Black Holes' Dark Dress

Mergers of primordial black holes and the impact of Dark Matter halos

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16th November 2018

GRAPPA

GRavitation AstroParticle Physics Amsterdam

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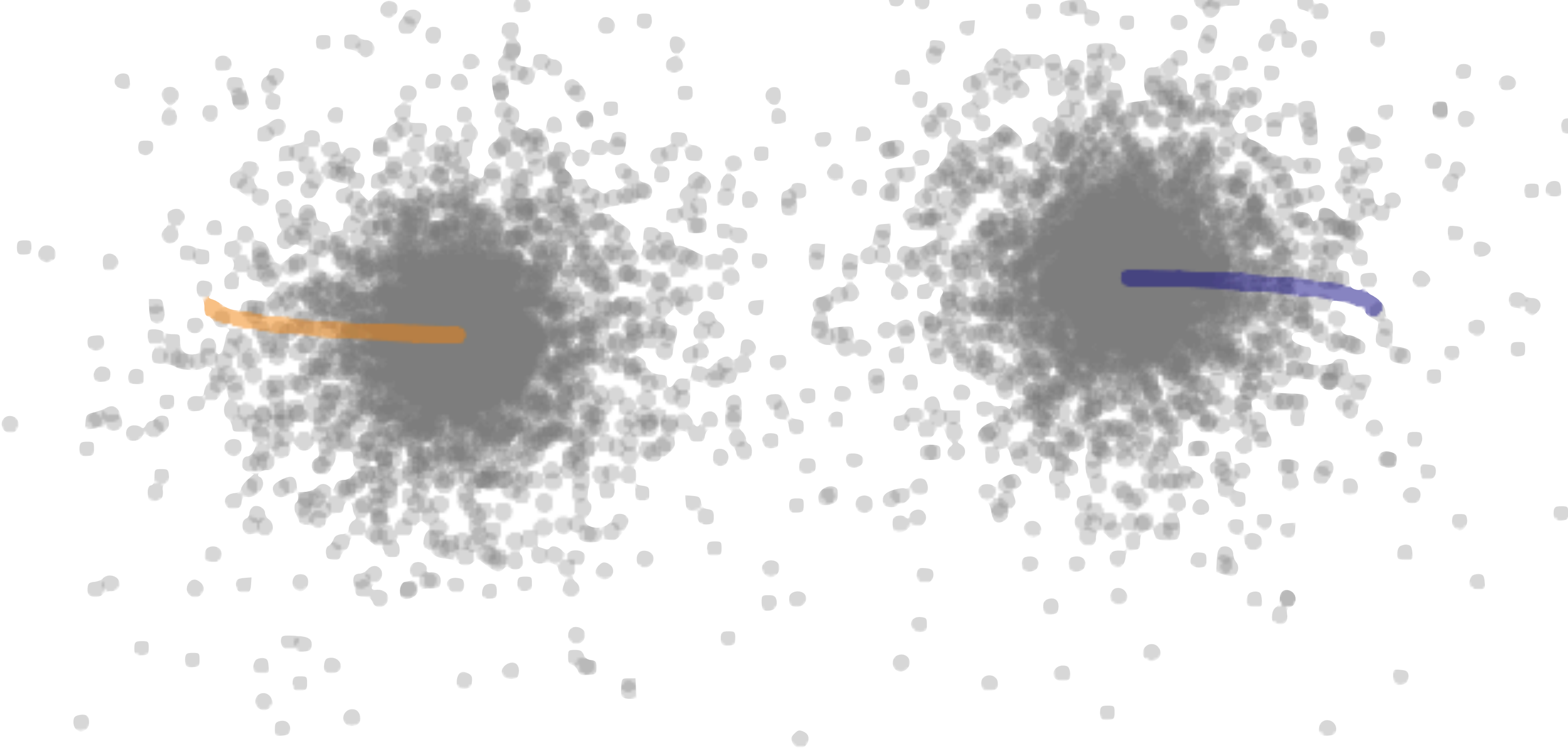
“Like I say, I very much hope you choose to come here.
We're a young and vibrant group that is making a big impression.”

- Tony Padilla, 9 March 2011



arXiv:1805.09034, PRD 98, 023536 (2018)

BJK, Daniele Gaggero & Gianfranco Bertone

Movies at tinyurl.com/BlackHolesDarkDress

Could the observed LIGO events be due to merging Primordial Black Holes (PBHs)?

How do local Dark Matter (DM) halos affect the merger rate of PBHs?

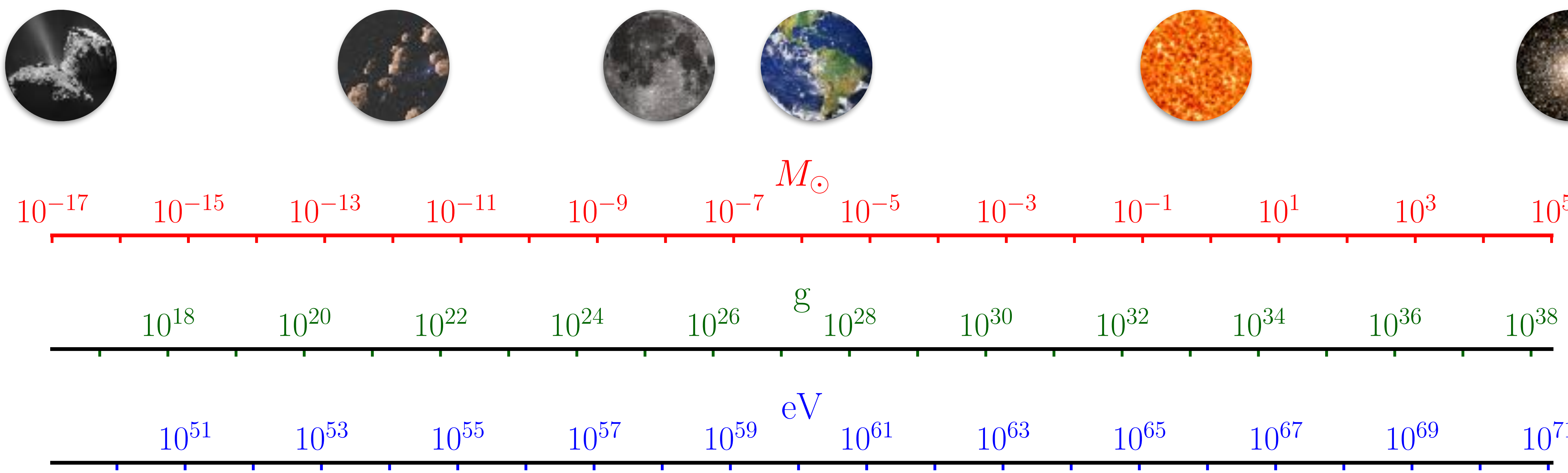
How does DM affect other Gravitational Wave (GW) signals?

What are Primordial Black Holes?

Primordial Black Holes (PBHs) 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]

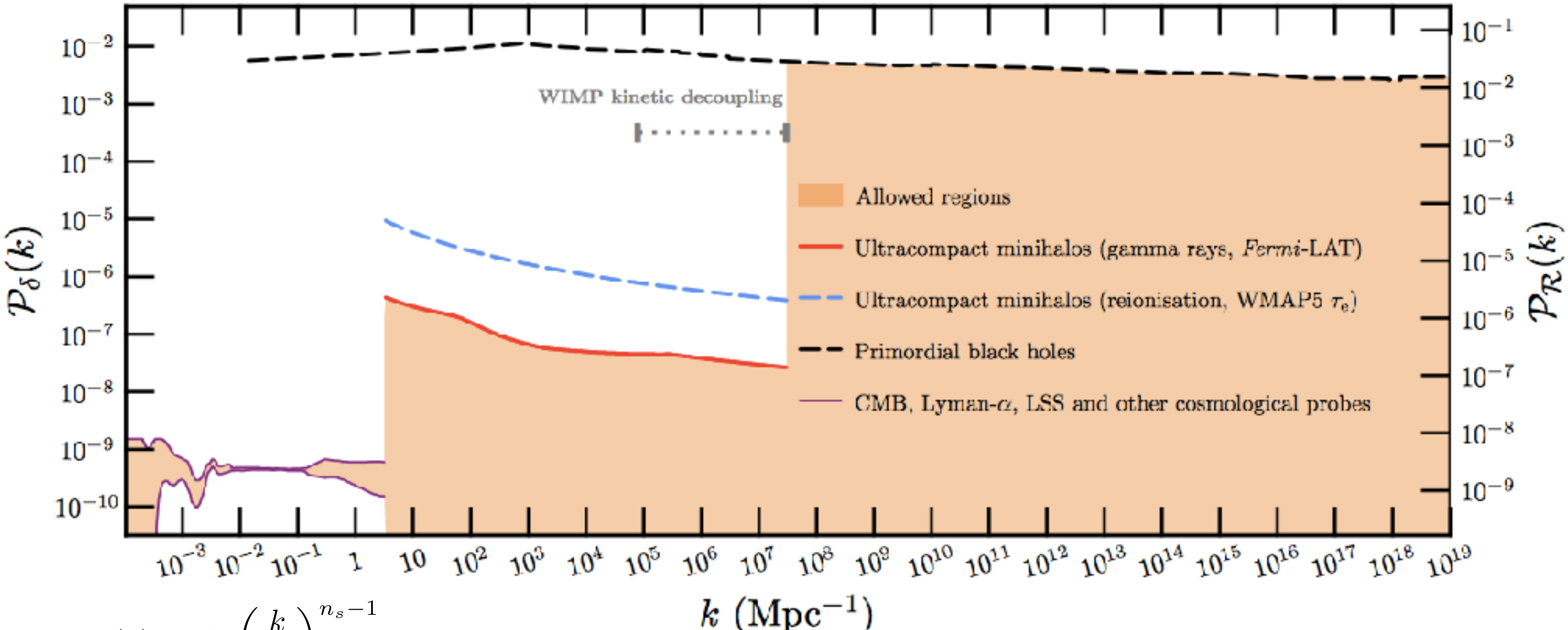


[Y. B. Zel'dovich and I. D. Novikov, Soviet Astronomy 10, 602 (1967)]
[S. Hawking, Mon. Not. R. Astron. Soc. 152, 75 (1971)]
[Carr and Hawking, MNRAS 168 (1974); Carr, Astrophys. J. 201, 1 (1975)]

PBH formation

Extrapolating the primordial power spectrum from Planck, fluctuations big enough to produce PBHs should be negligible…

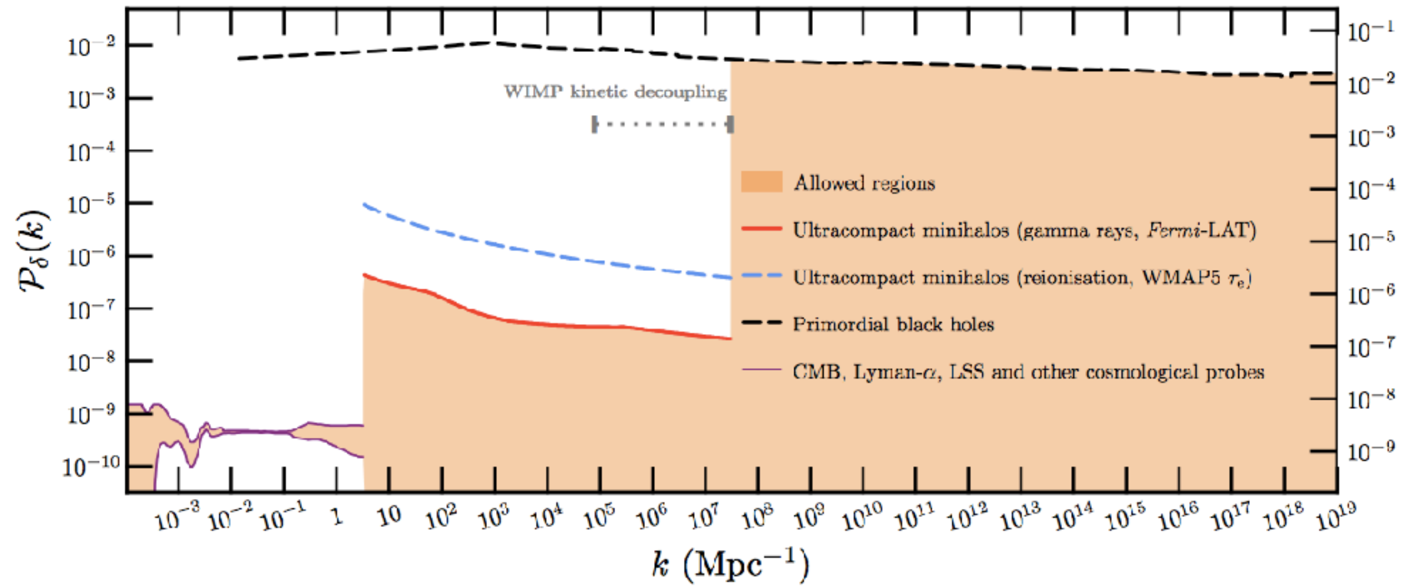
[1110.2484]



$$\mathcal{P}_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

…but small scale power spectrum is largely unconstrained…

PBH formation



How then could we make PBHs?

- Enhancement/feature in power spectrum

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

- Cosmic String Loops

  [Hawking (1987), Polnarev & Zembowicz (1991), Caldwell & Caspar (1996)]

- Bubble collisions

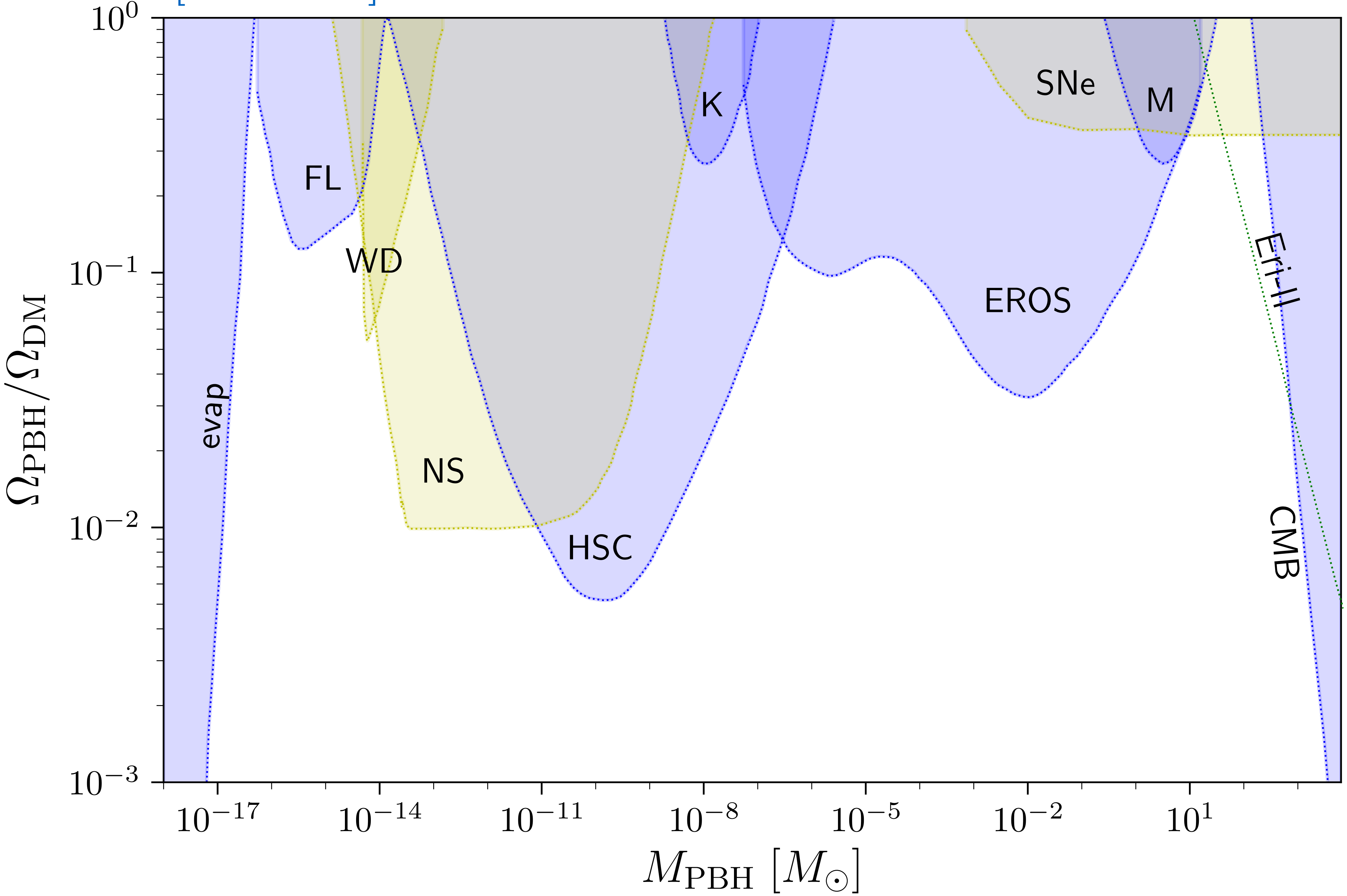
  [Hawking, Moss & Stewart (1982); La & Steinhart (1989)]

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

[Green, 1403.1198; Sasaki et al, 1801.05235]

PBHs as Dark Matter

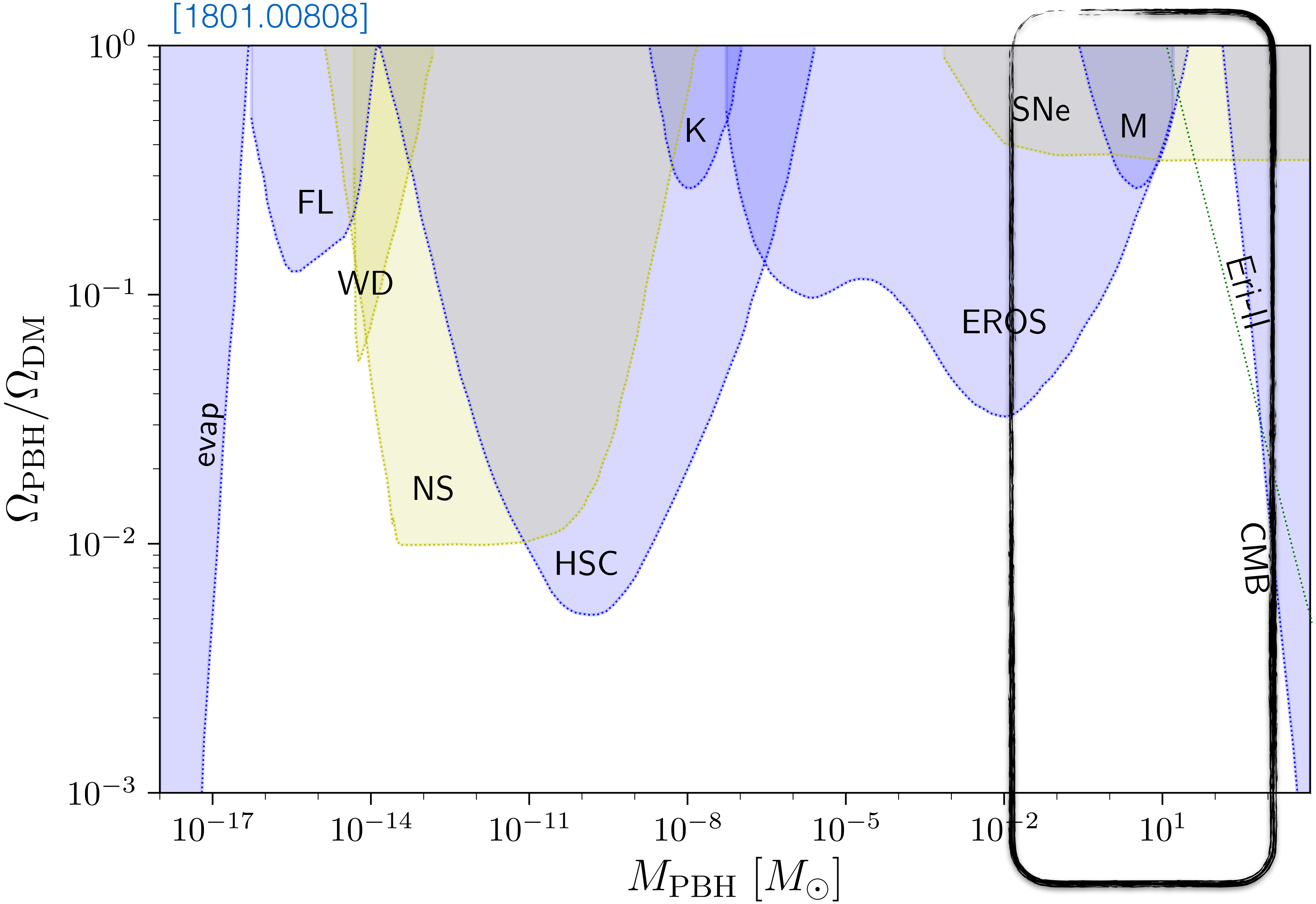
[1801.00808]



[See 1607.06077, 1806.05195 and references therein]

PBHs as Dark Matter

[1801.00808]

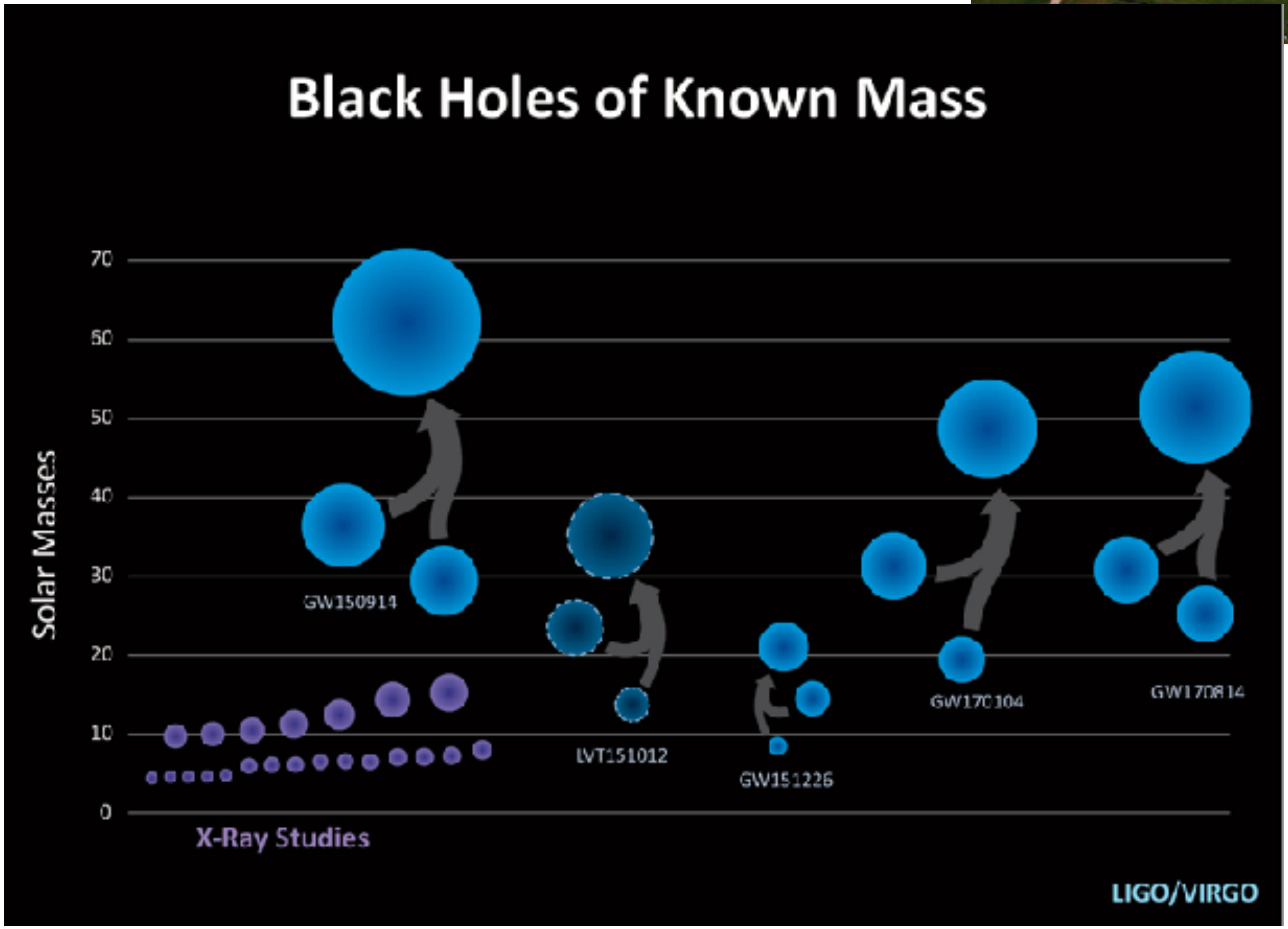


[See 1607.06077, 1806.05195 and references therein]

LIGO/Virgo Mergers

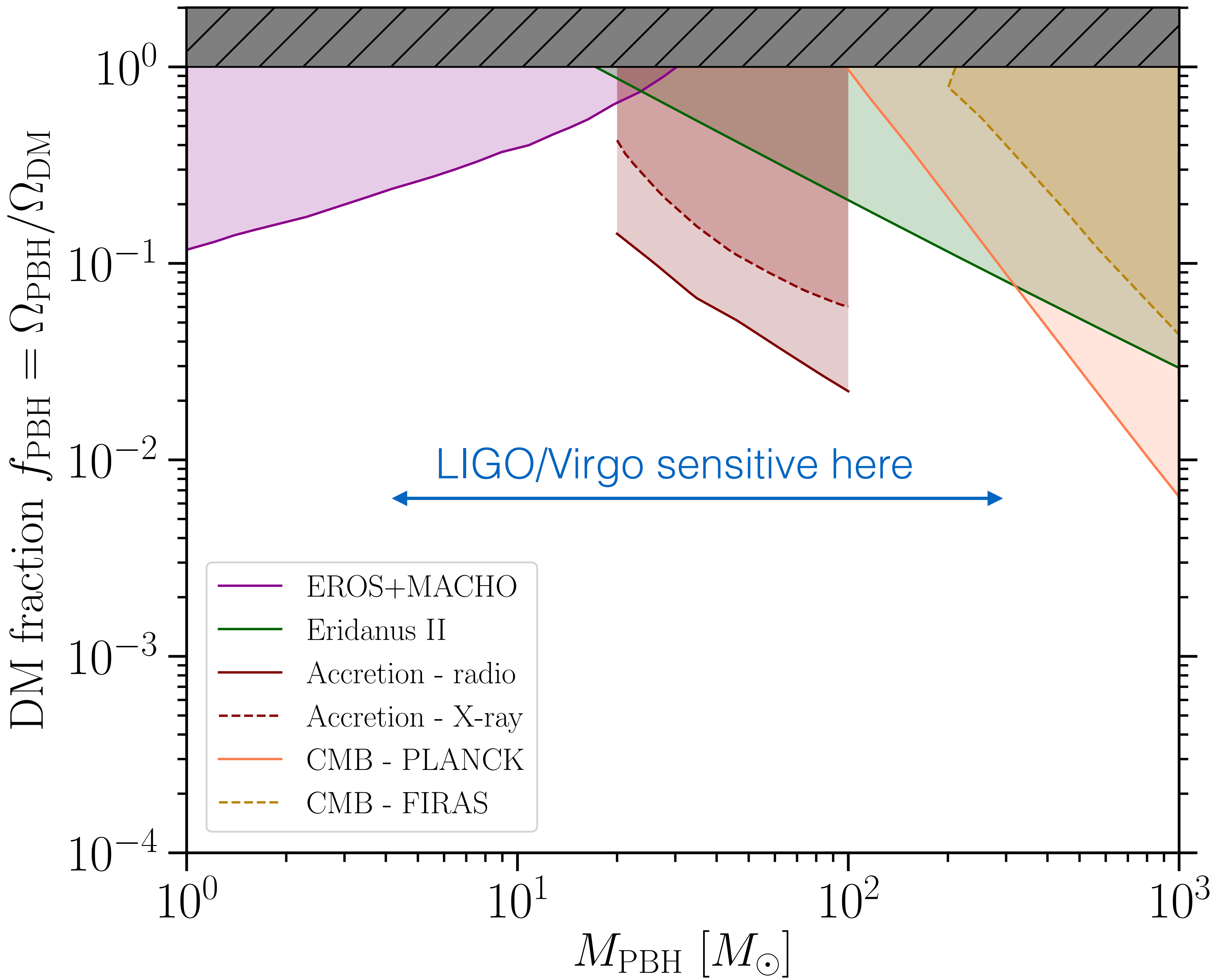
The Virgo collaboration/CCO 1.0

LIGO/Caltech/Sonoma State (Aurore Simonnet)



