Black Hole Inspirals: Lessons for Dark Matter

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Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN
IFCA Instituto de Física de Cantabria
CSIC Consejo Superior de Investigaciones Científicas
50 UC Universidad de Cantabria

Instituto de Física de Cantabria

Keep an eye out for our biannual conference:

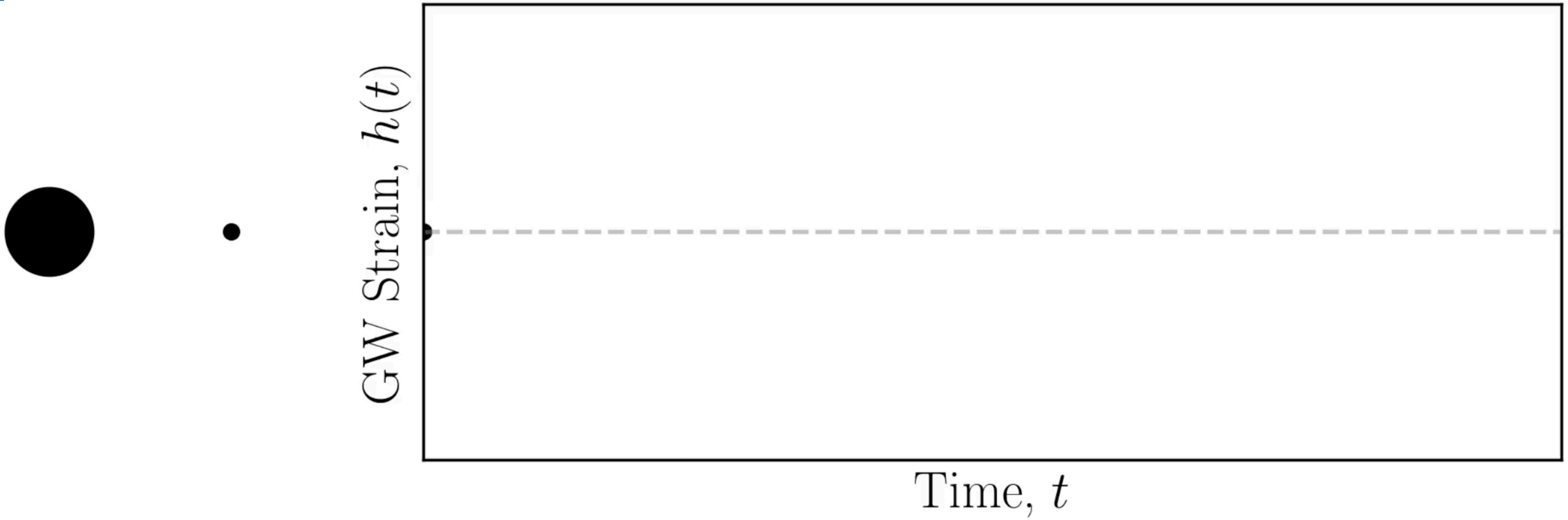
Dark Matter 2025: From the Smallest to the Largest Scales

…Coming Spring/Summer 2025

[Previous edition: DM2023]

Gravitational Wave Dephasing

[Animations online]



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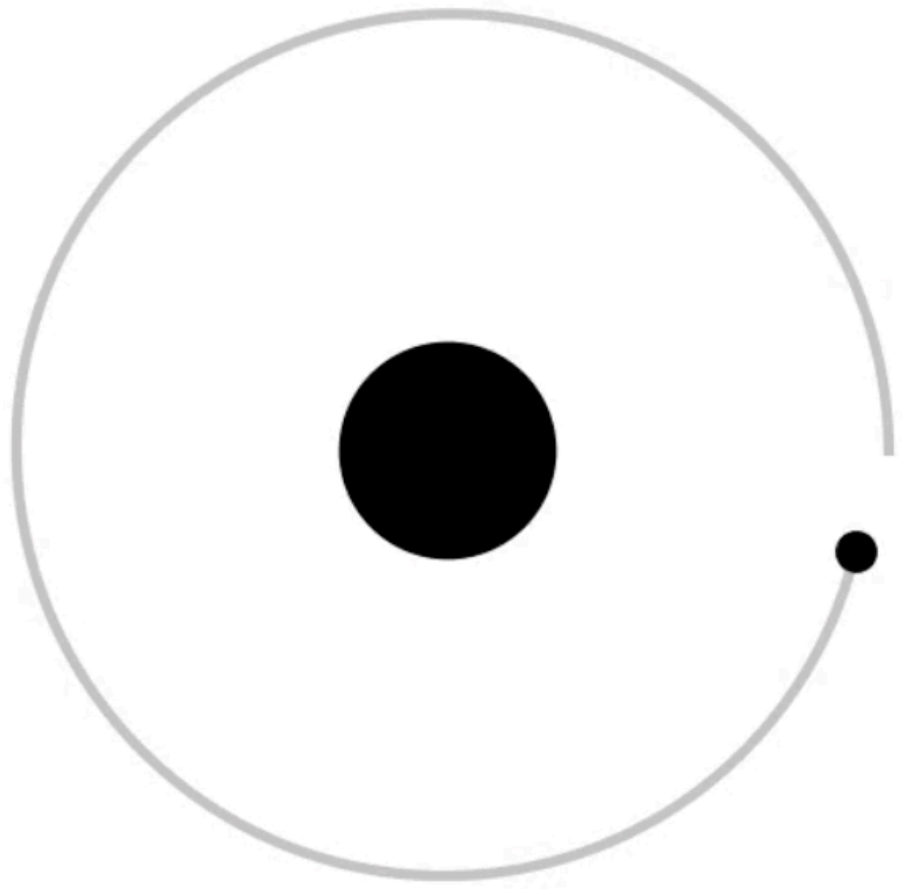

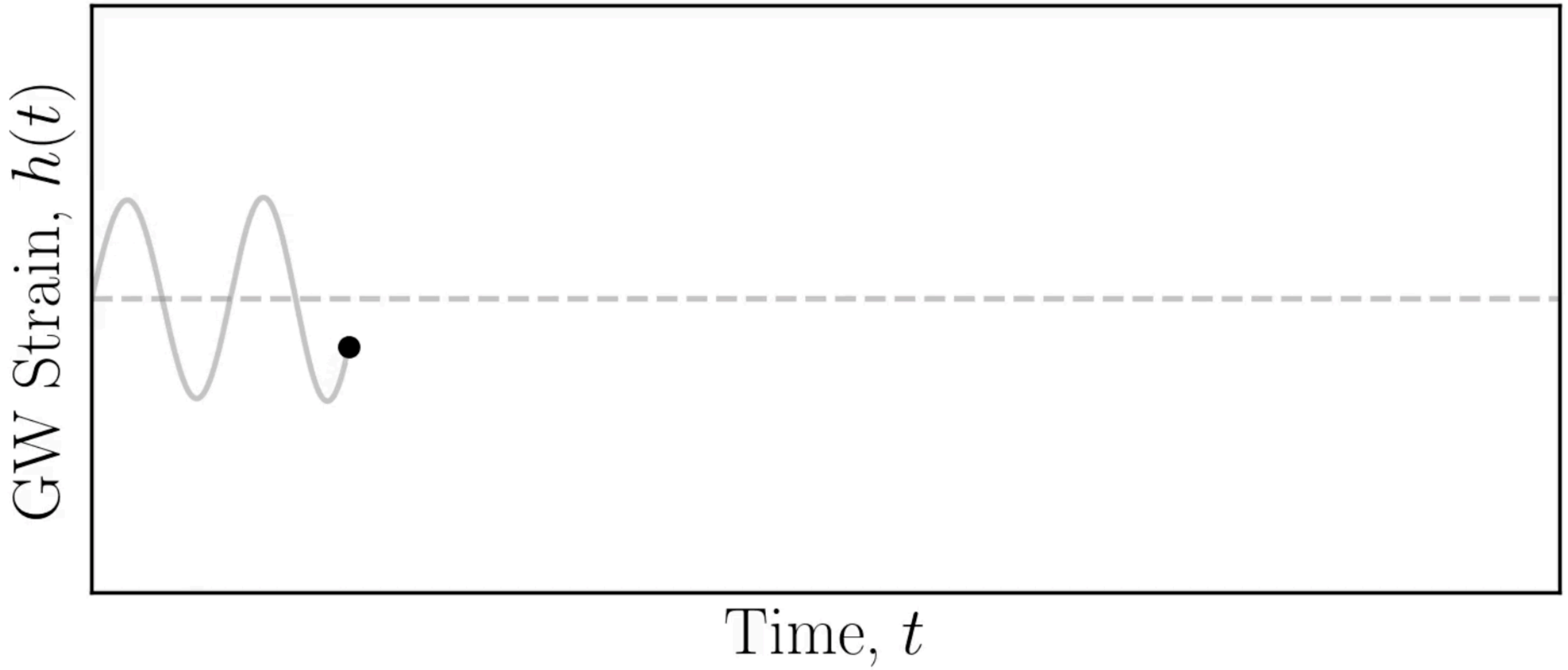

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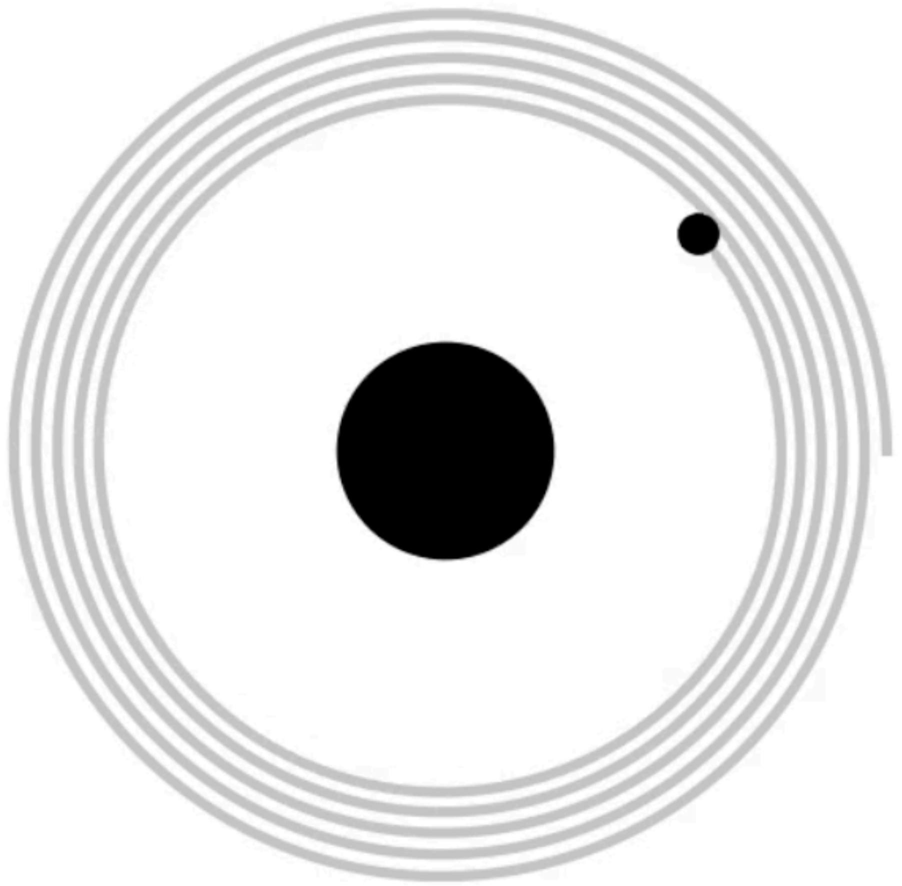

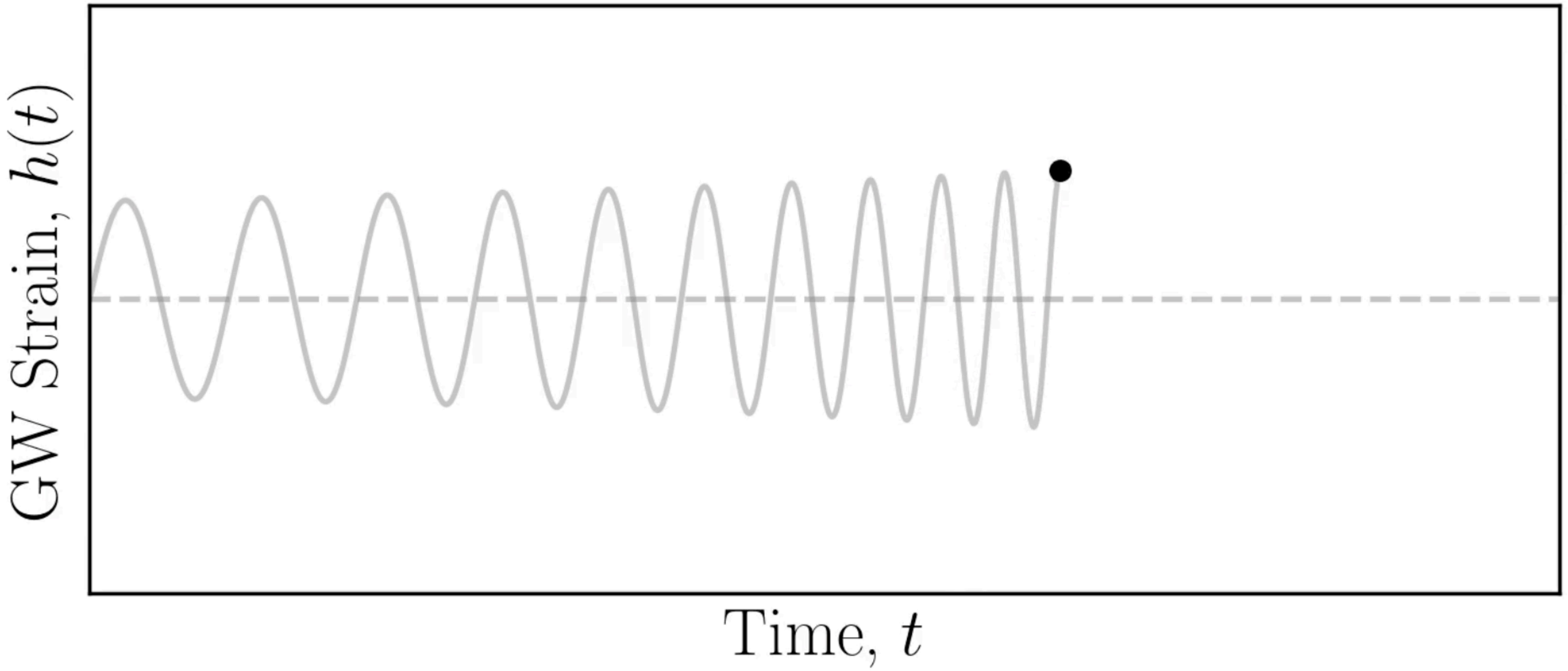

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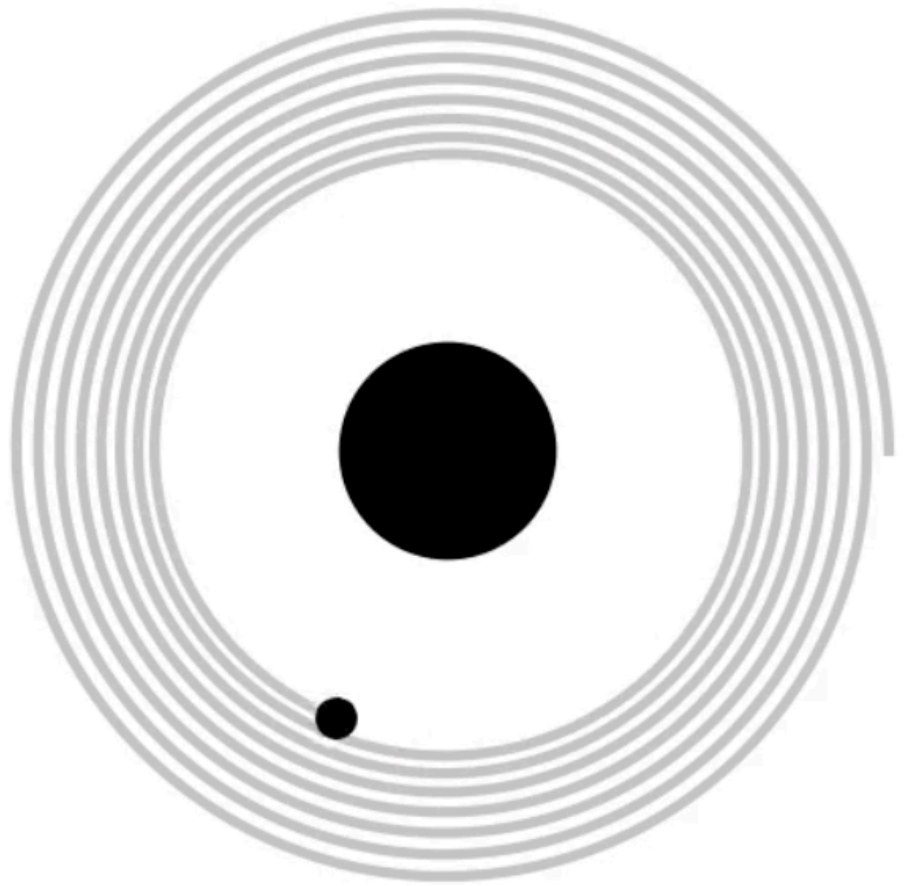

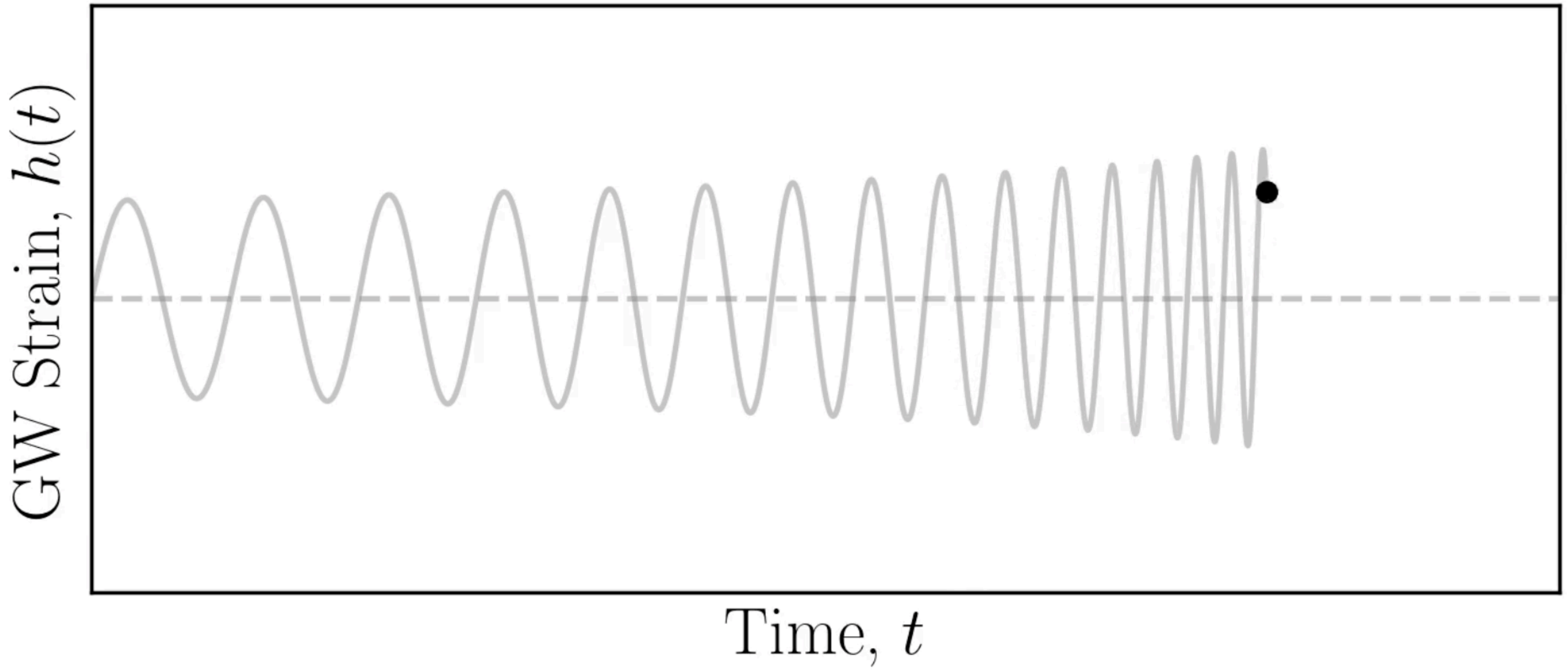

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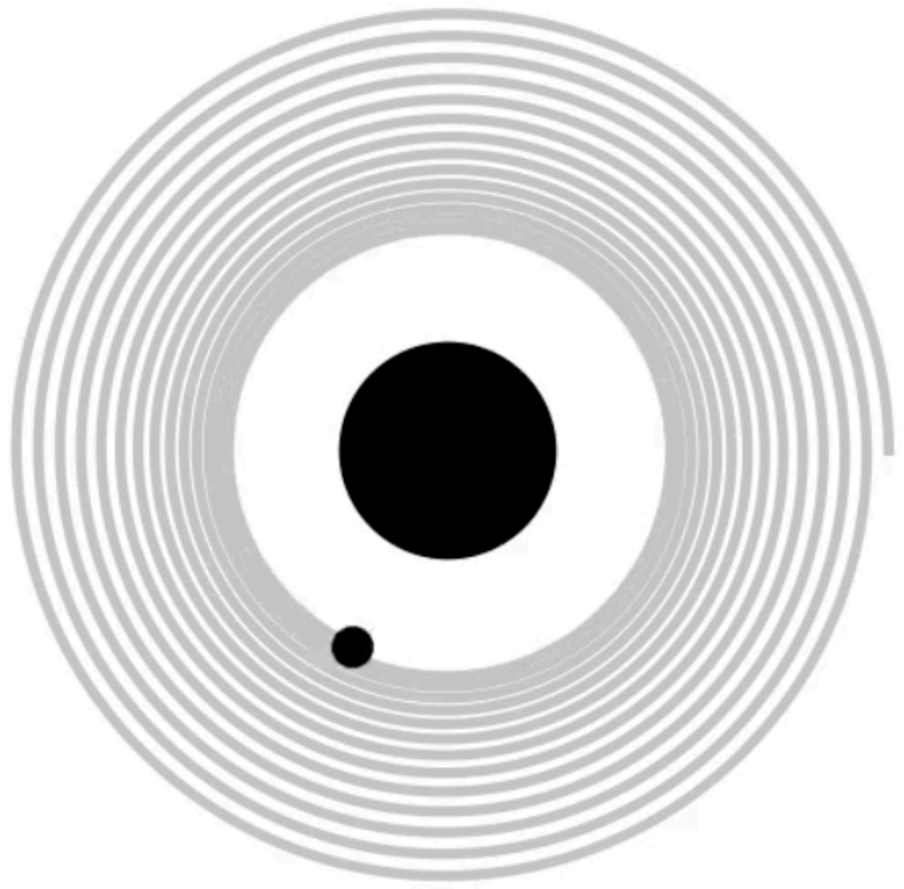

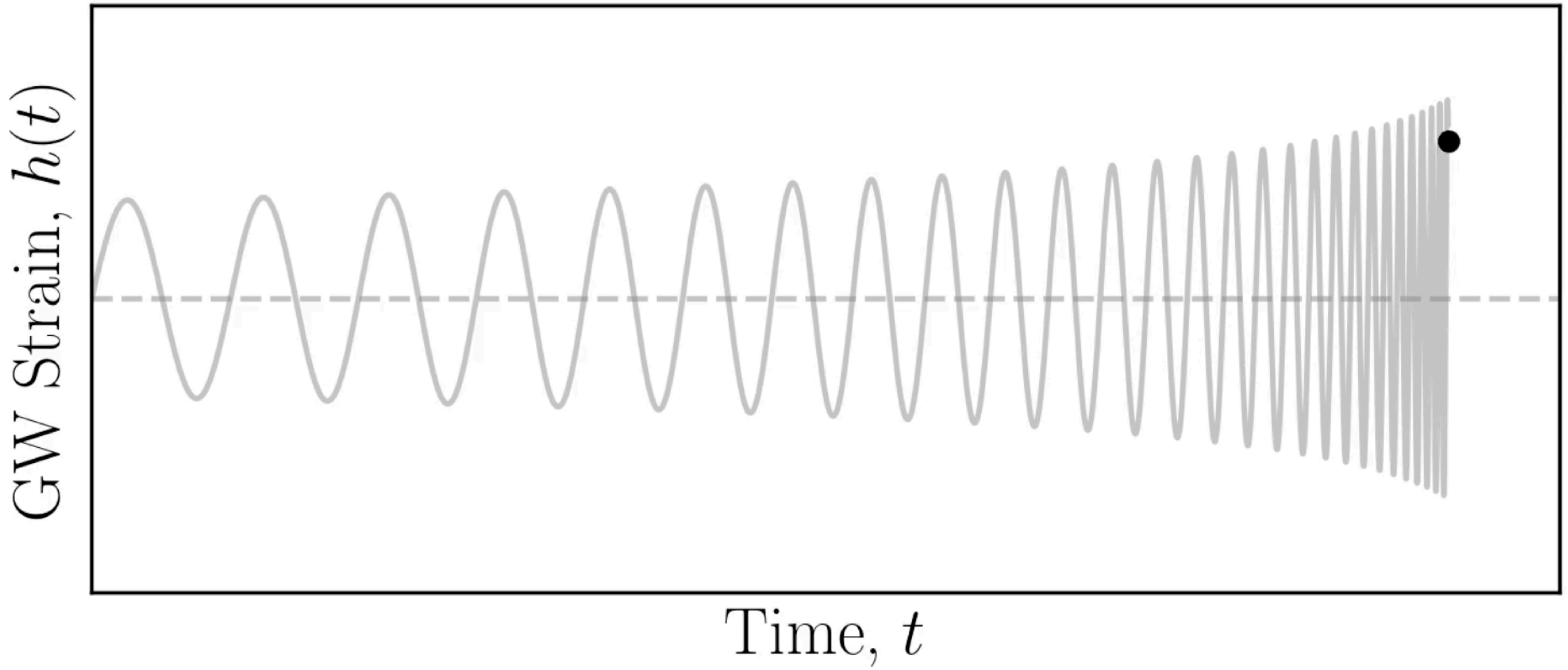

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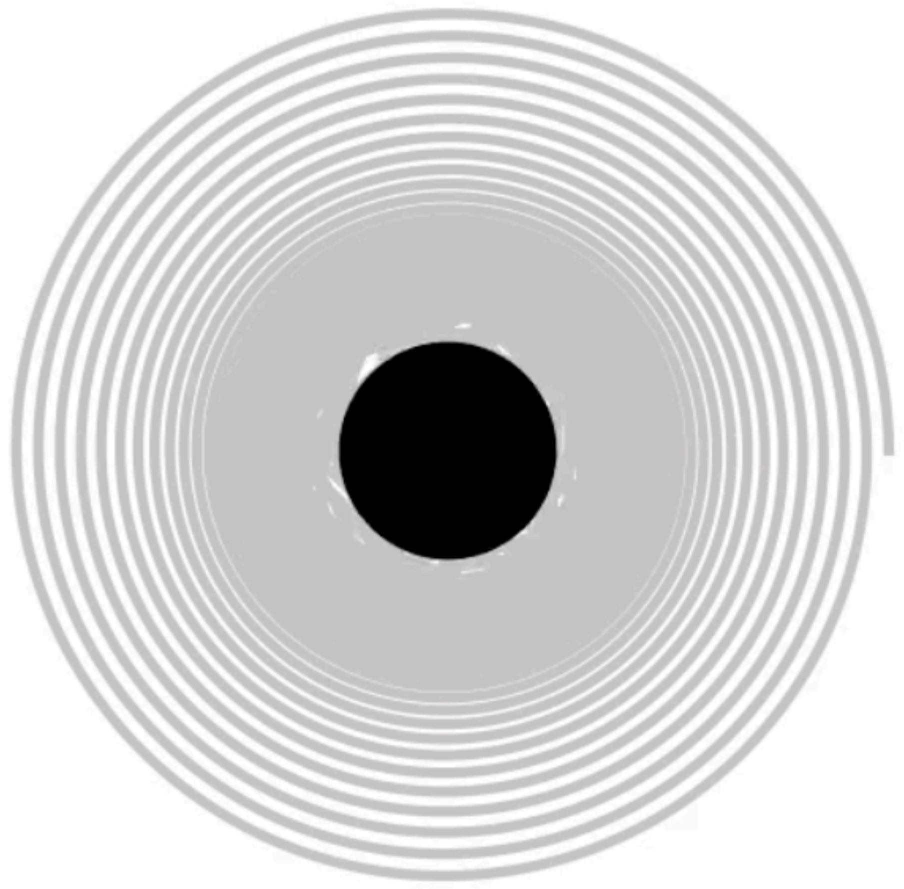

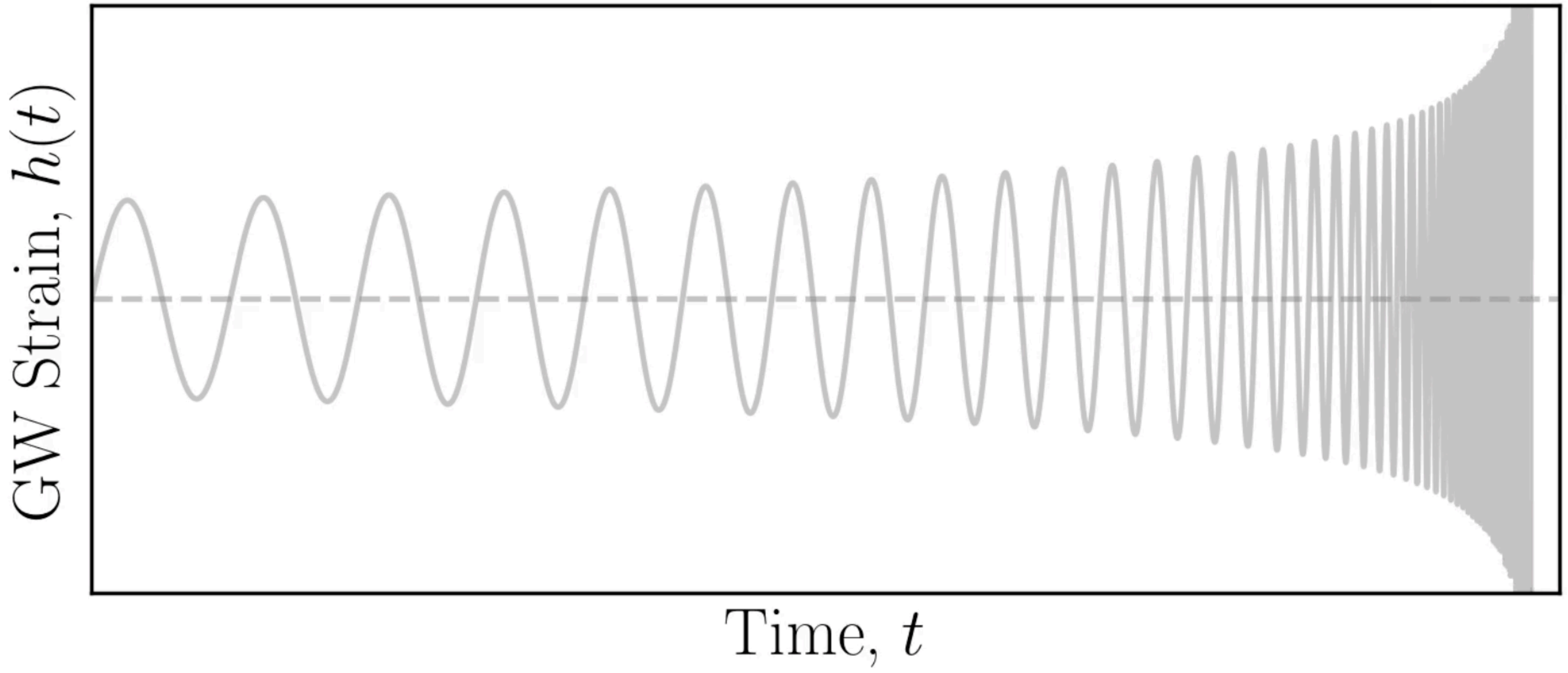

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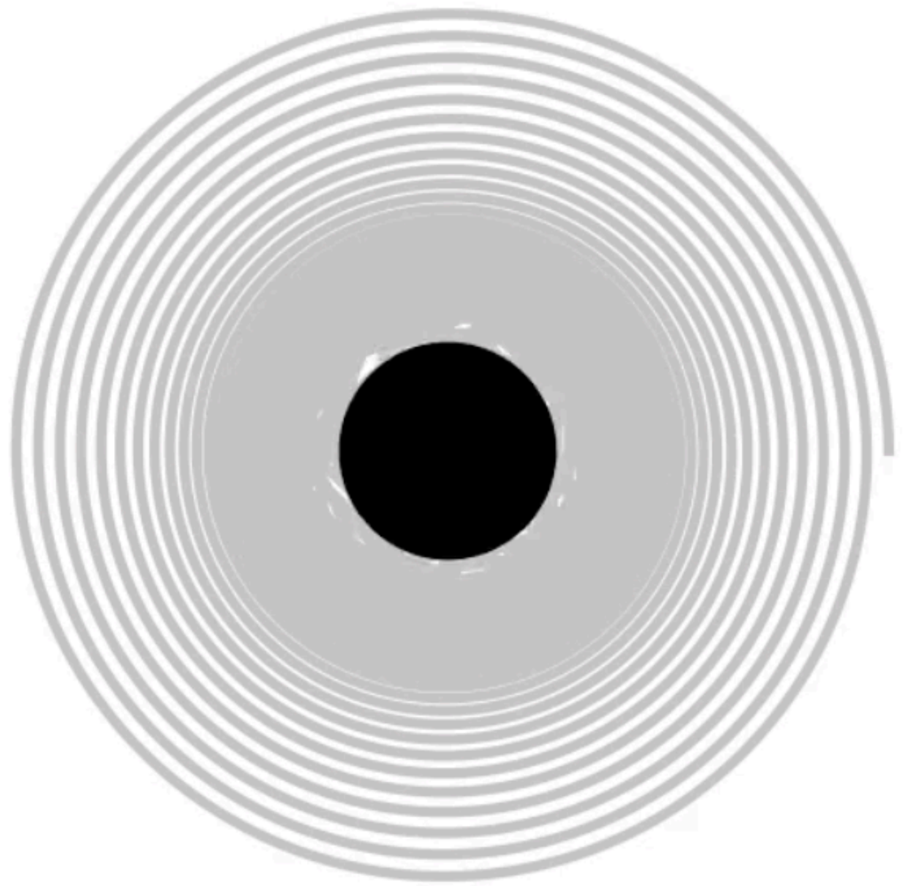

