Detecting, Discovering and Measuring Dark Matter around Black Holes with Gravitational Waves

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Instituto de Física de Cantabria

EXCELENCIA MARÍA DE MAEZTU

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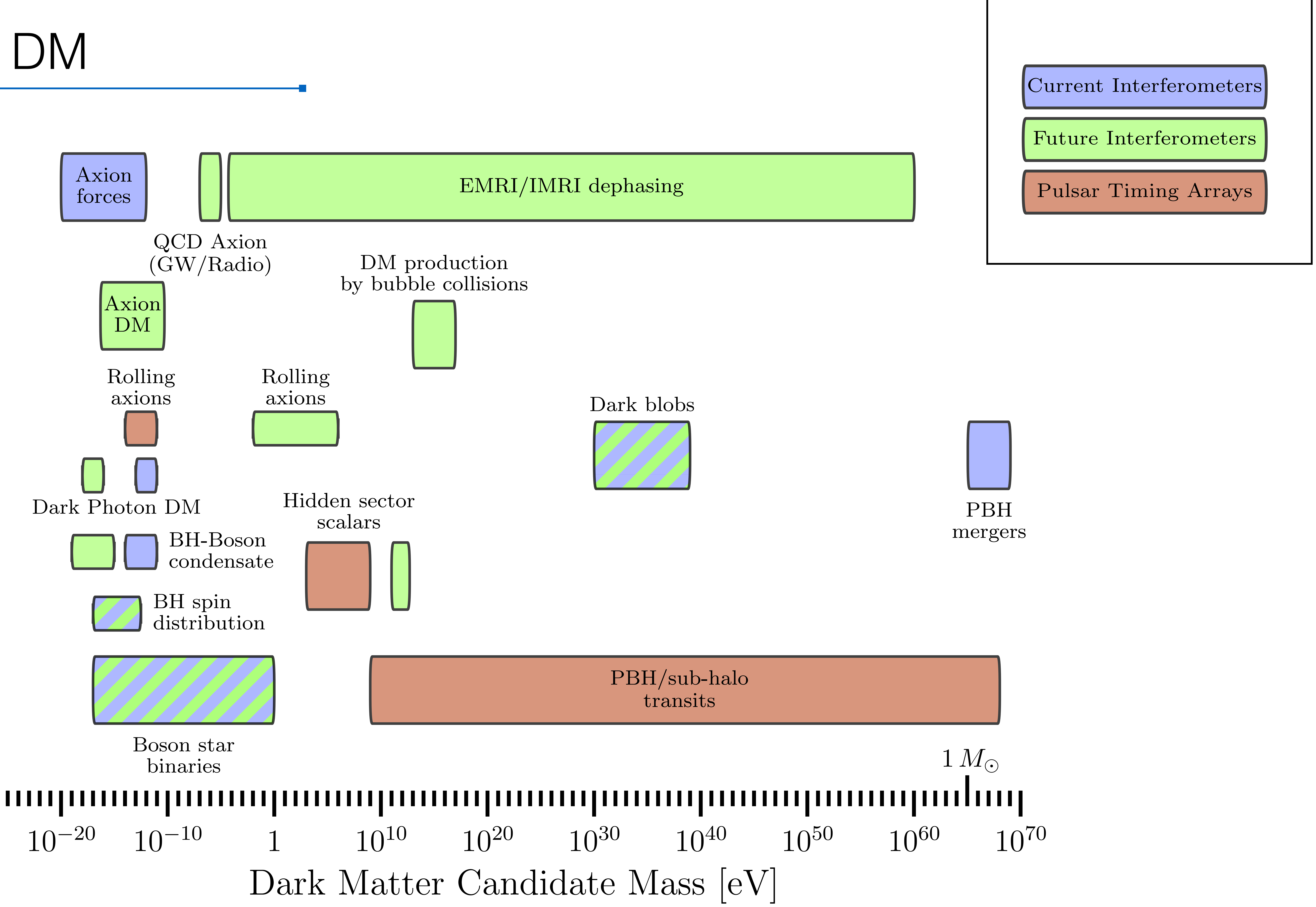
GW probes of DM



[Bertone, Croon, et al (including **BJK**), 1907.10610]

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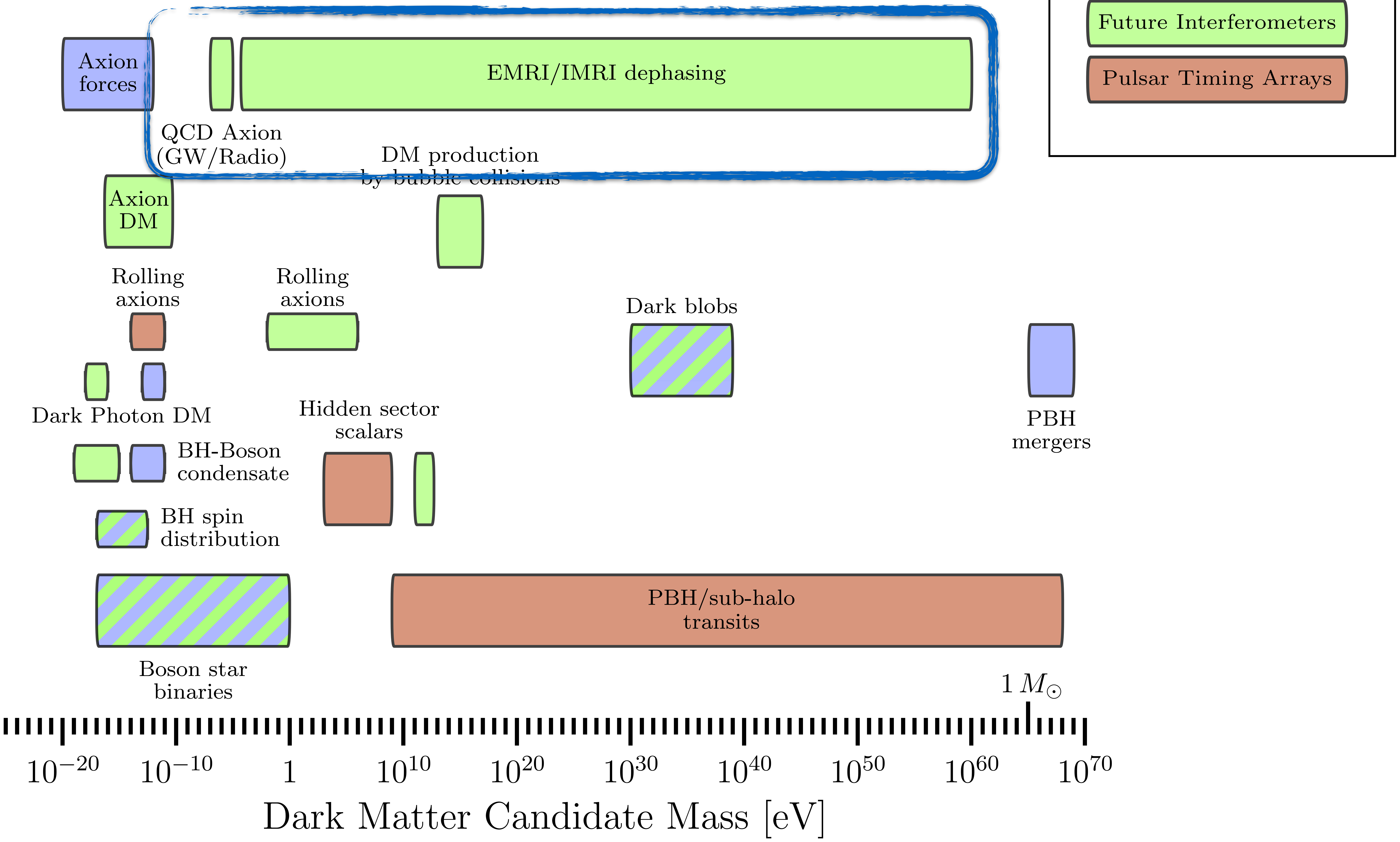
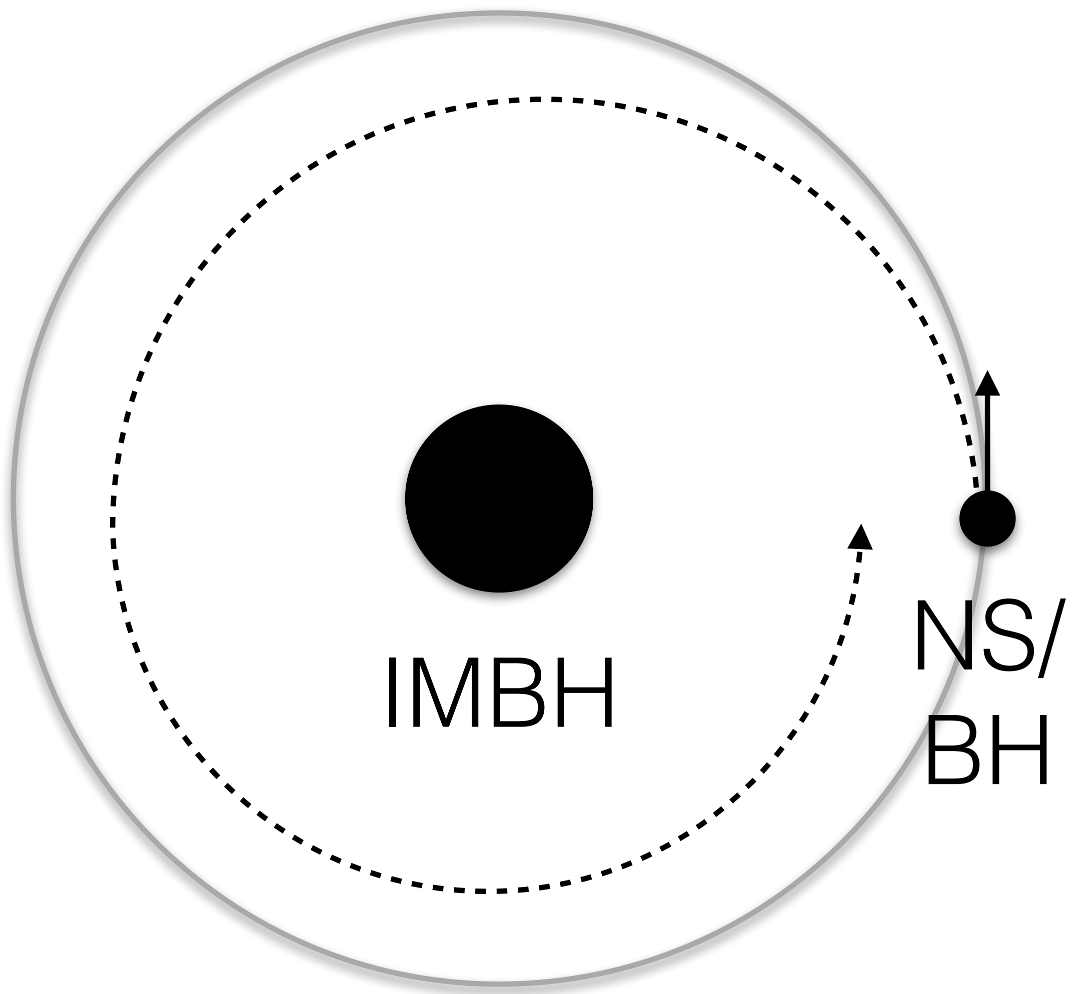


[Bertone, Croon, et al (including **BJK**), 1907.10610]

Intermediate Mass Ratio Inspiral (IMRI)



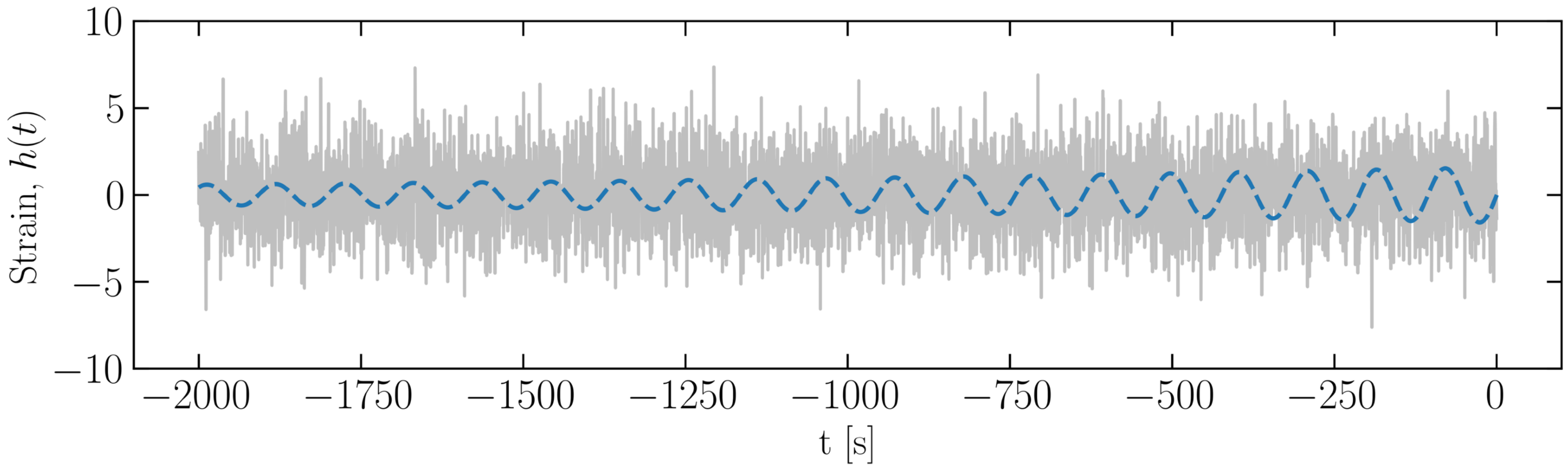
Stellar mass compact object (NS/BH) inspirals towards intermediate mass black hole (IMBH)

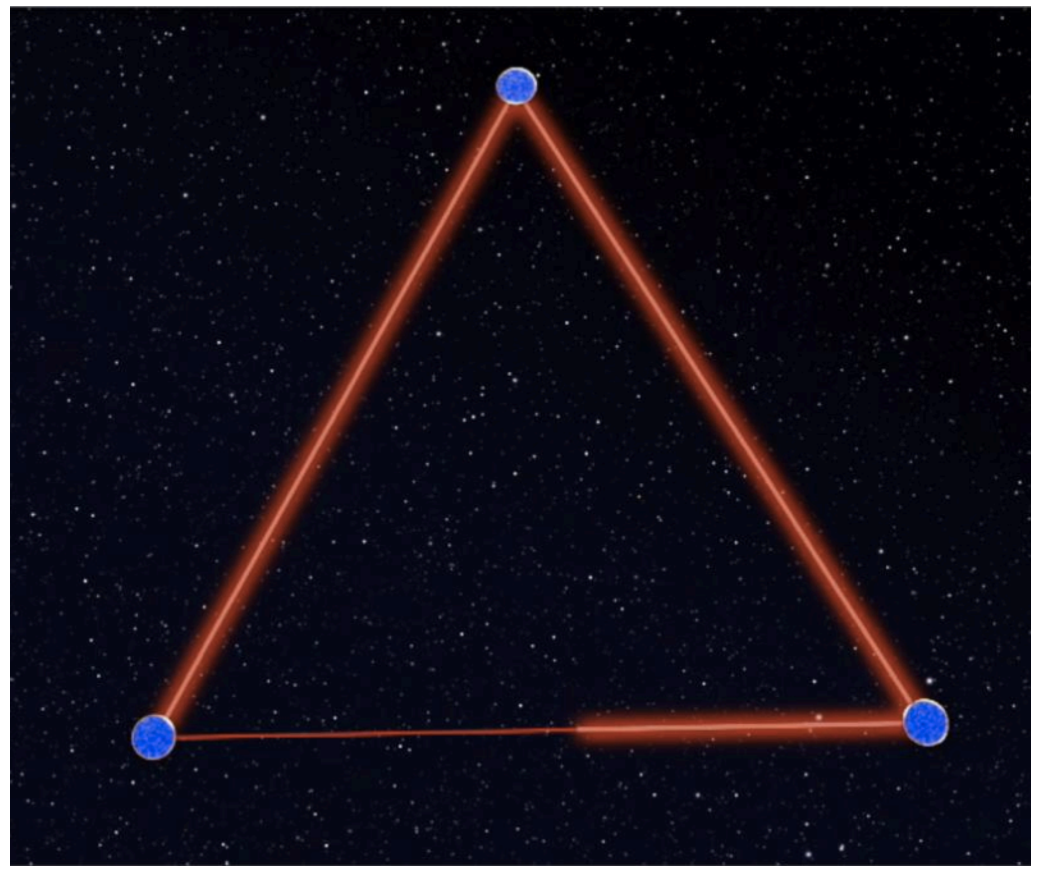
$$M_{\rm IMBH} \sim 10^3 - 10^5\, M_\odot$$

GW emission causes long, slow inspiral:

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

Until the innermost stable circular orbit: $f_{\rm ISCO} = 0.44 \left(\frac{10^4\, M_\odot}{M_1}\right)\,\mathrm{Hz}$ → Detectable at LISA frequencies: $f_{\rm GW} \sim 10^{-2} - 1\,\mathrm{Hz}$

