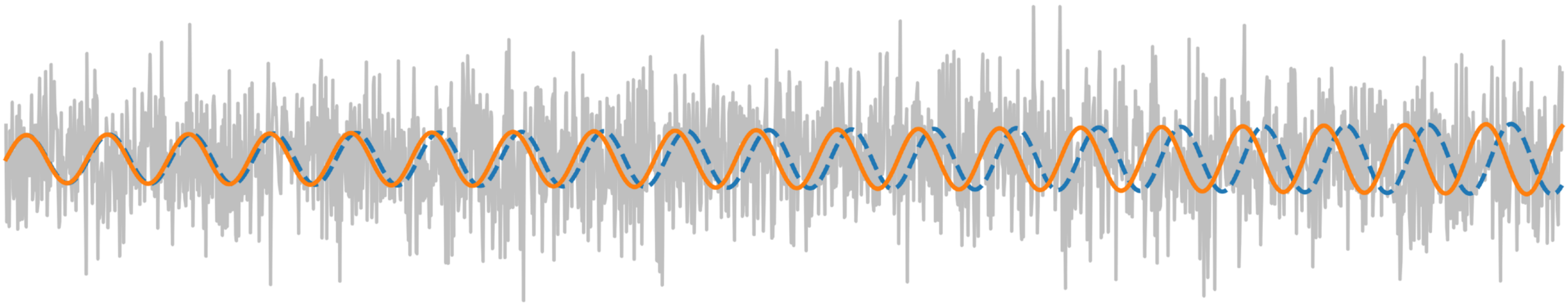
Detecting Dark Matter in the LISA era:

Gravitational Waves from Intermediate Mass Ratio Inspirals



Bradley J Kavanagh

GRAPPA, University of Amsterdam

SLAP2019, 27th September 2019

GRAPPA
GRavitation AstroParticle Physics Amsterdam

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b.j.kavanagh@uva.nl

@BradleyKavanagh

Preliminary work in collaboration with:

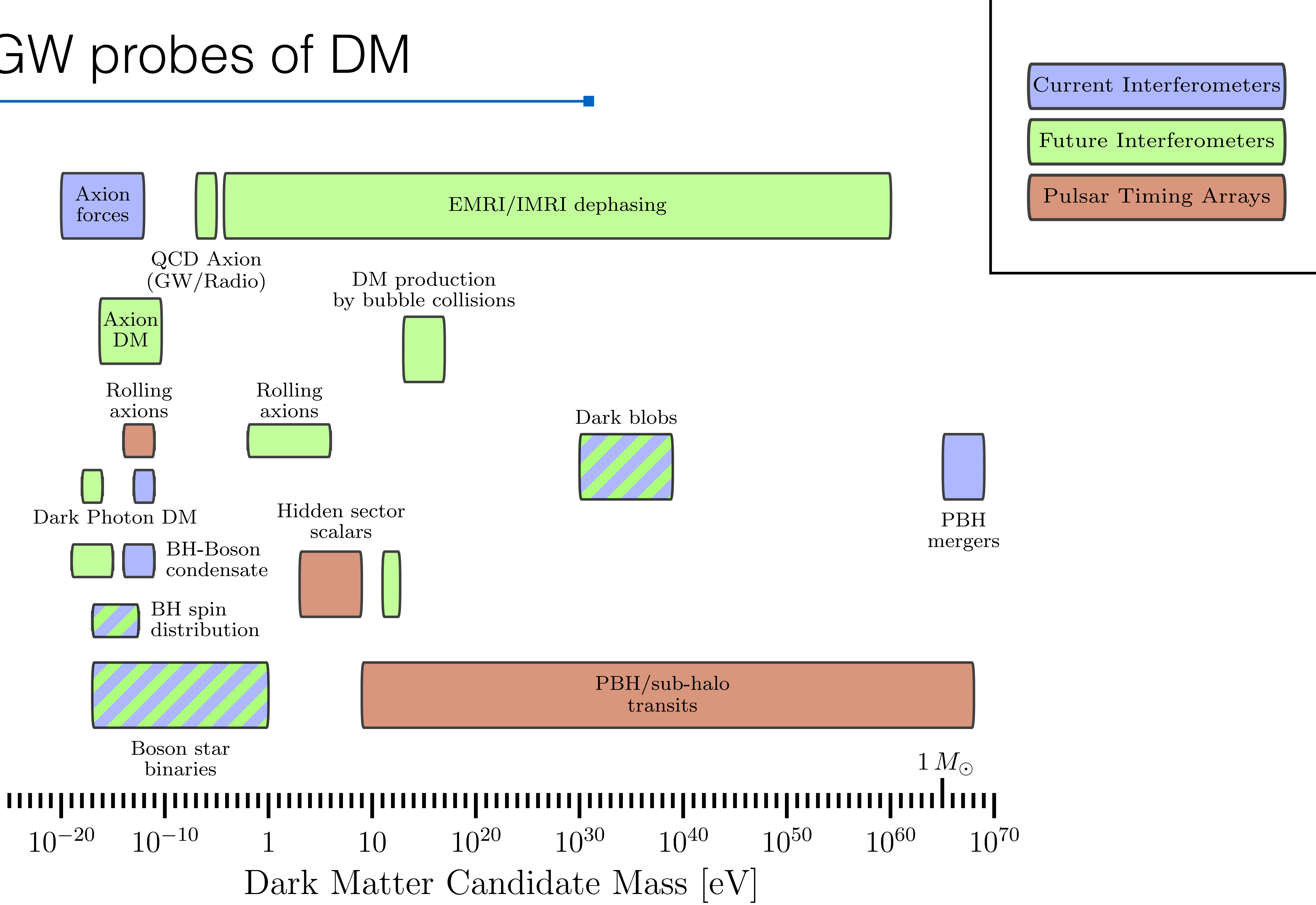
David Nichols
[University of Virginia,
formerly GRAPPA]

Gianfranco Bertone
[GRAPPA]

Daniele Gaggero
[IFT Madrid,
formerly GRAPPA]

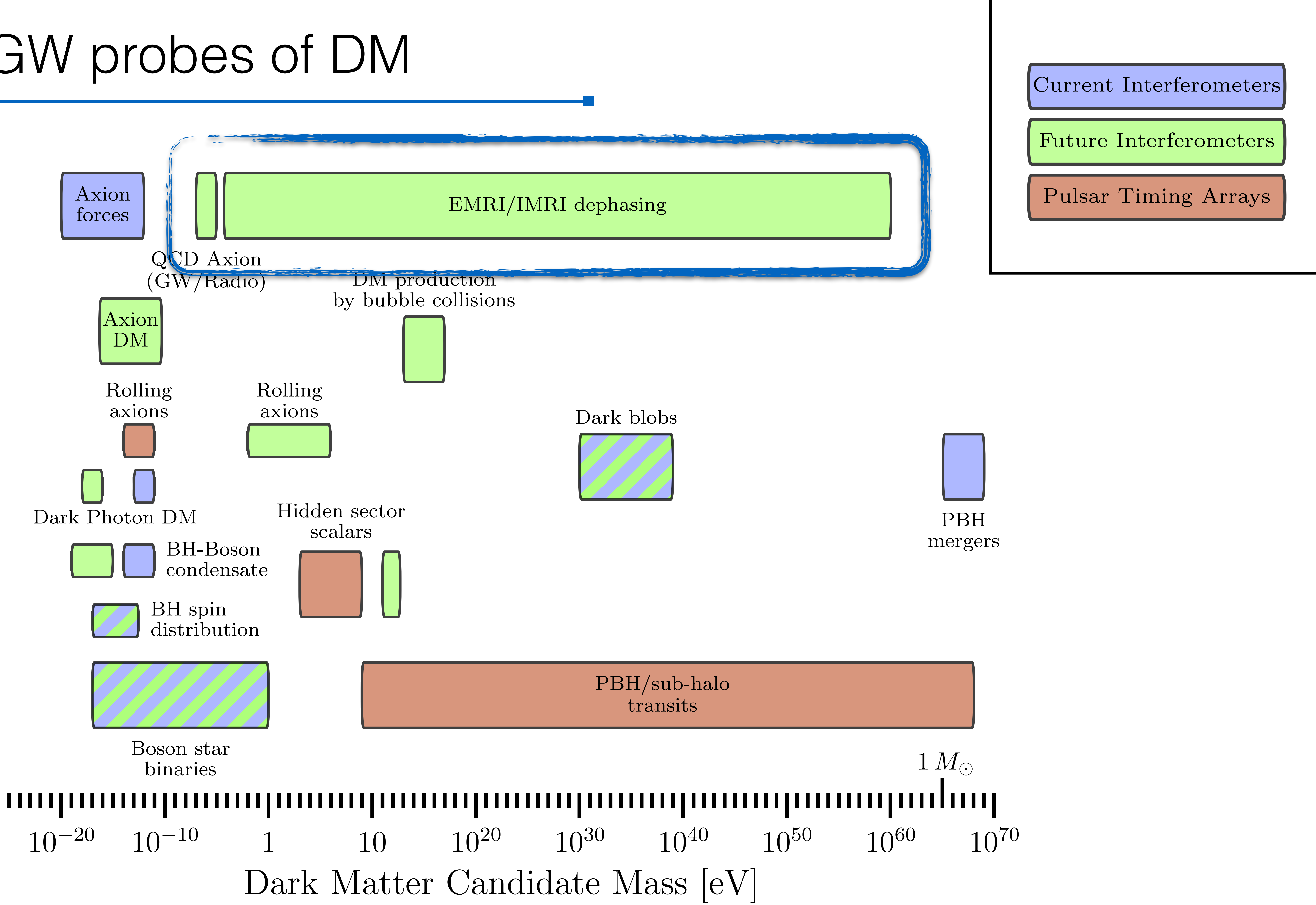
but working closely with everyone at GRAPPA.

GW probes of DM



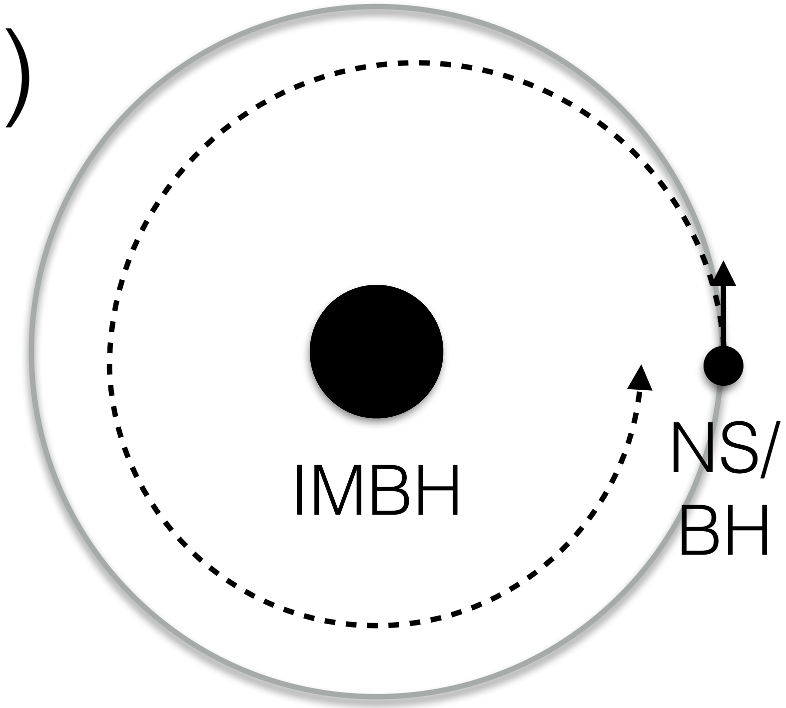
[1907.10610]

GW probes of DM



[1907.10610]

Intermediate Mass Ratio Inspiral (IMRI)

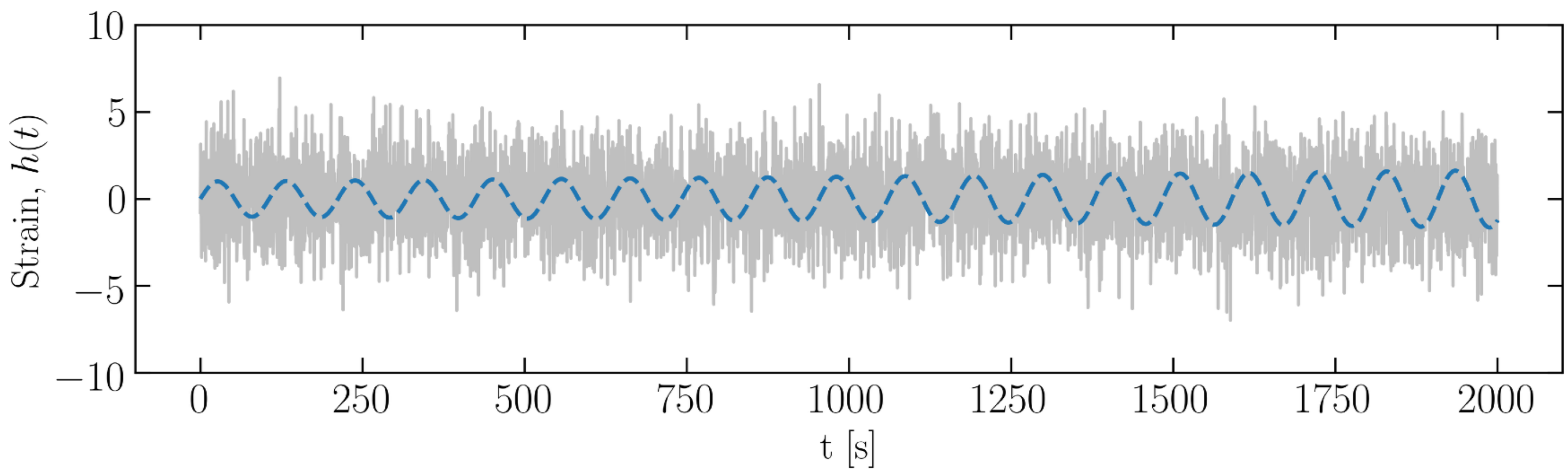


Stellar mass compact object (NS/BH) inspirals towards intermediate mass black hole (IMBH)

