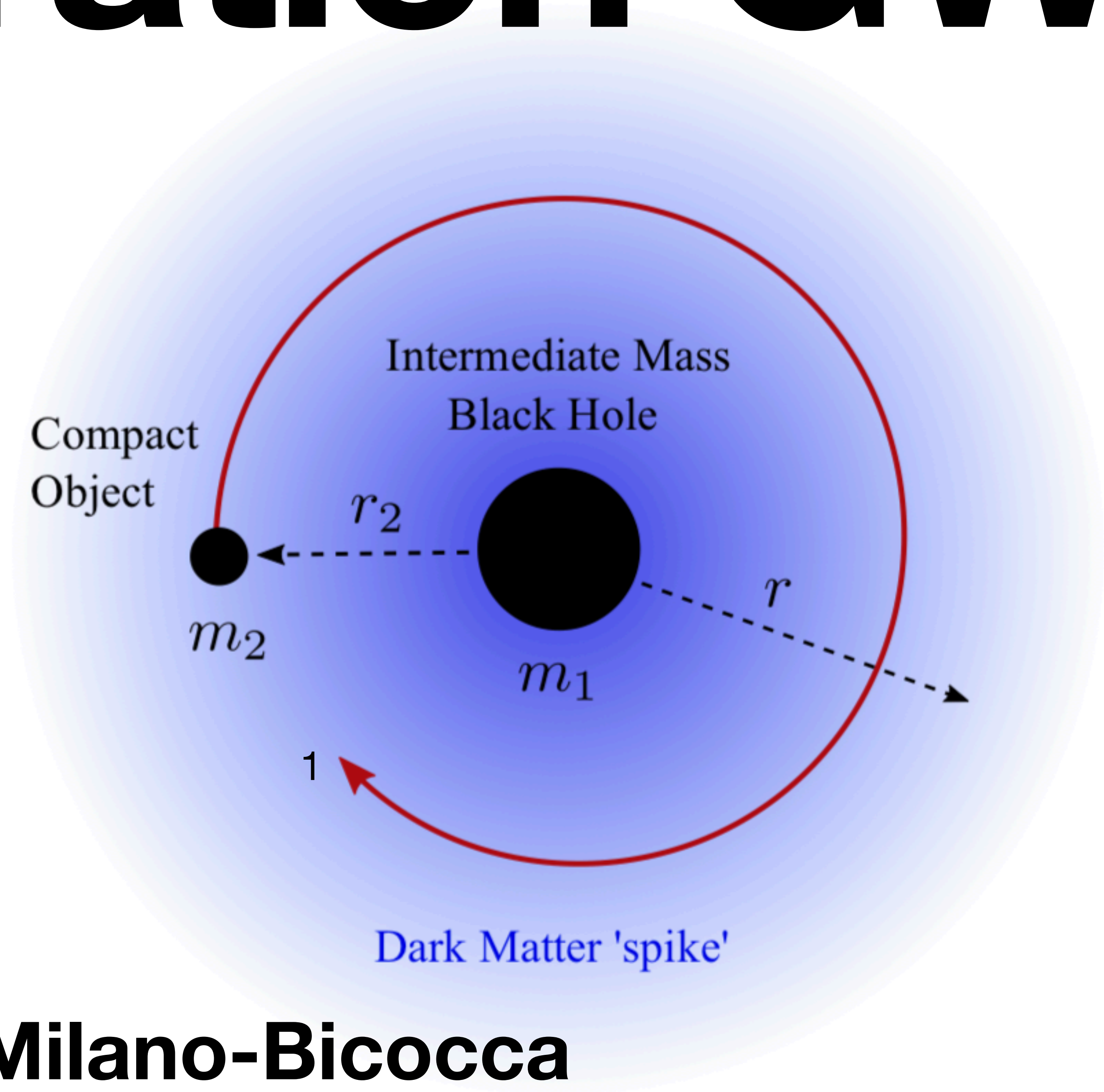
Searching for dark matter with long duration GW signals



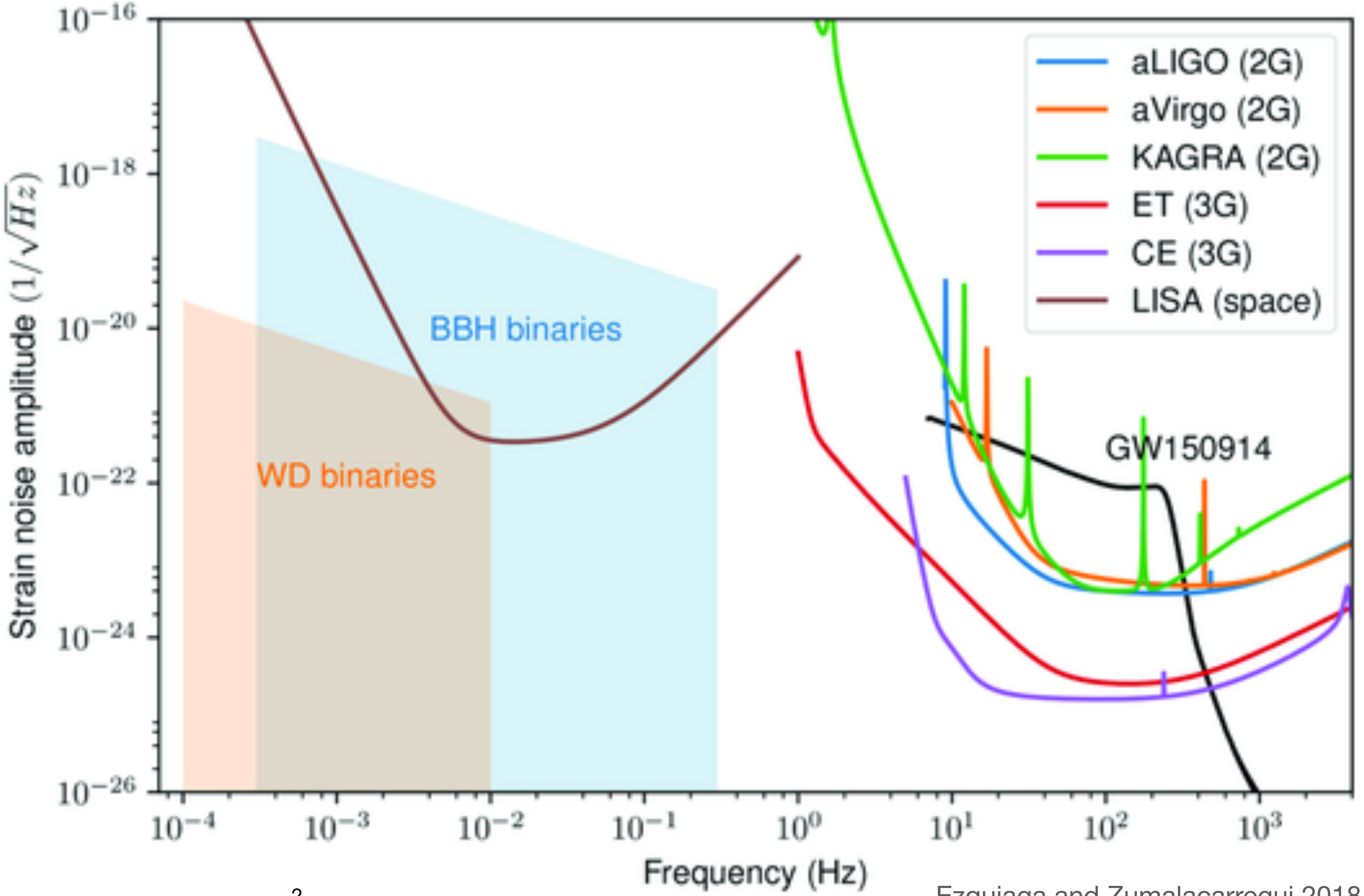
Philippa (Pippa) Cole, University of Milano-Bicocca