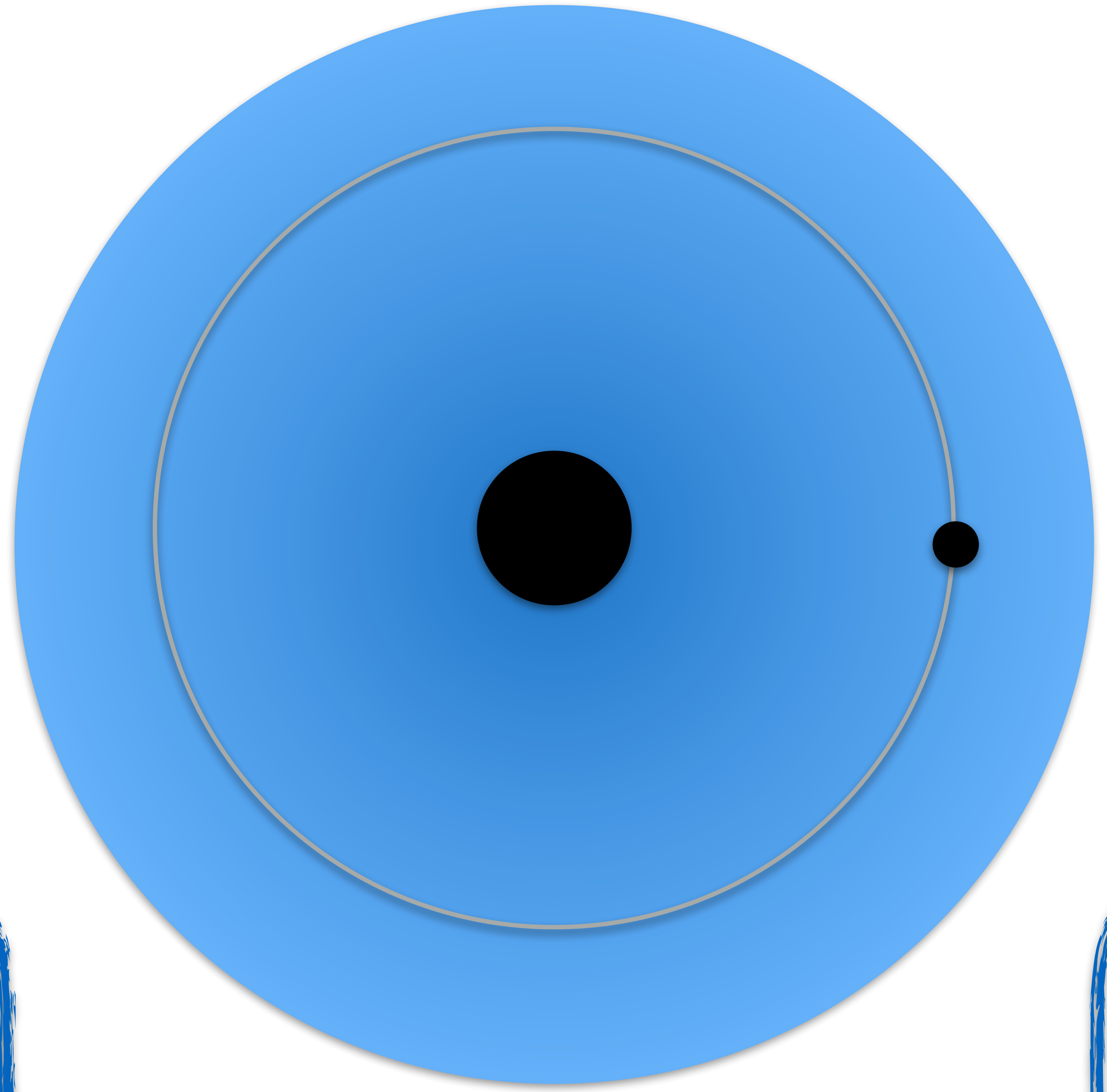




[1702.00786]

Dark Matter Spikes

Consider now a cold **DM** '**spike**' or '**dress**' around the central BH (not to be confused with ultralight boson clouds).



Study the following benchmarks:

$$m_1 = 10^3\, M_\odot$$
$$m_2 = 1\, M_\odot$$
$$\rho_{\rm DM} = \rho_6 \left(\frac{10^{-6}\,\mathrm{pc}}{r}\right)^{\gamma_{\rm sp}}$$

Astrophysical scenario

$$\gamma_{\rm sp} = 7/3 \approx 2.3333\ldots$$
$$\rho_6 \approx 5.45 \times 10^{15}\, M_\odot\, \mathrm{pc}^{-3}$$

…depending on a number of environmental factors…

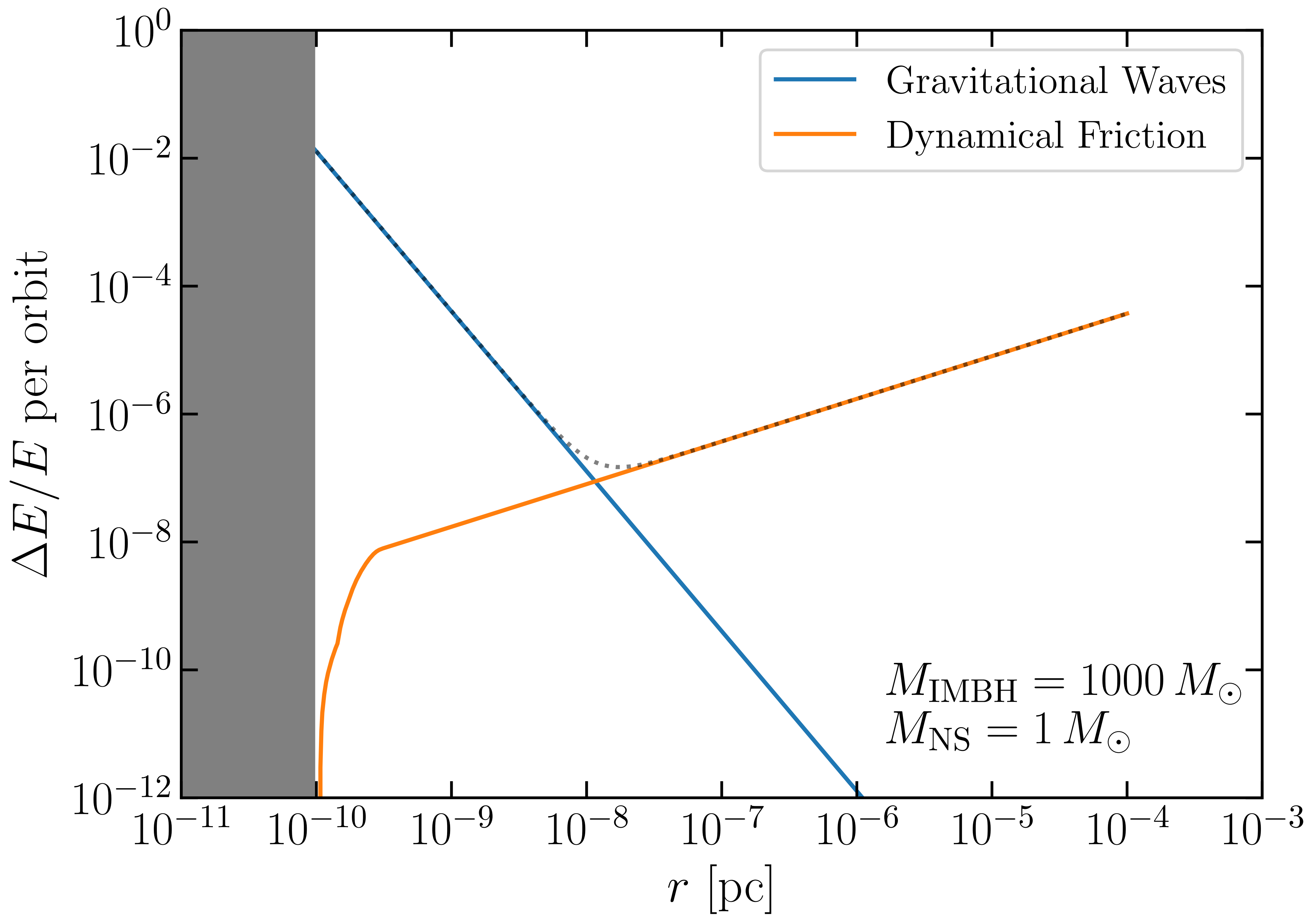
[astro-ph/9906391, astro-ph/0509565, 1305.2619, …]

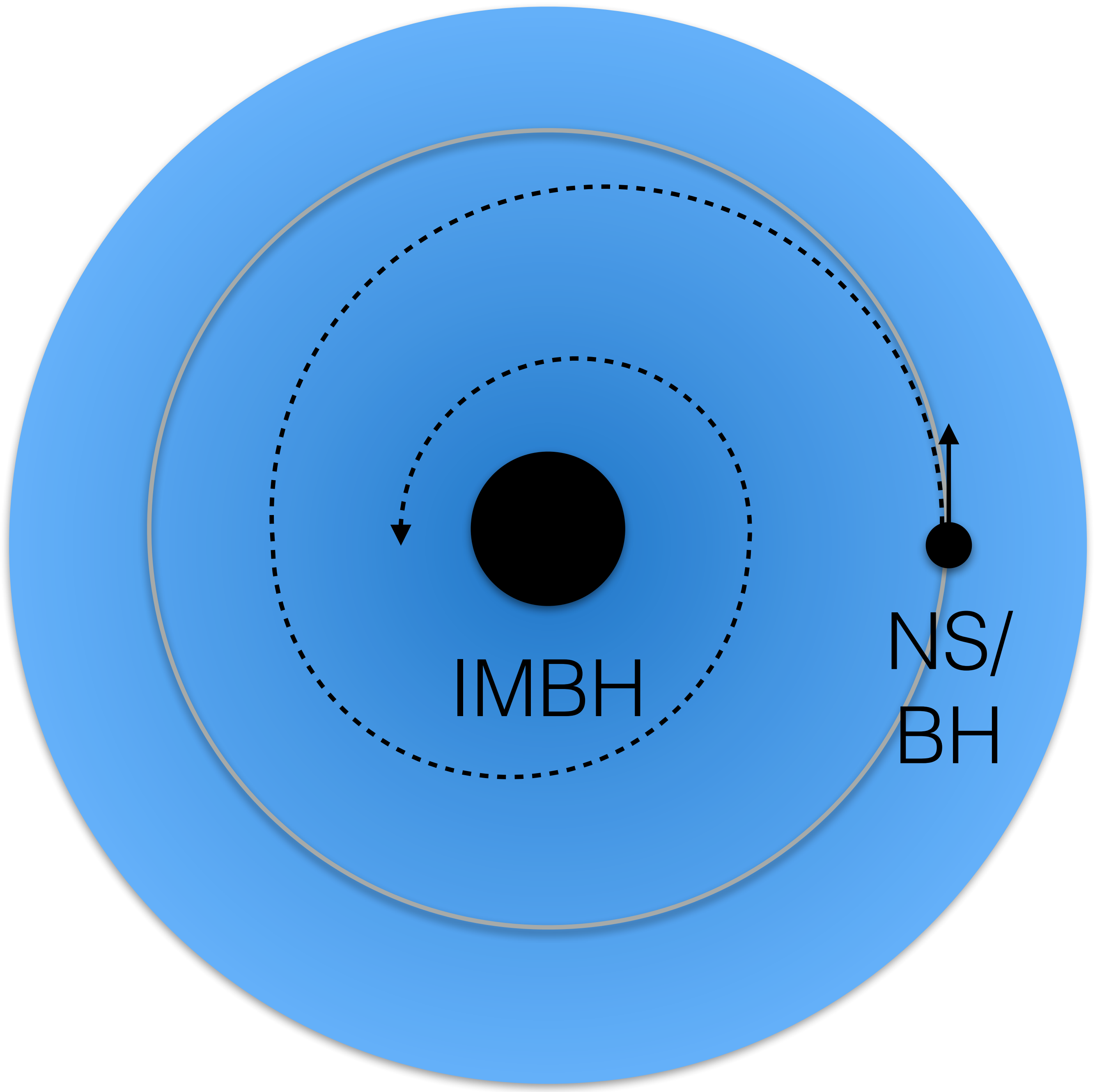
PBH scenario

$$\gamma_{\rm sp} = 9/4 \approx 2.25$$
$$\rho_6 \approx 5.35 \times 10^{15}\, M_\odot\, \mathrm{pc}^{-3}$$

[Bertschinger (1985), astro-ph/0608642, 1901.08528, …]

IMRI + Dark Matter

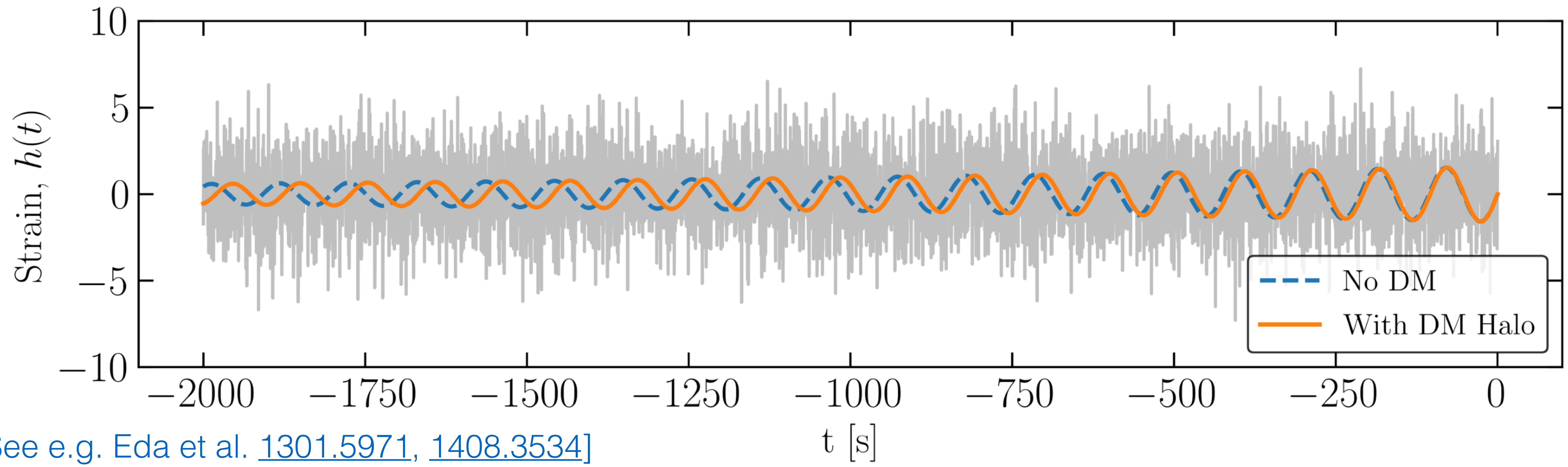




$$-\dot{E}_{\rm orb} = \dot{E}_{\rm GW} + \dot{E}_{\rm DF}$$

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

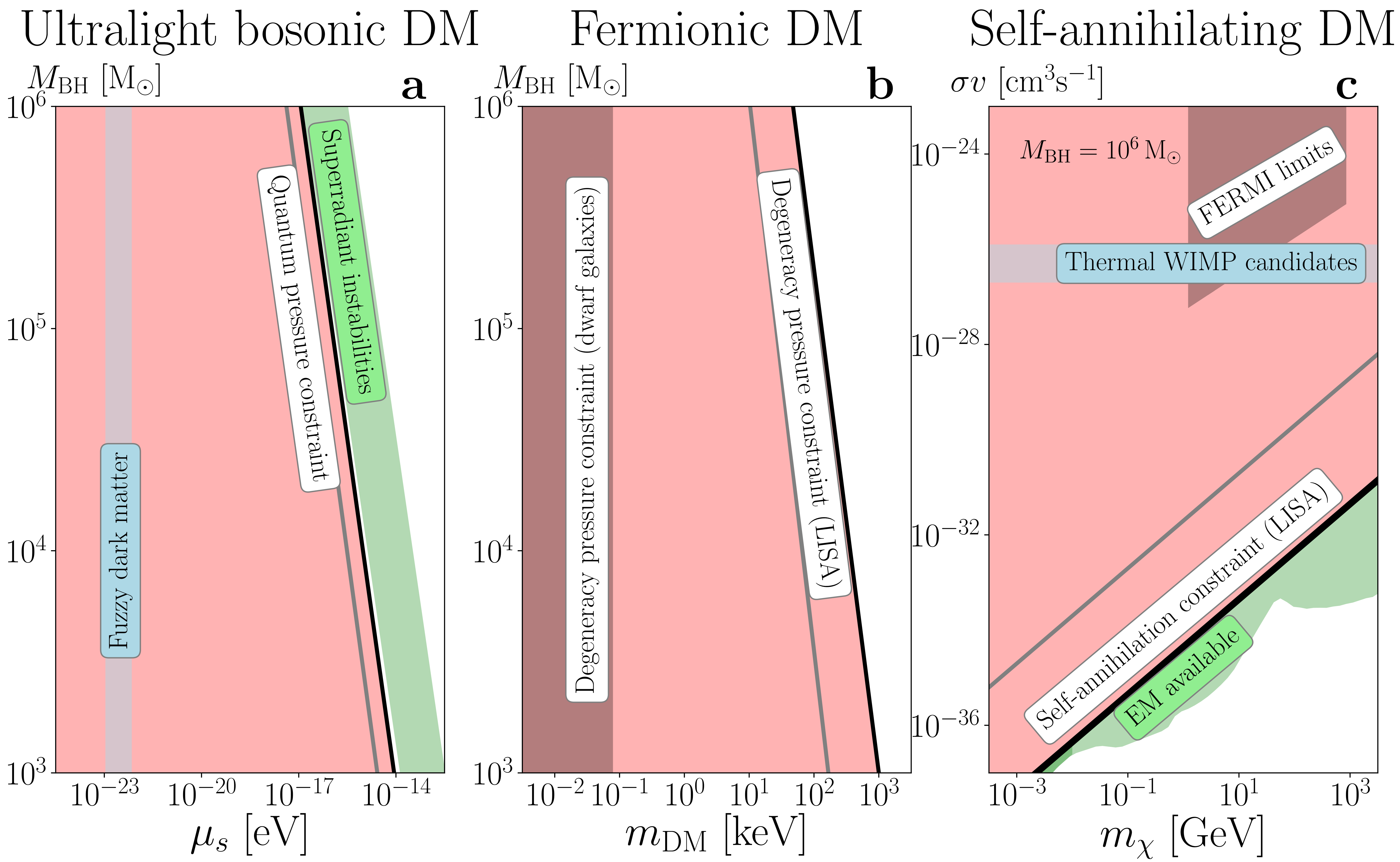
[Chandrasekhar, 1943]



[See e.g. Eda et al. 1301.5971, 1408.3534]