Solar Mass PBHs

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

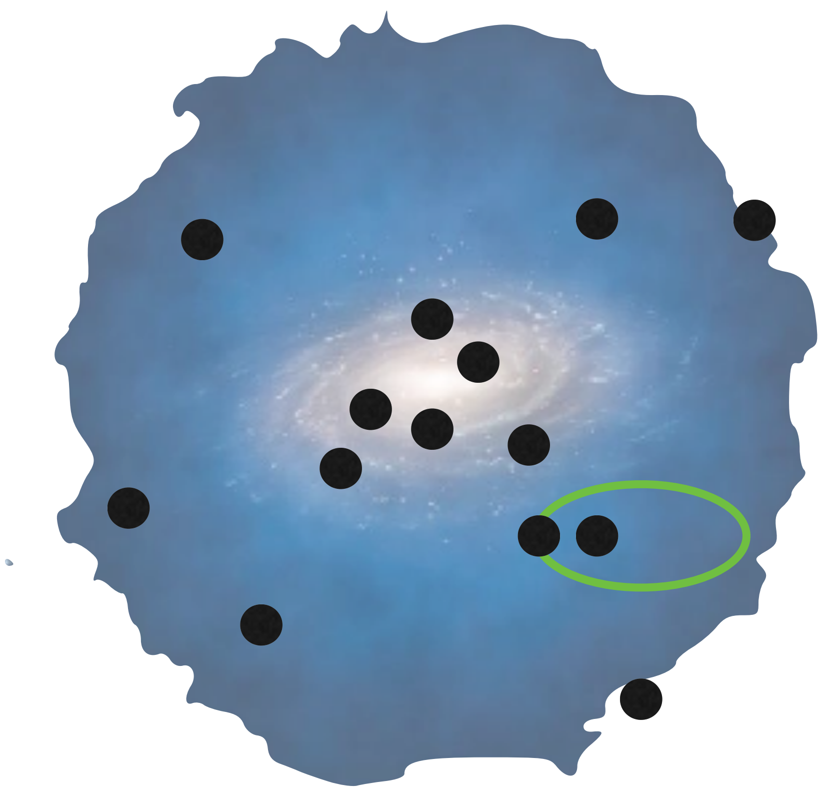


Merger rates of PBHs

A tale of two binaries

A) Binaries formed after close encounters

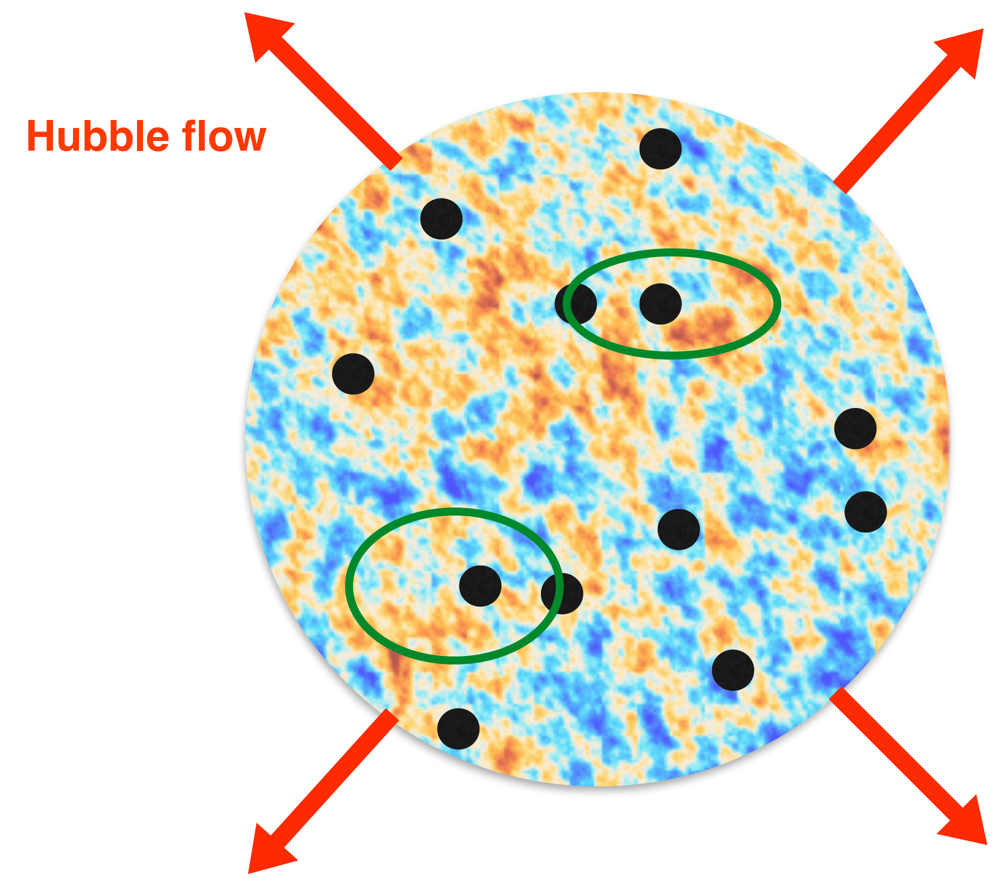
[Bird et al., 1603.00464]



$$\sigma = \pi \left(\frac{85\,\pi}{3}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$$
$$= 1.37 \times 10^{-14}\, M_{30}^2\, v_{\rm pbh-200}^{-18/7}\, {\rm pc}^2$$

B) Binaries formed in the early Universe

[Sasaki et al, 1603.08338]



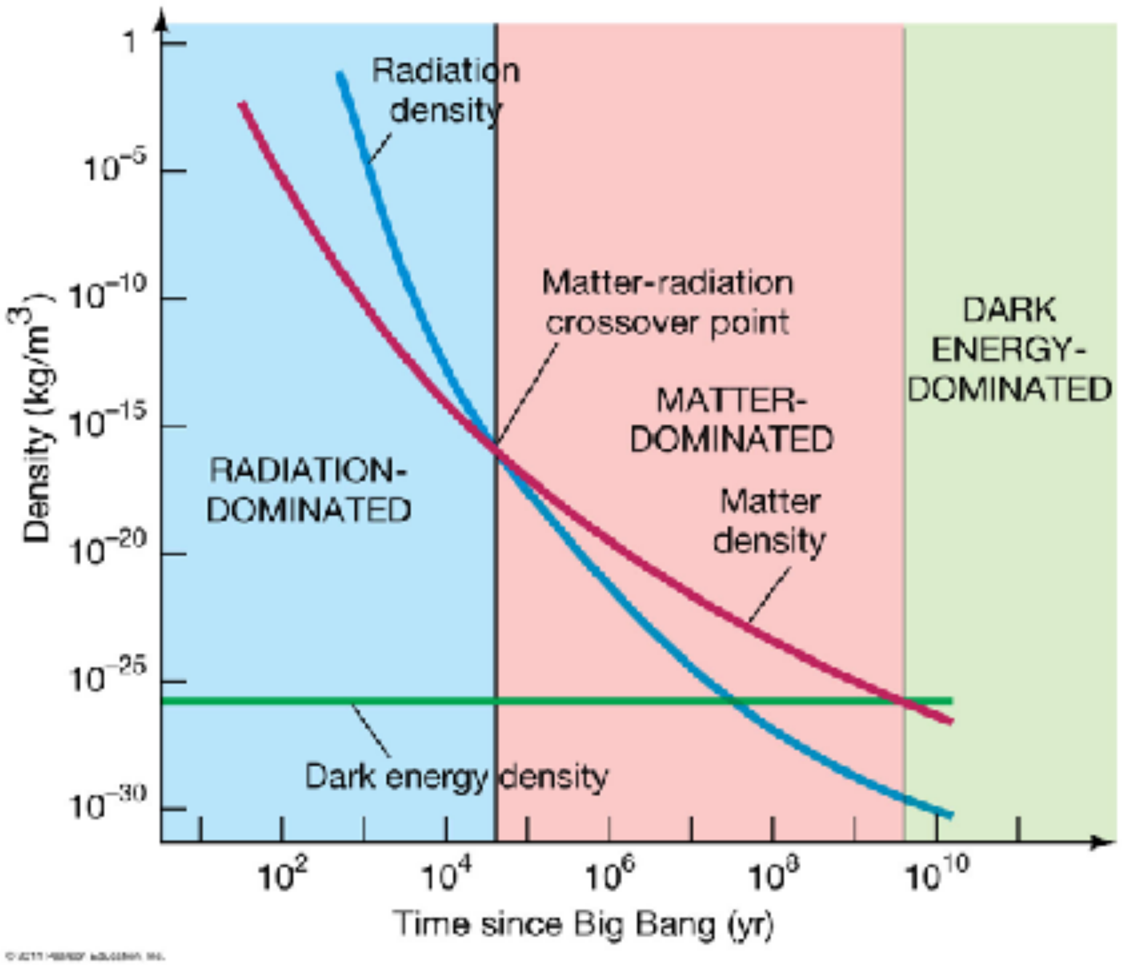
Require:

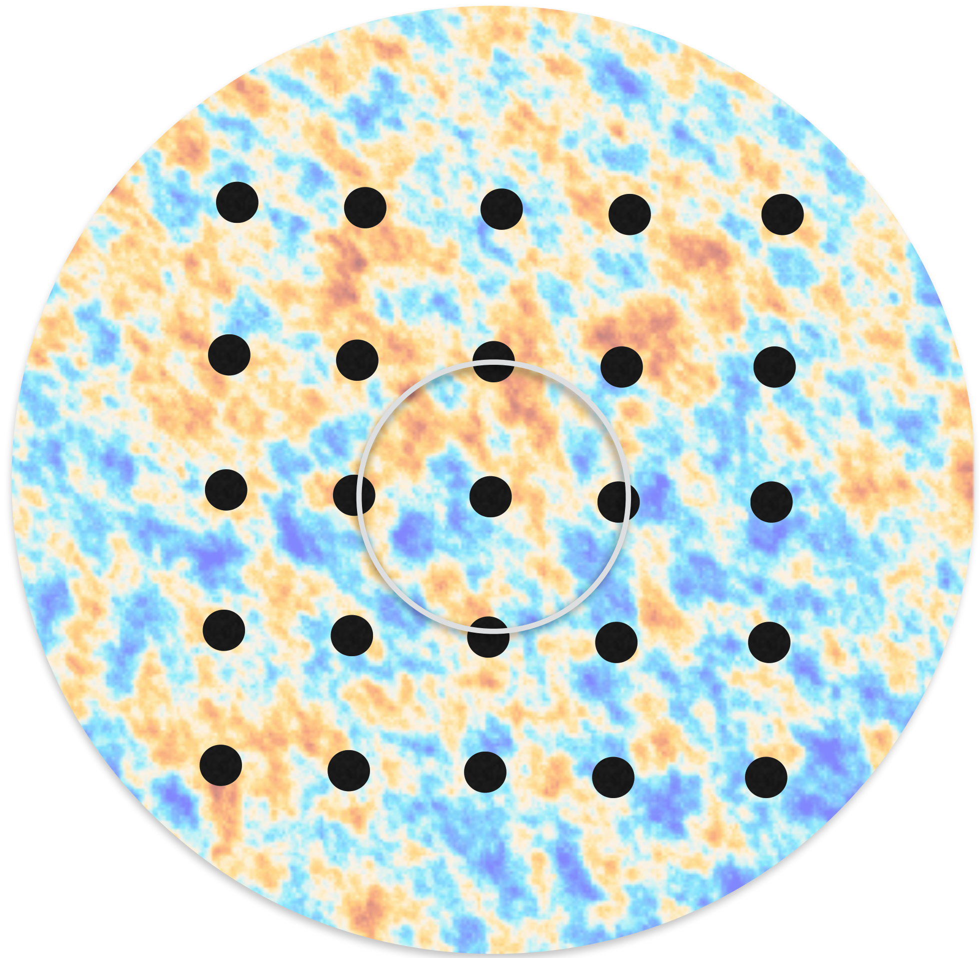
$$M_{\rm BH} R^{-3} > \rho(z) \text{ before } z_{\rm eq}$$

[Daniele Gaggero, UCI 20/02/2018]

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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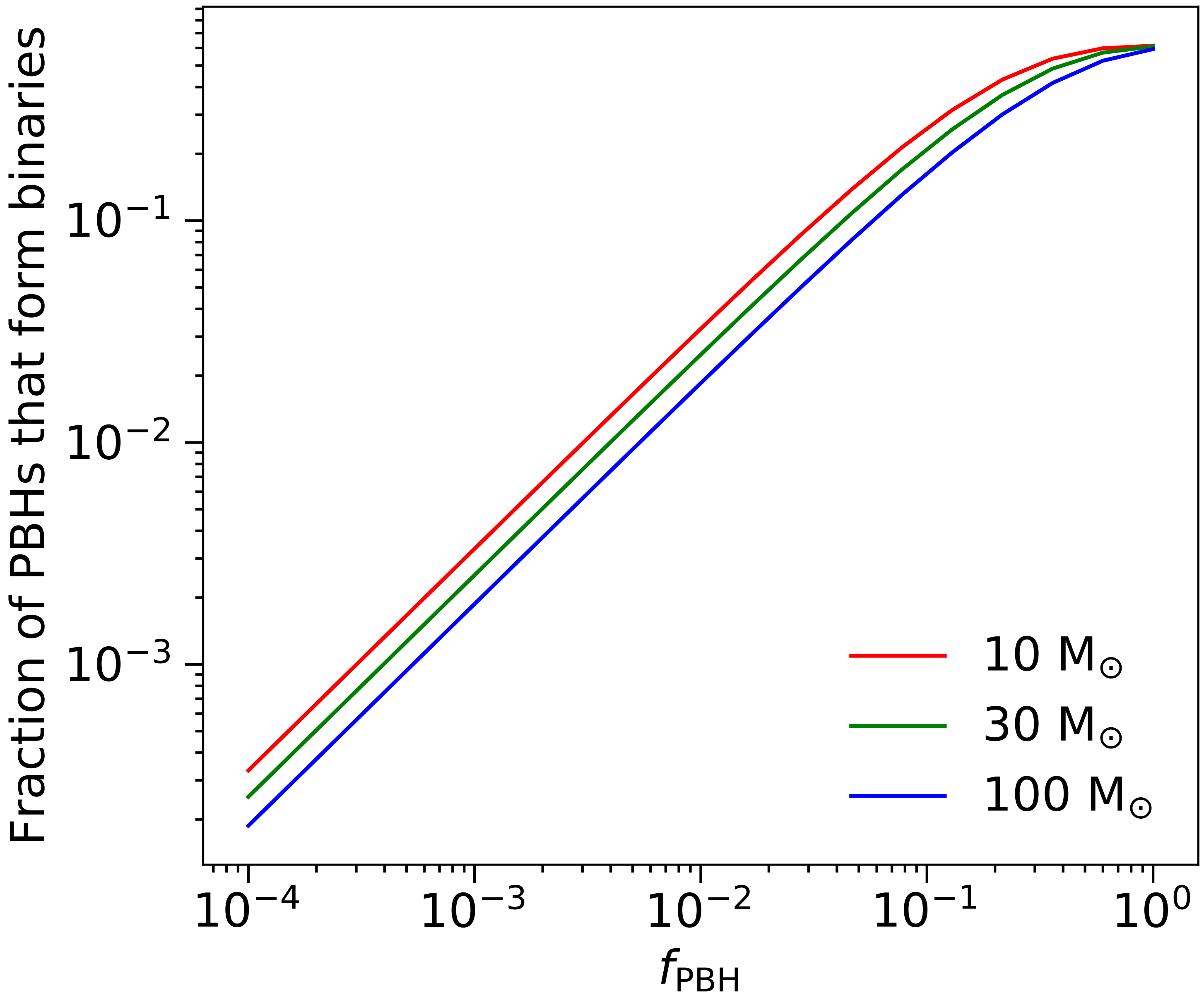
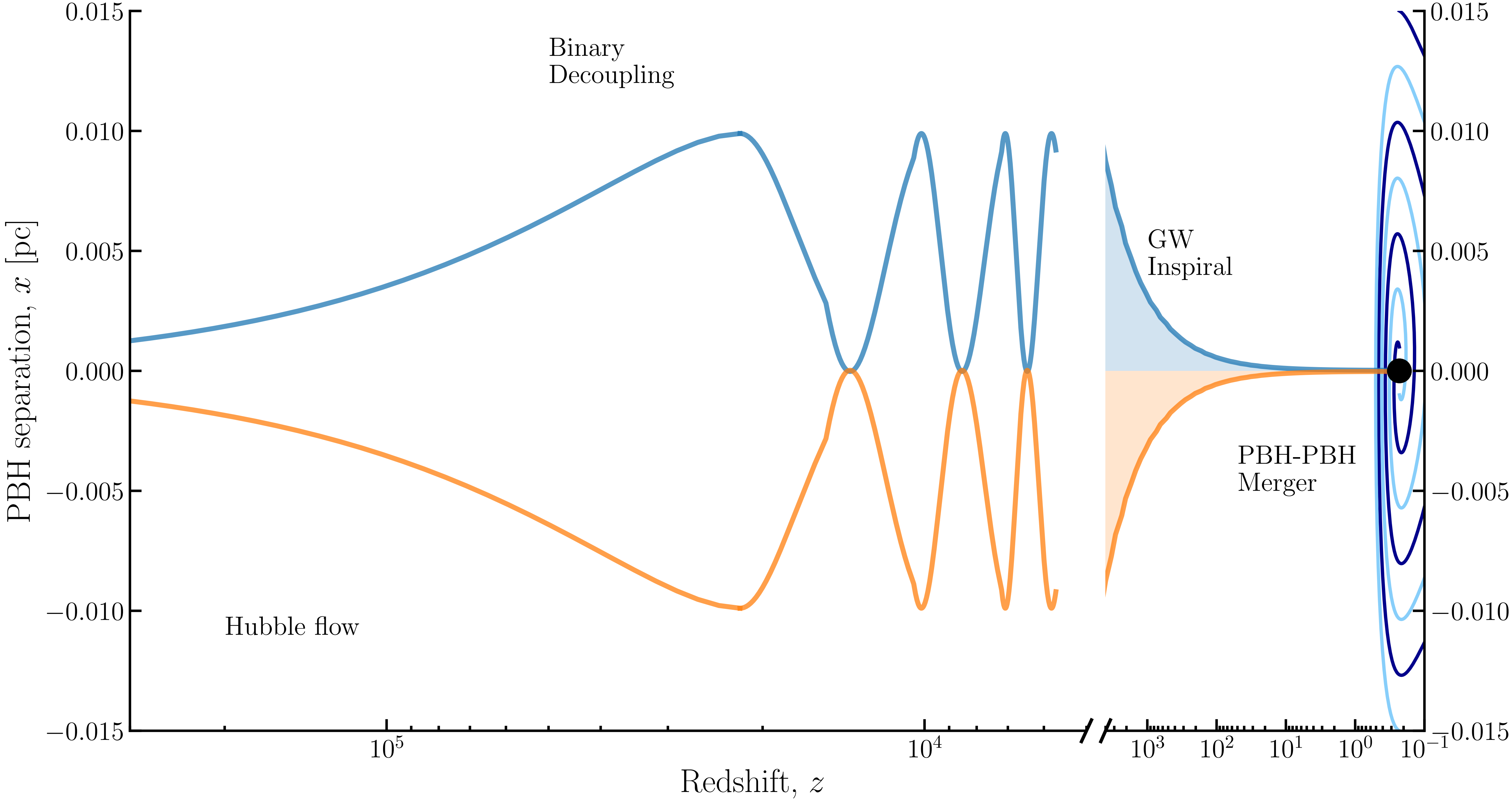


As f decreases, only 'nearby' pairs form binaries.

Life of a PBH binary



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

$e = 0.995$

PBH Binary Population

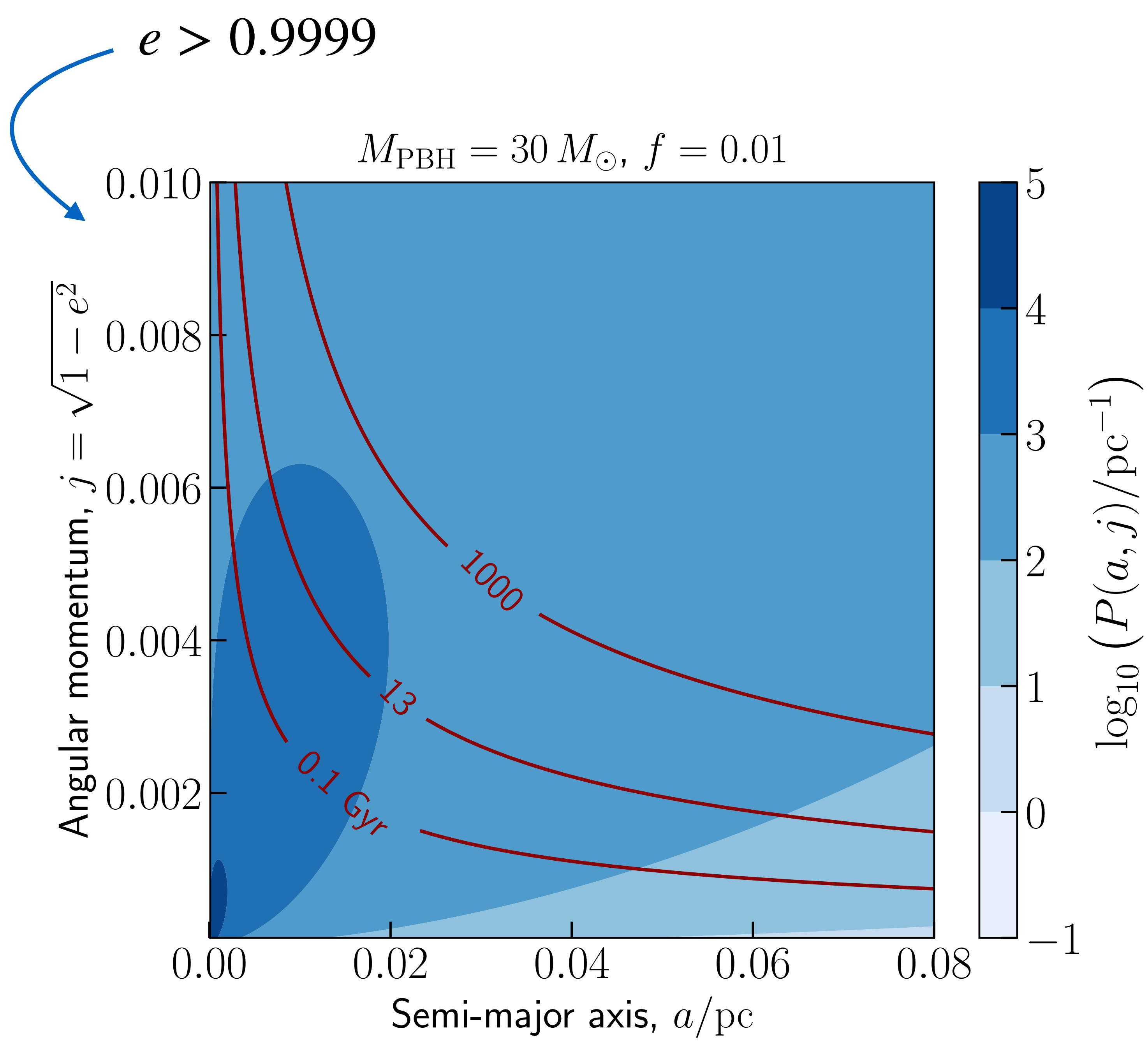
Randomly distributed (unclustered) PBHs

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

Close, eccentric binaries merge today:

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

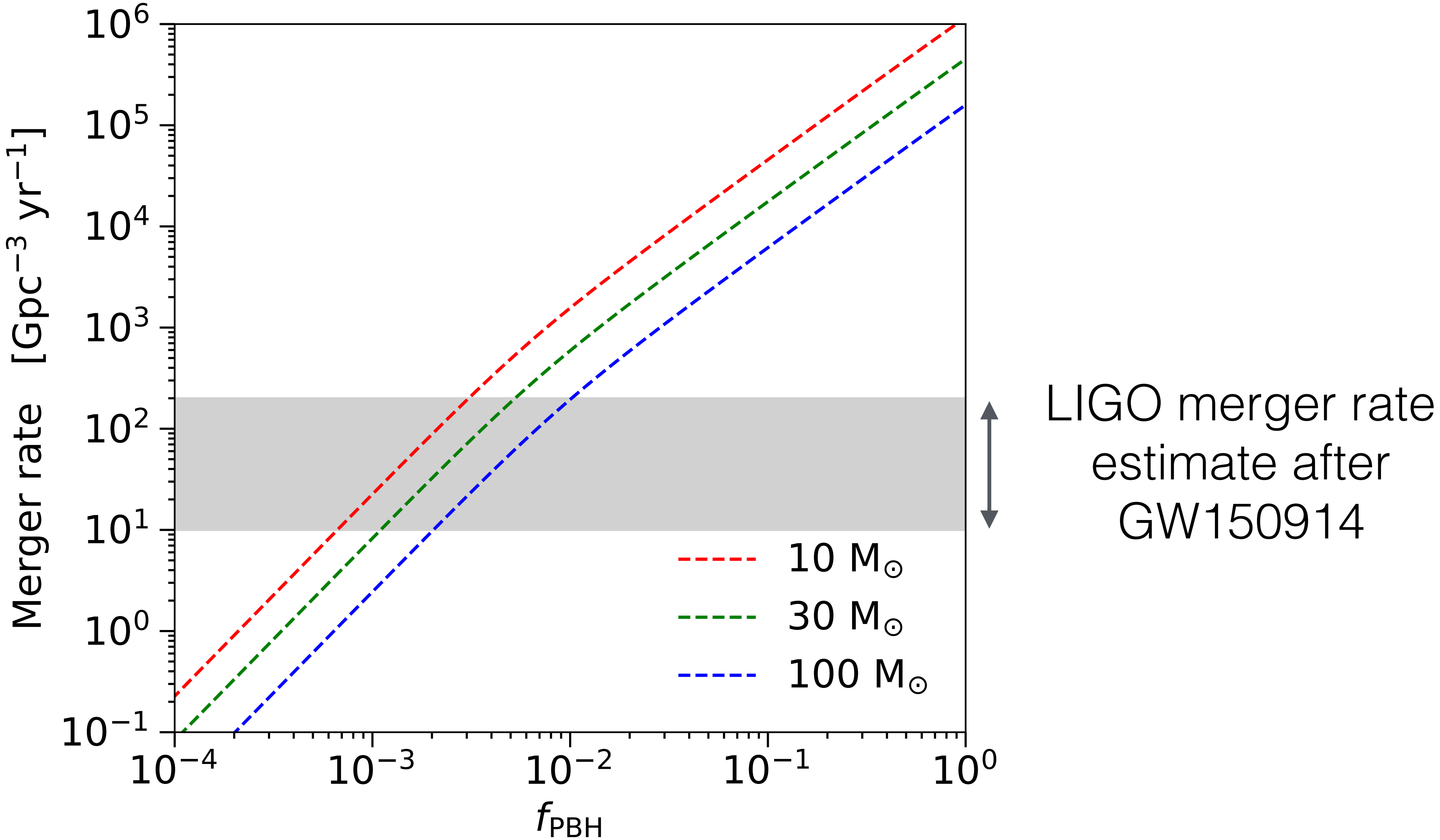
$$j = \sqrt{1-e^2}$$



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

Merger rate estimate

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

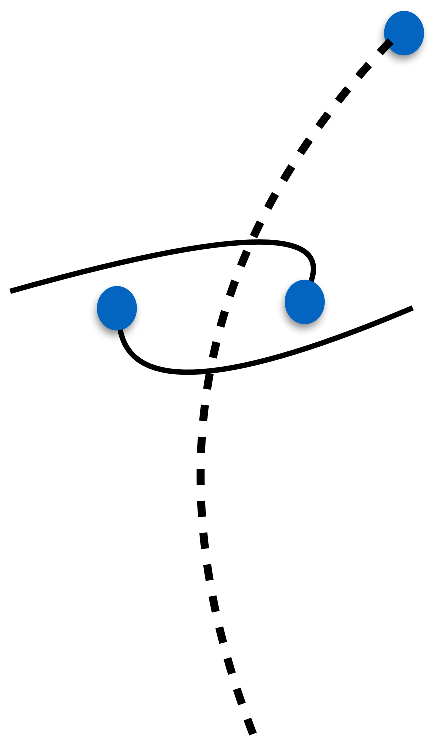


Solar mass PBHs should only be a sub-dominant (%-level) contribution to the DM density in the Universe

[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?

