Black Holes' Dark Dress

The impact of local Dark Matter halos on the mergers of primordial black hole binaries

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DESY Theory Workshop

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GRavitation AstroParticle Physics Amsterdam

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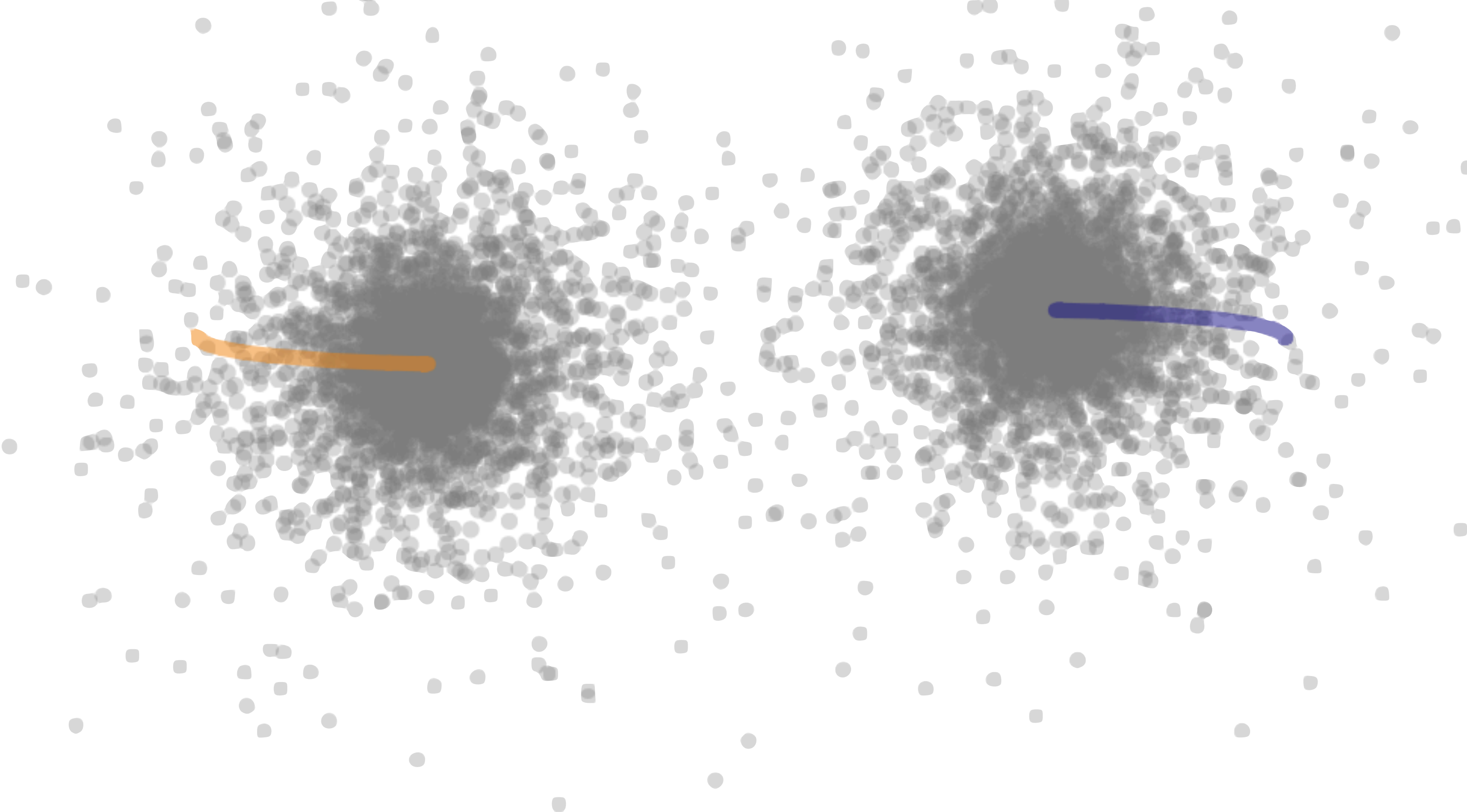


arXiv:1805.09034, PRD 98, 023536 (2018)
BJK, Daniele Gaggero & Gianfranco Bertone

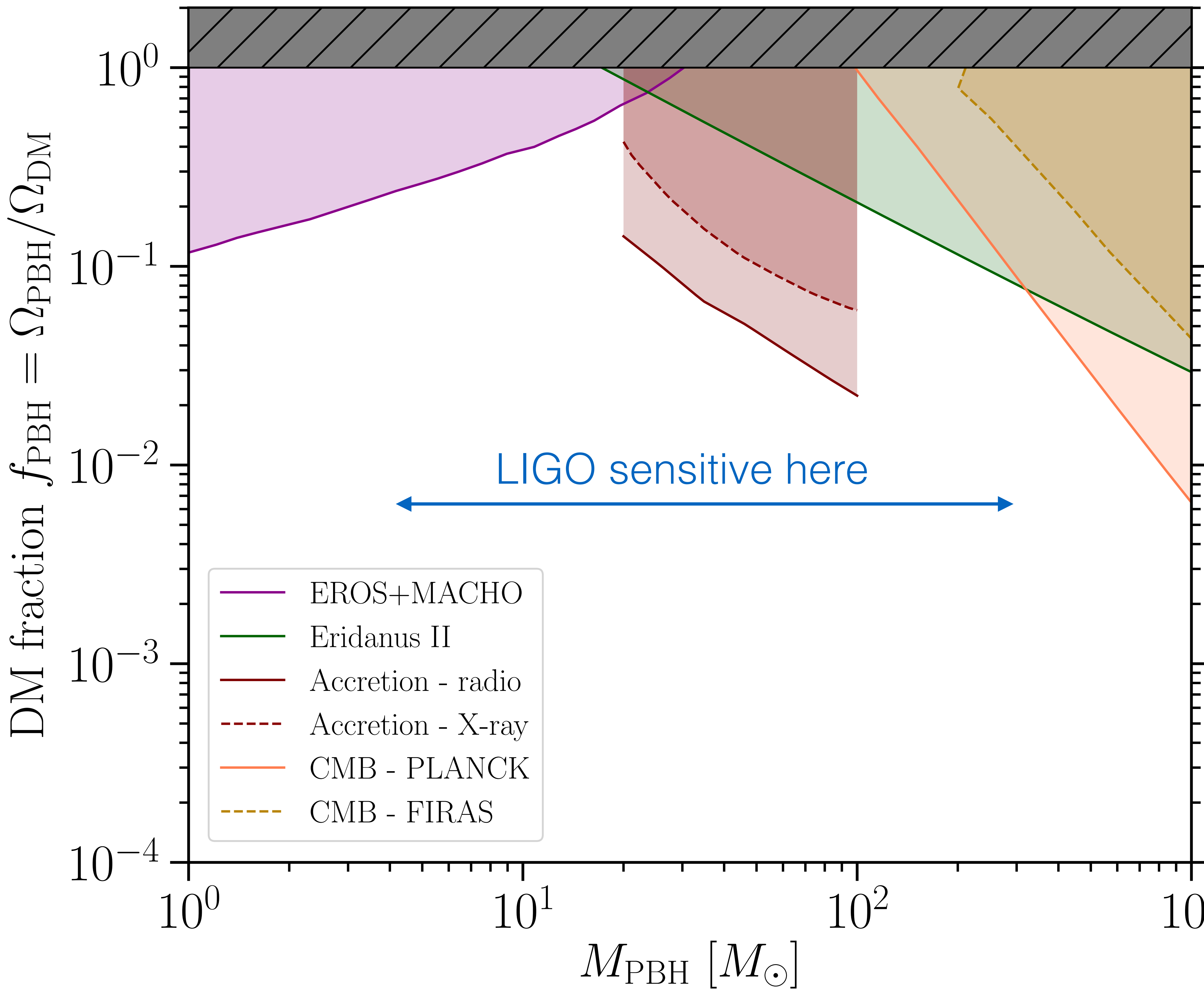
Could the observed LIGO events be due to merging Primordial Black Holes (PBHs)?

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

Movies at tinyurl.com/DESYDarkDress

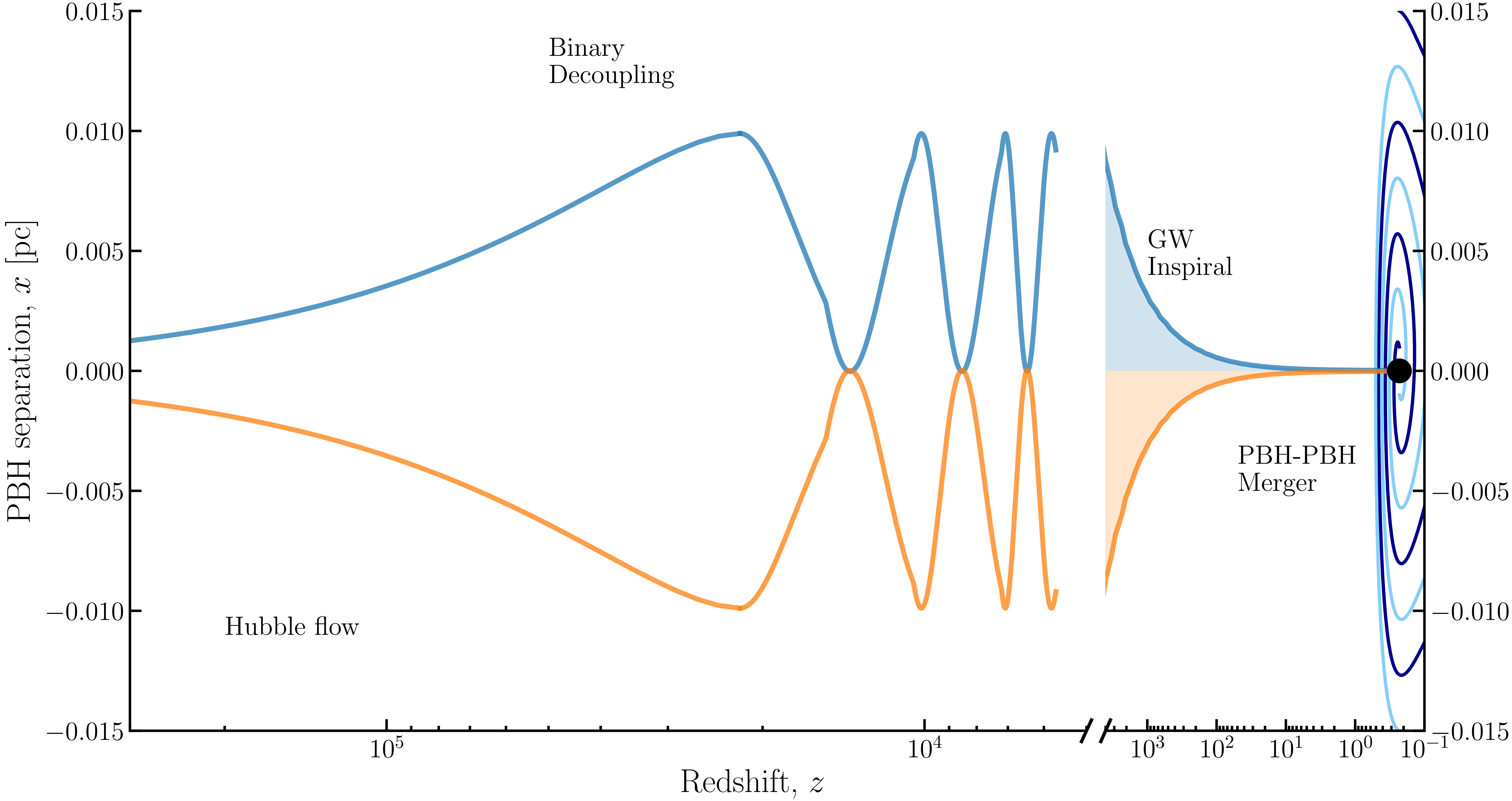
Primordial Black Holes

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



Life of a PBH binary

PBH binaries form predominantly from 'nearby' PBH pairs in the Early Universe:



$a = 0.01$

$e = 0.995$

[Sasaki et al., 1603.08338 and others, but see also Bird et al., 1603.00464]

PBH Binary Population

Randomly distributed (unclustered) PBHs

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

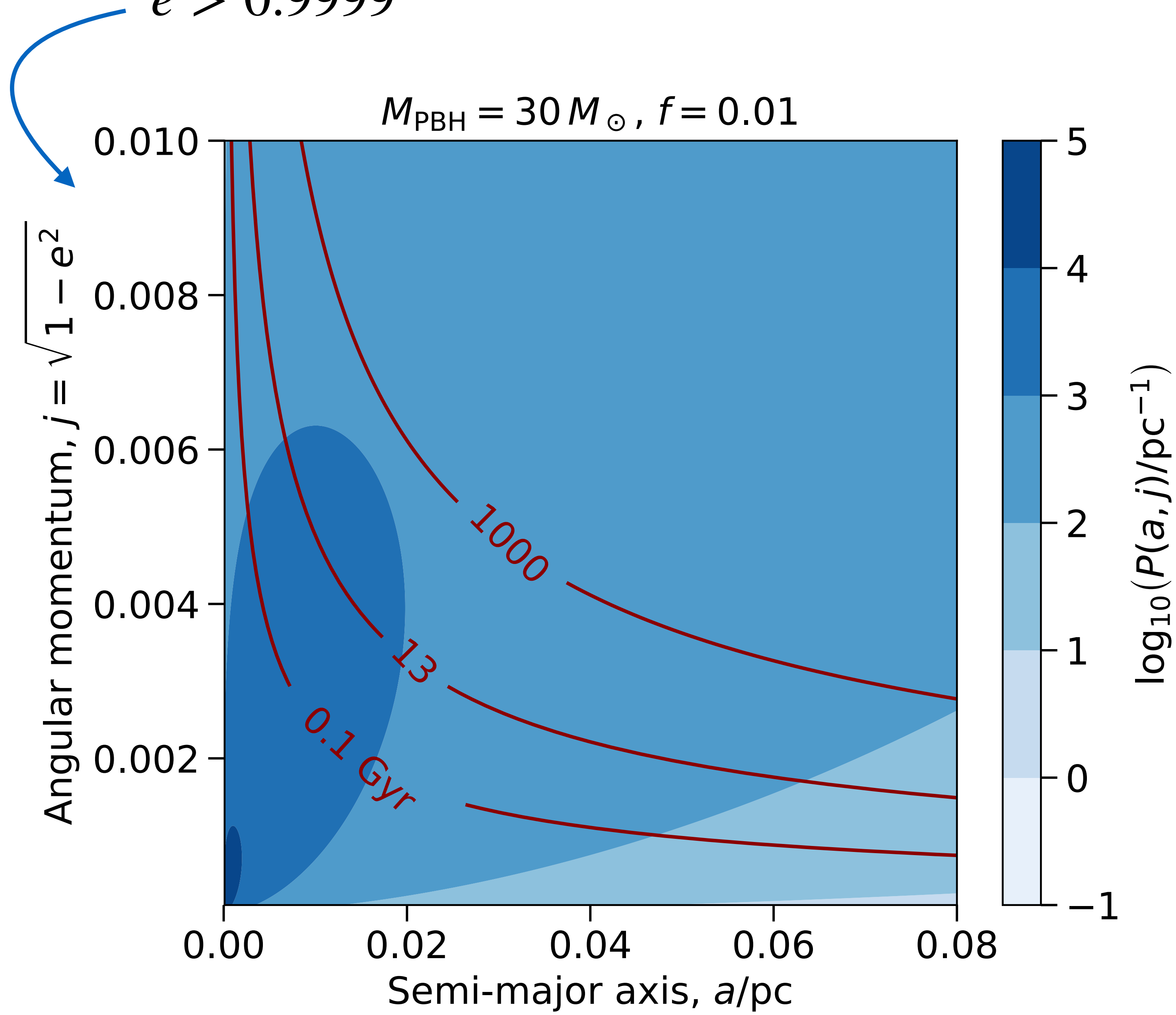
Close, eccentric binaries merge today:

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

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

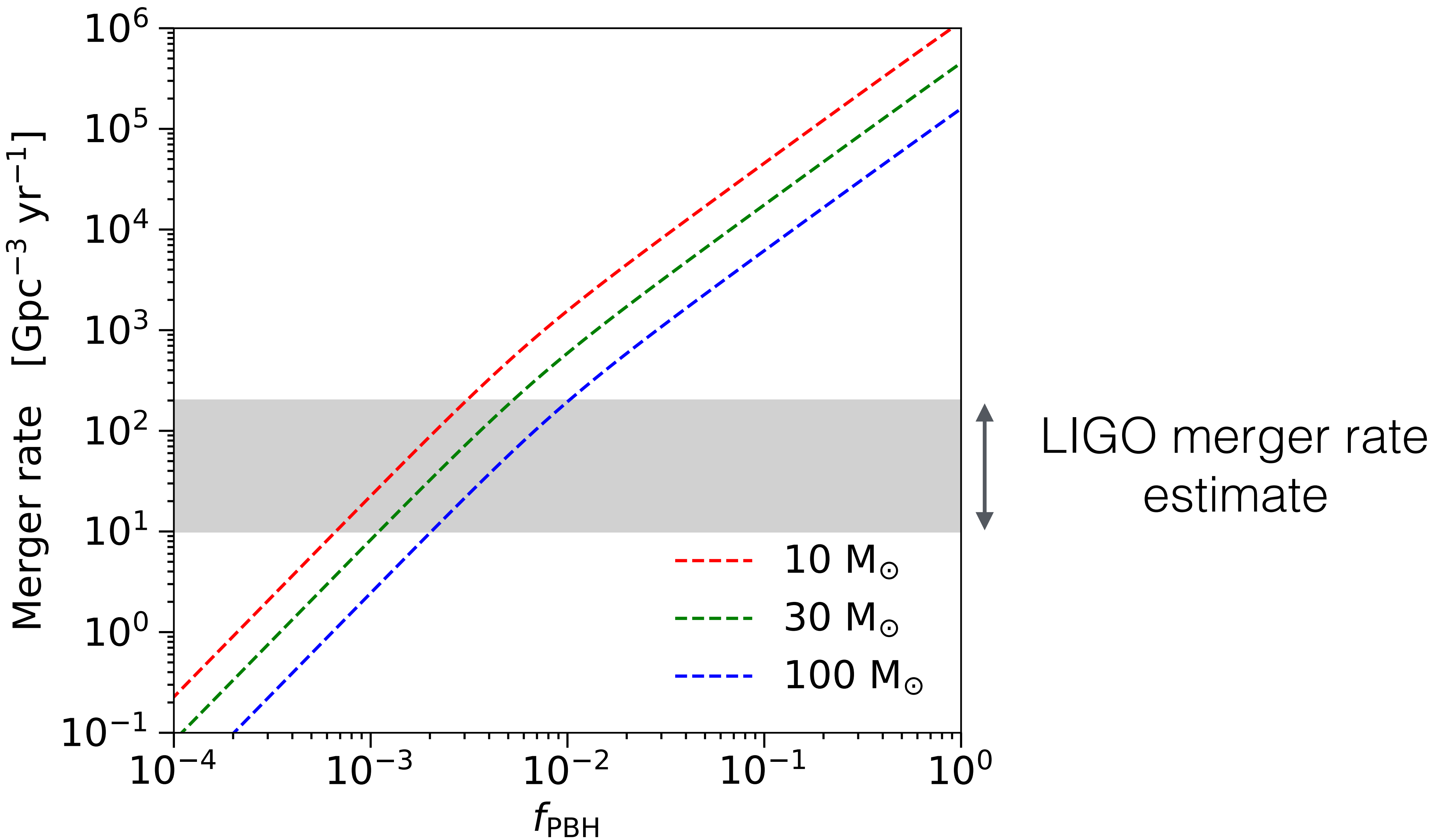
$$\mathcal{R}(t_{\rm merge}) = \frac{1}{2} n_{\rm PBH} P(t_{\rm merge})$$

$e > 0.9999$



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

Merger rate estimate

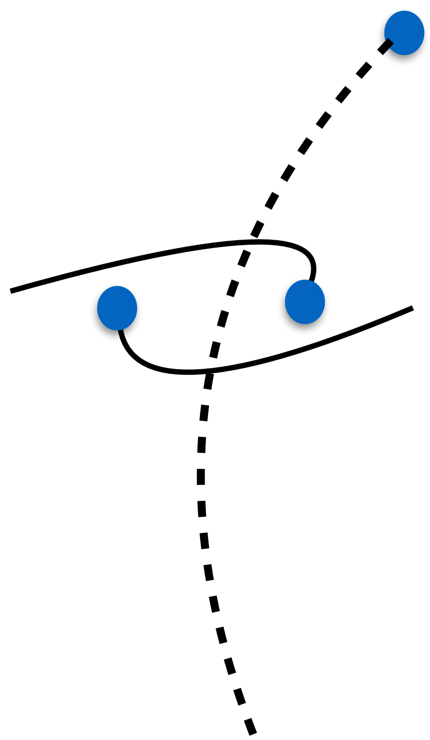


Solar mass PBHs should only be a sub-dominant (%-level) contribution to the DM density in the Universe

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

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



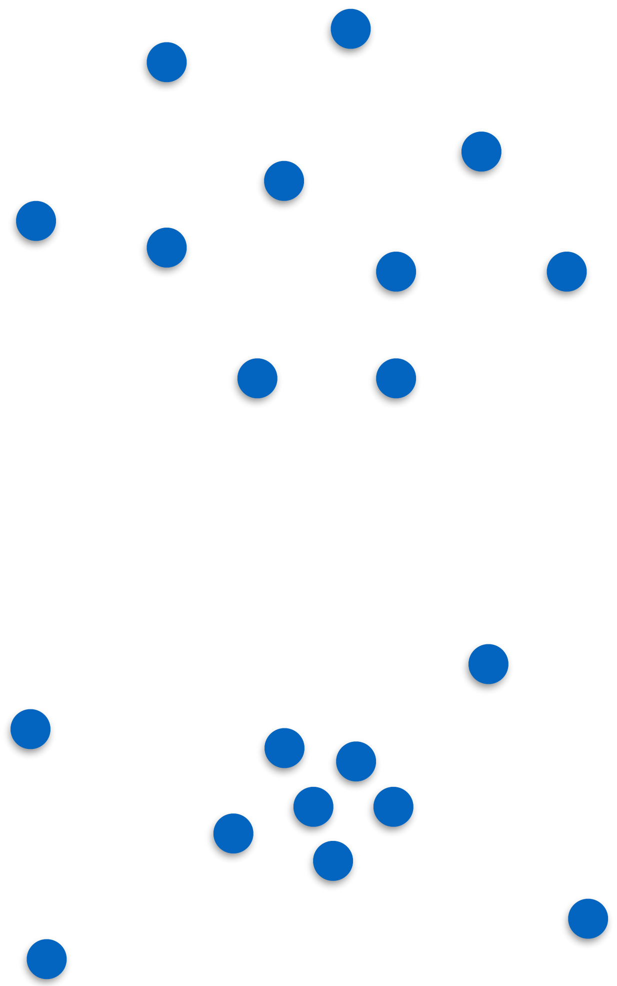
Do these binaries survive for the age of the Universe?

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

[Ali-Haïmoud et al., 1709.06576]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



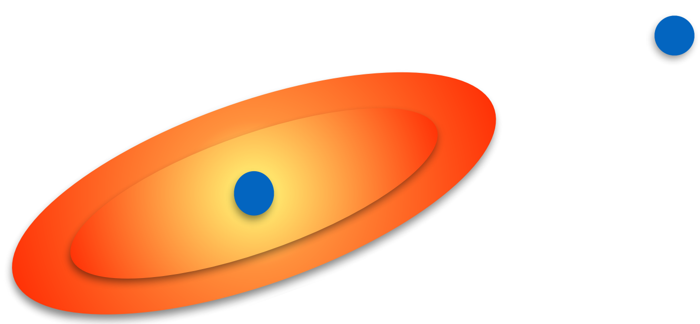
How does the distribution of PBHs affect the merger rate?

See Paul Depta's talk (which we just watched)

[1805.05912, 1807.02084, 1808.05910 and others]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



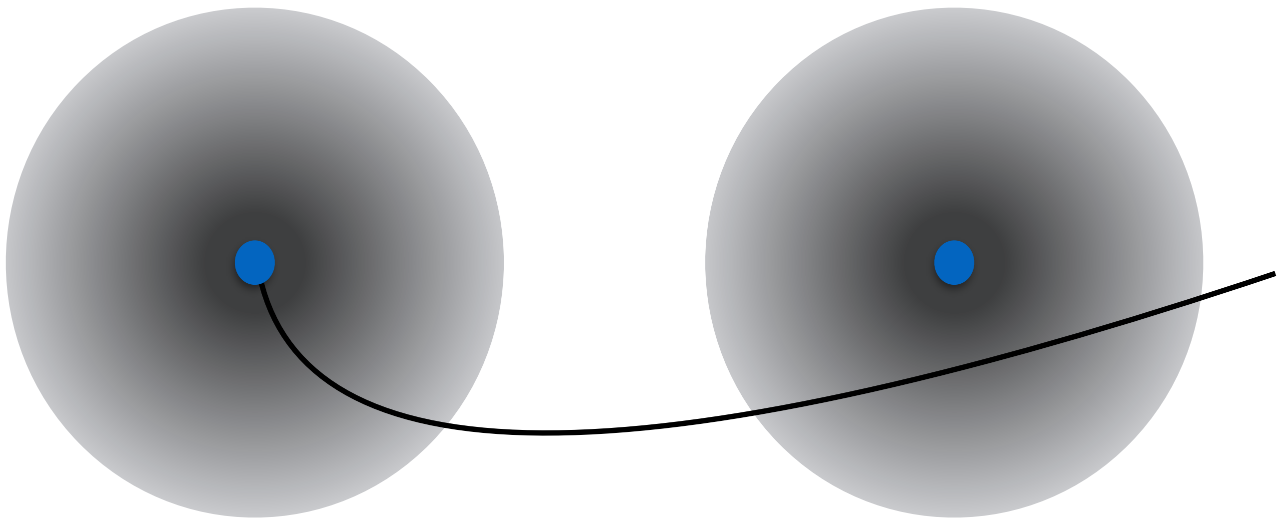
Does baryonic accretion disrupt the binary?

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**

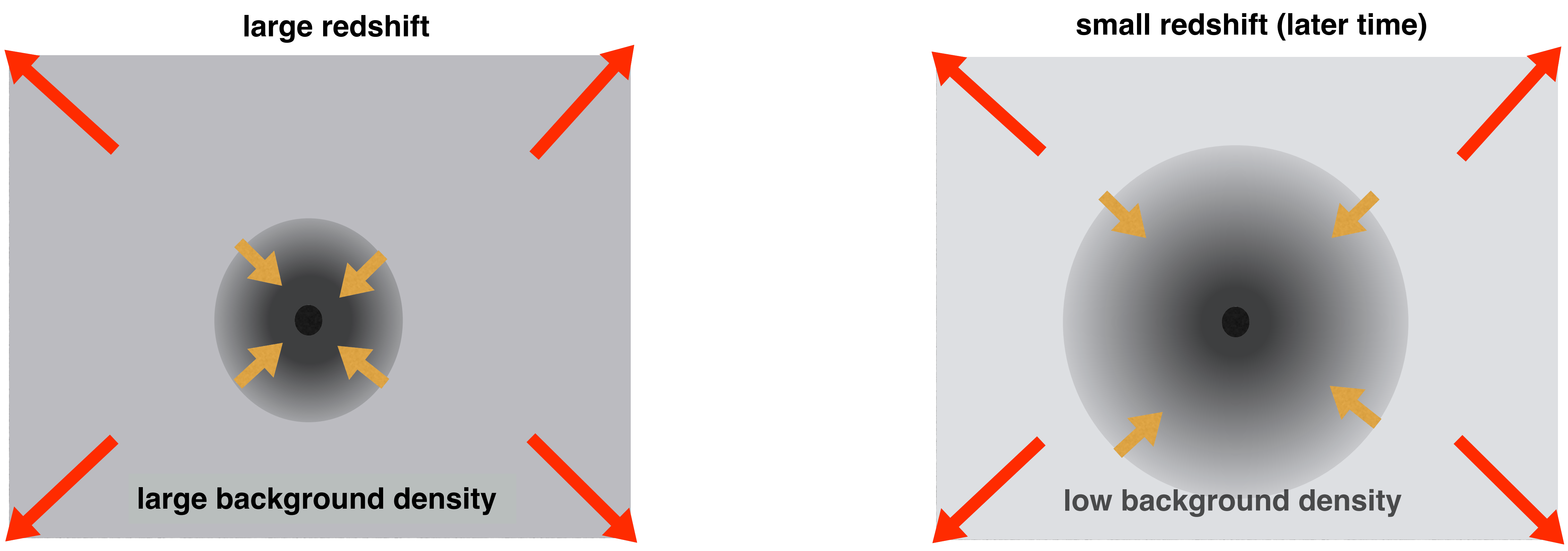


Do *local* Dark Matter halos disrupt PBH binaries?

Dynamical friction as the PBHs move through DM halos may affect the orbital properties…

Dark Dresses

PBHs seed the formation of `local' DM halos:



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

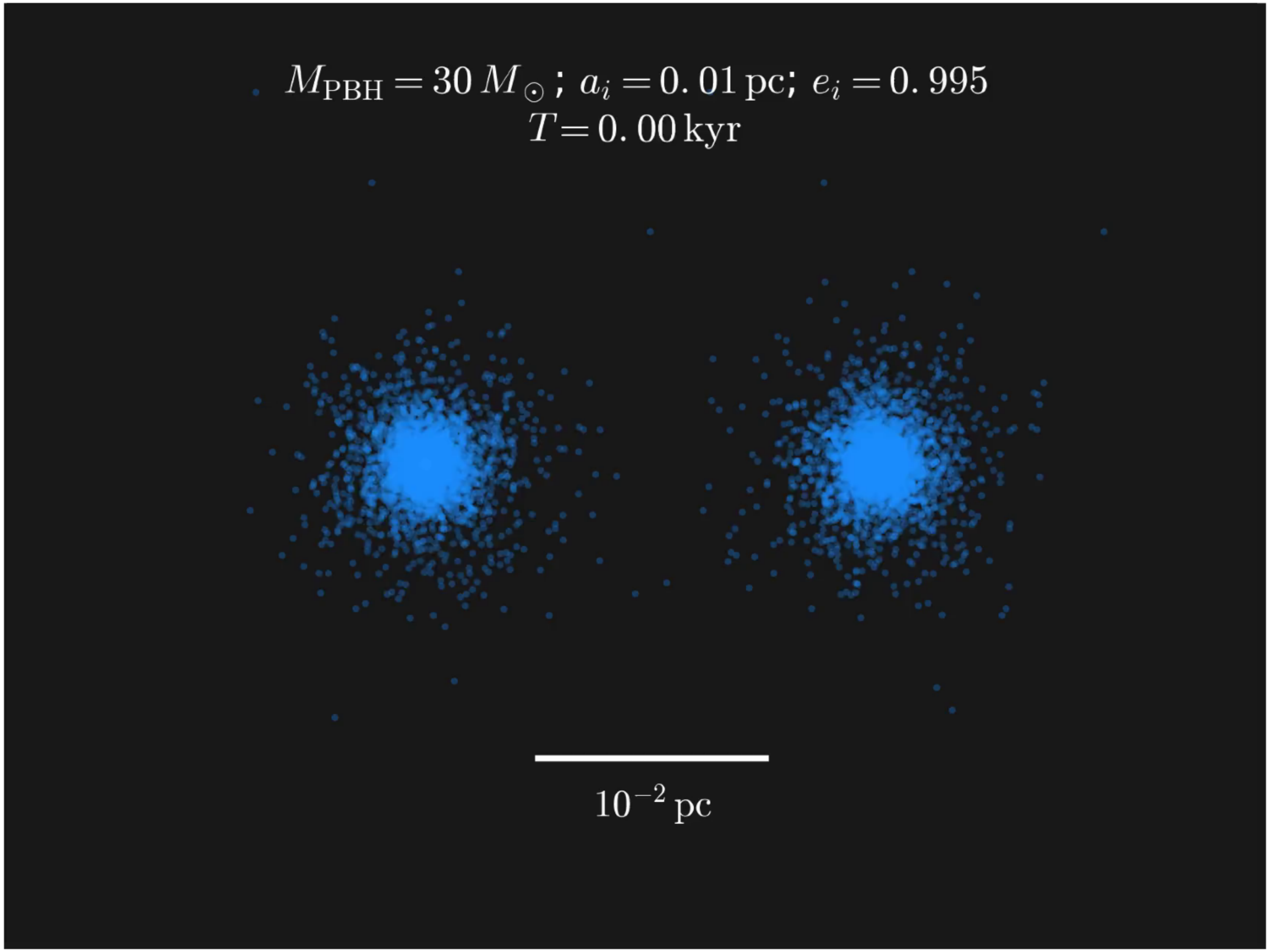
$$\rho(r) \propto r^{-3/2}$$

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]

Simulations

Use GADGET-2 as a pure N-body solver and follow the binary from decoupling: [Springel, astro-ph/0505010]



