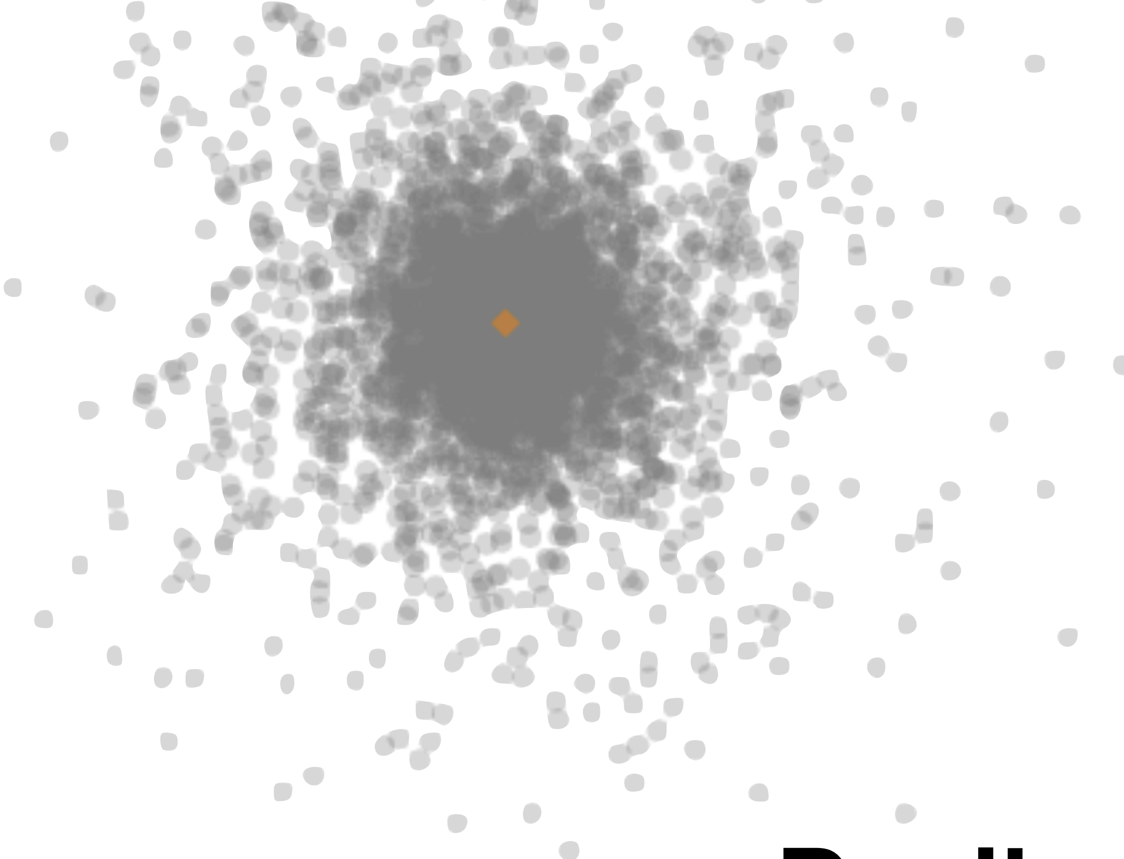

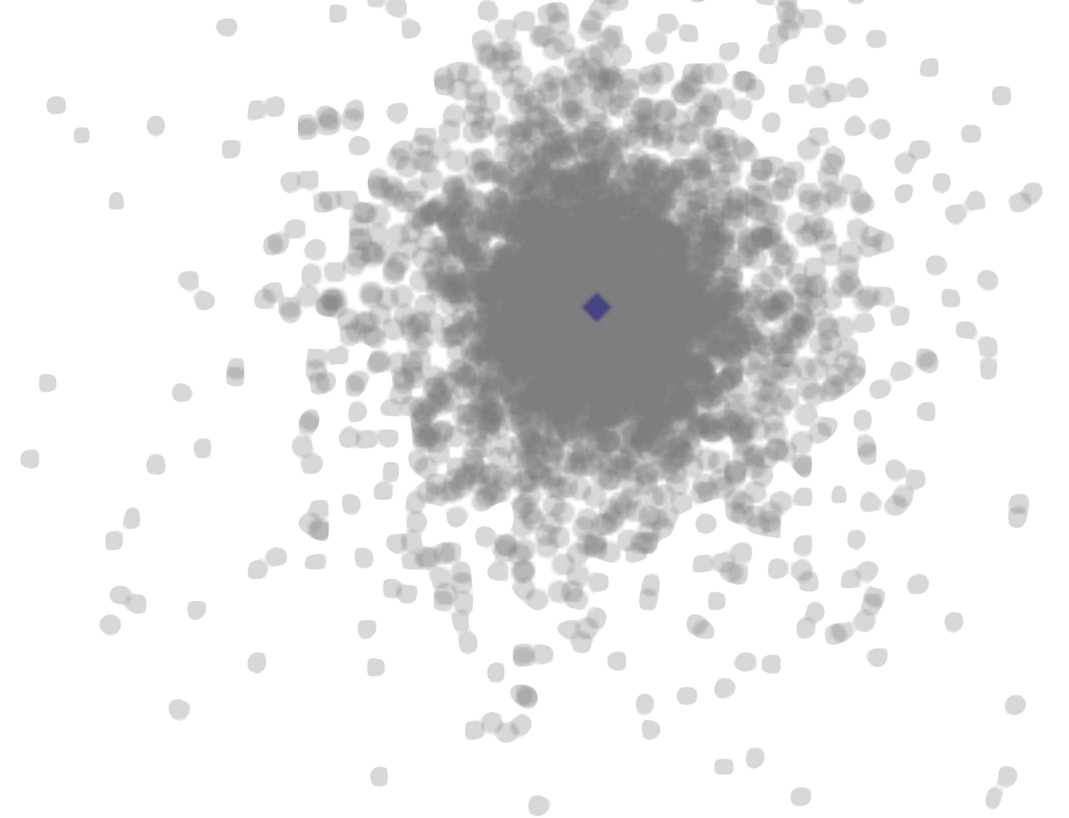

Decihertz Dark Matter:

Gravitational Waves from Dark Matter Spikes and Primordial Black Holes

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IFCA (CSIC-UC), Santander, Spain

LGWA White Paper Kick-off Meeting
10 February 2023

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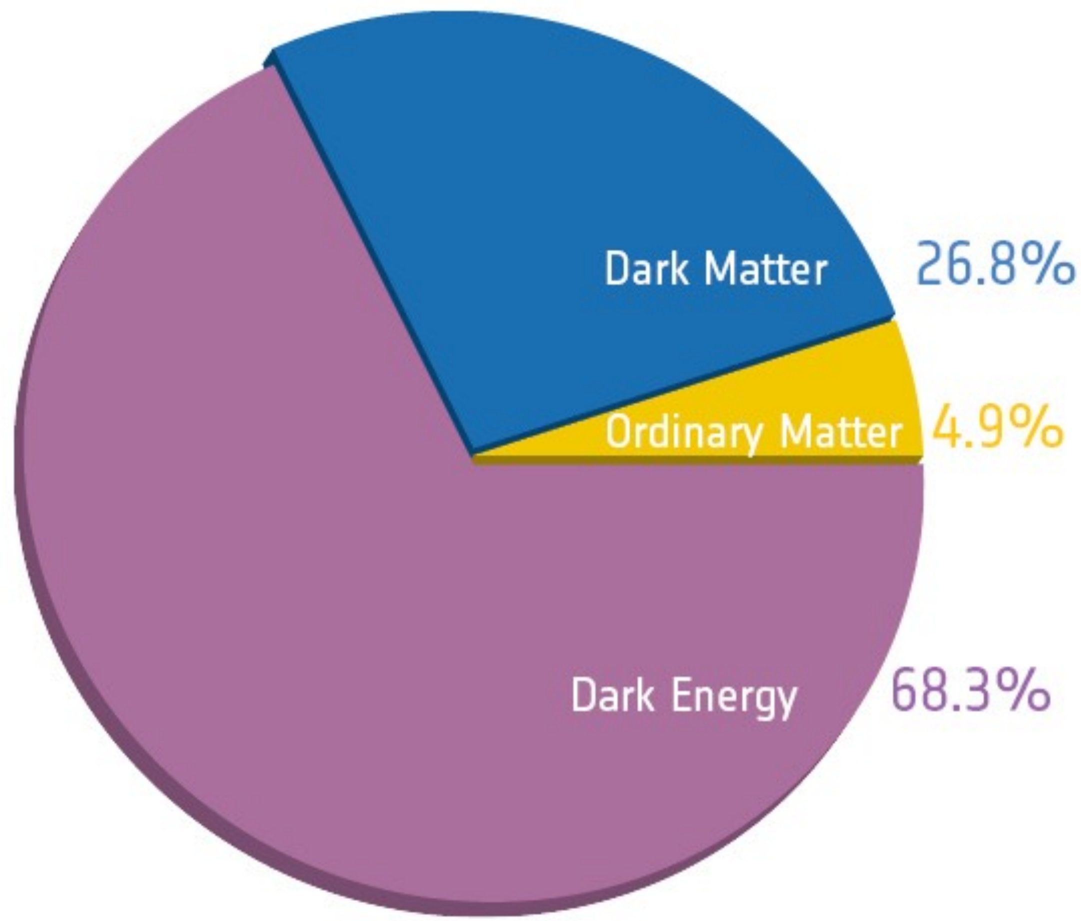
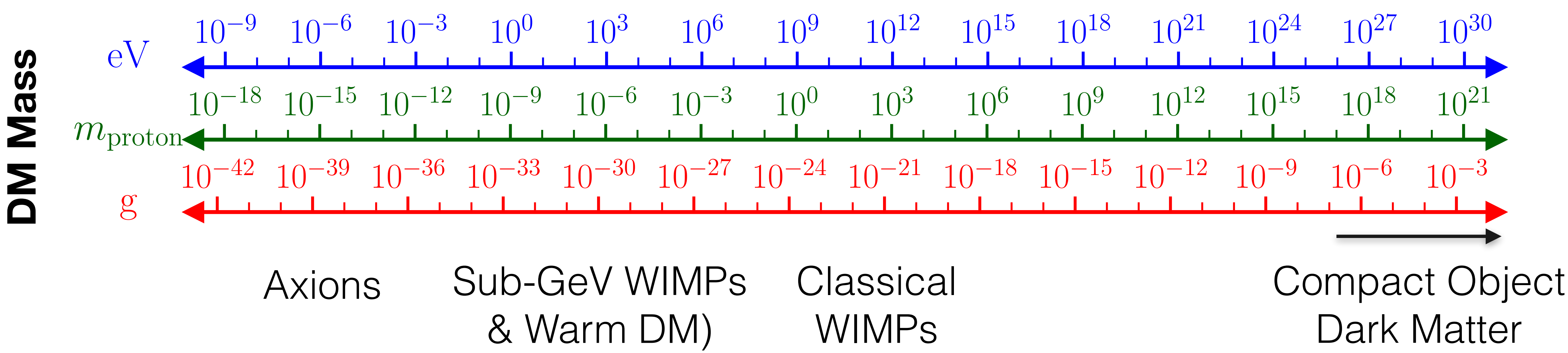
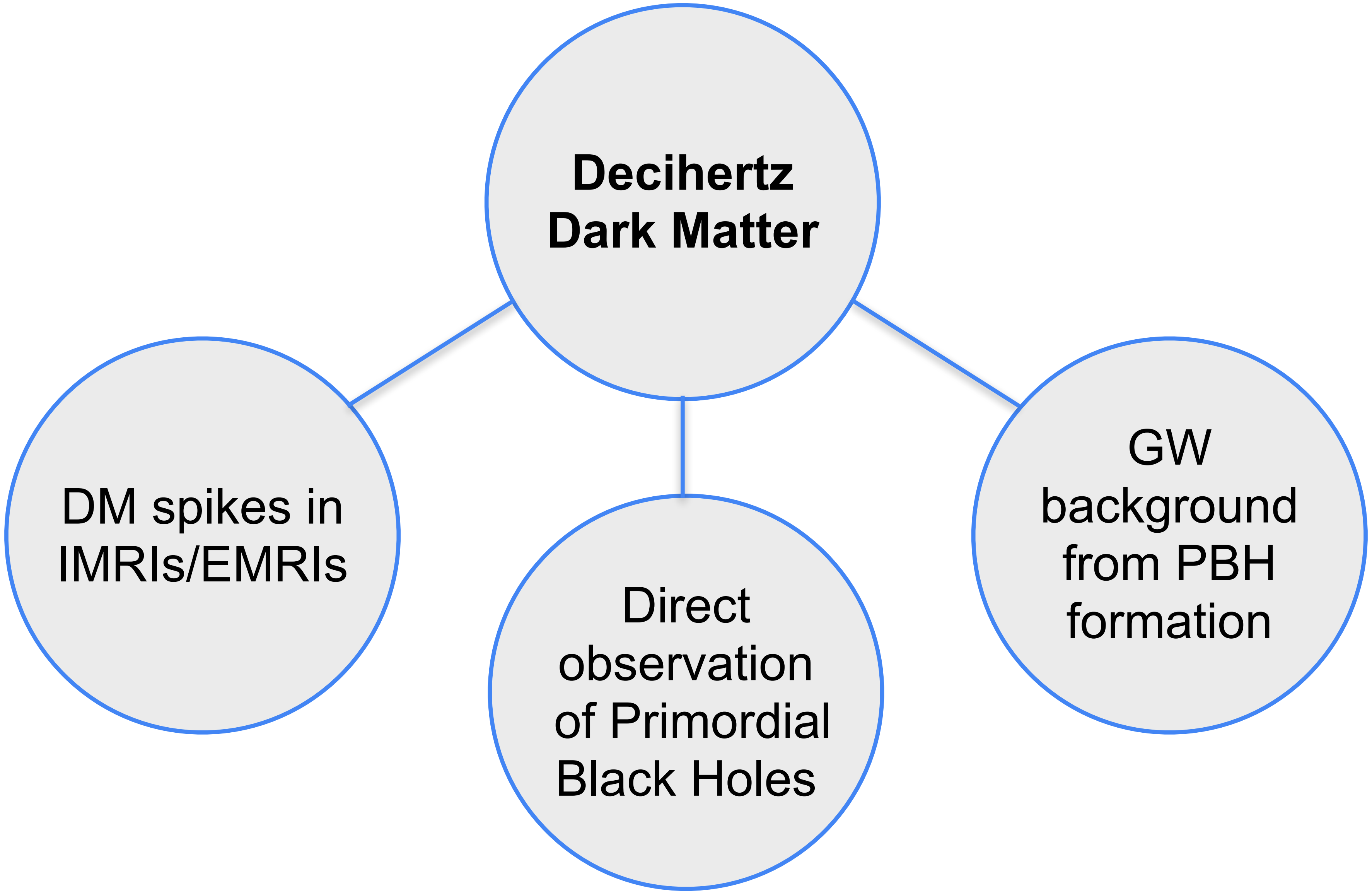
Consejo Superior de Investigaciones Científicas
Universidad de Cantabria

The Dark Matter Landscape



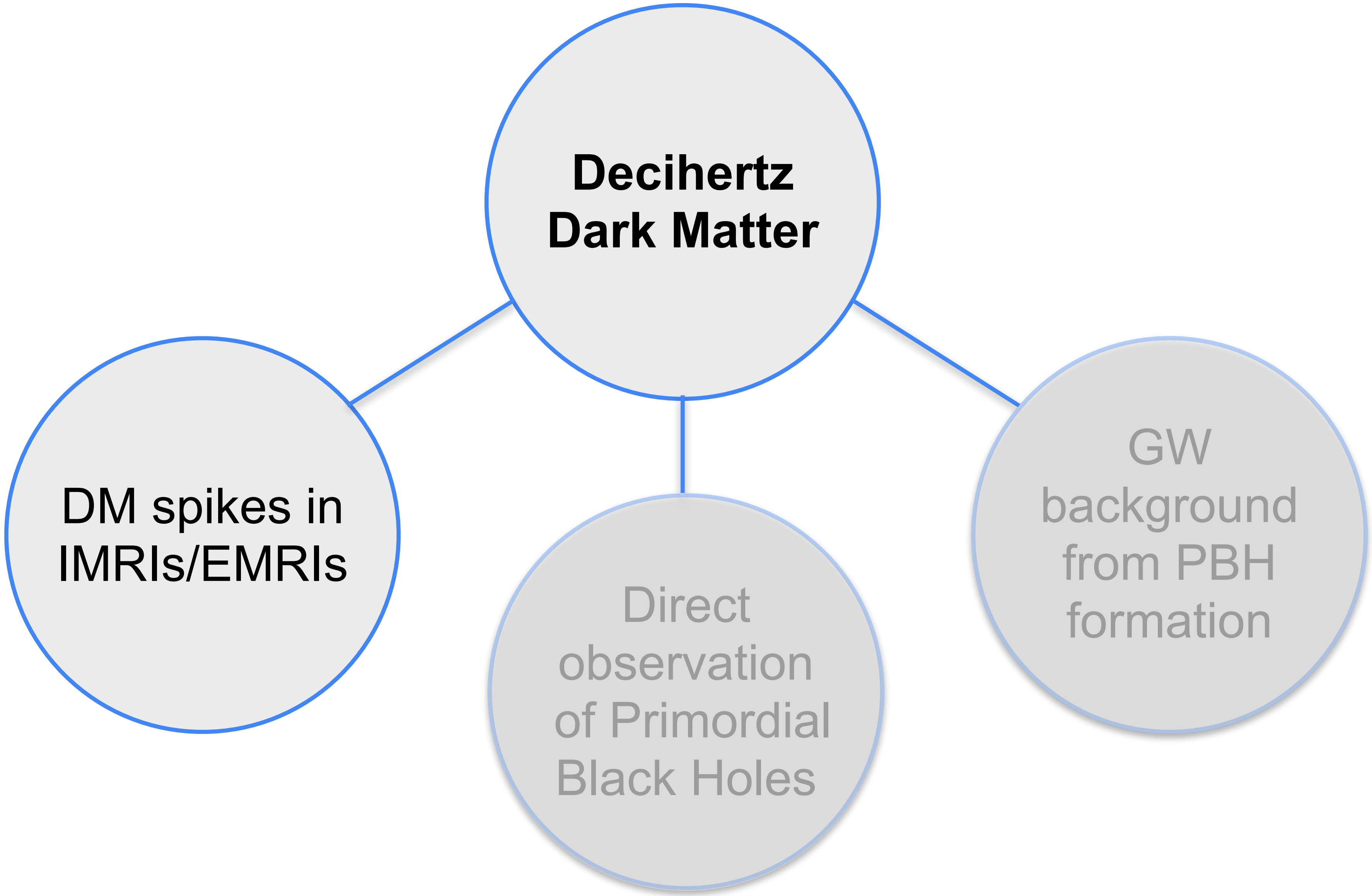


Overview



Gravitational waves can allow us to very precisely probe **dense Dark Matter environments** in the present day Universe. But they also allow us to probe the **conditions in the very early Universe**.

Overview



Gravitational waves can allow us to very precisely probe **dense Dark Matter environments** in the present day Universe. But they also allow us to probe the **conditions in the very early Universe**.

Dark Matter Spikes

'**Spikes**' or '**dresses**' of cold, particle-like DM may form around BHs:

From the slow ('adiabatic') growth of a BH at the centre of a DM halo

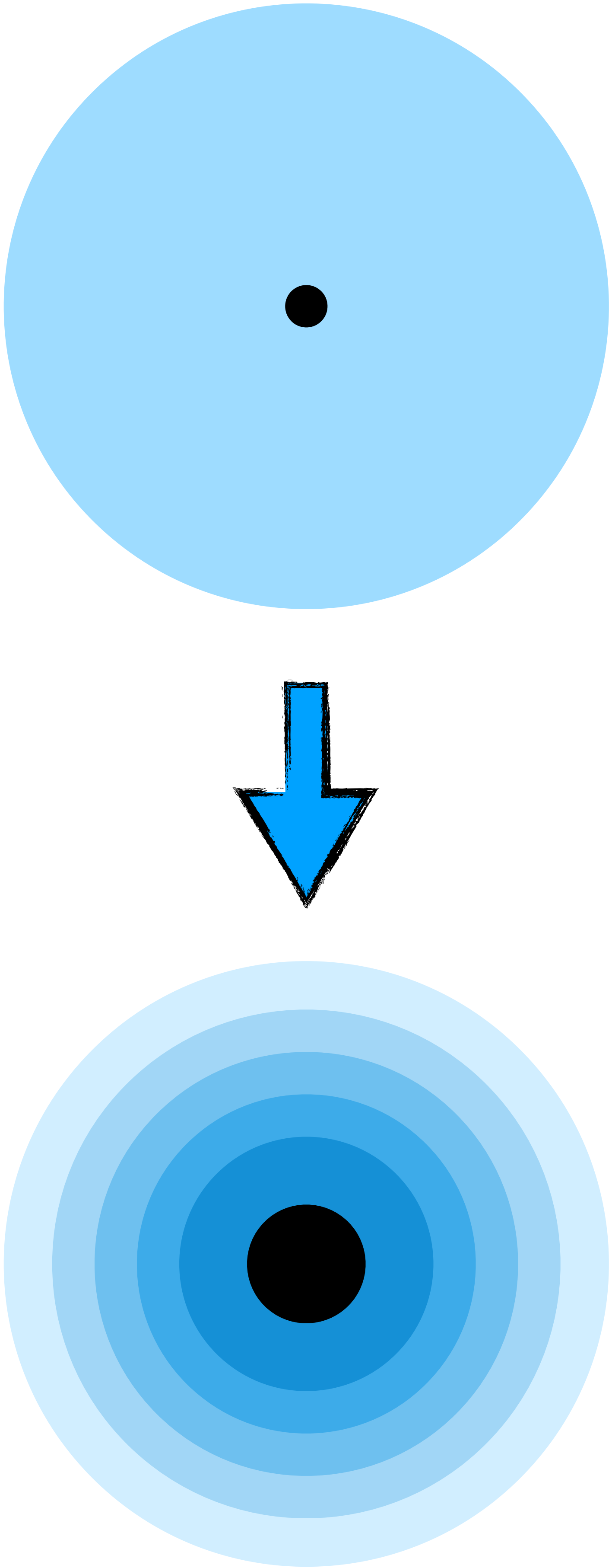
"Astrophysical scenario"

[astro-ph/9906391, astro-ph/0509565, 1305.2619, …]

Around BHs which form from large density fluctuations in the early Universe (i.e. Primordial Black Holes)

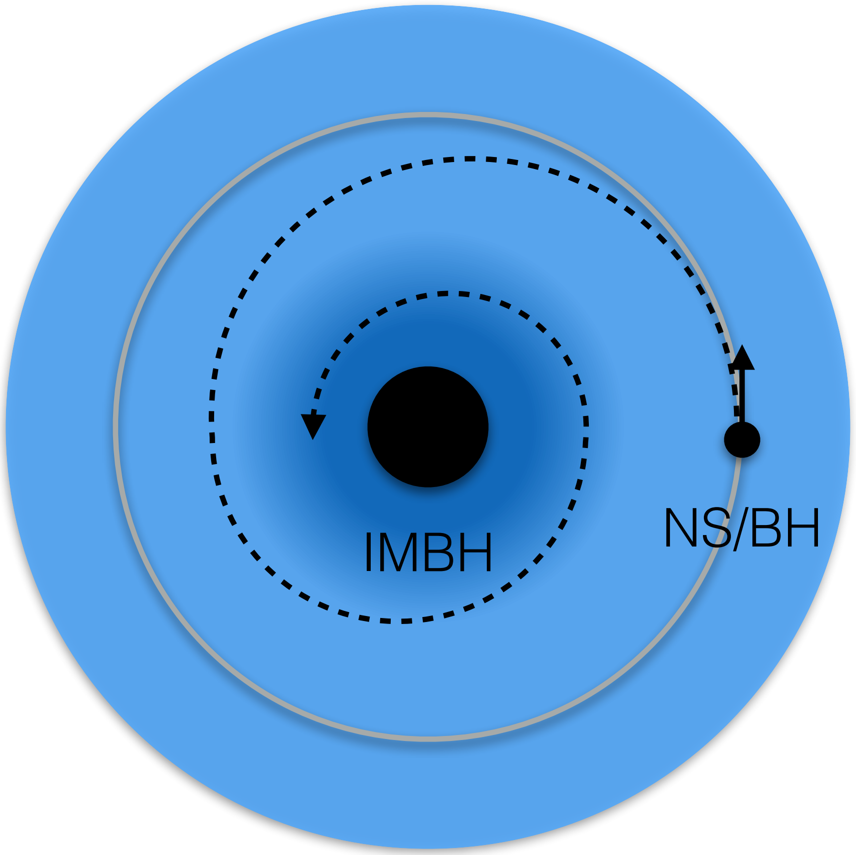
"PBH scenario"

