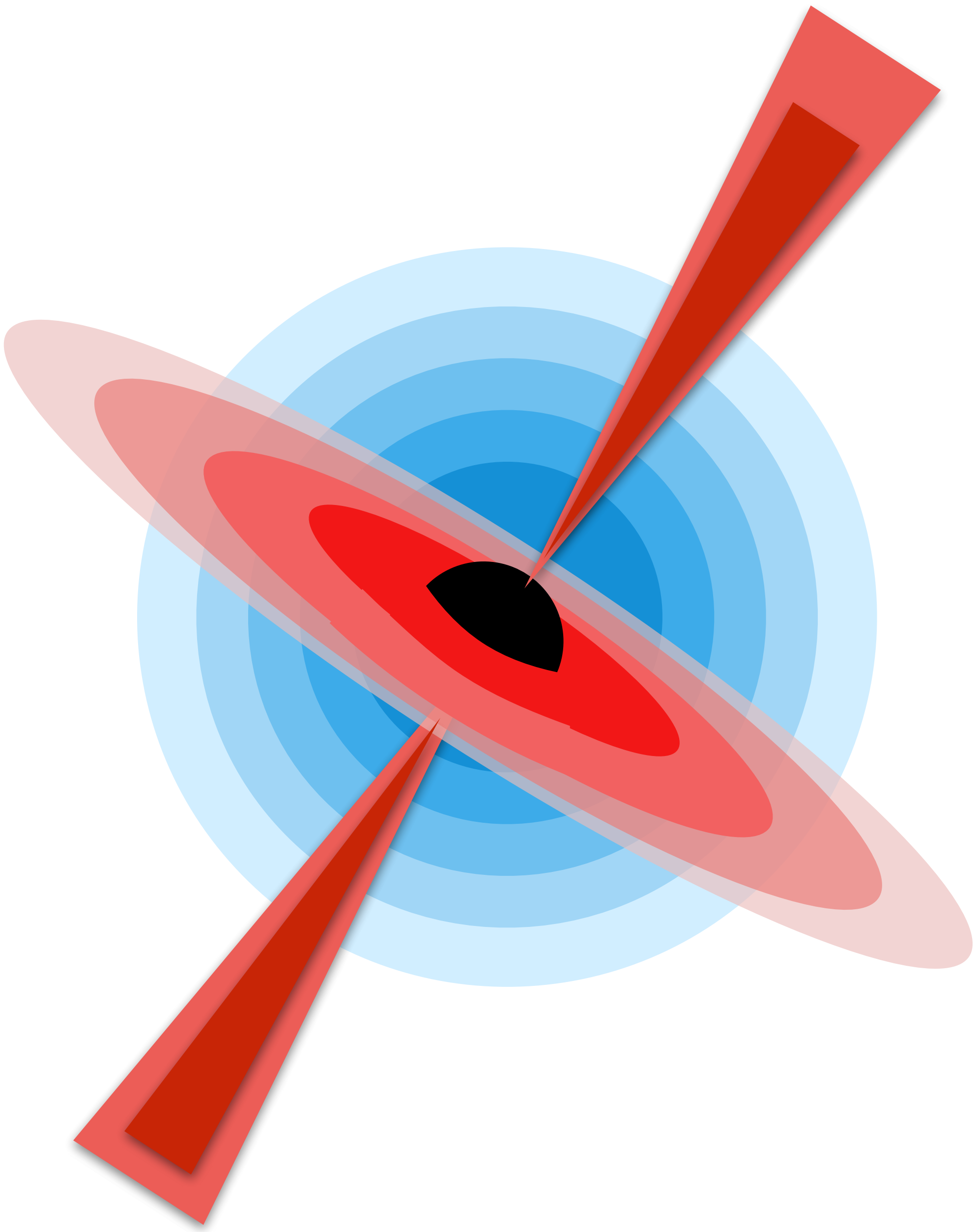
The birth, life (and death?) of Dark Matter spikes around Black Holes



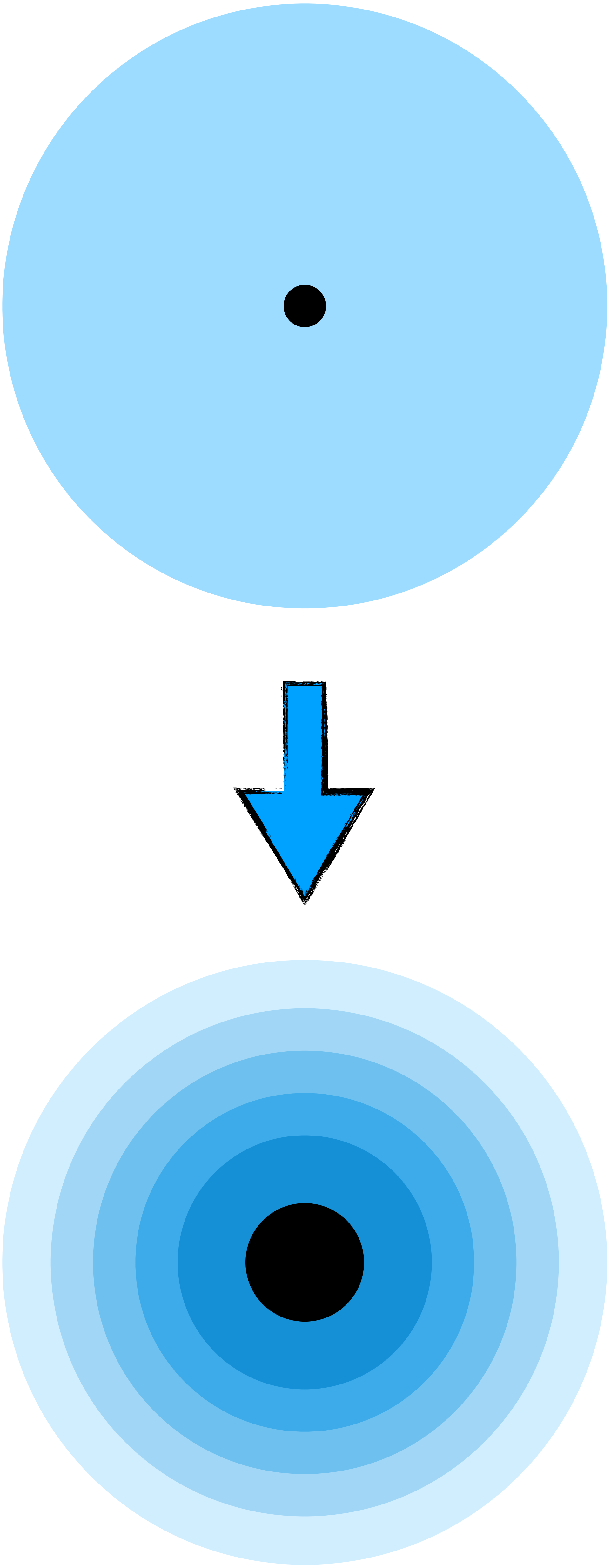
Bradley J Kavanagh [he/him]
Instituto de Fisica de Cantabria (CSIC-UC)
kavanagh@ifca.es

AGN as Dark Sector Laboratories
IFPU, 17th June 2026

MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
UC Universidad de Cantabria
IFCA Instituto de Física de Cantabria

The Birth of Dark Matter Spikes

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, …]

Adiabatic Growth

- BH grows by gas accretion from an infinitesimal seed, at the centre of an NFW DM halo

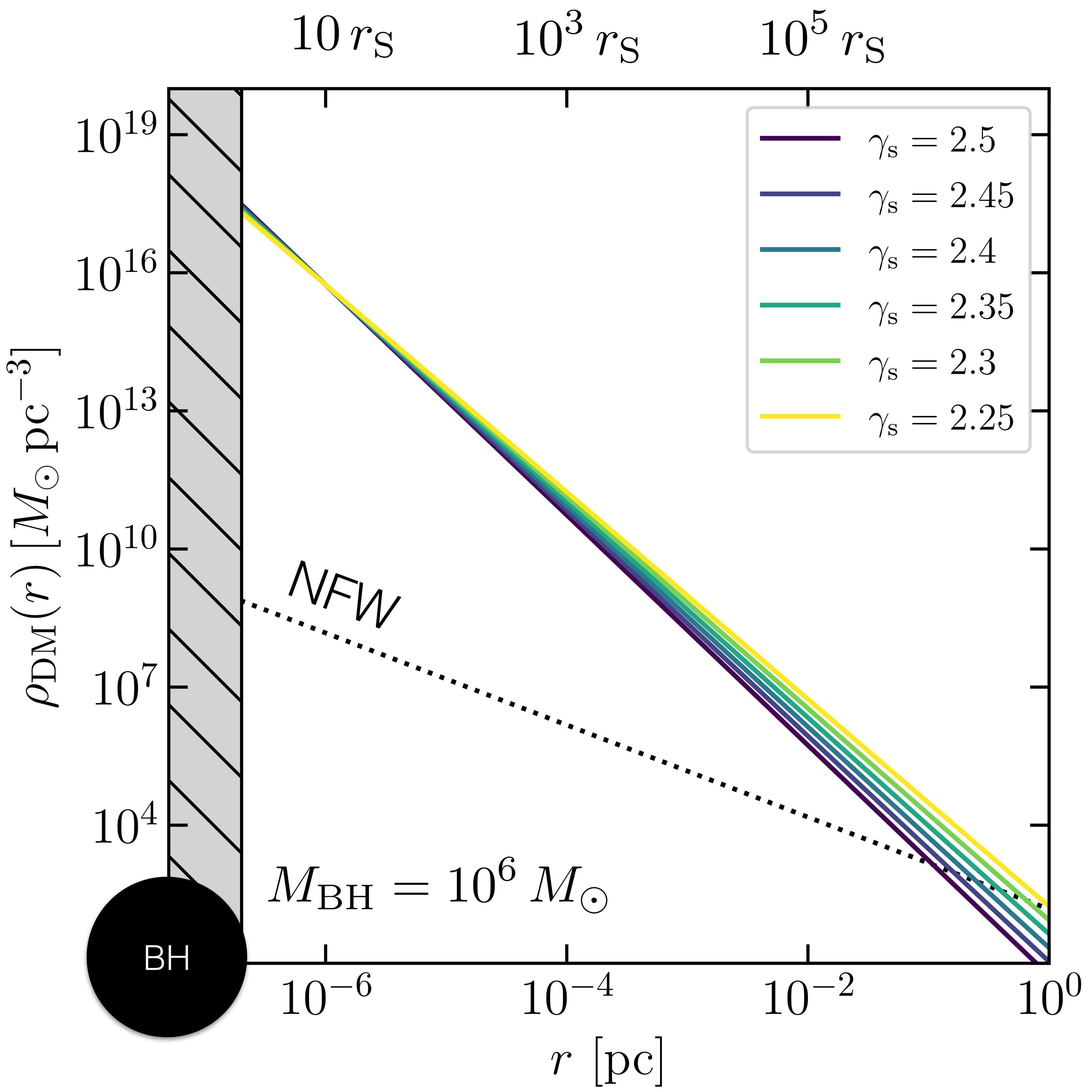
- DM density can be enhanced within the 'spike radius' r_{sp}, comparable to the sphere of influence of the BH

$$\int_0^{r_{sp}} 4\pi r^2 \rho_{NFW}(r)\,\mathrm{d}r = \beta\, M_{BH} \qquad [\beta \approx 0.1]$$

- **Adiabatic:** Timescale for growth is much longer than the dynamical timescale of the DM

Angular momentum L and radial action I are preserved, allowing us to map between initial and final DM energy $\mathscr{E}$.

Radial Action: $I(\mathcal{E}, L) = \frac{1}{\pi}\int_{r_{min}}^{r_{max}} v_r(r, \mathcal{E}, L)\,\mathrm{d}r$

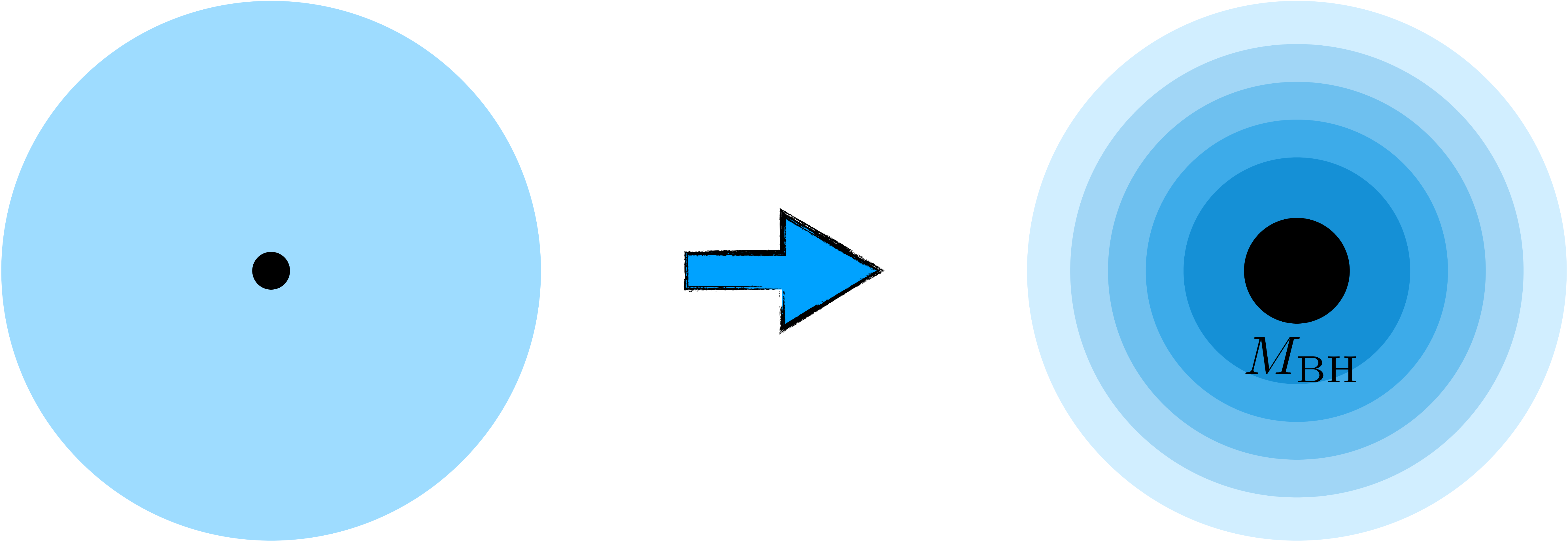


DM orbits contract, leading to steep 'spike' density profile: $\rho_{DM} = \rho_{sp}\left(\frac{r_{sp}}{r}\right)^{\gamma_{sp}}$

[Gondolo & Silk, astro-ph/9906391; Sadeghian et al., 1305.2619]

Spike Density Profile

$$\rho_i(r) \approx \rho_0 (r_0/r)^\gamma$$



$$\rho_{\rm DM}(r) = \rho_{\rm sp} \left(\frac{r_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

Spike ‘parameters’ are correlated:

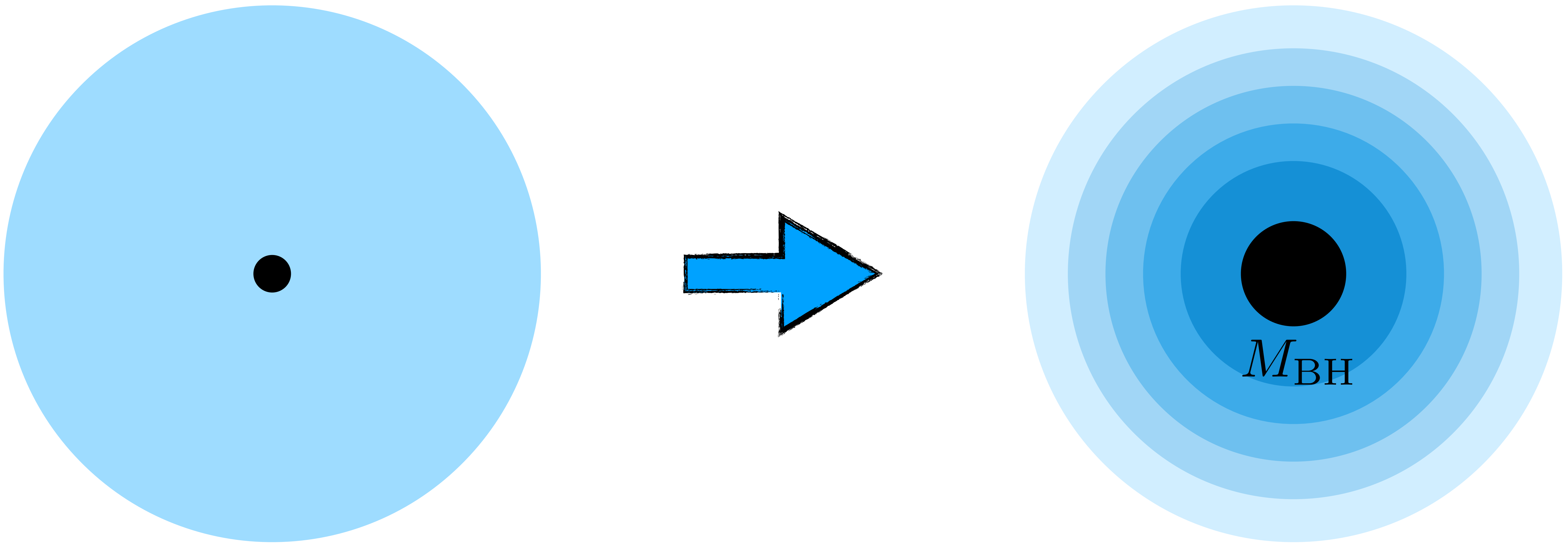
$$r_{\rm sp} = \beta \left(\frac{(3-\gamma) M_{\rm BH}}{2\pi \rho_0 r_0^\gamma}\right)^{\frac{1}{3-\gamma}}$$

$$\rho_{\rm sp} = \rho_0 (r_{\rm sp}/r_0)^\gamma$$

$$\gamma_{\rm sp} = (9-4\gamma)/(4-\gamma)$$

Spike Density Profile

$$\rho_i(r) \approx \rho_0 (r_0/r)^{\gamma}$$



$$\rho_{\rm DM}(r) = \rho_{\rm ref}\left(\frac{r_{\rm ref}}{r}\right)^{\gamma_{\rm sp}}$$

Spike ‘parameters’ are correlated:

$$r_{\rm sp} = \beta\left(\frac{(3-\gamma)M_{\rm BH}}{2\pi\rho_0 r_0^{\gamma}}\right)^{\frac{1}{3-\gamma}}$$