Based on *Phys.Rev.D* 107 (2023) 8, 083006 arXiv:2207.07576 [astro-ph.CO] with Adam Coogan, Bradley Kavanagh and Gianfranco Bertone.

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

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

↓

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

Frequency evolution

↗

Phase evolution

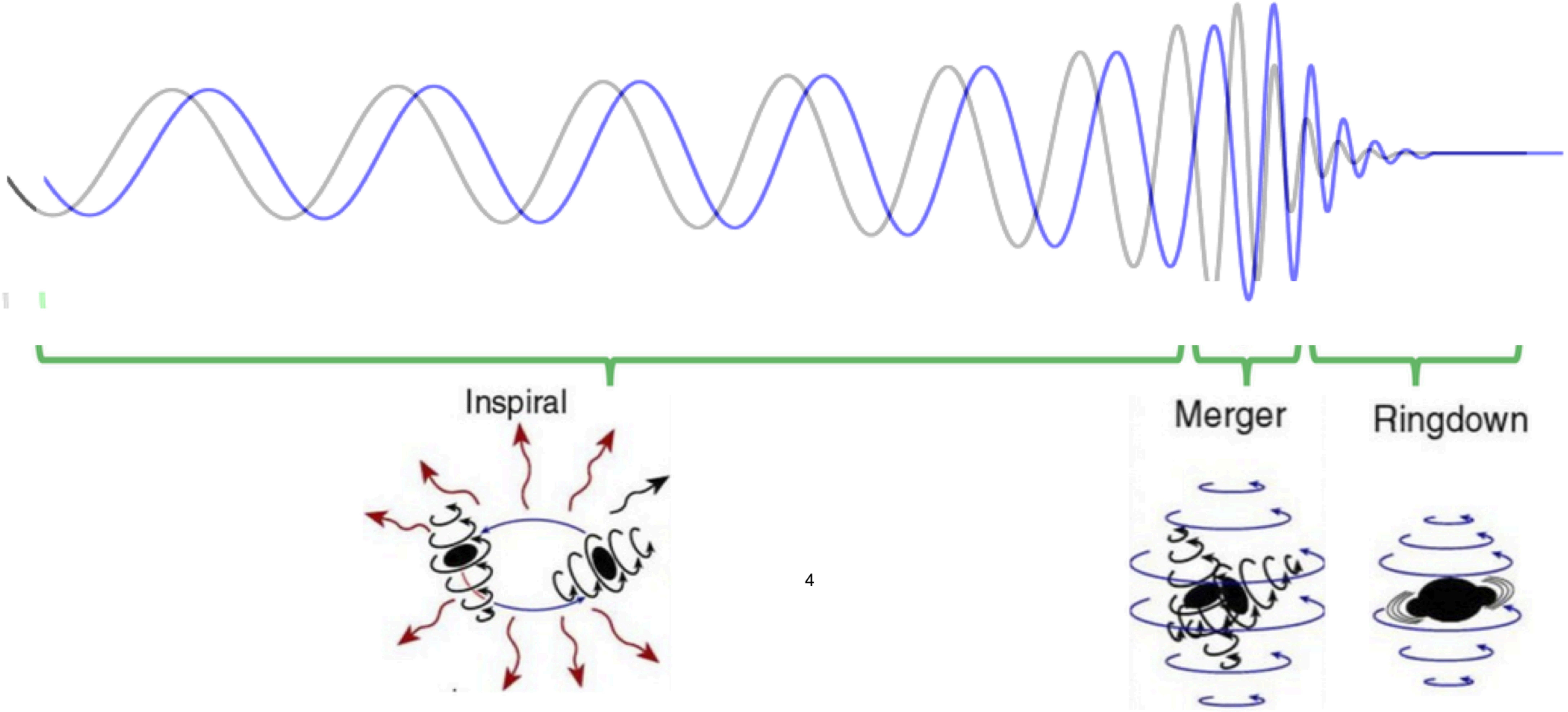
$$\Phi(f) = \int_f^{f_{\mathrm{ISCO}}} \frac{\mathrm{d}t}{\mathrm{d}f'} f' \, \mathrm{d}f'$$

↓

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

Gravitational wave strain (amplitude)

