Learning about dark matter from binary black hole mergers

Philippa (Pippa) Cole, University of Amsterdam

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

Based on arXiv:2207.07576 and arXiv:2211.01362

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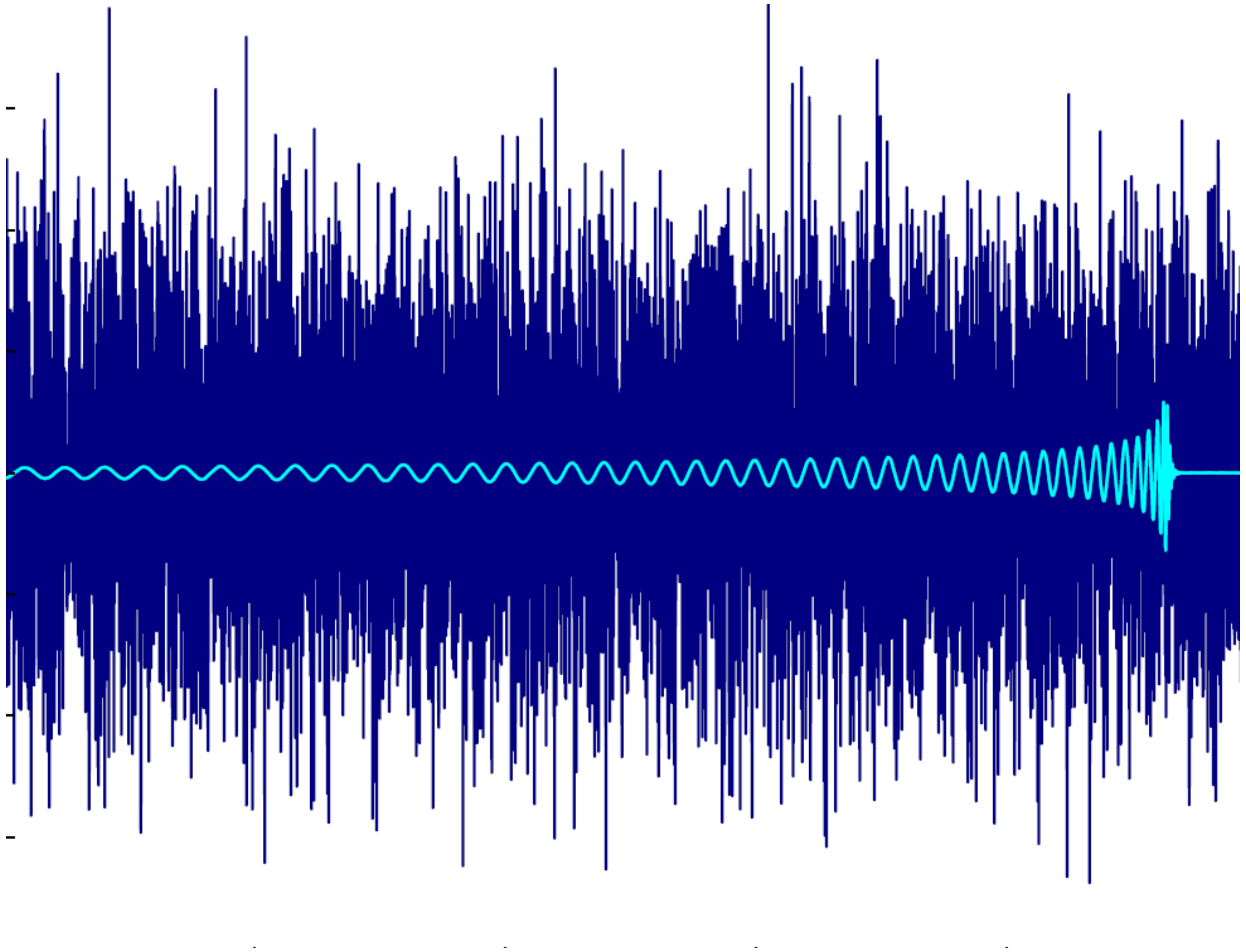
PARTNER INVESTIGATORS

Vacuum or non-vacuum

that is the question

- 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, 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

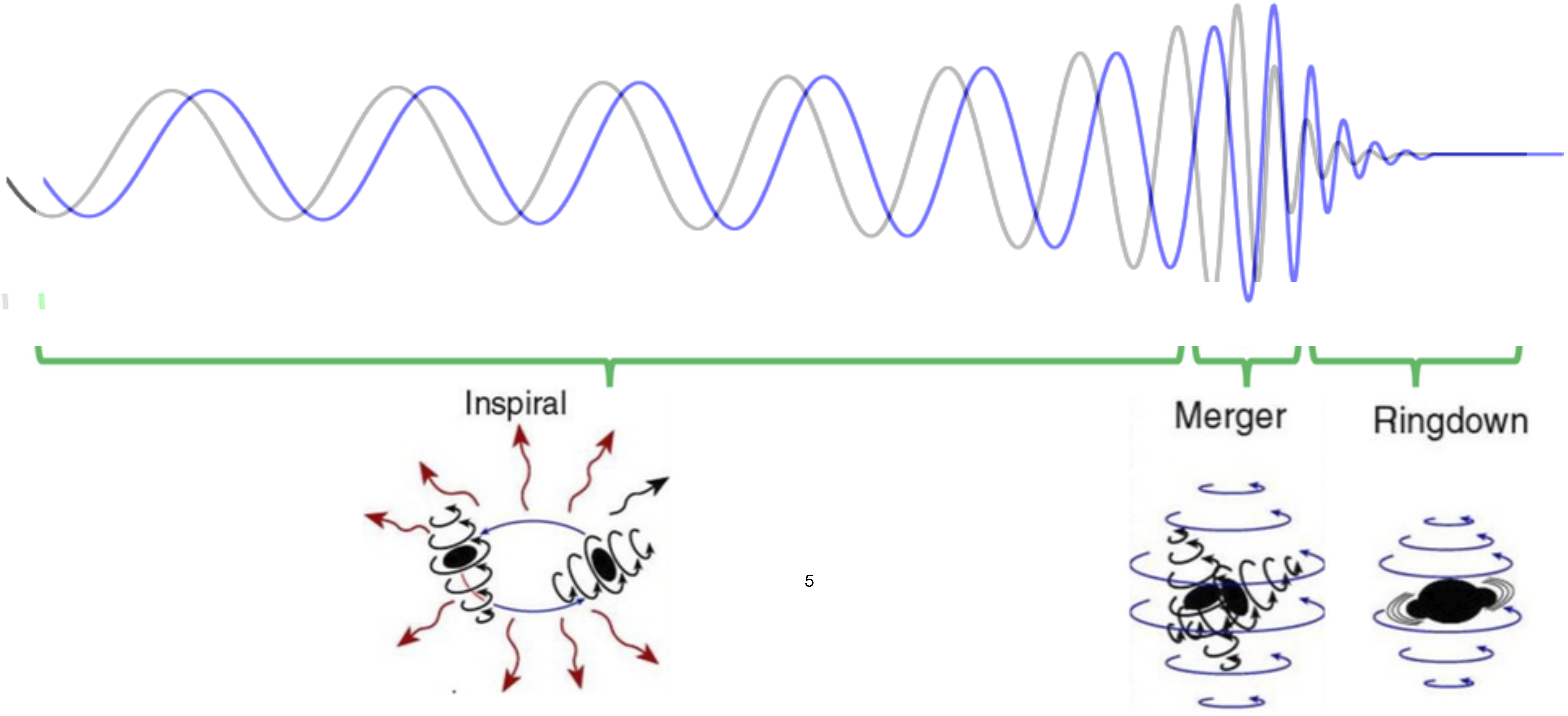
$$\dot{r} = \dot{r}_{\mathrm{GW}} + \dot{r}_{\mathrm{env}}$$

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

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

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

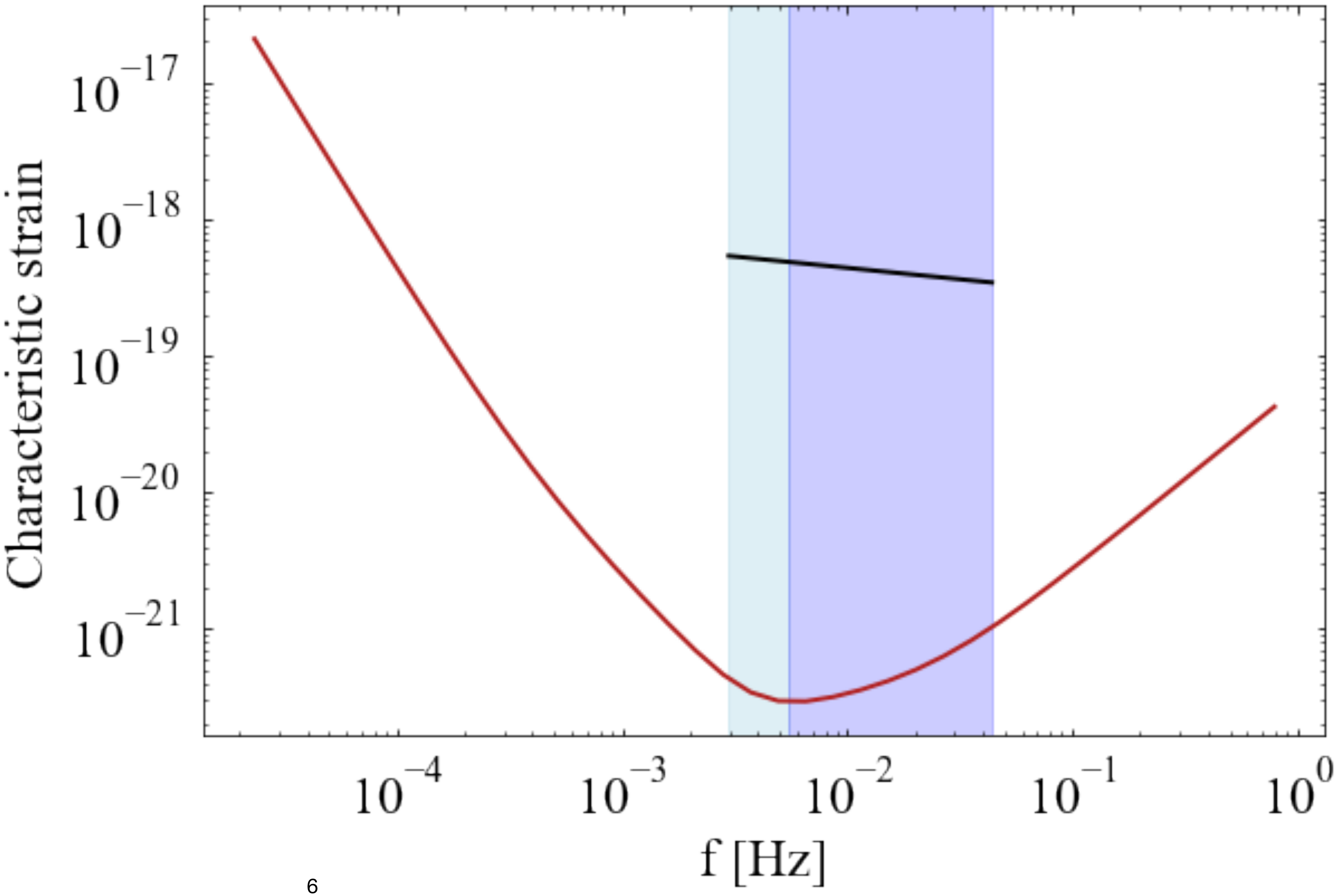
Hunting for the phase difference which accumulates over the course of the inspiral



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

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

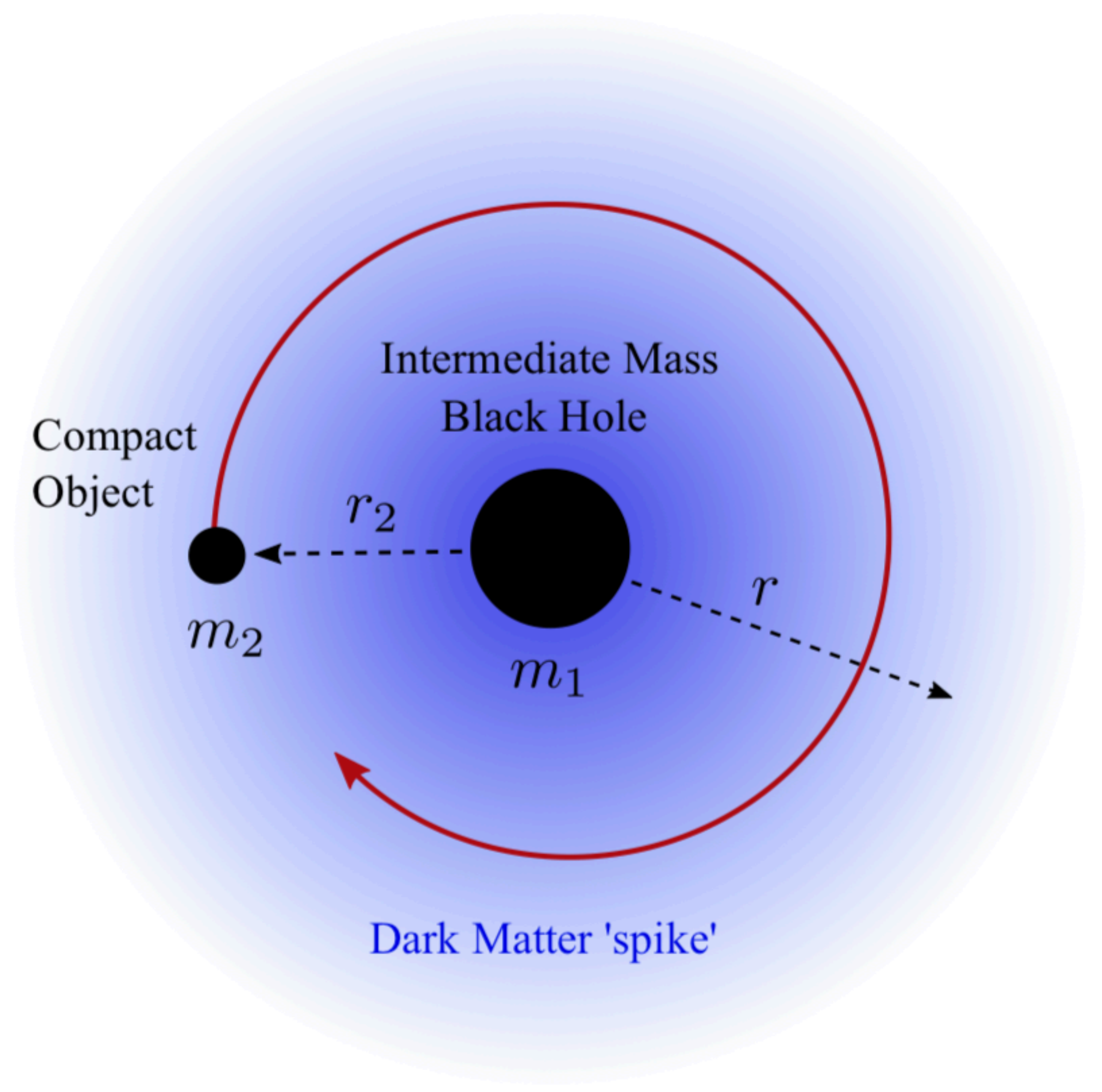


Why should we care about environmental effects?