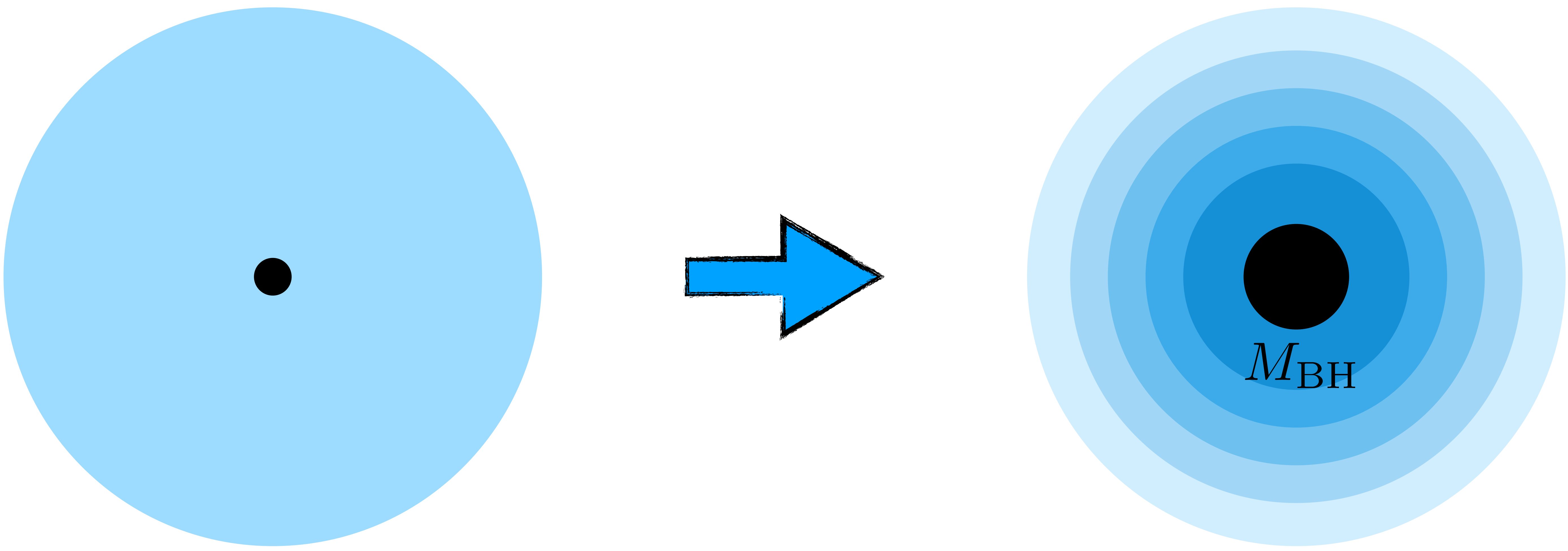
$$\rho_{\rm sp} = \rho_0 (r_{\rm sp}/r_0)^{\gamma}$$

$$\gamma_{\rm sp} = (9-4\gamma)/(4-\gamma)$$

$$\rho_{\rm ref} = \rho_{\rm sp}\left(\frac{r_{\rm sp}}{r_{\rm ref}}\right)^{\gamma_{\rm sp}} \sim \beta^{\frac{(\gamma_{\rm sp}-3)^2}{\gamma_{\rm sp}-2}}\,\rho_0^{\gamma_{\rm sp}-2}\,r_0^{(4\gamma_{\rm sp}-9)}\,M_{\rm BH}^{3-\gamma_{\rm sp}}$$

Spike Density Profile

$$\rho_i(r) \approx \rho_0 (r_0/r)^\gamma$$



$$\rho_{\rm DM}(r) = \rho_{\rm ref} \left(\frac{r_{\rm ref}}{r}\right)^{\gamma_{\rm sp}}$$

Spike ‘parameters’ are correlated:

$$r_{\rm sp} = \beta \left(\frac{(3-\gamma) M_{\rm BH}}{2\pi \rho_0 r_0^\gamma}\right)^{\frac{1}{3-\gamma}}$$

$$\rho_{\rm sp} = \rho_0 (r_{\rm sp}/r_0)^\gamma$$

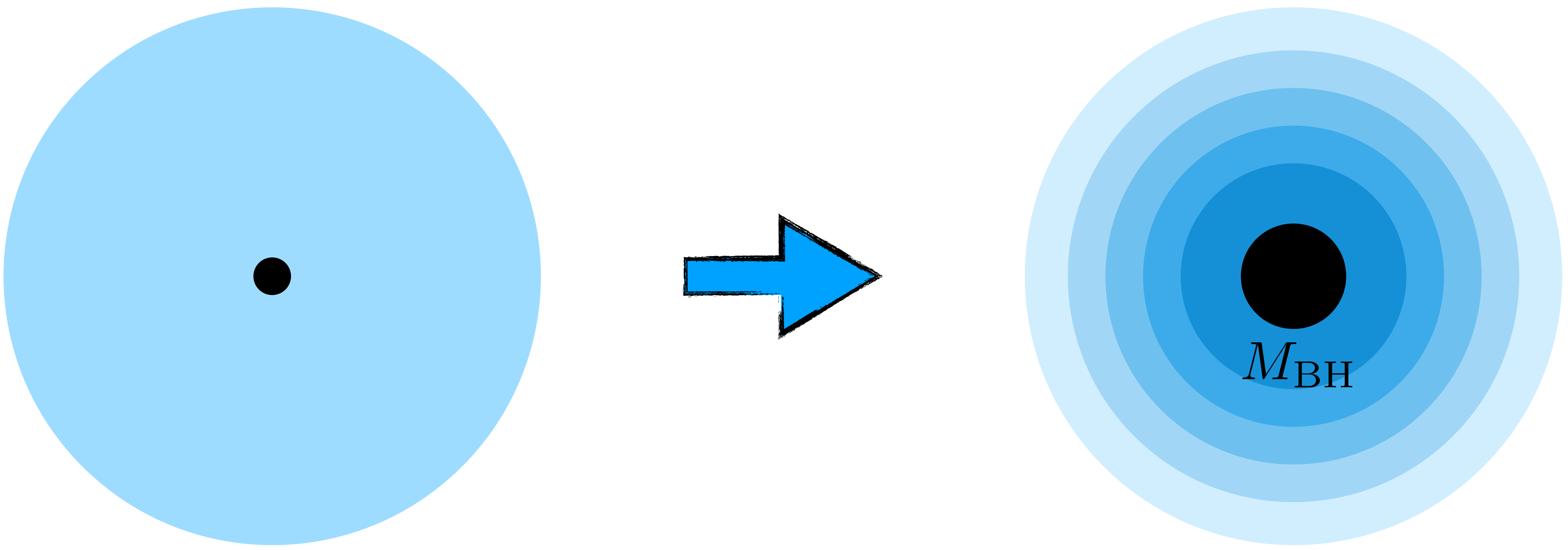
$$\gamma_{\rm sp} = (9-4\gamma)/(4-\gamma)$$

For an initial NFW profile, $\gamma = 1 \quad \rightarrow \quad \gamma_{\rm sp} = 7/3$

$$\rho_{\rm ref} = \rho_{\rm sp} \left(\frac{r_{\rm sp}}{r_{\rm ref}}\right)^{\gamma_{\rm sp}} \sim \beta^{4/3}\, \rho_0^{1/3}\, r_0^{1/3}\, M_{\rm BH}^{2/3}$$

Spike Density Profile

$$\rho_i(r) \approx \rho_0 (r_0/r)^\gamma$$



$$\rho_{\rm DM}(r) = \rho_{\rm ref}\left(\frac{r_{\rm ref}}{r}\right)^{\gamma_{\rm sp}}$$

Spike 'parameters' are correlated:

$$r_{\rm sp} = \beta\left(\frac{(3-\gamma)M_{\rm BH}}{2\pi\rho_0 r_0^\gamma}\right)^{\frac{1}{3-\gamma}}$$

$$\rho_{\rm sp} = \rho_0 (r_{\rm sp}/r_0)^\gamma$$

$$\gamma_{\rm sp} = (9-4\gamma)/(4-\gamma)$$

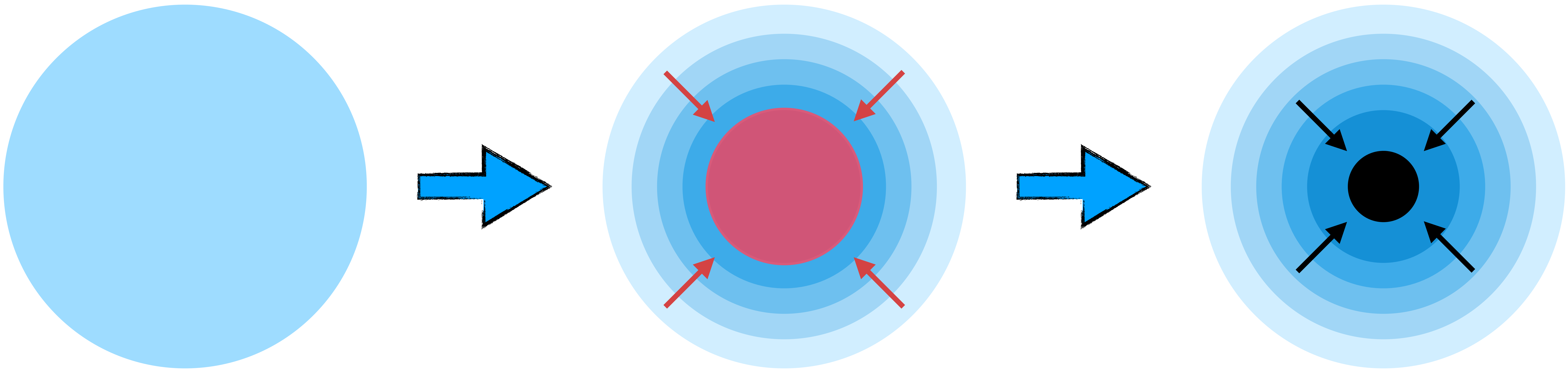
For an initial NFW profile, $\gamma = 1 \quad \rightarrow \quad \gamma_{\rm sp} = 7/3$

$$\rho_{\rm ref} = \rho_{\rm sp}\left(\frac{r_{\rm sp}}{r_{\rm ref}}\right)^{\gamma_{\rm sp}} \sim \beta^{4/3}\,\rho_0^{1/3}\,r_0^{1/3}\,M_{\rm BH}^{2/3}$$

Alternatively parametrise in terms of halo mass and concentration: $\rho_{\rm ref} \sim \beta^{4/3}\,M_{\rm halo}^{1/9}\,c^{1/2}\,M_{\rm BH}^{2/3}$

Dark Matter Mounds

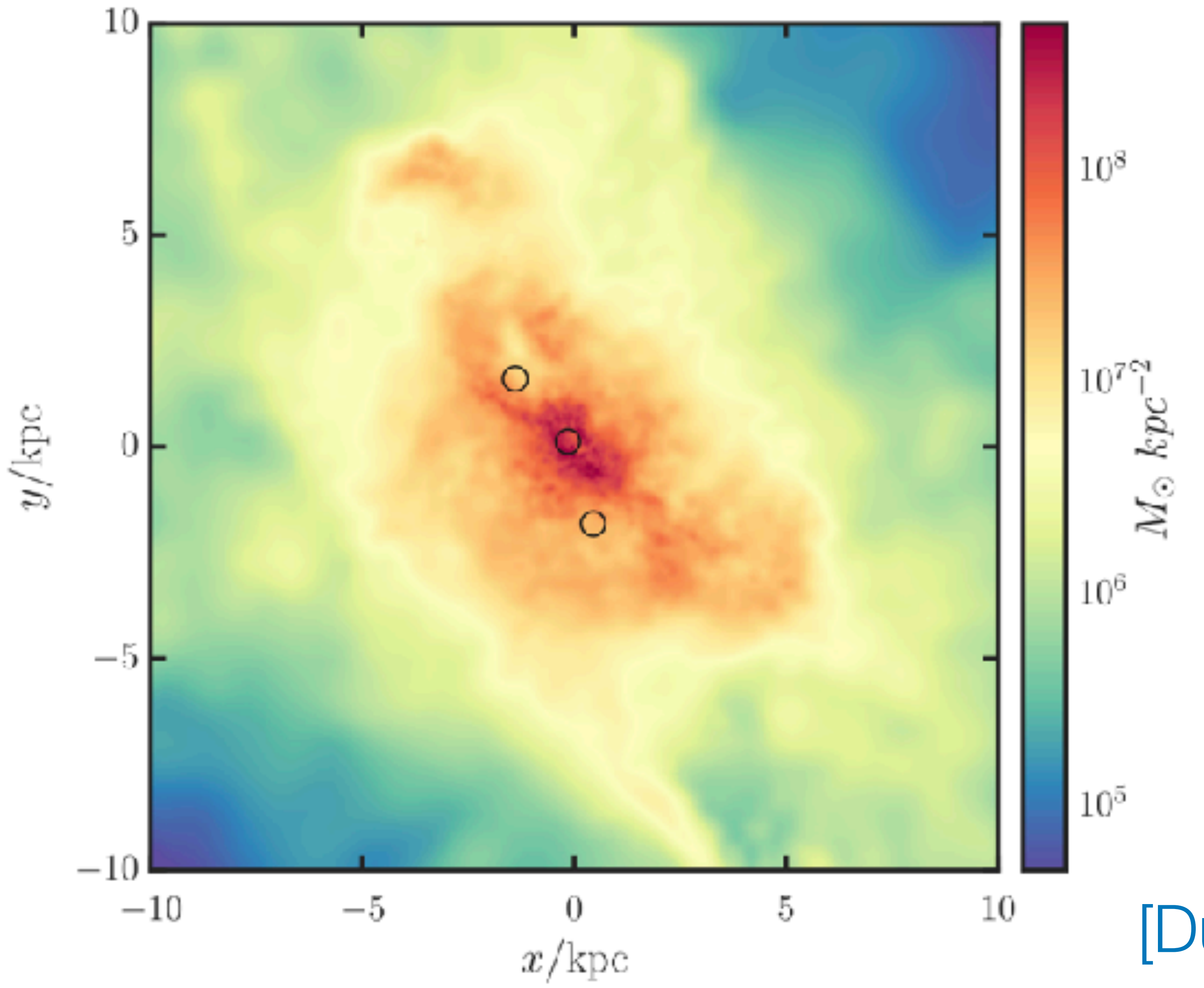
*Precise details of formation affect slope and density of DM very close to BH



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

Supermassive 'star'

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



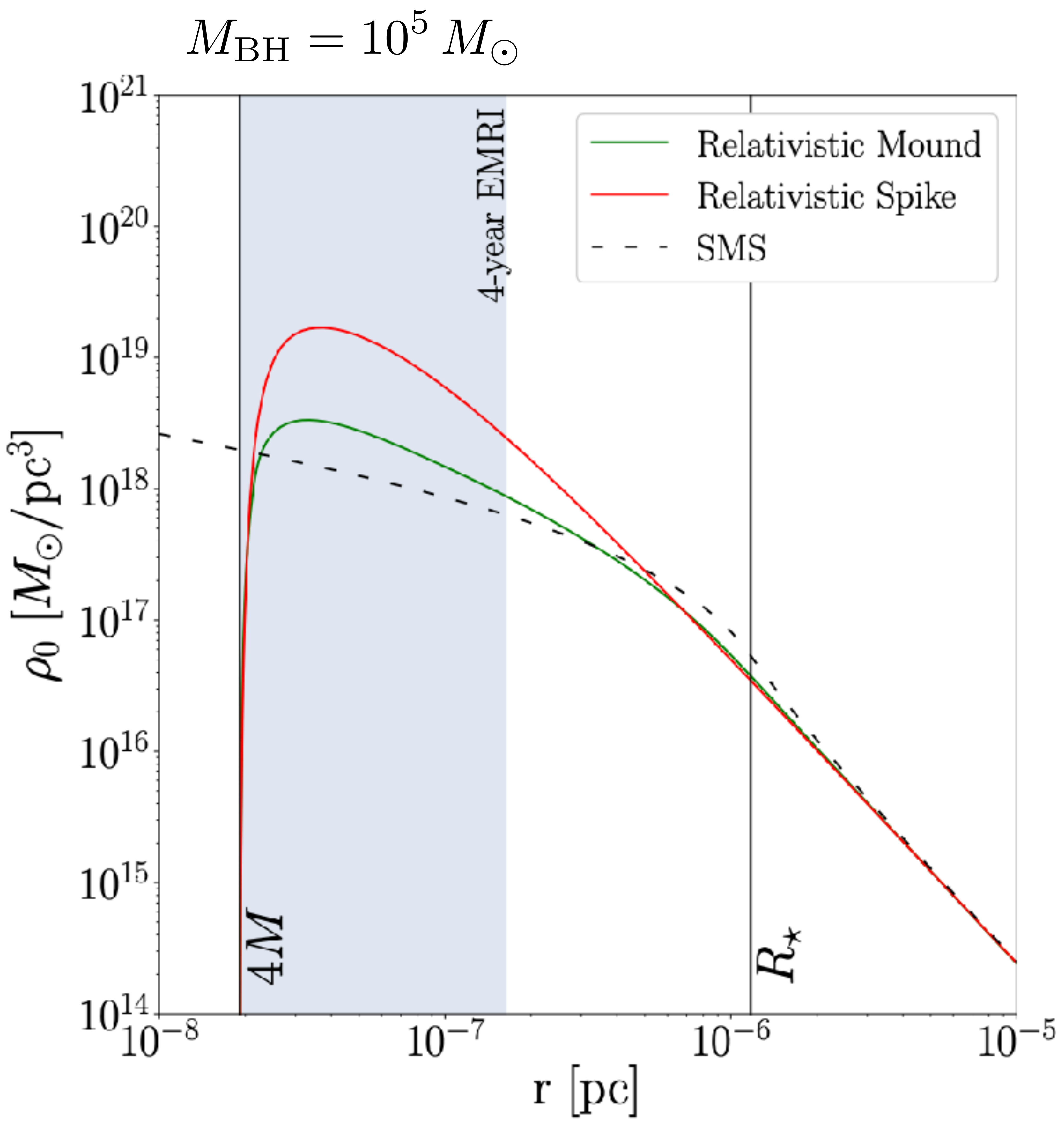
$$m_{\rm DCBH} \sim 10^3 - 10^5\, M_\odot$$

The BH may experience subsequent growth to become supermassive

[Bertone et al. (including **BJK**), 2404.08731]
[Caiozzo et al. (including **BJK**), 2512.09985]