[Bertschinger (1985), astro-ph/0608642, 1901.08528, …]



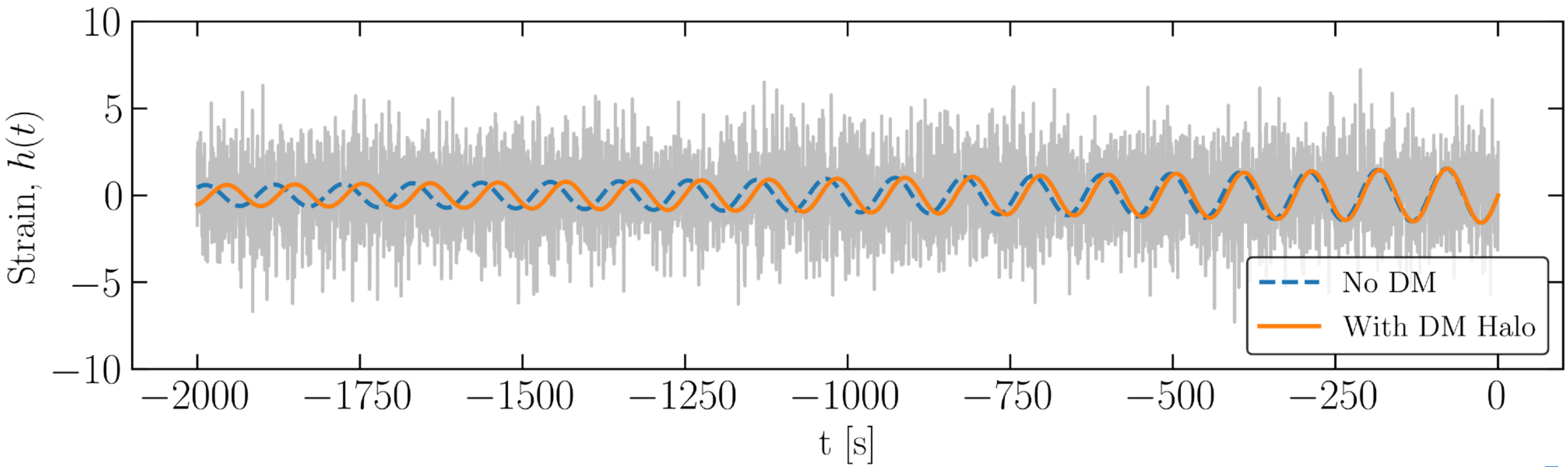
DM-induced "Dephasing"

Consider an intermediate-mass ratio inspiral (IMRI):
A stellar mass compact object (NS/BH) inspirals towards intermediate mass black hole (IMBH)



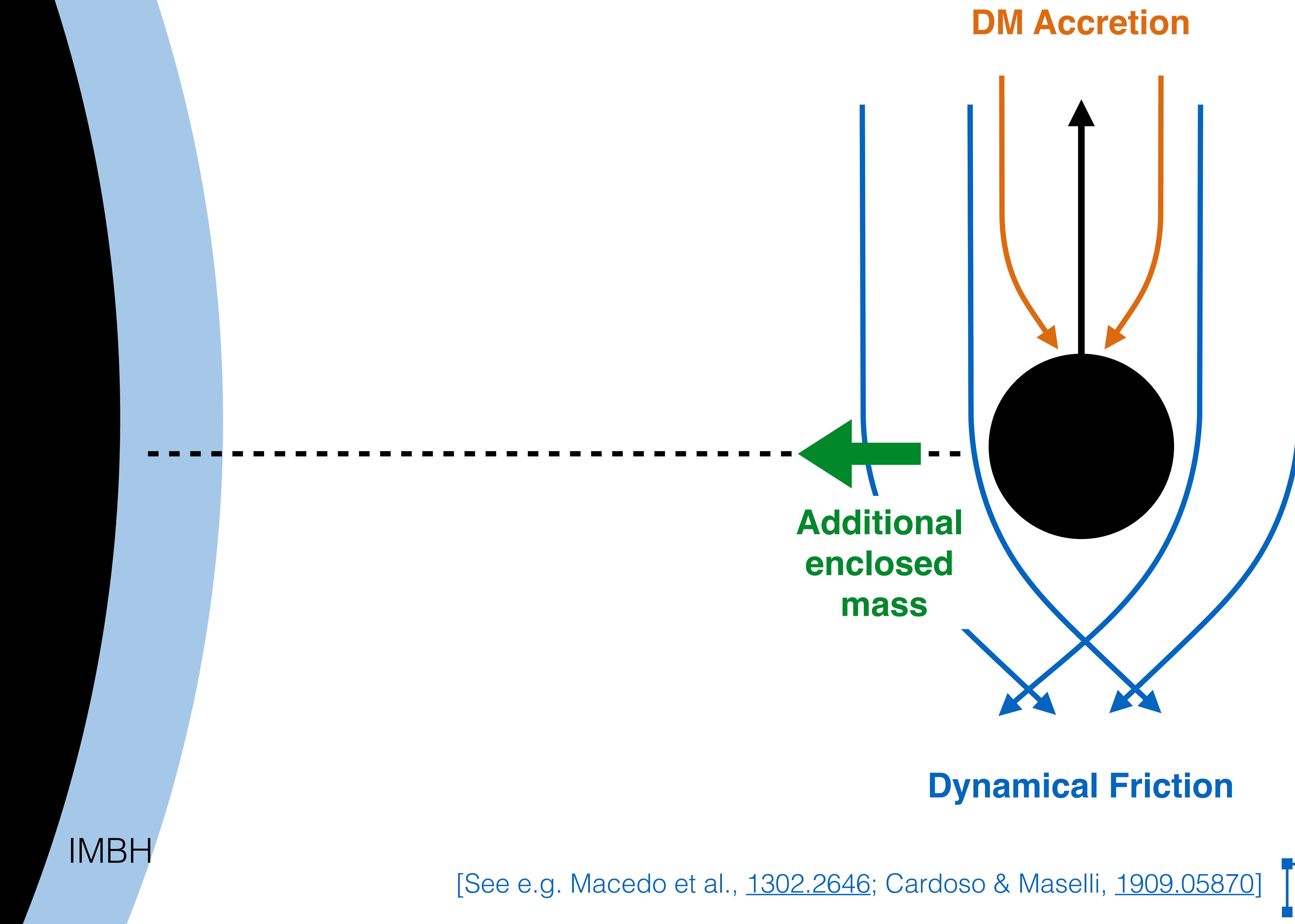
$$M_{\rm IMBH} \sim 10^3 - 10^5\, M_\odot$$

Until the innermost stable circular orbit: $f_{\rm ISCO} = 0.44 \left(\frac{10^4\, M_\odot}{M_1}\right)$ Hz



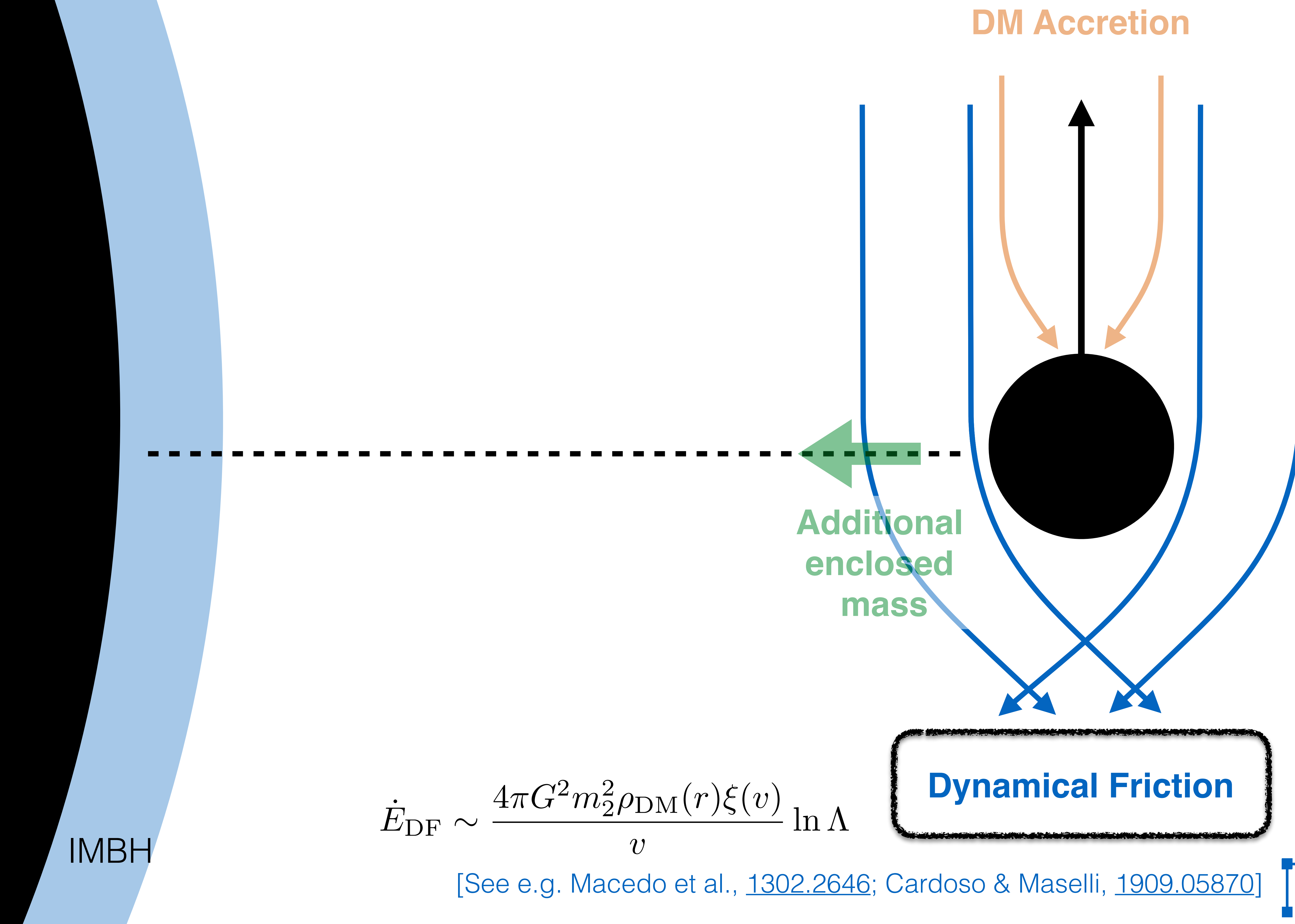
[Eda et al. 1301.5971, 1408.3534; see also 1302.2646, 1404.7140, 1404.7149 and others…]

Impact of DM Spikes



[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Impact of DM Spikes



$$\dot{E}_{\rm DF} \sim \frac{4\pi G^2 m_2^2 \rho_{\rm DM}(r)\xi(v)}{v} \ln \Lambda$$

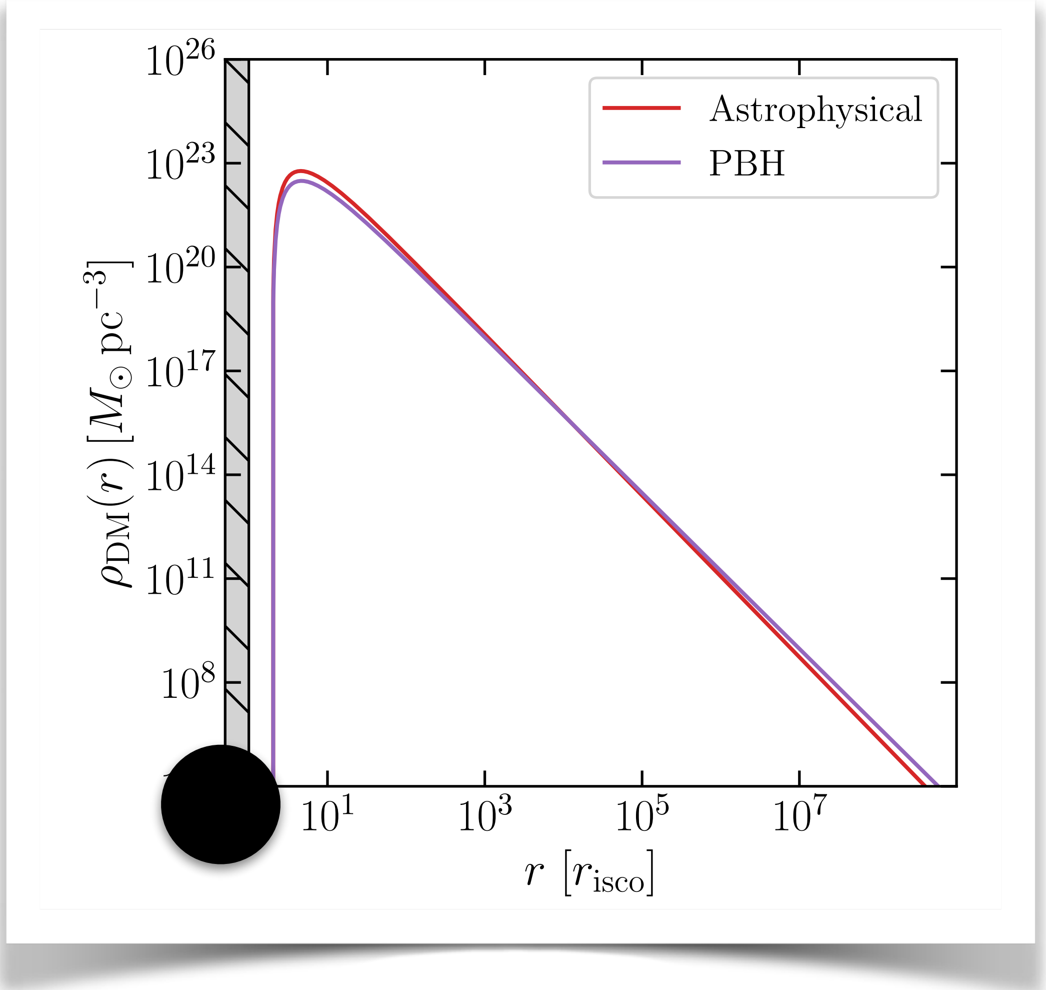
[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Why these systems?

$$\rho_{\rm DM} = \rho_6 \left(\frac{10^{-6}\,{\rm pc}}{r}\right)^{\gamma_{\rm sp}}$$

$$\gamma_{\rm sp} \sim 2 - 2.5$$

1) **Spike formation:** Typically need a massive central BH which has grown slowly, in order to form a dense DM spike.



[E.g. Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

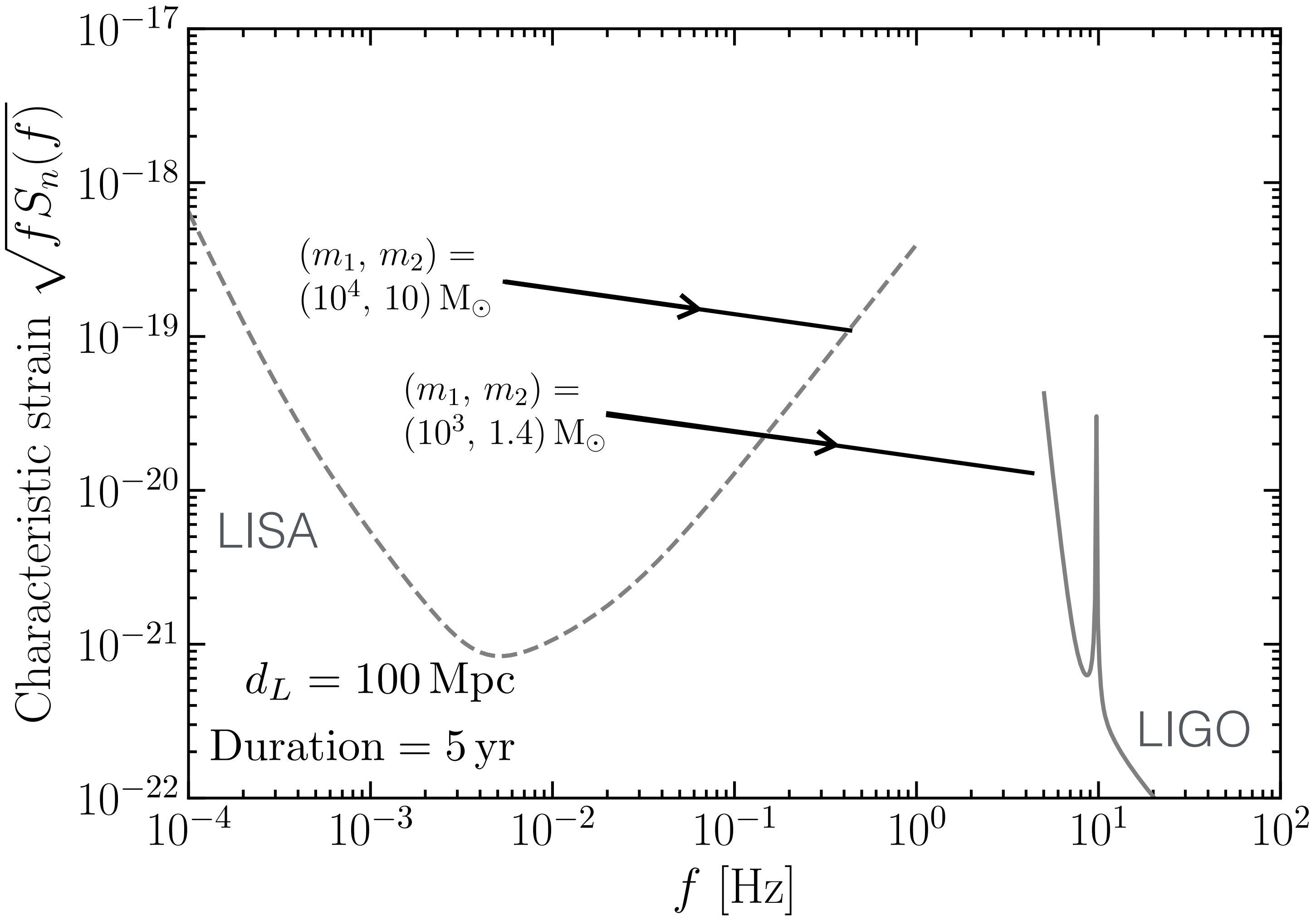
2) **Tracing the DM density:** Need a lighter orbiting compact object in order to trace the DM density (but not disrupt the DM spike too much)

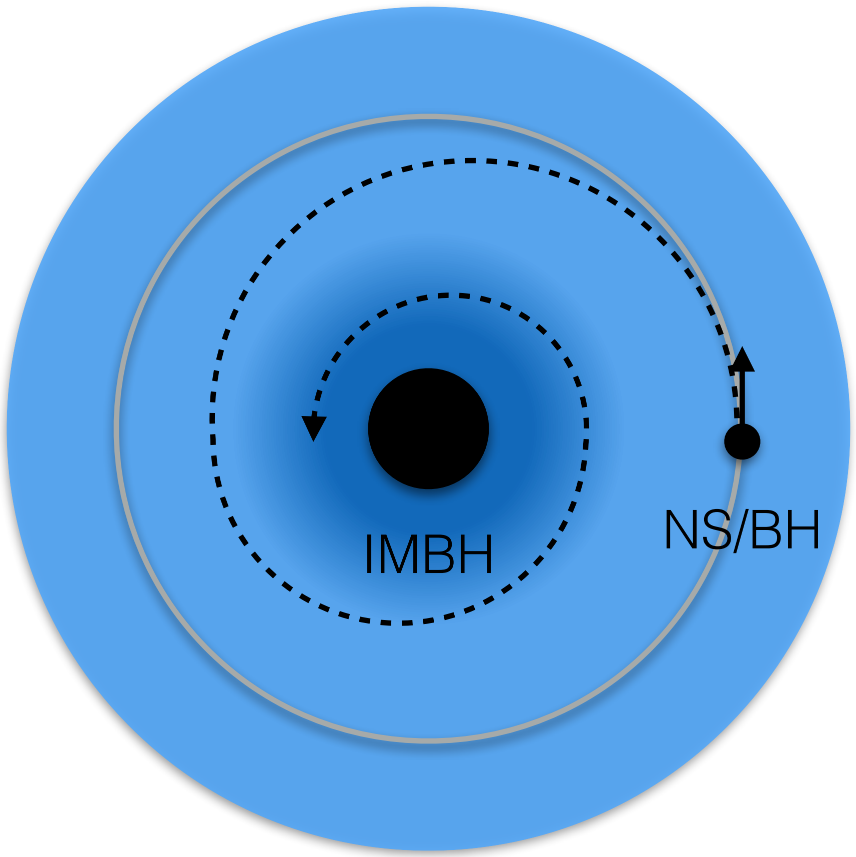
3) **BH environment:** Need a quiet life for the BH, not too many major mergers

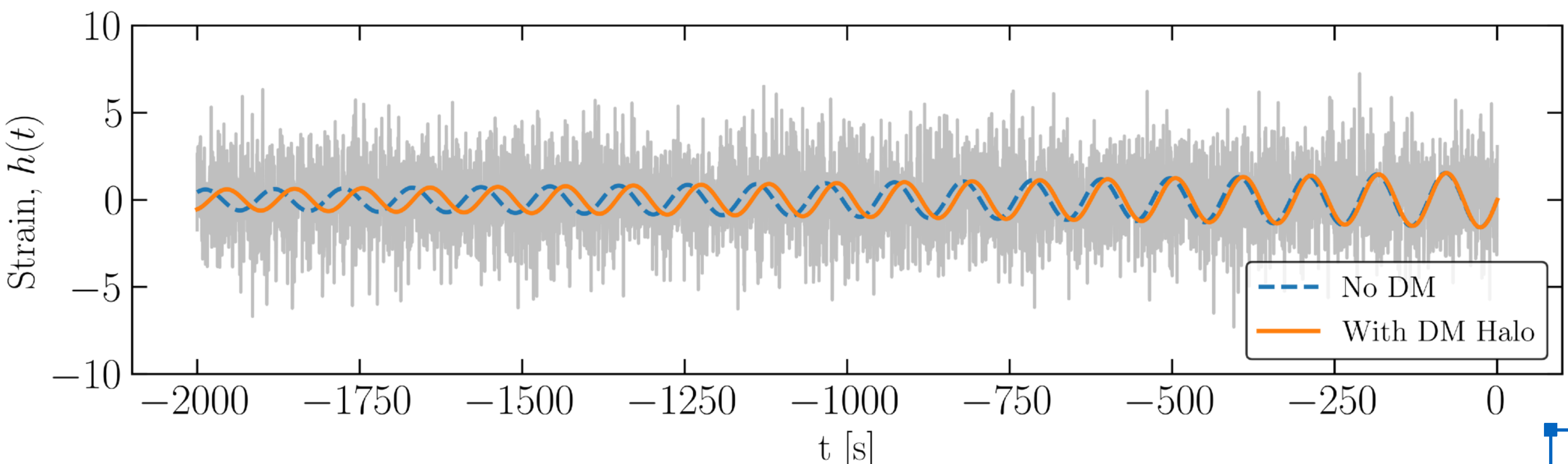
[E.g. Bertone & Merritt, astro-ph/0501555]

Focus on IMBHs and IMRIs!