- 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

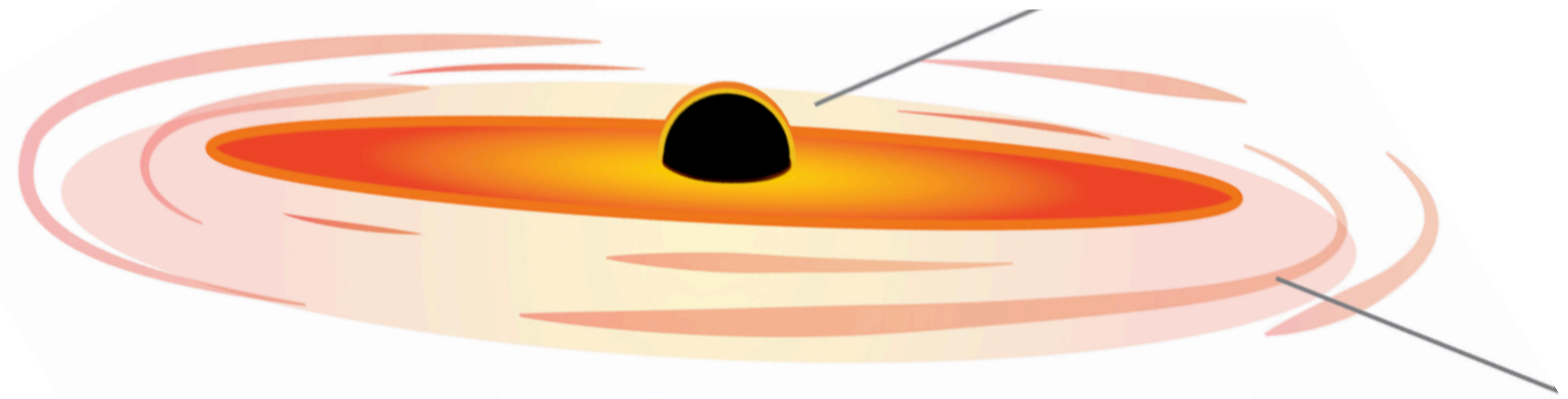
Dark dress



Cold, collisionless dark matter

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

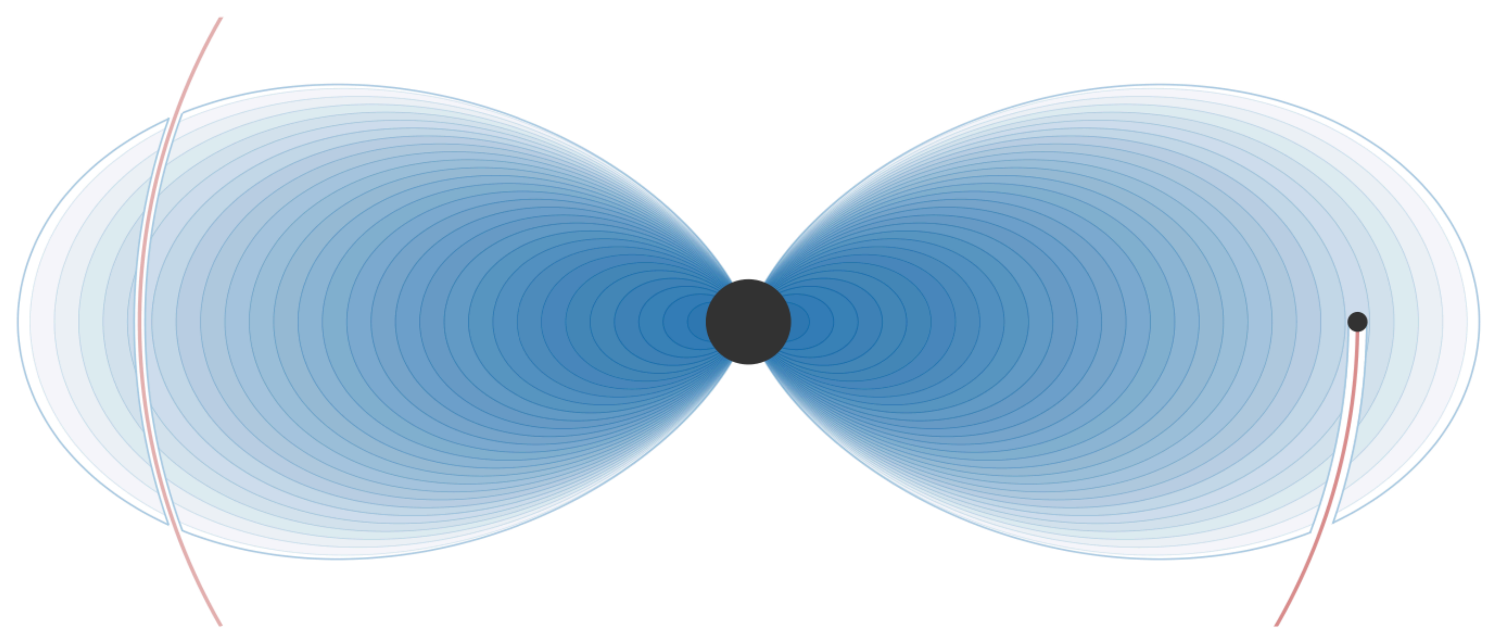
Accretion disc



Baryonic matter

Goldreich & Tremaine 1980
Tanaka 2002
Derdzinski et al. 2020

Gravitational atom

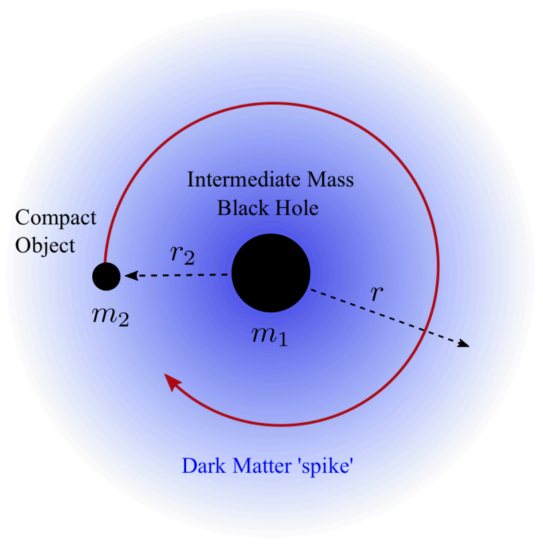


Ultra-light bosons

Baumann et al. 2019
Nielsen 2019
Bauman et al. 2021, 2022

Credit: Sophia Dagnello, NRAO/AUI/NSF

Dark dress

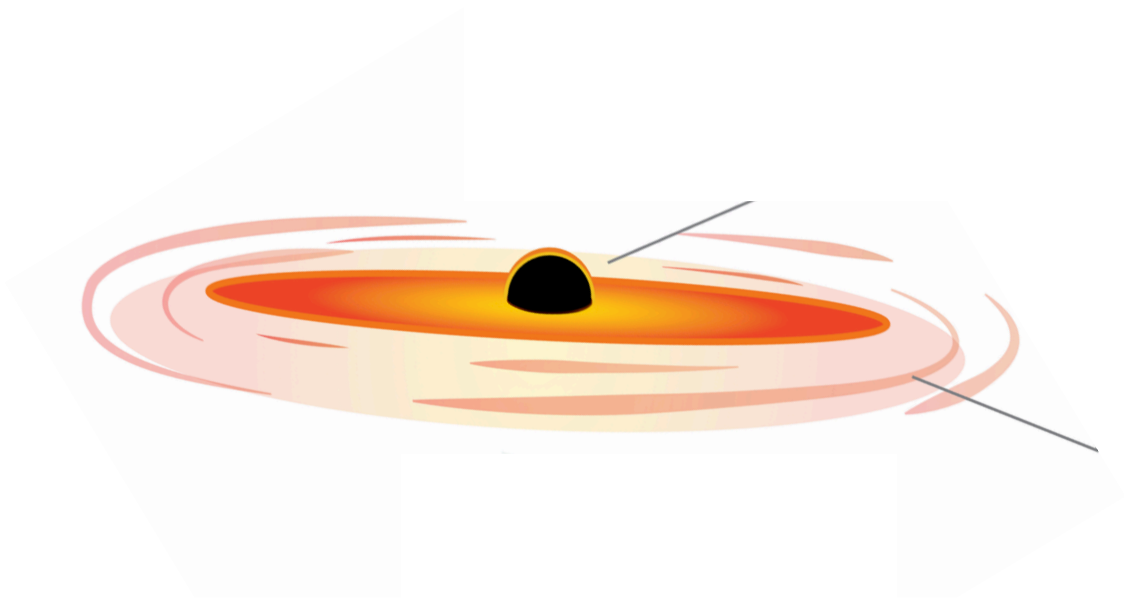


$$\rho(r) = \rho_6 \left(\frac{r_6}{r}\right)^{\gamma_s}$$

Spike density normalisation

Spike power law slope

Accretion disc



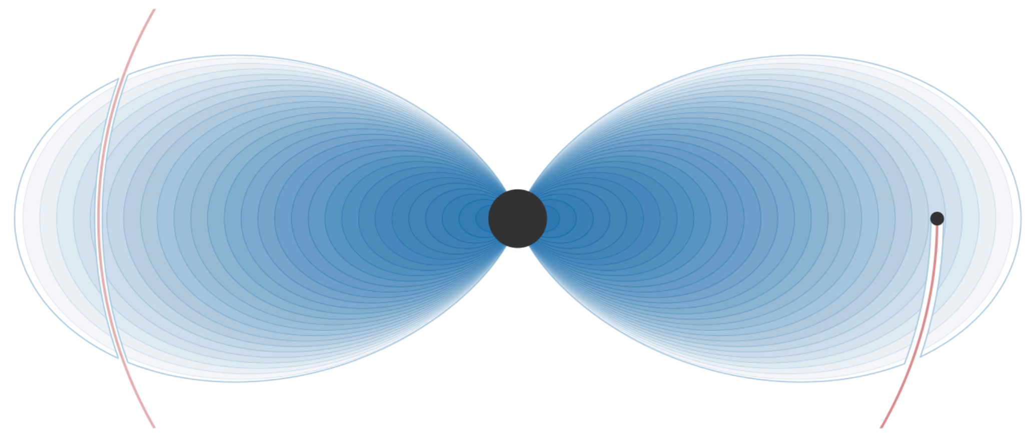
$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1/2}$$

$$M = r/h$$

Surface density normalisation

Mach number

Gravitational atom



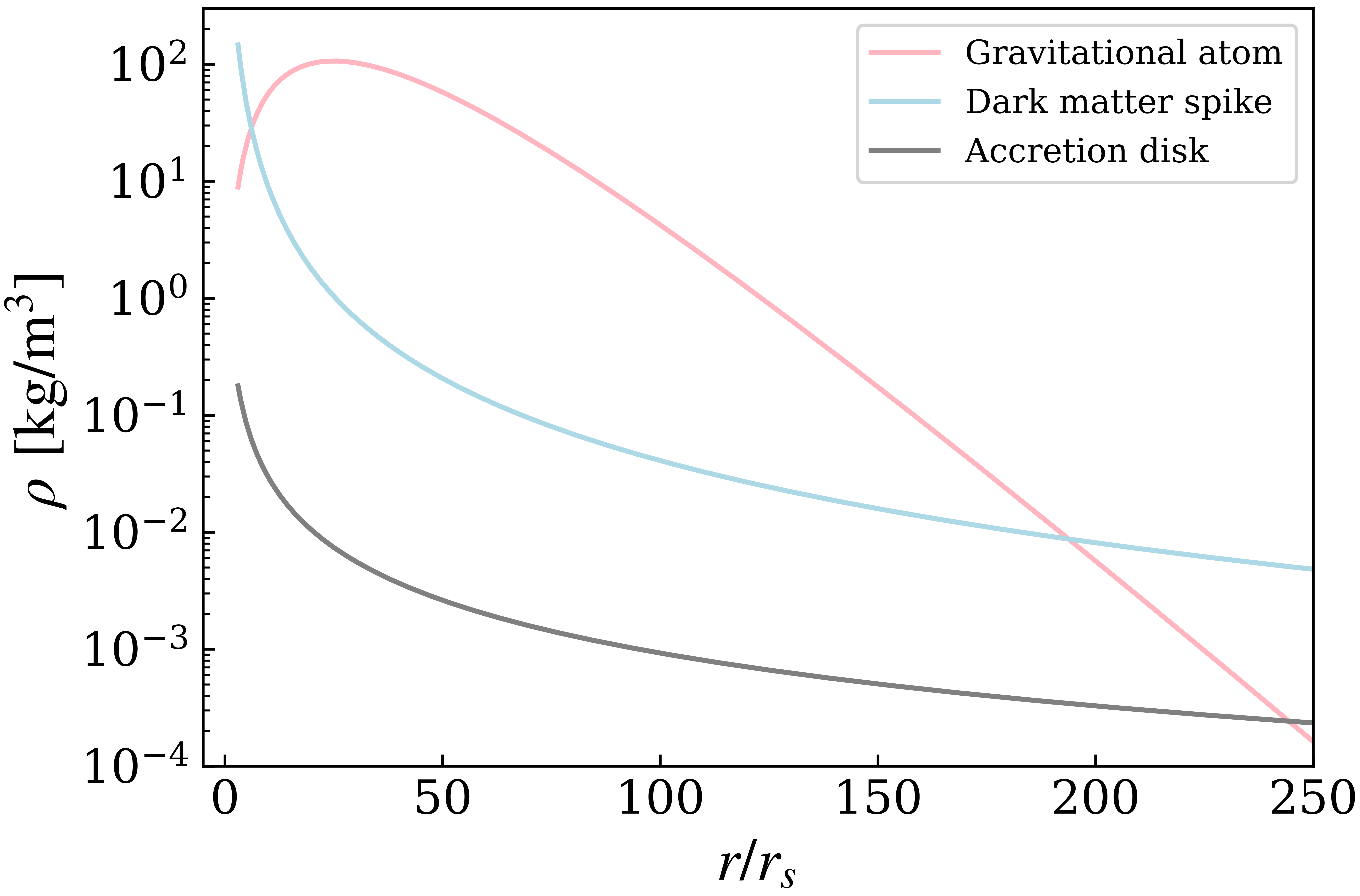
$$\rho(\vec{r}) = M_{\mathrm{c}} |\psi(\vec{r})|^2$$

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

Mass of cloud

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

What kind of densities?



