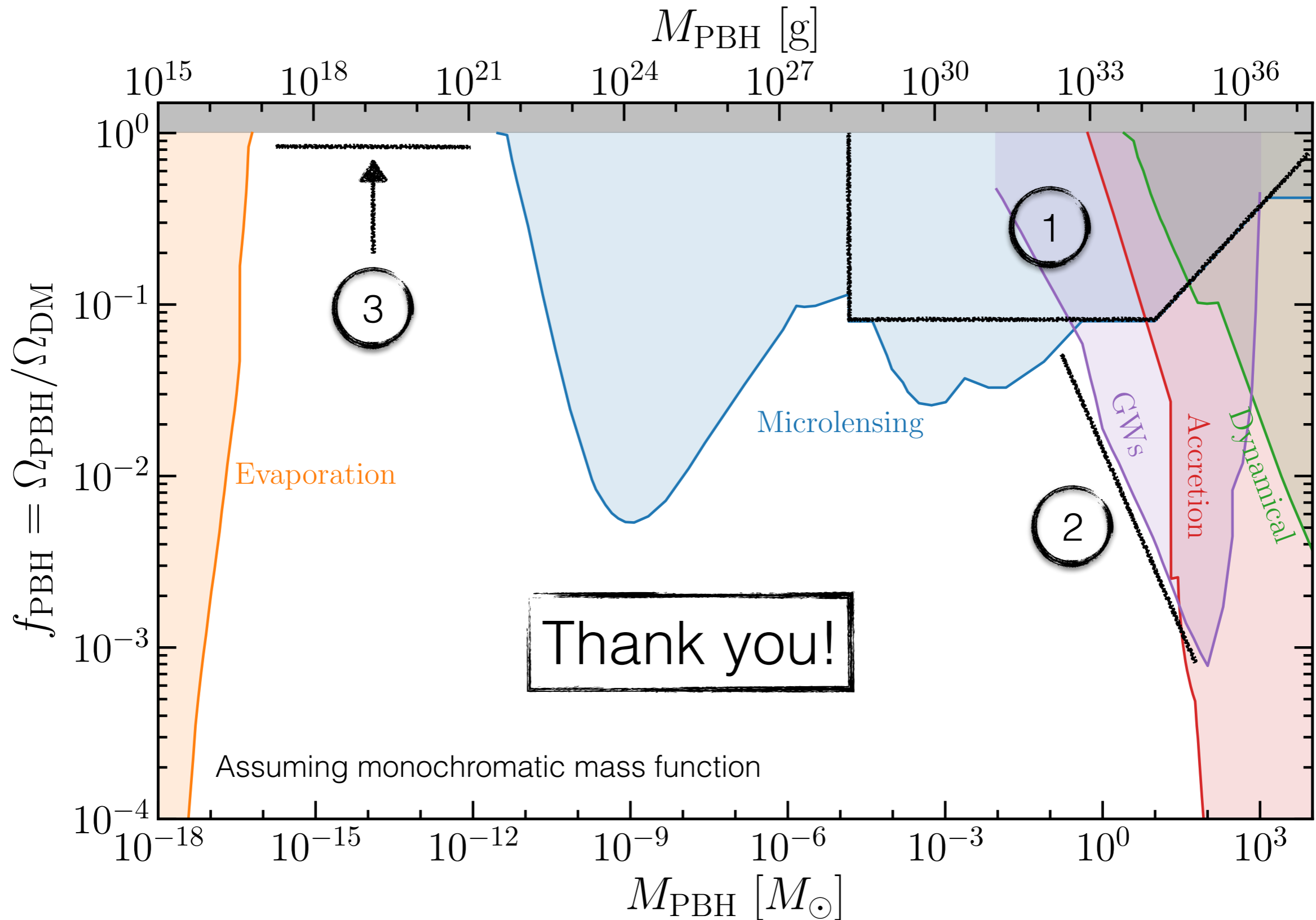
[Code online: github.com/bradkav/PBHbounds]



PBH bounds

[Green & **BJK**, 1709.06576]