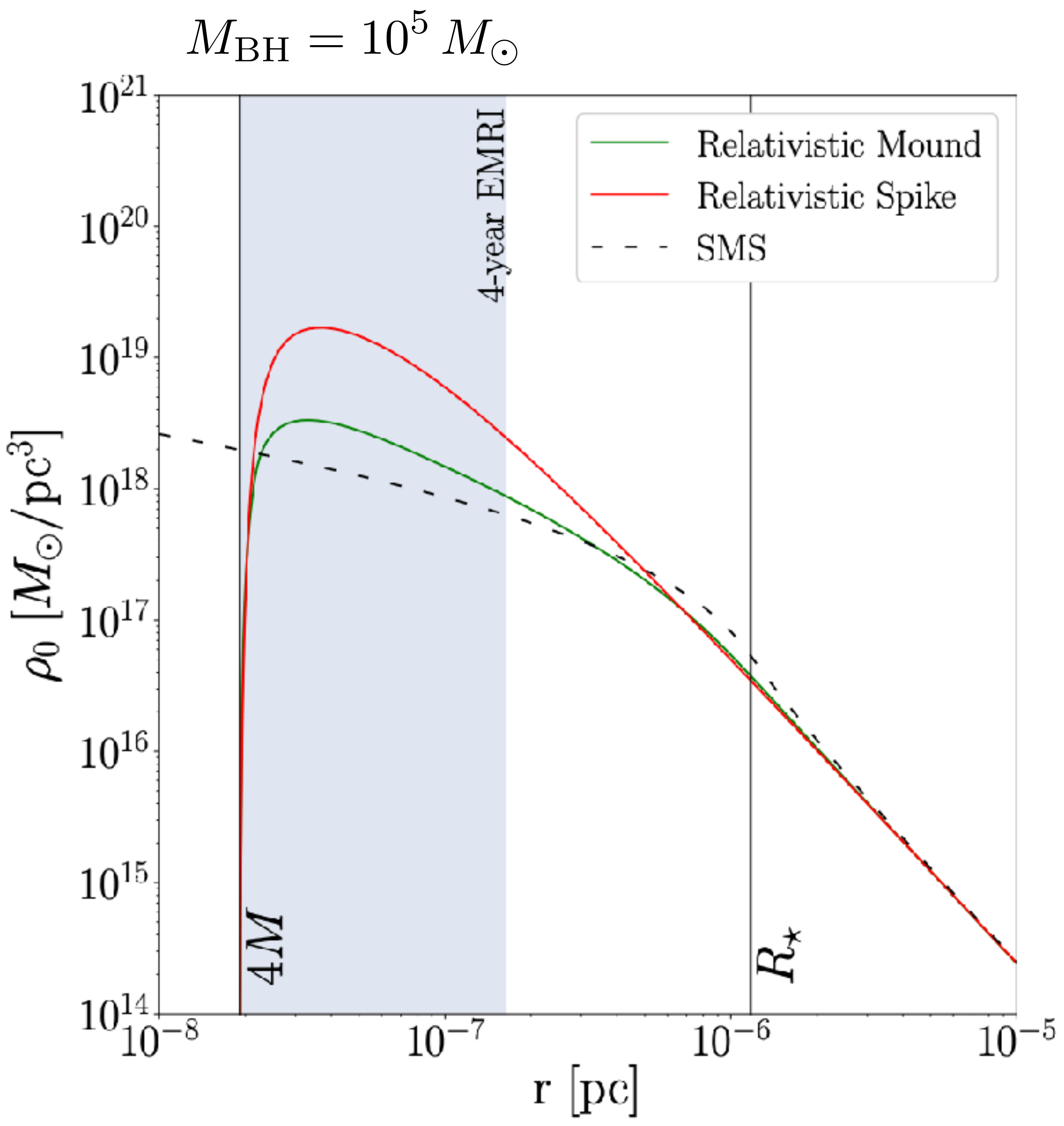
[Dunn et al., 1803.01007]

Dark Matter Mounds

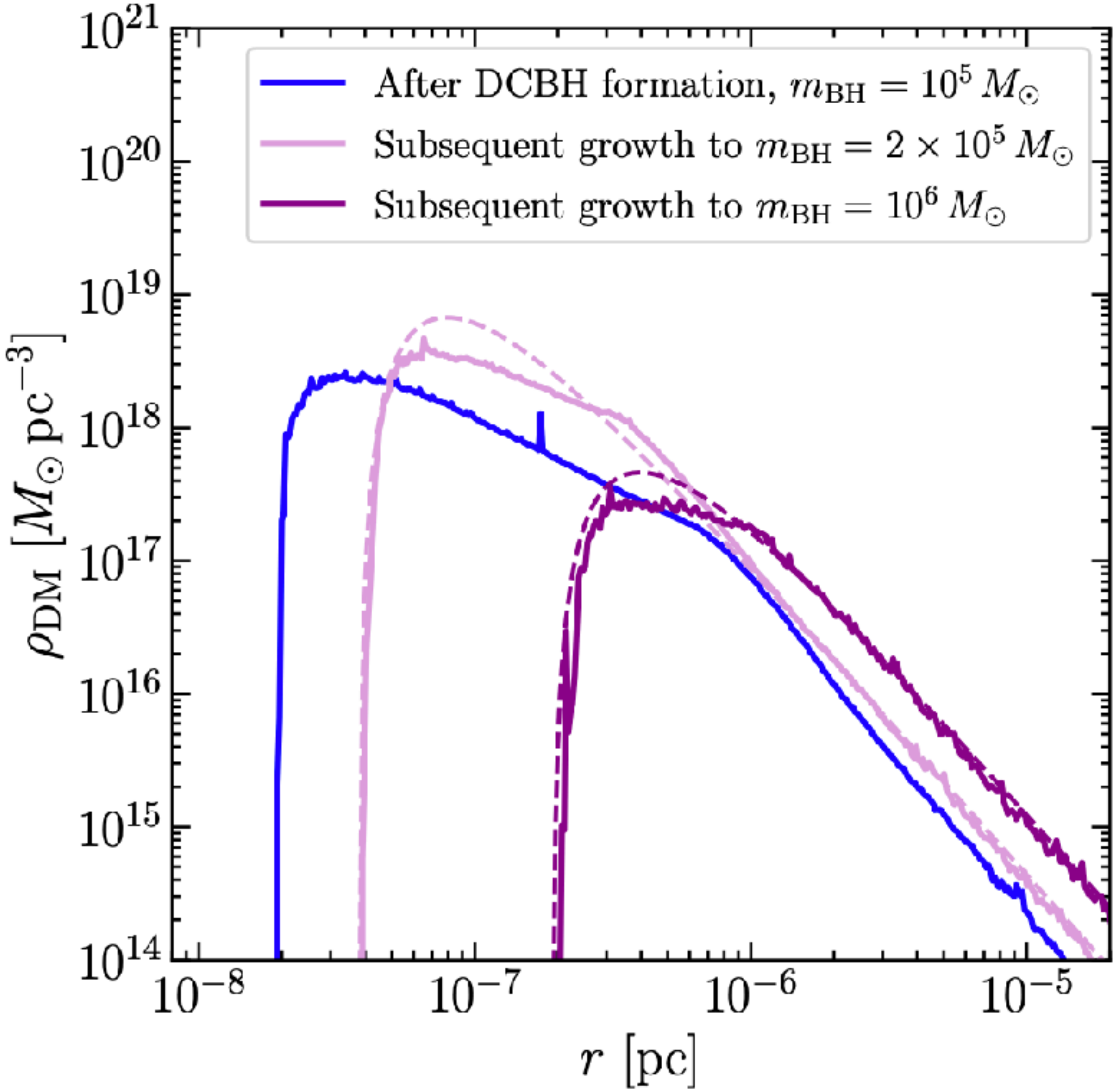


[Caiozzo et al. (including **BJK**), 2512.09985]

Dark Matter Mounds



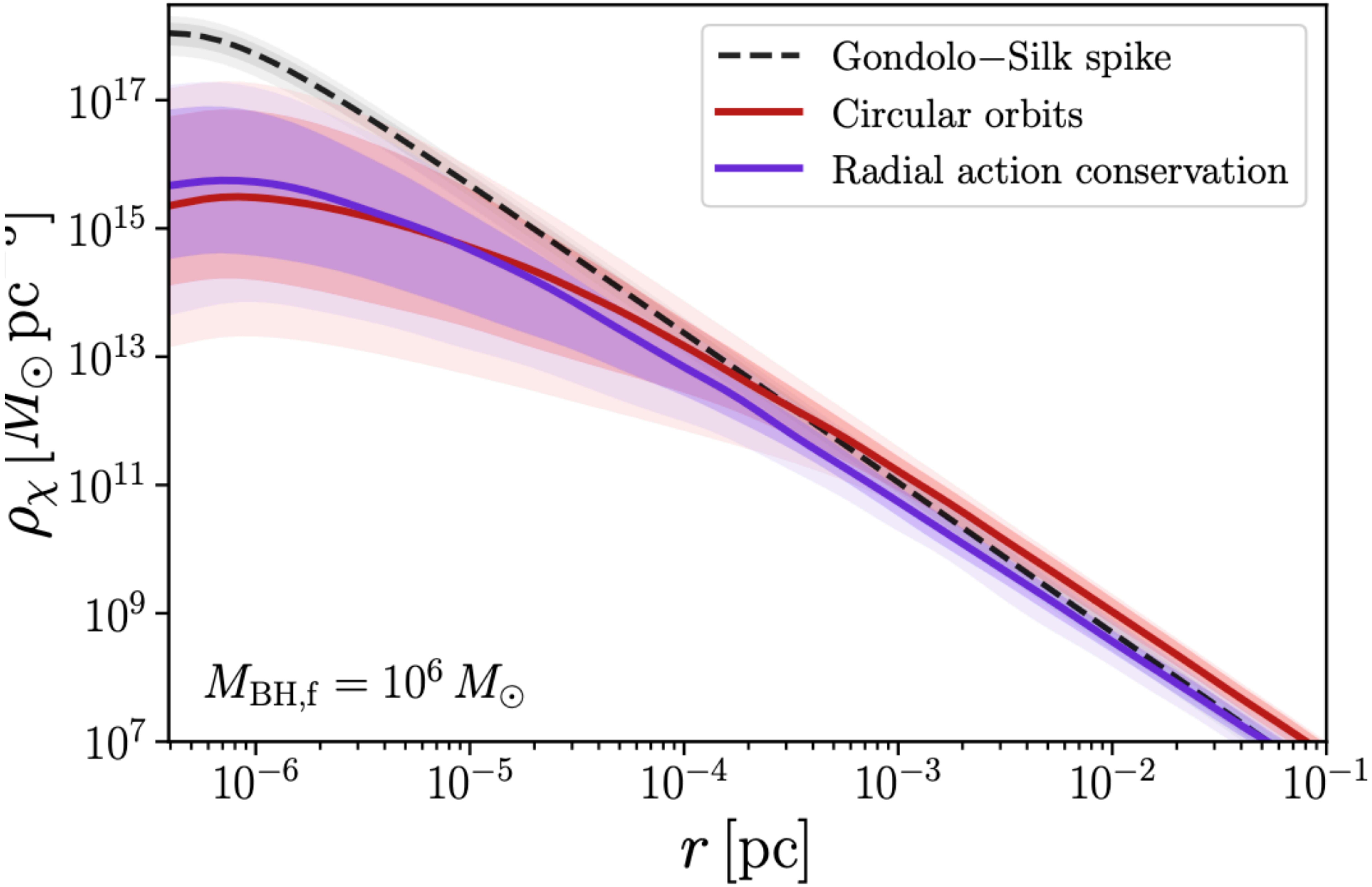
[Caiozzo et al. (including **BJK**), 2512.09985]



[Bertone et al. (including **BJK**), 2404.08731]

Growth with stars

Consider spike growth including potential due to BH, DM and Stars:

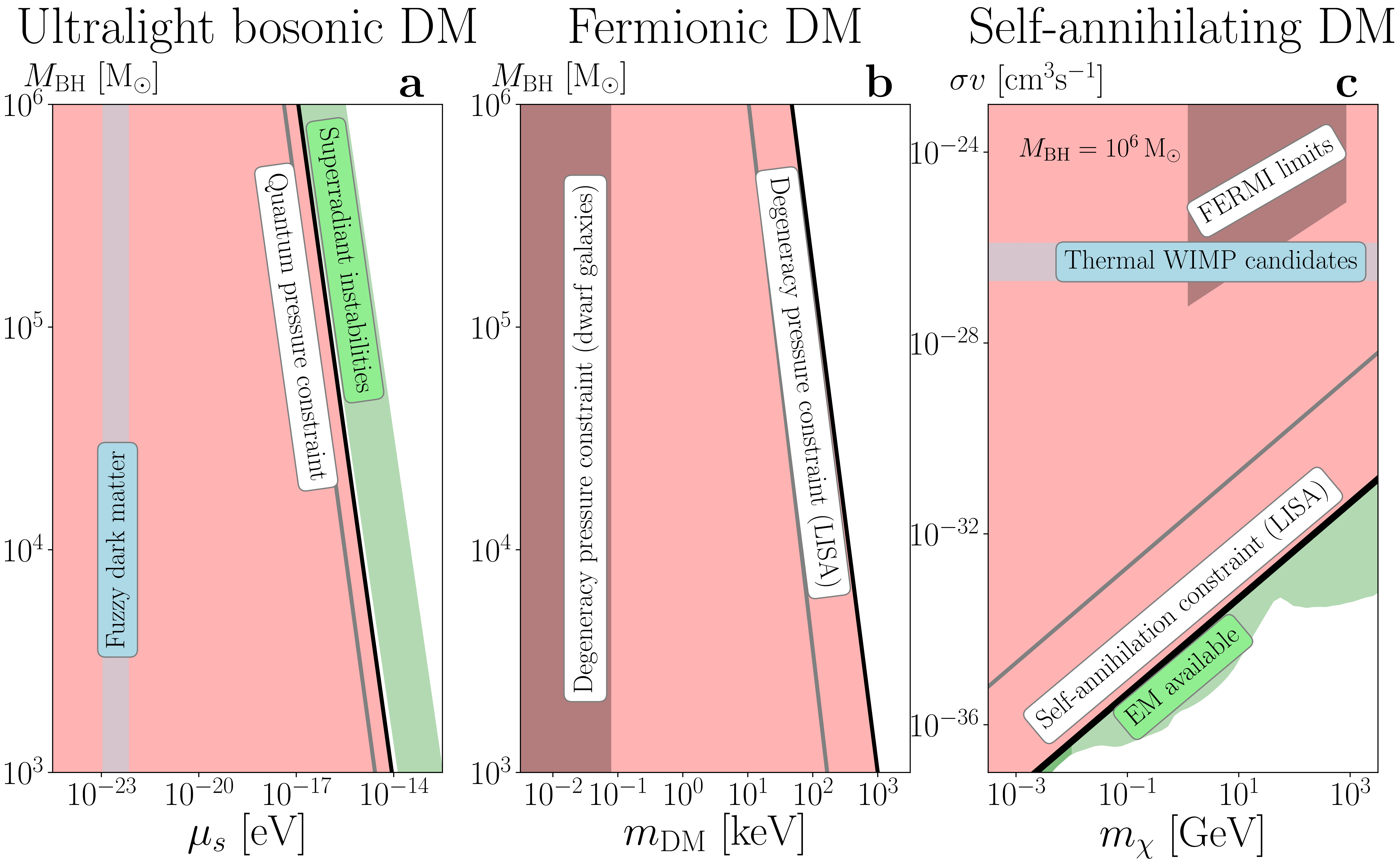


[Herrera et al., 2605.01023]

Spikes for particle physics!

[Hannuksela et al., 1906.11845]

