Constantly changing constraints on

Primordial Black Hole Dark Matter

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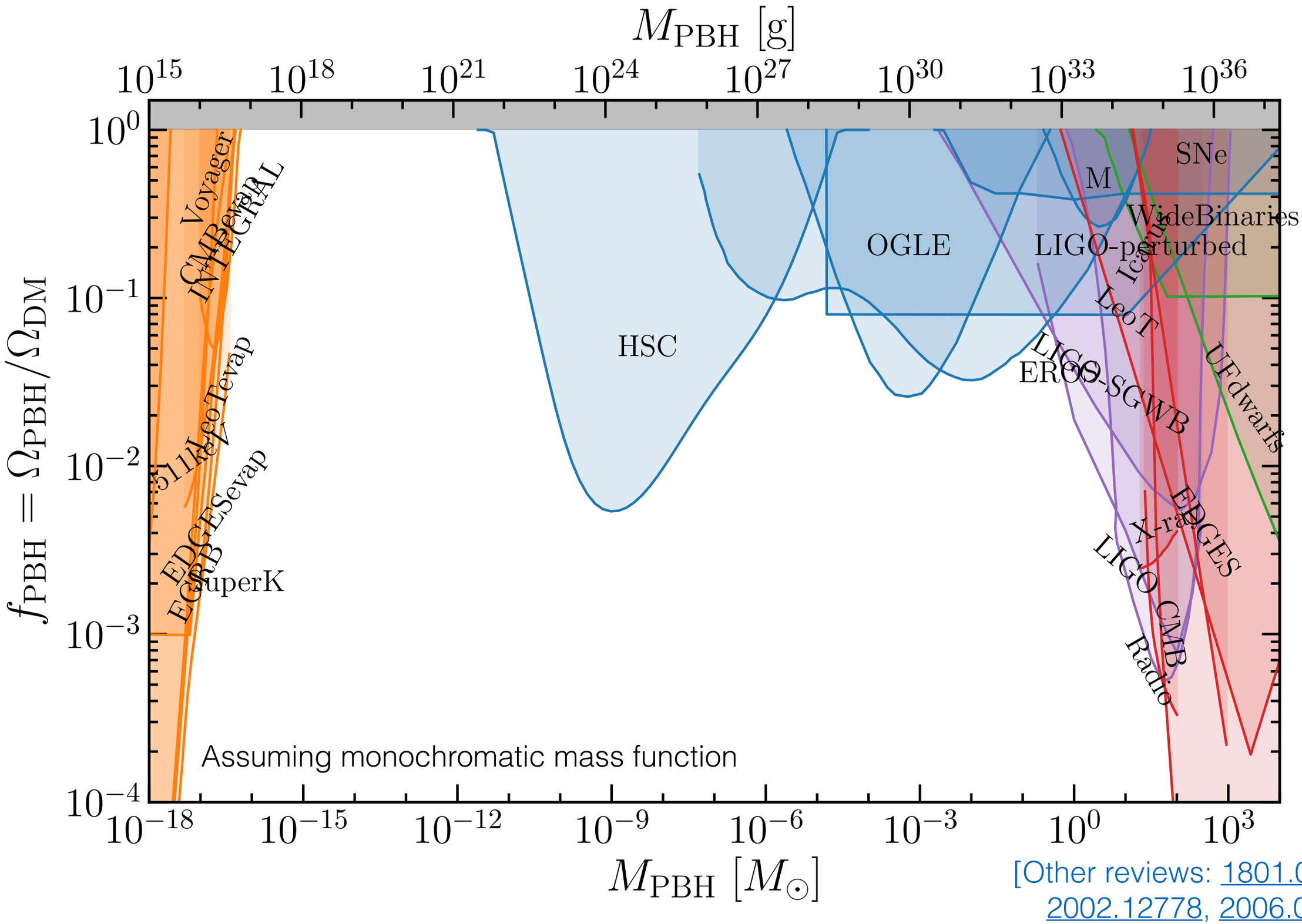
PBH bounds

[Green & **BJK**, 1709.06576]

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



[Other reviews: 1801.05235, 2002.12778, 2006.02838]

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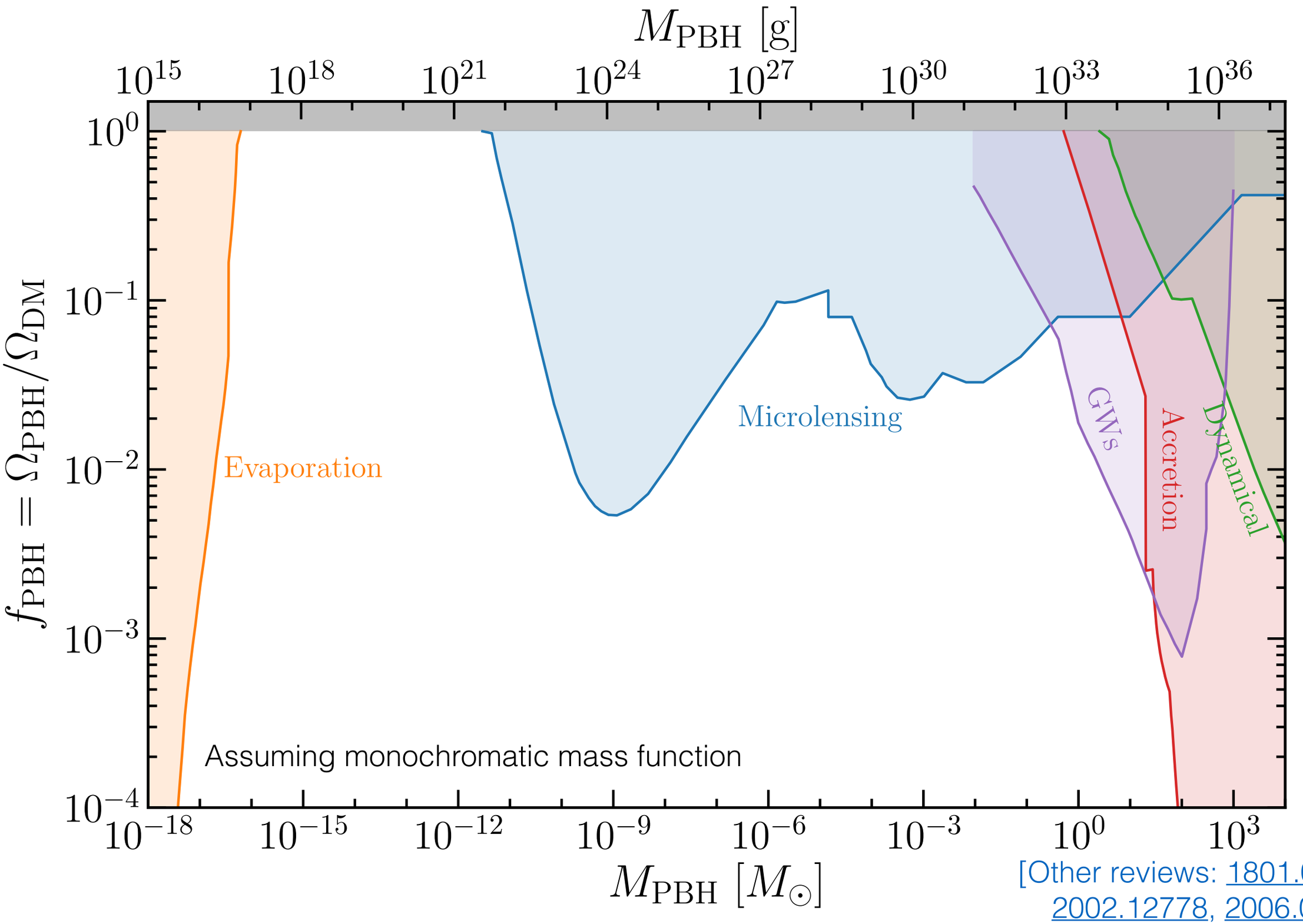

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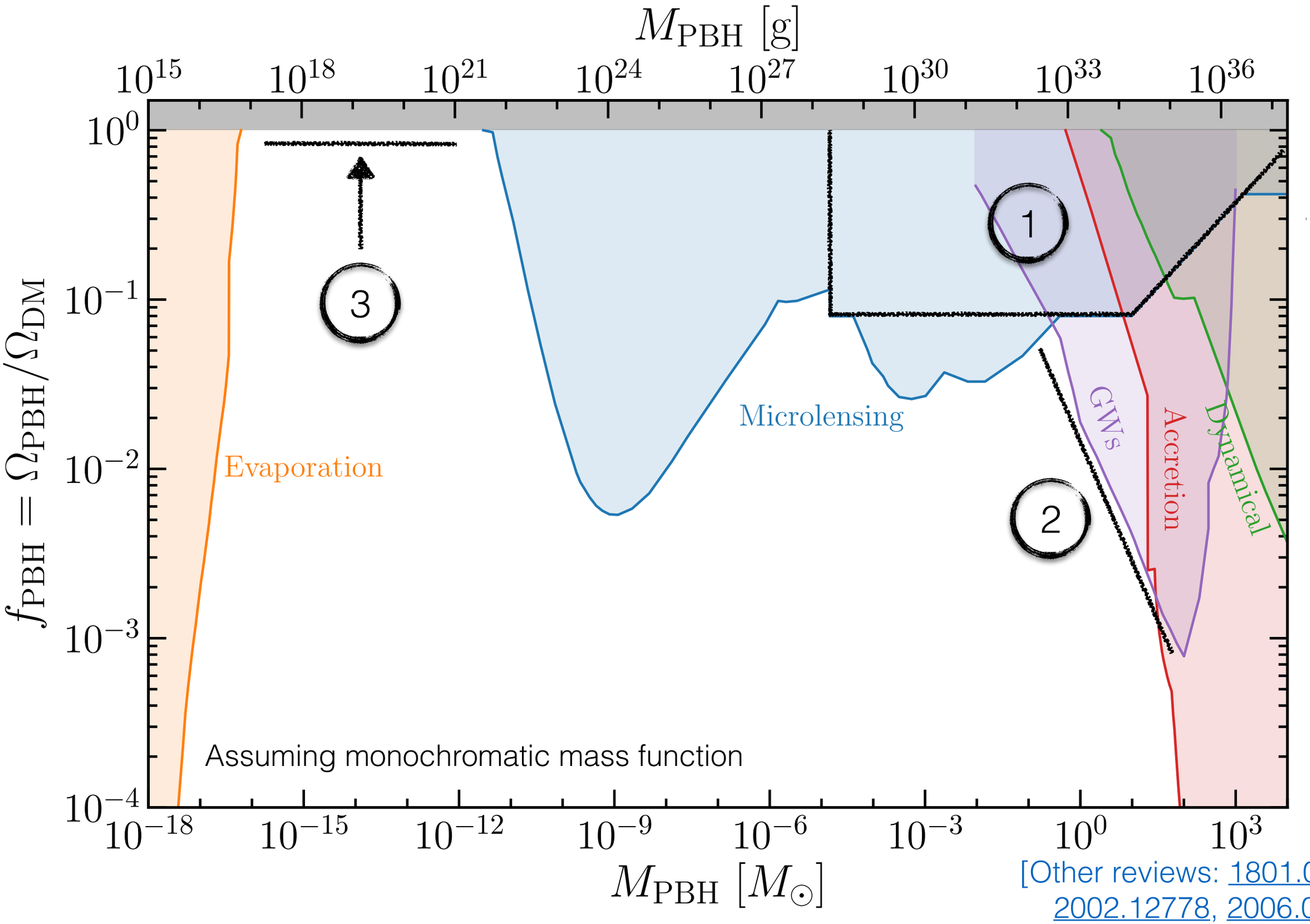

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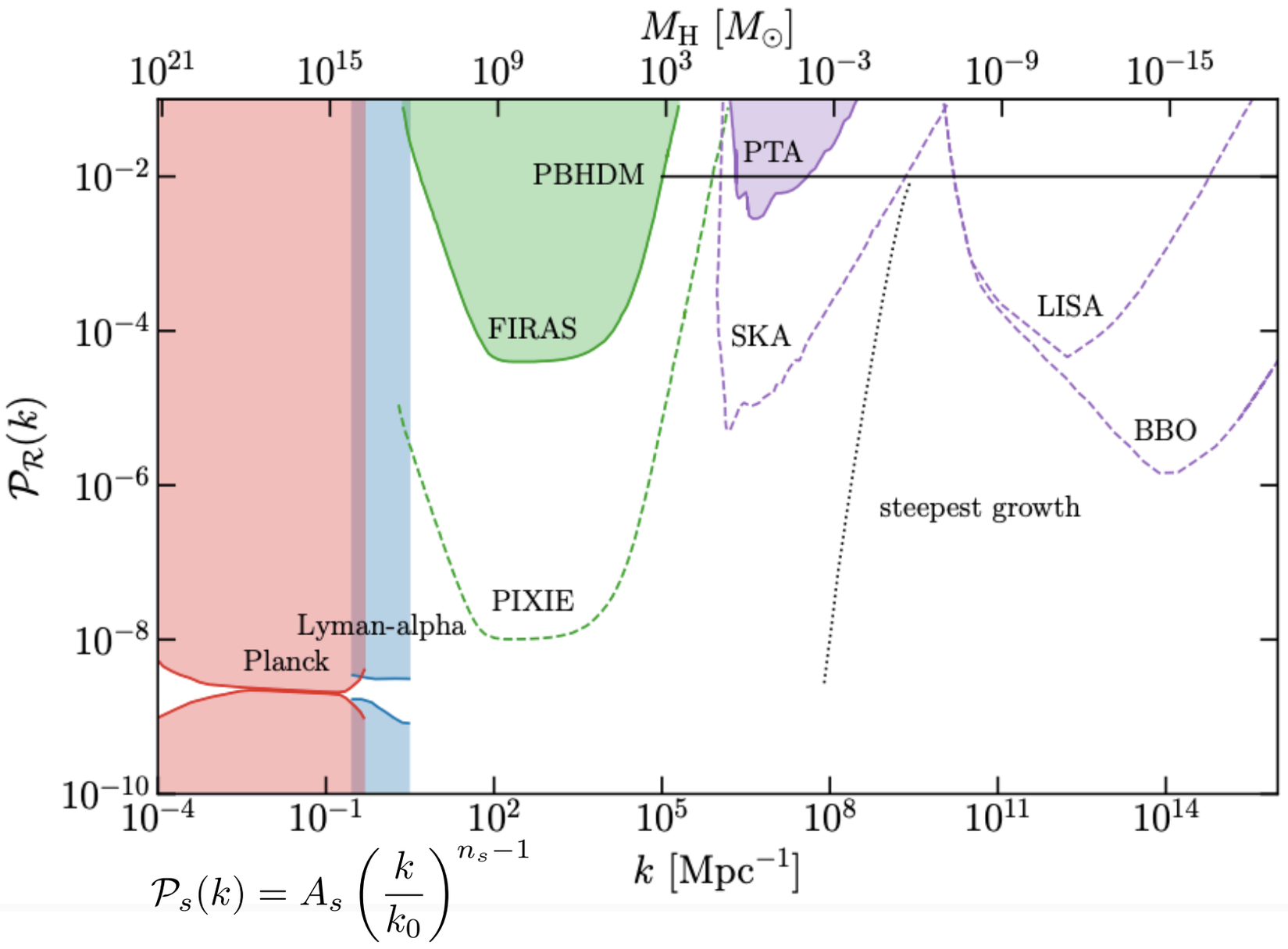
Primordial Black Holes

