Gravitational Wave Signatures of Dark Matter around Black Holes

kavanagh@ifca.unican.es

@BradleyKavanagh

Bradley J Kavanagh
Instituto de Física de Cantabria
(CSIC-Universidad de Cantabria)

5th July 2023 - GRAPPA@10

Instituto de Física de Cantabria

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CSIC Consejo Superior de Investigaciones Científicas

GRAPPA Introduction

Postdoc at GRAPPA:
September 2017 - February 2020

GRAPPA Introduction Document

The idea of this document is to gather all the useful information for when a new member of GRAPPA joins the group. Hopefully it will help with a smooth transition to working at a new institution, possibly in a new country too. Lots of useful information can also be found on the University A-Z - https://medewerker.uva.nl/en/science/az/a-z.html.

First Days

One of the first things to do is to get yourself on the GRAPPA mailing list (GRAPPA-

Coffee

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- Free coffee/hot chocolate/etc. is available from the big black coffee machines in the kitchen areas scattered around the building. Just scan your staff card on the contactless reader.
- Free coffee capsules are also available from the IoP secretaries' office. These can be used in the silver coffee machines in the theory lounge (C4.278) and the coffee lounge (at the opposite end of the building from GRAPPA).
- Note that there are also nice tea bags and occasionally sweet treats in the IoP secretaries' office so visit often.
- Lovely take-away coffee can be bought downstairs at the coffee bar in the main hall.
- Hipster coffee is available from Coffee Virus, in the start-up village a few minutes walk from Science Park 904. Since February 2019 CoffeeVirus runs two restaurants in Science Park, the other being in building Science Park 408/410, just behind Universum. They also sell take-away sandwiches and salads.

In collaboration with
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16-18 October • Amsterdam Science Park

GRAPPA 5

Celebrating 5 years of the GRAPPA Centre of Excellence in Astroparticle Physics

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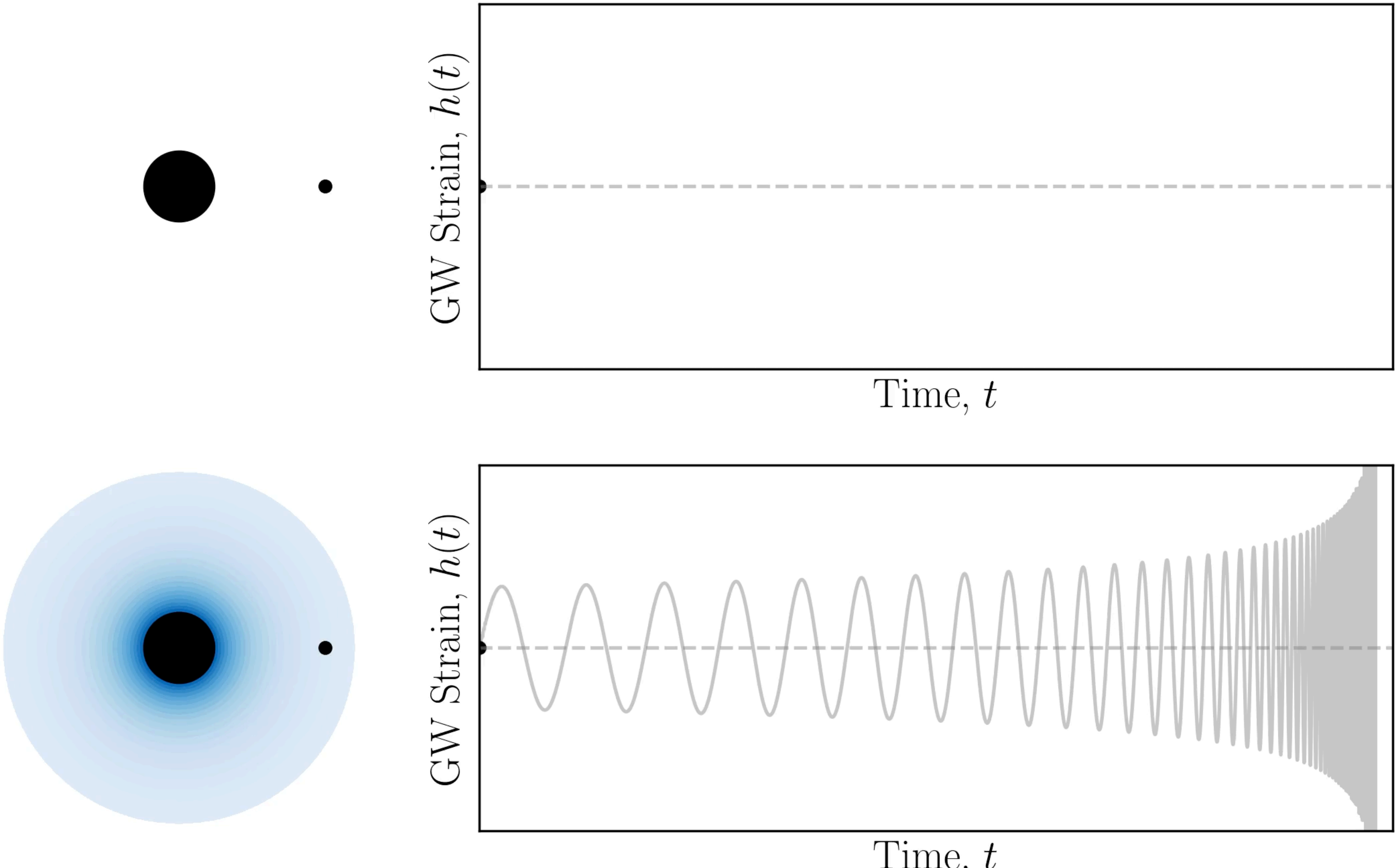
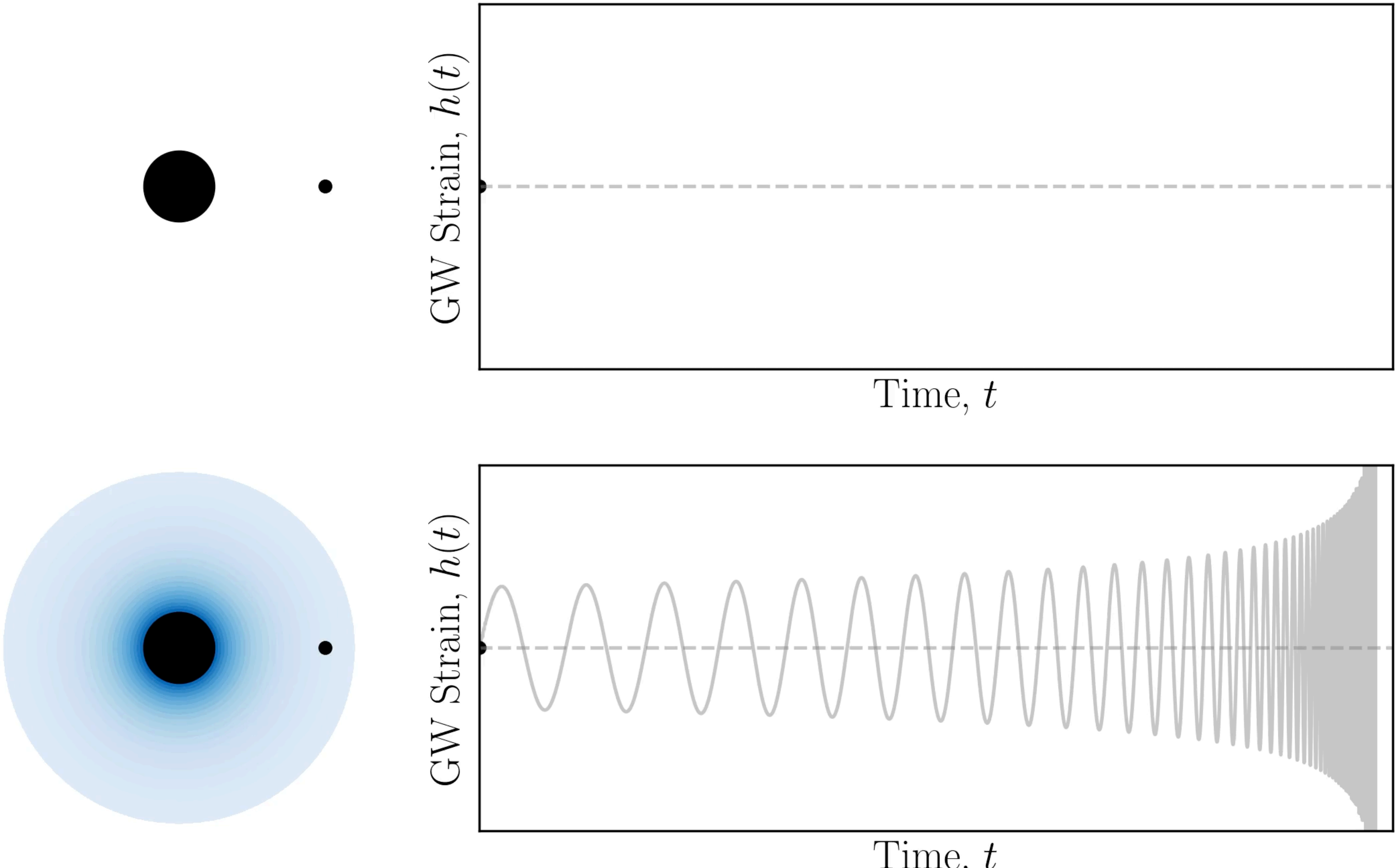
National Science Foundation
LIGO-VIRGO COLLABORATION
UPDATE ON THE SEARCH FOR GRAVITATIONAL WAVES
LIGO
LSC
Physics with Industry
PHYSICS
@VELDHOVEN


GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0 5 10 15 20 25 30 35 40 45 50 55
time observable (seconds)
LIGO/University of Oregon/Ben Farr

"De-phasing" of GWs



"De-phasing" of GWs



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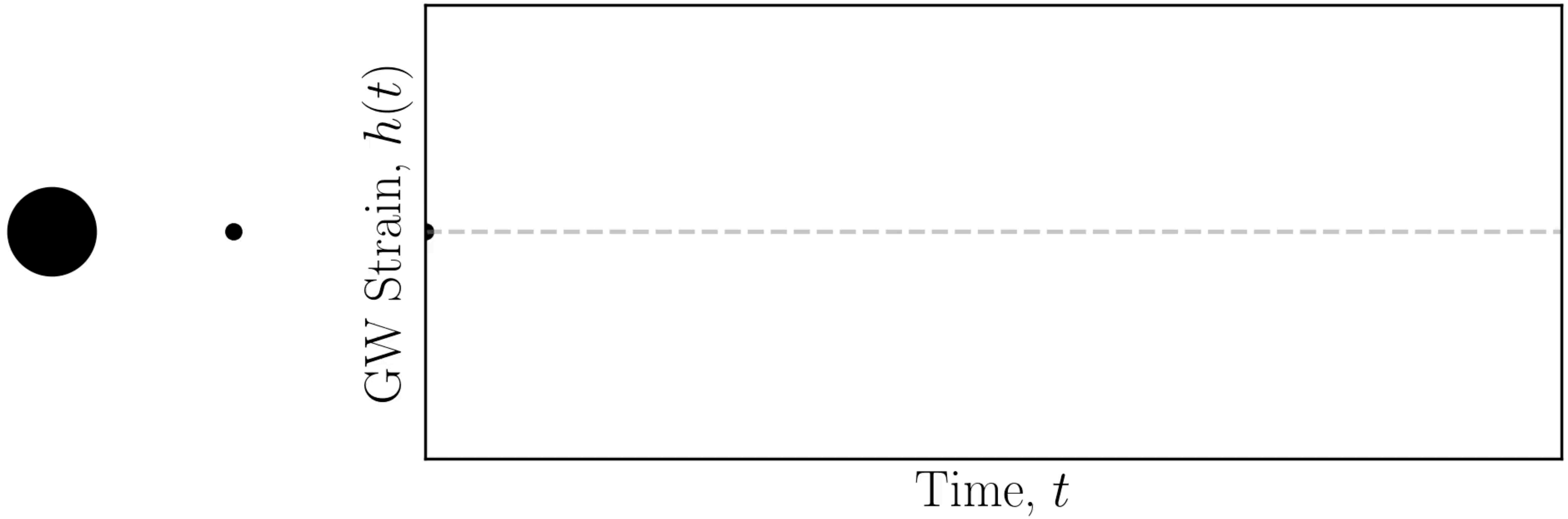
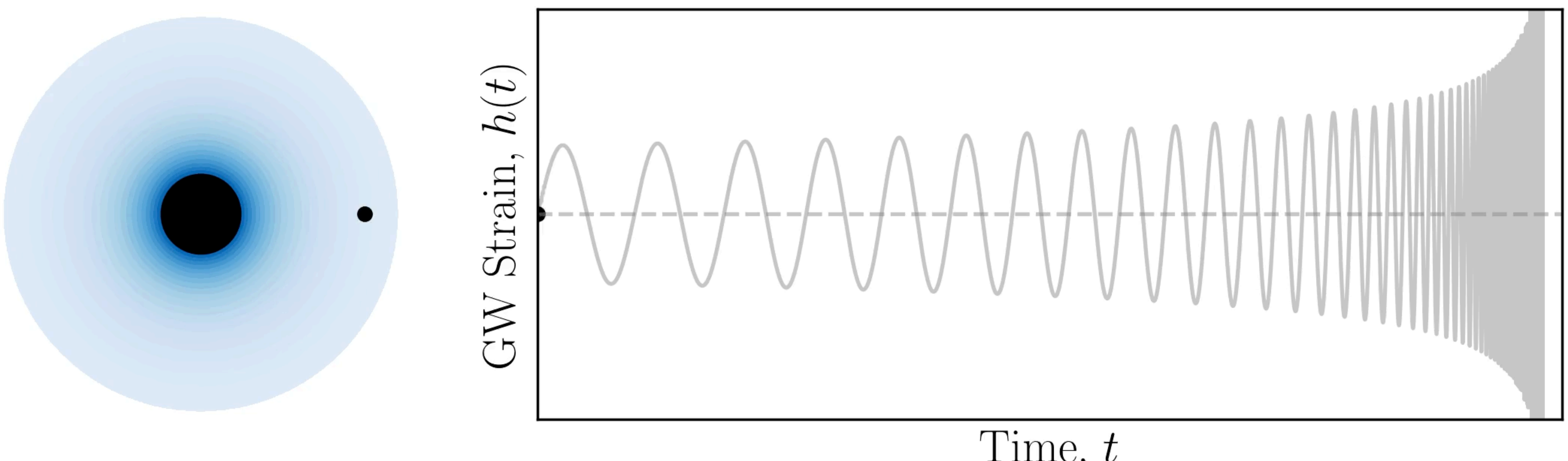
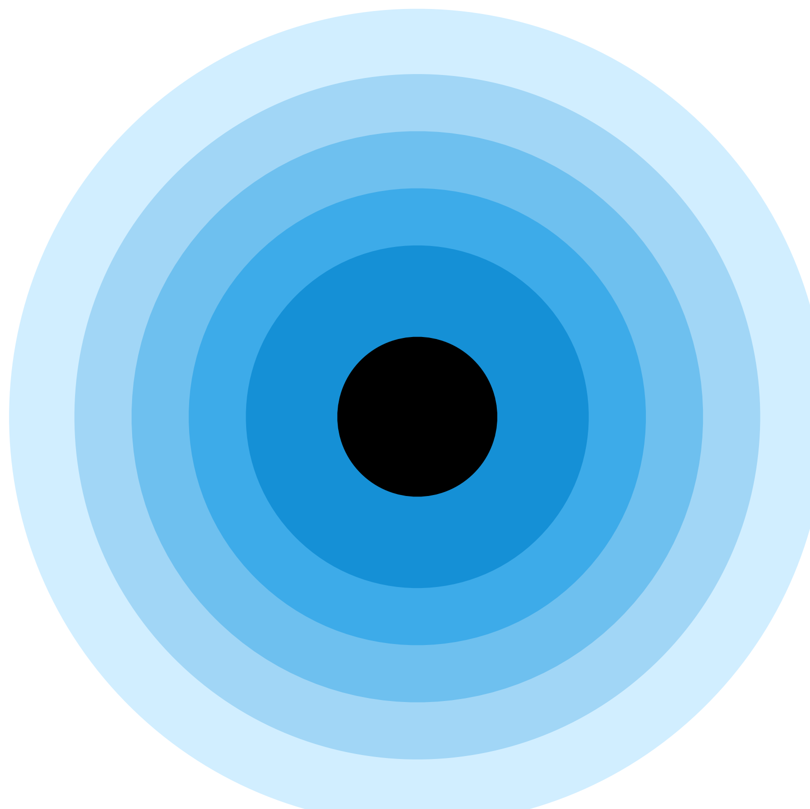
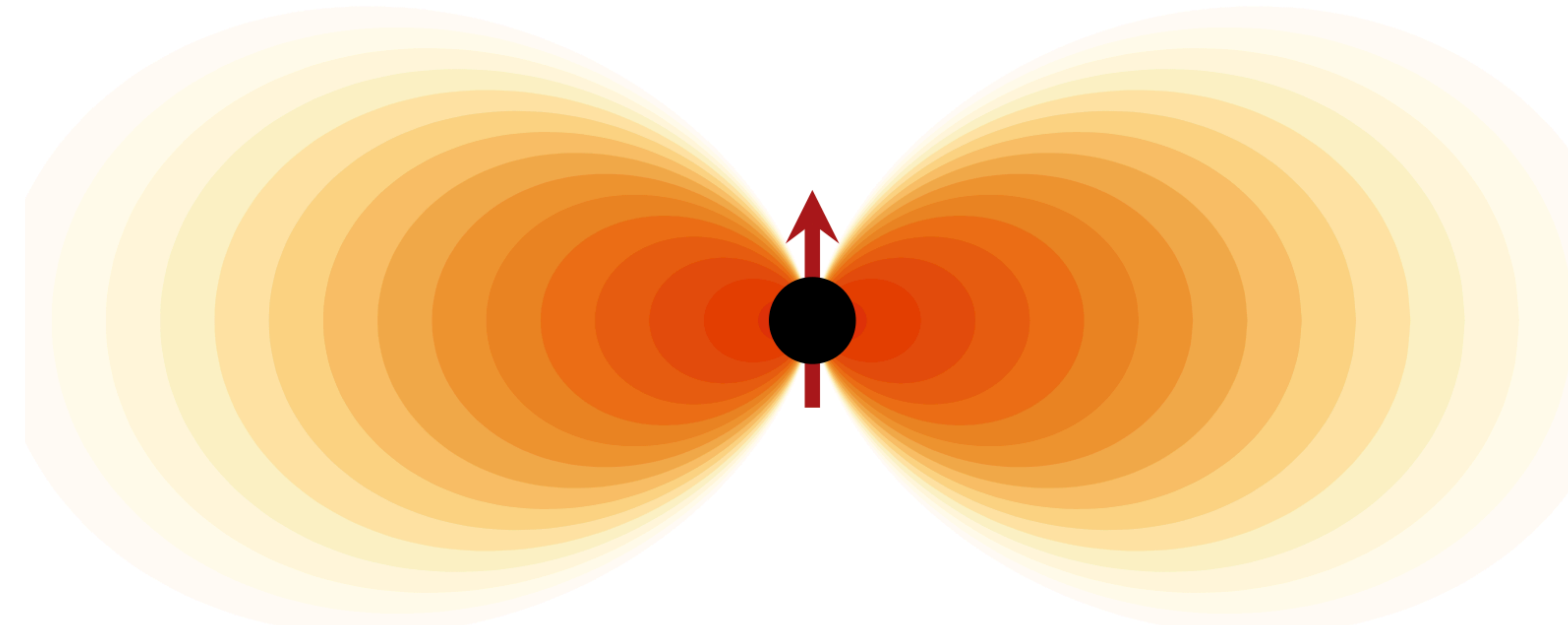




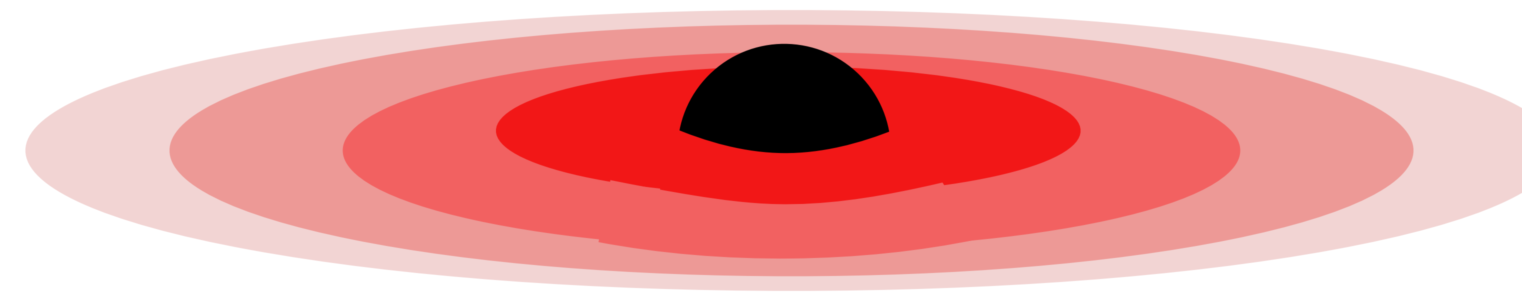
Black Hole Environments



Particle Dark Matter
'**Spikes**' or '**Dresses**'



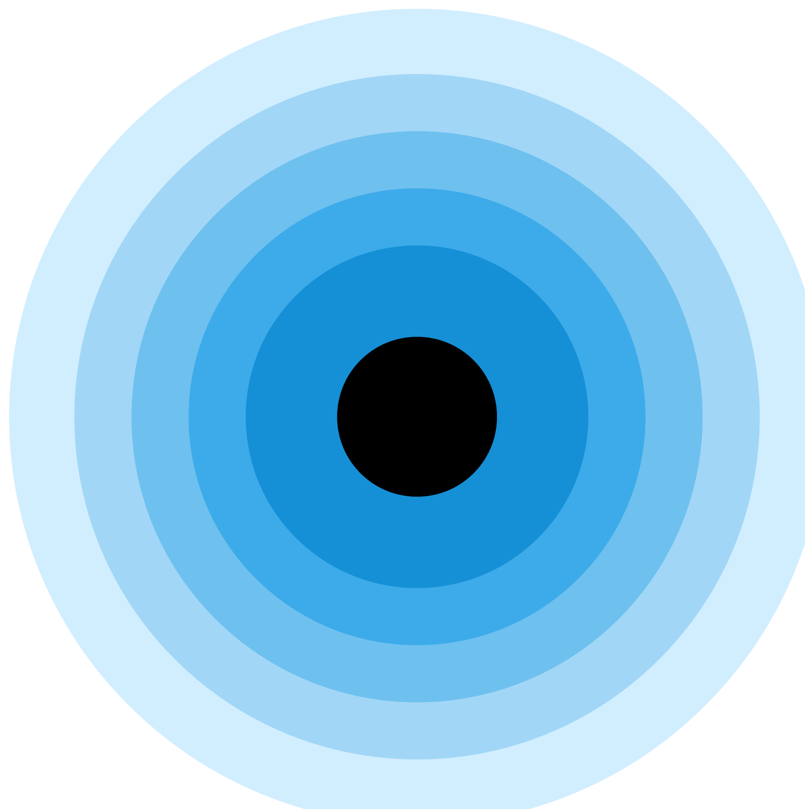
'**Gravitational Atoms**' of
Ultralight Bosons



Baryonic
Accretion Disks

Black Holes (BHs) are extreme environments allowing us to probe high densities, long timescales…

Black Hole Environments



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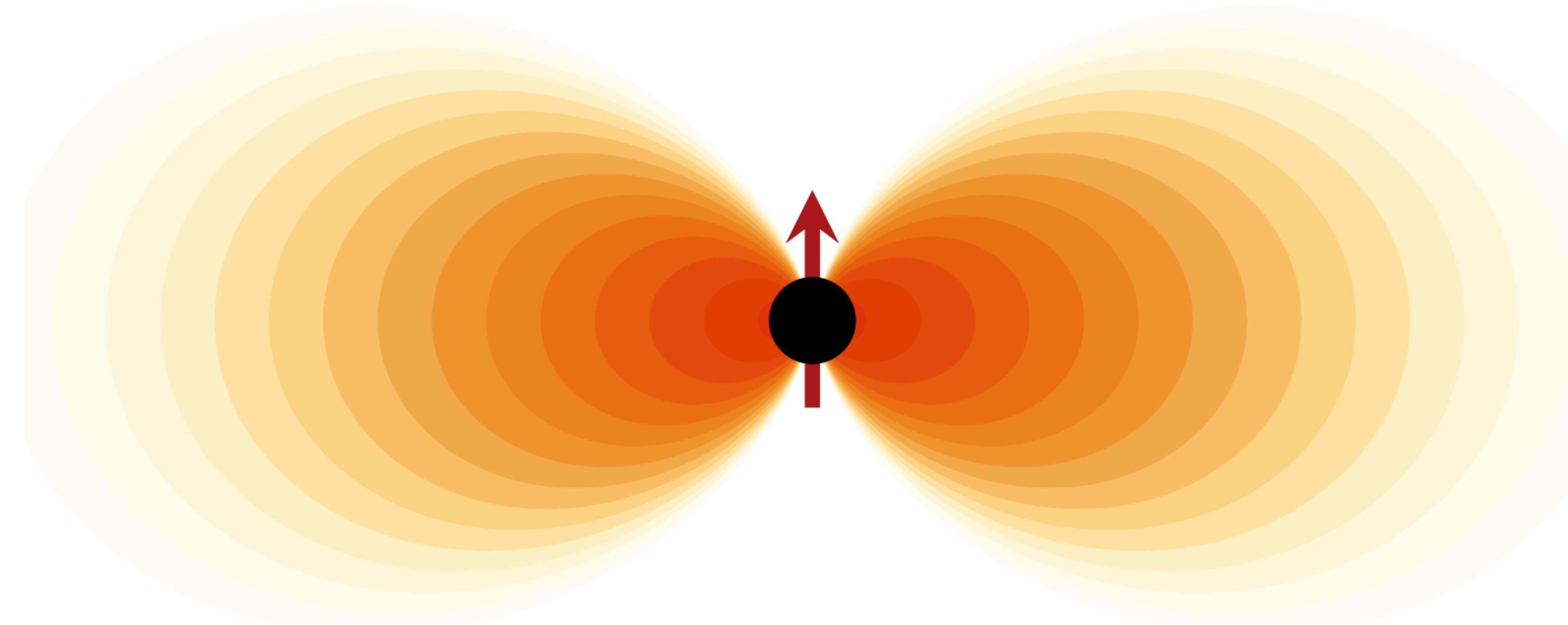

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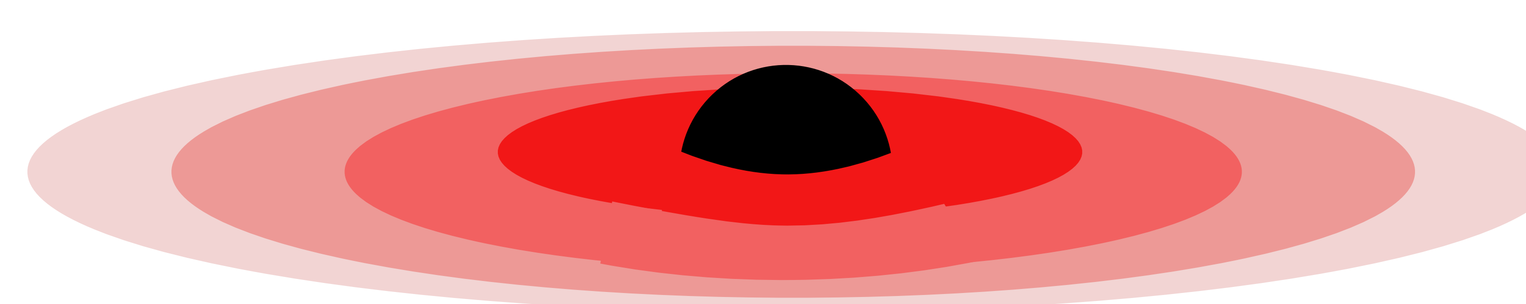

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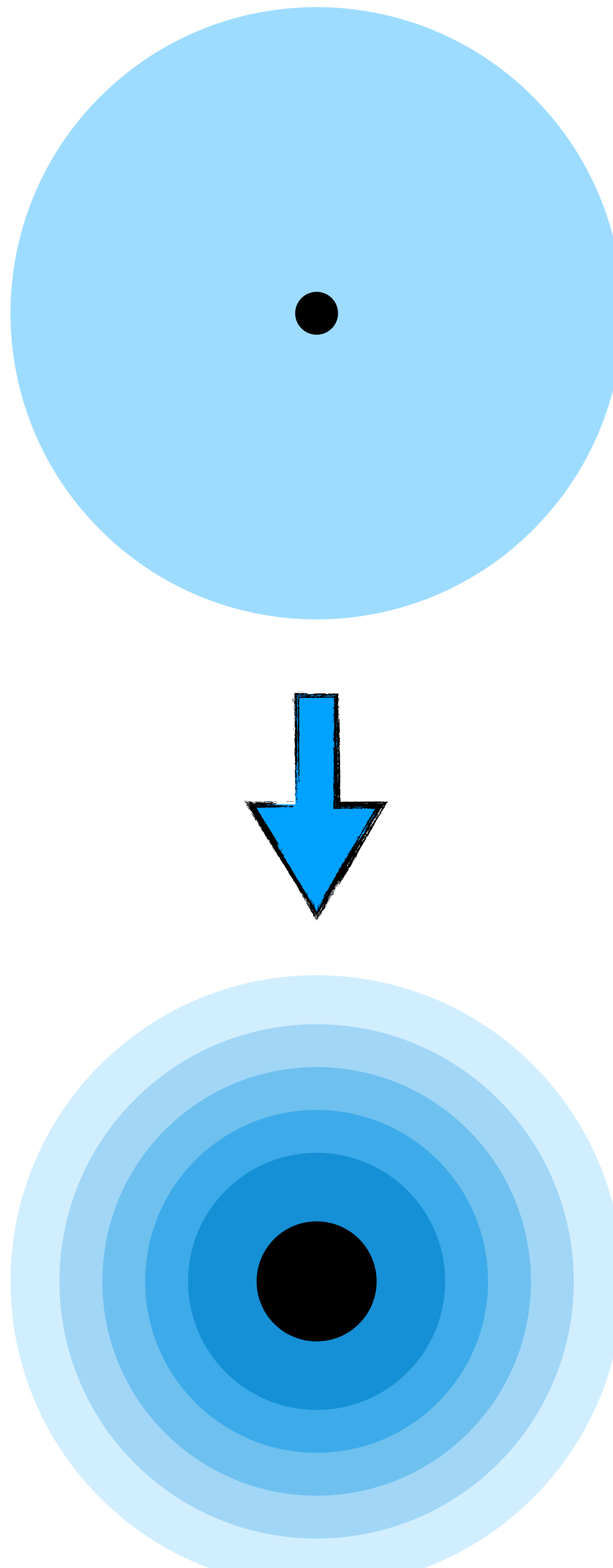
Dark Matter Spikes (1)



'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, …]

