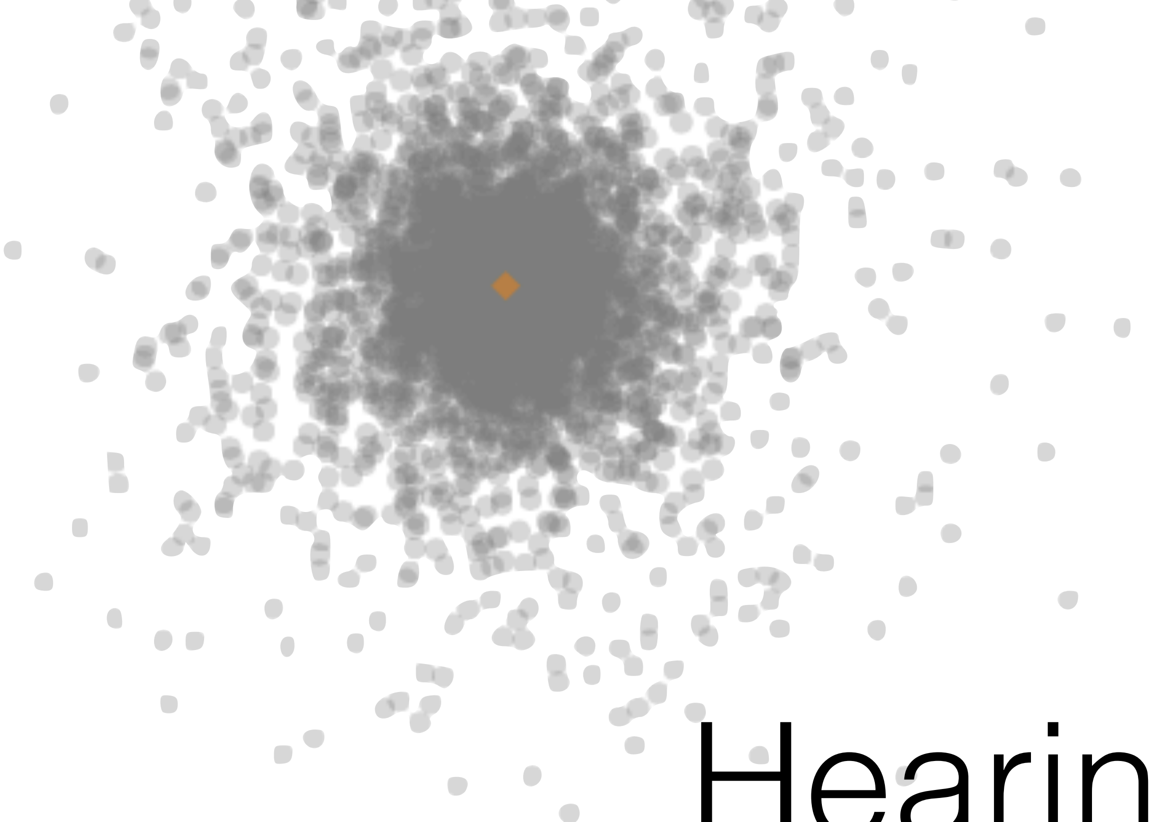

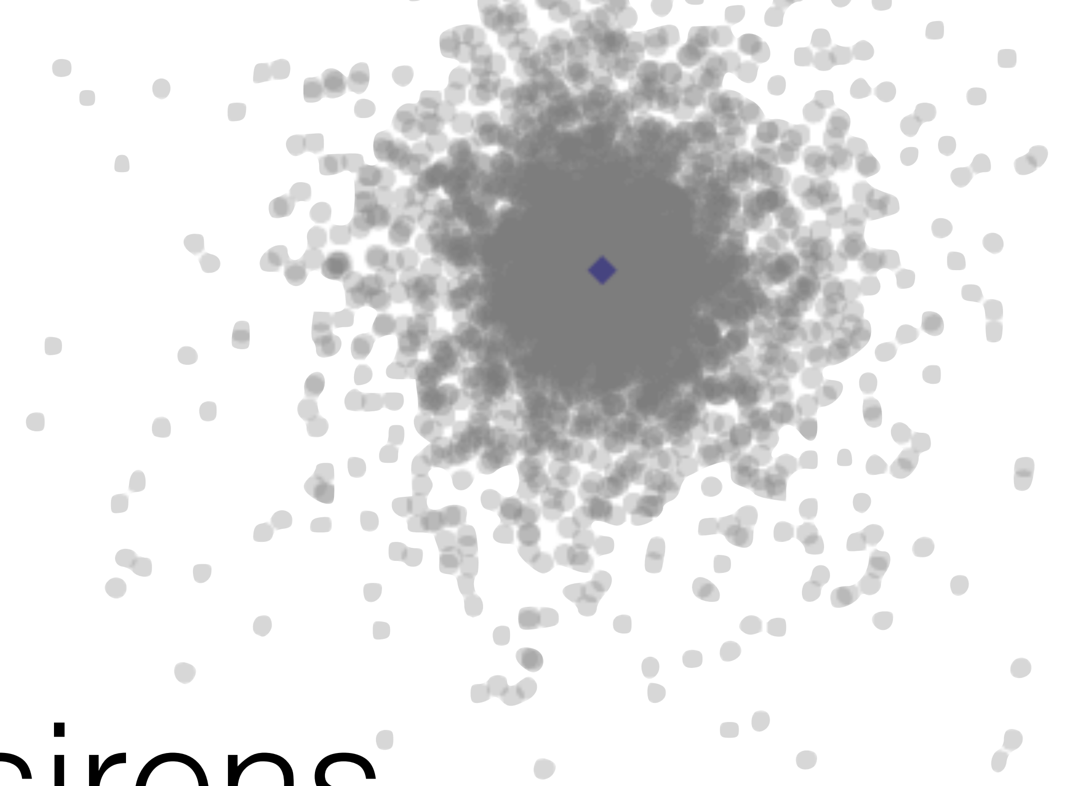

Hearing the sirens of the early Universe:

Primordial Black Holes & Gravitational Waves

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GRavitation AstroParticle Physics Amsterdam

#GW4FP

12 Nov 2019

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Disclaimer

This talk contains references to mythical creatures, which *may* or *may not* exist.

For example:

Sirens

www.maicar.com

Werewolves

aaronsimscompany

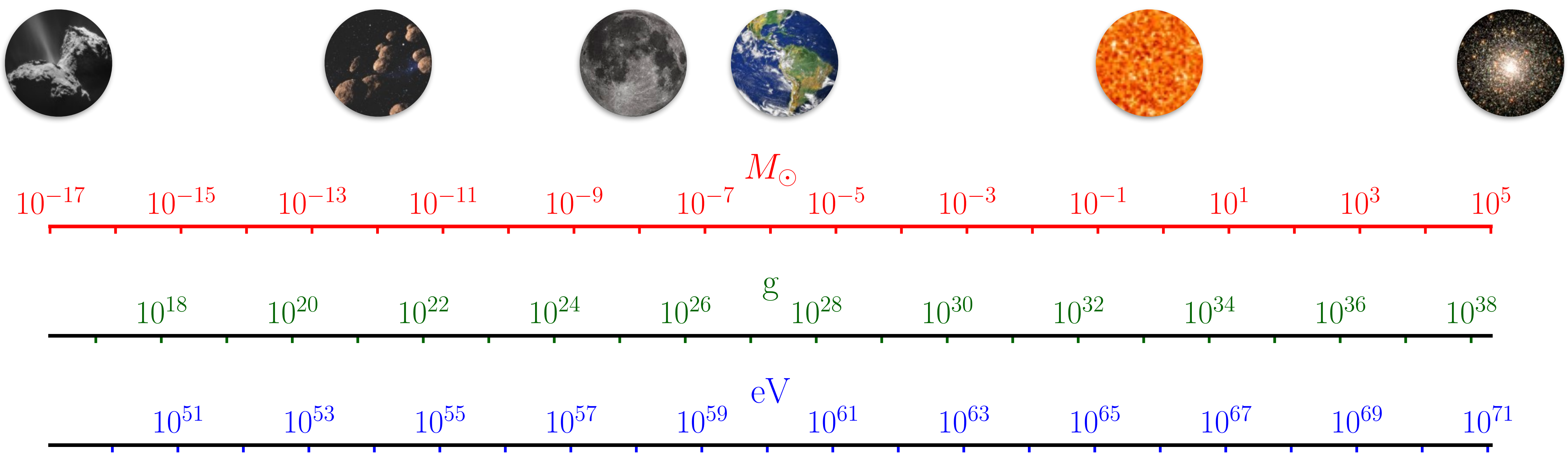
and primordial black holes…

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]

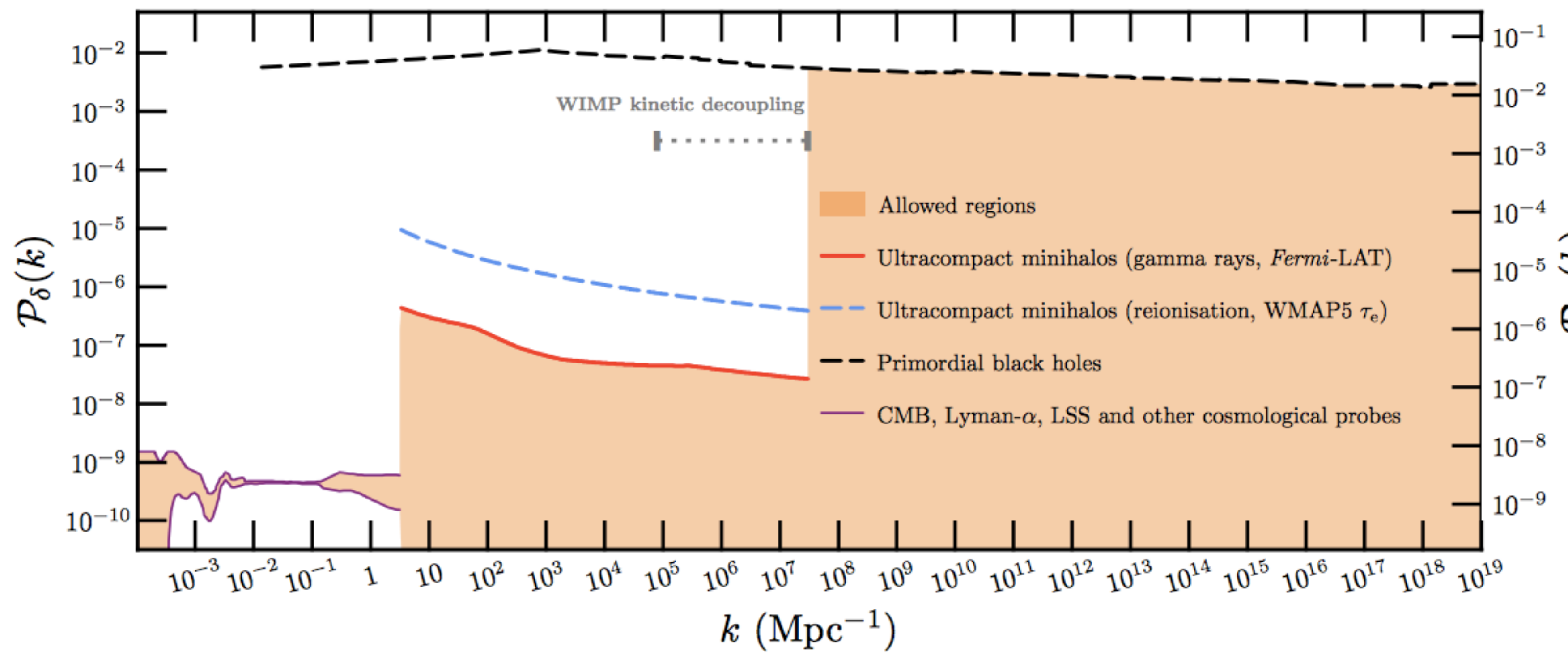


[Zel'dovich & Novikov (1967), Hawking (1971), Carr & Hawking (1974), Carr (1975)]

PBH formation

[1110.2484]

How can we make a PBH?



- Enhancement/feature in power spectrum

  [e.g. astro-ph/9509027, astro-ph/9605094, hep-ph/9710259, 1206.4188, 1709.05565]

- Cosmic String Loops

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

- Bubble collisions

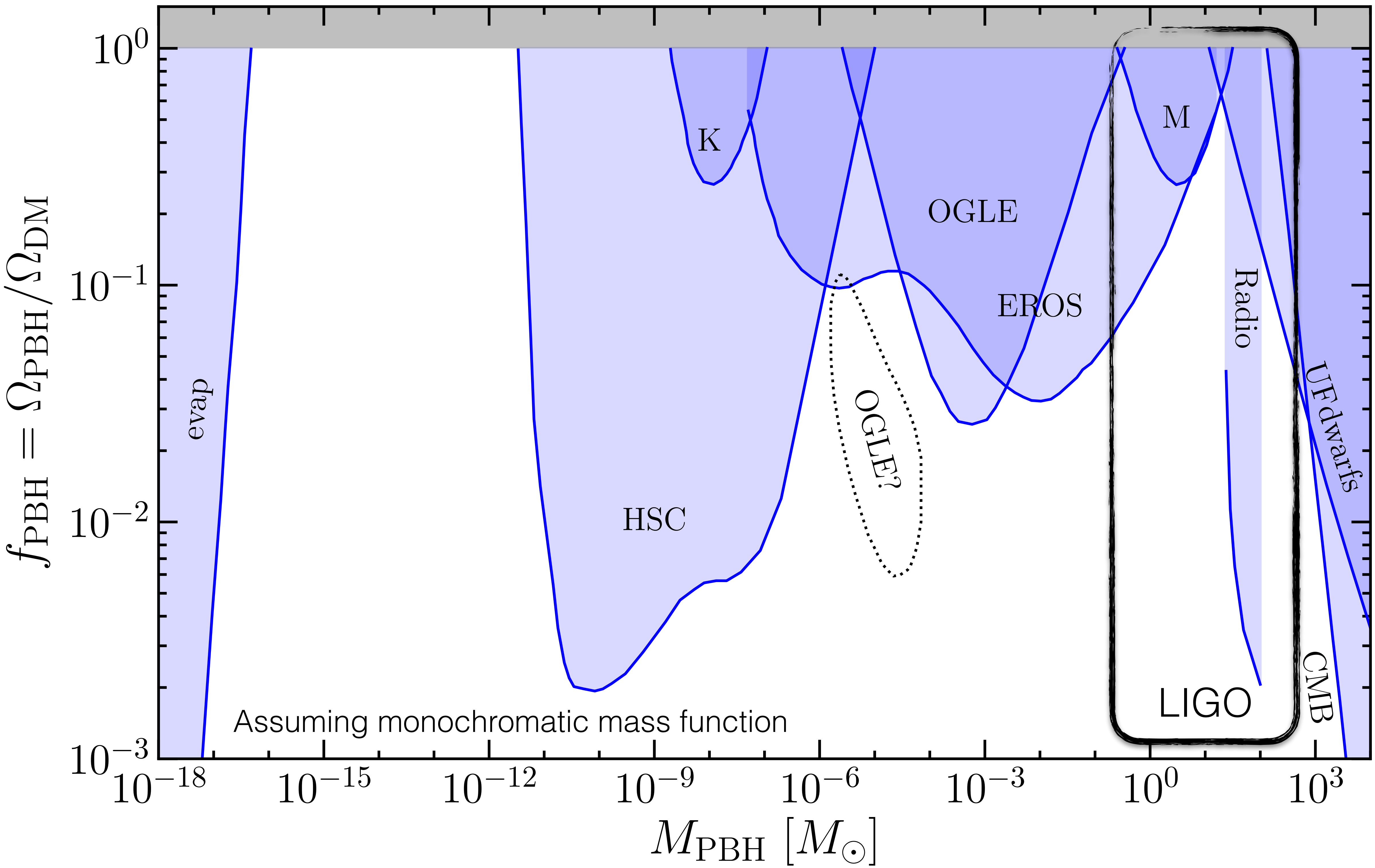
  [e.g. Hawking, Moss & Stewart (1982); La & Steinhart (1989)]

Primordial Black Holes are a probe of the physics of the early Universe:

"**Sirens** of the early Universe" [Green, 1403.1198]

PBH Constraints

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



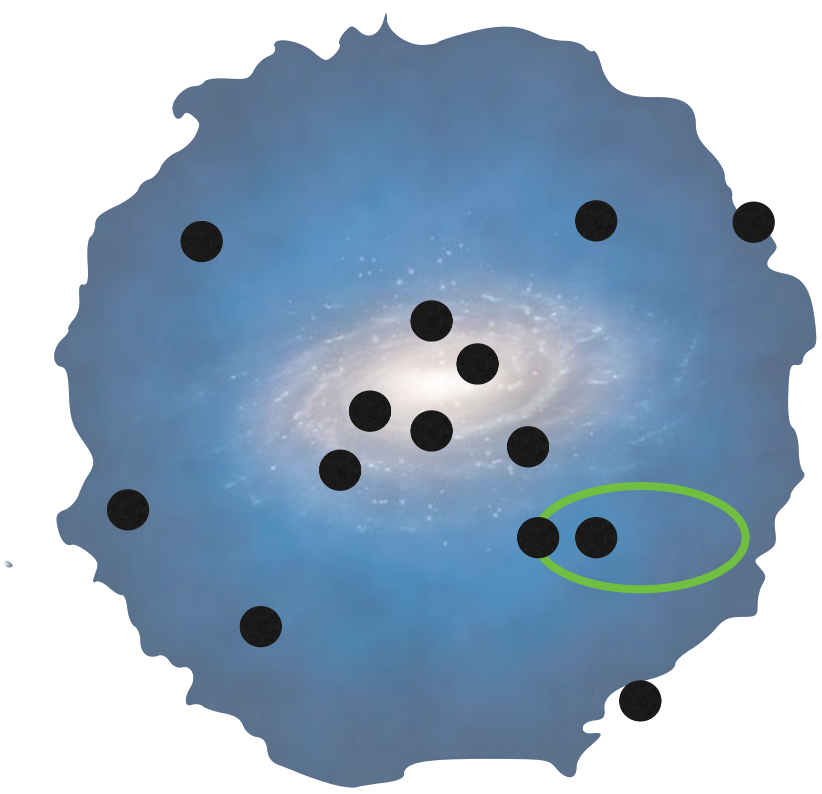
[See e.g. 1607.06077, 1801.00808, **1806.05195**]

[Some dispute: 1712.06574, 1906.05950]

A tale of two binaries

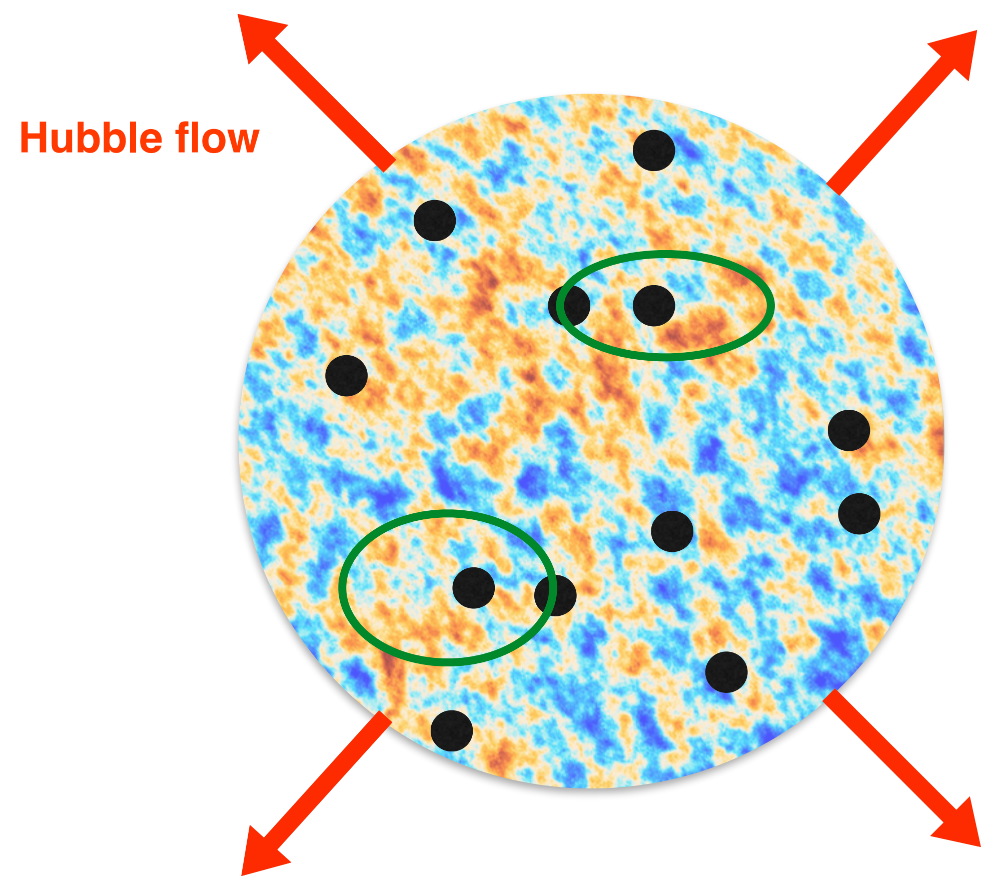
A) Binaries formed after close encounters

[Bird et al., 1603.00464]