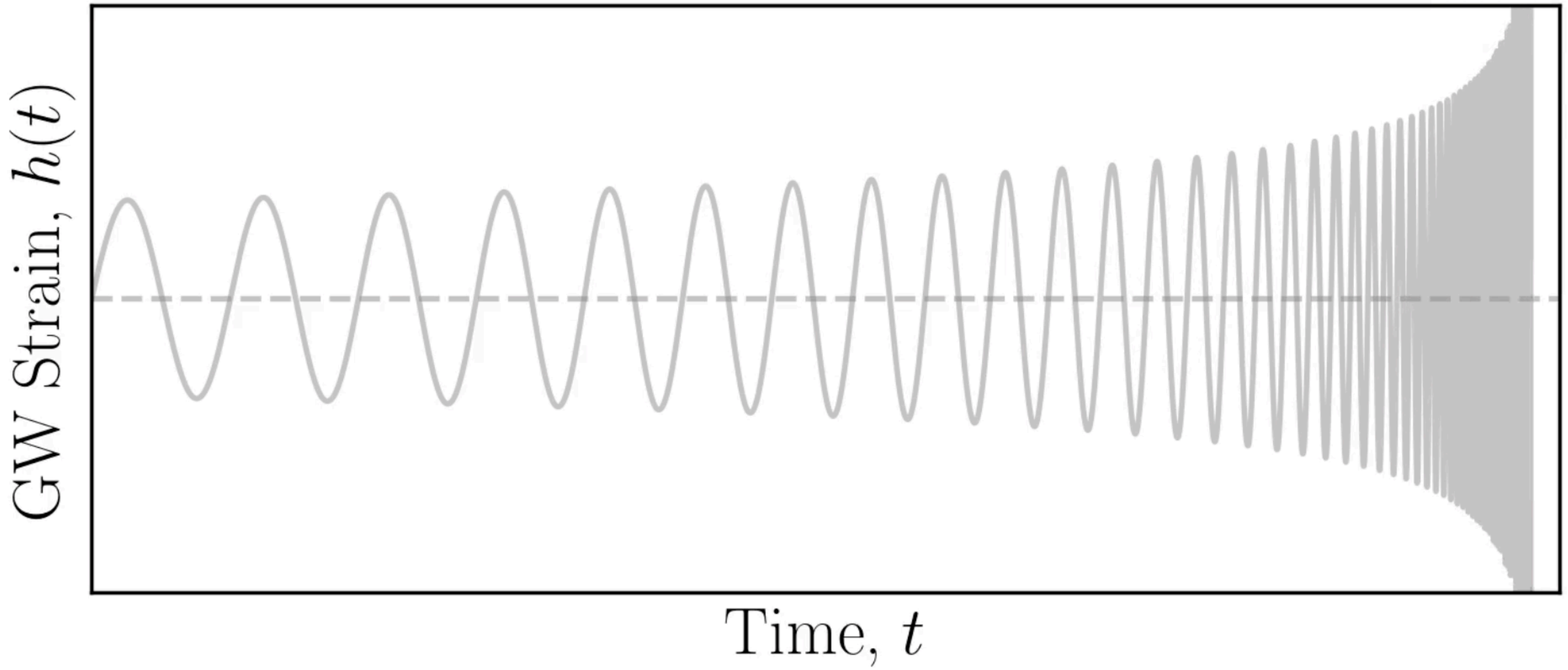

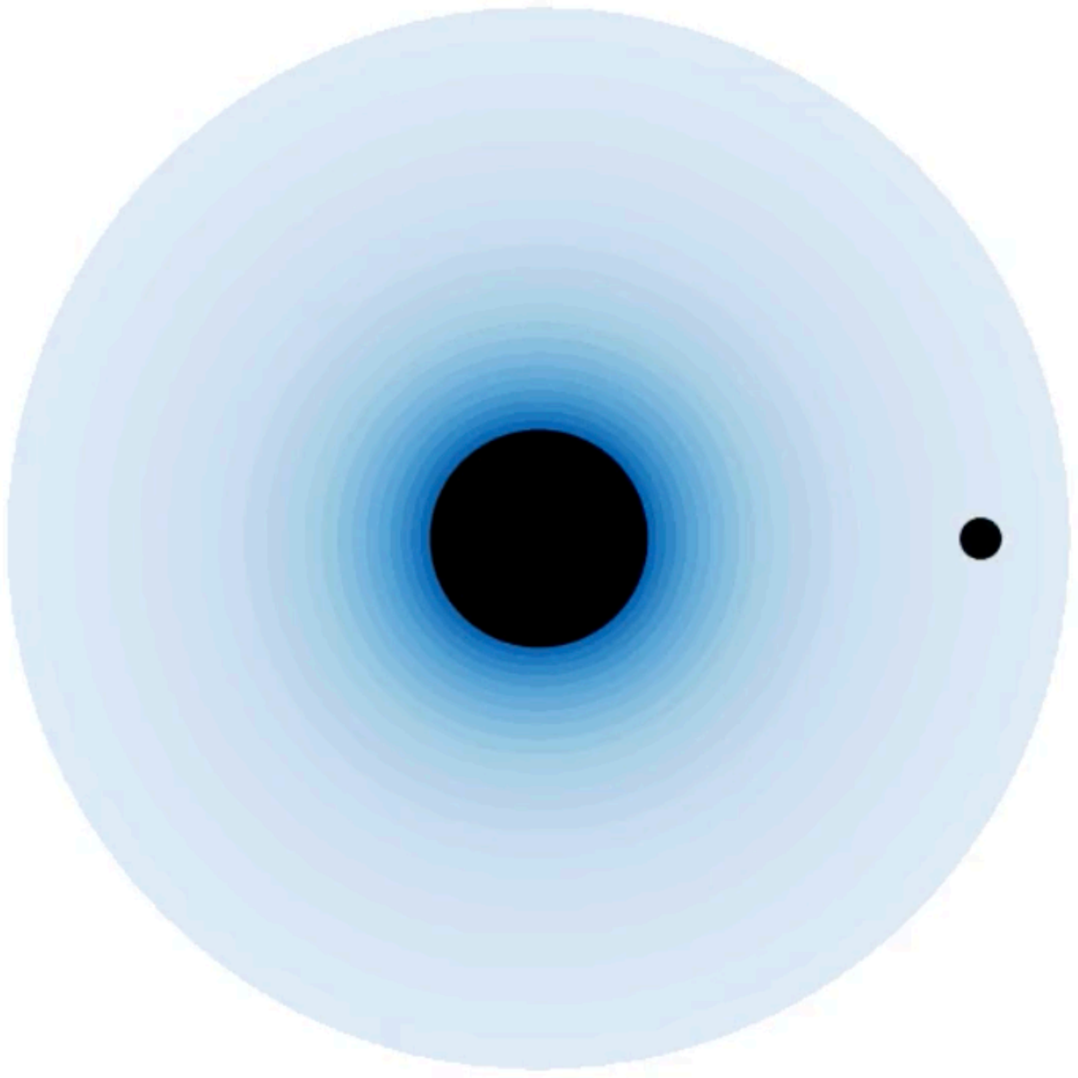

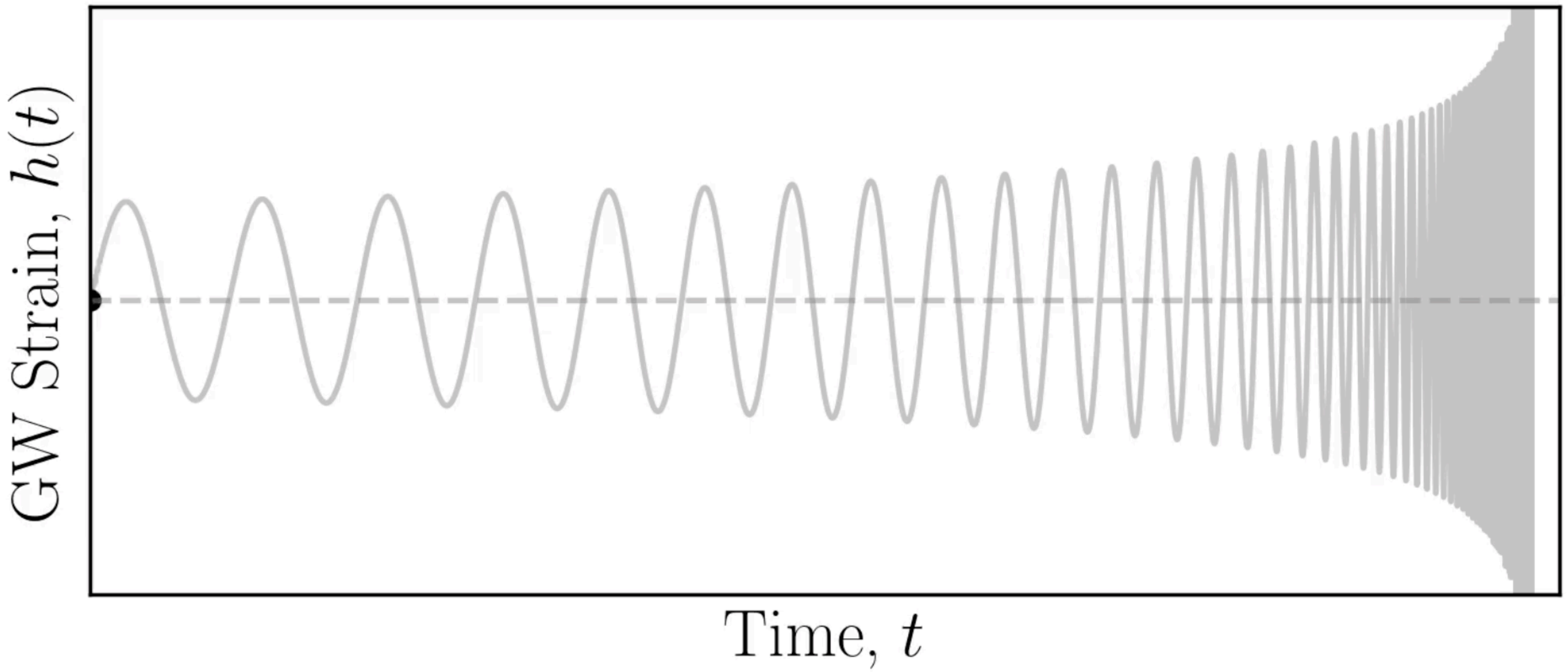

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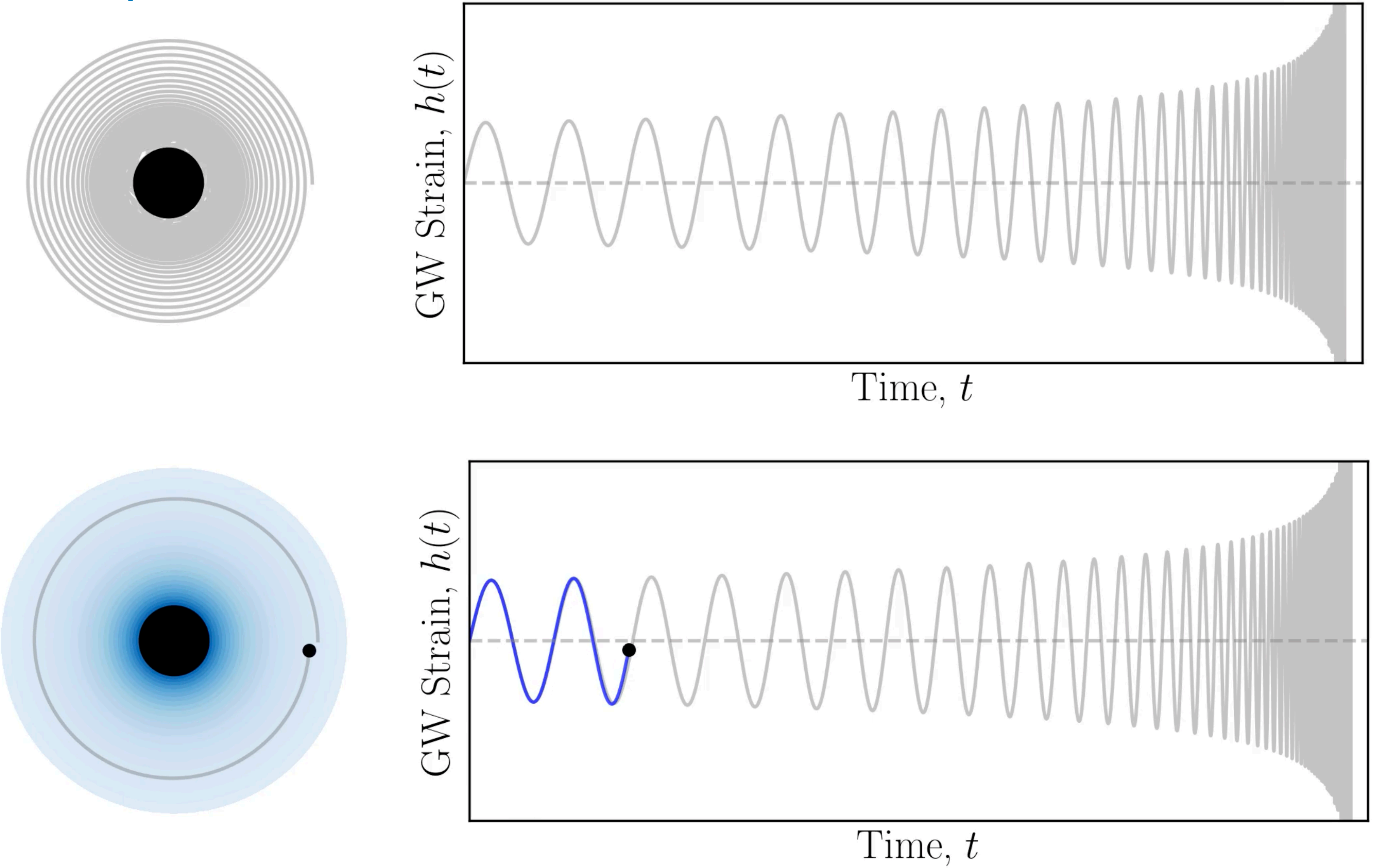

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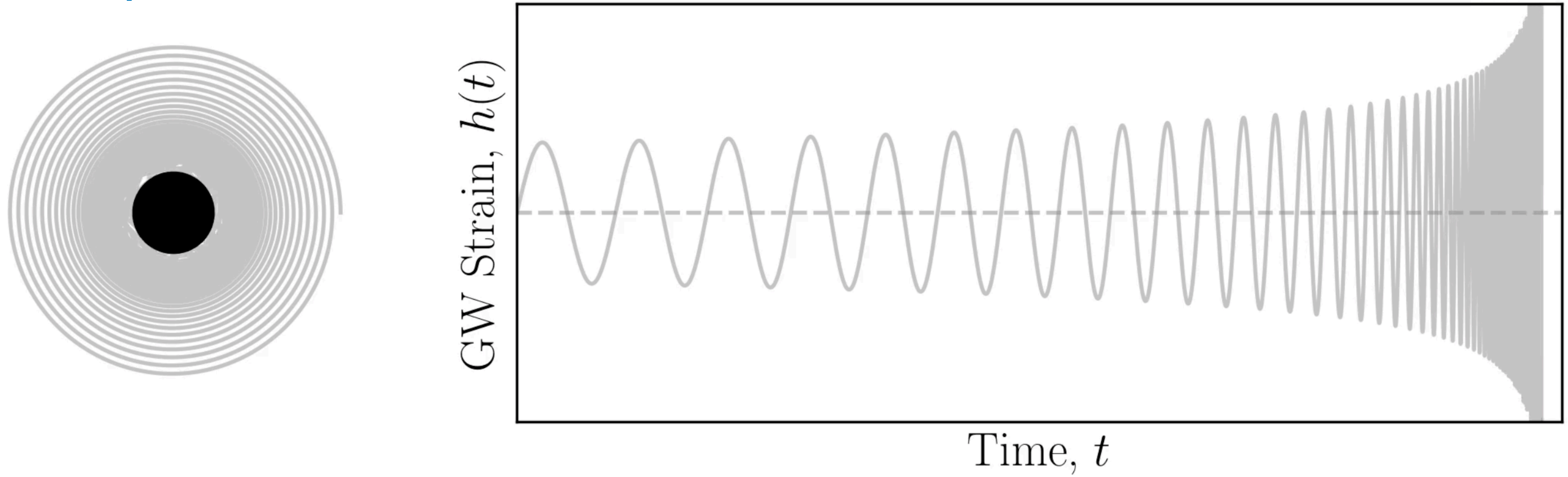

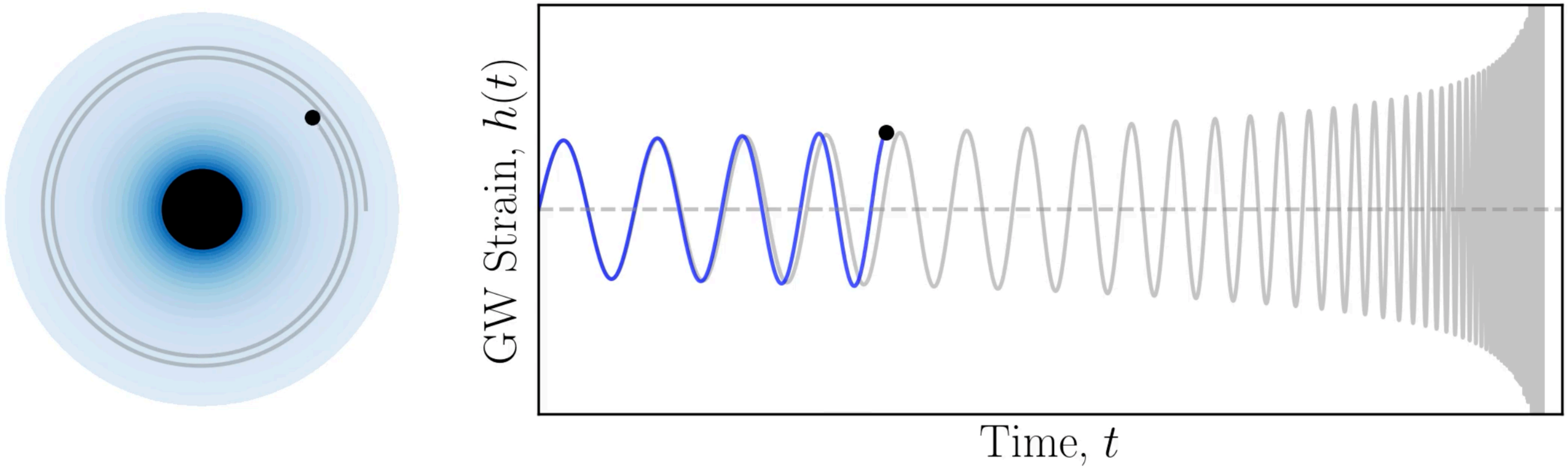

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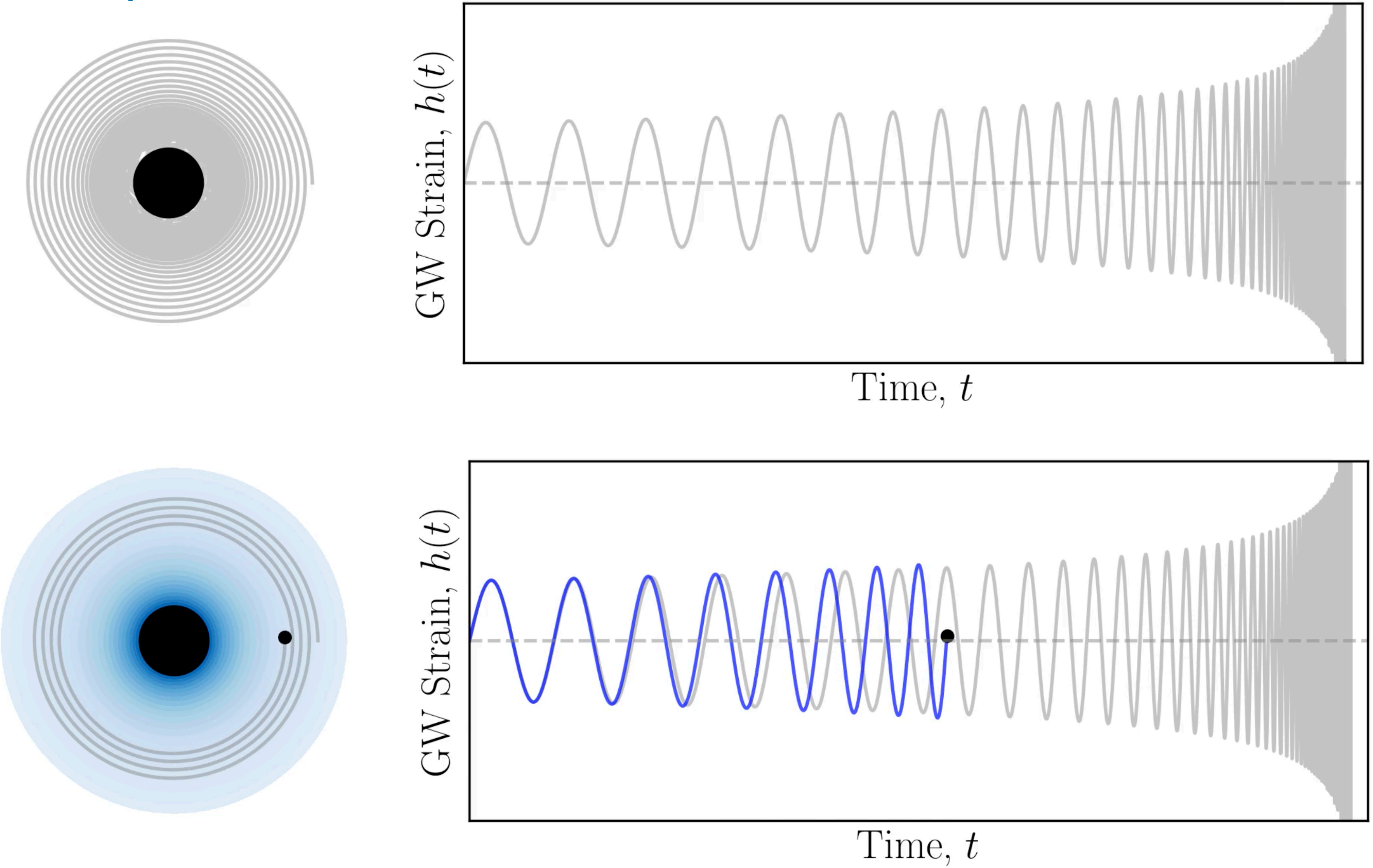

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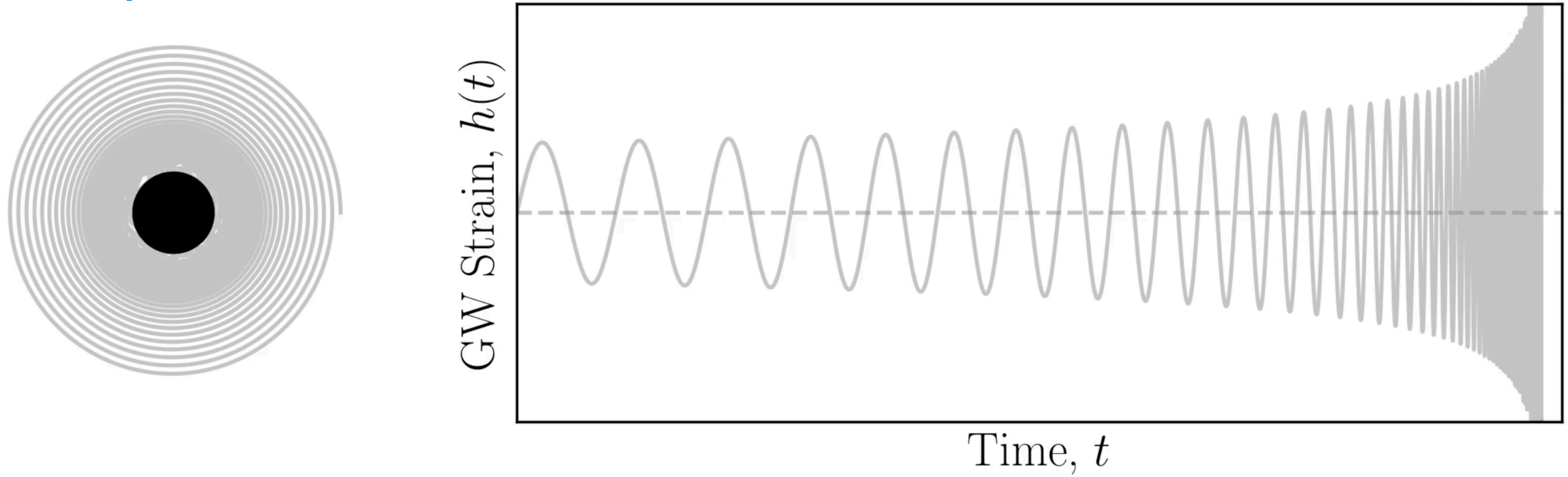

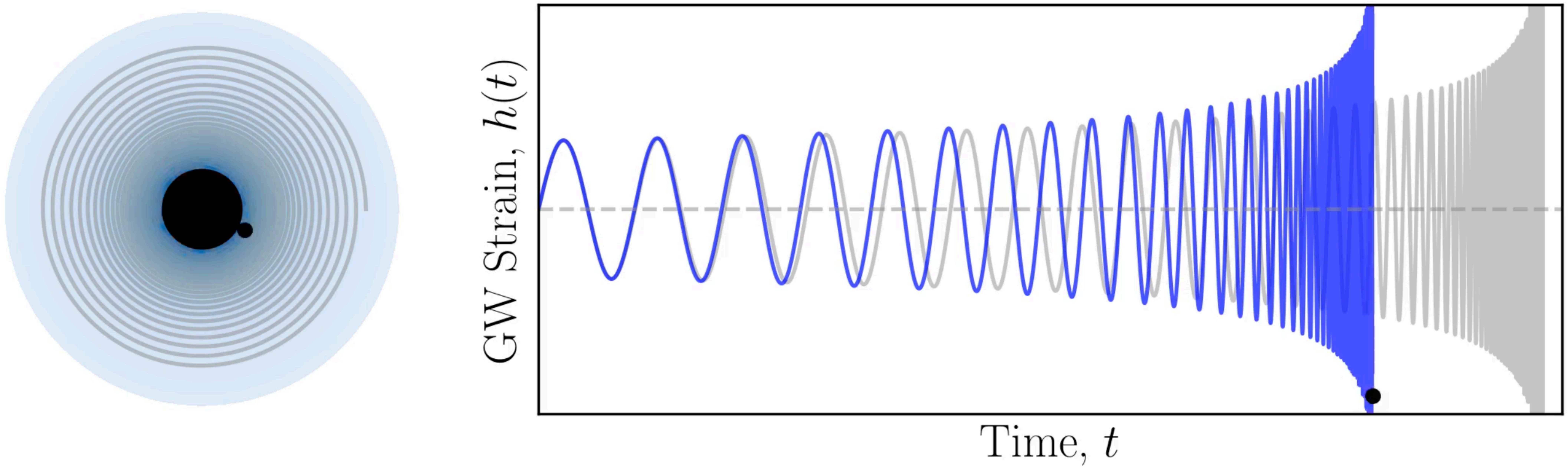

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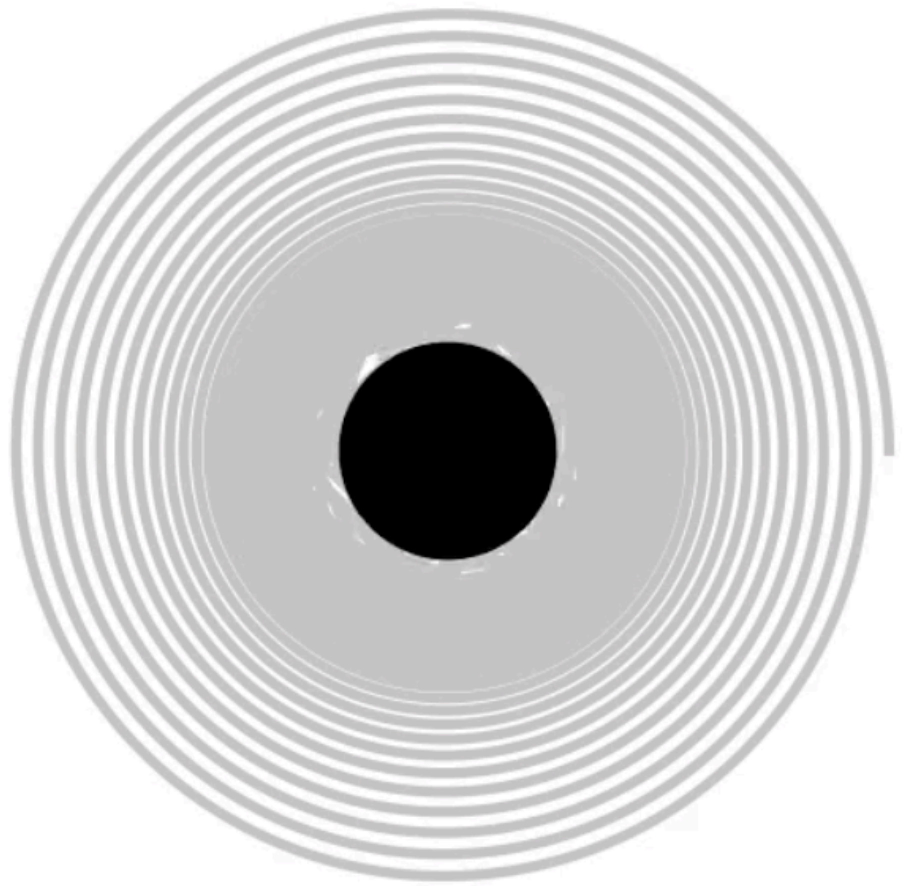
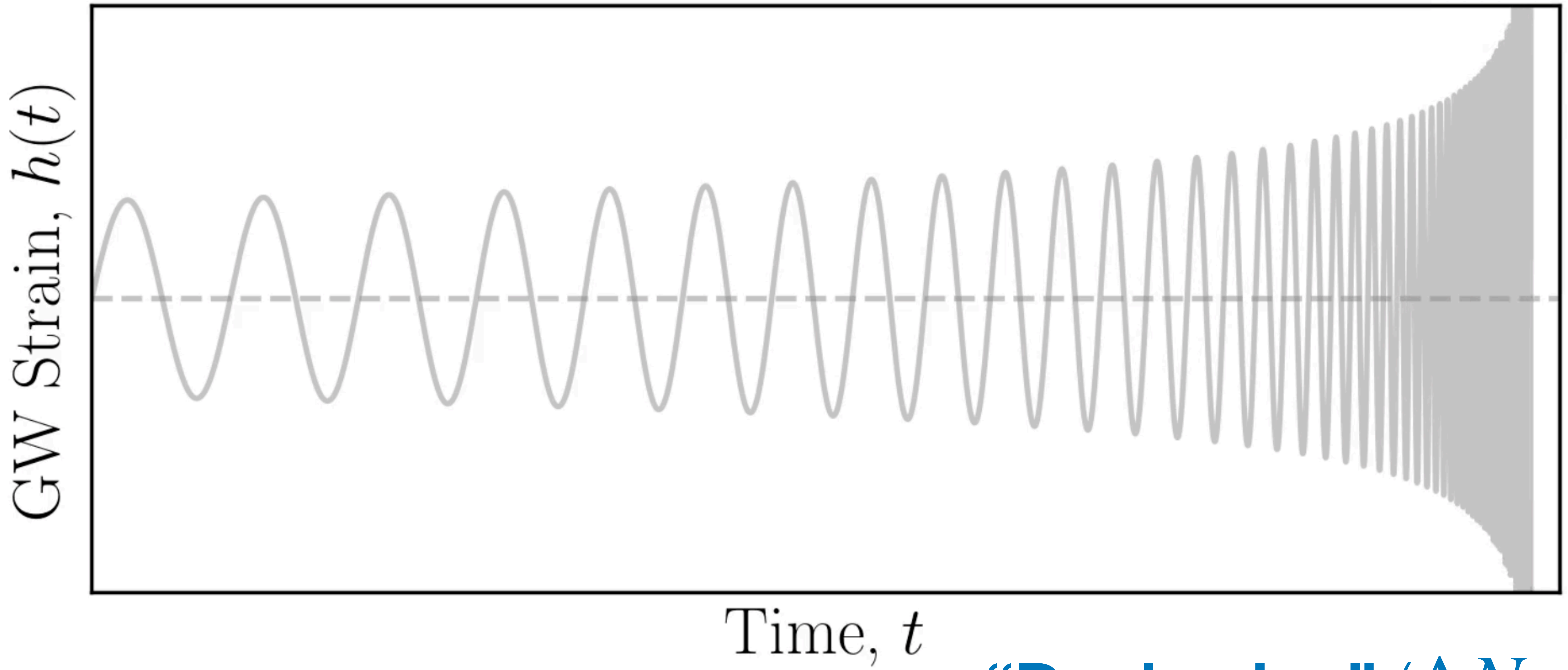
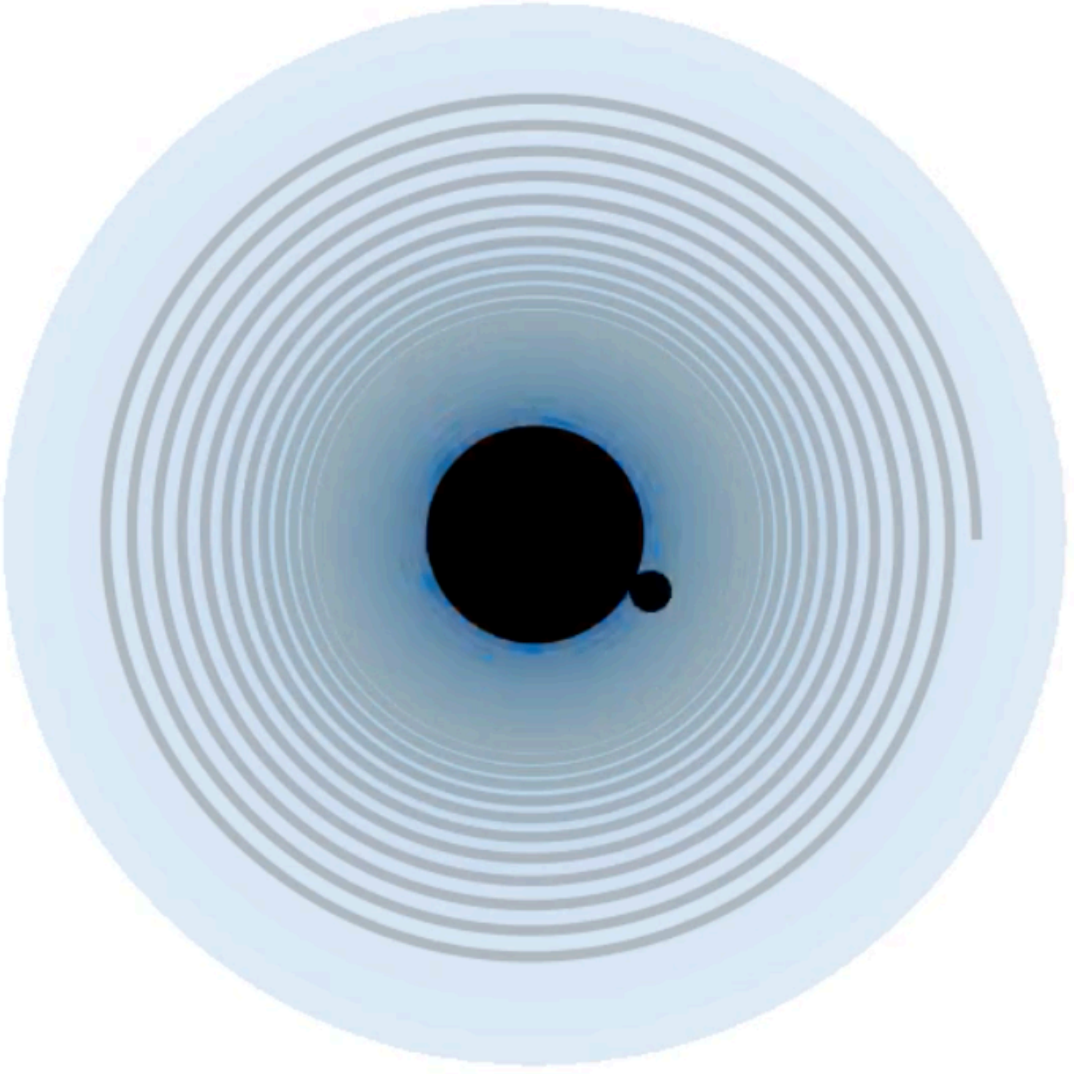
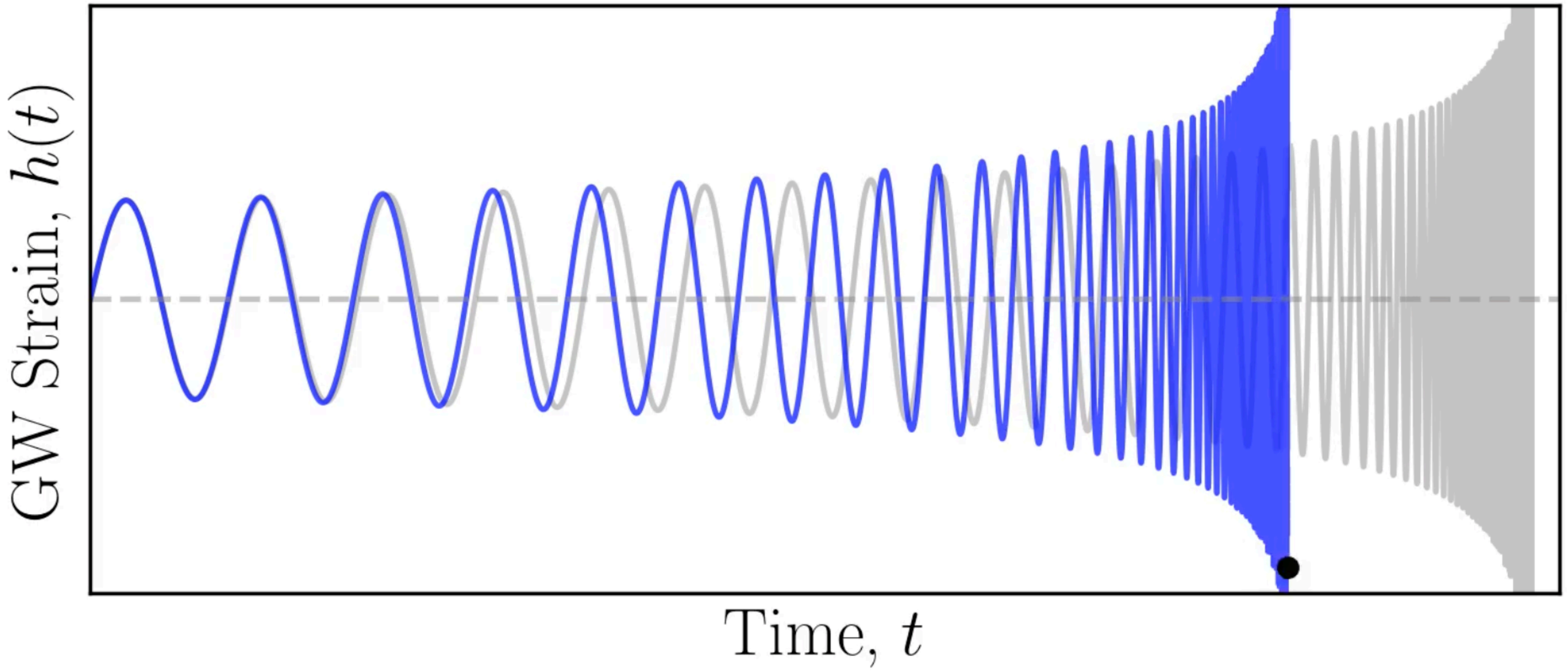