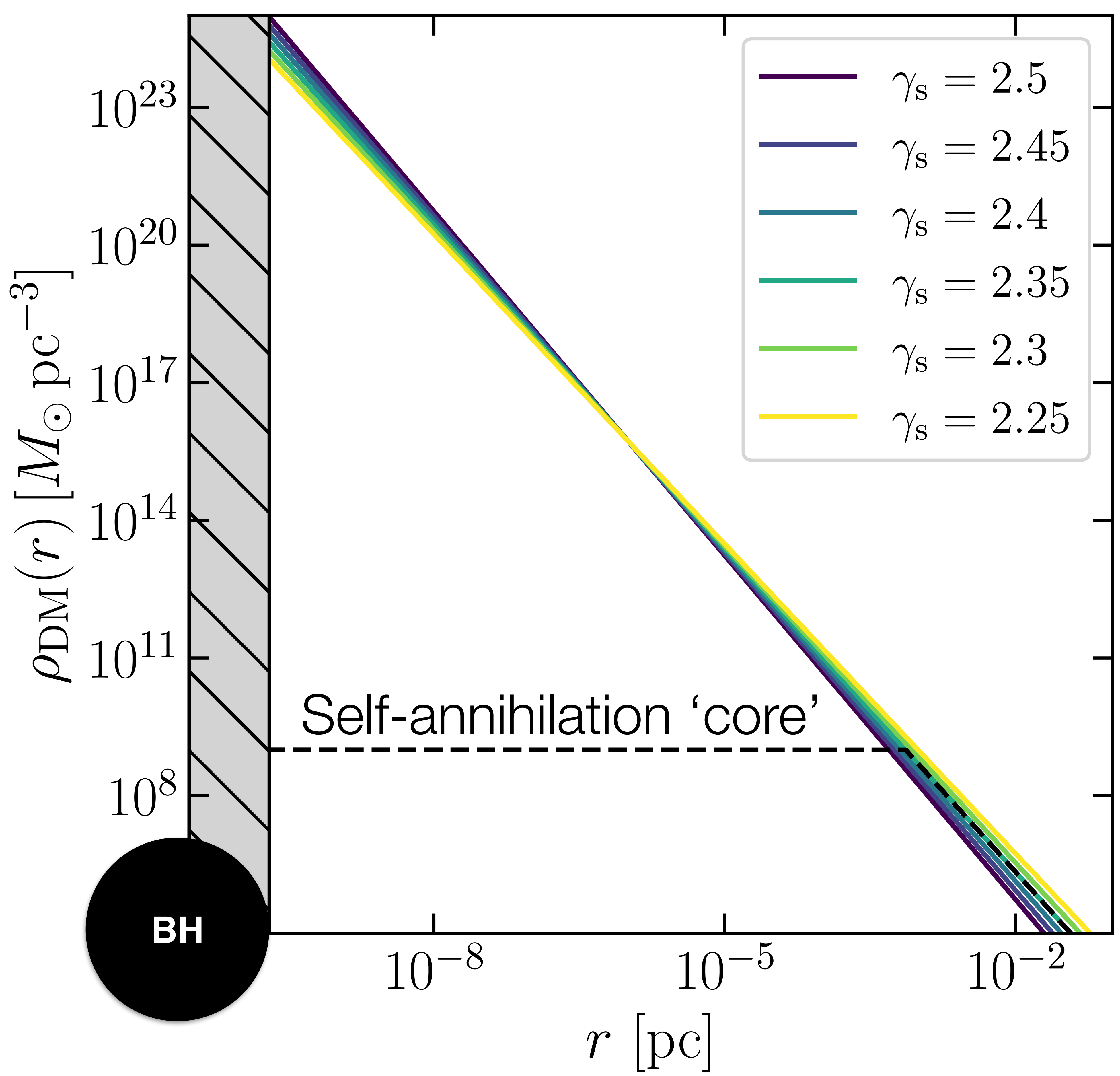
Around BHs which form from large density fluctuations in the early Universe (i.e. Primordial Black Holes)

"PBH scenario"

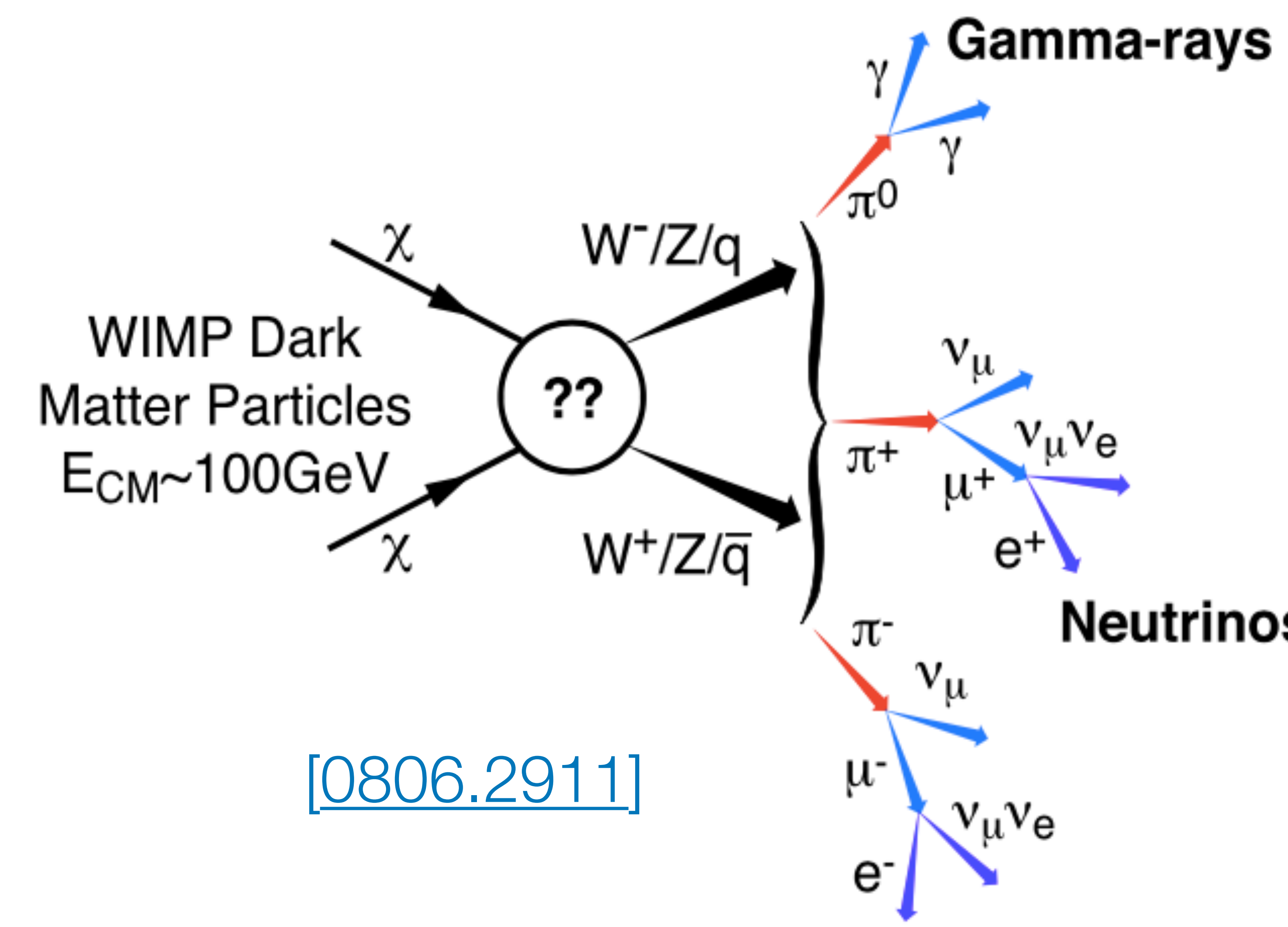
[Bertschinger (1985), astro-ph/0608642, 1901.08528, …]

Dark Matter Spikes (2)

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



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



[0806.2911]

DM self-annihilation can suppress the spike density, but can still lead to large (diffuse and point source) fluxes of gamma-rays and neutrinos

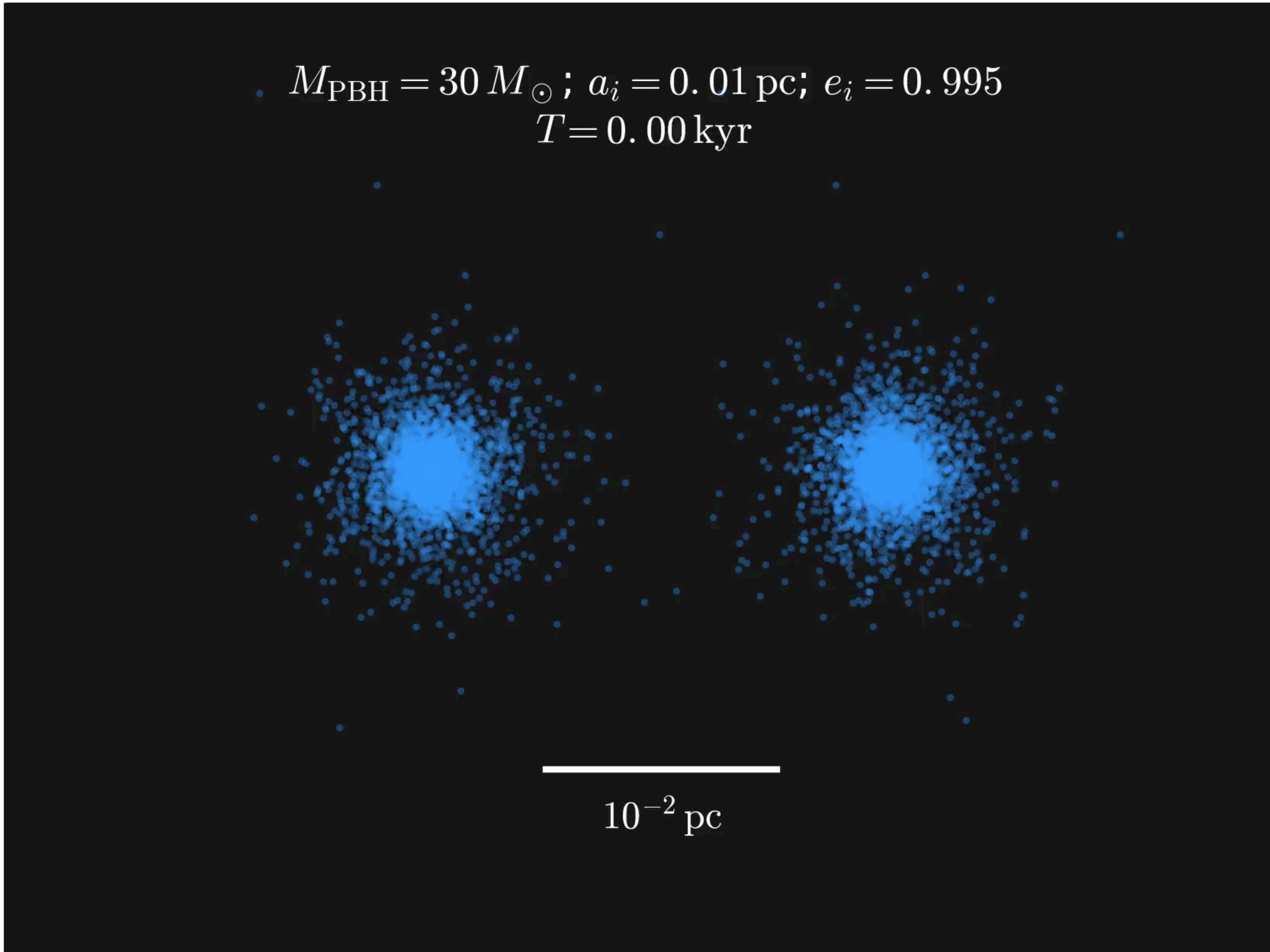
[E.g. Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

*Think instead about **non-annihilating DM***

Equal-mass binaries

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

[Movies here]



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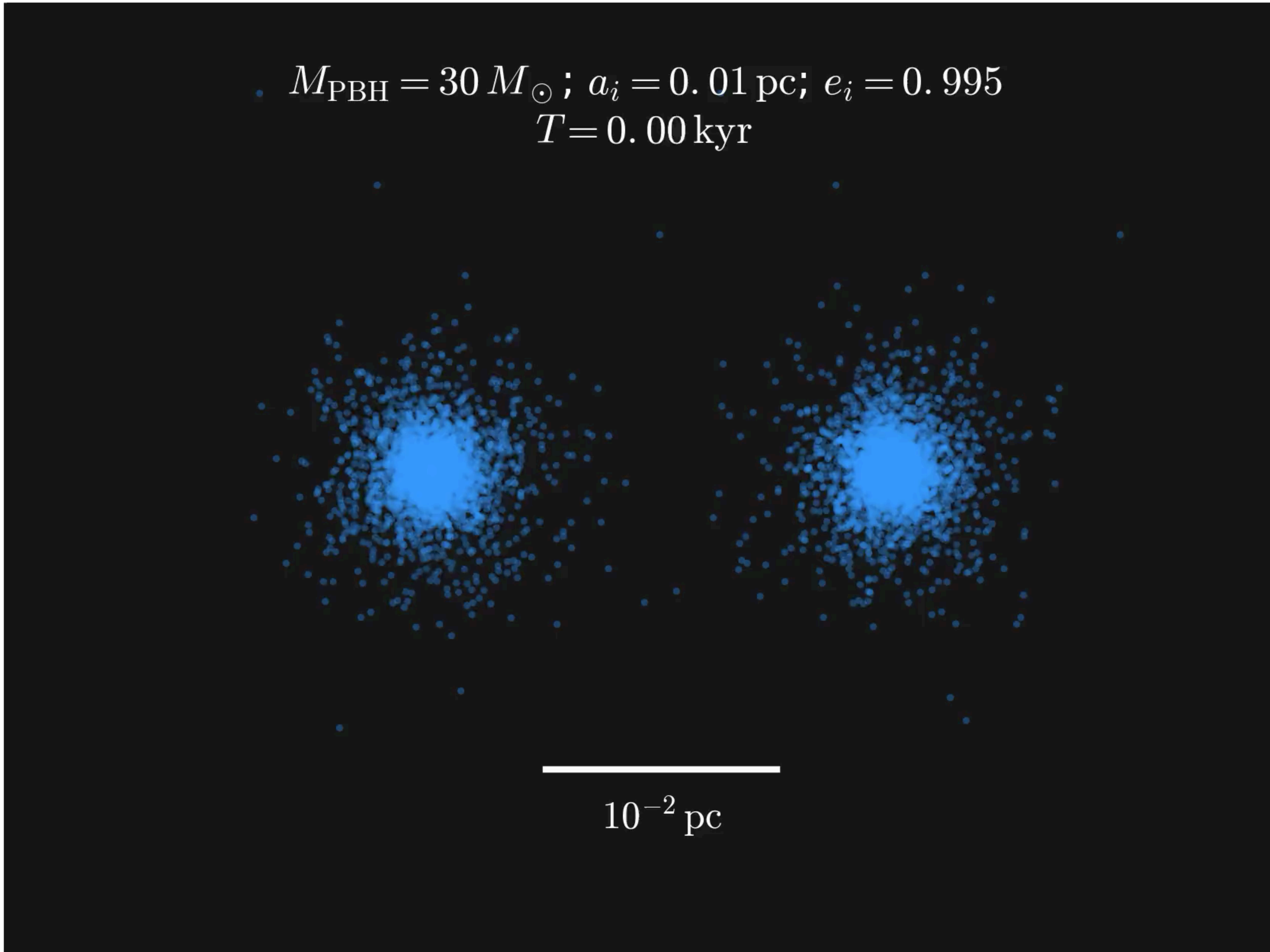
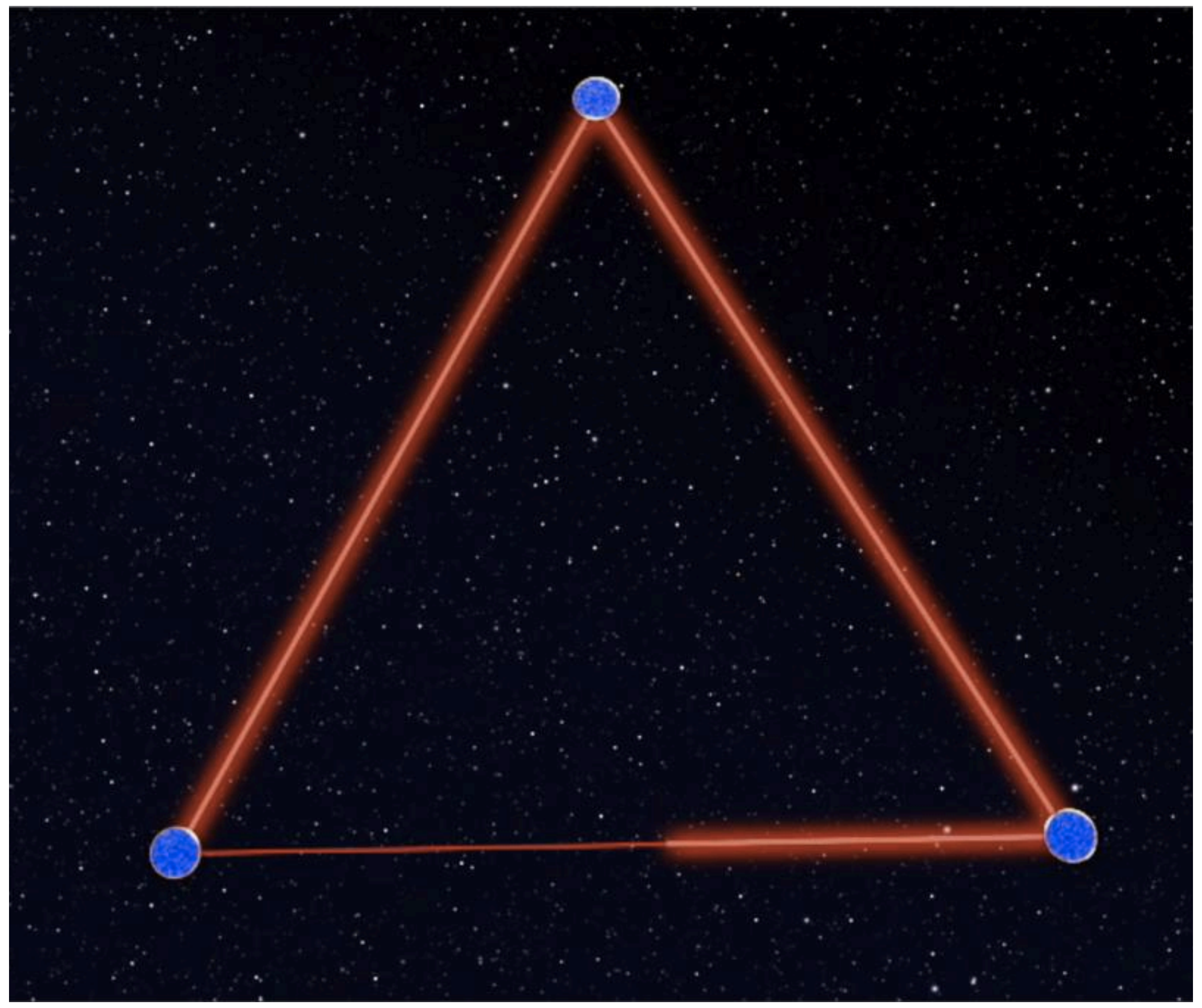


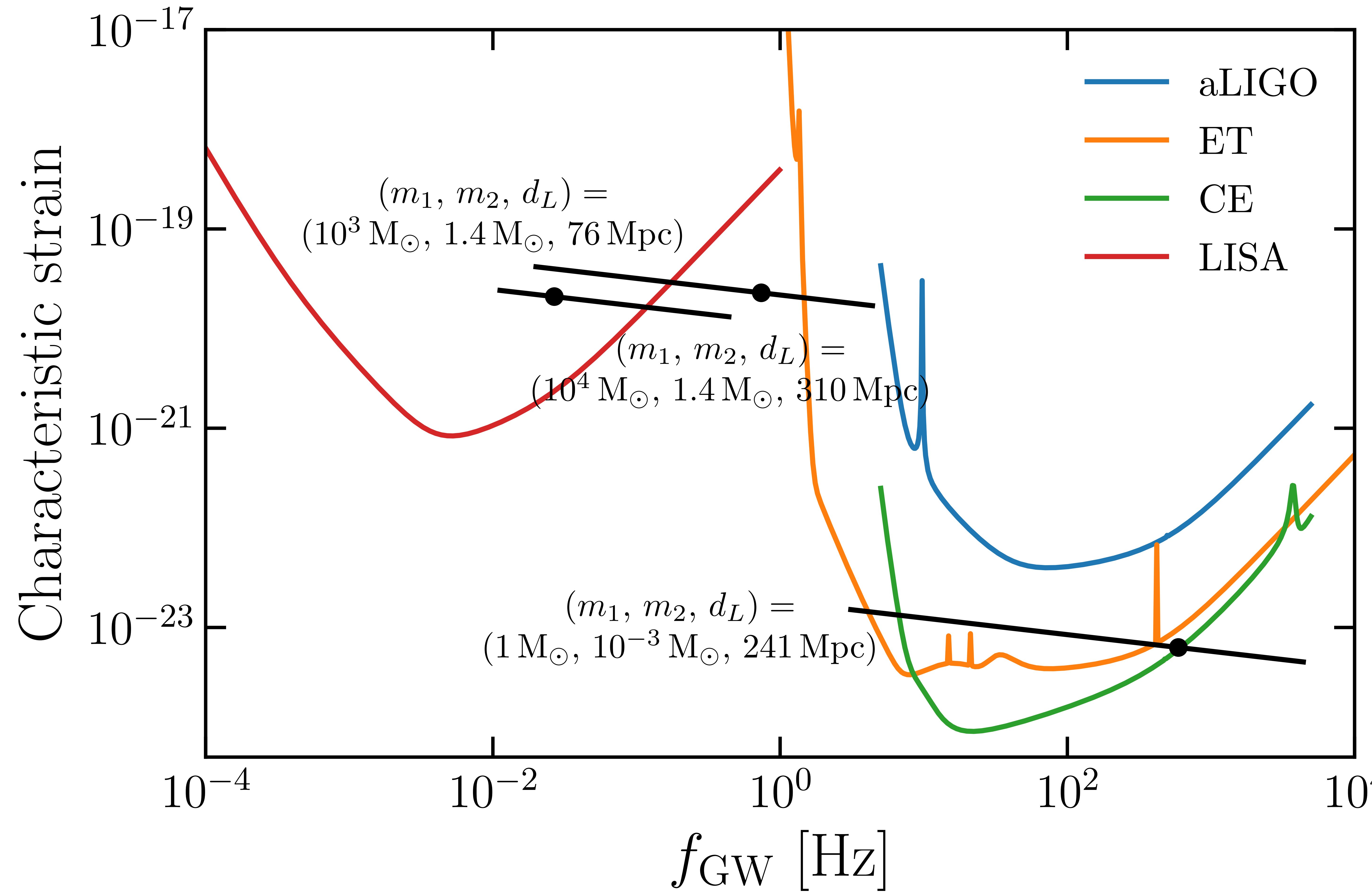
GW Sensitivity

© AEI / MM / exozet



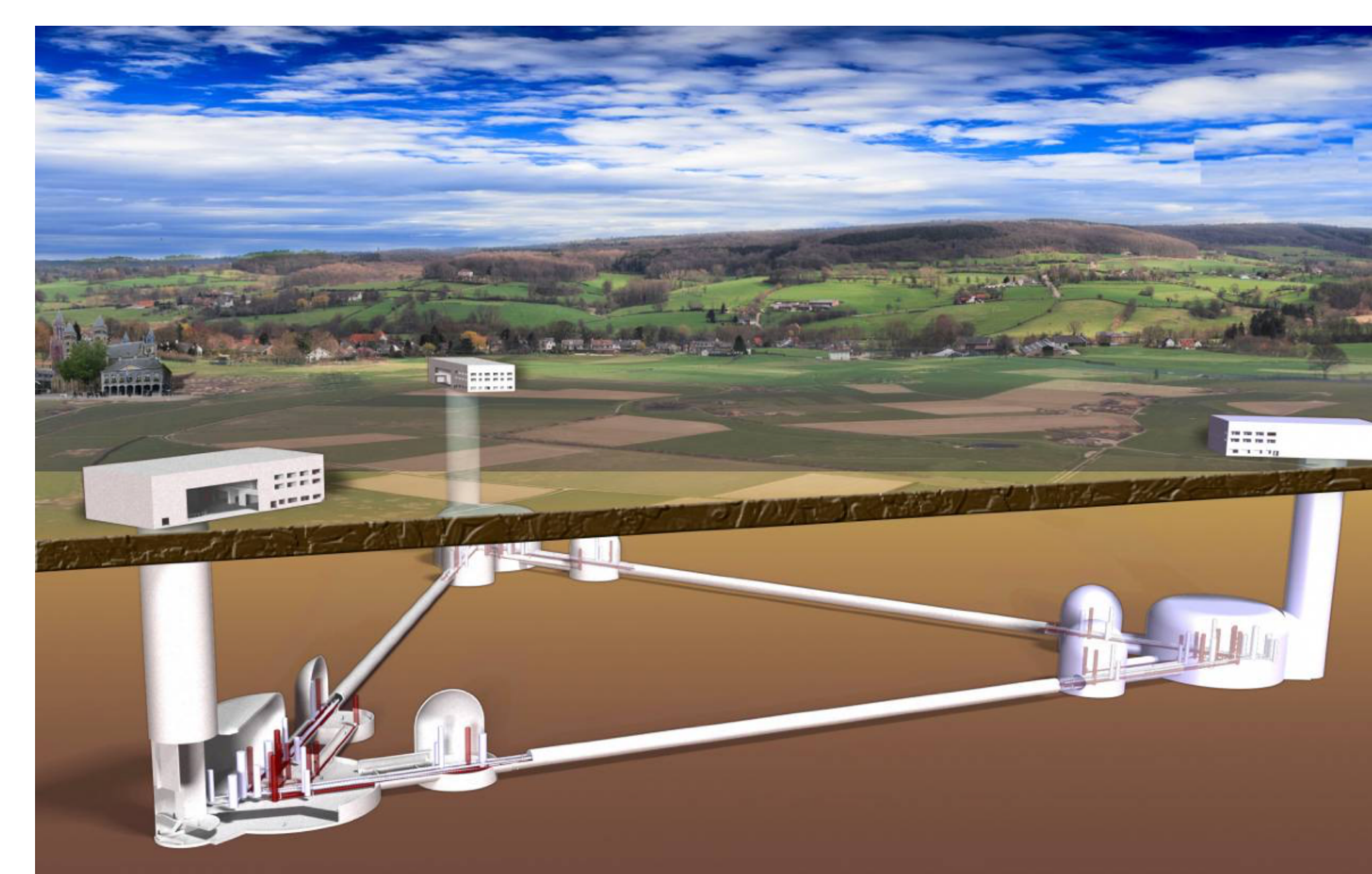
Laser **I**nterferometer **S**pace **A**ntenna
(planned for the 2030s)

[1907.06482]

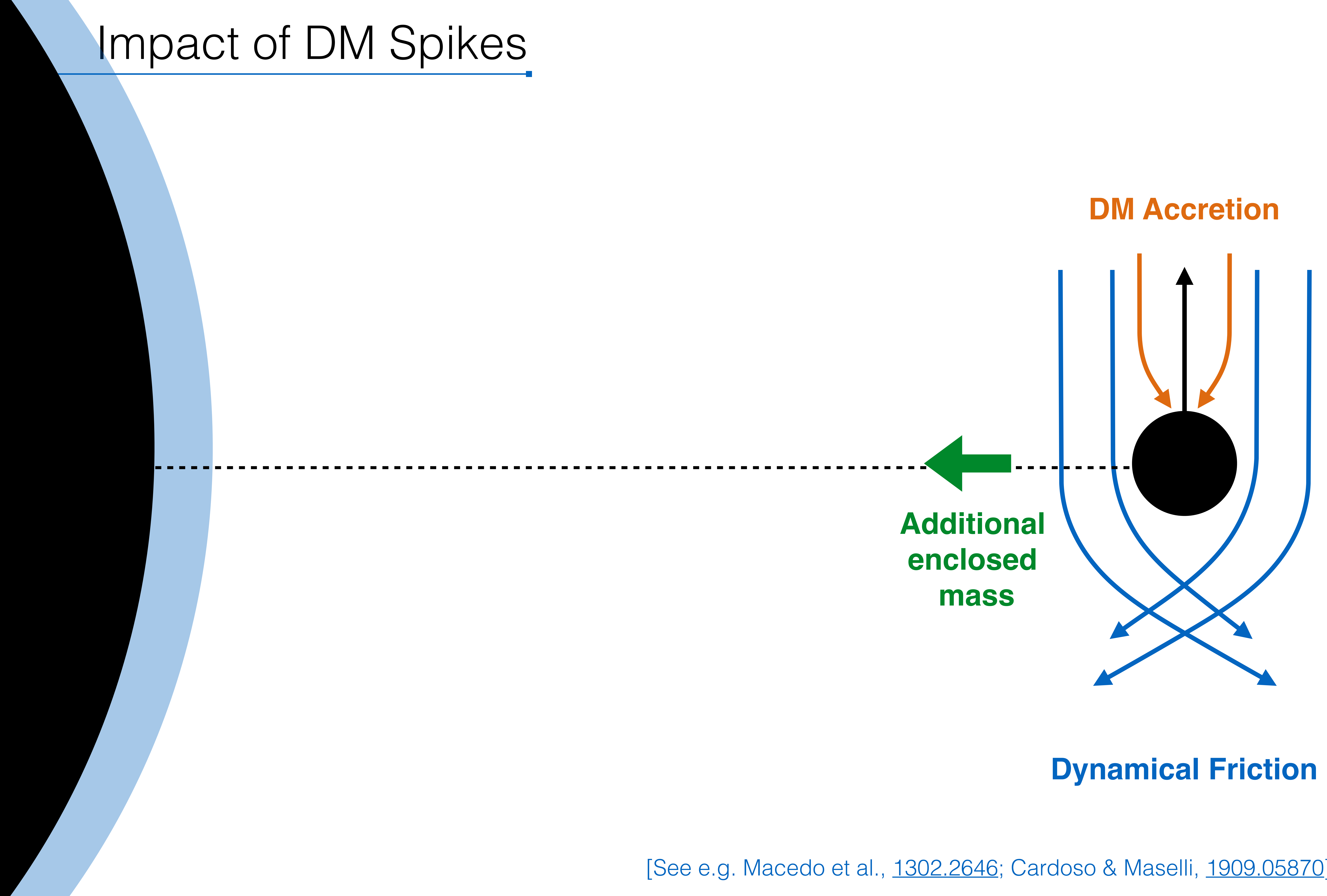


Einstein **T**elescope

[1912.02622]



Impact of DM Spikes



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

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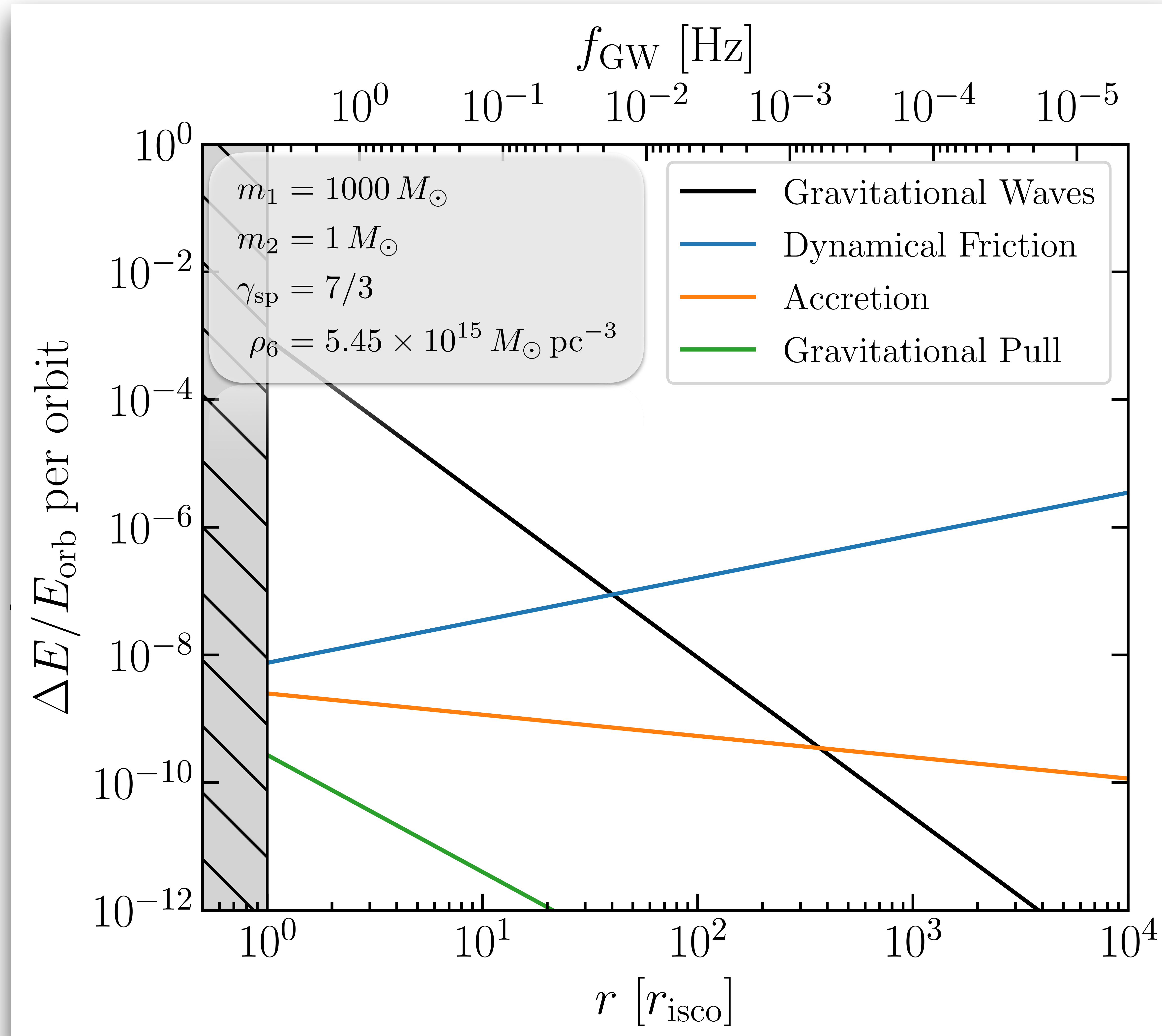