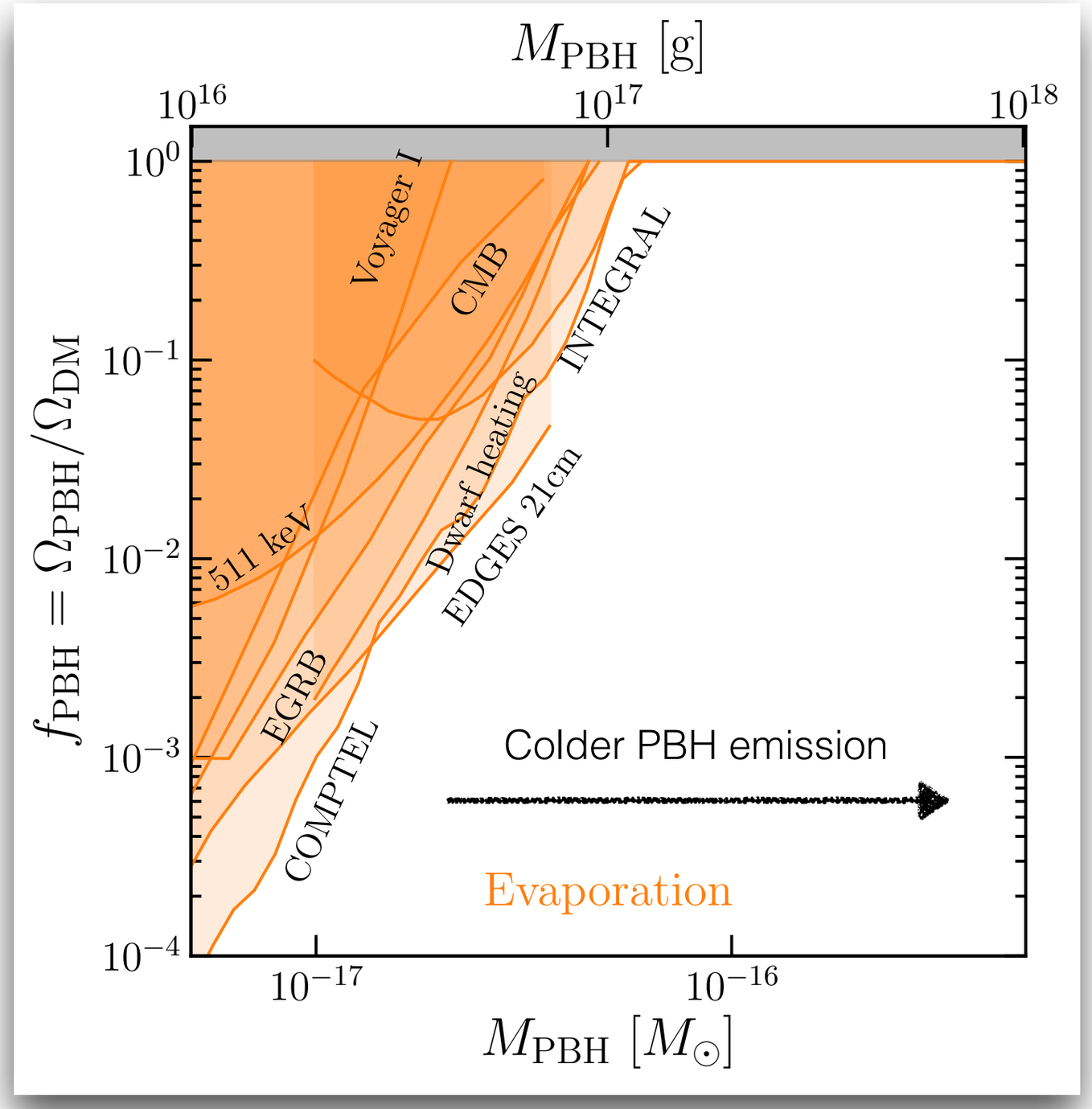
[1811.11158]
[Green & **BJK,** 1709.06576]

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



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

Evaporation



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

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

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

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

Voyager I

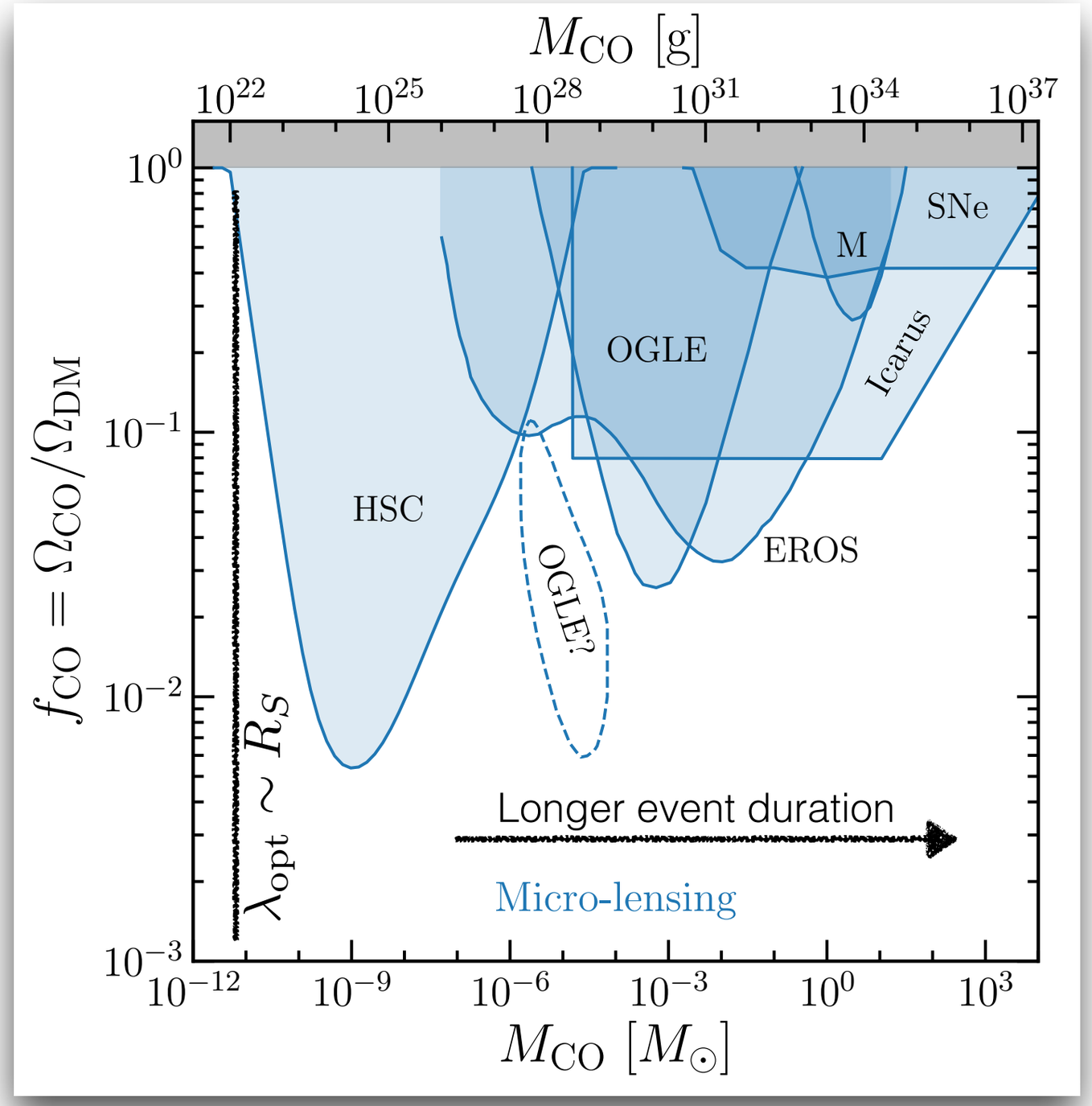
[Boudaud & Cirelli, 1807.03075]

COMPTEL

[Coogan et al., 2010.04797]

Micro-lensing

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



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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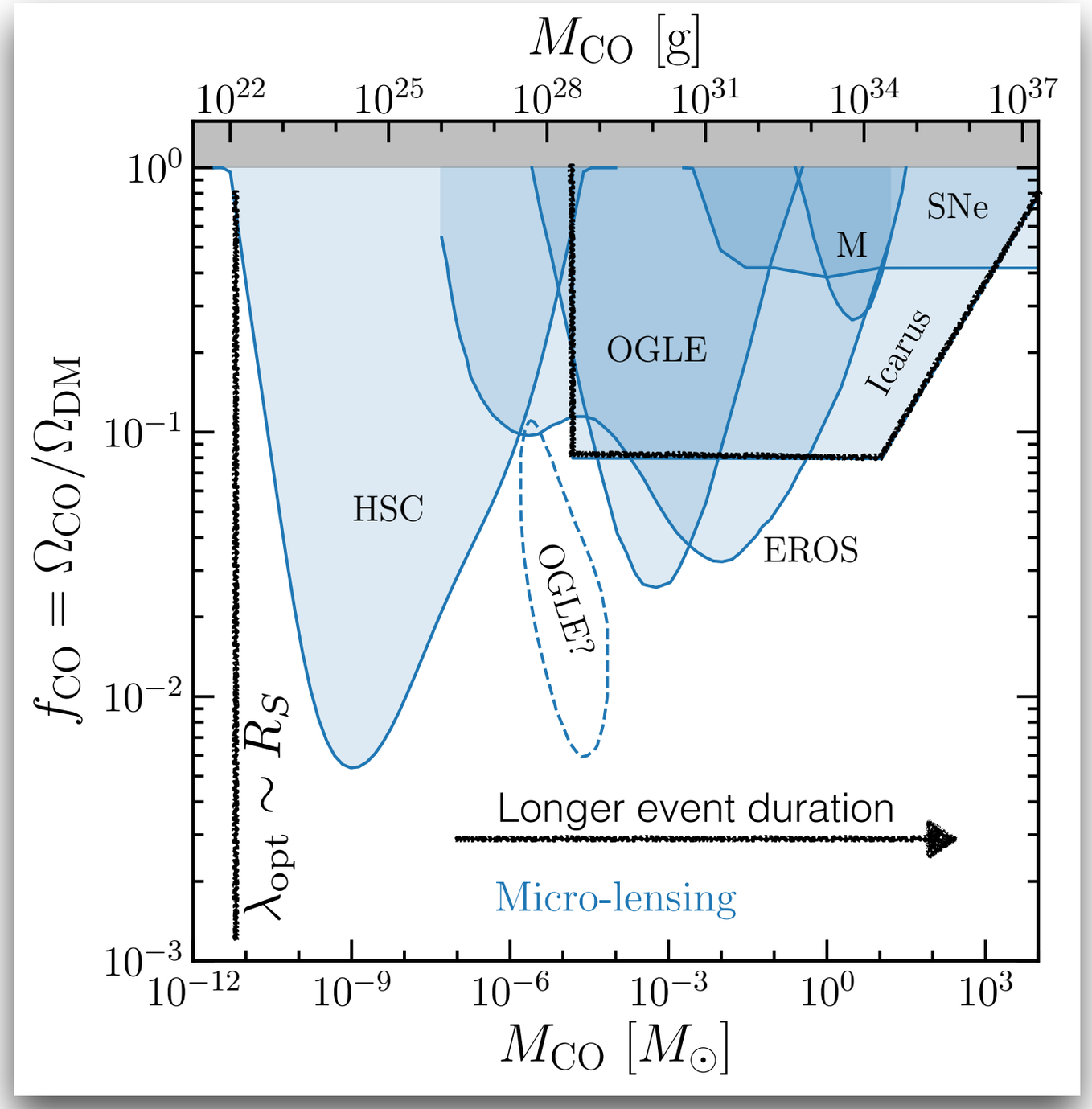

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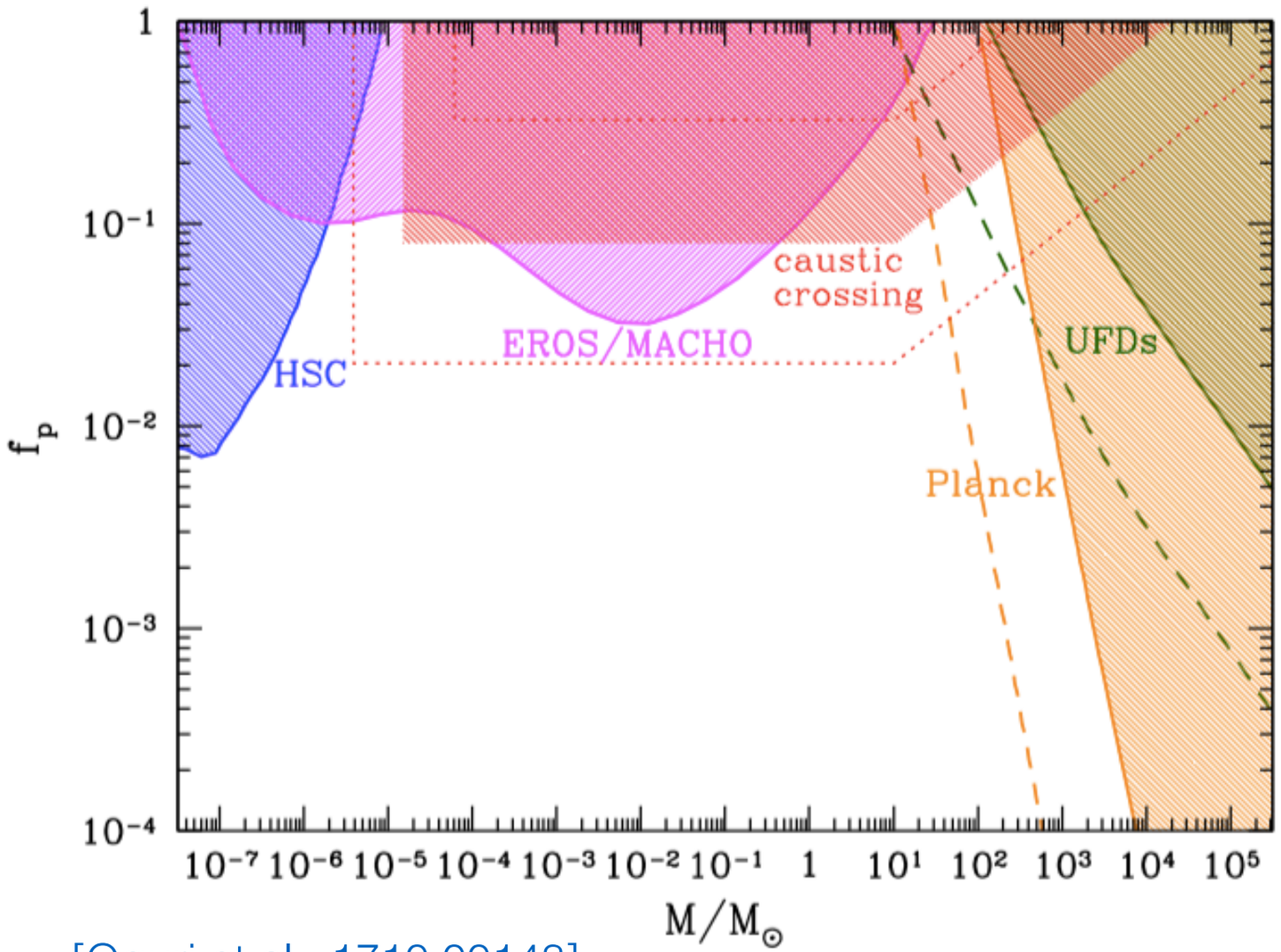
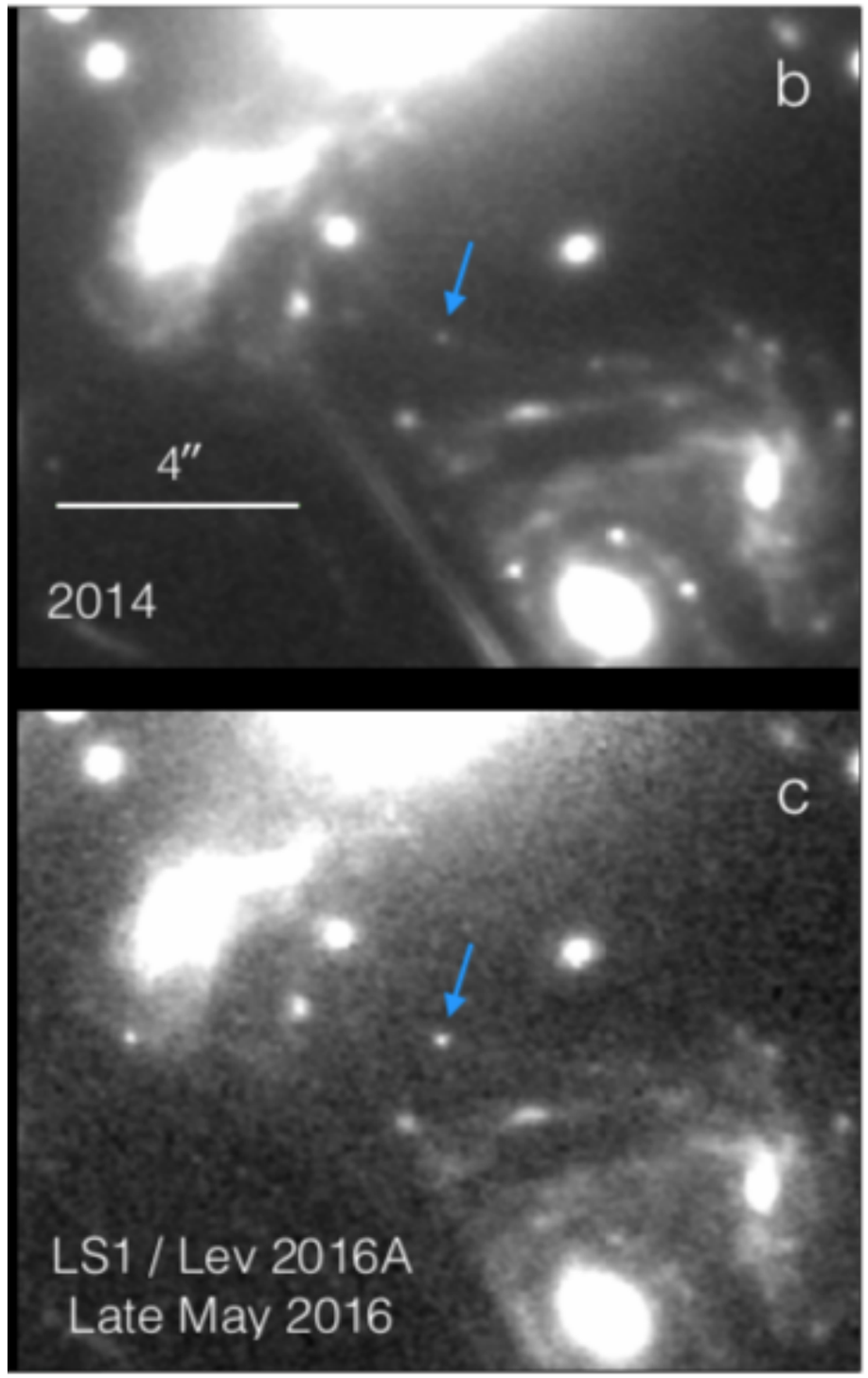
Icarus

