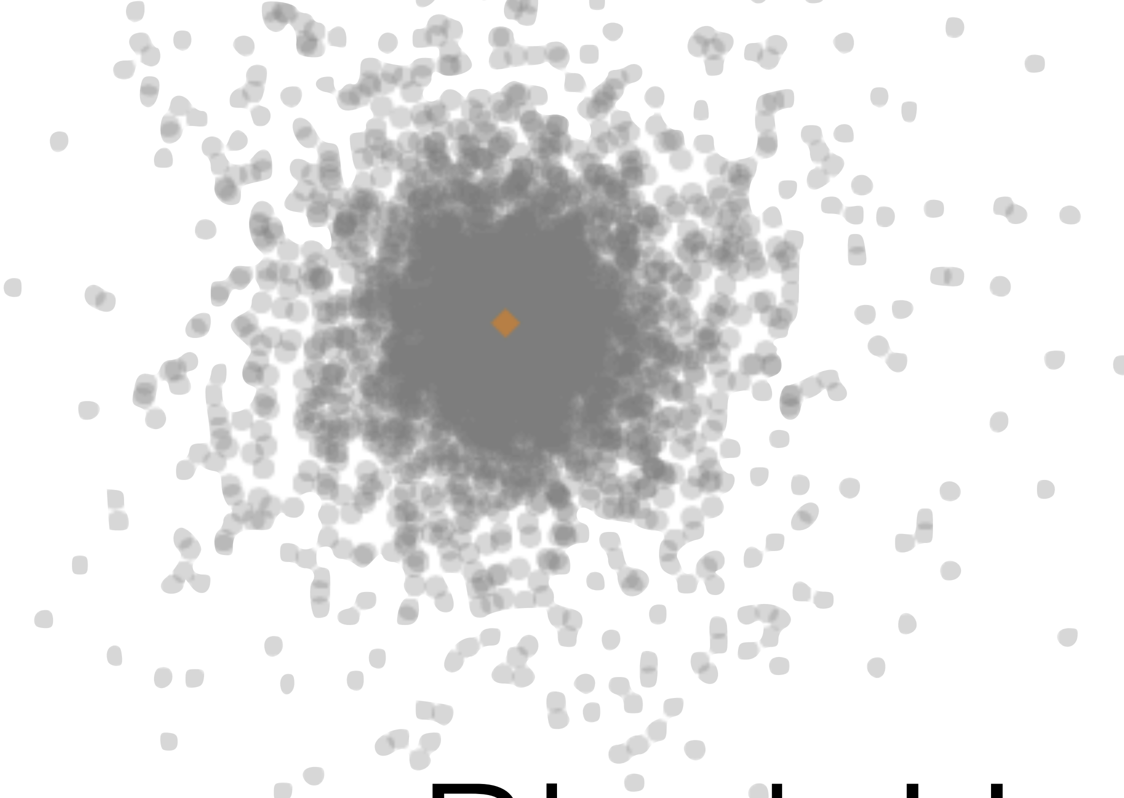
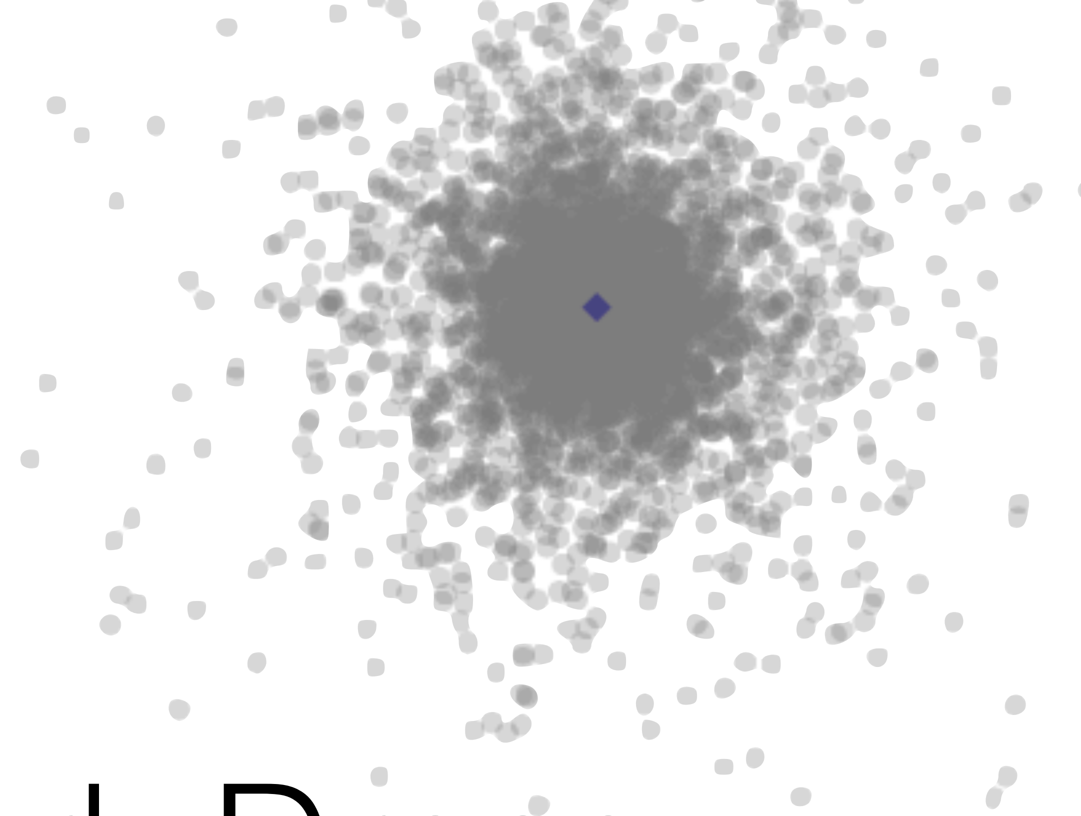



Black Holes' Dark Dress

Merging Black Holes and the Dark Matter around them

Bradley J Kavanagh
GRAPPA, University of Amsterdam

18th December 2018

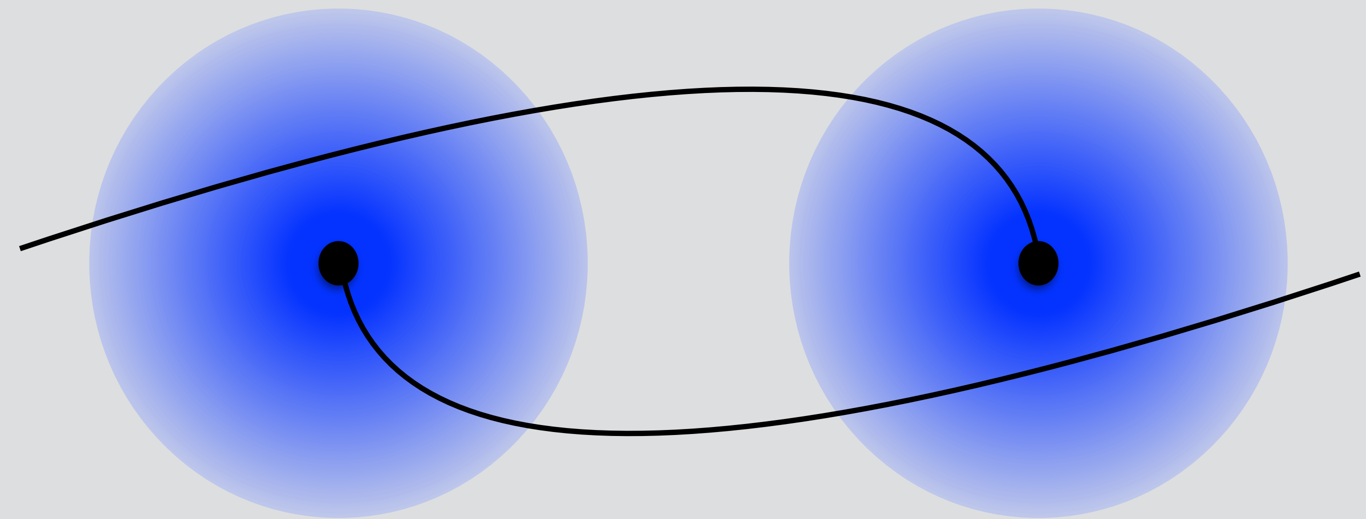
GRAPPA
GRavitation AstroParticle Physics Amsterdam

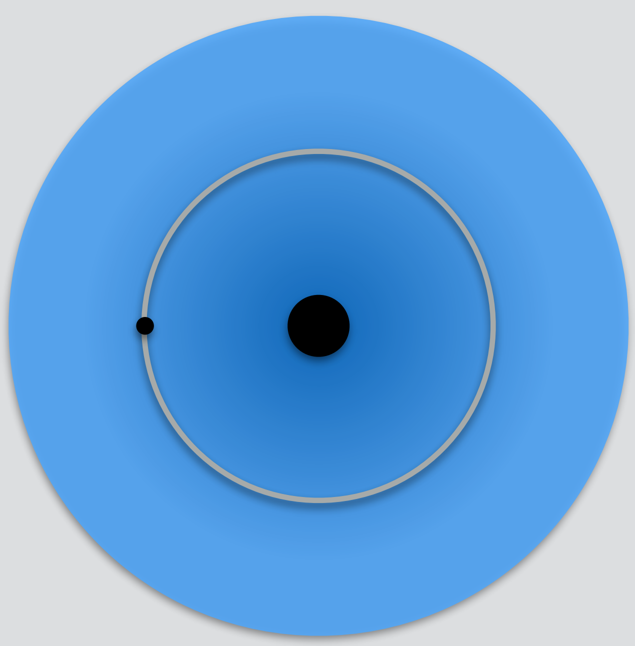
SURF SARA
Powered by

b.j.kavanagh@uva.nl
@BradleyKavanagh

In collaboration with Gianfranco Bertone, Adam Coogan,
Daniele Gaggero, David Nichols and pretty much everyone at GRAPPA…

Merging Primordial Black Holes (PBHs)





Intermediate Mass-Ratio Inspirals (IMRIs)

Merger rates of PBHs

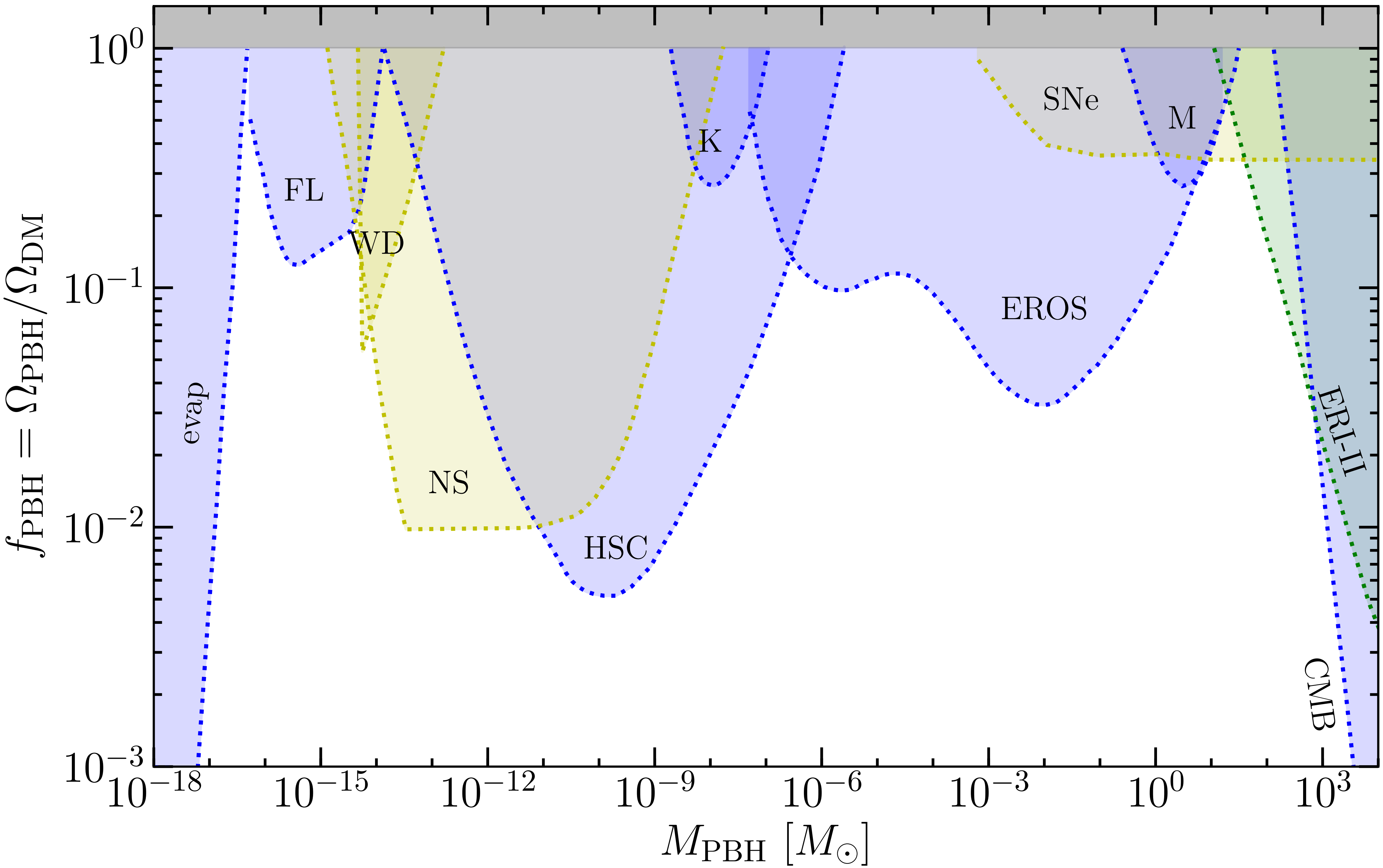
arXiv:1805.09034, PRD 98, 023536 (2018)

BJK, Daniele Gaggero & Gianfranco Bertone

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

PBHs as Dark Matter

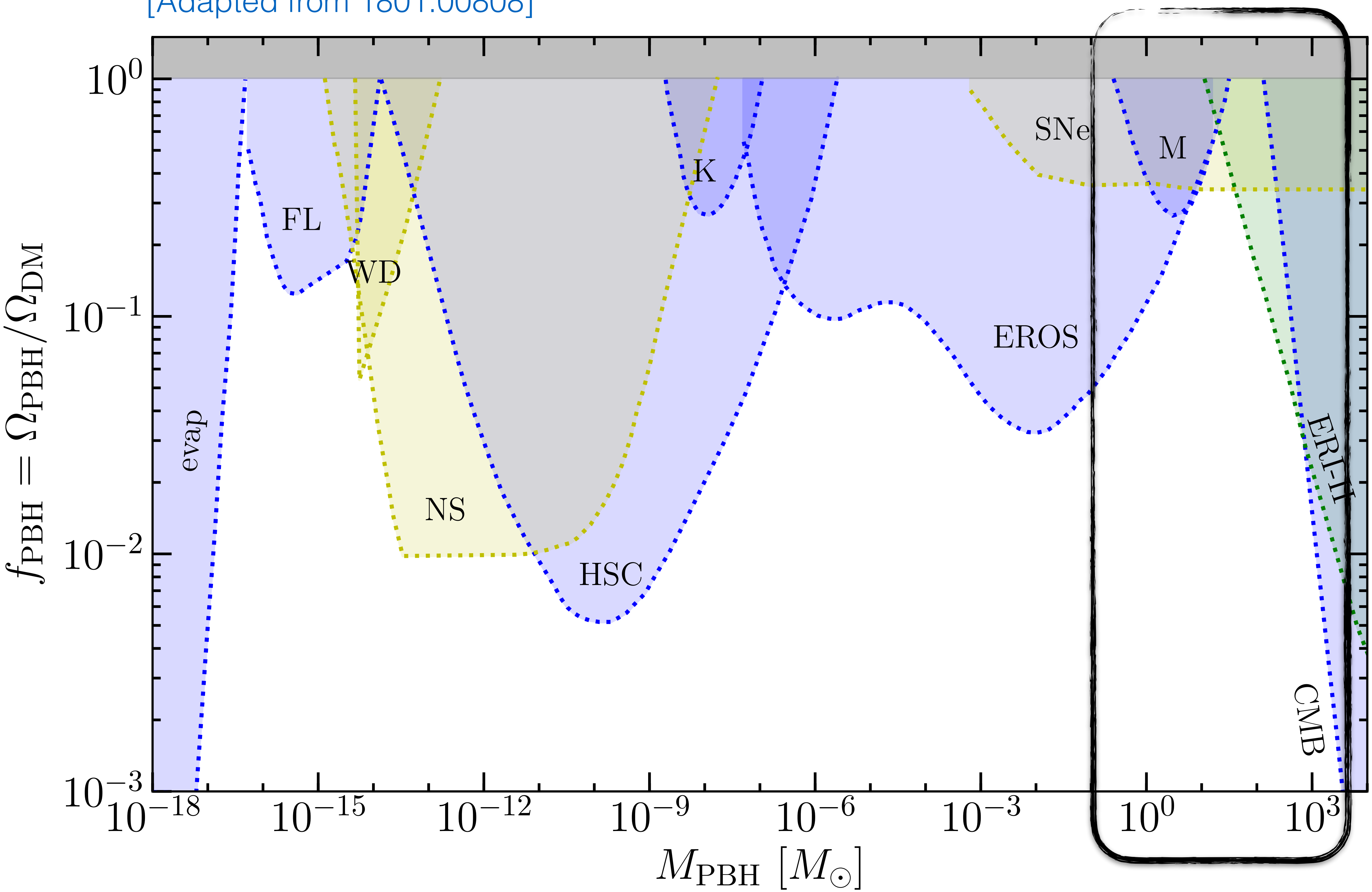
[Adapted from 1801.00808]



[See 1607.06077, 1806.05195 and references therein]

PBHs as Dark Matter

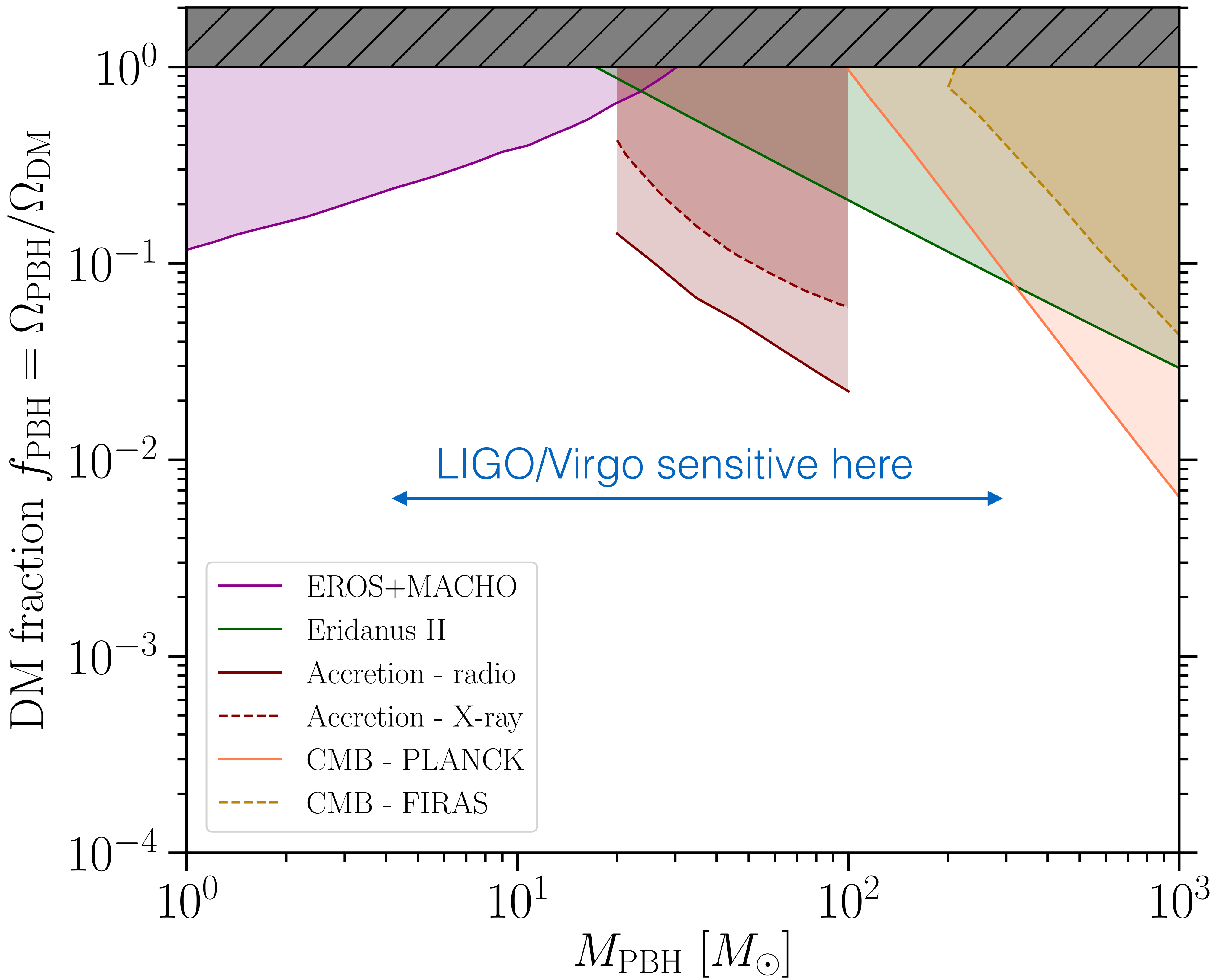
[Adapted from 1801.00808]



[See 1607.06077, 1806.05195 and references therein]

