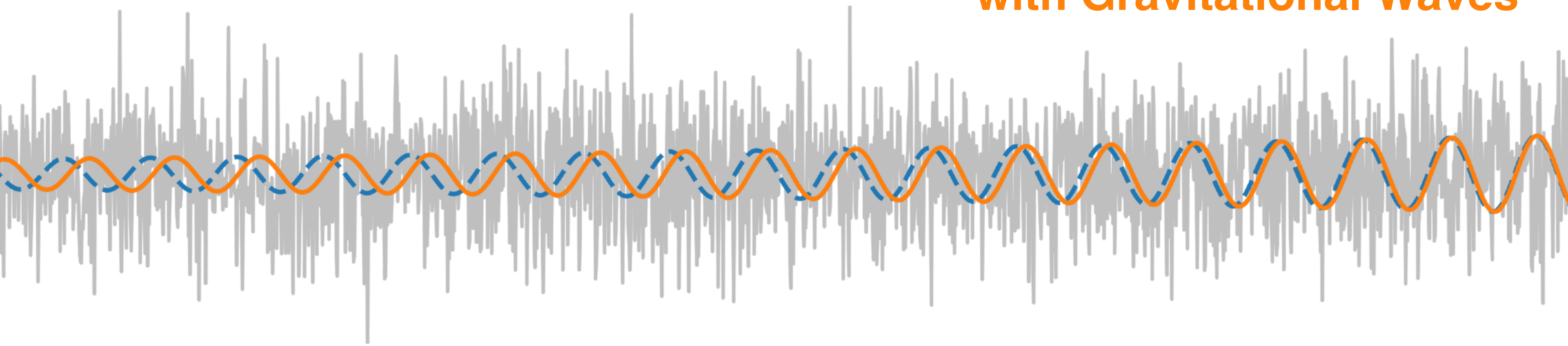
Black Holes’ Dark Dress

Detecting Particle Dark Matter around Primordial Black Holes with Gravitational Waves



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NEHOP, Naples, 20th June 2023

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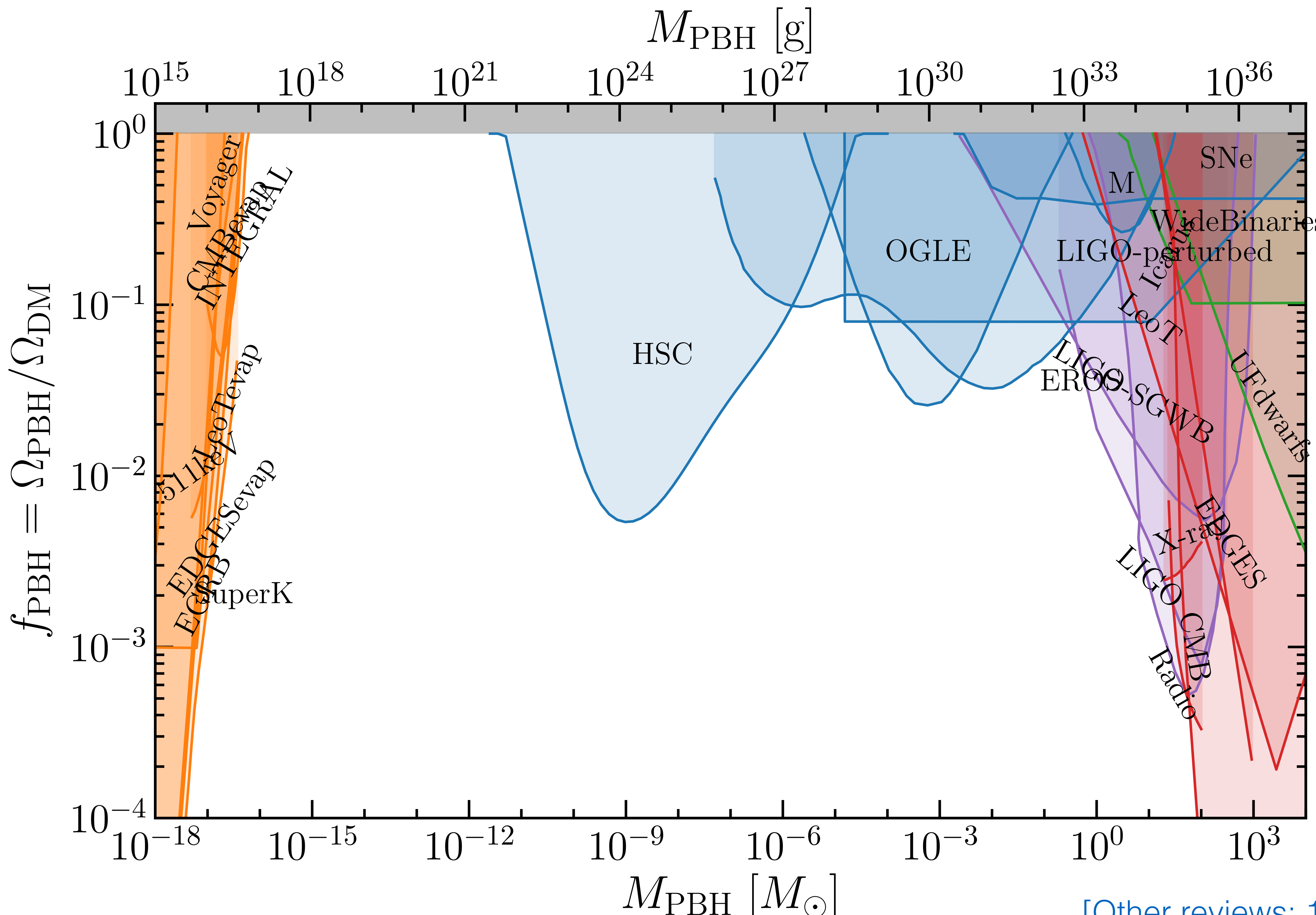
PBH Constraints

[Green & **BJK**, 2007.10722]
[Code online: github.com/bradkav/PBHbounds]



[Other reviews: 1801.05235, 2002.12778, 2006.02838]

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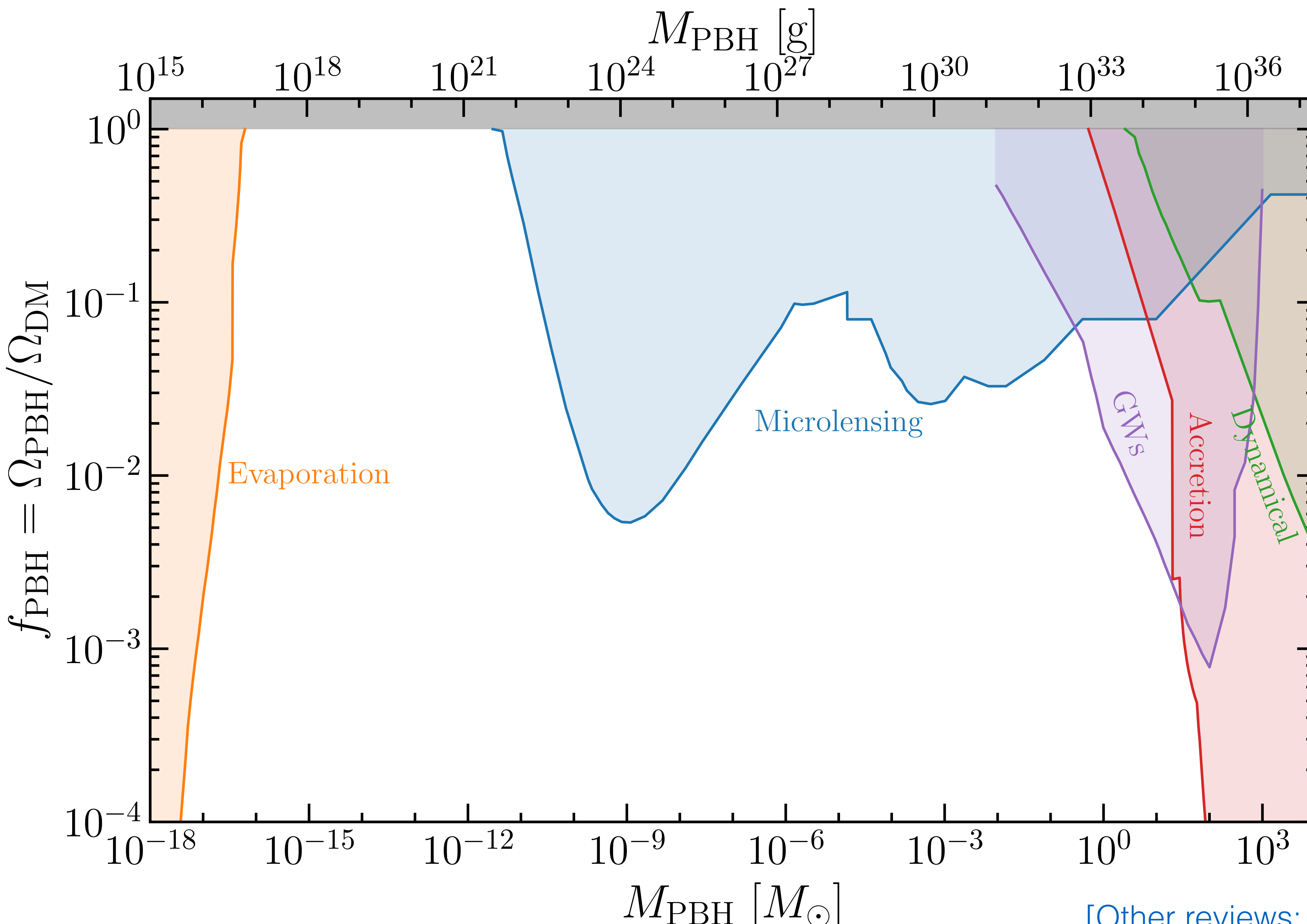

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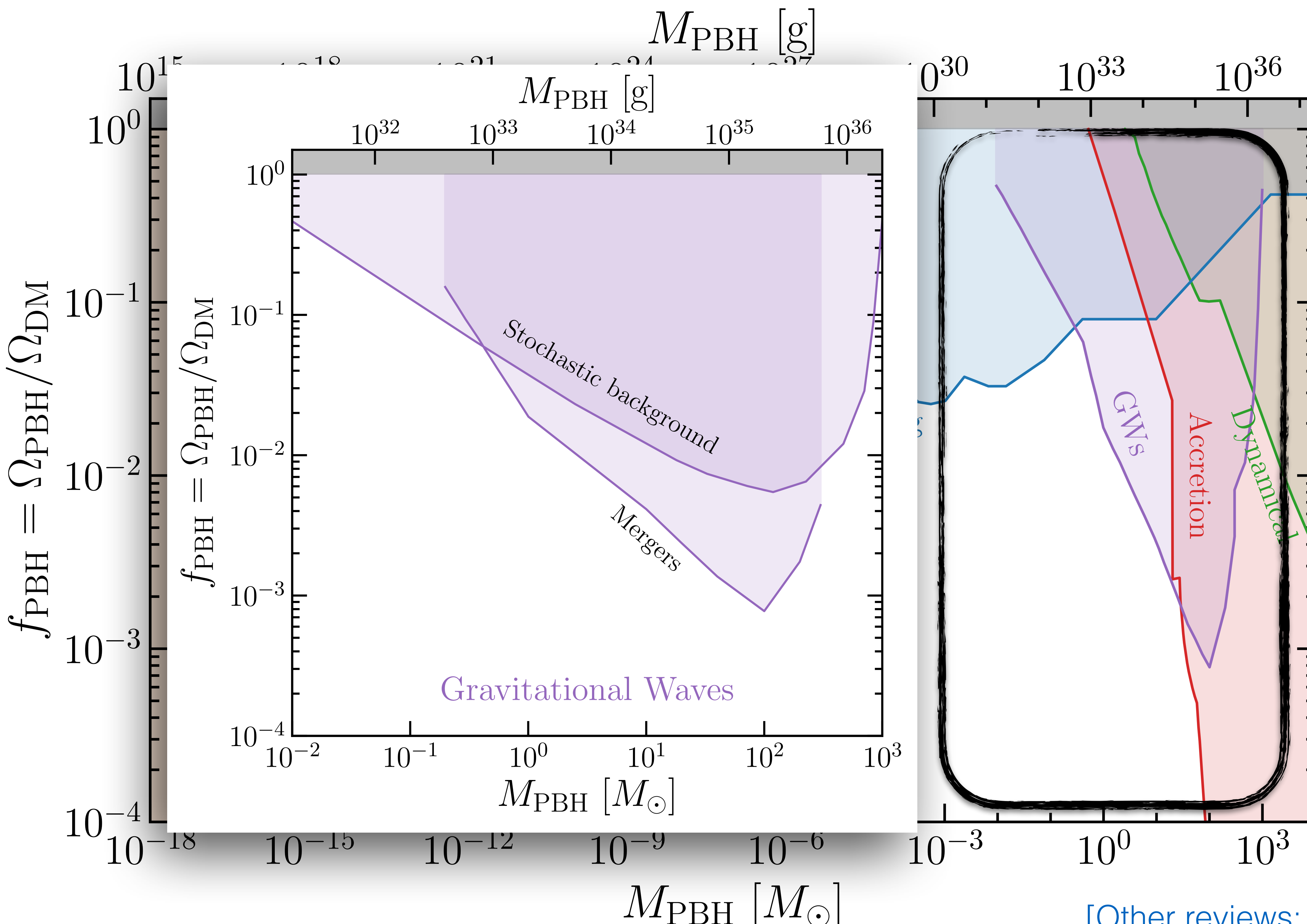

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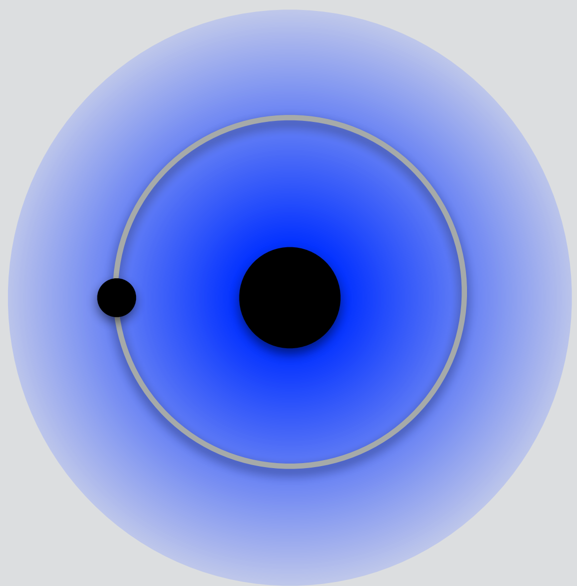
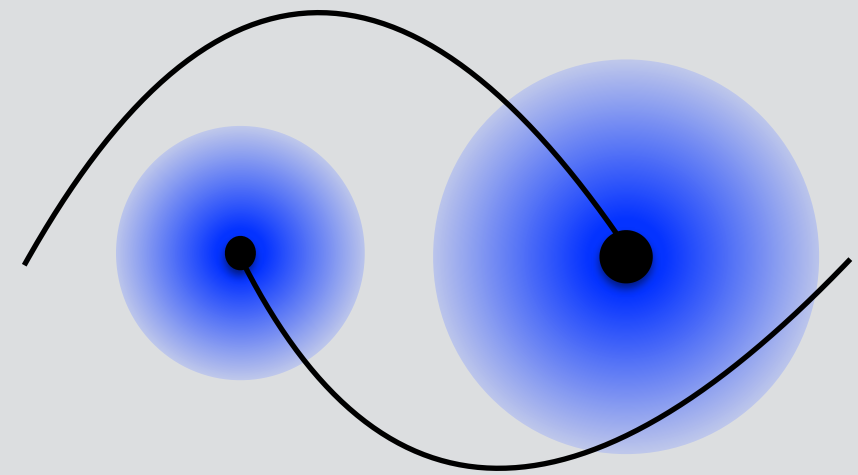
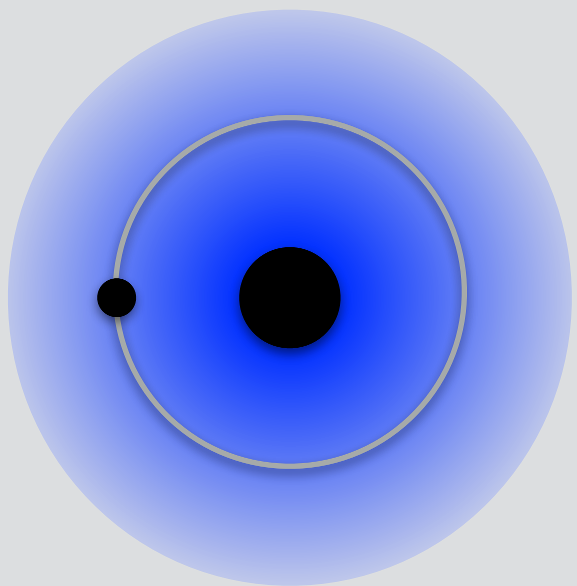


Dark Matter 'de-phasing' of GW signals



Merger rates of dressed PBH Binaries



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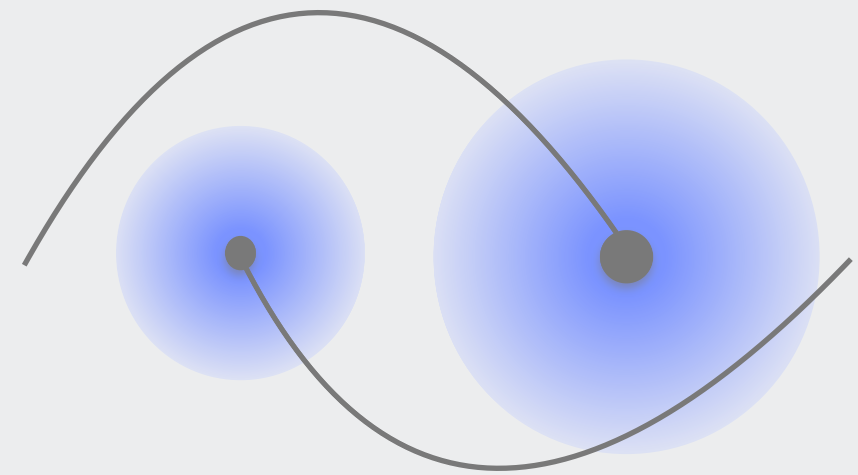
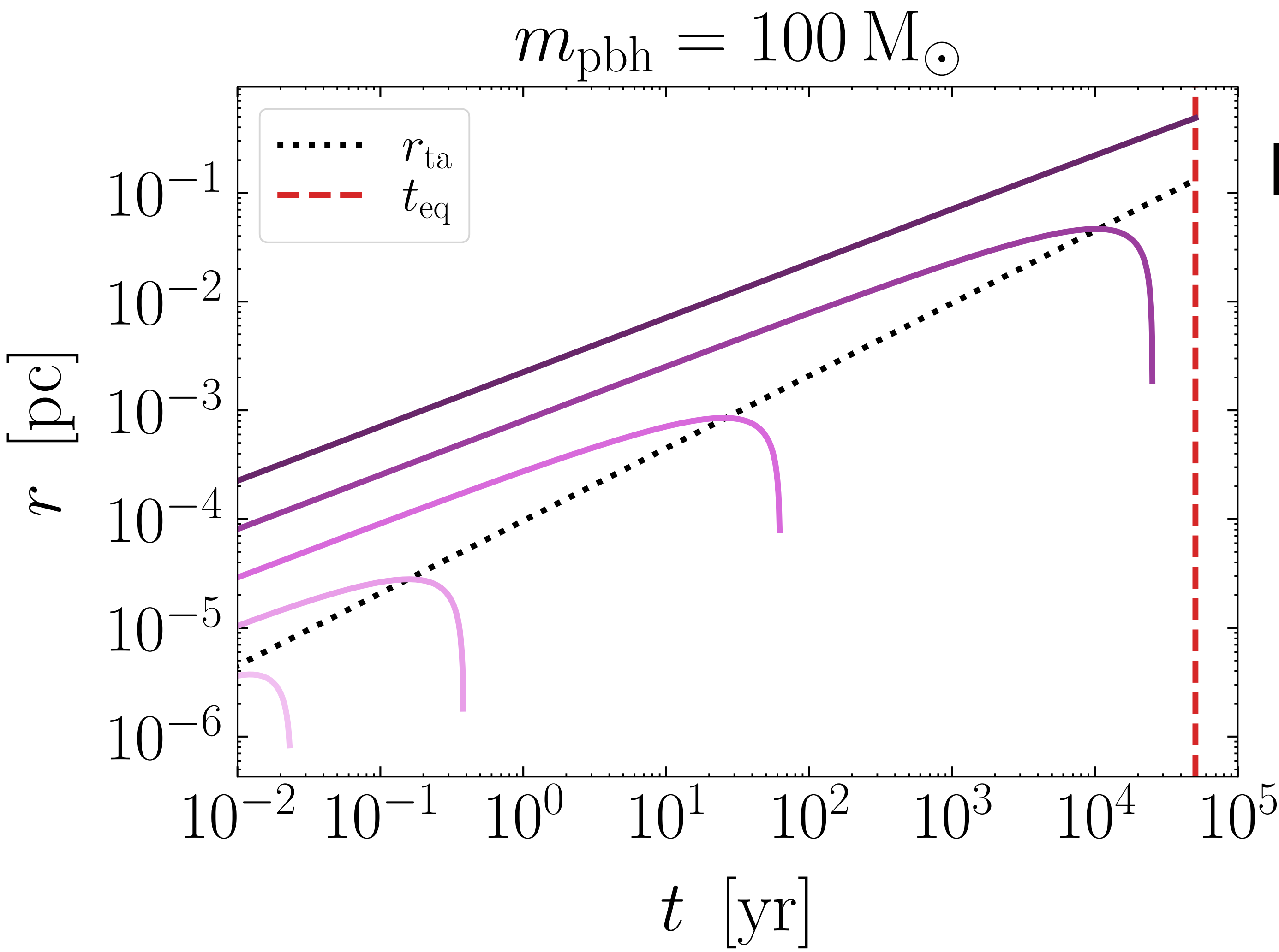
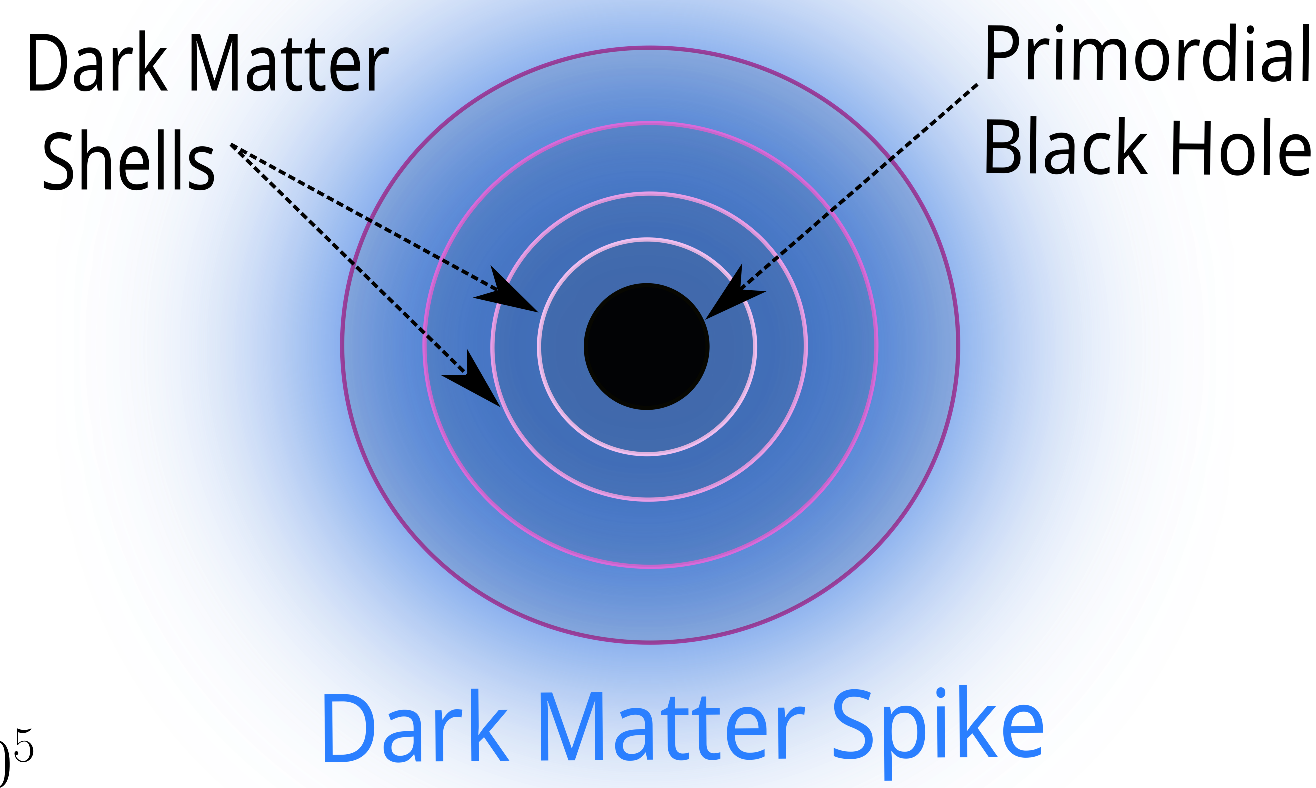


Merger rates of dressed PBH Binaries

Particle DM Spikes

[Mack et al., astro-ph/0608642;
Ricotti, 0706.0864,
Sten Delos et al., 1712.05421,
Boudaud et al., 2106.07480, …]



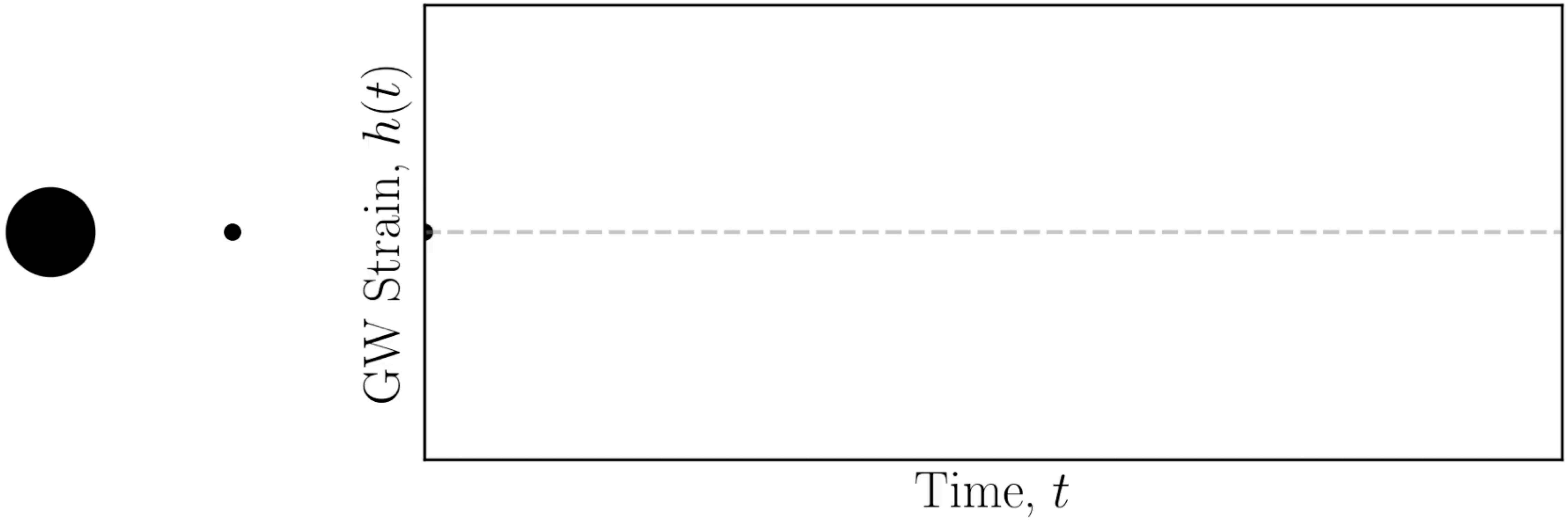


[Jangra, **BJK**, Diego, 2304.05892]

Spike grows to $M_{\rm spike} \sim M_{\rm PBH}$ by matter-radiation equality.