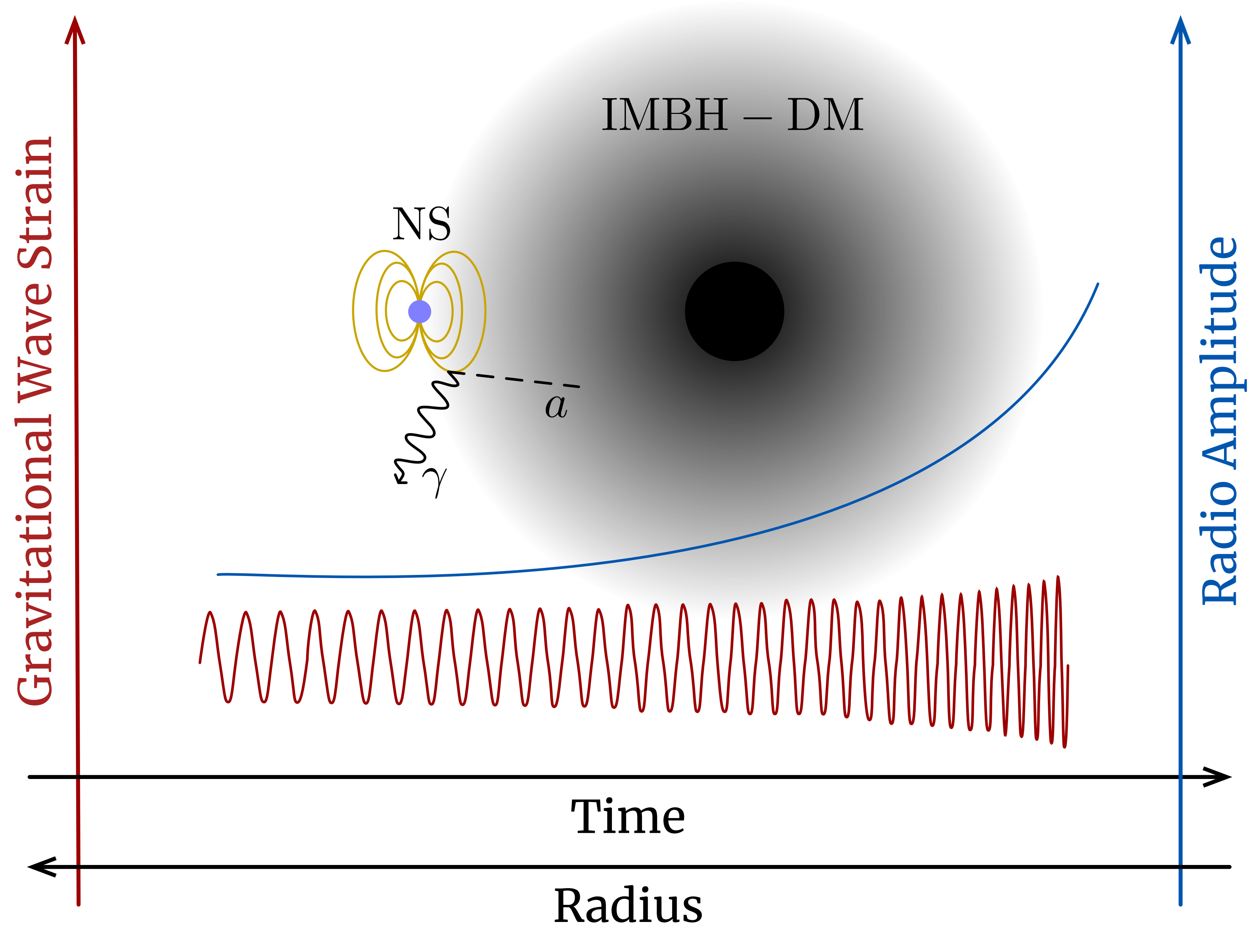
Nature of Dark Matter

Red regions would be ruled out by observation of a DM spike!
[1906.11845]



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

DM dephasing offers a unique multi-messenger signature of e.g. QCD axion DM



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

BUT - need to model the signal very carefully…

Halo Feedback

Follow semi-analytically the phase space distribution of DM:

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

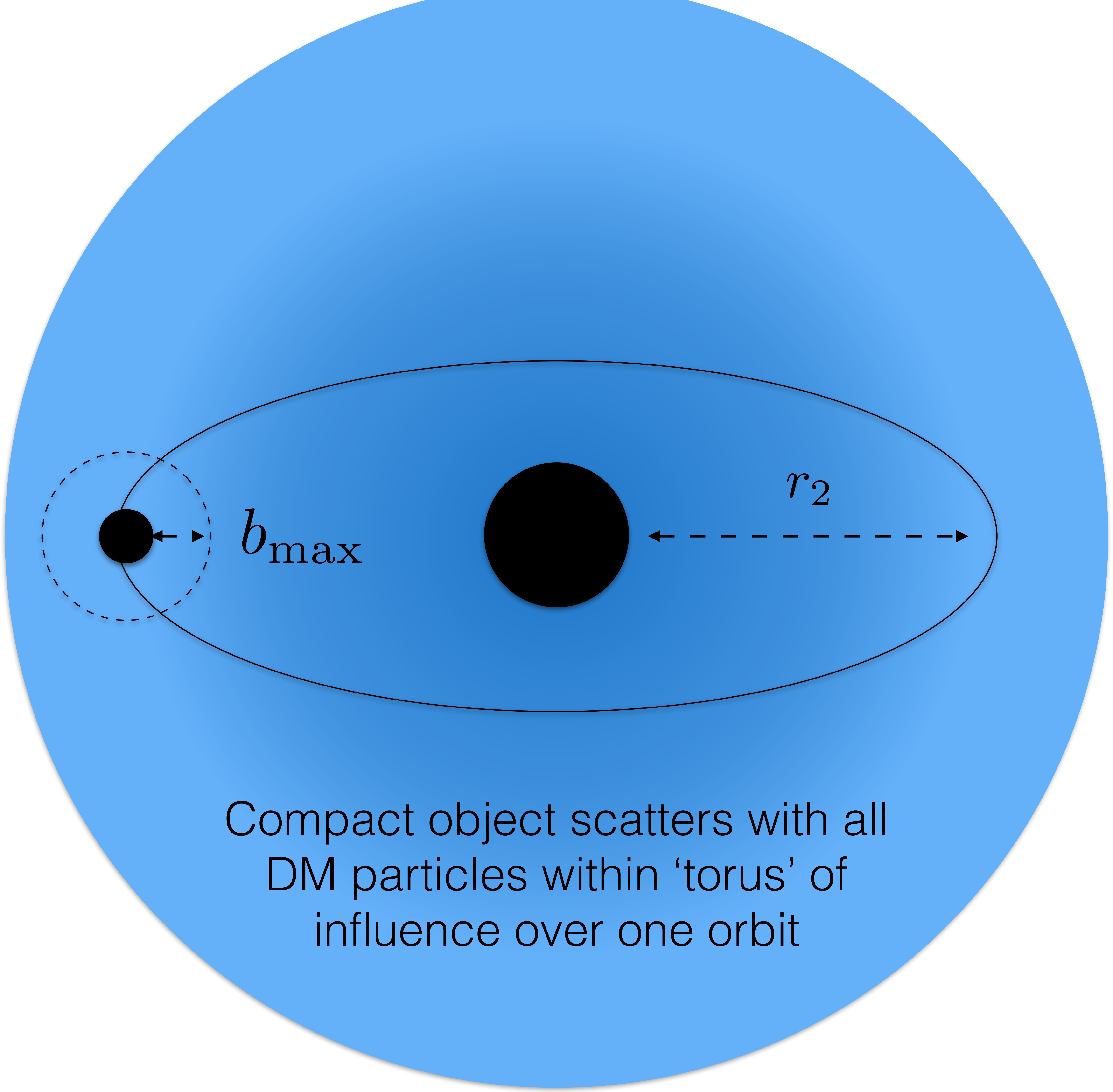
$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Each particle receives a 'kick' through gravitational scattering

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

Reconstruct density from distribution function:

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



[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

[Code available online: github.com/bradkav/HaloFeedback]

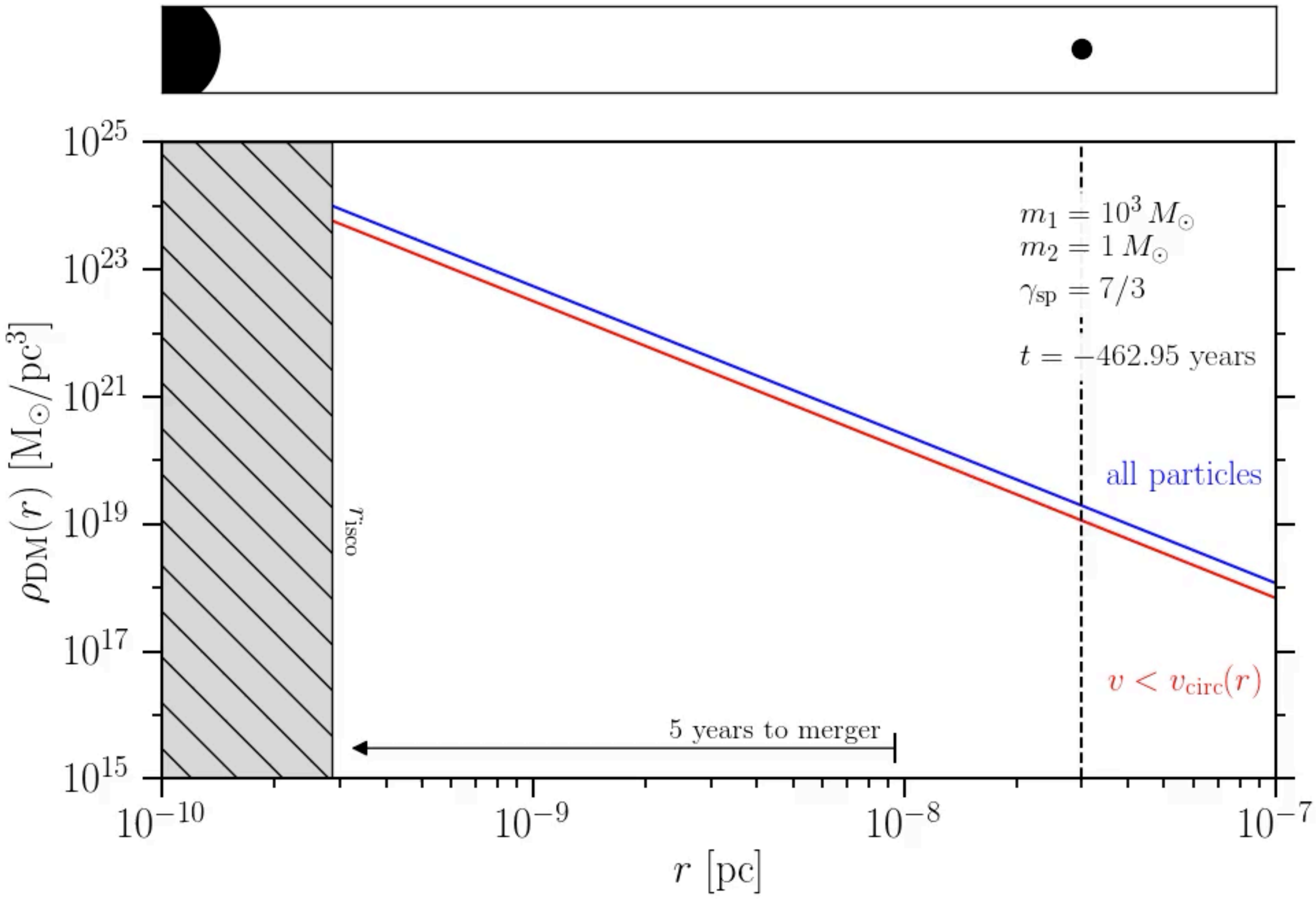
Full evolution of the system

[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

Movies: tinyurl.com/GW4DM

Newtonian motion of the binary,
Taking into account:

- GW emission
- Dynamical Friction
- DM Halo Feedback



Density of the DM spike is depleted (and replenished…)

This is one of the reasons we want to look at IMRIs/EMRIs…

Full evolution of the system

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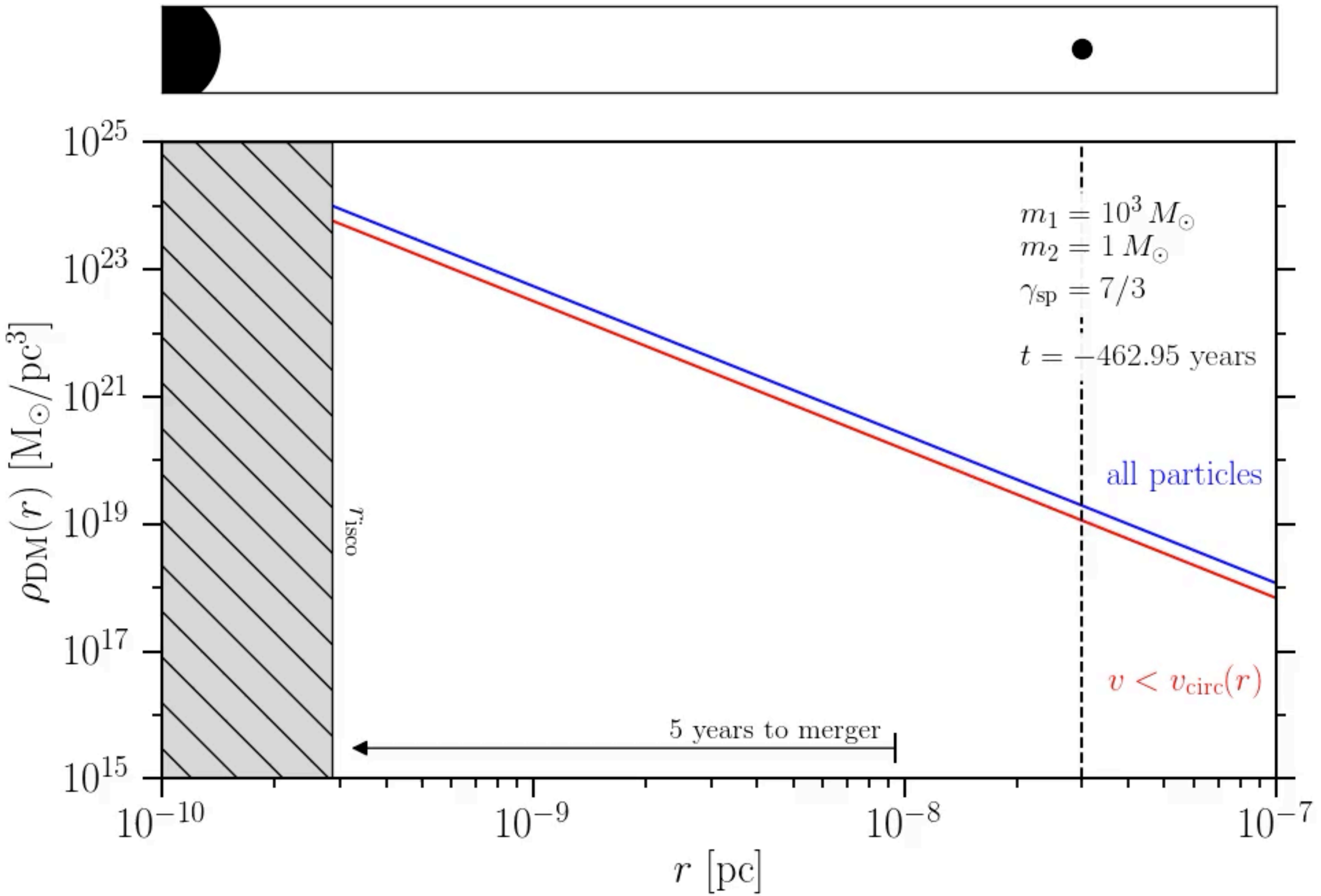

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Self-consistent dephasing

[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

Consider our astro benchmark system, starting at some initial separation:

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

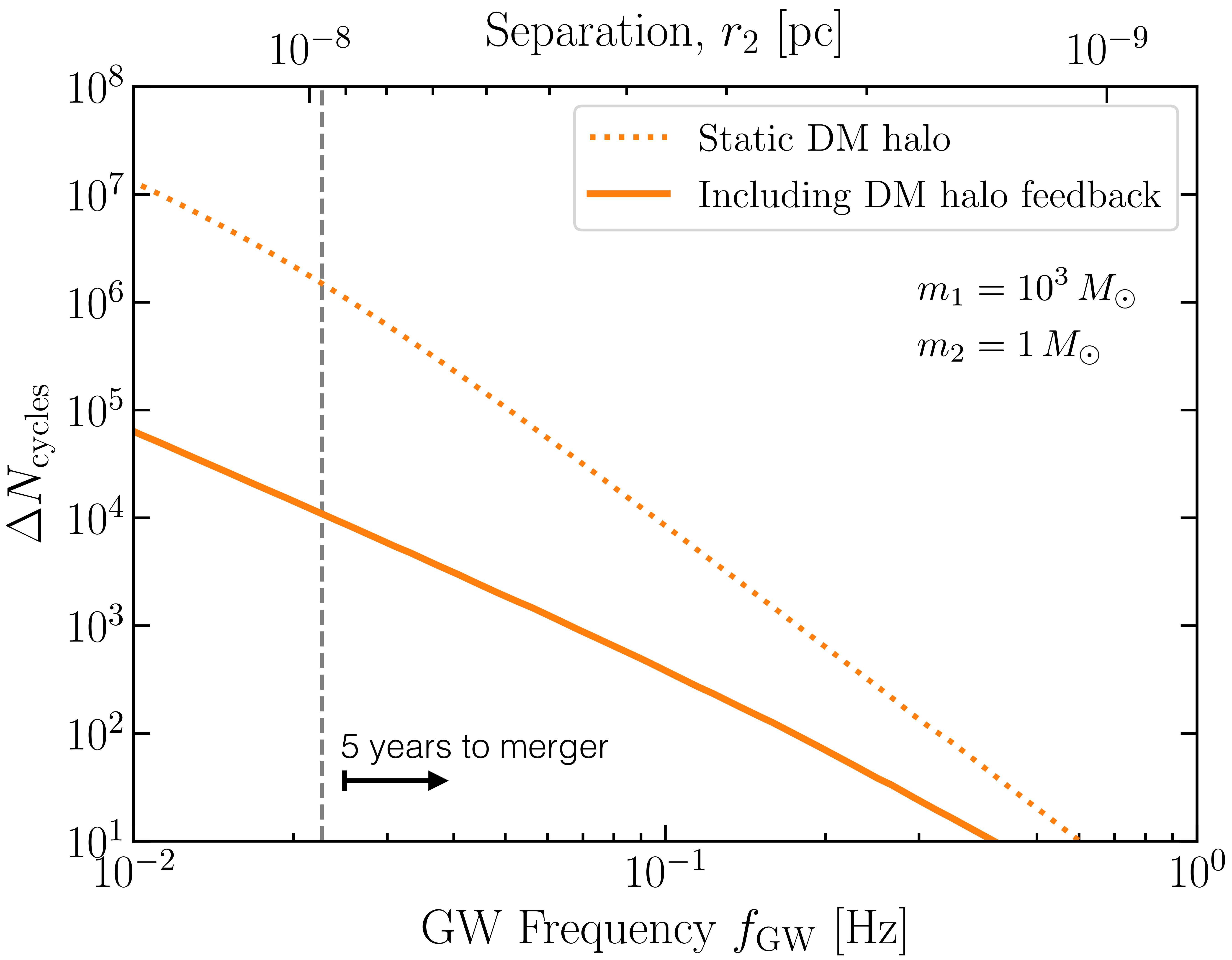
$$t_{\rm merge}^{\rm vacuum} \sim 5\,\mathrm{yr}$$