Star at z ~ 1.49, magnified by >2000x

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

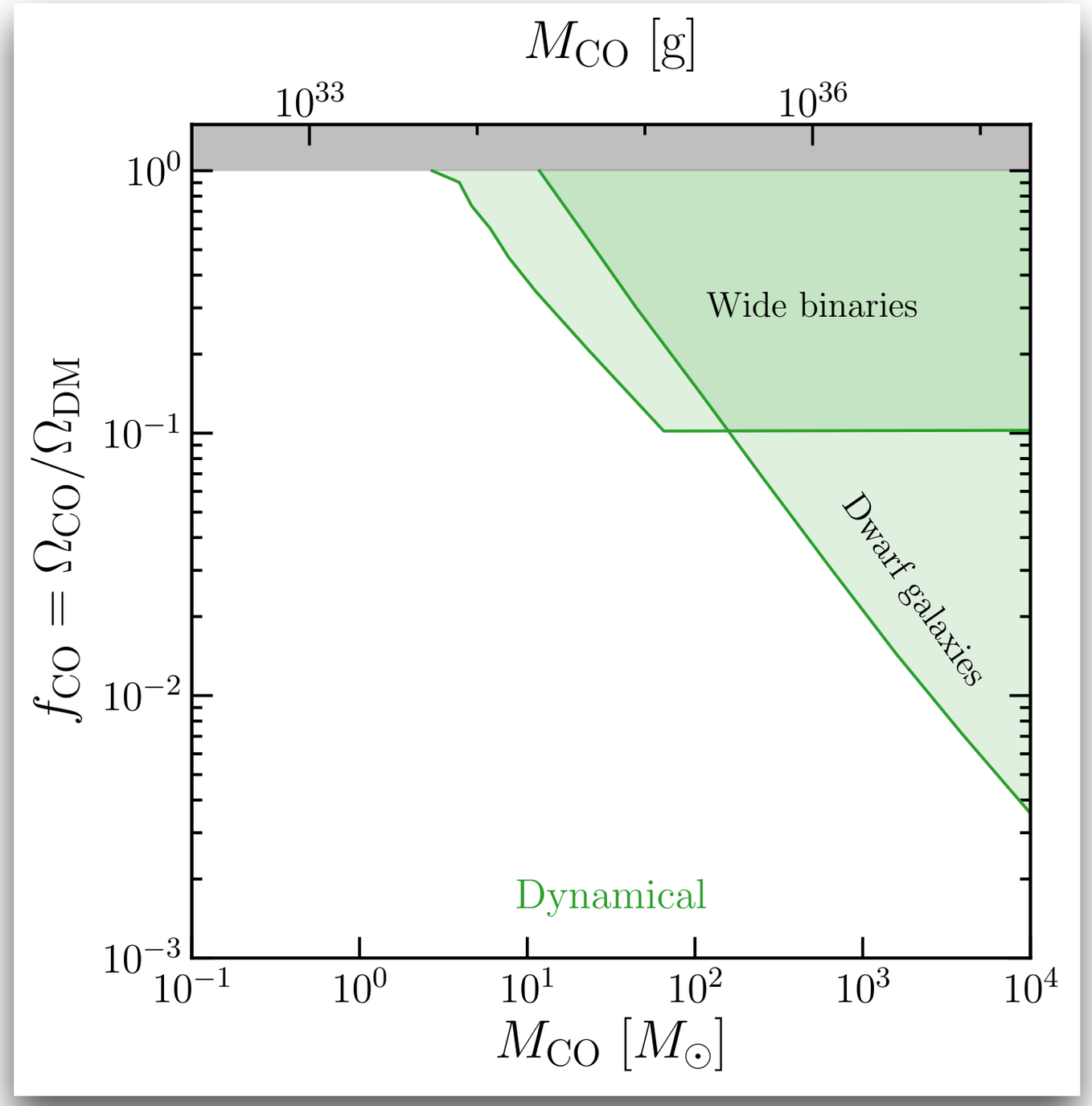


[Oguri et al., 1710.00148]



[Kelly et al., 1706.10279]

Dynamical constraints



Heavy PBHs can 'inject' energy and disrupt bound systems

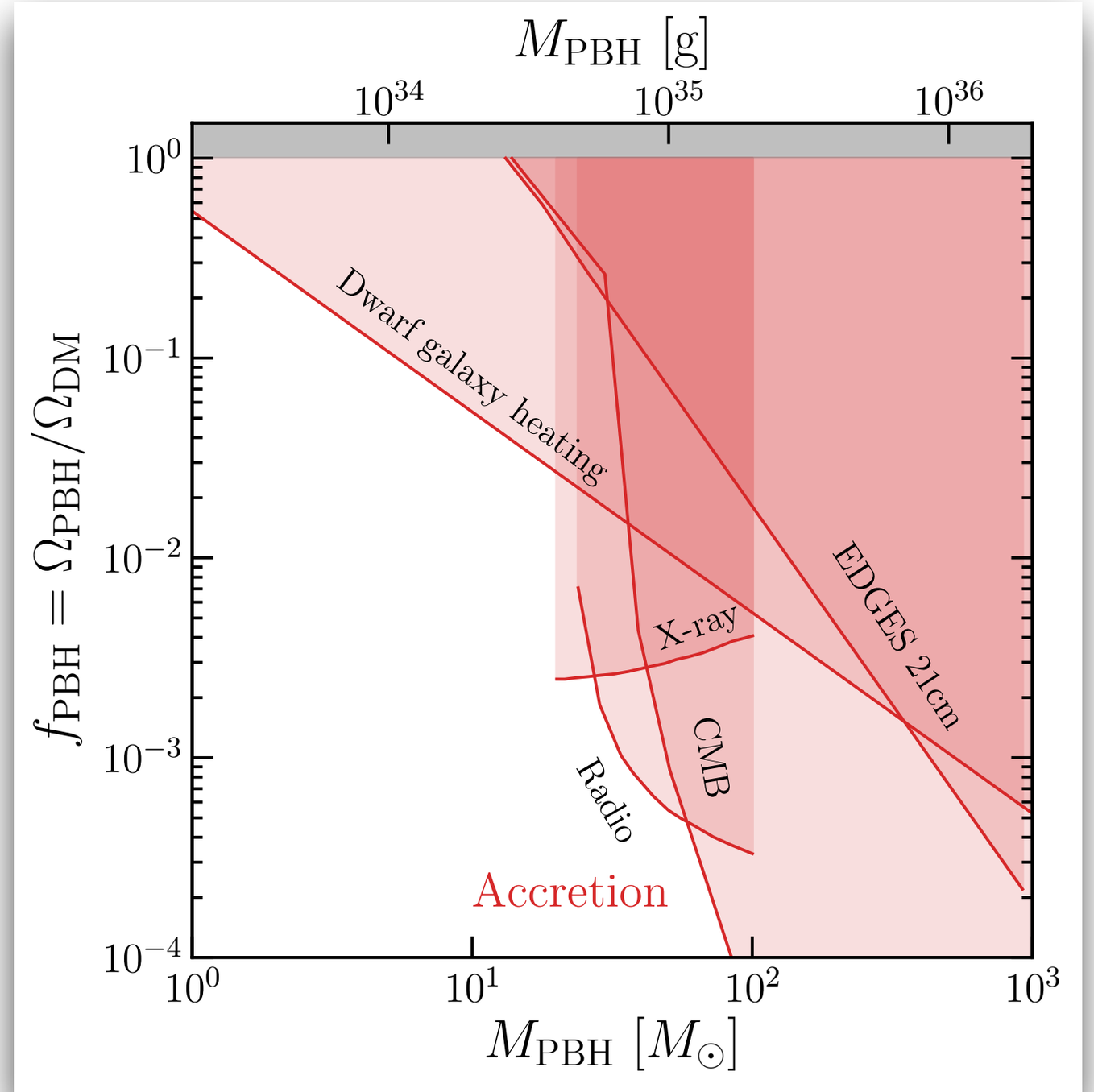
Wide binary constraints should improve with *Gaia*

[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]

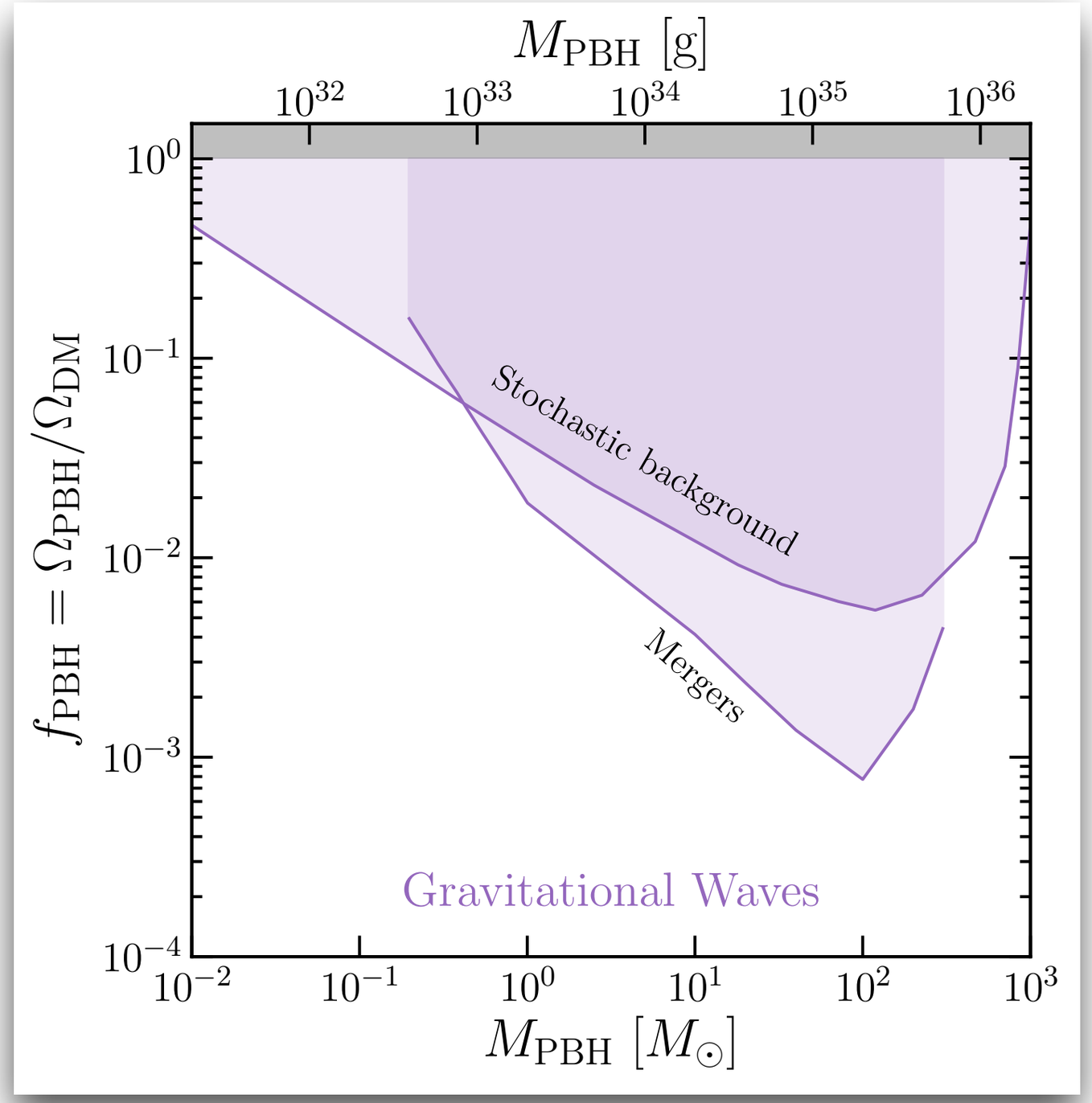
CMB bounds now on solid ground (and getting stronger)

[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]

