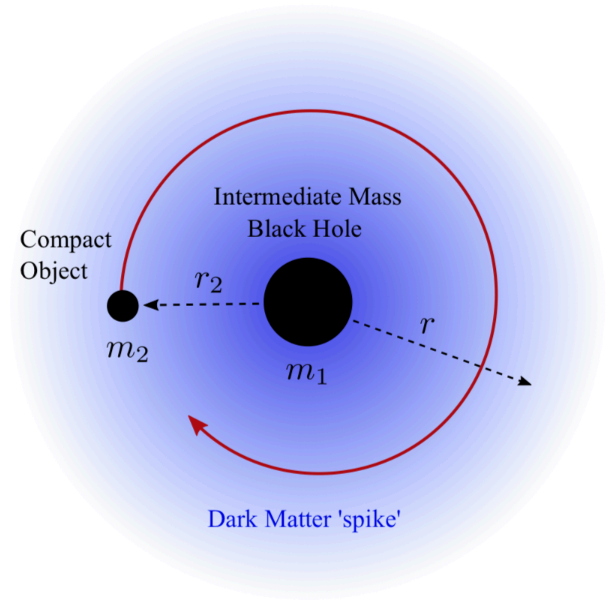
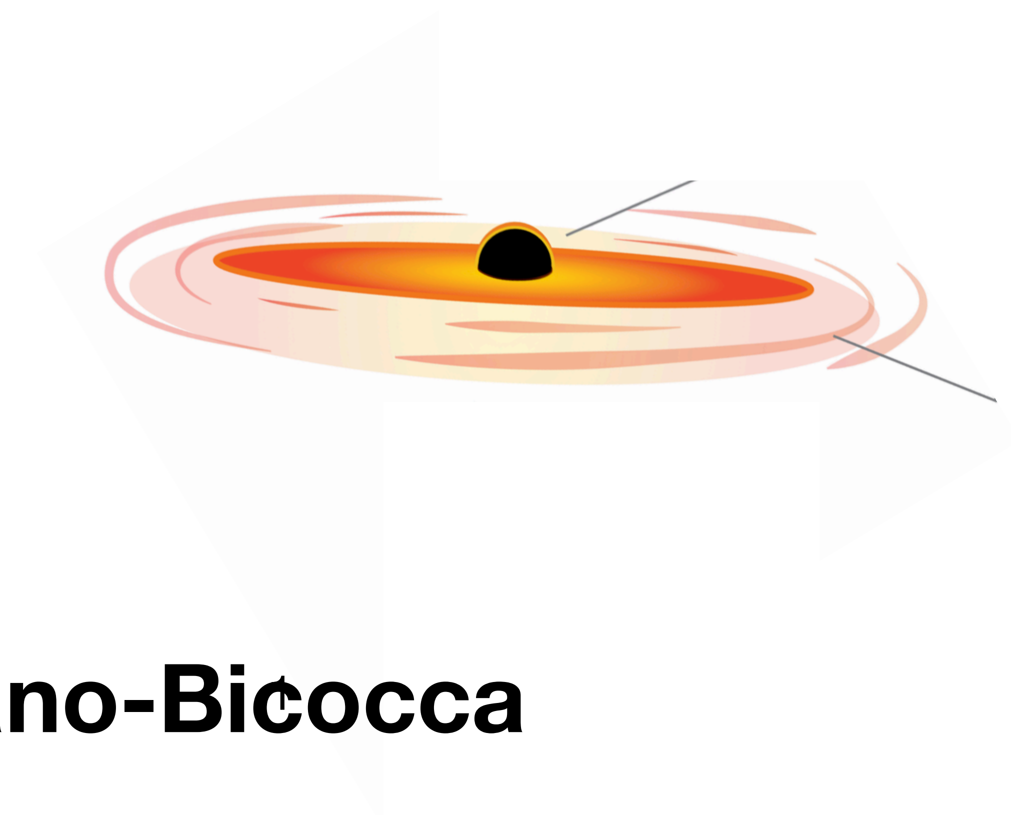
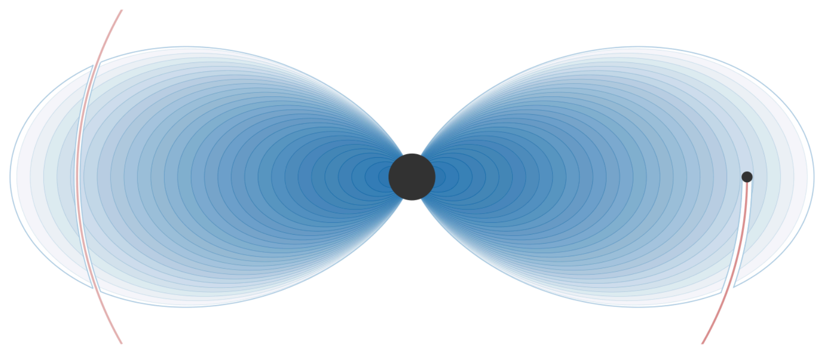
Searching for dark matter with gravitational waves





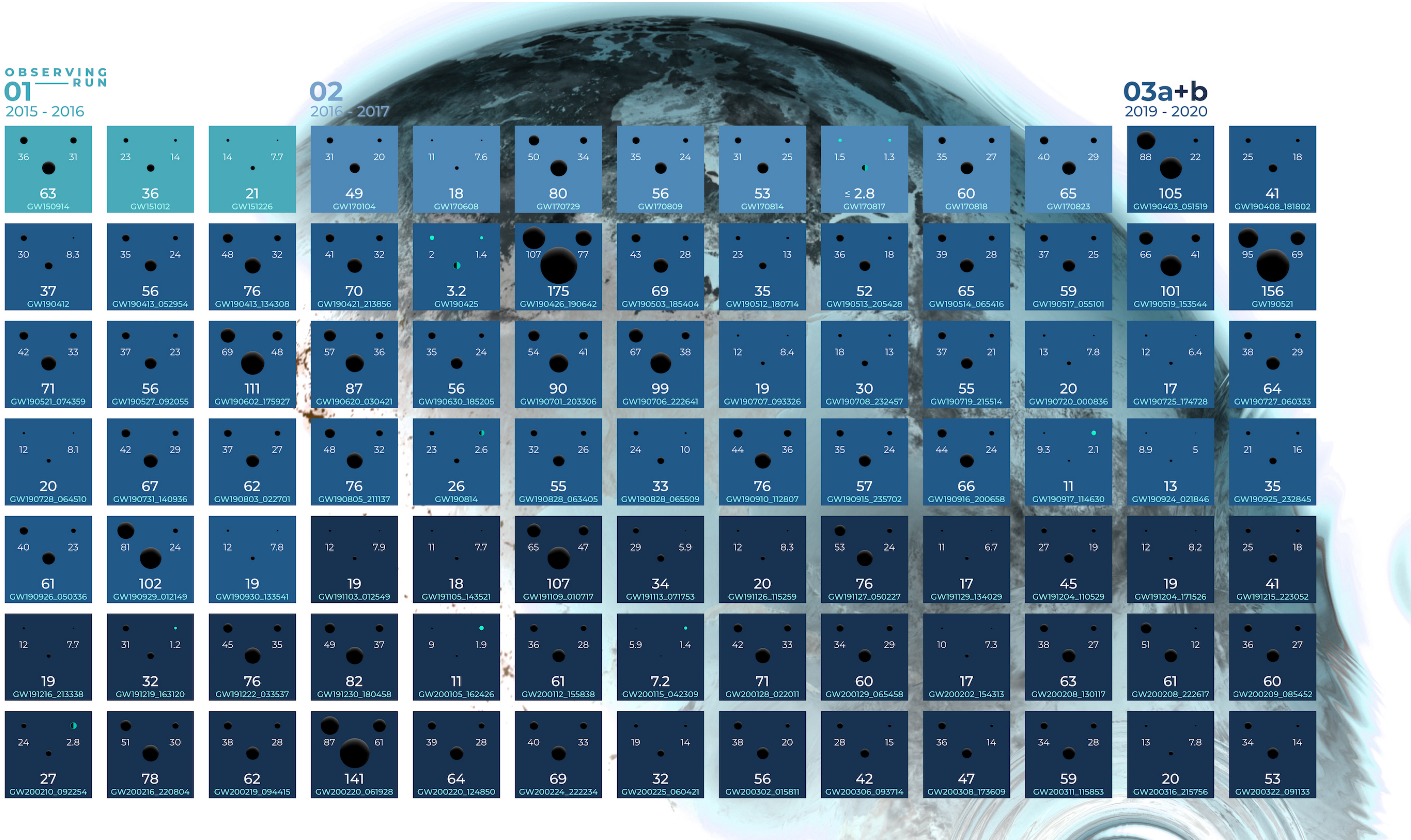


Philippa (Pippa) Cole, University of Milano-Bicocca

with James Alvey, Gianfranco Bertone, Uddipta Bhardwaj, Adam Coogan, Daniele Gaggero, Bradley Kavanagh, Theophanes Karydas, Thomas Spieksma and Giovanni Maria Tomaselli

Based on Cole, P.S., Bertone, G., Coogan, A. *et al.* Distinguishing environmental effects on binary black hole gravitational waveforms, *Nature Astron.* 7 (2023) 8, 943-950 https://doi.org/10.1038/s41550-023-01990-2

So far, order 100 gravitational wave events detected from black hole and neutron star mergers



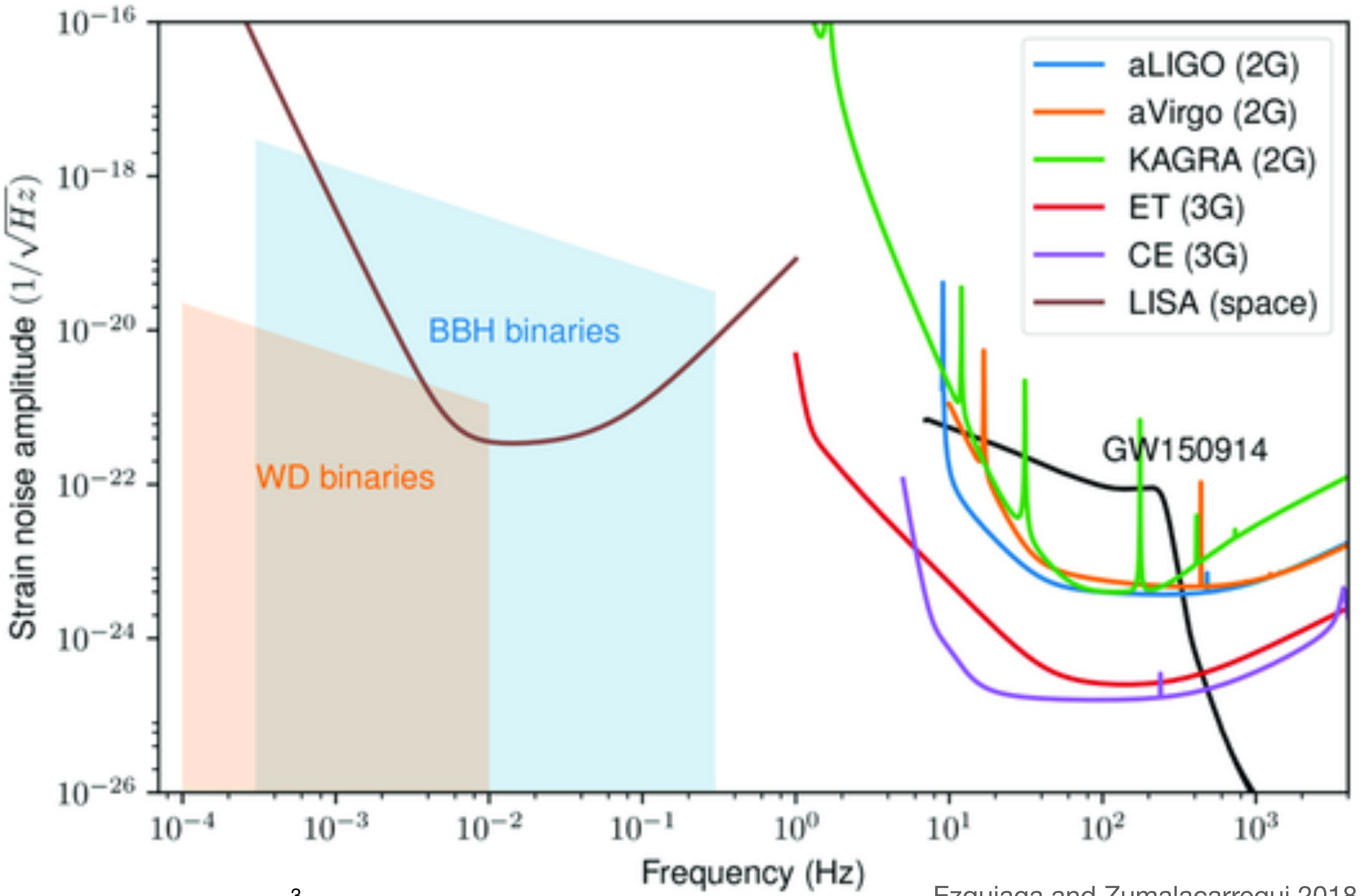
LVK collaboration

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 can cause inspiral 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

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

Frequency evolution

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

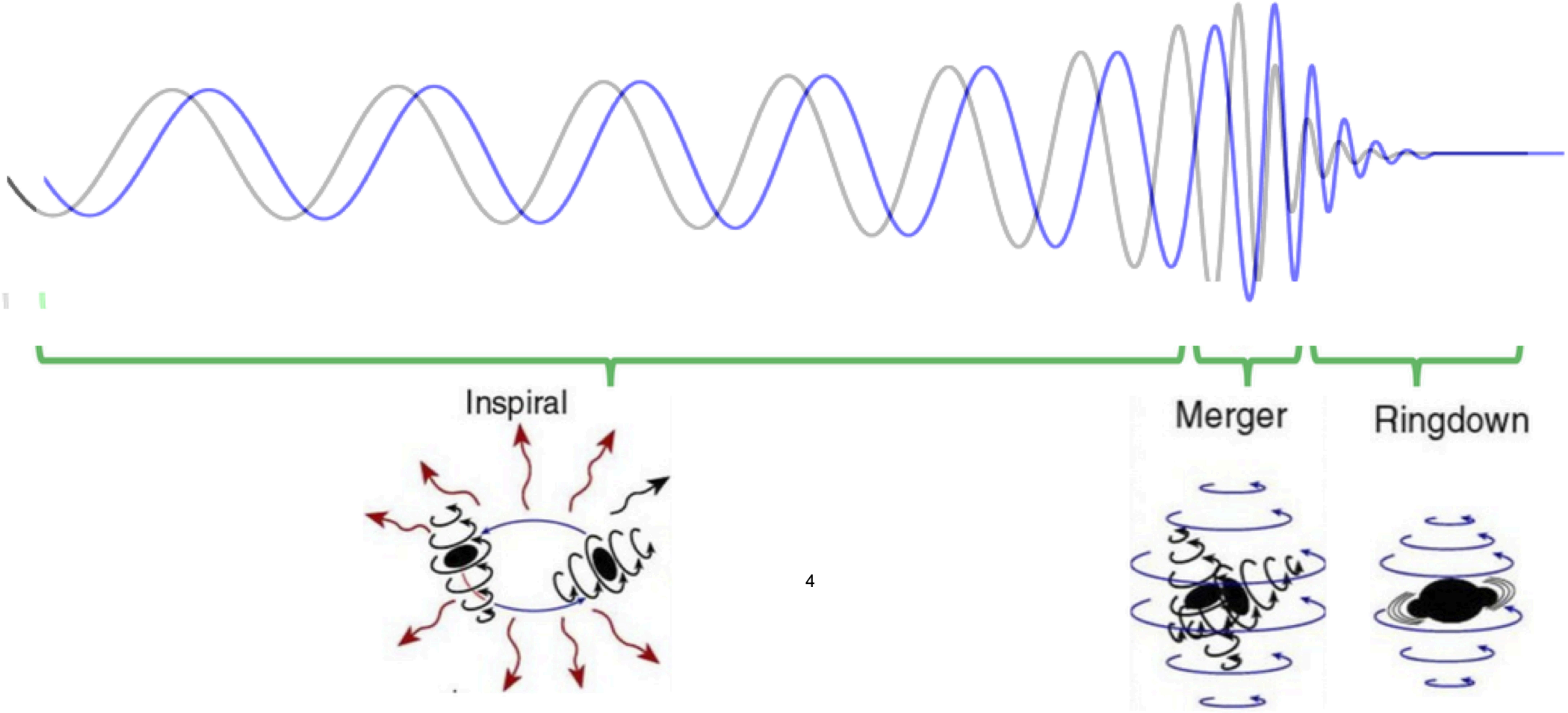
Phase evolution

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

Gravitational wave strain (amplitude)

