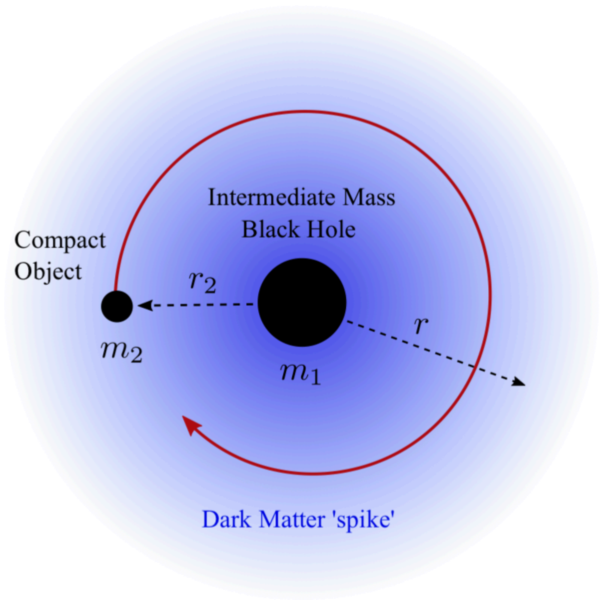
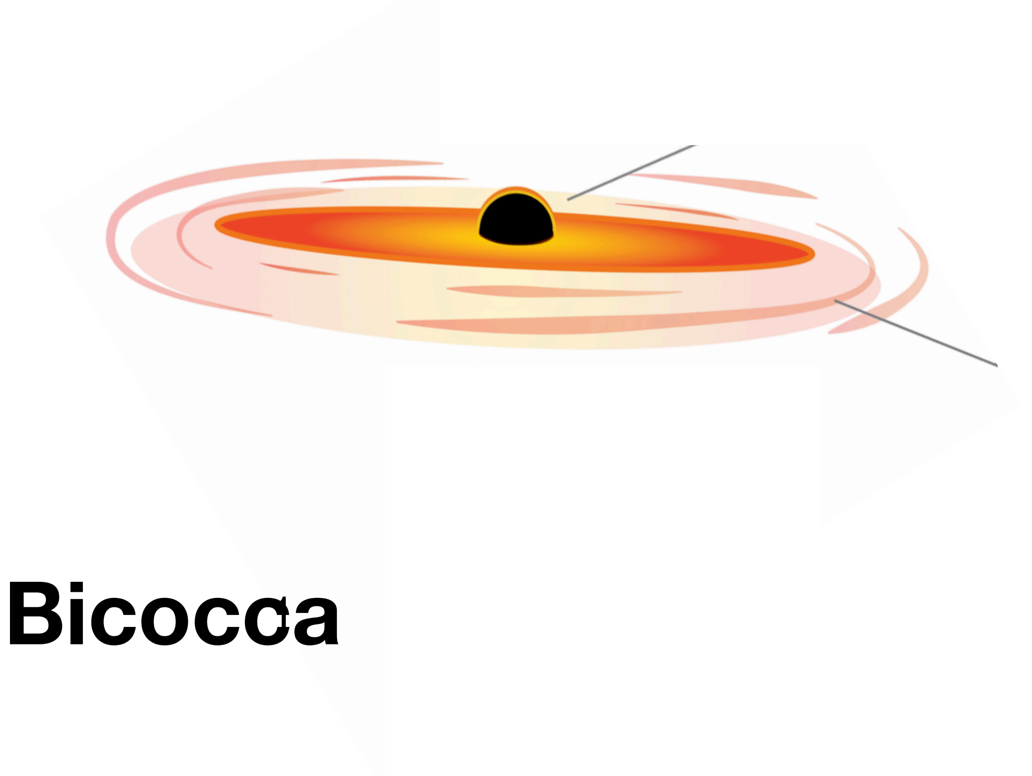
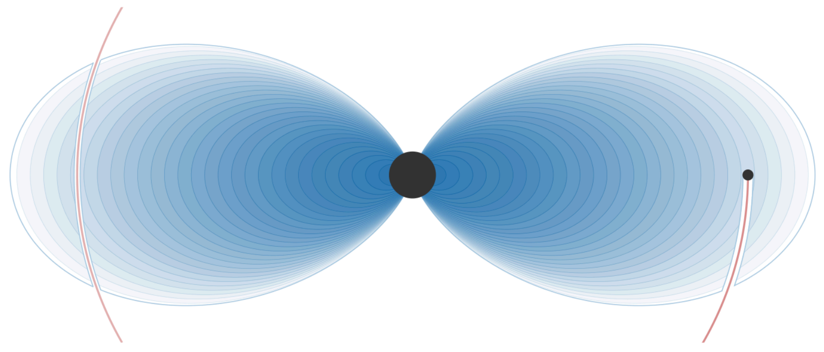
Searching for dark matter with future gravitational wave detectors







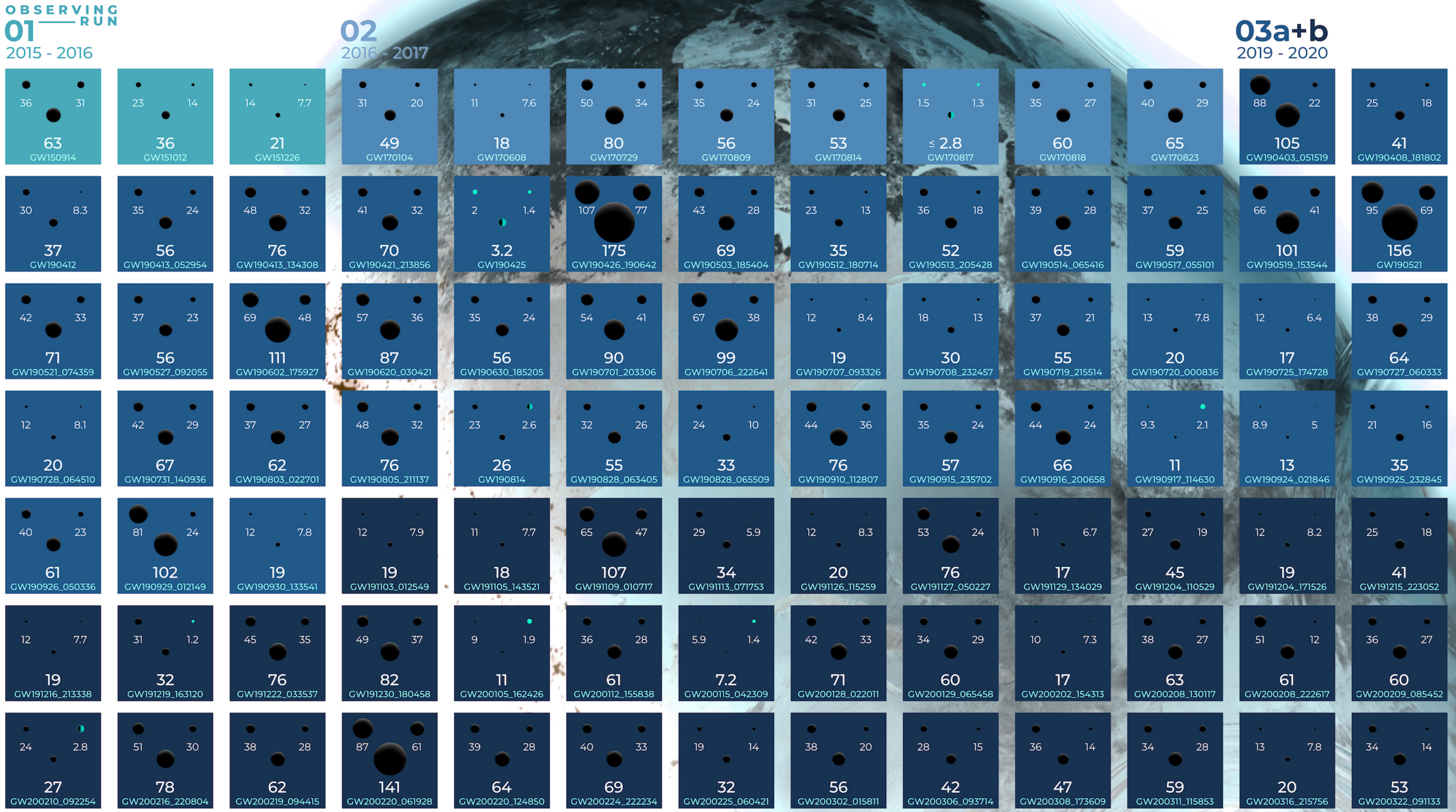
Philippa (Pippa) Cole, University of Milano-Bicocca

with James Alvey, Gianfranco Bertone, Uddipta Bhardwaj, Adam Coogan, Daniele Gaggero, Davide Gerosa, Bradley Kavanagh, Theophanes Karydas, Lorenzo Speri, Thomas Spieksma, Giovanni Maria Tomaselli and Christoph Weniger

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 and work in prep.

8th April, Beyond WIMPs 2025

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



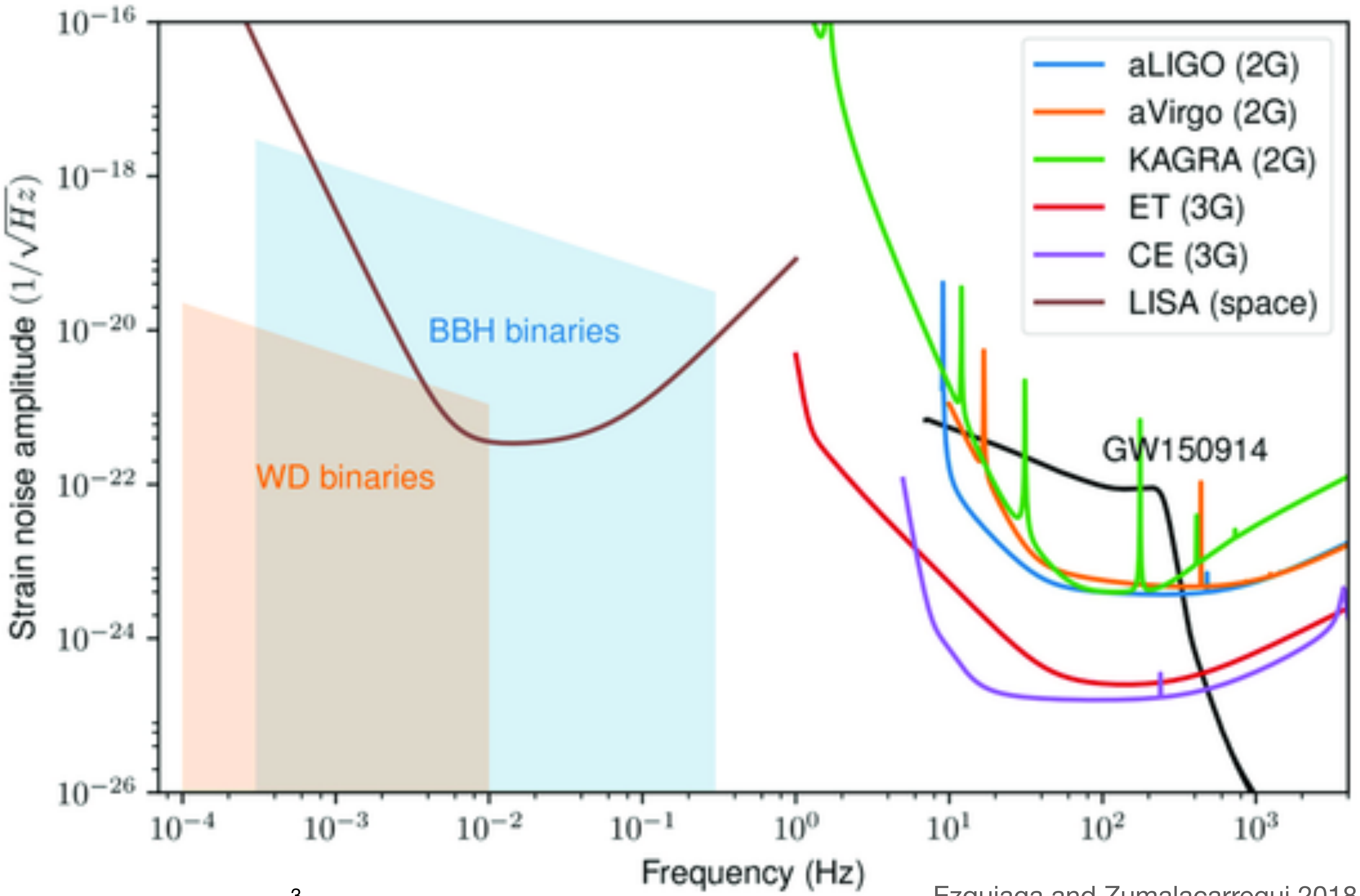
~200 more significant events in O4 so far

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

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

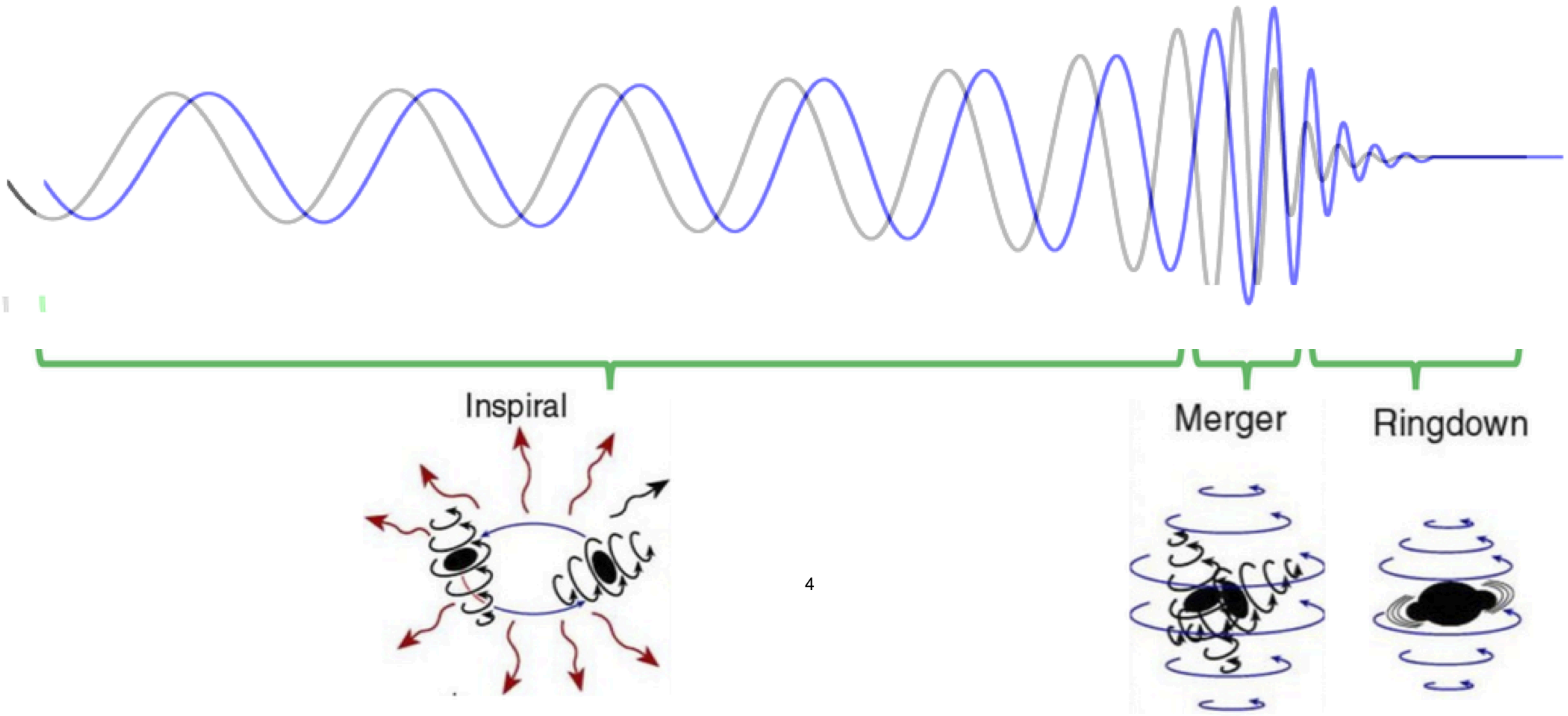
Phase evolution

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

Gravitational wave strain (amplitude)