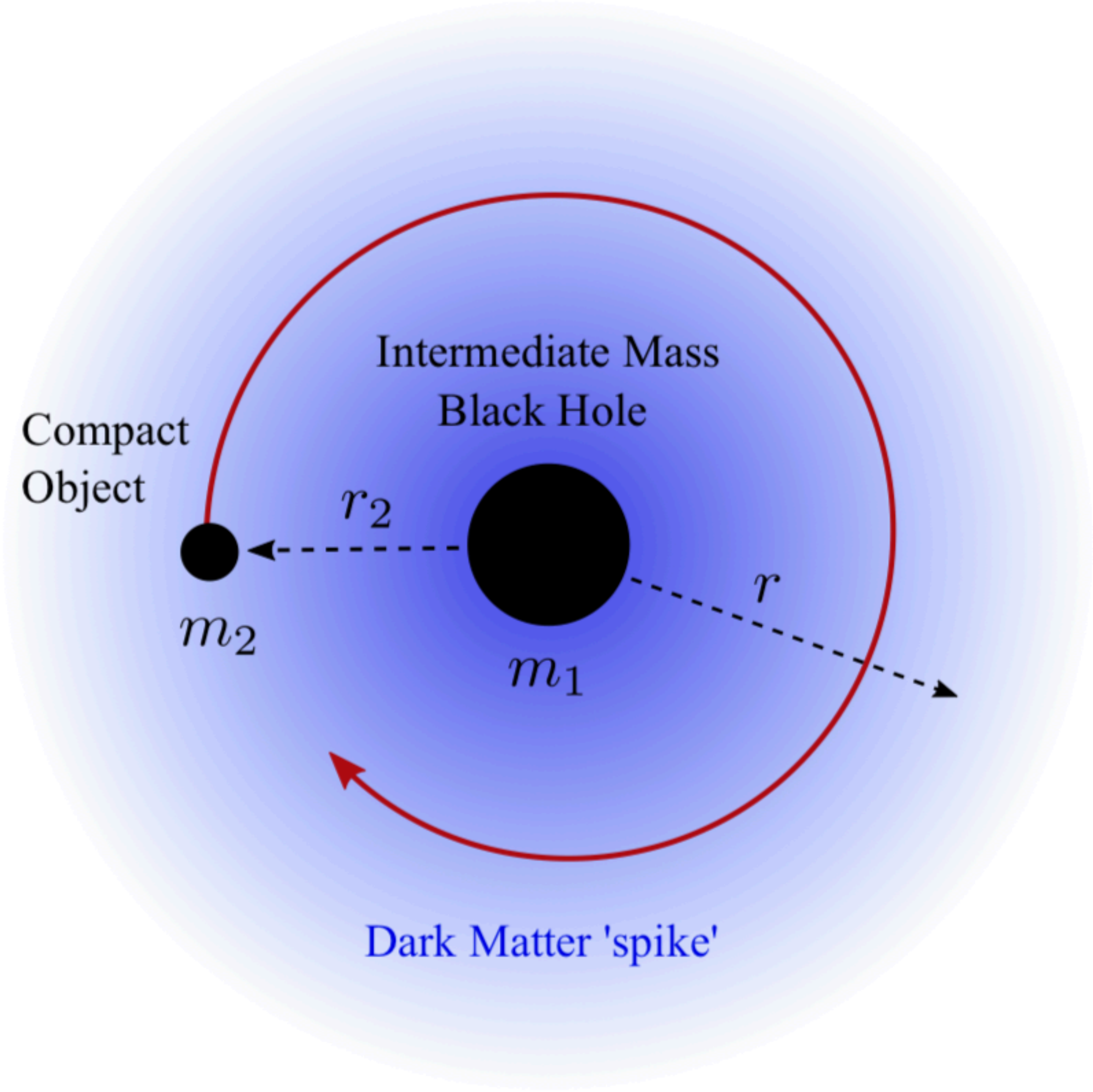
Form of energy losses

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

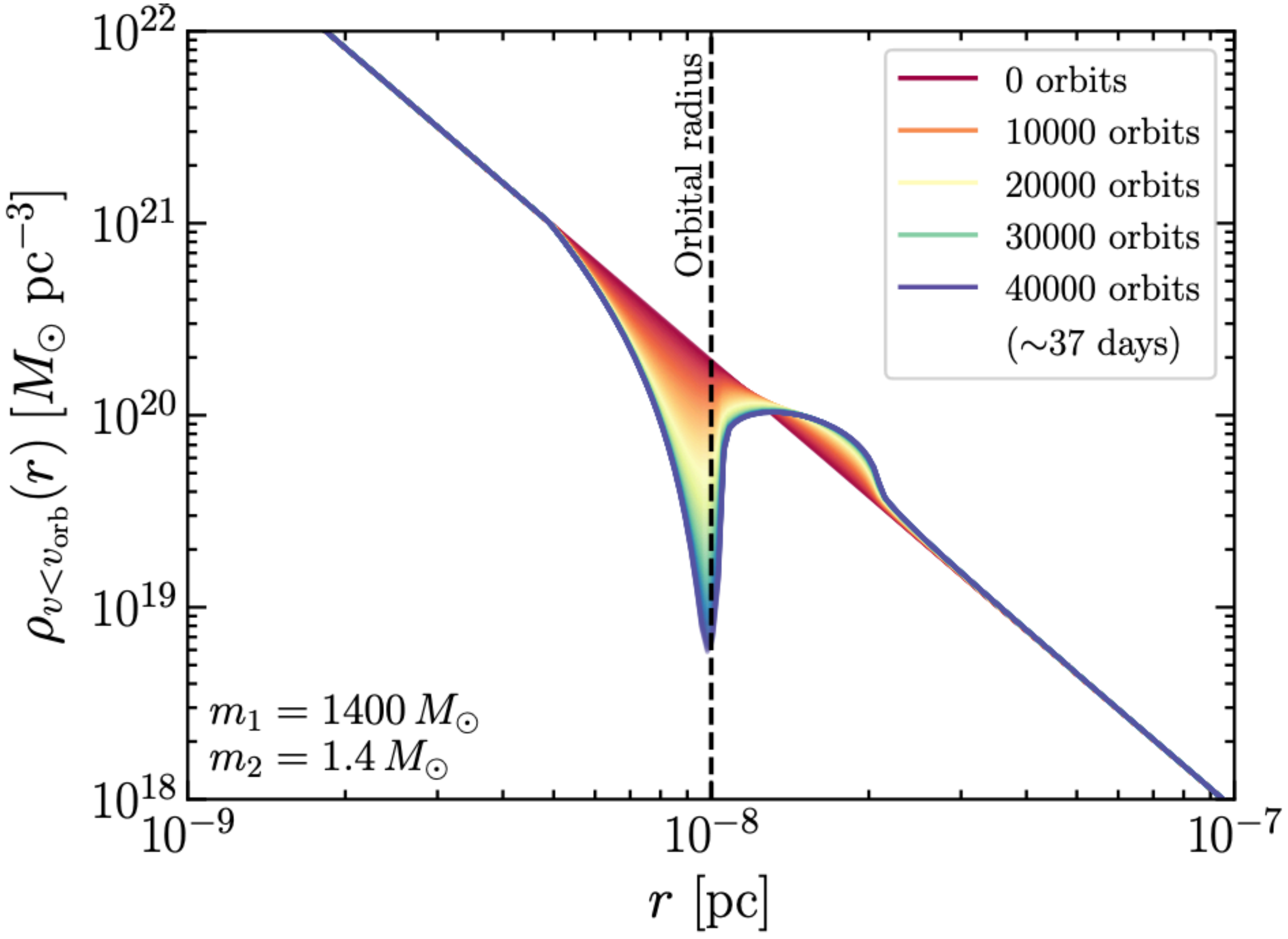
Dark dress	Accretion disk	Gravitational atom
$\dot{r}_{\rm env} = \dot{r}_{\rm DF}$ Dynamical friction according to Chandrasekhar formula plus feedback on spike with HaloFeedback (Kavanagh et al. 2020)	$\dot{r}_{\rm env} = \dot{r}_{\rm gas}$ Gas torques according to Type I migration, analytic prescription including Lindblad and corotation torques	$\dot{r}_{\rm env} = \dot{r}_{\rm ion} + \dot{r}_{\rm acc}$ Ionization (dynamical friction-like) and accretion of scalar field onto companion object

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

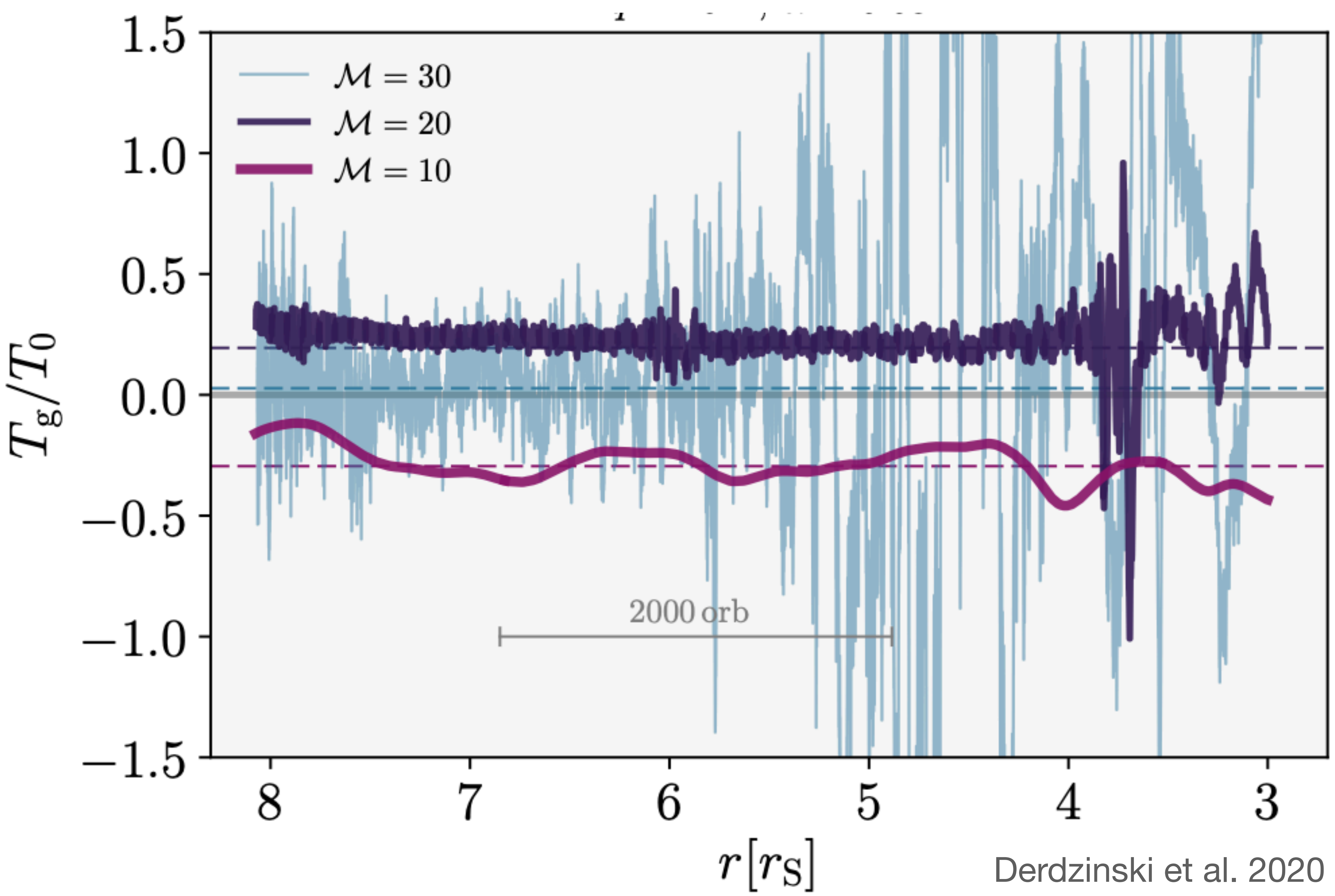


Kavanagh, Nichols, Bertone, Gaggero 2020

Gas torques

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

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



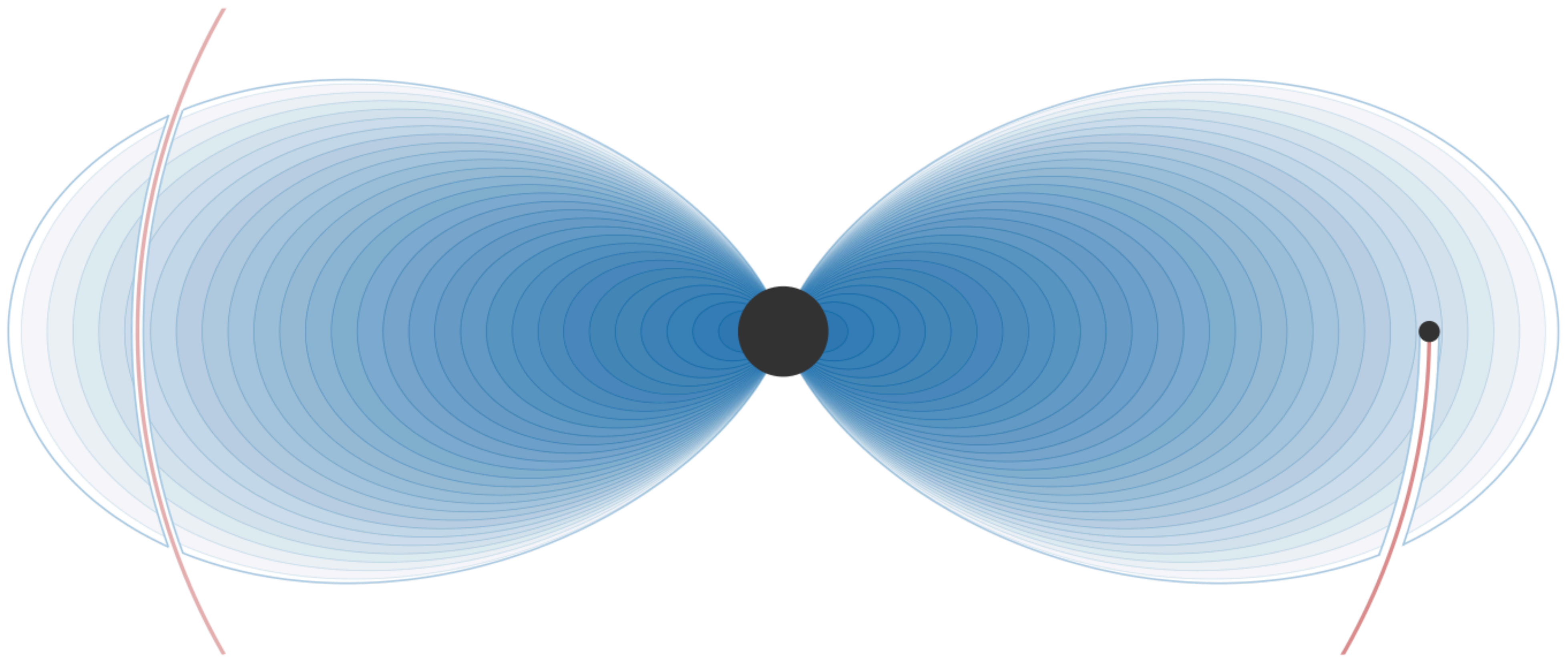
Derdzinski et al. 2020

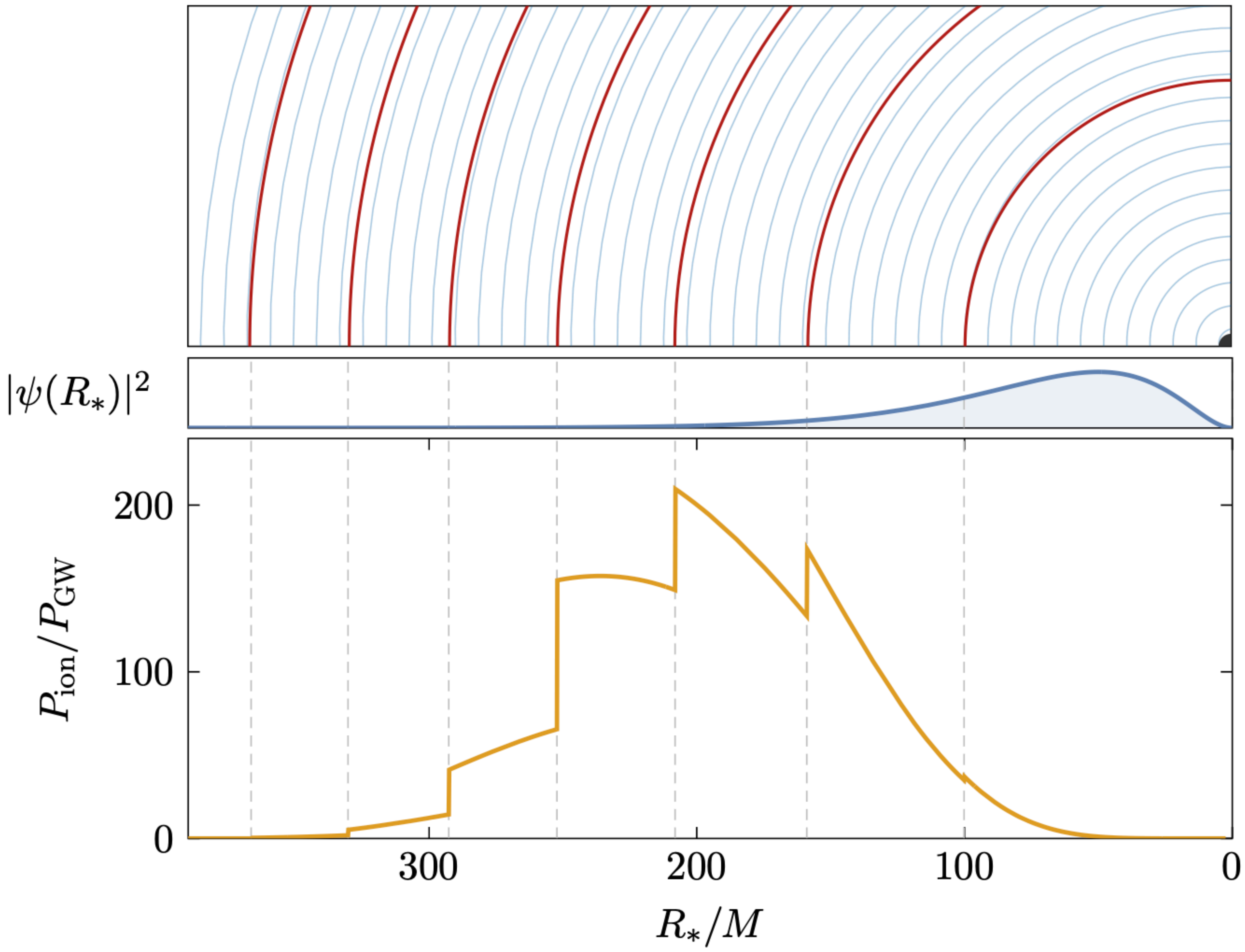
Assume gas in the disc is corotating with the companion object, which is orbiting in the plane of the disc.