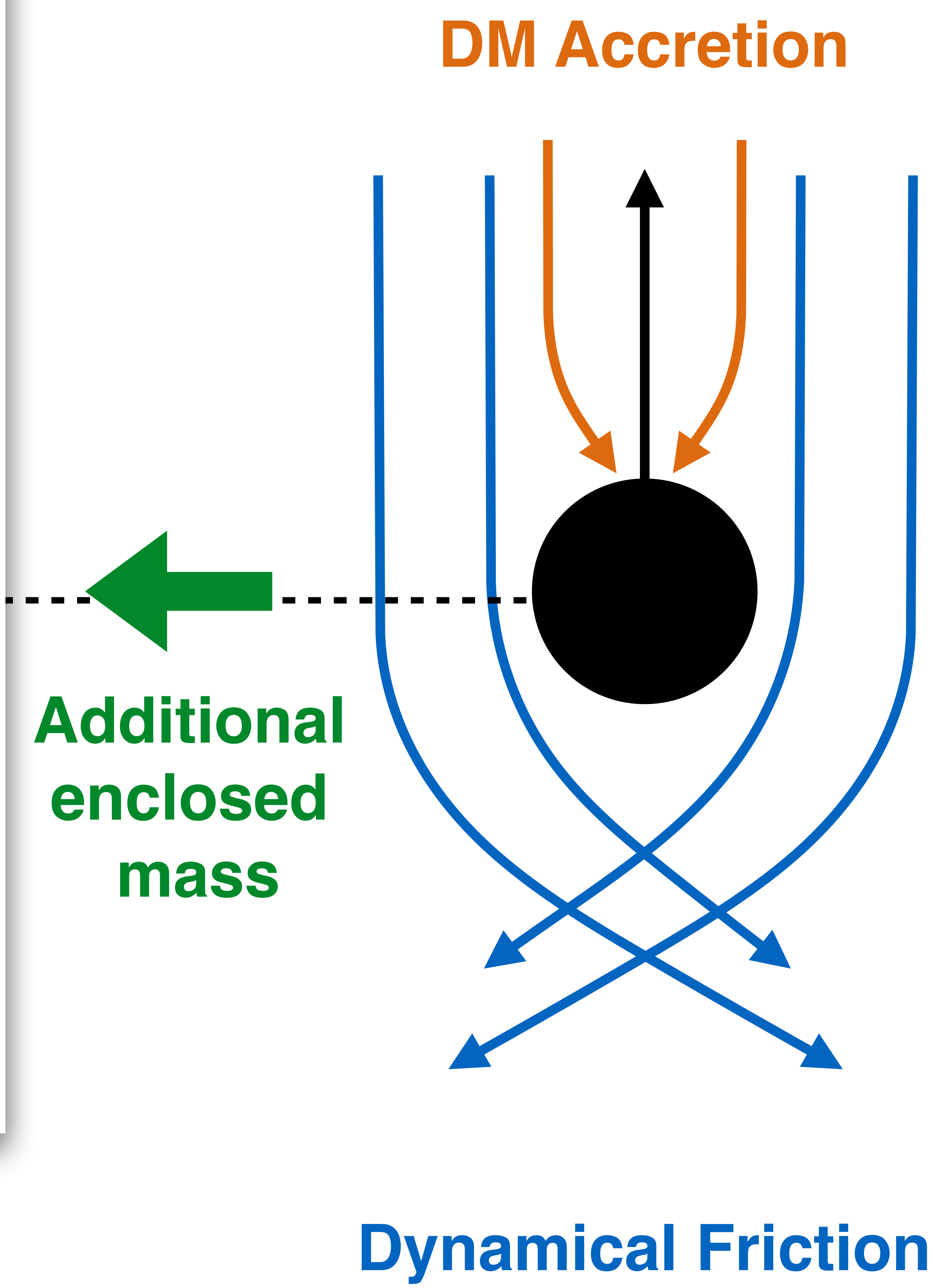

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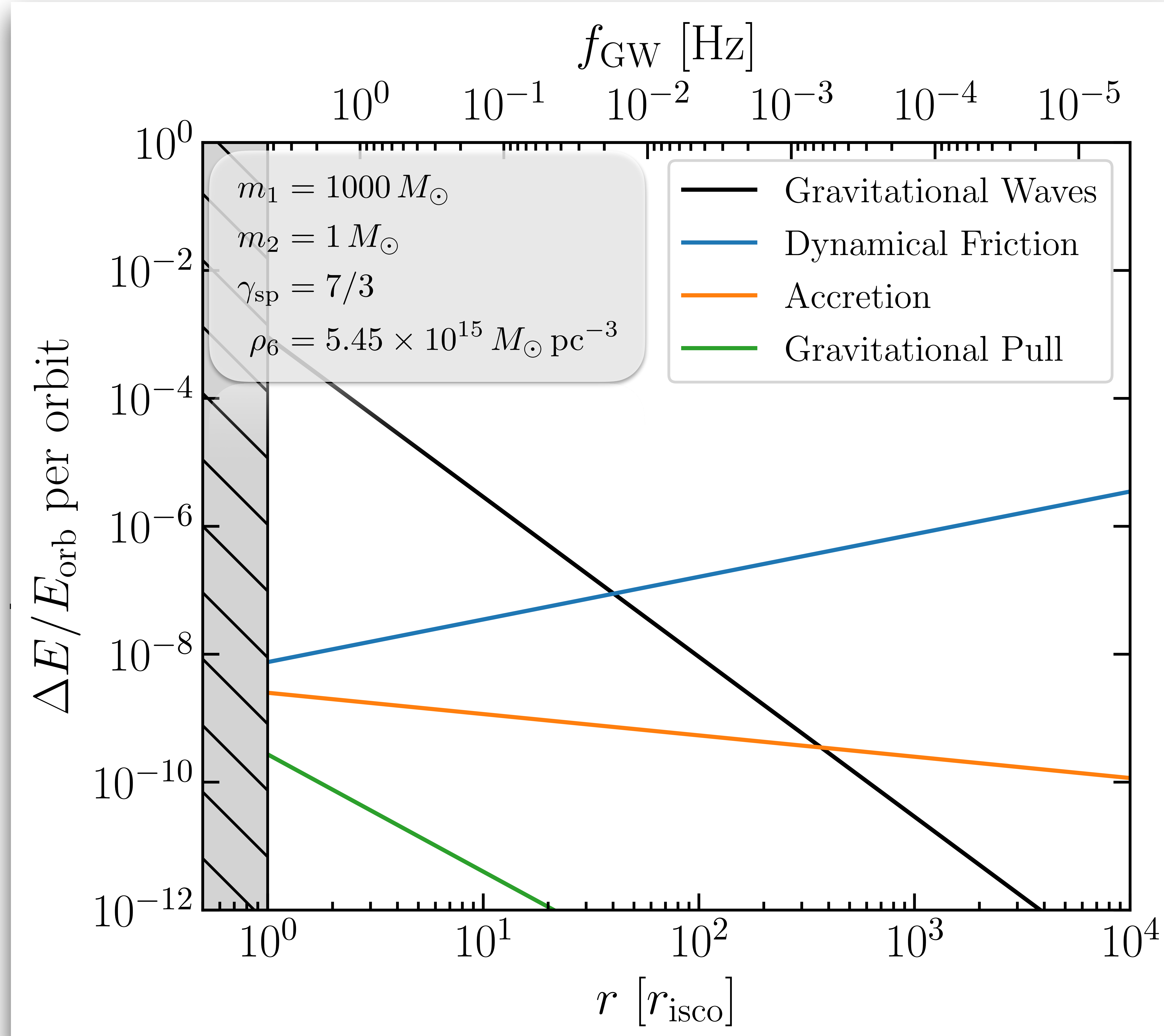
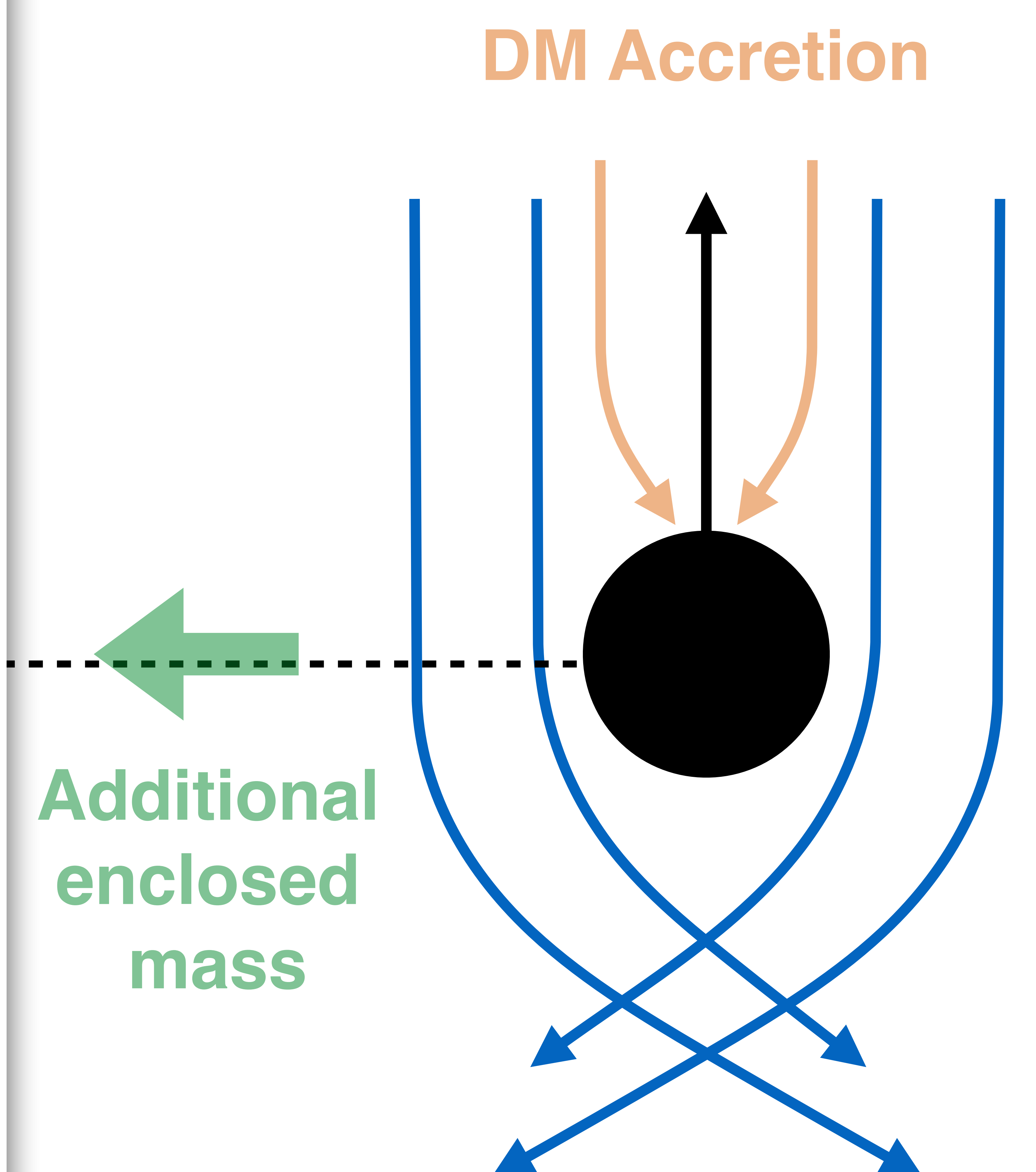


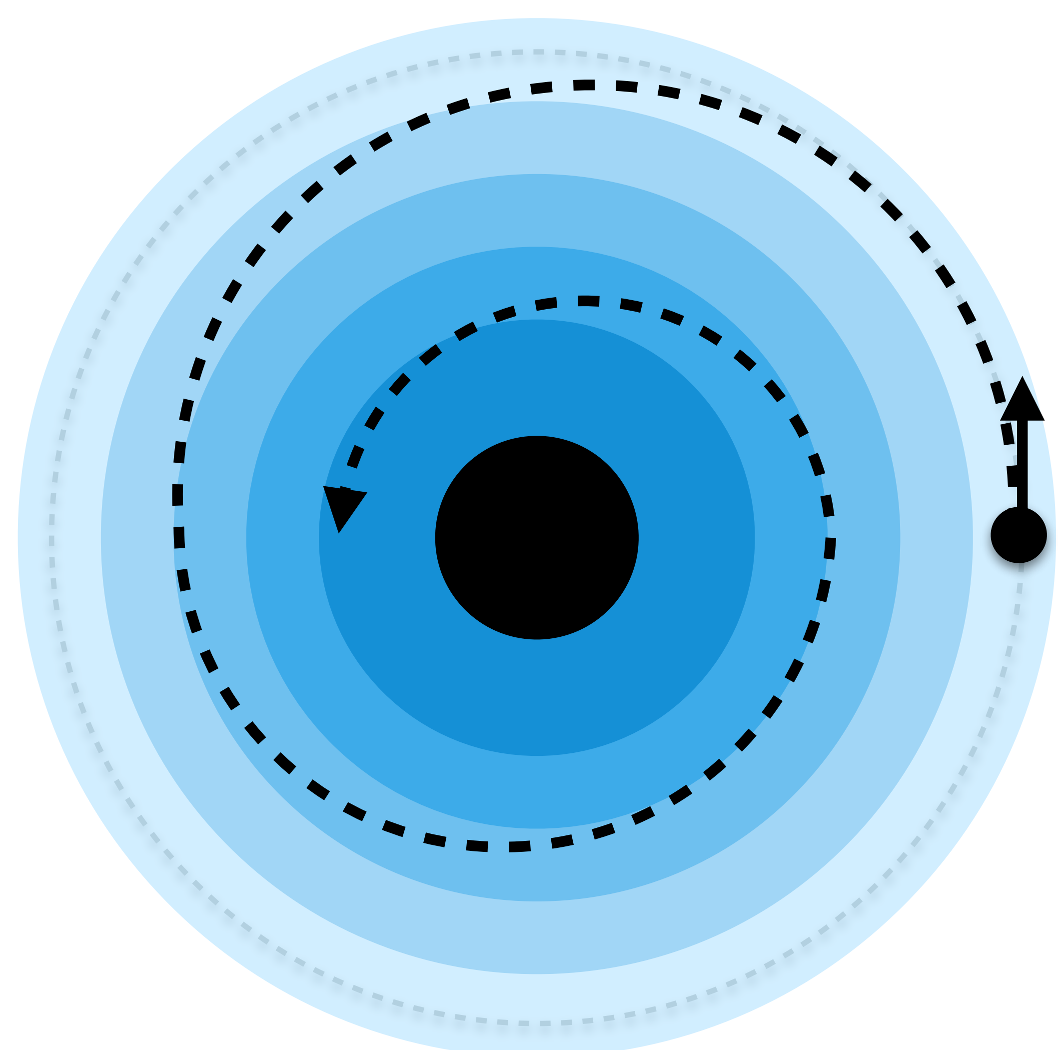


$$\dot{E}_{\rm DF} \sim \frac{4\pi G^2 m_2^2 \rho_{\rm DM}(r) \xi(v)}{v} \ln \Lambda$$

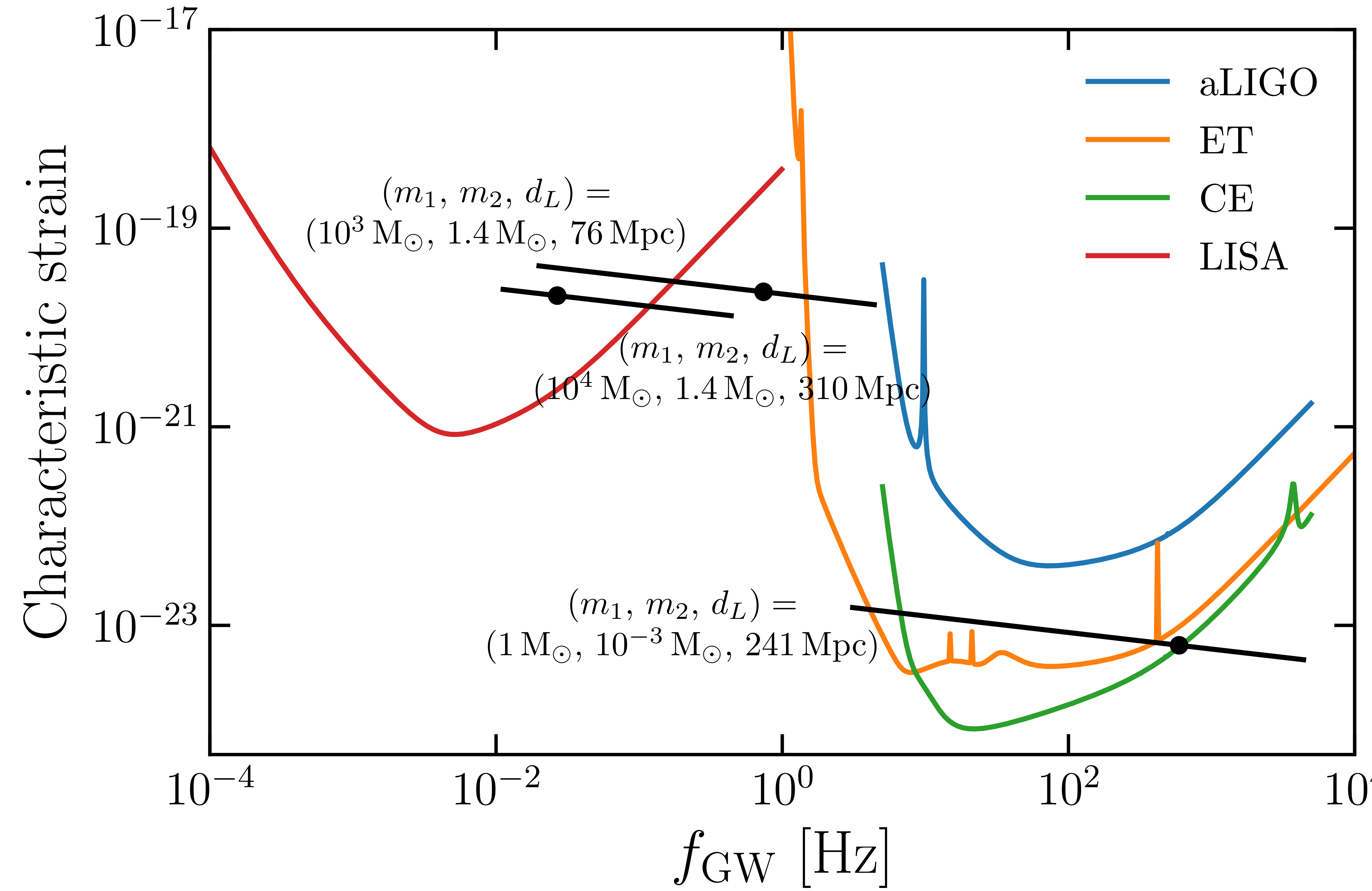
Dynamical Friction

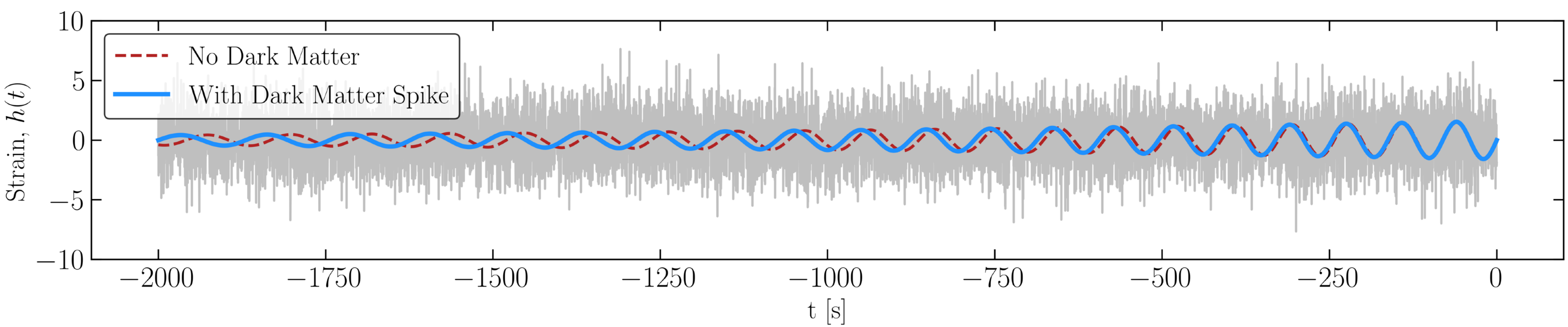
[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Dephasing of IMRIs



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





[See e.g. Eda et al. 1301.5971, 1408.3534, Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Halo Feedback

Follow semi-analytically the phase space distribution of DM:

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

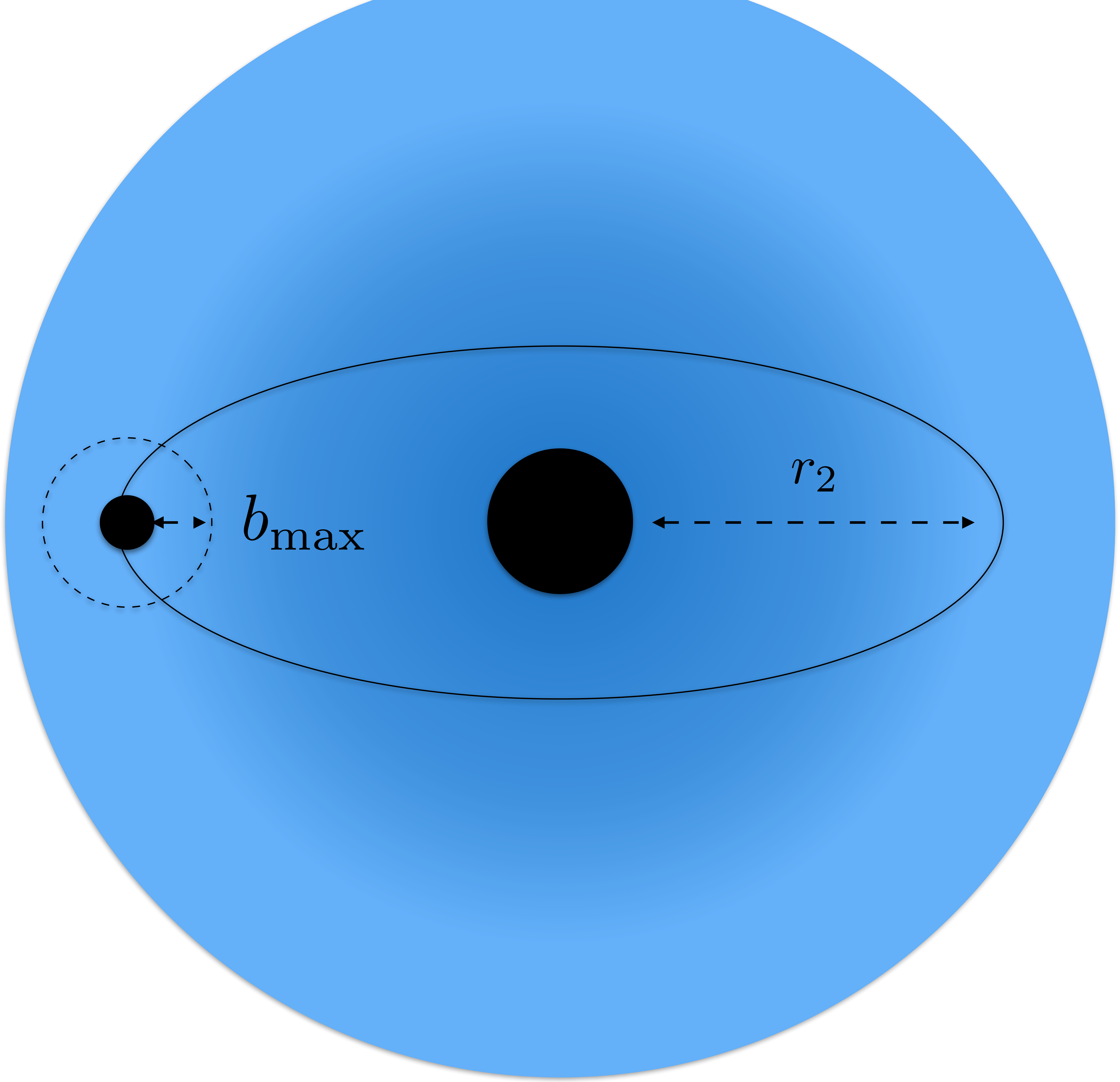
$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Each particle receives a 'kick' through gravitational scattering

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

Reconstruct density from distribution function:

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



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

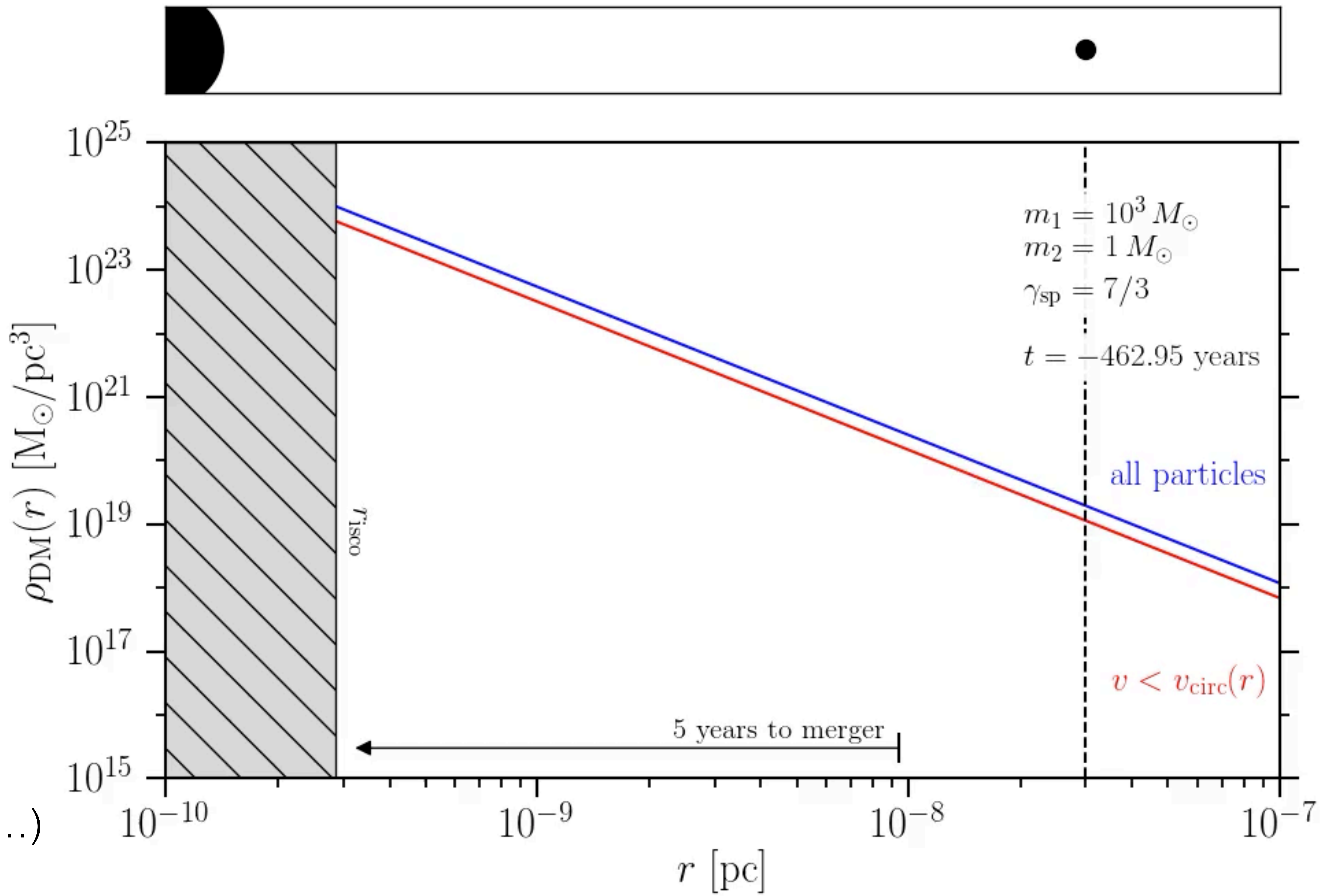
[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

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

Co-evolution

Newtonian motion of the binary, taking into account:

- GW emission
- Dynamical Friction
- **DM Halo Feedback**



Density of the DM spike is depleted (and replenished…)

This is one of the reasons we want to look at IMRIs/EMRIs…

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

[Movies: tinyurl.com/GW4DM]

[Code: github.com/bradkav/HaloFeedback]

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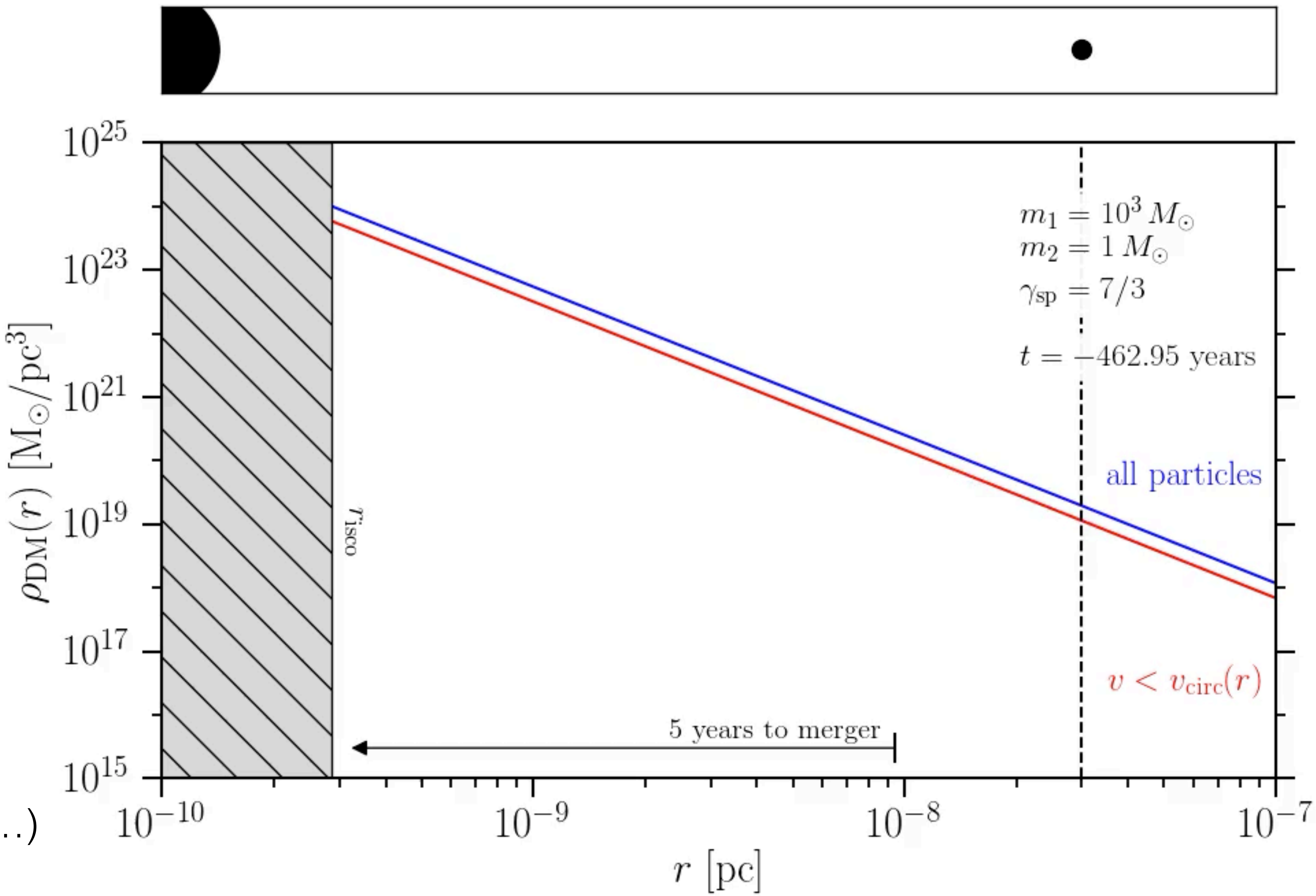

