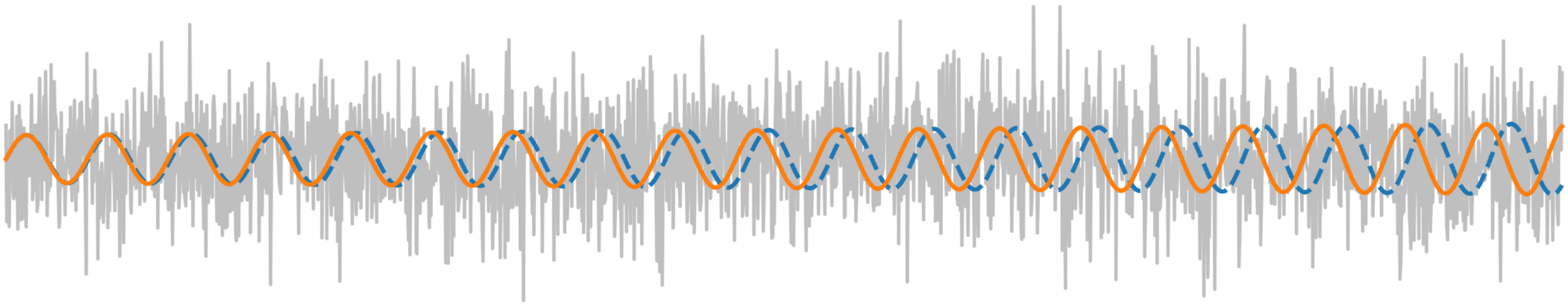
Dark Matter, Black Holes, Gravitational Waves and Werewolves



Bradley J Kavanagh
GRAPPA, University of Amsterdam

IFCA, 7th October 2019

GRAPPA
GRavitation AstroParticle Physics Amsterdam

SURF SARA
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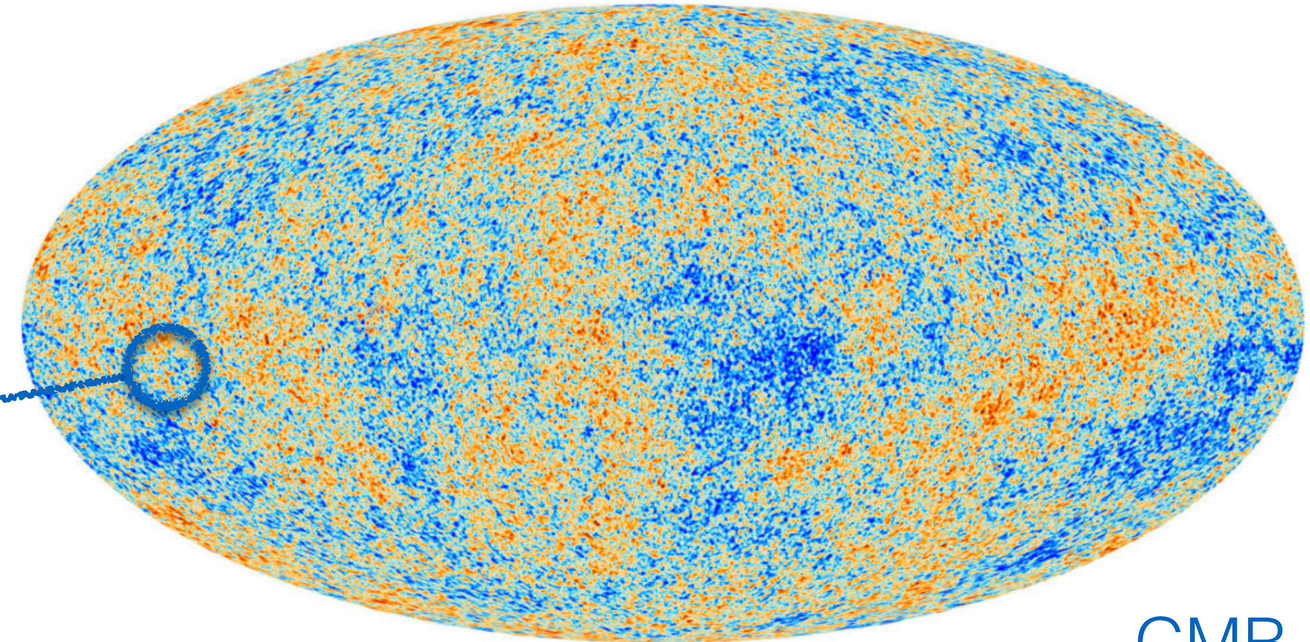
@BradleyKavanagh

Werewolves

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

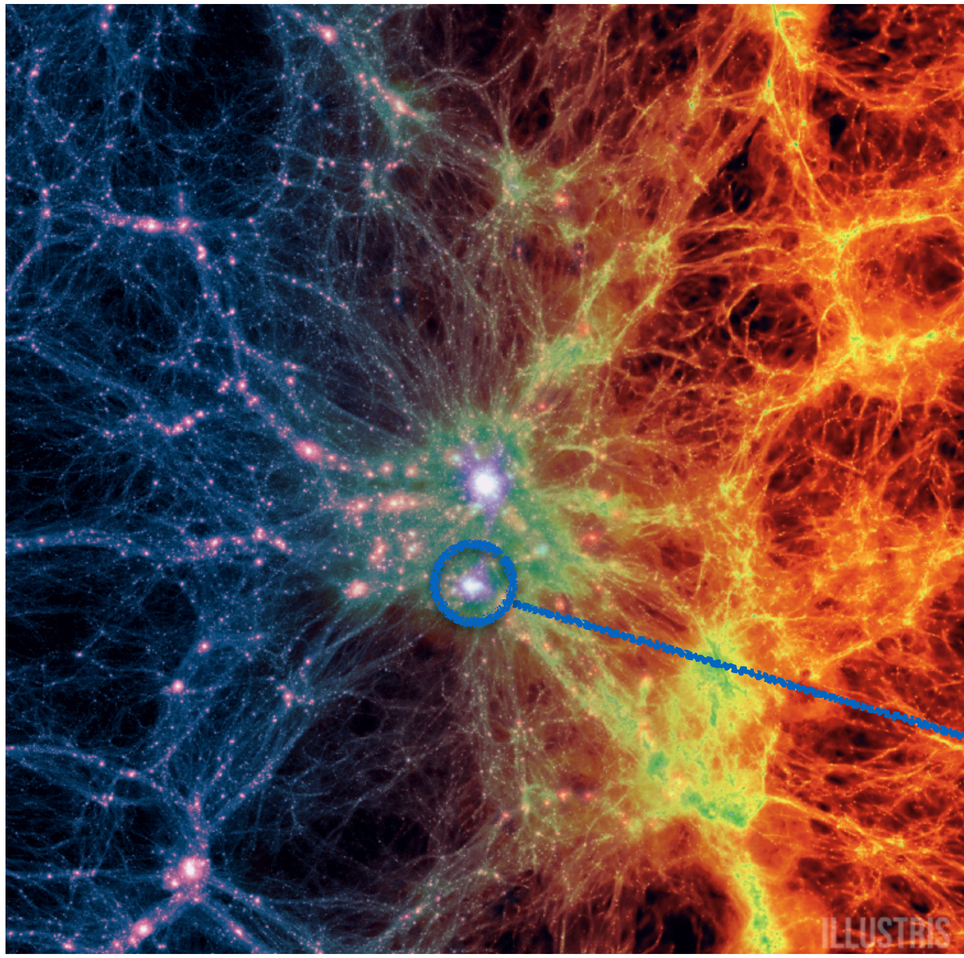
aaronsimscompany

Dark Matter on all scales



CMB

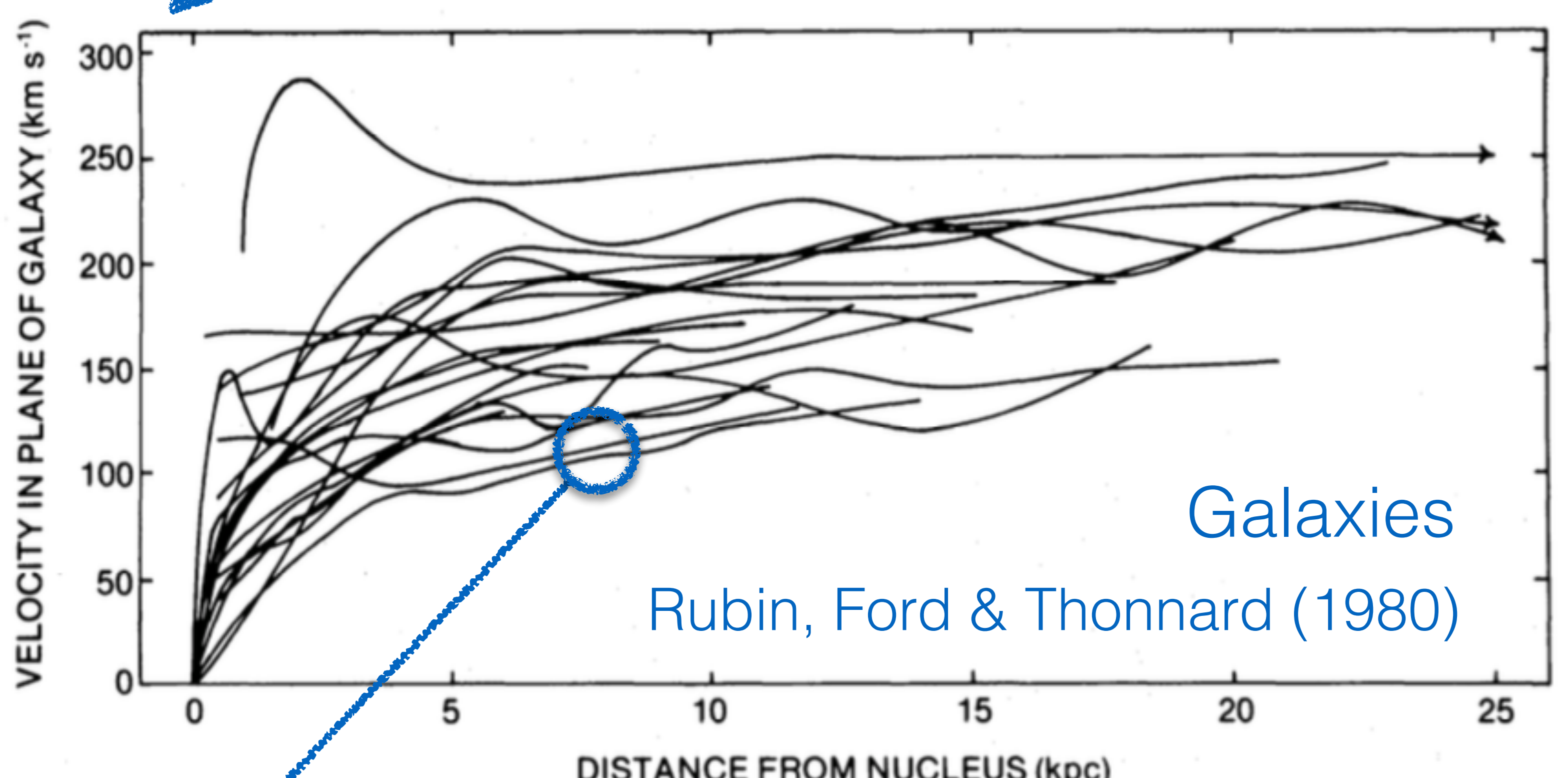
Planck [1502.01589]



Galaxy clusters

[Illustris, 1405.2921]

[astro-ph/0006397]

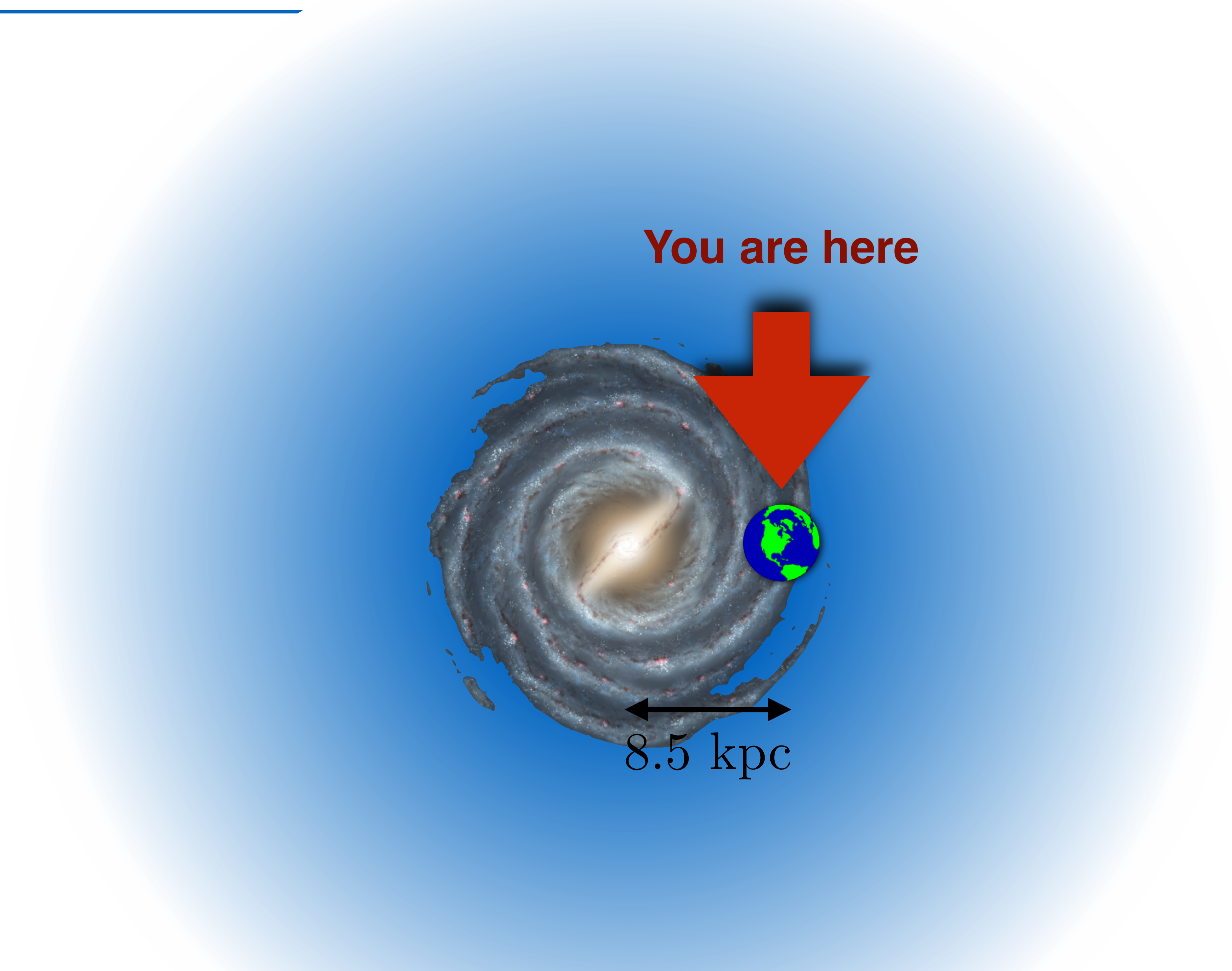


Galaxies

Rubin, Ford & Thonnard (1980)

Dark Matter at Earth

NOT TO SCALE

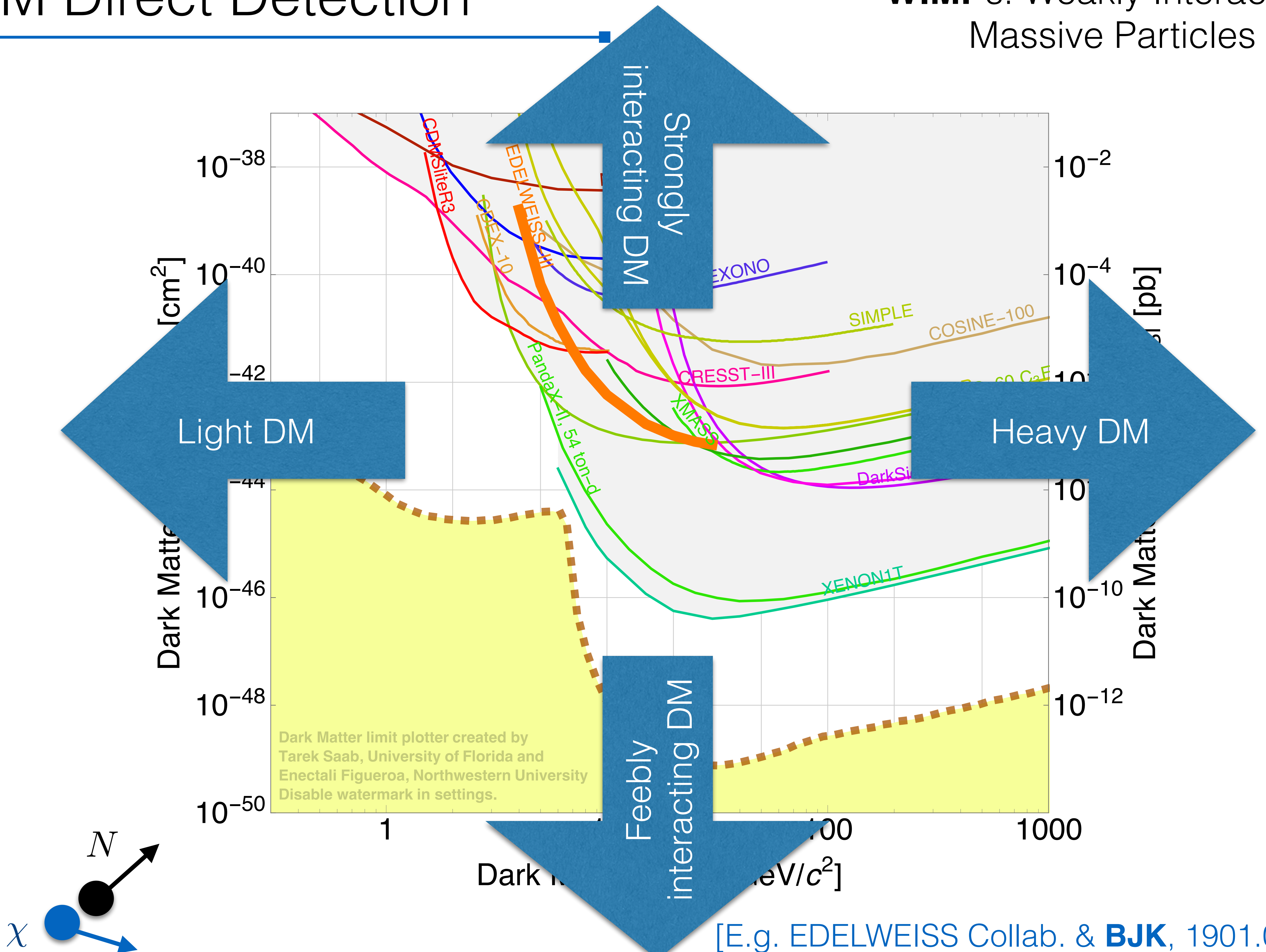


Global and local estimates of
DM at Solar radius give: $\rho_\chi \sim 0.2 - 0.8 \ \mathrm{GeV\ cm^{-3}}$

E.g. Iocco et al. [1502.03821],
Garbari et al. [1206.0015],
Read [1404.1938]

DM Direct Detection

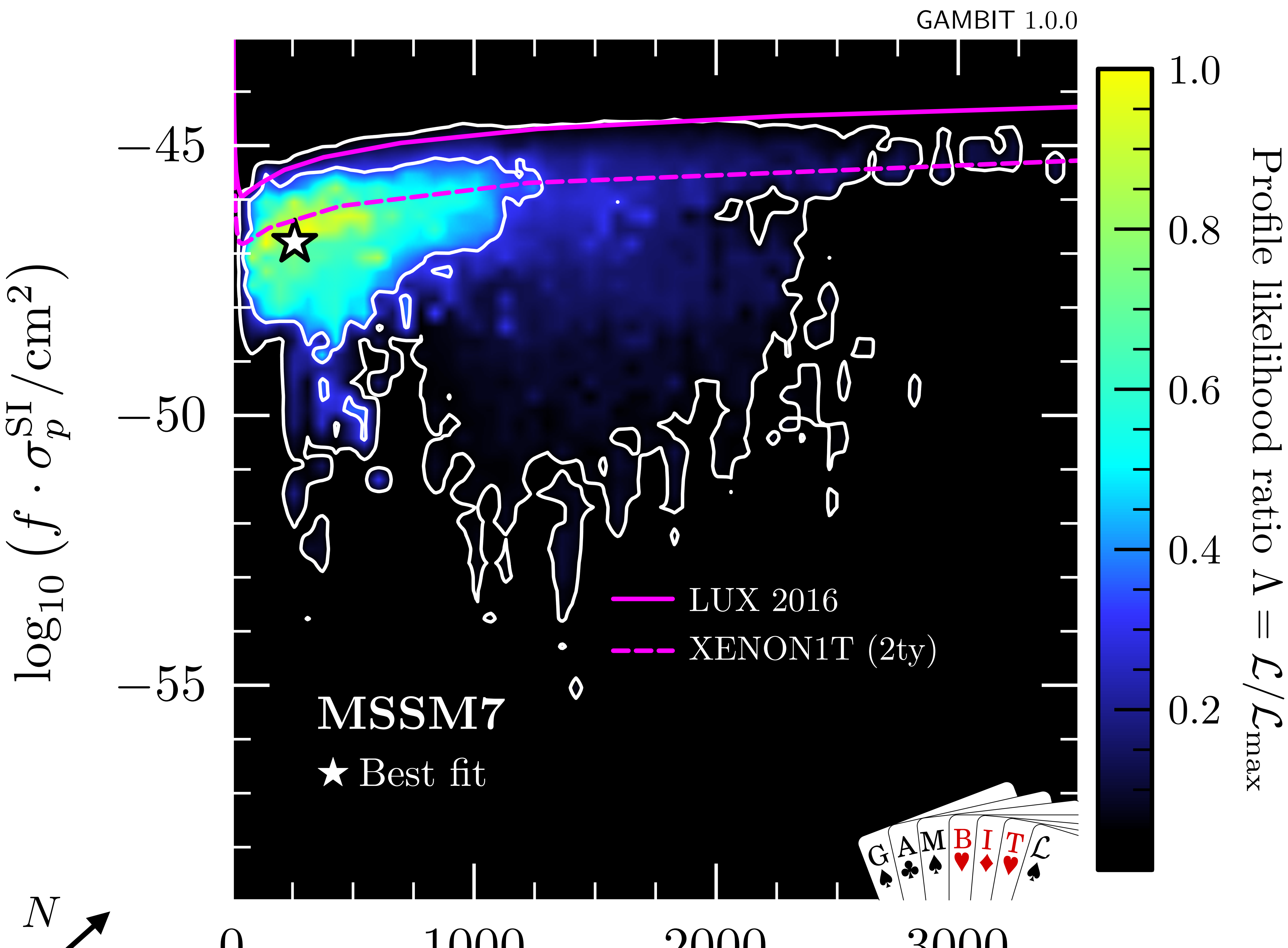
WIMPs: Weakly Interacting Massive Particles

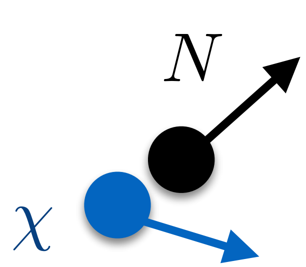


[E.g. EDELWEISS Collab. & **BJK**, 1901.03588]

DM Direct Detection

WIMPs: Weakly Interacting Massive Particles



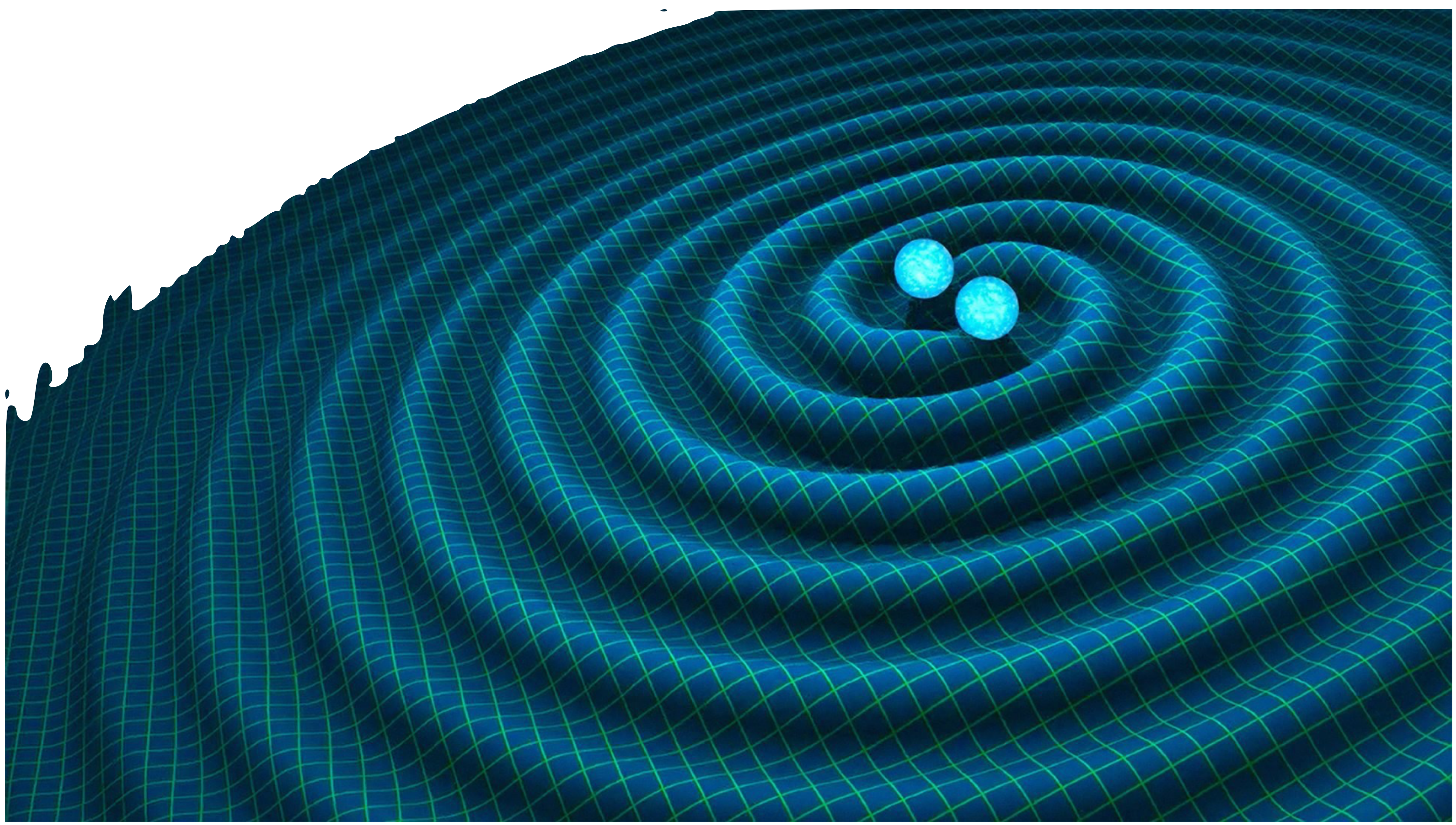


[GAMBIT, 1705.07917]

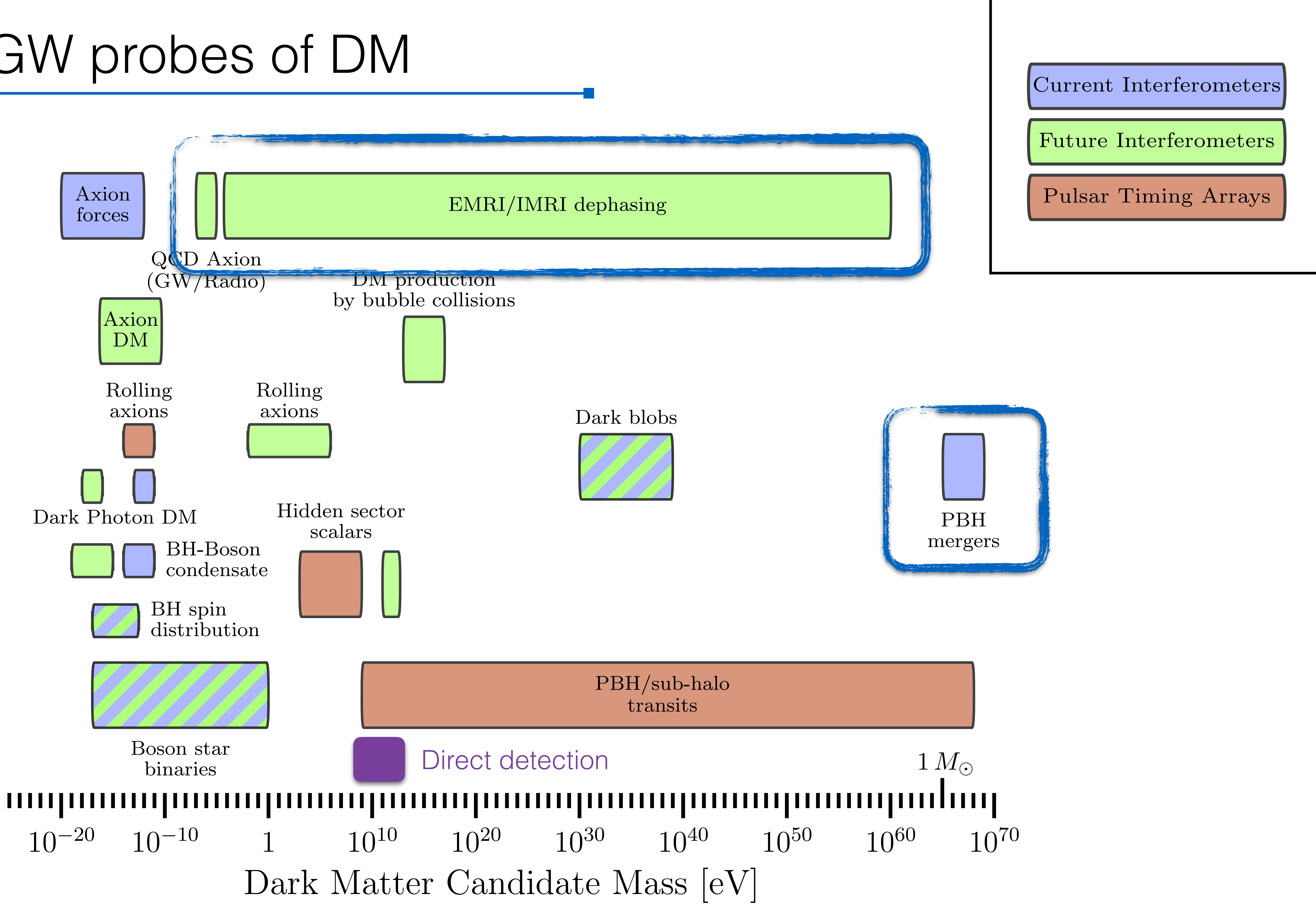
Gravitational Waves

Waves in space-time, generated by a changing mass quadrupole moment

R. HURT / CALTECH-JPL / HANDOUT/ ESA

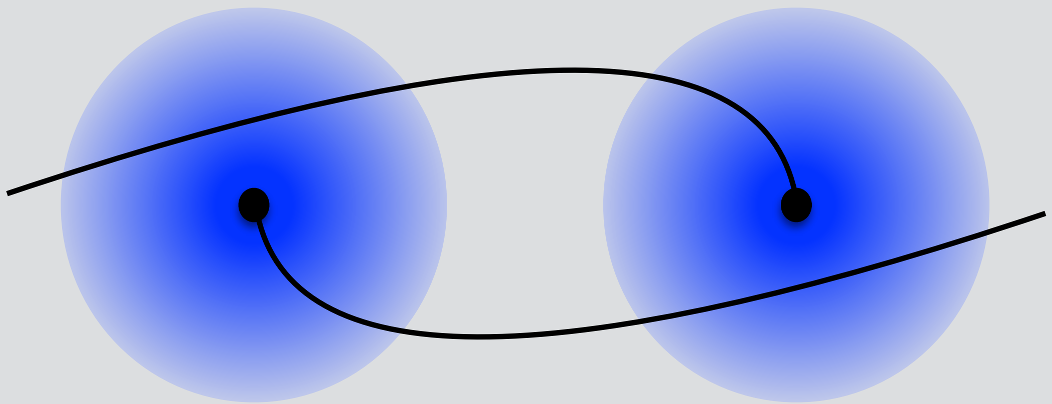


GW probes of DM



[1907.10610]

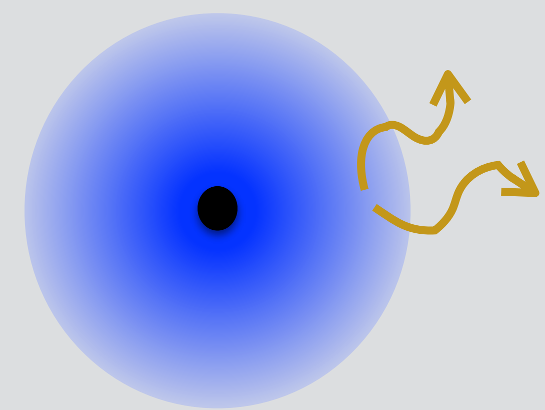
Overview



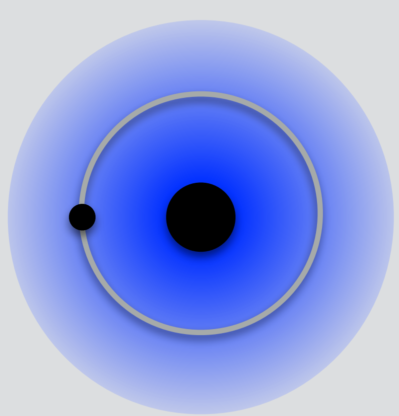
Merging Primordial Black Holes (PBHs)

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

DM Annihilation around PBHs



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



Intermediate Mass-Ratio Inspirals (IMRIs)

