Particle dark matter

And how to search for it with gravitational waves

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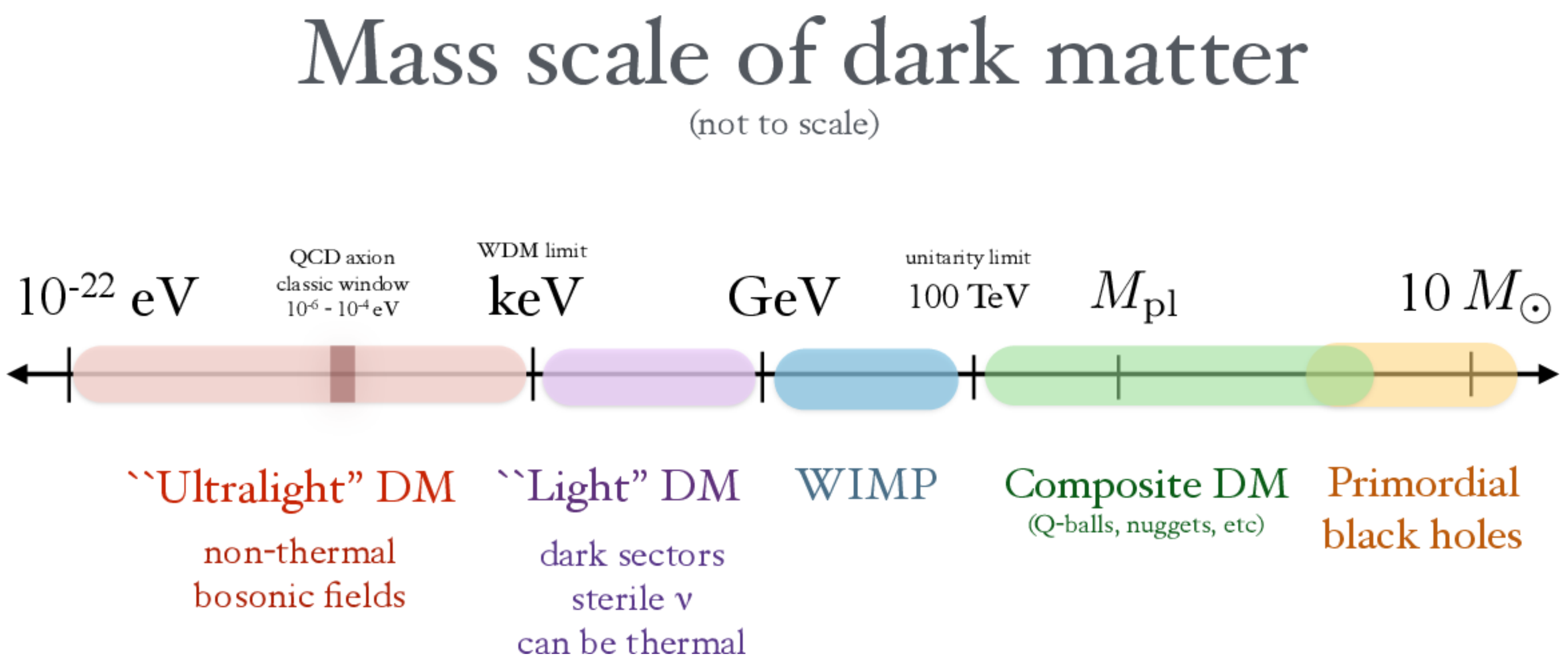
Wide mass range = wide range of probes

Bertone et al. 2020

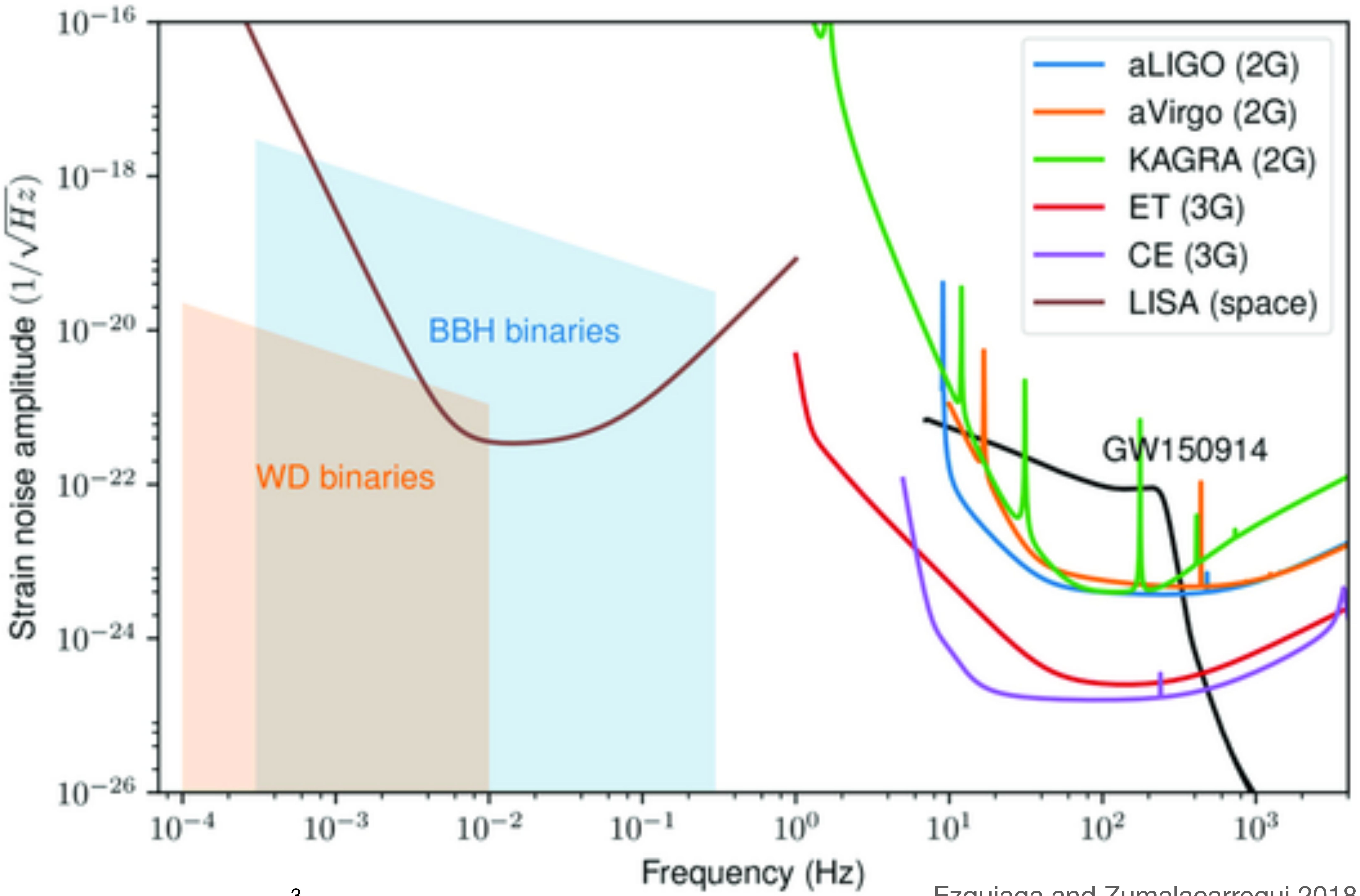


Lin 2019

Vacuum or non-vacuum

Higher frequencies
= smaller masses

- So far, all LIGO/Virgo/KAGRA binary black hole mergers have been detected and measured assuming that they occurred in vacuum
- OK for short duration signals (seconds - minutes for current detectors), but looking towards future interferometers, long duration signals may be affected by their environment



Ezquiaga and Zumalacarregui 2018

Environmental effects

- Cause inspiral of black hole binary to either speed up or slow down with respect to vacuum case

- A dephasing accumulates, which alters the gravitational waveform from the binary's inspiral

Change in separation of the binary

$$\dot{r} = \dot{r}_{\mathrm{GW}} + \dot{r}_{\mathrm{env}}$$

Frequency evolution

$$f(t) = \frac{1}{\pi}\sqrt{\frac{GM}{r(t)^3}}$$

Phase evolution

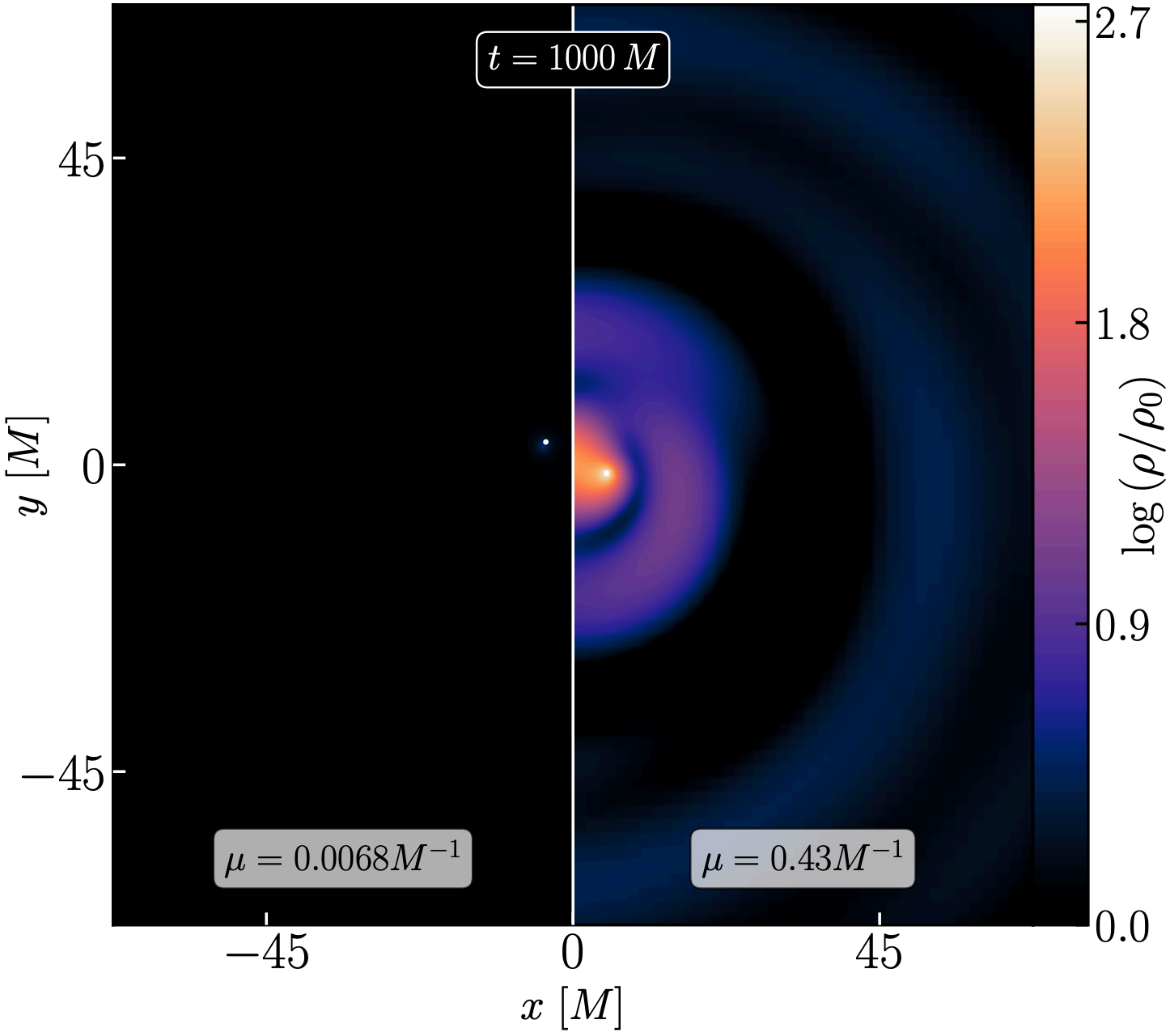
$$\Phi(f) = \int_f^{f_{\mathrm{ISCO}}} \frac{\mathrm{d}t}{\mathrm{d}f'} f' \,\mathrm{d}f'$$