Density profile $\rho_{\rm DM}(r) \sim r^{-9/4}$, can achieve densities up to $\rho_{\rm DM} \gtrsim 10^{20}\, M_\odot/{\rm pc}^3$

Dark Matter “De-phasing”



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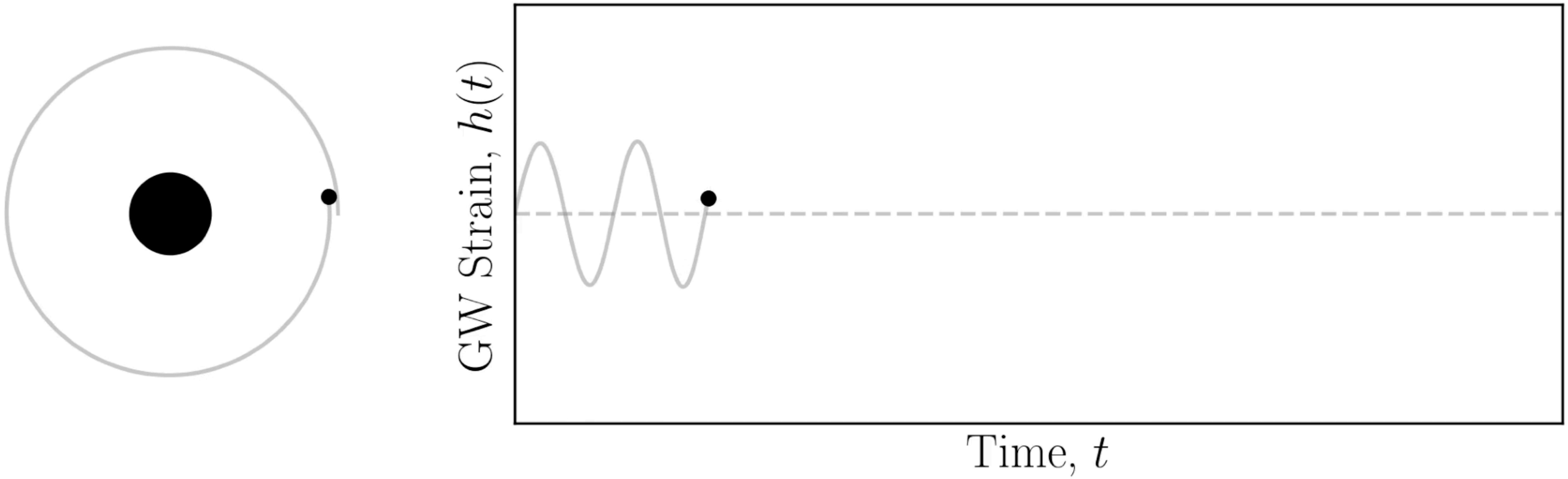

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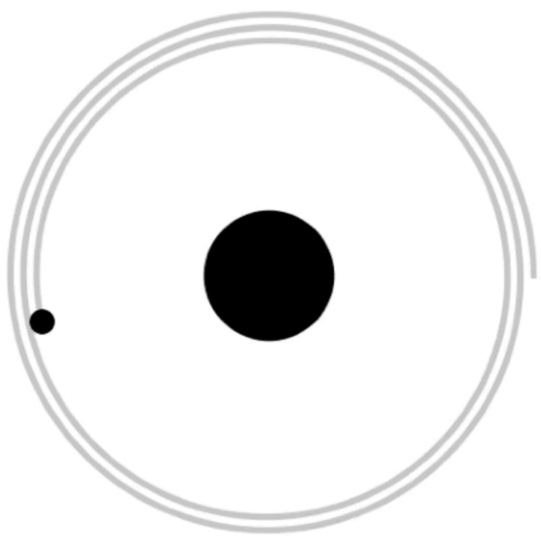

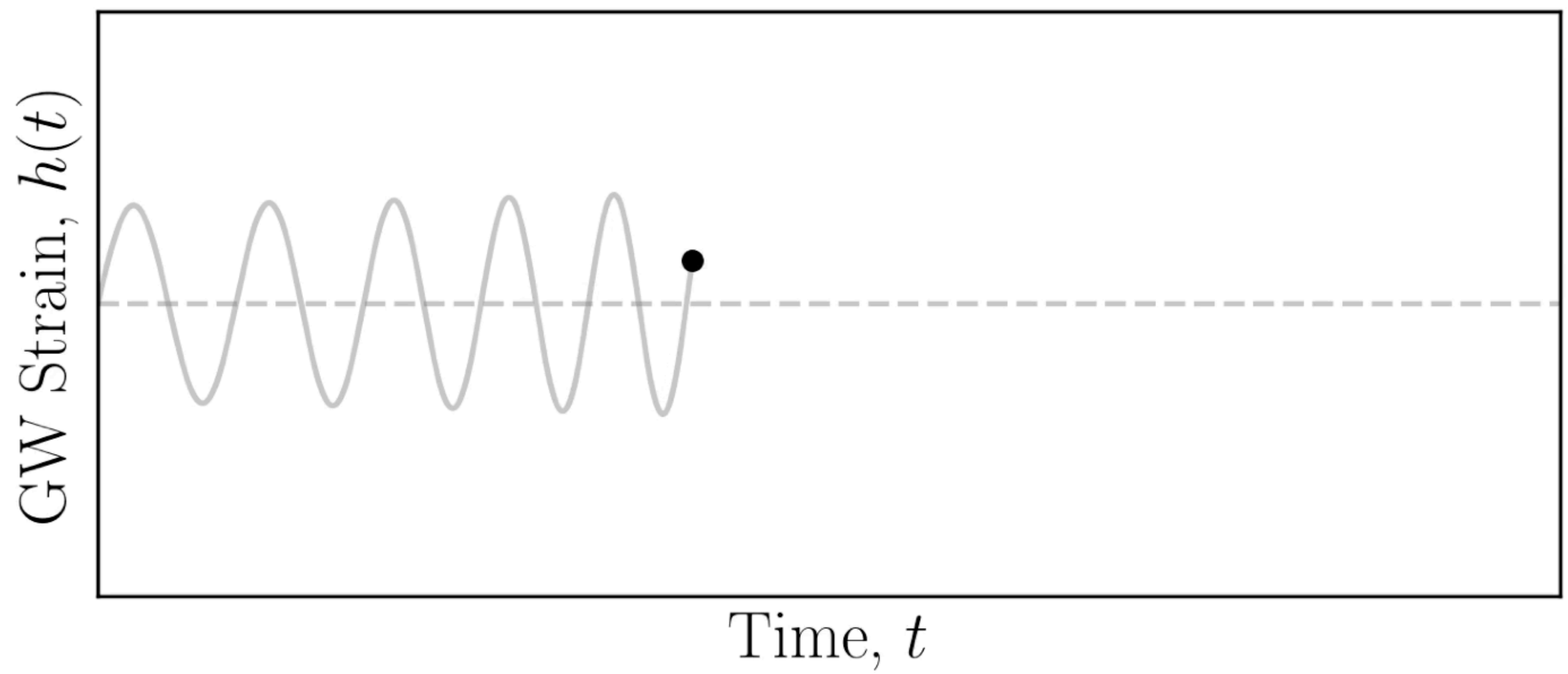

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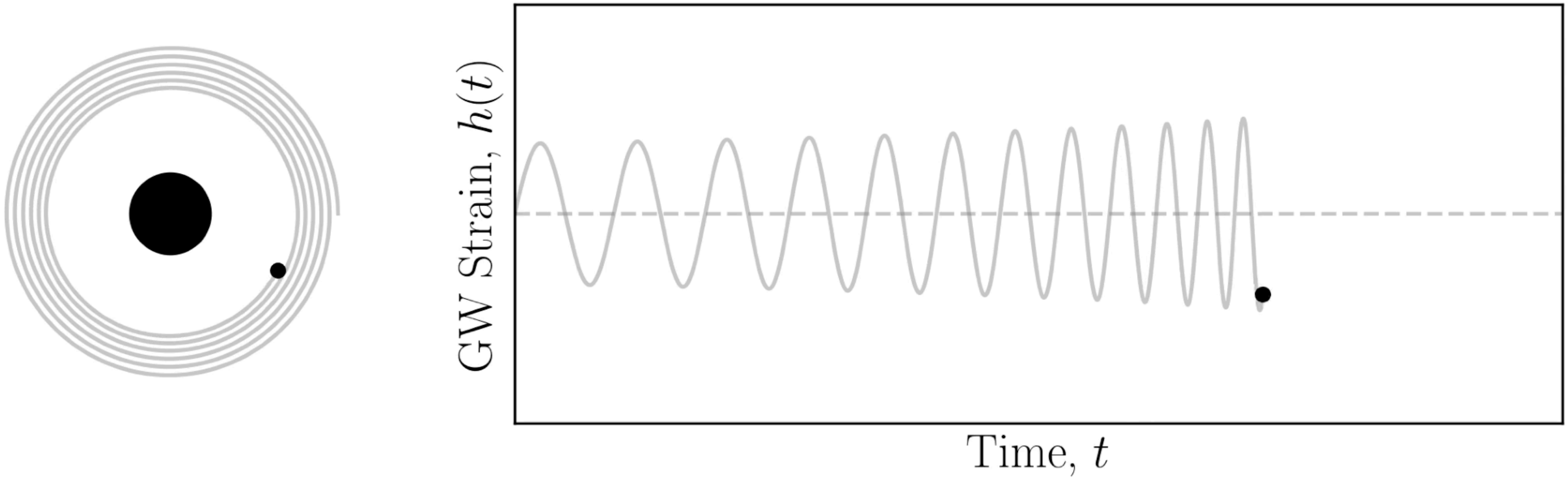

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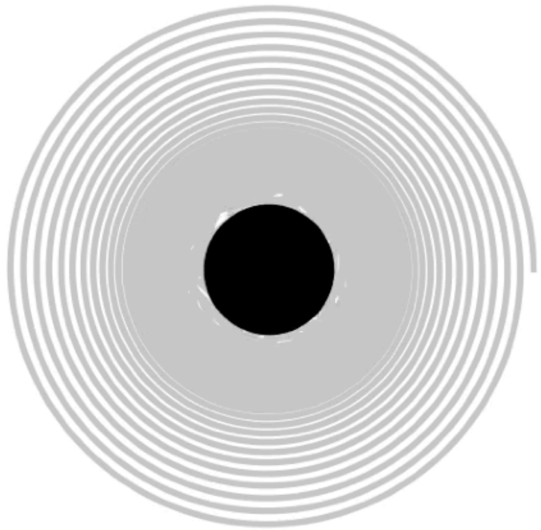

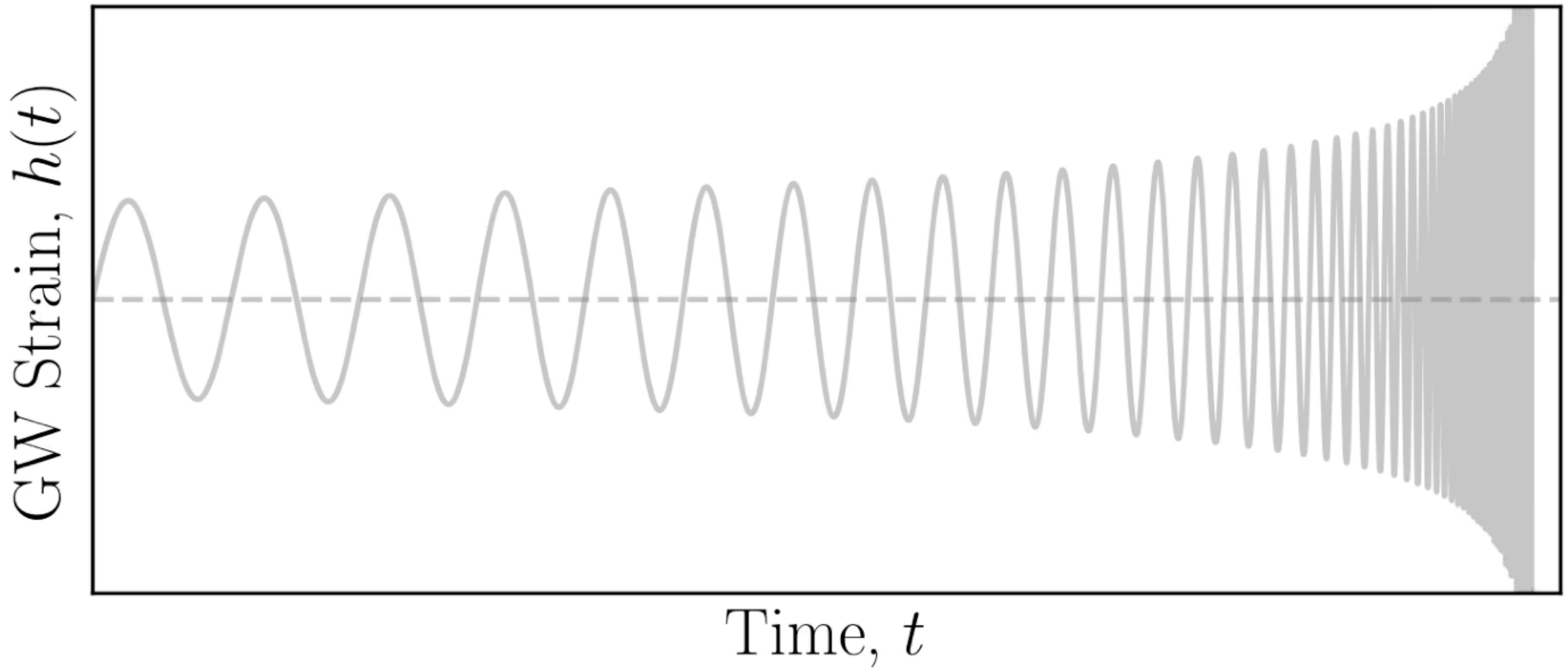

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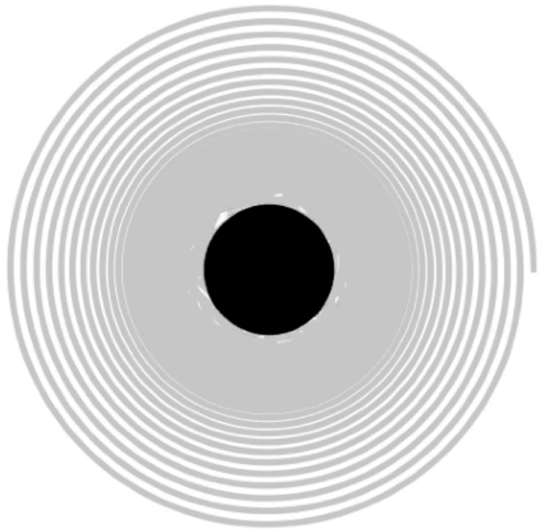

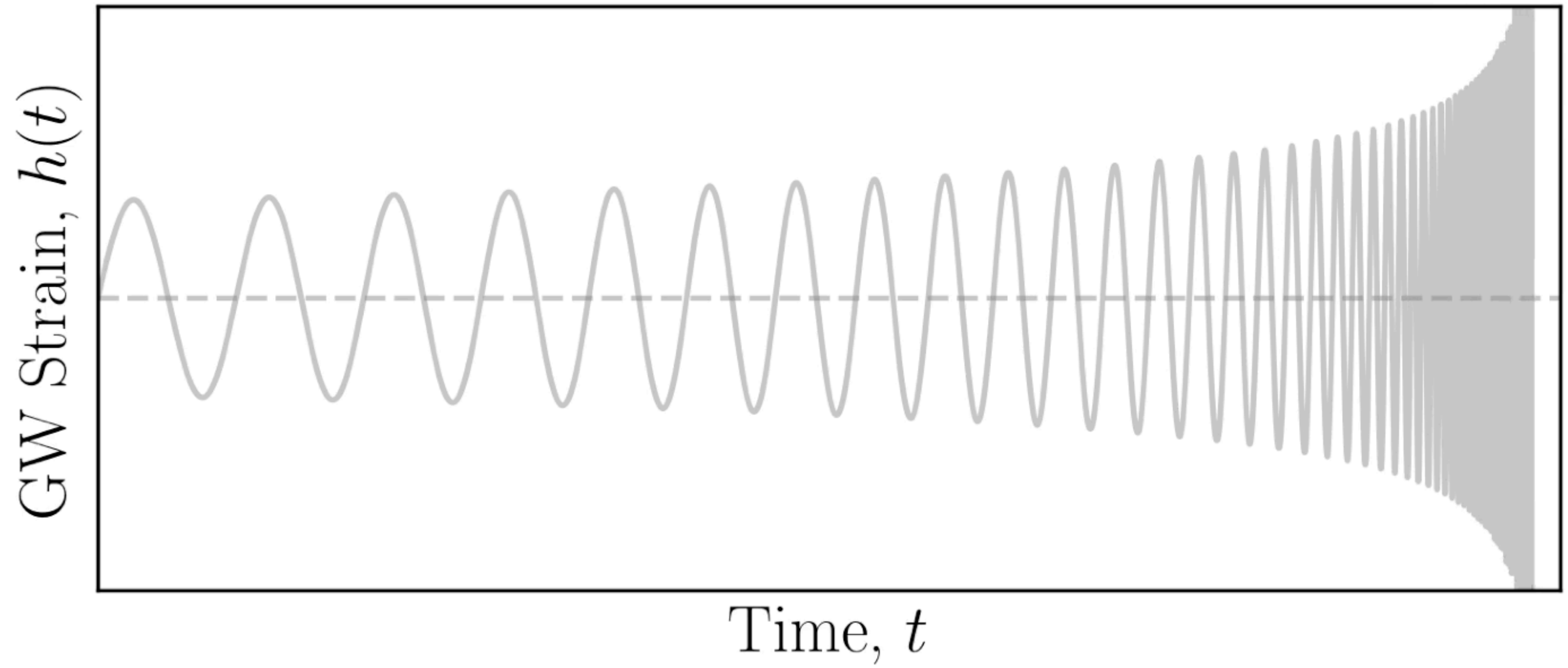

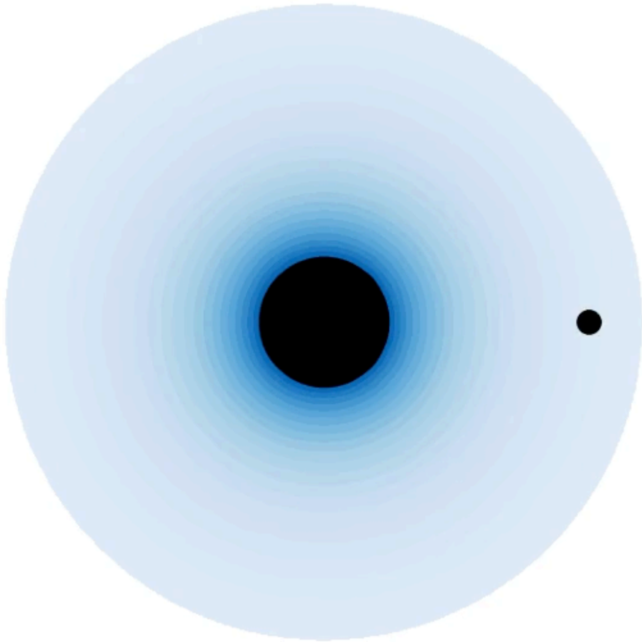

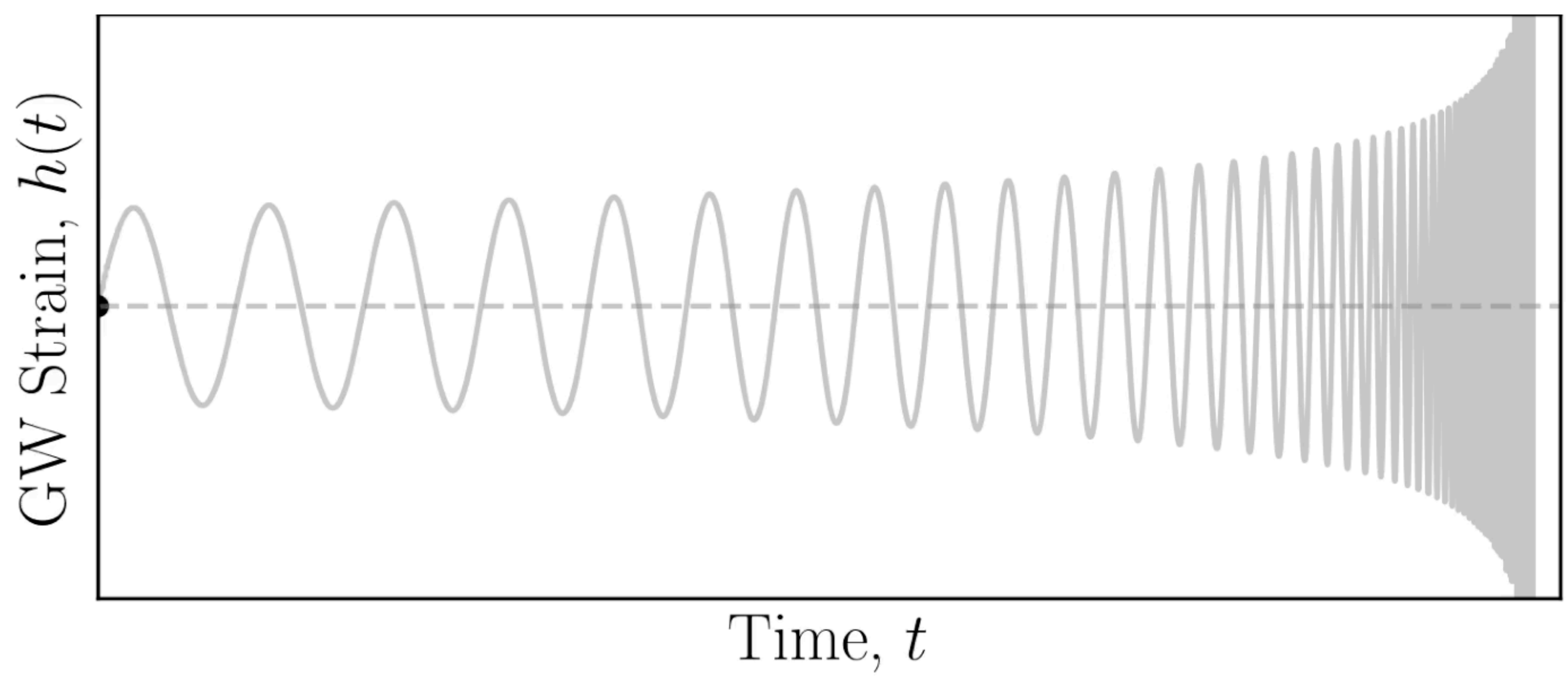

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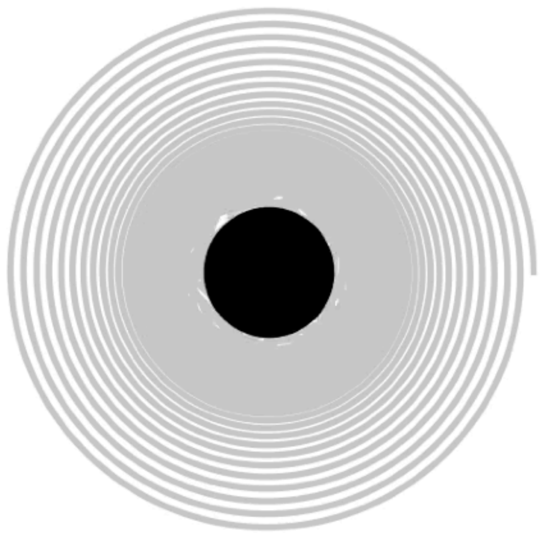

