Collisionless Dark Matter Spikes:
Open questions in formation, evolution and gravitational wave detection

Bradley J. Kavanagh (IFCA, CSIC-UC)

EuCAPT Workshop: GW probes of BH environments
Rome, 16 June 2022

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Instituto de Física de Cantabria

EXCELENCIA MARÍA DE MAEZTU

CSIC Consejo Superior de Investigaciones Científicas

UC Universidad de Cantabria

A broad effort

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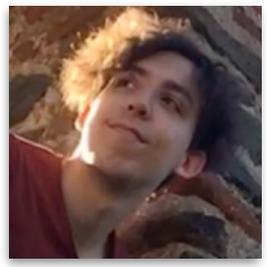
Pratibha Jangra
(IFCA, Santander)

Pippa Cole
(GRAPPA, Amsterdam)



Theophanes Karydas
(GRAPPA, Amsterdam)

Adam Coogan
(Mila, Montreal)

David Nichols
(U. Virginia)

Jose Maria Diego
(IFCA, Santander)

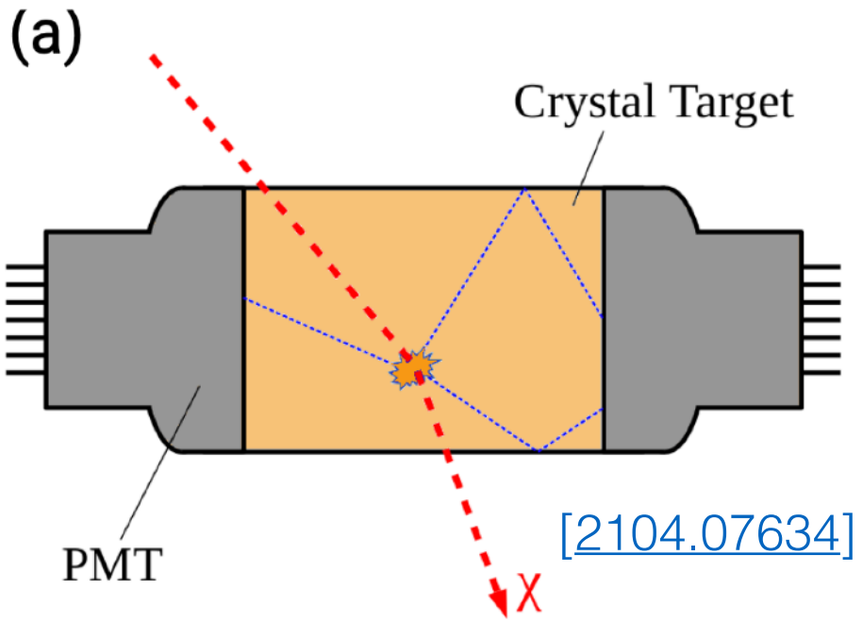
Abram Perez Herrero
(IFCA, Santander)

Daniele Gaggero
(IFIC, Valencia)

Francesca Scarcella
(IFT, Madrid)

…and many others…

Searches for Dark Matter in the Galactic Halo



[2104.07634]

$$\rho_{\rm DM} \sim 10^{-2}\, M_\odot\, {\rm pc}^{-3}$$

[Read, 1404.1938]

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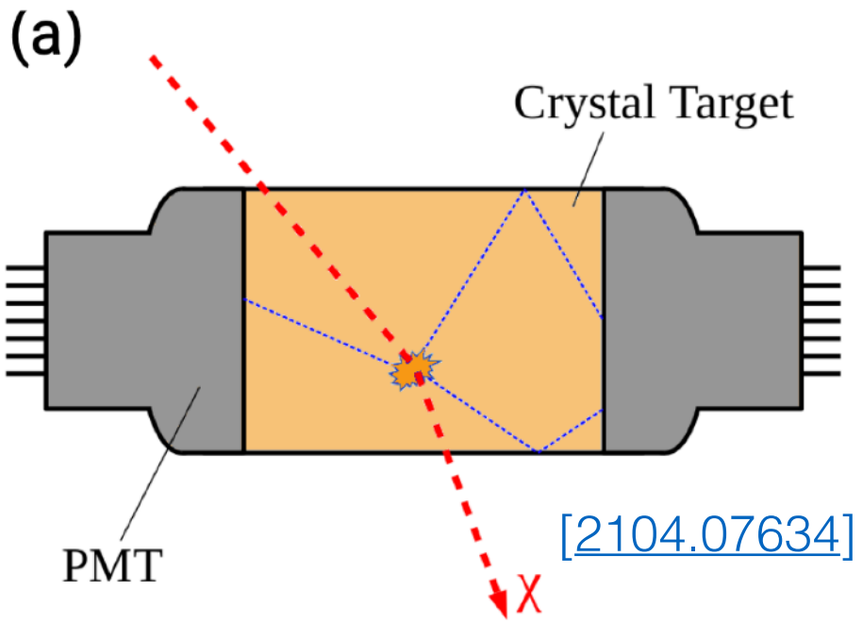

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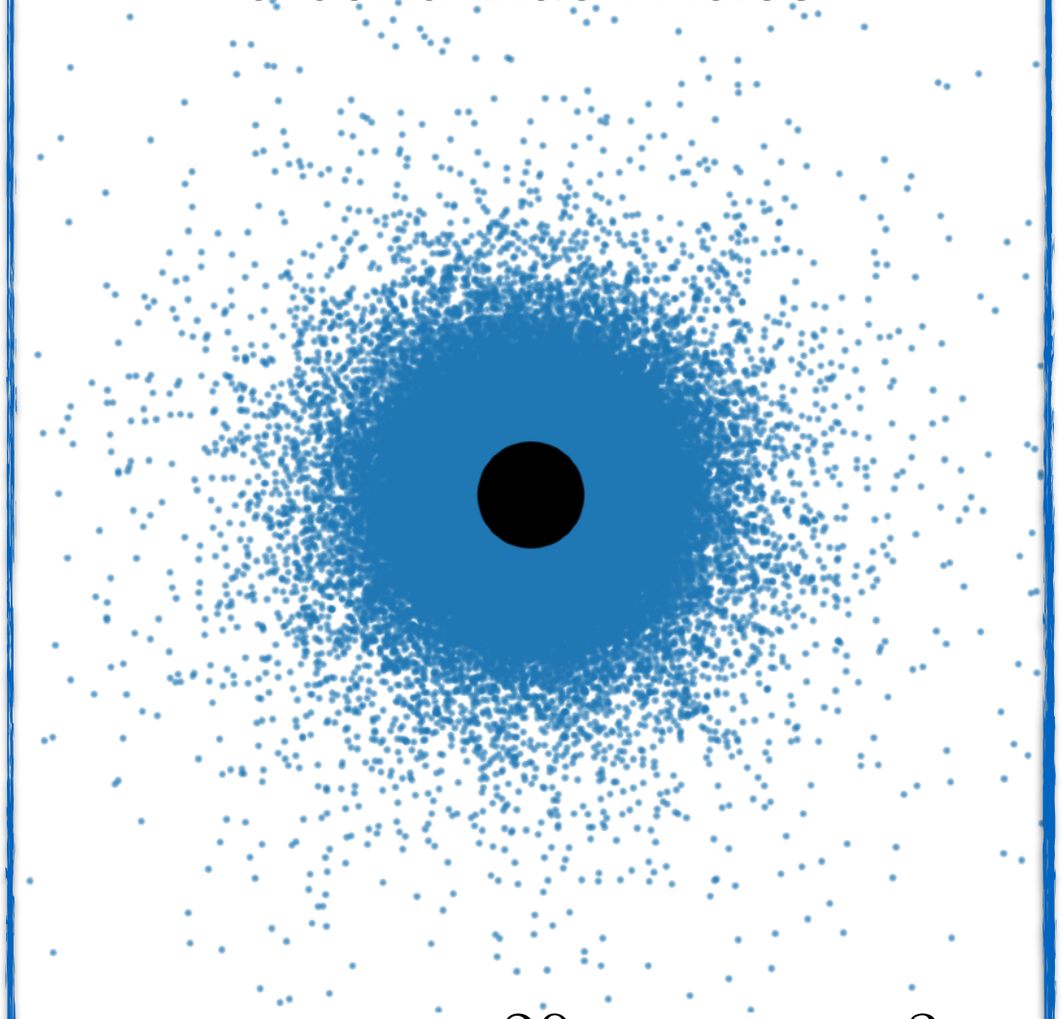
Dark Matter Spikes around Black Holes



$$\rho_{\rm DM} \gtrsim 10^{20}\, M_\odot\, {\rm pc}^{-3}$$

[Gondolo & Silk, astro-ph/9906391]

Dark Matter Spikes

$$m_1 \gtrsim 10^3\, M_\odot$$

Collisionless **DM** '**spike**' or '**dress**' around an **IMBH**:

Astrophysical scenario

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

More on this later…

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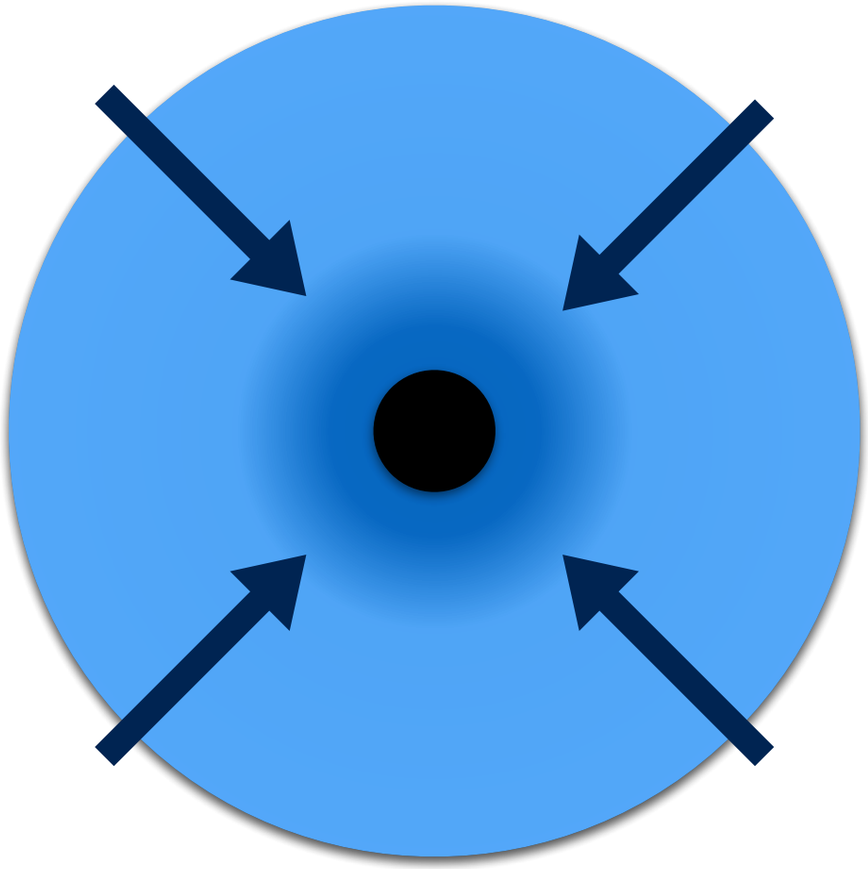

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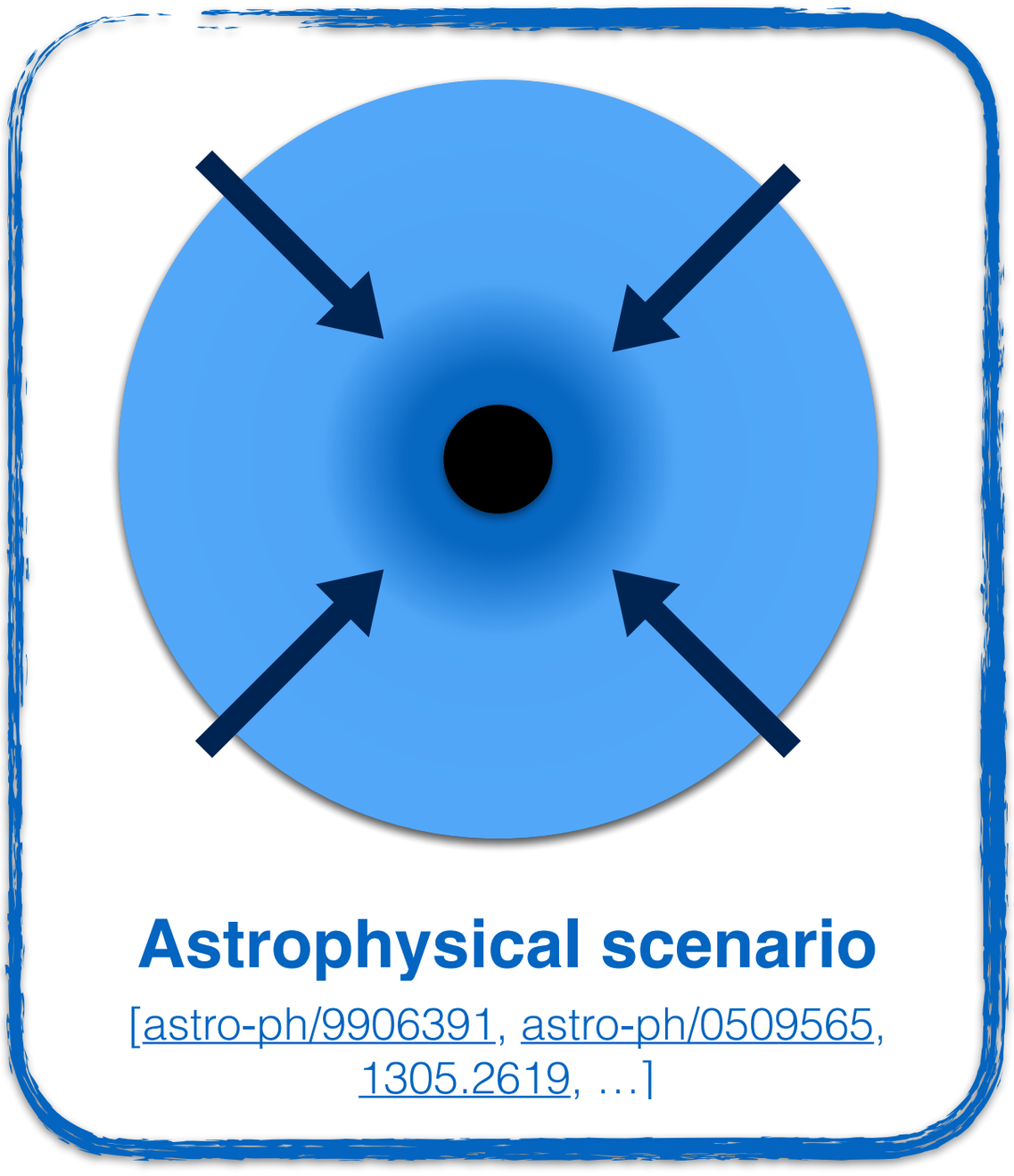

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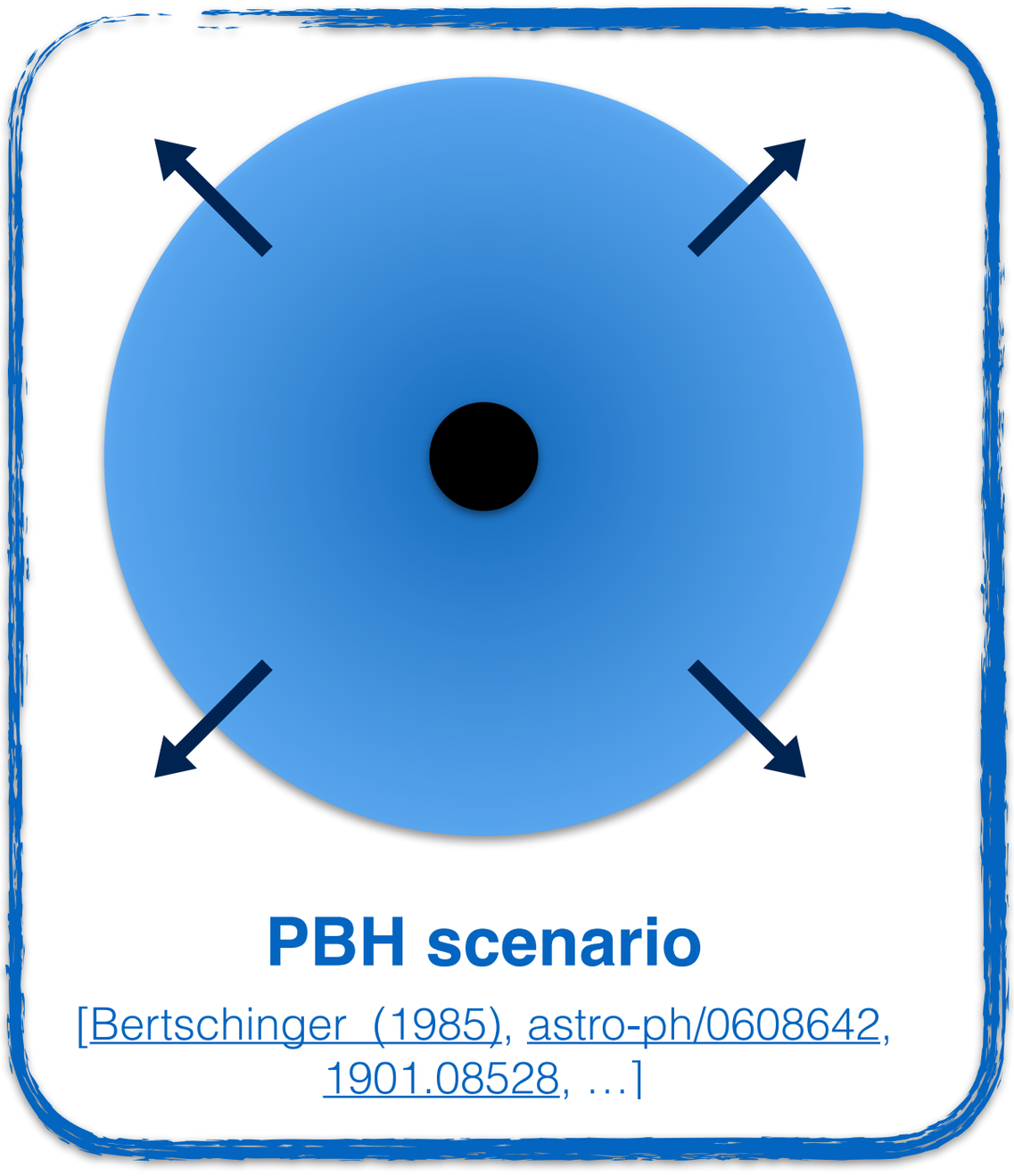

PBH scenario

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

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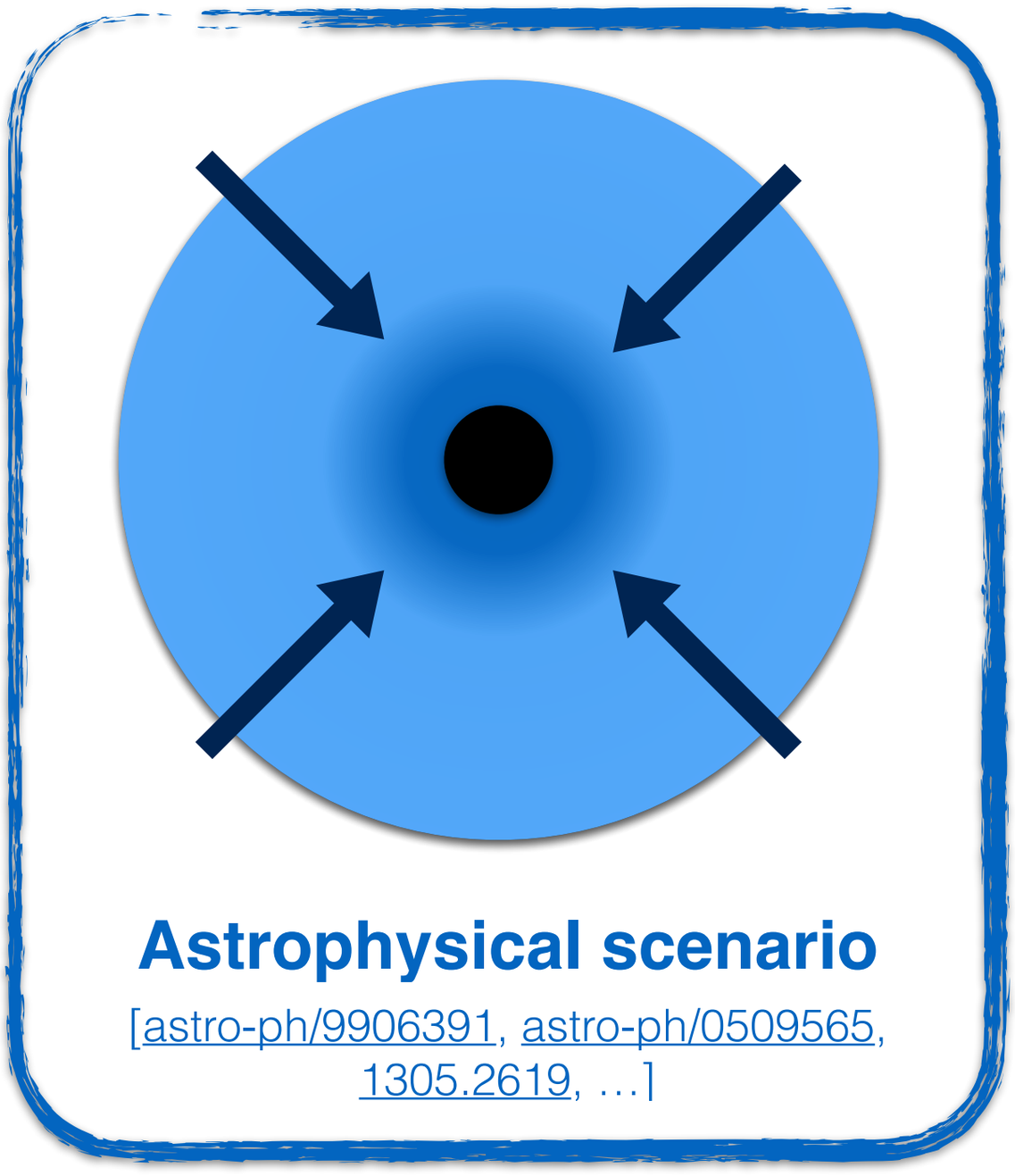