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[Movies: tinyurl.com/GW4DM]

[Code: github.com/bradkav/HaloFeedback]

Self-consistent Dephasing

Consider our astro benchmark system, starting at some initial separation:

$$r_{\rm ini} \sim 10^{-8}\,\mathrm{pc}$$

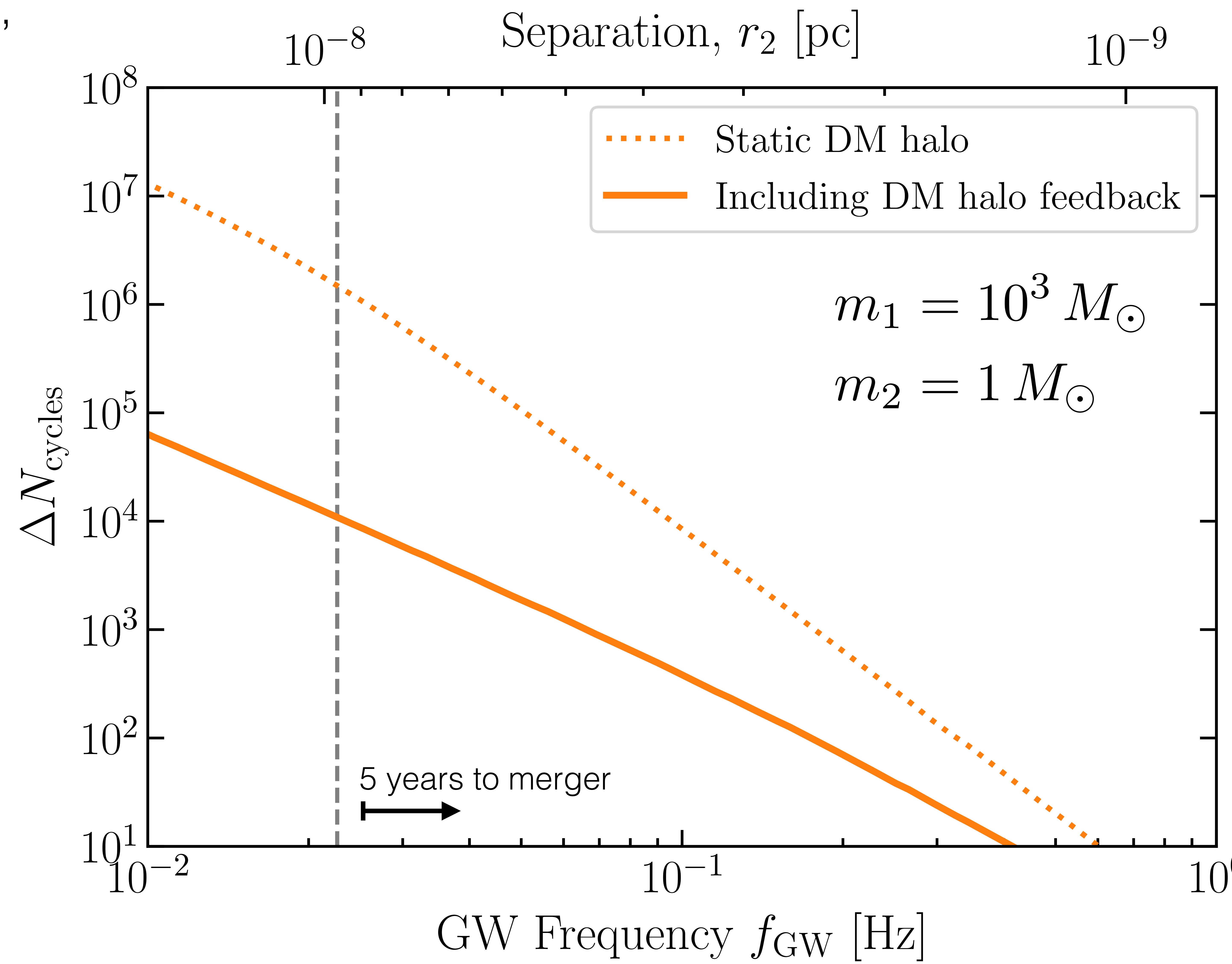
$$t_{\rm merge}^{\rm vacuum} \sim 5\,\mathrm{yr}$$

$$N_{\rm cycles}^{\rm vacuum} \sim 6 \times 10^{6}$$

DM dephasing

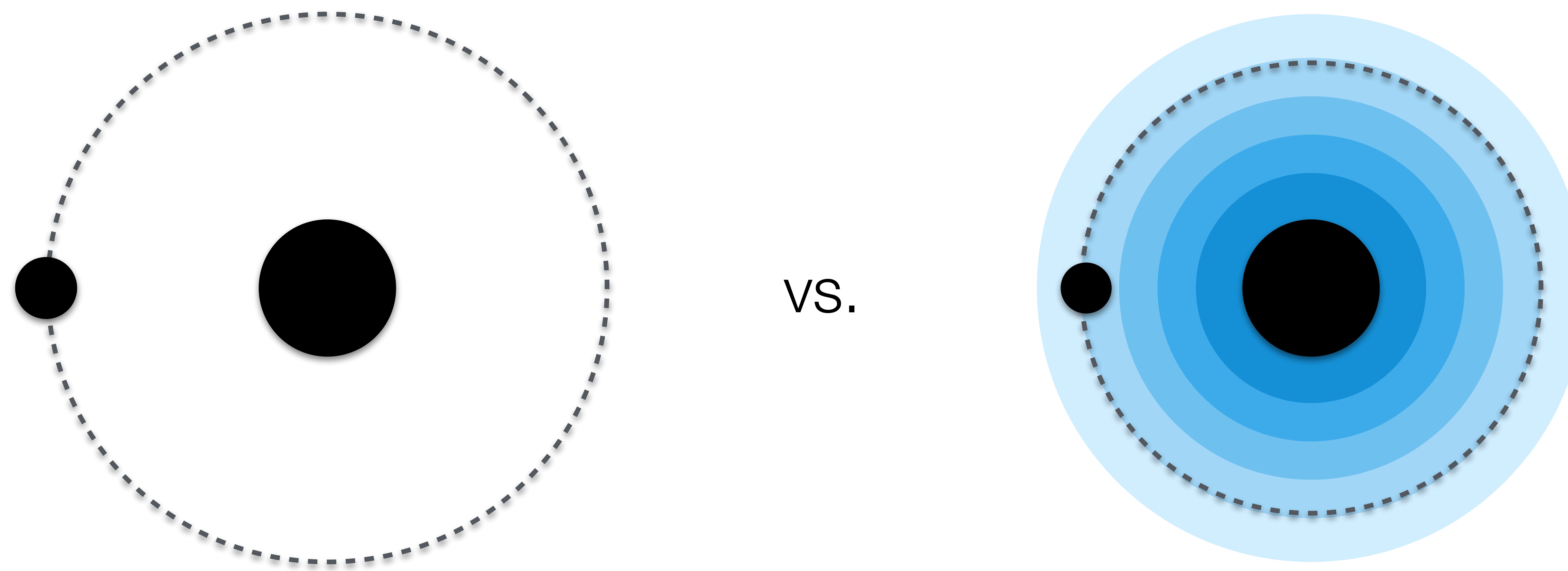
$$\Delta N_{\rm cycles} \sim \mathcal{O}(10^4)\ \text{cycles} \sim \%\ \text{level}$$

Change in the number of GW cycles to merger, starting at some initial frequency/separation:

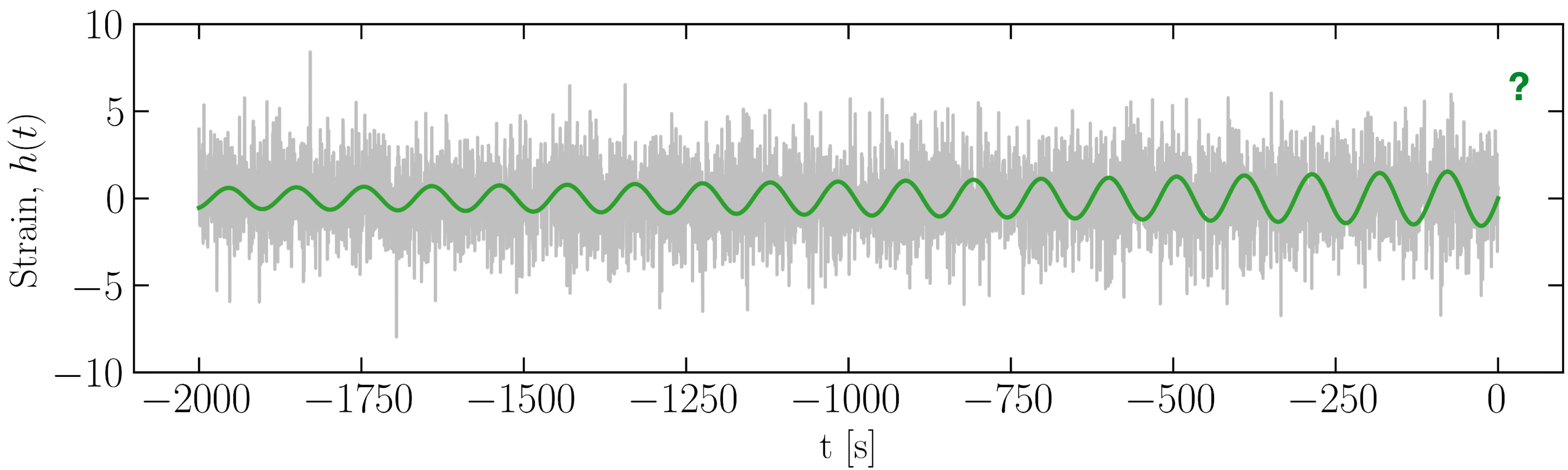


Detectability and more

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



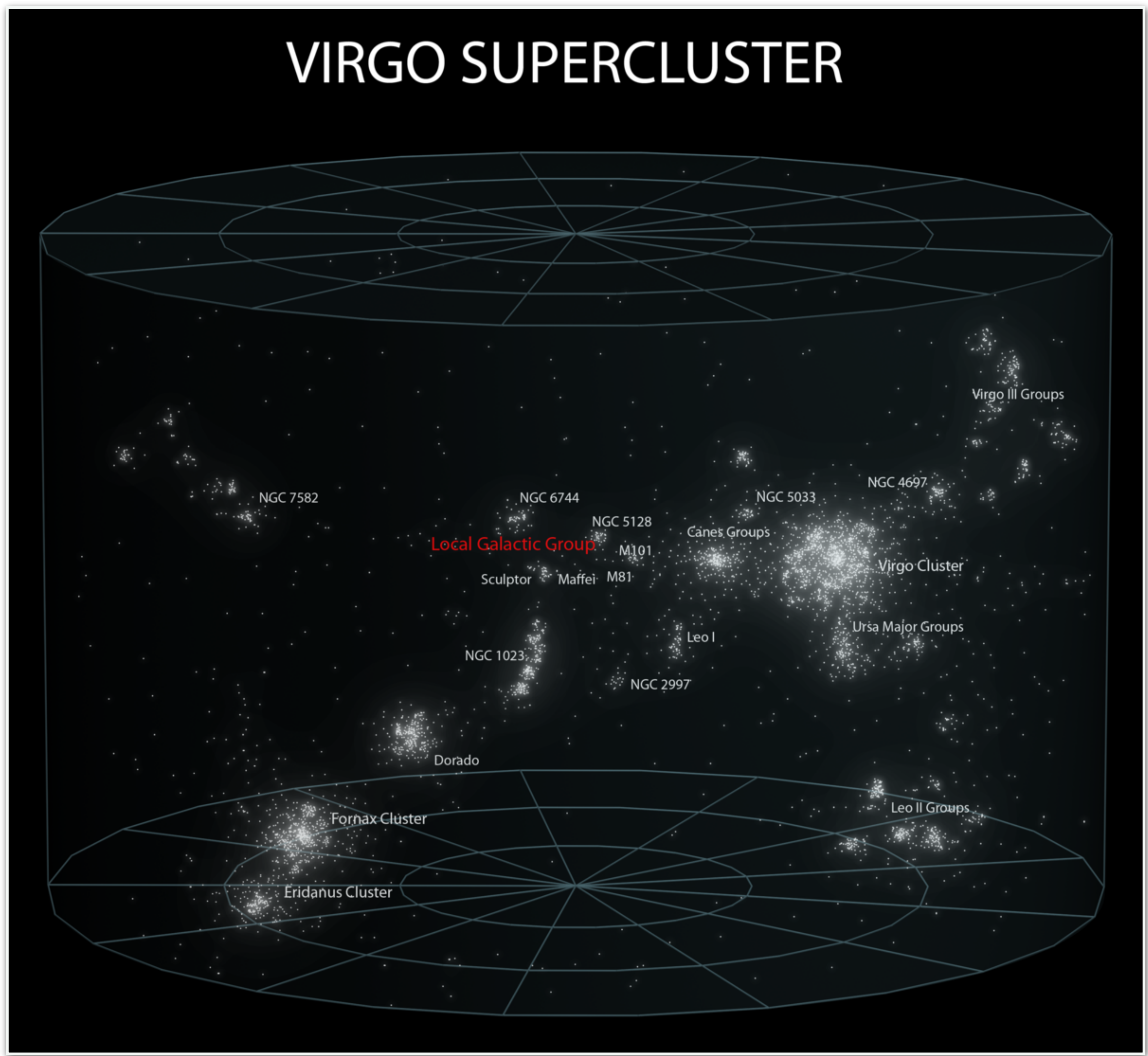
Detectability? Discoverability? Measurability?

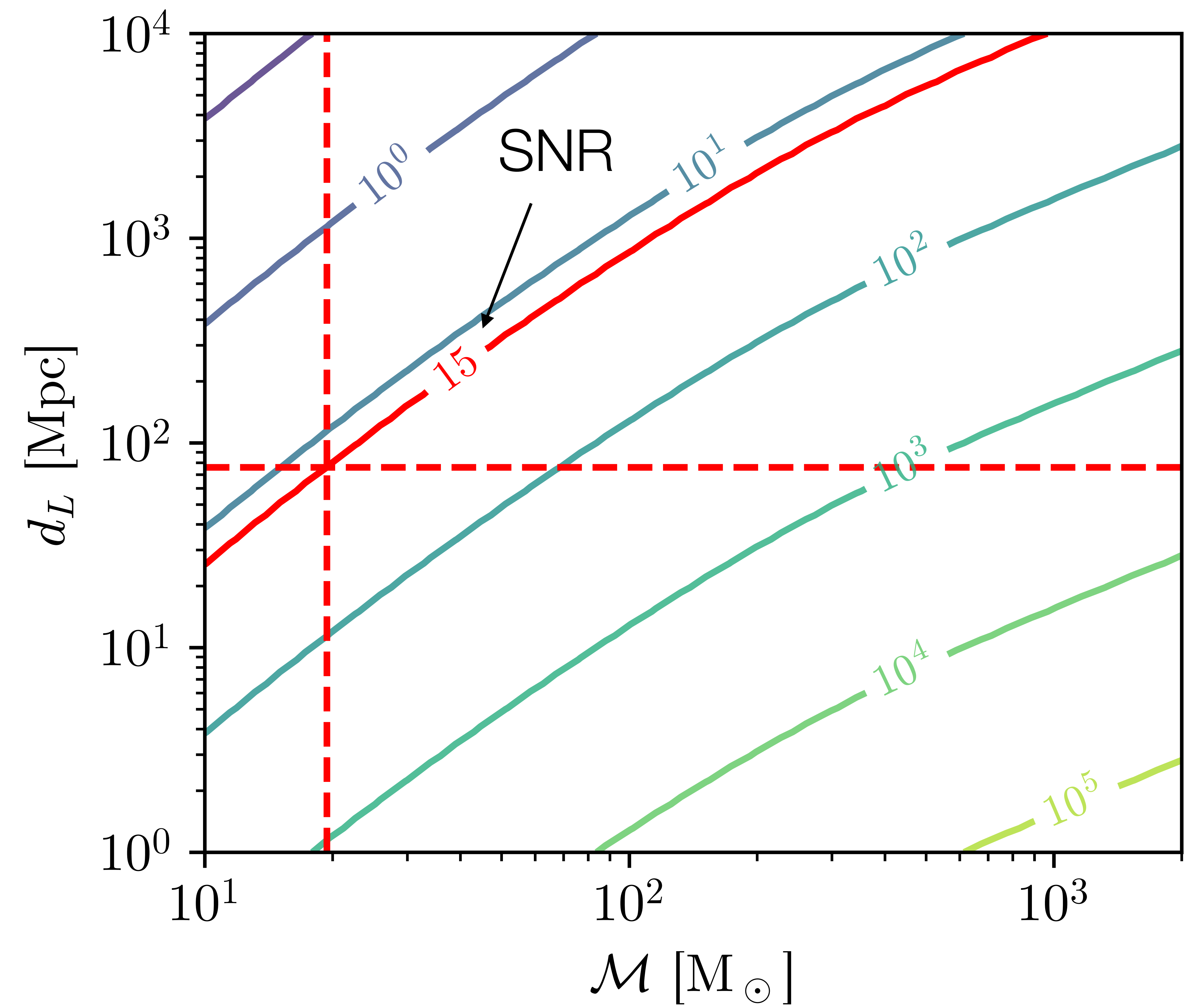


Detectability

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

Assume a signal may be **detectable** with LISA using matched filtering with a signal-to-noise ratio (SNR) $\gtrsim 15$... [1905.11998]





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

Discoverability

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

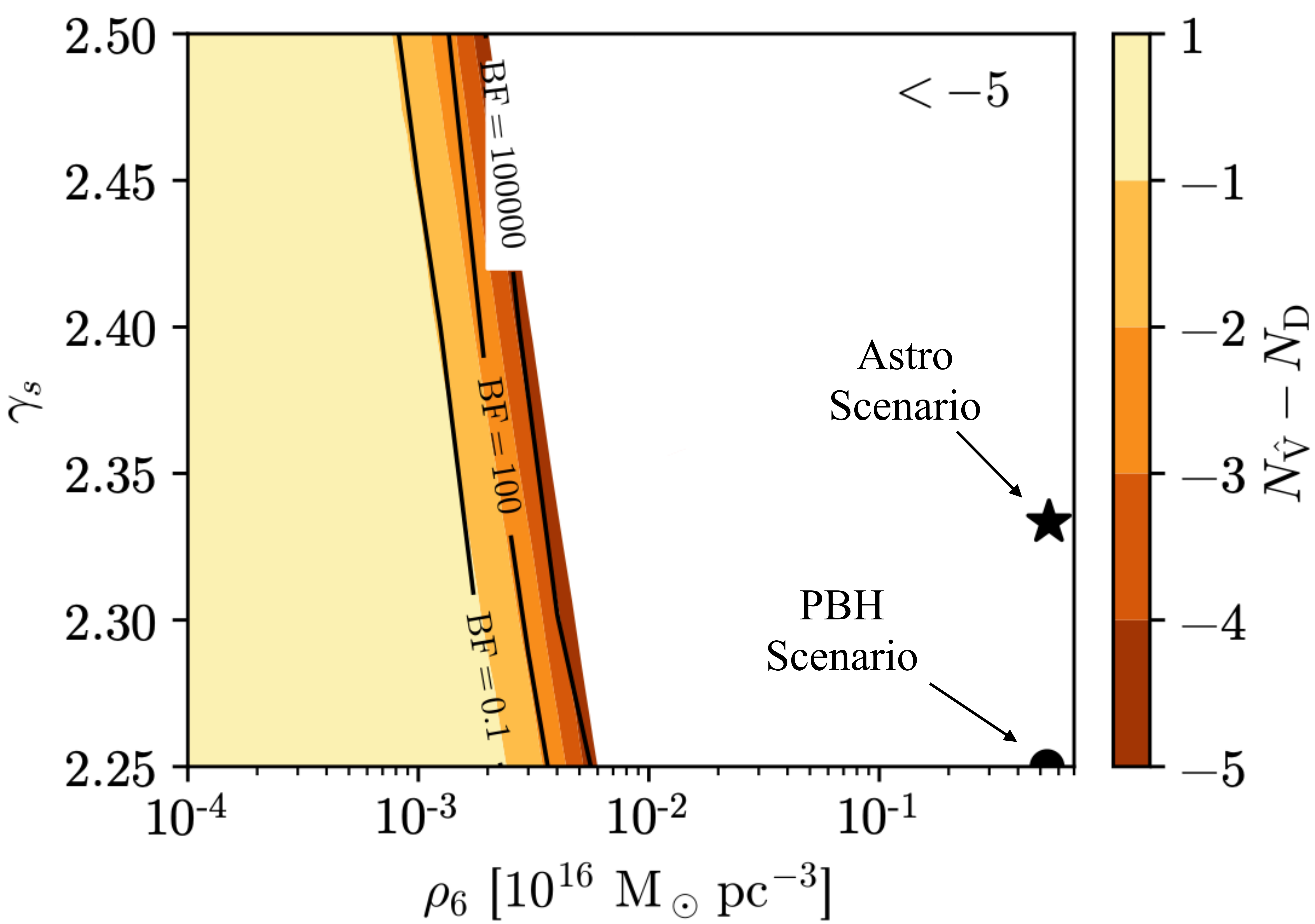
$$q = m_2/m_1$$

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

Given the data d, compare Bayesian evidence $p(d)$ for **V**acuum and **D**ressed systems:

$$\boldsymbol{\theta}_\mathrm{V} = \{\mathcal{M}\} \quad \text{vs.} \quad \boldsymbol{\theta}_\mathrm{D} = \{\gamma_\mathrm{sp}, \rho_6, \mathcal{M}, \log_{10} q\}$$

(maximising over extrinsic variables $\boldsymbol{\theta}_\mathrm{ext} \equiv \{D_L, \phi_c, \tilde{t}_c\}$)



$$p(d) = \int \mathrm{d}\boldsymbol{\theta}\, \mathcal{L}(\boldsymbol{\theta})\, p(\boldsymbol{\theta})$$

Likelihood

Prior

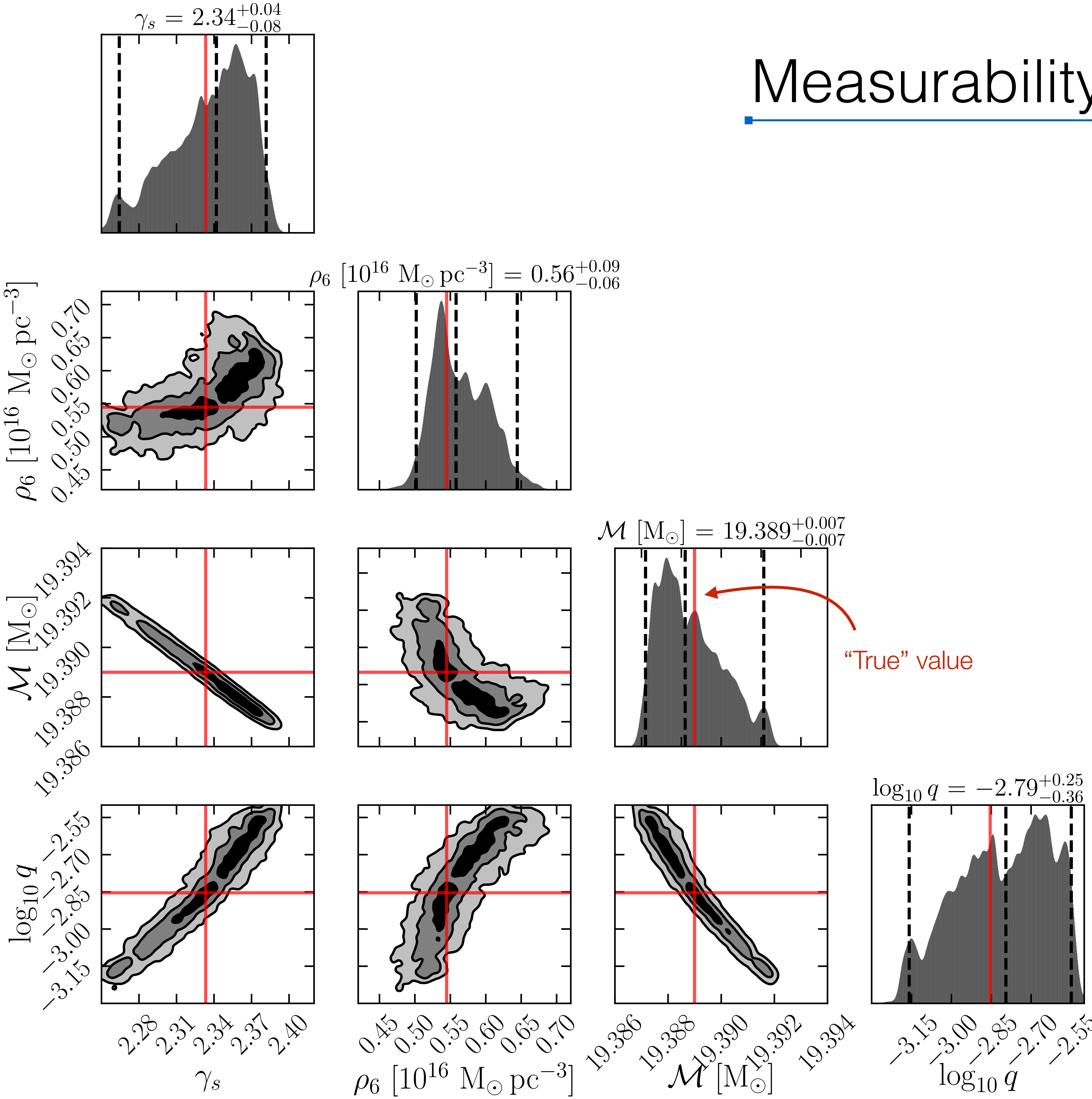
$$\mathrm{BF}(d) \equiv \frac{p(d|\mathrm{D})}{p(d|\mathrm{V})}$$

Use an approximate waveform parametrisation in terms of $\boldsymbol{\theta}_\mathrm{D}$

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

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

Measurability



Astrophysical scenario

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

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

Dressed PBHs

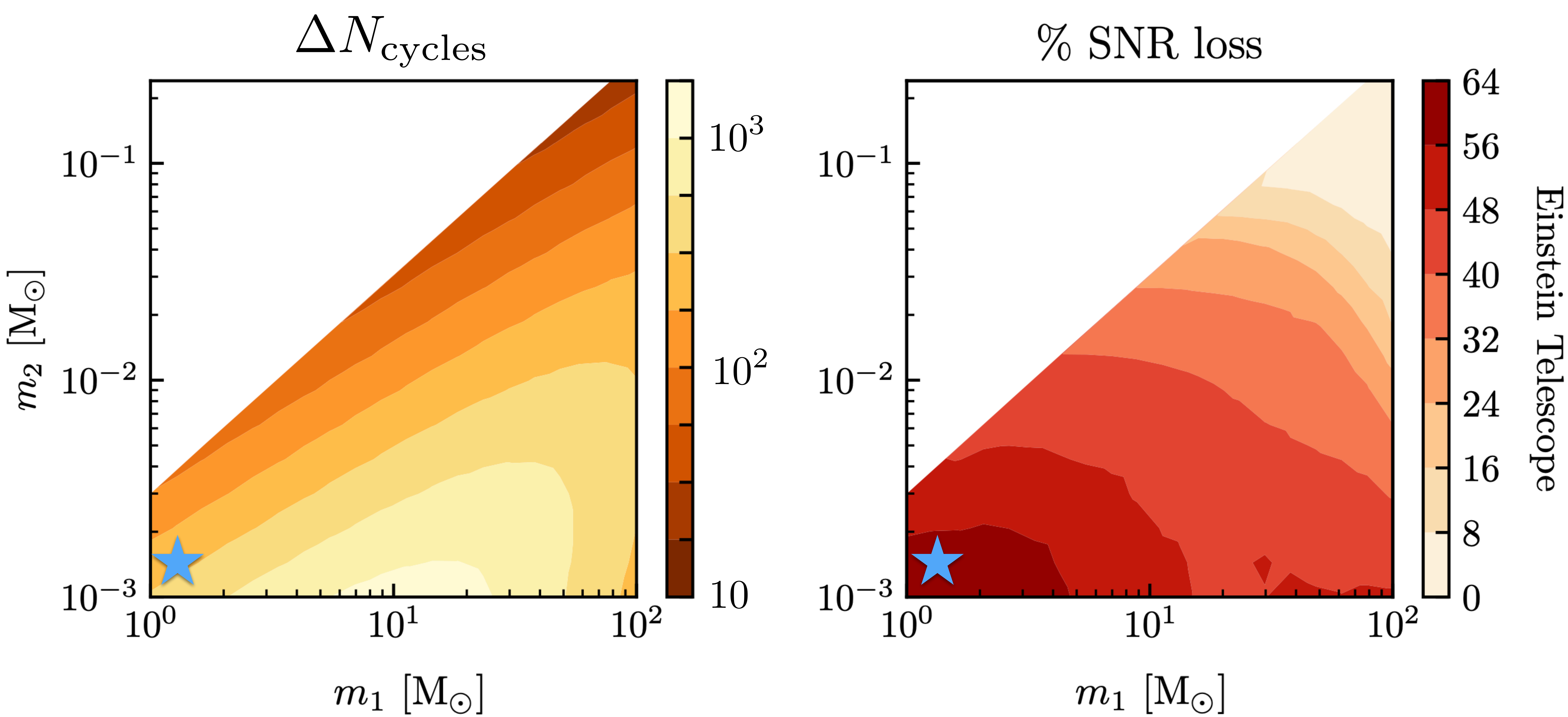
[Cole, Coogan, **BJK** & Bertone, 2207.07576]

Pippa Cole

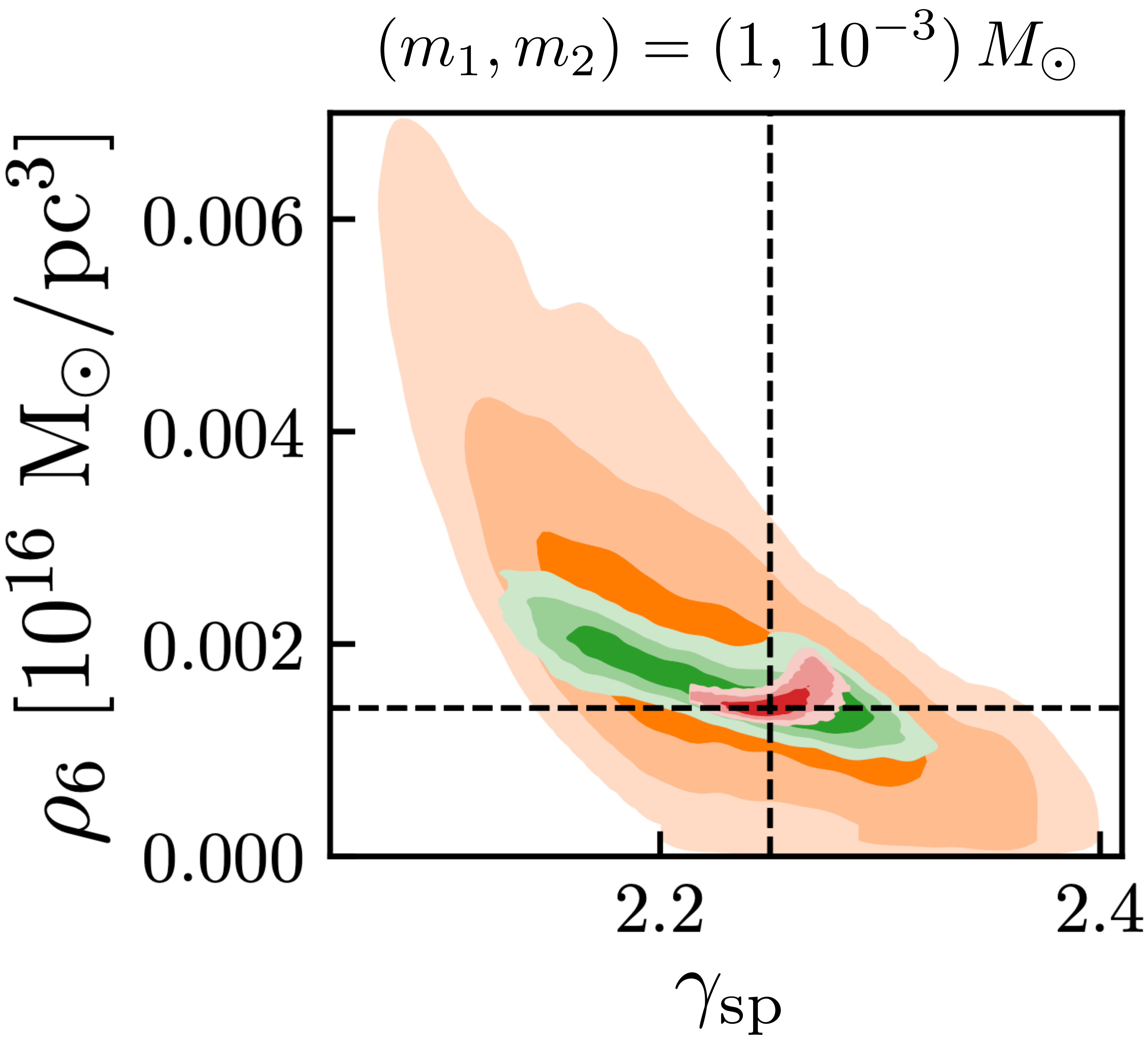
Consider now a binary of sub-solar mass PBHs,
observed with future ground-based detectors:

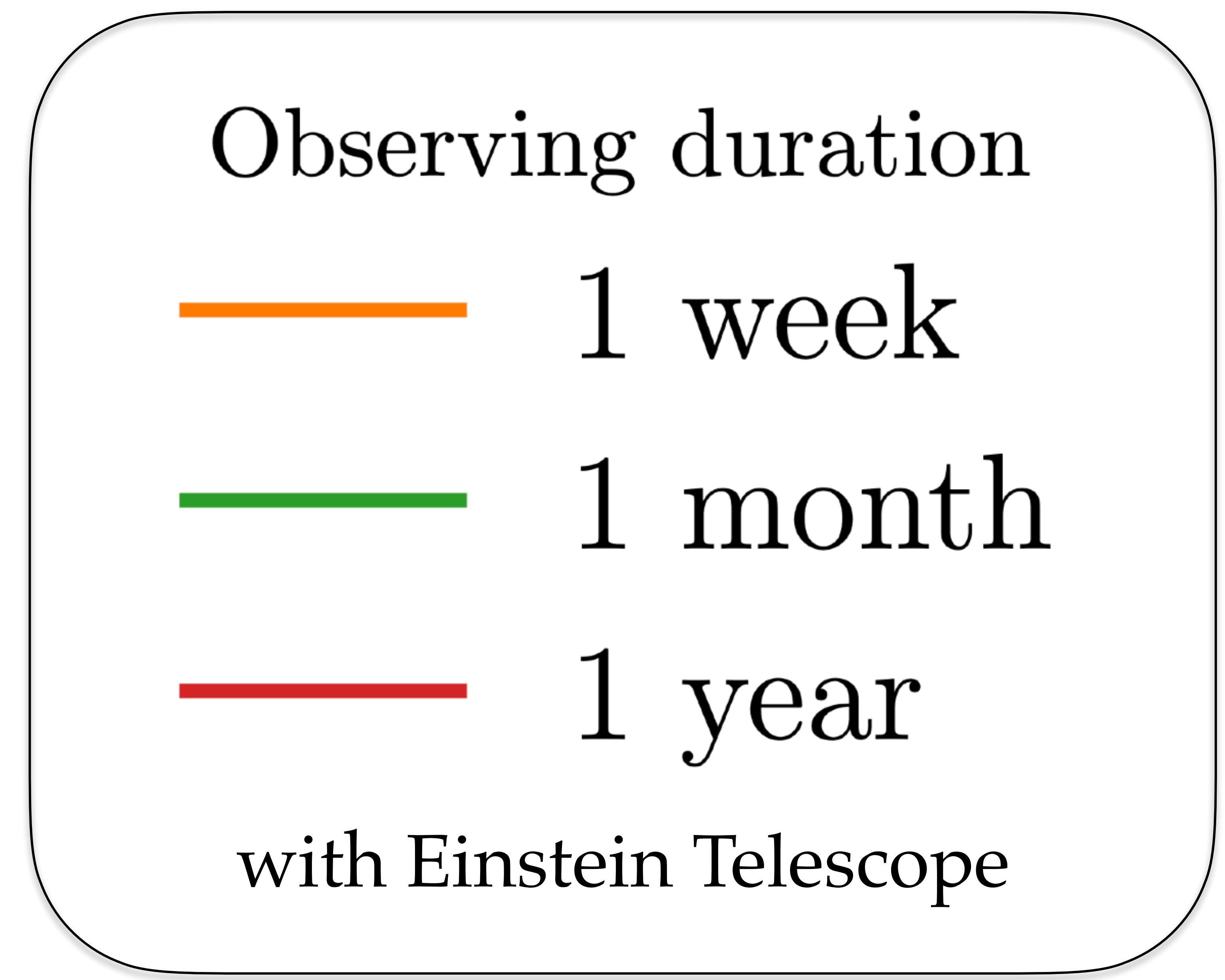
$$\bigstar \; (m_1, m_2) = (1,\, 10^{-3})\, M_\odot$$

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



Spike properties



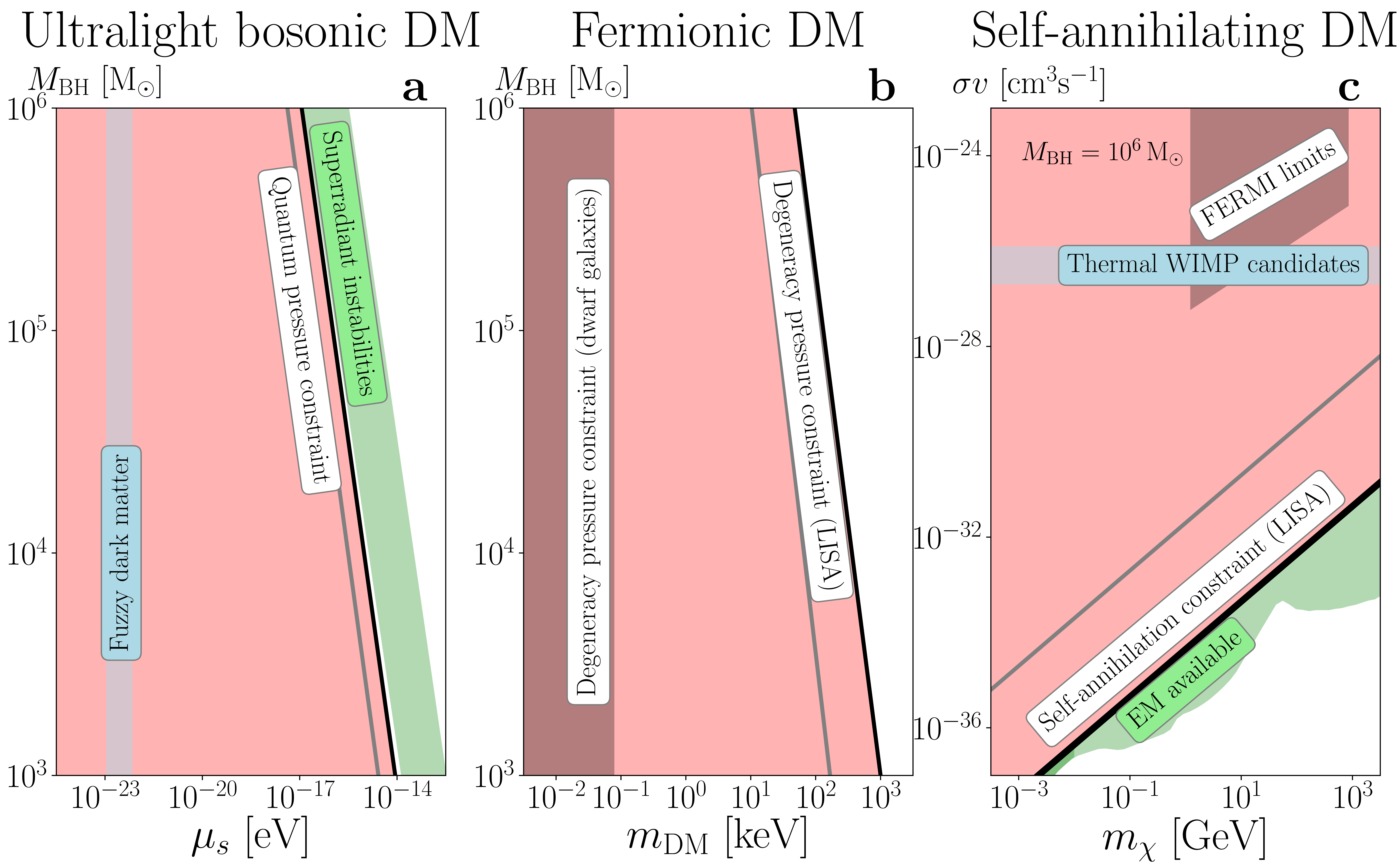


$$\rho_{\rm DM}(r) = \rho_6 \left(\frac{r}{10^{-6}\,{\rm pc}} \right)^{-\gamma_{\rm sp}}$$

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

Nature of Dark Matter

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



[Hannuksela, Ng & Li, 1906.11845]

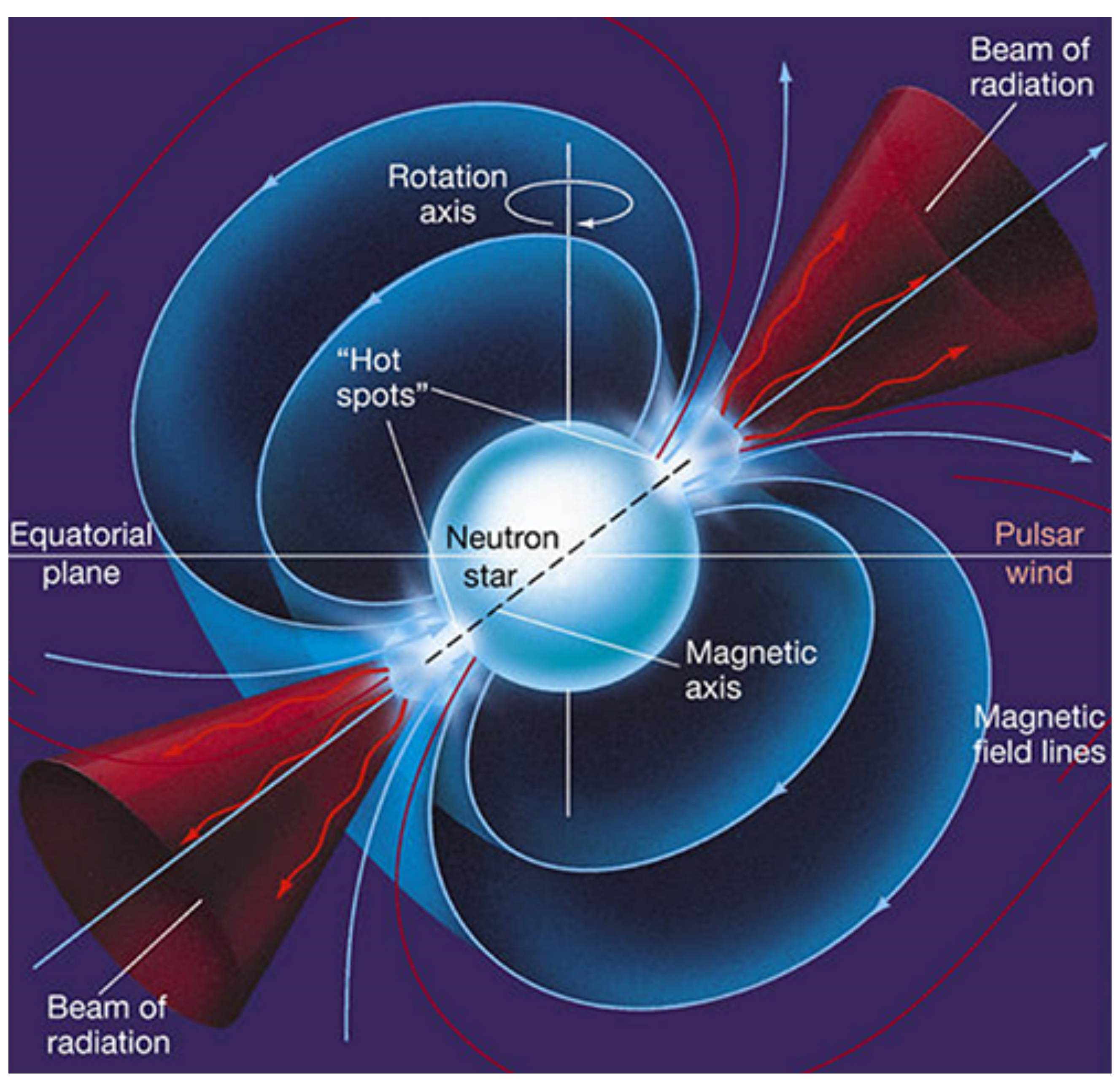
[See also Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

Multimessenger QCD Axions

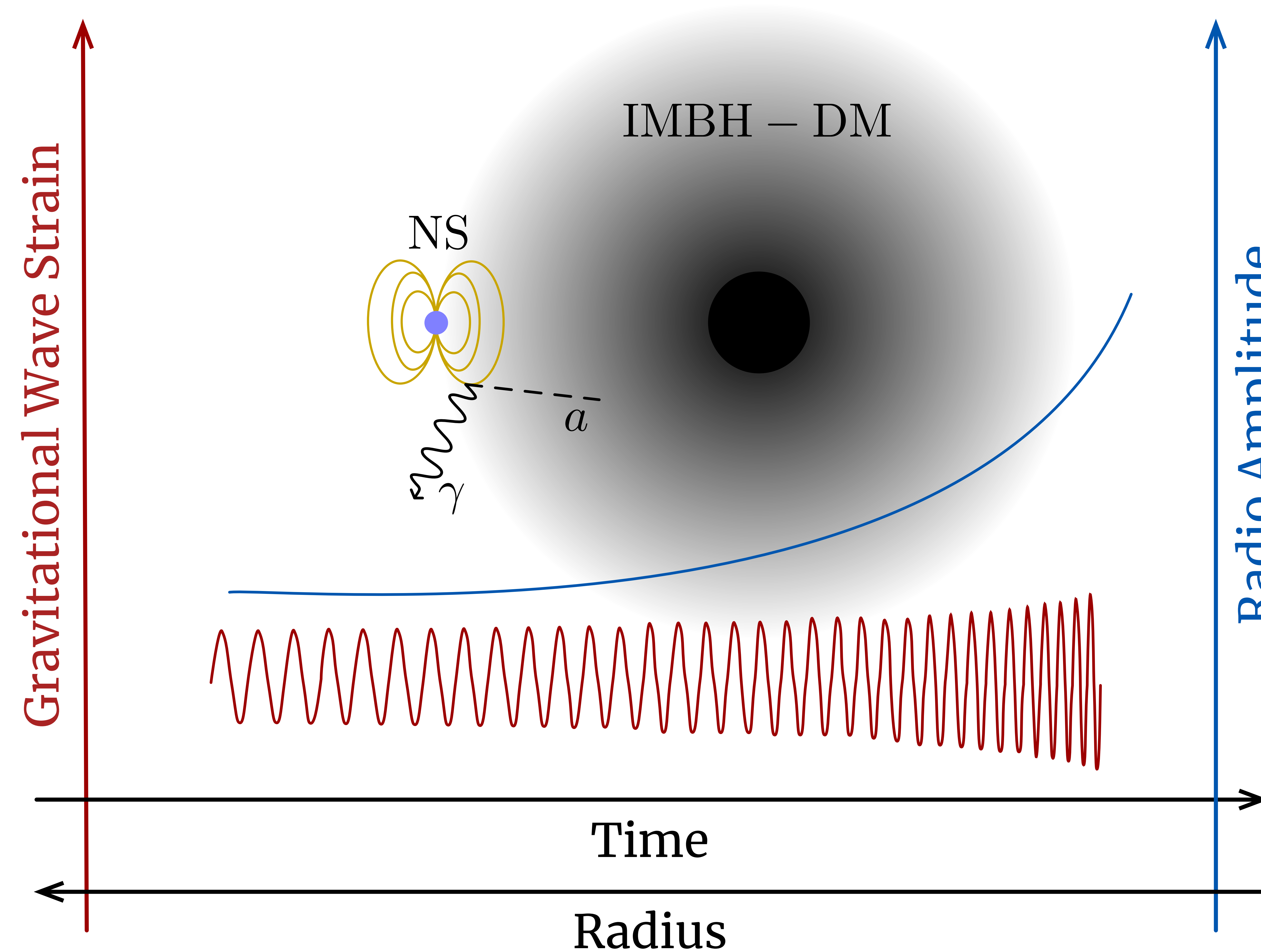
Consider a DM spike consisting of QCD axions ($m_a \in [10^{-7}, 10^{-5}]\,\mathrm{eV}$):

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

Tom Edwards



[See also 1803.08230, 1804.03145, 1811.01020, 1910.11907]



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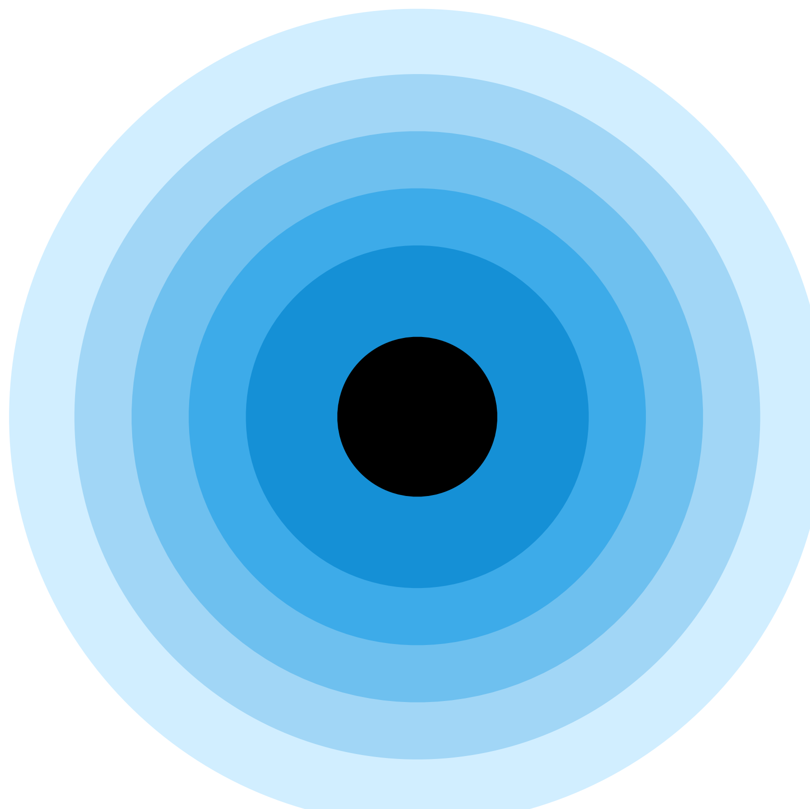

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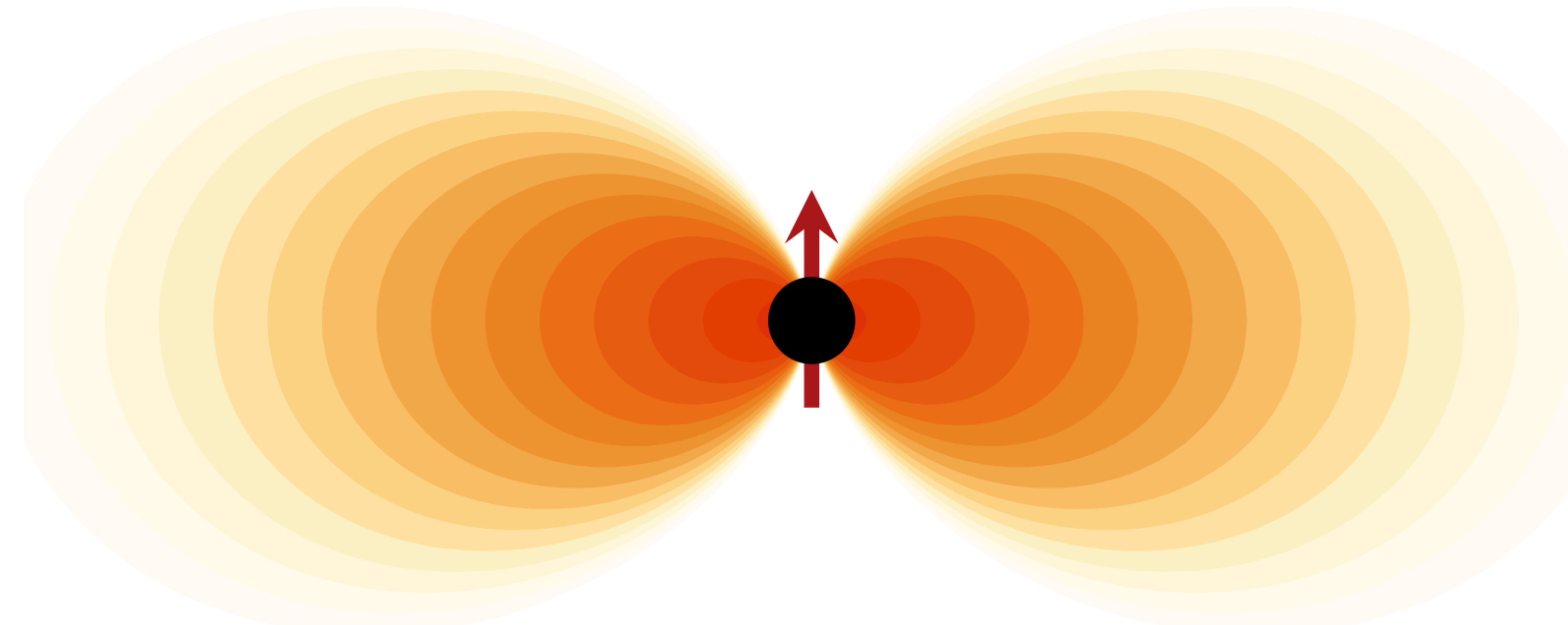
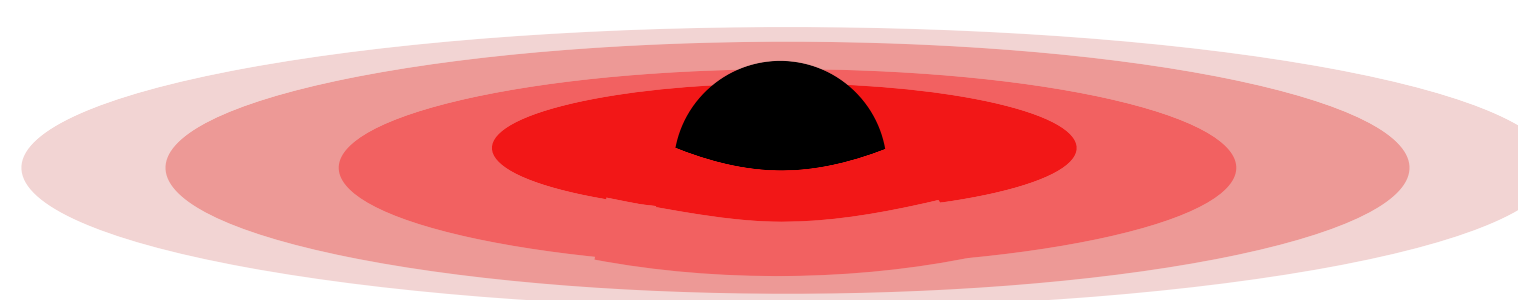


‘**Gravitational Atoms**’ of
Ultralight Bosons

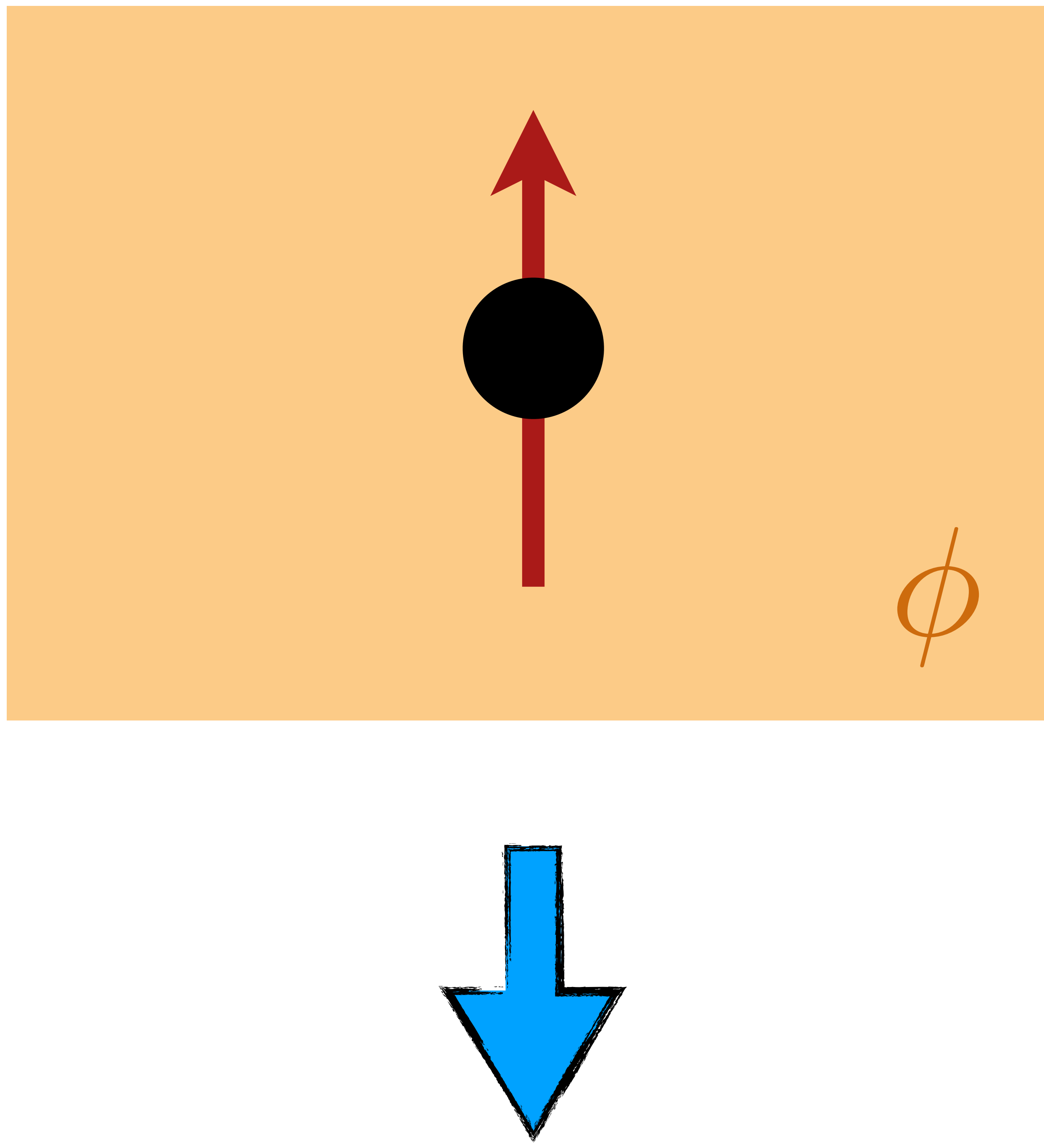


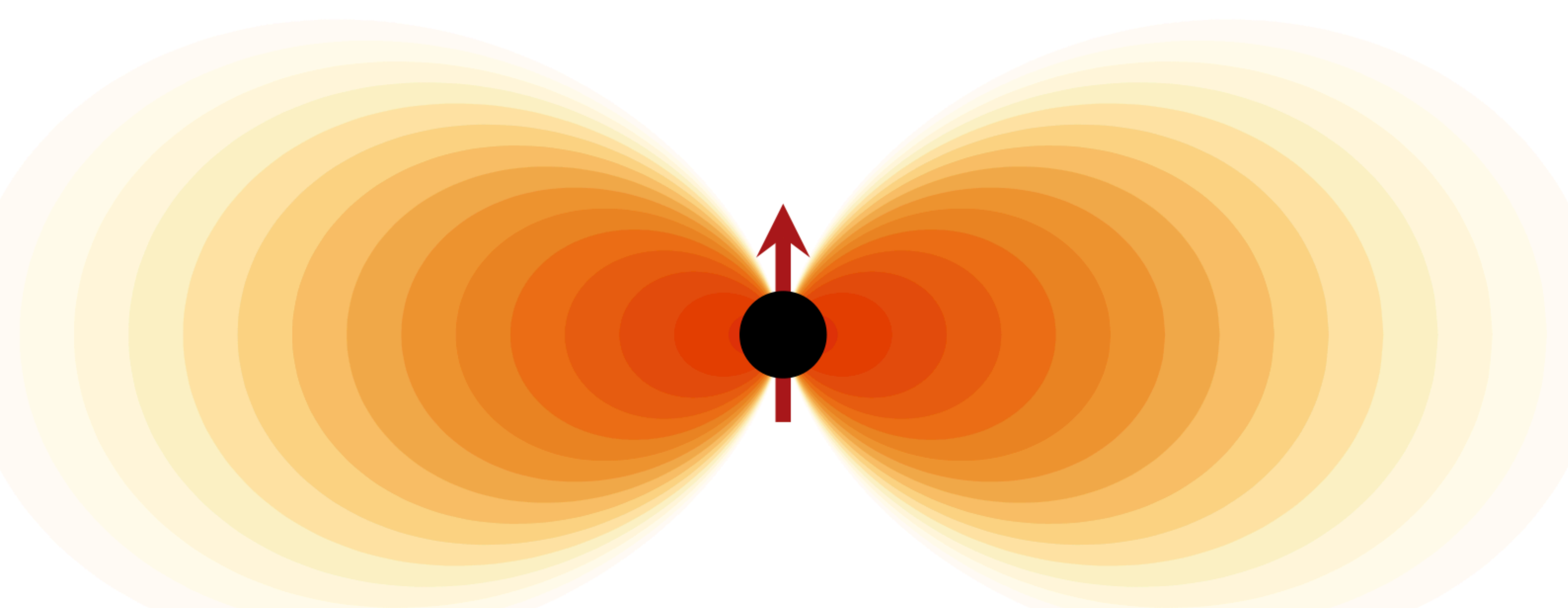
Baryonic
Accretion Disks

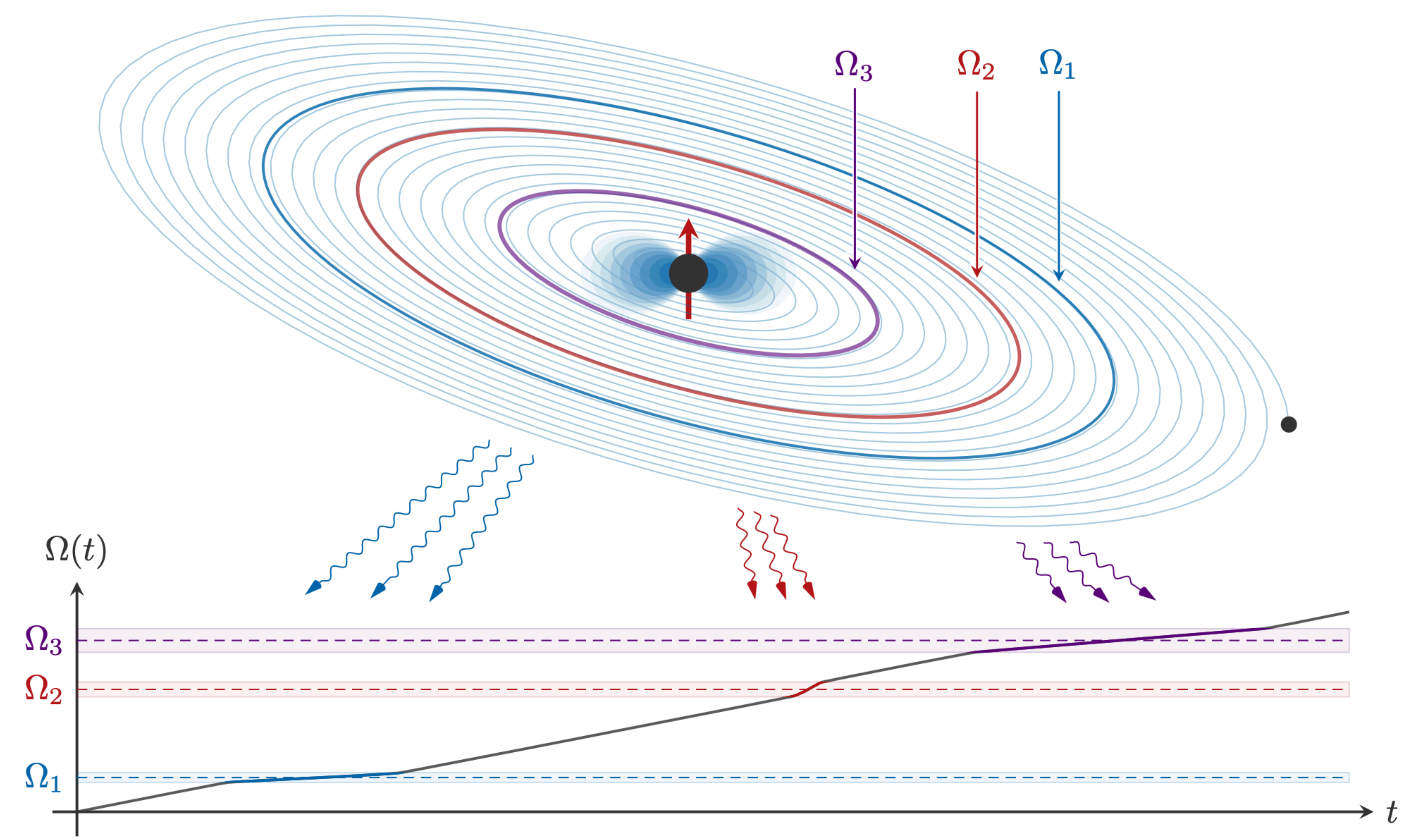
Black Holes (BHs) are extreme environments allowing us to probe high densities, long timescales…

Gravitational Atoms

[Baumann, Bertone, Stout & Tomaselli, 2206.01212, 2112.14777; Tomaselli, Spieksma & Bertone, 2305.15460]





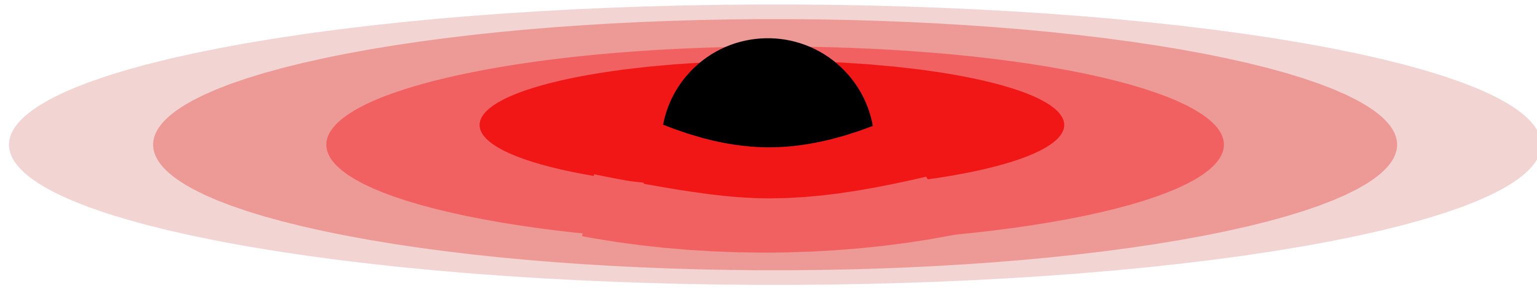


[See also Baumann et al., 1804.03208, 1908.10370, 1912.04932]

[See Gimmy's talk this afternoon]

Accretion Disks

Risk of confusion between New Physics and accretion disks?



