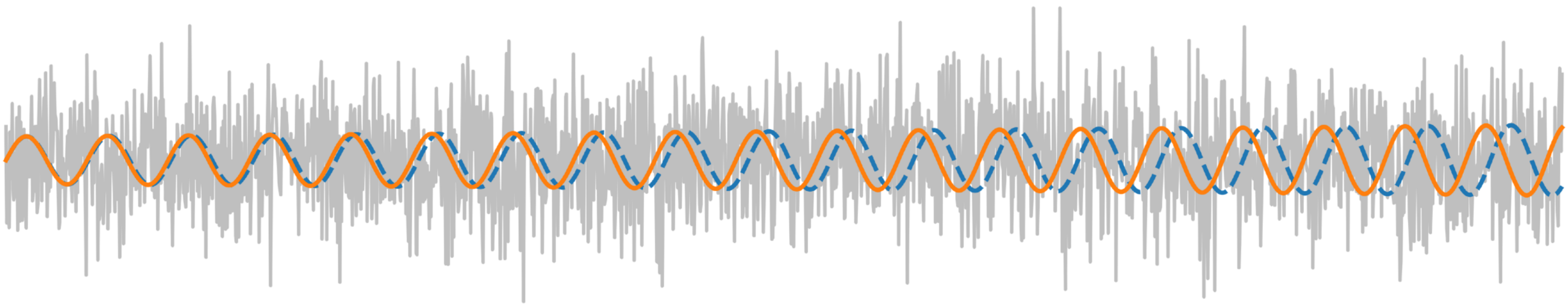
Detecting Dark Matter around Black Holes with Gravitational Waves



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DESY Theory Seminar, 27th January 2020

GRAPPA GRavitation AstroParticle Physics Amsterdam

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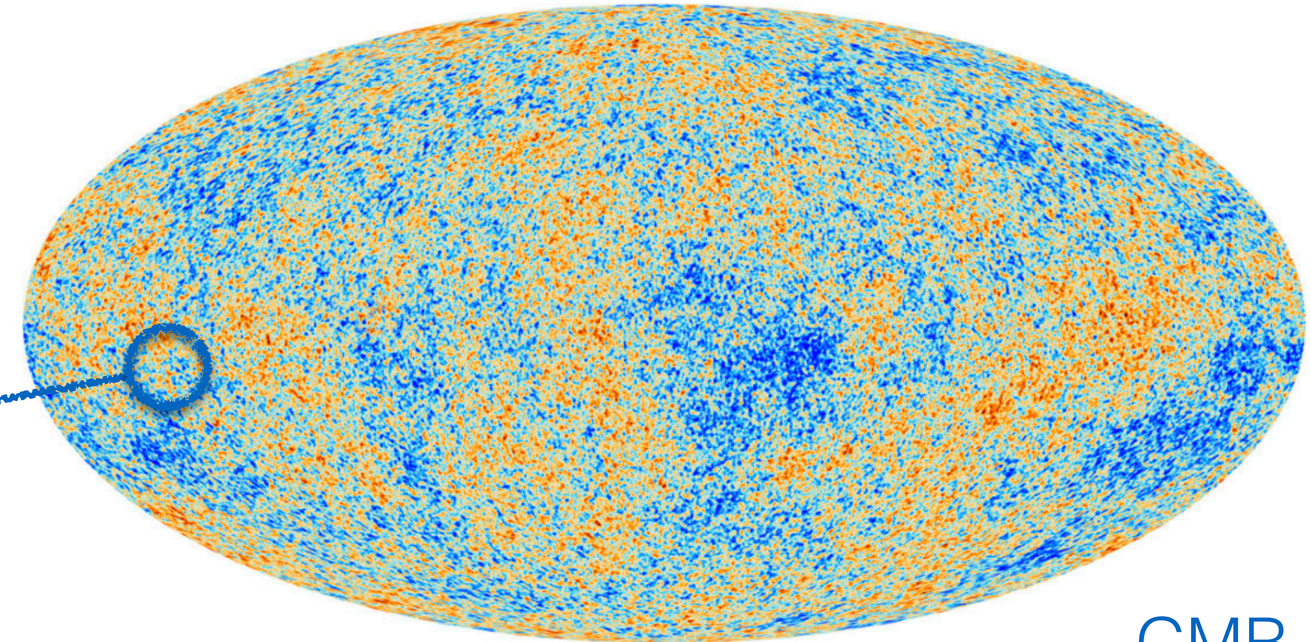
Abstract. With growing agony of not finding a dark matter (DM) particle in direct search experiments so far (for example in XENON1T), frameworks where the freeze-out of DM is driven by number changing processes within the dark sector itself and do not contribute to direct search, like Strongly Interacting Massive Particle (SIMP) are gaining more attention. In this analysis, we ideate a simple scalar DM framework stabilised by $\mathcal{Z}_2$ symmetry to serve

From 'SIMPler realisation of Scalar Dark Matter' [1904.07562]

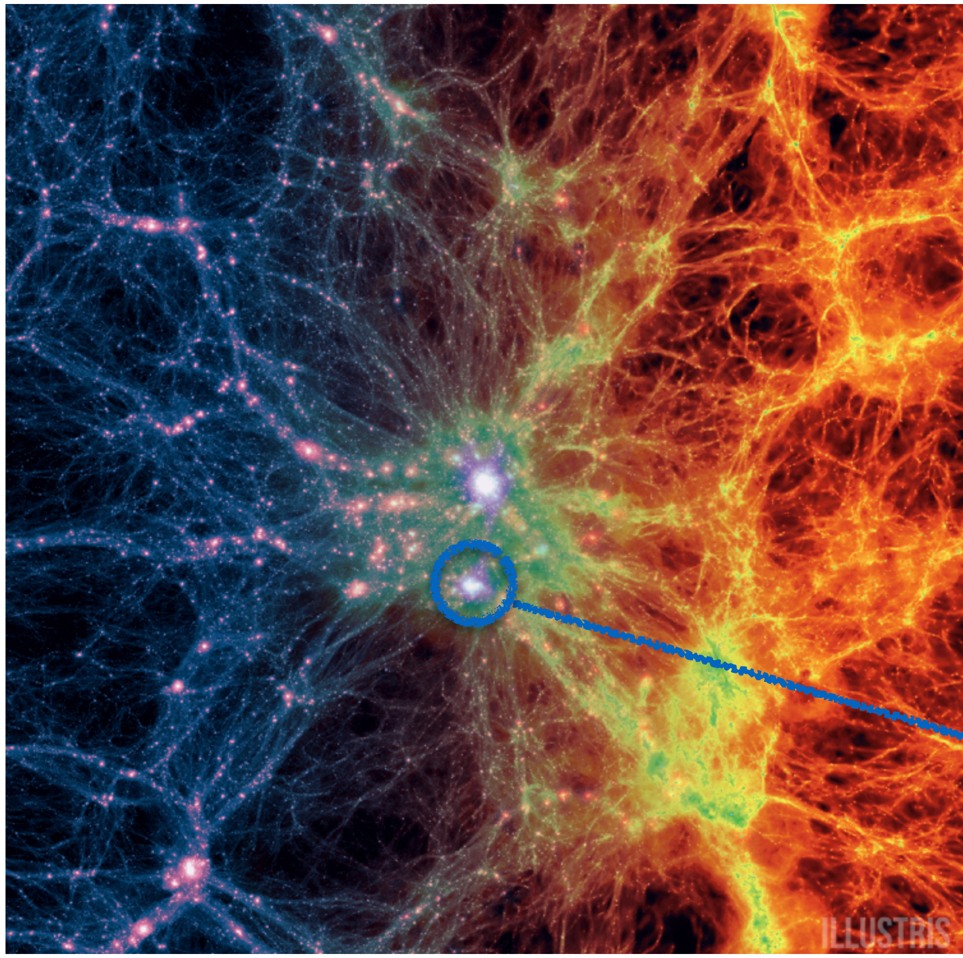
[With thanks to @TimonEmken]

Dark Matter on all scales



CMB

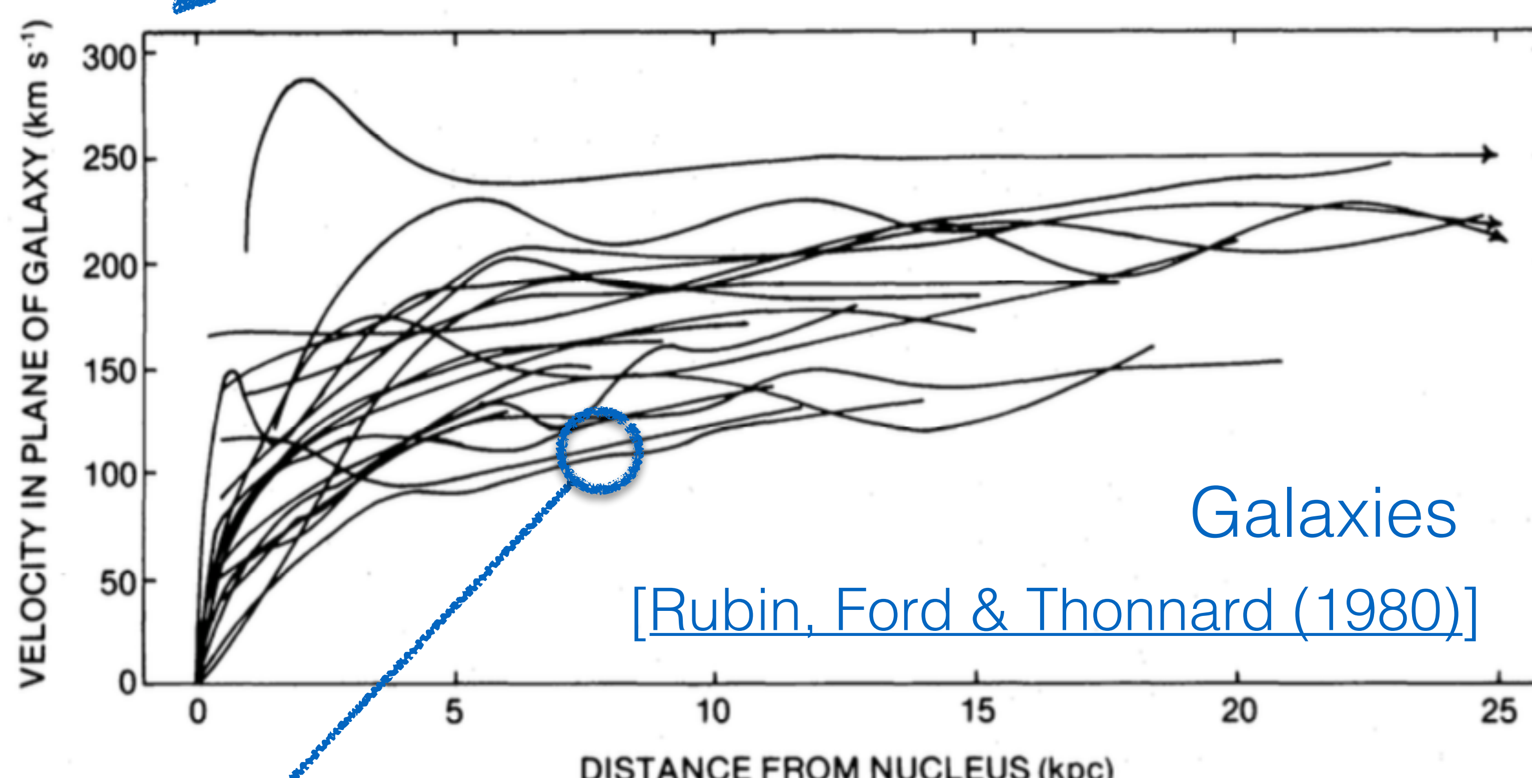
Planck [1502.01589]



Galaxy clusters

[Illustris, 1405.2921]

[astro-ph/0006397]

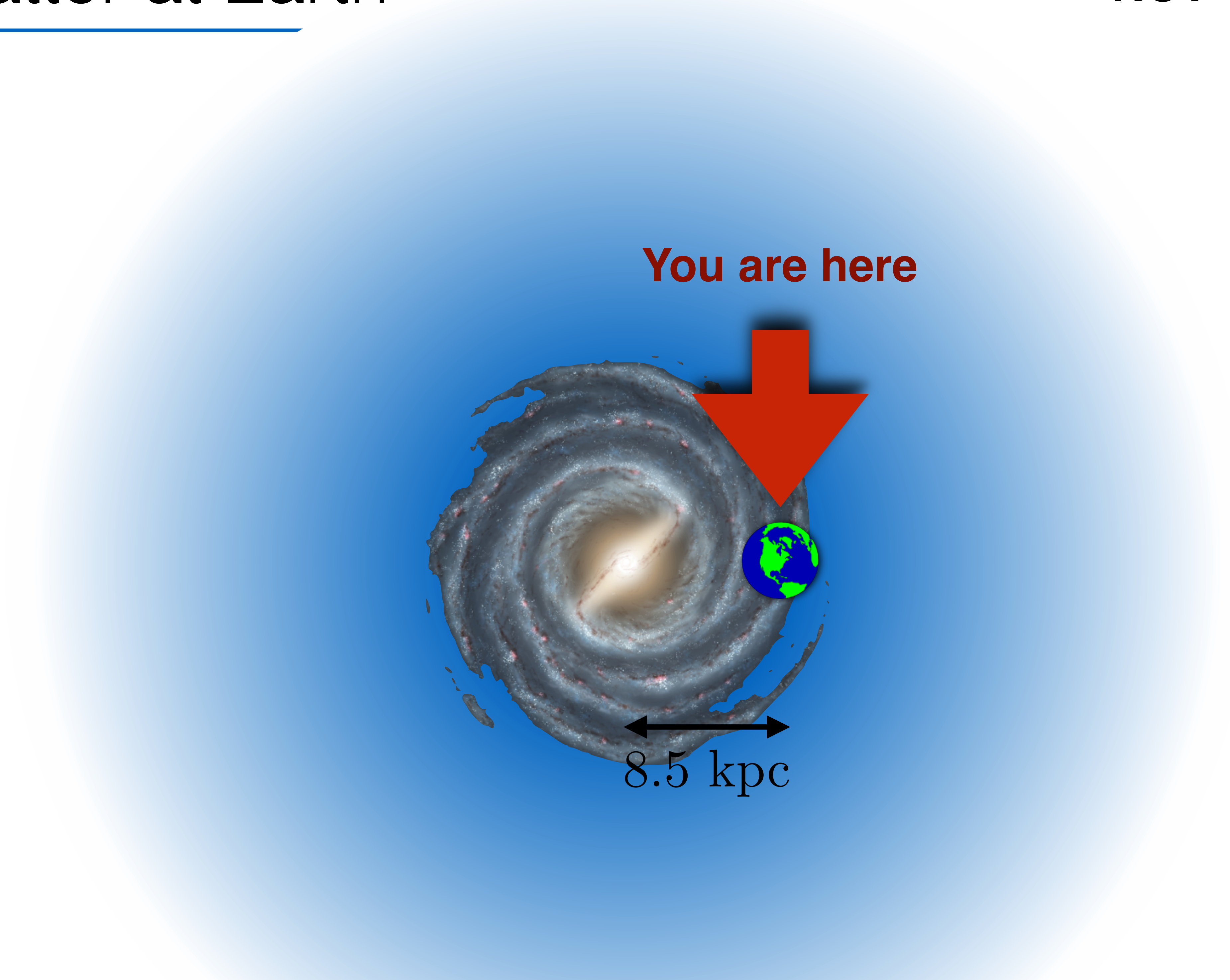


Galaxies

[Rubin, Ford & Thonnard (1980)]

Dark Matter at Earth

NOT TO SCALE

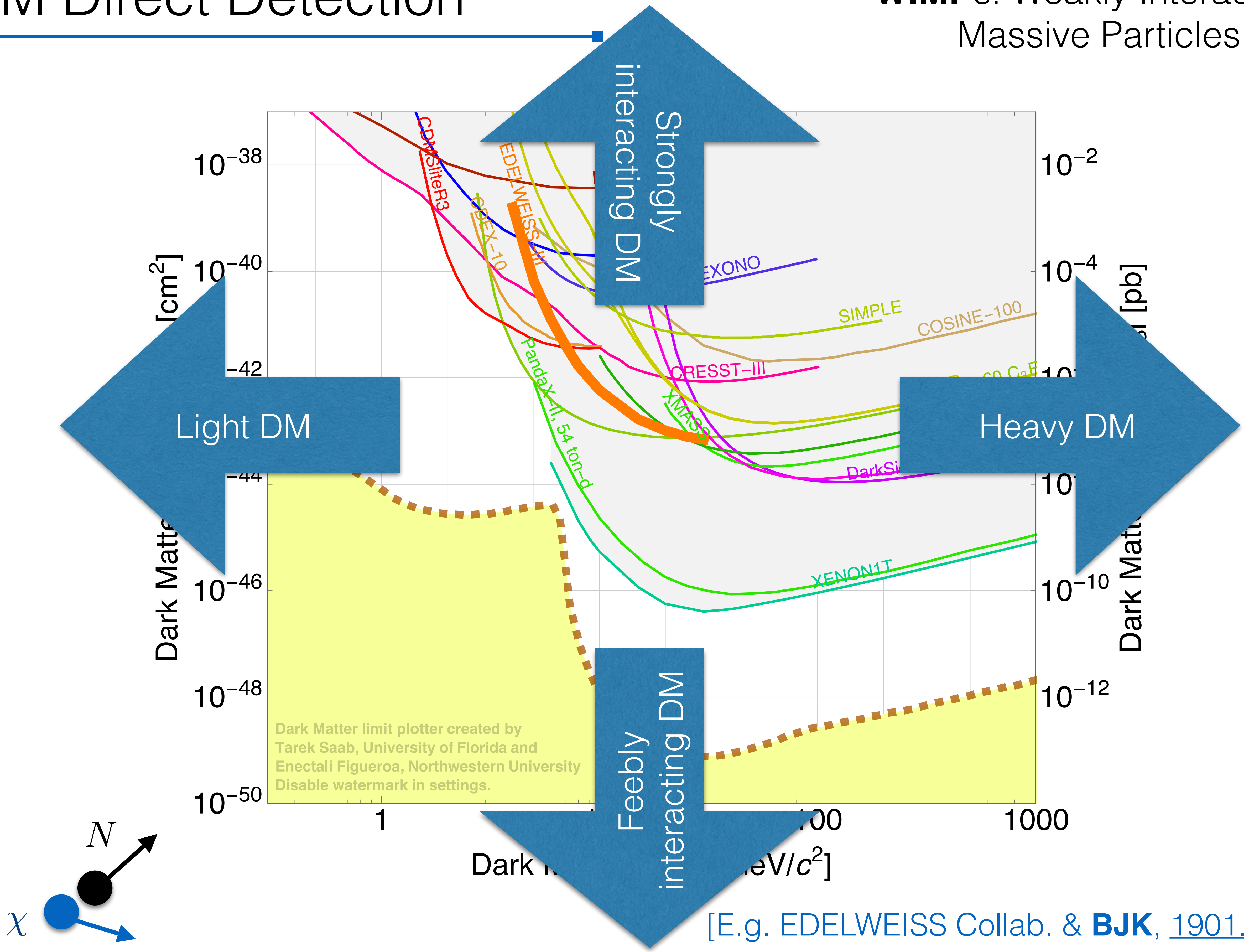


Global and local estimates of DM at Solar radius give: $\rho_\chi \sim 0.2 - 0.8 \text{ GeV cm}^{-3}$

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

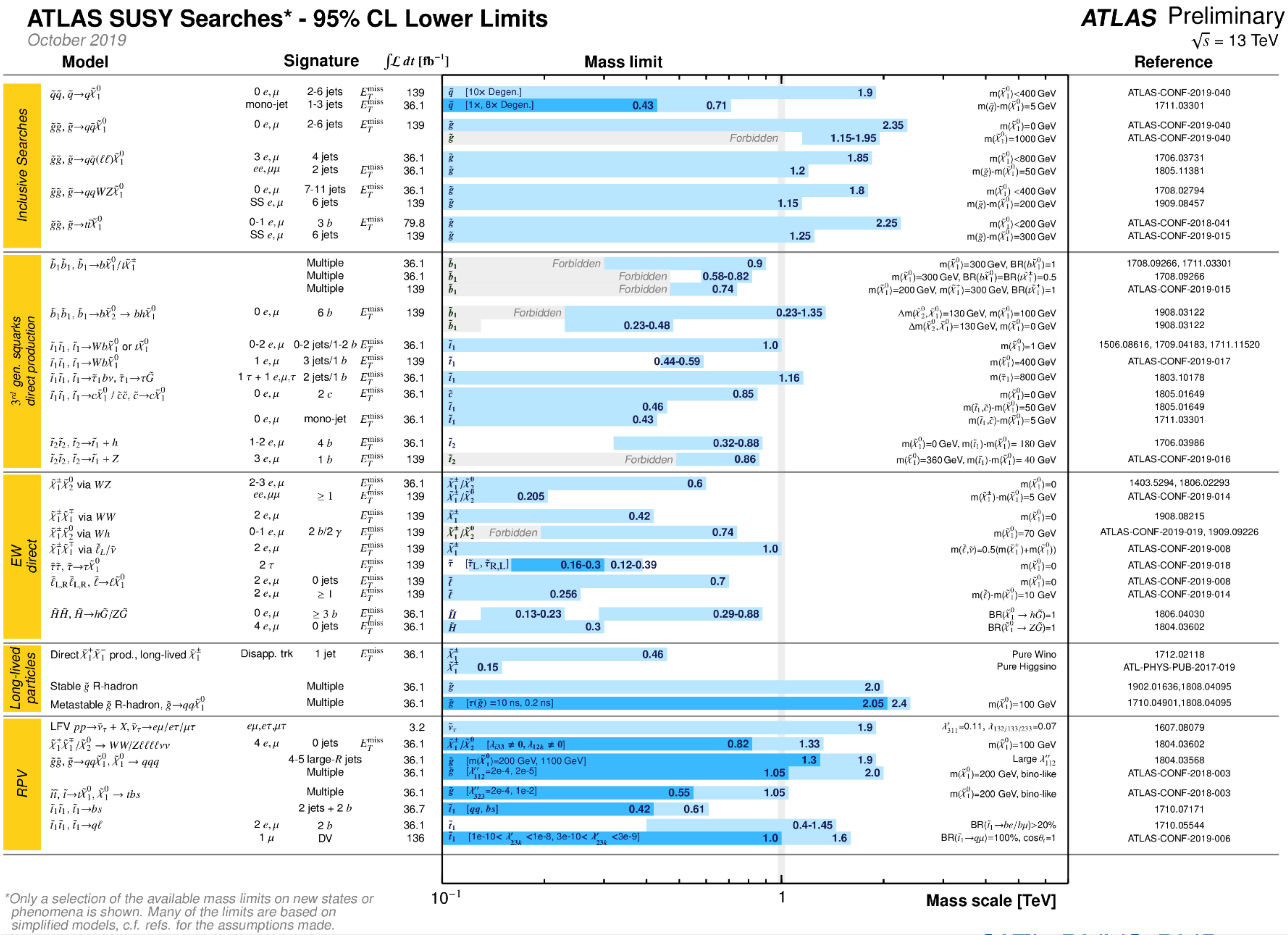
DM Direct Detection

WIMPs: Weakly Interacting Massive Particles



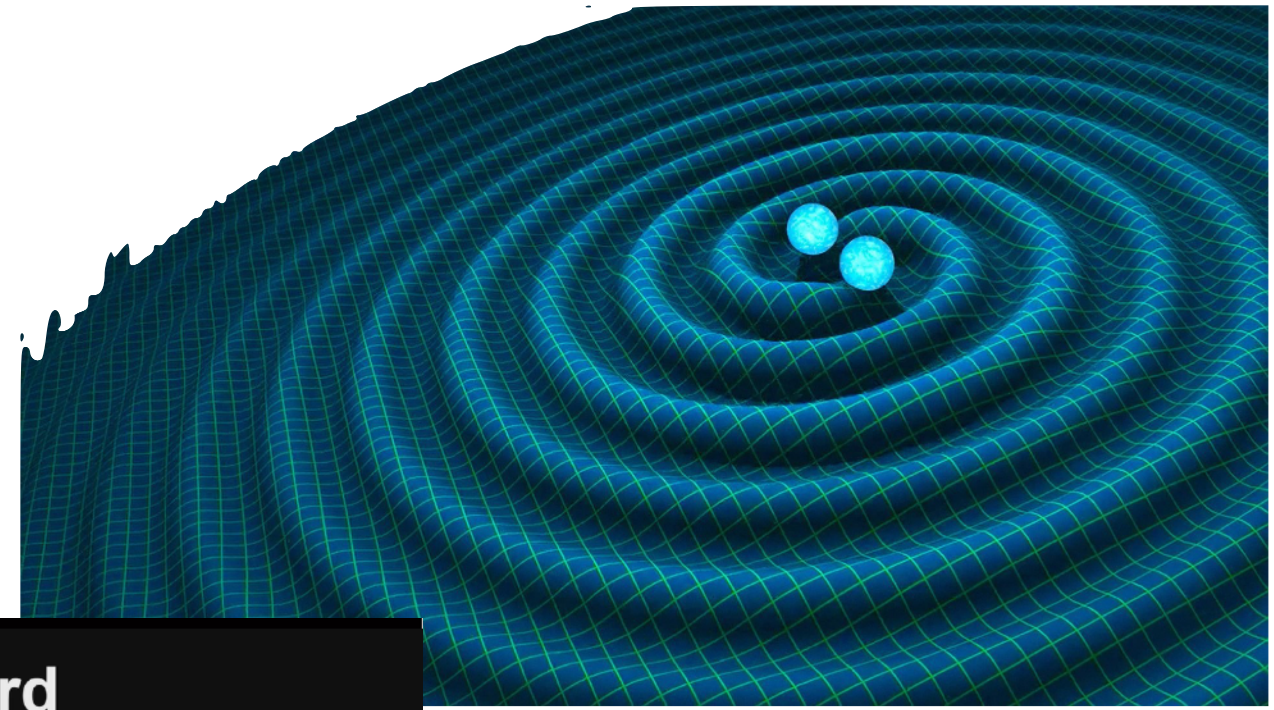
[E.g. EDELWEISS Collab. & **BJK**, 1901.03588]