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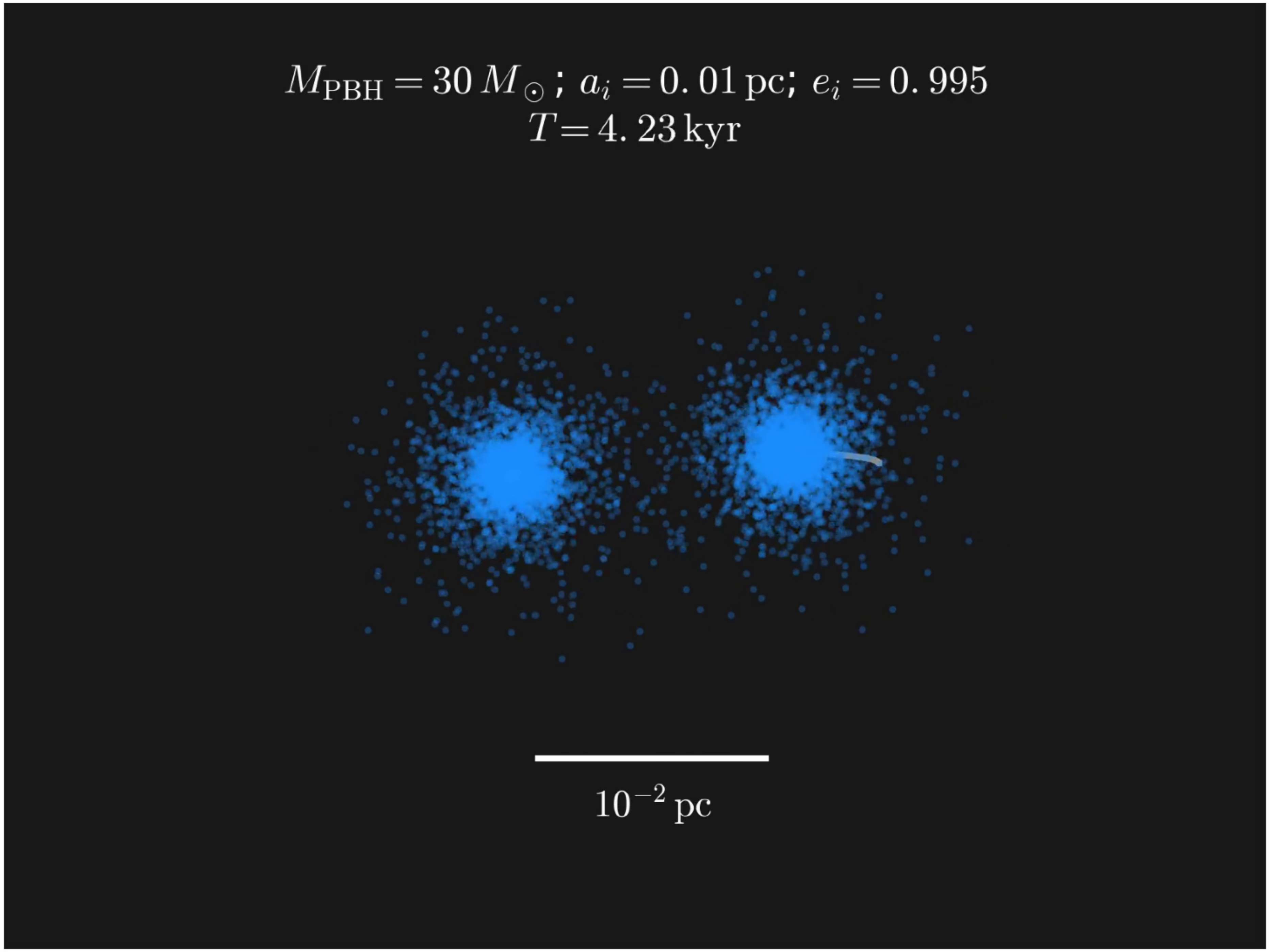

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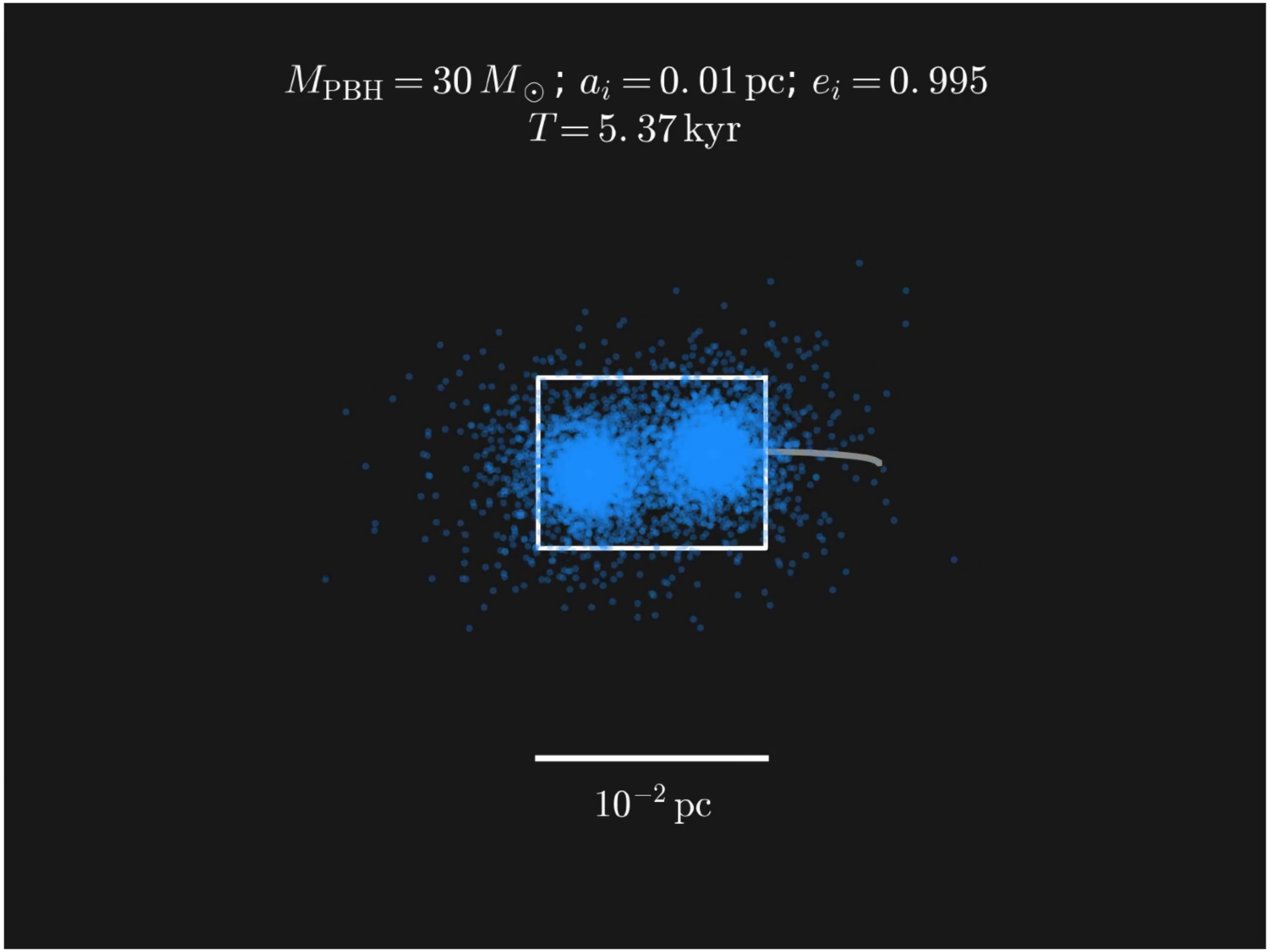

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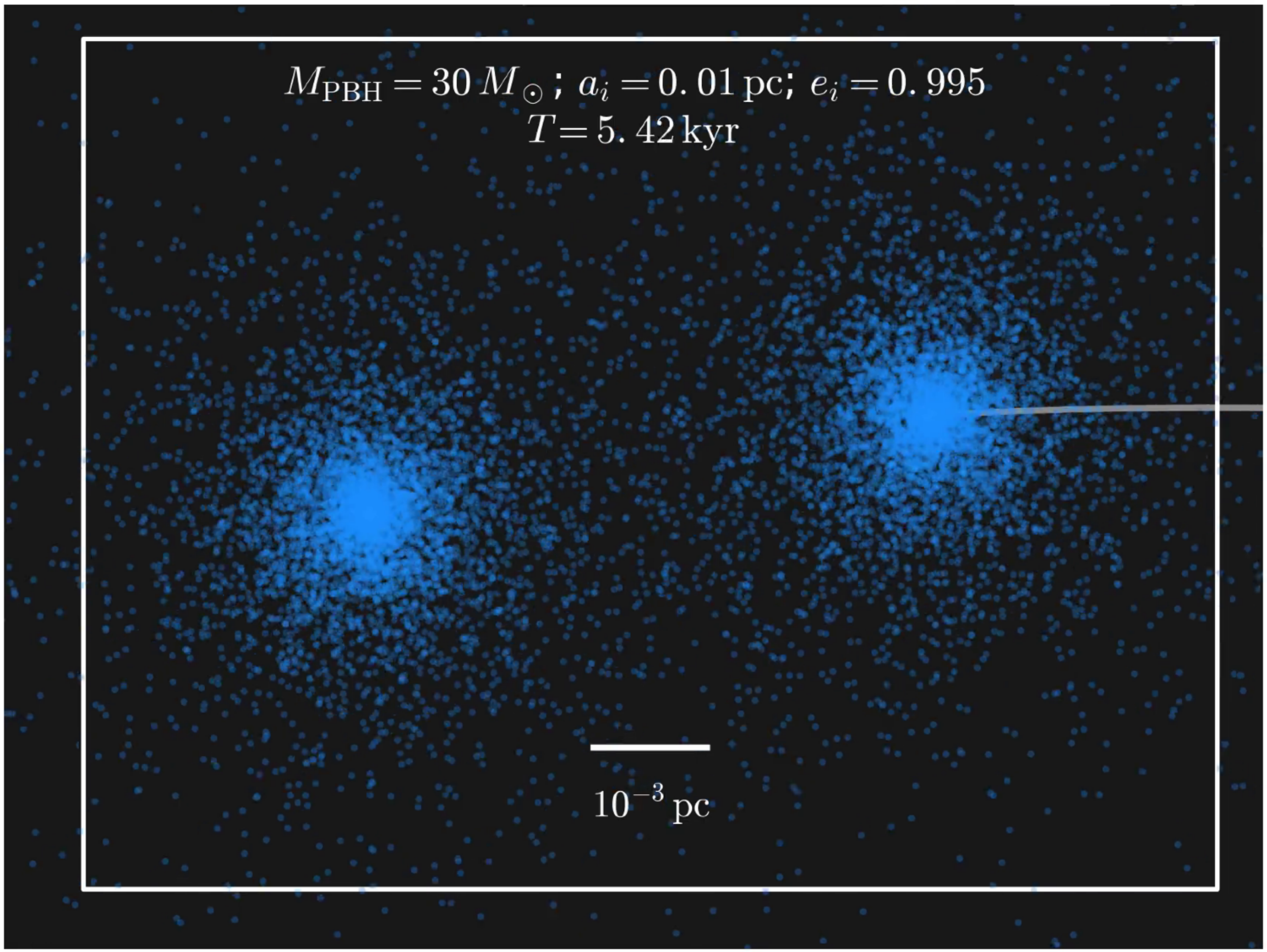

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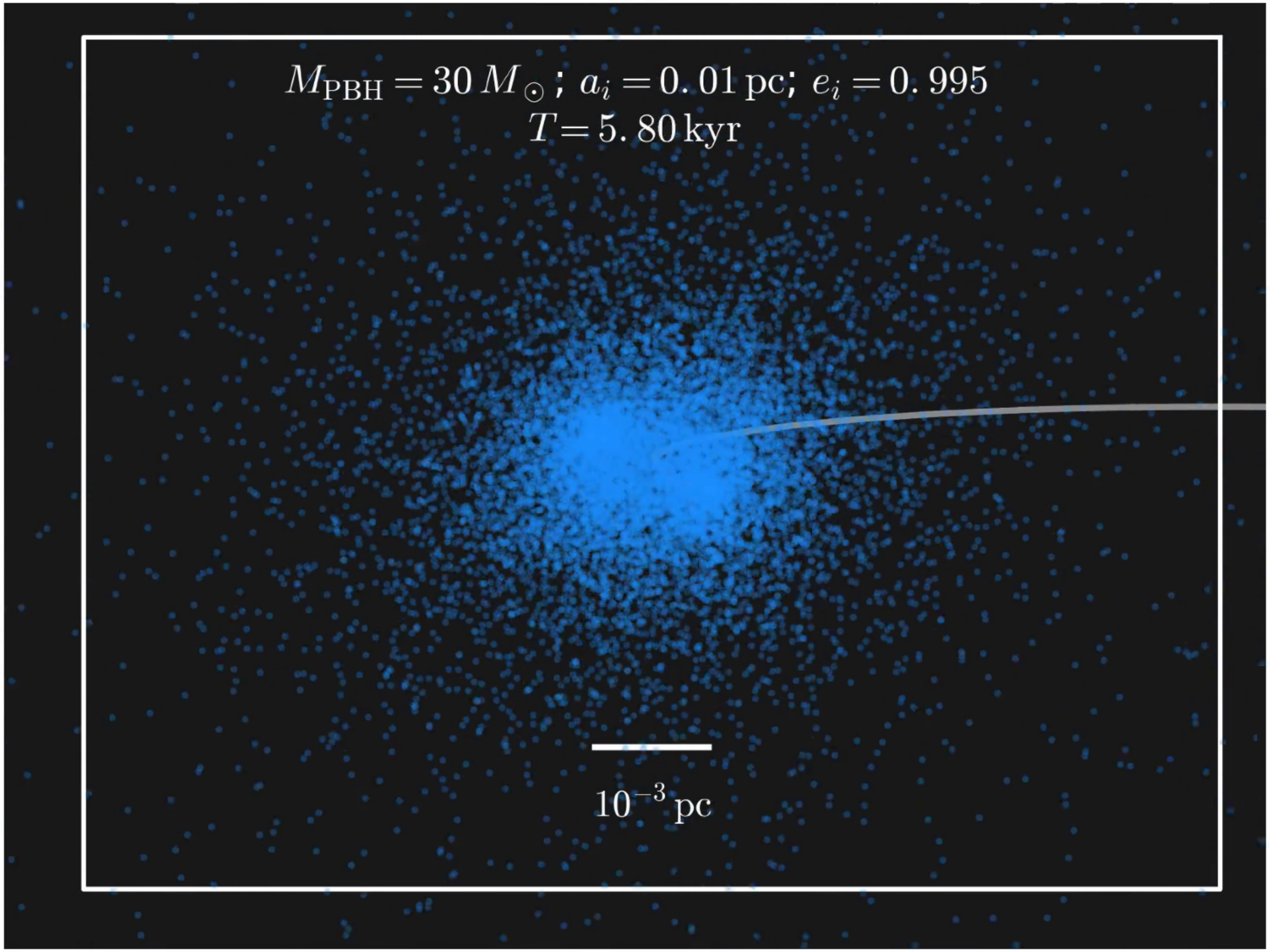

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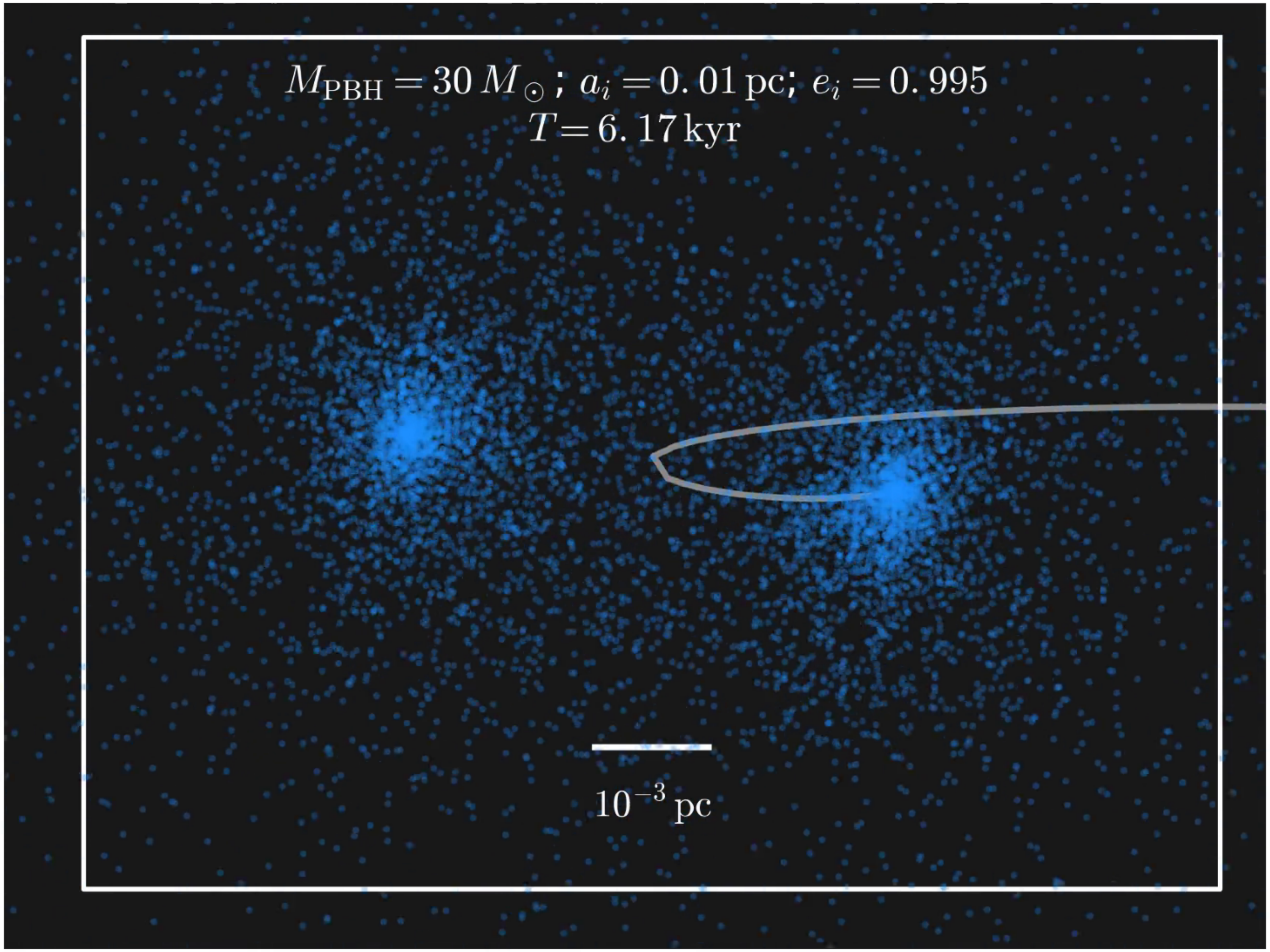