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

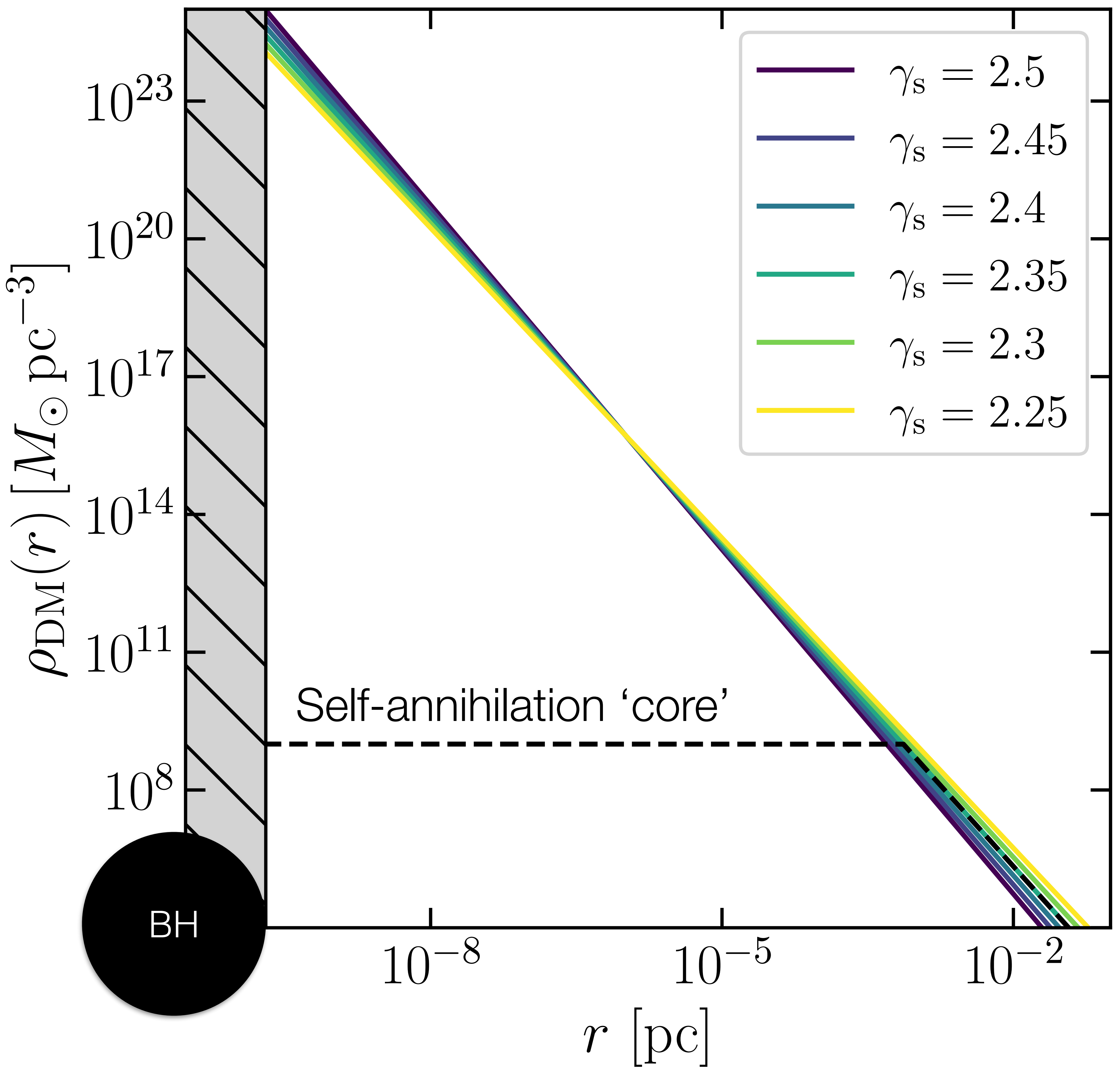


[See also Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

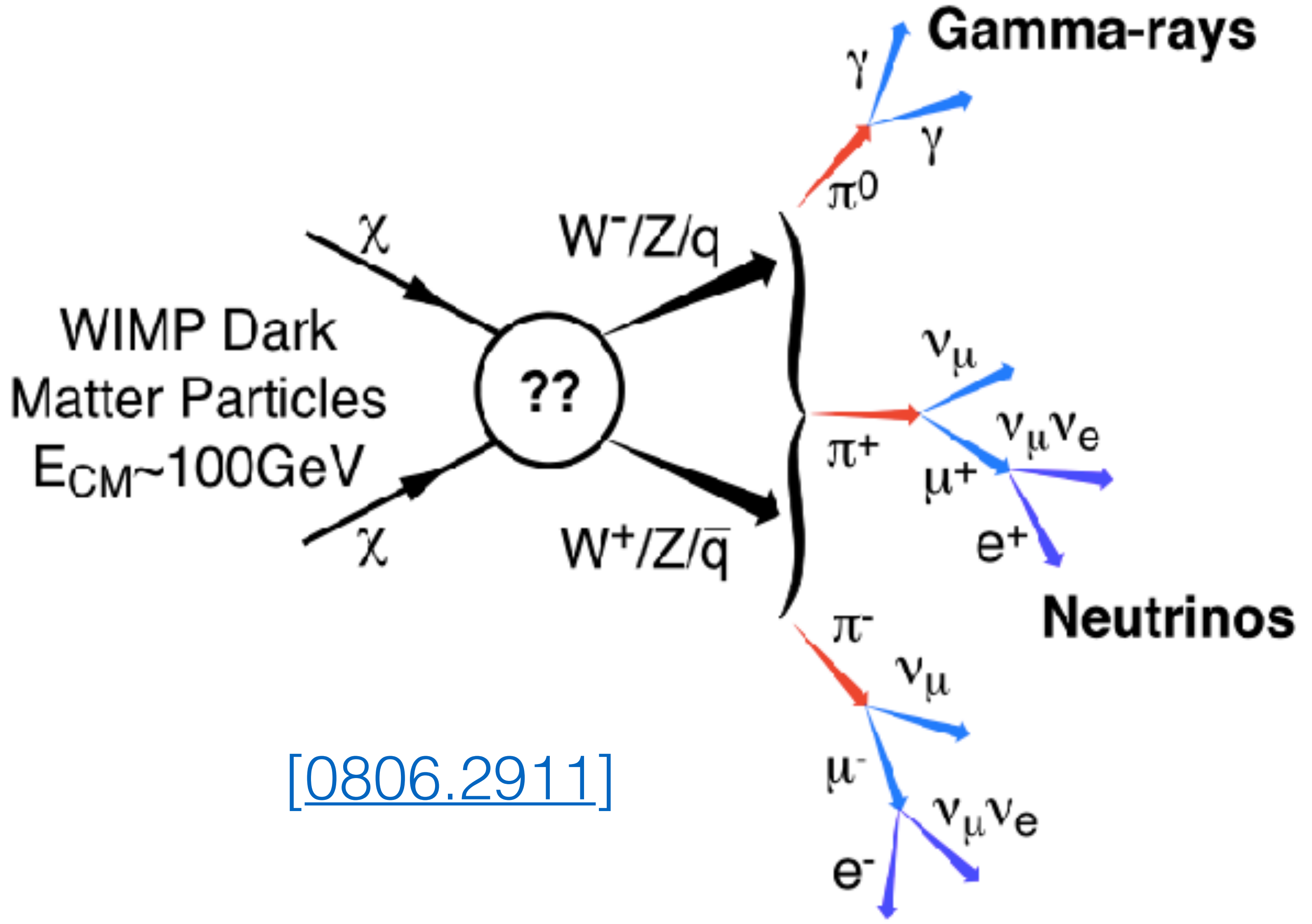
The Life of Dark Matter Spikes

DM Annihilation Signals

$$\rho_{\rm DM} = \rho_{\rm sp}\left(\frac{r_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$



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



[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

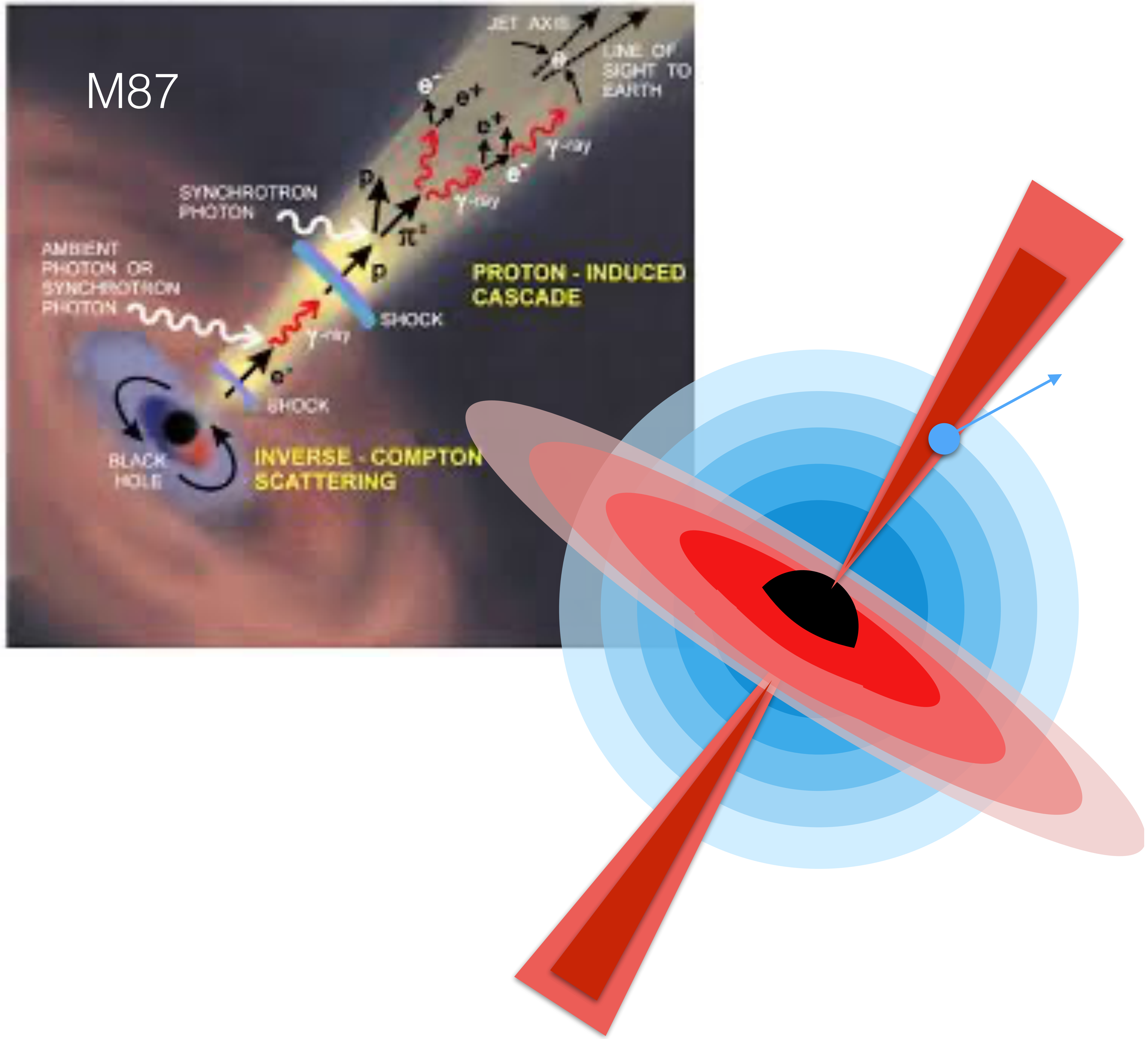
Could be used to constrain DM annihilation around SMBHs and IMBHs in the Milky Way (but there are still many uncertainties)

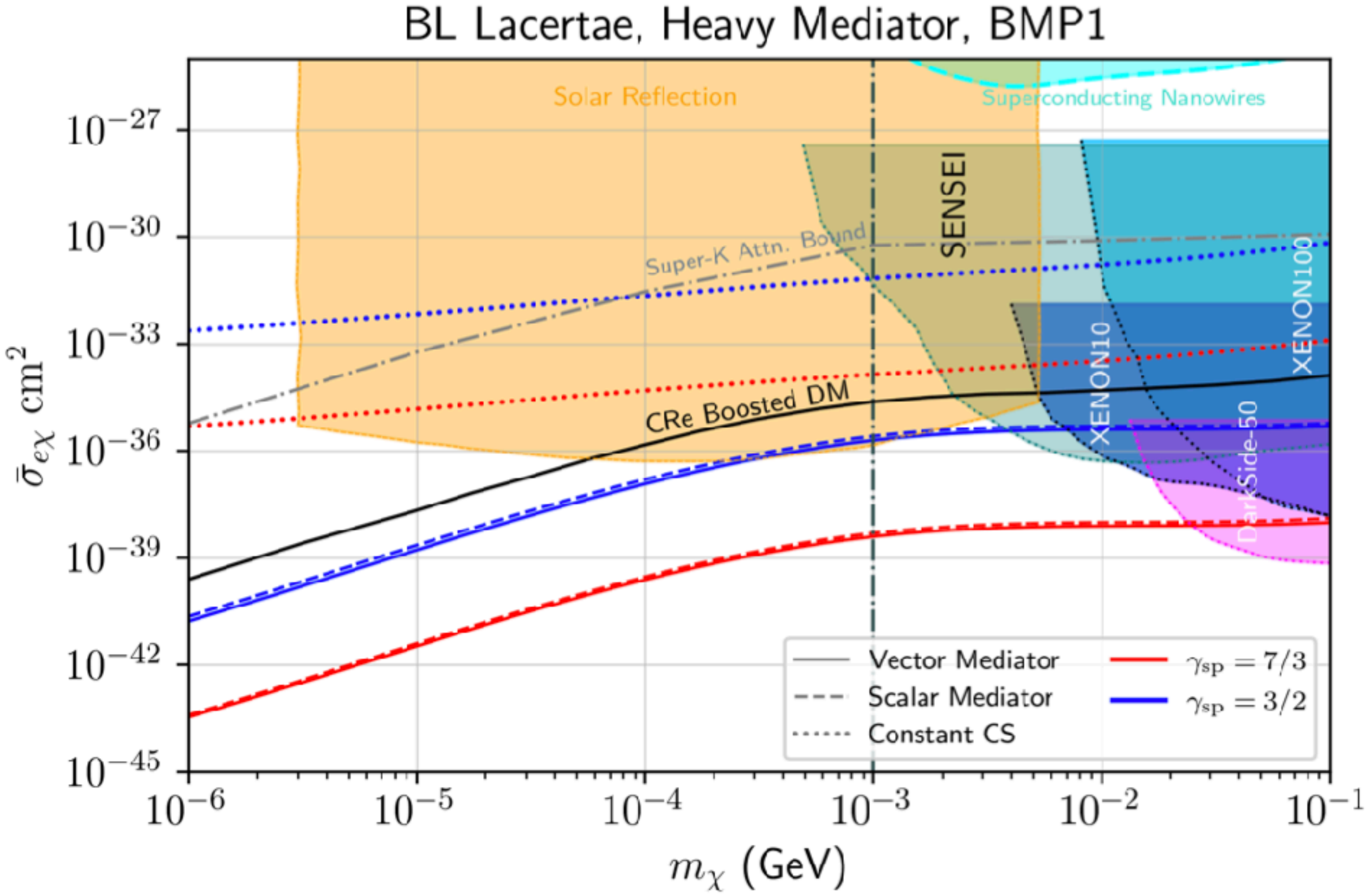
[E.g. Lacroix & Silk, 1712.00452, Freese et al., 2202.01126, Balaji et al., 2303.12107]

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

Blazar-boosted DM

Blazars: SMBHs at the centres of distant galaxies launching relativistic jets towards us ($\gamma \gtrsim 3$)



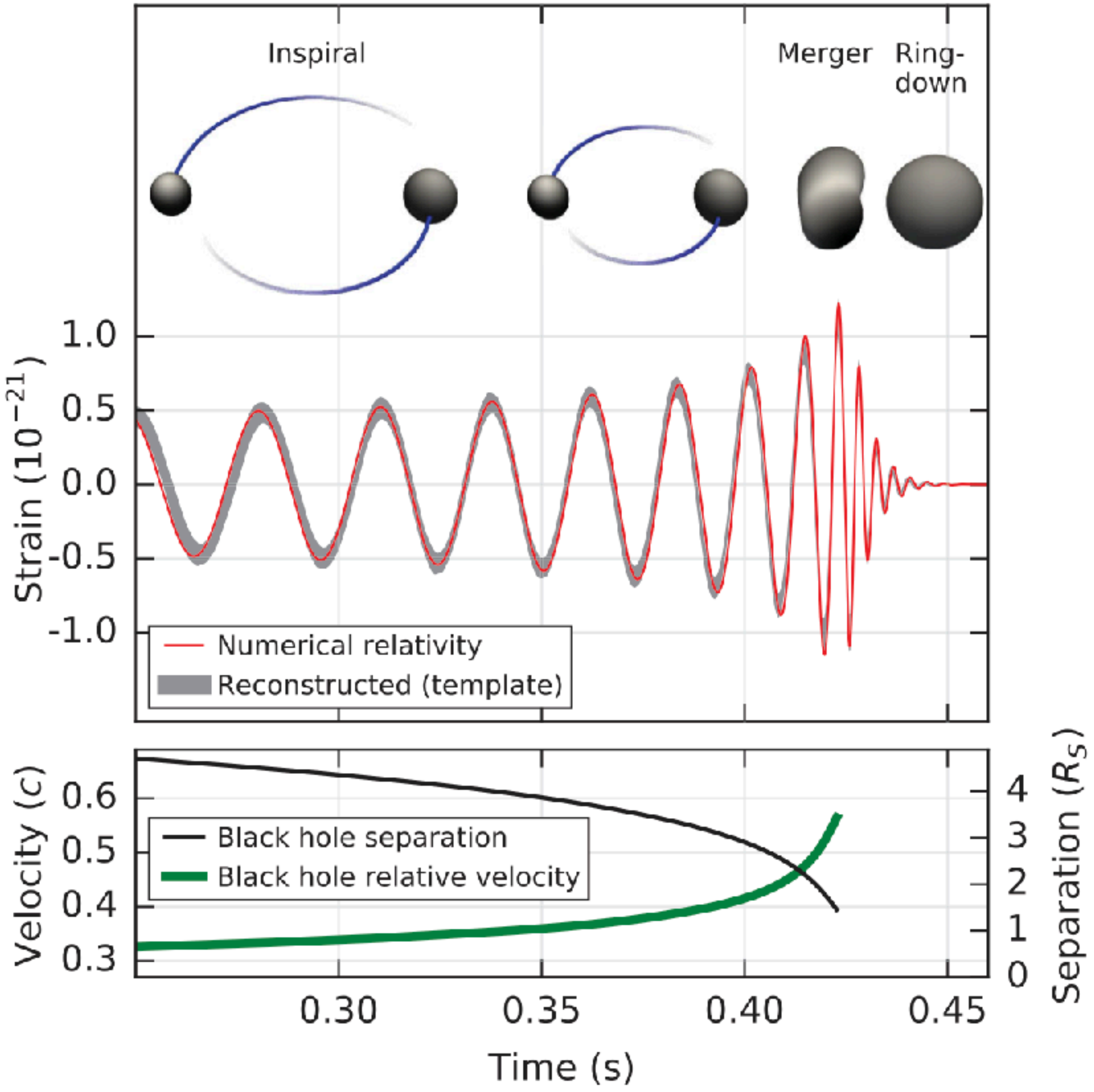


[E.g. Bhowmick et al., 2301.00209; Barillier et al., 2509.07265, De Marchi et al., 2507.12278]

Gain sensitivity due to enhanced DM density *and* boosted kinetic energy!