Solar Mass PBHs

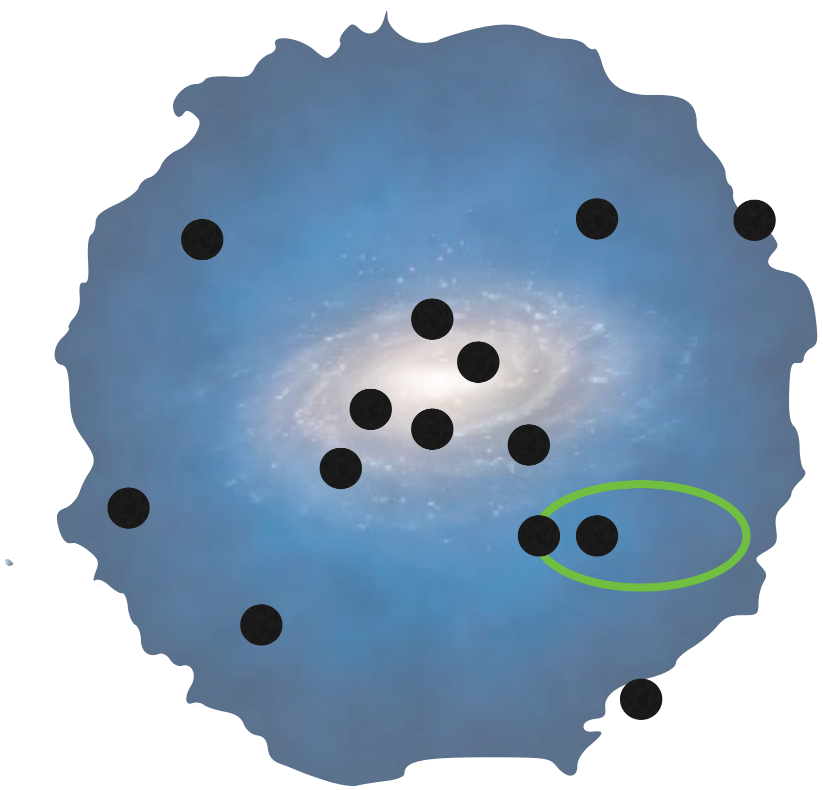
[**BJK**, Gaggero & Bertone,1805.09034]



A tale of two binaries

A) Binaries formed after close encounters

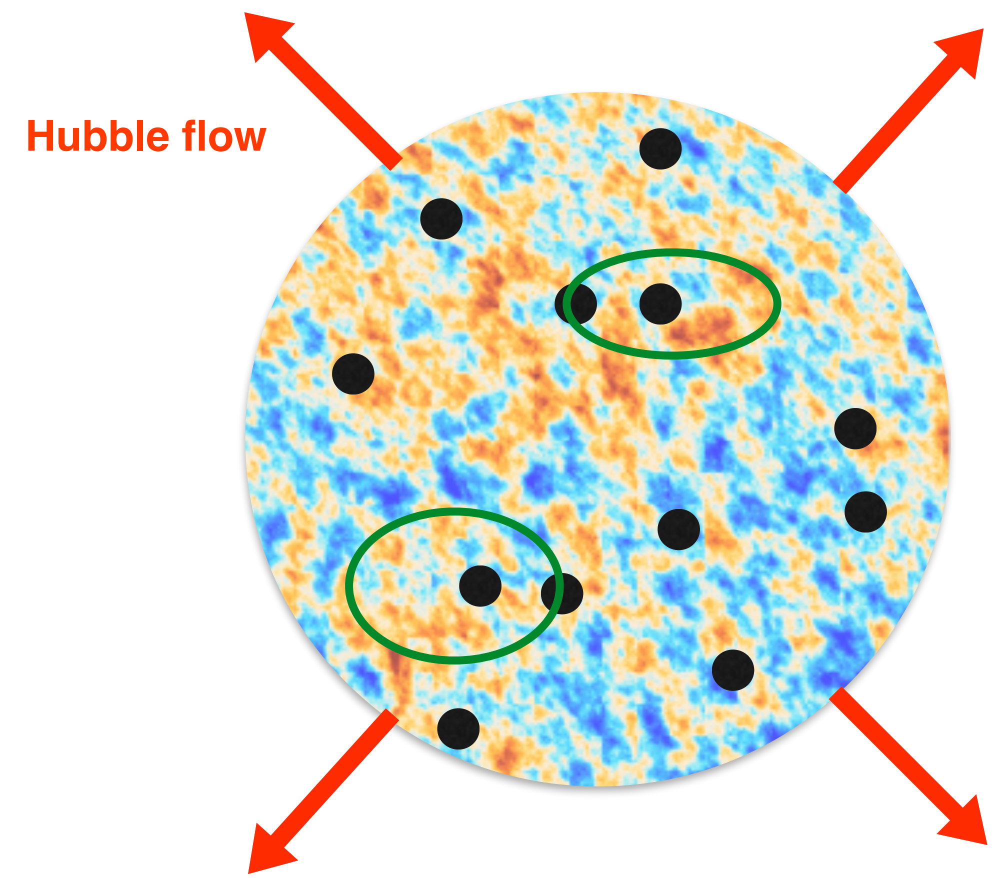
[Bird et al., 1603.00464]



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

B) Binaries formed in the early Universe

[Sasaki et al, 1603.08338]



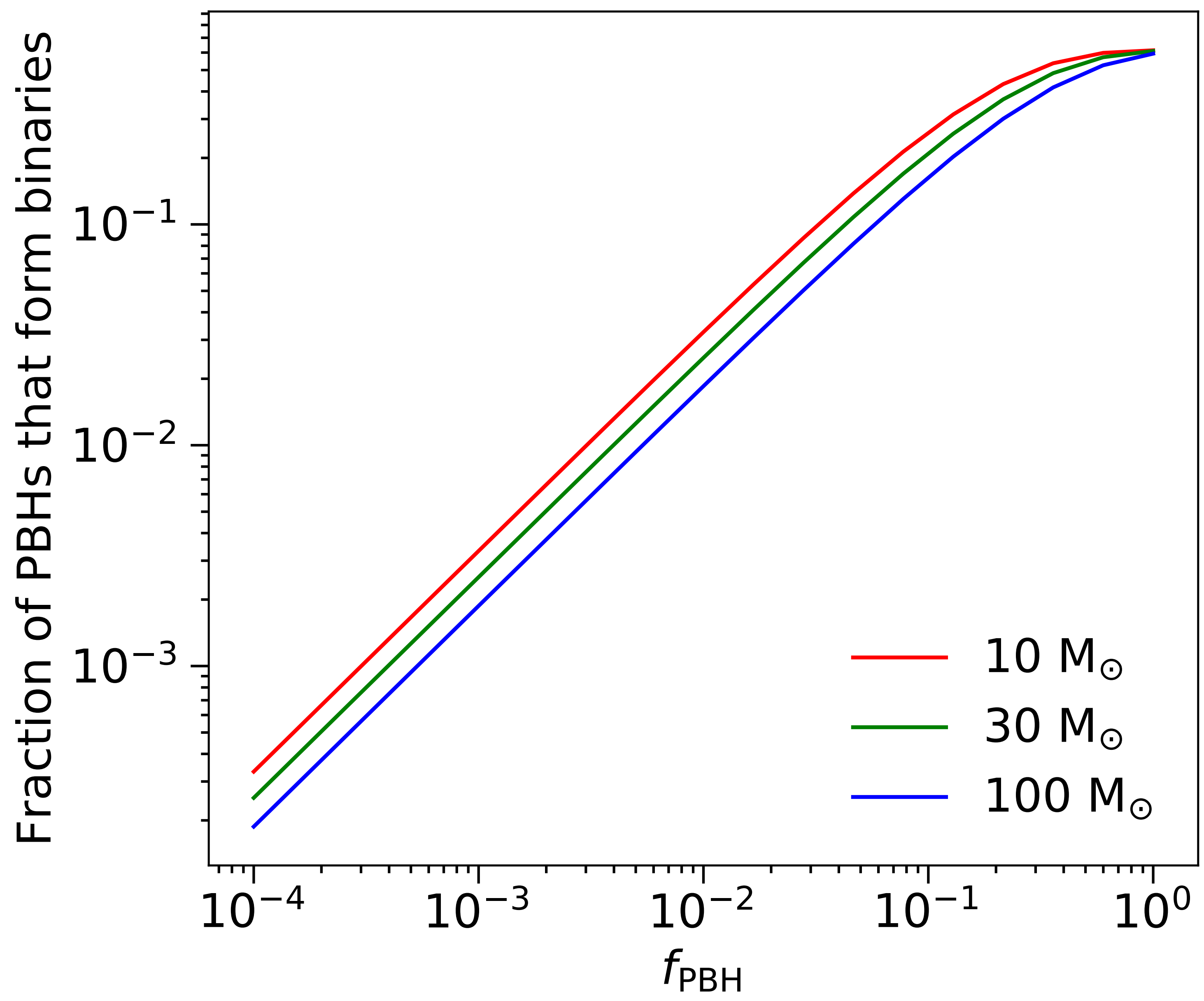
Require:

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

[Daniele Gaggero, UCI 20/02/2018]

Early Universe Binaries

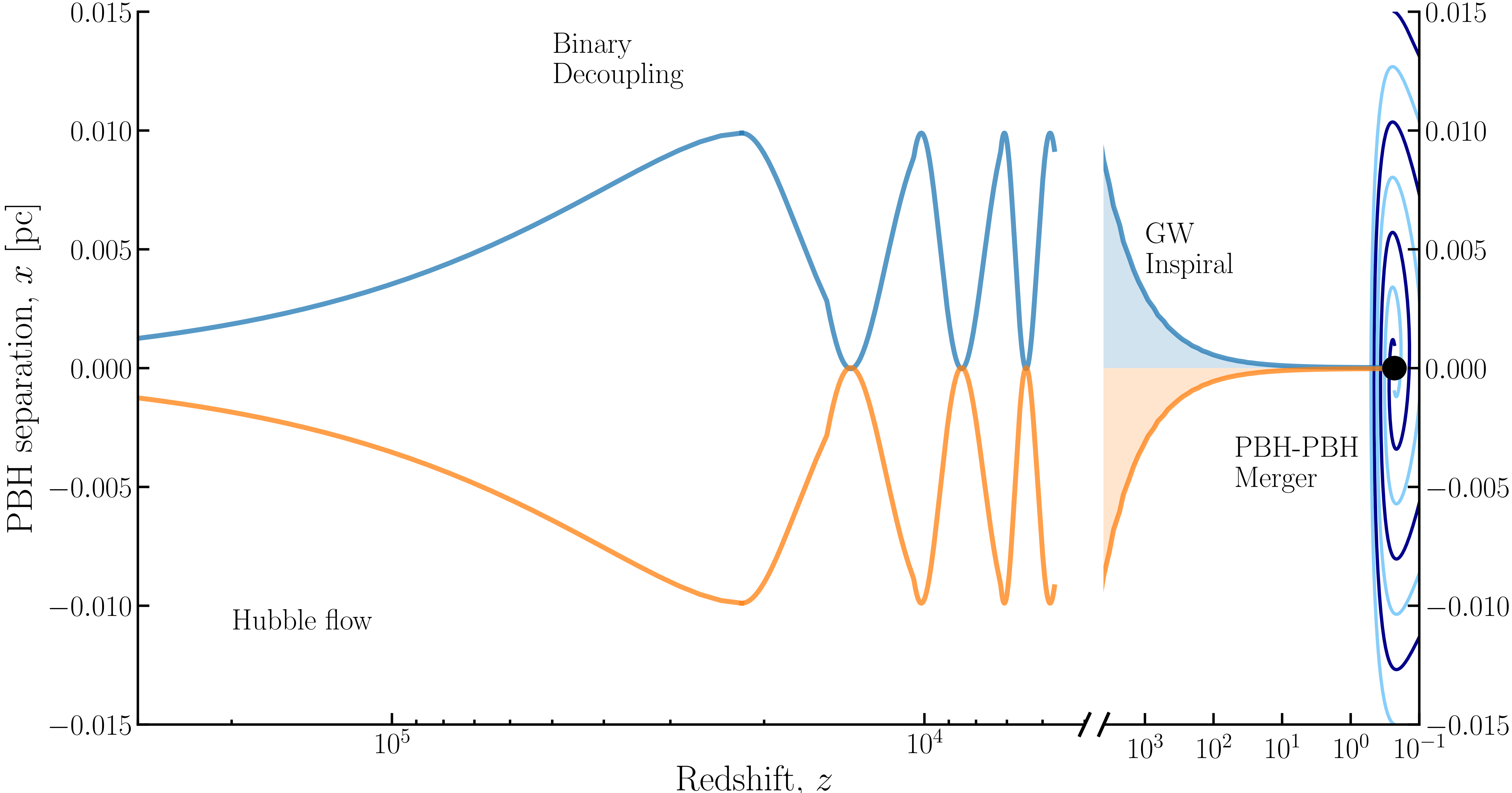
If f ~ 1, the relative density of PBHs *equals* the background radiation density at matter-radiation equality. All PBHs form binaries…



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

[See also 1812.01930, 1812.05376]

Life of a PBH binary



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

$e = 0.995$

PBH Binary Population

Randomly distributed (unclustered) PBHs

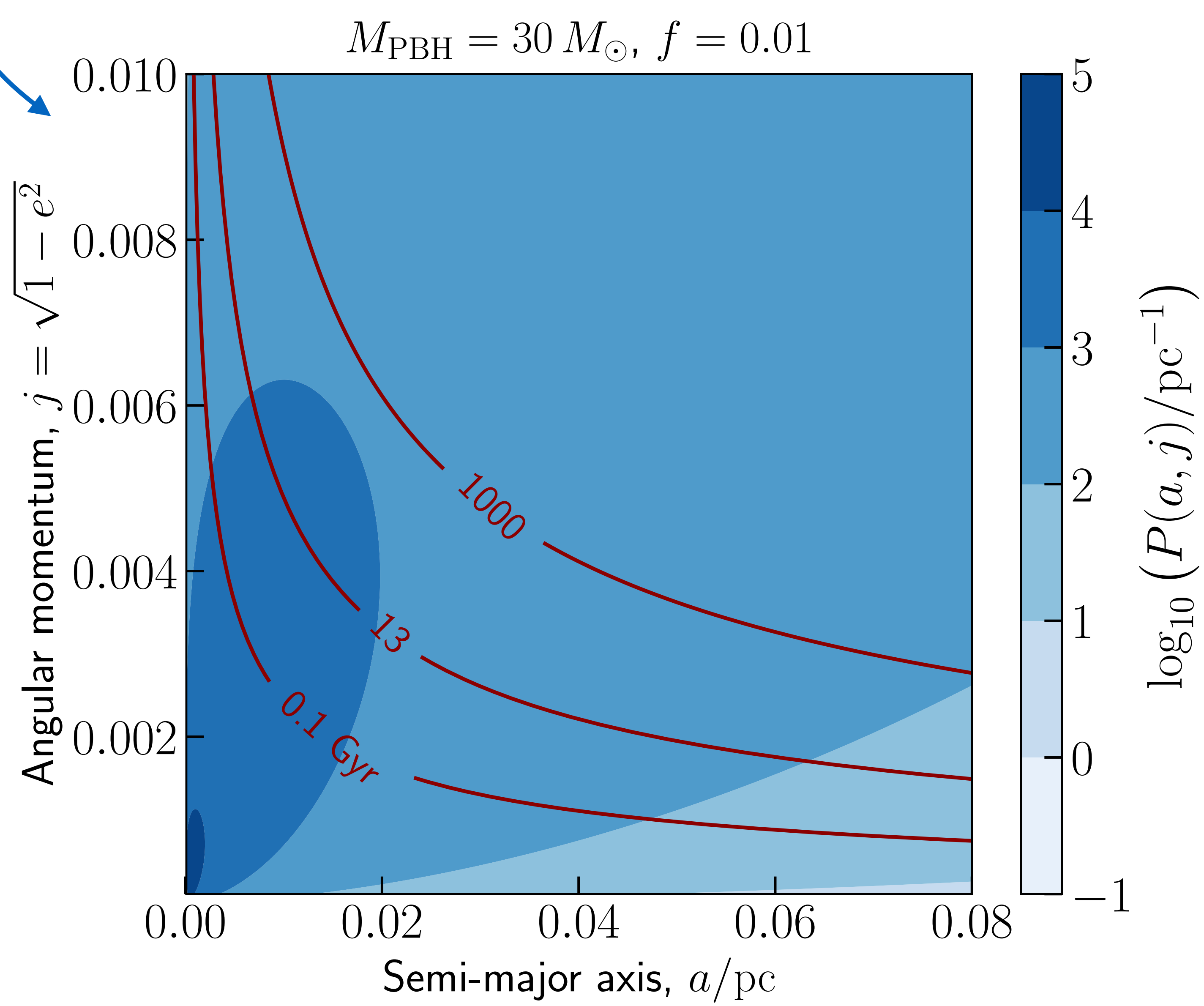
Angular momentum set by torques from smooth density perturbations and *all other PBHs*

Close, eccentric binaries merge today:

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

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

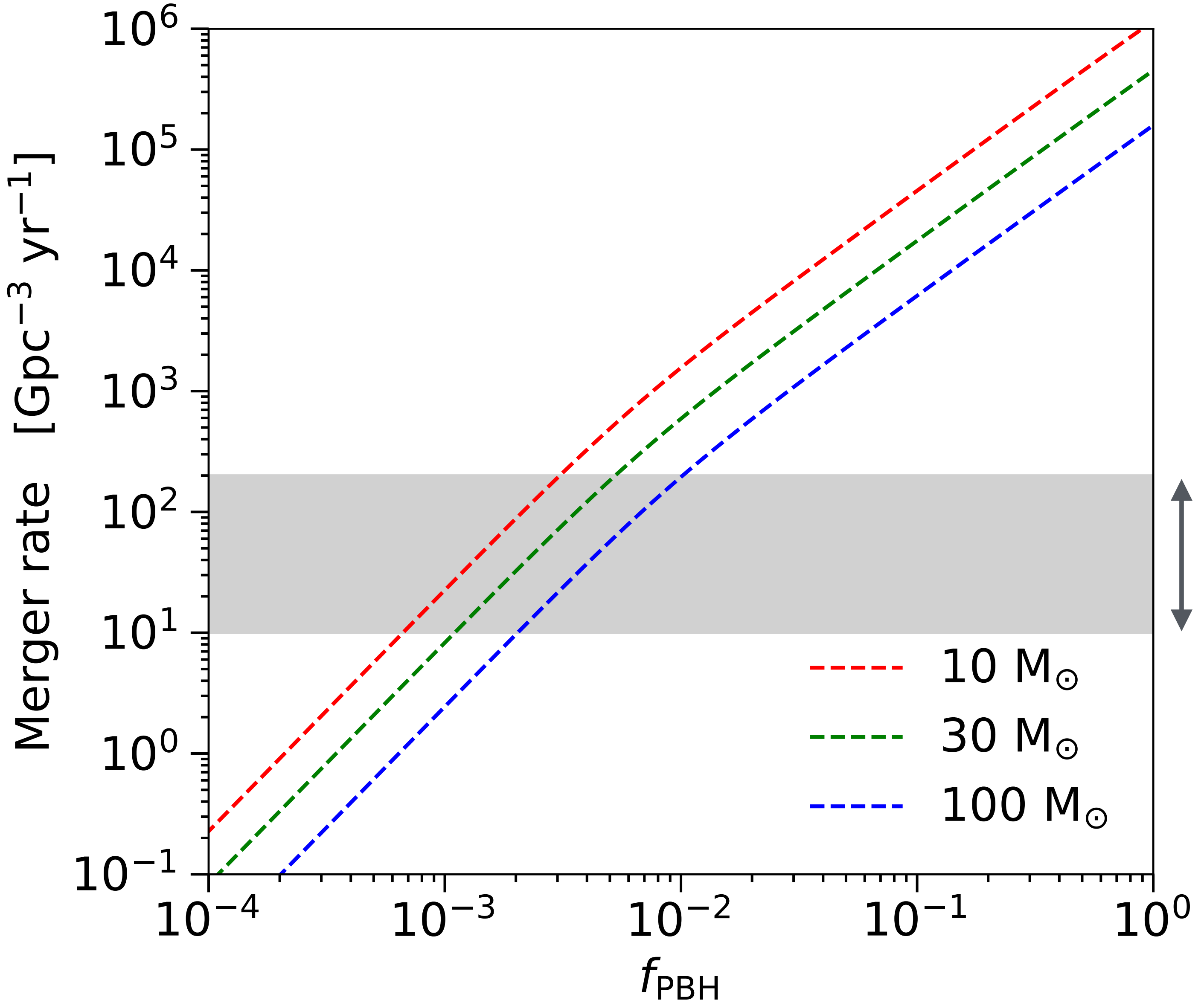
$e > 0.9999$



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

Merger rate estimate

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



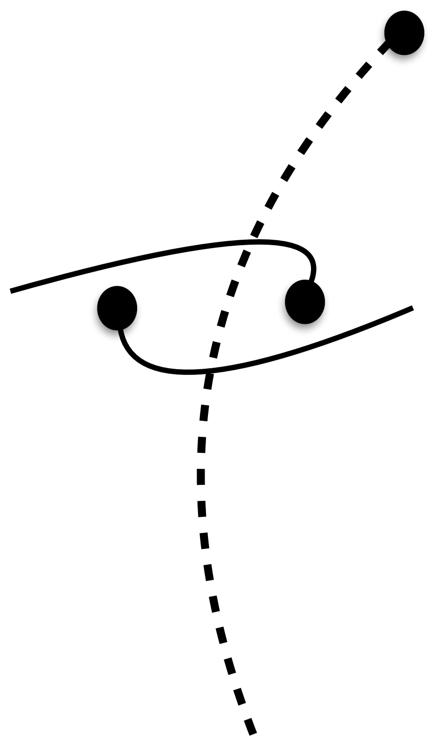
LIGO merger rate estimate after GW150914

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?