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

DM dephasing

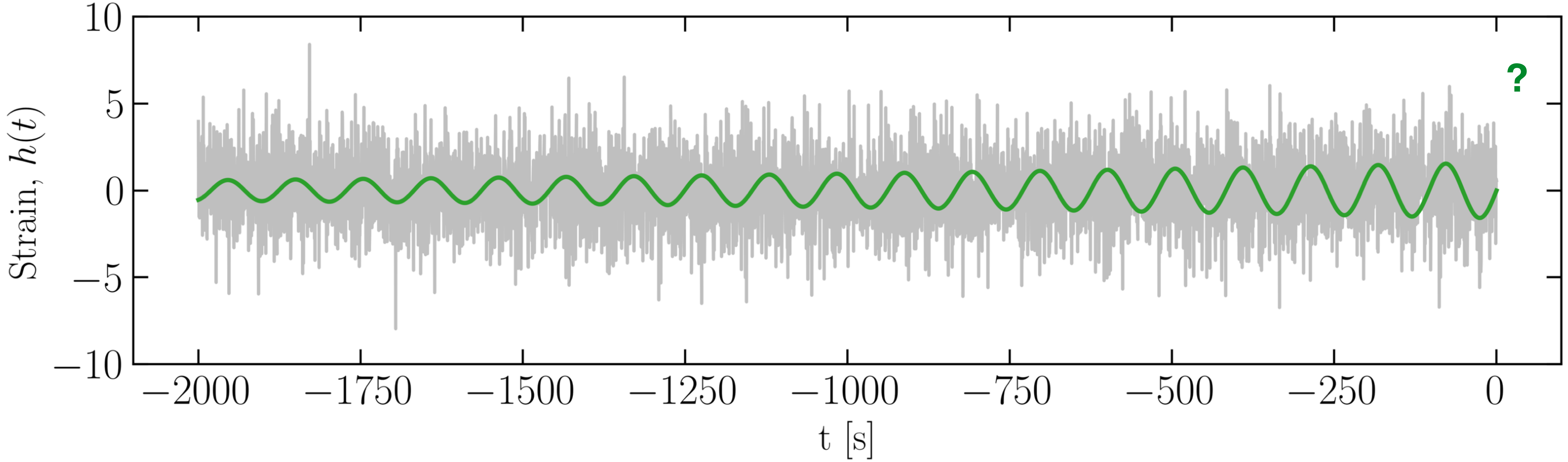
$$\Delta N_{\rm cycles} \sim \mathcal{O}(10^4)\ \mathrm{cycles} \sim \%\ \mathrm{level}$$

Change in the number of GW cycles to merger, starting at some initial frequency/separation:



A more realistic scenario

[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]



Want to address questions of:

- **Detectability** - is the event loud enough to detect?
- **Discoverability** - can we tell it apart from a *GR-in-vacuum* waveform?
- **Measurability** - can we pin down the properties of the system (*especially the DM*)?

Detectability

A signal may be **detectable** with LISA using matched filtering with a signal-to-noise ratio (SNR) $\gtrsim 15$...

[1905.11998]

Match between waveforms a and b defined as:

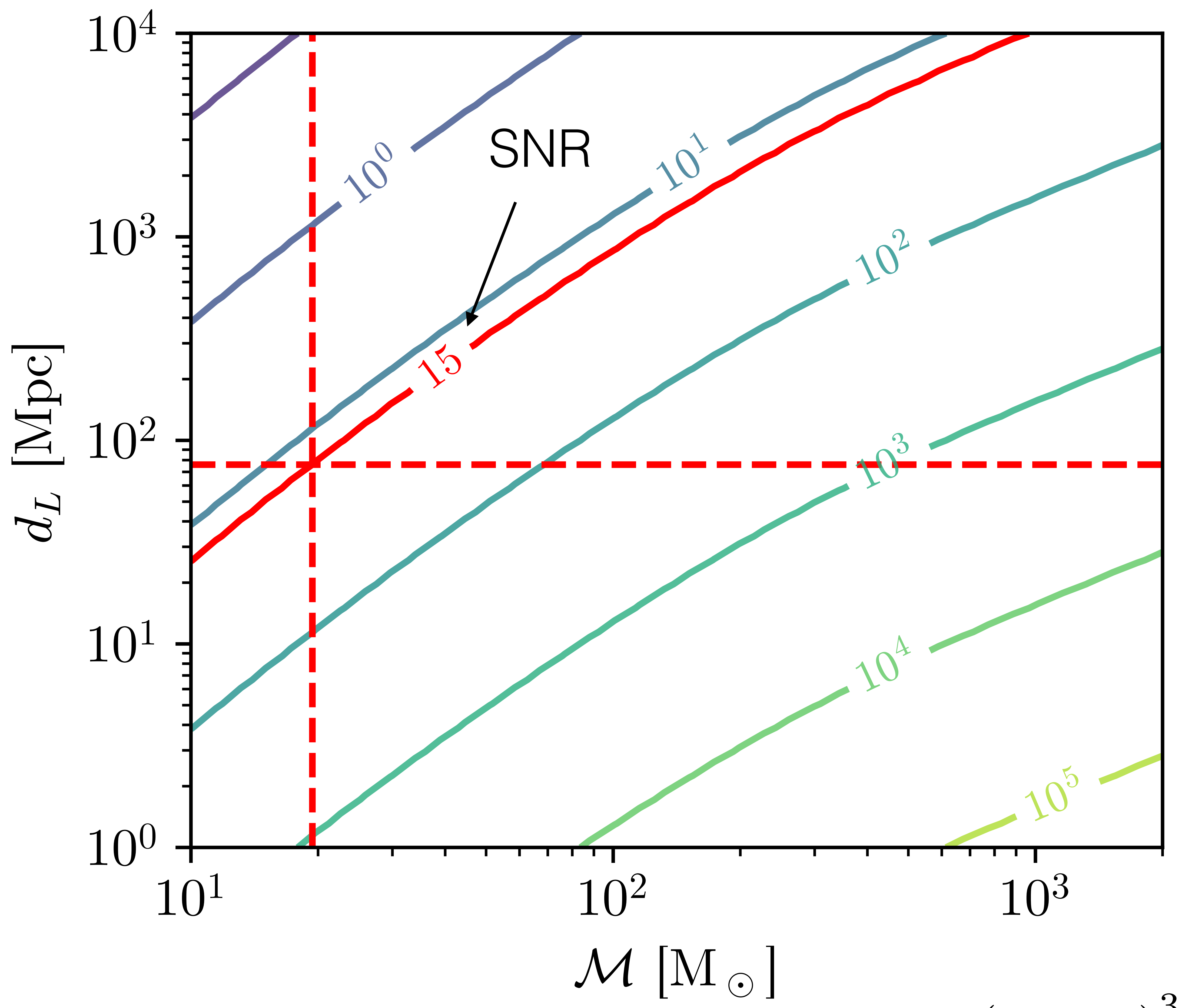
$$\langle a \mid b \rangle = 4\,\mathrm{Re} \int_0^\infty \mathrm{d}f \, \frac{\tilde{a}(f)^* \tilde{b}(f)}{S_n(f)}$$

LISA noise curve

Optimal SNR for waveform s is then:

$$\mathrm{SNR}(s) = \sqrt{\langle s | s \rangle}$$

NB: Presence of the dark dress does not substantially affect SNR



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Discoverability

$$q = m_2/m_1$$

We'll call a DM spike **discoverable** if it can be distinguished from a GR-in-vacuum system.

Compare Bayesian evidence for **V**acuum and **D**ressed systems:

$$\mathrm{BF}(d) \equiv \frac{p(d|\mathrm{D})}{p(d|\mathrm{V})}$$

$$p(d) = \int \mathrm{d}\boldsymbol{\theta}\,\underbrace{\mathcal{L}(\boldsymbol{\theta})}_{\text{Likelihood}}\,\underbrace{p(\boldsymbol{\theta})}_{\text{Prior}}$$

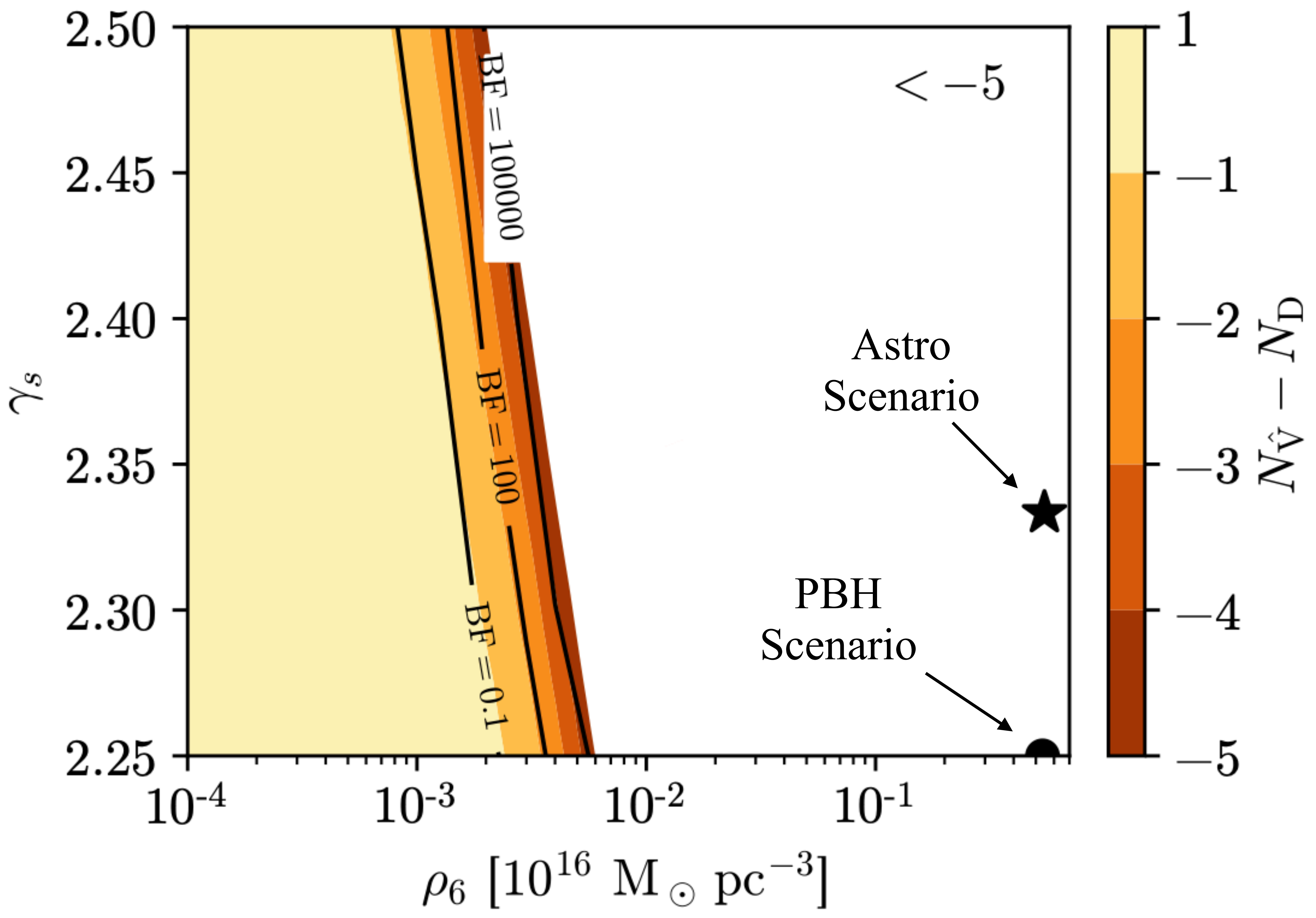
$$\boldsymbol{\theta}_\mathrm{V} = \{\mathcal{M}\}$$

$$\boldsymbol{\theta}_\mathrm{D} = \{\gamma_\mathrm{sp}, \rho_6, \mathcal{M}, \log_{10} q\}$$

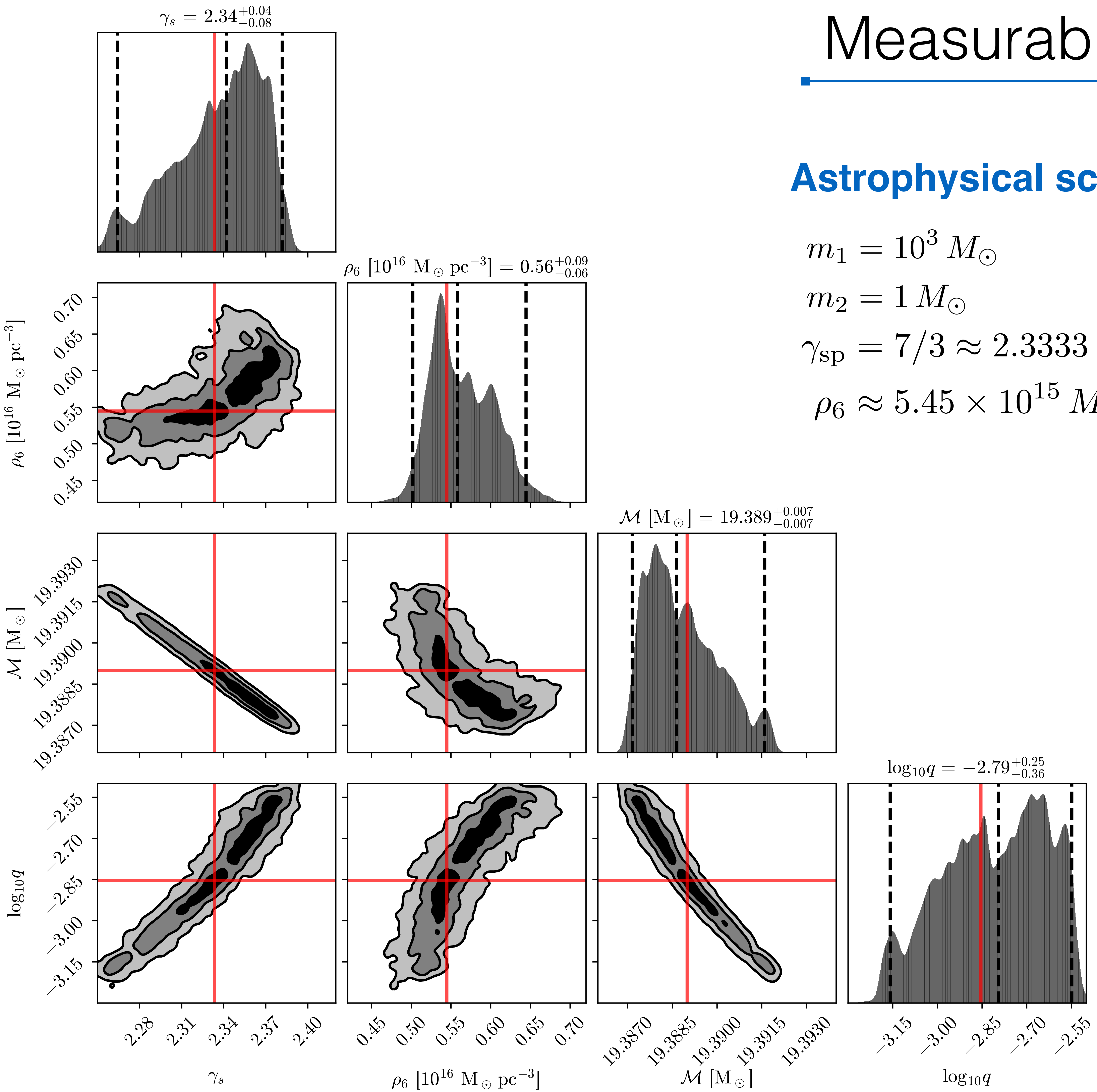
$$\boldsymbol{\theta}_\mathrm{ext} \equiv \{D_L, \phi_c, \tilde{t}_c\}$$

Use an approximate waveform parametrisation in terms of $\boldsymbol{\theta}_\mathrm{D}$

[Code available online: https://github.com/adam-coogan/pydd]