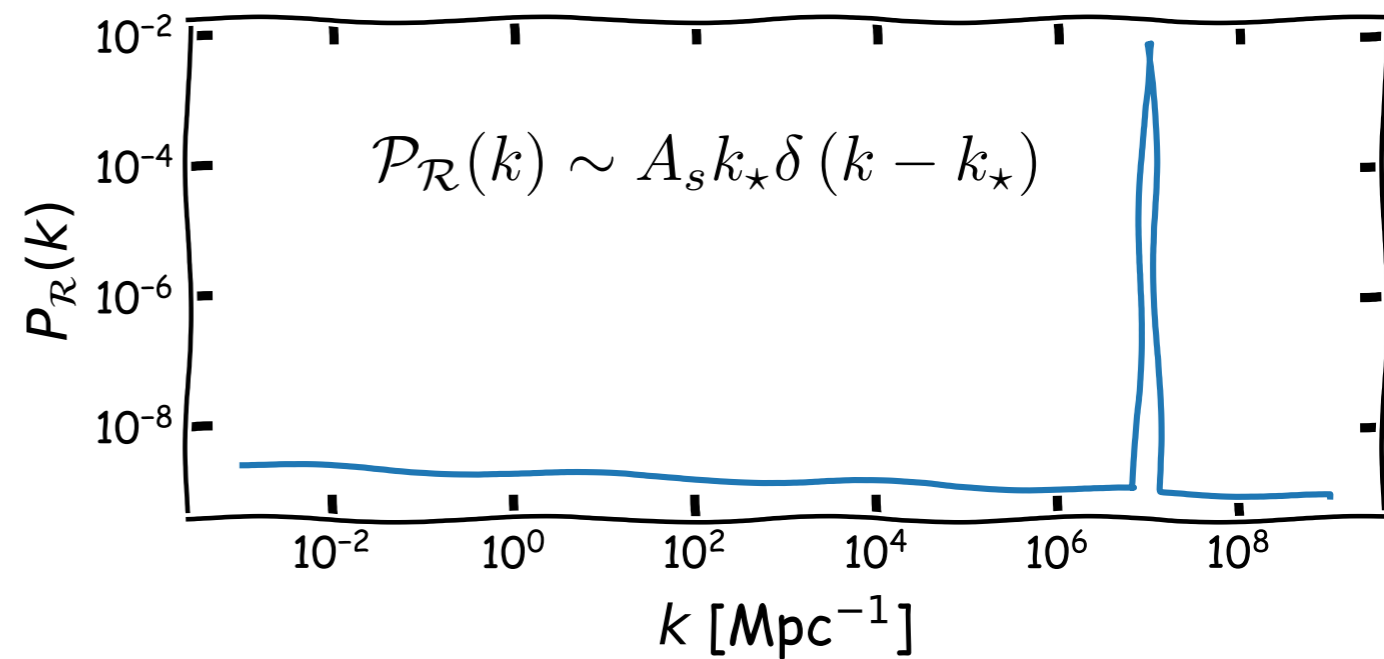
[Code online: github.com/bradkav/PBHbounds]



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_* , $M_{\text{PBH}} \simeq 1.4 \times 10^{13} M_{\odot} \left(\frac{k_*}{\text{Mpc}^{-1}} \right)^{-2}$