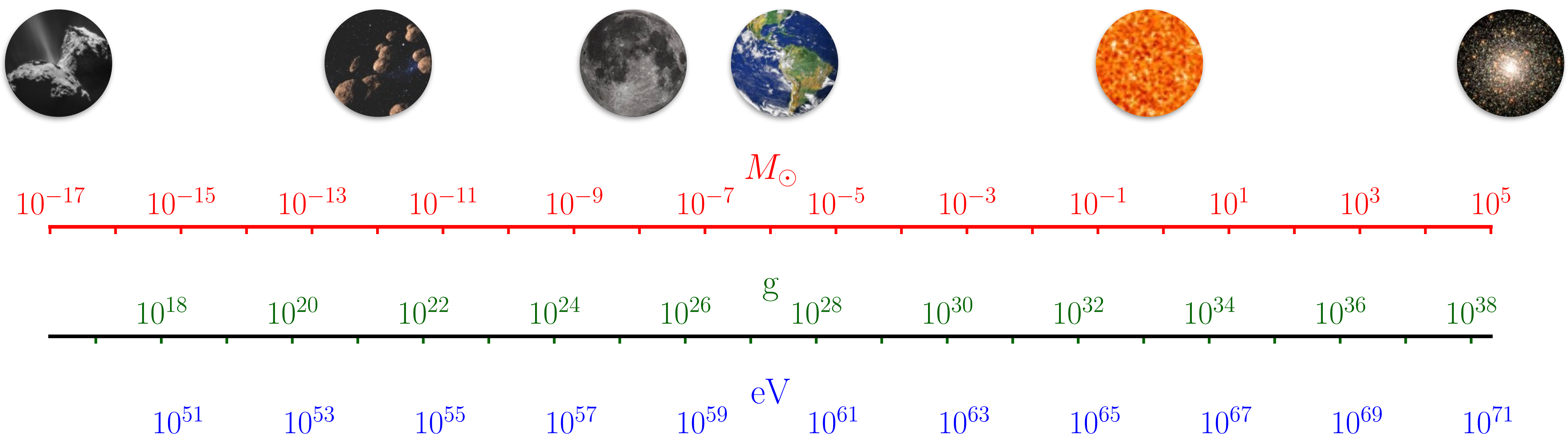
[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

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]

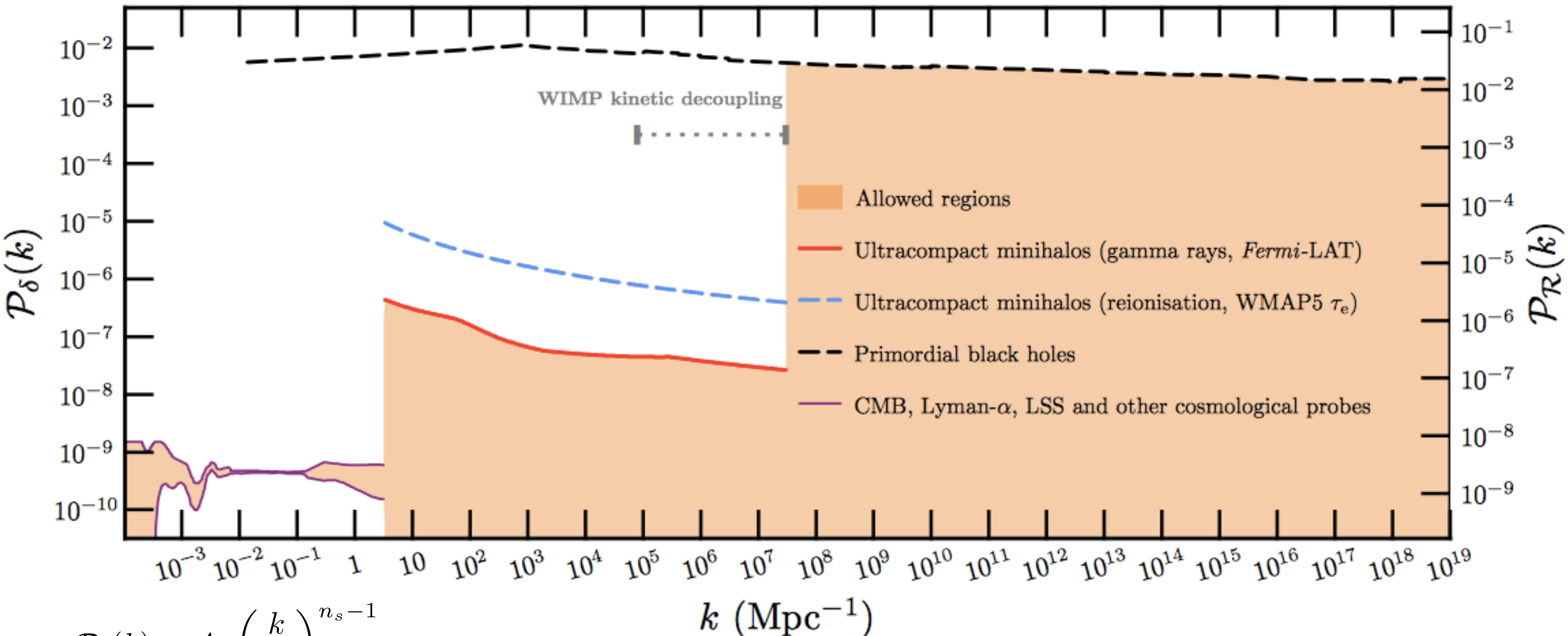


[Y. B. Zel'dovich and I. D. Novikov, Soviet Astronomy 10, 602 (1967)]
[S. Hawking, Mon. Not. R. Astron. Soc. 152, 75 (1971)]
[Carr and Hawking, MNRAS 168 (1974); Carr, Astrophys. J. 201, 1 (1975)]

Primordial Black Holes

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

[1110.2484]



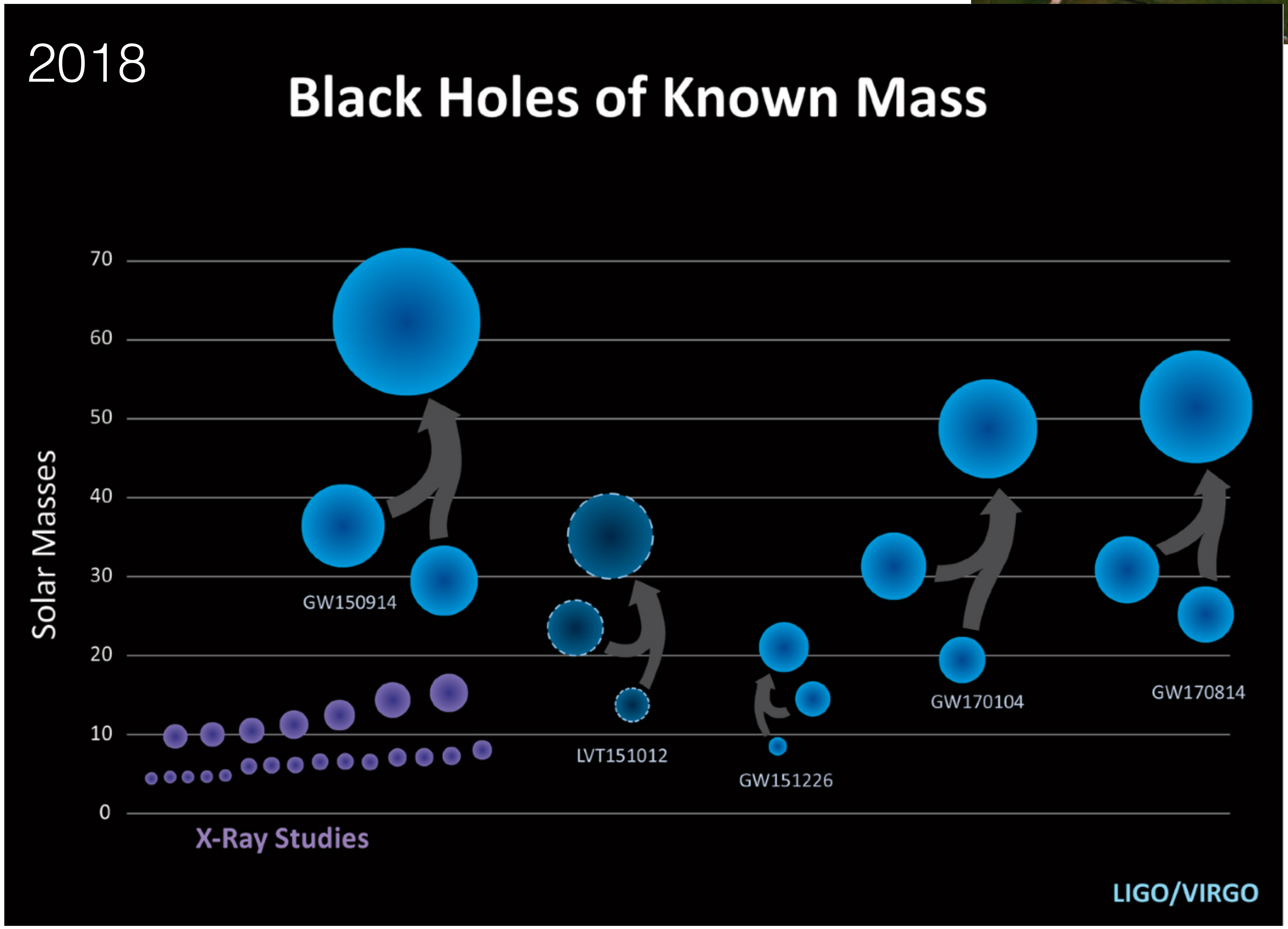
$$\mathcal{P}_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

…but small scale power spectrum is largely unconstrained.

LIGO/Virgo Mergers

The Virgo collaboration/CCO 1.0

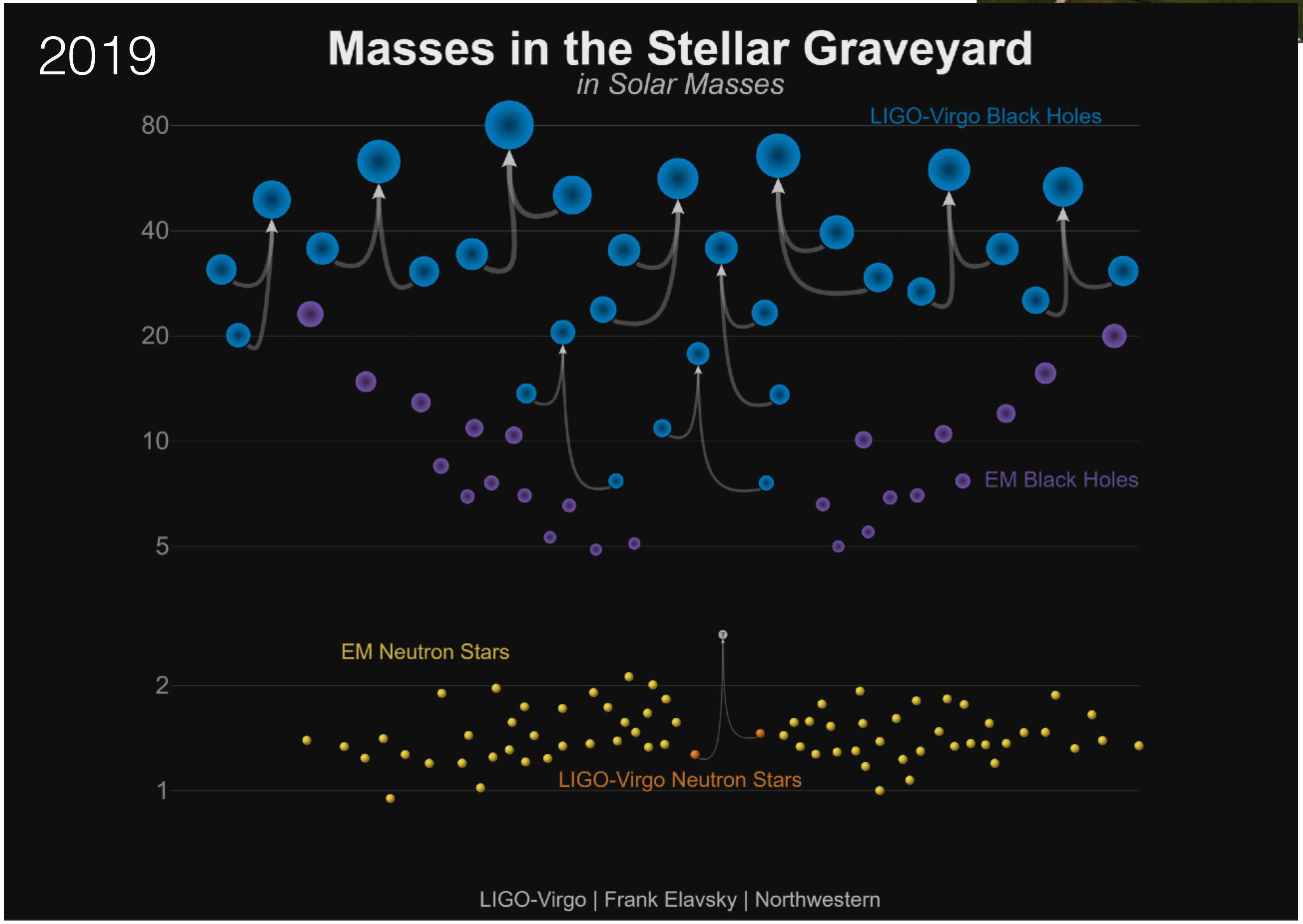
LIGO/Caltech/Sonoma State (Aurore Simonnet)



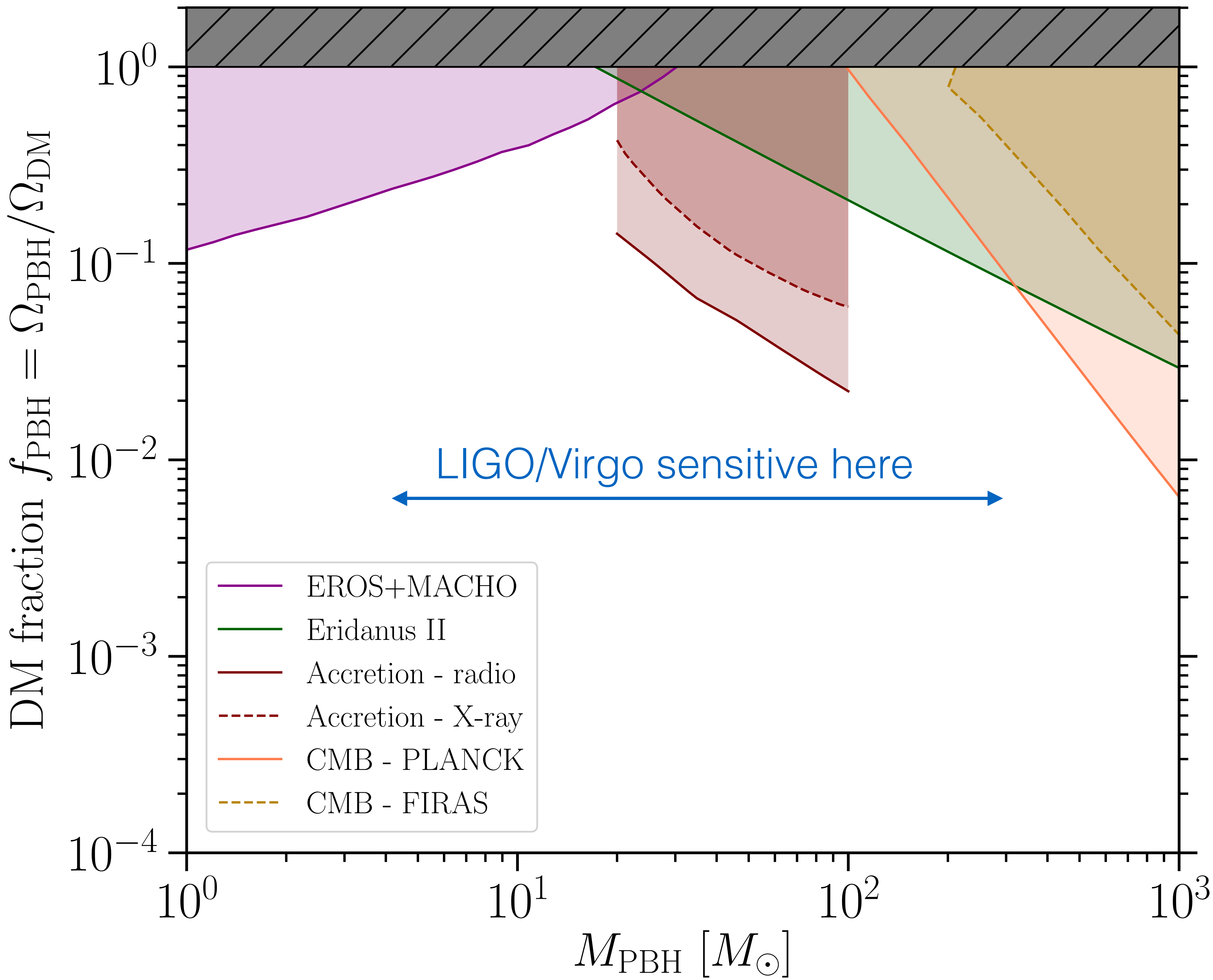
LIGO/Virgo Mergers

The Virgo collaboration/CCO 1.0

LIGO/VIrgo/Northwestern Univ. (Frank Elavsky)



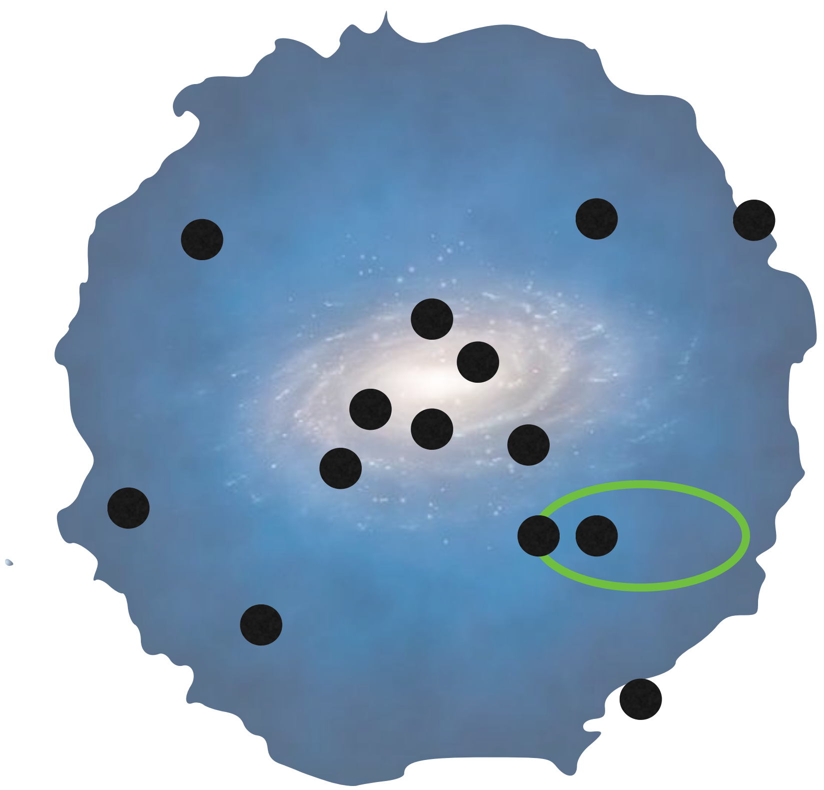
PBHs as Dark Matter



A tale of two binaries

A) Binaries formed after close encounters

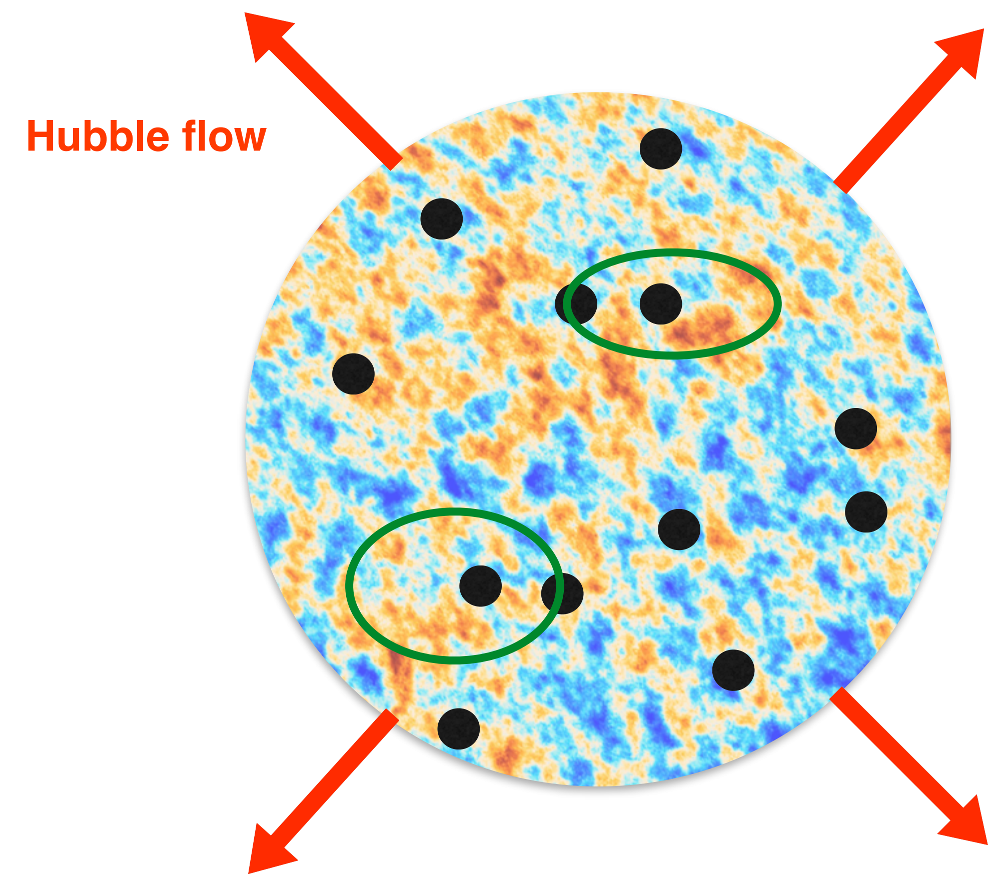
[Bird et al., 1603.00464]



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

B) Binaries formed in the early Universe

[Sasaki et al, 1603.08338]

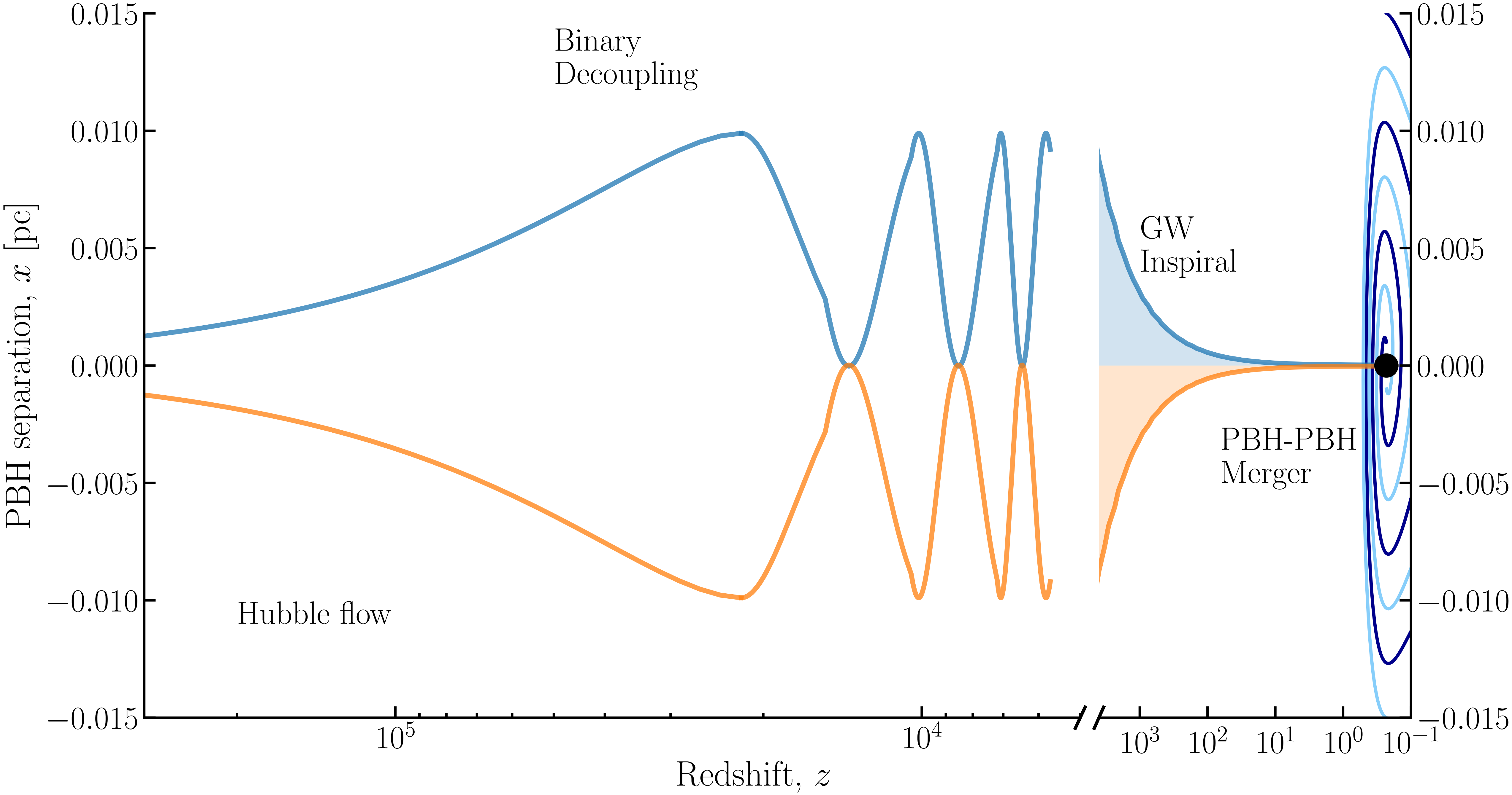


Require:

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

[Daniele Gaggero, UCI 20/02/2018]

Life of a PBH binary



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

$e = 0.995$

PBH Binary Population

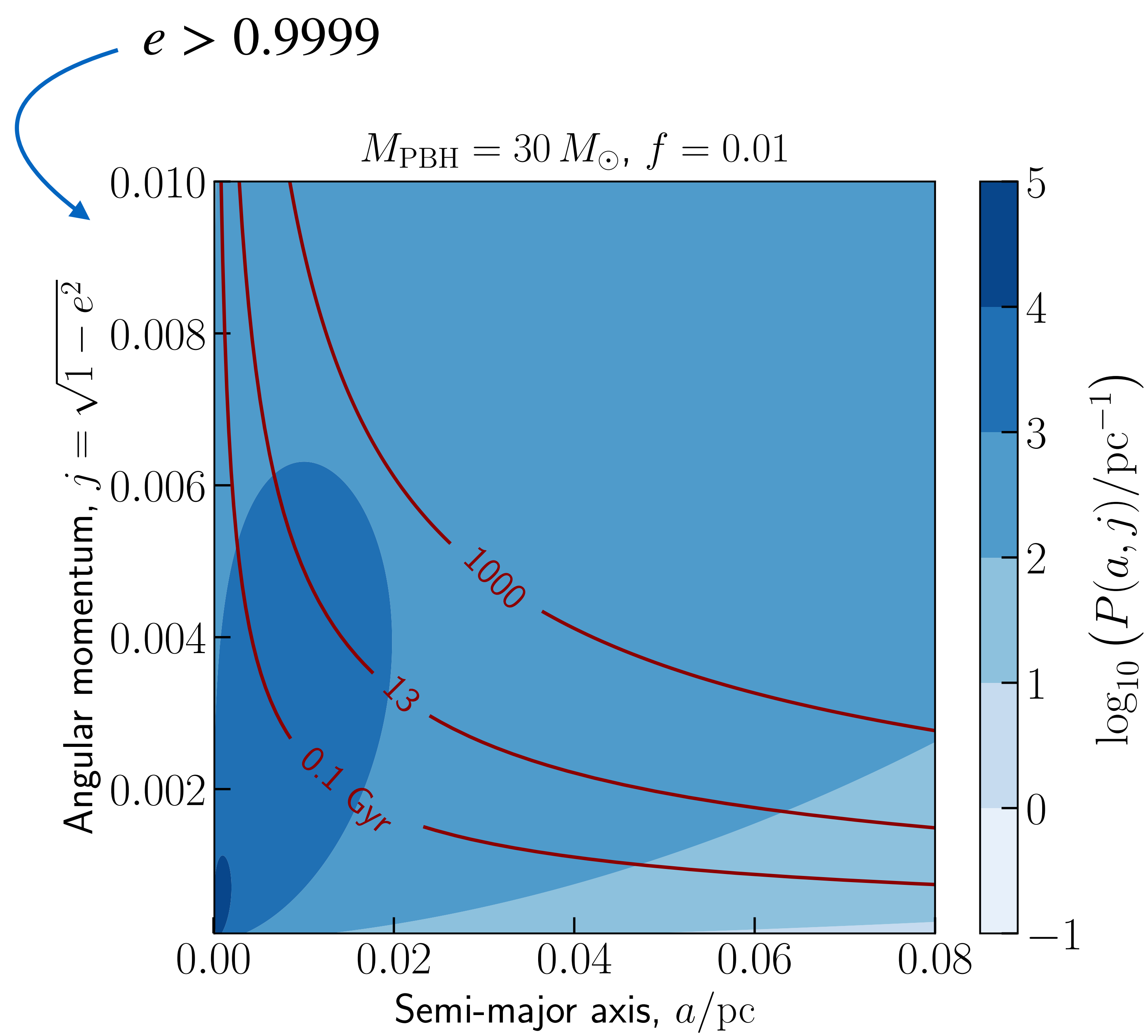
$j = \sqrt{1 - e^2}$

Randomly distributed (unclustered) PBHs

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

Close, eccentric binaries merge today:

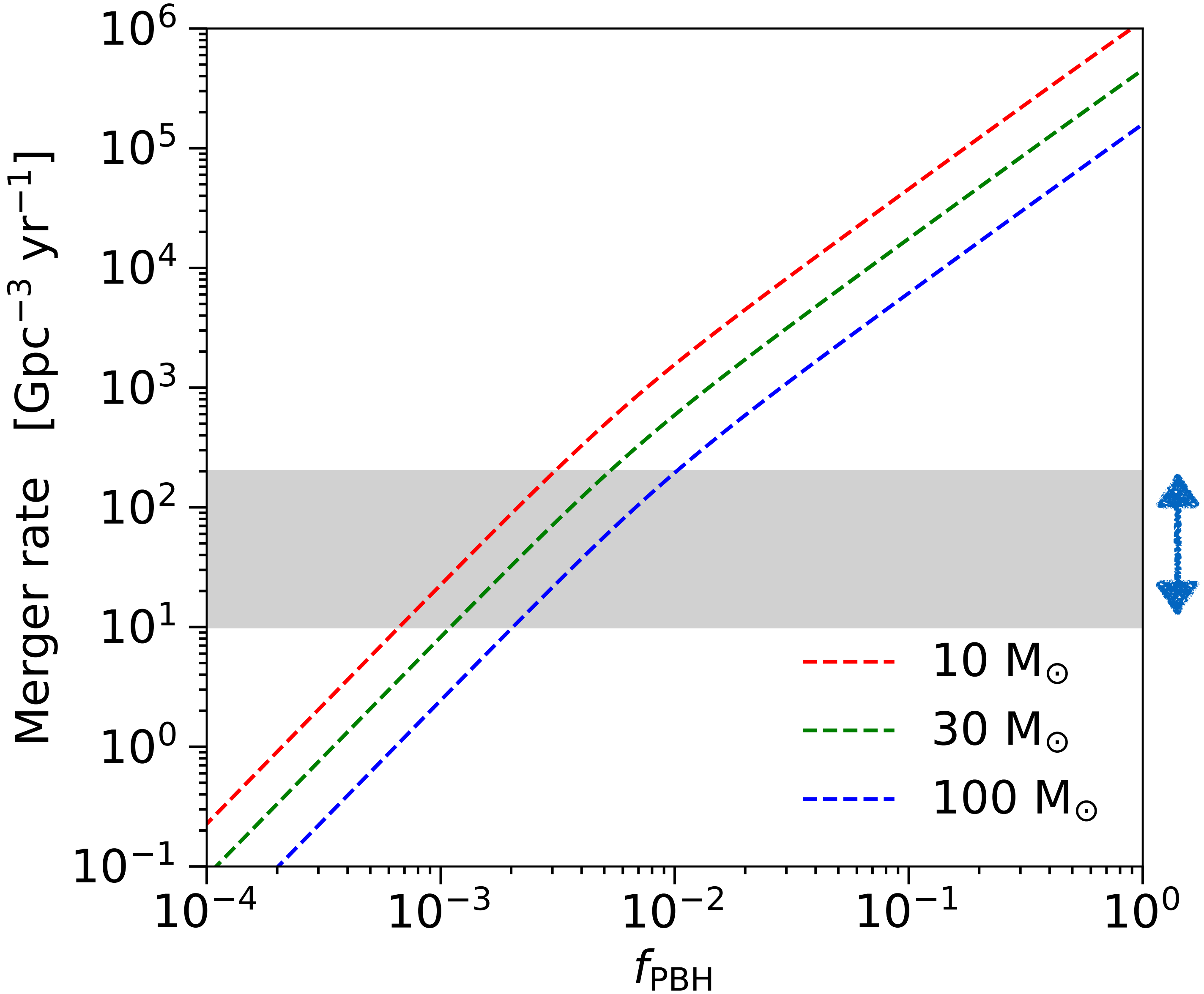
$$t_{\mathrm{merge}} = \frac{3\,c^5}{170\,G_N^3}\frac{a^4 j^7}{M_{\mathrm{PBH}}^3}$$



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

Merger Rate Estimate

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



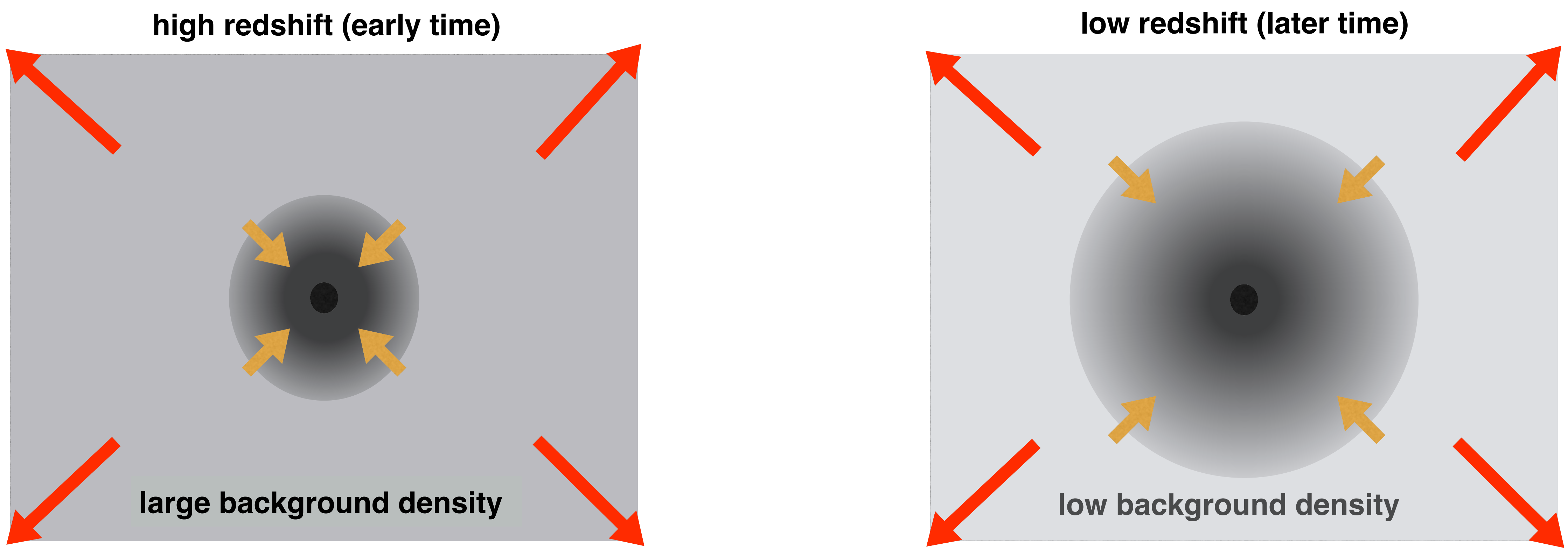
LIGO merger rate estimate after GW150914