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

GW emission causes long, slow inspiral:

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

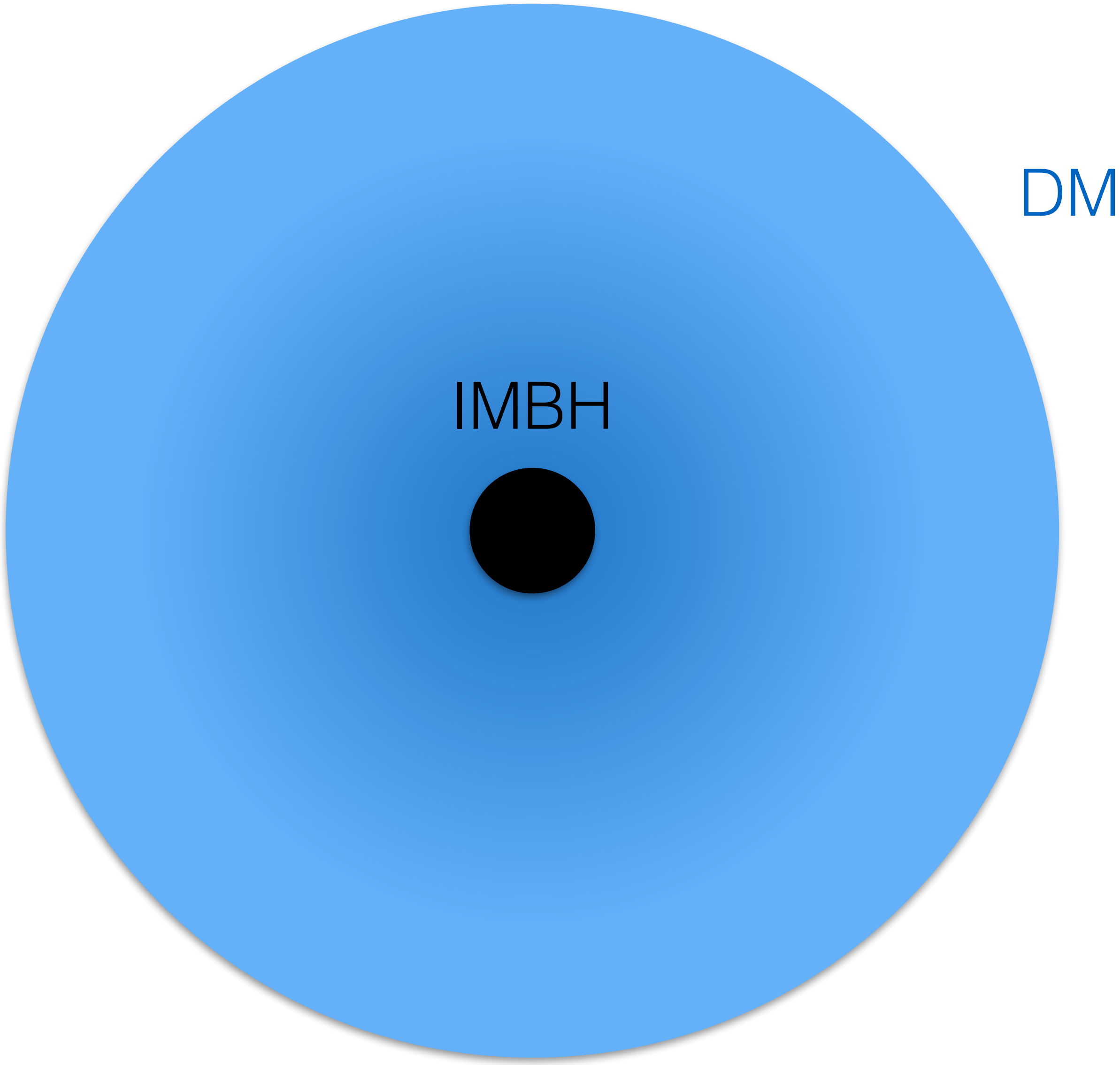


LISA should detect ~ 3 - 10 IMRIs per year [1711.00483]

Dark Matter 'Mini-spikes'

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

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



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

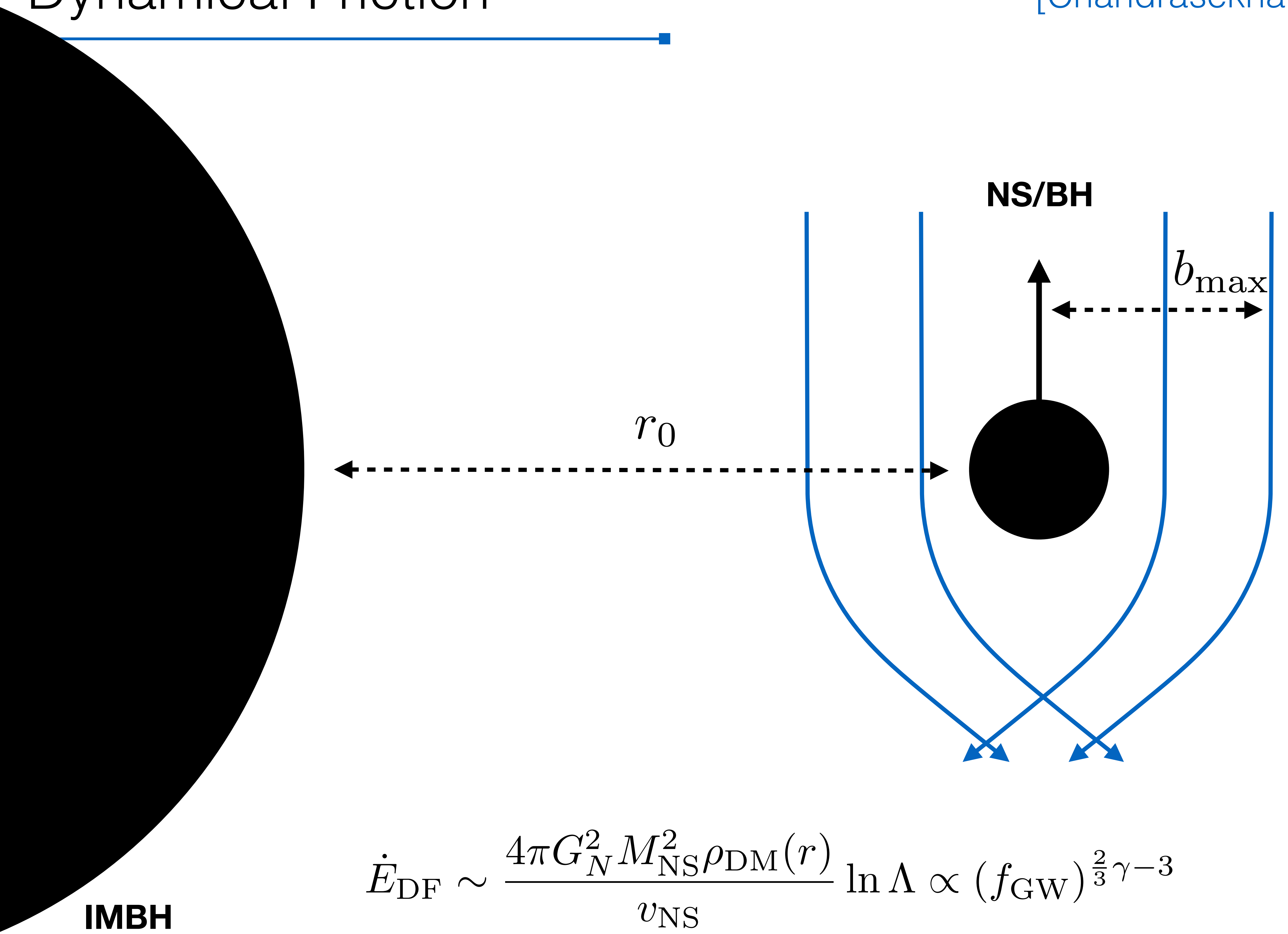
$$\gamma_{\mathrm{sp}} = 7/3$$

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]

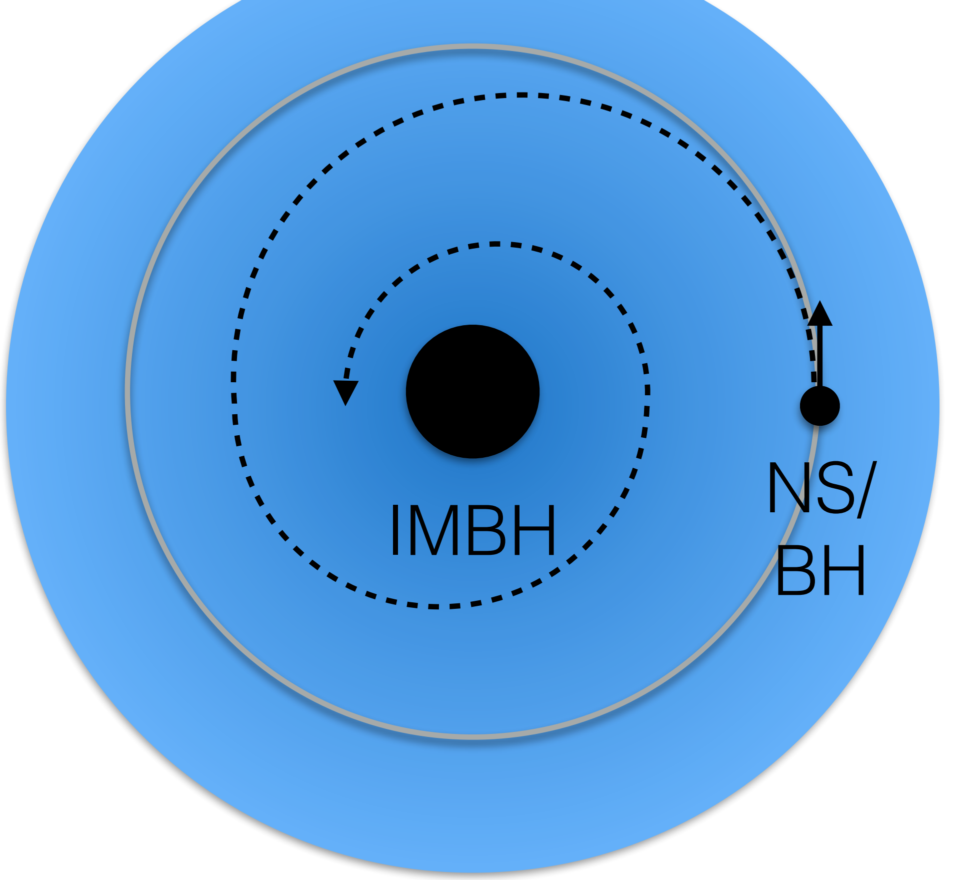
Dynamical Friction

[Chandrasekhar, 1943]



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

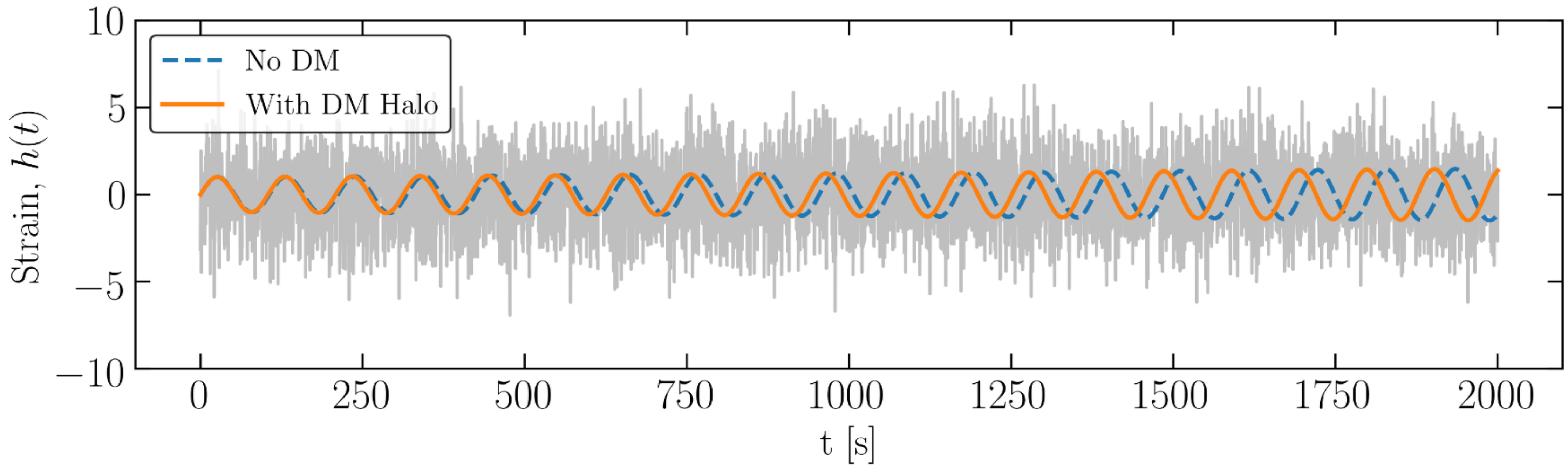
IMRI + Dark Matter



DM makes the compact object spiral in faster, primarily due to *dynamical friction*