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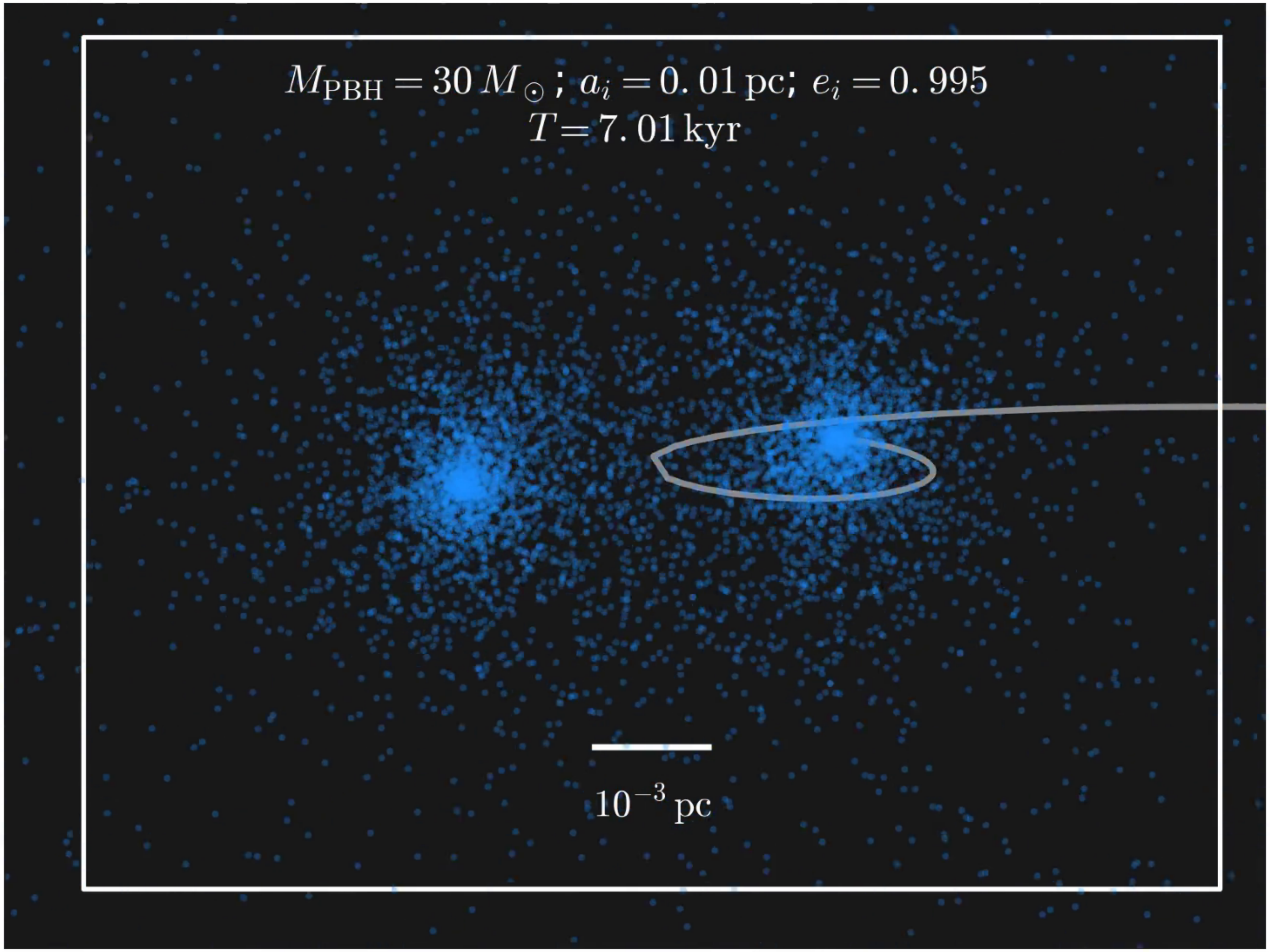

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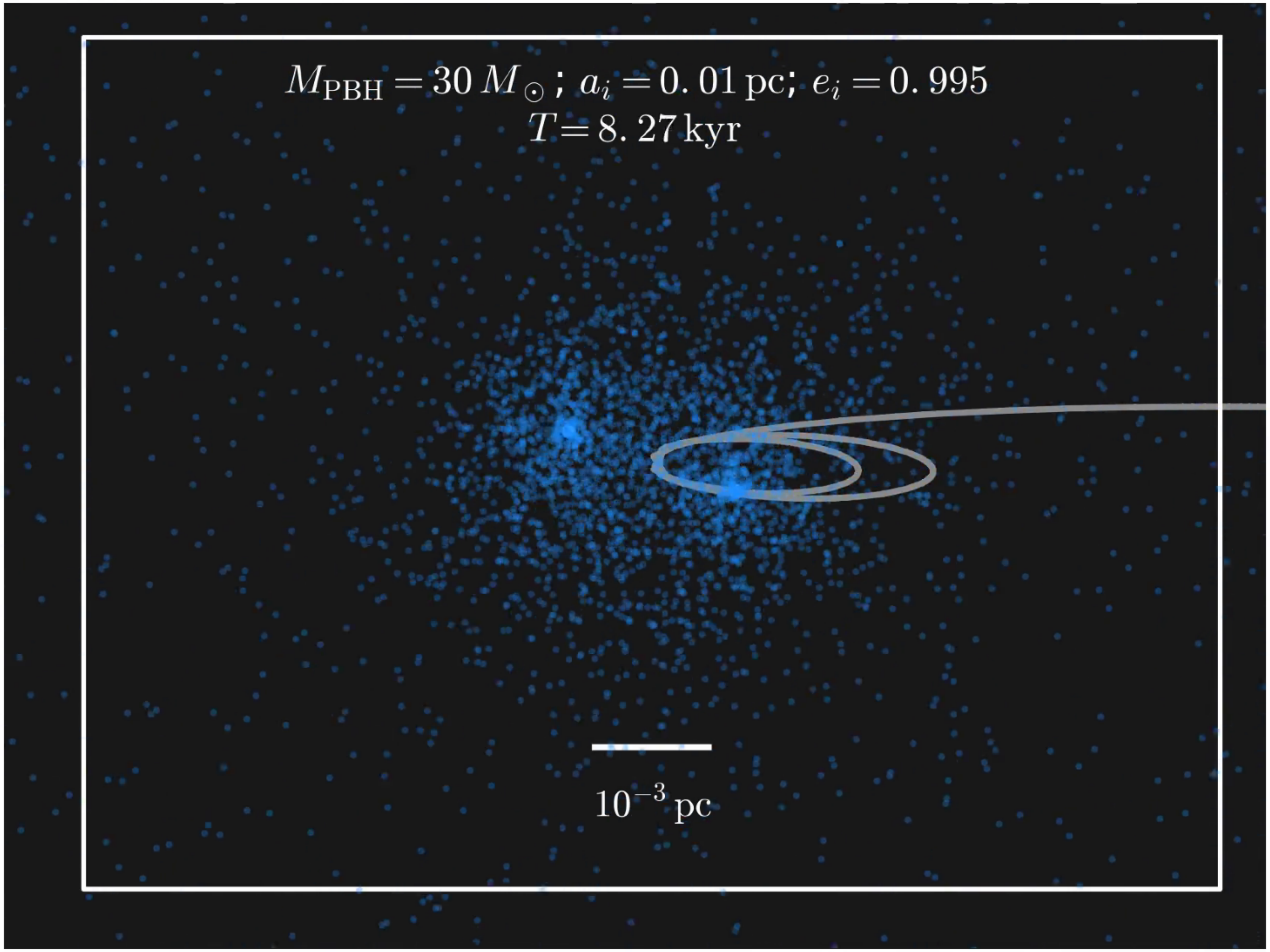

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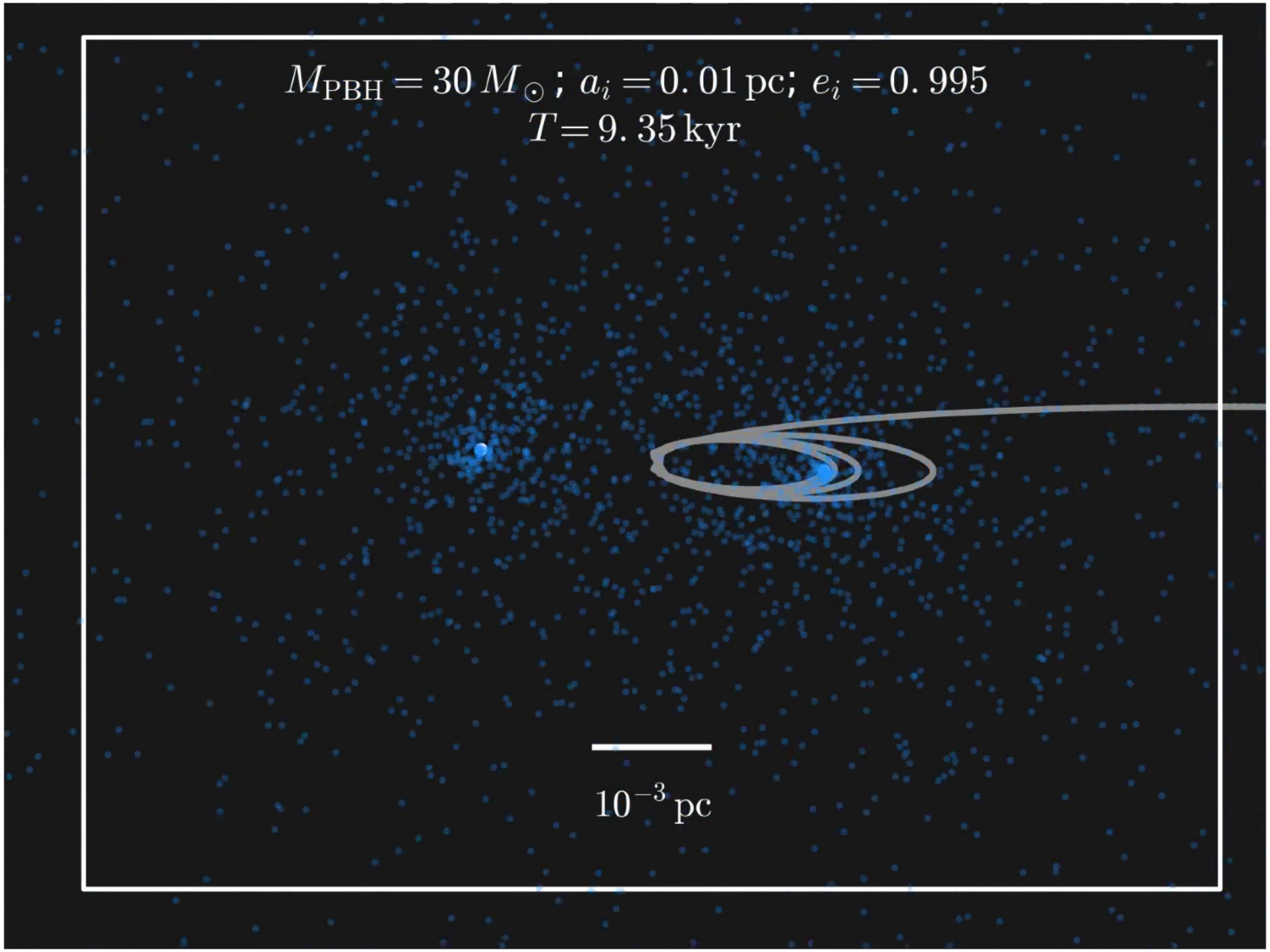

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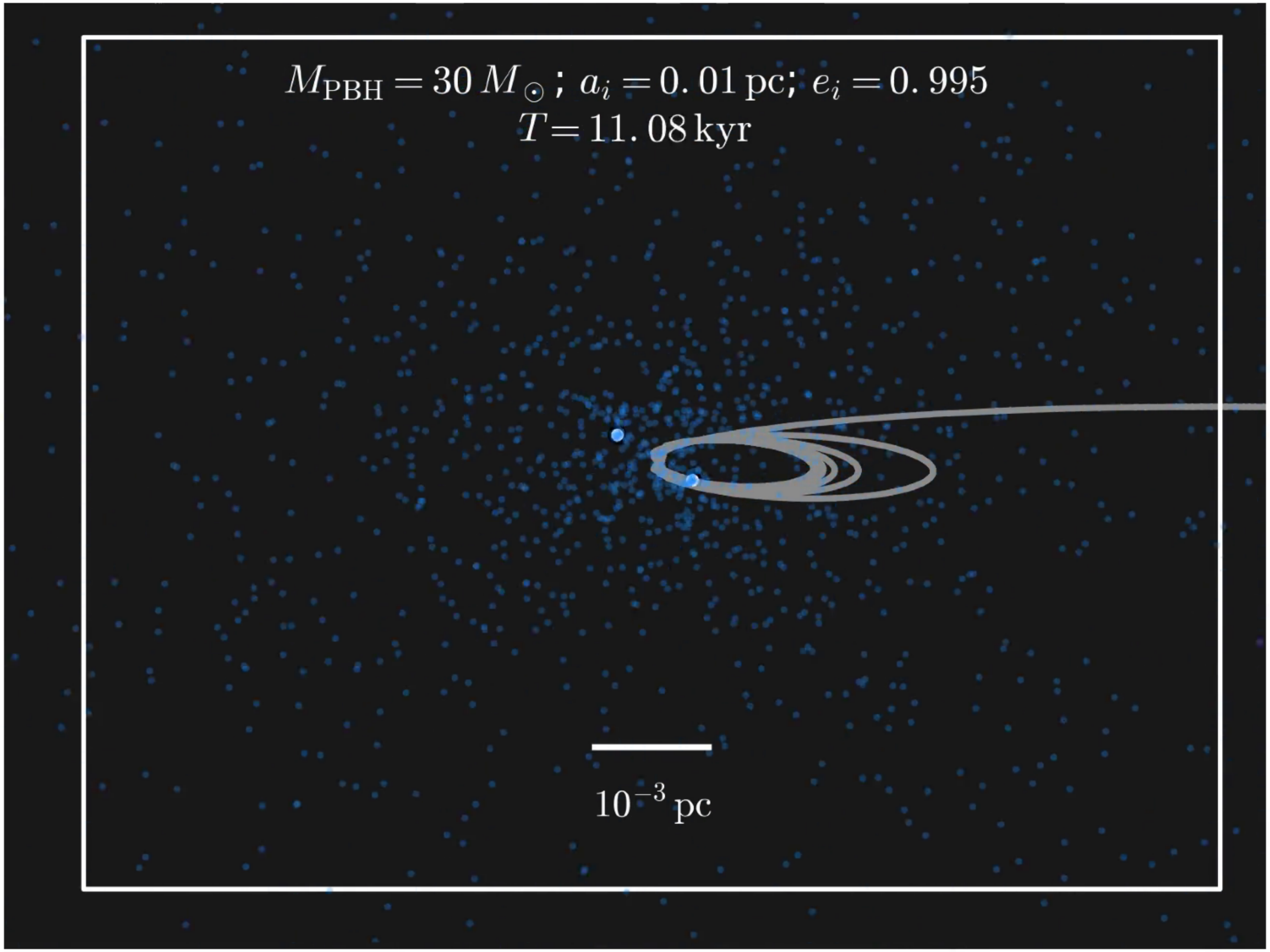