Gravitational wave amplitude

$$h_0(f) = \frac{1}{2}\frac{4\pi^{2/3}G_N^{5/3}\mathcal{M}^{5/3}f^{2/3}}{c^4}\sqrt{\frac{2\pi}{\ddot{\Phi}}}$$

Equal mass ratios

- Dark matter spike disperses for WIMP-like particle dark matter
- But for ultra-light dark matter, simulations suggest that it may survive even an equal mass ratio merger

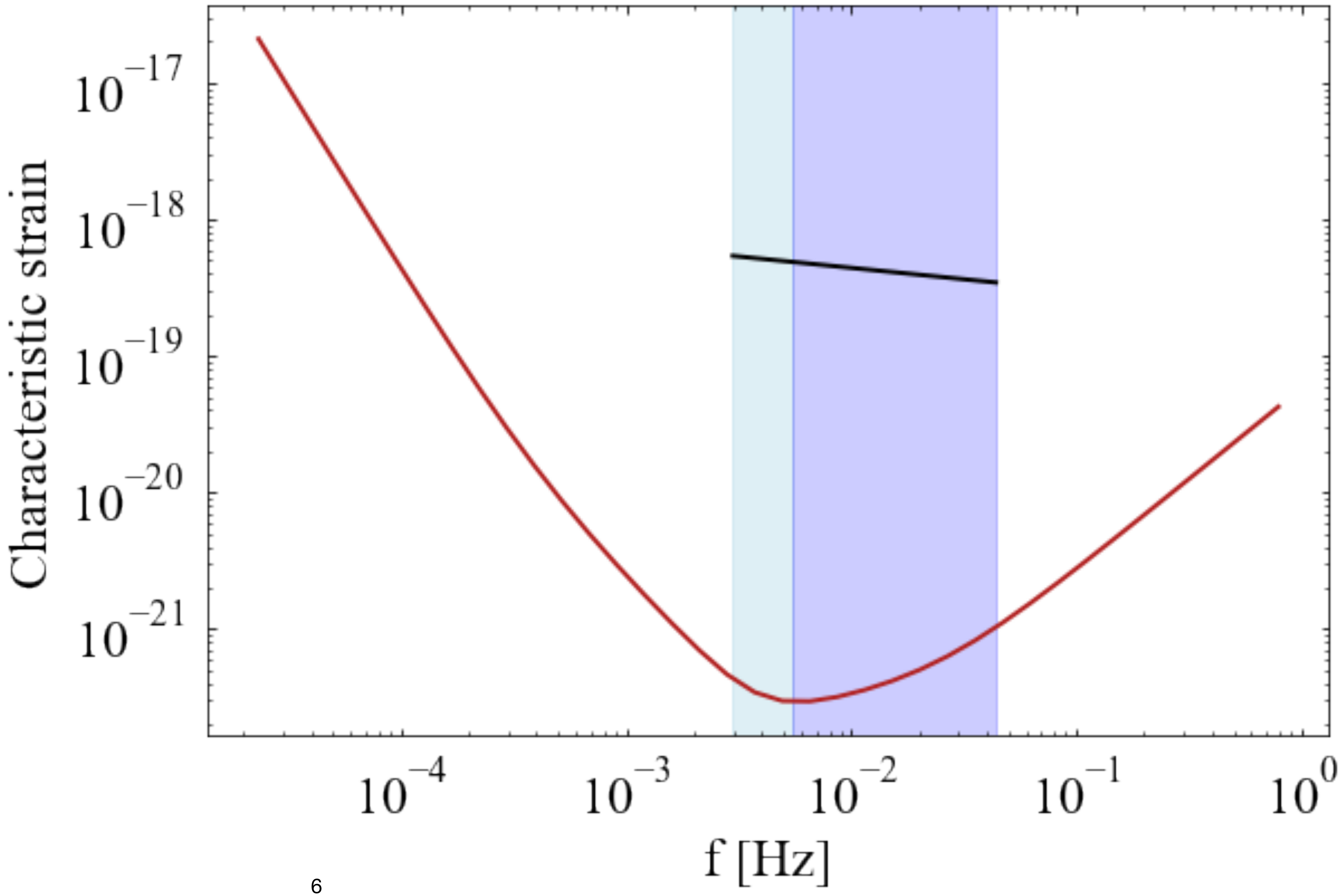


Aurrekoetxea et al. *Phys.Rev.Lett.* 132 (2024) 21, 211401

Extreme mass ratios

- dephasing accumulates over thousands or millions of cycles
- small mass ratio $q = \dfrac{m_2}{m_1} < 10^{-2.5}$ so that environment survives
- systems possible sources for LISA and Einstein Telescope/Cosmic Explorer

$m_1 = 10^5\,\mathrm{M}_\odot, \quad m_2 = 10\,\mathrm{M}_\odot$



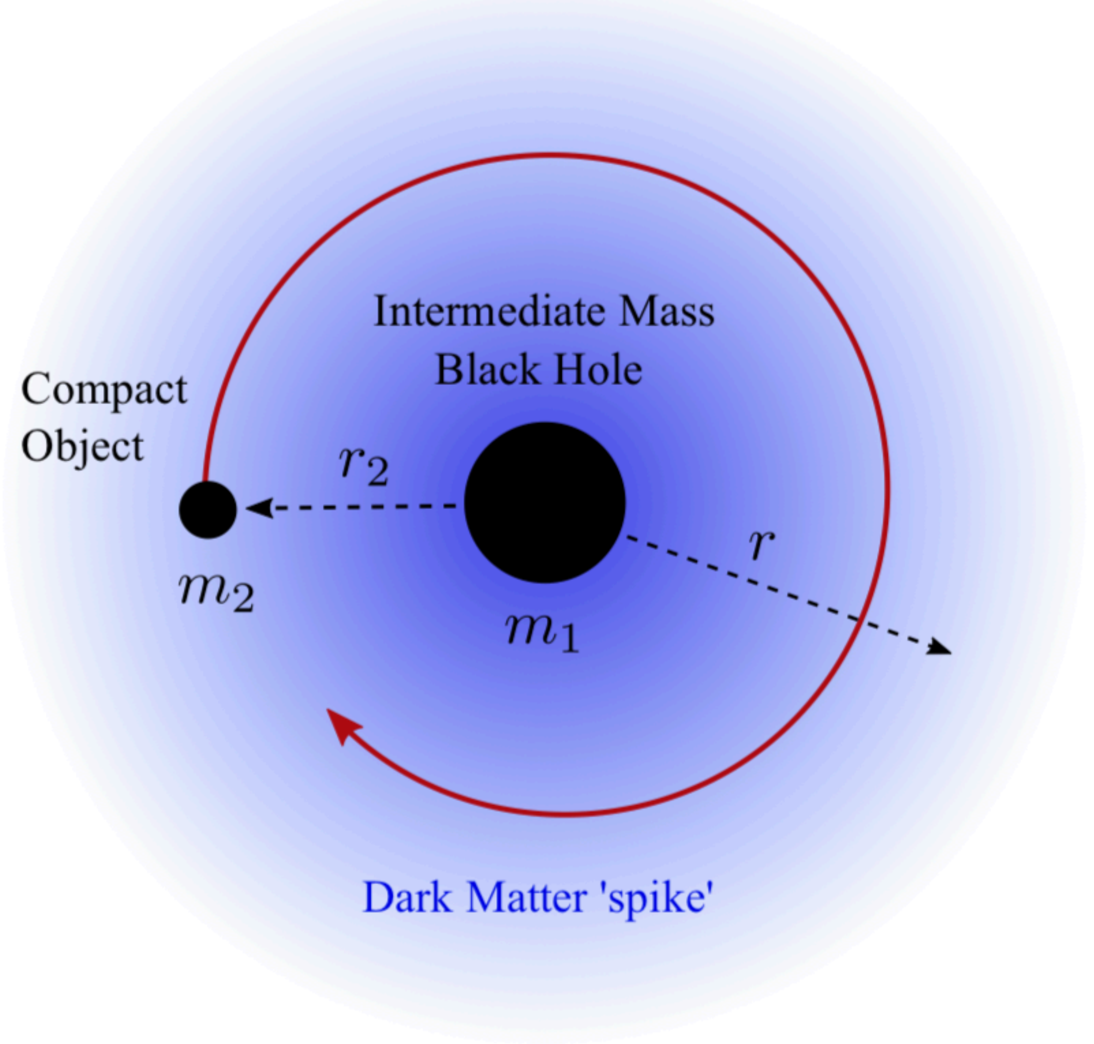
Why should we care about environmental effects?

- We have a chance to learn about the environment itself (which could involve dark matter) via the dephasing in the waveform.
- If we search the data with the wrong ‘template’ we might miss the signal
- If we do parameter estimation with the ‘wrong’ parameters, we might come up with biased results