This can be seen in the rate at which the GW signal accumulates phase

→ 'De-phasing'



‘De-phasing’ signal

Benchmark:

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

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

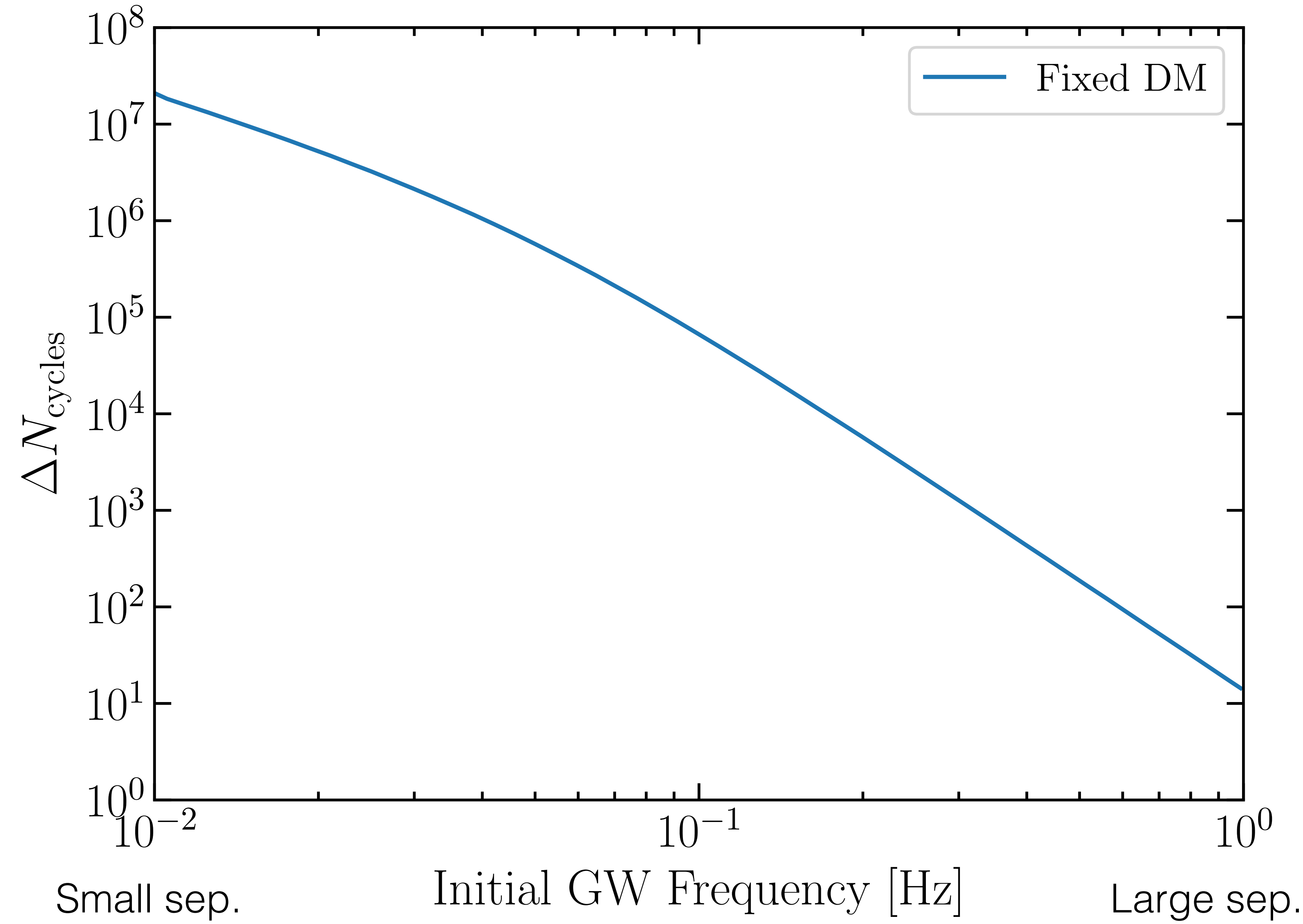
$$r_{\rm ini} \sim 10^{-8}\,{\rm pc}$$

↓

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

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

How does DM affect the number of cycles?



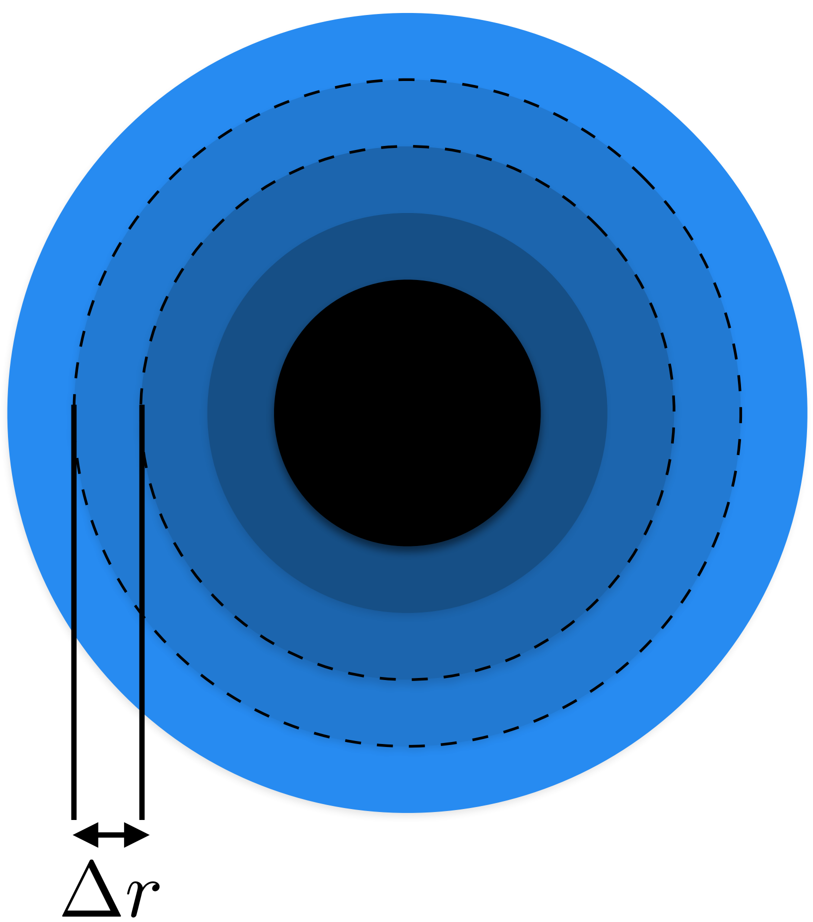
Need to know the signal to better than ~1 part in 10^6!

[Eda et al. 1301.5971, 1408.3534]

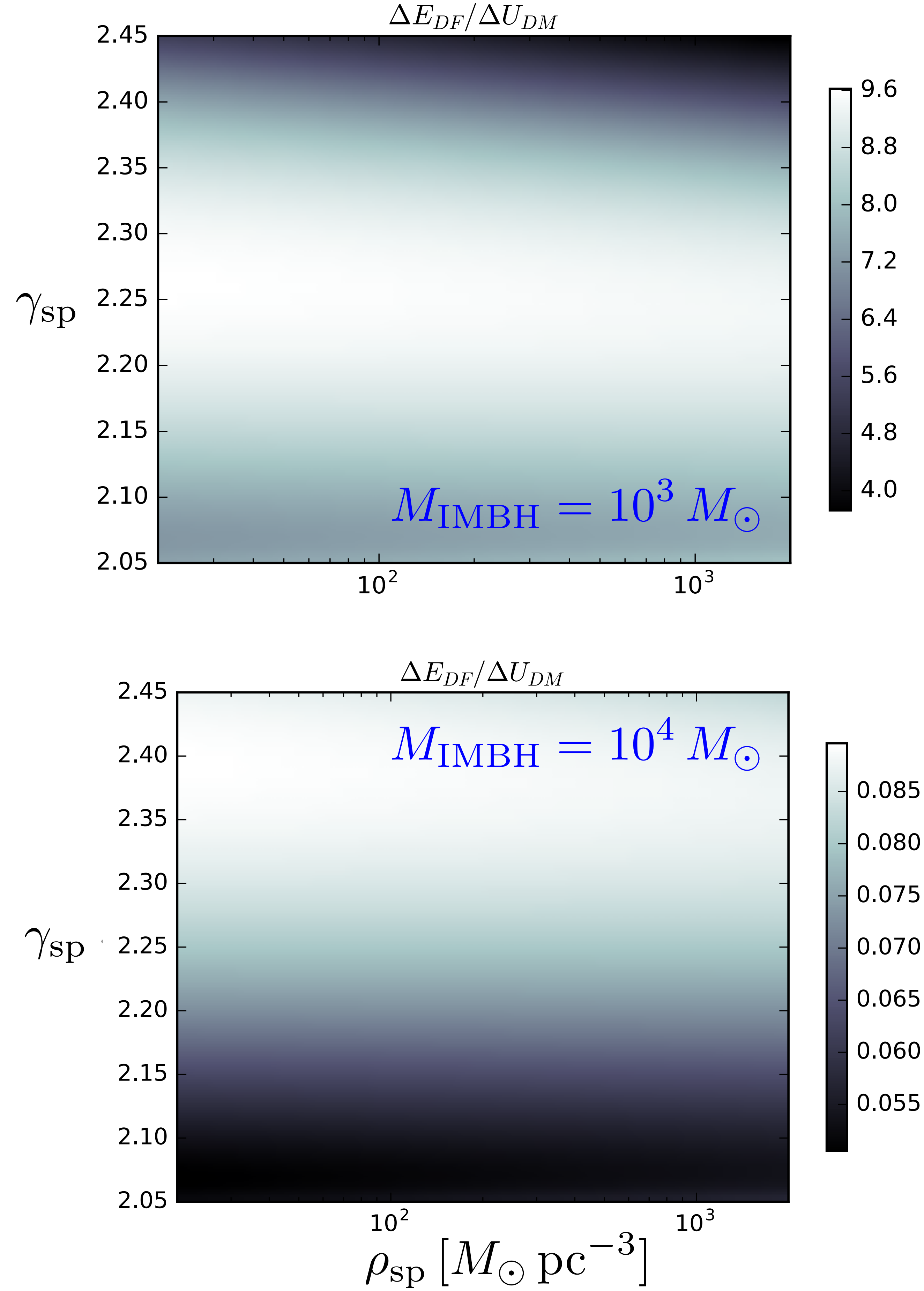
[See also 1302.2646, 1404.7140, 1404.7149]