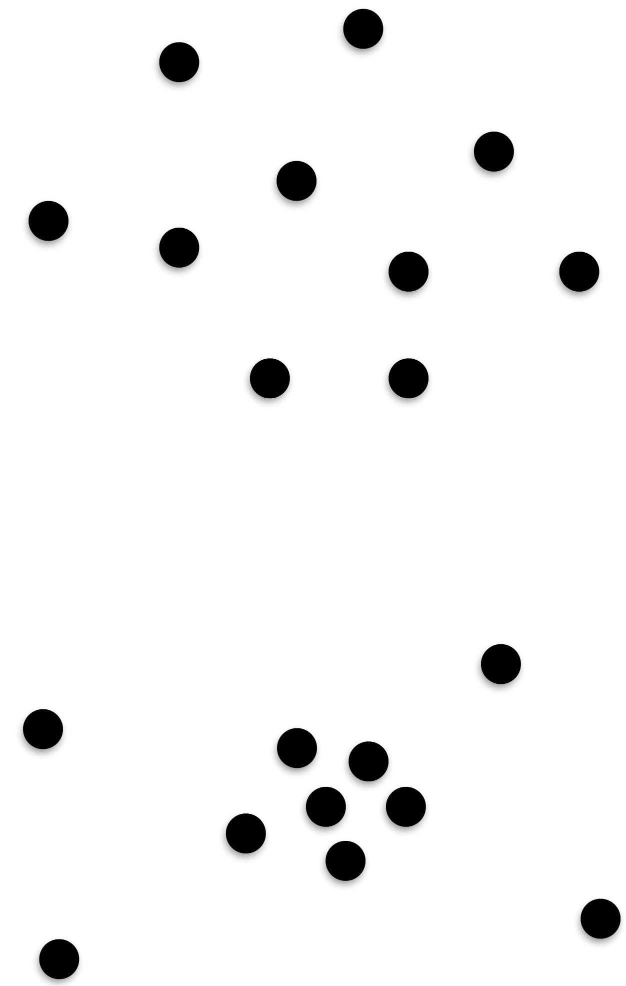
Smooth density perturbations and close encounters
are unlikely to disrupt the binaries

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

[Ali-Haïmoud et al., 1709.06576]

Caveats

- Survival ✓
- Clustering
- Baryons
- Dark Matter



How does the distribution of PBHs affect the merger rate?

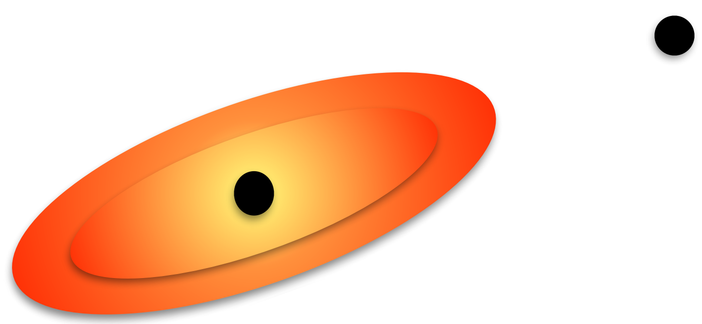
Clustering could substantially enhance the merger rate ('cascade' mergers) but PBHs are unlikely to form in clusters…

[1808.05910] [1807.02084]

[See also 1805.05912,1806.10414 and others]

Caveats

- Survival ✓
- Clustering ✓
- Baryons
- Dark Matter



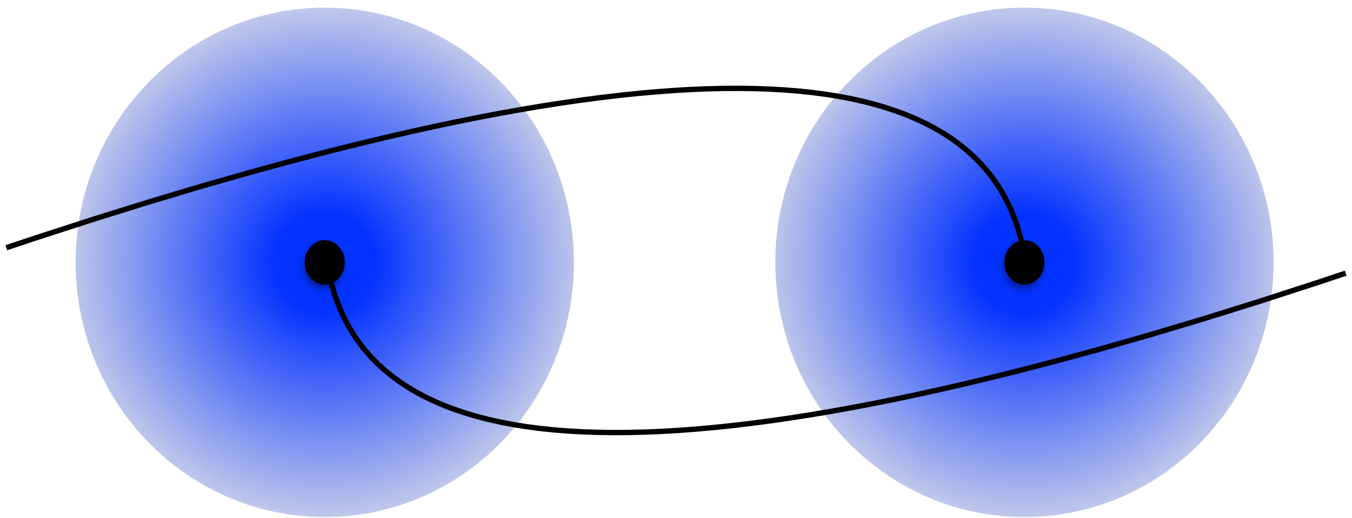
Does baryonic accretion disrupt the binary?

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

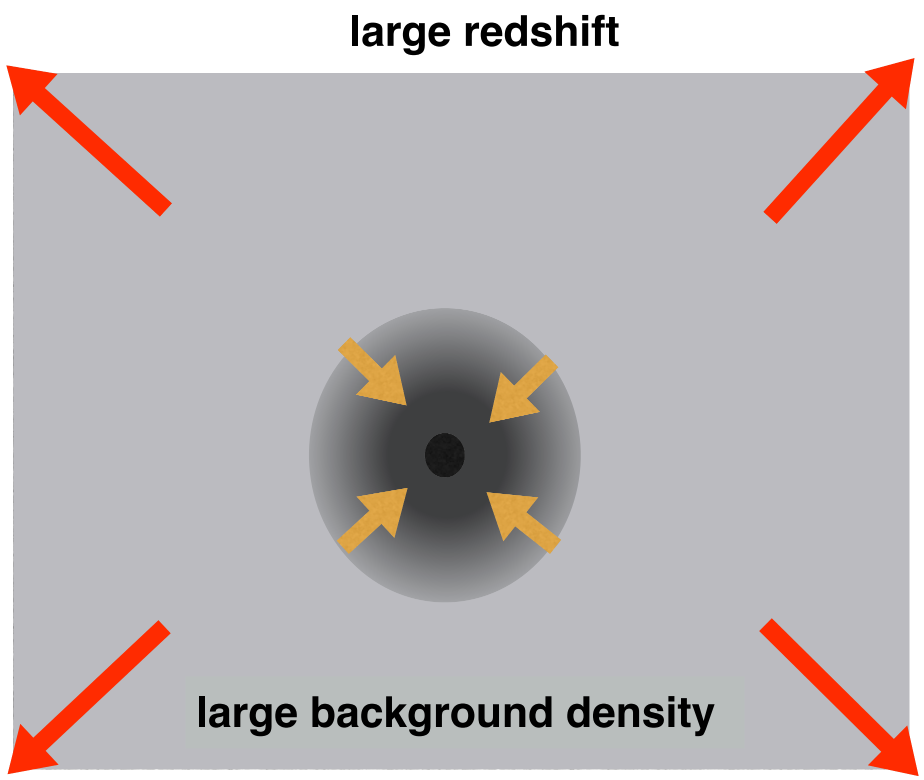
- Survival ✓
- Clustering ✓
- Baryons ?
- **Dark Matter**

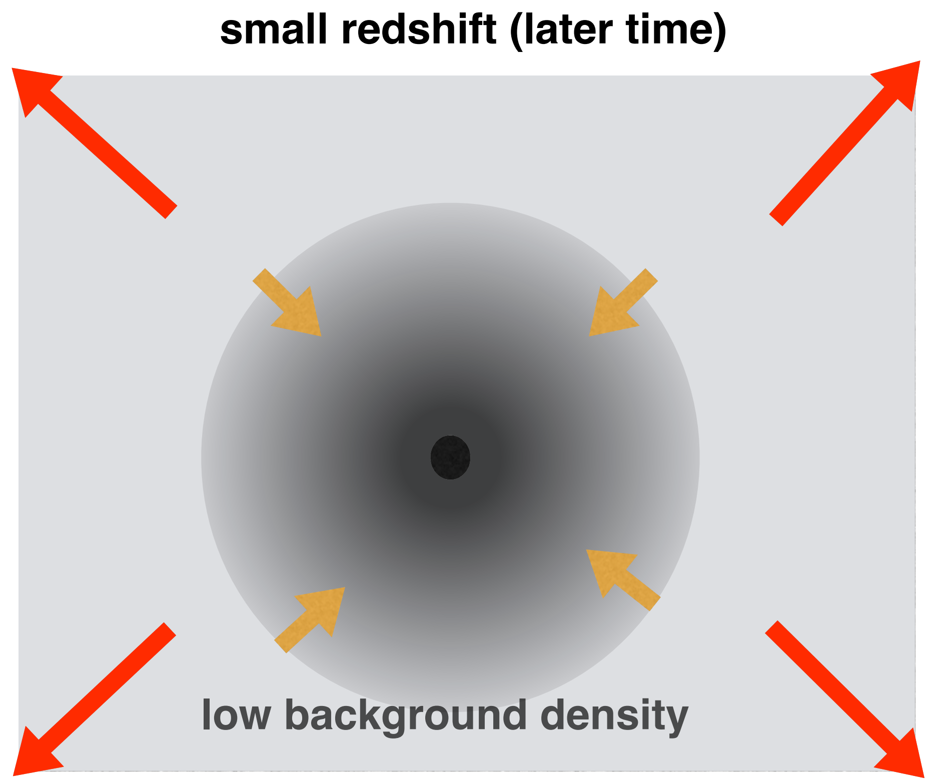


Do *local* Dark Matter halos disrupt PBH binaries?

Dark Dresses

PBHs seed the formation of `local' DM halos:





$$R_{\mathrm{tr}}(z) = 0.0063 \left(\frac{M_{\mathrm{PBH}}}{M_\odot}\right)^{1/3} \left(\frac{1+z_{\mathrm{eq}}}{1+z}\right) \mathrm{pc}$$

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

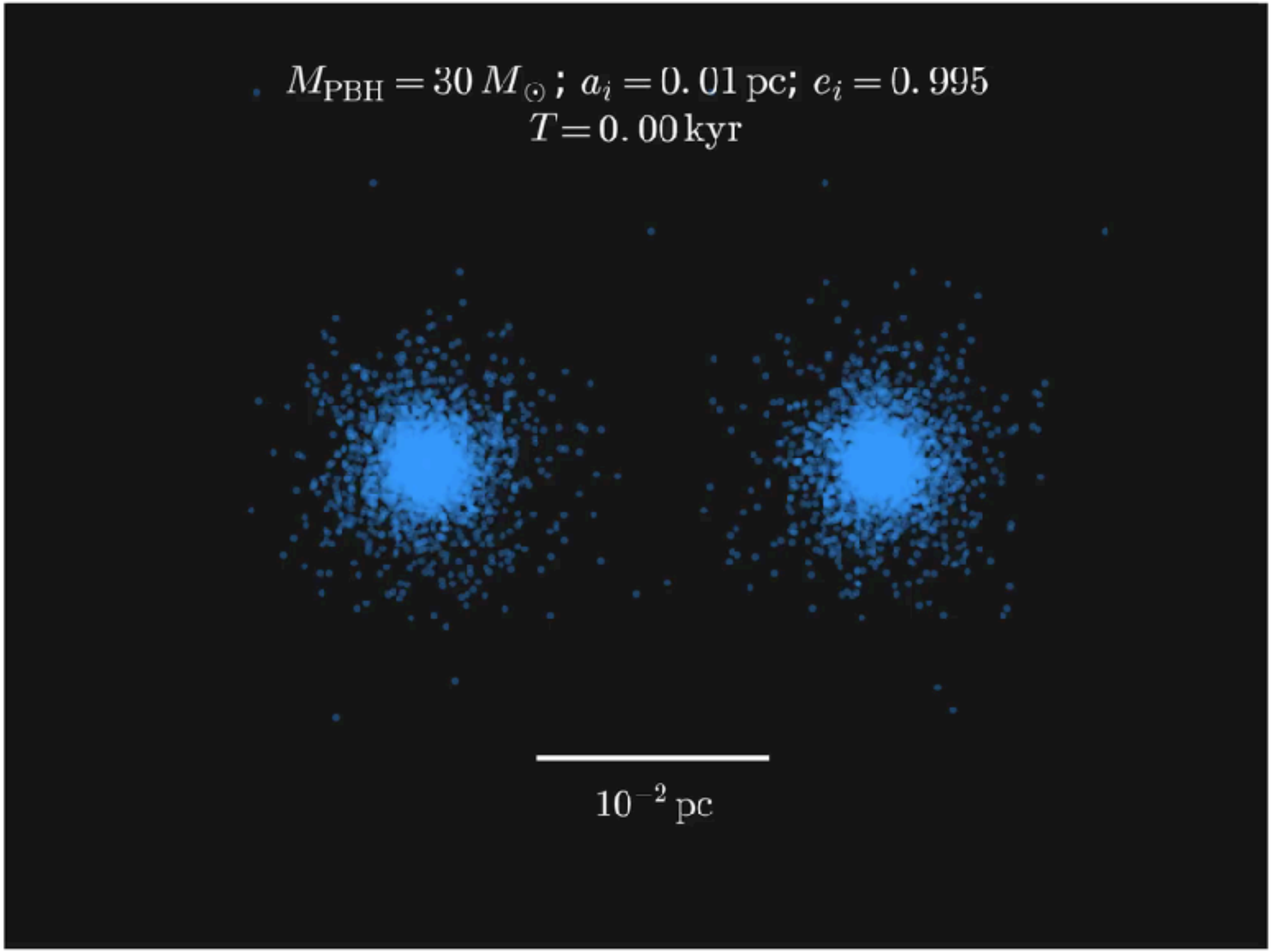
By matter-radiation equality, $M_{\mathrm{halo}} \sim M_{\mathrm{PBH}}$

Slide shamelessly ripped off from Daniele Gaggero [astro-ph/0608642, 0706.0864,1710.02055, 1712.05421]

Simulations

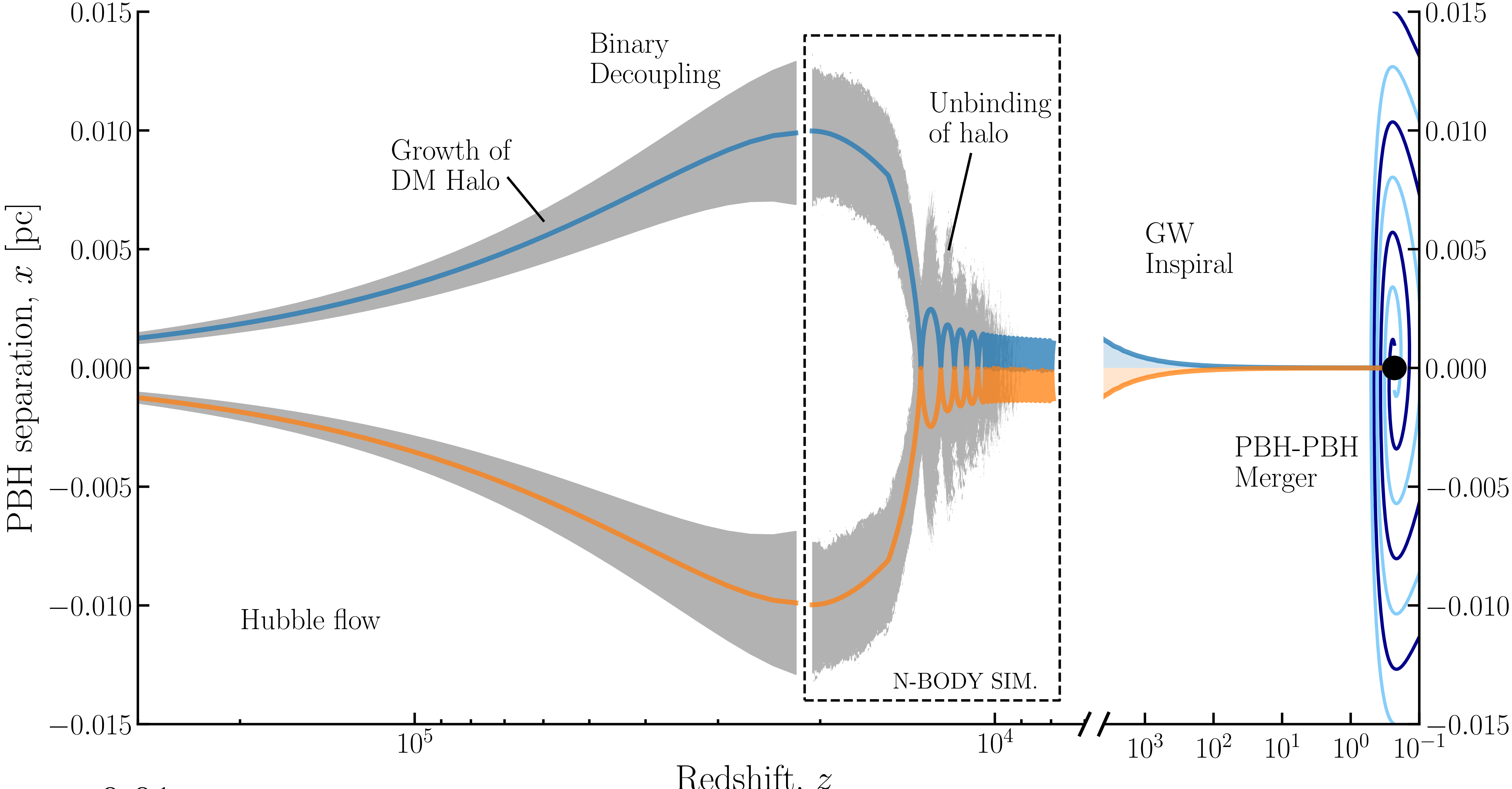
Use GADGET-2 as a pure N-body solver:

[Springel, astro-ph/0505010]