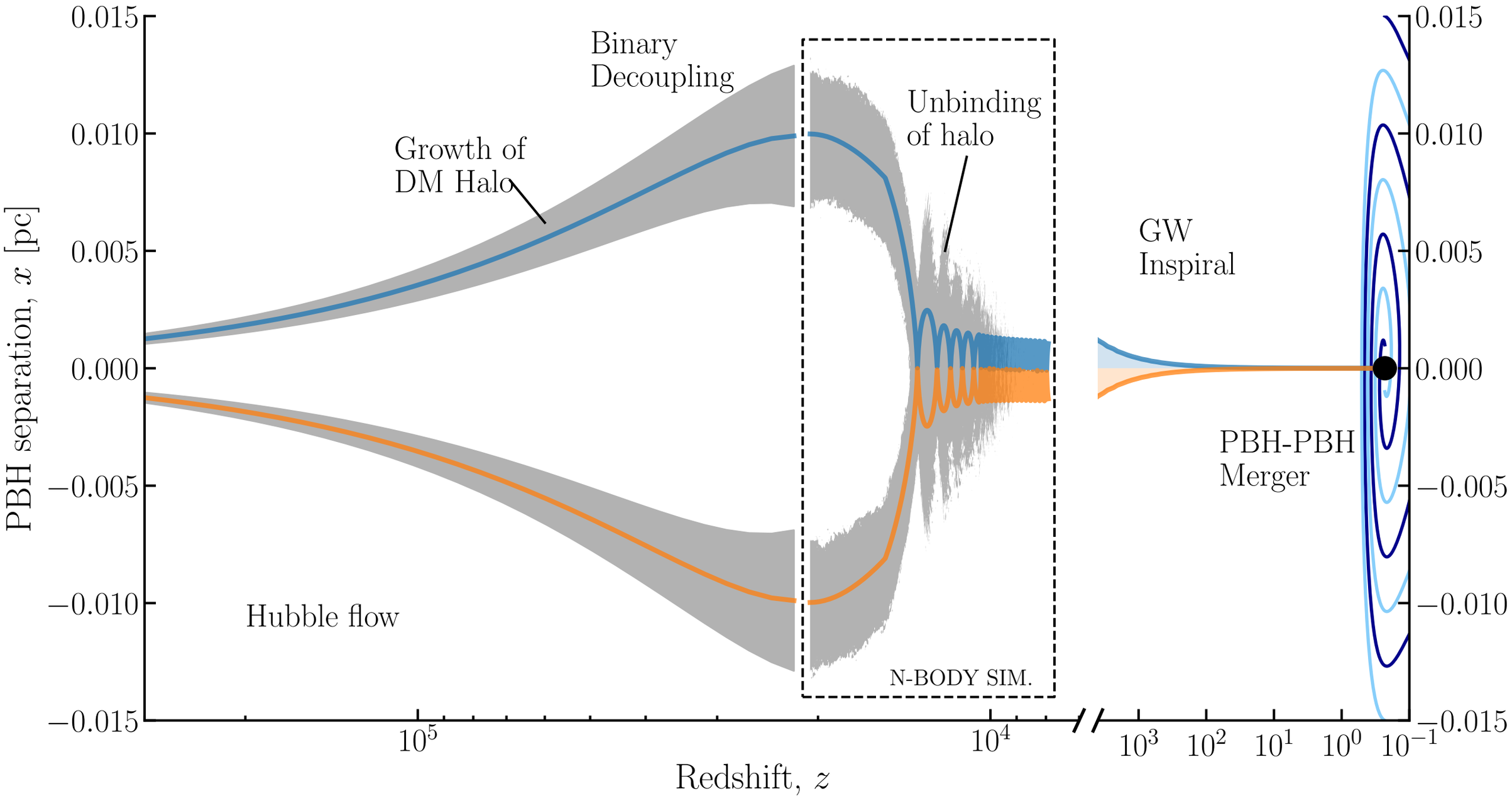
…but dominate rate comes from early Universe binaries…

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

or so we (?) thought…

Life of a PBH binary

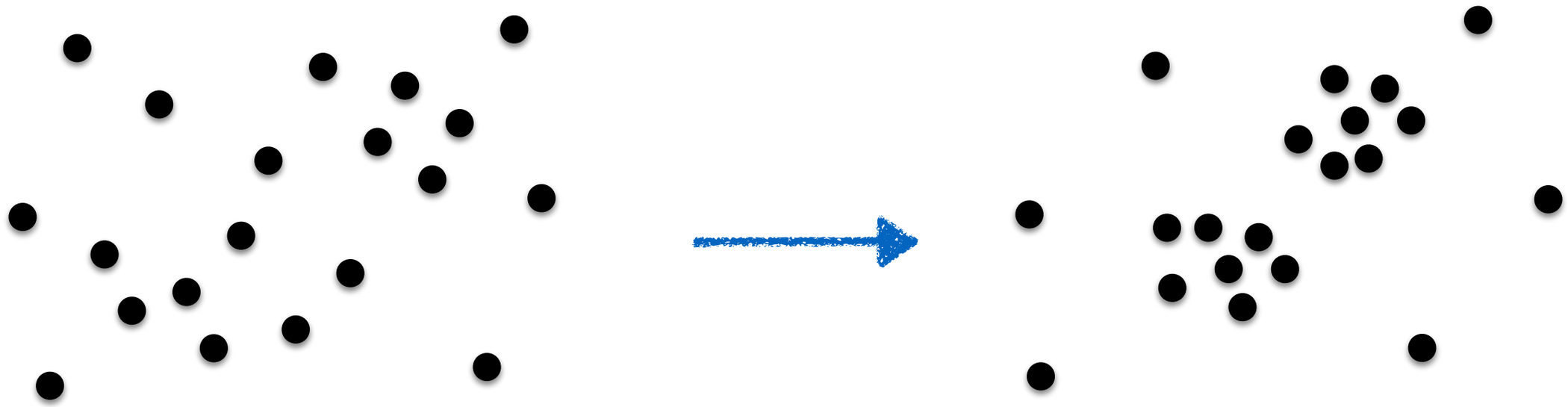
$$a_i = 0.01\,\mathrm{pc}$$
$$e_i = 0.995$$



[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



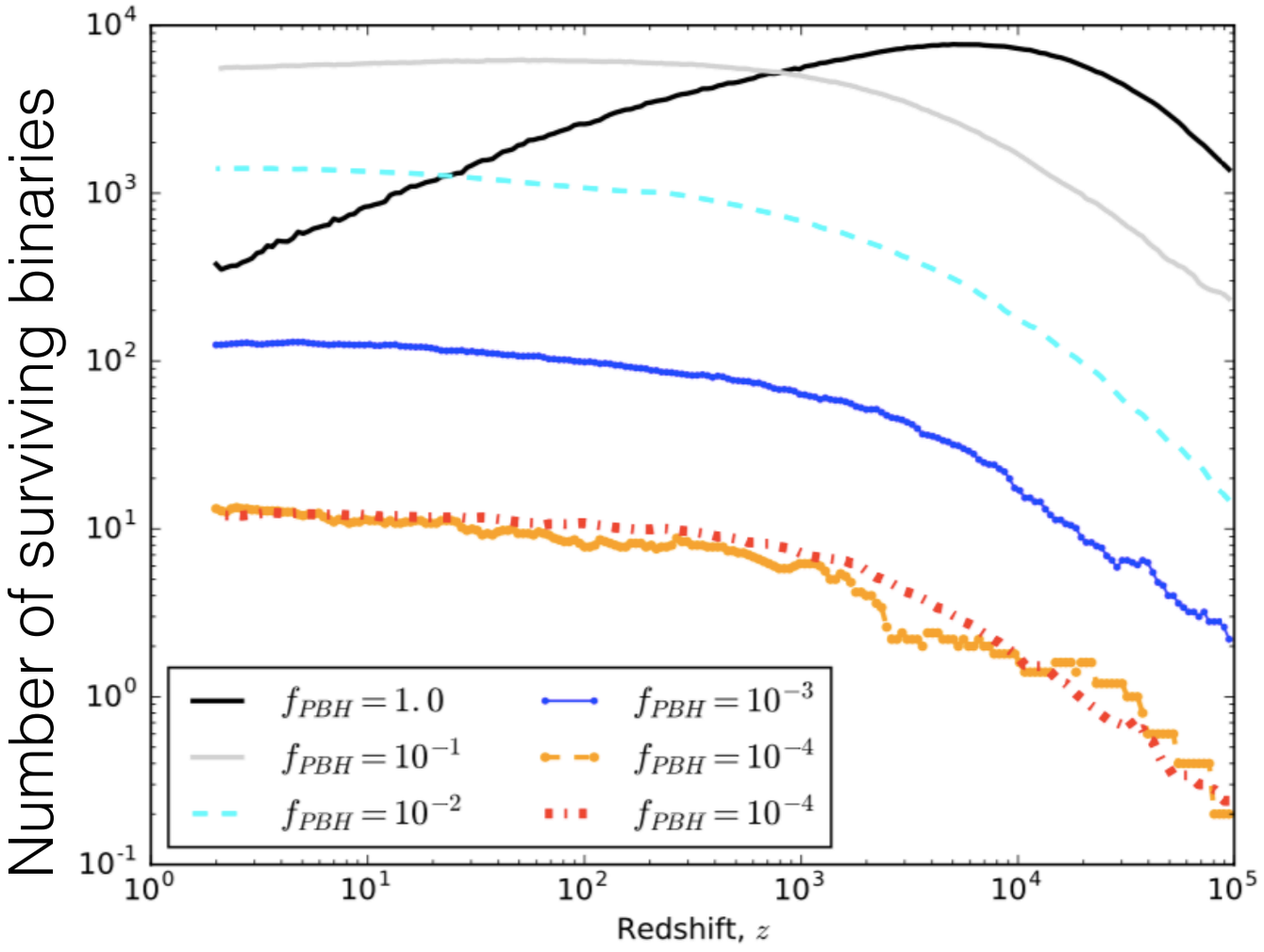
$z \gg 10^4$ $z \lesssim 100$

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

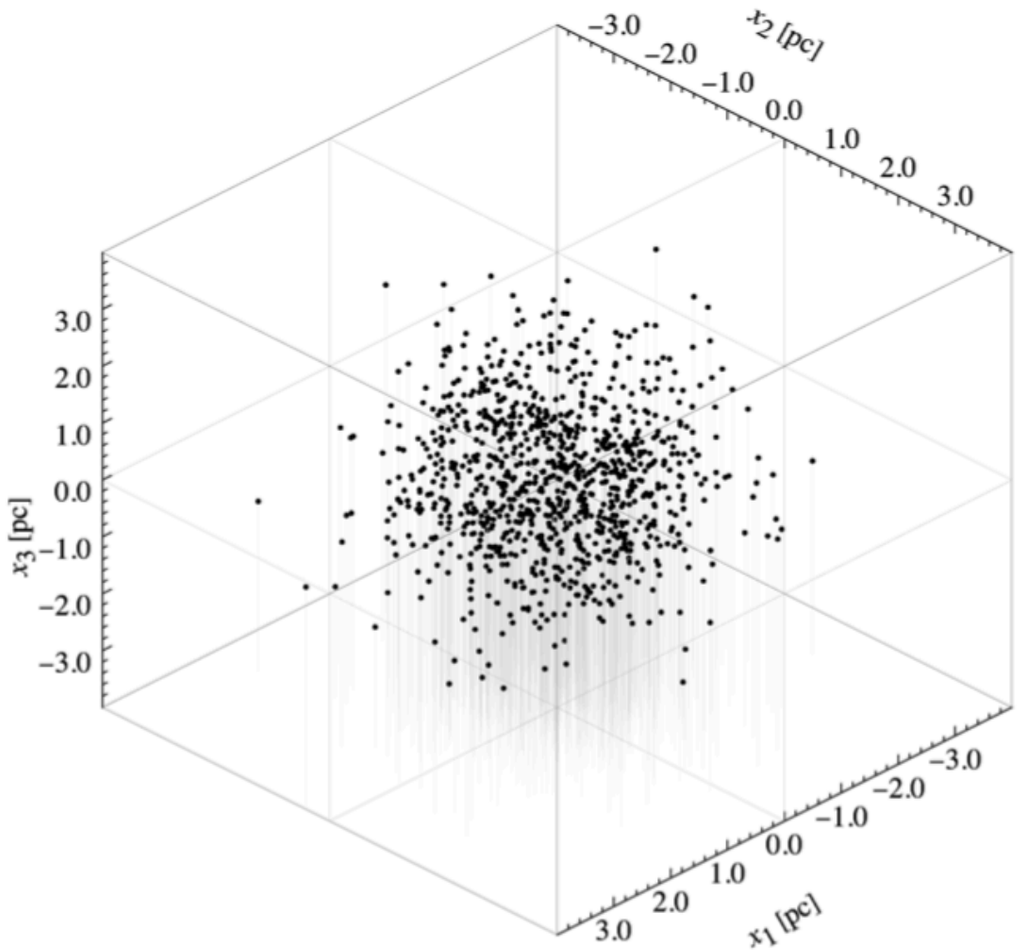
[Chisholm - astro-ph/0509141, 1110.4402, Inman & Ali-Haïmoud, 1907.08129]

Simulations

Simulate isolated clusters or attempt something cosmological:



[Tkachev, Pilipenko & Yepes - 2009.07813]



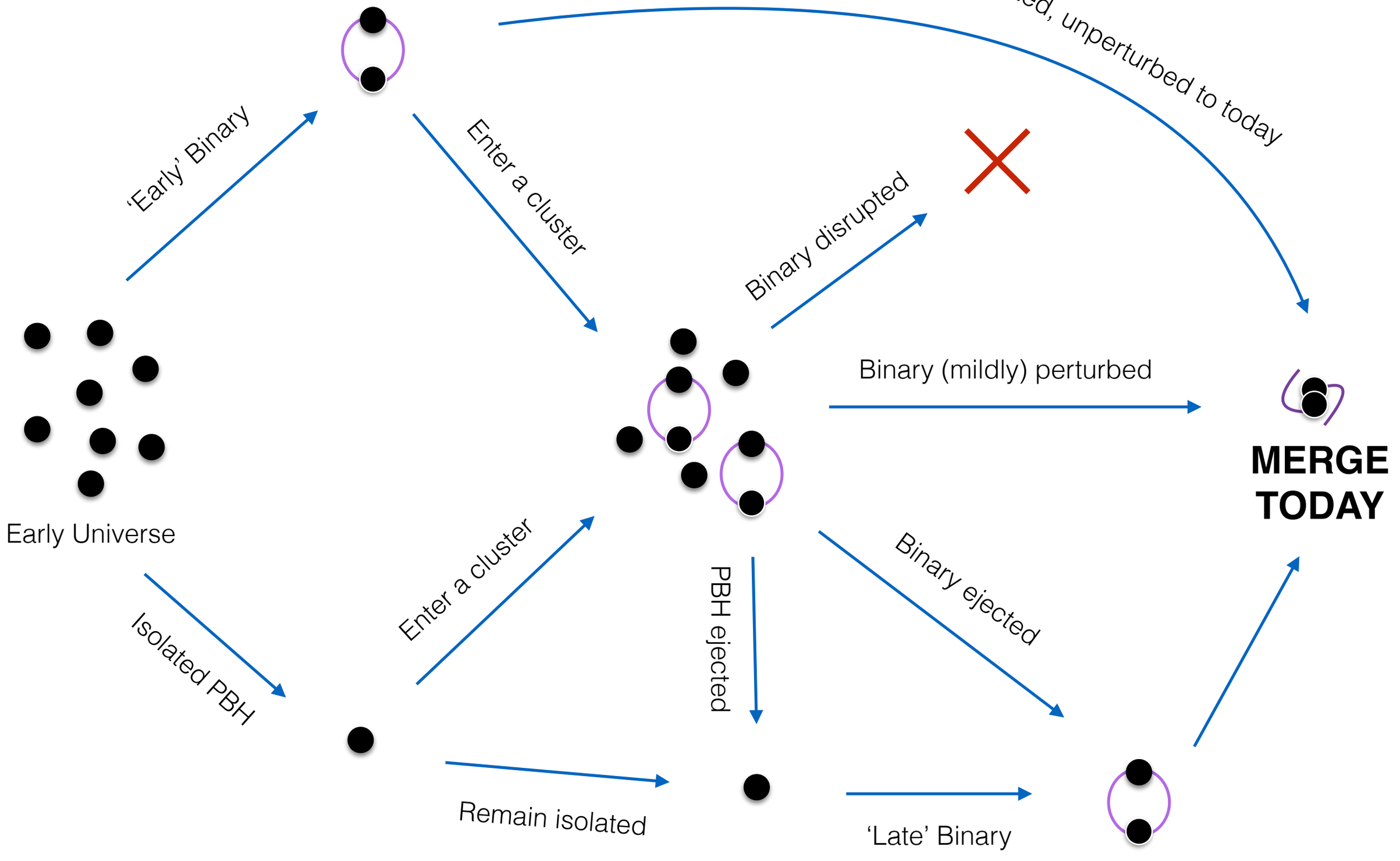
[Trashorras et al., 2006.15018]