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

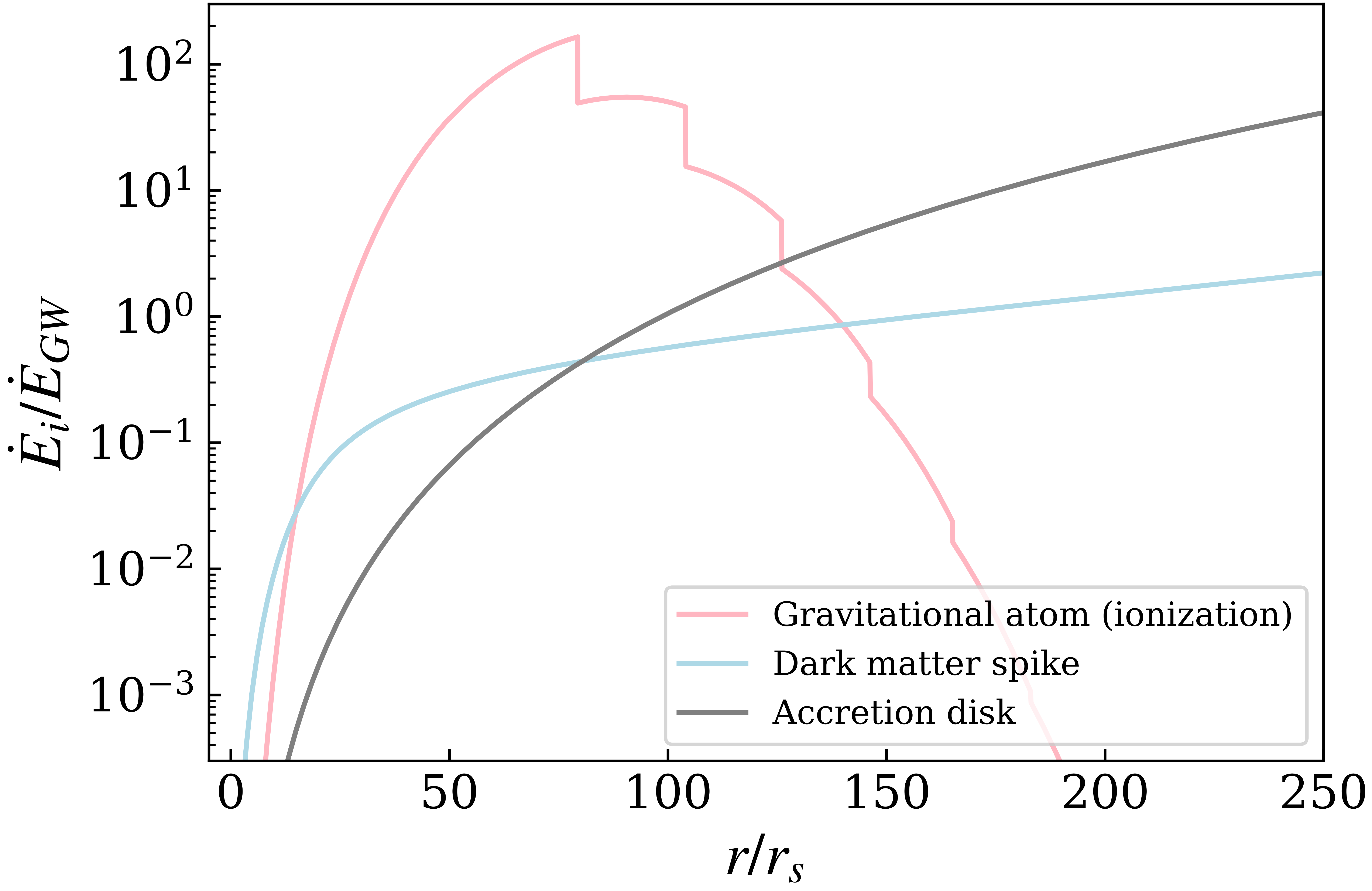




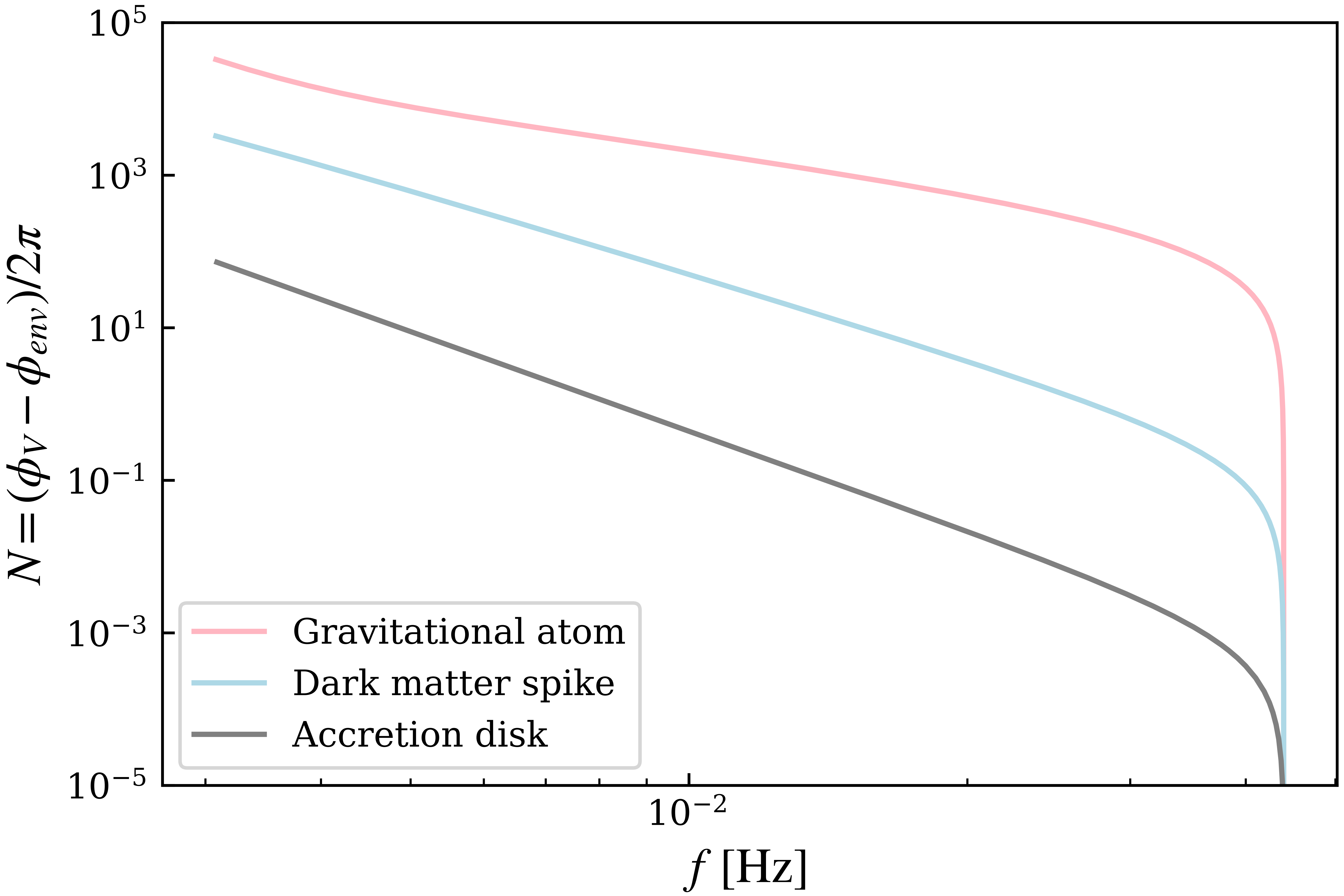
Perturber excites resonances in the cloud and it transitions from bound states to unbound states as the orbital frequency of the perturber hits the frequency of the energy difference between states