Movies at tinyurl.com/BlackHolesDarkDress

Life of a *dressed* PBH binary

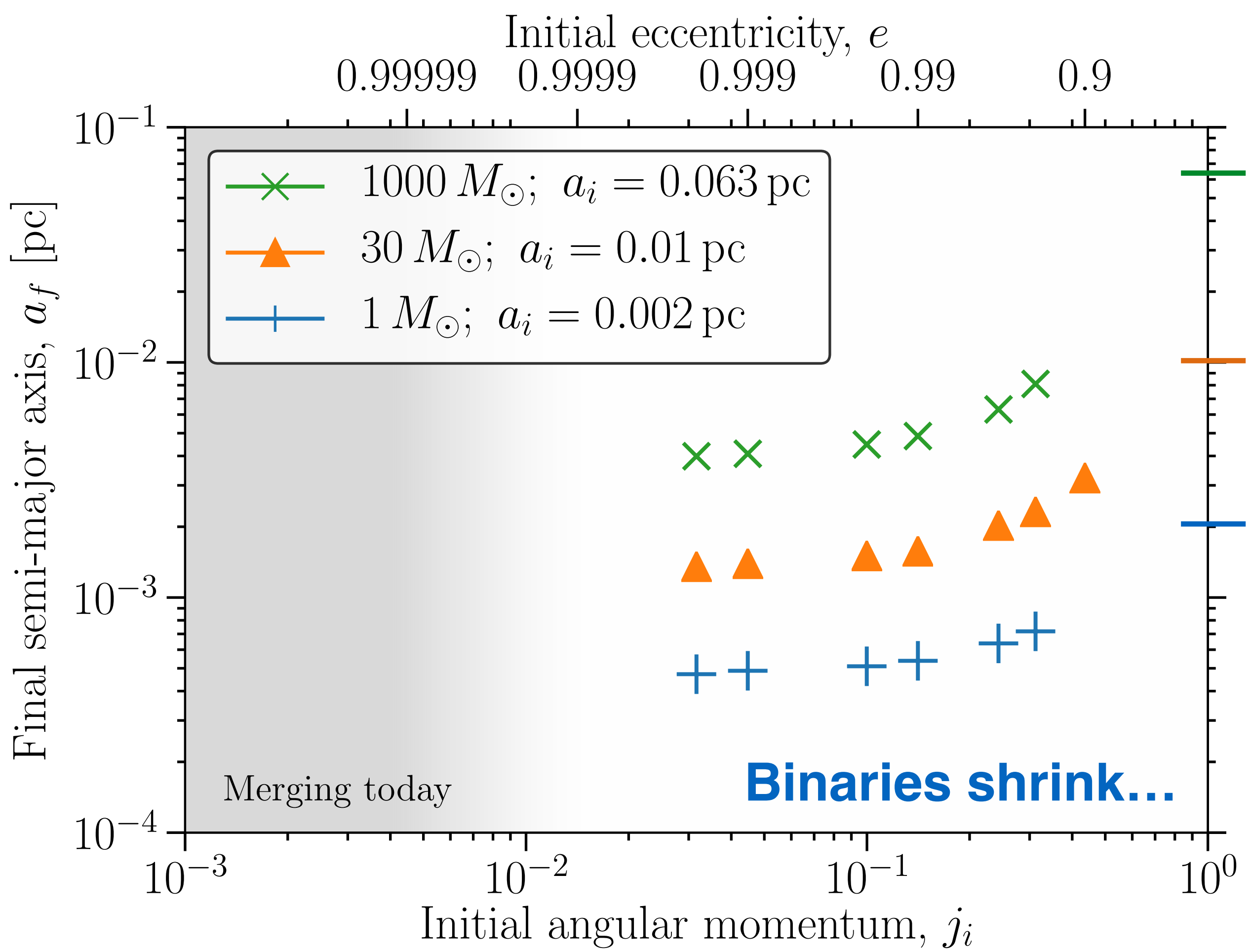


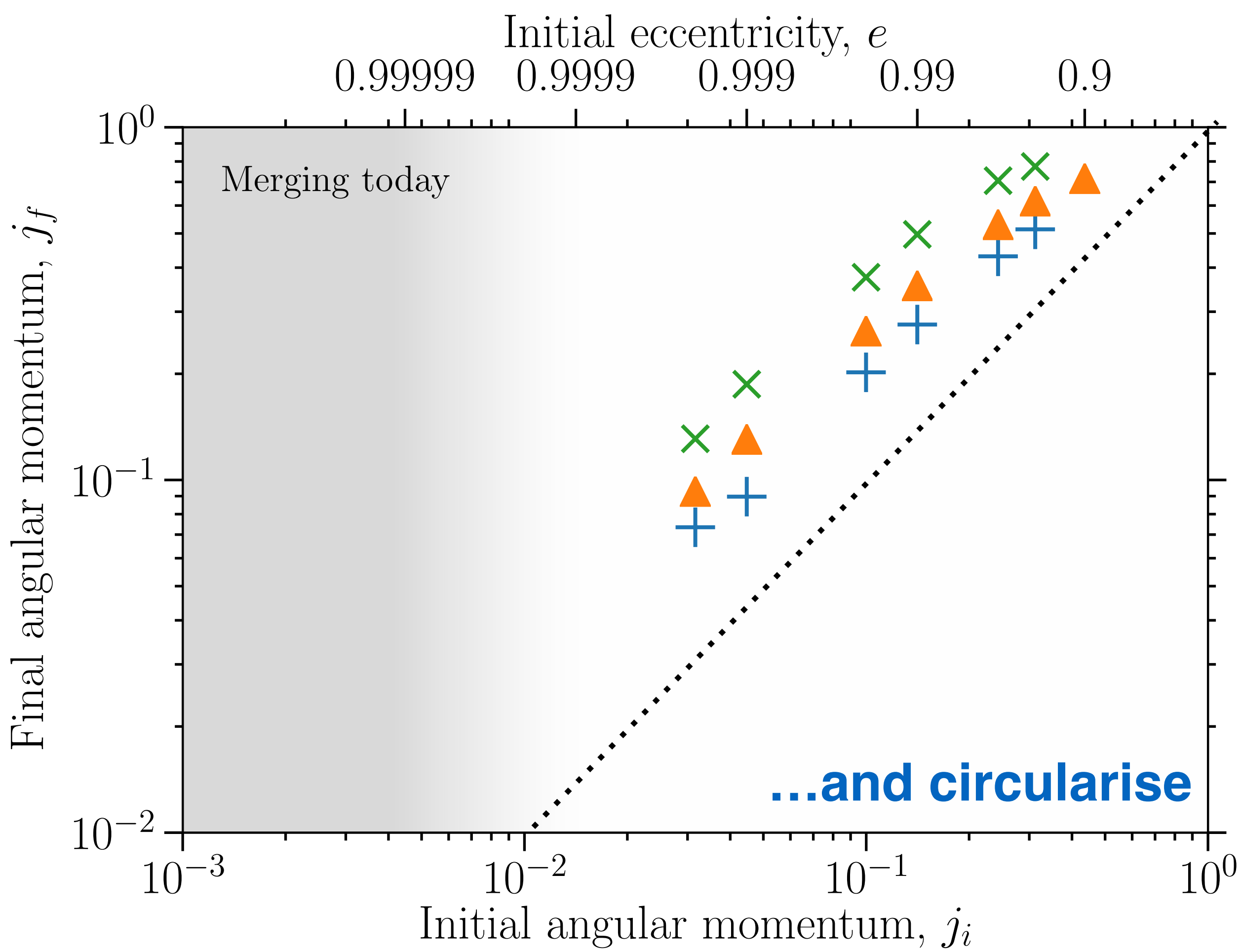
$a_i = 0.01\,\mathrm{pc}$

$e_i = 0.995$

Simulation Results

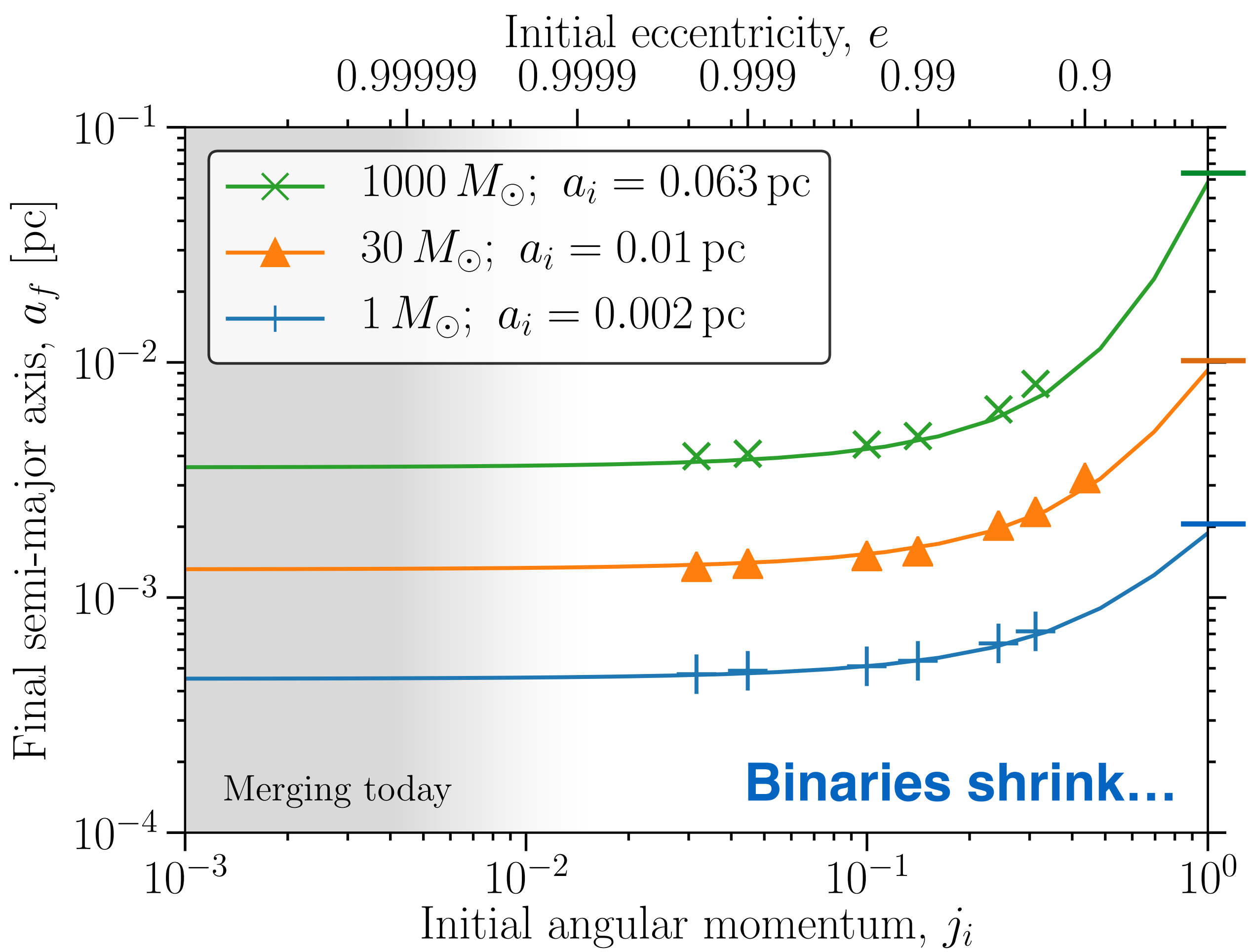
$$j = \sqrt{1-e^2}$$

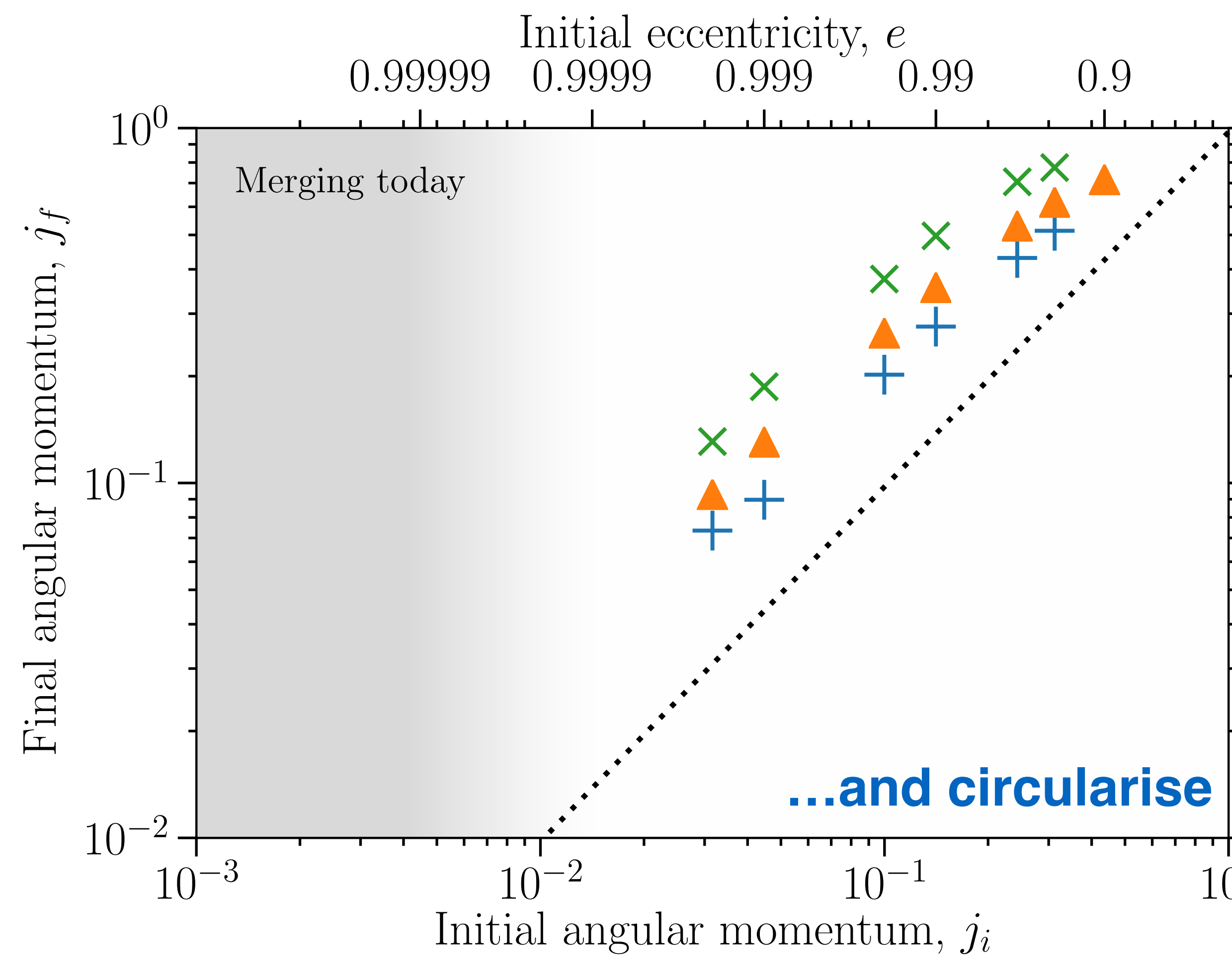




Results: Semi-major Axis

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

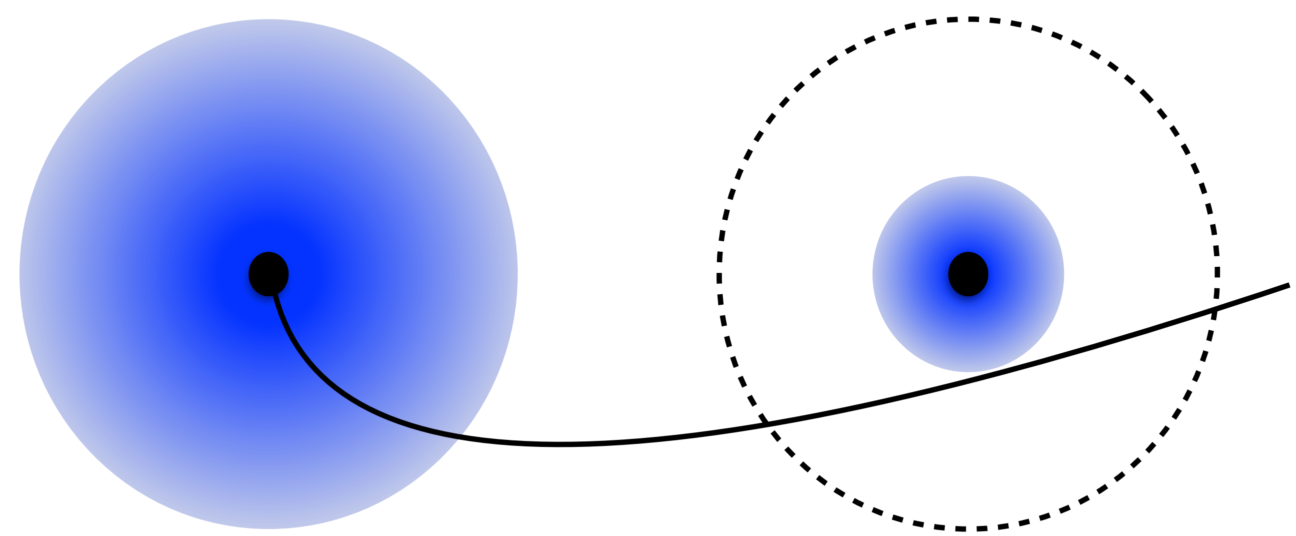




Conservation of energy

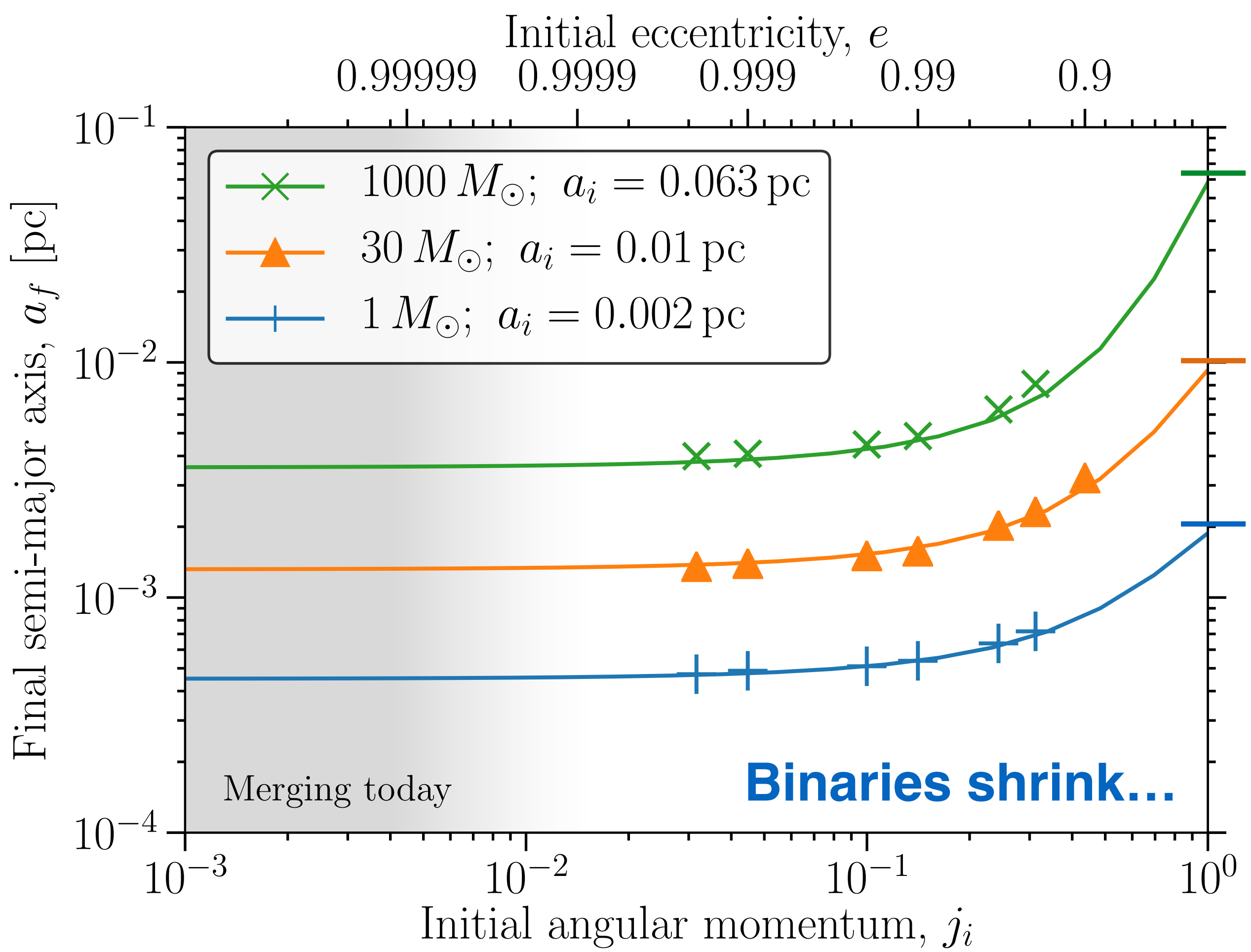
$$E_i^{\mathrm{orb}} + 2\,U^{\mathrm{bind}} = E_f^{\mathrm{orb}}$$