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

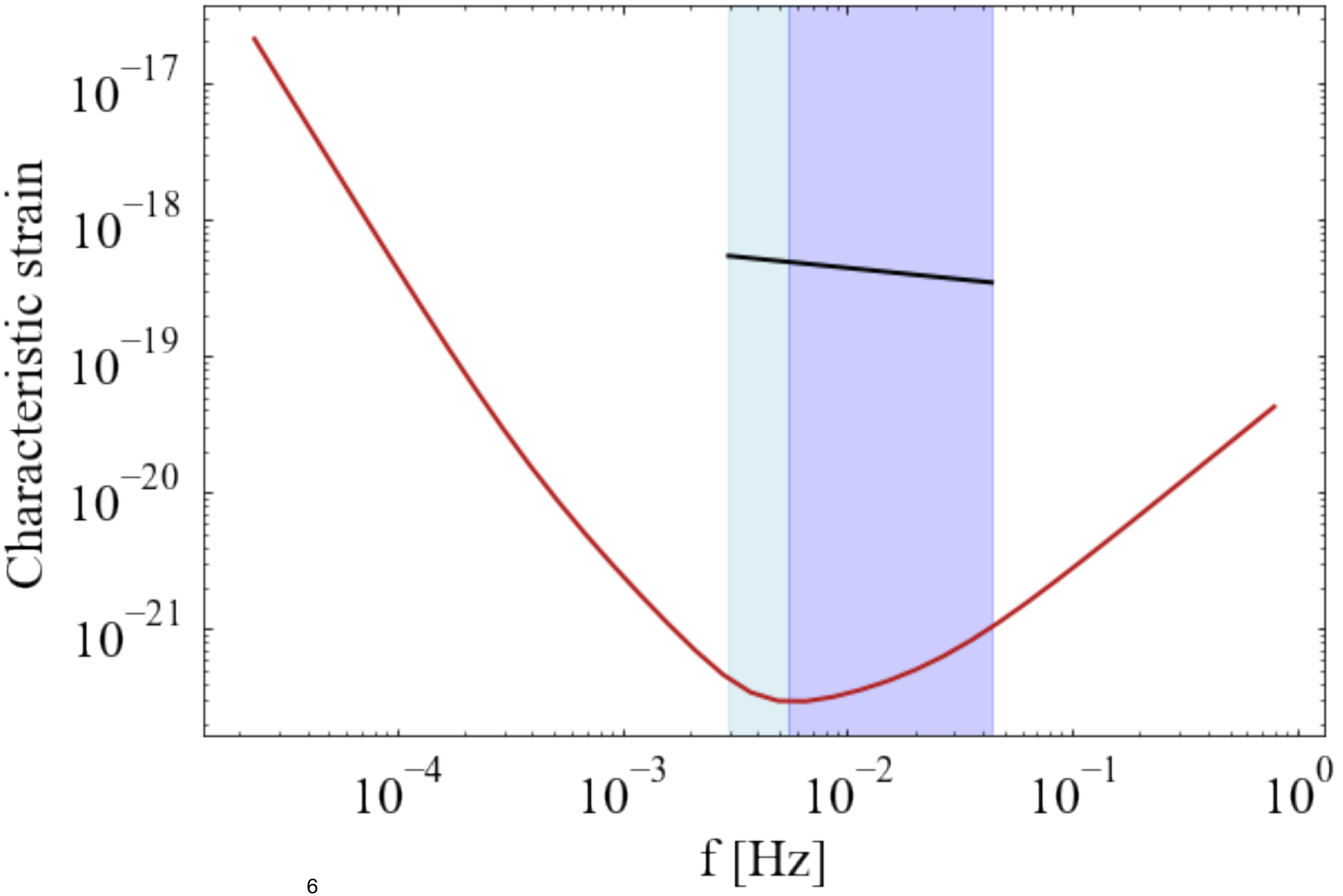
Hunting for the phase difference which accumulates over the course of the inspiral



Need to observe many cycles

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

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



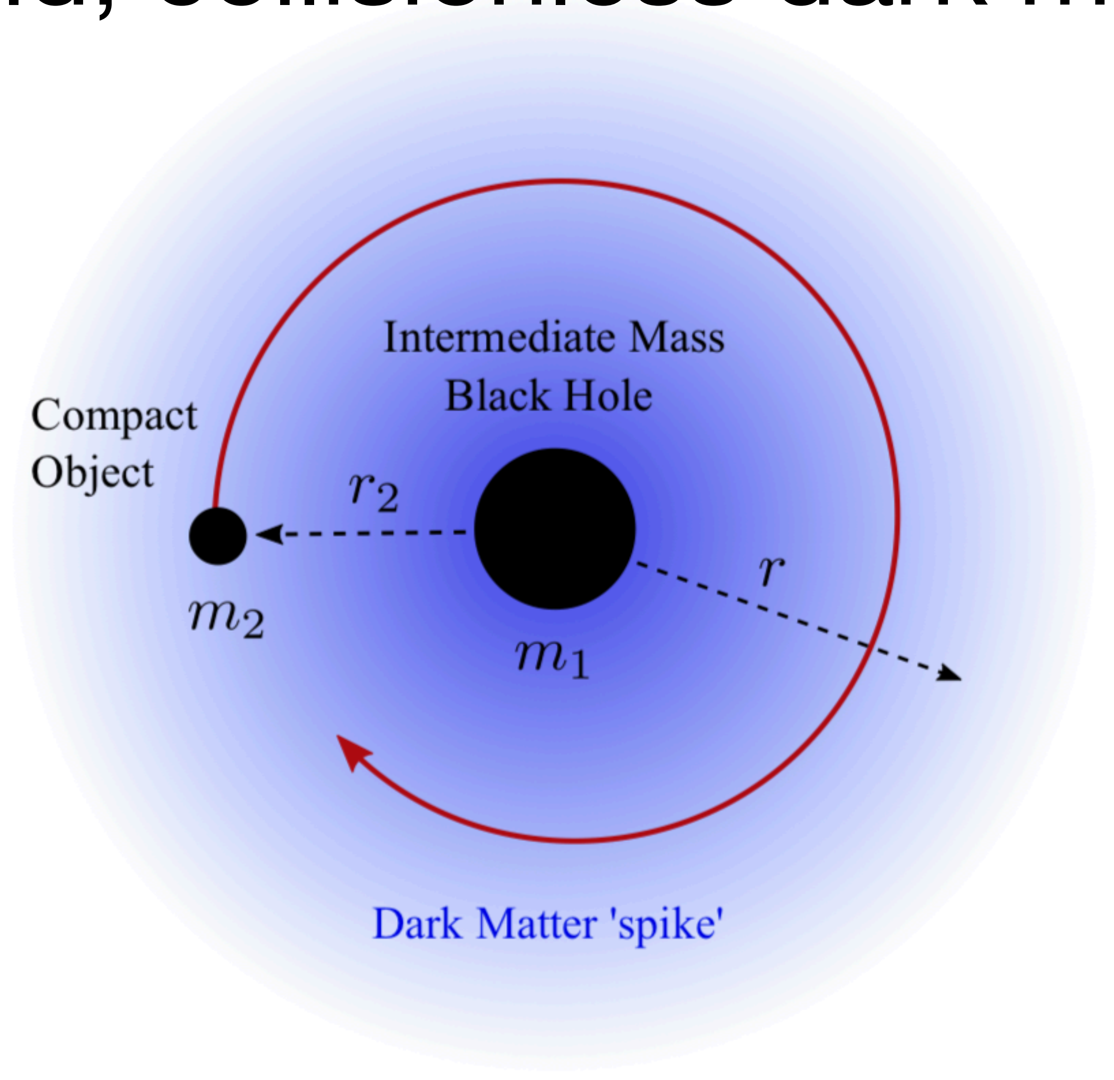
Why should we care about environmental effects?

- 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

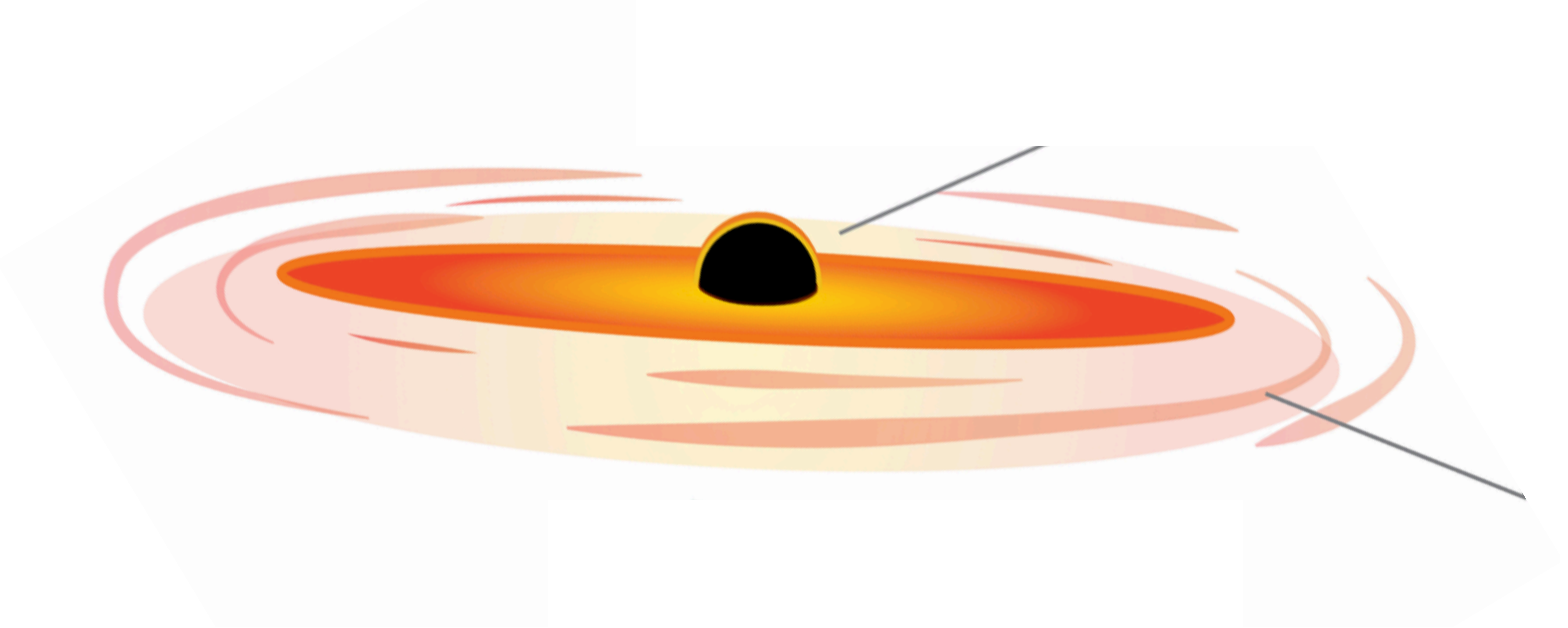


$$\rho(r) = \rho_6 \left(\frac{r_6}{r}\right)^{\gamma_s}$$

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

Accretion disk

Baryonic matter



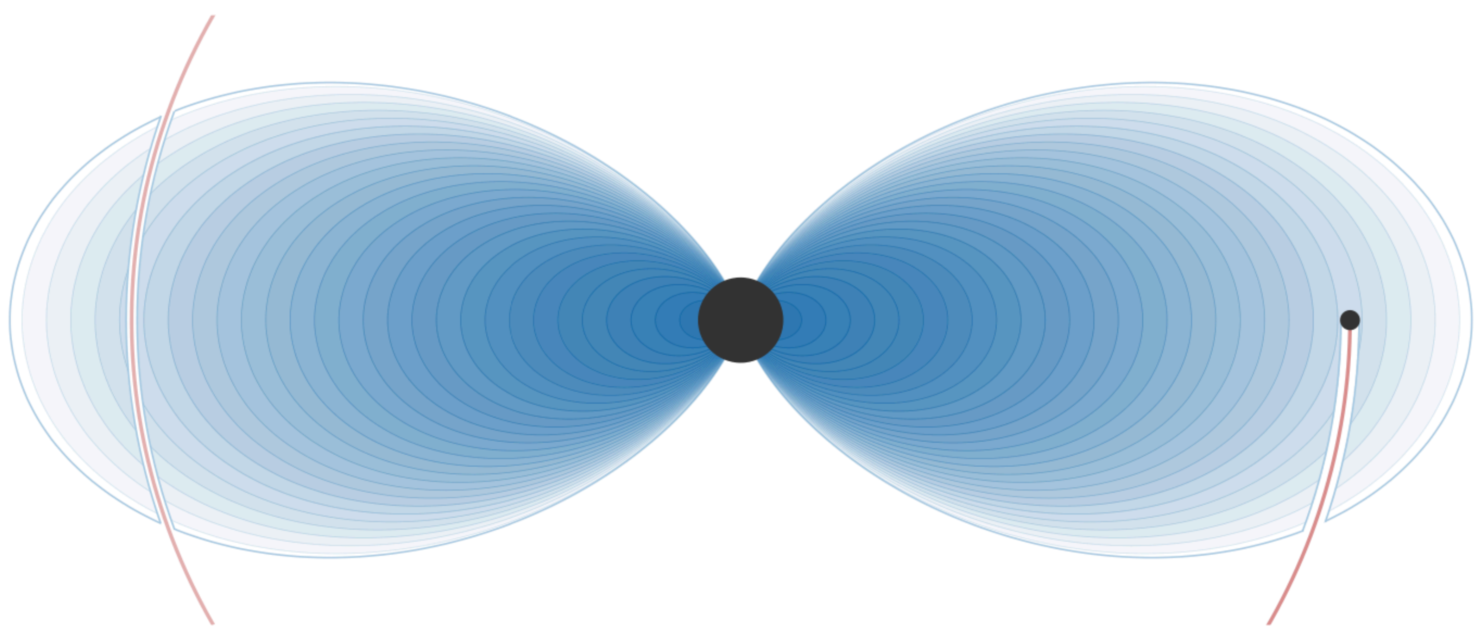
$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1/2}$$