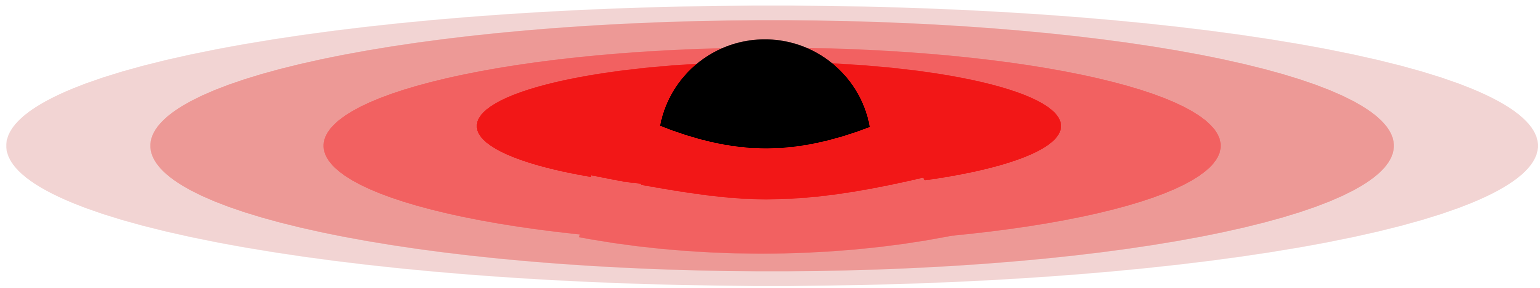


“Dephasing” (ΔN_{GW})

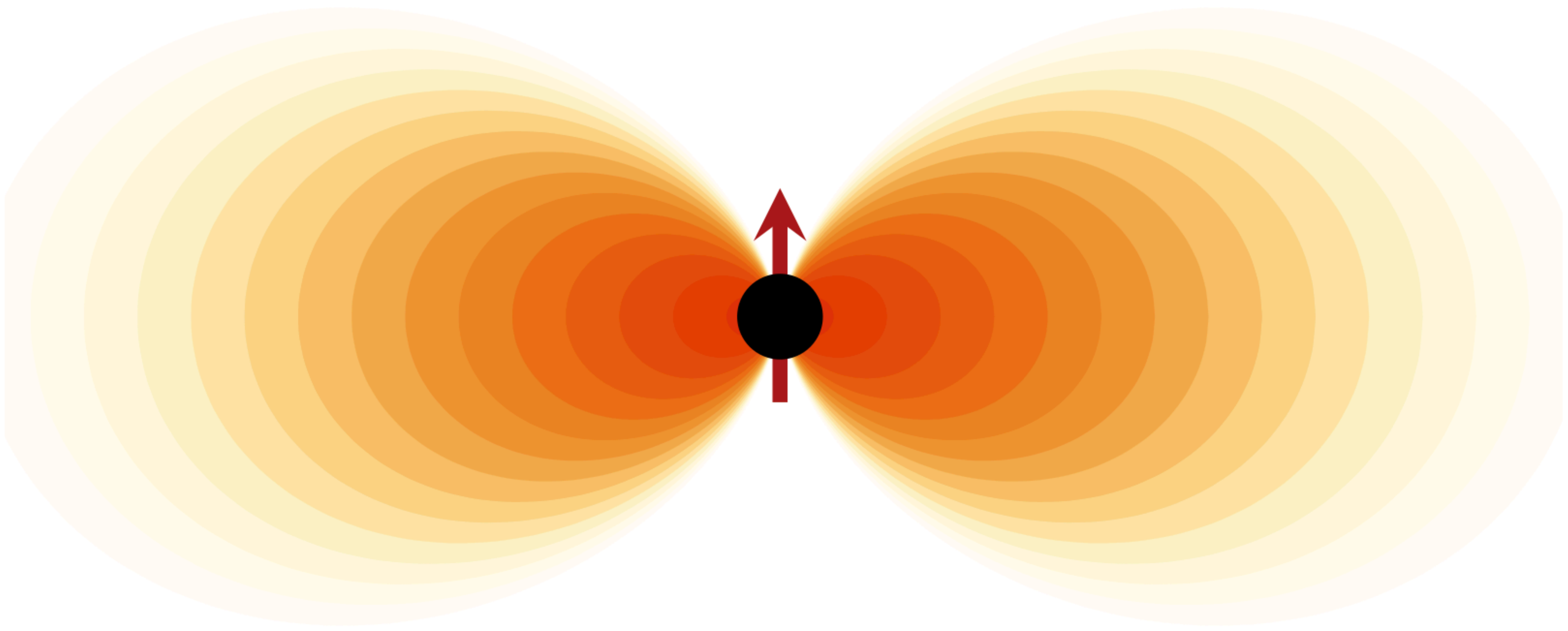




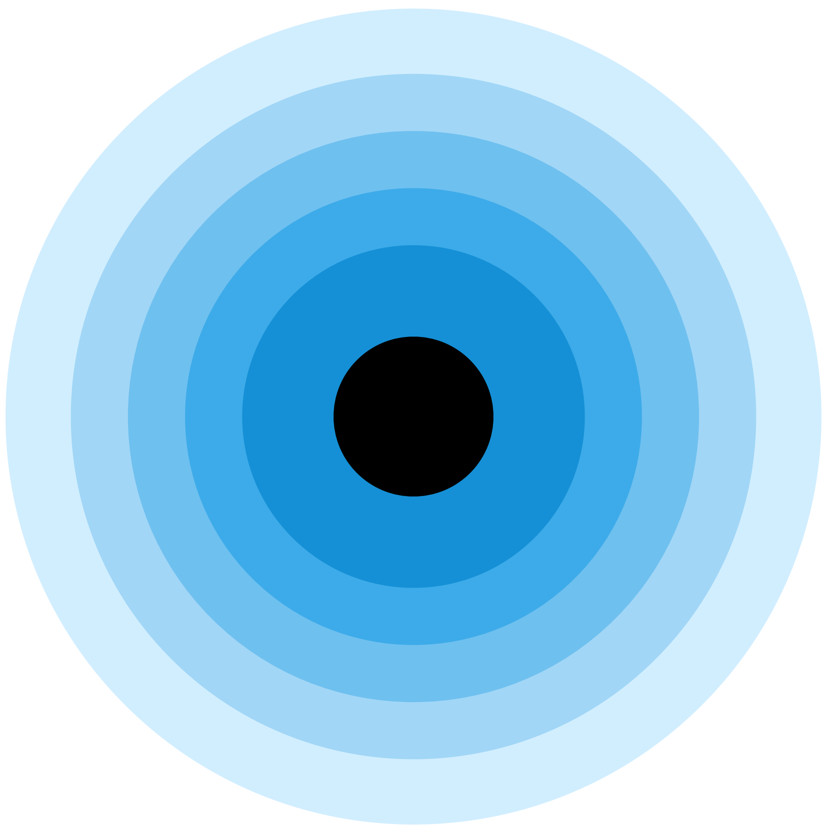
Black Hole Environments



Baryonic
Accretion Disks

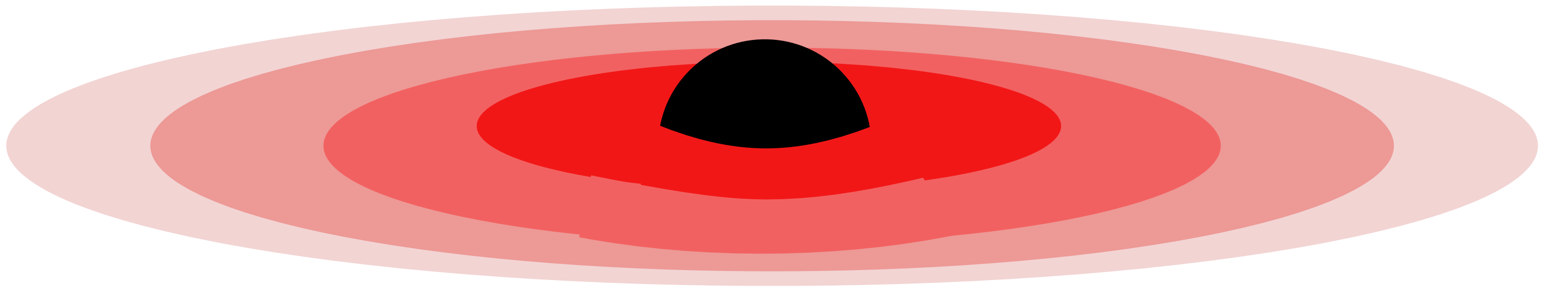


'**Gravitational Atoms**' of
Ultralight Bosons



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

Black Hole Environments



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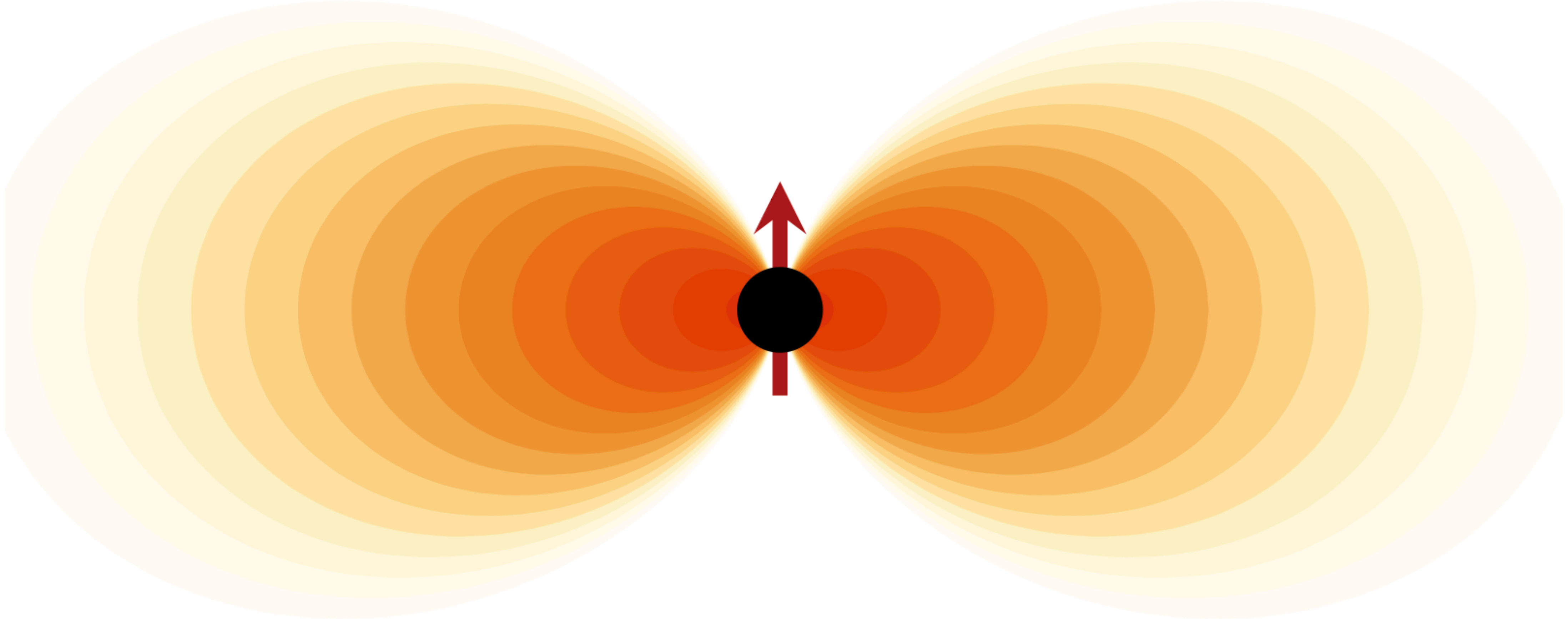

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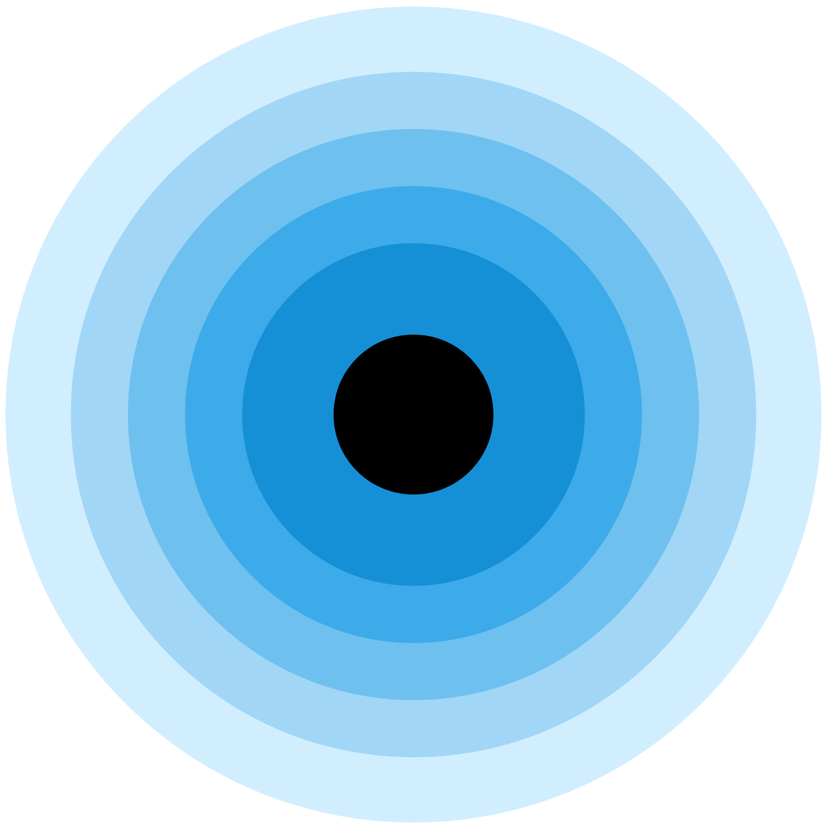
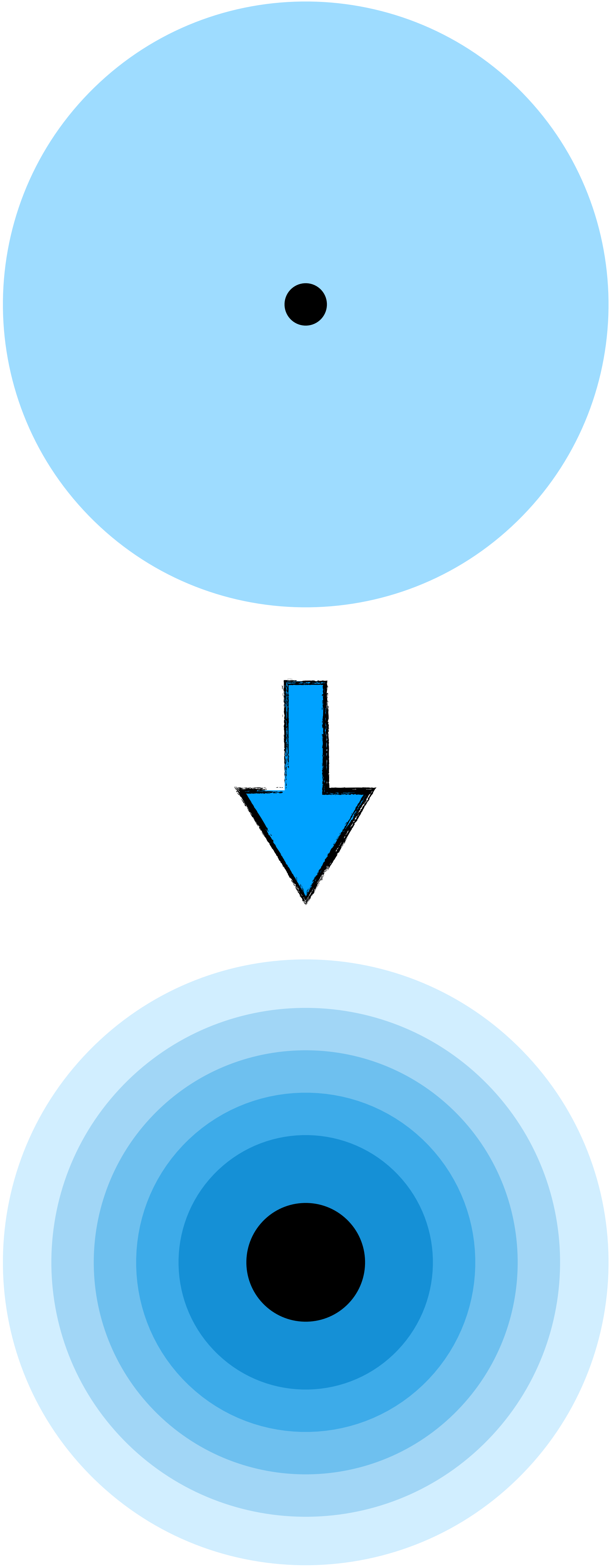


Particle Dark Matter
‘**Spikes**’ or ‘**Dresses**’

Dark Matter Spikes



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

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

“PBH scenario”

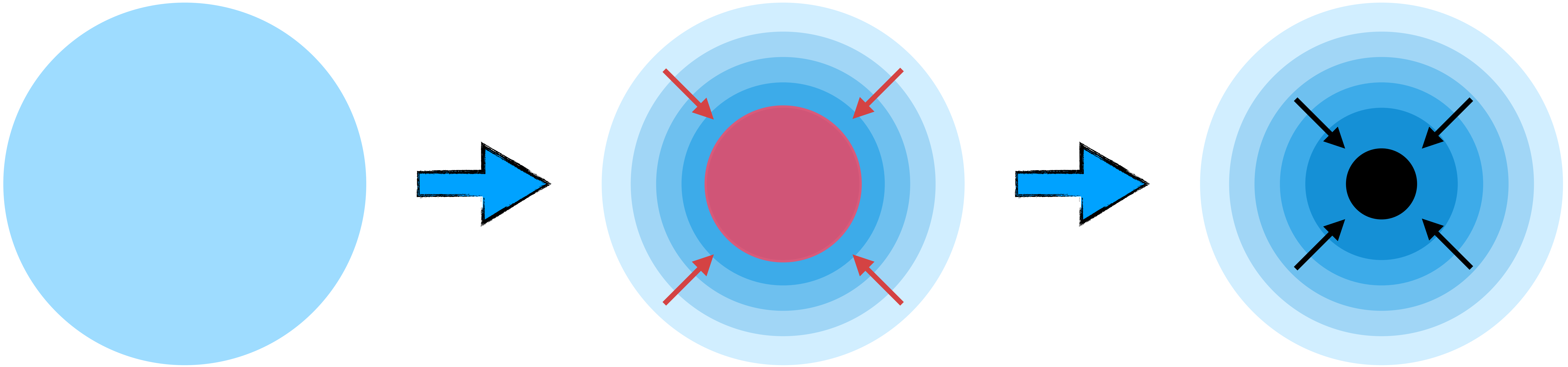
[Bertschinger (1985), astro-ph/0608642, 1901.08528, …]

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, …]

Dark Matter 'Mounds'

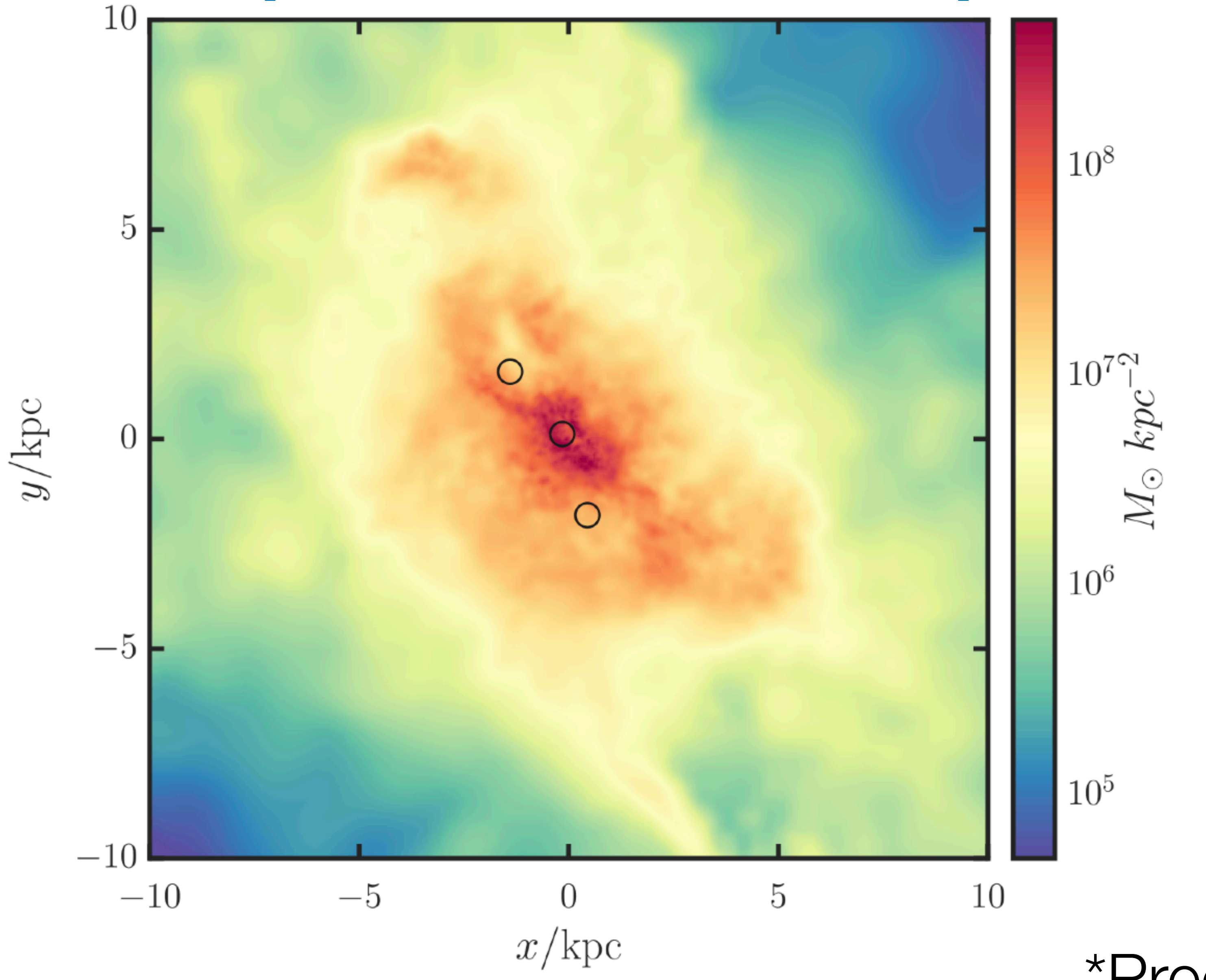


NFW Dark Matter Halo
at high redshift $z \gtrsim 15$

Supermassive 'star'

Direct Collapse Black Hole
+ Dense **DM Spike/Mound***

[Dunn et al., 1803.01007]



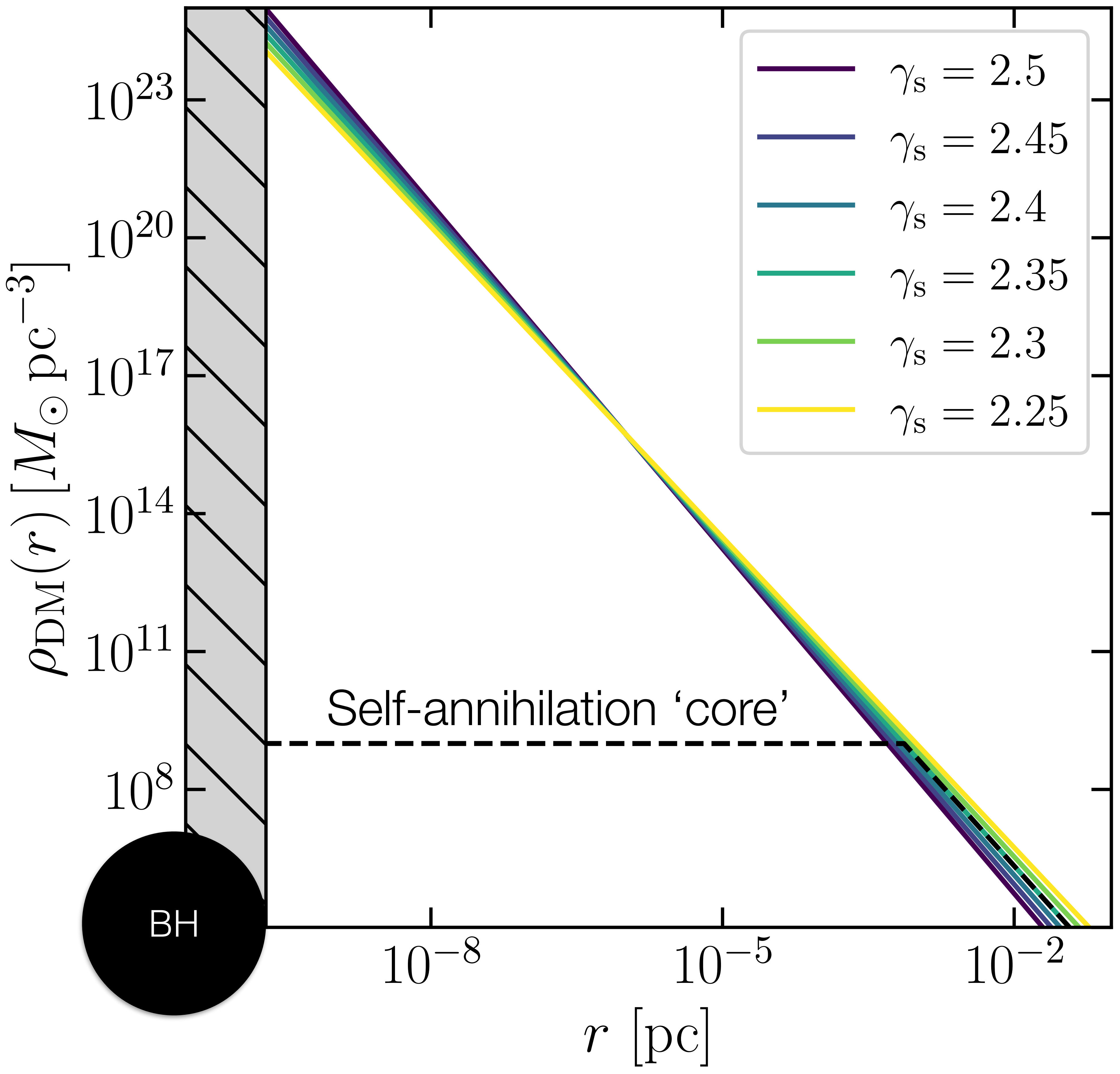
$$m_{\rm DCBH} \sim 10^3 - 10^5\, M_\odot$$

[Bertone et al. (including **BJK**), 2404.08731;
and work in progress with Abram Perez and Pratika Dayal]

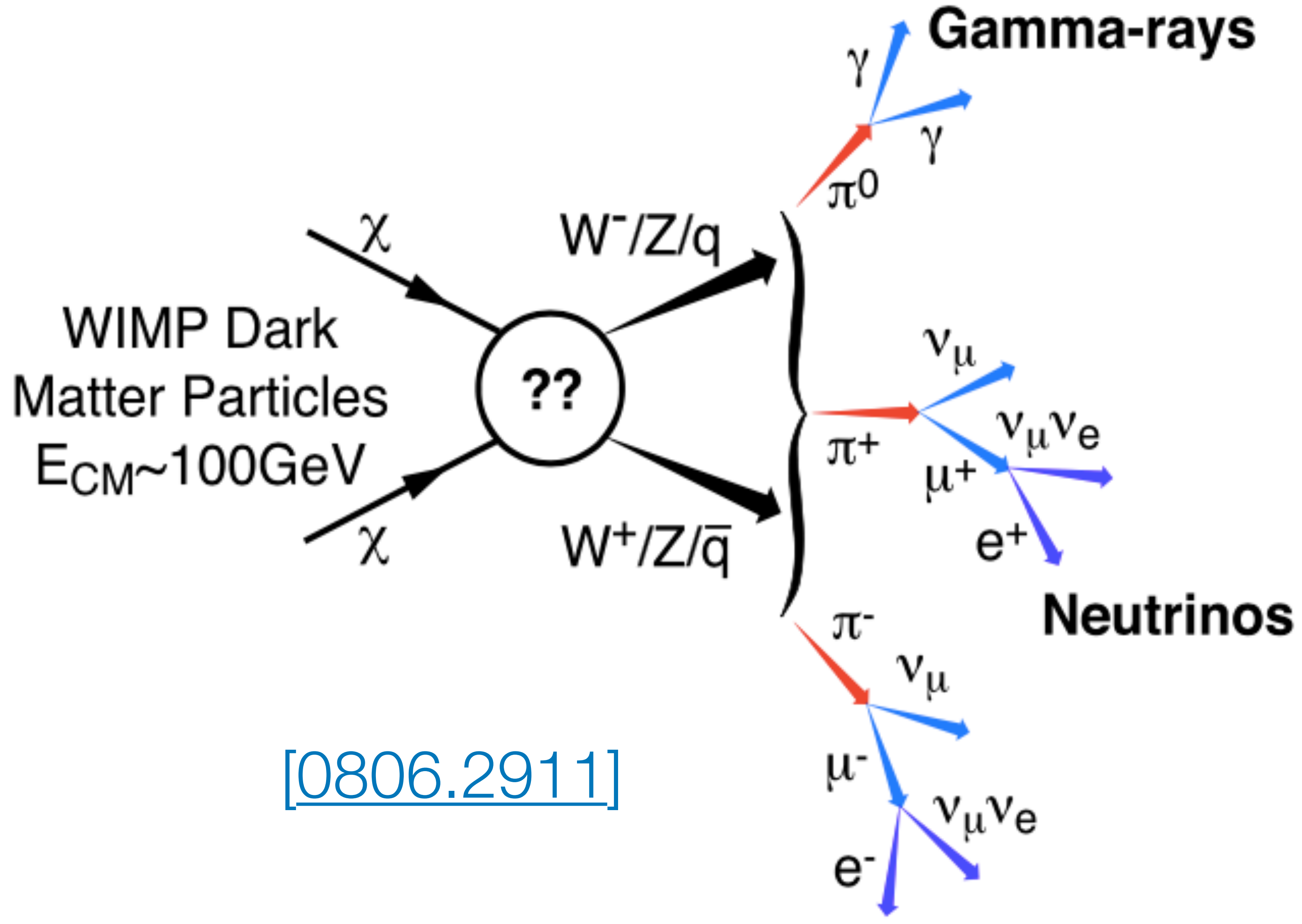
*Precise details of formation may affect slope and density of DM very close to BH

DM annihilation?