Baumann, Bertone, Stout, Tomaselli 2021

Energy losses



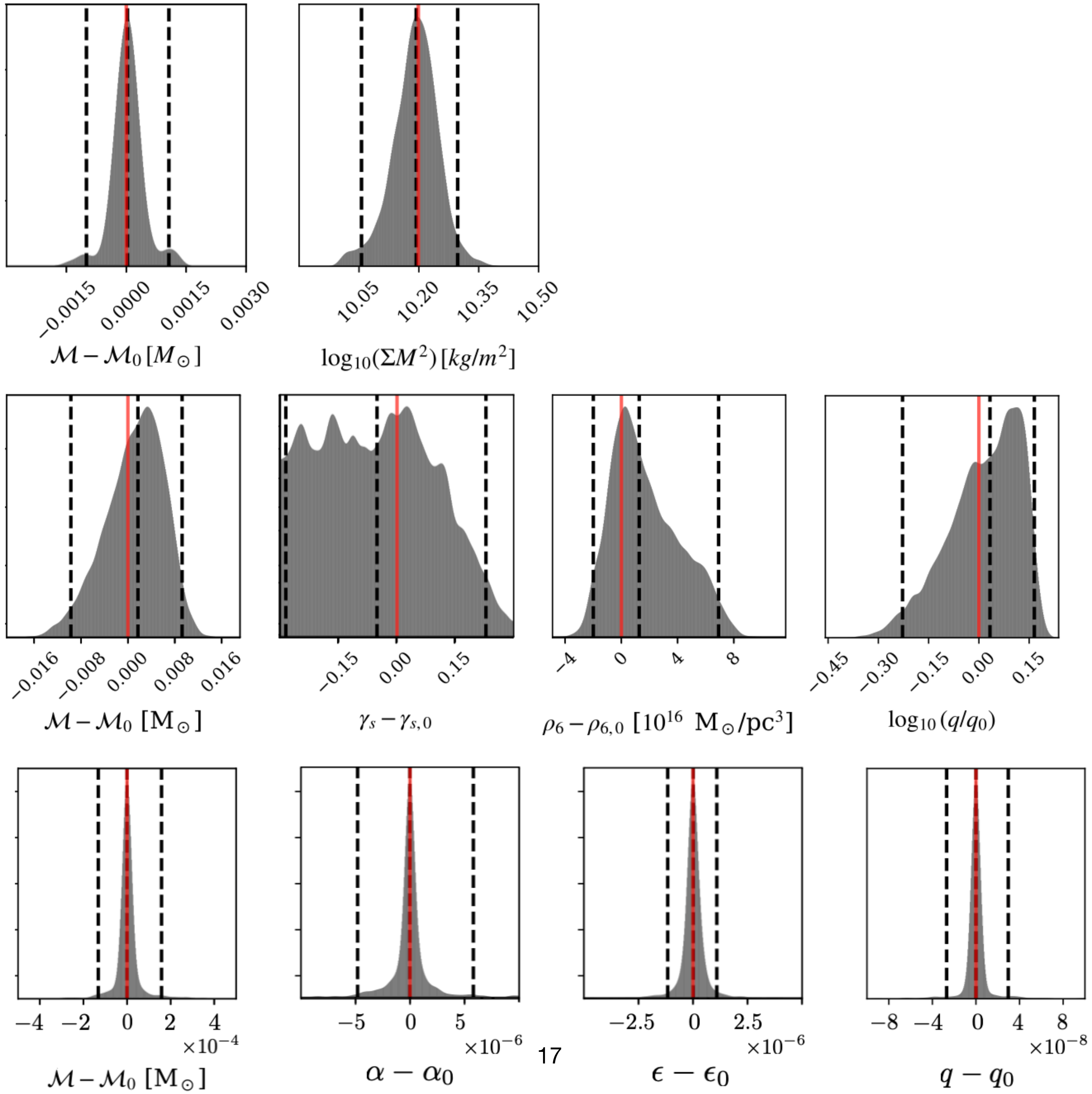
Dephasing



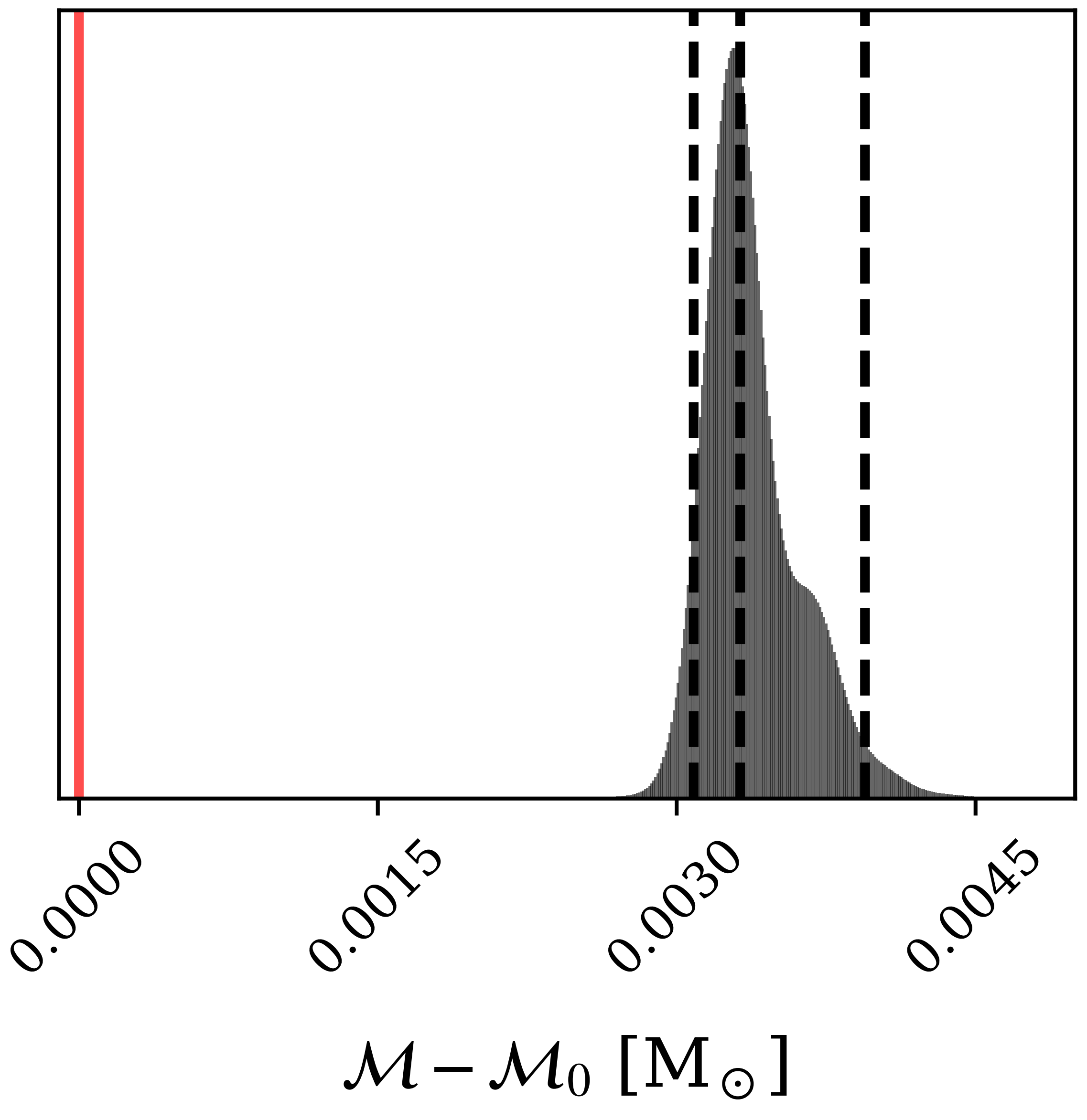
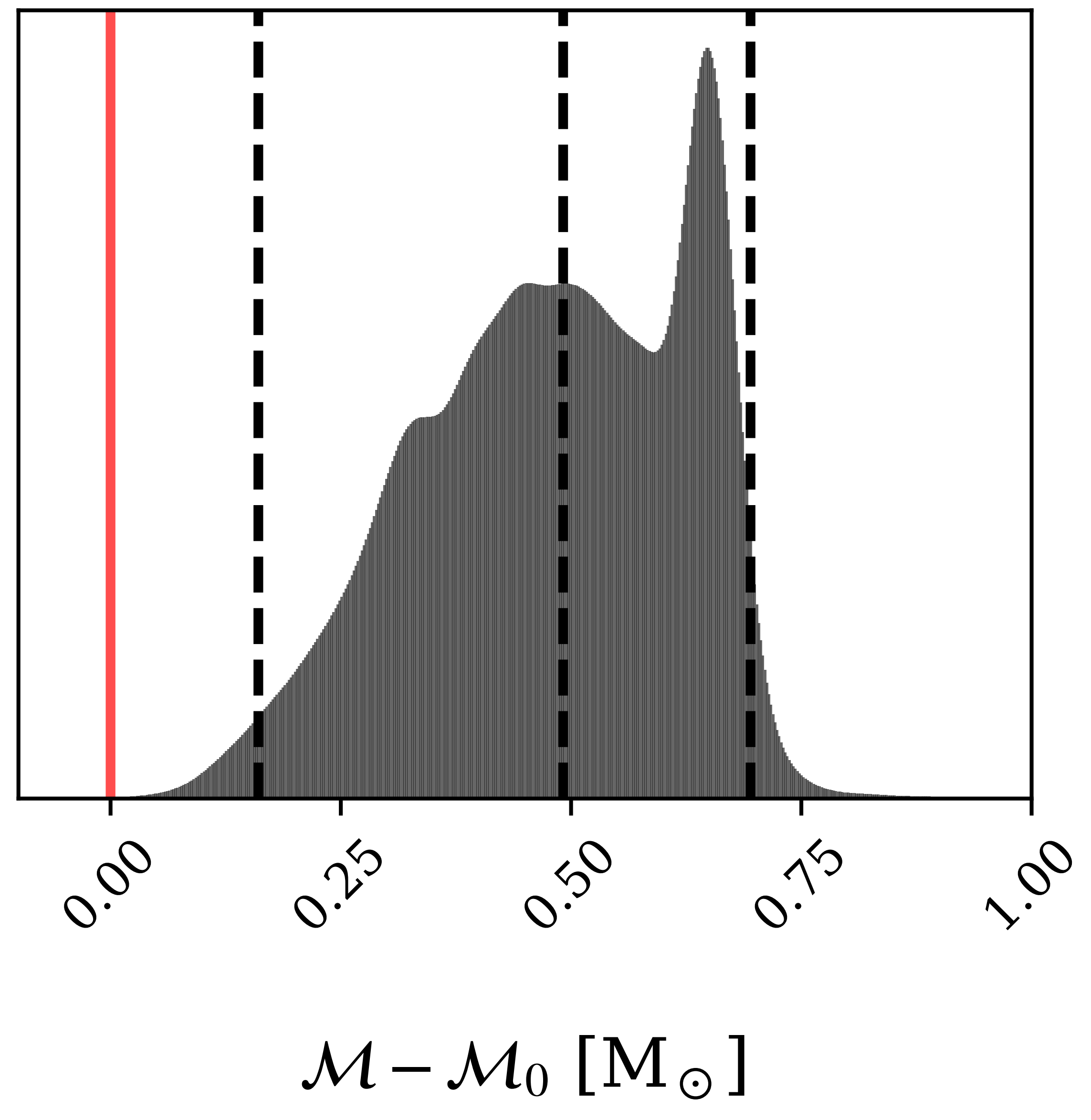
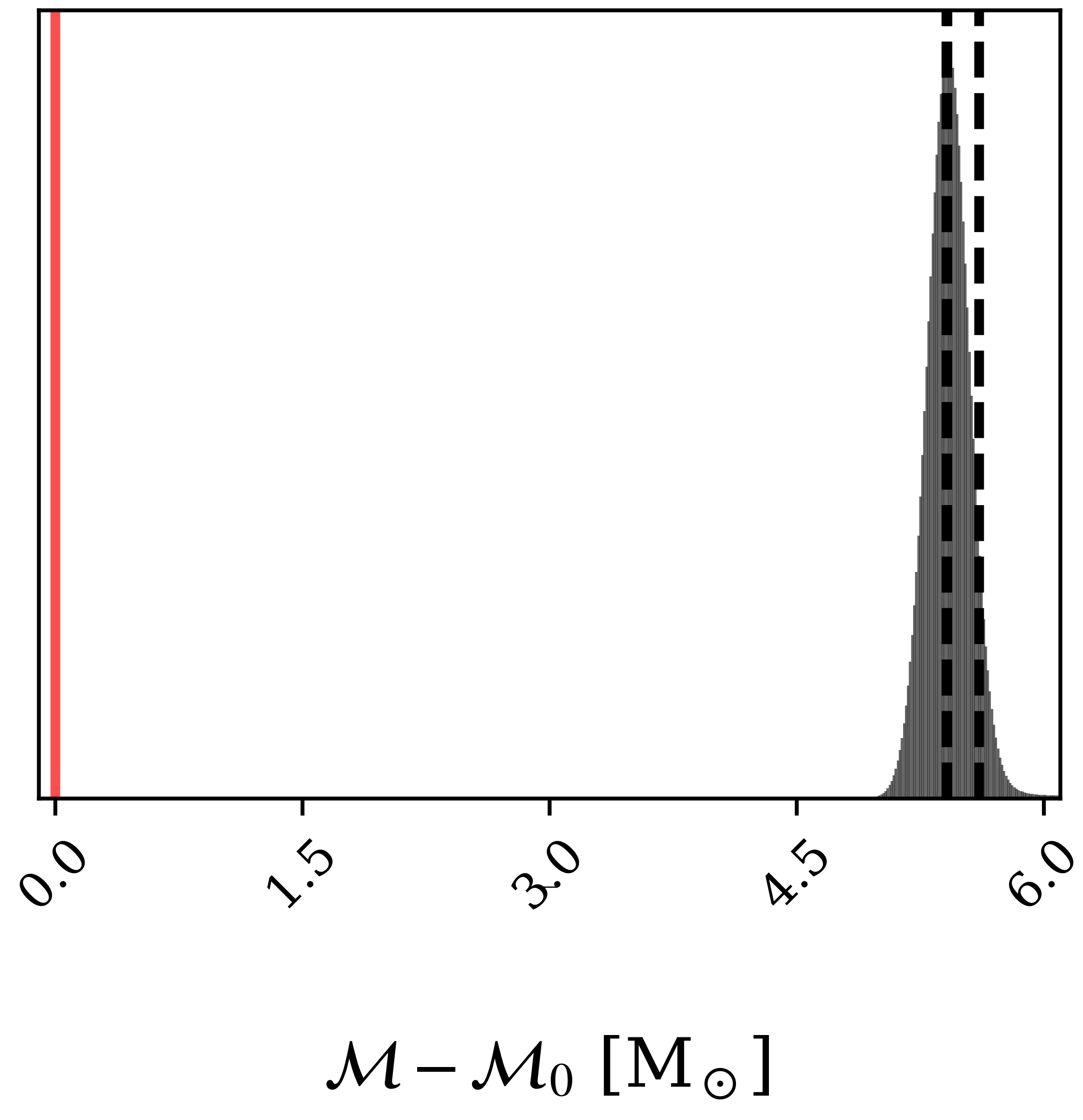
10^5
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
$N = (\phi_V - \phi_{env})/2\pi$
Gravitational atom
Dark matter spike
Accretion disk
10^{-2}
f [Hz]

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

Parameter estimation with correct model



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>
</td></tr>
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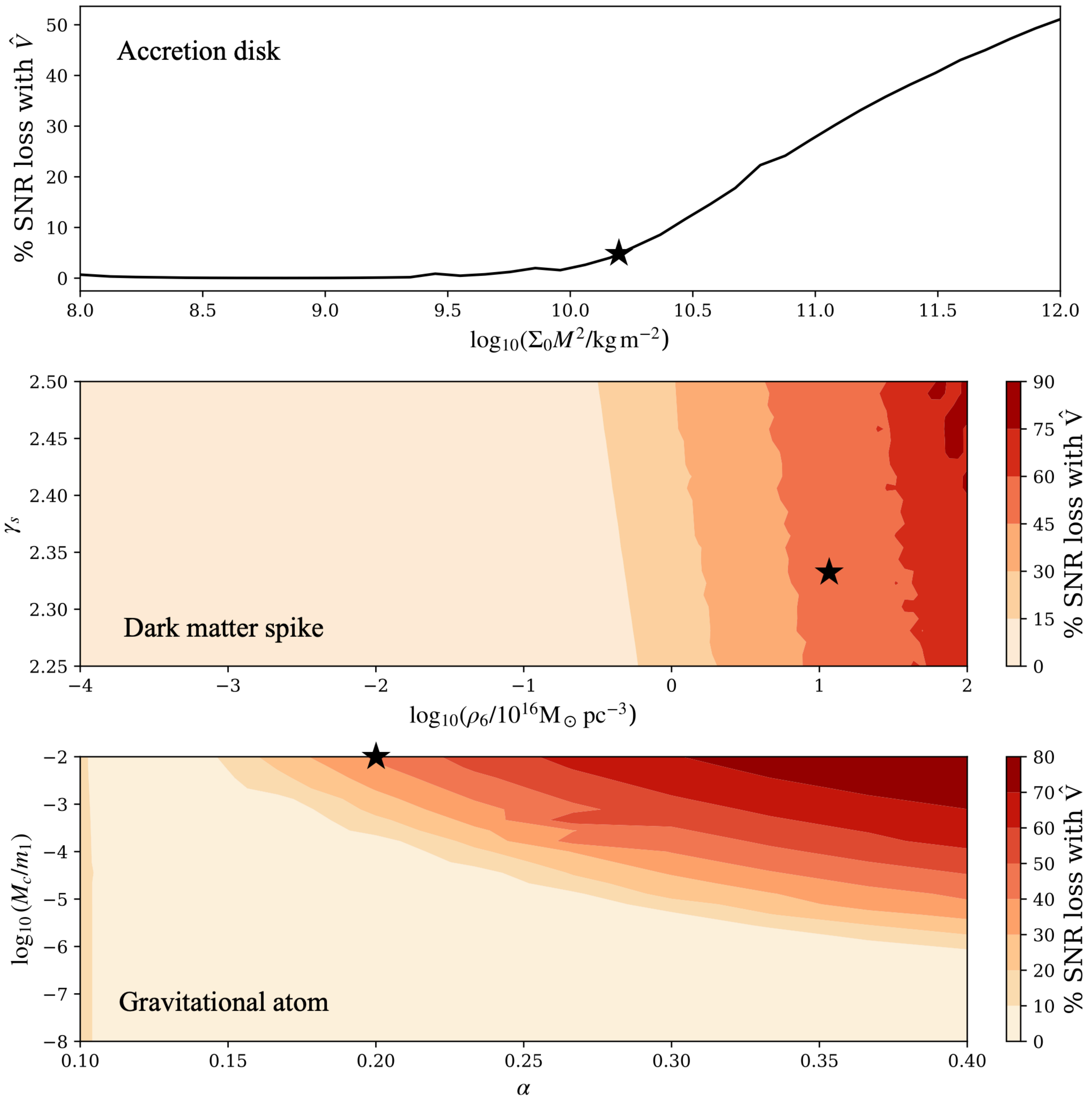
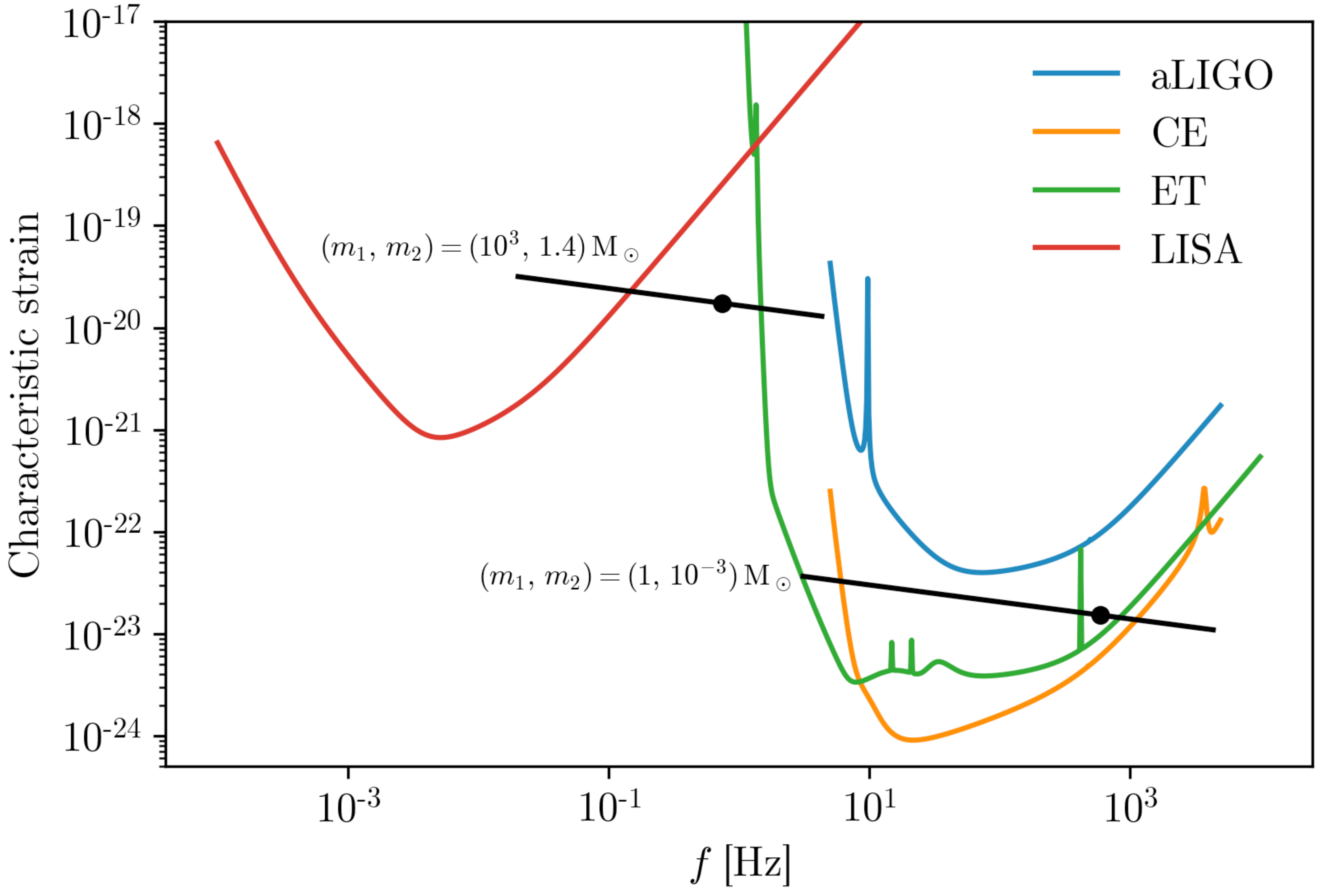
SNR loss: biased PE or miss signal entirely