See also Barausse, Cardoso, Pani 2011

Dark dress

Cold, collisionless dark matter

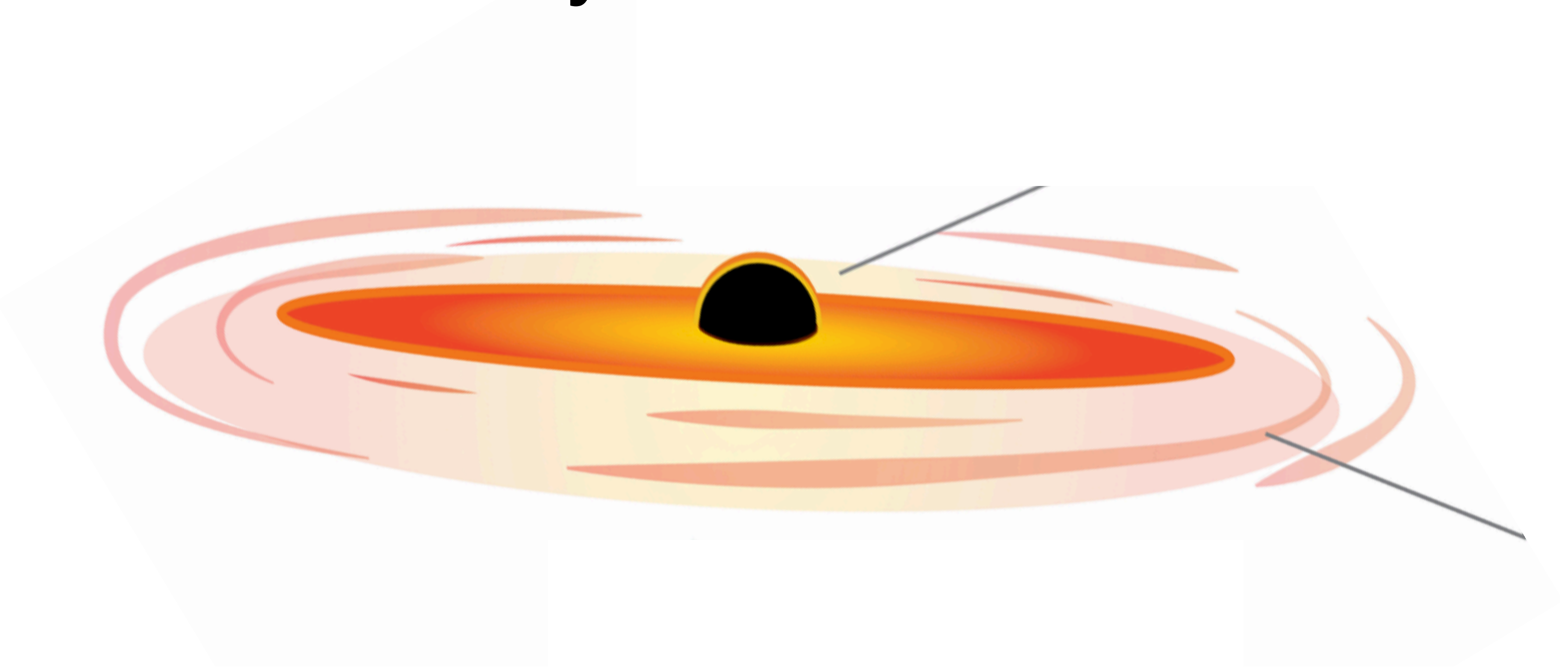


$$\rho(r) = \rho_6 \left(\frac{r_6}{r}\right)^{\gamma_s}$$

Eda et al. 2013, 2014
Gondolo, Silk 1999
Kavanagh et al. 2020
Coogan et al. 2021

Accretion disk

Baryonic matter



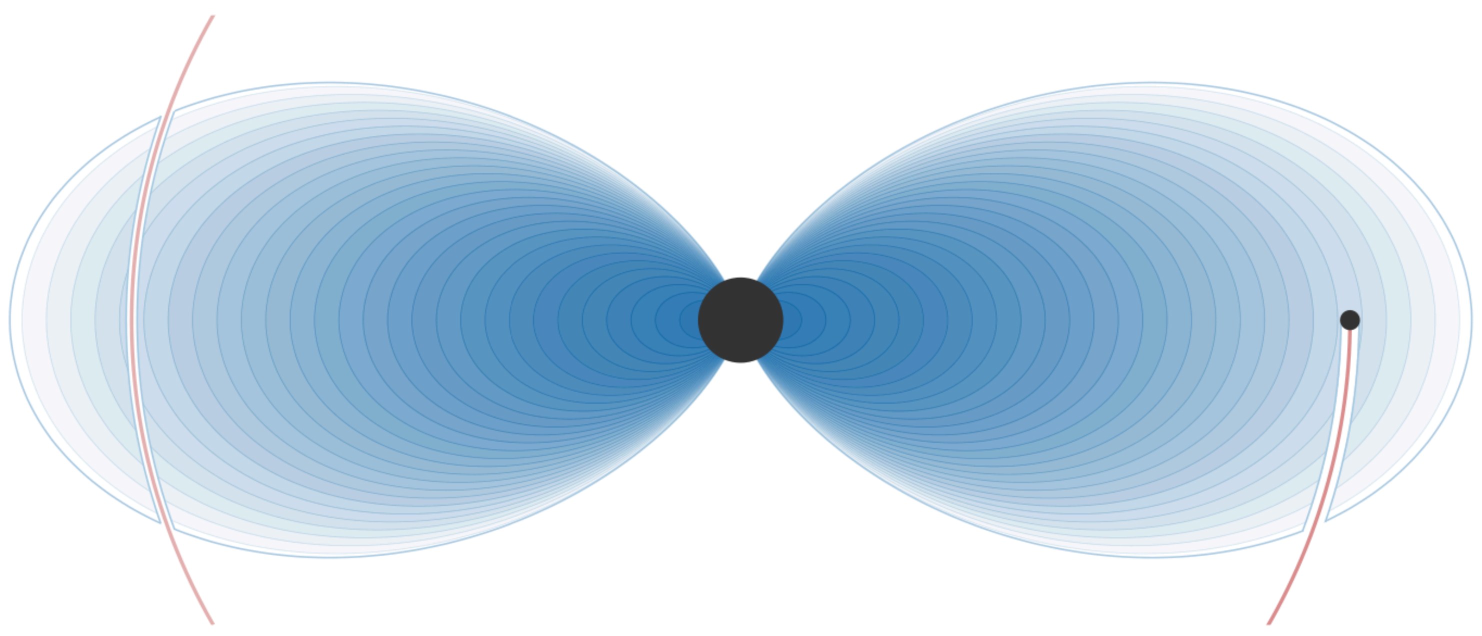
$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1/2}$$

$$M = r/h$$

Goldreich & Tremaine 1980
Tanaka 2002
Derdzinski et al. 2020
Speri et al. 2023

Gravitational atom

Ultra-light bosons



$$\rho(\vec{r}) = M_c |\psi(\vec{r})|^2$$

$$\alpha \equiv G m_1 \mu \ll 1$$

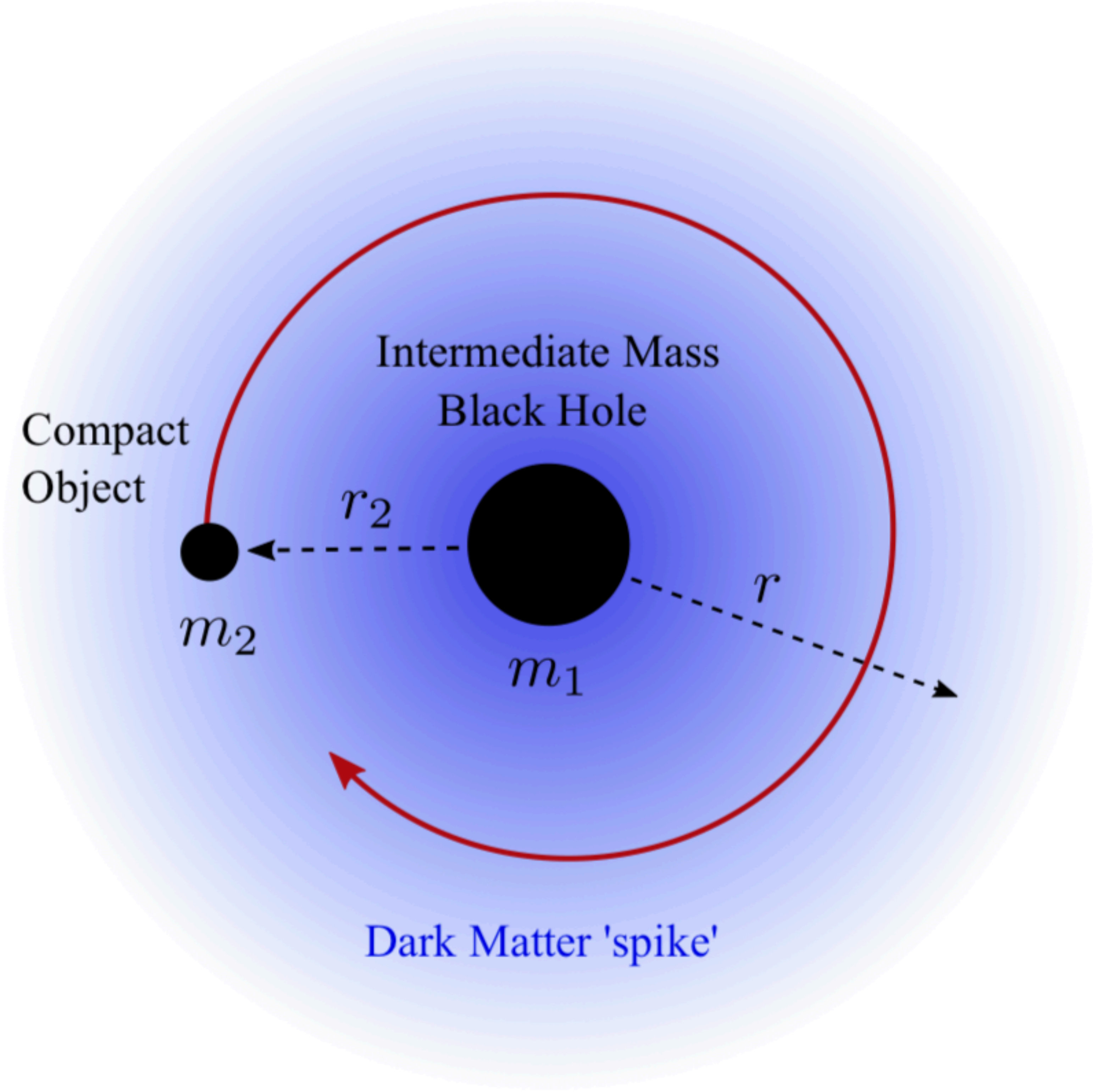
Mass of light scalar field
$(10^{-10} - 10^{-20}\,\mathrm{eV})$

Baumann et al. 2019
Arvanitaki & Dubovsky 2010
Bauman et al. 2021, 2022

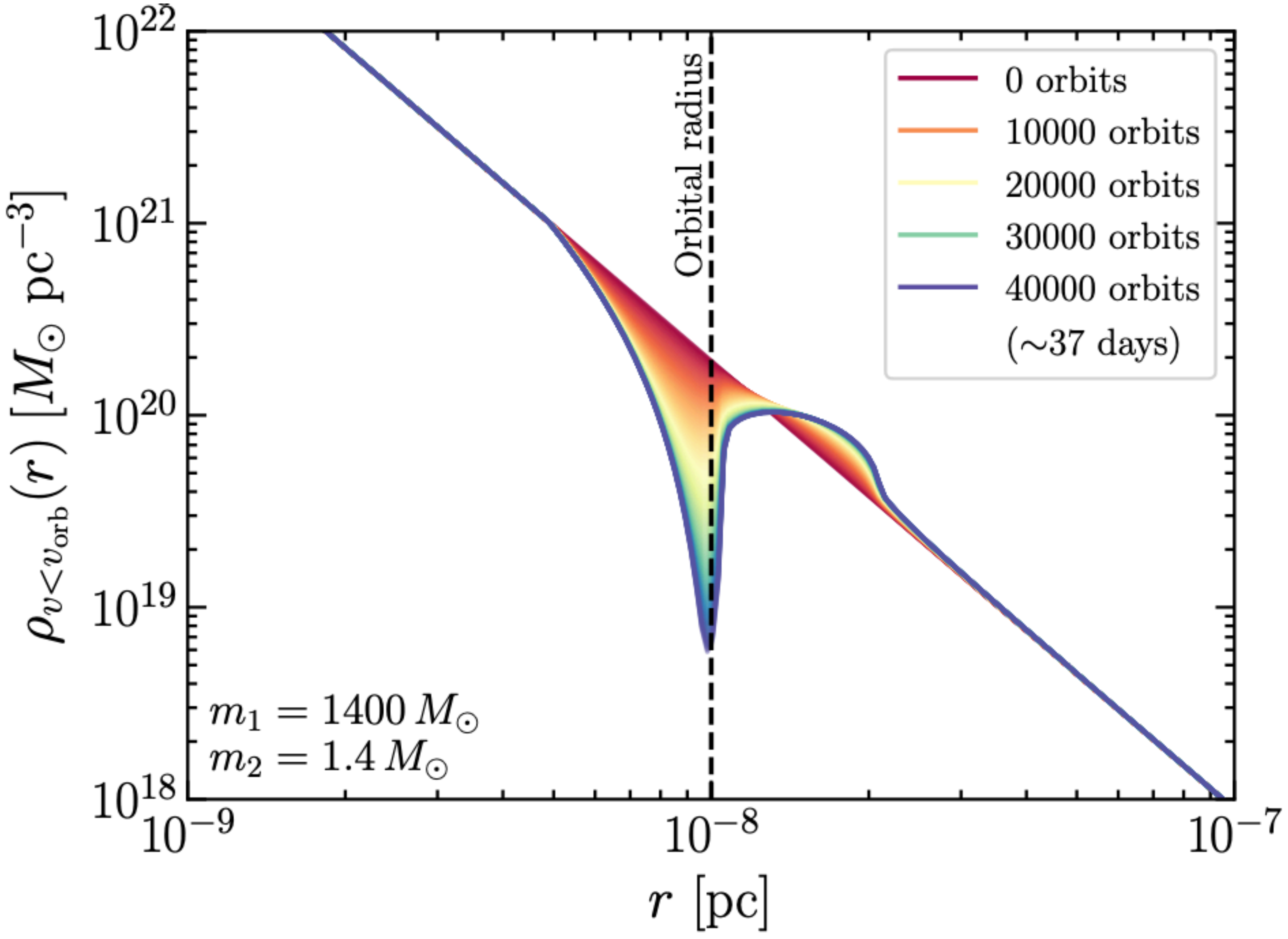
Credit: Sophia Dagnello, NRAO/AUI/NSF

Dynamical friction

$$\dot{r}_{\rm DF} = -\frac{8\pi\, G_N^{1/2}\, m_2\, \log\Lambda r_2^{5/2}\, \rho_{\rm DM}(r_2,t)\,\xi(r_2,t)}{\sqrt{M}m_1}$$