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

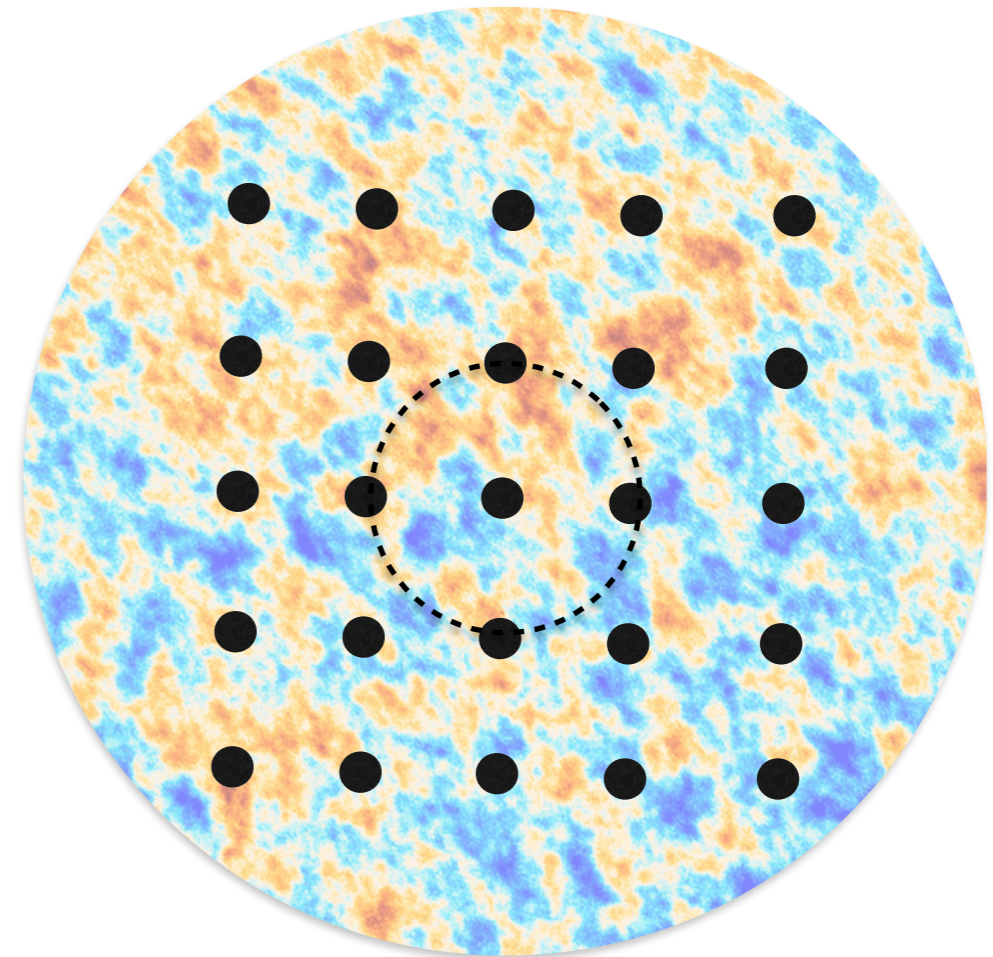
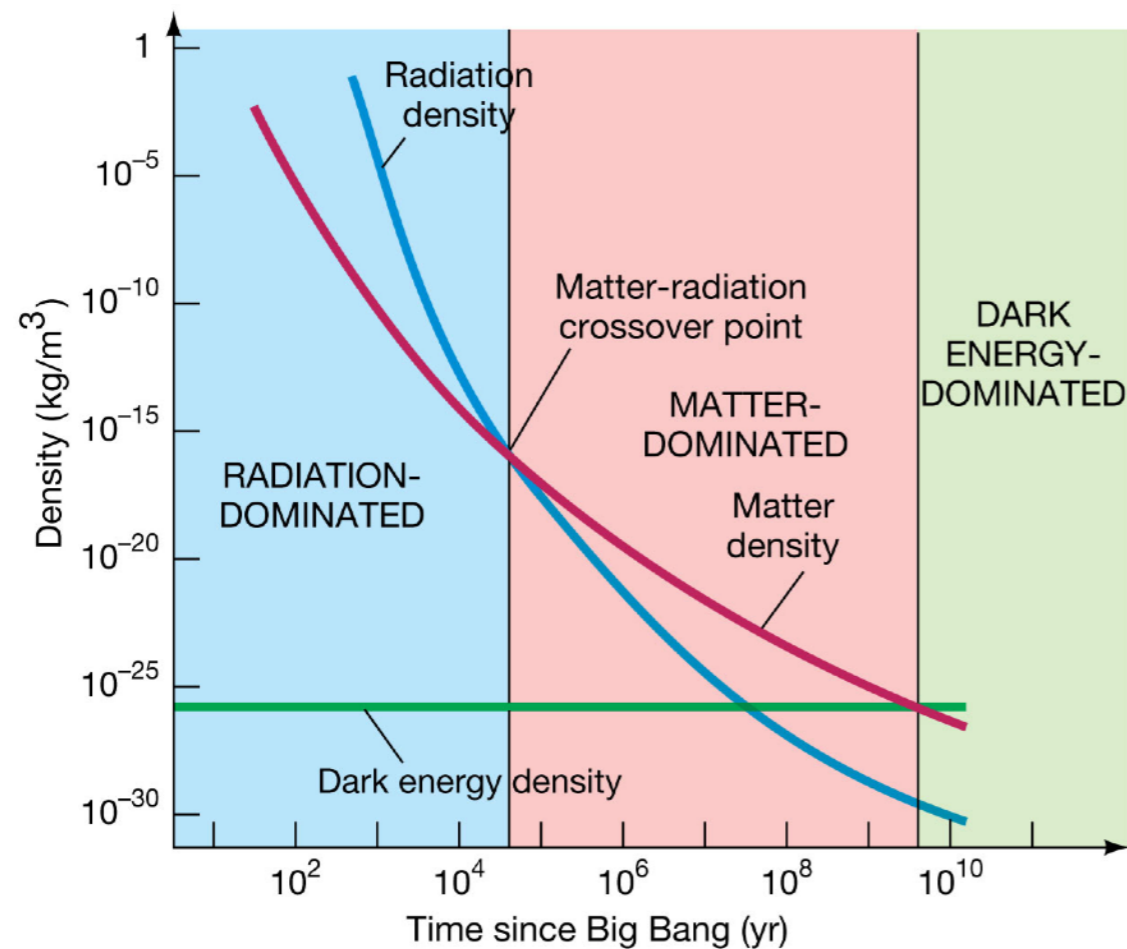
$$f_{\text{GW}}^{\text{peak}} = 3 \times 10^{-9} \left(\frac{M_{\text{PBH}}}{M_{\odot}} \right)^{-1/2} \text{ Hz}$$

[[astro-ph/0407611](#), [0812.4339](#), [1012.4697](#)]

[See recent NanoGRAV results...]

Early Universe Binaries

If $f_{\text{PBH}} \sim 1$, the relative density of PBHs *equals* the background radiation density at matter-radiation equality.
(Almost) all PBHs form binaries...