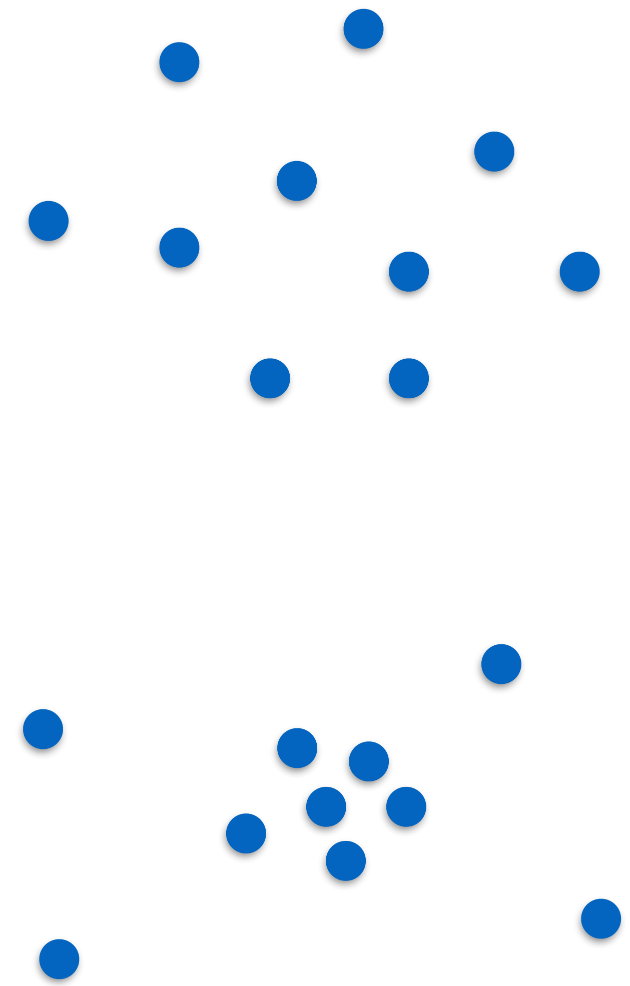
Smooth density perturbations and close encounters
are unlikely to disrupt the binaries

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

[Ali-Haïmoud et al., 1709.06576]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



How does the distribution of PBHs affect the merger rate?

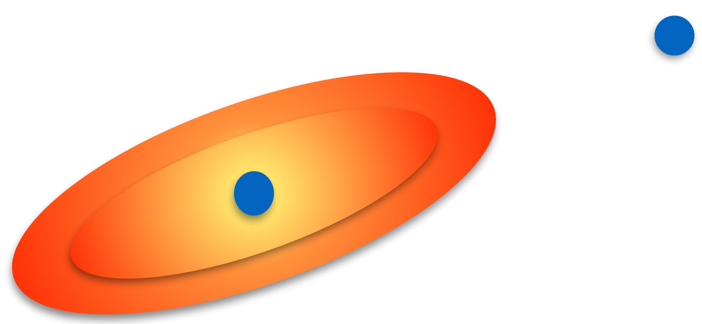
Clustering could substantially enhance the merger rate ('cascade' mergers) but PBHs are unlikely to form in clusters…

[1808.05910] [1807.02084]

[See also 1805.05912,1806.10414 and others]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



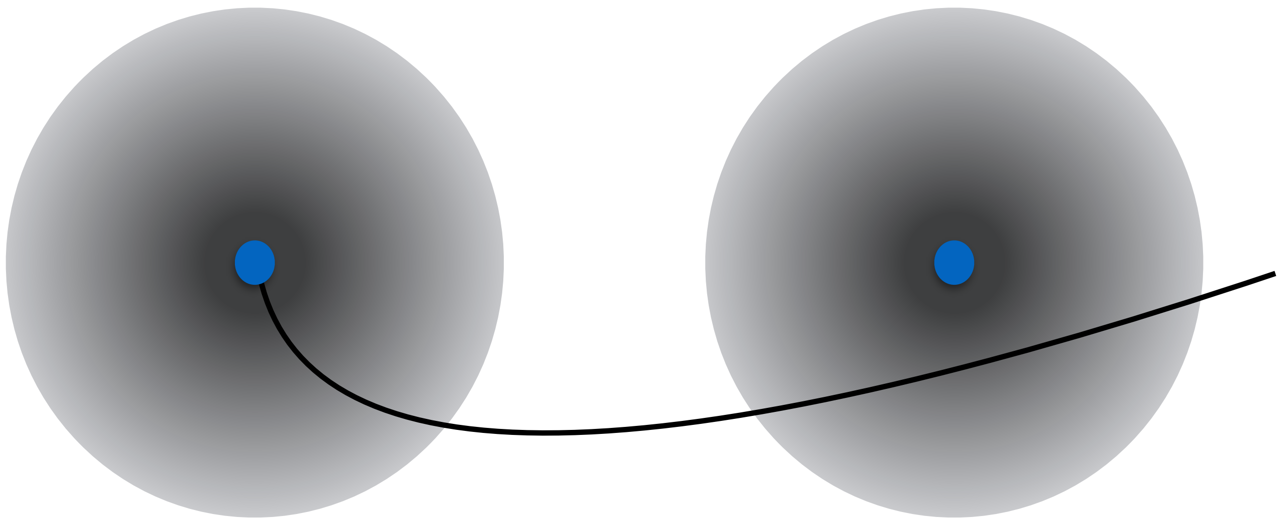
Does baryonic accretion disrupt the binary?

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

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

Caveats

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

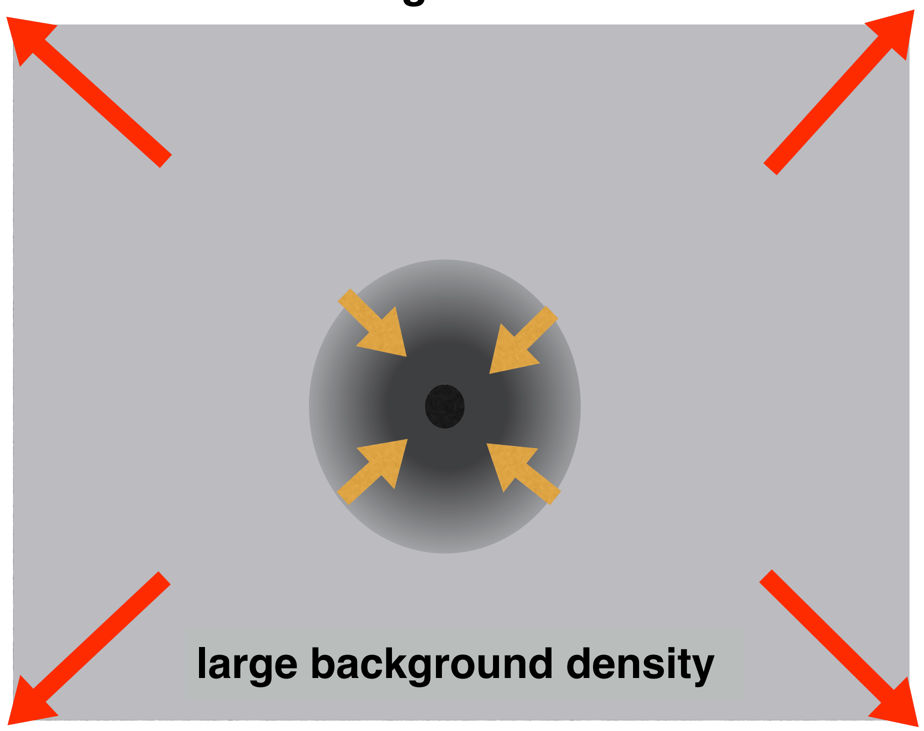


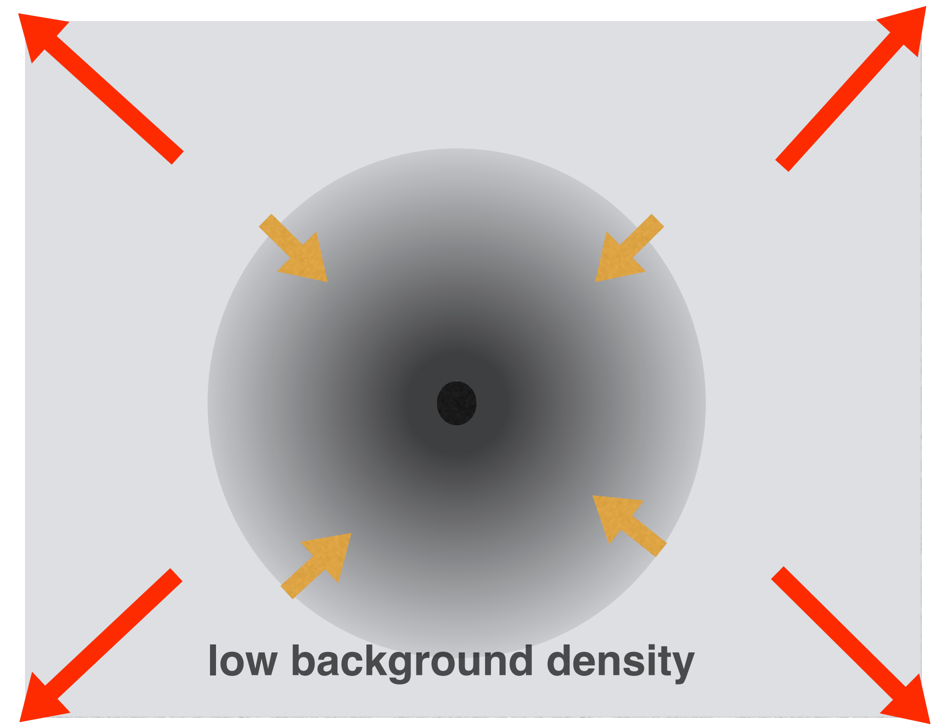
Do *local* Dark Matter halos disrupt PBH binaries?

Local DM Halos

Dark Dresses

PBHs seed the formation of `local' DM halos:





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

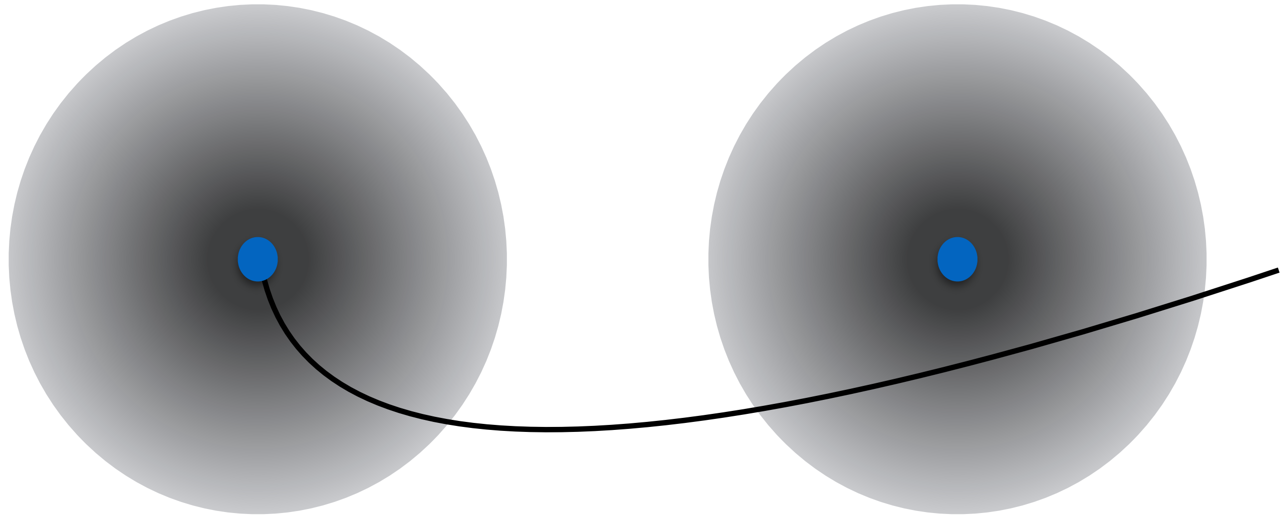
$$\rho(r) \propto r^{-3/2}$$

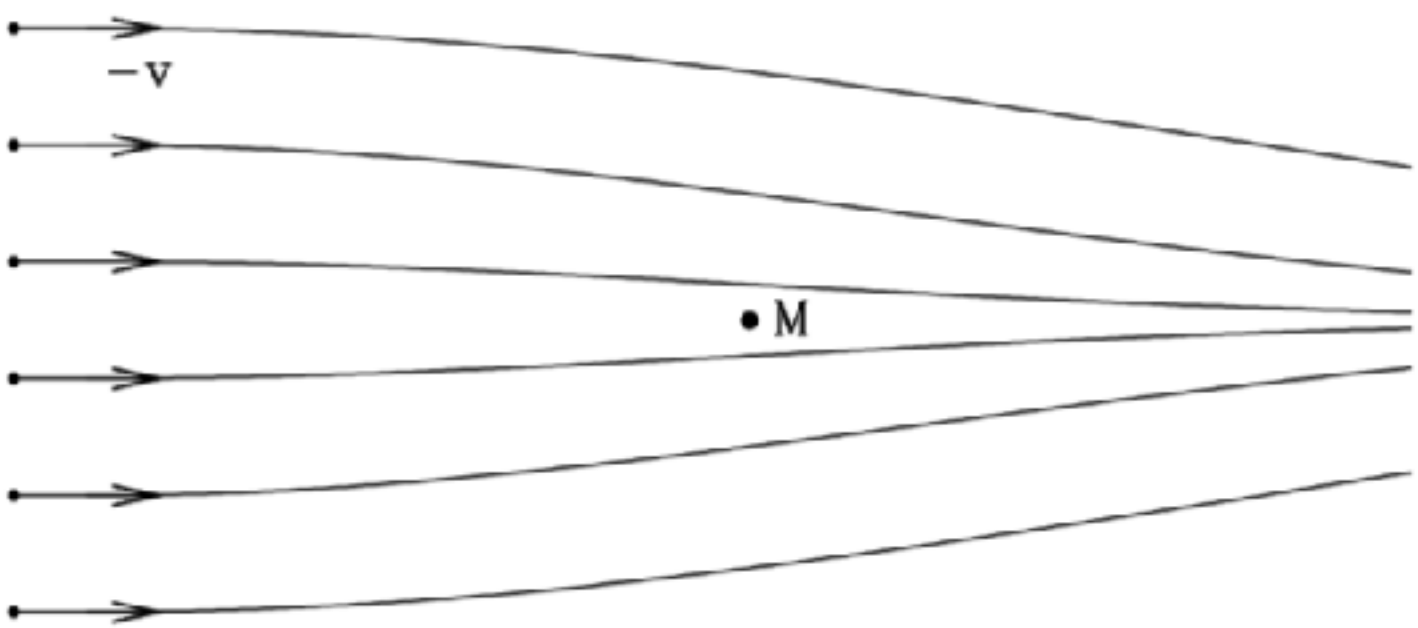
By matter-radiation equality, $M_{\rm halo} \sim M_{\rm PBH}$

Slide shamelessly ripped off from Daniele Gaggero

[astro-ph/0608642, 0706.0864,1712.05421]

Dynamical Friction





$$\vec{F}_{\mathrm{DF}} = -\frac{\vec{v}}{v^3} 4\pi\rho \left(G M_{\mathrm{BH}}\right)^2 \ln\Lambda$$

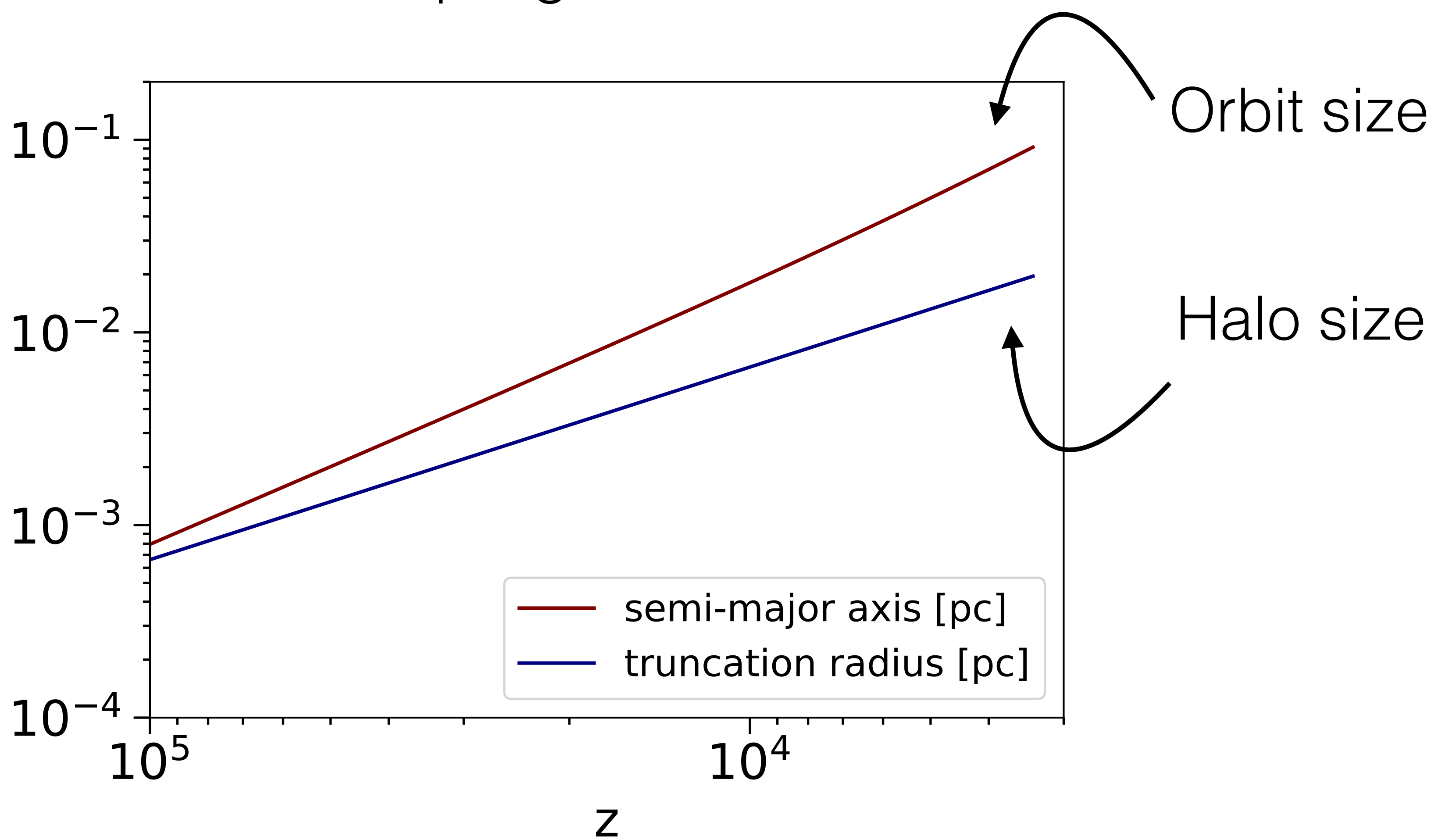
tinyurl.com/DynamicalFriction

[Chandrasekhar (1943abc)]

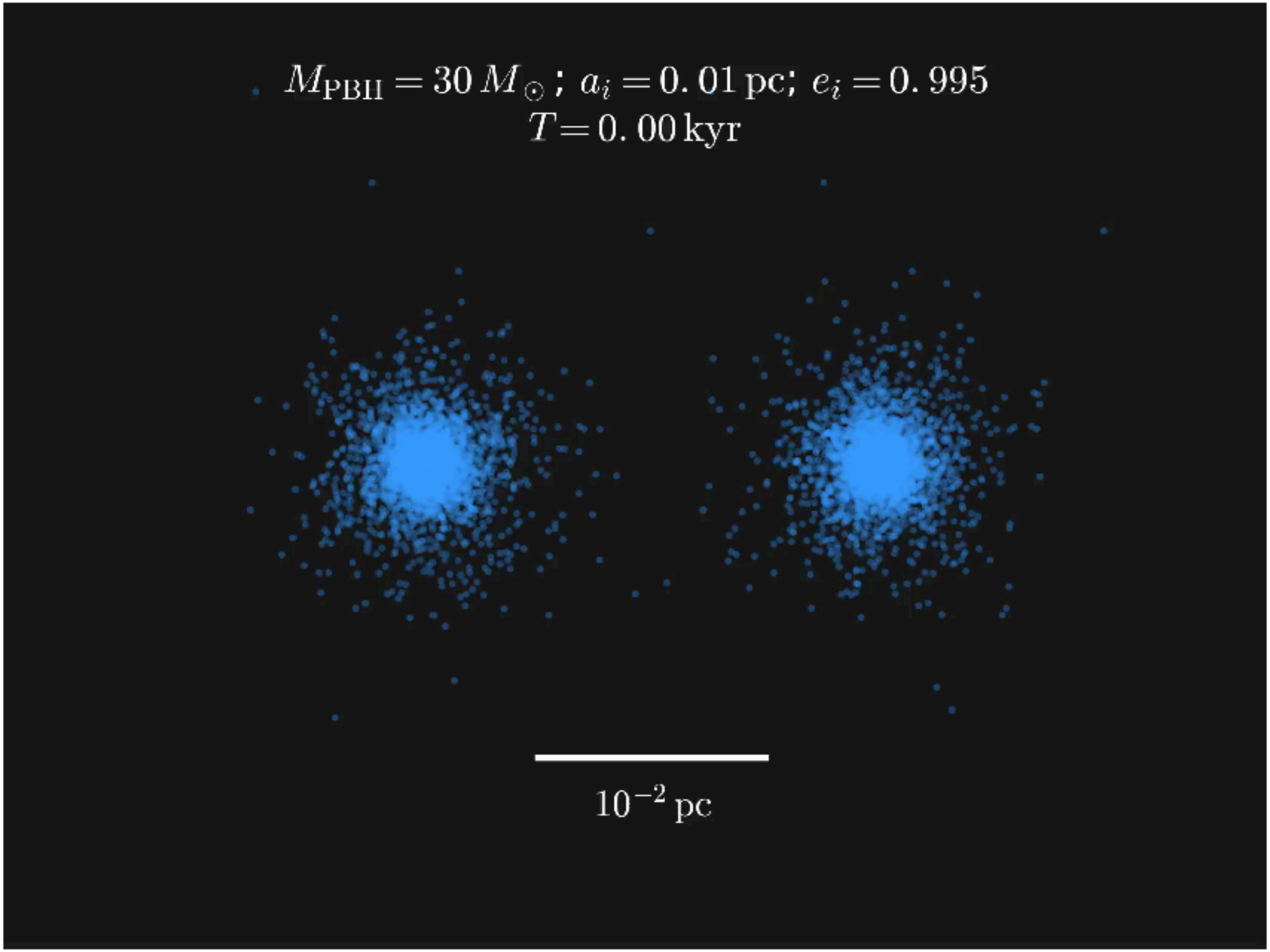
Simulations

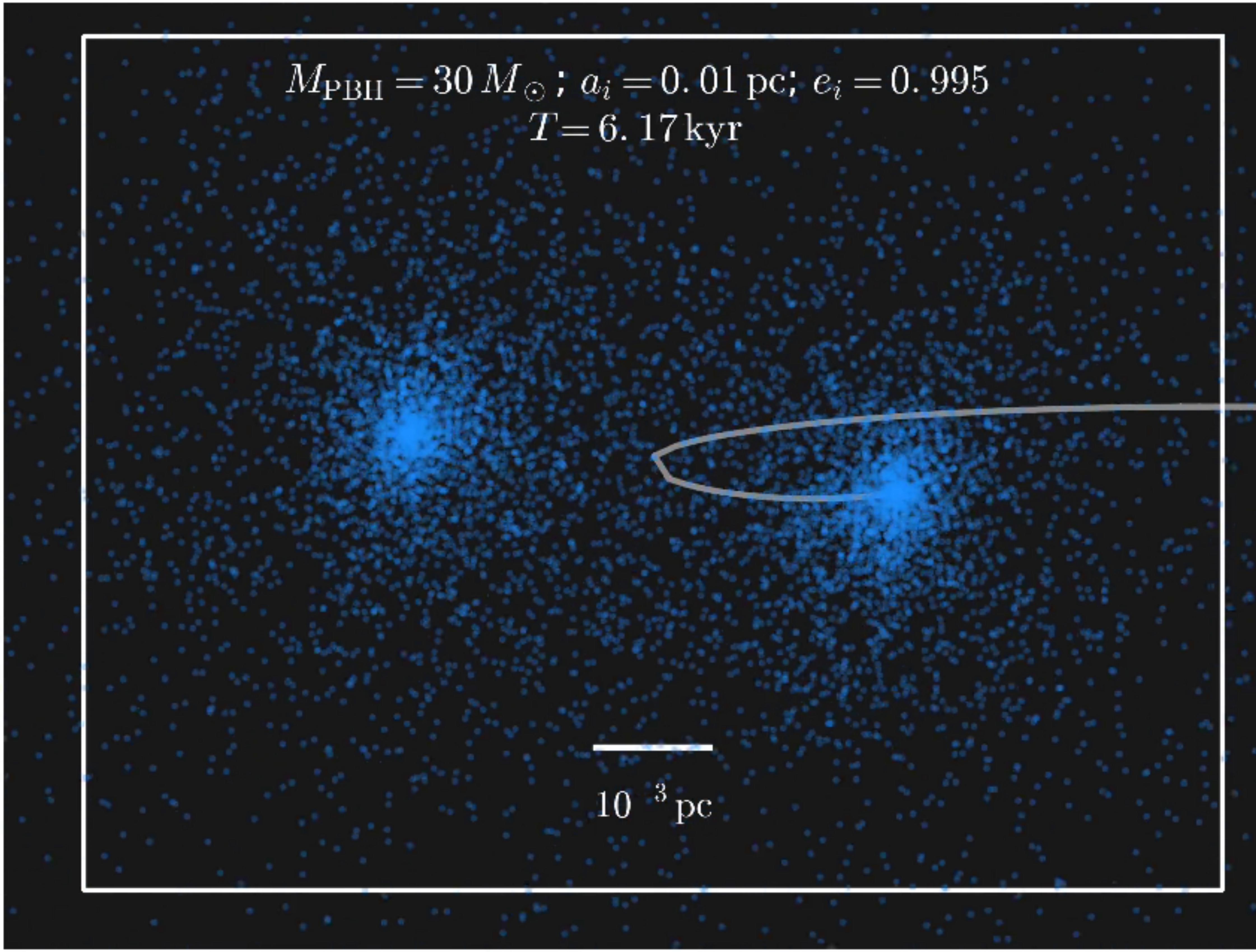
Use GADGET-2 as a pure N-body solver [Springel, astro-ph/0505010]