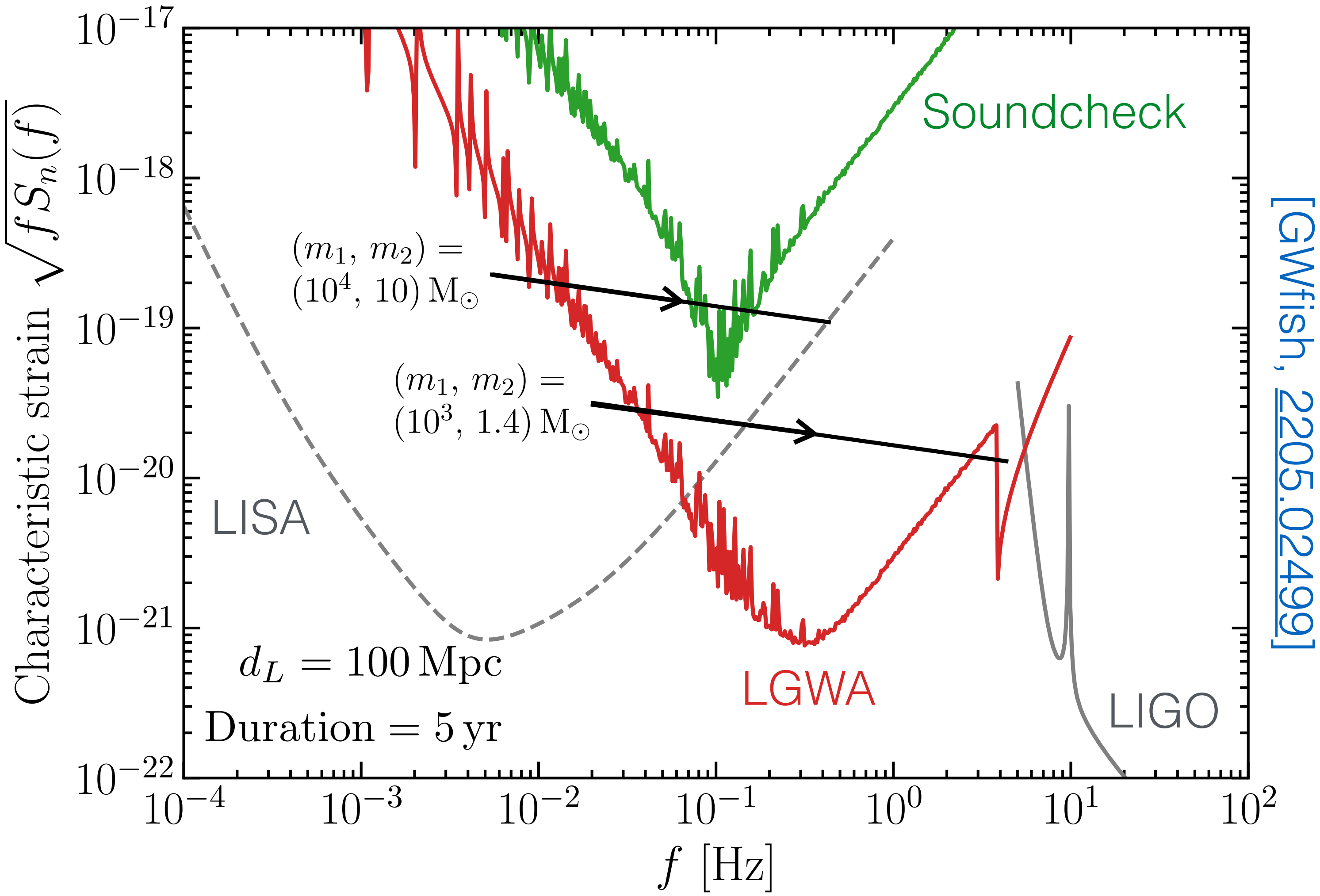
DM-induced Dephasing

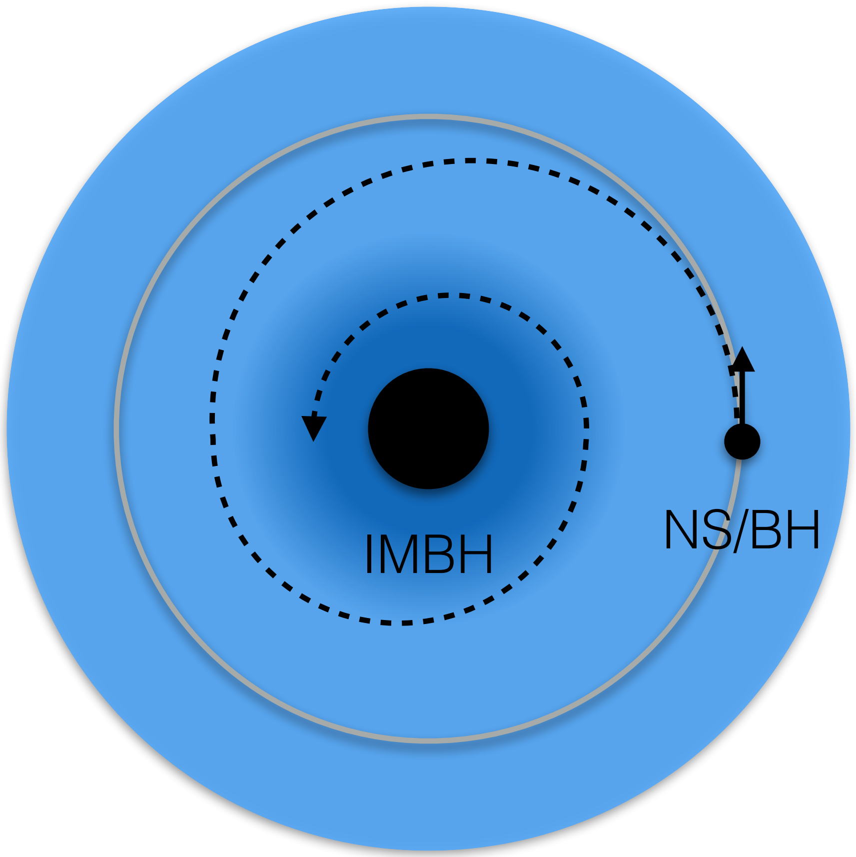


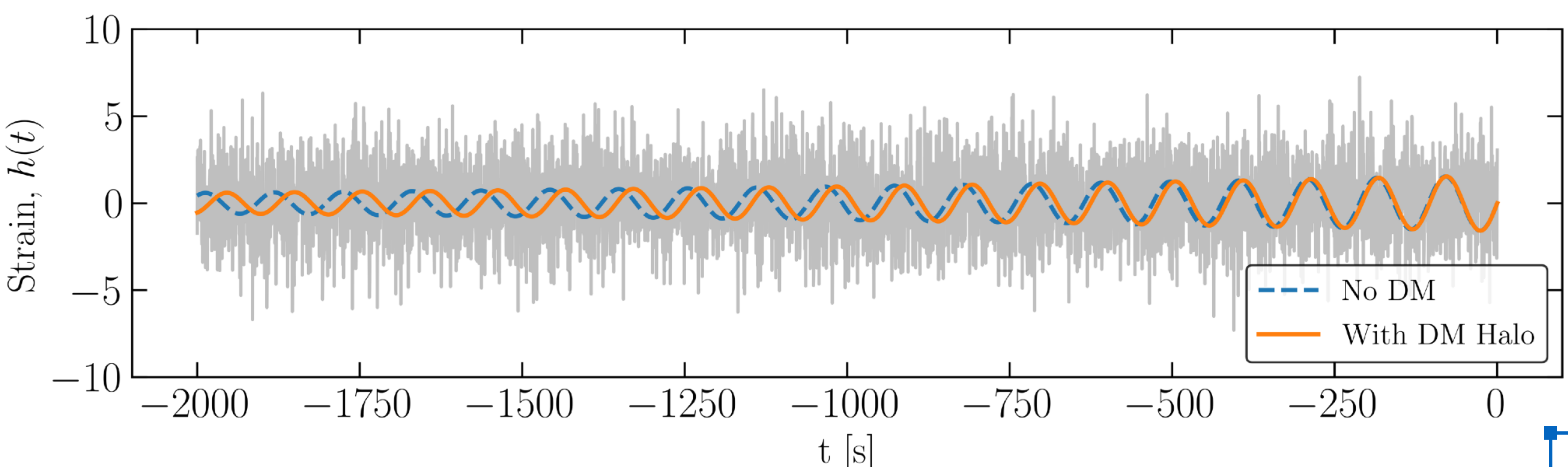




DM-induced Dephasing

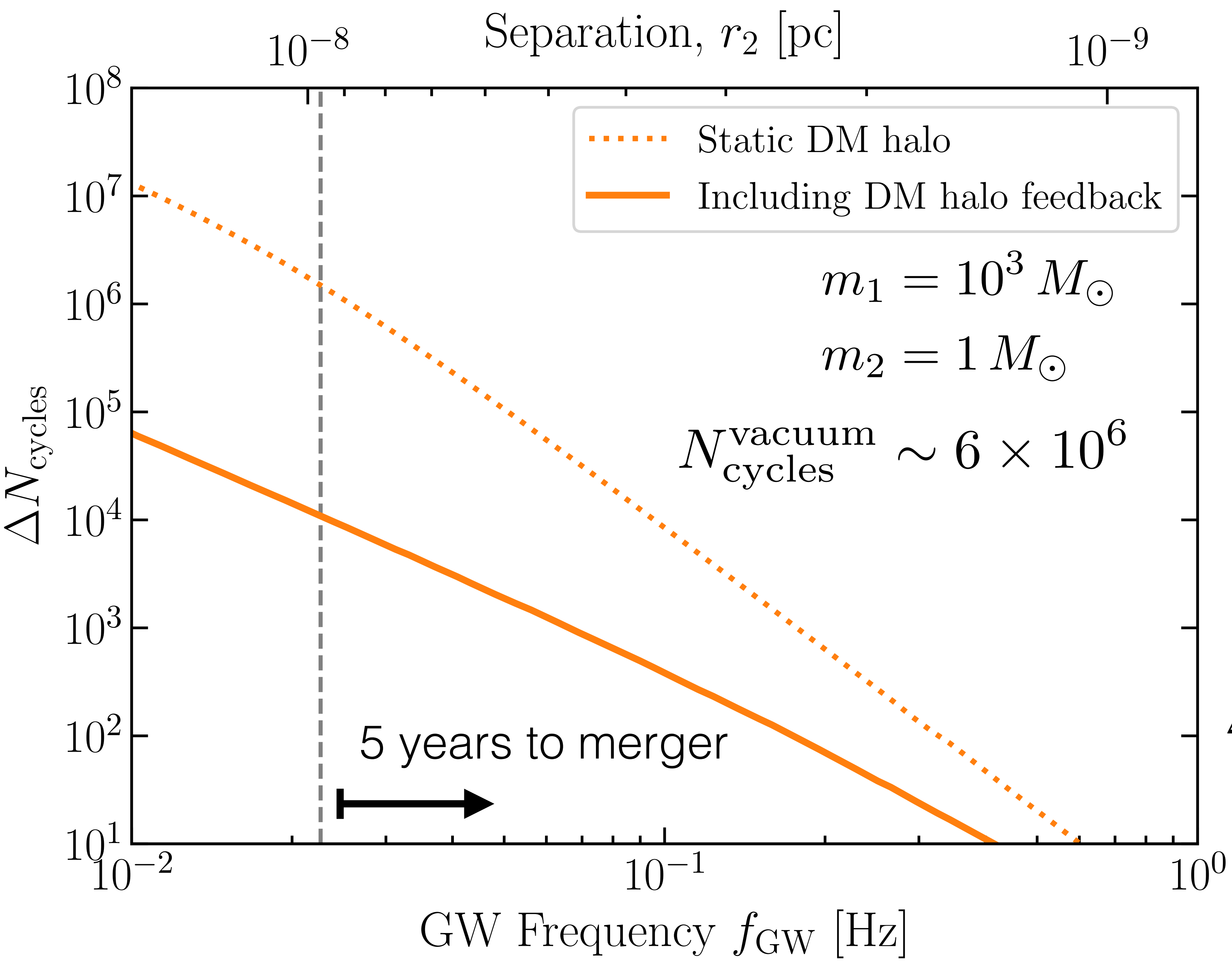






Sizing up the dephasing

[**BJK**, Nichols, Gaggero & Bertone, 2002.12811]



Assuming:

- quasi-circular orbits
- Newtonian dynamics
- Isotropic DM spike

$$\Delta N_\mathrm{cycles} \sim \mathcal{O}\left(10^4\right) \text{ cycles}$$
$$\sim \%\text{-level effect}$$

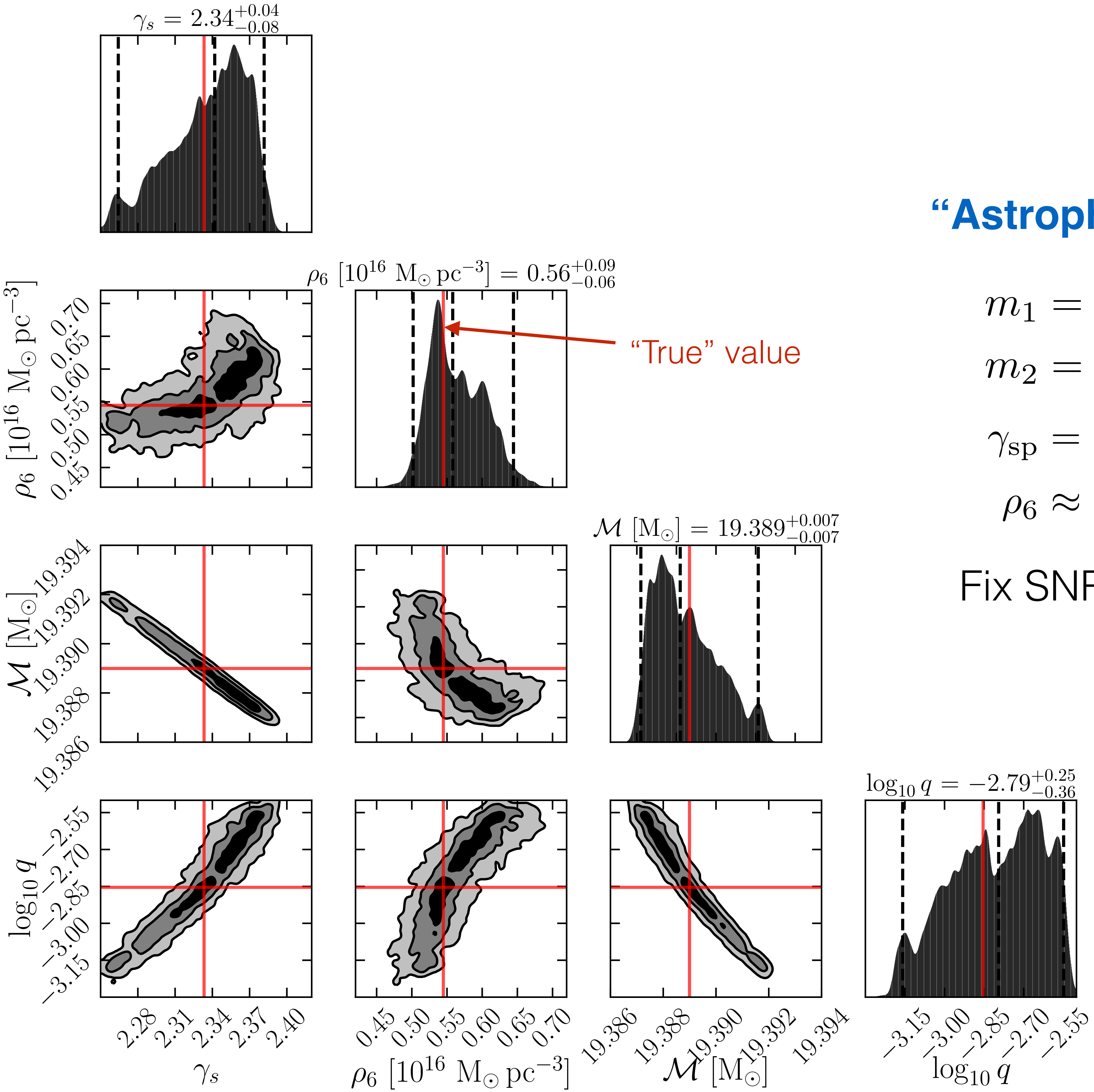
These systems are **statistically distinguishable** from a GR-in-vacuum system (and from other environmental effect)!

[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154; Cole et al., 2211.01362]

Measurability

[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]

[Code: https://github.com/adam-coogan/pydd]



"Astrophysical" scenario

$$m_1 = 10^3\ M_\odot$$

$$m_2 = 1\ M_\odot$$

$$\gamma_{\rm sp} = 7/3 \approx 2.3333\ldots$$

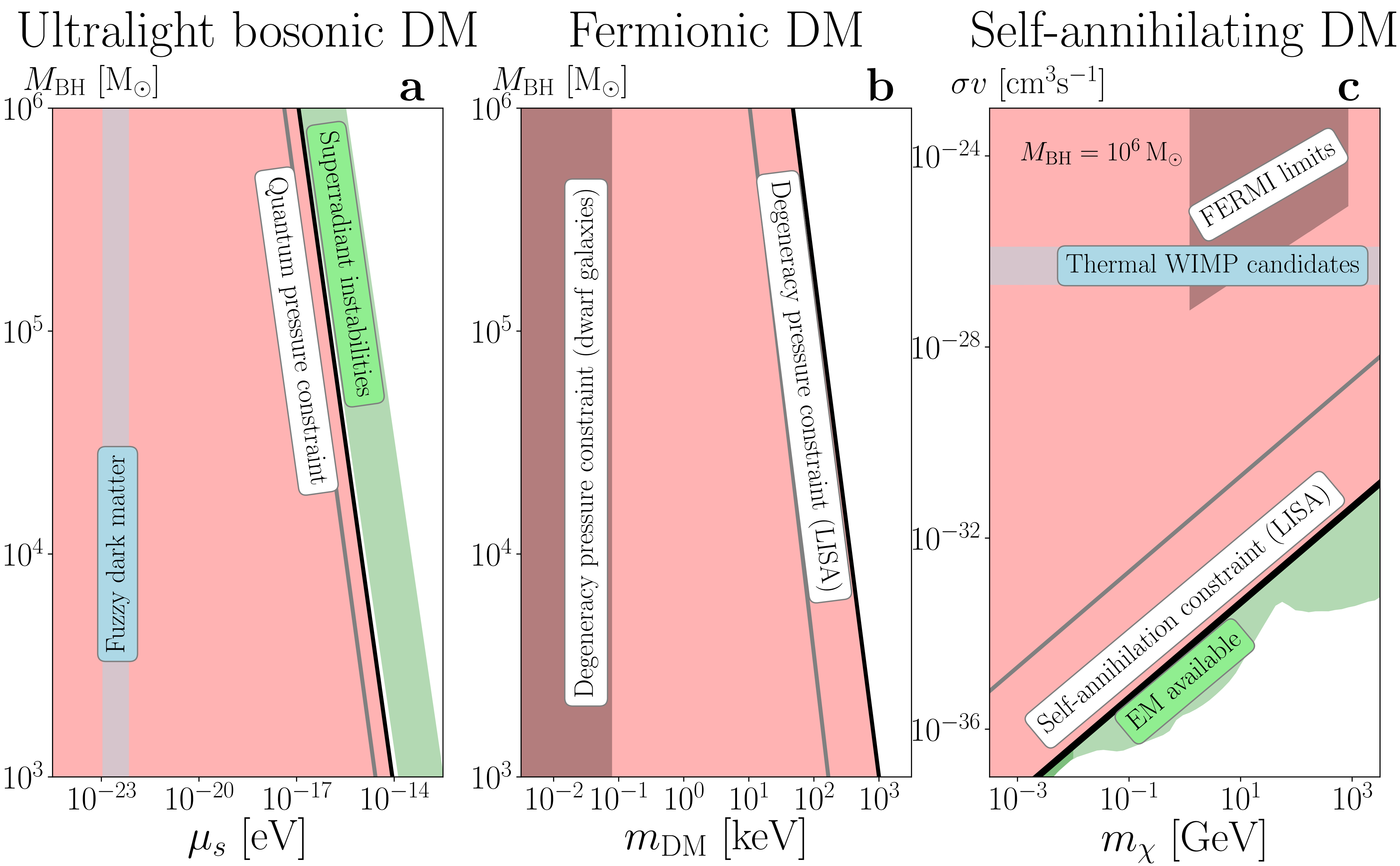
$$\rho_6 \approx 5.45 \times 10^{15}\ M_\odot\,\mathrm{pc}^{-3}$$

Fix SNR = 15 (~ 76 Mpc)

Projections done with LISA.
Next stop: LGWA!

Nature of Dark Matter

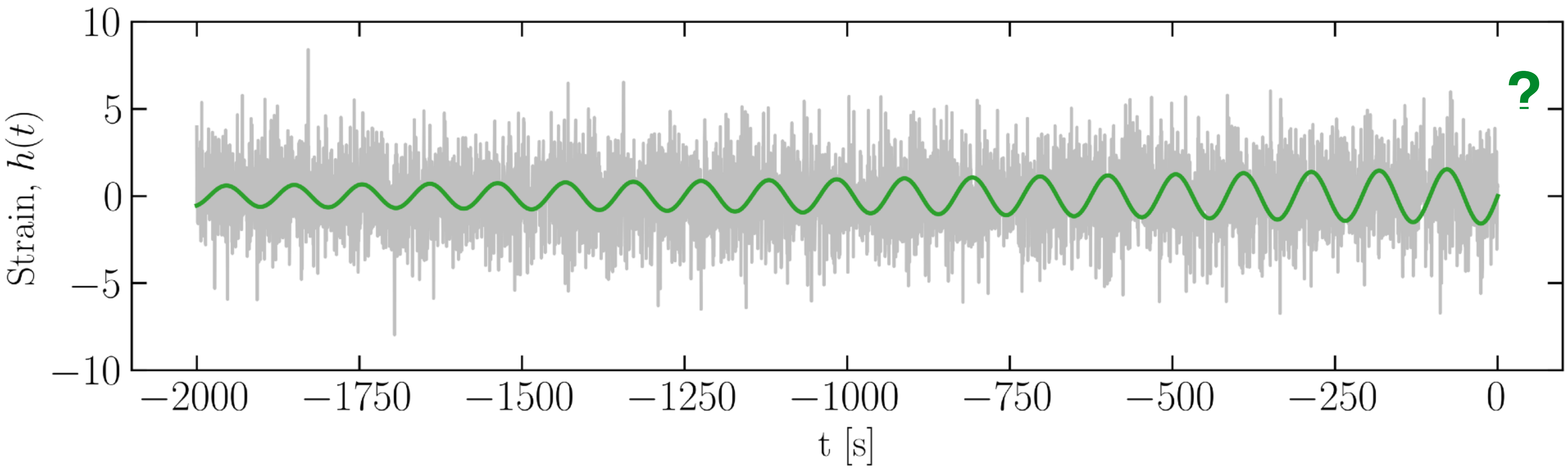
Red regions would be ruled out by observation of a DM spike!



Measurement of density profile would allow us to distinguish DM models and spike formation mechanisms!

