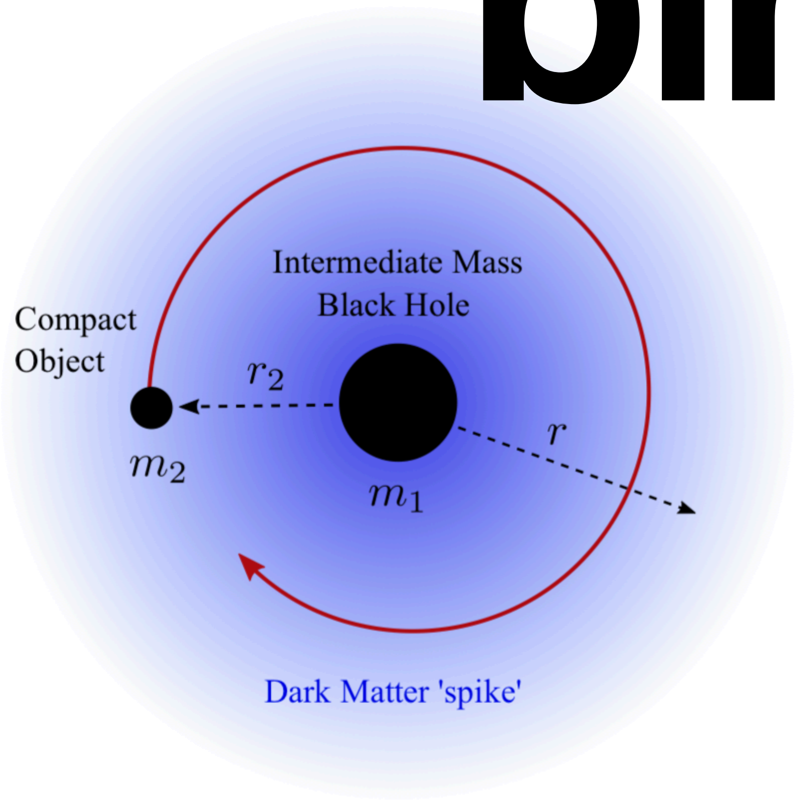
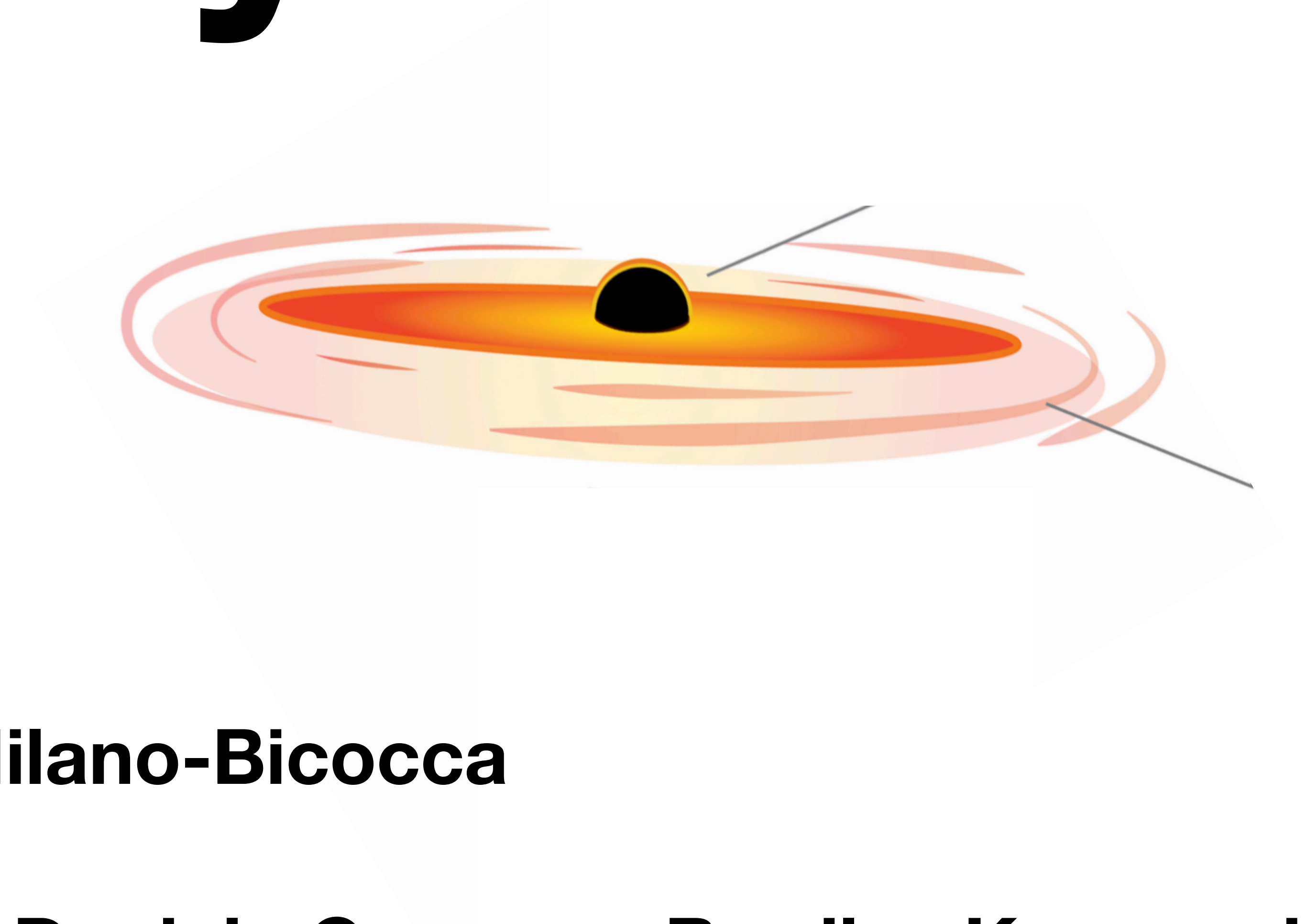
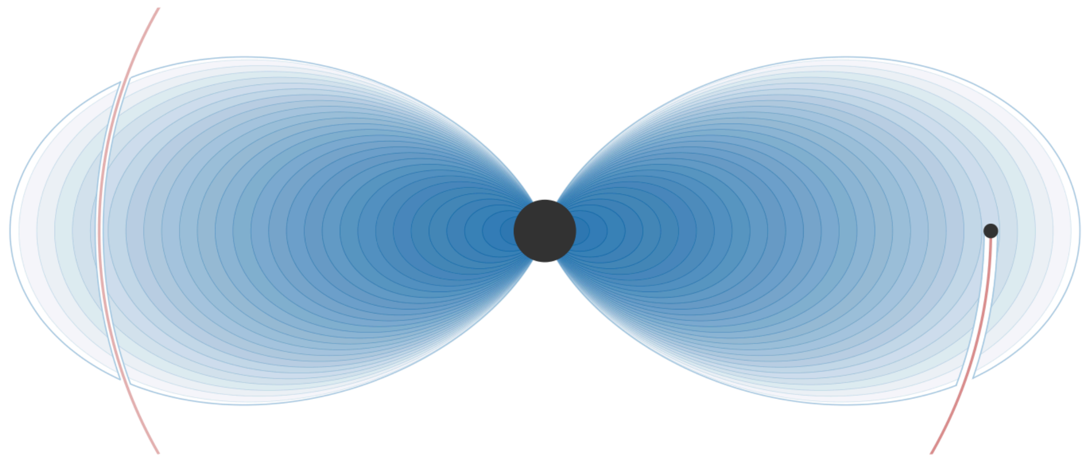
Distinguishing between environmental effects around binary black holes







Philippa Cole, Postdoc at University of Milano-Bicocca

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

Based on

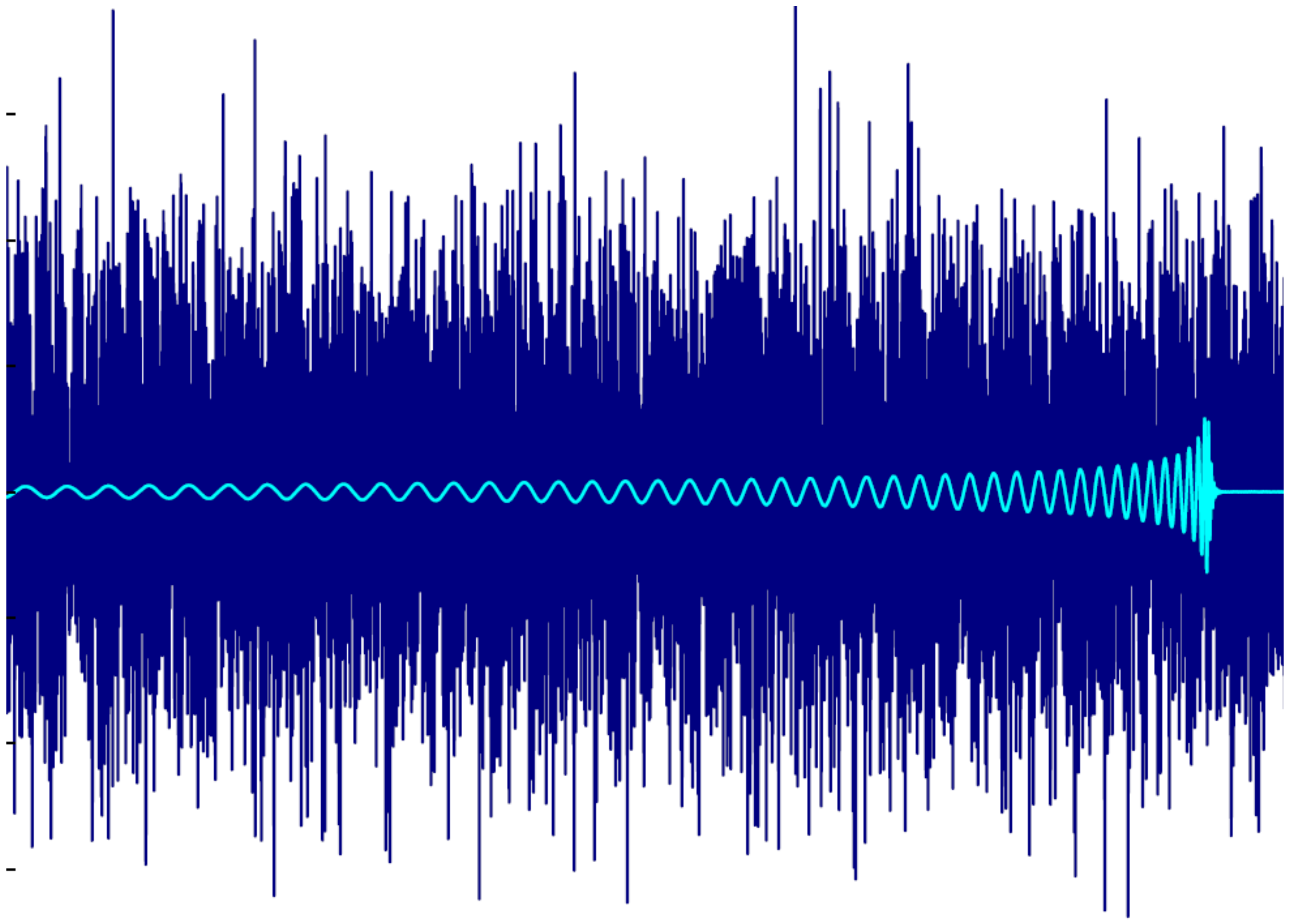
Cole, P.S., Bertone, G., Coogan, A. *et al.* Distinguishing environmental effects on binary black hole gravitational waveforms. *Nat Astron* (2023). arXiv:2211.01362

Cole P.S., Coogan, A., Kavanagh, B. J., Bertone, G. Measuring dark matter spikes around primordial black holes with Einstein Telescope and Cosmic Explorer. Phys. Rev. D (2023), arXiv:2207.07576

JENAS Initiative "Gravitational Wave Probes of Fundamental Physics" Feb 2024

Vacuum or non-vacuum

- 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, (possible caveat, see Katy Clough's talk) but looking towards future interferometers, long duration signals may be affected by their environment



- Environmental effects can cause inspiral to either speed up or slow down with respect to vacuum case
- A dephasing to accumulate, which alters the gravitational waveform from the binary's inspiral

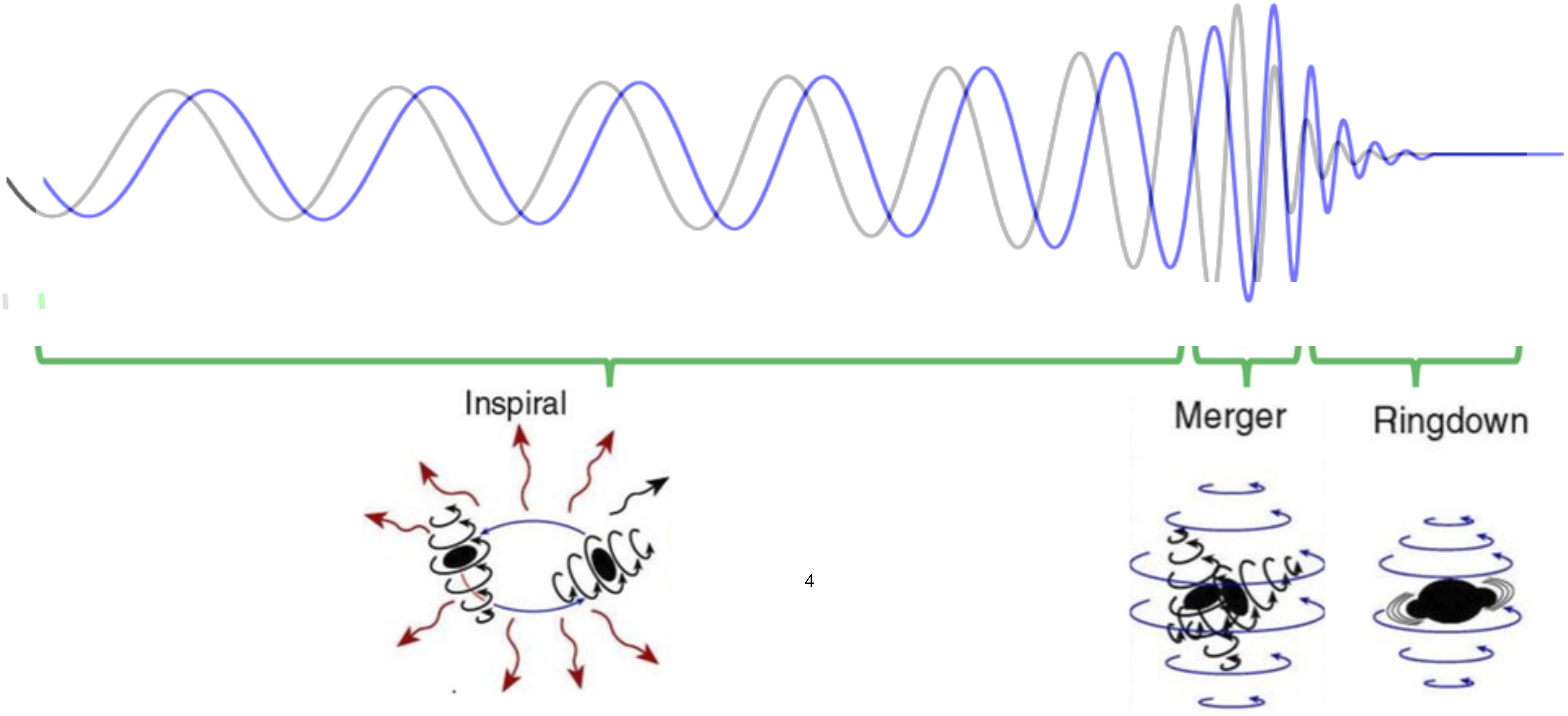
$$\dot{r} = \dot{r}_{\mathrm{GW}} + \dot{r}_{\mathrm{env}}$$

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

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

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

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



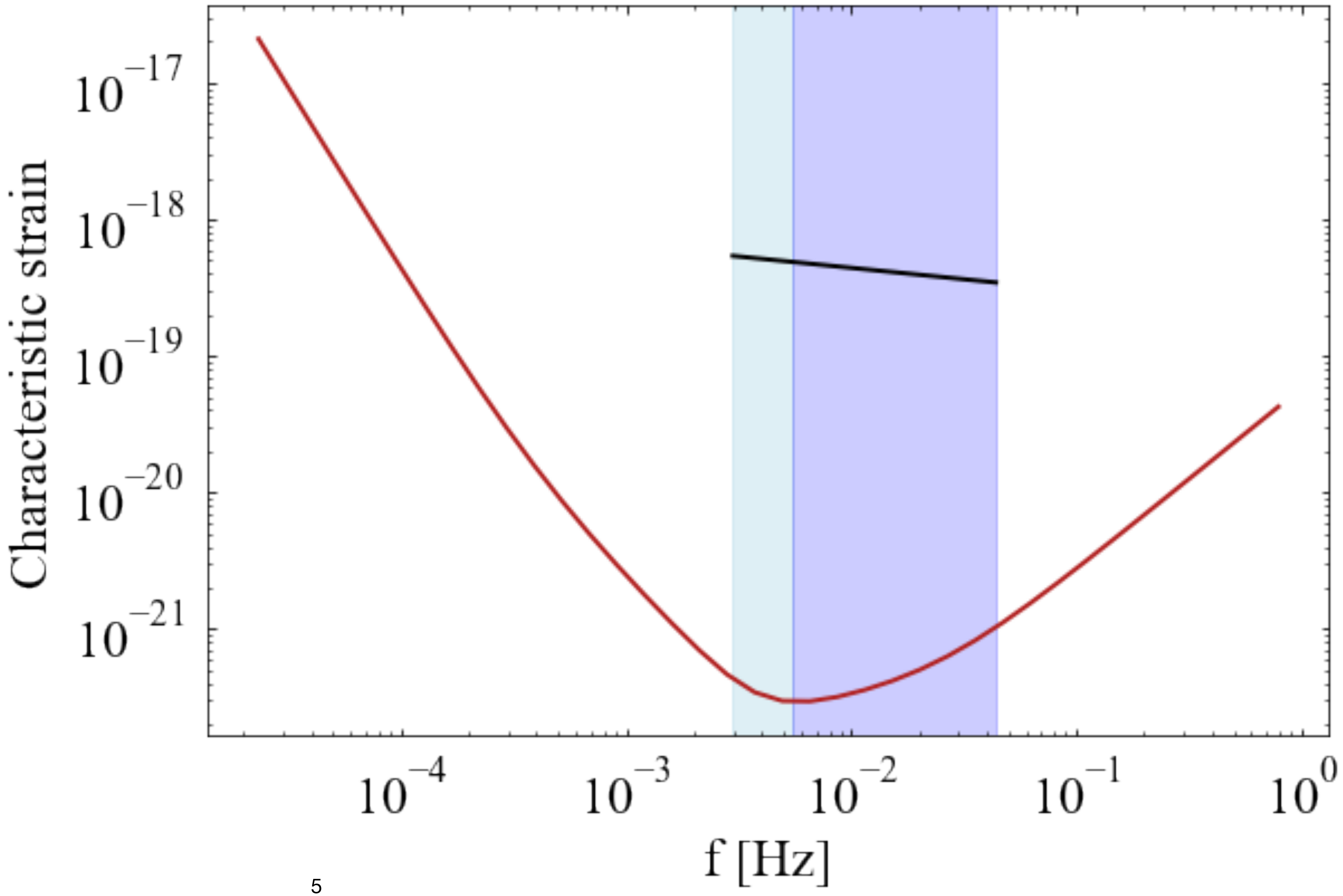
Need to observe many cycles

- dephasing accumulates over thousands or millions of cycles

- small mass ratio $q = \dfrac{m_2}{m_1} < 10^{-2.5}$ so that environment survives