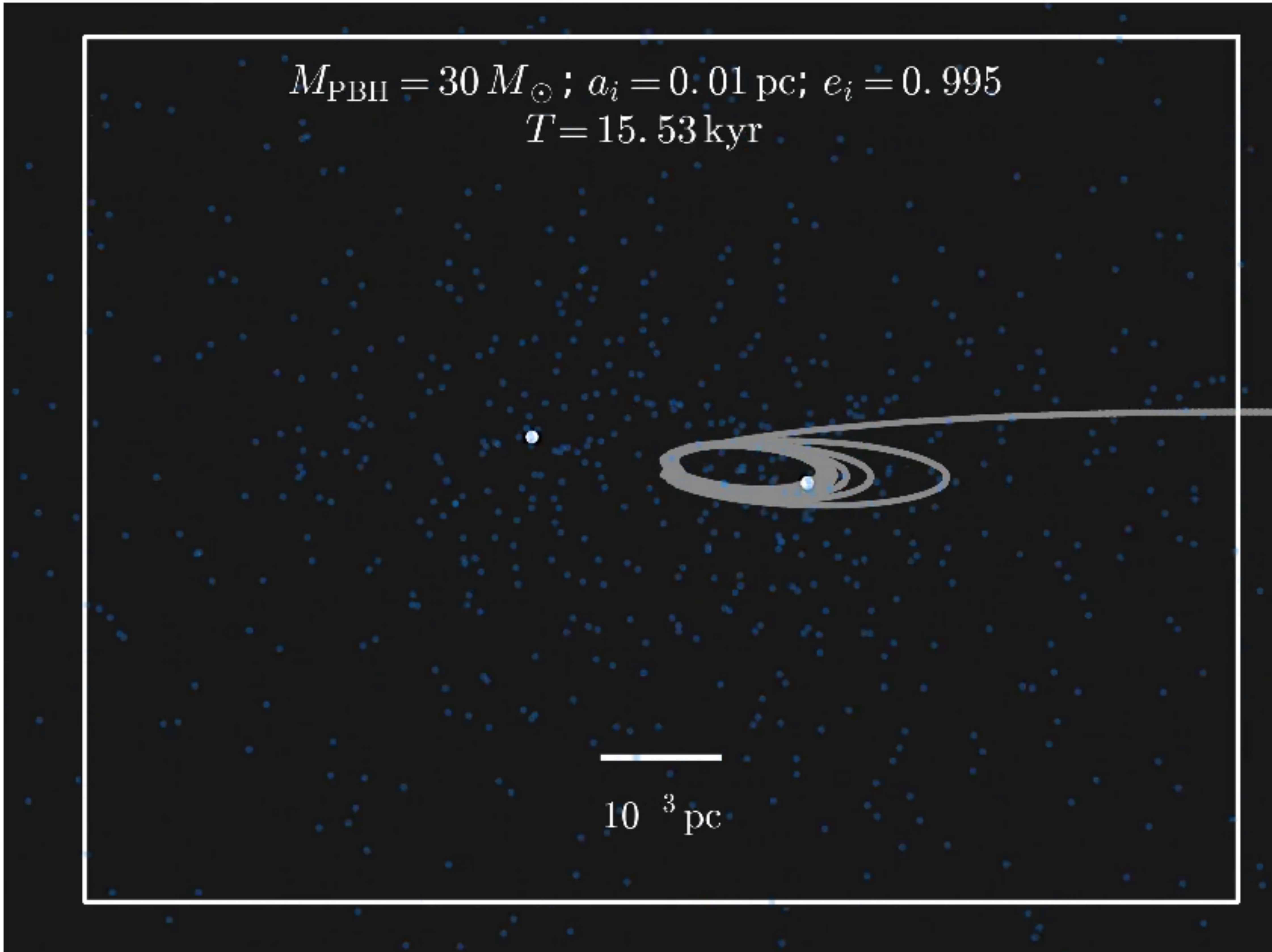
Initialise the PBHs self-consistently, with DM halos of the correct size, depending on the redshift of decoupling…



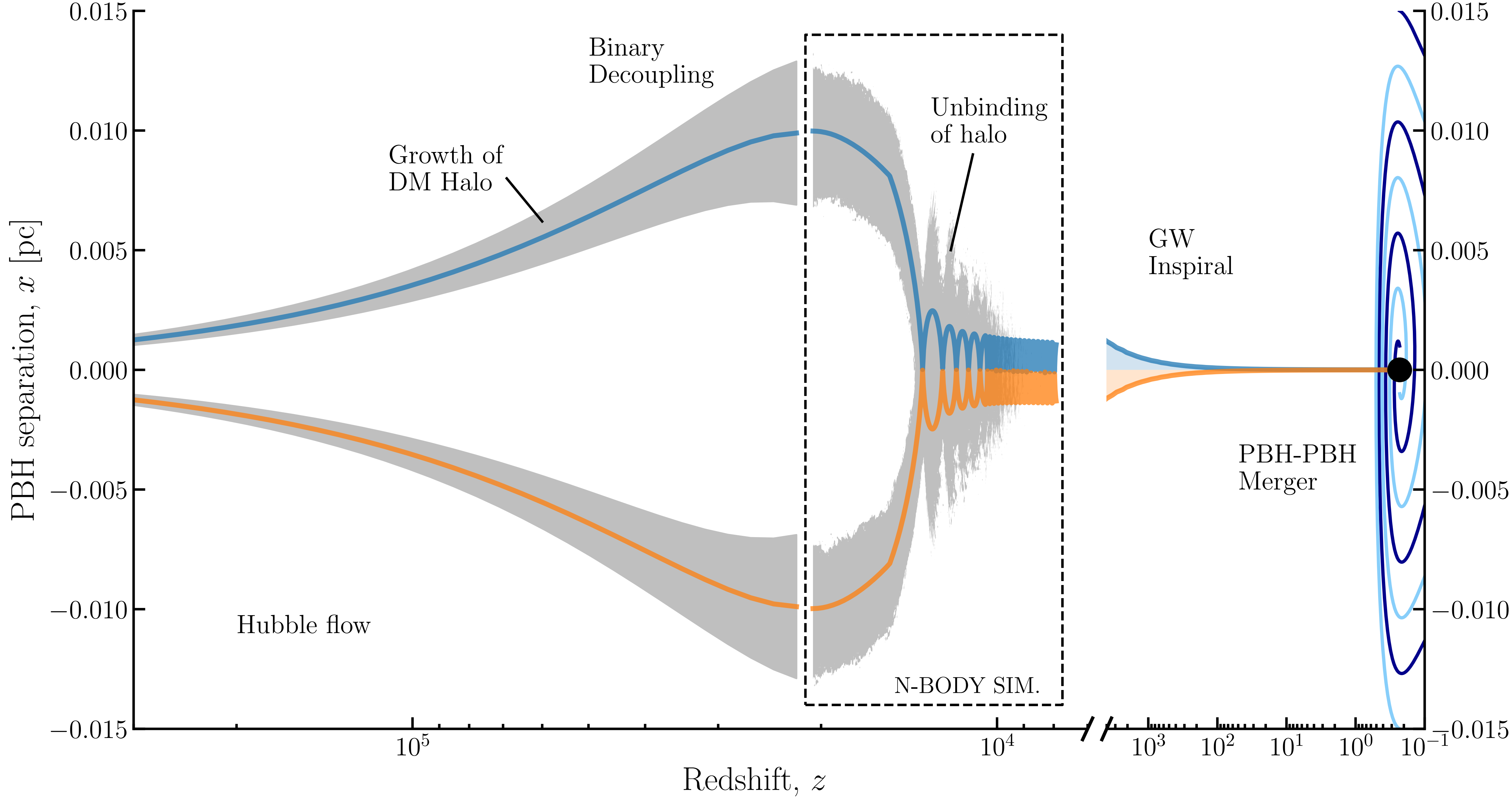
…then follow the evolution of the PBH binary…


$M_{\rm PBH} = 30\, M_\odot$; $a_i = 0.01$ pc; $e_i = 0.995$
$T = 0.00$ kyr
10^{-2} pc


$M_{\rm PBH} = 30\, M_\odot$; $a_i = 0.01$ pc; $e_i = 0.995$
$T = 6.17$ kyr
$10\ ^{3}$ pc


$M_{\mathrm{PBH}} = 30\,M_\odot$; $a_i = 0.01$ pc; $e_i = 0.995$
$T = 15.53$ kyr
10 ^{3} pc