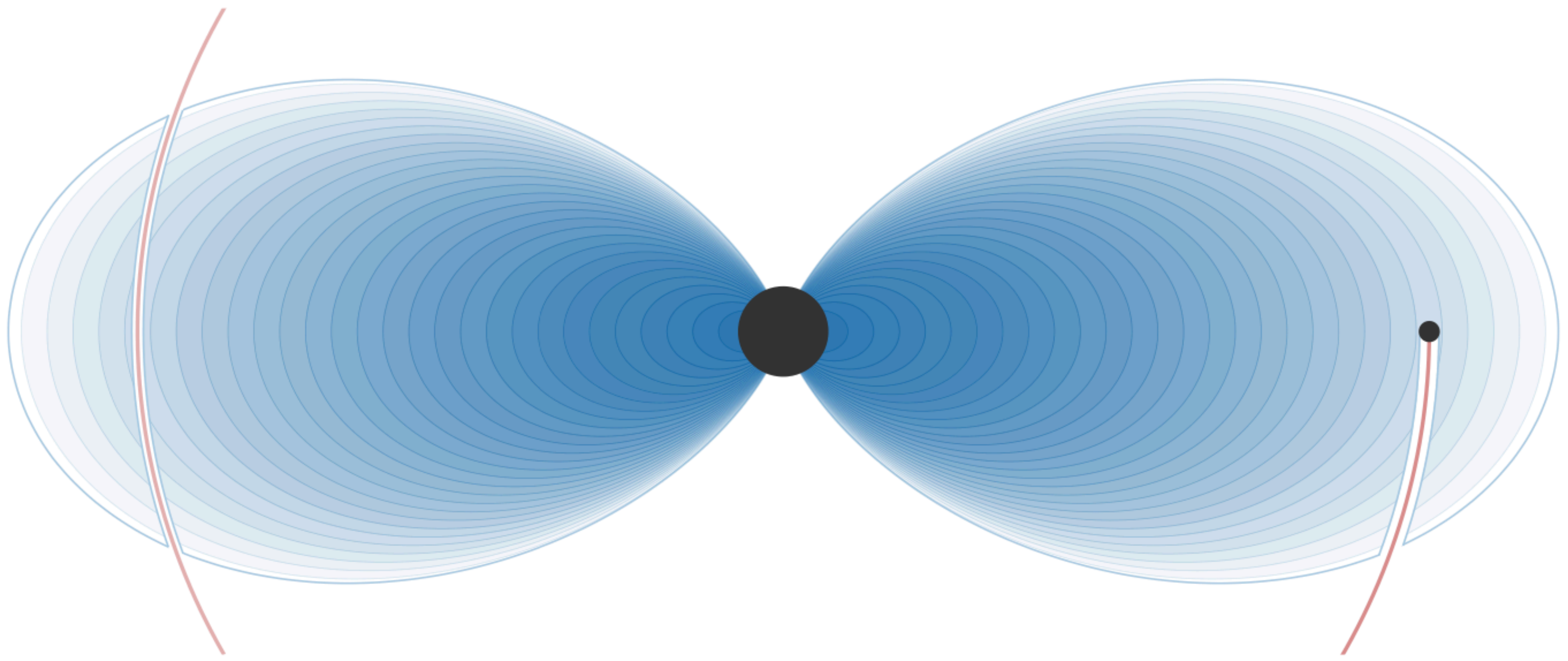


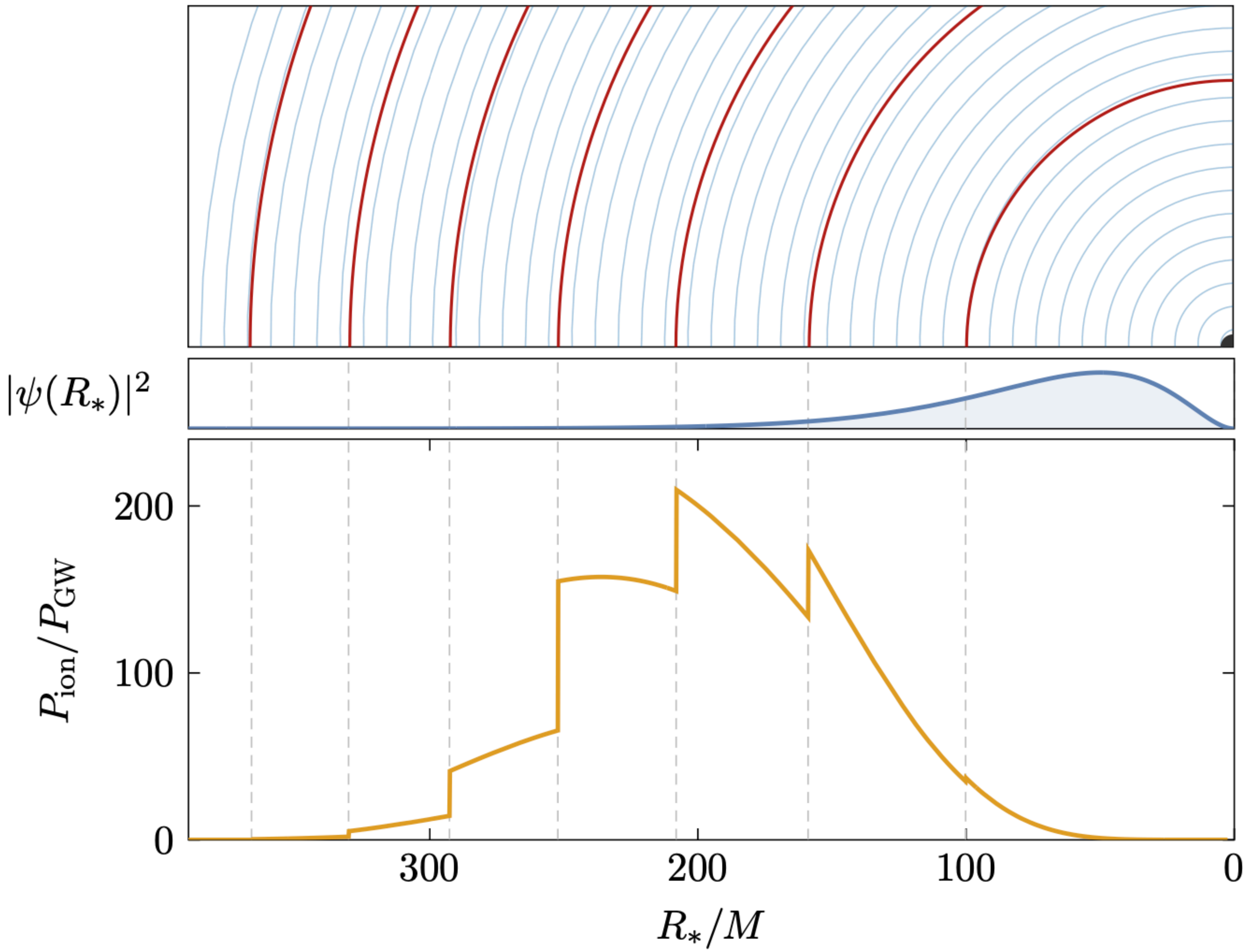
HaloFeedback



Kavanagh, Nichols, Bertone, Gaggero 2020

Ionization





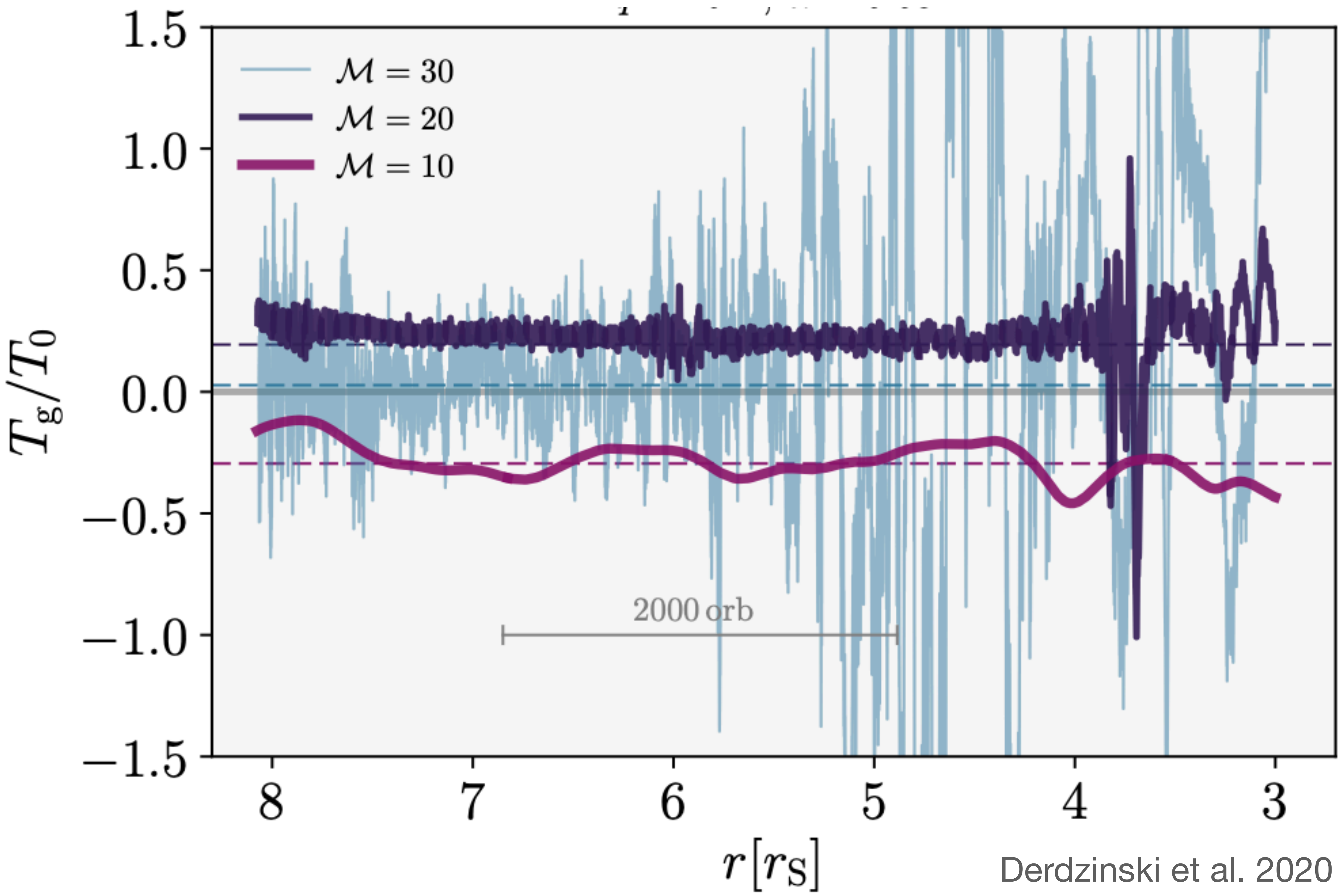
Perturber excites resonances in the cloud and it transitions from bound states to unbound states as the orbital frequency of the perturber hits the frequency of the energy difference between states