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PBH Binary Population

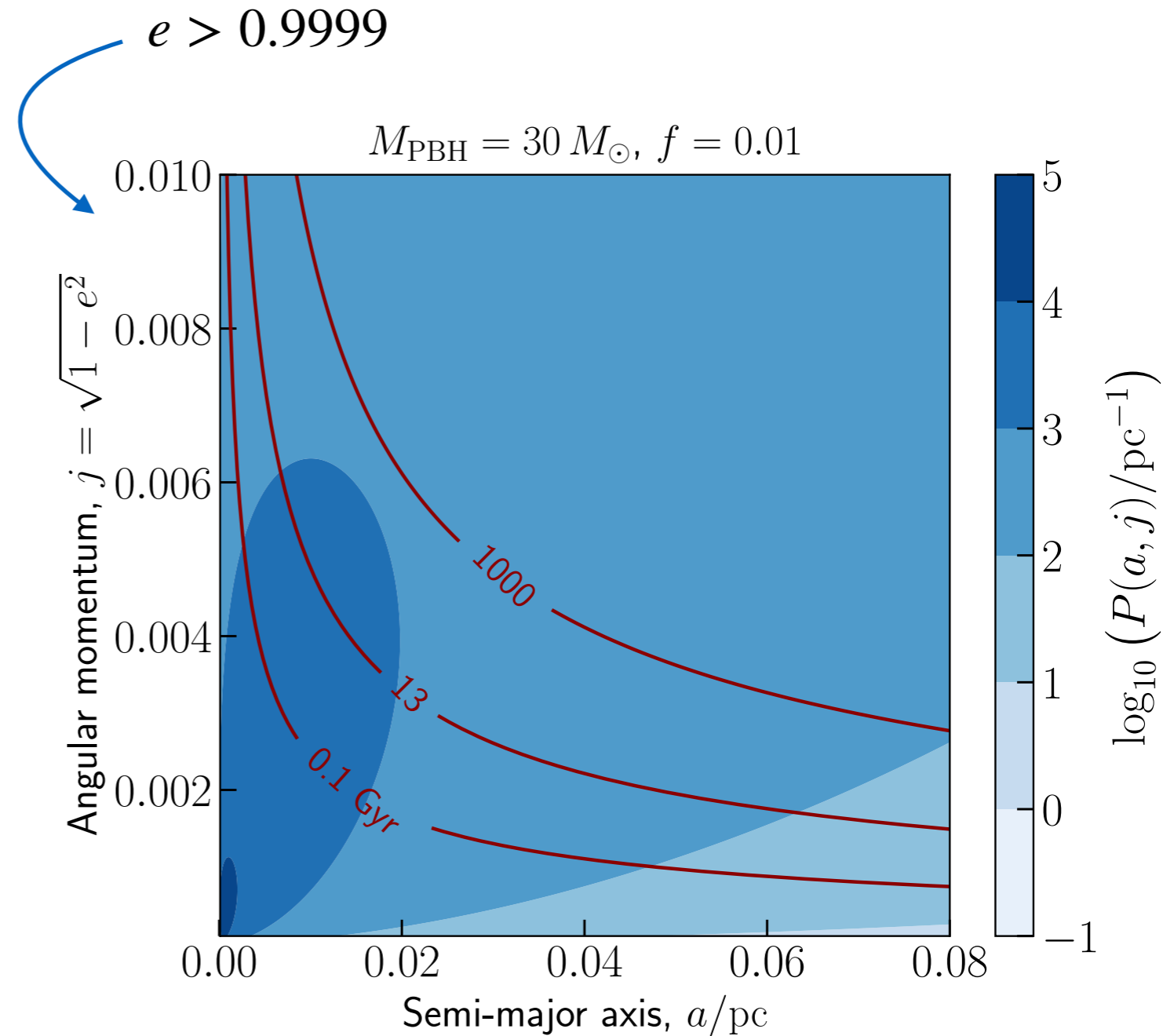
$$j = \sqrt{1 - e^2}$$

Randomly distributed
(unclustered*) PBHs

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

Close, eccentric binaries
merge today:

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

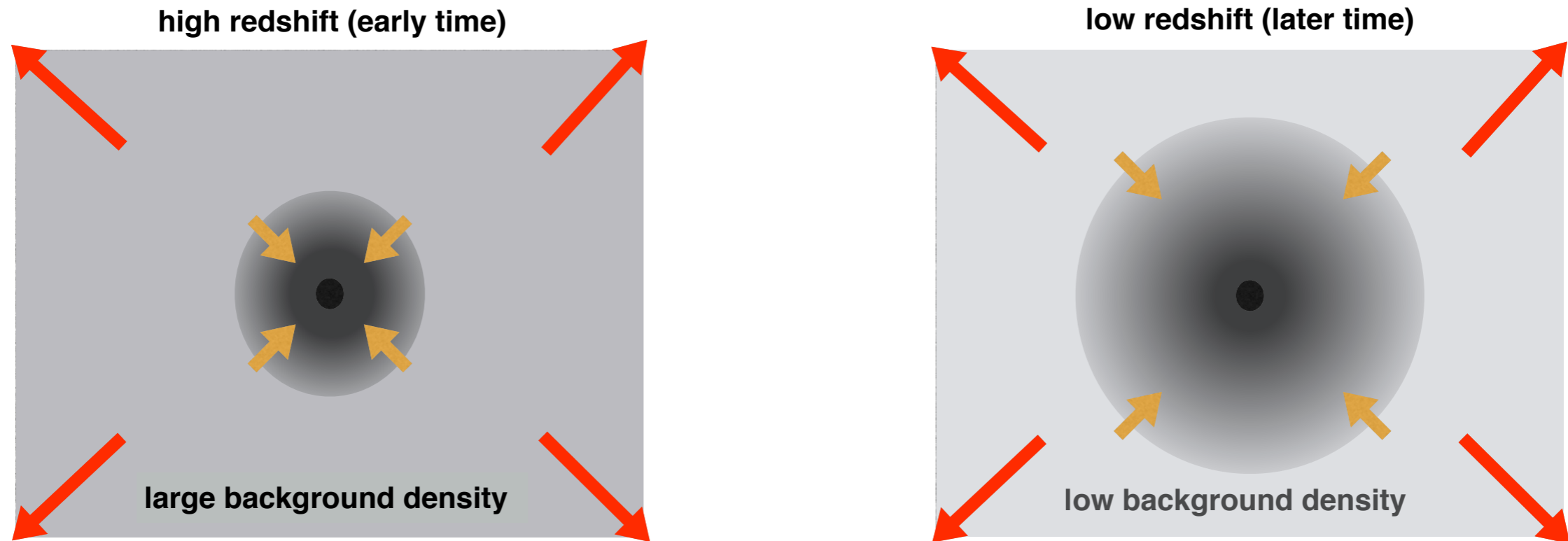


[**BJK**, Gaggero & Bertone, [1805.09034](#)]

[[0909.1738](#), [1606.07437](#), [1707.01480](#), **[1709.06576](#)**, [1907.01455](#), and many others.]

Black Holes' Dark Dress

PBHs seed the formation of 'local' DM halos:



$$R_{\text{tr}}(z) = 0.0063 \left(\frac{M_{\text{PBH}}}{M_{\odot}} \right) \left(\frac{1 + z_{\text{eq}}}{1 + z} \right) \text{pc} \quad \rho(r) \propto r^{-9/4}$$

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

Slide shamelessly ripped off from Daniele Gaggero

[[Bertschinger \(1985\)](#)]
[[0706.0864](#), [1901.08528](#)]

GW detection of sub-solar mass BHs

(LIGO O3, now!)

GW detection of high redshift BHs ($z > 40$)

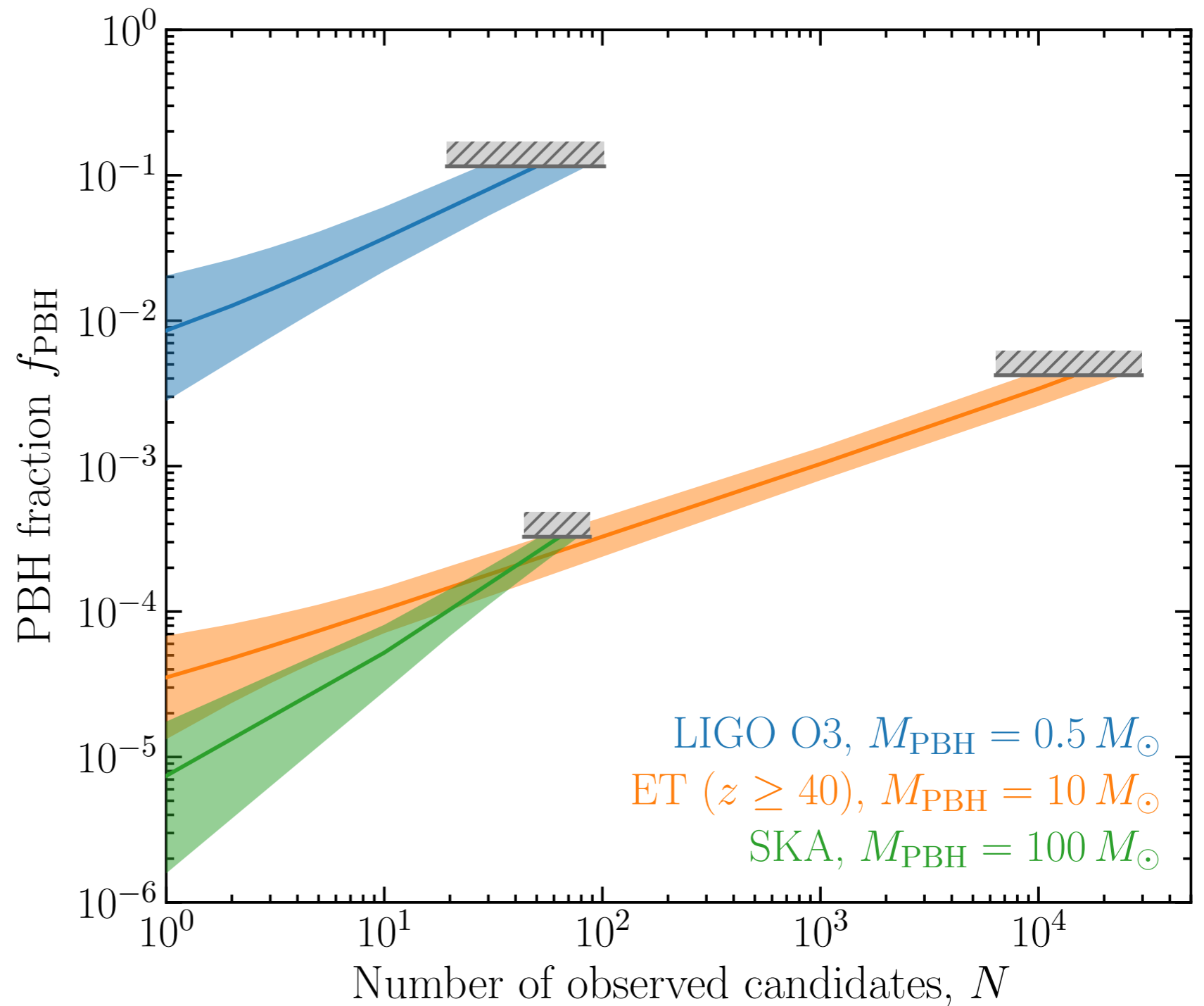
(Einstein Telescope, mid-late 2020s)