Collider Searches for DM



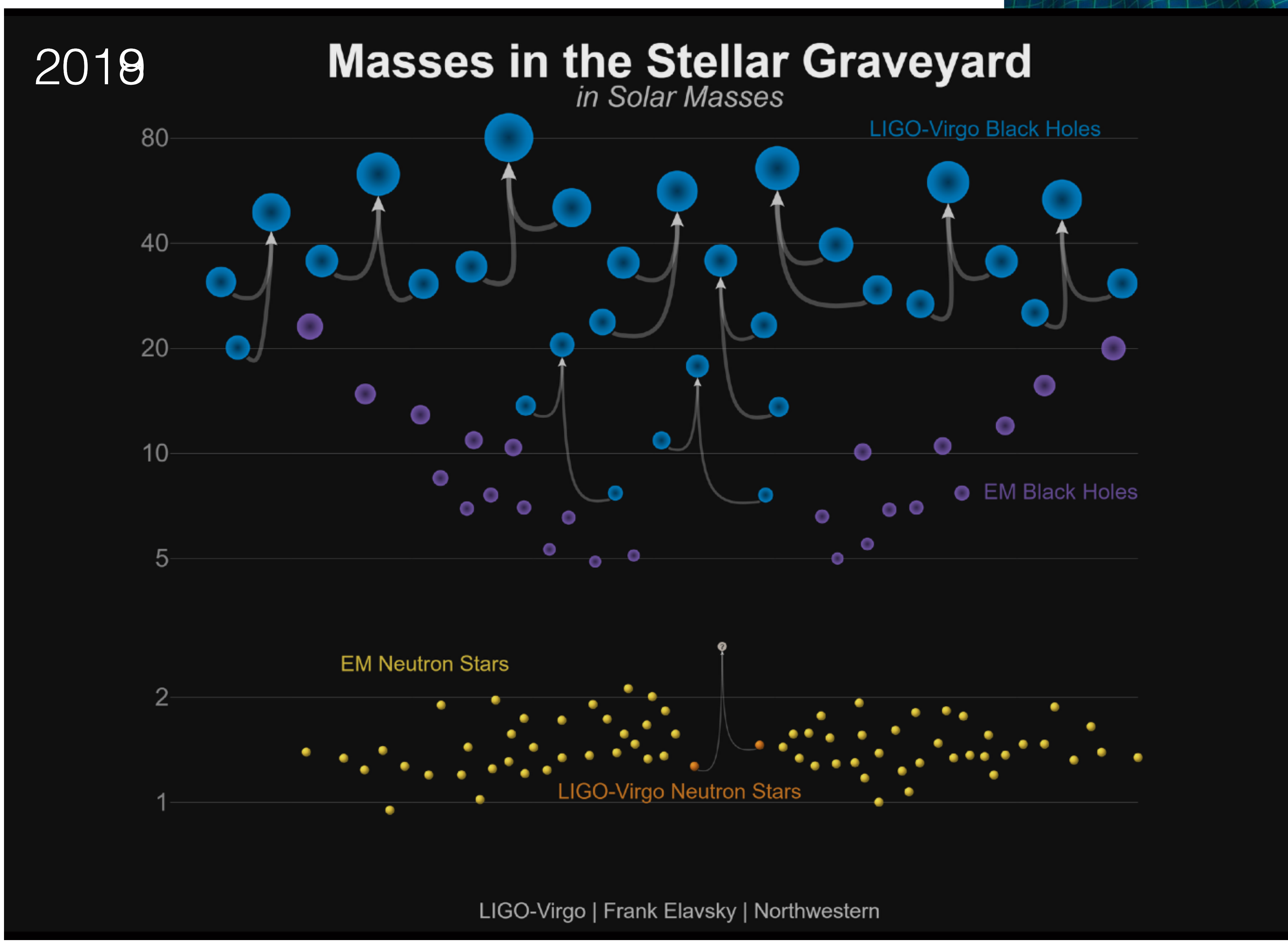
[ATL-PHYS-PUB-2019-044]

Gravitational Waves (GWs)

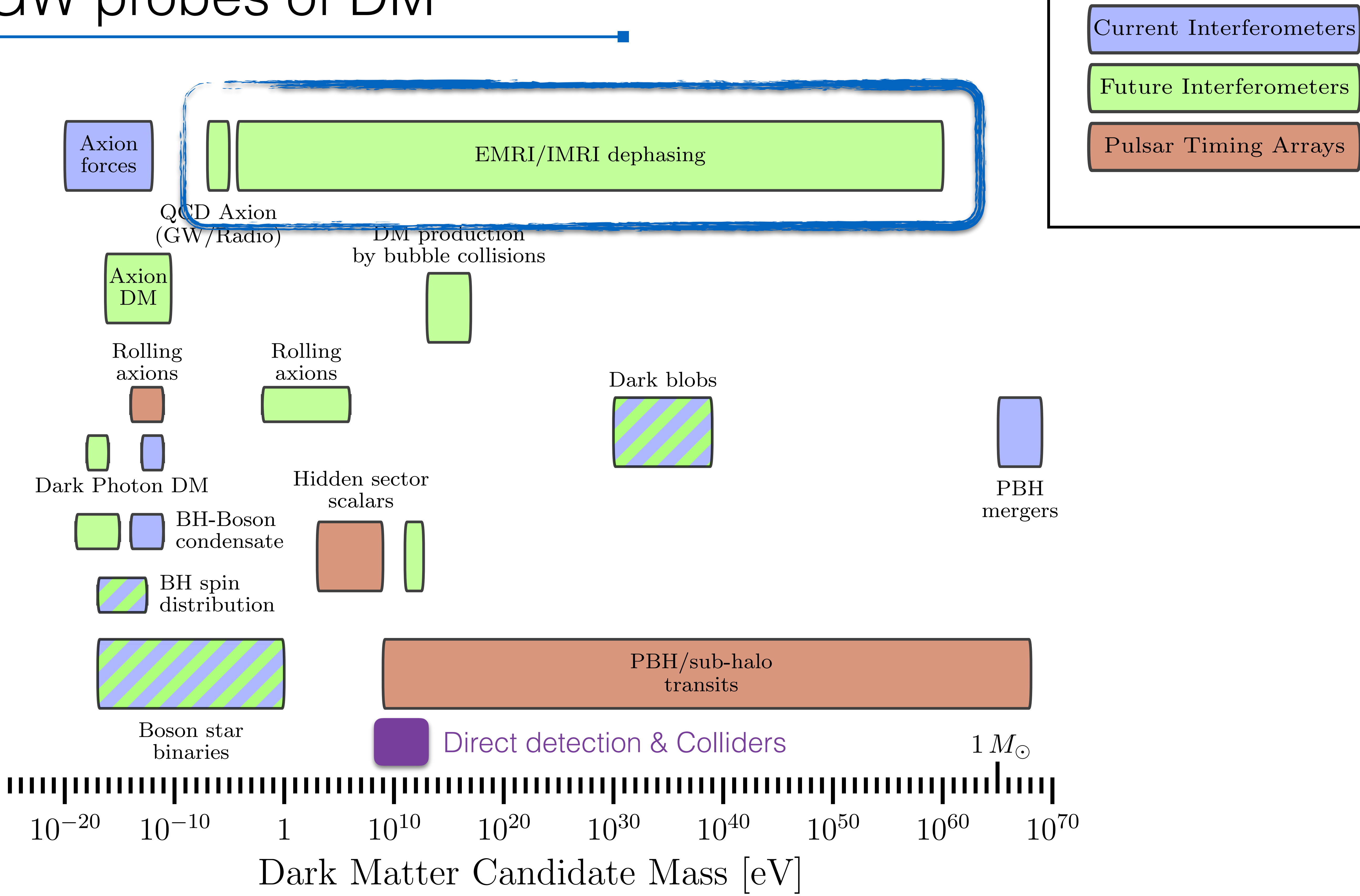


R. HURT / CALTECH-JPL / HANDOUT/ ESA

LIGO/Virgo/Northwestern Univ. (Frank Elavsky)



GW probes of DM

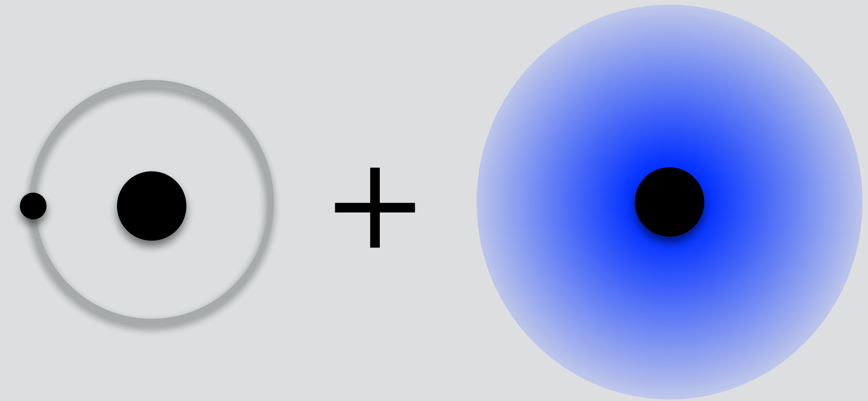


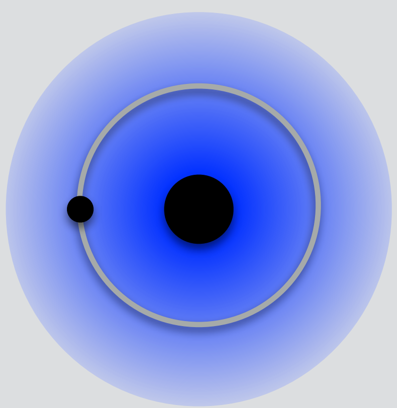
[1907.10610]

Overview

Intermediate Mass-Ratio Inspirals (IMRIs) and Dark Matter spikes

[Eda et al, 1301.5971, and others]



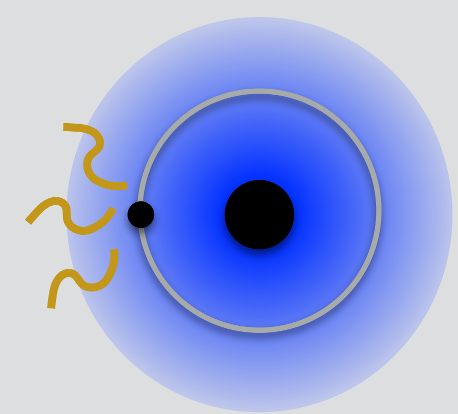


Dark Matter 'de-phasing' revisited

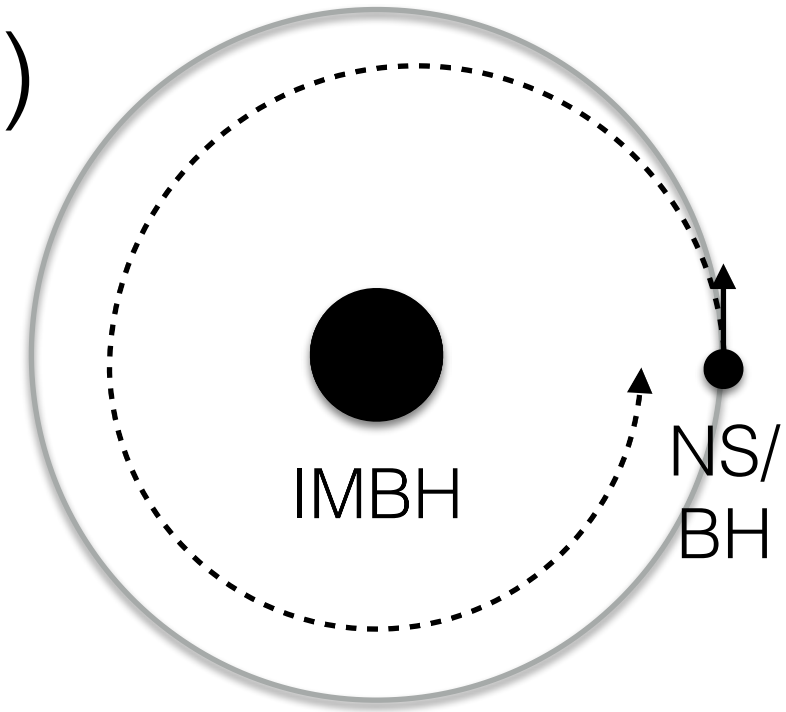
[**BJK**, Nichols, Gaggero, Bertone, 2001.XXXX]

GW + EM signals of QCD axion Dark Matter

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



Intermediate Mass Ratio Inspiral (IMRI)

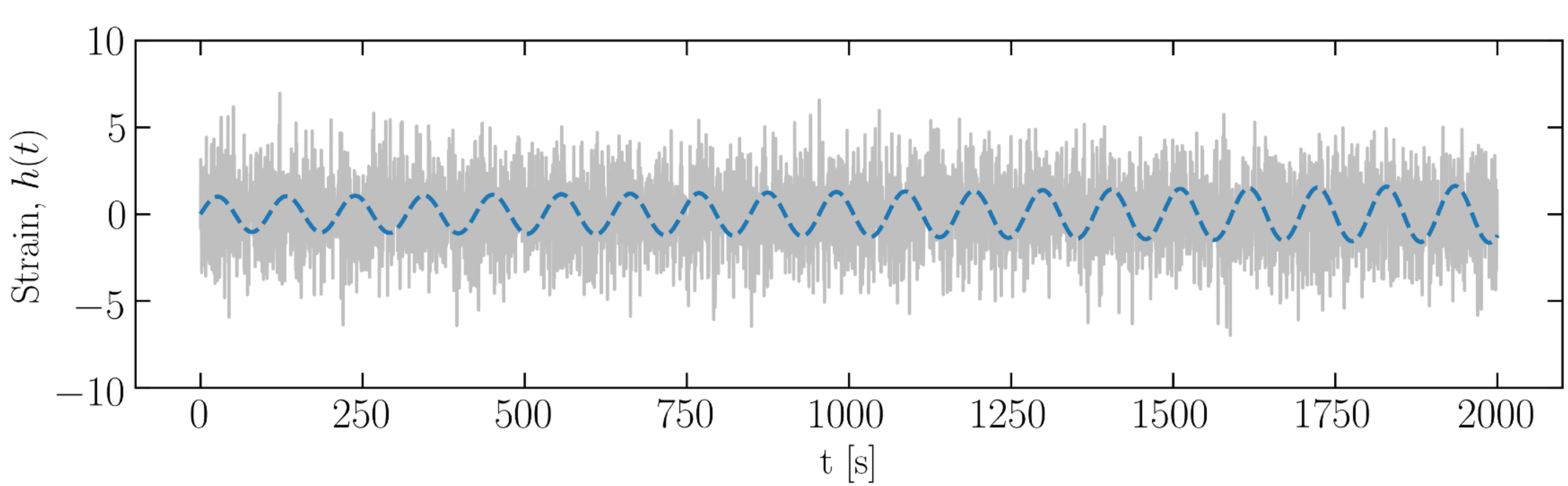


Stellar mass compact object (NS/BH) inspirals towards intermediate mass black hole (IMBH)

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

GW emission causes long, slow inspiral:

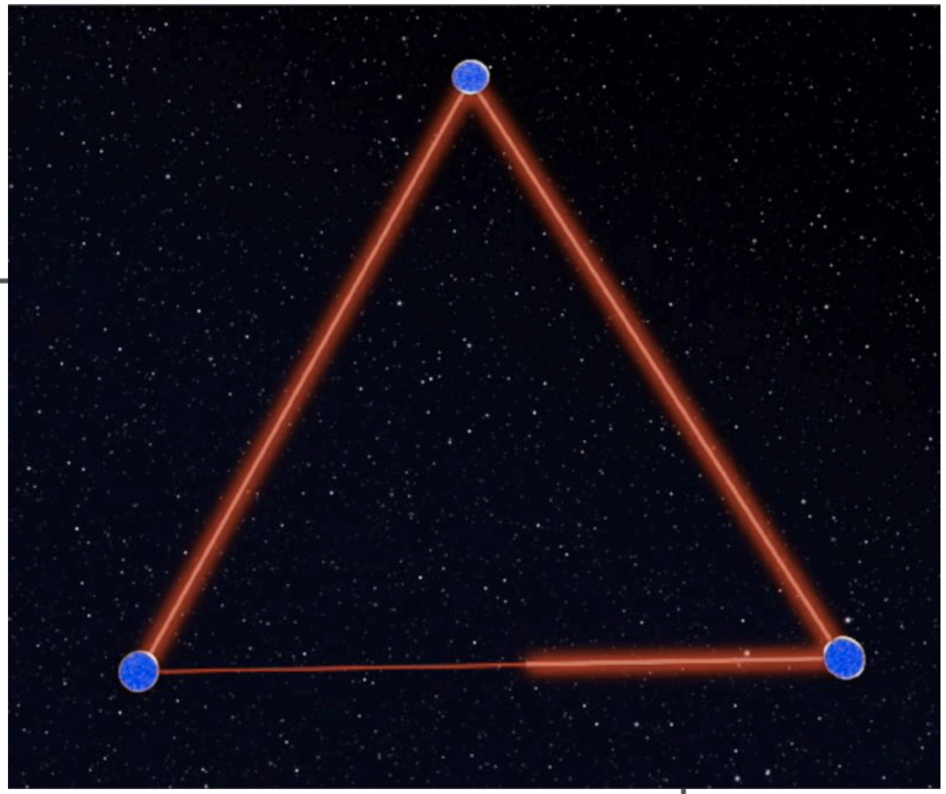
$$\dot{E}_{\mathrm{GW}} \approx \frac{32 G^4}{5 c^5} \frac{{M_{\mathrm{IMBH}}}^3 {M_{\mathrm{NS}}}^2}{r^5} \propto (f_{\mathrm{GW}})^{10/3}$$

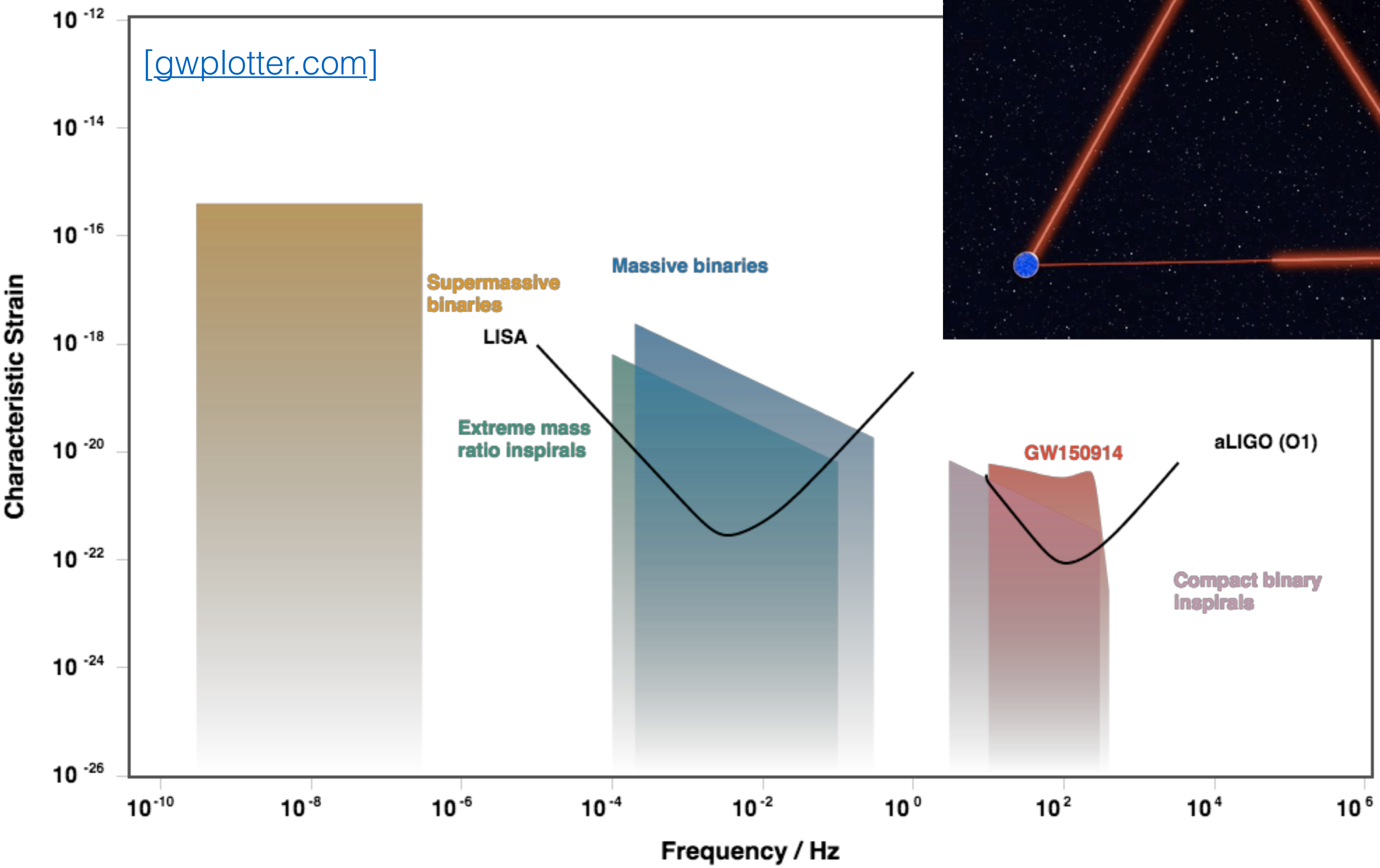


LISA: GWs in Space

Laser **I**nterferometer **S**pace **A**ntenna
(planned for the 2030s) [1702.00786]