Clusters may perturb/disrupt binaries or encourage binary formation…

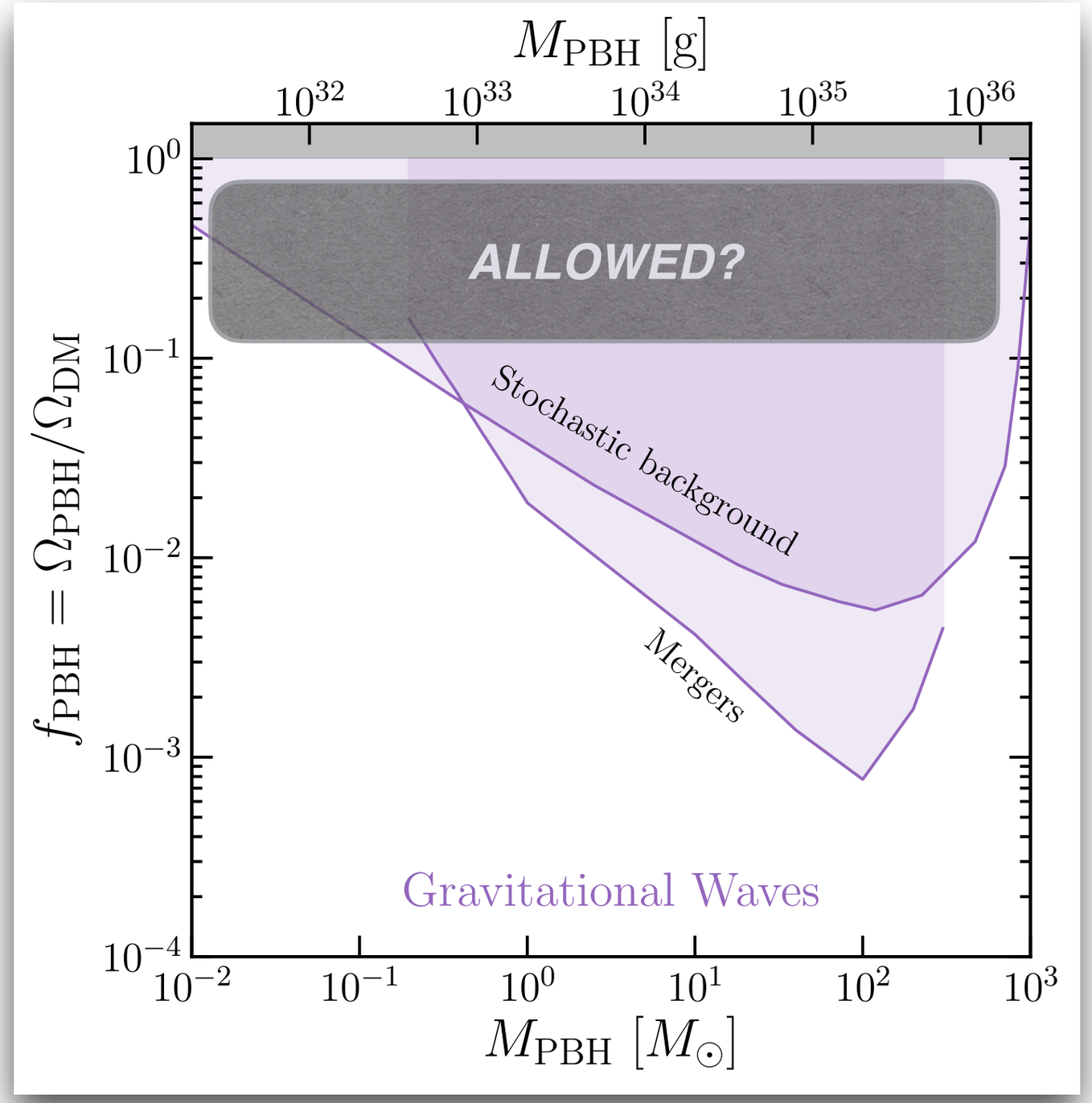
[Jedamzik - 2006.11172, 2007.03565]

Paths to PBH mergers

[See e.g. 1812.01930, 1908.09752, 2007.07212, 2009.04731]



Gravitational Waves



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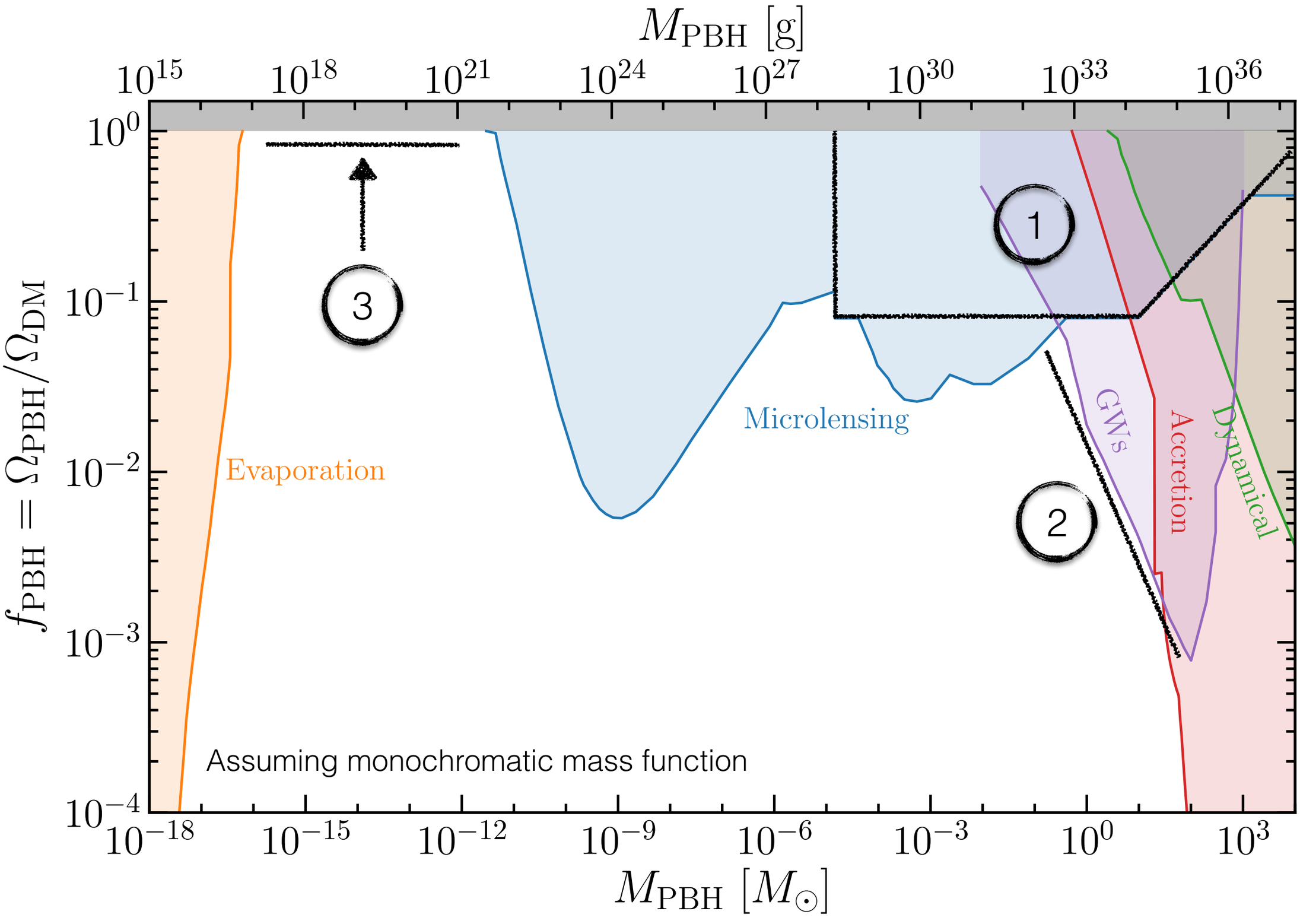
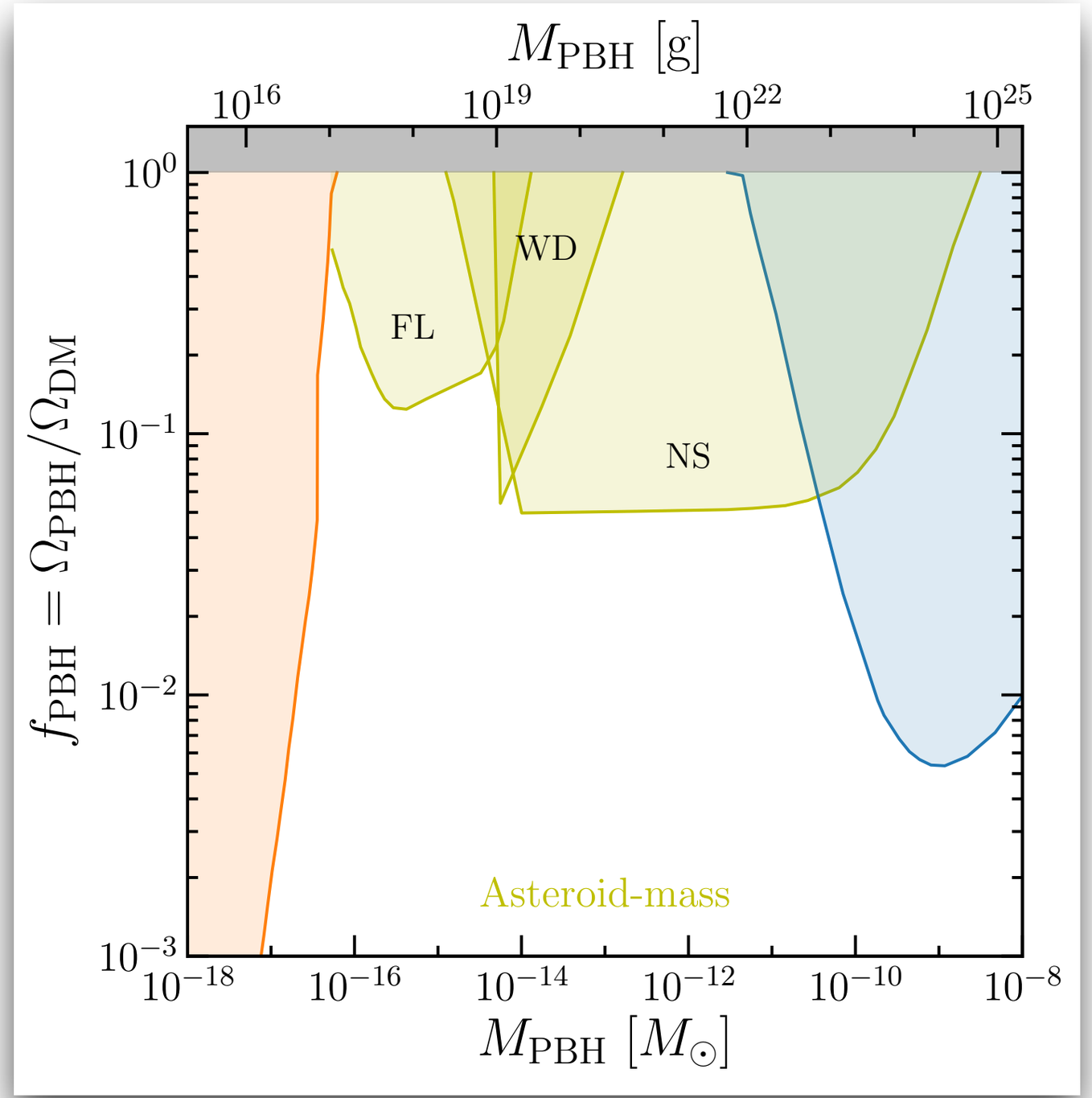


Asteroid-mass PBHs



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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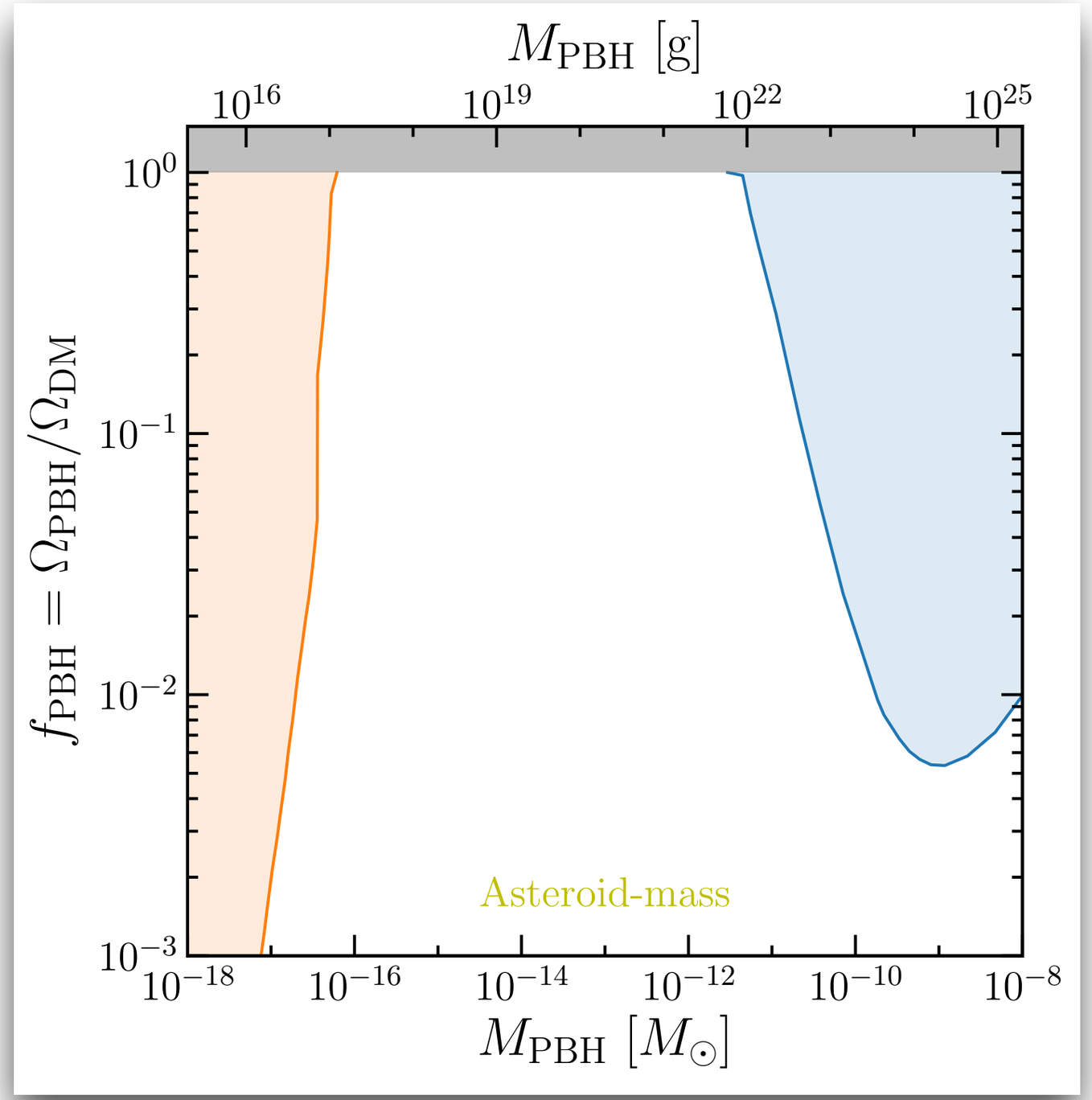

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[Katz et al., 1807.11495]

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[Montero-Camacho et al., 1906.05950]