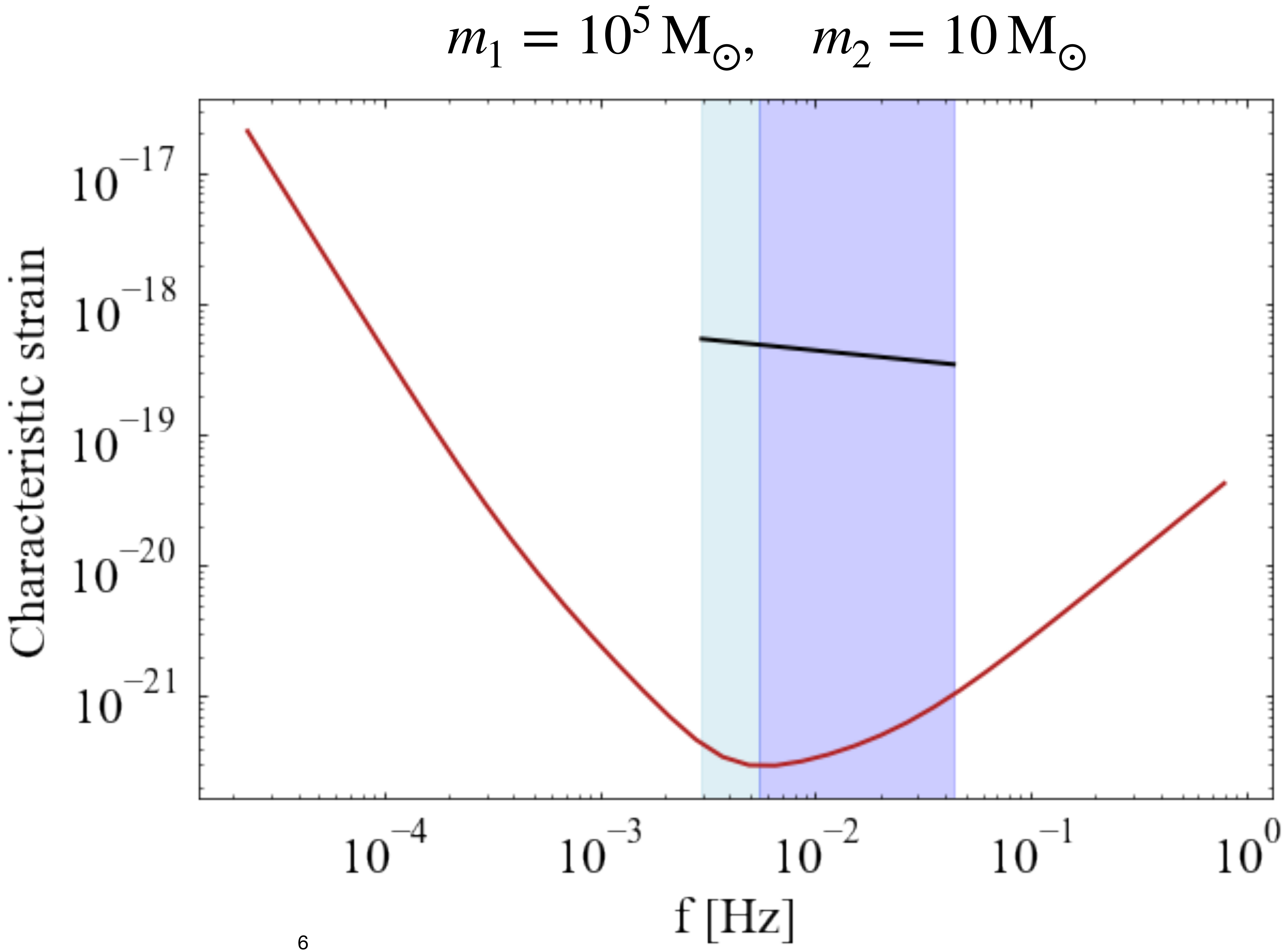
$$h_0(f) = \frac{1}{2}\frac{4\pi^{2/3}G_N^{5/3}\mathcal{M}^{5/3}f^{2/3}}{c^4}\sqrt{\frac{2\pi}{\ddot{\Phi}}}$$

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



The key is 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



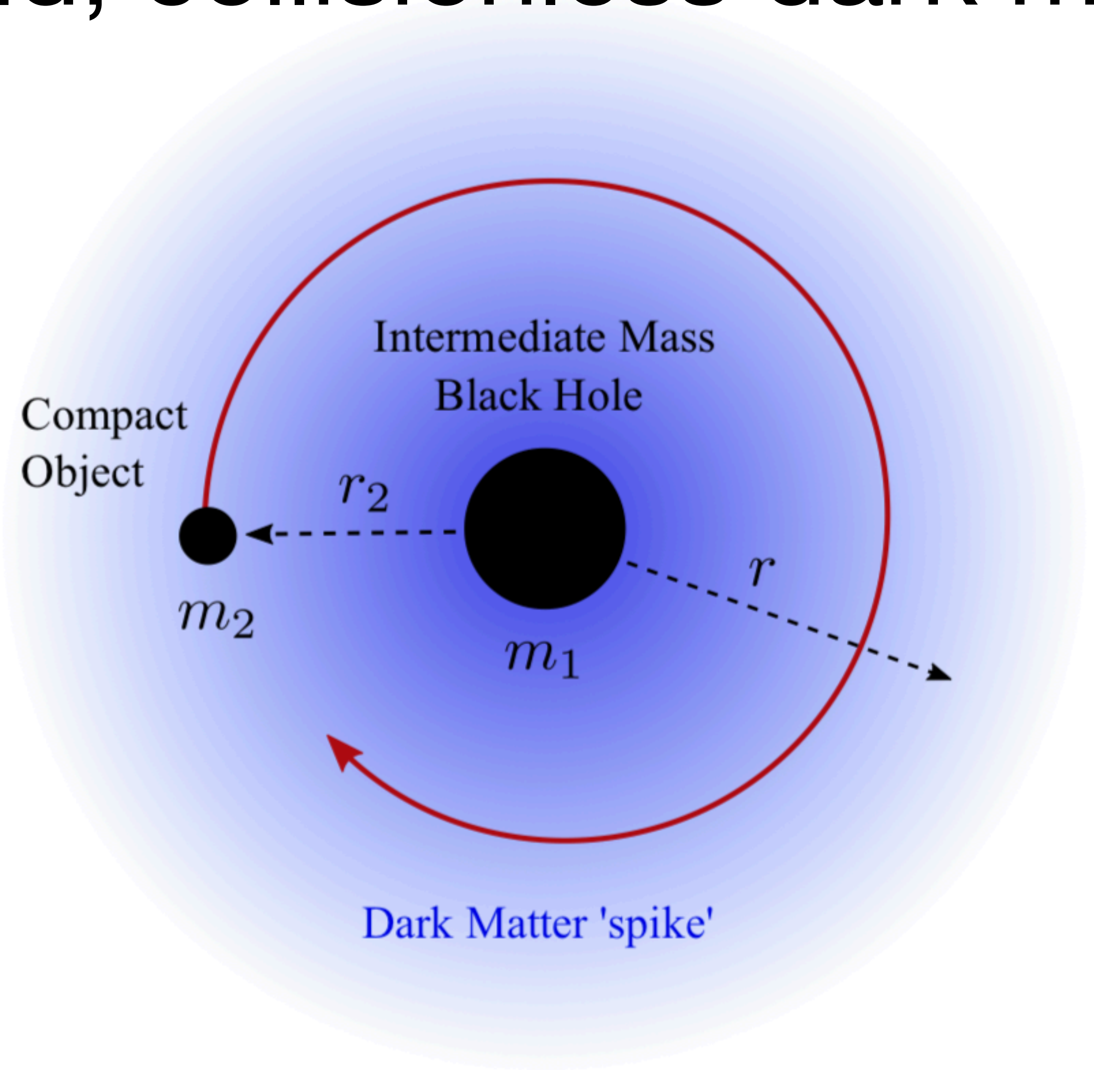
Why should we care about environmental effects?

- 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

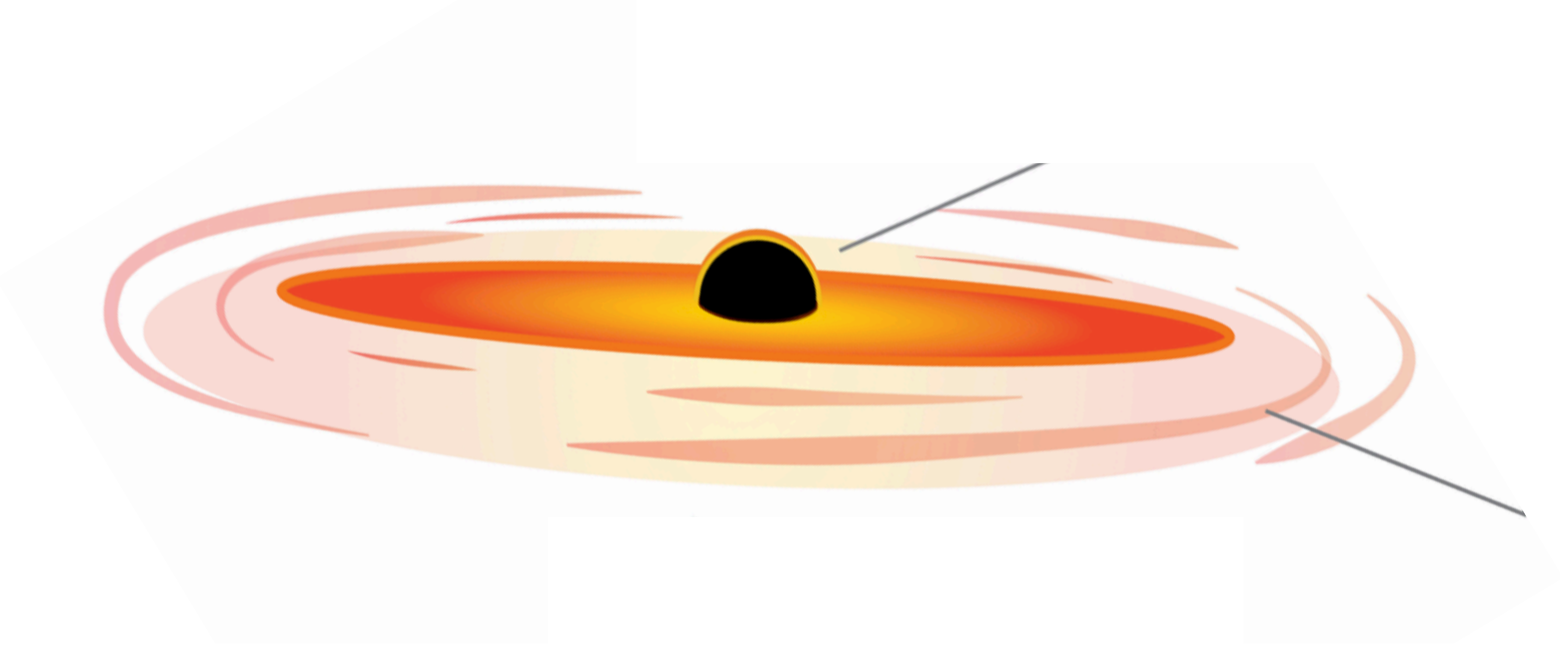


$$\rho(r) = \rho_6 \left(\frac{r_6}{r}\right)^{\gamma_s}$$

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

Accretion disk

Baryonic matter



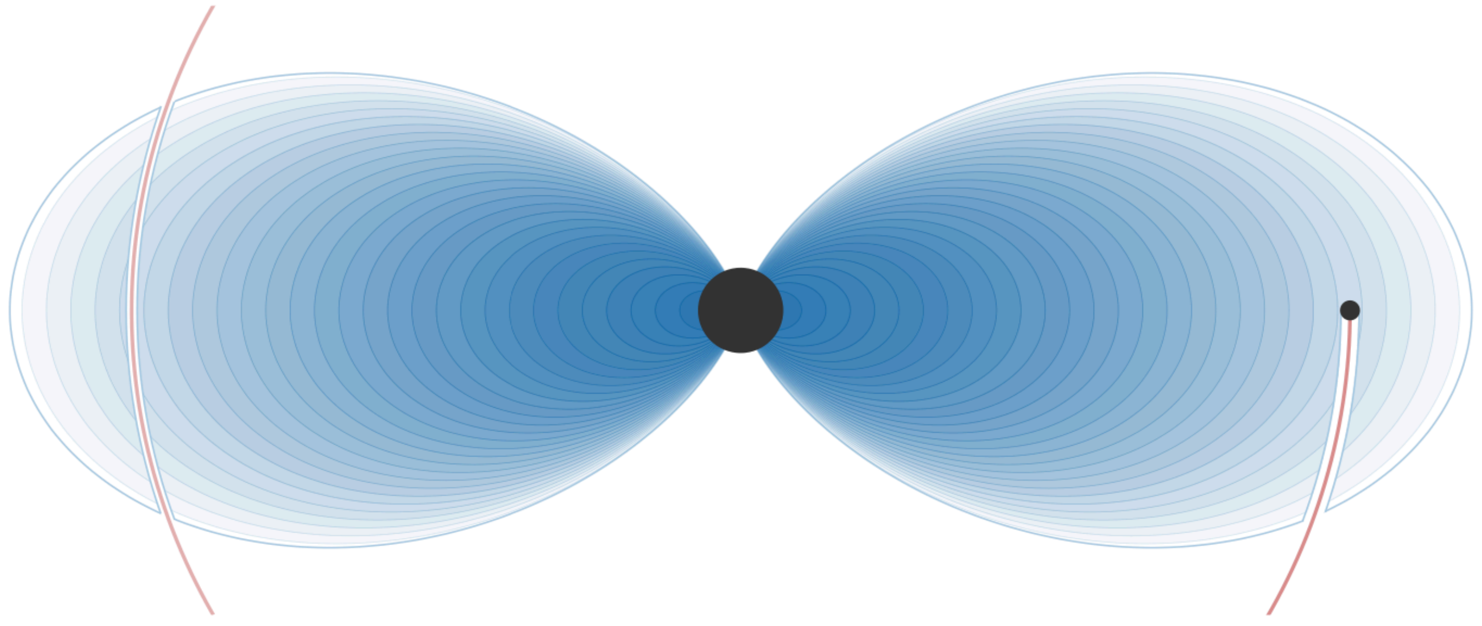
$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1/2}$$