Life of a *dressed* PBH binary

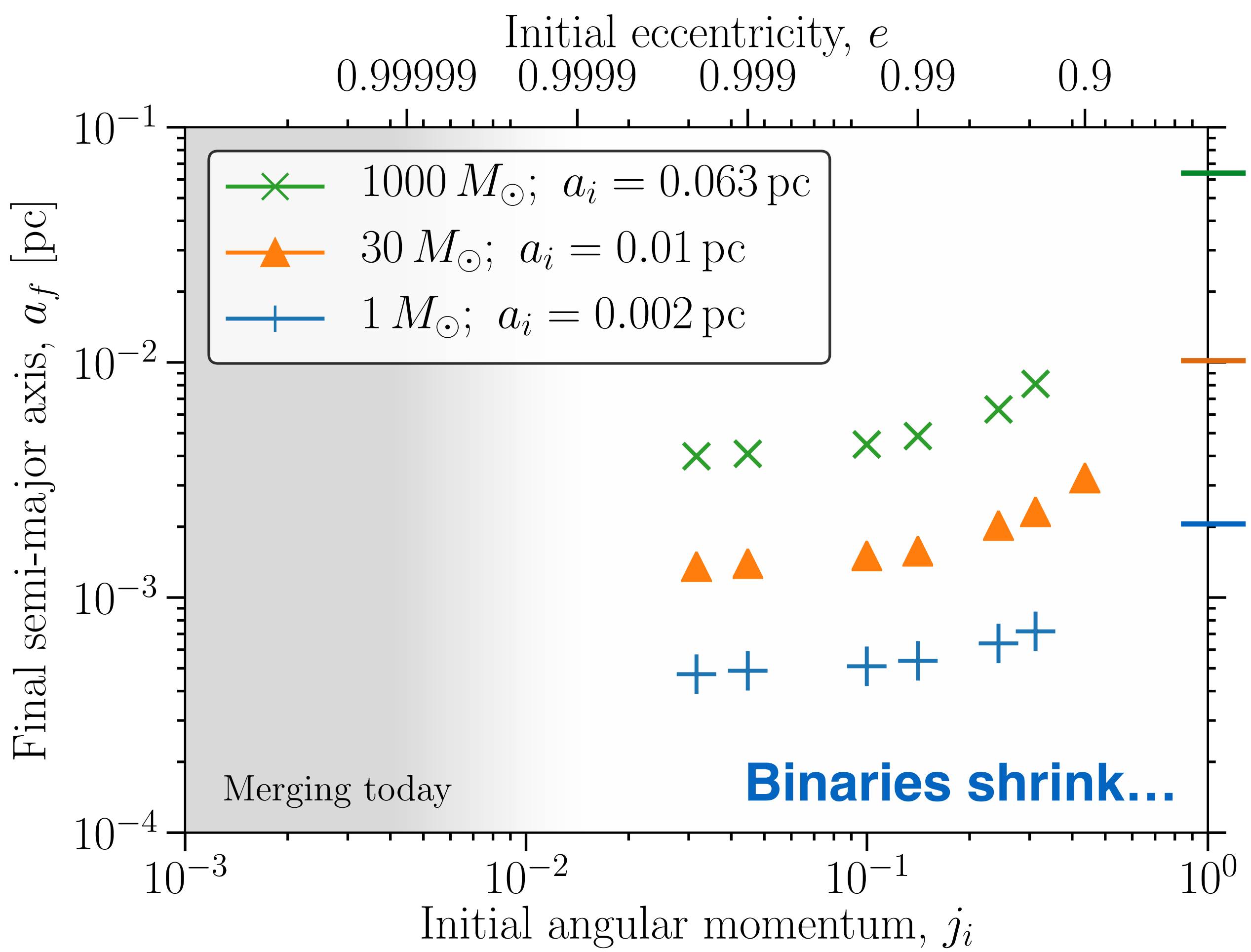


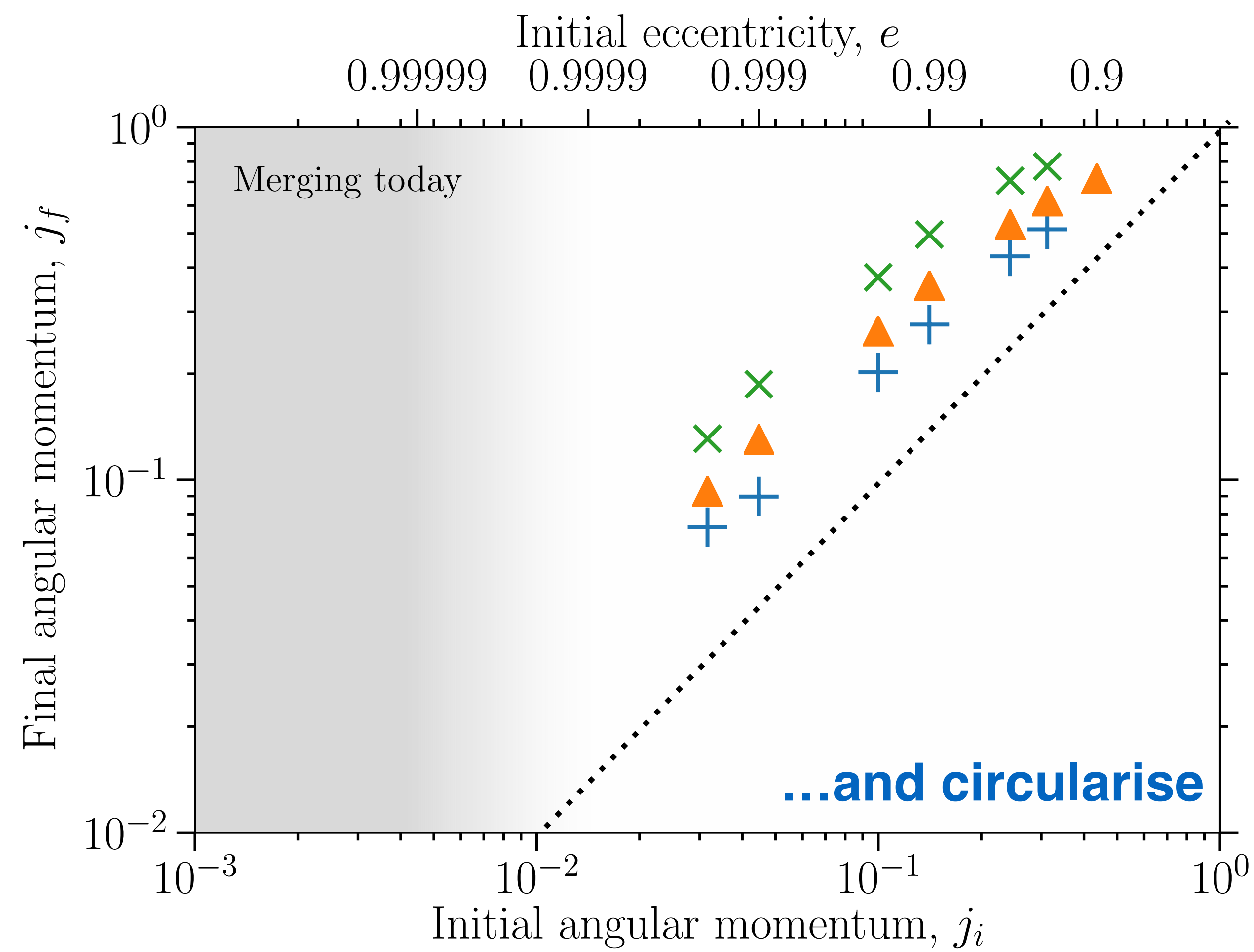
$$a_i = 0.01\,\mathrm{pc}$$

$$e_i = 0.995$$

Simulation Results

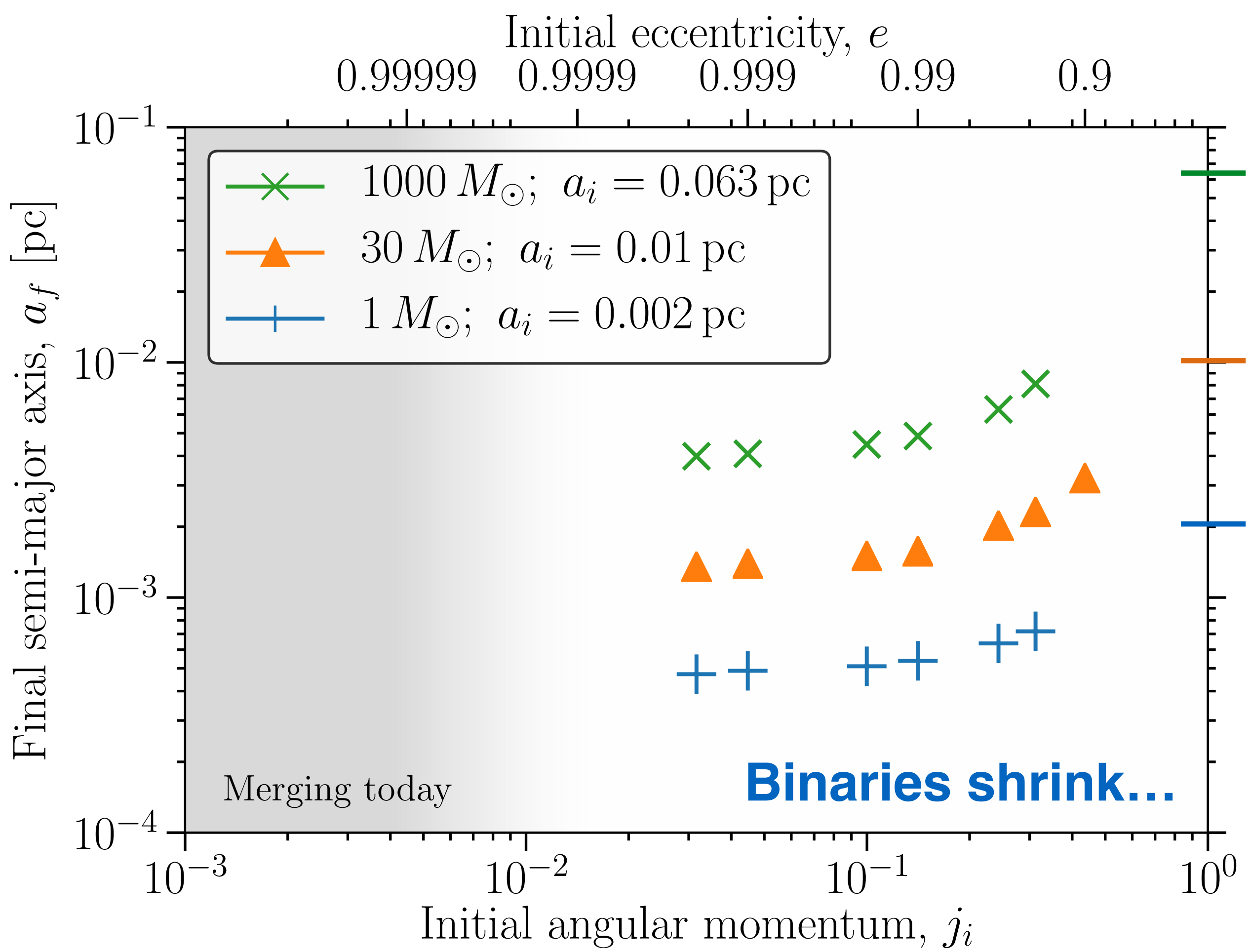
$$j = \sqrt{1 - e^2}$$

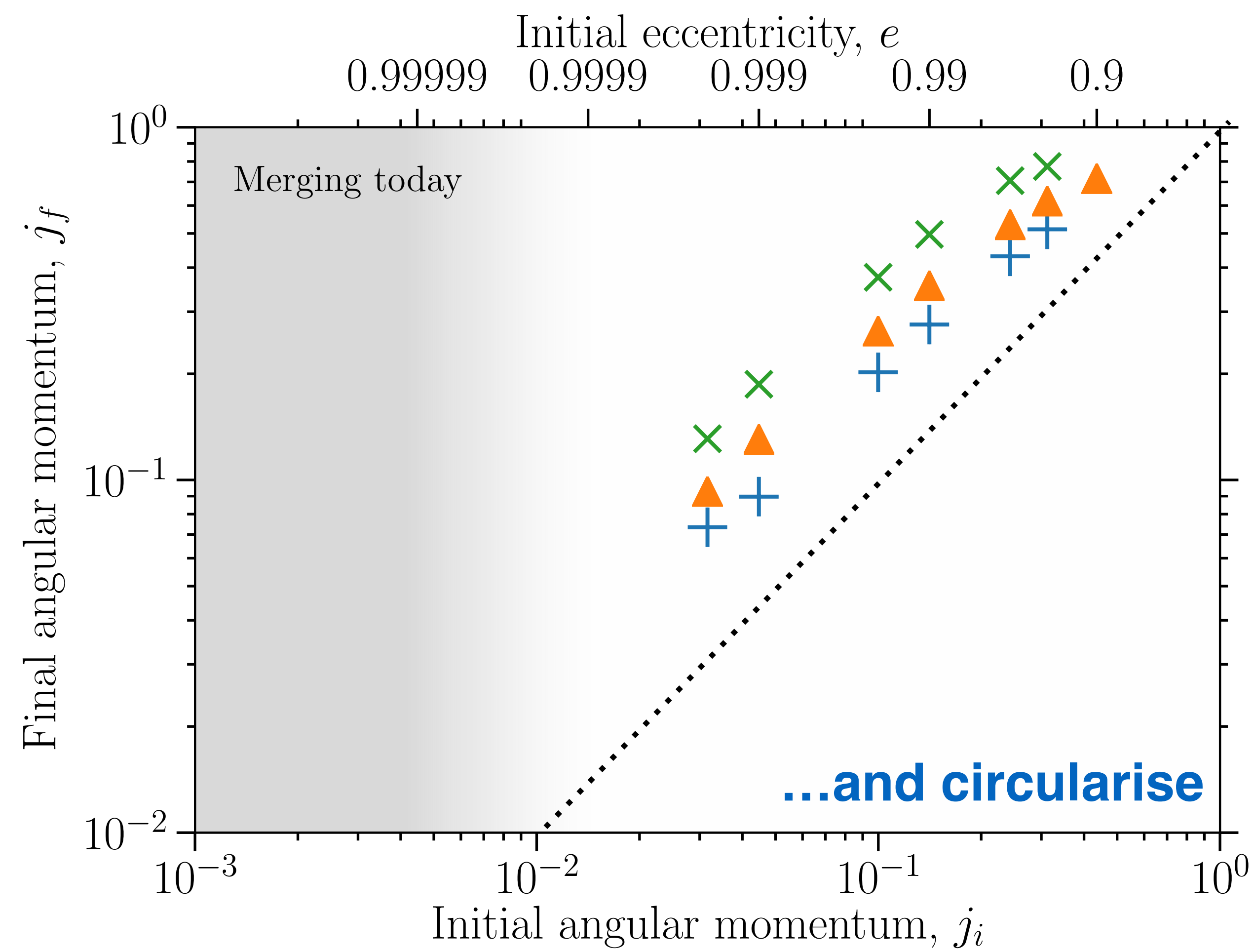




Results: Semi-major Axis

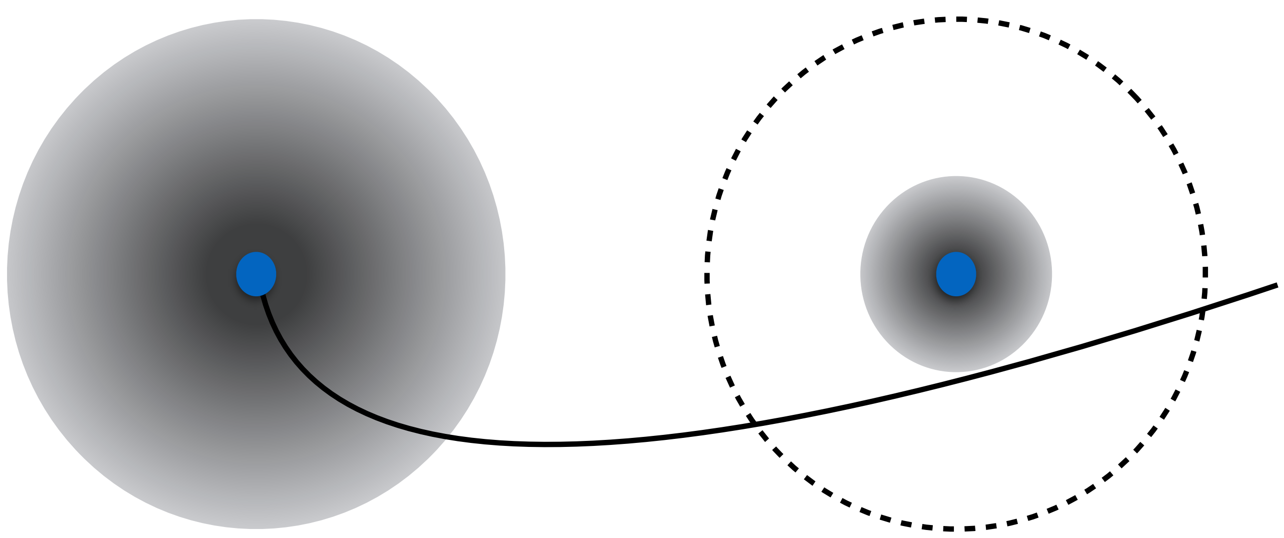
$$j = \sqrt{1 - e^2}$$





Conservation of energy

$$E_i^{\mathrm{orb}} + 2\,U^{\mathrm{bind}} = E_f^{\mathrm{orb}}$$



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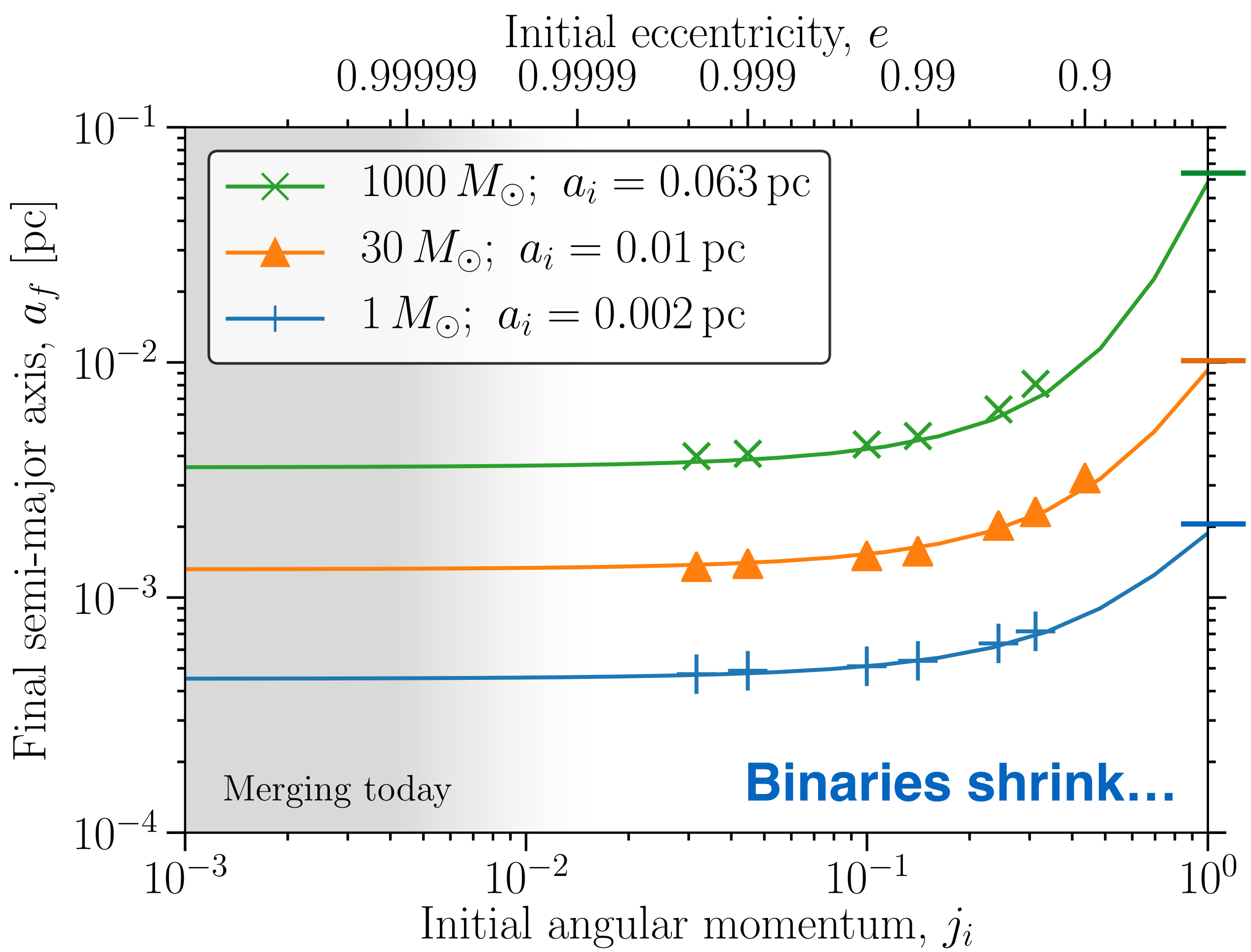
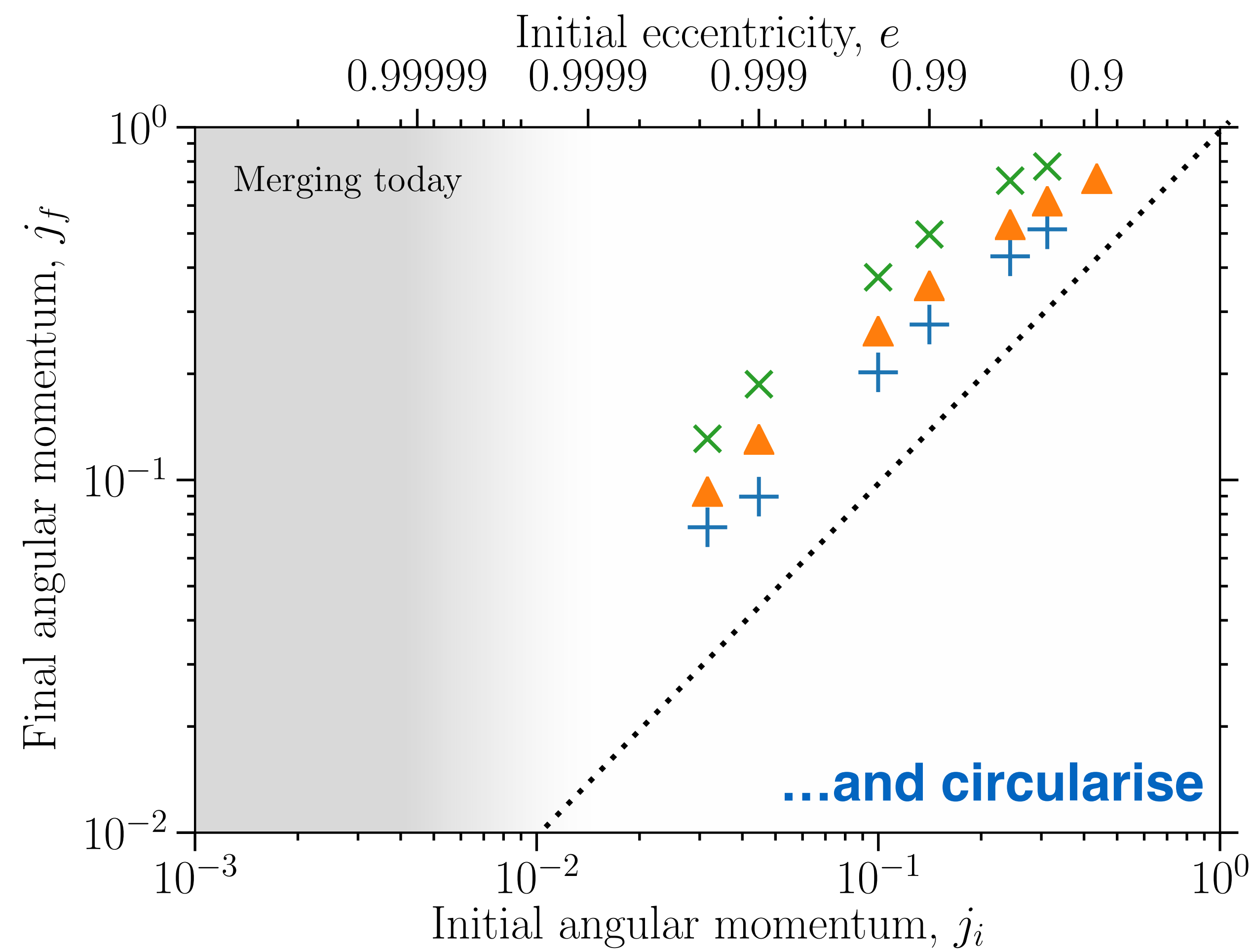
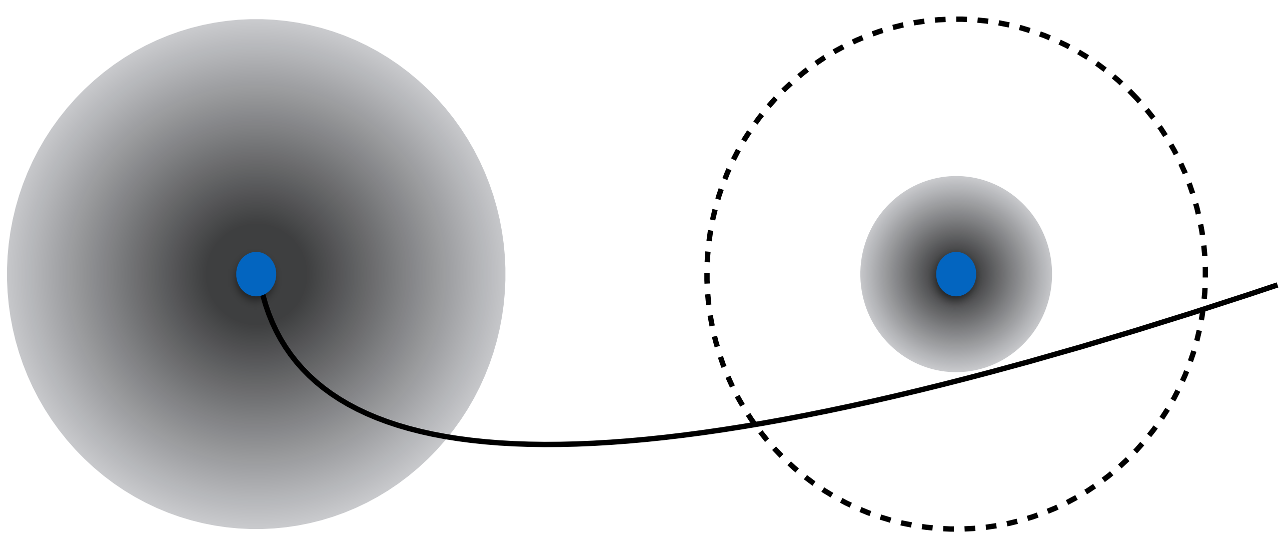




Conservation of energy

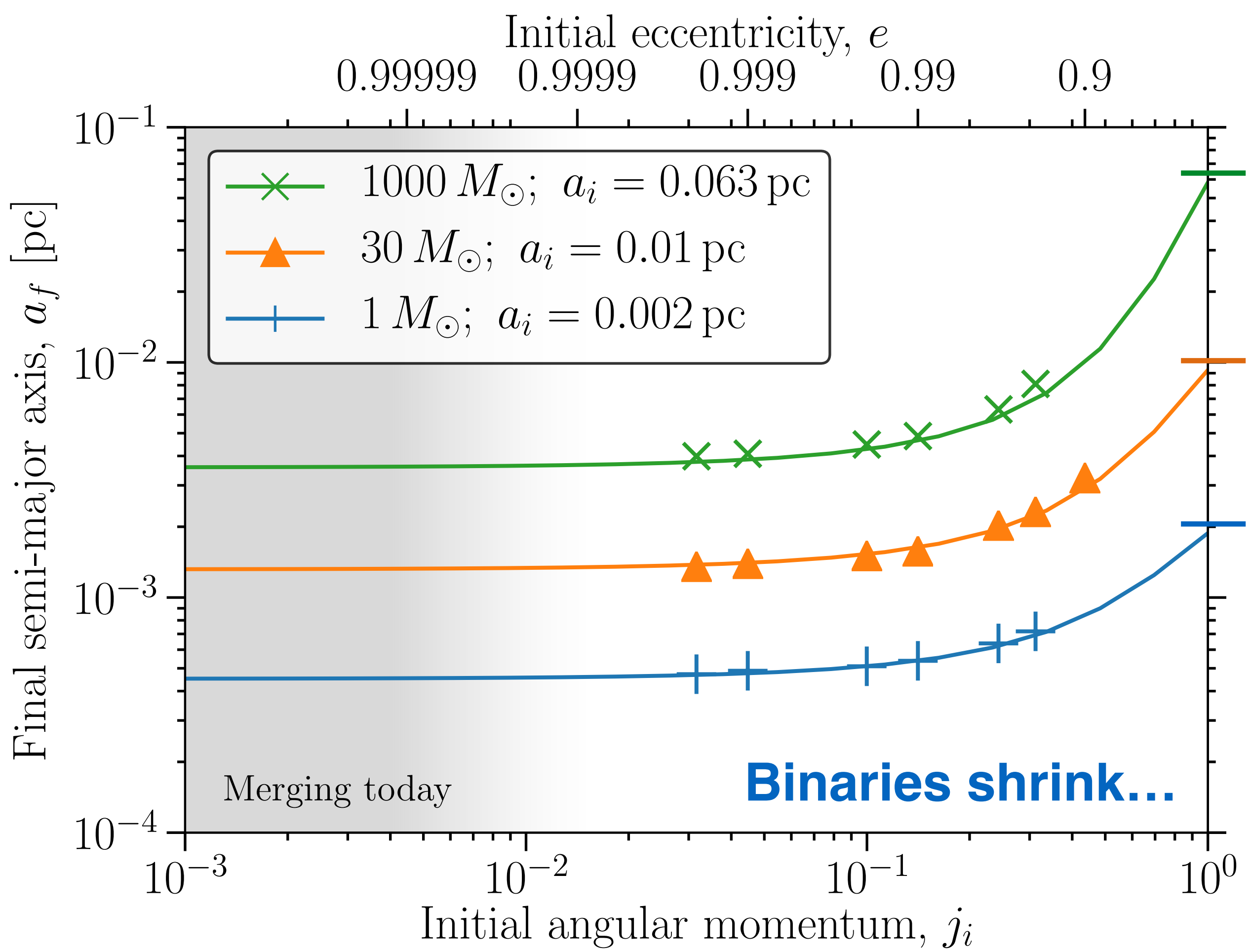
$$E_i^{\rm orb} + 2\,U^{\rm bind} = E_f^{\rm orb}$$

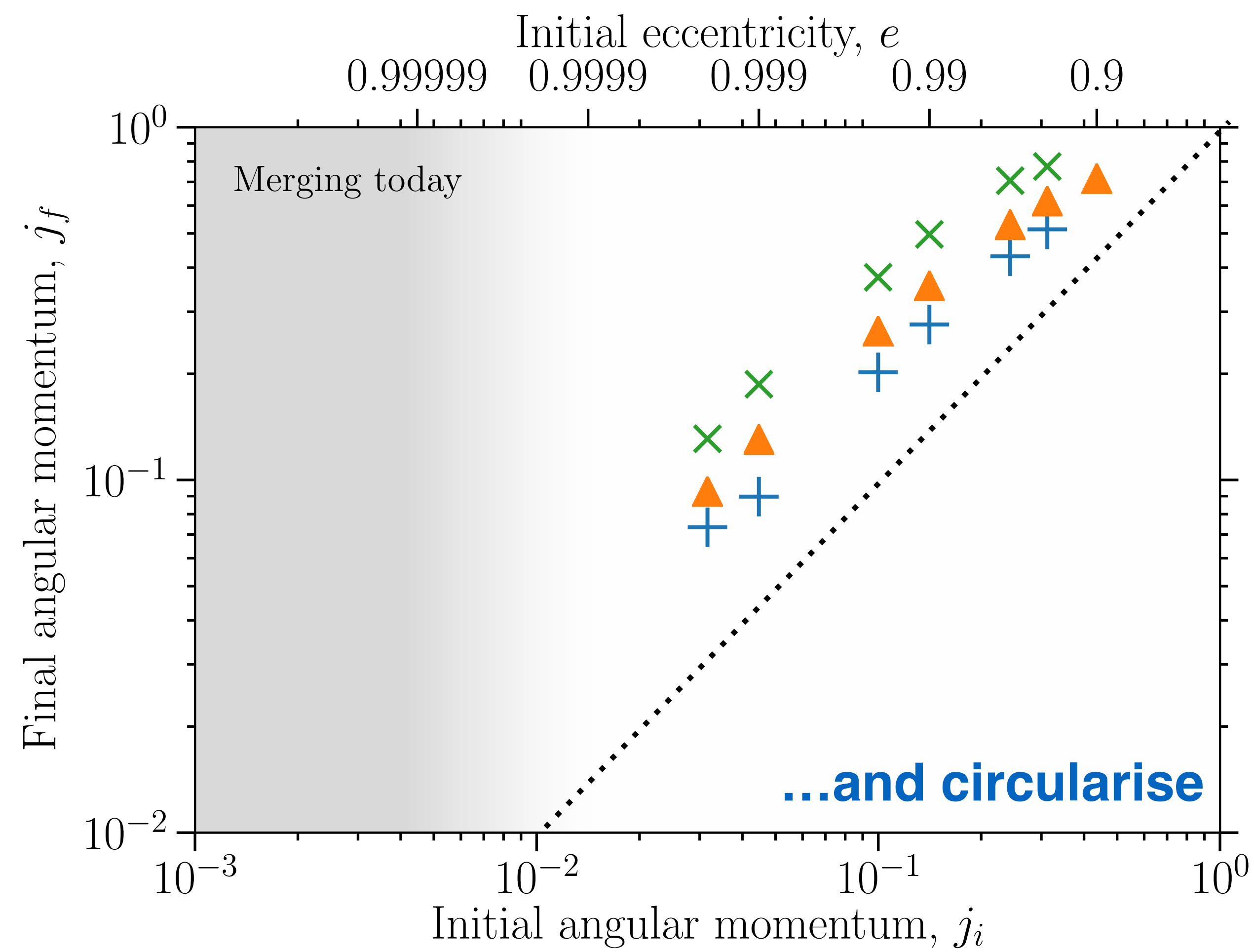
fixes semi-major axis, a

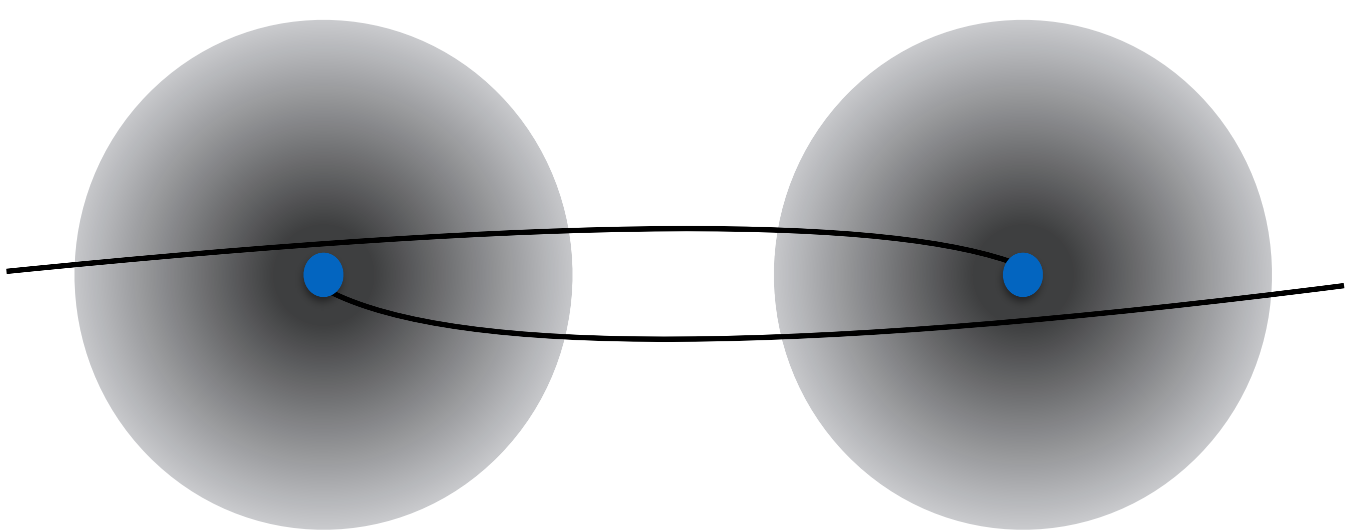


Results: Angular Momentum

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





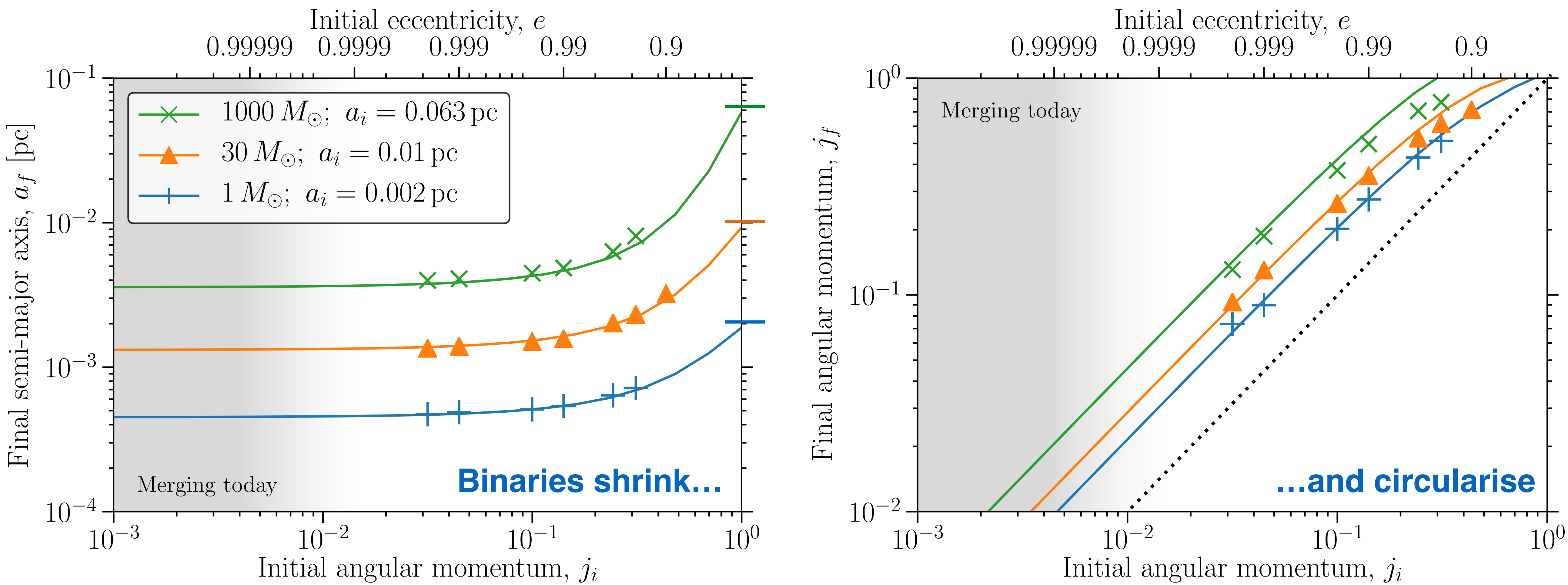


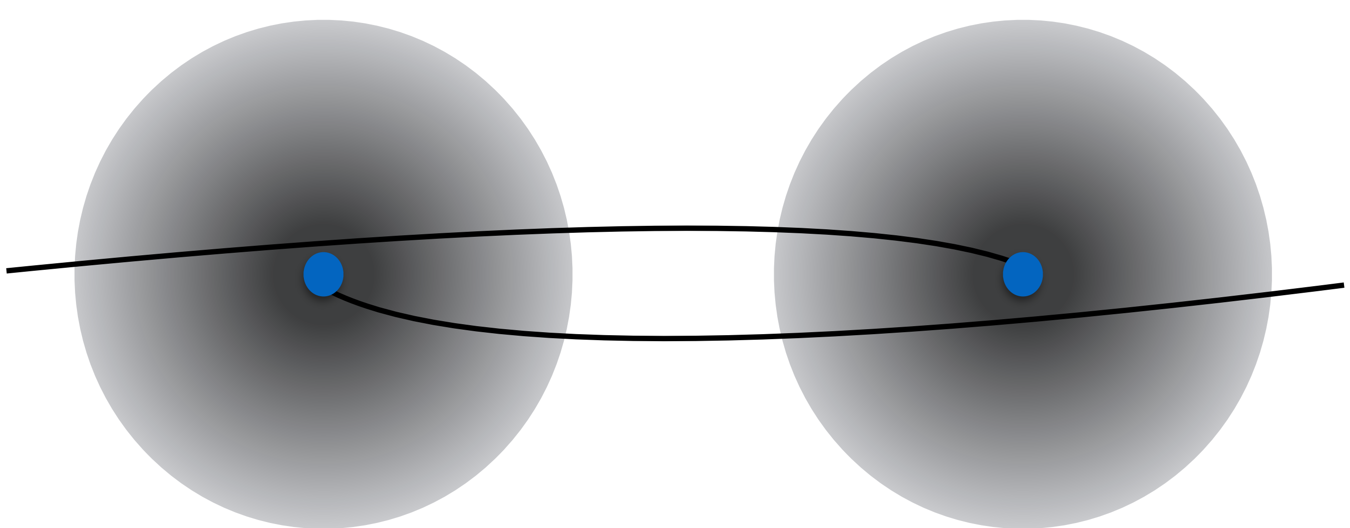
Conservation of angular momentum

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

Results: Angular Momentum

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





Conservation of angular momentum

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

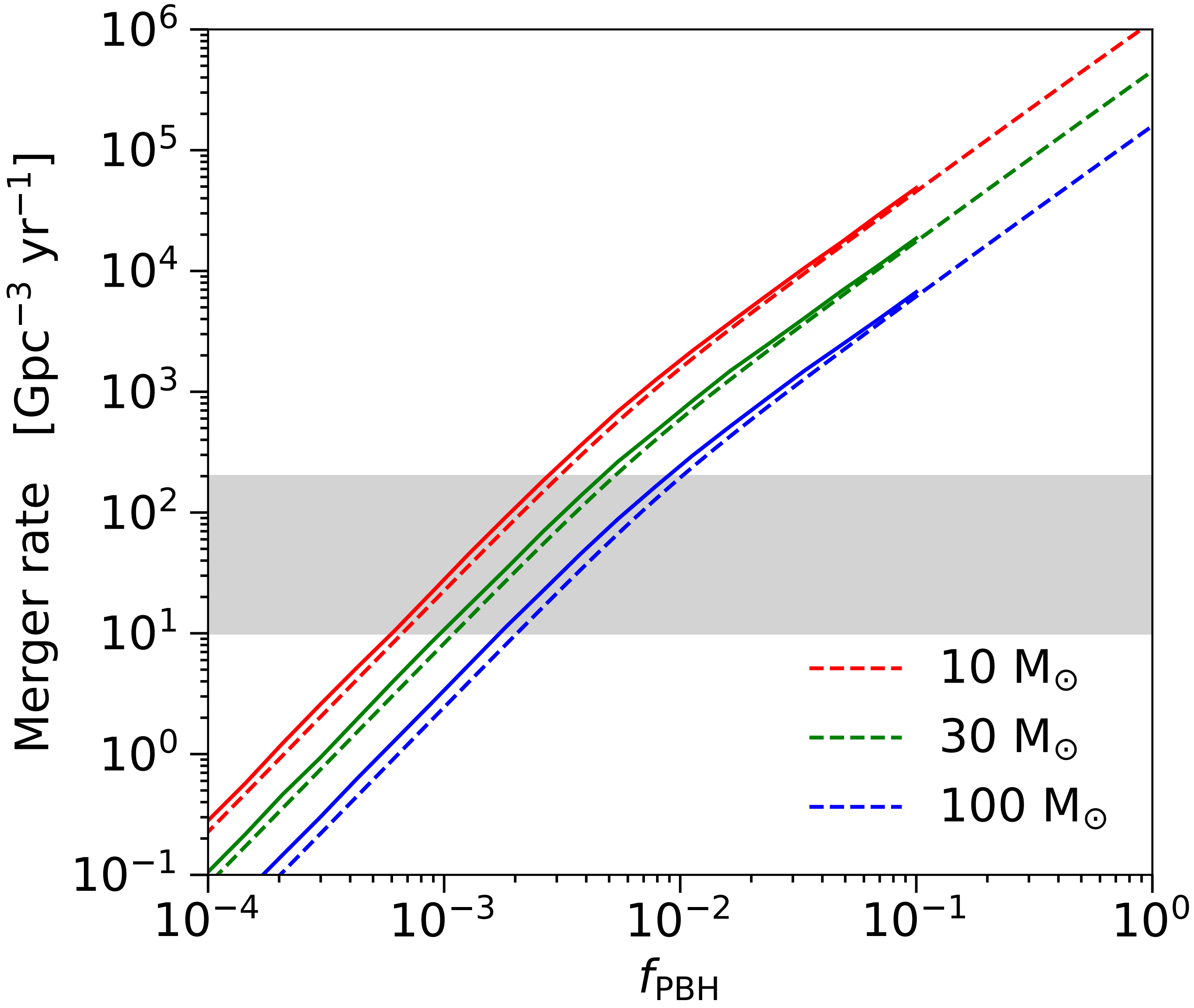
fixes $j_f = j_i \sqrt{a_i/a_f}$

Calculating the final merger rate

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

Draw PBH binaries from the distribution of (a, e)