[[1708.07380](#)]

Radio detection of accreting galactic PBHs

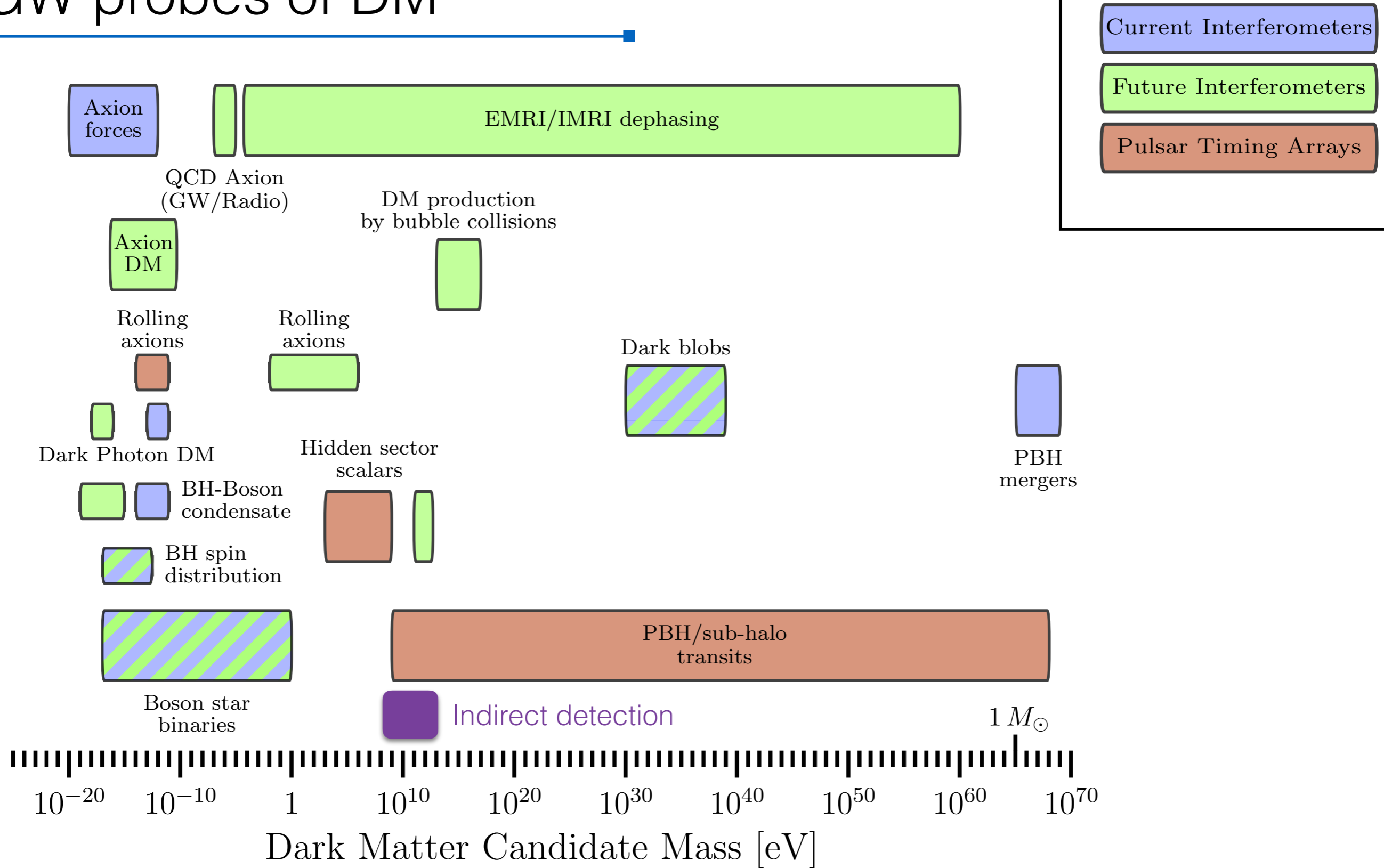
(Square Kilometre Array, late 2020s)

[[1812.07967](#)]



[Bertone, Coogan, Gaggero, **BJK** & Weniger, [1905.01238](#)]