Baumann, Bertone, Stout, Tomaselli 2021

Gas torques

$$\dot{r}_{\rm gas} = \frac{\dot{L}_{\rm gas} r^{1/2}}{2\sqrt{G(m_1+m_2)}m_2)}$$

$$\dot{L}_{\rm gas} = T_{\rm gas} = \pm\,\Sigma(r) r^4 \Omega^2 q^2 M^2$$



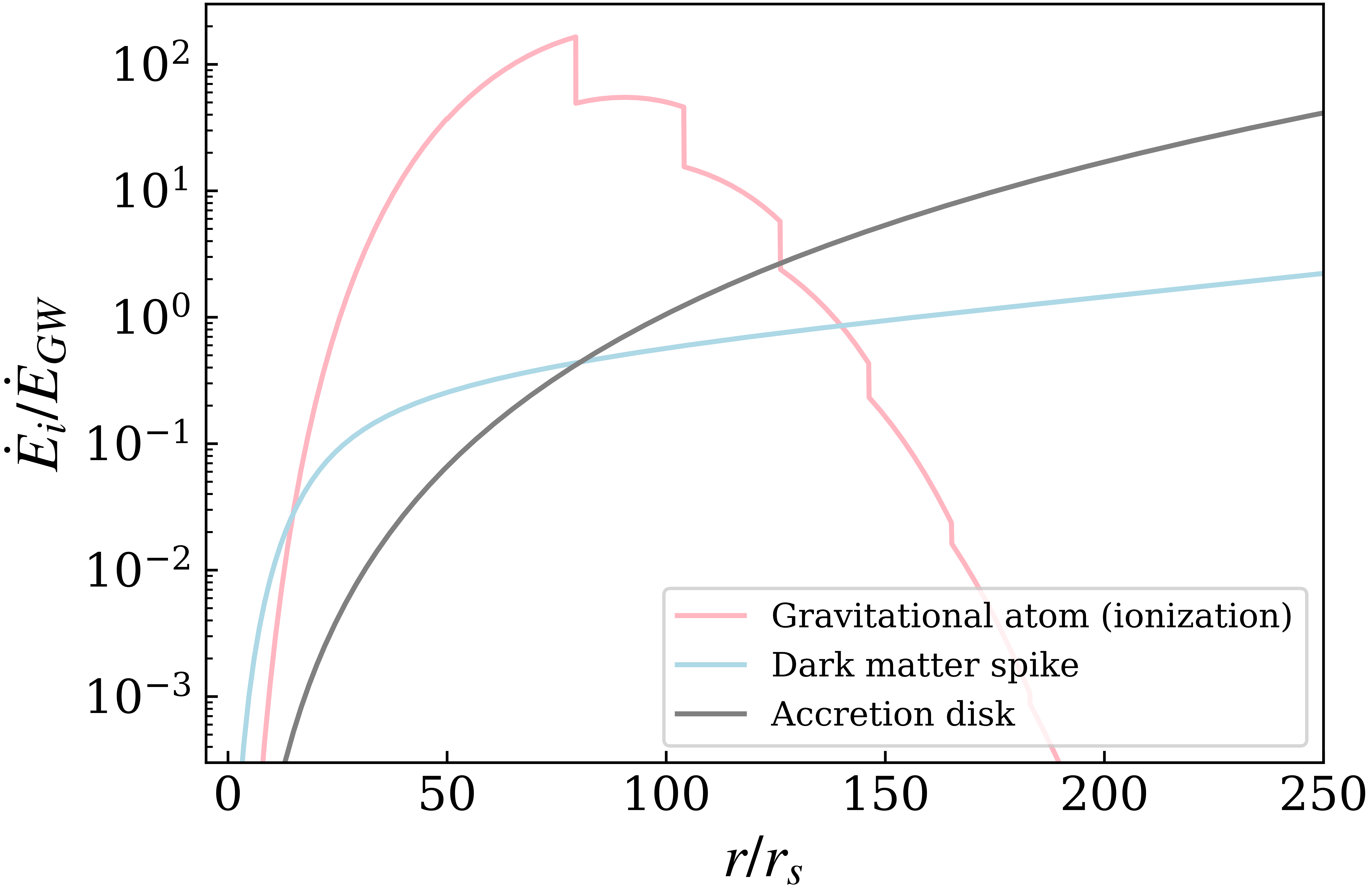
Derdzinski et al. 2020

Assume gas in the disk is corotating with the companion object, which is orbiting in the plane of the disc.

Assume Mach number is locally constant, independent of r, i.e. locally isothermal.

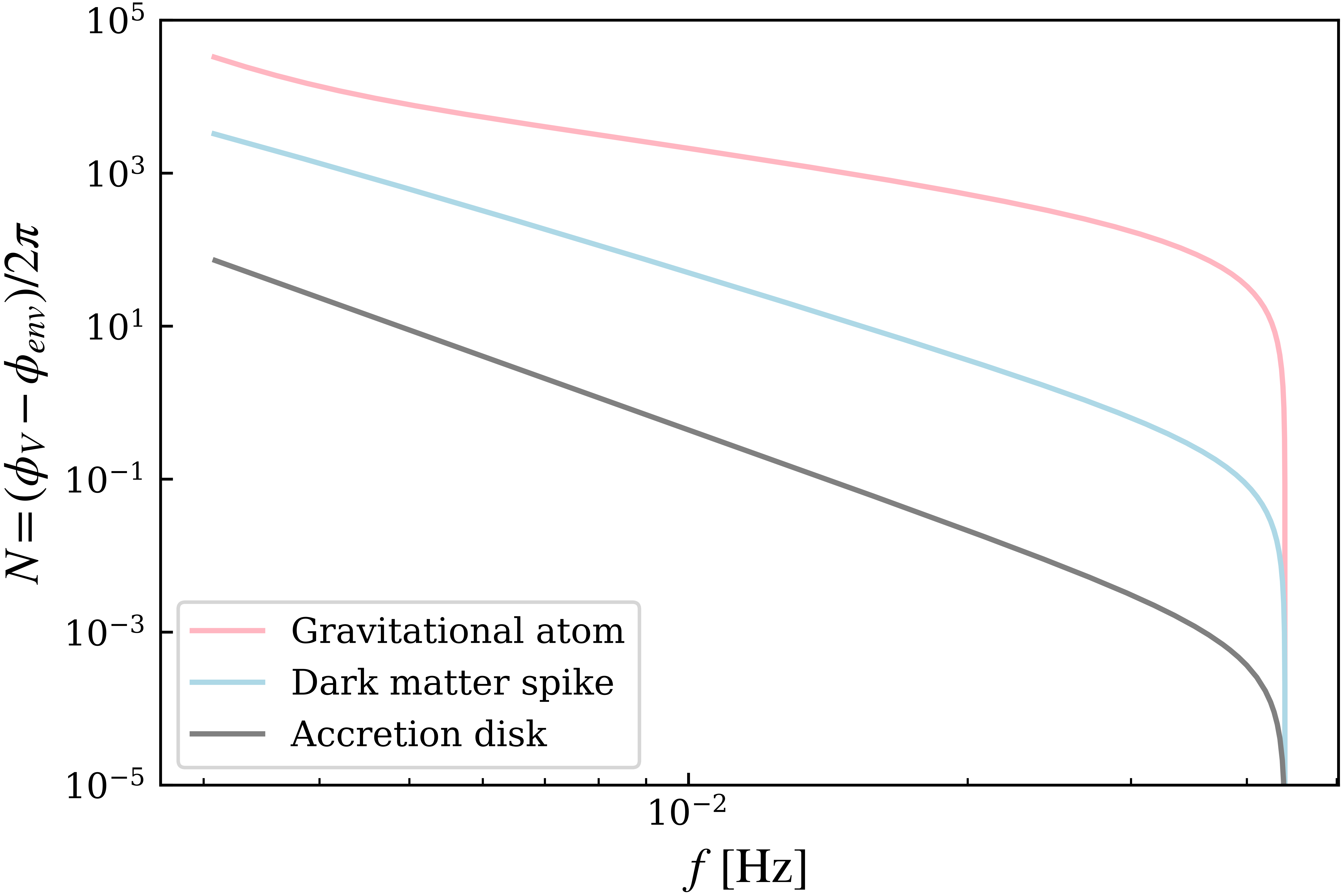
See e.g. Goldreich & Tremaine 1980, Tanaka 2002, Derdzinski et al. 2020

Energy losses



Cole et al. 2023

Dephasing



Cole et al. 2023

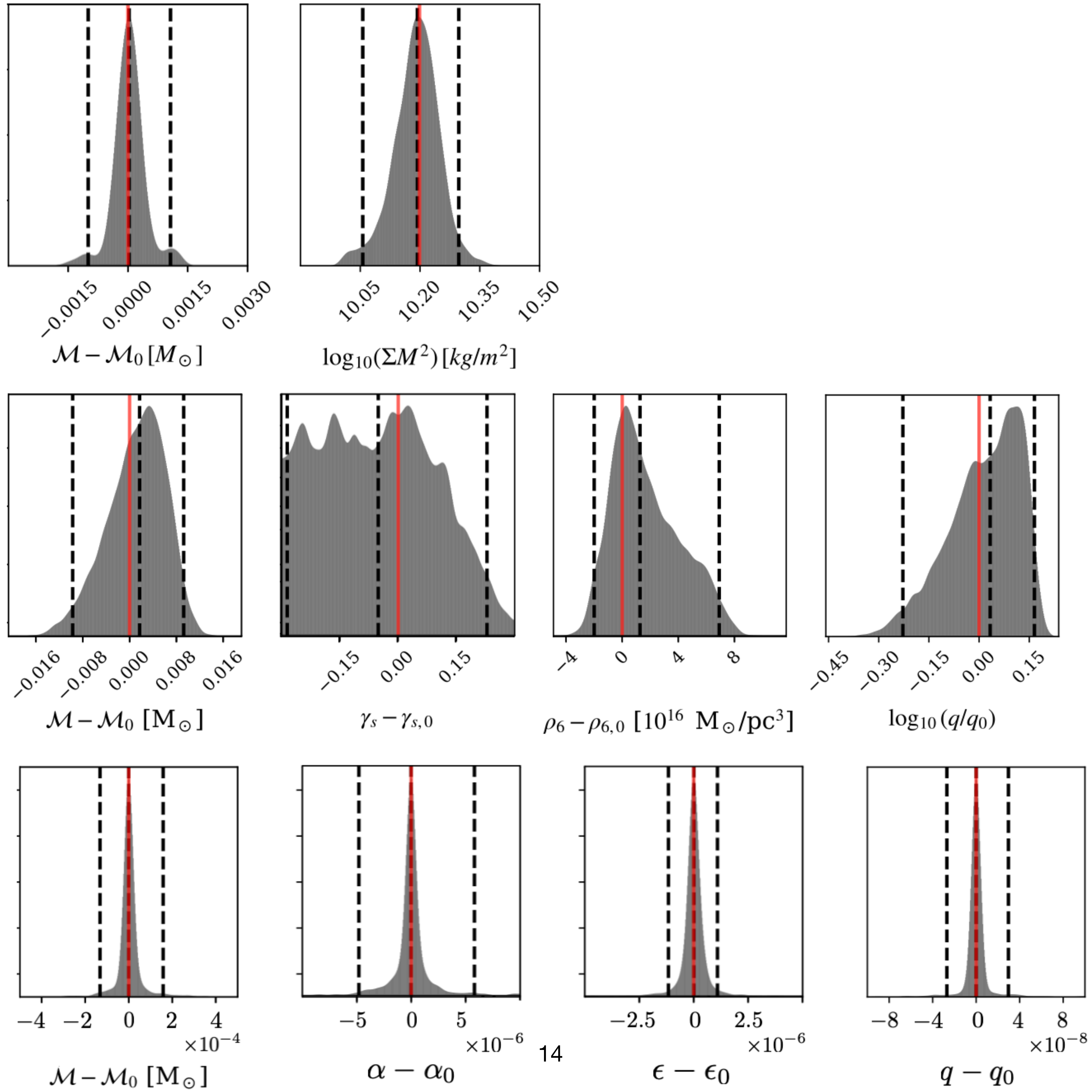
Assuming we've detected a signal, can we measure the parameters?