$$\mathcal{M} = r/h$$

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

Gravitational atom

Ultra-light bosons



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

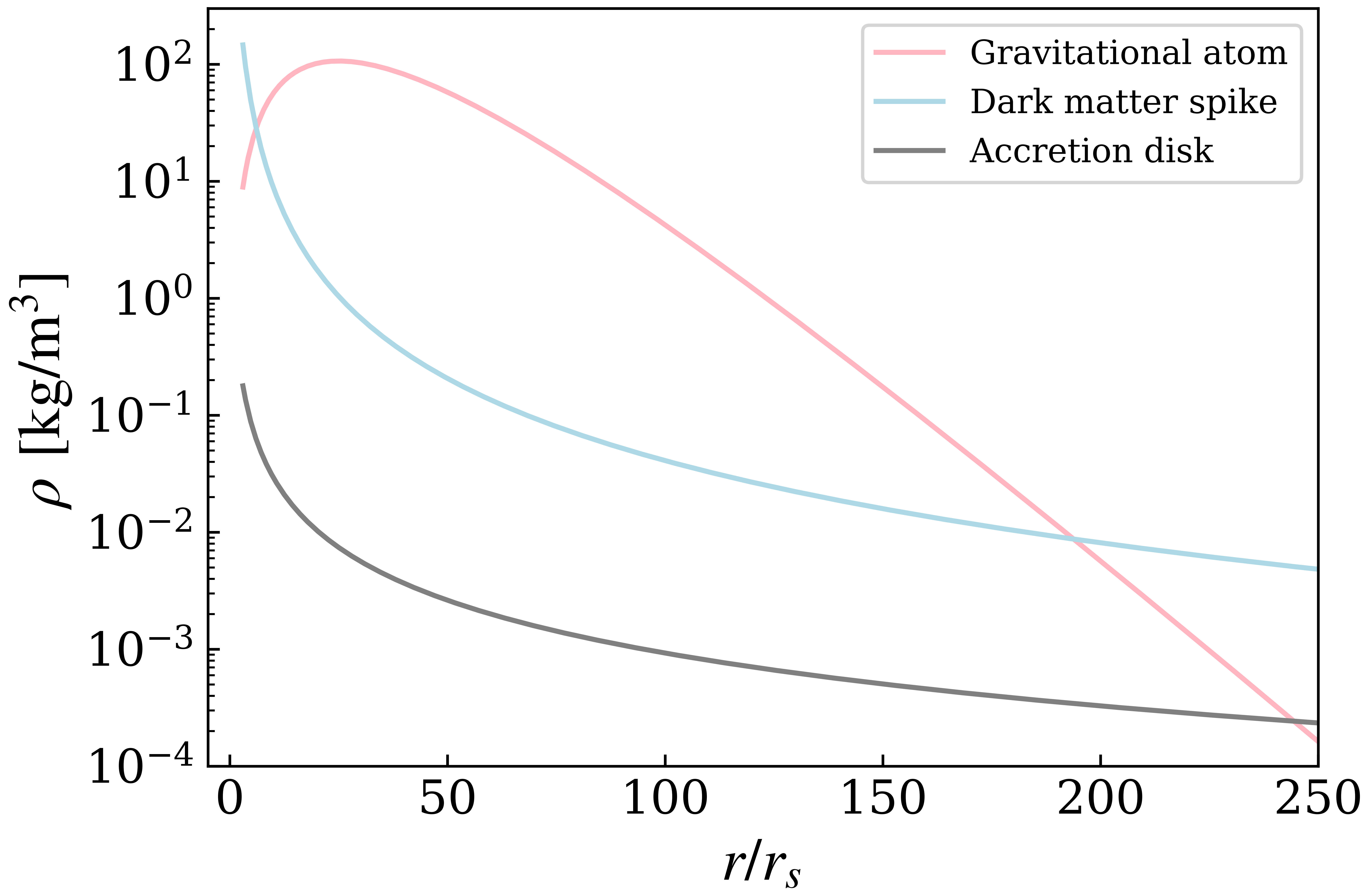
$$\alpha \equiv G m_1 \mu \ll 1$$

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

What kind of densities?