- systems possible sources for LISA and Einstein Telescope/Cosmic Explorer

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



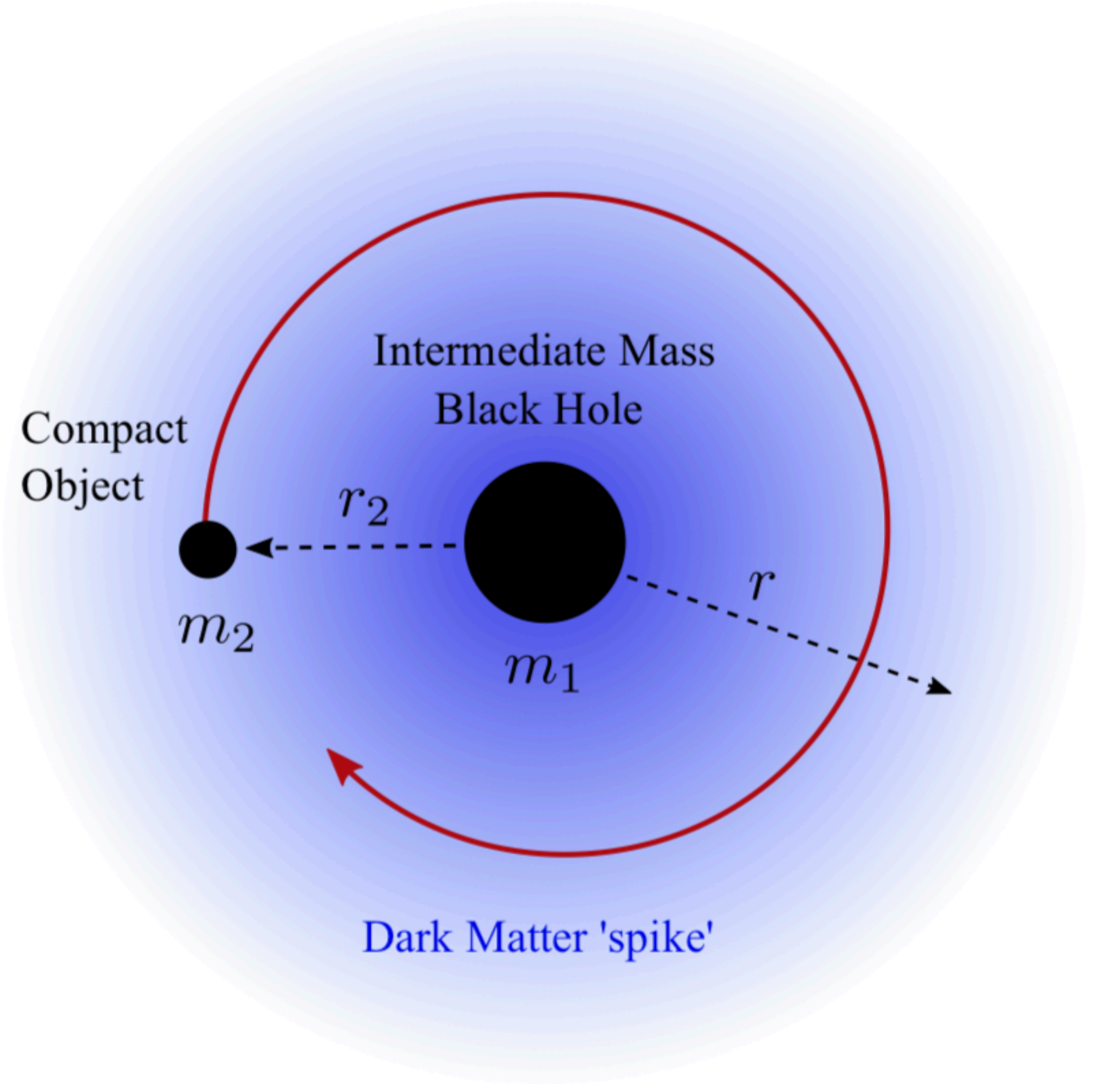
Why should we care about environmental effects?

- If we can measure the parameters of the environment via the dephasing in the waveform, chance to learn about the environment
- 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

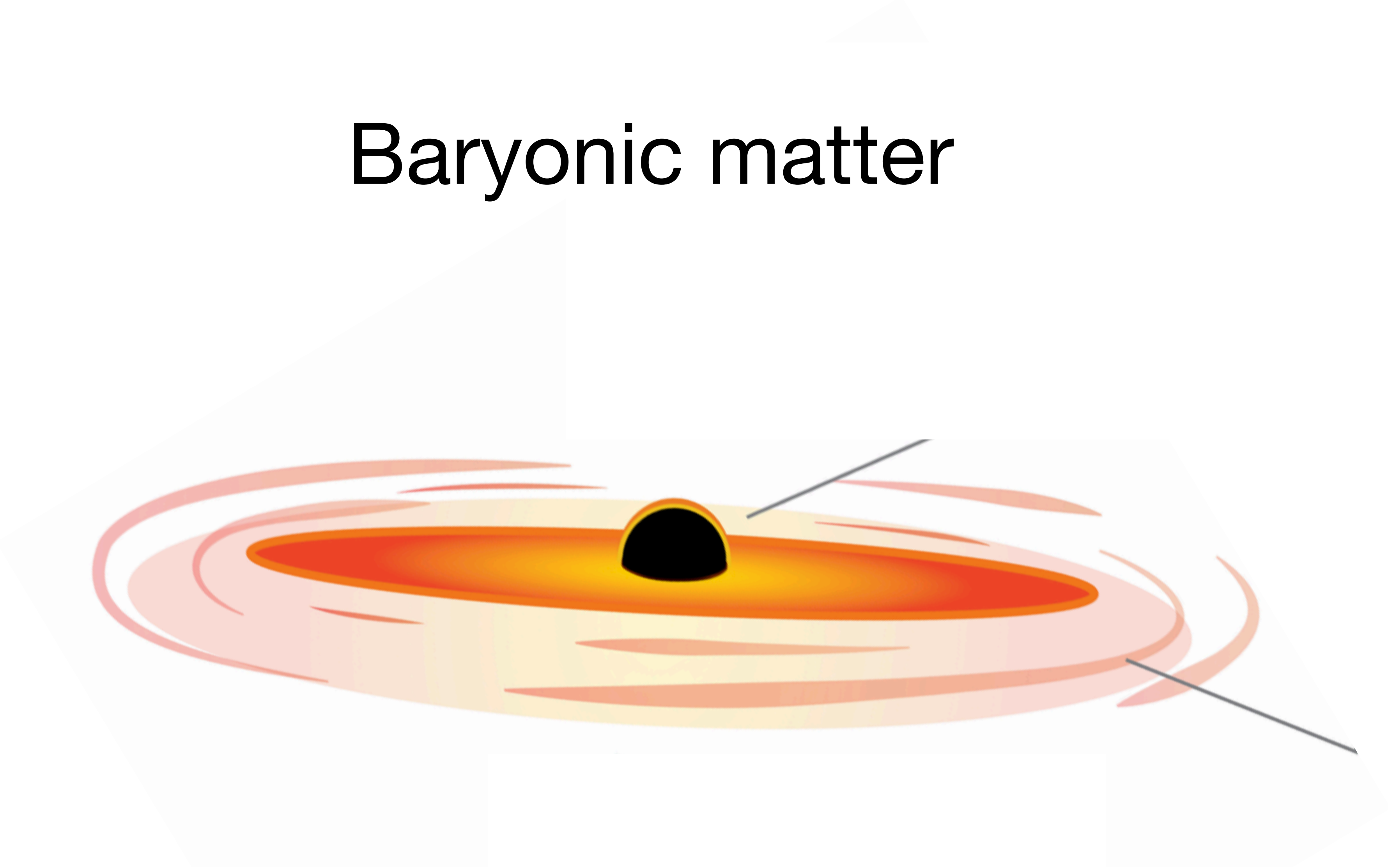


$$\rho(r) = \rho_6 \left(\frac{r_6}{r}\right)^{\gamma_s}$$

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

Accretion disk

Baryonic matter



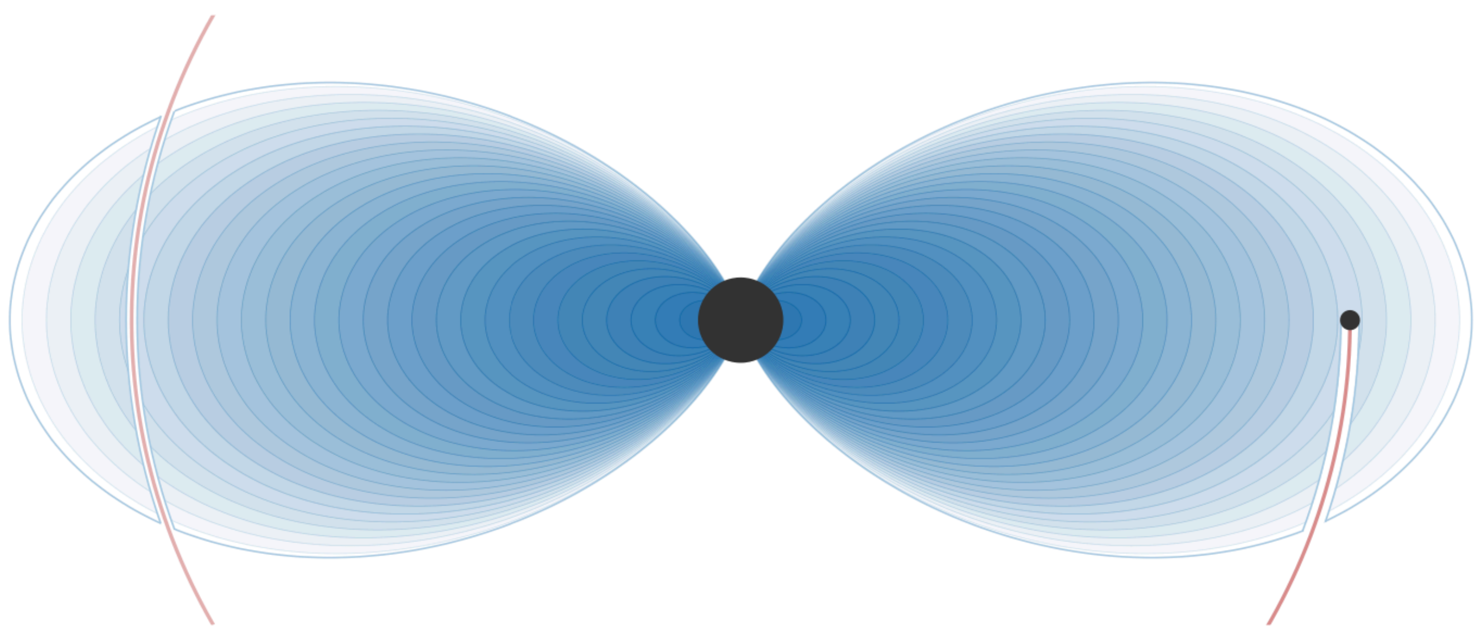
$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1/2}$$

$$M = r/h$$

Goldreich & Tremaine 1980
Tanaka 2002
Derdzinski et al. 2020

Gravitational atom

Ultra-light bosons



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

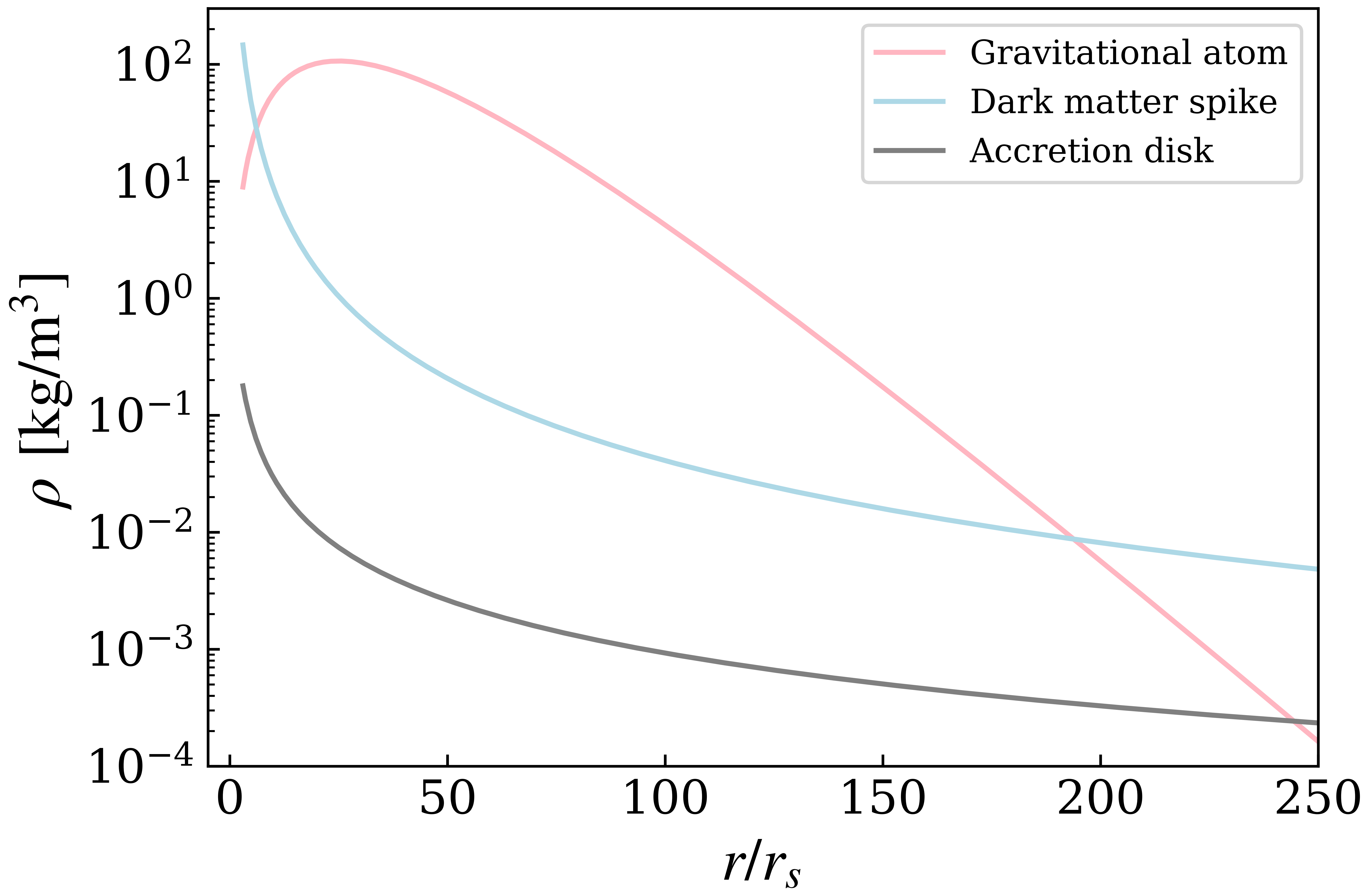
$$\alpha \equiv G m_1 \mu \ll 1$$

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

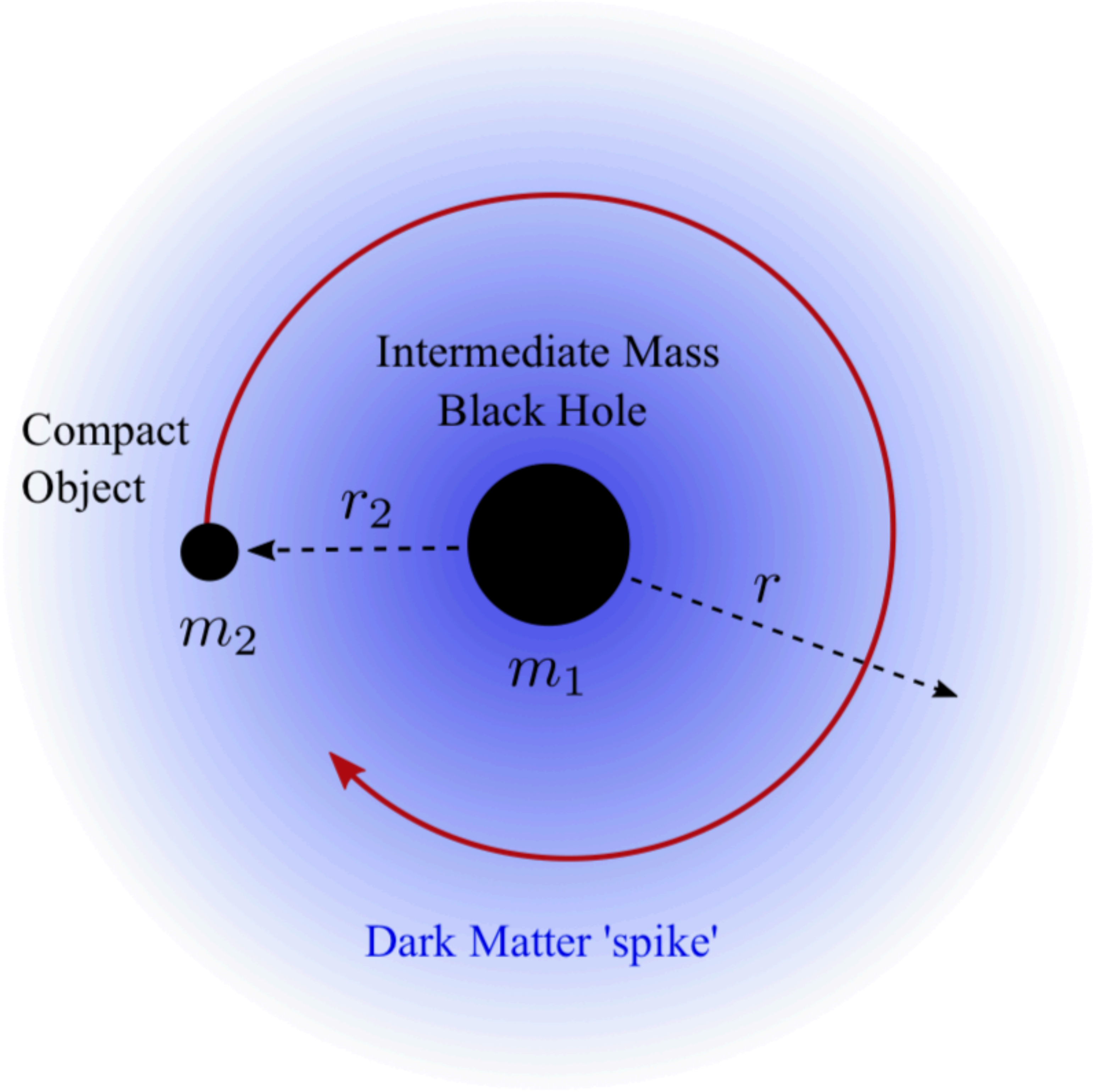
What kind of densities?