© AEI / MM / exozet





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

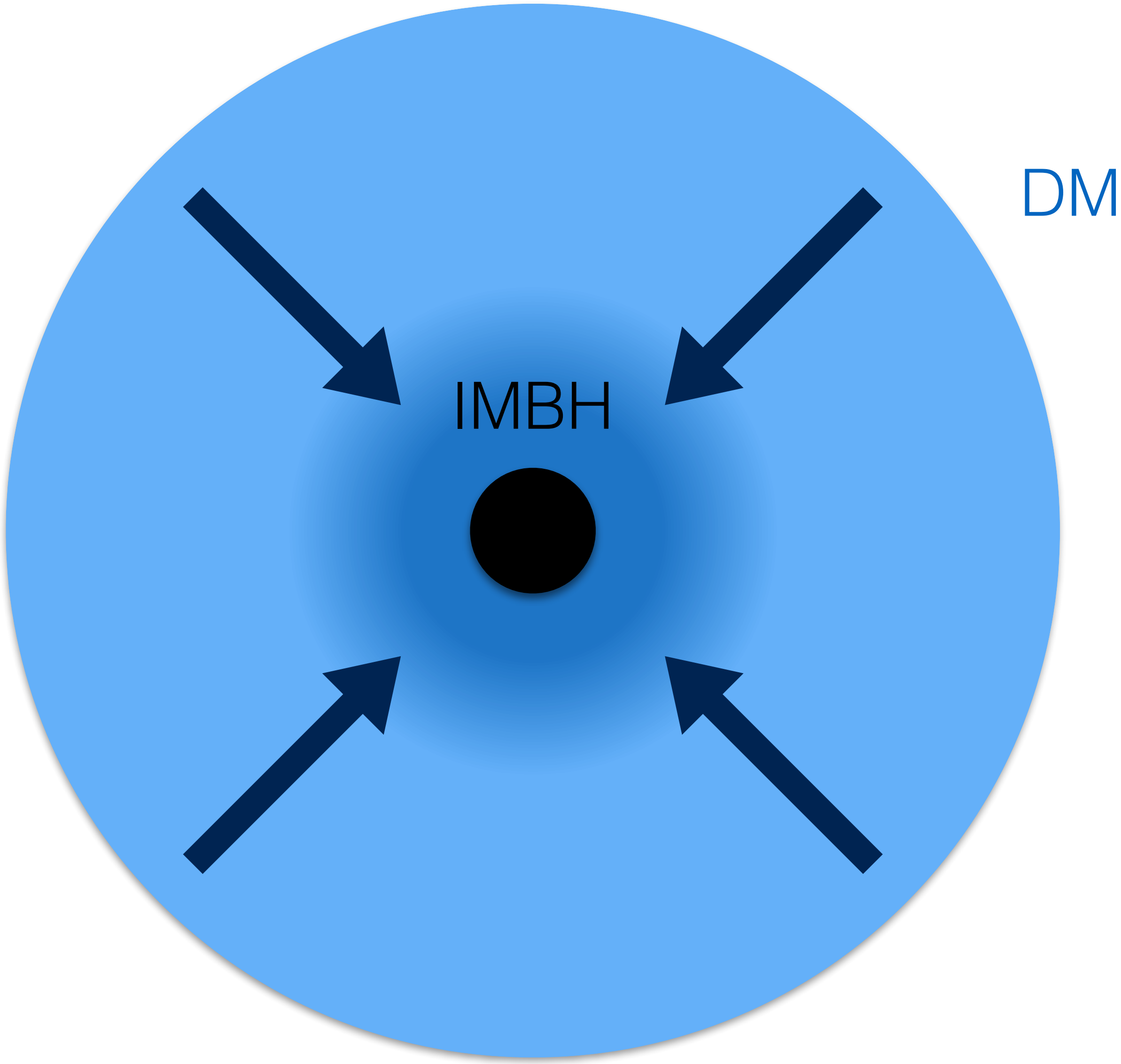
Dark Matter ‘Mini-spikes’

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:

$$\gamma_{\mathrm{sp}} = 7/3 \approx 2.333$$



For 1000 Solar mass IMBH, forming at z ~ 20, get typical values:

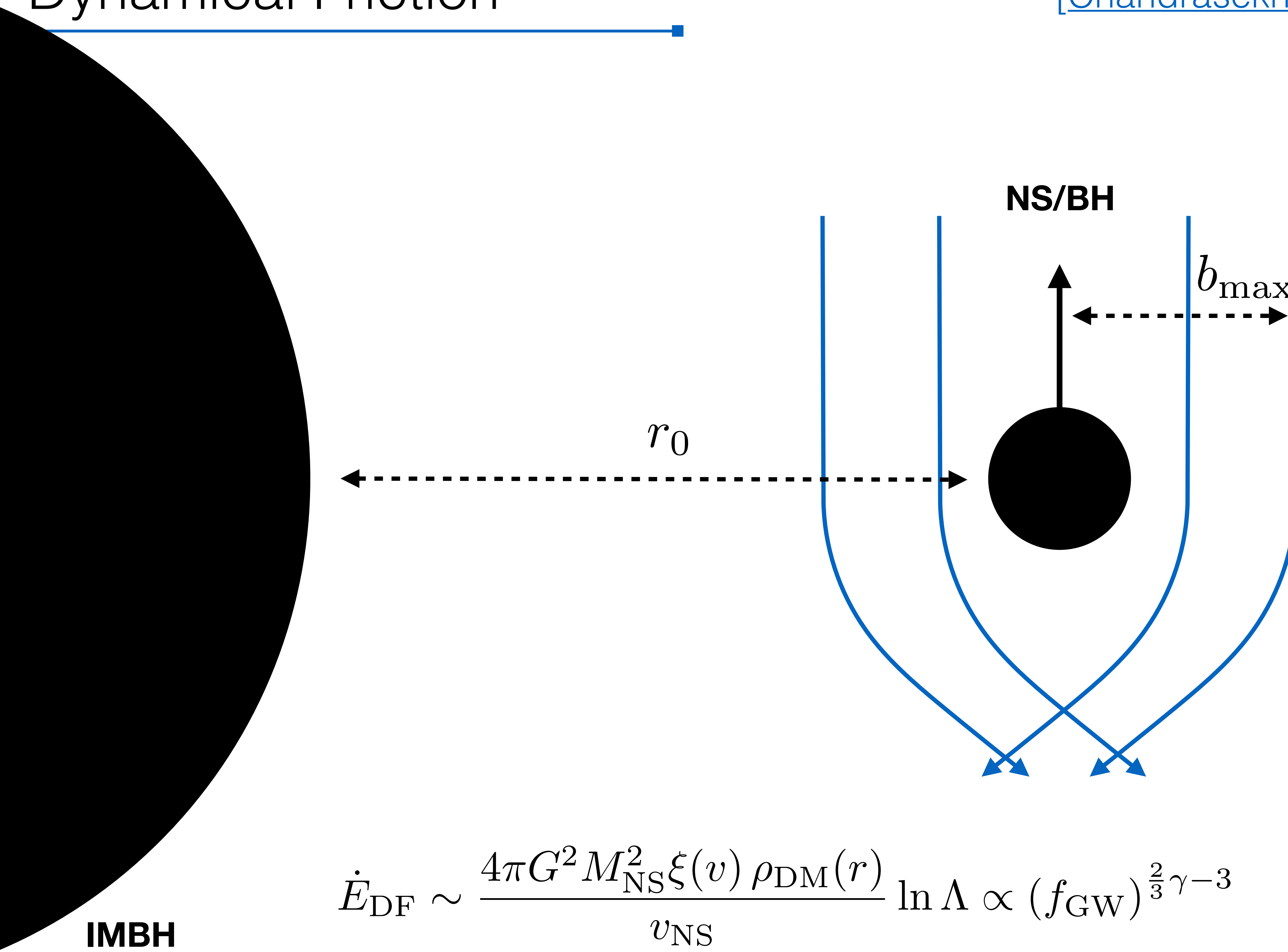
$$\rho_{\mathrm{sp}} = 200\, M_\odot\, \mathrm{pc}^{-3}$$
$$r_{\mathrm{sp}} = 0.5\, \mathrm{pc}$$

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]

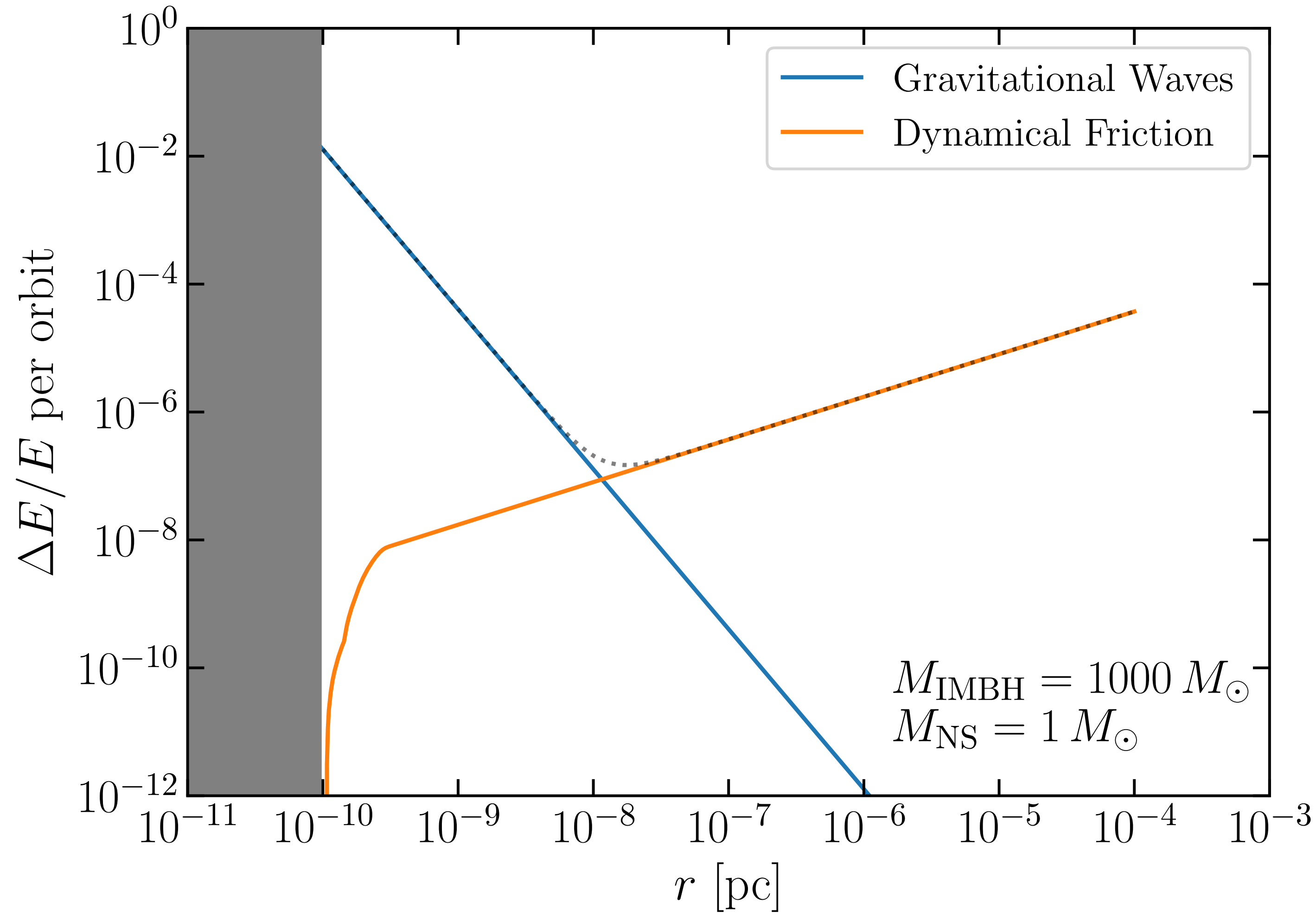
Dynamical Friction

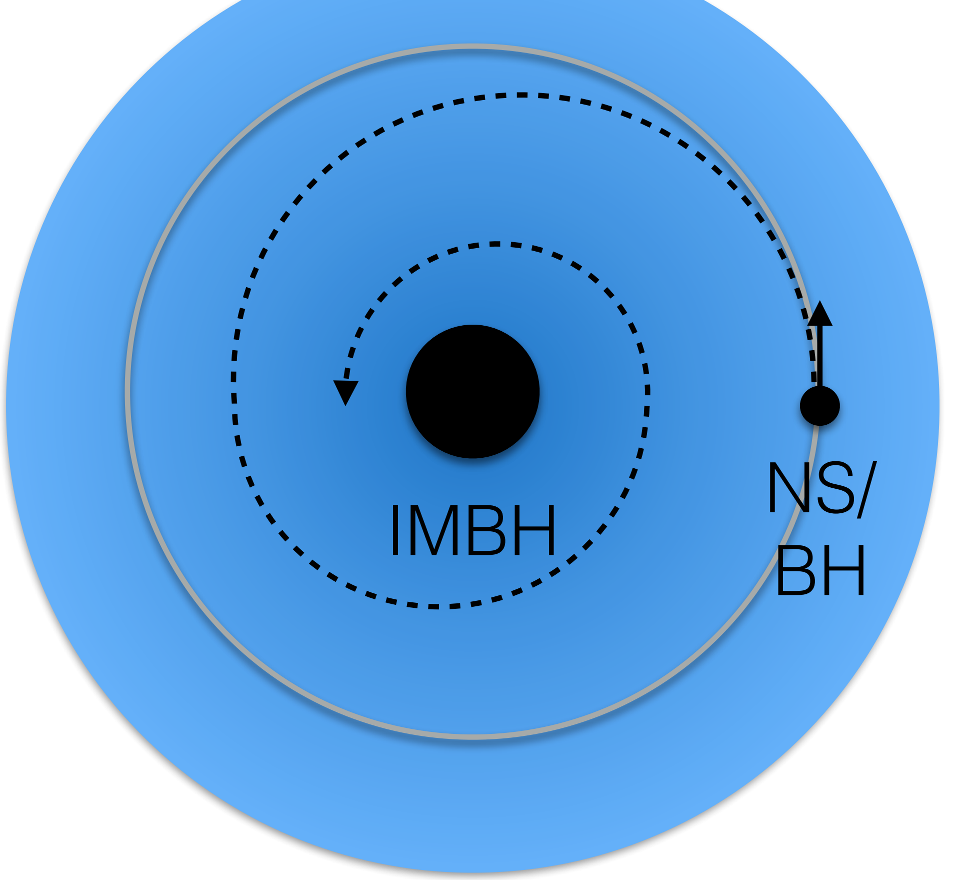
[Chandrasekhar, 1943]



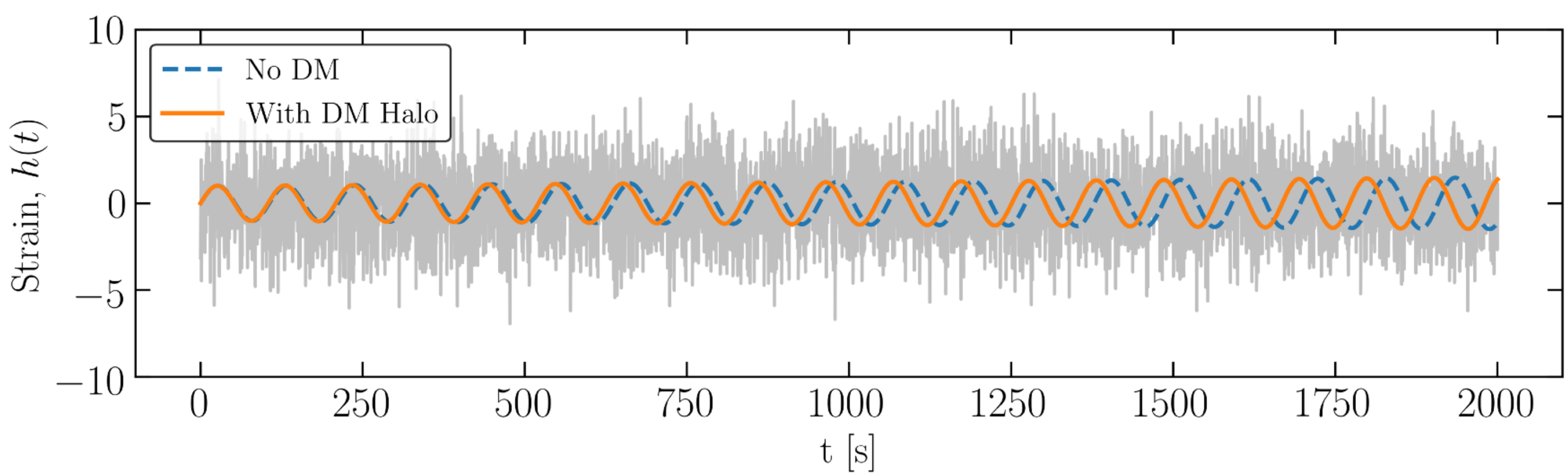
$$\dot{E}_{\mathrm{DF}} \sim \frac{4\pi G^2 M_{\mathrm{NS}}^2 \xi(v)\, \rho_{\mathrm{DM}}(r)}{v_{\mathrm{NS}}} \ln\Lambda \propto (f_{\mathrm{GW}})^{\frac{2}{3}\gamma - 3}$$

IMRI + Dark Matter





$$-\dot{E}_{\rm orb} = \dot{E}_{\rm GW} + \dot{E}_{\rm DF}$$



‘De-phasing’ signal

How does DM affect the number of cycles?

Benchmark:

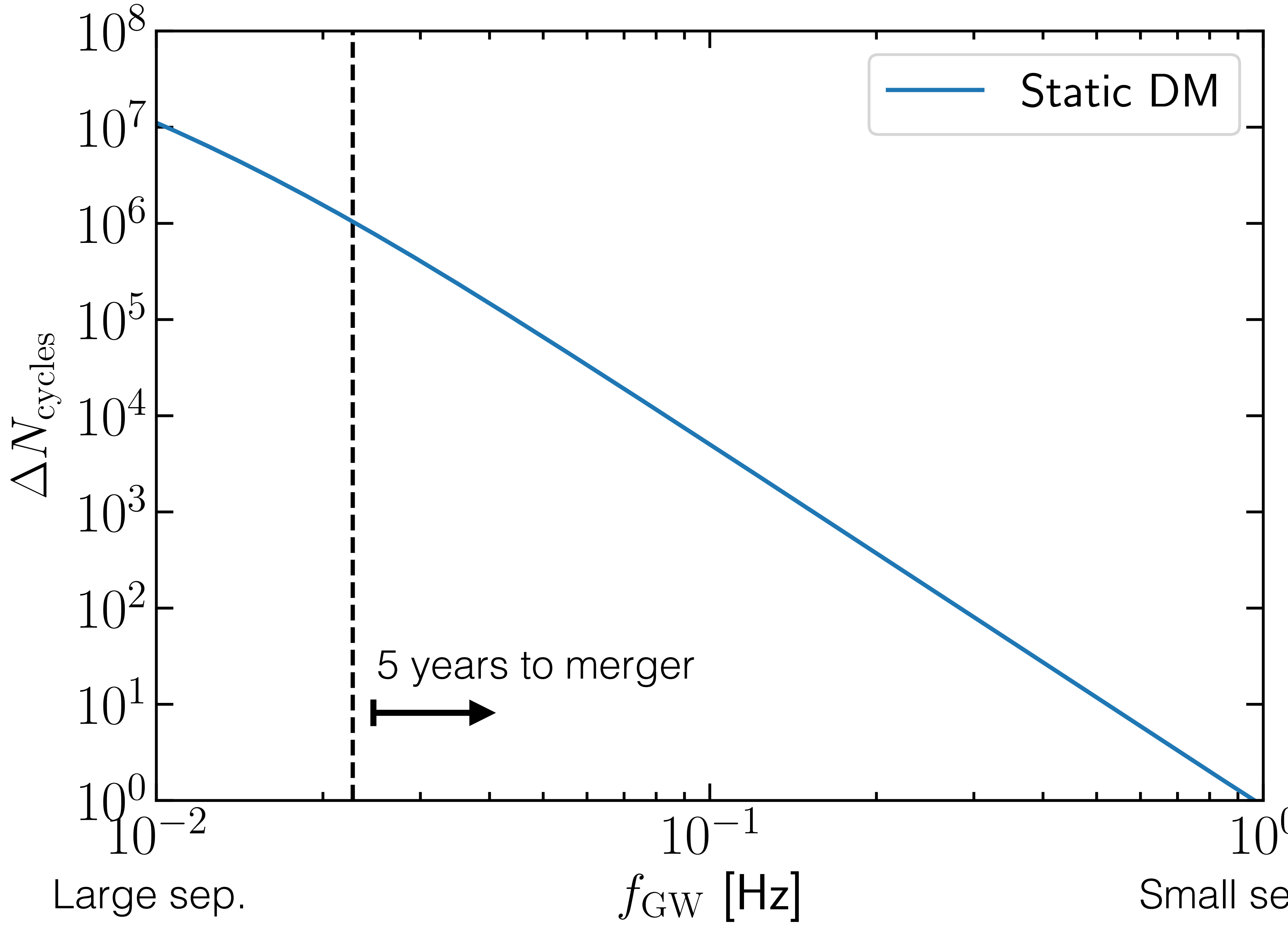
$$M_{\rm IMBH} = 10^3\,M_\odot$$

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

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

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

$$N_{\rm cycles}^{\rm vacuum} \sim 6\times 10^6$$



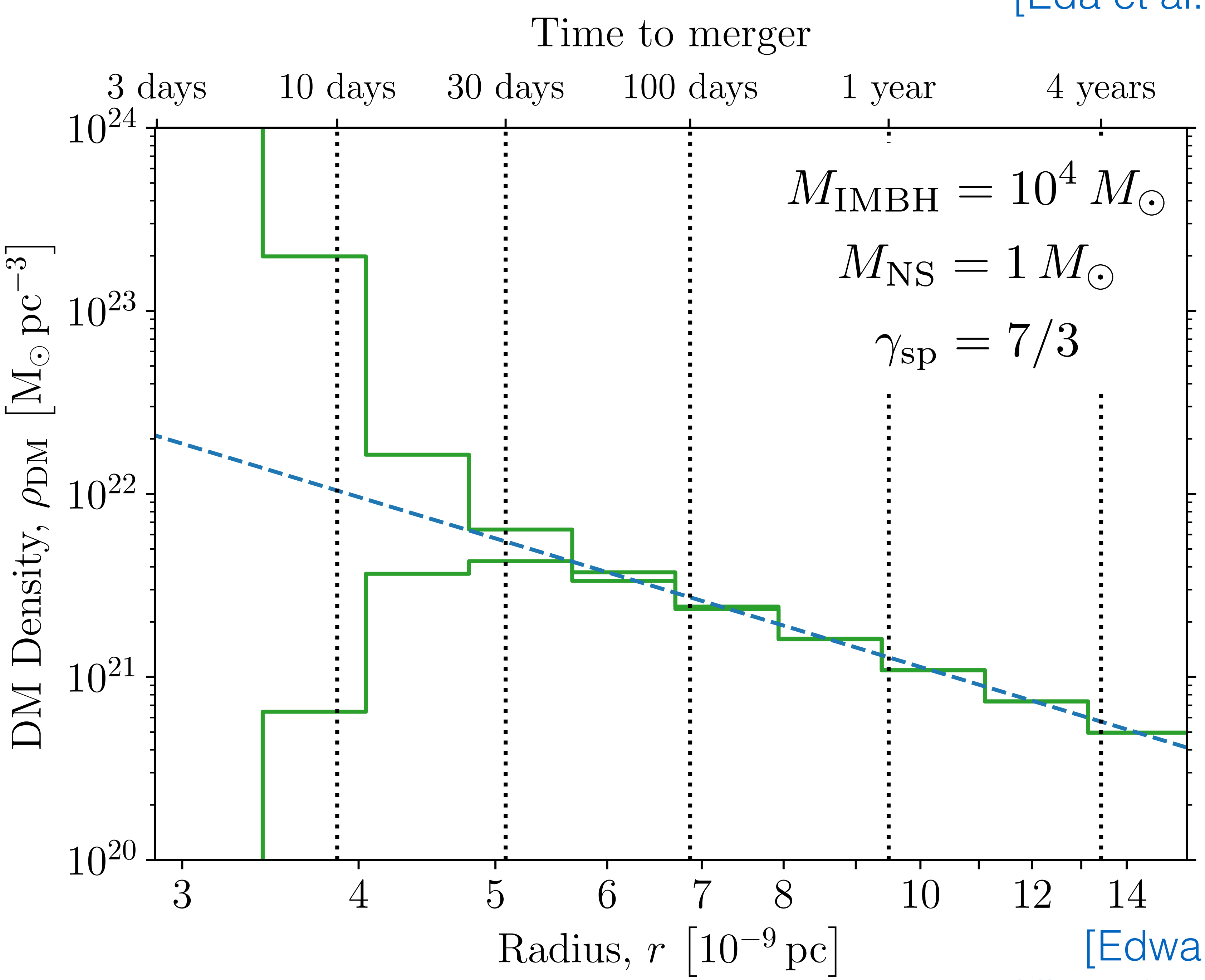
Need to know the signal to better than ~1 part in 10^6!

[Eda et al. 1301.5971, 1408.3534]
[See also 1302.2646, 1404.7140, 1404.7149]

Extracting DM Properties

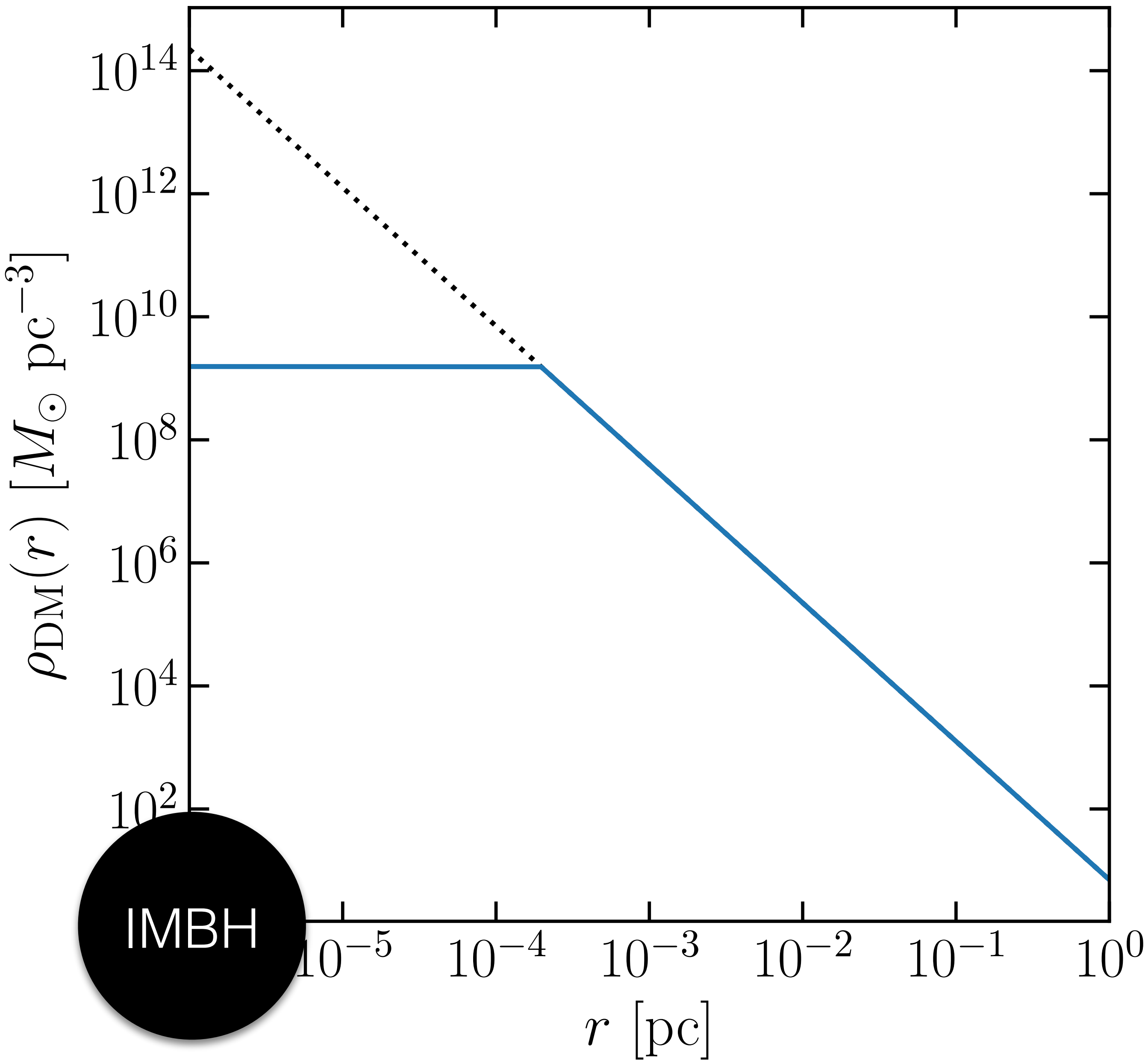
With LISA, should be able to detect this 'de-phasing' and reconstruct chirp mass and DM spike properties to high precision

[Eda et al. 1301.5971, 1408.3534]

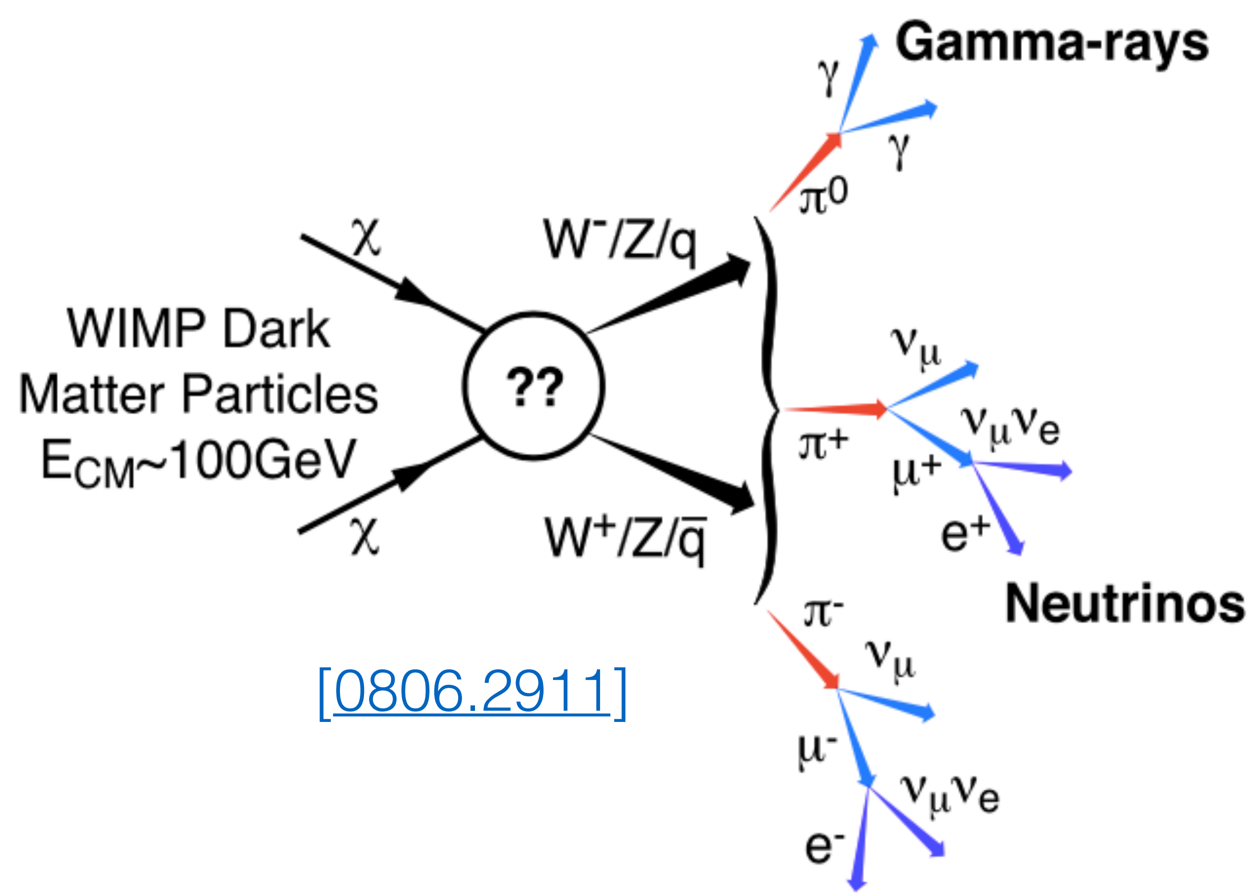


[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

Nature of Dark Matter



Consequences for self-interacting (WIMP) Dark Matter…

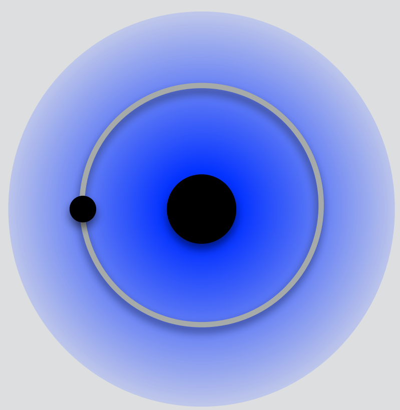


[0806.2911]

and for ultralight boson DM, fermionic DM, primordial black hole DM…

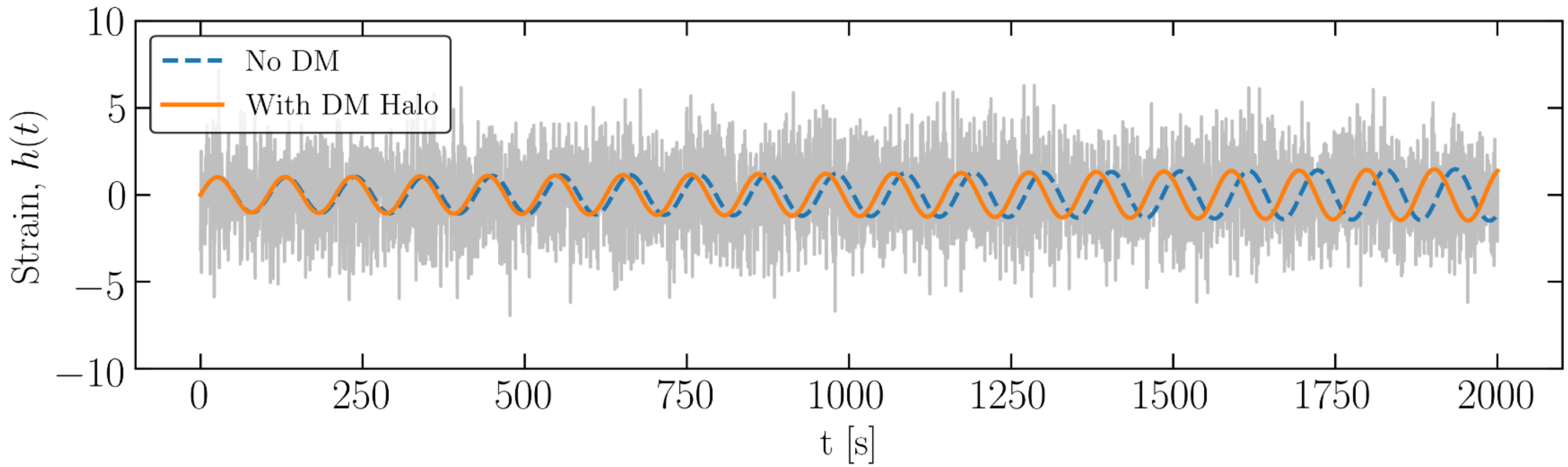
[1906.11845]

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



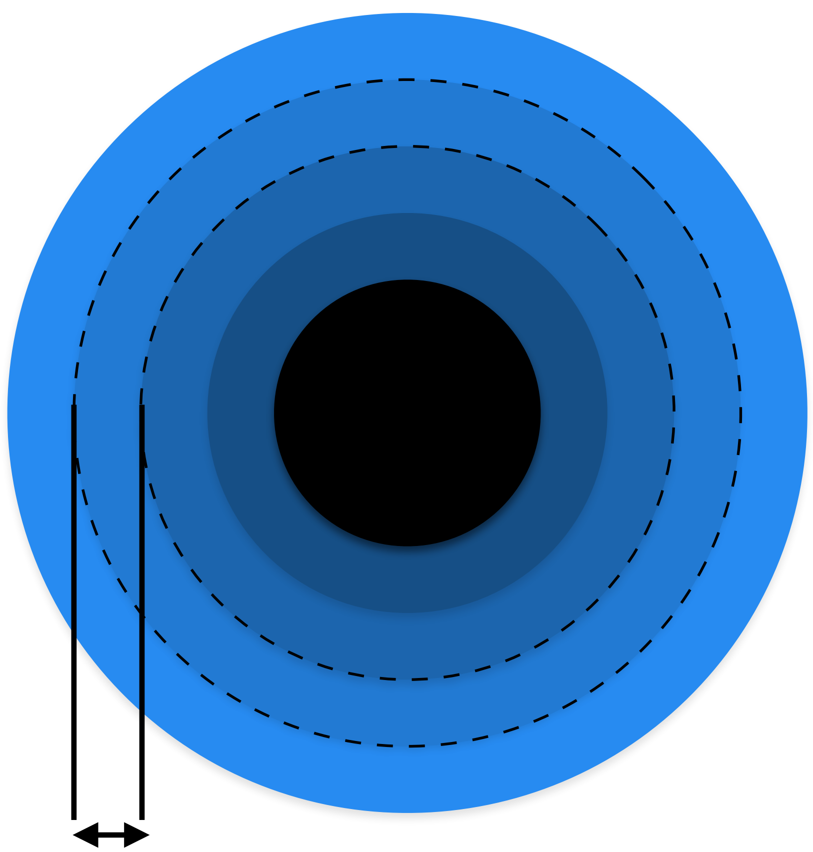
Dark Matter ‘de-phasing’ revisited

[**BJK**, Nichols, Gaggero, Bertone, 2001.XXXX]