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

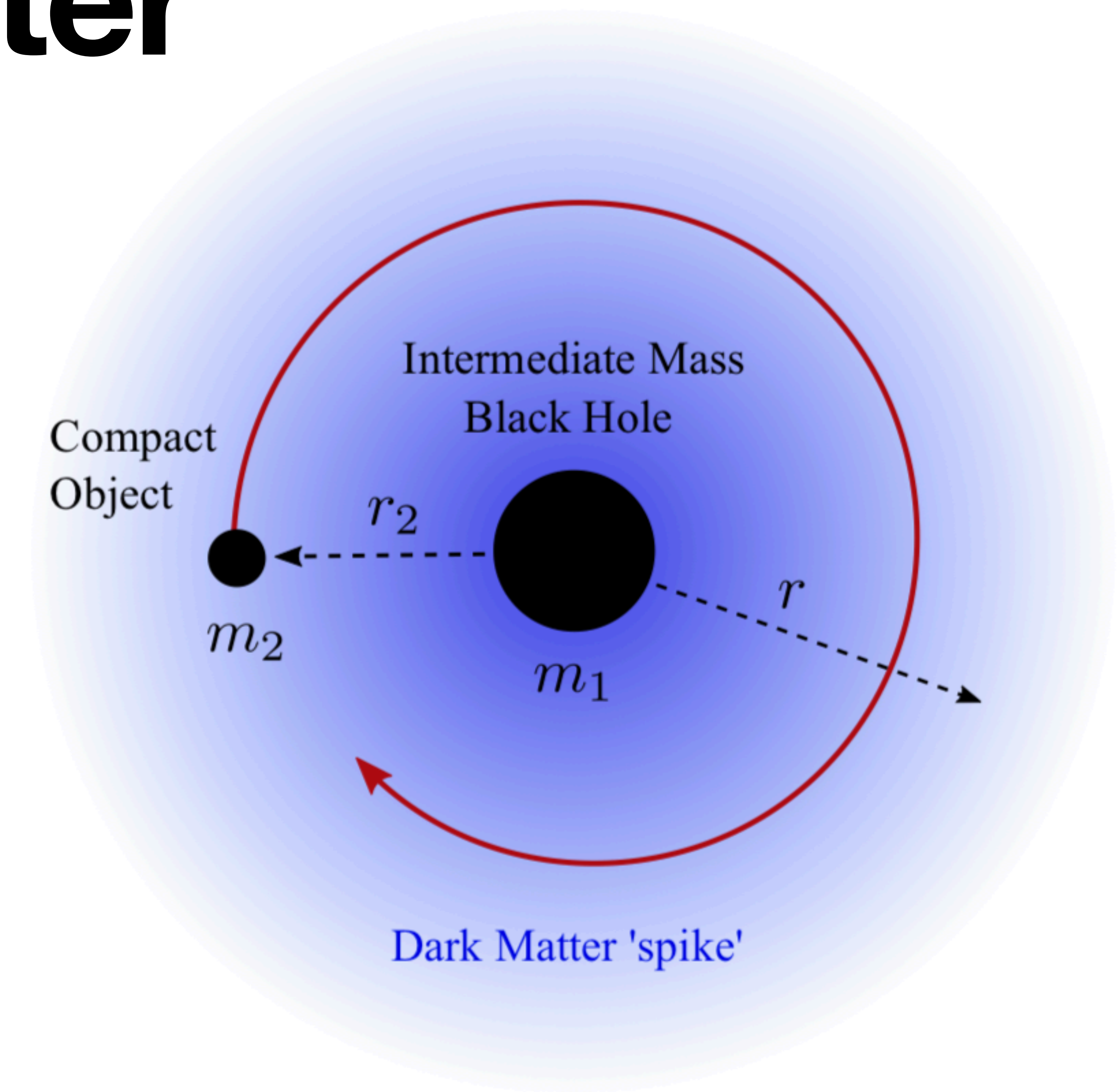


One environment we could look for: cold collisionless dark matter

Power law density profile

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

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



Key impact on binary dynamics from dynamical friction

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

Kavanagh, Nichols, Bertone, Gaggero 2020