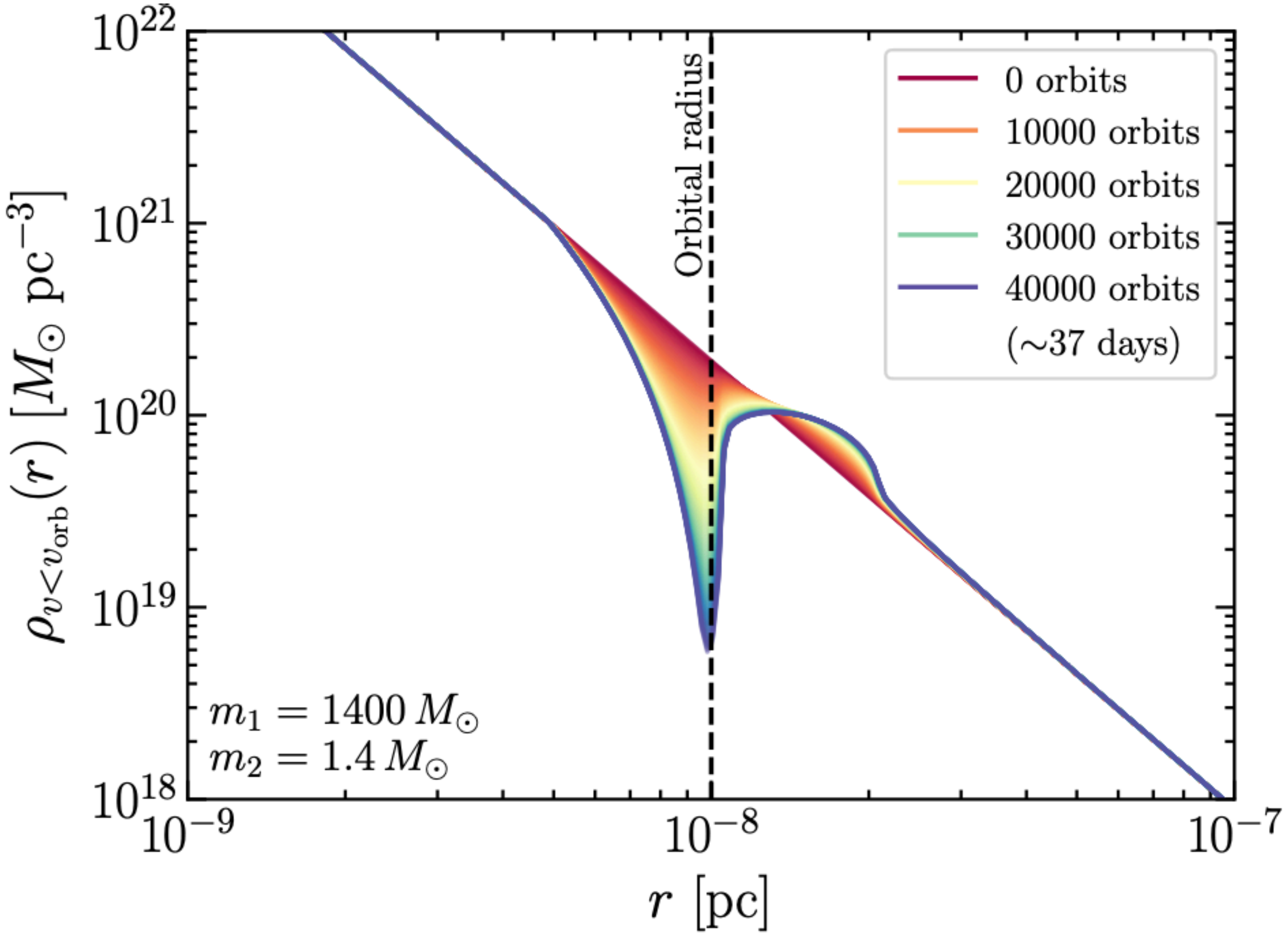
Cole et al. 2023

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

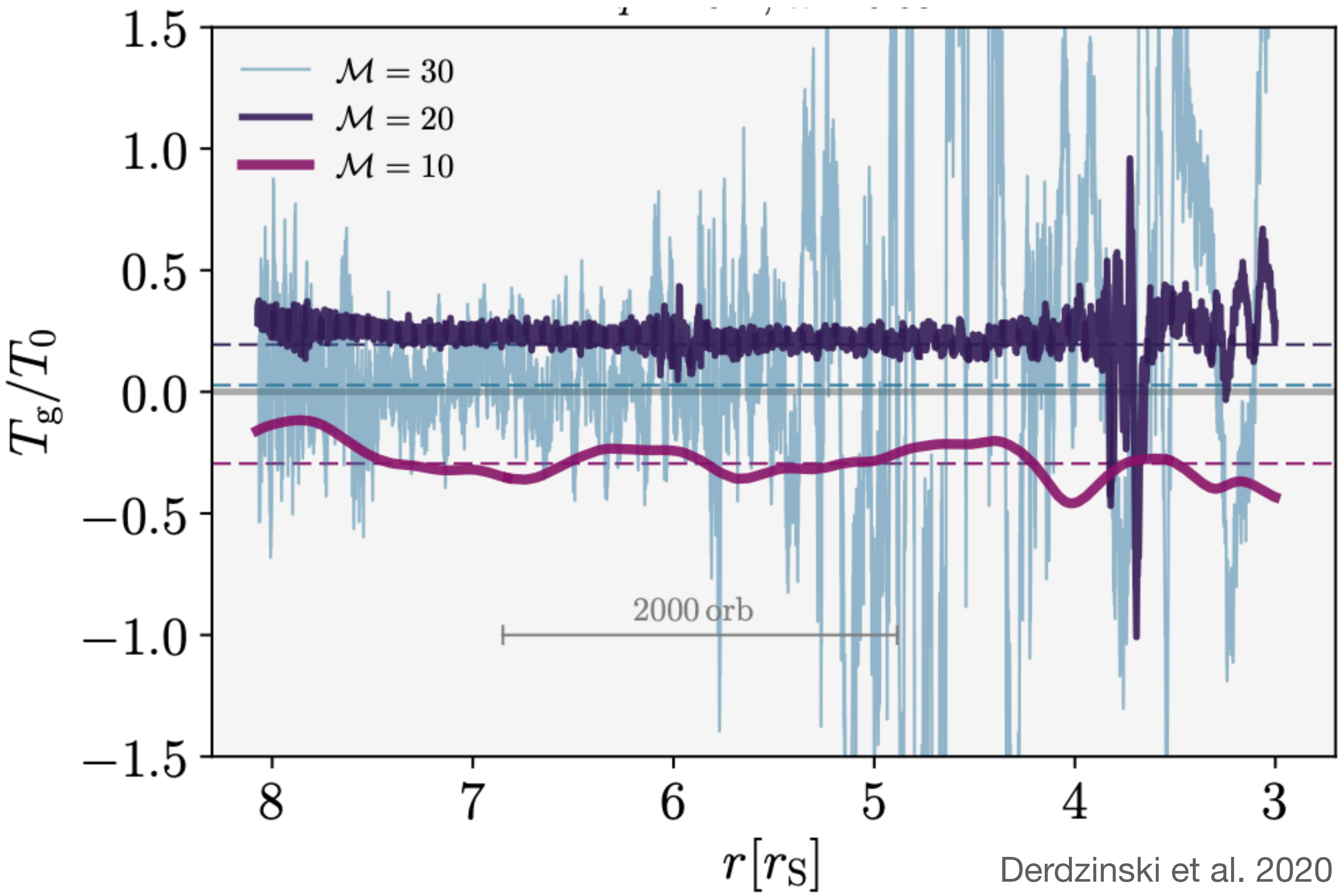


Kavanagh, Nichols, Bertone, Gaggero 2020

Gas torques

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

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



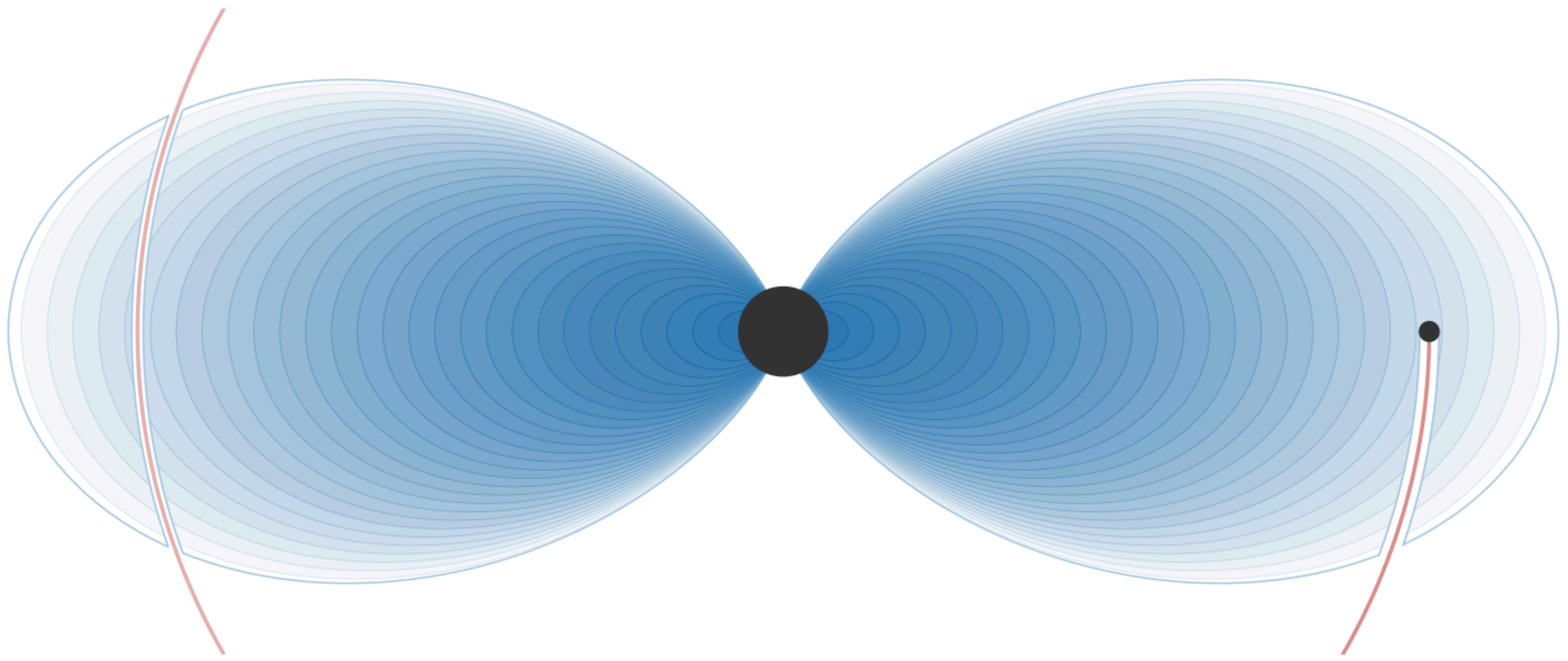
Derdzinski et al. 2020

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

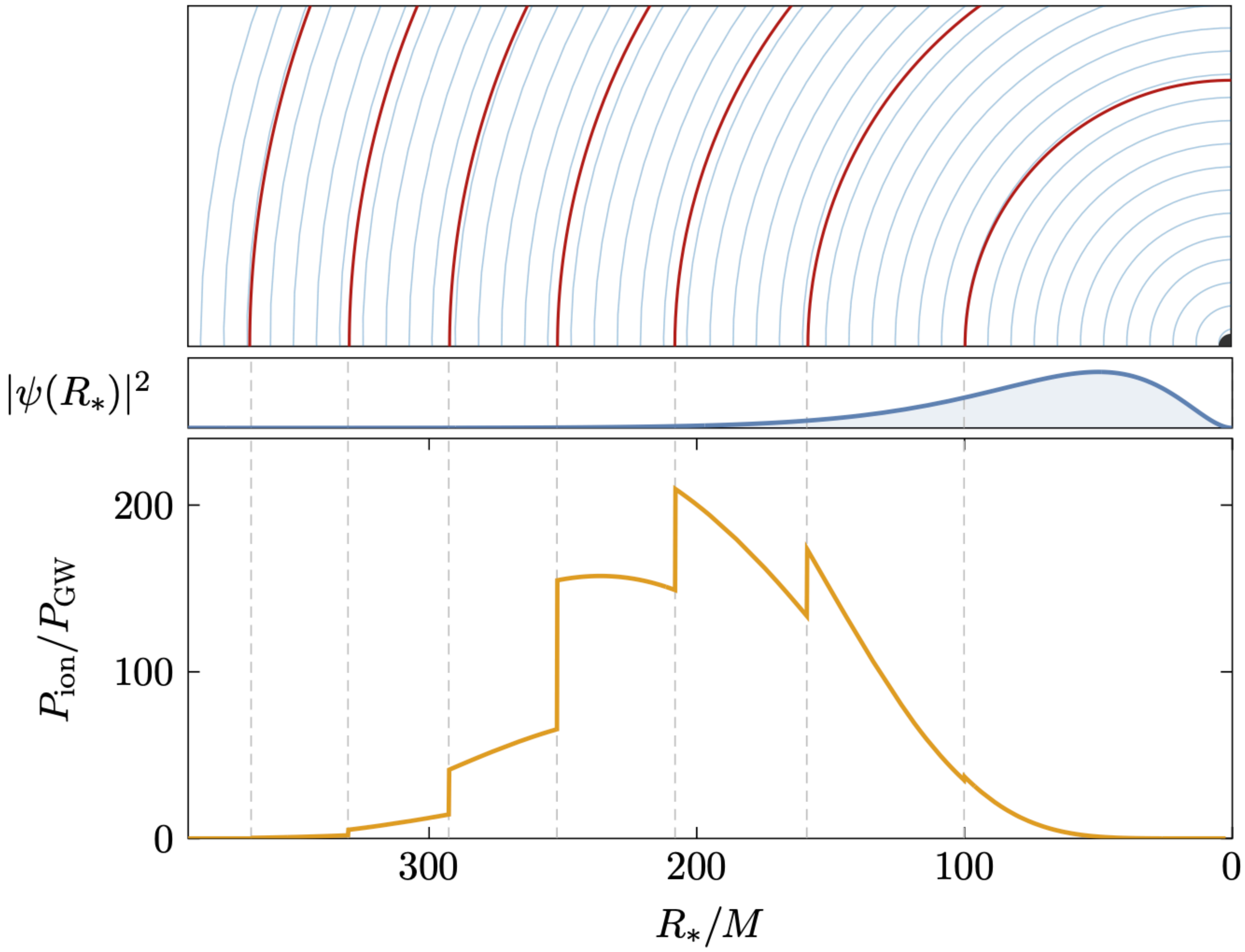
Assume Mach number is locally constant, independent of r, i.e. locally isothermal.

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

Ionization

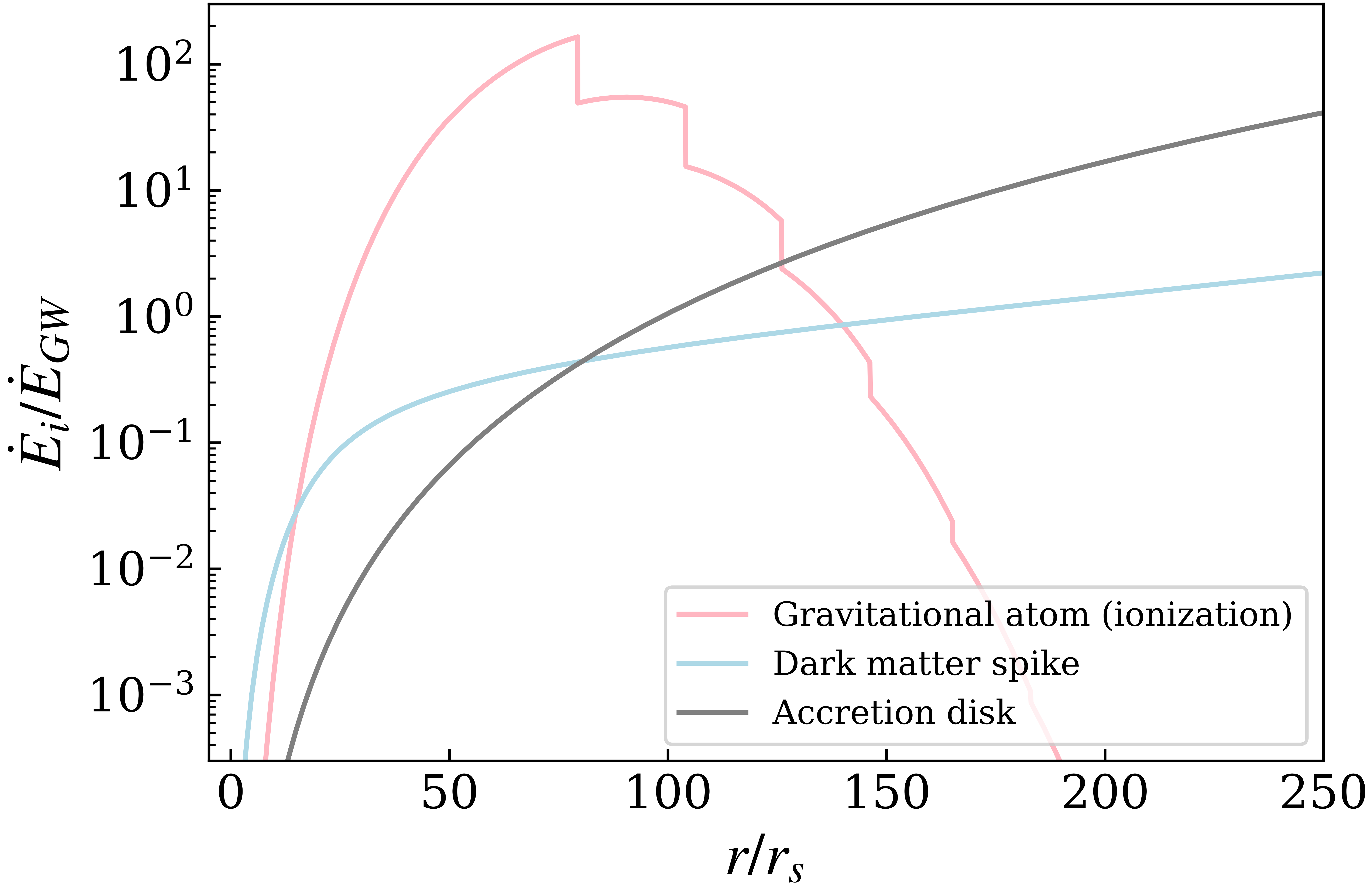


Perturber excites resonances in the cloud and it transitions from bound states to unbound states