Energy Budget

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



A: Binding energy of DM ΔU_{DM} over radius Δr



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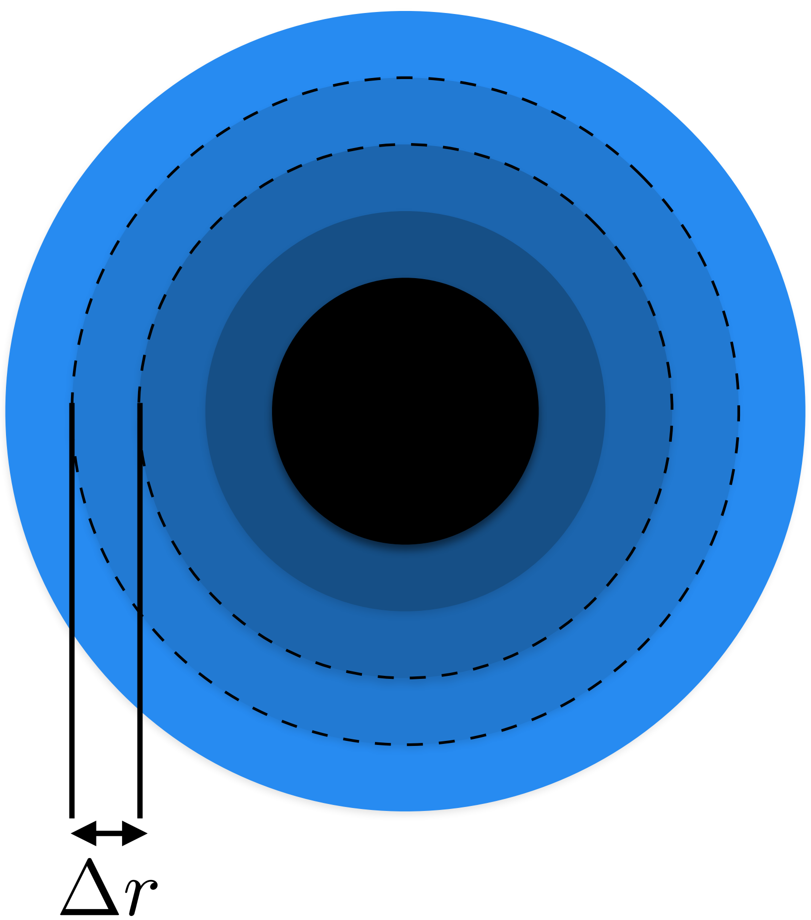
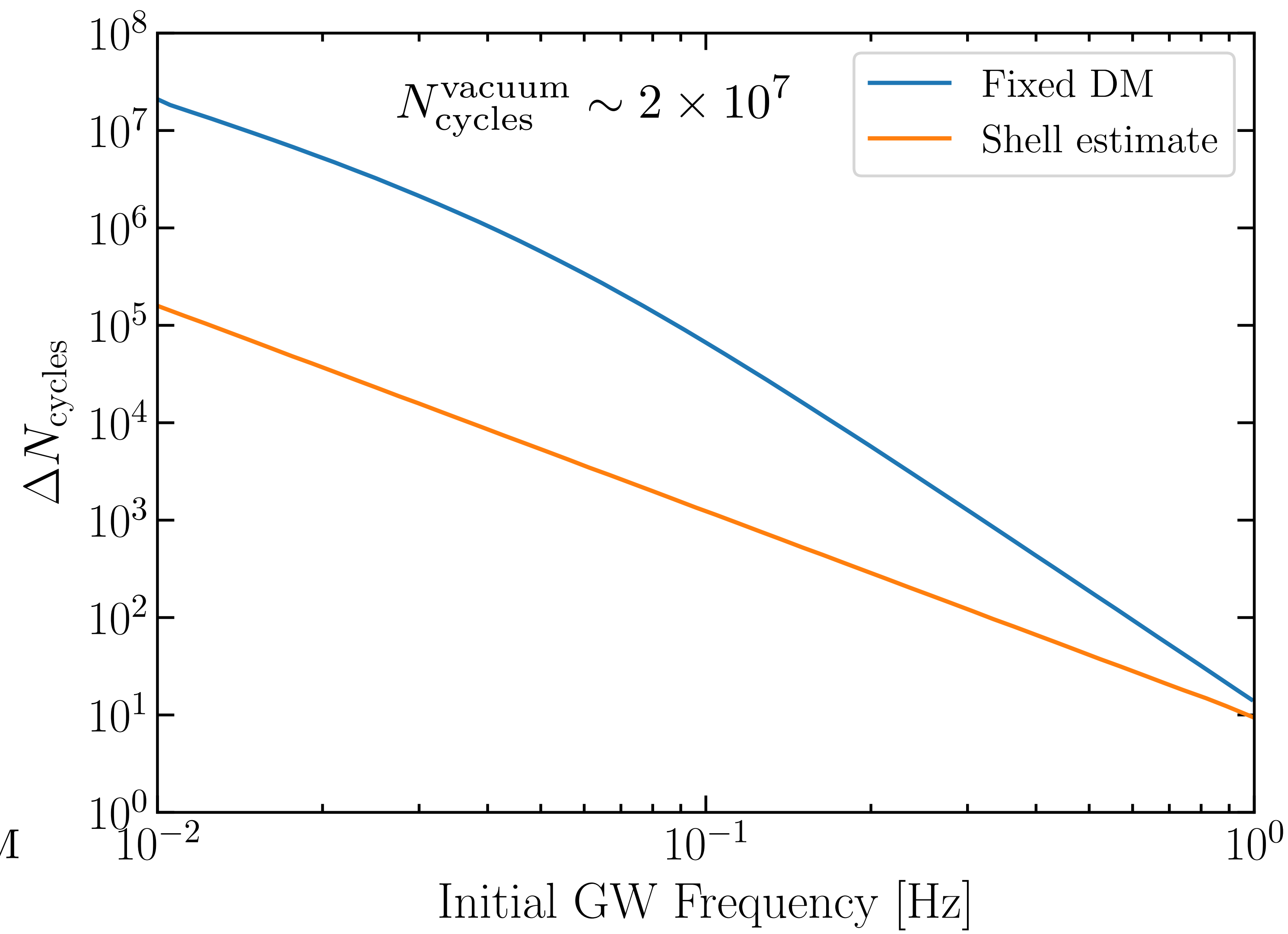


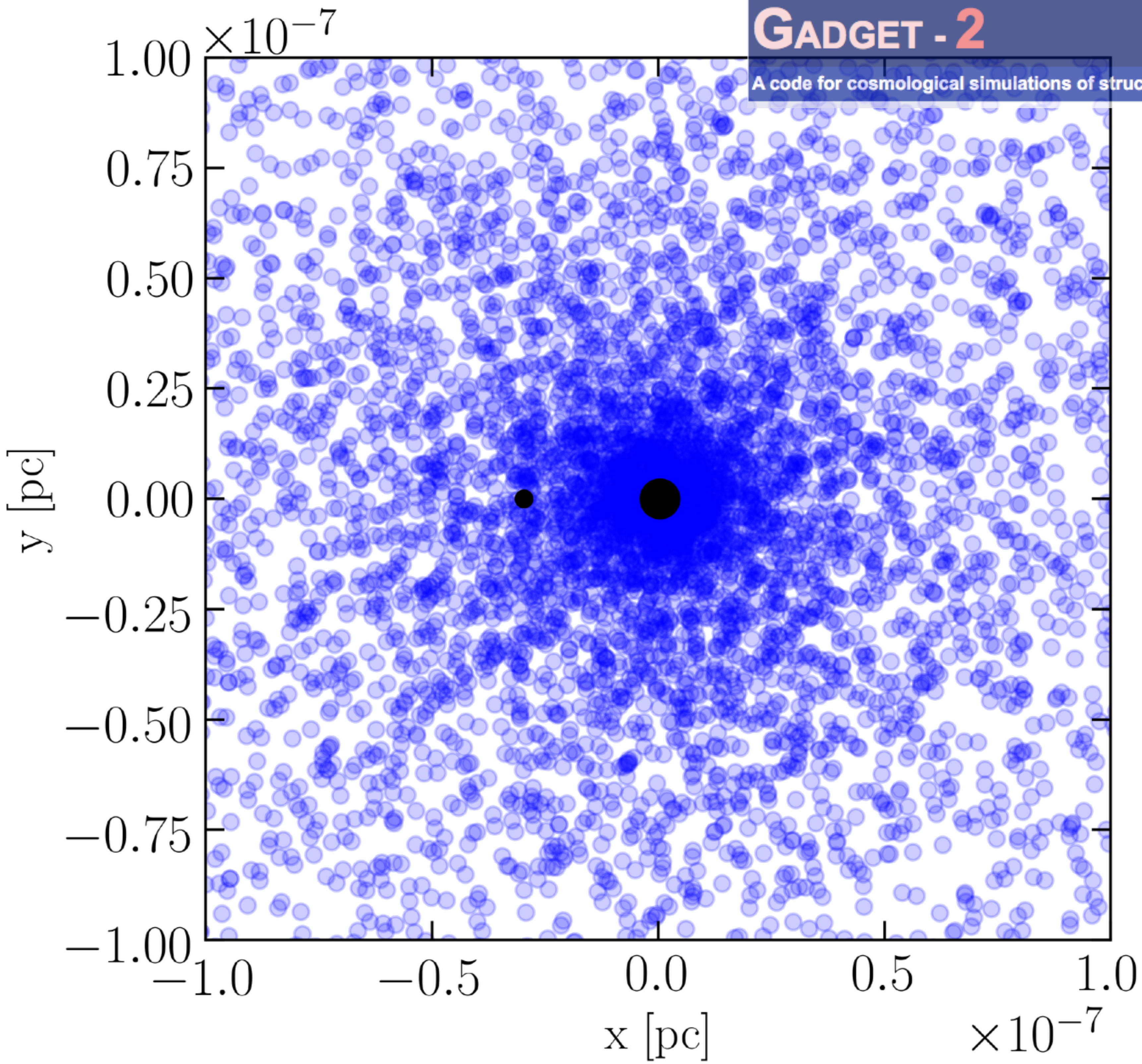
A: Binding energy of DM ΔU_DM over radius Δr

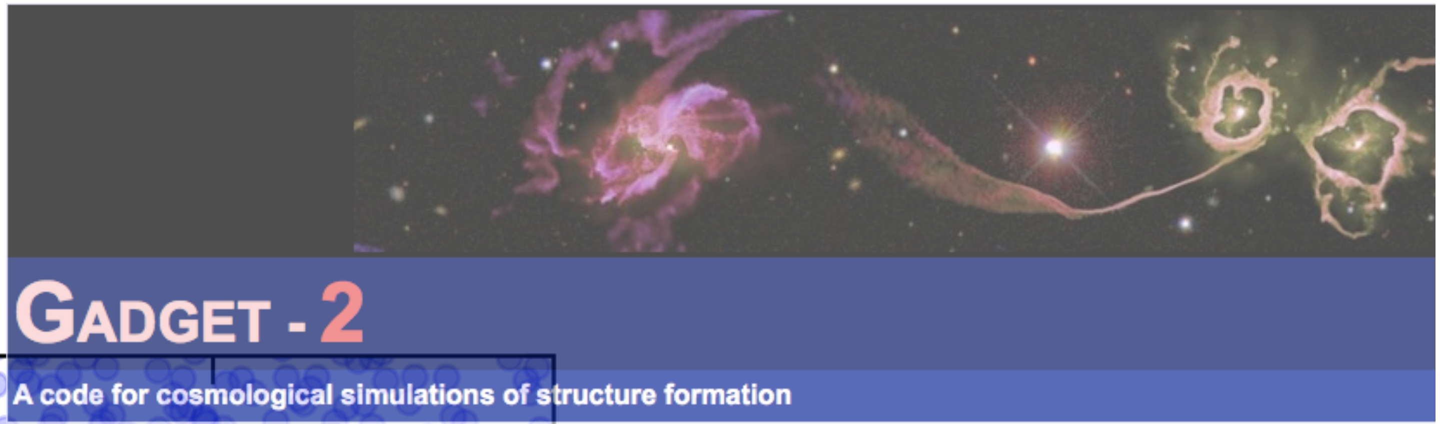
Evolve the system by fixing the dynamical friction force to extract *all* binding energy from a shell at a given radius:

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



N-body simulations





[astro-ph/0505010]

High precision N-body sims

Gadget-II code:

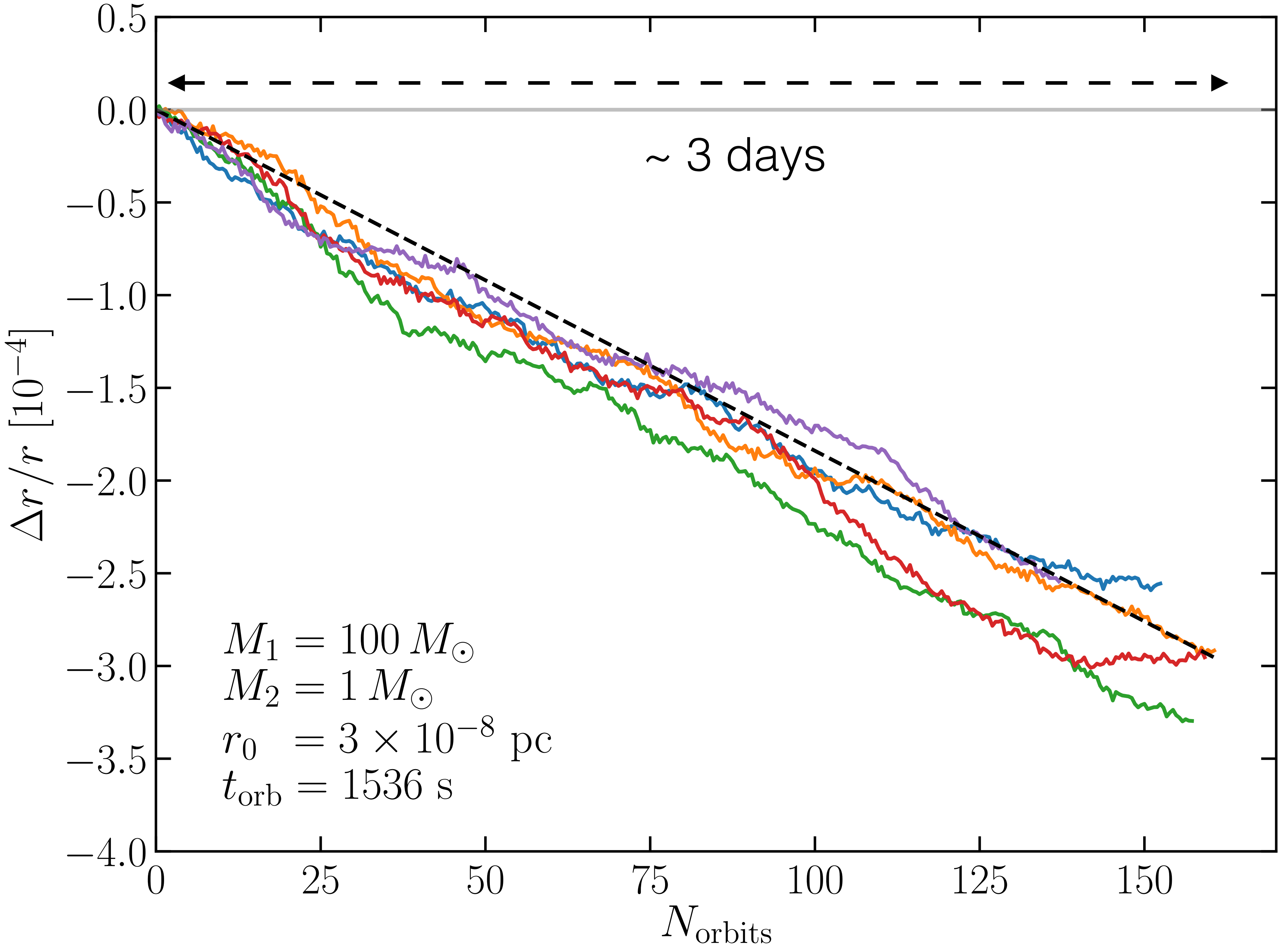
```
/* Some physical constants in cgs units */

#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:

$$G_N = 6.67\textcolor{red}{4} \times 10^{-8}\,\mathrm{m}^3\,\mathrm{g}^{-1}\mathrm{s}^{-2}$$

N-body simulations



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

Self-consistent evolution

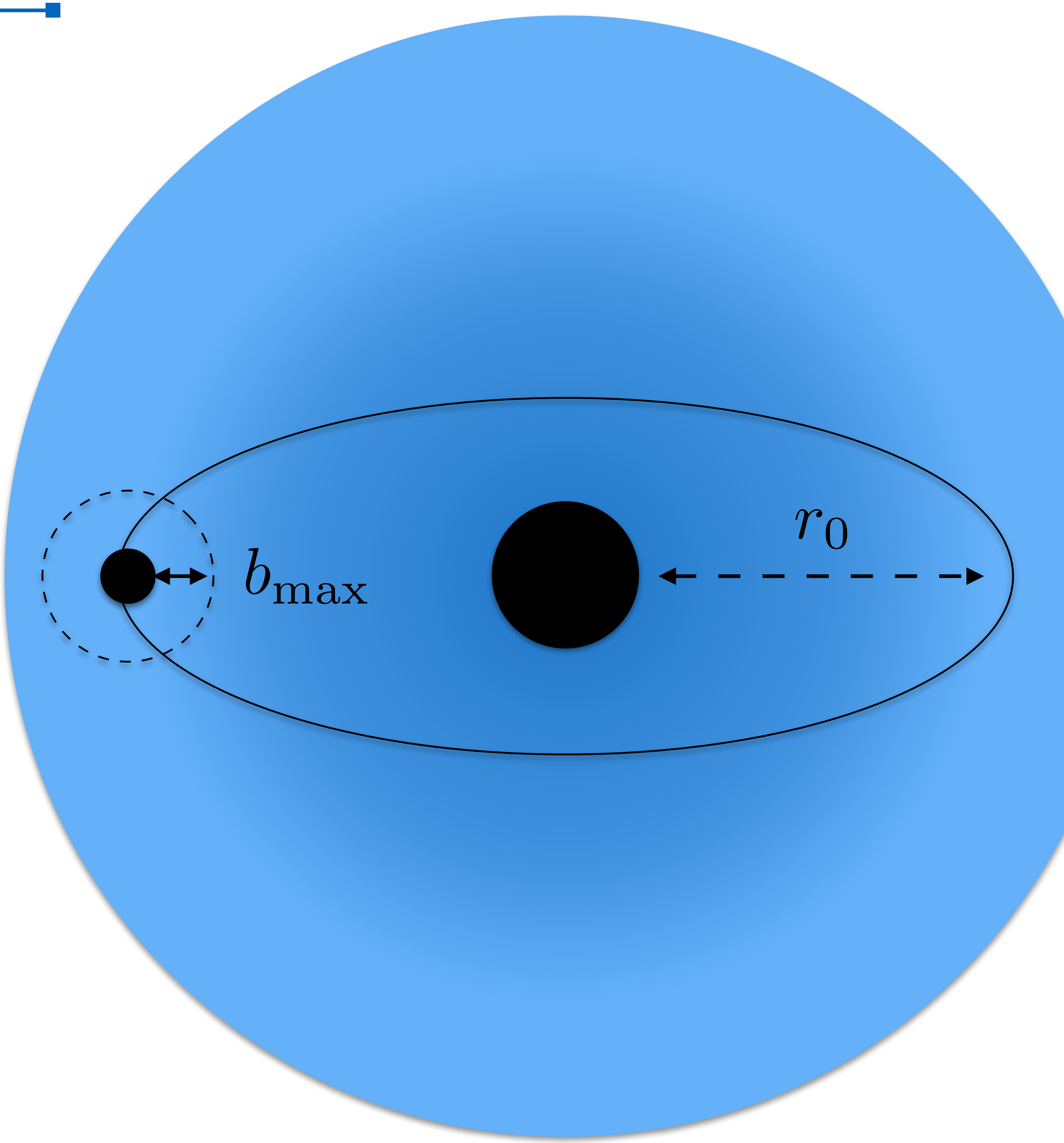
Phase space of DM described by distribution function $f(\mathcal{E})$ where

$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Compact object scatters with all DM particles within 'torus' of influence over one orbit

Each particle receives a 'kick' of typical size $\Delta\mathcal{E}$ through gravitational scattering:

$$\mathcal{E} \to \mathcal{E} + \Delta\mathcal{E}$$



Self-consistent evolution

Assuming orbit evolves slowly compared to the orbital period:

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

$P_{\rm scatter}(r_0,\mathcal{E})$ - 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

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

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