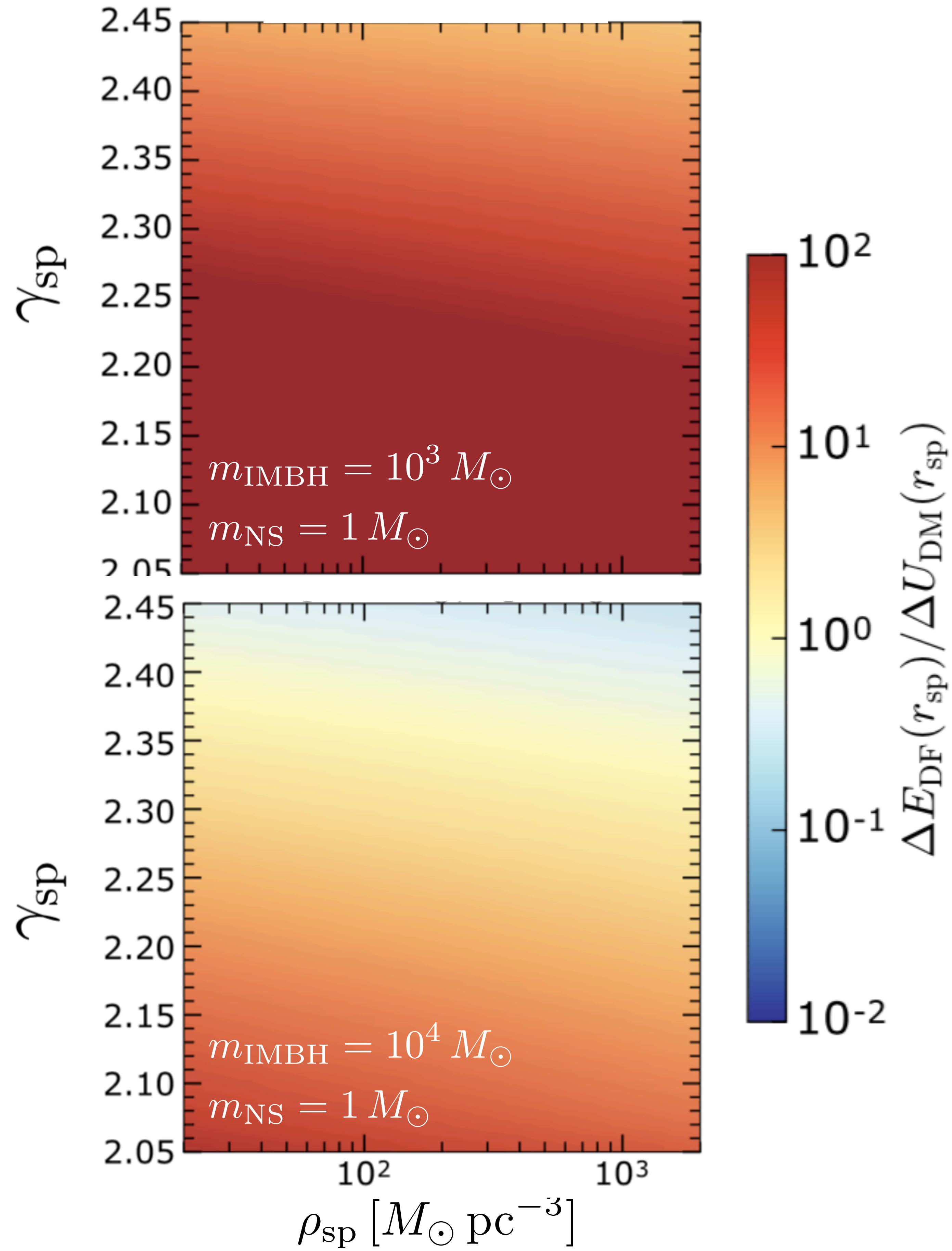


Energy Budget

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



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

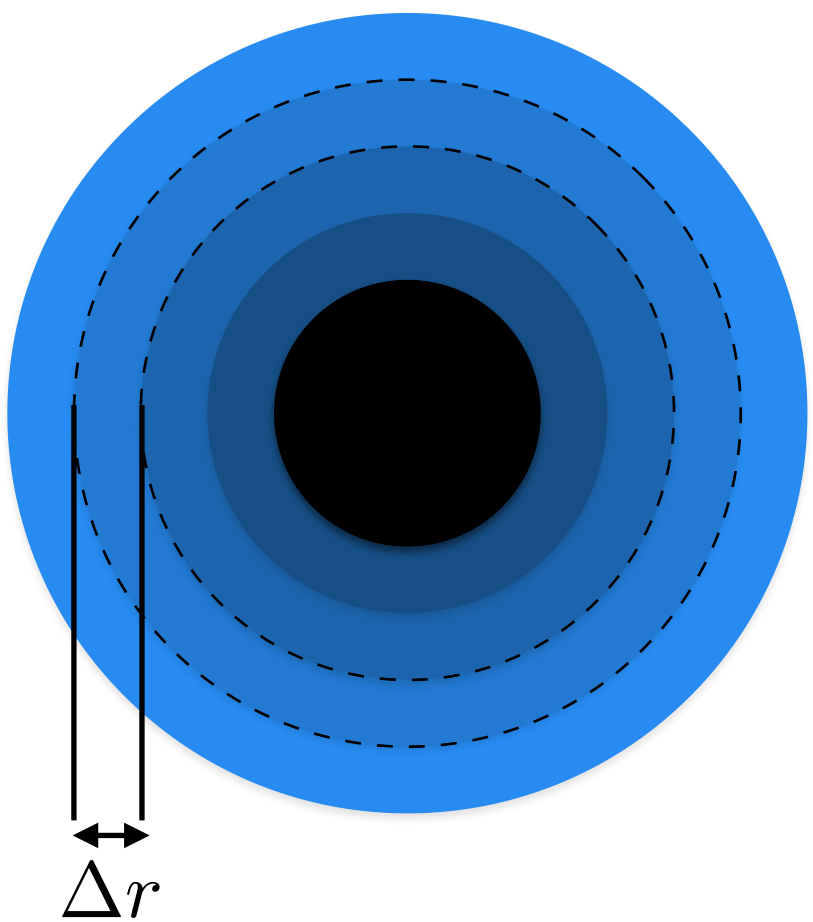


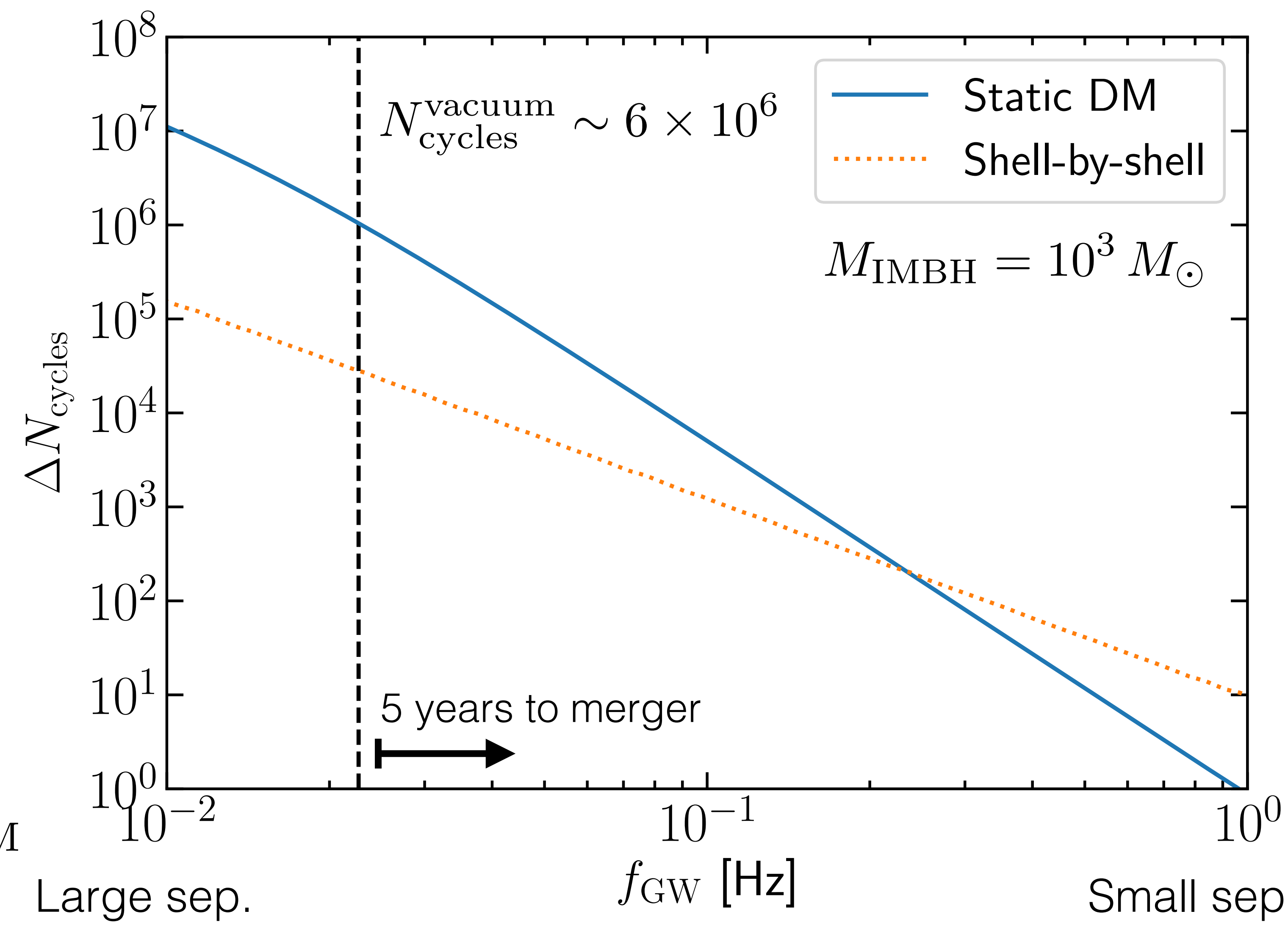
Energy Budget

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

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

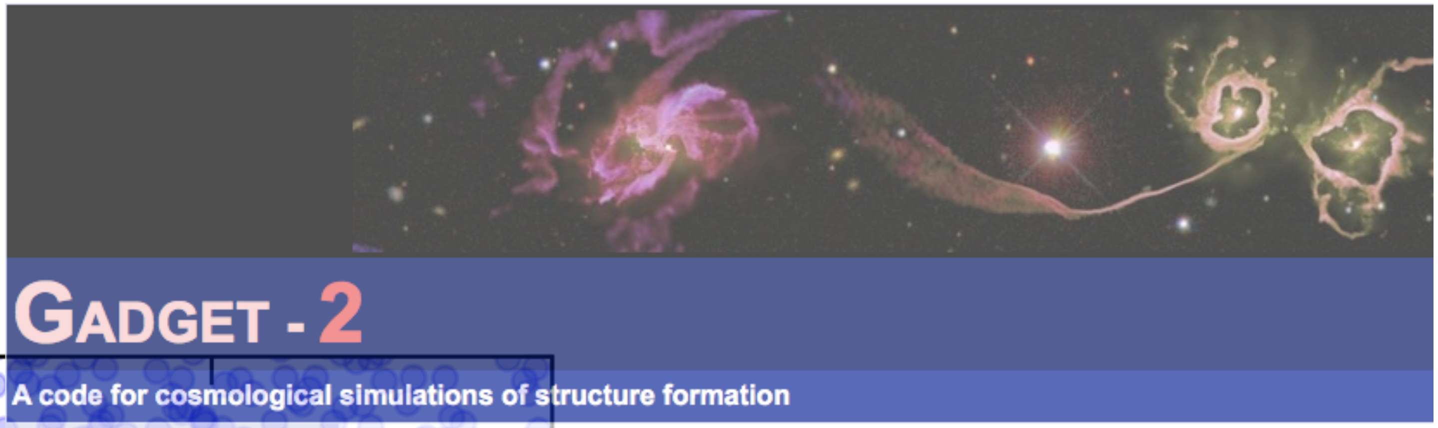
$$\dot{E}_\mathrm{DF} = \dot{r}\,\frac{\mathrm{d}U_\mathrm{DM}}{\mathrm{d}r}$$

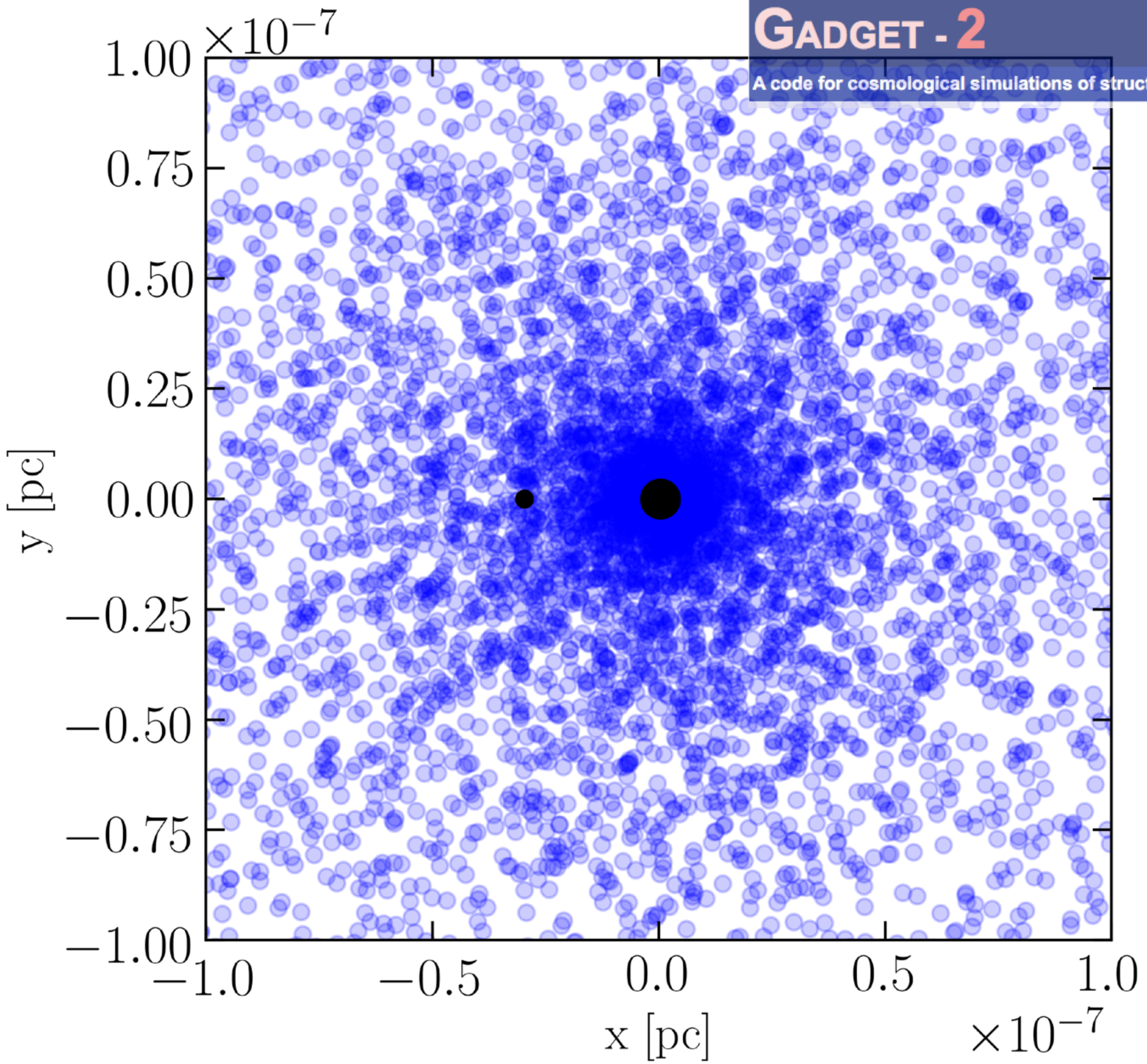




A: Binding energy of DM ΔU_DM over radius Δr

N-body Simulations





[astro-ph/0505010]

High Precision N-body Sims

Gadget-II code:

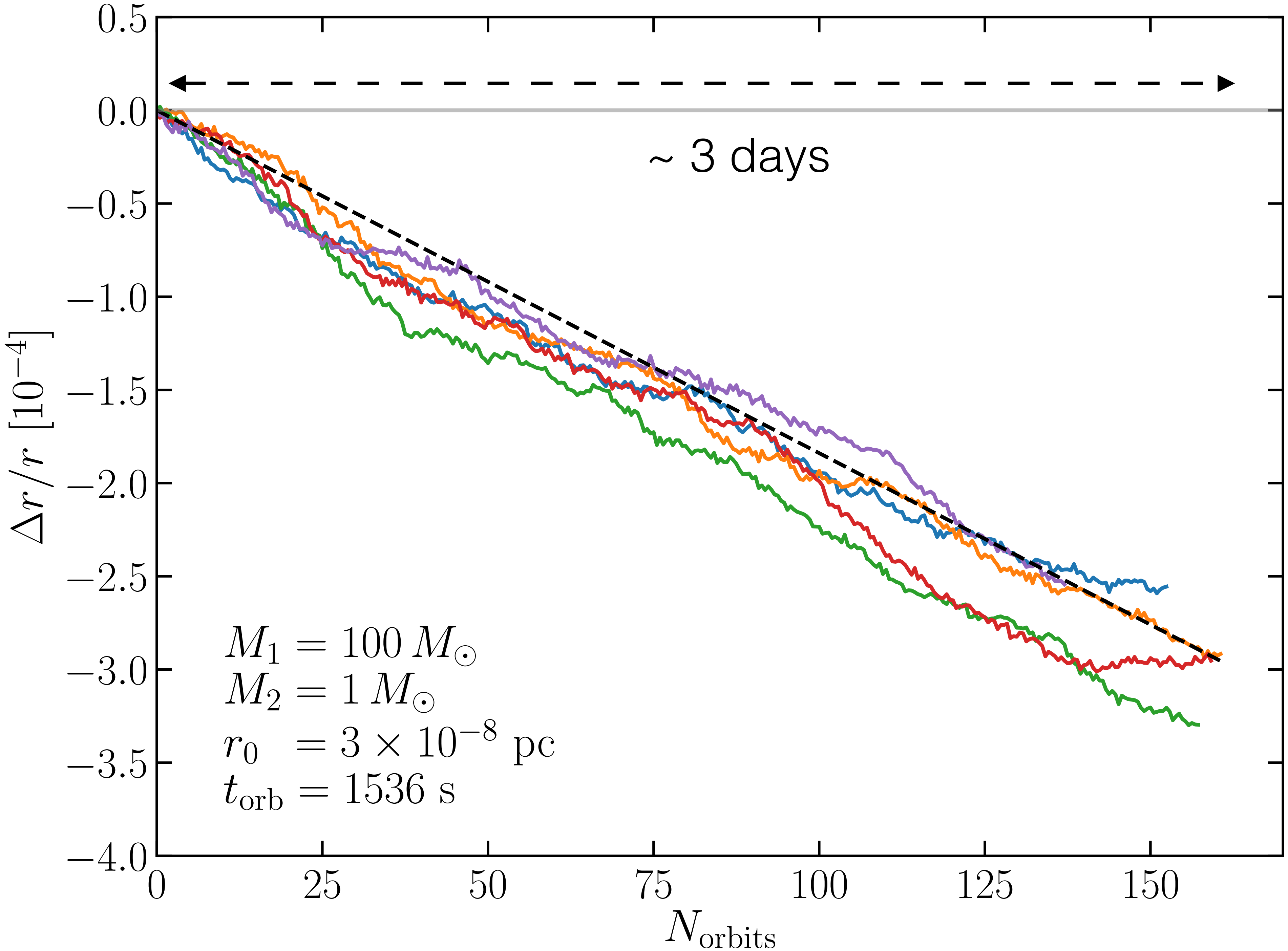
```
/* Some physical constants in cgs units */

#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:

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

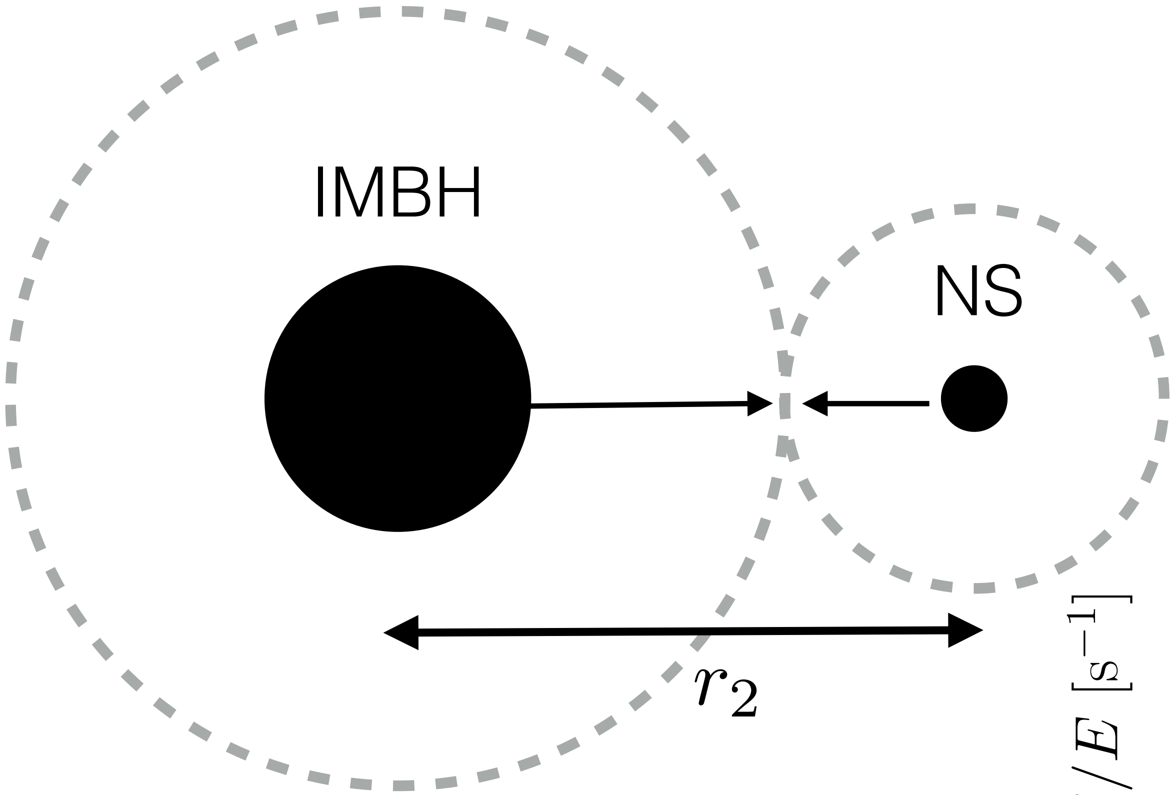
N-body Results



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

N-body results

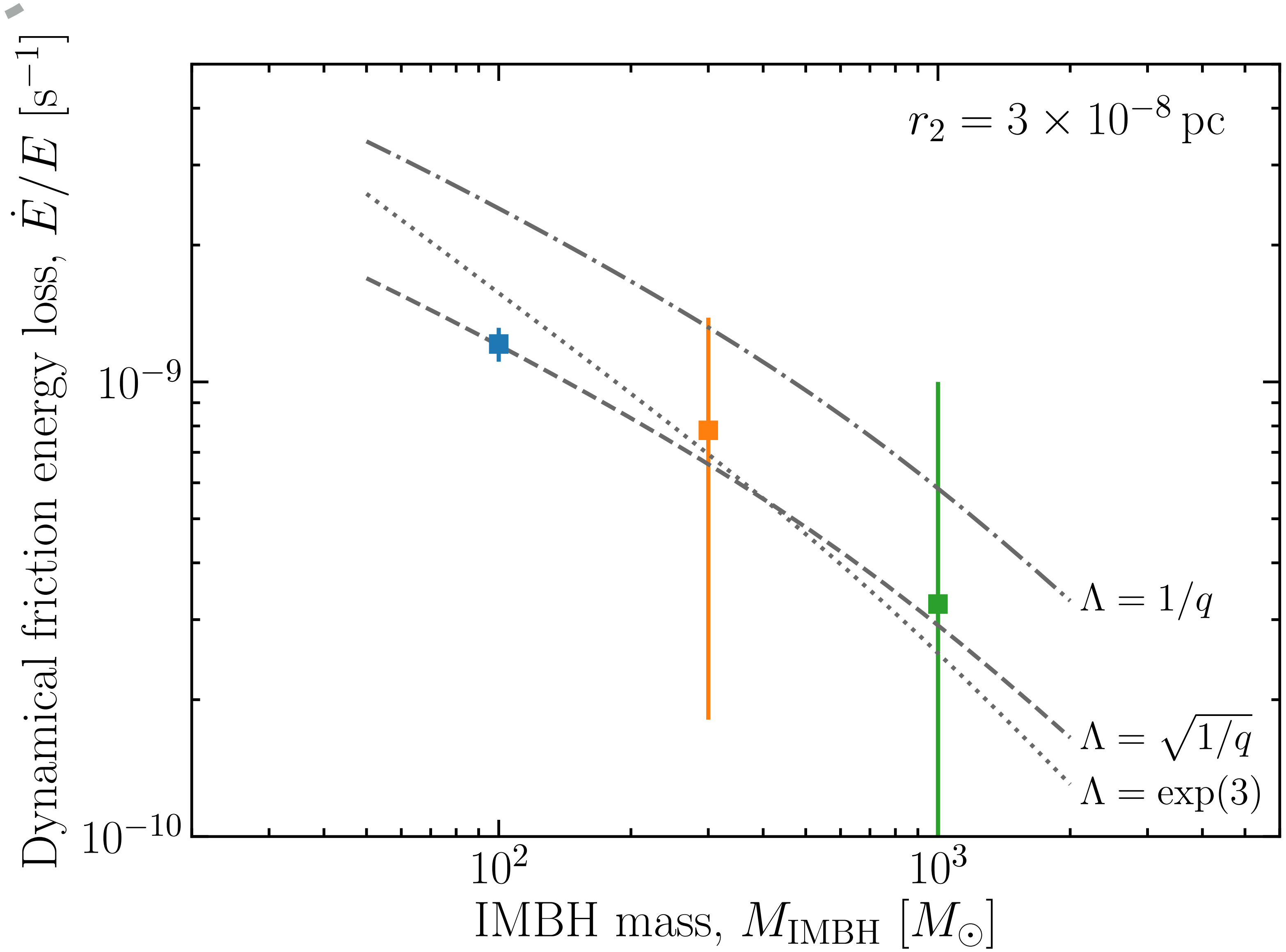
$$q \equiv m_{\mathrm{NS}}/m_{\mathrm{IMBH}} \ll 1$$



Allows us to calibrate the maximum impact parameter; tells us which particles scatter with the NS.

$$b_{\mathrm{max}} = \sqrt{q}\, r_2 \sim 3\%\, r_2$$

$$\Lambda = b_{\mathrm{max}} \frac{v_0^2}{G m_{\mathrm{NS}}} = \frac{b_{\mathrm{max}}}{q\, r_2} = 1/\sqrt{q}$$



Self-consistent evolution

Follow semi-analytically the phase space distribution of DM:

$$f = \frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{r}\,\mathrm{d}^3\mathbf{v}} \equiv f(\mathcal{E})$$

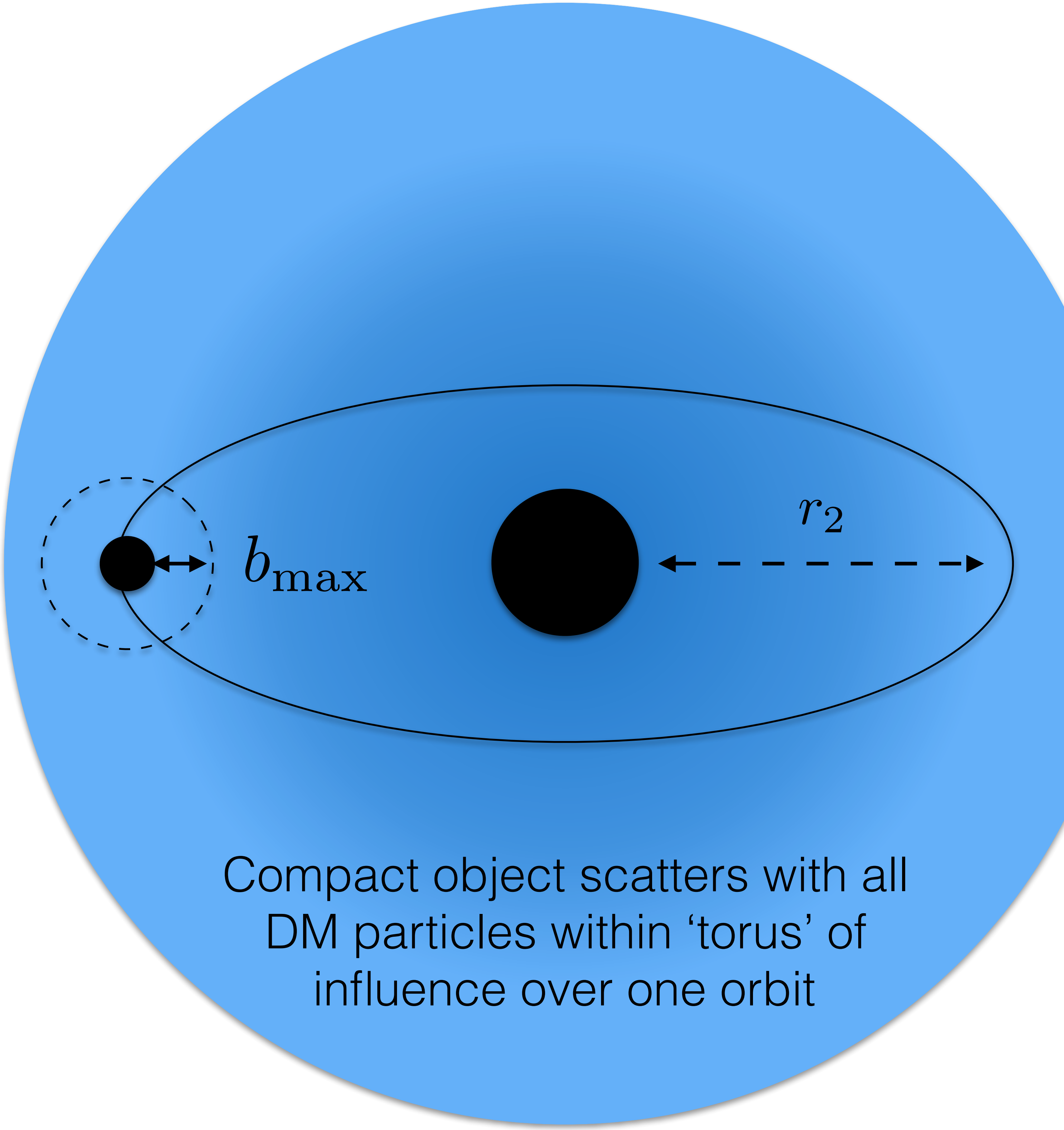
$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Each particle receives a 'kick' through gravitational scattering

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

Reconstruct density from distribution function:

$$\rho(r) = \int \mathrm{d}^3\mathbf{v} f(\mathcal{E})$$



Self-consistent evolution

Assuming everything evolves slowly compared to the orbital period:

$$T_\mathrm{orb}\frac{f(\mathcal{E})}{\mathrm{d}t} = \boxed{-f(\mathcal{E})P_s(\mathcal{E}) +}$$

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

$$\boxed{\int \left(\frac{\mathcal{E}}{\mathcal{E} - \Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E} - \Delta\mathcal{E})P_s(\mathcal{E} - \Delta\mathcal{E}, \Delta\mathcal{E})\,\mathrm{d}\Delta\mathcal{E}}$$

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

$P_s(\mathcal{E}, \Delta\mathcal{E})$ - probability for a particle with energy $\mathcal{E}$ to scatter and receive a 'kick' $\Delta\mathcal{E}$

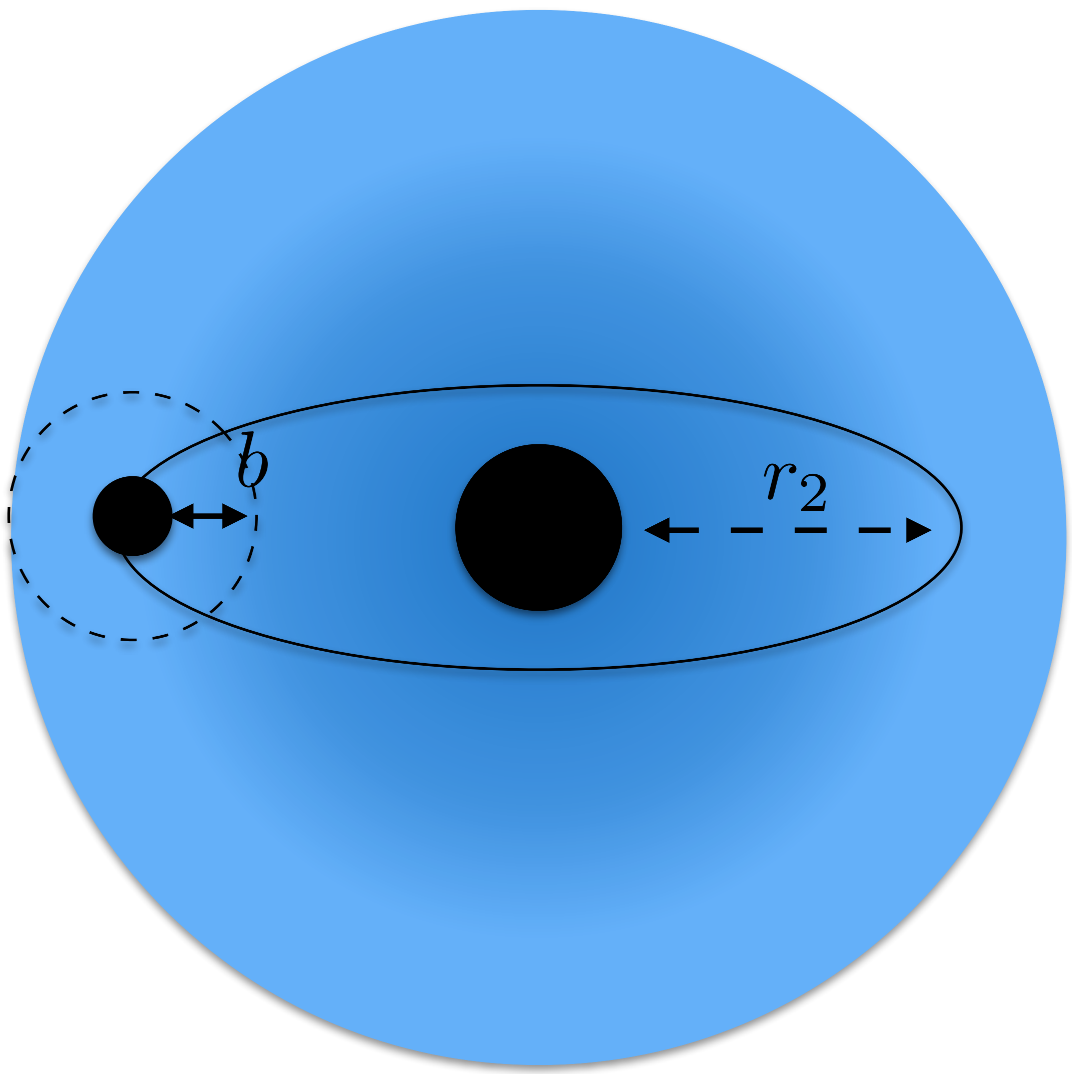
$P_s(\mathcal{E}) = \int P_s(\mathcal{E}, \Delta\mathcal{E})\,\mathrm{d}\Delta\mathcal{E}$ - total probability for a particle with energy $\mathcal{E}$ to scatter

Scattering probability

Two body scattering problem relates energy exchange to impact parameter:

$$\Delta\mathcal{E}(b) = -2v_0^2\left[1 + \frac{b^2 {v_0}^4}{G^2 {m_2}^2}\right]^{-1}$$

$$P_s(\mathcal{E}, \Delta\mathcal{E}) \propto \iint \delta\left(\mathcal{E}(r,v) - \mathcal{E}\right) \times \delta\left(\Delta\mathcal{E}(b) - \Delta\mathcal{E}\right)\, \mathrm{d}^3\mathbf{r}\, \mathrm{d}^3\mathbf{v}$$



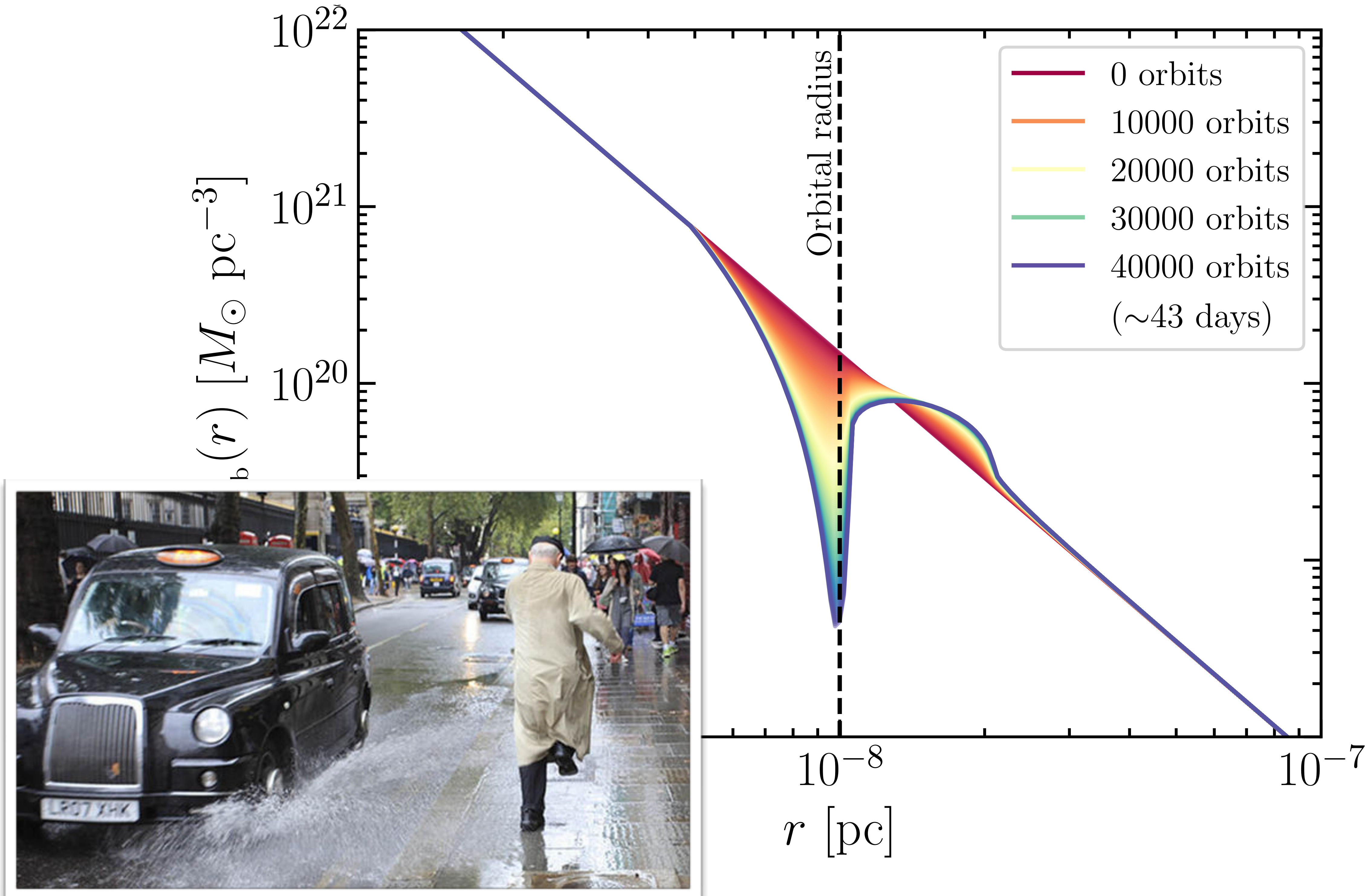
Integrate over the surface of the 'torus of influence'

Working to first order in b/r, the result can be written in terms of elliptic integrals

Code available online:
github.com/bradkav/HaloFeedback

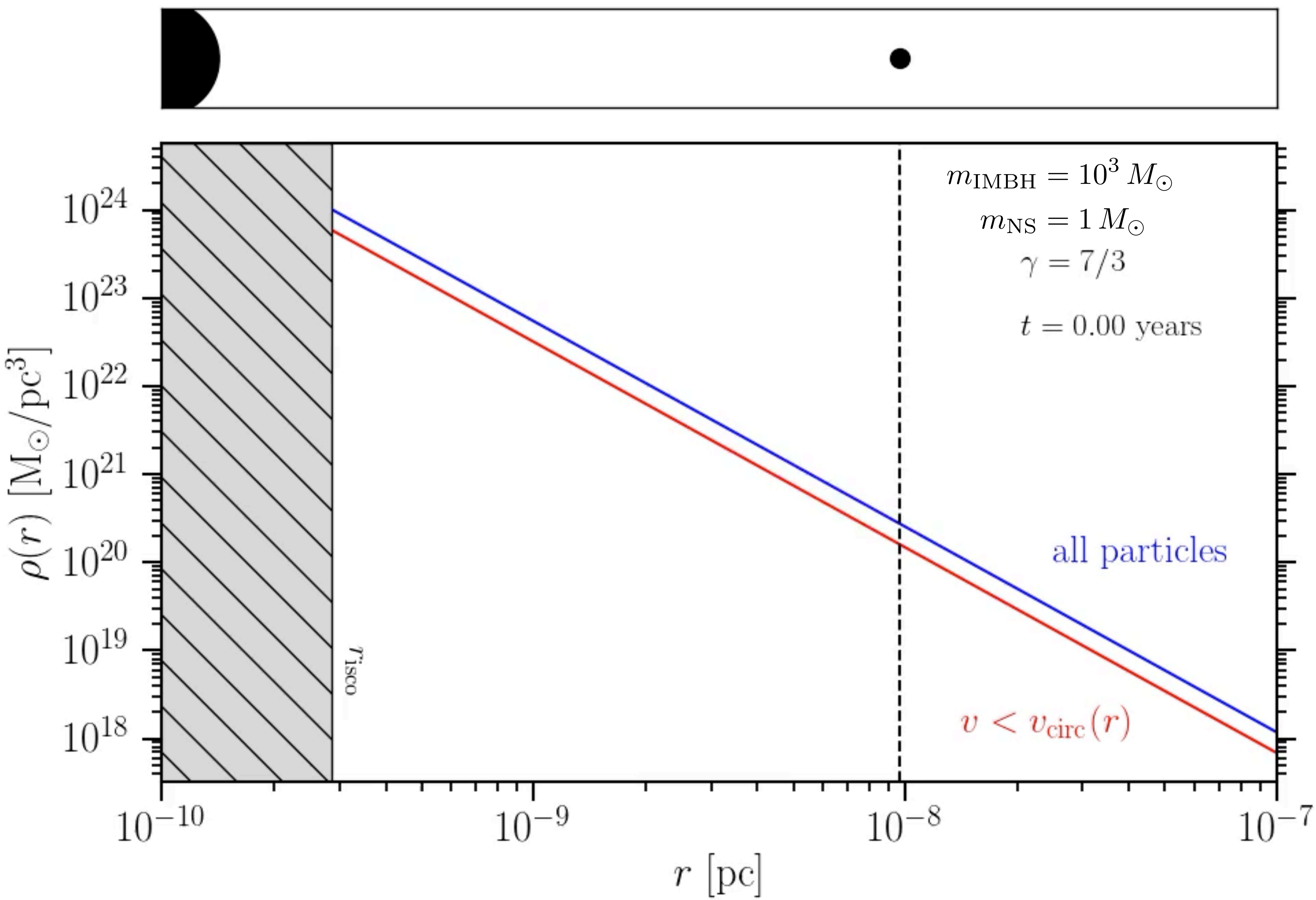
Evolution of density profile

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

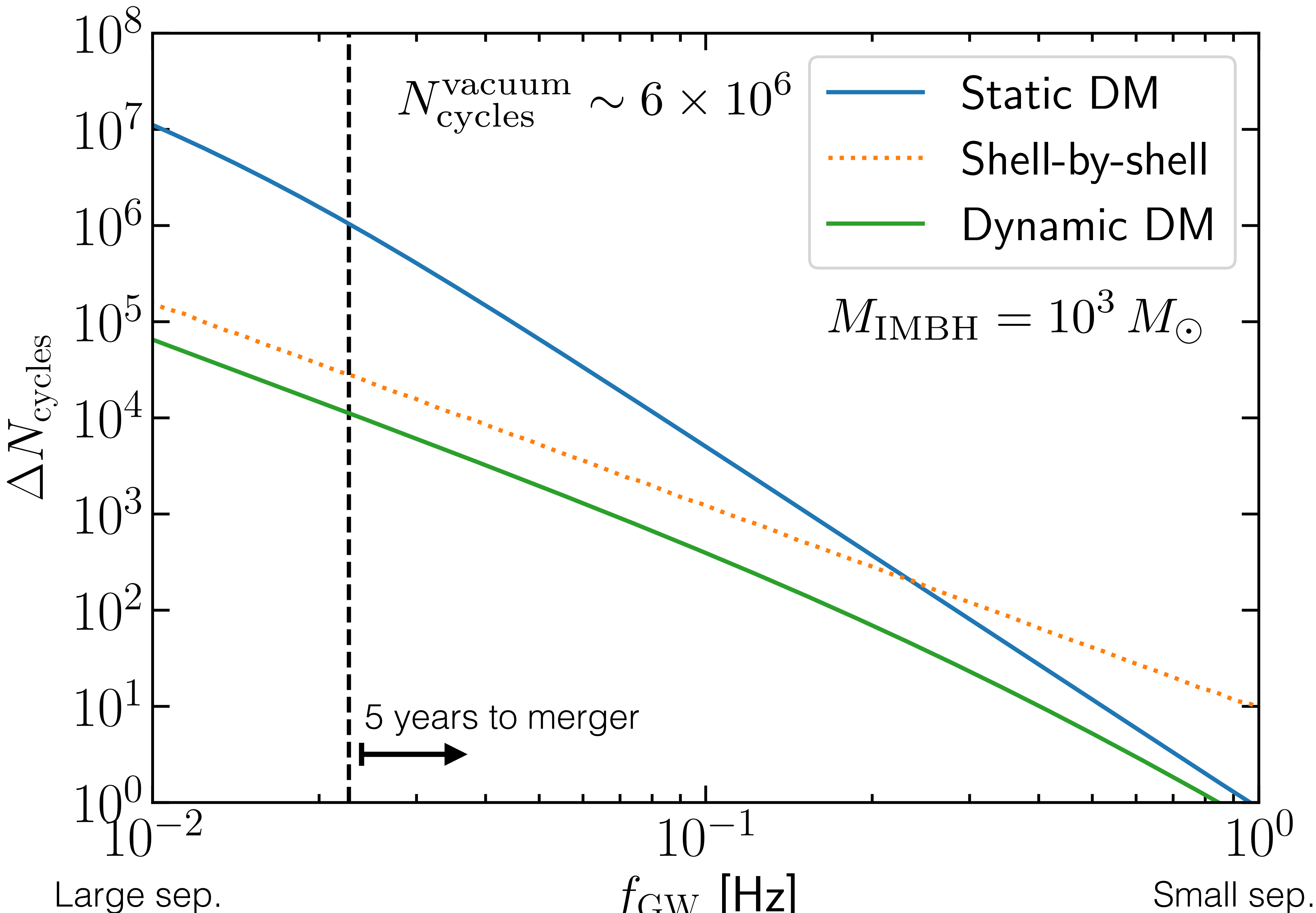


Subtlety: plotting here only ‘slow moving’ particles

Full evolution of the system



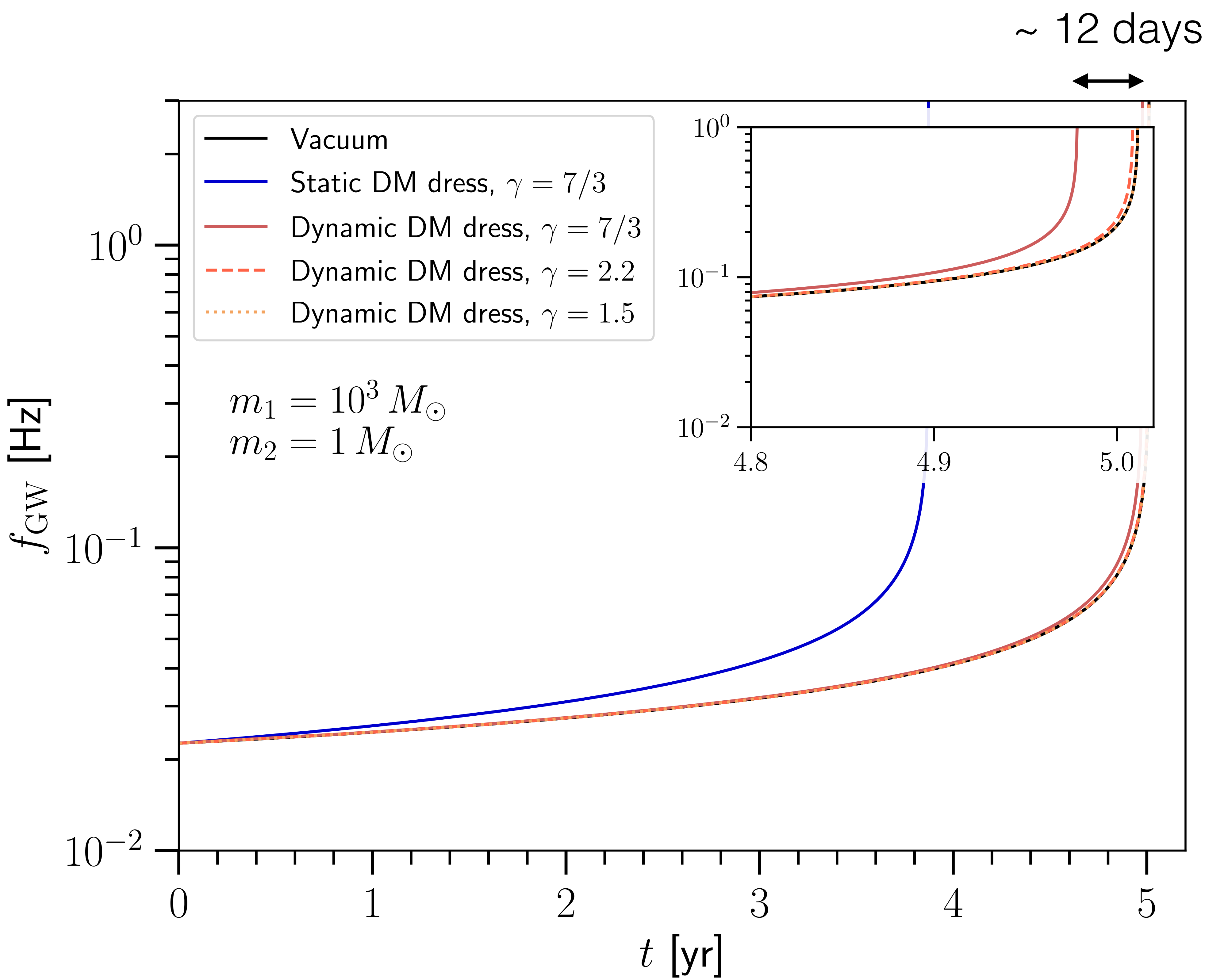
Self-consistent results



$$\Delta N_{\rm cycles}(\text{static}) \approx 10^6 \;\rightarrow\; \Delta N_{\rm cycles}(\text{dynamic}) \approx 10^4$$

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

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

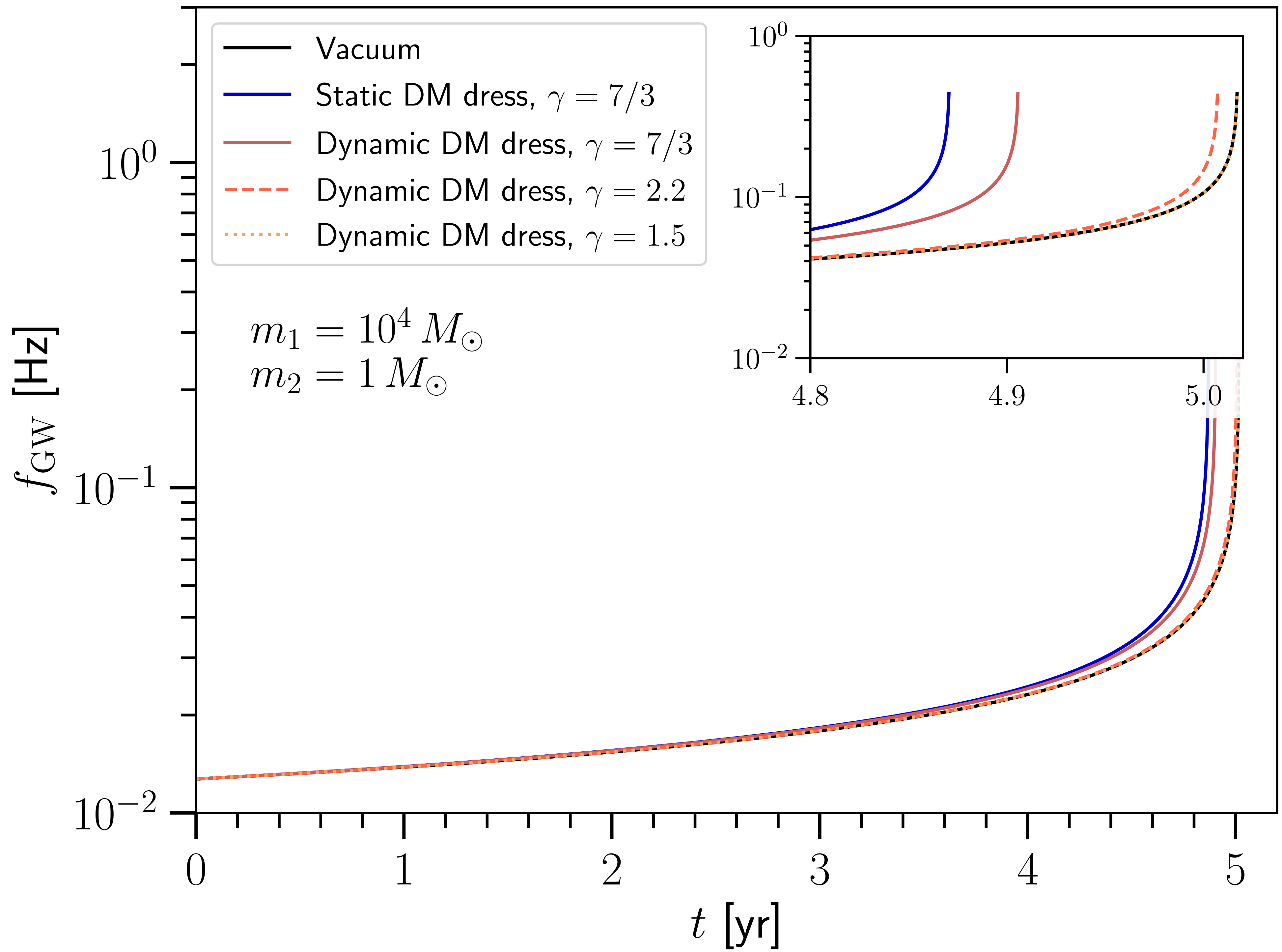


NB: $7/3 \approx 2.333$

Spectrograms: $m_{\rm IMBH} = 10^4\,M_\odot$