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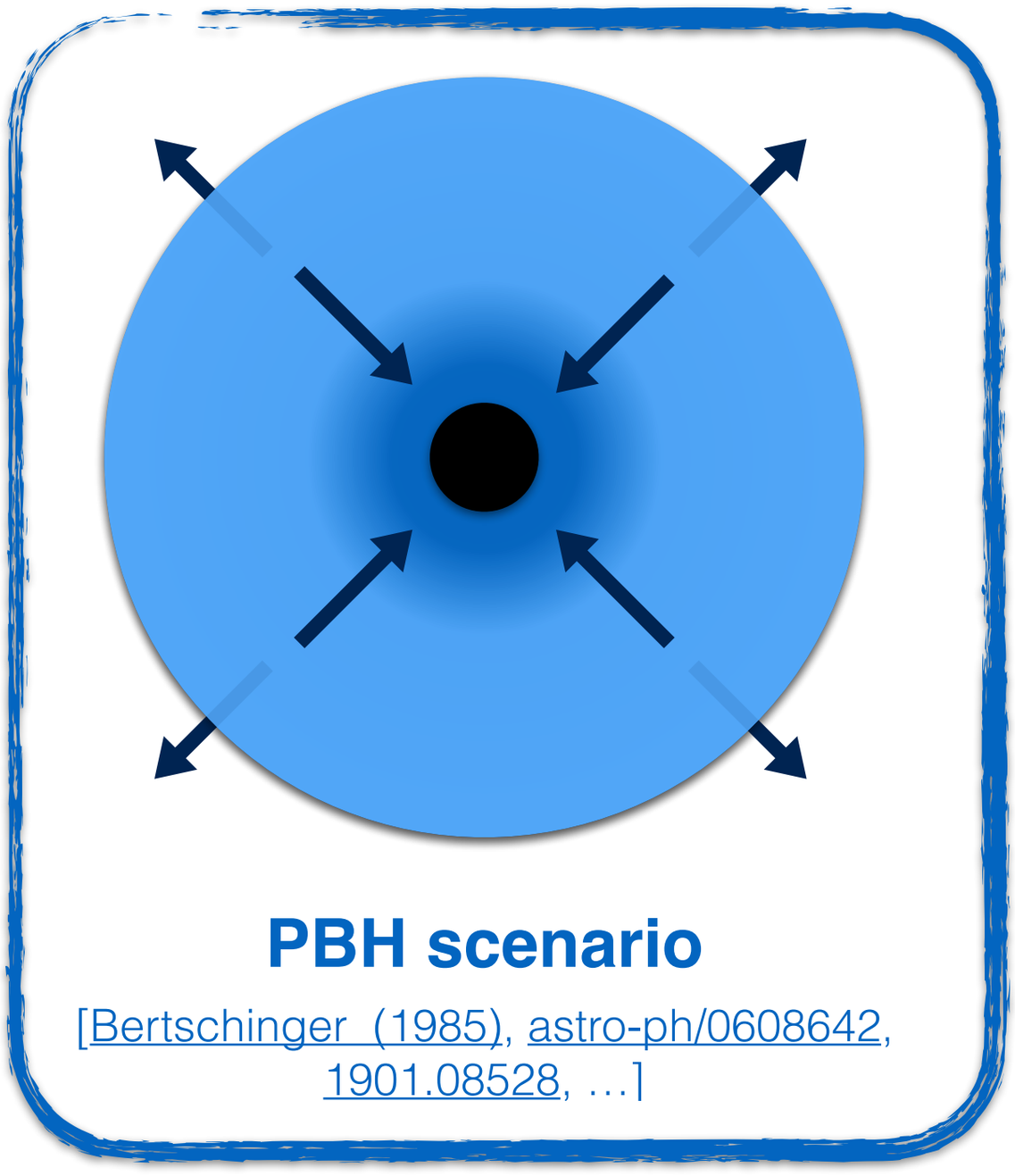


PBH scenario

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

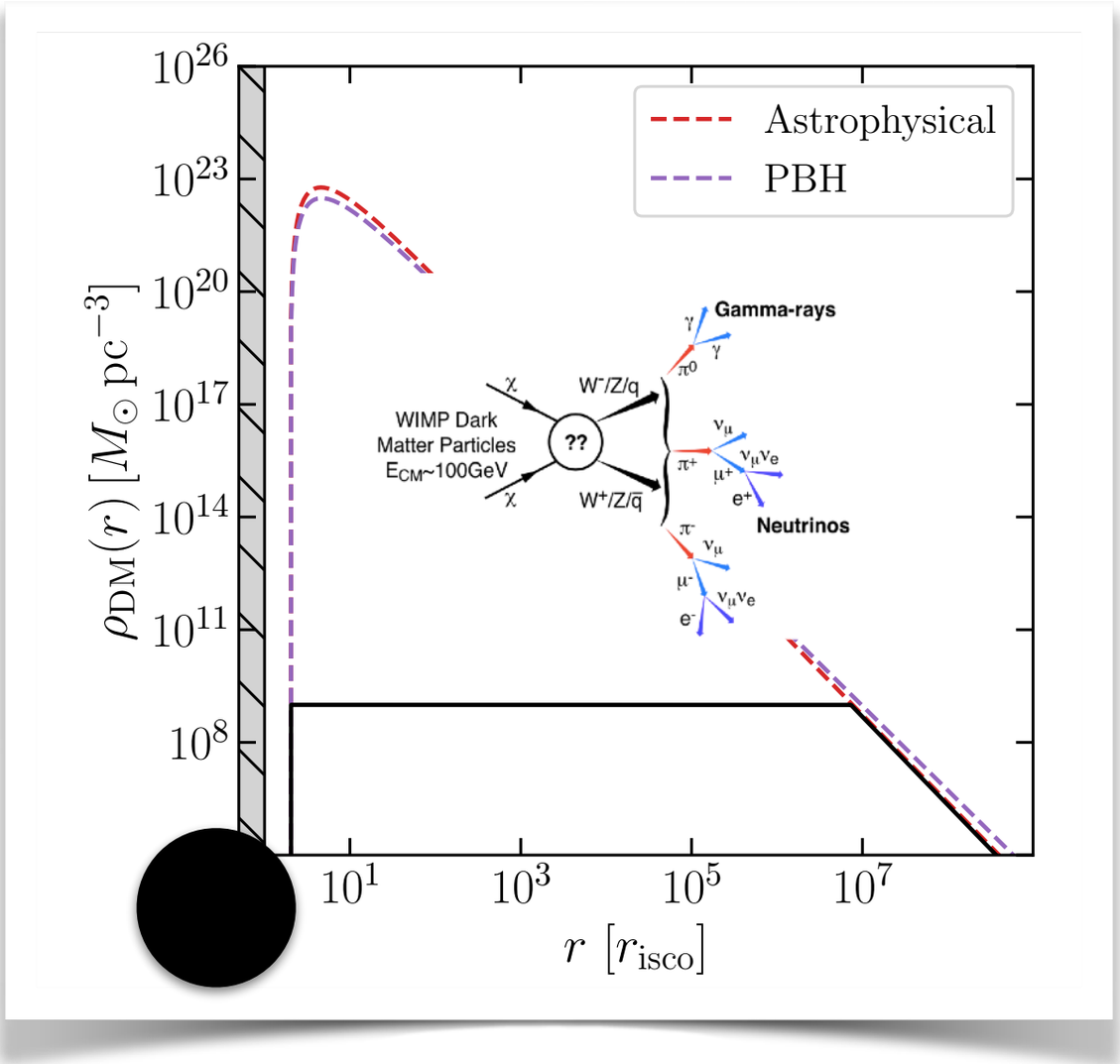
More on this later…

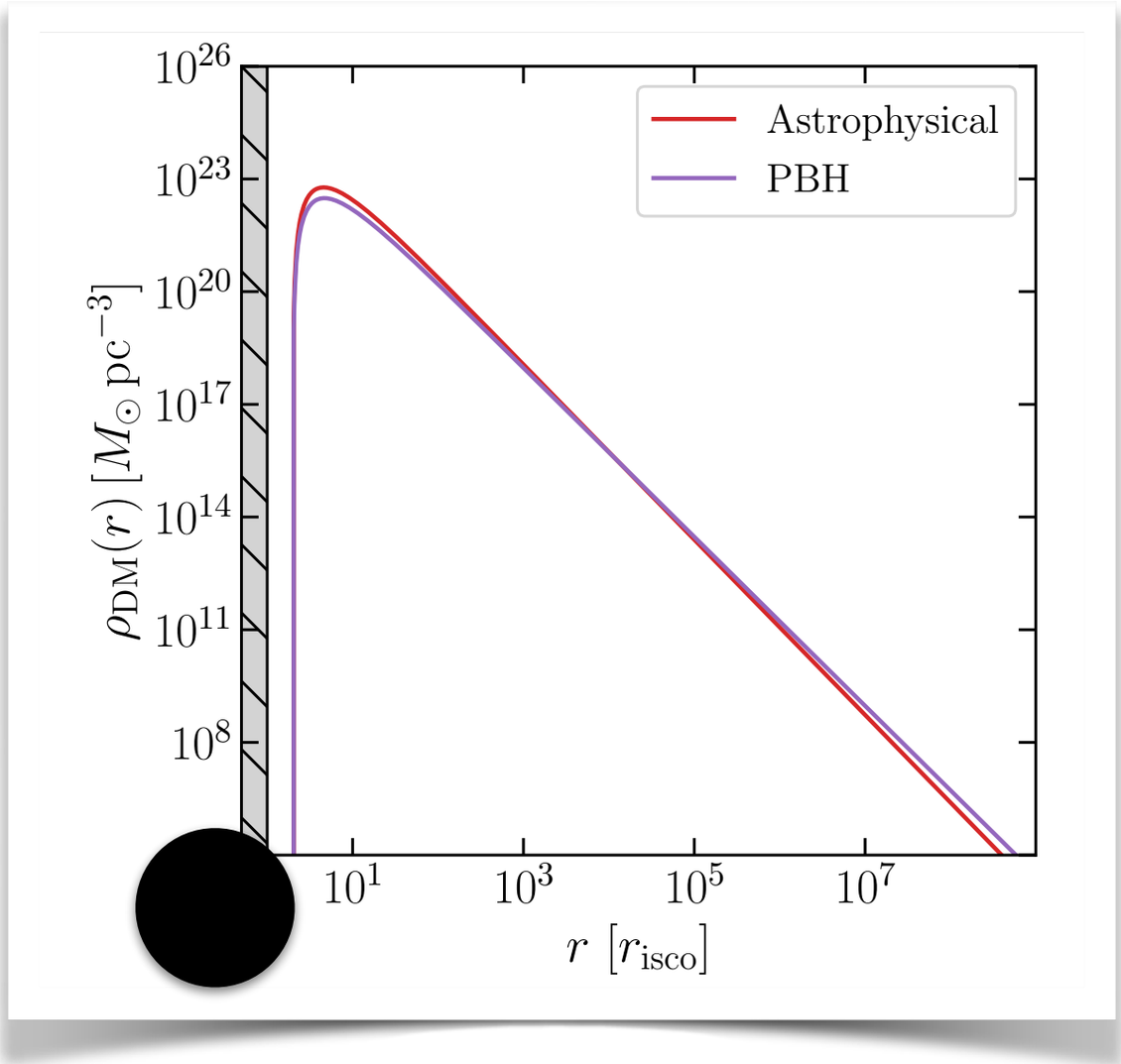
Survival of the Spike

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

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

1) **DM properties:**





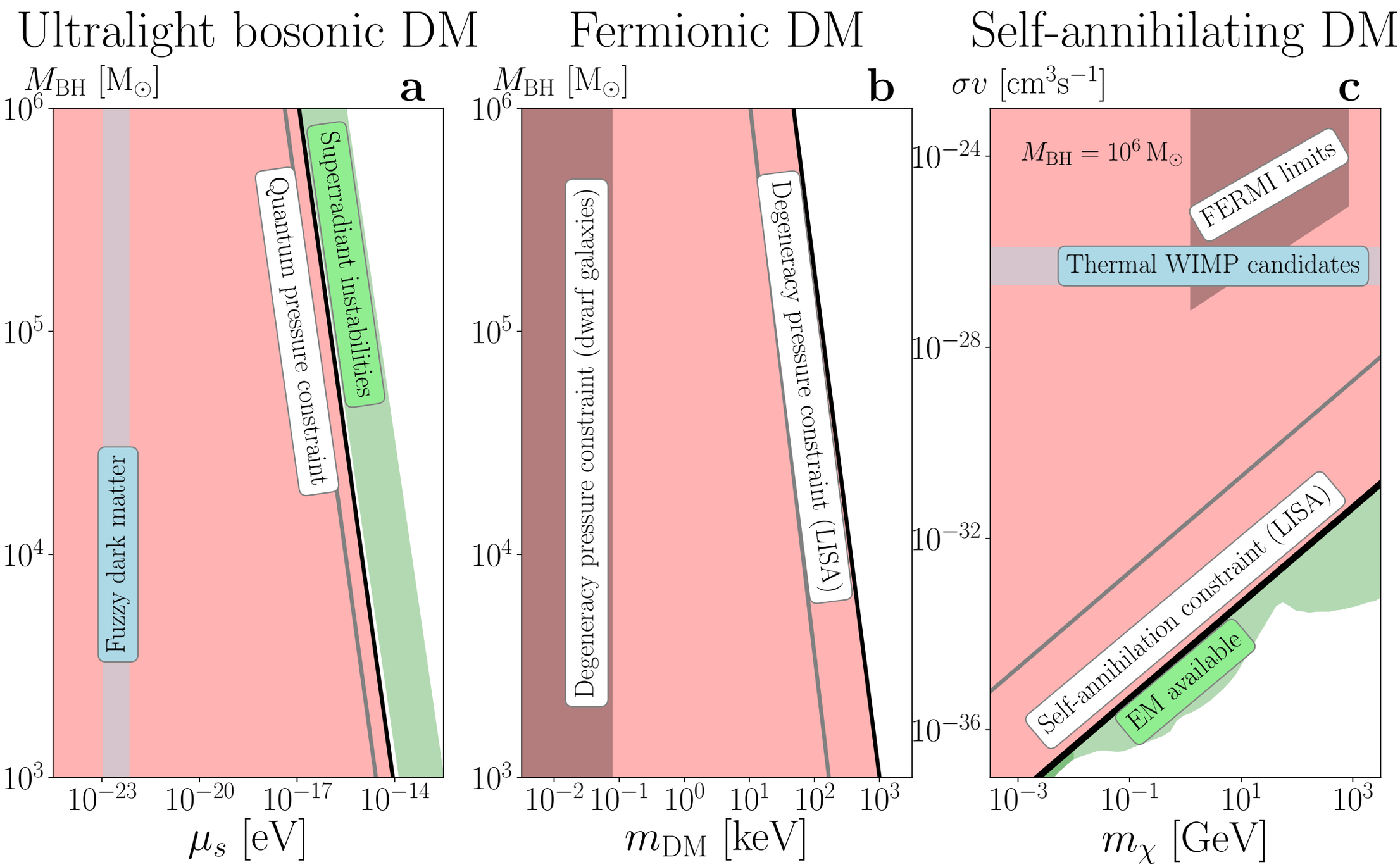
[E.g. Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

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

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

Focus on IMBHs

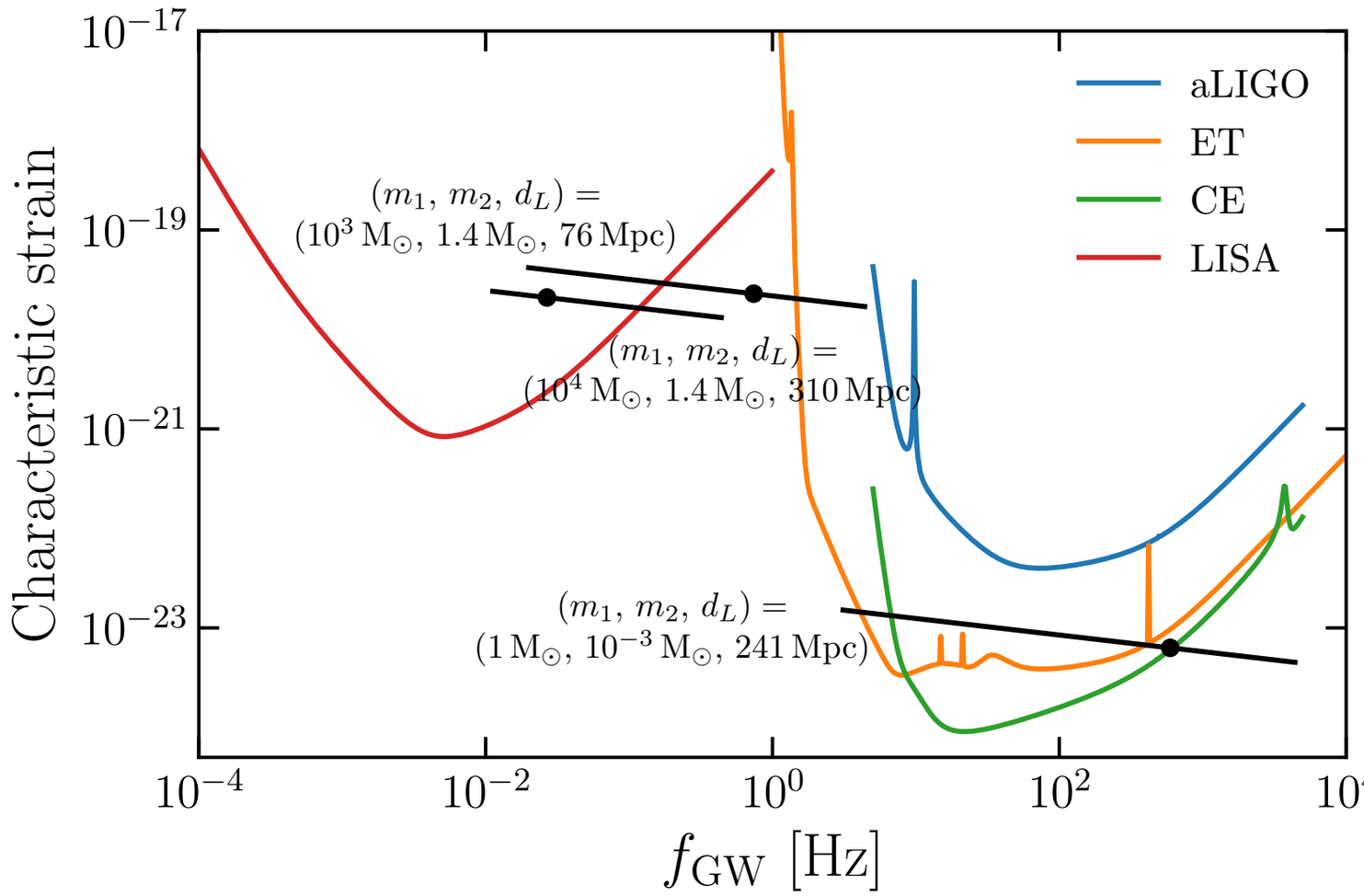
Nature of Dark Matter

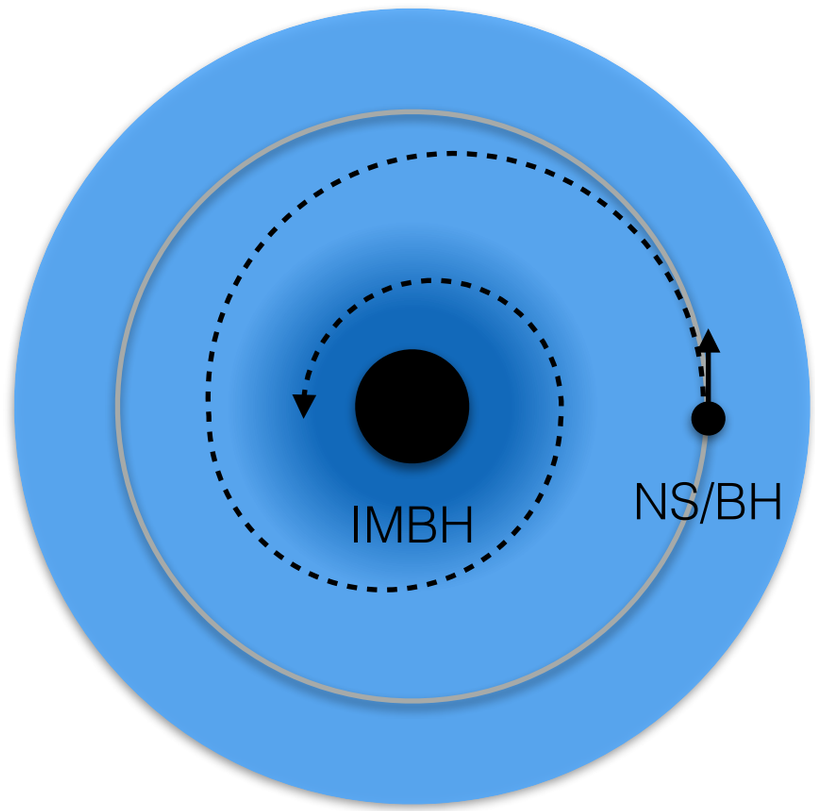


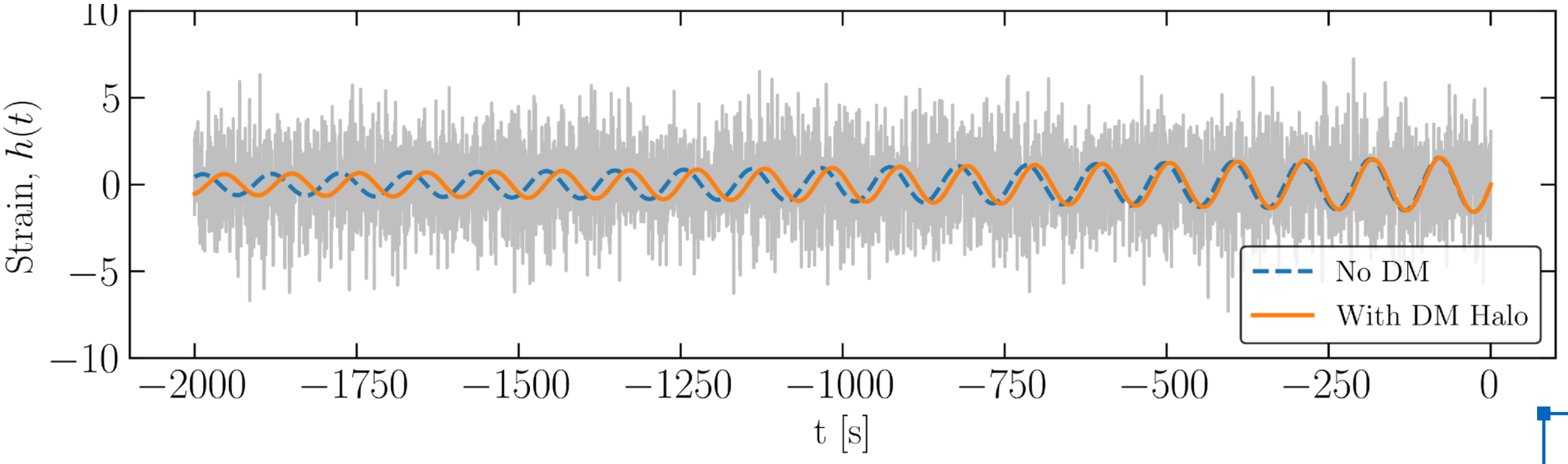
Red regions would be ruled out by observation of a DM spike!