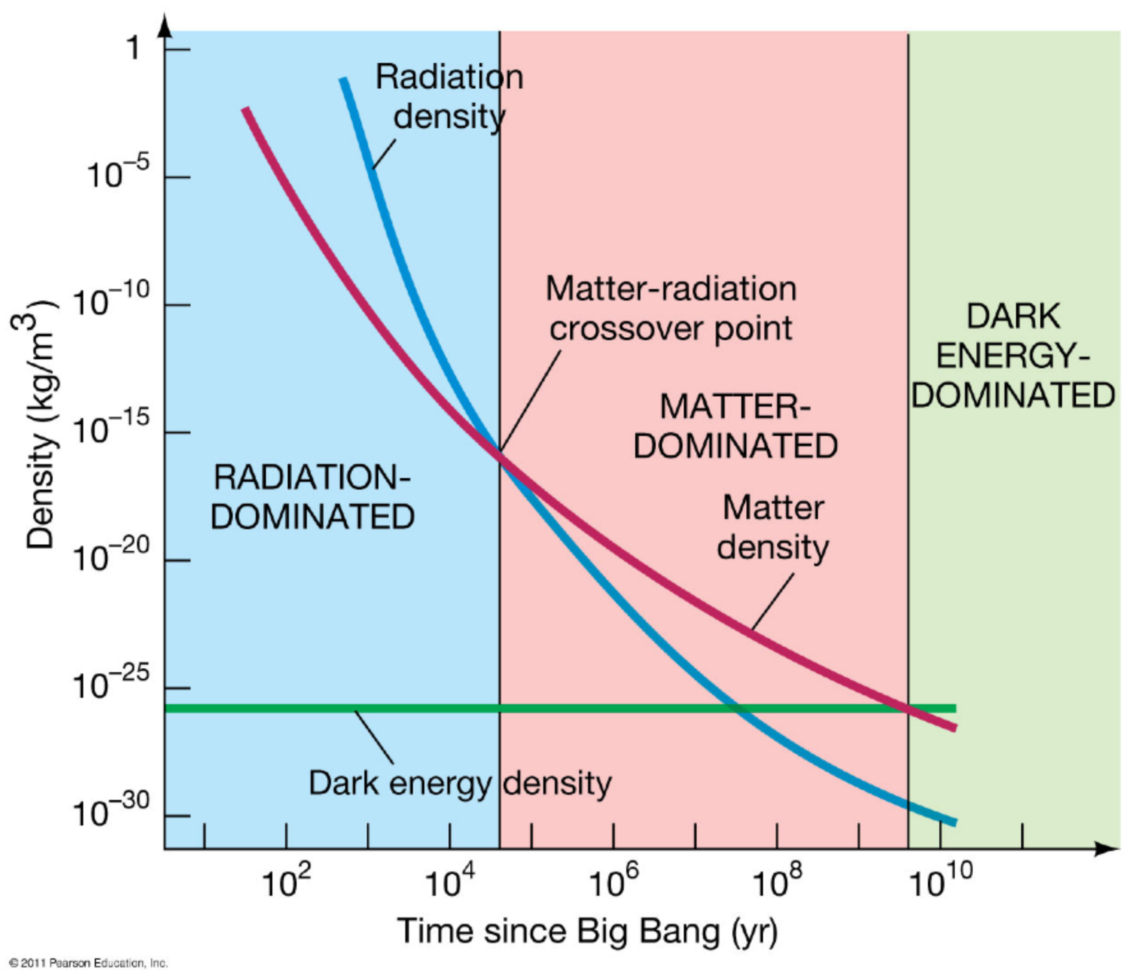
B) Binaries formed in the early Universe

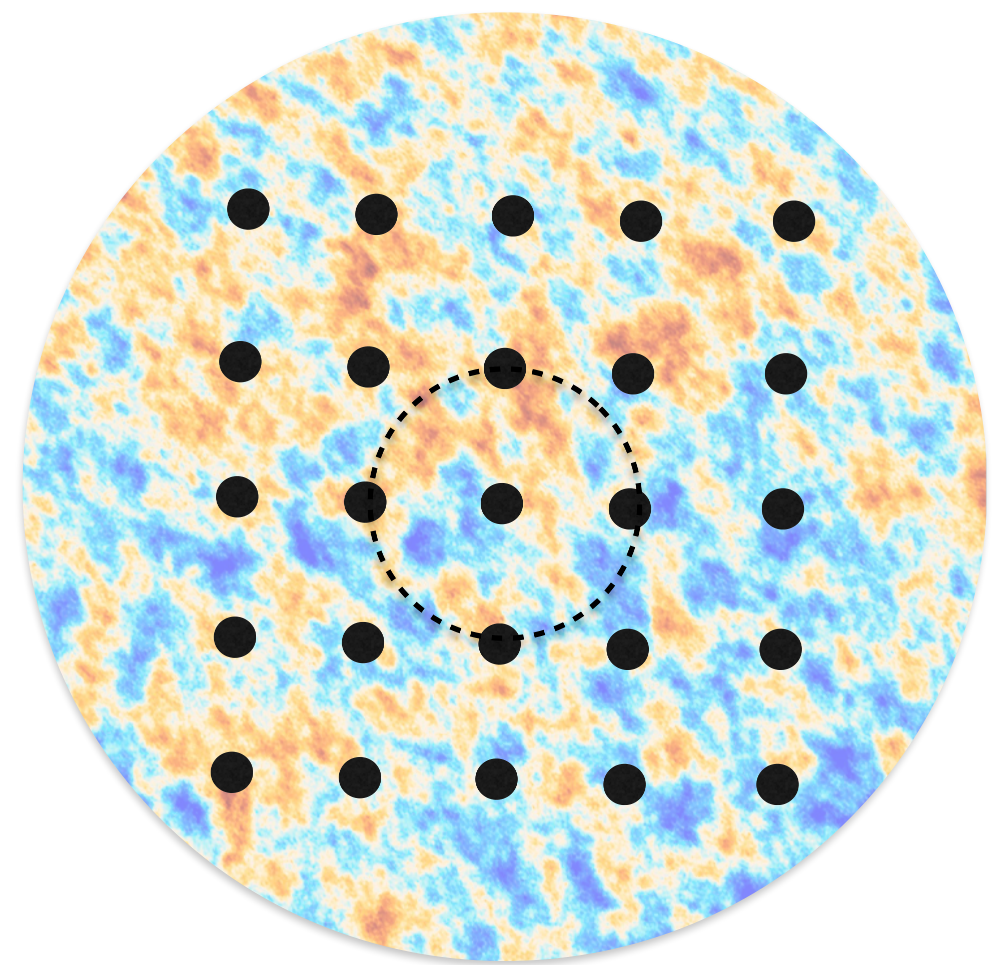
[Nakamura et al, astro-ph/9708060, Sasaki et al, 1603.08338]



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

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

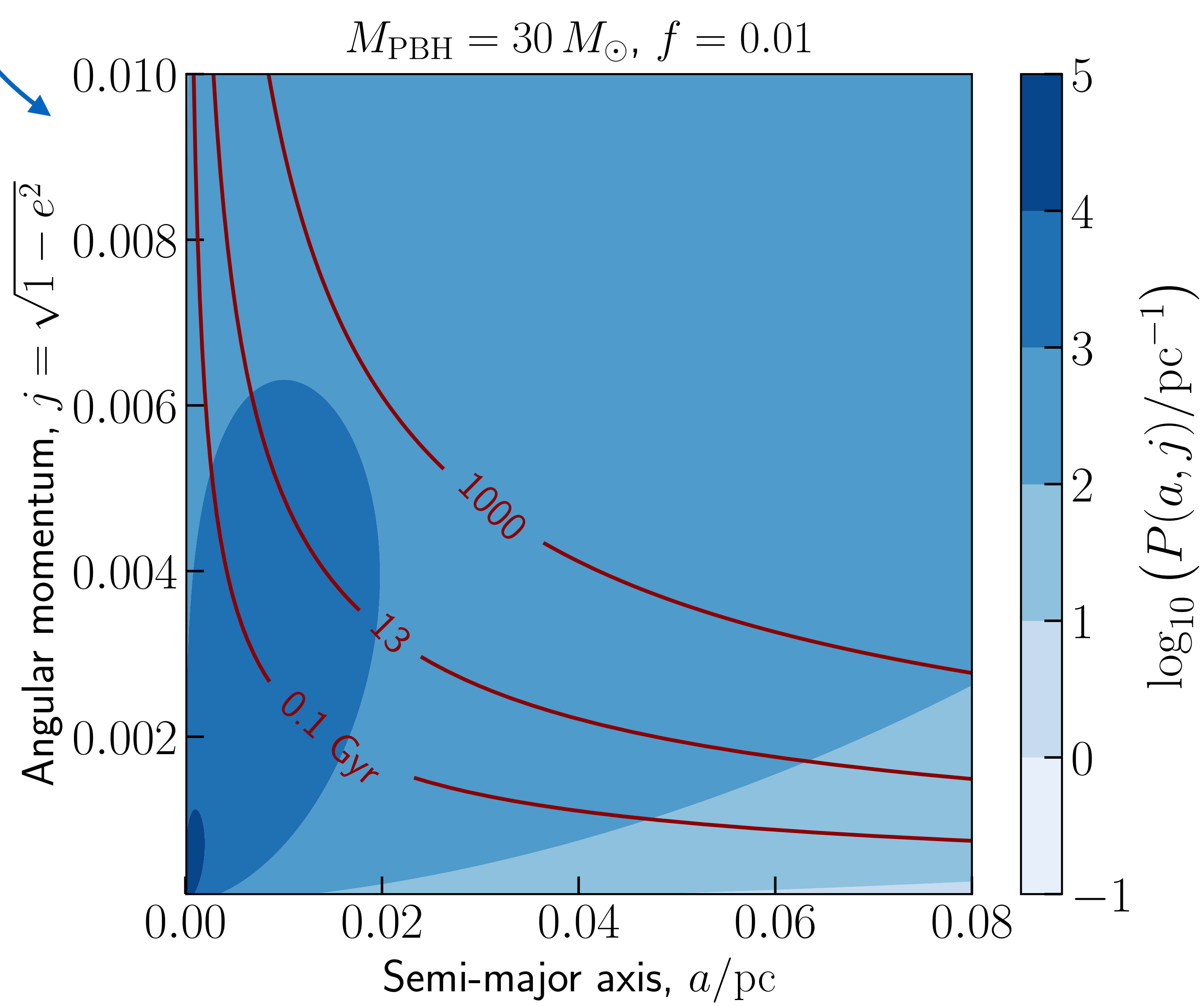
Randomly distributed (unclustered) PBHs

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

Close, eccentric binaries merge today:

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

$e > 0.9999$

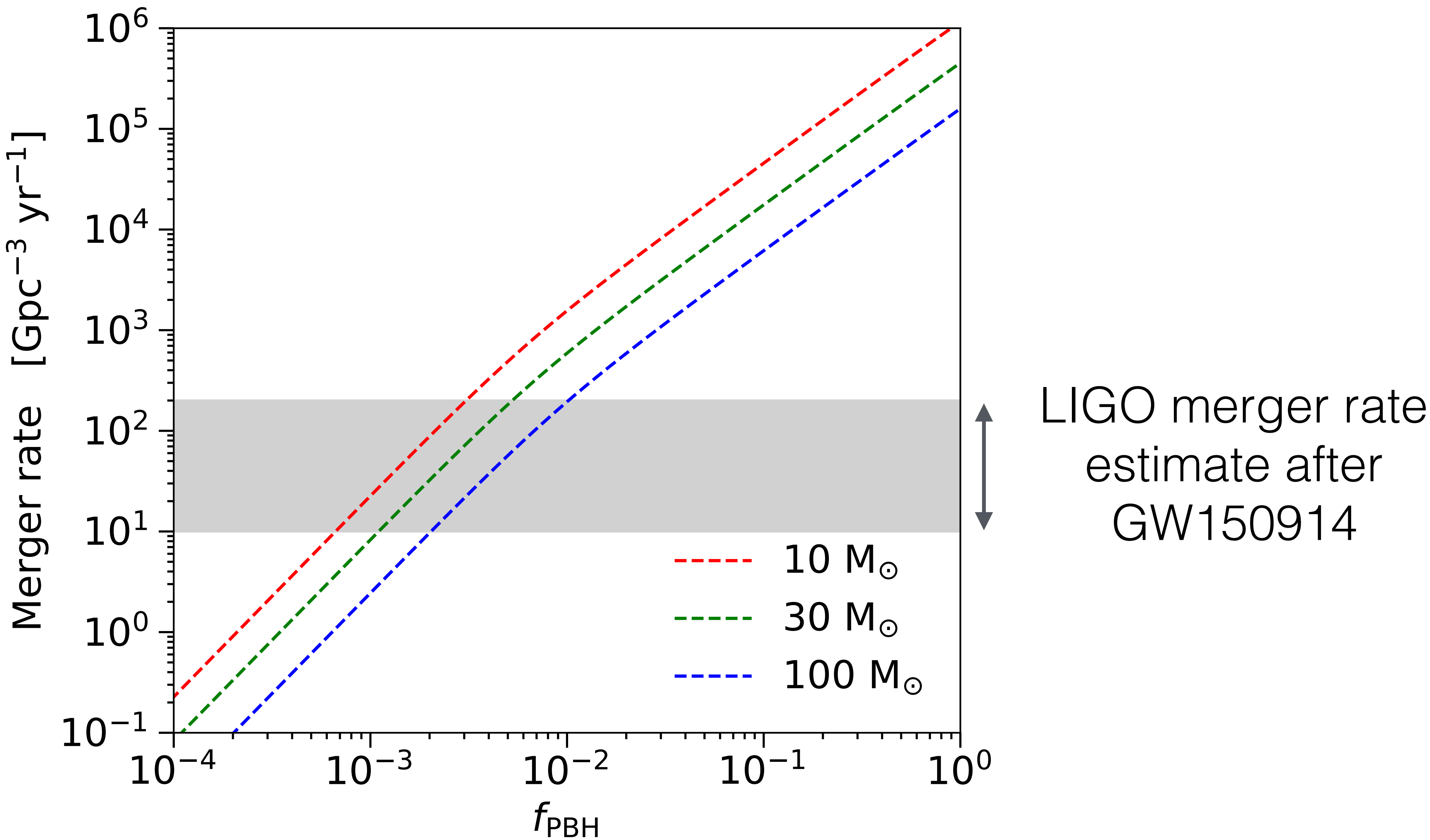


[**BJK**, Gaggero & Bertone, 1805.09034]

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

Merger rate estimate

$$\mathcal{R}\left(t_{\mathrm{merge}}\right) = \frac{1}{2} n_{\mathrm{PBH}} P_{\mathrm{binary}}\, P\left(t_{\mathrm{merge}}\right)$$

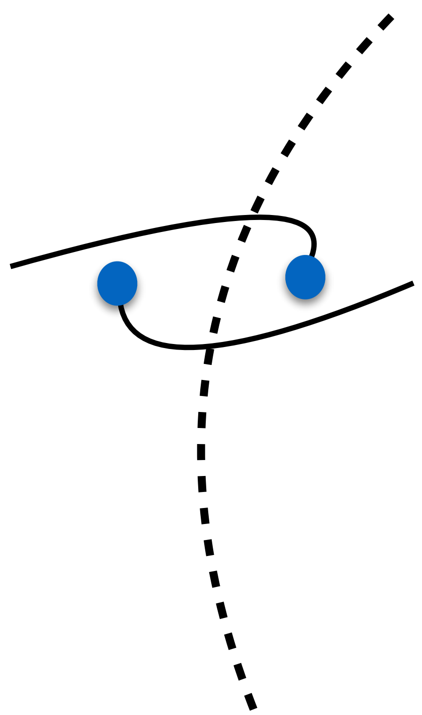


Solar mass PBHs should only be a sub-dominant (%-level) contribution to the DM density in the Universe

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

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



Do these binaries survive for the age of the Universe?

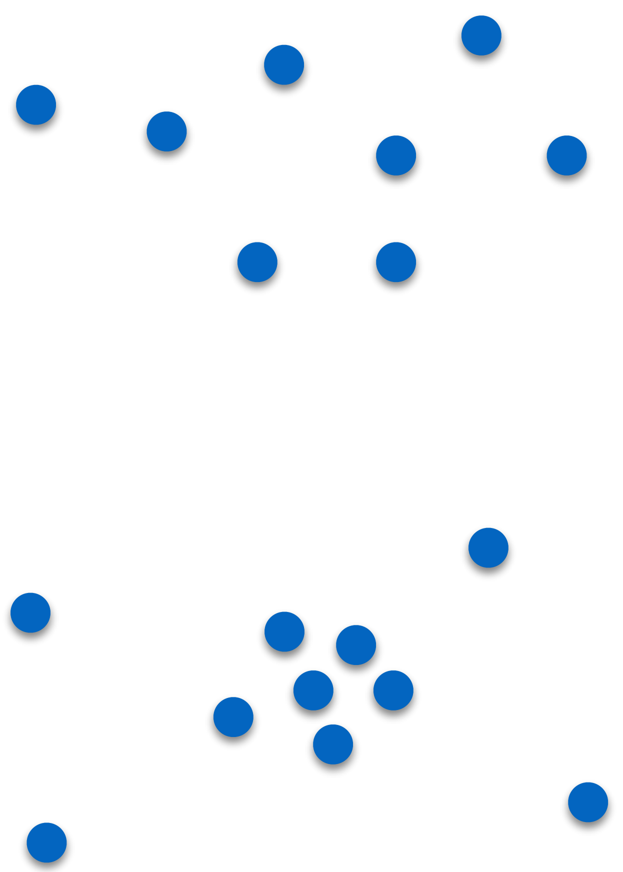
Smooth density perturbations and close encounters
are unlikely to disrupt the binaries

$$a \lesssim 10^{-2}\,\mathrm{pc}$$

[1709.06576, 1908.09752]

Caveats

- Survival
- **Clustering**
- Baryons
- Dark Matter



How does the distribution of PBHs affect the merger rate?

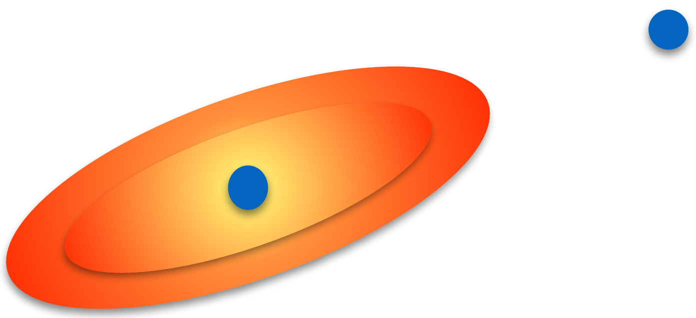
PBHs may cluster (depending on how they are formed) - this could substantially increase the merger rate

[This could be a good topic for the discussion session.]

[1805.05912, 1807.02084, 1808.05910, 1910.06077 and others]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



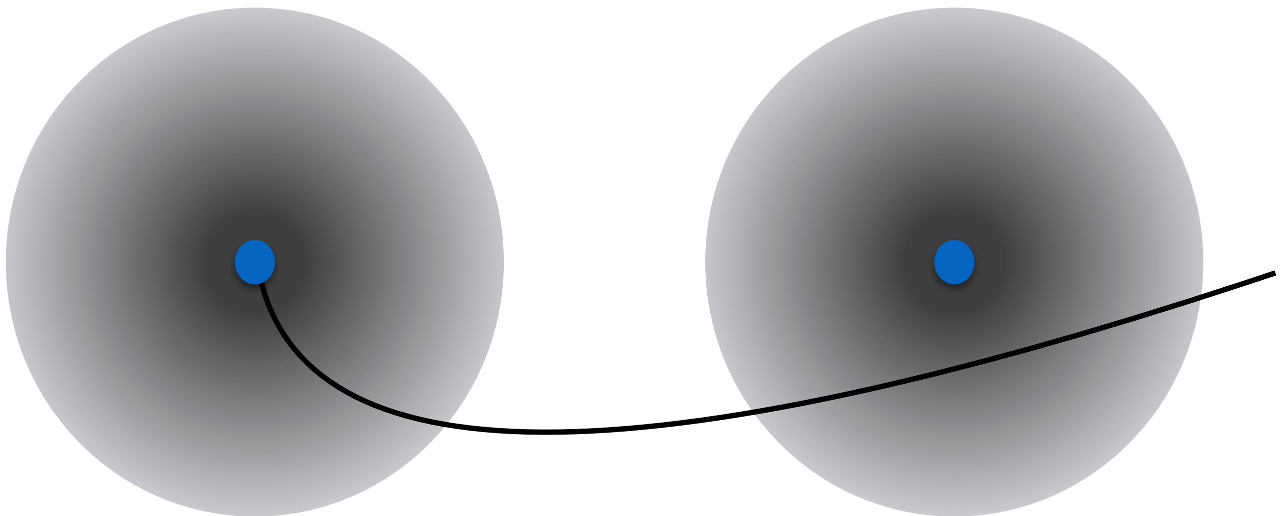
Does baryonic accretion disrupt the binary?