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

As we increase the IMBH mass, the correction from having a dynamic DM halo decreases (but can still be very relevant)



NB: $7/3 \approx 2.333$

Detectability

$$\Delta N_{\mathrm{cycles}}(\mathrm{static}) \approx 10^6 \;\rightarrow\; \Delta N_{\mathrm{cycles}}(\mathrm{dynamic}) \approx 10^4$$

In many systems, a more realistic treatment leads to a huge reduction in the size of the 'de-phasing' effect.

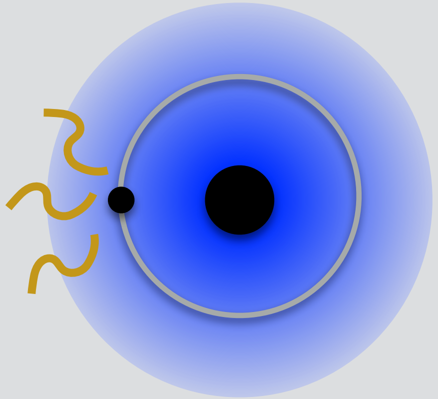
For a 1000 solar mass IMBH, a de-phasing of 10,000 cycles could still be detectable.

Even for very massive BHs, small corrections can spoil our ability to find the signal in data (so they must be accounted for)

In future, aim to assess in detail parameter reconstruction and model discrimination (*what can we learn?*)

GW + EM signals of
QCD axion Dark Matter

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



QCD Axion Dark Matter

[Slide credit: Marco Chianese]

QCD Lagrangian could have a large CP violating term:

$$\mathcal{L}_{\rm QCD} \supset -\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \theta_{\rm QCD}$$

But non-observation of neutron dipole moment implies $|\theta| \leq 10^{-10}$

Why is θ so small?

Solve dynamically, by promoting θ to a scalar field with a global U(1) symmetry

$$\theta_{\rm QCD} \to \theta_{\rm QCD}(x) = \frac{a(x)}{f_a} \quad \longrightarrow \quad \theta = \frac{\langle a \rangle}{f_a} \sim 0 \quad \text{at } f_a \gg 10^7 \, \text{GeV}$$

[Peccei & Quinn, 1977]

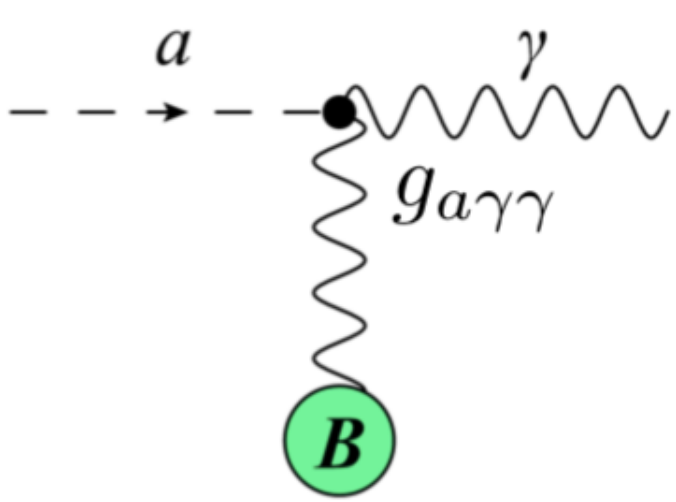
The resulting light goldstone boson - the QCD axion *a* - can be produced with the correct DM relic abundance, e.g. through vacuum misalignment

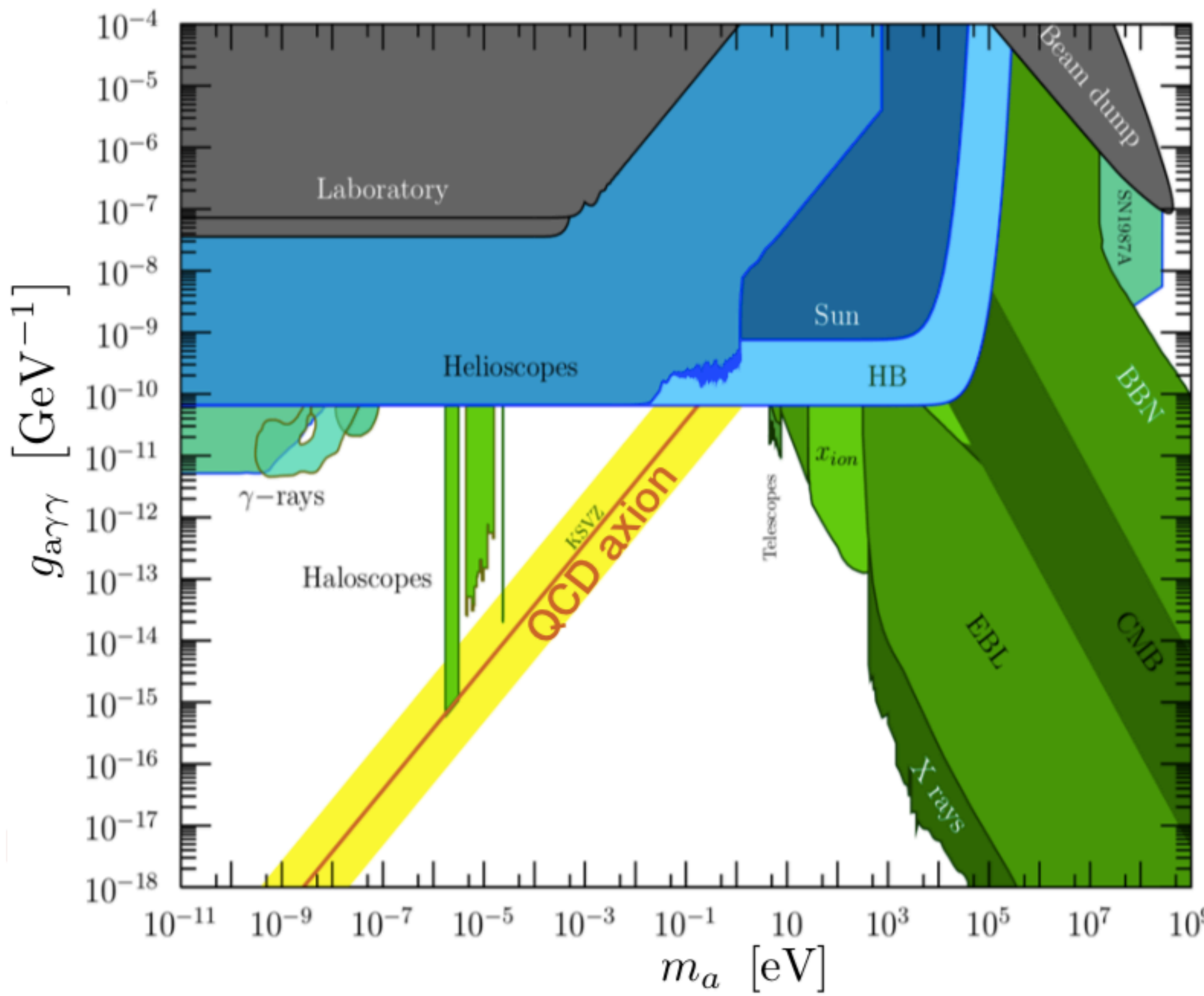
[1510.07633]

Axion-photon Conversion

Axions can convert to photons (and vice versa) in an external magnetic field:

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$= -\frac{1}{4} g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$





[Irastorza & Redondo, https://arxiv.org/abs/1801.08127]

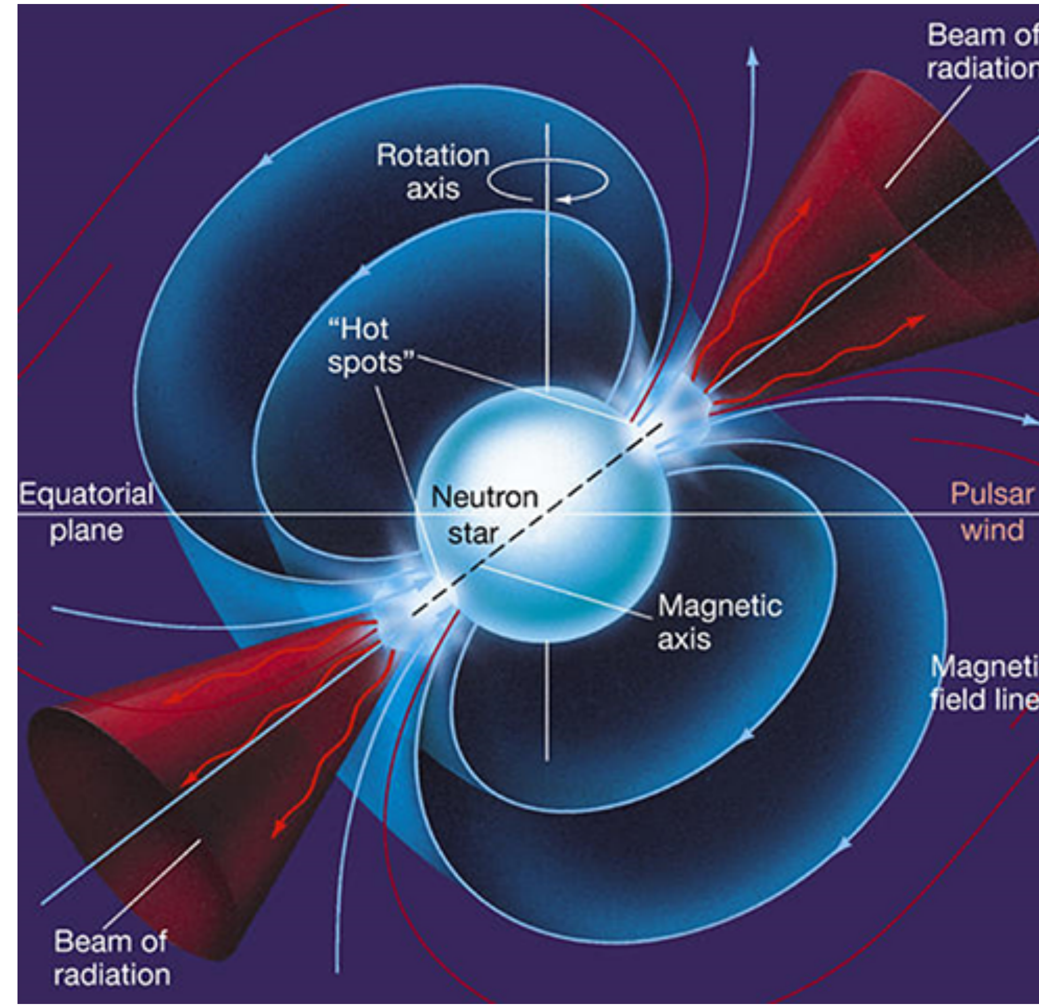
Axions and neutron stars

Old neutron stars can have extremely high magnetic fields:

$$B_0 = 10^{12} - 10^{15}\, G$$

Surrounded by a dense plasma which allows 'resonant' conversion when axion mass matches plasma mass:

$$\omega_p\,(B_0, P) = m_a/2\pi$$



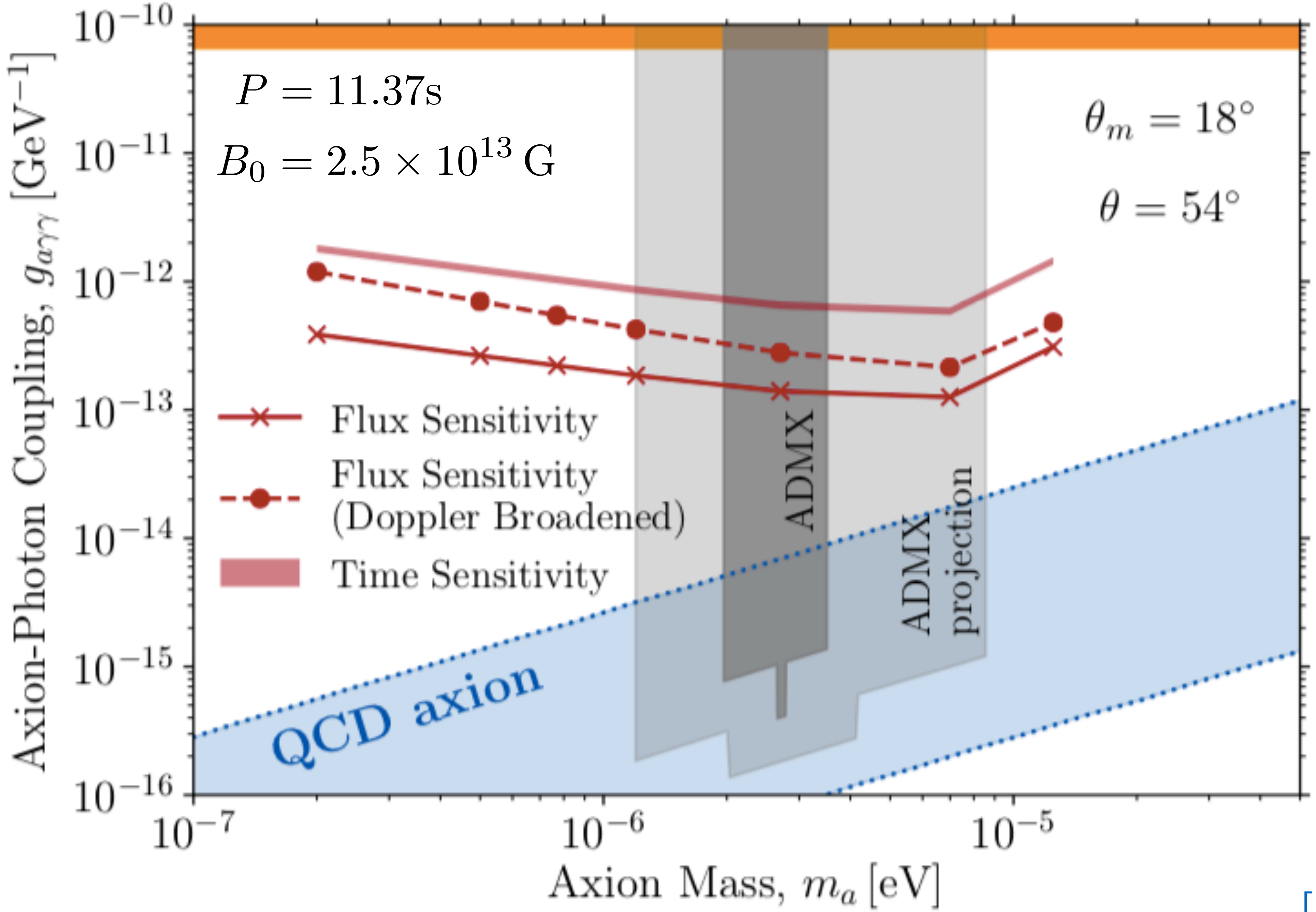
Magnetic field and plasma frequency varies as a function of radius from NS; NS can effectively 'scan' over a range of axion masses.

For conversion radius r_c , radiated power is: $$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega} \sim 2 \times p_{a\gamma}\rho_{\mathrm{DM}}\,(r_c)\, v_c r_c^2$$

[1803.08230, 1804.03145, 1811.01020, 1910.11907]

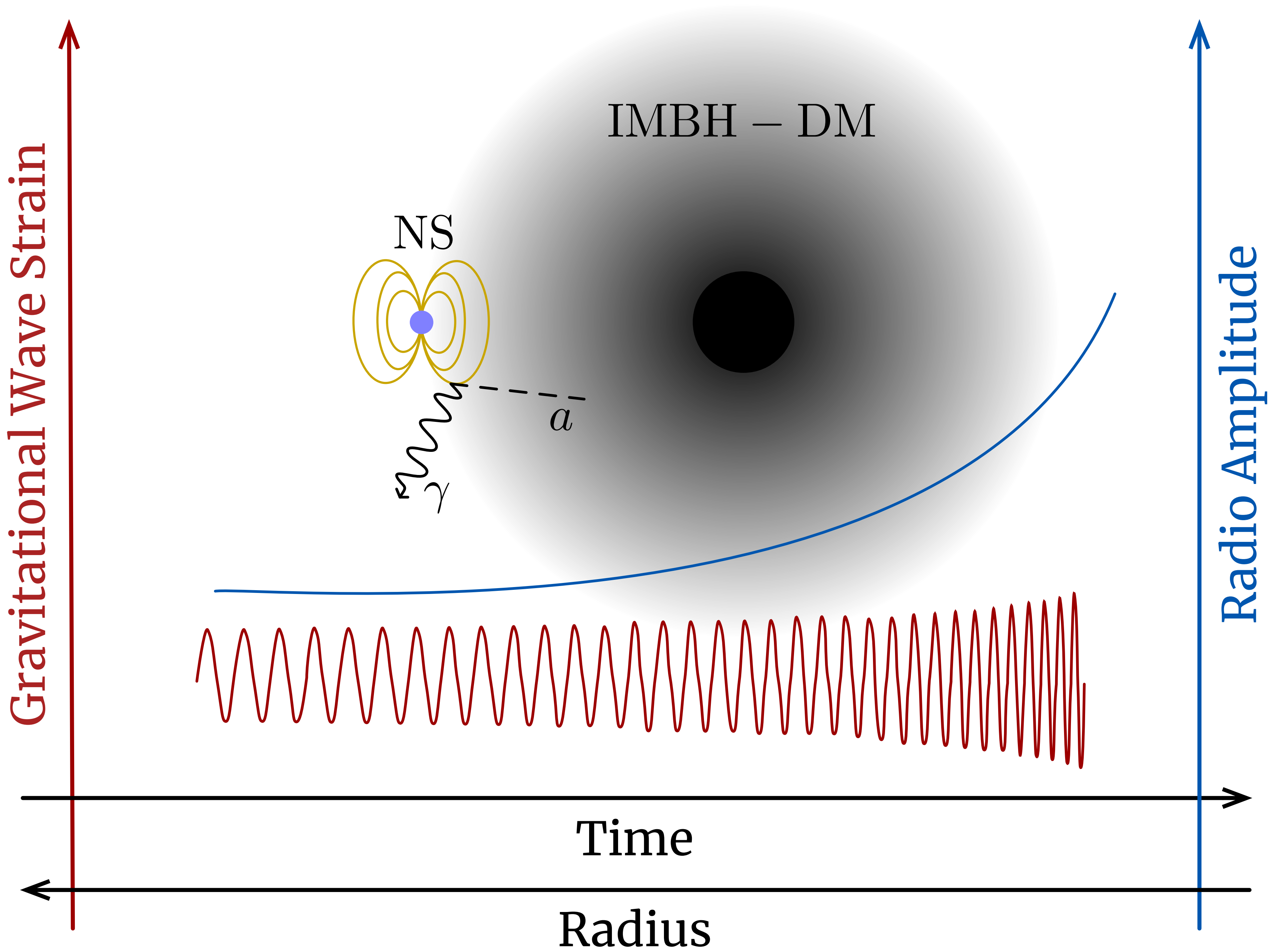
Axion coupling sensitivity

Consider a single isolated NS (J0806.4-412).
How strong does the coupling have to be to give a detectable radio signal in SKA?



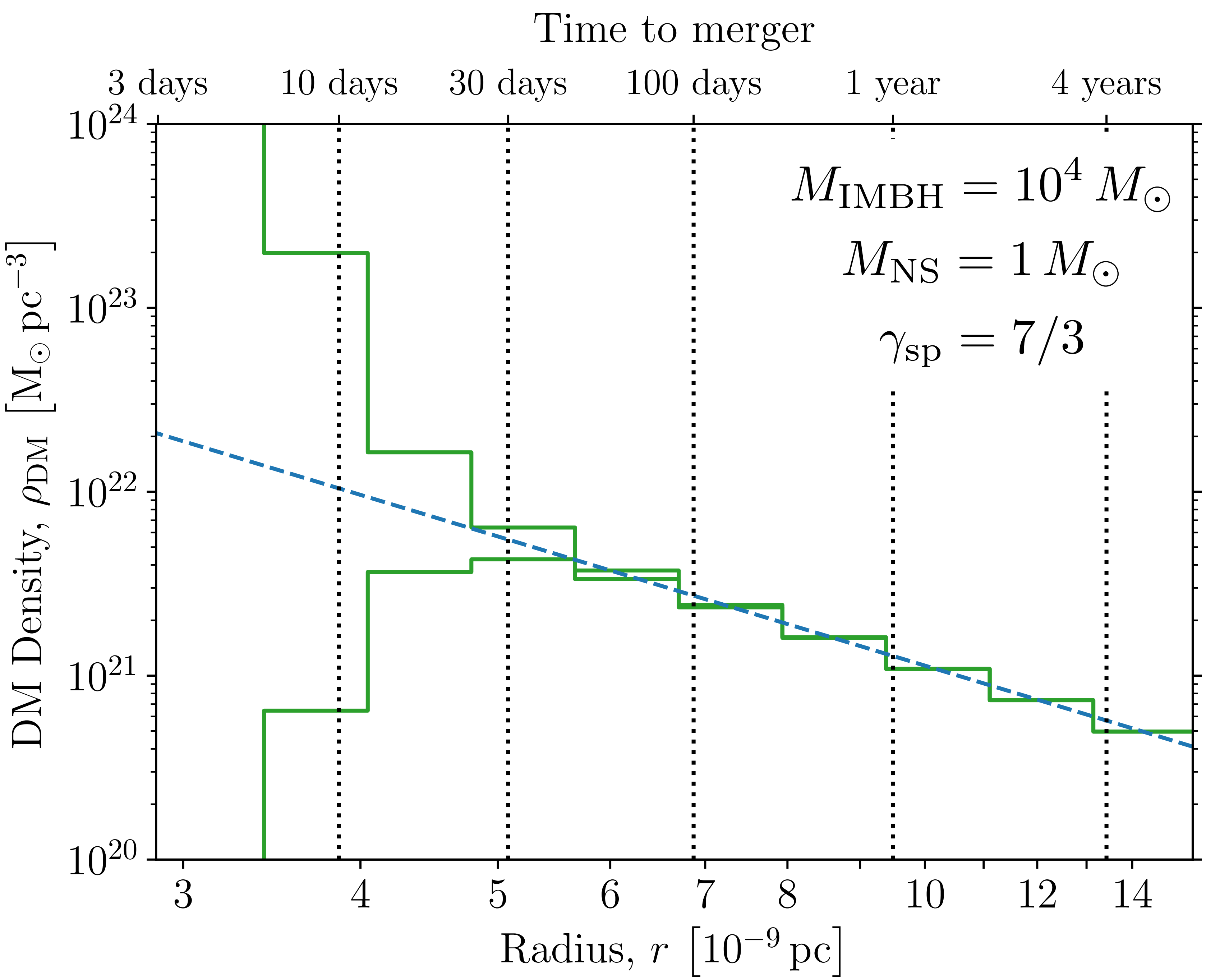
[1912.08815]

A unique signature



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

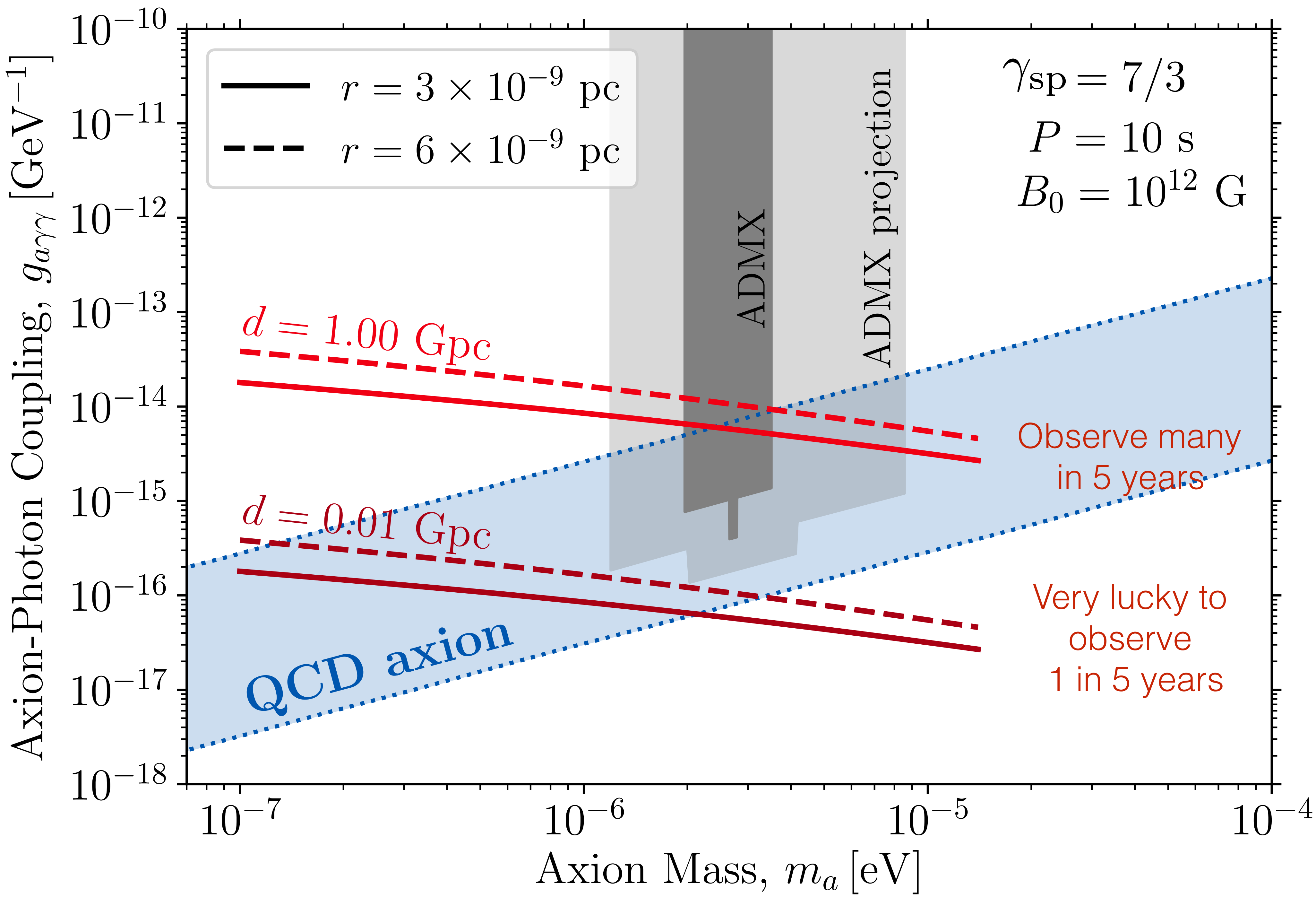
Density reconstruction



$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega} \sim 2 \times p_{a\gamma}\rho_{\rm DM}\left(r_c\right) v_c r_c^2$$

QCD Axion Reach

SKA should be able to probe QCD axion DM in the range 10^{-7} - 10^{-5} eV.



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