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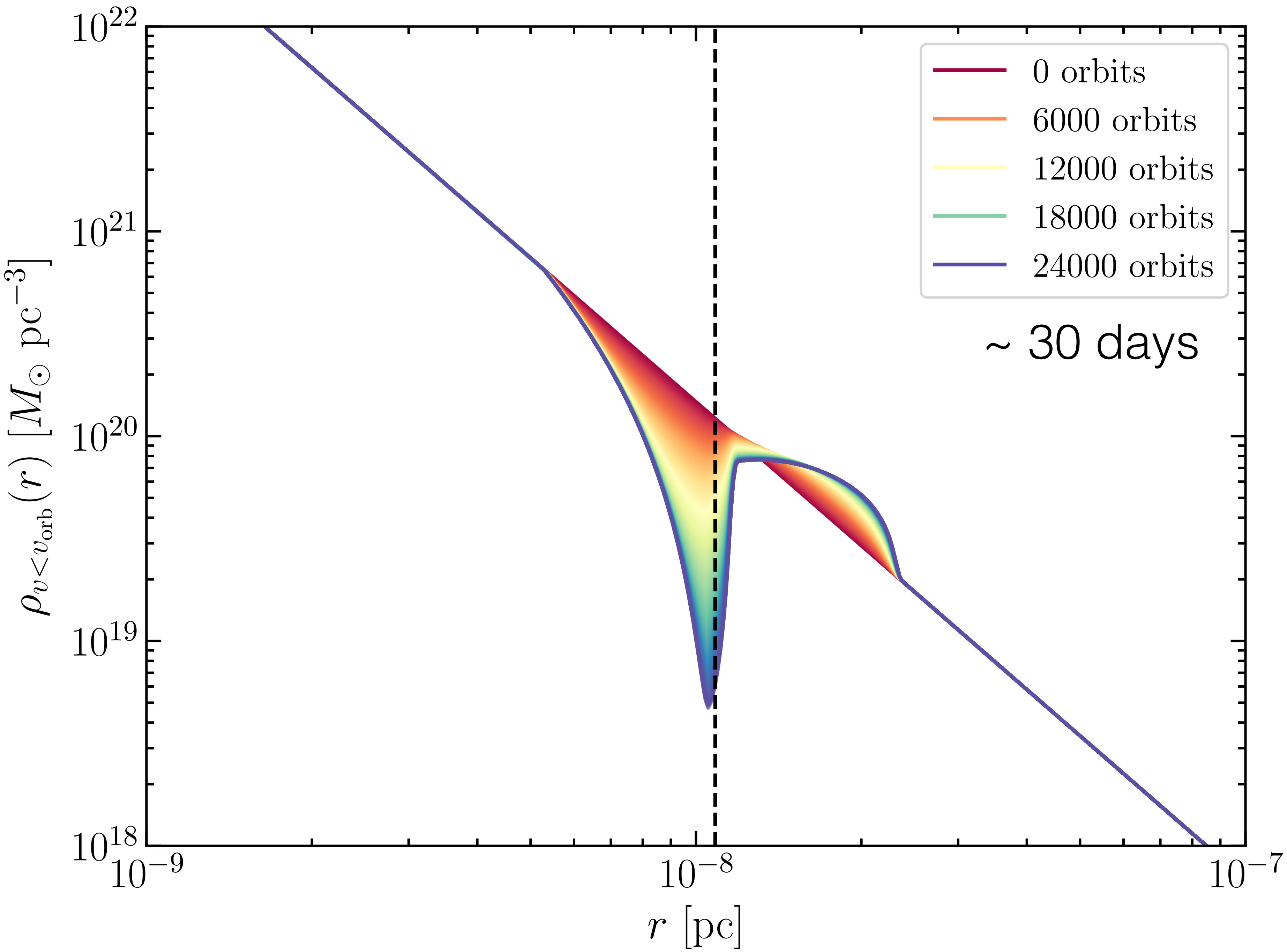
Evolution of density profile

As a 'test', keep the NS fixed at a given radius and see how the DM halo reacts to its orbit:



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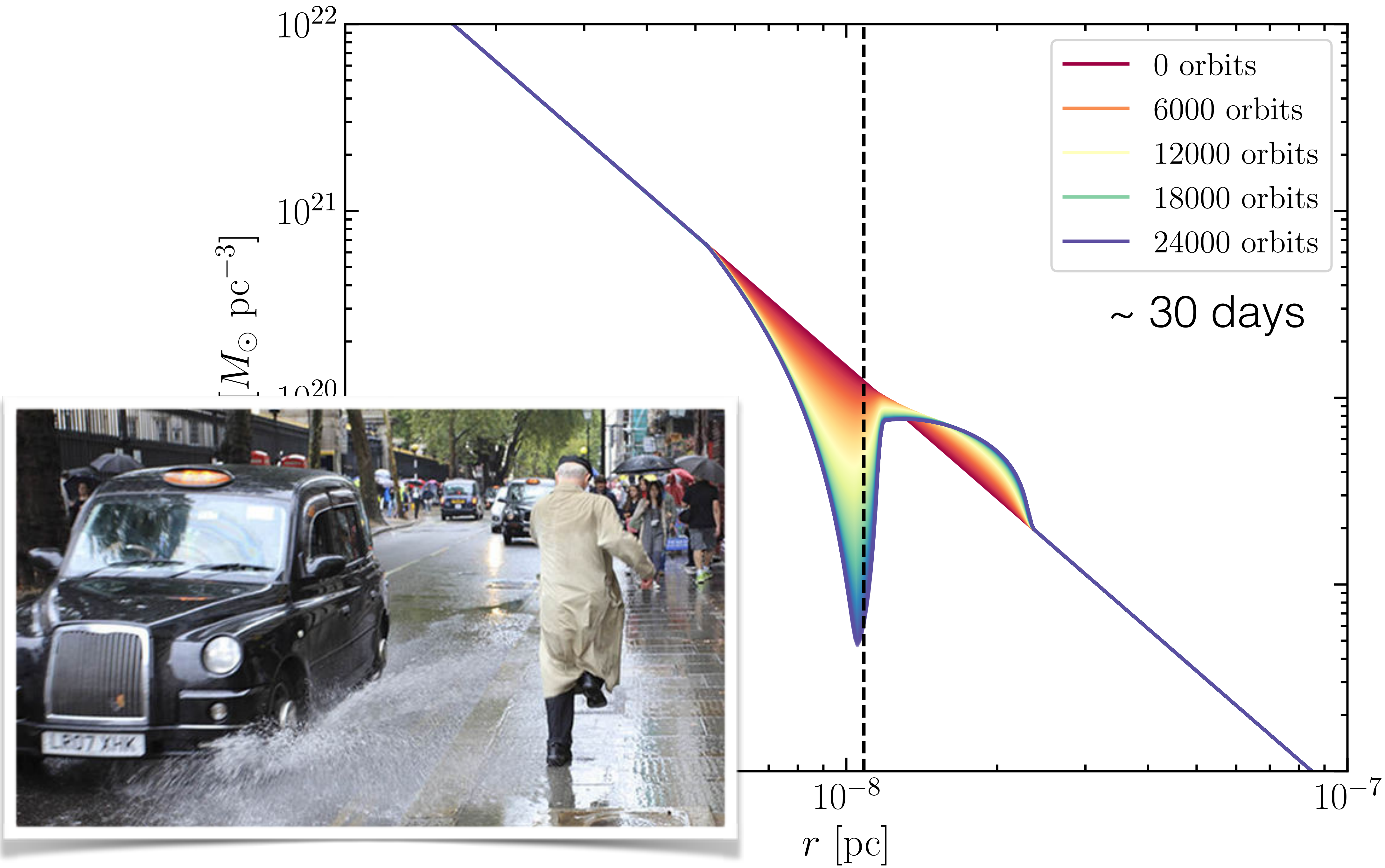
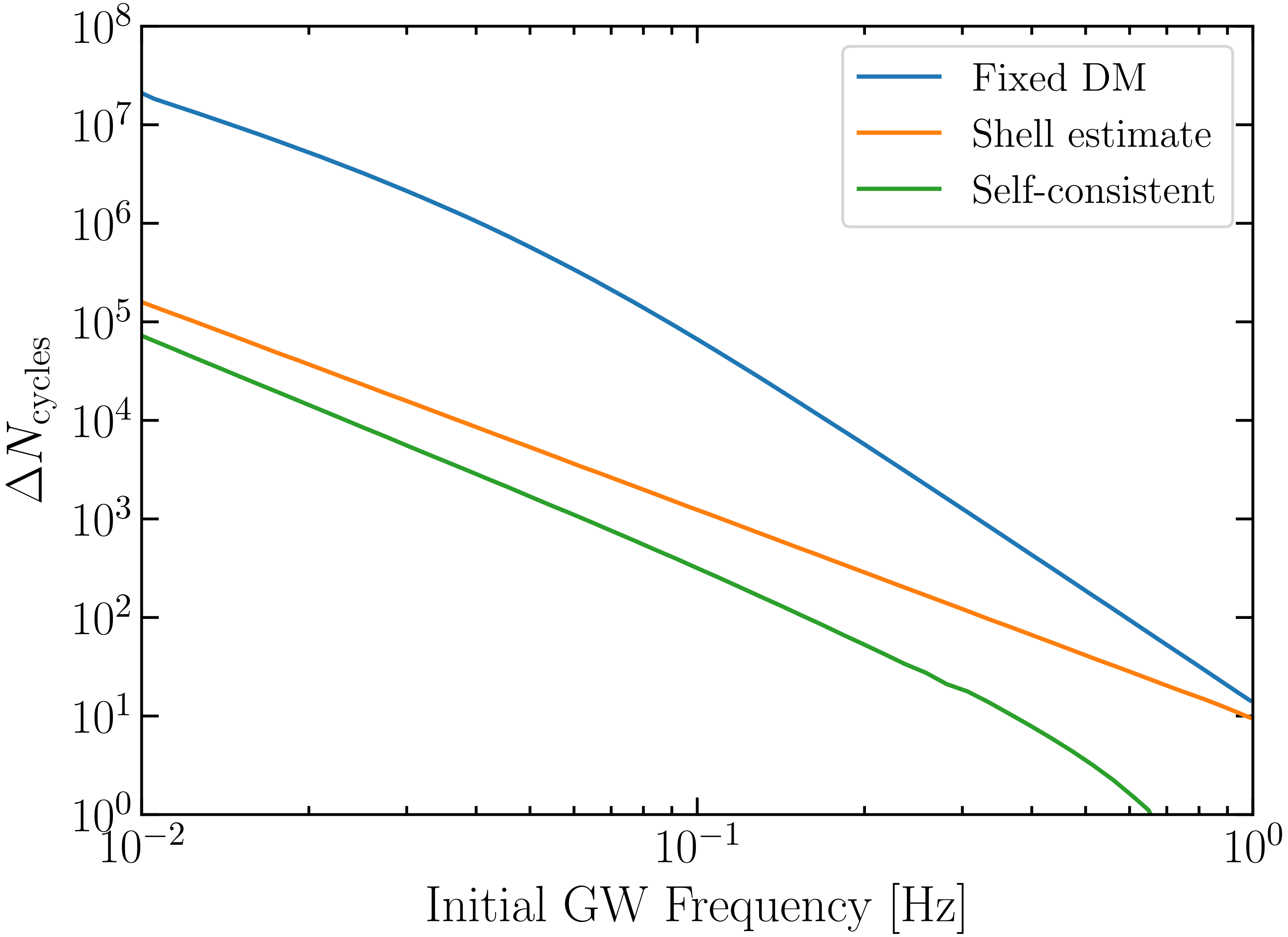


Impact on de-phasing

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

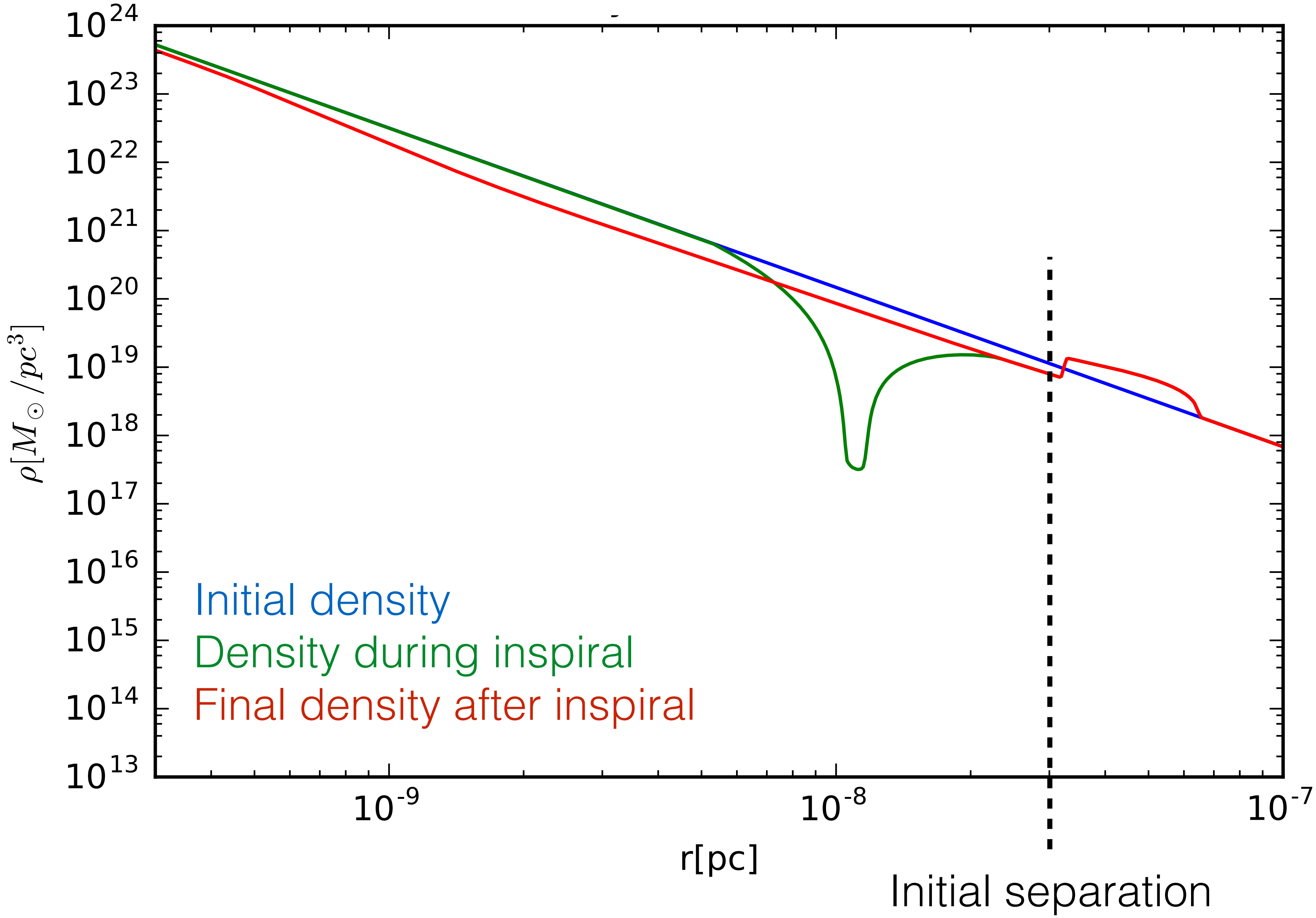
How much shorter is the inspiral compared to the 'vacuum' case (with no DM?)



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

Survival of density profile

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



Prospects for the future

So far we're in the early stages of exploring these effects:

- For which binary parameters does this effect matter?
- What if we go beyond circular orbits in the Newtonian regime?
- How common are these DM halos around astrophysical BHs?

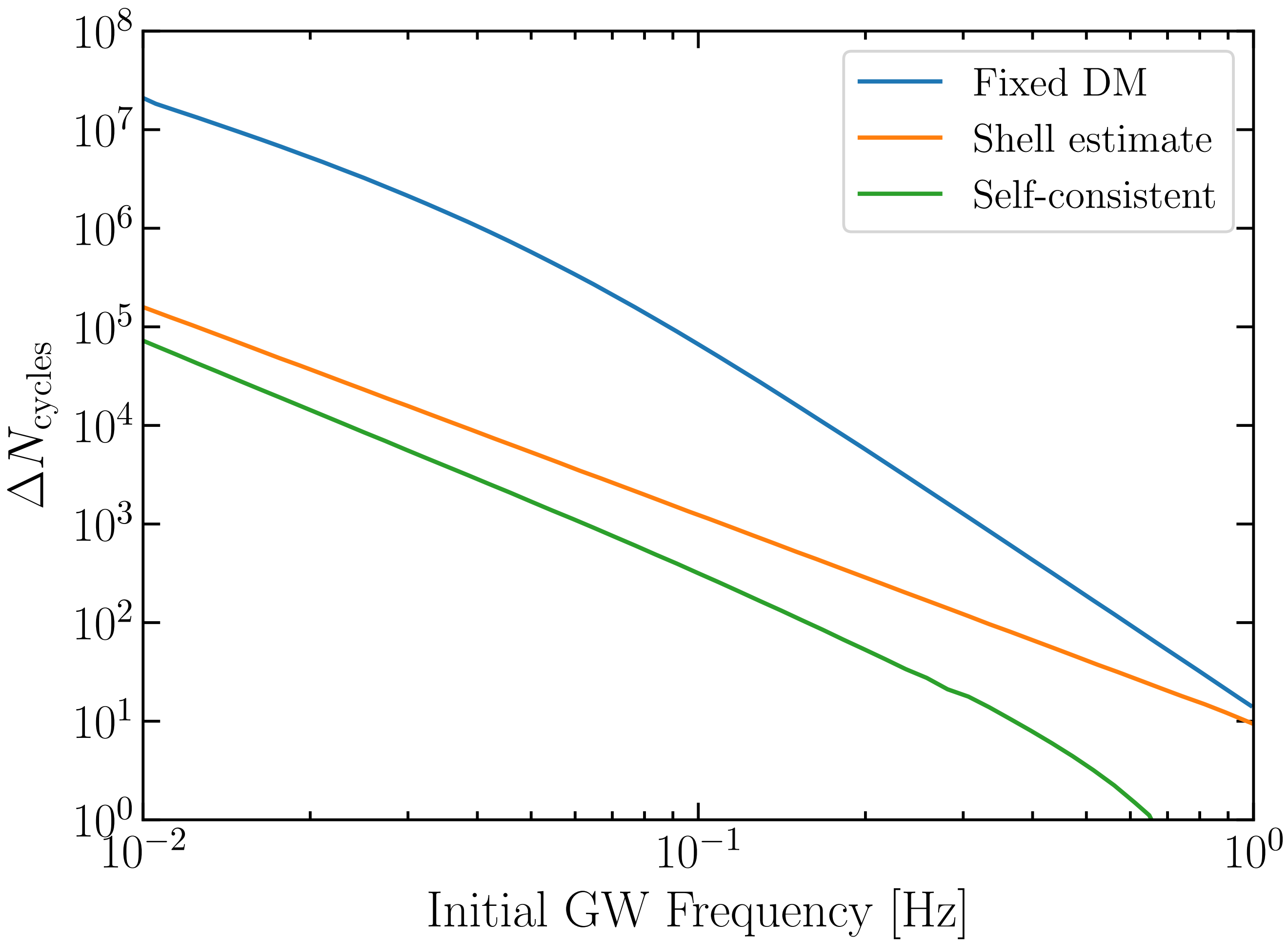
These signals are only detectable with dedicated templates, so careful signal modelling is needed.

↓

Ultimately, aim to develop IMRI+DM template banks and study parameter reconstruction.