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,
and many many others]

Black Holes' Dark Dress

PBHs seed the formation of `local' DM halos:



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

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

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

[Bertschinger (1985)]
[0706.0864, 1901.08528]

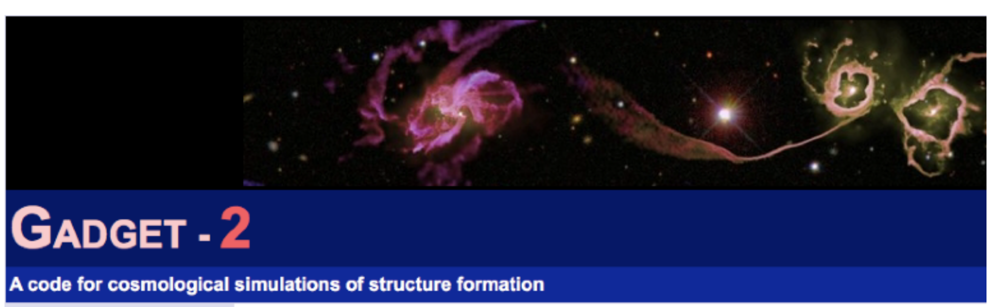
Slide shamelessly ripped off from Daniele Gaggero

Impact of Dark Dresses

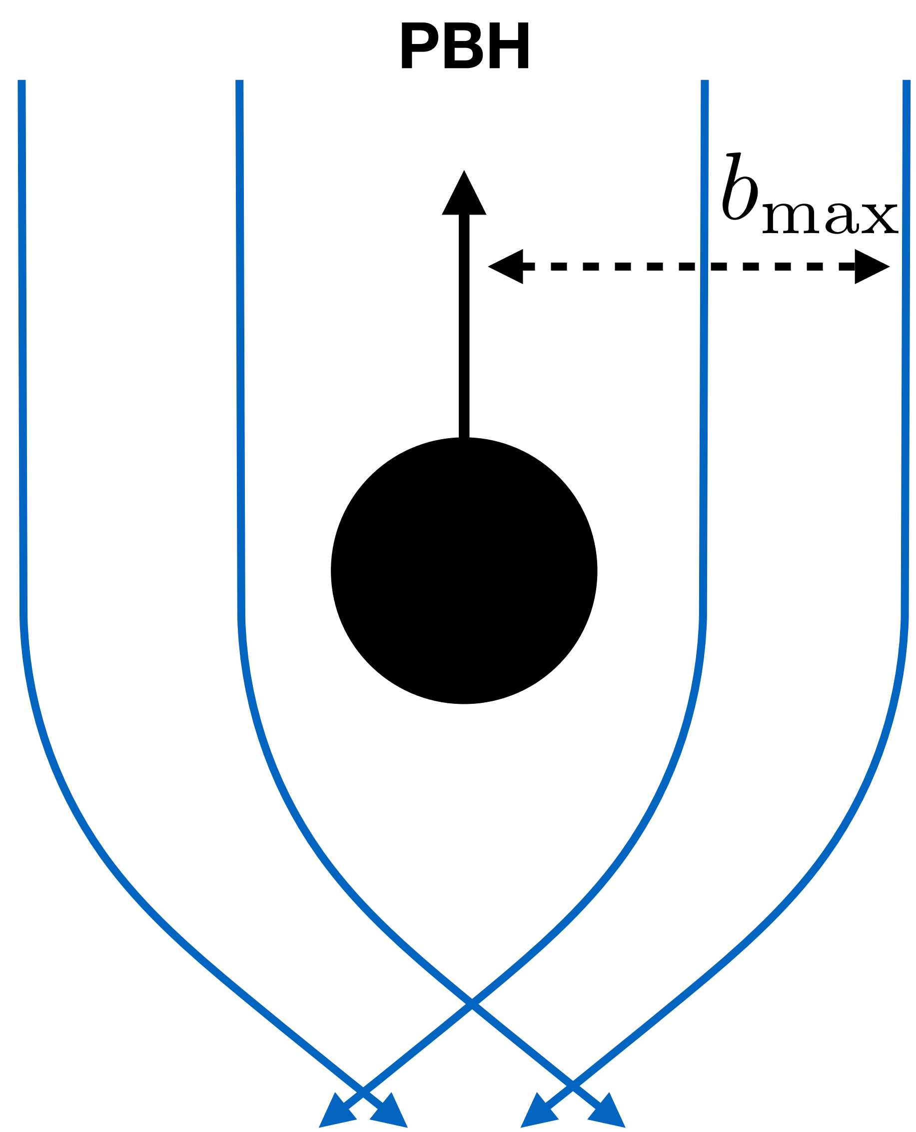
[Chandrasekhar, 1943]

Dynamical friction due to DM exerts a force on the PBHs

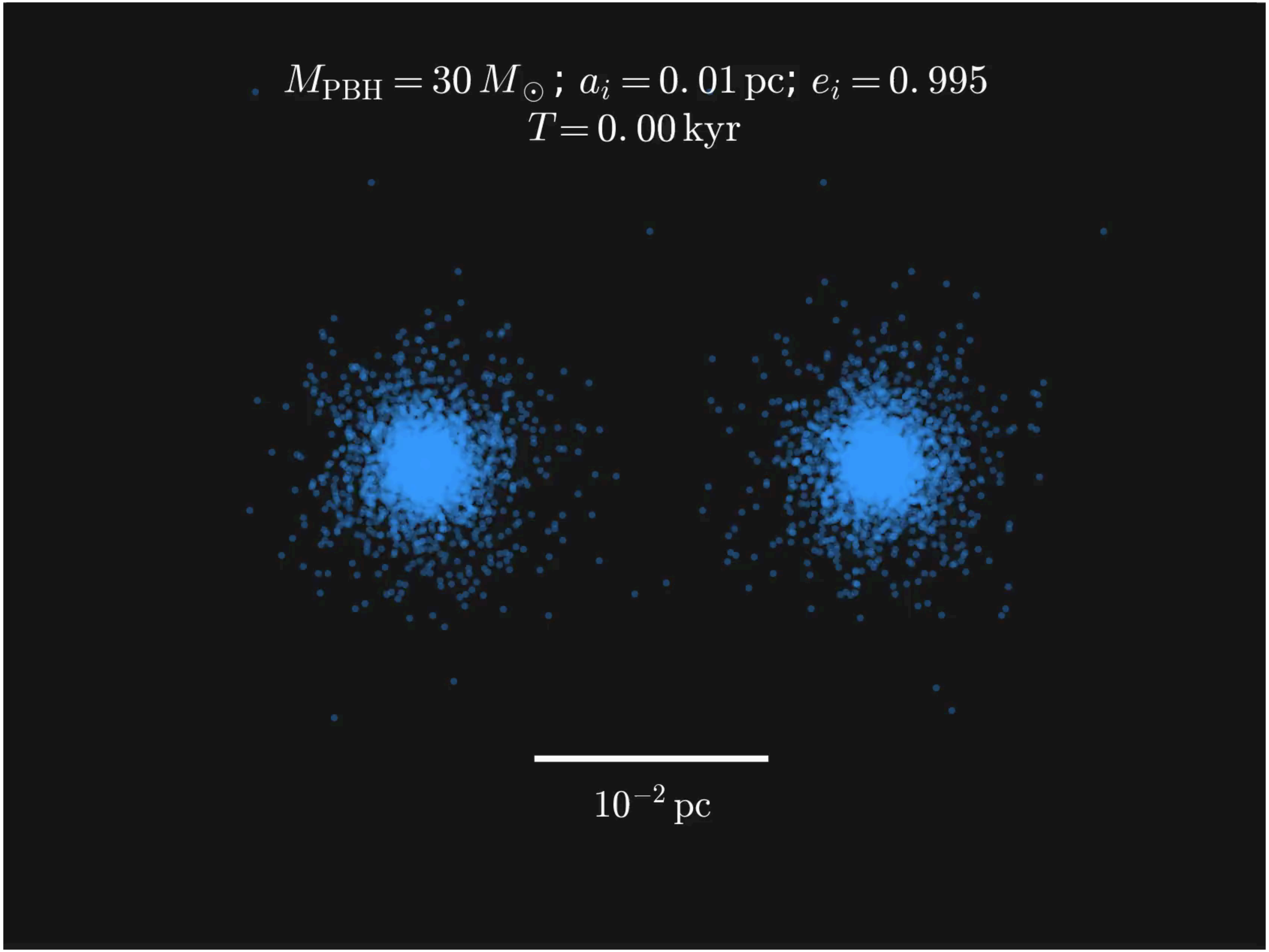
Study the binaries self-consistently using N-body simulations:



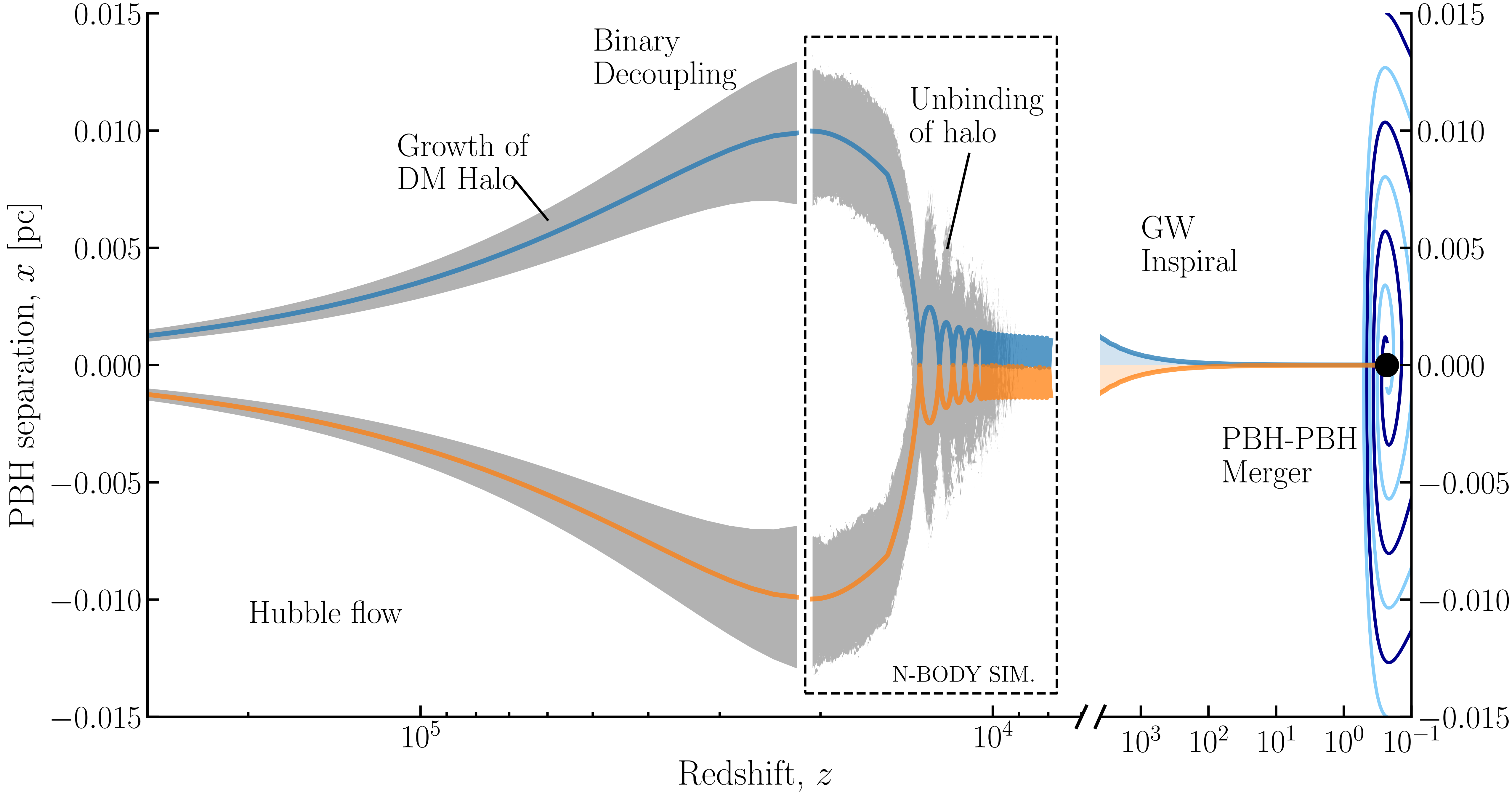
[astro-ph/0505010]



$$\dot{E}_{\mathrm{DF}} \sim \frac{4\pi G_N^2 M_{\mathrm{NS}}^2 \rho_{\mathrm{DM}}(r)}{v_{\mathrm{NS}}} \ln \Lambda$$


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

Life of a ‘dressed’ PBH binary



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

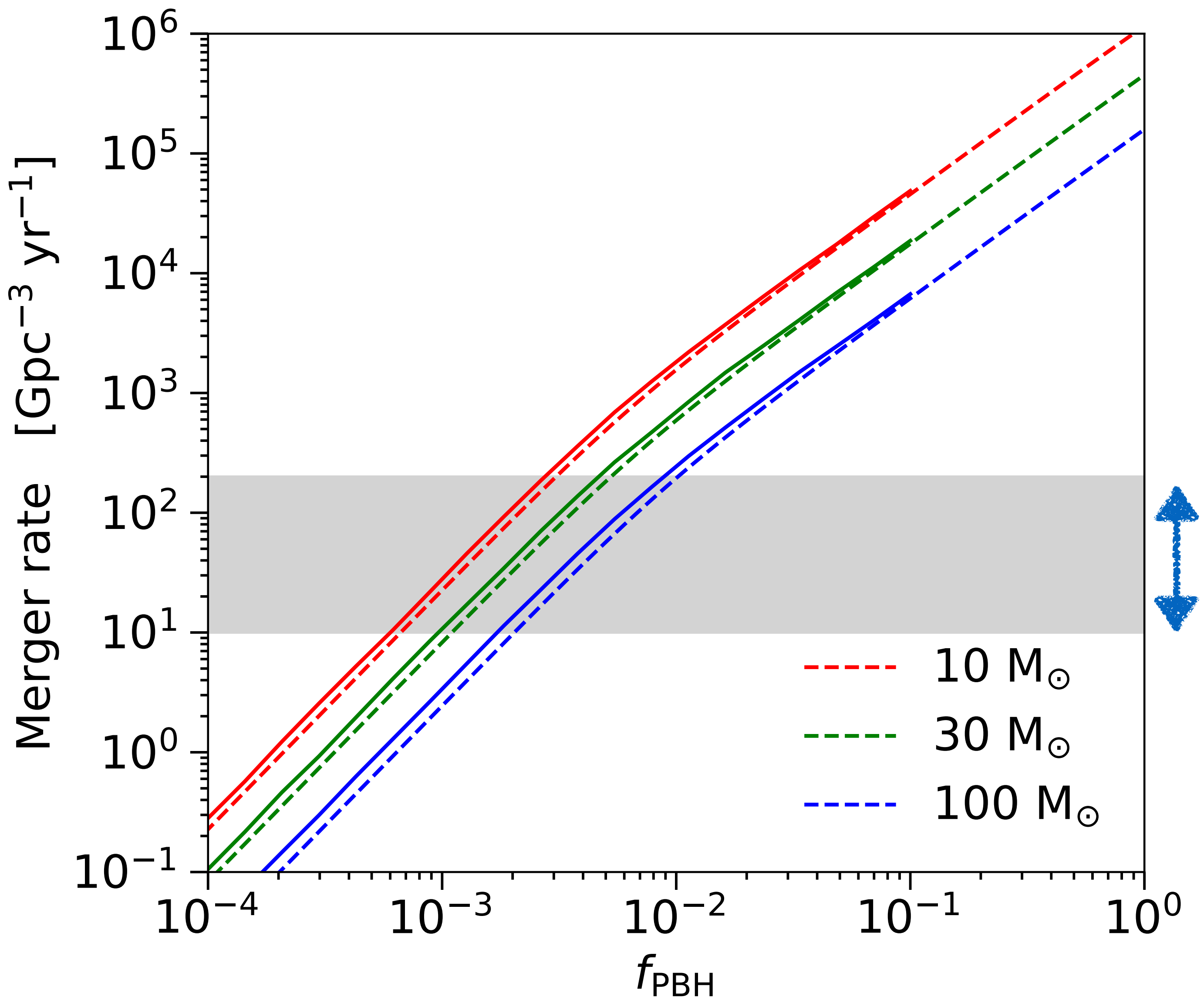
$$e_i = 0.995$$

Final Merger Rate

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

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

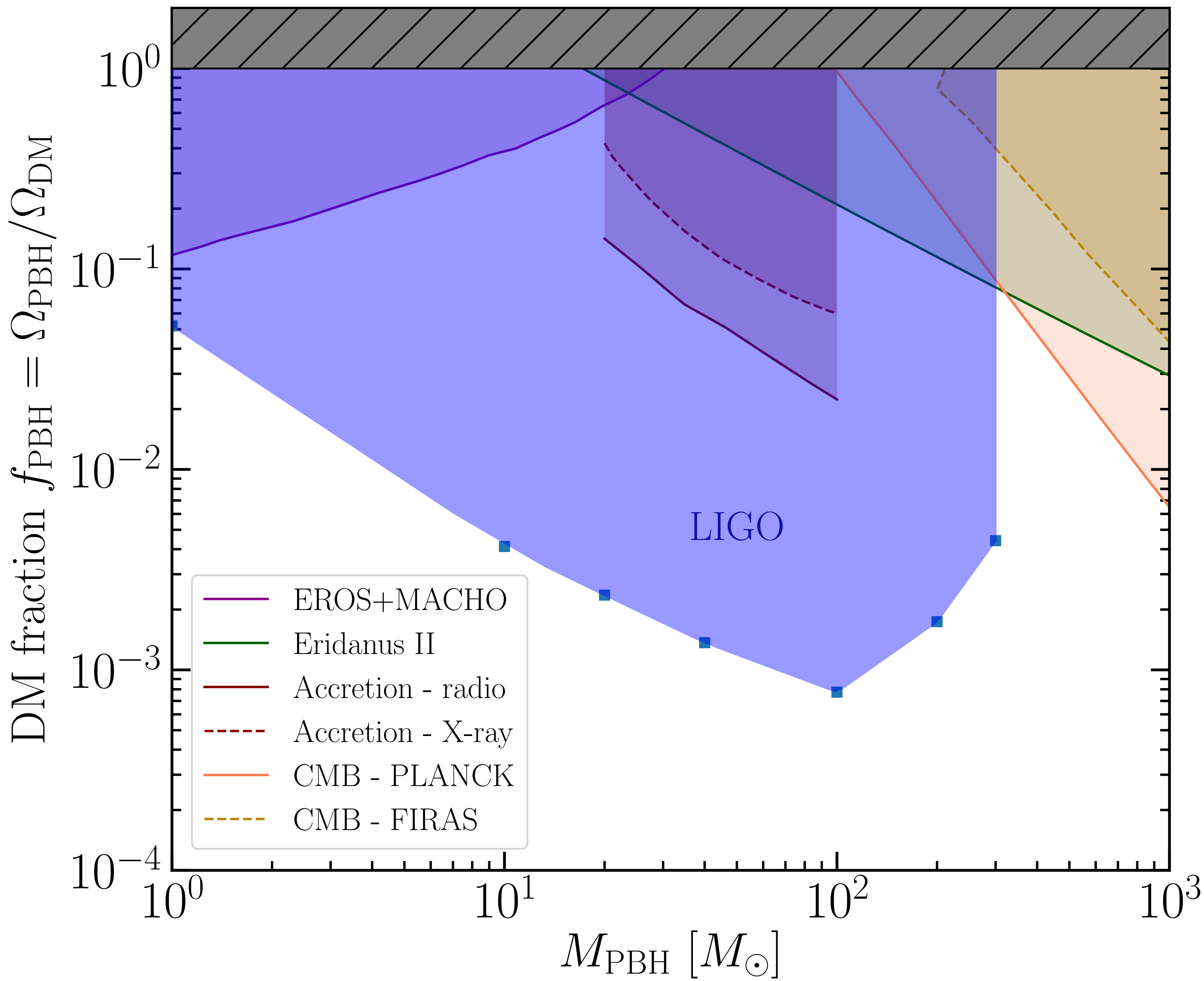
Merger time $t_{\mathrm{merge}} = \dfrac{3\,c^5}{170\,G_N^3}\dfrac{a^4 j^7}{M_{\mathrm{PBH}}^3}$ is almost conserved: $t_f = \sqrt{\dfrac{a_i}{a_f}}\,t_i$



LIGO merger rate estimate after GW150914

Limits from LIGO

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



But what if we discover primordial black holes?

Detection prospects

GW detection of sub-solar mass BHs

(LIGO O3, now!)

GW detection of high redshift BHs (z > 40)

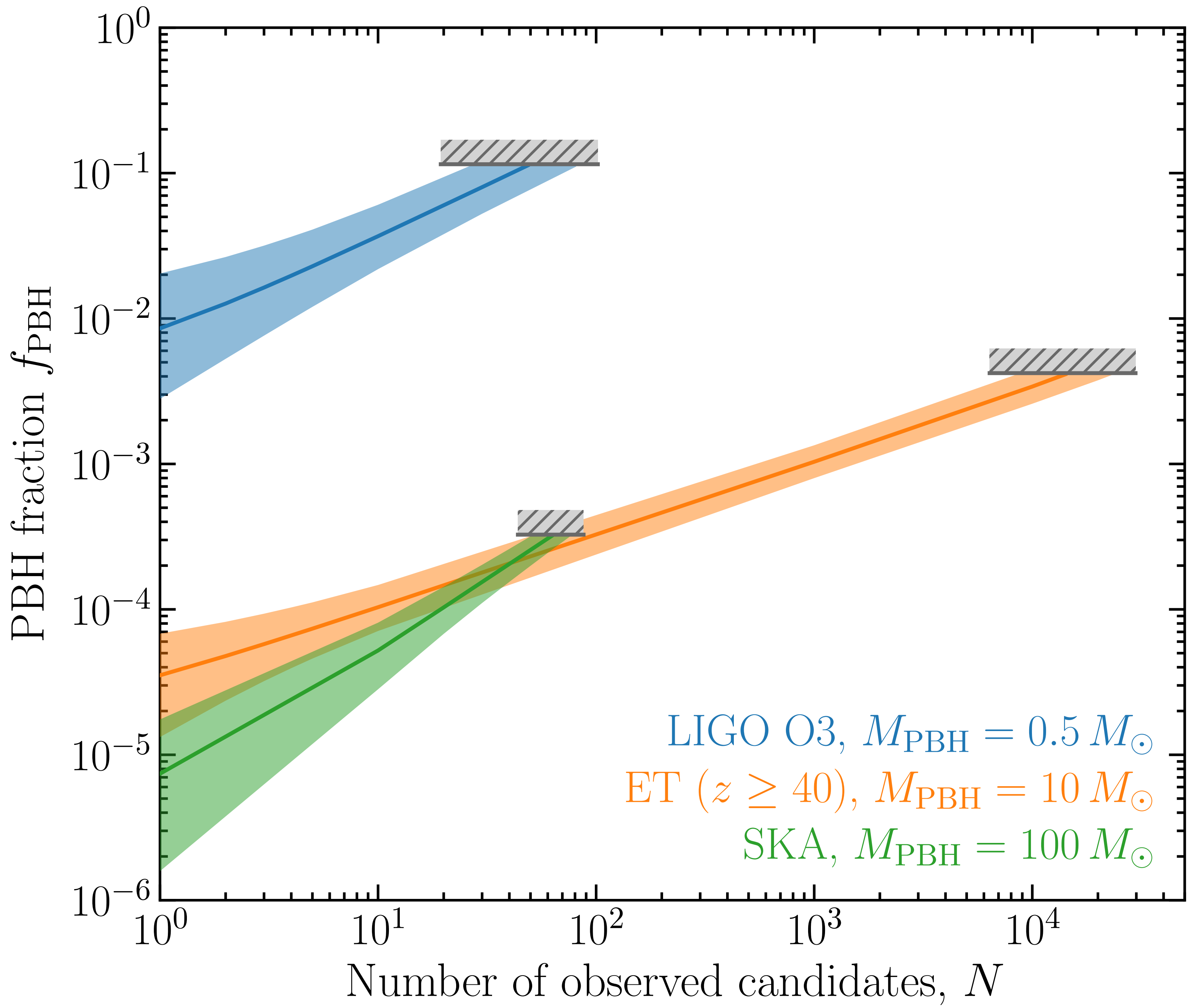
(Einstein Telescope, mid-late 2020s)

[1708.07380]

Radio detection of accreting galactic PBHs

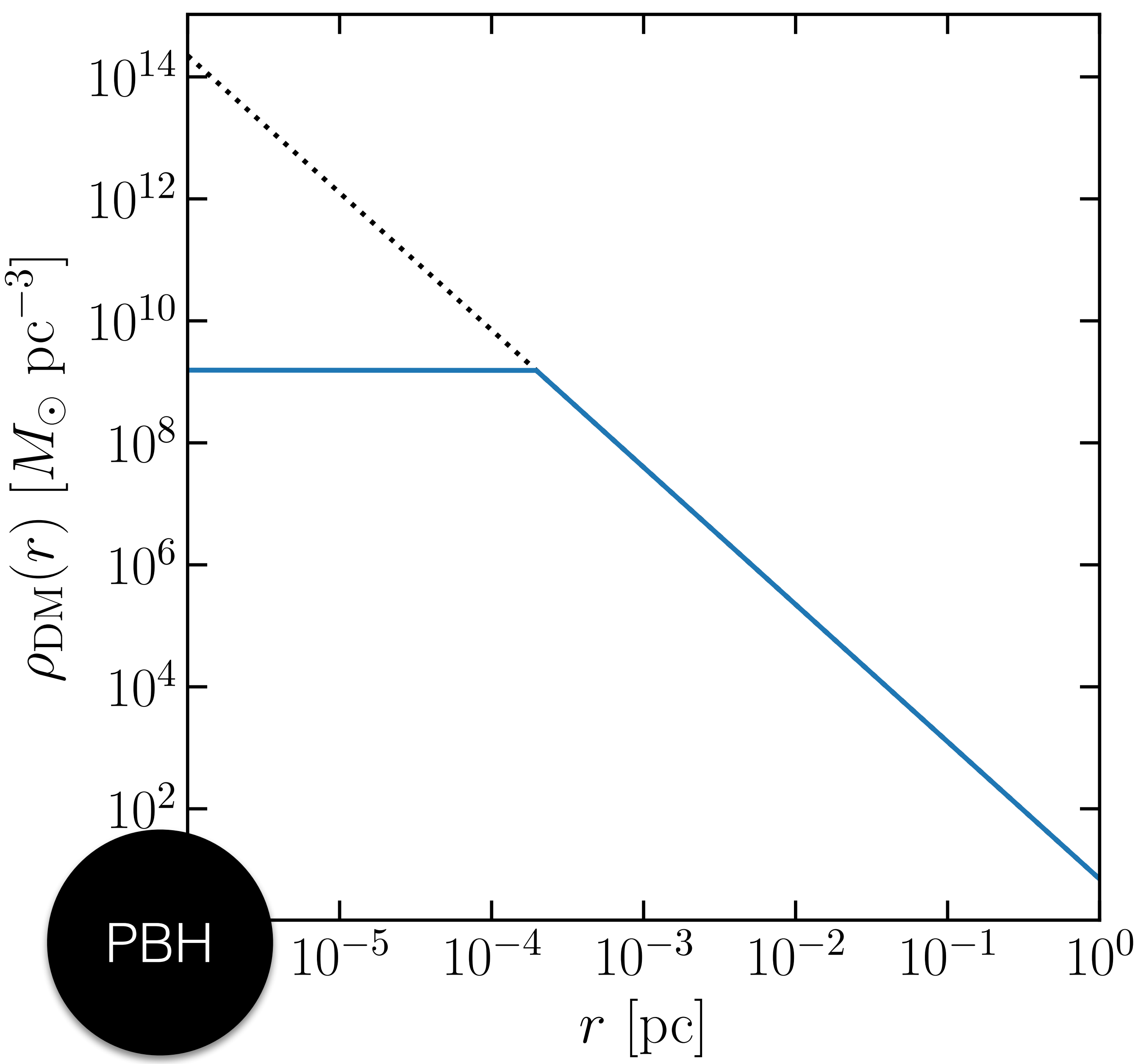
(Square Kilometre Array, late 2020s)

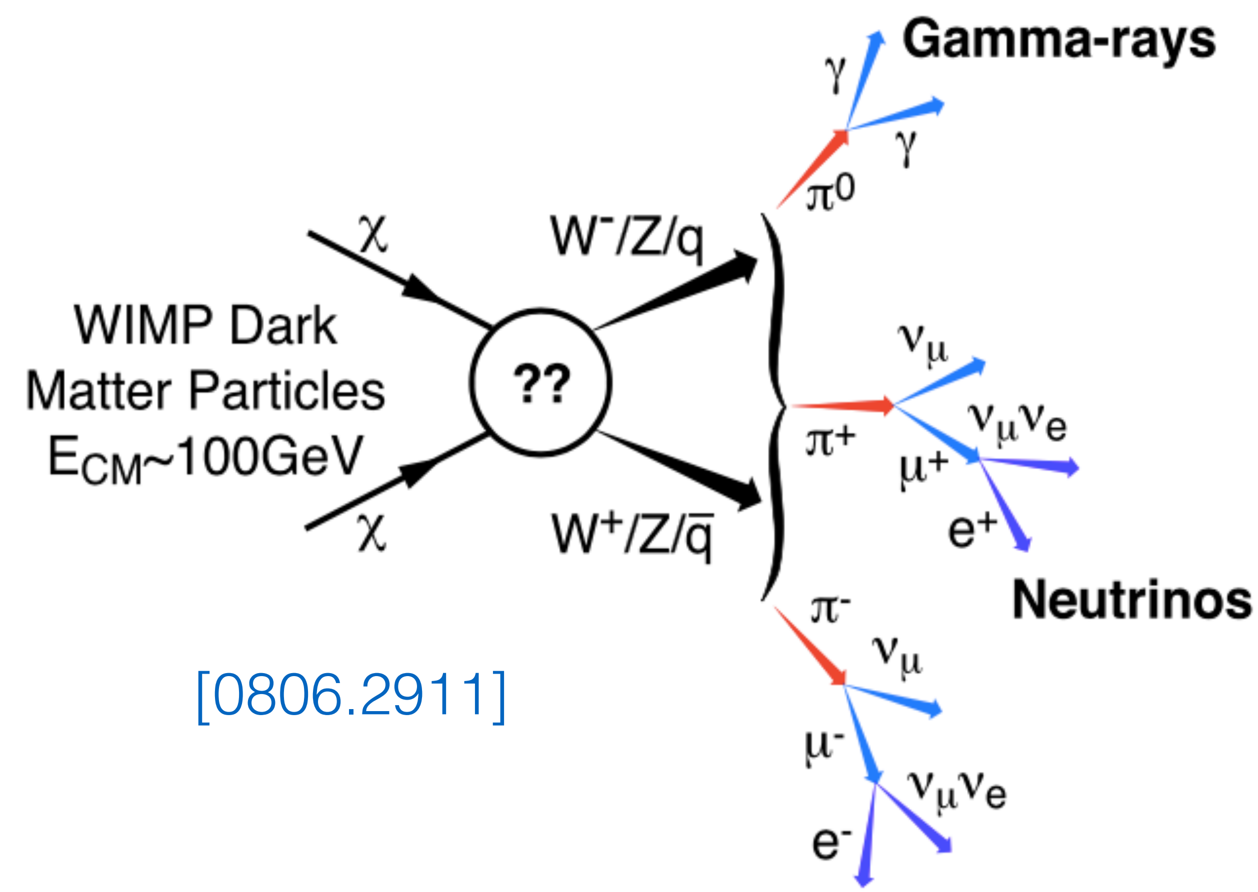
[1812.07967]



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

DM annihilation





[0806.2911]

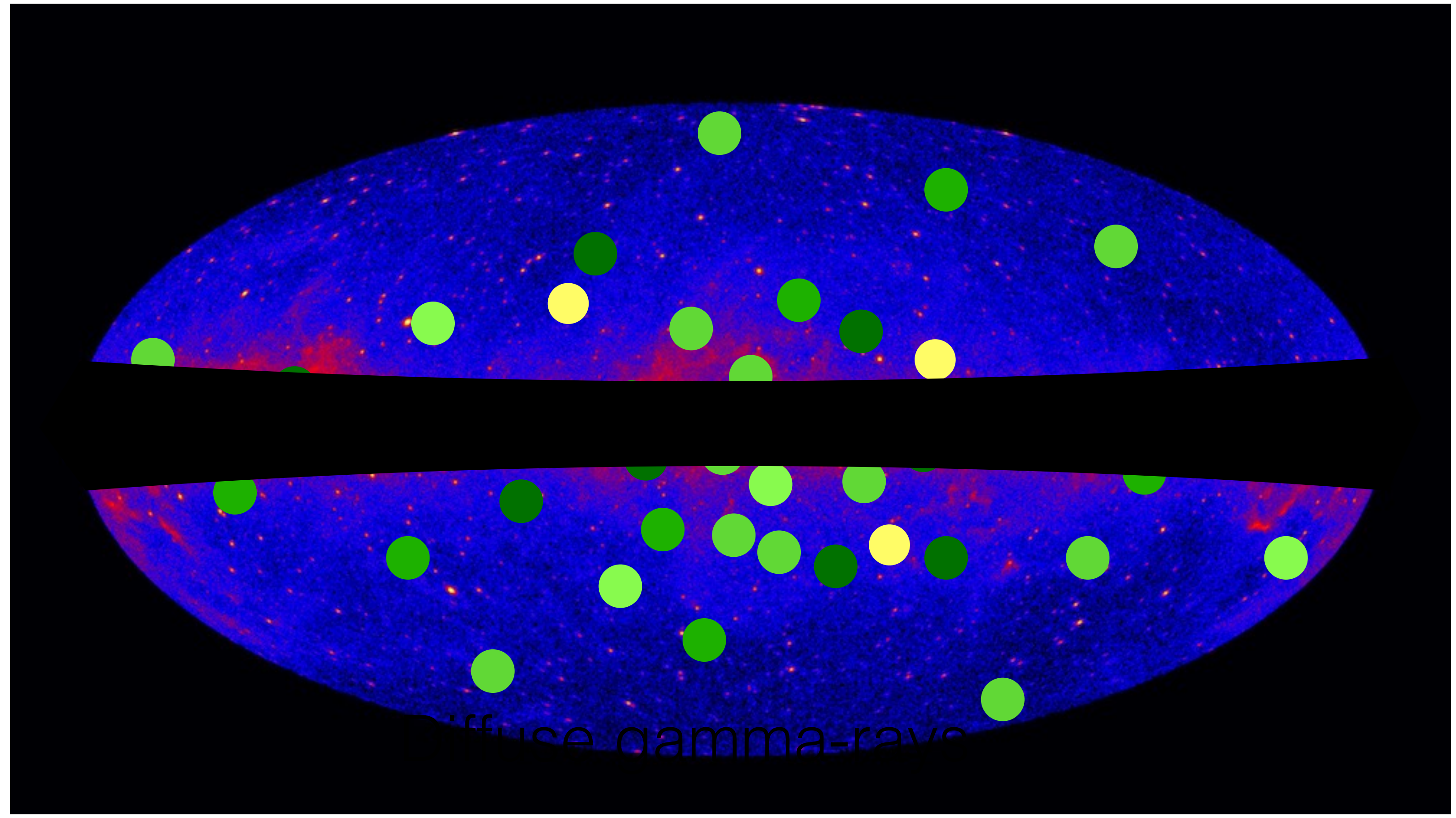
$$\Gamma \propto \rho_\chi^2\, (\sigma v)_0\, f_\chi^{4/3}$$

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

Gamma-ray constraints

[Credit: Adam Coogan]

Point Sources in the Milky Way:



Fermi/NASA

Diffuse (cosmological) background:

UCO/Lick

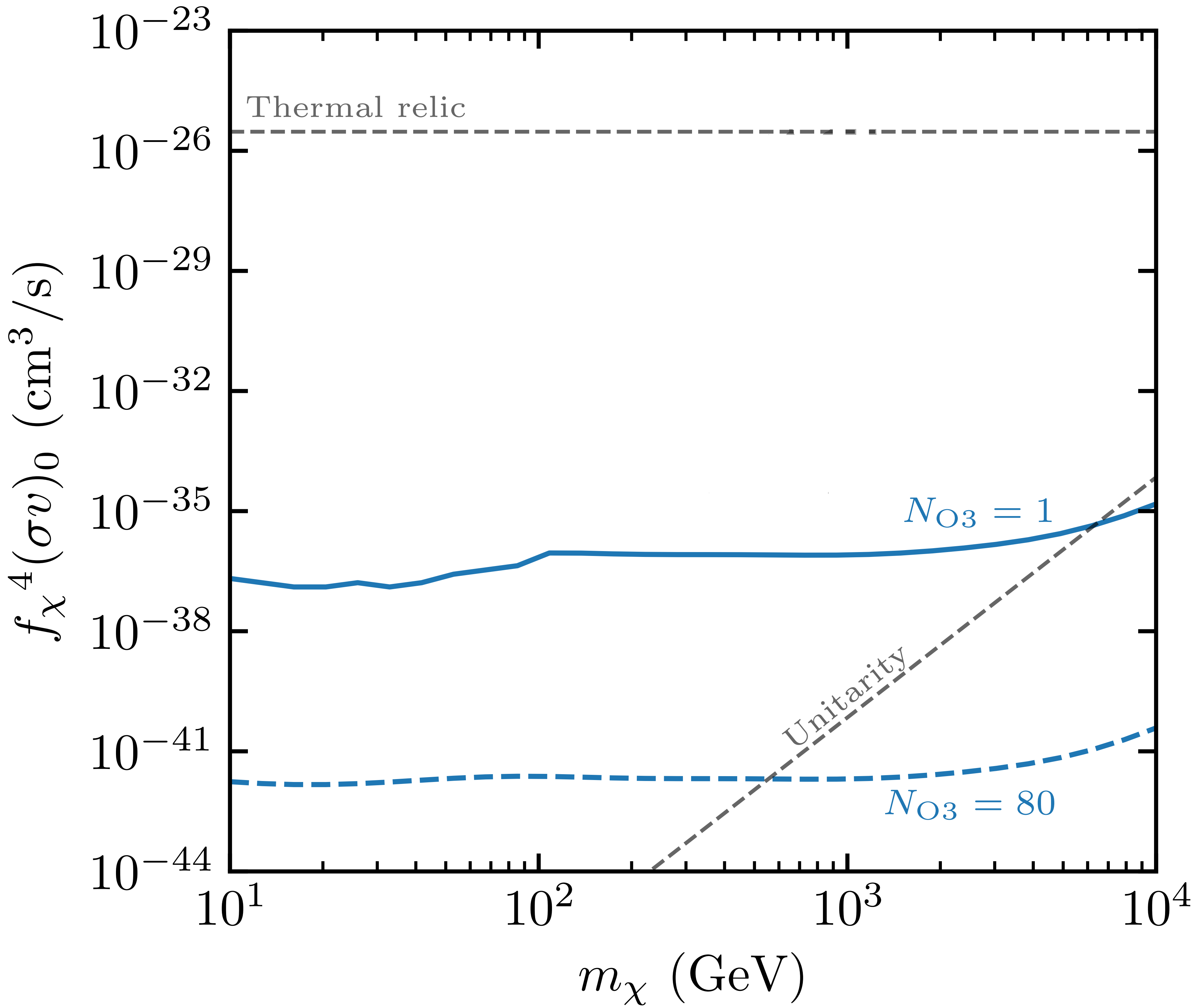
NASA

Redshifting

Gamma rays from DM ann.