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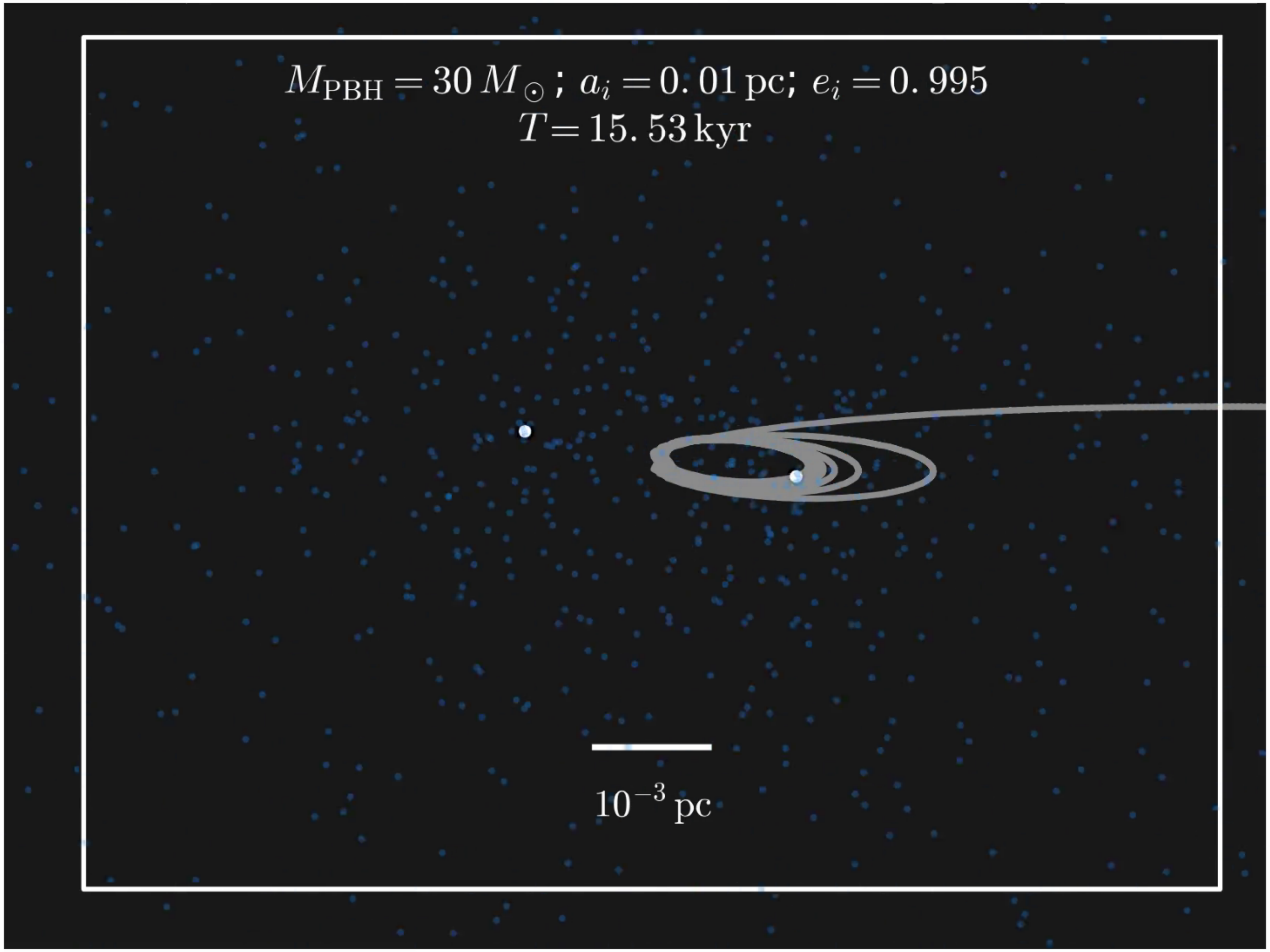
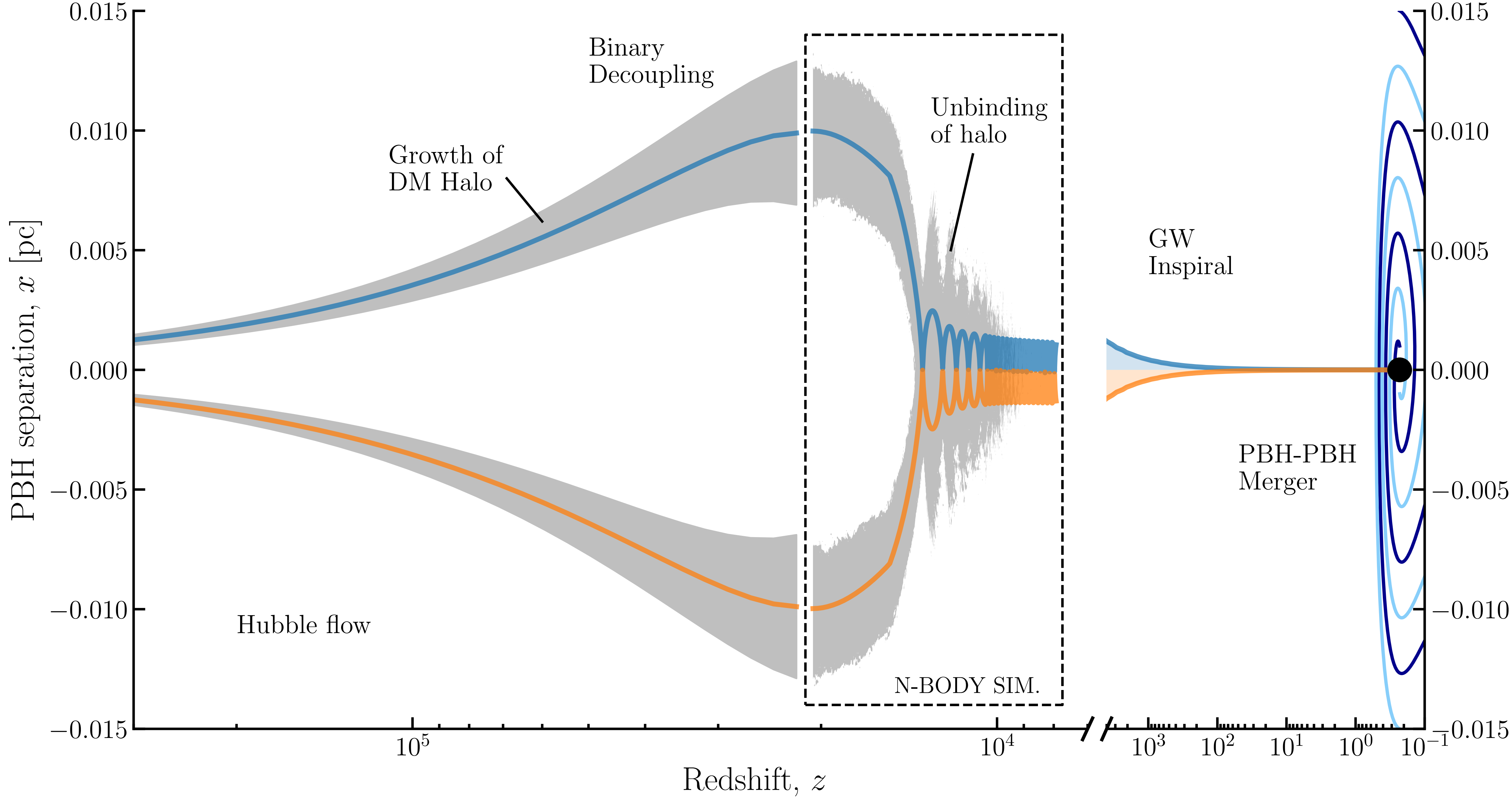


Life of a *dressed* PBH binary

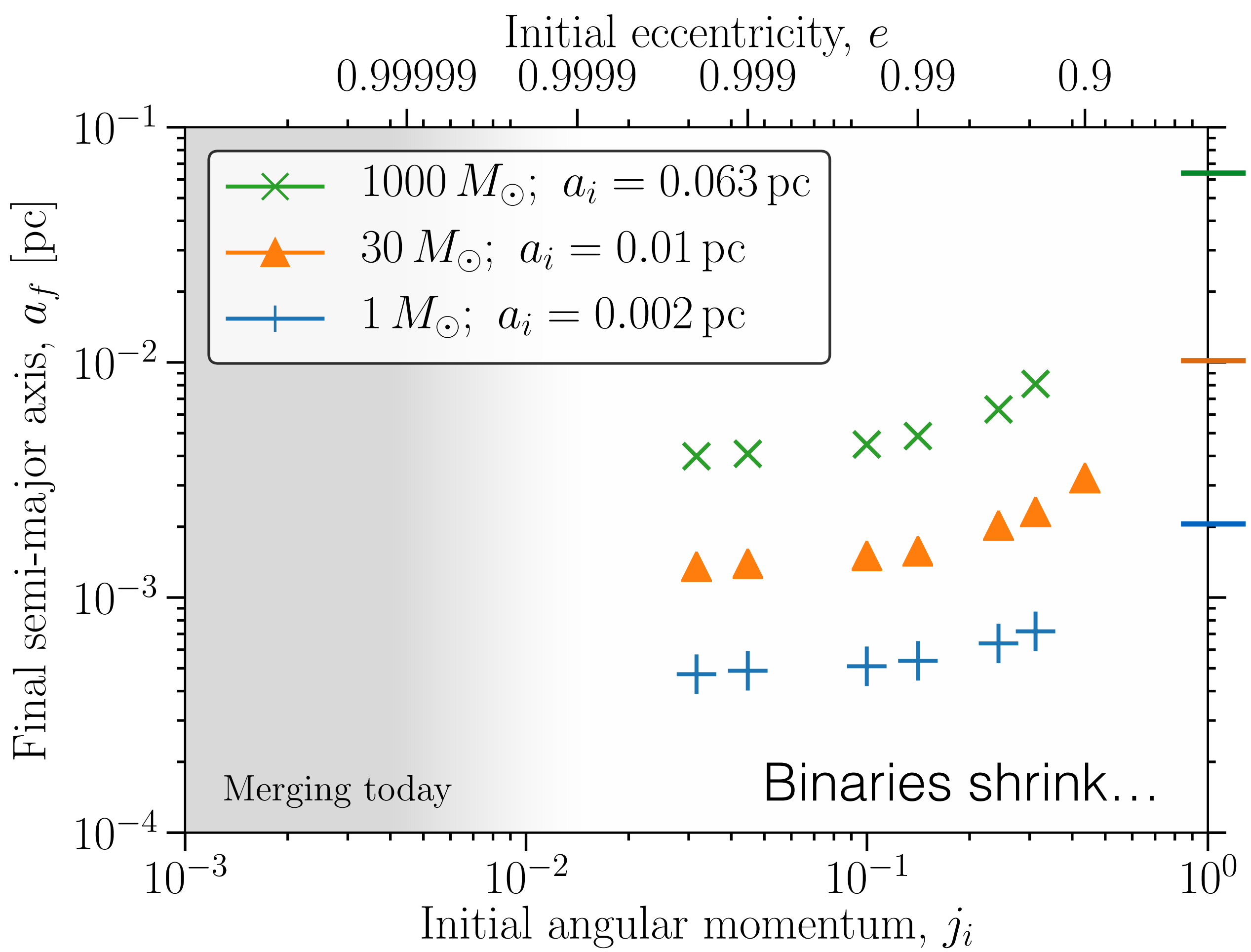


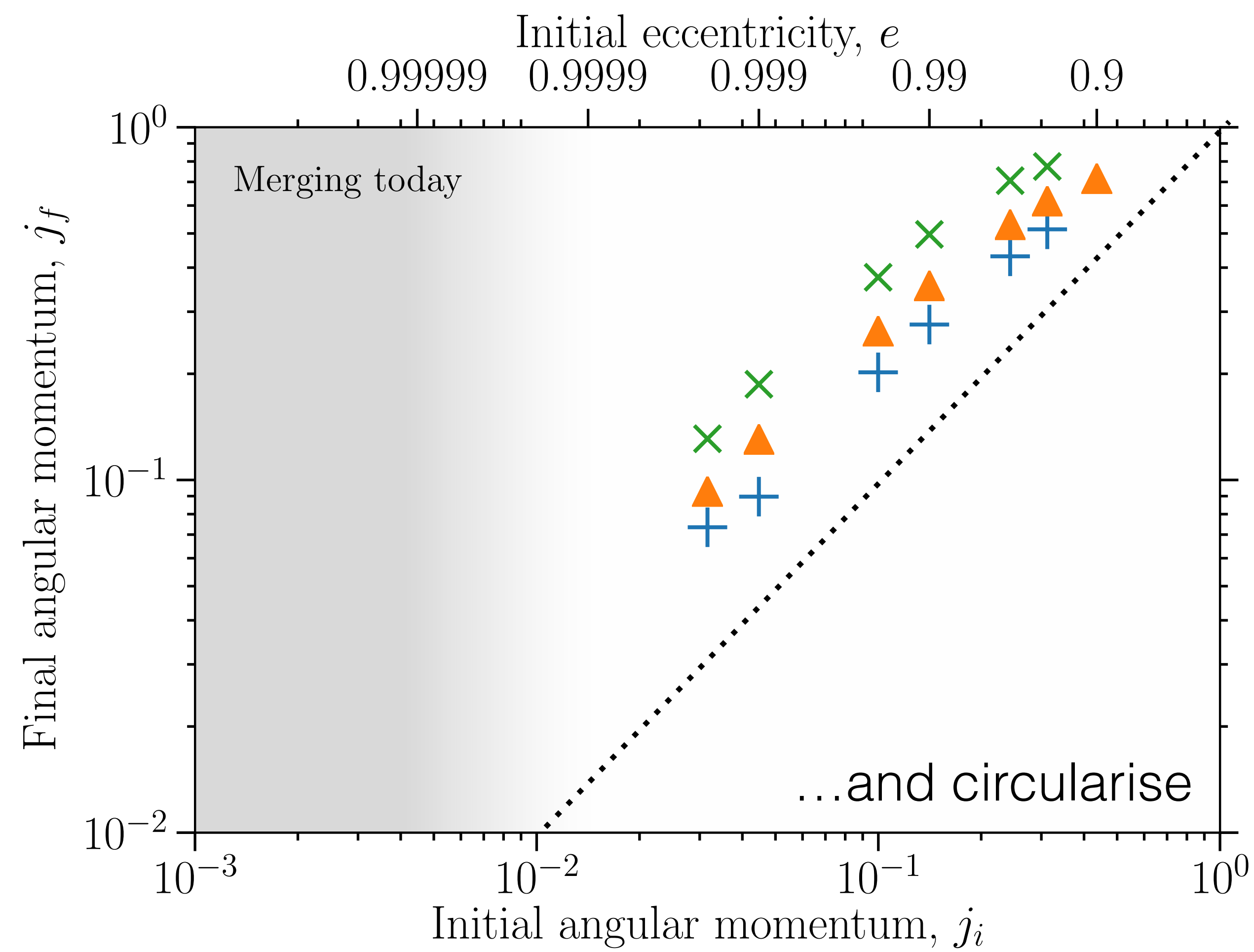
$$a_i = 0.01$$

$$e_i = 0.995$$

Interpreting the simulations

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





Conservation of energy

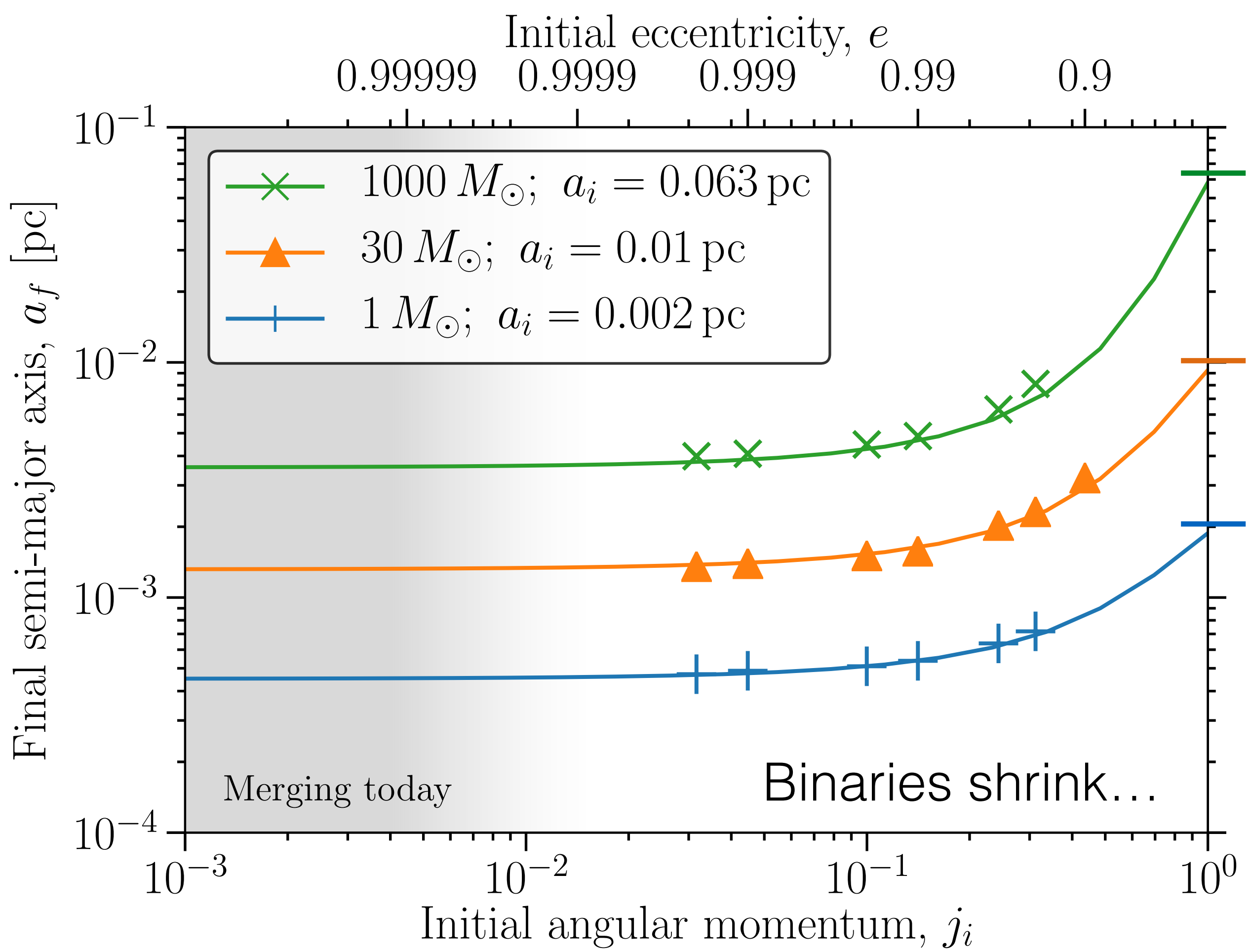
$$E_i^{\mathrm{orb}} + 2\,U^{\mathrm{bind}} = E_f^{\mathrm{orb}}$$