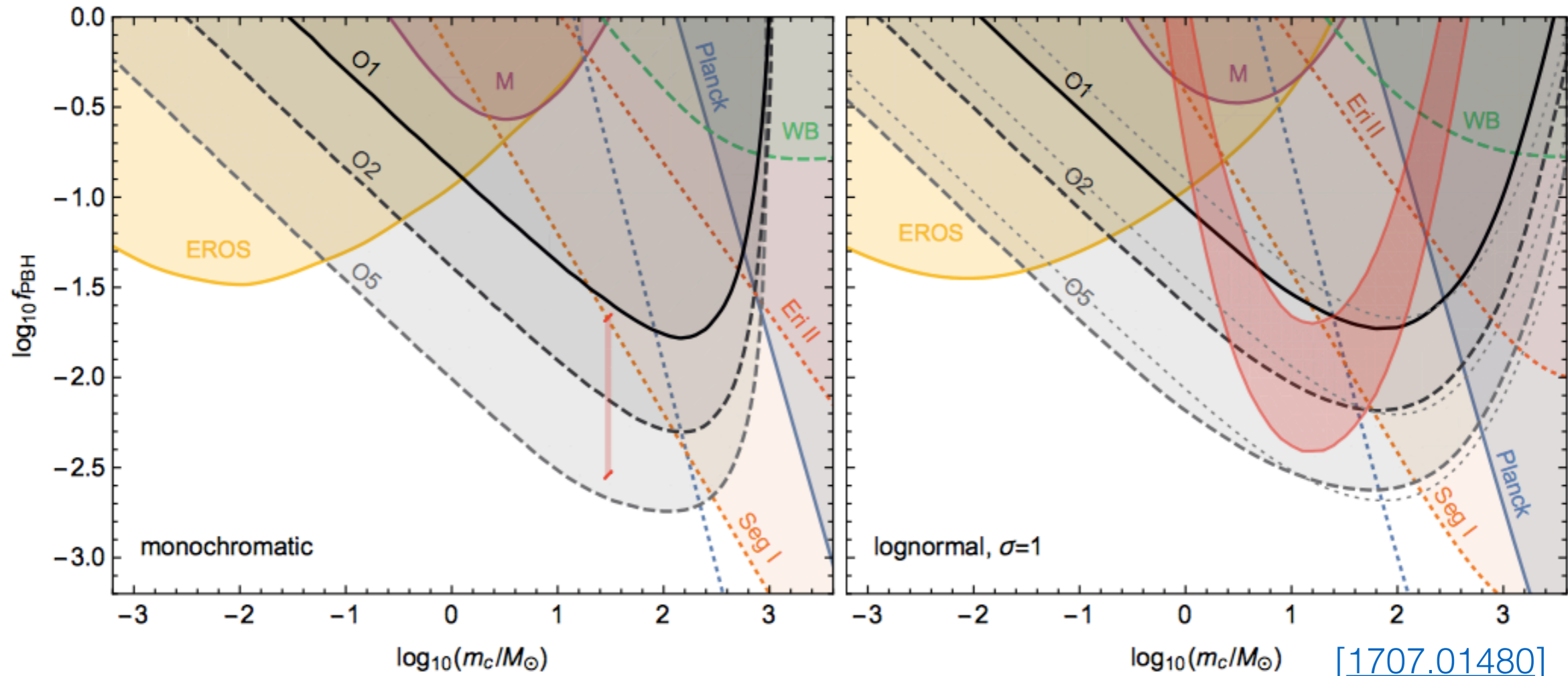
GW probes of DM



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

Extended Mass Function

LIGO O1 Limit 



[See also [1801.10327](#)]

In general, you can apply a remapping between monochromatic & extended mass functions. But it's hard to 'poke a hole' in the overlapping constraints

[Carr et al., [1705.05567](#)]