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

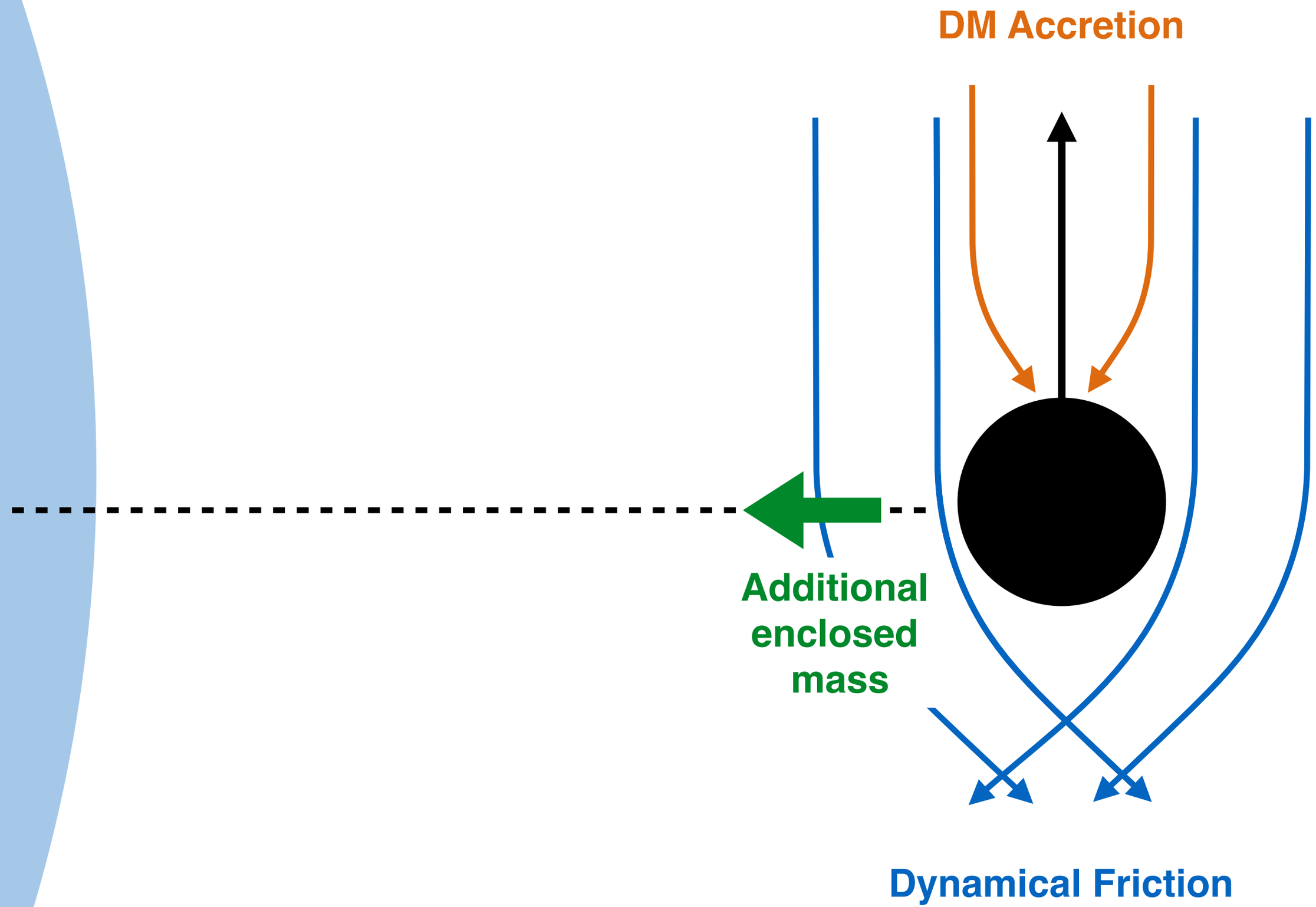
DM-induced Dephasing







Impact of DM Spikes



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

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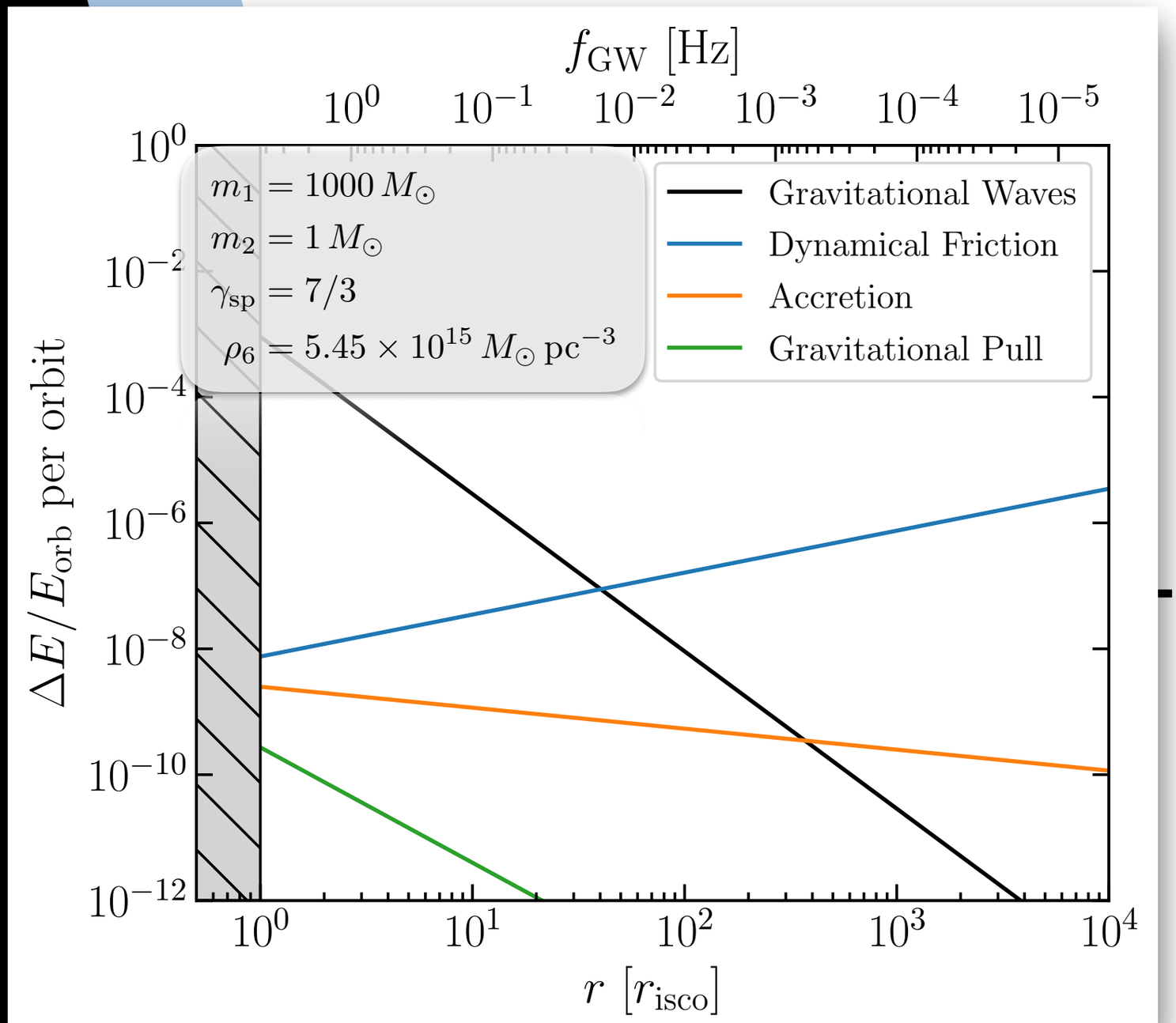
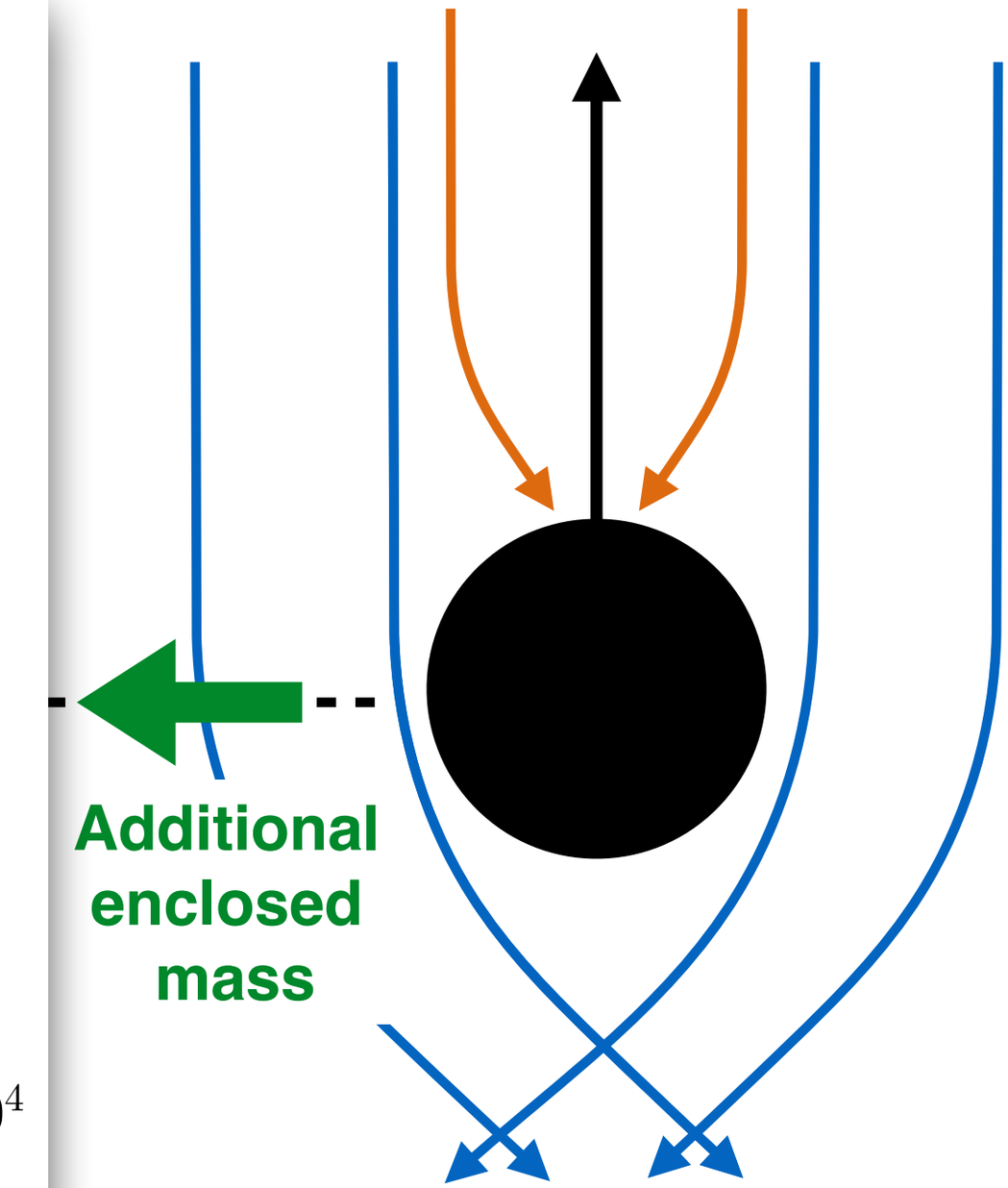


IMBH

DM Accretion



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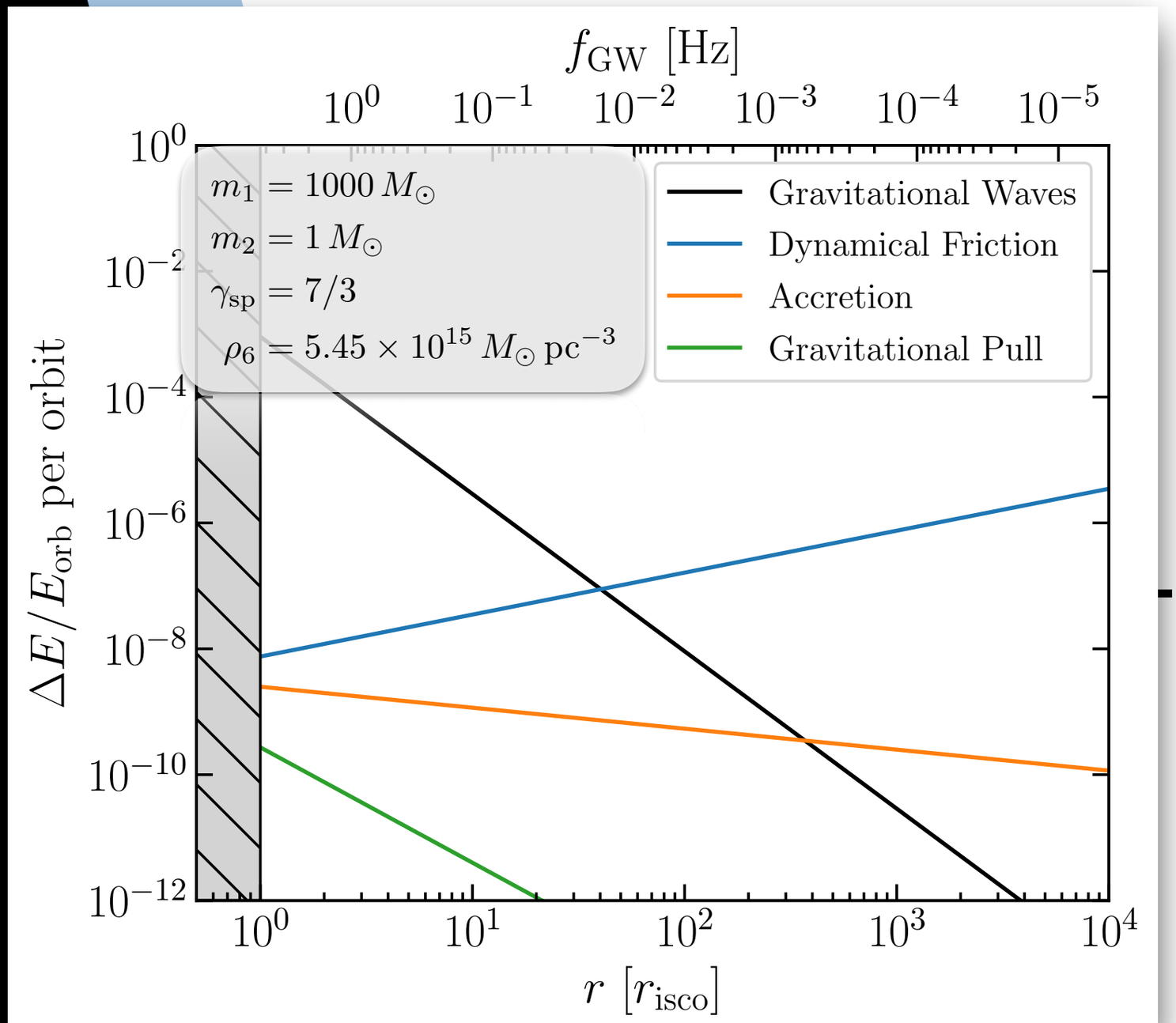
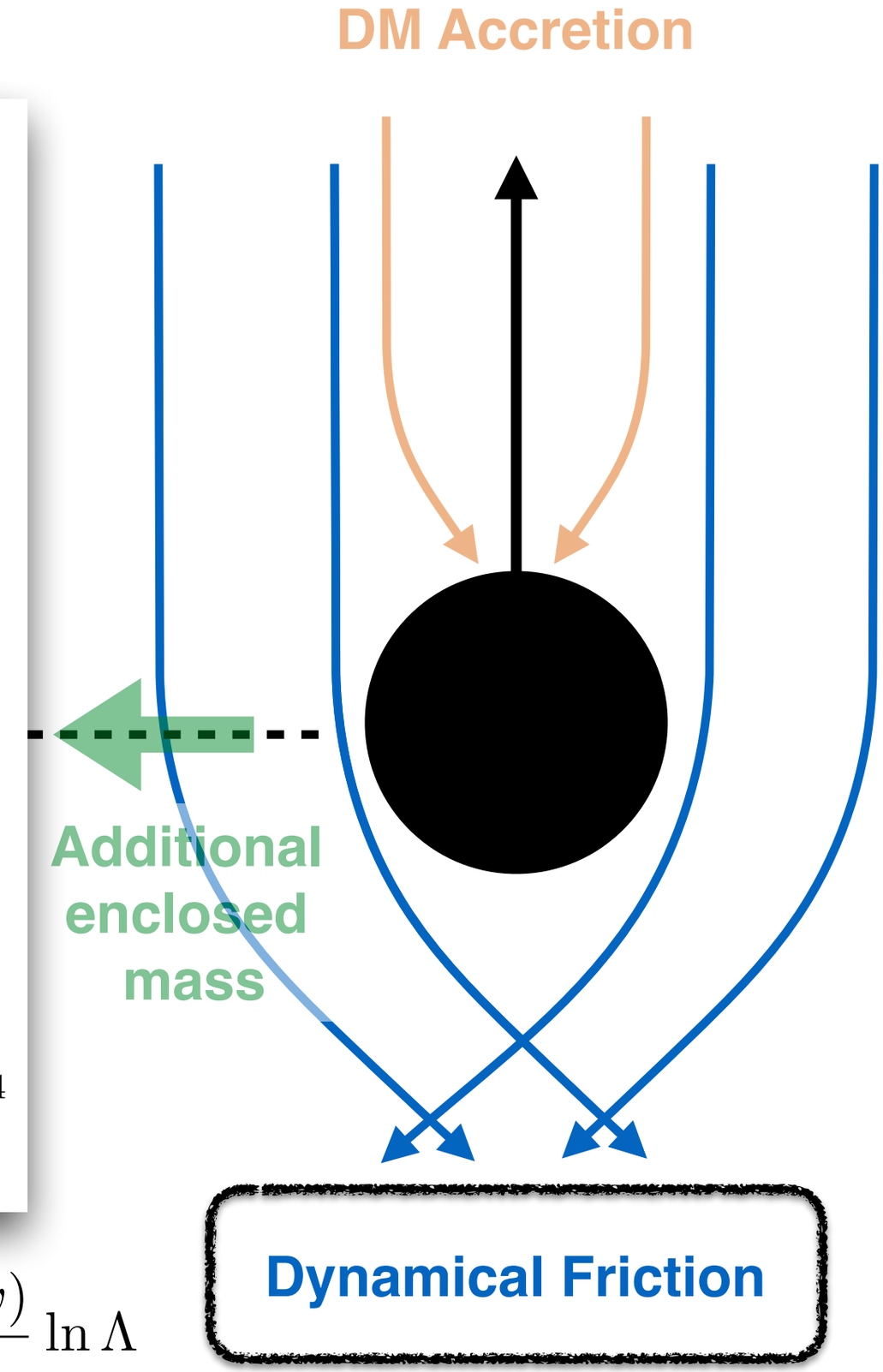