Measurability



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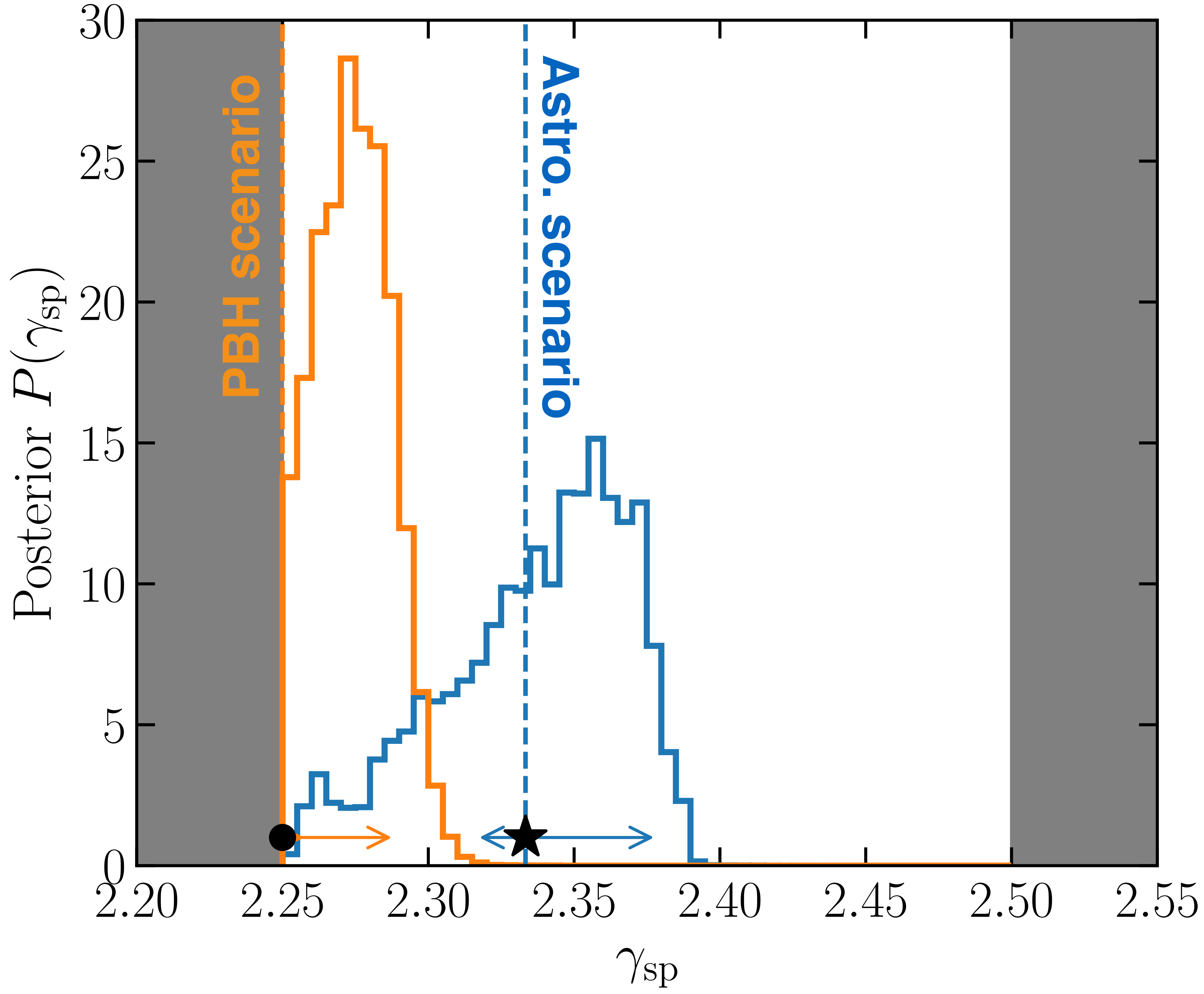

We may be able to distinguish different *shapes* of spike
→ Different DM models and formation mechanisms!

Plans for the future

Improved modelling

- Injection and evolution of angular momentum in the spike
- Orbital eccentricity
- Post-Newtonian corrections
- Better N-body approaches [AMUSE?]

Detection methods

- Producing template banks for LISA searches
- Surrogate models for waveform generation
- Incoherent searches for continuous GWs
- ‘General’ de-phased waveform templates [2004.06729]

Detection prospects

- How many IMRI systems form? How many with BH/NSs?
- How many systems have a (surviving) spike?
- Comparison with dephasing due to baryons, or due to ultralight bosons (gravitational atoms)
- *What about ground-based detectors? Low mass PBHs?*

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David Nichols
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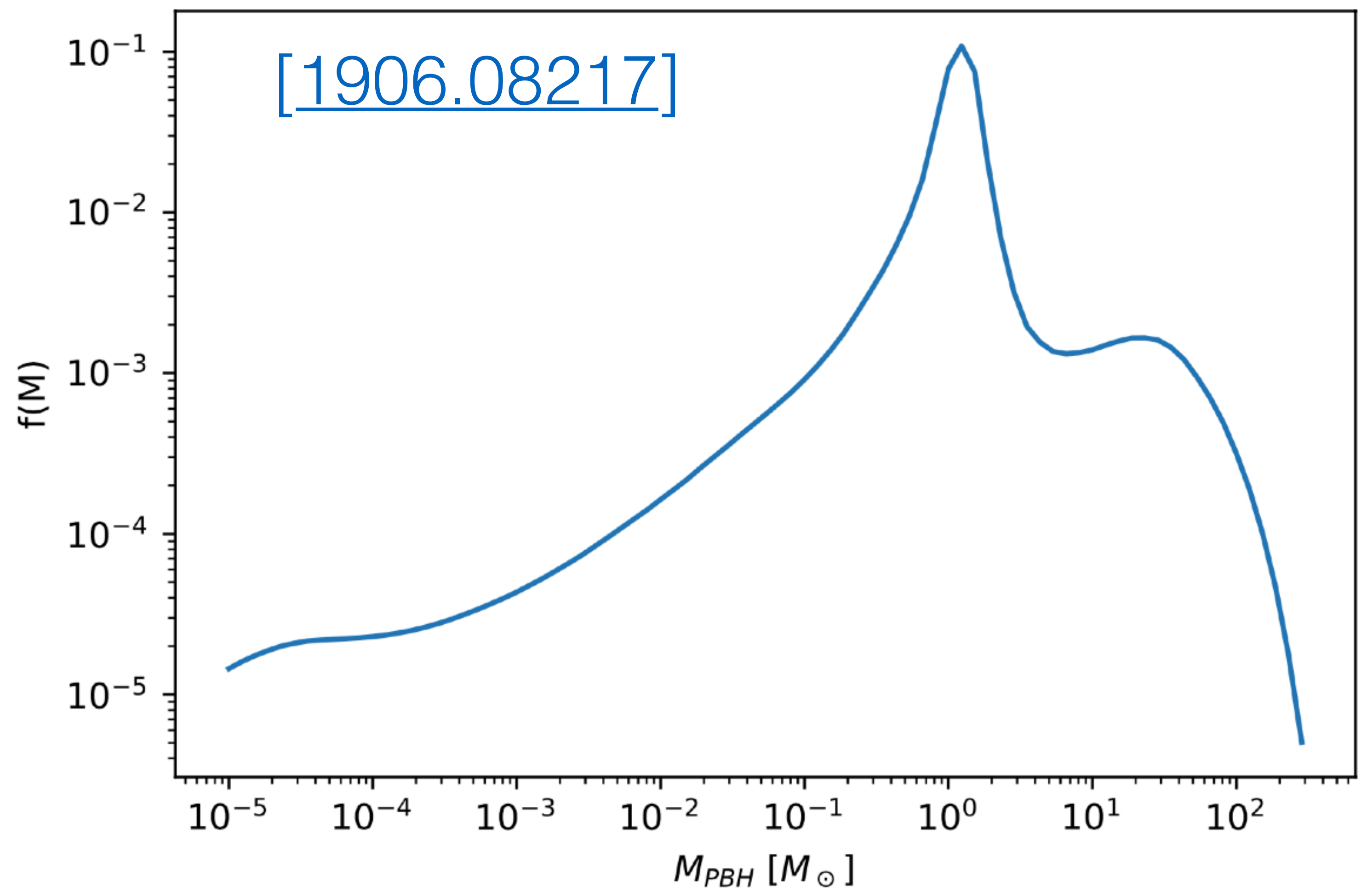
Francesca Scarcella
(IFT, Madrid)

…and others…

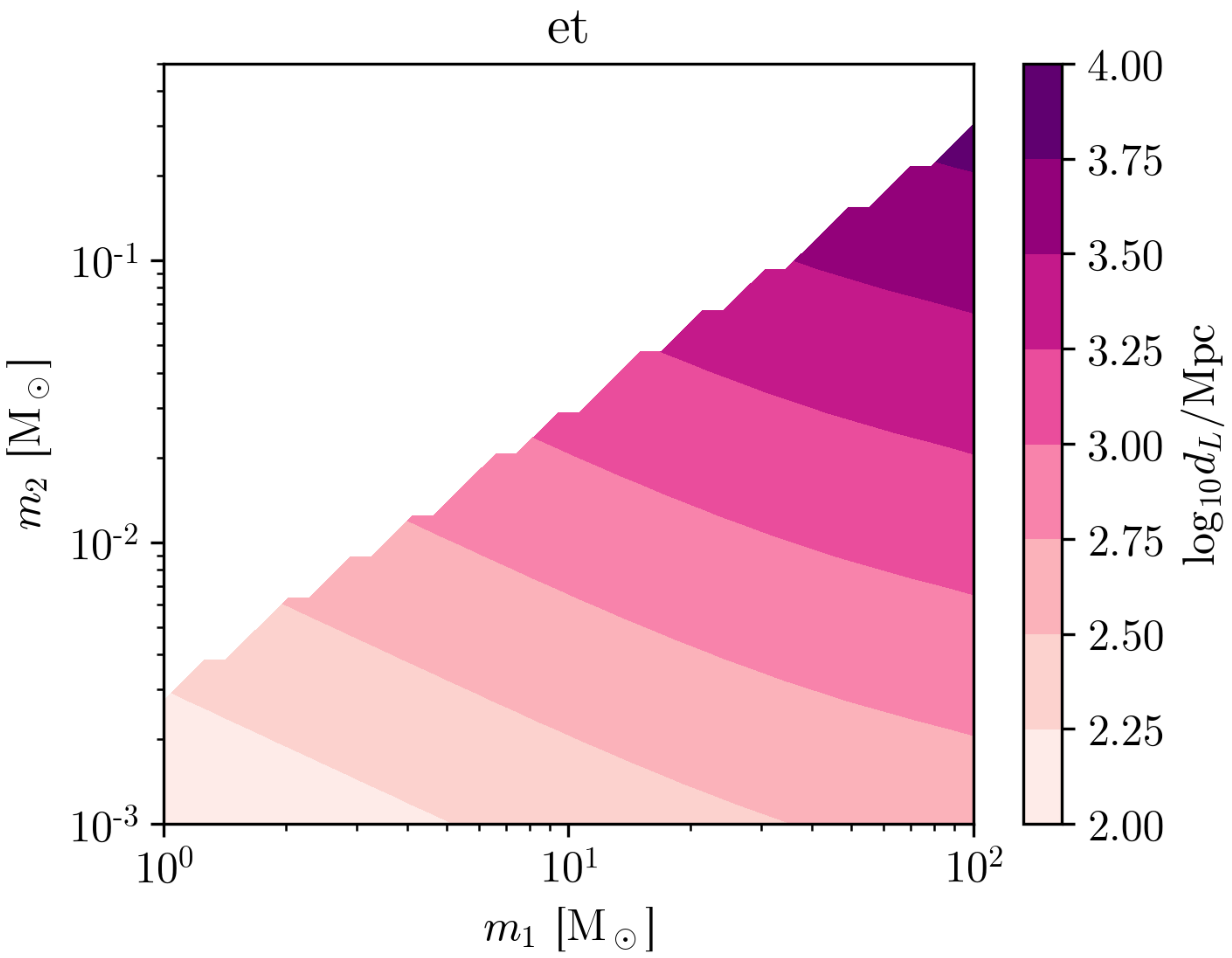
Low mass PBH binaries

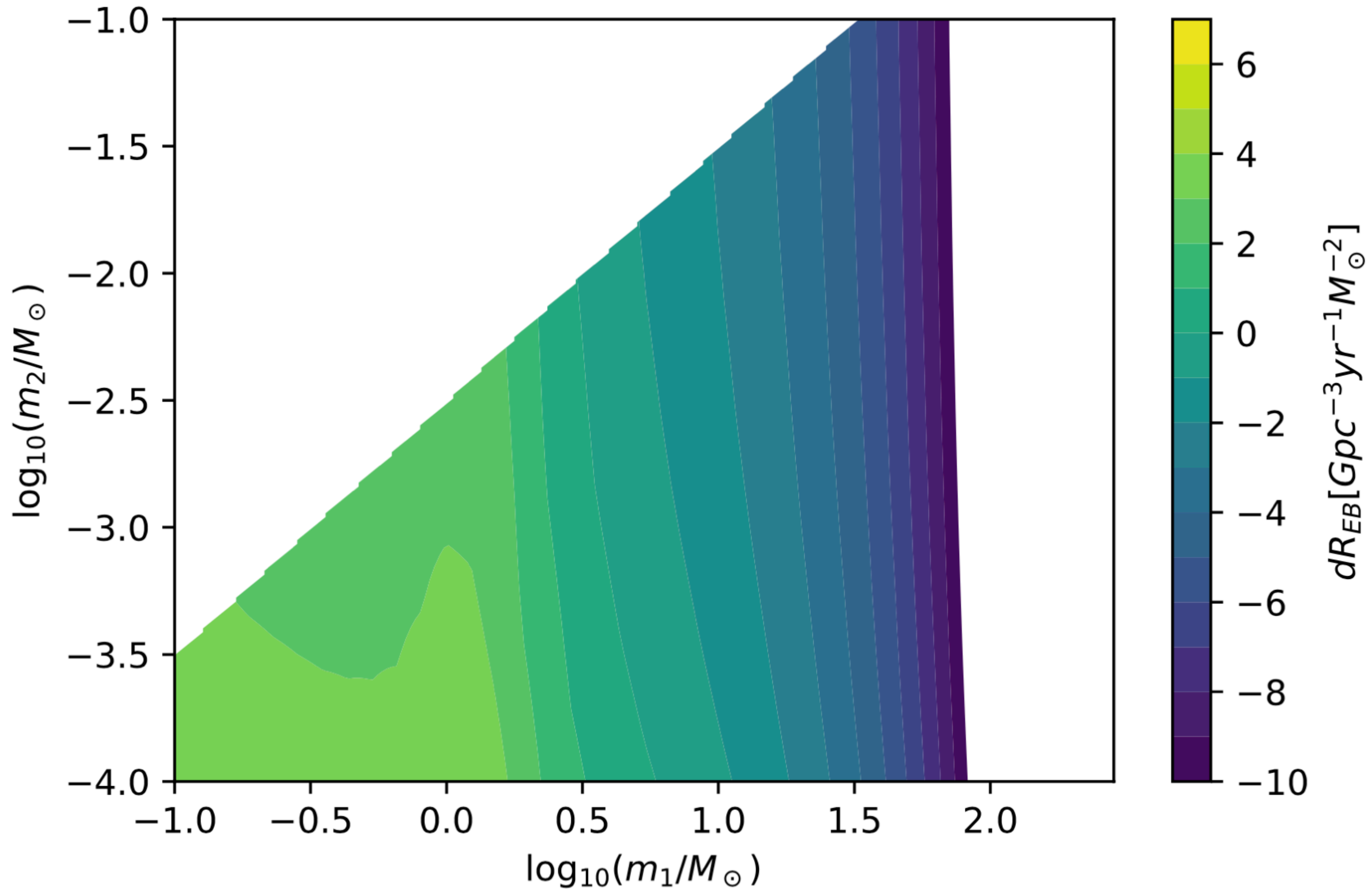
Low mass PBH binaries could be detected with ground based detectors such as LIGO or Einstein Telescope

PRELIMINARY



(b) $k_p = 5 \times 10^5\ \mathrm{Mpc}^{-1},\ f_{PBH} = 0.085.$





Conclusions

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

[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

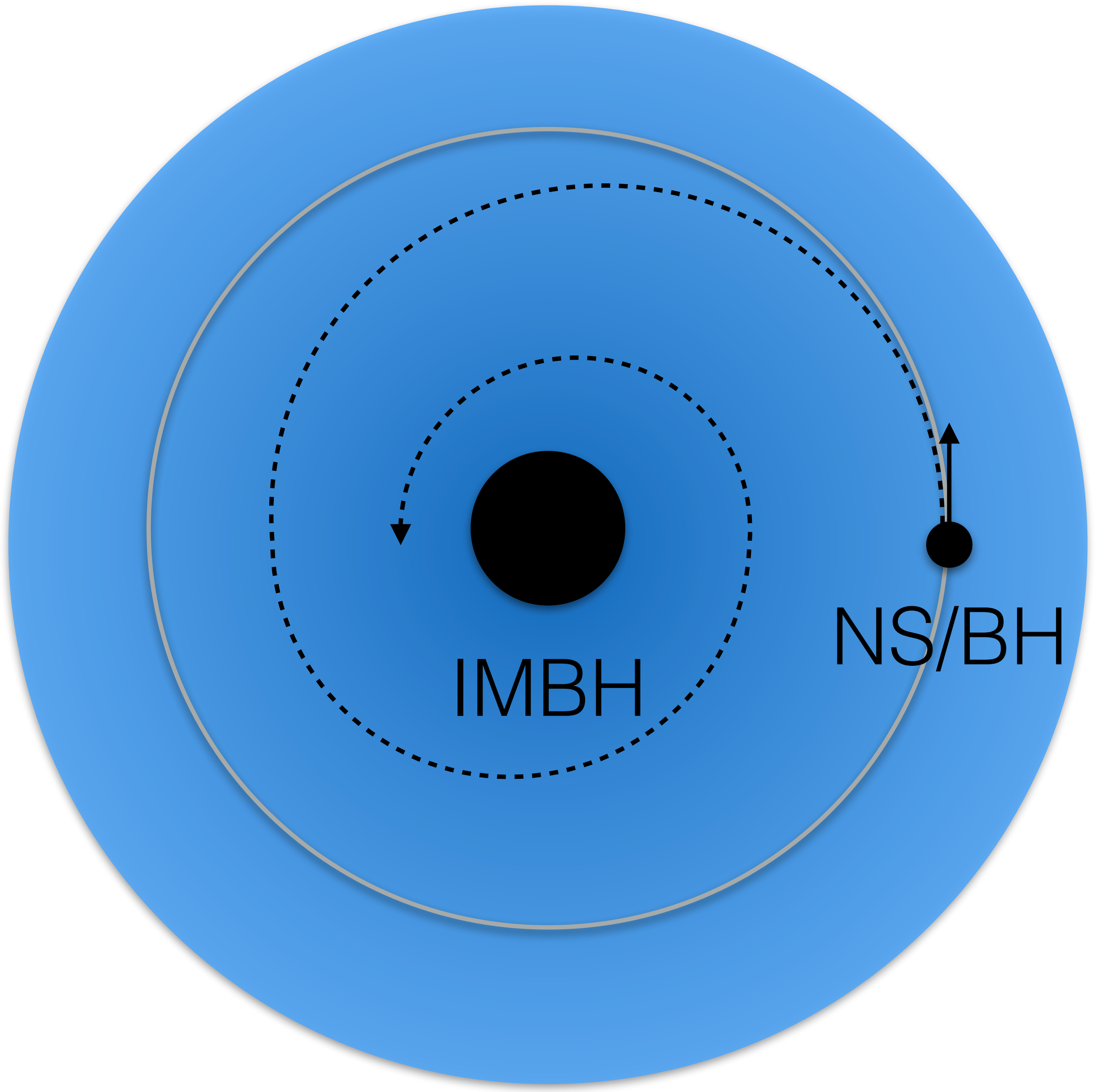
With LISA, such systems should be **detectable**, **discoverable** against vacuum-only systems, and the properties **measurable**.