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



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



[0806.2911]

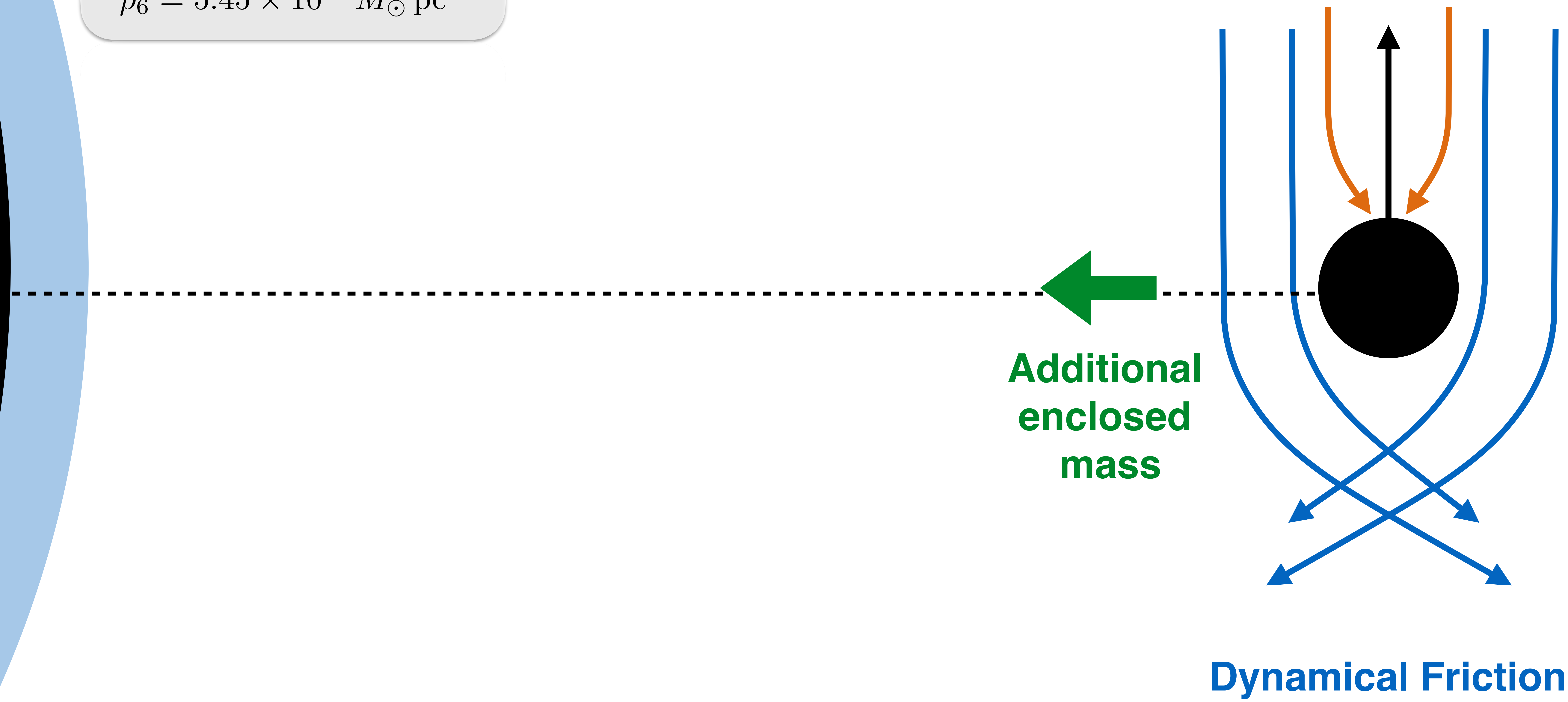
DM self-annihilation can suppress the spike density, but can still lead to large (diffuse and point source) fluxes of gamma-rays and neutrinos

[E.g. Lacroix & Silk, 1712.00452, Bertone et al., 1905.01238, Freese et al., 2202.01126]

*What about **non-annihilating DM**?*

Impact of DM Spikes

$m_1 = 1000\, M_\odot$
$m_2 = 1\, M_\odot$
$\gamma_{\rm sp} = 7/3$
$\rho_6 = 5.45 \times 10^{15}\, M_\odot\, {\rm pc}^{-3}$



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

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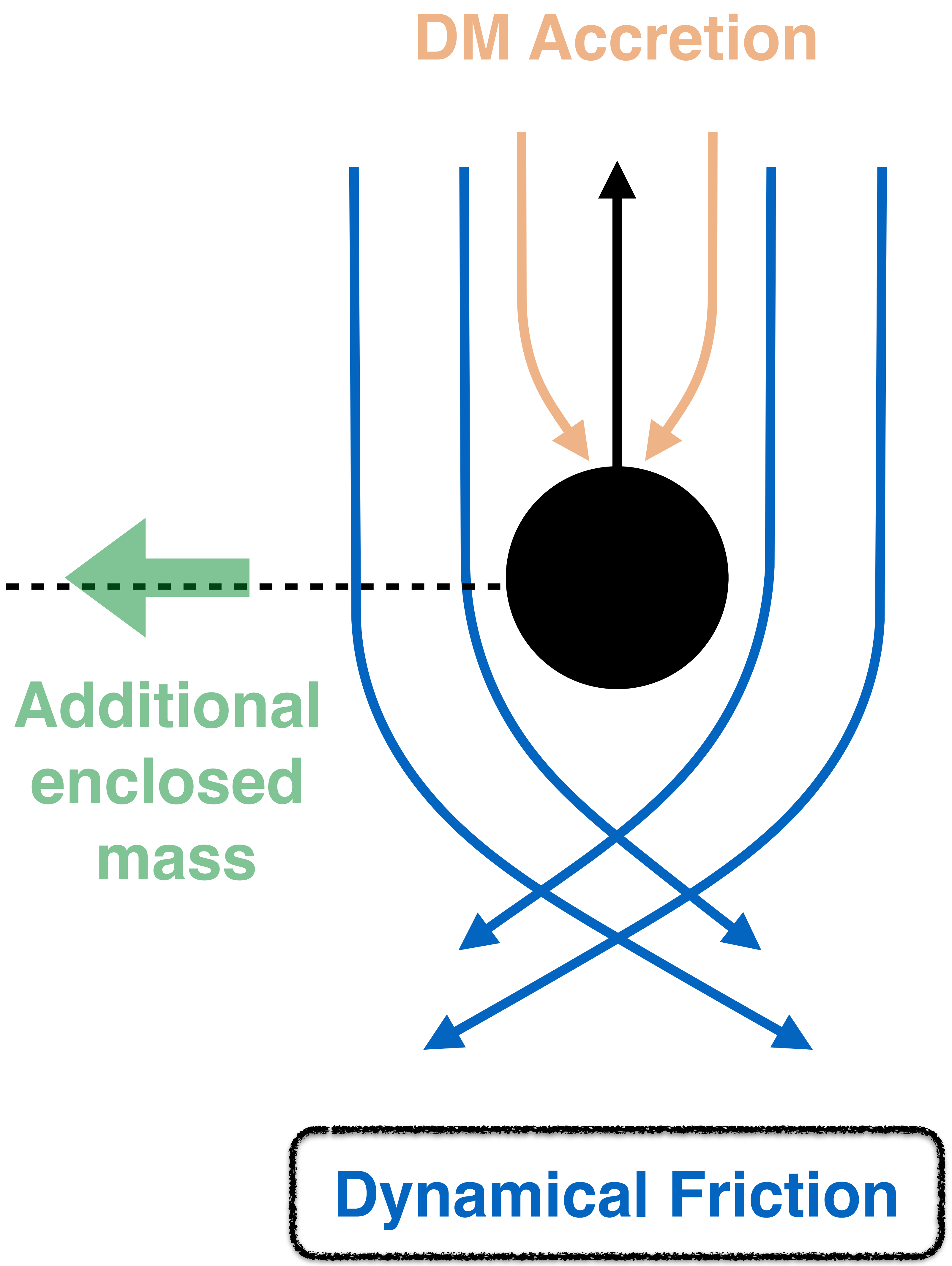


$$\dot{E}_\mathrm{DF} \sim \frac{4\pi G^2 m_2^2 \rho_\mathrm{DM}(r)\xi(v)}{v} \ln\Lambda$$

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

Halo Feedback

Solve the Newtonian system of a quasi-circular inspiral $r_2(t)$:

$$\left[\begin{array}{c} -\dot{E}_\mathrm{orb} = \dot{E}_\mathrm{GW} + \dot{E}_\mathrm{DF} \\ E_\mathrm{orb} \approx -\frac{G m_1 m_2}{2 r_2} \end{array}\right]$$

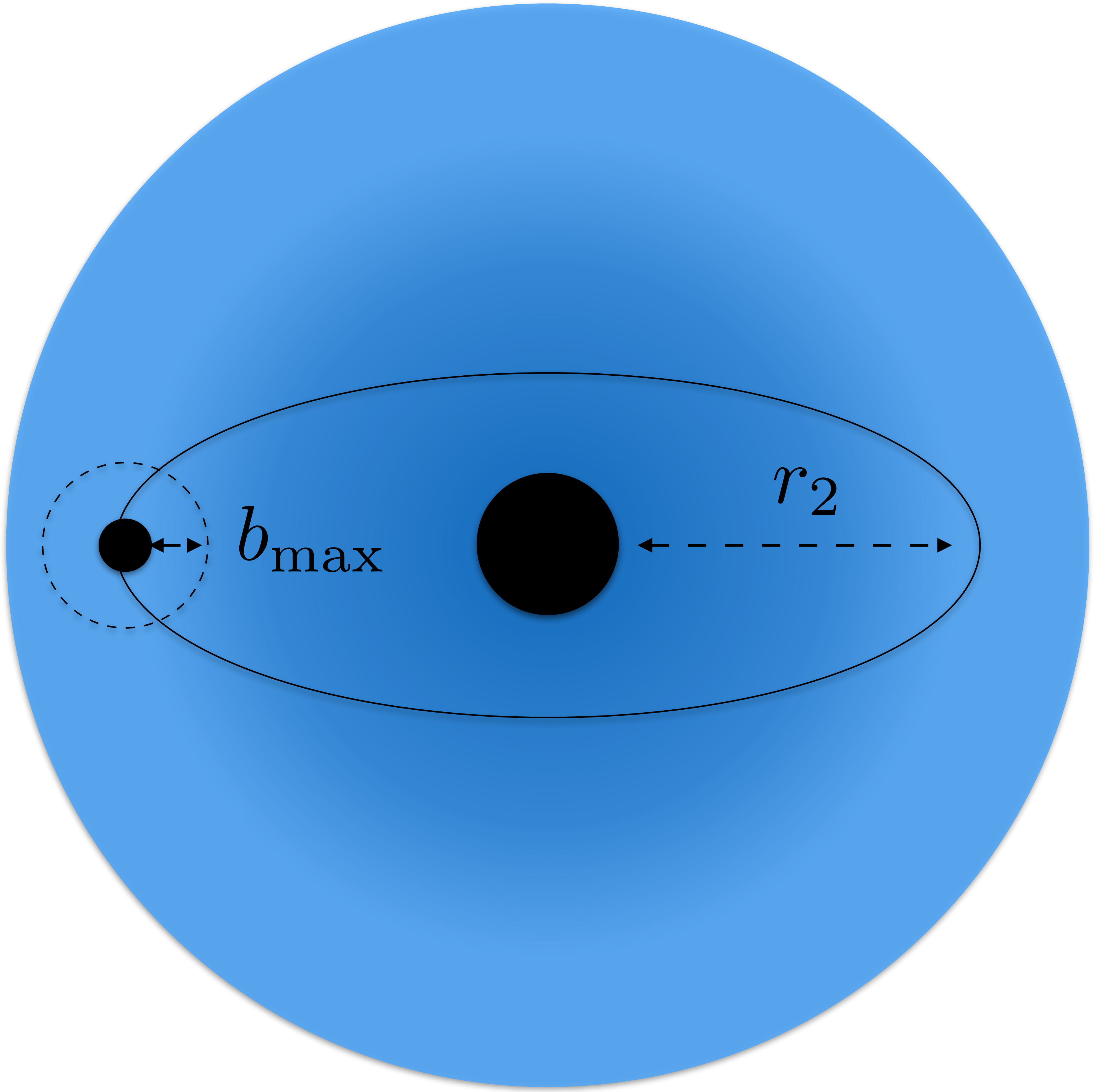
But dynamical friction injects (a lot of) energy into the DM spike!

Each particle passing close to the orbiting BH receives a ‘kick’ through gravitational scattering:

$$\mathcal{E} \rightarrow \mathcal{E} + \Delta\mathcal{E} \qquad \text{with} \quad \mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Simultaneously evolve the DM distribution function: $\frac{\partial f(\mathcal{E})}{\partial t}$

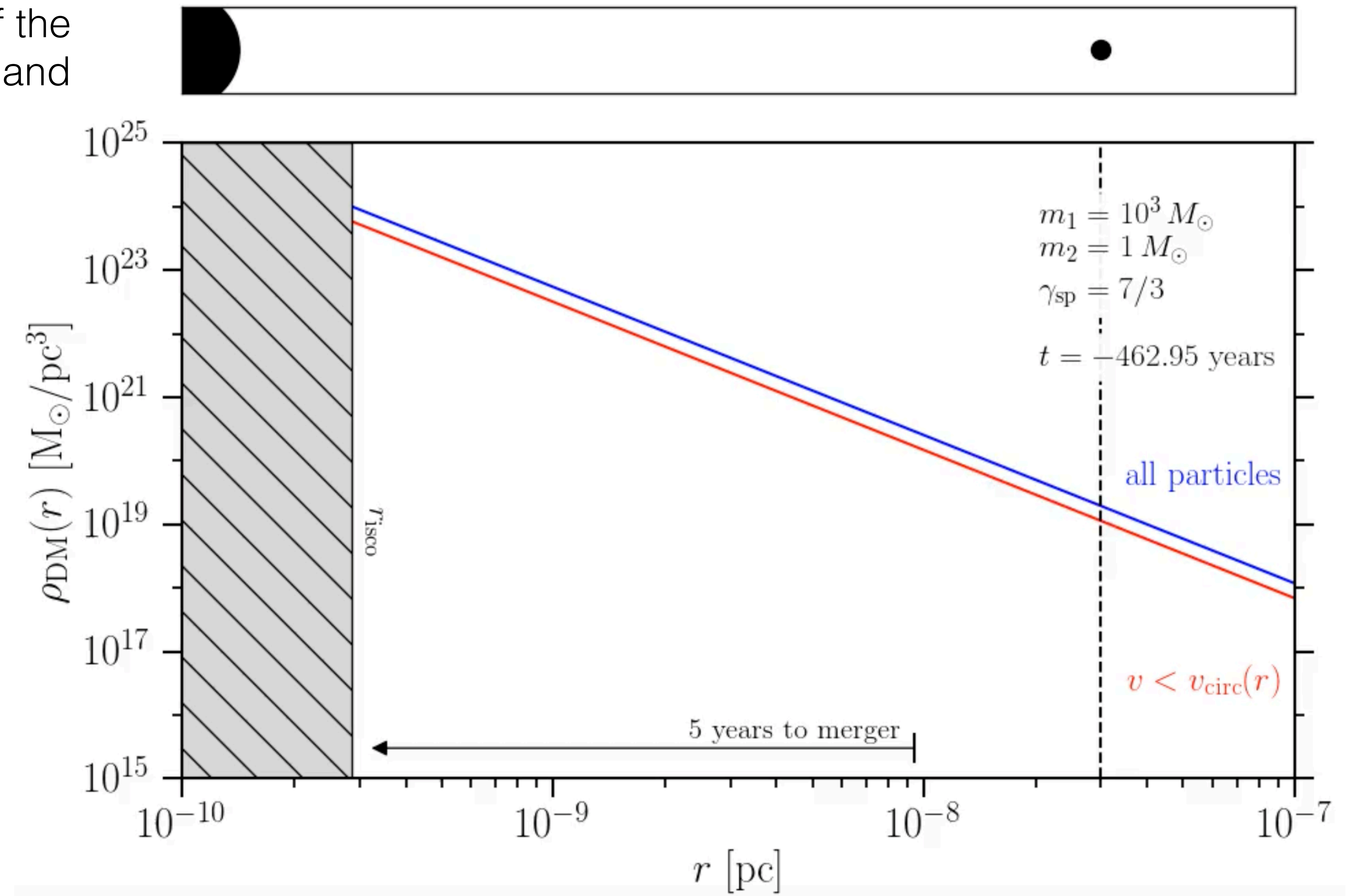
[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]



HaloFeedback

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

Find that the density of the DM spike is depleted (and replenished…)



Size of the dephasing effect is **reduced from $\mathcal{O}(1)$ to $\mathcal{O}(1\%)$.**

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

[Movies: tinyurl.com/GW4DM]

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

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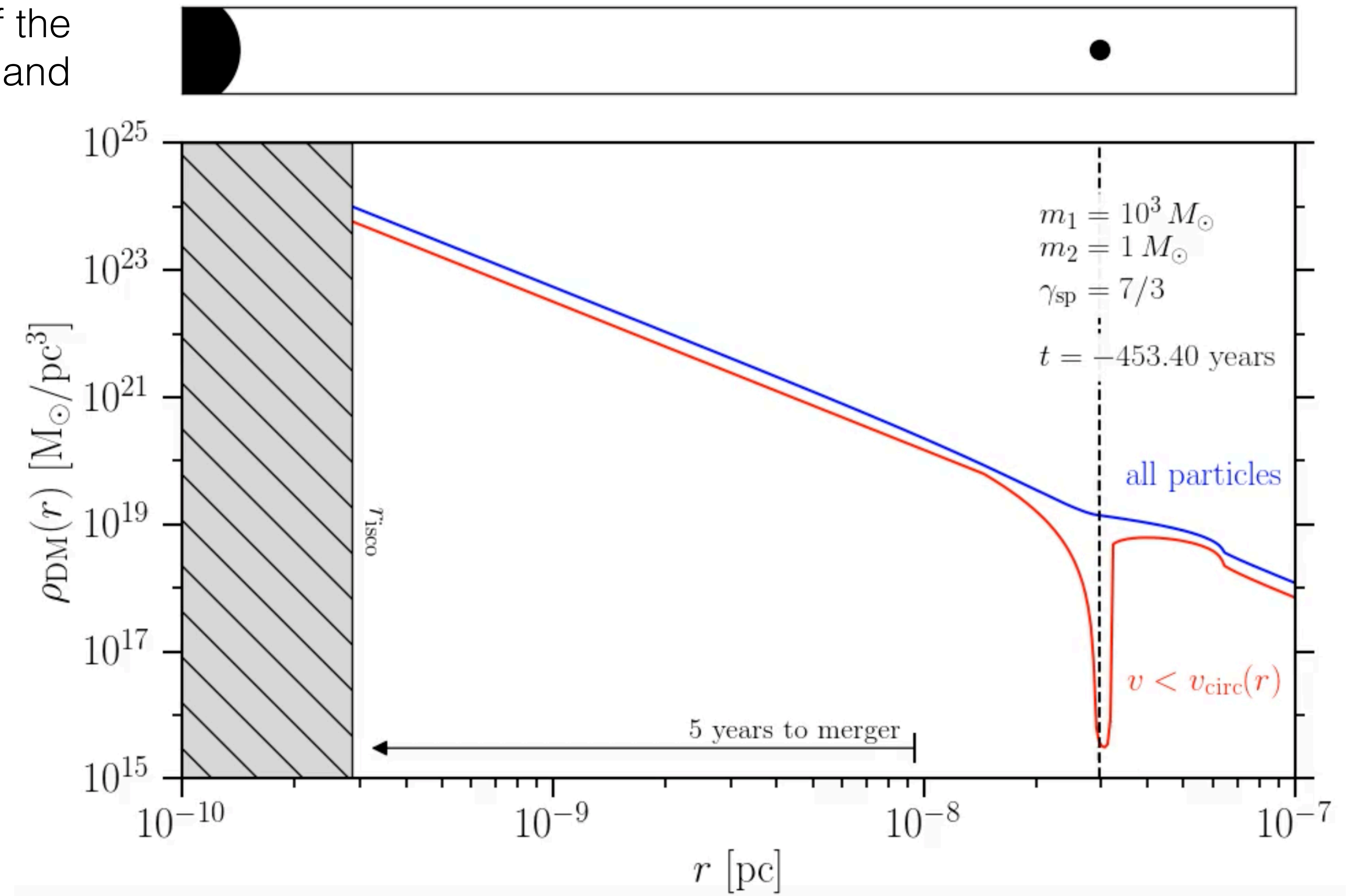

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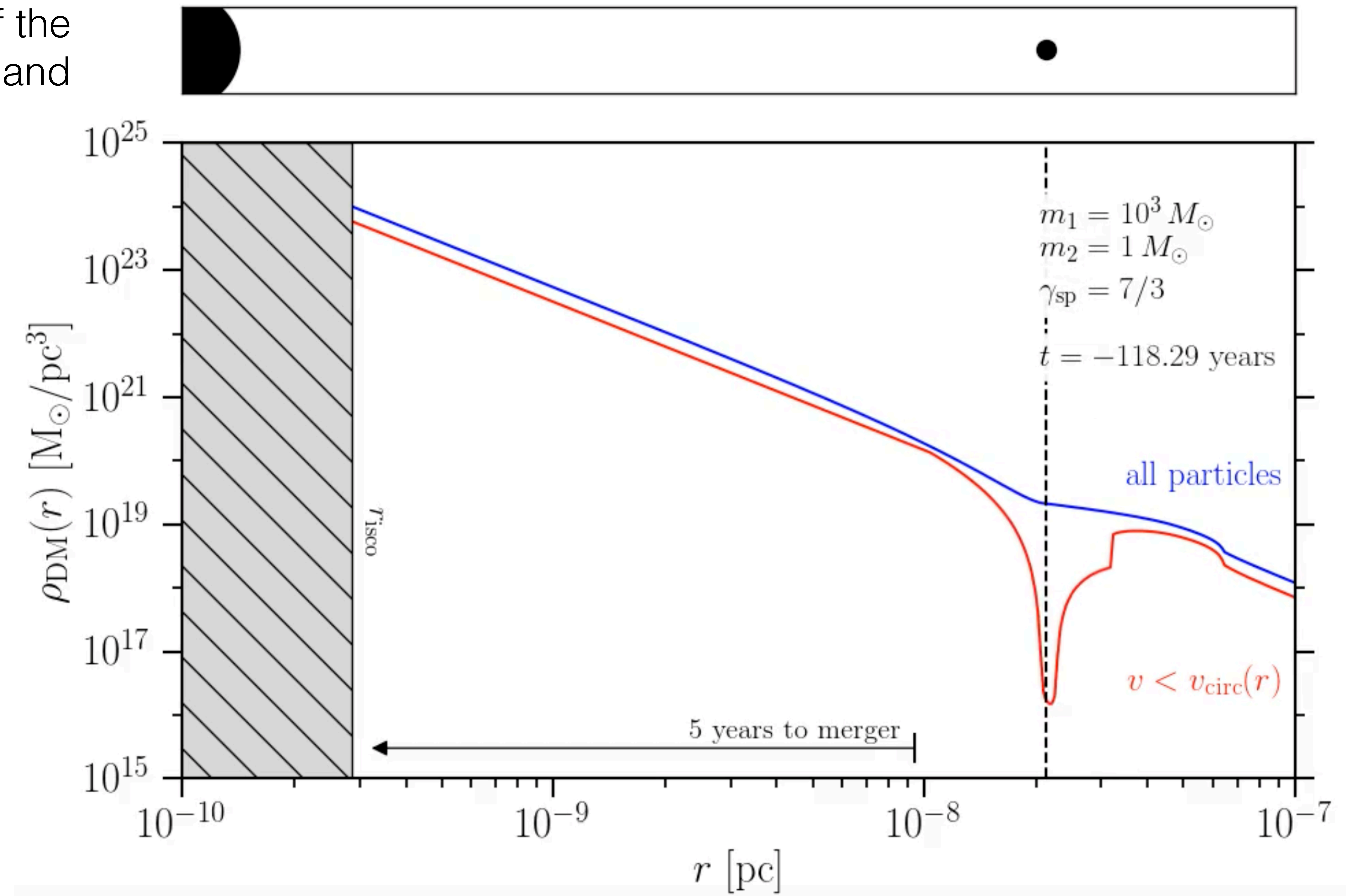

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Co-evolution

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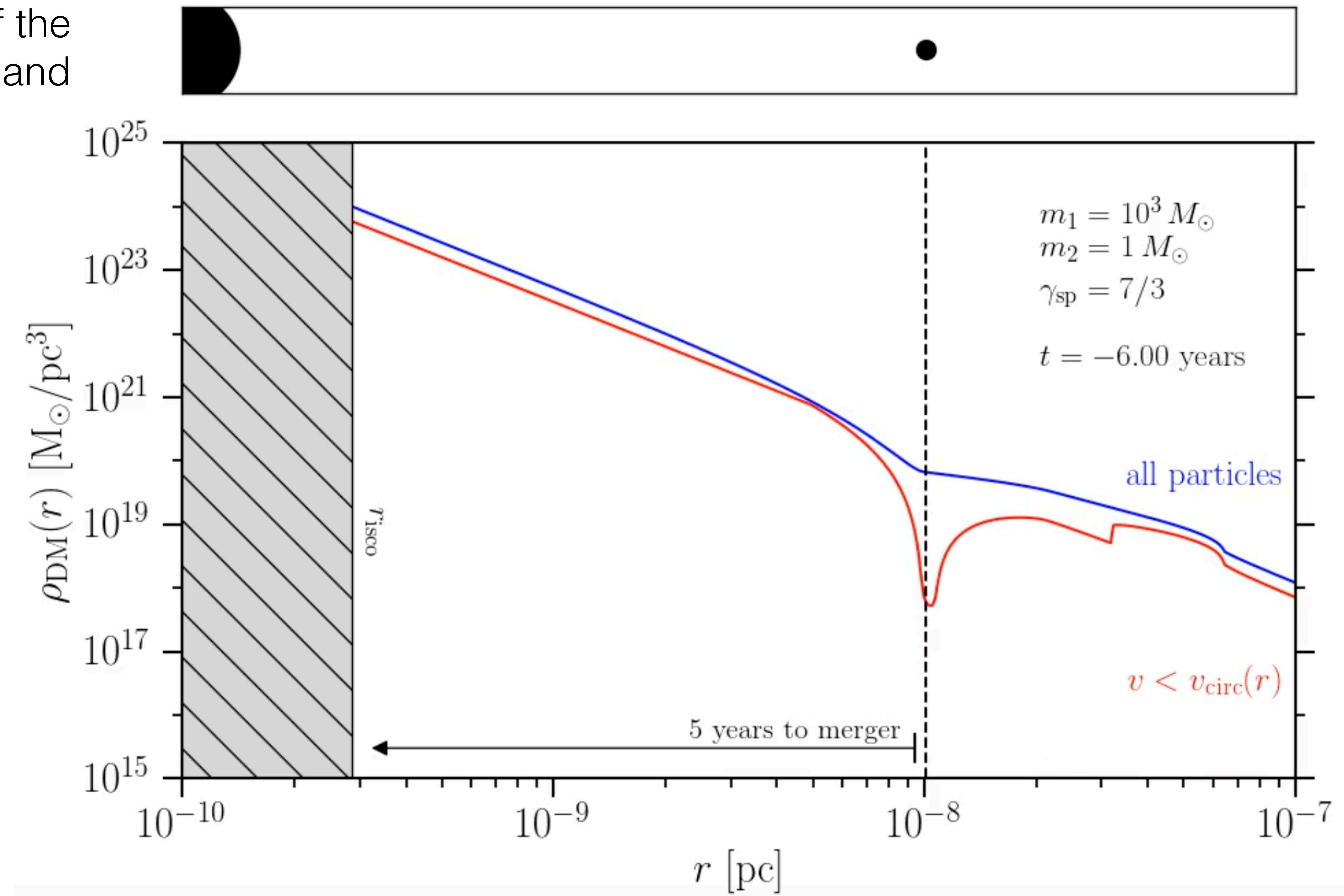

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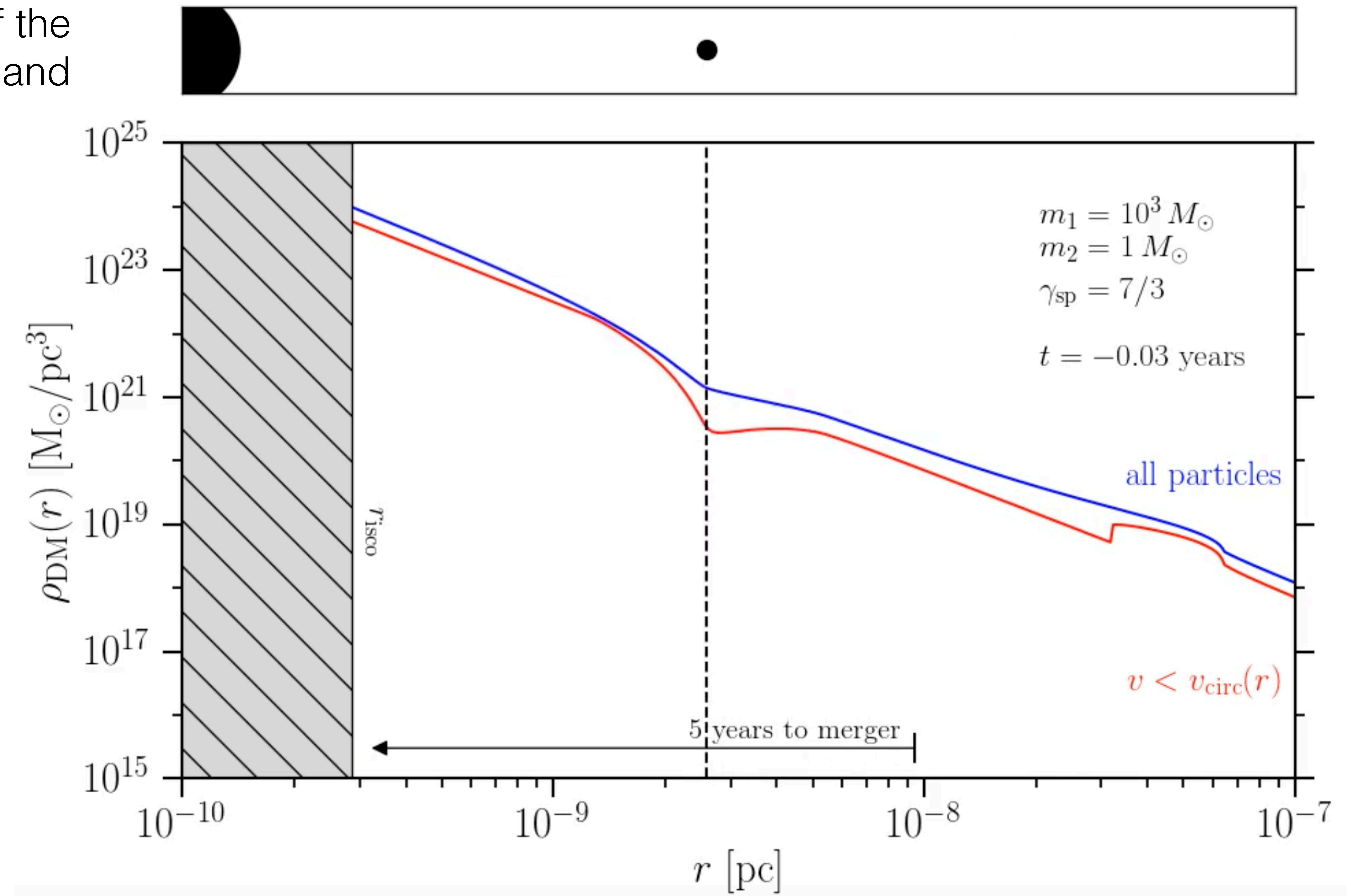

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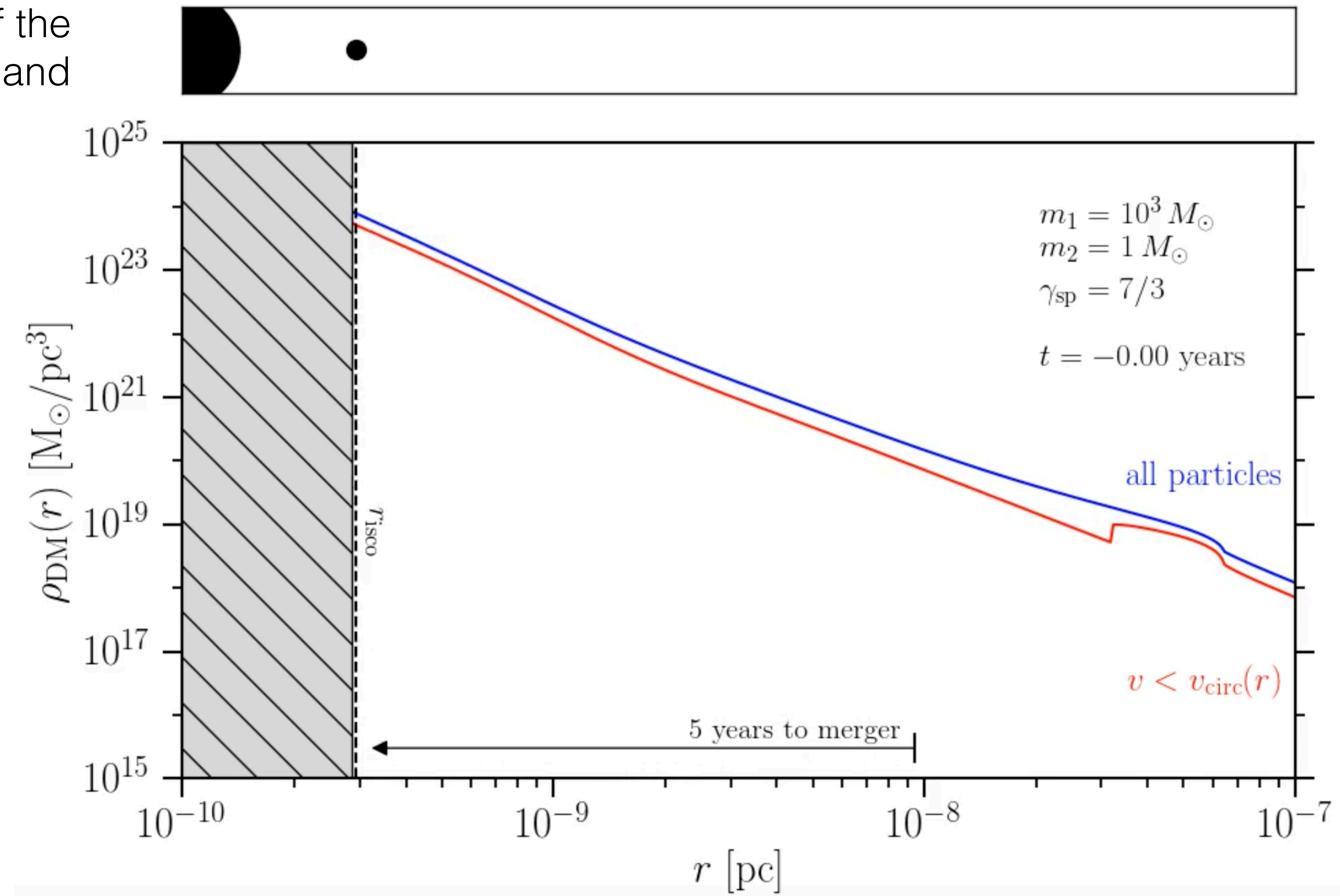