Baryonic
Accretion Disks

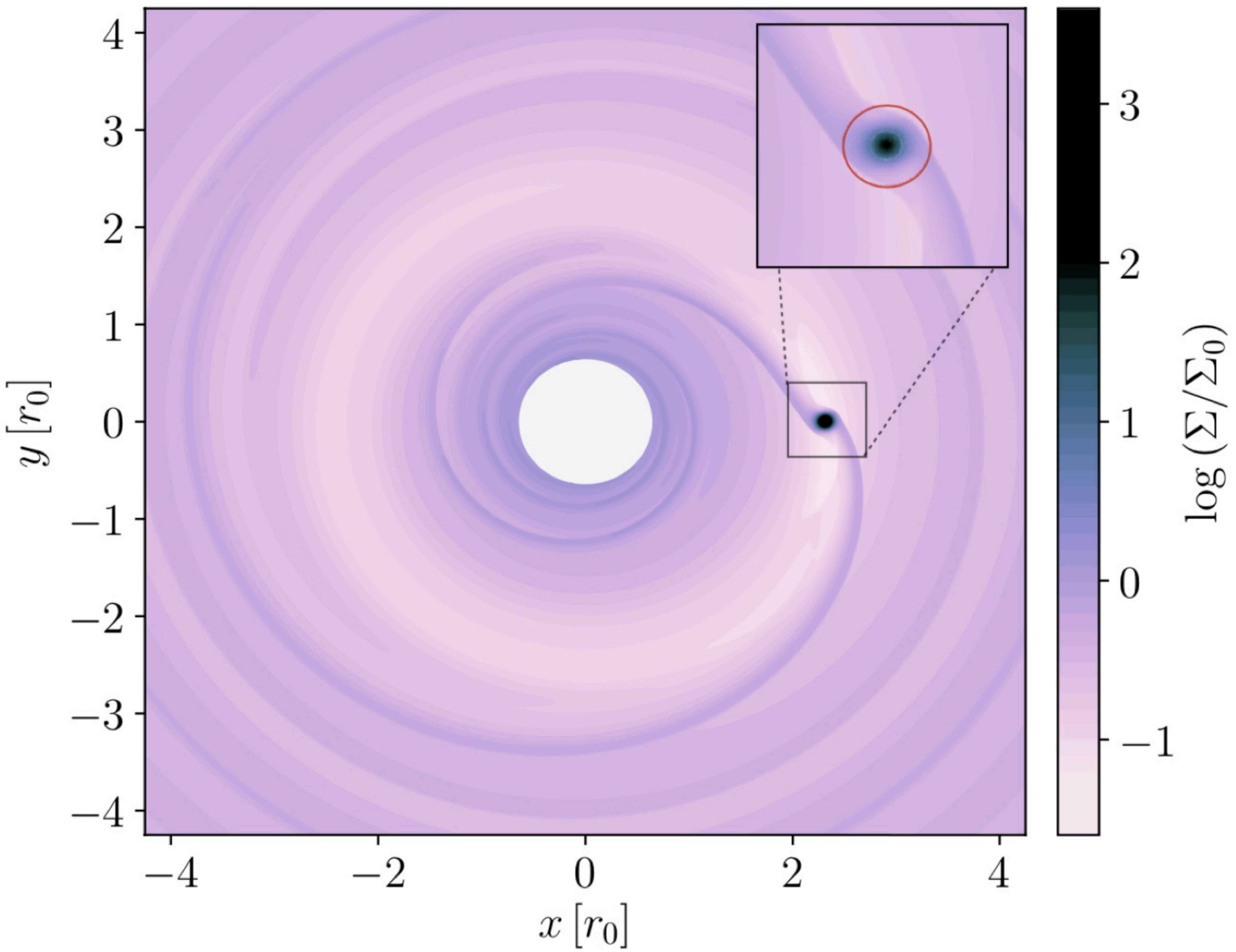
Many possible geometries and parameters, but focus on dense, thin disks.

Dominant cause of dephasing is *not* dynamical friction but *gas torques*.

Perturbation of the disk leads to a build up of gas inward or outward of the inspiraling BH.

↓

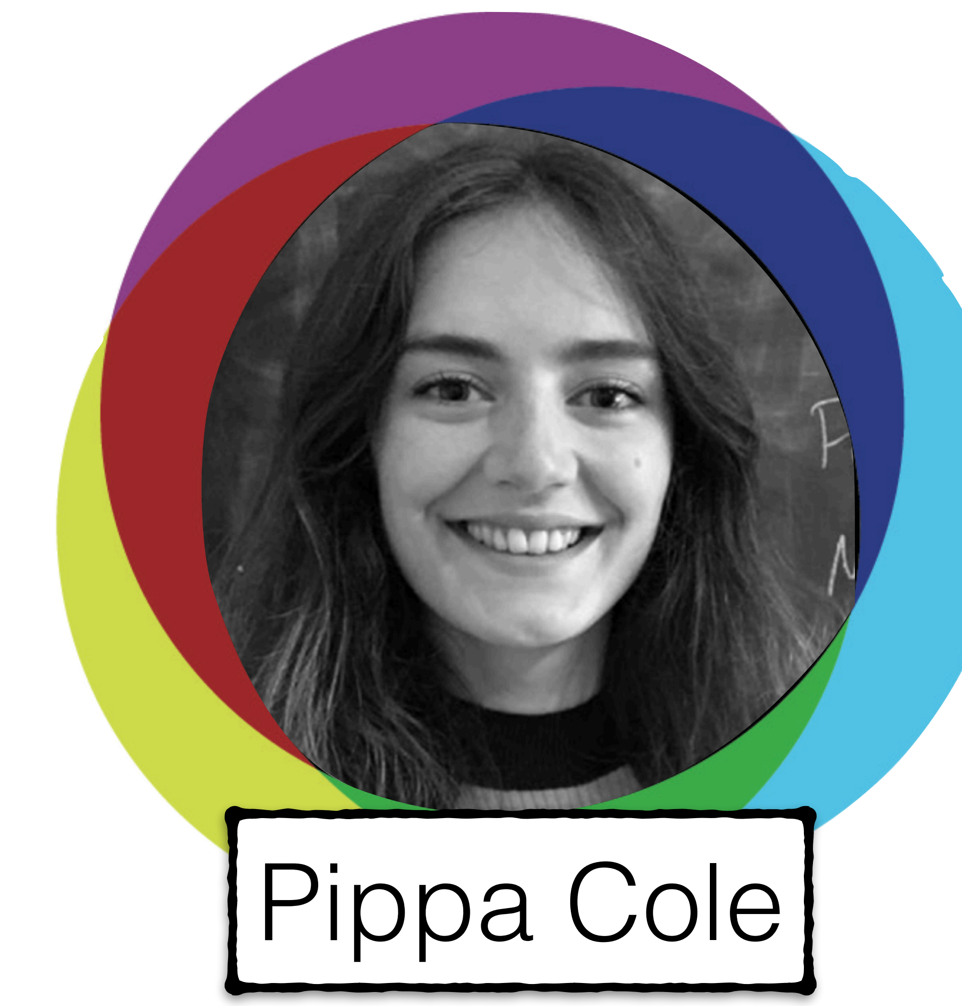
Dependence of energy losses on BH separation is *different* from DM spikes!

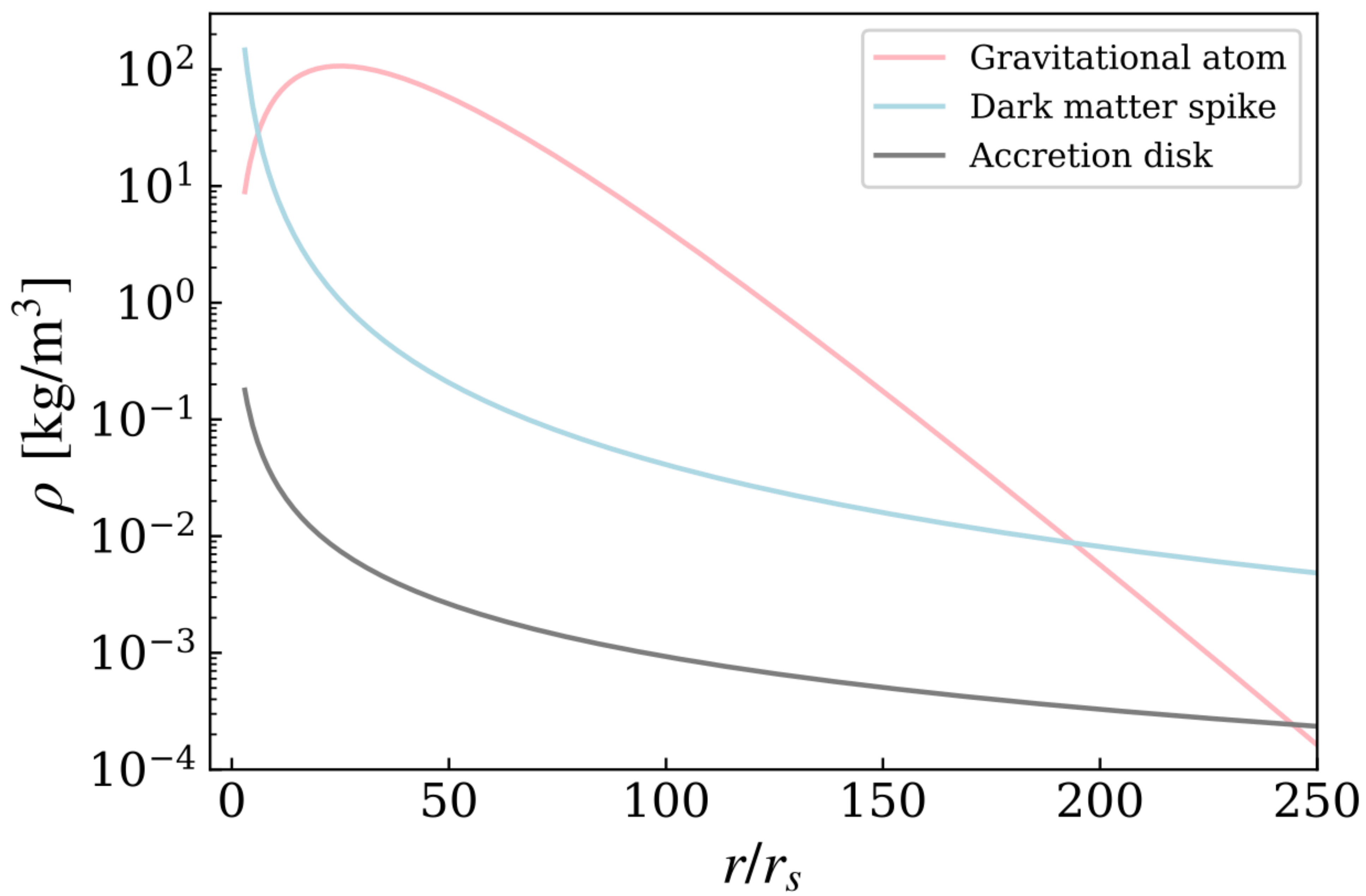


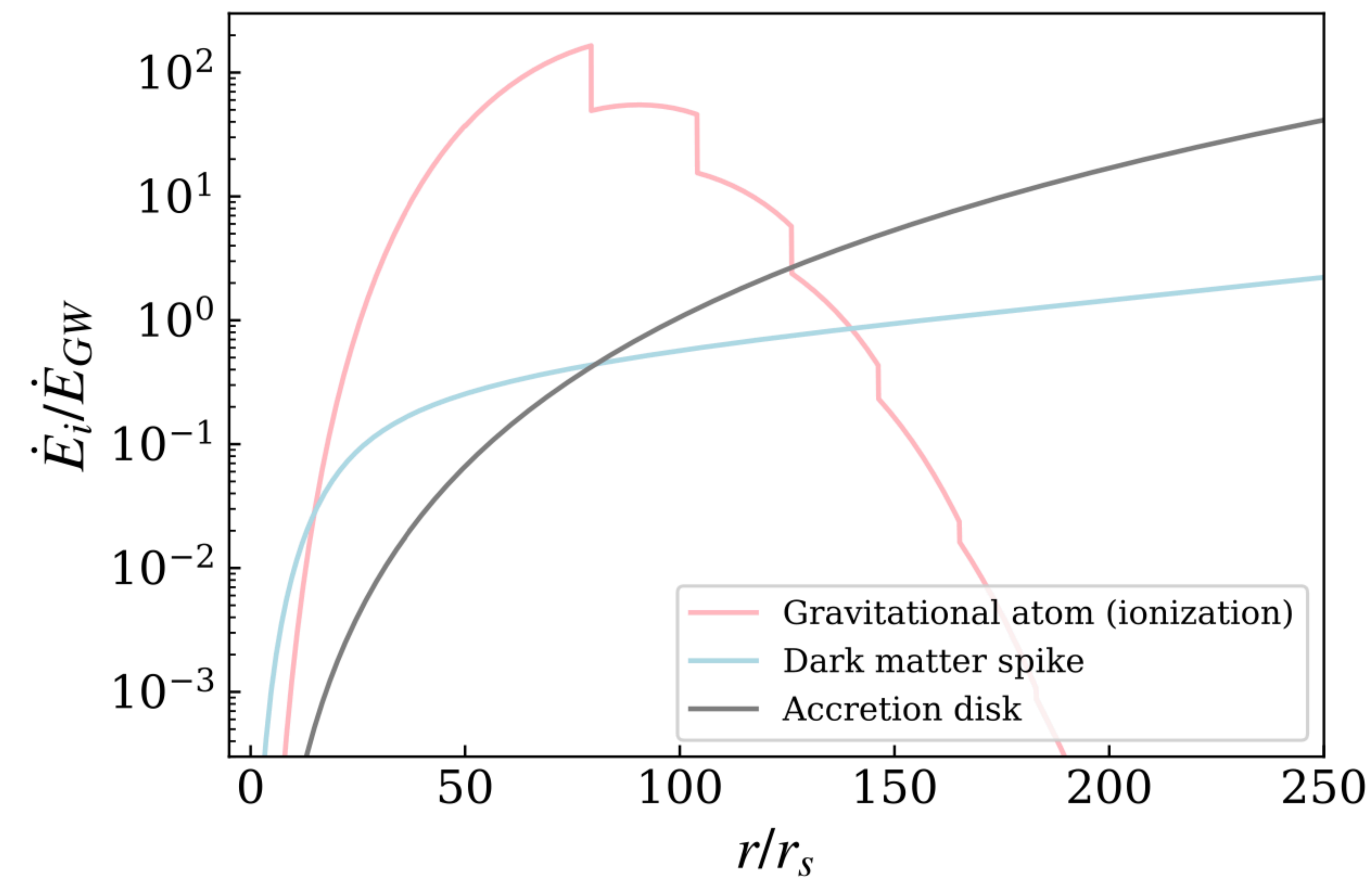
[Derdzinski et al., 2005.11333]

Discriminability

[Cole, Bertone, Coogan, Gaggero, Karydas, **BJK**, Spieksma, Tomaselli, 2211.01362, Nature Astronomy]





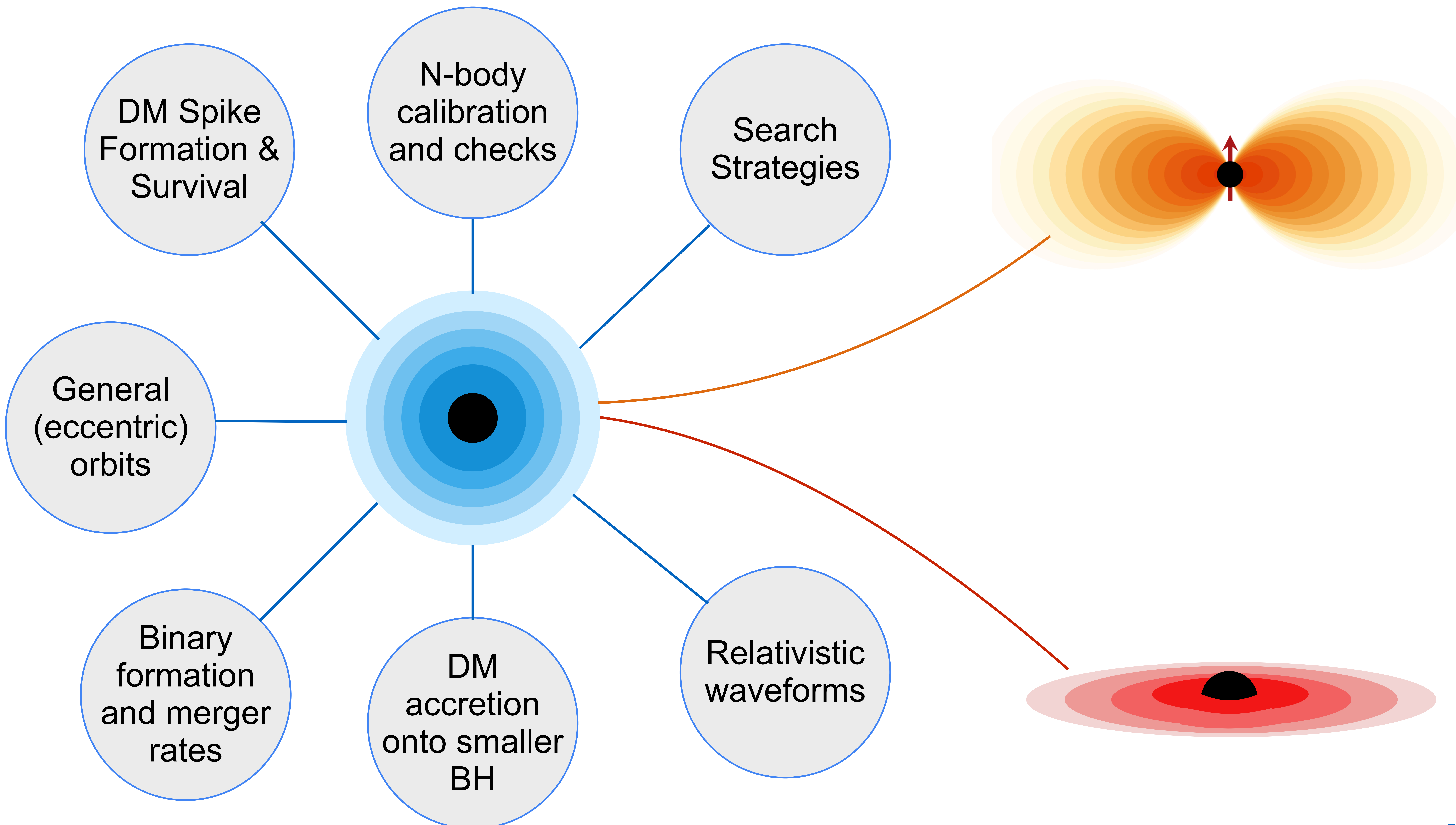


Signals **very hard to confuse** in 1 year of LISA data (huge Bayes factors!)

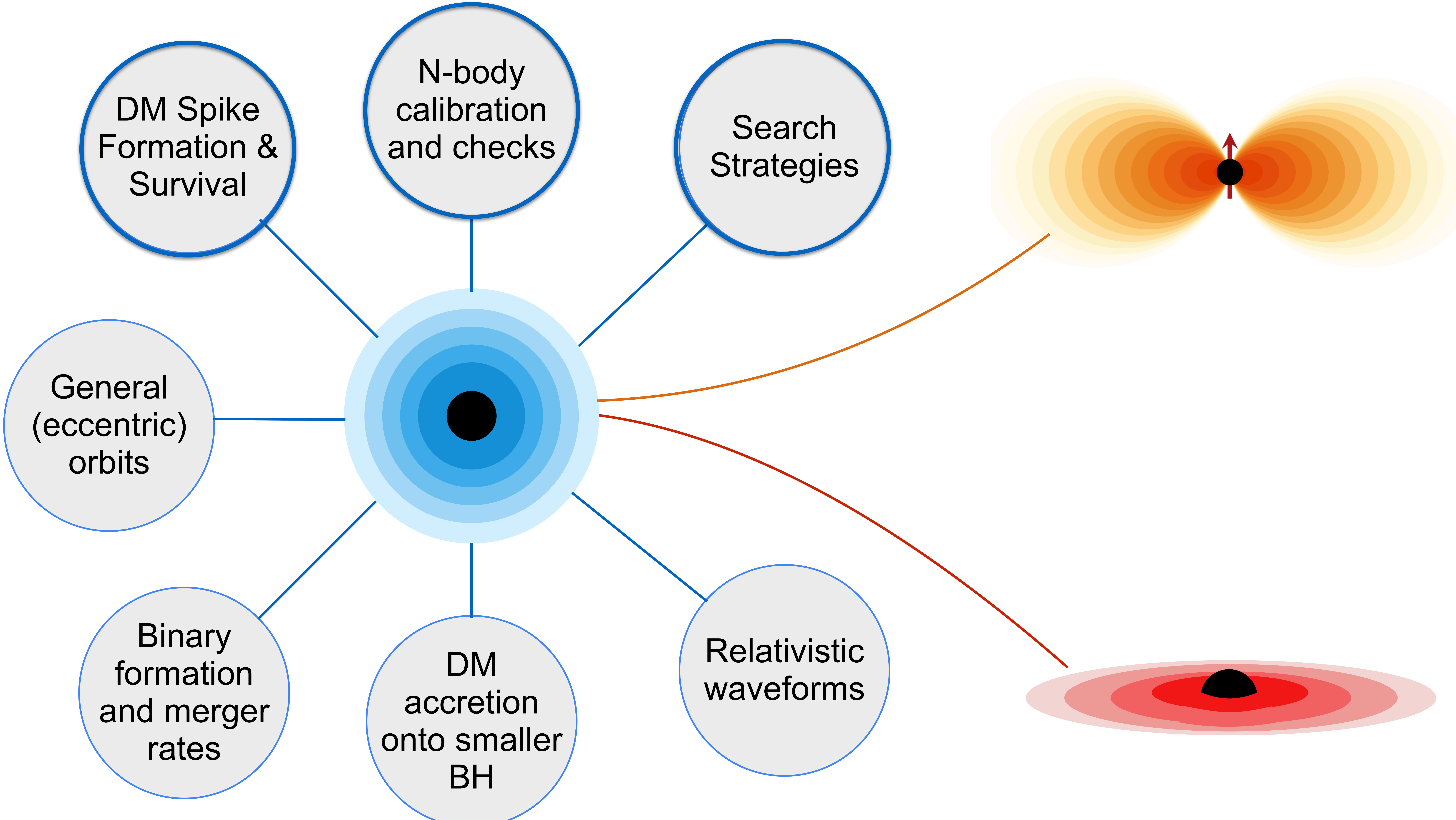
$\log_{10} \mathcal{B}$	Dark dress signal	Accretion disk signal	Gravitational atom signal
Vacuum template	34	6	39
Dark dress template	-	3	39
Accretion disk template	17	-	33
Gravitational atom template	24	6	-

[See Pippa's talk yesterday]

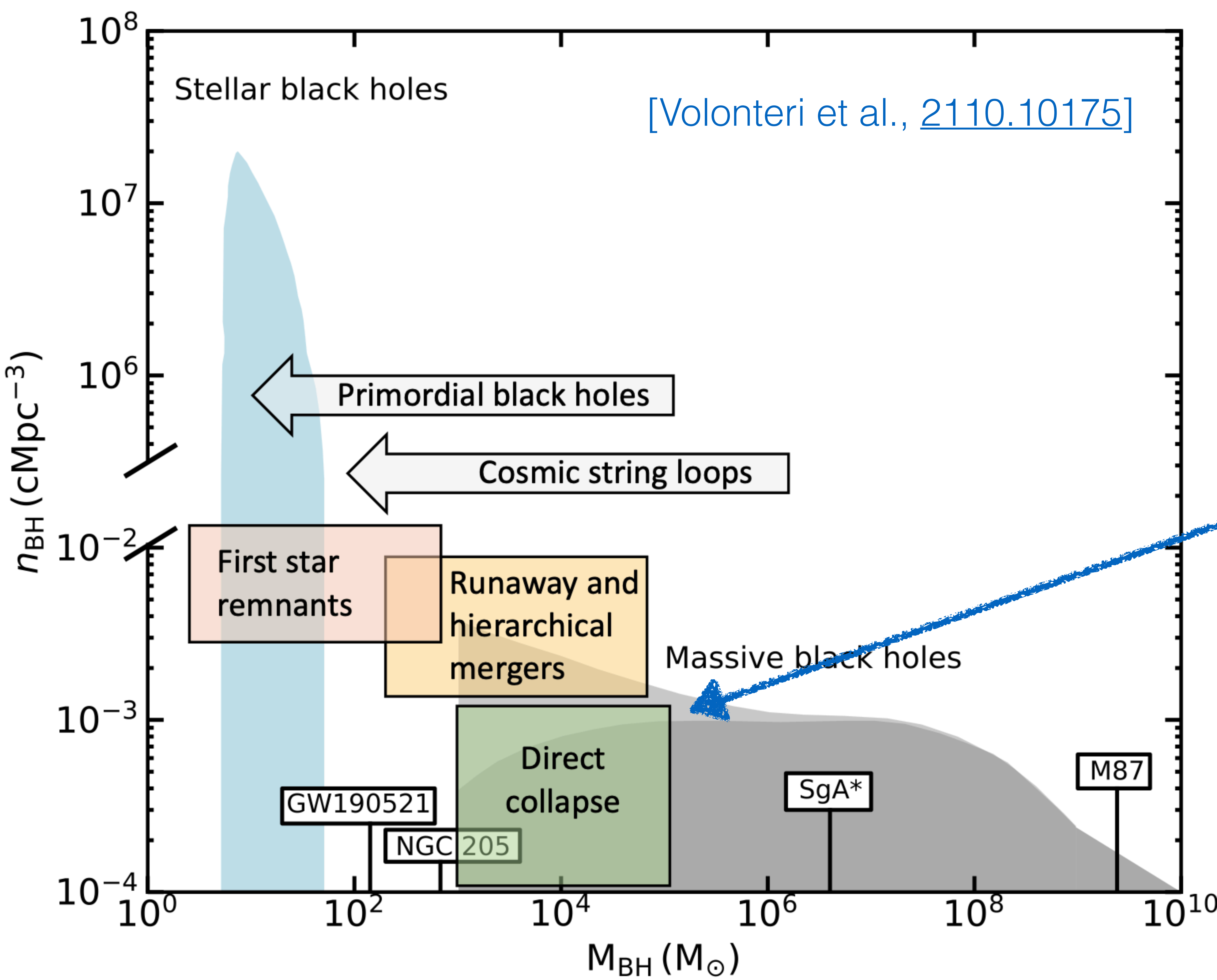
Many future directions



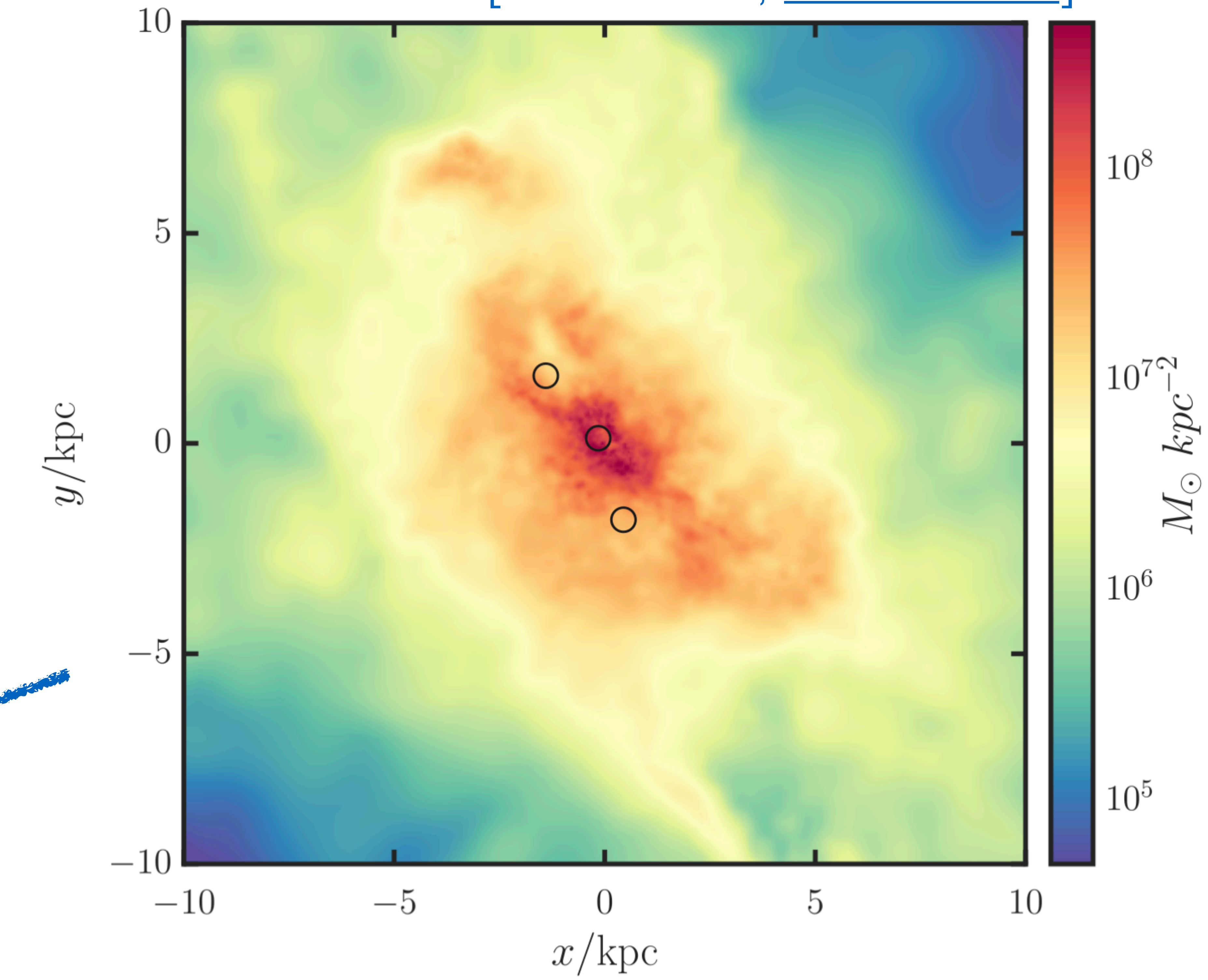
Many future directions



BH and Spike Formation



[Dunn et al., 1803.01007]



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

Carefully model the evolution of DM through the formation of the DCBH and subsequent growth by accretion.