[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]

These signals could probe the **nature of Dark Matter** and pave the way towards a **multi-messenger detection** of Dark Matter

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

There are lots of open questions remaining, but they’re well worth answering!



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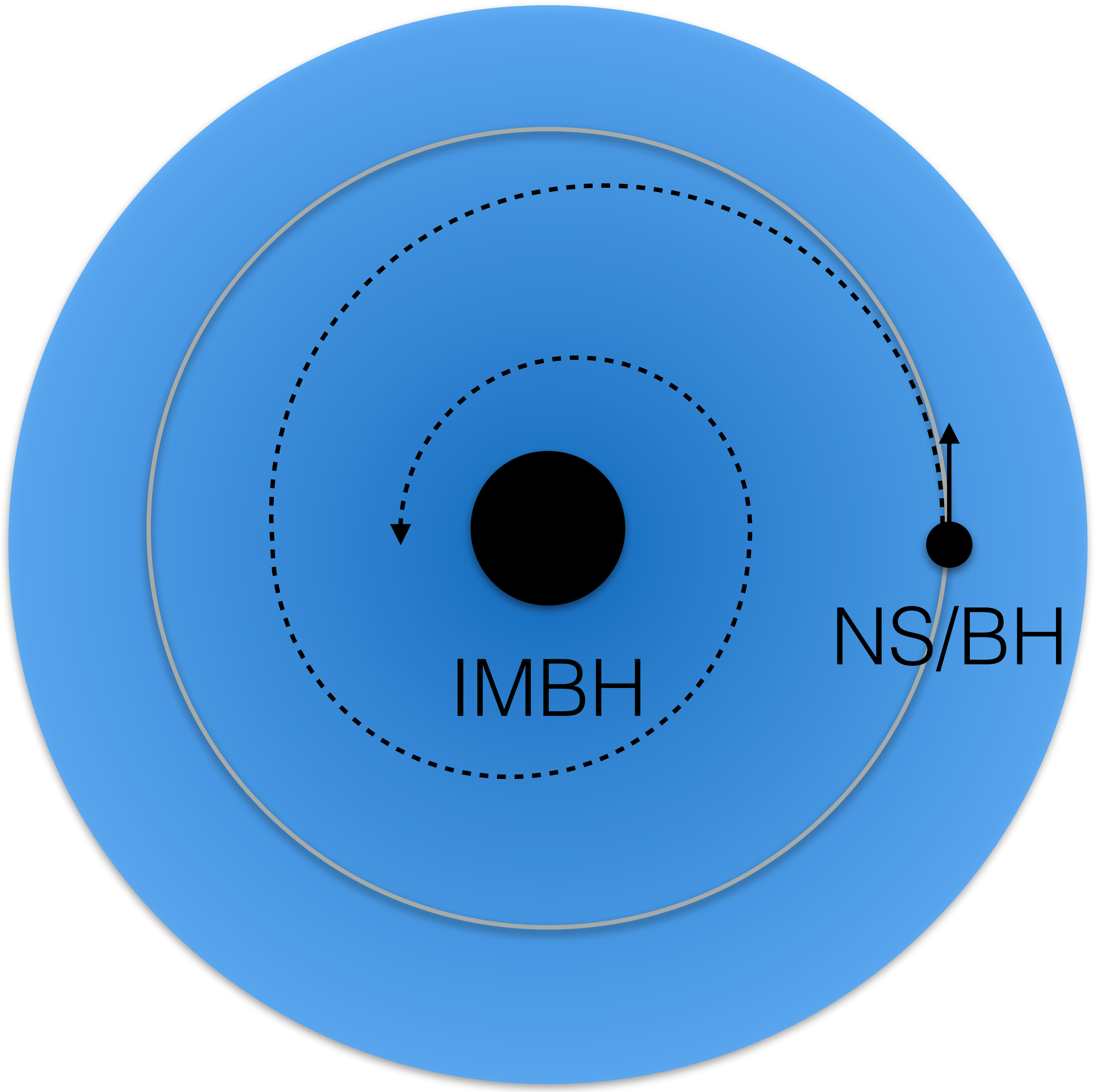

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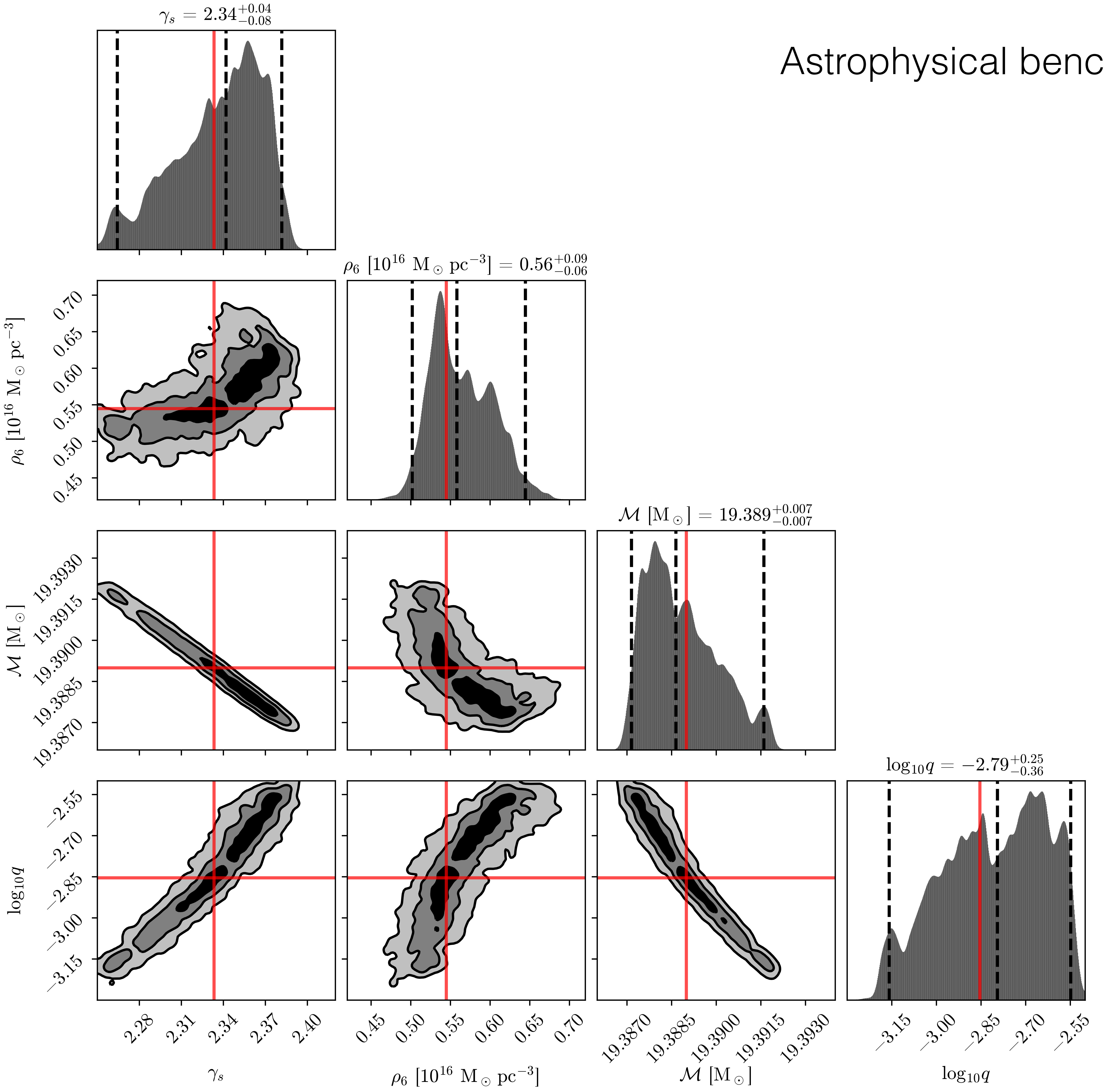
Thank you!

Backup Slides

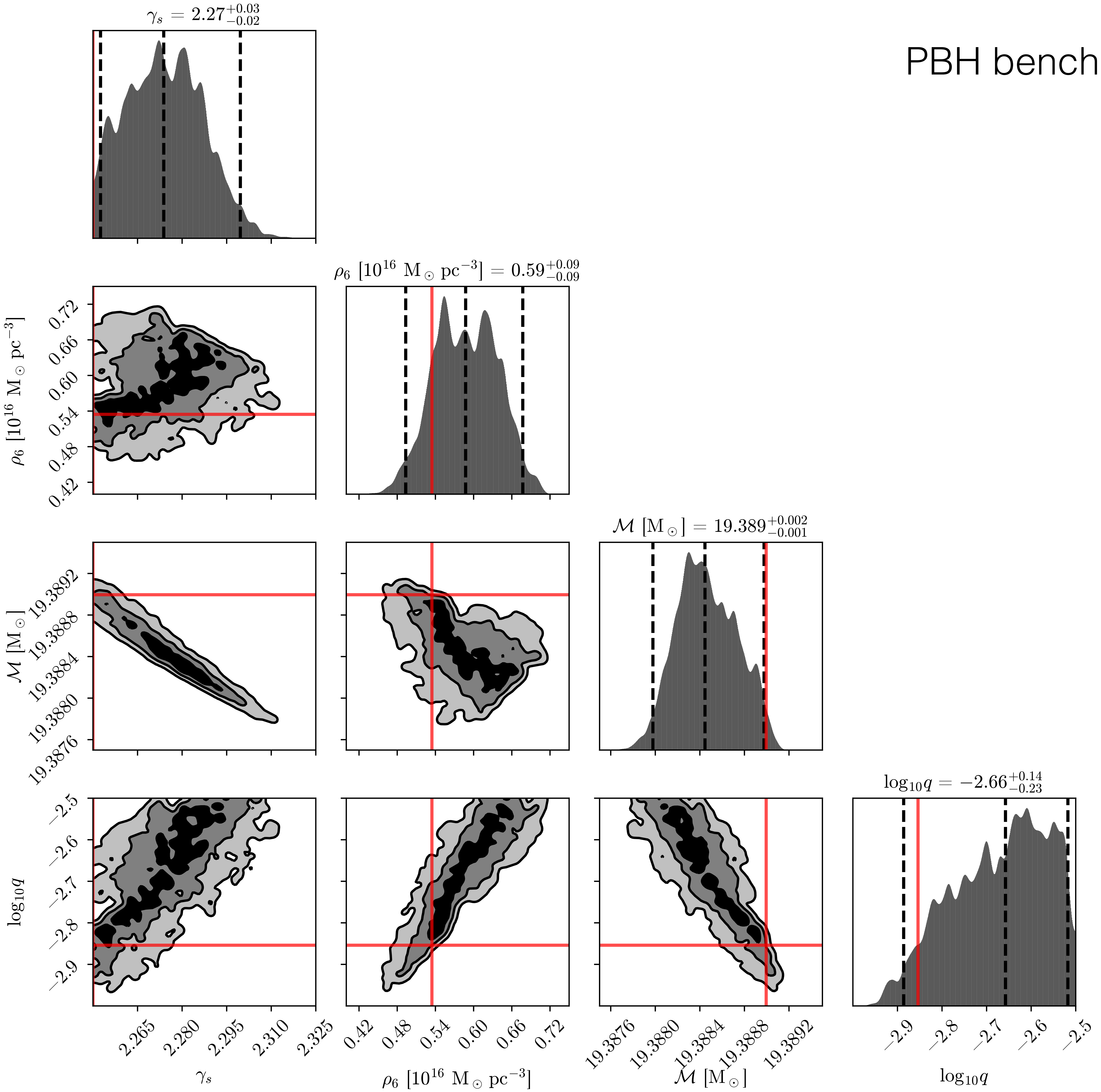
Measurability

Astrophysical benchmark



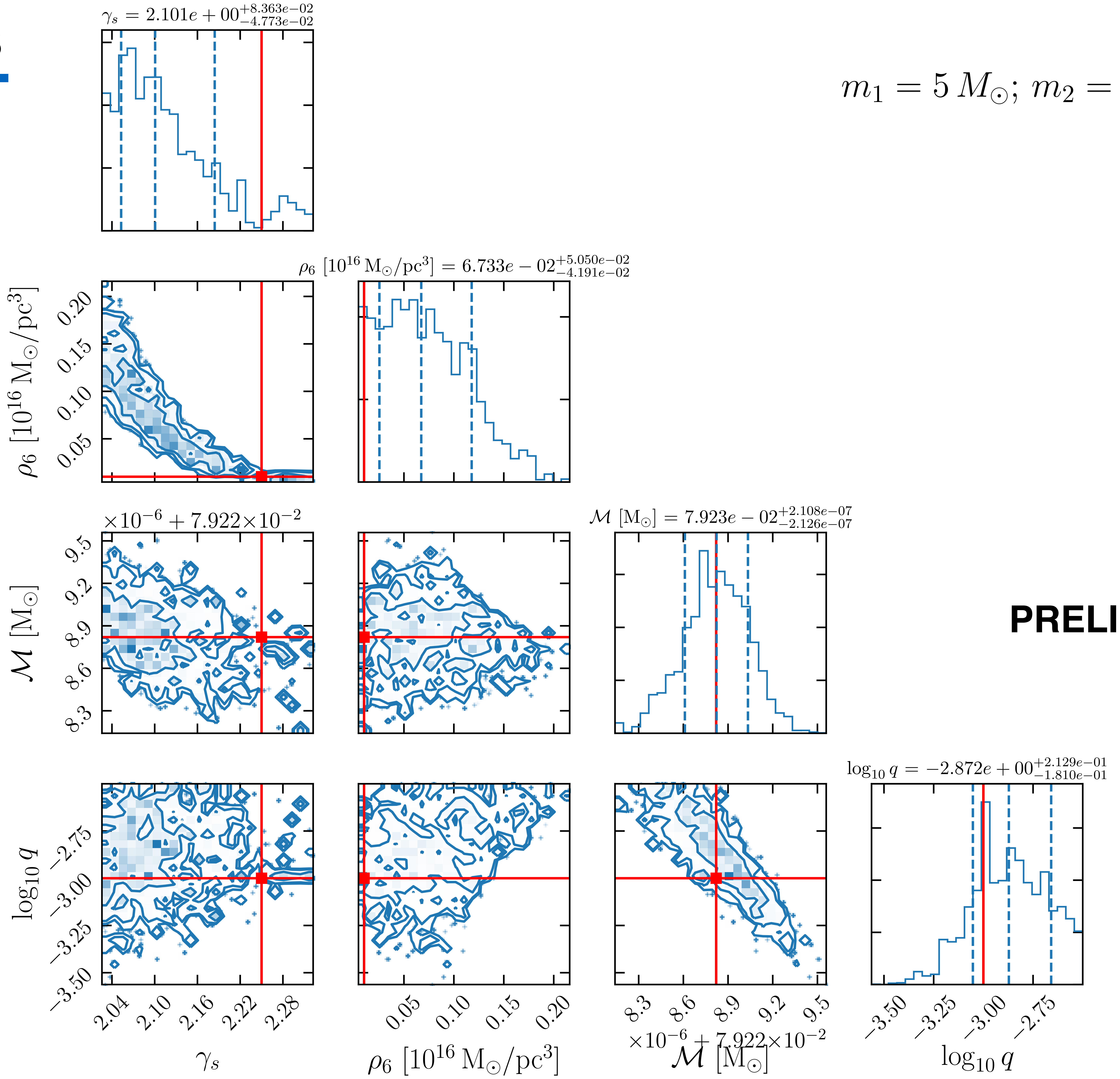
Measurability

PBH benchmark



Low mass PBHs

$m_1 = 5\,M_\odot$; $m_2 = 0.005\,M_\odot$; aLIGO



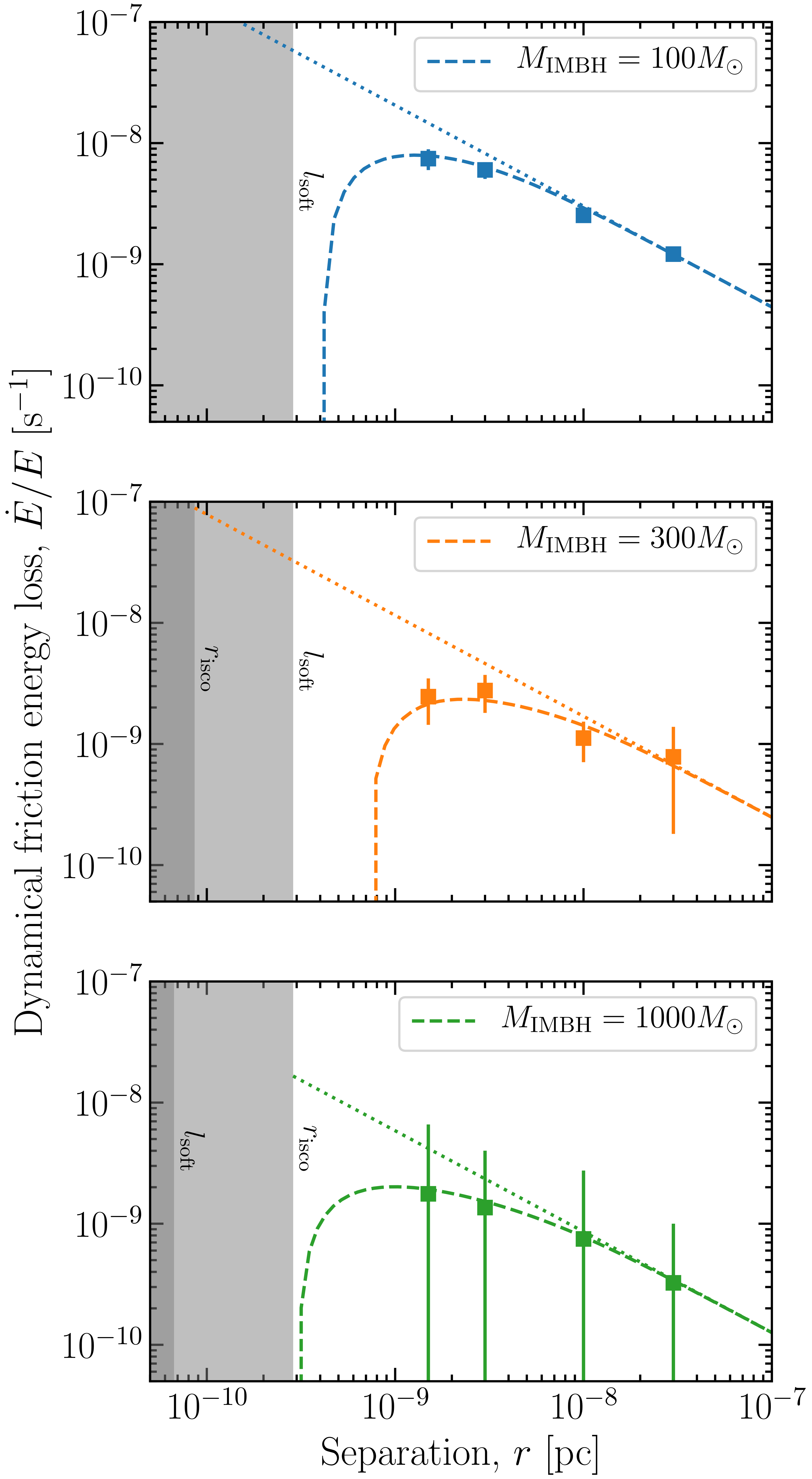
PRELIMINARY

N-body results

Dependence of dynamical friction force on mass and separation matches expectations