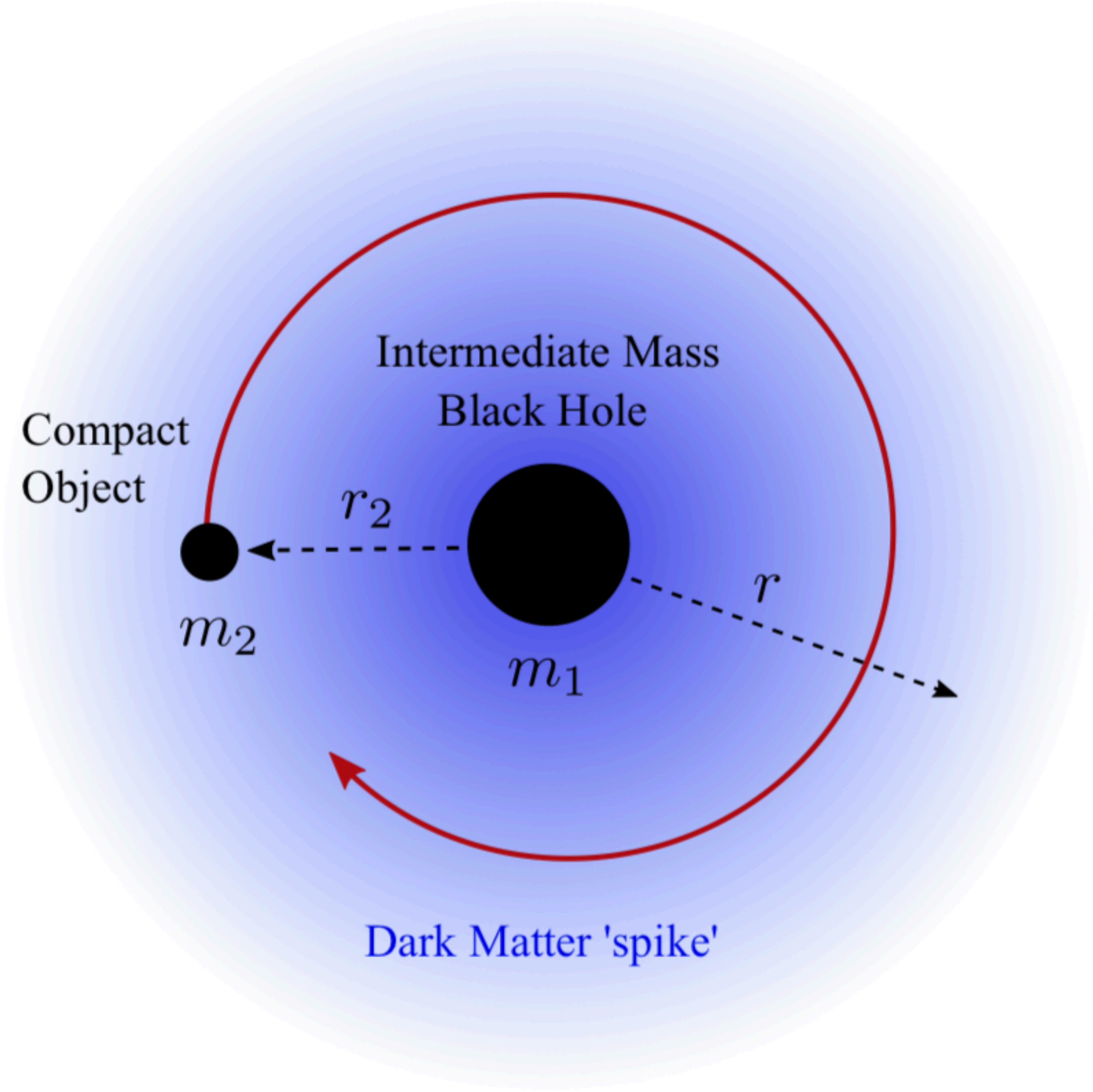


$r_s \sim 10^{-8}$ pc

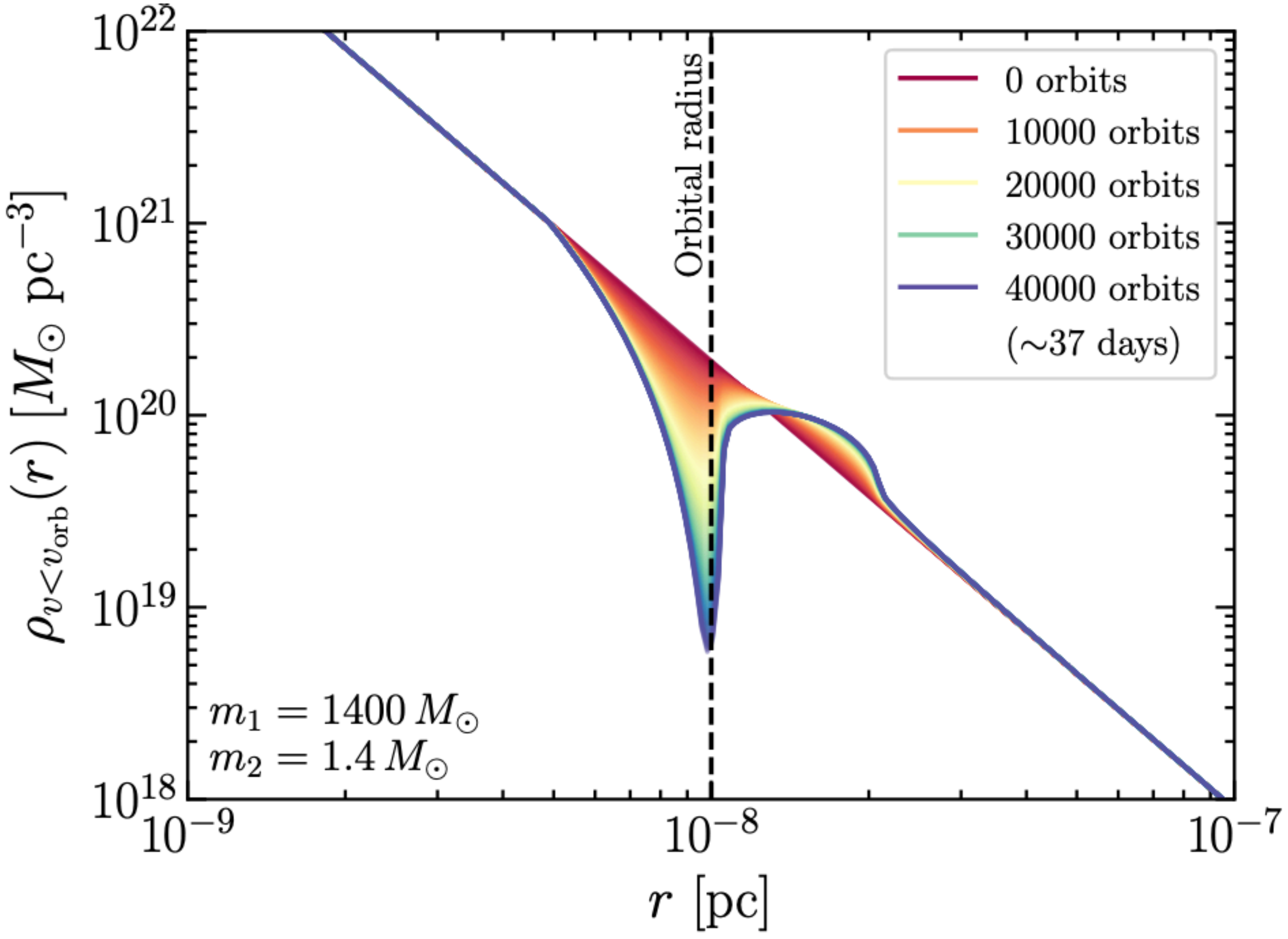
Cole et al. 2023

Dynamical friction

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



HaloFeedback

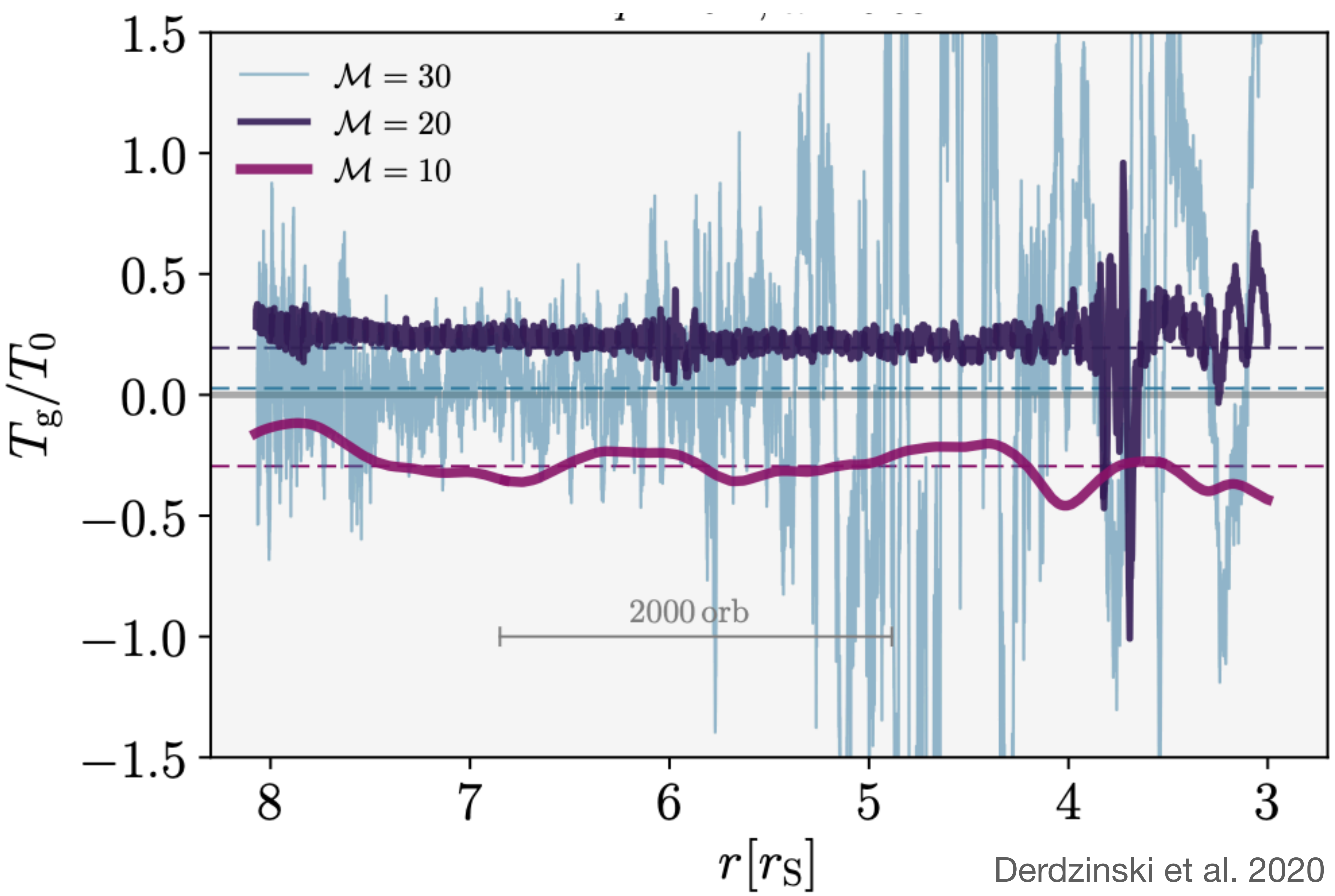


Kavanagh, Nichols, Bertone, Gaggero 2020

Gas torques

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

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



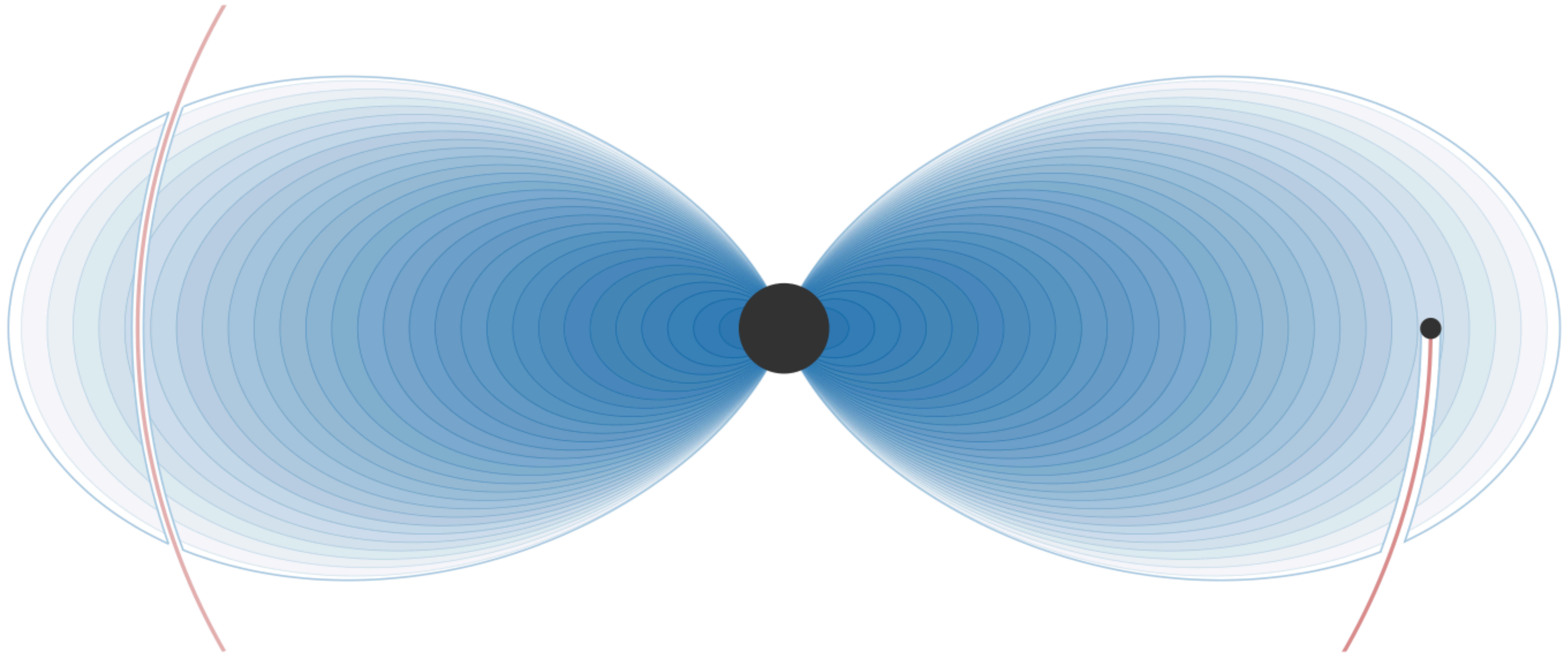
Derdzinski et al. 2020

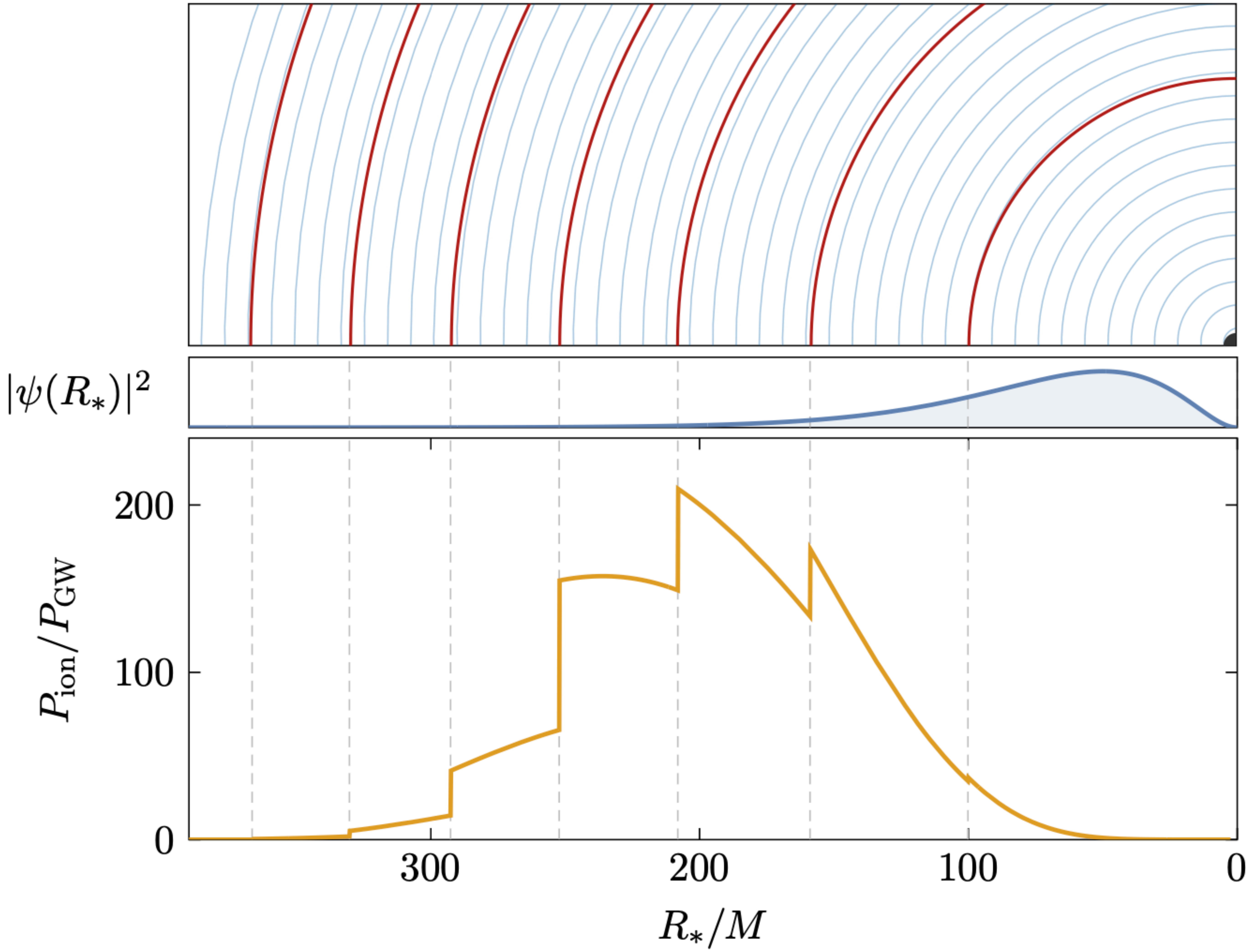
Assume gas in the disk is corotating with the companion object, which is orbiting in the plane of the disc.

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

Ionization

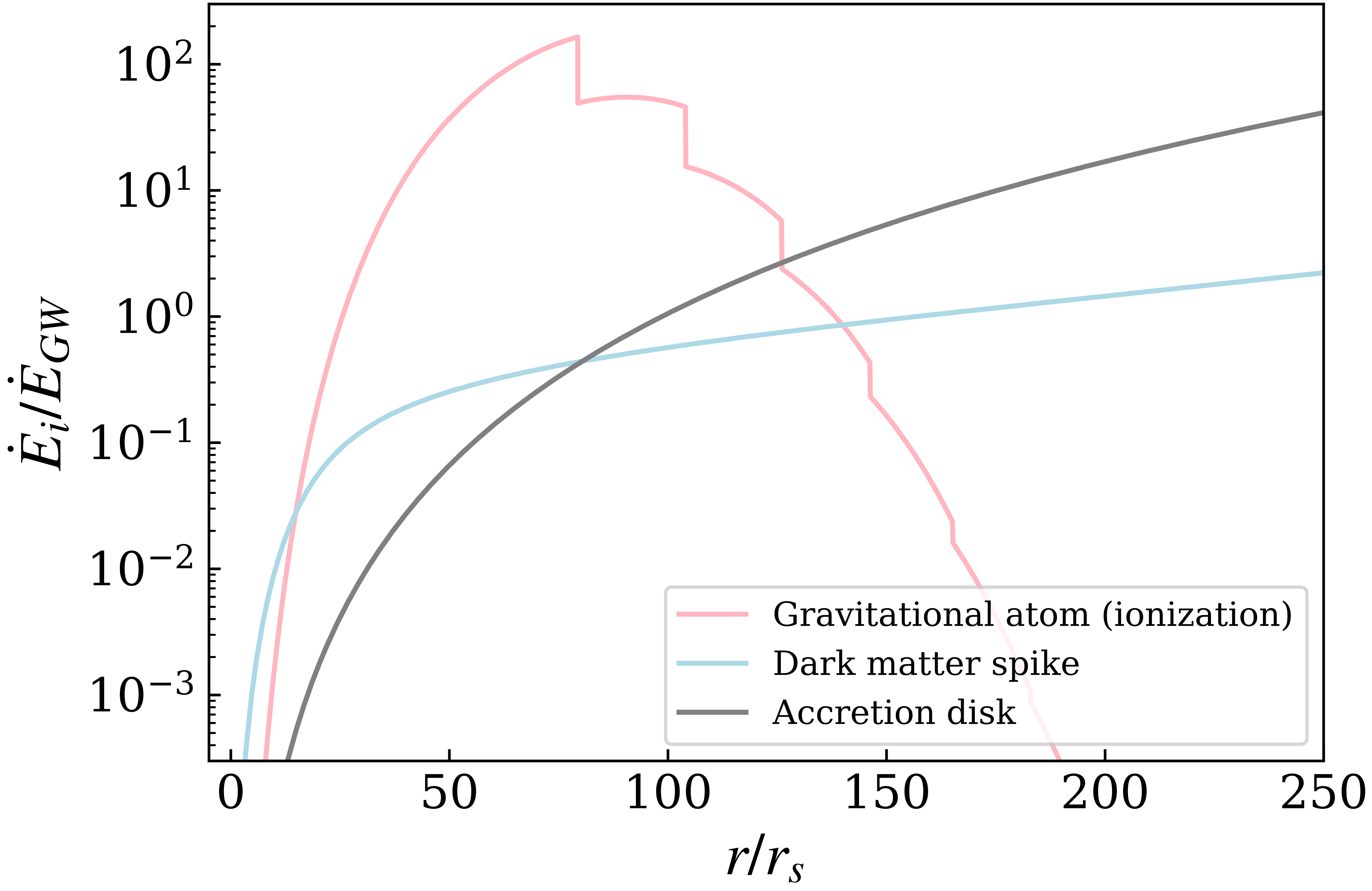




Perturber excites resonances in the cloud and it transitions from bound states to unbound states as the orbital frequency of the perturber hits the frequency of the energy difference between states