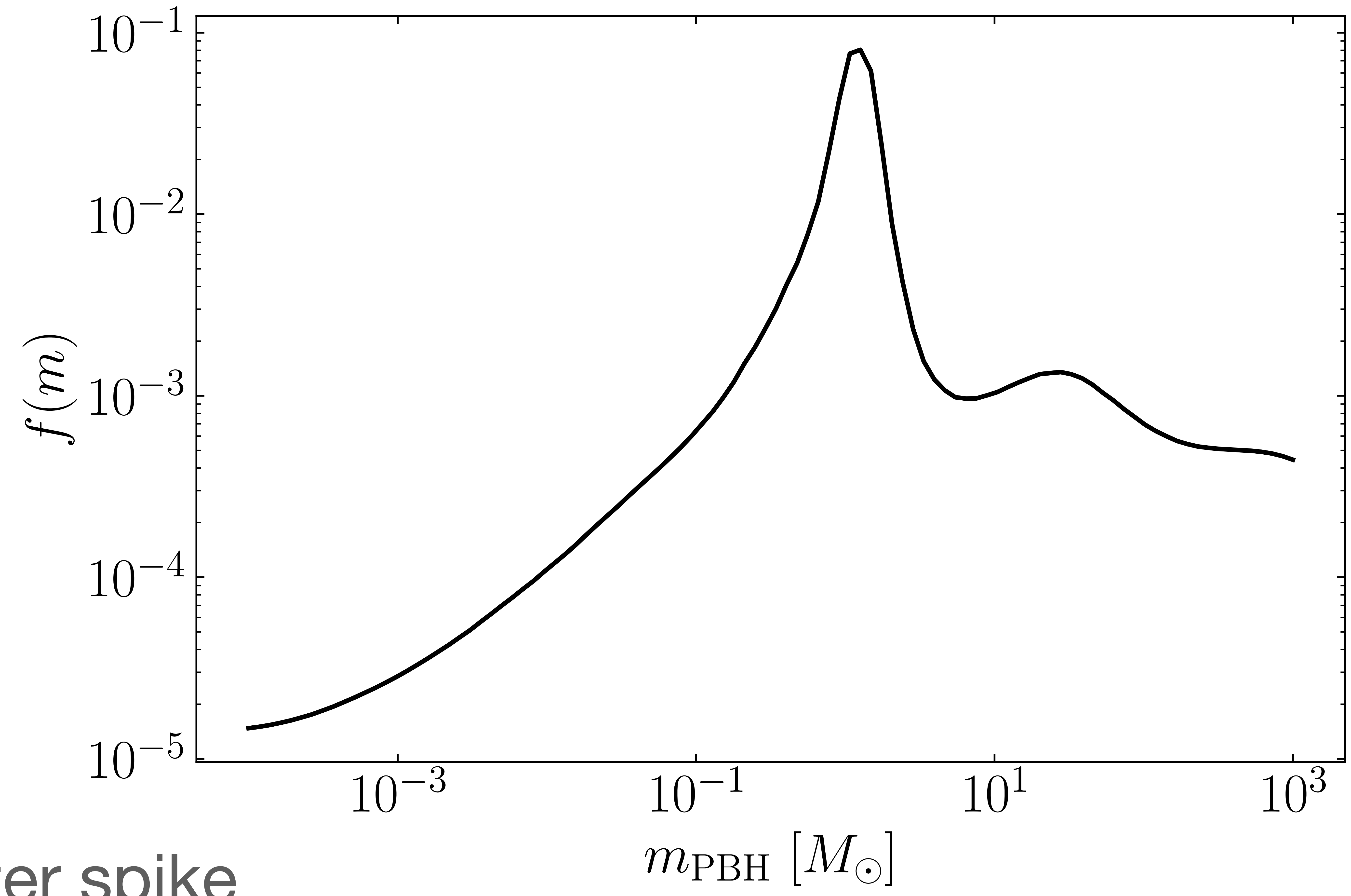


Bayesian model comparison shows confident preference for correct model over any other environment

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

What about future ground-based detectors?



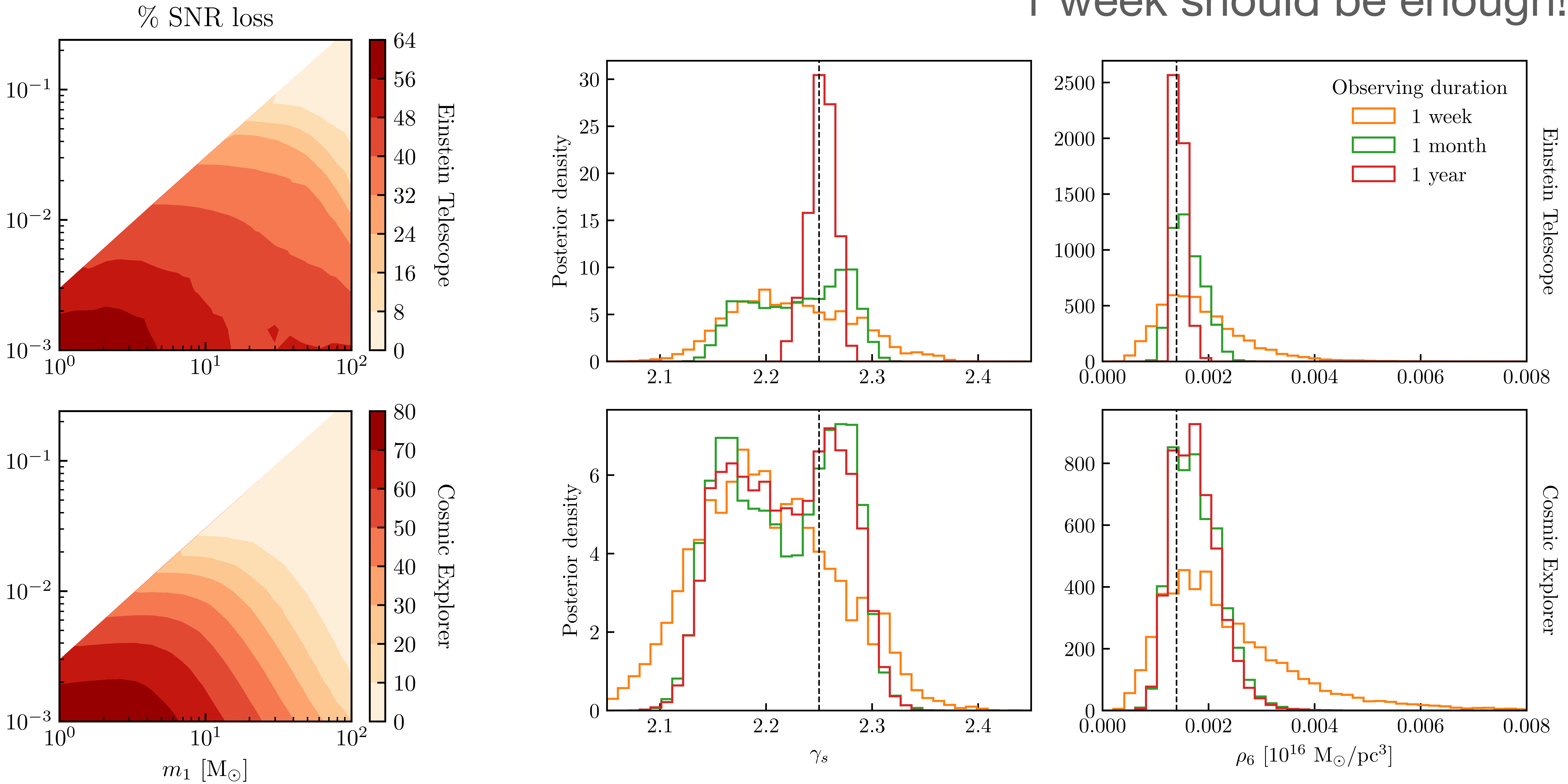


IMRI PBHs must have a dark matter spike

Cole, Coogan, Kavanagh, Bertone 2022

What about future ground-based detectors?

1 week should be enough!



Cole, Coogan, Kavanagh, Bertone 2022

Conclusions

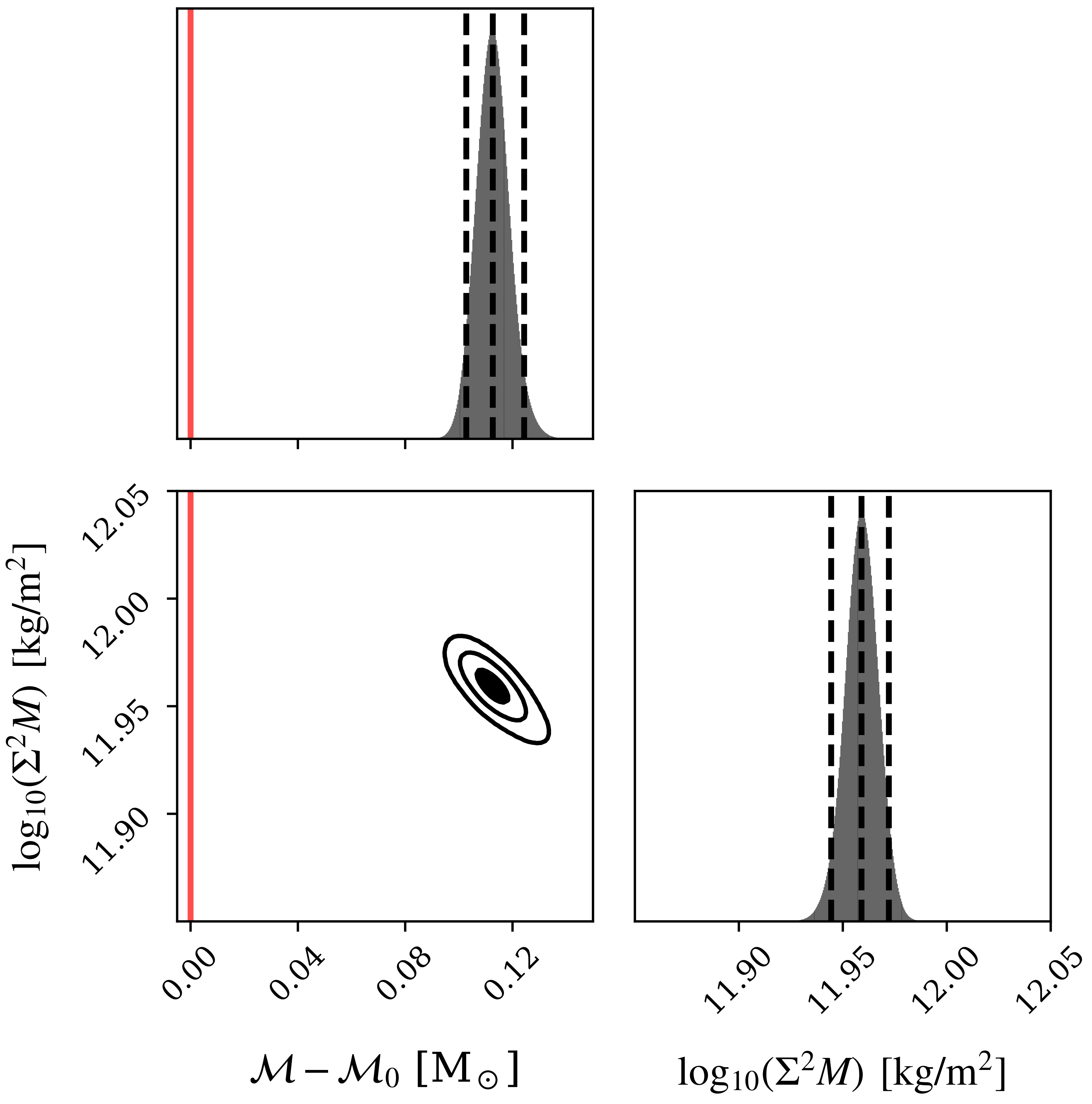
- We can measure the properties of environments around binaries with future GW detectors
- We have an opportunity to learn about the nature of dark matter from IMRI gravitational waveforms
- We can distinguish between environments and avoid confusion with, for example, accretion disks
- Biased parameter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

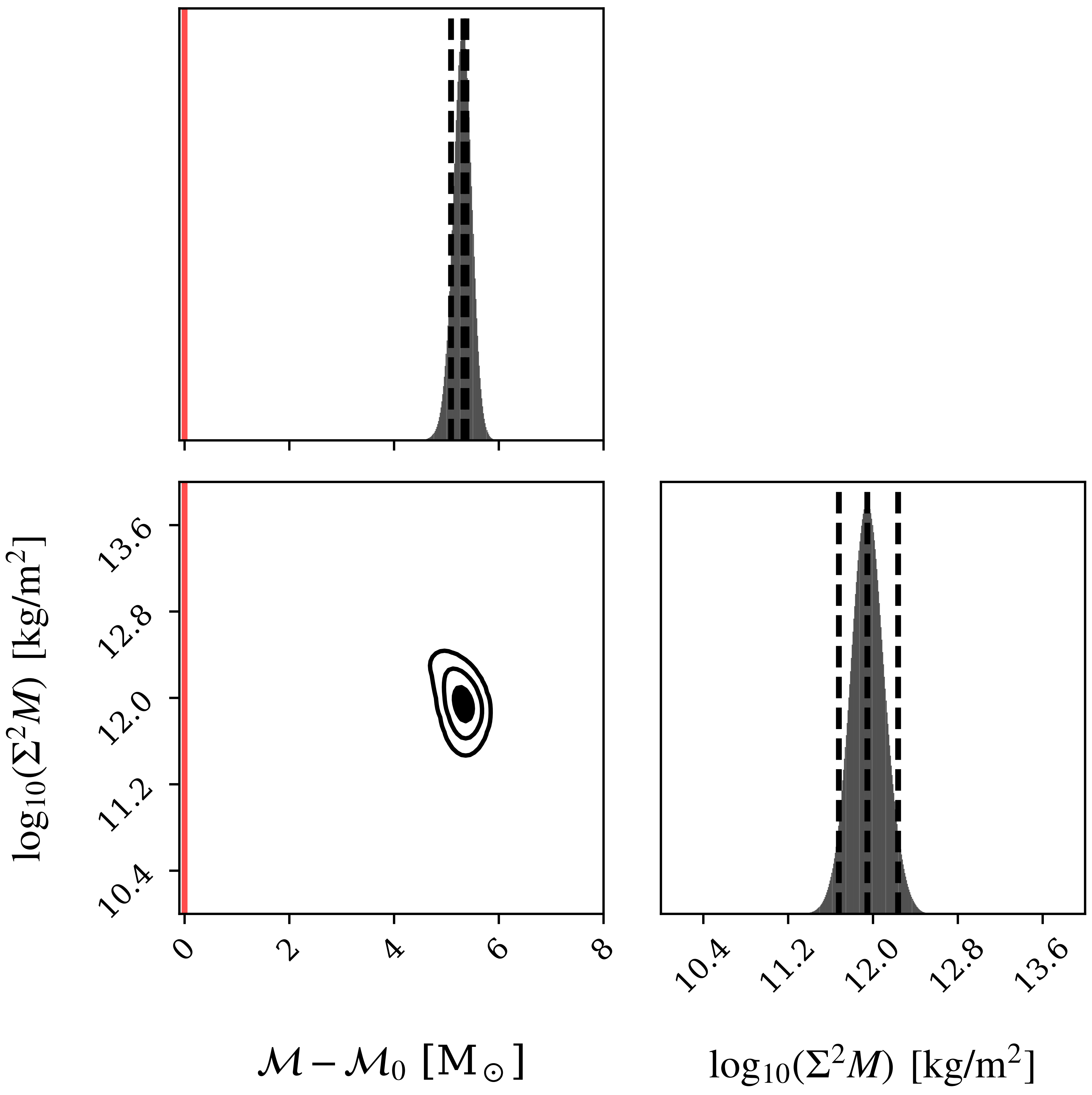
Future work:

- More accurate waveforms required
- Include for example eccentricity, spins…
- Go to higher dimensions in parameter estimation to check for degeneracies with extrinsic parameters

Thank you for listening!