[Hannuksela et al., 1906.11845; see also Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

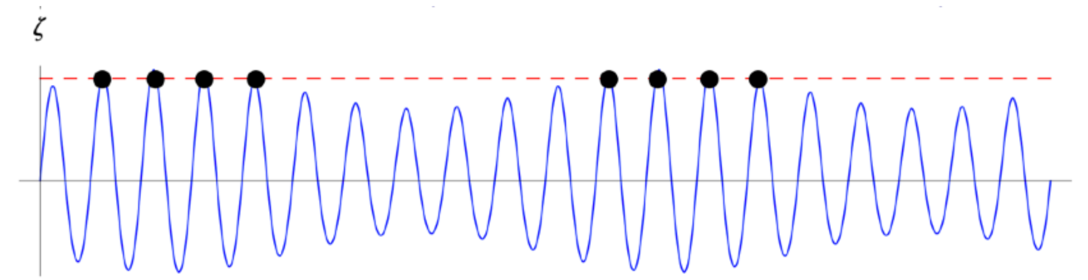
Next Steps in



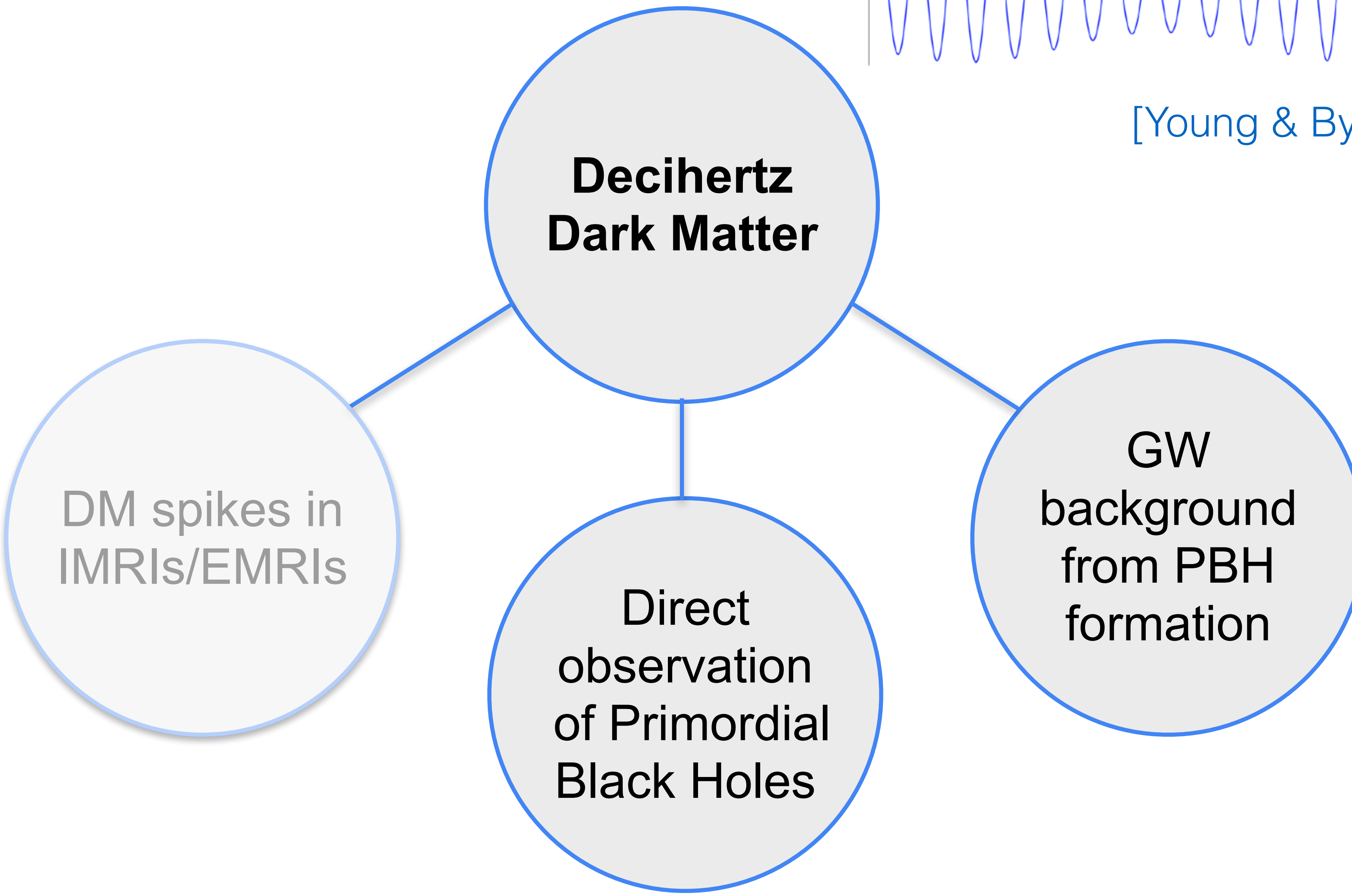
Still need to address:

- **Realistic Waveforms** - need to go post-Newtonian, extend to eccentric orbits etc.
- **Spike formation scenarios** - how common are DM spikes in the Universe? What are their typical properties?
- **Search strategies** - how do we pick these signals out of the noise? (Large parameter space of possible models - template searches may be challenging)

Primordial Black Holes



[Young & Byrnes, 1411.4620]



Primordial Black Holes (PBHs) could form in the early Universe ($z \gg 10^8$) from large over-densities

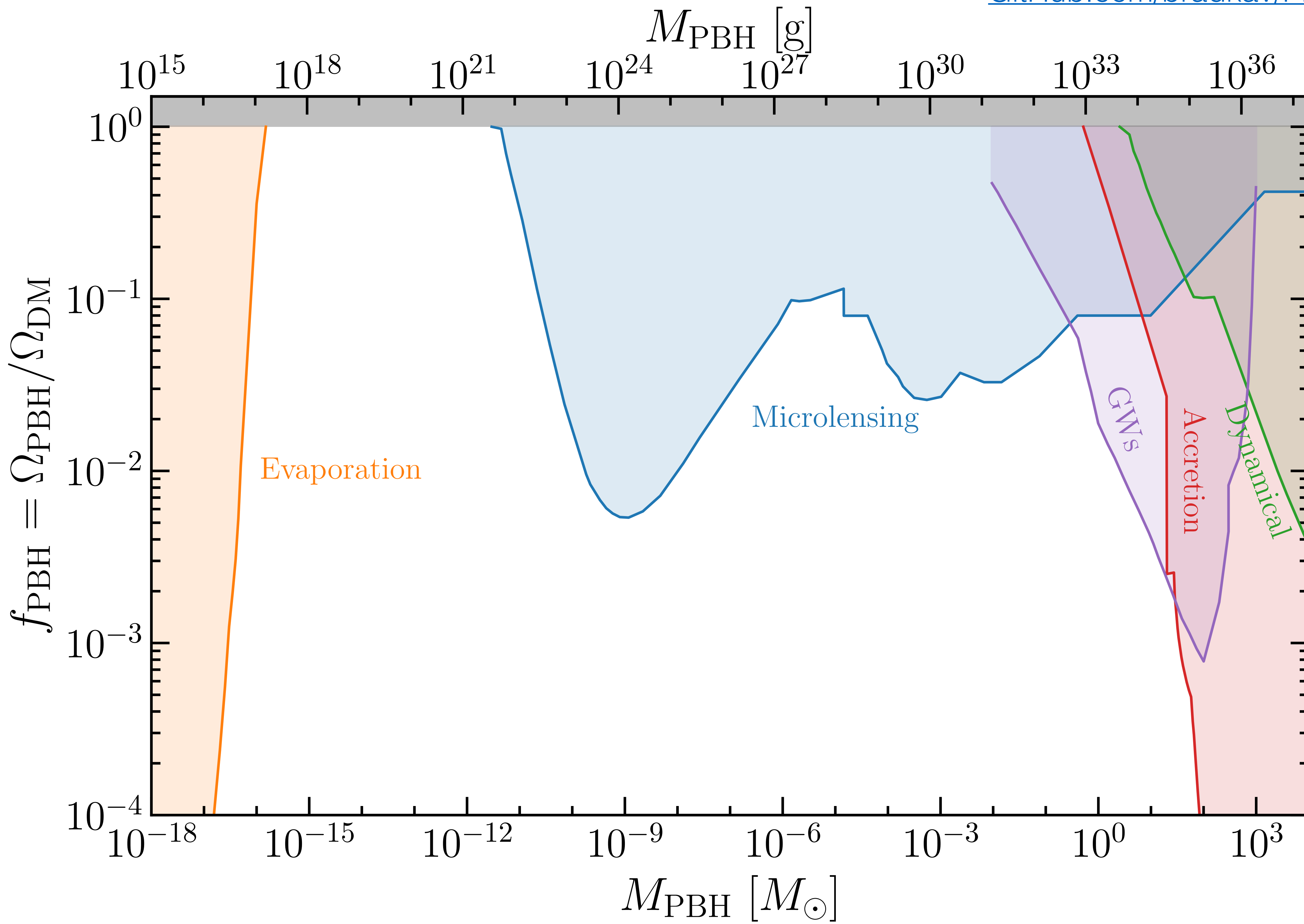
[Zel'dovich & Novikov (1967), Hawking (1971), Carr & Hawking (1974), Carr (1975)]

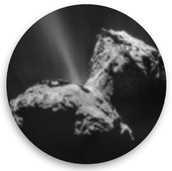
Mass roughly given by mass inside horizon at time of formation:

[Green & Liddle, astro-ph/9901268]

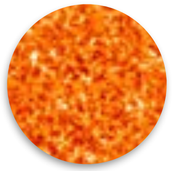
PBH Constraints

[Green & **BJK**, 2007.10722;
GitHub.com/bradkav/PBHbounds]

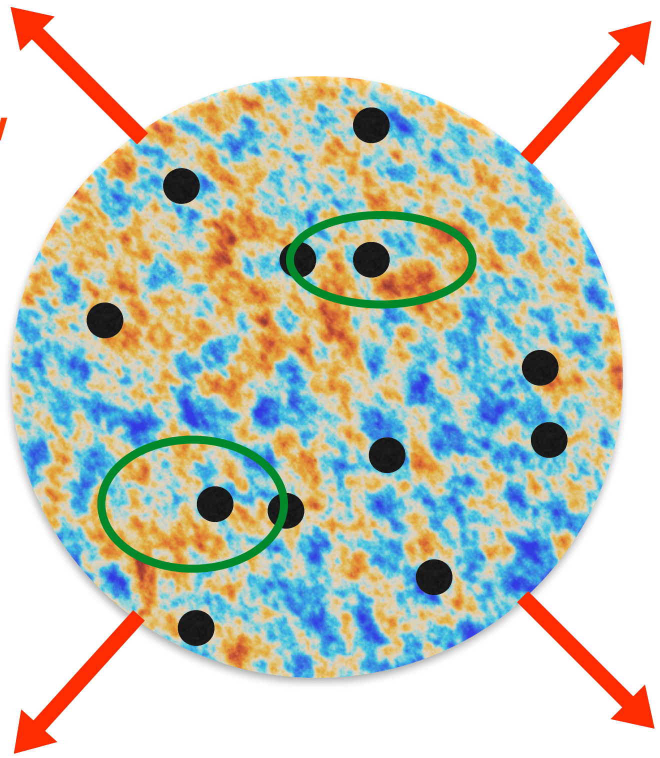






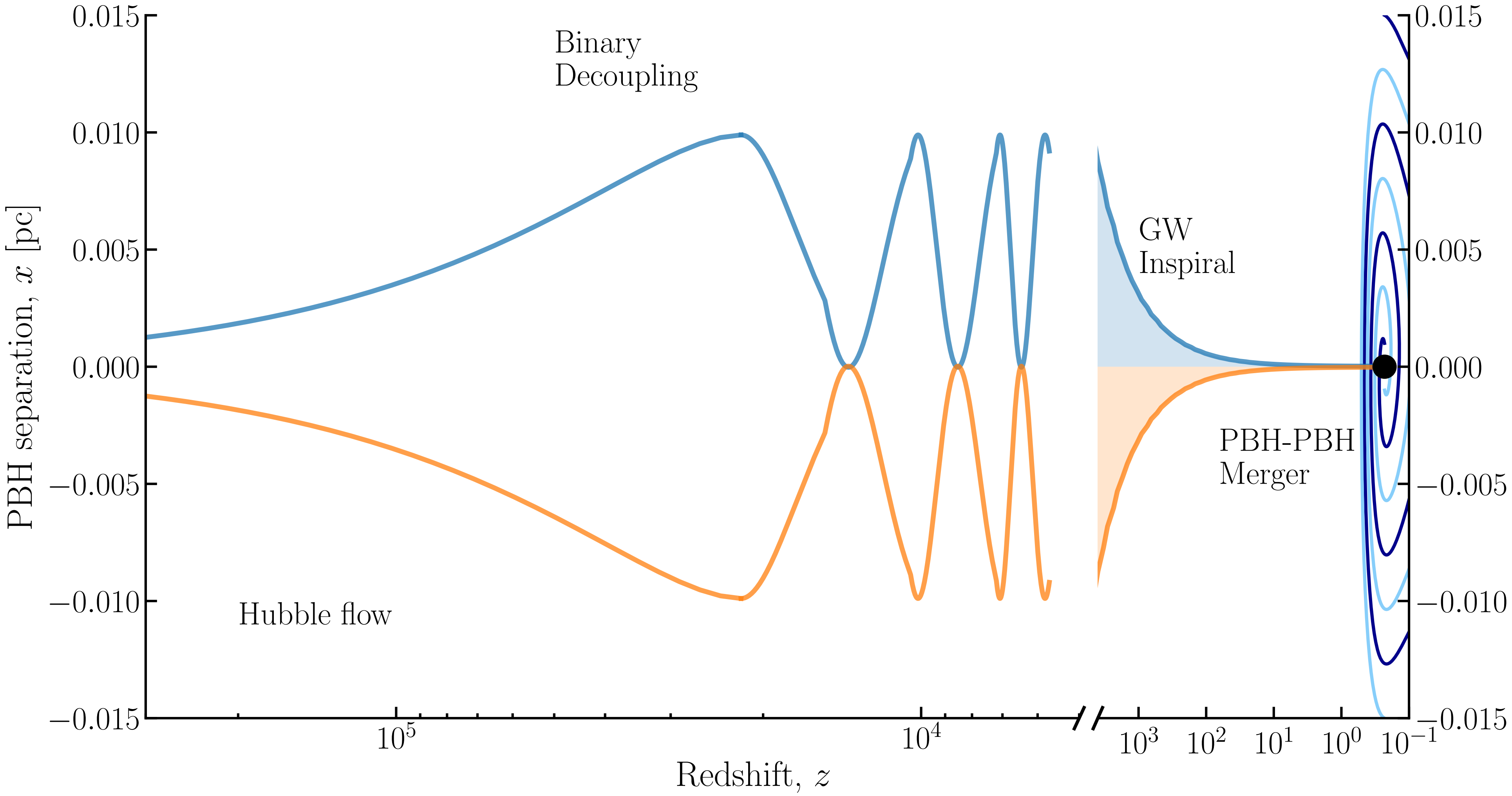



PBH Binary Formation



PBHs which are close enough to each other in the early Universe may form binaries!

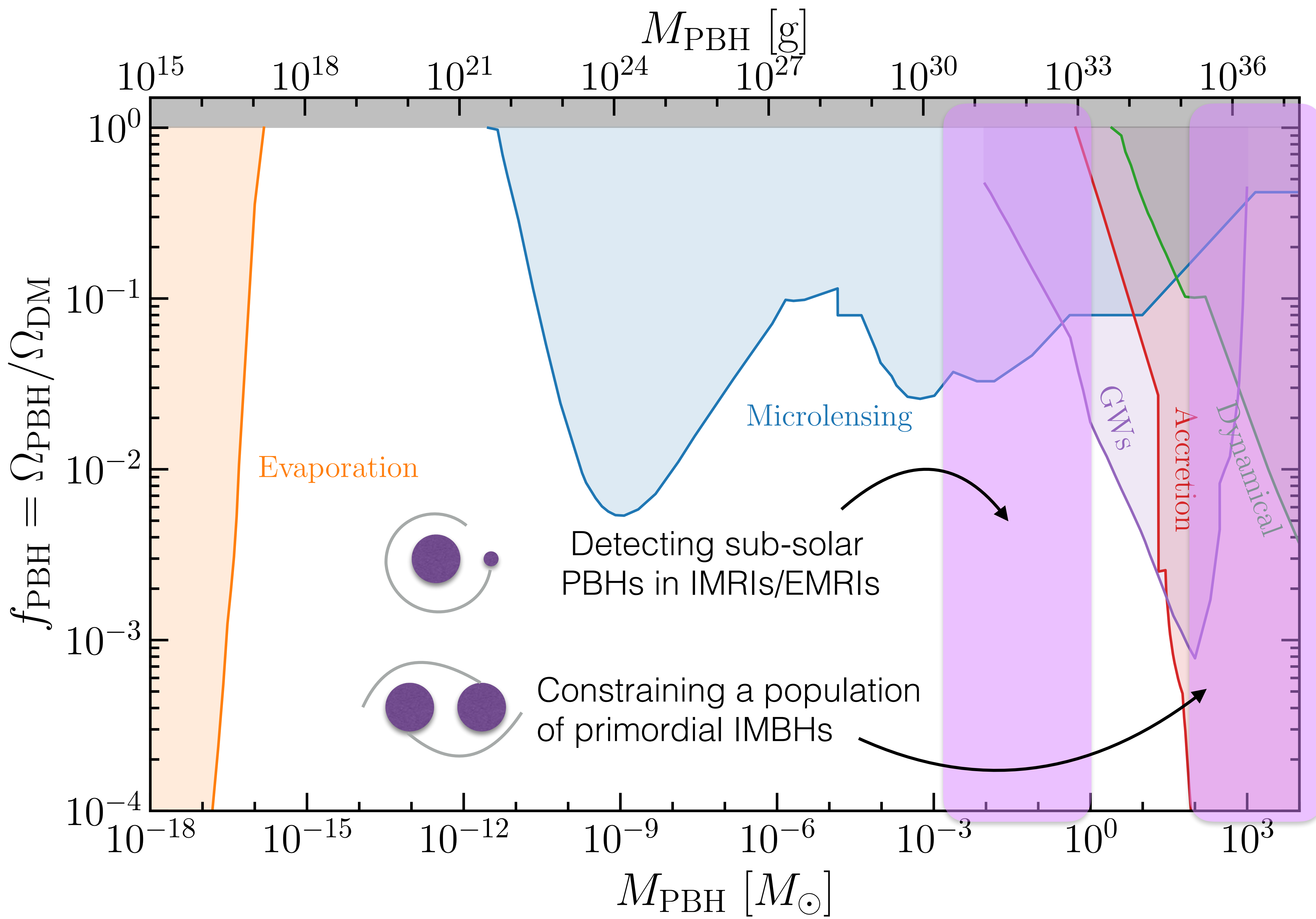
[Nakamura et al, astro-ph/9708060,
Sasaki et al, 1603.08338, and others]



[Ali-Haïmoud et al., 1709.06576, **BJK**, Gaggero & Bertone, 1805.09034]

Merger Rate Constraints?

[Green & **BJK**, 2007.10722;
GitHub.com/bradkav/PBHbounds]

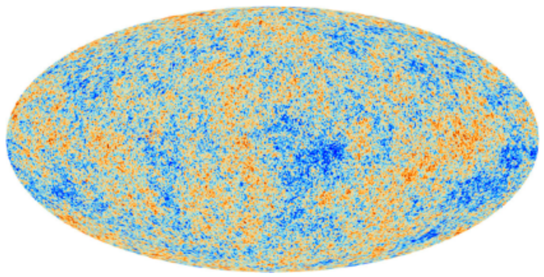


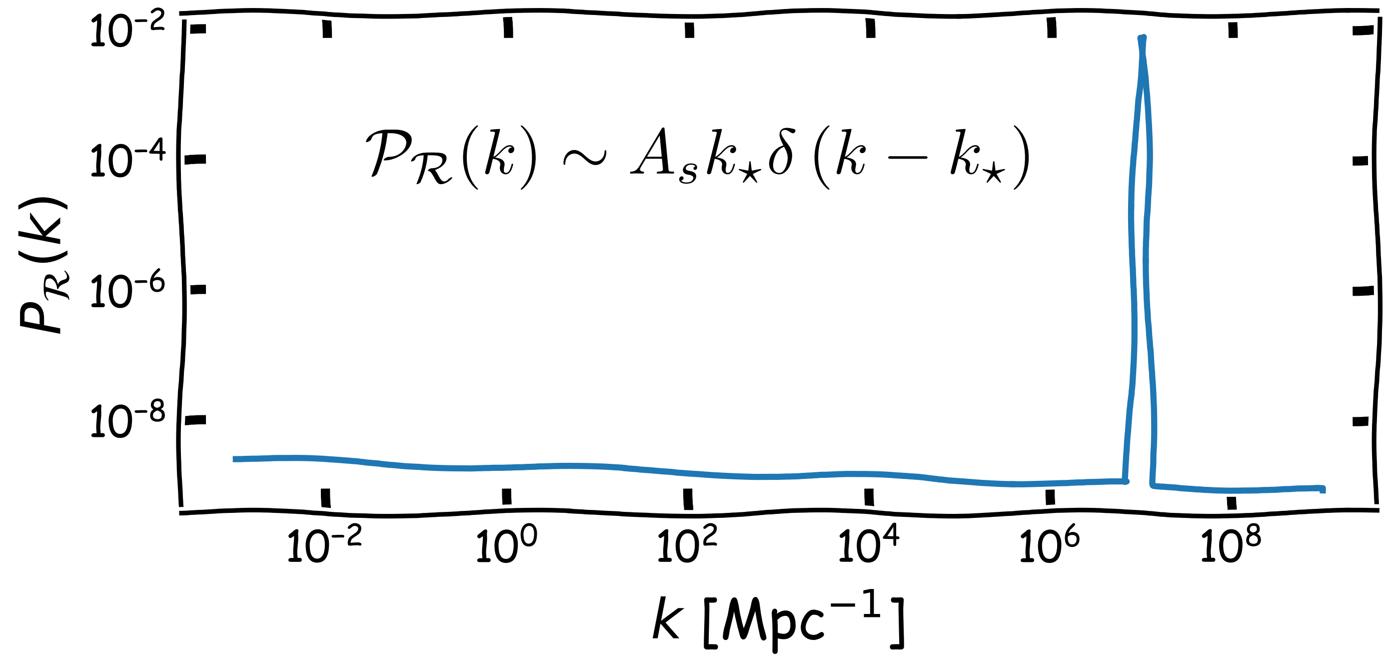
Decihertz GWs

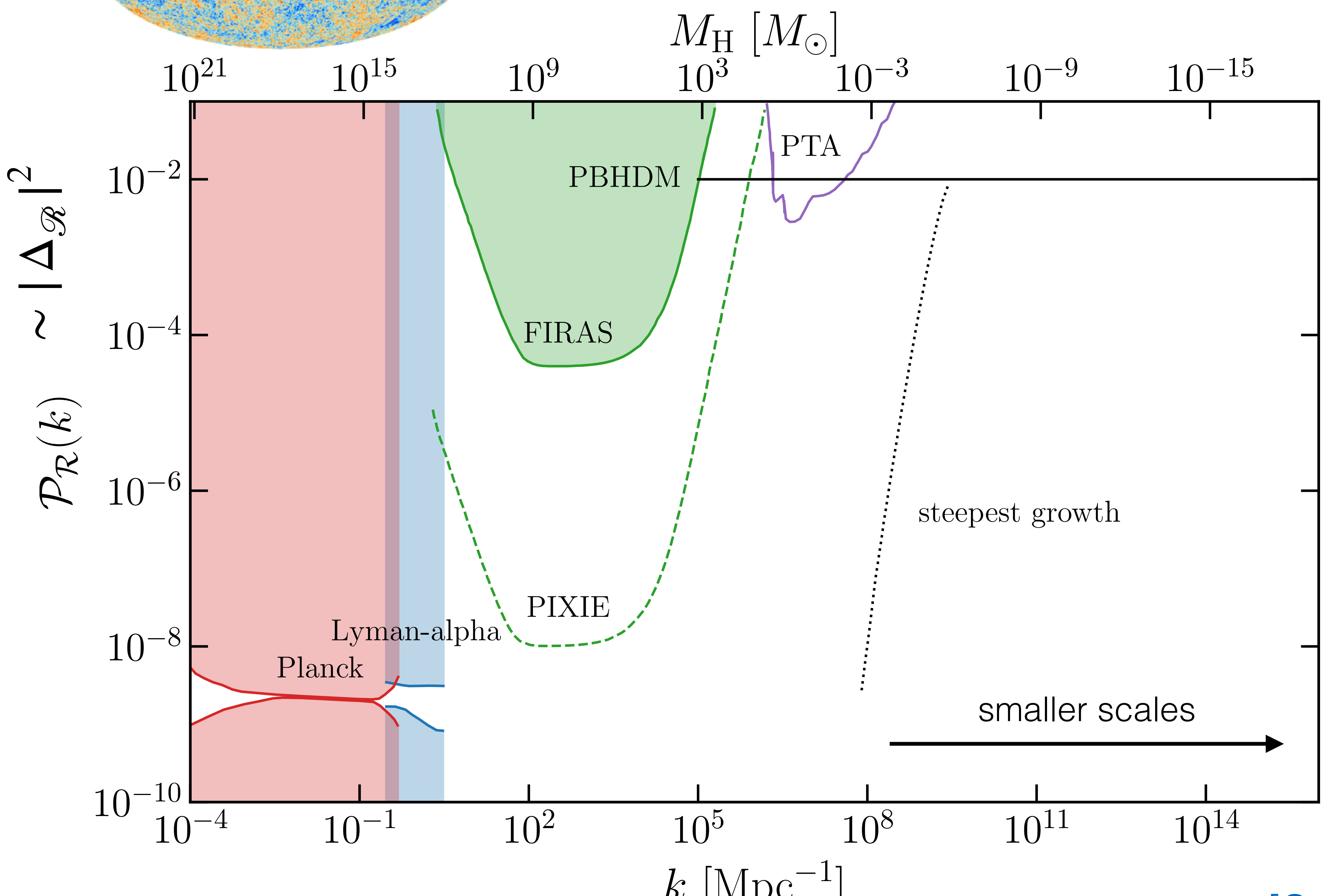
[See e.g. 2012.02786, 2109.02170]

Making a PBH

Consider adding a ‘spike’ in the primordial power spectrum:

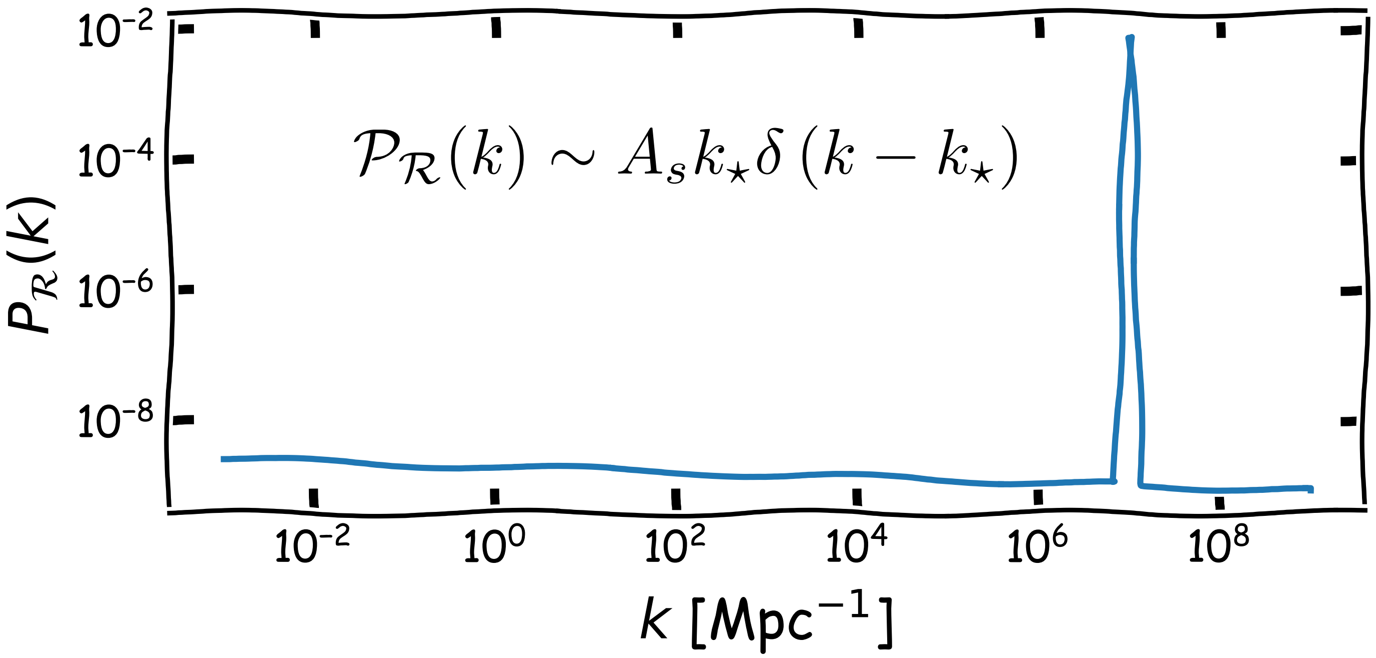




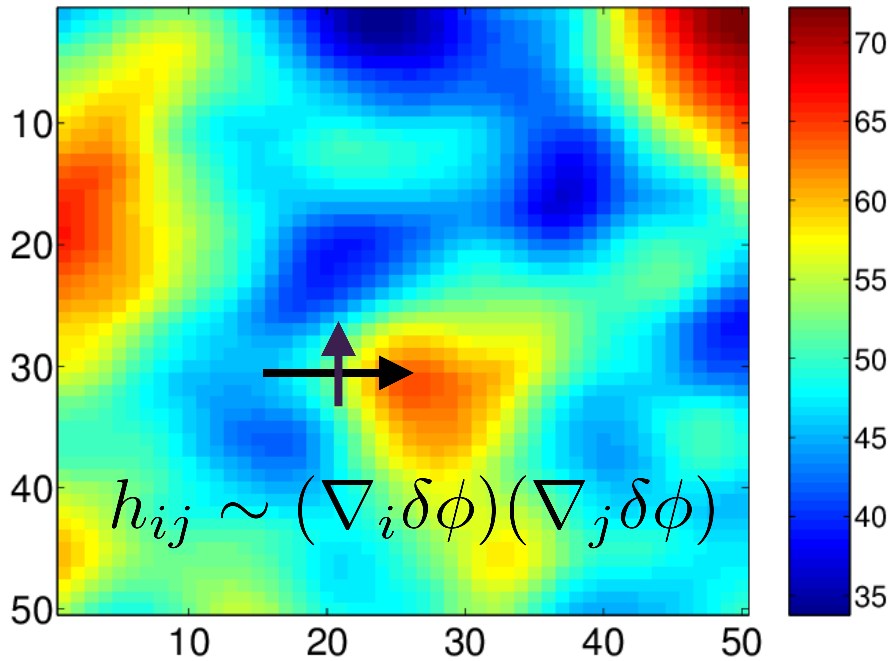


[Green & **BJK**, 2007.10722]

GWs from PBH Formation



PBHs may be formed from enhanced primordial scalar perturbations



At second order, these scalar perturbations can source tensor perturbations, leading to stochastic Gravitational waves

↓

Scalar-induced Gravitational Waves (**SIGWs**)

For perturbations on a scale $k_\star$, $M_{\rm PBH} \simeq 1.4 \times 10^{13} M_\odot \left(\frac{k_\star}{\rm Mpc^{-1}}\right)^{-2}$

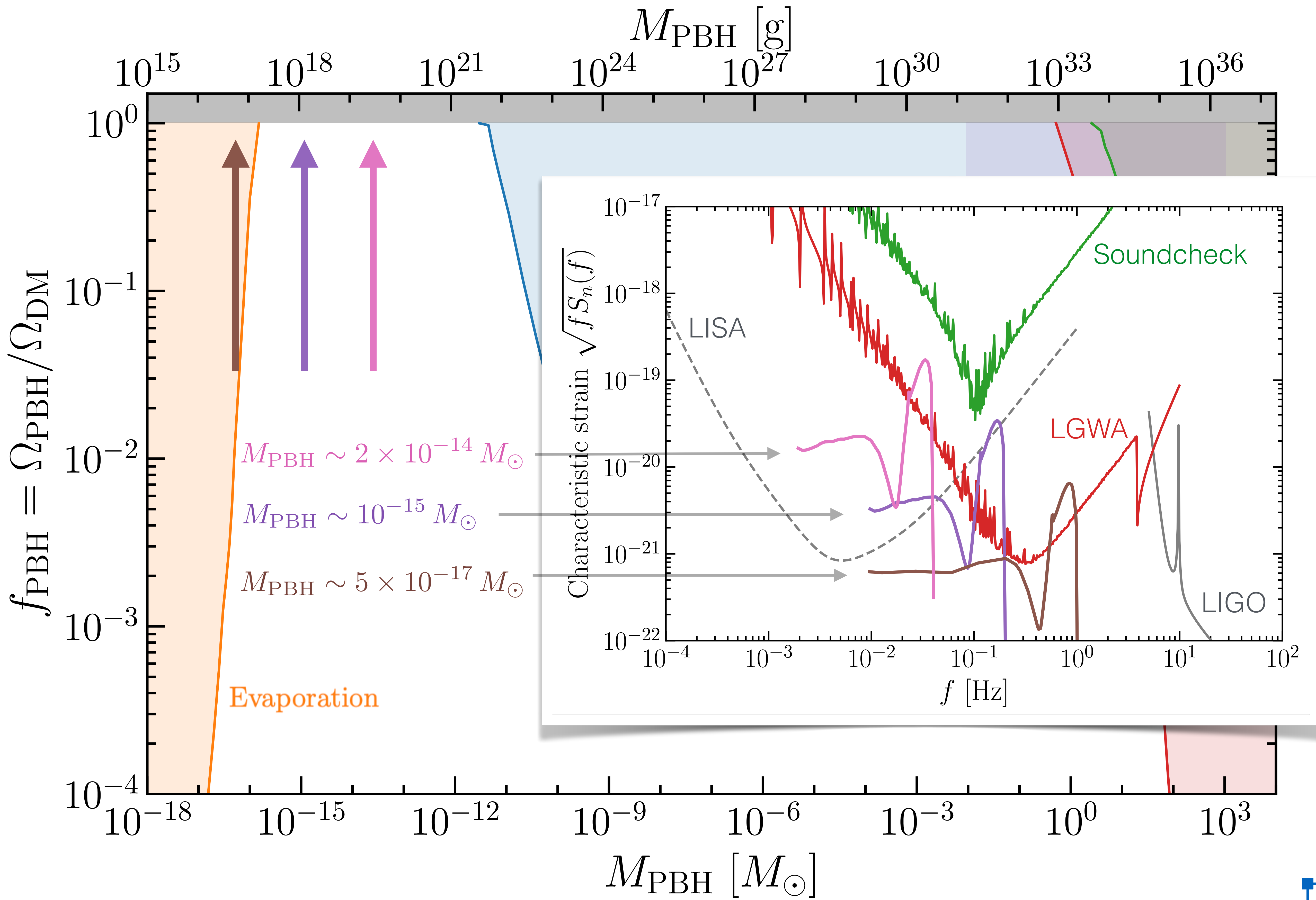
The typical GW frequency scales as $f_{\rm GW}^{\rm peak} \sim k_\star$, giving:

$$f_{\rm GW}^{\rm peak} = 3 \times 10^{-9} \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2} {\rm Hz}$$

[Domènech, 2109.01398]
[astro-ph/0407611, 0812.4339, 1012.4697]

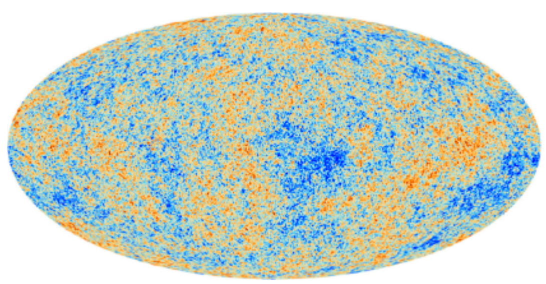
Scalar-induced GWs

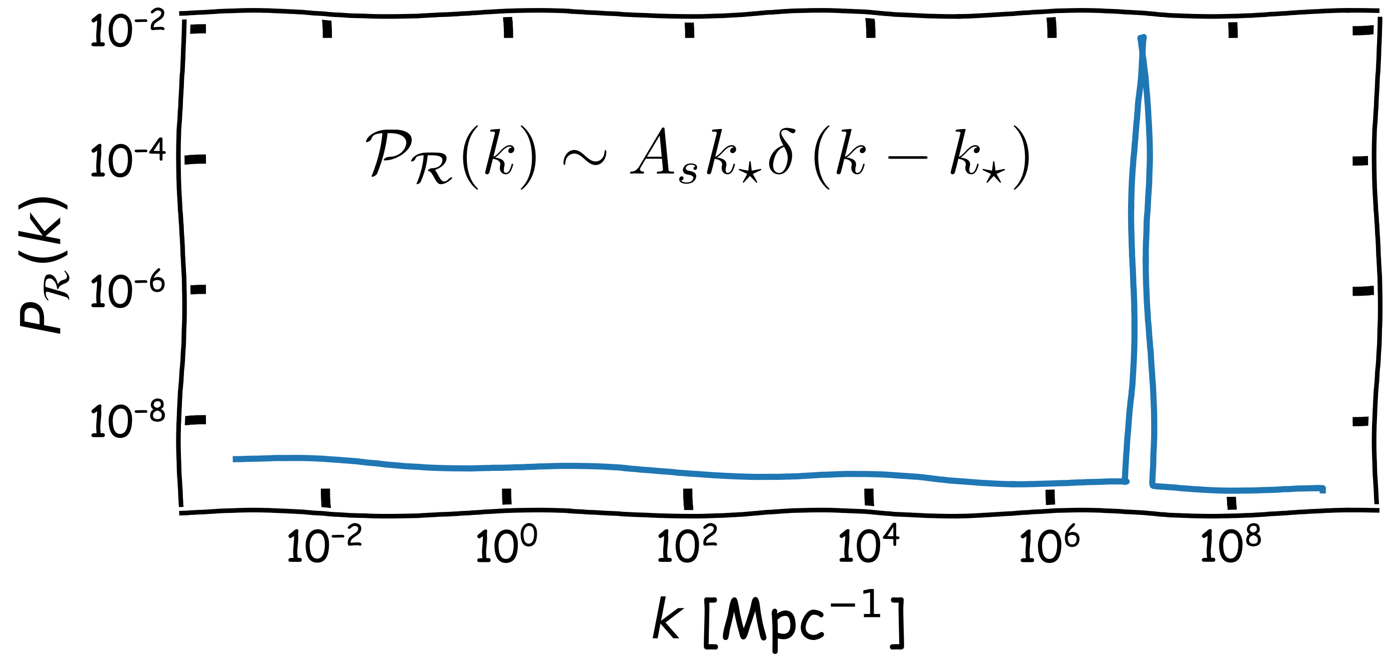
[Preliminary calculations by Marco Chianese]

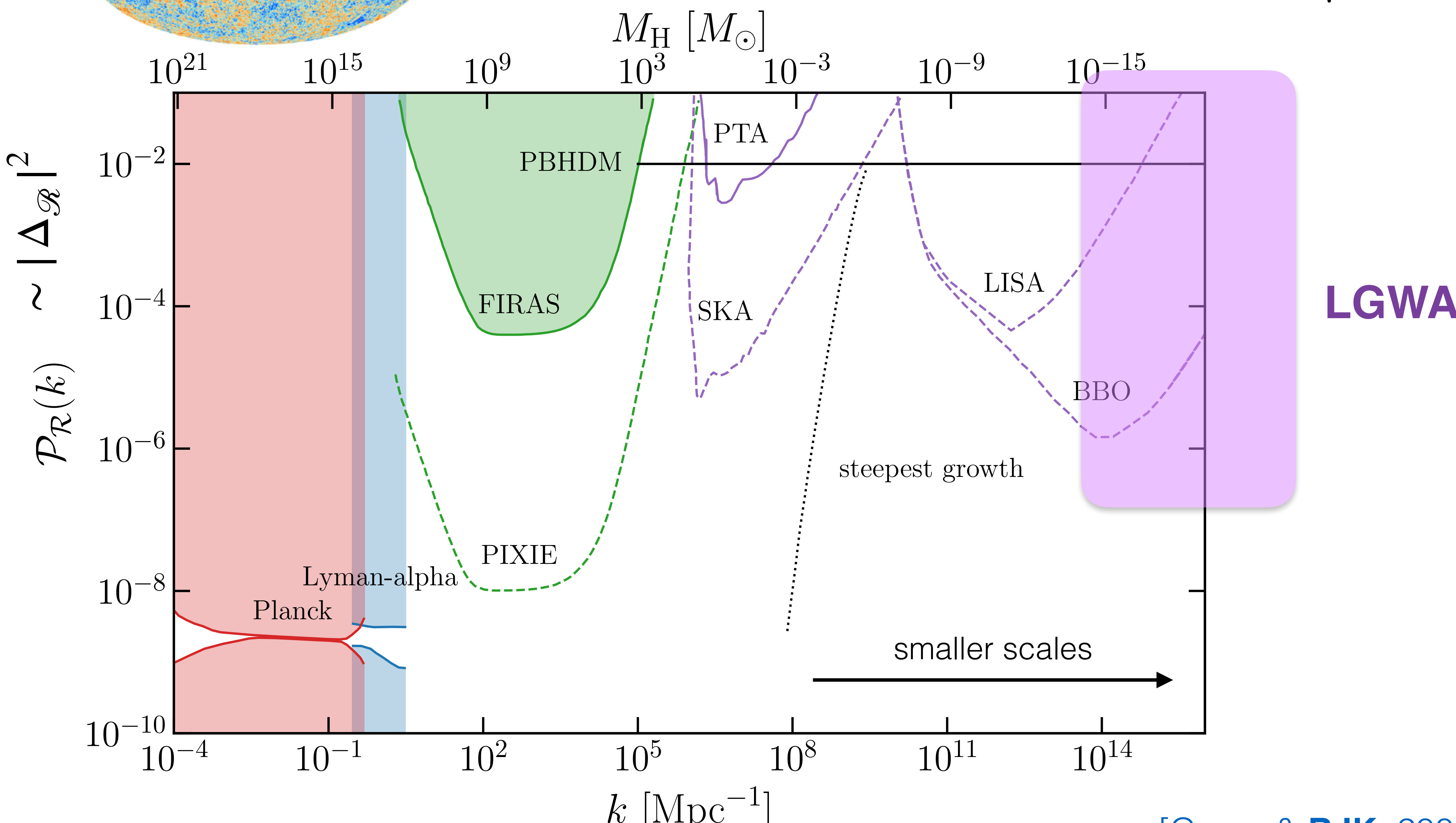


Constraining the power spectrum

Consider adding a 'spike' in the primordial power spectrum:







[Green & **BJK**, 2007.10722]

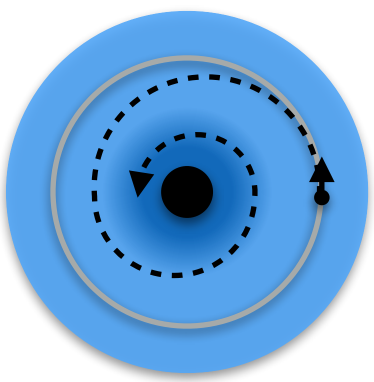
Conclusions

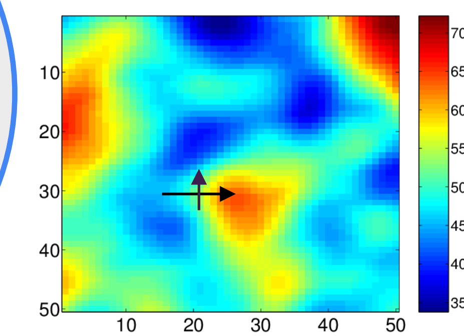
Decihertz Dark Matter

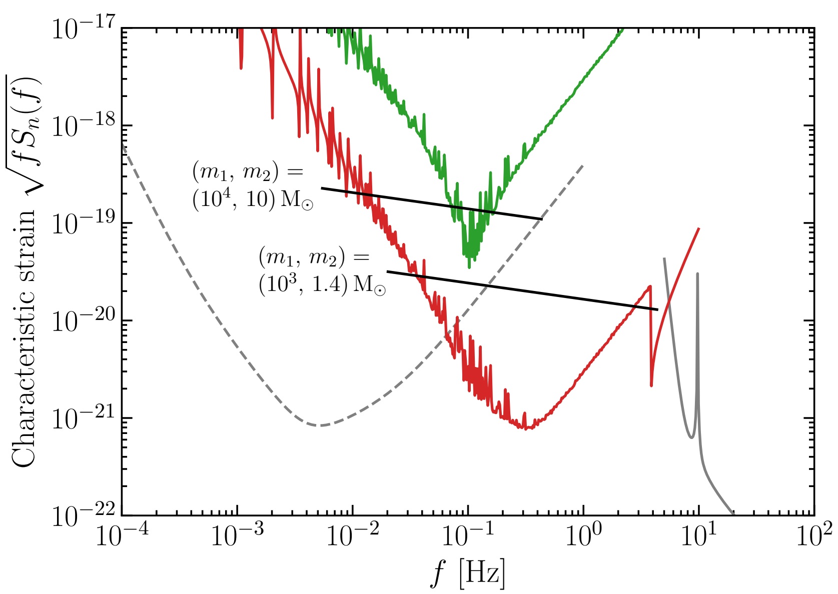
DM spikes in IMRIs/EMRIs

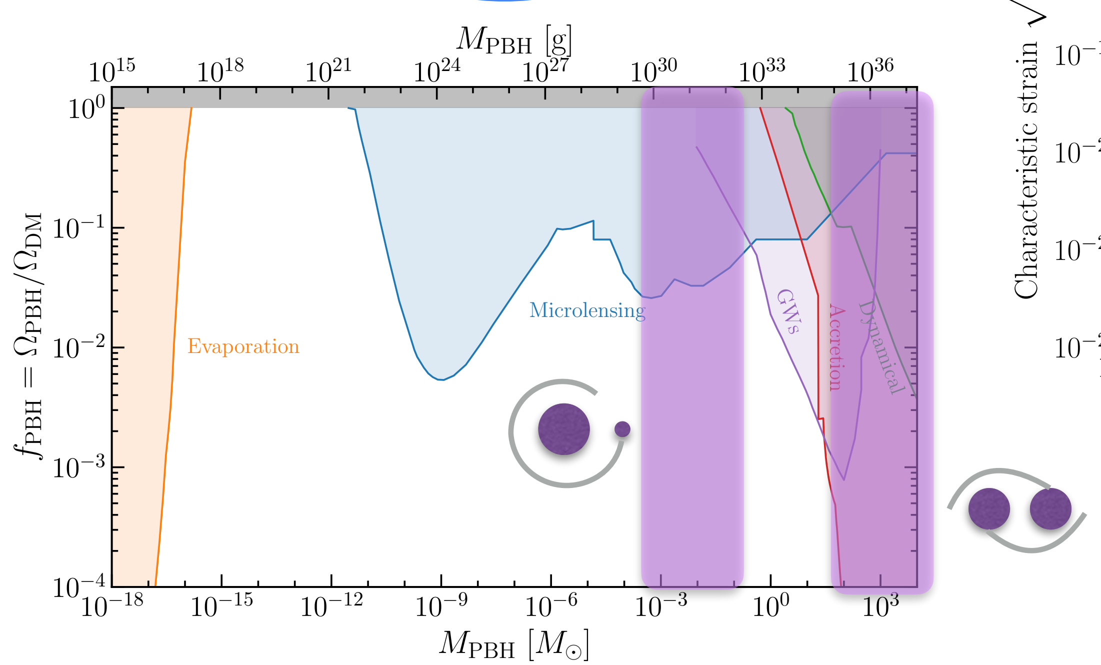
Direct observation of Primordial Black Holes