Time-dependence of dark matter distribution is important

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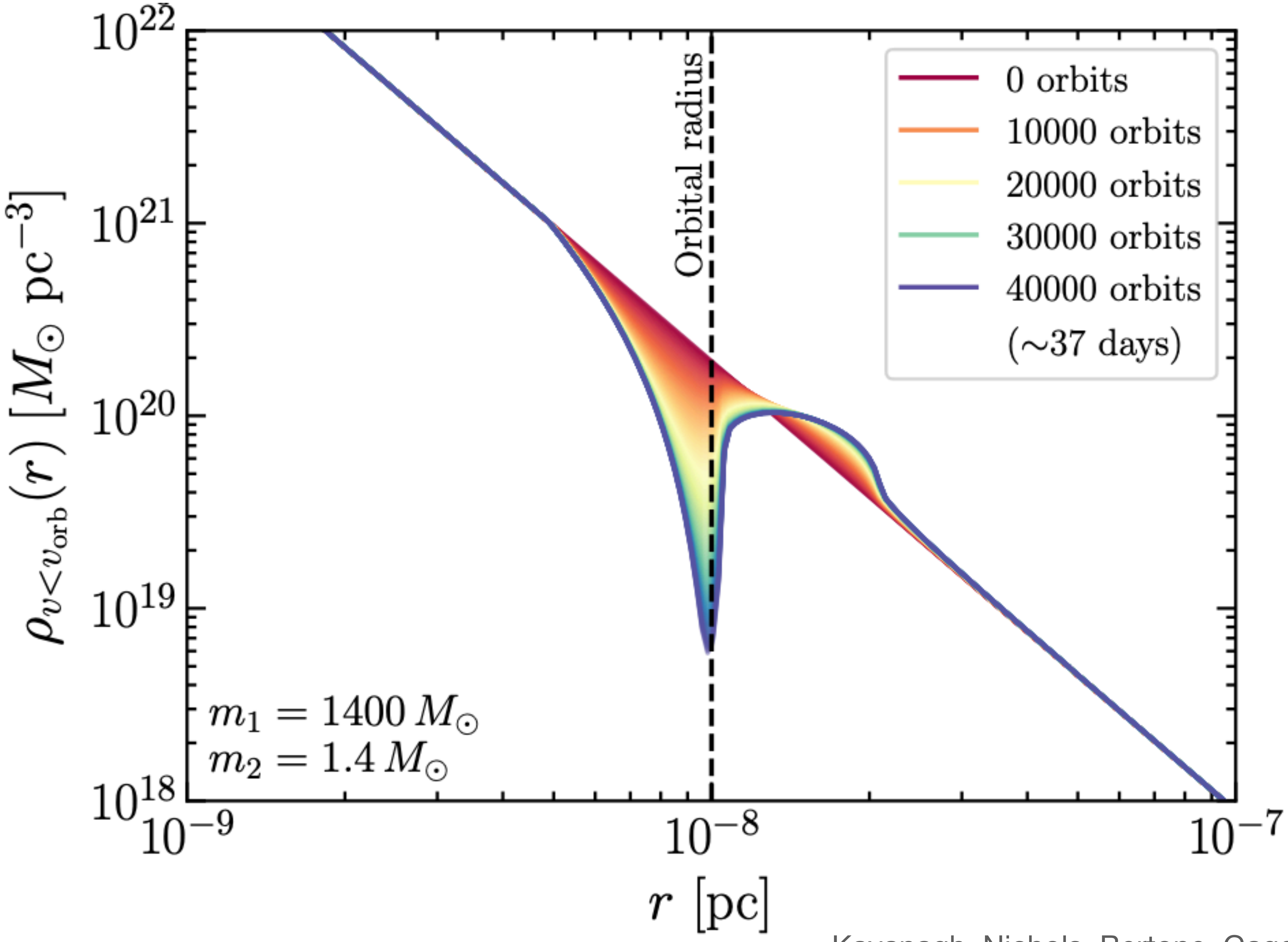
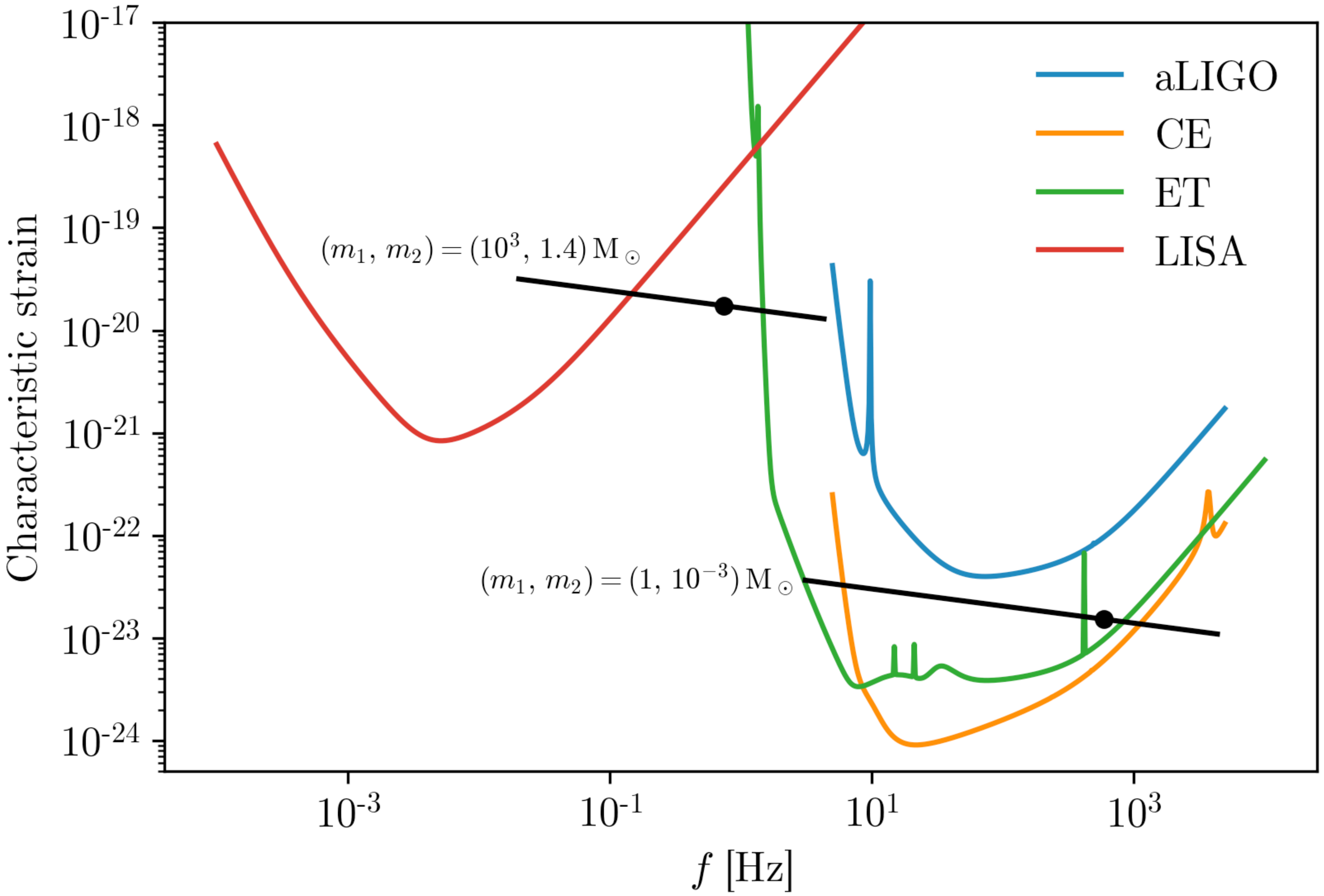
HaloFeedback



Kavanagh, Nichols, Bertone, Gaggero 2020

Need to observe many cycles + small mass ratio*

- 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



Cole, Coogan, Kavanagh, Bertone 2022

Small mass ratio*

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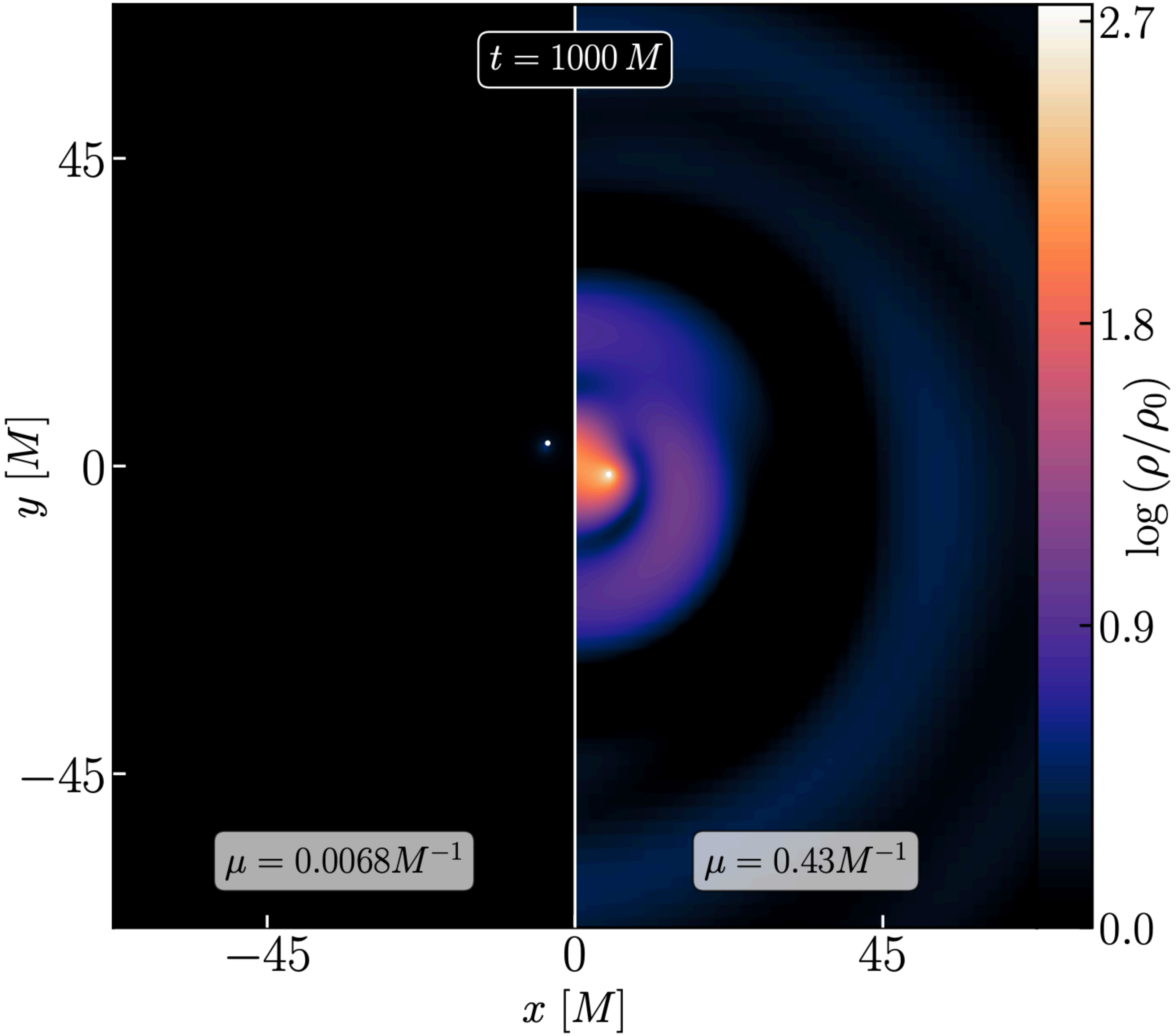