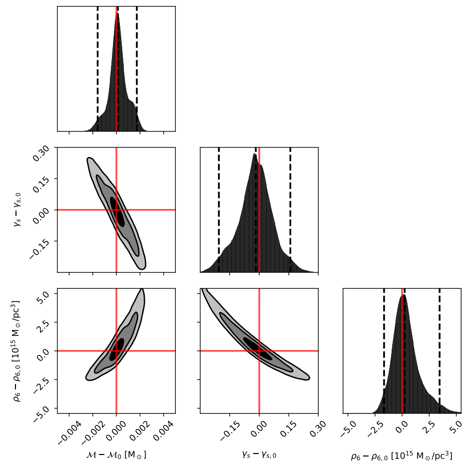
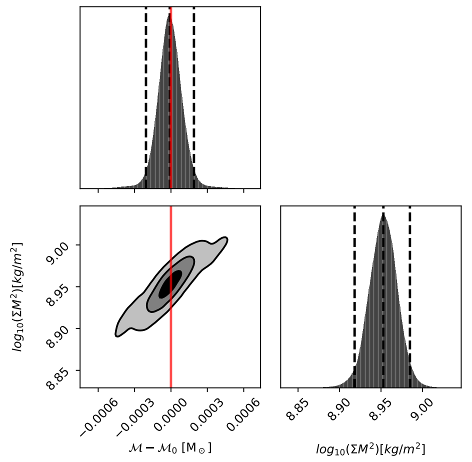
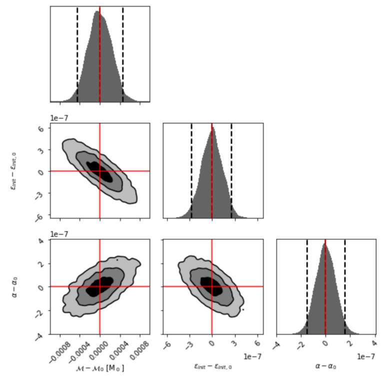
Fit dark dress and GA with accretion disk



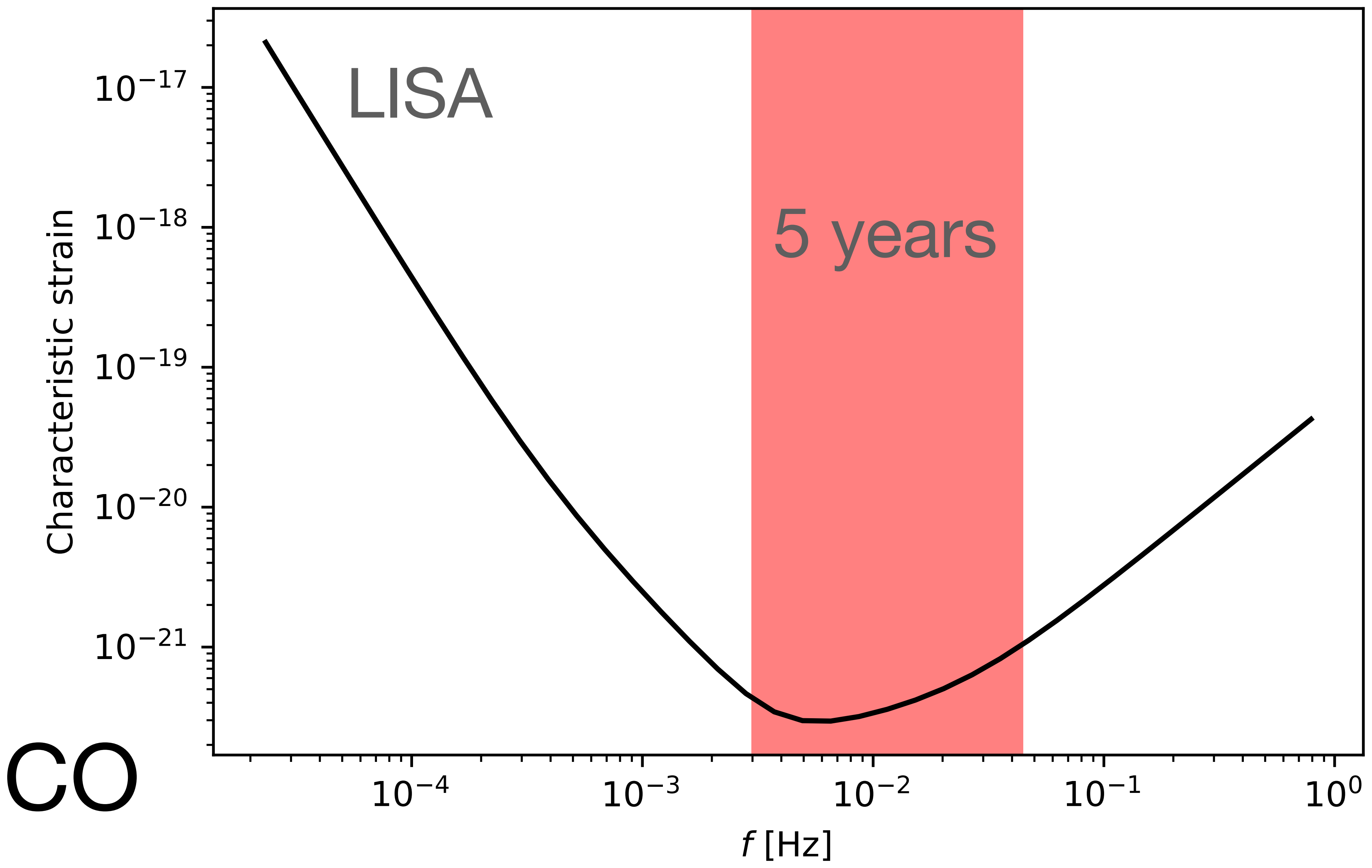


Model preference

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

	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

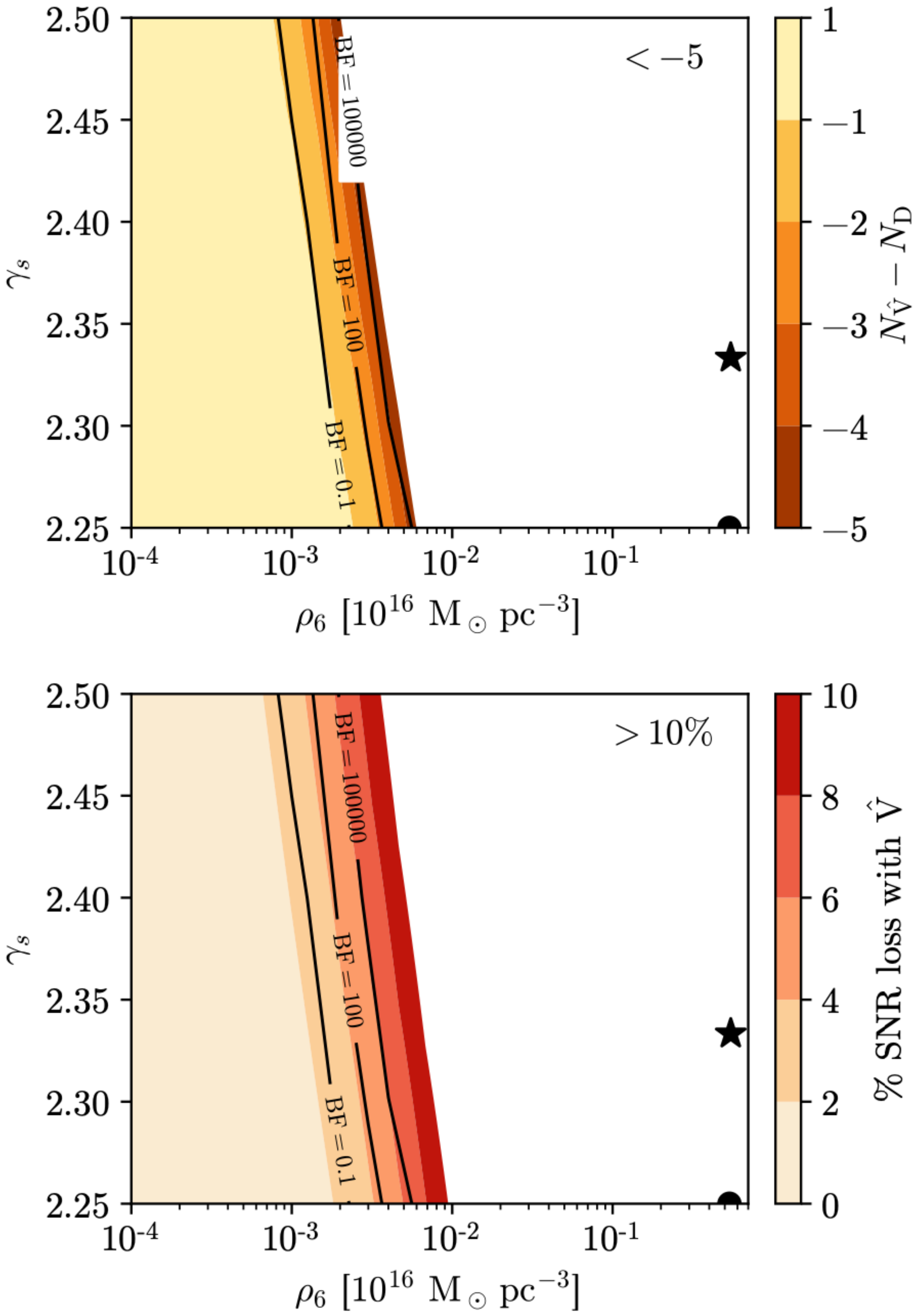


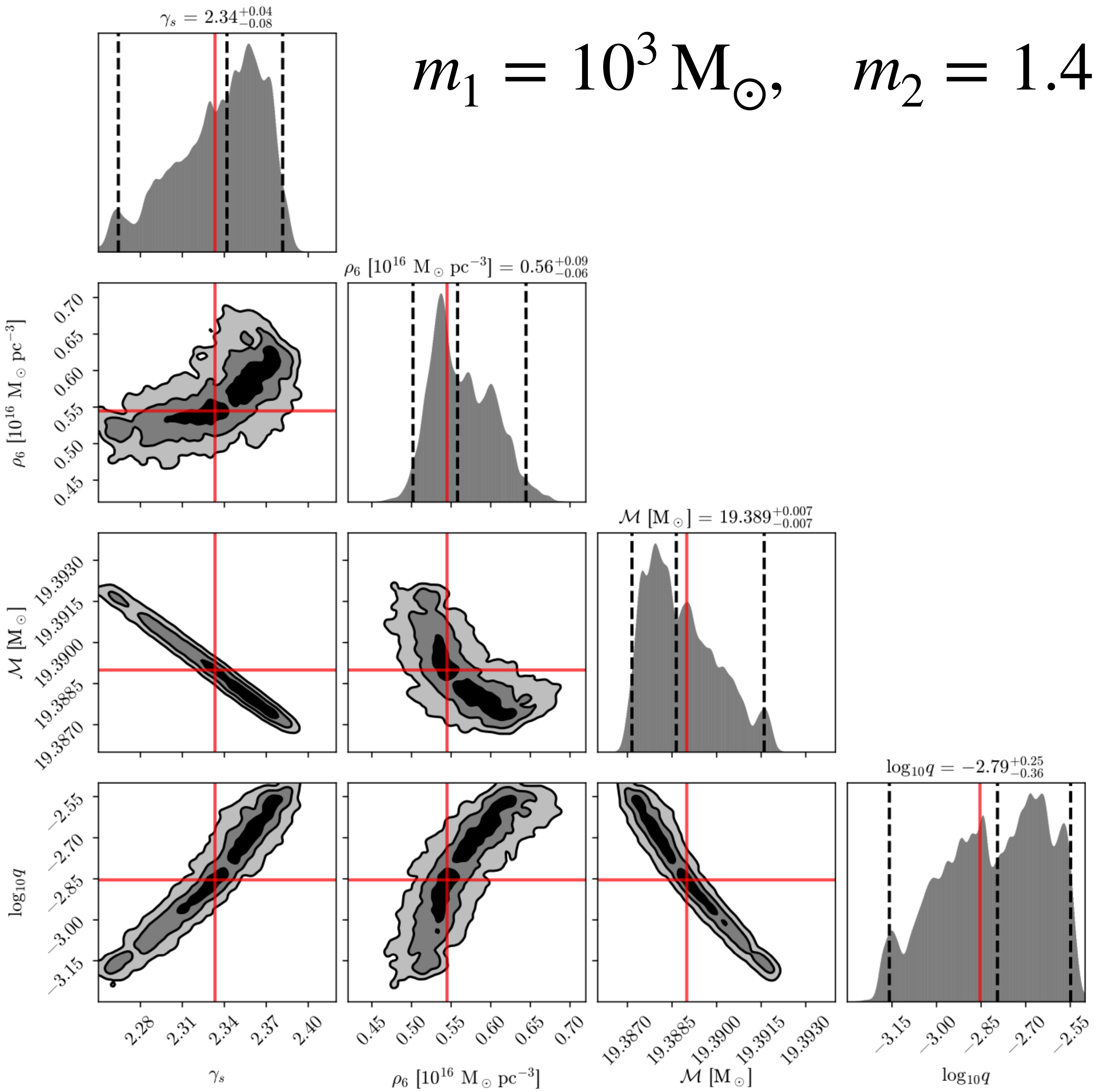
$$m_1 = 10^5\,\mathrm{M}_\odot, \quad m_2 = 10\,\mathrm{M}_\odot \qquad \mathscr{M}_c \approx 400\,\mathrm{M}_\odot$$