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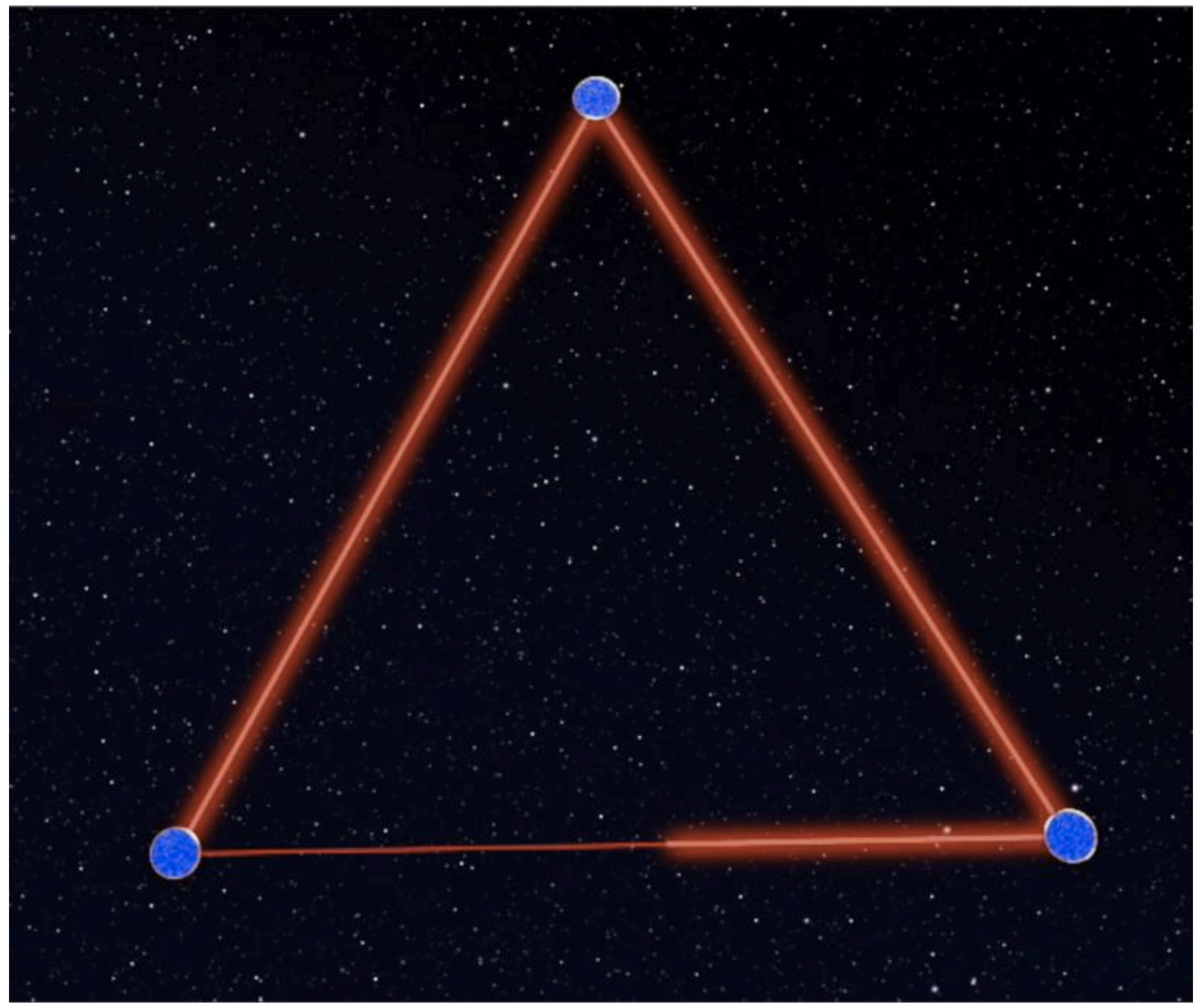
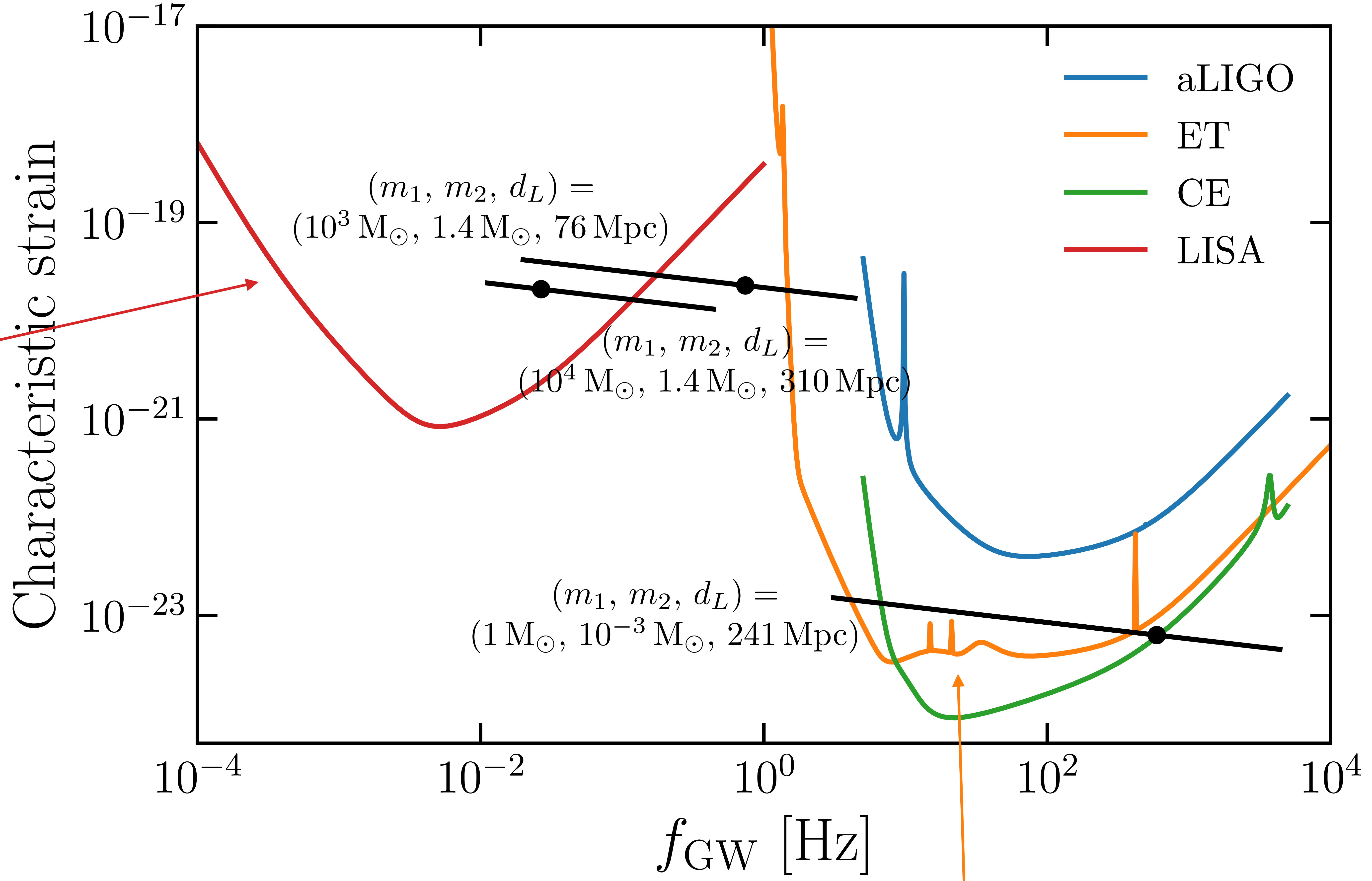
[Code: github.com/bradkav/HaloFeedback]

GW Sensitivity

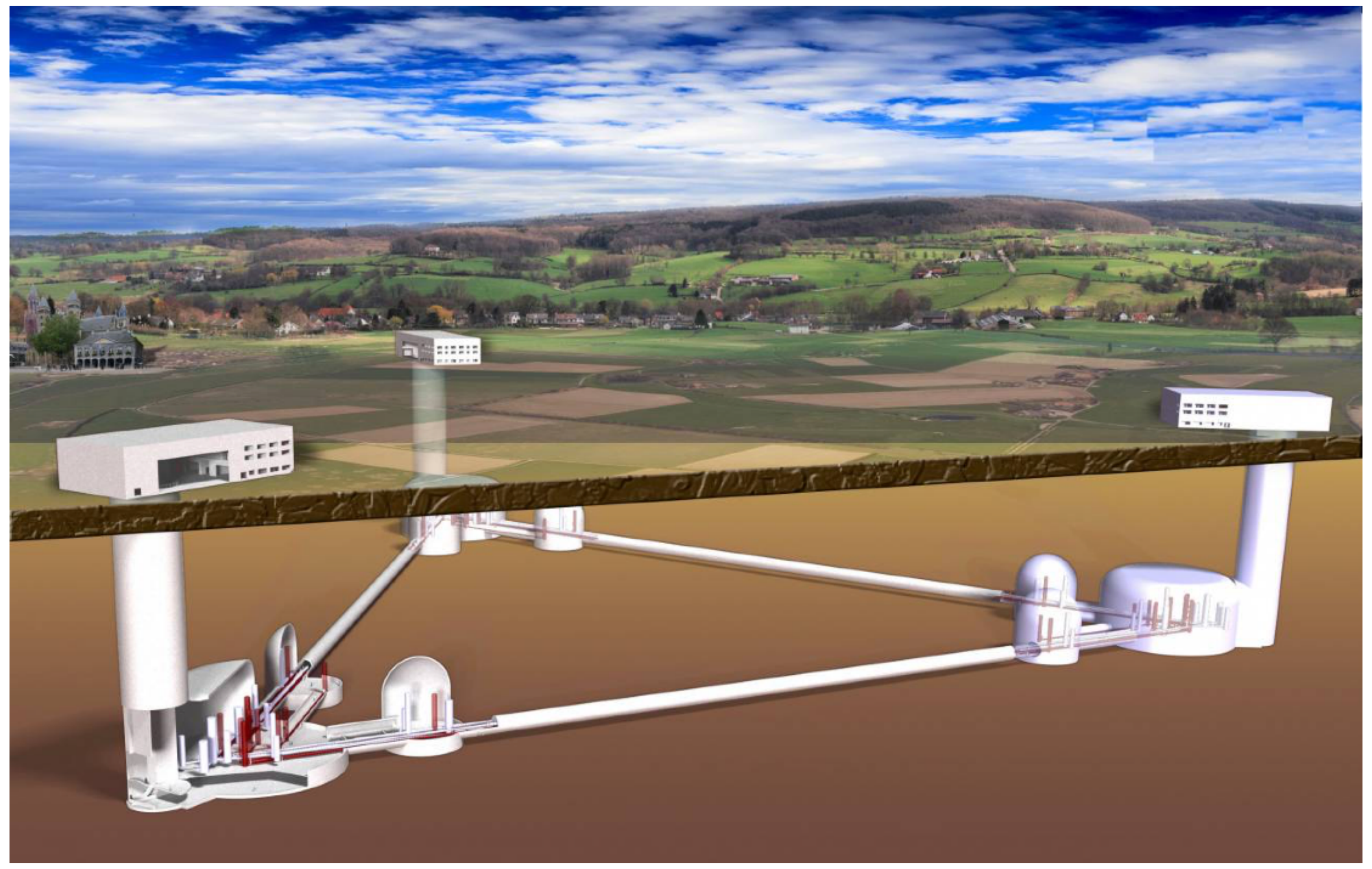
© AEI / MM / exozet



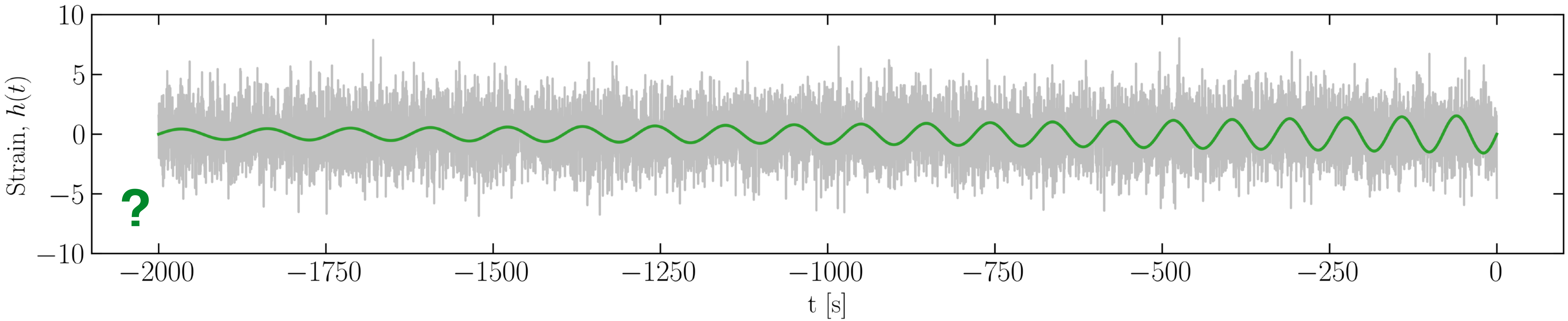
Laser **I**nterferometer **S**pace **A**ntenna
(planned for the 2030s)
[1907.06482]

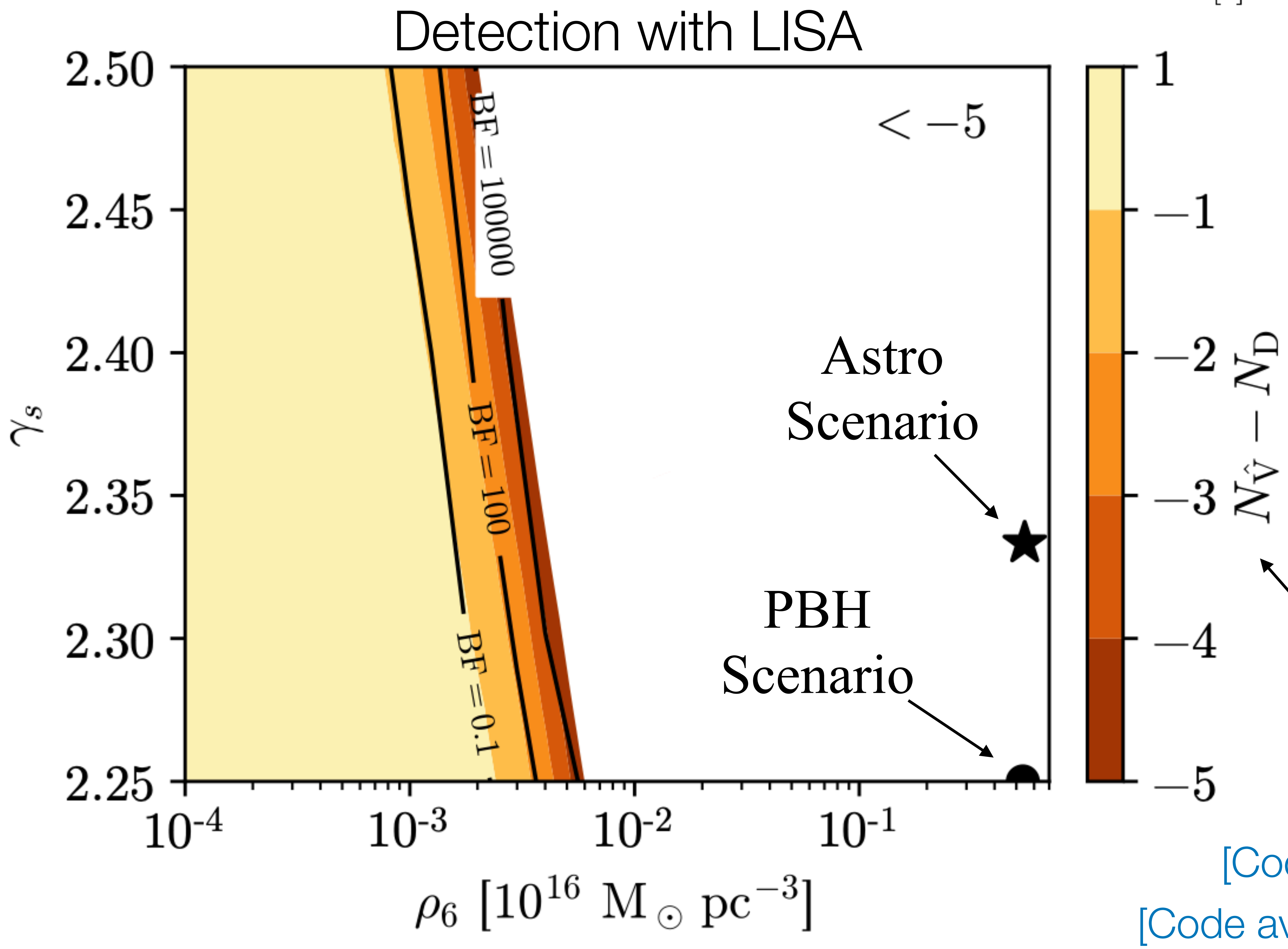


Einstein **T**elescope
[1912.02622]



Discoverability





Number of GW cycles of dephasing

Compare **Bayes factor (BF)** for the vacuum case (V) and the DM dressed case (D)

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

vs.

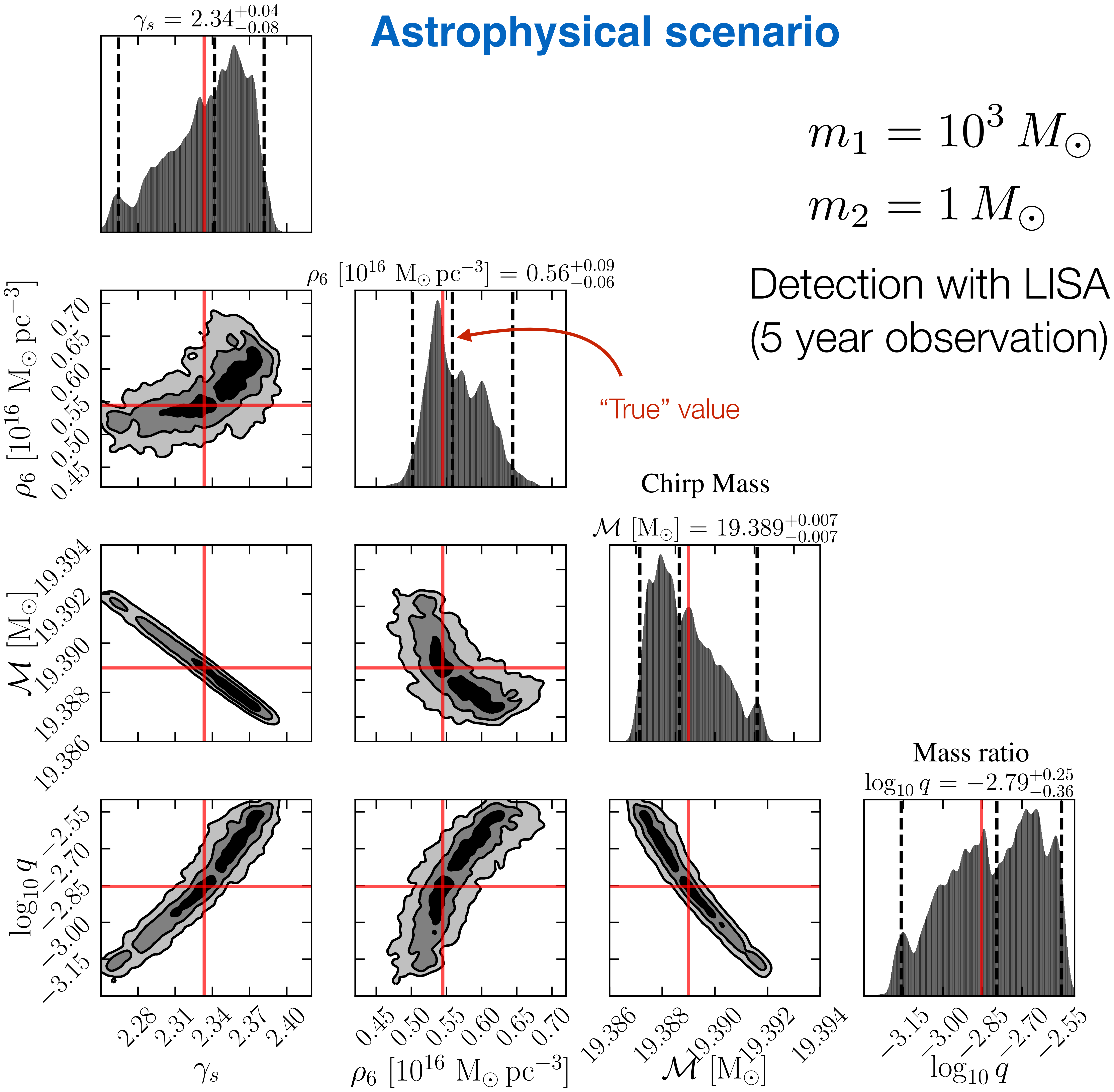
$$\boldsymbol{\theta}_\mathrm{D} = \{\gamma_\mathrm{sp}, \rho_6, \mathcal{M}, \log_{10} q\}$$

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

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

Measurability

Astrophysical scenario



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

Detection with LISA
(5 year observation)

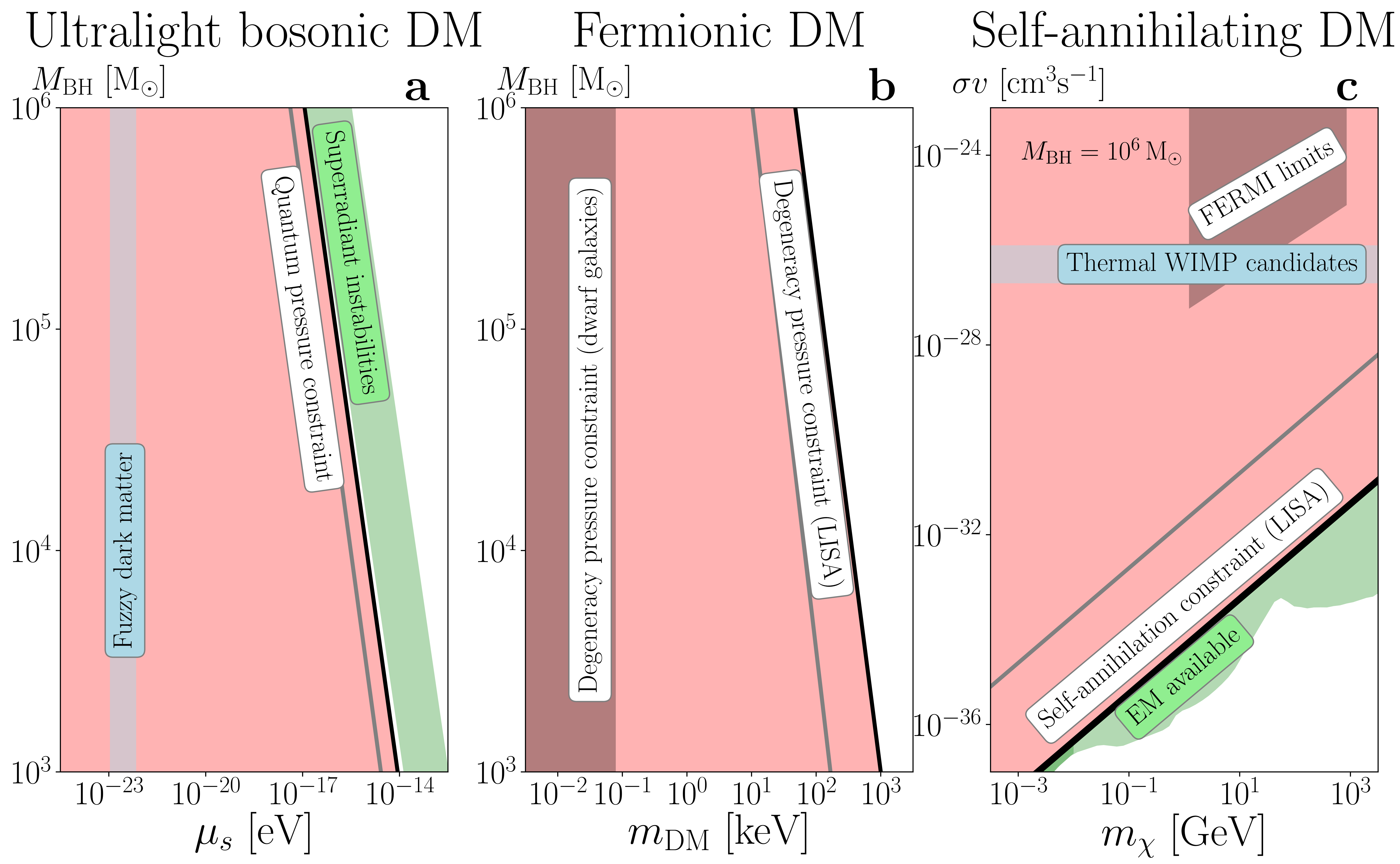
[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]

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

[See also Cole, Coogan, **BJK**, Bertone, 2207.07576 for the PBH scenario]

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

[1906.11845]

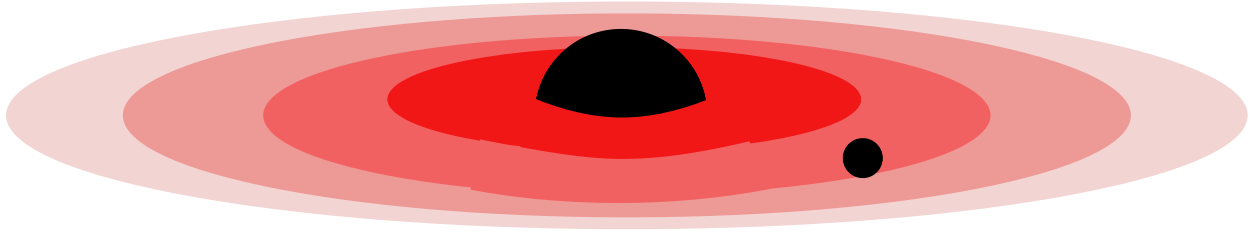


[See also Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

Environmental confusion?

Generate waveform assuming:

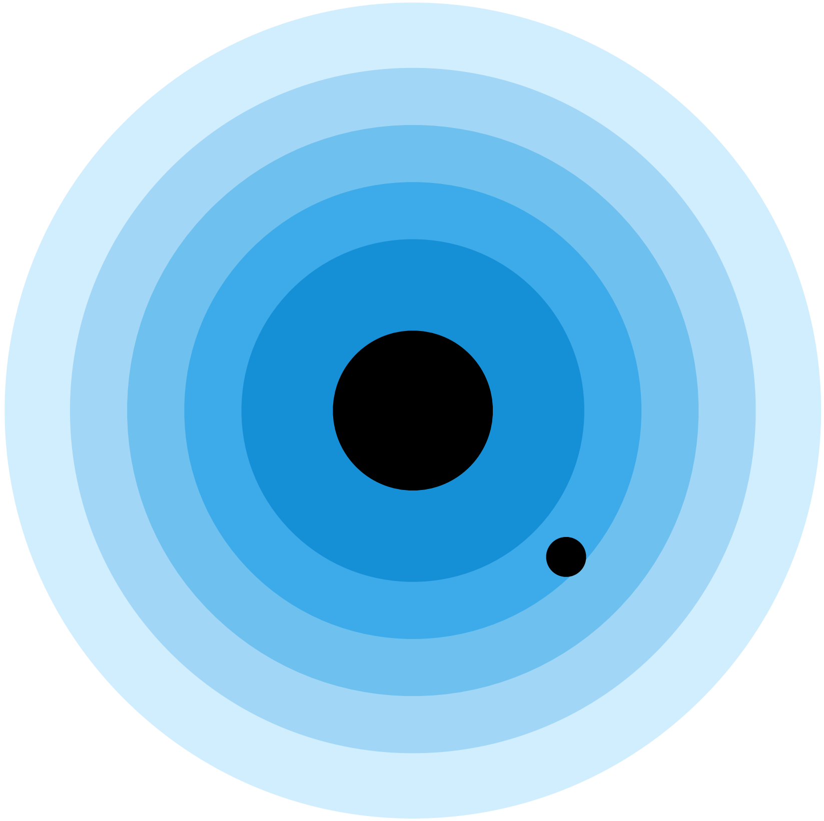
baryonic
Accretion Disk



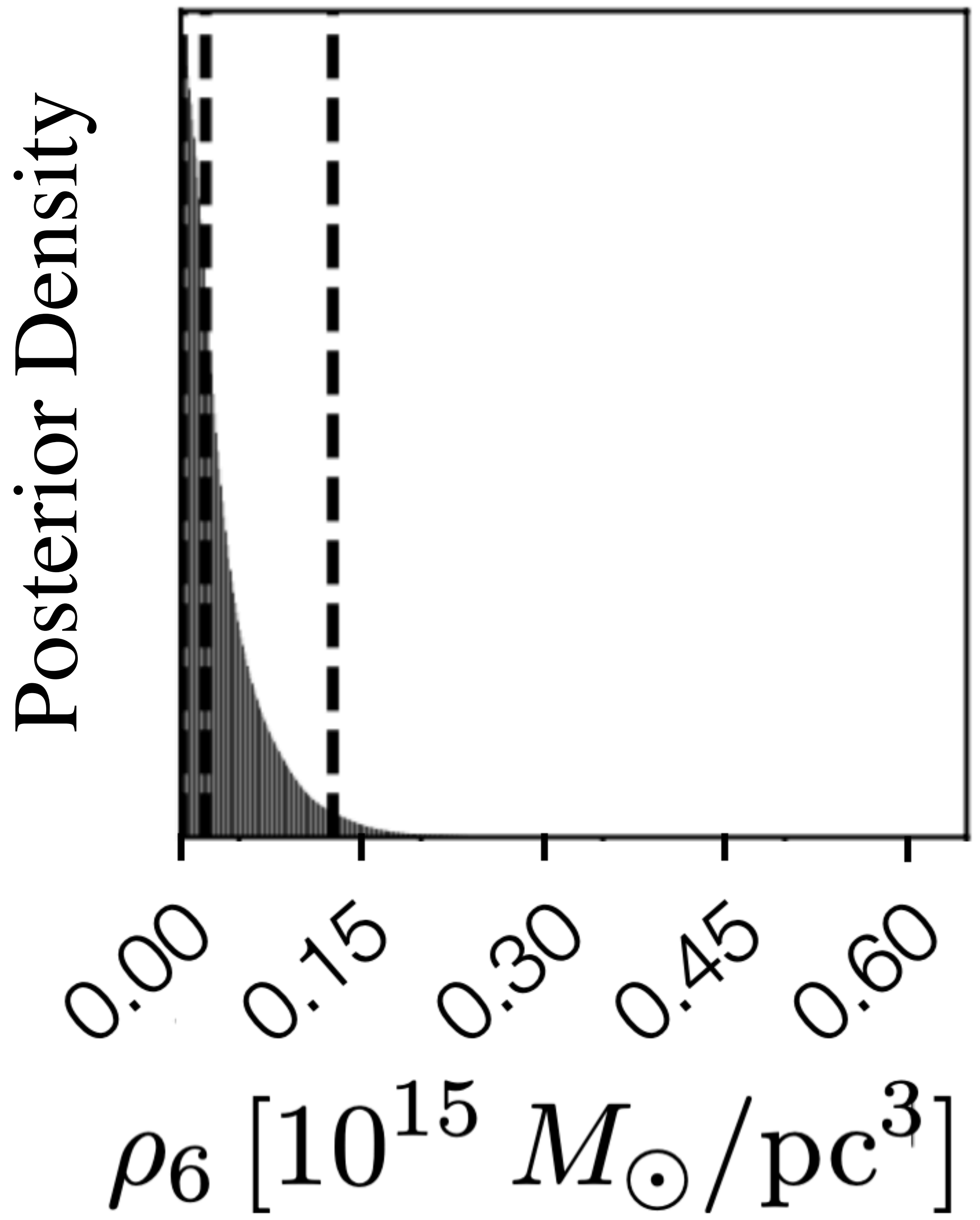
$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1/2}$$

Fit signal assuming:

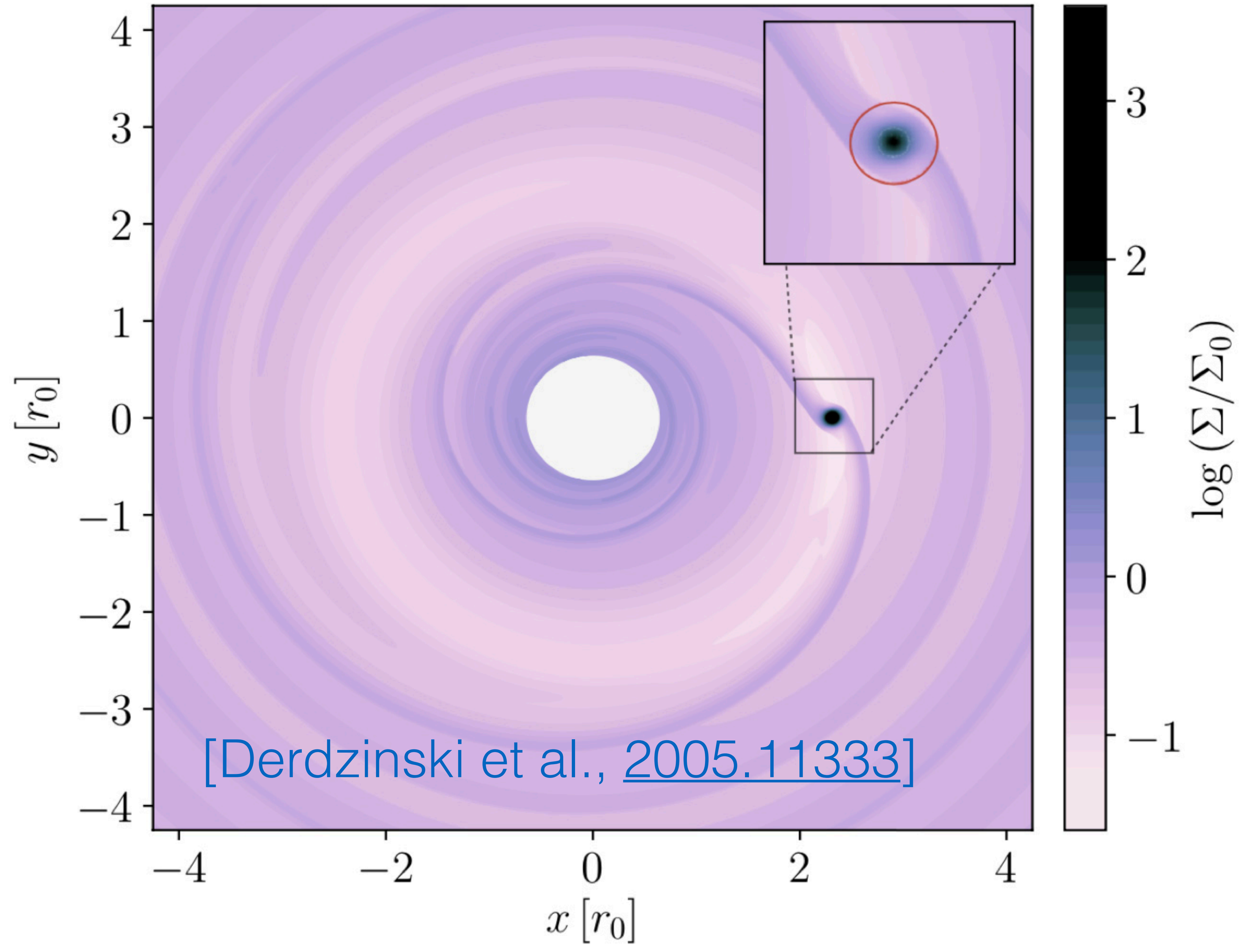
DM Spike



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



Energy loss mechanisms in an accretion disk are very different!