Some simulations have been performed, but the effects are still unclear (especially for highly eccentric binaries)…

[astro-ph/0607467, 0909.1738, 0805.3408, 1703.03913]

Caveats

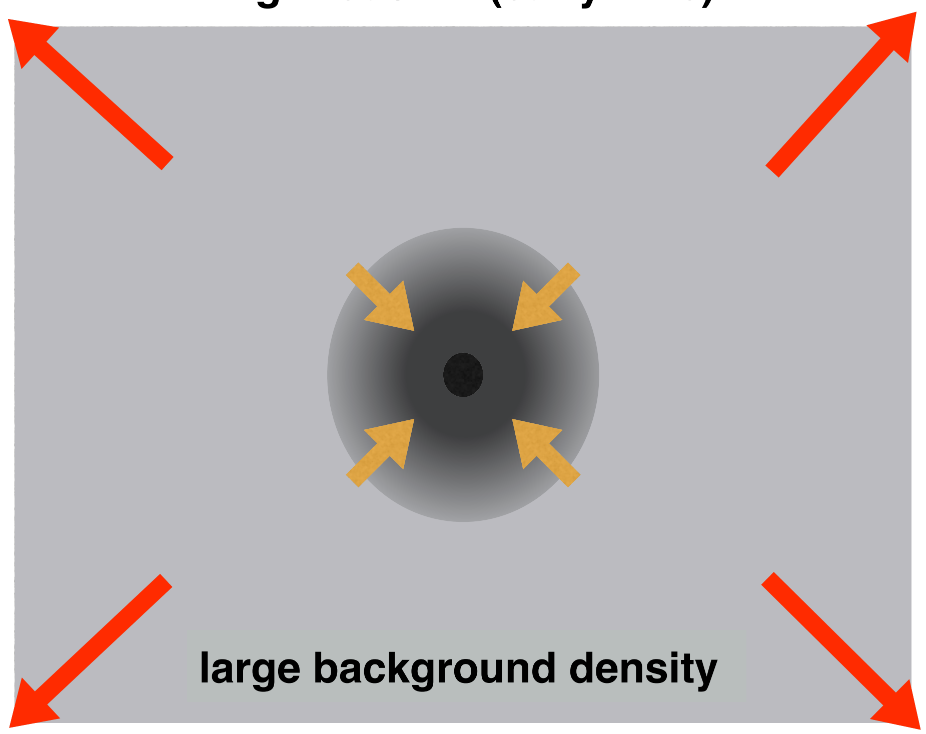
- Survival
- Clustering
- Baryons
- **Dark Matter**

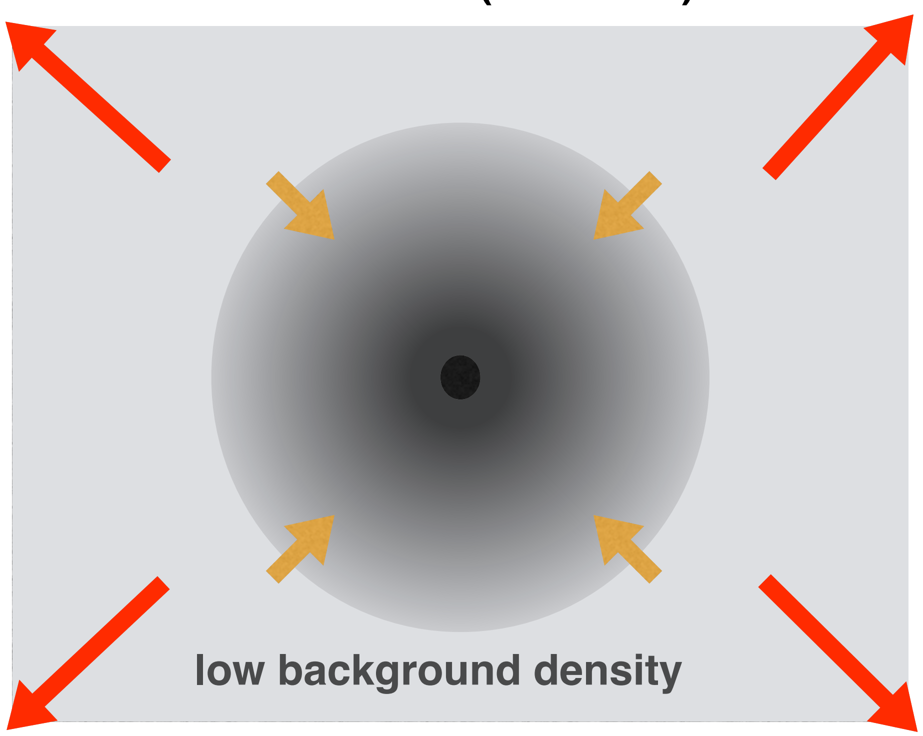


Do *local* Dark Matter halos disrupt PBH binaries?

Black Holes' Dark Dress

PBHs seed the formation of `local' DM halos:





$$R_{\rm tr}(z) \;=\; 0.0063 \left(\frac{M_{\rm PBH}}{M_\odot}\right) \left(\frac{1+z_{\rm eq}}{1+z}\right) \rm pc$$

$$\rho(r) \propto r^{-9/4}$$

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

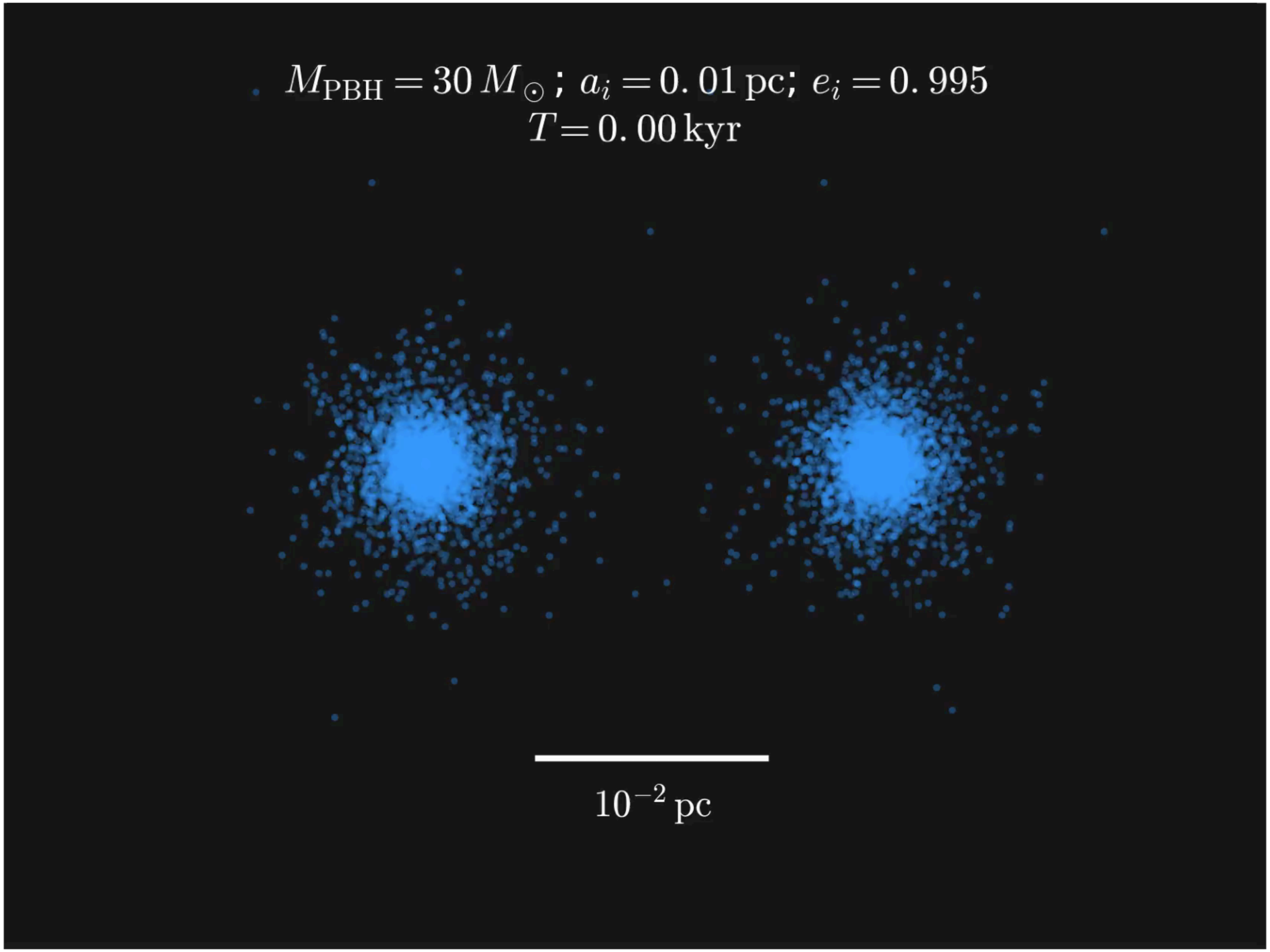
[Bertschinger (1985)]
[0706.0864, 1901.08528]

Slide shamelessly ripped off from Daniele Gaggero

Simulations

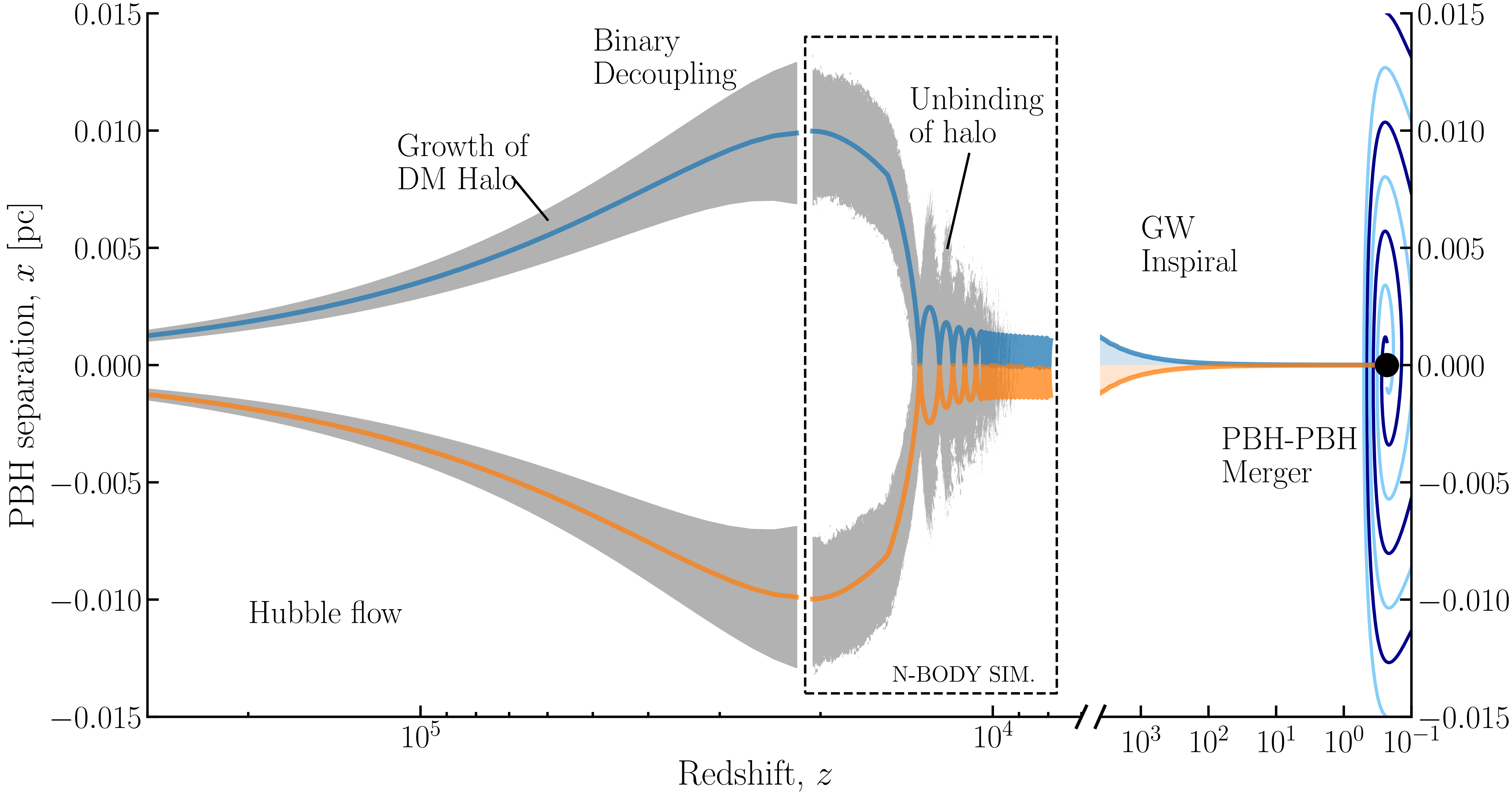
Use GADGET-2 as a pure N-body solver:

[Springel, astro-ph/0505010]



Movies at tinyurl.com/BlackHolesDarkDress

Life of a 'dressed' PBH binary



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

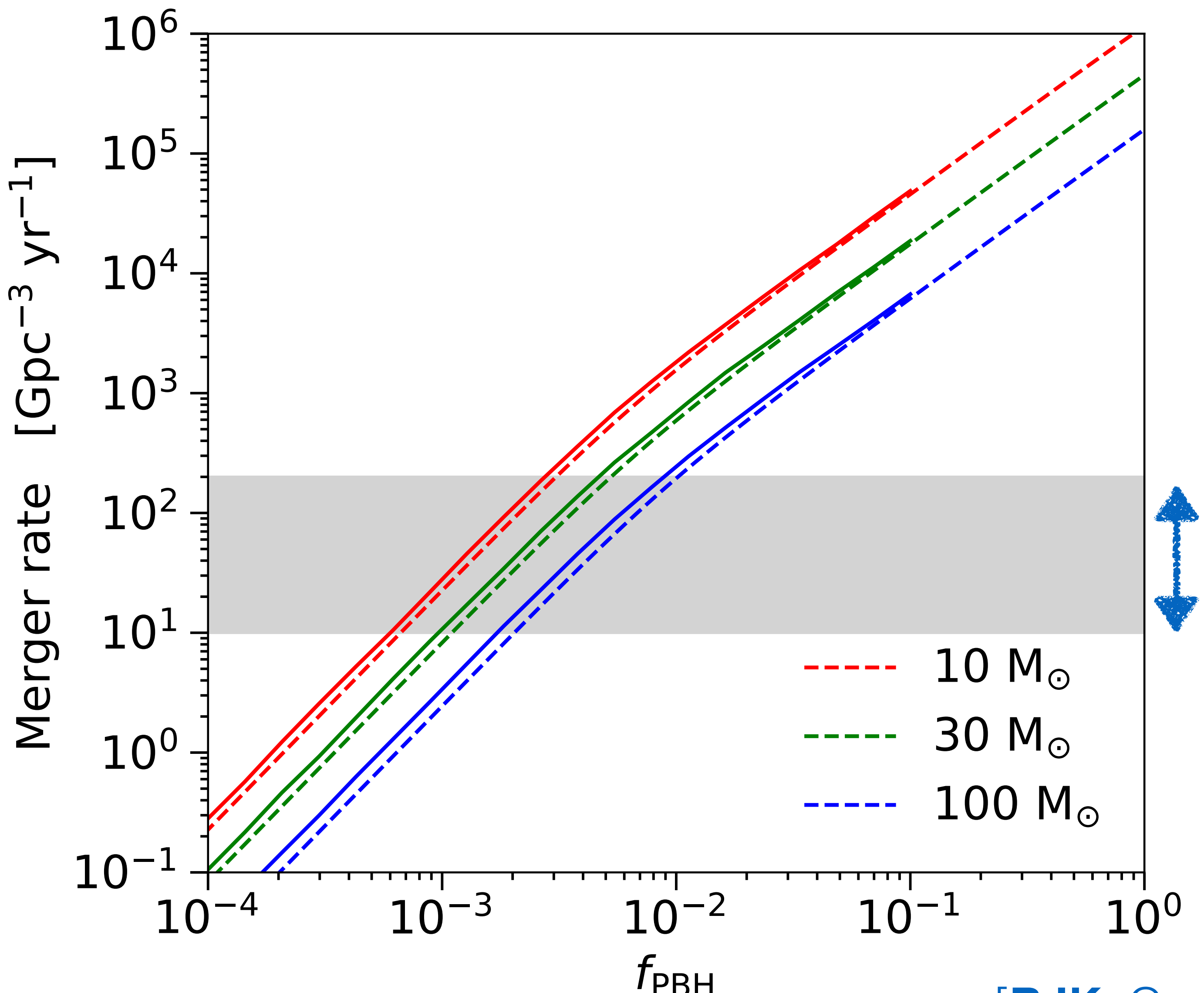
$$e_i = 0.995$$

Final Merger Rate

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

Guided by the simulations, map $(a_i, e_i) \to (a_f, e_f)$

Merger time $t_\mathrm{merge} = \frac{3\,c^5}{170\,G_N^3}\frac{a^4 j^7}{M_\mathrm{PBH}^3}$ is almost conserved: $t_f = \sqrt{\frac{a_i}{a_f}}\,t_i$



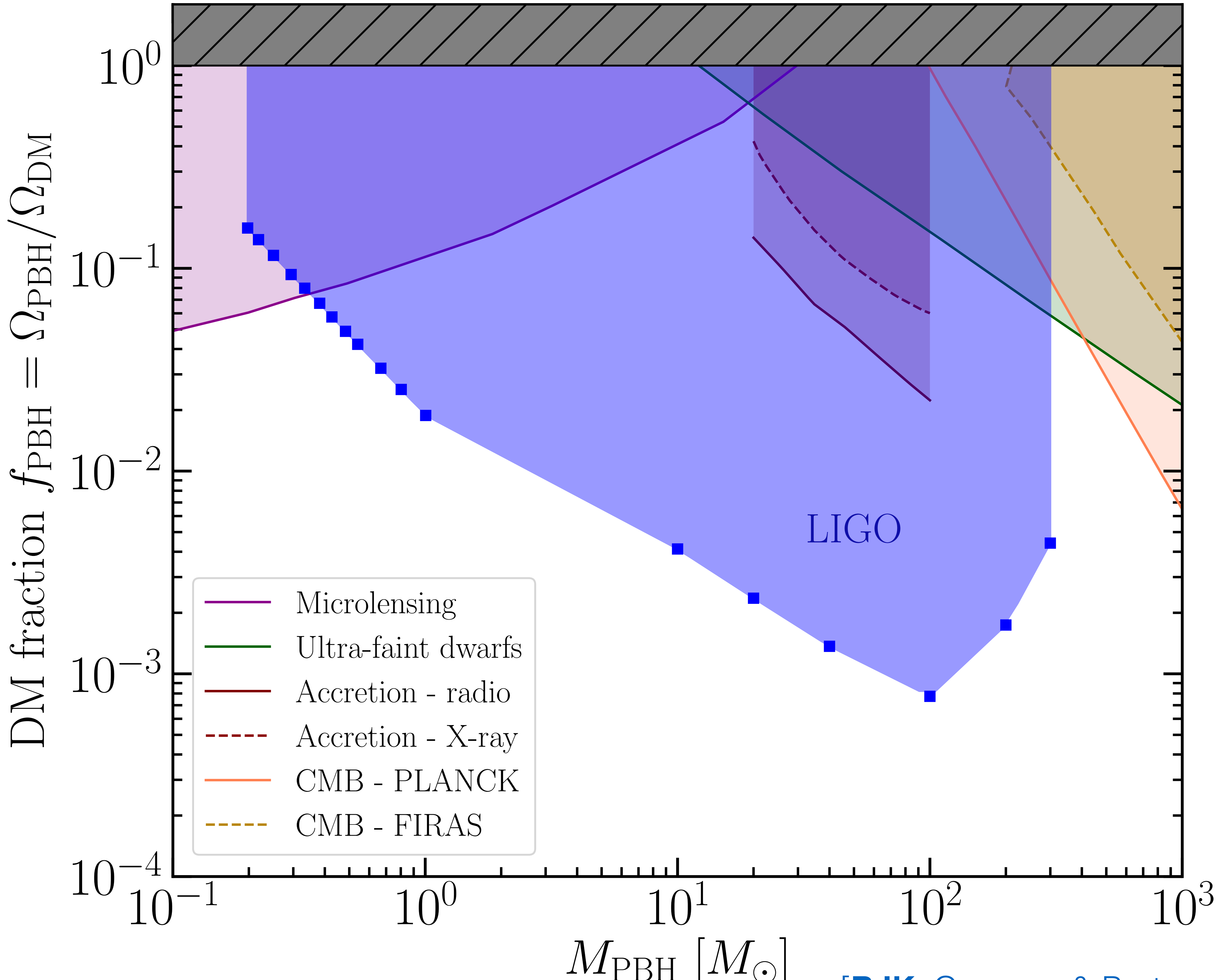
LIGO merger rate estimate after GW150914

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

Limits from LIGO mergers

+ more recent sub-solar limits from LIGO

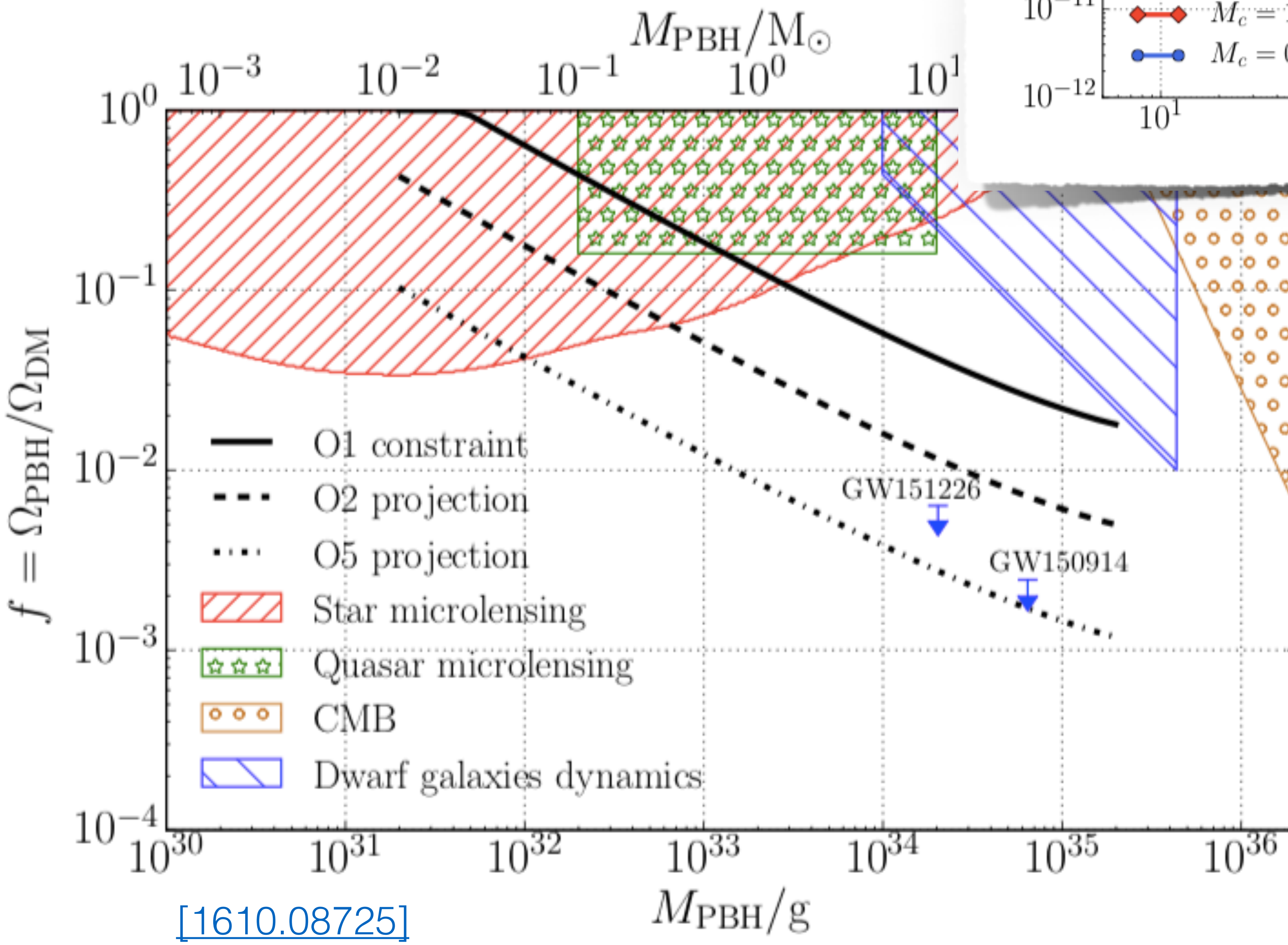
[1808.04771, 1808.04772, 1904.08976]