- 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	$\Sigma_0 M^2 = 9 \times 10^8\,\mathrm{kg\,m}^{-2}$	$M_c = \dfrac{m_1}{100}$ $\alpha = 0.2$

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



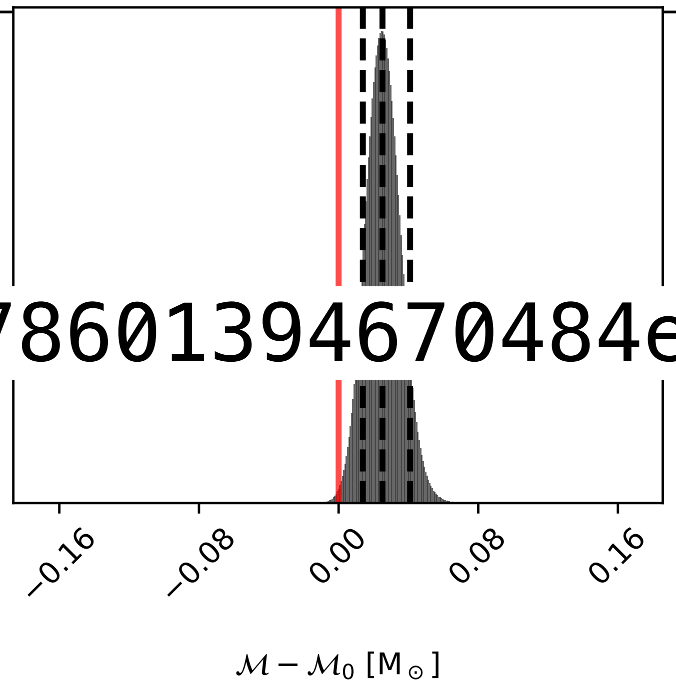
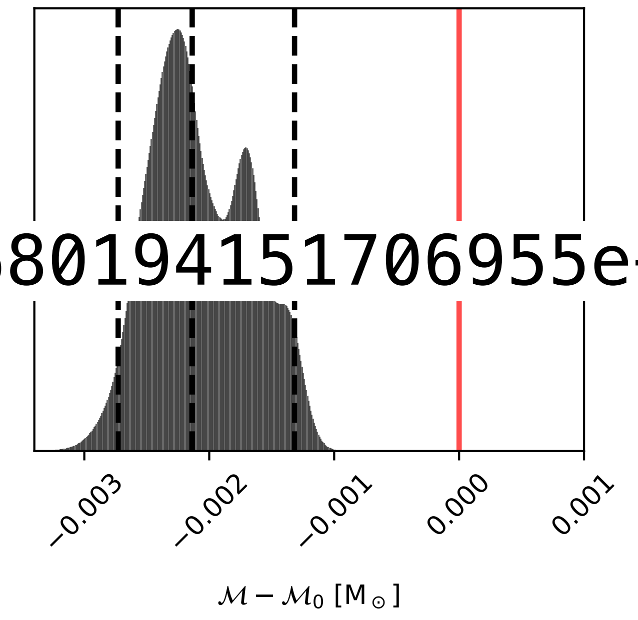
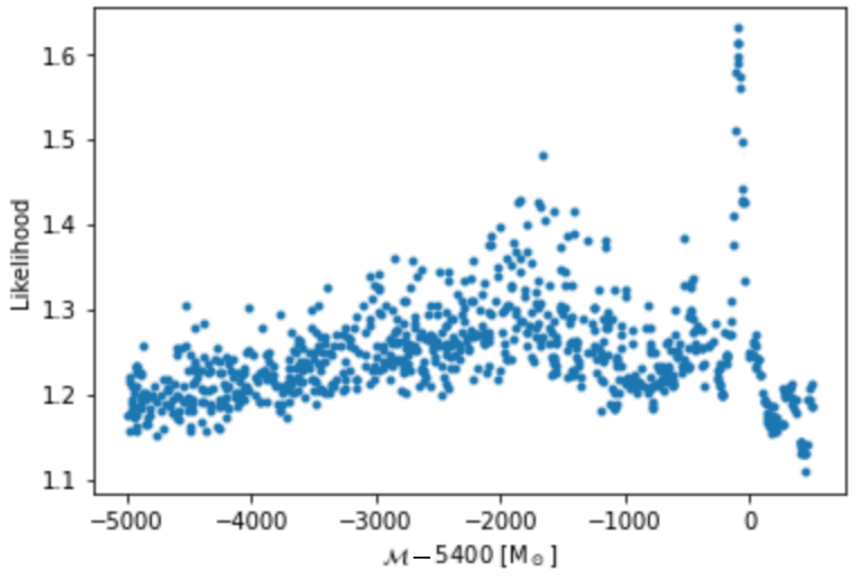
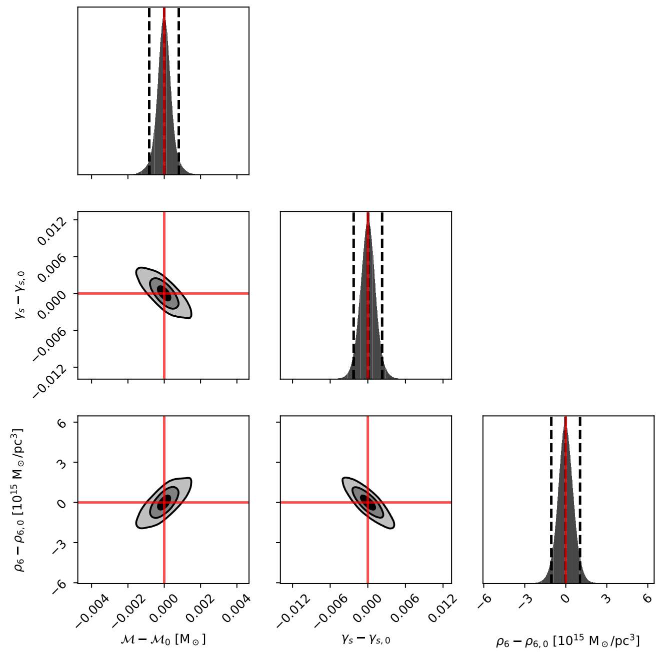
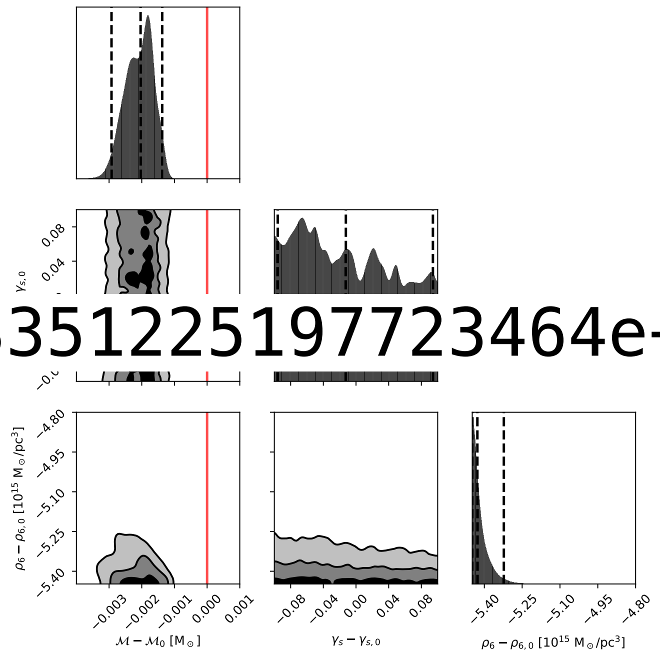
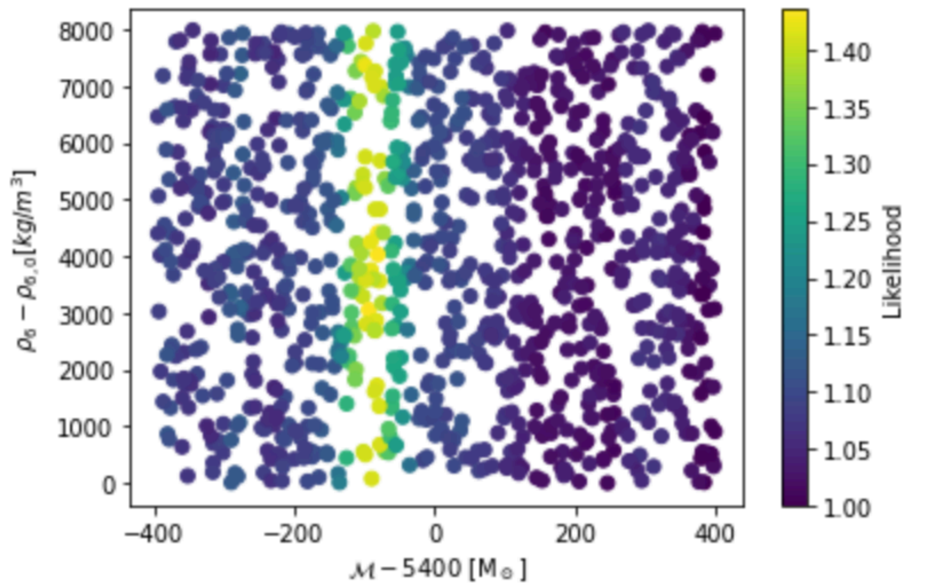
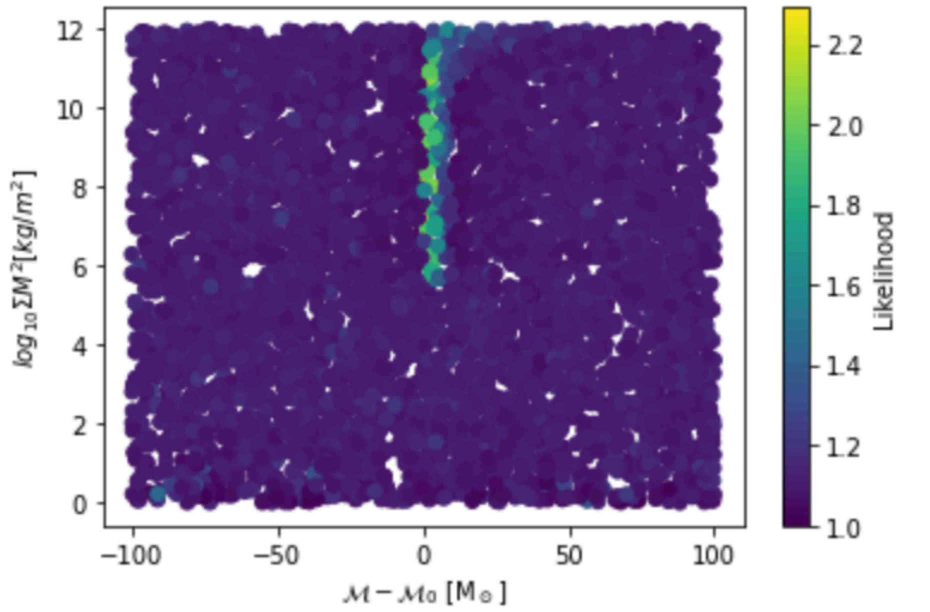
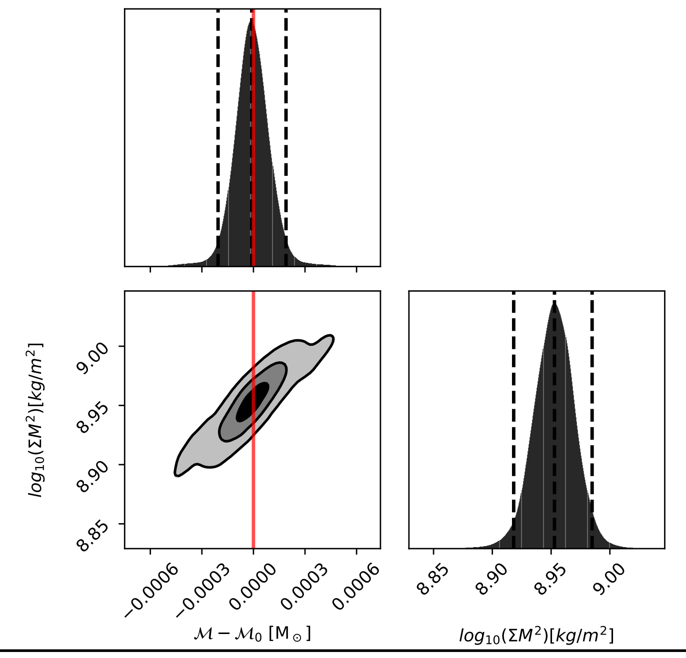
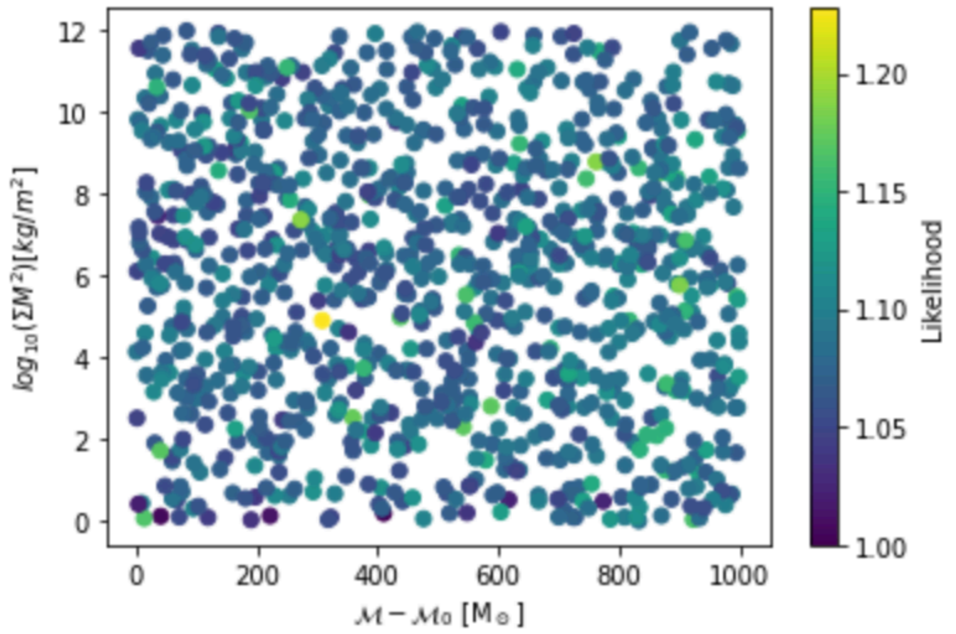
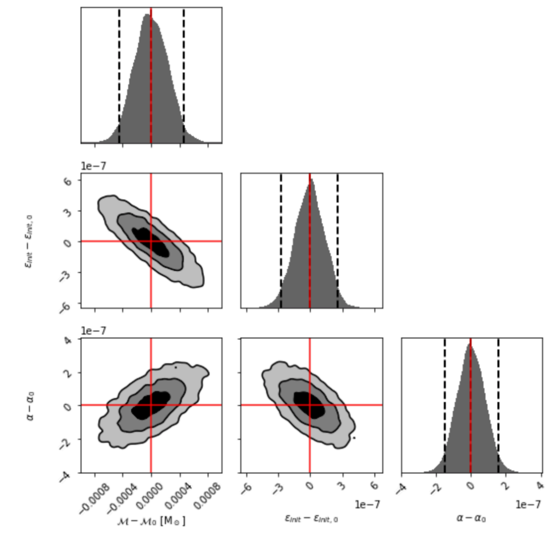


$$m_1 = 10^3\,\mathrm{M}_\odot, \quad m_2 = 1.4\,\mathrm{M}_\odot$$

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				
Dark dress template				
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

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

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