Attenuation

Cross section constraints



GW detection of sub-solar mass BHs

(LIGO O3, now!)

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

Werewolves

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

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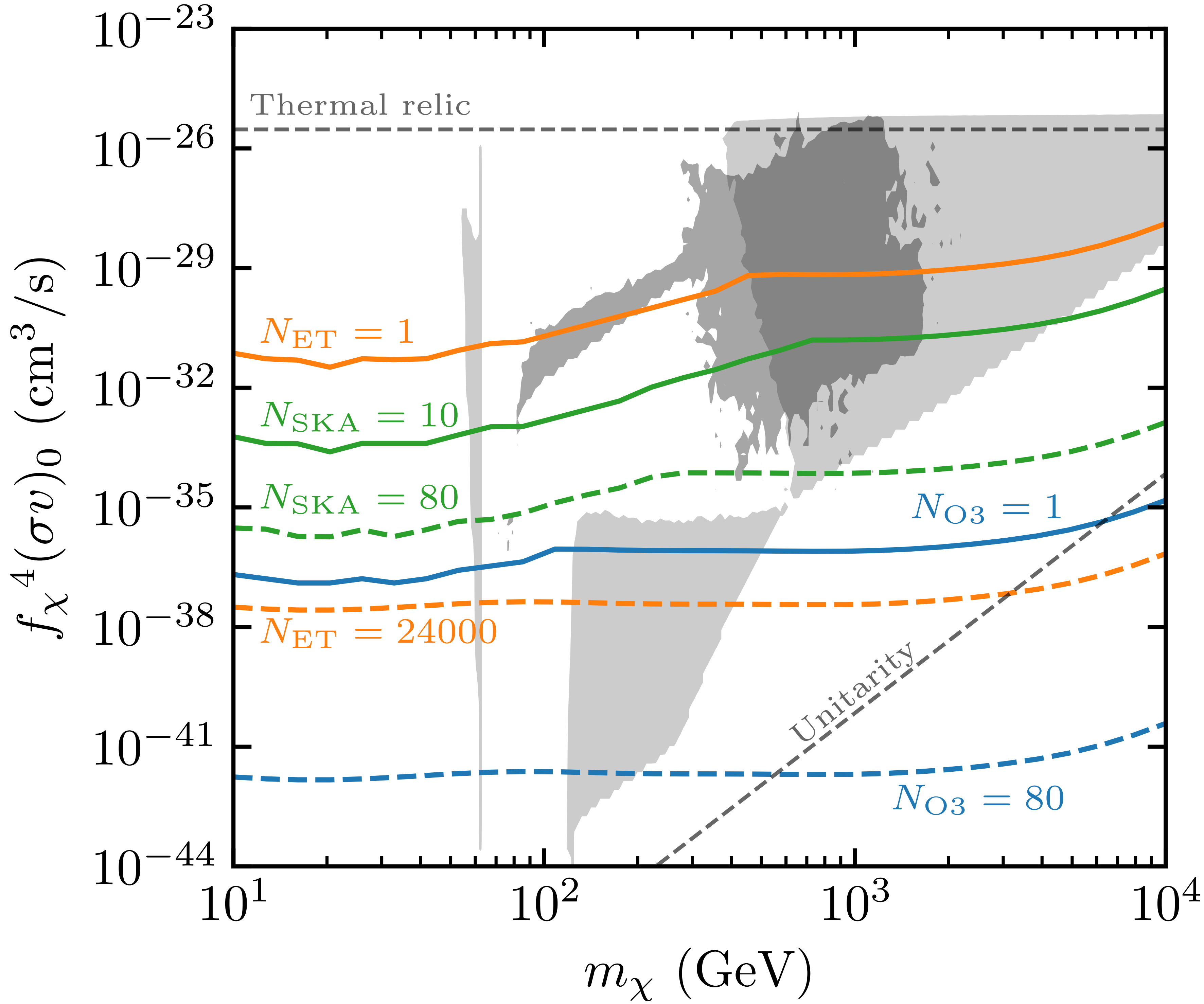
Can be killed with **Silver Bullets**

Silver Bullets

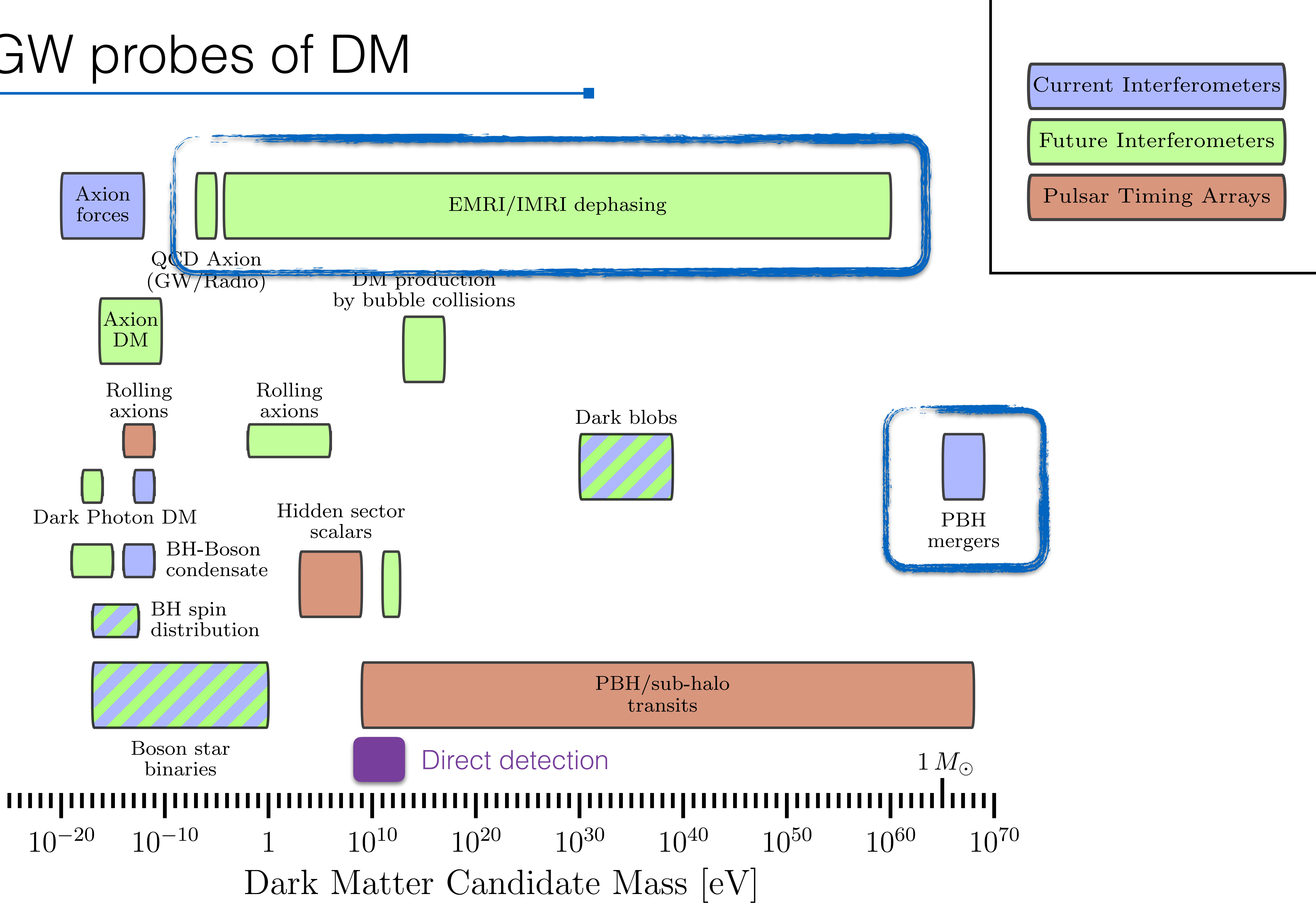
WIMPs: Weakly Interacting Massive Particles, which are notoriously hard to kill



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

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

GW probes of DM

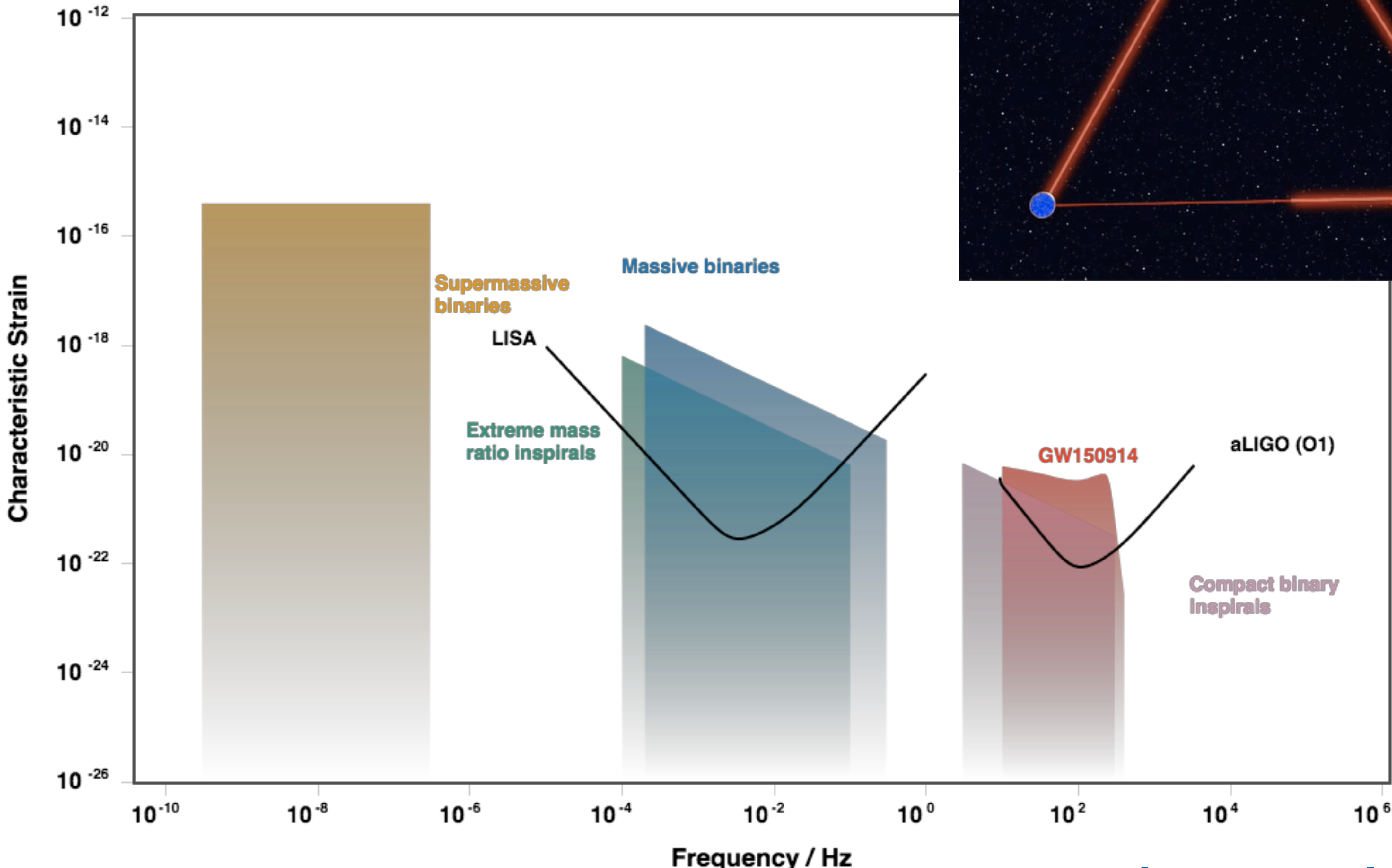


[1907.10610]

LISA: GWs in Space

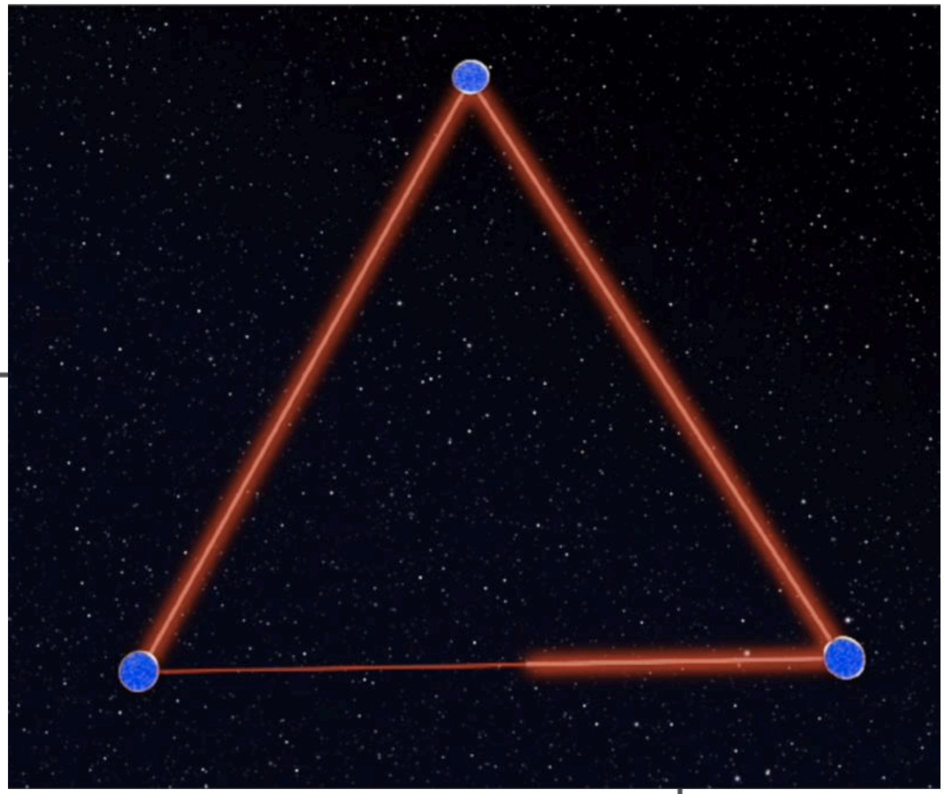
Laser **I**nterferometer **S**pace **A**ntenna
(planned for the 2030s)

[1702.00786]

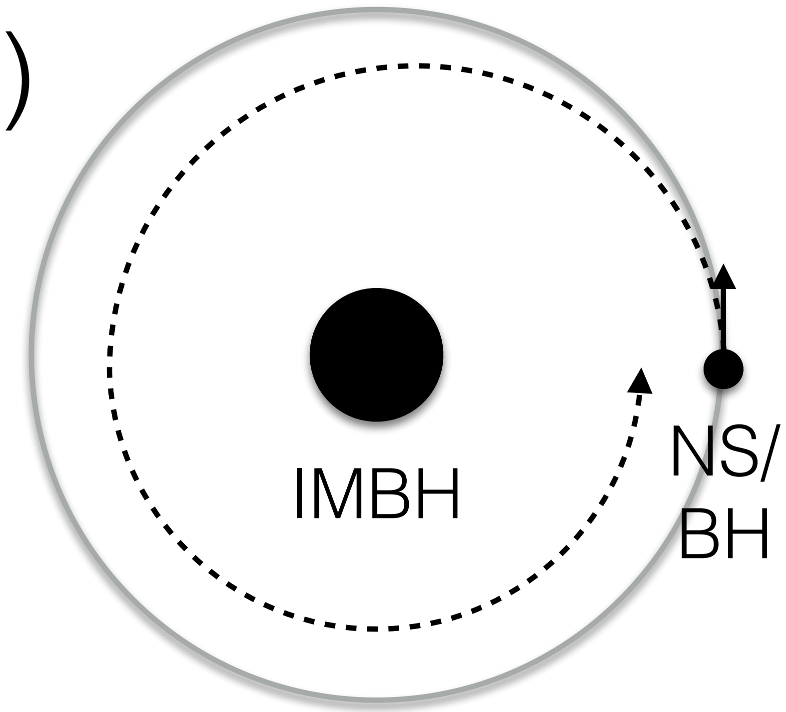


[gwplotter.com]

© AEI / MM / exozet



Intermediate Mass Ratio Inspiral (IMRI)

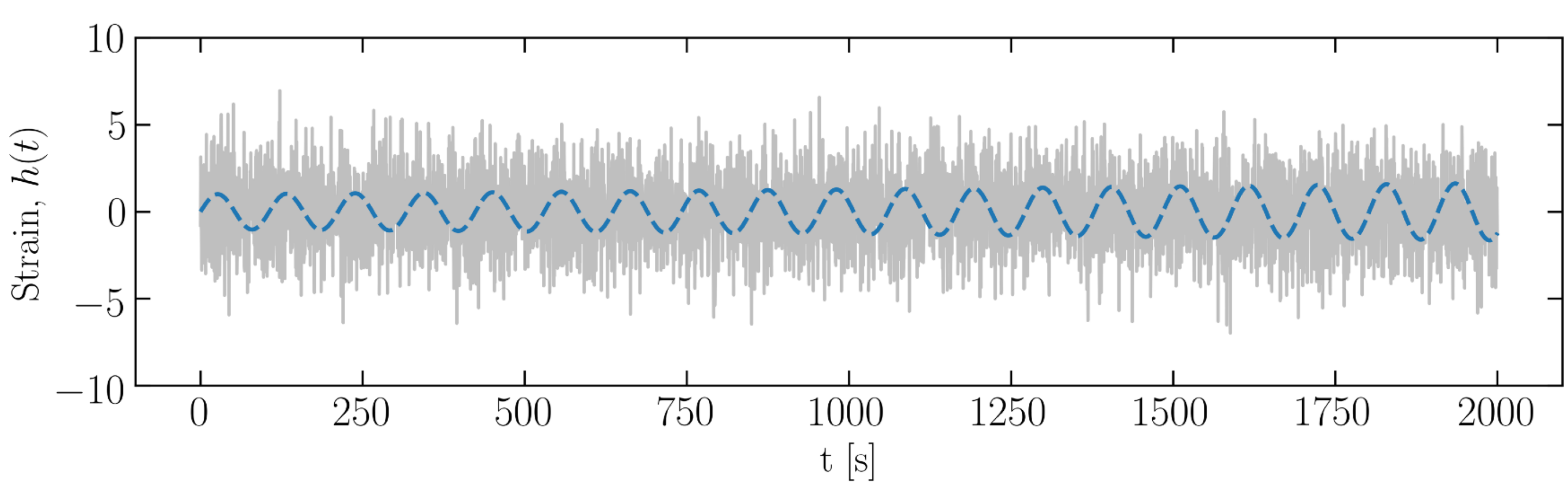


Stellar mass compact object (NS/BH) inspirals towards intermediate mass black hole (IMBH)

$$M_{\mathrm{IMBH}} \sim 10^3 - 10^5 \, M_\odot$$

GW emission causes long, slow inspiral:

$$\dot{E}_{\mathrm{GW}} \approx \frac{32G^4}{5c^5} \frac{{M_{\mathrm{IMBH}}}^3 {M_{\mathrm{NS}}}^2}{r^5} \propto (f_{\mathrm{GW}})^{10/3}$$

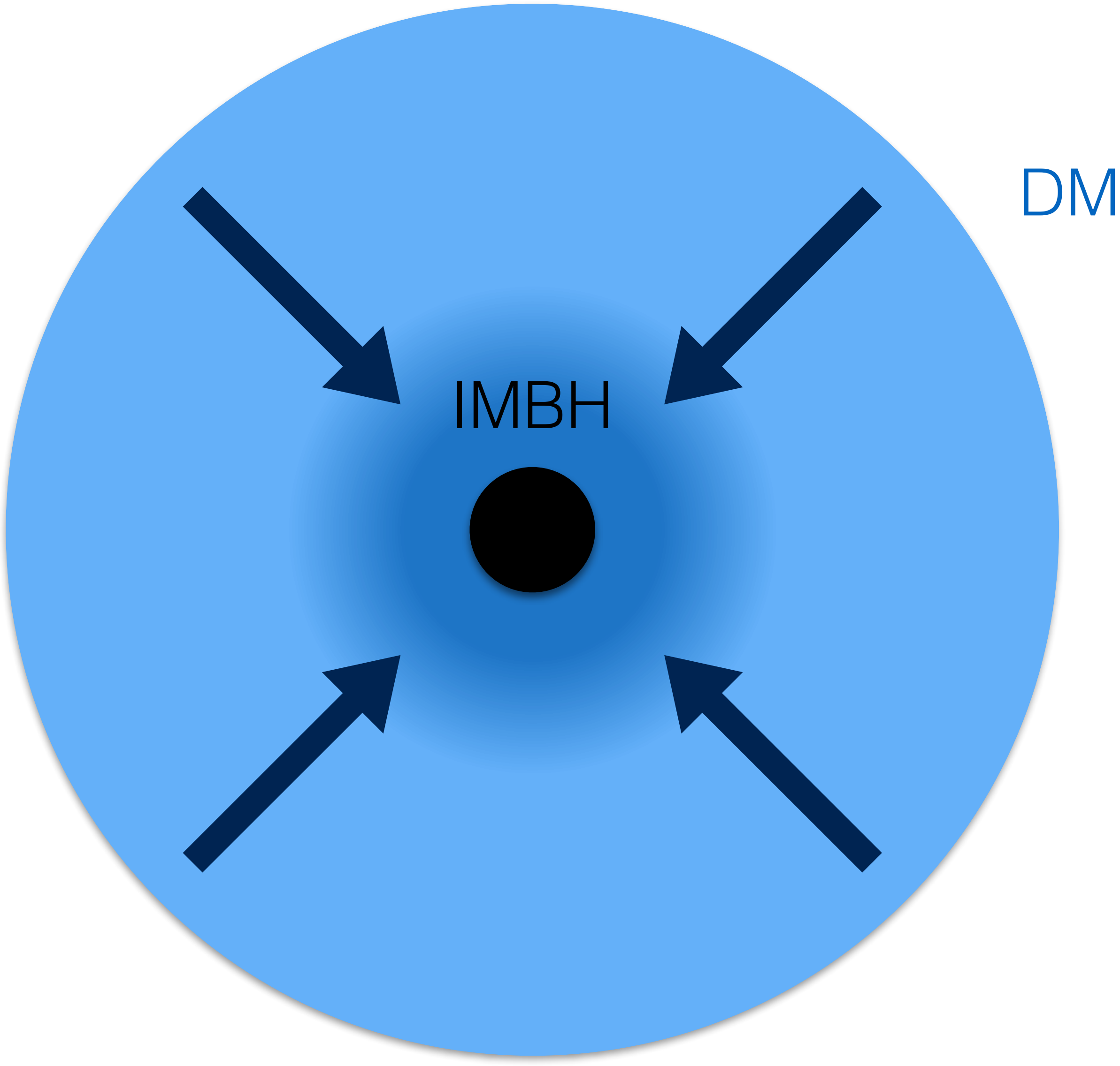


LISA should detect ~ 3 - 10 IMRIs per year [1711.00483]

Dark Matter ‘Mini-spikes’

Depending on the formation mechanism of the IMBH, expect an over-density of DM:

$$\rho_{\rm DM}(r) = \rho_{\rm sp}\left(\frac{r_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$



For BH forming in an NFW halo, from adiabatic growth expect:

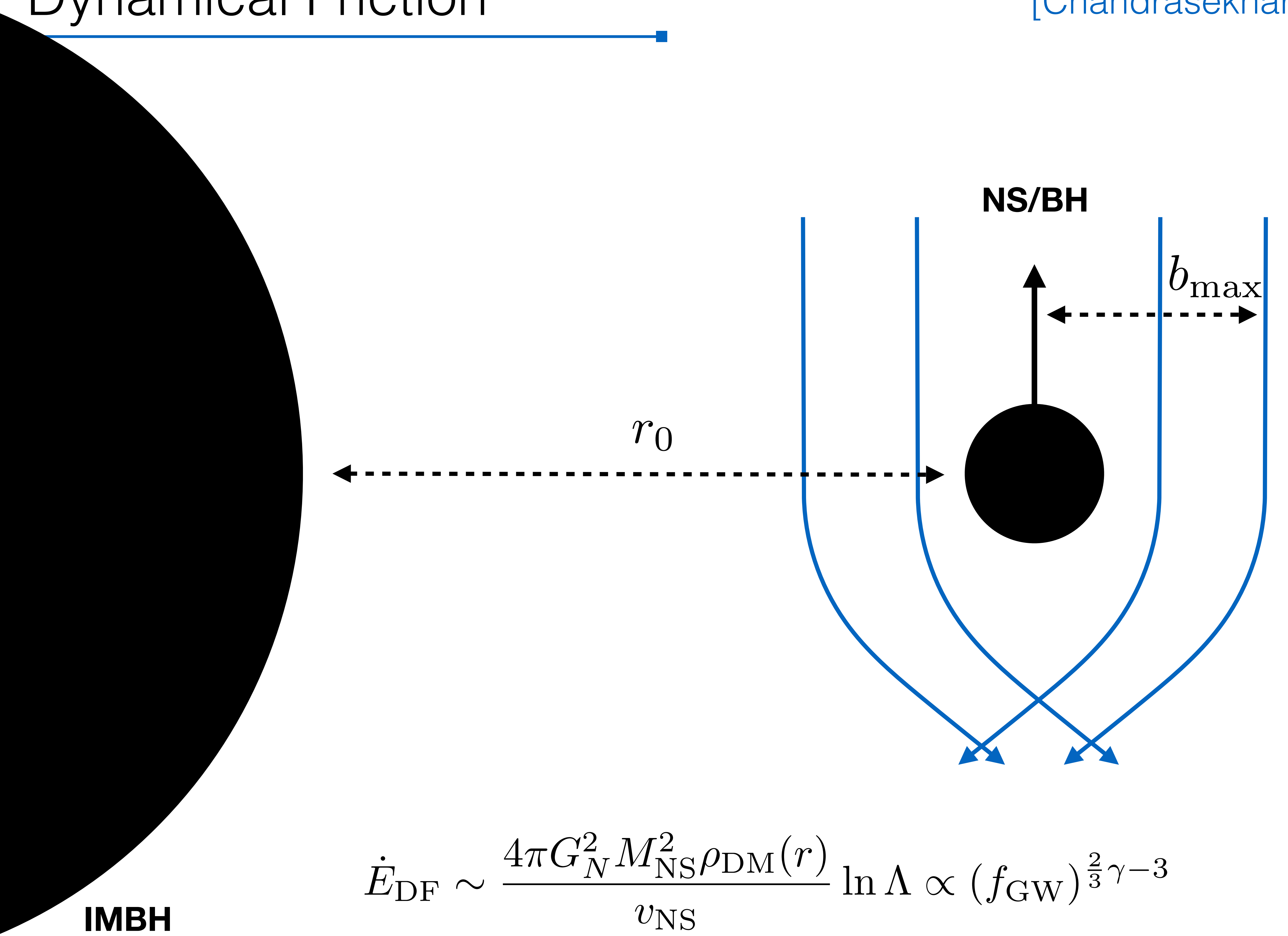
$$\gamma_{\rm sp} = 7/3$$

Density can reach $\rho \sim 10^{24}\,M_\odot\,\mathrm{pc}^{-3}$
(~10^{24} times larger than local density)

[astro-ph/9906391, astro-ph/0501555, astro-ph/0501625, astro-ph/0509565, 0902.3665, 1305.2619]