Parameter estimation with correct model

Accretion disk

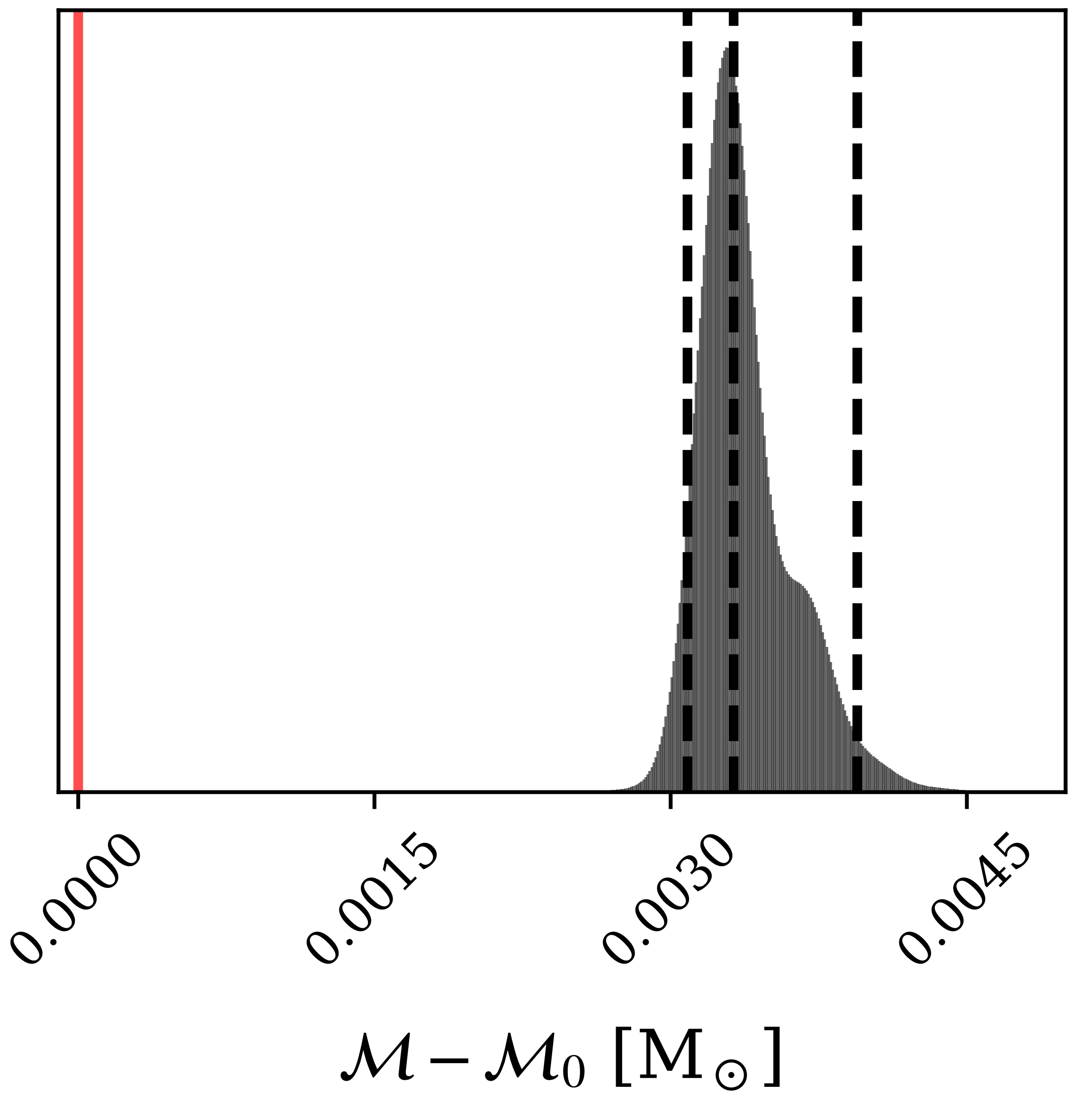
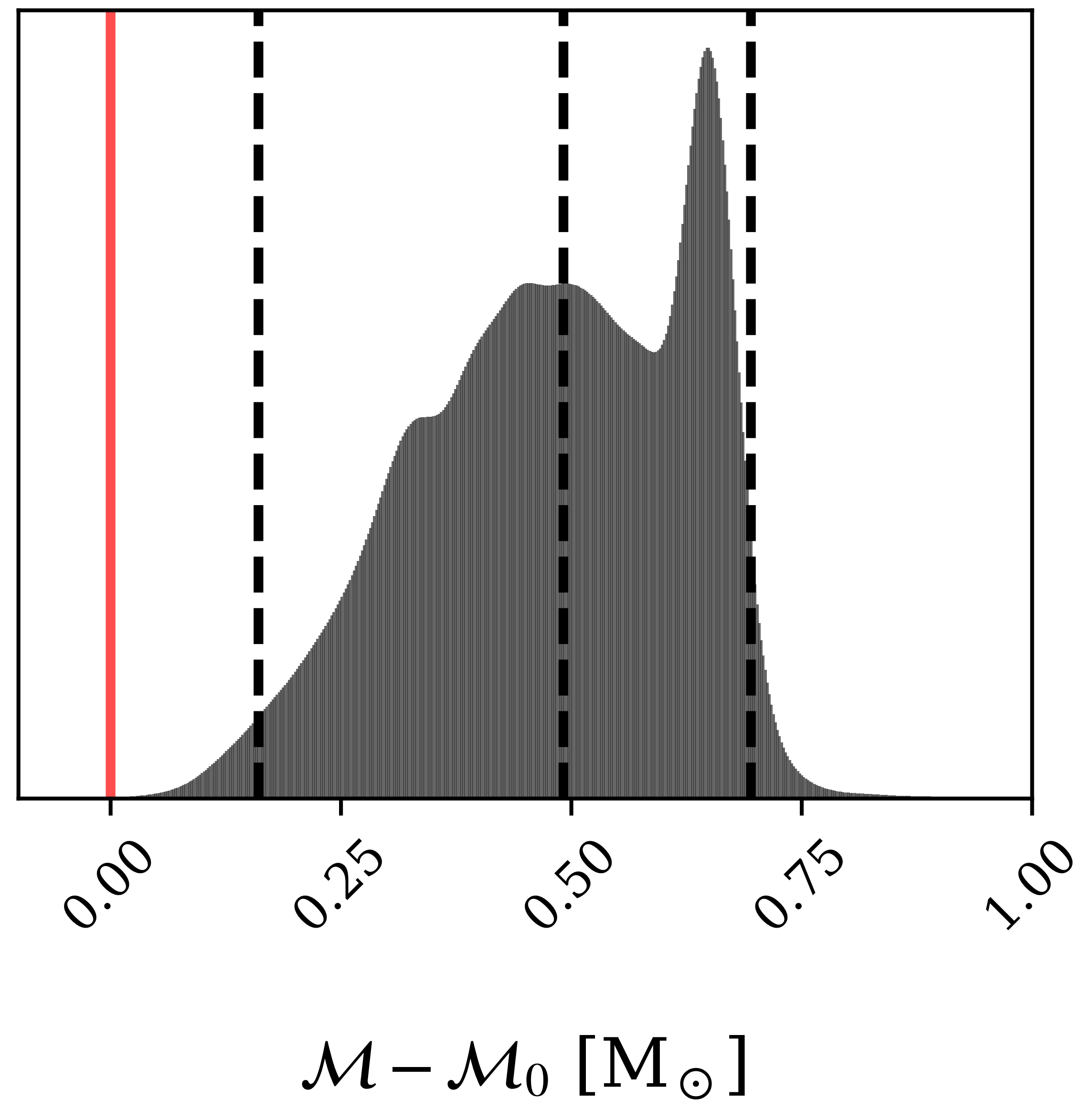
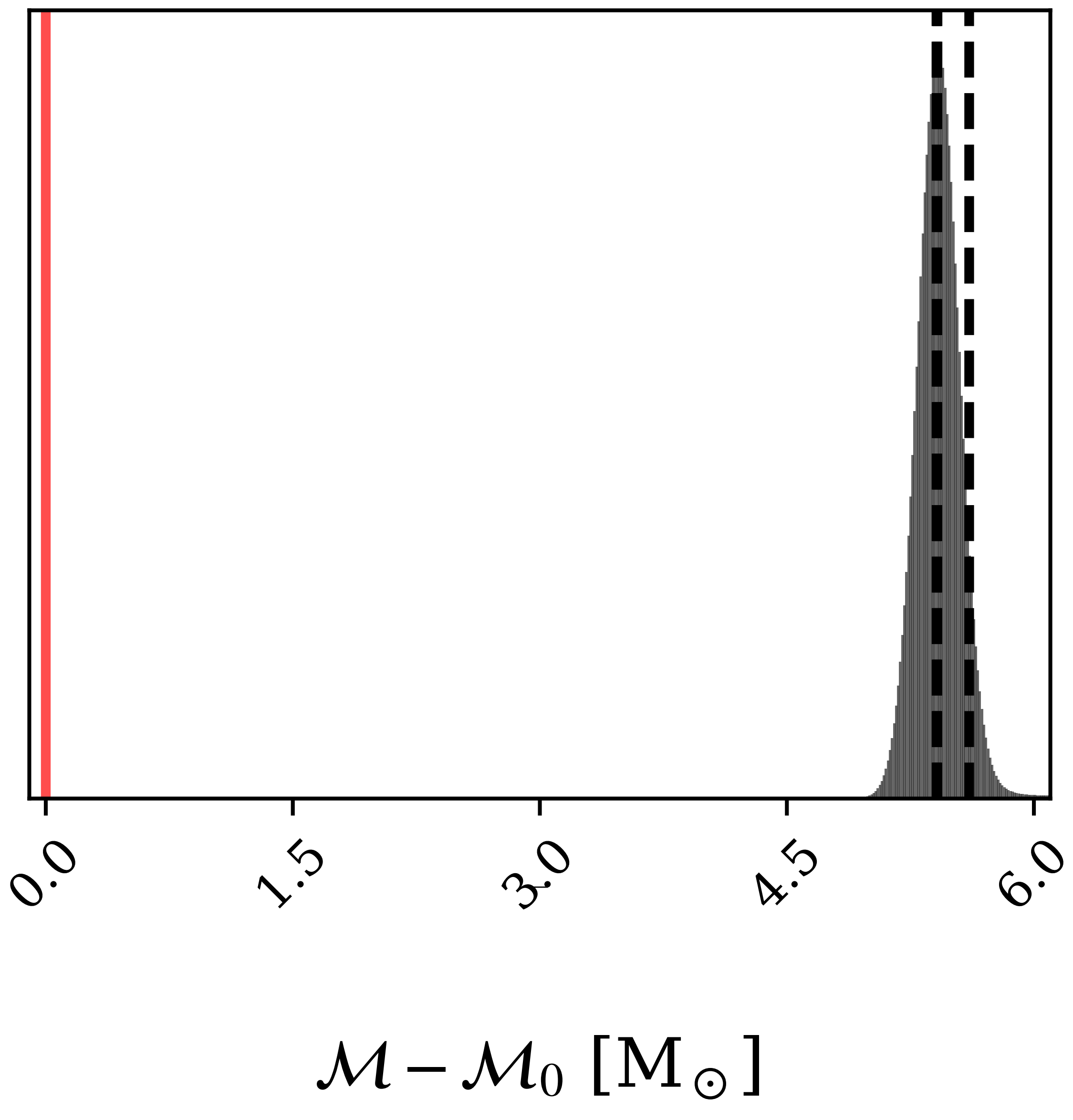
Dark dress