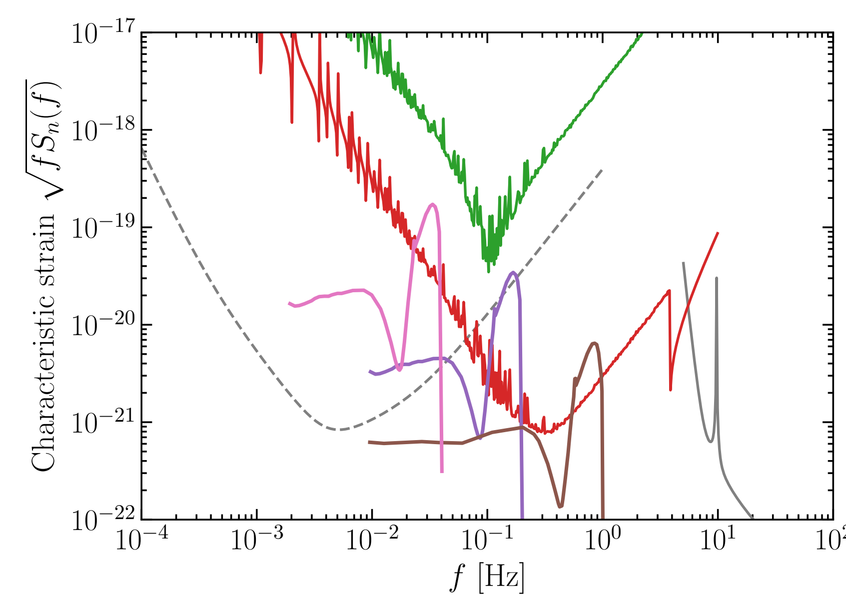
GW background from PBH formation











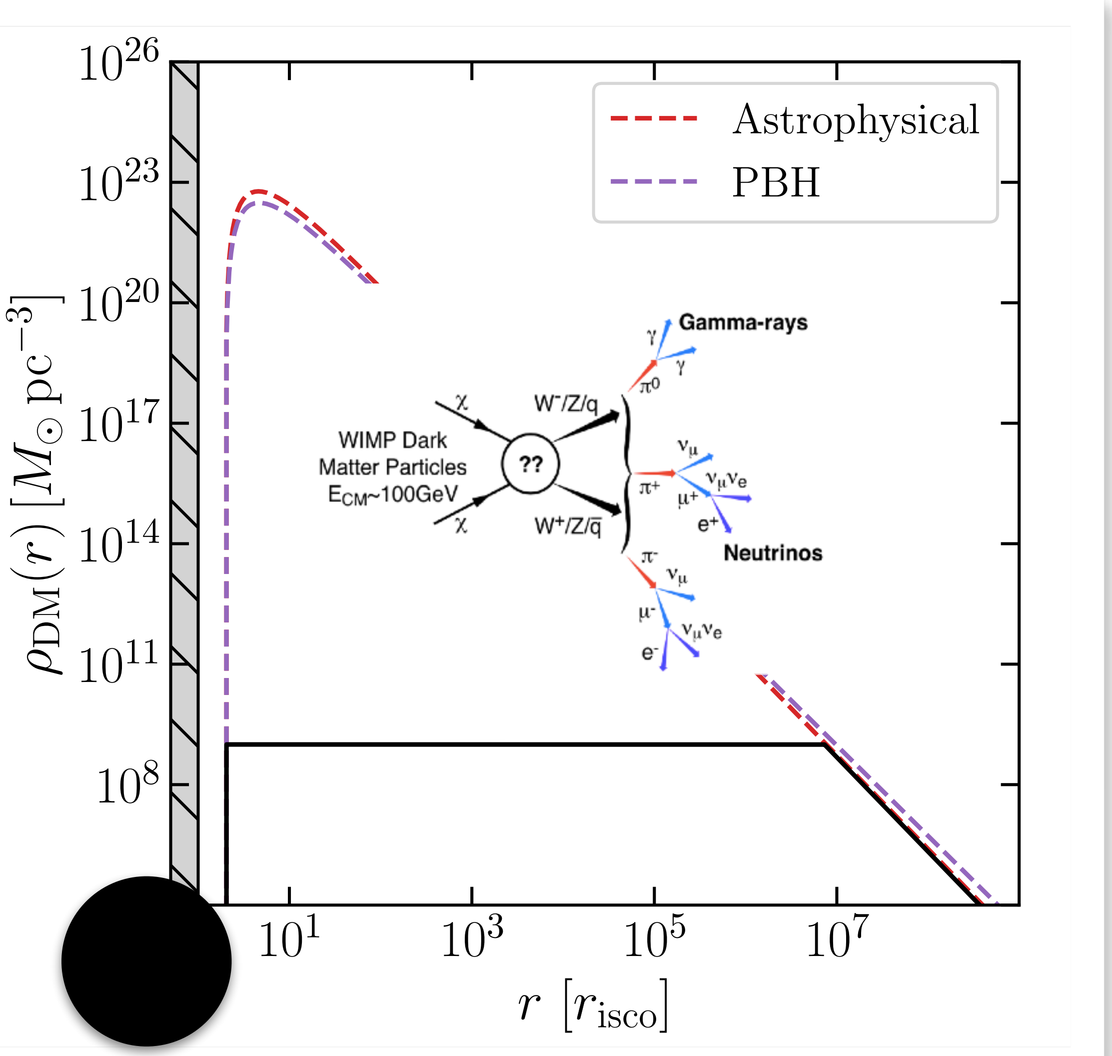
Backup Slides

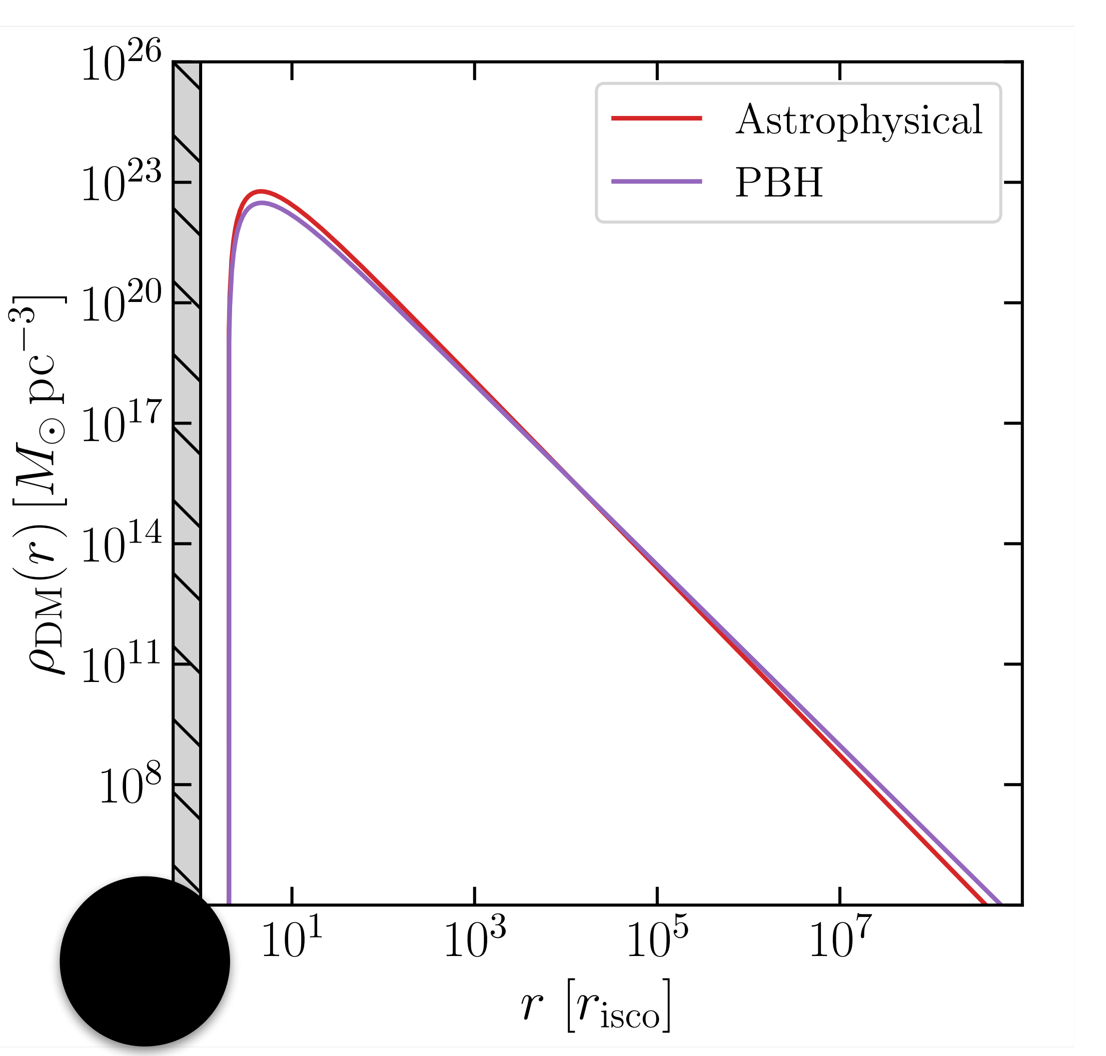
Survival of the Spike

$$m_1 = 10^3\, M_\odot \qquad \rho_\mathrm{DM} = \rho_6 \left(\frac{10^{-6}\,\mathrm{pc}}{r}\right)^{\gamma_\mathrm{sp}}$$

1) **DM properties:**

$$\gamma_\mathrm{sp} \sim 2 - 2.5$$





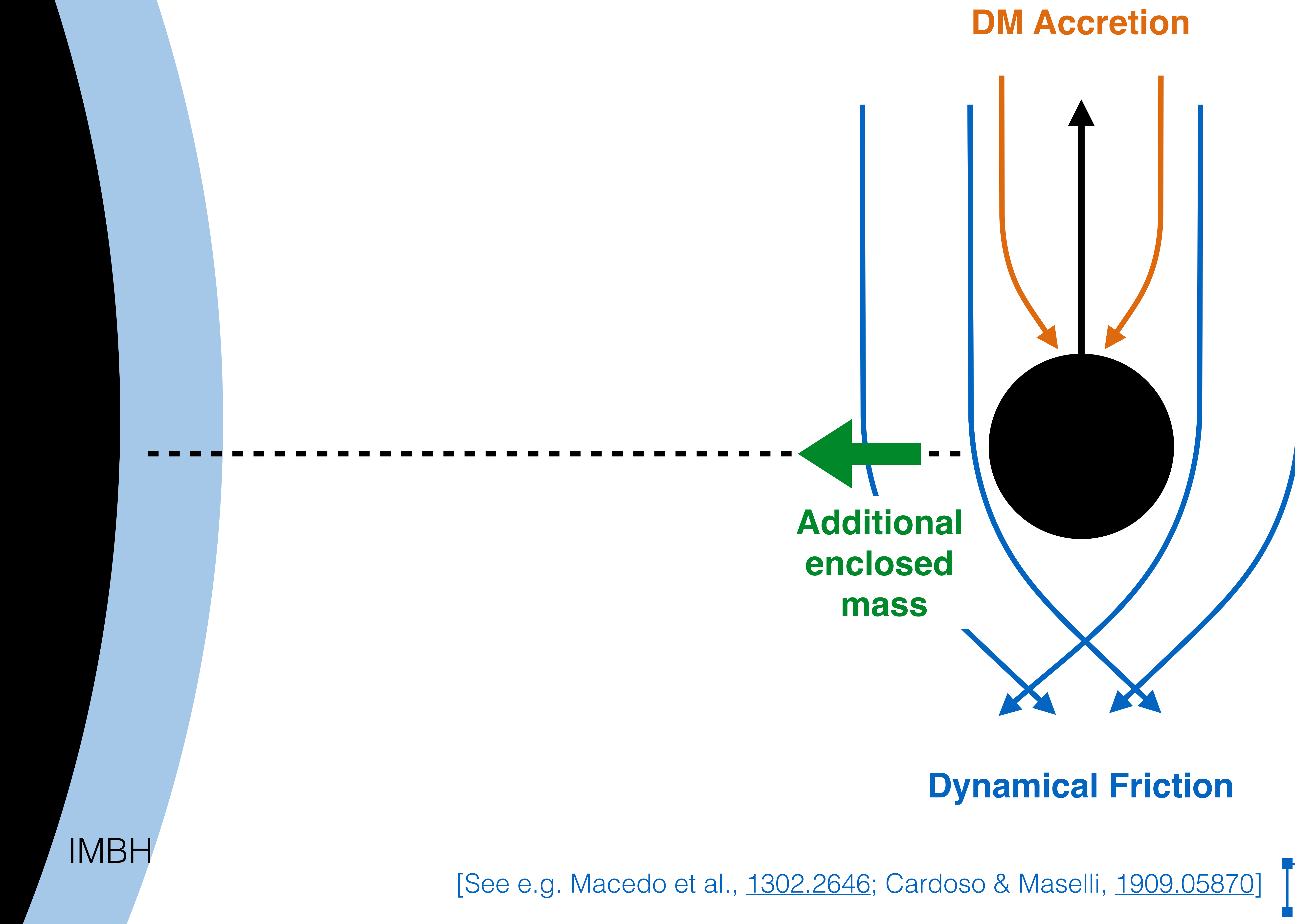
[E.g. Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

2) **BH environment:** Need a quiet life for the BH, not too many major mergers

→ Focus on IMBHs

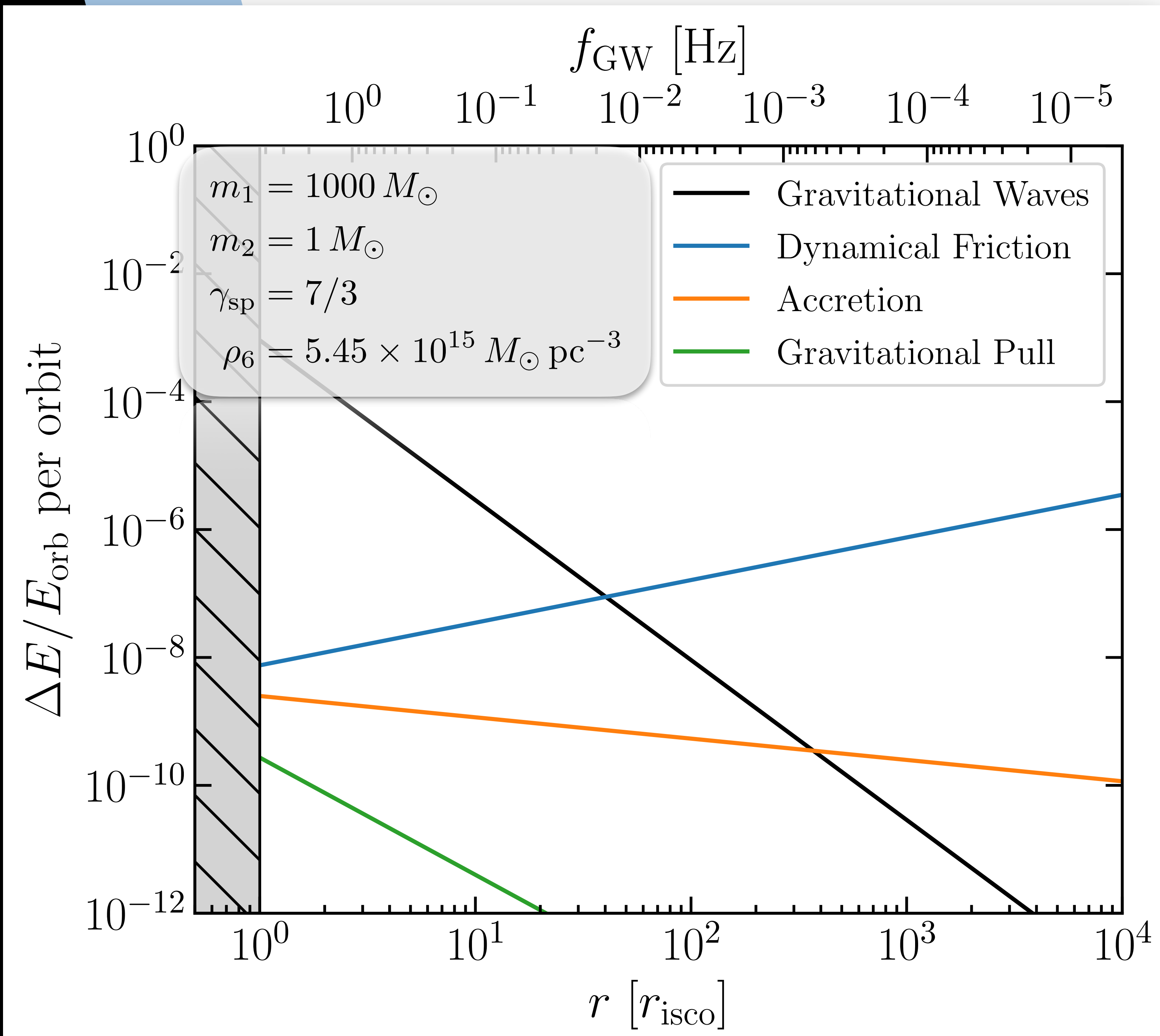
[E.g. Bertone & Merritt, astro-ph/0501555]

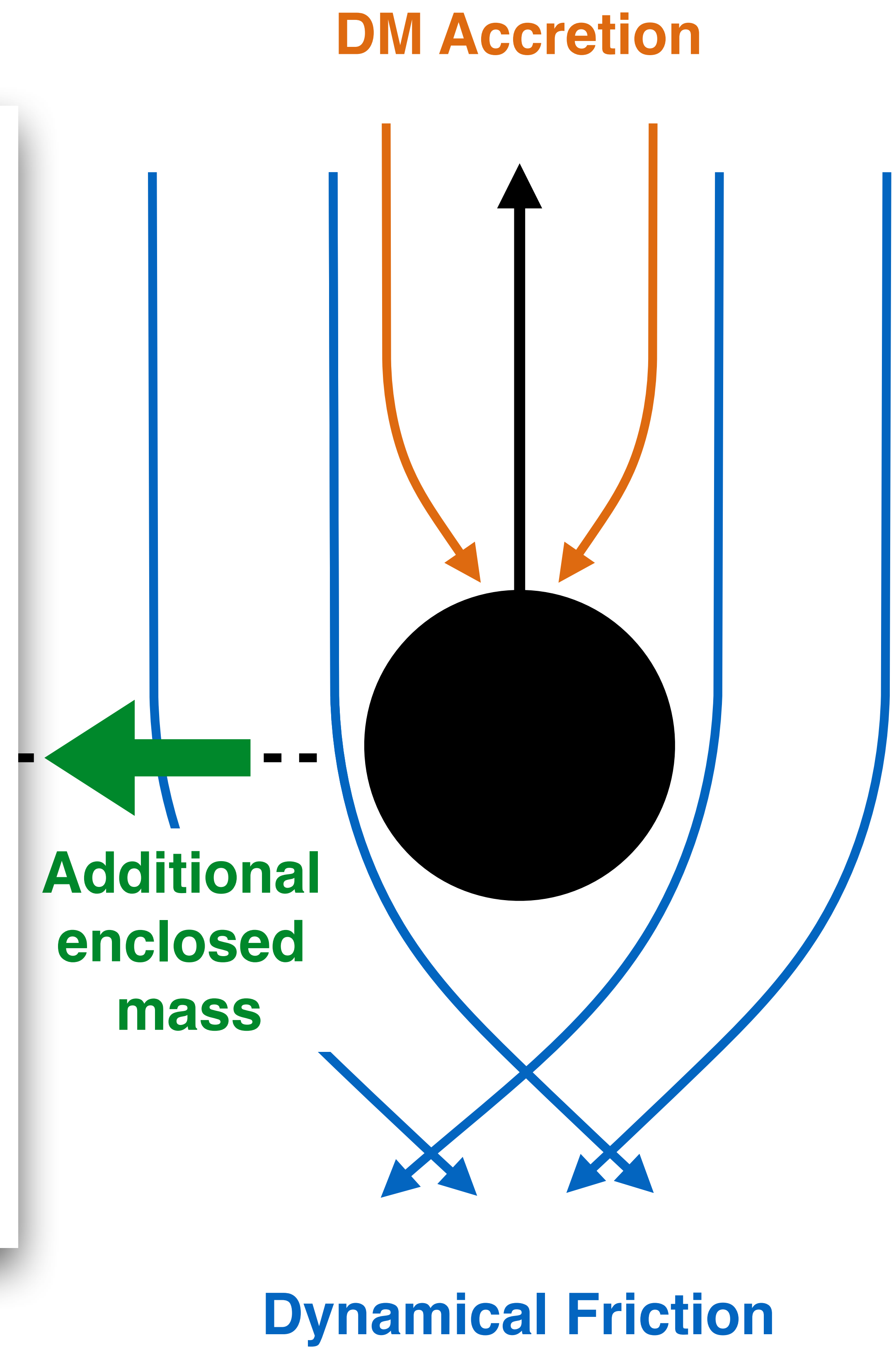
Impact of DM Spikes



[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Impact of DM Spikes

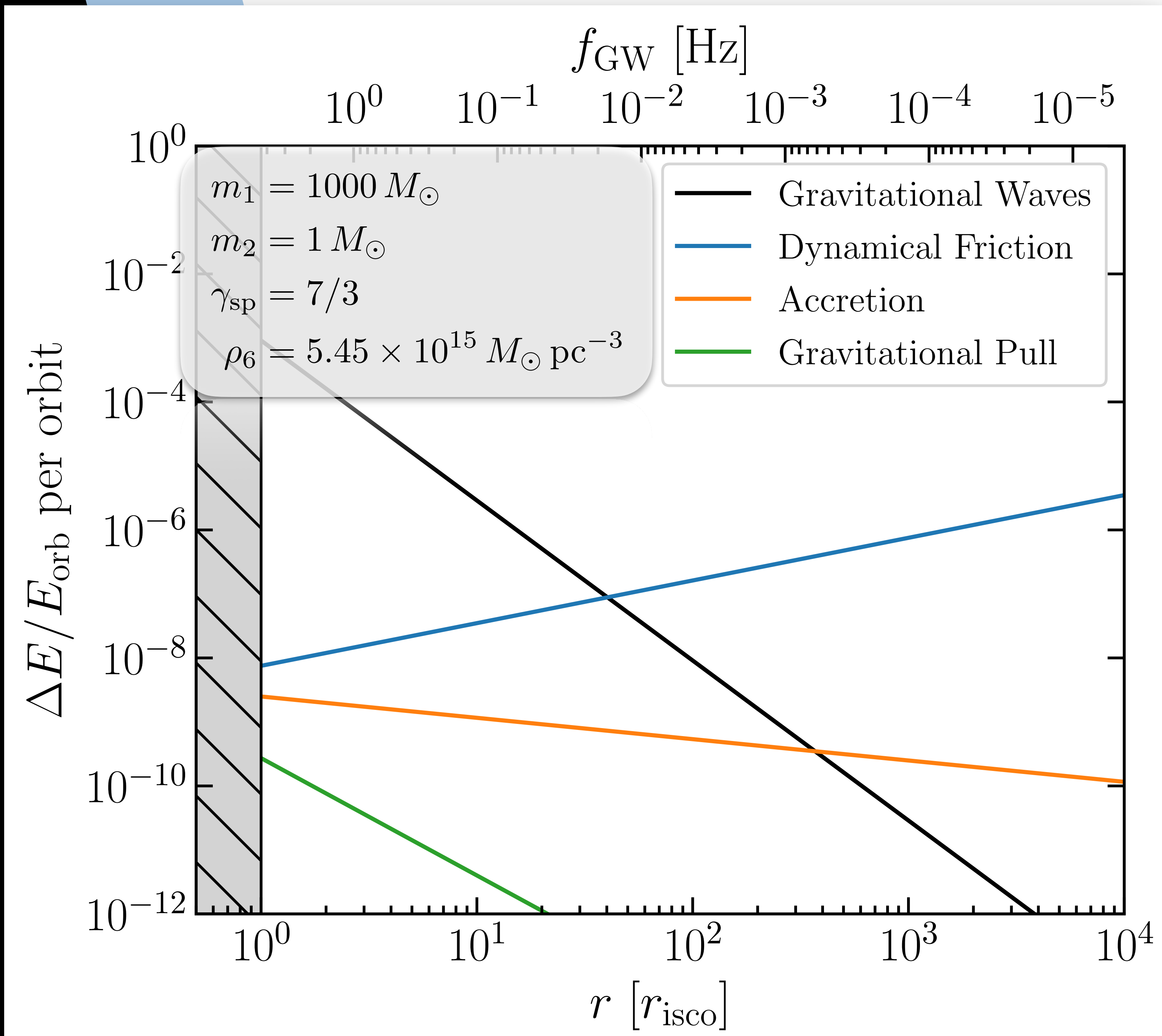


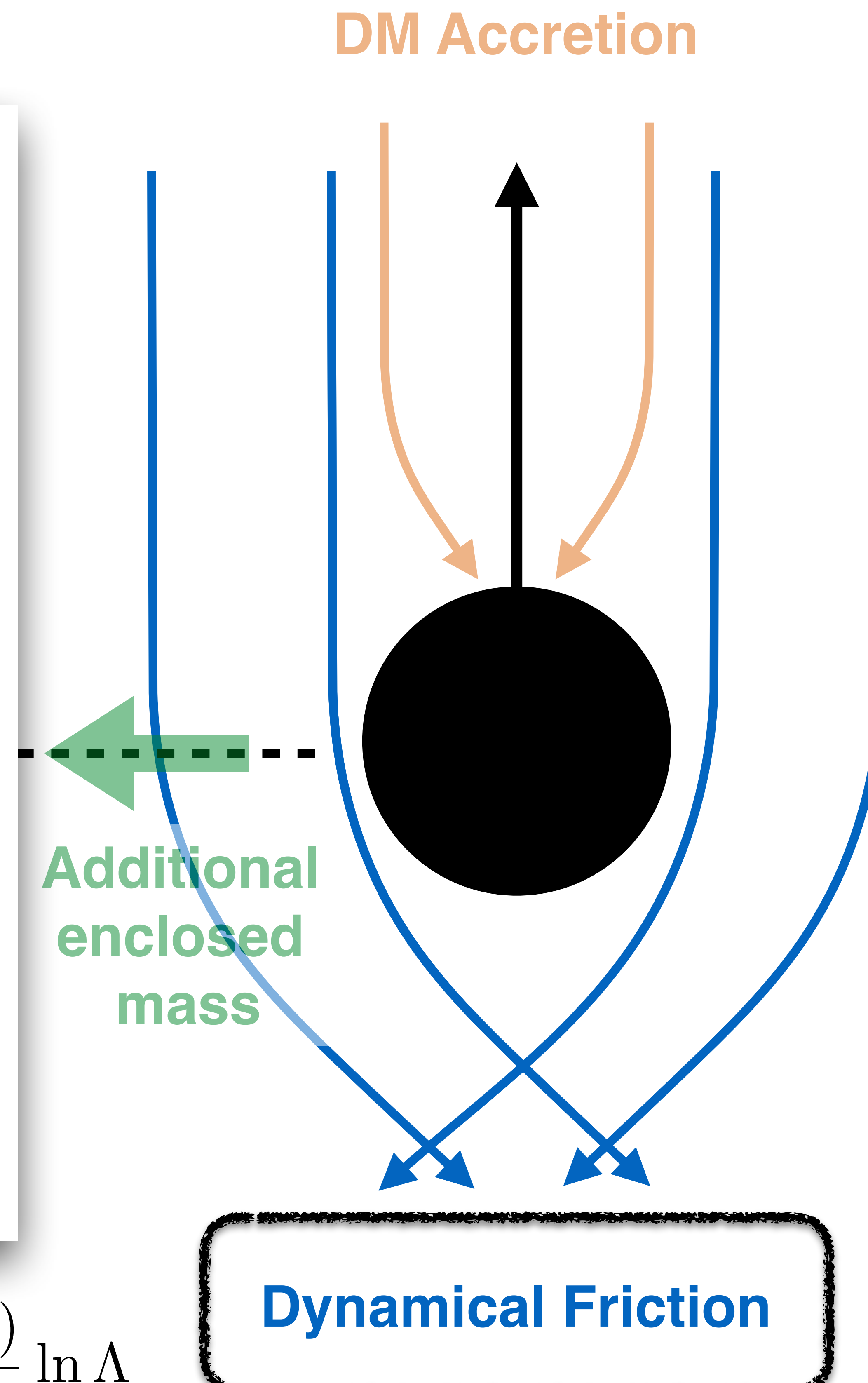


IMBH

[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Impact of DM Spikes

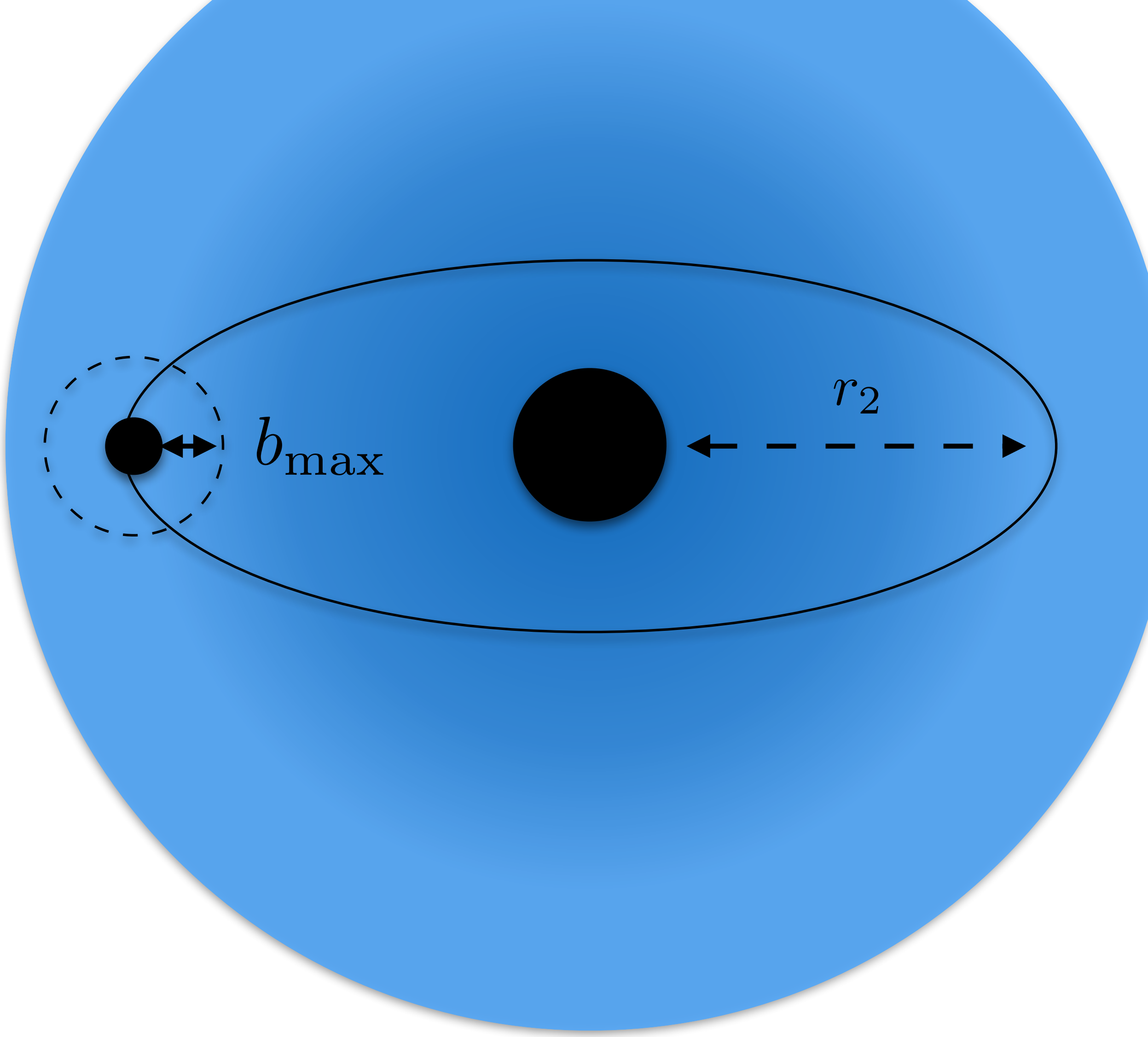




$$\dot{E}_{\rm DF} \sim \frac{4\pi G^2 m_2^2 \rho_{\rm DM}(r)\xi(v)}{v} \ln\Lambda$$