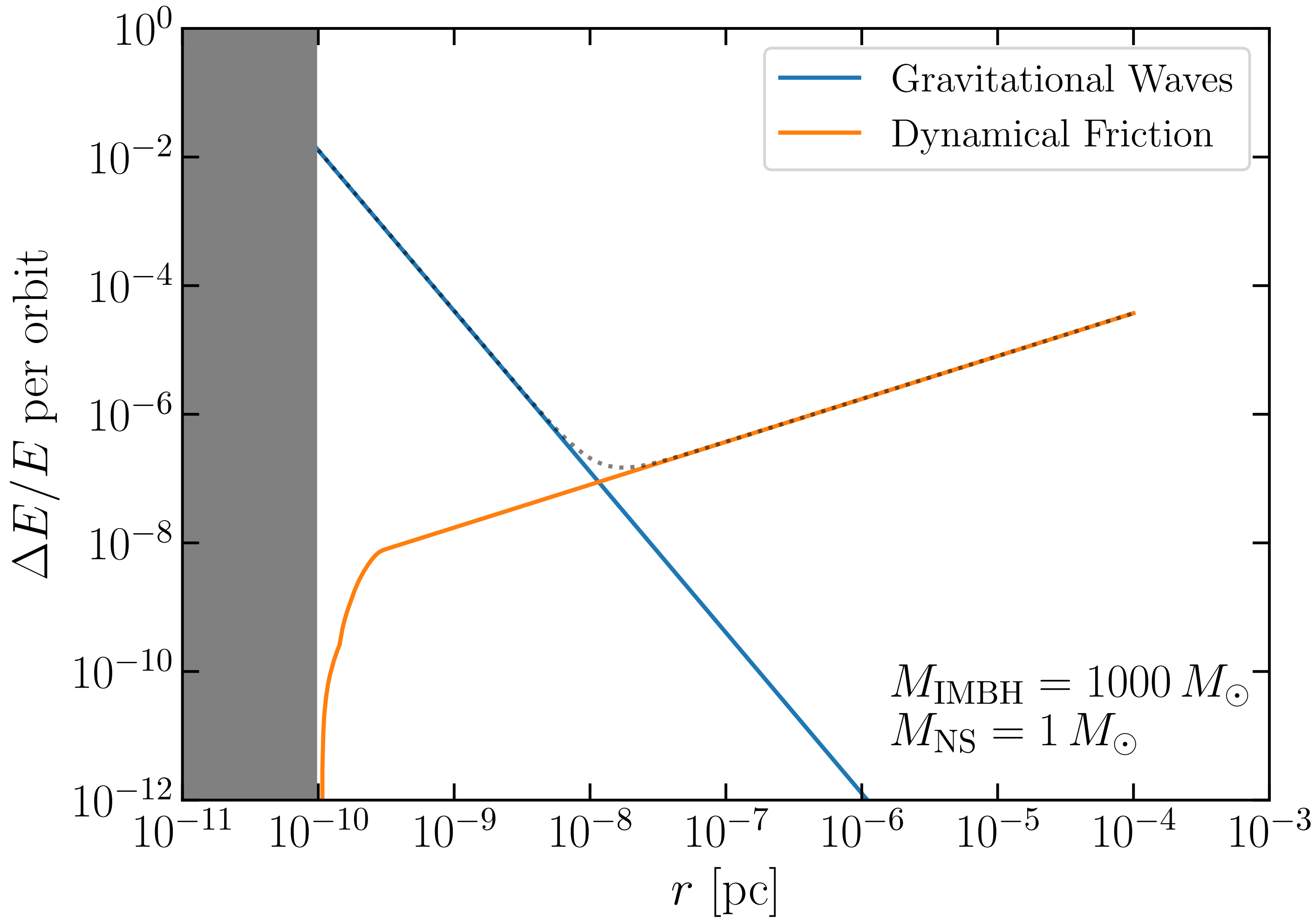
Dynamical Friction

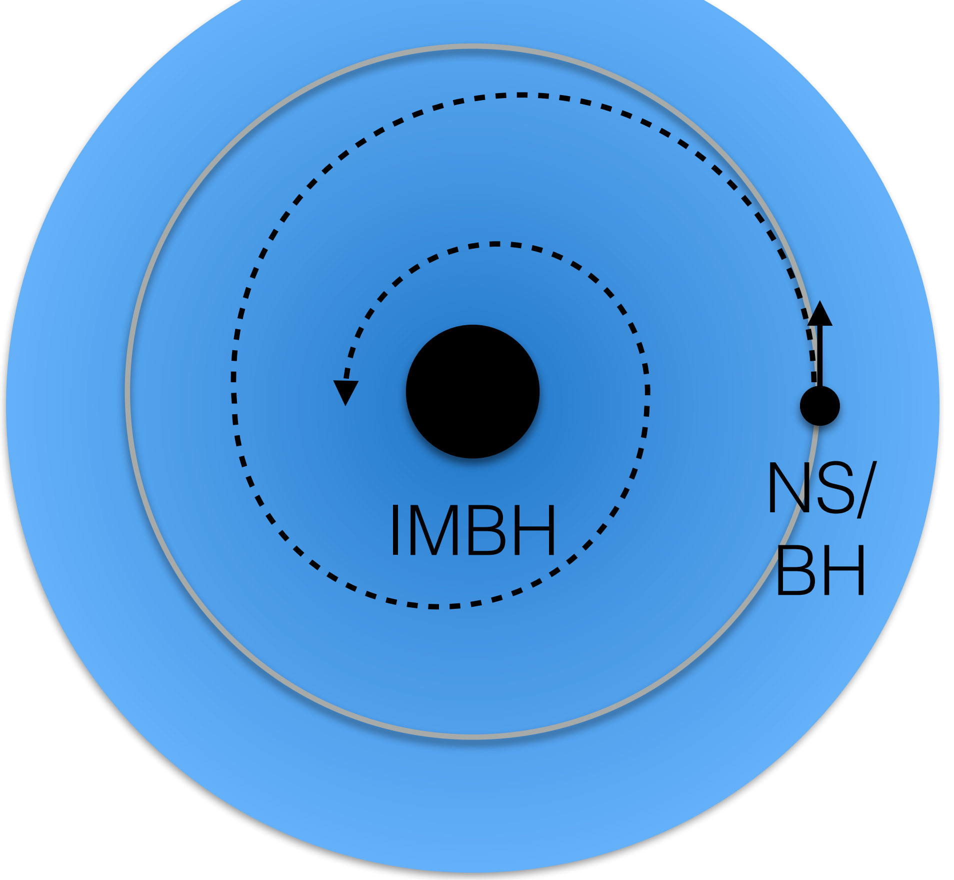
[Chandrasekhar, 1943]

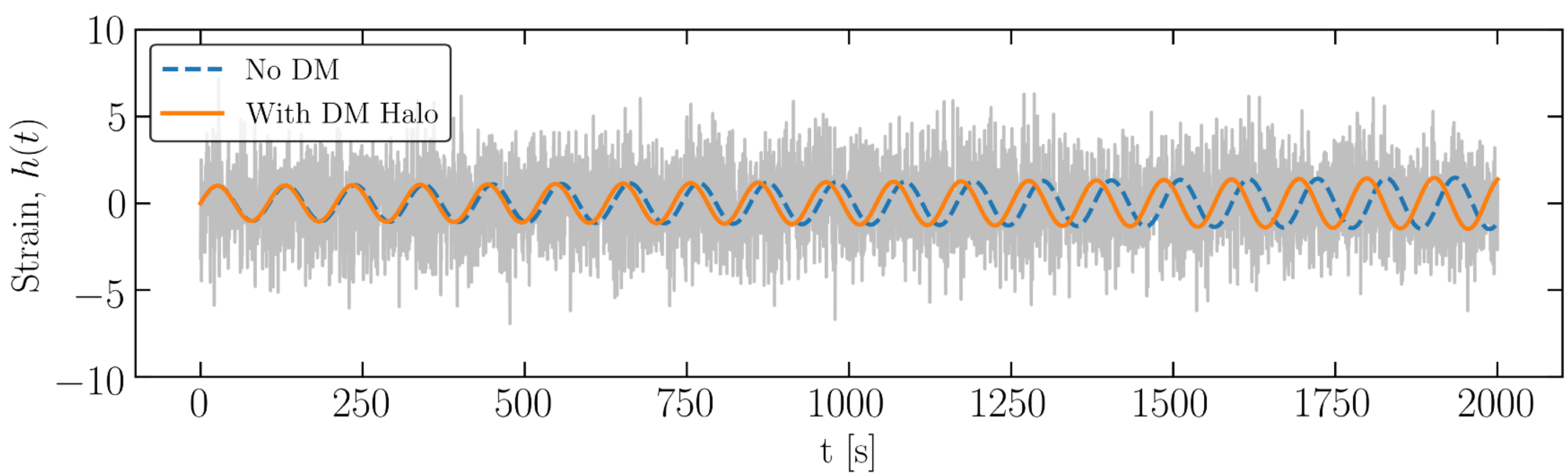


$$\dot{E}_{\rm DF} \sim \frac{4\pi G_N^2 M_{\rm NS}^2 \rho_{\rm DM}(r)}{v_{\rm NS}} \ln\Lambda \propto (f_{\rm GW})^{\frac{2}{3}\gamma - 3}$$

IMRI + Dark Matter







‘De-phasing’ signal

How does DM affect the number of cycles?

Benchmark:

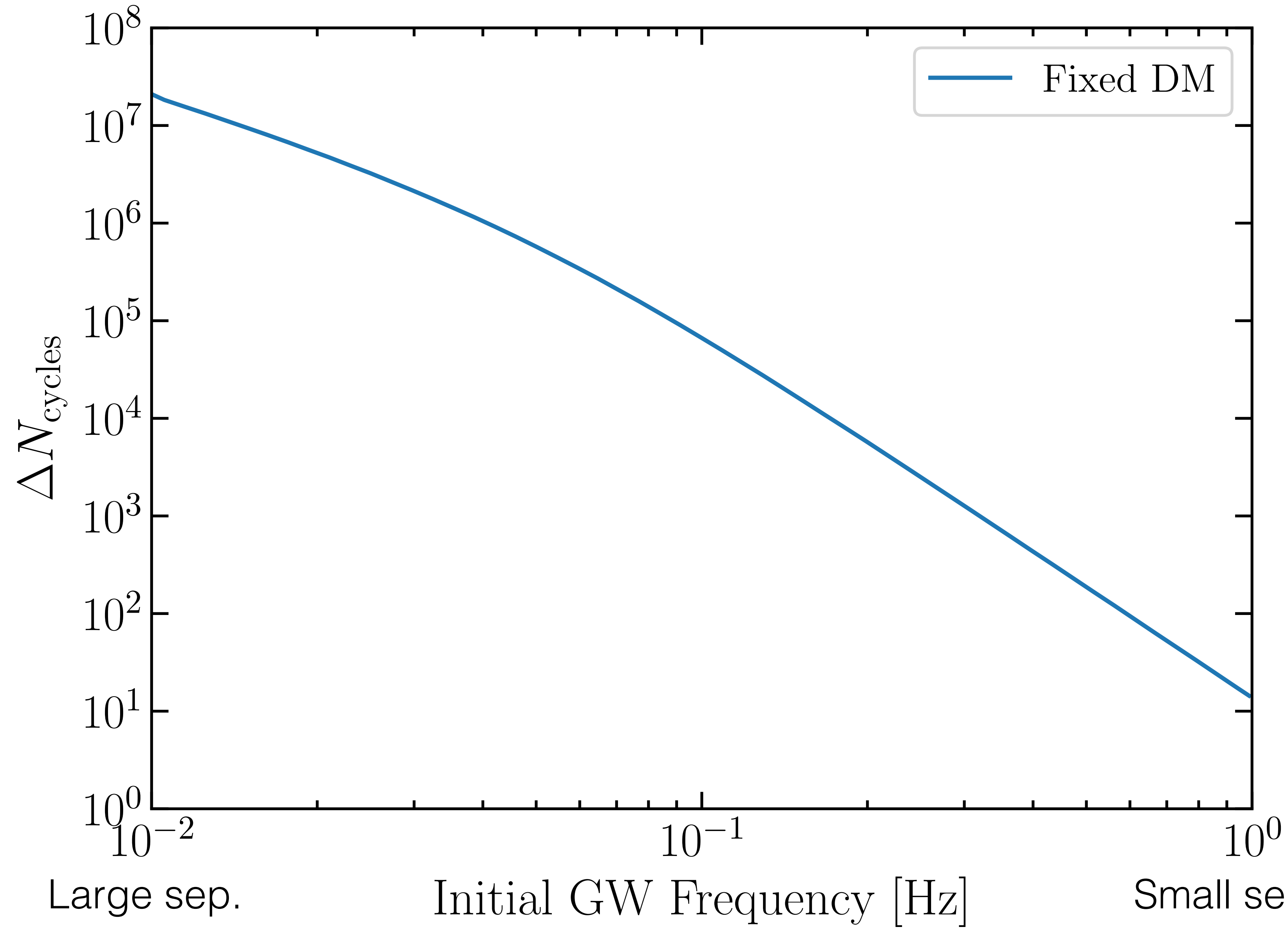
$$M_{\rm IMBH} = 10^3\,M_\odot$$

$$M_{\rm NS} = 1\,M_\odot$$

$$r_{\rm ini} \sim 10^{-8}\,{\rm pc}$$

$$t_{\rm merge} \sim 5\,{\rm yr}$$

$$N_{\rm cycles}^{\rm vacuum} \sim 2\times 10^7$$



Large sep.

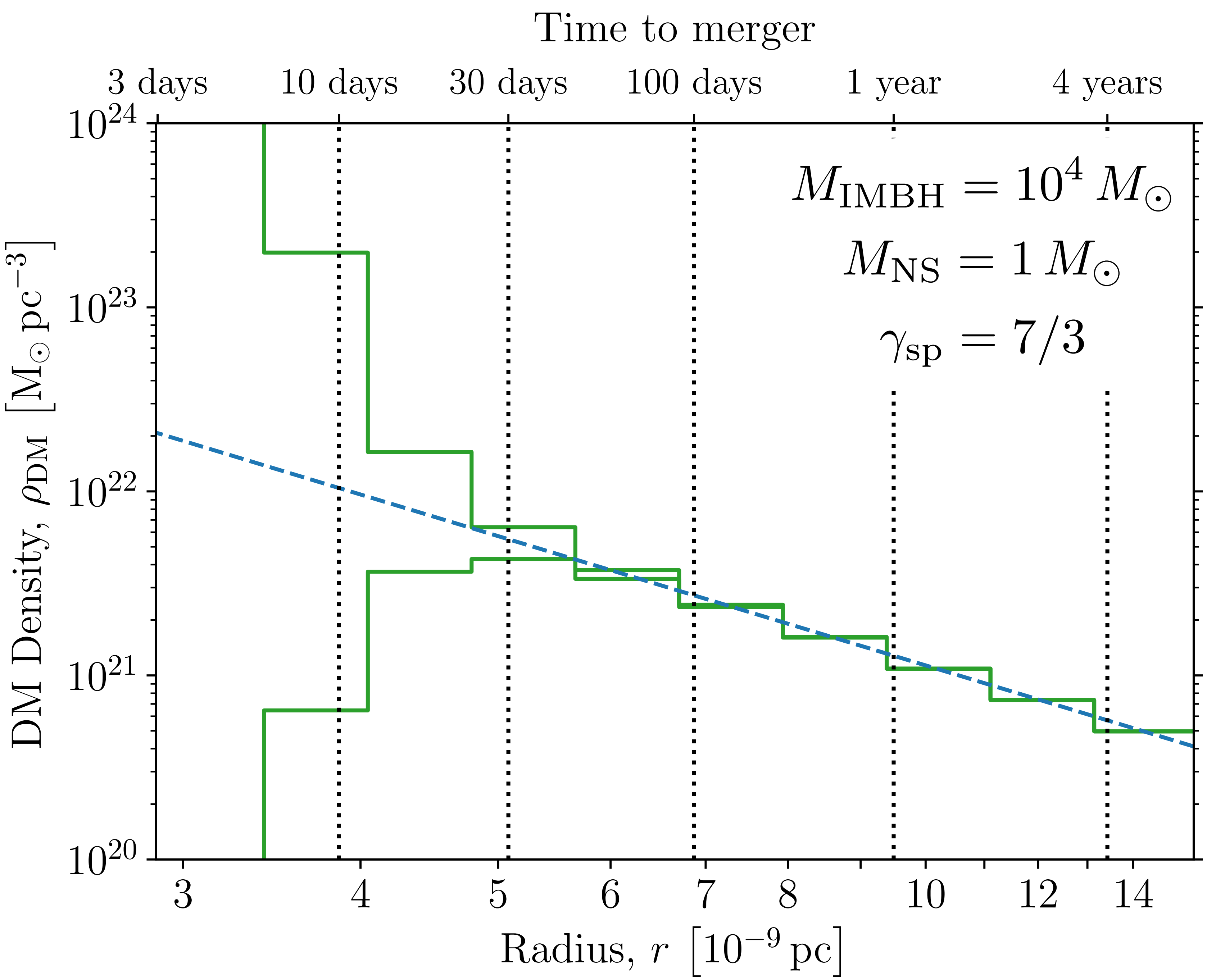
Small sep.

Need to know the signal to better than ~1 part in 10^6!

[Eda et al. 1301.5971, 1408.3534]

[See also 1302.2646, 1404.7140, 1404.7149]

DM Density Reconstruction



Would allow us to:

Detect DM in GWs
[1909.05870]

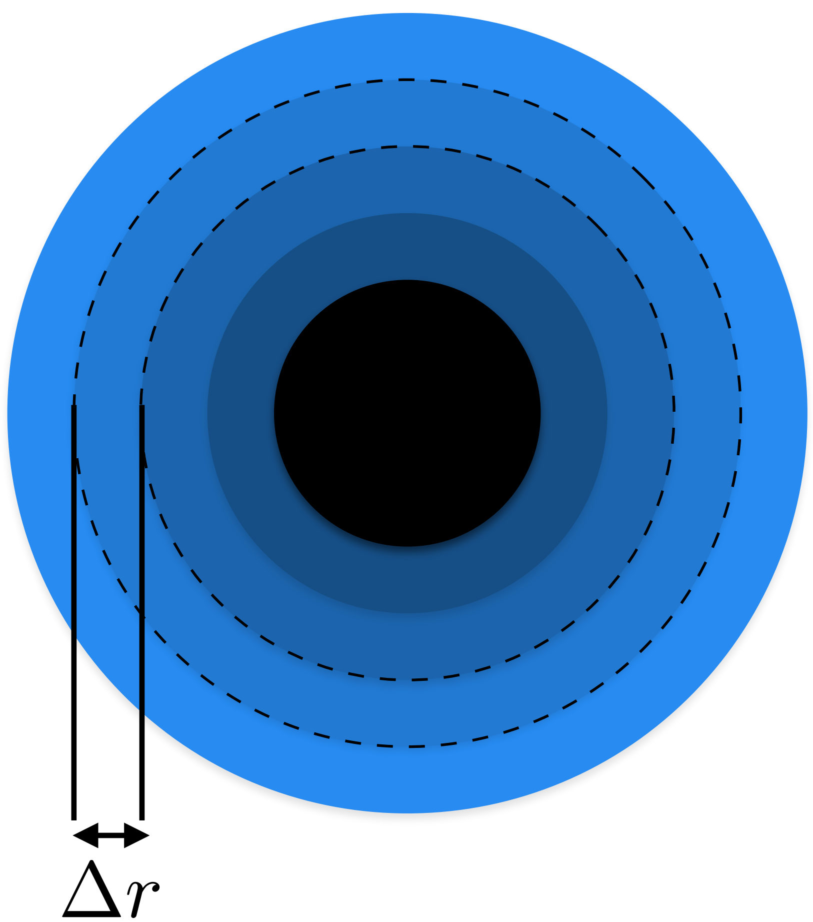
Probe DM nature
[1906.11845]

Predict EM signals from DM
[1905.04686]

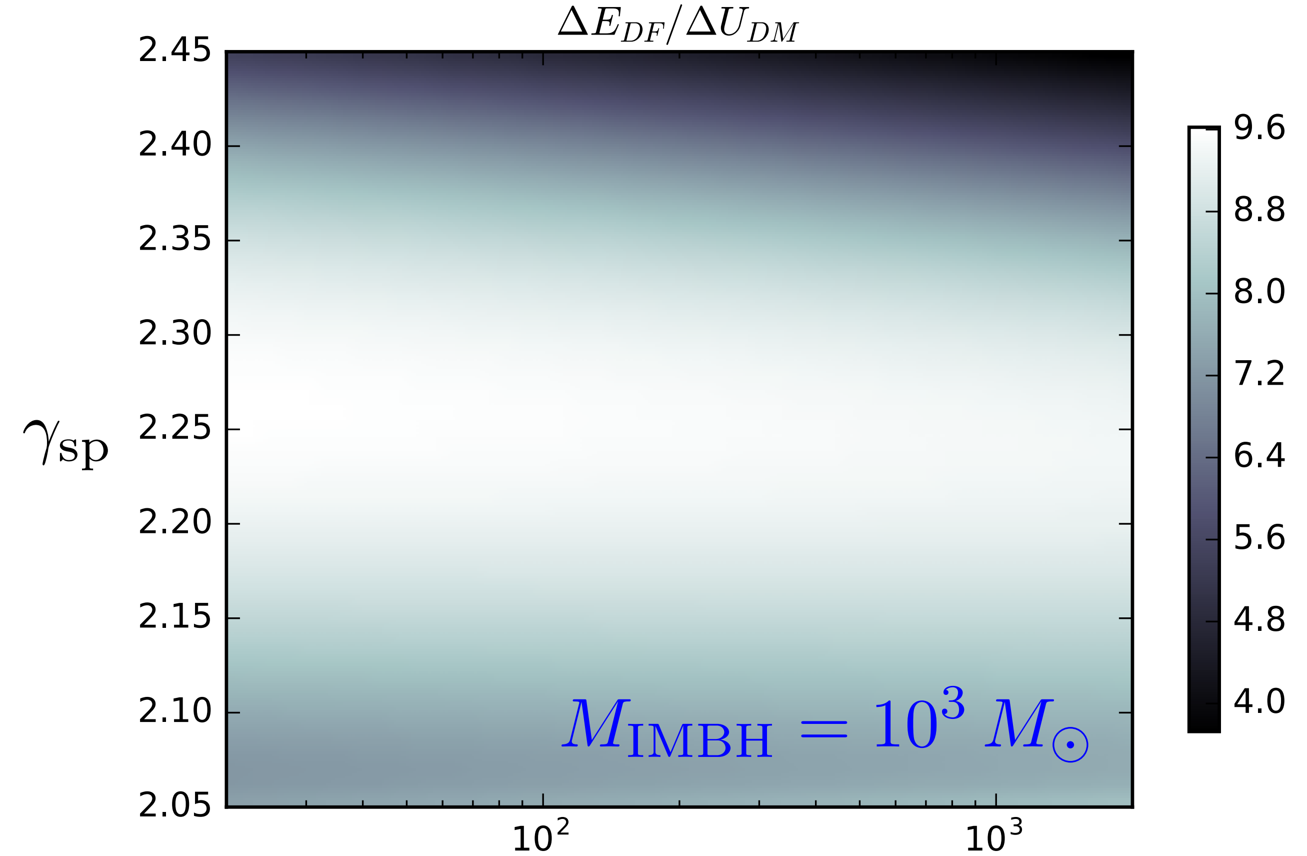
[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

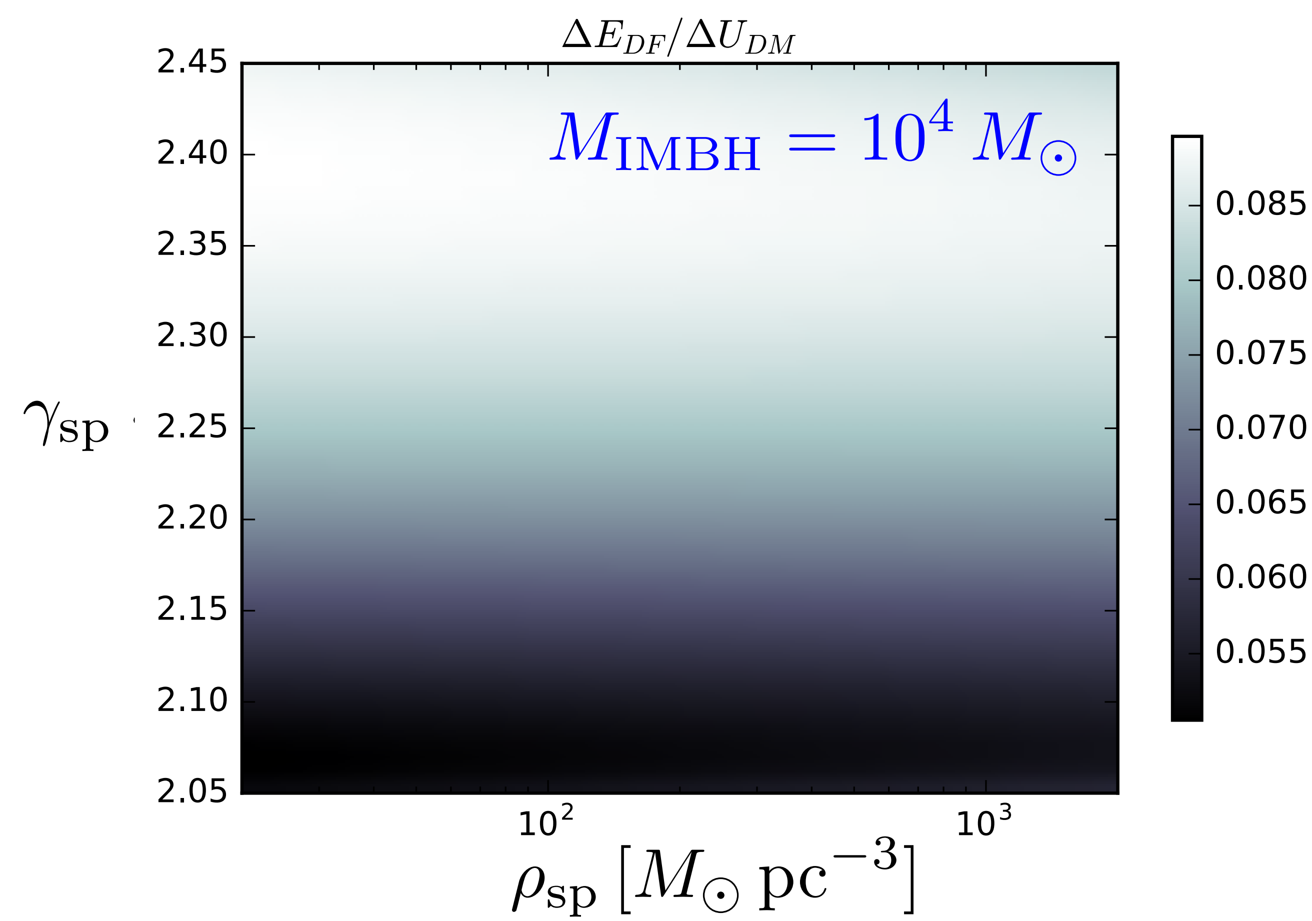
Energy Budget

Q: How much energy is *available* for dynamical friction?



A: Binding energy of DM $\Delta U_{\rm DM}$ over radius Δr





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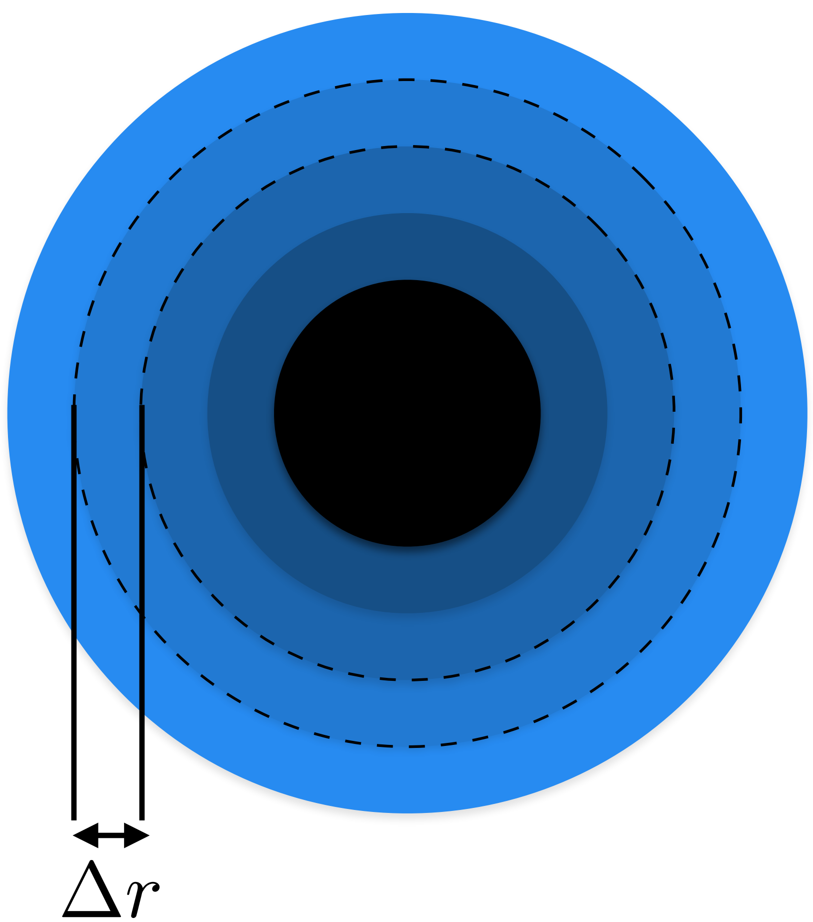
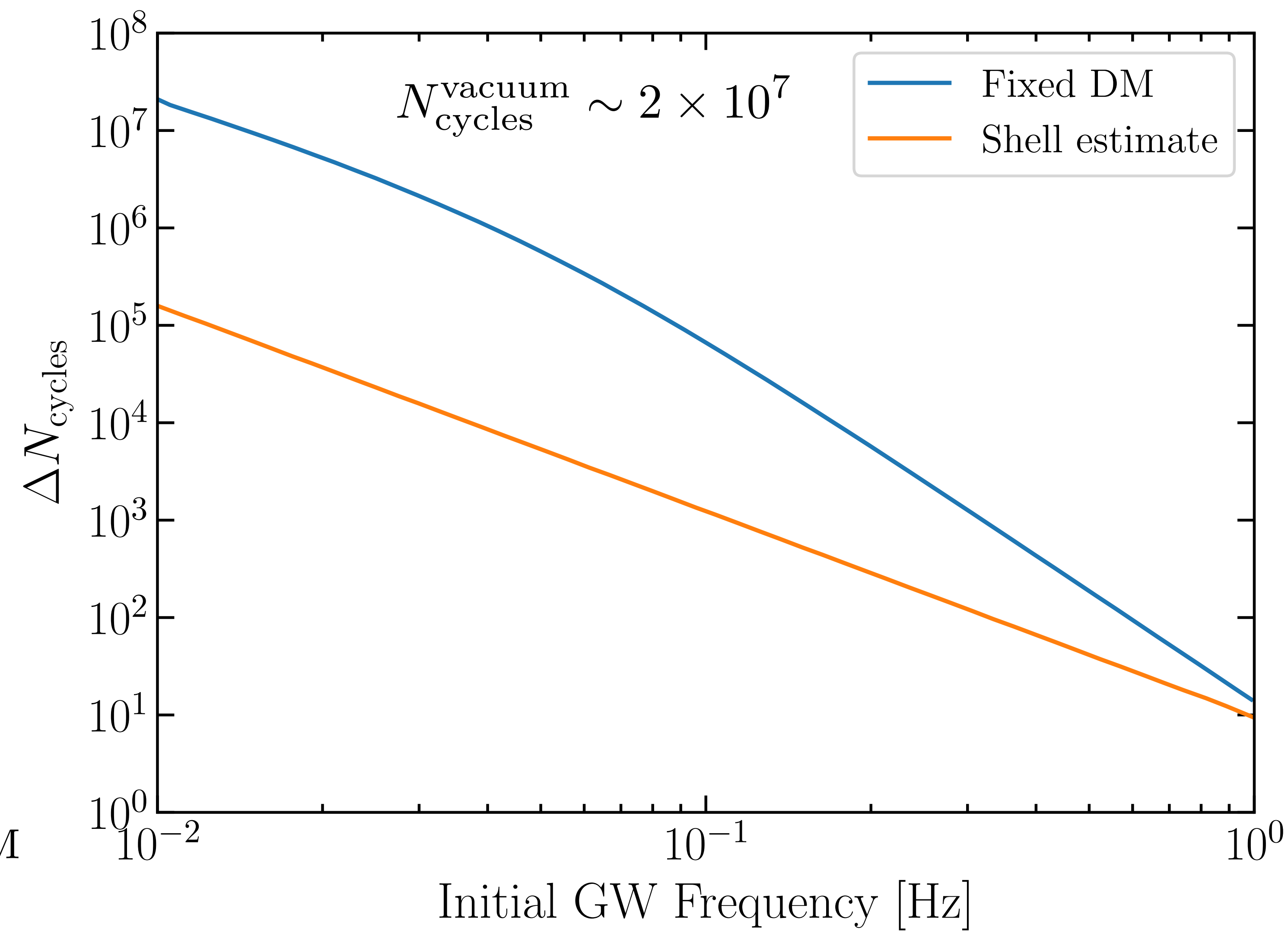


A: Binding energy of DM ΔU_DM over radius Δr

Evolve the system by fixing the dynamical friction force to extract *all* binding energy from a shell at a given radius:

$$\dot{E}_\mathrm{DF} = \dot{r}\,\frac{\mathrm{d}U_\mathrm{DM}}{\mathrm{d}r}$$



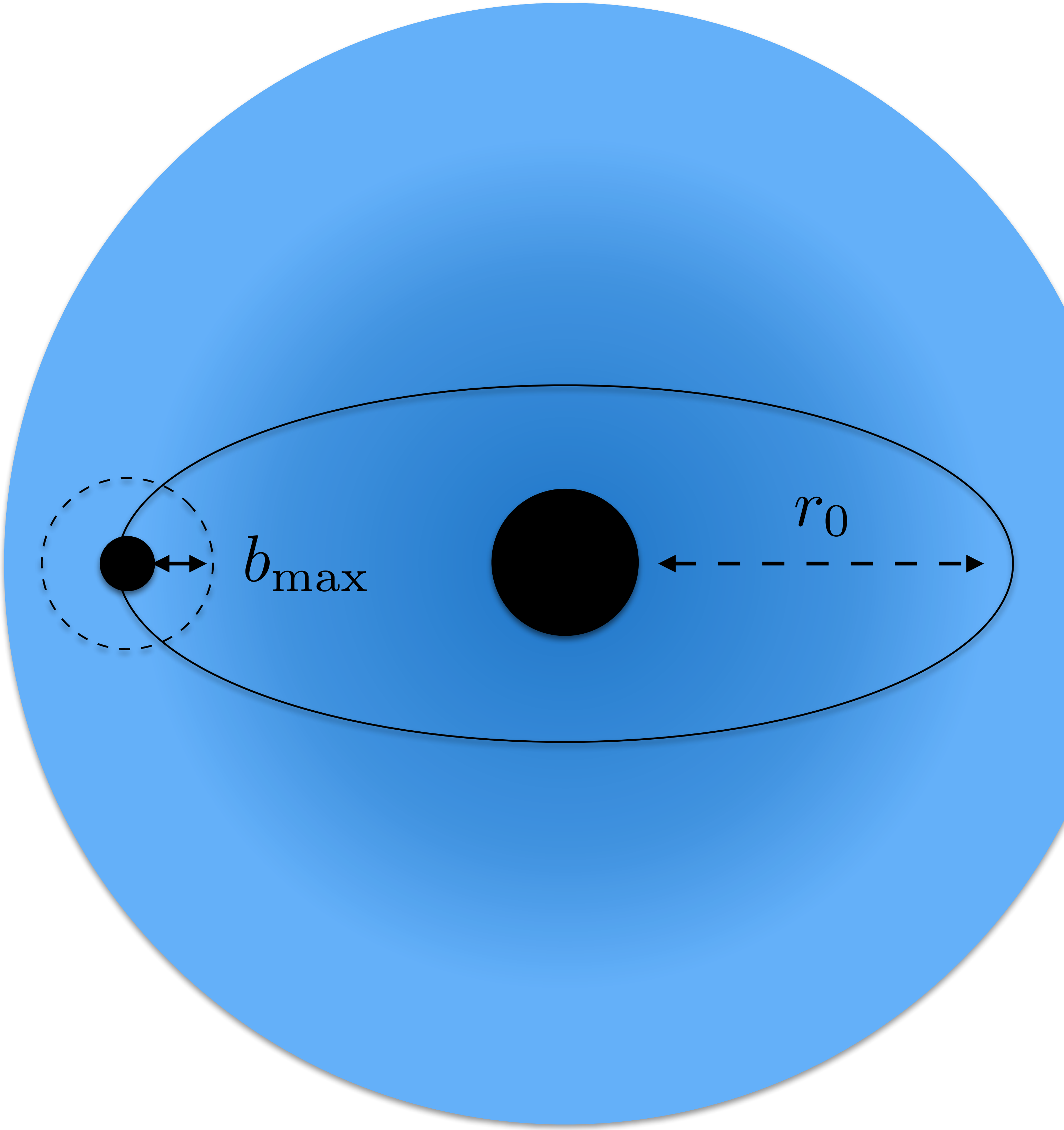
Self-consistent evolution

Current focus:

Follow phase-space evolution of the DM halo as energy is injected by the orbiting compact object