$$M = r/h$$

Goldreich & Tremaine 1980
Tanaka 2002
Derdzinski et al. 2020

Gravitational atom

Ultra-light bosons



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

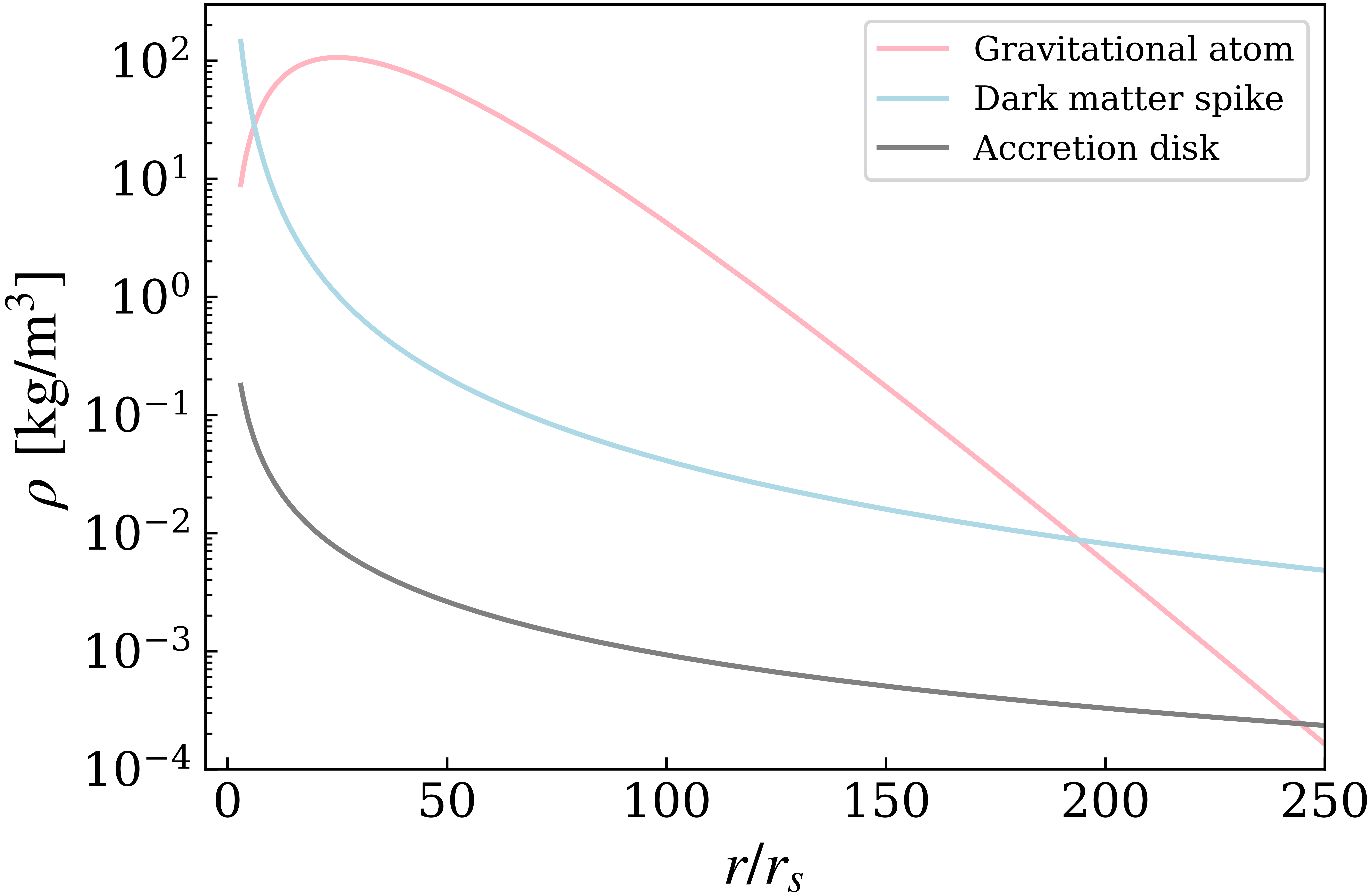
$$\alpha \equiv G m_1 \mu \ll 1$$

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?