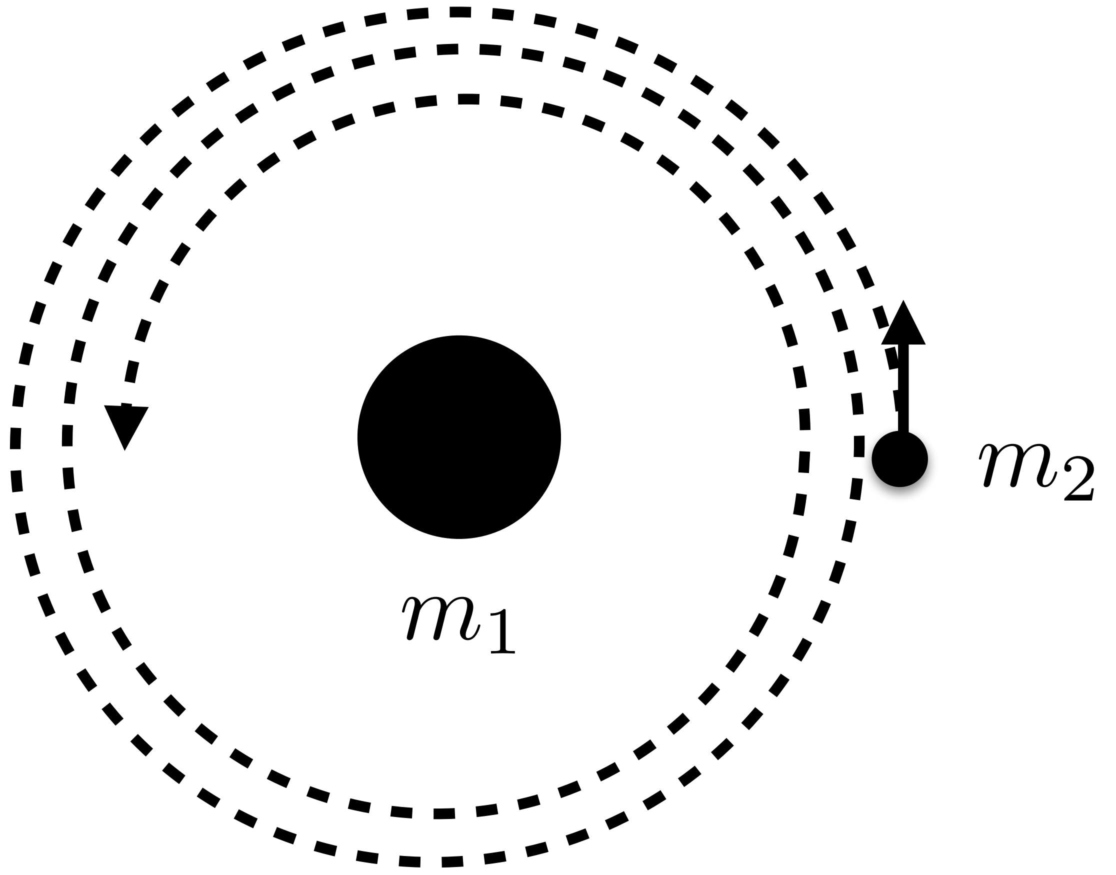
Gravitational Waves (GW)

An ~equal mass inspiral: GW150914



[LIGO/Virgo, arXiv:1602.03837]

Intermediate and extreme mass ratio inspirals:

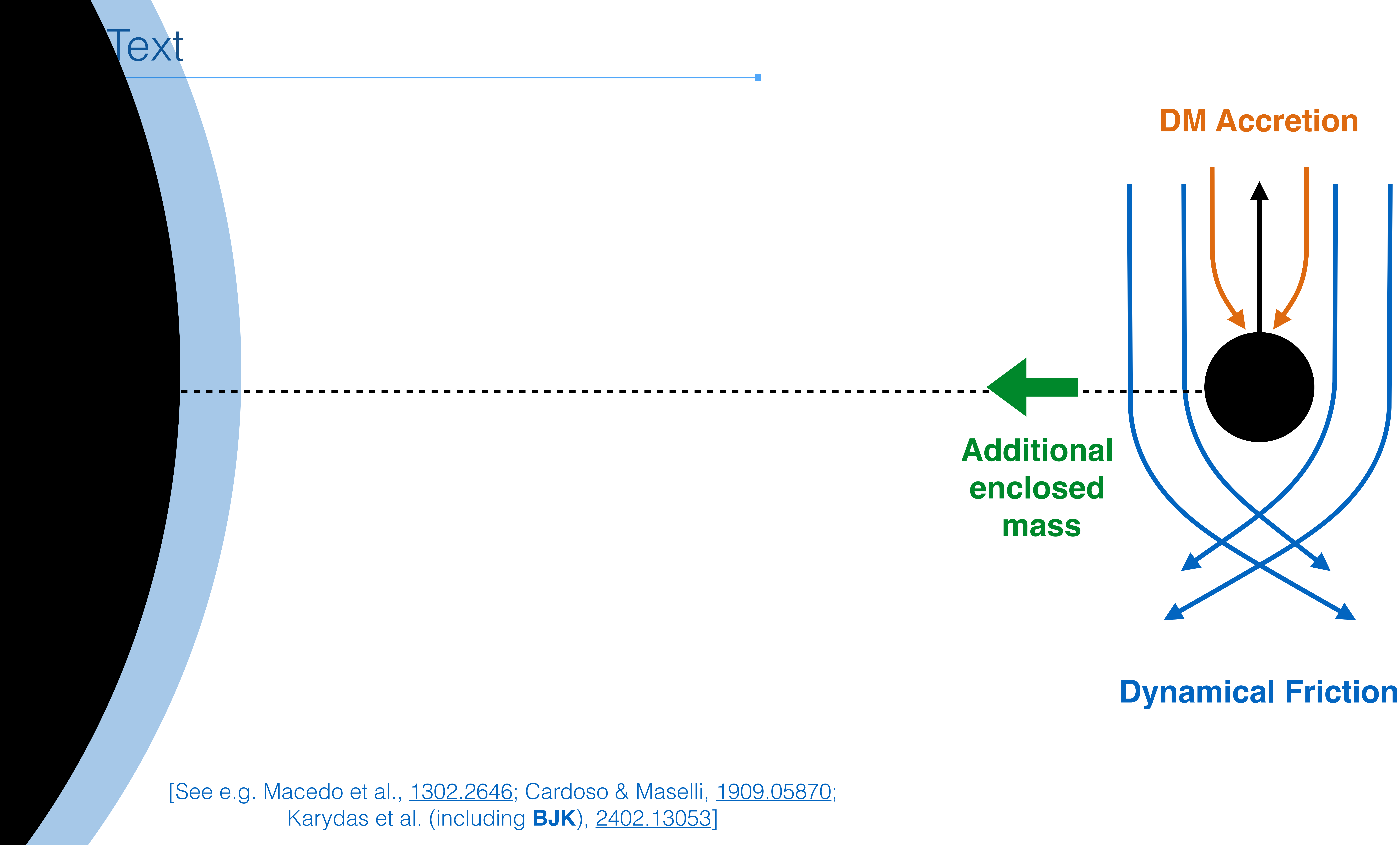


$m_2/m_1 \ll 1$

Binary may be observed during *millions of orbits*

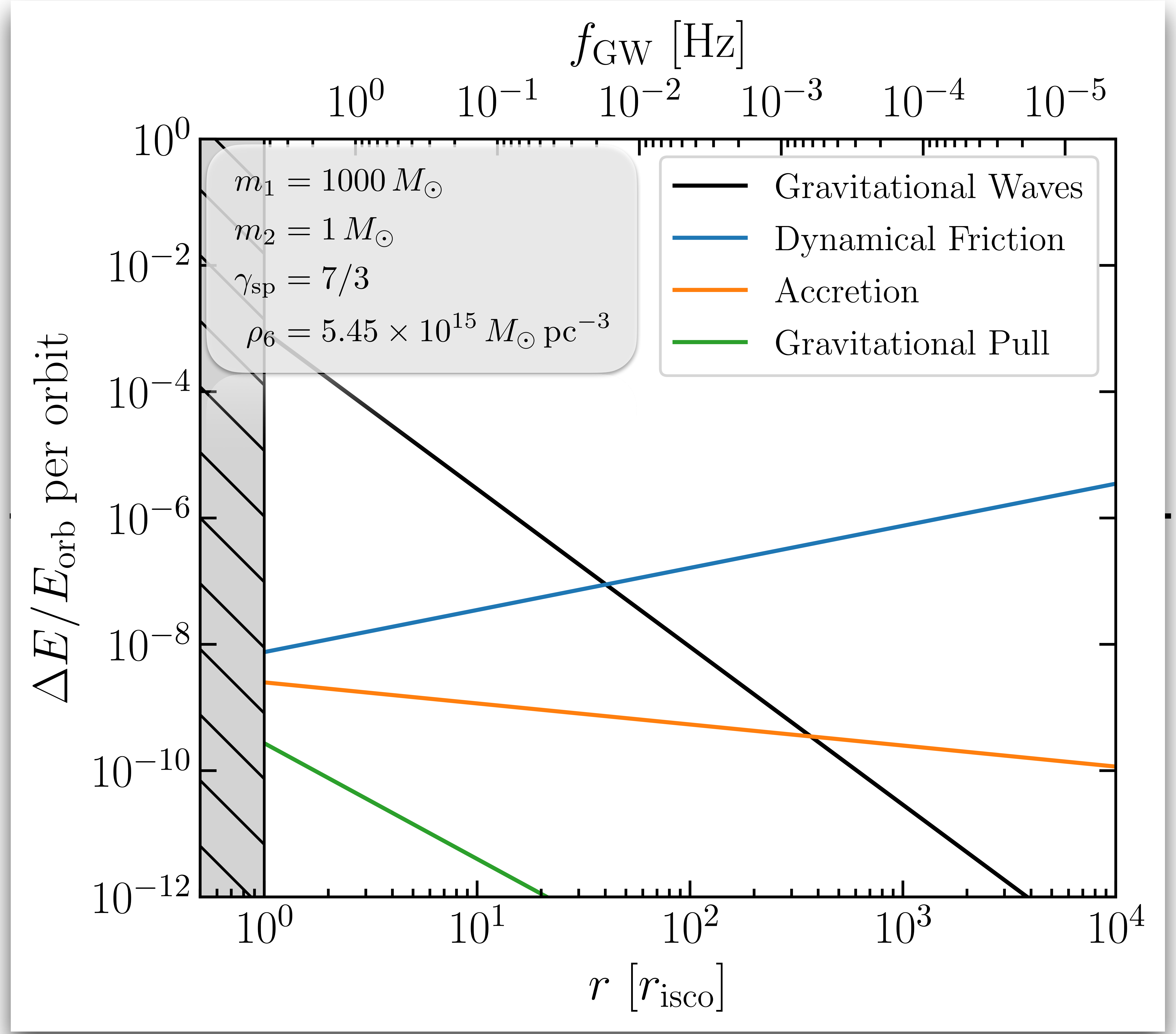
Evolution of the GW signal can be used to **trace the dynamical influence of the environment** around the larger black hole

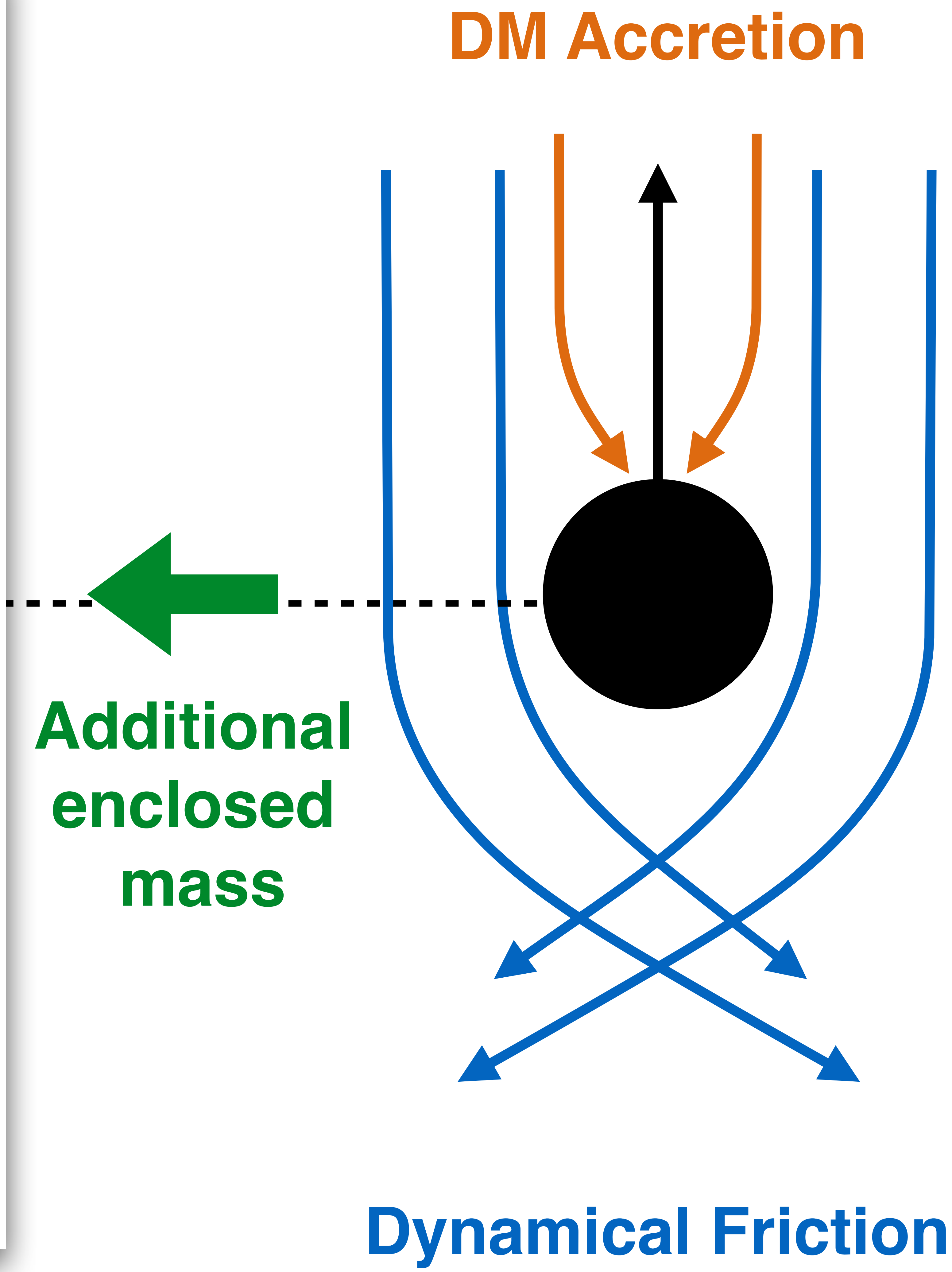
Text



[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870;
Karydas et al. (including **BJK**), 2402.13053]

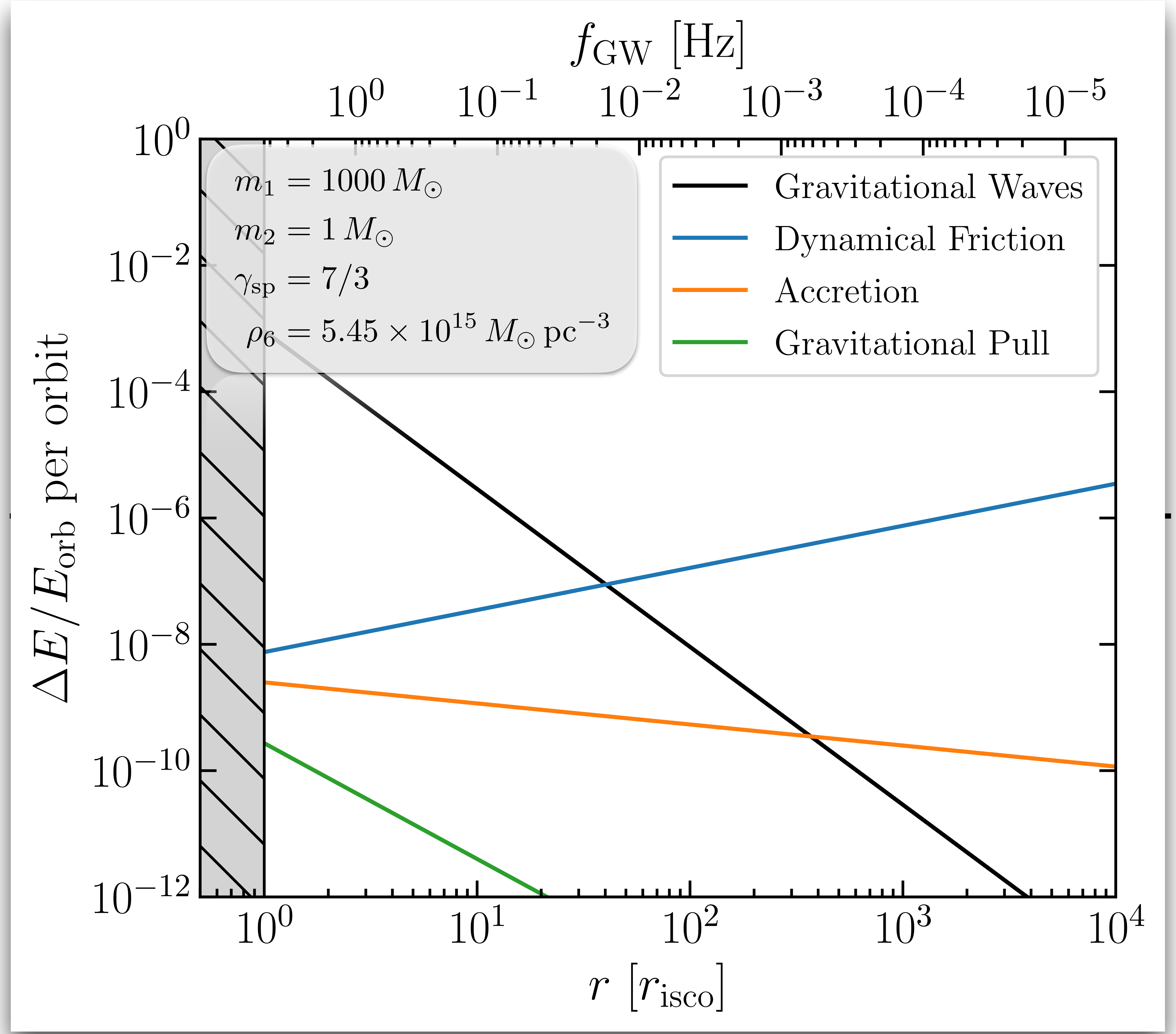
Text

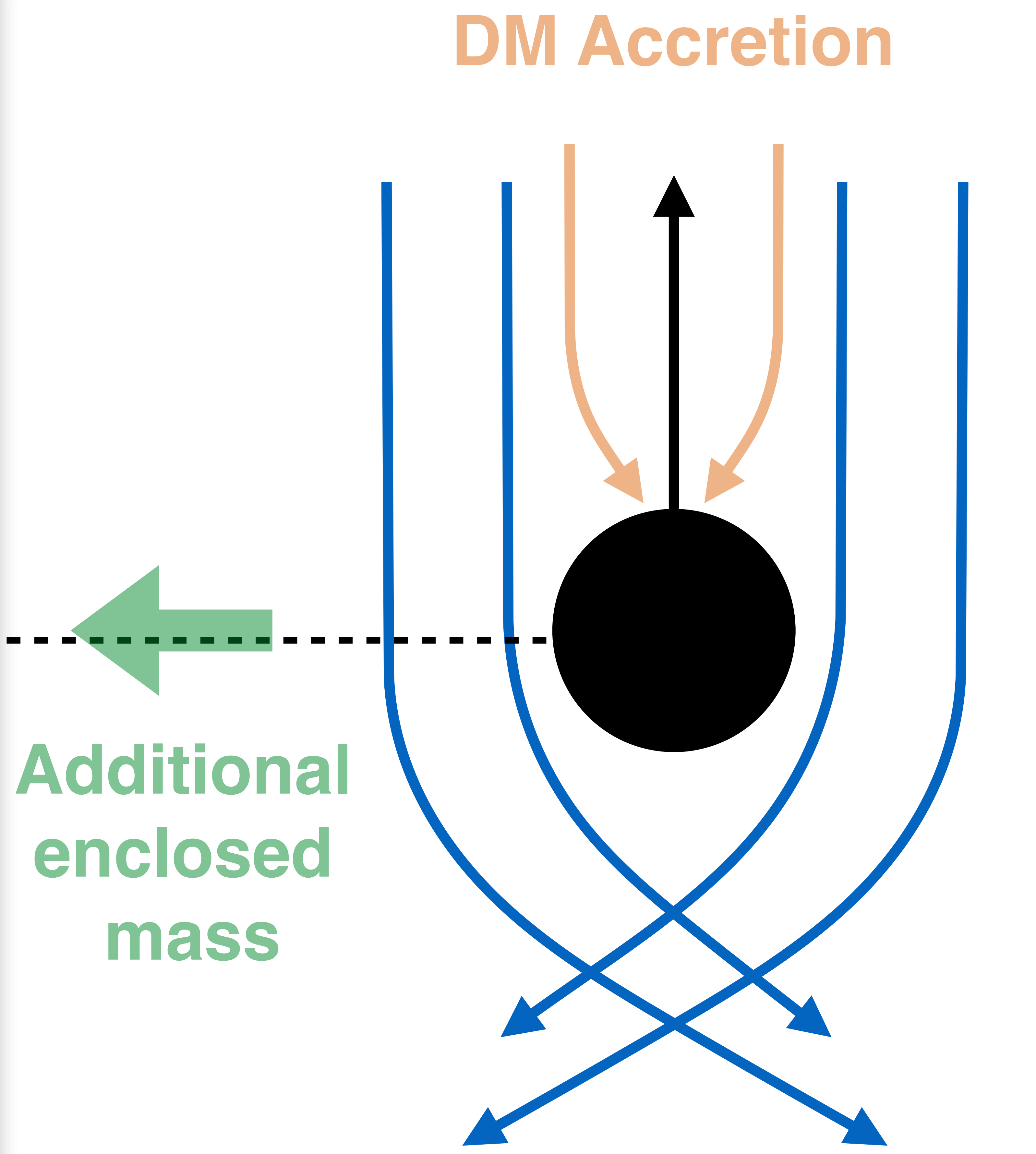




[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870; Karydas et al. (including **BJK**), 2402.13053]