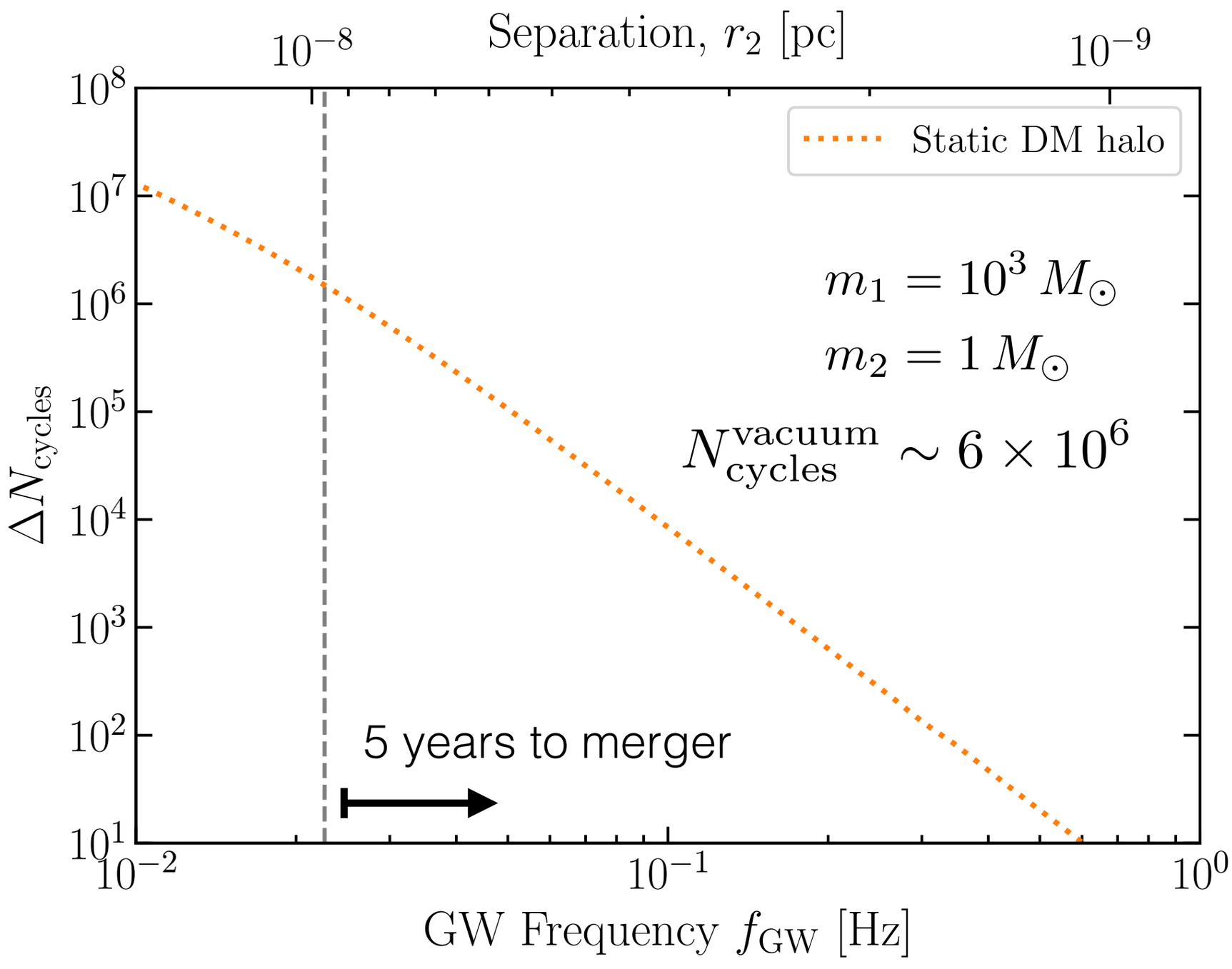


$$\dot{E}_{\rm DF} \sim \frac{4\pi G^2 m_2^2 \rho_{\rm DM}(r)\xi(v)}{v} \ln\Lambda$$

IMBH

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

Sizing up the dephasing



Assuming:

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

$$\Delta N_{\rm cycles} \sim \mathcal{O}(10^6)\,{\rm cycles} \sim \mathcal{O}(1)\,{\rm effect}$$

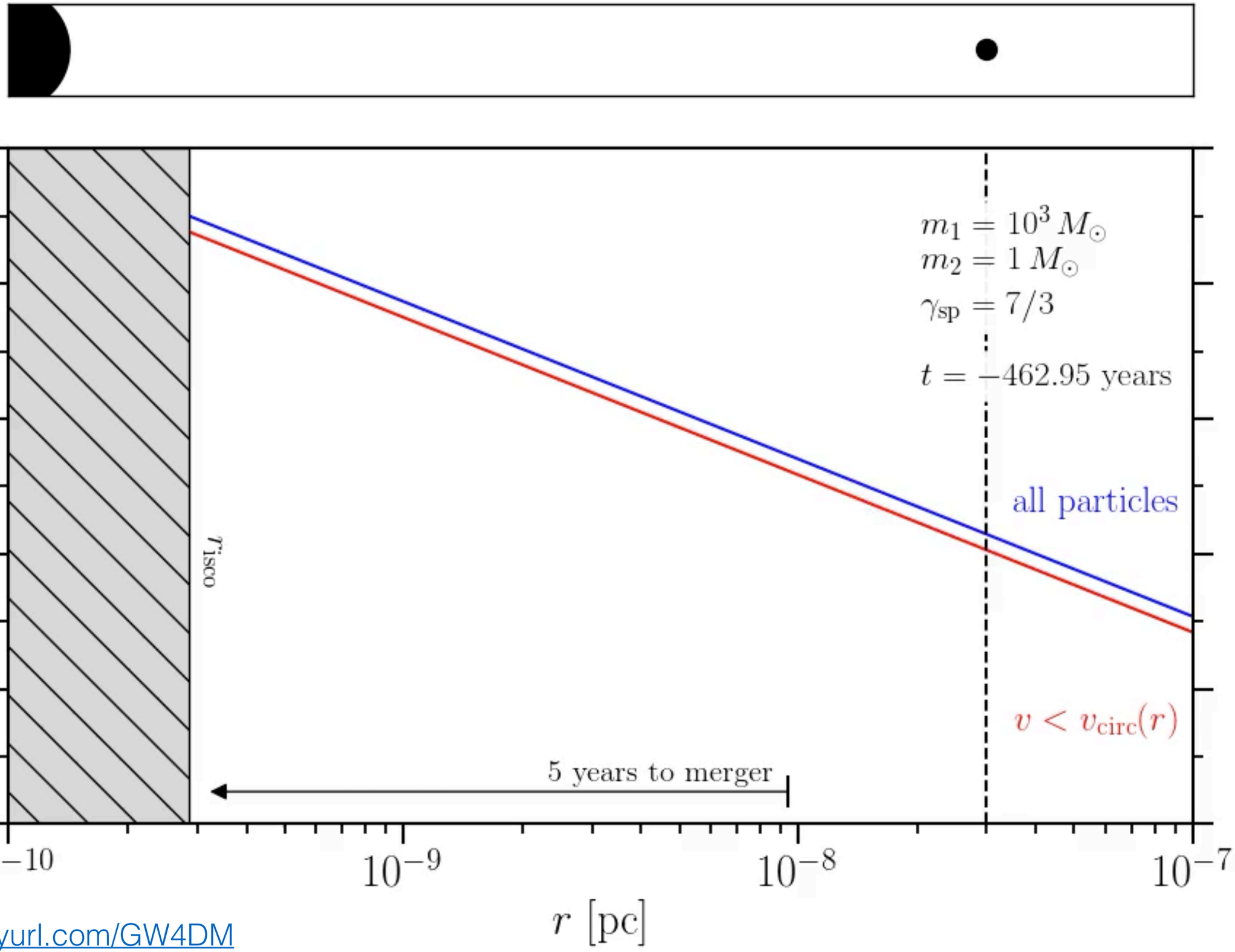
[Eda et al. 1301.5971, 1408.3534; see also 1302.2646, 1404.7140, 1404.7149 and others (sorry)]

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

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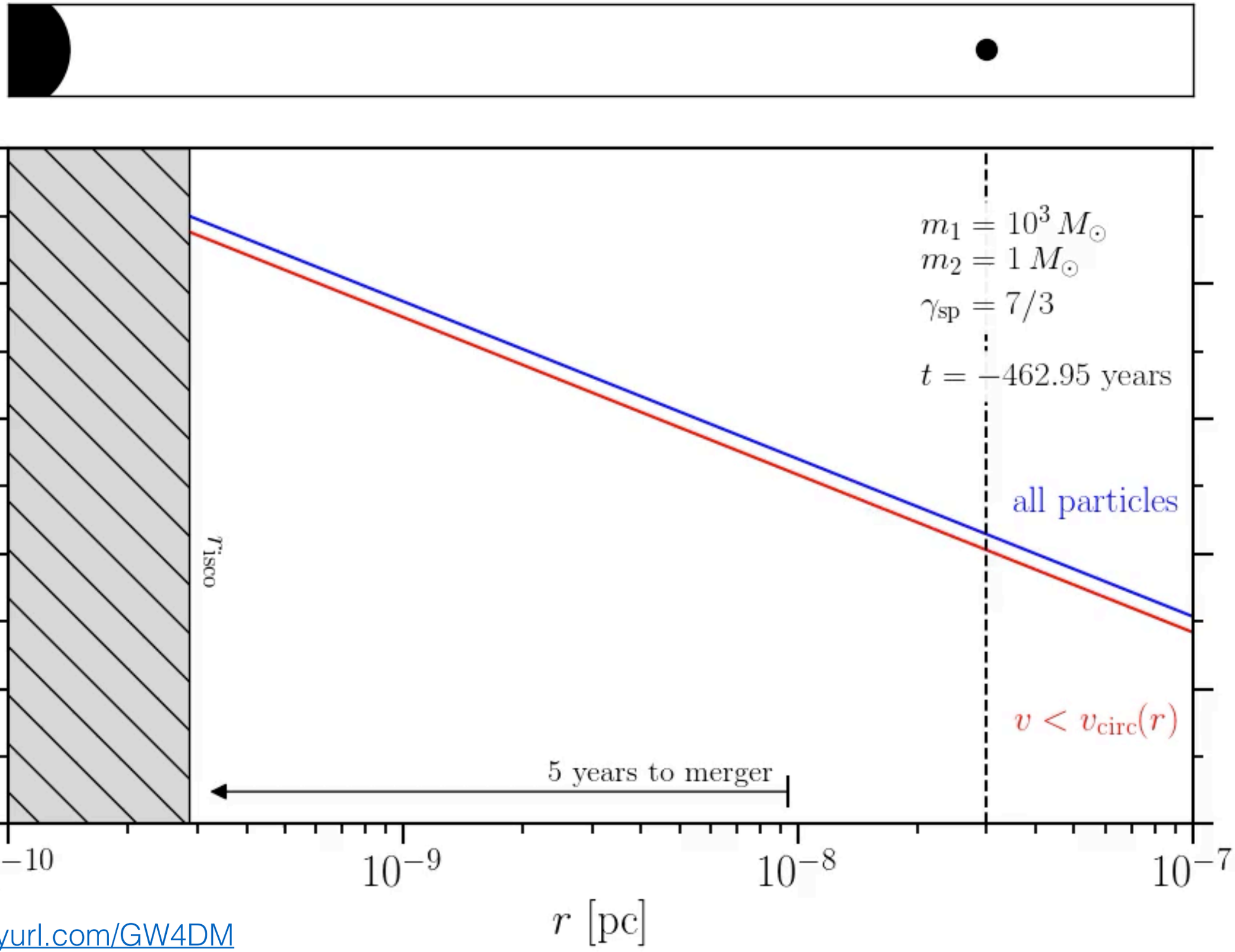

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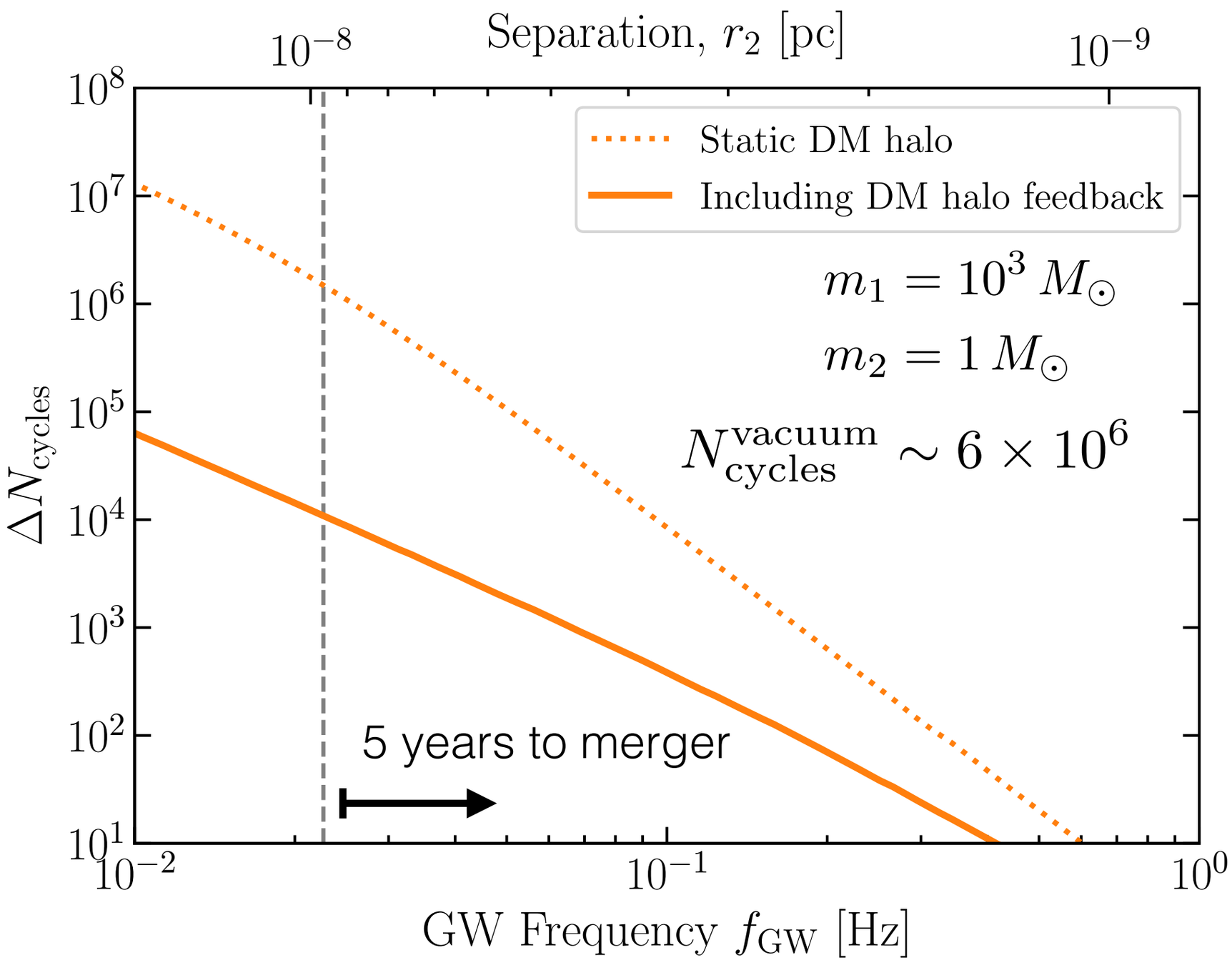

Assuming:

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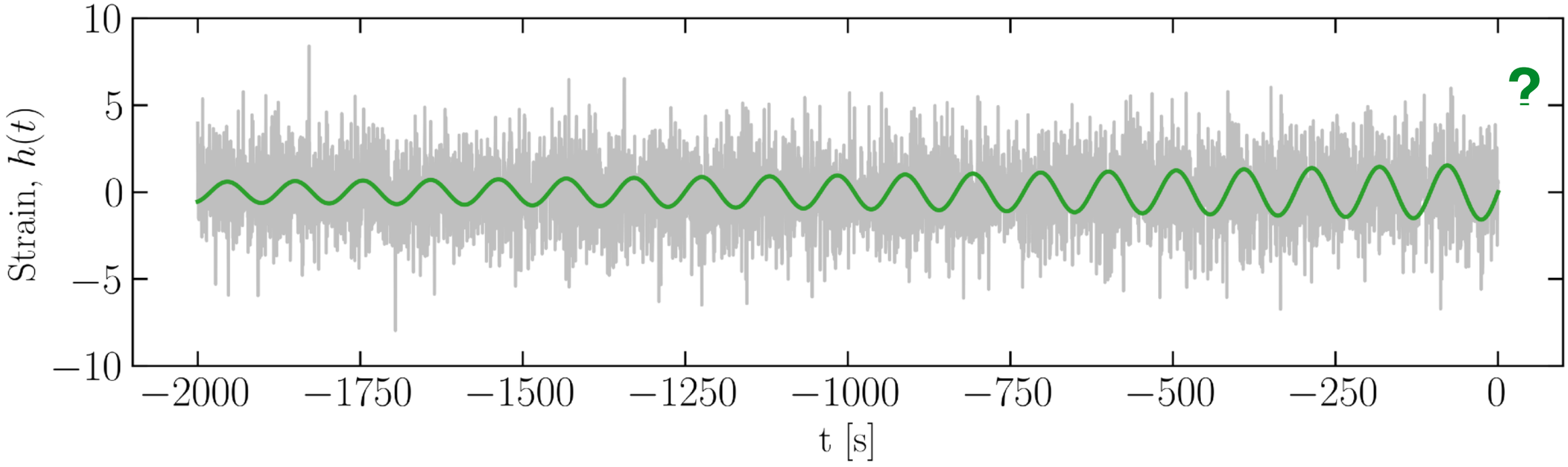
- Newtonian dynamics
- Isotropic DM spike

Feedback effect becomes smaller as q decreases, but so does the size of the dephasing effect…

$$\Delta N_{\rm cycles} \sim \mathcal{O}(10^4)\,{\rm cycles} \sim \%\,{\rm level\ effect}$$

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

A more realistic scenario



Want to address questions of:

- **Discoverability** - can we tell it apart from a *GR-in-vacuum* waveform?
- **Measurability** - can we pin down the properties of the system (*especially the DM*)?

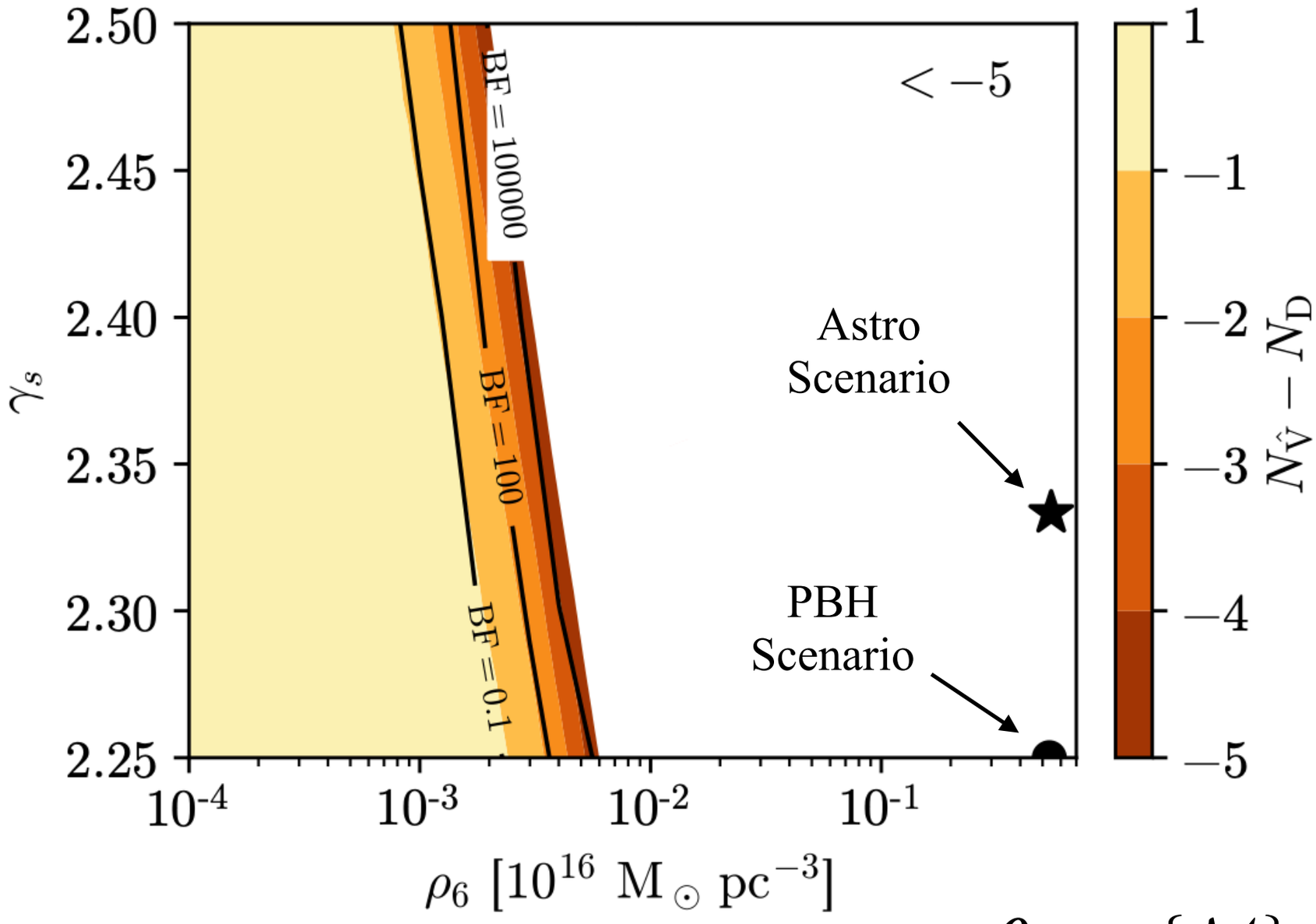
[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]

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:

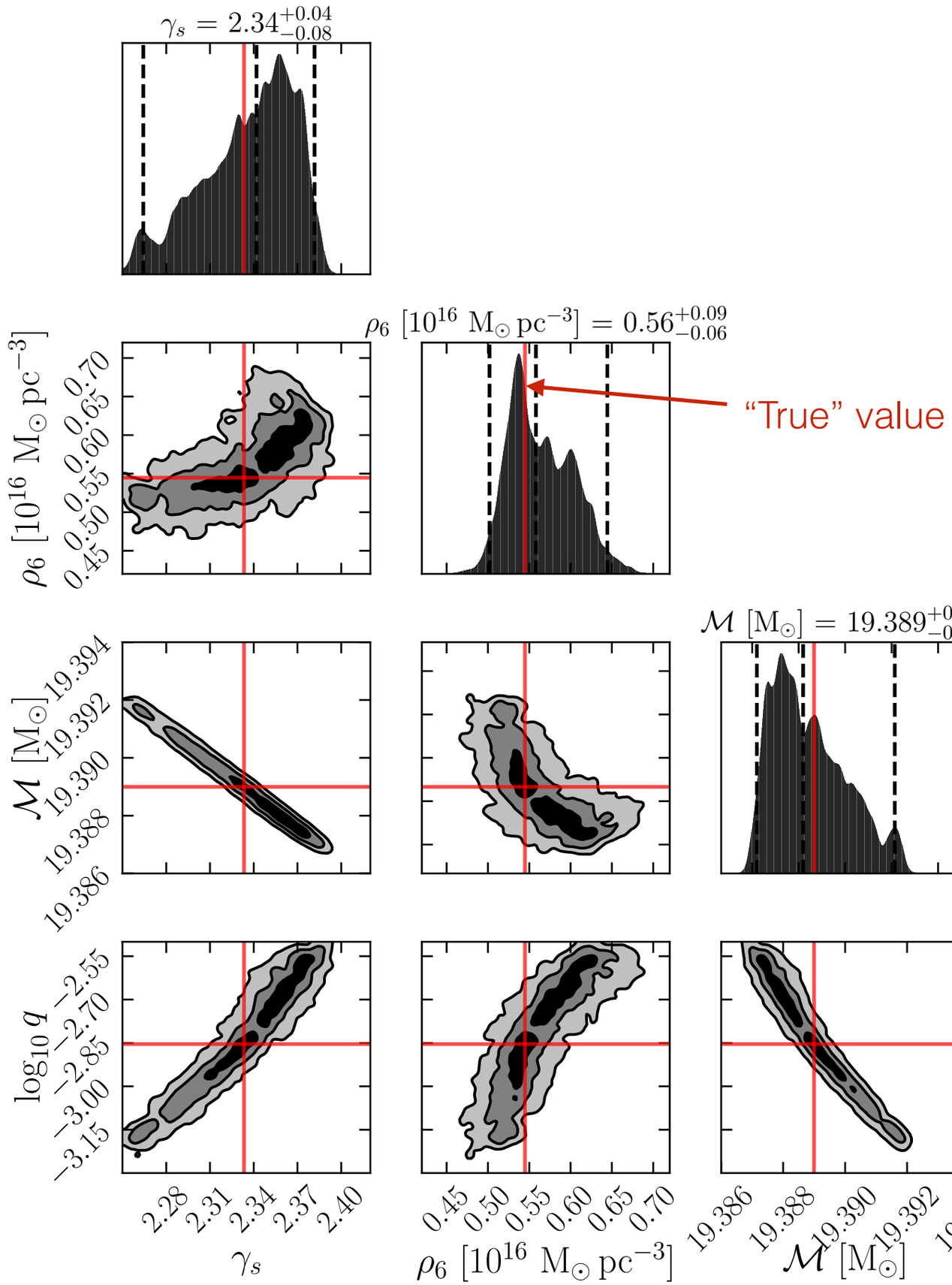
$$\boldsymbol{\theta}_{\mathrm{V}} = \{\mathcal{M}\}$$

vs.