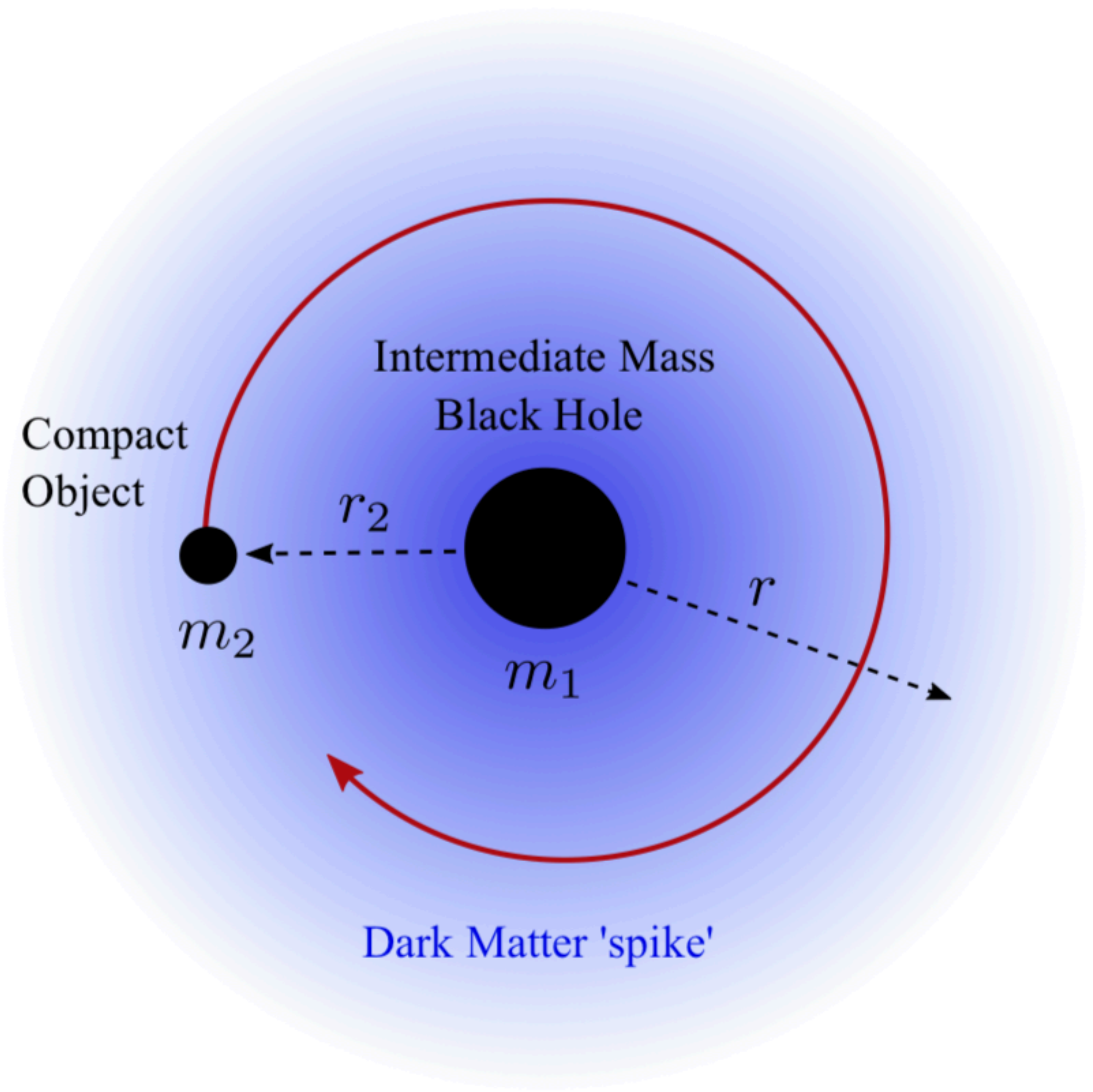


$r_s \sim 10^{-8}$ pc

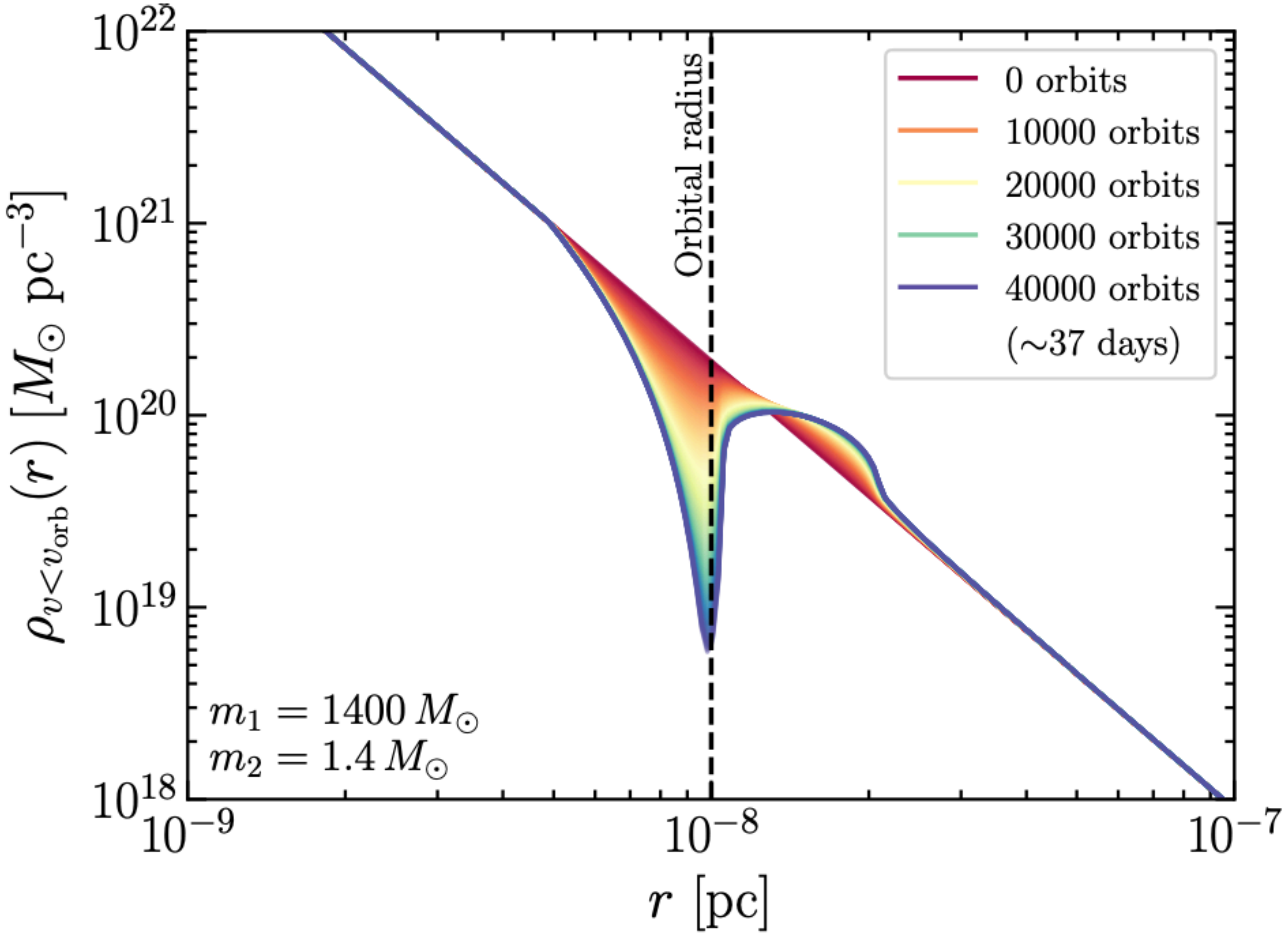
Cole et al. 2023

Dynamical friction

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



HaloFeedback

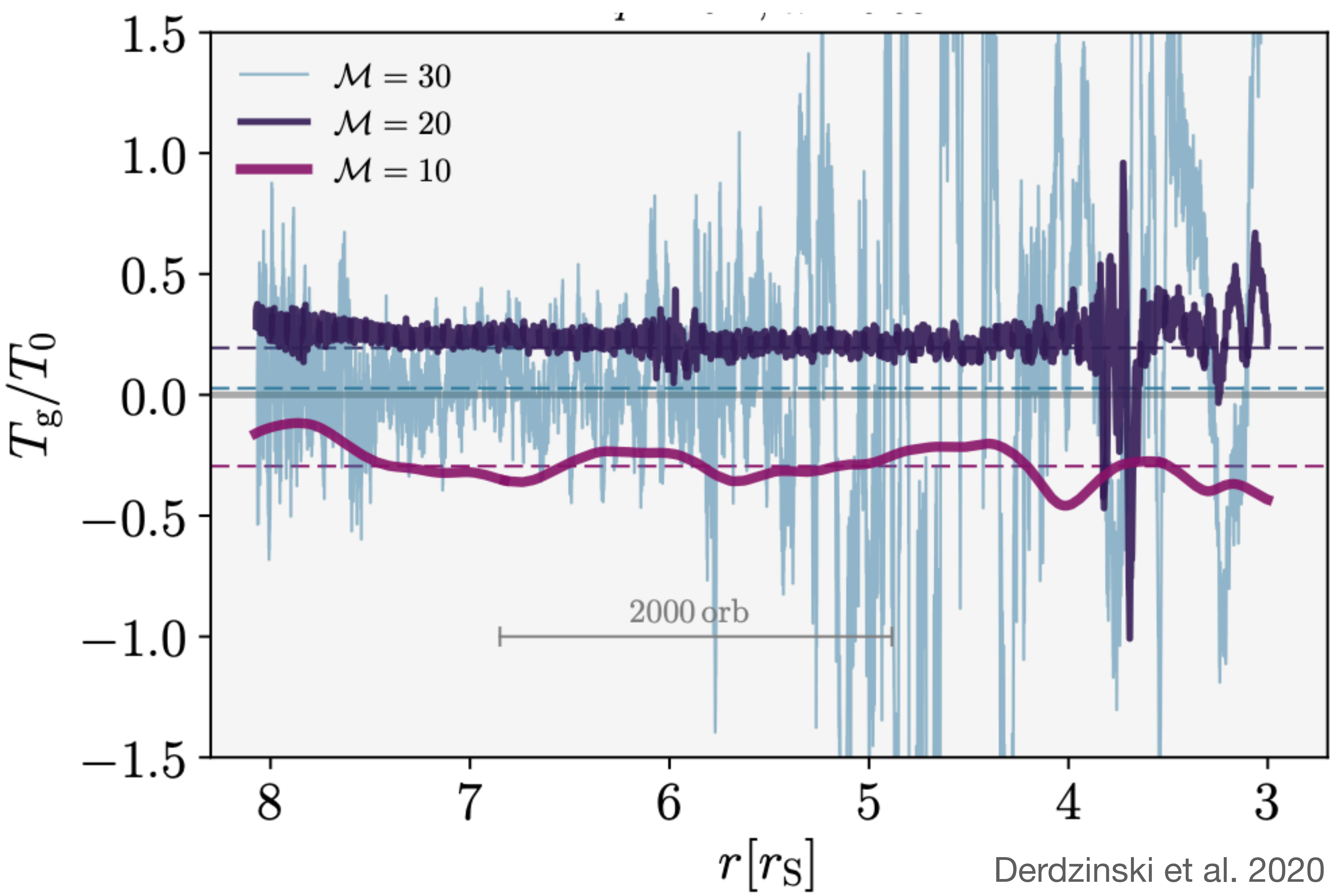


Kavanagh, Nichols, Bertone, Gaggero 2020

Gas torques

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

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



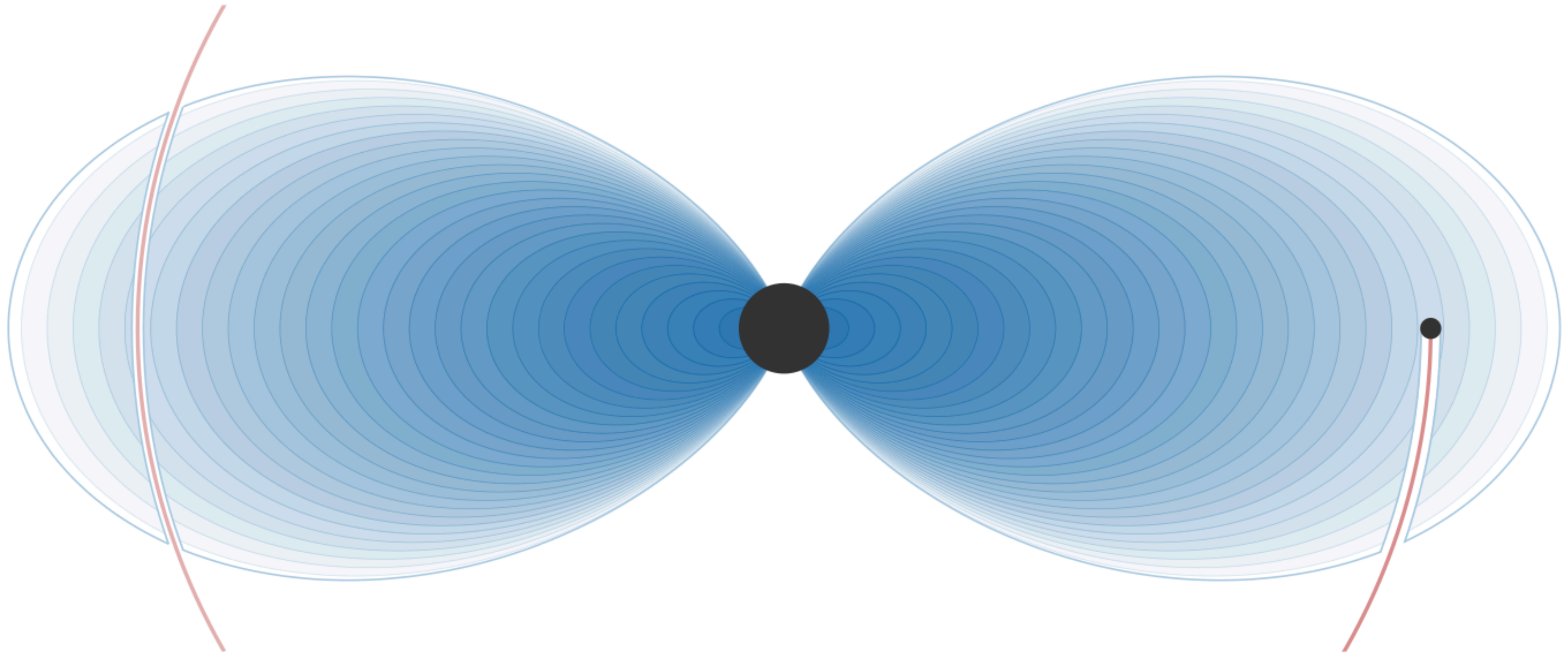
Derdzinski et al. 2020

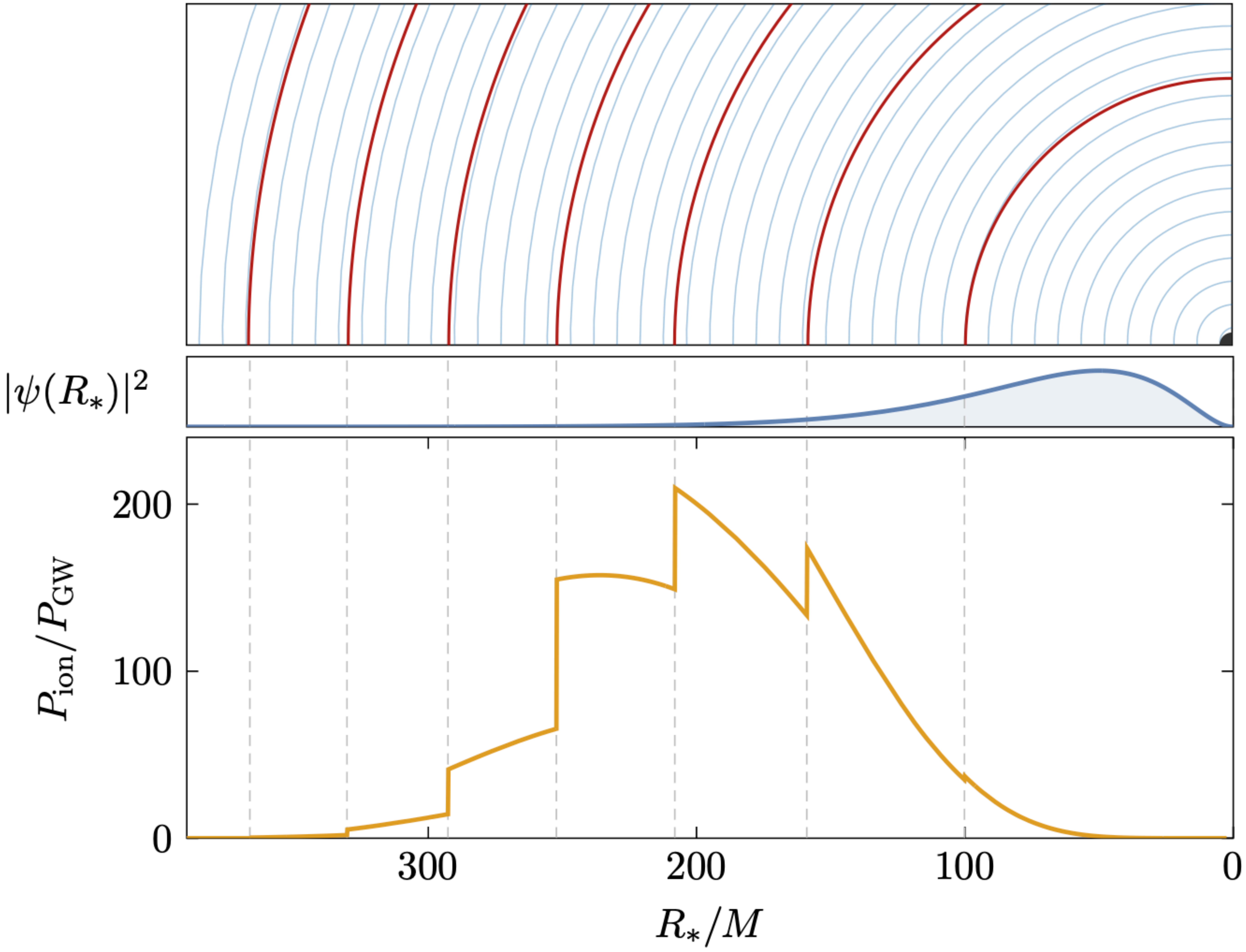
Assume gas in the disk is corotating with the companion object, which is orbiting in the plane of the disc.

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

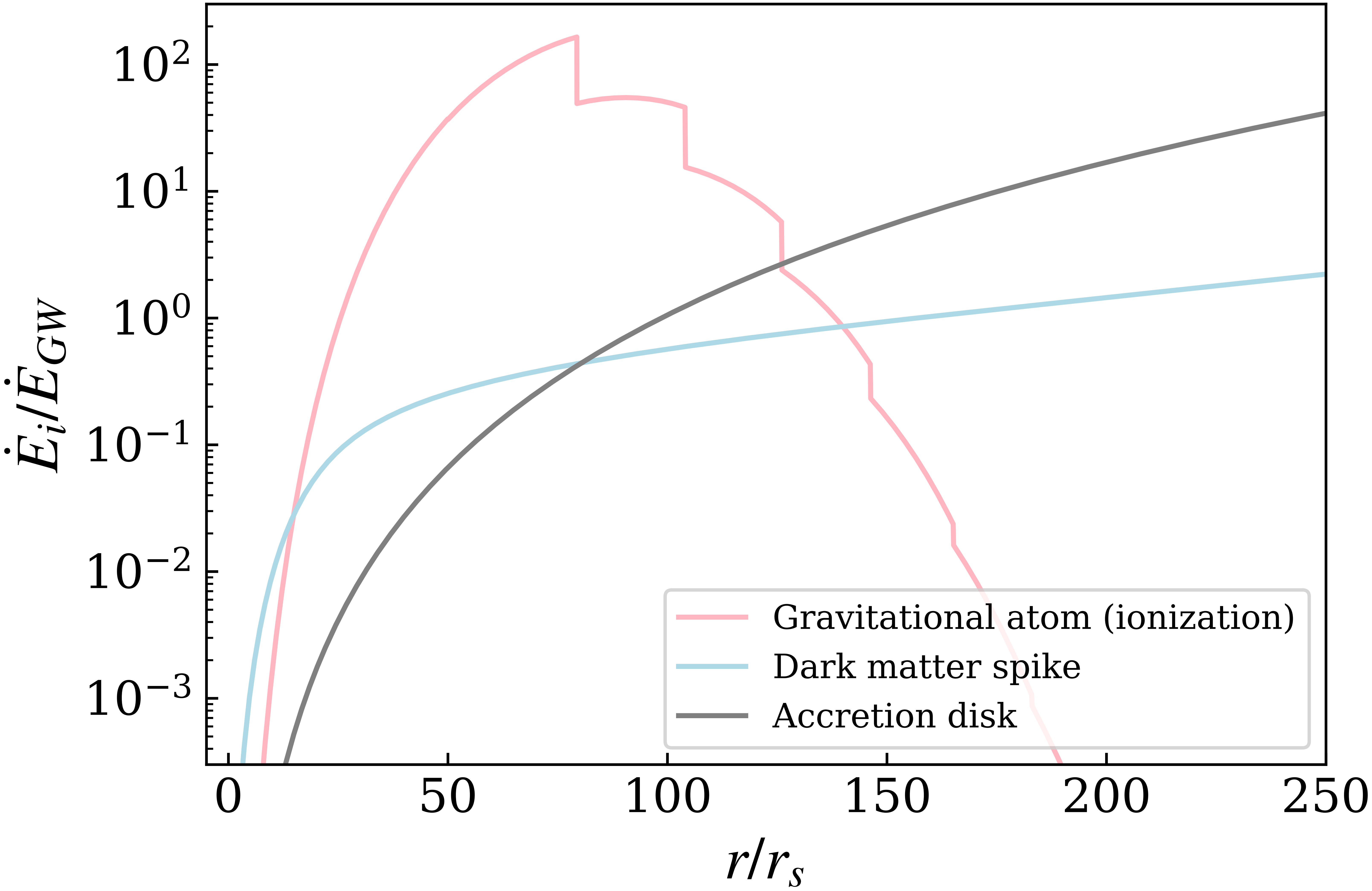




Perturber excites resonances in the cloud and it transitions from bound states to unbound states as the orbital frequency of the perturber hits the frequency of the energy difference between states