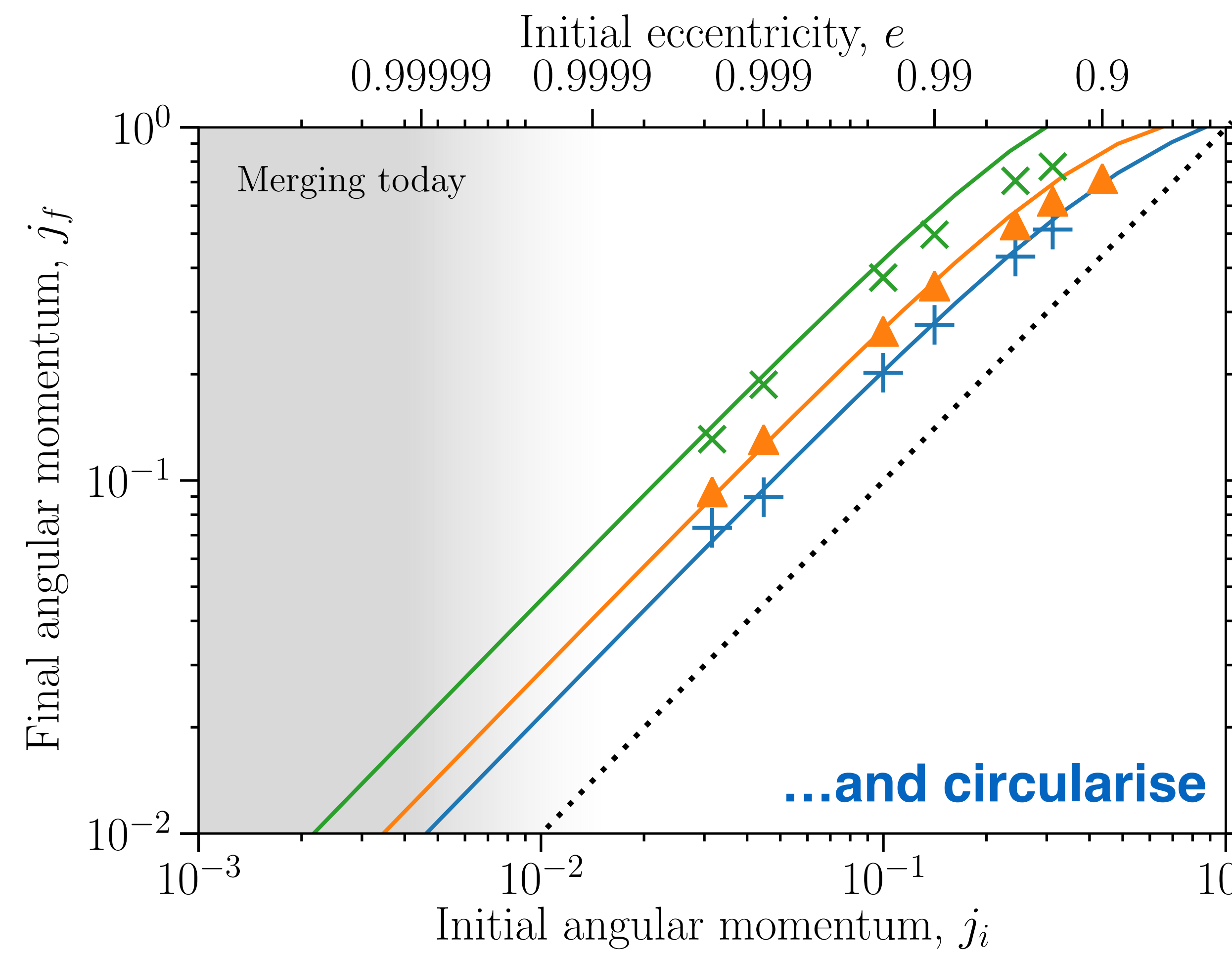
fixes semi-major axis, a

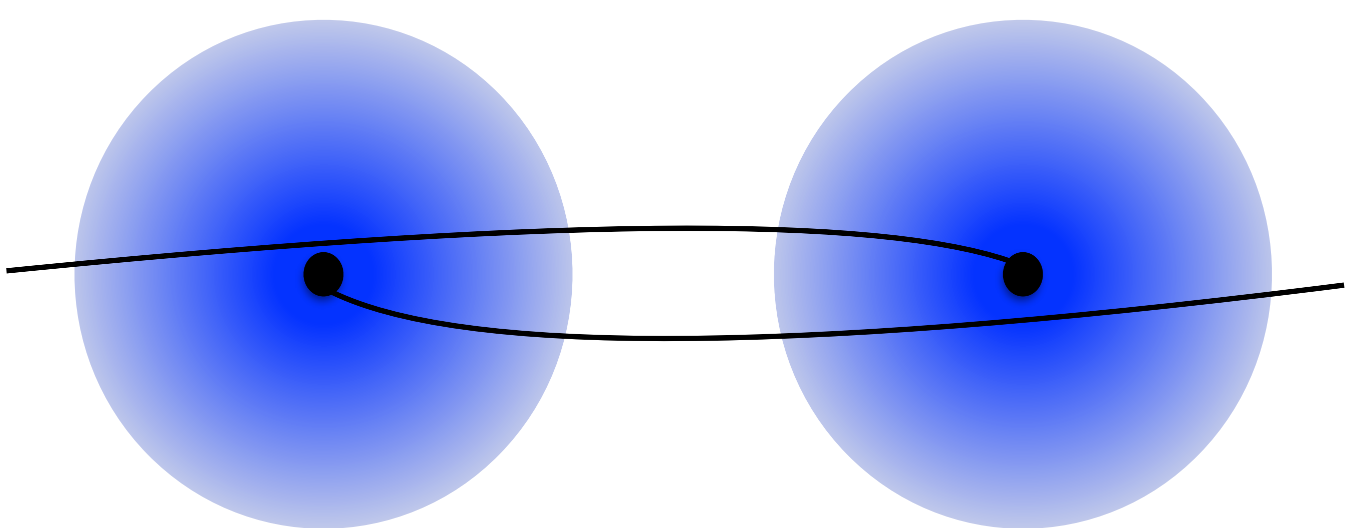


Results: Angular Momentum

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







Conservation of angular momentum

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

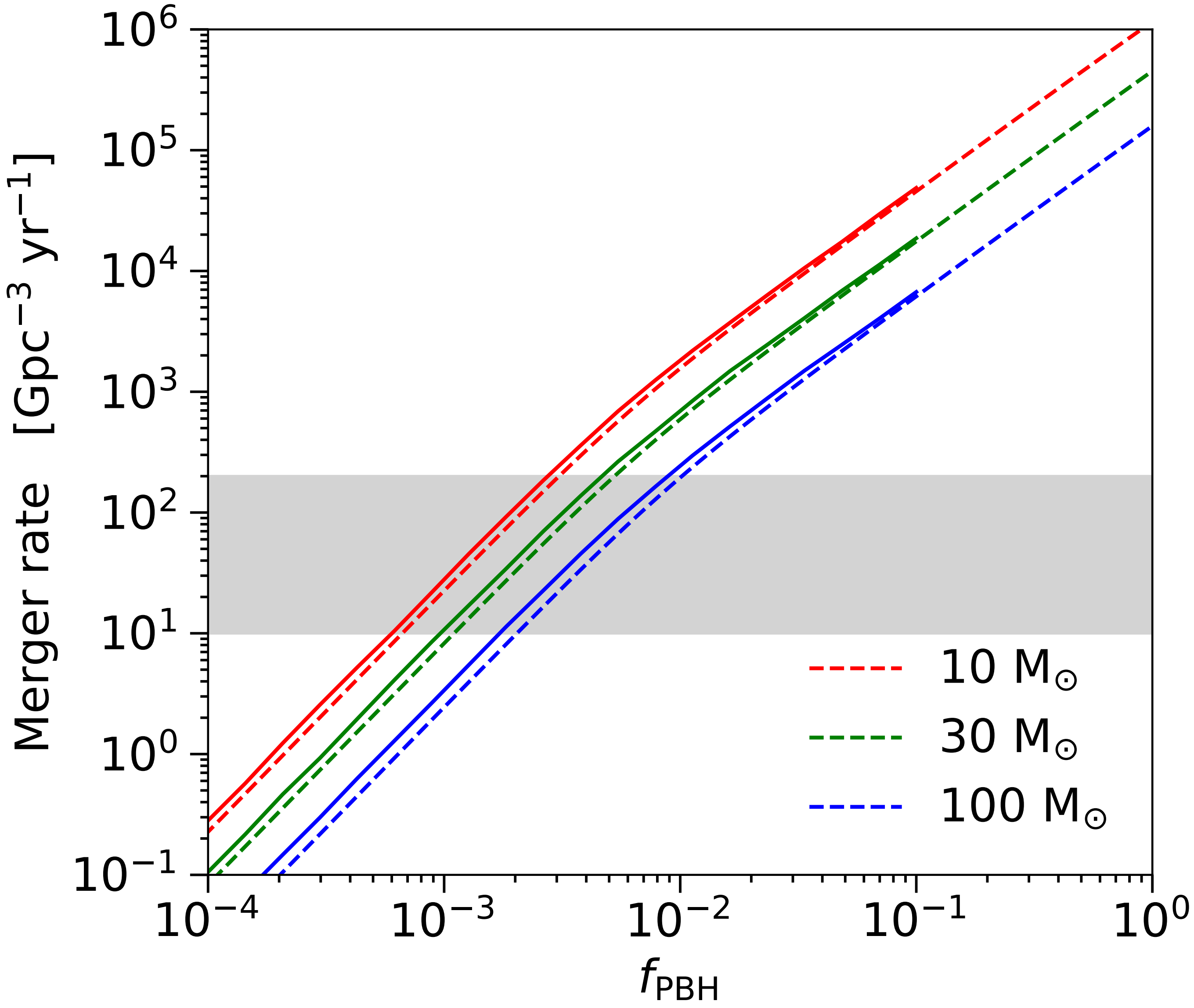
fixes $j_f = j_i\sqrt{a_i/a_f}$

Calculating the final merger rate

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

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

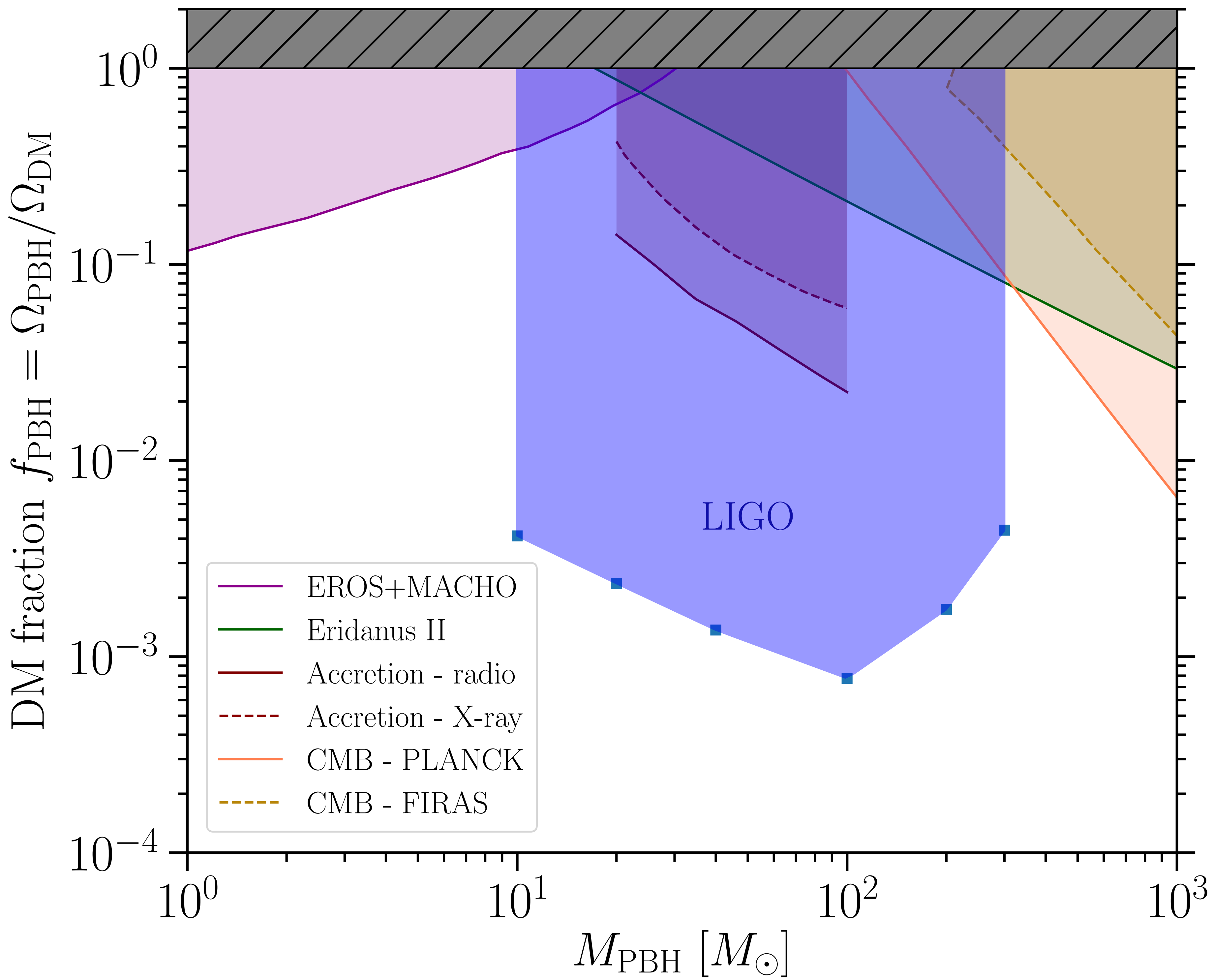
Guided by the simulations, map $(a_i, e_i) \rightarrow (a_f, e_f)$



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]

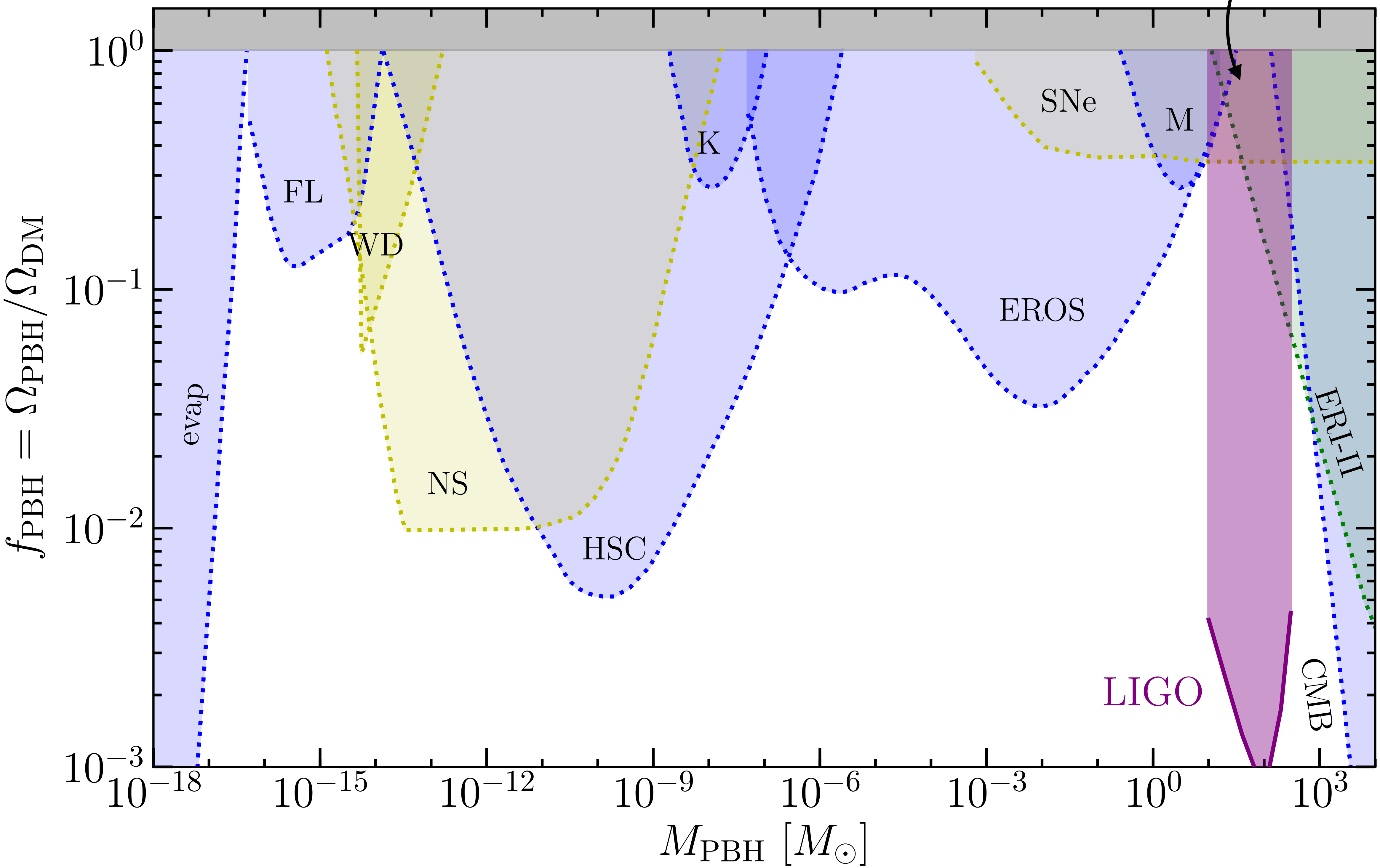


Local DM halos strengthen constraints by around a factor of 2.

PBHs and their DM Halos

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

[Adapted from 1801.00808]



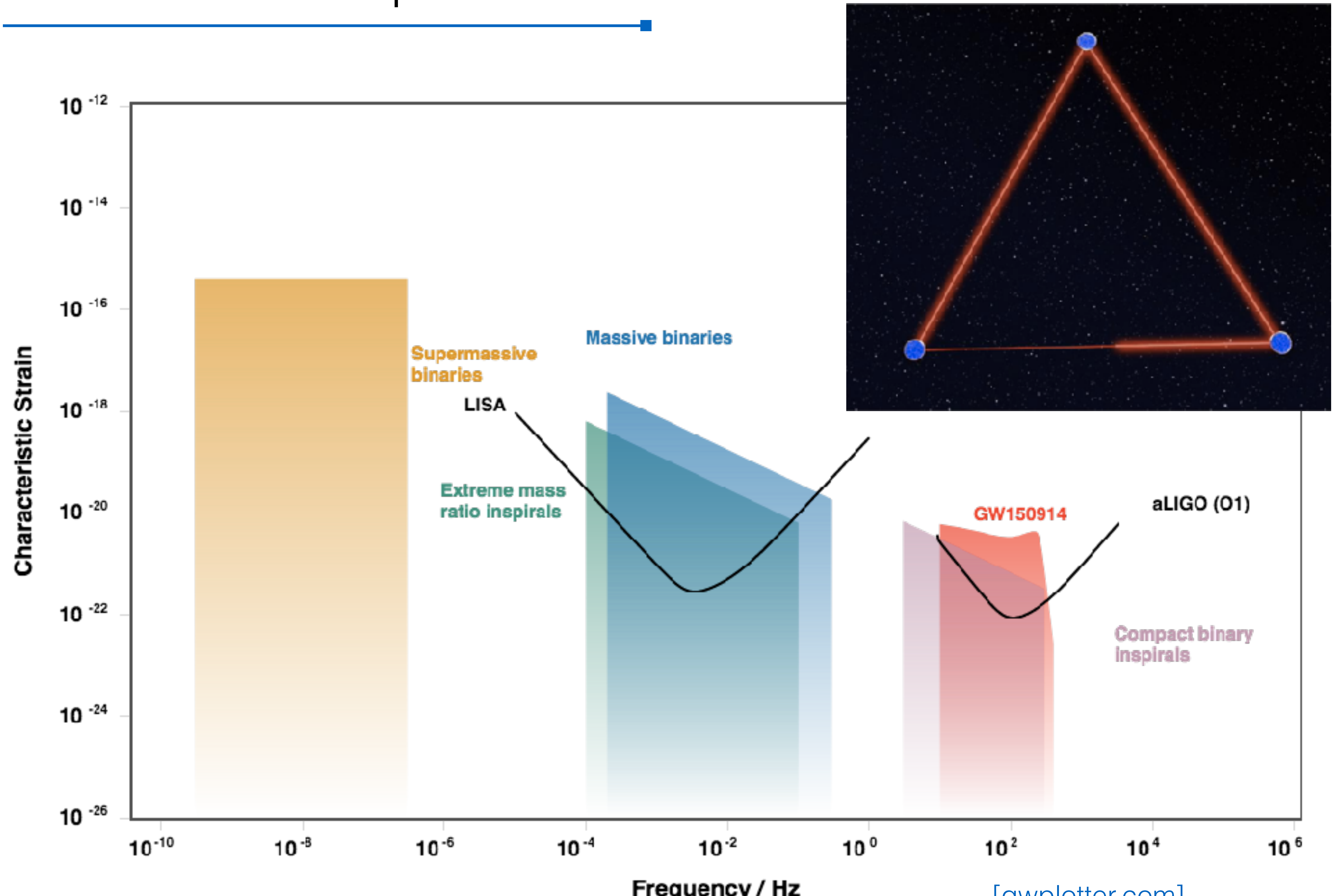
Where else can DM halos have an influence?

Dark Dresses at LISA

Work in progress with Gianfranco Bertone, Daniele Gaggero and David Nichols

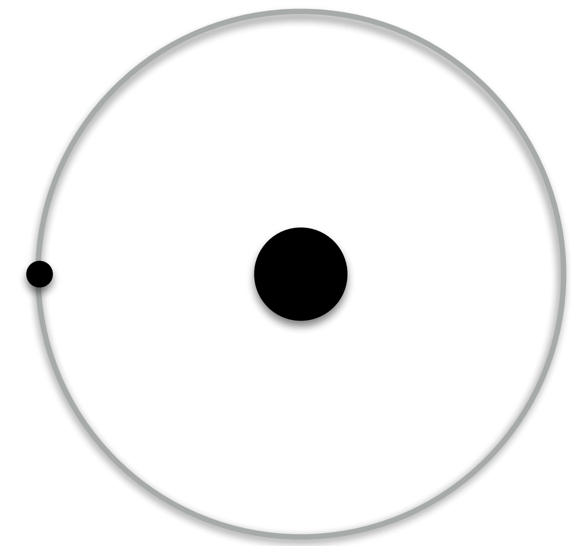
LISA: GWs in Space

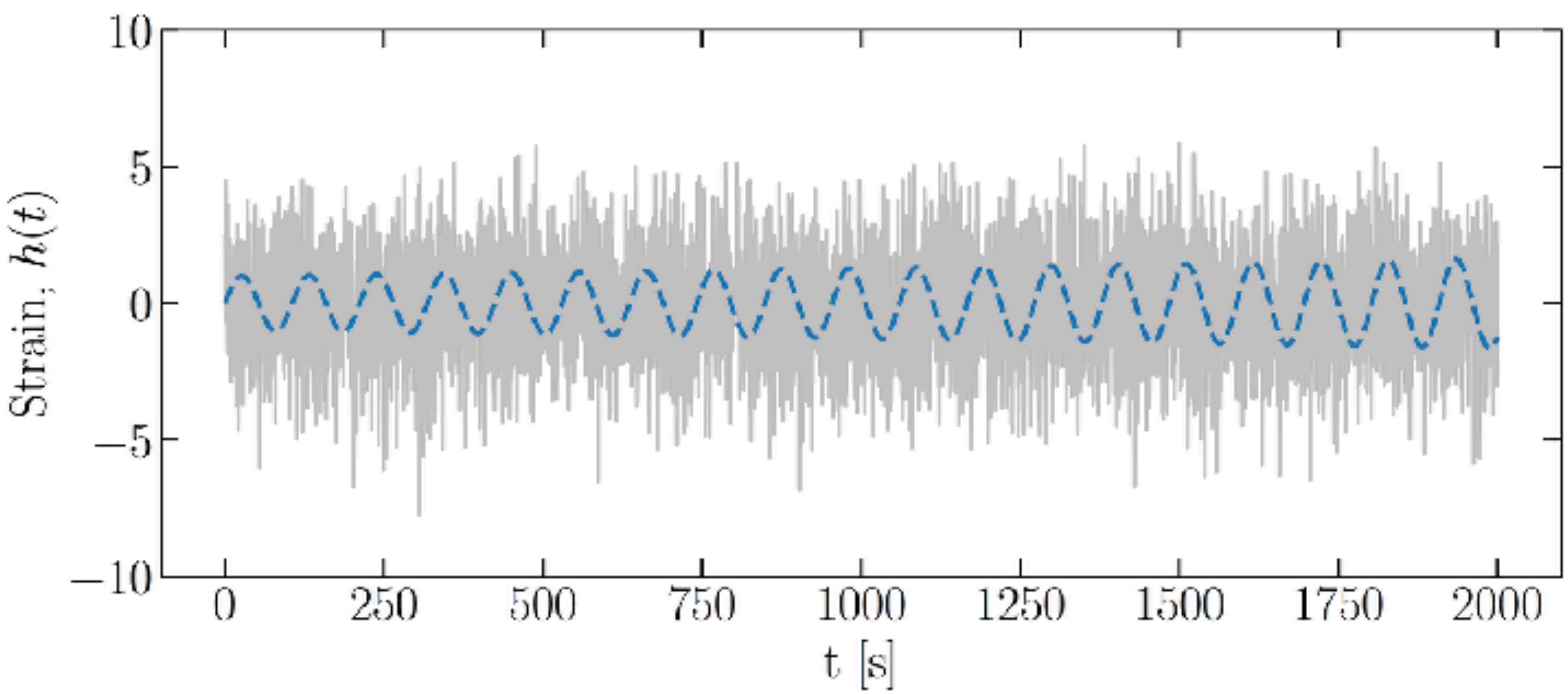
© AEI / MM / exozet



[gwplotter.com]

Intermediate Mass Ratio Inspirals (IMRIs)