Gravitational atom



Cole et al. 2023

Parameter estimation with vacuum waveform

<table>
<tr><th></th><th>Accretion disk signal</th><th>Dark dress signal</th><th>Grav atom signal</th></tr>
<tr><td>Vacuum template</td><td>
</td><td>
</td><td>
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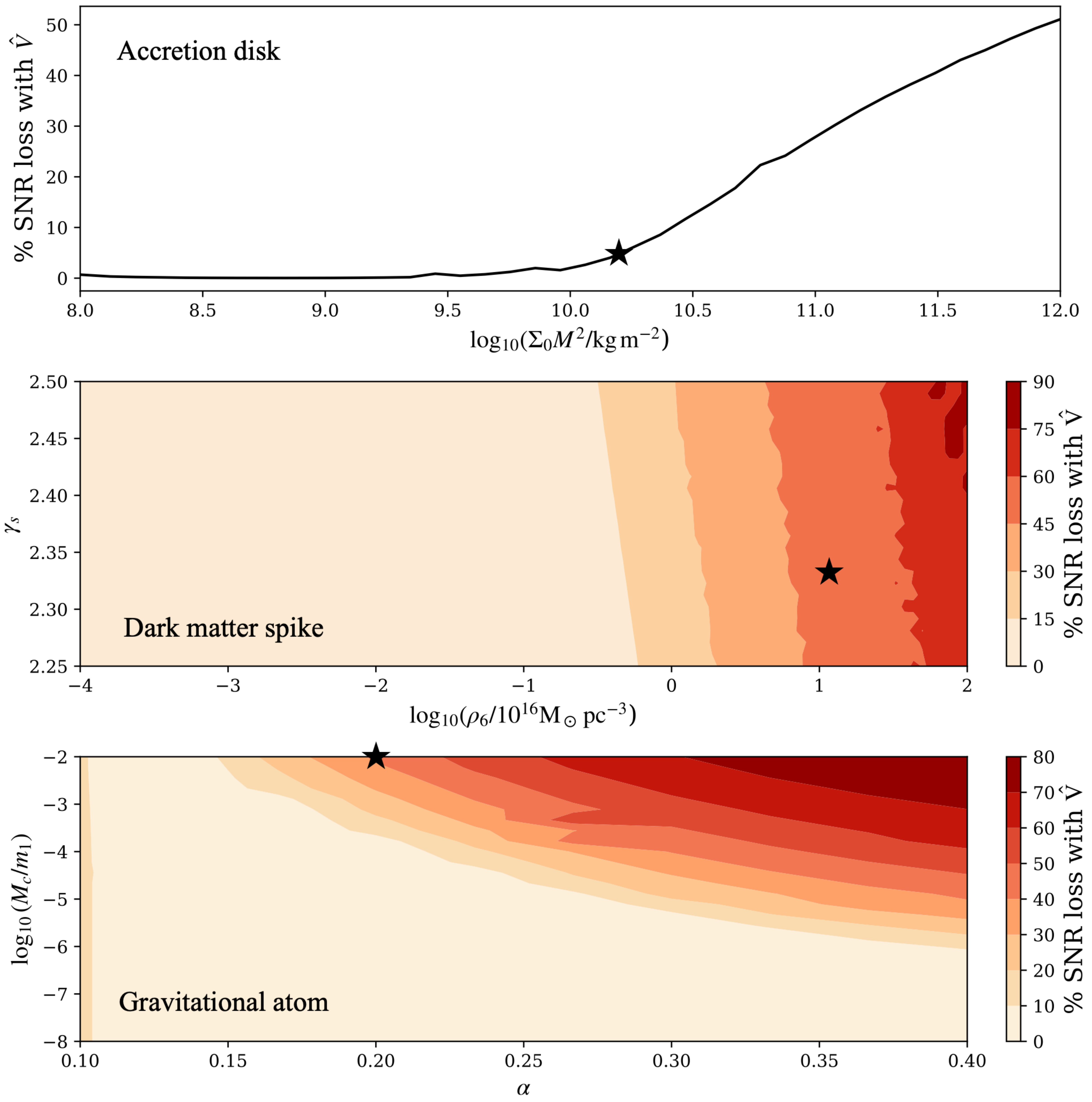
Cole et al. 2023

SNR loss: biased PE or miss signal entirely



Cole et al. 2023

Bayesian model comparison shows confident preference for correct model over any other environment

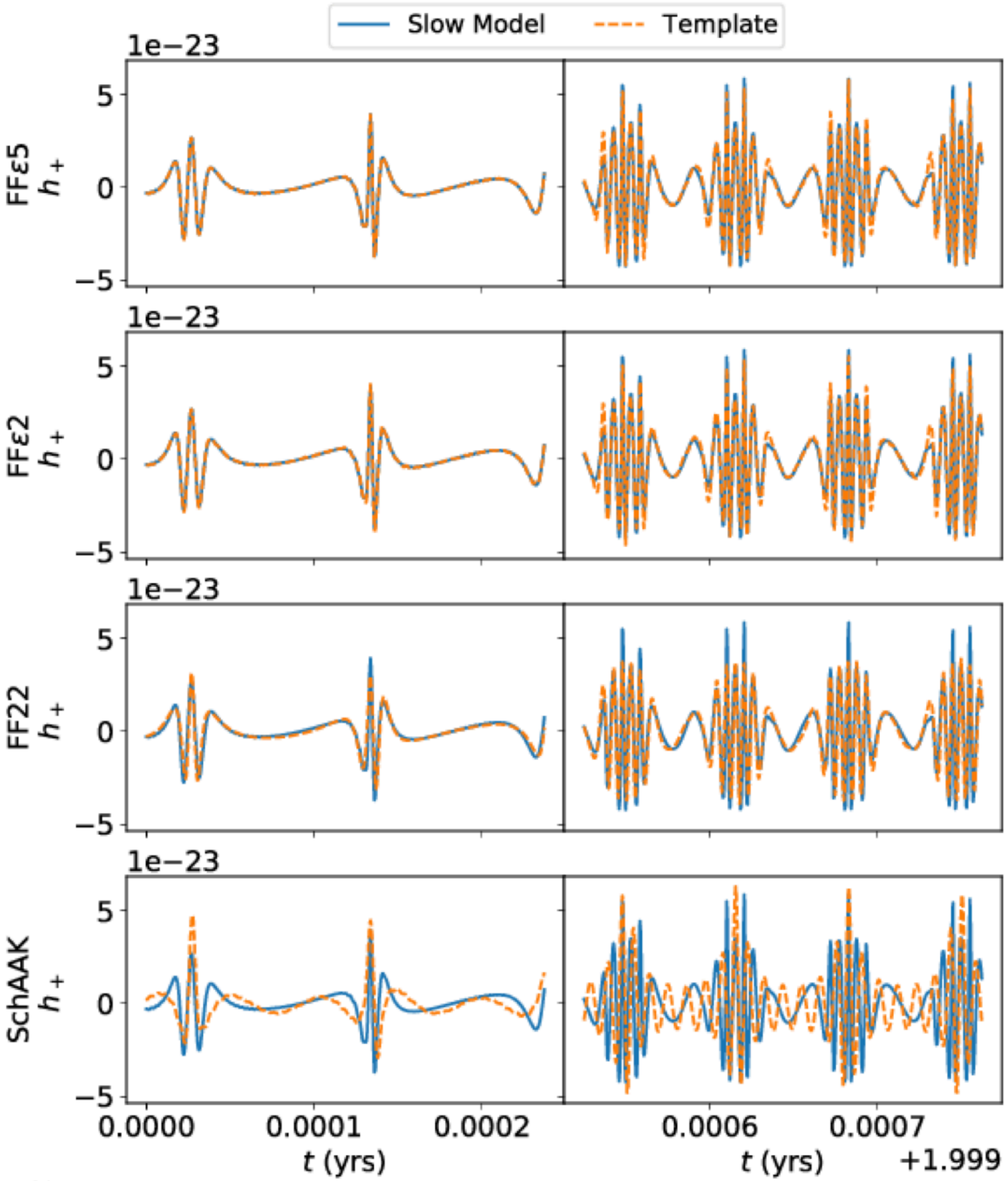
$\log_{10} \mathcal{B}$	Dark dress signal	Accretion disk signal	Gravitational atom signal
Vacuum template	34	6	39
Dark dress template	-	3	39
Accretion disk template	17	-	33
Gravitational atom template	24	6	-

Improvements to signal modelling

- Use higher order waveforms
- For example Fast EMRI Waveforms (FEW)
- Improvements to environmental modelling also required