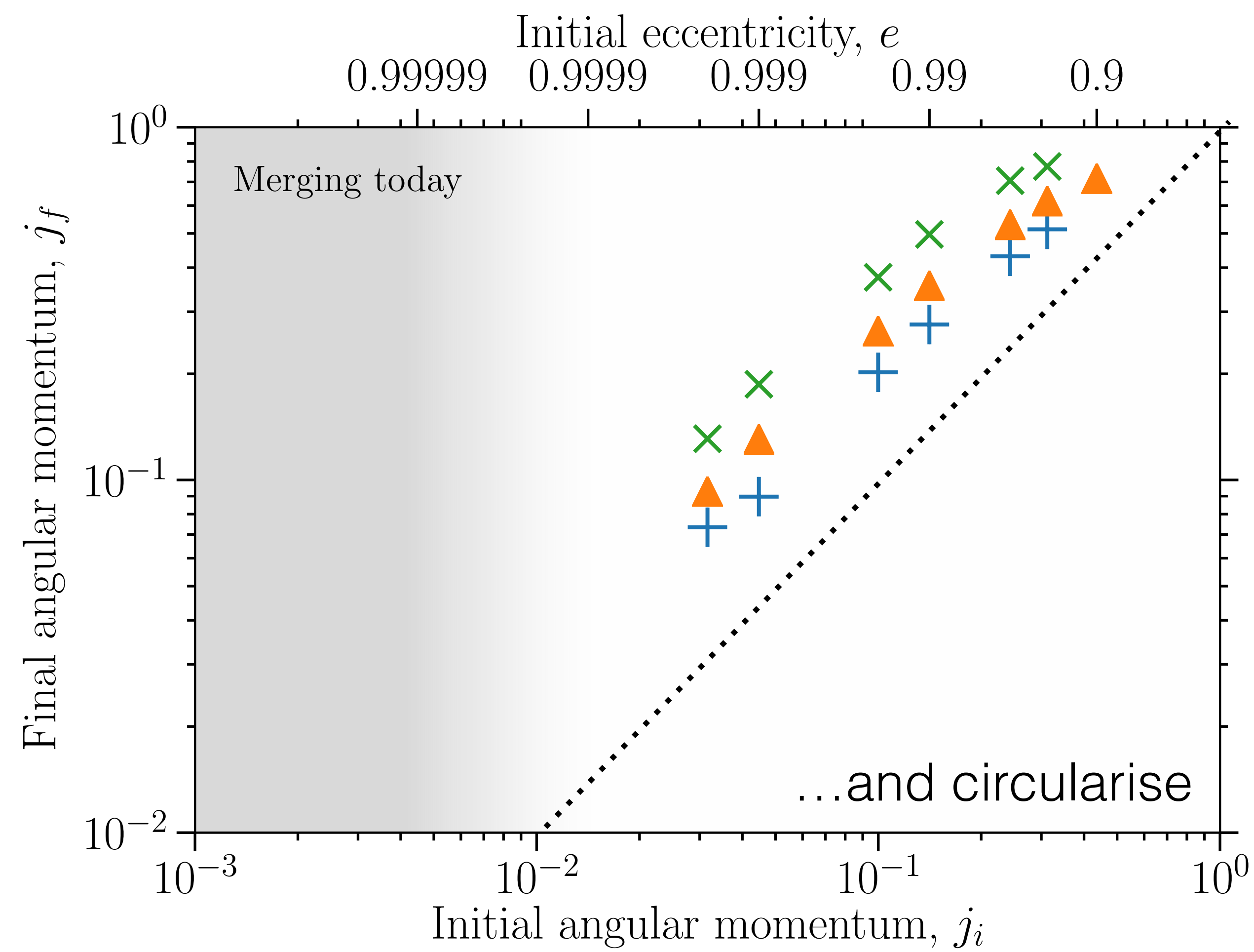
Conservation of angular momentum

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

Interpreting the simulations

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





Conservation of energy

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

fixes semi-major axis, a

Conservation of angular momentum

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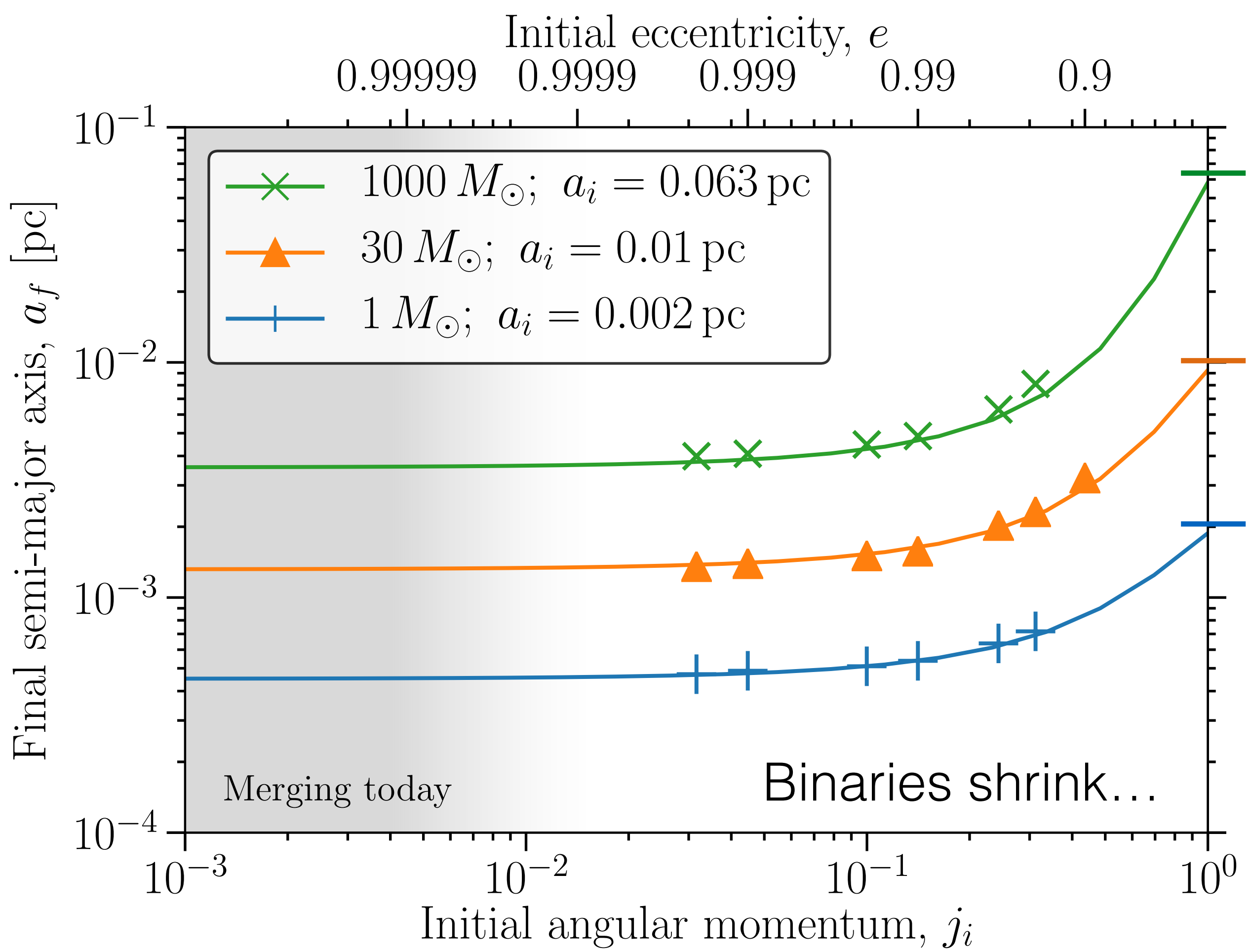

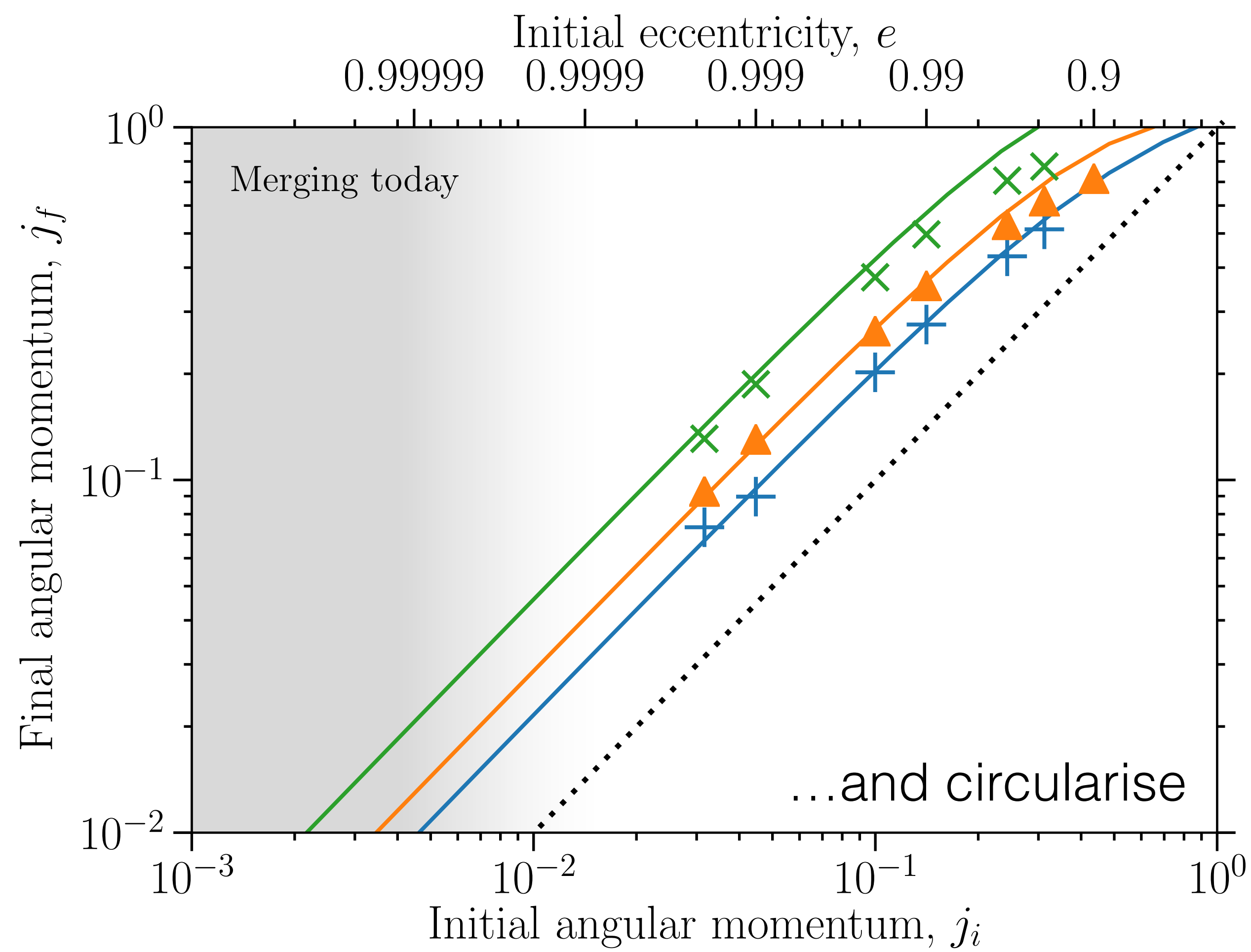

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Conservation of angular momentum

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

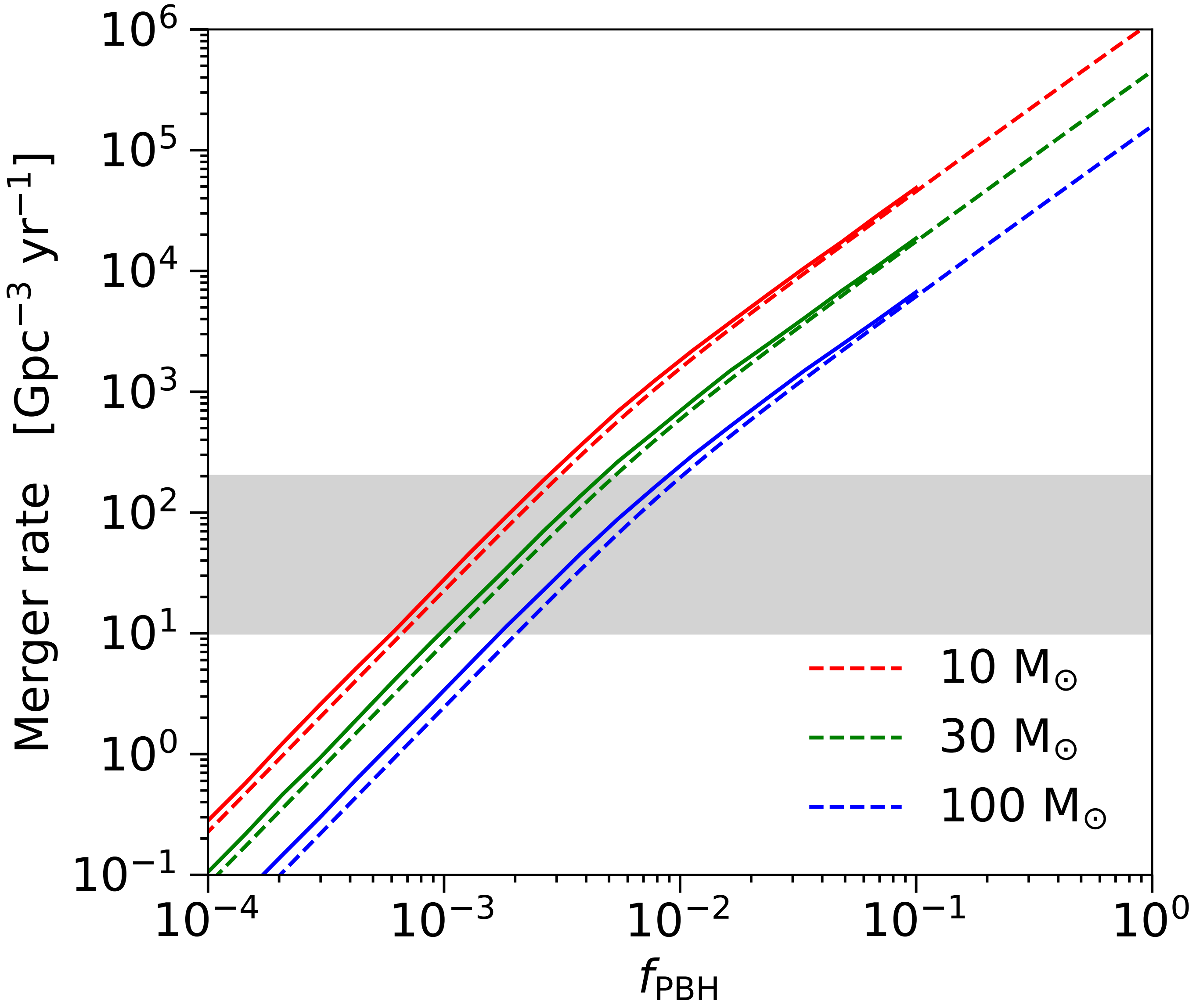
fixes $j_f = j_i\sqrt{a_i/a_f}$

Calculating the final merger rate

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

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

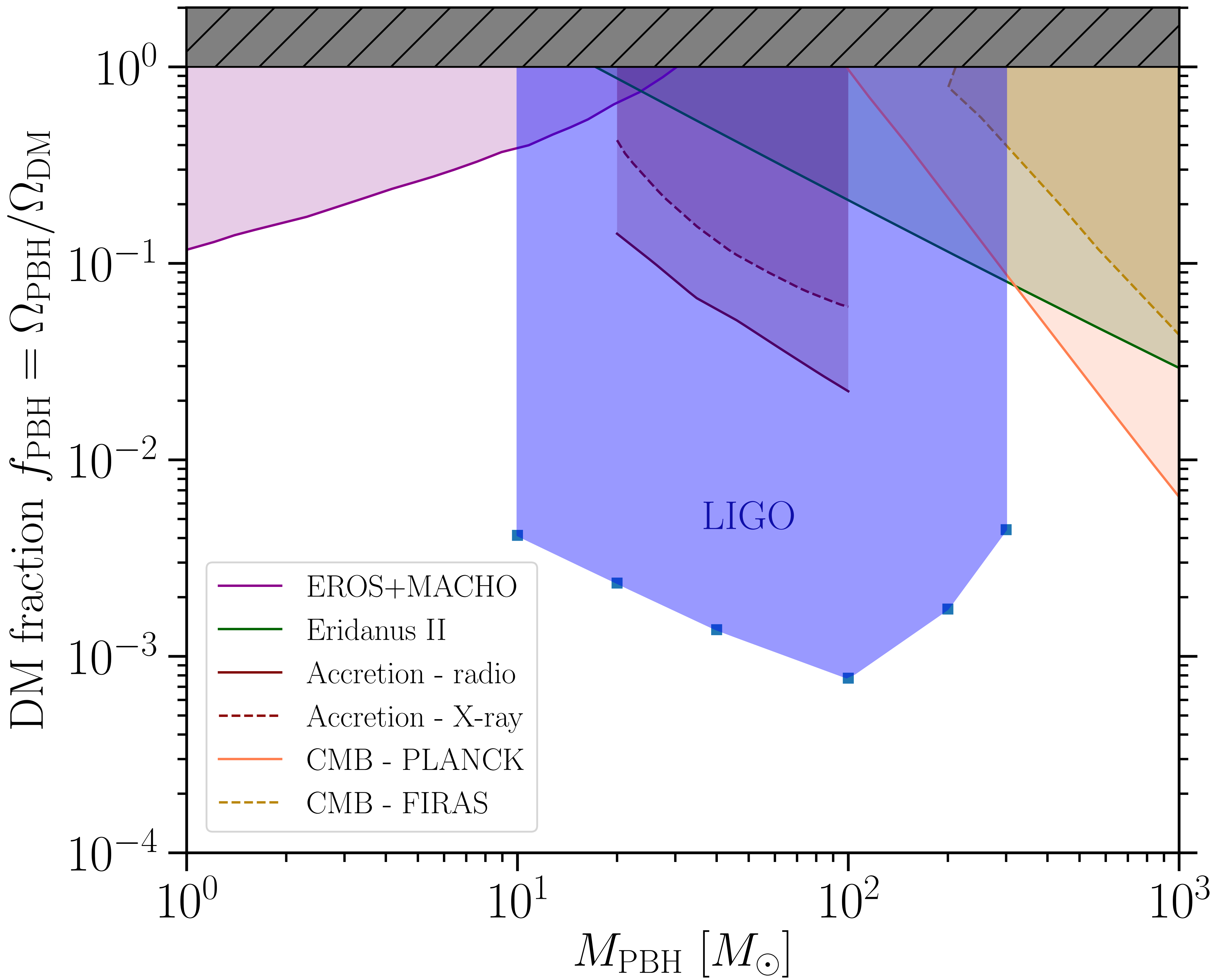
Guided by the simulations, map $(a_i, e_i) \to (a_f, e_f)$



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

Limits from LIGO

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



Caveats (once again)

- Survival ✓ [Ali-Haïmoud et al., 1709.06576]
- Clustering ✓ [See Paul Depta's talk]
- 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!