Aurrekoetxea et al. *Phys.Rev.Lett.* 132 (2024) 21, 211401

Future ground-based detectors most likely to tell us about dark matter spikes around *primordial* black holes

1. For small mass ratio systems, at least one black hole must be sub-solar -> primordial!
2. Even if primary mass is super solar, no known mechanism for forming spike around 1-100 solar mass astrophysical black holes, whereas primordial black holes must have a dark matter spike if not 100% of the dark matter

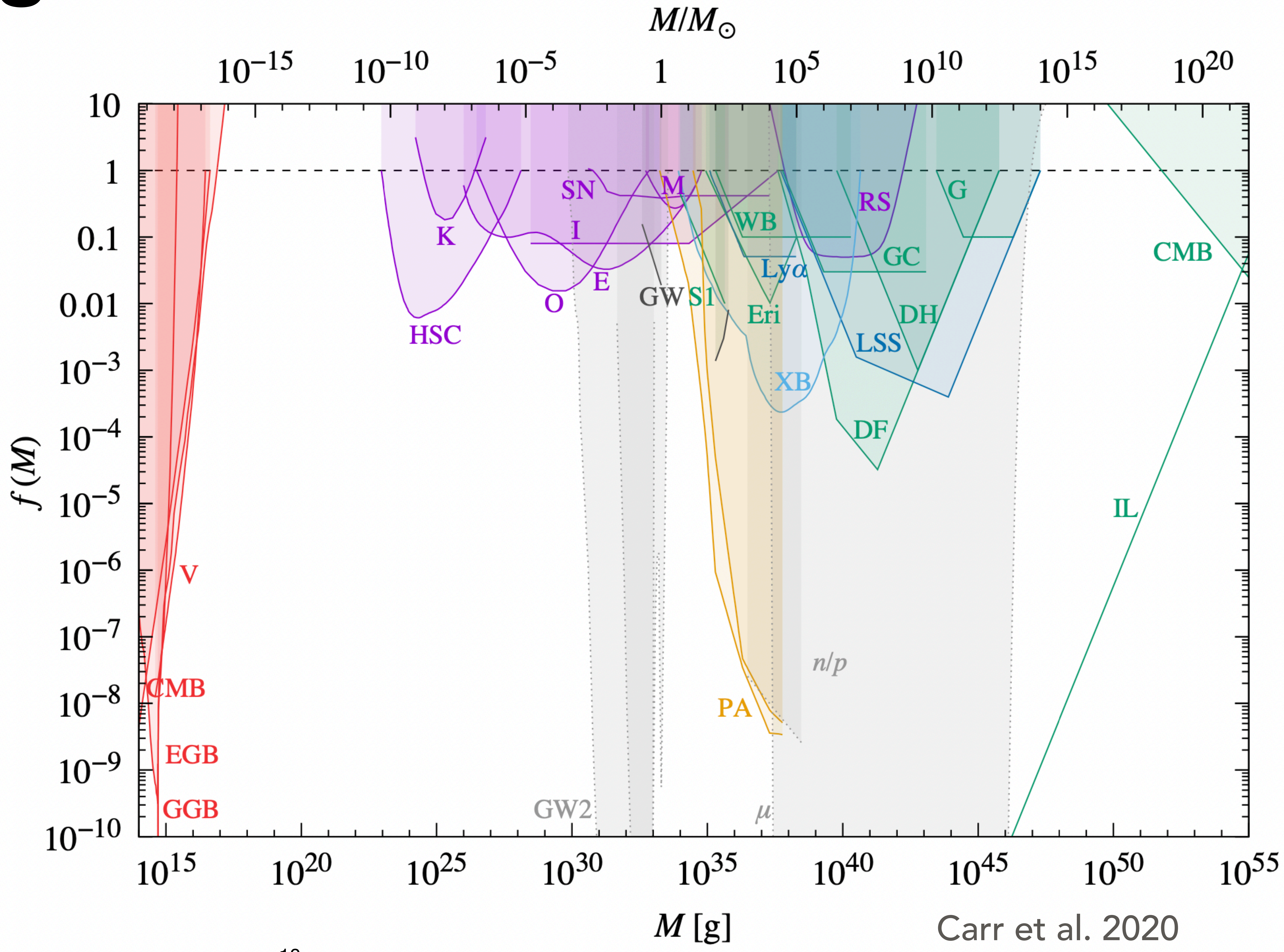
Cole, Coogan, Kavanagh, Bertone 2022

PBH constraints

Bounds available at
https://github.com/bradkav/PBHbounds

What is a PBH?