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

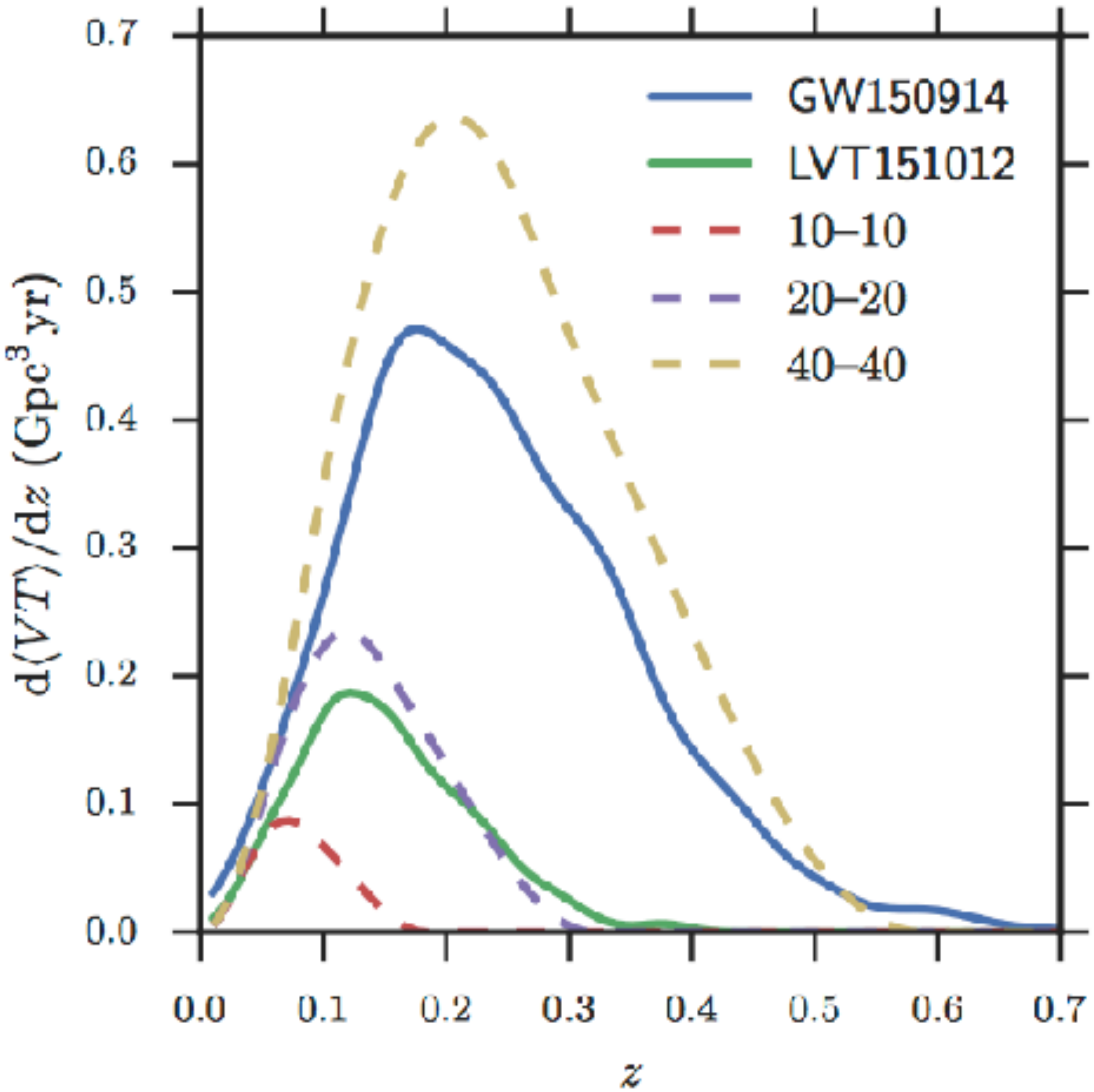


Merger time $t_{\rm merge} = \dfrac{3\,c^5}{170\,G_N^3} \dfrac{a^4 j^7}{M_{\rm PBH}^3}$ is almost conserved: $t_f = \sqrt{\dfrac{a_i}{a_f}}\, t_i$

LIGO Sensitivity

$$\mathcal{R}_{\rm LIGO} = \frac{1}{2} n_{\rm PBH} P_{\rm binary} \frac{\int S(z) P(t[z]) \mathrm{d}z}{\int S(z) \mathrm{d}z}$$

$$S(z) = \mathrm{d}\langle VT \rangle / \mathrm{d}z$$

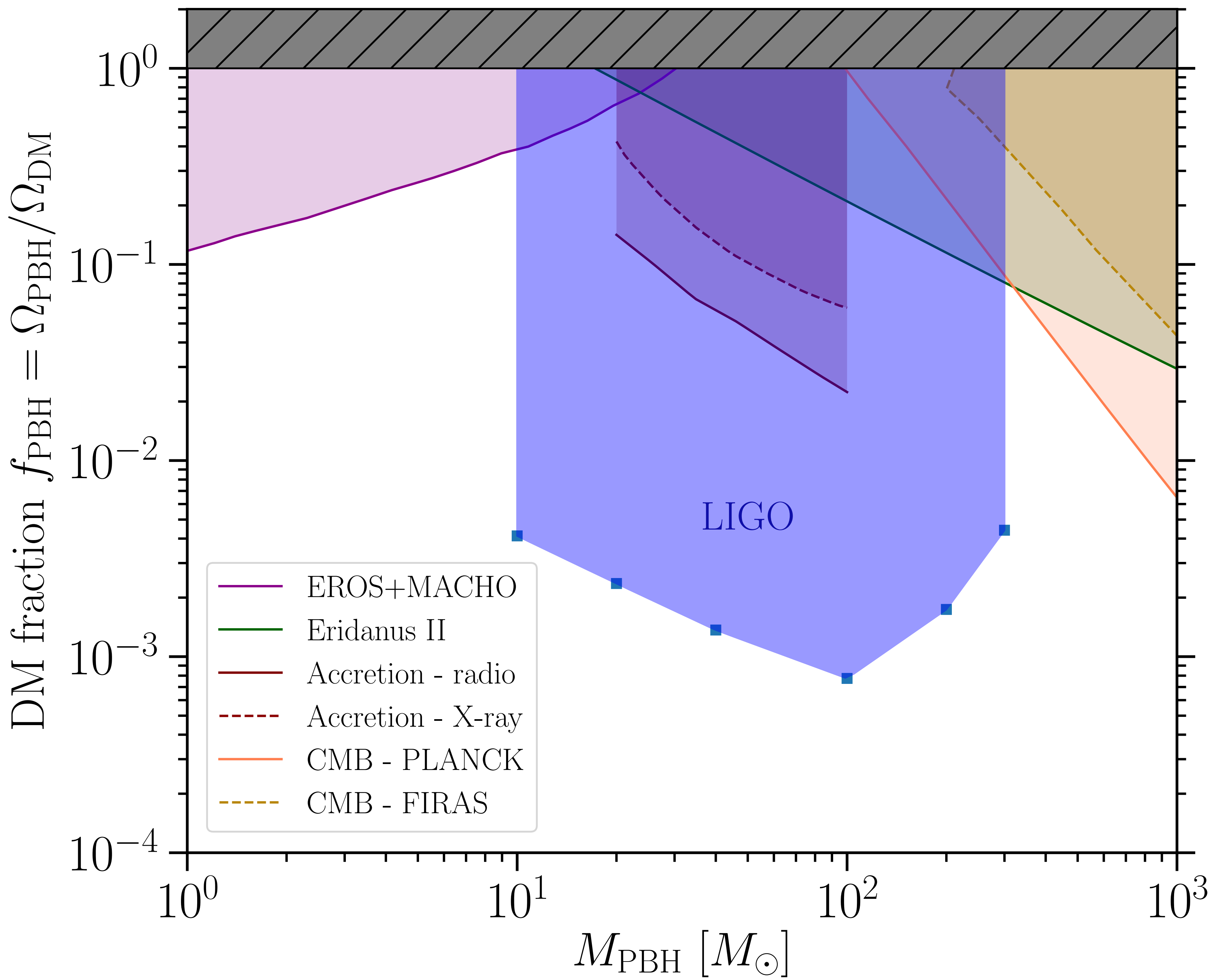


Compare expected LIGO-Virgo rate with reported 90% upper limit…

[1606.03939, 1704.04628, recently extended to sub-solar mass binaries in 1808.04771]

Limits from LIGO

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



Local DM halos strengthen constraints by around a factor of 2.

Caveats (once again)

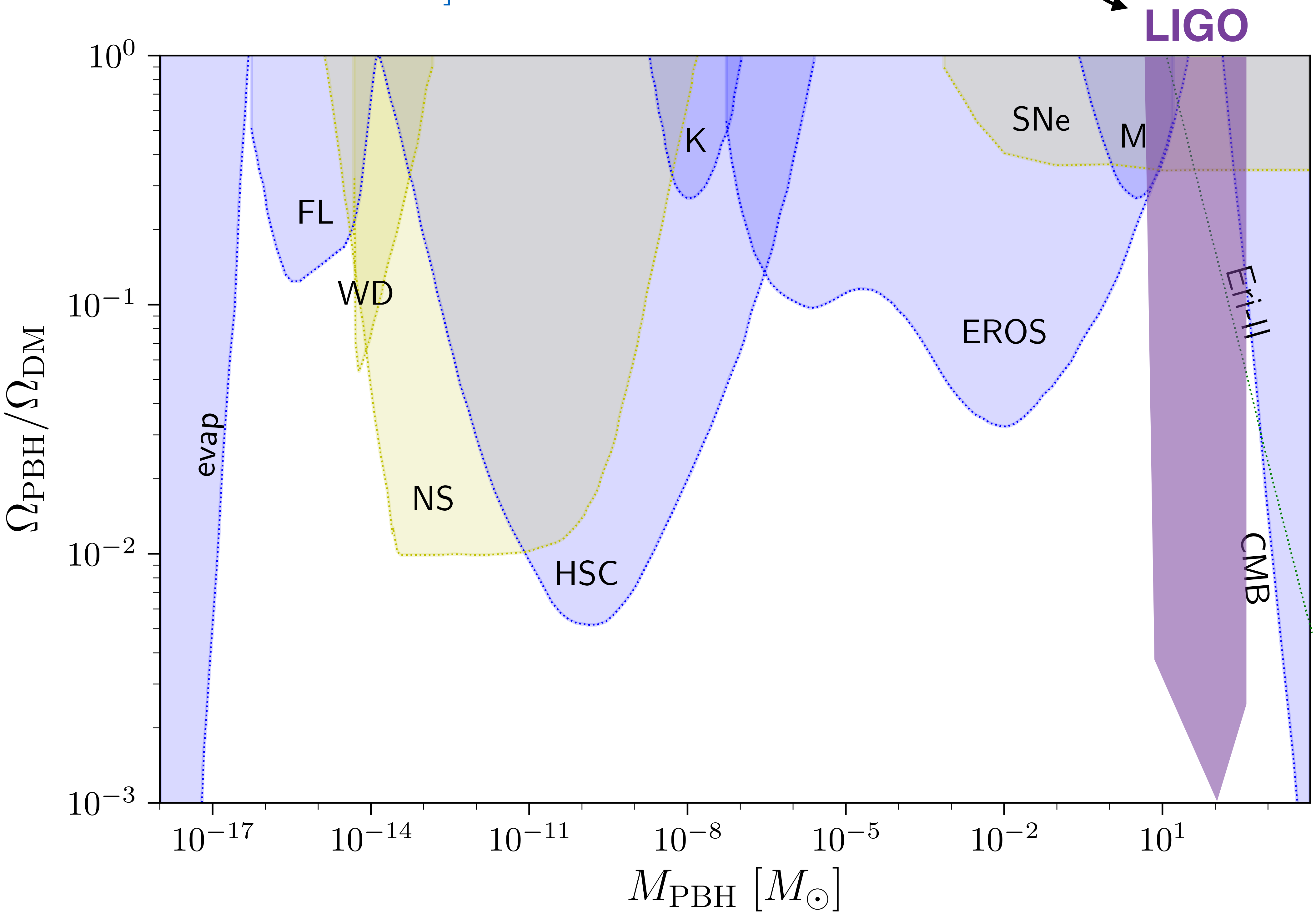
- Survival ✓ [Ali-Haïmoud et al., 1709.06576]
- Clustering ✓ [1807.02084,1808.05910]
- Baryons ? [More (tough) simulation needed]
- Dark Matter ✓ [**BJK**, Gaggero & Bertone, 1805.09034]

Bounds from merging PBHs are being placed on
a more and more solid footing!

PBHs and their DM Halos

[LIGO Bound from
BJK, Gaggero & Bertone,1805.09034]

[Selected bounds from 1801.00808]



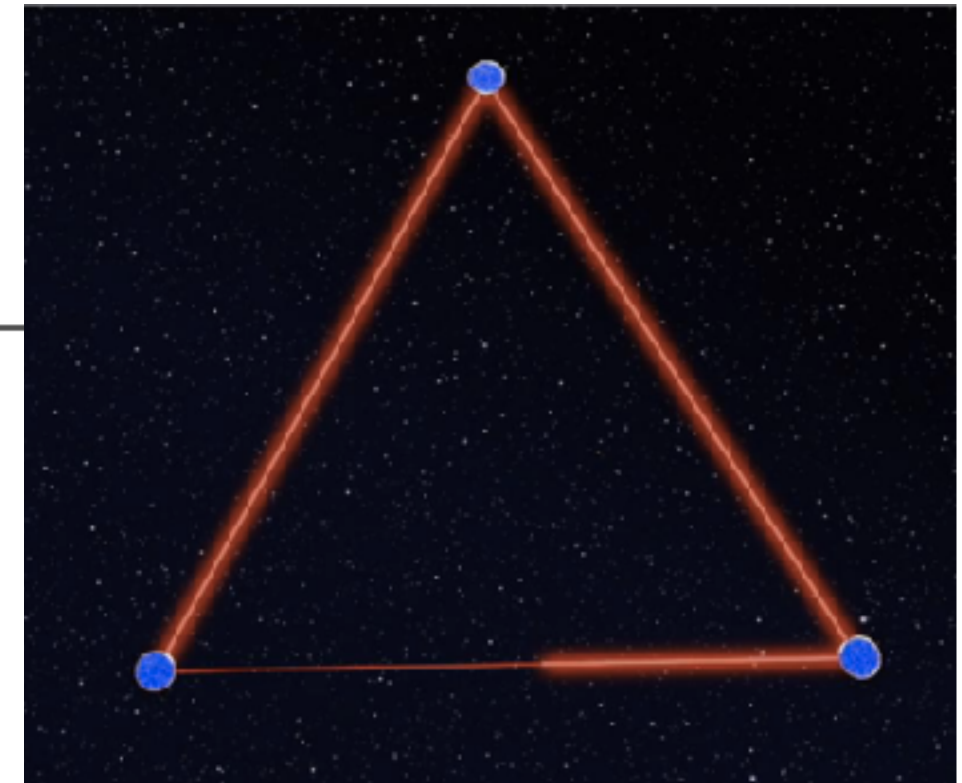
Where else can DM halos have an influence?

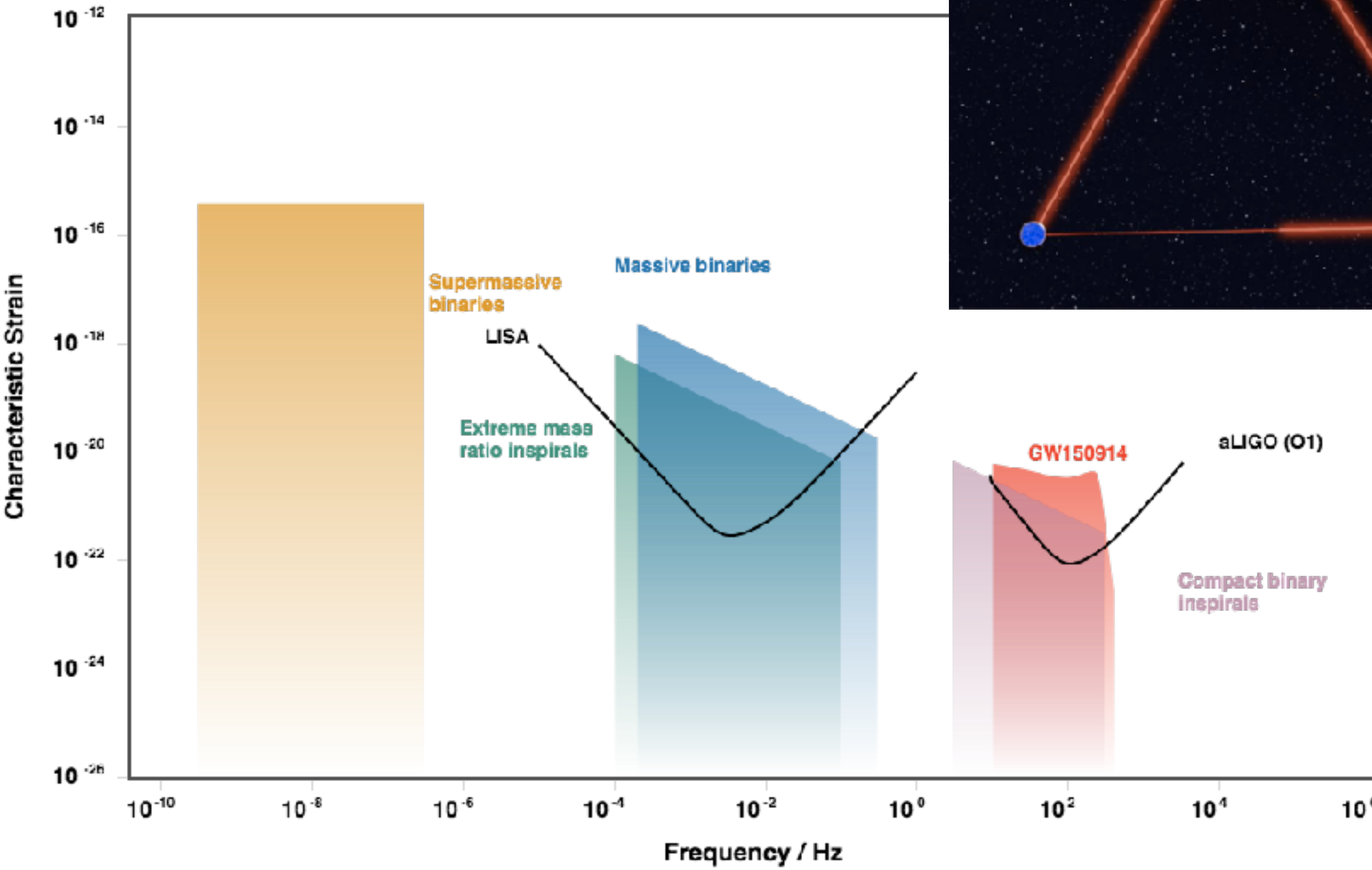
Dark Dresses at LISA

[Preliminary work with Daniele Gaggero,
David Nichols and Gianfranco Bertone]

LISA: GWs in Space

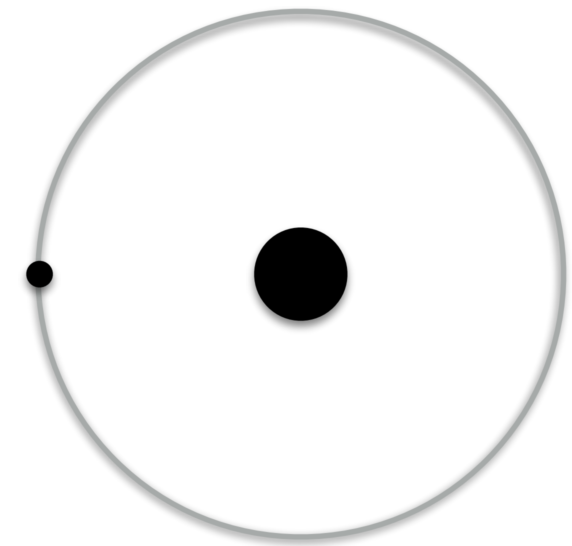
© AEI / MM / exozet

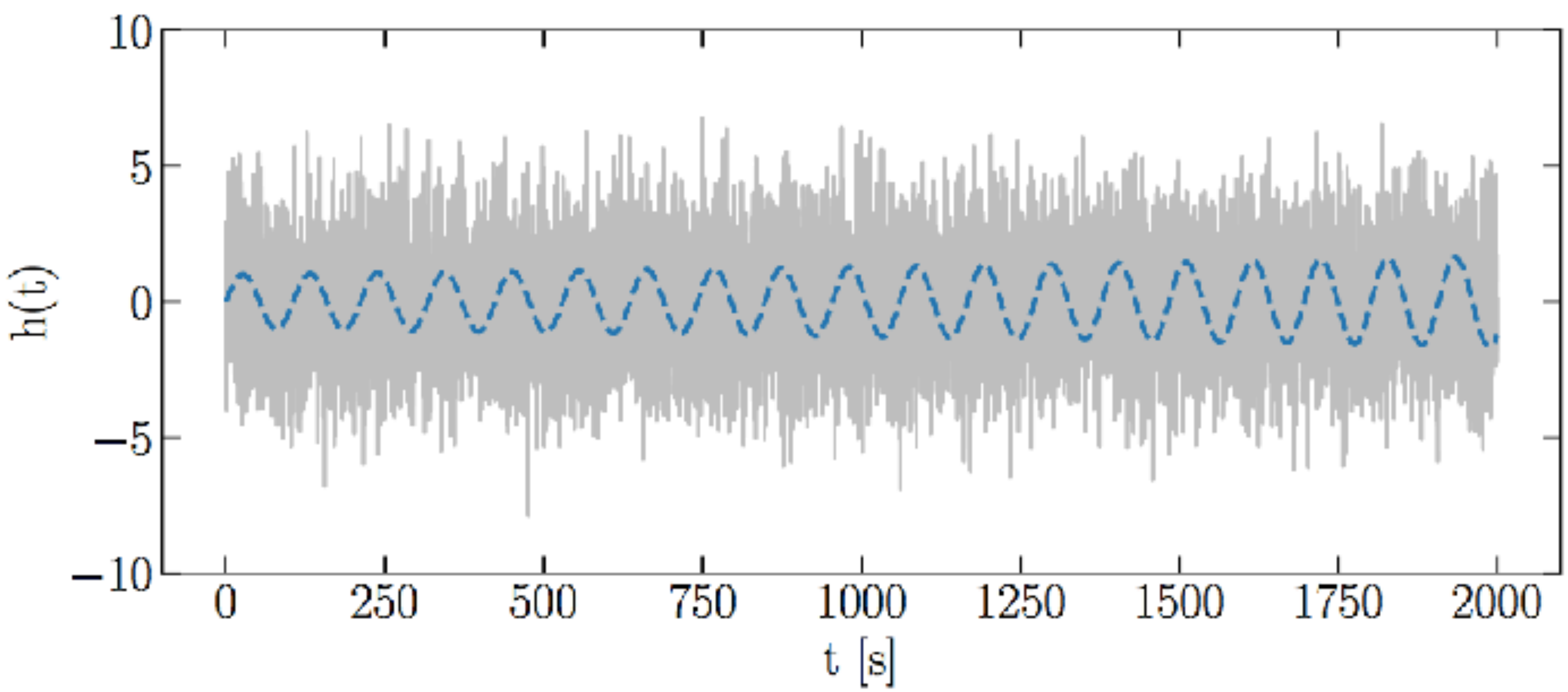




[gwplotter.com]

Intermediate Ratio Mass Inspirals (IMRIs)

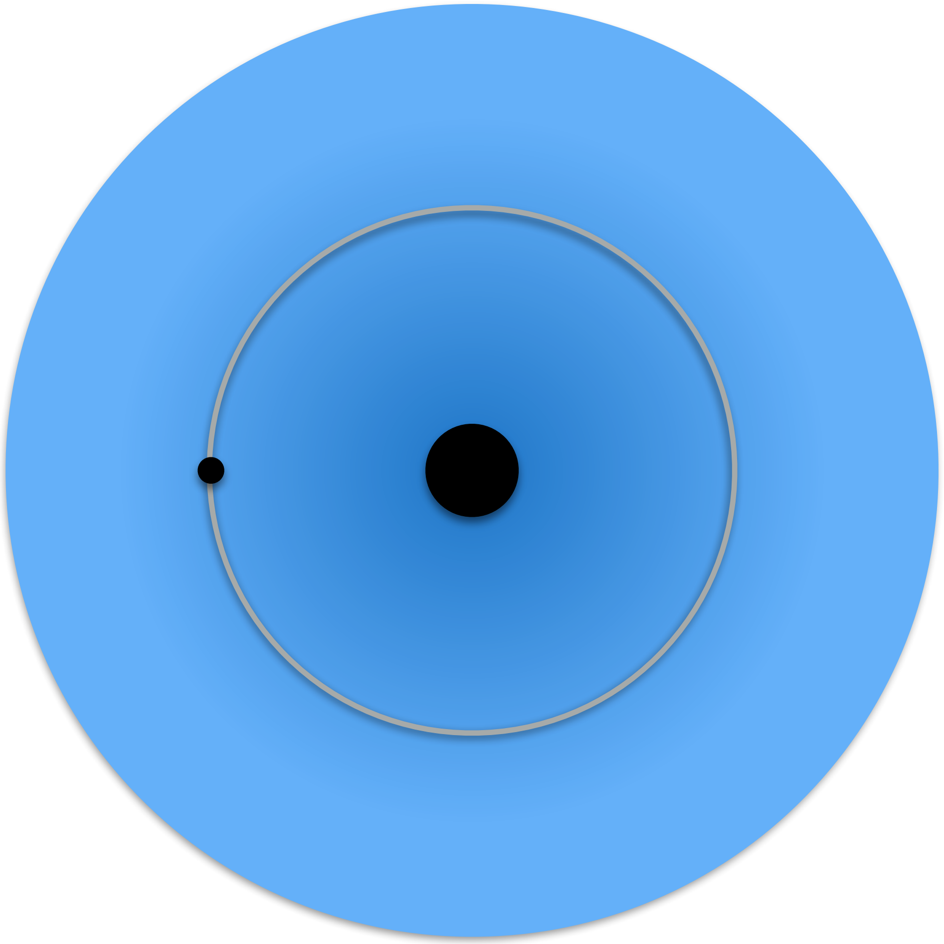


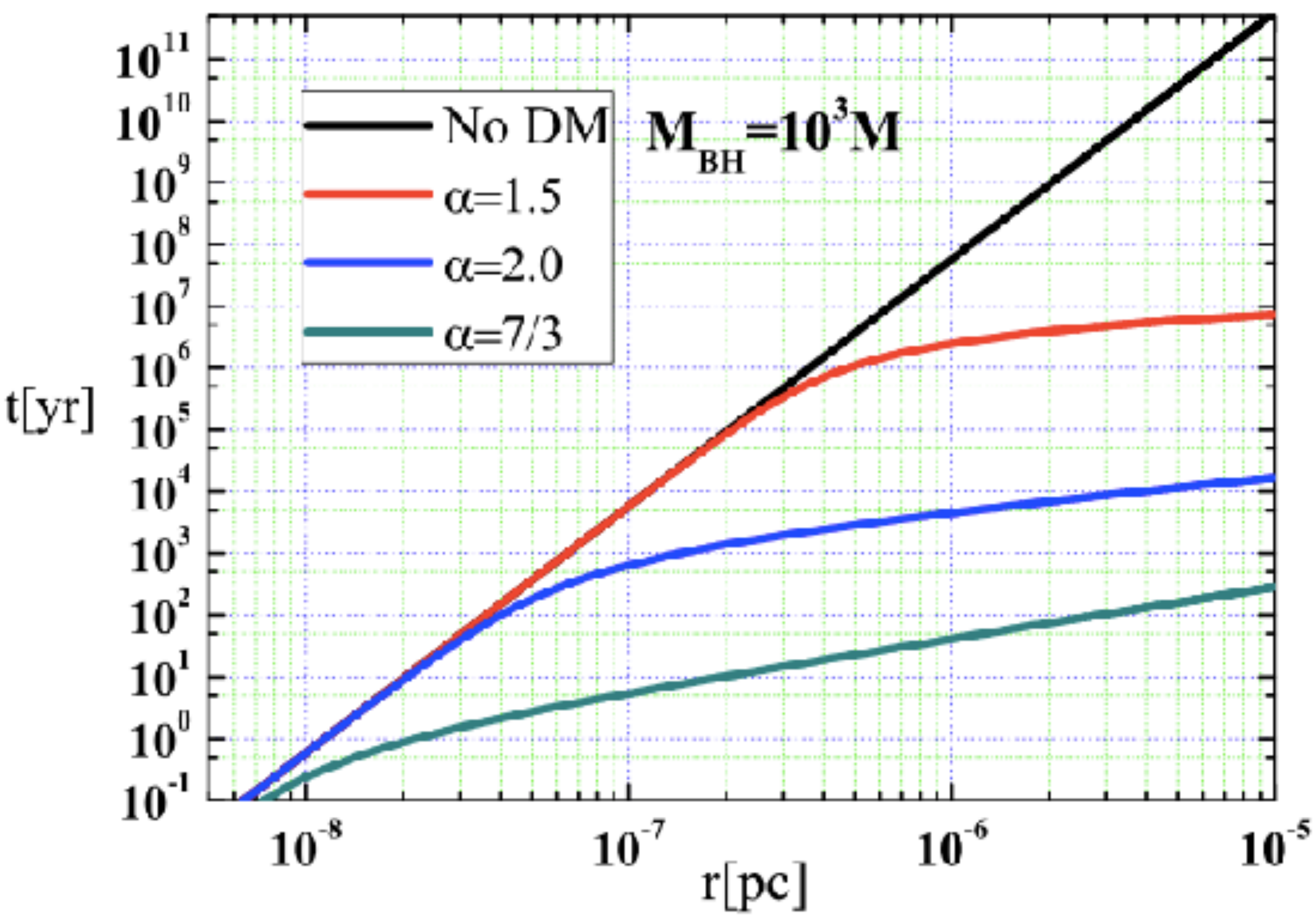


$$M_{\rm IMBH} = 1000\,M_\odot$$
$$\mu = 1\,M_\odot$$

[1705.09421,1807.03824]