[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Phase space distribution



Follow semi-analytically the phase space distribution of DM:

$$f = \frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{r}\,\mathrm{d}^3\mathbf{v}} \equiv f(\mathcal{E})$$

$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Each particle receives a 'kick'

$$\mathcal{E} \to \mathcal{E} + \Delta\mathcal{E}$$

through gravitational scattering

Compact object scatters with all DM particles within 'torus' of influence over one orbit

Reconstruct density from distribution function:

$$\rho(r) = \int \mathrm{d}^3\mathbf{v}\, f(\mathcal{E})$$

[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

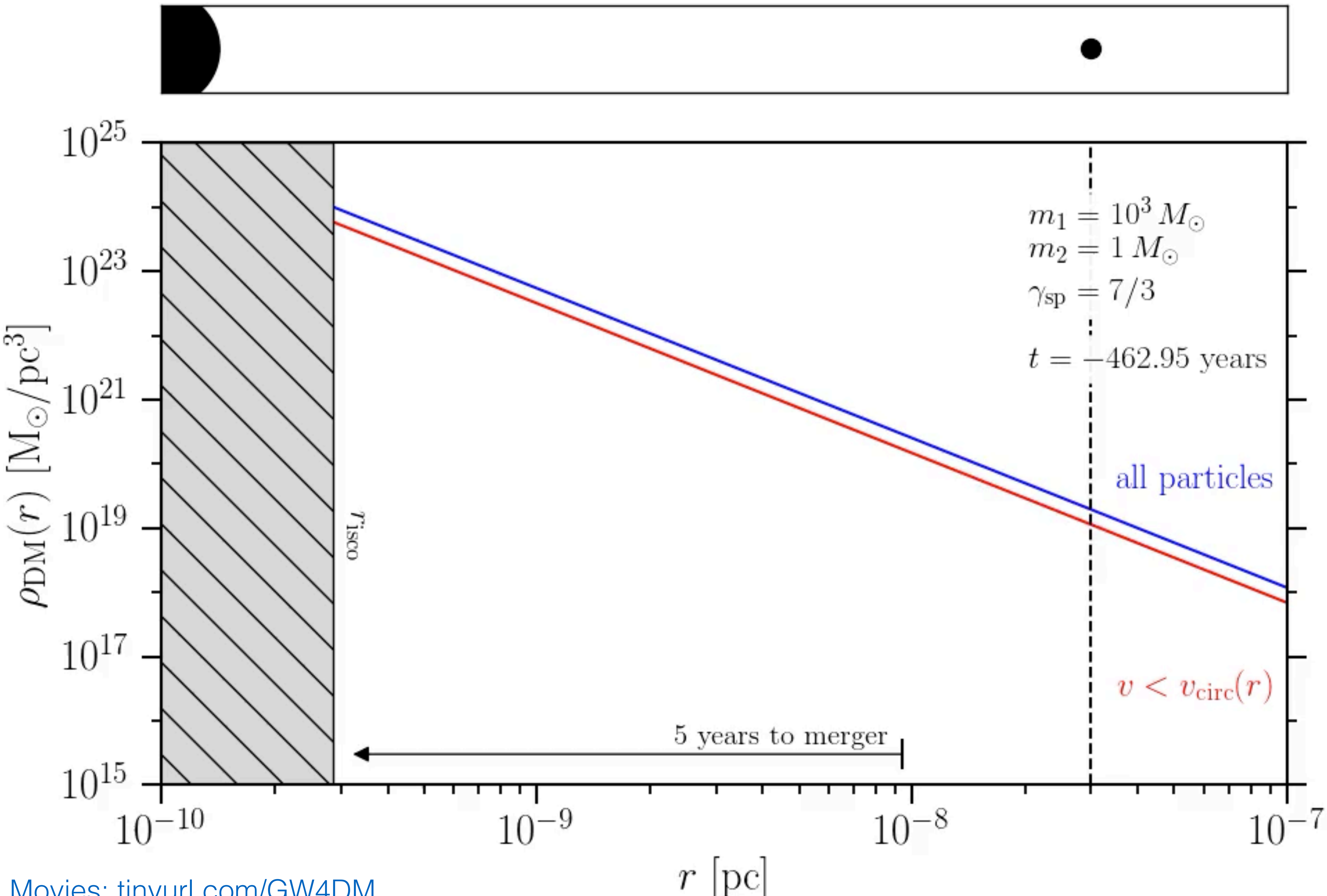
[Code available online: github.com/bradkav/HaloFeedback]

Full evolution of the system

[**BJK**, Nichols, Gaggero & Bertone, 2002.12811]

[Code available online: github.com/bradkav/HaloFeedback]

Need to include **feedback** on the DM spike:



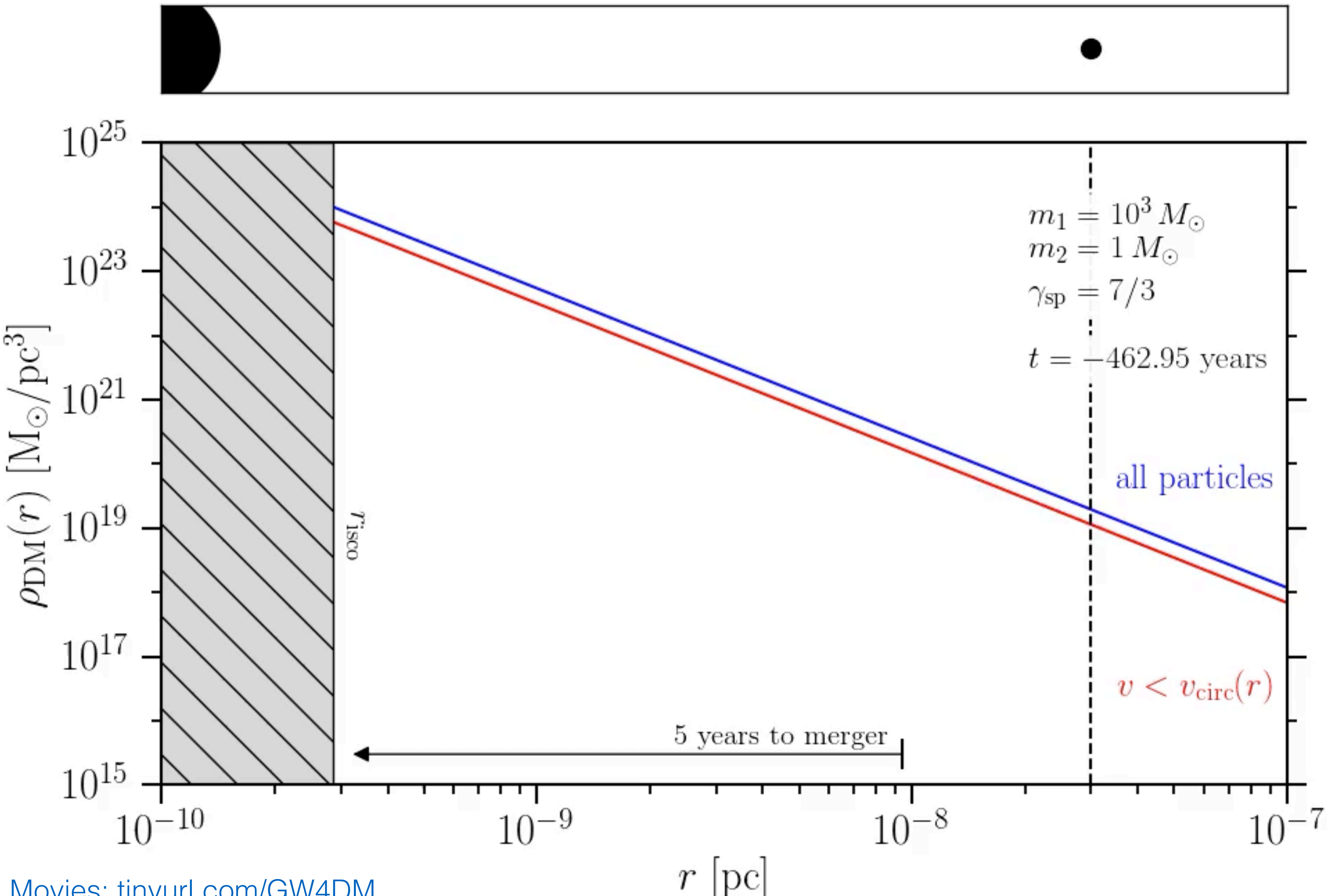
Movies: tinyurl.com/GW4DM

Full evolution of the system

[**BJK**, Nichols, Gaggero & Bertone, 2002.12811]

[Code available online: github.com/bradkav/HaloFeedback]

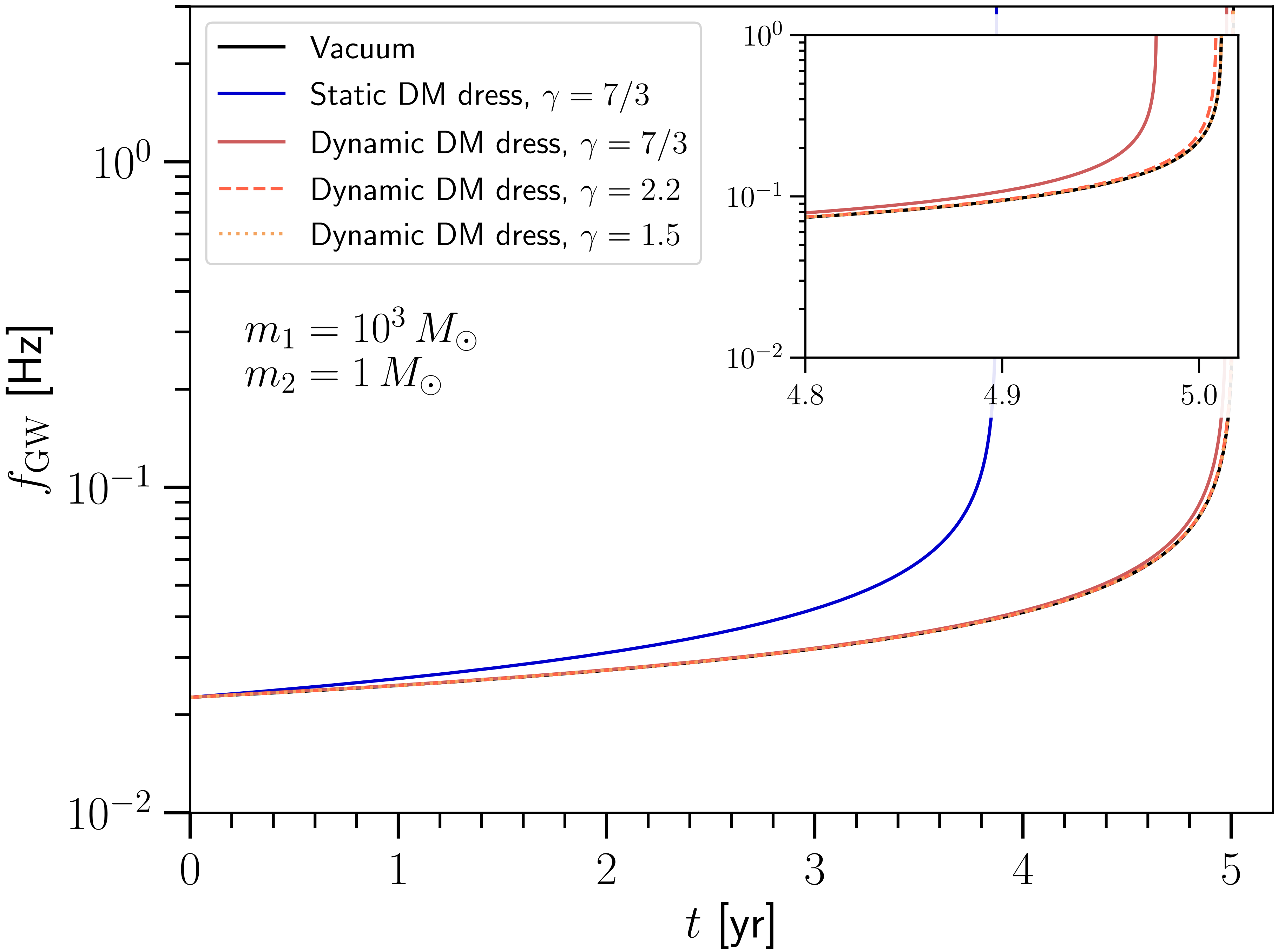
Need to include **feedback** on the DM spike:



Movies: tinyurl.com/GW4DM

Time to Merger

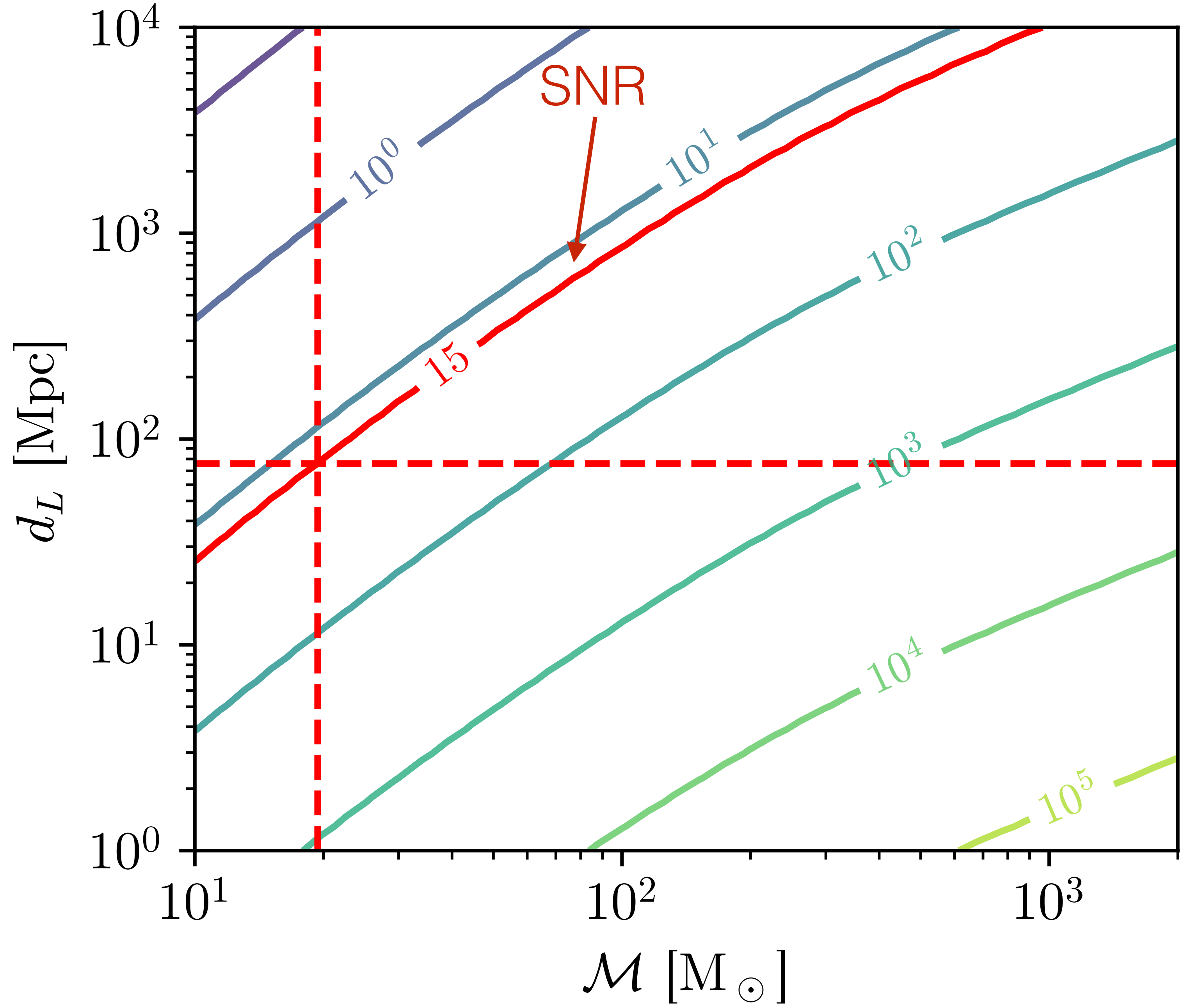
Change in time-frequency evolution of the GW inspiral:



'Dressed' system mergers ~days earlier than 'vacuum' system

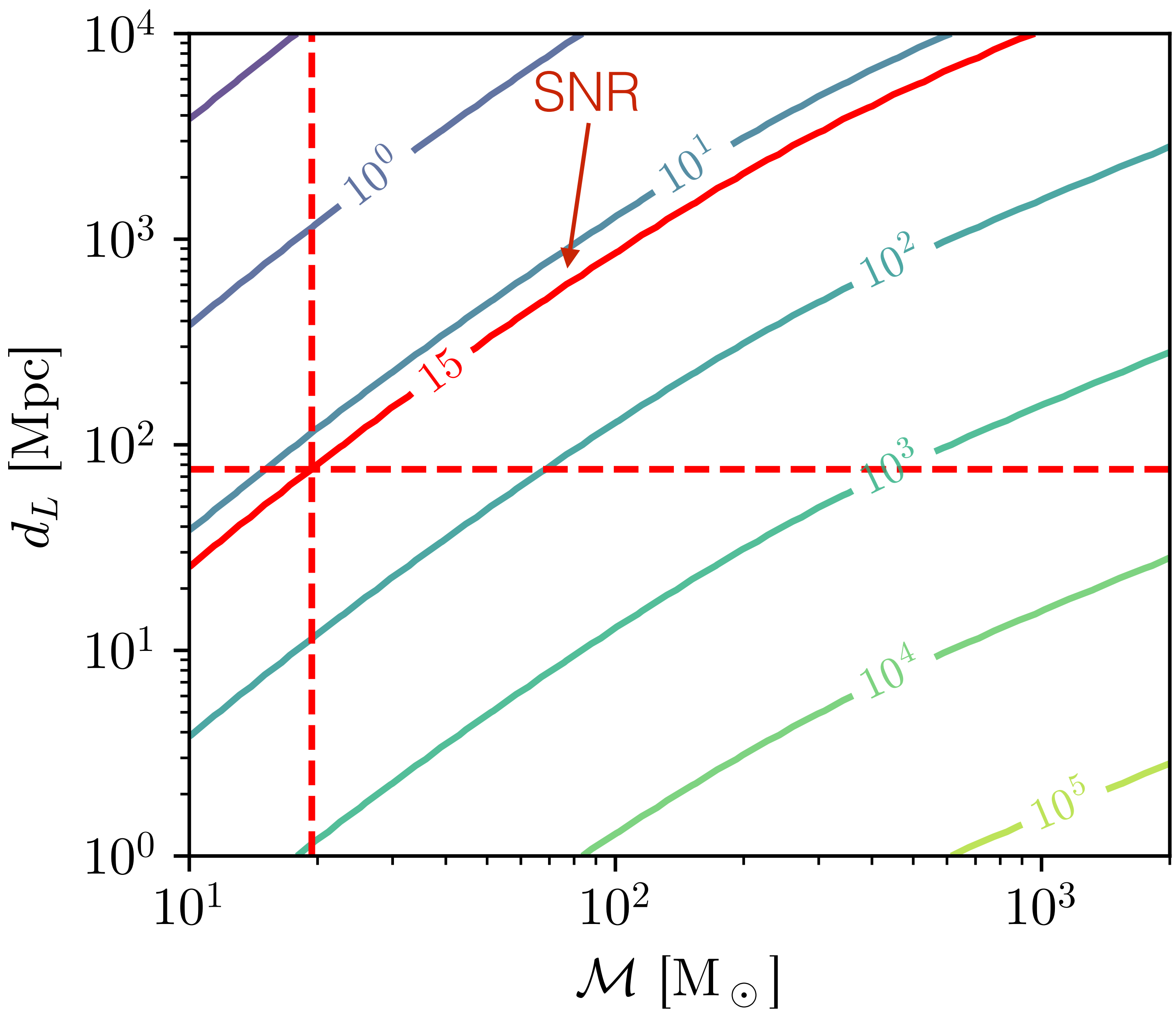
Detectability

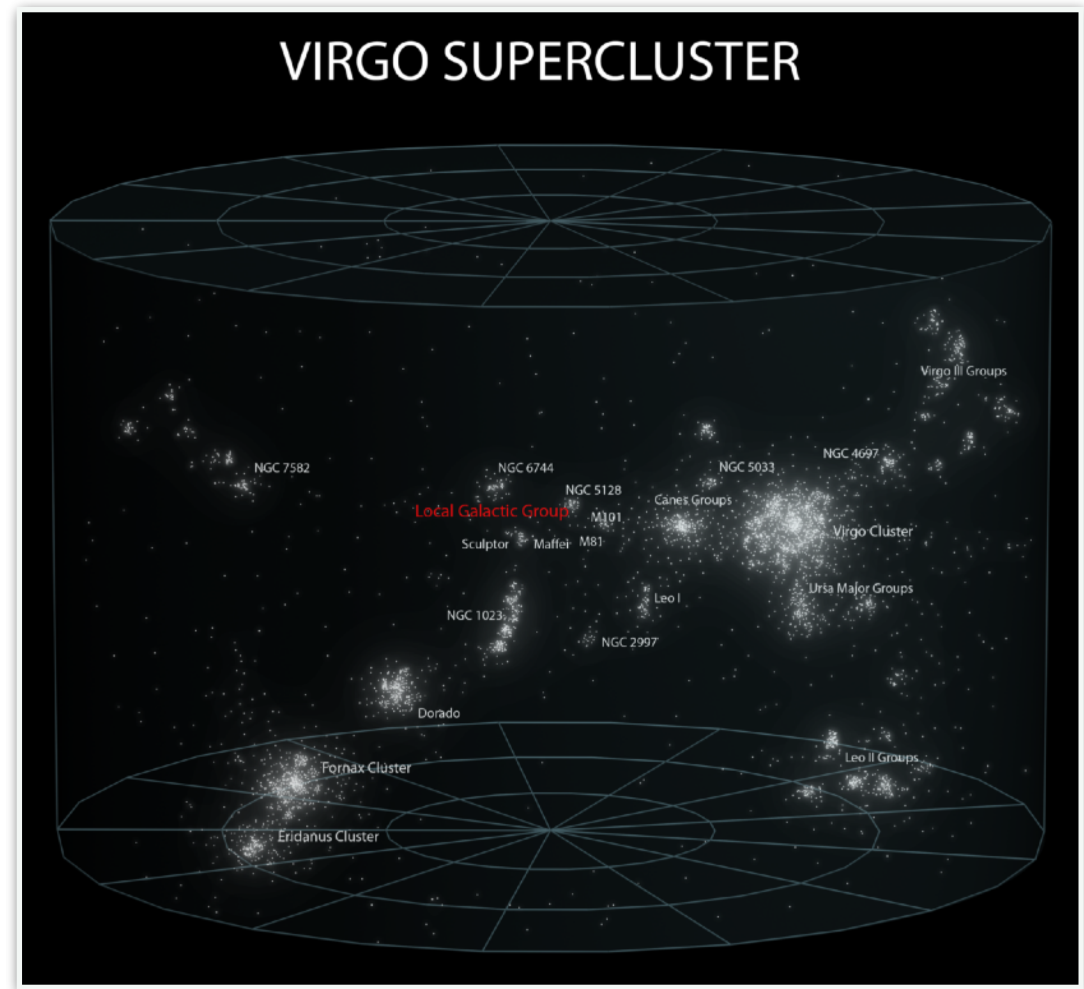
Estimate optimal match-filtered SNR for detection with LISA.
(Presence of Dark Dress has almost no impact on SNR):