A little more work is still needed…

Conclusions

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

Many PBH binaries can be formed in the early Universe

Their mergers could be observable by LIGO today

Local DM halos affect the size and shape of PBH binaries
but (surprisingly) have only a small effect on their merger rate

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

Primordial Black Holes

Primordial Black Holes (PBHs) could form at $z \gg 10^6$ from:

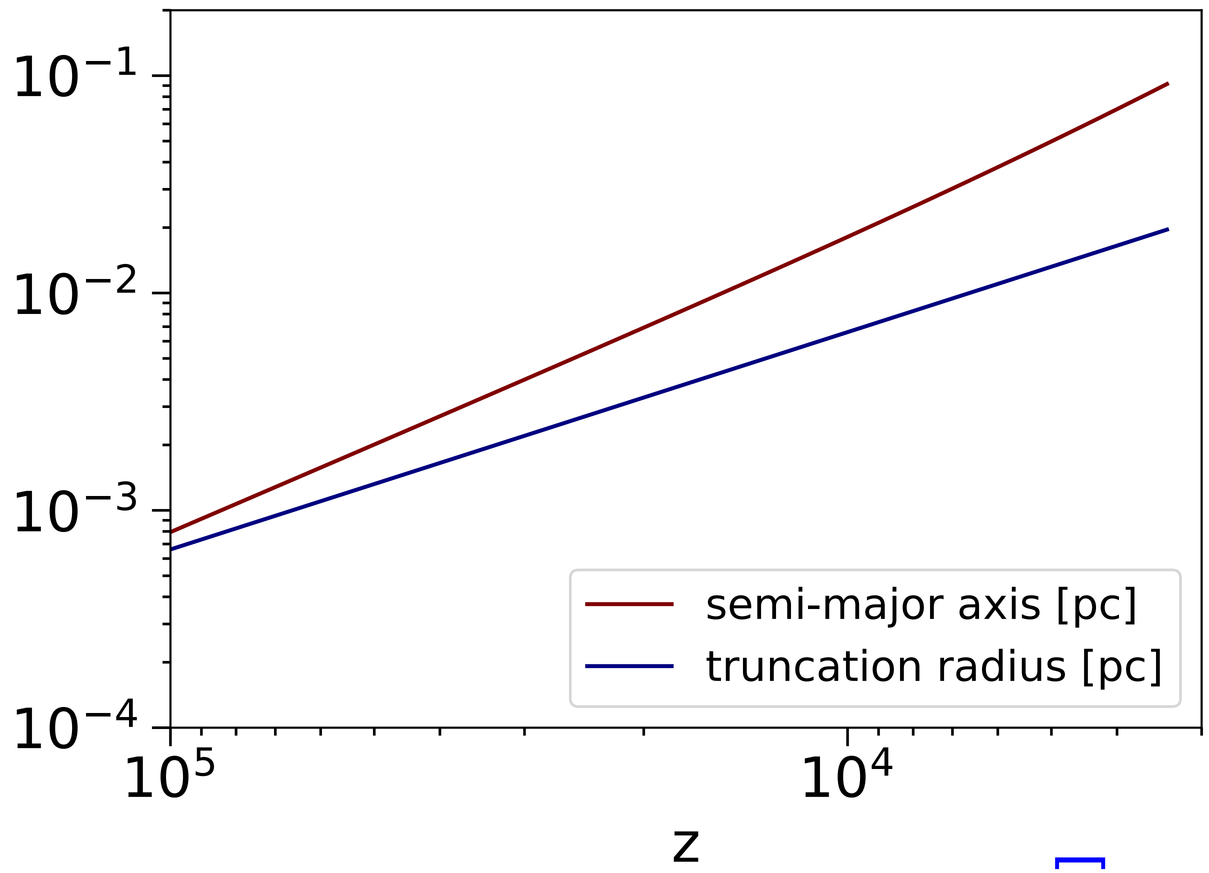
- Collapse of large density perturbations
- Cosmic String Loops
- Bubble collisions
- …

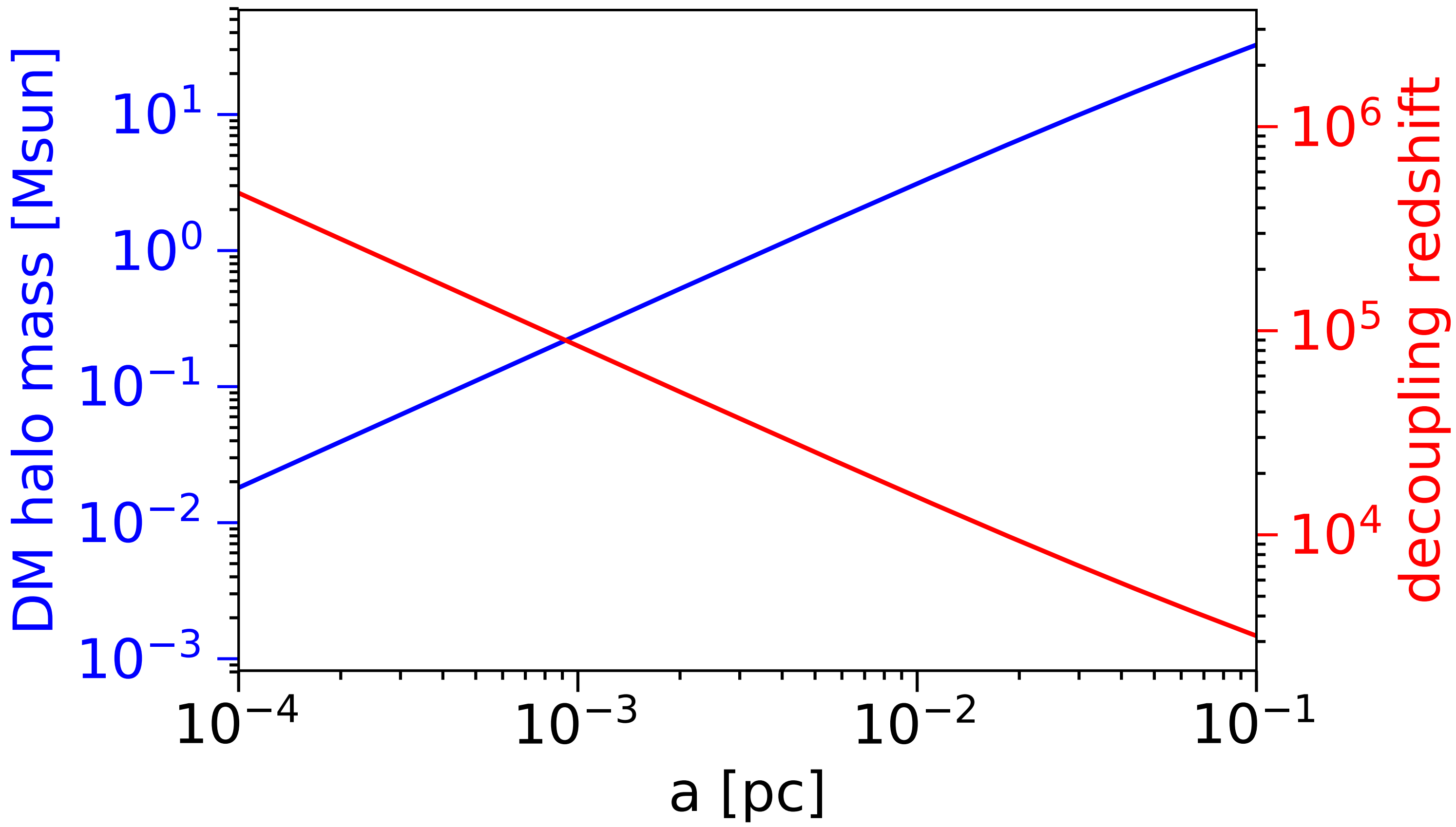
A sign of New Physics and a probe of the early universe.
A possible contribution to Dark Matter?

[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)]
[Garcia-Bellido, Linde & Wands, astro-ph/9605094]
[Green, 1403.1198]
[Sasaki et al, 1801.05235]