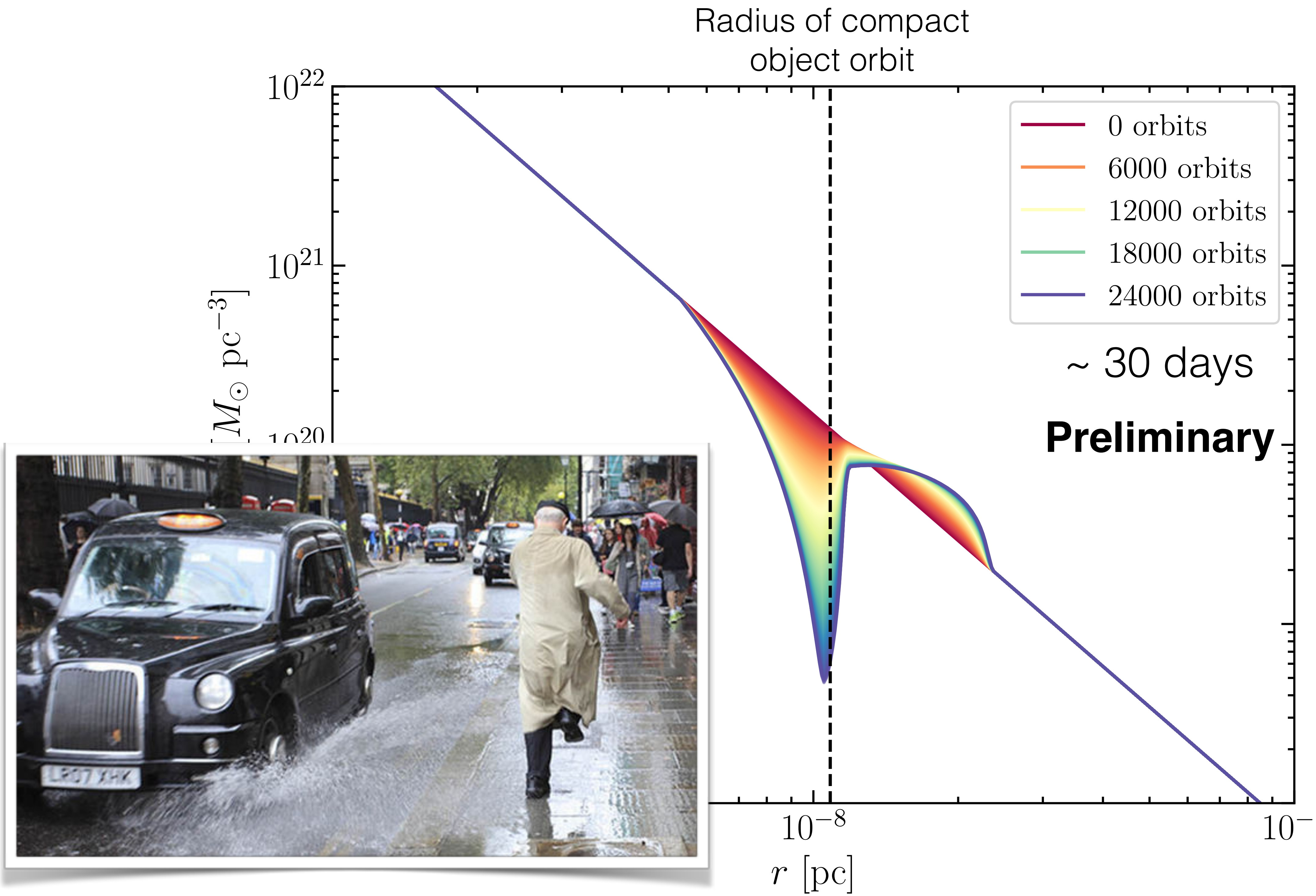
Check and calibrate with N-body simulations

Build 'template banks' of LISA GW waveforms

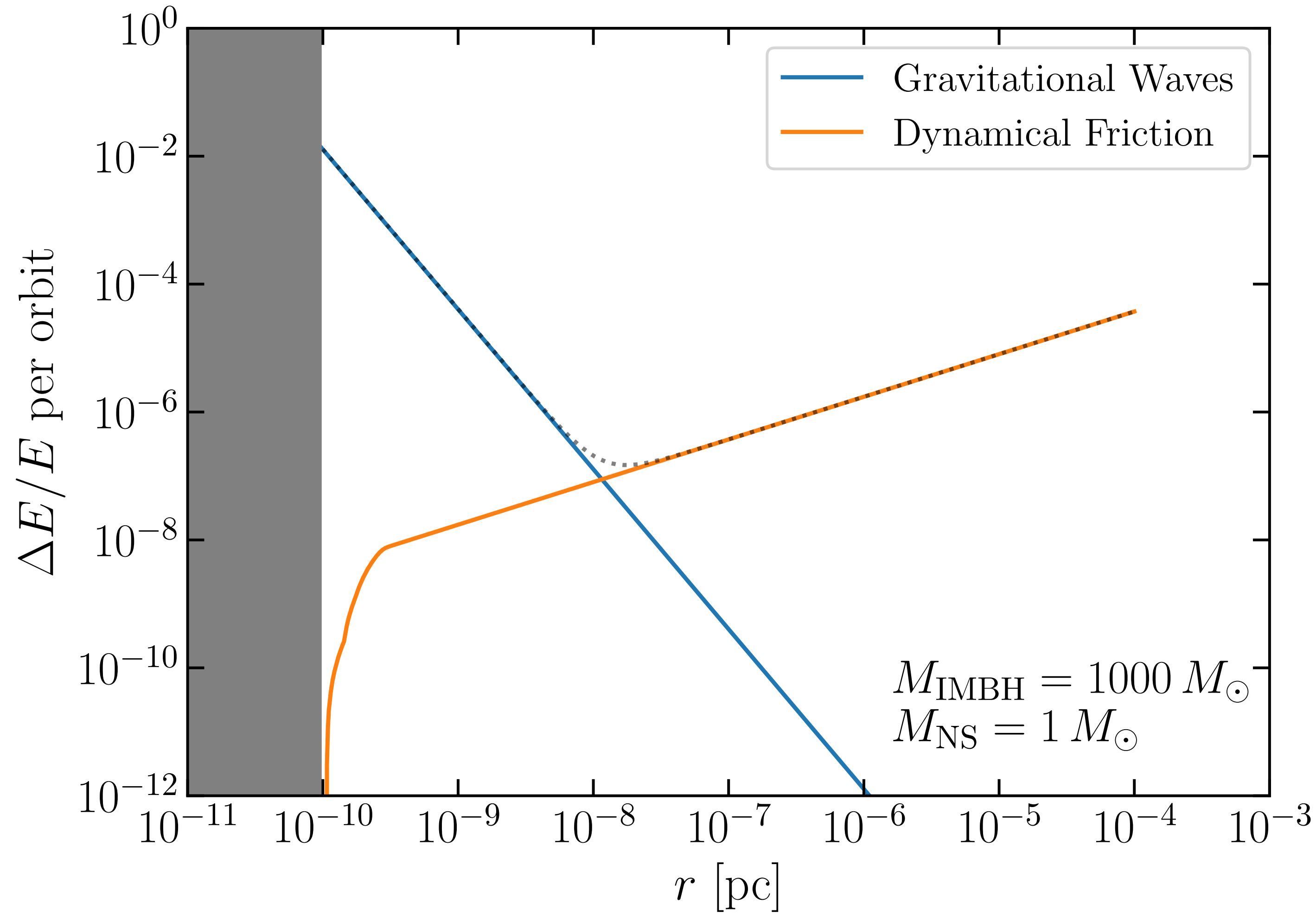


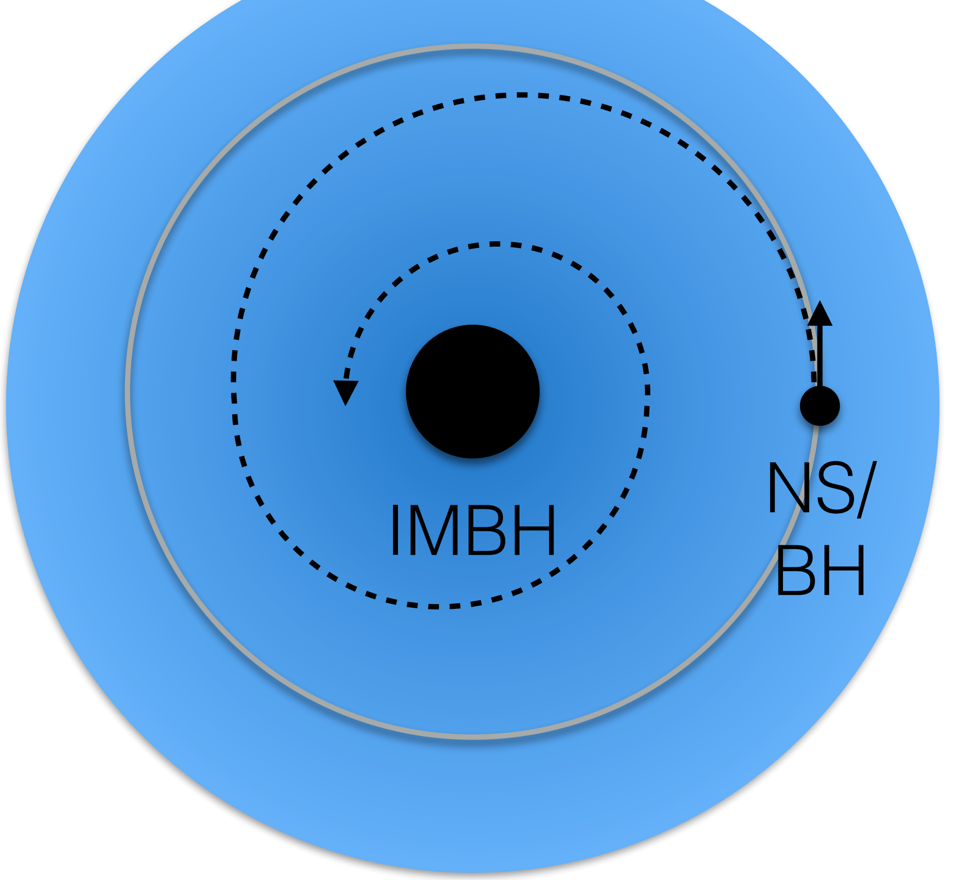
Evolution of density profile

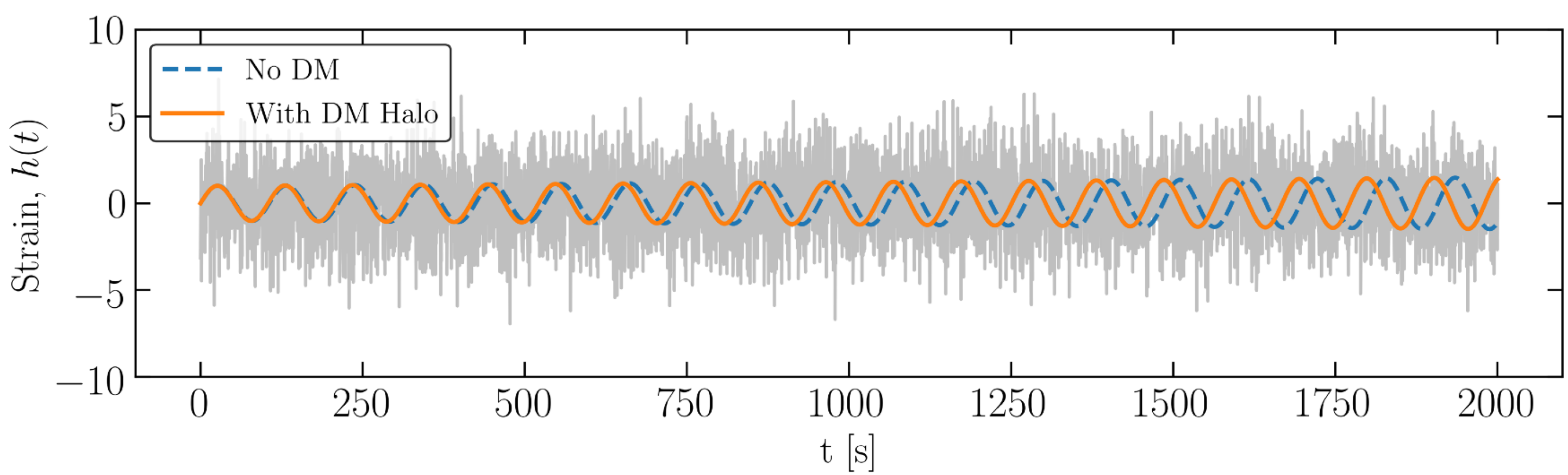
How does the DM halo ‘react’ to the orbiting compact object?



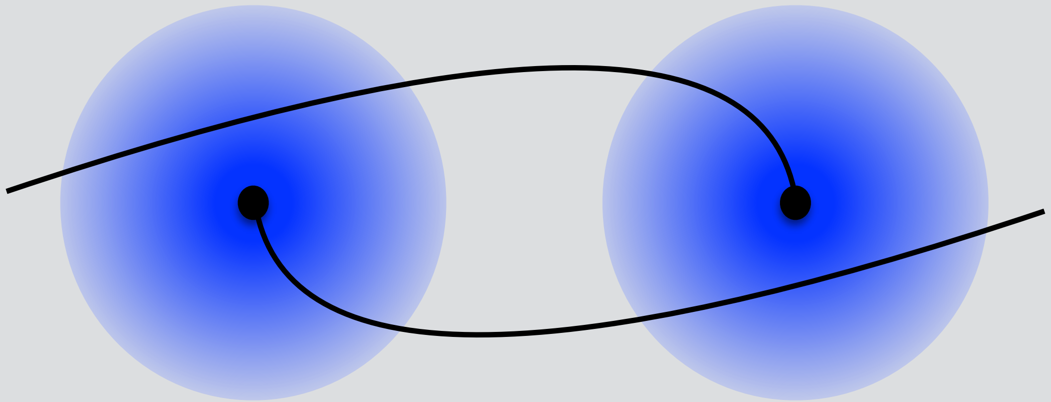
IMRI + Dark Matter







Conclusions

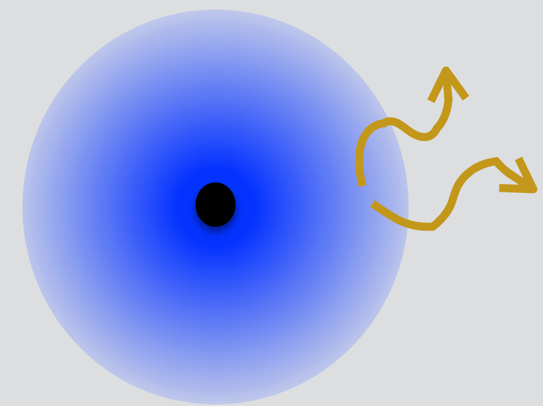


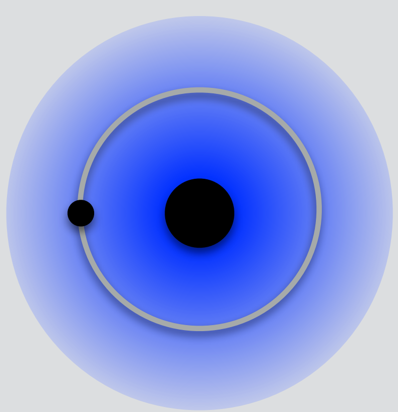
Merging Primordial Black Holes (PBHs)

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

DM Annihilation around PBHs

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

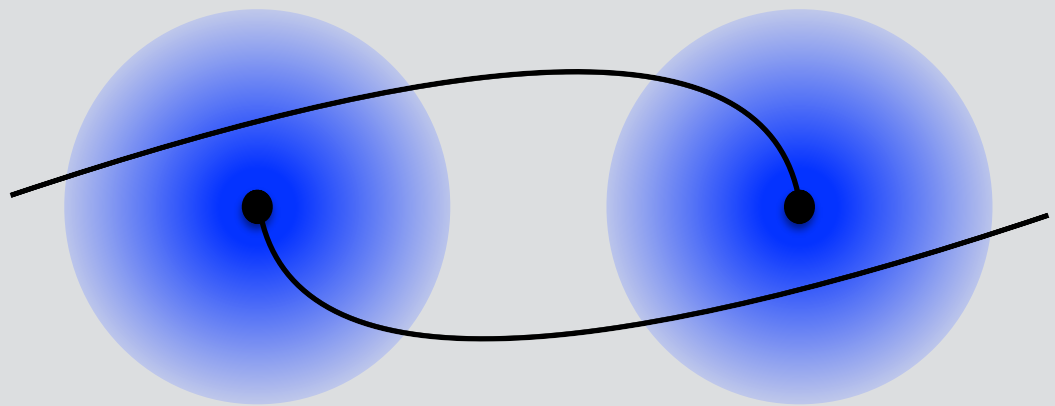




Intermediate Mass-Ratio Inspirals (IMRIs)

[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

Conclusions



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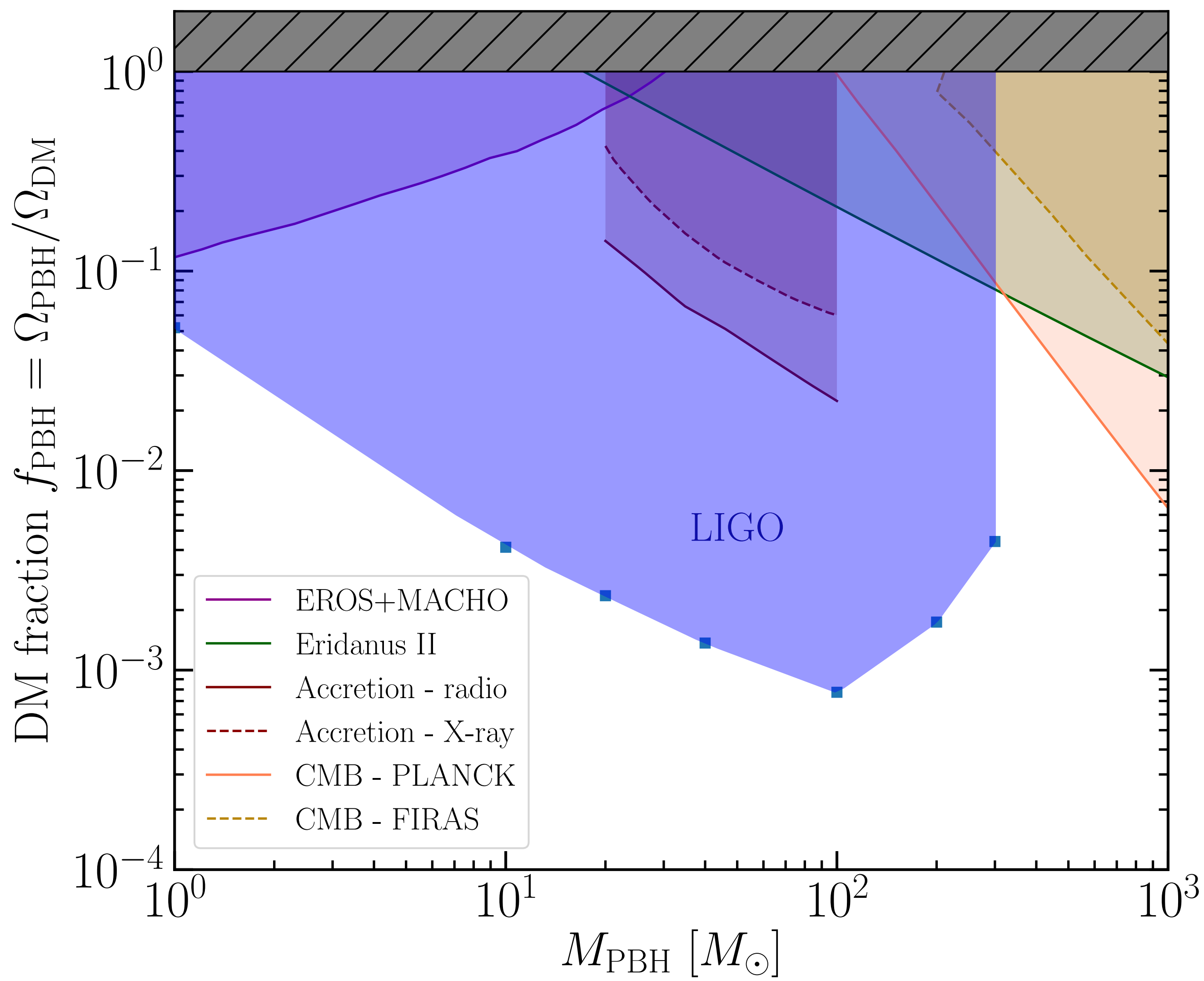

Conclusions

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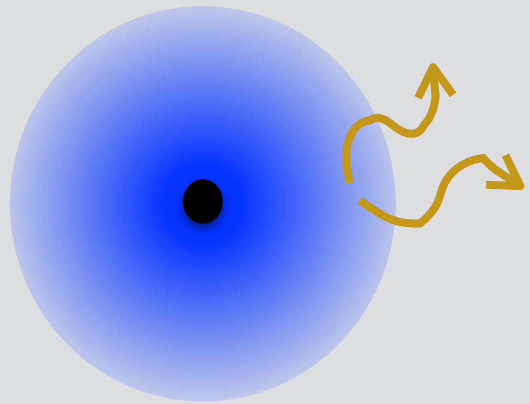
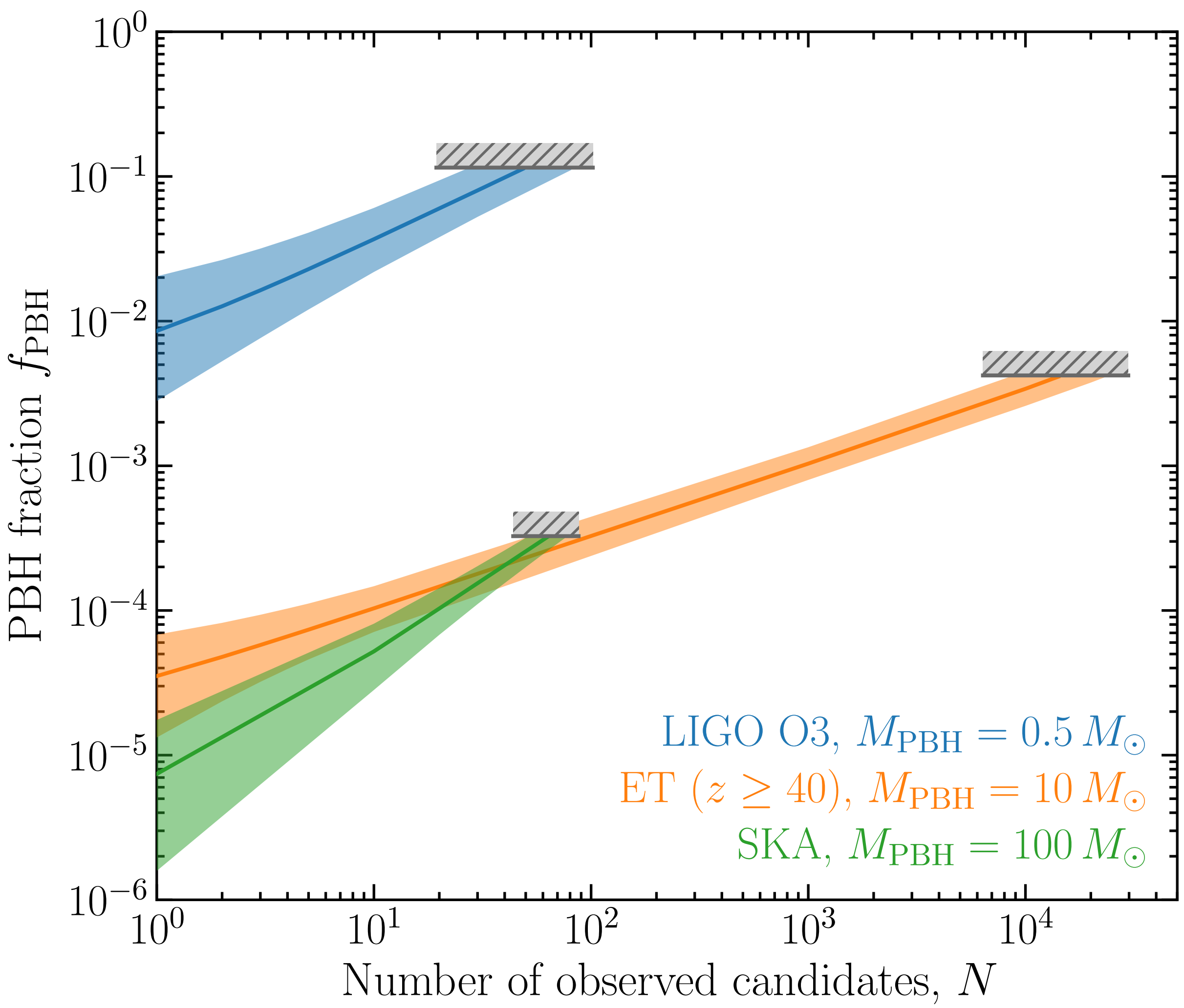
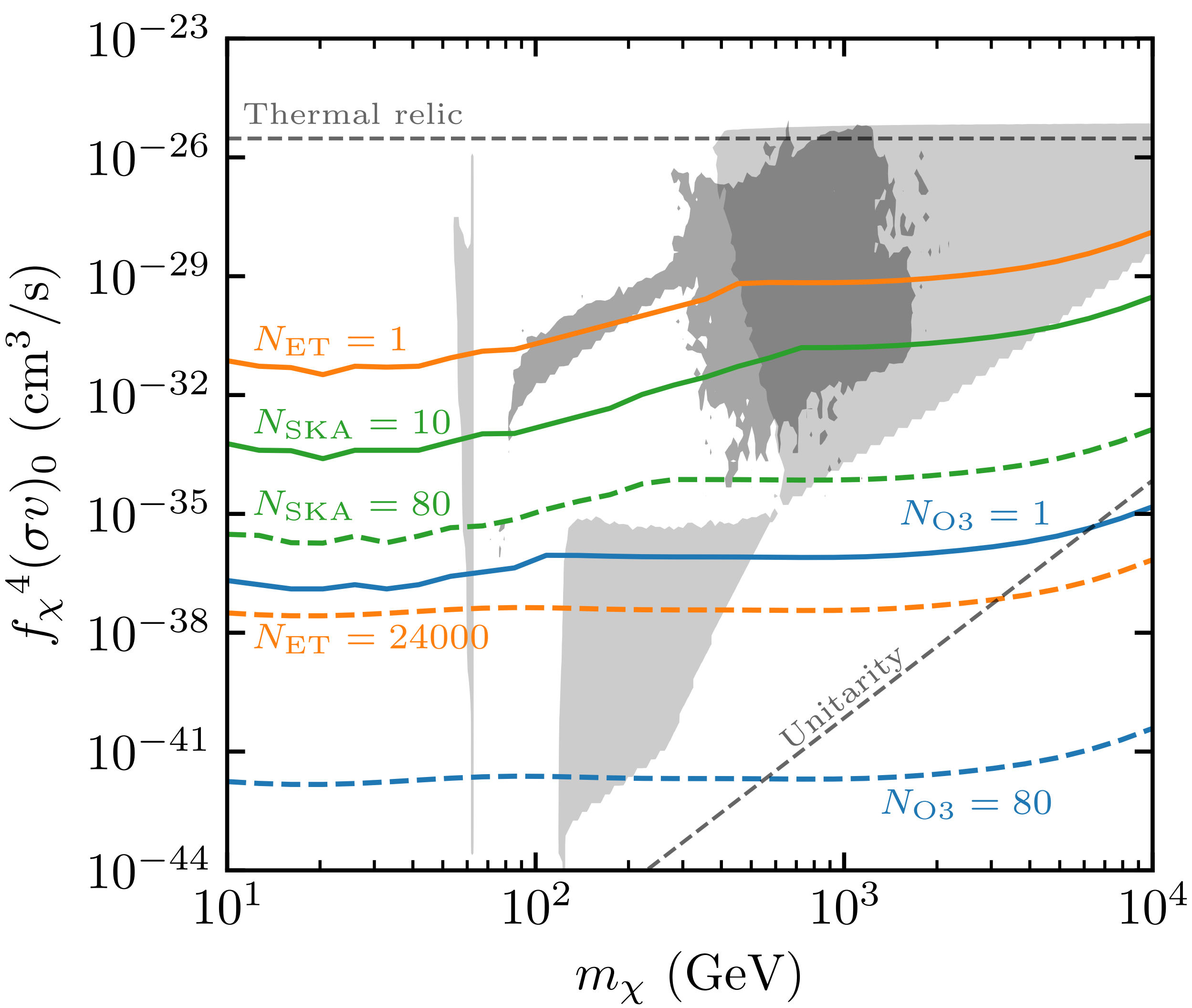
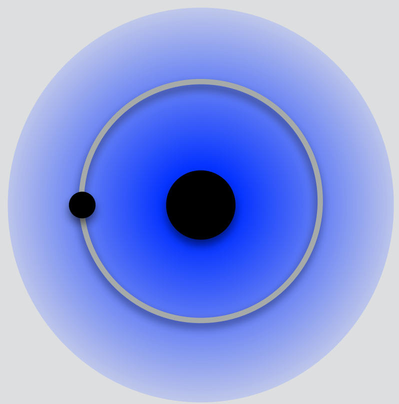
[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]







Conclusions



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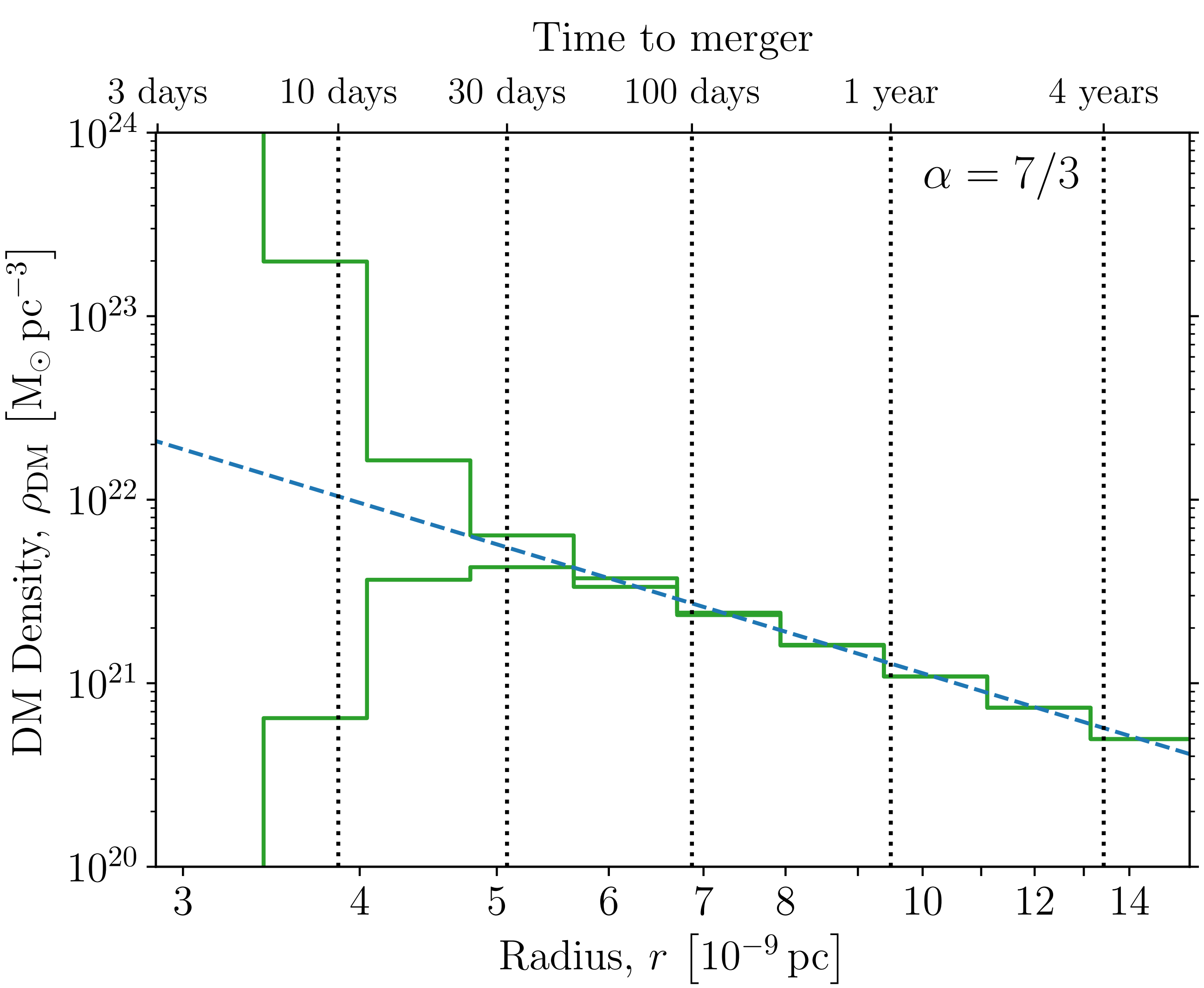
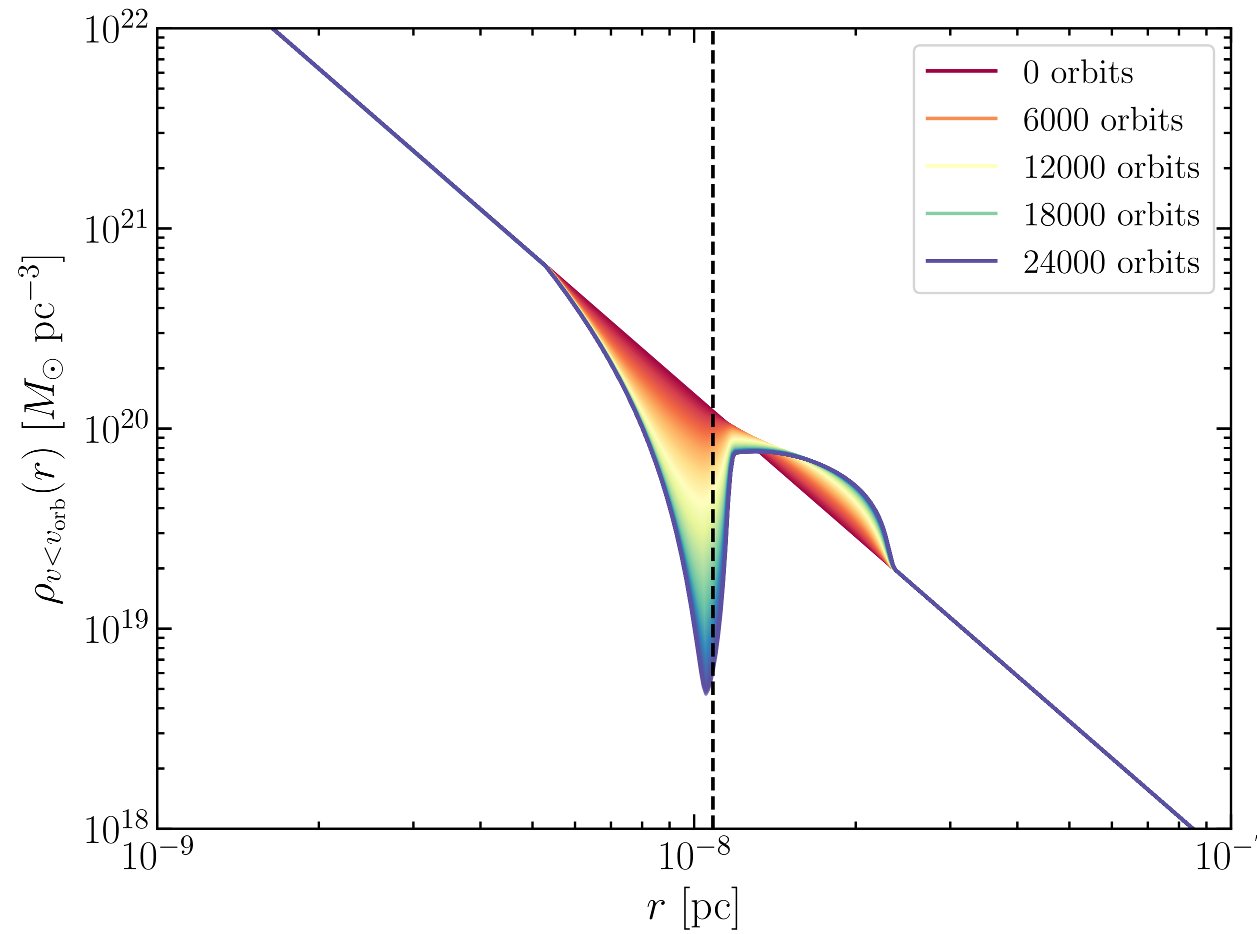
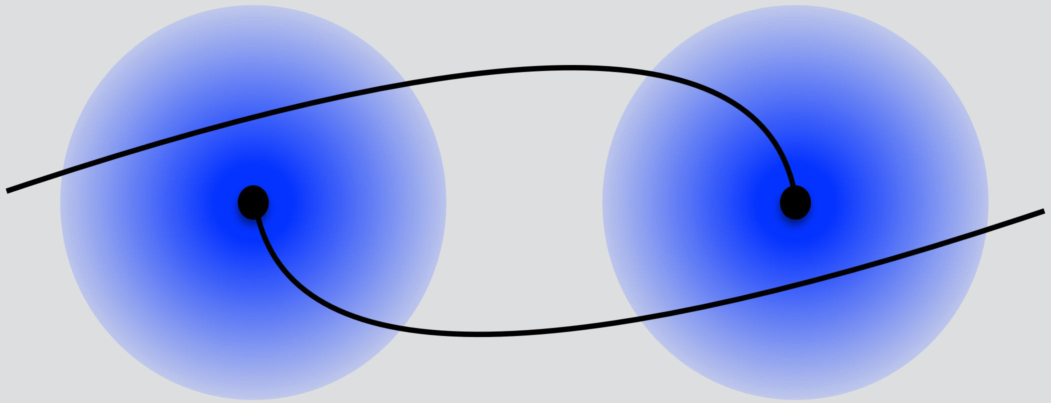
[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]





Conclusions

Thank you!