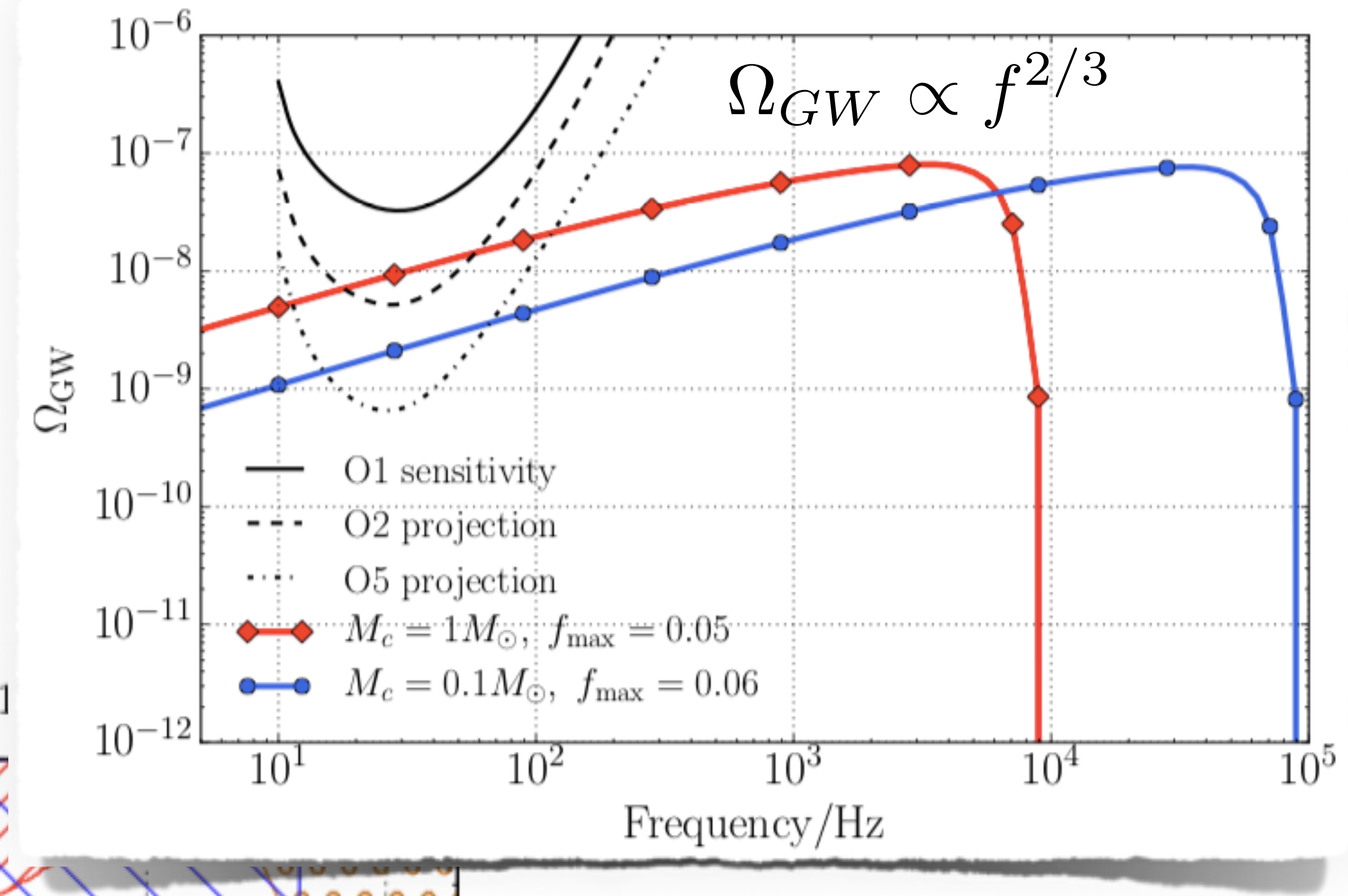


[**BJK**, Gaggero & Bertone, 1805.09034]

Stochastic Background

Background from PBH binary mergers over all of cosmic time





[1610.08725]

[See also:
1610.08479,
1903.02886,
1904.02396]

Discovery prospects

GW detection of sub-solar mass BHs

(LIGO O3, now!)

GW detection of high redshift BHs (z > 40)

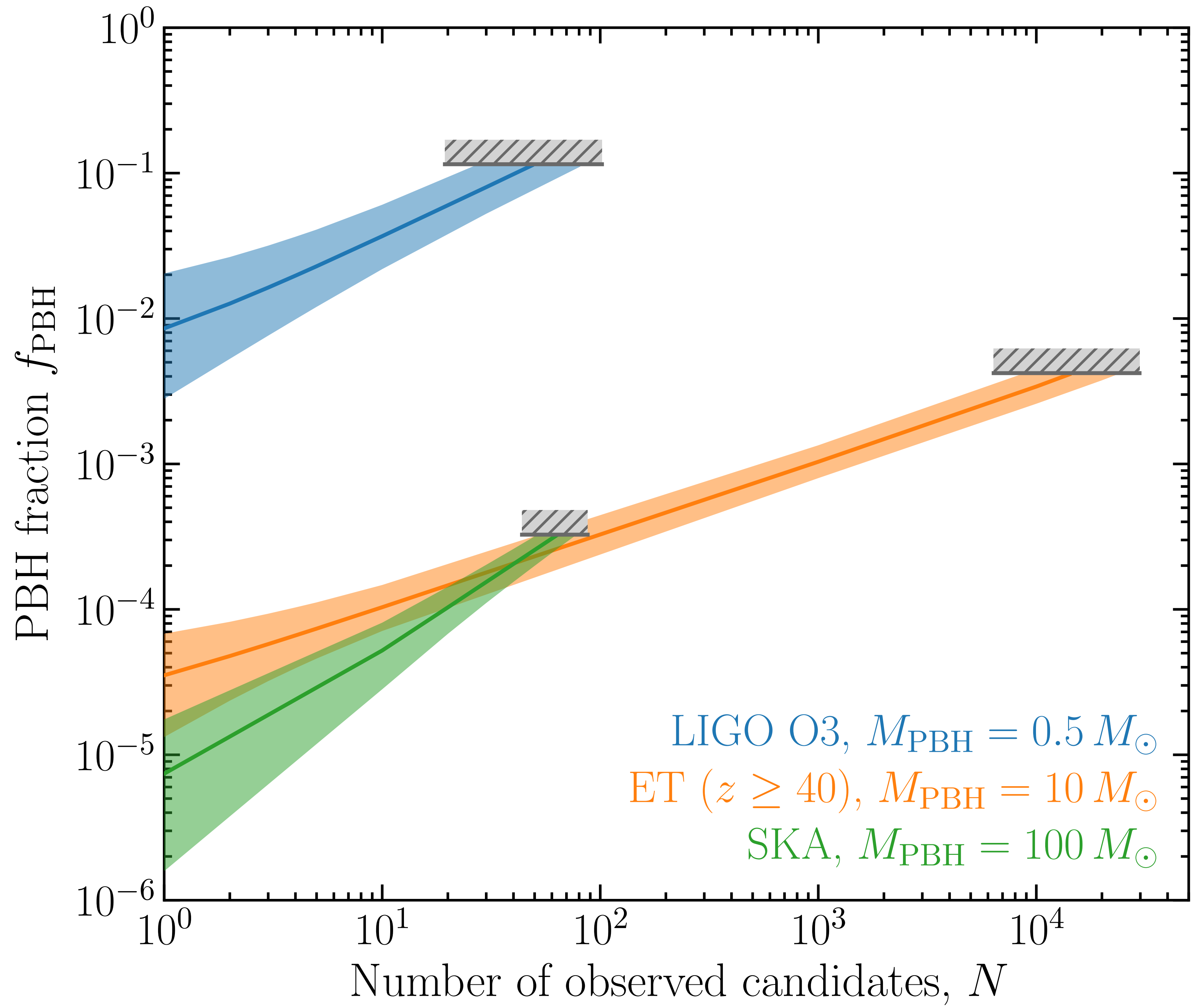
(Einstein Telescope, mid-late 2020s)

[1708.07380]

Radio detection of accreting galactic PBHs

(Square Kilometre Array, late 2020s)

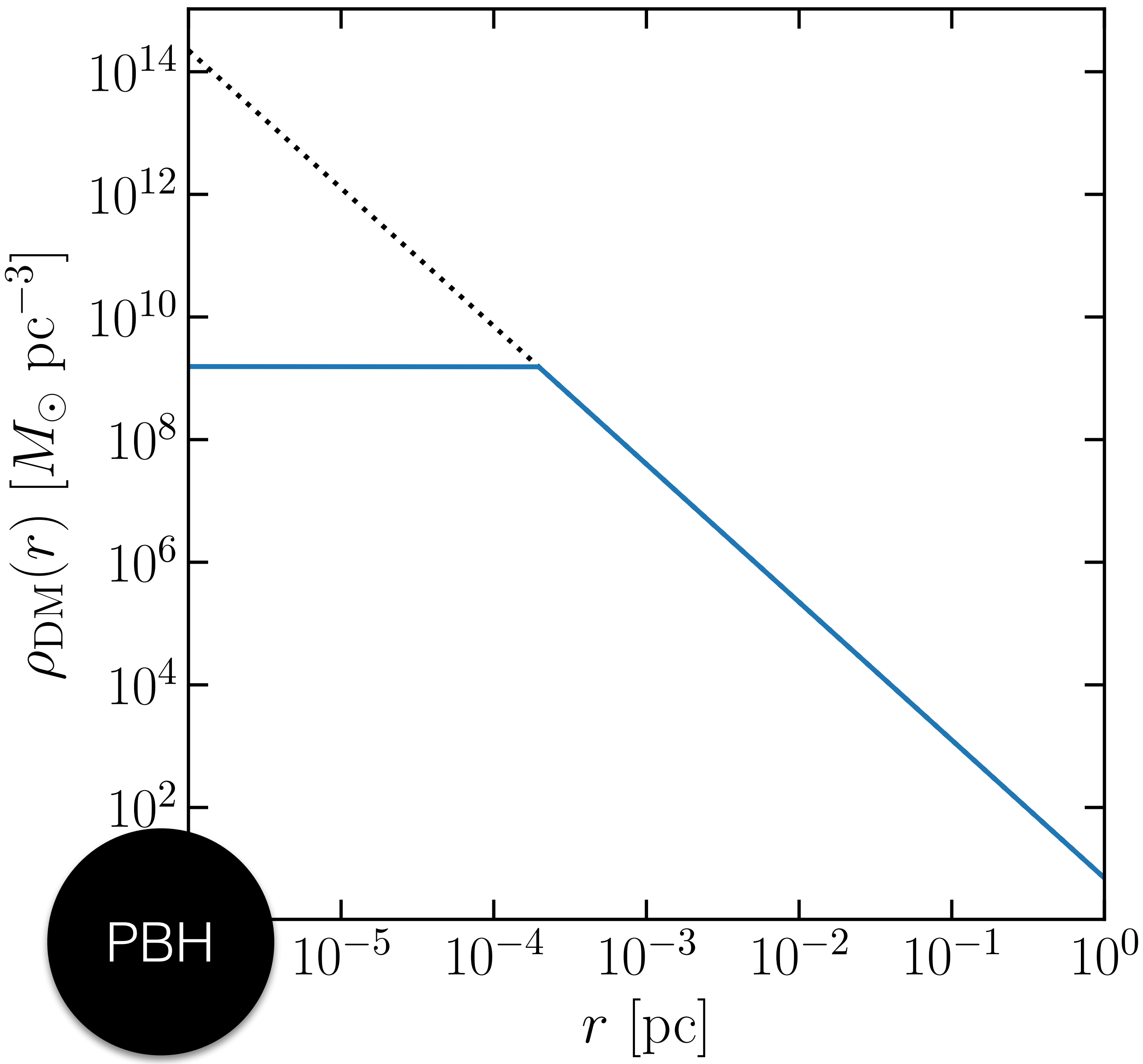
[1812.07967]

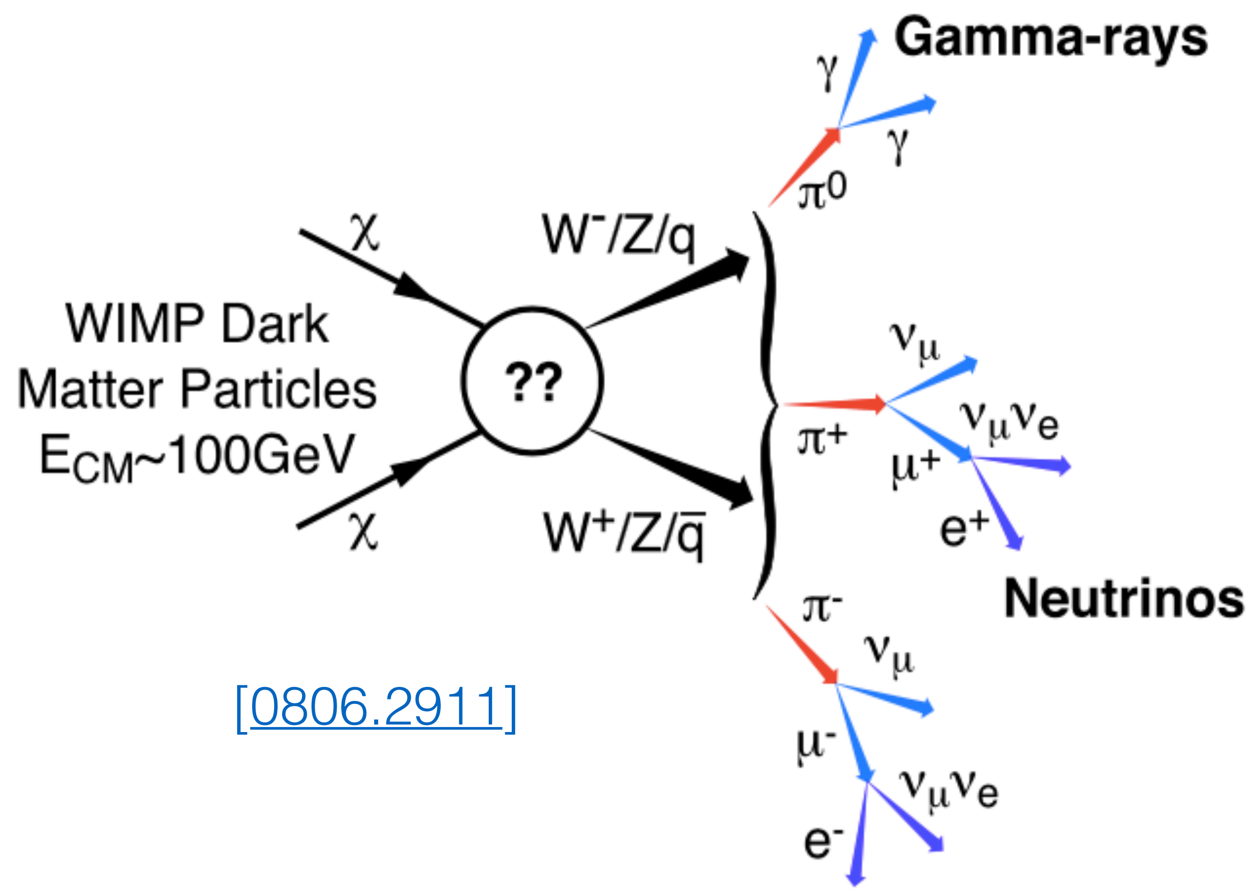


[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

WIMP annihilation

If the DM is a Weakly Interacting Massive Particle (WIMP), it can self-annihilate:





[0806.2911]

$$\Gamma \propto \rho_\chi^2 \, (\sigma v)_0 \, f_\chi^{4/3}$$

PBH population would act as bright *gamma-ray sources*

[1003.3466]

Werewolves

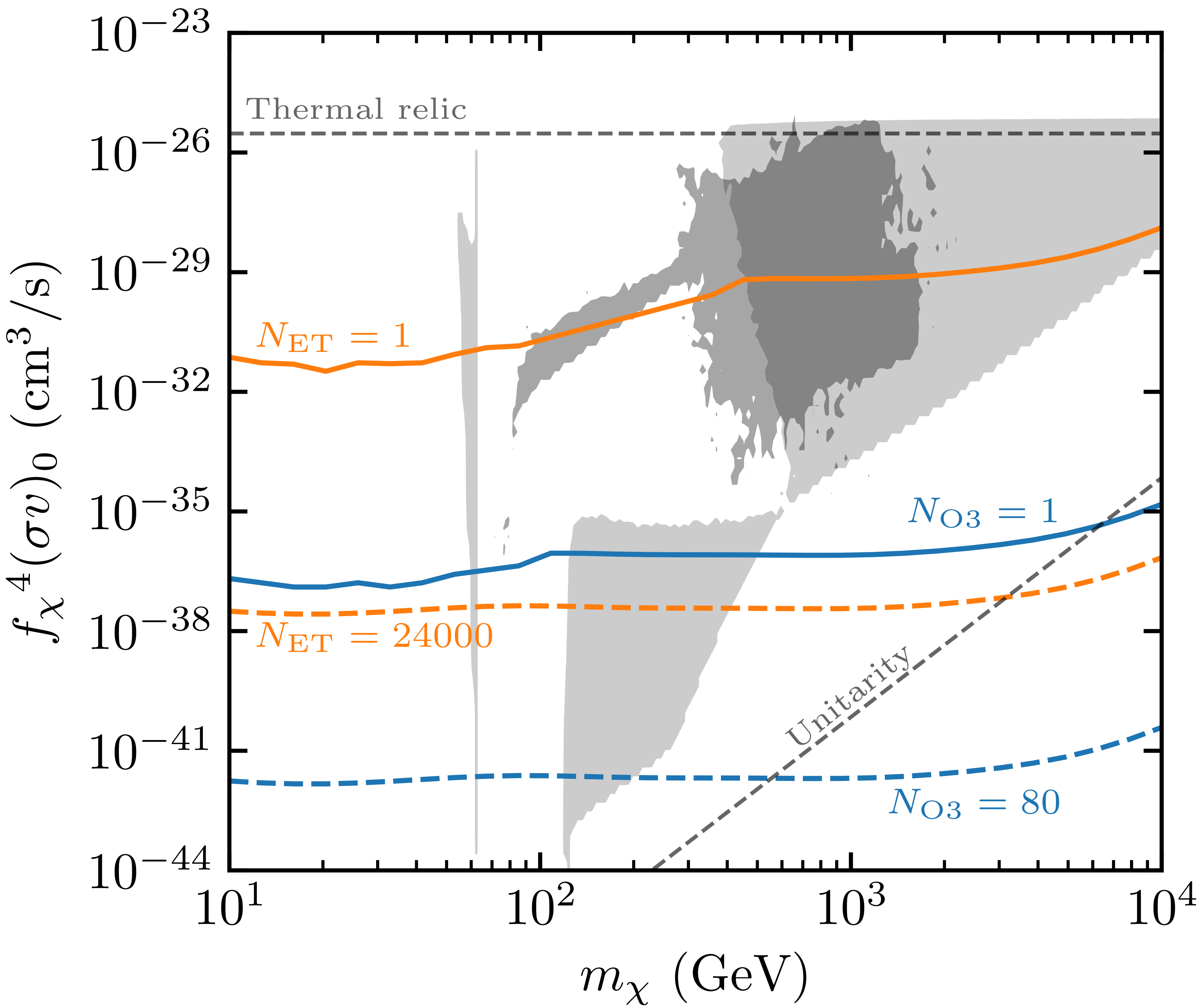
Werewolves: humans with the ability
to shapeshift into a wolf,
which are notoriously hard to kill

aaronsimscompany

Can be killed with **Silver Bullets**

Silver Bullets

WIMPs: Weakly Interacting Massive Particles, which are notoriously hard to kill

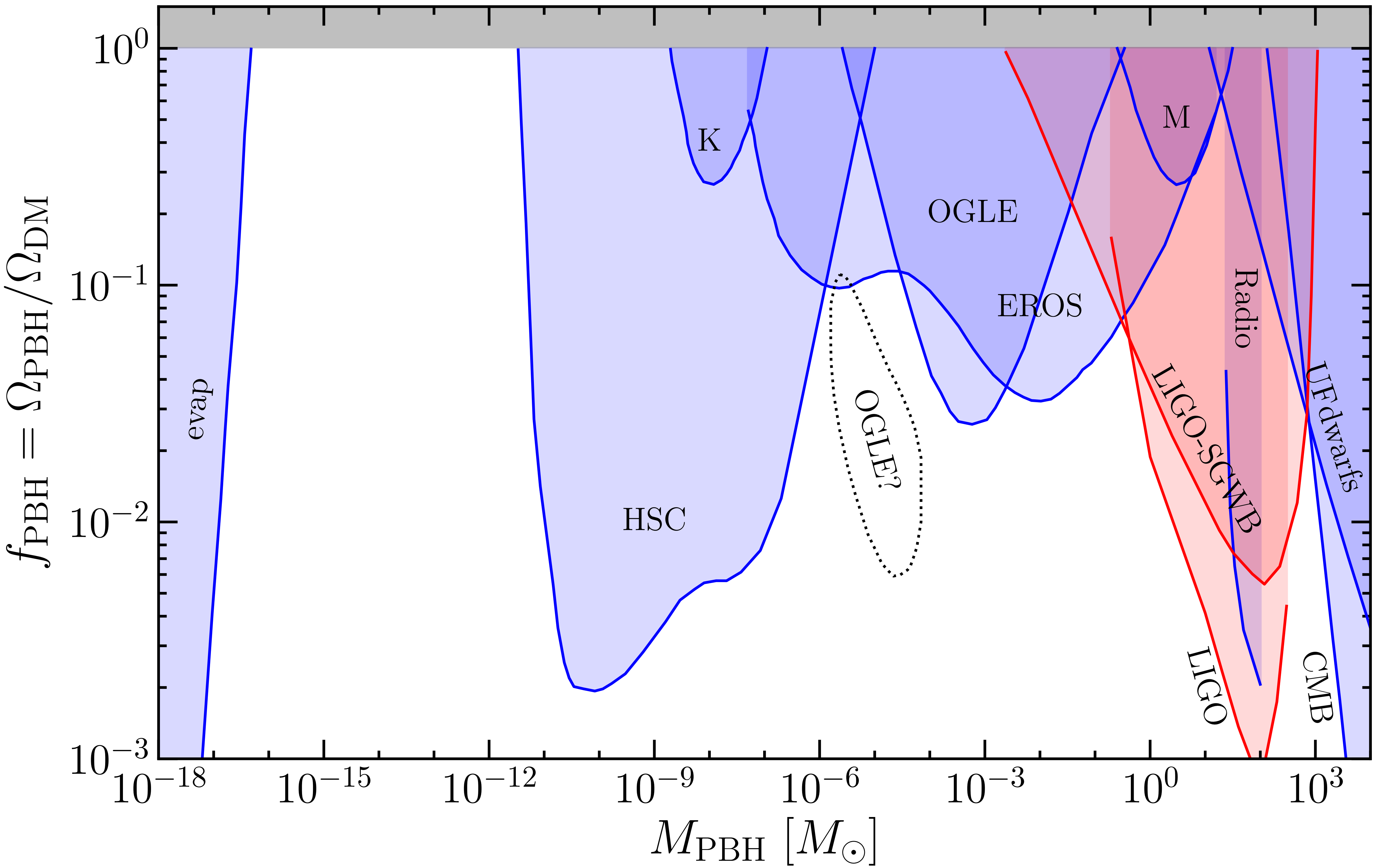


*Primordial Black Holes as '**Silver Bullets**' for New Physics at the Weak Scale*