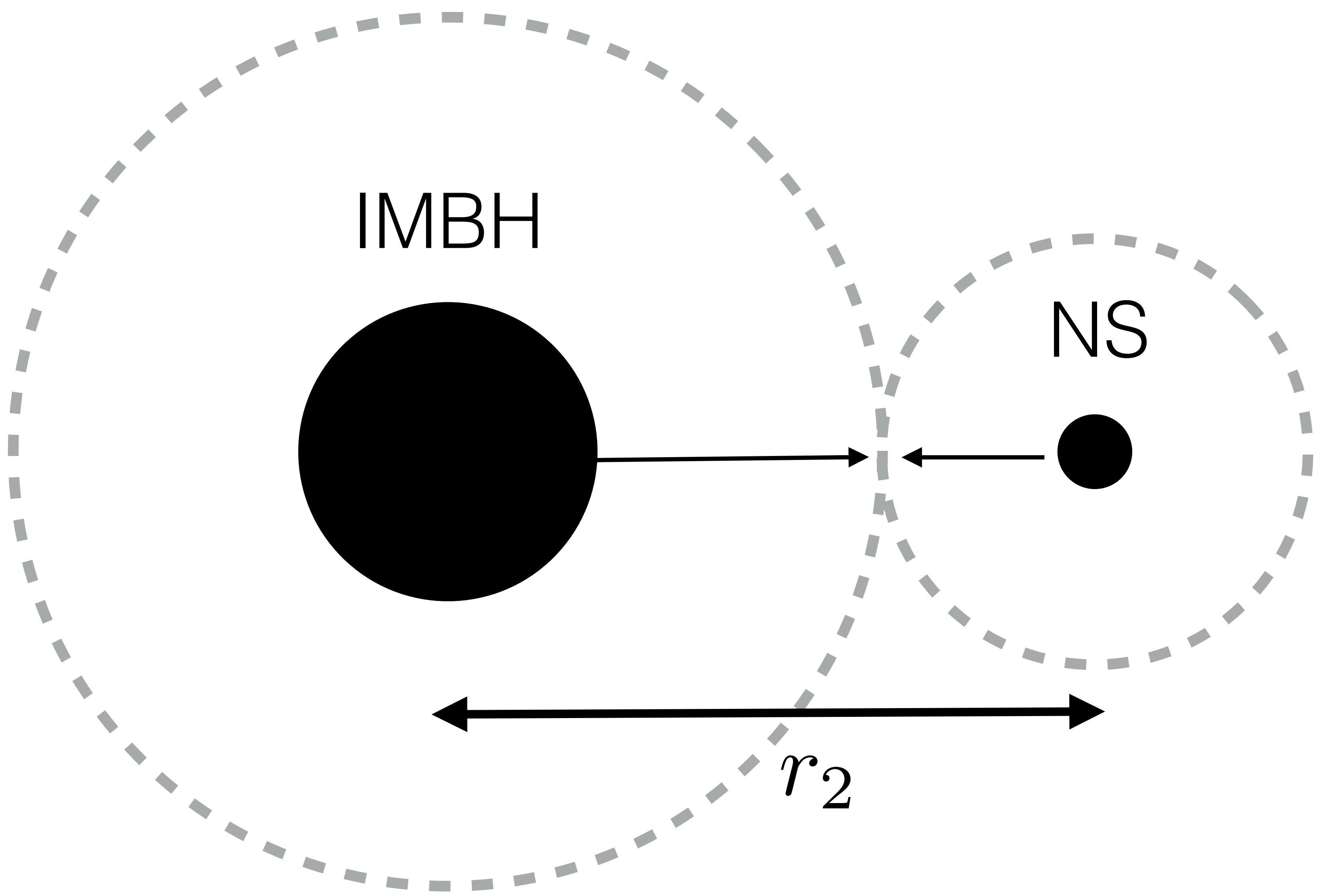
Dynamical friction traces local DM density (to better than 1%)

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



N-body results

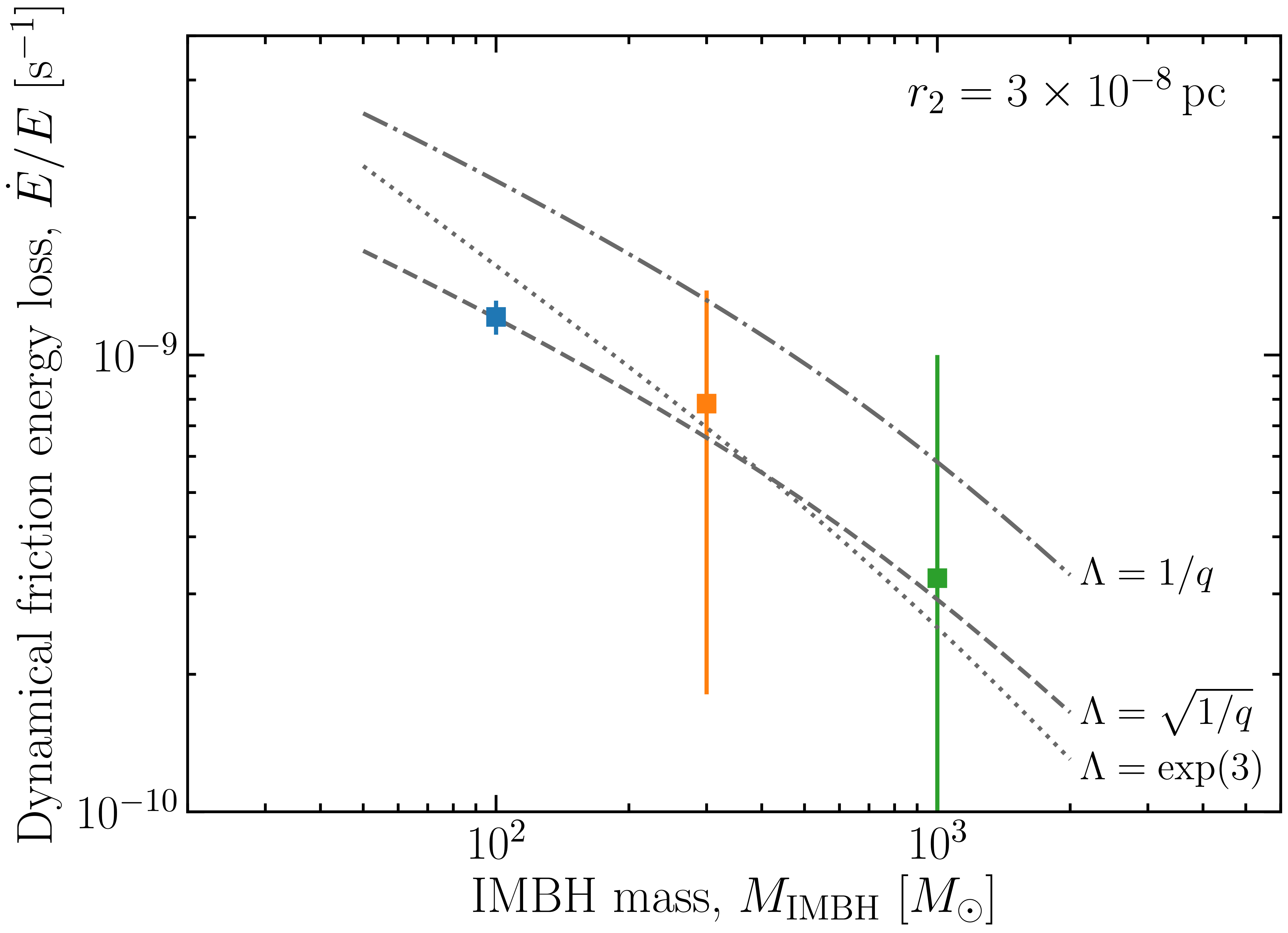
$$q \equiv m_{\rm NS}/m_{\rm IMBH} \ll 1$$



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

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

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



Assumptions

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

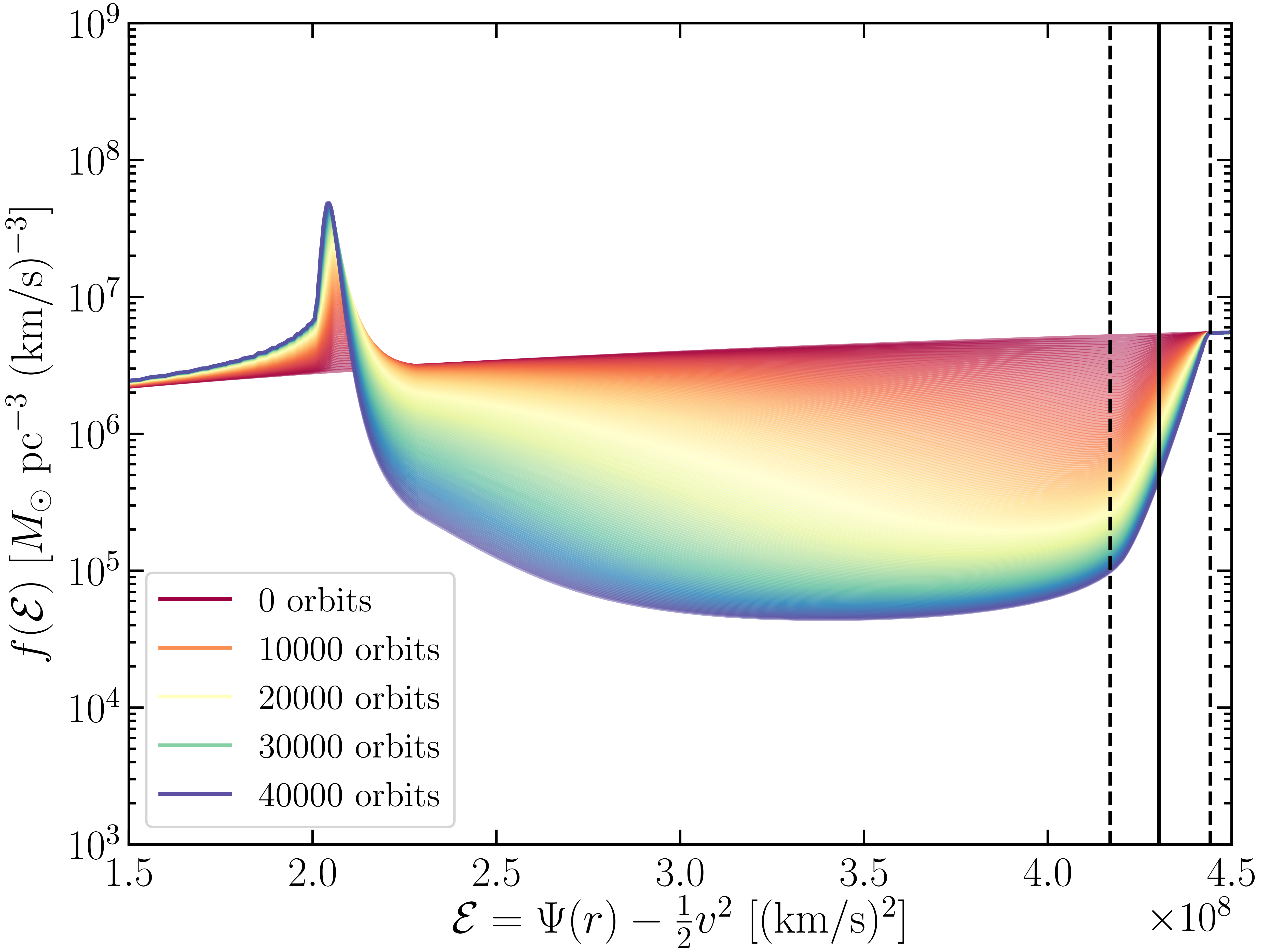
$$b < b_{\rm max} = \Lambda \times G_N M_{\rm NS}/v_{\rm NS}^2$$

- DM distribution is 'locally' uniform

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

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

Distribution function



Self-consistently reconstruct density from distribution function:

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

Numbers of cycles

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

	$\gamma_{\text{sp}} = 1.5$	$\gamma_{\text{sp}} = 2.2$	$\gamma_{\text{sp}} = 2.3$	$\gamma_{\text{sp}} = 2.\overline{3}$
Static	< 1	2.4×10^4	1.6×10^5	2.9×10^5
Dynamic	< 1	2.7×10^2	1.9×10^3	3.5×10^3

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

	$\gamma_{\text{sp}} = 1.5$	$\gamma_{\text{sp}} = 2.2$	$\gamma_{\text{sp}} = 2.3$	$\gamma_{\text{sp}} = 2.\overline{3}$
Static	< 1	1.4×10^3	8.7×10^3	1.6×10^4
Dynamic	< 1	6.2×10^2	4.0×10^3	7.4×10^3

TABLE I. **Change in the number of cycles ΔN_{cycles} during the inspiral.** Change in the total number of GW cycles due to dynamical friction, starting 5 years from the merger.