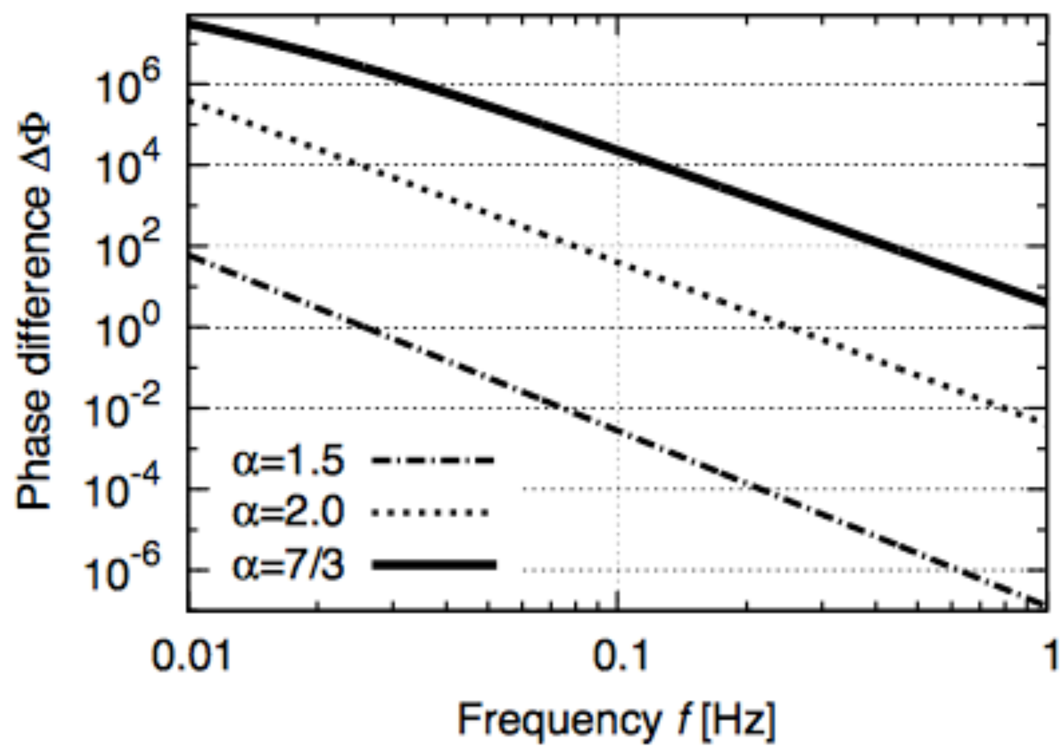


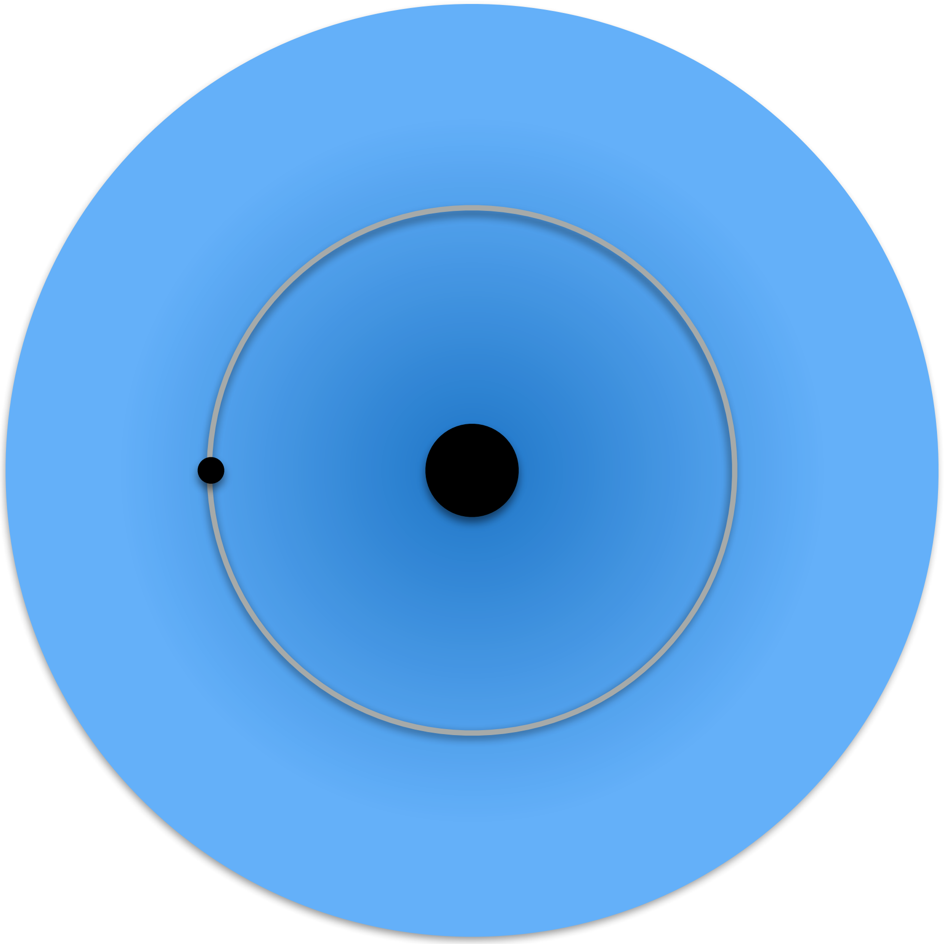


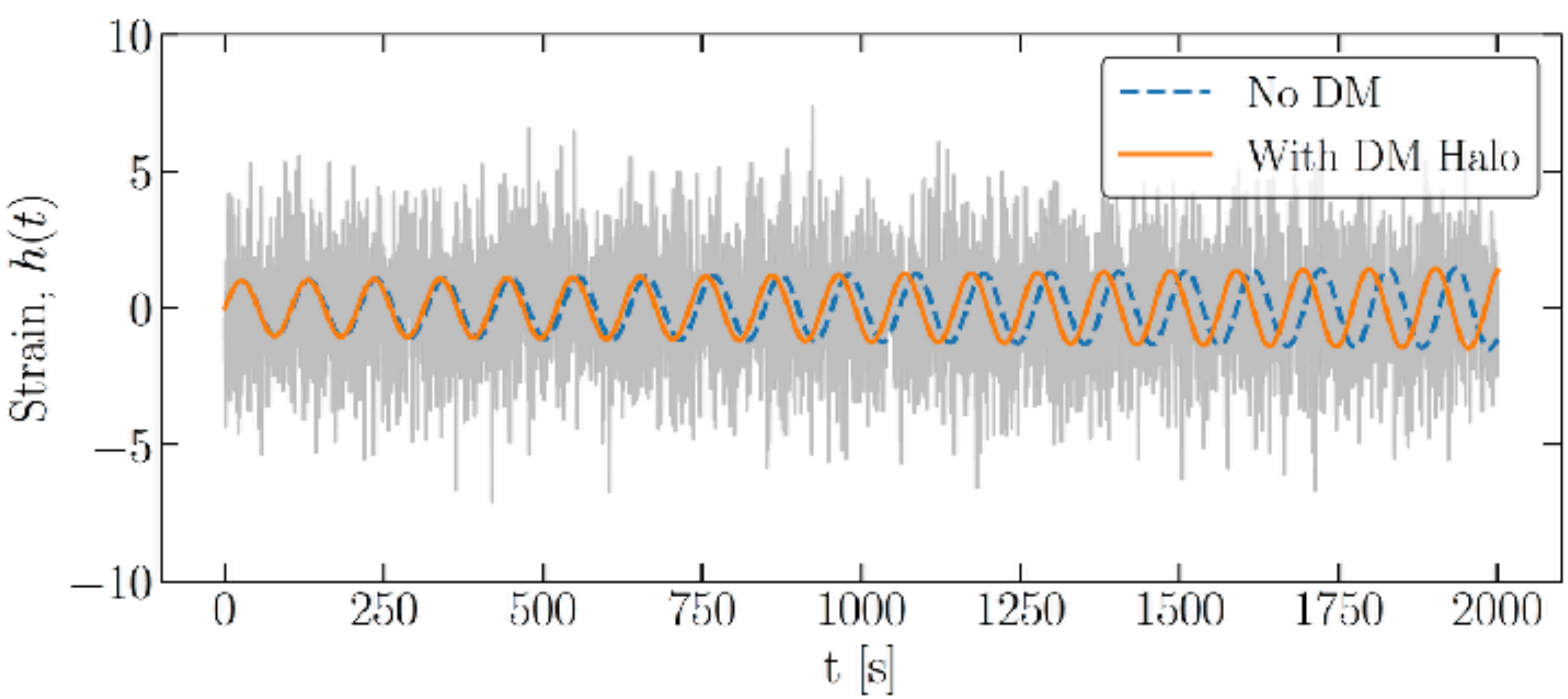
$$M_{\mathrm{IMBH}} = 1000\, M_\odot$$
$$\mu = 1\, M_\odot$$

[1705.09421,1807.03824]

Dark Matter de-phasing





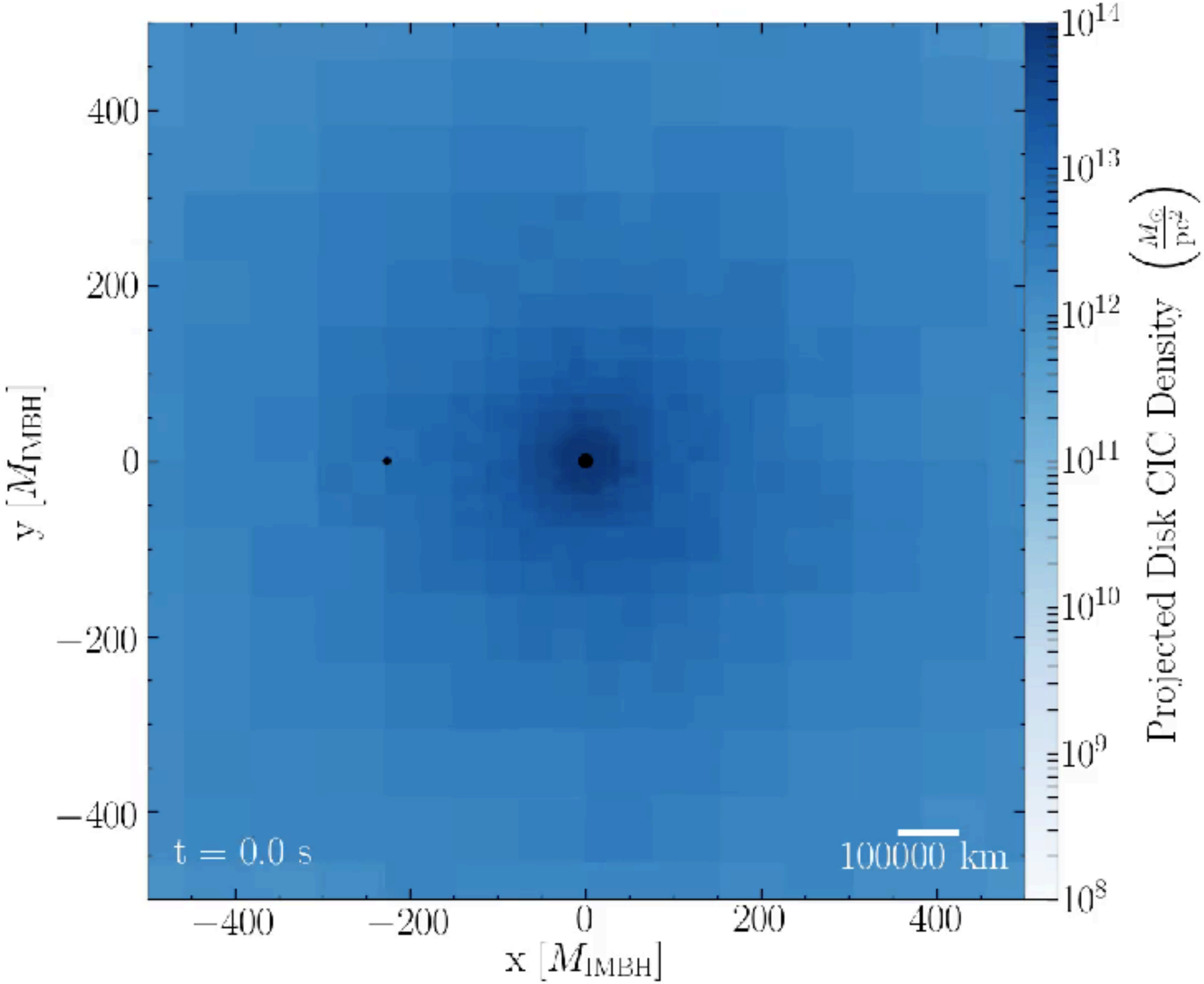


$$M_{\mathrm{IMBH}} = 1000\, M_\odot$$

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

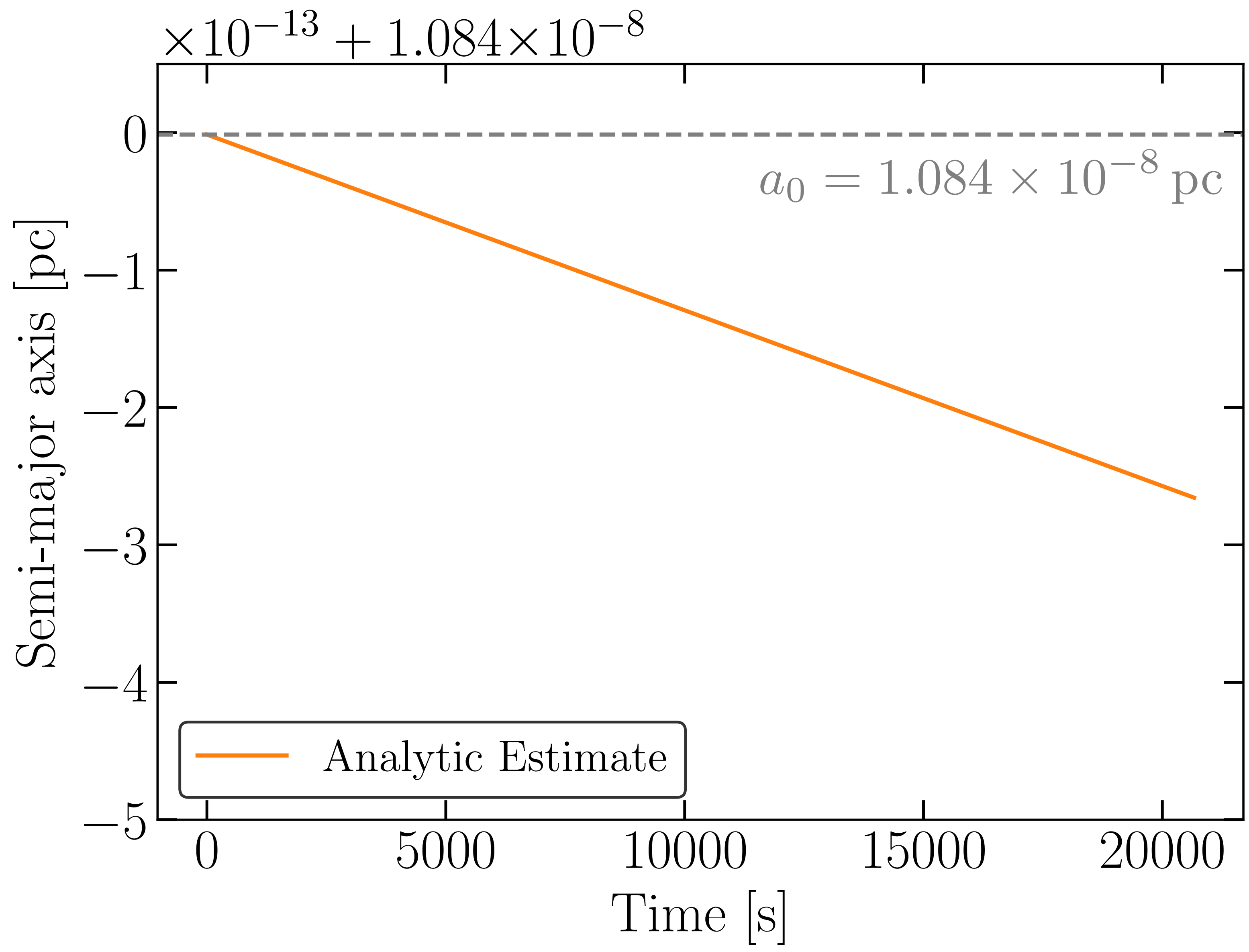
[Eda et al., 1408.3534]

Simulations



Preliminary Results

Examine change in size of the orbit
(i.e. how much faster is the binary spiralling in?)



High precision N-body sims

Gadget-II code:

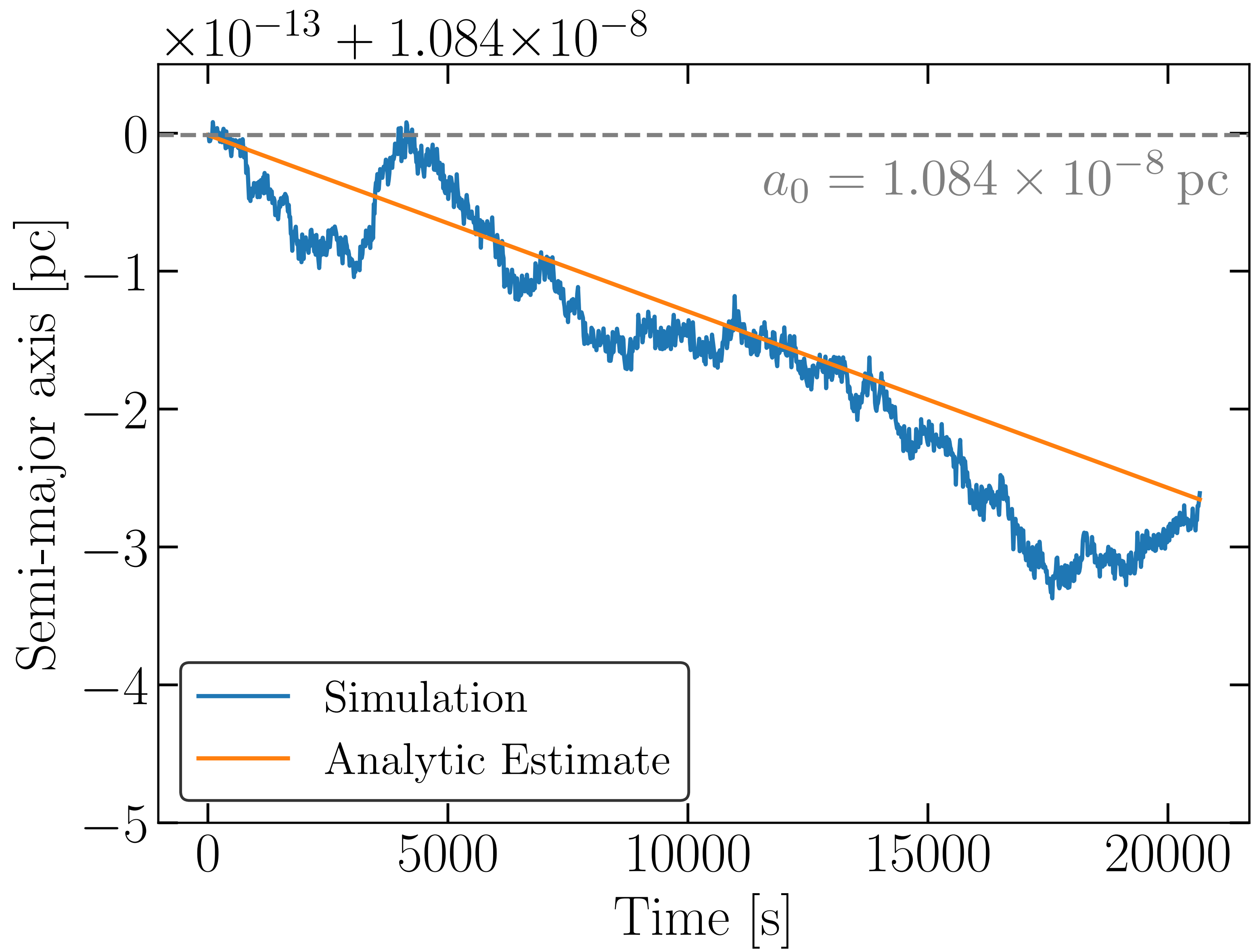
```
/* Some physical constants in cgs units */

#define  GRAVITY          6.672e-8   /*!< Gravitational constant (in cgs units) */
#define  SOLAR_MASS       1.989e33
#define  SOLAR_LUM        3.826e33
#define  RAD_CONST        7.565e-15
#define  AVOGADRO         6.0222e23
#define  BOLTZMANN        1.3806e-16
#define  GAS_CONST        8.31425e7
#define  C                2.9979e10
#define  PLANCK           6.6262e-27
#define  CM_PER_MPC       3.085678e24
#define  PROTONMASS       1.6726e-24
#define  ELECTRONMASS     9.10953e-28
#define  THOMPSON         6.65245e-25
#define  ELECTRONCHARGE   4.8032e-10
#define  HUBBLE           3.2407789e-18    /* in h/sec */
```

The Universe:

$$G_N = 6.674 \times 10^{-8}\,\mathrm{m}^3\,\mathrm{g}^{-1}\mathrm{s}^{-2}$$

Preliminary Results

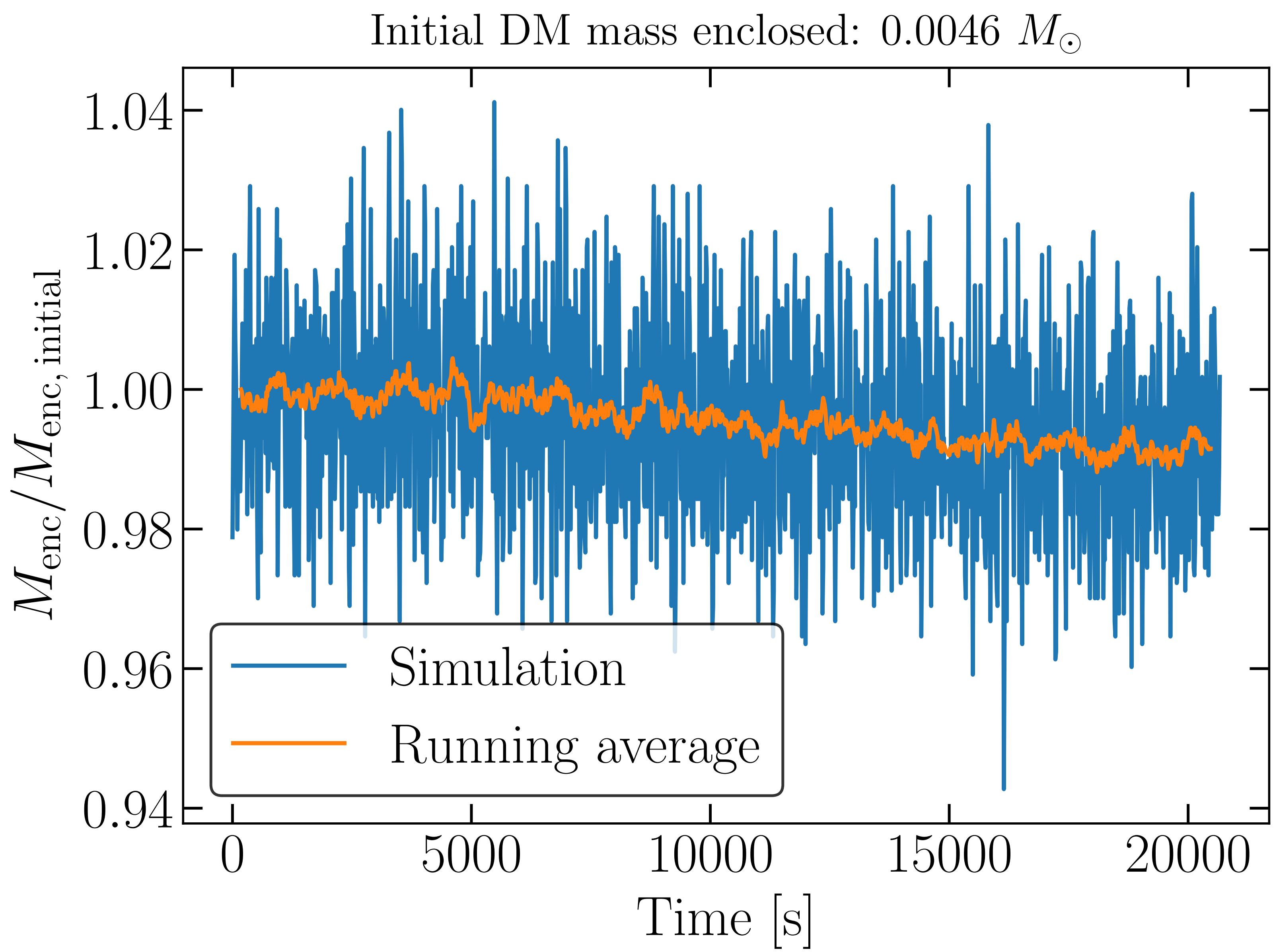
Examine change in size of the orbit
(i.e. how much faster is the binary spiralling in?)