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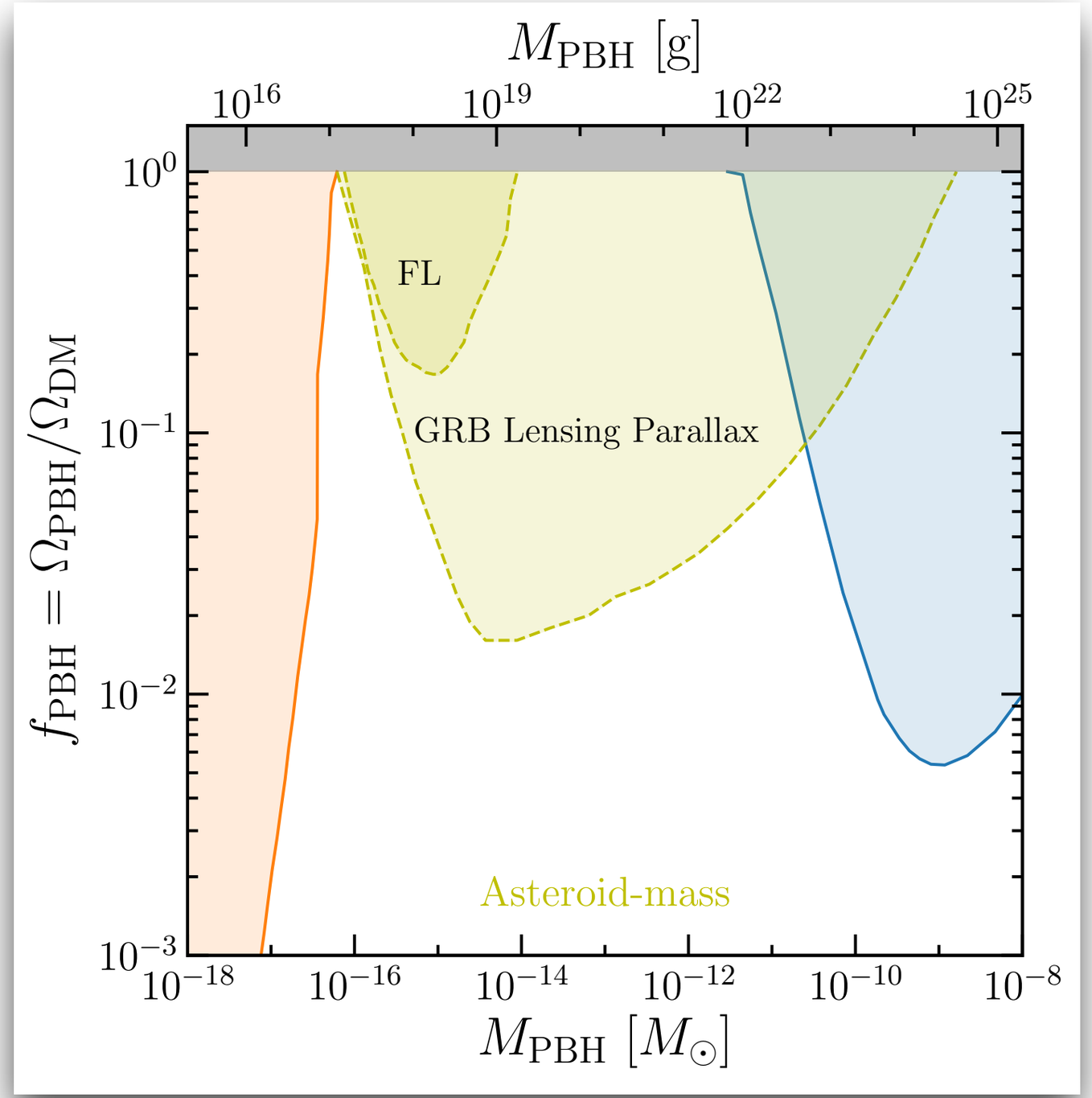

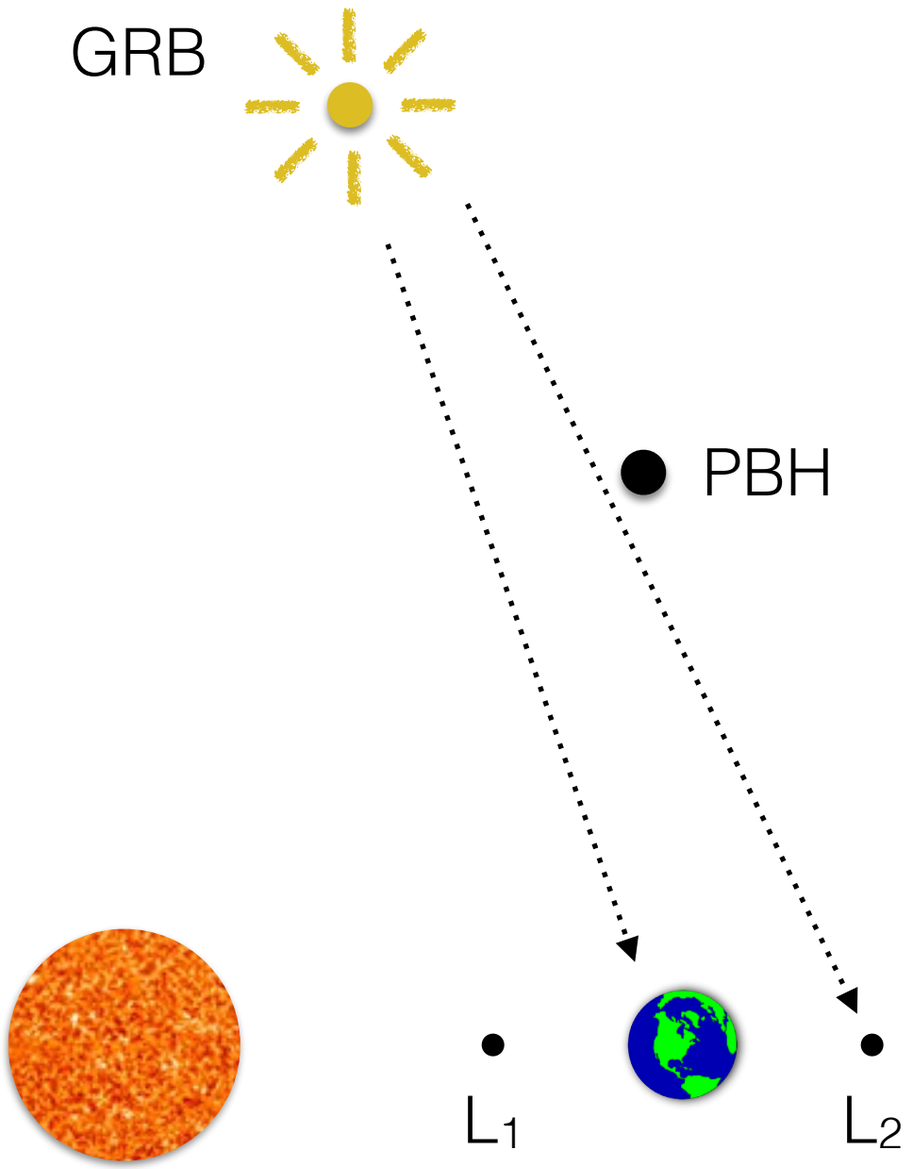

[Nemiroff & Gould, astro-ph/9505019, Jung & Kim, 1908.00078]

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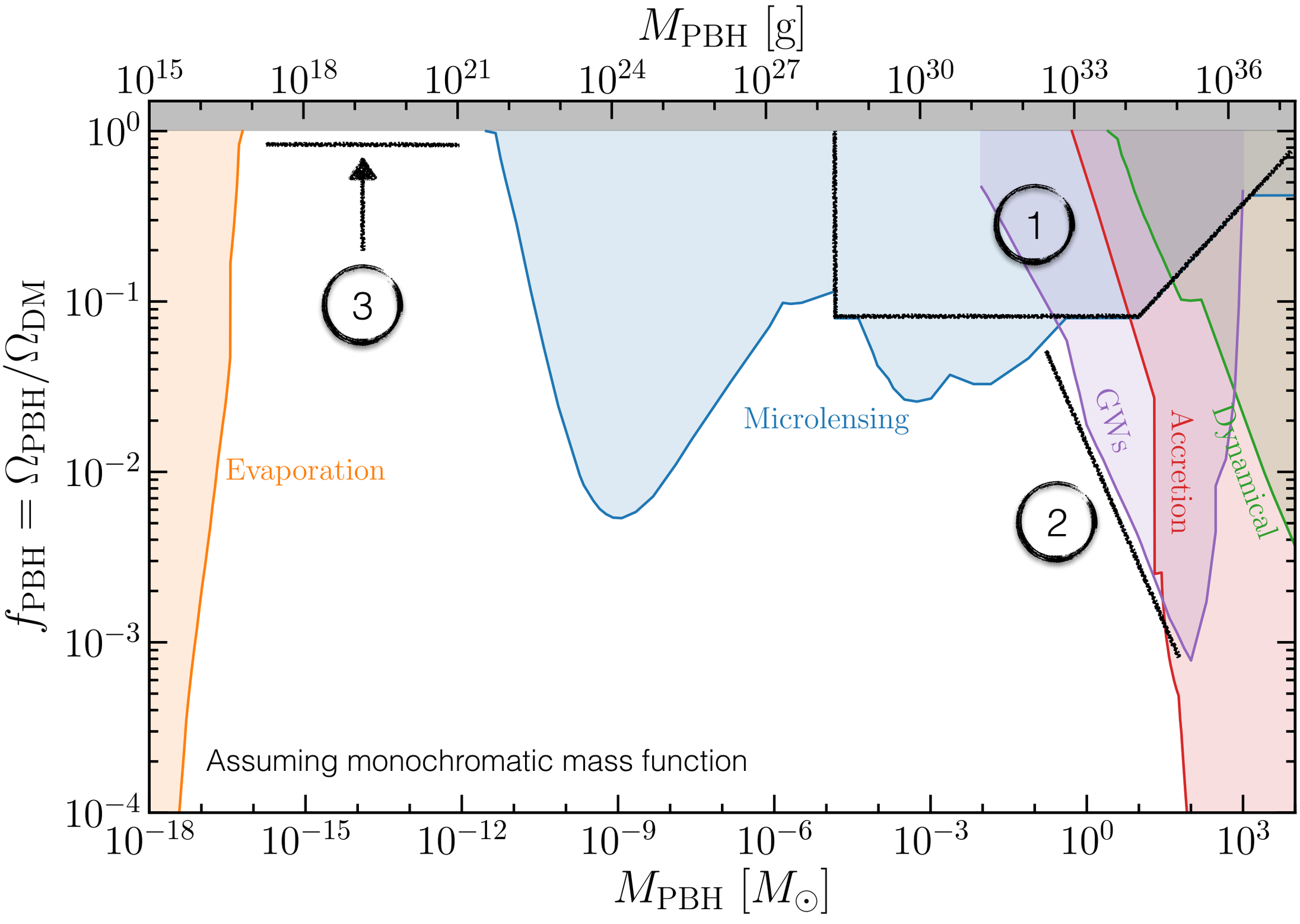

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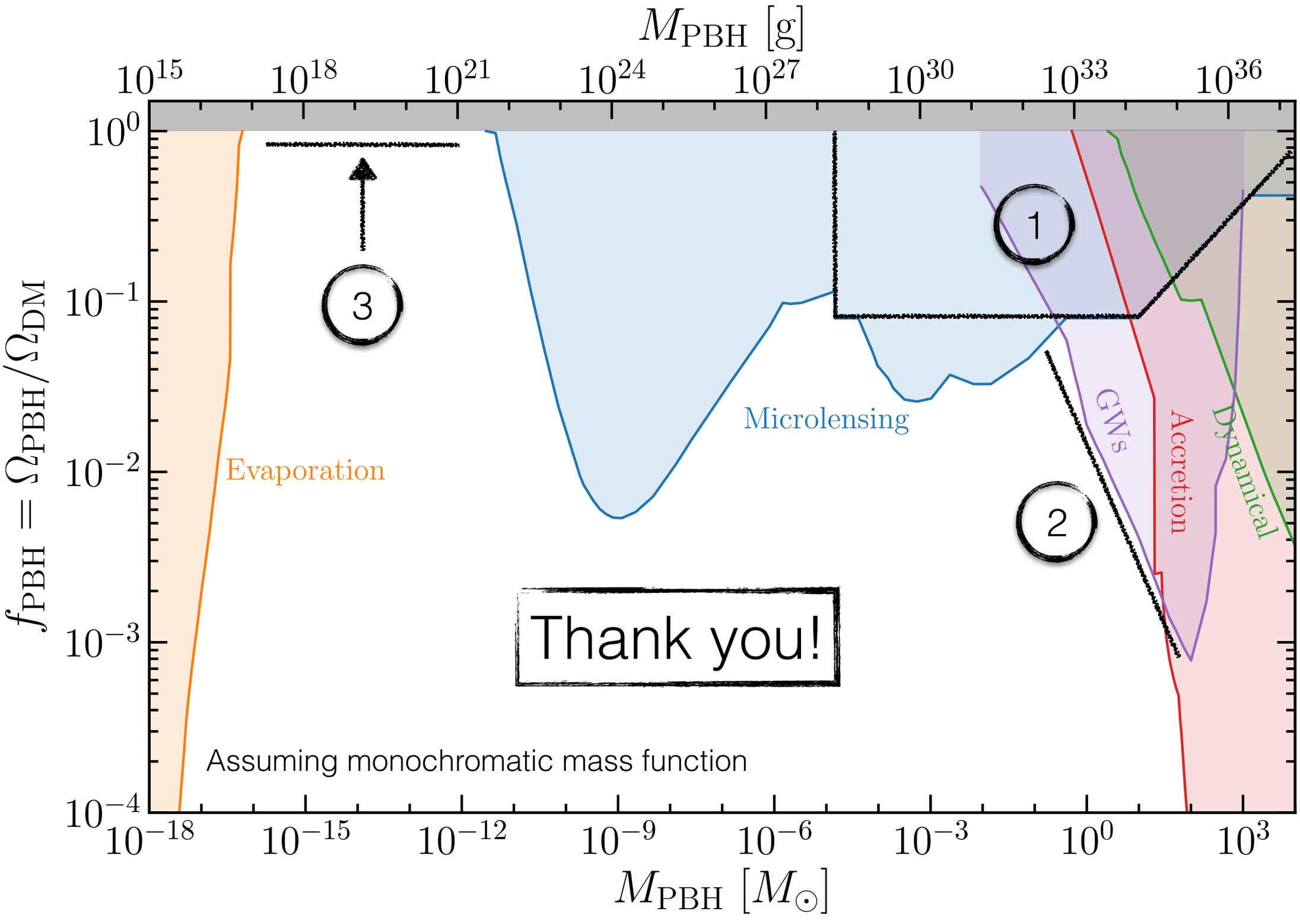
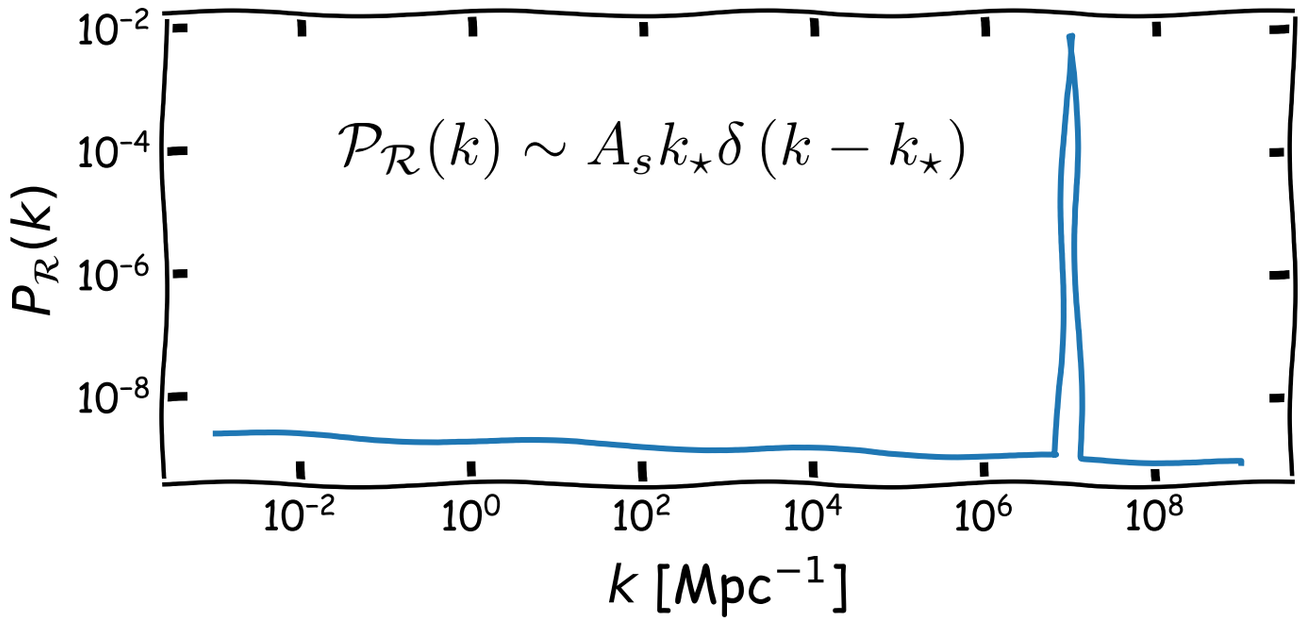