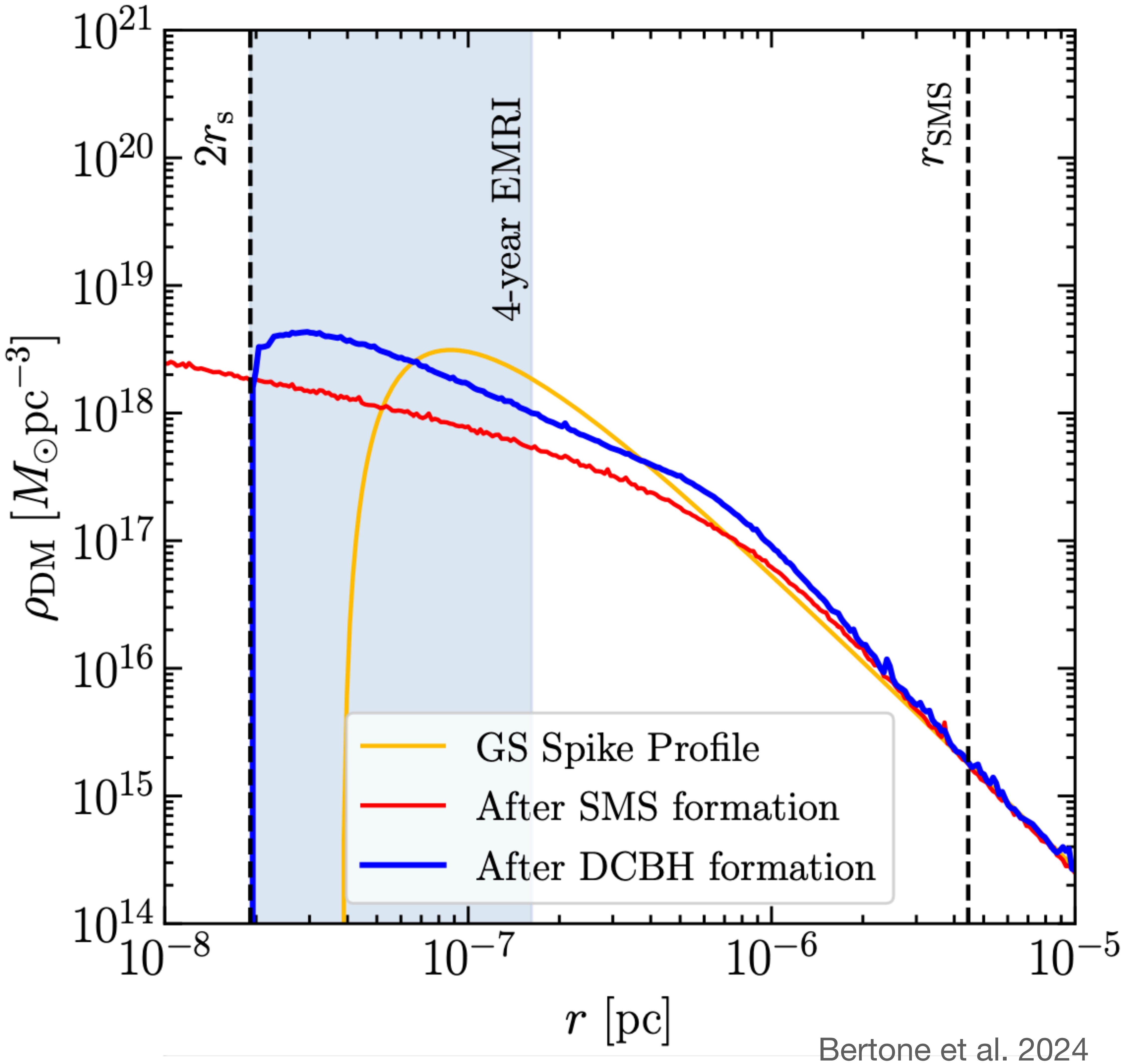
e.g. Speeney et al. 2022

Katz et al. *Phys.Rev.D* 104 (2021) 6, 064047



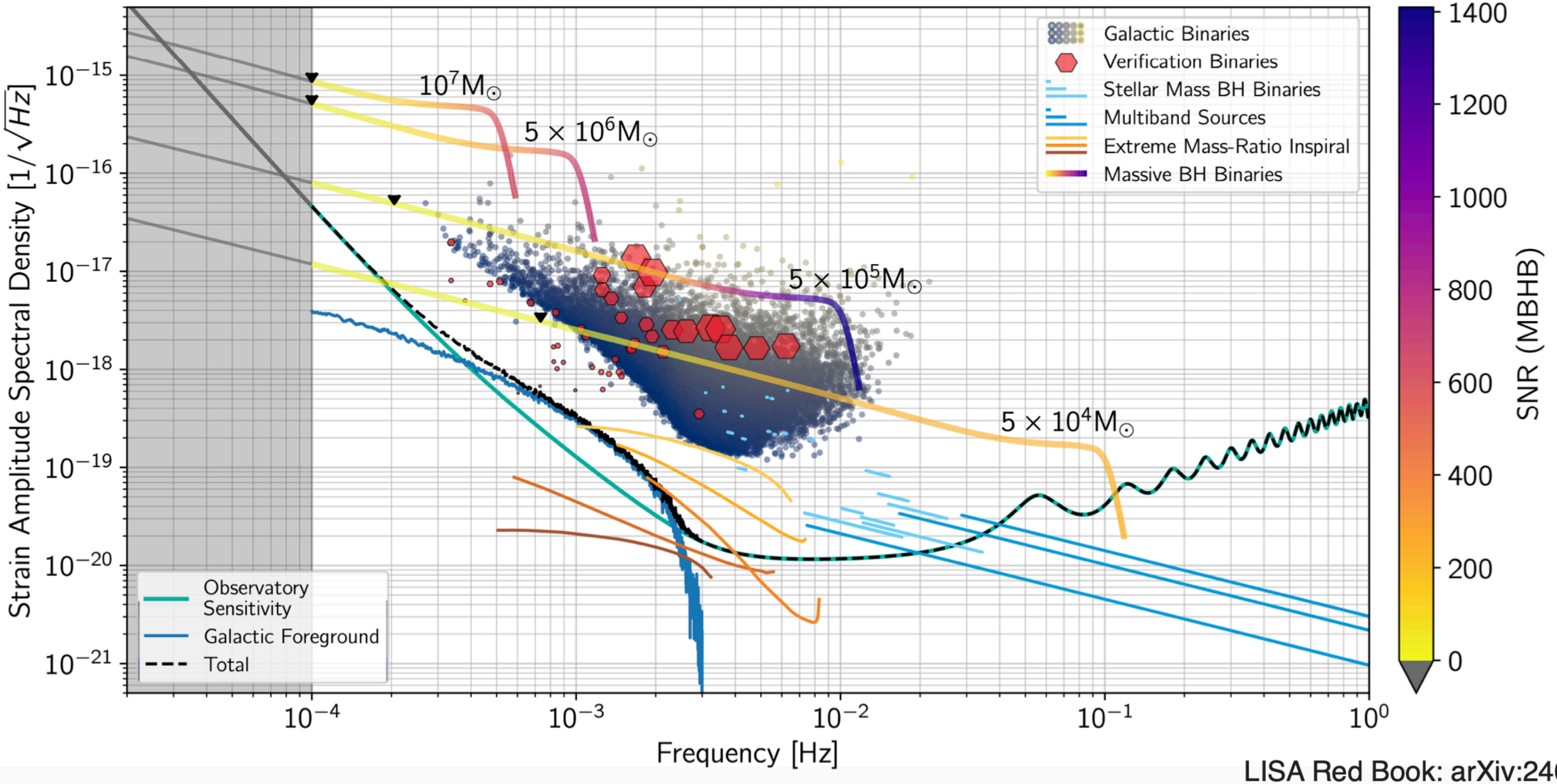
Improvements to environment modelling

- Dark matter “mounds” instead of spikes result from a more realistic formation mechanism
- Supermassive star forms inside dark matter spike, then directly collapses to form a black hole



Bertone et al. 2024

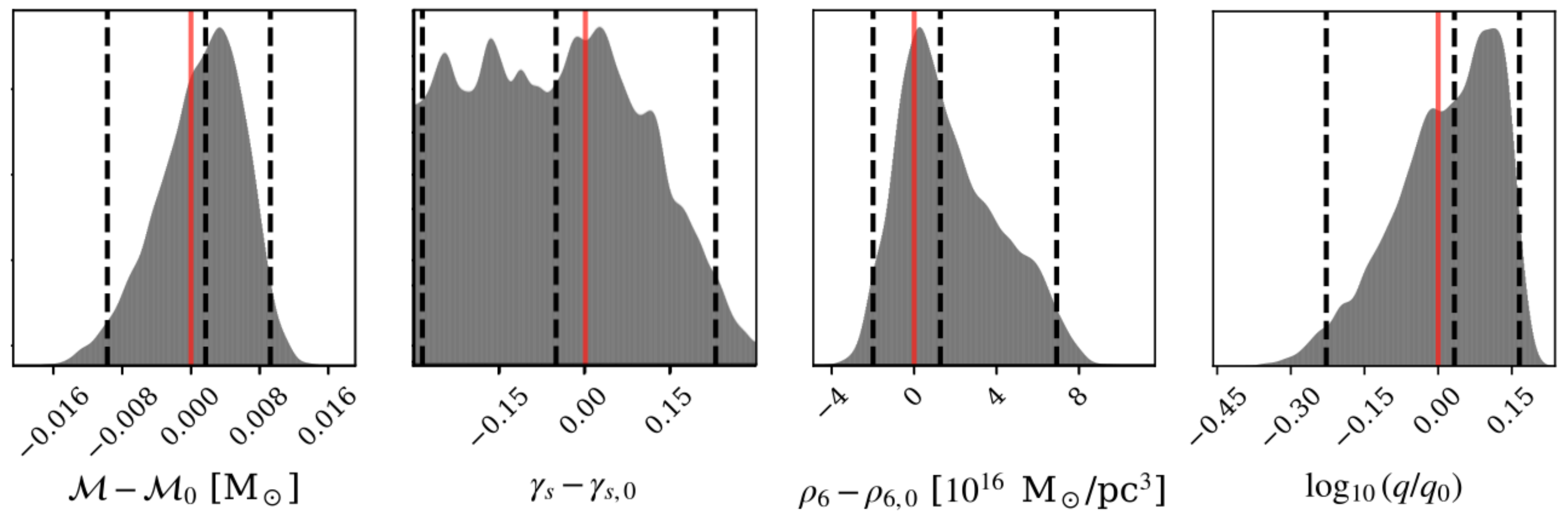
Coping with real LISA noise

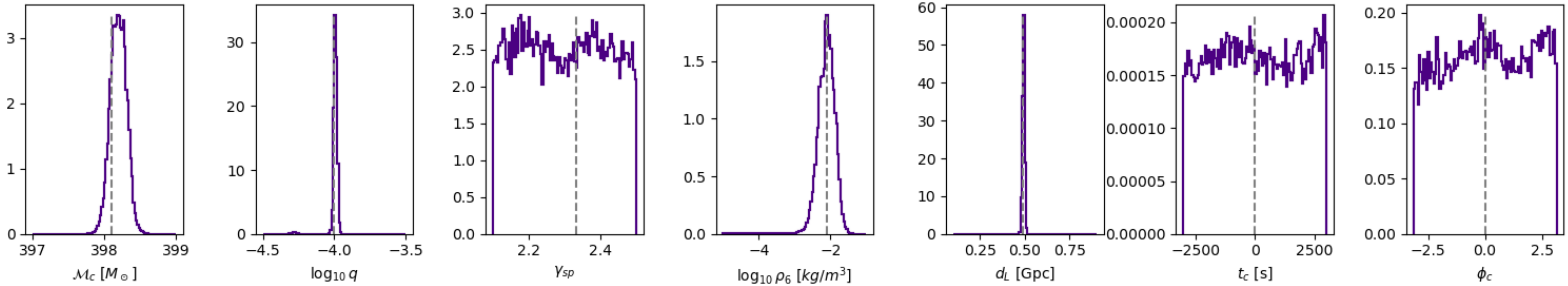


LISA Red Book: arXiv:2402.07571

Towards a realistic data analysis strategy

- Dark matter system as before, including extrinsic parameters and noise
- Using simulation-based inference, 30K simulations instead of 2million likelihood evaluations



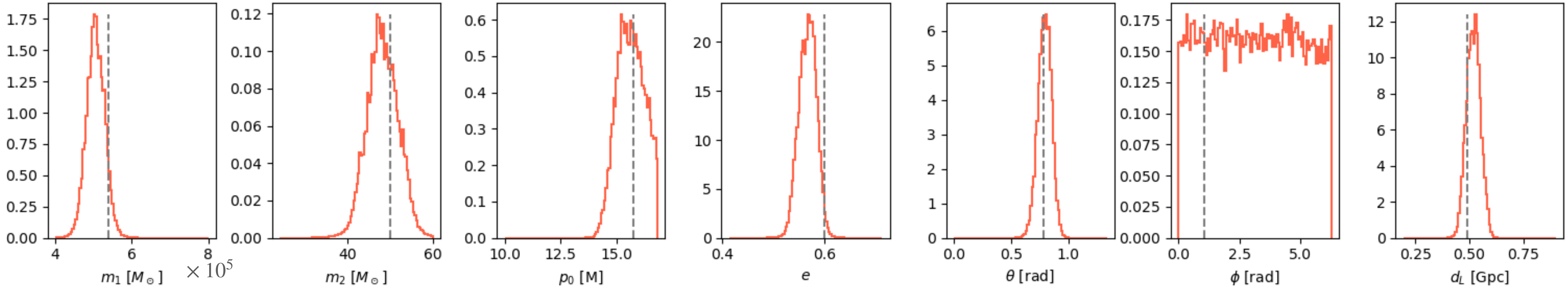


SBI using PEREGRINE package developed in Bhardwaj et al. 2023

Towards a realistic data analysis strategy

- Aim to increase complexity of signal using Fast EMRI Waveforms

- Preliminary results for Schwarzschild EMRI waveforms including the LISA response (no noise yet…)



- Fold in the dark matter effects to these higher order waveforms

Conclusions

- There are many ways to probe the nature of dark matter with gravitational waves.
- LISA offers a particularly exciting avenue for searching for dark matter environments around extreme mass ratio inspirals.
- We need to include the possible presence of environments in our data analysis pipelines so that we don't miss the chance to measure the properties of dark matter, and to avoid unknown biases even for vacuum signals.
- Machine-learning tools may be a fruitful avenue for combating the complexity of the next generation of gravitational wave data.