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

Measurability

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



Astrophysical scenario

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

$$m_2 = 1\, M_\odot$$

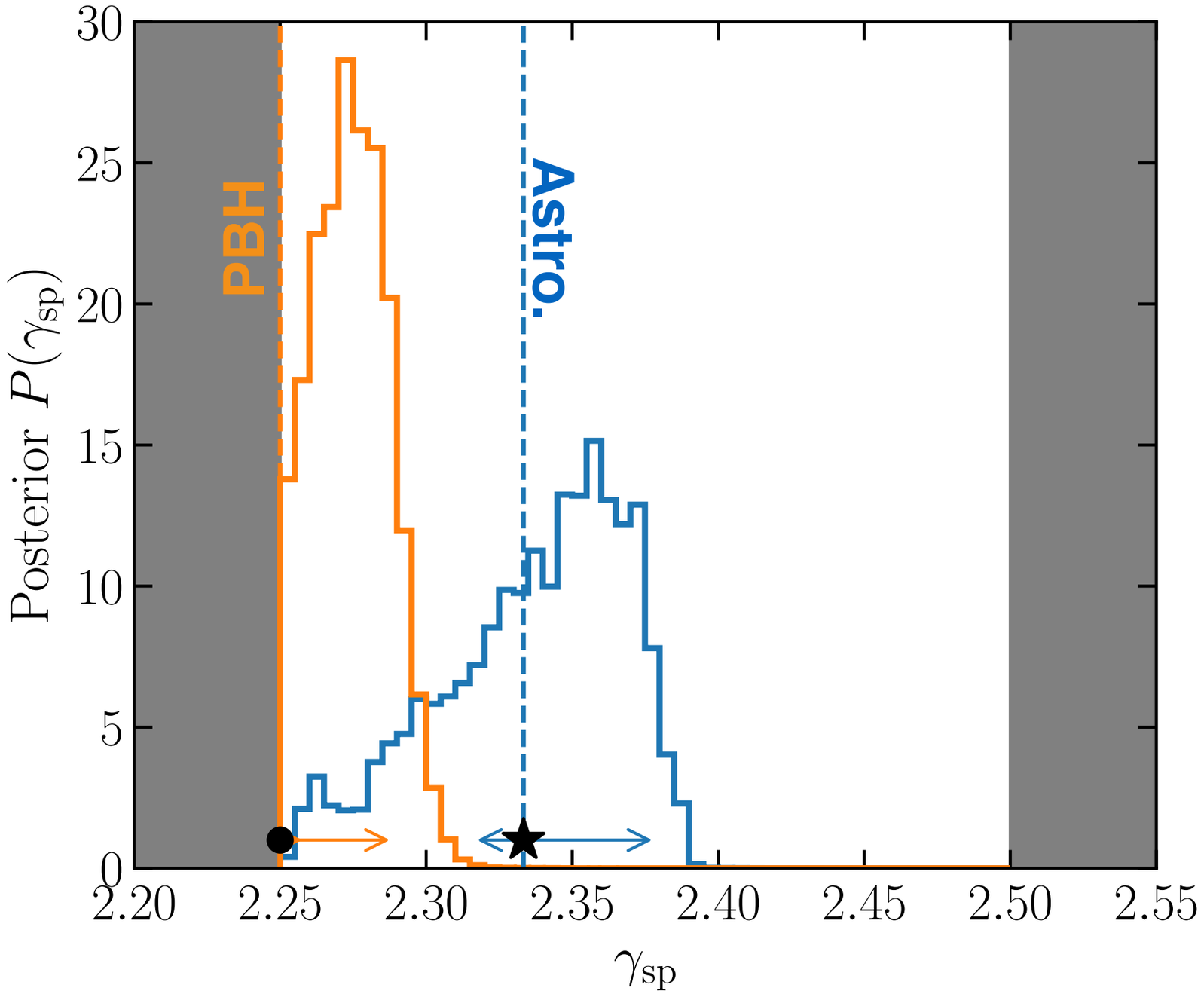
$$\gamma_{\rm sp} = 7/3 \approx 2.3333\ldots$$

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

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

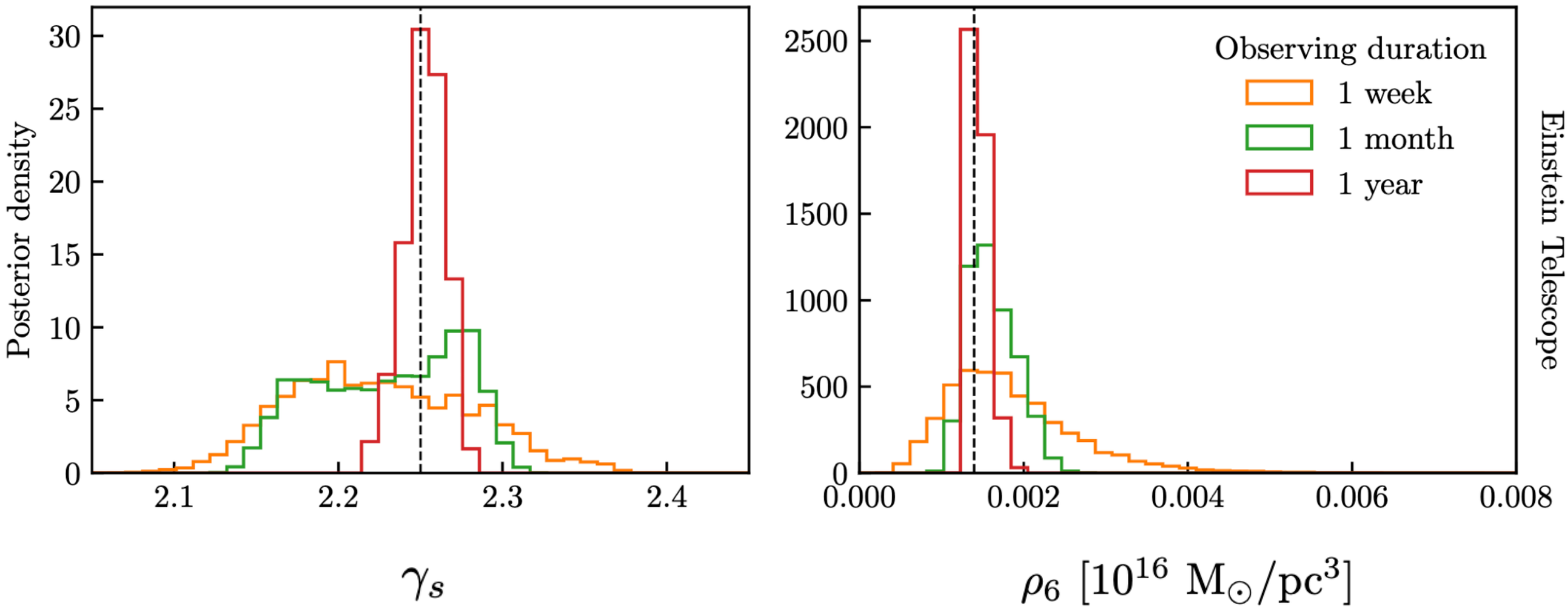
→ Different DM models and formation mechanisms!

Light PBH Binaries

[Bertone, Cole, Coogan & **BJK**, in preparation]

Ground-based telescopes (Einstein Telescope, Cosmic Explorer, perhaps even LVK) could also measure DM spikes in **lighter binaries** (in this case PBHs):

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



Detectable out to ~100 Mpc, with the ‘dressed’ system massively favoured, even with ‘short’ observations (~ 1 week)

Towards better spikes

Realistic spike formation scenarios

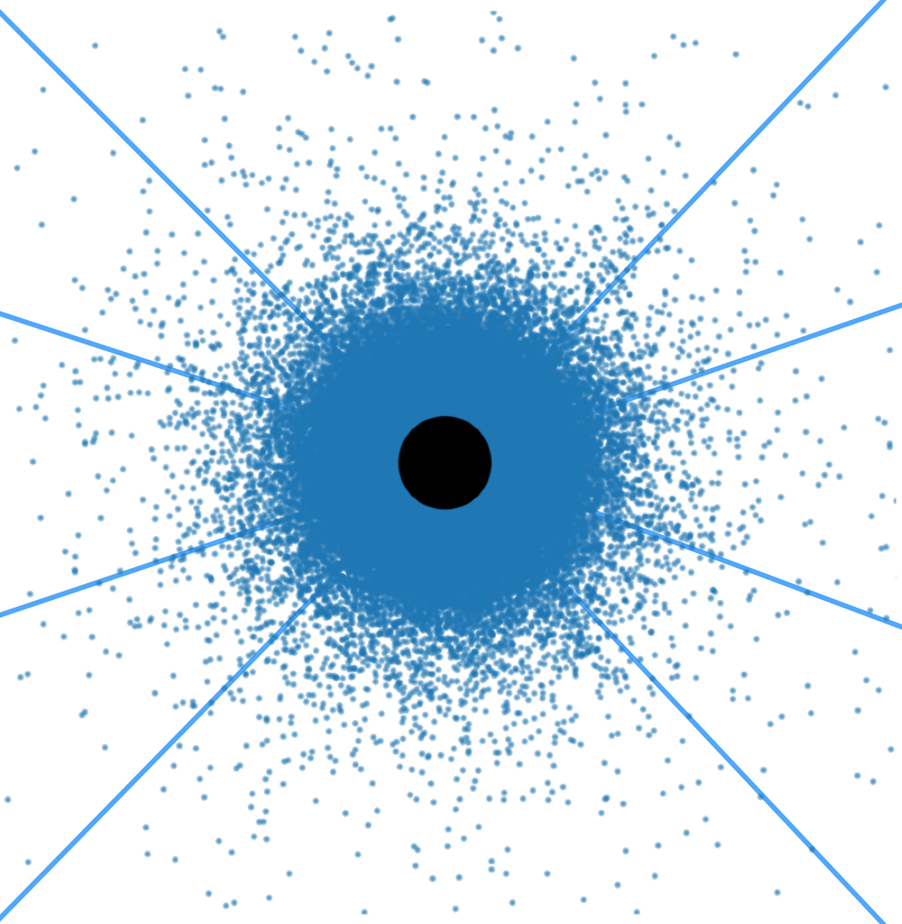
Accretion (for BHs)

[See Theophanes Karydas' lightning talk (today)]

Eccentric orbits

[See e.g. Becker et al., 2112.09586]

More realistic feedback



Confusion with other environmental effects

[See Pippa Cole's talk (today) and Niklas Becker's talk (tomorrow)]

Relativistic effects

[See e.g. 2204.12508 and Nicholas Speeney's talk (today)]

Integration with realistic IMRI/EMRI waveforms

[See e.g. FastEMRIWaveforms, 2104.04582]

Search strategies

[C.f. Andrea Antonelli's talk (yesterday)]

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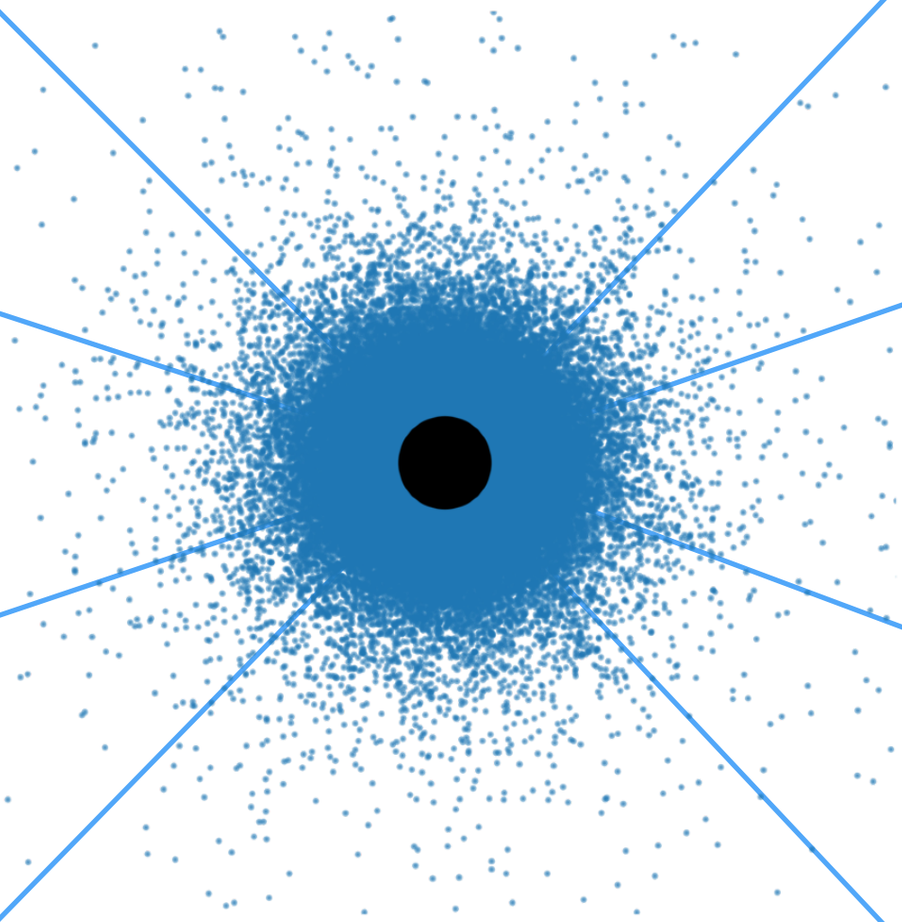

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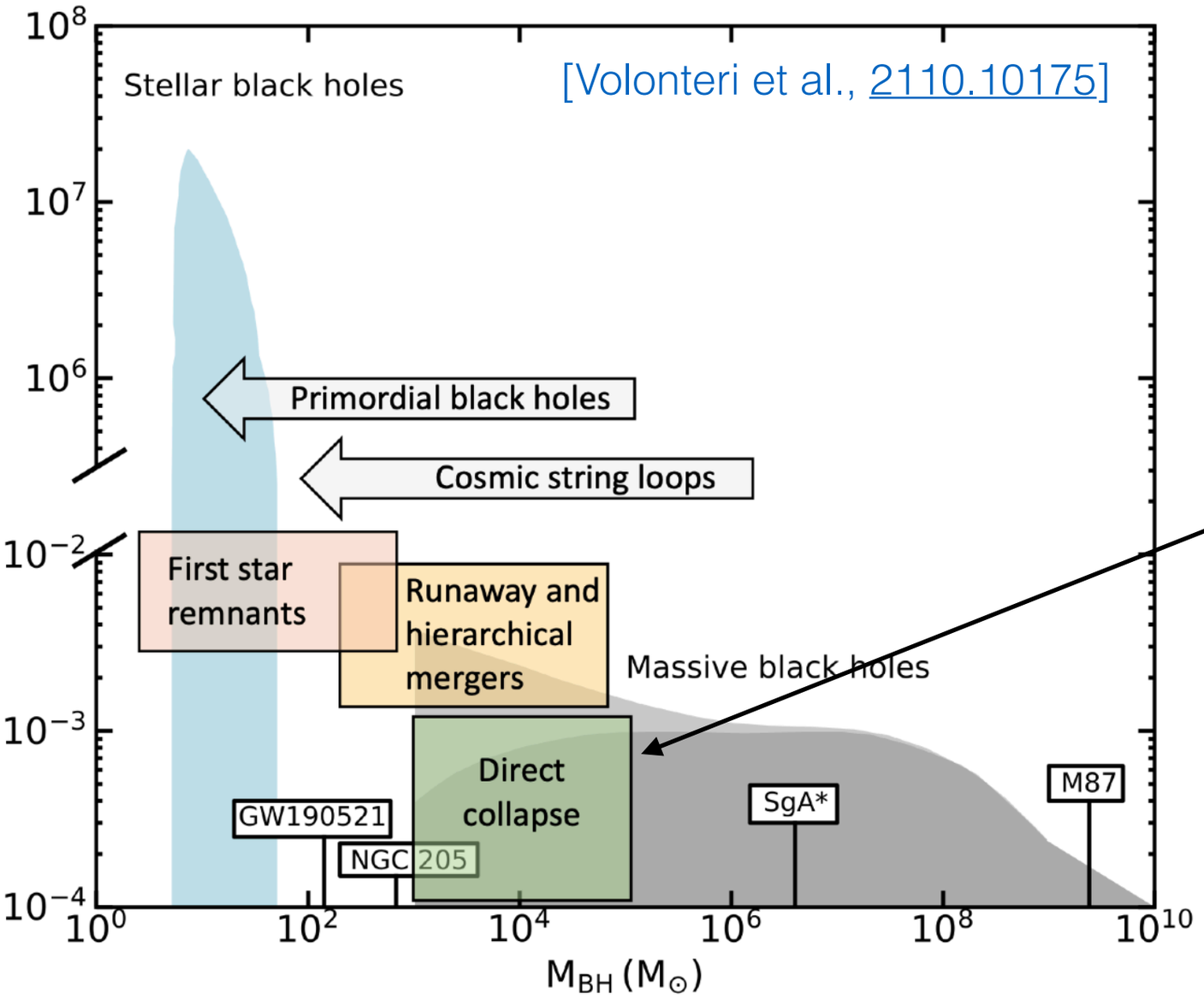
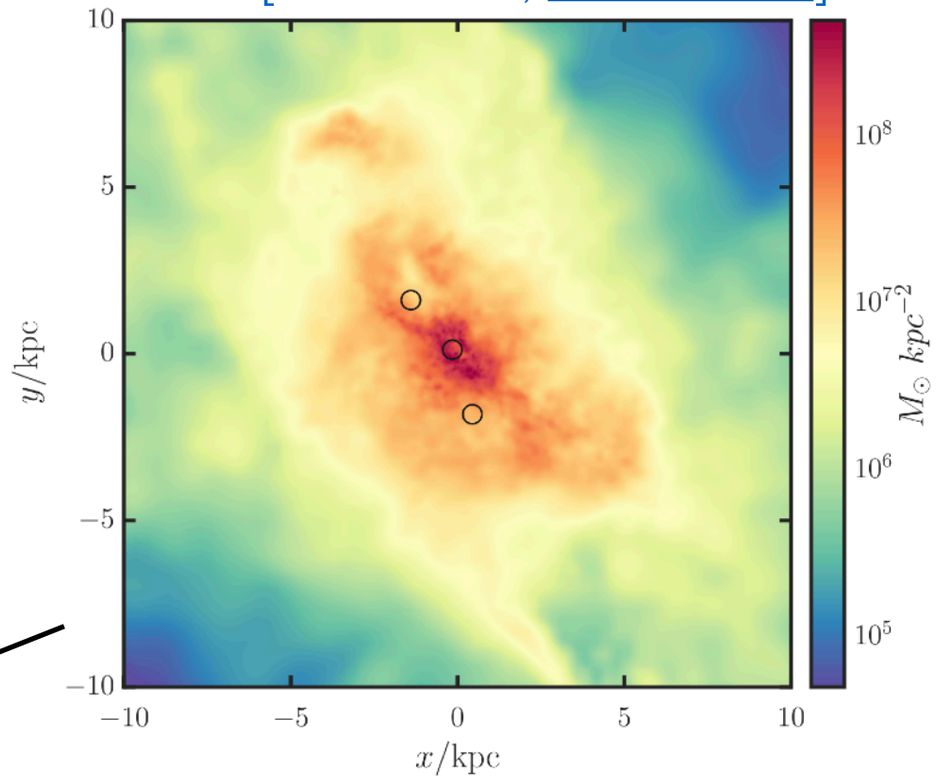
Black Hole and Spike Formation

[Volonteri et al., 2110.10175]



[Dunn et al., 1803.01007]