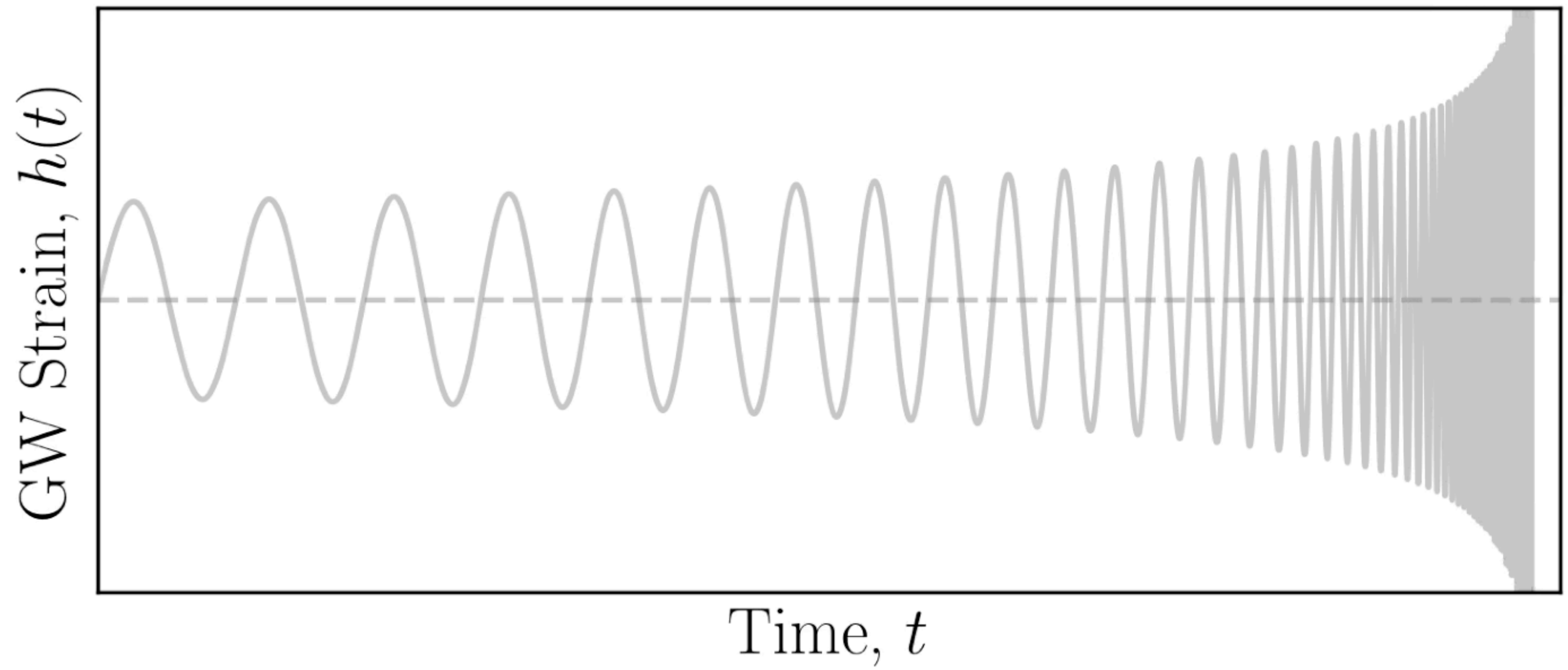

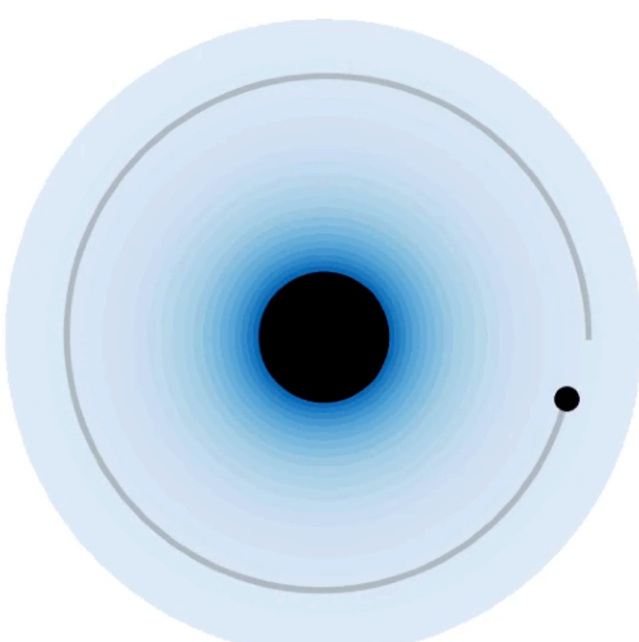

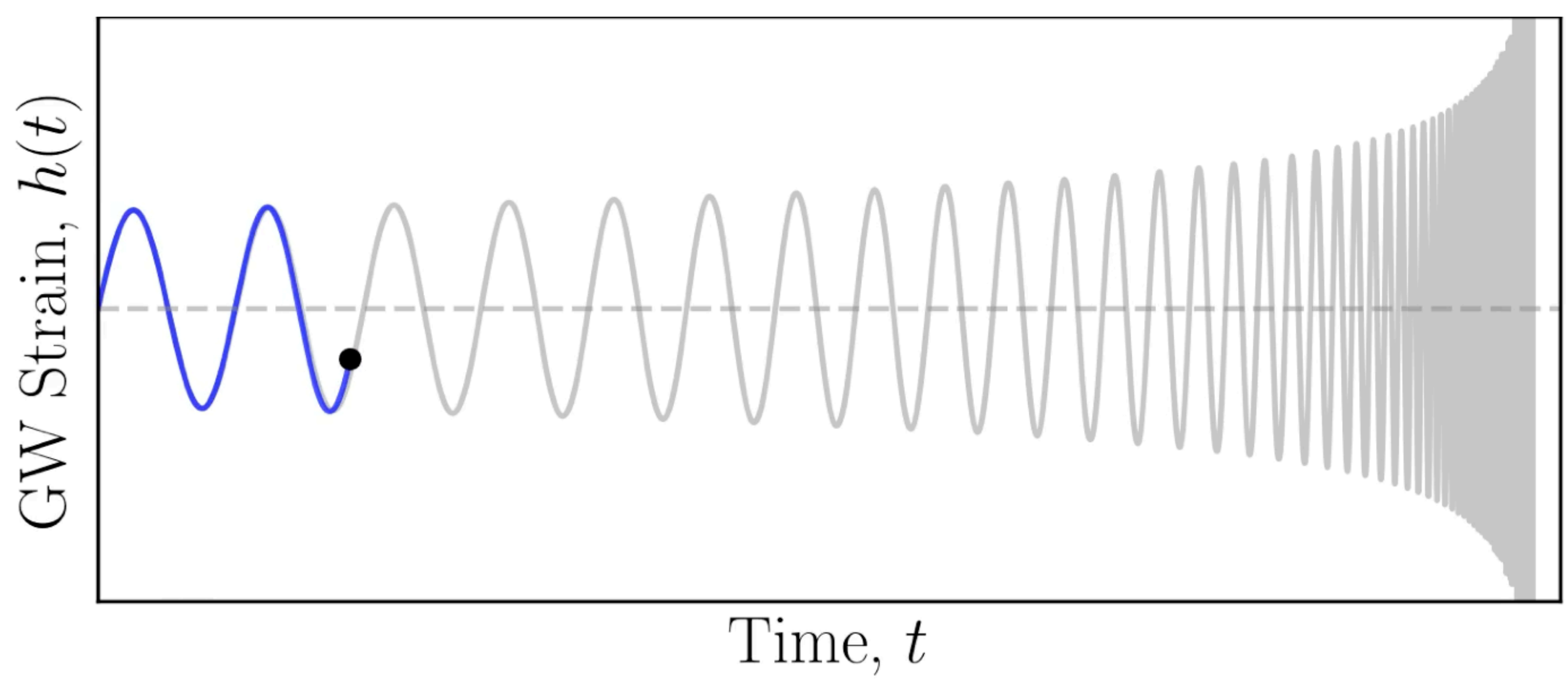

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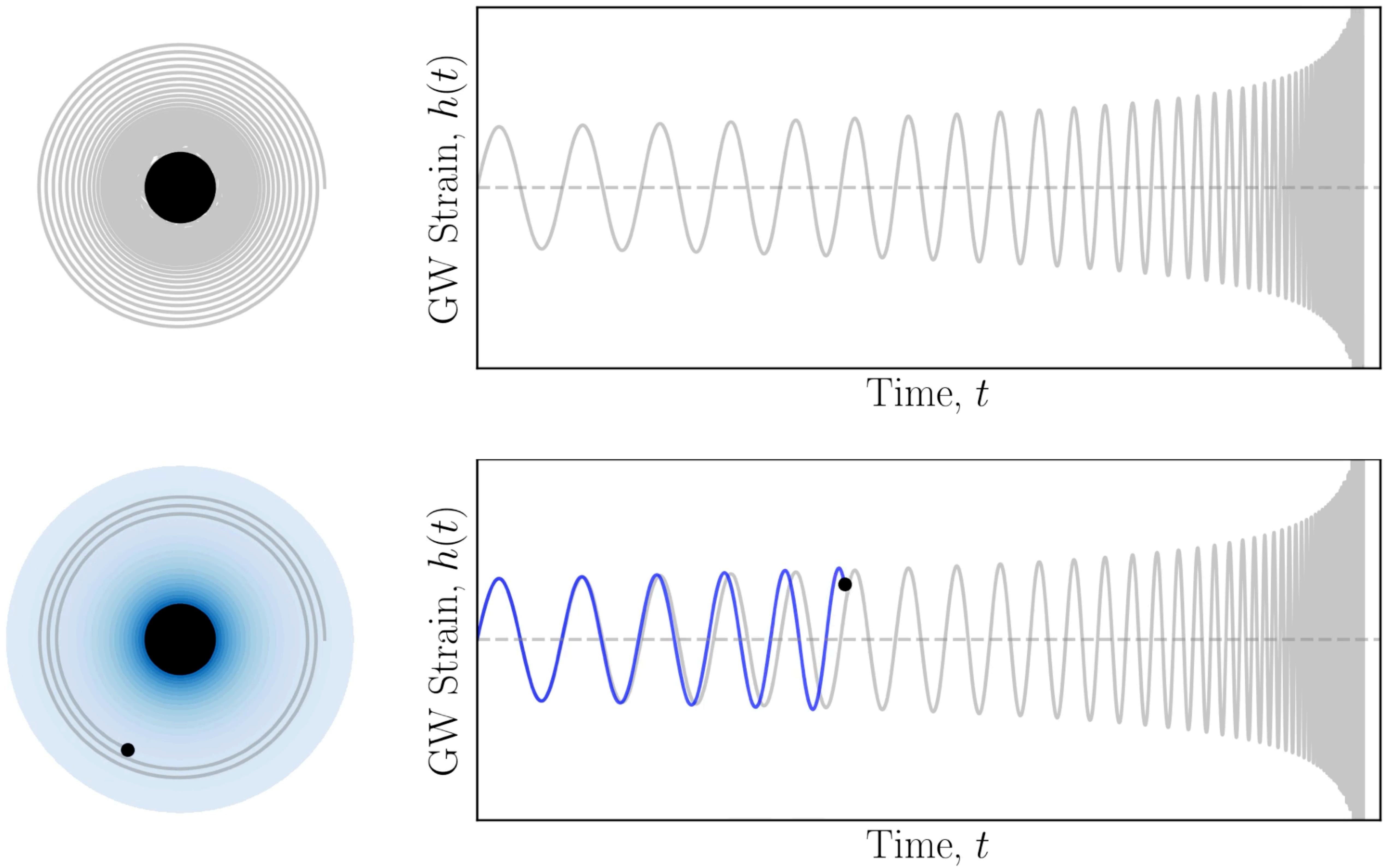

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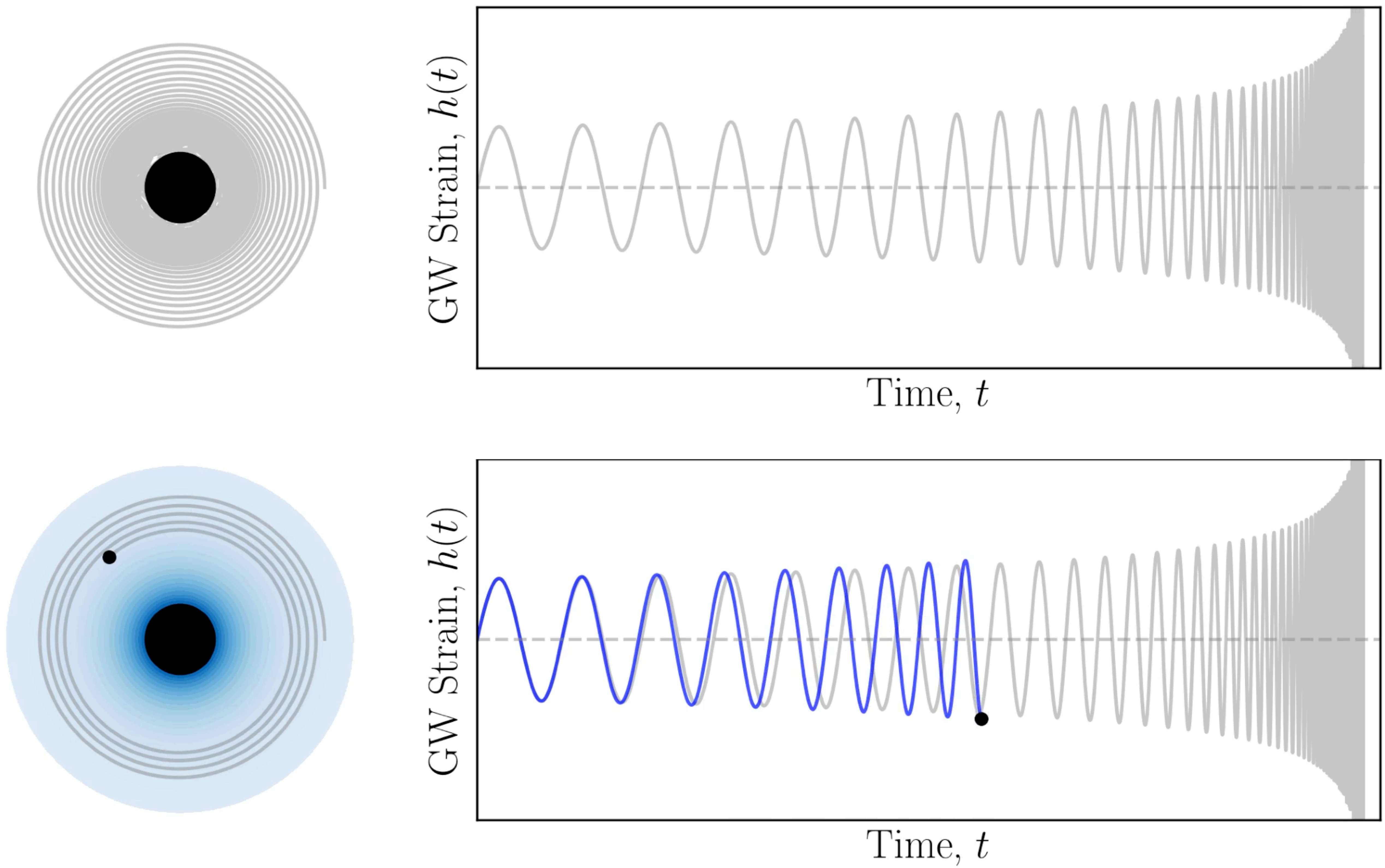

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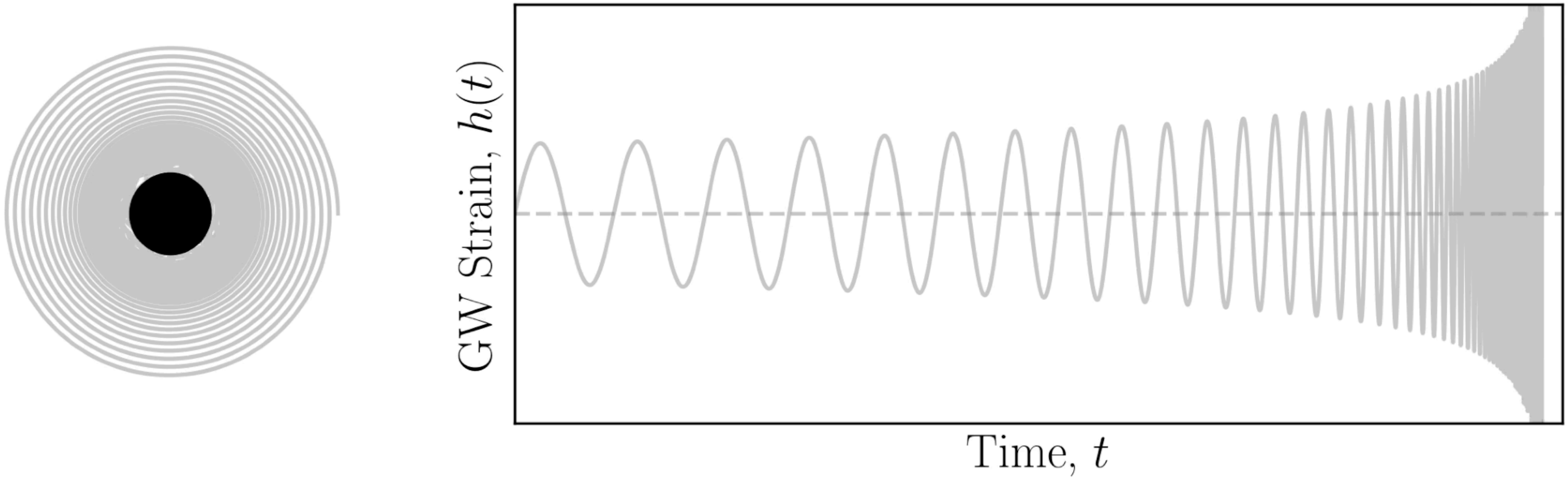
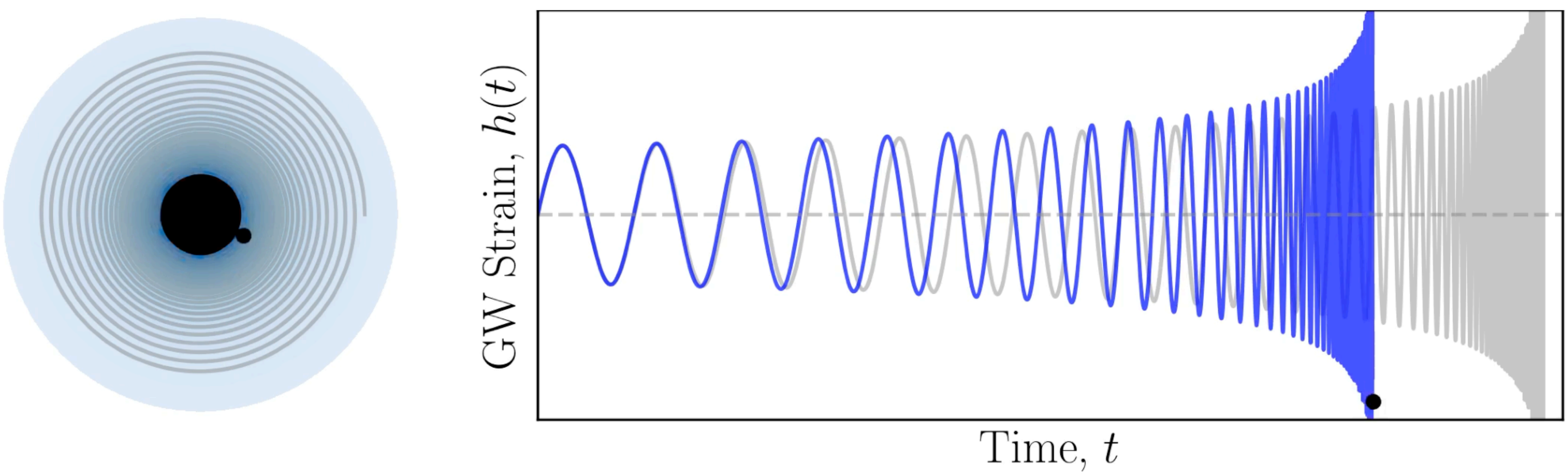
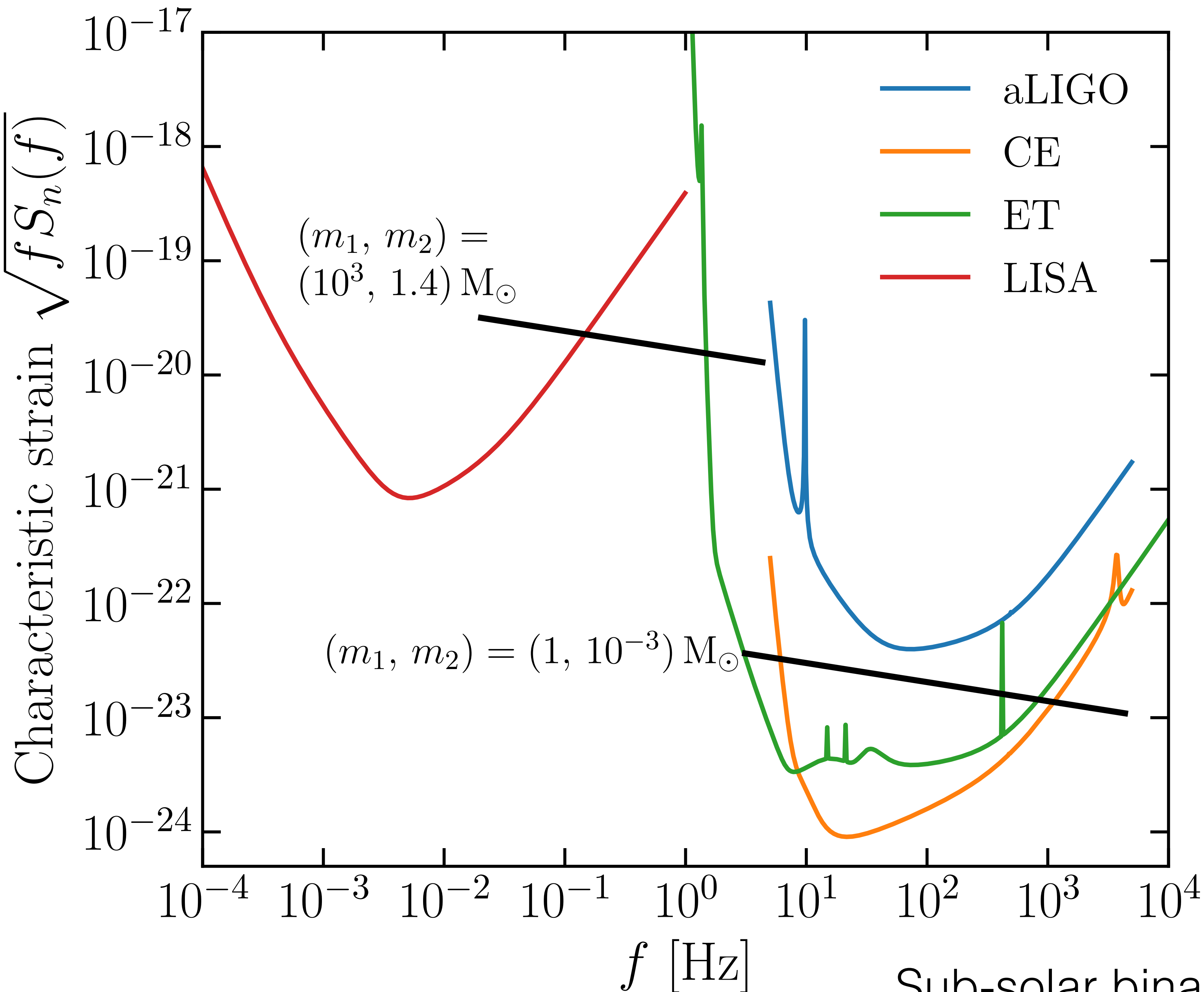




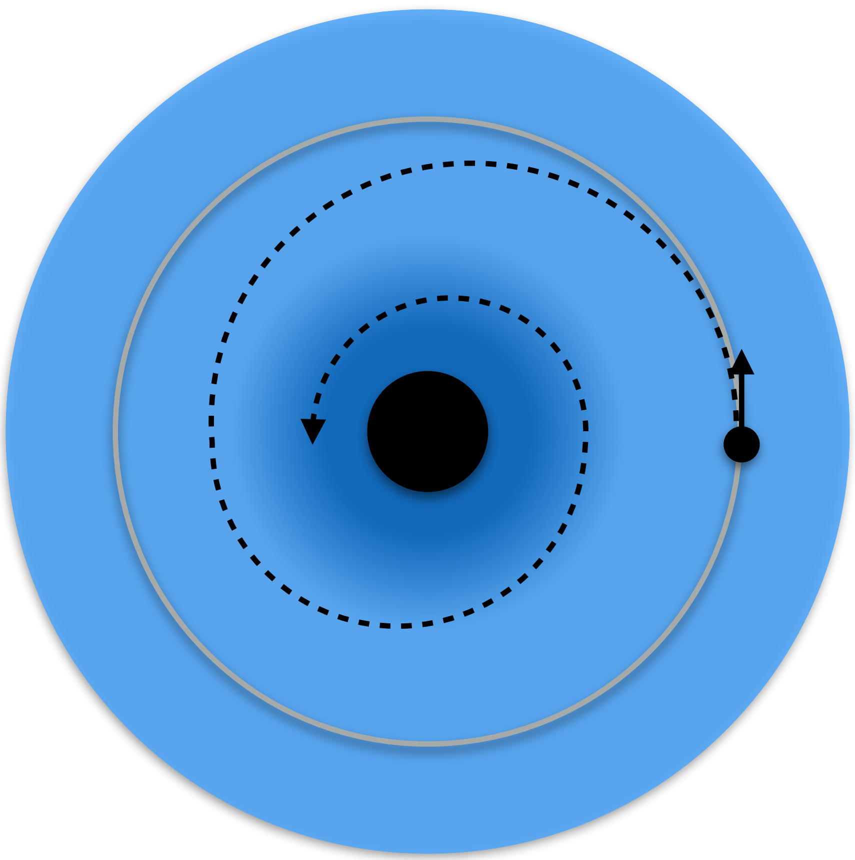
GW Sensitivity



Sub-solar binaries detectable out to ~100 Mpc with future GW observatiories

Modelling the dephasing

Assume quasi-circular, Newtonian orbits in the limit $q = m_2/m_1 \ll 1$:

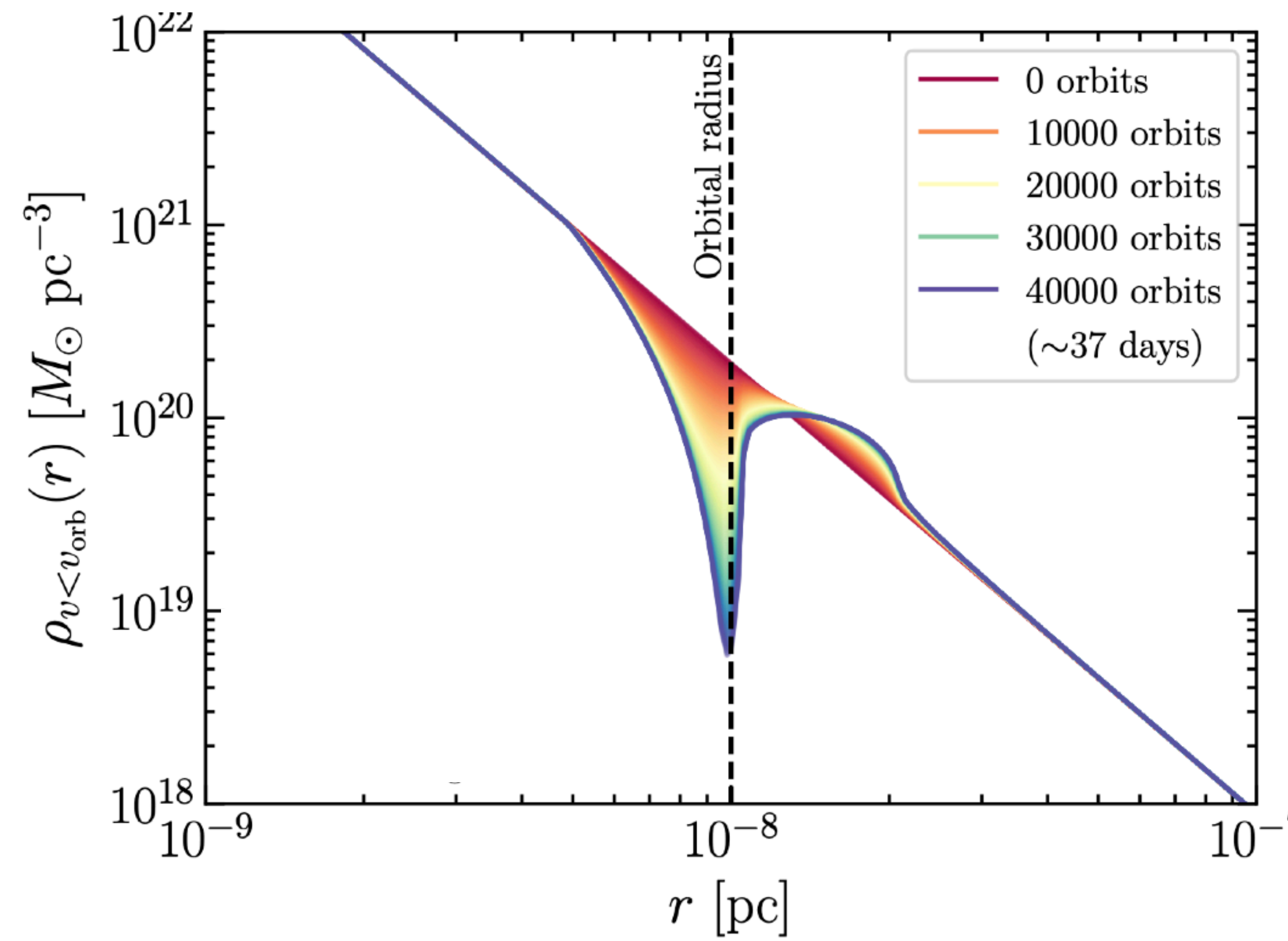


$$-\dot{E}_{\mathrm{orb}} = \dot{E}_{\mathrm{GW}} + \dot{E}_{\mathrm{DF}}$$

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

Model also the feedback on the DM spike:

$$\frac{\mathrm{d}f(\mathcal{E})}{\mathrm{d}t} \to \rho_{\mathrm{DM}}(r,t)$$

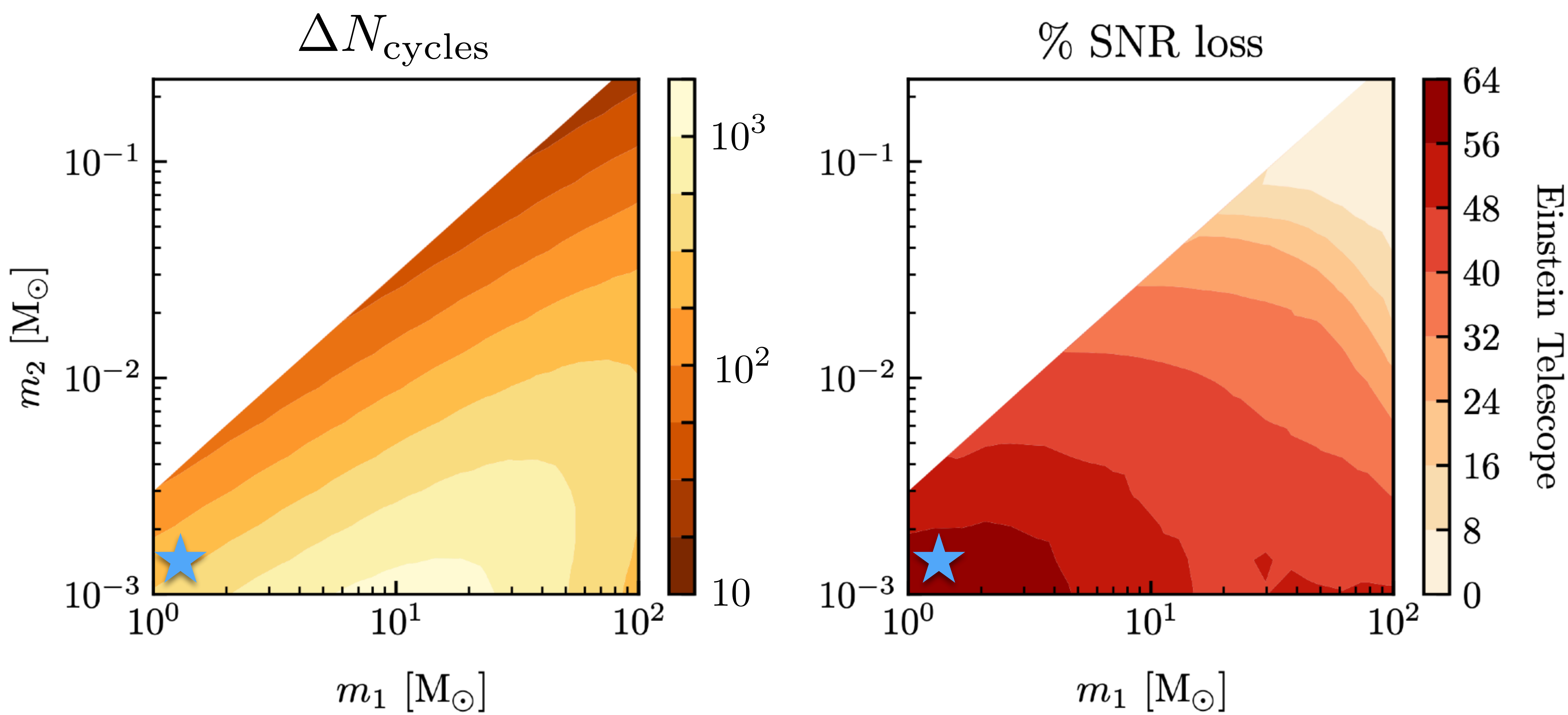


[HaloFeedback Code, **BJK** et al., 2002.12811;
Coogan et al. (including **BJK)**, 2108.04154;
See Backup Slides]

Quantifying the dephasing

★ $(m_1, m_2) = (1,\ 10^{-3})\ M_\odot$

In vacuum, expect ~10^7 GW cycles during a one year observation.
But with a DM spike:

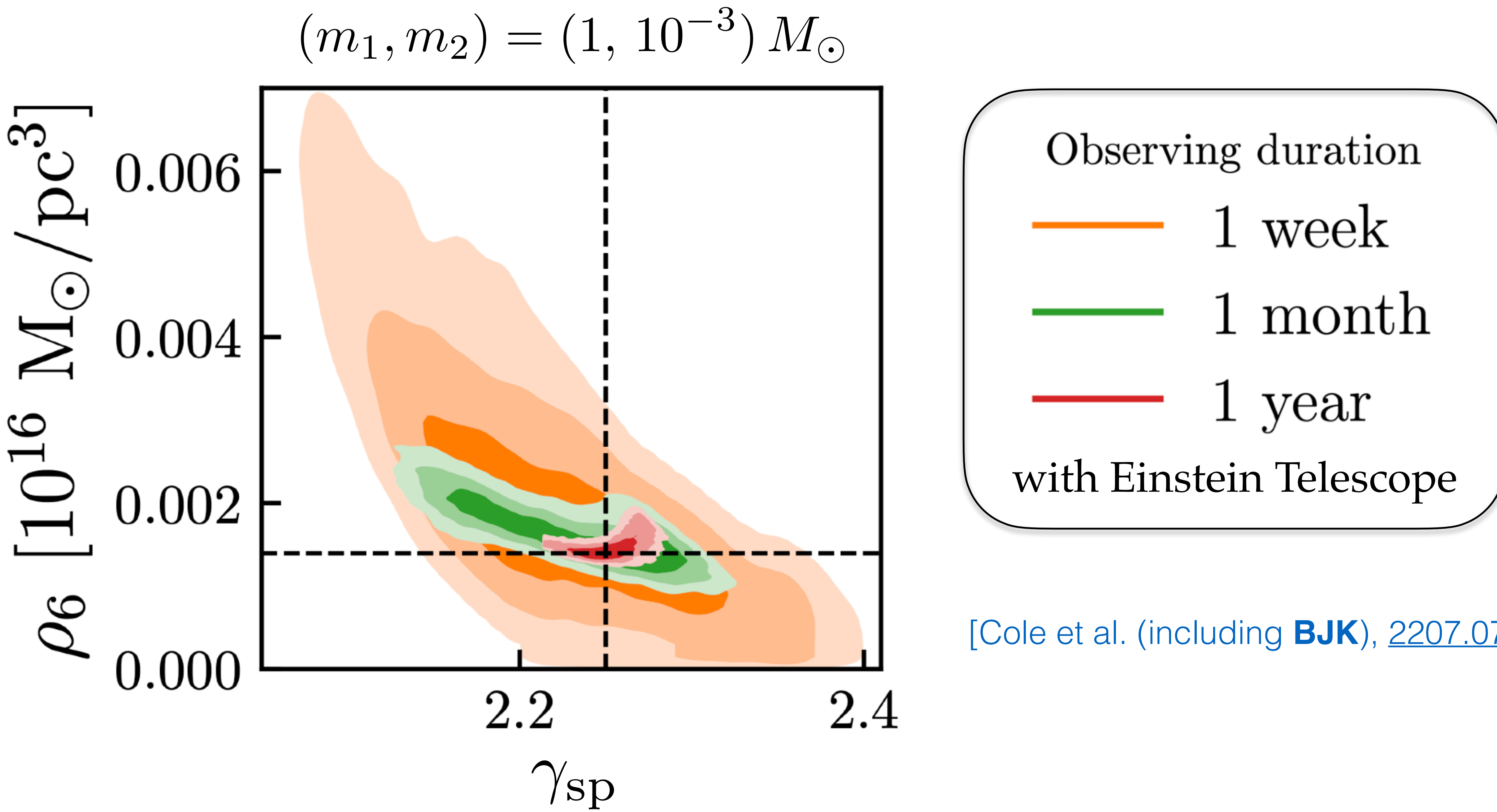


With sufficiently large SNR loss, signal could be missed altogether!

[Cole et al. (including **BJK**), 2207.07576]

Measuring the DM Spike

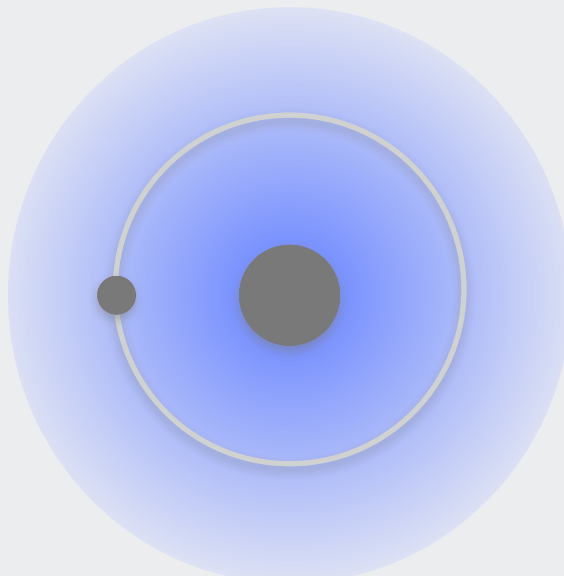
$$\rho_{\mathrm{DM}}(r) = \rho_6 \left(\frac{r}{10^{-6}\,\mathrm{pc}}\right)^{-\gamma_{\mathrm{sp}}}$$



[Cole et al. (including **BJK**), 2207.07576]

Distinguishable from other environmental effects (baryons, light bosonic fields, …)!

[Cole et al. (including **BJK**), 2211.01362]



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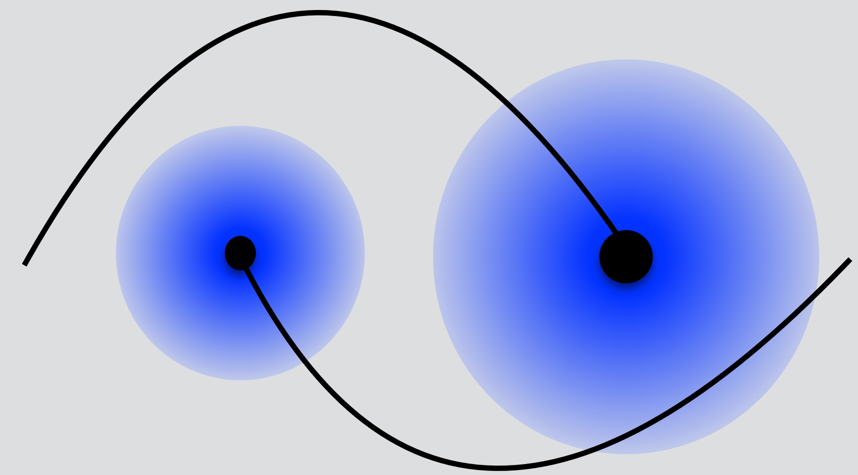
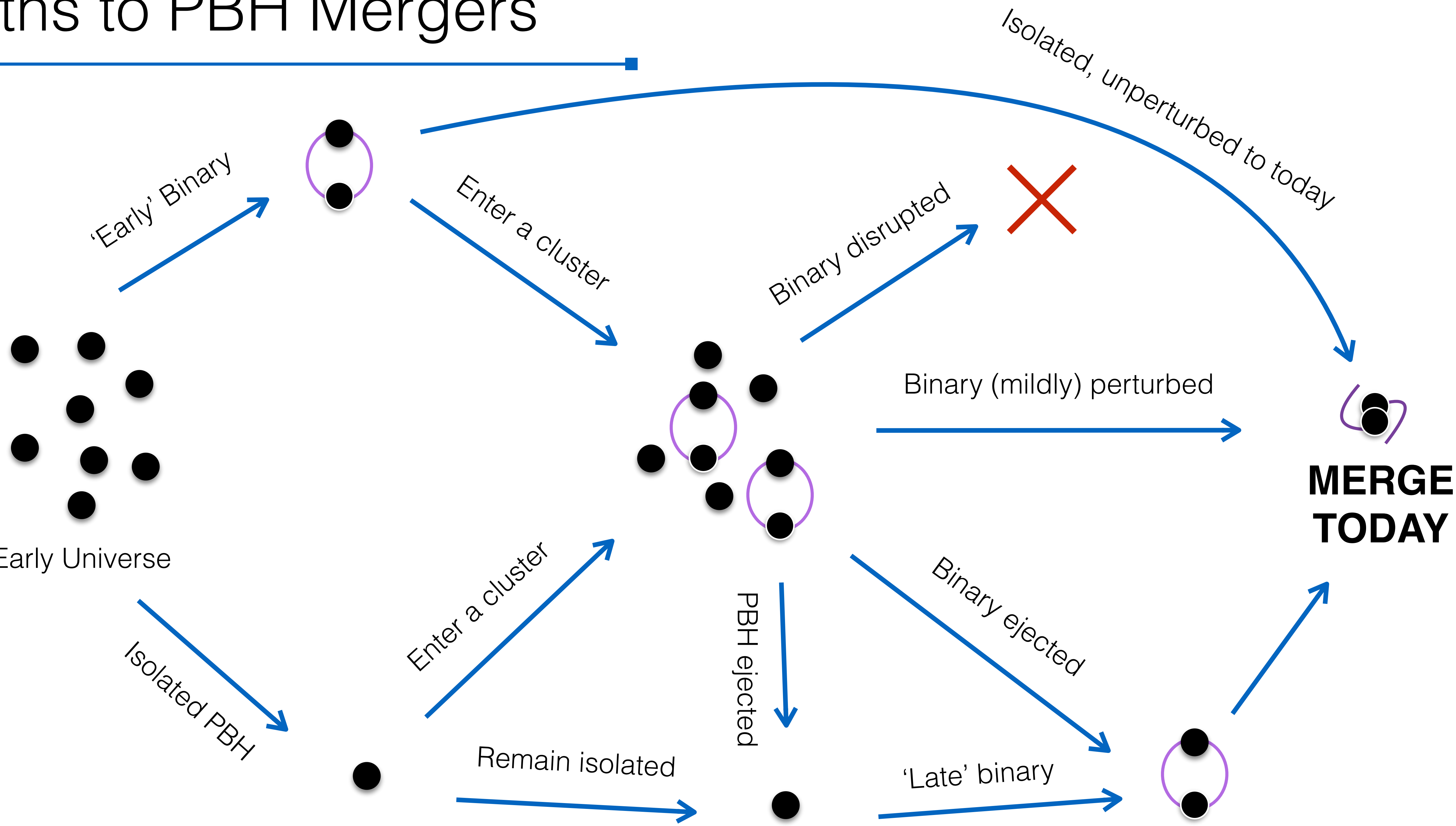


Merger rates of dressed PBH Binaries

Paths to PBH Mergers



+ particle DM halos?
  [**BJK**, Gaggero & Bertone, 1805.09034;
  Jangra, **BJK**, Diego, 2304.05892]

+ baryonic accretion?
  [De Luca et al., 2003.12589]

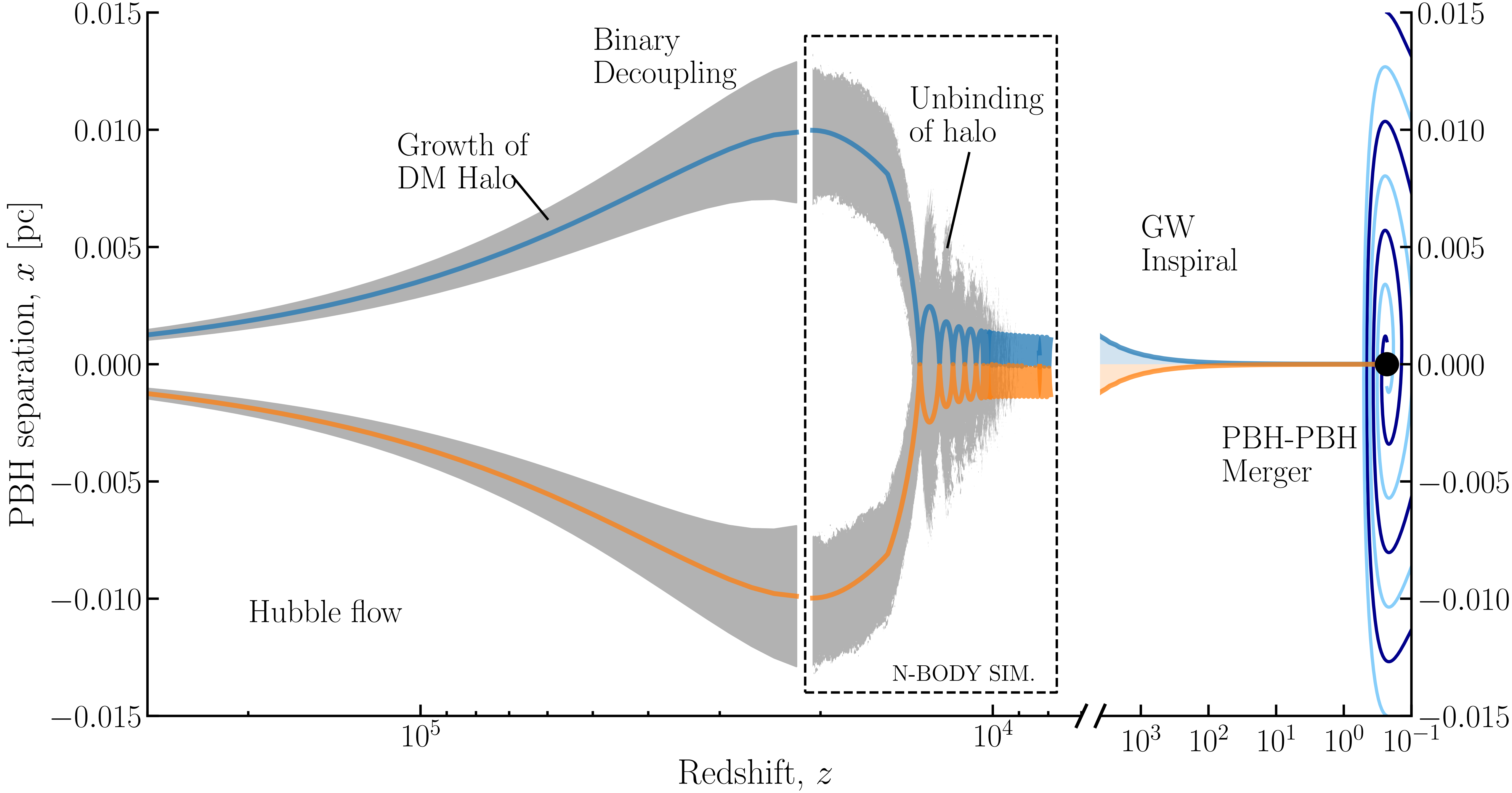
[Raidal+, 1812.01930; Vaskonen & Veermäe, 1908.09752;
Atal+, 2007.07212; De Luca+, 2009.04731 and others…]

Life of a PBH binary

$a_i = 0.01\,\mathrm{pc}$

$e_i = 0.995$

Consider a ~equal-mass PBH binary:



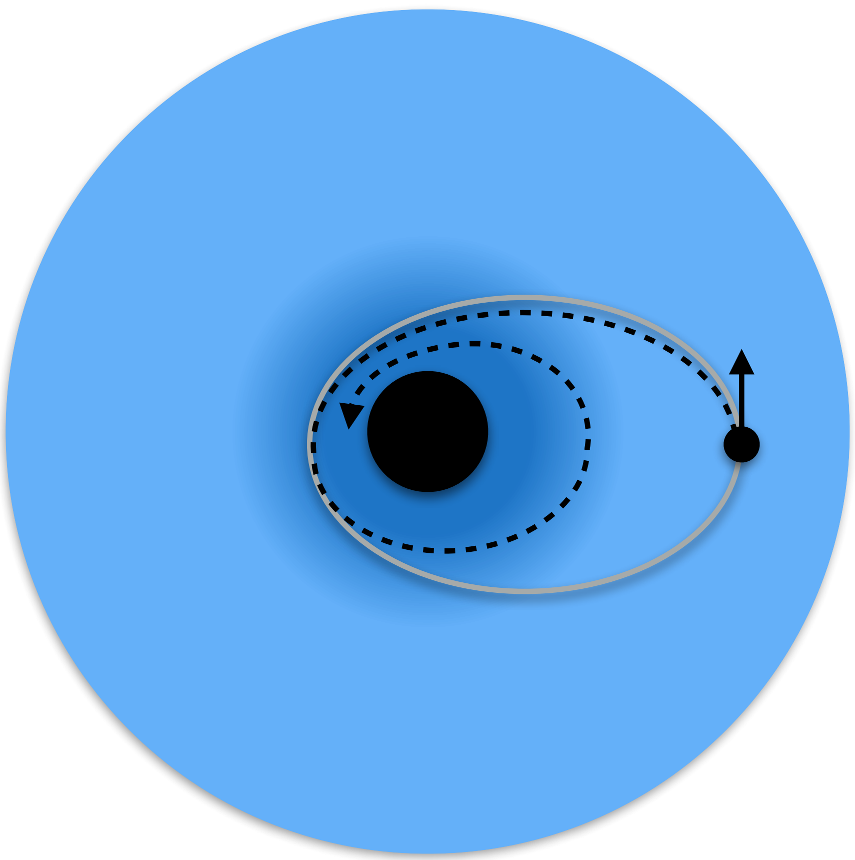
[Movies here]

[**BJK**, Gaggero & Bertone, 1805.09034]

Large mass-ratio binaries

[Jangra, **BJK**, Diego, 2304.05892]