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

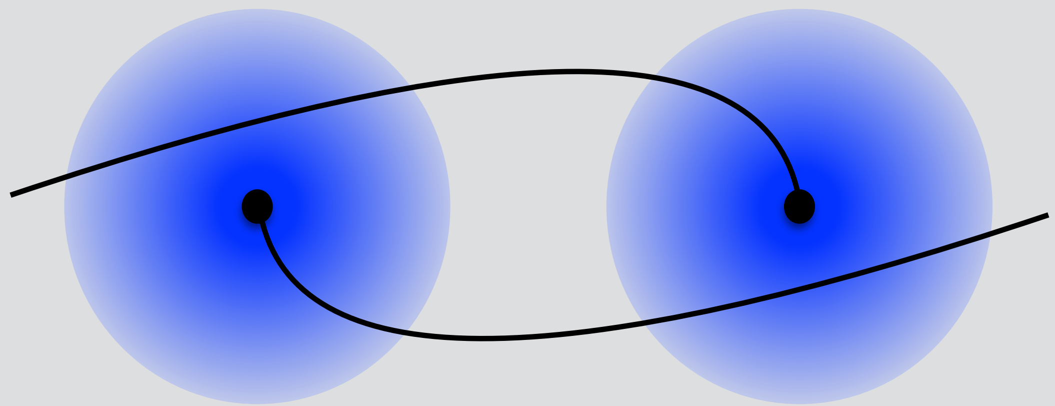
Preliminary Results

Does the DM halo survive?

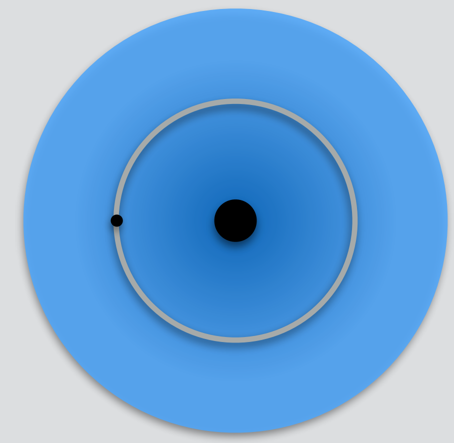


Can extract the expected GW frequency and phase.
Could we measure the halo properties this way?

Black Holes' Dark Dress



Merging Primordial Black Holes (PBHs)



Intermediate Mass-Ratio Inspirals (IMRIs)

How are BHs influenced by the \`Dark Dresses' around them?

What other effects can Dark Matter have on gravitational wave signals?

What is the relationship between PBHs and UCMHs?

What gravitational wave frequencies should we focus on in the future?

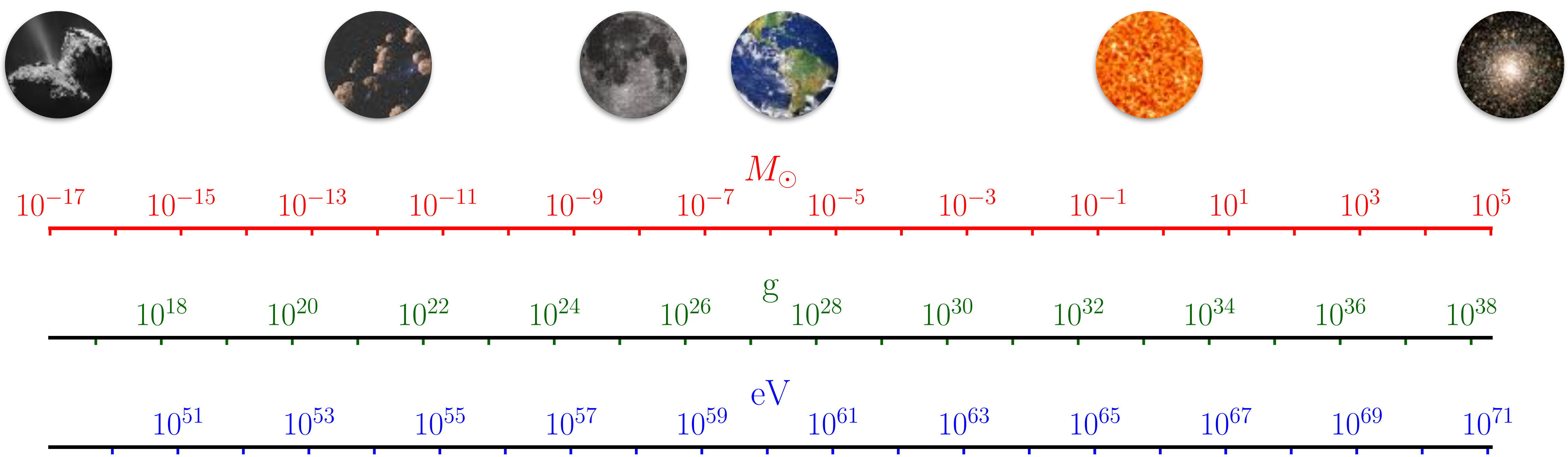
Backup Slides

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]

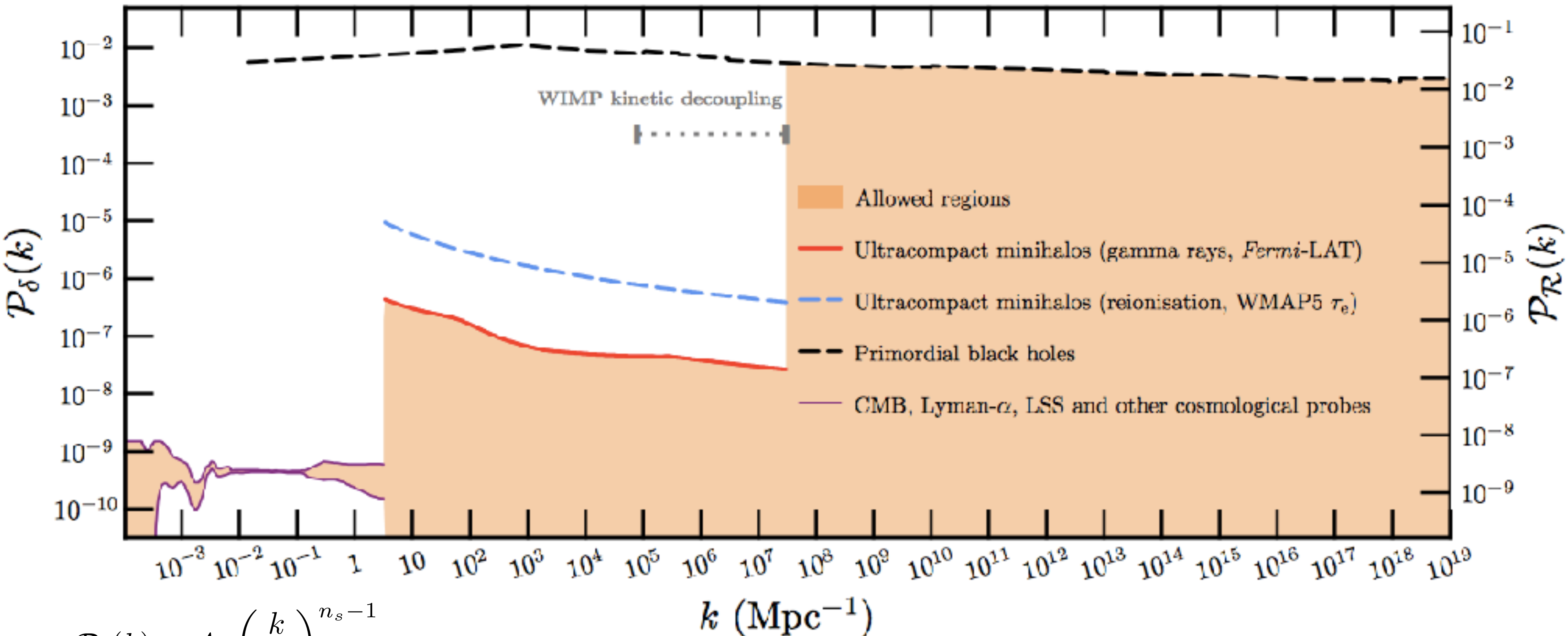


[Y. B. Zel'dovich and I. D. Novikov, Soviet Astronomy 10, 602 (1967)]
[S. Hawking, Mon. Not. R. Astron. Soc. 152, 75 (1971)]
[Carr and Hawking, MNRAS 168 (1974); Carr, Astrophys. J. 201, 1 (1975)]

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…

First Remapping

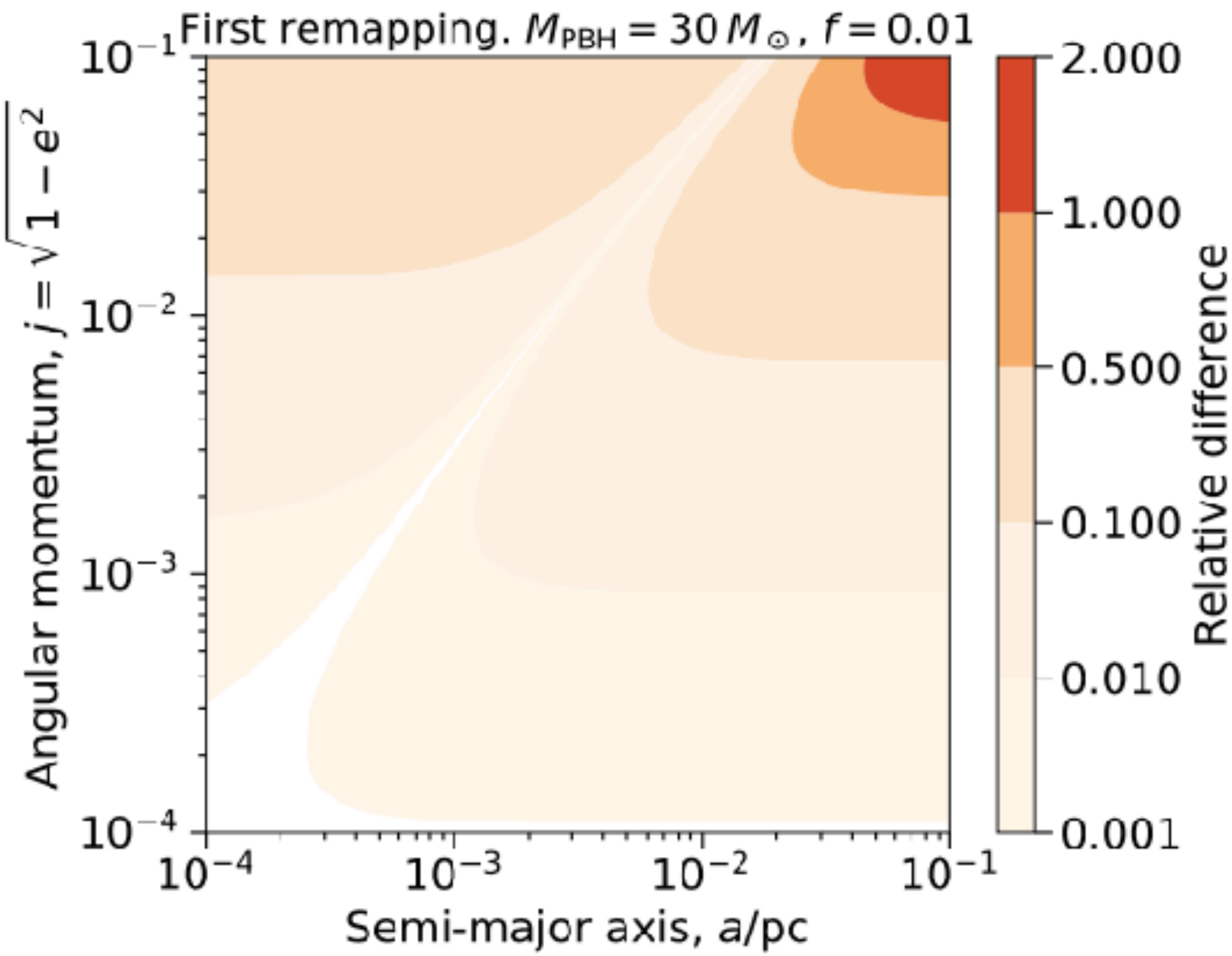
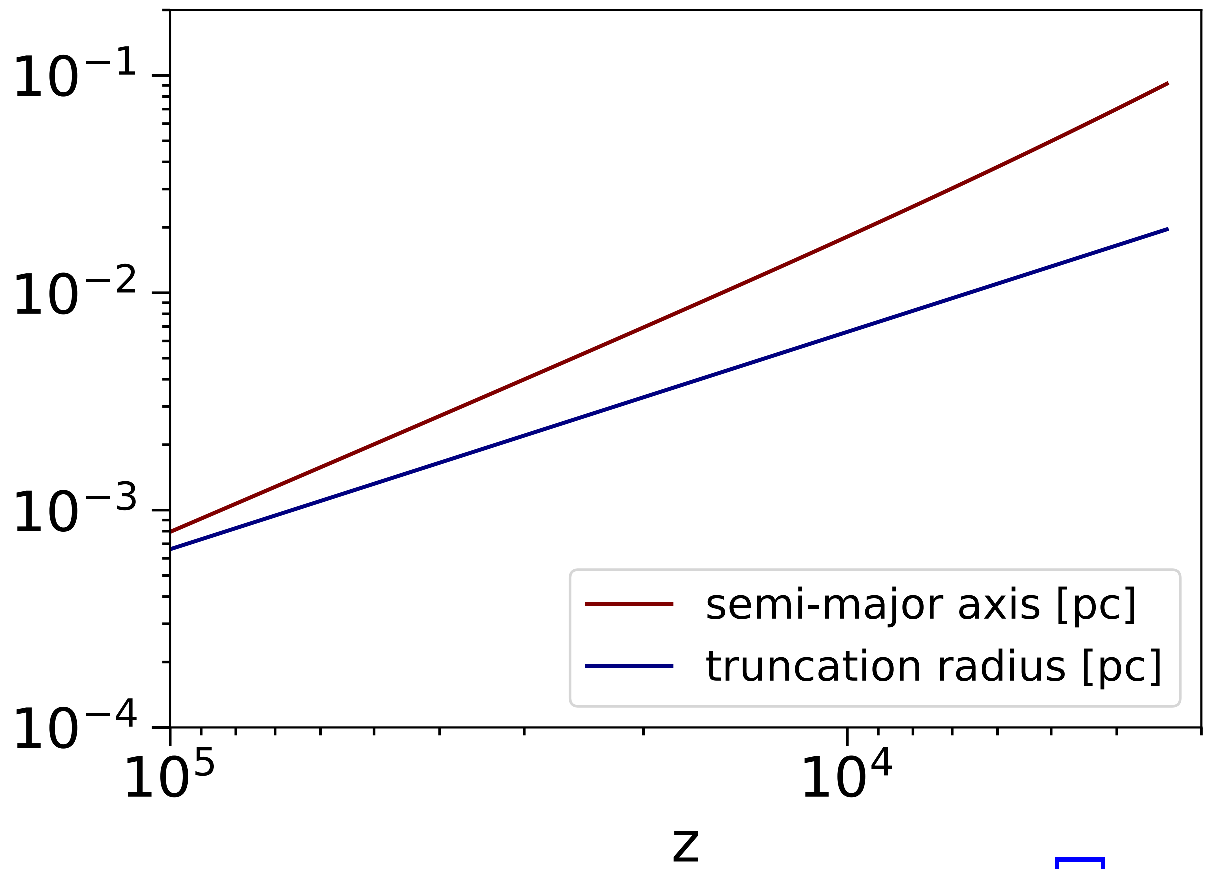
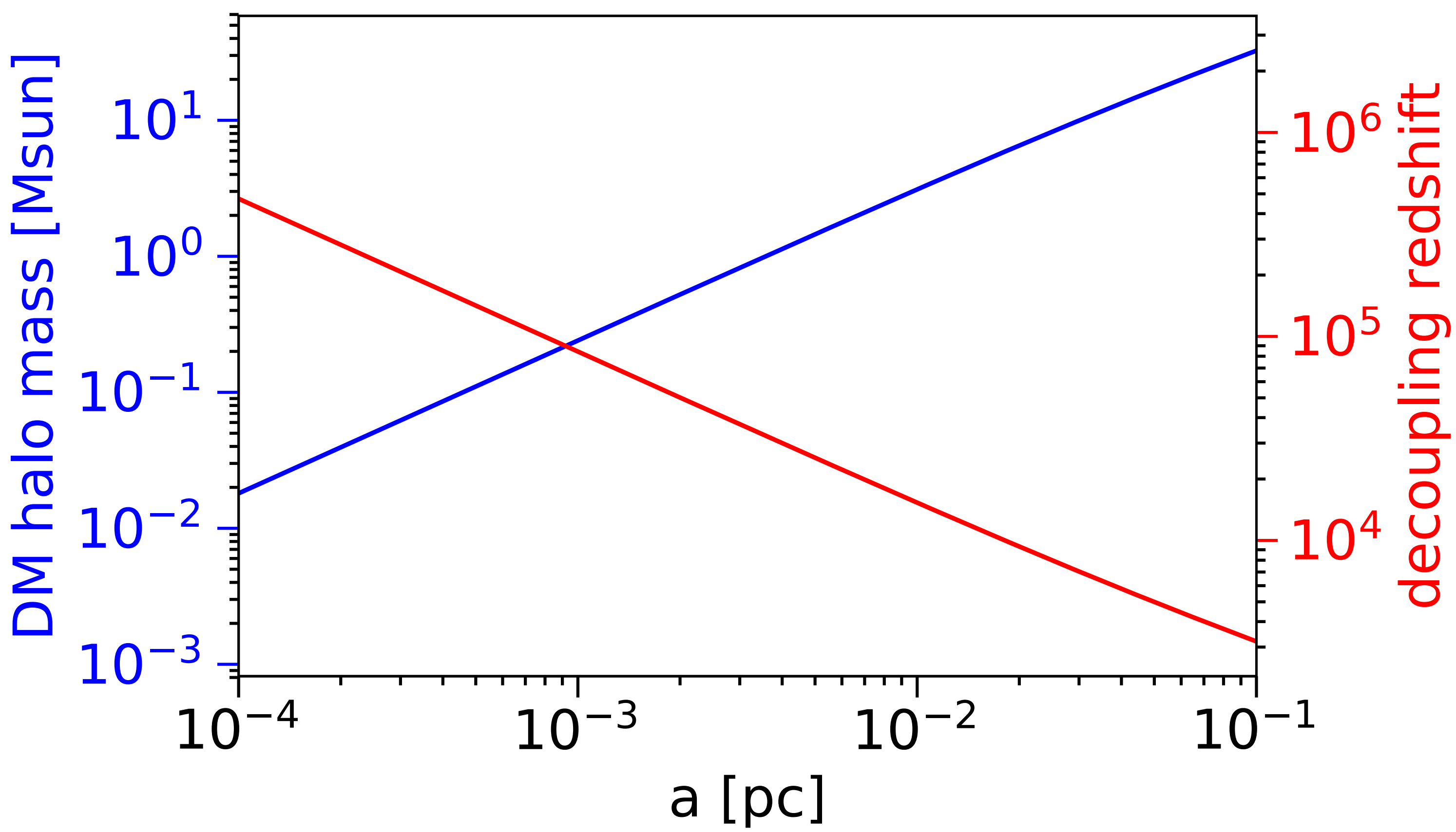


FIG. 5. **First remapping.** We represent the relative difference between the original PDF in the (a, j) parameter space and the one which takes into account the presence of the mini-halos (as described in Sec. II C). We remark that this initial remapping is mainly based on a rescaling of the mass parameter,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