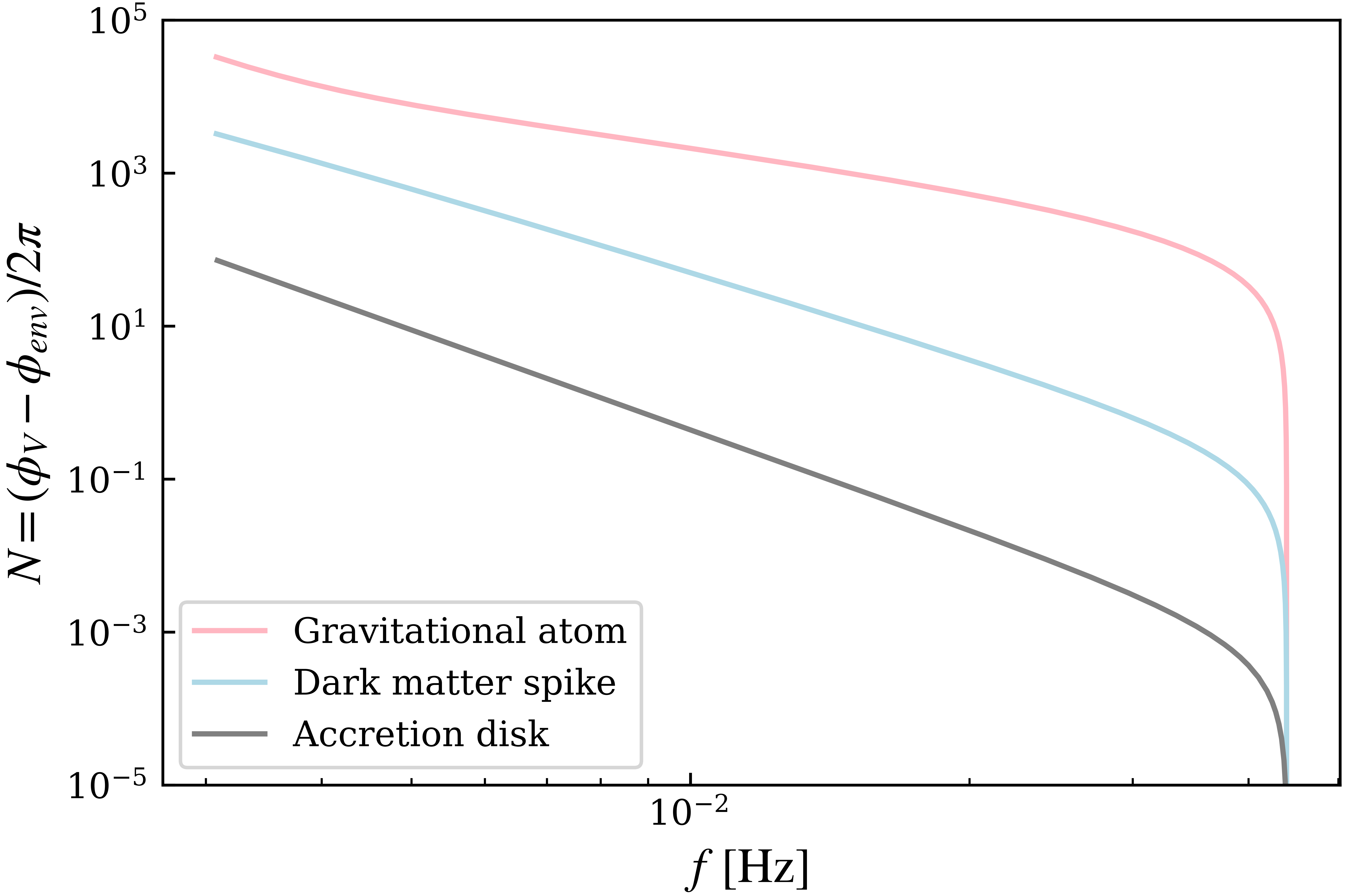
Baumann, Bertone, Stout, Tomaselli 2021

Energy losses



Cole et al. 2023

Dephasing

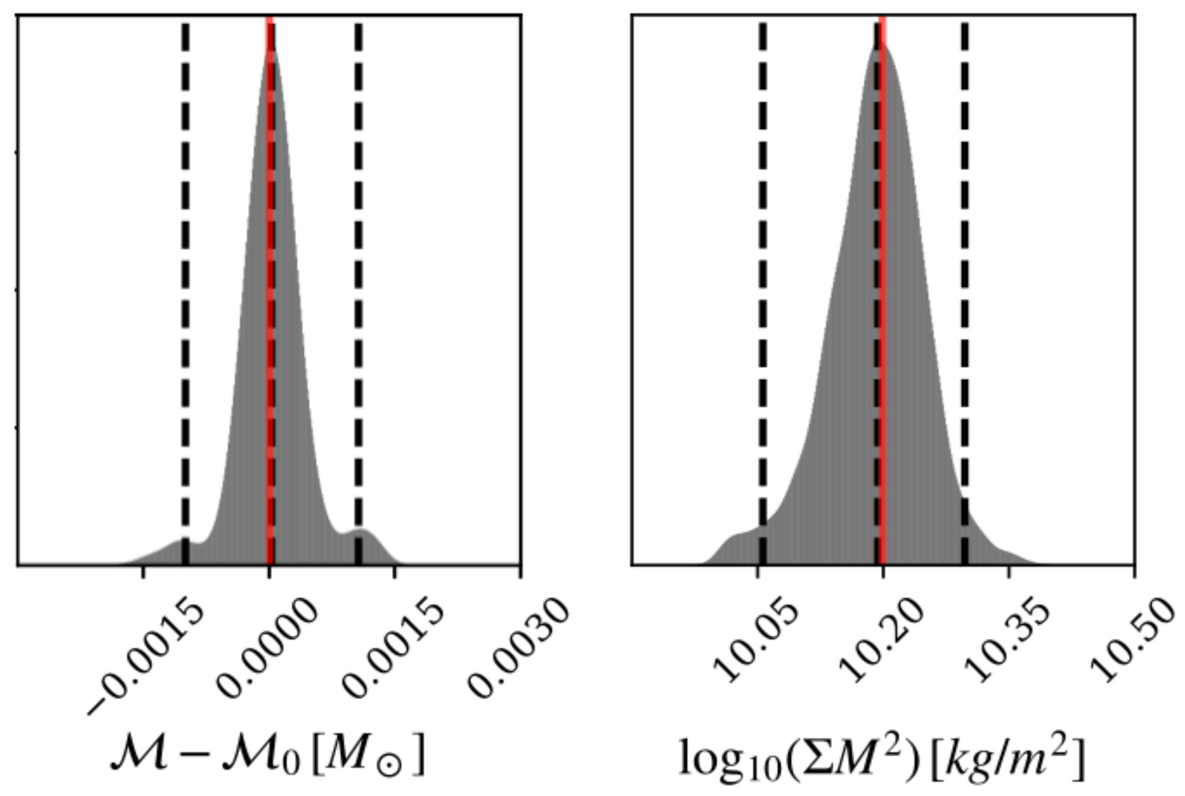


Cole et al. 2023

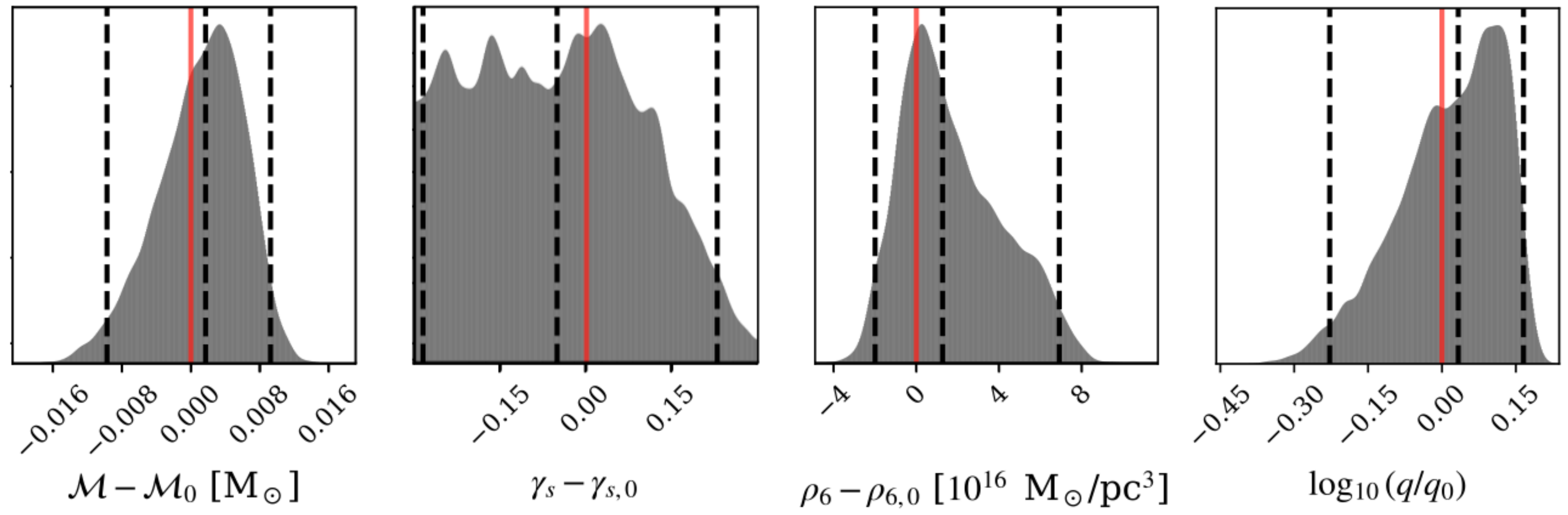
Assuming we've detected a signal, can we measure the parameters?