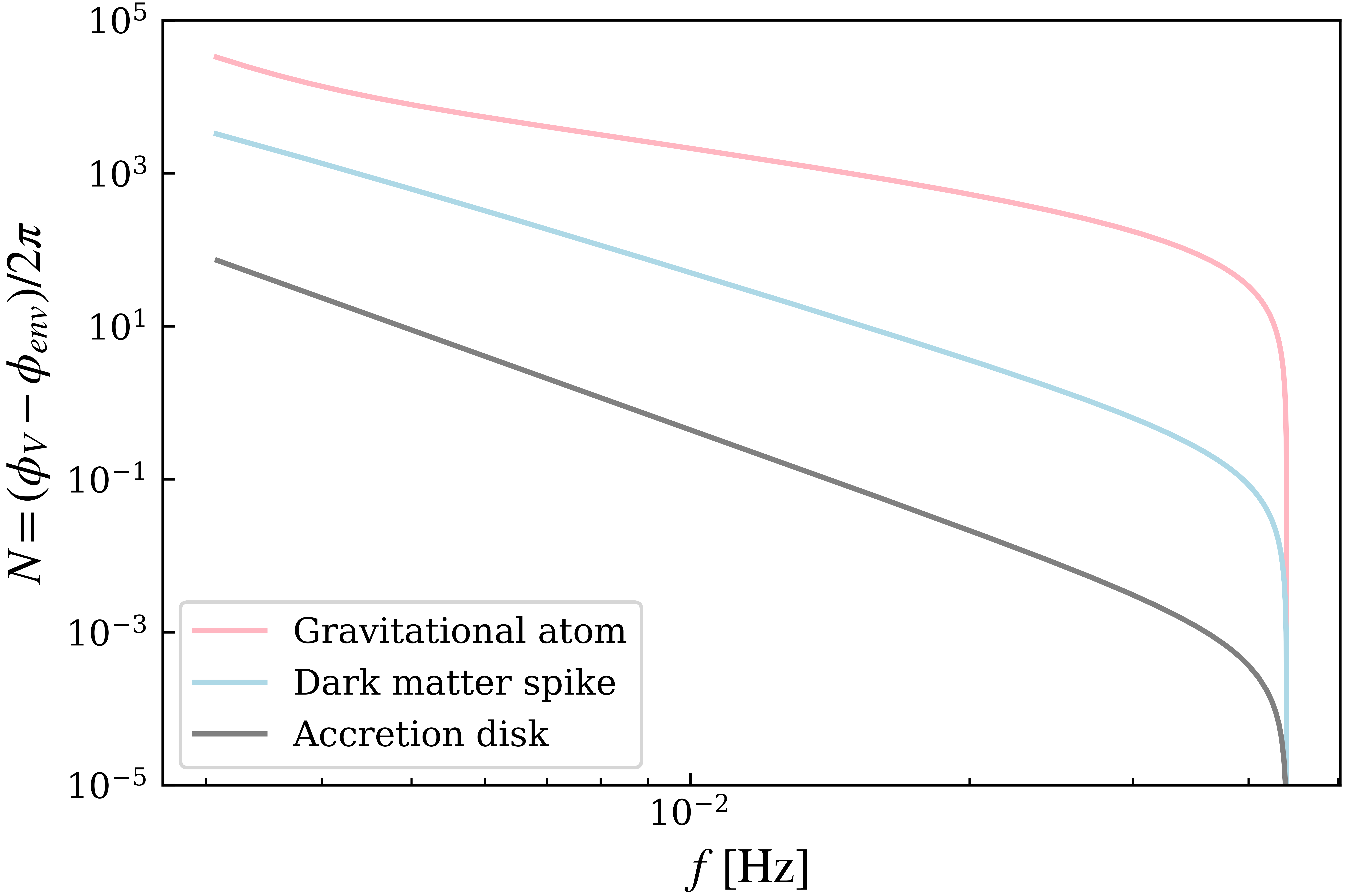
Baumann, Bertone, Stout, Tomaselli 2021

Energy losses



Cole et al. 2023

Dephasing



Cole et al. 2023

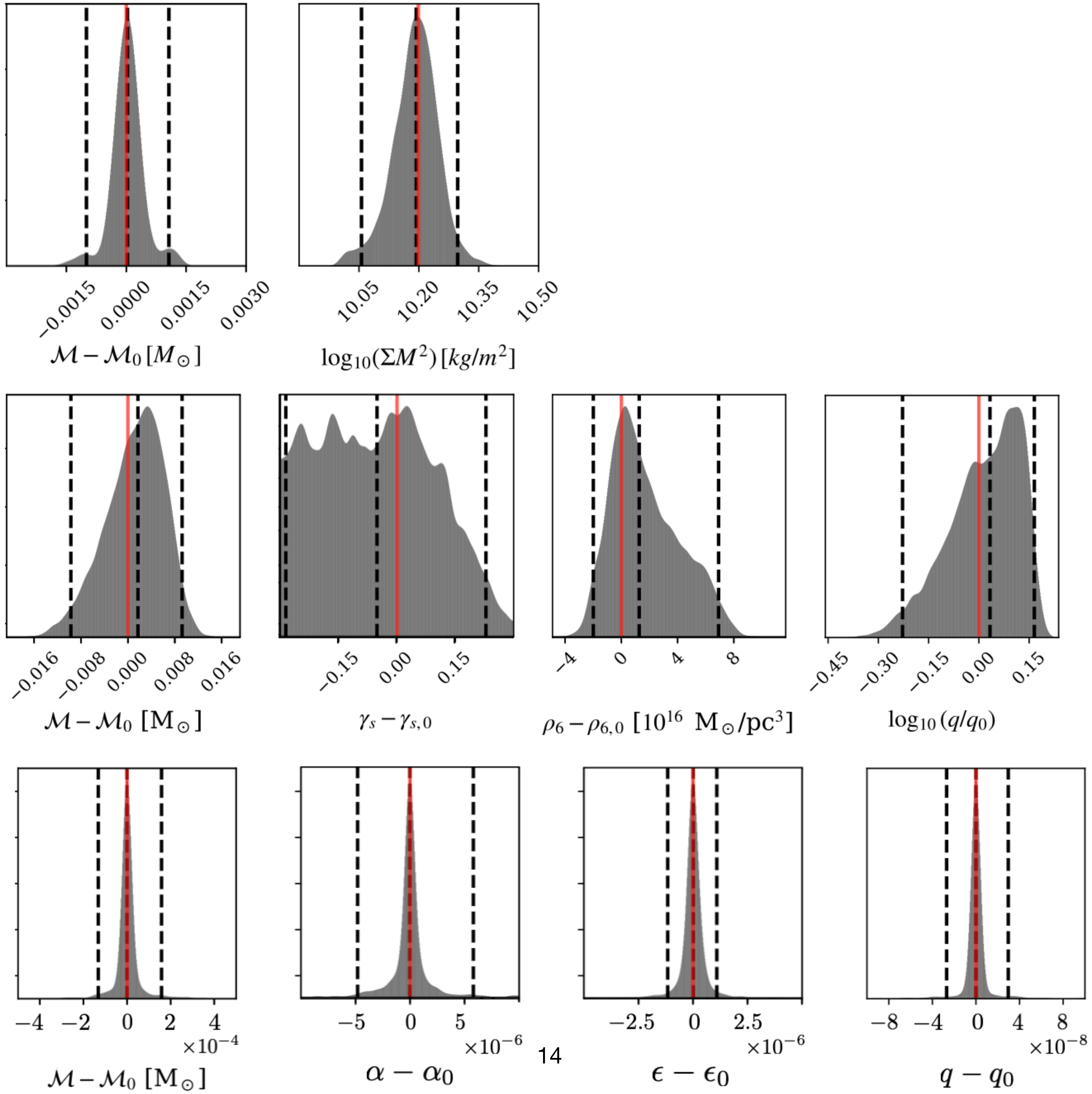
Assuming we've detected a signal, can we measure the parameters?

Parameter estimation with correct model

Accretion disk

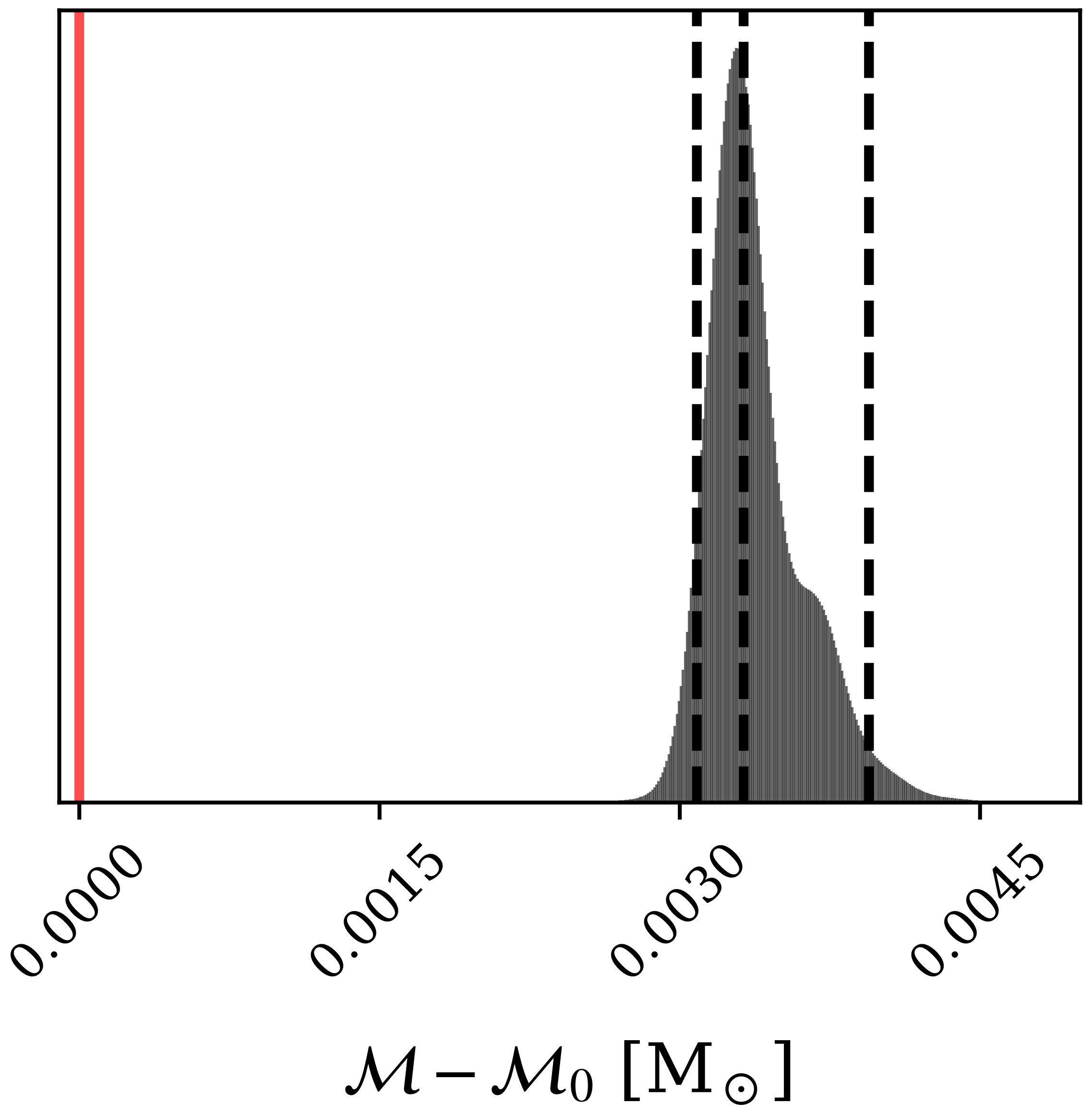
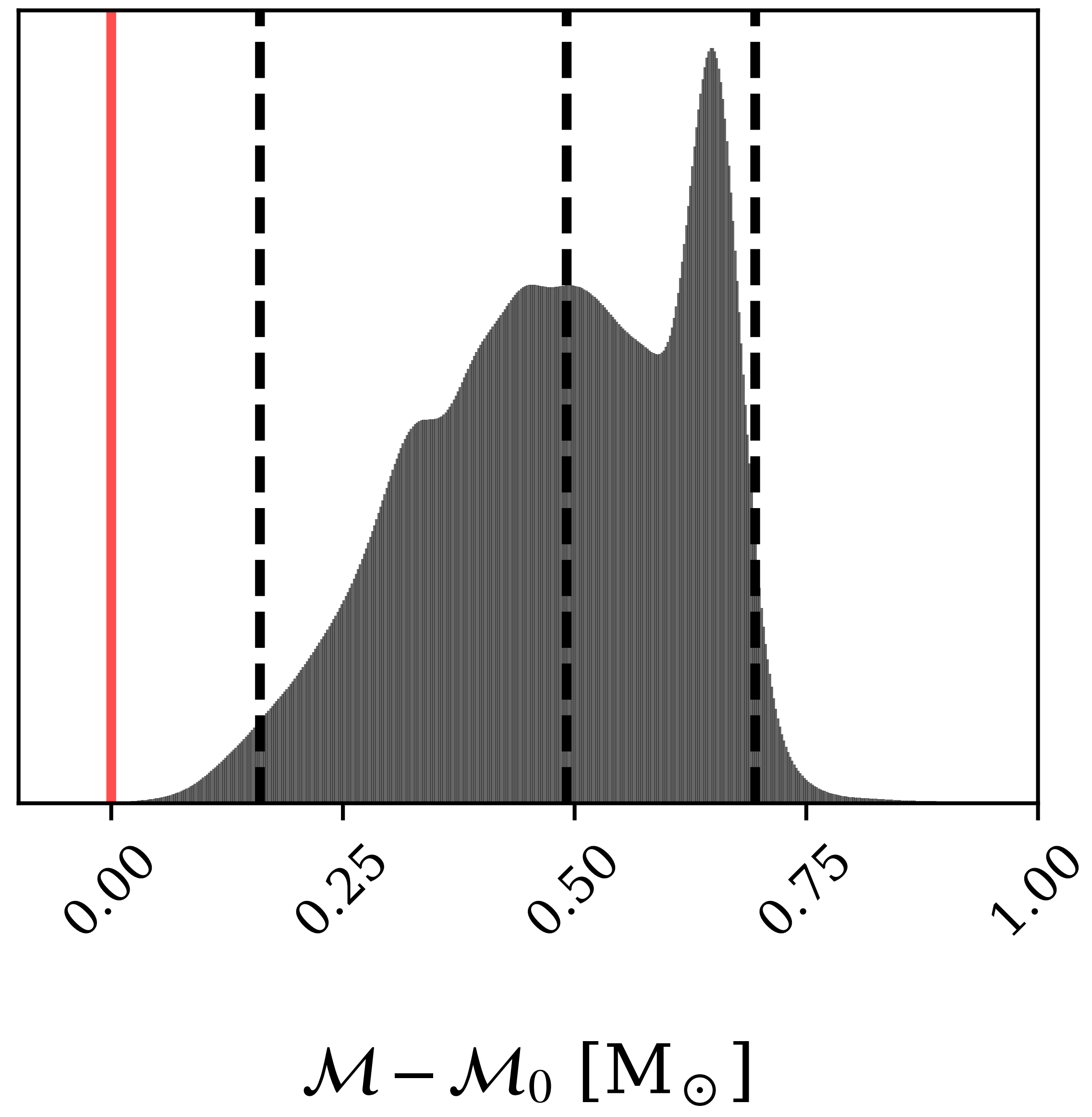
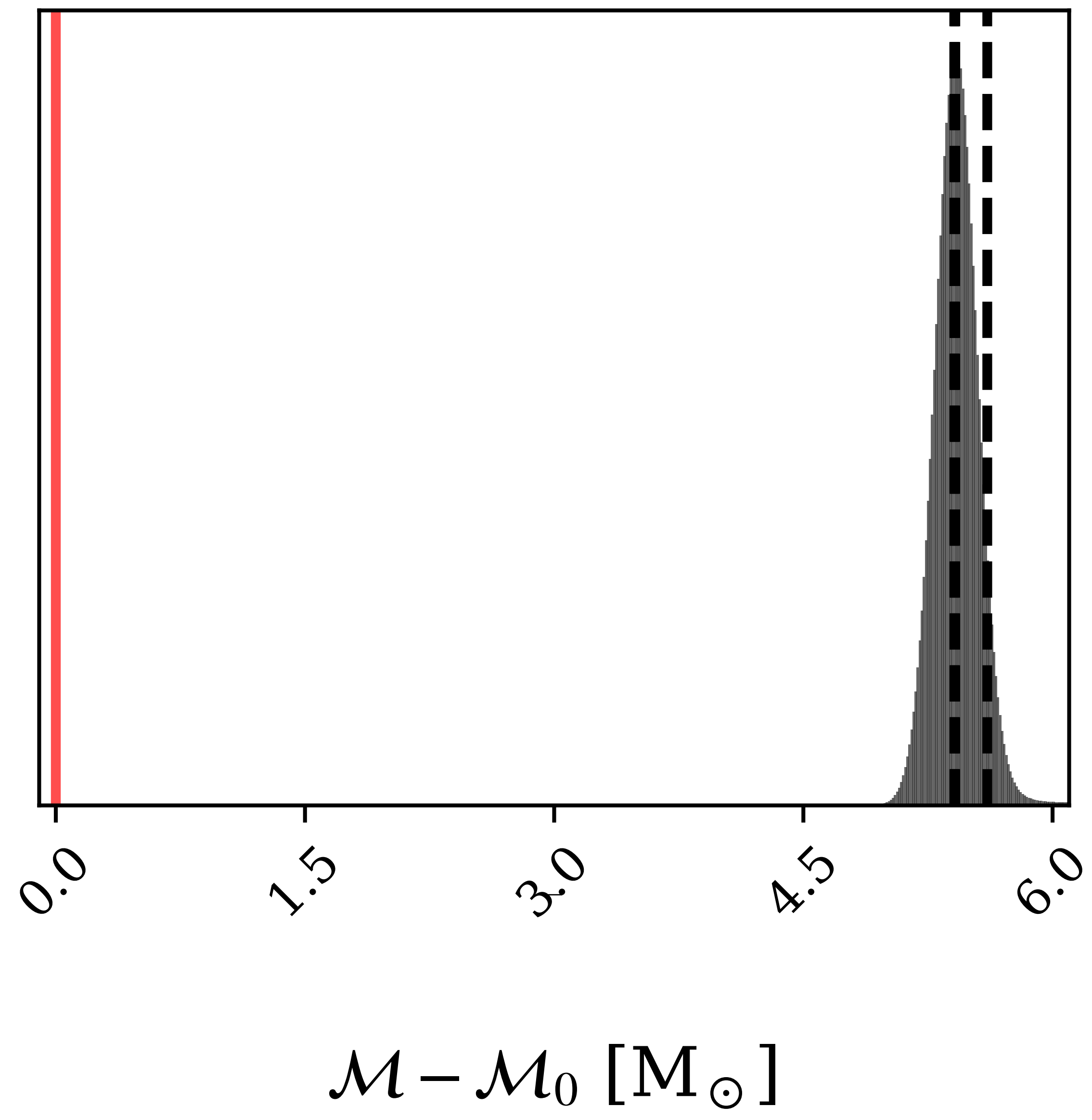
Dark dress