Text

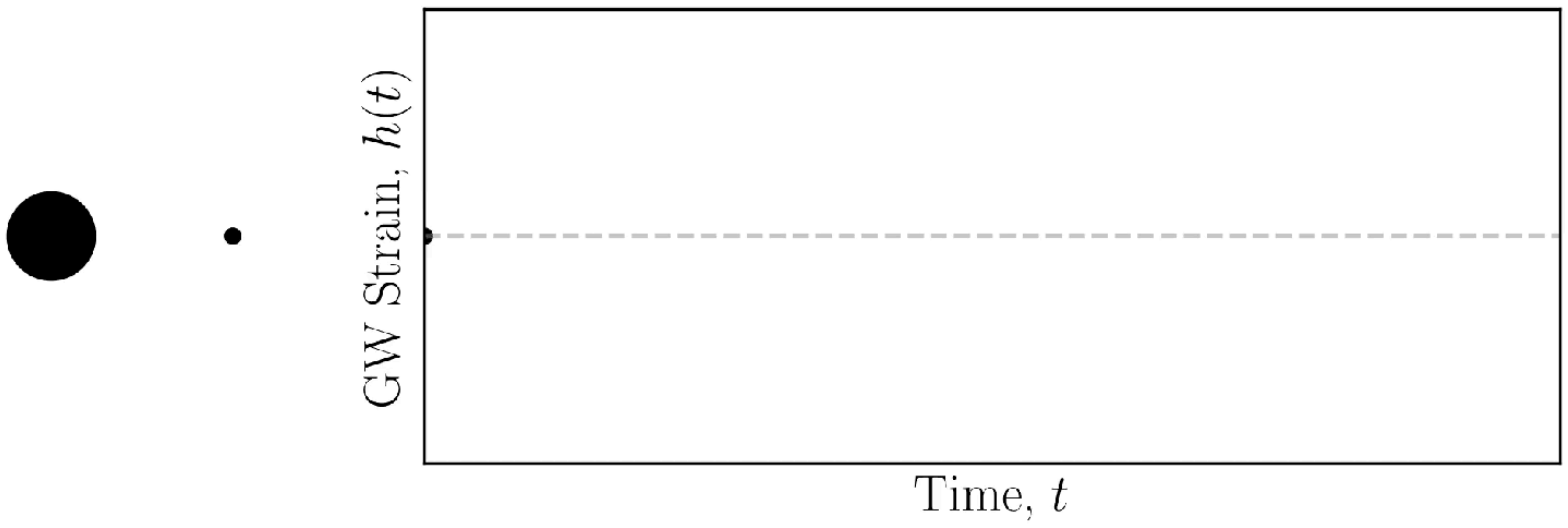


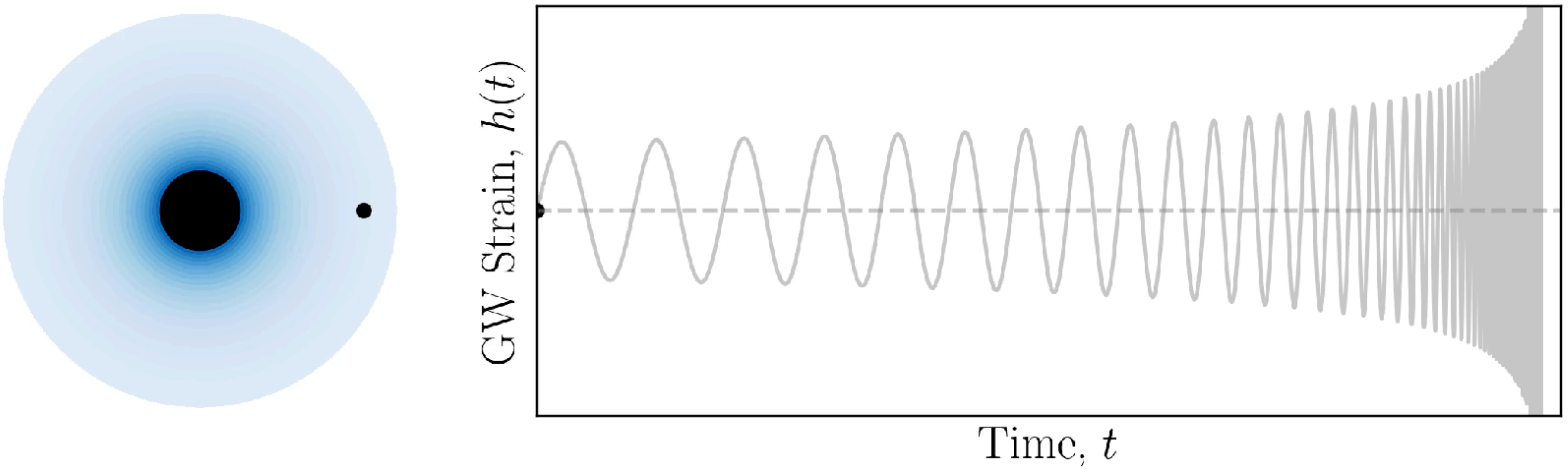


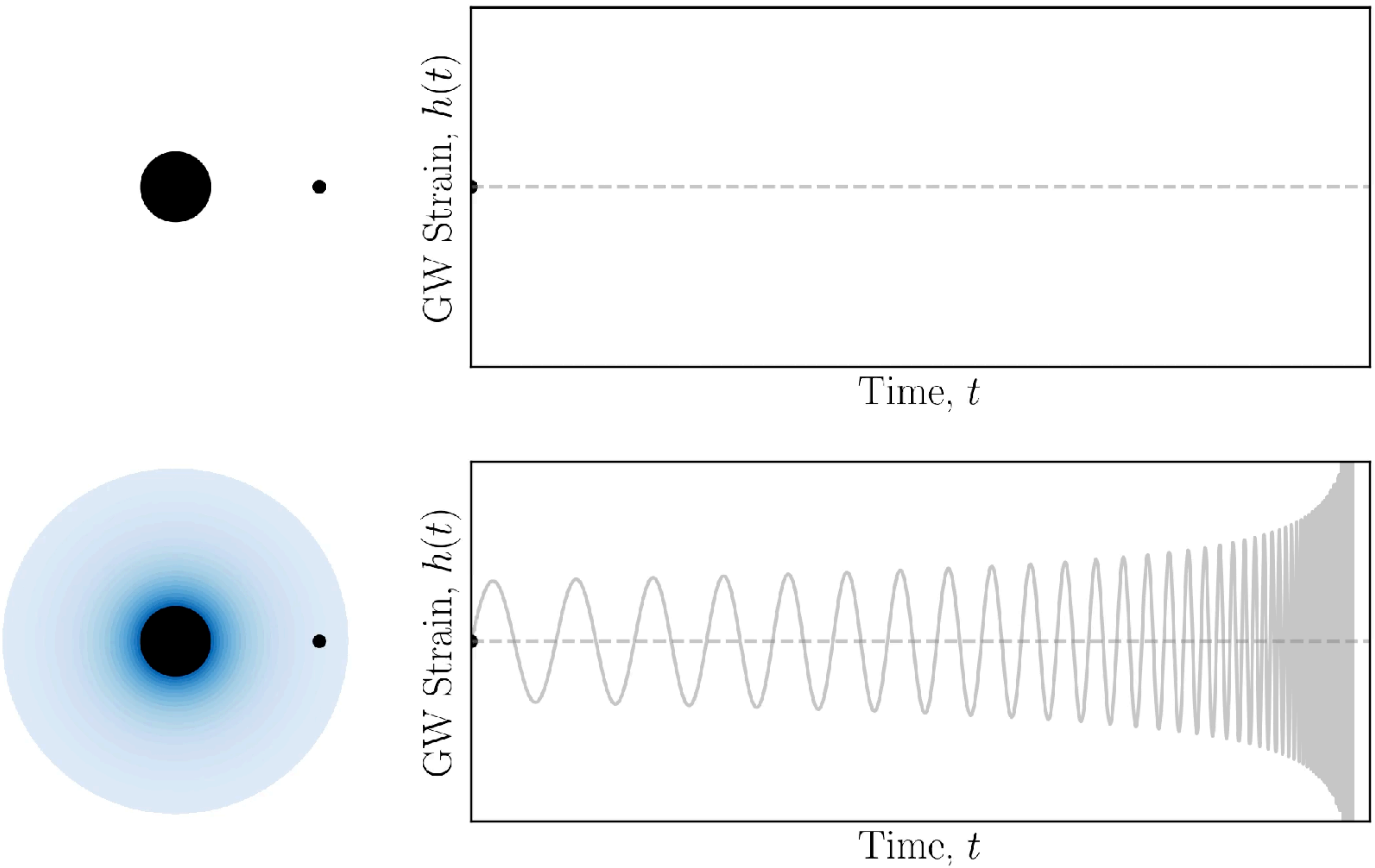
Dynamical Friction

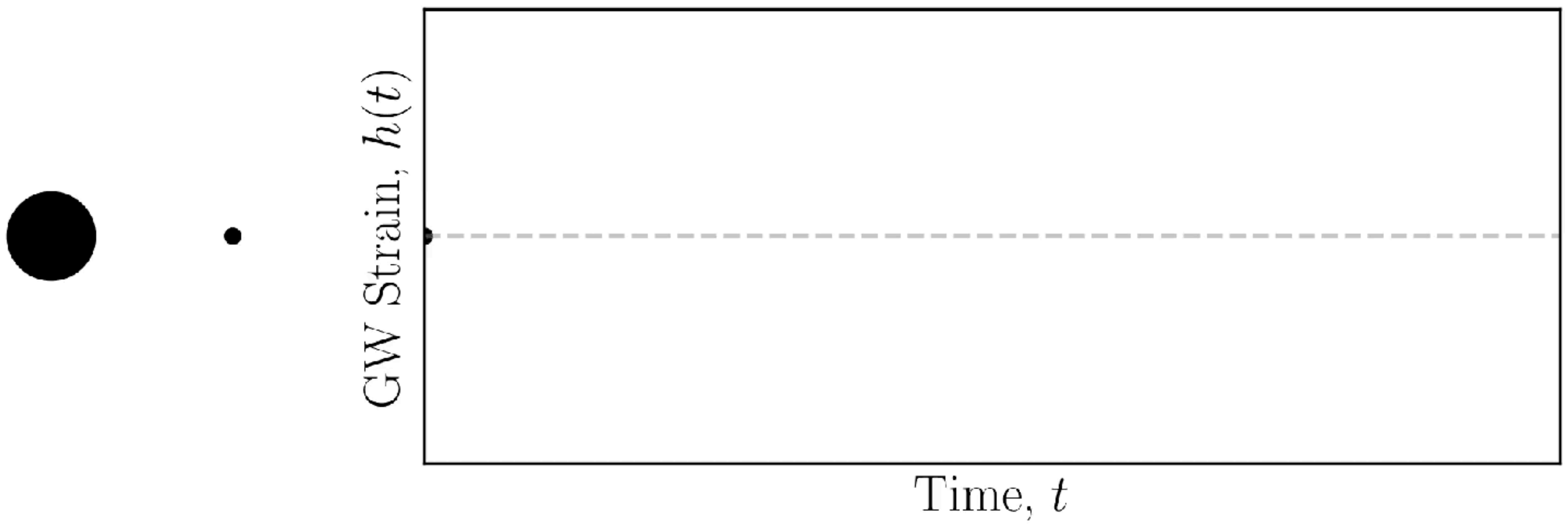
$$\dot{E}_{\mathrm{DF}} \sim \frac{4\pi G^2 m_2^2 \rho_{\mathrm{DM}}(r)\xi(v)}{v} \ln \Lambda$$

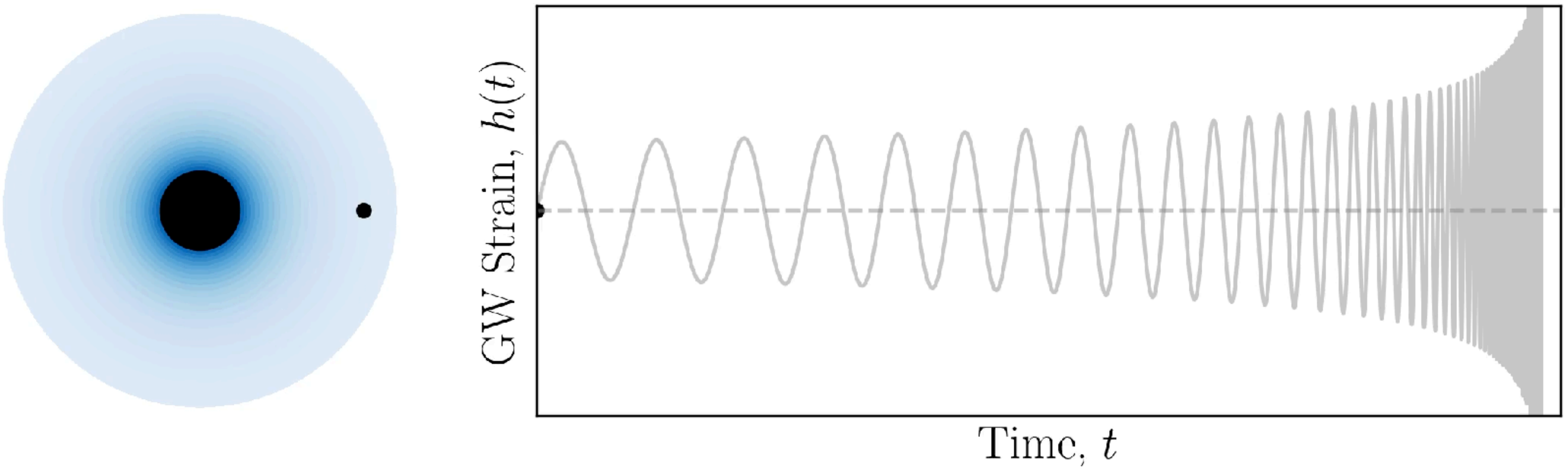
[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870; Karydas et al. (including **BJK**), 2402.13053]

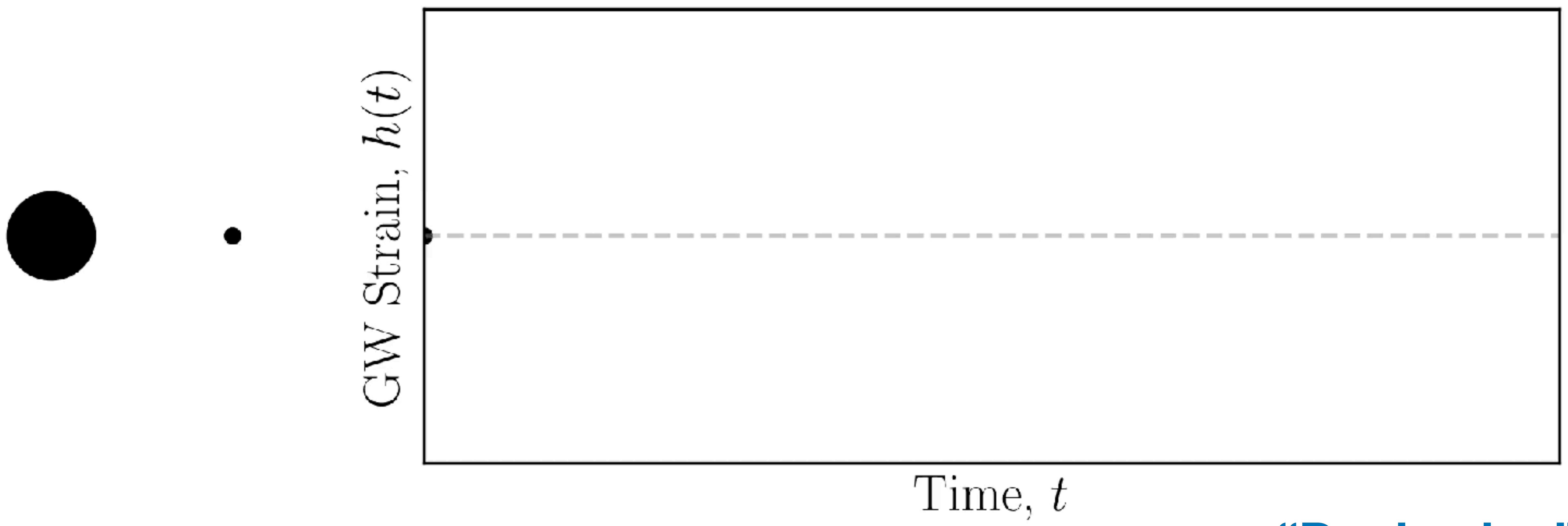

GW Strain, $h(t)$
Time, t


GW Strain, $h(t)$
Time, t

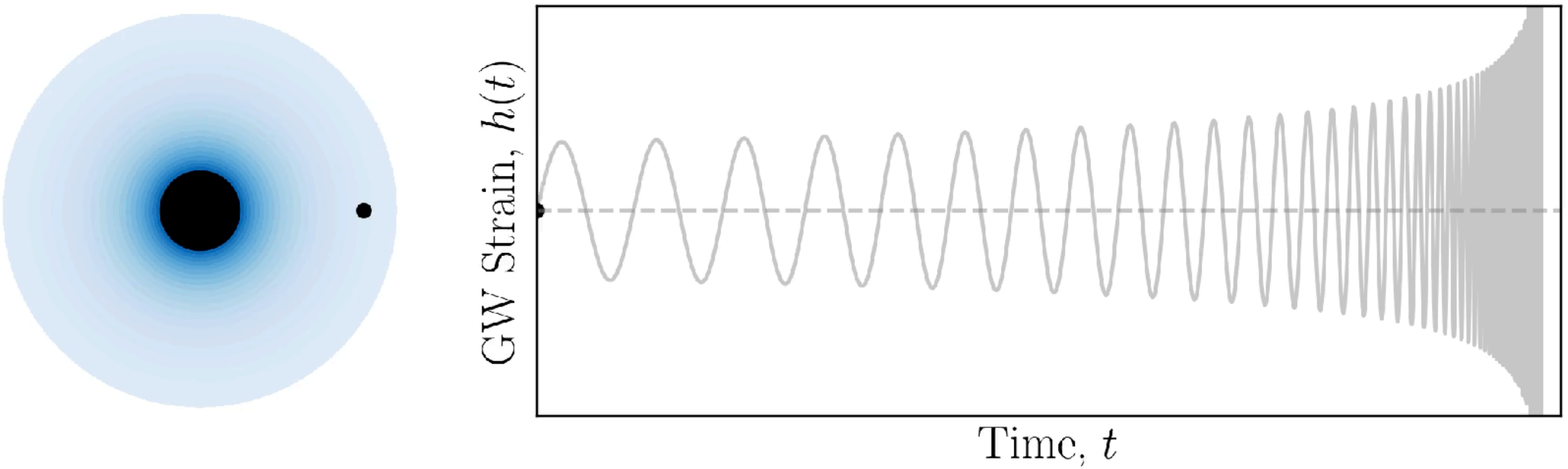

GW Strain, $h(t)$
Time, t
GW Strain, $h(t)$
Time, t


GW Strain, $h(t)$
Time, t


GW Strain, $h(t)$
Time, t



“Dephasing”