Parameter estimation with correct model

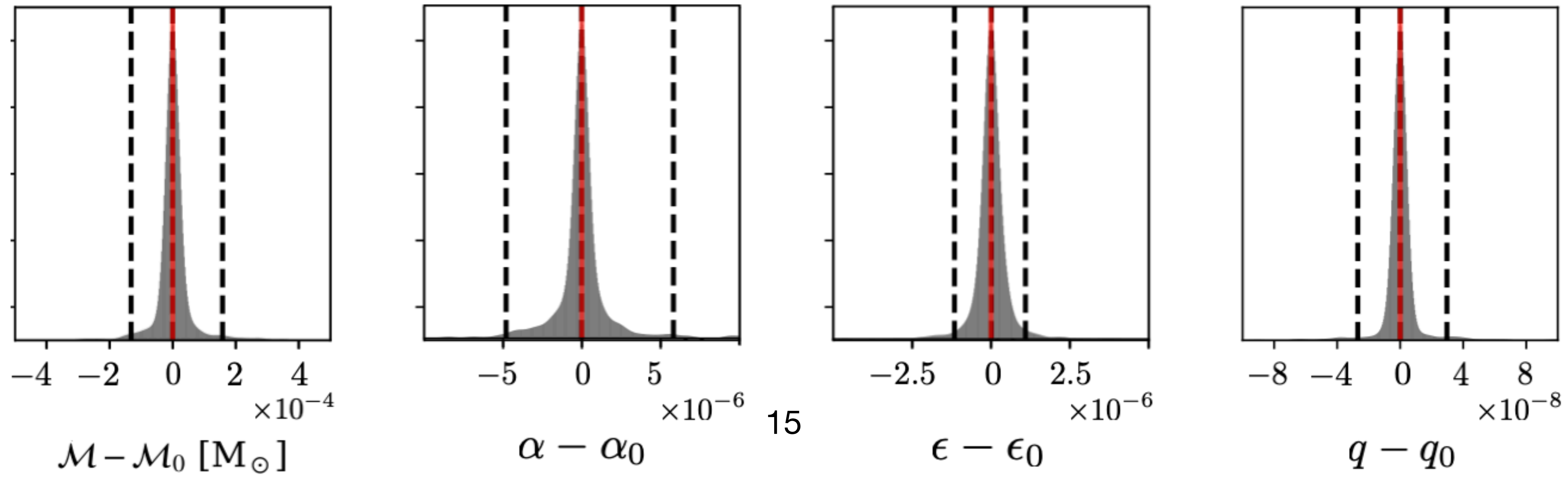
Accretion disk



Dark dress

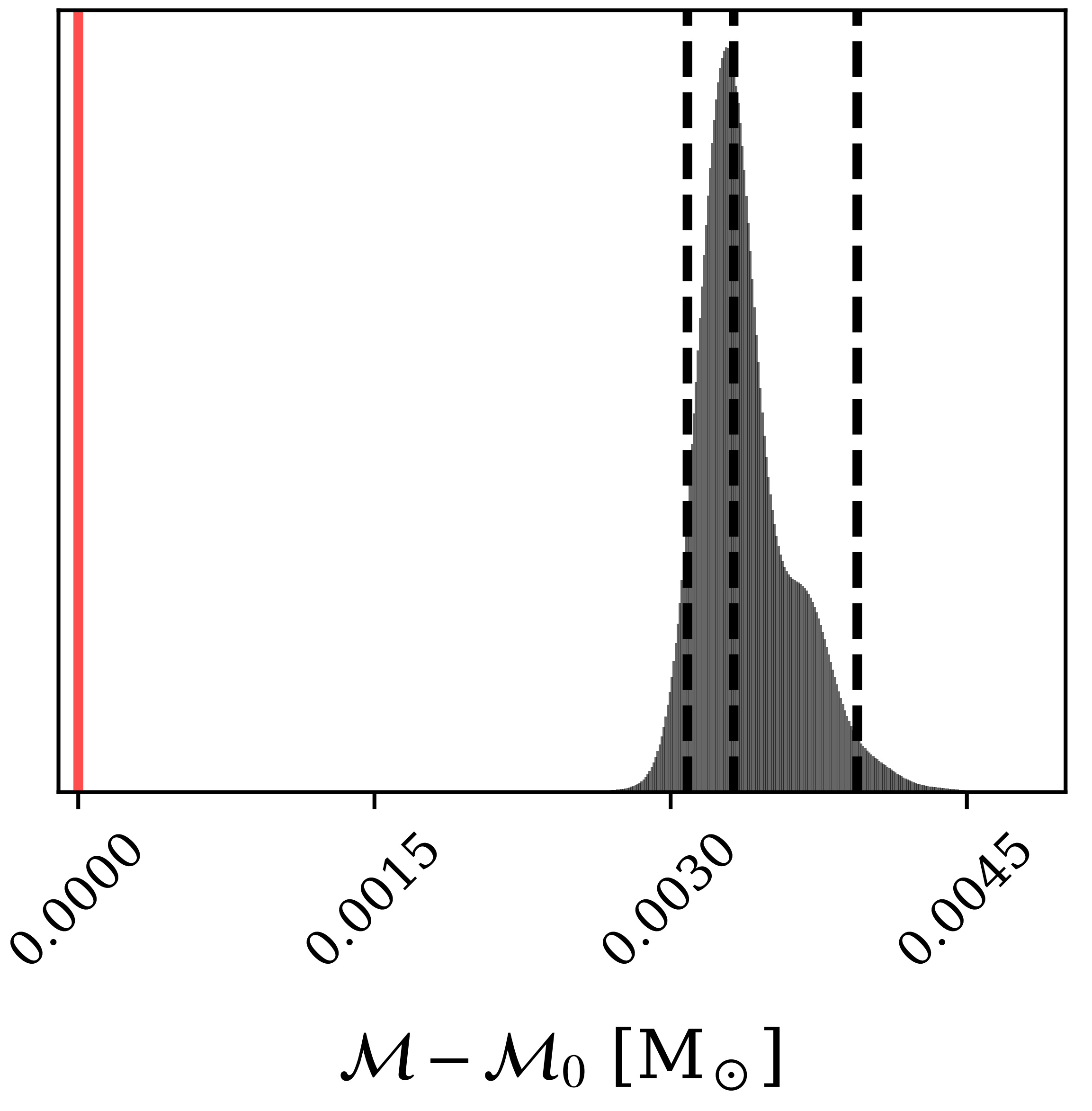


Gravitational atom



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>
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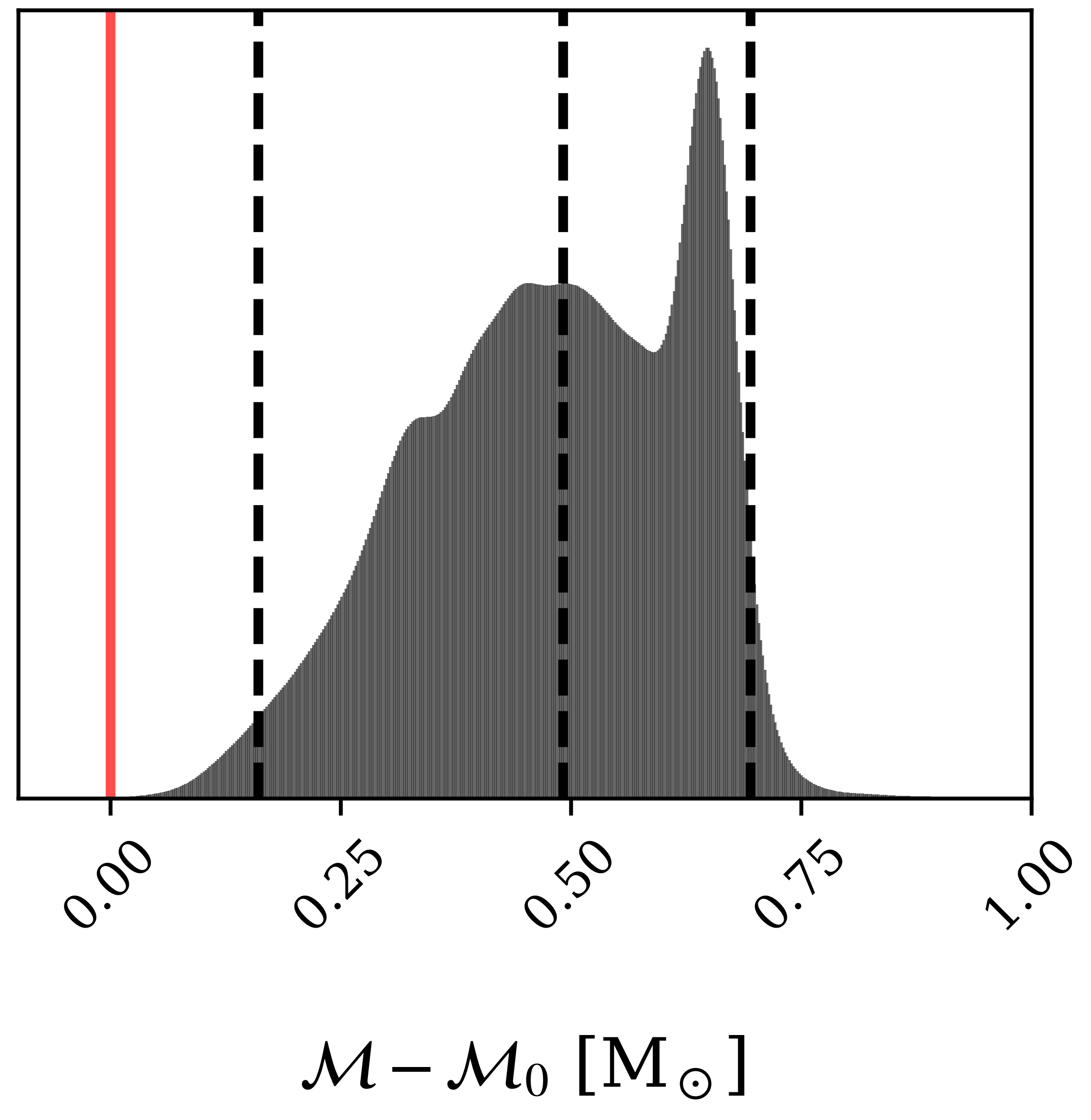
<td>
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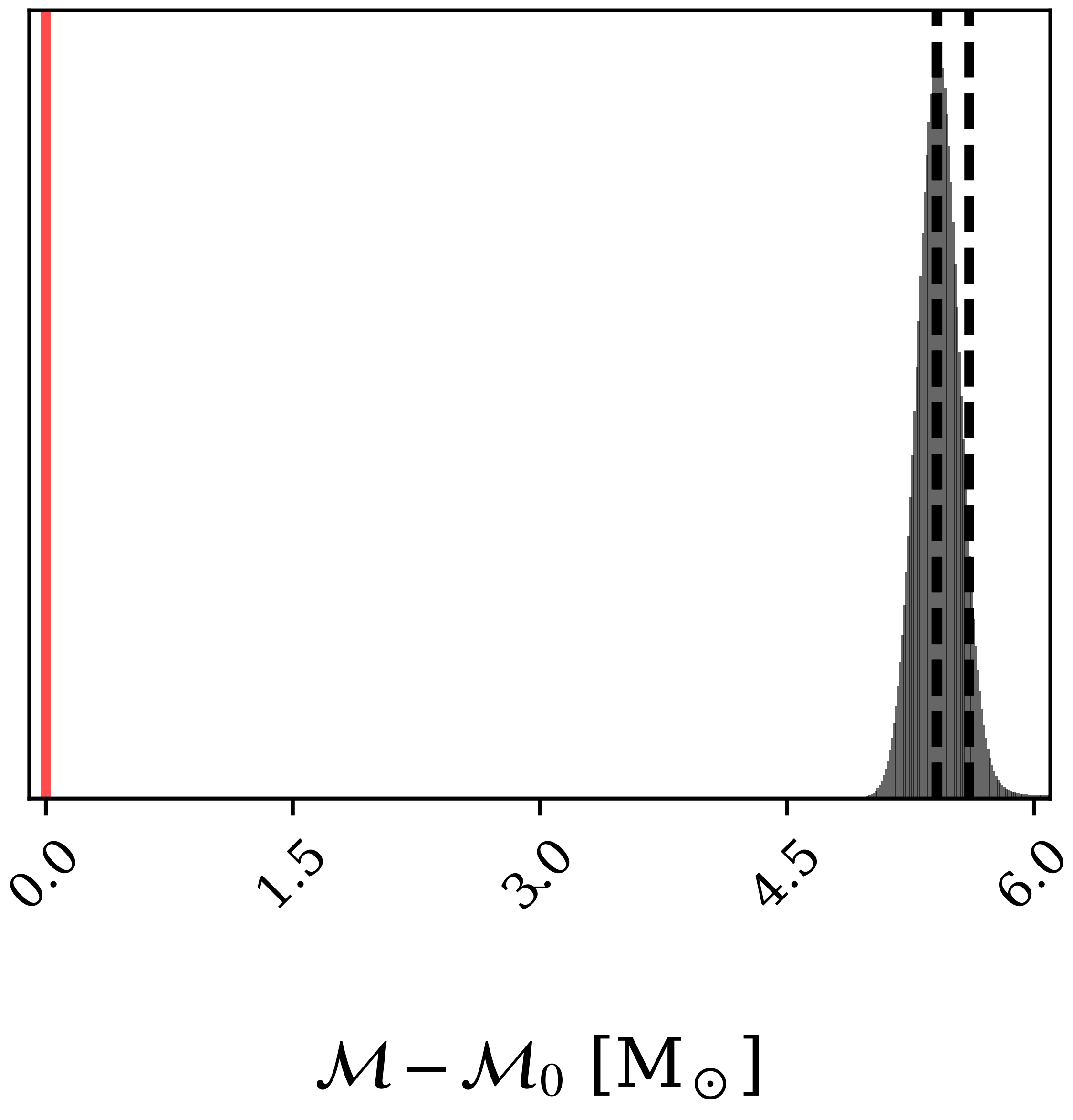
<td>
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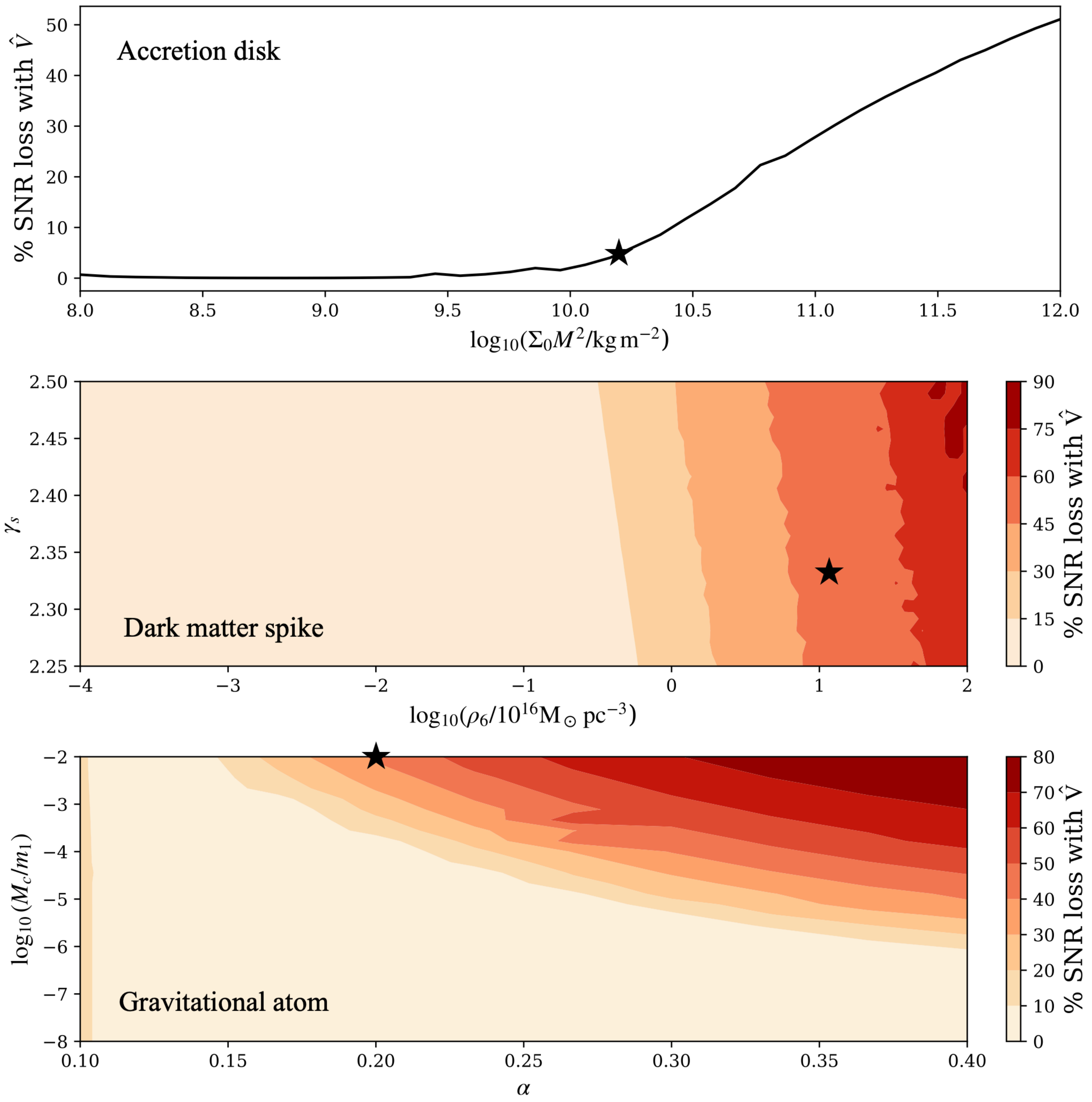
Cole et al. 2023

SNR loss: biased PE or miss signal entirely



Cole et al. 2023

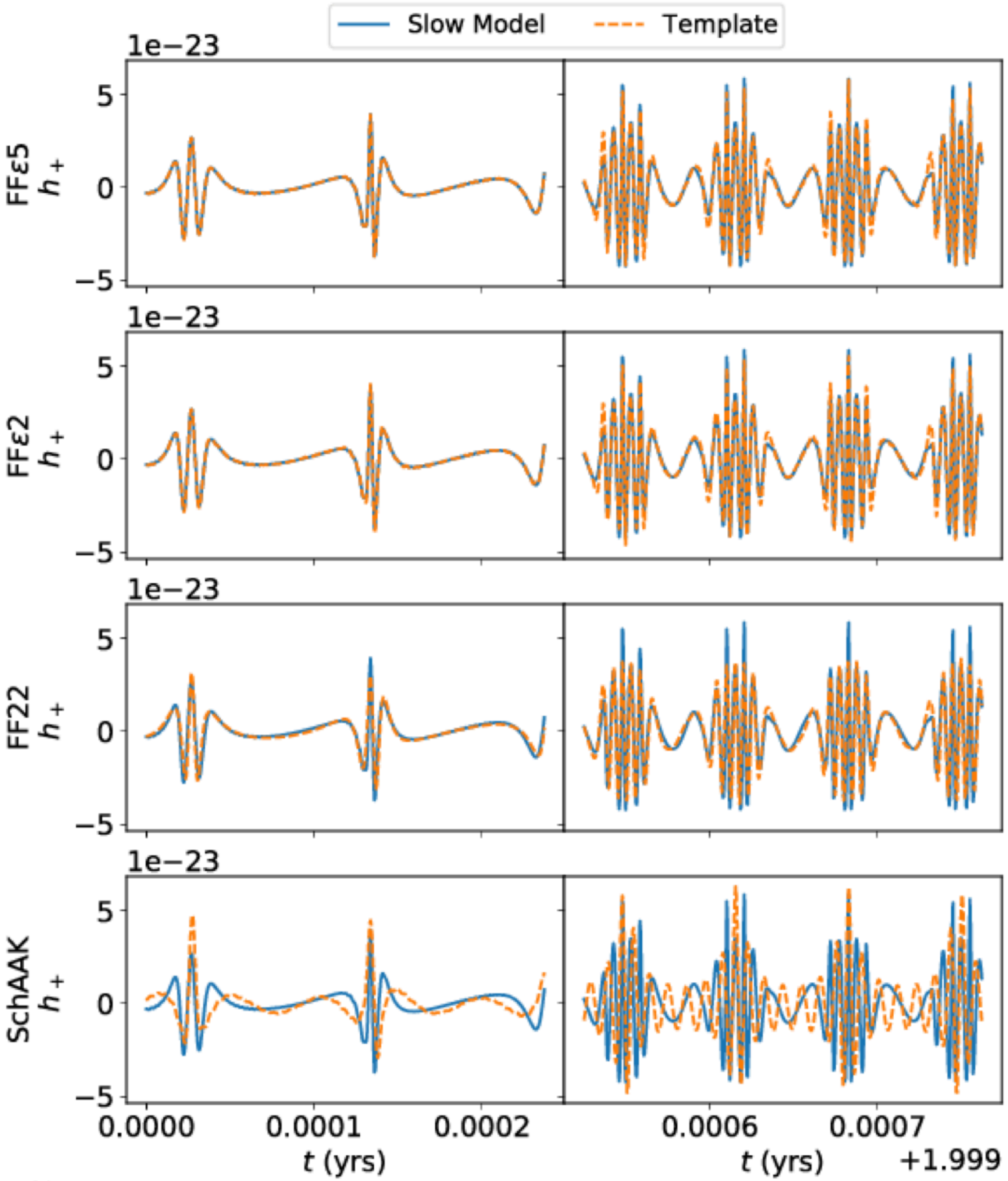
Bayesian model comparison shows confident preference for correct model over any other environment

$\log_{10} \mathcal{B}$	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

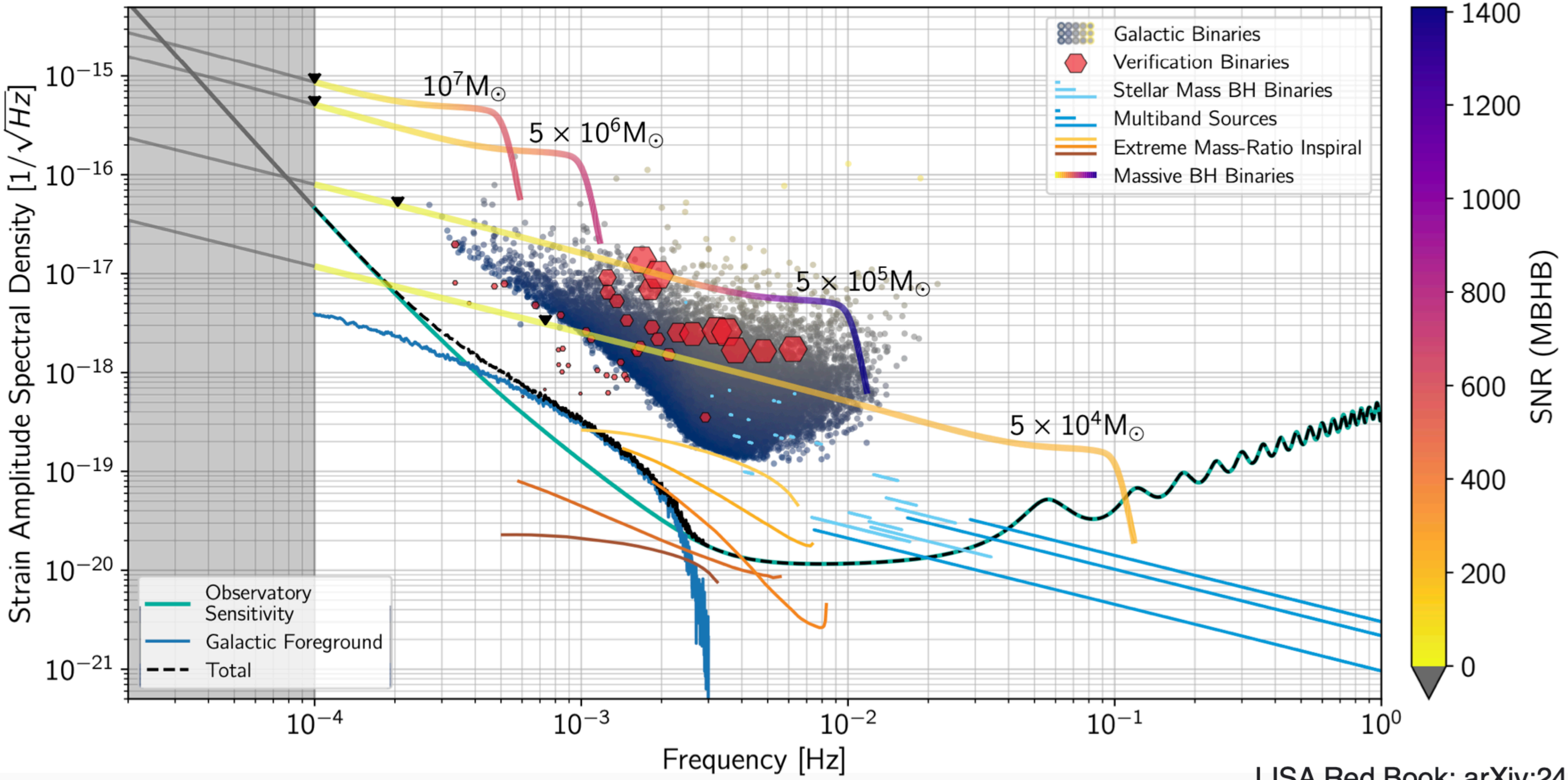
- Use higher order waveforms
- For example Fast EMRI Waveforms (FEW)
- Improvements to environmental modelling also required