Backup Slides

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

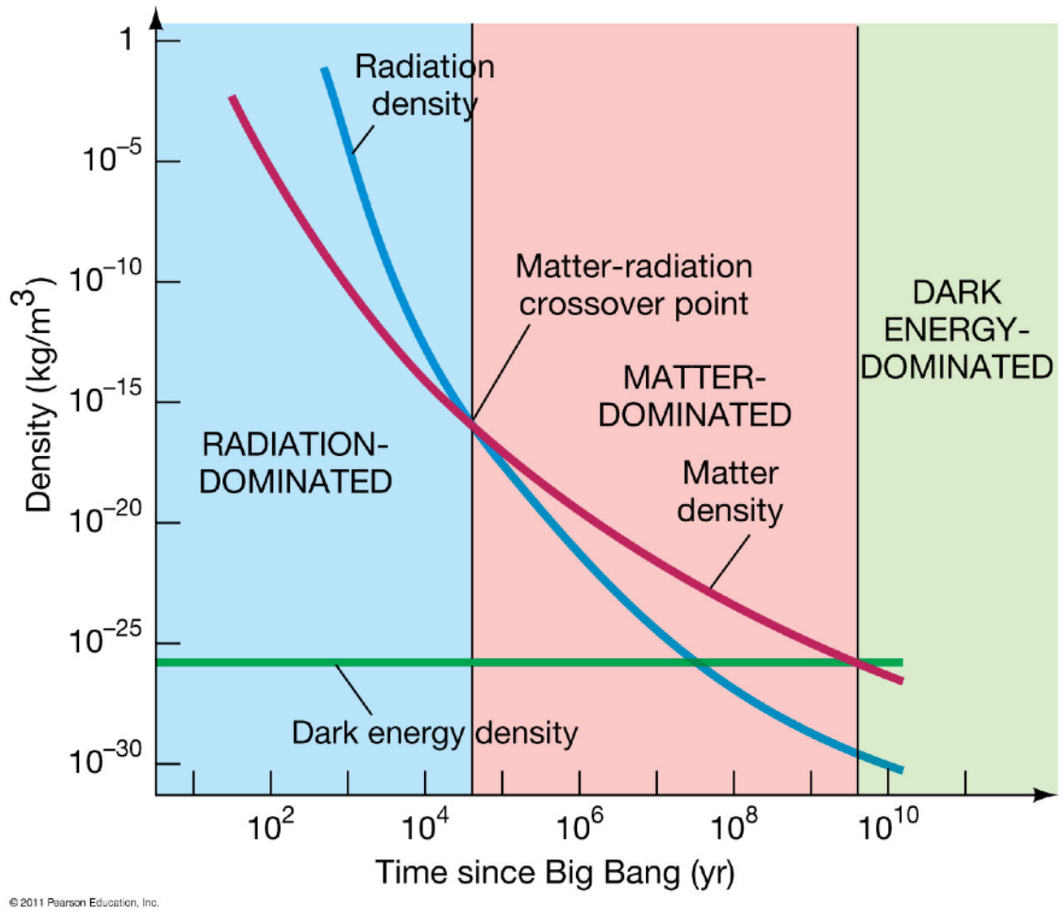
The typical GW frequency scales as $f_{\rm GW}^{\rm peak} \sim k_\star$, giving:

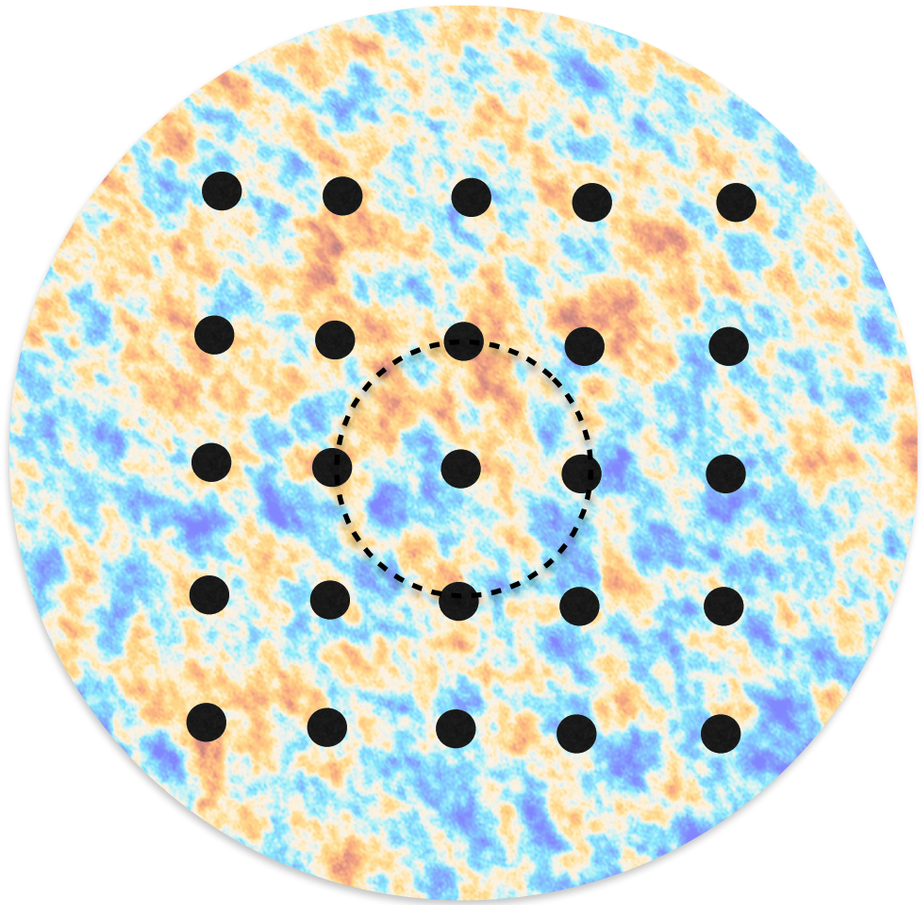
$$f_{\rm GW}^{\rm peak} = 3 \times 10^{-9} \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2} {\rm Hz}$$

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

Early Universe Binaries

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





PBH Binary Population

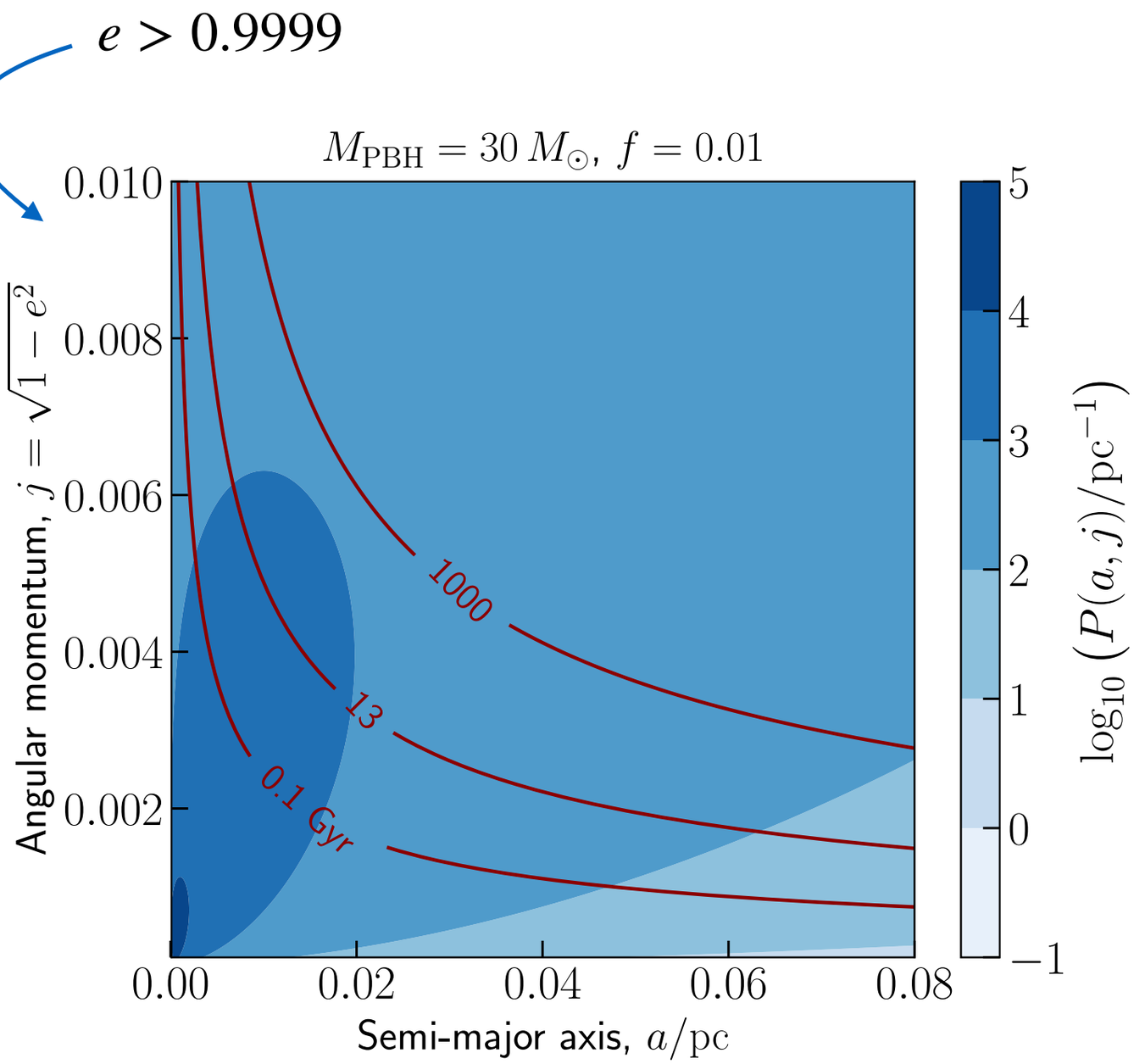
$$j = \sqrt{1 - e^2}$$

Randomly distributed (unclustered*) PBHs

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

Close, eccentric binaries merge today:

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

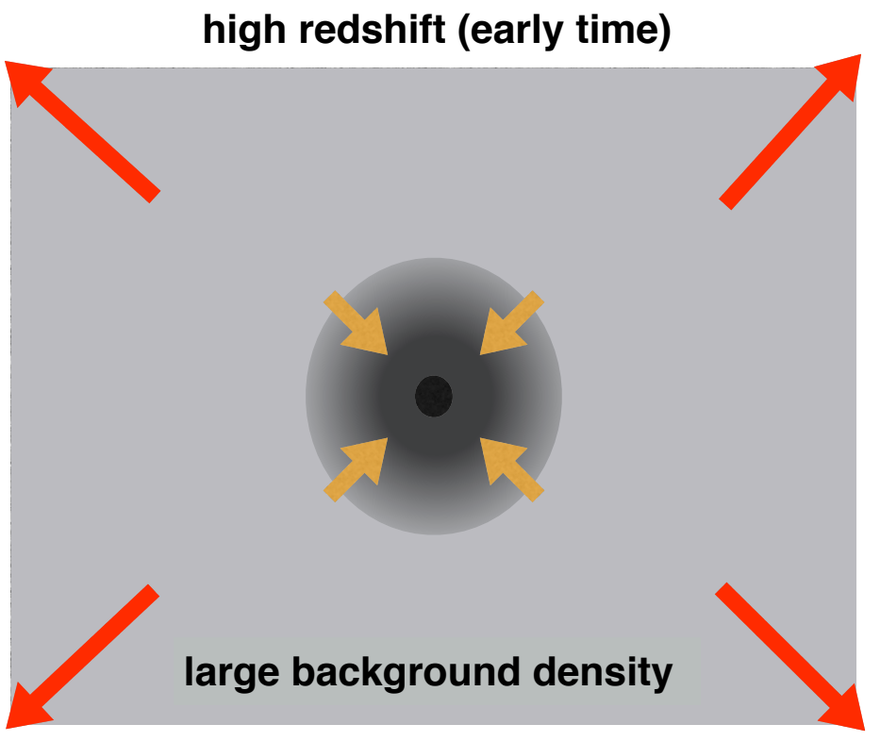


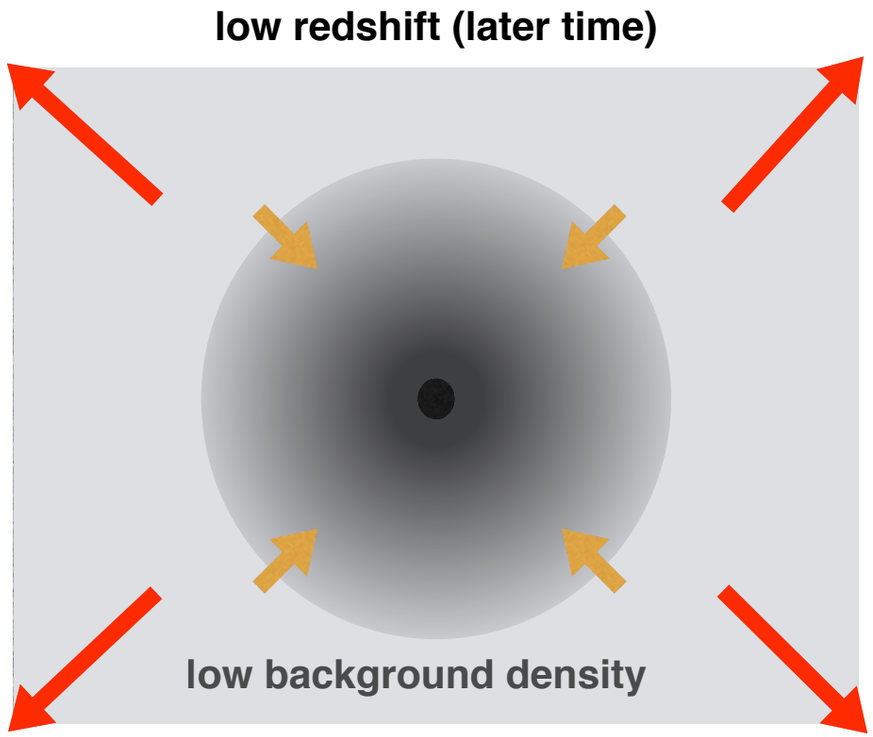
[**BJK**, Gaggero & Bertone, 1805.09034]

[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:





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

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

[Bertschinger (1985)]
[0706.0864, 1901.08528]

Slide shamelessly ripped off from Daniele Gaggero

Detection prospects

[See also 2007.00021]

GW detection of sub-solar mass BHs

(LIGO O3, now!)