How common are DM spikes around DCBHs, and what are their properties?

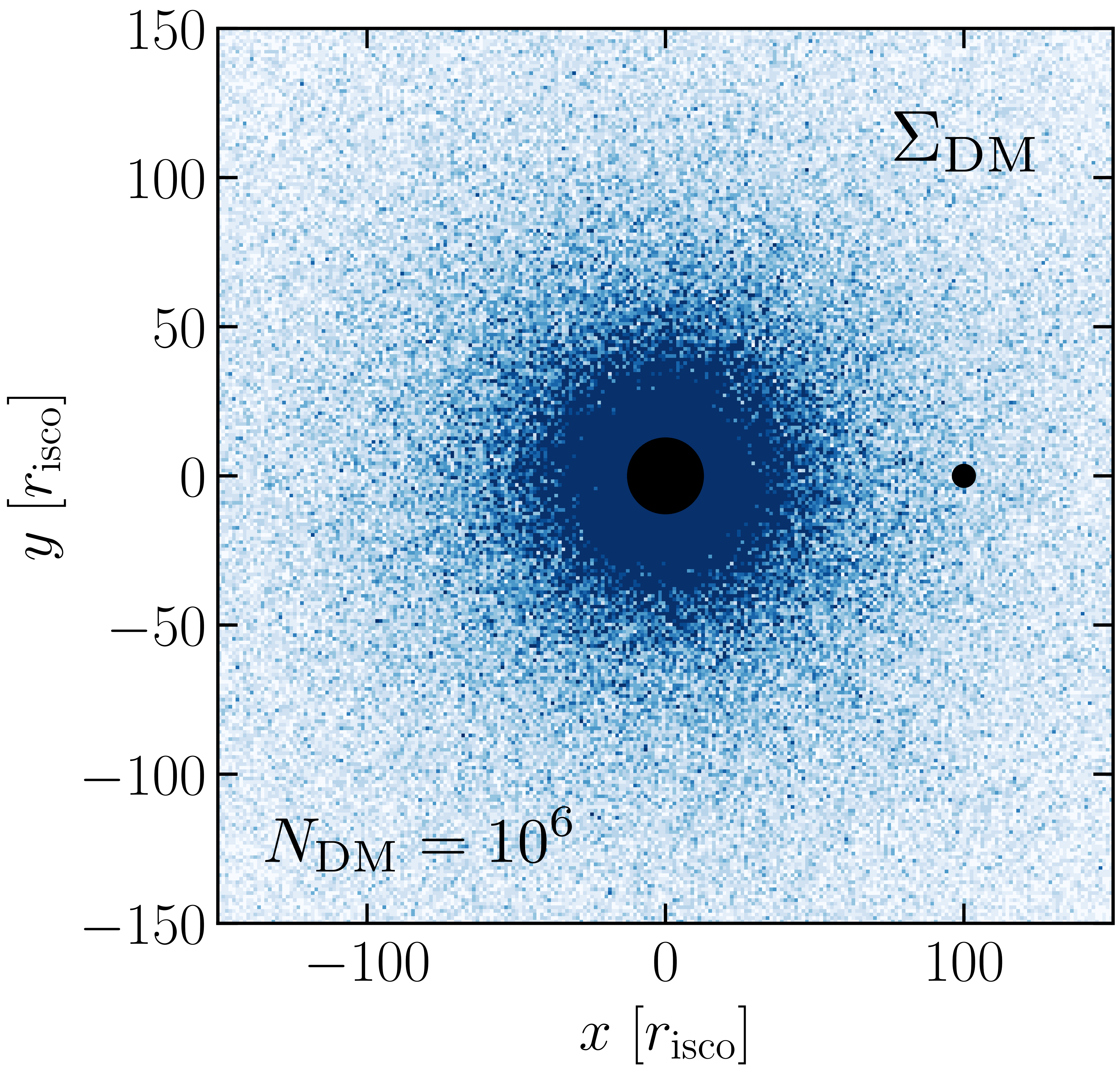
[Work in progress with Gianfranco Bertone, Daniele Gaggero, Renske Wierda, Leon Kamermans, Abram Perez, Pratika Dayal, & others]

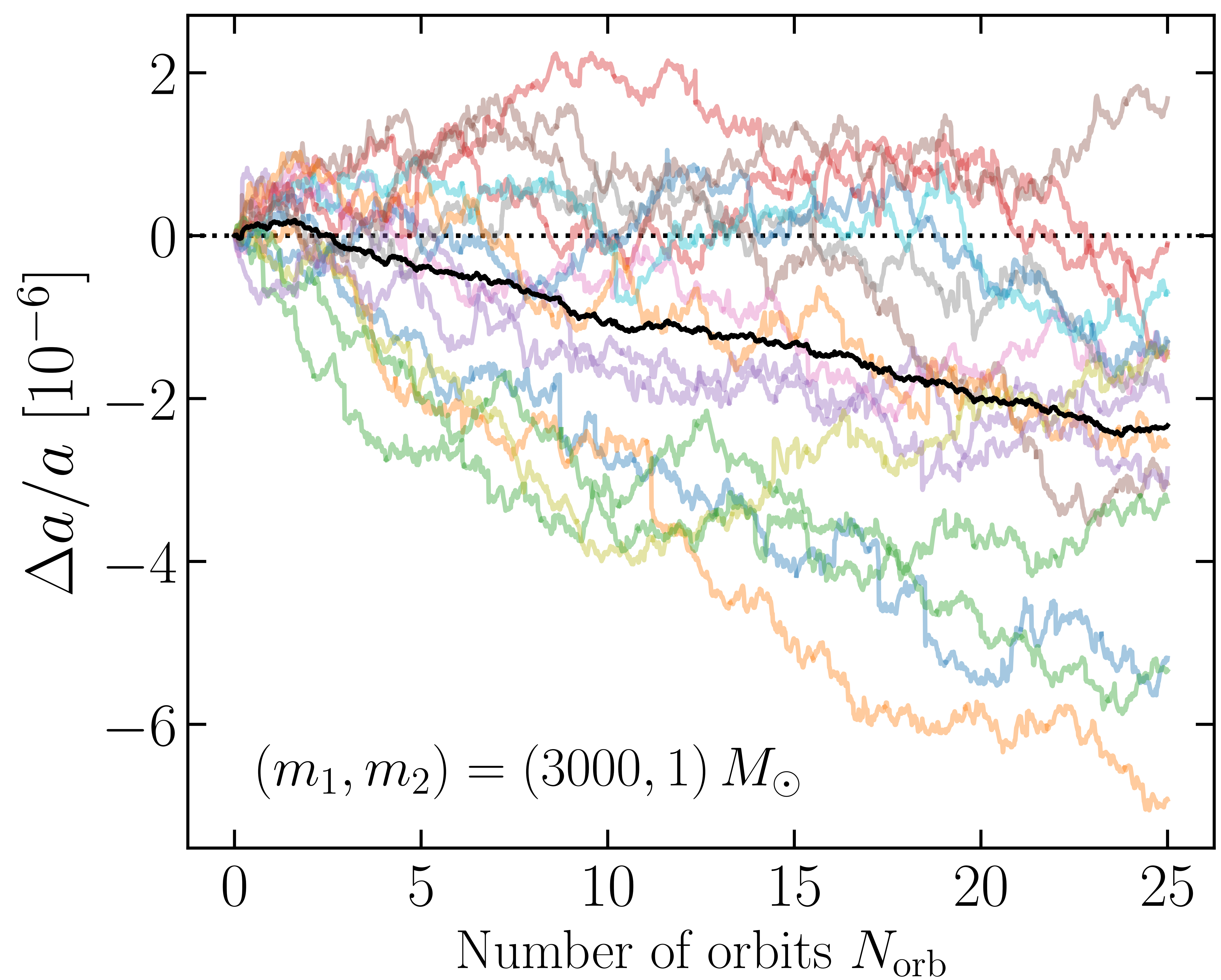
Simulations

Eventually need to expand and verify our description of dynamical friction and feedback in the DM spike (also include anisotropy, accretion, post-Newtonian corrections…)

NbodyIMRI: N-body solver tailored to DM spikes

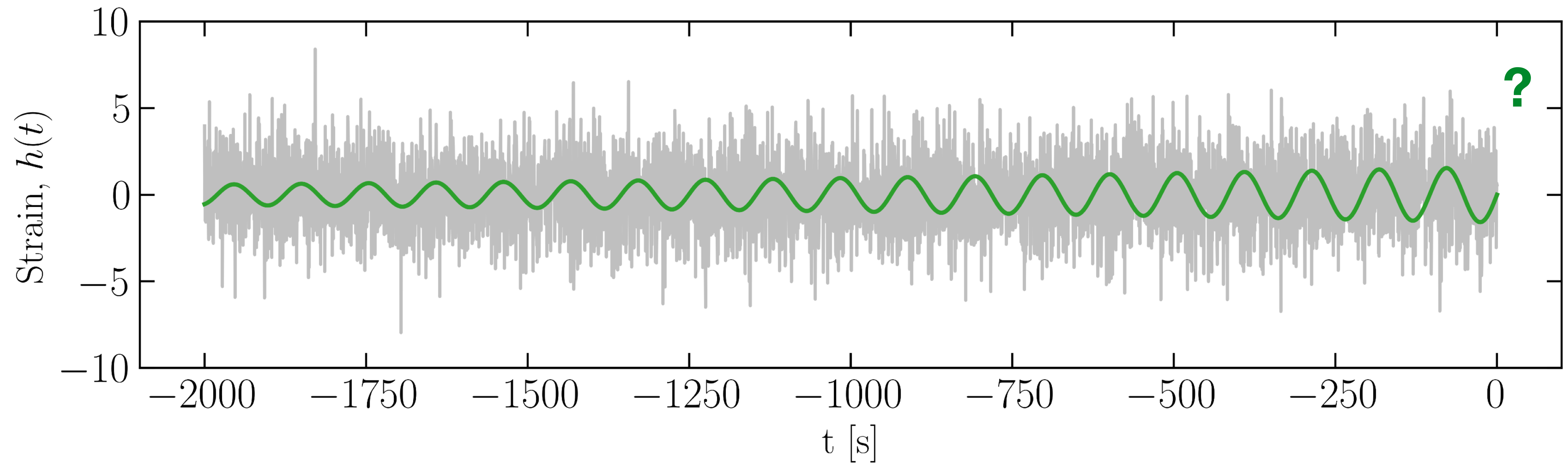
[Code here: github.com/bradkav/NbodyIMRI]





Search Strategies

Possible options:



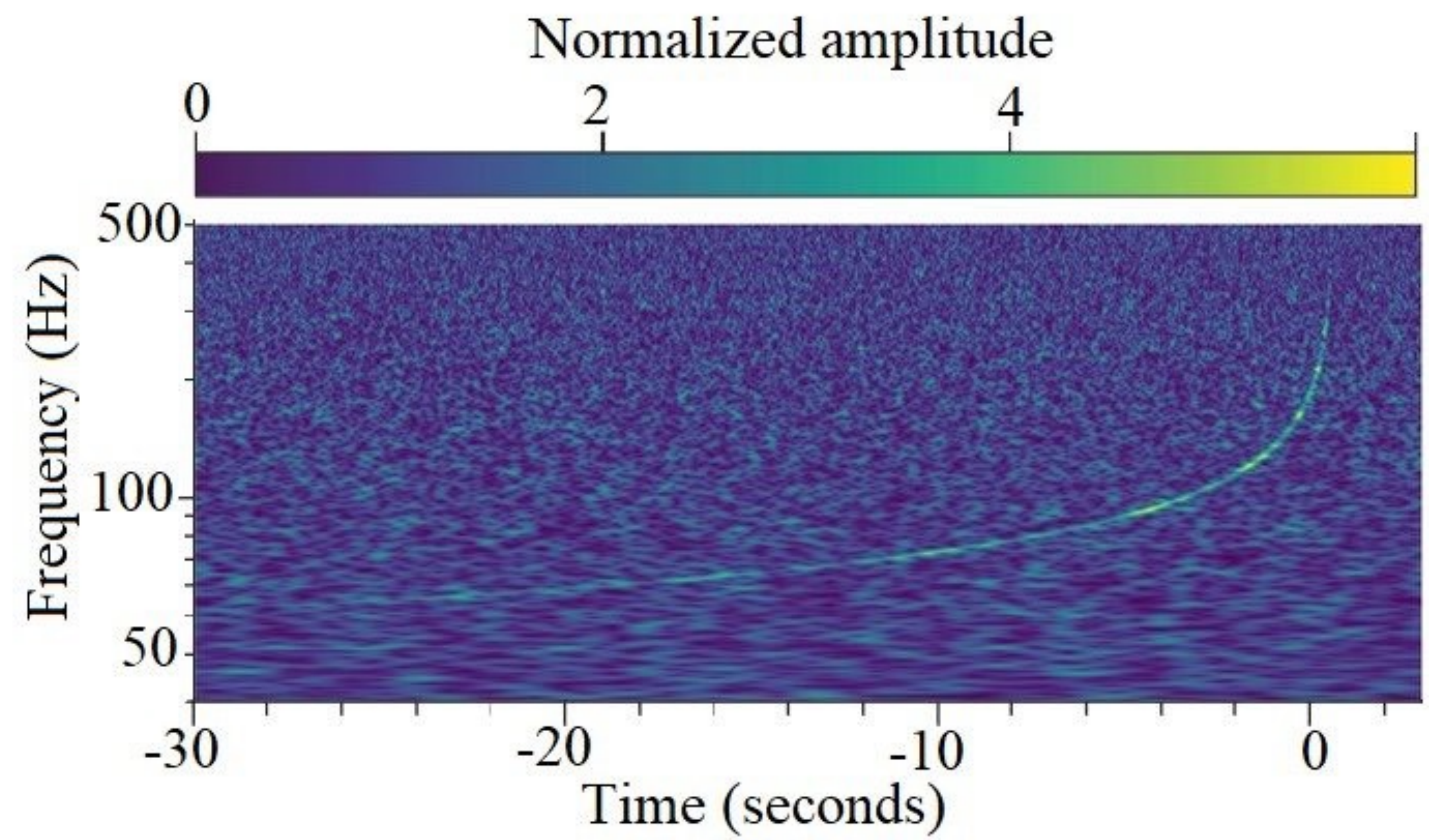
- Detect **GW signal close to merger** (where dephasing is small) then 'track back' through the data (as dephasing increases)

- Use '**generalised inspiral**' waveforms to parametrise the dephasing

[Chia & Edwards, 2004.06729]

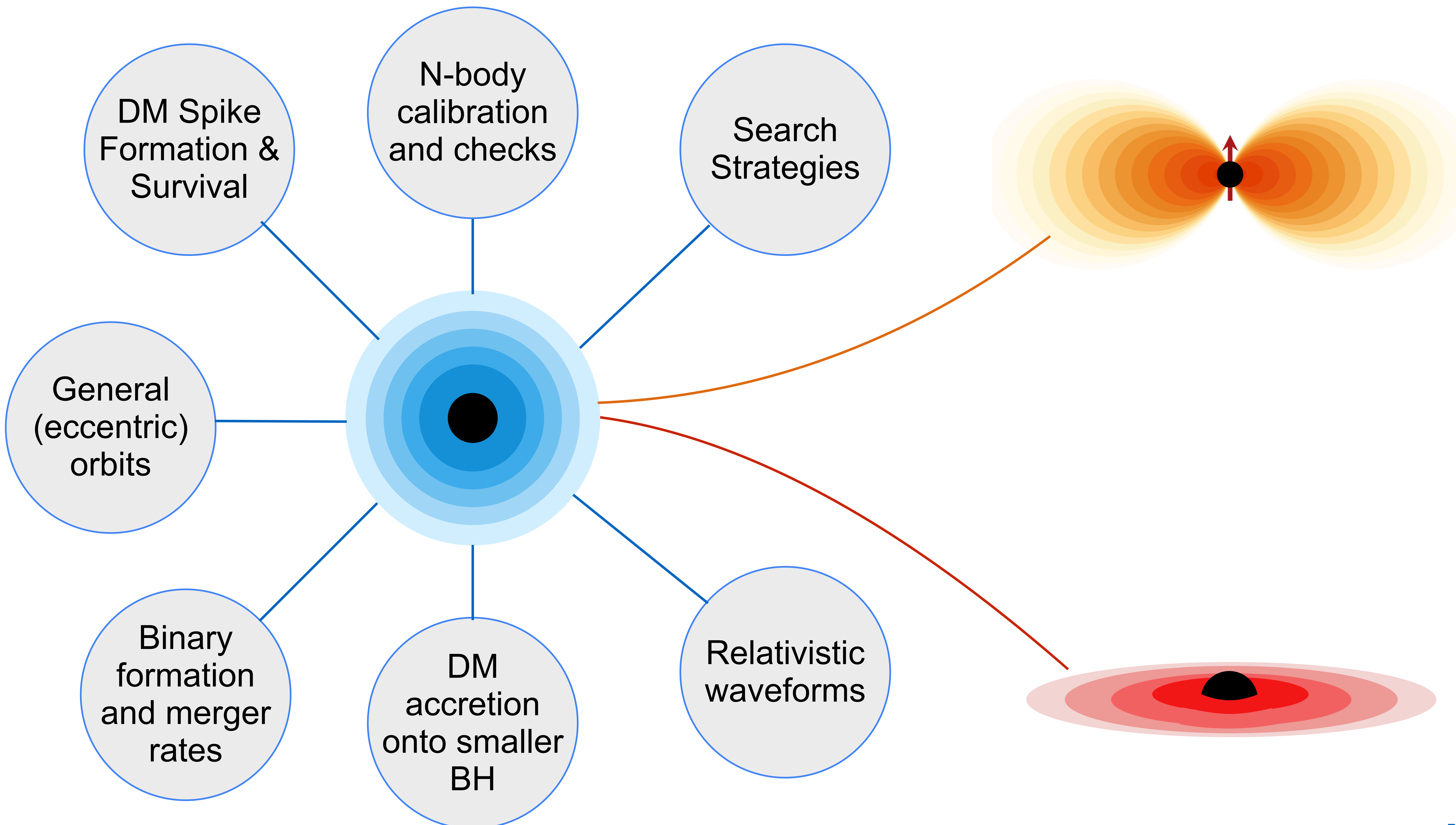
- Use tools from **continuous-wave searches**, breaking the inspiral into 'chunks' and looking for quasi-monochromatic signals in each chunk (e.g. Hough transform)

[Guo & Miller, 2205.10359]



Map $f(t) \rightarrow (f, \dot{f})$?

Many future directions

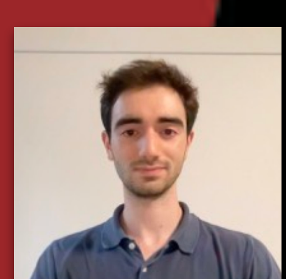


A Collective Effort

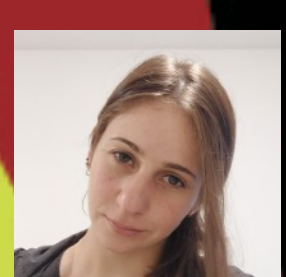

Gianfranco Bertone
(GRAPPA, Amsterdam)


Pippa Cole
(GRAPPA, Amsterdam)

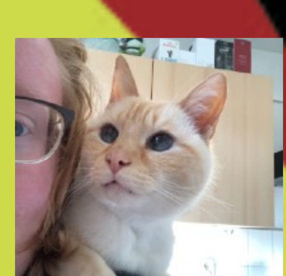

Samaya Nissanke
(GRAPPA, Amsterdam)

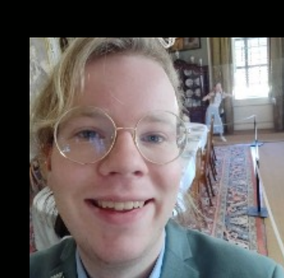

Gimmy Tomaselli
(GRAPPA, Amsterdam)


Alessandro Parisi
(GRAPPA, Amsterdam)


Ismini Andrianou
(GRAPPA, Amsterdam)


Daniel Baumann
(GRAPPA, Amsterdam)


Renske Wierda
(GRAPPA, Amsterdam)

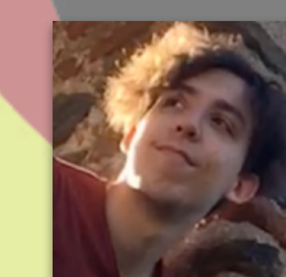

Leon Kamermans
(GRAPPA, Amsterdam)


Adam Coogan
(Mila, Montreal)

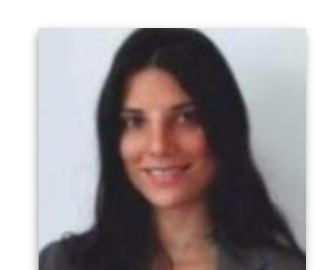

Tom Edwards
(Johns Hopkins)

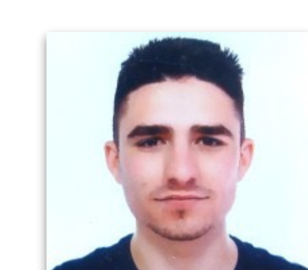

Daniele Gaggero
(IFT, Madrid)


David Nichols
(U. Virginia)


Theophanes Karydas
(GRAPPA, Amsterdam)


Jose Maria Diego
(IFCA, Santander)


Francesca Scarcella
(IFT, Madrid)


Abram Perez Herrero
(IFCA, Santander)

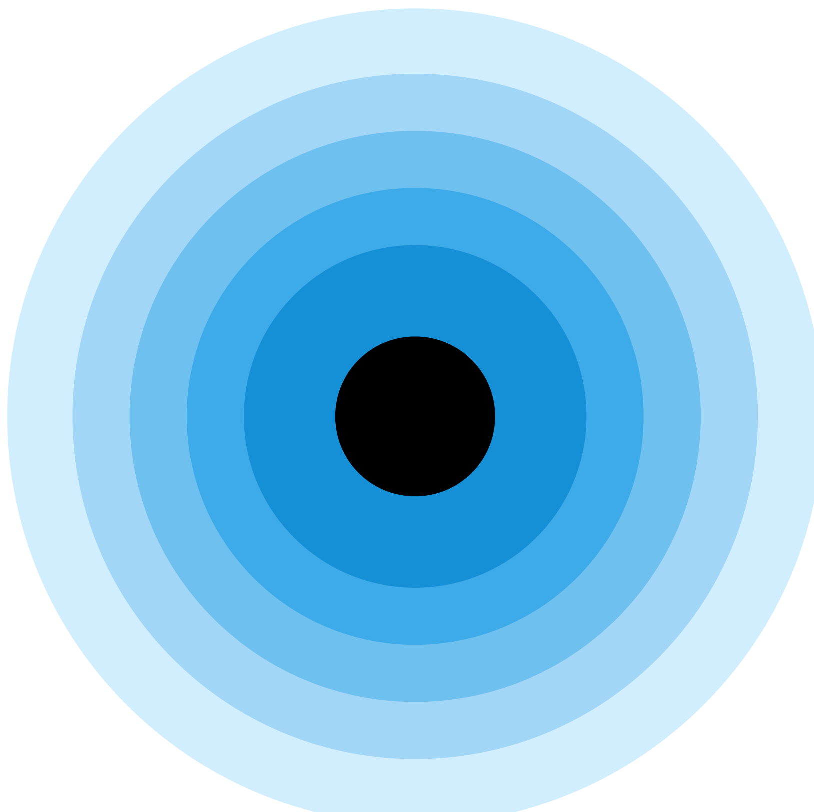

Pratibha Jangra
(IFCA, Santander)

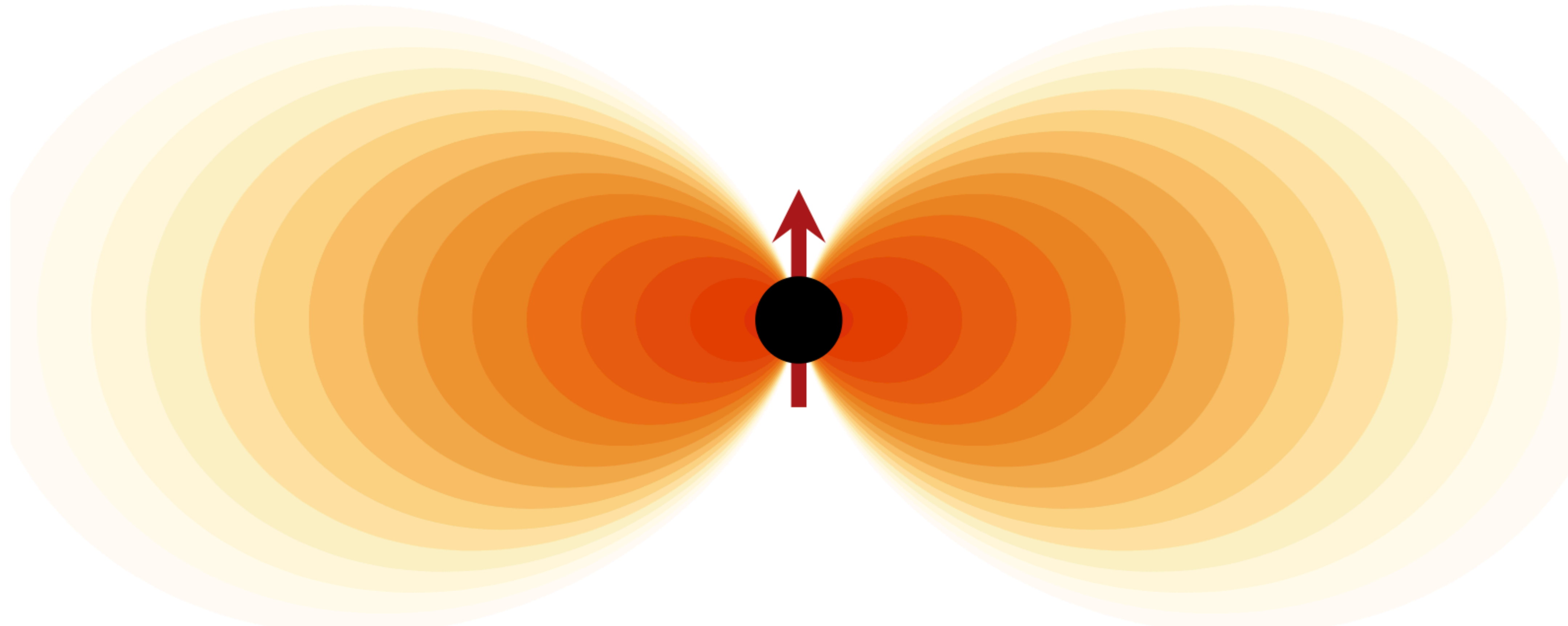
…and others…

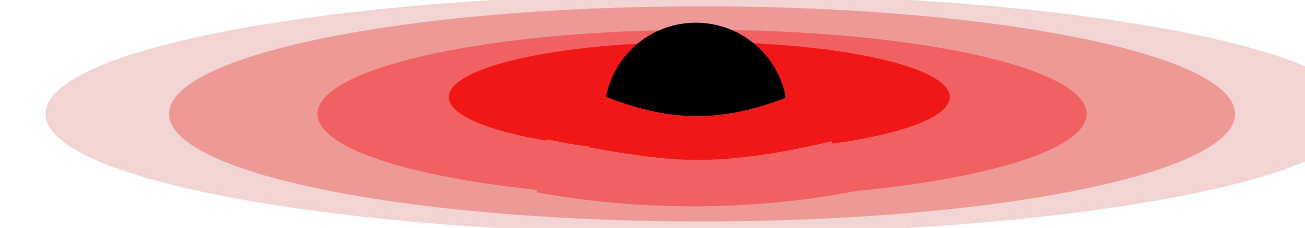
A Collective Effort

Fuel for Science

Conclusions





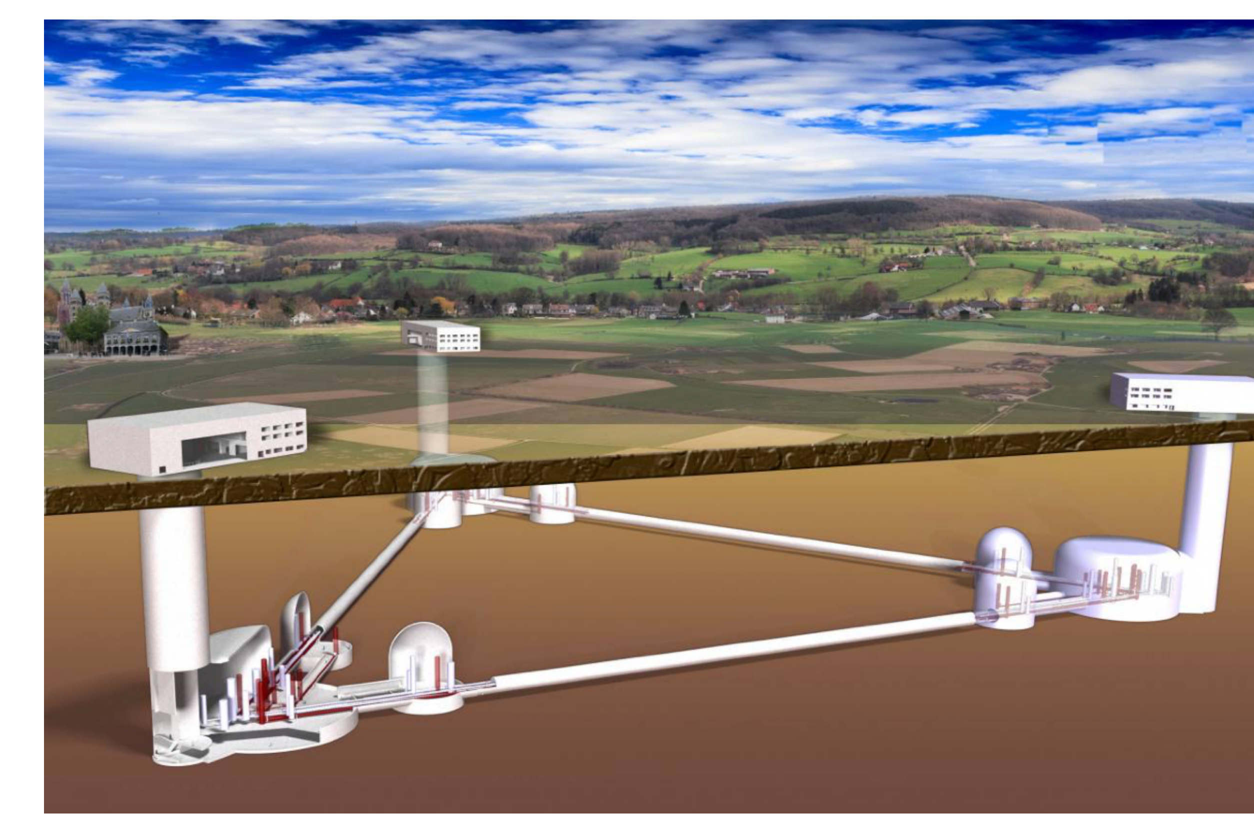


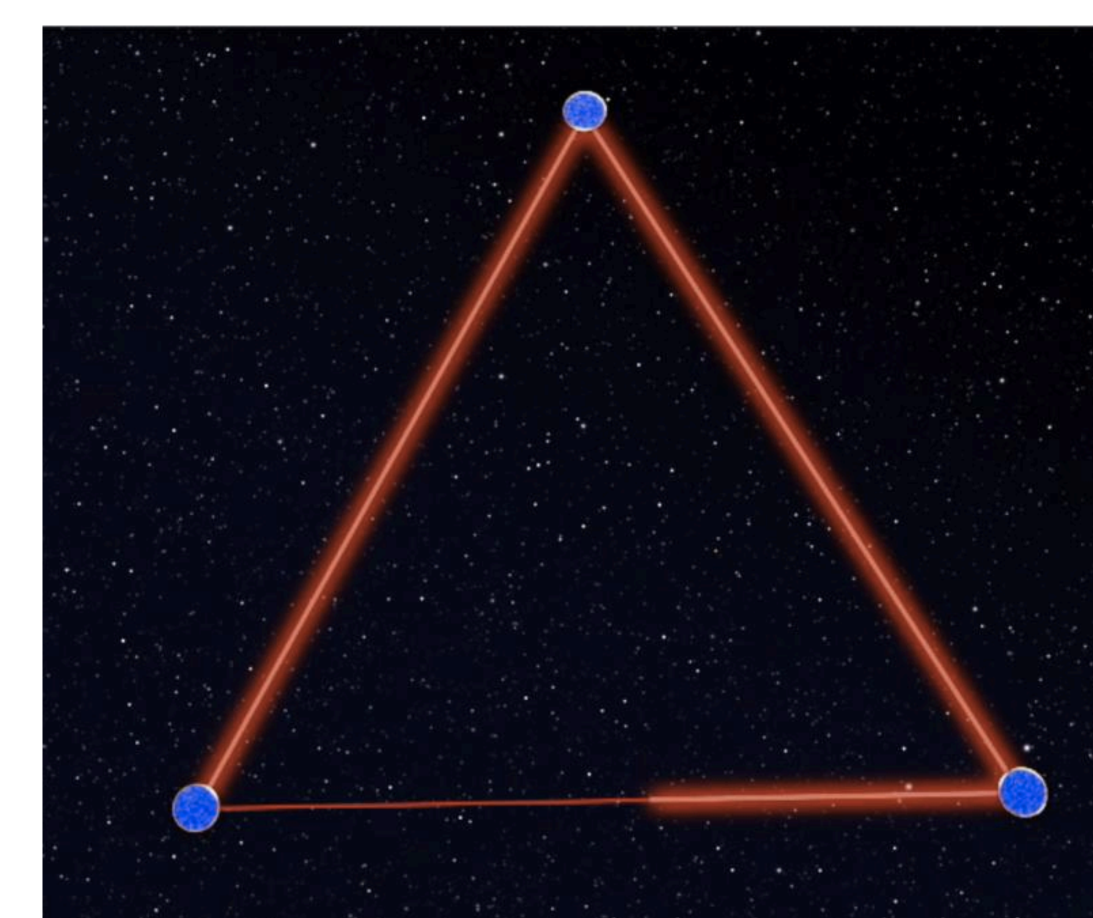
Understanding Black Hole environments represents both a **great challenge** and a **great opportunity** for future GW searches.