e.g. Speeney et al. 2022



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

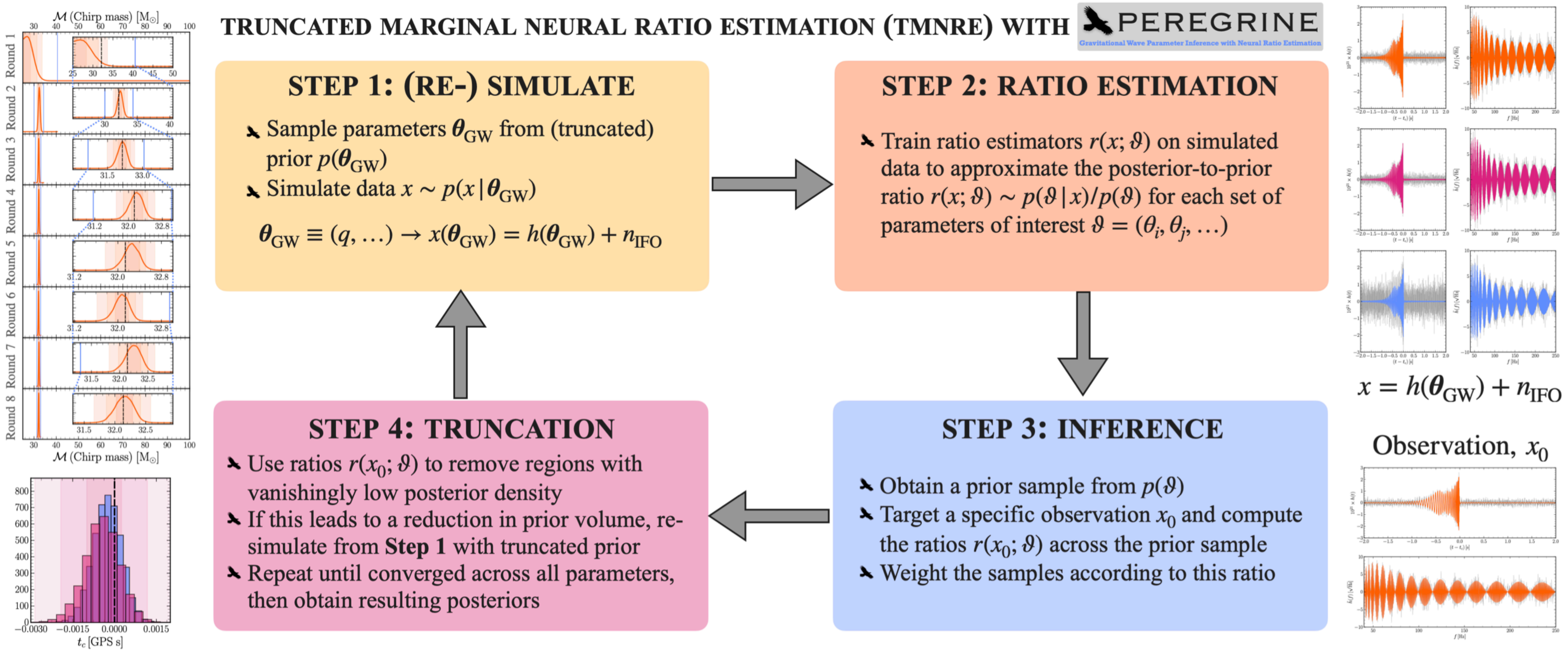
Coping with real LISA noise



LISA Red Book: arXiv:2402.07571

Towards a realistic data analysis strategy

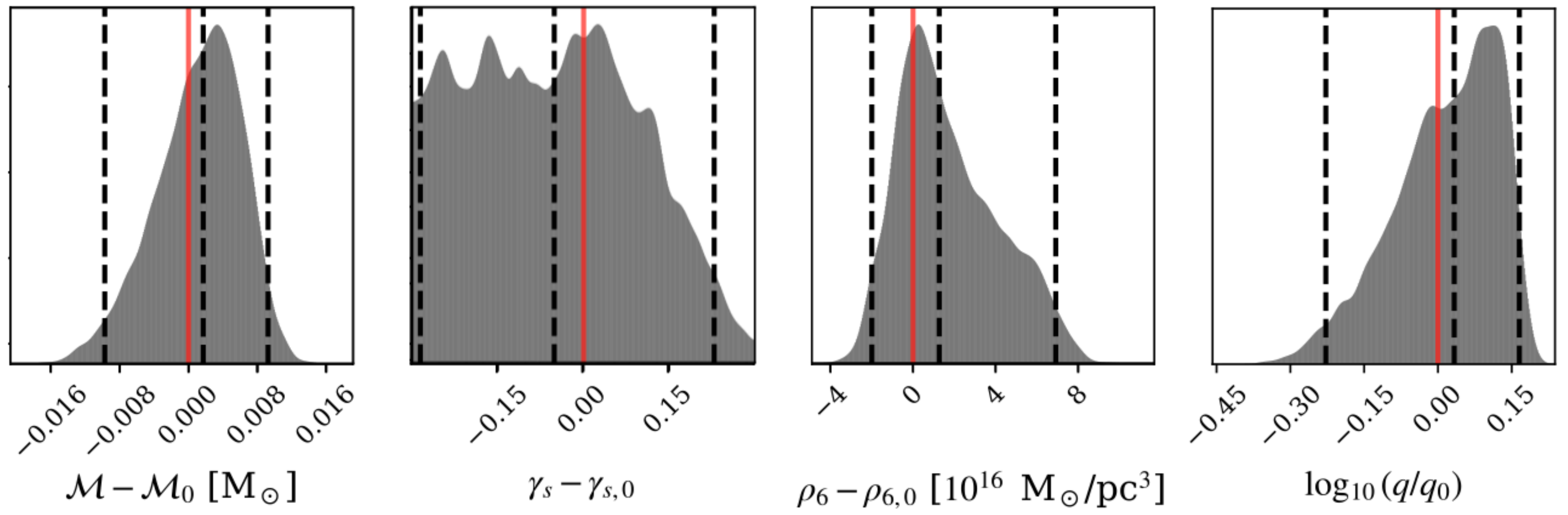
- Want to be able to flexibly add complexity to both the signal and the noise
- Deal with situations where the noise is not stationary and Gaussian
- Likelihood-free or simulation based inference methods may help

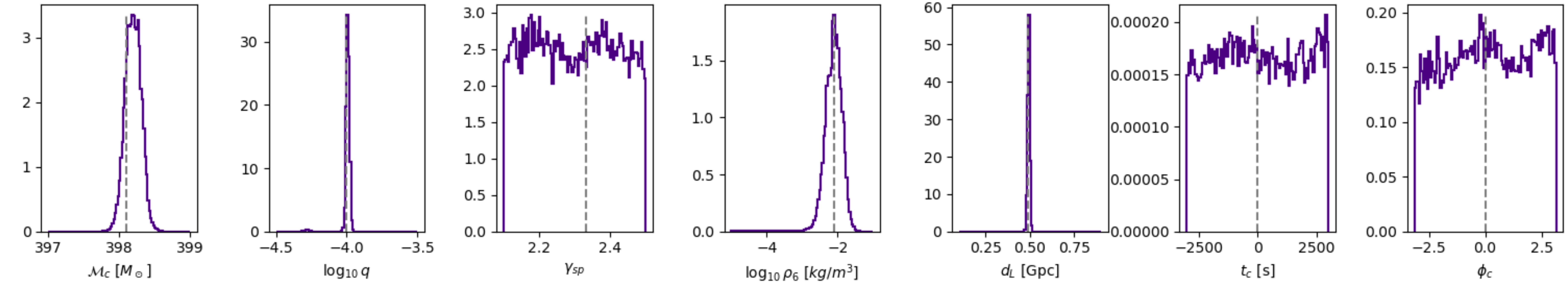


Bhardwaj et al. 2023

Towards a realistic data analysis strategy

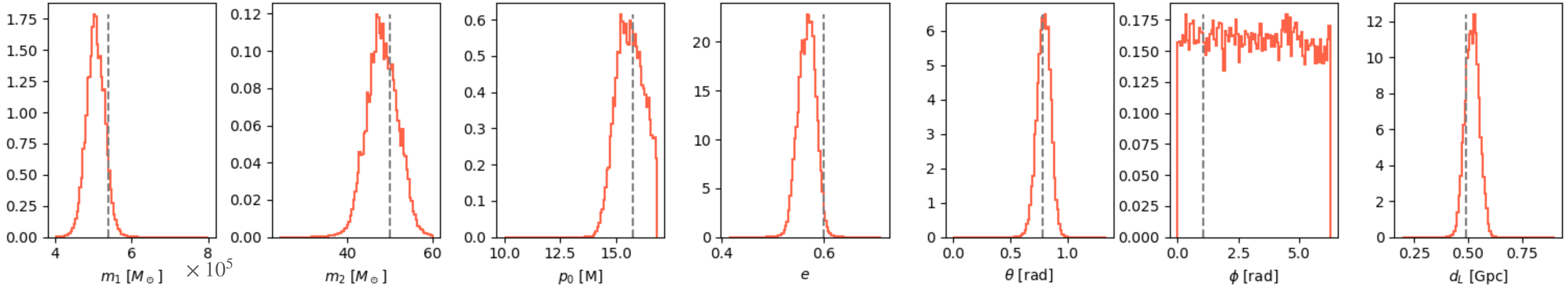
- Dark matter system as before, including extrinsic parameters and noise
- 30K simulations instead of 2million likelihood evaluations





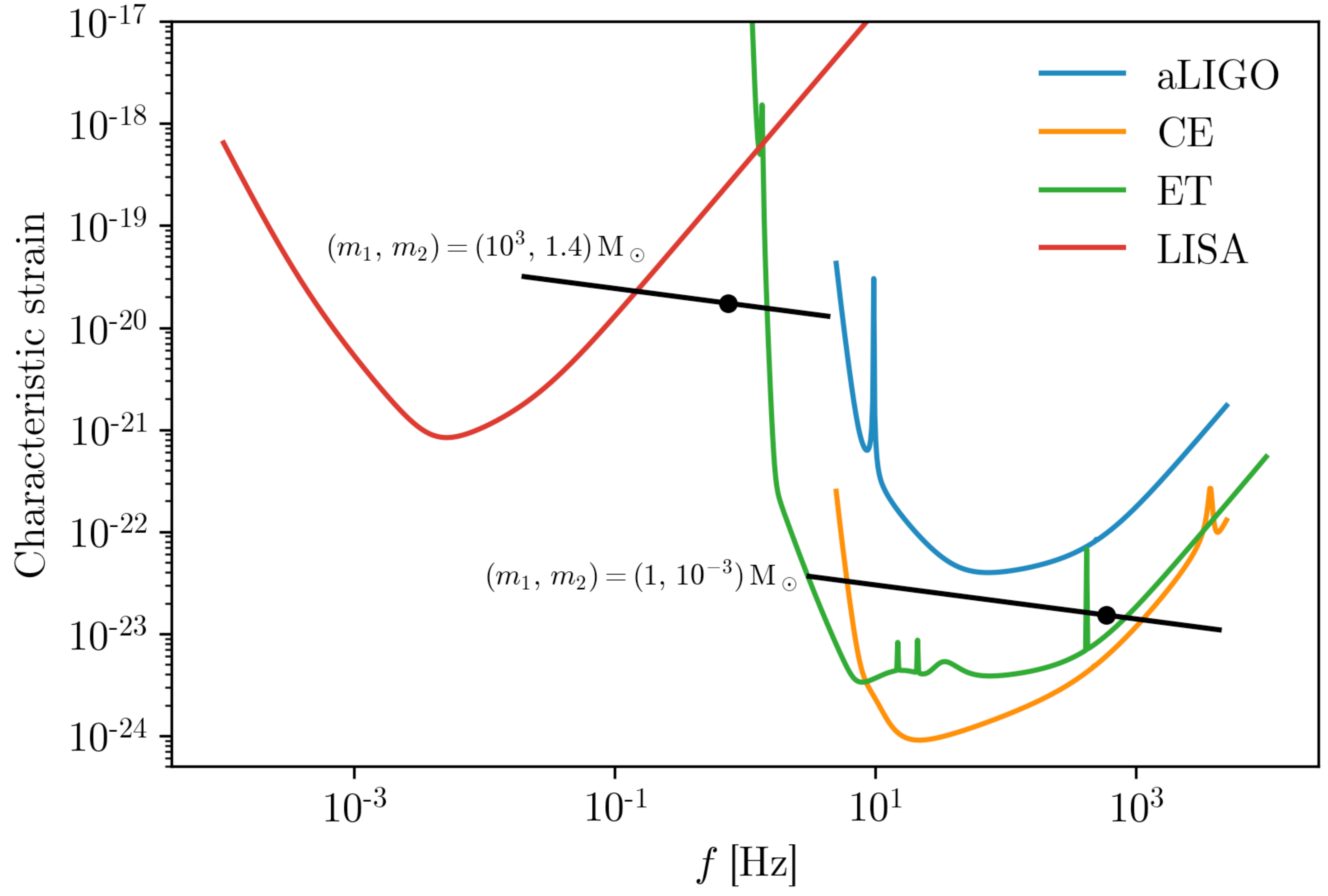
Towards a realistic data analysis strategy

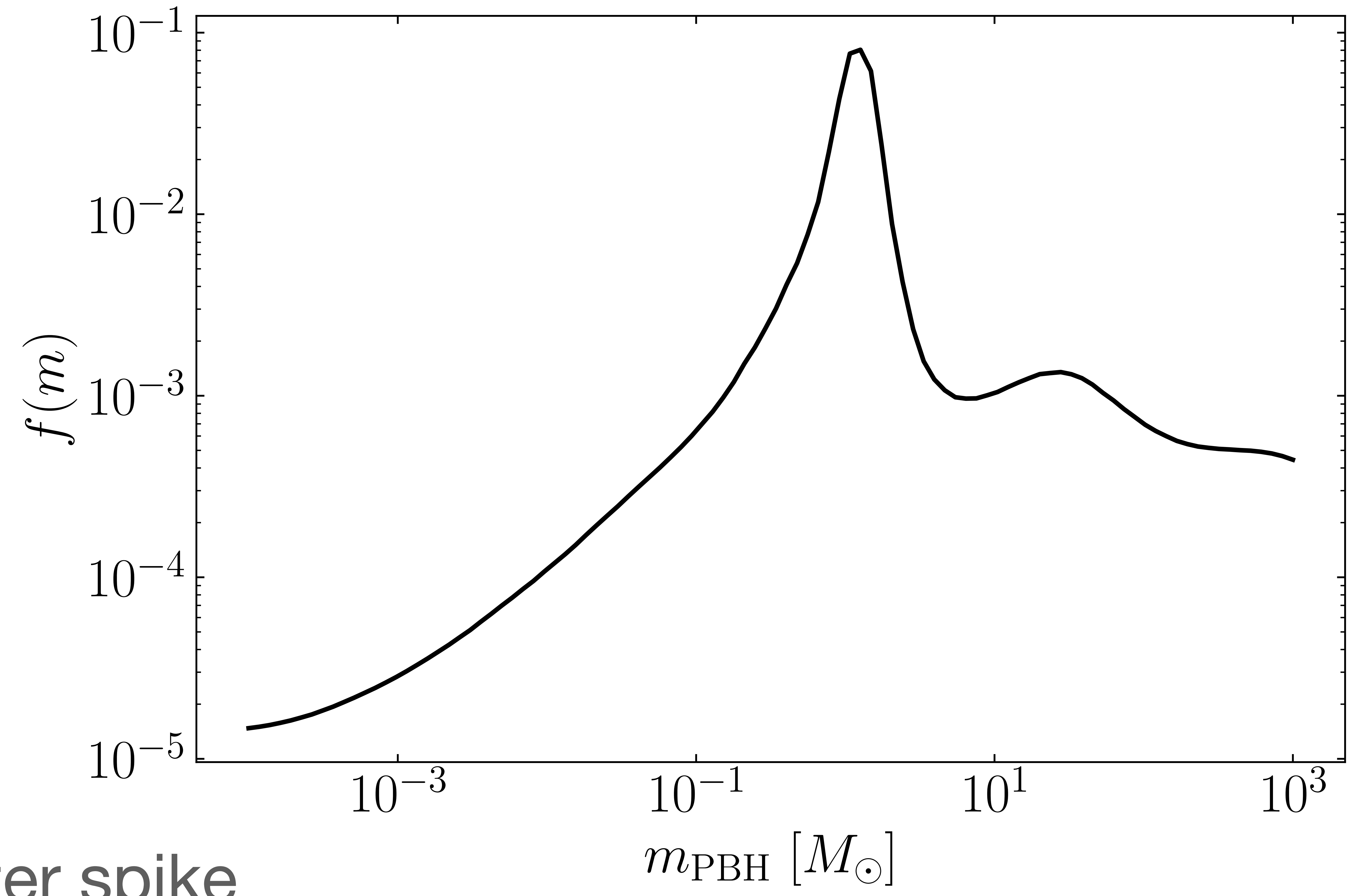
- Aim to increase complexity of signal using Fast EMRI Waveforms
- Preliminary results for Schwarzschild EMRI waveforms including the LISA response (no noise yet…)



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

What about future ground-based detectors?