Merging Primordial Black Holes (PBHs)

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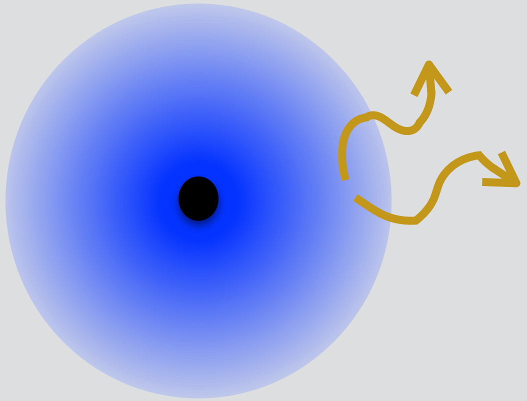
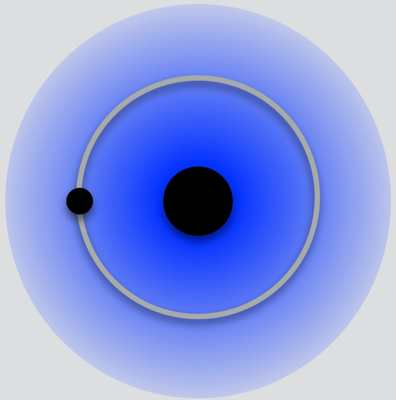


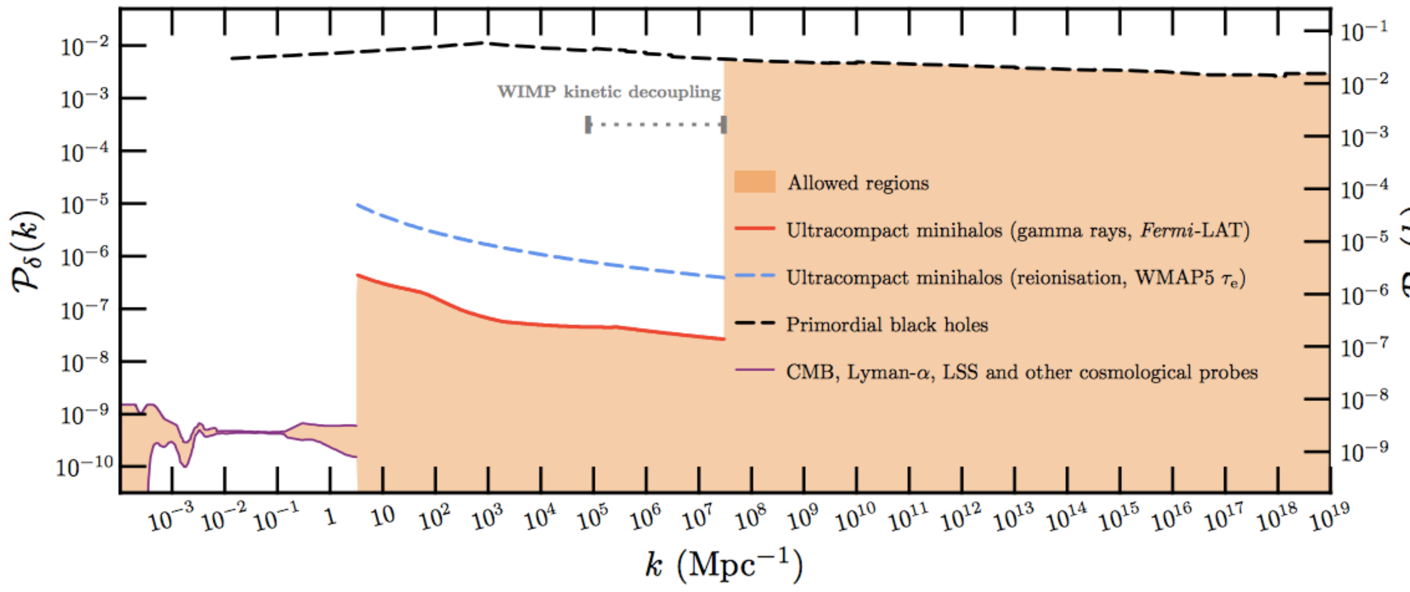


Intermediate Mass-Ratio Inspirals (IMRIs)

[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

Backup Slides

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

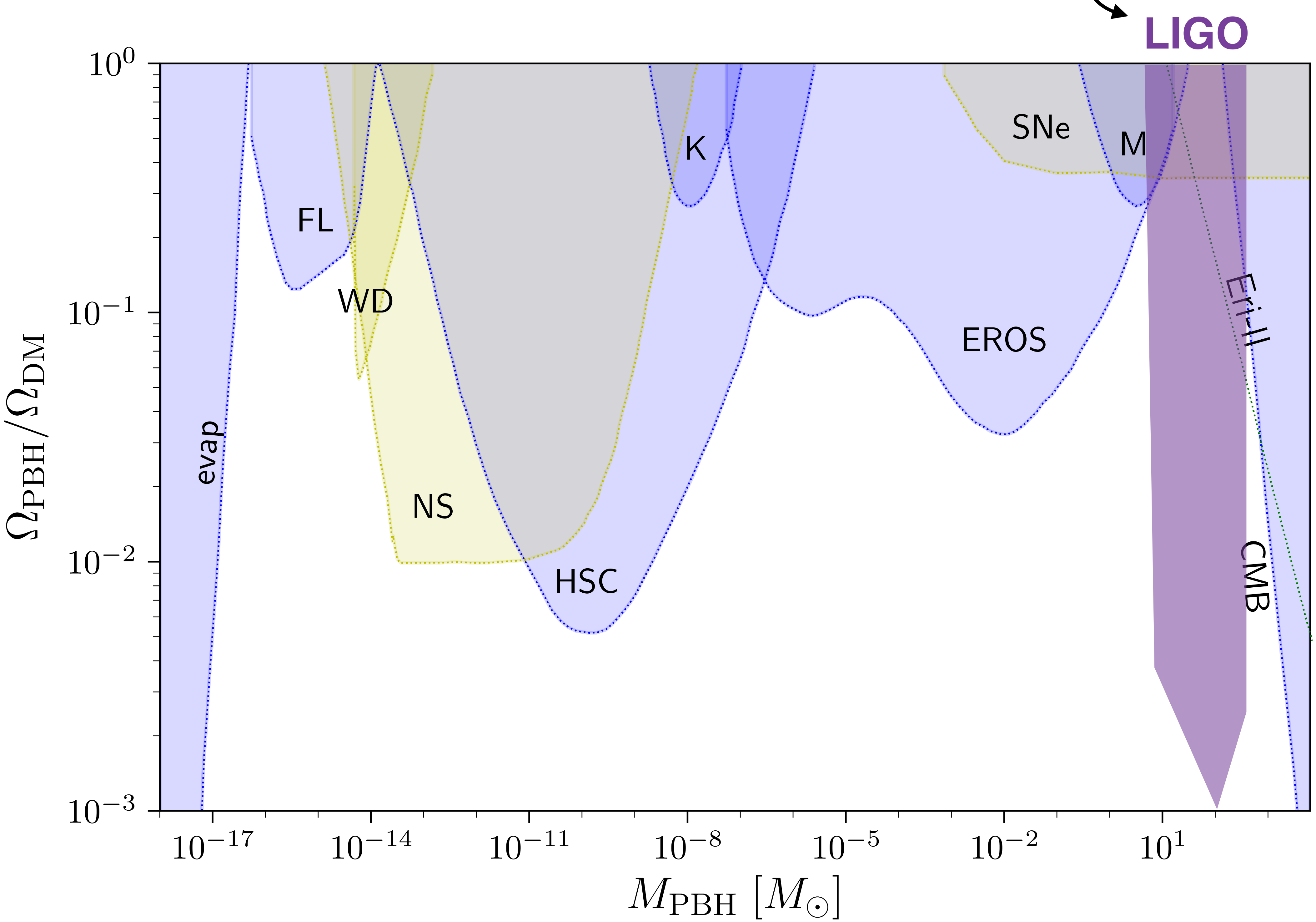
  [Hawking, Moss & Stewart (1982); La & Steinhart (1989)]

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

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



[See 1607.06077, 1806.05195 and references therein]

A peculiar coincidence

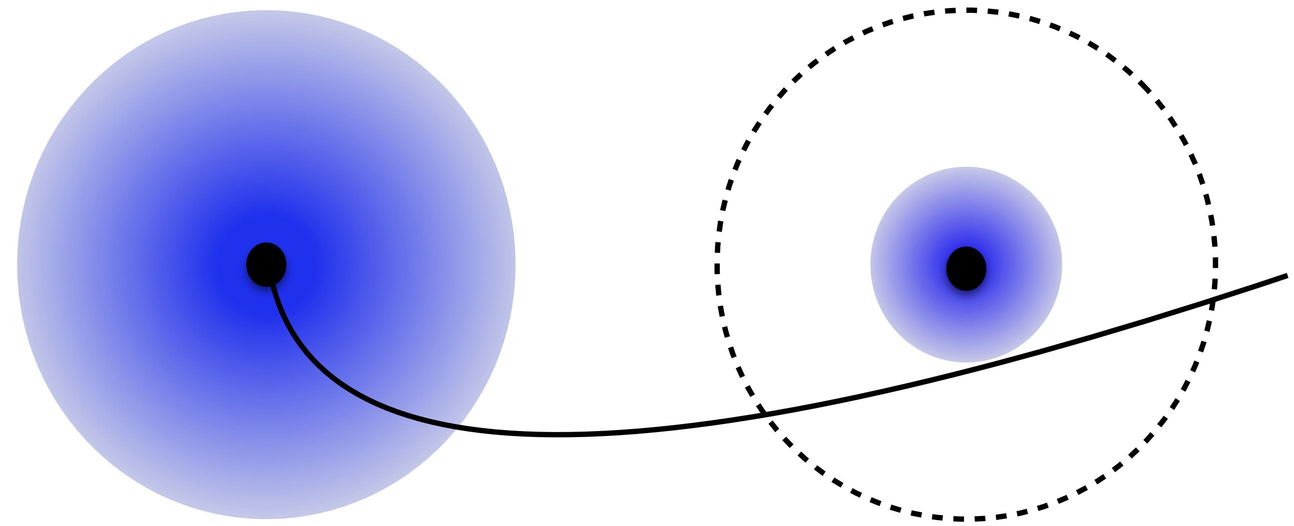
Binaries shrink…

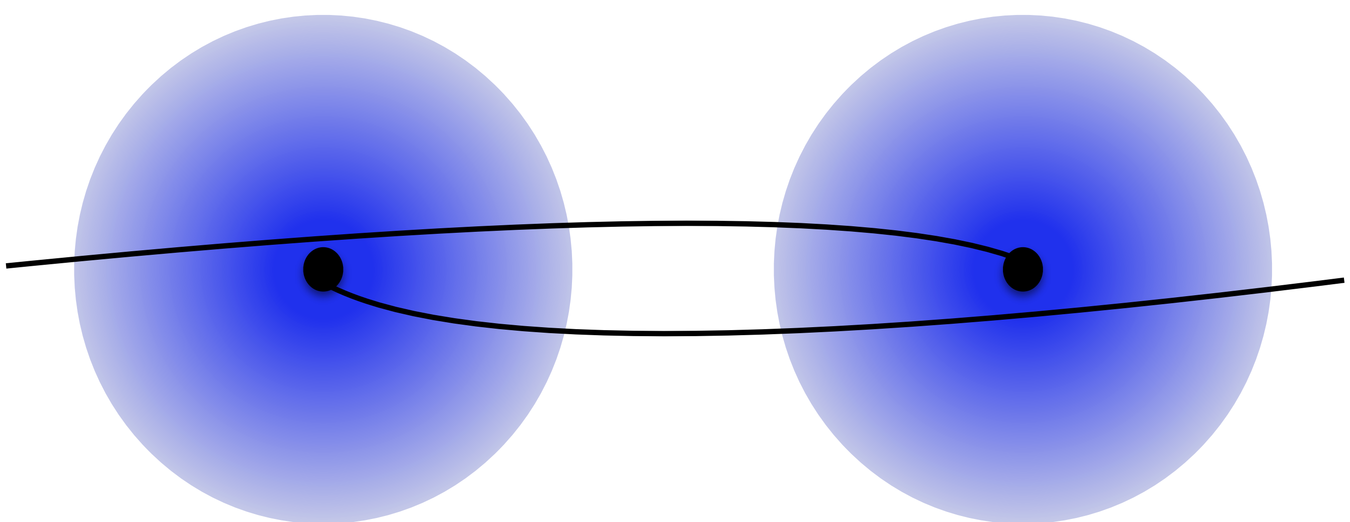
…and circularise

Conservation of energy:

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

fixes semi-major axis, a





Conservation of angular momentum:

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

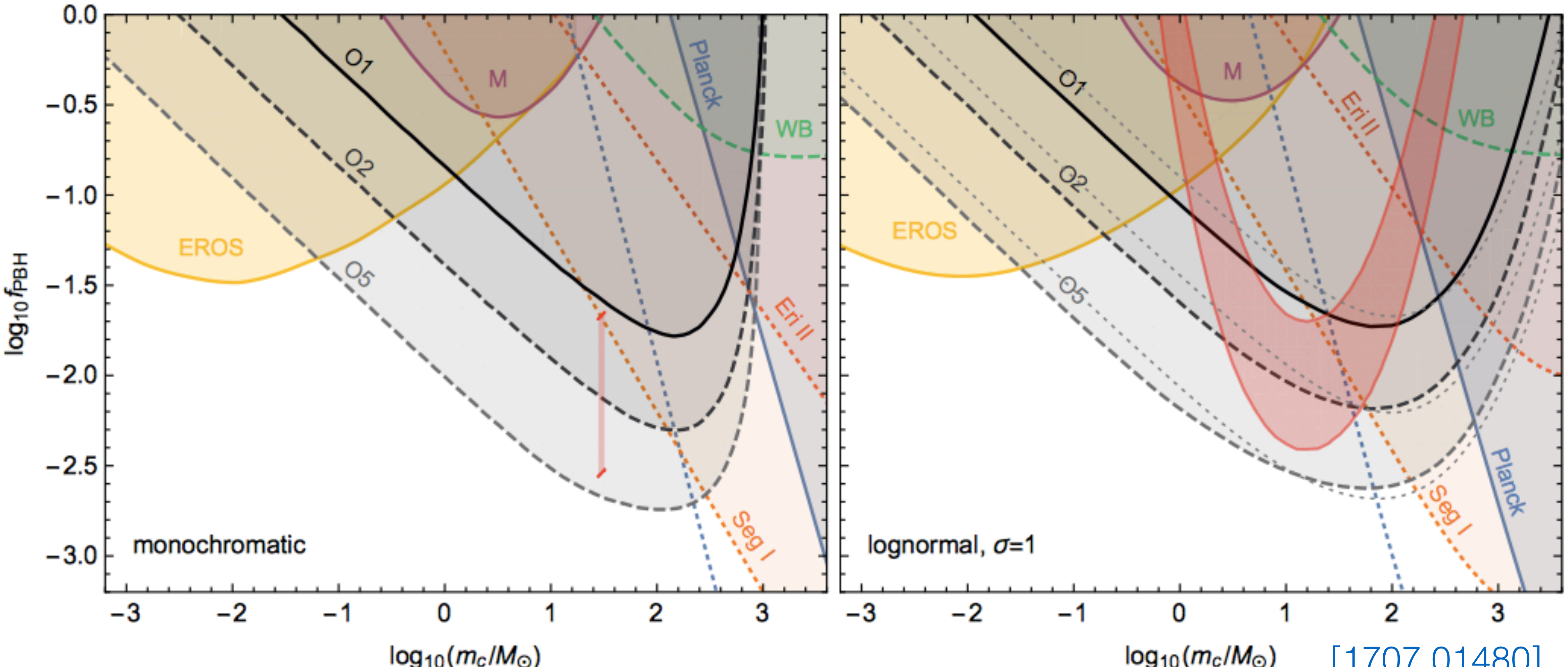
$$L_i^{\mathrm{halo}} = L_f^{\mathrm{halo}}$$

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

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: $t_f = \sqrt{\dfrac{a_i}{a_f}}\,t_i$

Extended Mass Function

LIGO O1 Limit



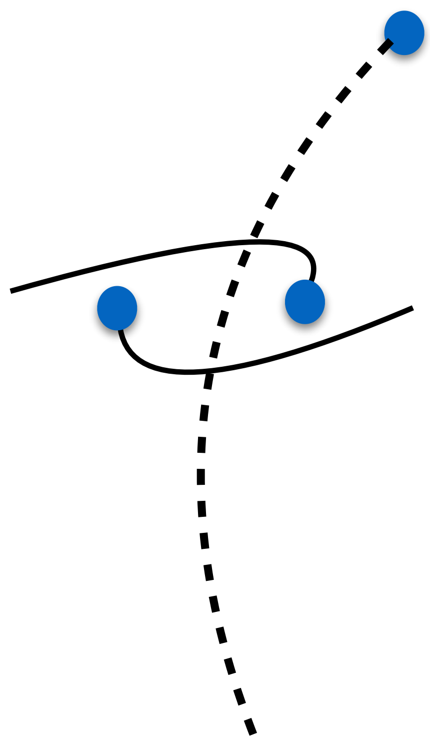
[1707.01480]

"Old" merger rate calculation *à la* Sasaki et al.,
but picture doesn't change too much…

[See also 1801.10327]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



Do these binaries survive for the age of the Universe?

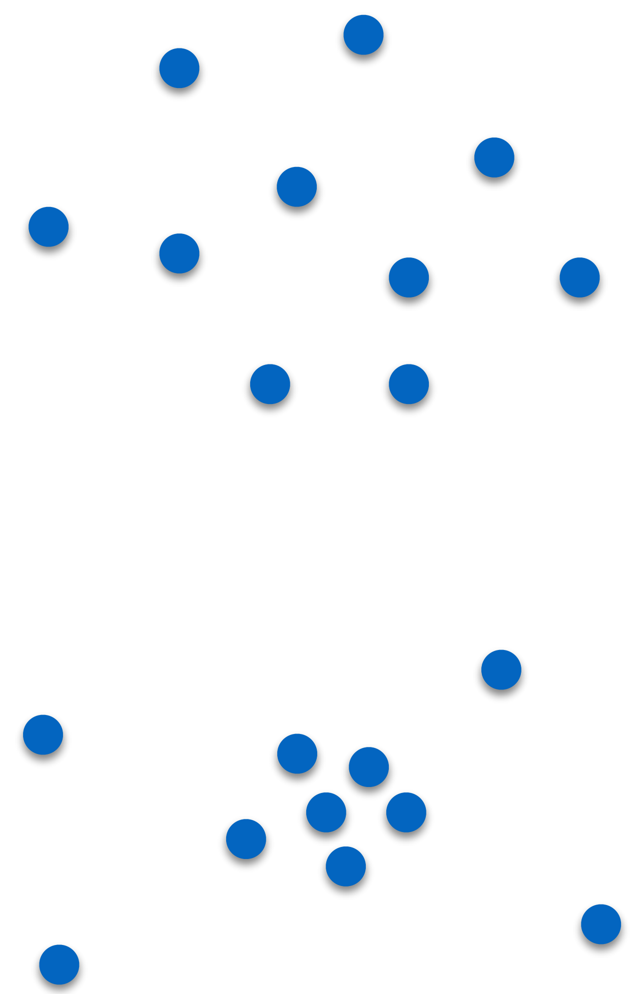
Smooth density perturbations and close encounters
are unlikely to disrupt the binaries

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

[Ali-Haïmoud et al., 1709.06576]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



How does the distribution of PBHs affect the merger rate?

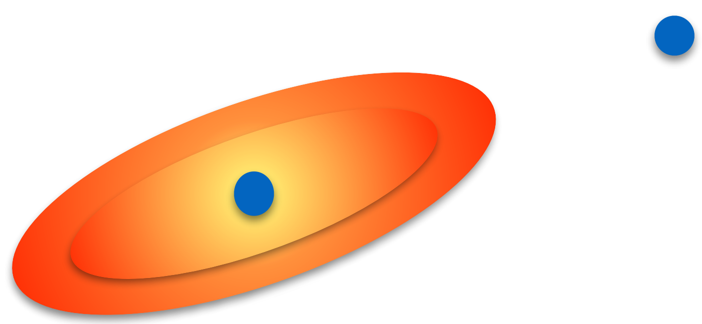
Clustering could substantially enhance the merger rate ('cascade' mergers) but PBHs are unlikely to form in clusters…

[1808.05910] [1807.02084]

[See also 1805.05912,1806.10414 and others]

Caveats

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



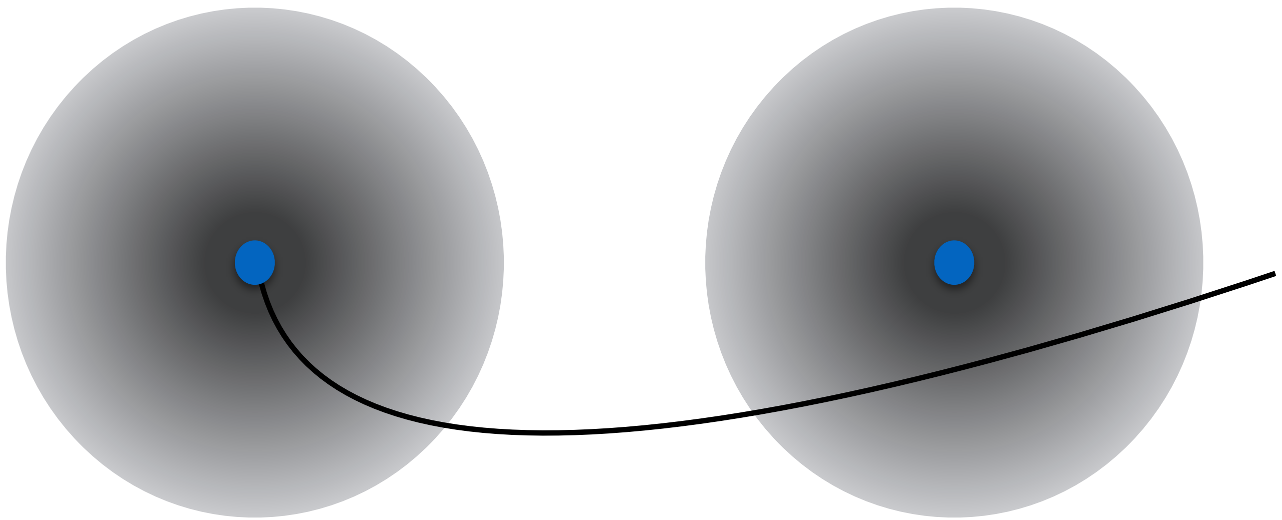
Does baryonic accretion disrupt the binary?

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]

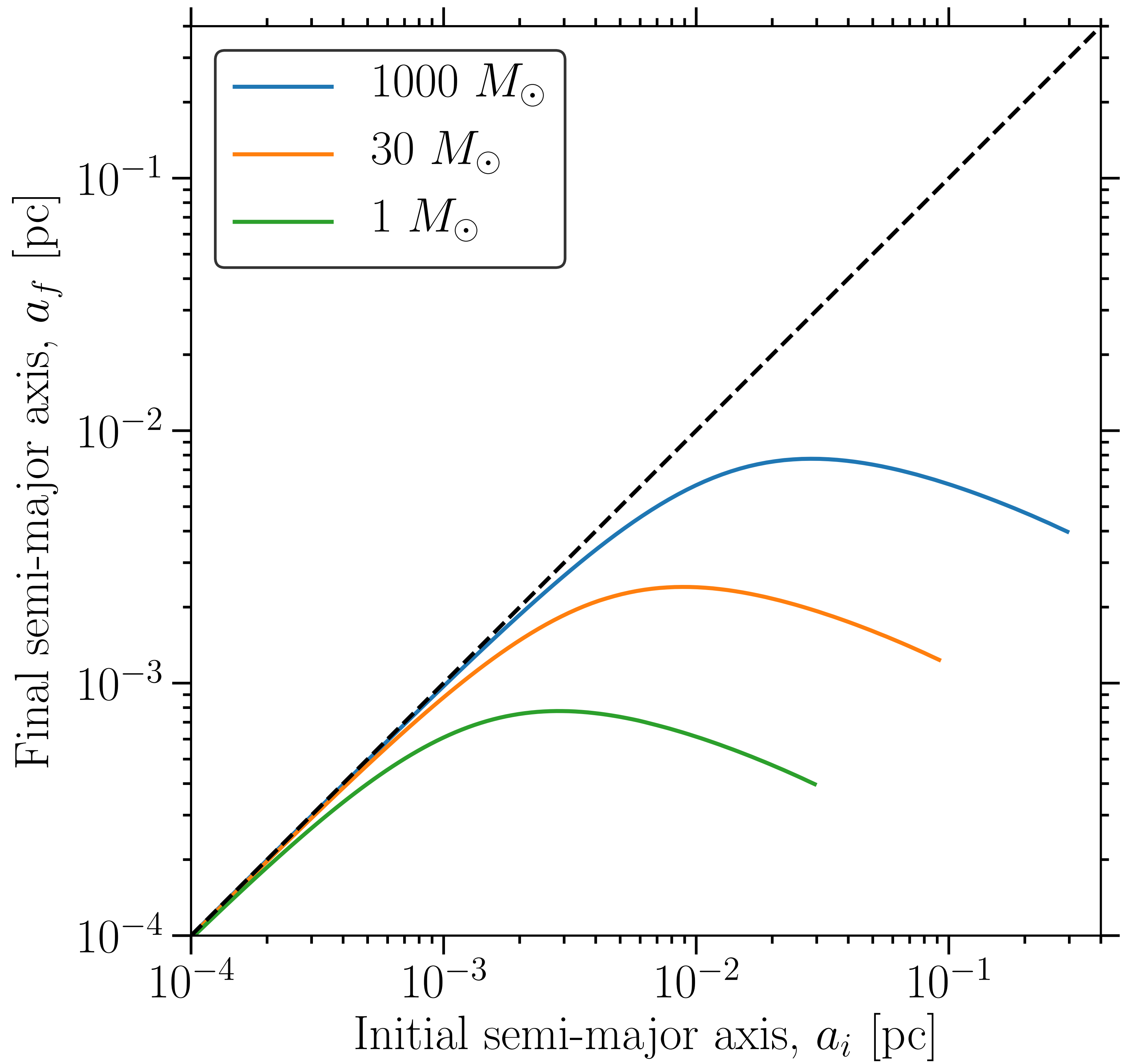
Caveats

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



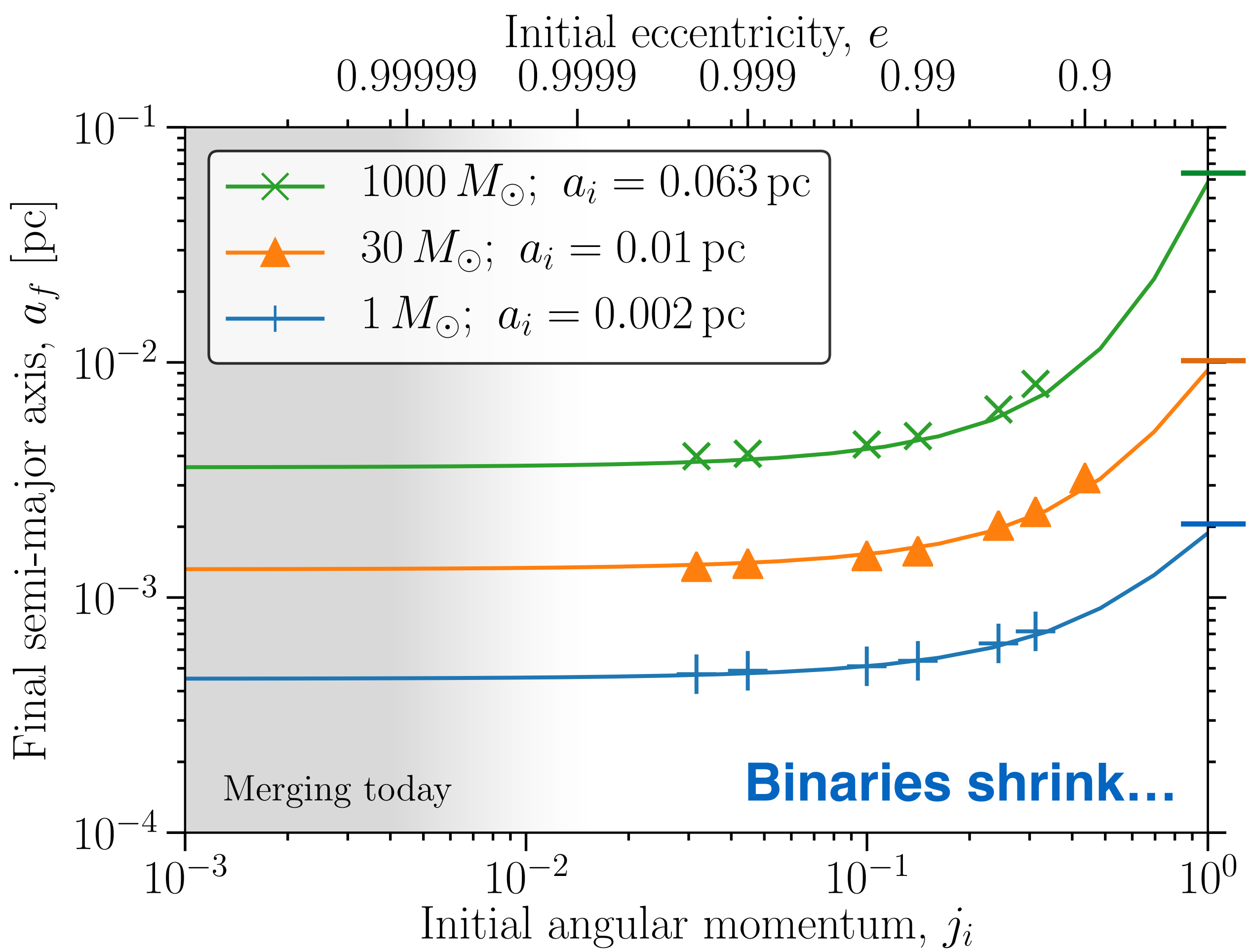
Do *local* Dark Matter halos disrupt PBH binaries?