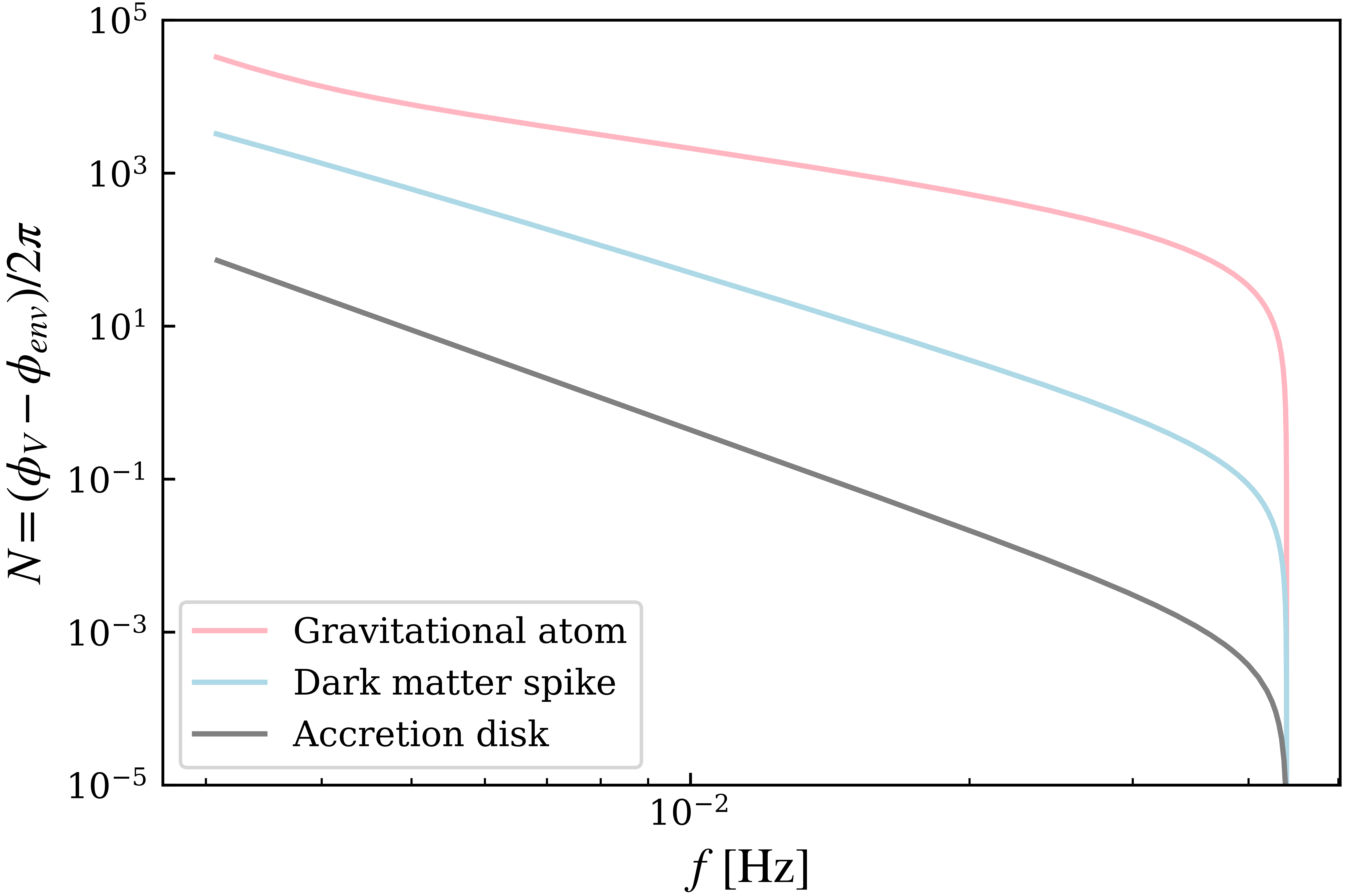
Baumann, Bertone, Stout, Tomaselli 2021

Energy losses



Cole et al. 2023

Dephasing



Cole et al. 2023

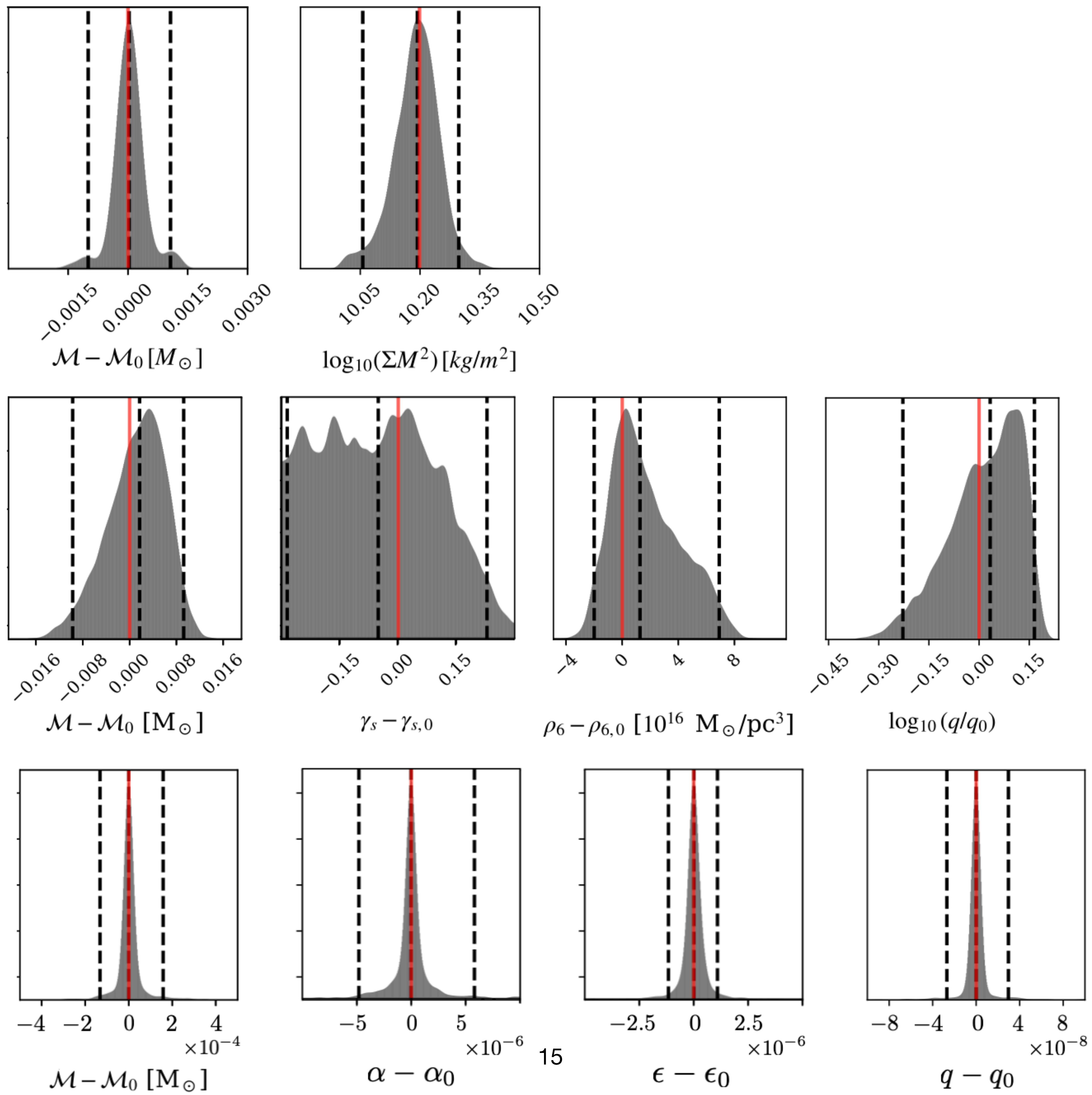
Assuming we've detected a signal, can we measure the parameters?

Parameter estimation with correct model

Accretion disk

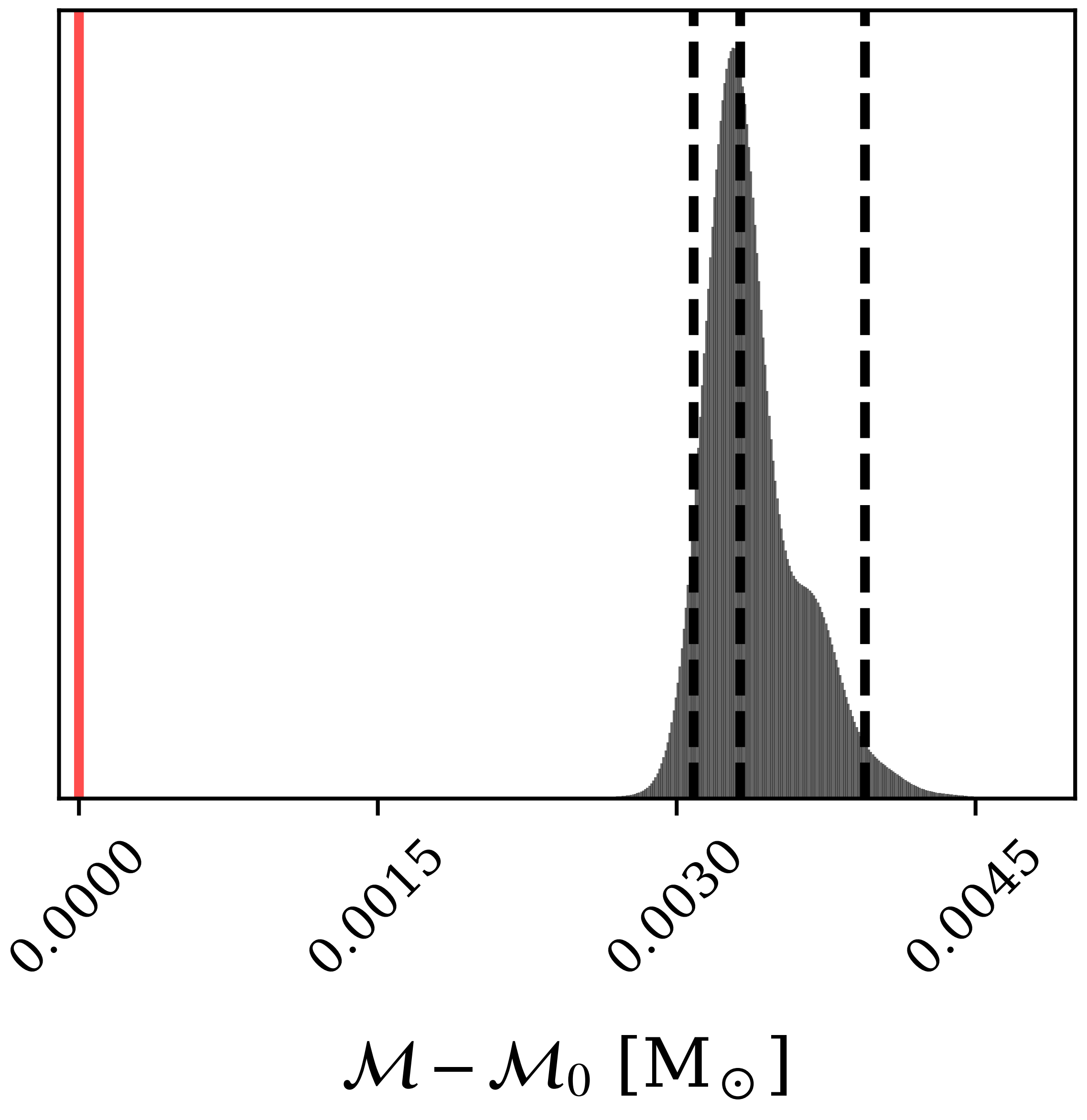
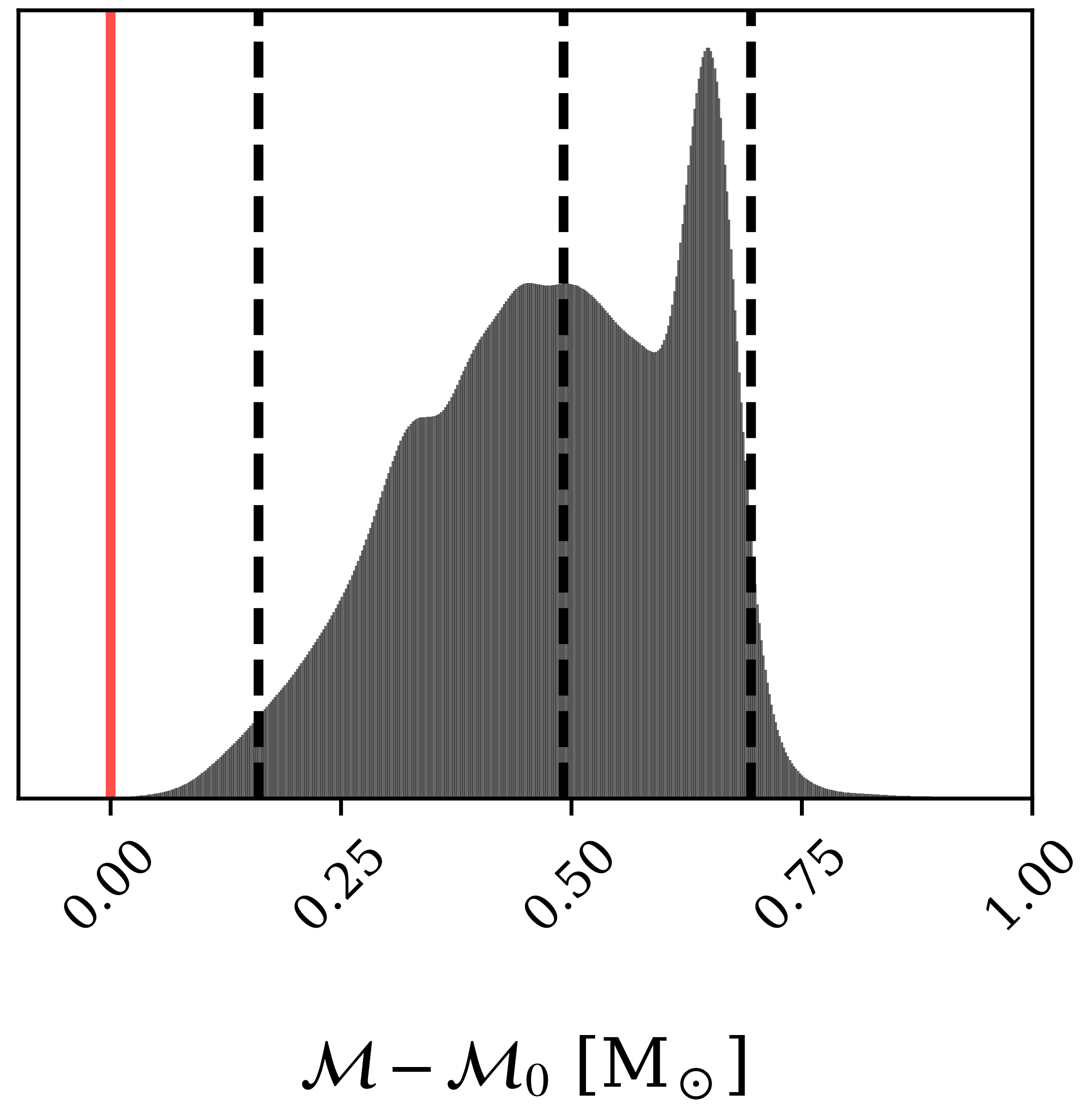
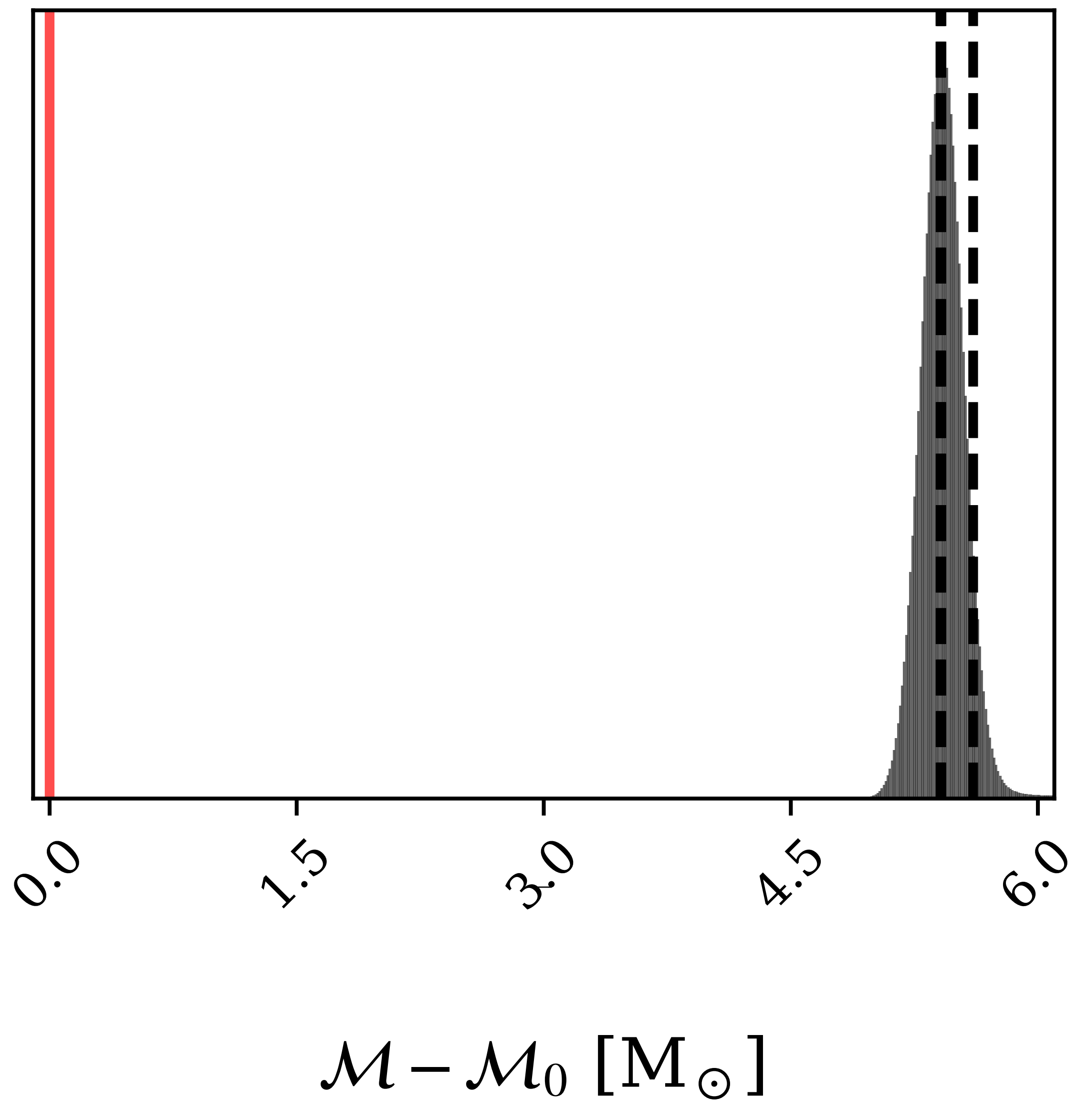
Dark dress