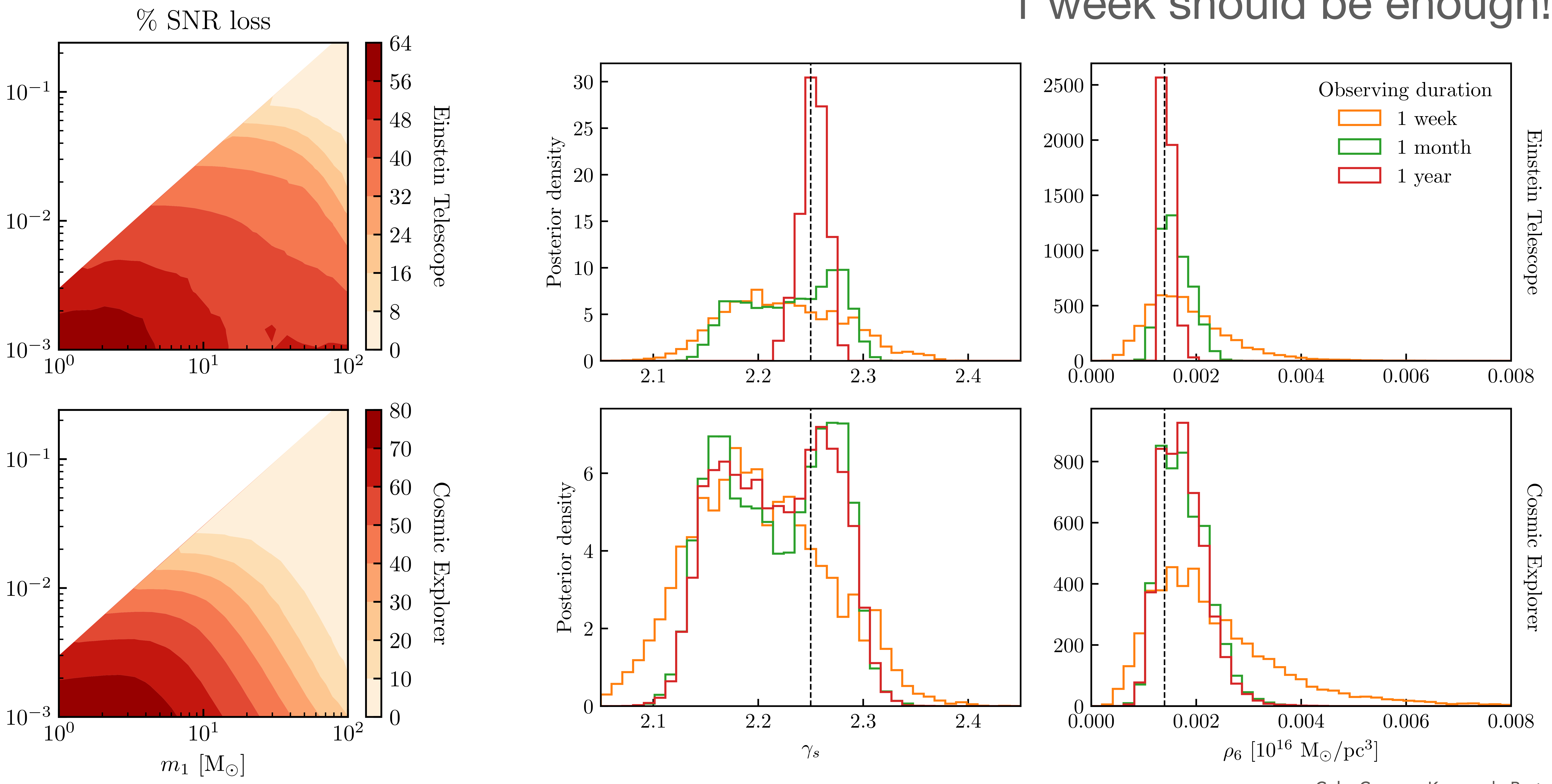


IMRI PBHs must have a dark matter spike

Cole, Coogan, Kavanagh, Bertone 2022

What about future ground-based detectors?

1 week should be enough!



Cole, Coogan, Kavanagh, Bertone 2022

Conclusions

- We can measure the properties of environments around binaries with future GW detectors
- We have an opportunity to learn about the nature of dark matter from IMRI gravitational waveforms
- We can distinguish between environments and avoid confusion with, for example, accretion disks
- Biased parameter reconstruction is possible if the wrong model is used

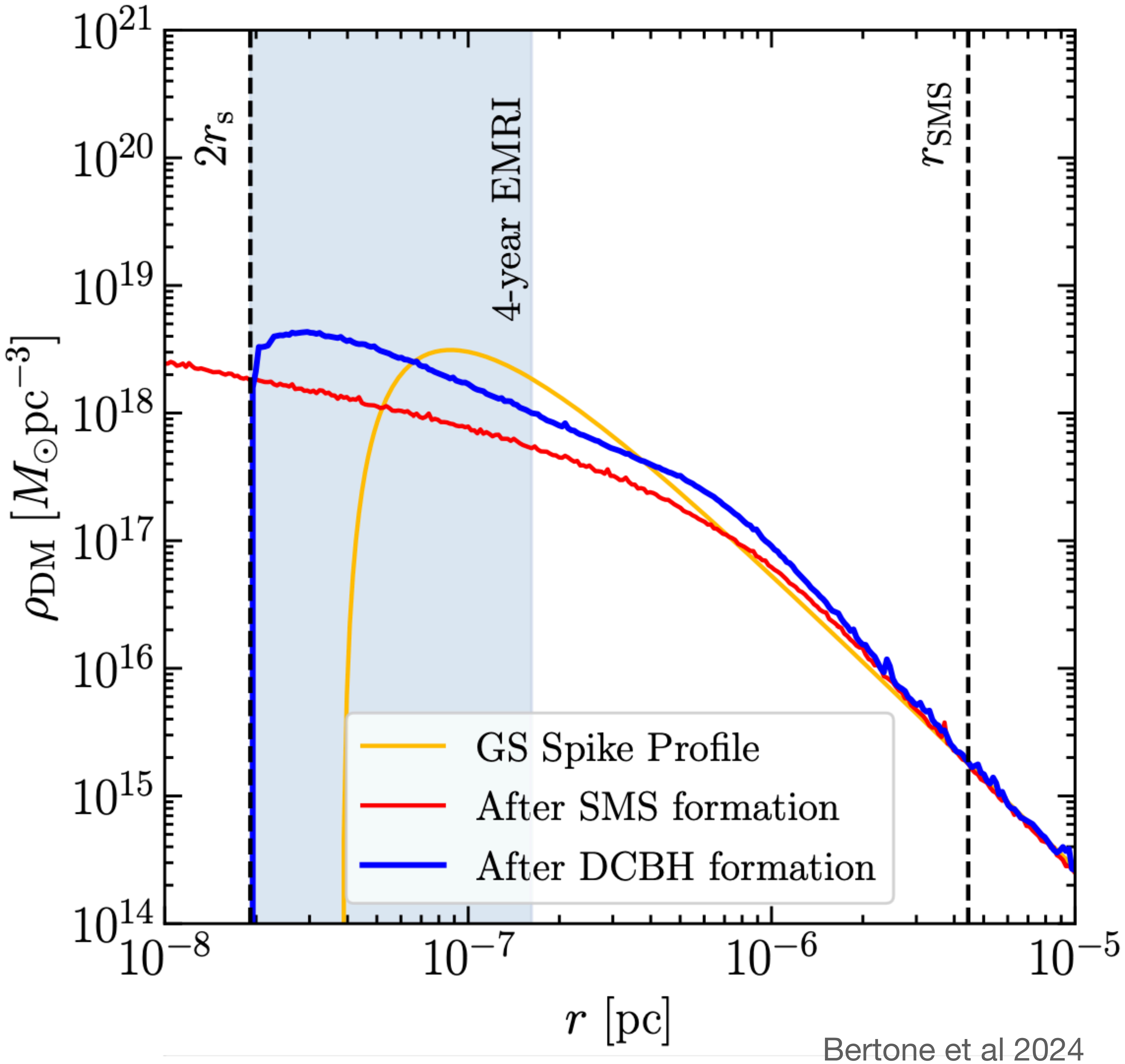
Current/future work:

- Use simulation based inference to tackle data analysis problems
- Demonstrate that signatures of dark matter survive these additional complexities in signal and noise modelling!

Thank you for listening!

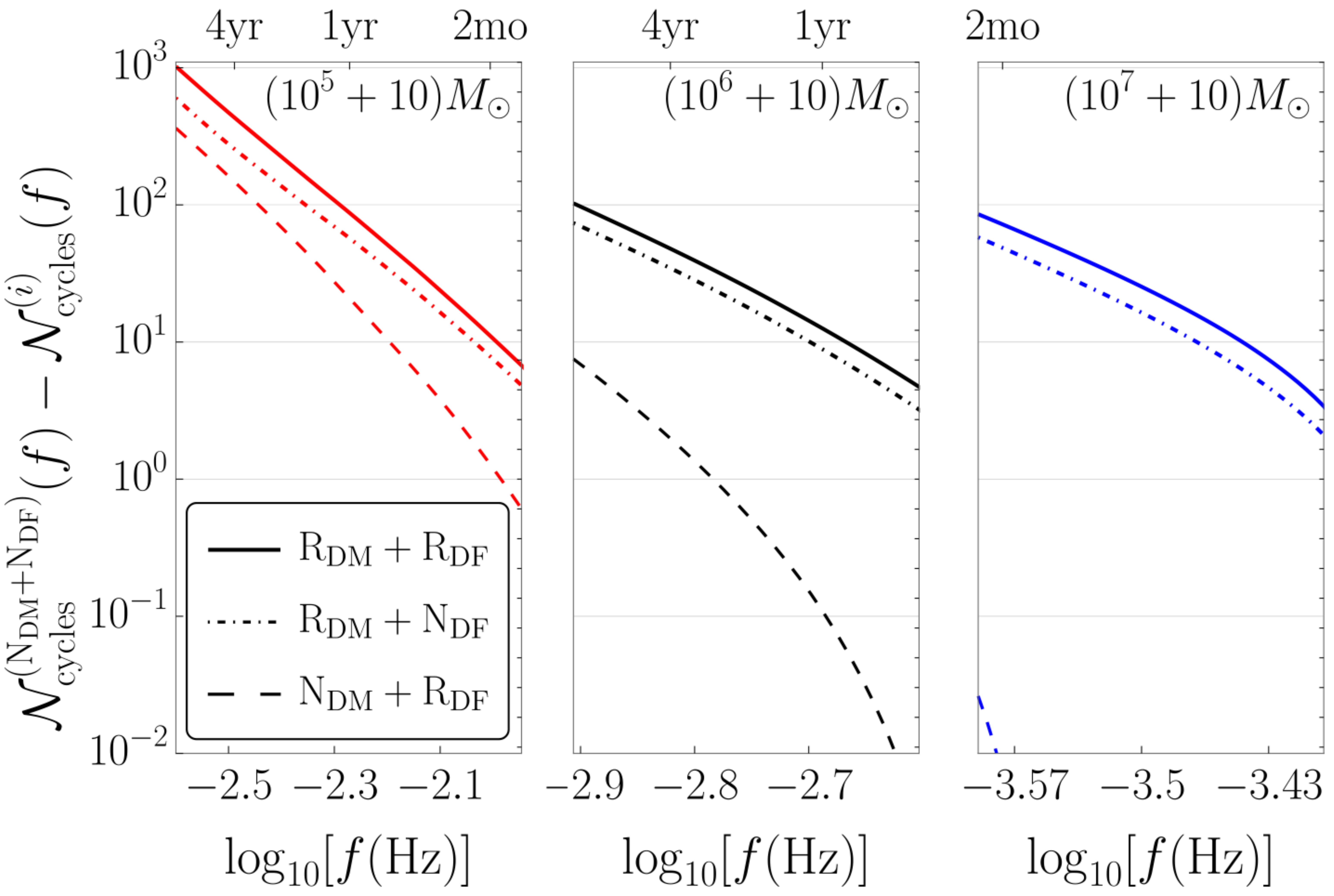
Dark matter mounds

- Supermassive star forms inside dark matter spike, then directly collapses to form a BH



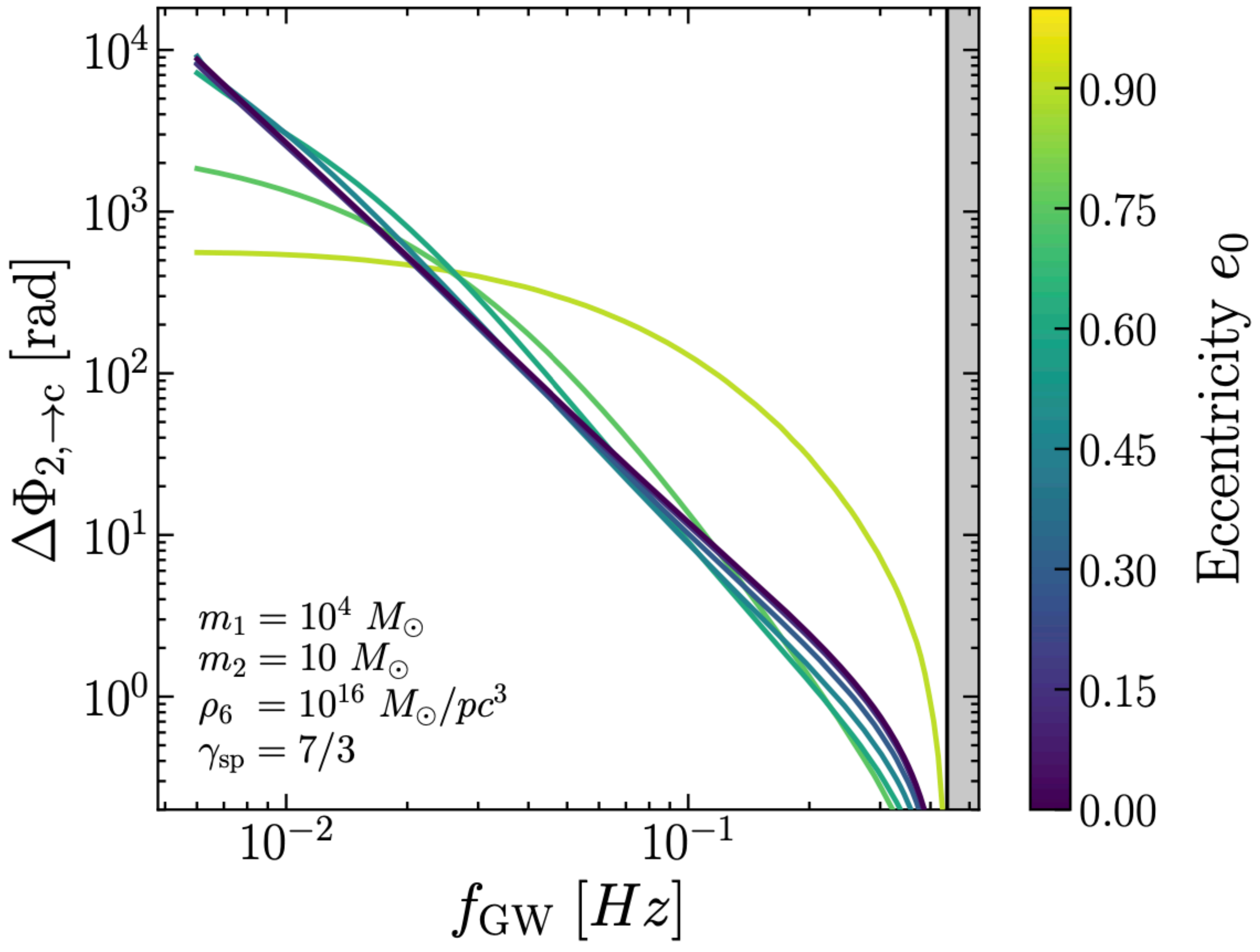
Bertone et al 2024

Relativistic effects



Speeney et al 2022

Eccentricity



Karydas 2024