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

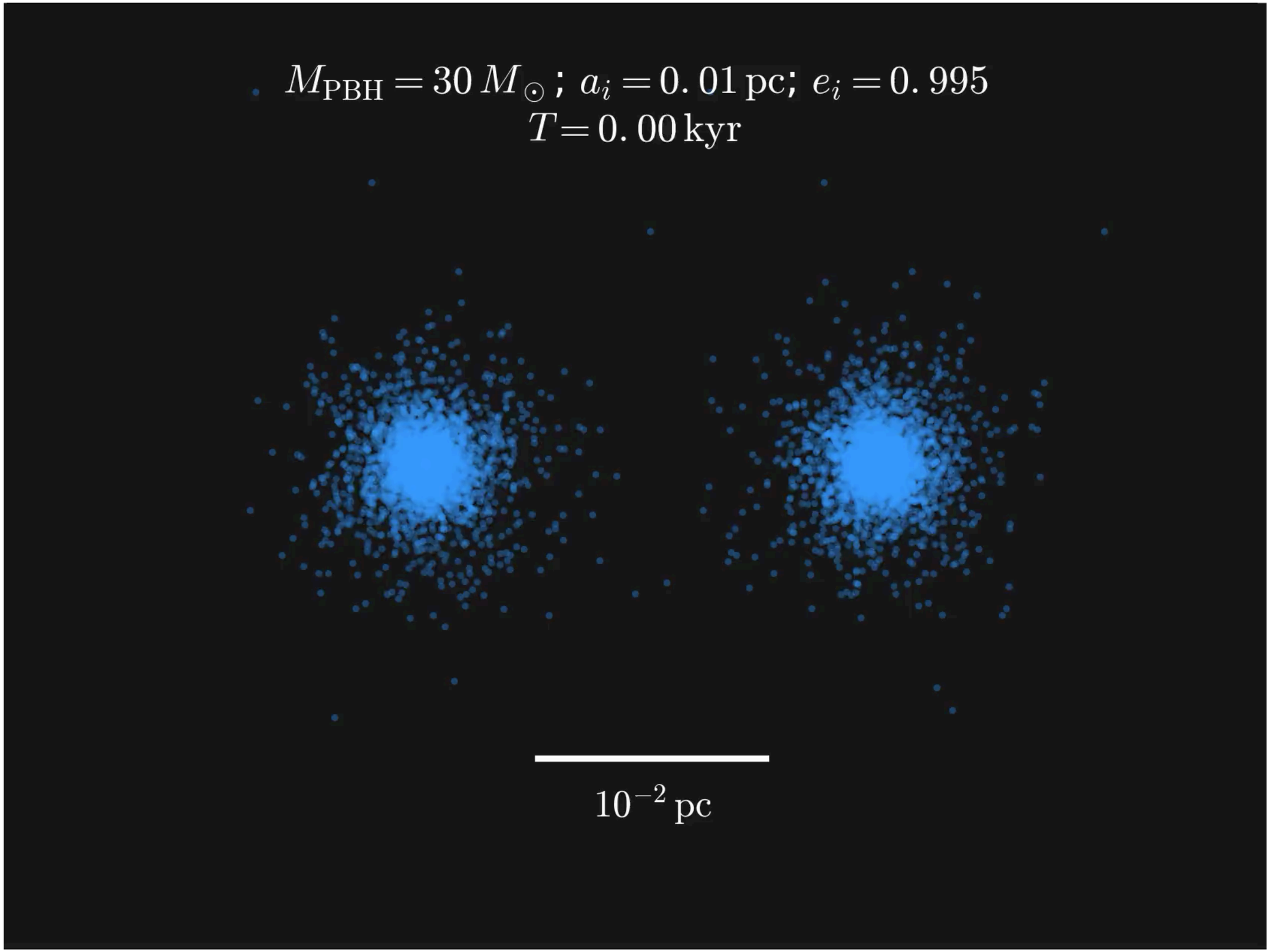
Preliminary results suggest that large densities are possible $\rho_6 \gtrsim 10^{16}\, M_\odot\, \mathrm{pc}^{-3}$ but do these systems survive, and are they common?

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

Dressed PBHs

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

[Movies here]



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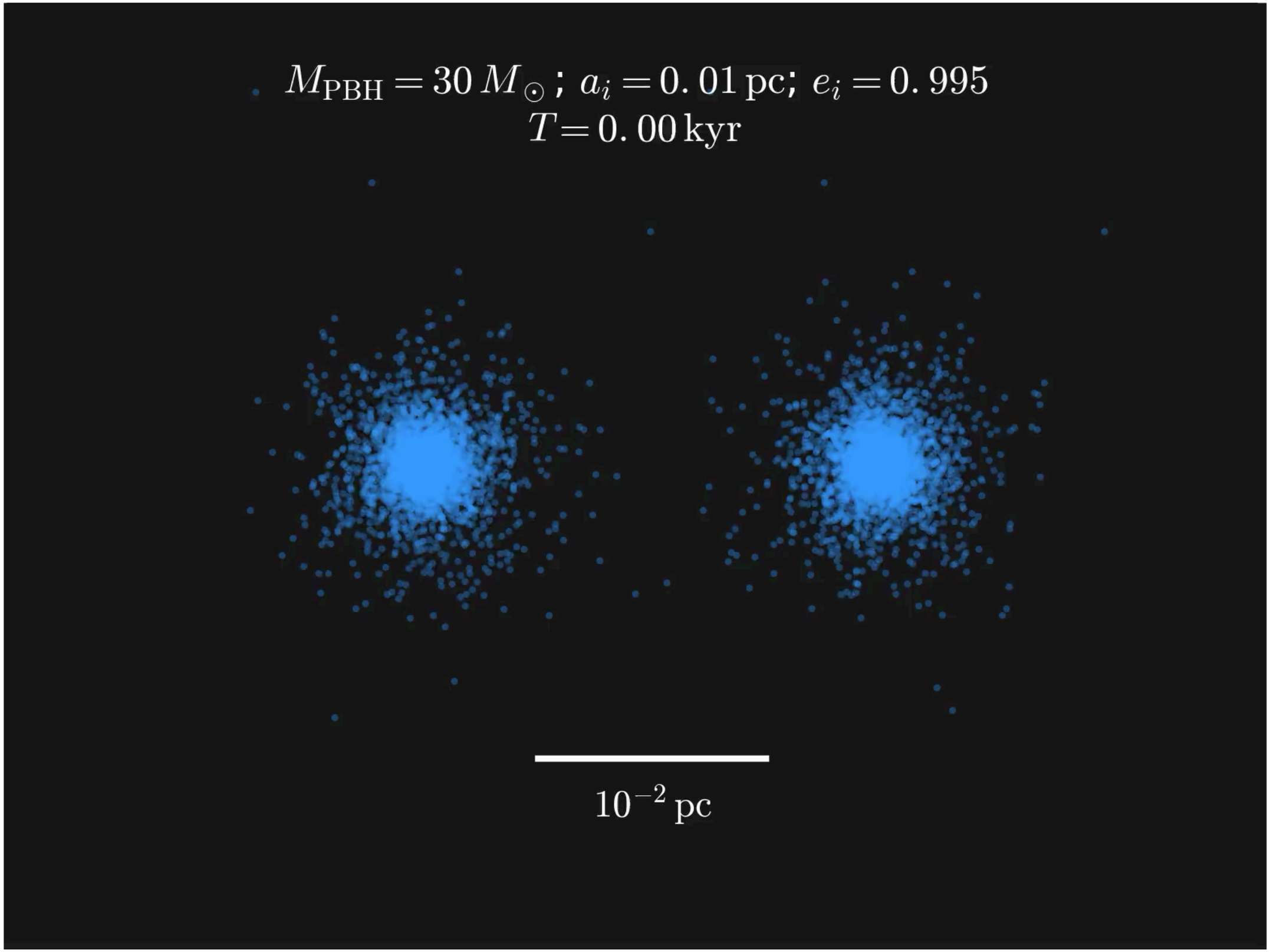
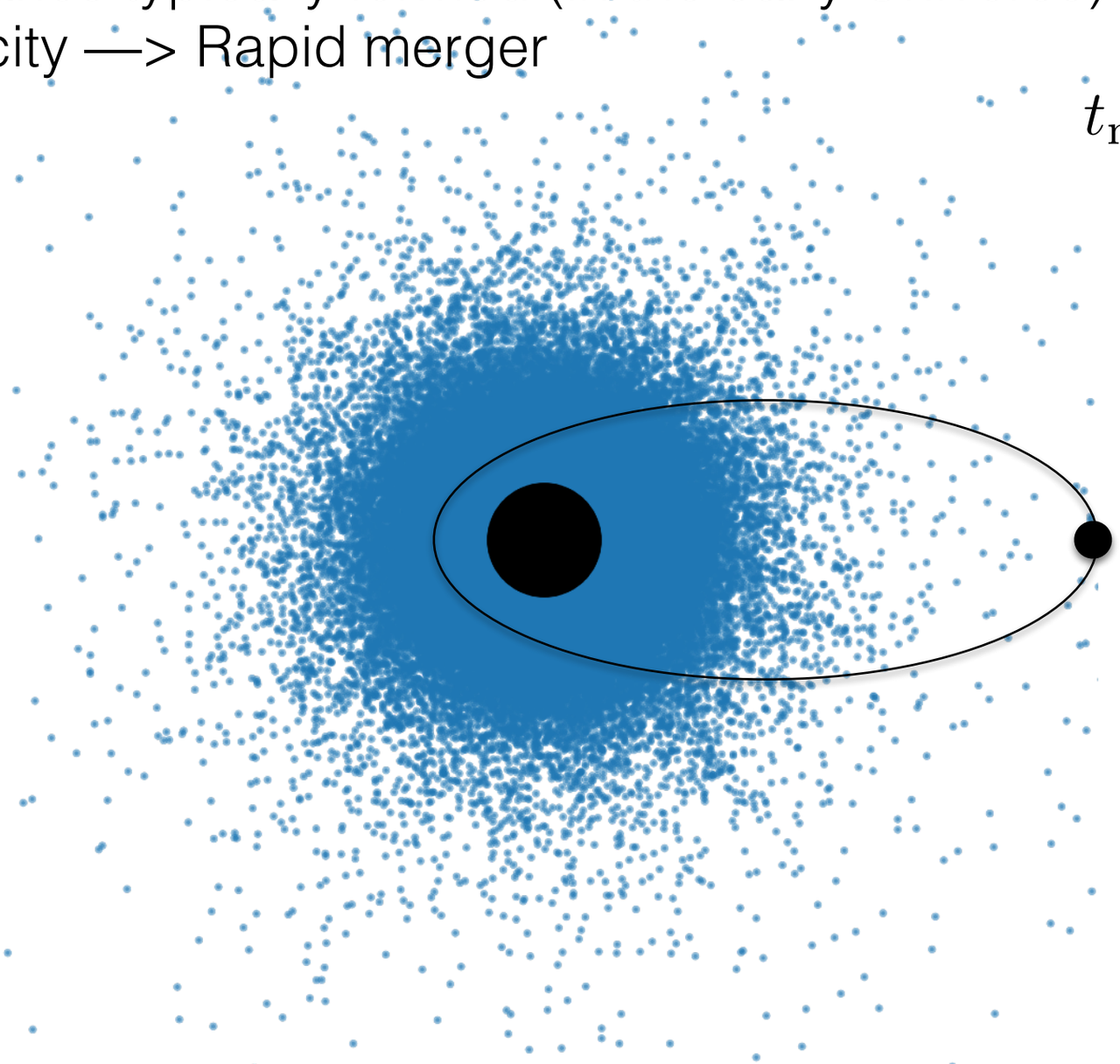
[Movies here]



Dressed PBH IMRIs

PBH binaries typically formed (in the early Universe) with very high eccentricity —> Rapid merger

$$t_{\rm merge} \sim a_i^4 (1-e_i^2)^{7/2}$$

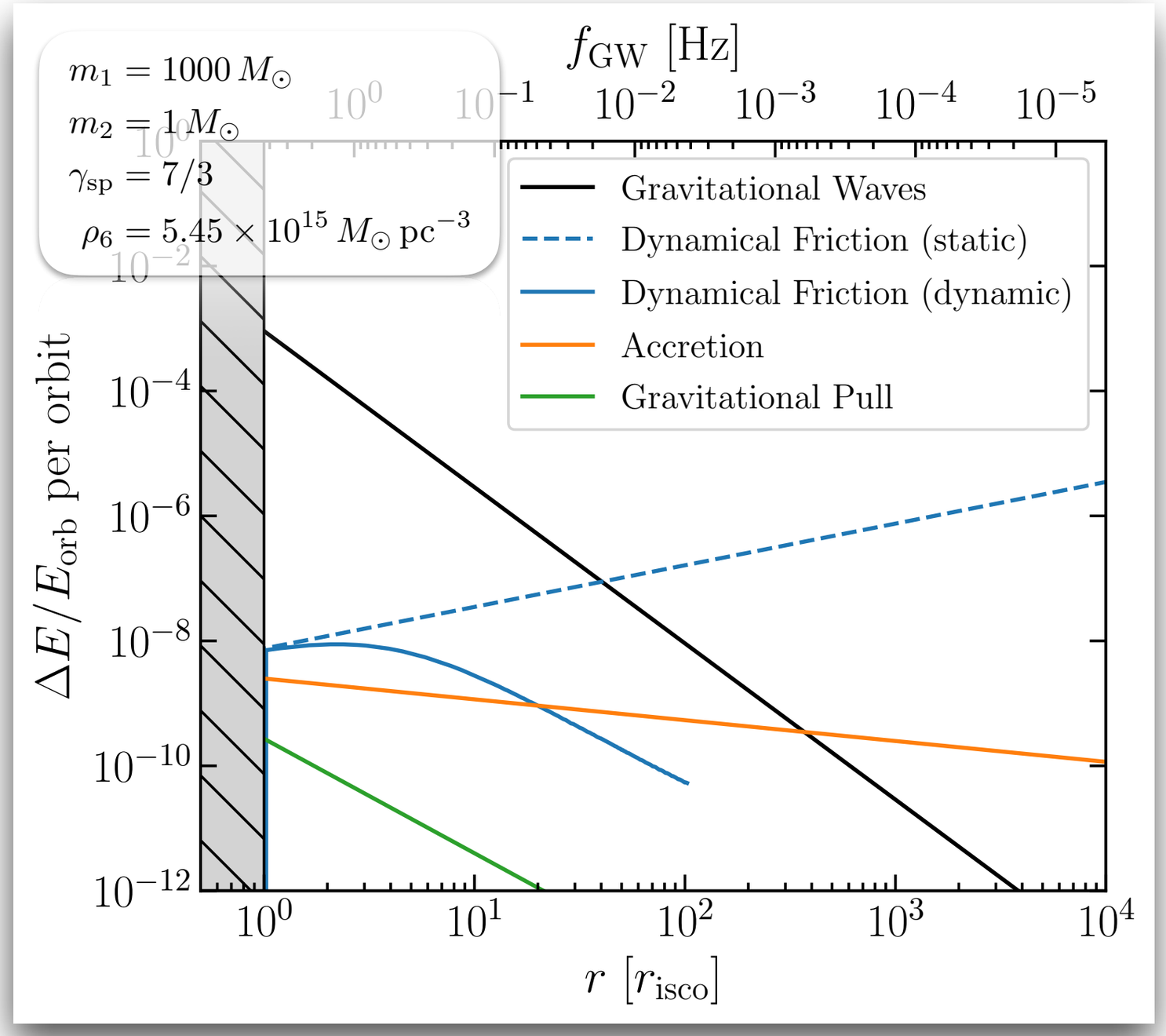


Dark Dresses around PBH IMRIs are likely to accelerate merger…

Do dressed PBH IMRIs merge slowly enough to be detected at low redshift?

[Work in progress with Pratibha Jangra & Chema Diego]

Accretion (and other effects)



Need to start including accretion, perhaps even effects of additional gravitational pull

May lead to additional feedback effects…

[See **Theophanes Karydas**' lightning talk (today)]

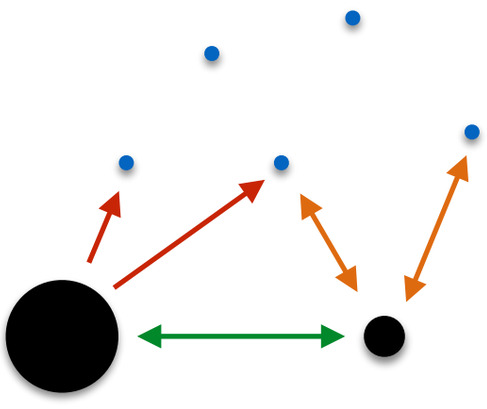
More realistic feedback

Eventually need to expand our description of feedback in the DM spike:

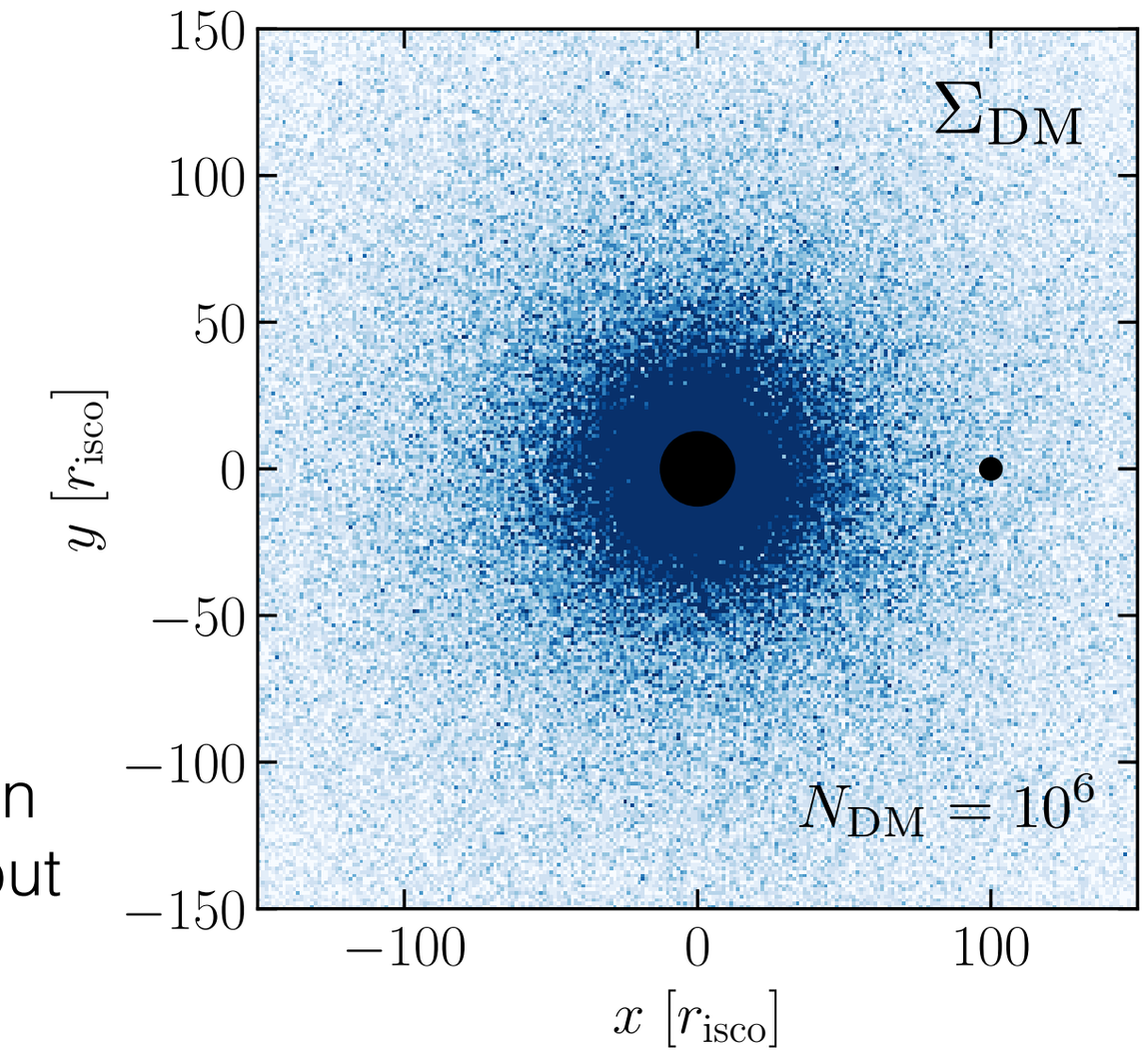
- Anisotropy in the DM distribution
- Multiple sources of feedback (dynamical friction, accretion, etc)
- Verify semi-analytic prescriptions

NbodyIMRI: solver tailored to DM spikes [Code here: github.com/bradkav/NbodyIMRI]

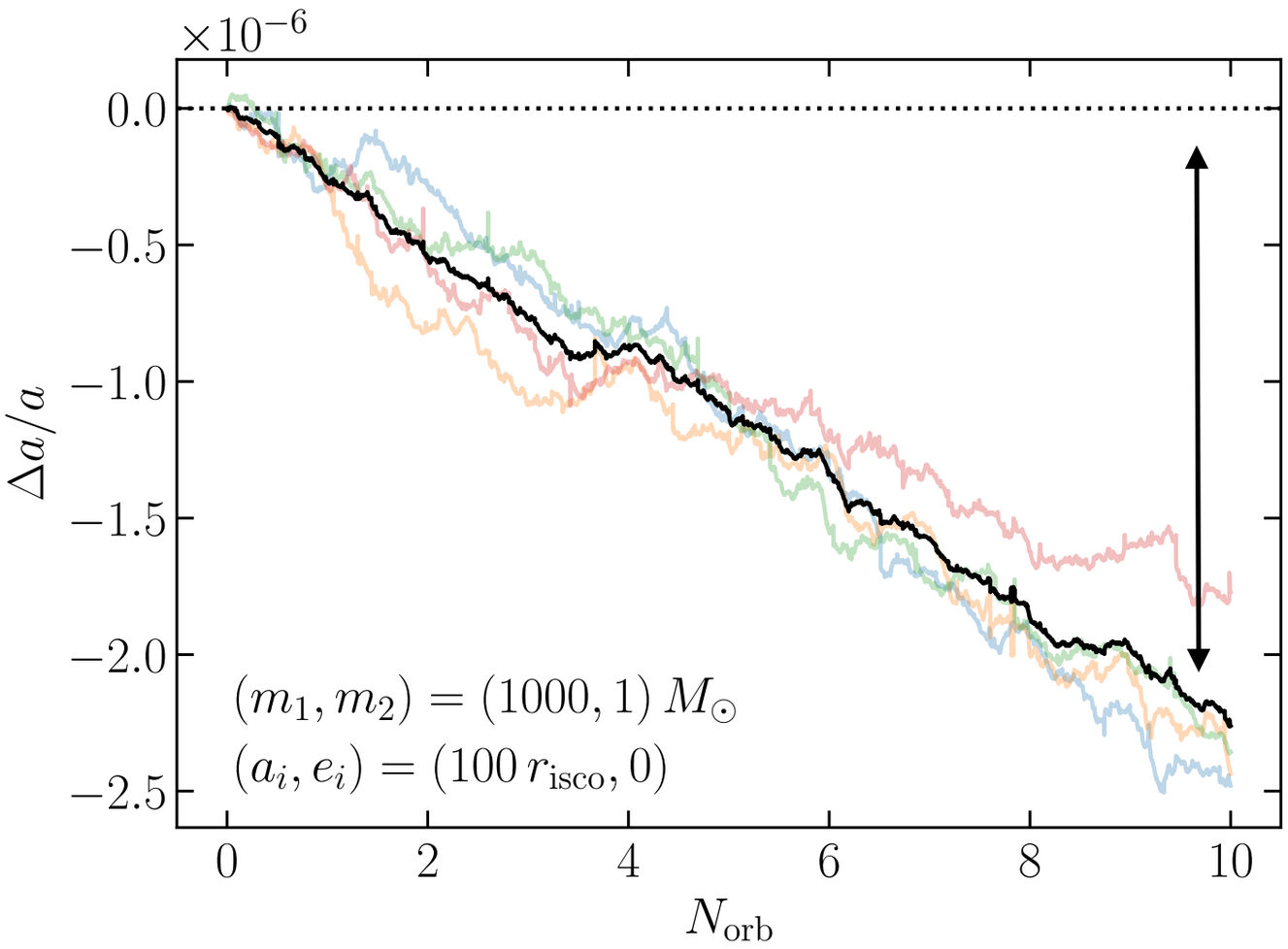
No DM-DM interparticle forces



Can follow the spike in high resolution (For now in Newtonian gravity only, but eventually include PN corrections)



More realistic feedback



Rate of energy loss allows us to calibrate dynamical friction force

Which particles are scattered by the secondary?