Feedback

Follow semi-analytically the phase space distribution of DM:

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

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

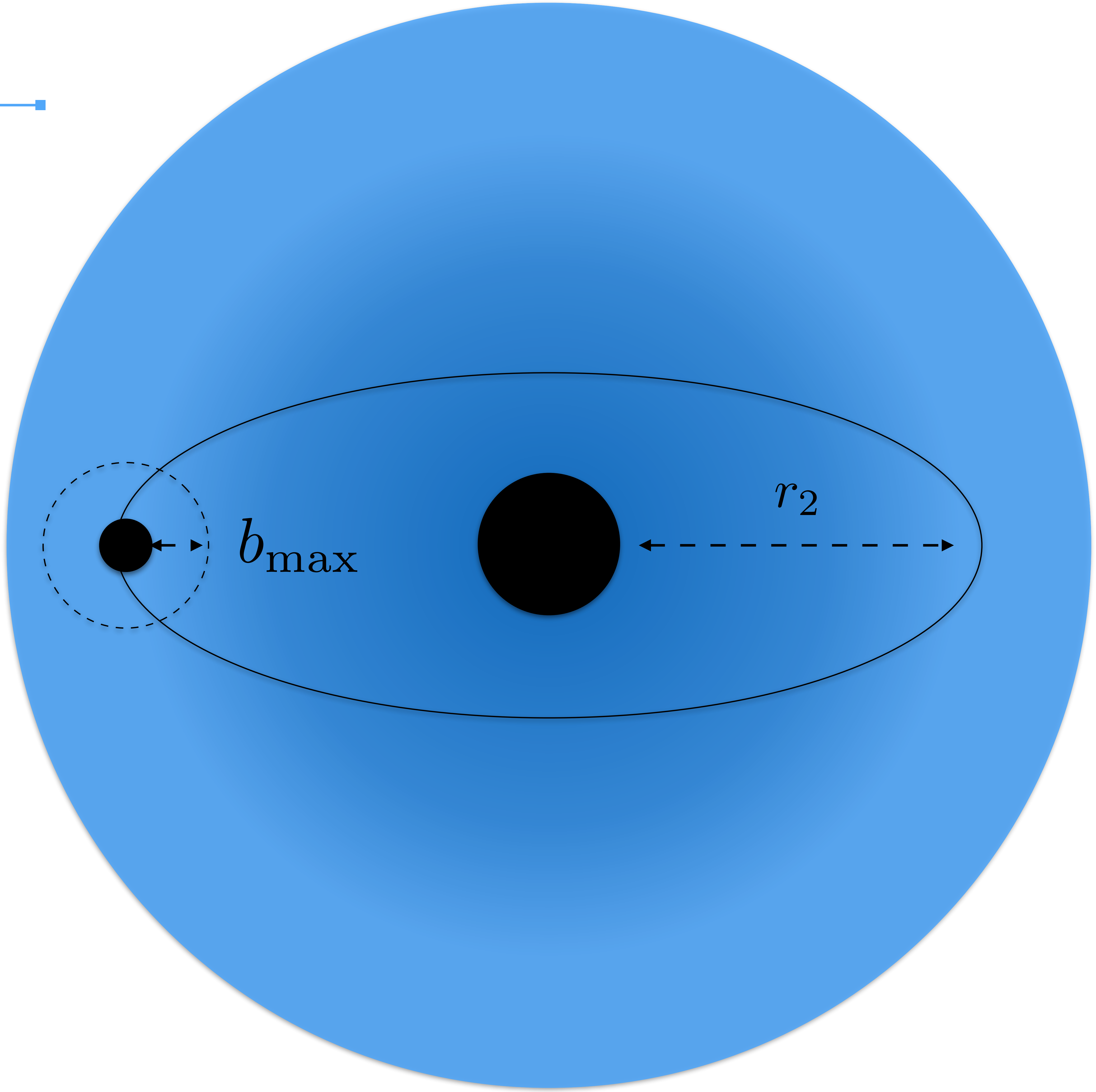
Each particle receives a ‘kick’ through gravitational scattering

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

Reconstruct density from distribution function:

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

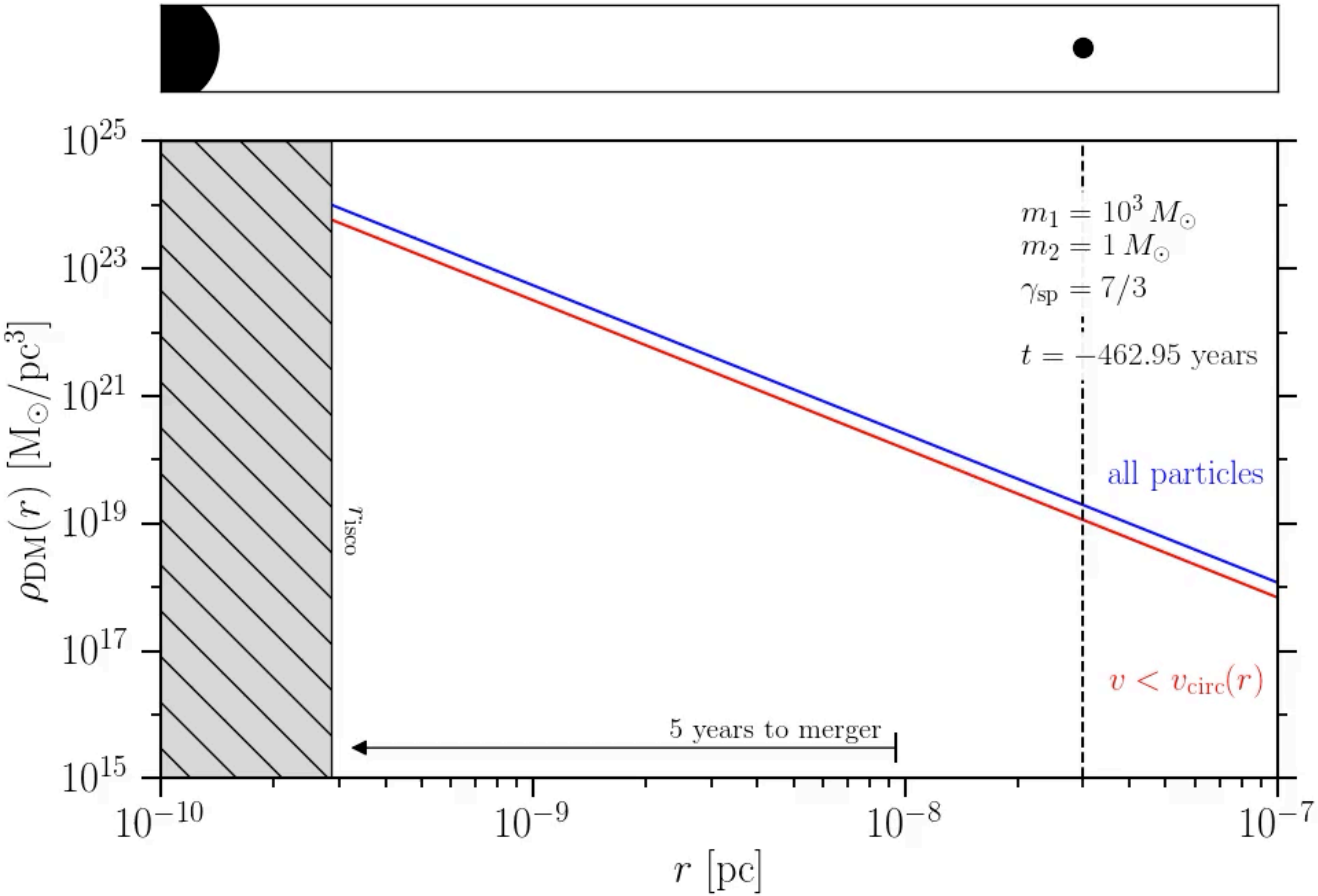
[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]



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

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

Feedback

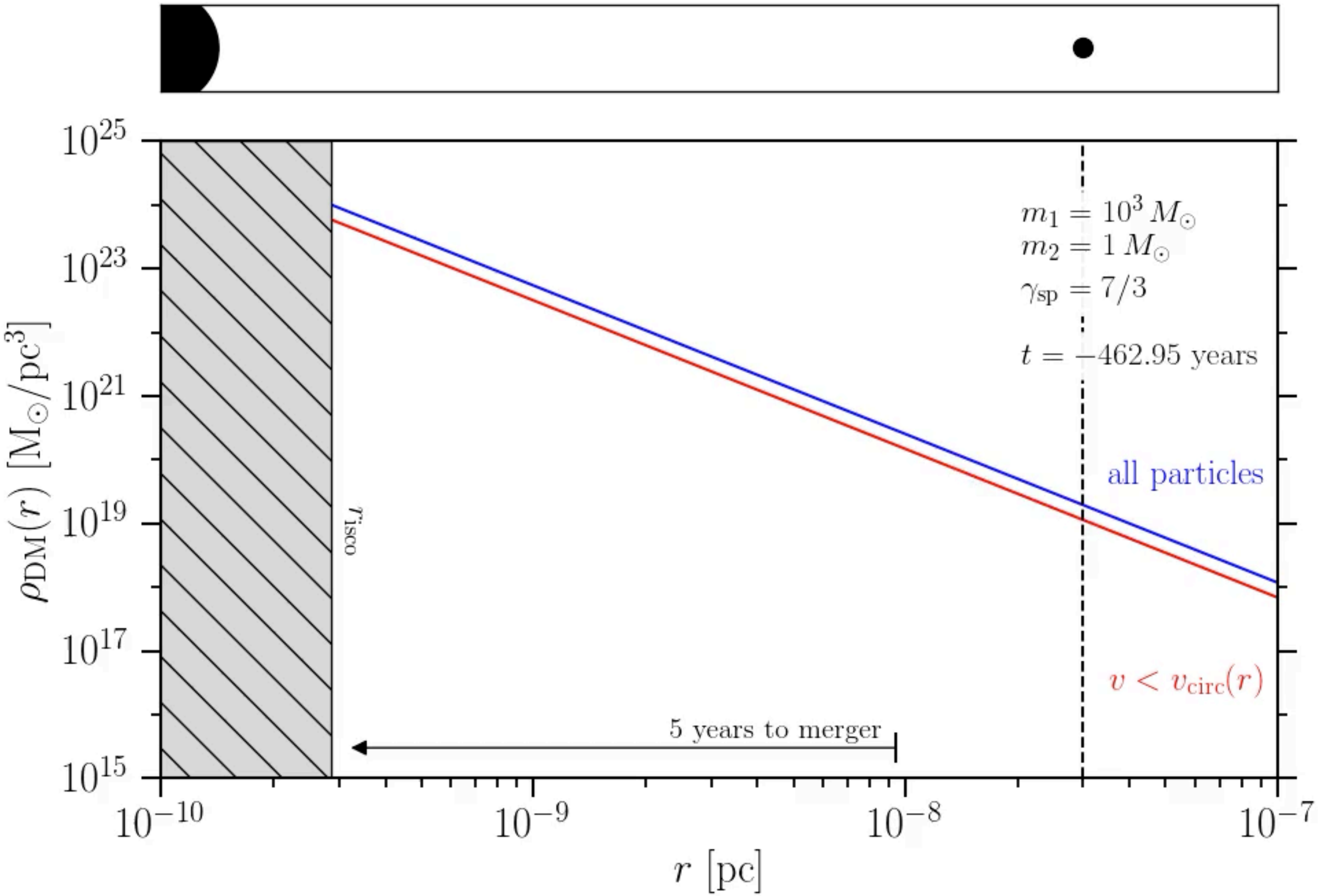


Find that the density of the DM spike is depleted (and replenished…)

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

"Strength" of feedback scales roughly as $q^2 = (m_2/m_1)^2$

Feedback



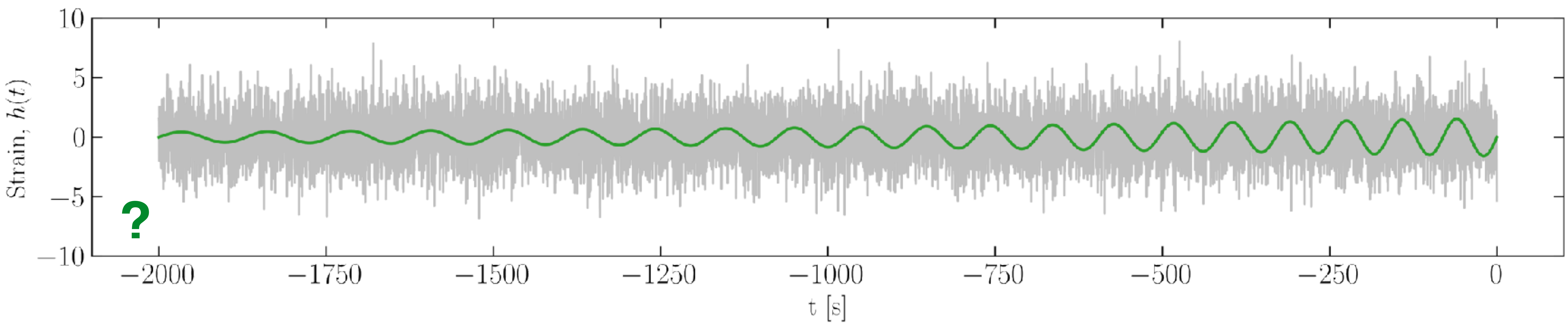
Find that the density of the DM spike is depleted (and replenished…)

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

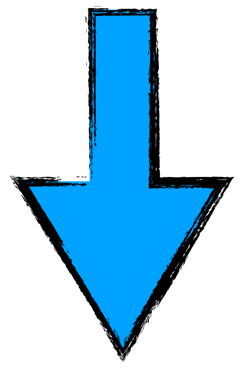
"Strength" of feedback scales roughly as $q^2 = (m_2/m_1)^2$

Can we measure this effect?