Conclusions

Gravitational Wave signatures of Dark Matter in intermediate mass ratio inspirals are more subtle and less pronounced than previously believed - *but should still be detectable with LISA.*



Important consequences for:

- the survival of DM spikes

  [See talk by Adam Coogan, 1905.01238]

- joint EM + GW signals

  [See talk by Marco Chianese, 1905.04686]

- fermionic DM

  [See talk by Kenny Ng, 1906.11845]

- detection of a broad range of DM candidates in the LISA era

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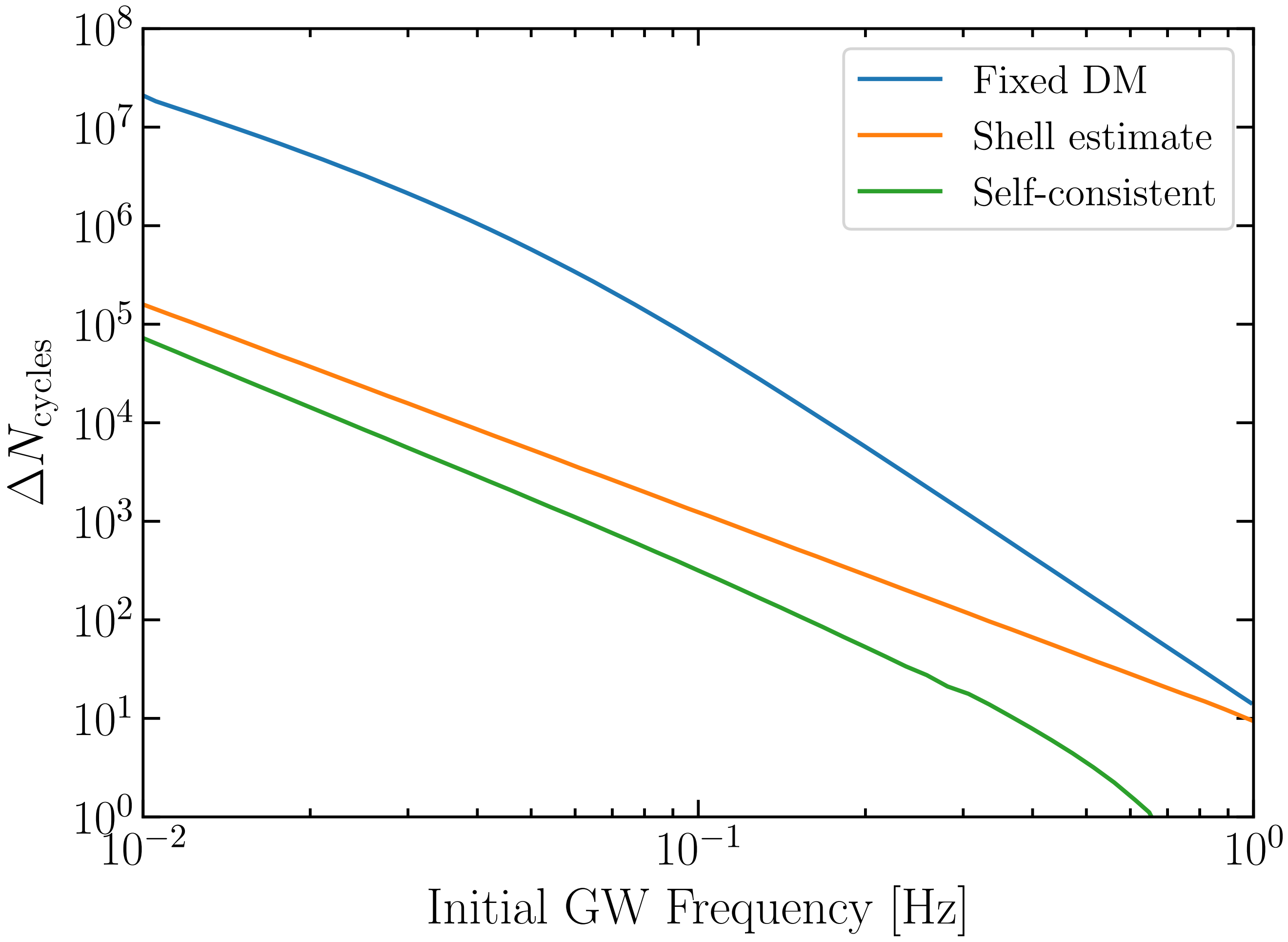

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- detection of a broad range of DM candidates in the LISA era

Thank you!

Backup Slides

Assumptions

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

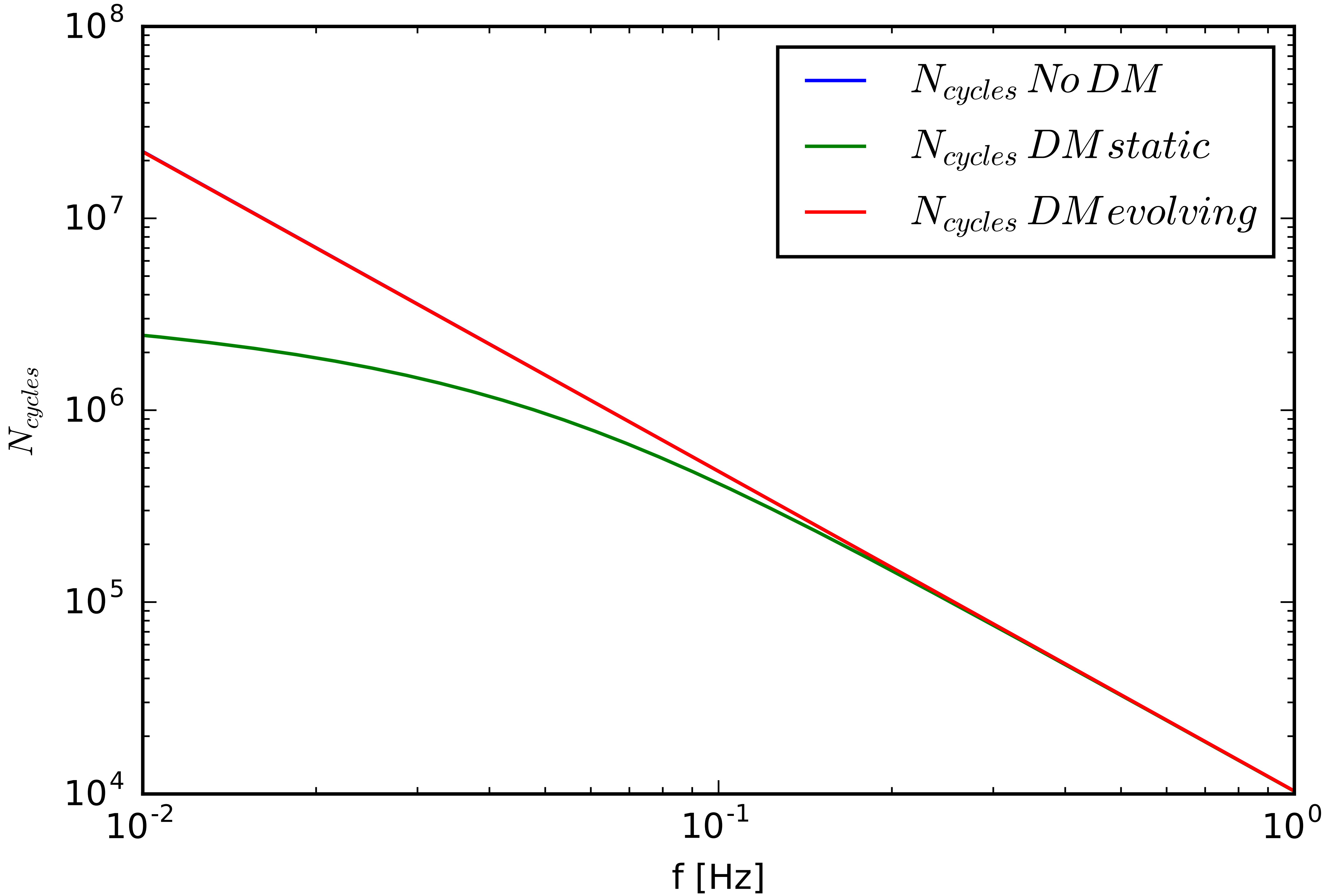
$$b < b_{\rm max} = \Lambda \times G_N M_{\rm NS}/v_{\rm NS}^2$$

- DM distribution is 'locally' uniform

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

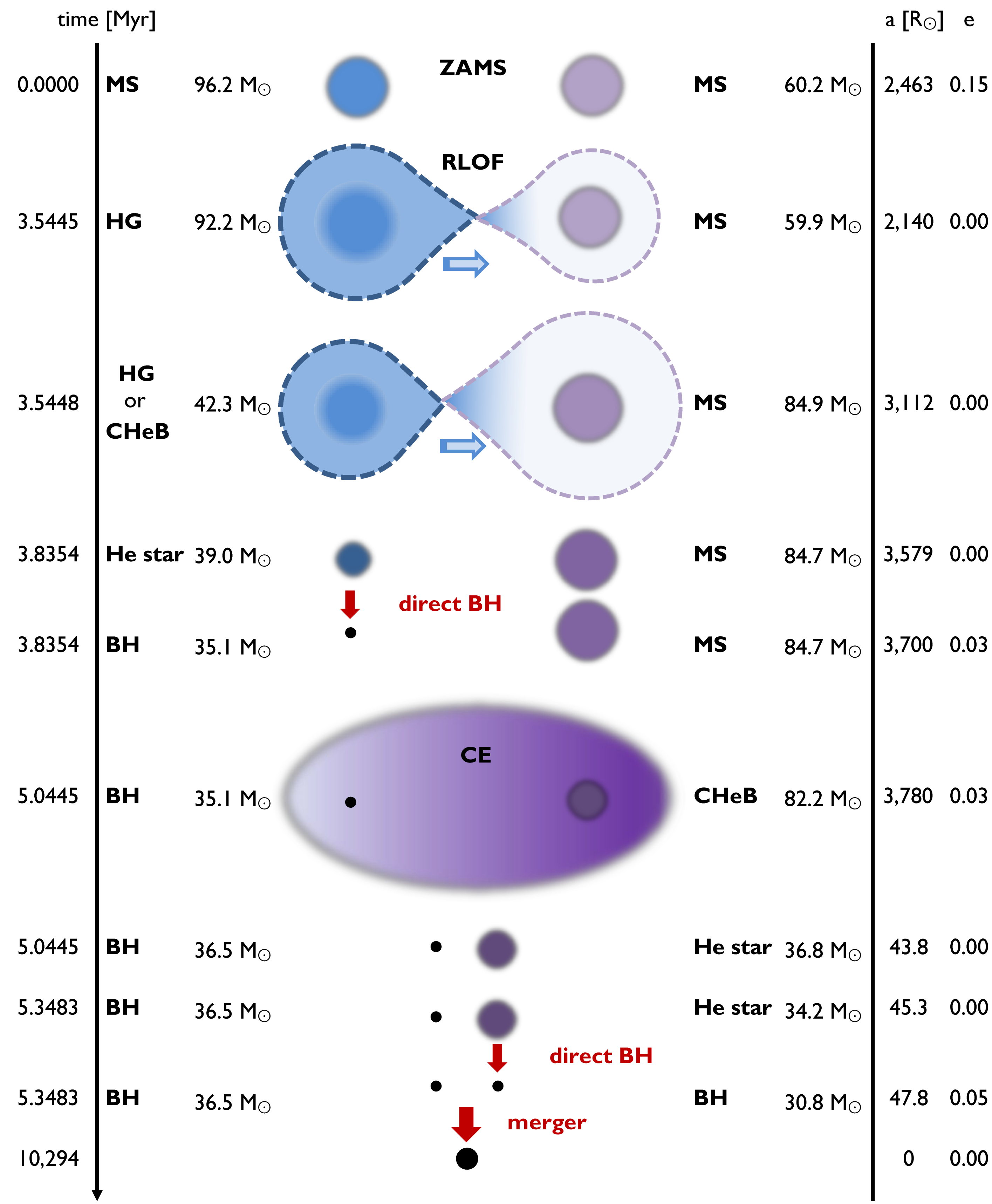
- Halo 'relaxation' is instantaneous
- Orbital properties evolve slowly compared to the orbital period