Promising Signal

Dark Matter de-phasing is a very exciting signal. It's on long timescales (with LISA planned for 2030s), but it would allow us to:

Detect Dark Matter in Gravitational waves
[1301.5971, 1909.05870]

Probe the nature of Dark Matter
[1906.11845]

Predict EM signals from Dark Matter
[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

But it can be very difficult to extract from the noise, and must be modelled very carefully…

Plans for the future

More detailed modelling in the future:

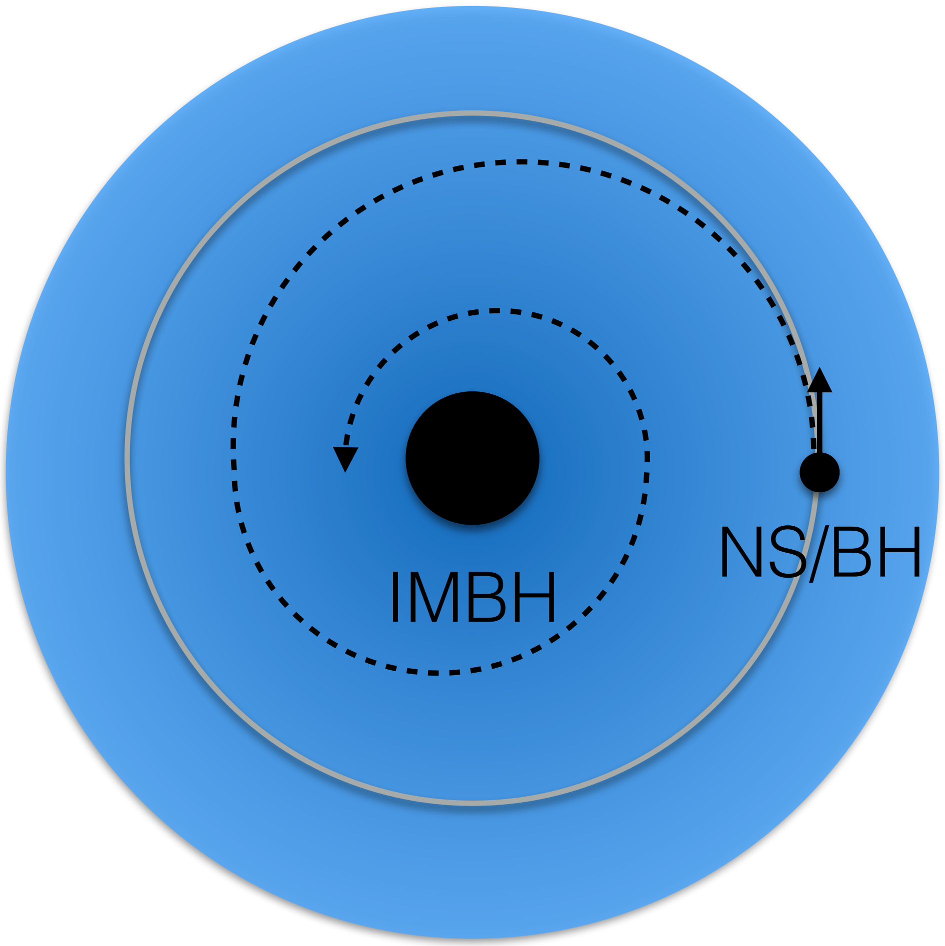
- Injection and evolution of angular momentum in the DM halo
- Post-Newtonian corrections
- Generating waveforms from orbital evolution

Pursuing both analytic & N-body approaches [Starlab?]

Ultimately aim to generate template banks for use with LISA searches

At the same time, address the prospects for detection: how many of these systems form? How many have a DM spike? How do these spikes form and evolve (and do they survive until today)?

Conclusions



Dark Matter 'de-phasing' is an extremely promising GW signature, which needs to be **modelled carefully**

For light IMBHs, the **correction due to DM halo feedback** can be huge!

More calculations are needed to build template banks, assess detectability and parameter reconstruction

This work could pave the way towards detecting Dark Matter almost **independent of its particle physics properties**

Thank you!

Backup Slides

Parameter Reconstruction

Prospects for parameter reconstruction in the *static DM* case:

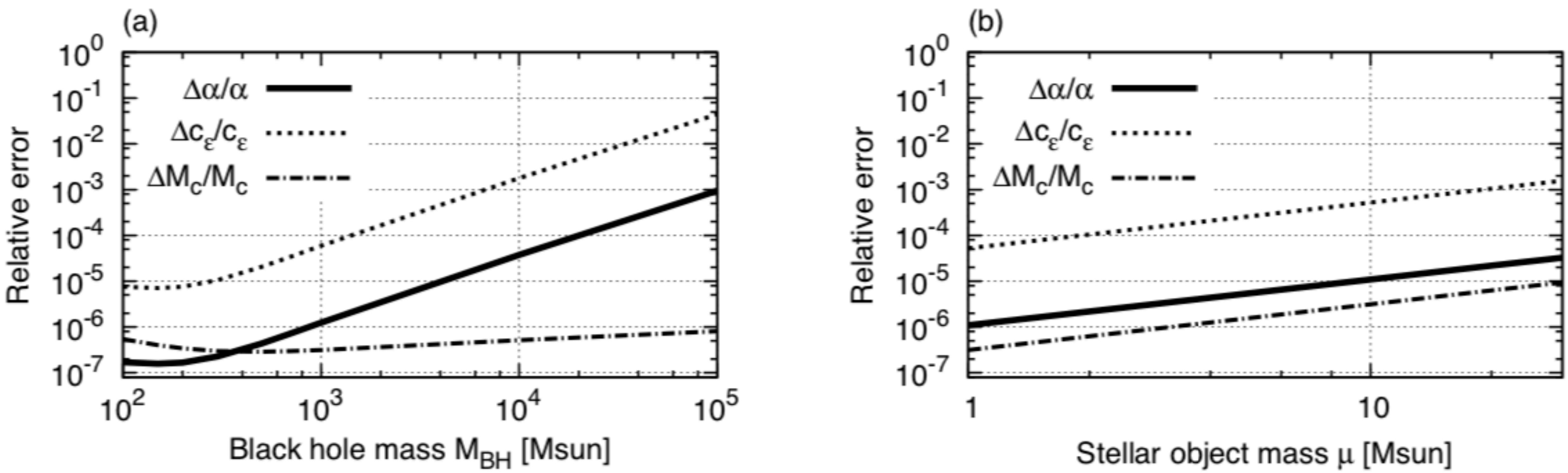


FIG. 4: The relative errors of the parameters in the phase $\tilde{\Phi}(f)$ versus (a) the central BH mass $M_{\rm BH}$ and (b) the stellar mass object mass μ for $S/N = 10$ and $\alpha = 7/3$. For this plot, $\rho_{\rm sp}$ and $r_{\rm sp}$ are taken from the table I. The other parameter is fixed to be $\mu = 1 M_\odot$ in the left and $M_{\rm BH} = 10^3 M_\odot$ in the right, respectively. Note that the both axes are in the logarithmic scales. The solid line, the dashed line, the dashed-dotted line correspond to $\Delta\alpha/\alpha, \Delta c_\varepsilon/c_\varepsilon, \Delta M_c/M_c$ respectively.

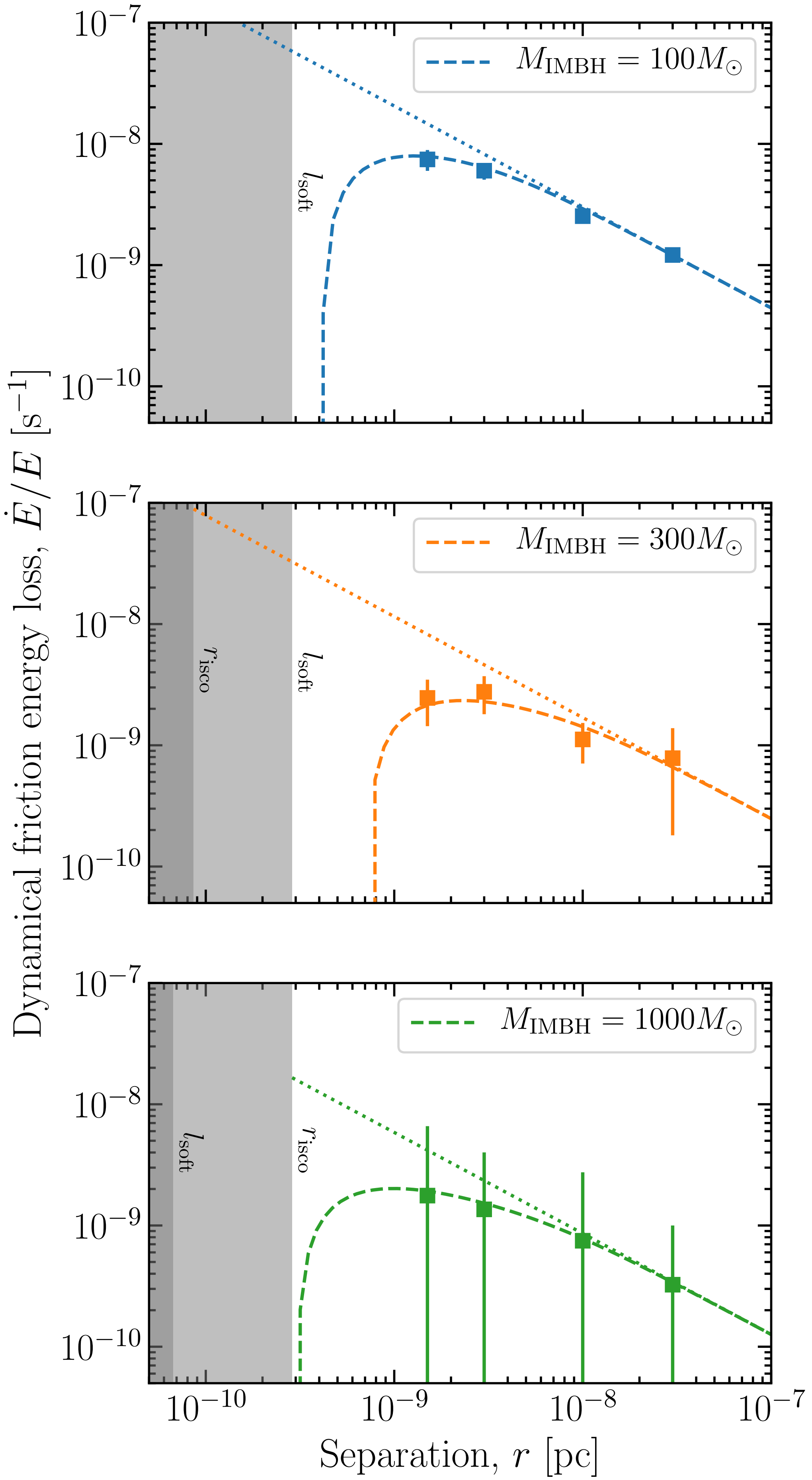
[Eda et al. 1301.5971, 1408.3534]

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



Assumptions

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

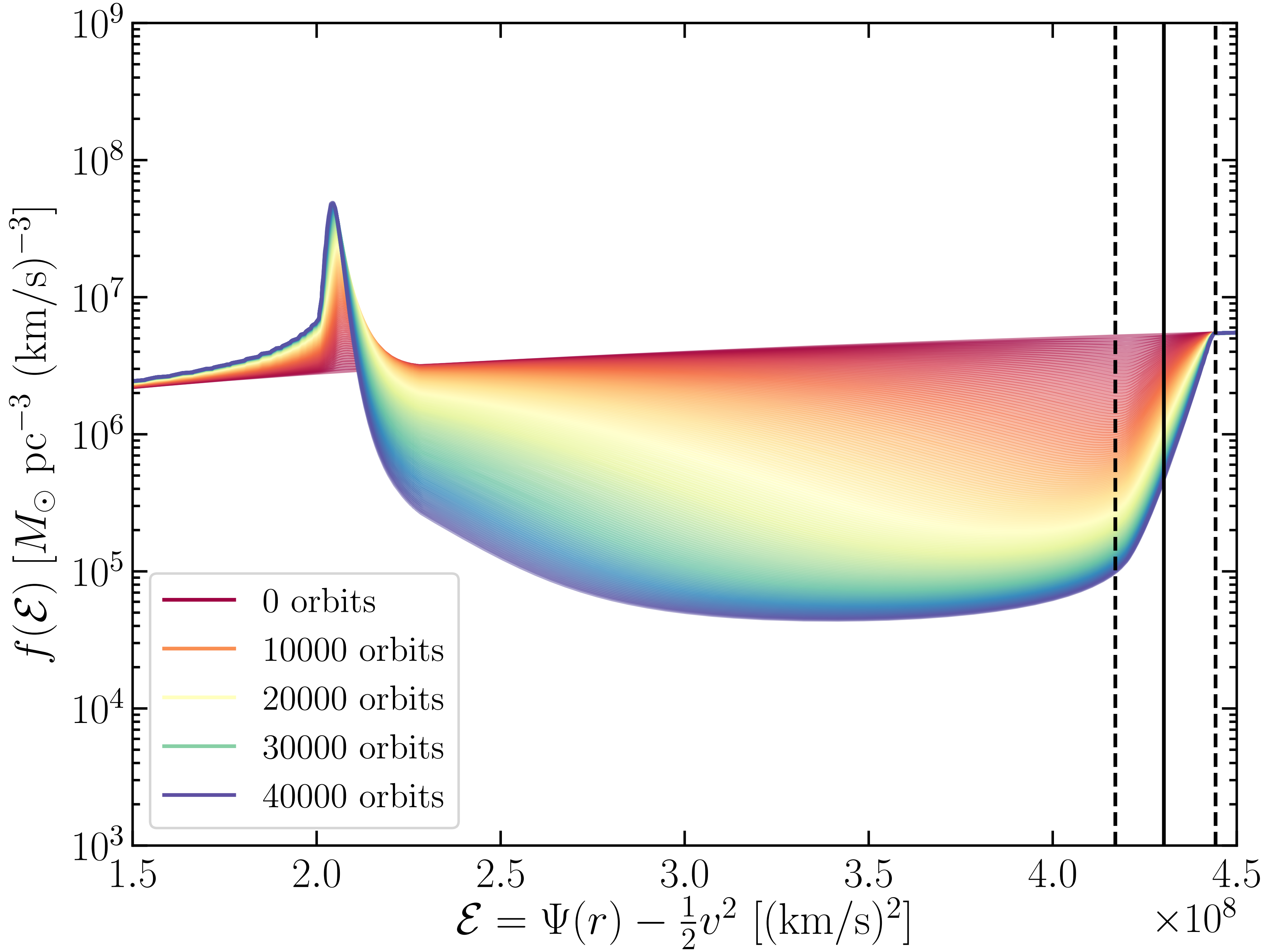
$$b < b_{\mathrm{max}} = \Lambda \times G_N M_{\mathrm{NS}} / v_{\mathrm{NS}}^2$$

- DM distribution is 'locally' uniform

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

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

Distribution function



Self-consistently reconstruct density from distribution function:

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

Numbers of cycles

$m_1 = 10^3\, M_\odot$, $N_{\rm cycles} = 5.71 \times 10^6$ in vacuum

$\Delta N_{\rm cycles}$	$\gamma = 1.5$	$\gamma = 2.2$	$\gamma = 2.3$	$\gamma = 7/3$
Static	< 1	1.1×10^5	6.4×10^5	1.0×10^6
Dynamic	< 1	8.8×10^2	6.0×10^3	1.1×10^4

$m_1 = 10^4\, M_\odot$, $N_{\rm cycles} = 3.20 \times 10^6$ in vacuum

$\Delta N_{\rm cycles}$	$\gamma = 1.5$	$\gamma = 2.2$	$\gamma = 2.3$	$\gamma = 7/3$
Static	< 1	6.7×10^3	4.1×10^4	7.4×10^4
Dynamic	< 1	2.5×10^3	1.6×10^4	2.9×10^4

TABLE I. **Change in the number of cycles during the inspiral.** Change in the total number of GW cycles (over