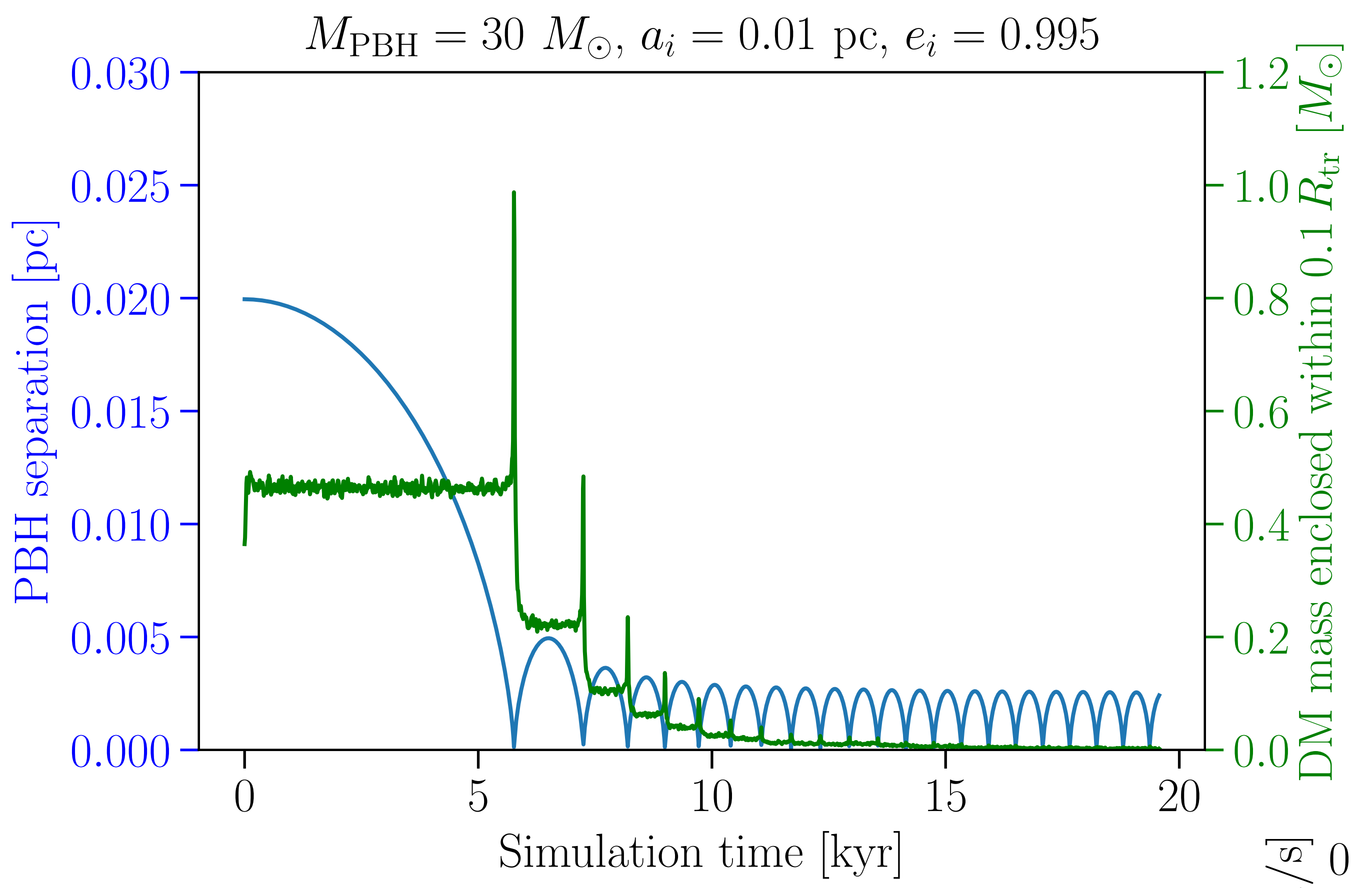
Decoupling and Halo Mass

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

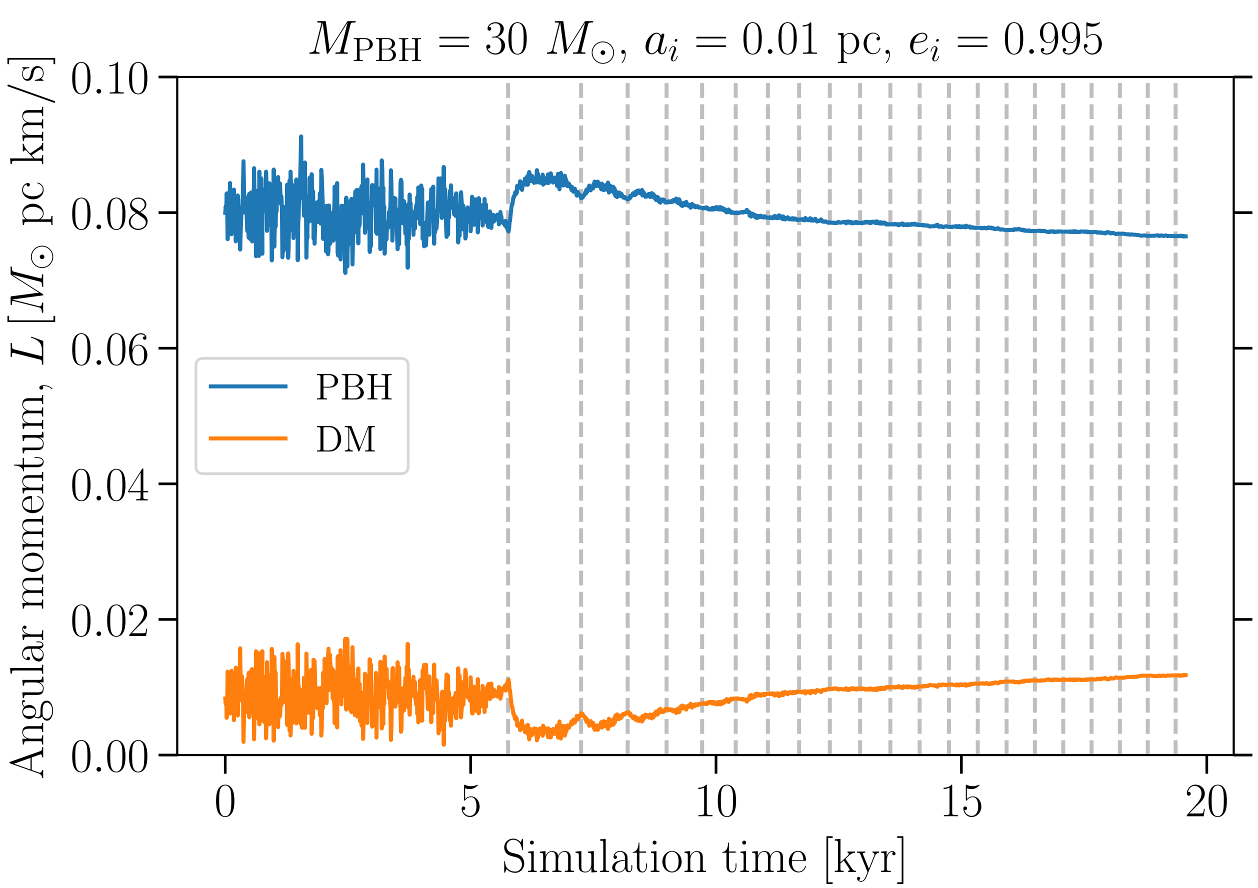




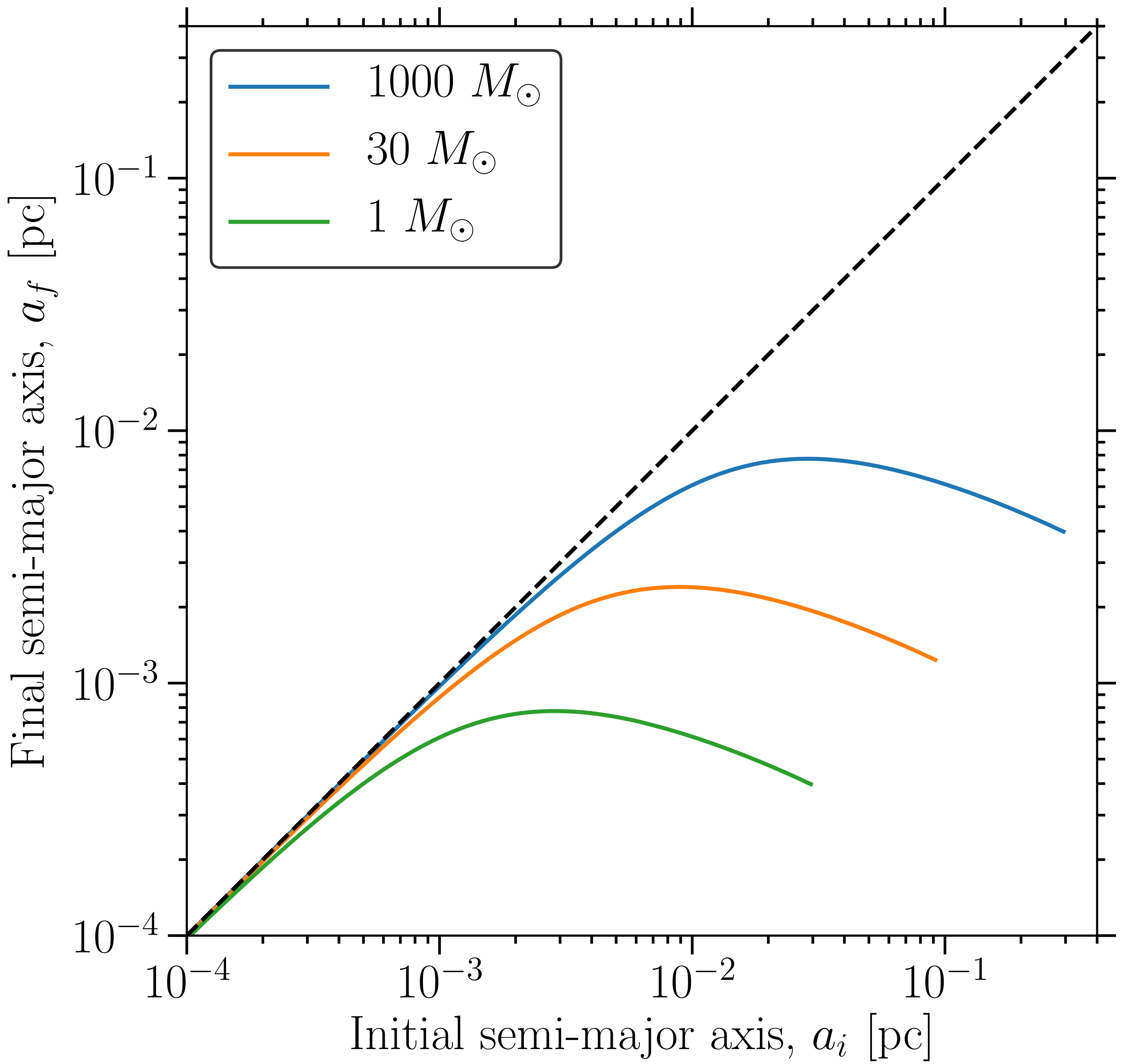
Binary Evolution



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



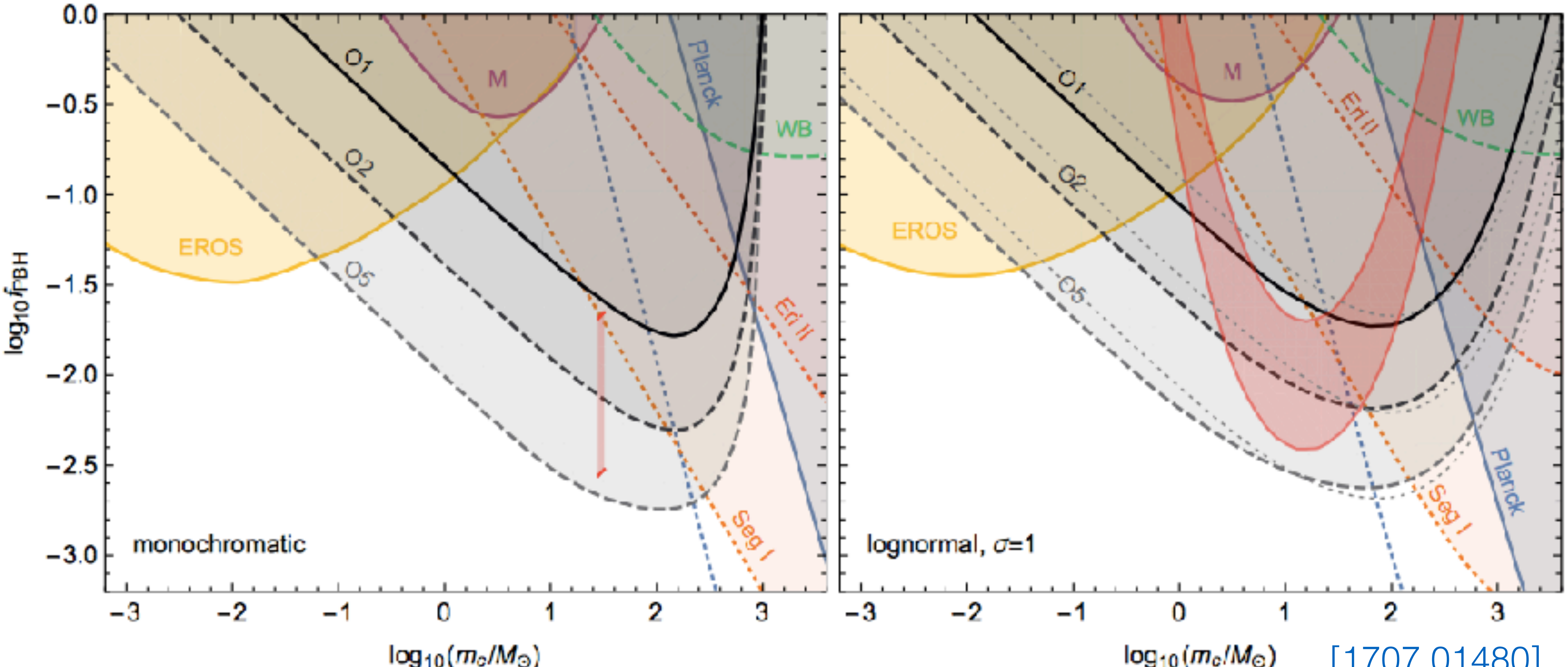
Remapping the semi-major axis



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

Extended mass functions

LIGO O1 Limit



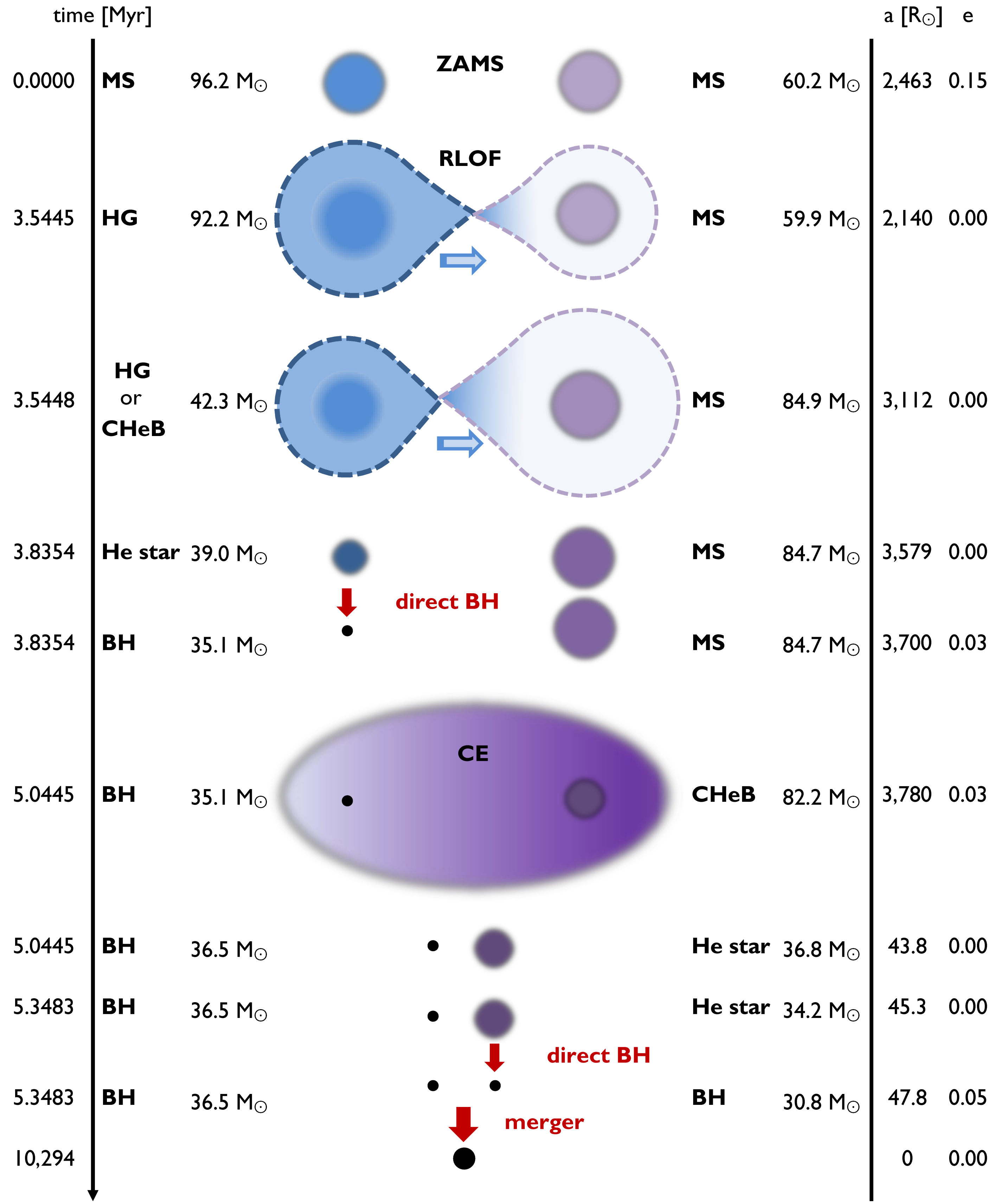
[1707.01480]

"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.

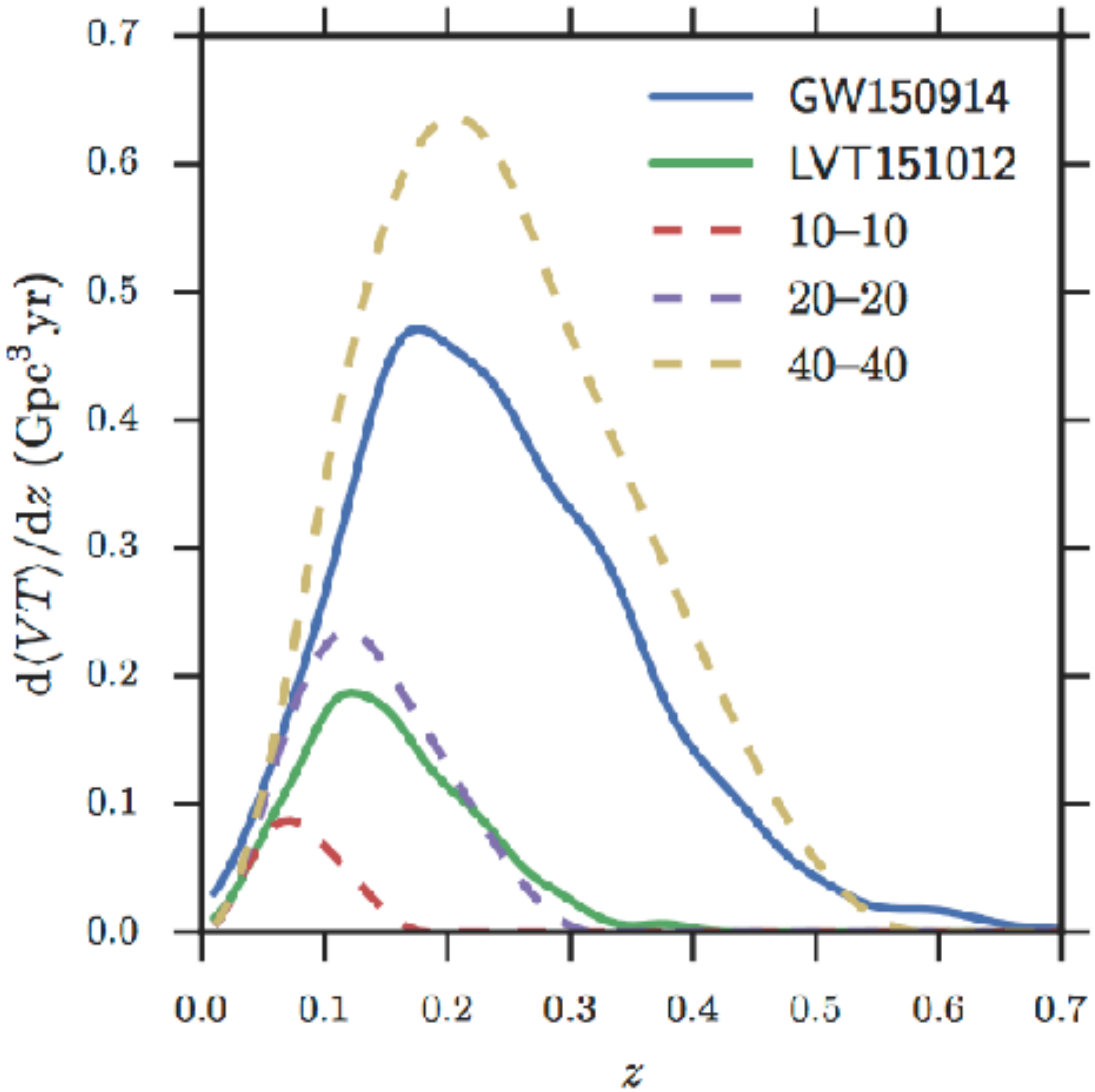
For 'high-resolution' simulations, we use a multi-mass scheme in which the DM halo is composed of 4 different masses of pseudo-particles.

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

LIGO Sensitivity

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

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



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

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