Speeding up IMRIs

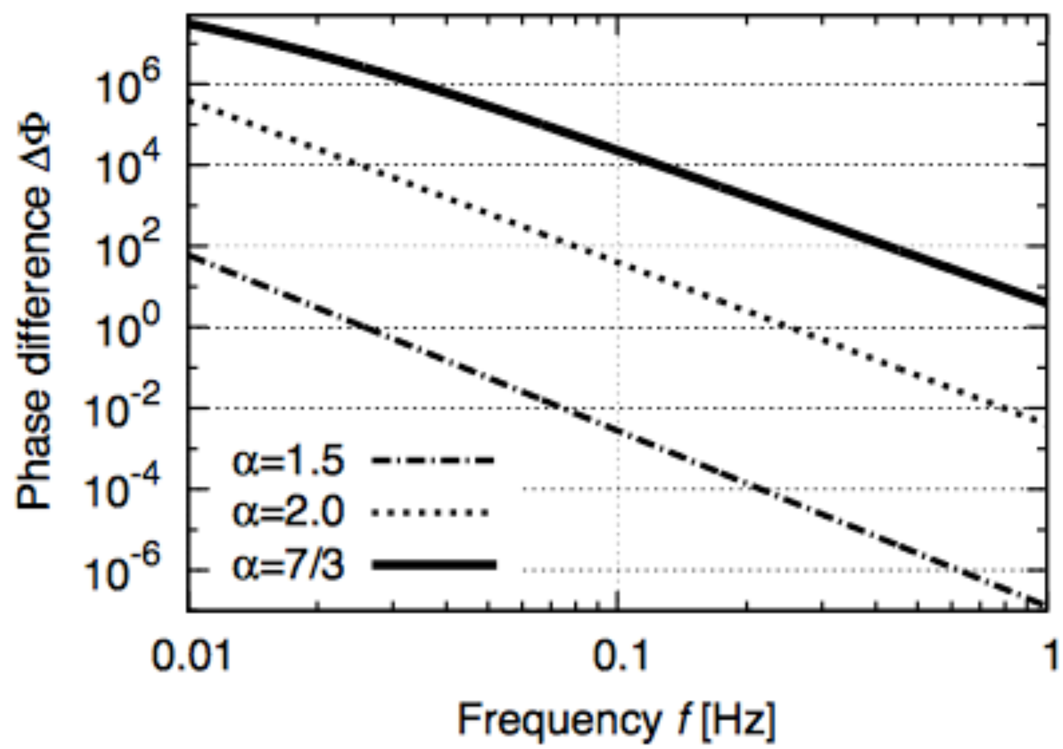


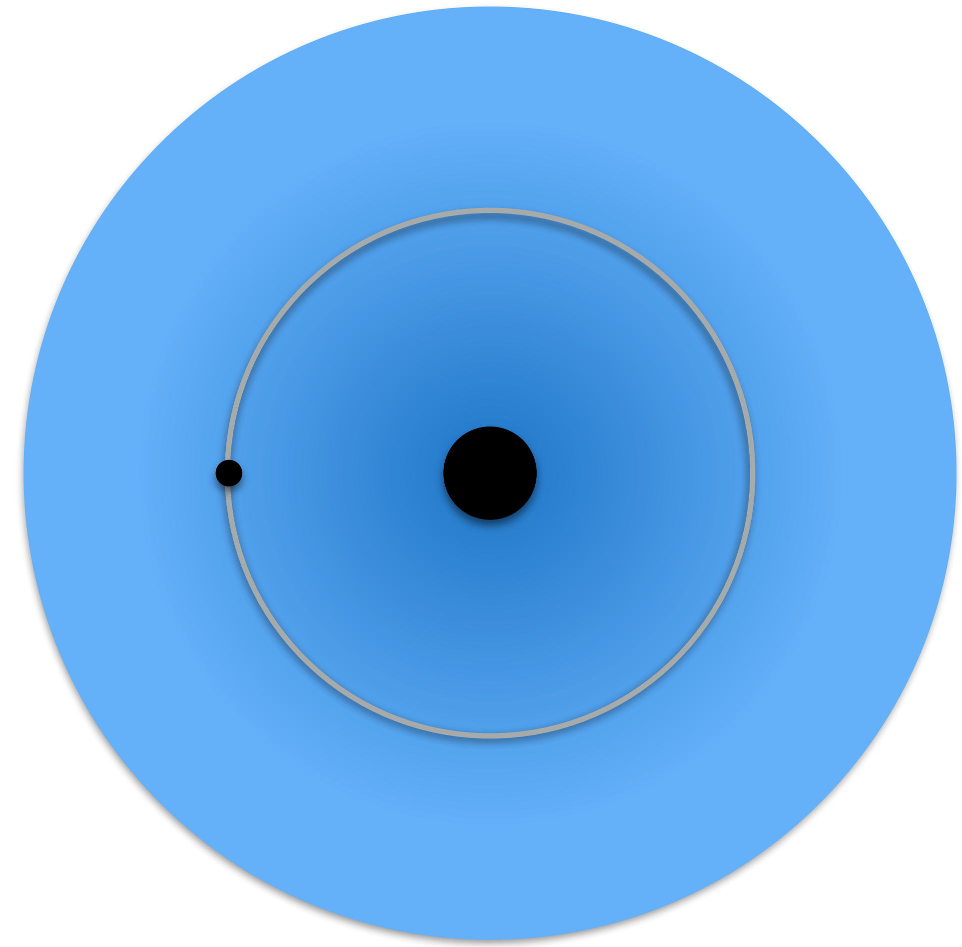


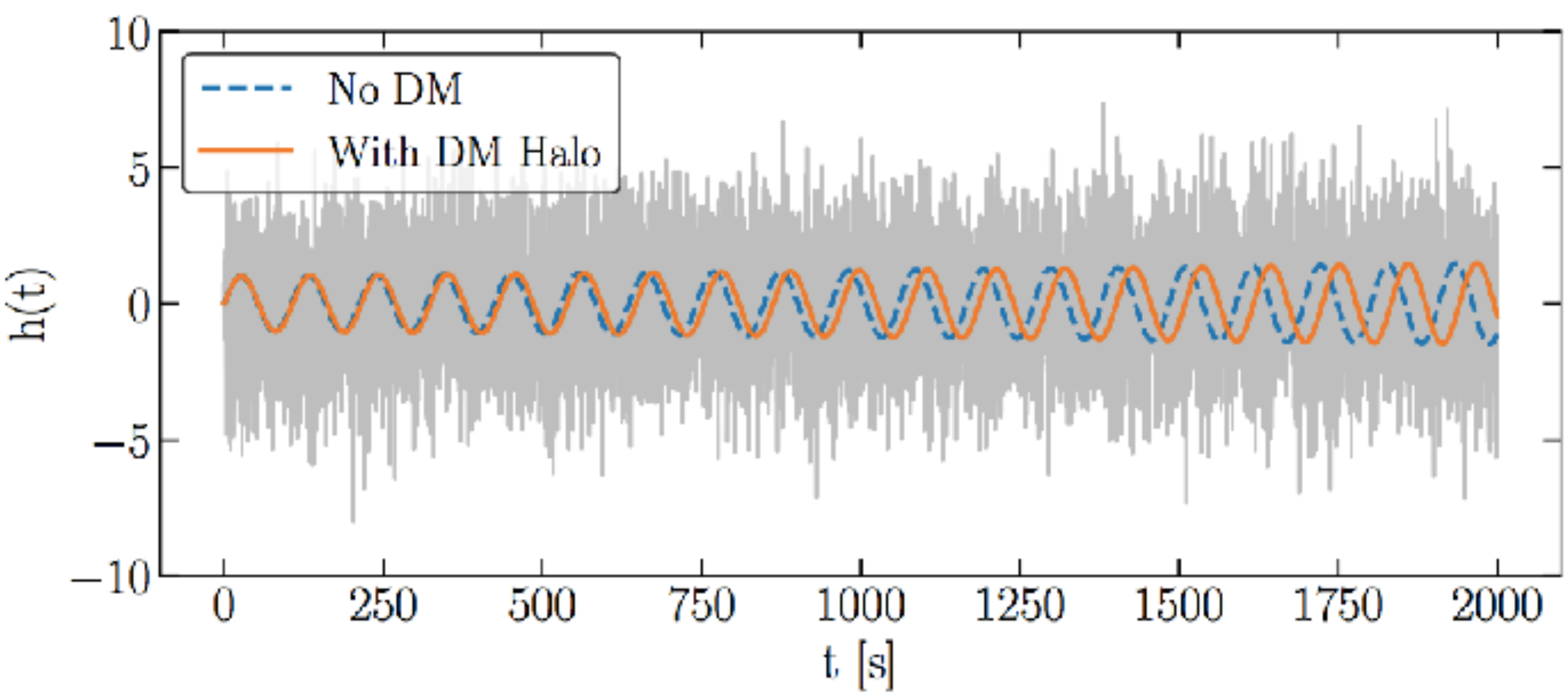
$$M_{\rm IMBH} = 1000\, M_\odot$$
$$\mu = 1\, M_\odot$$

[Yue & Han,1711.09706, 1802.03739]

Dark Matter de-phasing





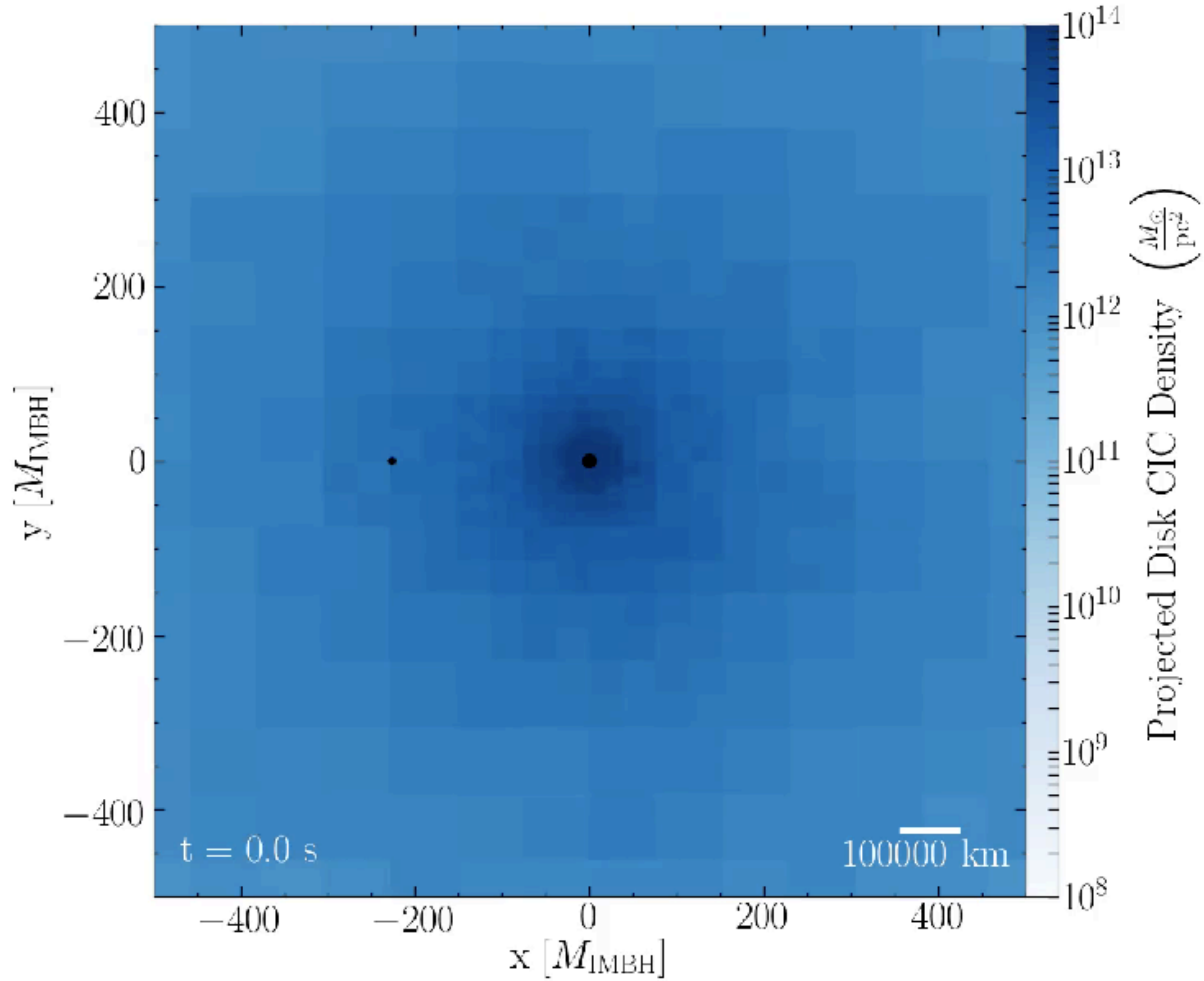


$$M_{\rm IMBH} = 1000\,M_\odot$$

$$\mu = 1\,M_\odot$$

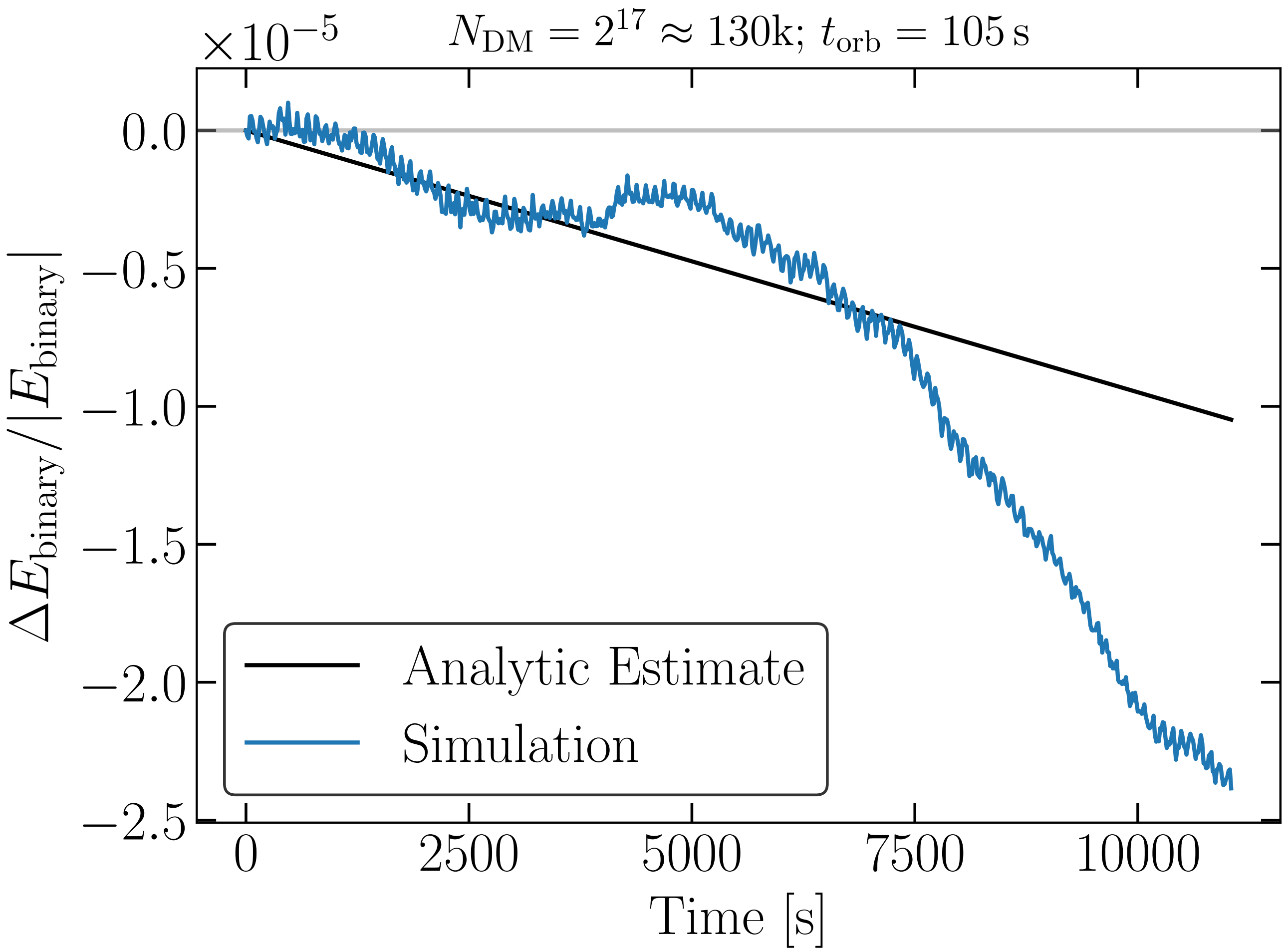
[Eda et al., 1408.3534]

Simulations

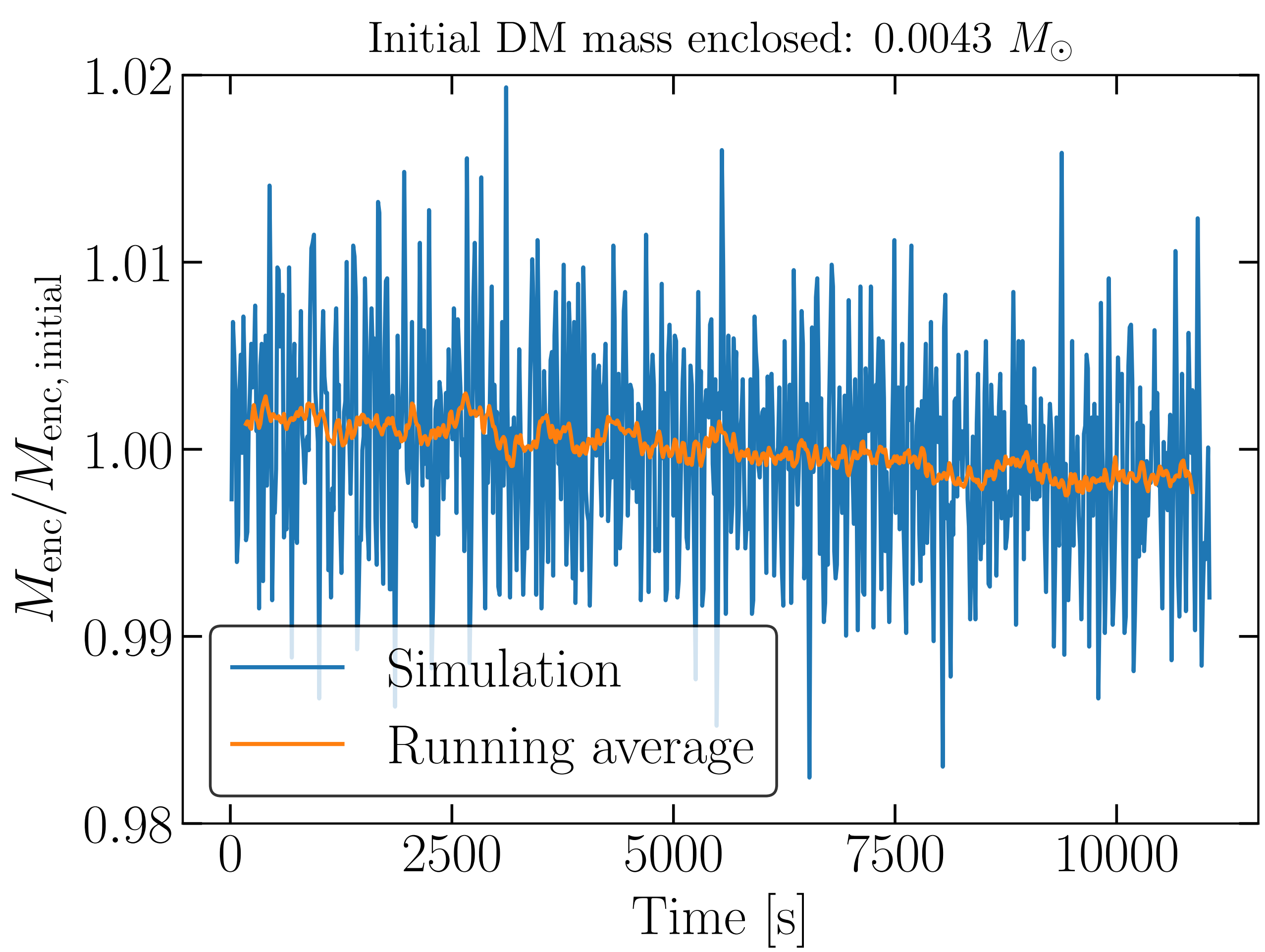


Preliminary Results

Examine change in binary energy and disruption of DM halo:



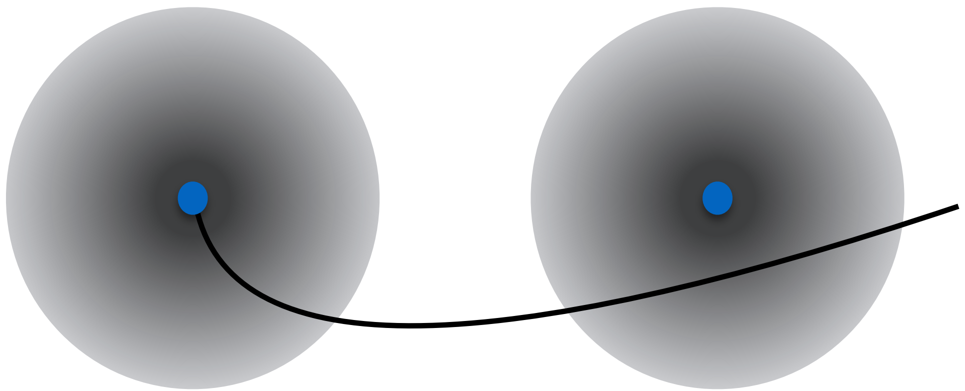
Can we measure these tiny effects over hundreds of thousands of orbits?



Can we extract the DM halo properties?

Black Holes' Dark Dress

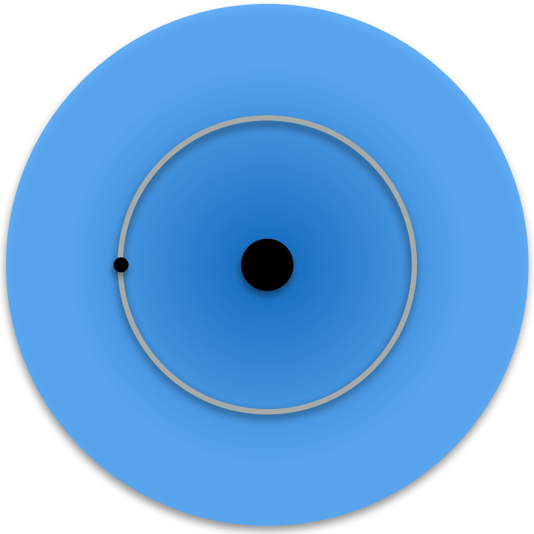
arXiv:1805.09034, PRD 98, 023536 (2018)
BJK, Daniele Gaggero & Gianfranco Bertone



Local DM halos affect the size and shape of PBH binaries but (surprisingly) only increase merger rate by a factor of 2

LIGO bounds set the strongest constraints on 10 - 300 Solar Mass PBHs, at the sub-percent level

Can Dark Matter influence other systems and their GW signals?