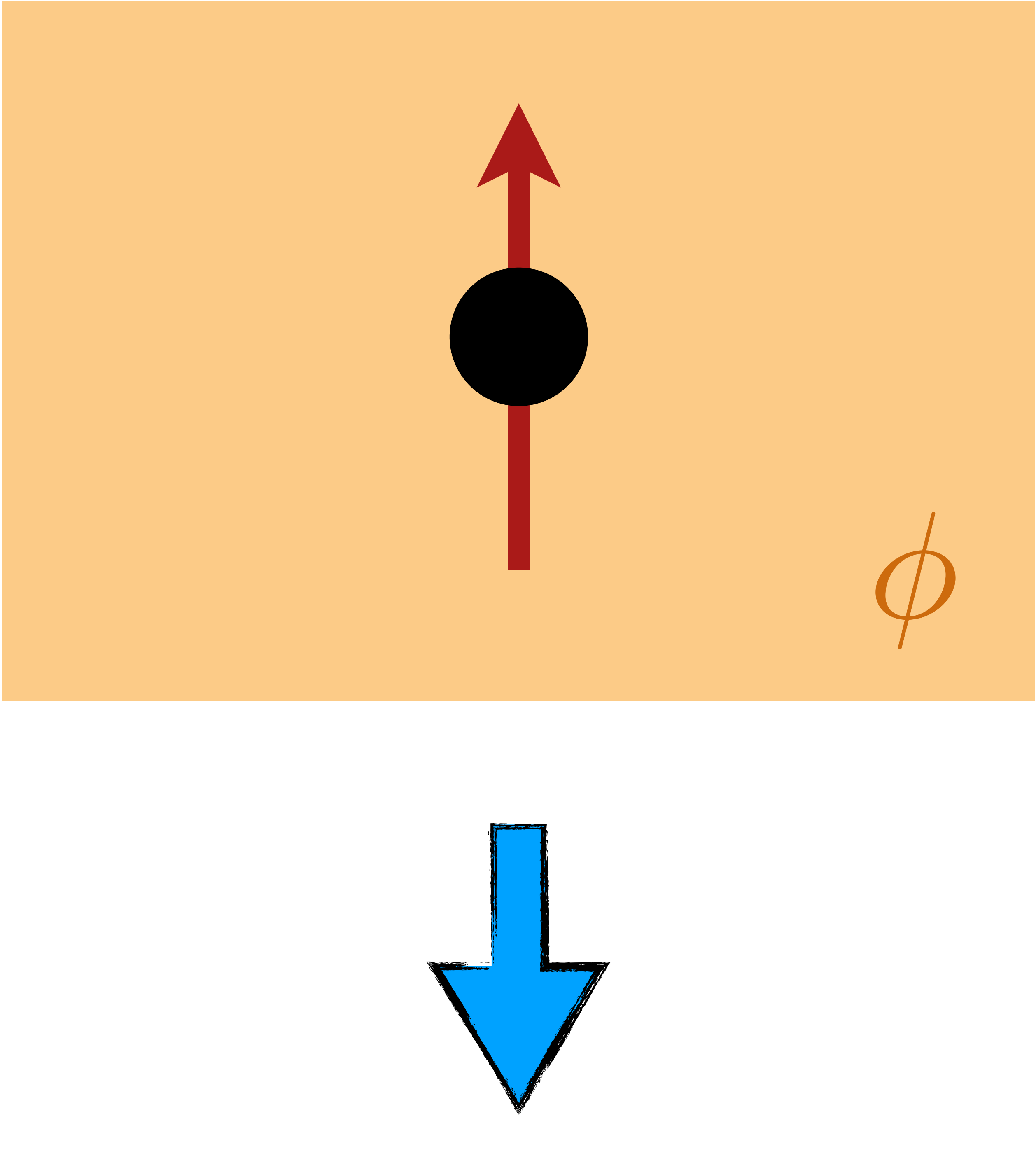


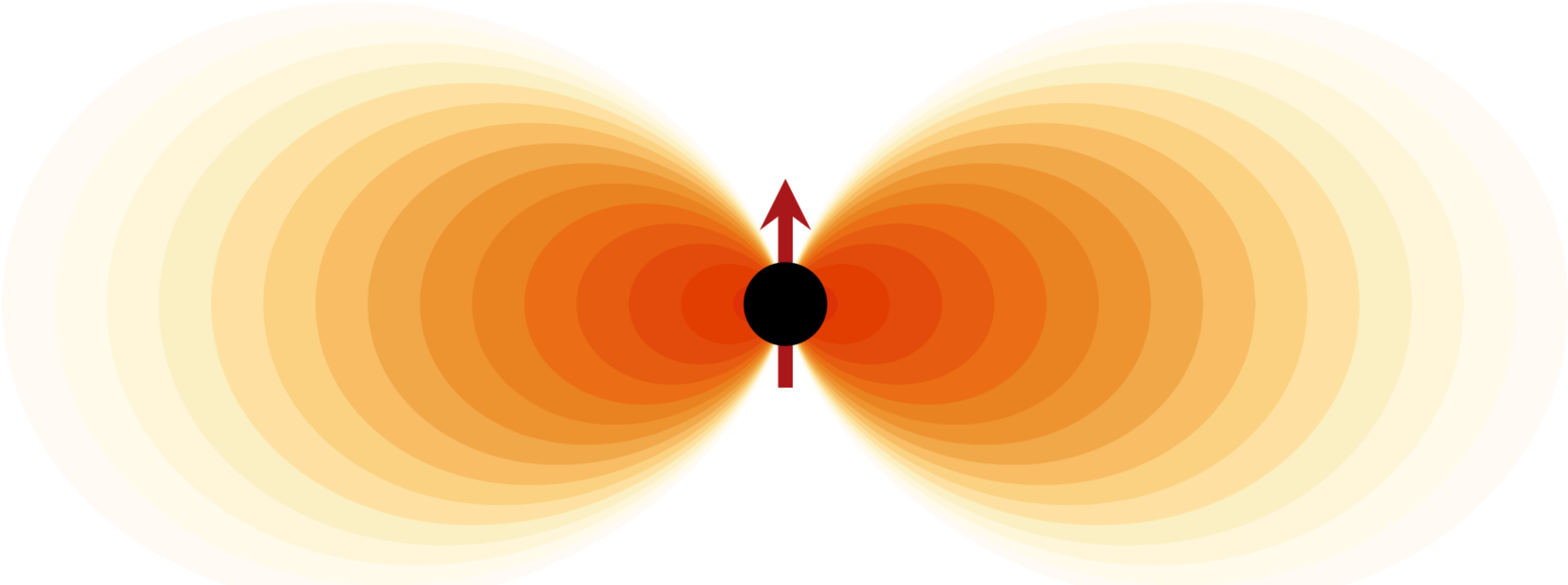
[Derdzinski et al., 2005.11333]

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

[See also Becker & Sagunski, 2211.05145]

Gravitational Atoms





Compton wavelength of a light scalar field:

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

Super-radiant growth of a scalar cloud extracts spin from the BH when:

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

[Zel'dovich (1972), Starobinsky (1973)]

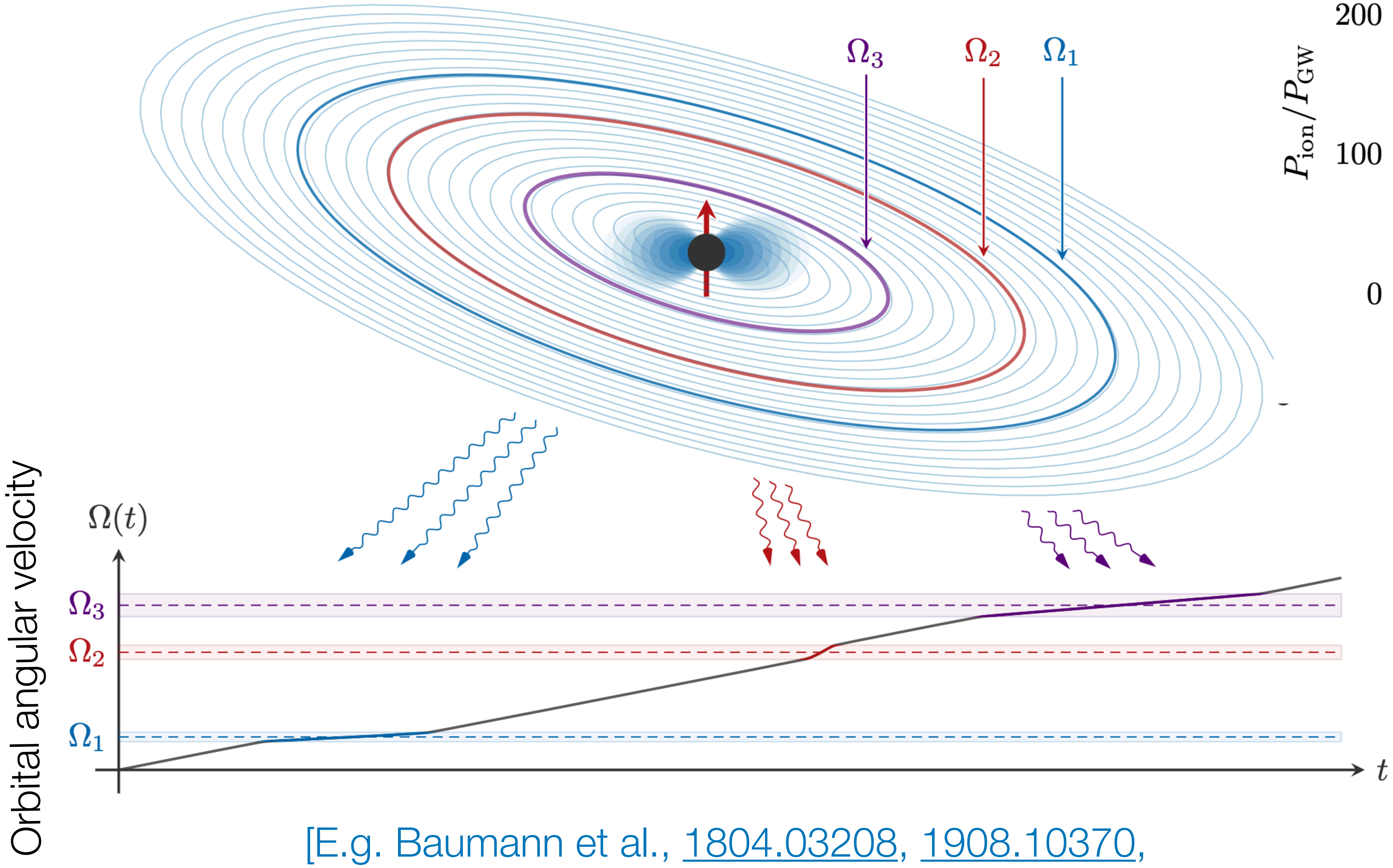
$$M_{\mathrm{BH}} \in [1, 10^{10}]\,M_\odot$$
$$\rightarrow m_\phi \in [10^{-20}, 10^{-10}]\,\mathrm{eV}$$

[Chia, 2012.09167]

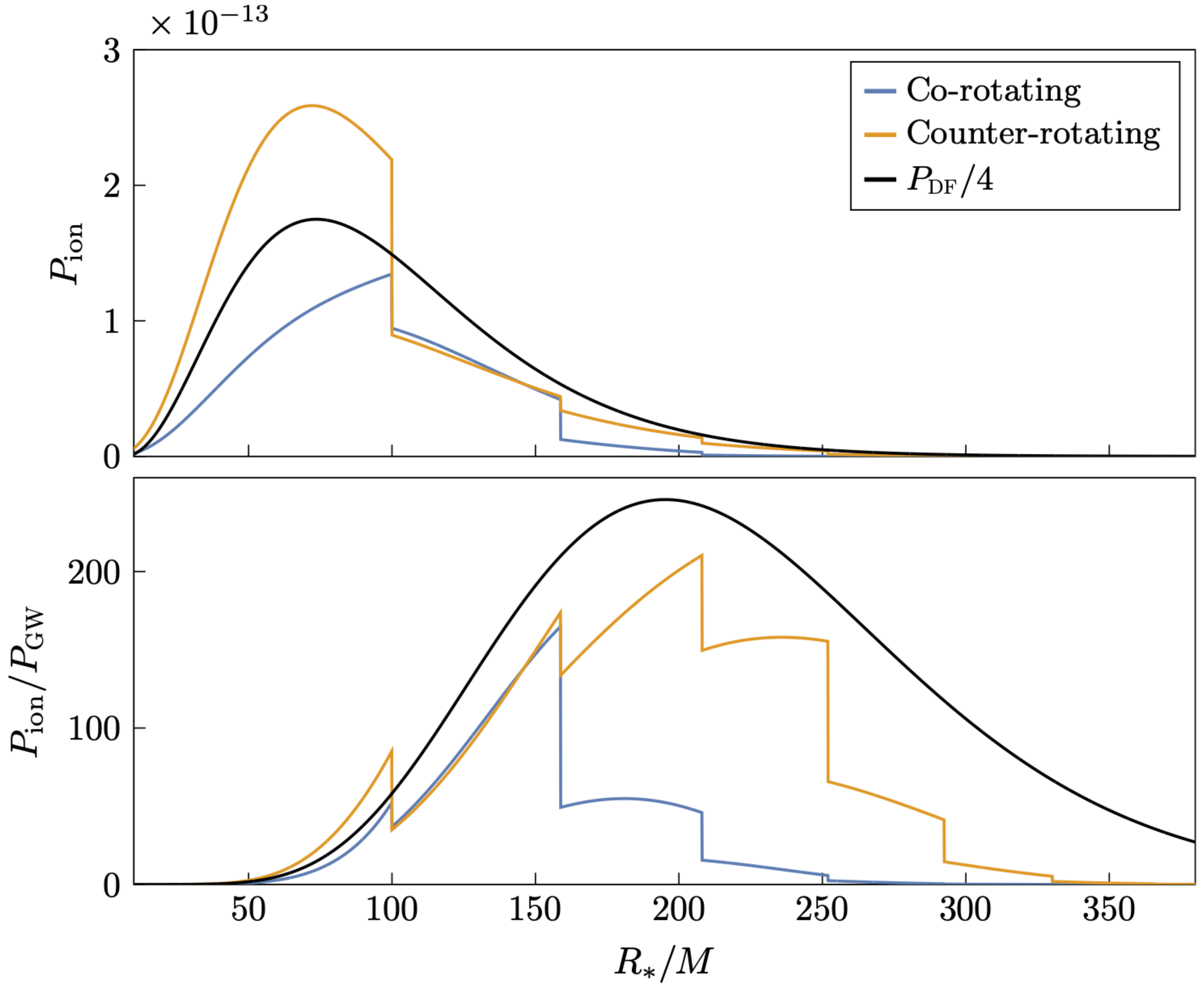
Bound states of the scalar field look like those of an electron in a hydrogen atom: '**gravitational atom**'

Orbiting BH can induce resonant transitions in the boson cloud.

Presence of a gravitational atom can lead to 'floating' or 'sinking' orbits.



[E.g. Baumann et al., 1804.03208, 1908.10370, 1912.04932, 2206.01212, 2112.14777]

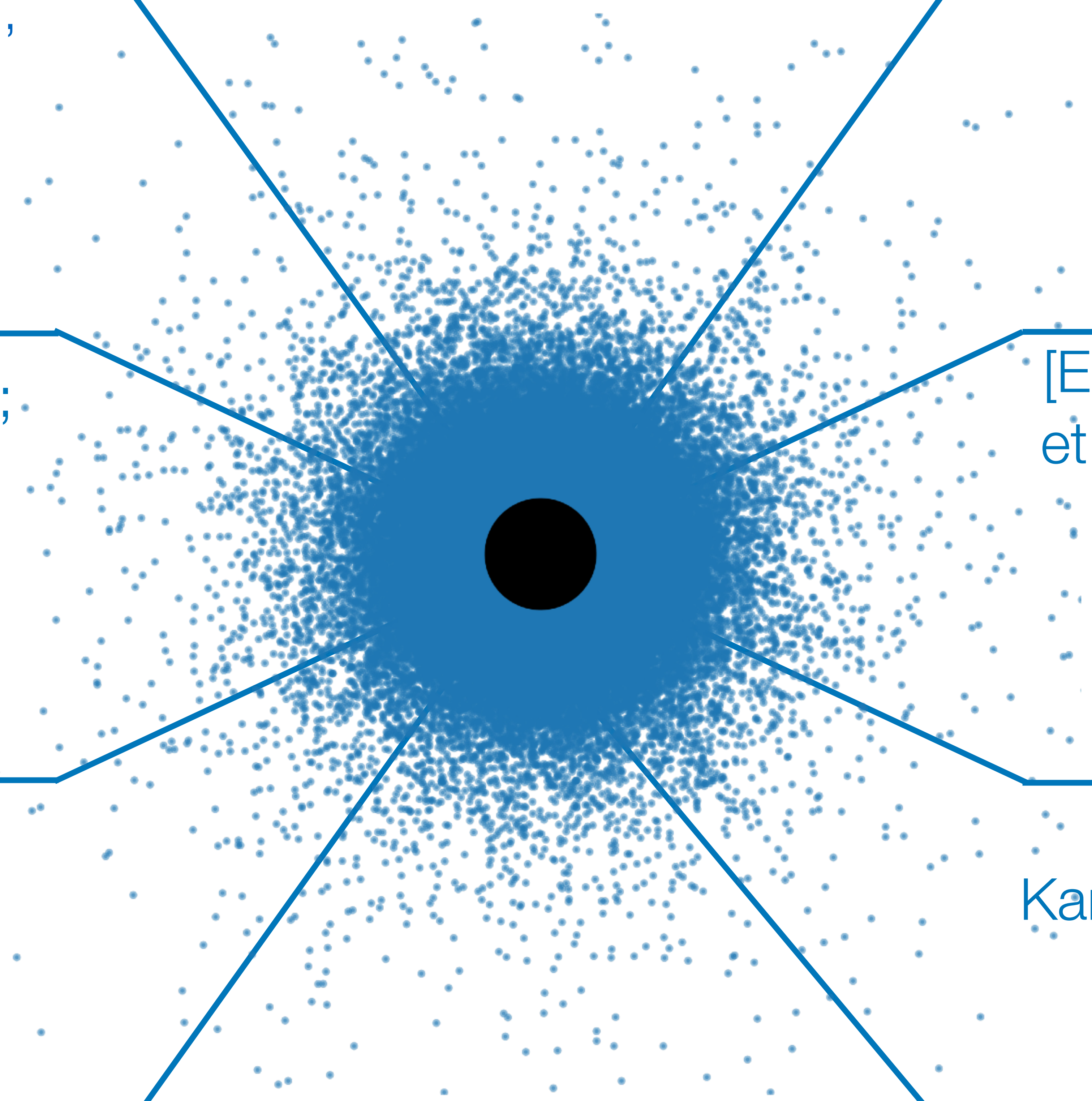


[Tomaselli, Spieksma, Bertone, 2305.15460, 2403.03147]

Also easily distinguished from cold DM spikes and accretion disks.

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

Towards better DM spikes



Confusion with other environmental effects

[E.g. Cole et al. (including **BJK**), 2211.01362; Becker & Sagunski, 2211.05145]

Relativistic effects

[E.g. Speeney et al., 2204.12508; Montalvo et al., 2401.06084]

Integration with realistic IMRI/EMRI waveforms

[E.g. Katz et al., 2104.04582]

Search strategies

Realistic spike formation and abundance

[E.g. Aschersleben et al., 2401.14072, Bertone et al. (including **BJK**), 2404.08731]

Eccentric orbits

[E.g. Becker et al., 2112.09586, Li et al., 2112.14041; Karydas, **BJK**, Bertone, 2402.13053]

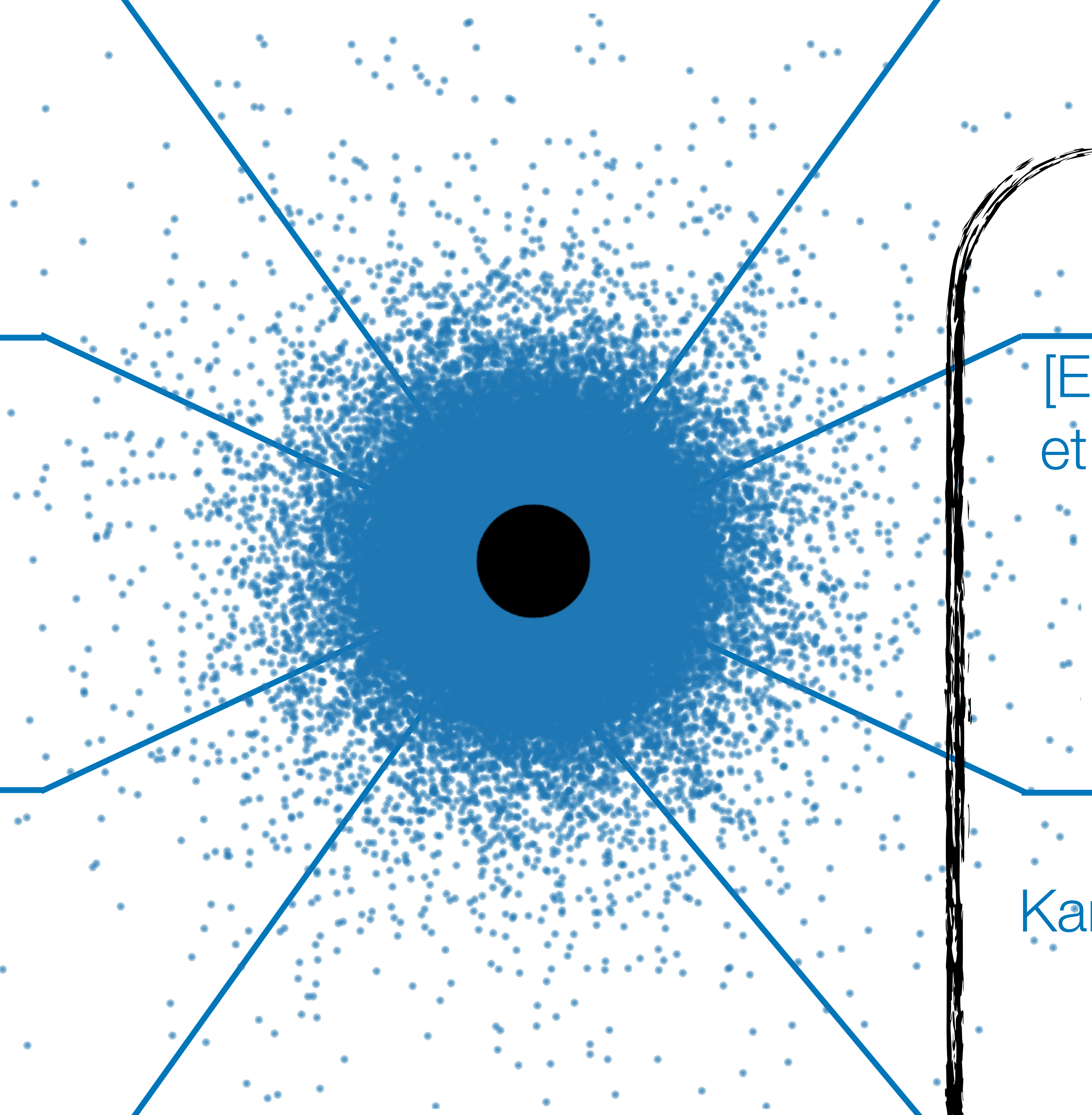
Accretion (for BHs)

[E.g. Nichols et al. 2309.06498, Karydas, **BJK**, Bertone, 2402.13053]

More realistic feedback

[**BJK** et al., 2402.13762]

Towards better DM spikes



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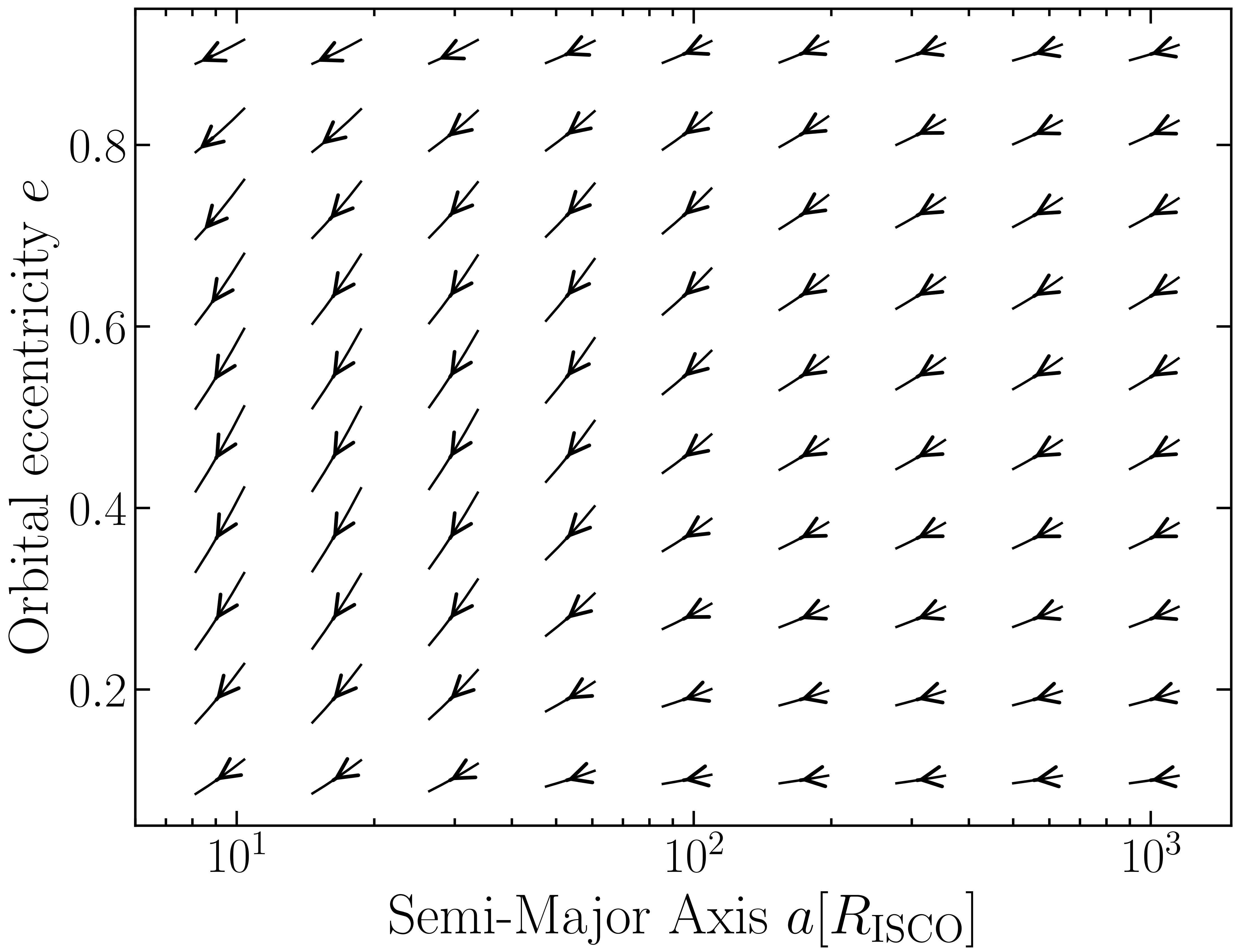
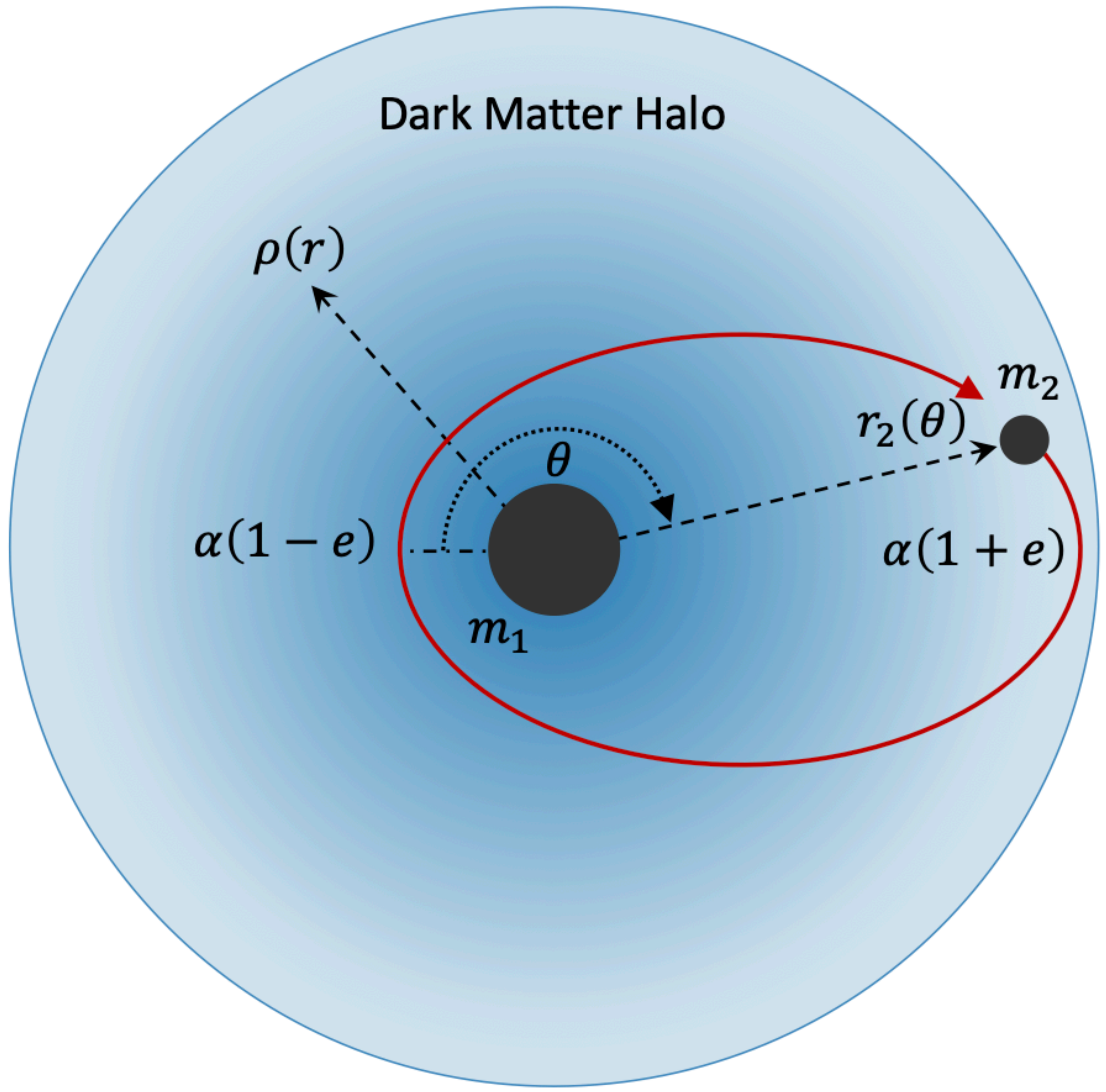
More realistic feedback

[**BJK** et al., 2402.13762]

Recently generalised feedback formalism to account for eccentric orbits and accretion onto the orbiting compact object. [Karydas, **BJK**, Bertone, 2402.13053]

Details are messy (need to co-evolve a, e and DM distribution), but ultimately find that the orbits tend to circularise during the inspiral:

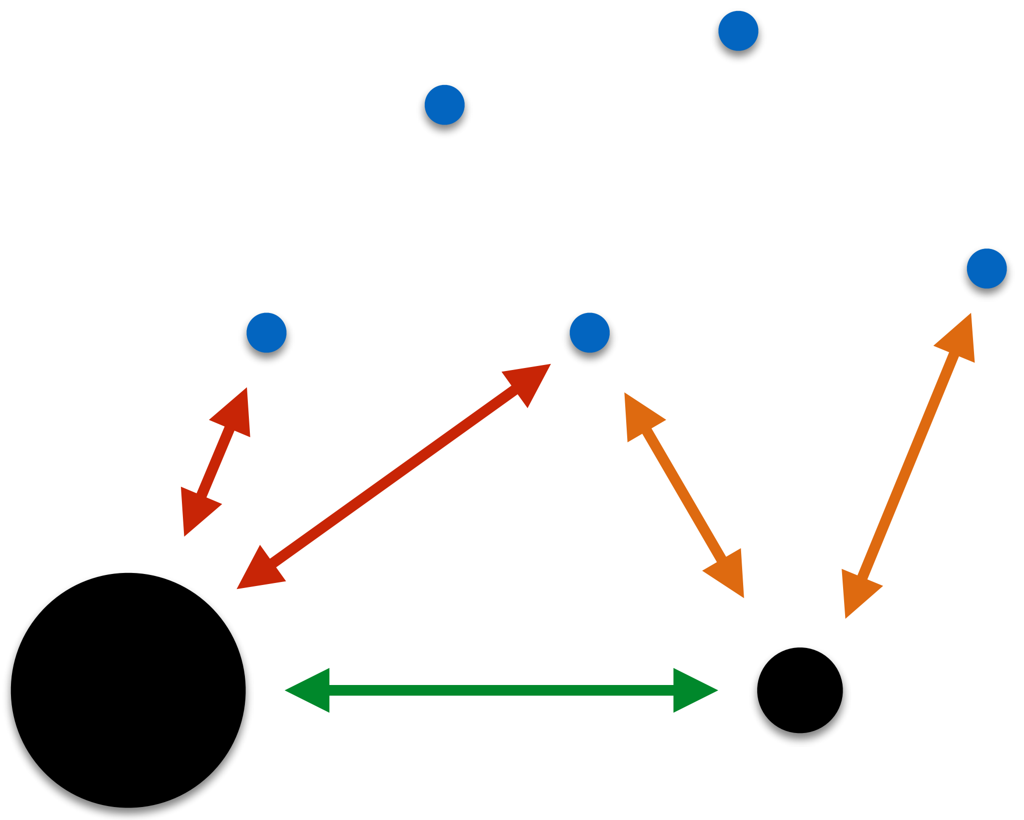




[More details on accretion in backup slides]

Eventually need to expand and verify our description of dynamical friction and feedback in the DM spike

NbodyIMRI: Newtonian N-body solver tailored to DM spikes.

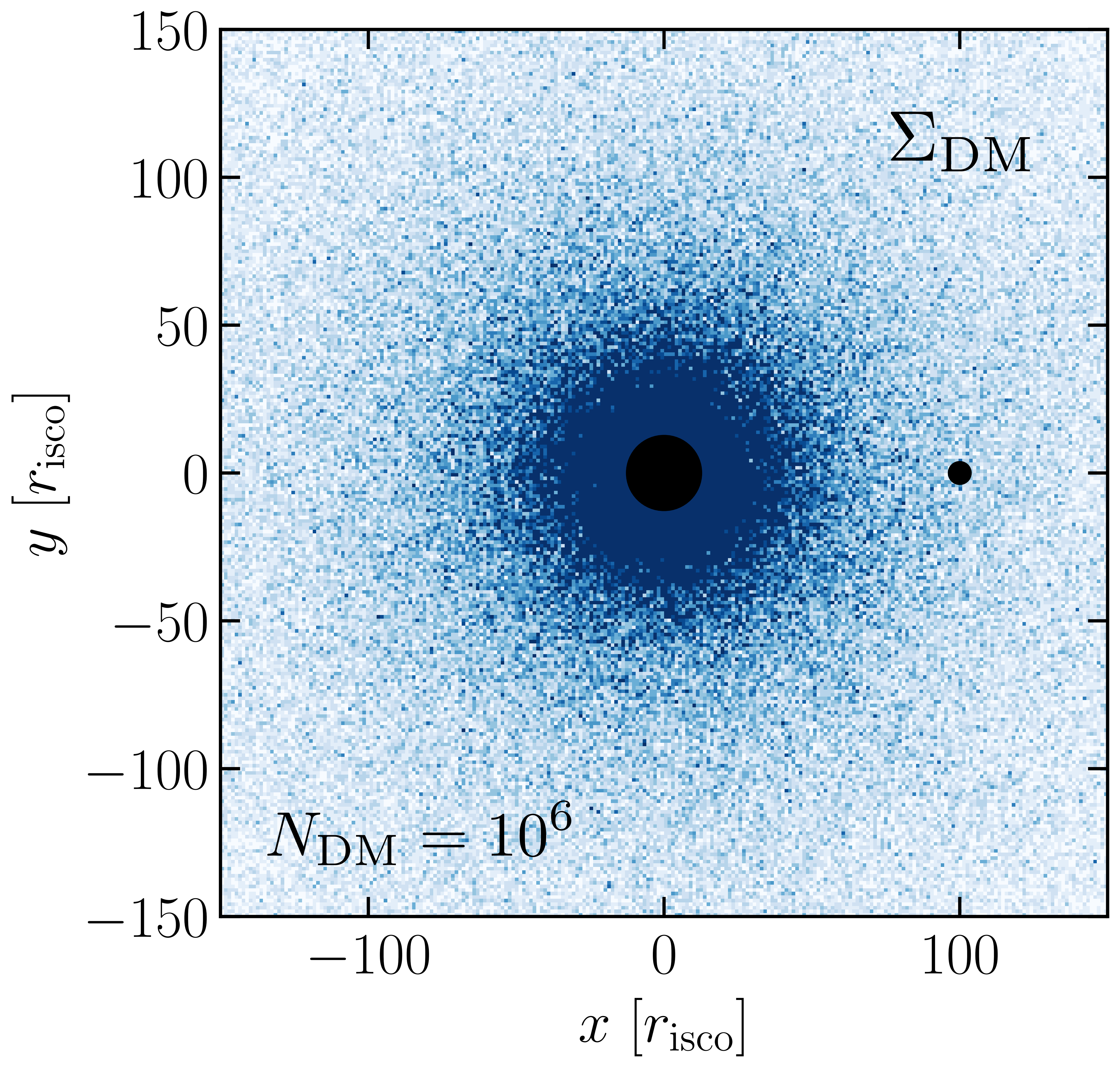


Neglect GW emission and *ignore DM-DM interparticle forces*.

Focus on understanding co-evolution of spike and binary.