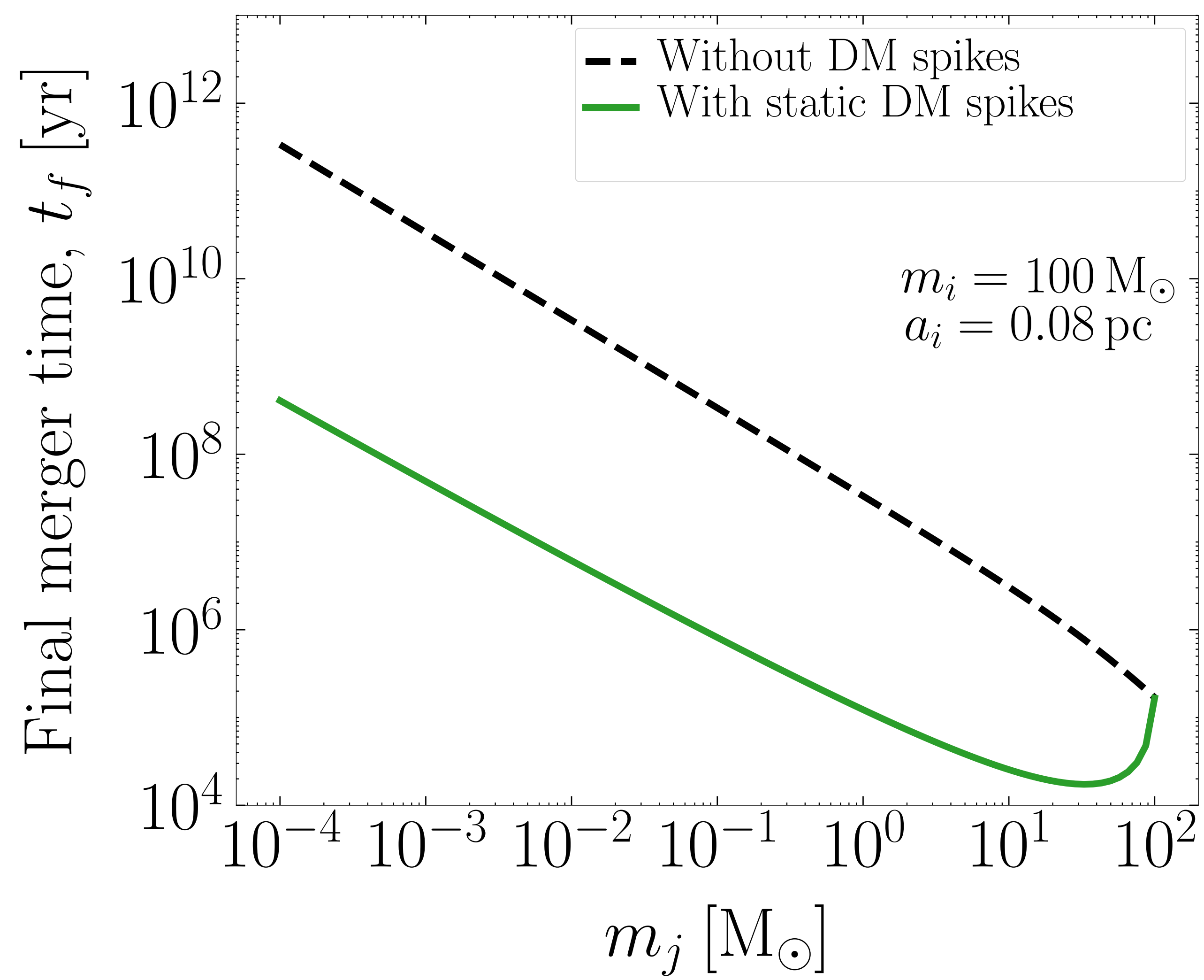
Starting from binary formation, model **highly-eccentric** Newtonian orbits:



$$-\dot{E}_{\rm orb} = \dot{E}_{\rm GW} + \dot{E}_{\rm DF}$$

$$-\dot{L}_{\rm orb} = \dot{L}_{\rm GW} + \dot{L}_{\rm DF}$$

$\longrightarrow t_{\rm m}$



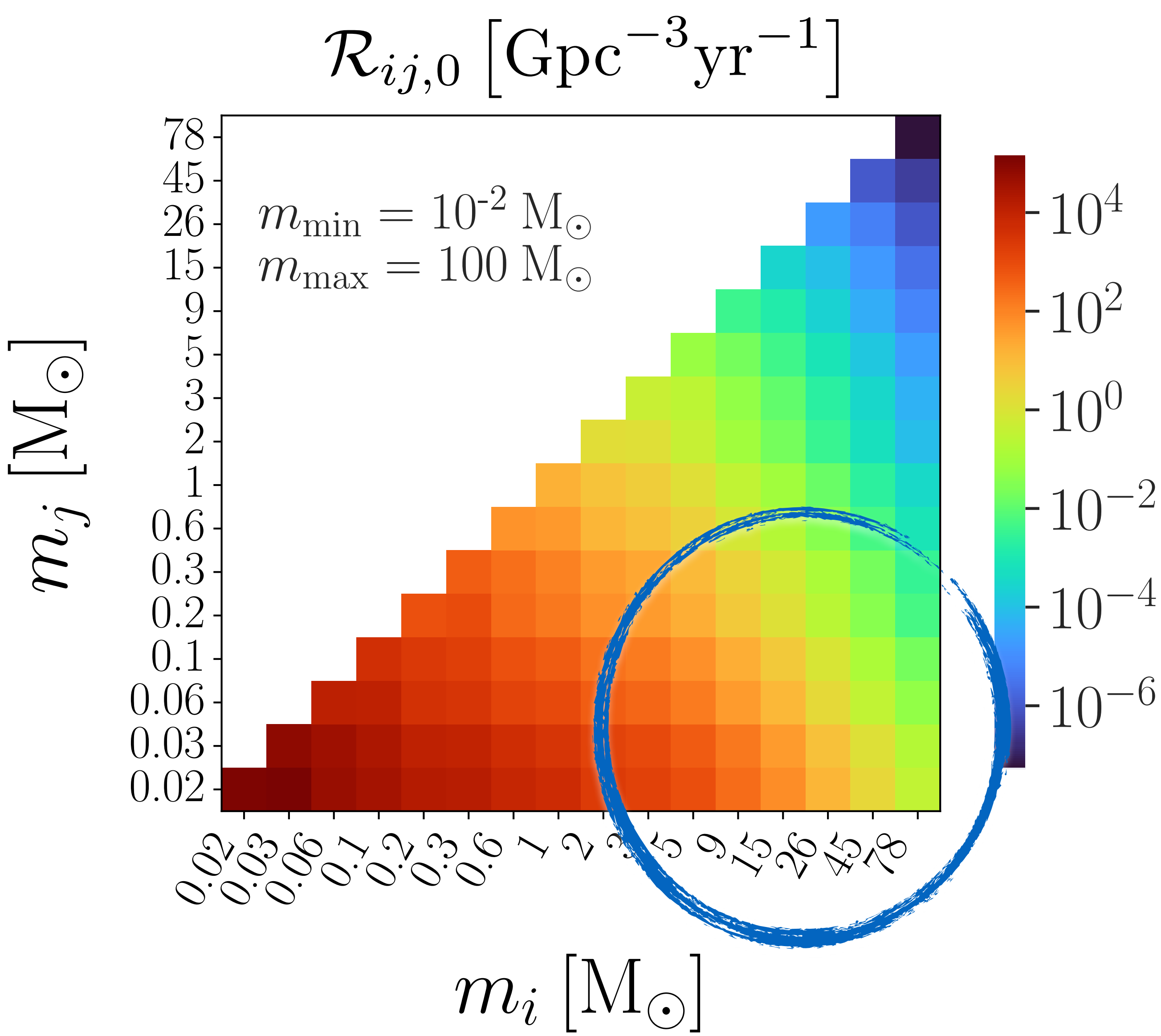
Assume "**static spikes**" (i.e. neglecting feedback). Formalism for eccentric orbits is being developed…

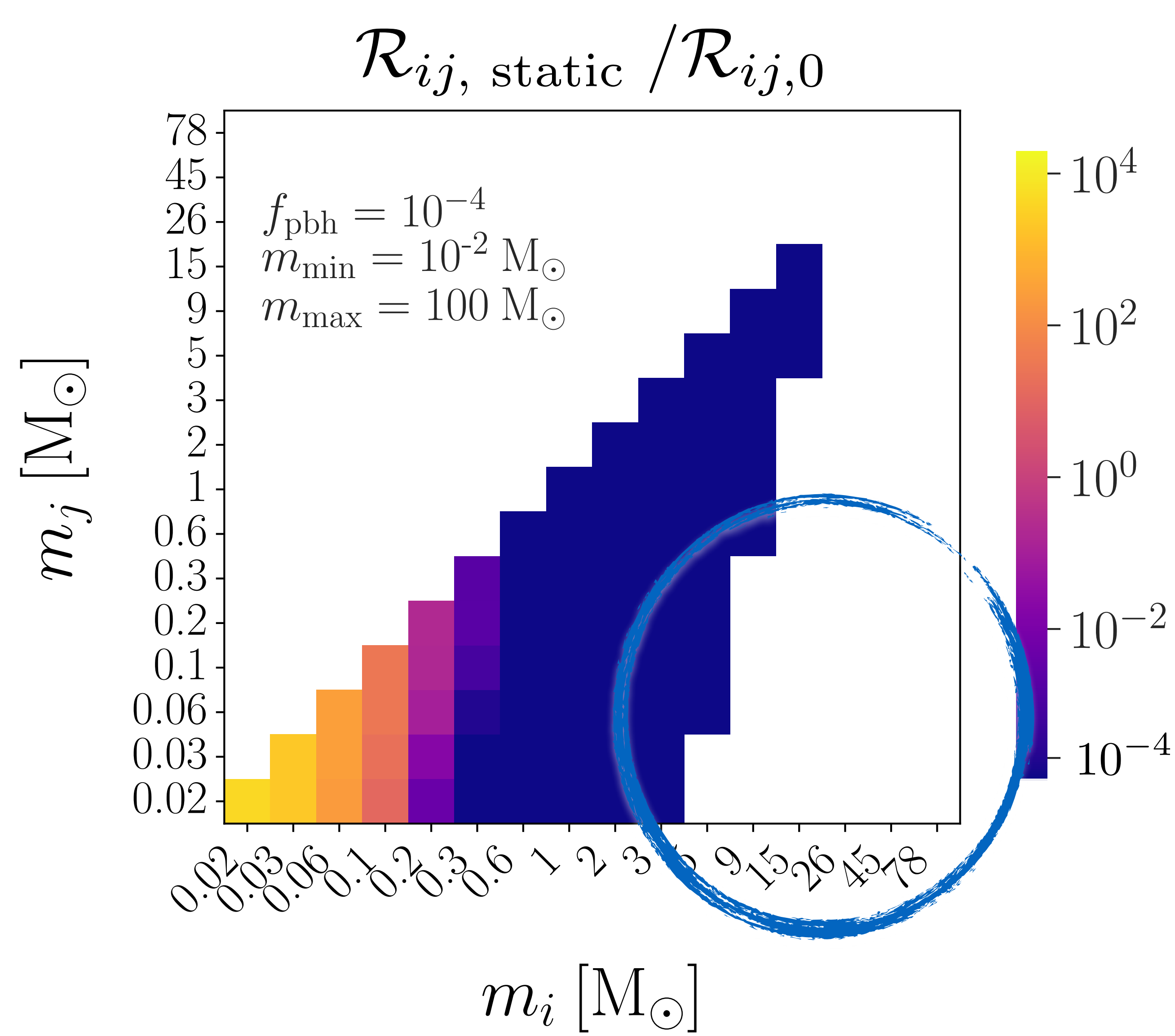
[IMRIpy Code; Becker at al., 2112.09586]

$$\frac{\mathrm{d}\mathcal{R}_{ij}}{\mathrm{d}m_i\,\mathrm{d}m_j} \sim \rho_m^0 \min\left(\frac{f_i}{m_i}, \frac{f_j}{m_j}\right) P(t_m)$$

Merger rate ratios

Assuming a power-law mass function, just below current LVK constraints:





Merger can be accelerated by a huge amount.
Binaries which would have merged today have already merged!

[Jangra, **BJK**, Diego, 2304.05892]

Many collaborators…

…and others…

Gianfranco Bertone
(GRAPPA, Amsterdam)

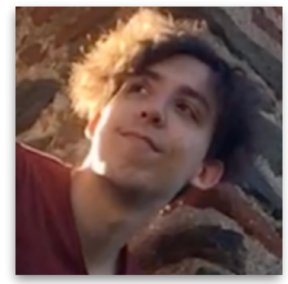
Pippa Cole
(GRAPPA, Amsterdam)

Adam Coogan
(Mila, Montreal)

Jose Maria Diego
(IFCA, Santander)

Daniele Gaggero
(INFN, Pisa)

Pratibha Jangra
(IFCA, Santander)



Theophanes Karydas
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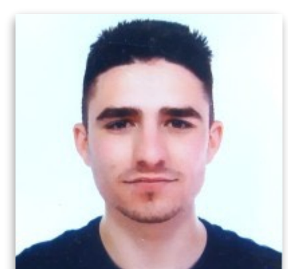
David Nichols
(U. Virginia)



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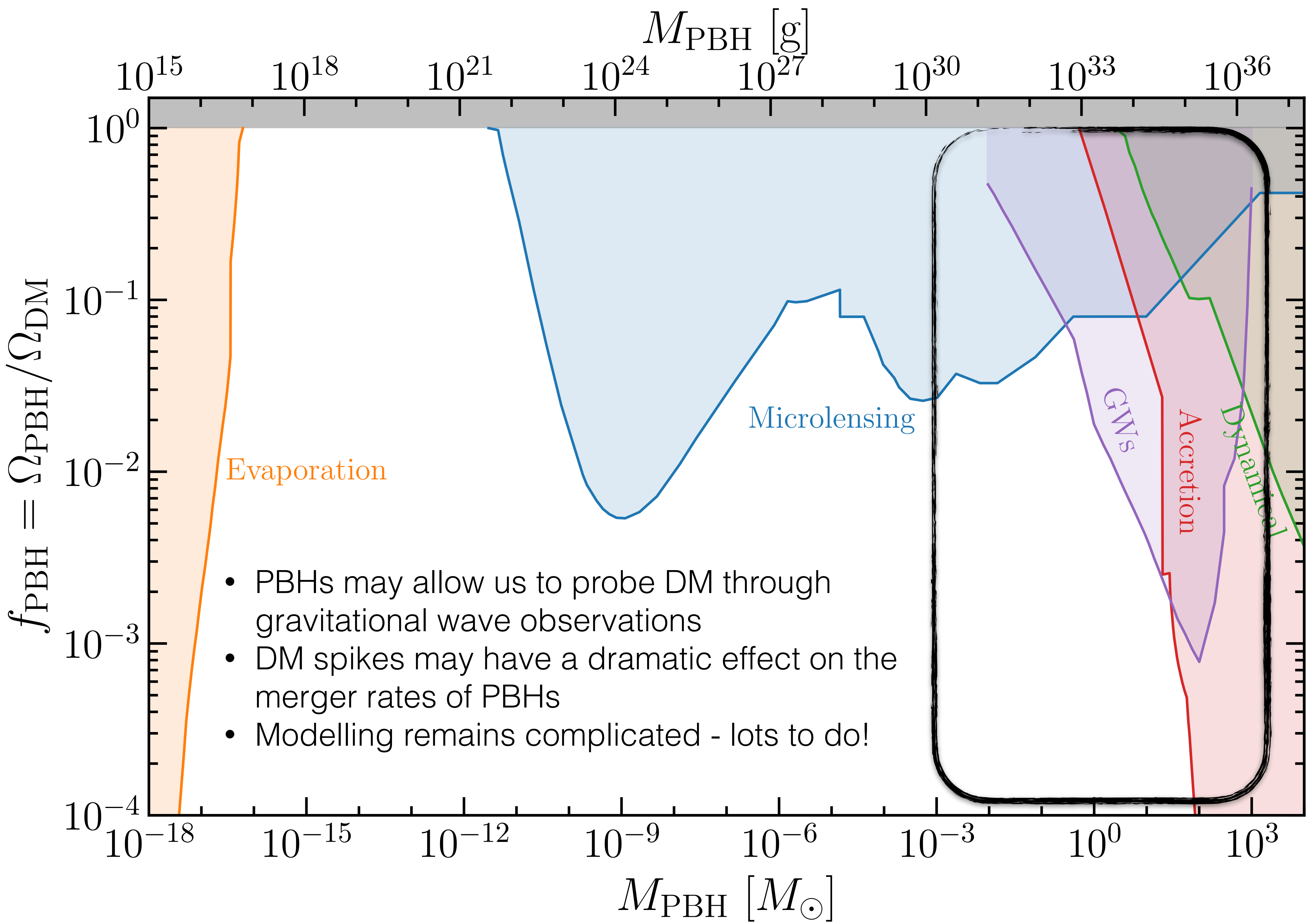
(IFT, Madrid)

Conclusions

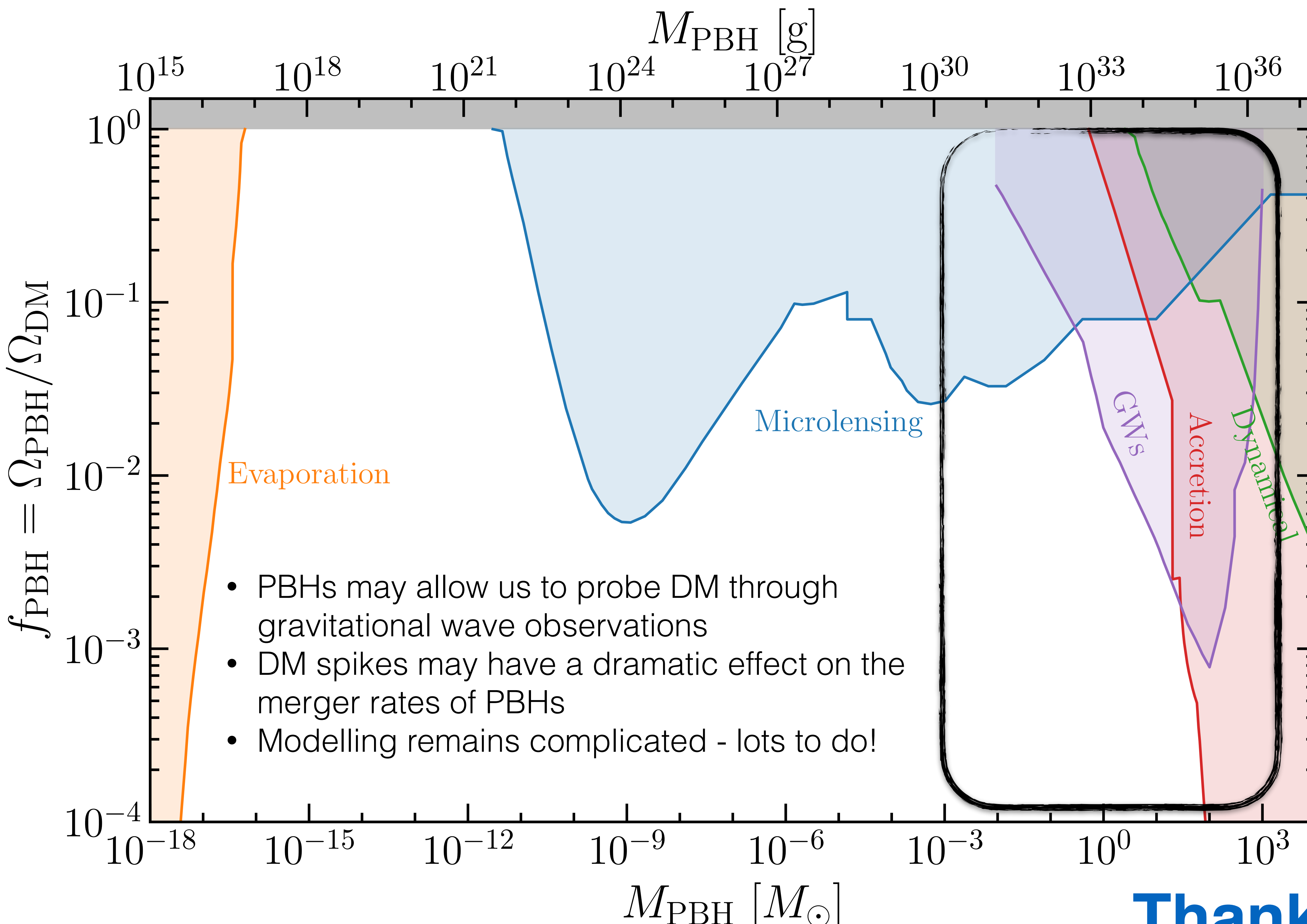
[Green & **BJK**, 2007.10722]
[Code online: github.com/bradkav/PBHbounds]



- PBHs may allow us to probe DM through gravitational wave observations
- DM spikes may have a dramatic effect on the merger rates of PBHs
- Modelling remains complicated - lots to do!

Conclusions

[Green & **BJK**, 2007.10722]
[Code online: github.com/bradkav/PBHbounds]



- PBHs may allow us to probe DM through gravitational wave observations
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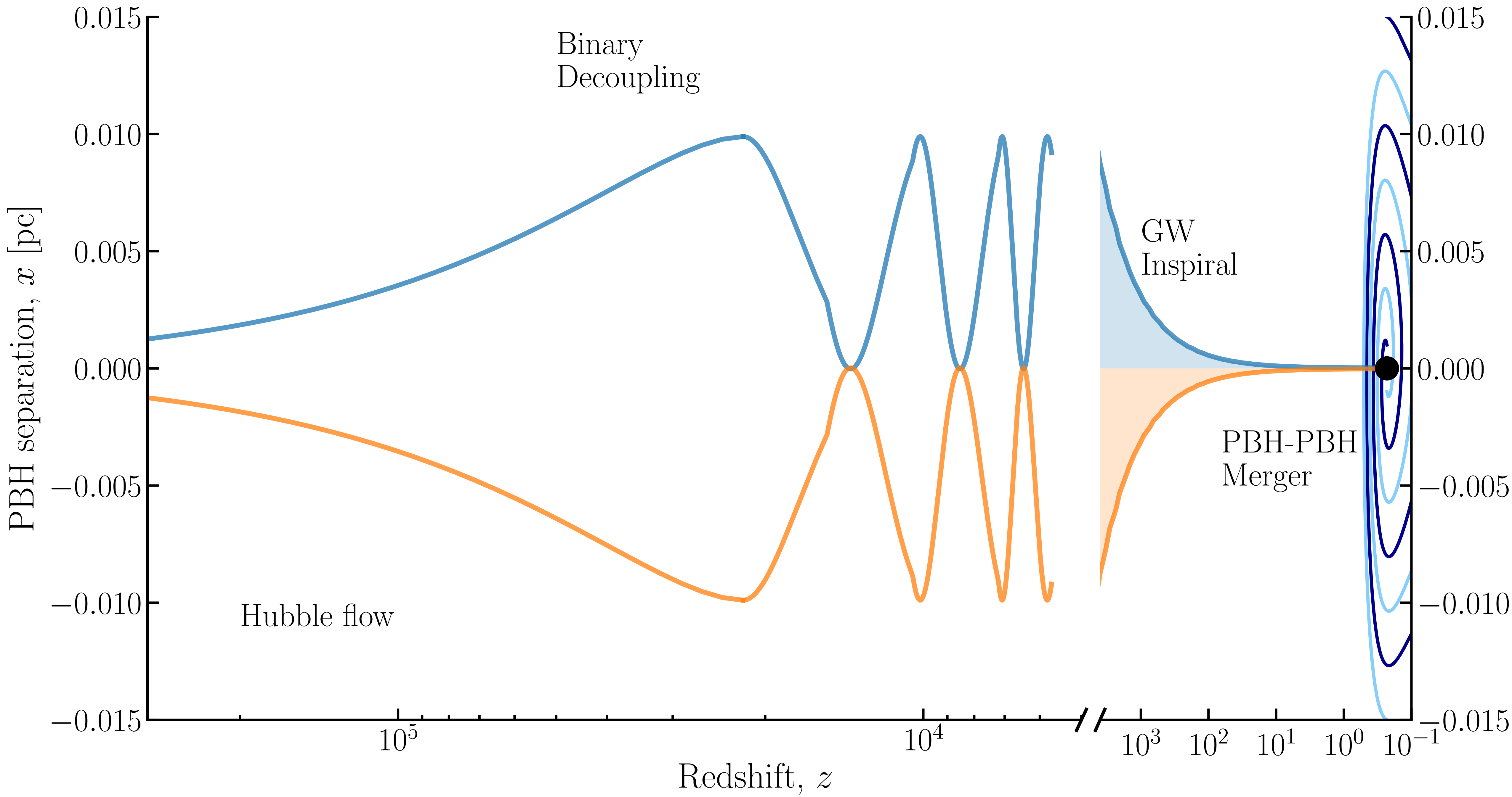
Thank you!