GW detection of high redshift BHs (z > 40)

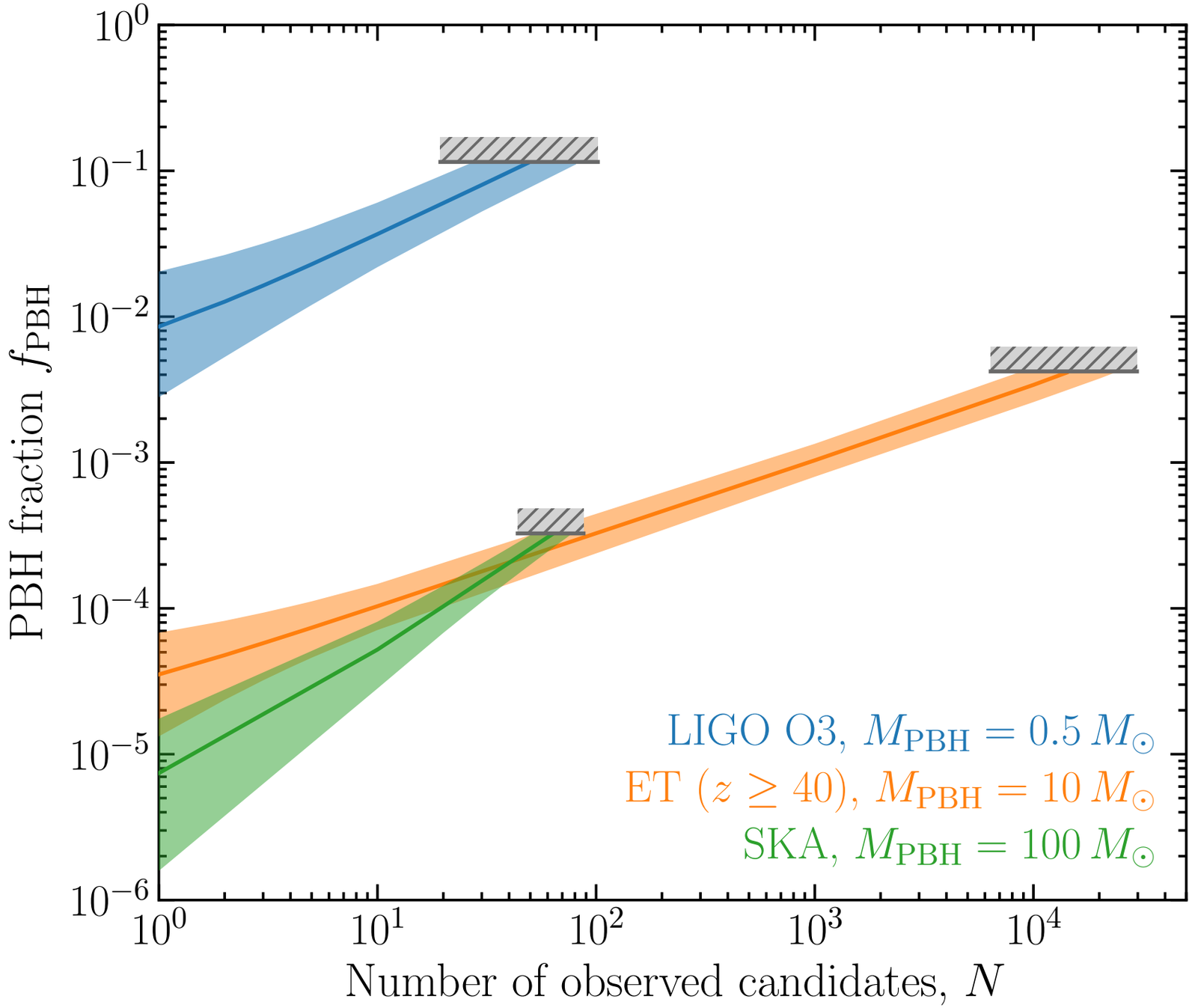
(Einstein Telescope, mid-late 2020s)

[1708.07380]

Radio detection of accreting galactic PBHs

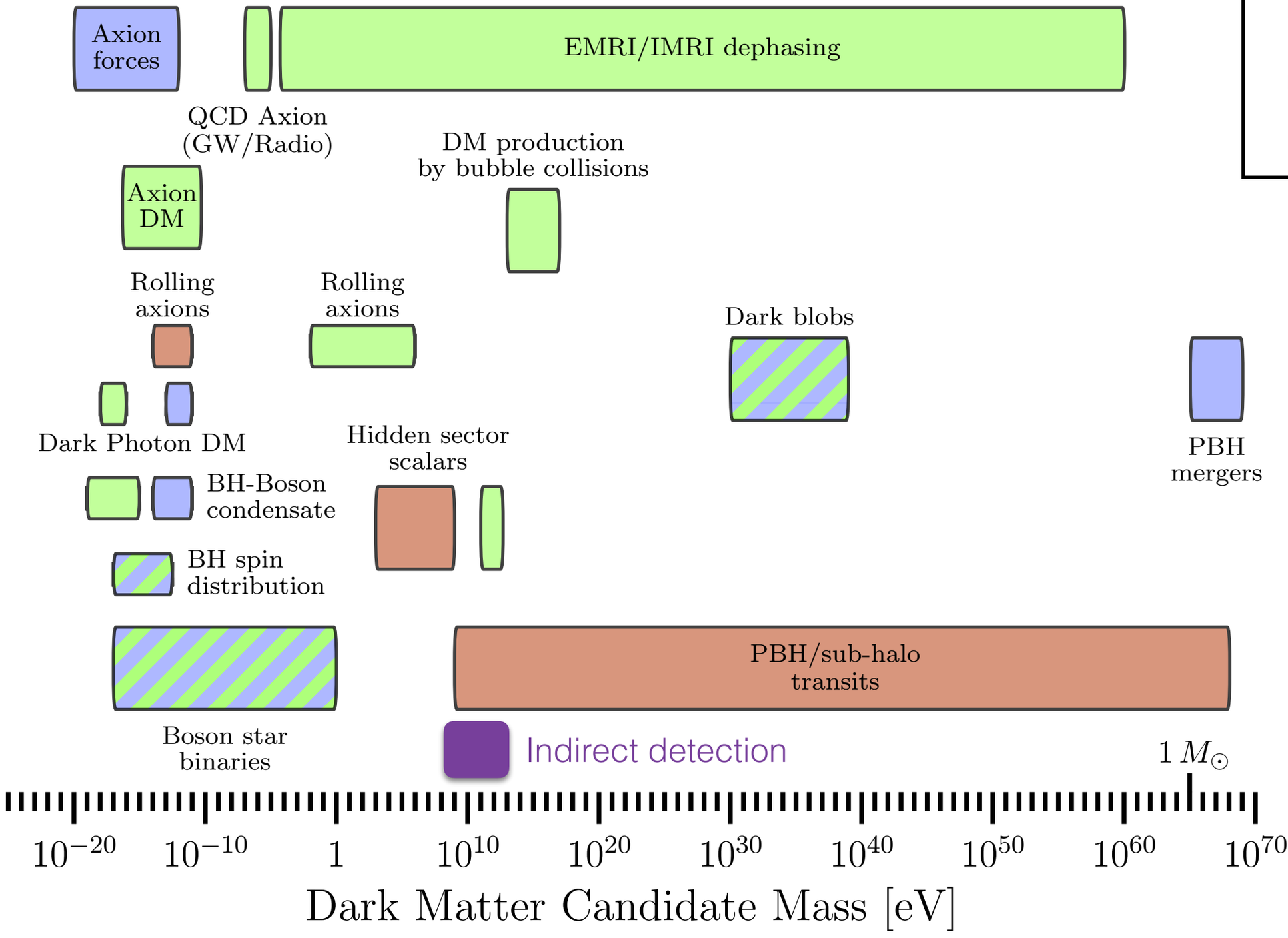
(Square Kilometre Array, late 2020s)

[1812.07967]



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

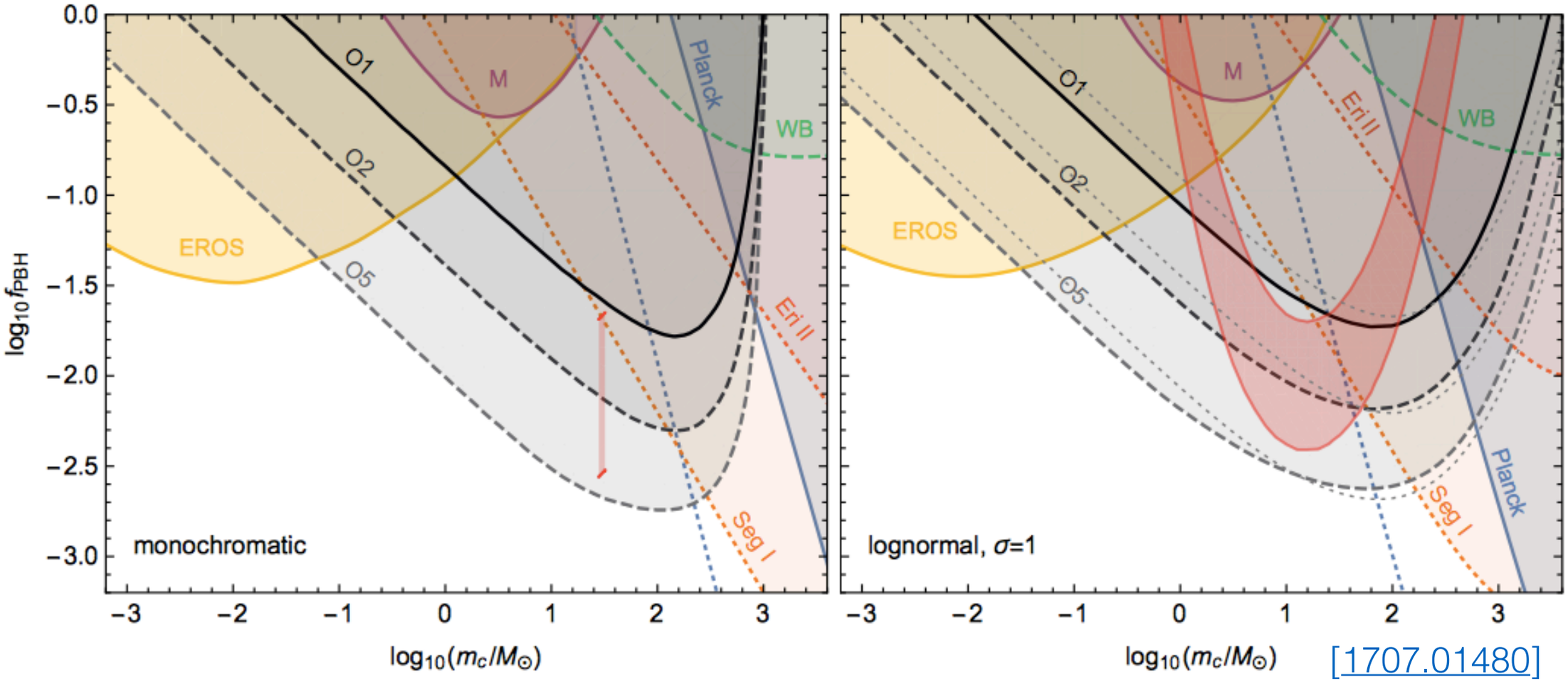
GW probes of DM



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

Extended Mass Function

LIGO O1 Limit



[1707.01480]

[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

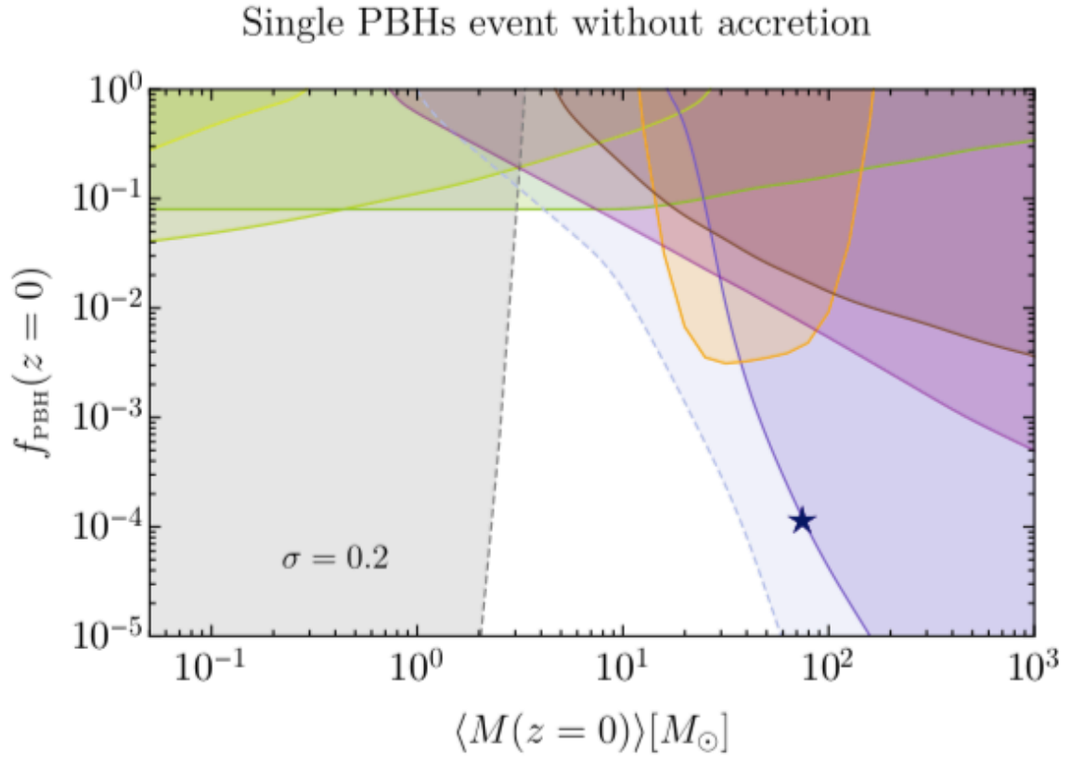
[Carr et al., 1705.05567]

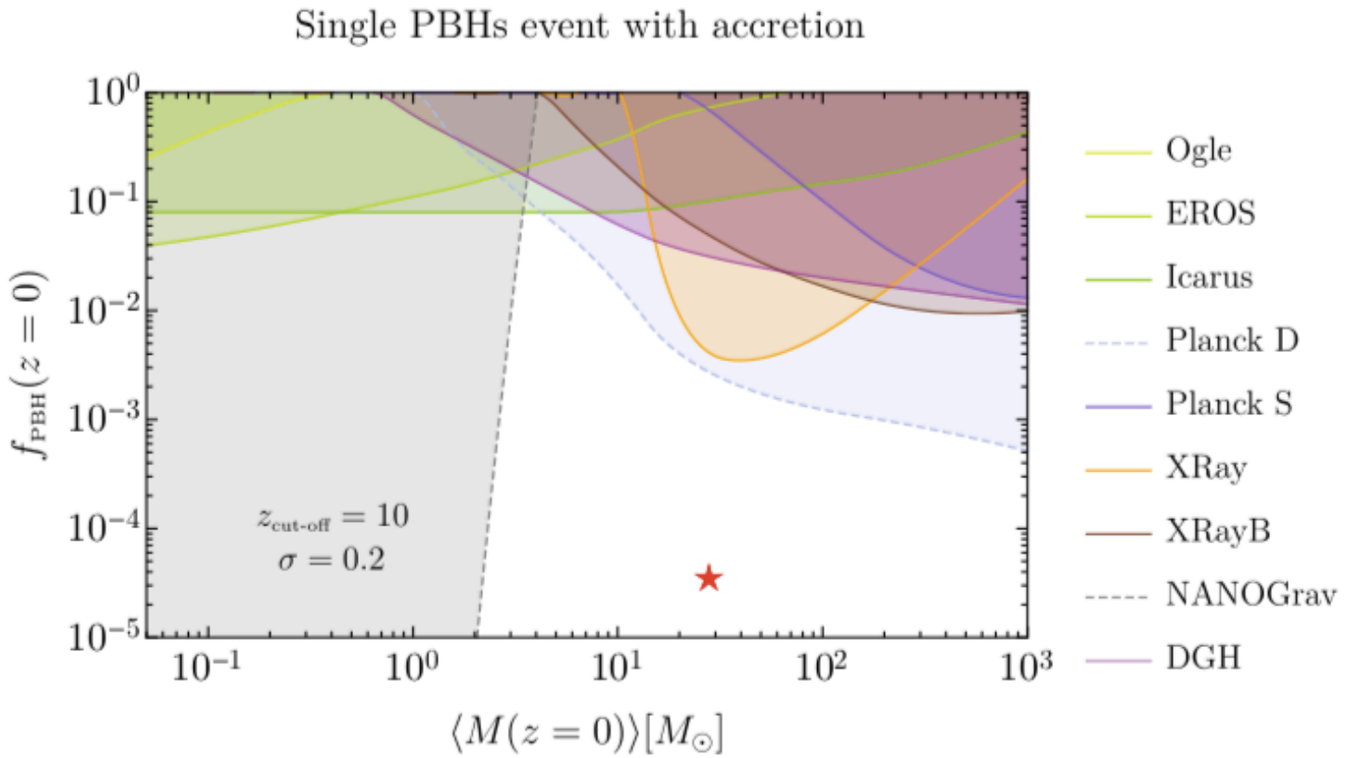
GW190521

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	$85^{+21}_{-14}\ M_\odot$
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]