Movies and code available at github.com/bradkav/BlackHolesDarkDress

Backup Slides

First Remapping

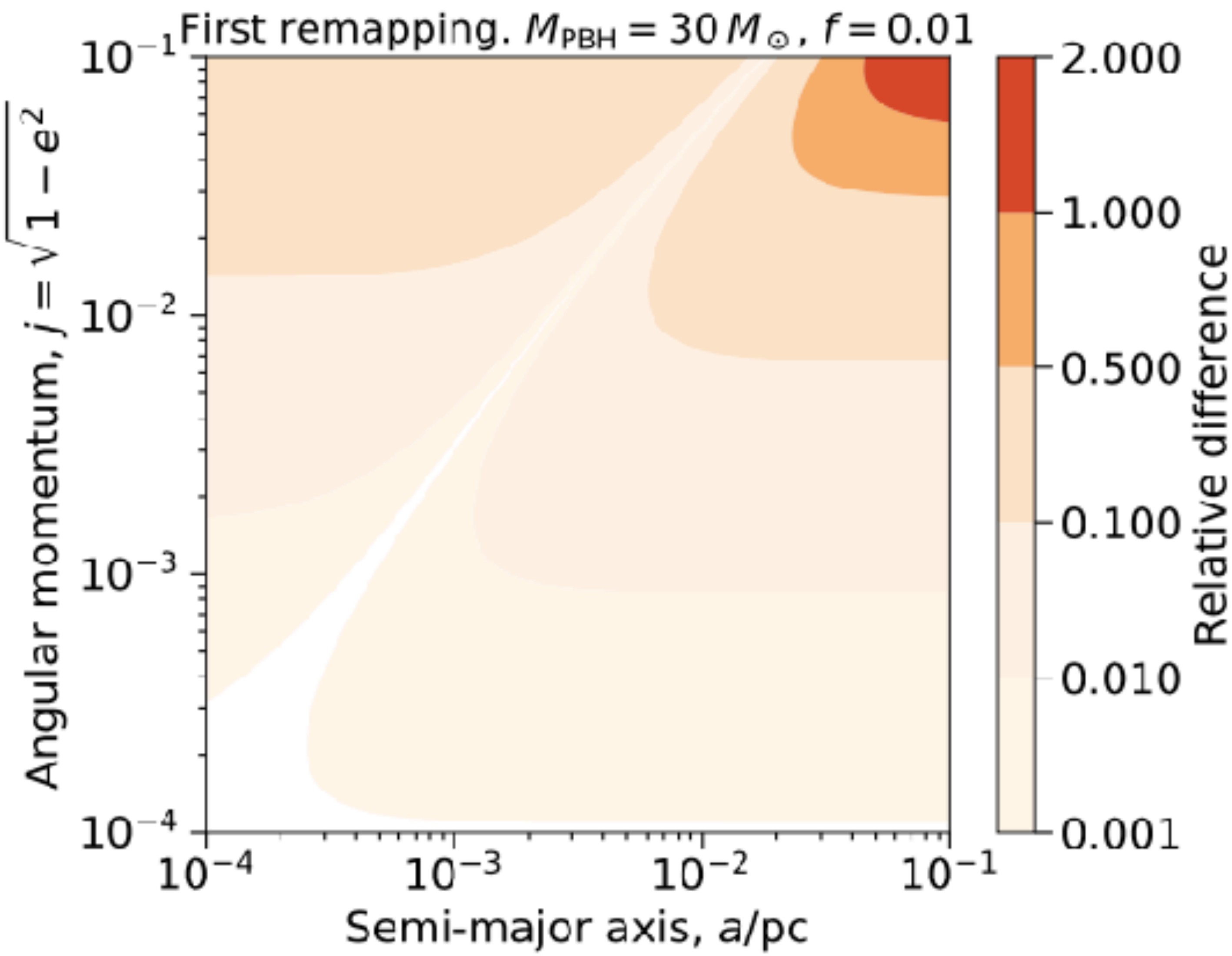
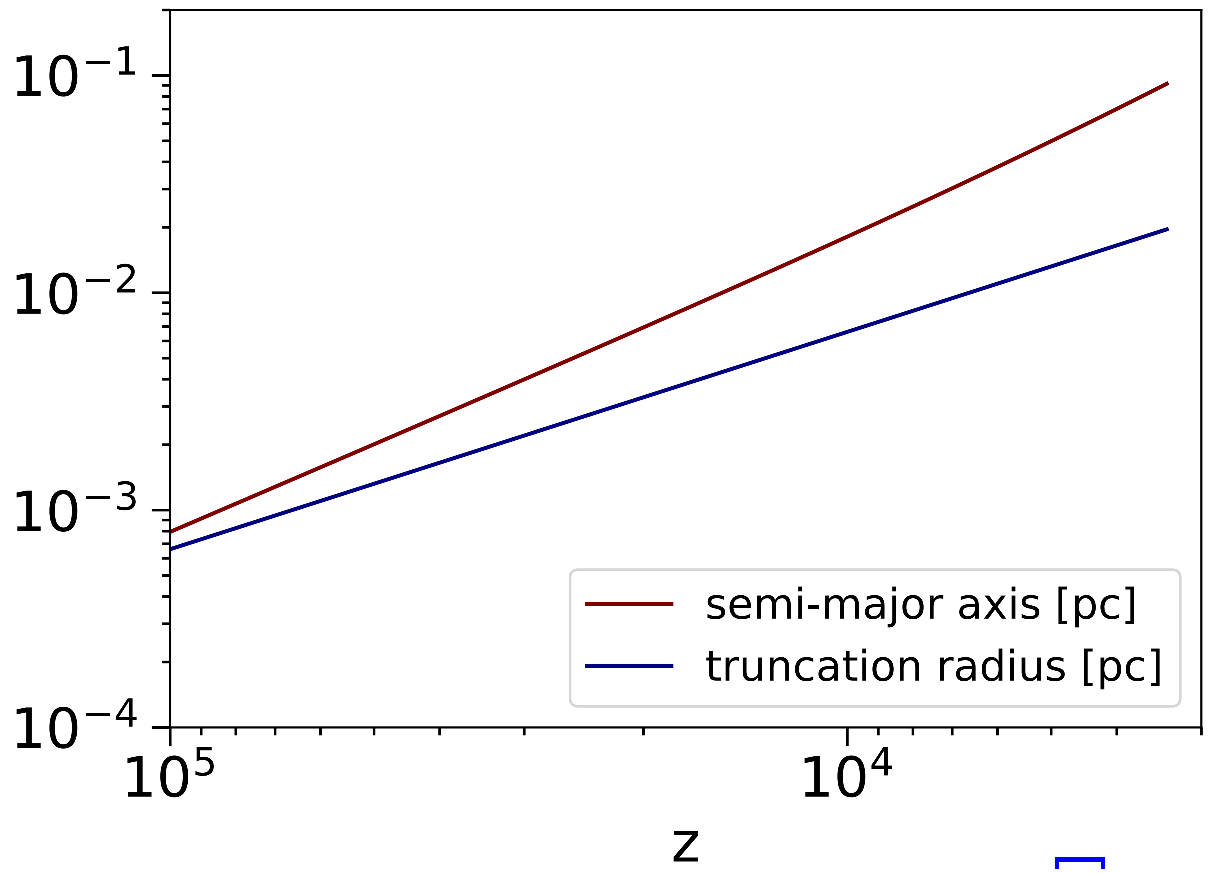
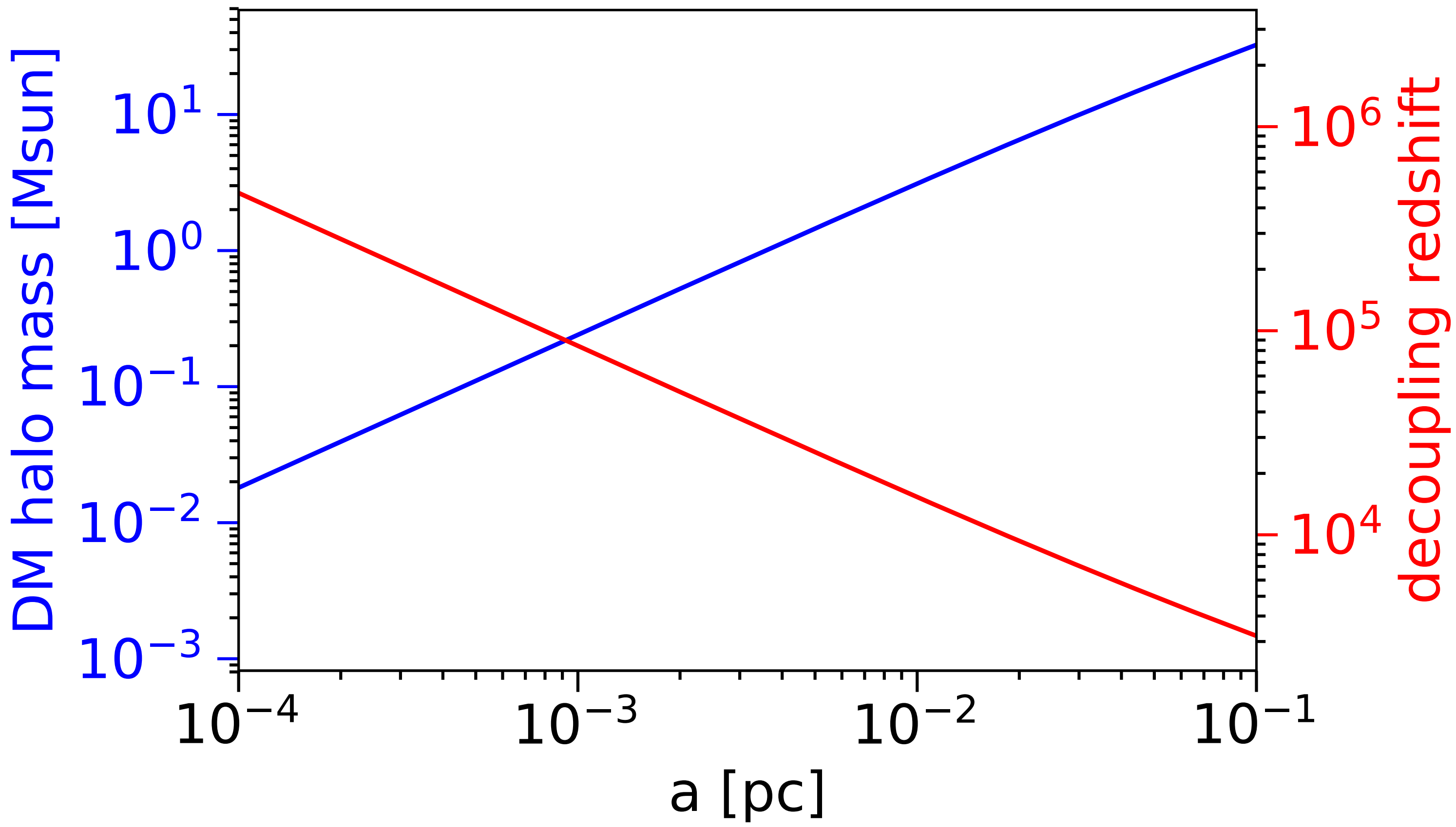


FIG. 5. **First remapping.** We represent the relative difference between the original PDF in the (a, j) parameter space and the one which takes into account the presence of the mini-halos (as described in Sec. II C). We remark that this initial remapping is mainly based on a rescaling of the mass parameter, and does not take into account the impact of the halos on the BBH orbits, which will be addressed in the next section.

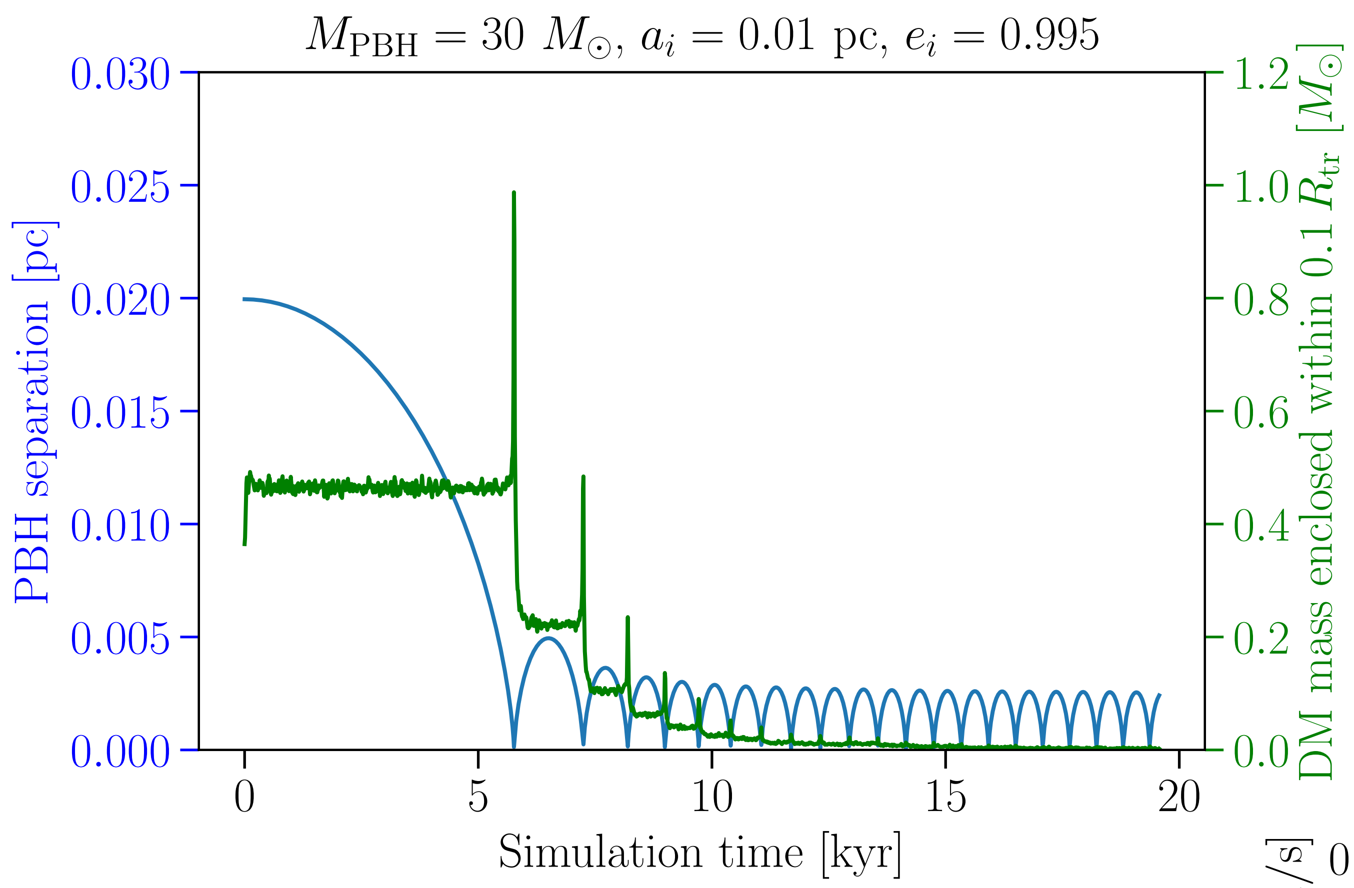
Decoupling and Halo Mass

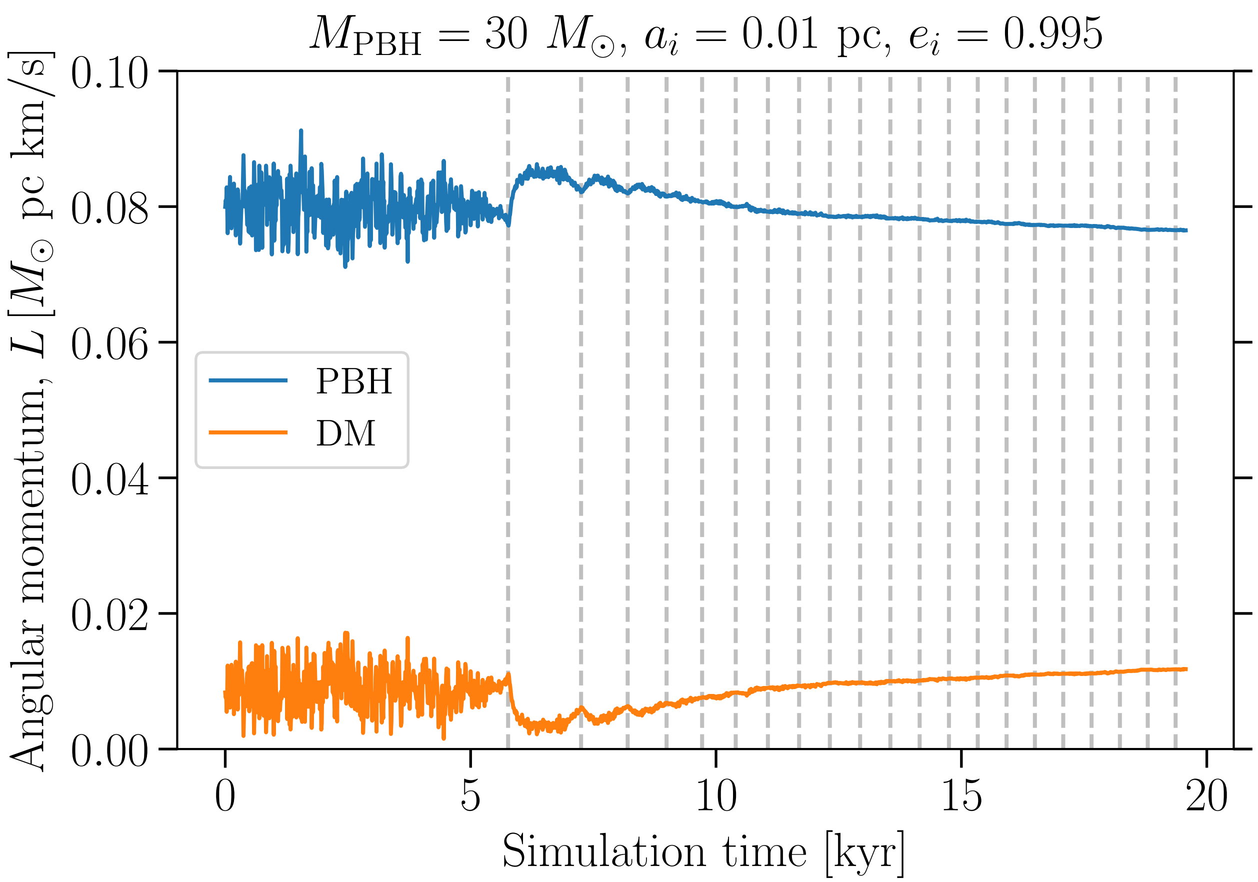
$M_{\rm PBH} = 30\, M_\odot$





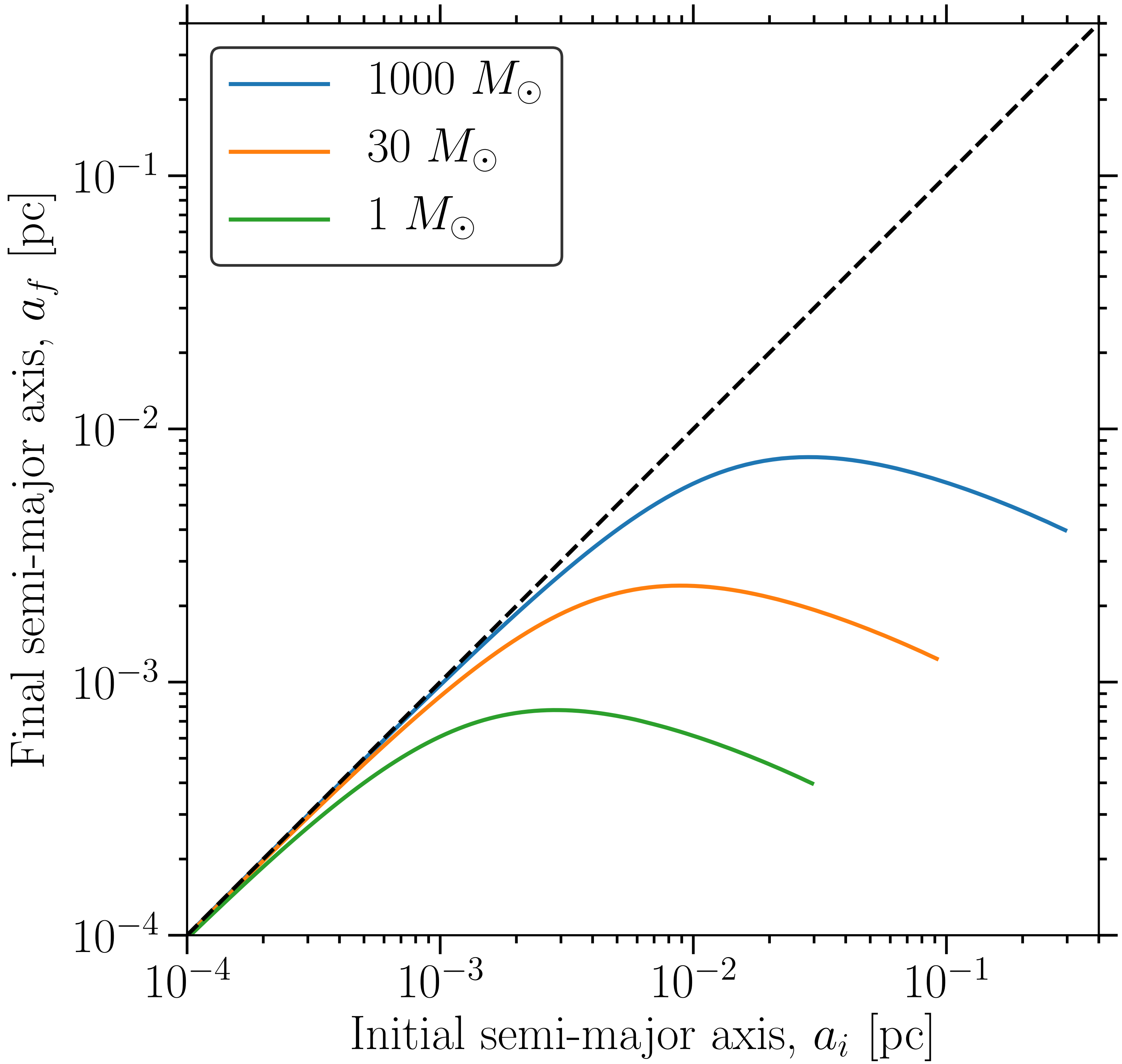
Binary Evolution





$$j_f = \sqrt{\frac{a_i}{a_f}} j_i \quad \text{for } j \ll 1$$

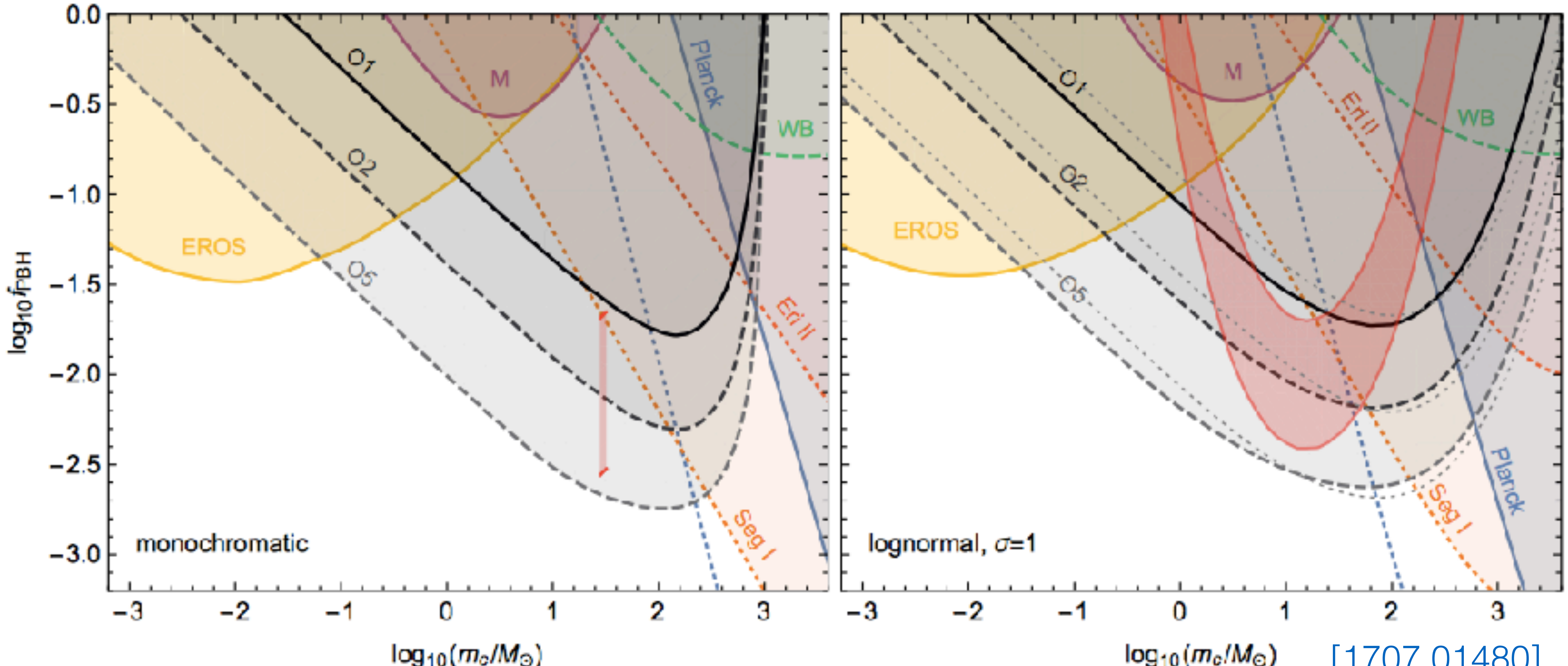
Remapping the semi-major axis



$$t_f = \sqrt{\frac{a_i}{a_f}}\, t_i$$

Extended mass functions

LIGO O1 Limit



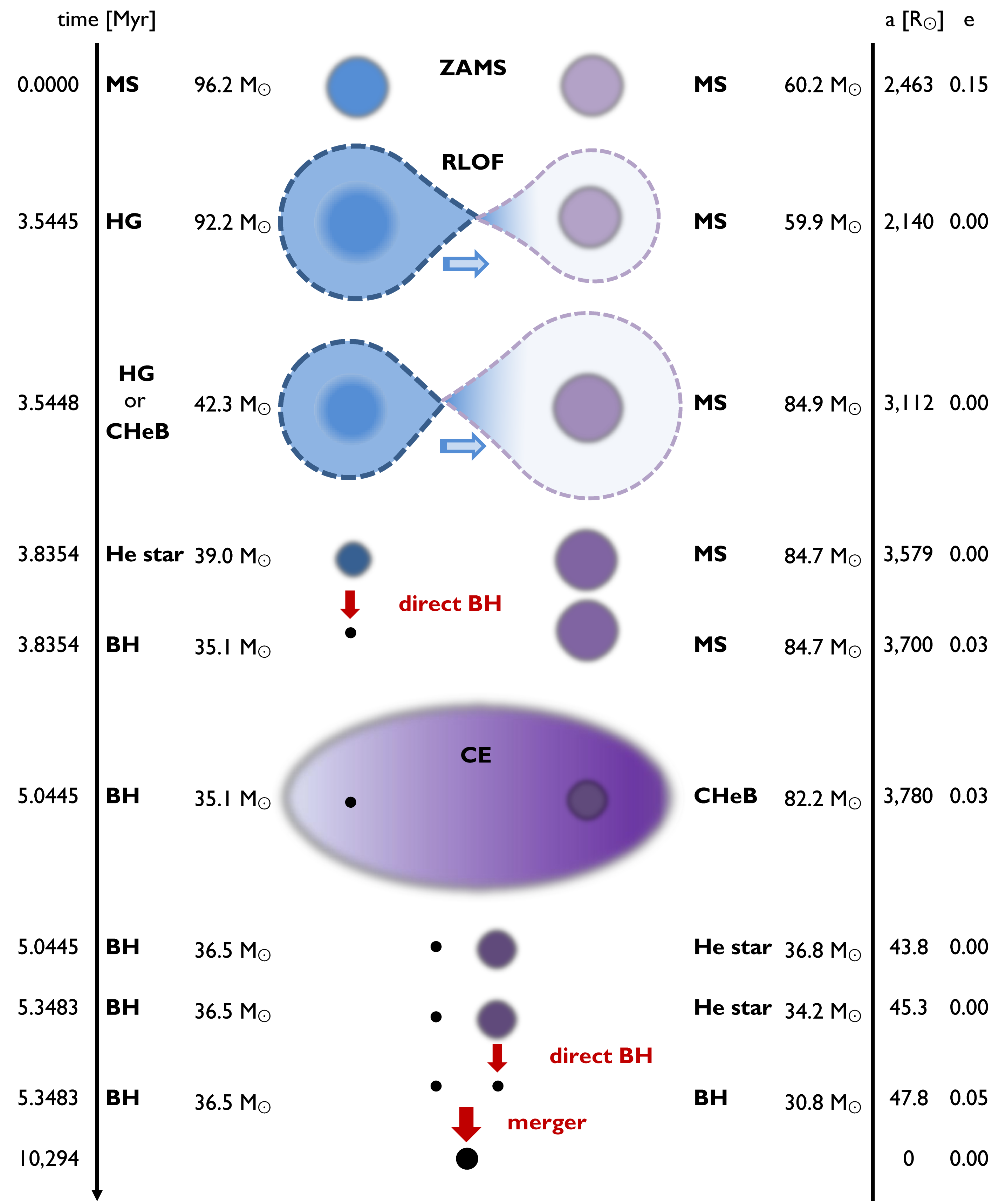
[1707.01480]

"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:



[1602.04531]

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

Simulation Details

ErrTolForceAcc	10^{-5}		
ErrTolIntAccuracy	10^{-3}		
MaxTimestep [yr]	10^{-2}		
$\ell_{\rm soft}$ (PBH) [pc]	10^{-7}		
$M_{\rm PBH}$ =	$1\,M_\odot$	$30\,M_\odot$	$1000\,M_\odot$
$\ell_{\rm soft}$ (DM, low-res) [pc]	2×10^{-6}	10^{-5}	5×10^{-5}
$\ell_{\rm soft}$ (DM, high-res) [pc]	2×10^{-7}	10^{-6}	5×10^{-6}

TABLE I. **Summary of Gadget-2 parameters.** The parameters ErrTolForceAcc and ErrTolIntAccuracy control the accuracy of force calculation and time integration respectively. We also specify the softening lengths $\ell_{\rm soft}$ of the simulations, as described in the text. Low-resolution simulations contain roughly 10^4 DM particles per halo, while high-resolution simulations use a multi-mass scheme with roughly 4×10^4 DM particles in total per halo.

For 'high-resolution' simulations, we use a multi-mass scheme in which the DM halo is composed of 4 different masses of pseudo-particles.

Each simulation takes ~ 3000 CPU-hours, with very poor scaling with $N_{\rm CPU}$