Gravitational atom



Cole et al. 2023

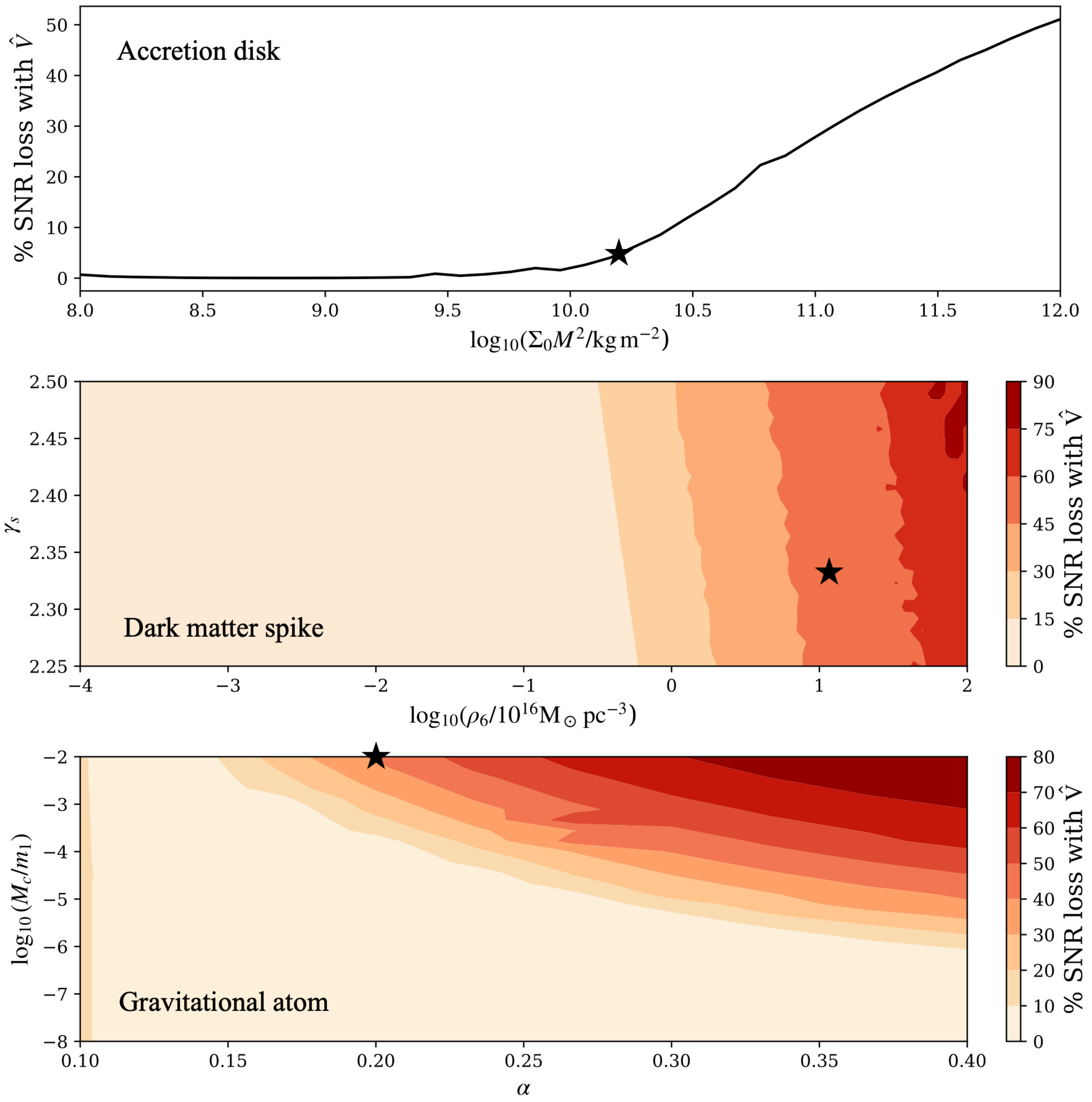
Parameter estimation with vacuum waveform

	Accretion disk signal	Dark dress signal	Grav atom signal
Vacuum template			

Cole et al. 2023

See also Hannuksela et al. arXiv:1804.09659
Maselli et al. arXiv:2106.11325

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

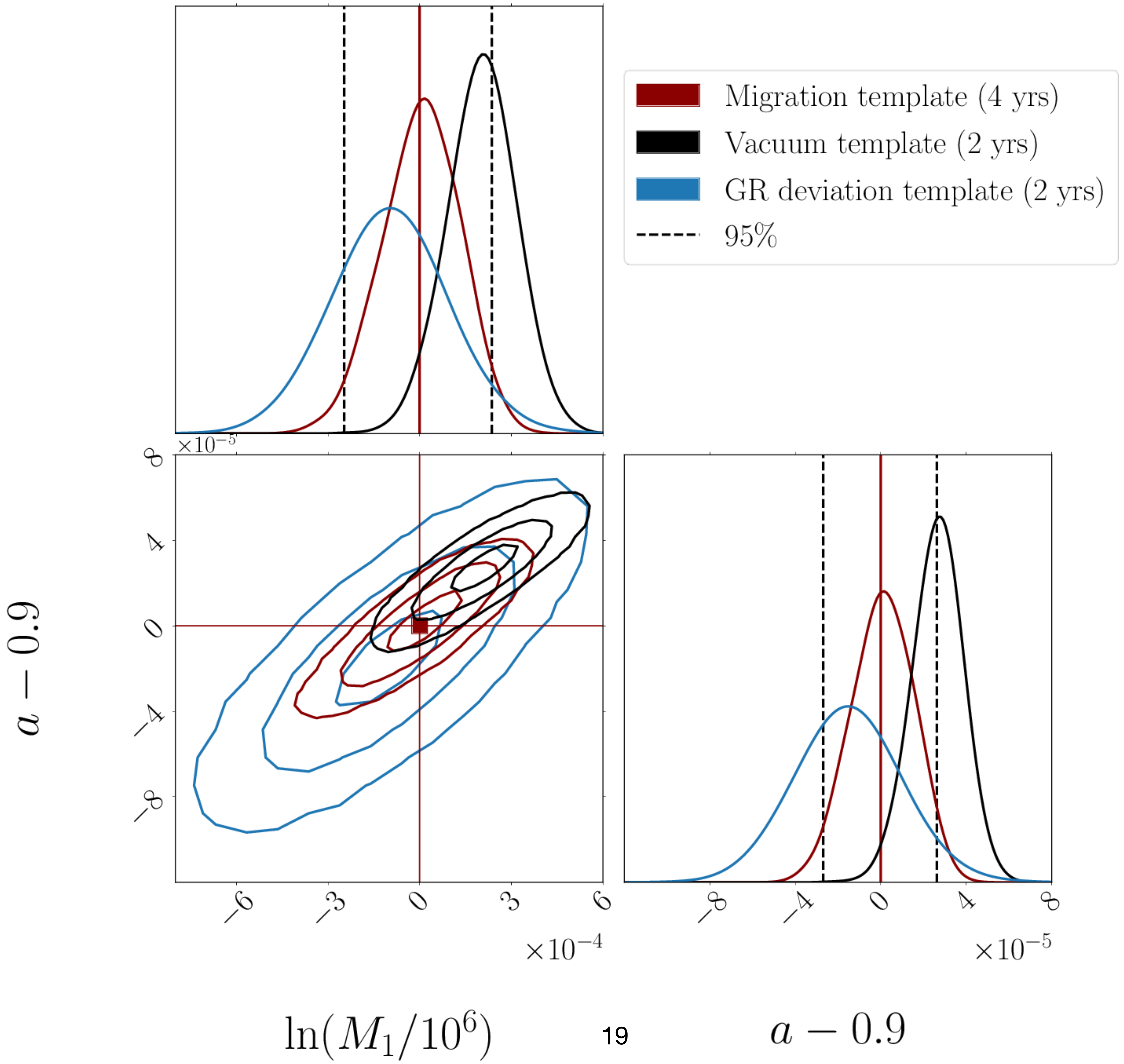
$\log_{10} \mathcal{B}$	**Dark dress signal**	**Accretion disk signal**	**Gravitational atom signal**
Vacuum template	34	6	39
Dark dress template	-	3	39
Accretion disk template	17	-	33
Gravitational atom template	24	6	-

List of additions: (signal)

- Full parameter space to check for degeneracies with extrinsic parameters
- Include spins, eccentricity (EMRI waveforms)
- Include relativistic corrections
- Improve modelling of environments
- Check for degeneracies with other environments e.g. modifications to GR

List of additions:

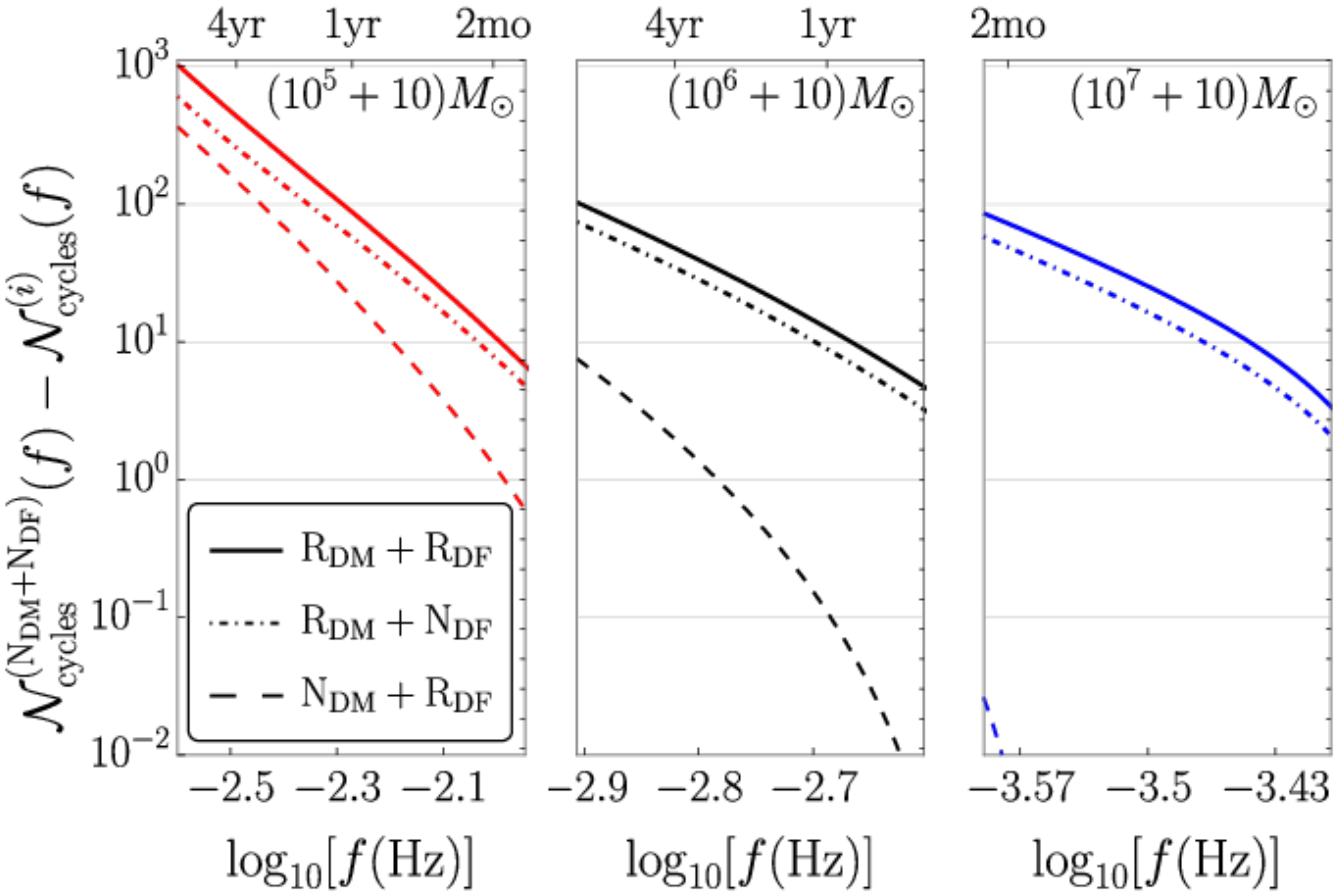
Deal with accretion disk more carefully, compare with GR deviation



Speri et al. *Phys.Rev.X* 13 (2023) 2, 021035

List of additions:

Include relativistic effects (both vacuum + dark matter spike)



(Not yet including feedback...)

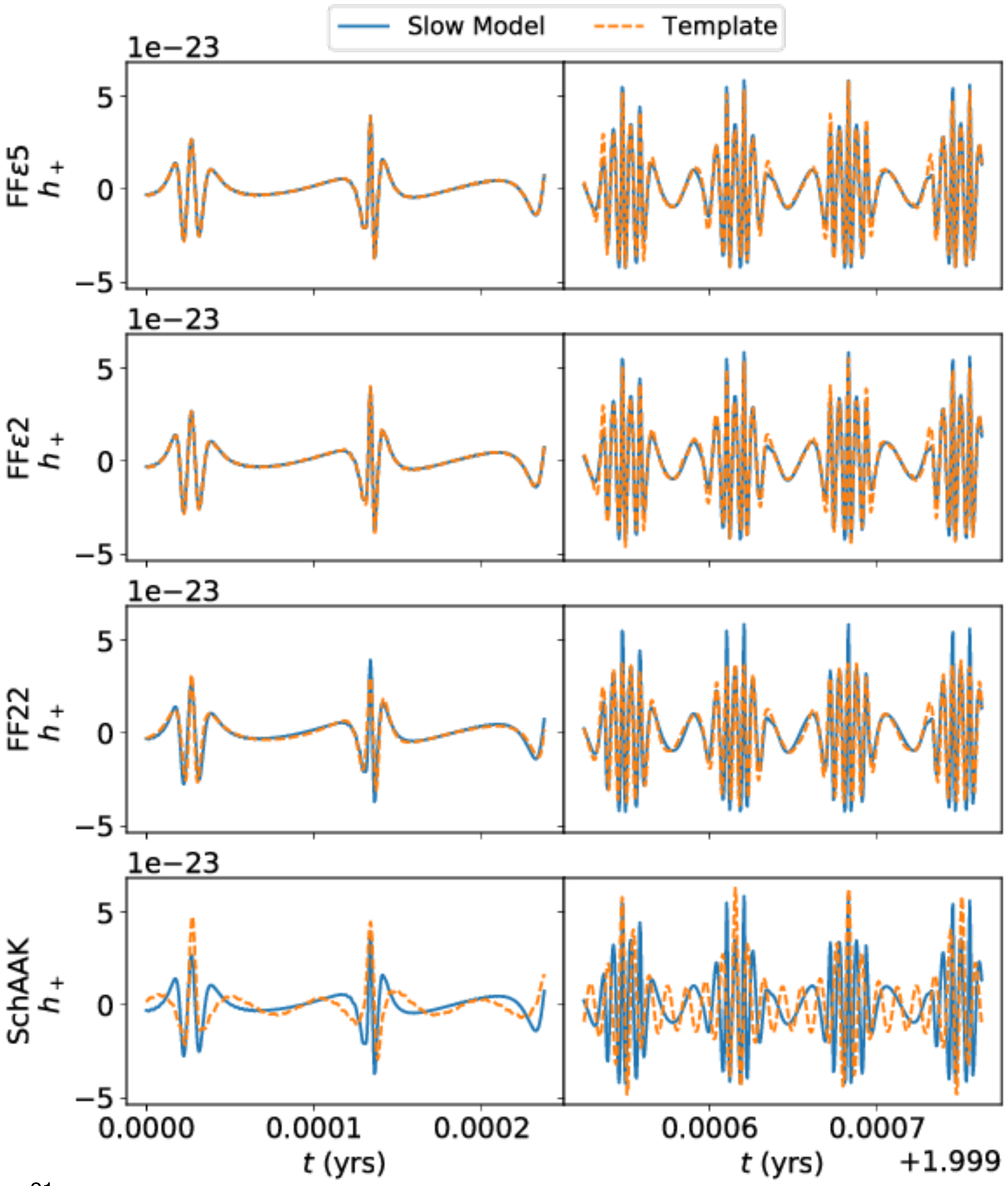
Sweeney et al. *Phys.Rev.D* 106 (2022) 4, 044027

List of additions:

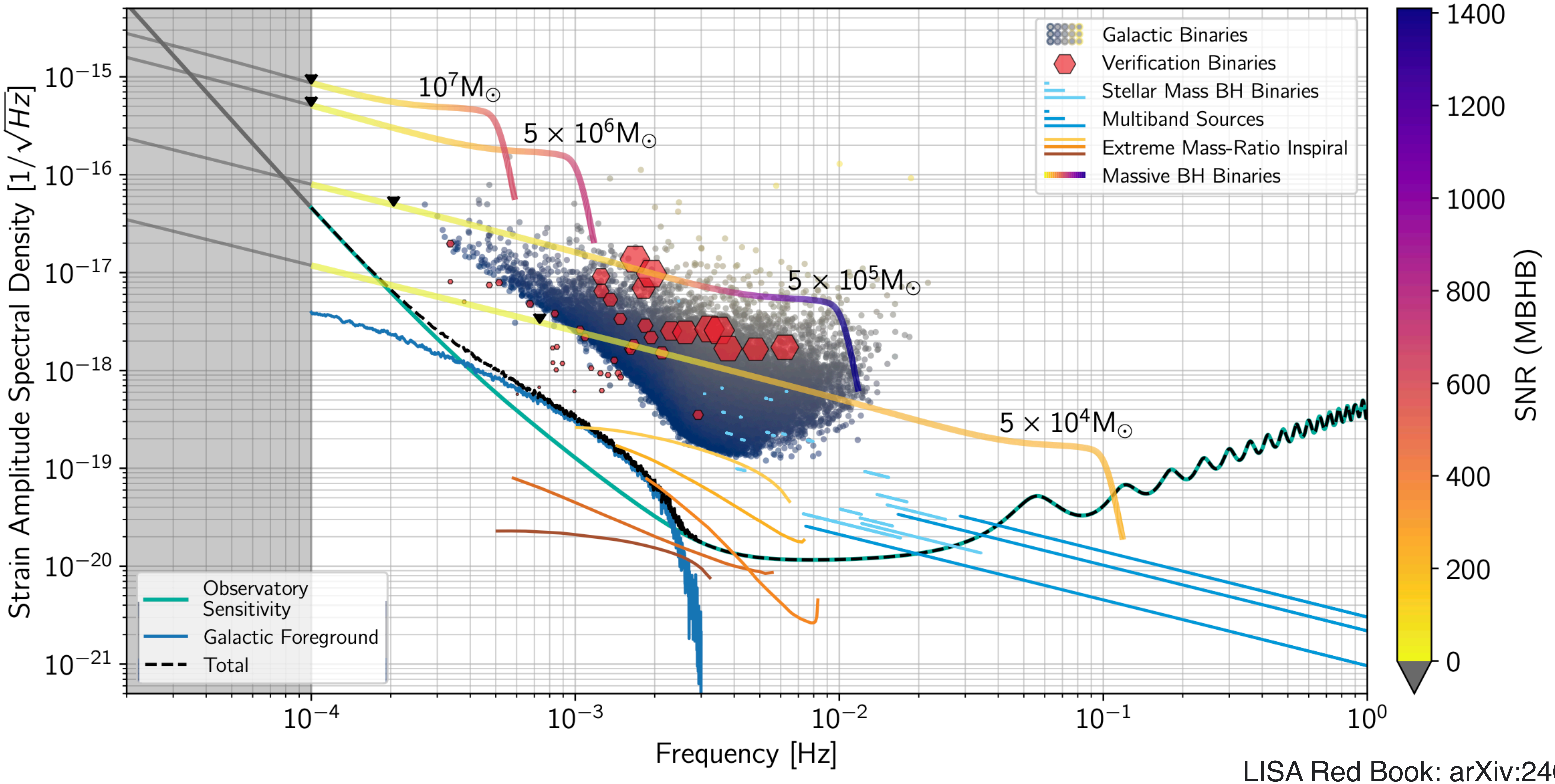
Use full EMRI waveforms

e.g. Fast EMRI Waveforms (FEW)

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



List of additions: (noise)



LISA Red Book: arXiv:2402.07571

Towards a realistic data analysis strategy

With James Alvey and Uddipta Bhardwaj

- Want to be able to flexibly add complexity to the signal and the noise models and keep computational cost of parameter estimation under control
- Likelihood-based methods expensive for long duration signals (even when analytical) - see Max Dax's talk yesterday

PEREGRINE

Gravitational Wave Parameter Inference with Neural Ratio Estimation

Bhardwaj et al, *Phys.Rev.D* 108 (2023) 4, 042004

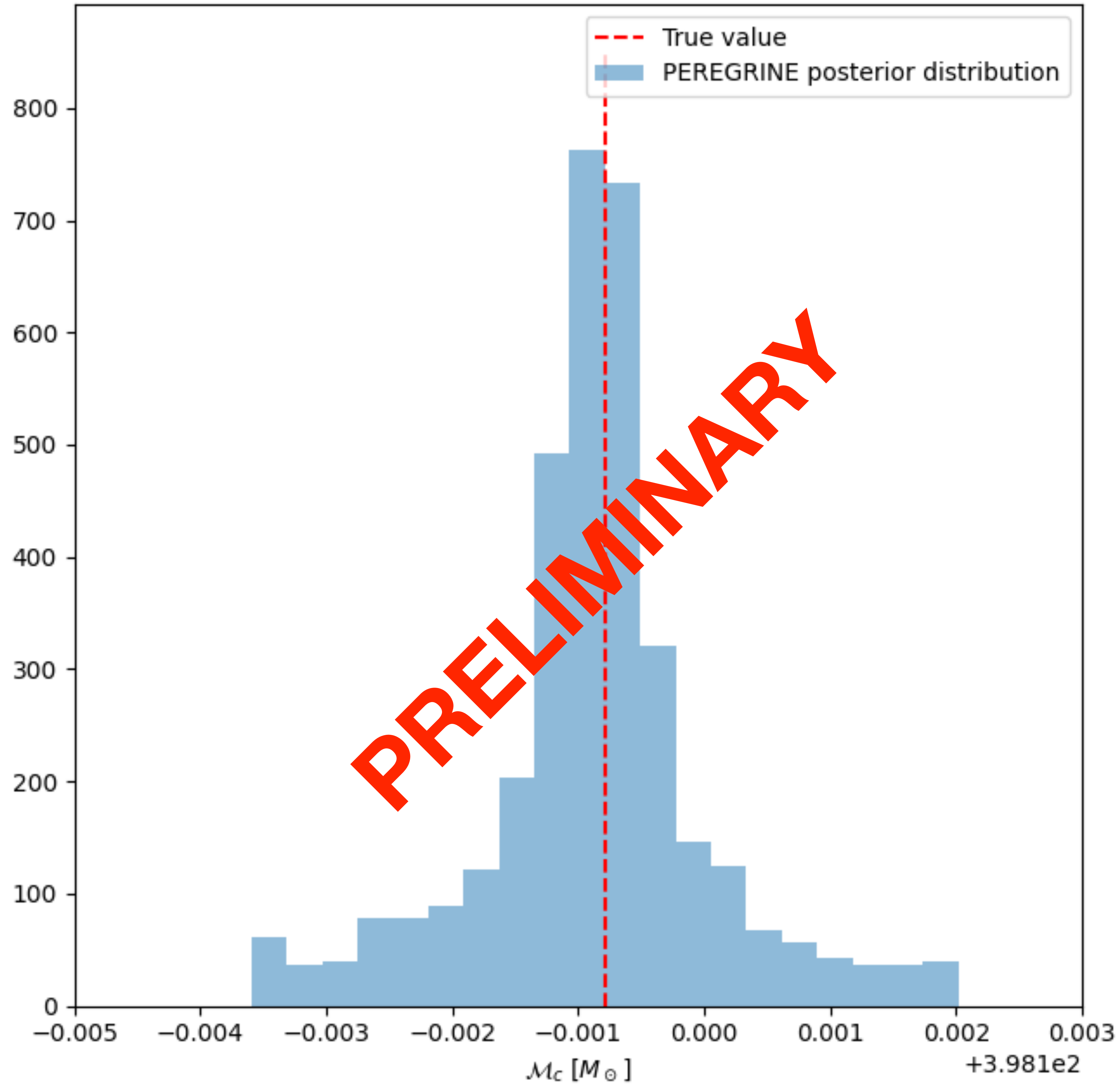
Towards a realistic data analysis strategy

With James Alvey and Uddipta Bhardwaj

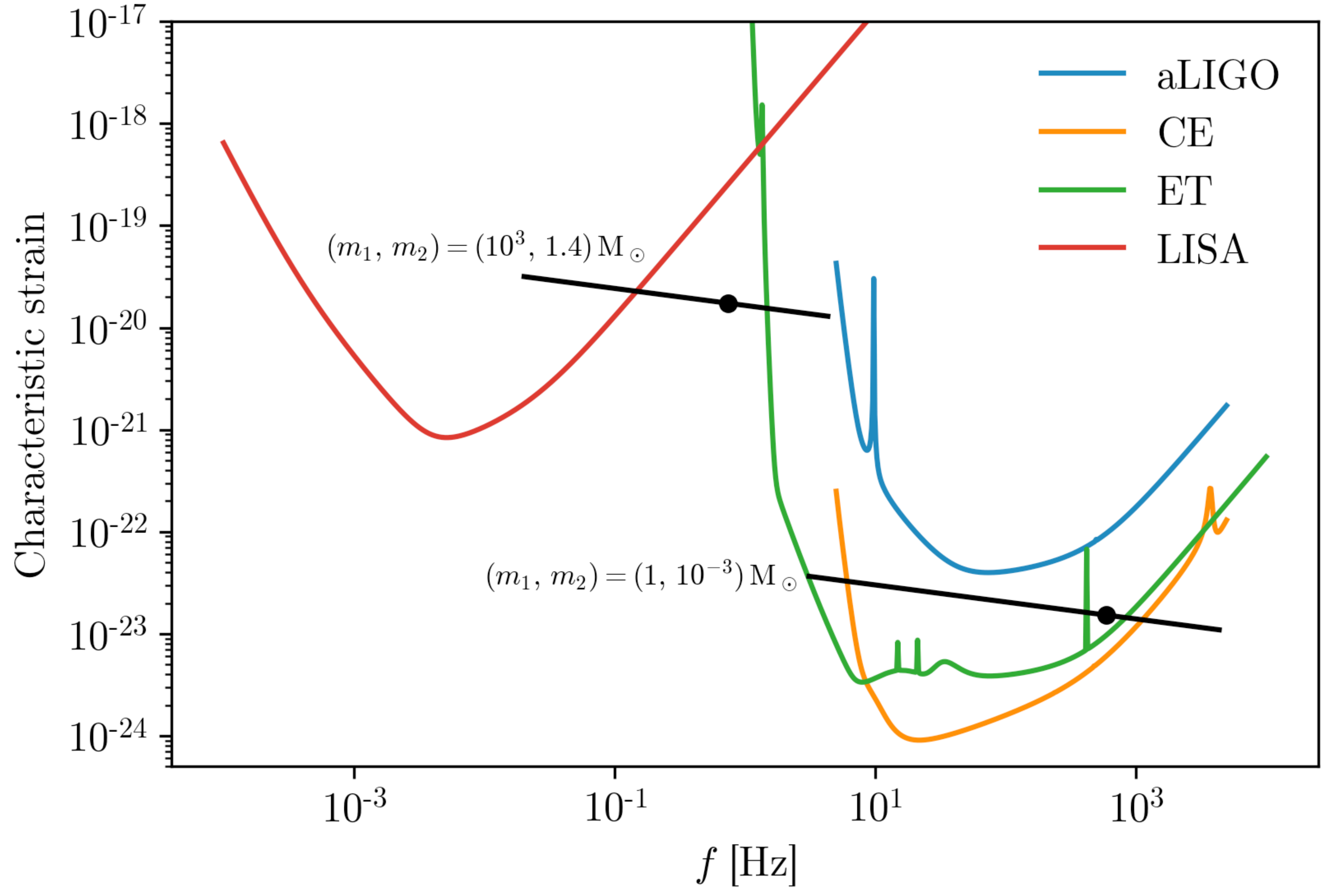
PEREGRINE

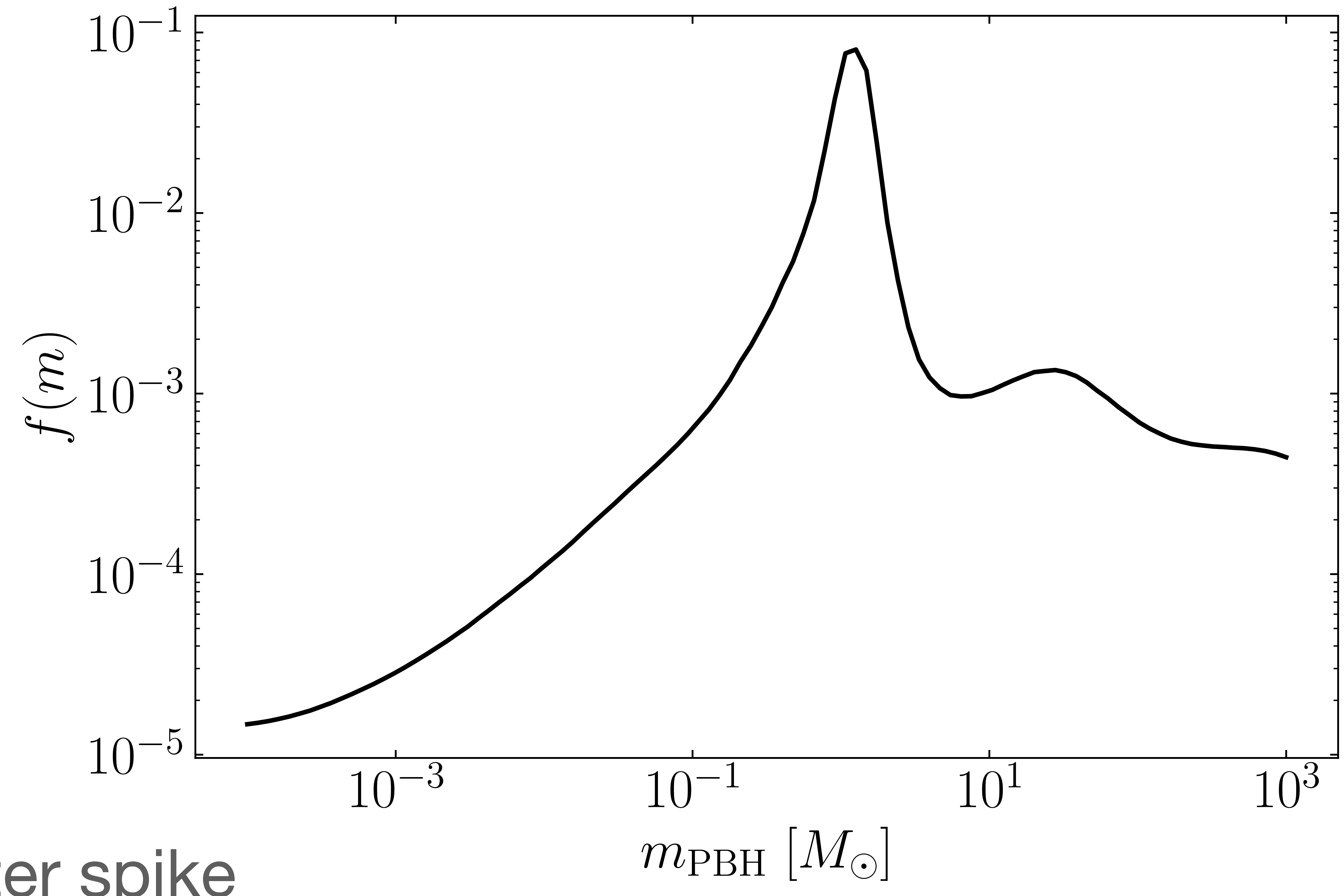
Gravitational Wave Parameter Inference with Neural Ratio Estimation

- Simulation-based inference package for GWs
- Using long duration dark matter influenced signals as a test case
- (Moonshot) aim: full parameter space, realistic noise, EMRI waveforms
- Work in progress…



What about future ground-based detectors?



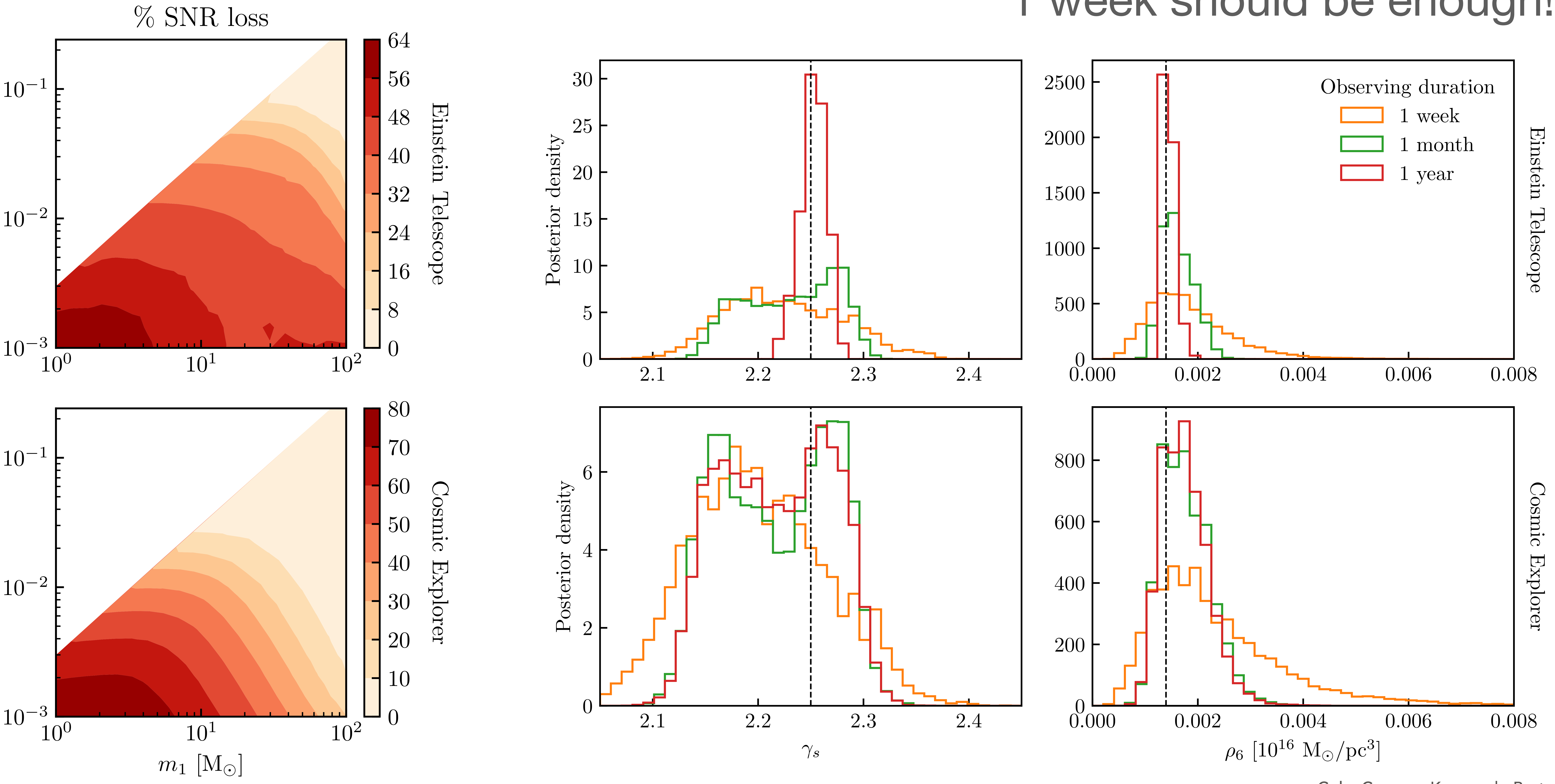


IMRI PBHs must have a dark matter spike

Cole, Coogan, Kavanagh, Bertone 2022

What about future ground-based detectors?

1 week should be enough!