How much of the spike is depleted?

N-body simulations will never be fast enough to generate waveforms, but they help inform and calibrate modelling.

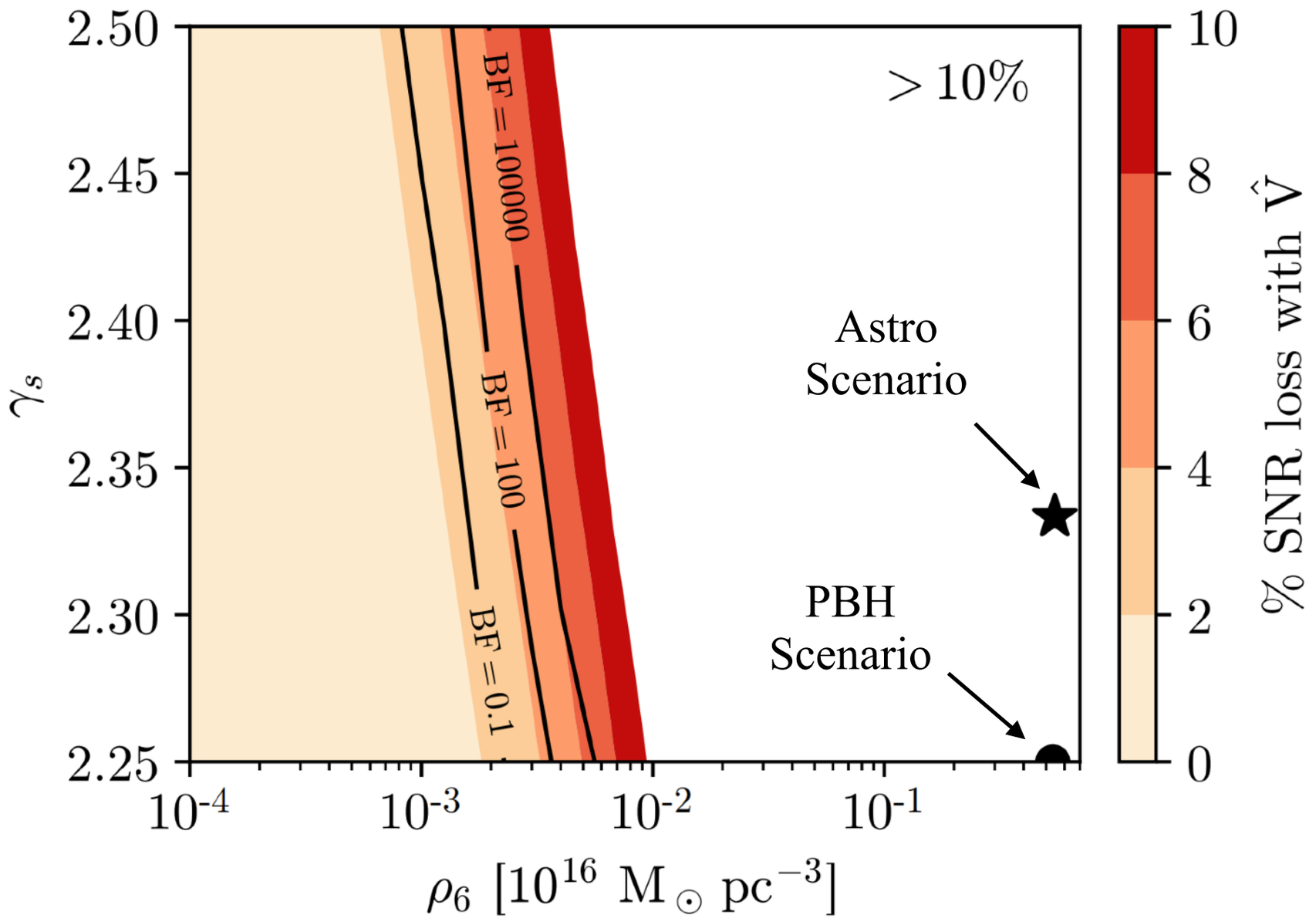
Ultimately need a fast method of generating waveforms (e.g. surrogate models?).

But even if we can eventually model the system perfectly (and quickly), we still have a challenge…

Discoverability

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

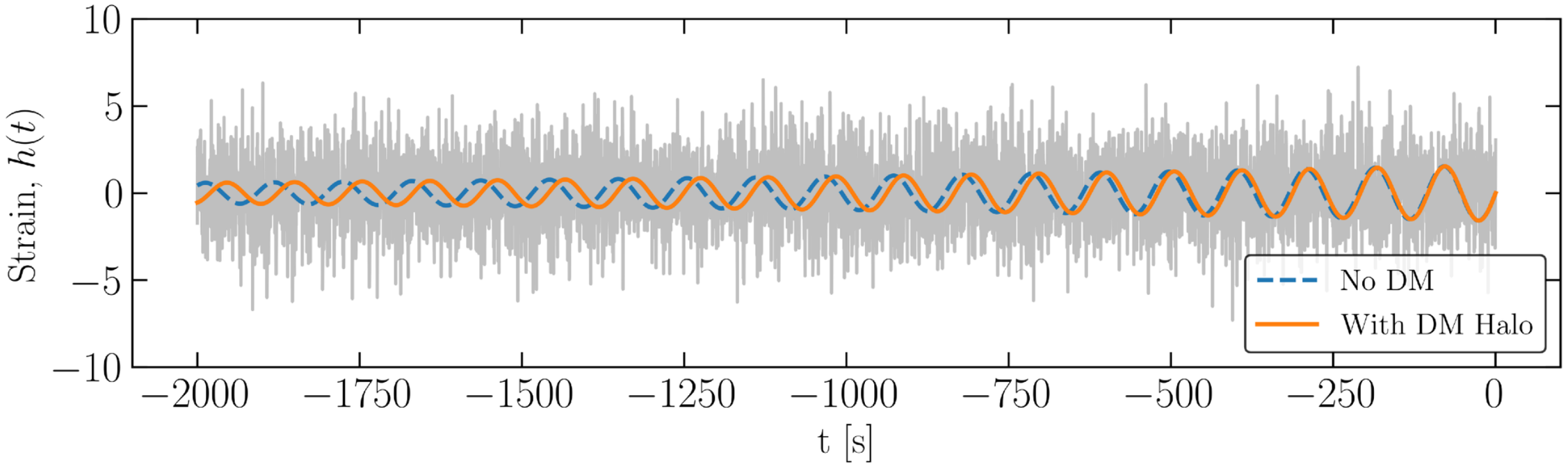
Substantial **loss of SNR** using GR-in-vacuum waveforms!



Space of templates would need to be expanded *a lot* (with possible complicated correlations…)

[See e.g. Alvin Chua's talk (yesterday)]

Search strategies?



Possible options (?):

- Detect **GW signal close to merger** (where dephasing is small) then ‘track back’ through the data (as dephasing increases)

- Use ‘**generalised inspiral**’ waveforms to parametrise the dephasing

[Chia & Edwards, 2004.06729]

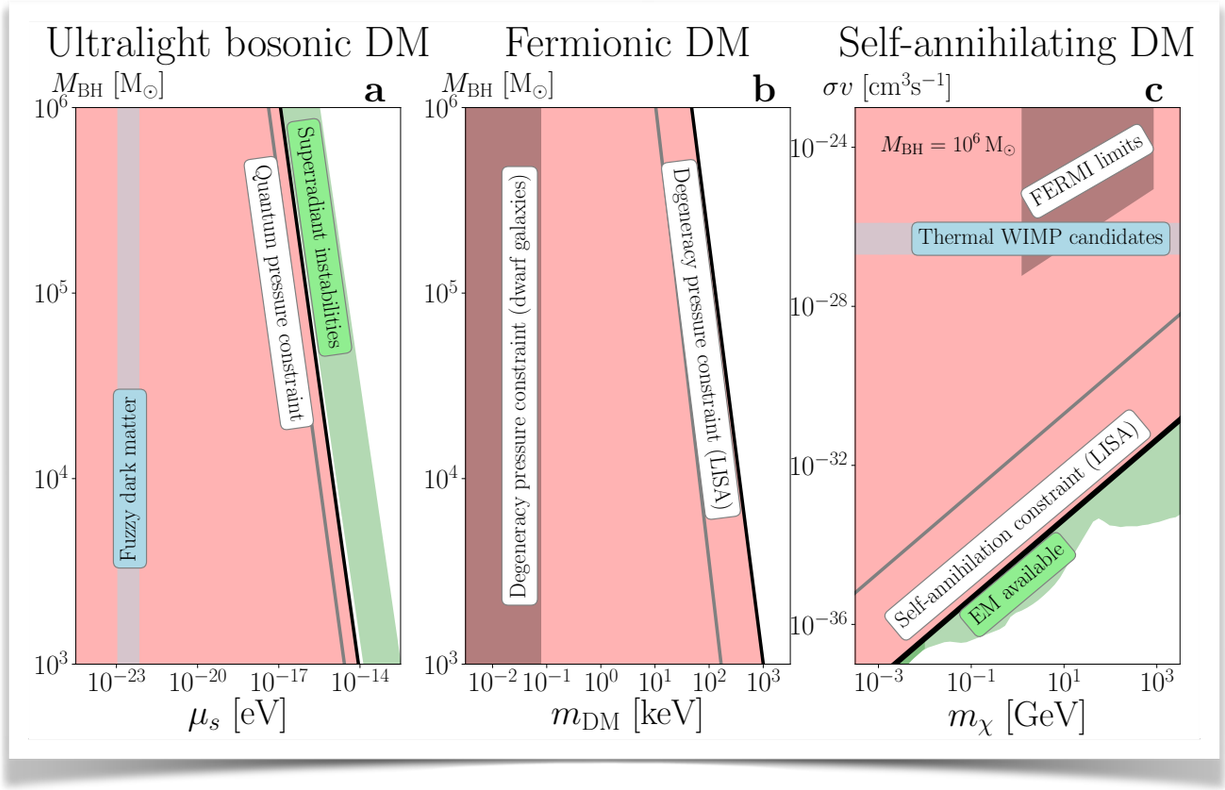
- Use tools from **continuous-wave searches**, breaking the inspiral into ‘chunks’ and looking for quasi-monochromatic signals in each chunk (e.g. Hough transform)

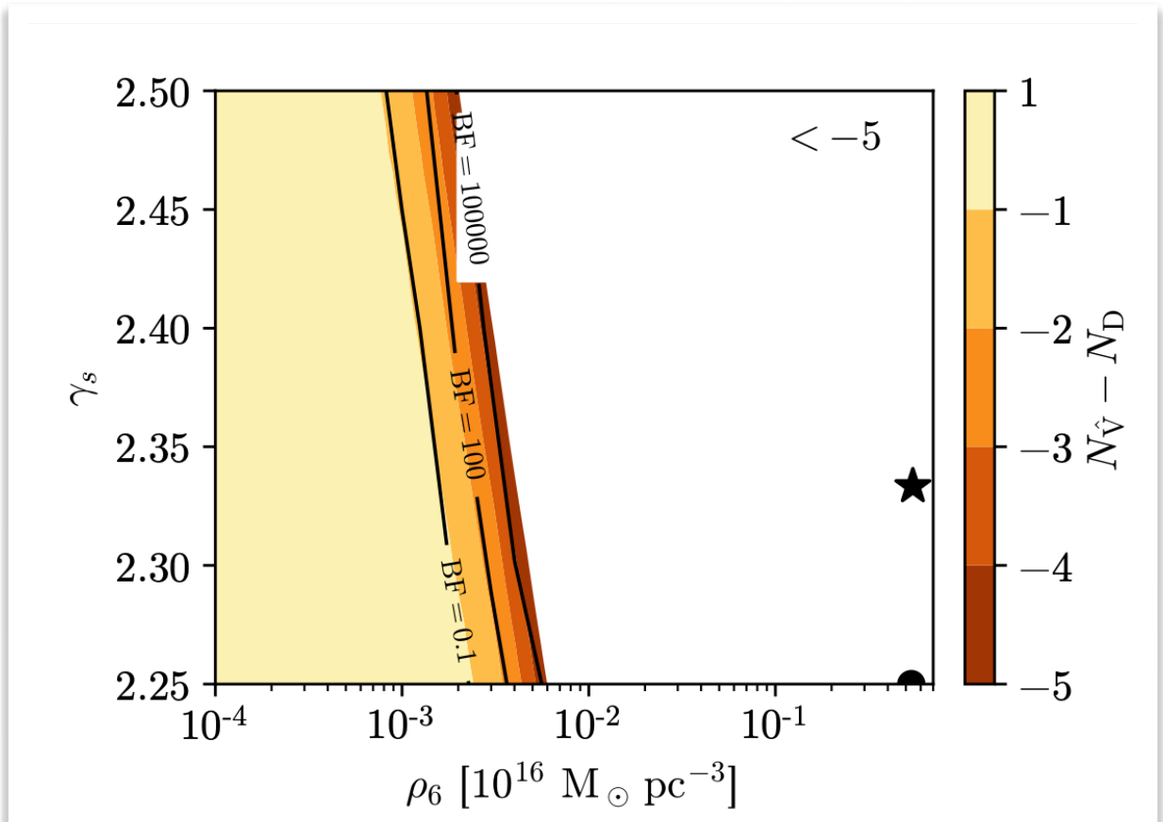
[Guo & Miller, 2205.10359]

- Hybrid of the above?

Conclusions

Detecting collisionless DM spikes would be revolutionary.





In simple models, with simplified searches, it's possible and powerful.

Now we just have a few things left to do…

Towards better spikes

Need to do all of these things accurately, quickly, all at the same time:

Realistic spike formation scenarios

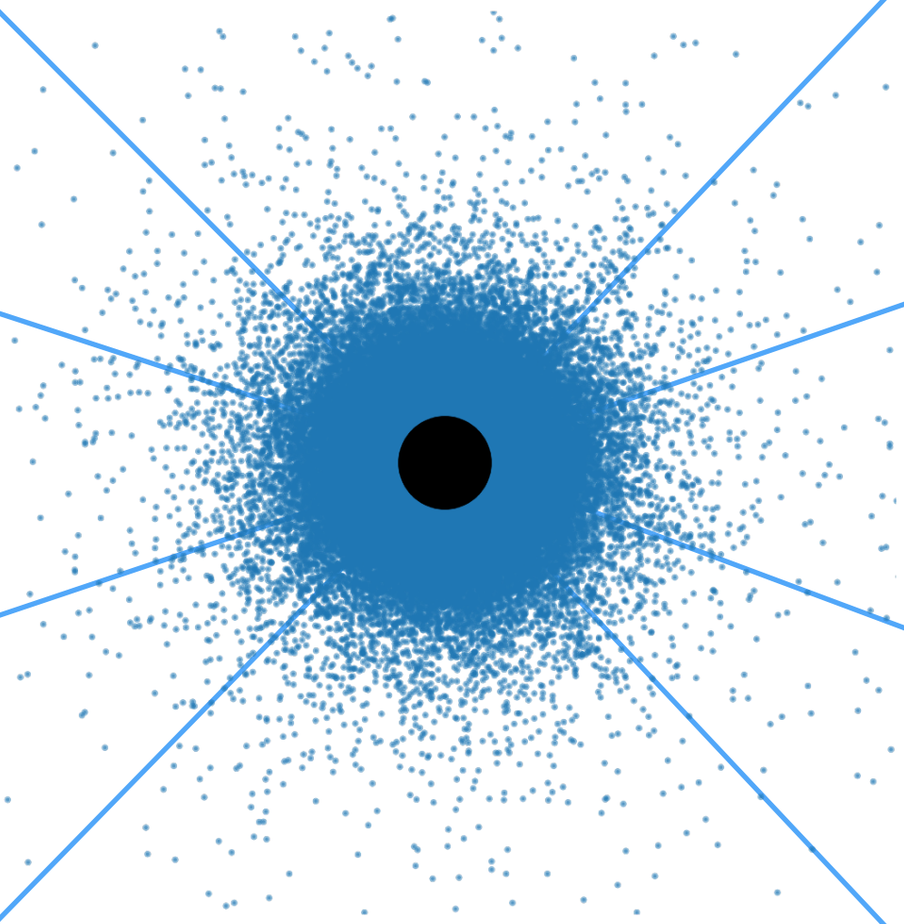
Accretion (for BHs)

[See Theophanes Karydas' lightning talk (today)]

Eccentric orbits

[See e.g. Becker et al., 2112.09586]

More realistic feedback



Confusion with other environmental effects

[See Pippa Cole's talk (today) and Niklas Becker's talk (tomorrow)]

Relativistic effects

[See e.g. 2204.12508 and Nicholas Speeney's talk (today)]

Integration with realistic IMRI/EMRI waveforms

[See e.g. FastEMRIWaveforms, 2104.04582]

Search strategies

[C.f. Andrea Antonelli's talk (yesterday)]

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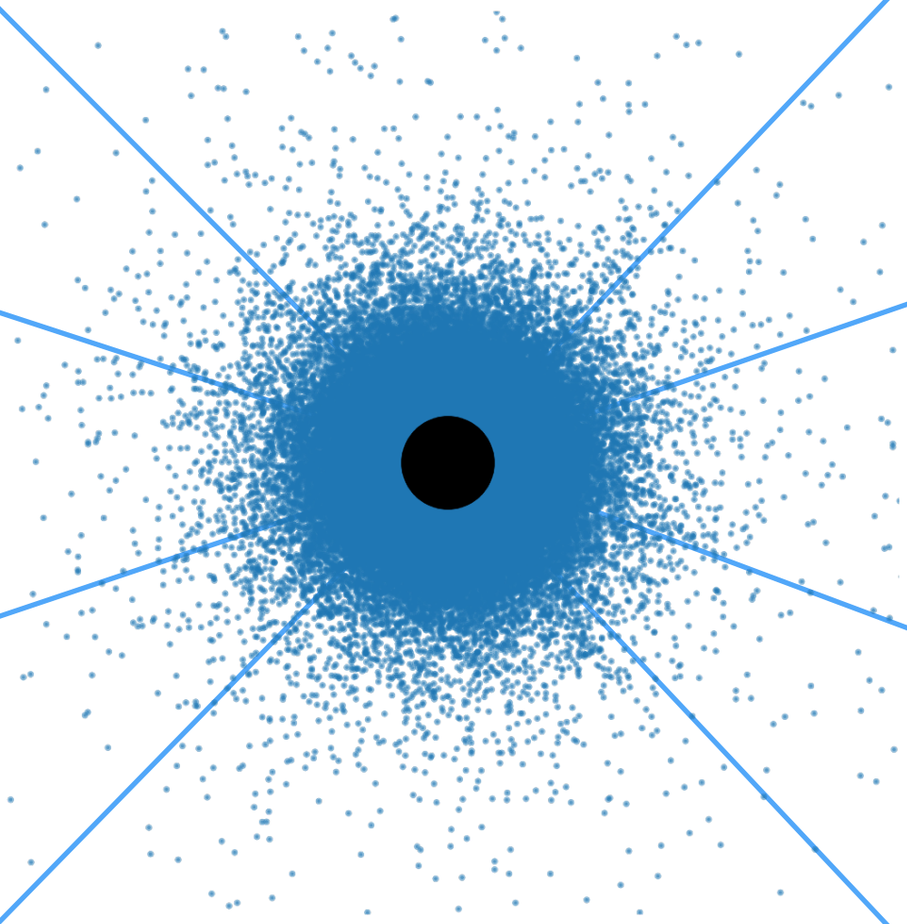