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

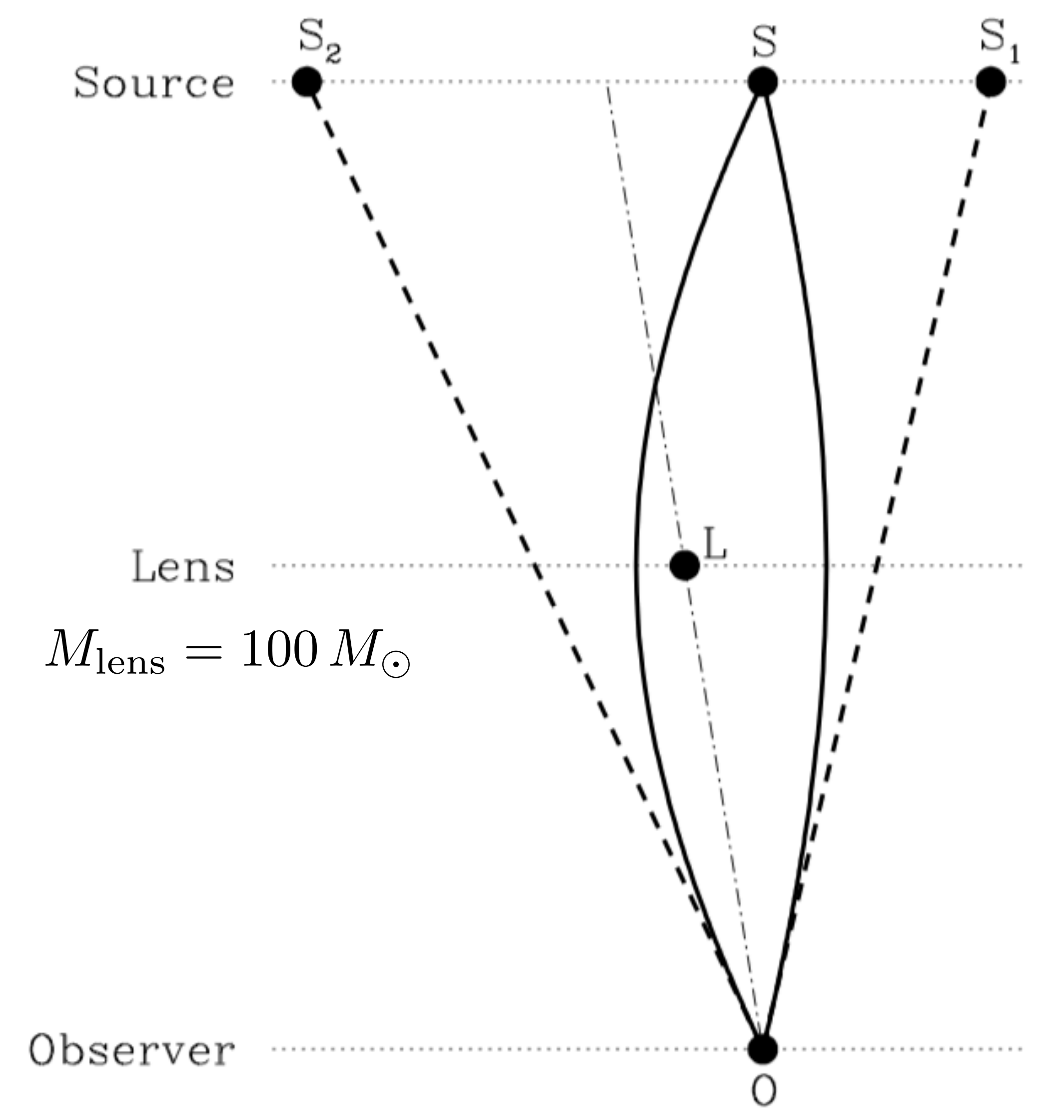
PBH Constraints

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



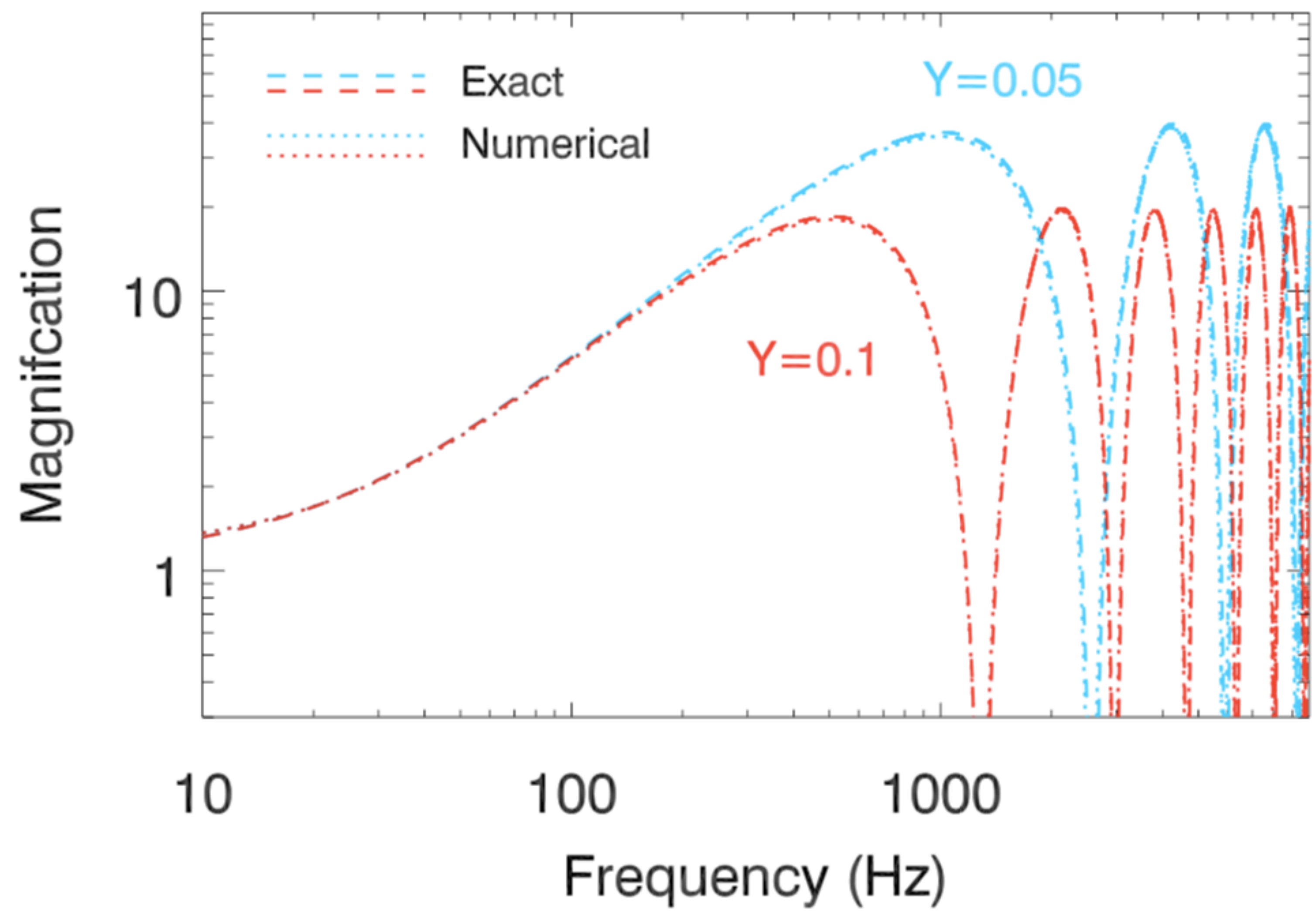
[See e.g. 1607.06077, 1801.00808, 1806.05195]

GW Microlensing



[astro-ph/9812021]

[1903.04513]



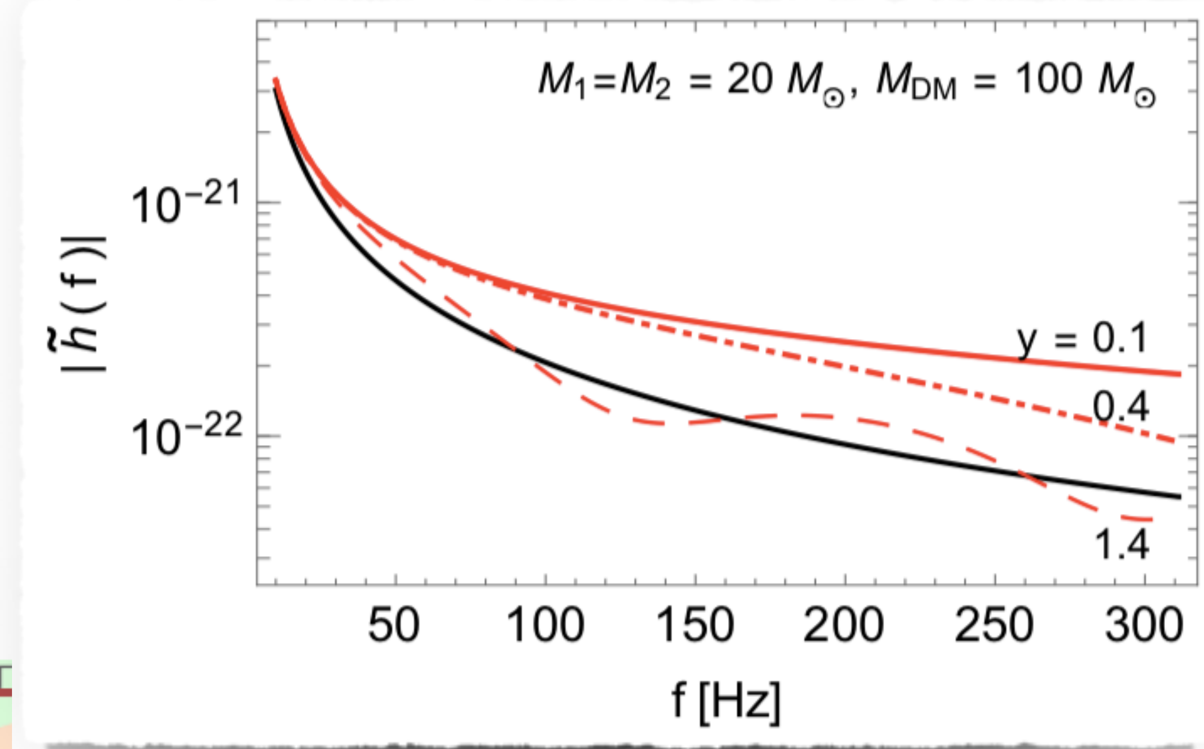
Relative time delay: Δt_d

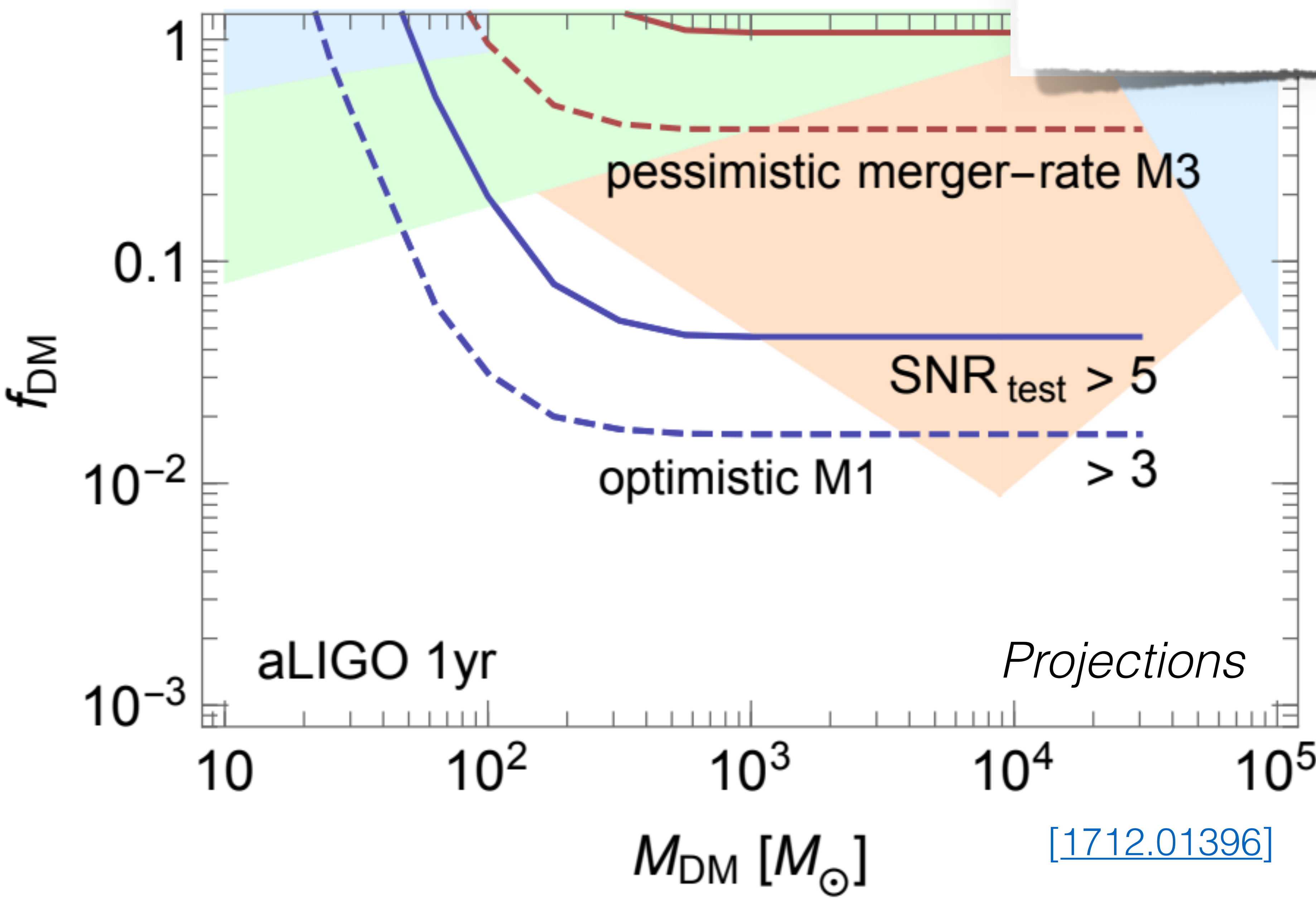
Relative phase: $\Delta\phi \sim f\Delta t_d$

Frequency dependent magnification

GW Microlensing

Could appear as unusual
GW lensing ‘fringes’ in waveforms…

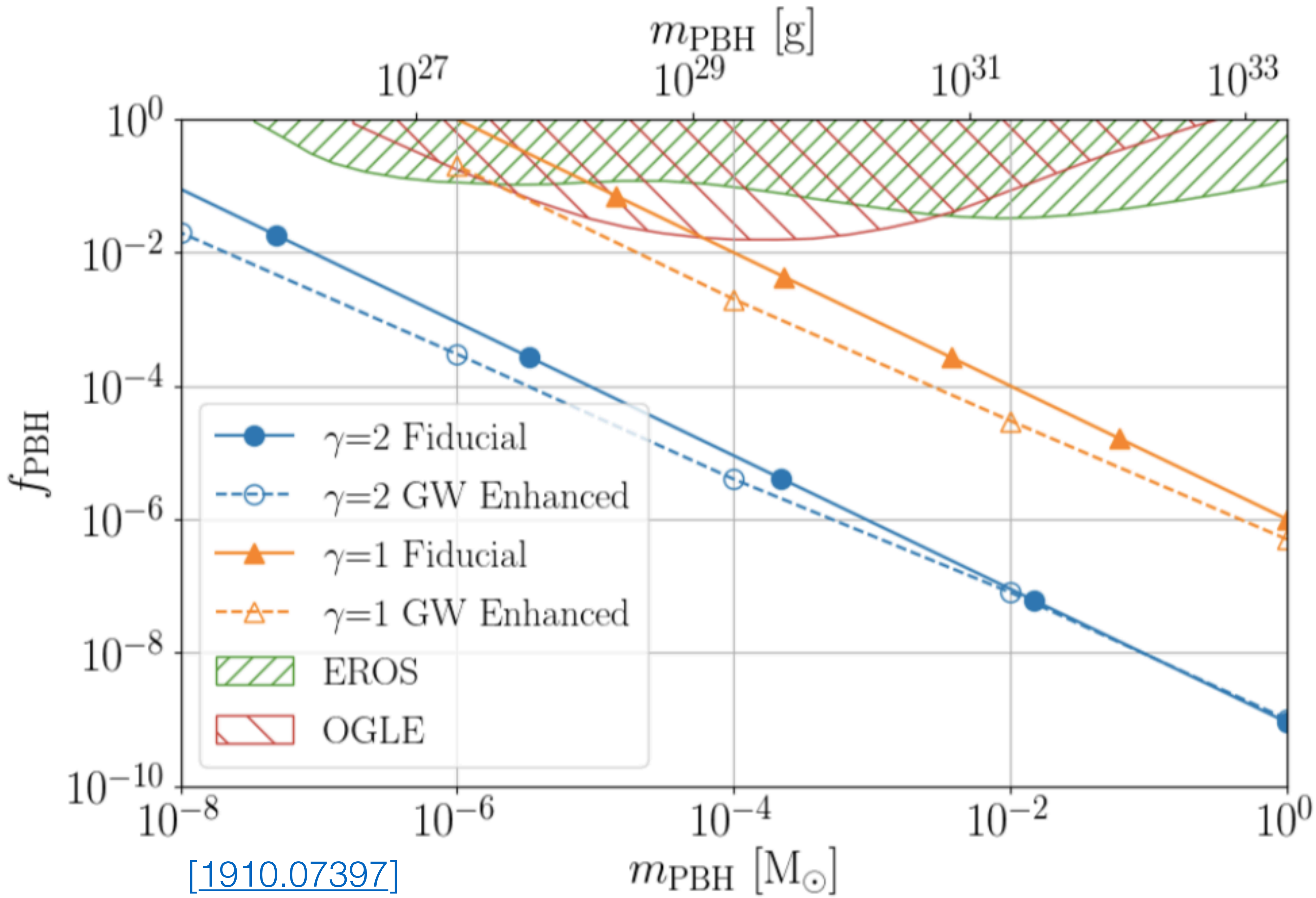




[1712.01396]