[**BJK** et al., 2402.13762]

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

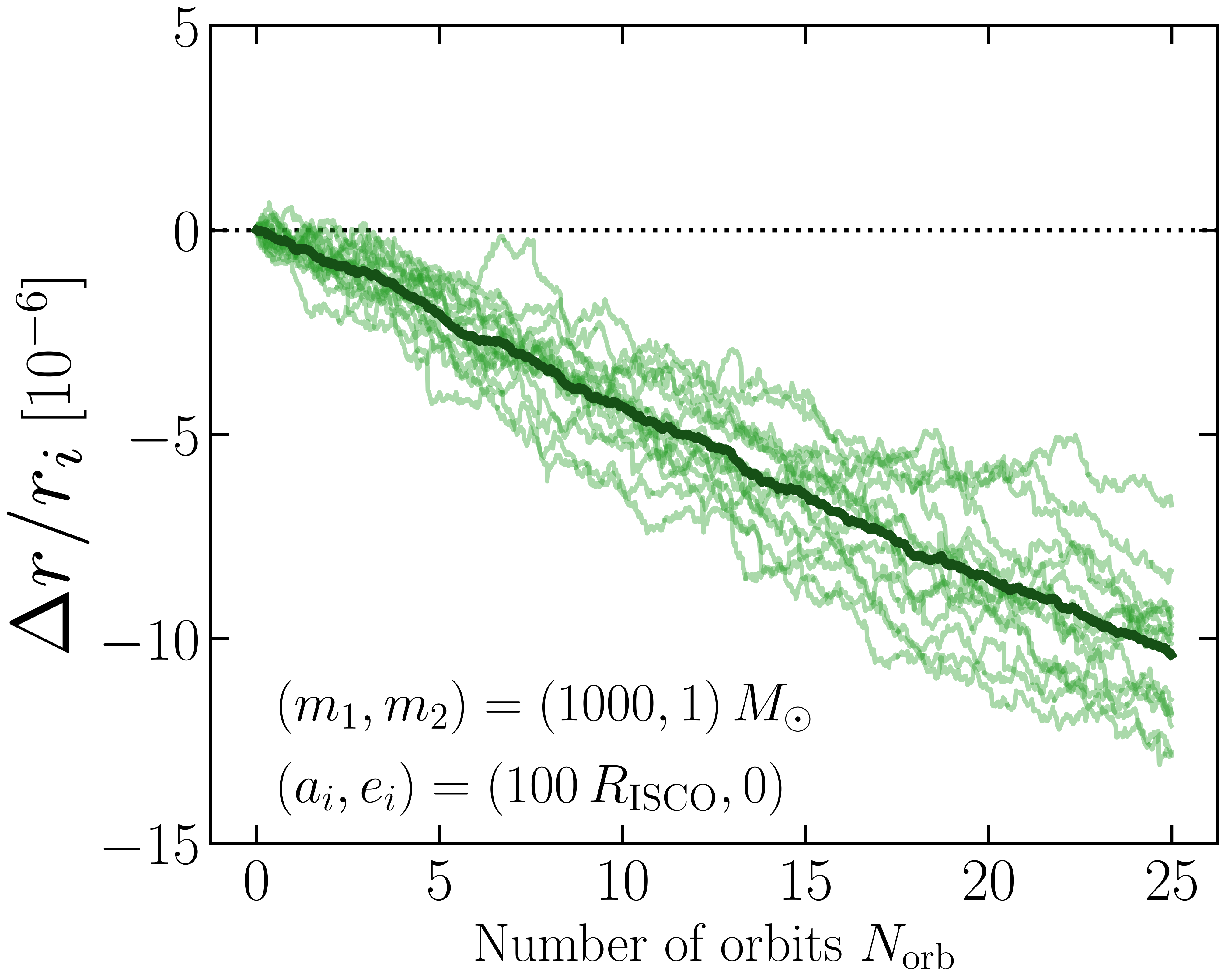


[See also Mukherjee et al., 2312.02275]

N-body Verification

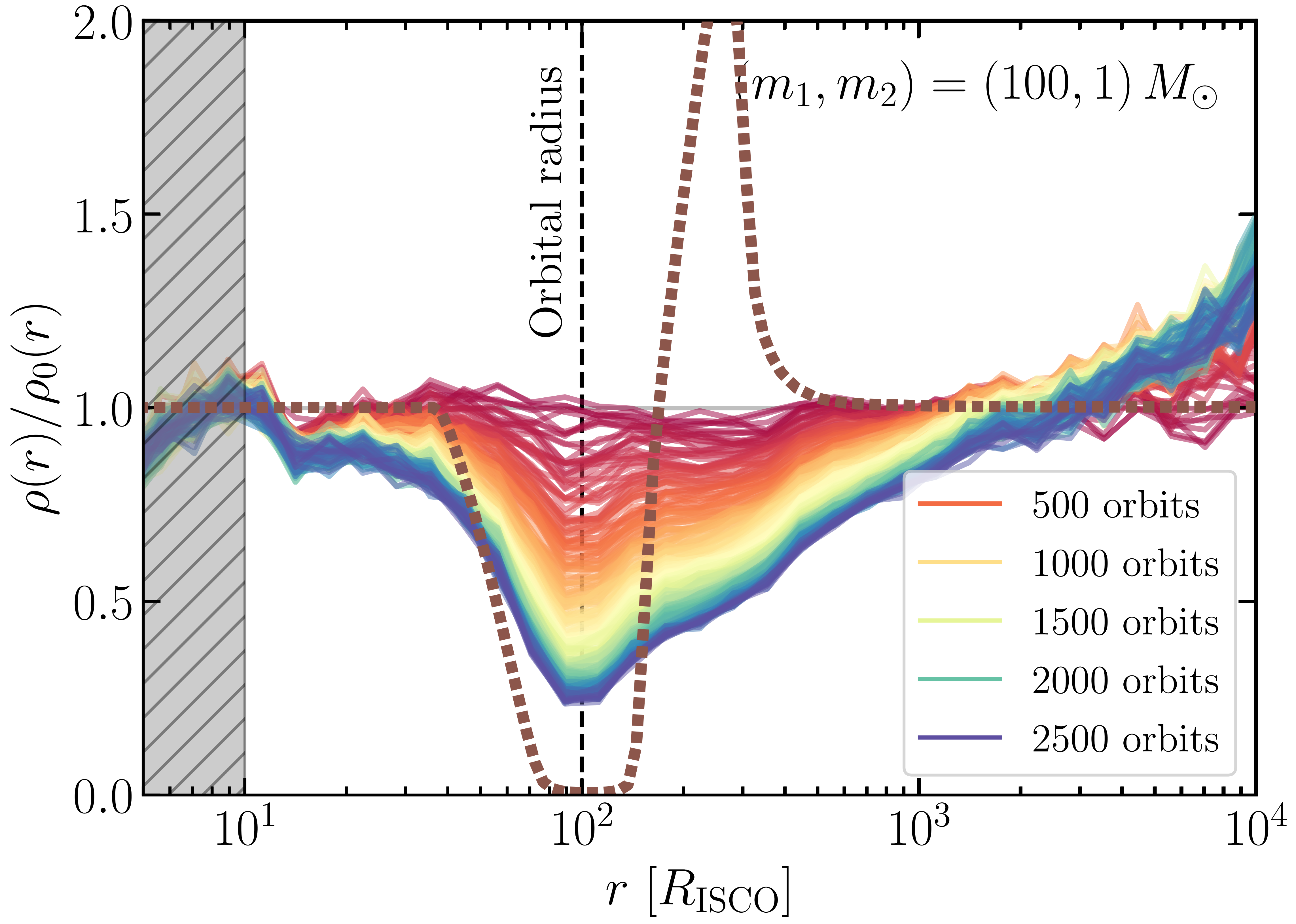
[**BJK** et al., 2402.13762]

Can use **NbodyIMRI** to verify the strength of the dynamical friction force…



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

…and to study the depletion of the DM spike 'in full'.



Find that the depletion is slower than using the previous **HaloFeedback formalism**!

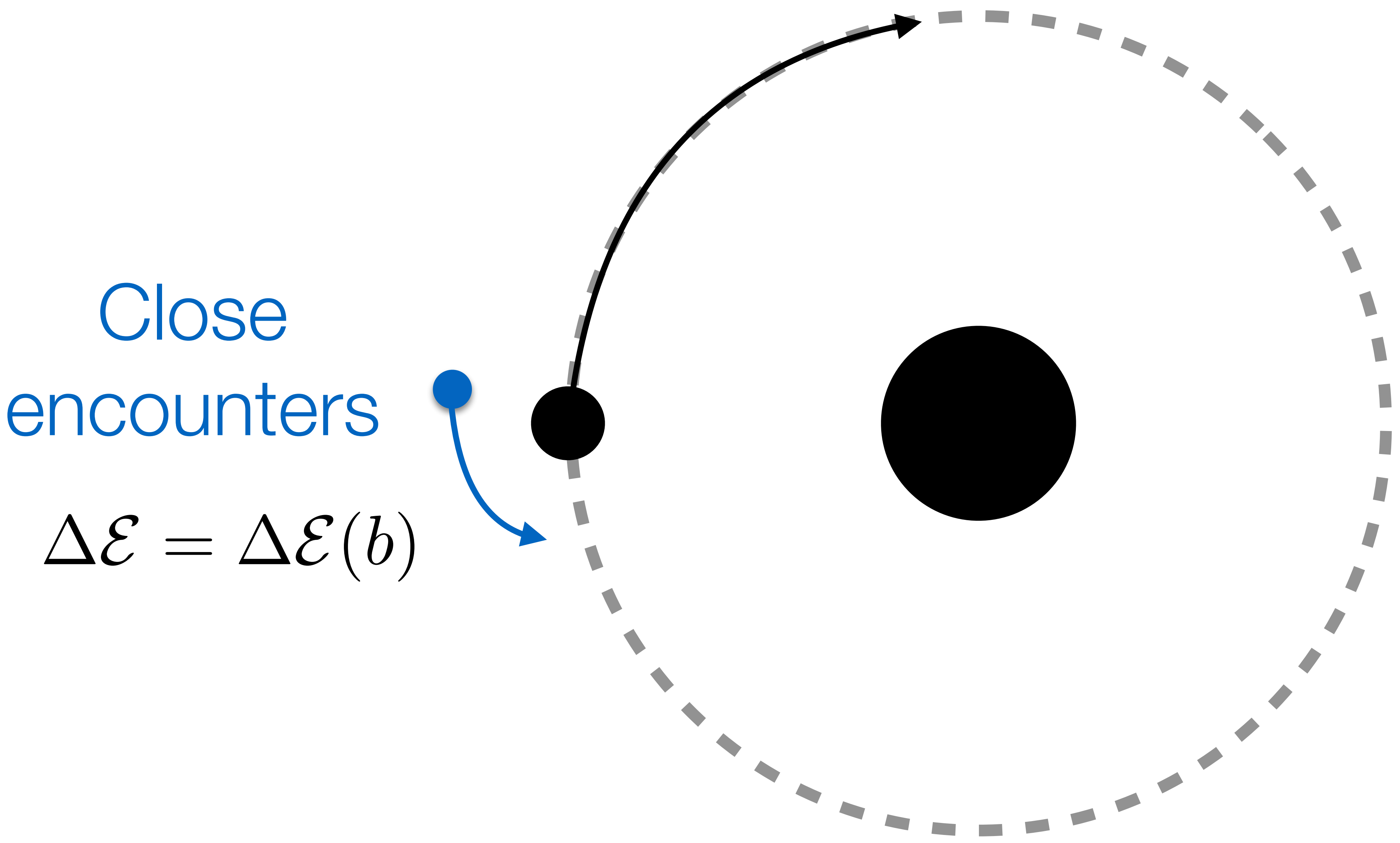
Three-body 'stirring' effects

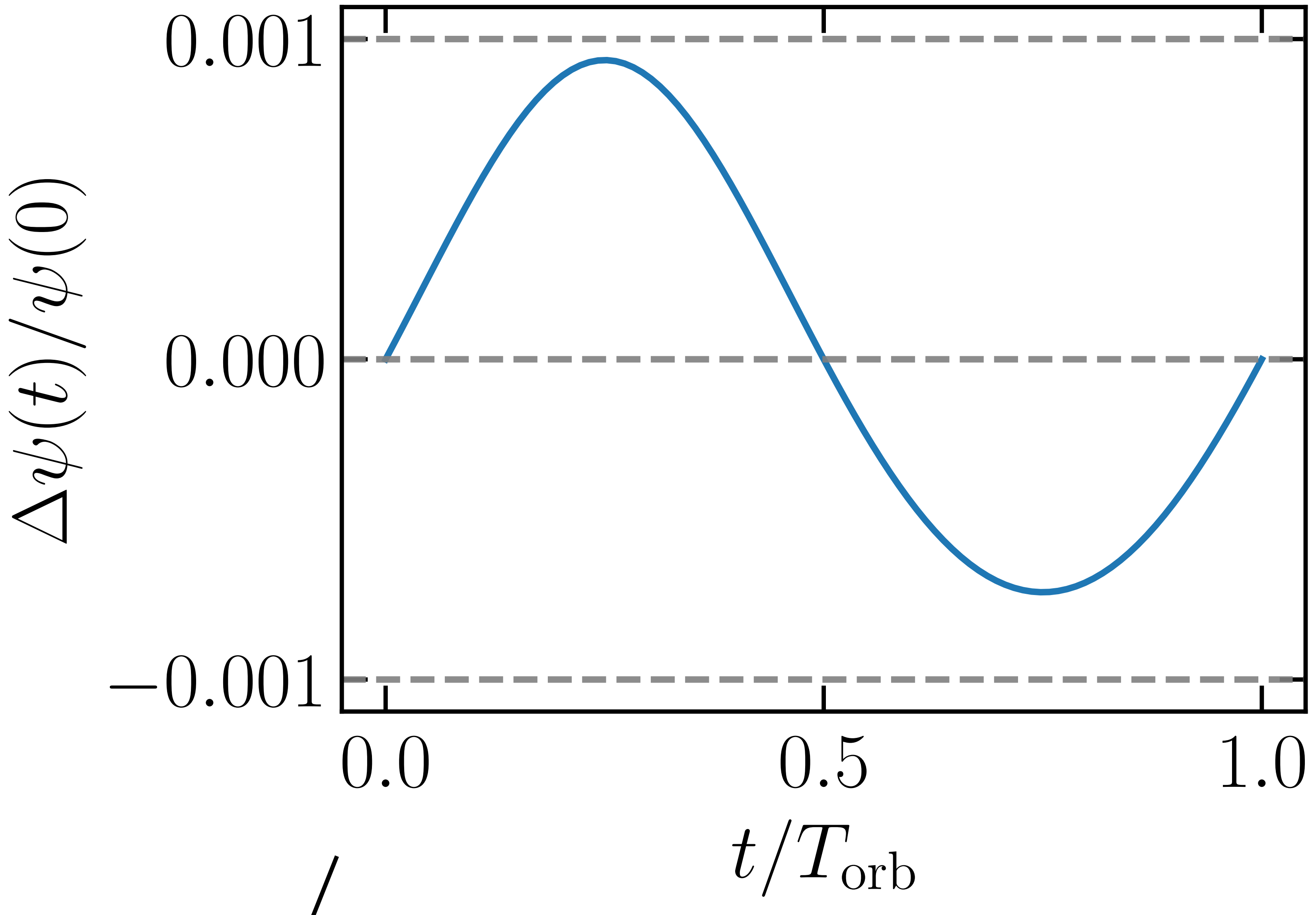
[**BJK** et al., 2402.13762]

[Similar results found by Mukherjee et al., 2312.02275]

Depletion of spike is not as rapid due to a new feedback mechanism, coming from the time dependent potential of the binary.

Three-body "**stirring**" effect.



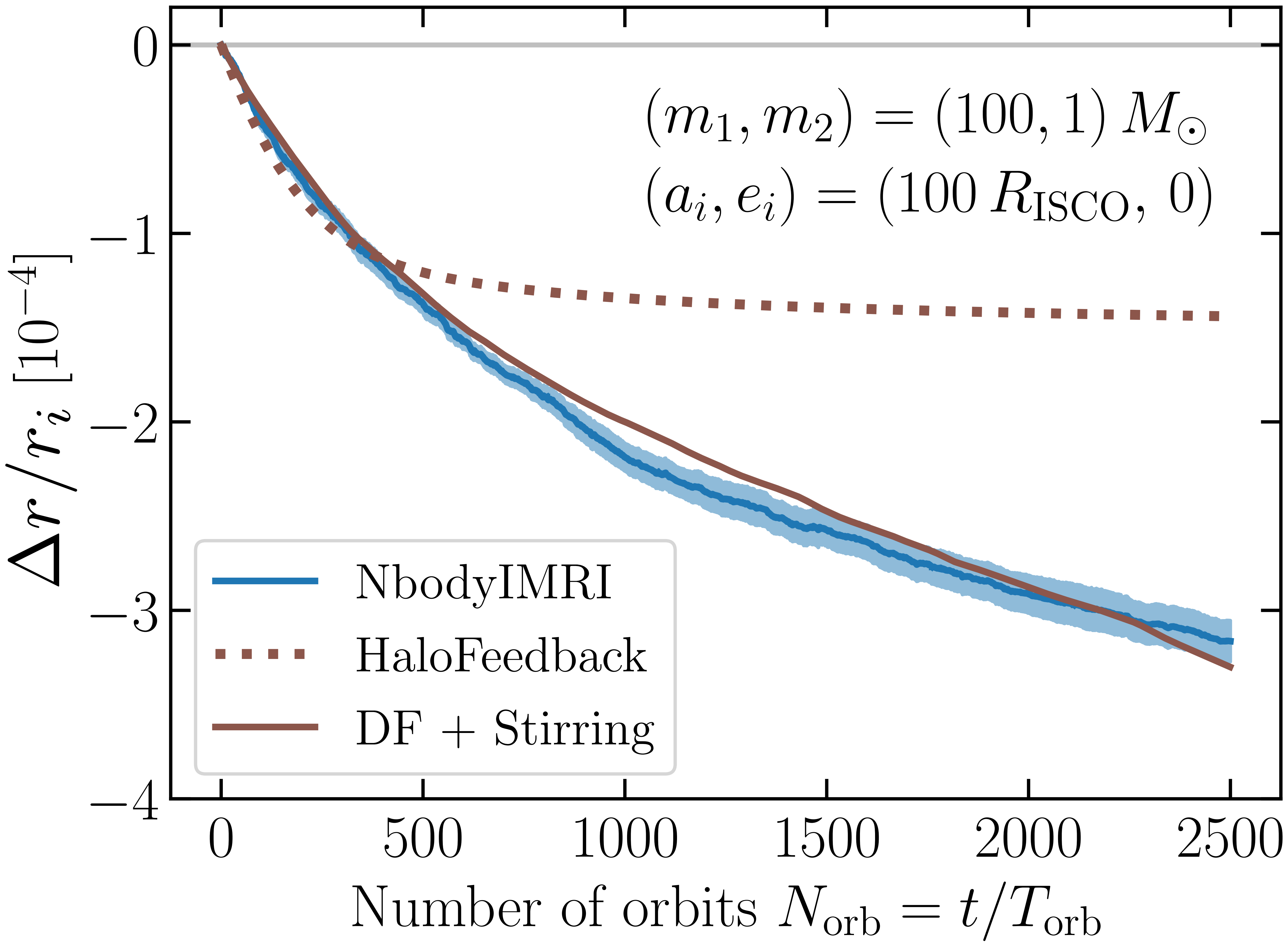


'Distant' particles

$$\Delta\mathcal{E} = \int_0^{\Delta t} \frac{\partial\psi}{\partial t}\,\mathrm{d}t$$

Orbits of distant particles are 'redistributed', slowing down the depletion.

Is dephasing larger than we thought?



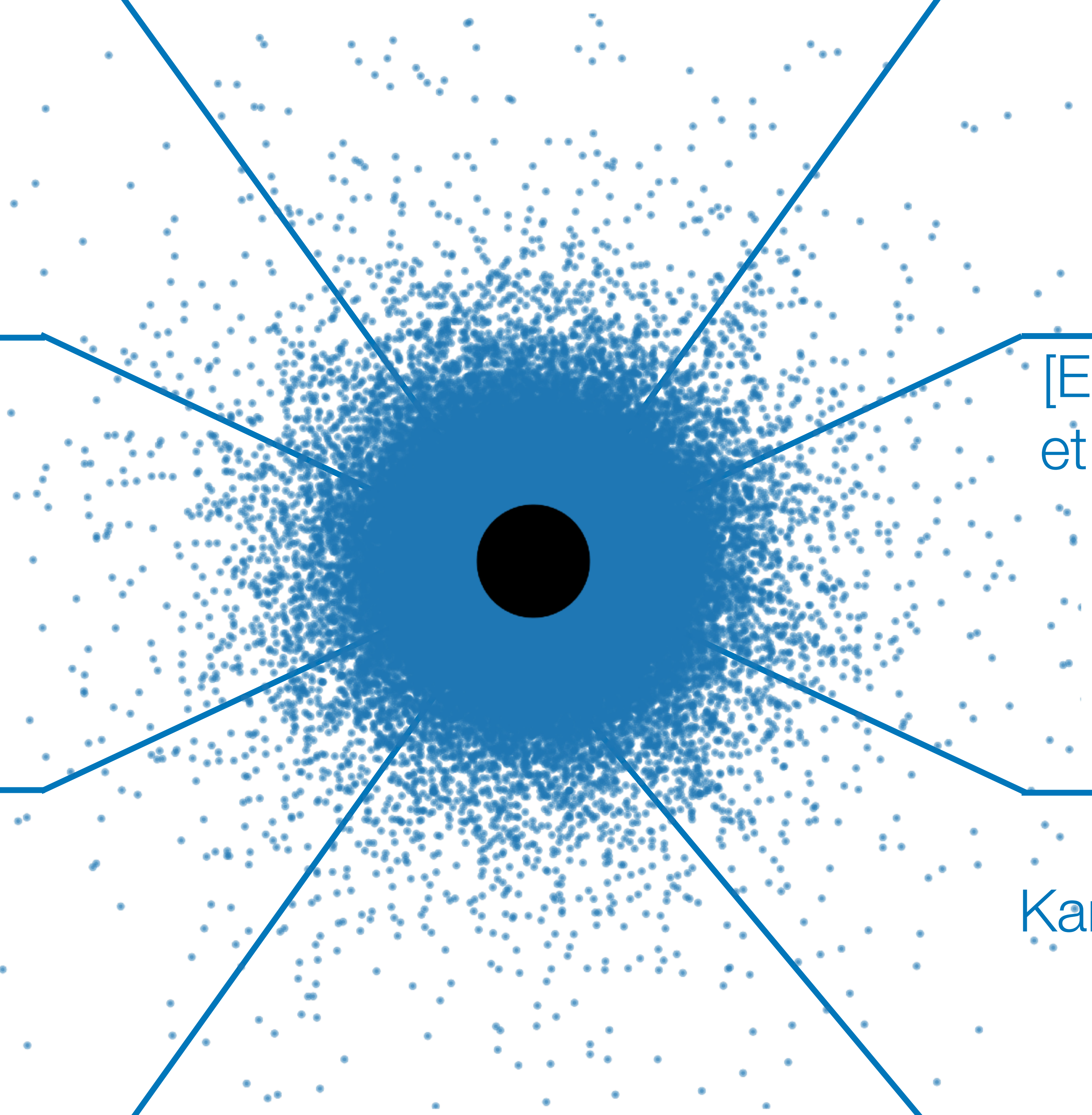
Inspiral of the binary is faster than predicted by previous 'HaloFeedback' estimates.

Dark Matter dephasing may be bigger than we thought!

Working on understanding simulations over much longer timescales ($N_\mathrm{orb} \gtrsim 10^5$) and extending the feedback formalism to incorporate this 'stirring' effect.

[**BJK** et al., 2402.13762]

Towards better DM spikes



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Towards better DM spikes

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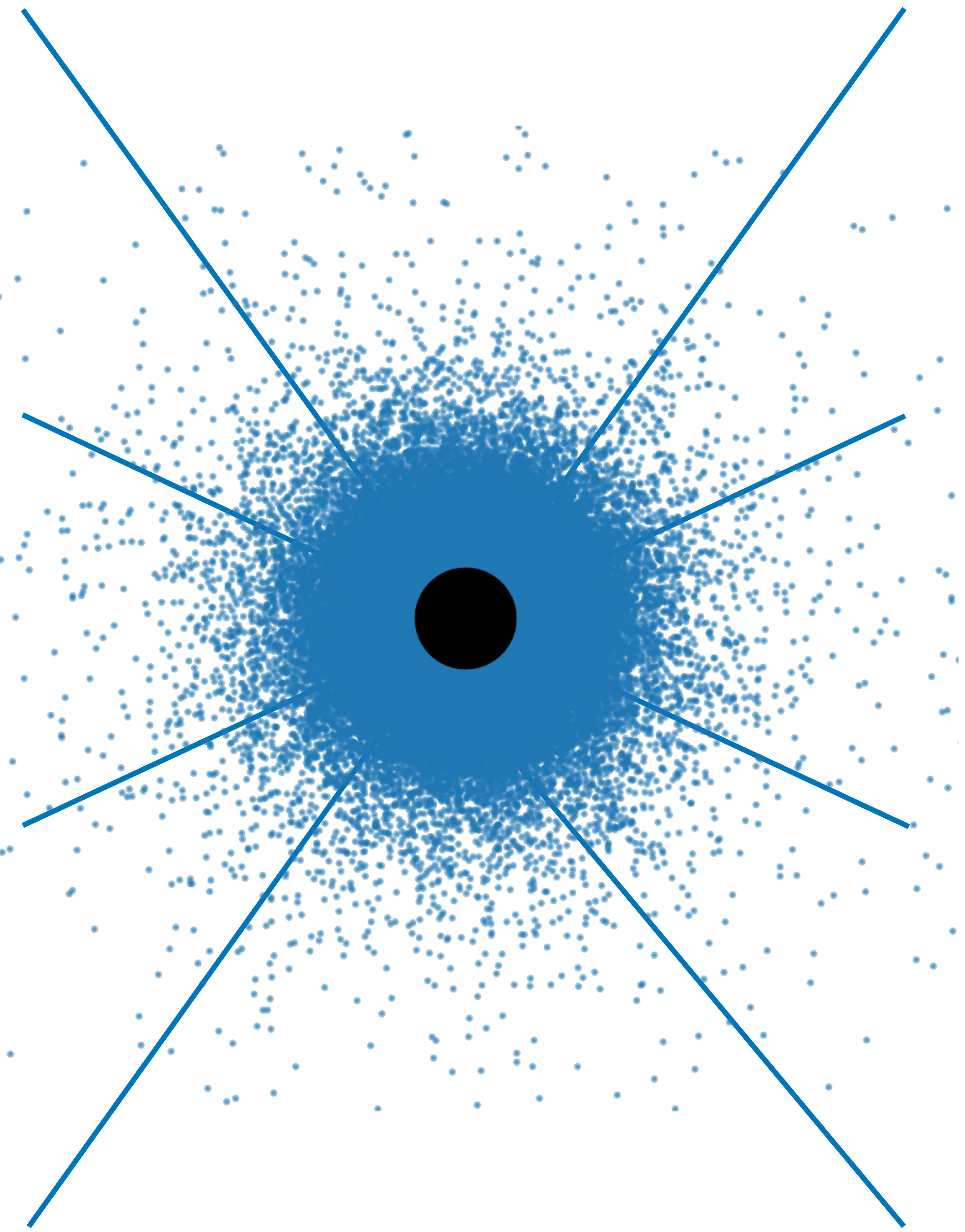
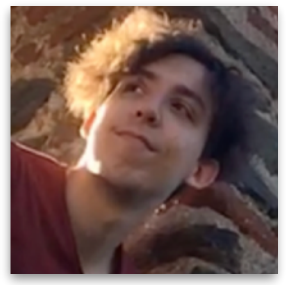


Pratibha Jangra
(IFCA, Santander)



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Gimmy Tomaselli
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[Special thanks also to Sonic Adventure 2 for graphic design inspiration]

…and others.

Thank you!

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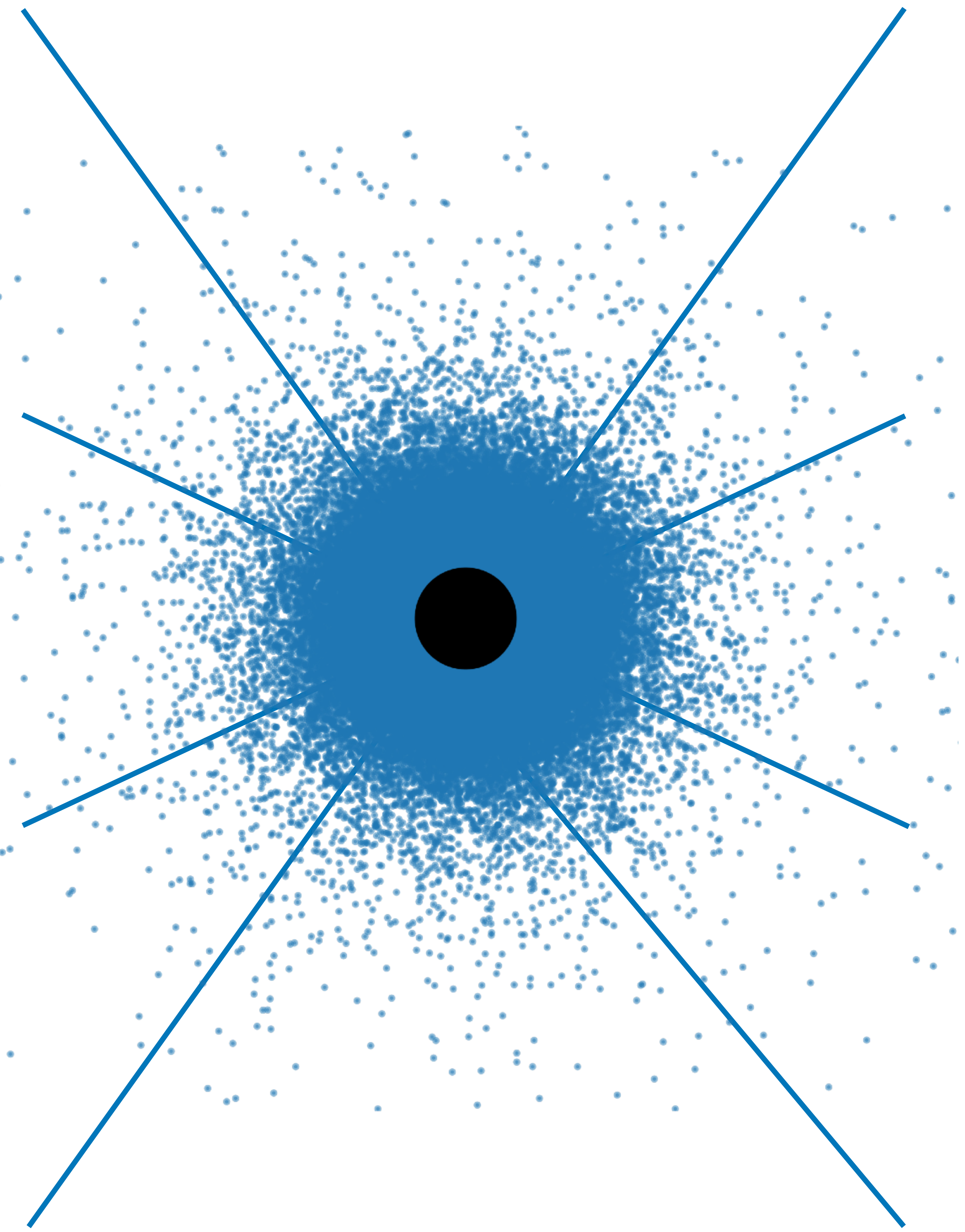

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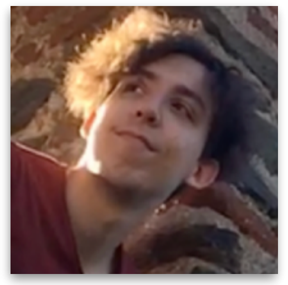

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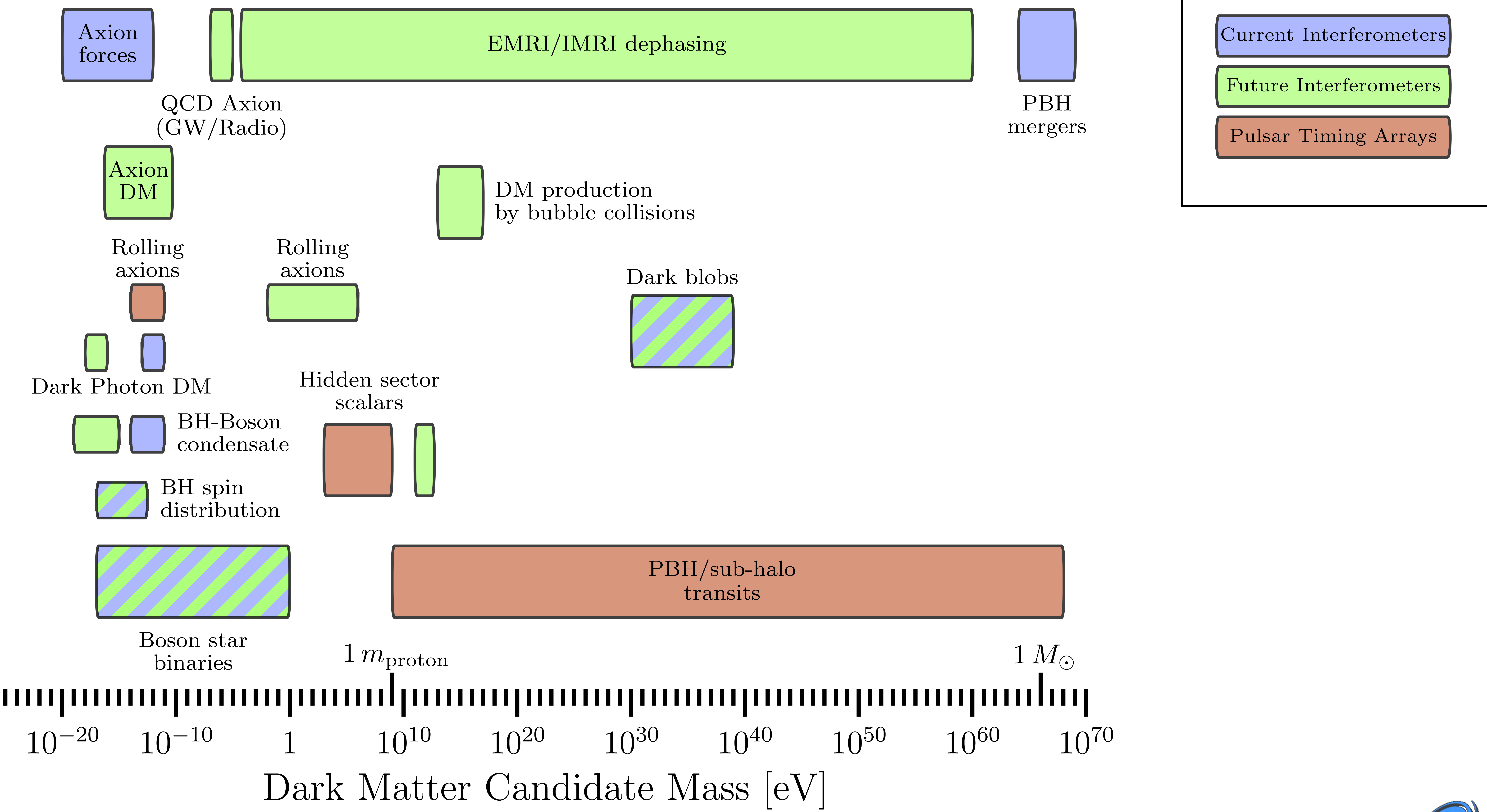
Backup Slides

GW Probes



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

Halo Feedback

Follow semi-analytically the phase space distribution of DM:

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

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

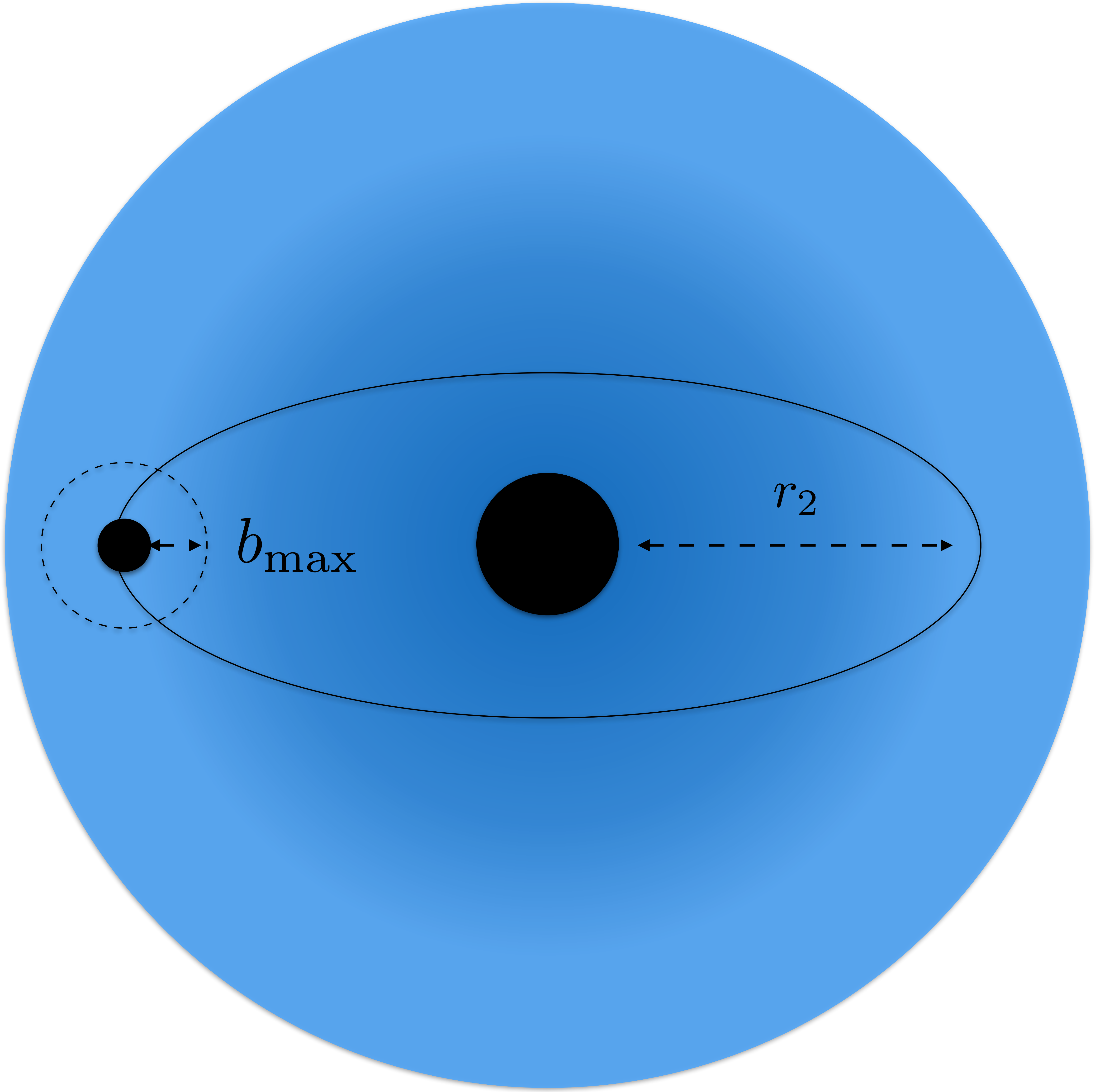
Each particle receives a 'kick' through gravitational scattering

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

Reconstruct density from distribution function:

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

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



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

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

Halo Feedback

Assuming everything evolves slowly compared to the orbital period:

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

$P_\mathcal{E}(\Delta\mathcal{E})$ - 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

[**BJK**, Nichols, Gaggero, Bertone, 2002.12811] [Code available online: github.com/bradkav/HaloFeedback]

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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' $\Delta\mathcal{E}$

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

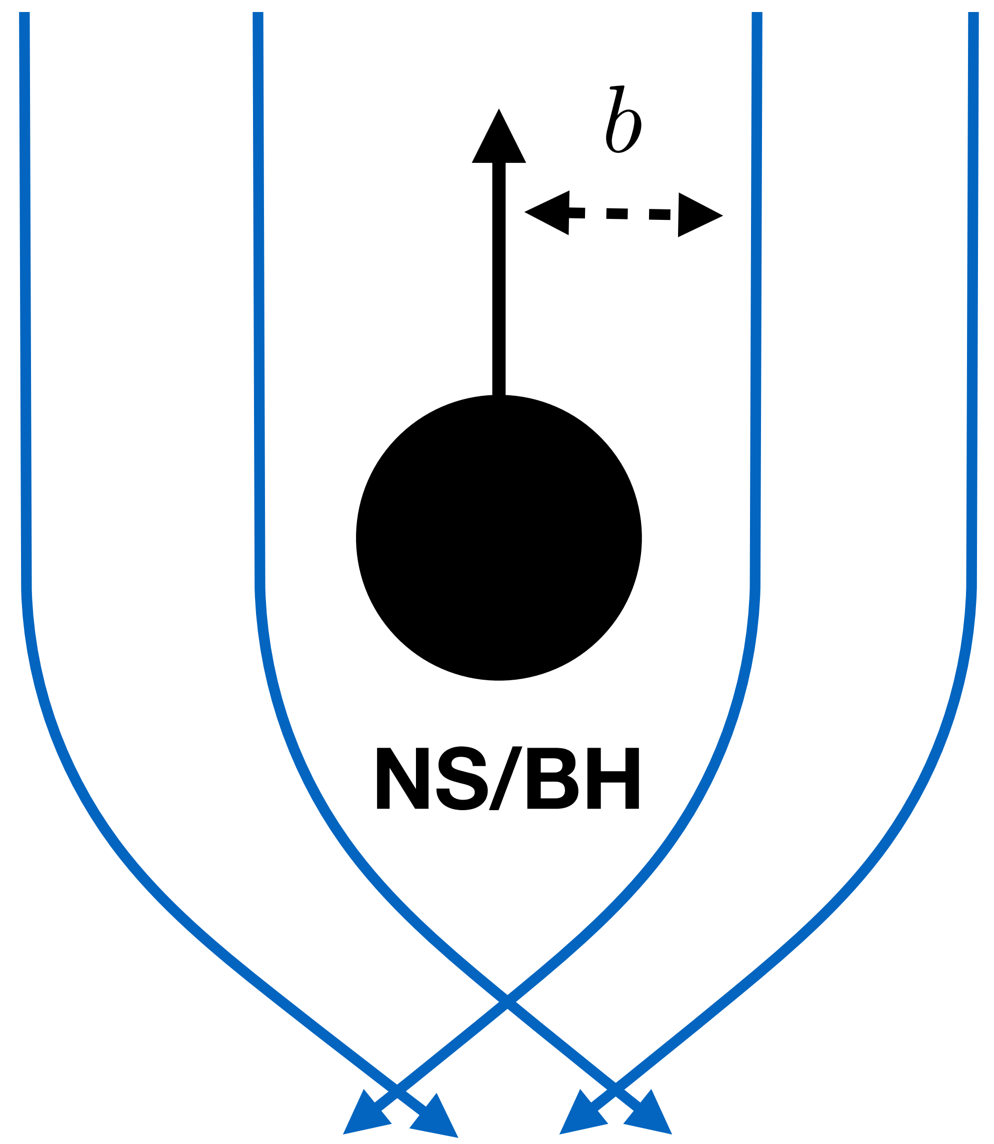
- total probability for a particle with energy $\mathcal{E}$ to scatter

[**BJK**, Nichols, Gaggero, Bertone, 2002.12811] [Code available online: github.com/bradkav/HaloFeedback]

DM Gravitational Scattering Probability

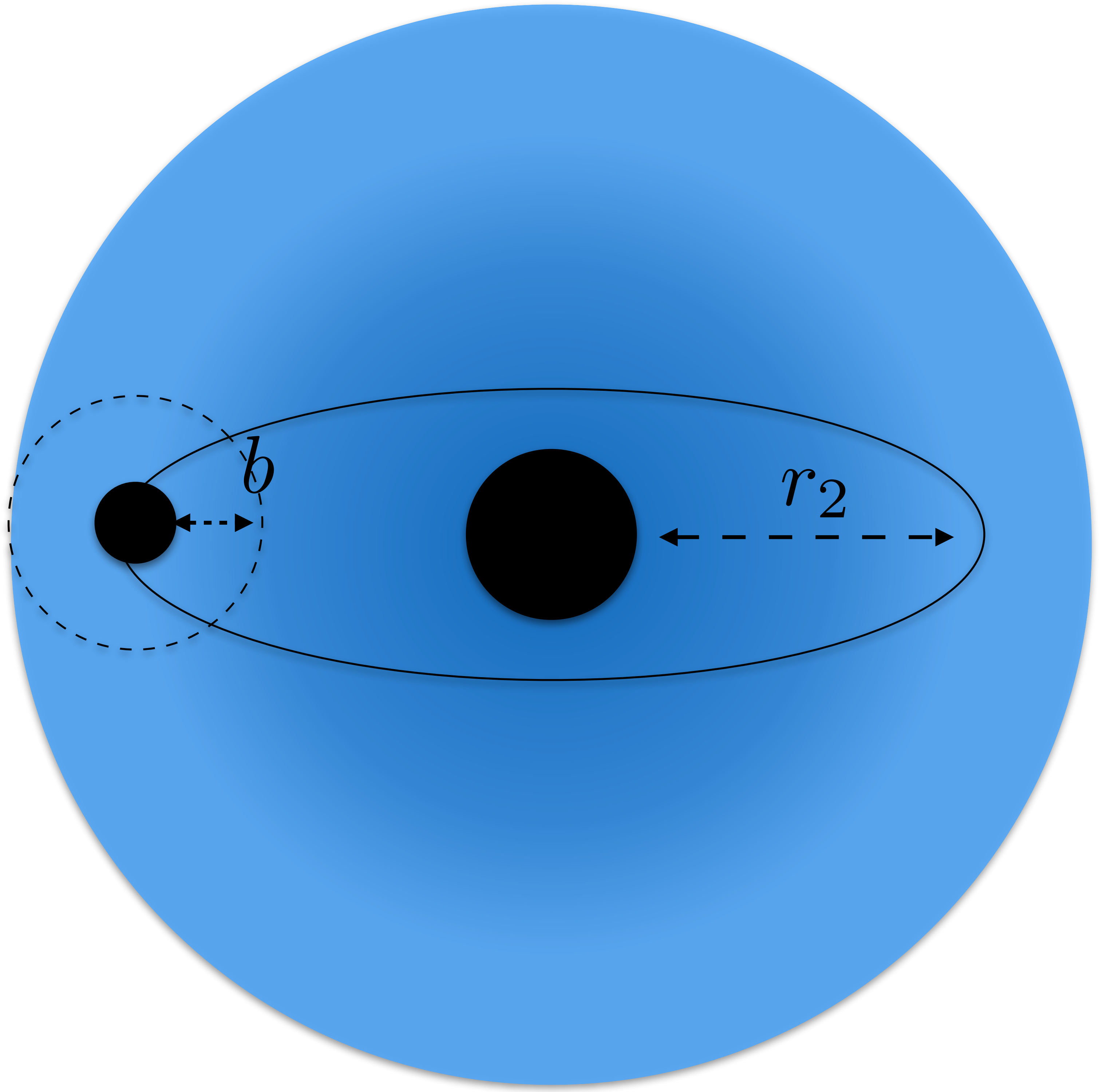
Two body scattering problem relates energy exchange to impact parameter:

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



Scattering probability becomes a *geometric* problem:

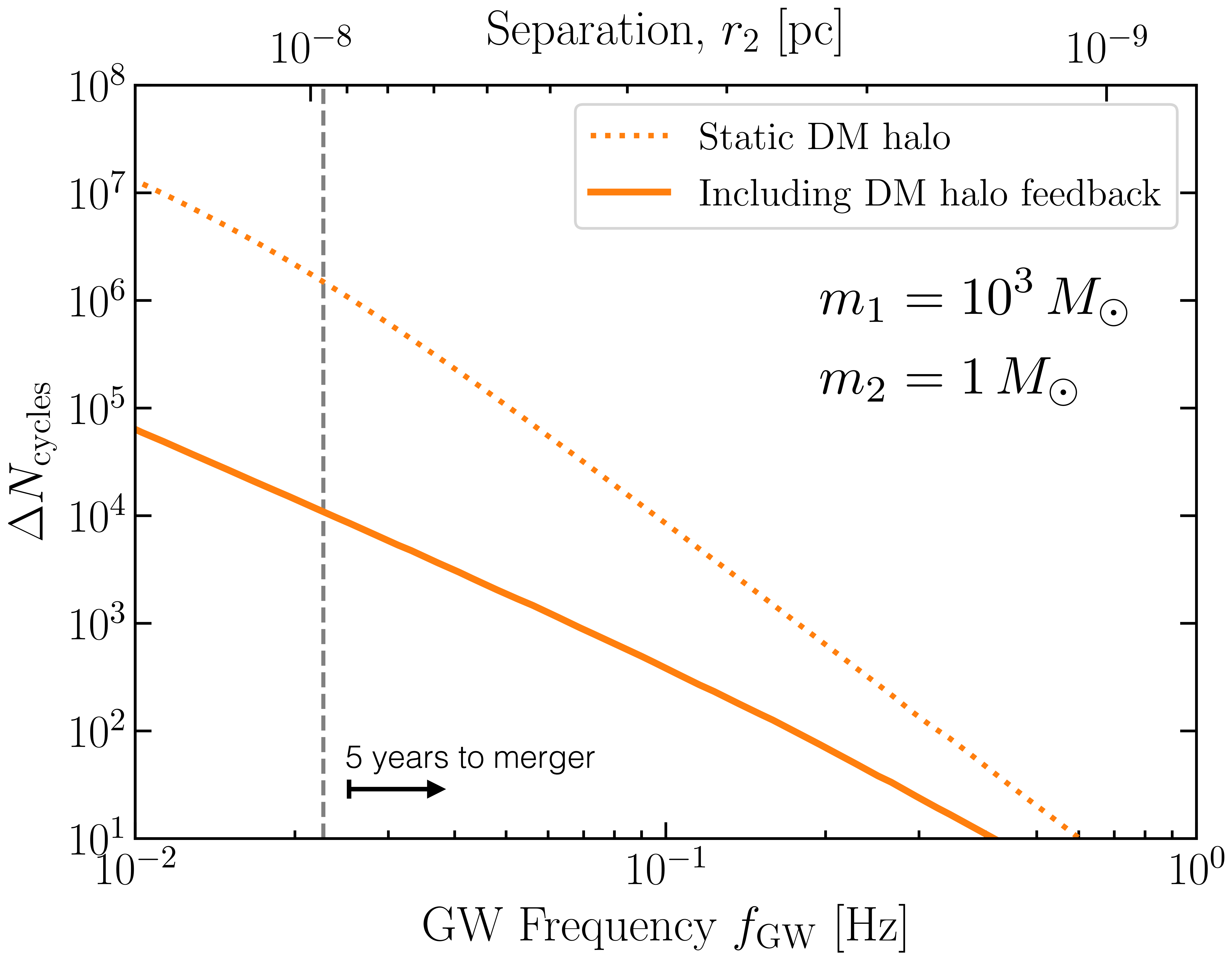
$$P_{\mathcal{E}}(\Delta\mathcal{E}) \propto P(b|\mathcal{E})$$



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

Size of the dephasing

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



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

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

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

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

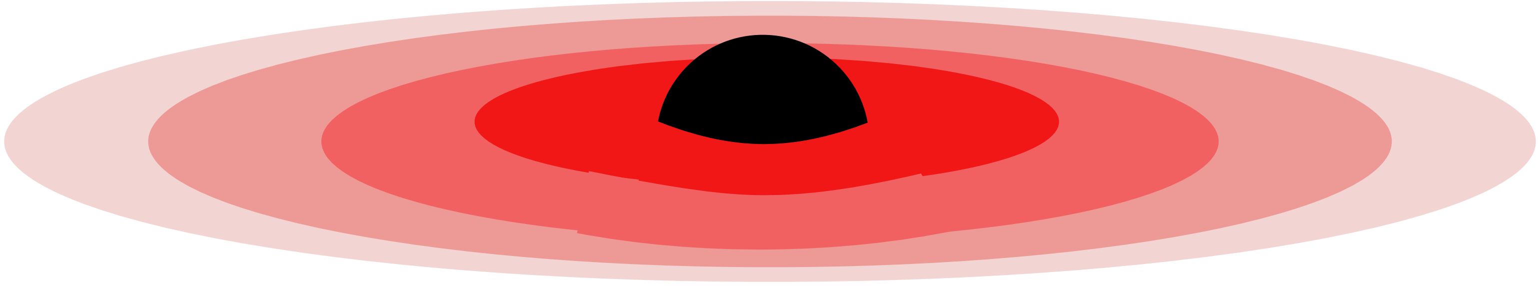
DM dephasing

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

$$\sim \%\ {\rm level}$$

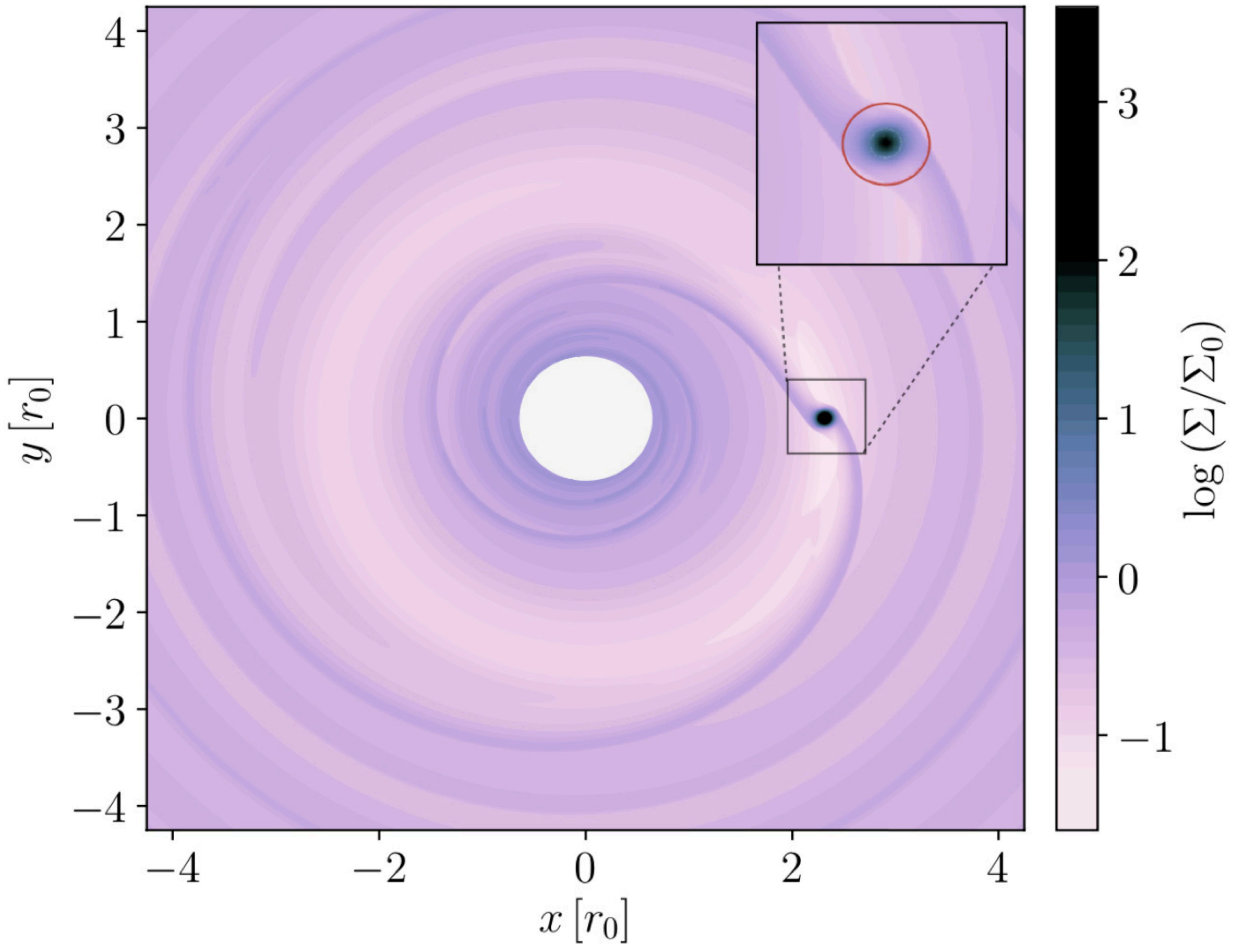
What about baryons?

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]

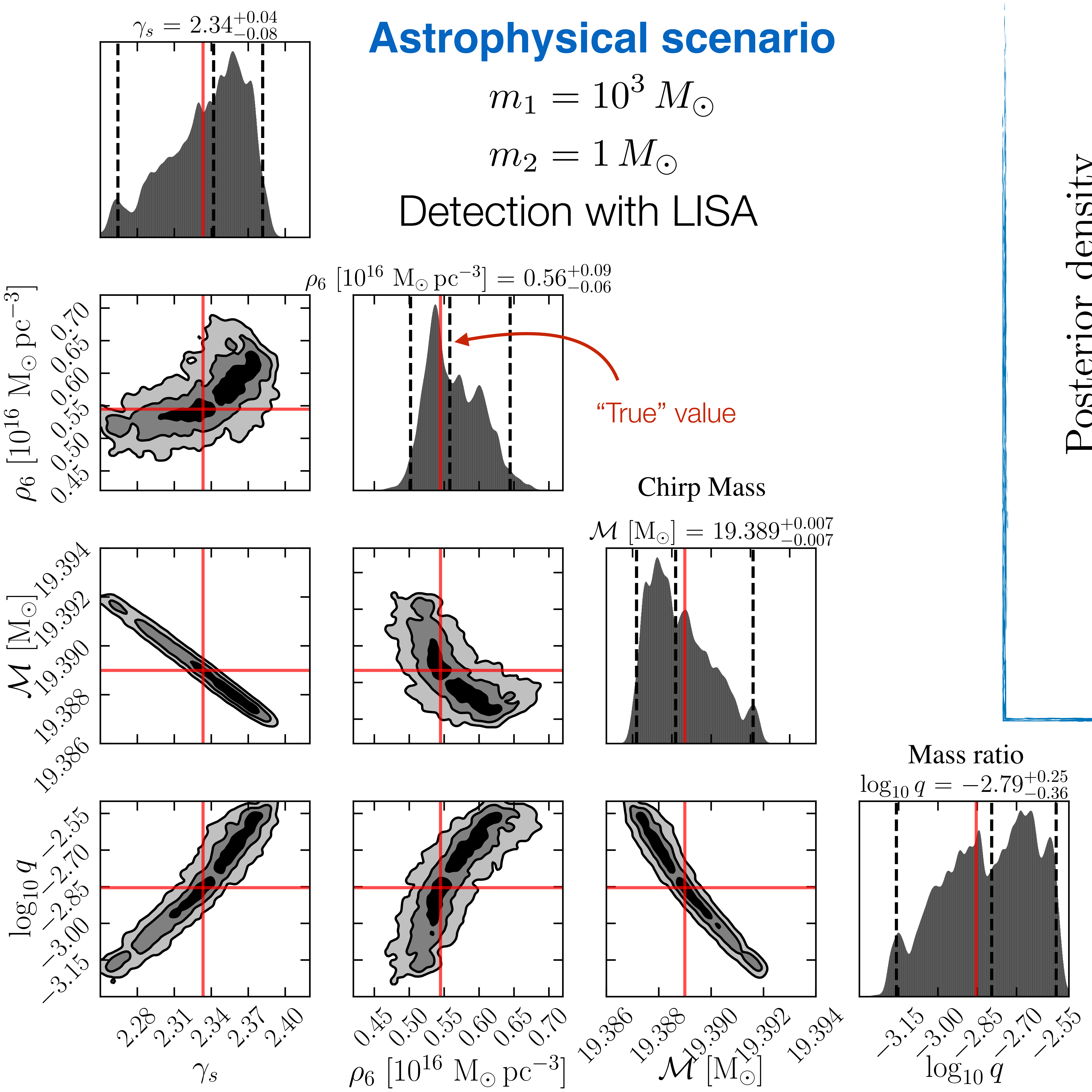
Measurability

Astrophysical scenario

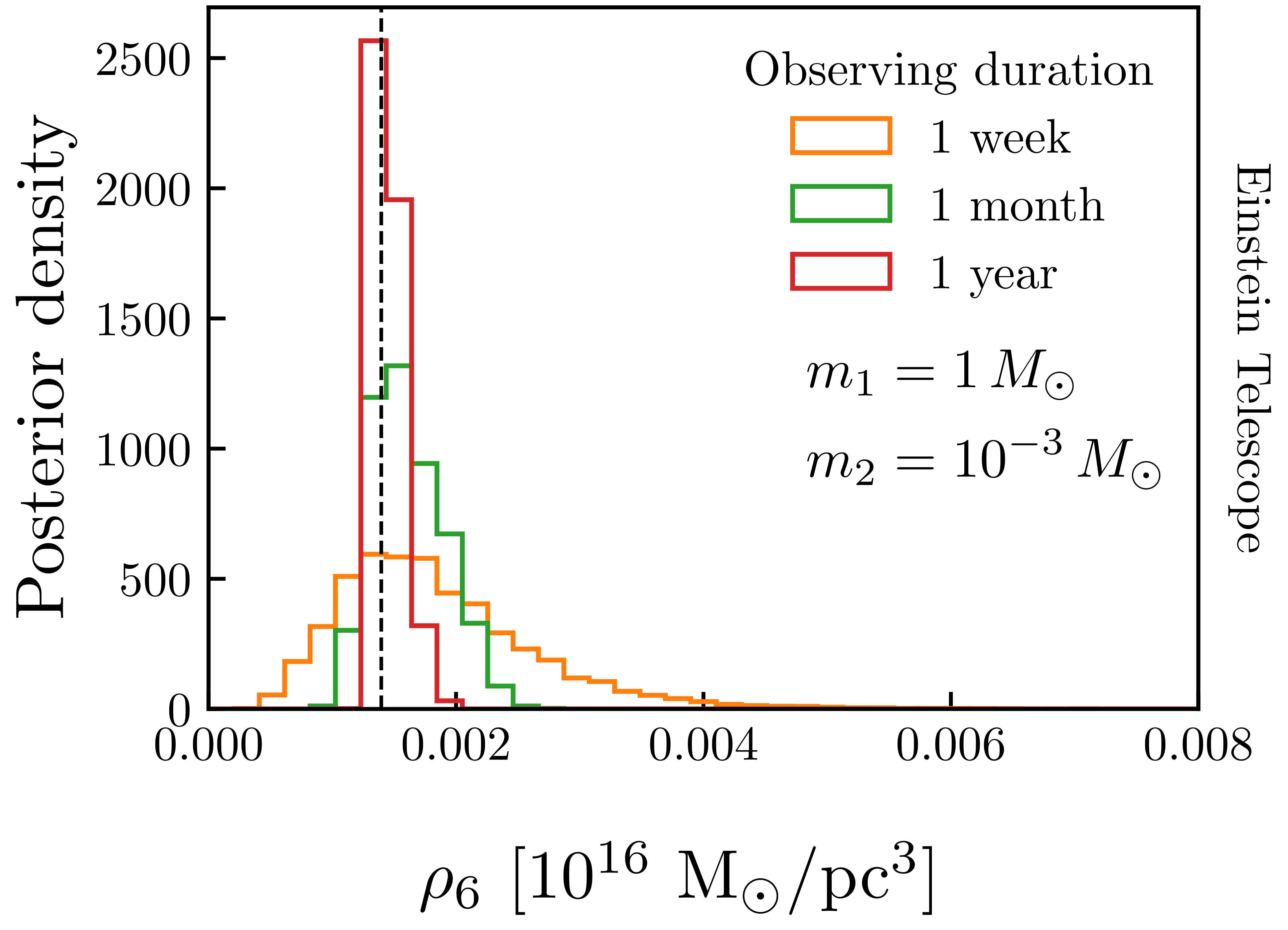
$$m_1 = 10^3\,M_\odot$$

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

Detection with LISA



PBH scenario



Detection with Einstein Telescope

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

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

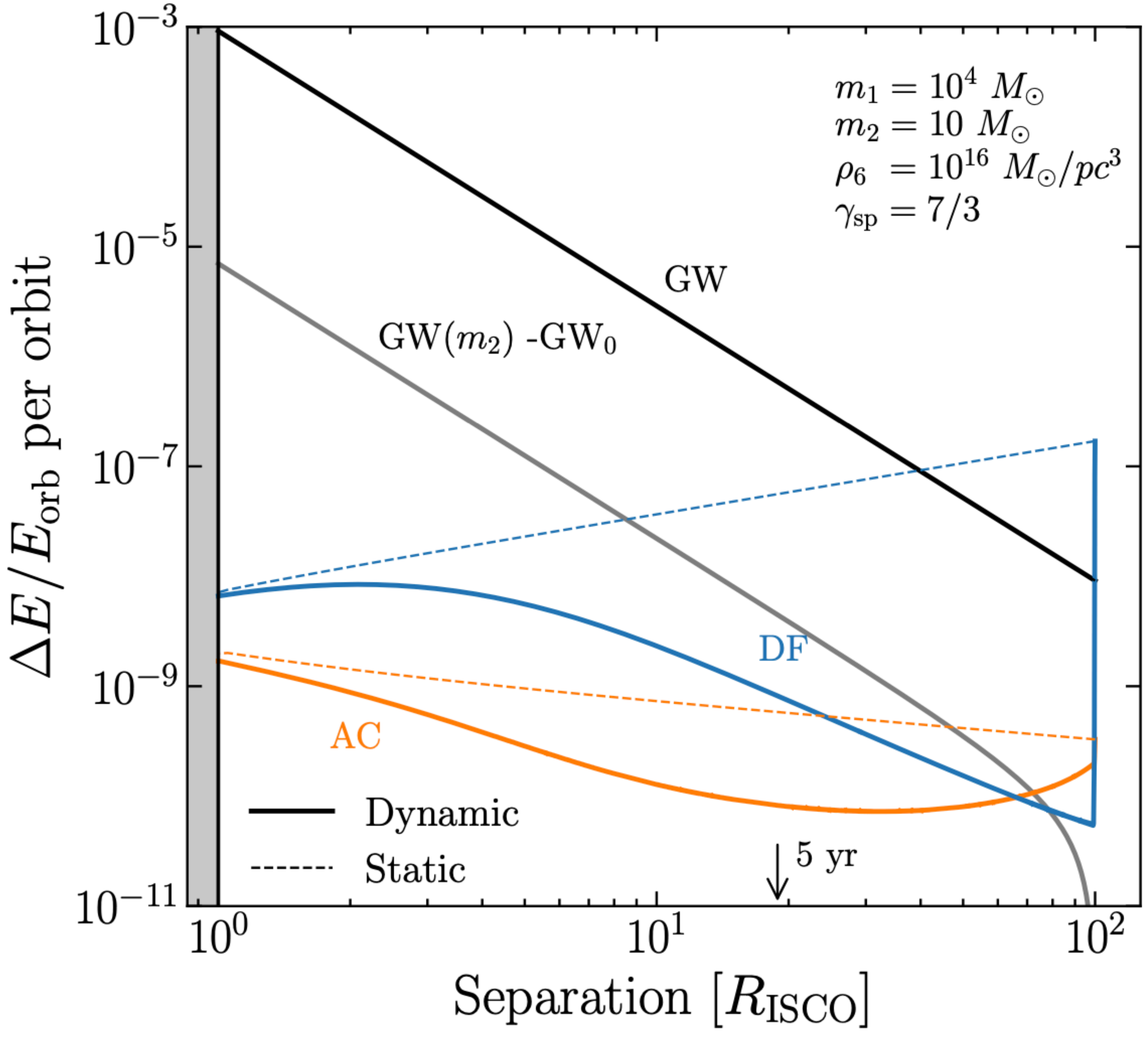
[Code: github.com/adam-coogan/pydd]

Accretion of DM by the secondary BH leads to an additional accretion force:

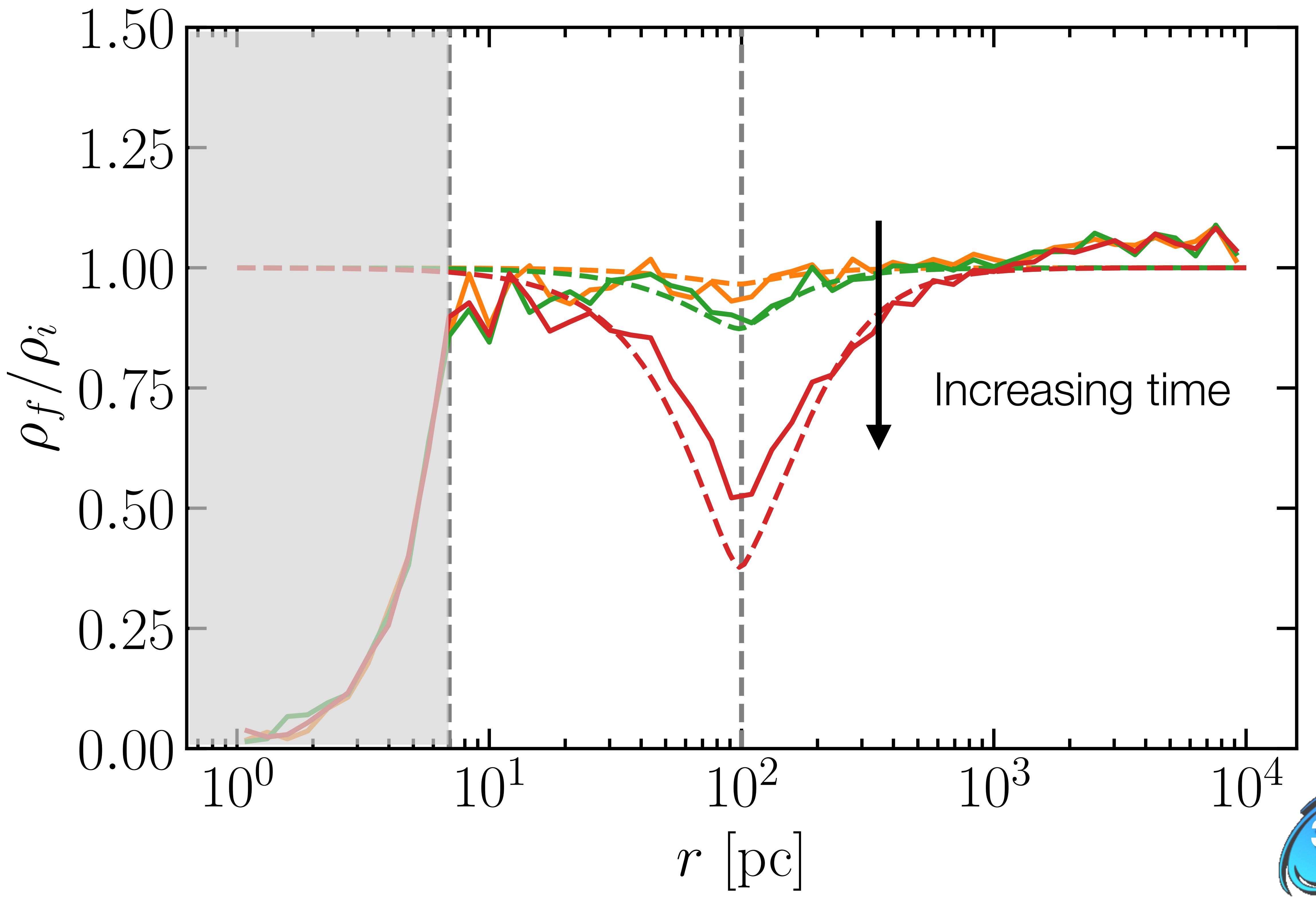
$$F_{\mathrm{acc}} = \int \mathrm{d}^3\mathbf{v}\, \pi b_{\mathrm{acc}}^2(\mathbf{v}_{\mathrm{rel}}) v_{\mathrm{rel}}\, \rho_\chi \mathbf{v}_{\mathrm{rel}} \qquad \mathbf{v}_{\mathrm{rel}} = \mathbf{v}_{\mathrm{orb}} - \mathbf{v}$$

[Karydas, **BJK**, Bertone, 2402.13053]

[See also Nichols et al. 2309.06498]



Use simulations to validate accretion force and DM spike depletion:



Change in energy due to time-dependent potential:

$$\Delta\mathcal{E} = \int_0^{\Delta t} \frac{\partial\psi}{\partial t}\,\mathrm{d}t$$

where the integral is taken over the path of the particle during a time Δt

For particles at large distances from the binary ($r \gg a$), we can estimate the change in energy over a single orbit of the binary:

$$\Delta\mathcal{E} = \left(\frac{Gm_2}{r}\frac{a^2}{r^2}\right)\left(\frac{vT_{\mathrm{orb}}}{r}\right)\mathcal{A}(\hat{\boldsymbol{r}}, \hat{\mathbf{v}})$$

Time-dependent component of the binary of the potential (Gravitational quadrupole $\sim 1/r^3$)

Fractional change in DM position of DM particle with speed v

Factor depending on orientation of the particle position and velocity with respect to the binary

The factor $\mathcal{A}(\hat{\boldsymbol{r}}, \hat{\mathbf{v}})$ can take positive or negative values -> these 'three-body' effects redistribute orbits and tend to smooth out the density profile. Though they don't extract any net energy from the binary (at least for circular binaries).