Cole, Coogan, Kavanagh, Bertone 2022

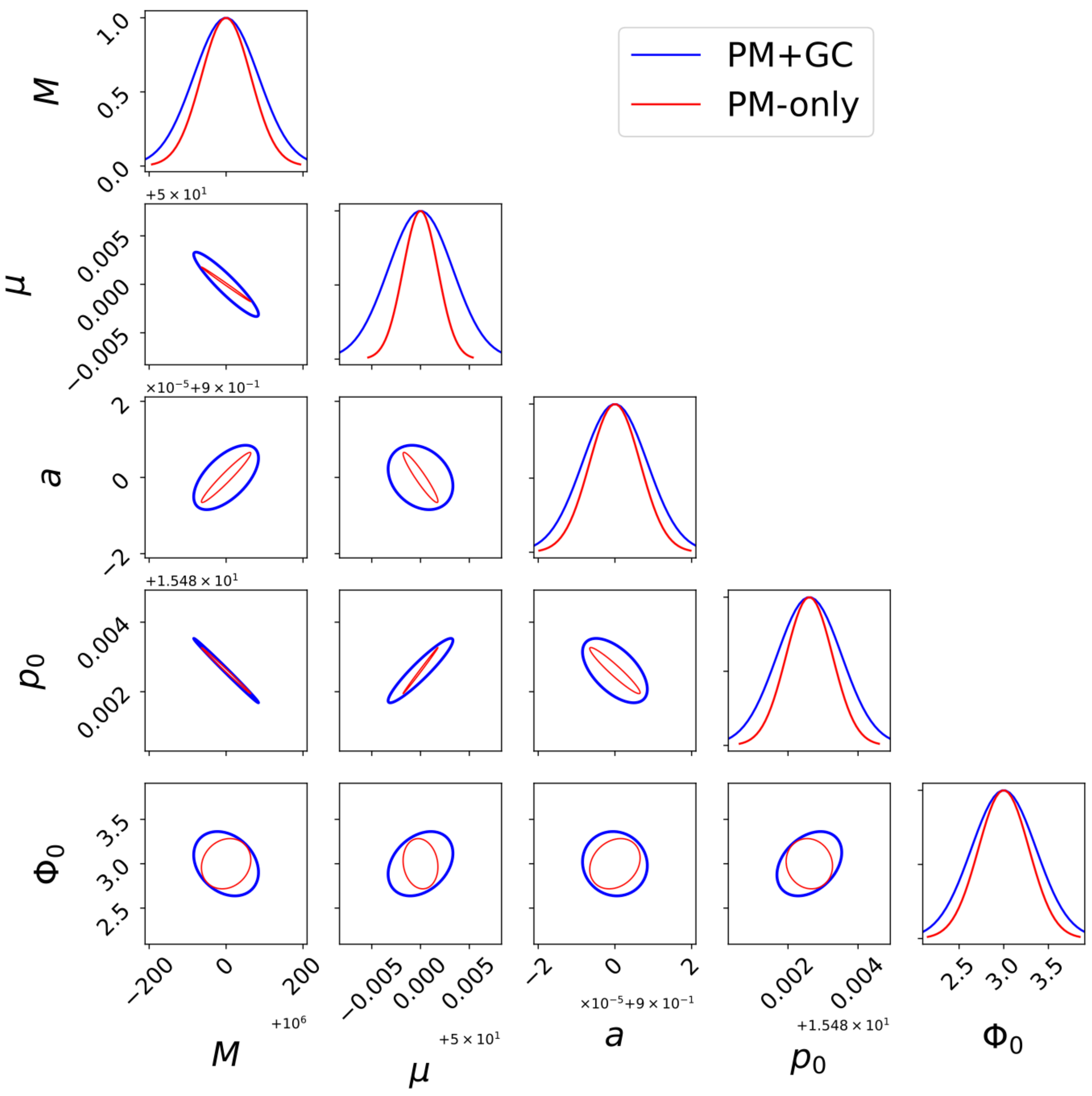
Conclusions

- We hope to 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 and future work

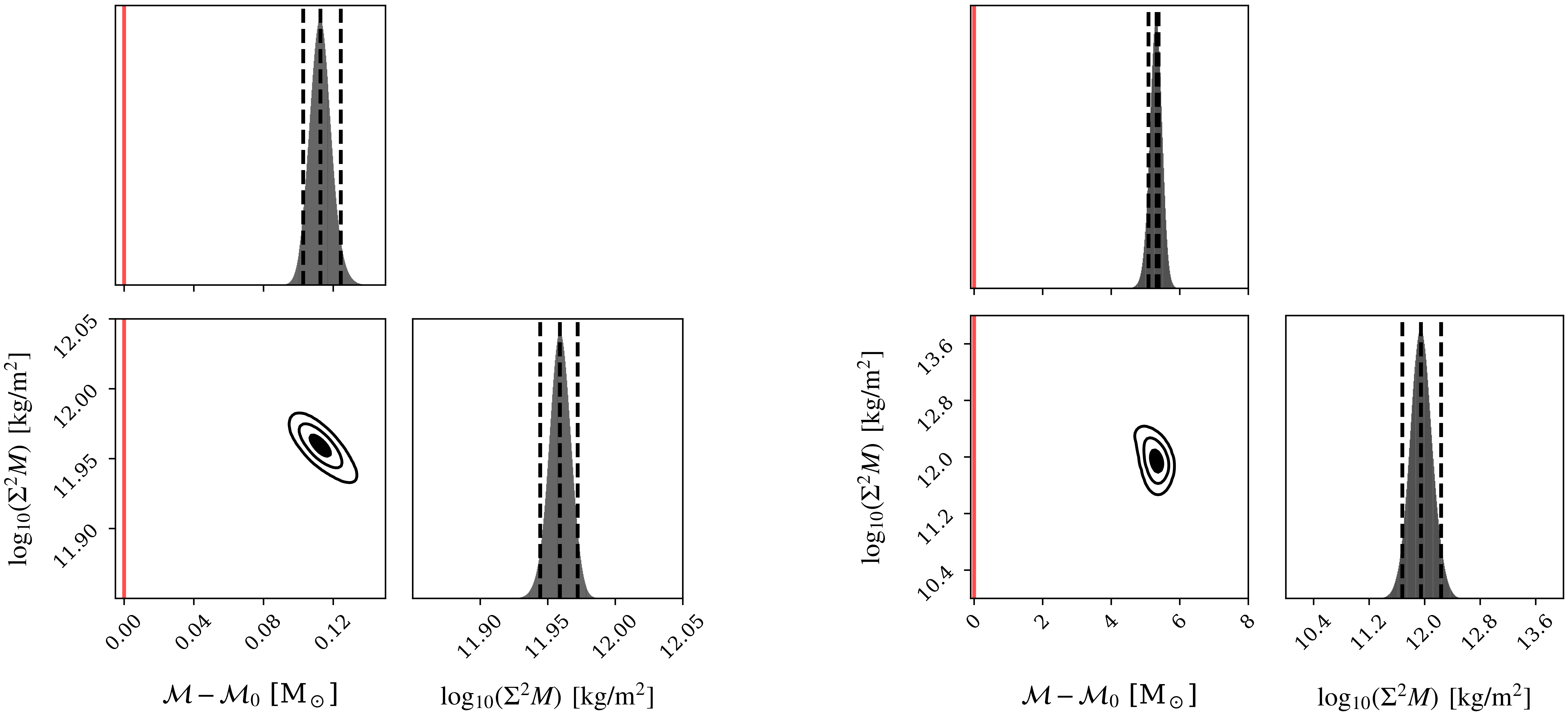
- More accurate waveforms required
- Account for more realistic noise
- Use simulation-based inference to show that this will be possible with real data

Beyond GR effects could also be degenerate



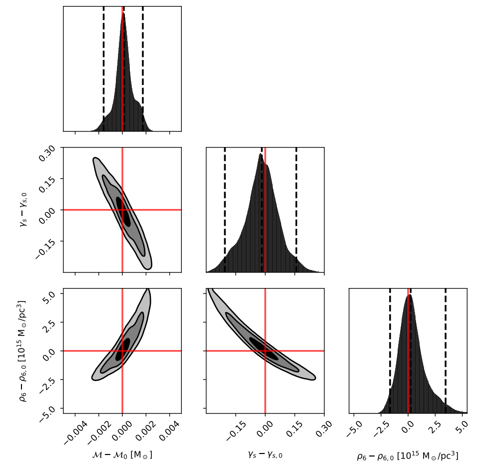
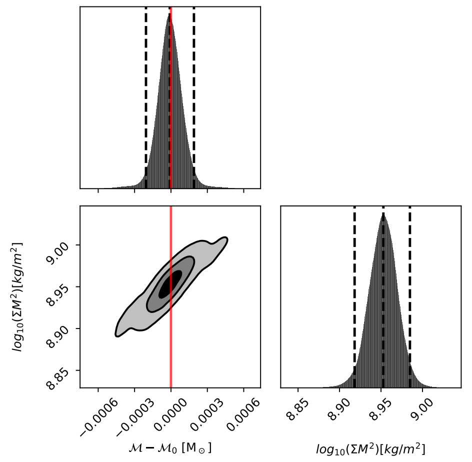
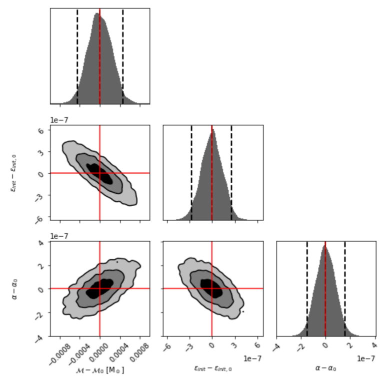
Kejriwal arXiv:2312.13028

Fit dark dress and GA with accretion disk

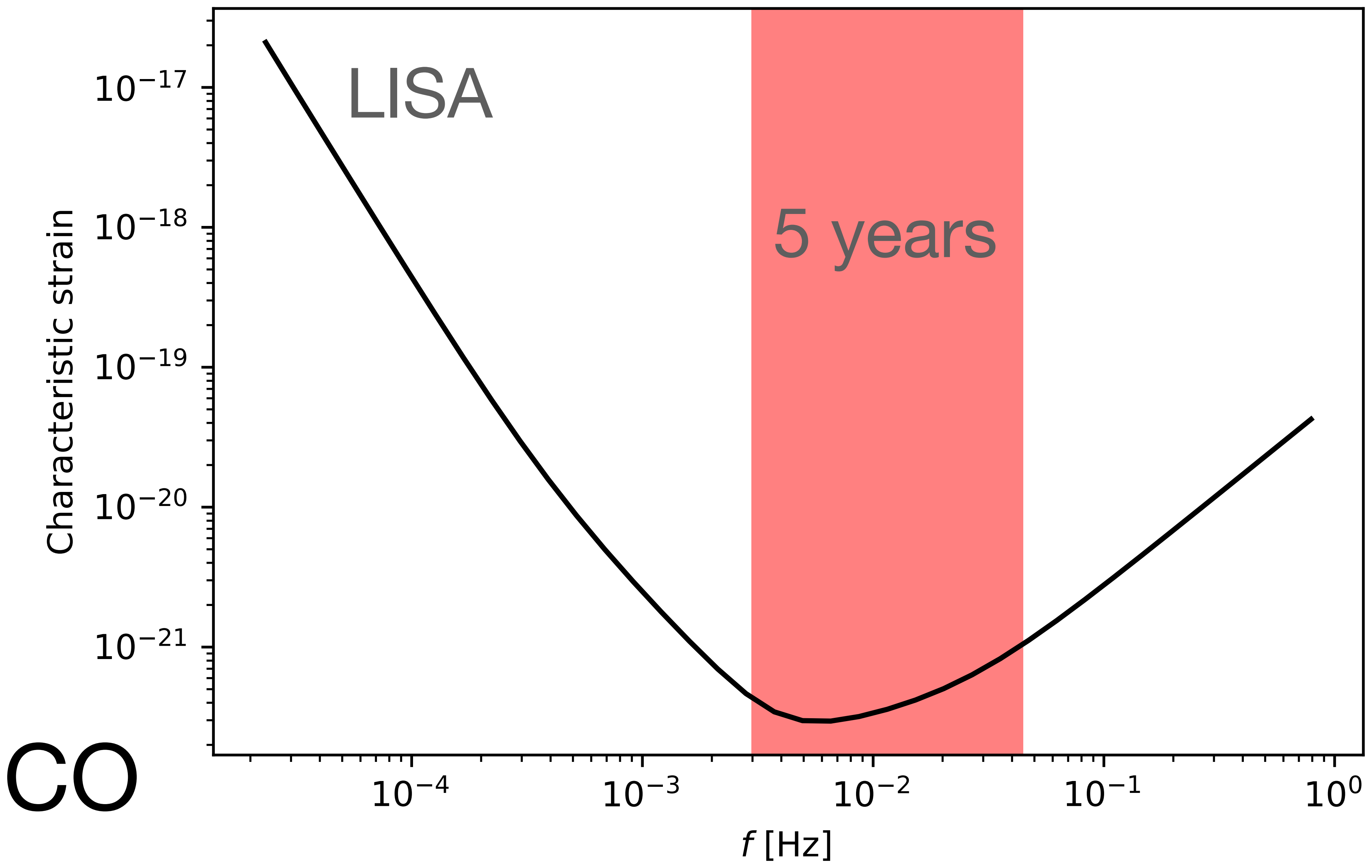


Model preference

$$BF = \frac{p(d\,|\,h_{\mathrm{corr}})}{p(d\,|\,h_{\mathrm{incorr}})}$$

	Dark dress signal	Accretion disk signal	Grav atom signal
Vacuum template	$BF \gg 100$	$BF \gg 100$	
Dark dress template		$BF \gg 100$	
Accretion disk template			
Grav atom template			

Benchmark system

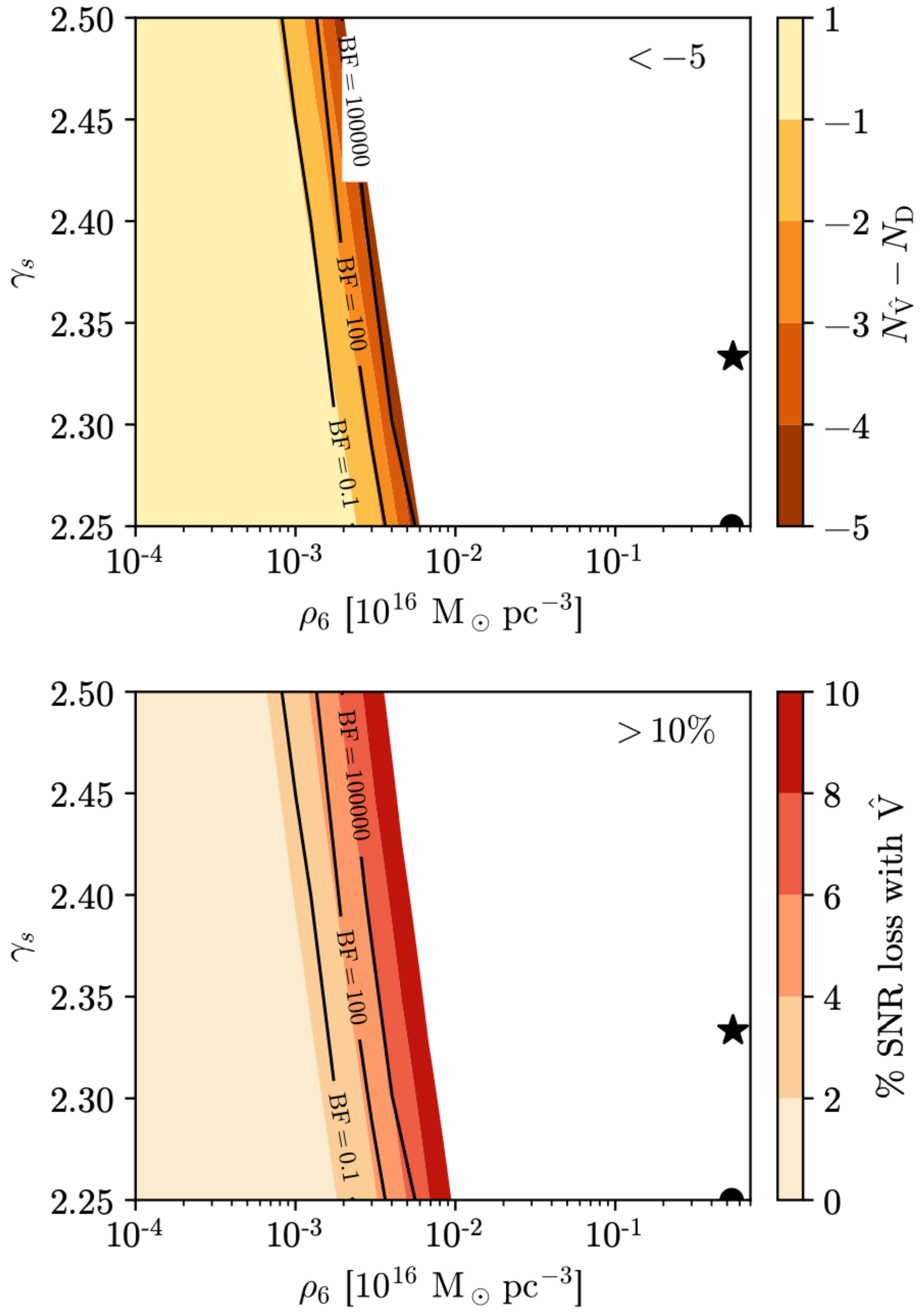


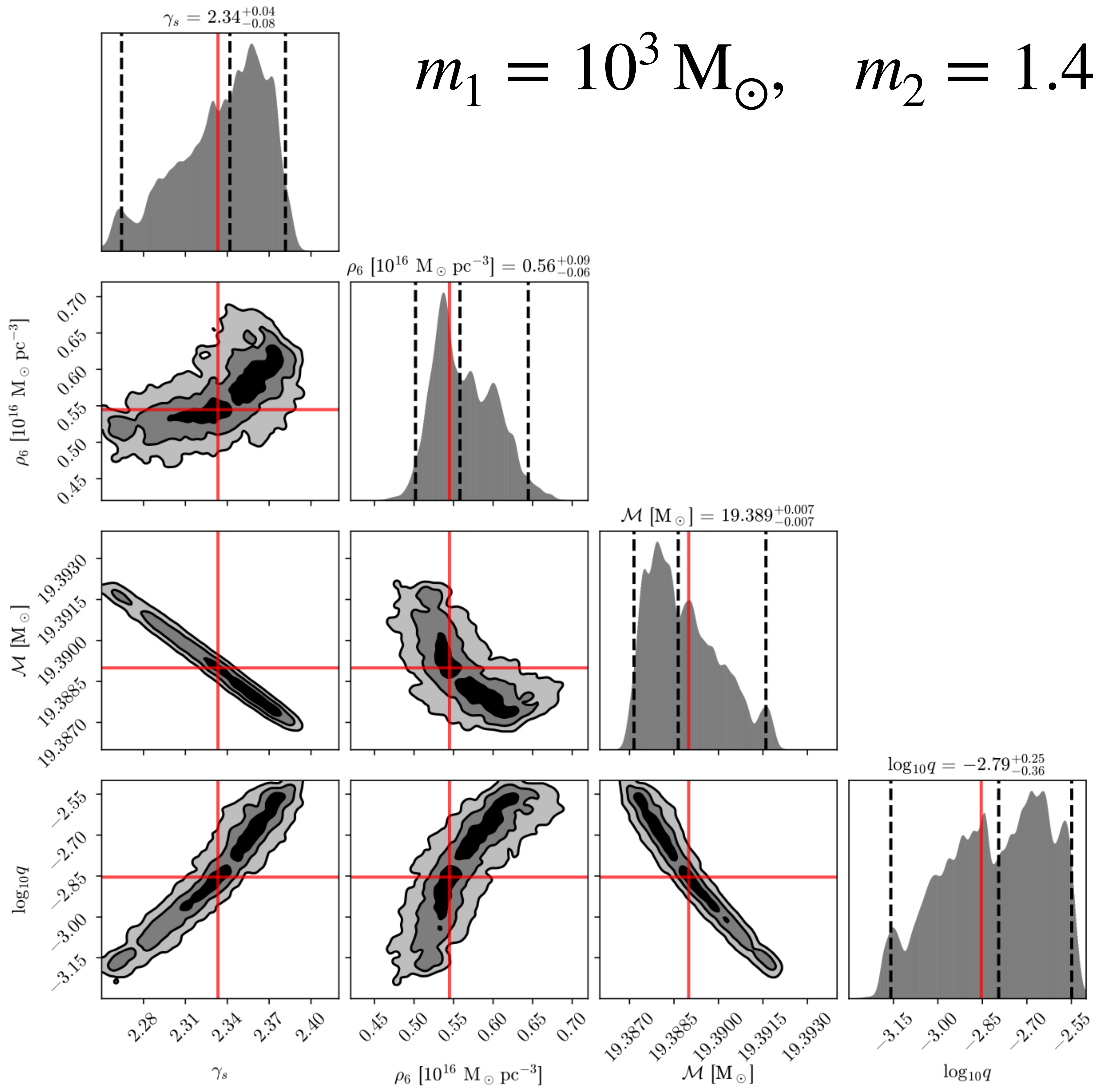
$$m_1 = 10^5\,\mathrm{M}_\odot, \quad m_2 = 10\,\mathrm{M}_\odot \qquad \mathscr{M}_c \approx 400\,\mathrm{M}_\odot$$