SGWB with LISA

EMRIs: (sub)-stellar mass PBHs in a spike around (e.g.) Sagittarius A*

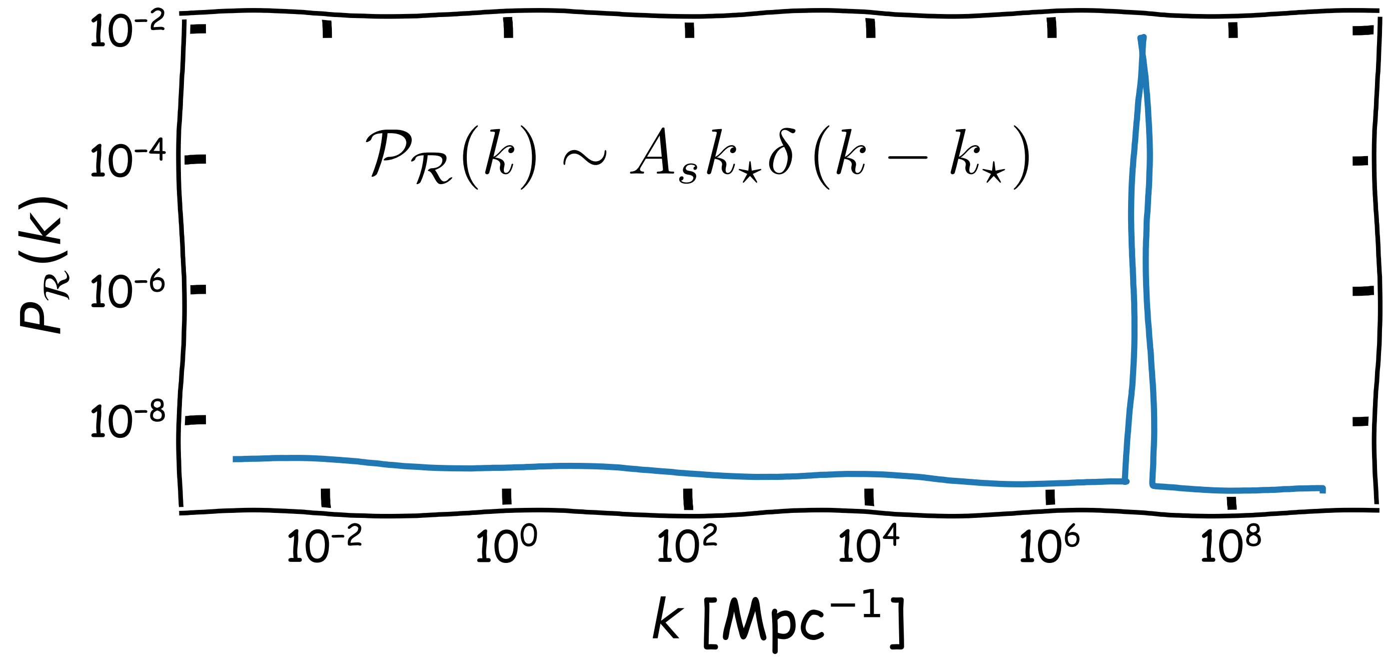


[1910.07397]

[See also 1709.03500]

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**)

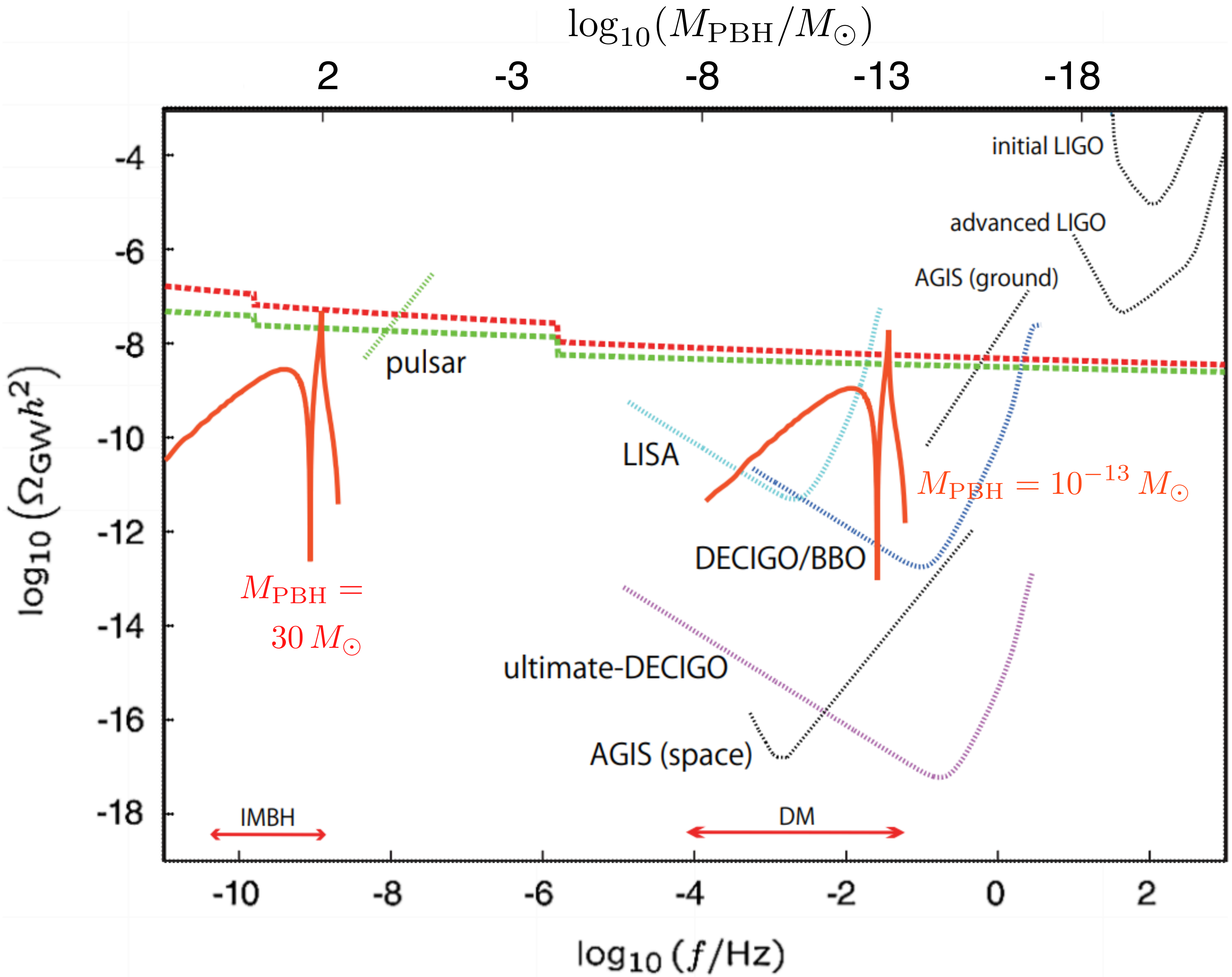
For perturbations on a scale $k_\star$, $M_\mathrm{PBH} \simeq 1.4 \times 10^{13} M_\odot \left(\frac{k_\star}{\mathrm{Mpc}^{-1}}\right)^{-2}$

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

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

[astro-ph/0407611, 0812.4339, 1012.4697]

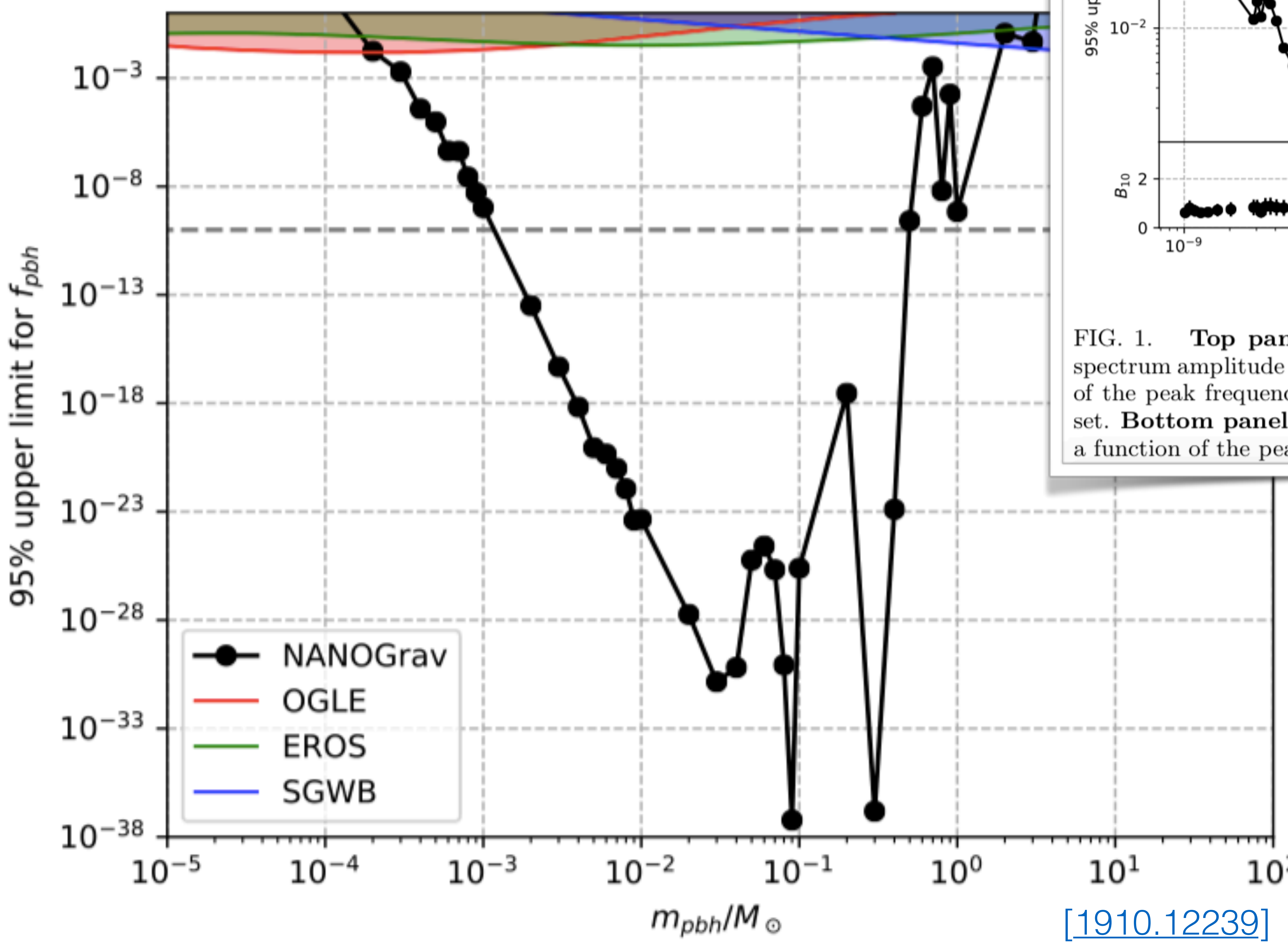
Scalar-induced GWs



[0812.4339]

[More recently - 1810.11000, 1810.12218, 1906.11549]

NANOGrav Constraints



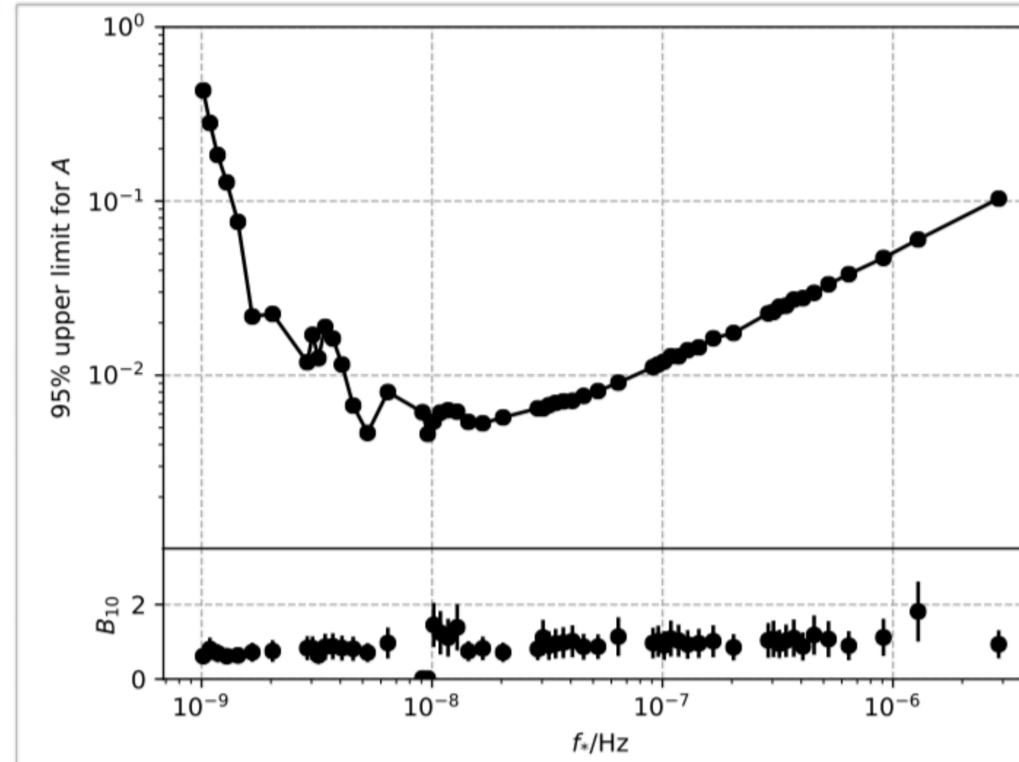


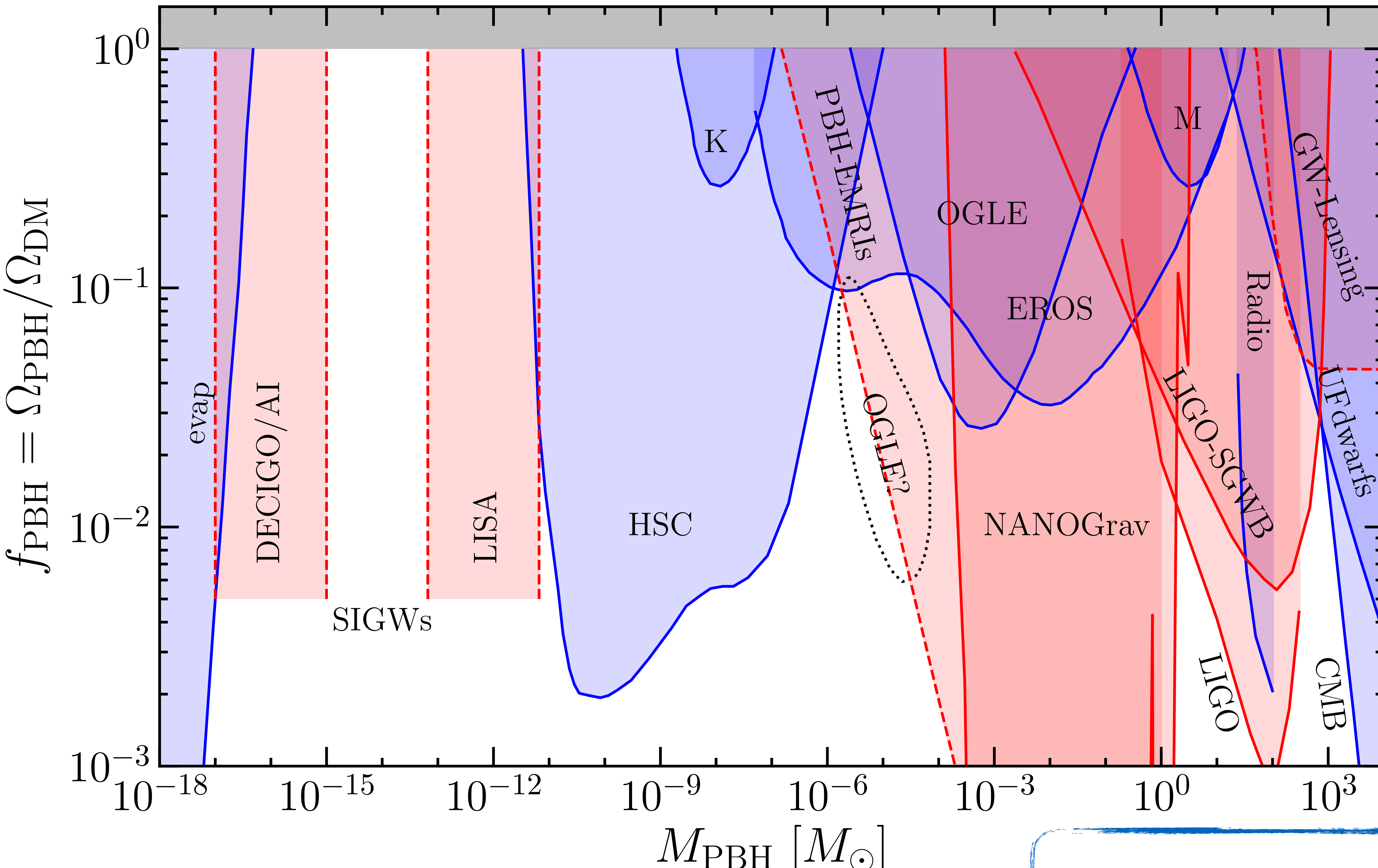
FIG. 1. **Top panel**: the 95% upper limits on the power spectrum amplitude A of curvature perturbation as a function of the peak frequency f_* from the NANOGrav 11-year data set. **Bottom panel**: the corresponding Bayes factors B_{10} as a function of the peak frequency f_*.

[1910.12239]

[See also Dan Stinebring's talk on NANOGrav, and 1801.01837]

PBHs + GWs

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

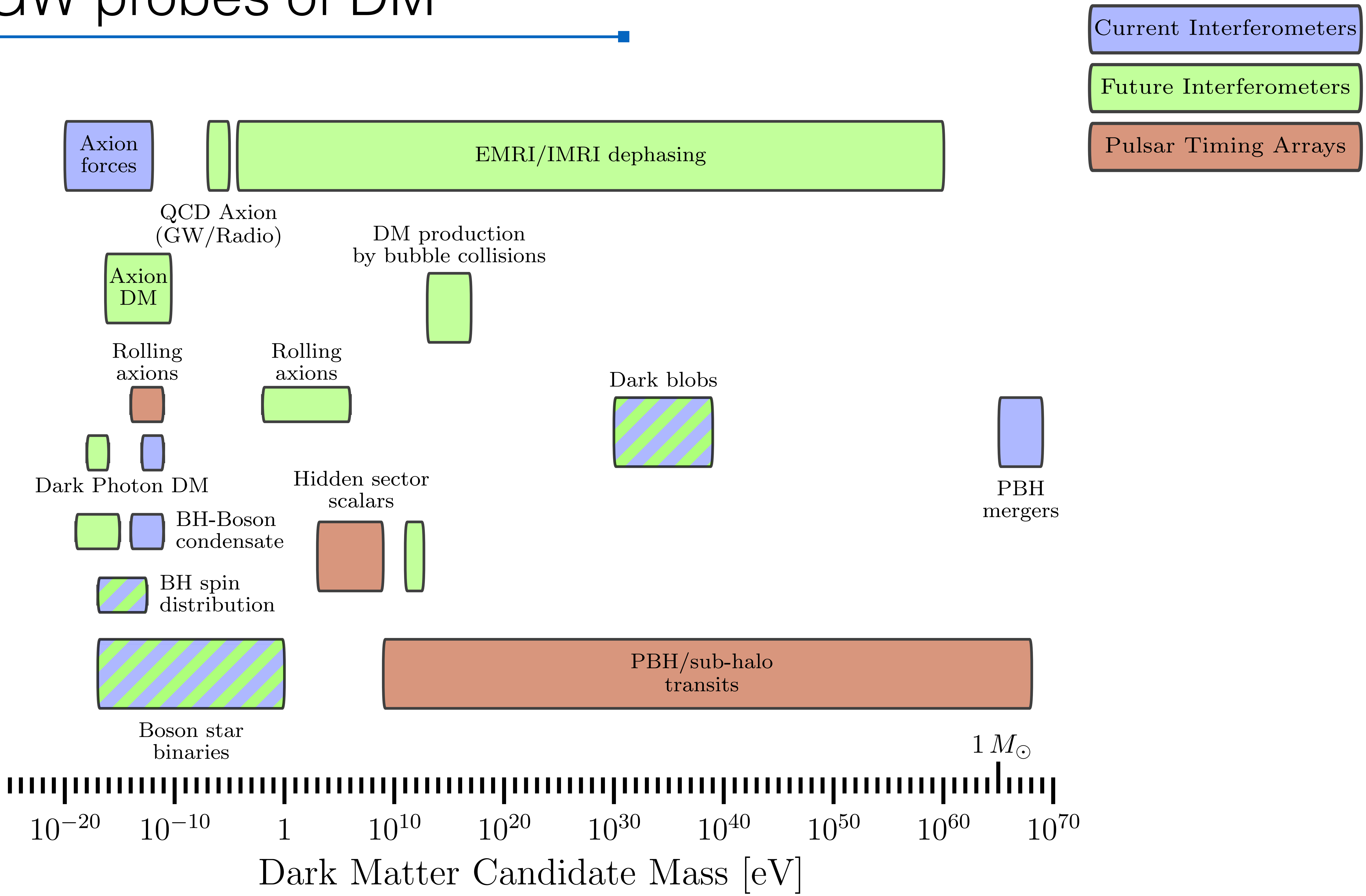


Thank you!