Backup Slides

Life of a PBH binary

$a_i = 0.01\,\mathrm{pc}$

$e_i = 0.995$



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

PBH Clustering

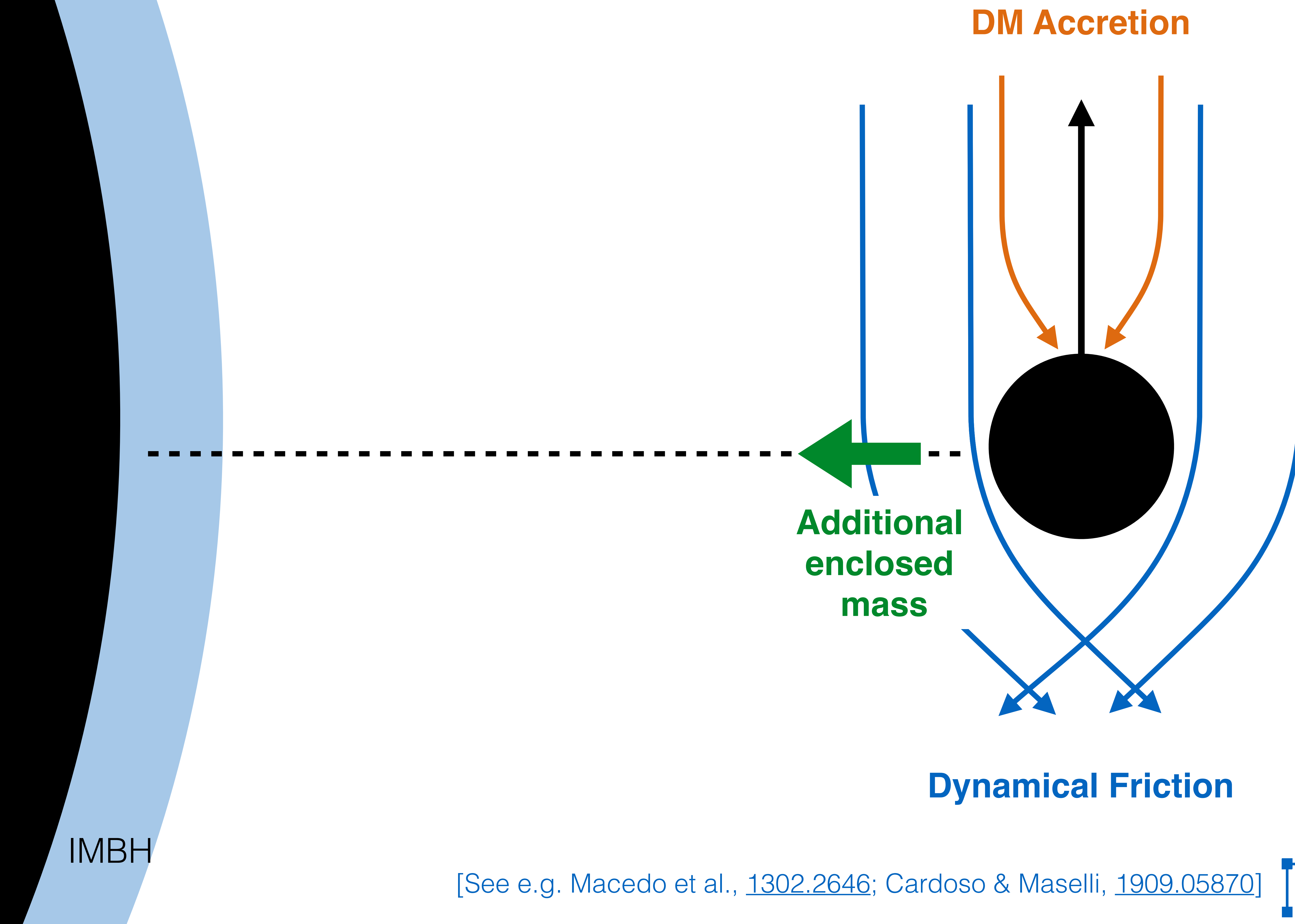
Even a distribution of PBHs which is initially Poisson distributed will cluster at late times

$z \gg 10^4$ $\qquad$ $z \lesssim 100$

A cluster of N PBHs is expected to form around $z_c \sim z_\mathrm{eq} f_\mathrm{PBH}/\sqrt{N}$

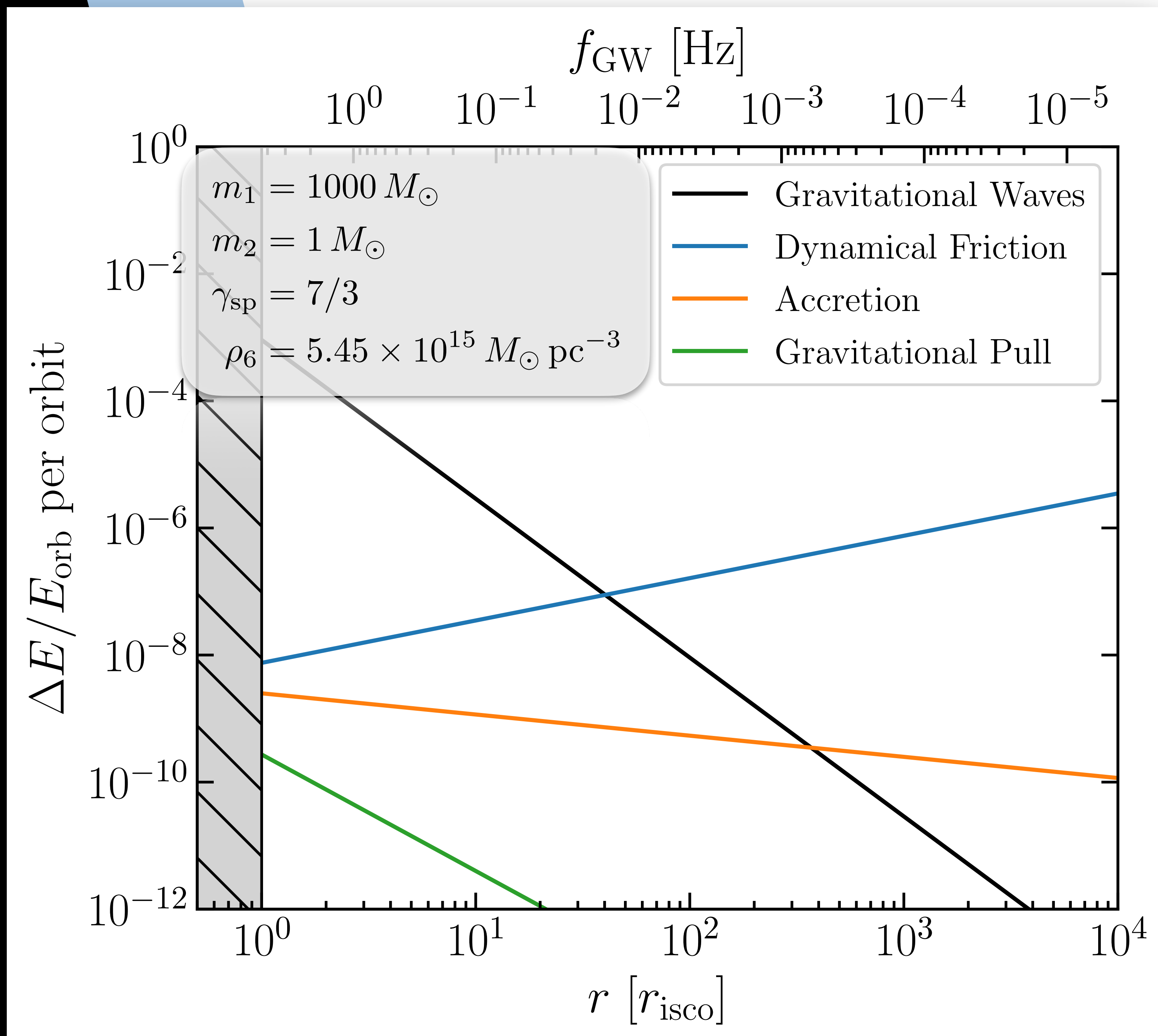
[Chisholm - astro-ph/0509141, 1110.4402; Inman & Ali-Haïmoud, 1907.08129]

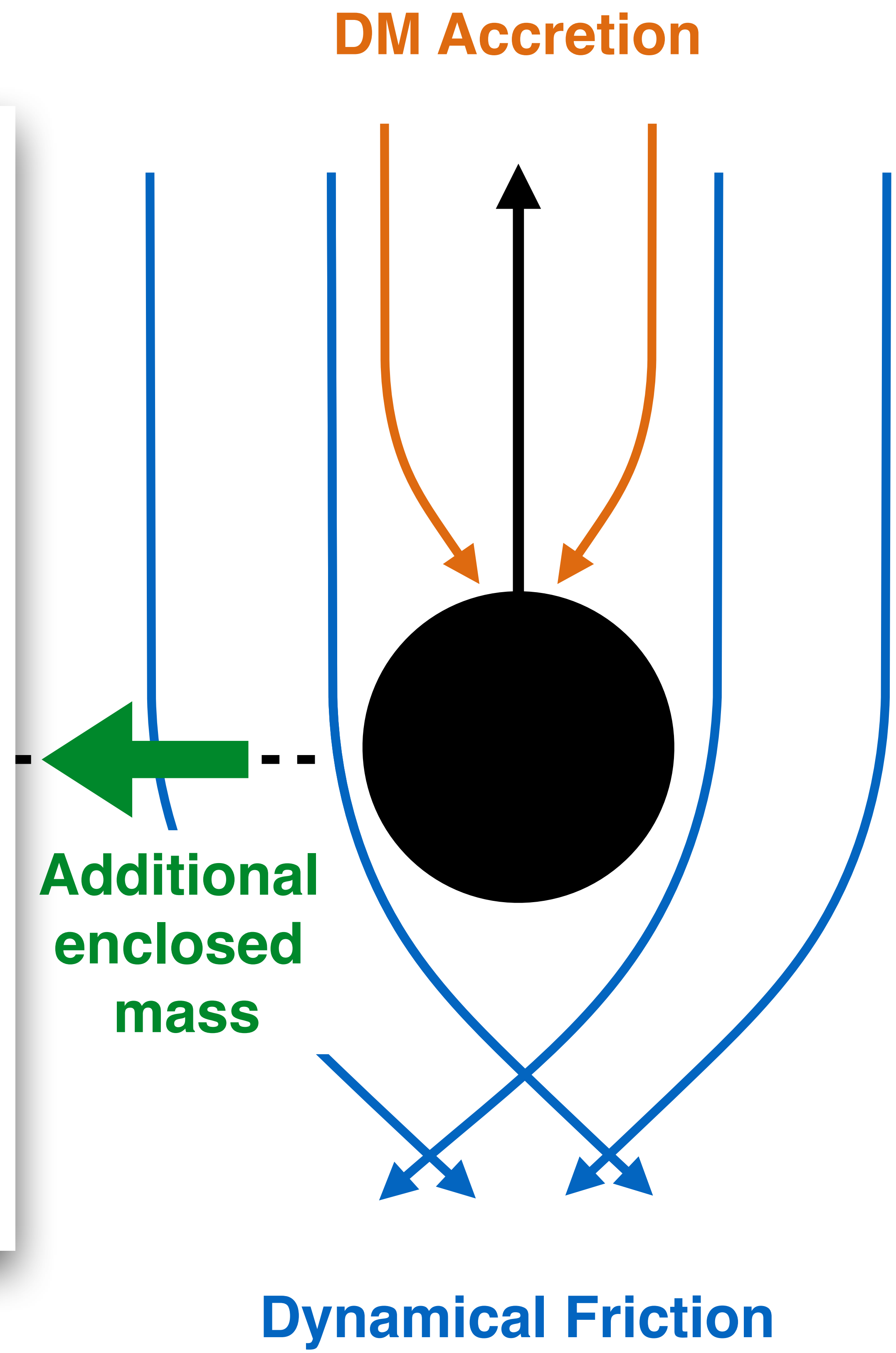
Impact of DM Spikes



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

Impact of DM Spikes

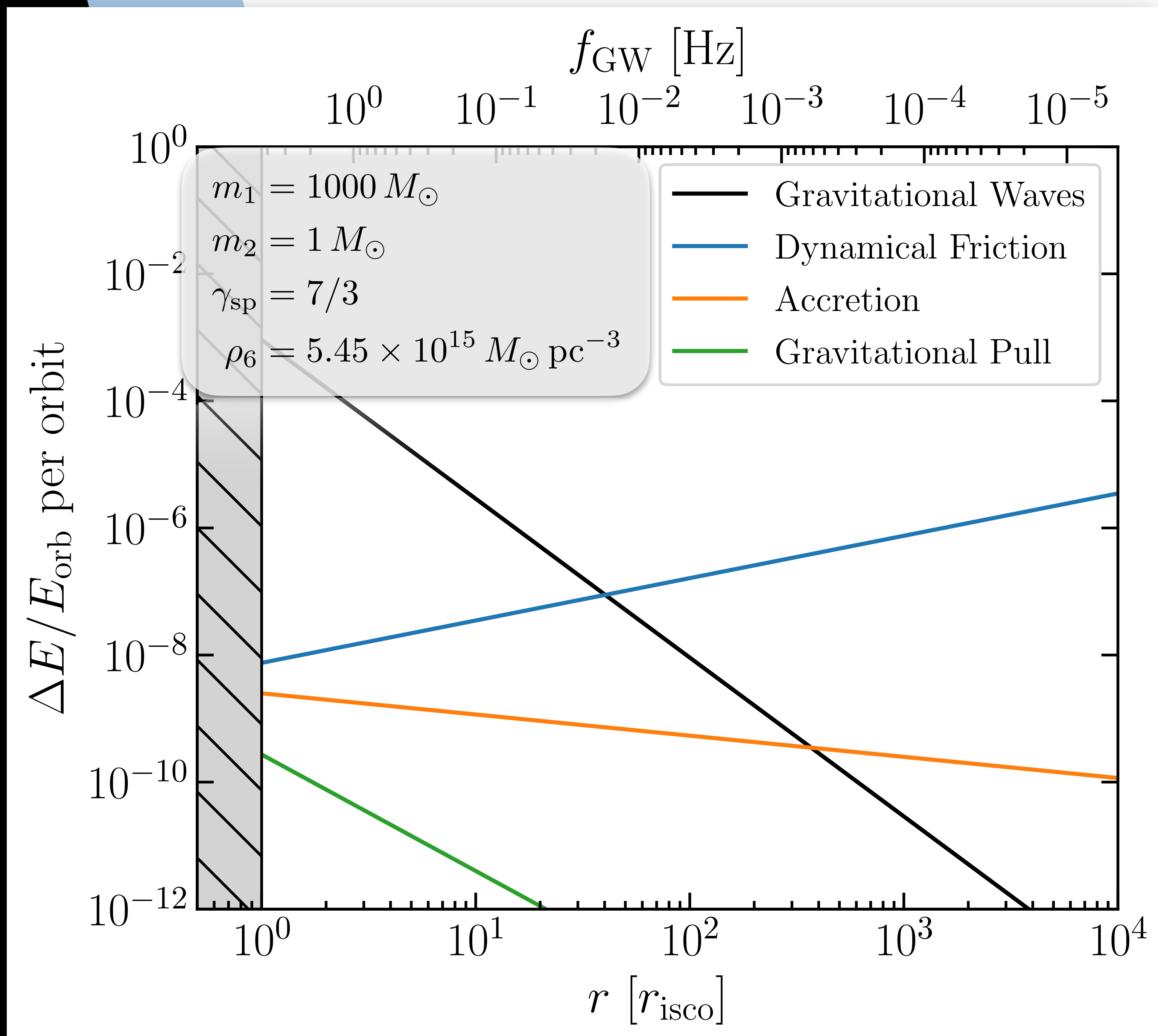


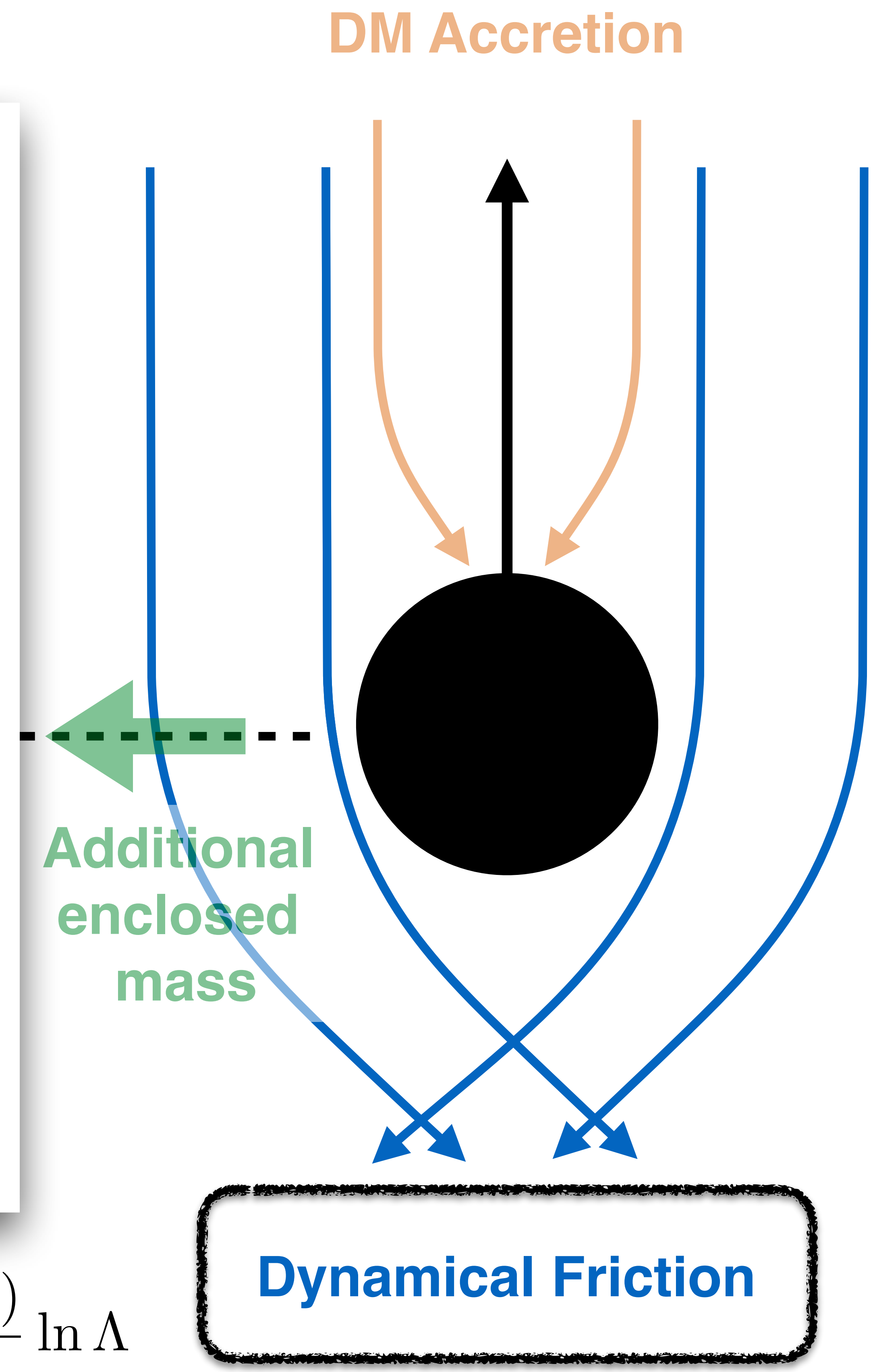


IMBH

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

Impact of DM Spikes





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

IMBH

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

DM Spike Feedback (1)

Follow semi-analytically the phase space distribution of DM:

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

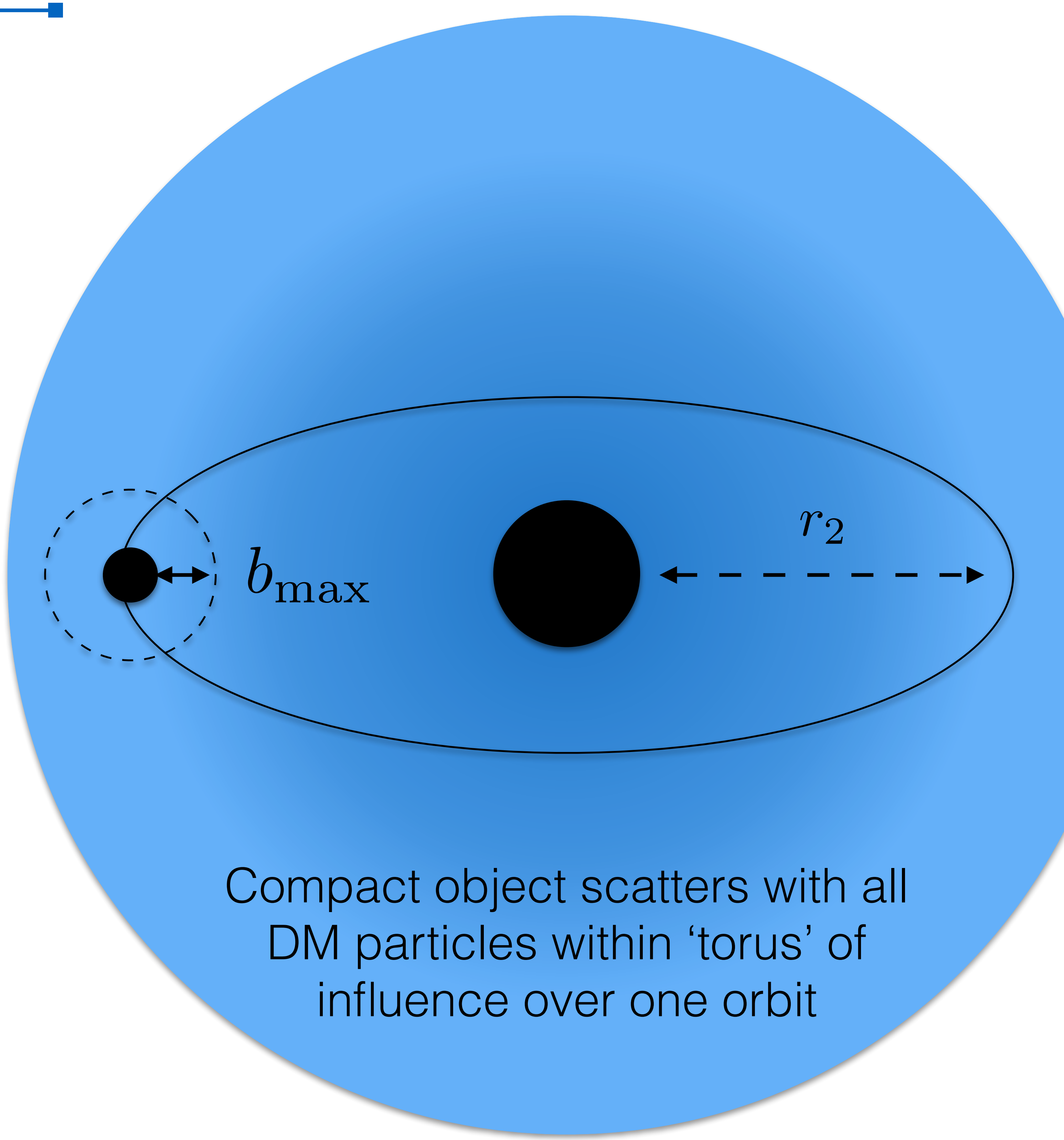
$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Each particle receives a ‘kick’ through gravitational scattering

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

Reconstruct density from distribution function:

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



DM Spike Feedback (2)

Assuming everything evolves slowly compared to the orbital period:

$$\Delta f(\mathcal{E}) = -p_{\mathcal{E}} f(\mathcal{E}) + \int \left(\frac{\mathcal{E}}{\mathcal{E} - \Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E} - \Delta\mathcal{E}) P_{\mathcal{E}-\Delta\mathcal{E}}(\Delta\mathcal{E})\,\mathrm{d}\Delta\mathcal{E}$$

$P_{\mathcal{E}}(\Delta\mathcal{E})$ - probability for a particle with energy $\mathcal{E}$ to scatter and receive a 'kick' $\Delta\mathcal{E}$

$$p_{\mathcal{E}} = \int P_{\mathcal{E}}(\Delta\mathcal{E})\,\mathrm{d}\Delta\mathcal{E}$$

- total probability for a particle with energy $\mathcal{E}$ to scatter

Formalism valid for small $q = m_2/m_1$

Code available online:
github.com/bradkav/HaloFeedback

DM Spike Feedback (2)

Assuming everything evolves slowly compared to the orbital period:

Particles scattering from
$\mathcal{E} \rightarrow \mathcal{E} + \Delta\mathcal{E}$

$$\Delta f(\mathcal{E}) = \boxed{-p_\mathcal{E} f(\mathcal{E}) +} \boxed{\int \left(\frac{\mathcal{E}}{\mathcal{E} - \Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E} - \Delta\mathcal{E}) P_{\mathcal{E}-\Delta\mathcal{E}}(\Delta\mathcal{E})\, \mathrm{d}\Delta\mathcal{E}}$$

Particles scattering from
$\mathcal{E} - \Delta\mathcal{E} \rightarrow \mathcal{E}$

$P_\mathcal{E}(\Delta\mathcal{E})$ - probability for a particle with energy $\mathcal{E}$ to scatter and receive a 'kick' $\Delta\mathcal{E}$

$$p_\mathcal{E} = \int P_\mathcal{E}(\Delta\mathcal{E})\, \mathrm{d}\Delta\mathcal{E}$$