Detectability

Estimate optimal match-filtered SNR for detection with LISA.
(Presence of Dark Dress has almost no impact on SNR):



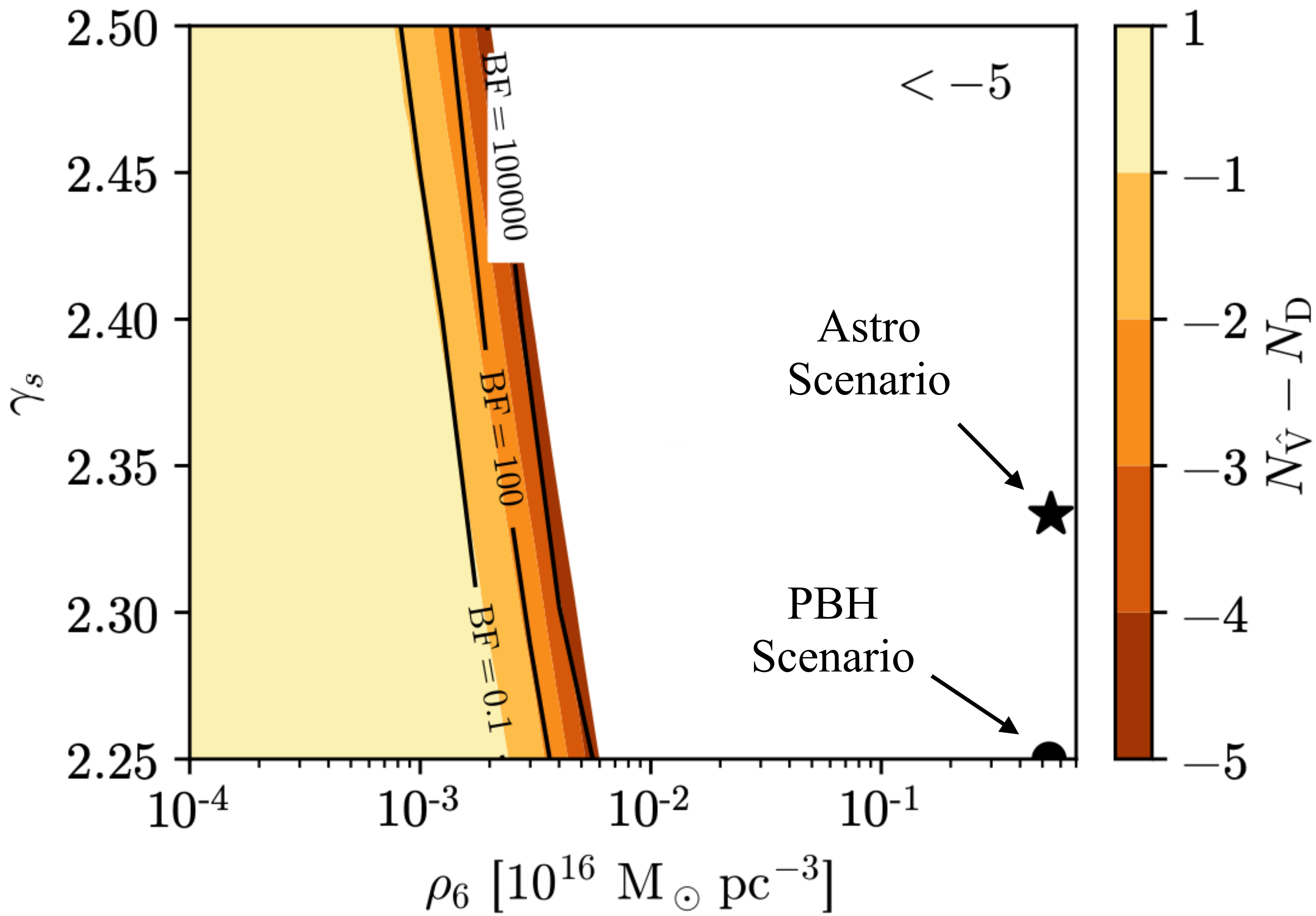


Discoverability

[Code available online:
https://github.com/adam-coogan/pydd]

$q = m_2/m_1$

We'll call a DM spike **discoverable** if it can be distinguished from a GR-in-vacuum system.



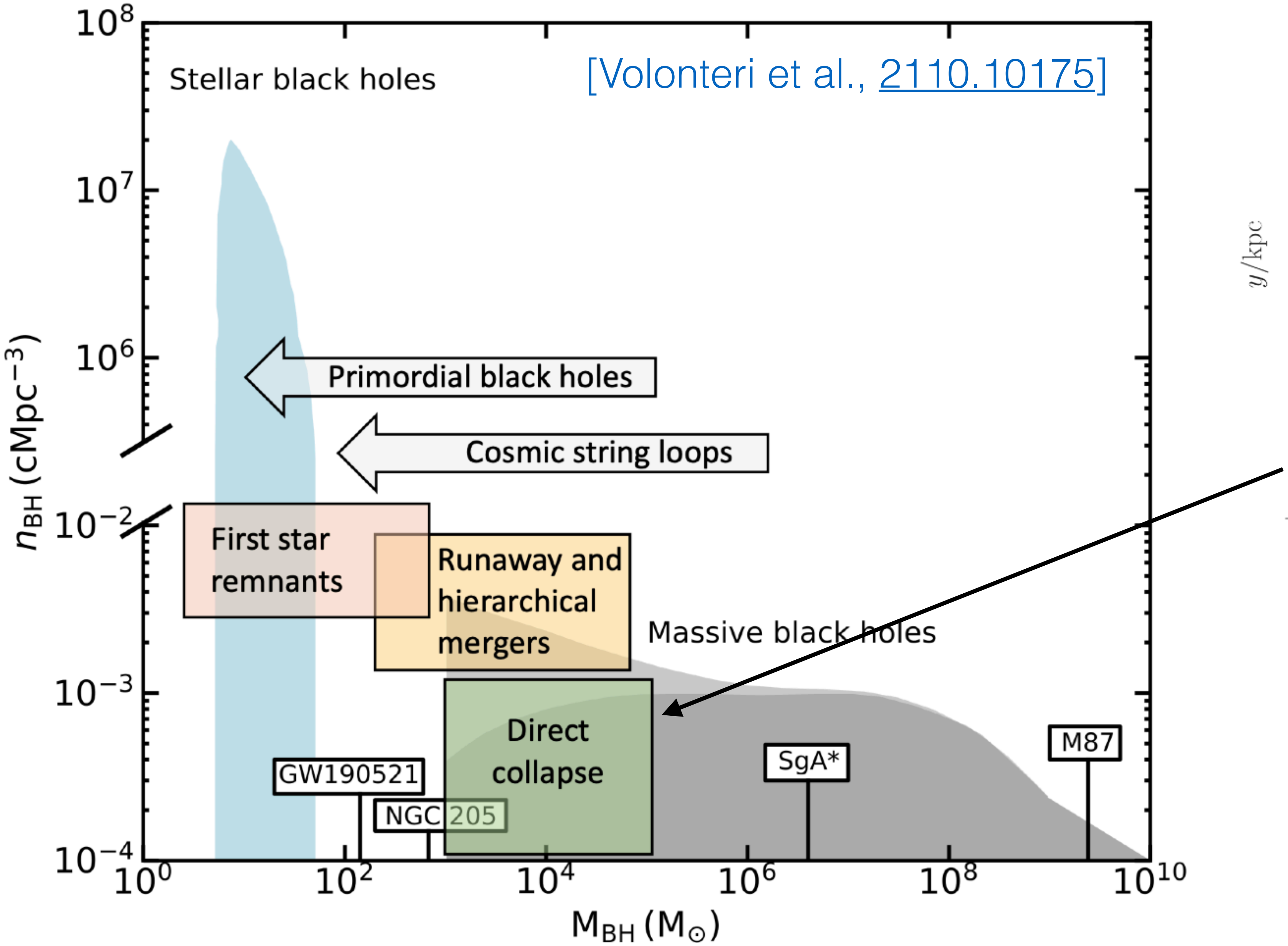
Compute Bayes Factor (BF) comparing Bayesian evidence for **V**acuum and **D**ressed systems, with parameters:

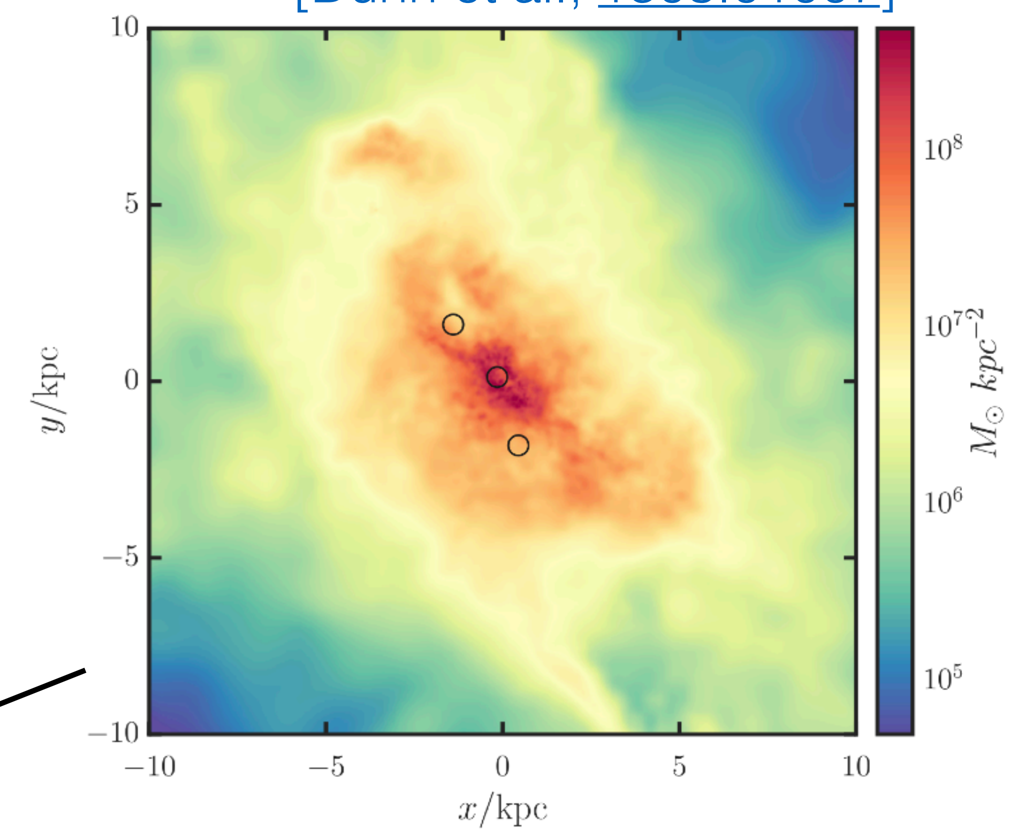
$$\boldsymbol{\theta}_{\rm V} = \{\mathcal{M}\}$$

vs.

$$\boldsymbol{\theta}_{\rm D} = \{\gamma_{\rm sp}, \rho_6, \mathcal{M}, \log_{10} q\}$$

Black Hole and Spike Formation



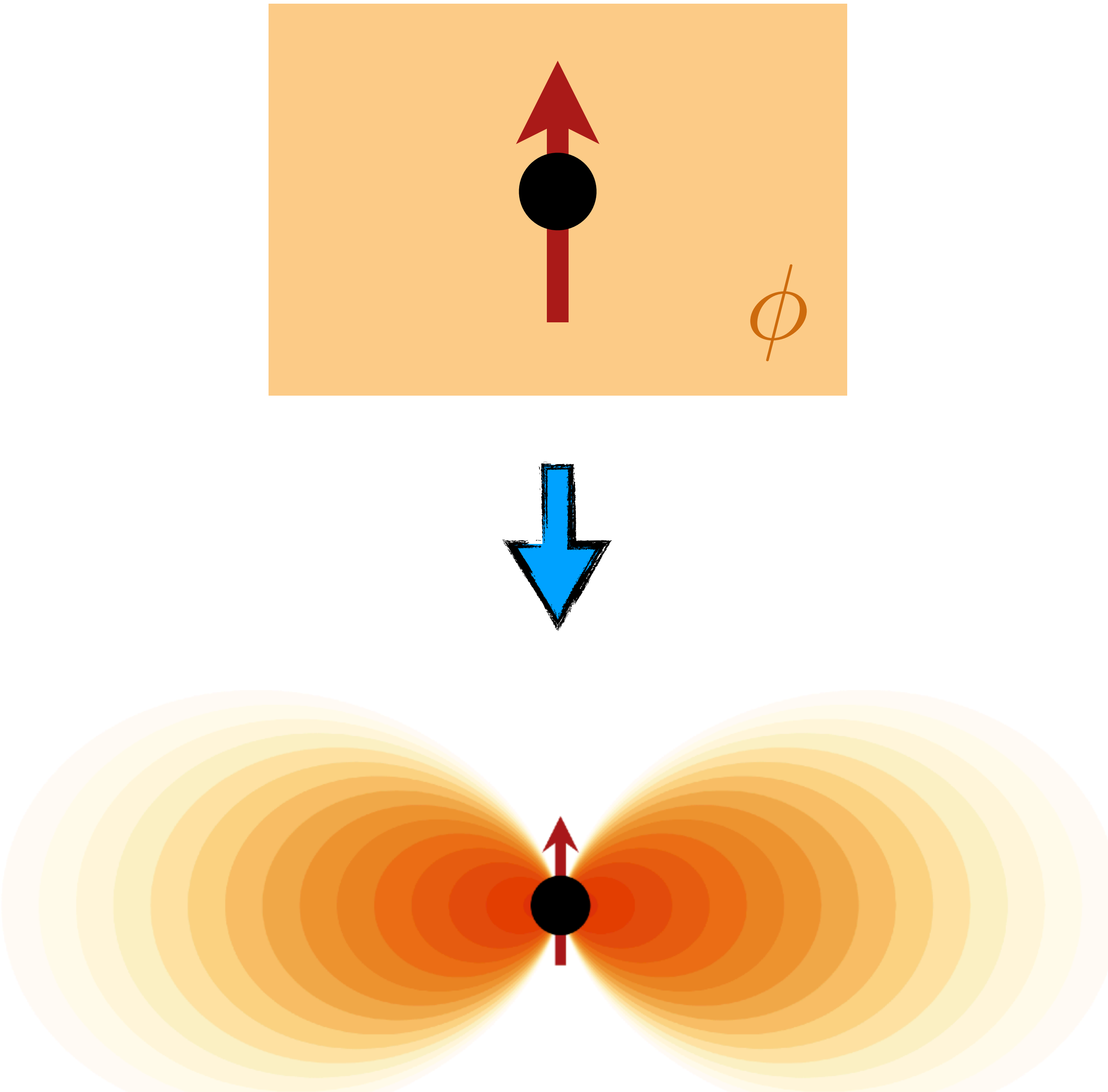


Use semi-analytic galaxy formation models to study the properties of Direct Collapse Black Holes and the halos they form in.

Preliminary results suggest that large densities are possible $\rho_6 \gtrsim 10^{16}\, M_\odot\, \mathrm{pc}^{-3}$ but do these systems survive, and are they common?

[Work in progress with Abram Perez, Pratika Dayal, and others]

Gravitational Atoms



Compton wavelength of
a light scalar field:

$$\lambda_c \simeq 2\,\text{km}\left(\frac{10^{-10}\,\text{eV}}{\mu}\right)$$

Super-radiance (and growth of a
'**gravitational atom**') when:

$$r_g \sim GM_{\text{BH}}/c^2 < \lambda_c$$

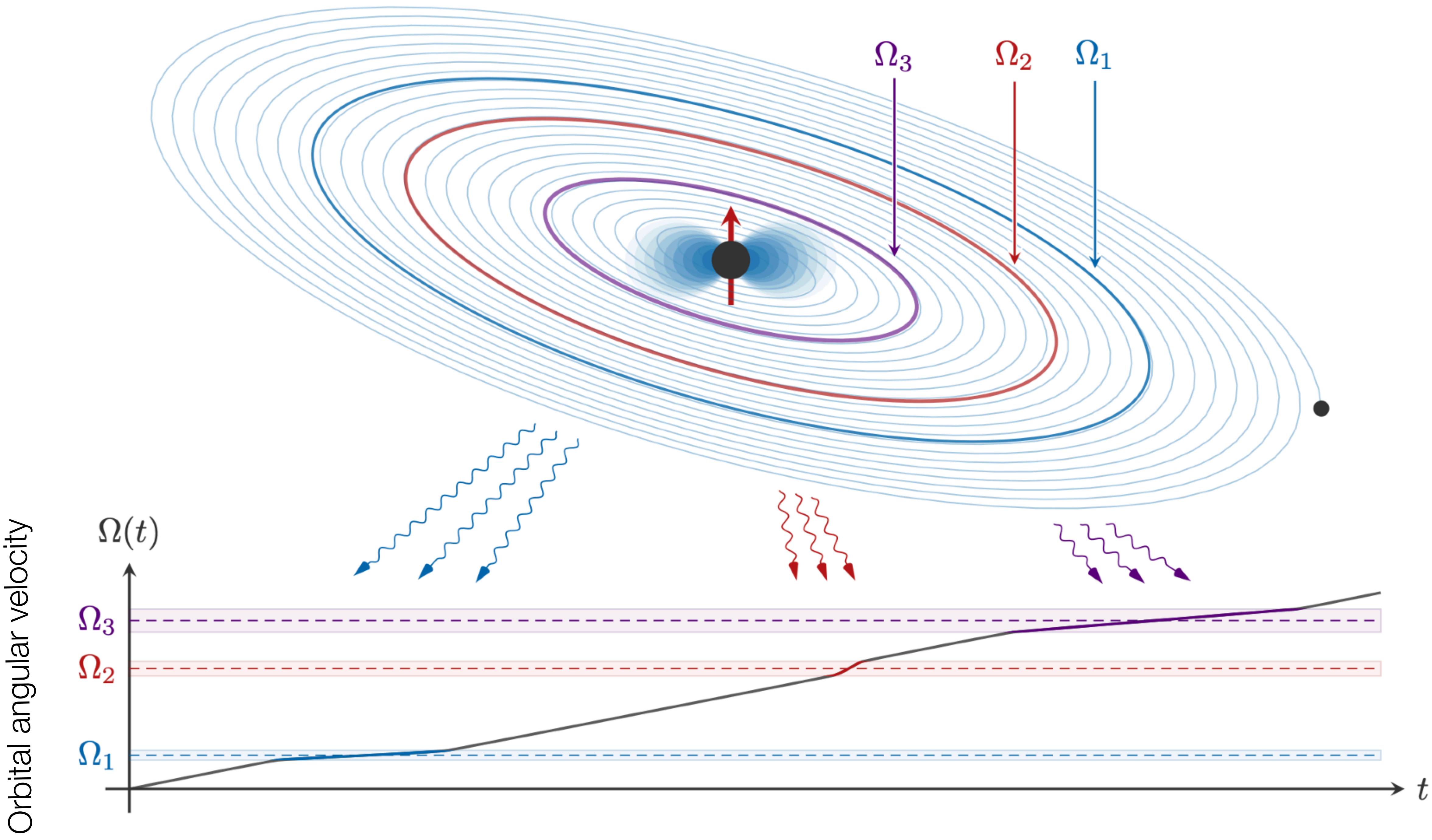
$$M_{\text{BH}} \in [1, 10^{10}]\,M_\odot$$

$$\rightarrow m_\phi \in [10^{-20}, 10^{-10}]\,\text{eV}$$

[Chia, 2012.09167]

[E.g. Baumann et al., 1804.03208, 1908.10370, 1912.04932, 2112.14777]

Gravitational Atoms



[E.g. Baumann et al., 1804.03208, 1908.10370, 1912.04932, 2112.14777]

Distinguishing Effects

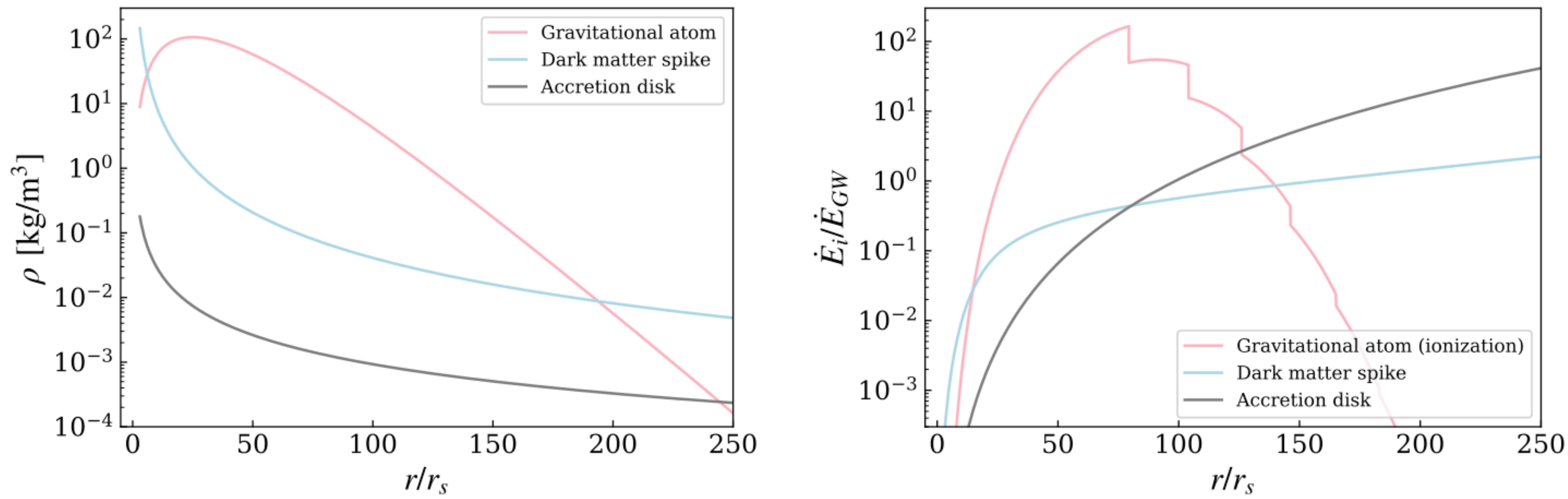


FIG. 1. Left: Initial density profiles of environments around a $10^5\,M_\odot$ black hole. Right: Energy losses due to environment normalised by the energy losses due to gravitational waves.

[Cole et al., 2211.01362]