[See e.g. 1607.06077, 1801.00808, 1806.05195]

Backup Slides

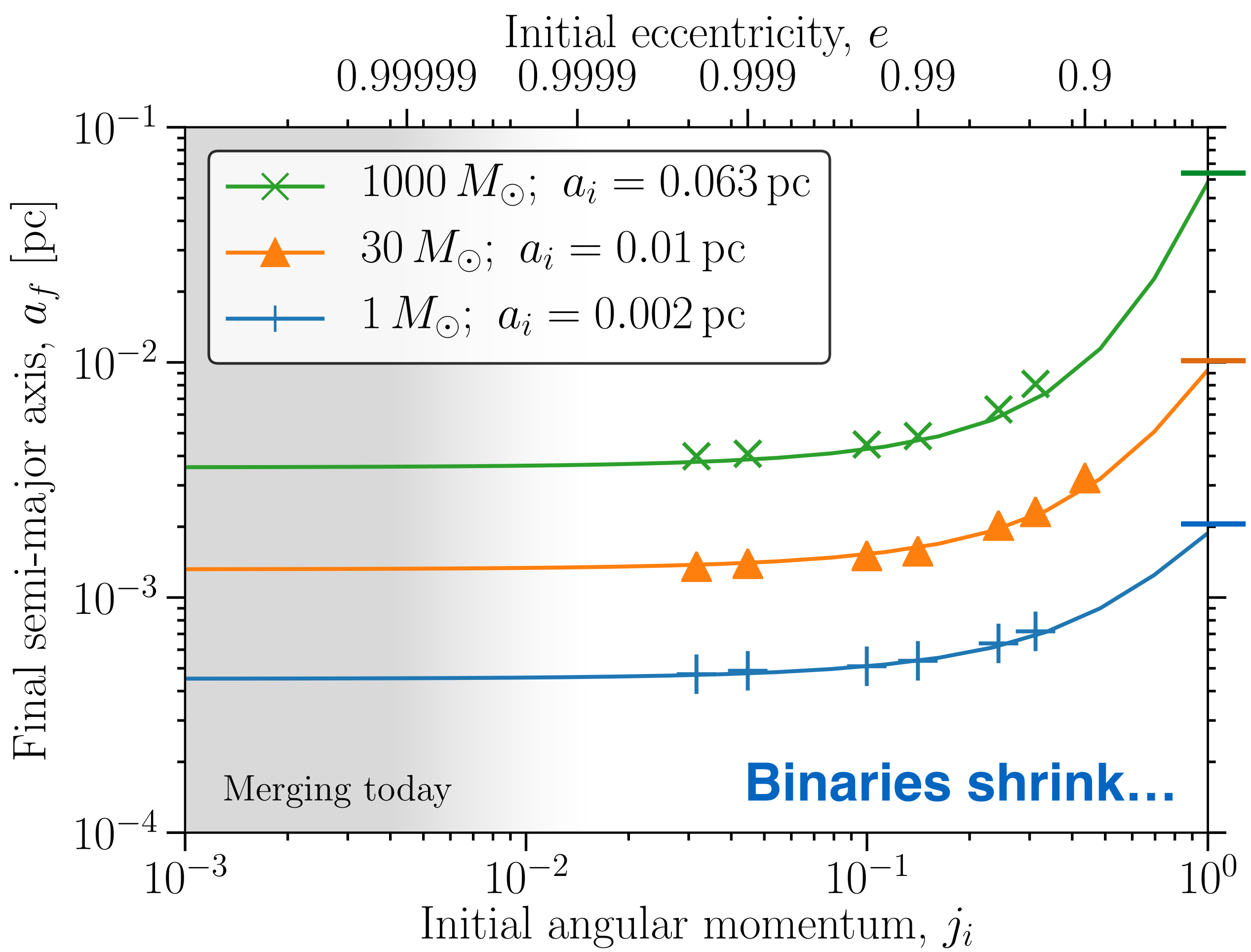
GW probes of DM

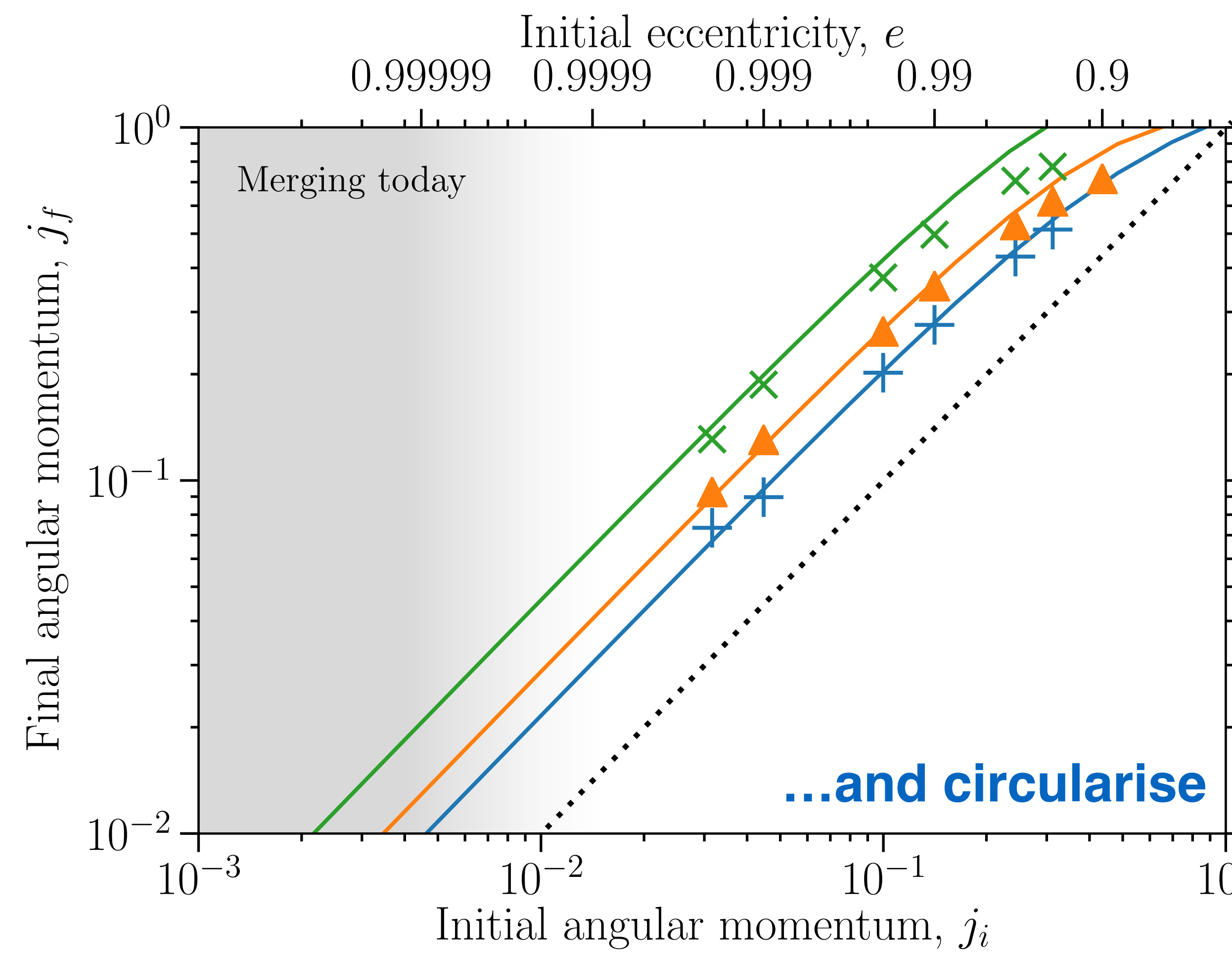


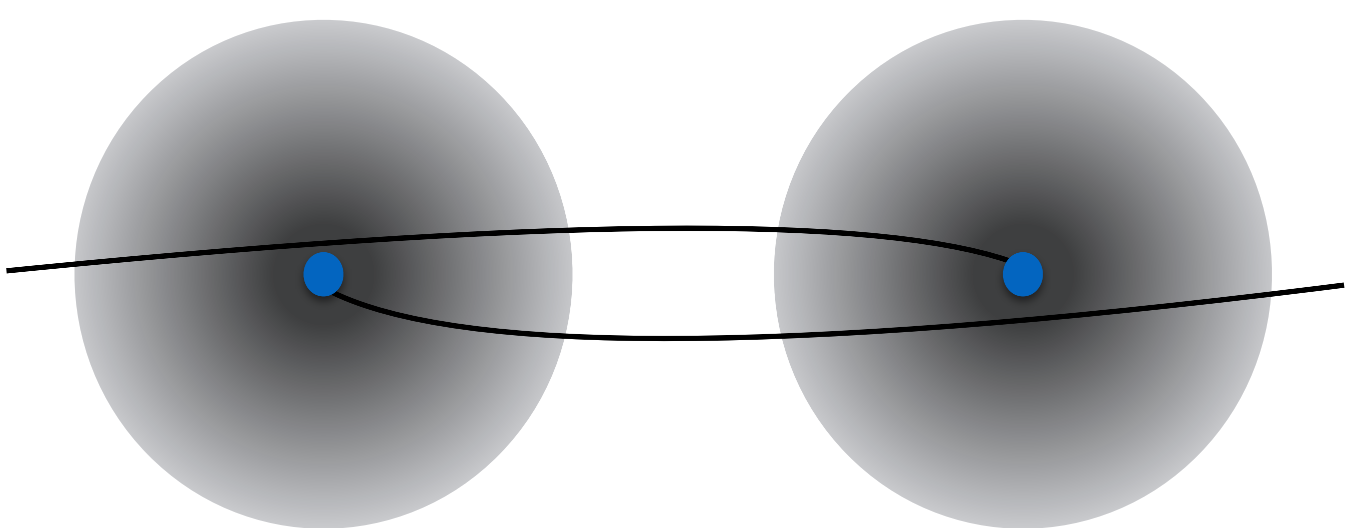
[1907.10610]

N-body Simulation Results

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







Conservation of angular momentum

$$L_i^{\mathrm{PBH}} = L_f^{\mathrm{PBH}}$$

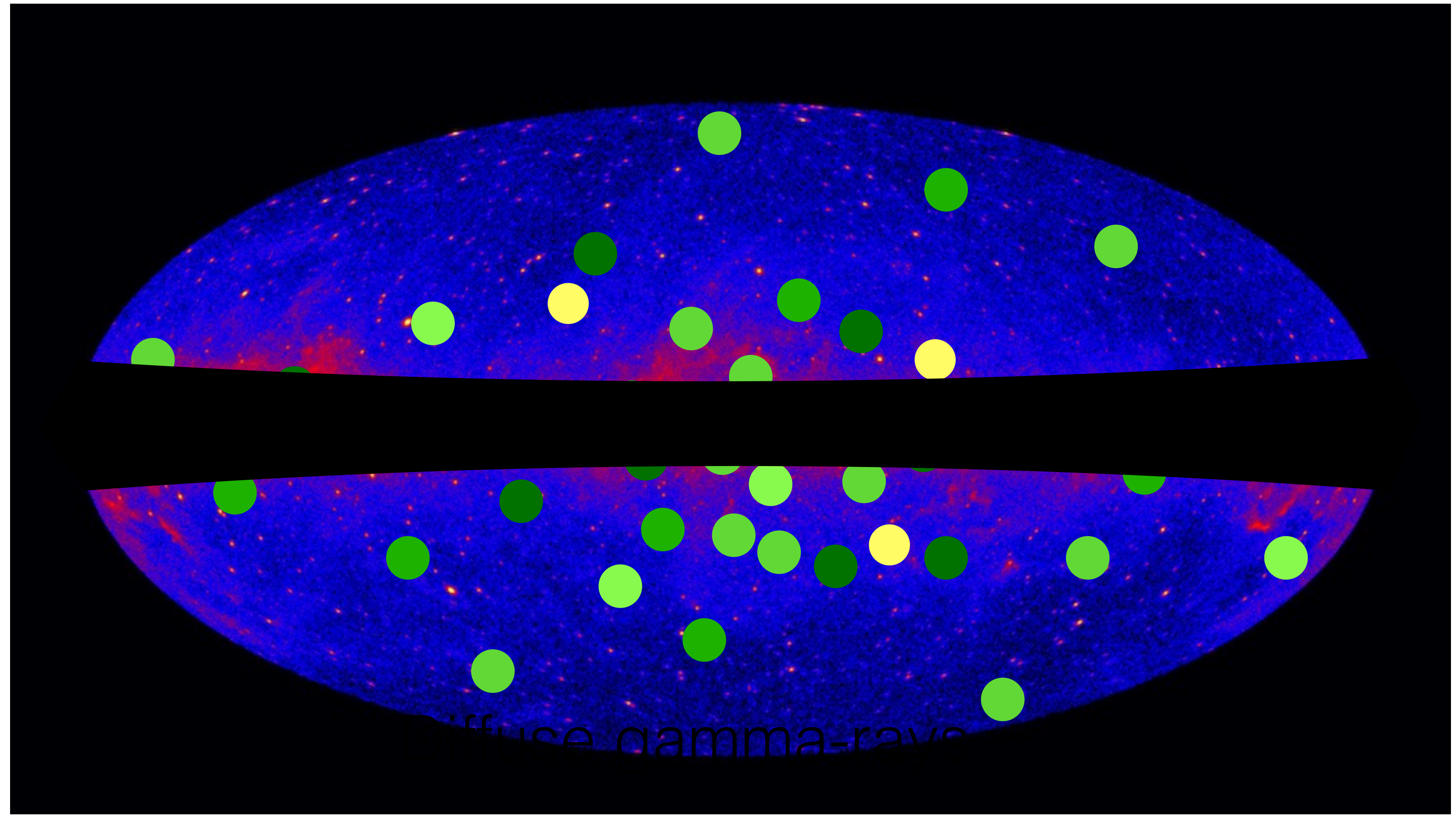
$$L_i^{\mathrm{halo}} = L_f^{\mathrm{halo}}$$

fixes $j_f = j_i\sqrt{a_i/a_f}$

Gamma-ray constraints

[Credit: Adam Coogan]

Point Sources in the Milky Way:



Fermi/NASA

Diffuse (cosmological) background:

UCO/Lick

NASA

Redshifting

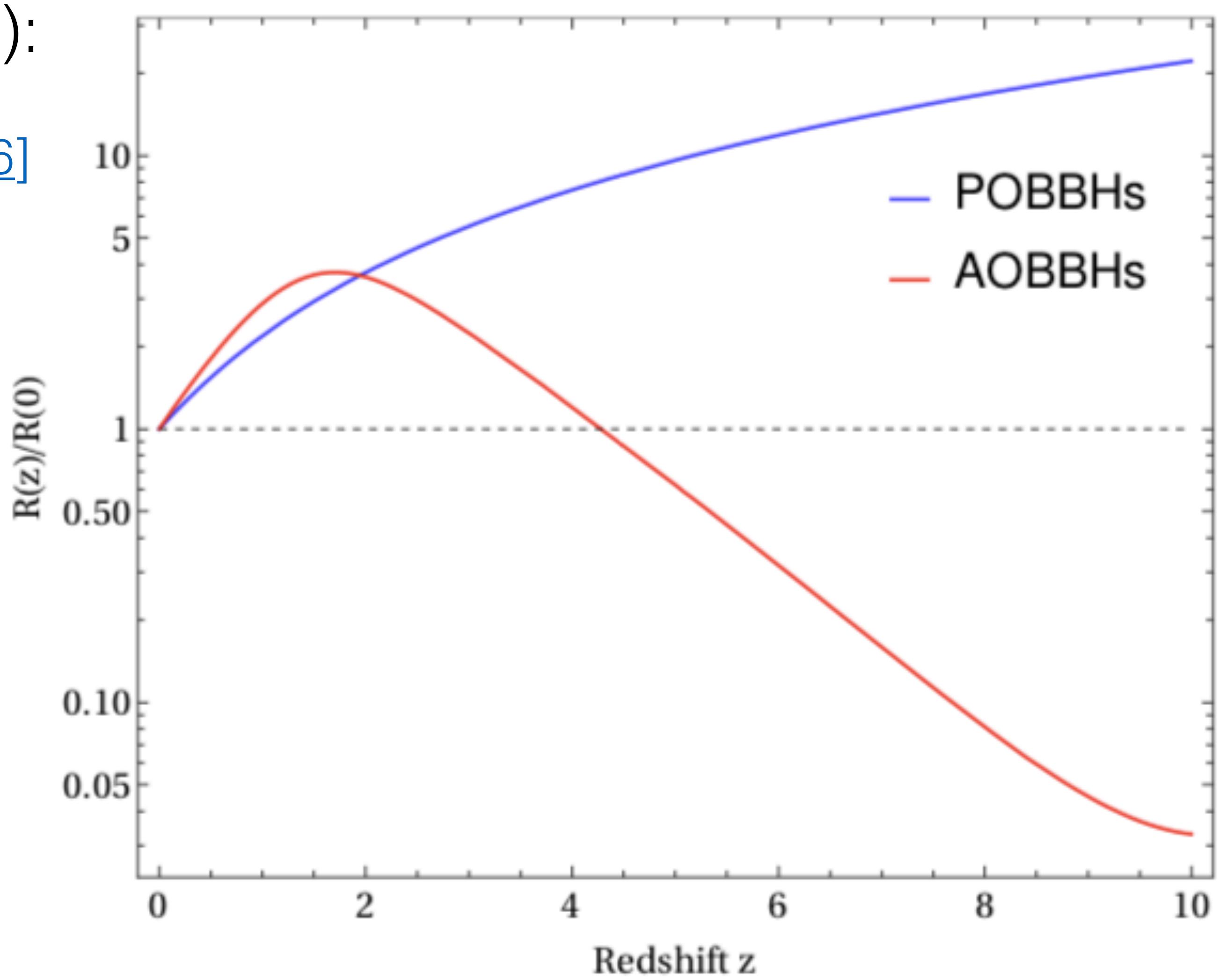
Gamma rays from DM ann.

Attenuation

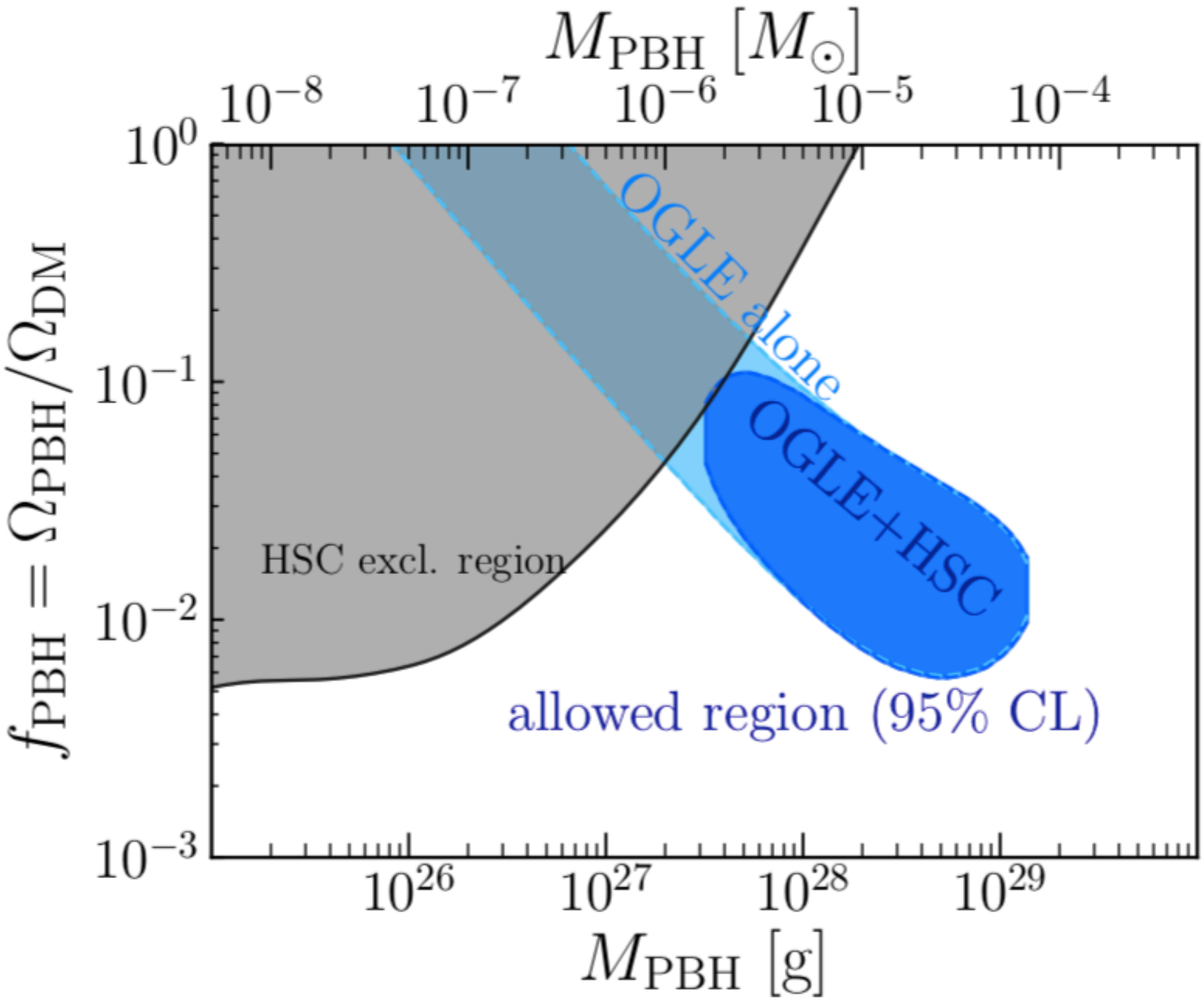
Astrophysical vs Primordial

- Spin measurements [1905.13019]
- Population study of X-ray and Radio sources [1612.00457, 1812.07967]
- Sub-solar mass black holes [1808.04771, 1808.04772]
- High redshift ($z > 40$) black holes [1708.07380]
- Merger rate (over cosmic time):

[1904.02396]



OGLE 'hint'