- total probability for a particle with energy $\mathcal{E}$ to scatter

Formalism valid for small $q = m_2/m_1$

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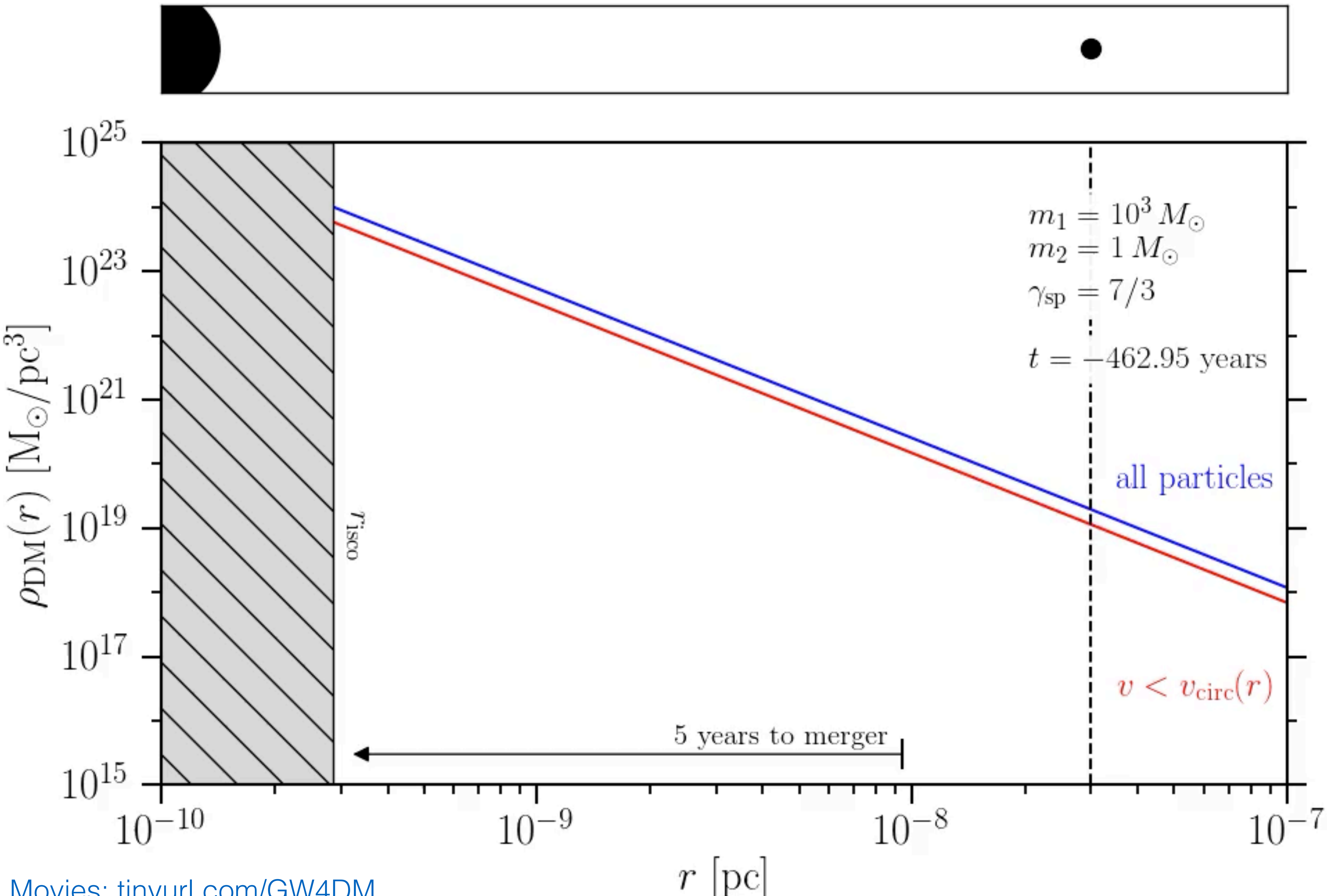
Feedback in Action

[**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

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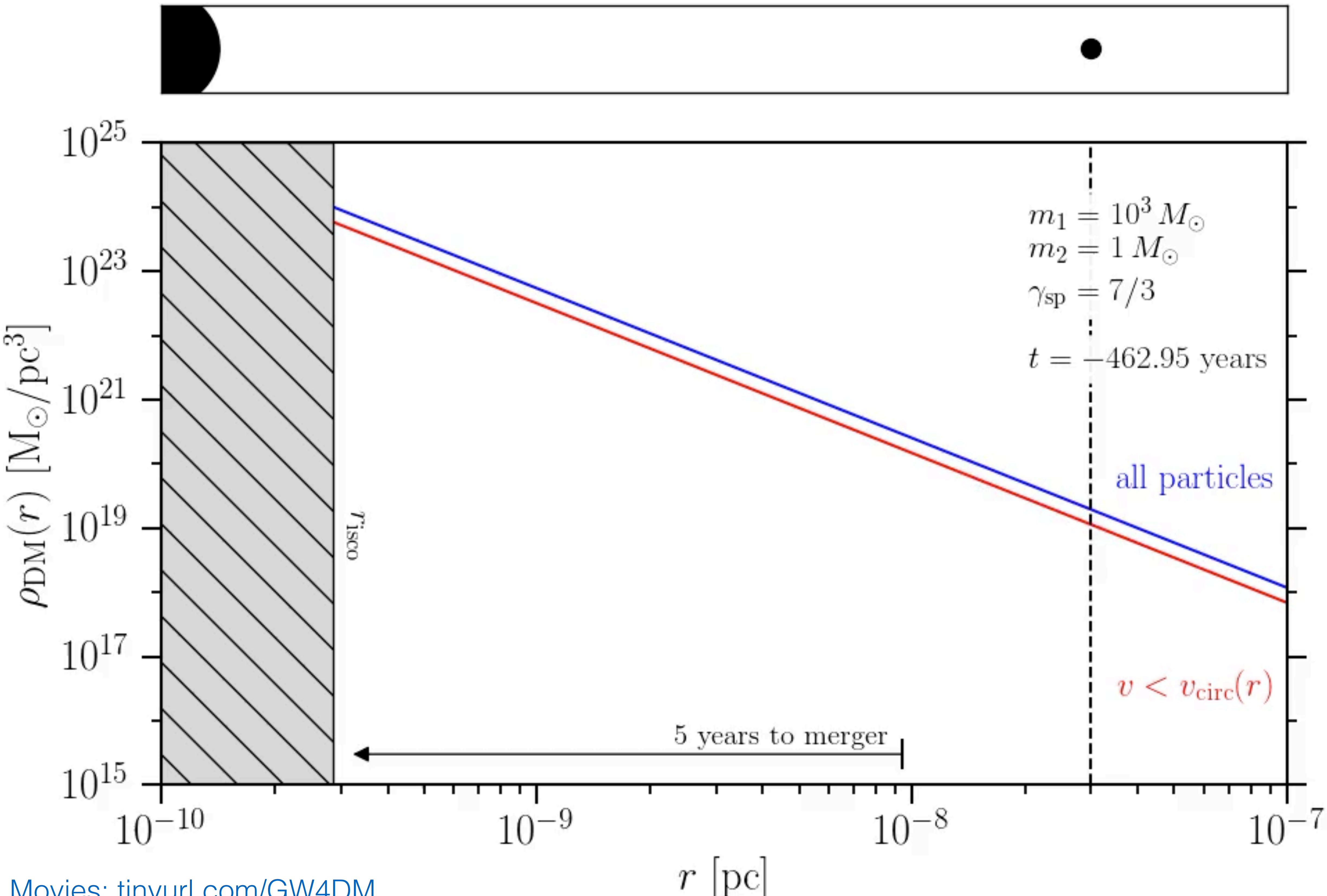

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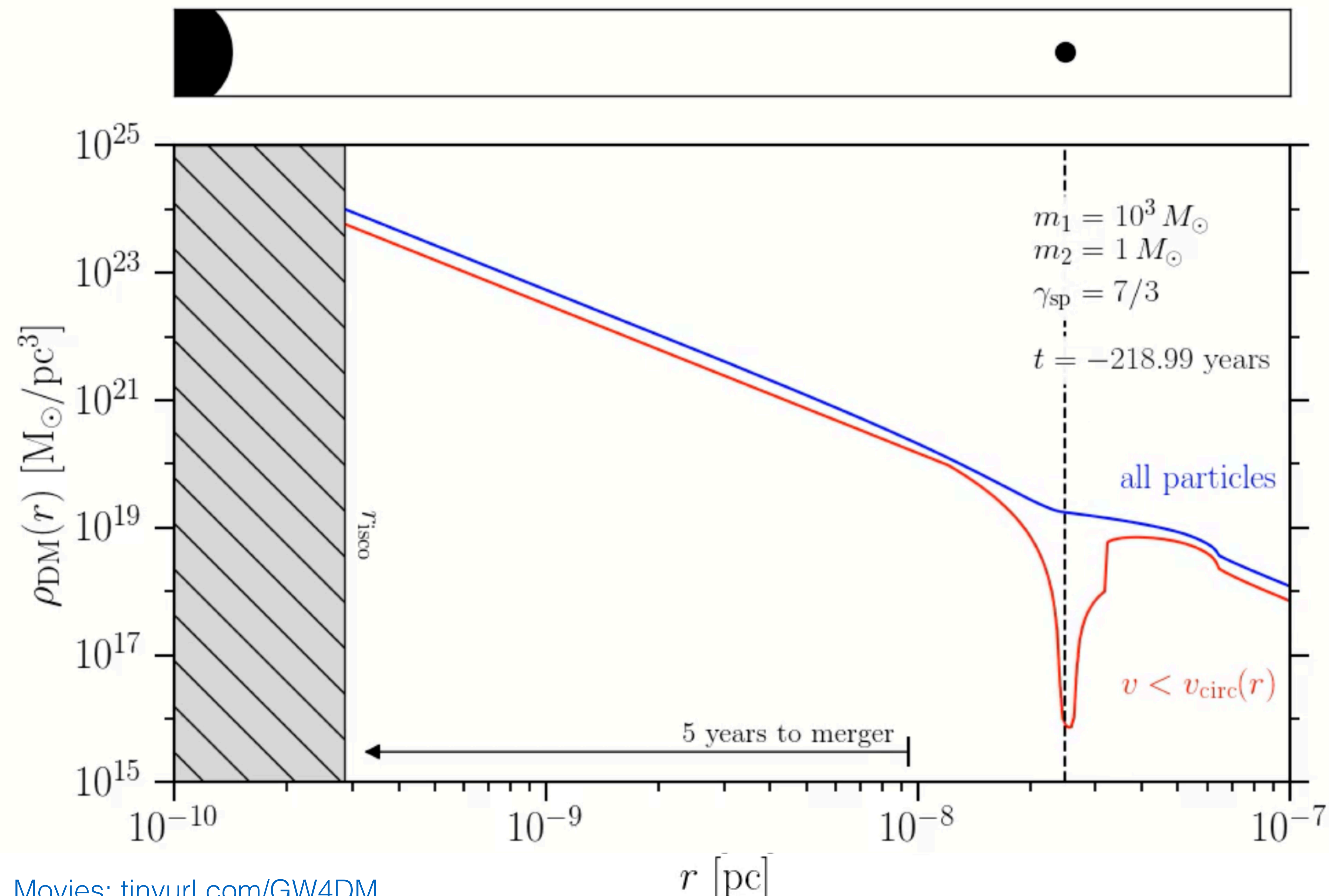

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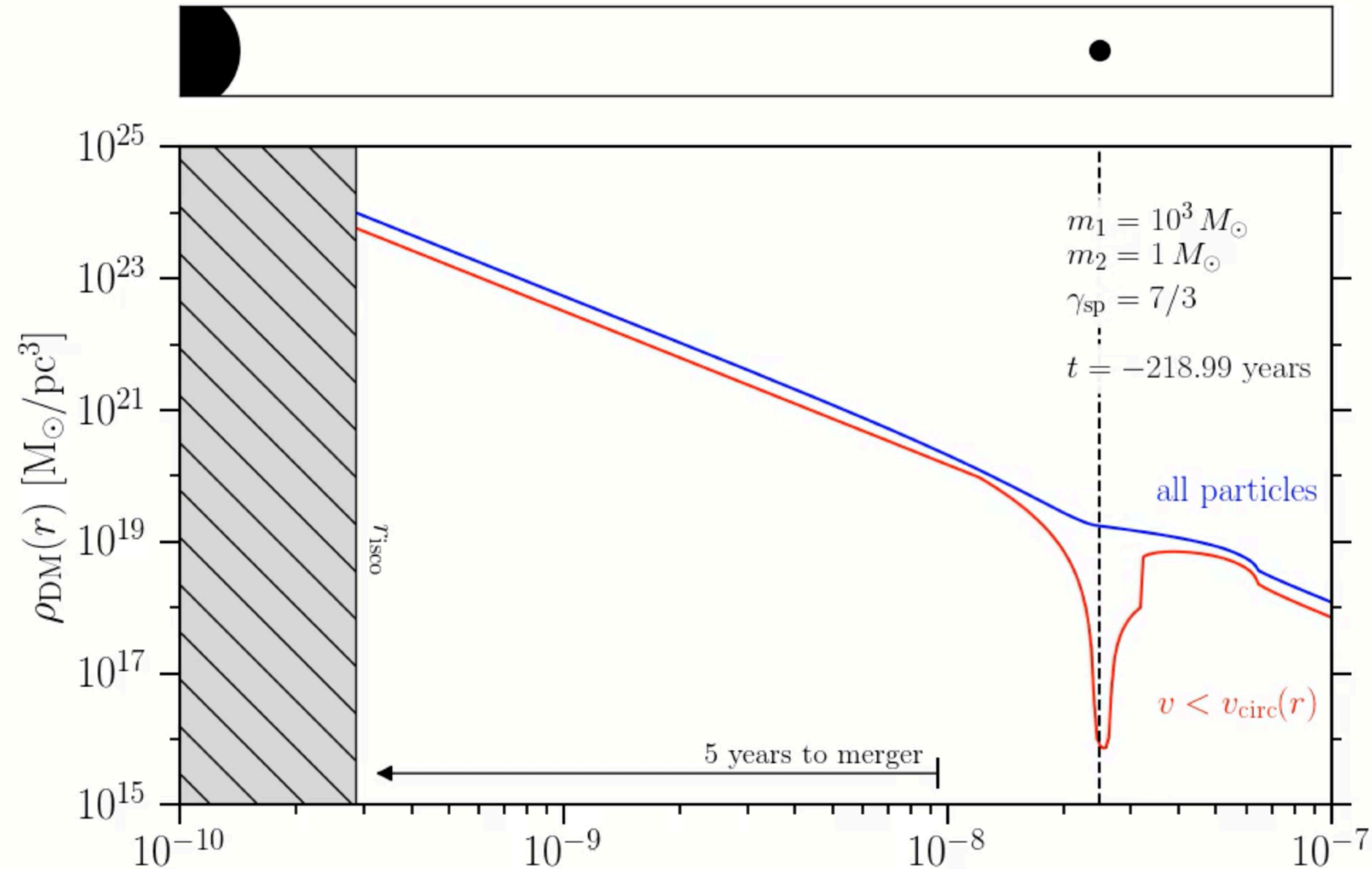
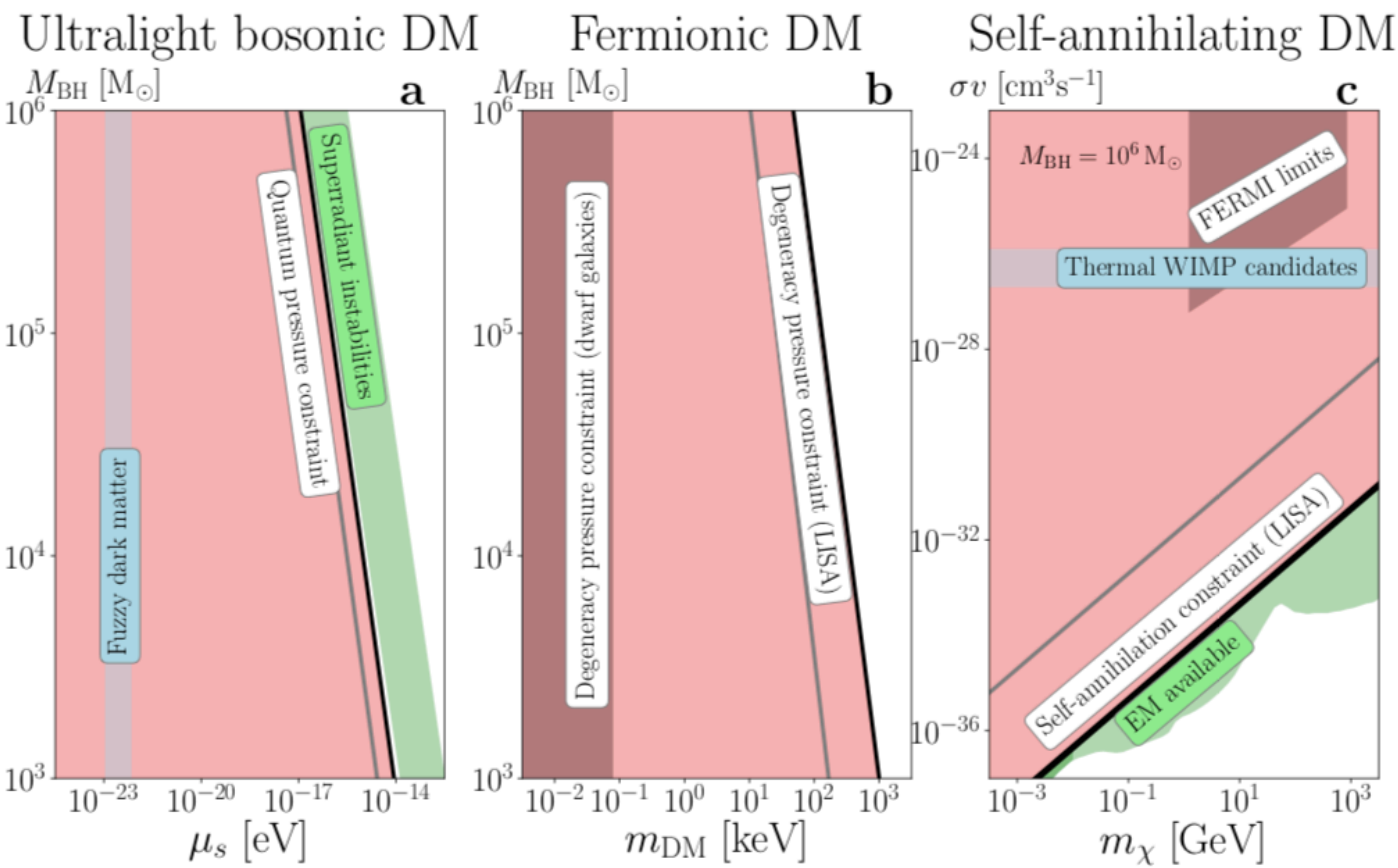


Movies: tinyurl.com/GW4DM

Probe the nature of DM!

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

[1906.11845]

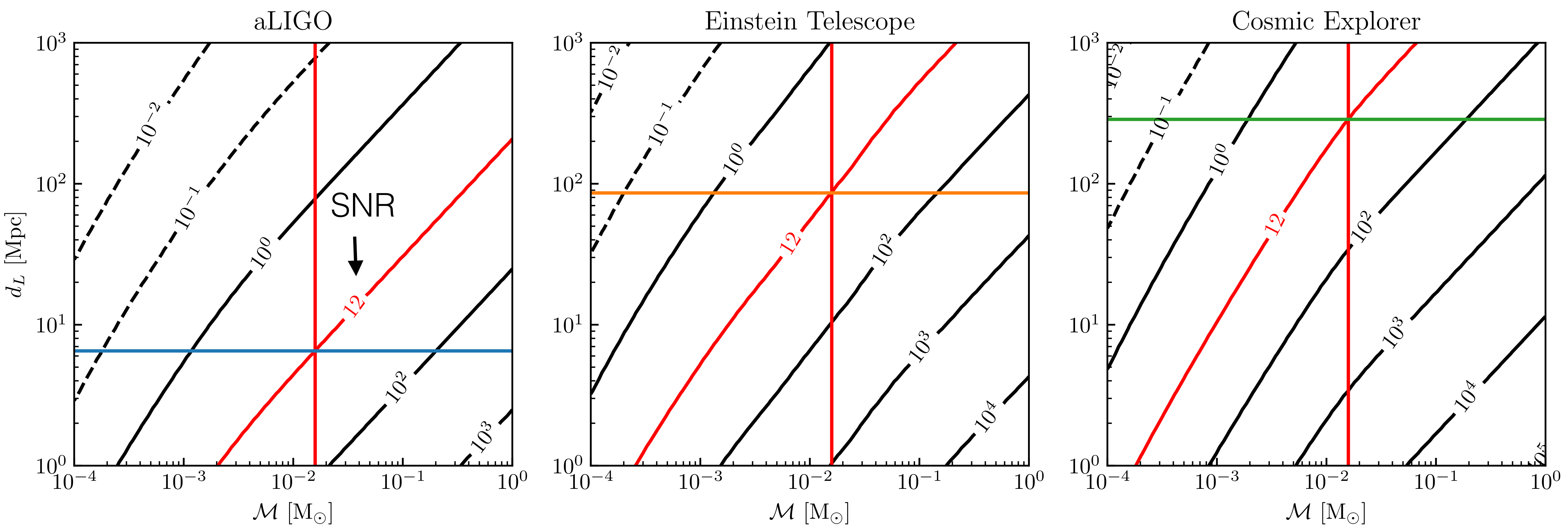


[See also Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

Detectability

[Cole et al. (including **BJK**), 2207.07576]

SNR as a function of chirp mass and luminosity distance:

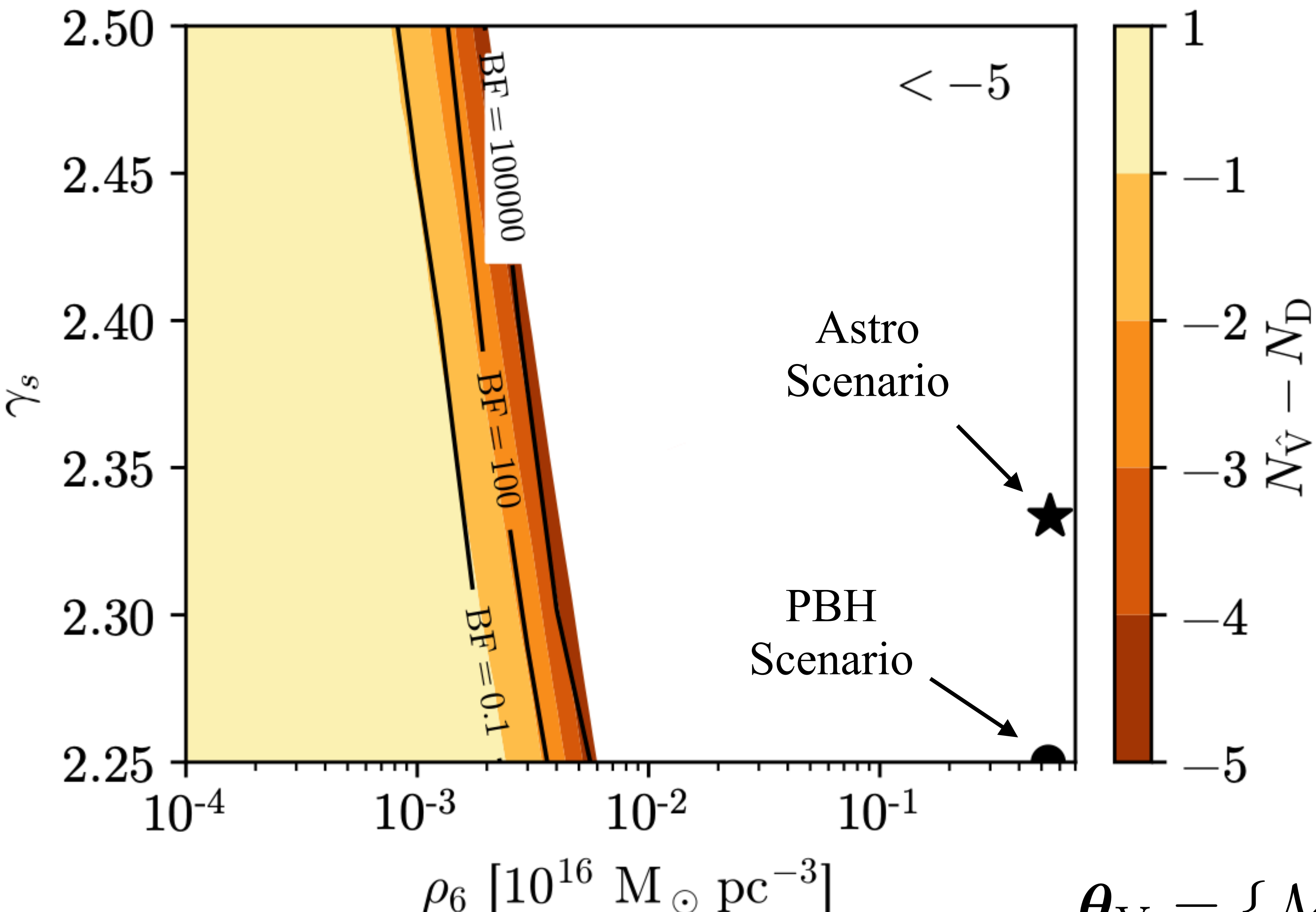


Discoverability

[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.



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

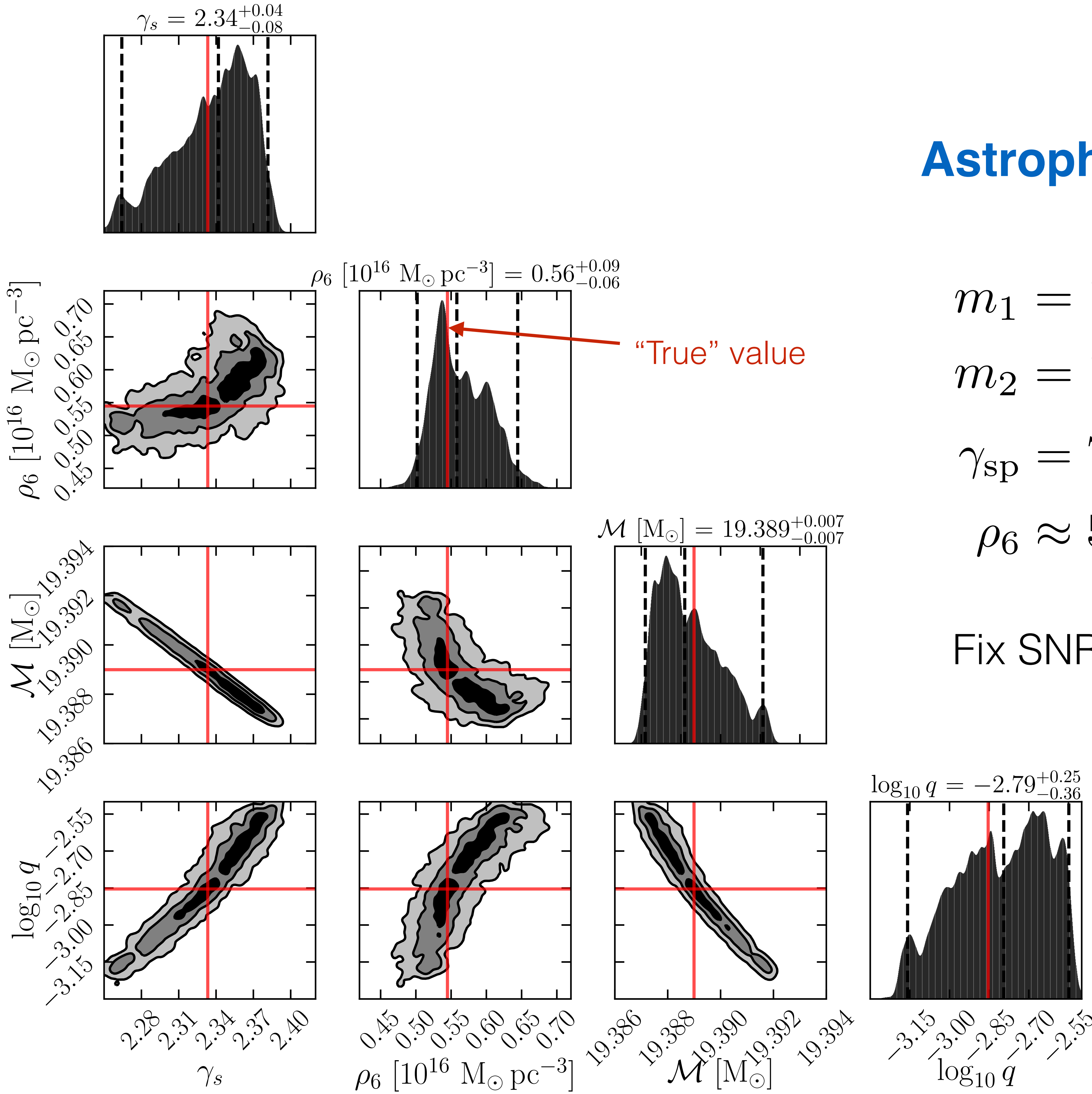
vs.