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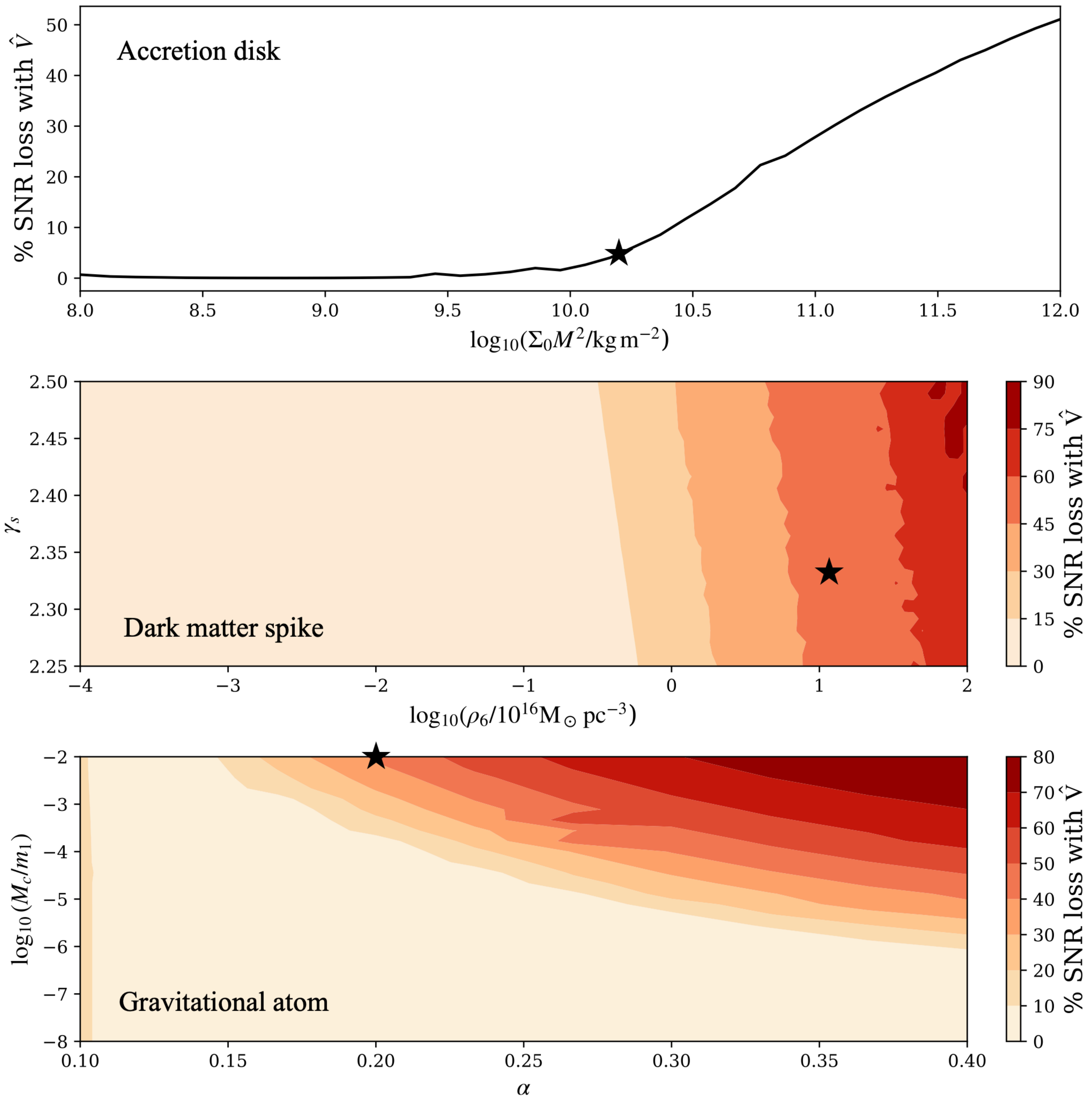
Cole et al. 2023

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	-

Opportunity to learn about new physics in the best case scenario…

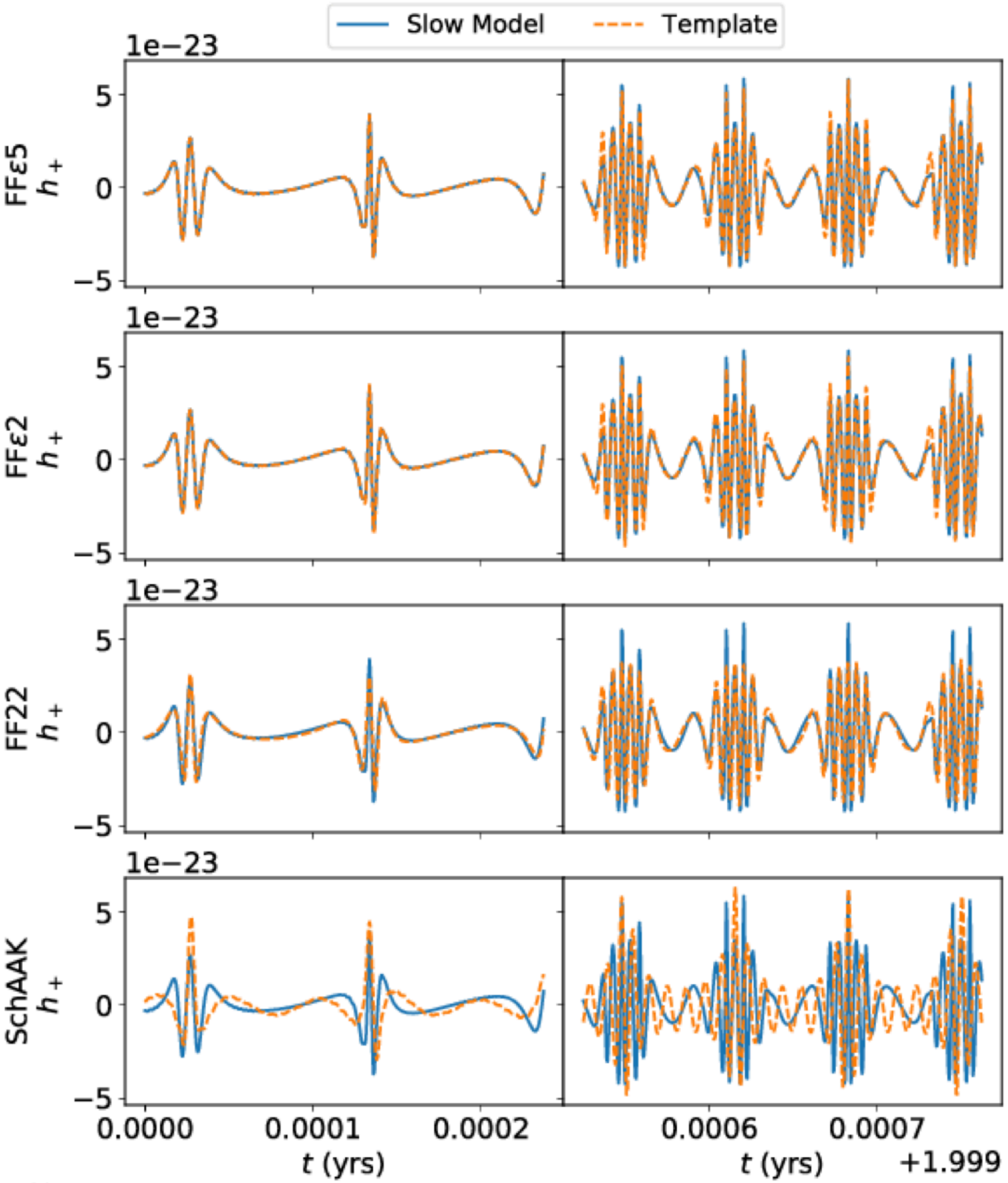
Can we do it in practice?

Improvements to signal modelling

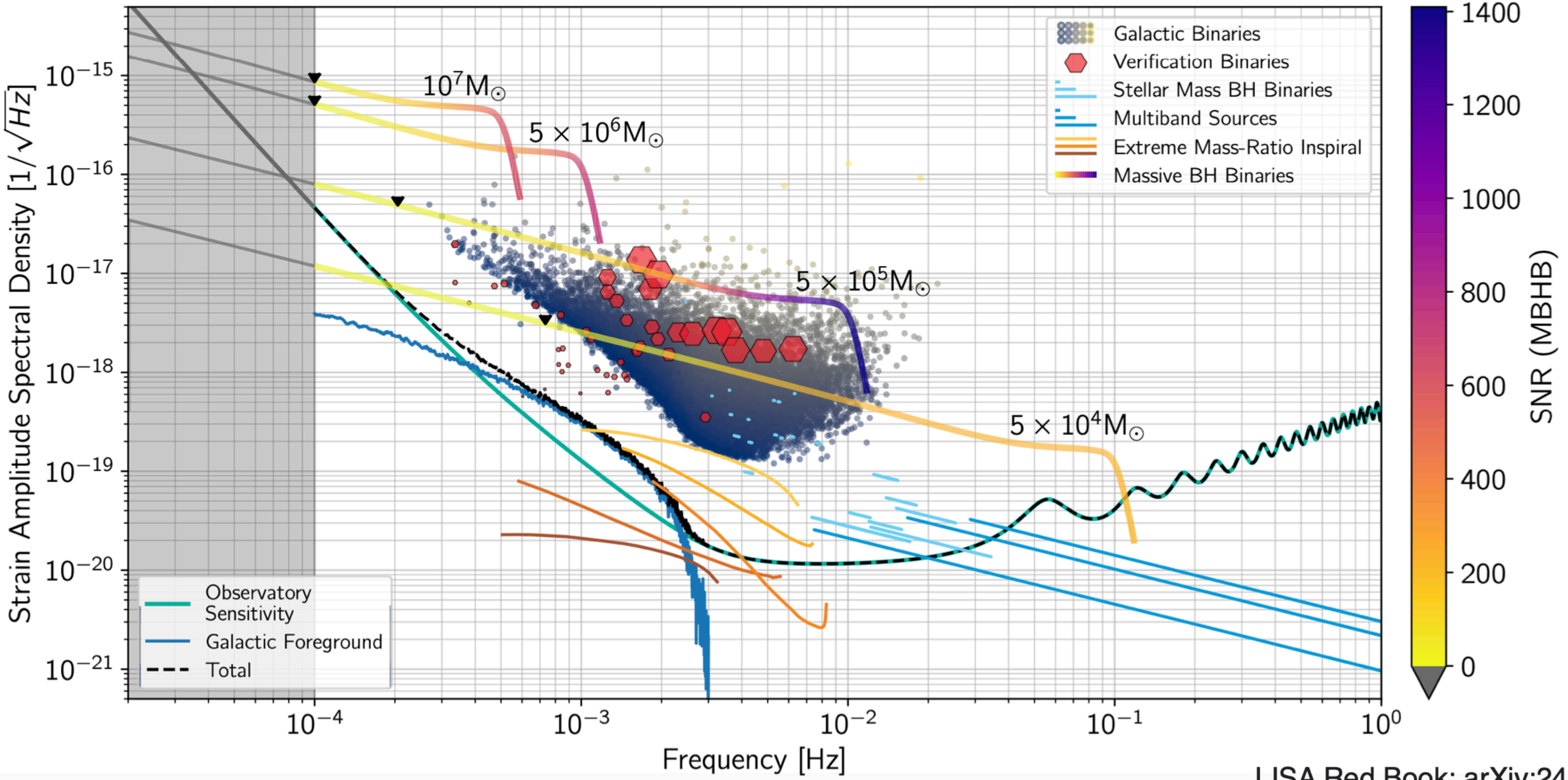
For example:

- Higher order waveforms
- For example Fast EMRI Waveforms (FEW) - 1st order in gravitational self-force
- Relativistic corrections to environment modelling
- Include detector response

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



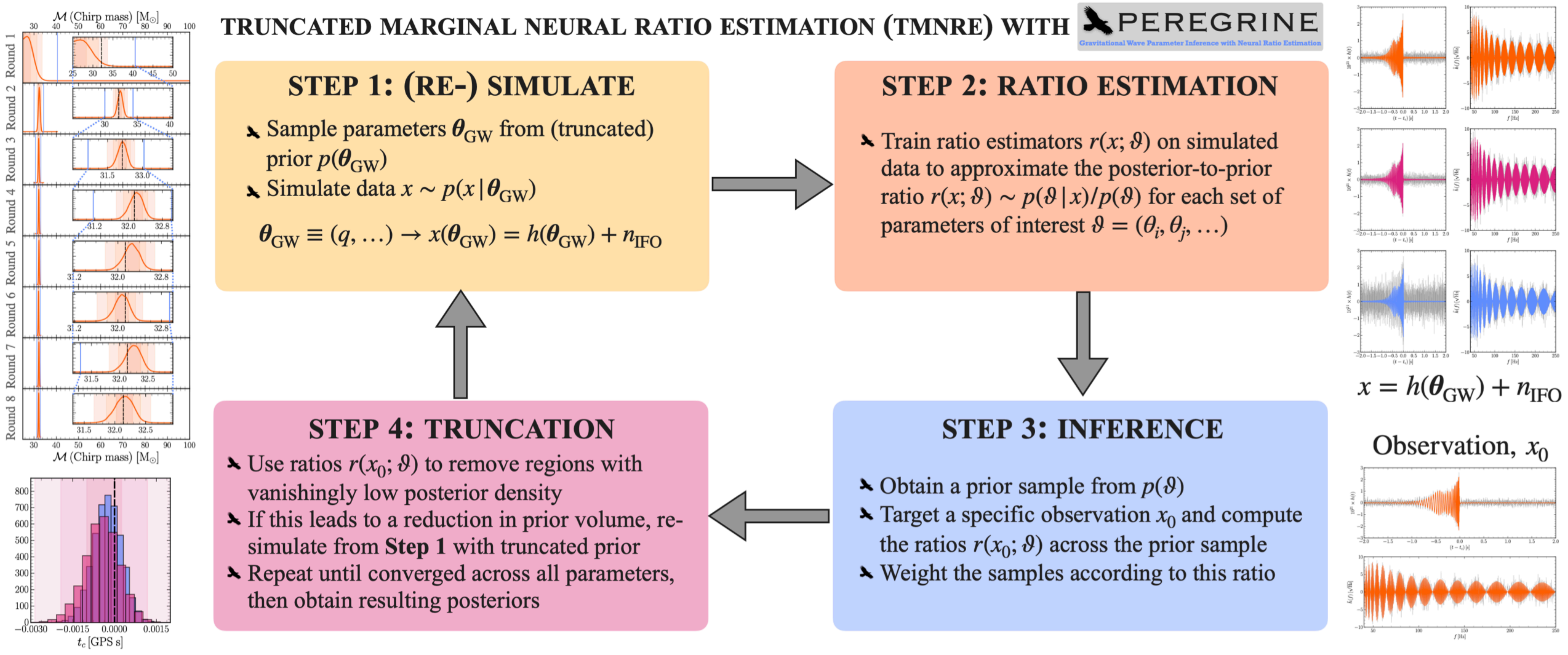
Coping with real LISA noise, as well as the global population of sources