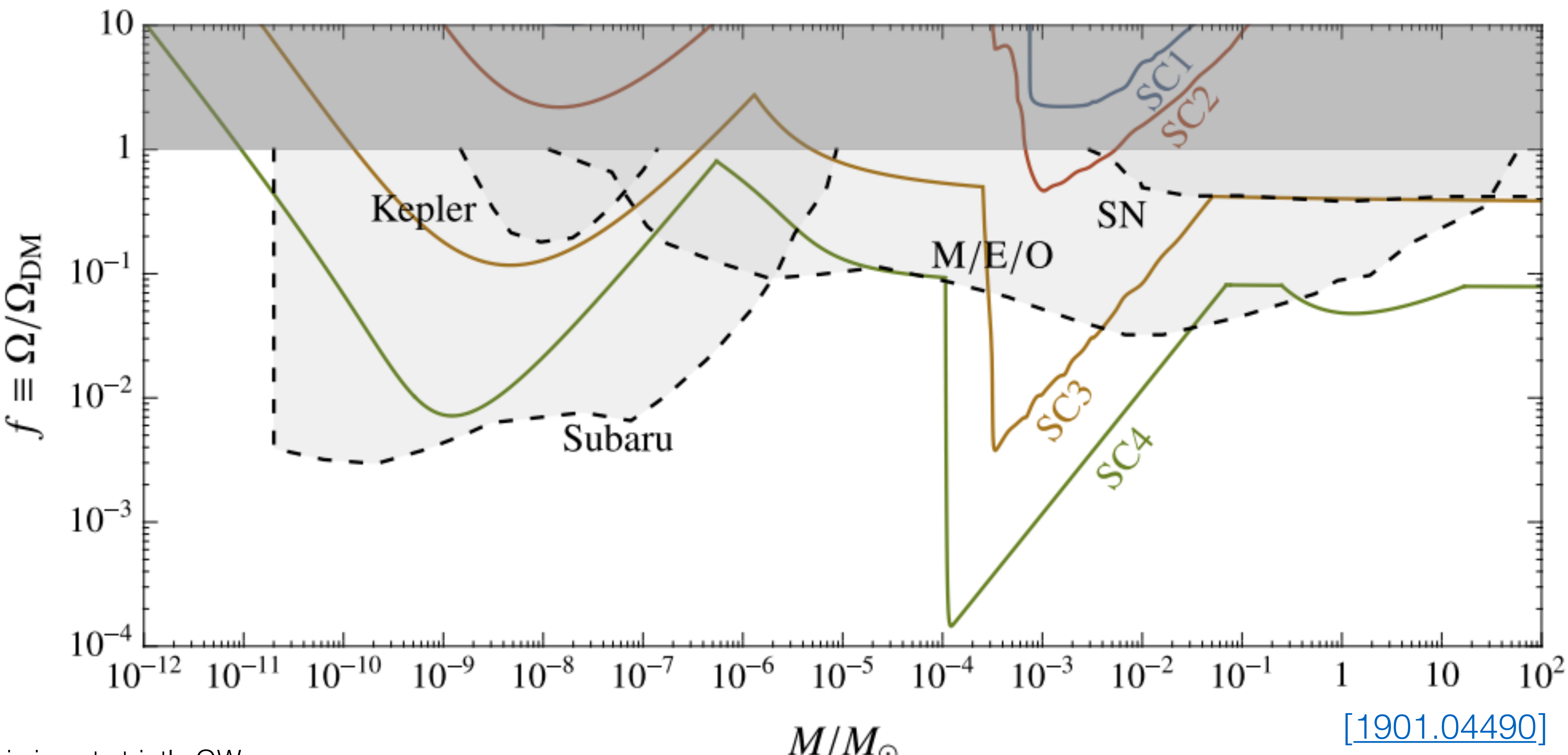
6 ultra-short timescale events

[OGLE - 1901.07120]

Perturbing PTAs

[astro-ph/0702586, astro-ph/0702546]

		T [yr]	$t_{\rm RMS}$ [ns]	Δt [wk]	d [kpc]	N_P
SC2	Current	$5-30$	$50-10^4$	$1-4$	$0.5-5$	73
SC3	SKA	20	50	2	5	200
SC4	Optimistic	20	25	1	10	1000

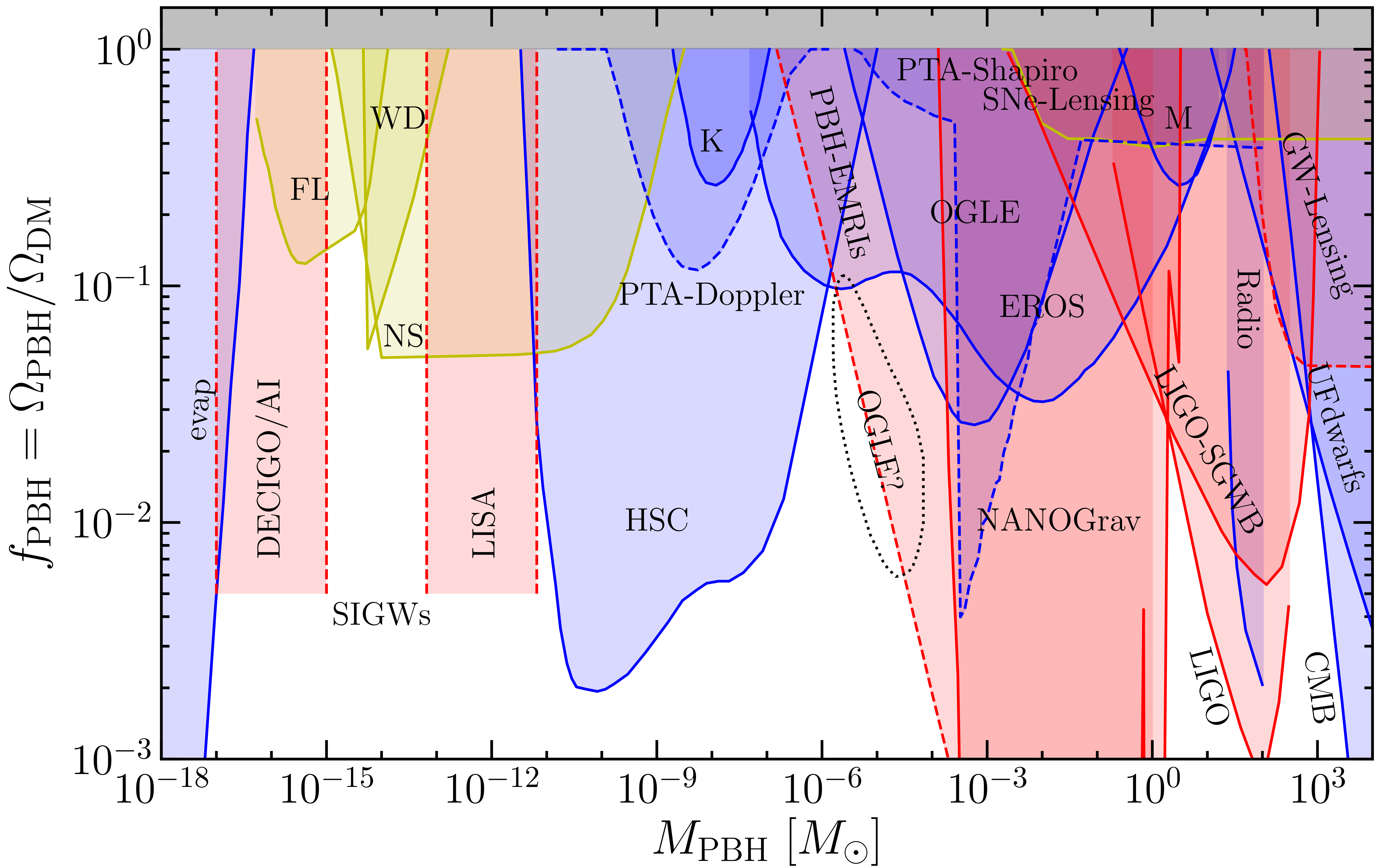


[1901.04490]

This is not strictly GWs…

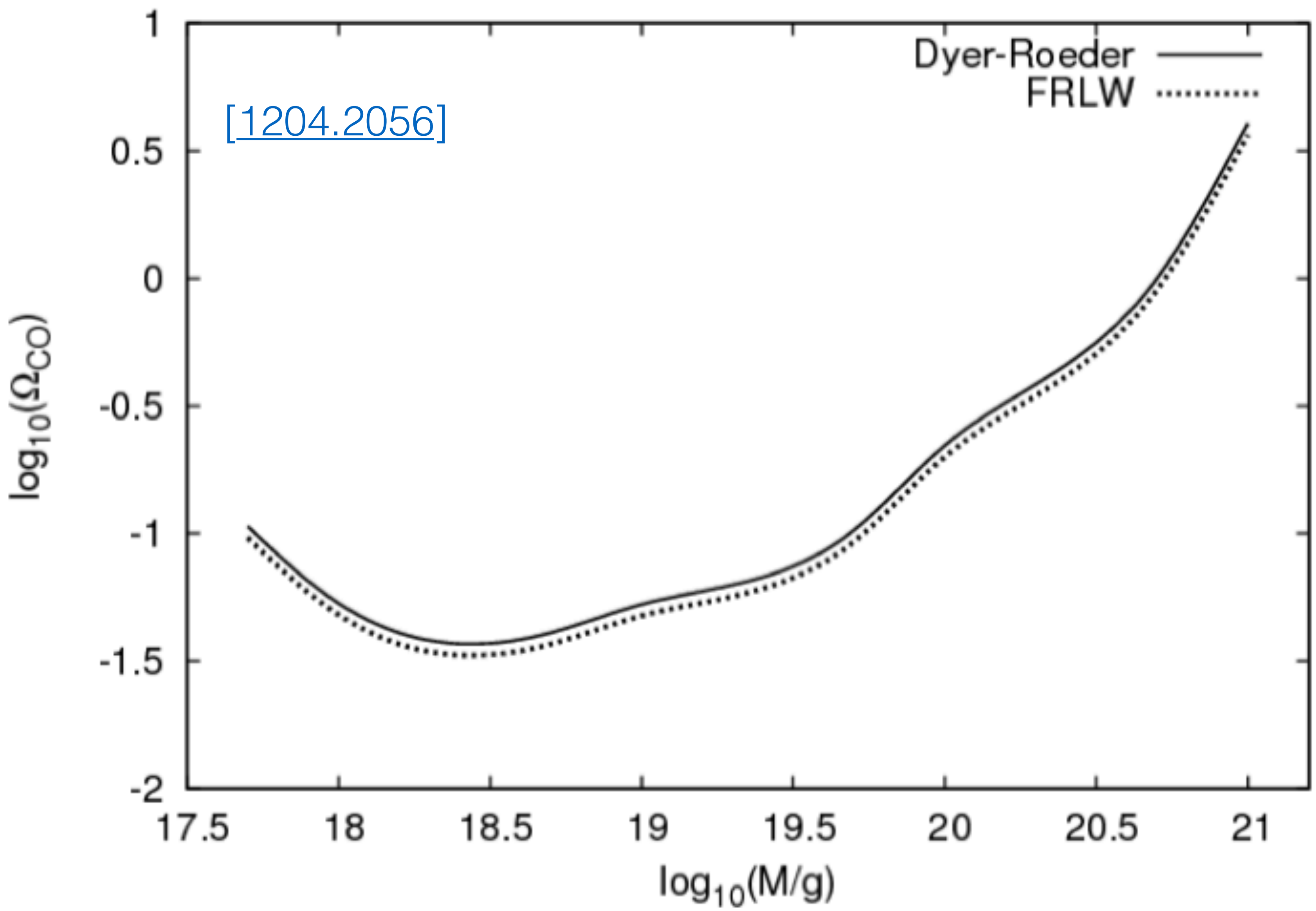
PBH Bounds

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



Femto-lensing

'Femto-lensing' of gamma-ray bursts



This turns out not to be valid - because GRBs are not 'point-like' in the lens plane, geometric optics no longer valid.

GRBs generally too extended to be useful for FL.

[1807.11495]

[1906.05950]

Broad Mass Functions

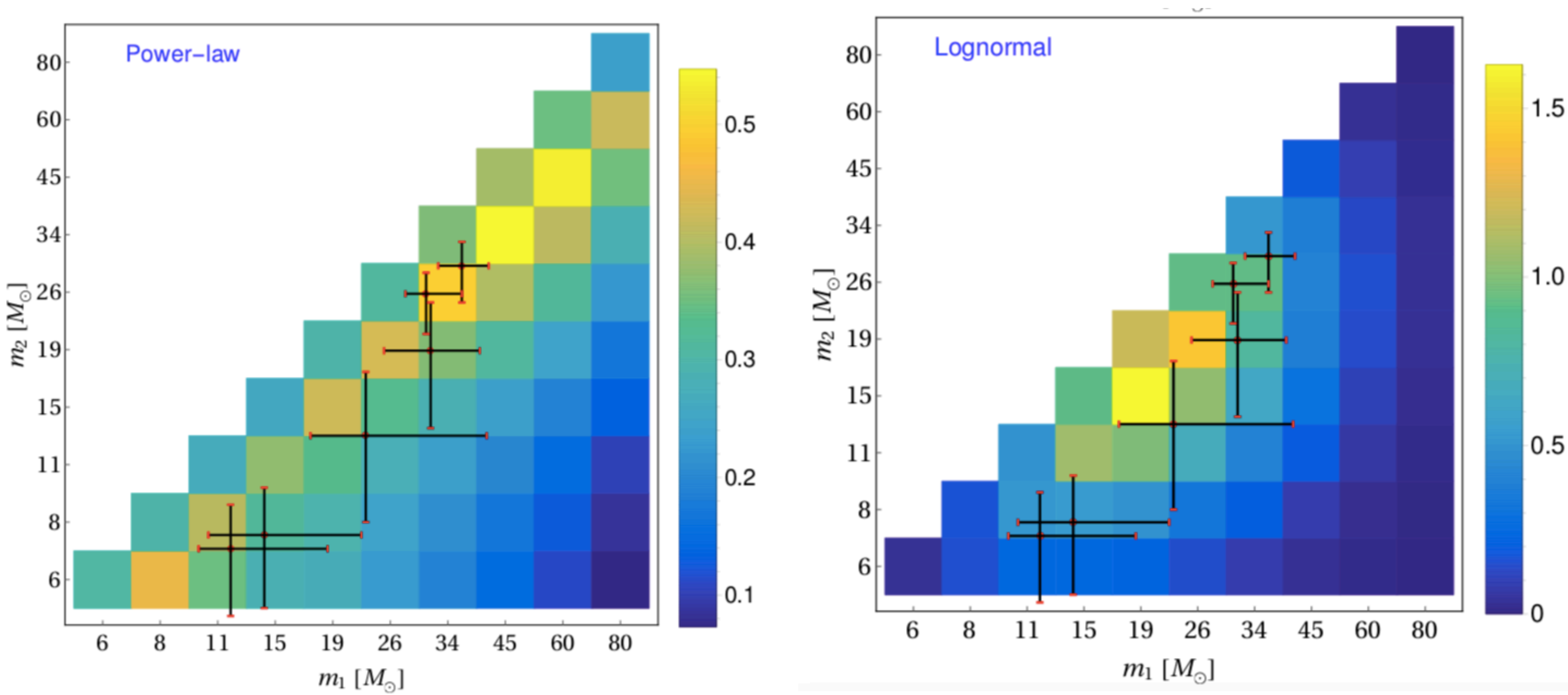
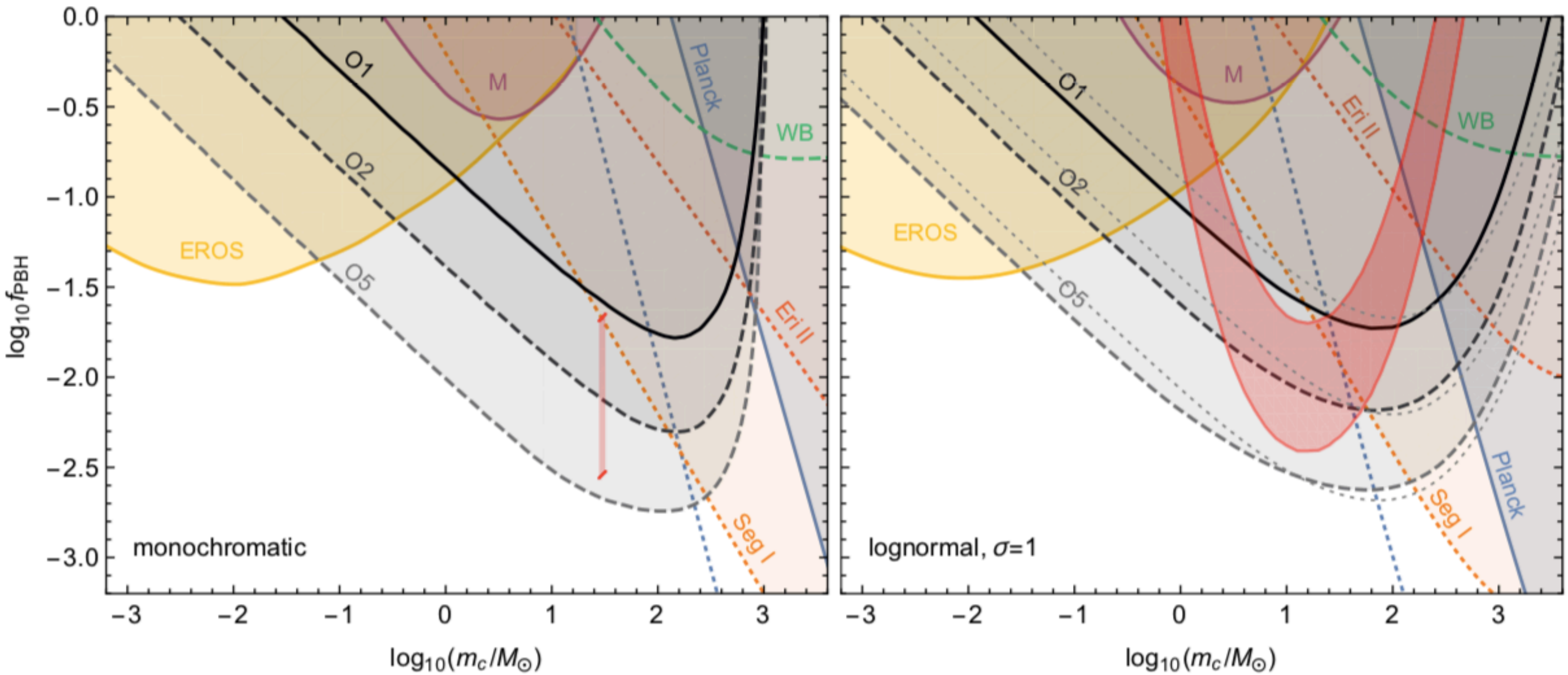


FIG. 4. The 2D distributions for Λ [see Eq. (40)], along with the 6 events detected by LIGO/VIRGO. The crosses indicate error bars for each event. The top and bottom panels correspond to the *power-law* PDF ($M = 5M_\odot$ and $\alpha = 1.6$) with $f_{\rm pbh} = 4.3 \times 10^{-3}$ and *lognormal* PDF ($m_c = 15M_\odot$ and $\sigma = 0.6$) with $f_{\rm pbh} = 3.7 \times 10^{-3}$, respectively.

[1801.10327]

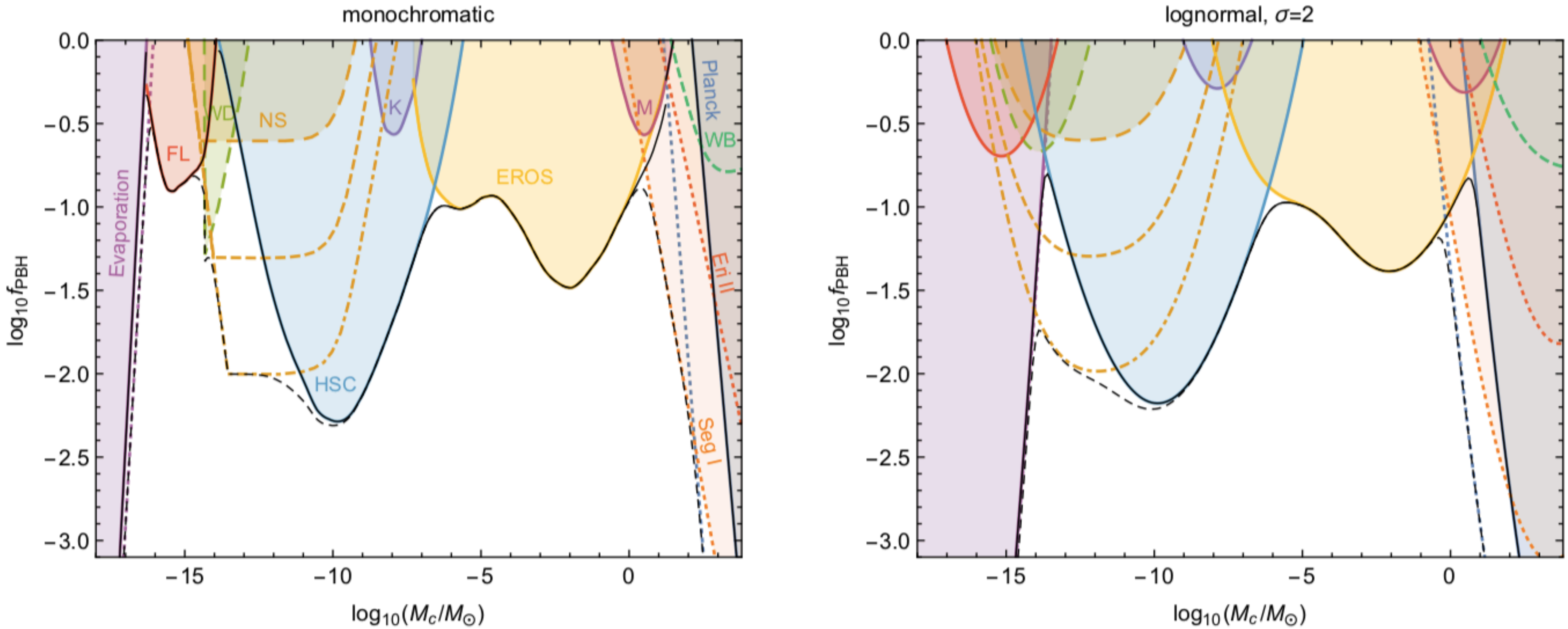
Broad Mass Functions

Projections for the SGWB from PBH-PBH mergers



[1707.01480]

Broad Mass Functions



[Carr et al, 2017 - 1705.05567]

[See also 1709.07467, 1801.00808]