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

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

Measurability

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



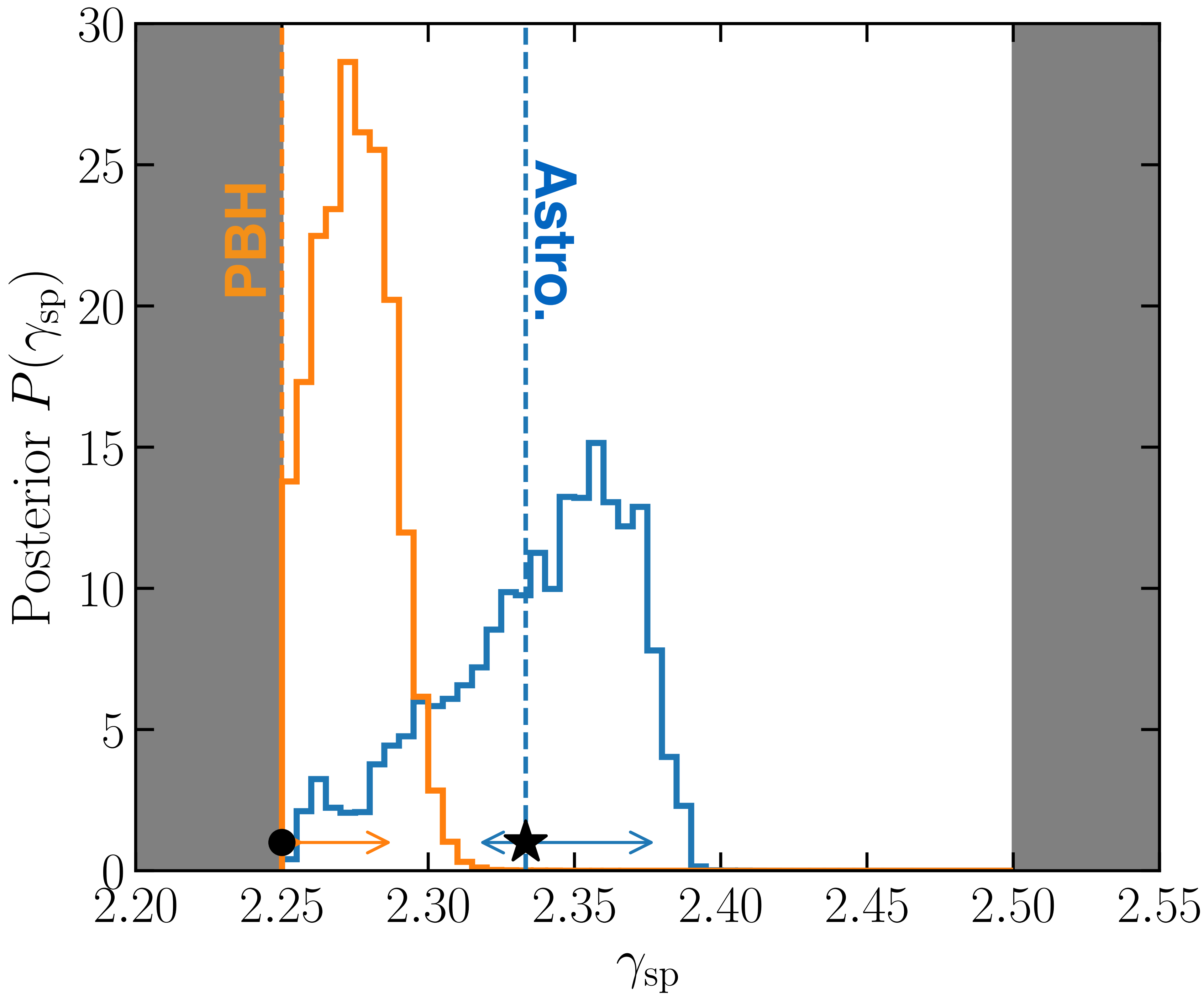
Astrophysical scenario

$$m_1 = 10^3\, M_\odot$$
$$m_2 = 1\, M_\odot$$
$$\gamma_{\rm sp} = 7/3 \approx 2.3333\ldots$$
$$\rho_6 \approx 5.45 \times 10^{15}\, M_\odot\, \mathrm{pc}^{-3}$$

Fix SNR = 15 (~ 76 Mpc)

Measurability - Spike Shape

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

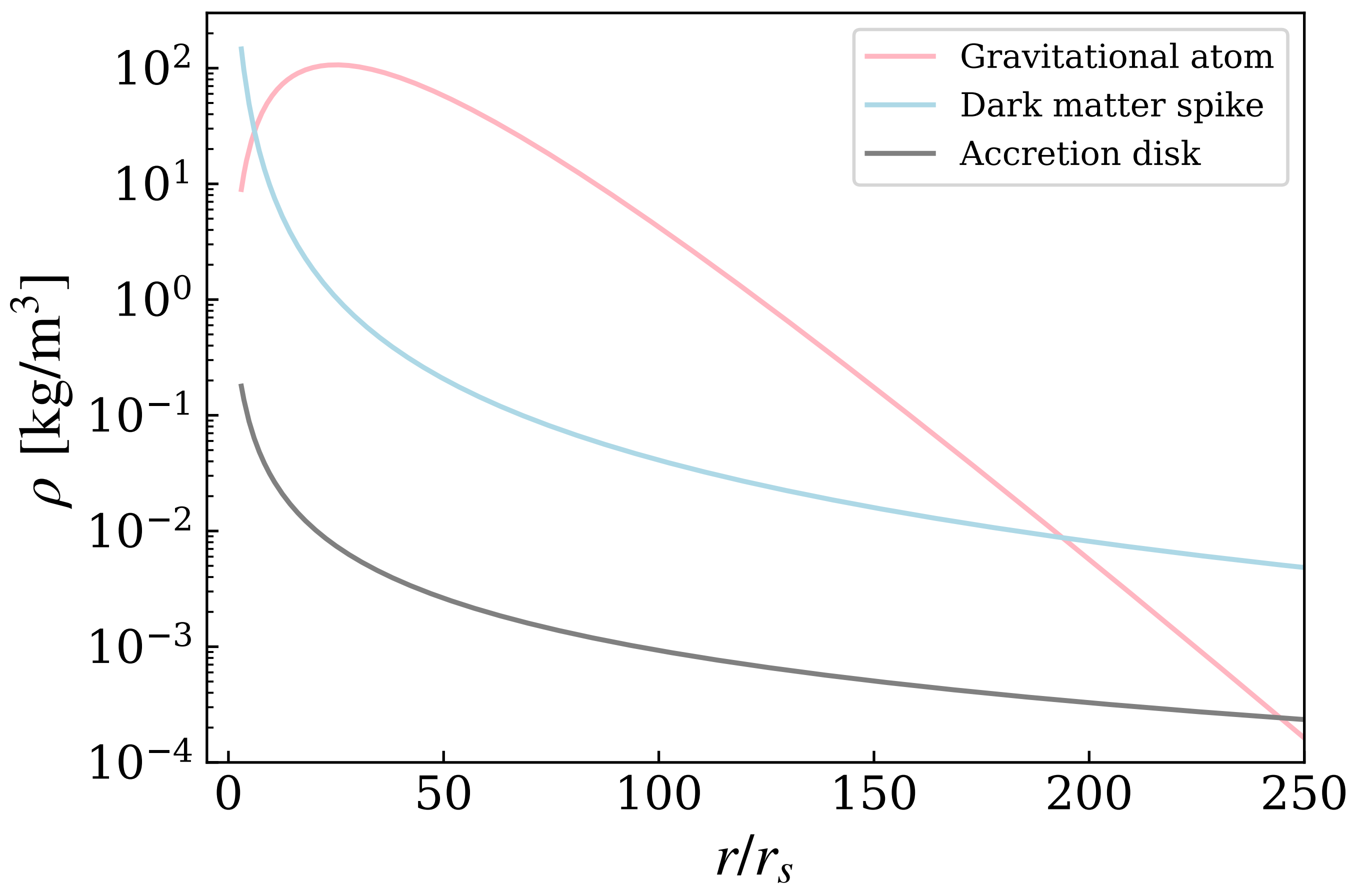


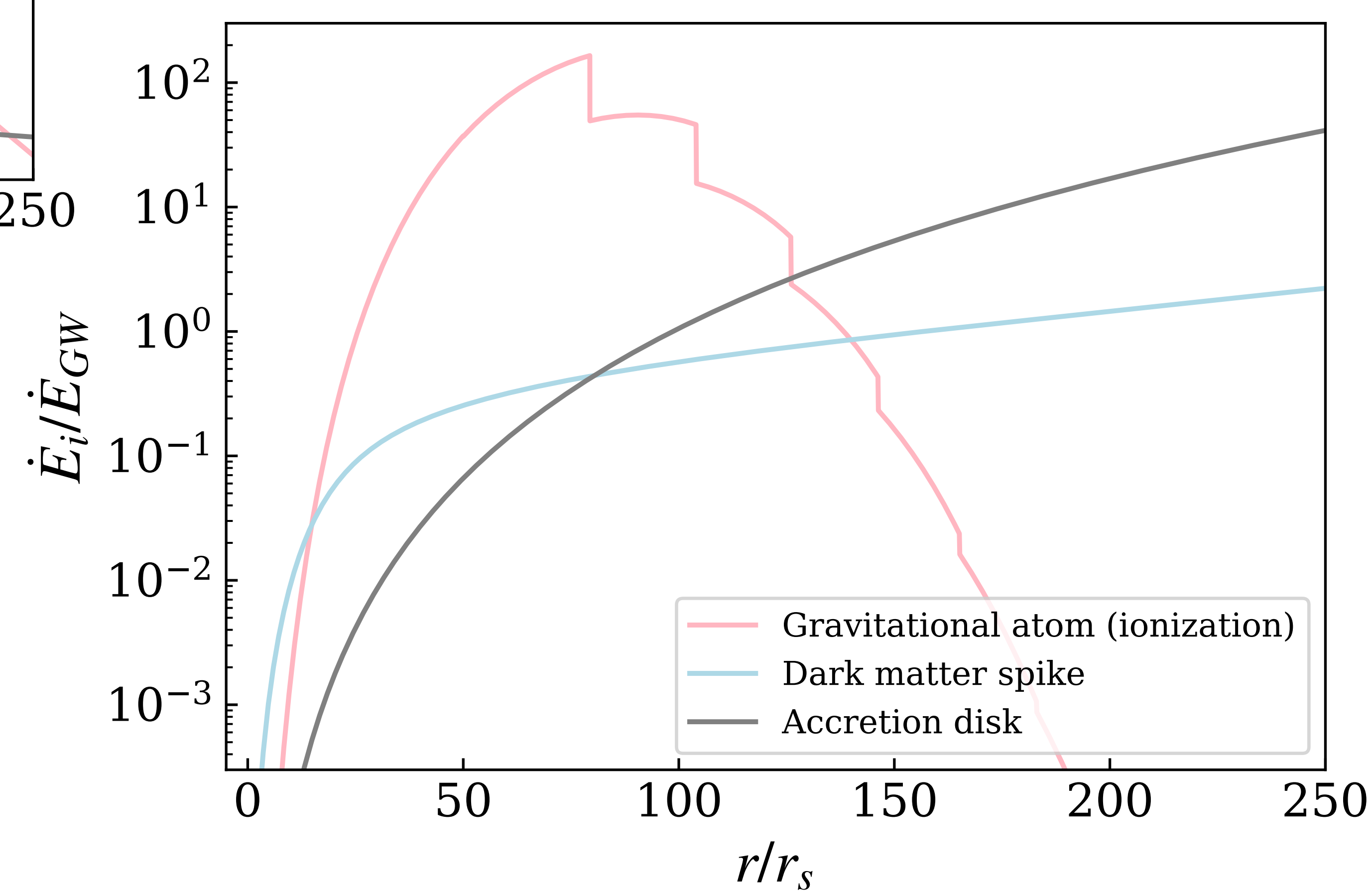
We may be able to distinguish different *shapes* of spike
→ Different DM models and formation mechanisms!

Distinguishability

[Cole et al. (including **BJK**), 2211.01362]

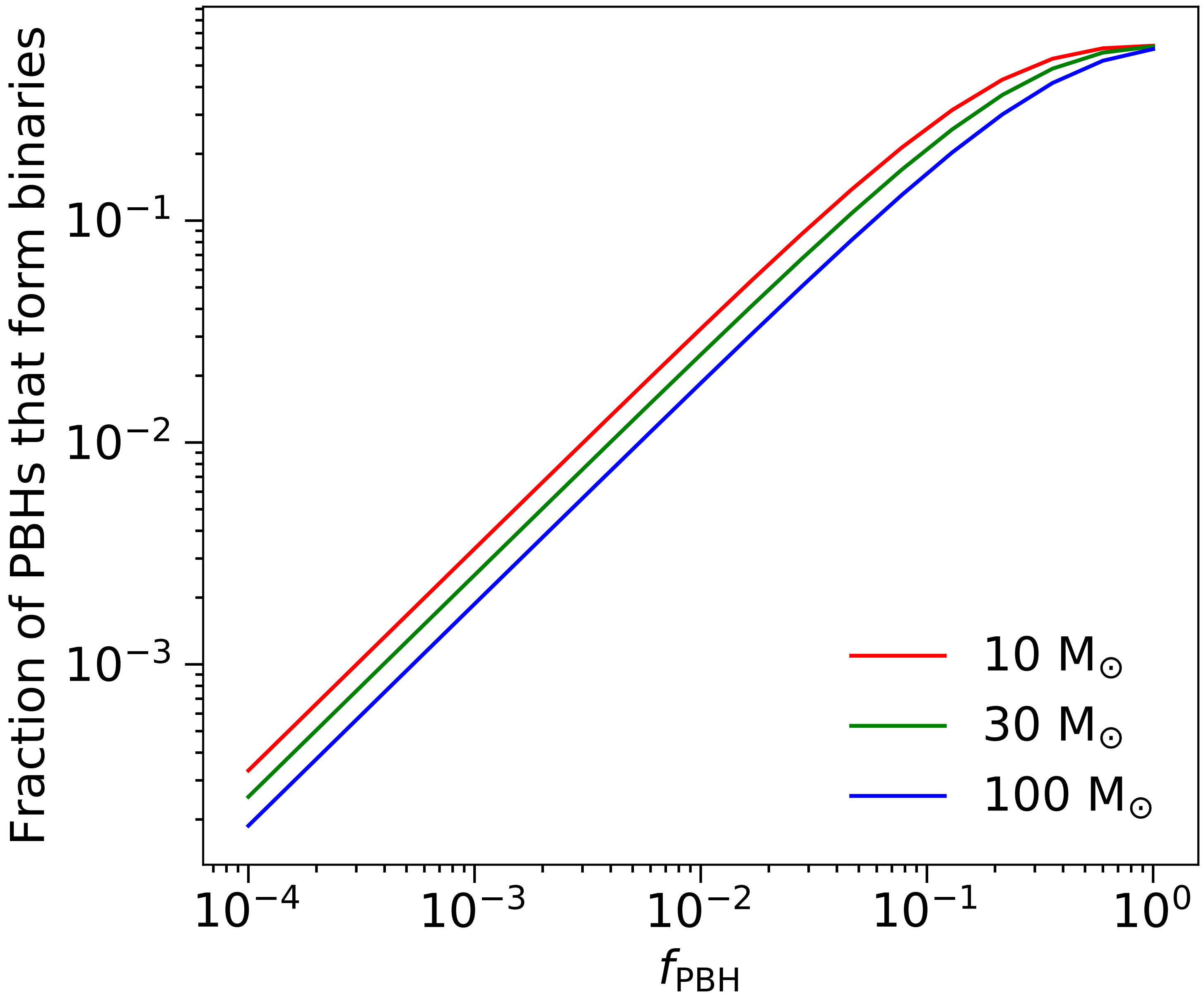
Distinguishable from other sources of dephasing:





Early Universe Binaries

If f ~ 1, the relative density of PBHs *equals* the background radiation density at matter-radiation equality. All PBHs form binaries…



As f decreases, only 'nearby' pairs form binaries.

PBH Binary Population

Randomly distributed (unclustered) PBHs

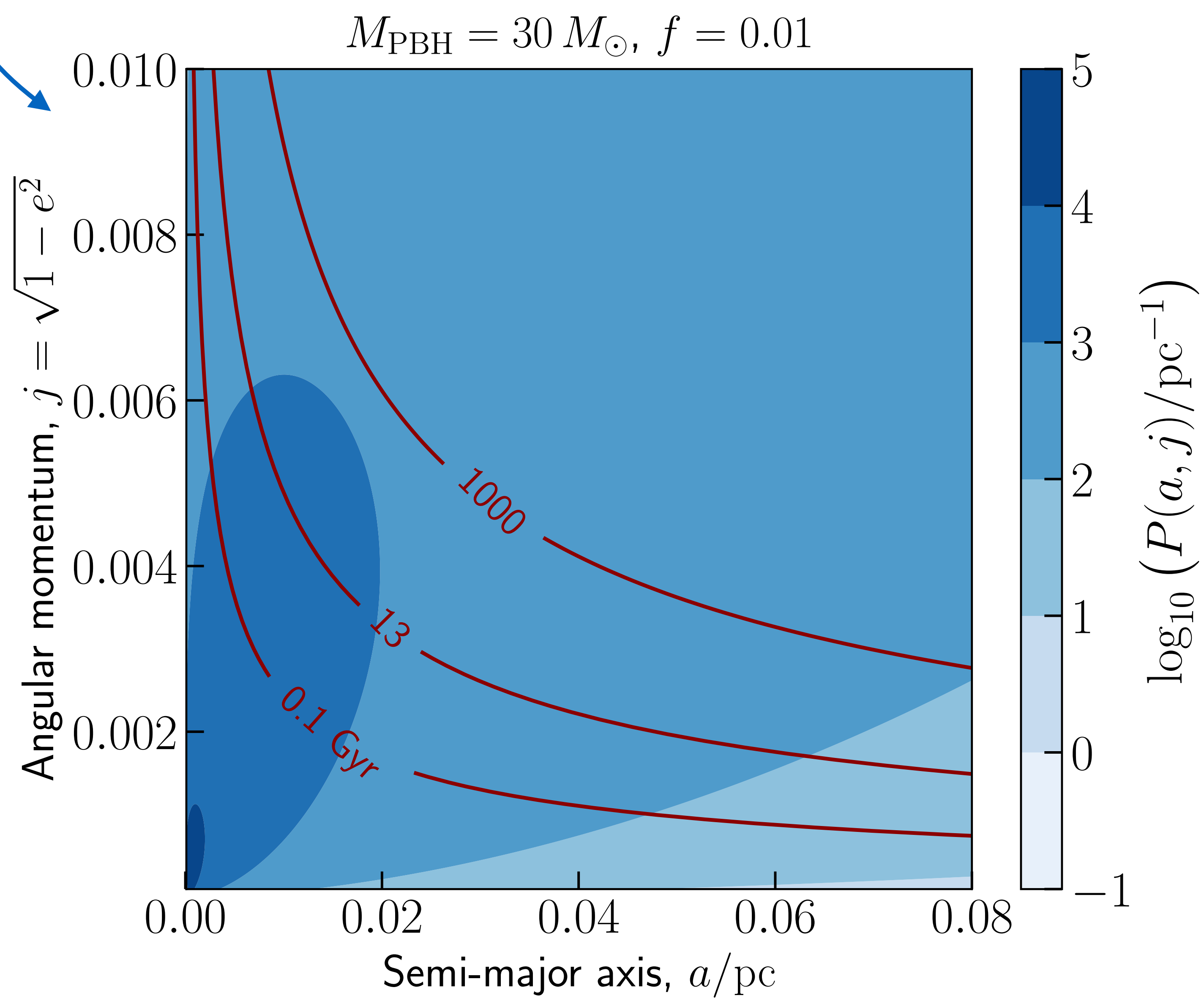
Angular momentum set by torques from smooth density perturbations and *all other PBHs*

Close, eccentric binaries merge today:

$$t_{\mathrm{merge}} = \frac{3\,c^5}{170\,G_N^3}\,\frac{a^4 j^7}{M_{\mathrm{PBH}}^3}$$

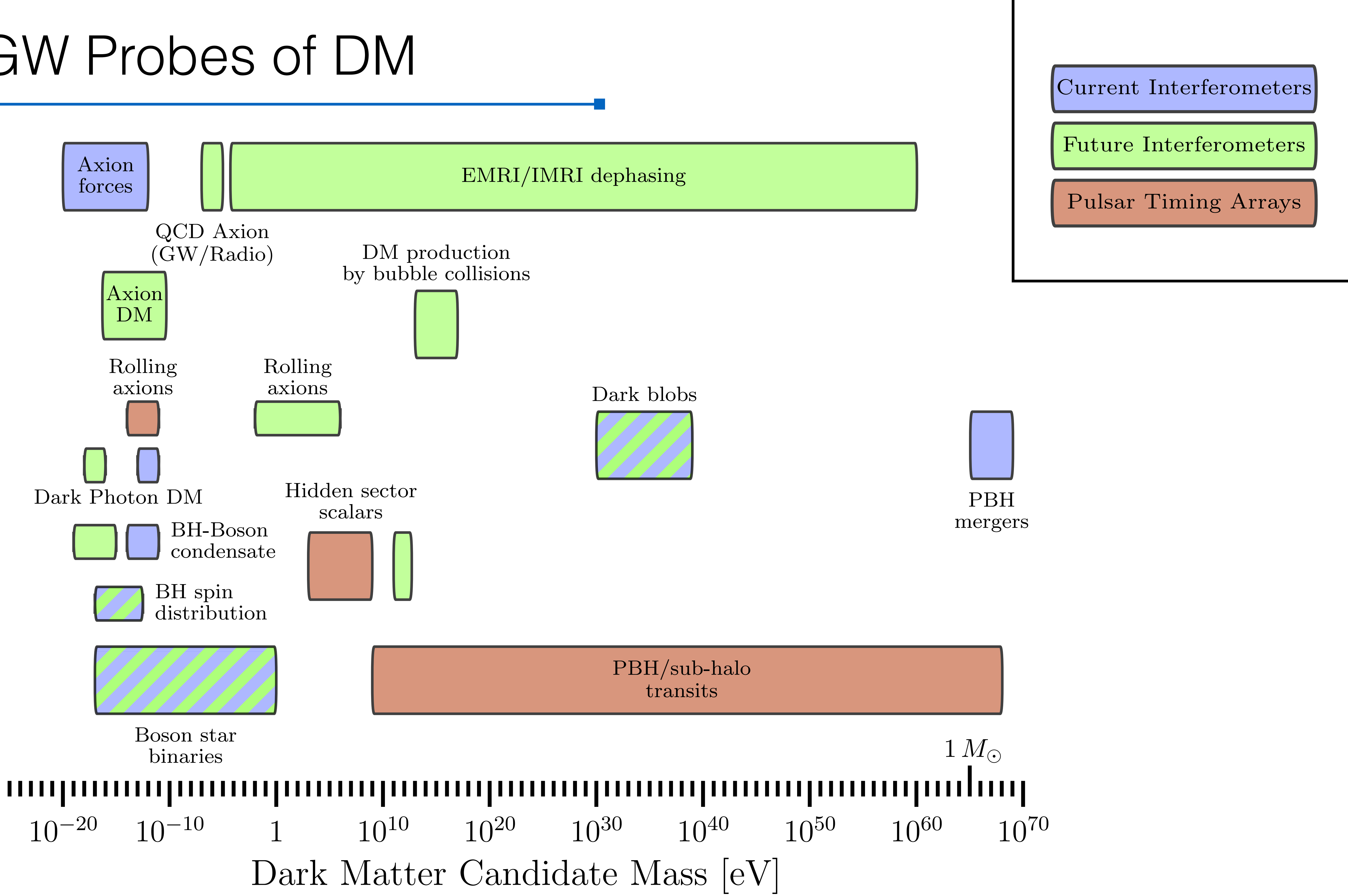
$$j = \sqrt{1 - e^2}$$

$e > 0.9999$



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

GW Probes of DM



[Bertone, Croon, Amin, Boddy, **BJK**, Mack, Natarajan, Opferkuch, Schutz, Takhistov, Weniger, Yu, SciPost Phys. Core 3, 007 (2020), 1907.10610]