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

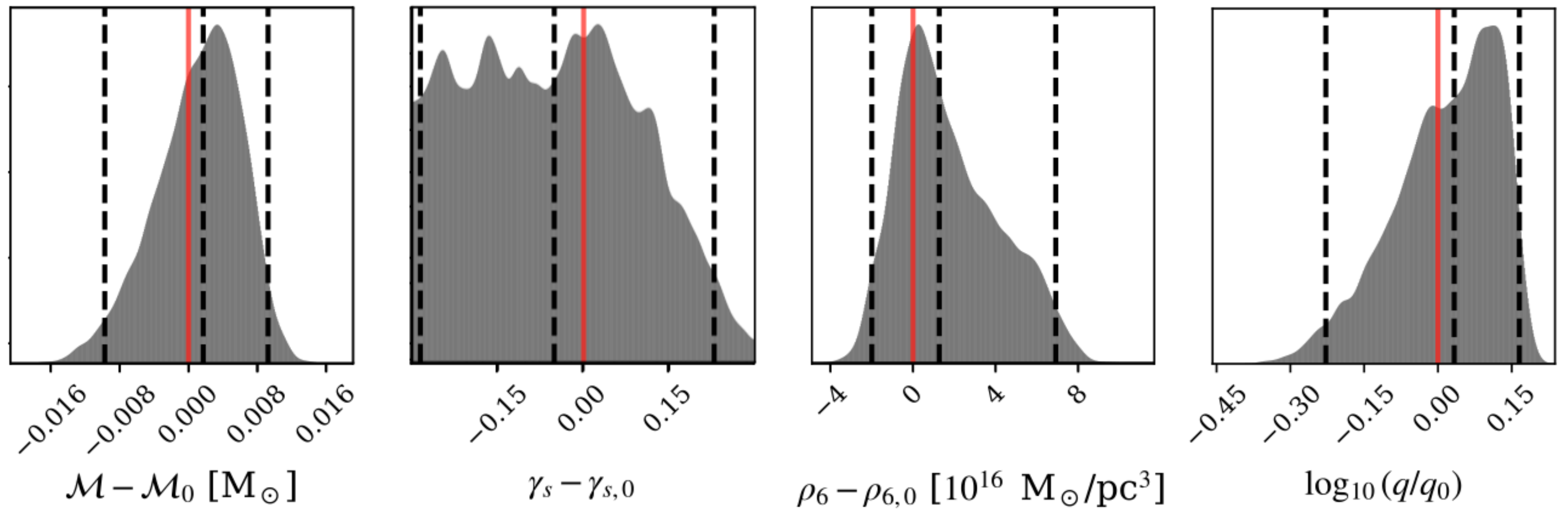


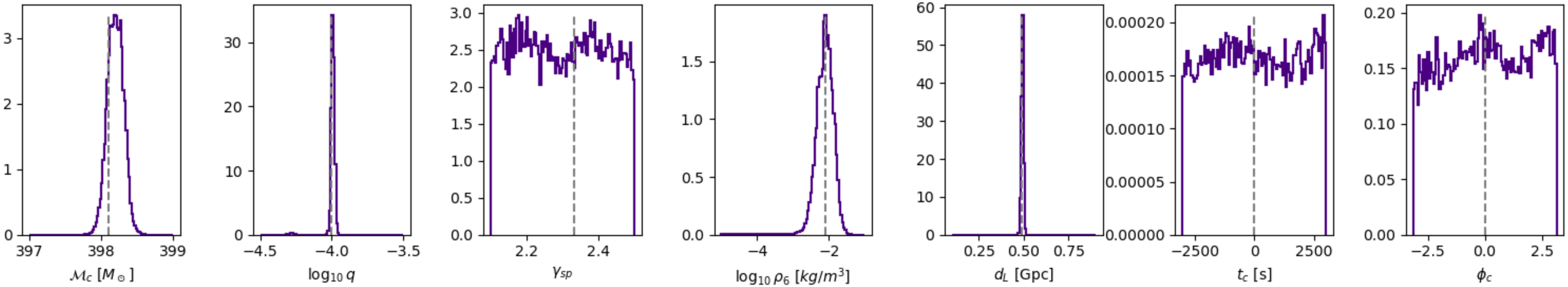
Miller et al. 2021
Bhardwaj et al. 2023

Dramatically decreases the number of waveform evaluations required

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

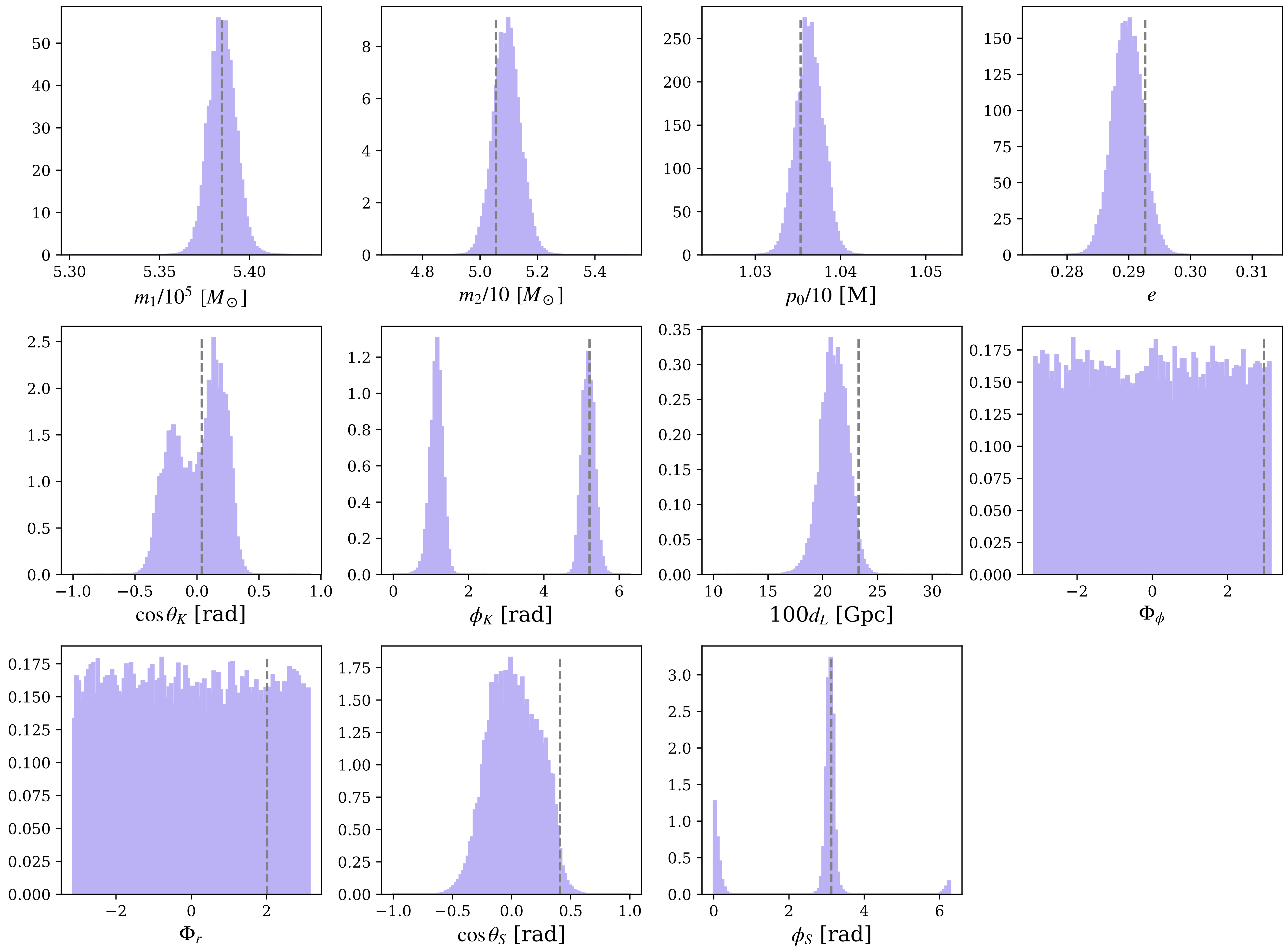
Nested sampling





Simulation-based inference

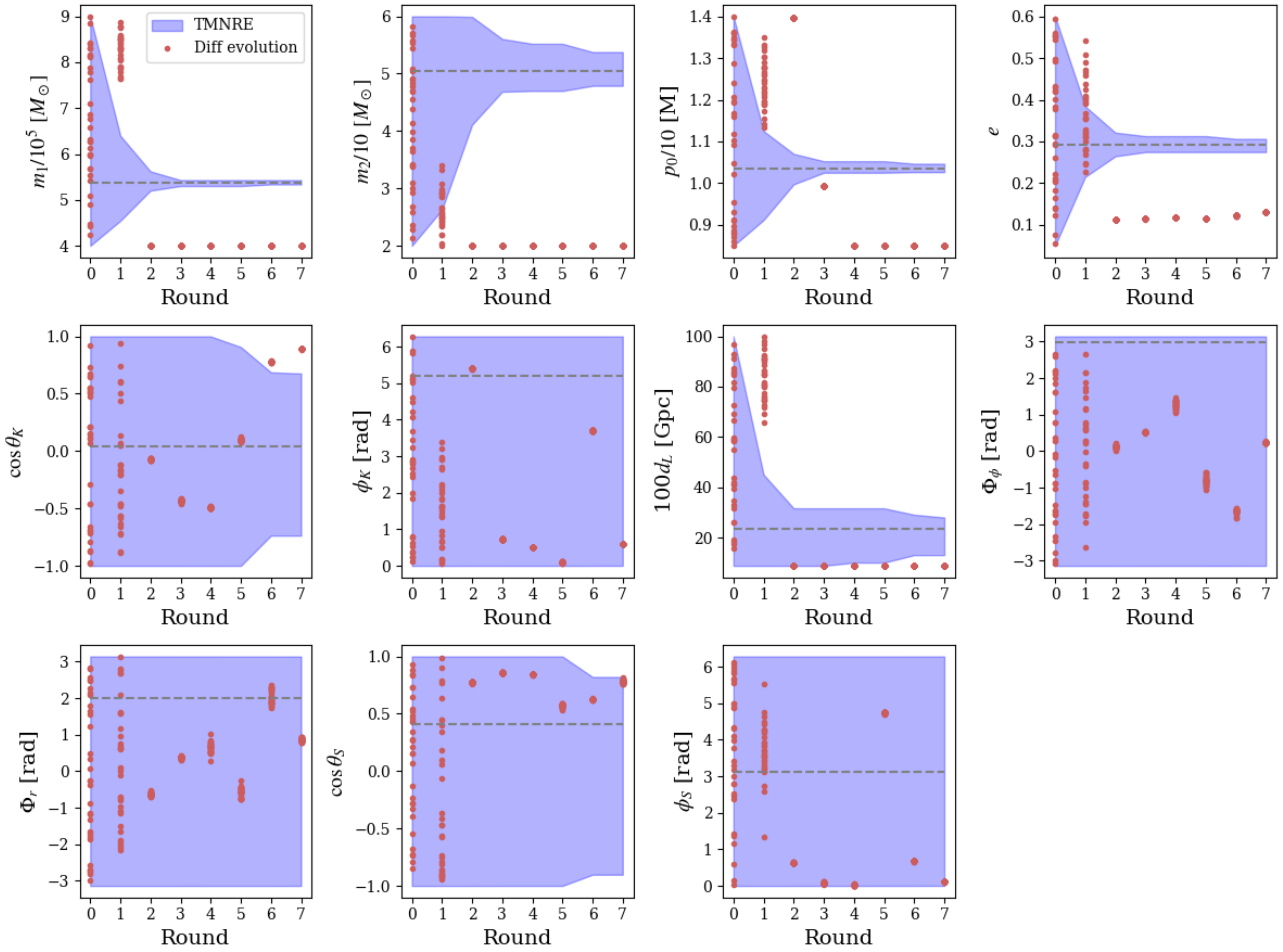
Ability to handle complex waveforms, detector response and noise



- All 11 parameters that describe **vacuum** Schwarzschild EMRI systems.
- Including stationary, Gaussian noise.
- Including LISA response.

Cole et al. in prep

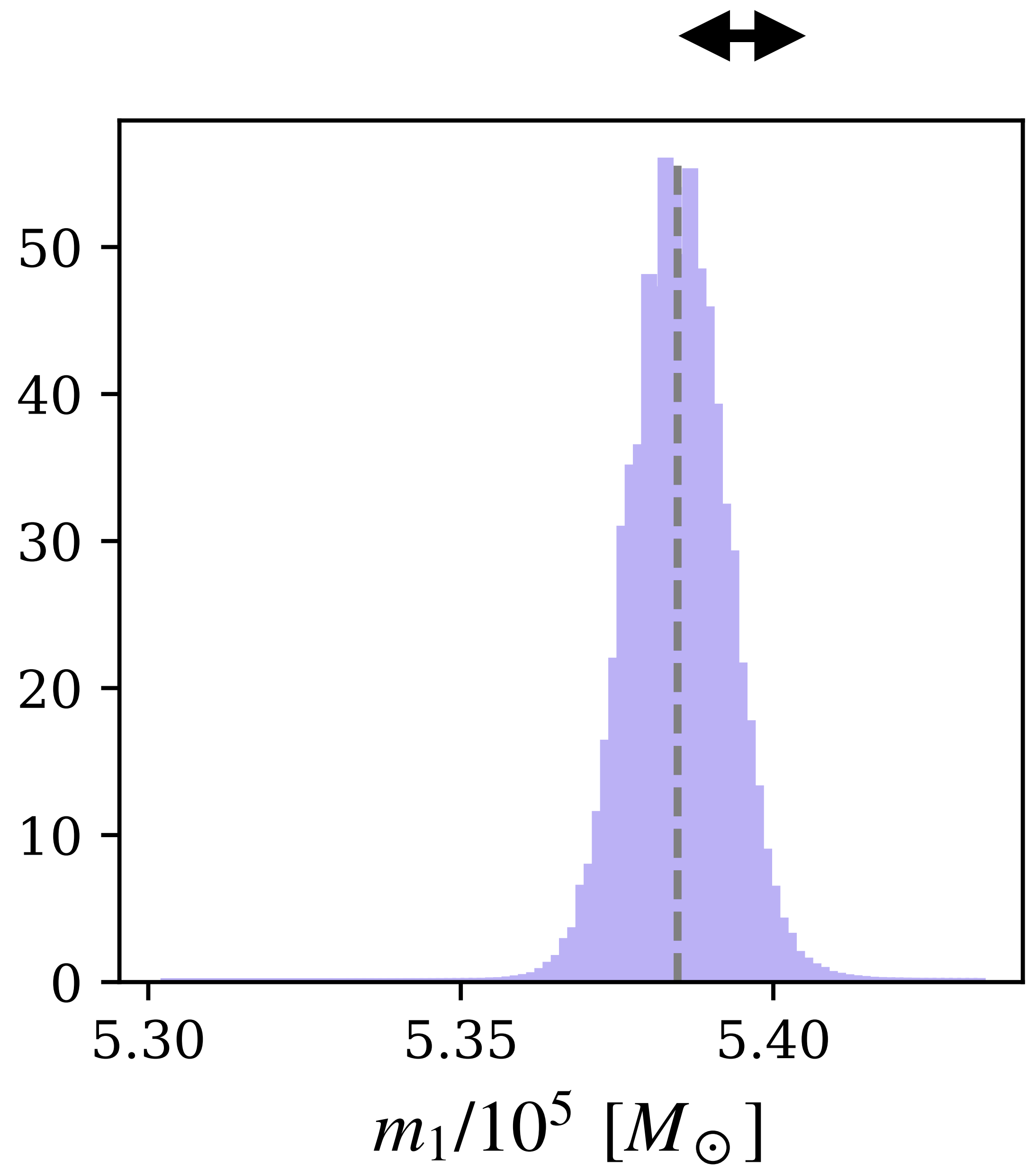
Narrowing down the viable parameter space significantly