A true GRAPPA problem: General Relativity, Gravitational Waves, Accretion, Dark Matter, complex data analysis.

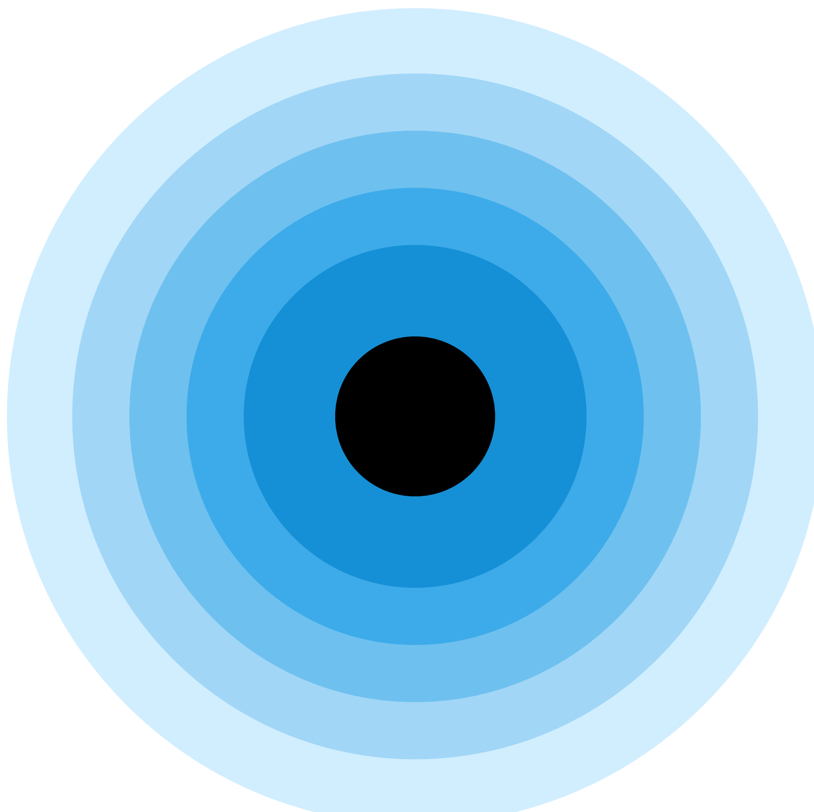
Many problems and questions still to tackle!

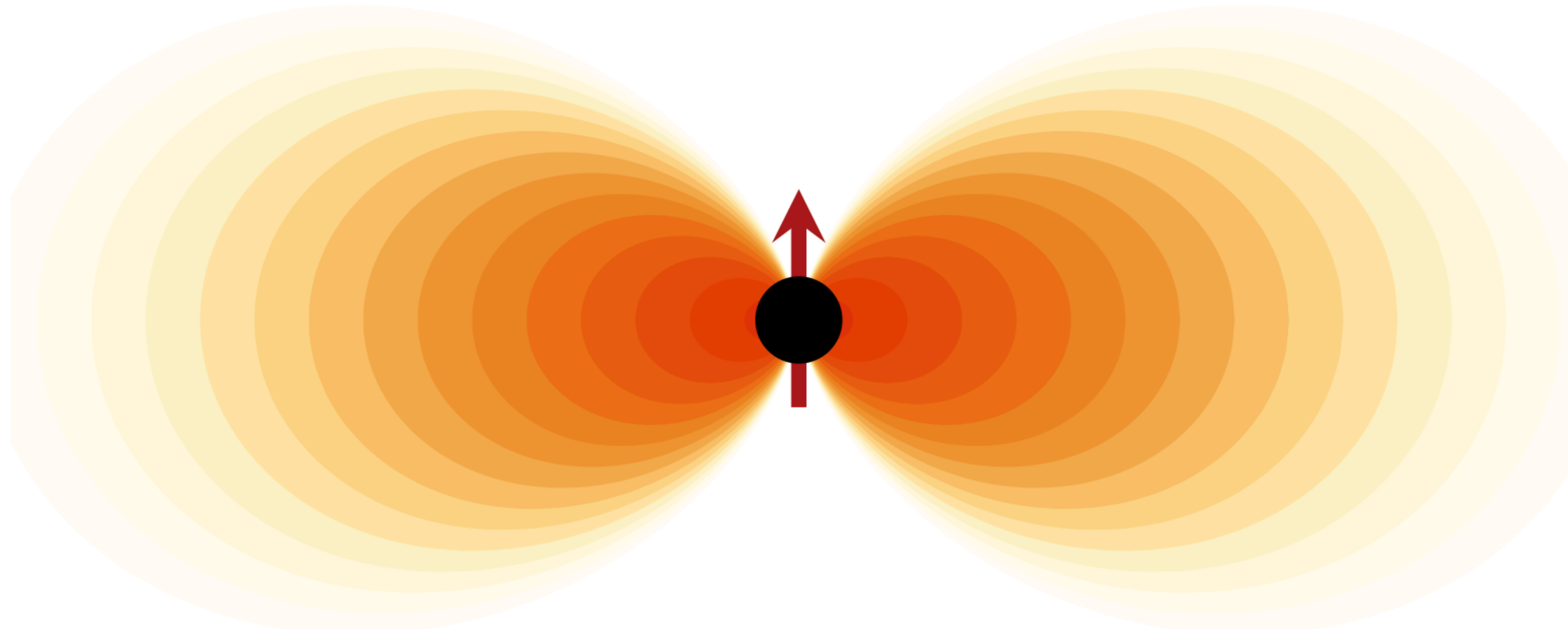
Many great people working hard with and within GRAPPA to solve them!

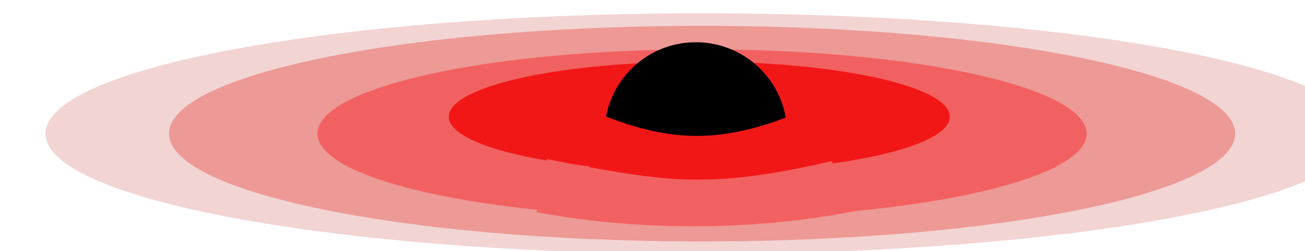




Conclusions







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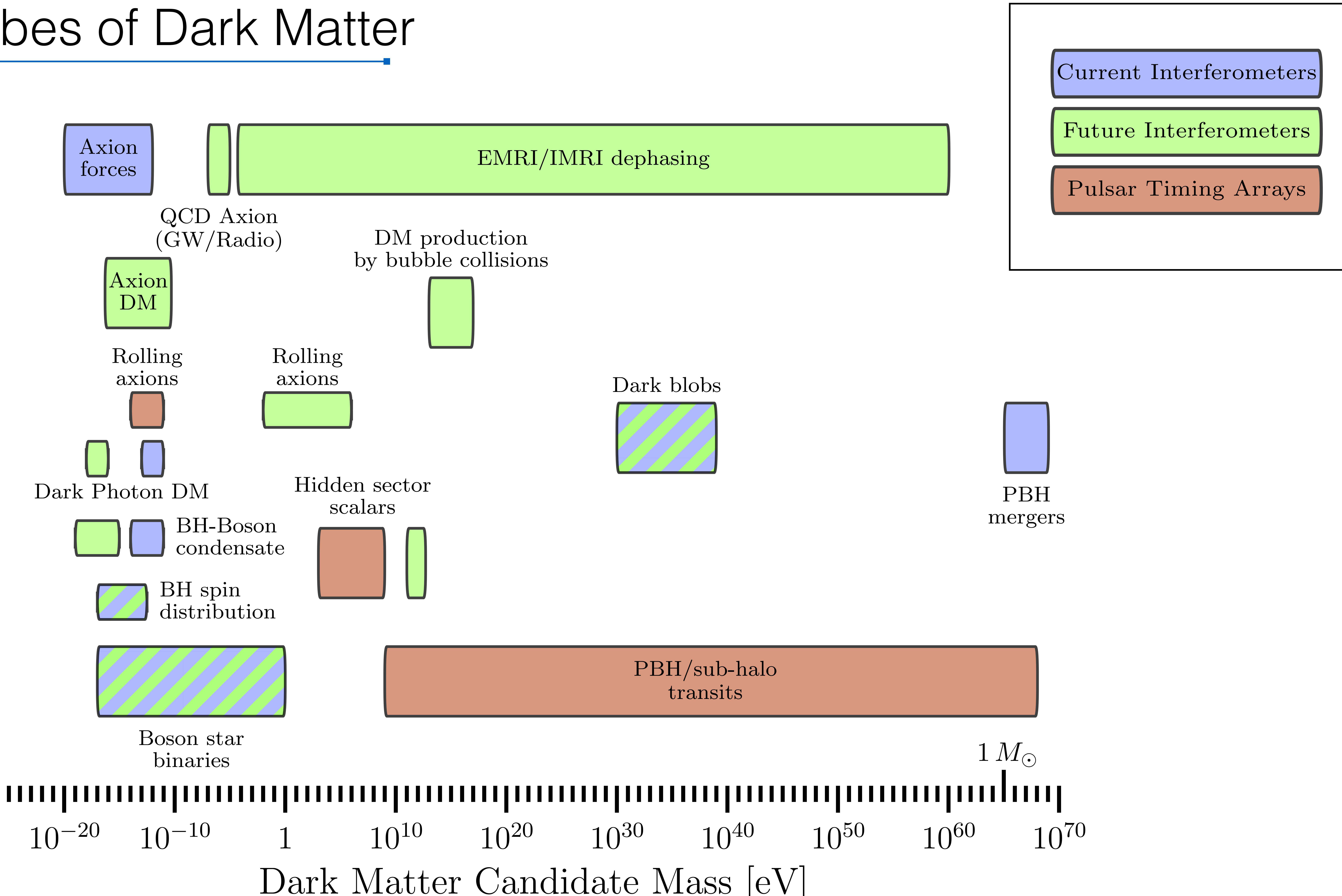
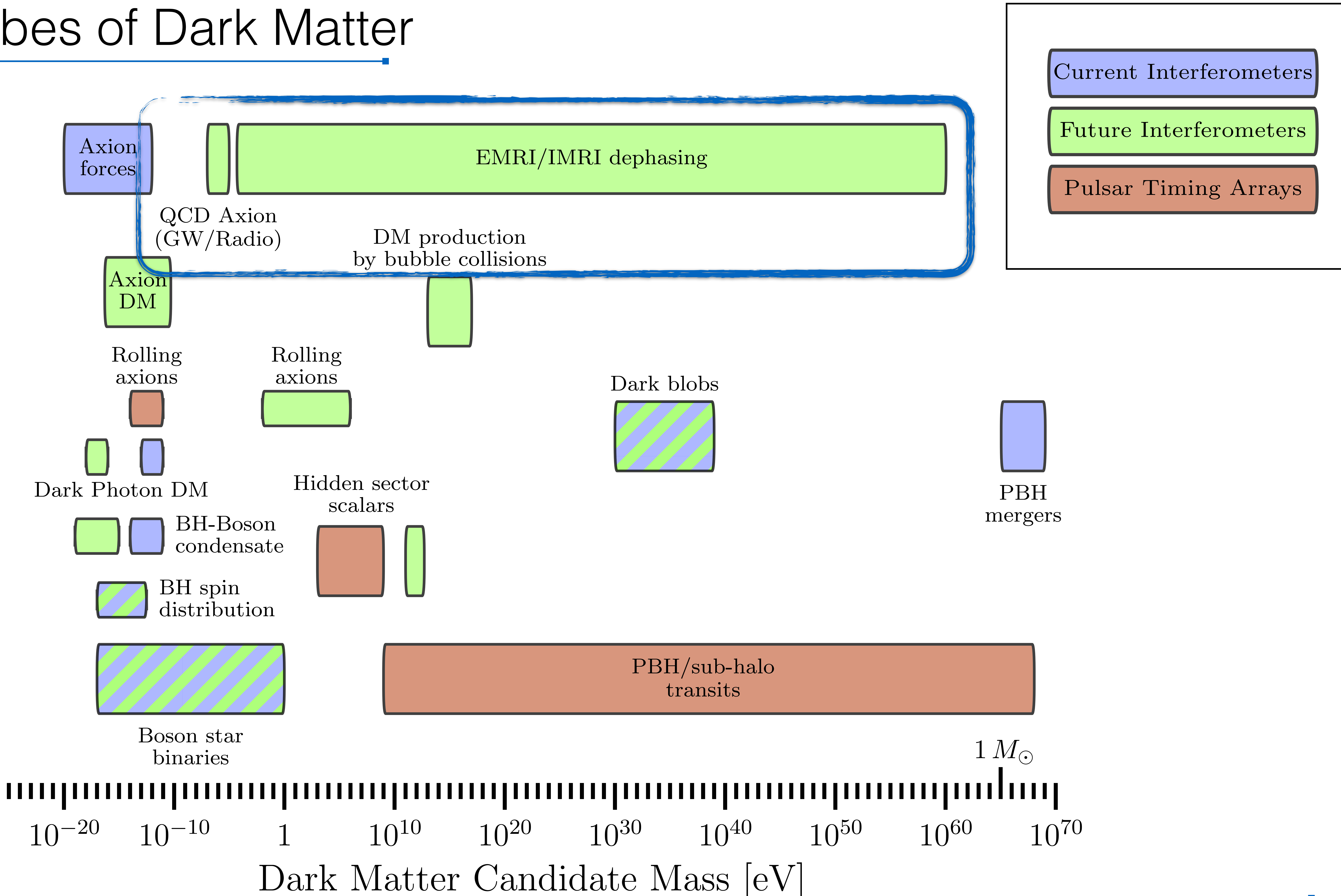
Backup Slides

GW Probes of Dark Matter



[Bertone, Croon, et al (including **BJK**), 1907.10610]

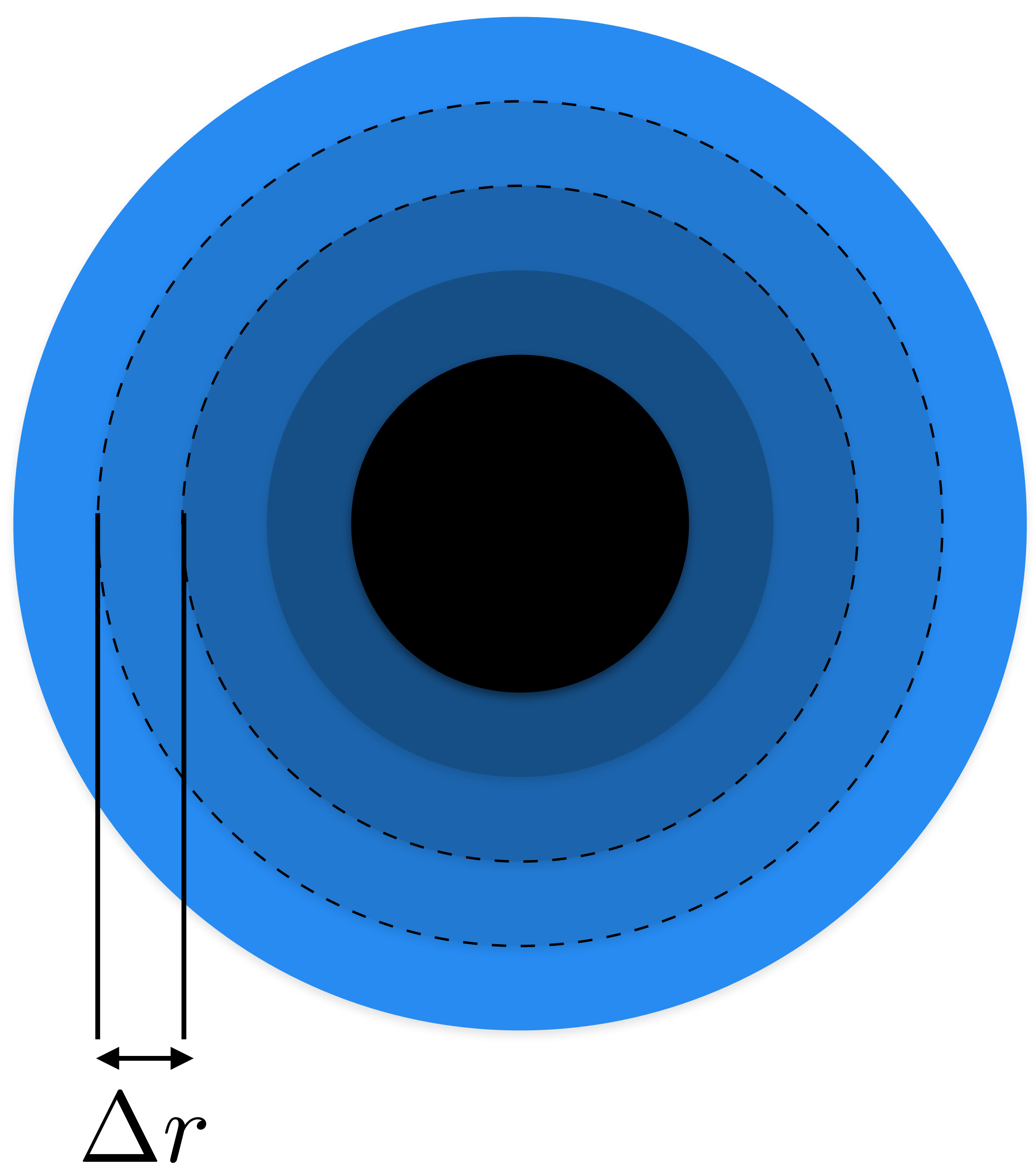
GW Probes of Dark Matter



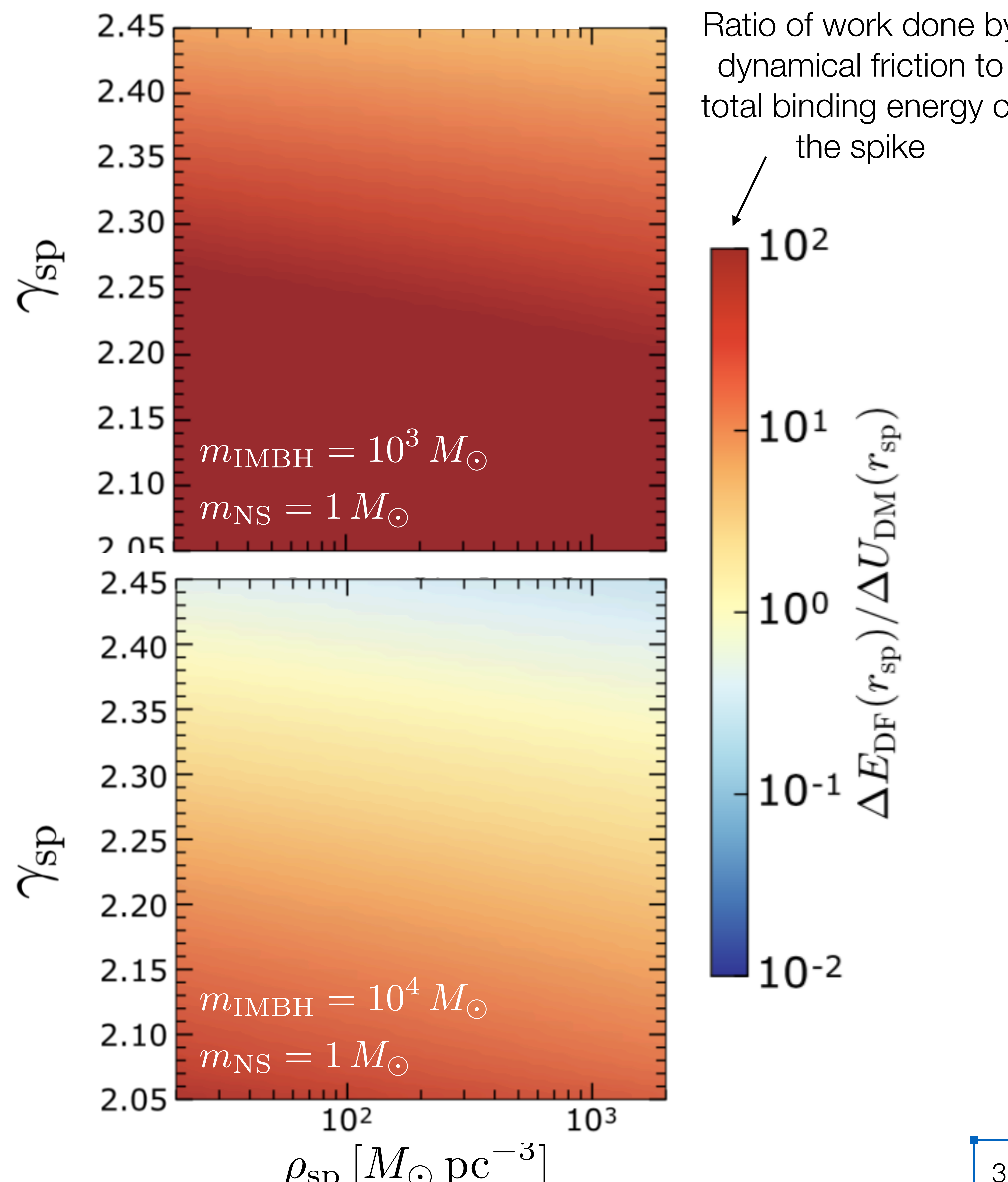
[Bertone, Croon, et al (including **BJK**), 1907.10610]

DM Spikes Energy Conservation

Q: How much energy is *available* for dynamical friction?



A: Binding energy of DM $\Delta U_{\rm DM}$ over radius Δr



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

Self-consistent Evolution

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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' $\Delta\mathcal{E}$

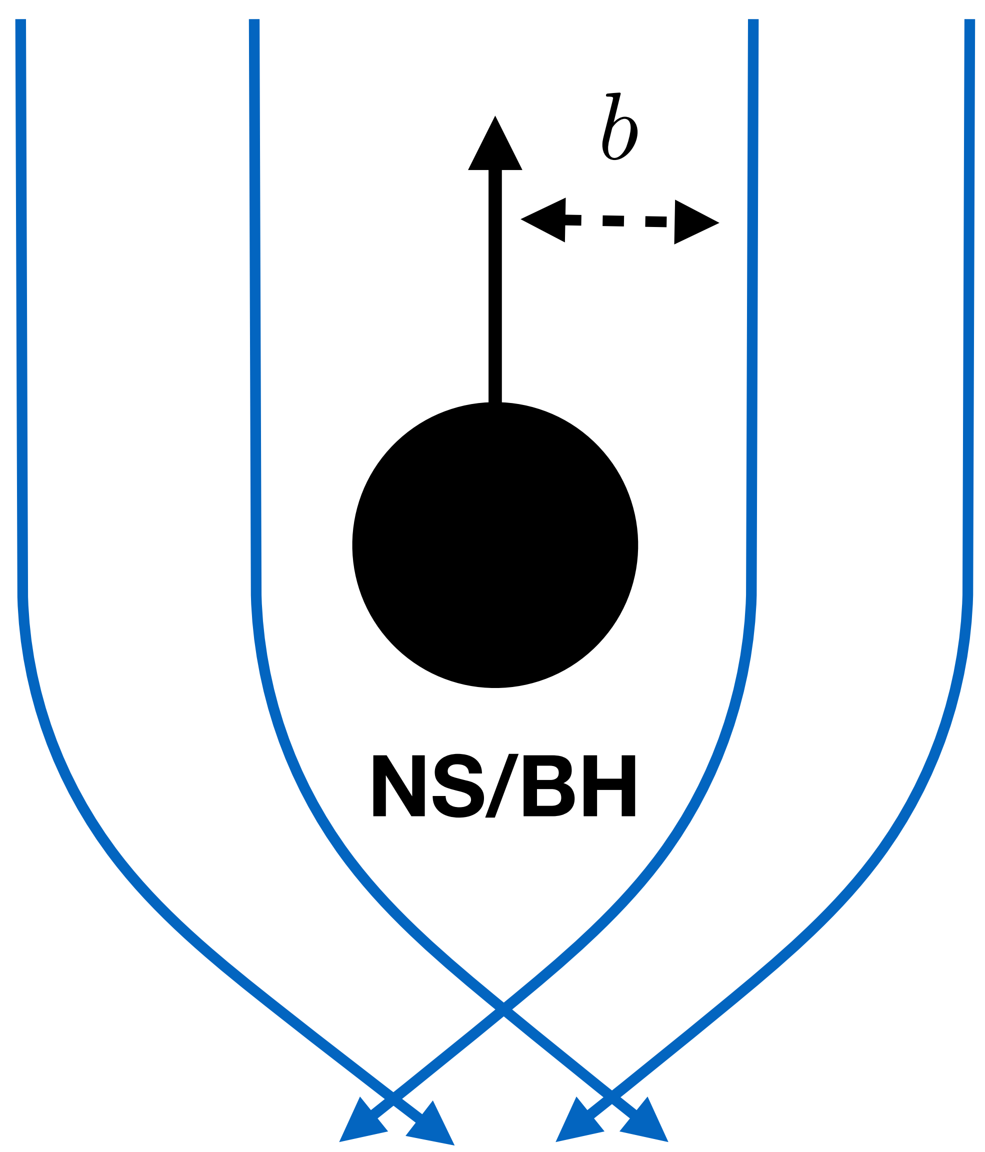
$$p_{\mathcal{E}} = \int P_{\mathcal{E}}(\Delta\mathcal{E})\,\mathrm{d}\Delta\mathcal{E}$$

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

Scattering Probability

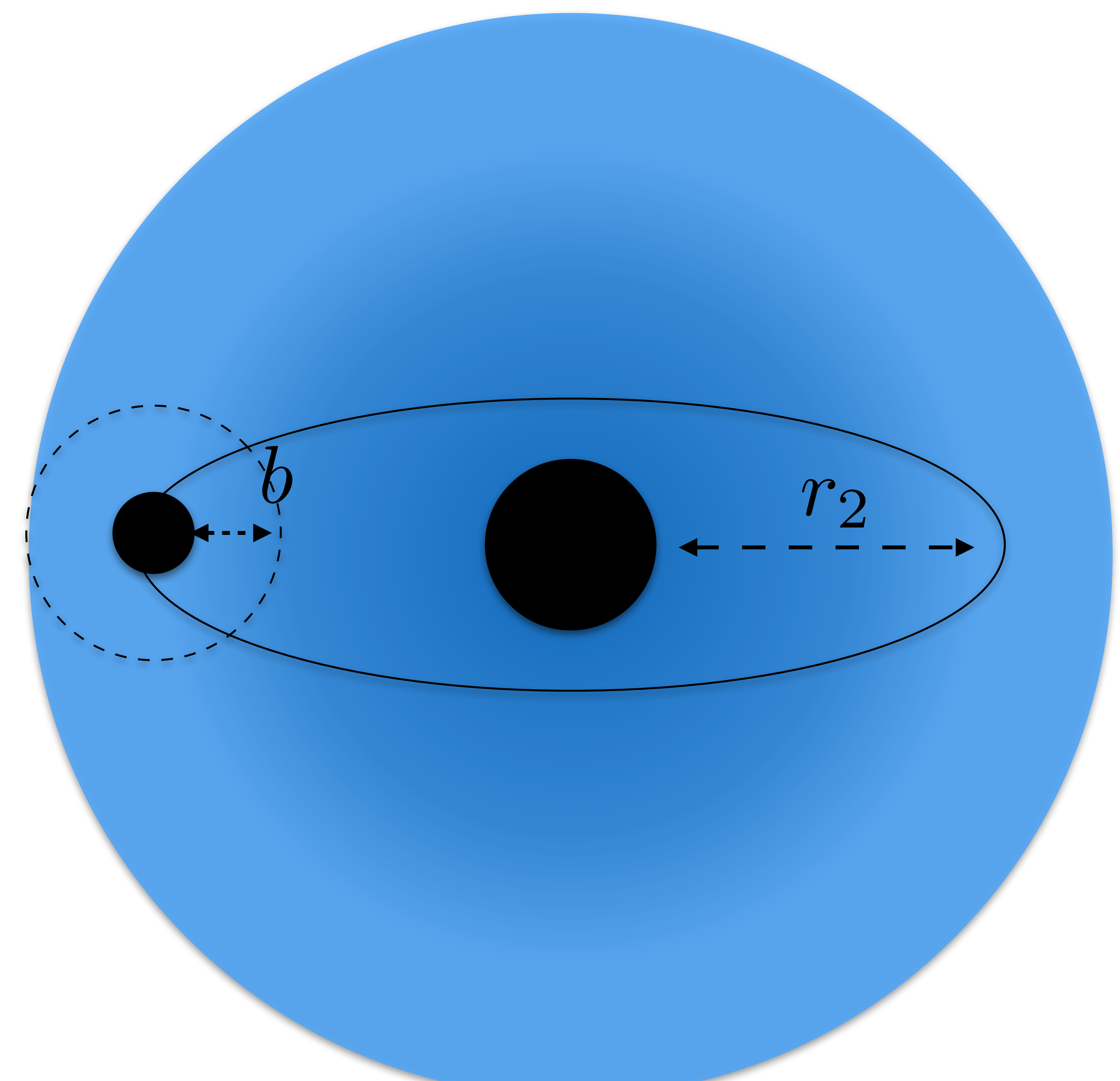
Two body scattering problem relates energy exchange to impact parameter:

$$\Delta\mathcal{E}(b) = -2v_0^2\left[1 + \frac{b^2 {v_0}^4}{G^2 {m_2}^2}\right]^{-1}$$



Scattering probability becomes a *geometric* problem:

$$P_\mathcal{E}(\Delta\mathcal{E}) \propto P(b|\mathcal{E})$$



Code available online: github.com/bradkav/HaloFeedback
(See also https://github.com/DMGW-Goethe/imripy)