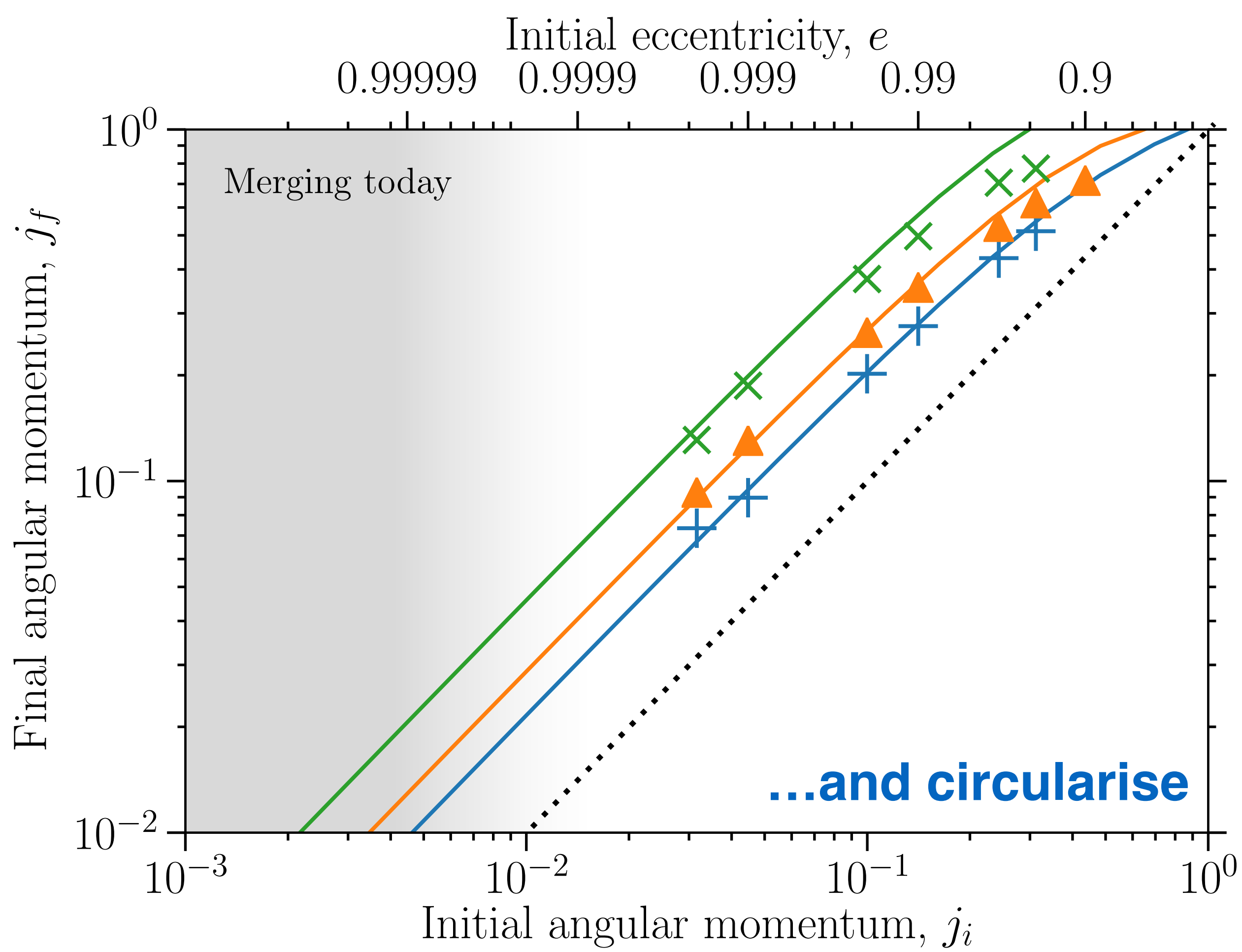
PBH Binaries: semi-major axis



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

PBH Simulation Results





High precision N-body sims

Gadget-II code:

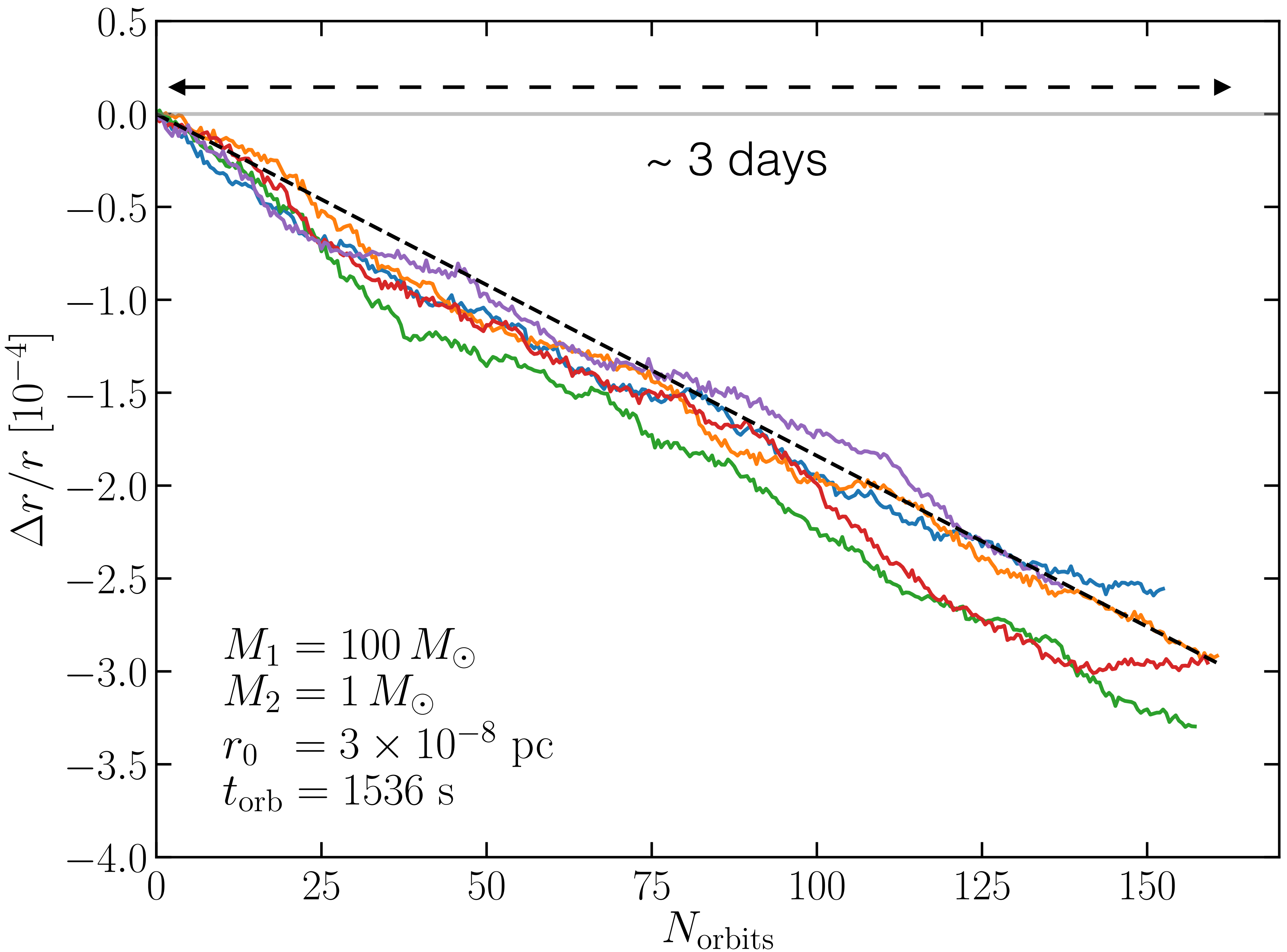
```
/* Some physical constants in cgs units */

#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:

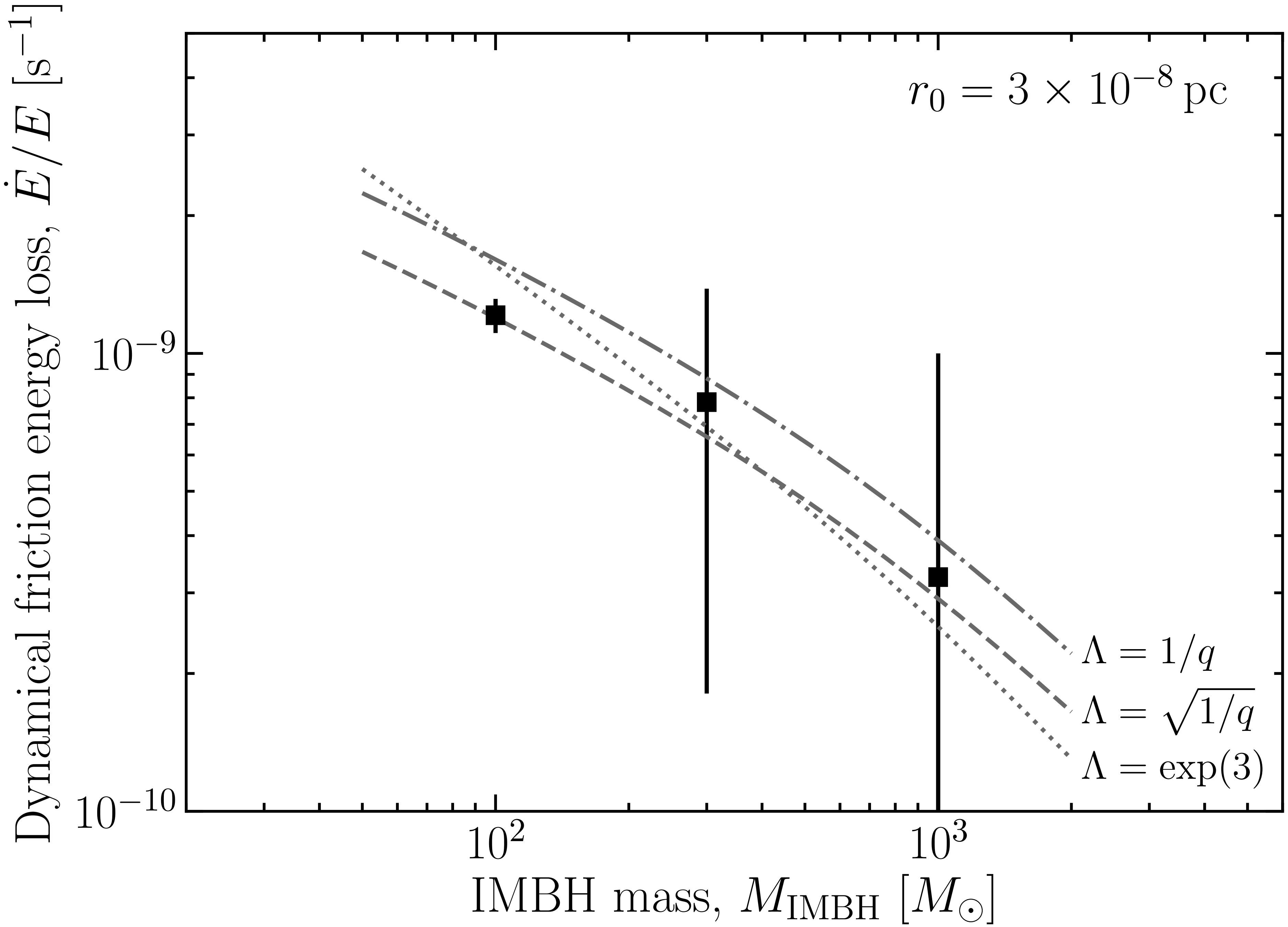
$$G_N = 6.674 \times 10^{-8}\,\mathrm{m}^3\,\mathrm{g}^{-1}\mathrm{s}^{-2}$$

N-body simulations



Allows us to check assumptions and fix normalisation of DF force (lnΛ), but can't simulate the whole 5 year inspiral!

N-body results



NS only scatters with particles where its gravity dominates over the IMBH's

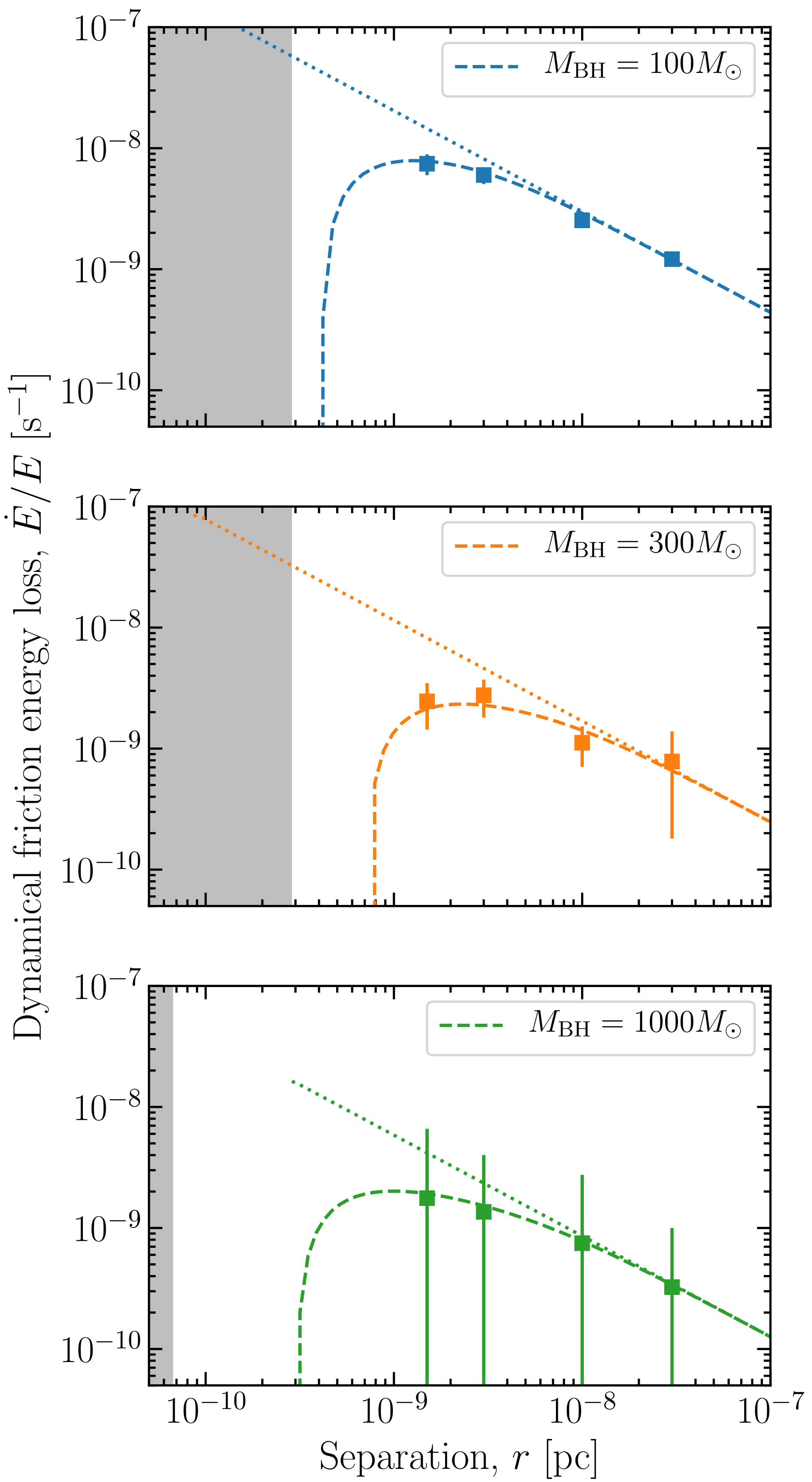
Fix 'Coulomb factor': $\Lambda = \sqrt{M_\mathrm{IMBH}/M_\mathrm{NS}} \sim 20 - 60$

N-body results

Dependence of dynamical friction force on mass and separation matches expectations

Dynamical friction traces local DM density (to better than 1%)

Drop off in DF force at small separations due to softening of simulations



Self-consistent evolution

Assuming orbit evolves slowly compared to the orbital period:

$$T_\mathrm{orb} \frac{\mathrm{d}f(\mathcal{E})}{\mathrm{d}t} = -f(\mathcal{E}) P_\mathrm{scatter}(r_0, \mathcal{E}) + \left(\frac{\mathcal{E}}{\mathcal{E}+\Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E}-\Delta\mathcal{E}) P_\mathrm{scatter}(r_0, \mathcal{E}-\Delta\mathcal{E})$$

$P_\mathrm{scatter}(r_0, \mathcal{E})$ - roughly the fraction of DM particles with energy $\mathcal{E}$ which lie within a distance b_{max} from the NS orbit

Density profile (and therefore dynamical friction force) can then be determined self-consistently from the distribution function

Self-consistent evolution

Assuming orbit evolves slowly compared to the orbital period:

$$T_\mathrm{orb}\frac{\mathrm{d}f(\mathcal{E})}{\mathrm{d}t} = \boxed{-f(\mathcal{E})P_\mathrm{scatter}(r_0,\mathcal{E})}$$

$$\boxed{+\left(\frac{\mathcal{E}}{\mathcal{E}+\Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E}-\Delta\mathcal{E})P_\mathrm{scatter}(r_0,\mathcal{E}-\Delta\mathcal{E})}$$

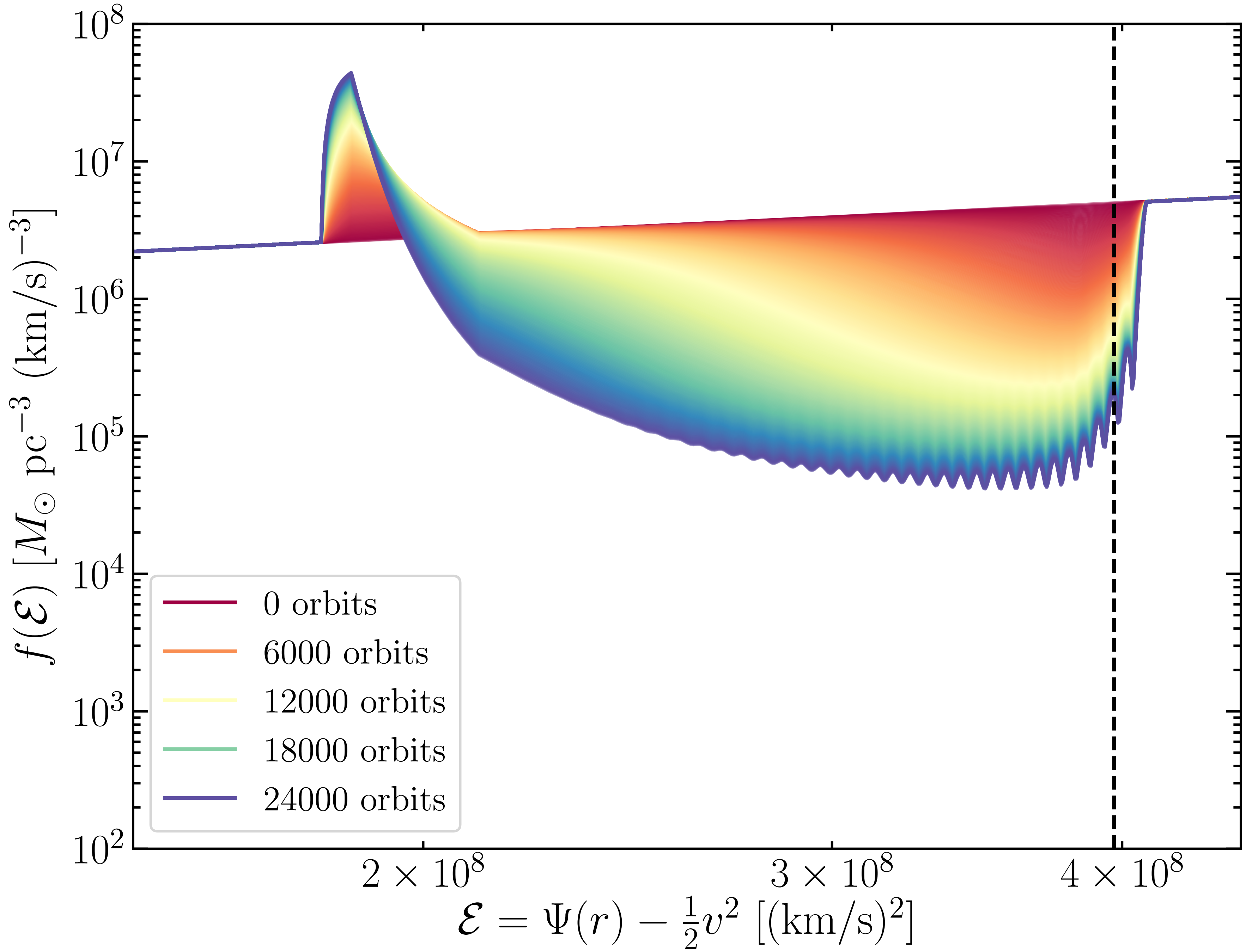
Particles scattering from
$\mathcal{E} \rightarrow \mathcal{E} + \Delta\mathcal{E}$

Particles scattering from
$\mathcal{E} - \Delta\mathcal{E} \rightarrow \mathcal{E}$

$P_\mathrm{scatter}(r_0,\mathcal{E})$ - roughly the fraction of DM particles with energy $\mathcal{E}$ which lie within a distance b_{max} from the NS orbit

Density profile (and therefore dynamical friction force) can then be determined self-consistently from the distribution function

Distribution function



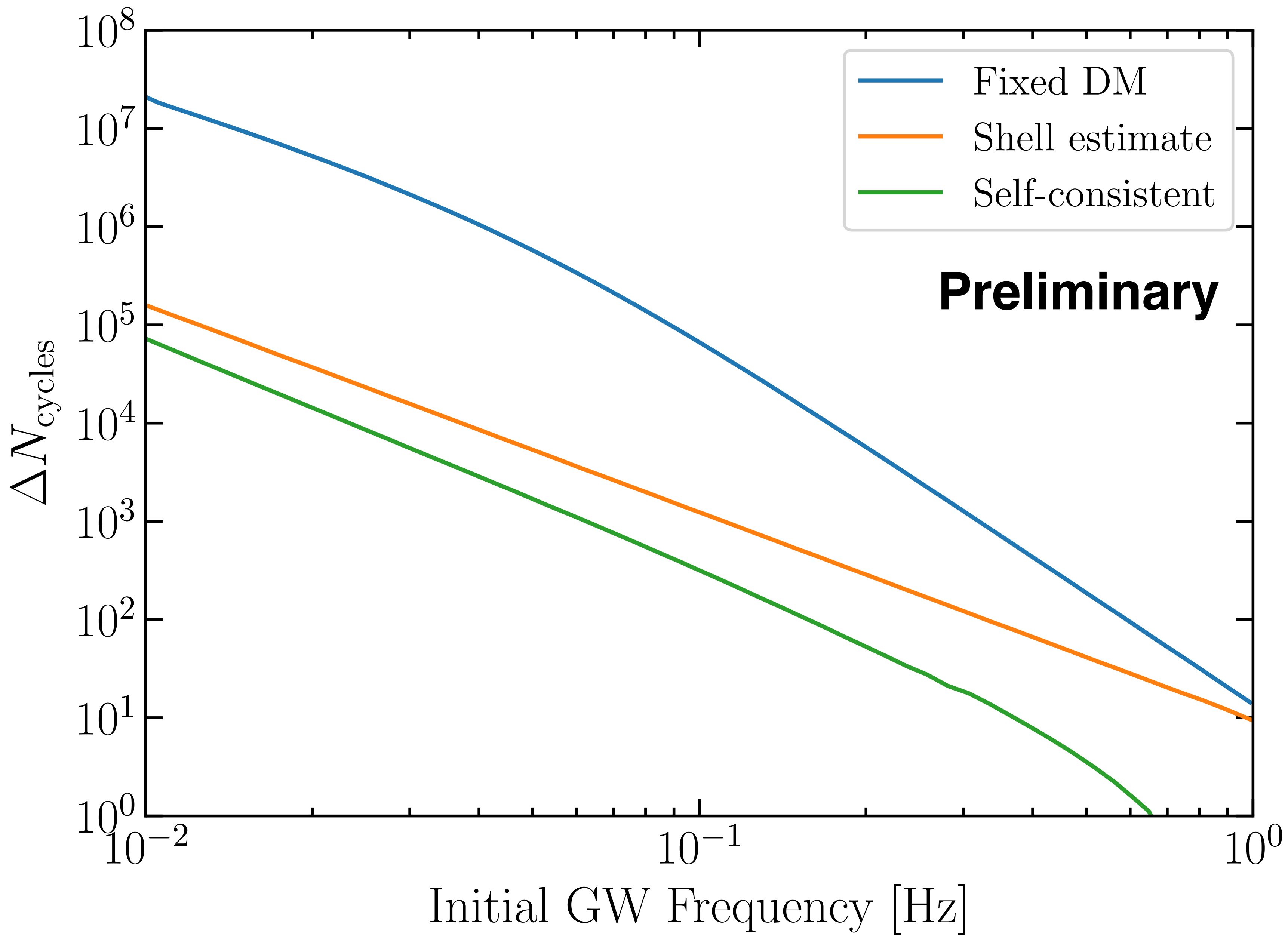
Self-consistently reconstruct density from distribution function:

$$\rho(r) = 4\pi \int_0^{v_\mathrm{max}(r)} v^2 f\left(\mathcal{E}\right) \mathrm{d}v$$

Impact on de-phasing

$N_{\rm cycles}^{\rm vacuum} \sim 2 \times 10^7$

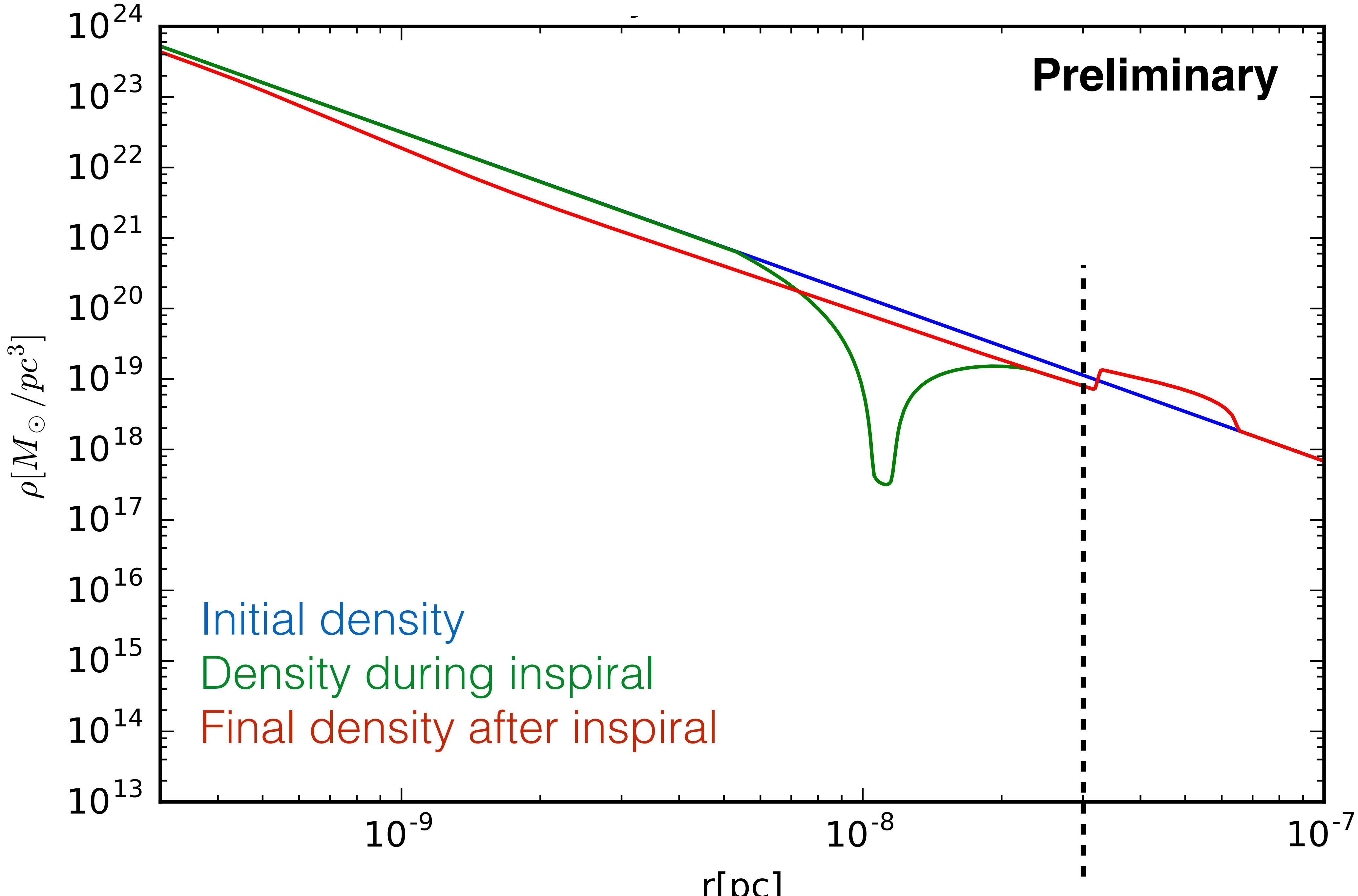
How much shorter is the inspiral compared to the 'vacuum' case (with no DM?)



De-phasing drastically reduced - *but still detectable!*

Survival of density profile

How does the density profile evolve during and after the inspiral?



Initial separation

Assumptions

- Spherical symmetry and isotropy of the DM halo
- DM particles only scatter within an impact parameter

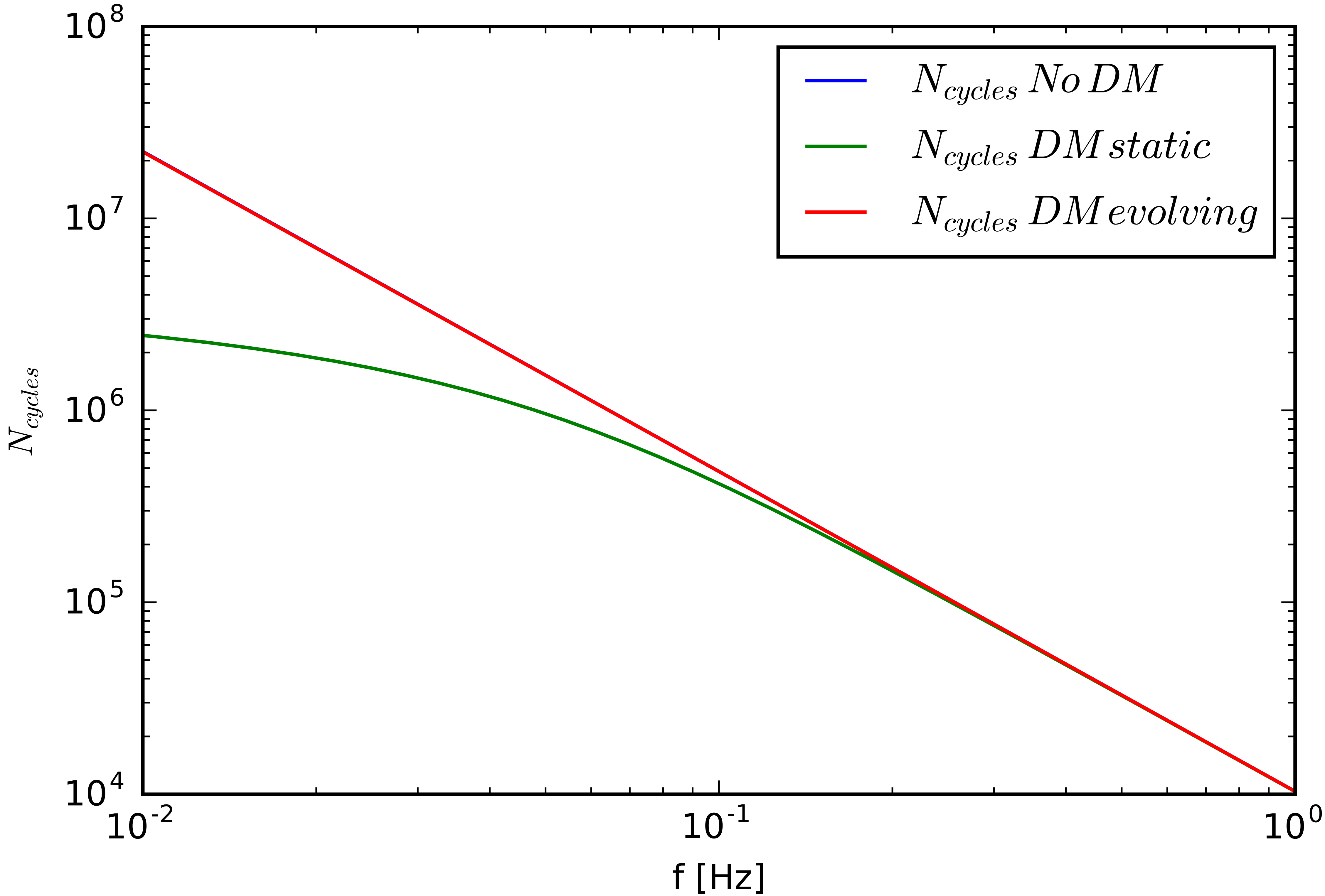
$$b < b_{\mathrm{max}} = \Lambda \times G_N M_{\mathrm{NS}} / v_{\mathrm{NS}}^2$$

- DM distribution is 'locally' uniform

$$b_{\mathrm{max}} \ll r_0$$

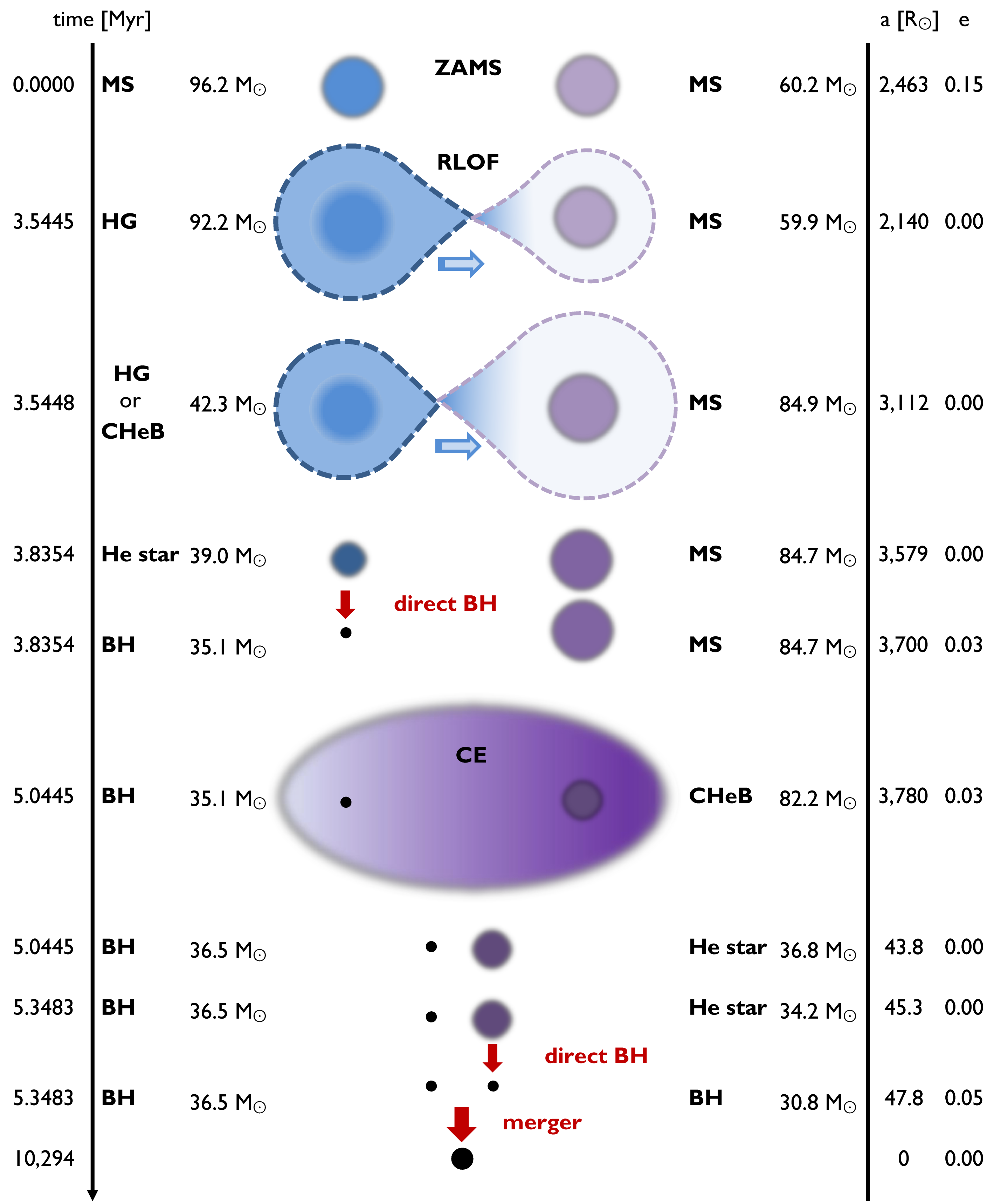
- Halo 'relaxation' is instantaneous
- Orbital properties evolve slowly compared to the orbital period

Total number of cycles



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…]