- Small mass ratio so that environment survives
- Masses are in the LISA band for 5 years + until ISCO
- Plausible formation mechanisms for all three environments

Dark dress	Accretion disk	Gravitational atom
$\rho_6 = 1.95 \times 10^{17}\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$ $\gamma_s = 7/3$ Eda et al. 2013, 2014	$\Sigma_0 M^2 = 9 \times 10^8\,\mathrm{kg\,m}^{-2}$	$M_c = \frac{m_1}{100}$ $\alpha = 0.2$

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



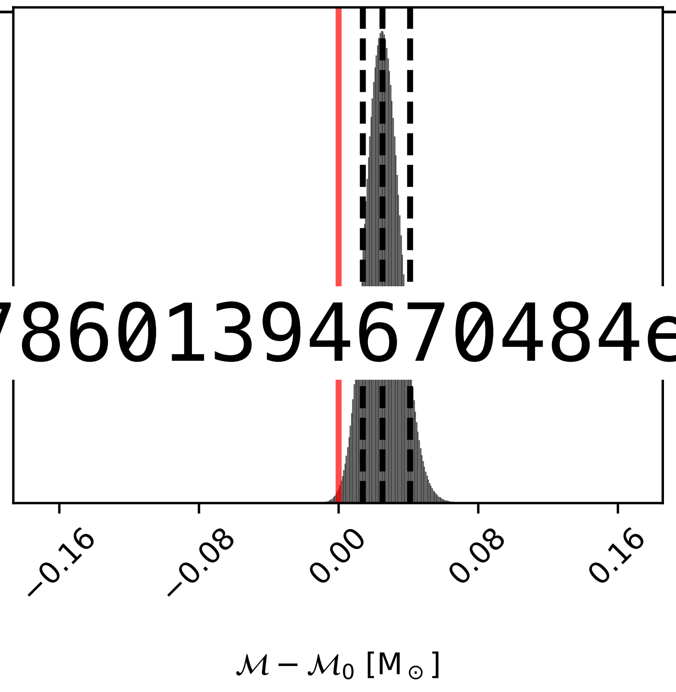
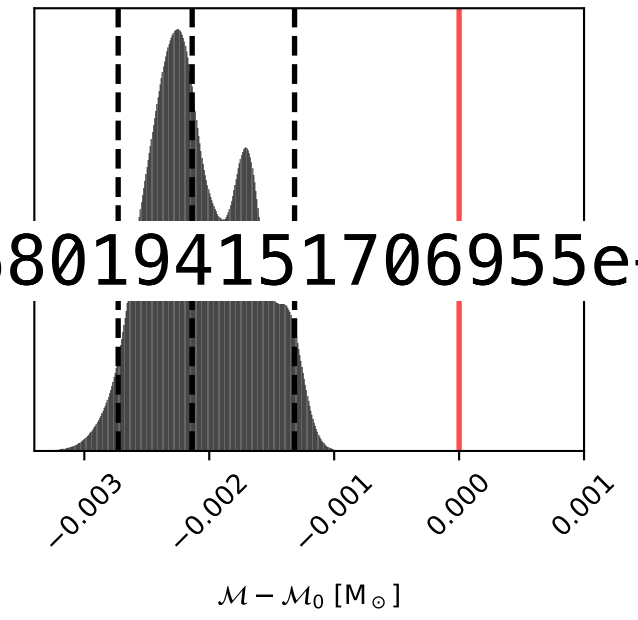
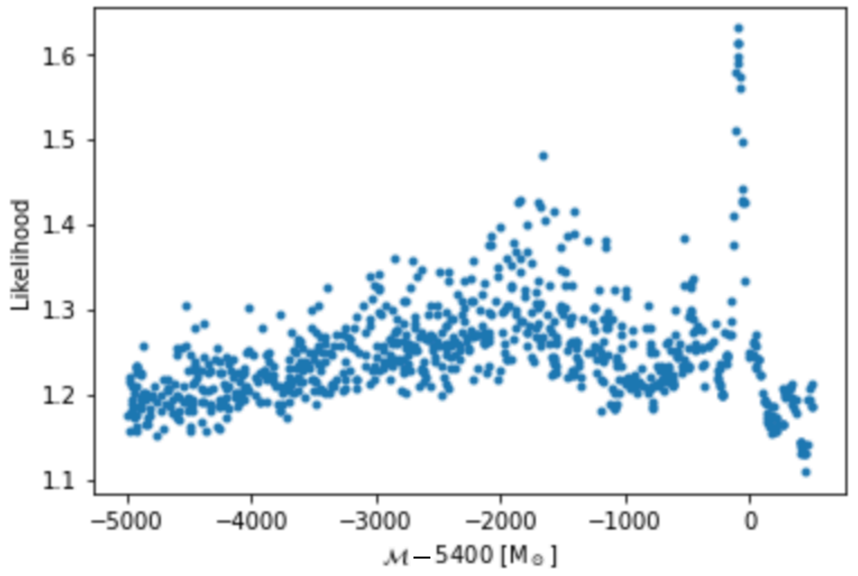
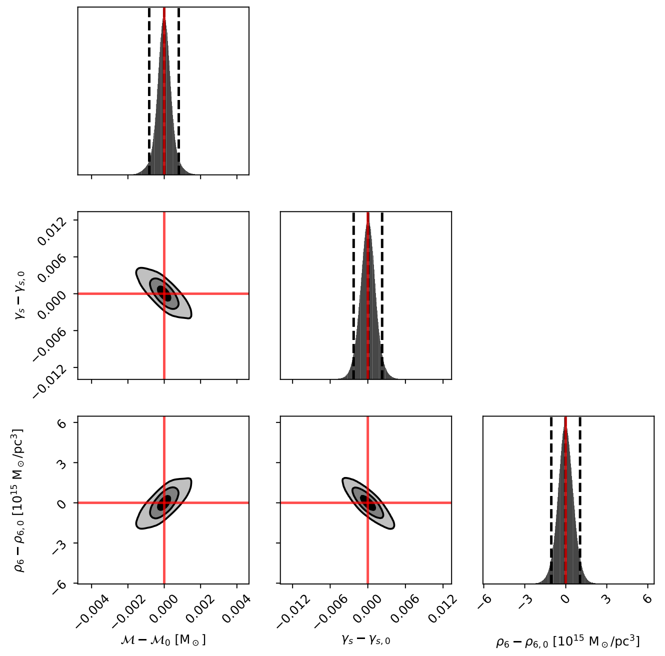
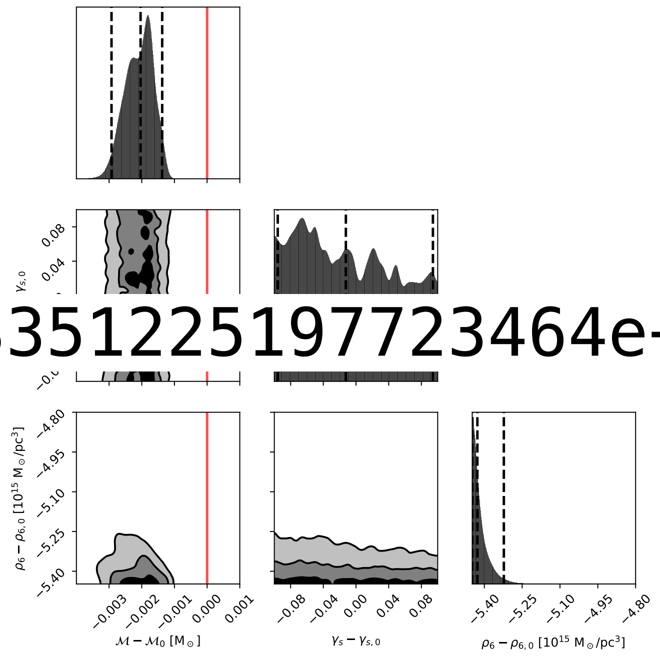
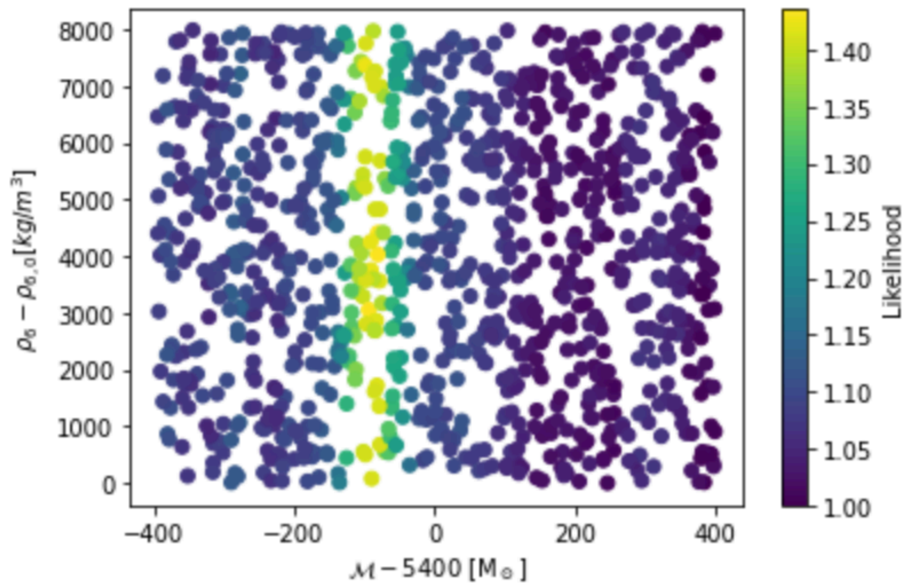
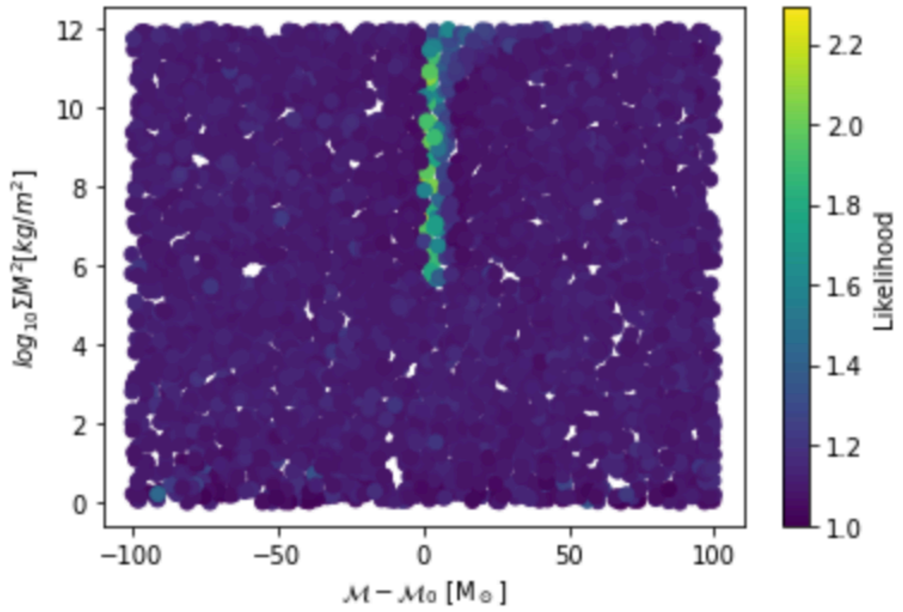
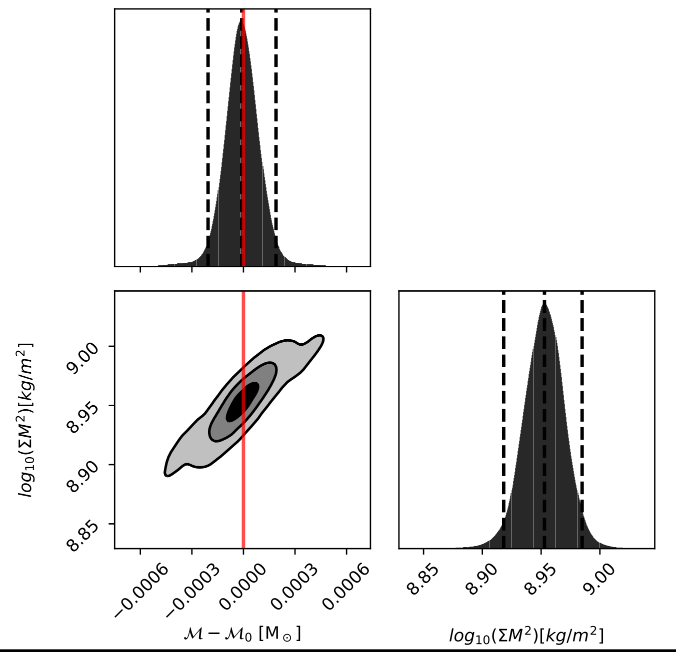
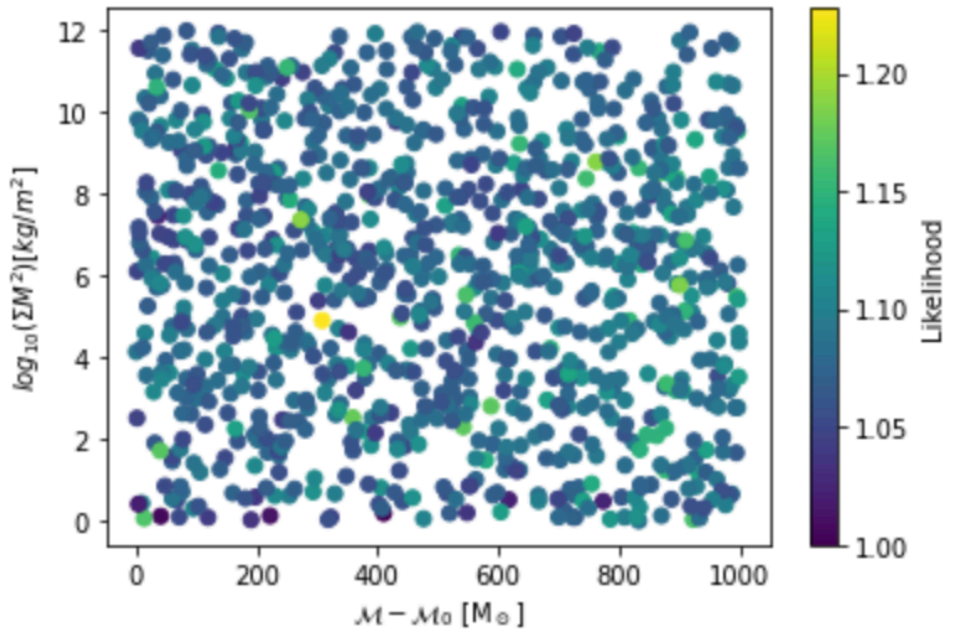
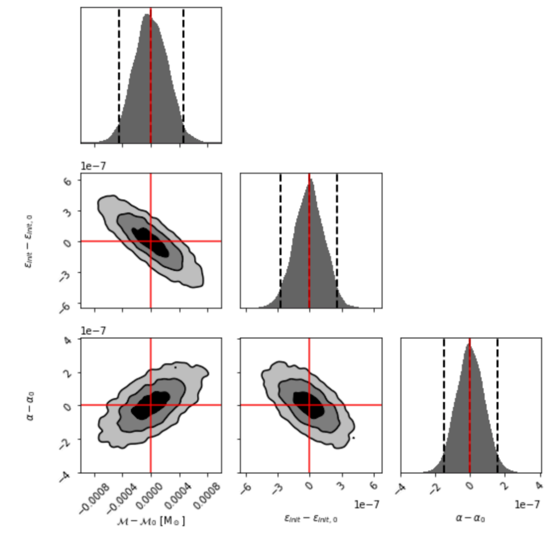


$$m_1 = 10^3\,\mathrm{M}_\odot, \quad m_2 = 1.4\,\mathrm{M}_\odot$$

Assume that our data is a linear combination of the signal plus the detector noise, which is Gaussian

Maximising w.r.t. extrinsic parameters: Owen 1996

Coogan et al. 2021

	Vacuum signal	Dark dress signal	Accretion disk signal	Grav atom signal
Vacuum template		 1.6878601394670484e+35	 1.680194151706955e+18	
Dark dress template			 2.3351225197723464e+21	
Accretion disk template				
Grav atom template				

Gravitational atom

$$\rho(\vec{r}) = M_{\rm c}|\psi(\vec{r})|^2$$

$$\psi(t, \vec{r}) = R_{n\ell}(r) Y_{\ell m}(\theta, \phi) e^{-iE_{n\ell m}t}$$

$$\Phi = \psi e^{-i\mu t}/\sqrt{2\mu}$$

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

$$p(d) = \int \mathrm{d}\boldsymbol{\theta}\, p_{\max}(d|h_{\boldsymbol{\theta}})\, p(\boldsymbol{\theta})\,,$$

Accretion disc

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

$$T_0 = -\Sigma(r) r^4 \Omega^2 q^2 \mathcal{M}^2$$