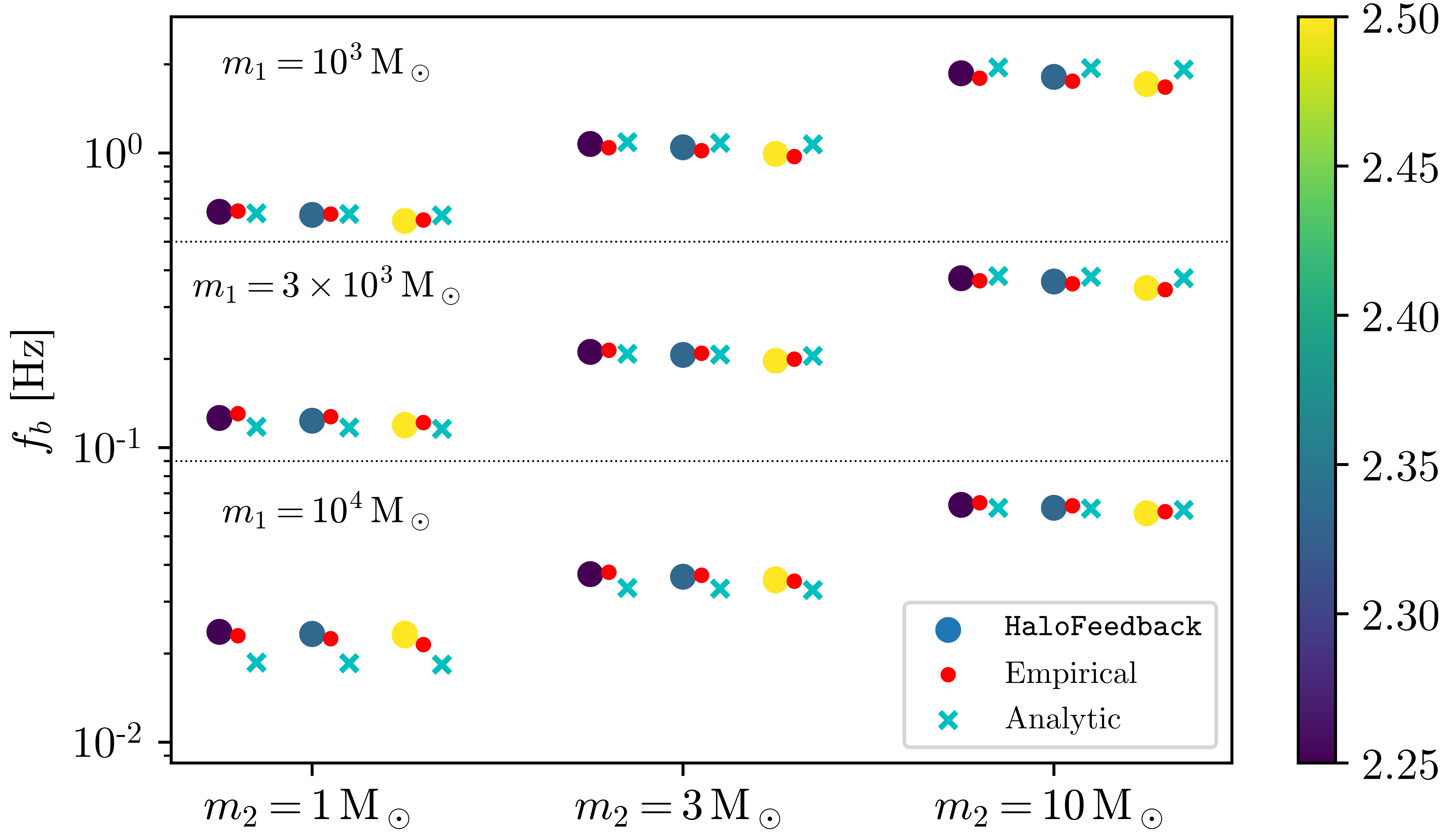
Phase parametrisation

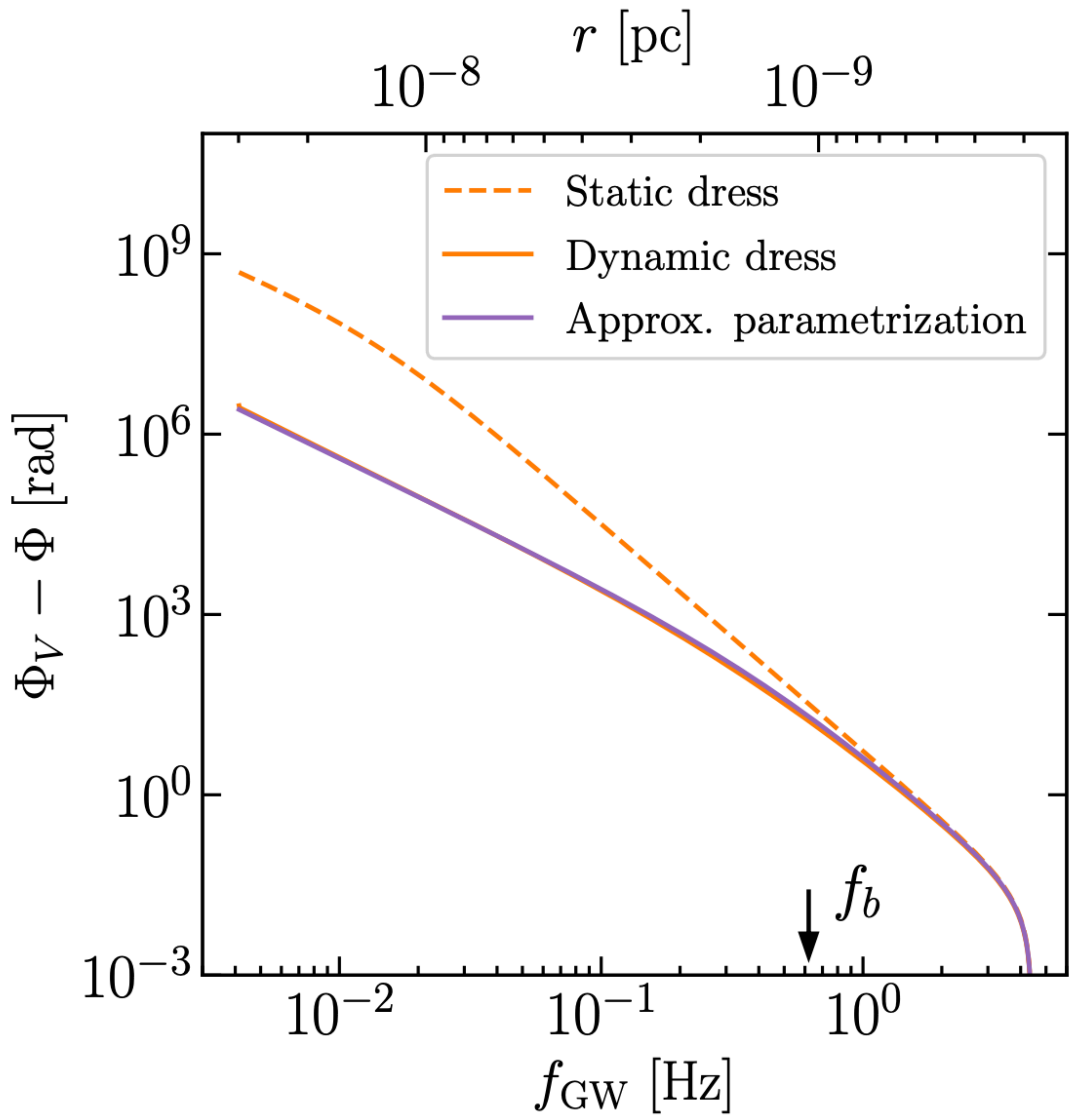
$$\hat{\Phi}(f) \equiv \Phi^{\mathrm{V}}(f) \times \left\{1 - \eta y^{-\lambda}\left[1 - {}_2\mathrm{F}_1\left(1, \vartheta, 1+\vartheta, -y^{-\frac{5}{3\vartheta}}\right)\right]\right\}$$

$$\vartheta = \frac{5}{2\gamma_e}\,, \quad \lambda = \frac{11 - 2\left(\gamma_{\mathrm{sp}} + \gamma_e\right)}{3}\,, \quad \eta = \frac{5 + 2\gamma_e}{2\left(8 - \gamma_{\mathrm{sp}}\right)}\left(\frac{f_{\mathrm{eq}}}{f_b}\right)^{\frac{11-2\gamma_{\mathrm{sp}}}{3}}$$

$$f_b = \beta\left(\frac{m_1}{1000\,\mathrm{M}_\odot}\right)^{-\alpha_1}\left(\frac{m_2}{\mathrm{M}_\odot}\right)^{\alpha_2}\left[1 + \zeta \log\frac{\gamma_{\mathrm{sp}}}{\gamma_r}\right], \quad (35)$$

where $\alpha_1 = 1.4412$, $\alpha_2 = 0.4511$, $\beta = 0.8163\,\mathrm{Hz}$, $\zeta = -0.4971$ and $\gamma_r = 1.4396$.





Axions and neutron stars

Produce a photon with axion energy $m_a \sim 10^{-6}\,\mathrm{eV} \sim 240\,\mathrm{MHz}$

Radio Signal

Conversion happens at a radius r_c, with probability: $p_{a\gamma} \propto \frac{g_{a\gamma\gamma}^2 B\left(r_c\right)^2}{2 v_c}$

Radiated power is given by: $$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega} \sim 2 \times p_{a\gamma} \rho_{\mathrm{DM}}\left(r_c\right) v_c r_c^2$$

Probe axions in the mass range

$m_a \sim 10^{-7}\,\mathrm{eV}$ up to $m_a \sim 10^{-5}\,\mathrm{eV}$

Frequency range of radio telescopes

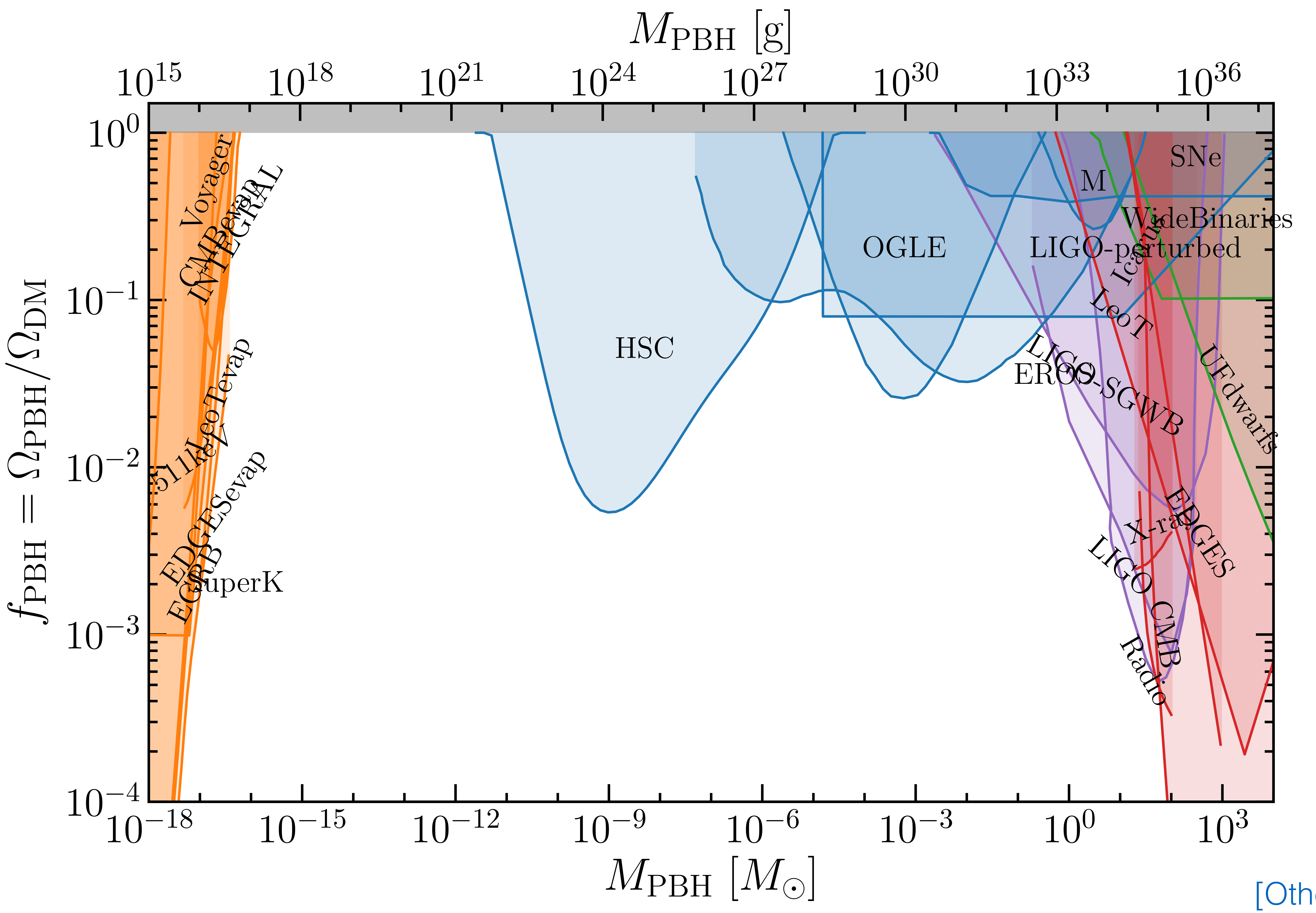
Require conversion *outside* NS

[1803.08230, 1804.03145, 1811.01020, 1910.11907]

PBH Constraints

[Green & **BJK**, 2007.10722]

[Code online: github.com/bradkav/PBHbounds]



[Other reviews: 1801.05235, 2002.12778, 2006.02838]

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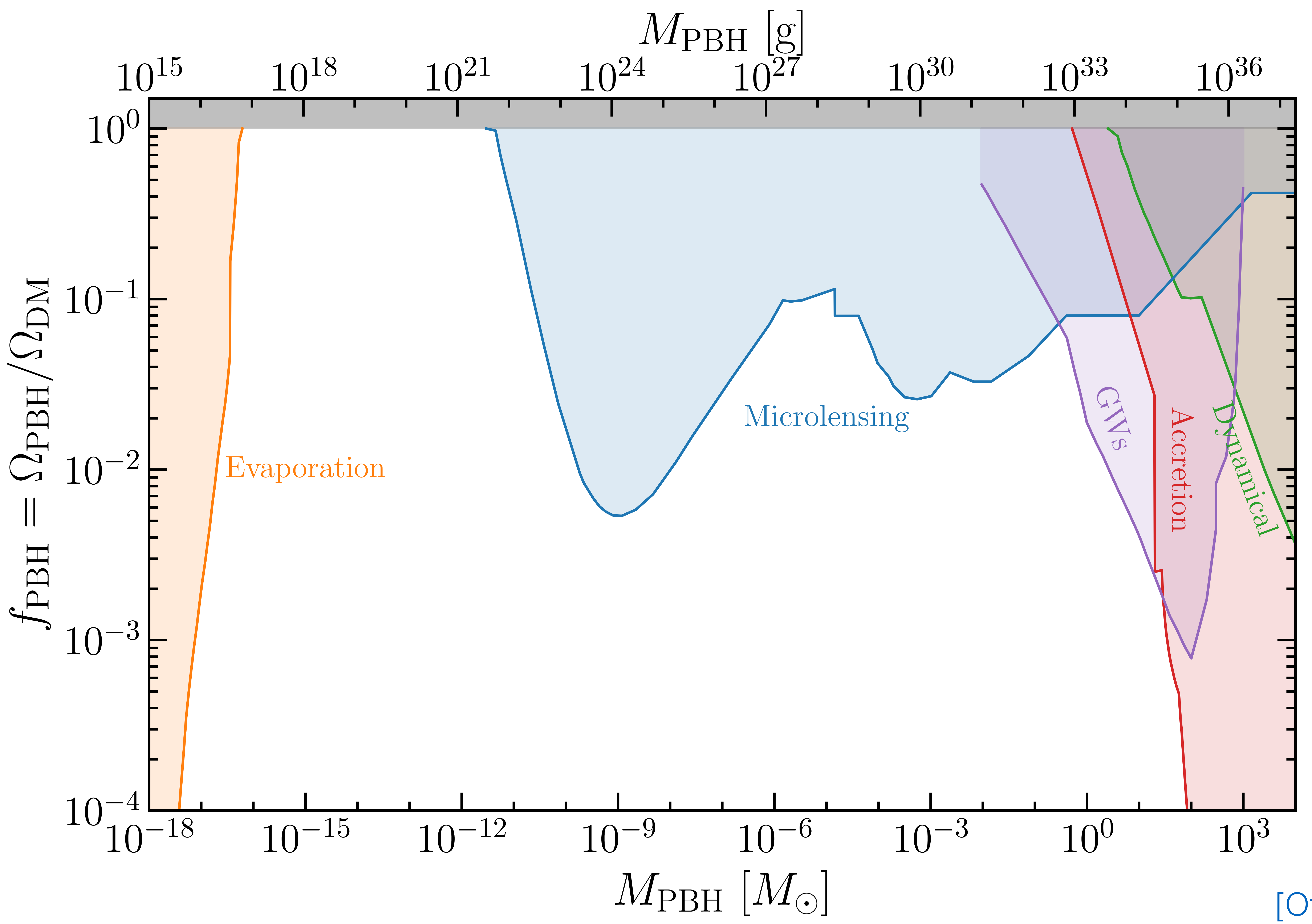

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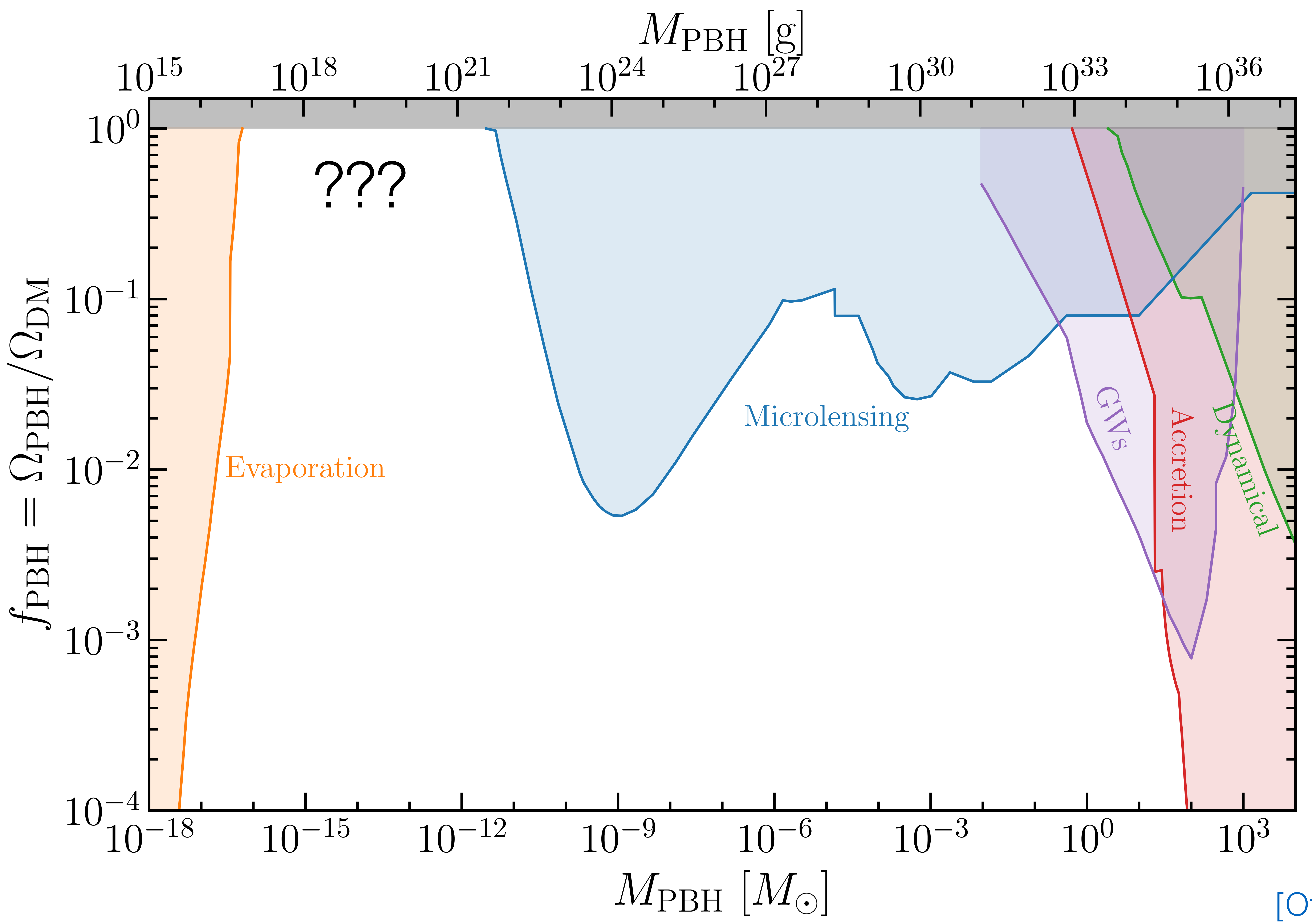
PBH Constraints

[Green & **BJK**, 2007.10722]

[Code online: github.com/bradkav/PBHbounds]



[Other reviews: 1801.05235, 2002.12778, 2006.02838]