- A black hole that formed in the very early universe.
- Can theoretically have any mass
- Satisfies the conditions for being a dark matter candidate.
- **Not** generically produced from standard inflationary mechanisms



Carr et al. 2020
See also Green & Kavanagh 2020

Future ground-based detectors most likely to tell us about dark matter spikes around primordial black holes

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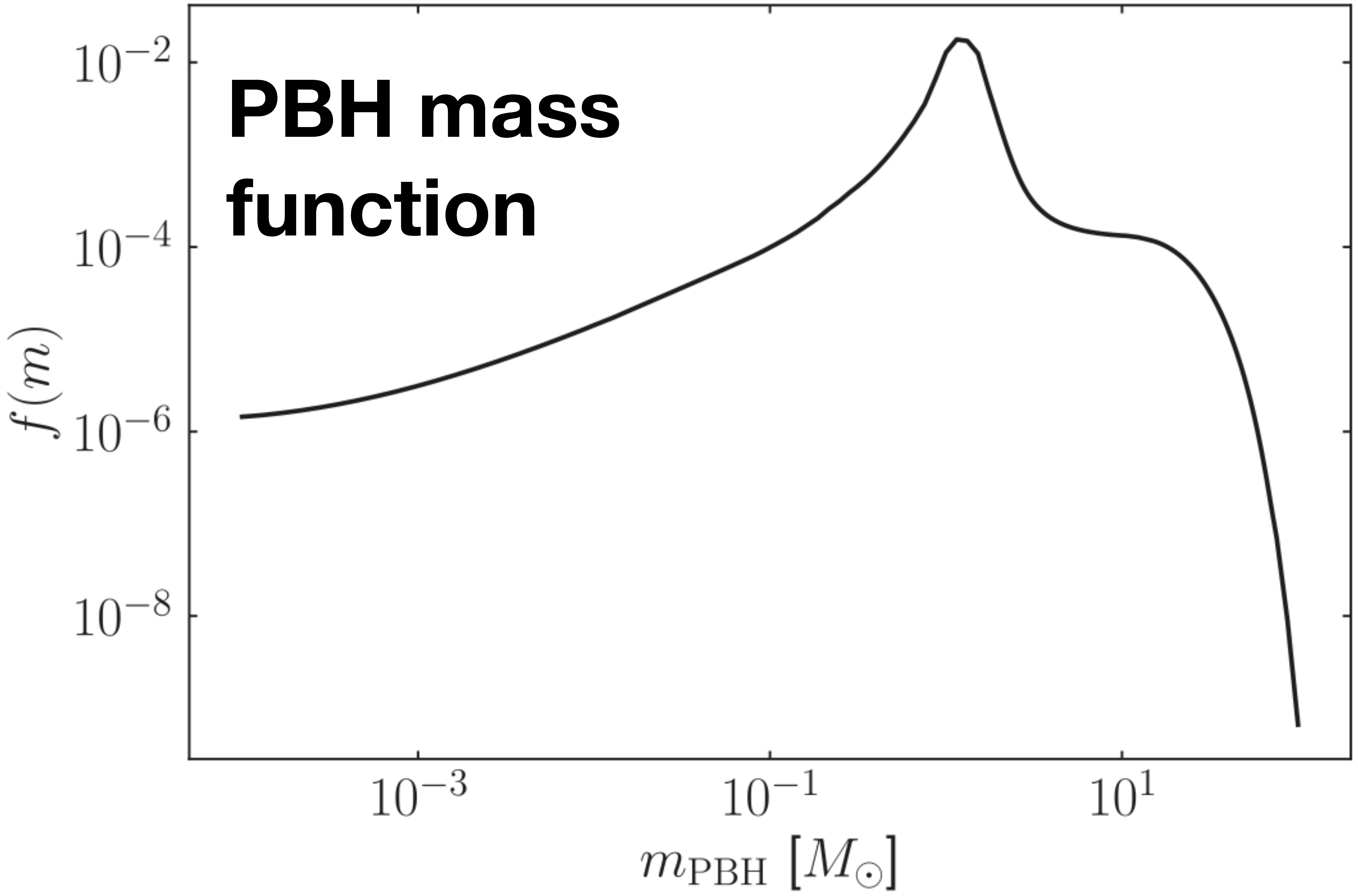
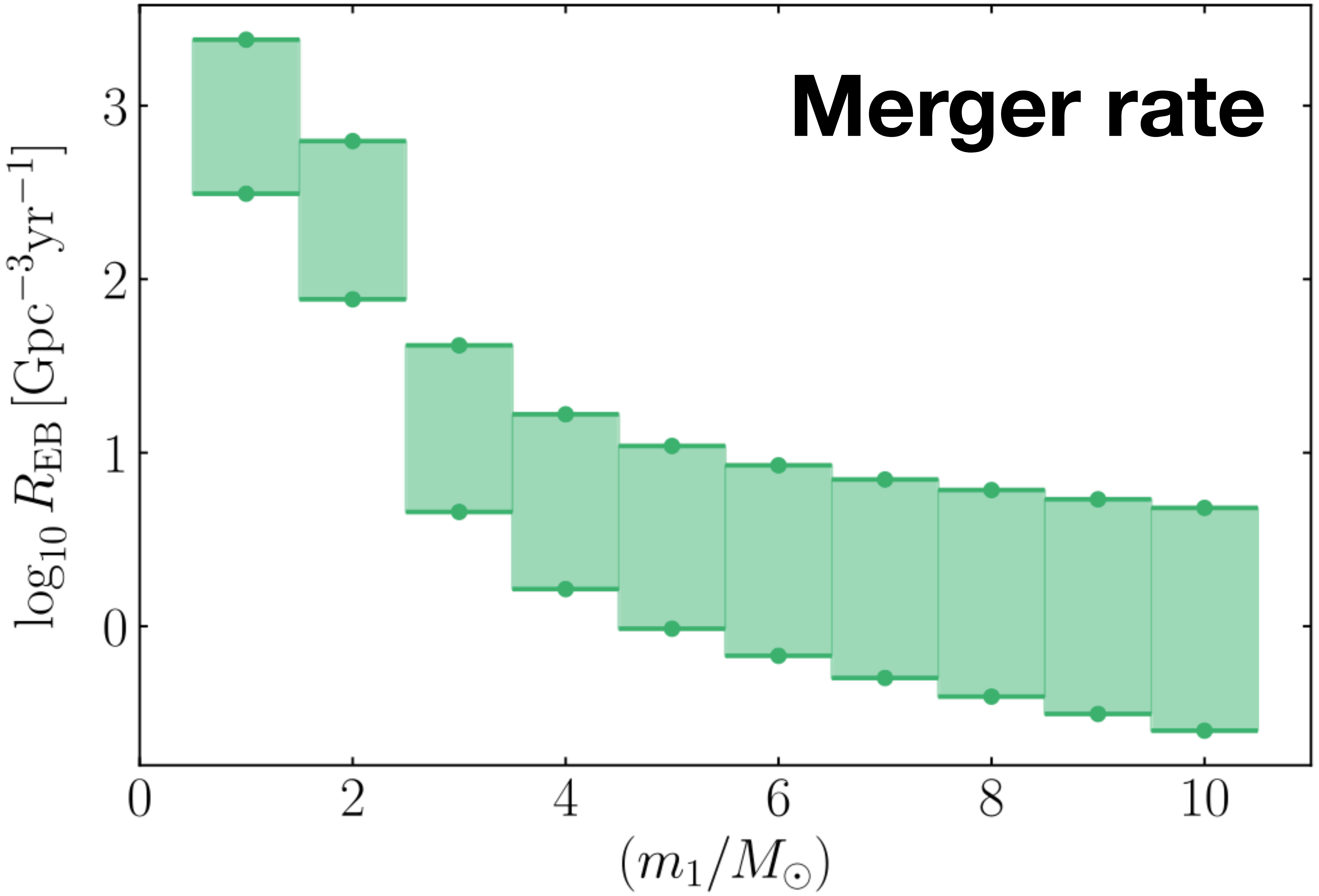
2. Even if primary mass is super solar, no known mechanism for forming spike around 1-100 solar mass astrophysical black hole, whereas primordial black holes must have a dark matter spike if not 100% of the dark matter