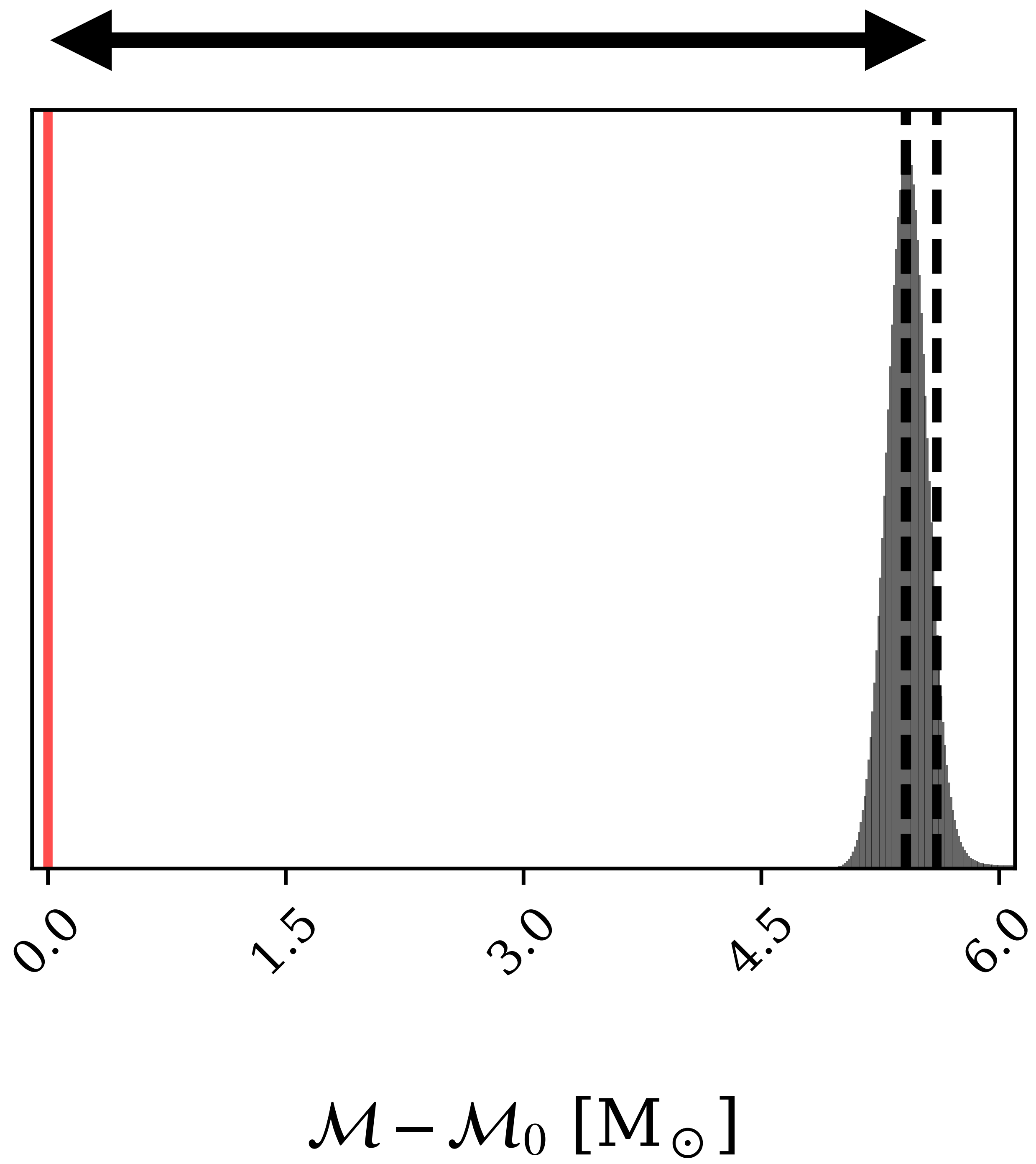


- Comparison with differential evolution (algorithm which seeks to minimise the negative log-likelihood)
- Open question - do we need to include environmental effects at this stage?

Cole et al. in prep

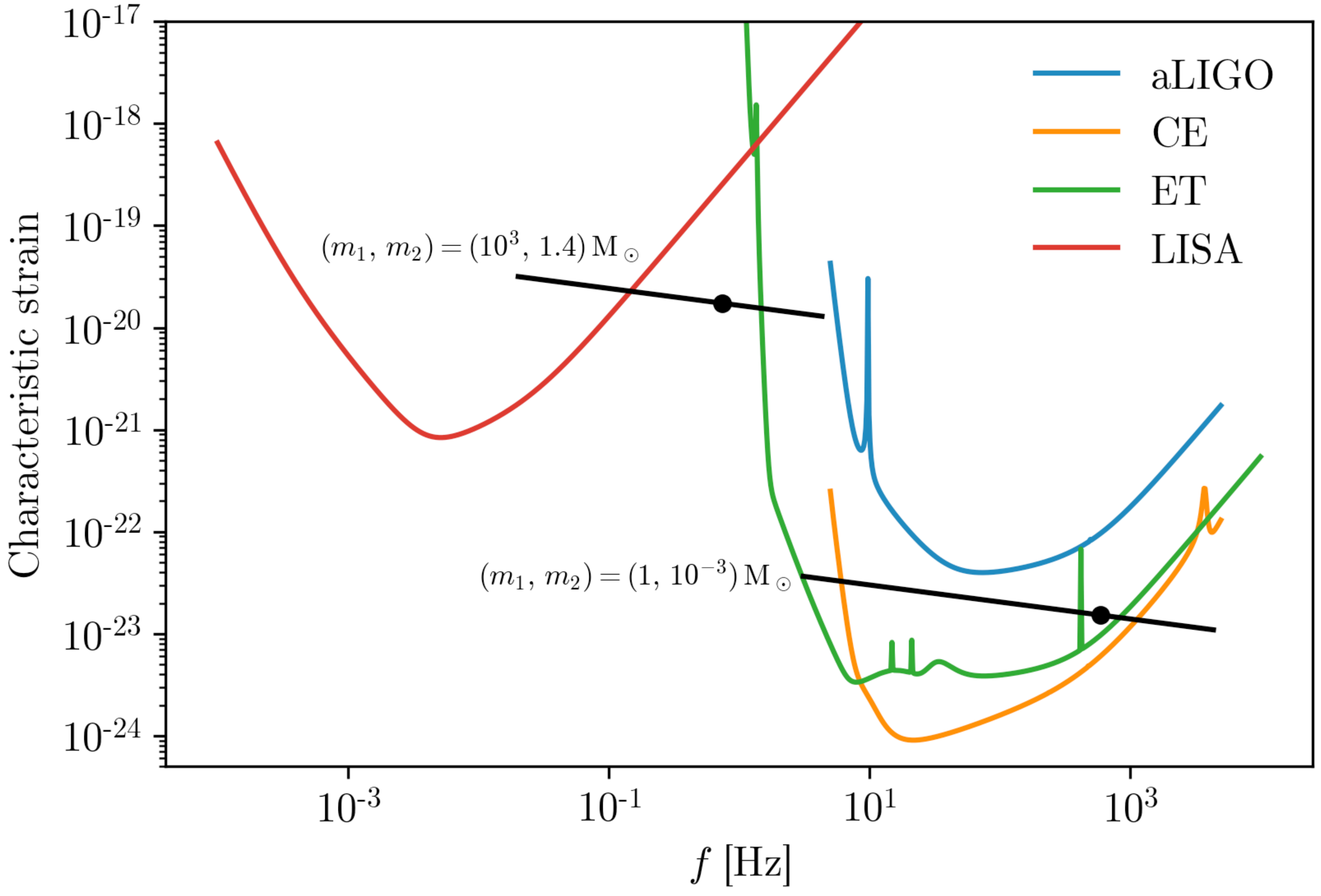
Measurement of new physics effects will require greater parameter estimation precision



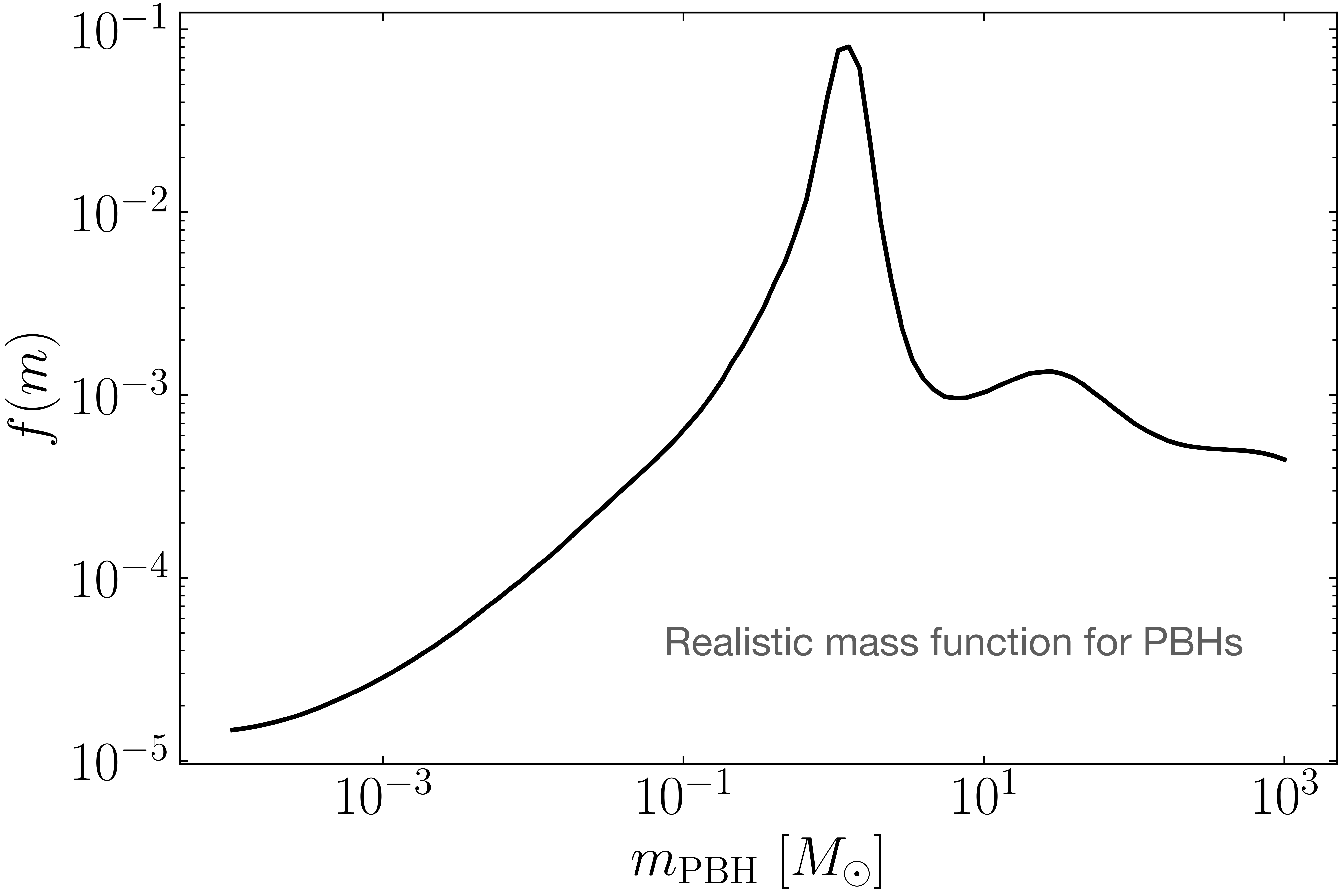


- Prospects for distinguishing environmental bias
- E.g. 2.5% precision on chirp mass
- 1.5% bias on chirp mass induced by gravitational atom

What about future ground-based detectors?



High frequencies -> lower mass black holes

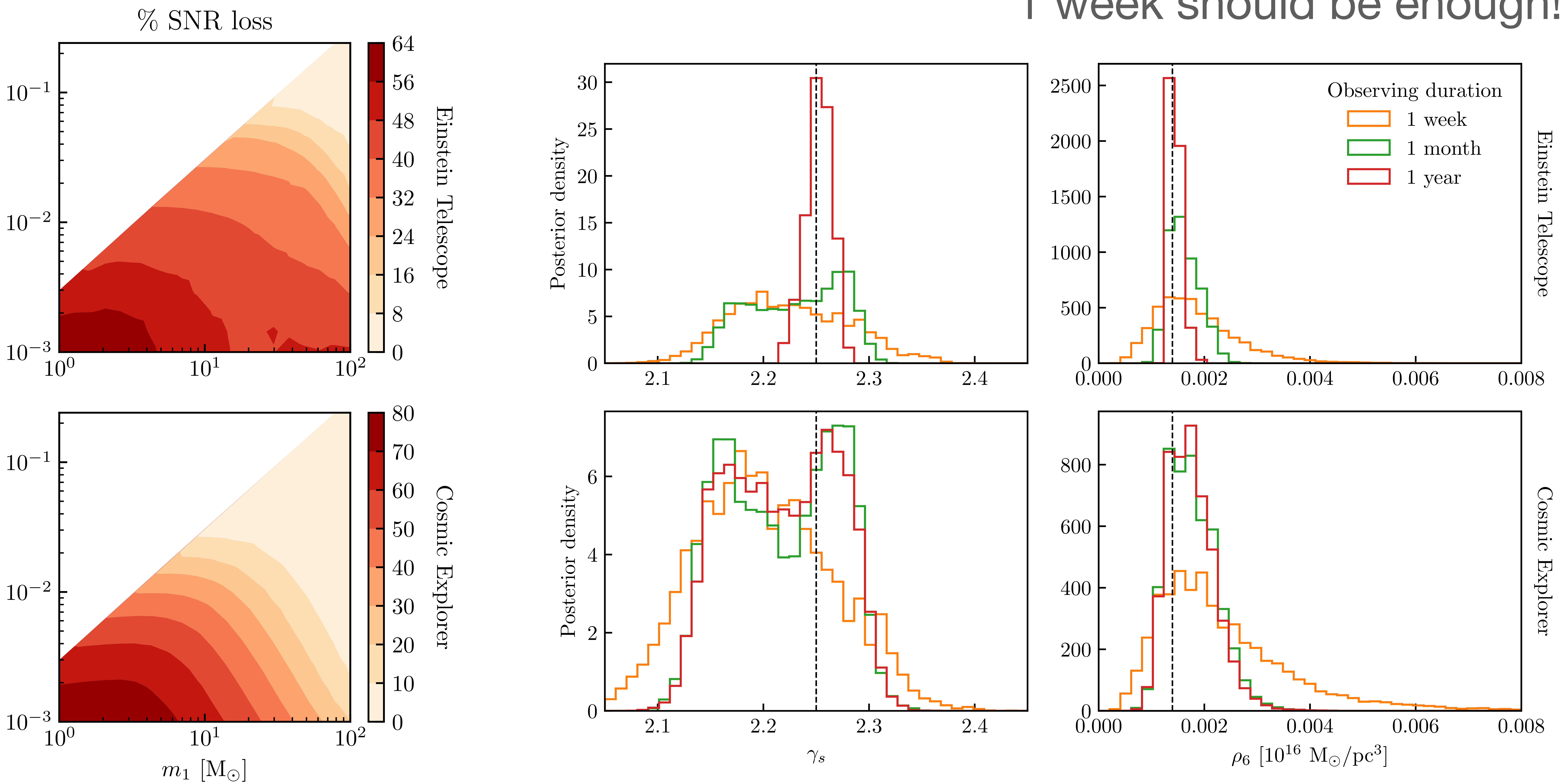


Extreme mass ratio PBHs must have a dark matter spike

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/EMRI 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 and future work:

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

Thank you for listening!