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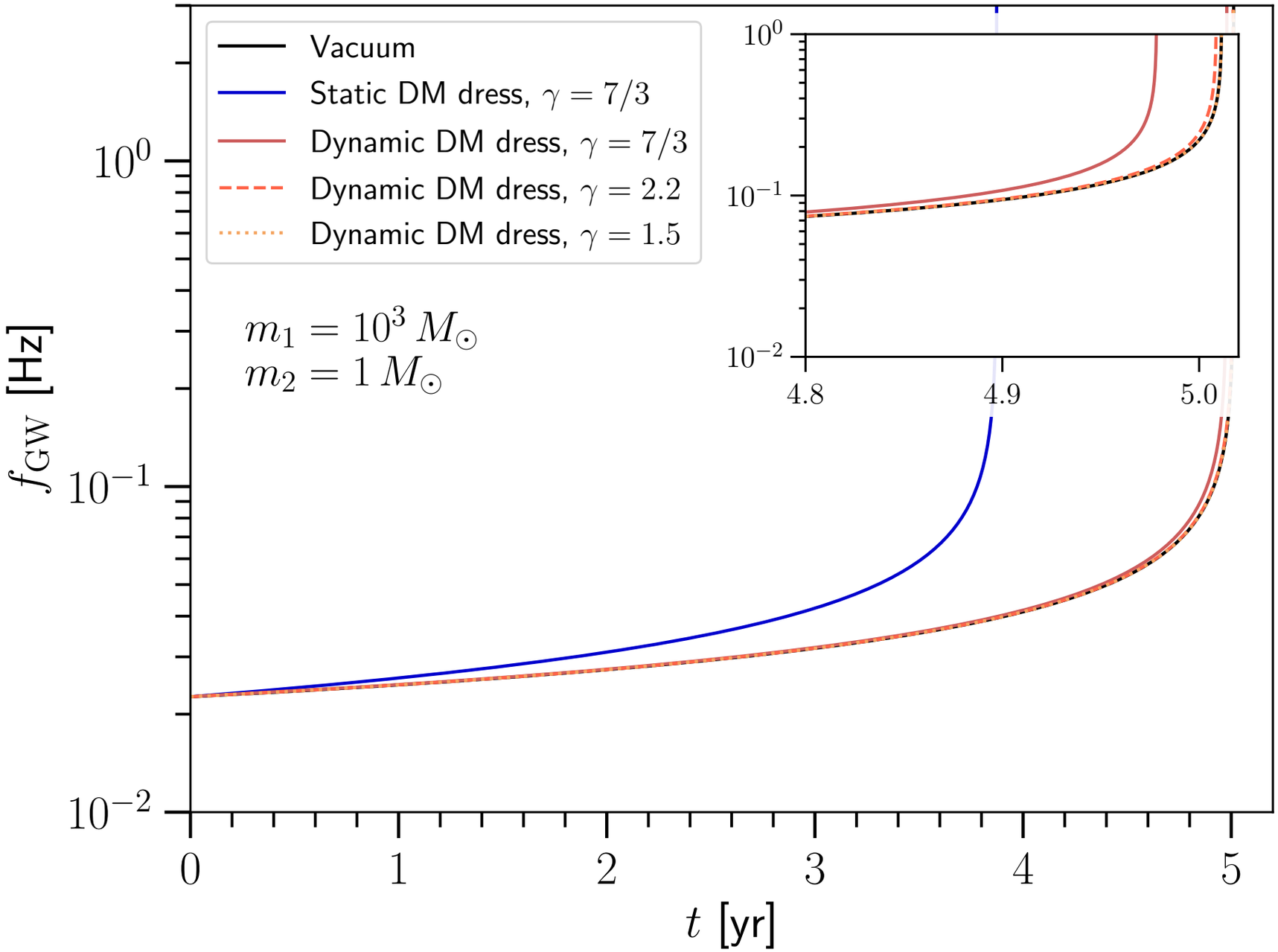
Thank you!

Backup Slides

Time to Merger

Change in time-frequency evolution of the GW inspiral:



‘Dressed’ system mergers ~days earlier than ‘vacuum’ system

Phase space distribution

Follow semi-analytically the phase space distribution of DM:

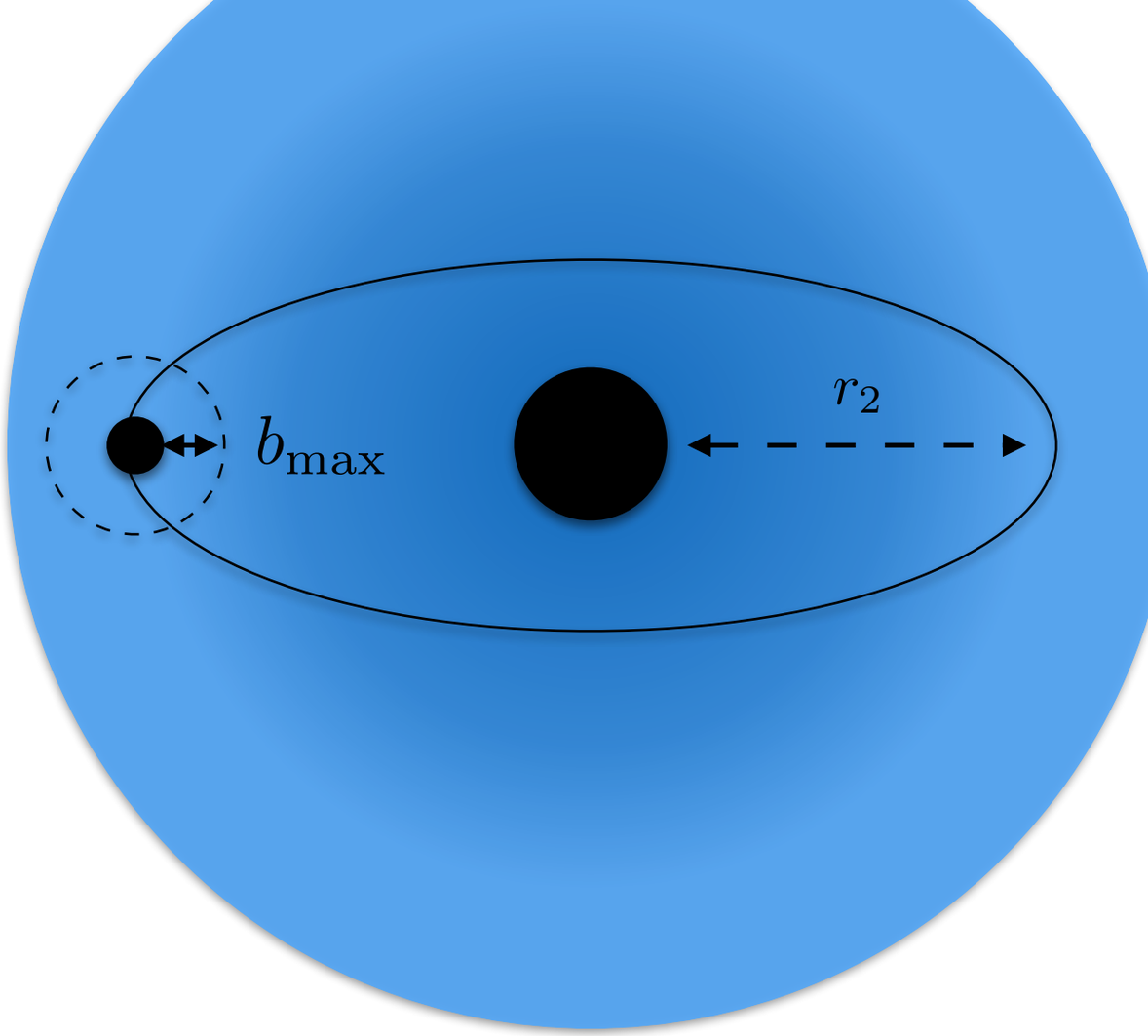
$$f = \frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{r}\,\mathrm{d}^3\mathbf{v}} \equiv f(\mathcal{E})$$

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

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]

Self-consistent evolution

Assuming everything evolves slowly compared to the orbital period:

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

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

$p_{\mathcal{E}} = \int P_{\mathcal{E}}(\Delta\mathcal{E})\,{\rm d}\Delta\mathcal{E}$ - total probability for a particle with energy $\mathcal{E}$ to scatter

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

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

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

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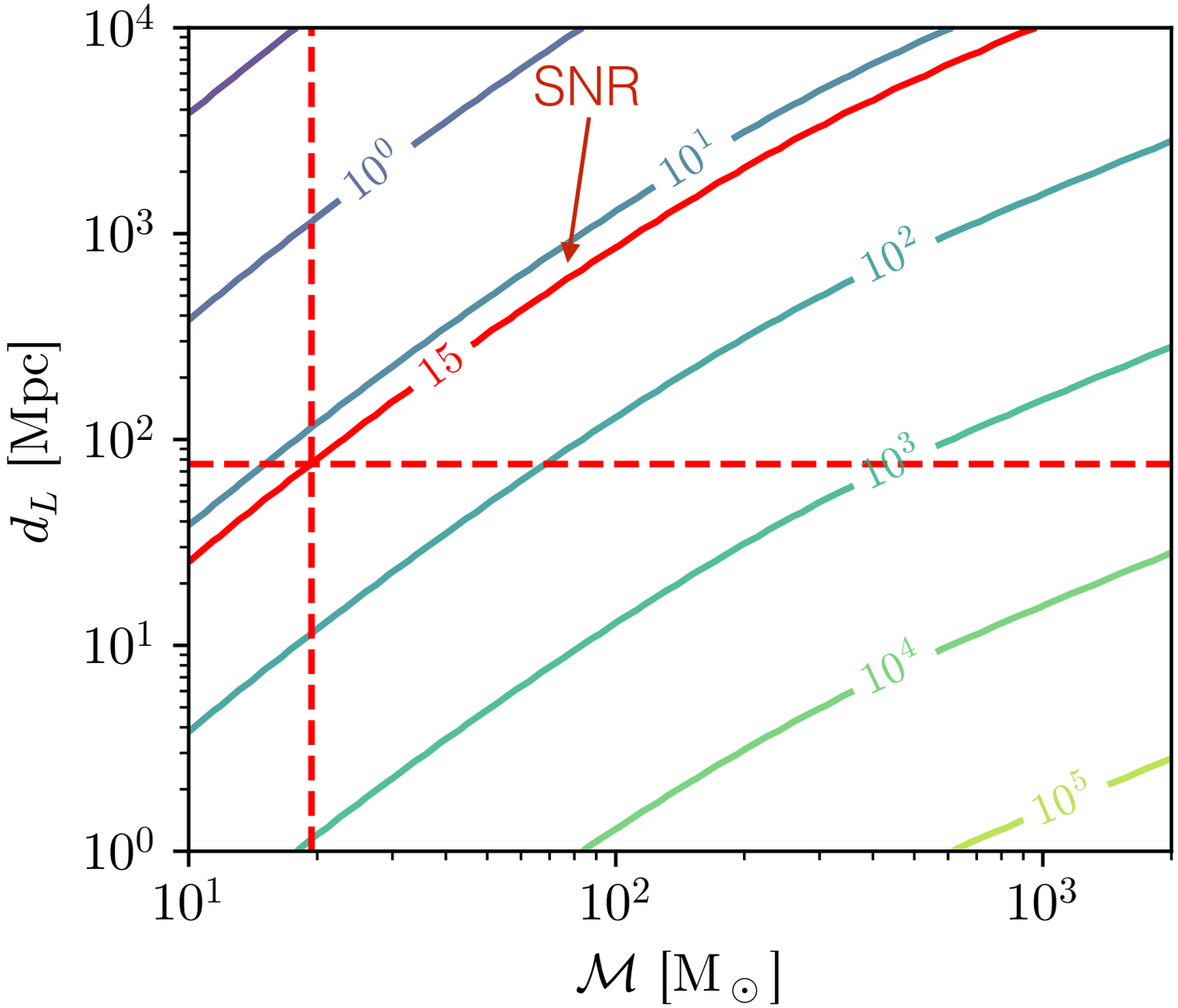
Detectability

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



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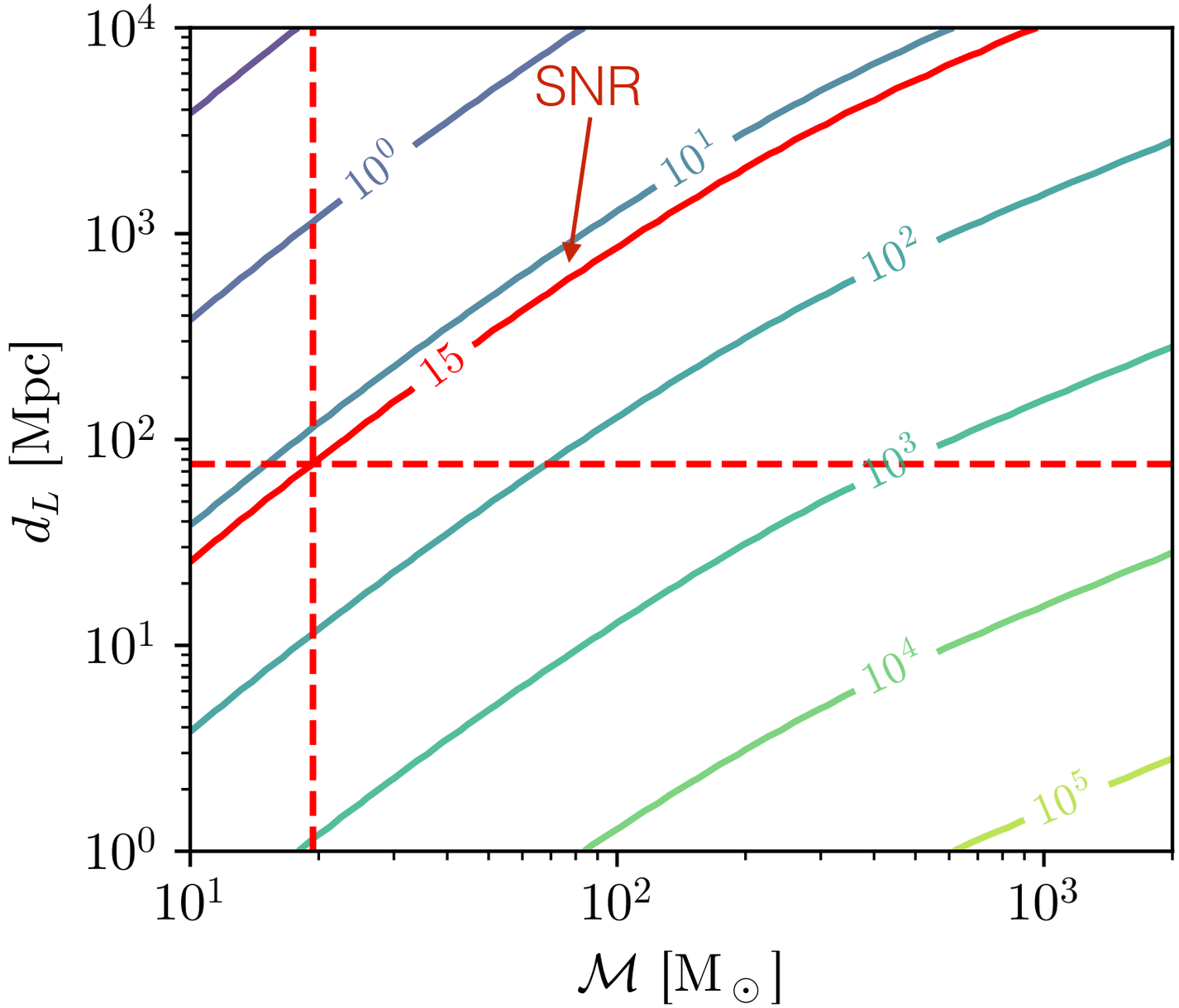
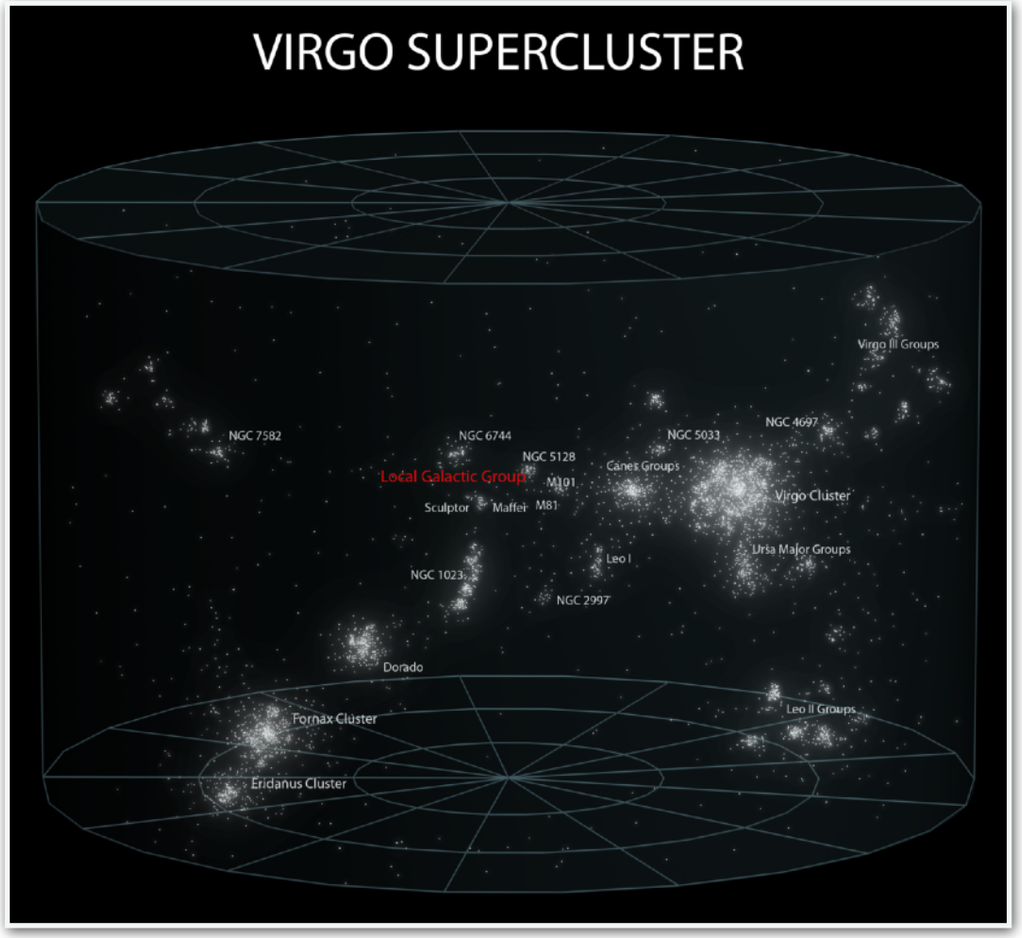
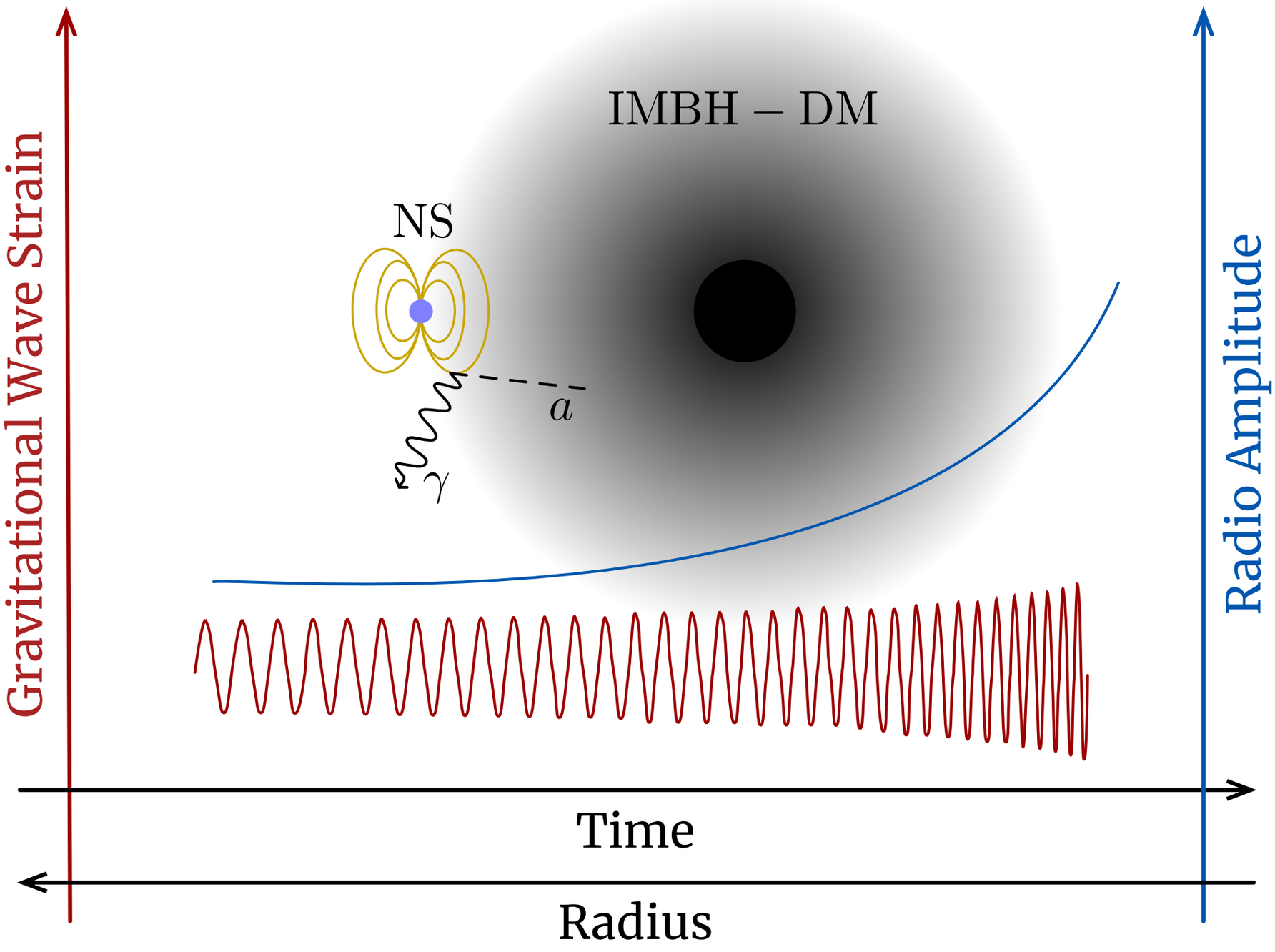




Multimessenger QCD Axions



[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]