To search for such light, small mass ratio systems, MUST include the presence of the dark matter spike

Using realistic formation mechanisms for PBHs and spikes, we can understand the prospects for measuring these effects





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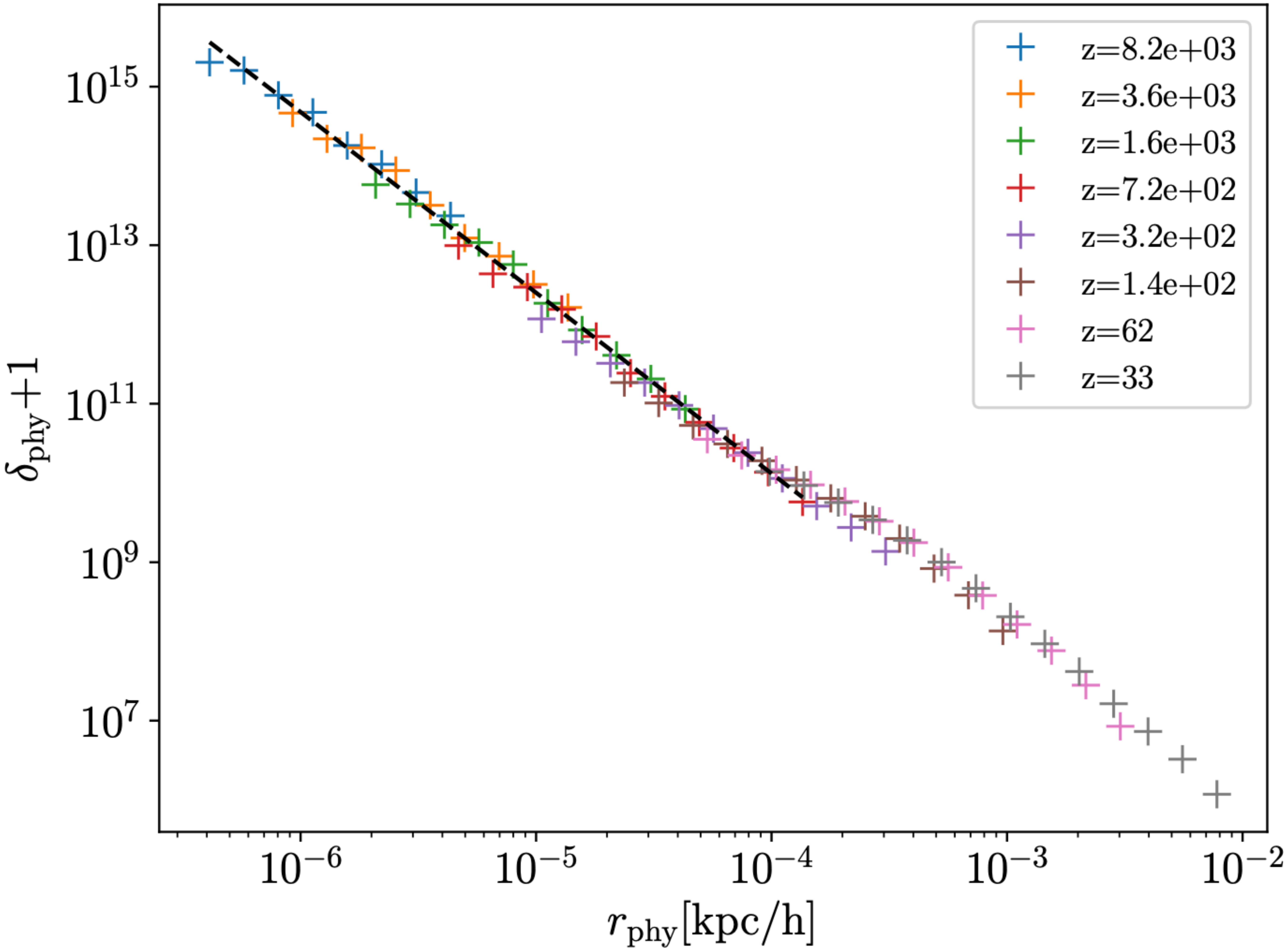
Using realistic formation mechanisms for PBHs and spikes, we can understand the prospects for measuring these effects