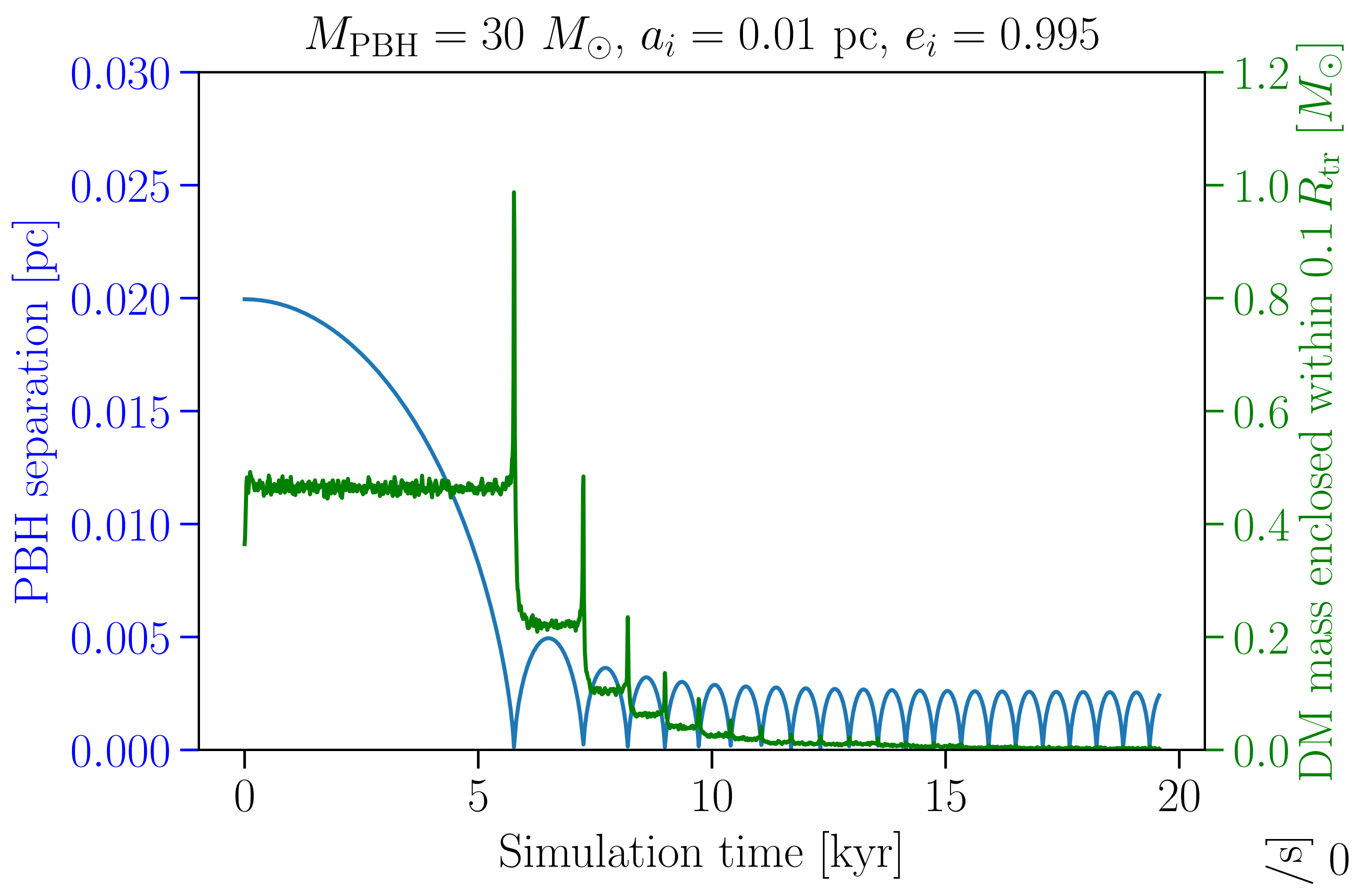
Decoupling and Halo Mass

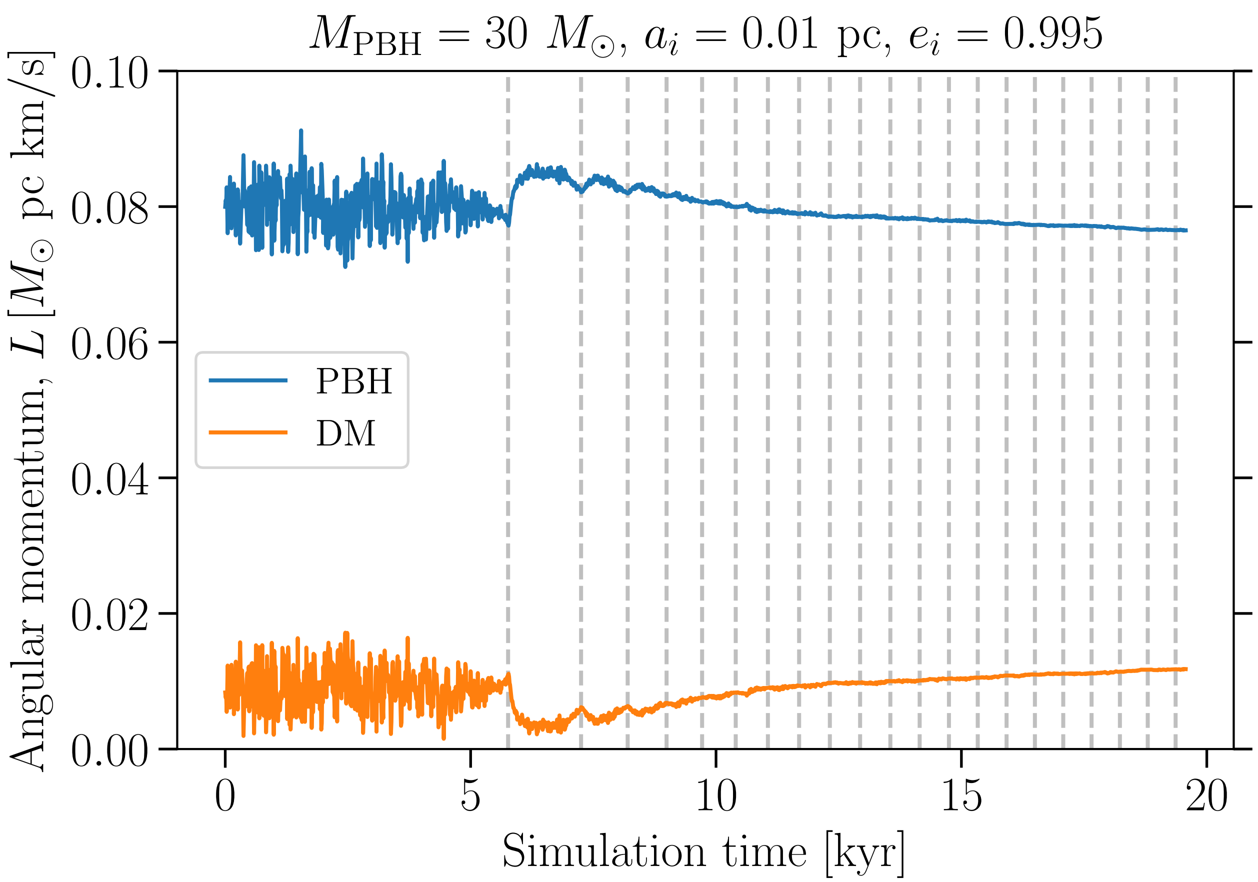
$$M_{\rm PBH} = 30\,M_\odot$$





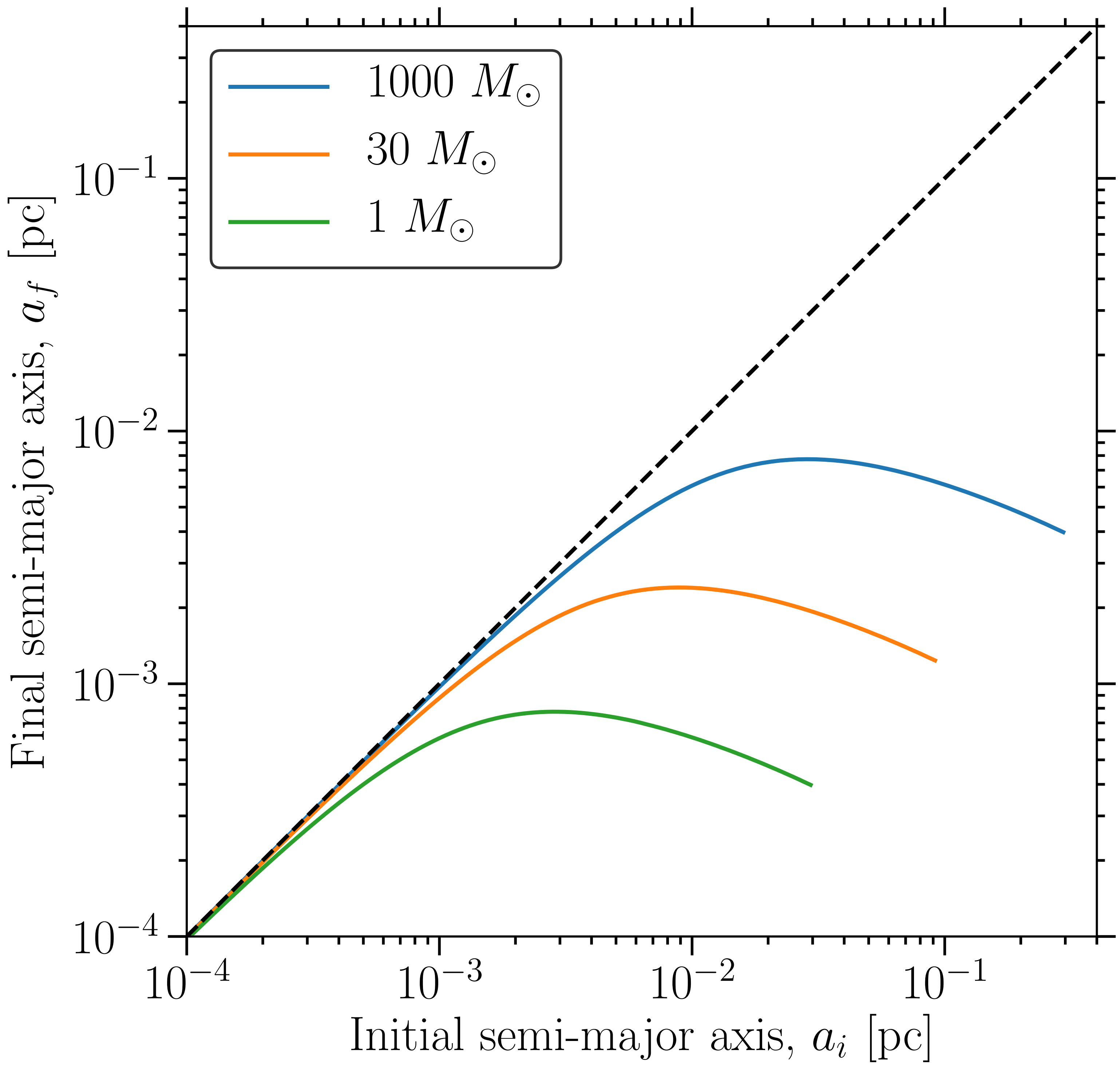
Binary Evolution





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

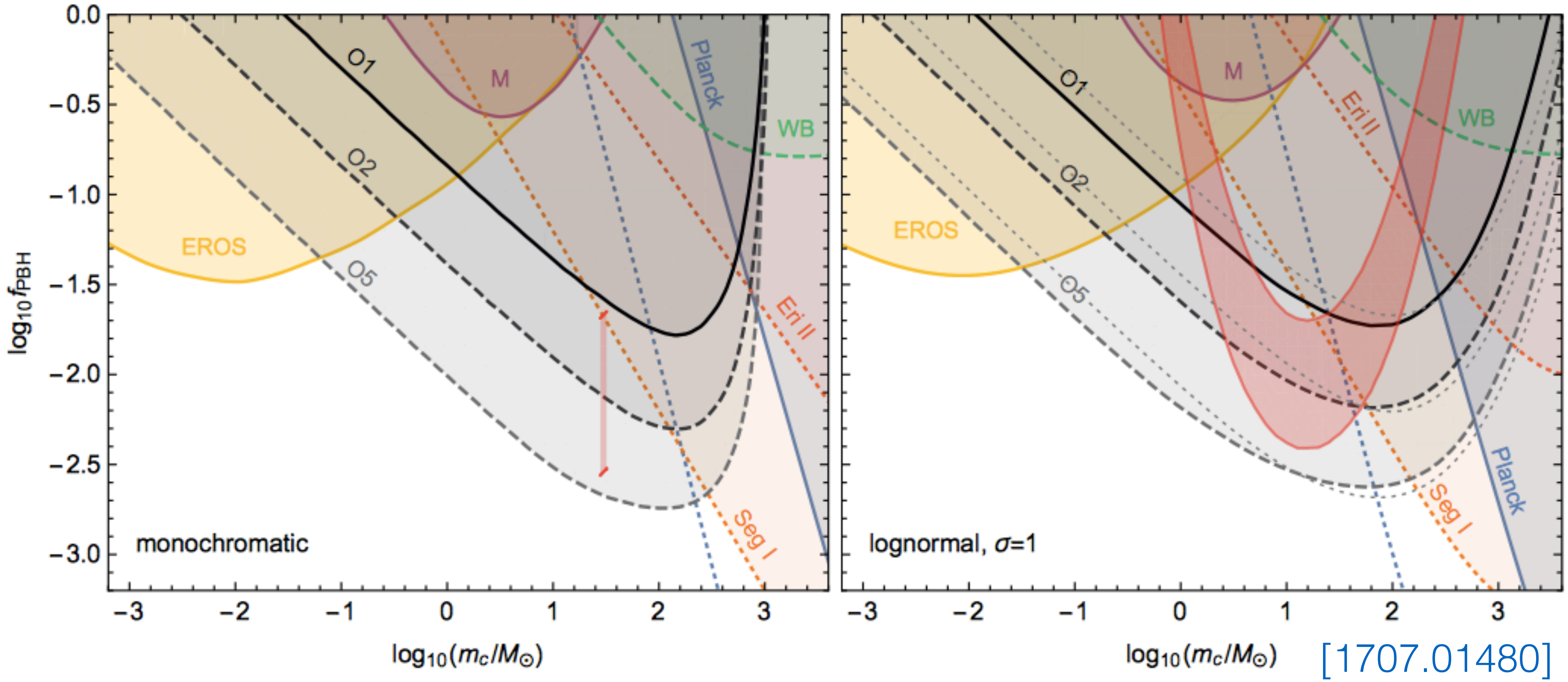
Remapping the semi-major axis



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

Extended mass functions

LIGO O1 Limit



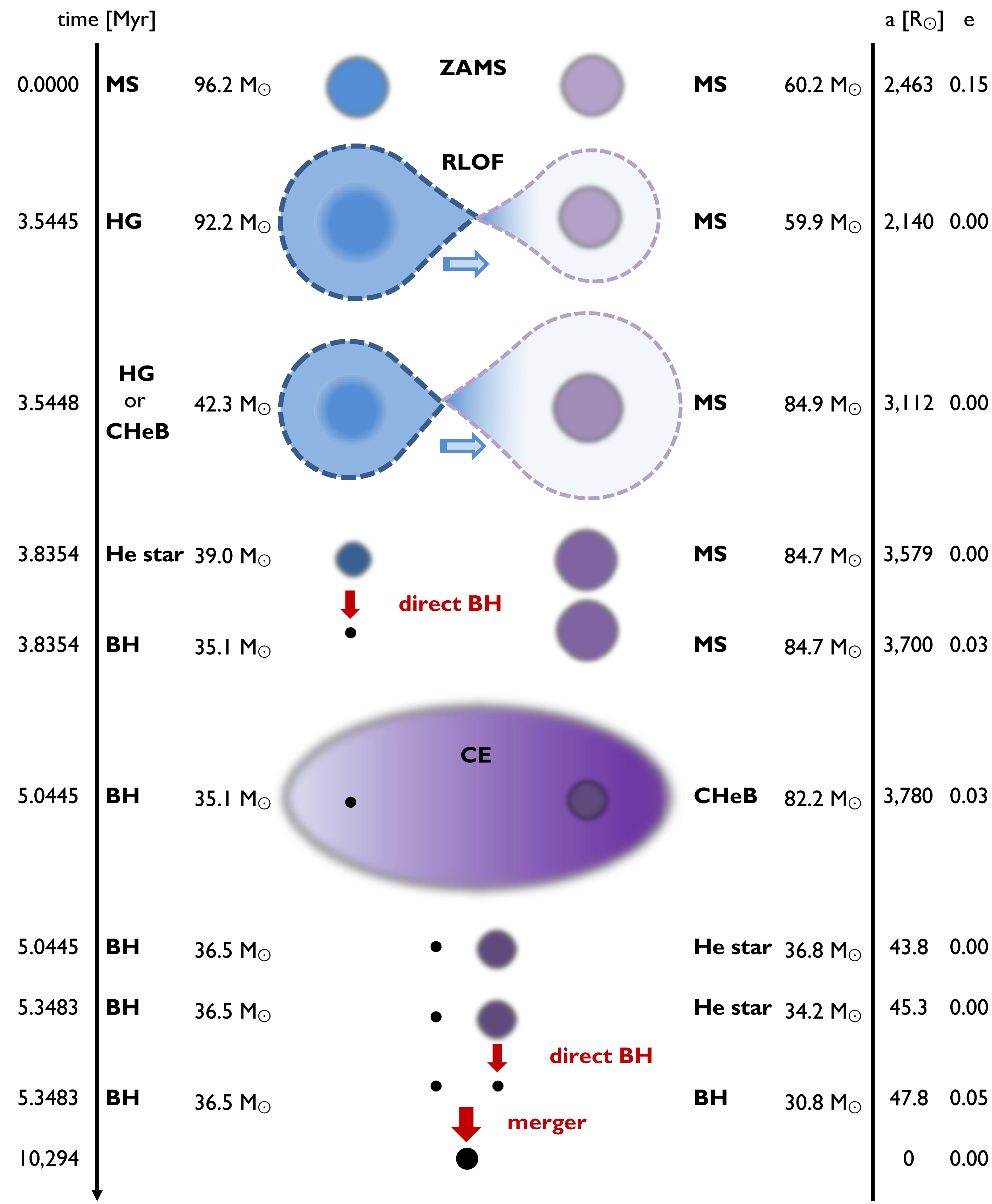
[1707.01480]

"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}		
ℓ_soft (PBH) [pc]	10^{-7}		
$M_\mathrm{PBH} =$	$1\,M_\odot$	$30\,M_\odot$	$1000\,M_\odot$
ℓ_soft (DM, low-res) [pc]	2×10^{-6}	10^{-5}	5×10^{-5}
ℓ_soft (DM, high-res) [pc]	2×10^{-7}	10^{-6}	5×10^{-6}

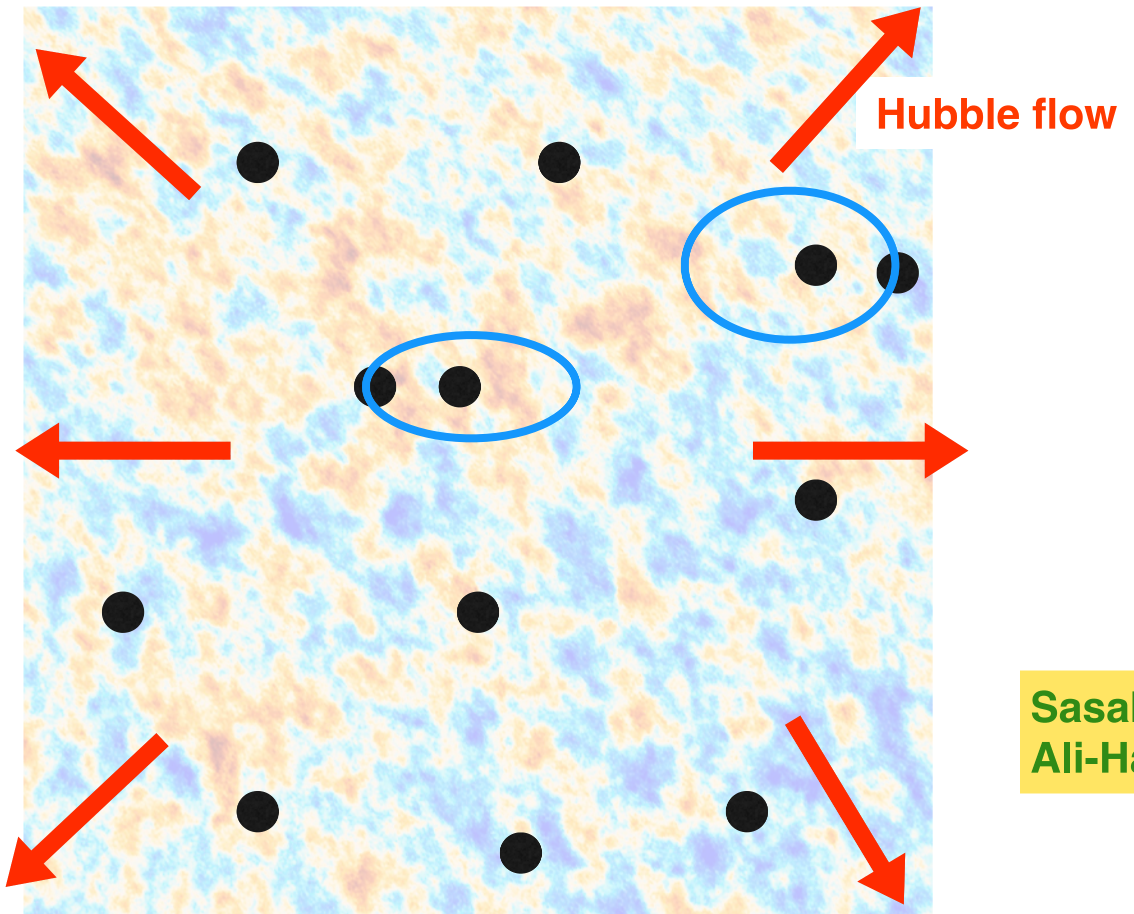
TABLE I. **Summary of Gadget-2 parameters.** The parameters `ErrTolForceAcc` and `ErrTolIntAccuracy` control the accuracy of force calculation and time integration respectively. We also specify the softening lengths ℓ_soft of the simulations, as described in the text. Low-resolution simulations contain 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_CPU

Part II: A closer look to merger rates

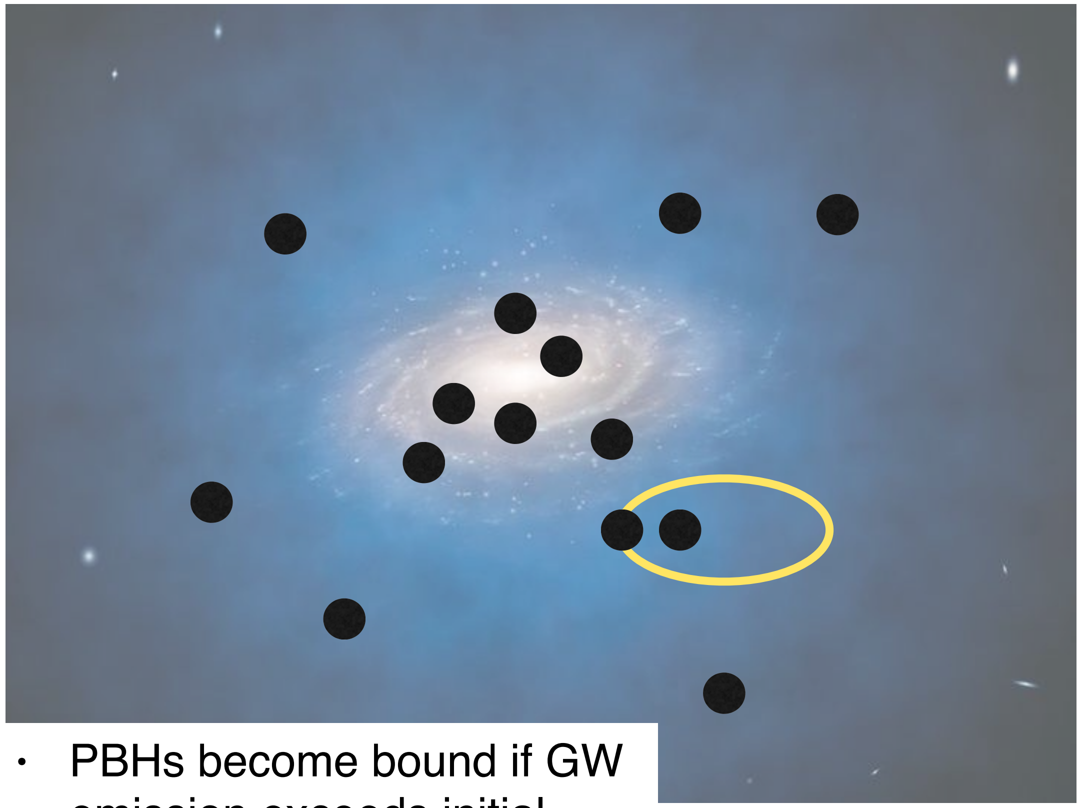
A) Binaries formed in the early Universe



Sasaki+ PRL 2017
Ali-Haimoud+ 2017

- If most of the DM is made of PBHs, **most pairs decouple from the Hubble flow** and form a binary deep in the radiation era.
- If f < 0.01, only **rare pairs with small separation form binary systems**.

B) Binaries formed after close encounters within a DM halo



- PBHs become bound if GW emission exceeds initial kinetic energy

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

$$\mathcal{R} = 4\pi \int_0^{R_{\rm vir}} r^2 \frac{1}{2} \left(\frac{\rho_{\rm nfw}(r)}{M_{\rm pbh}}\right)^2 \langle \sigma v_{\rm pbh} \rangle \; dr$$

Bird+ PRL 2017

[Daniele Gaggero, UCI 20/02/2018]