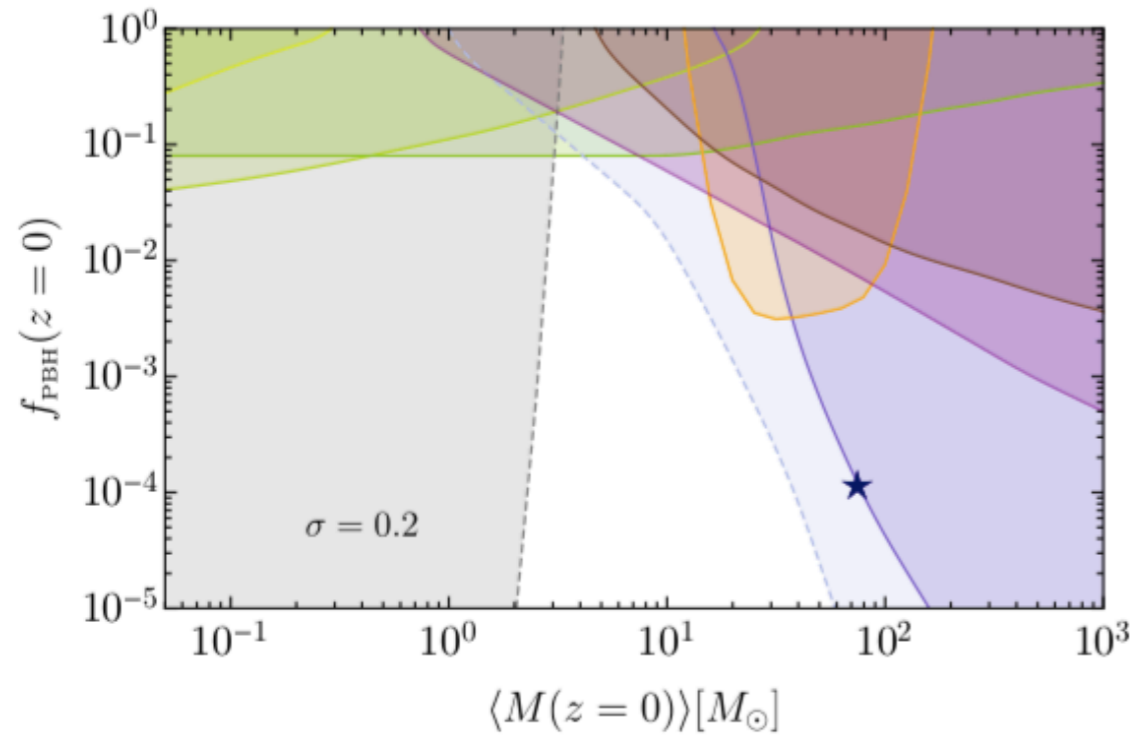
GW190521

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

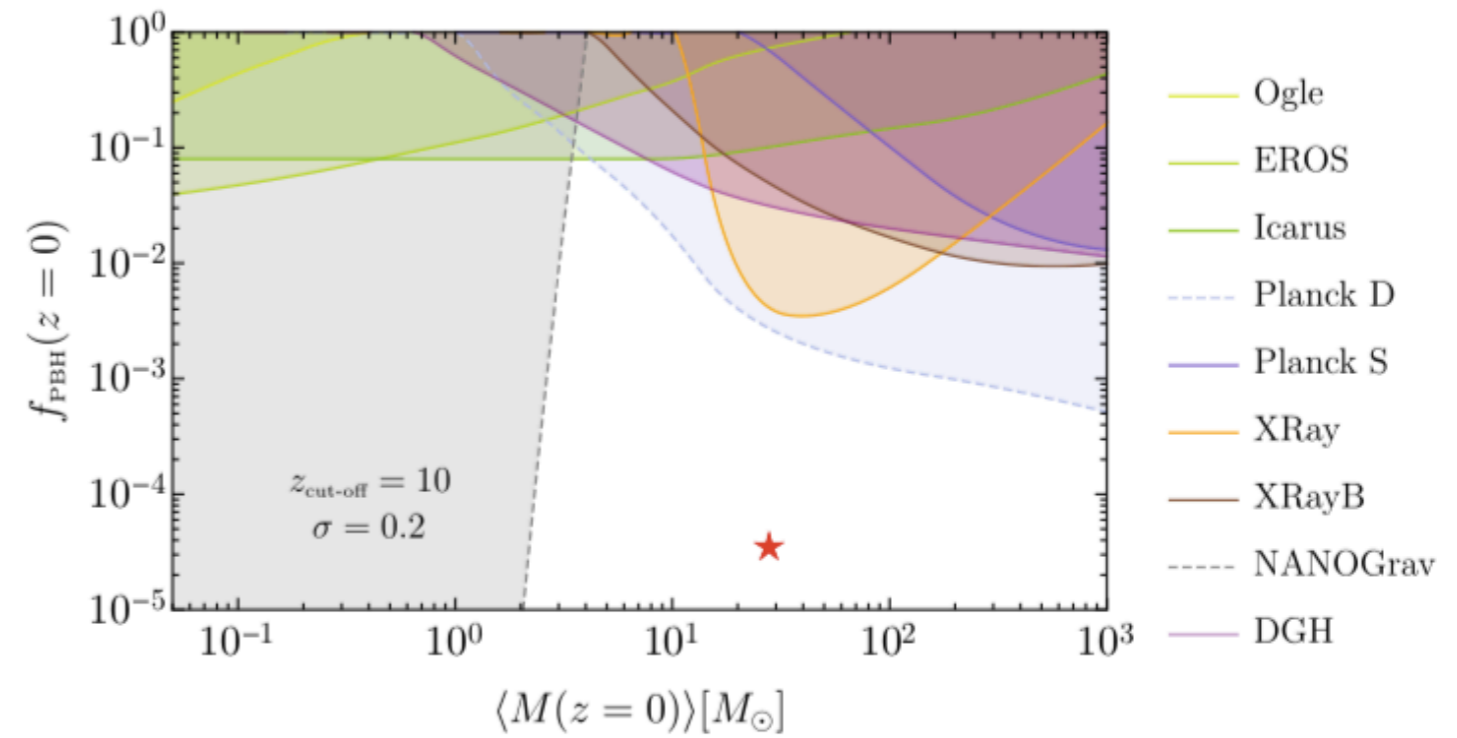
Parameter	
Primary mass	$85_{-14}^{+21} M_{\odot}$
Secondary mass	$66_{-18}^{+17} M_{\odot}$
Primary spin magnitude	$0.69_{-0.62}^{+0.27}$
Secondary spin magnitude	$0.73_{-0.64}^{+0.24}$
Total mass	$150_{-17}^{+29} M_{\odot}$

[LVC (GW190521), arXiv:2009.01075]

Single PBHs event without accretion



Single PBHs event with accretion



[De Luca et al., arXiv:2009.01728]