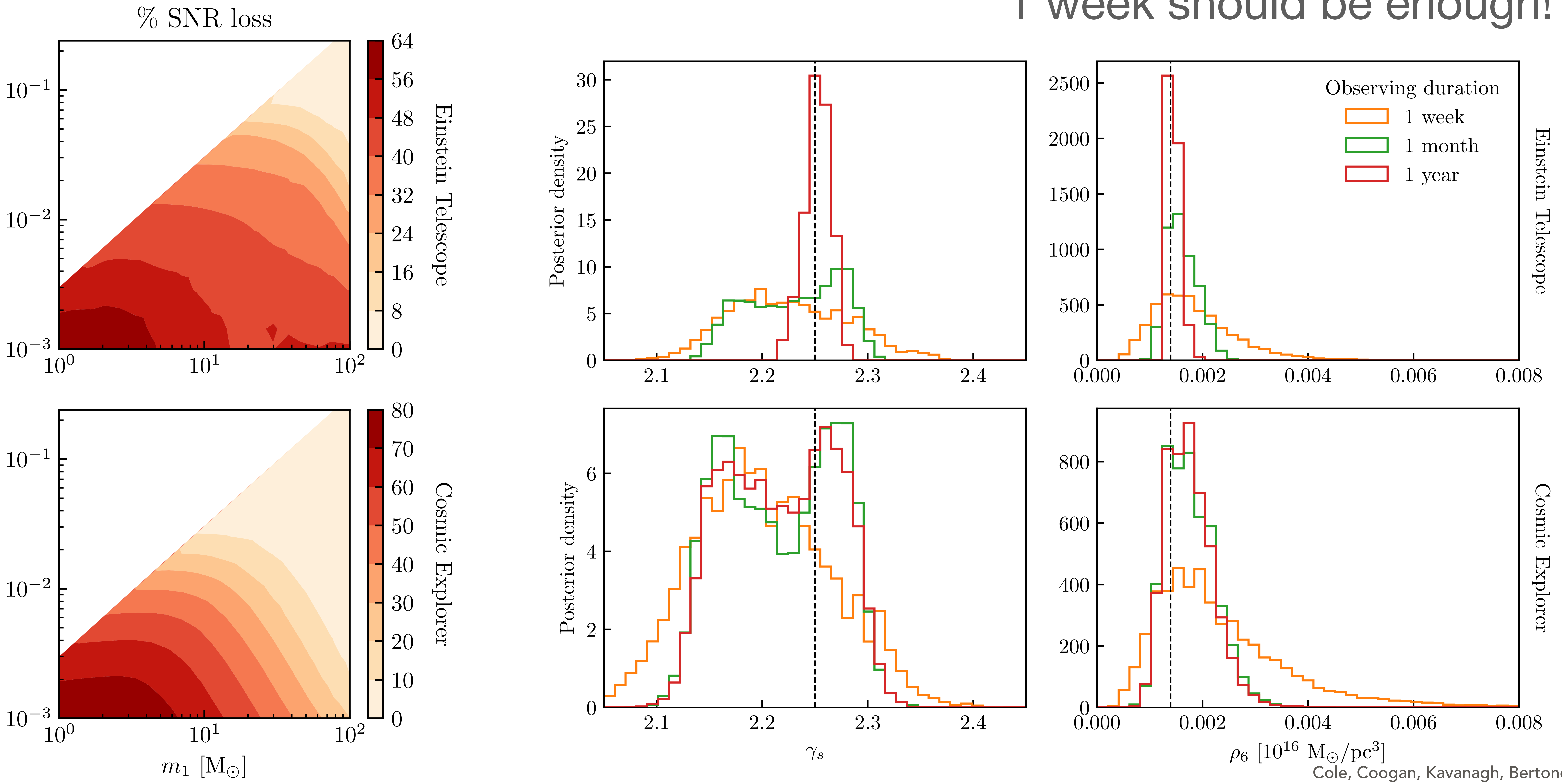
Slope of density profile = 9/4



Adamek et al. 2019

Effects measurable with template-based parameter estimation with Einstein Telescope and Cosmic Explorer

1 week should be enough!



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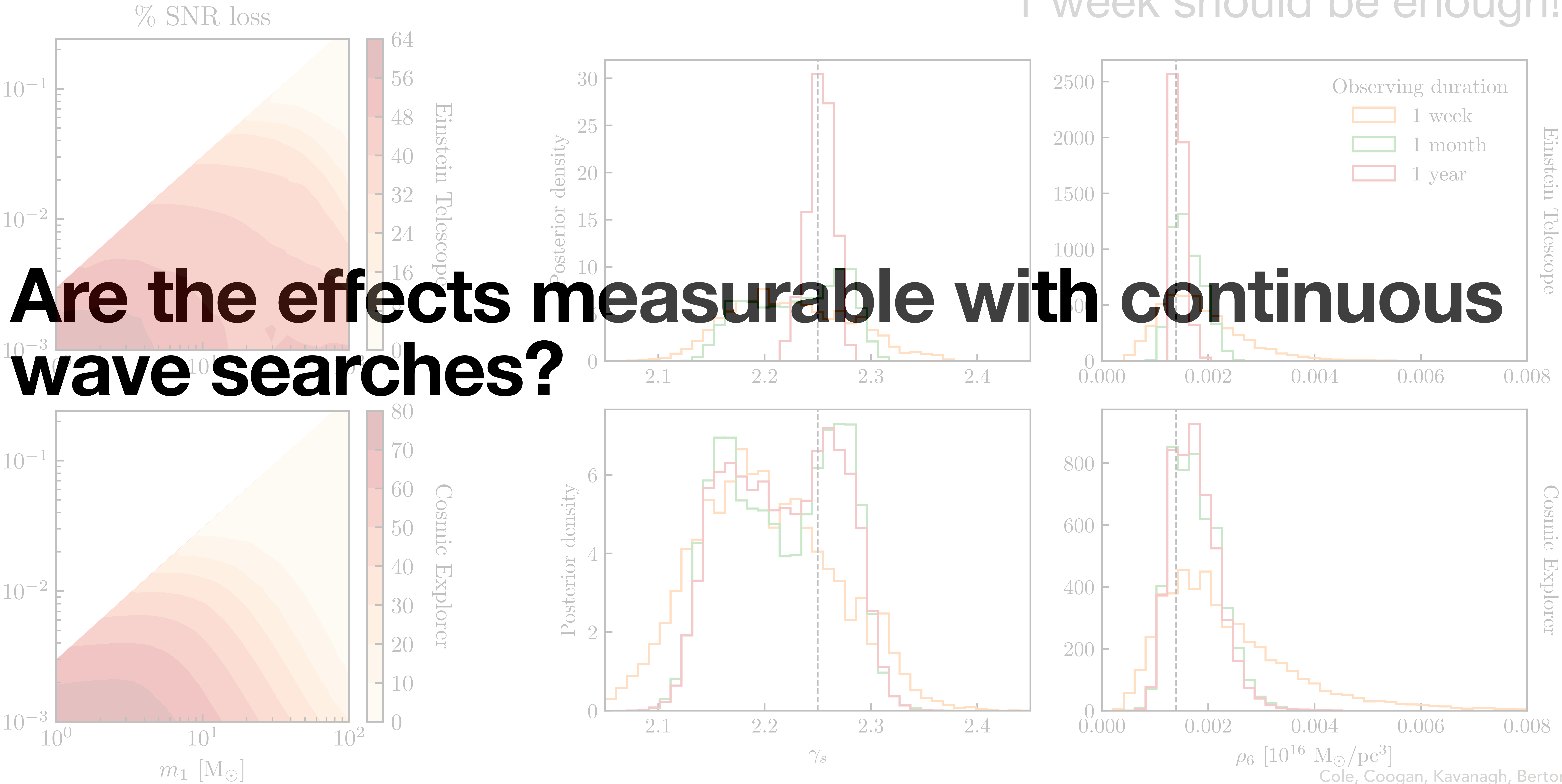
Are the effects measurable with continuous wave searches?

1 week should be enough!



Cole, Coogan, Kavanagh, Bertone 2022

Conclusions

- We can search for signatures of dark matter with future GW detectors
- With future ground-based detectors, small mass ratio PBH binaries are our best bet
- These systems MUST be accompanied by a specific dark matter spike profile
- Can't search the data for these systems without including the dark matter presence
- With 1 week signals, this effect should be measurable - but can we detect them with current data analysis techniques?

Thank you for listening!