Total number of cycles



Astrophysical BH binaries

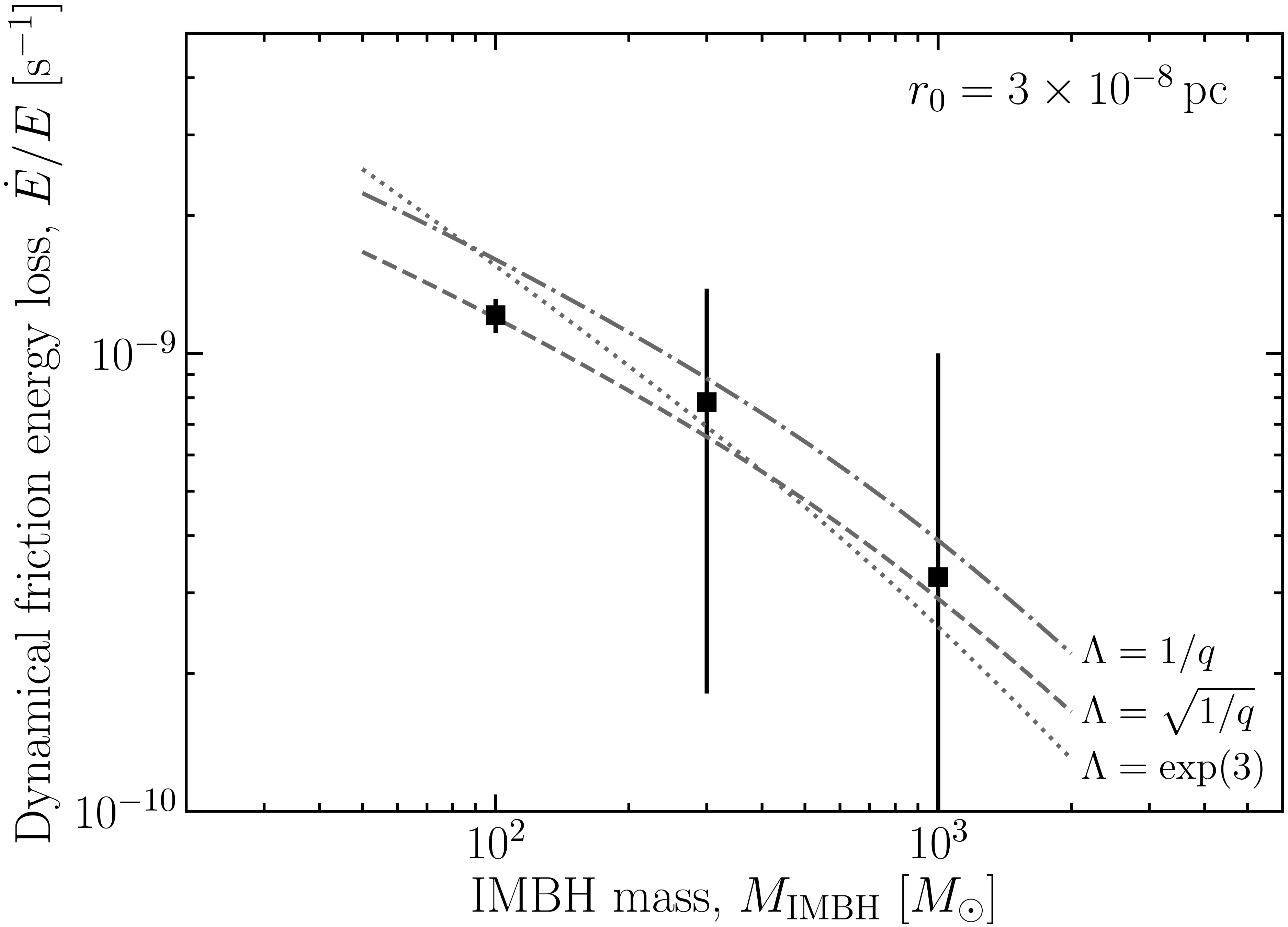
Astrophysical BH binaries could be formed dynamically, or through e.g. common envelope evolution:



[1602.04531]

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

N-body results



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

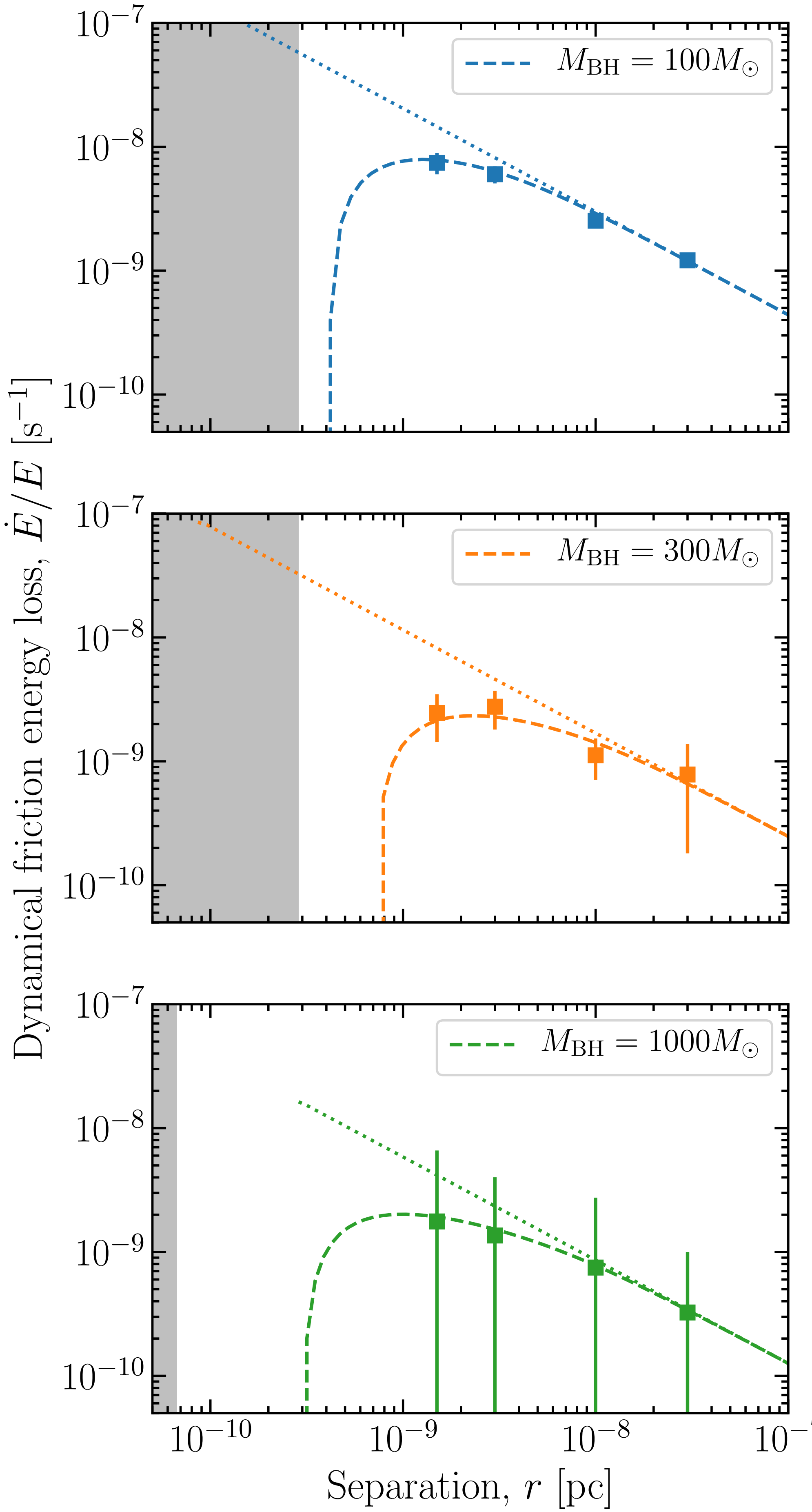
Fix 'Coulomb factor': $\Lambda = \sqrt{M_\mathrm{IMBH}/M_\mathrm{NS}} \sim 20 - 60$

N-body results

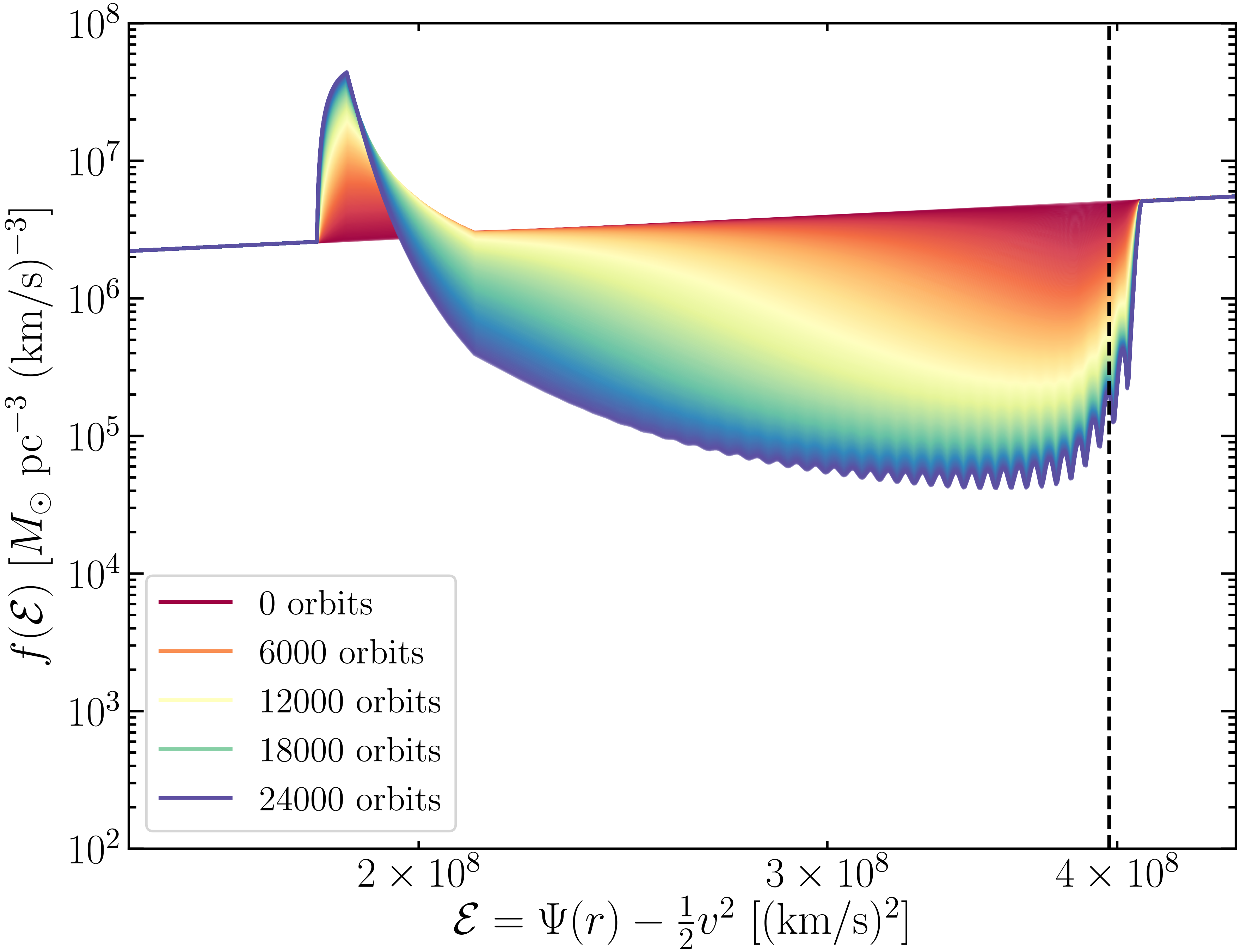
Dependence of dynamical friction force on mass and separation matches expectations

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

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



Distribution function

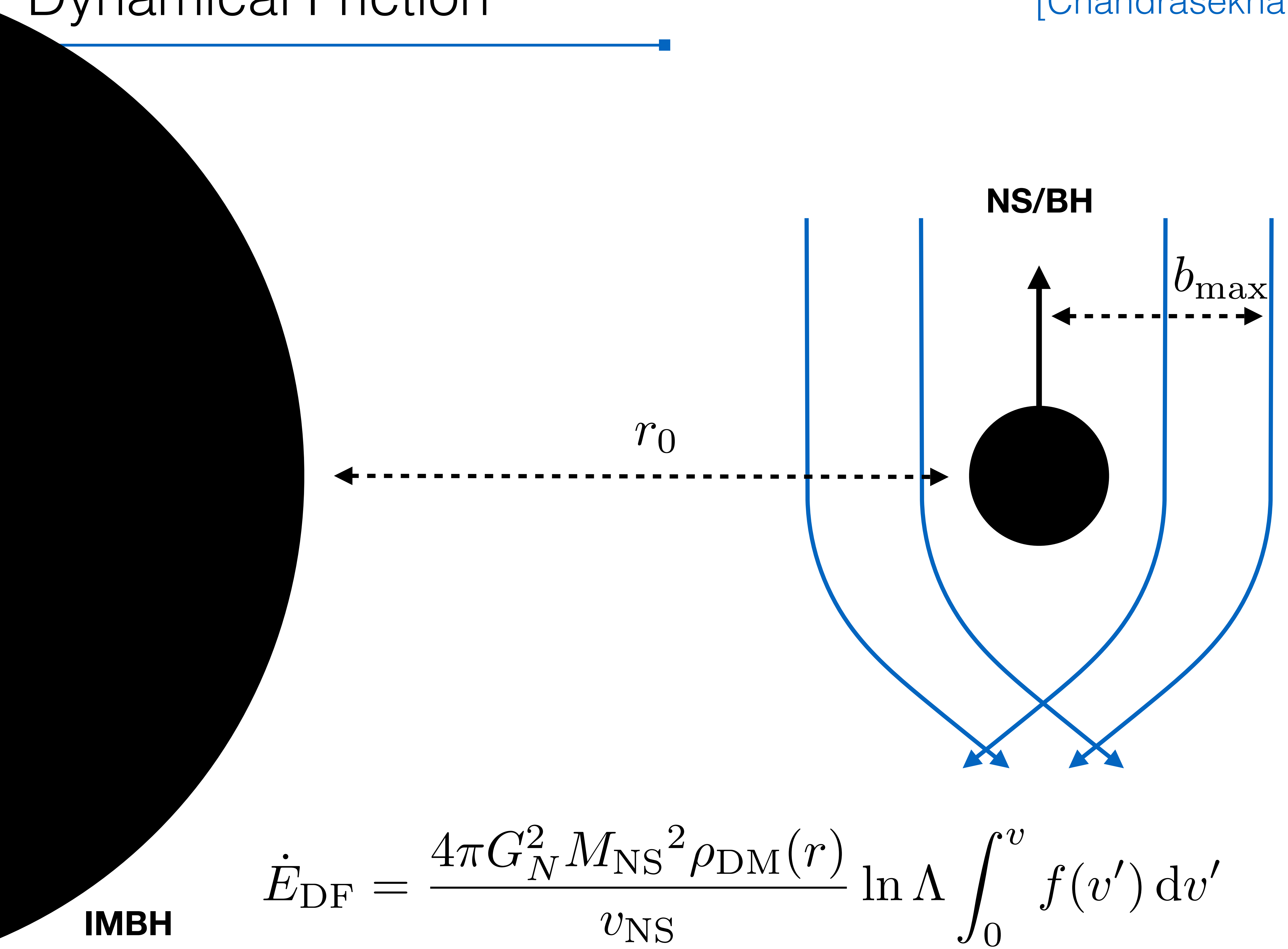


Self-consistently reconstruct density from distribution function:

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

Dynamical Friction

[Chandrasekhar, 1943]



$$\dot{E}_{\mathrm{DF}} = \frac{4\pi G_N^2 {M_{\mathrm{NS}}}^2 \rho_{\mathrm{DM}}(r)}{v_{\mathrm{NS}}} \ln\Lambda \int_0^v f(v')\,\mathrm{d}v'$$

Relaxation of the Halo