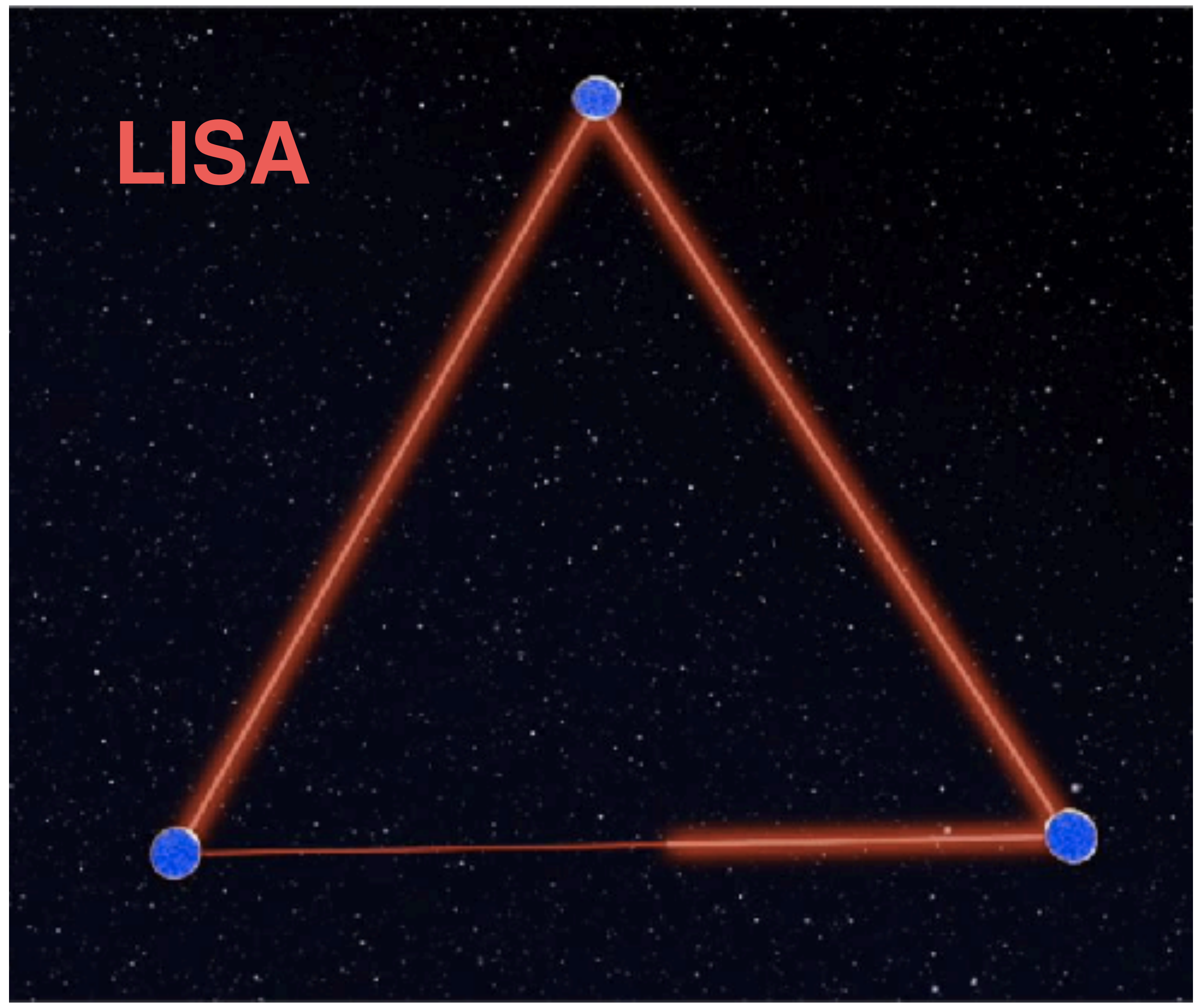
[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]
[Code available online: https://github.com/adam-coogan/pydd]



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

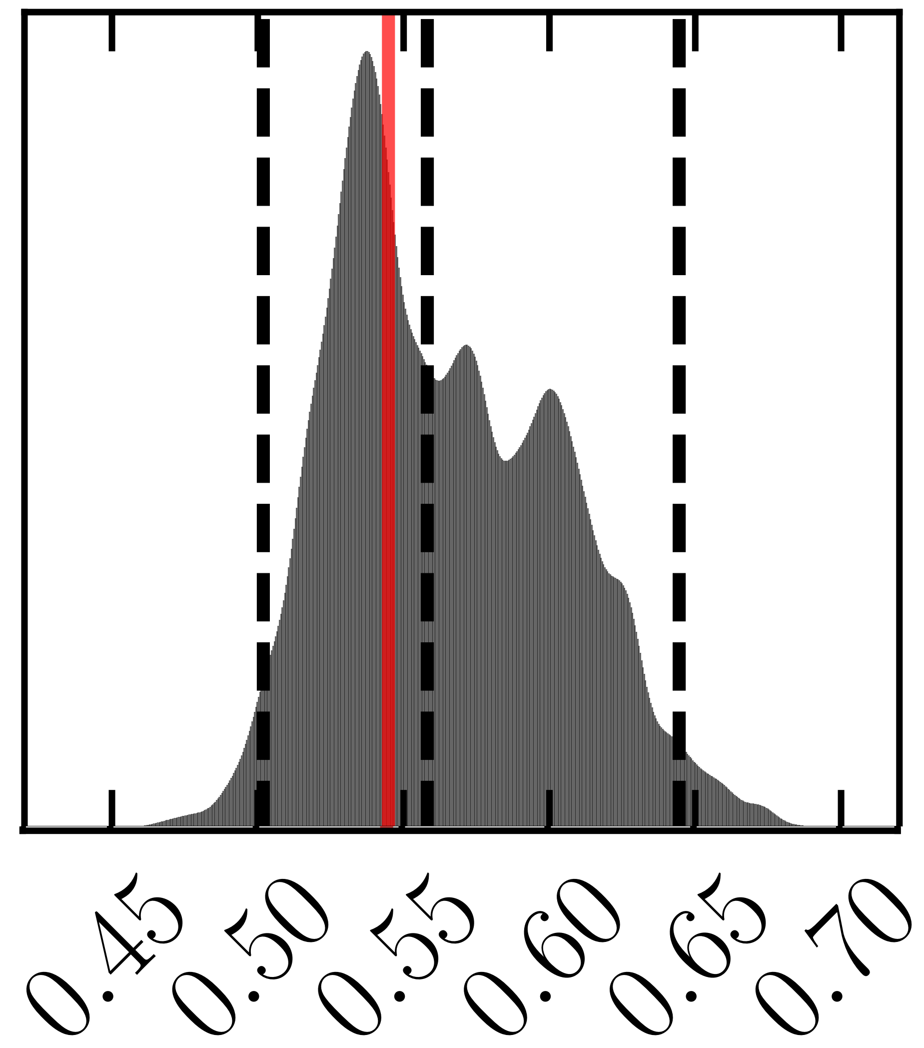


$f_{GW} \sim \mathrm{mHz} - \mathrm{Hz}$



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

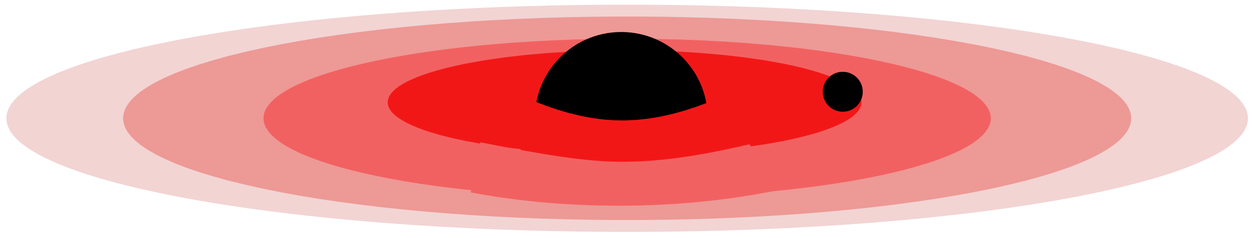
$\rho_6\ [10^{16}\ \mathrm{M_\odot\,pc^{-3}}] = 0.56^{+0.09}_{-0.06}$



Environmental Confusion

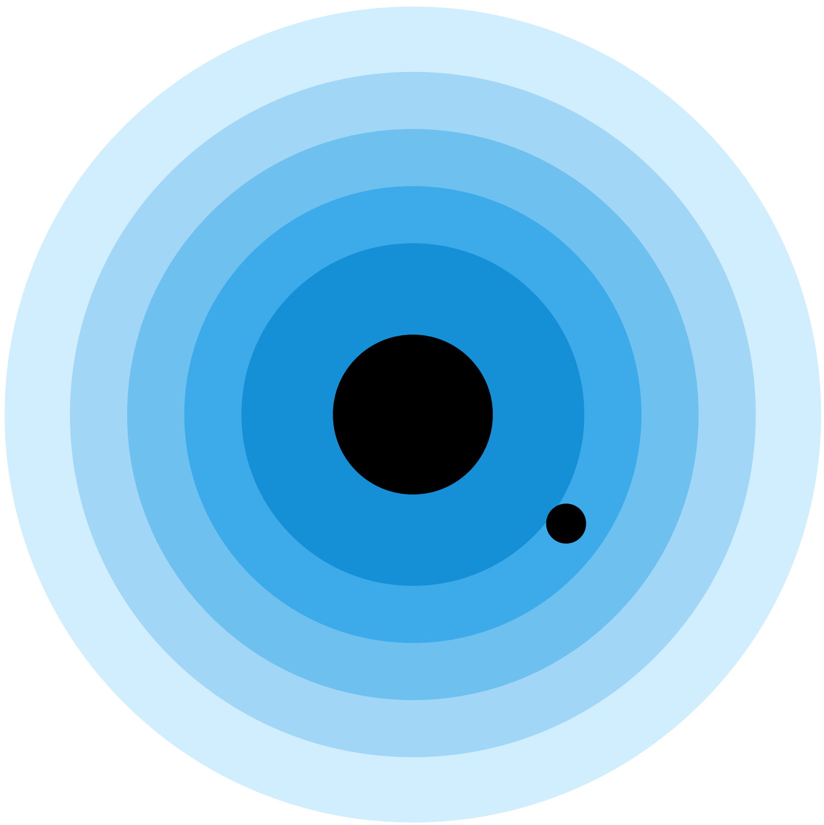
[Cole, Bertone, Coogan, Gaggero, Karydas, **BJK**, Spieksma, Tomaselli, 2211.01362, Nature Astronomy]

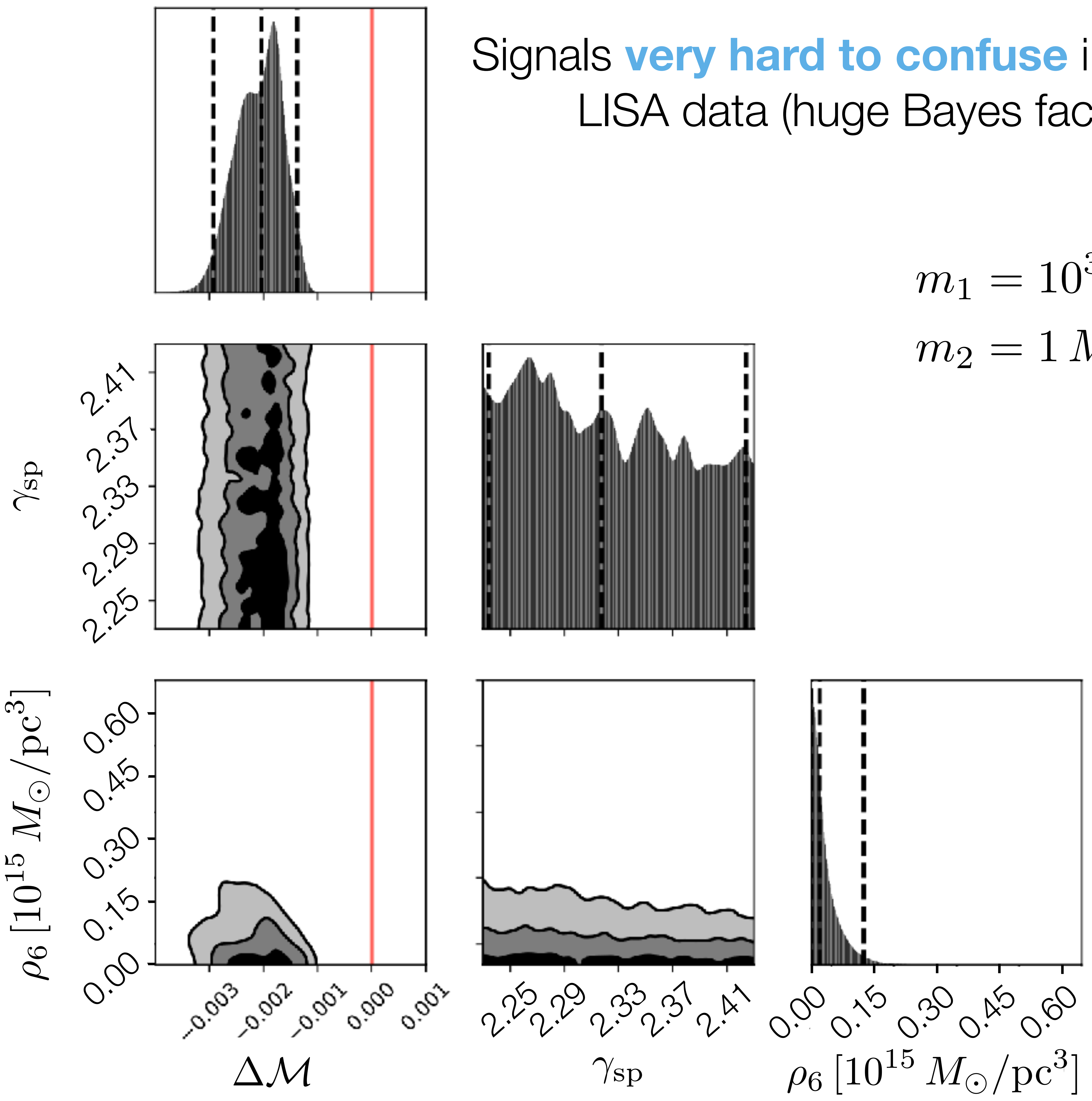
Generate waveform assuming:



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

Fit signal assuming:





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

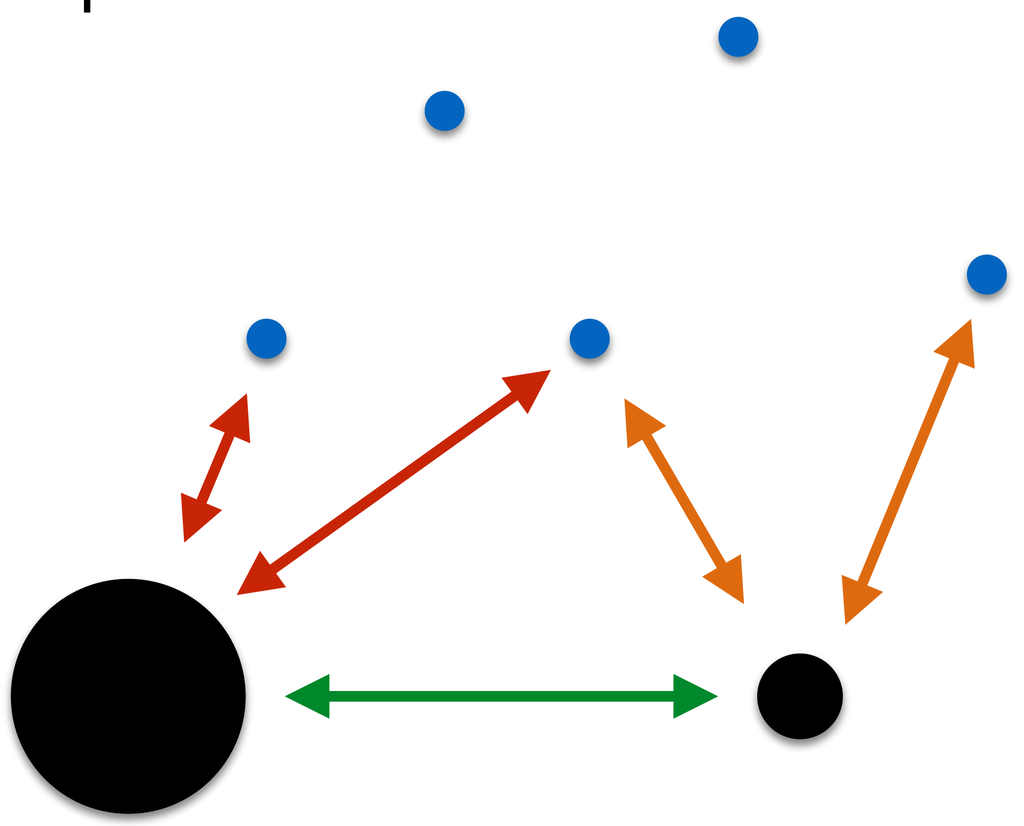
$$m_1 = 10^3\, M_\odot$$

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

N-body Simulations

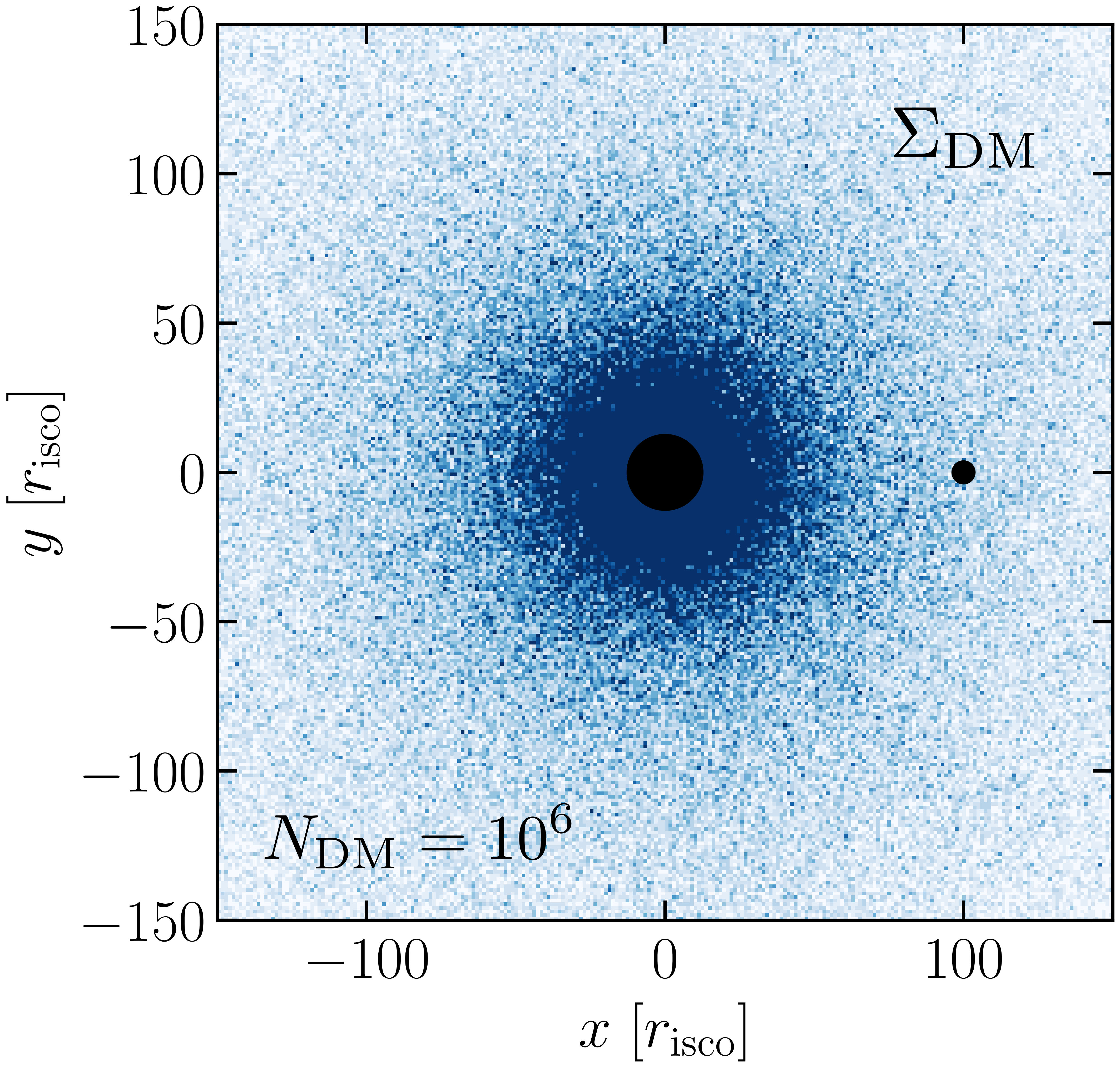
Eventually need to expand and verify our description of dynamical friction and feedback in the DM spike

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.



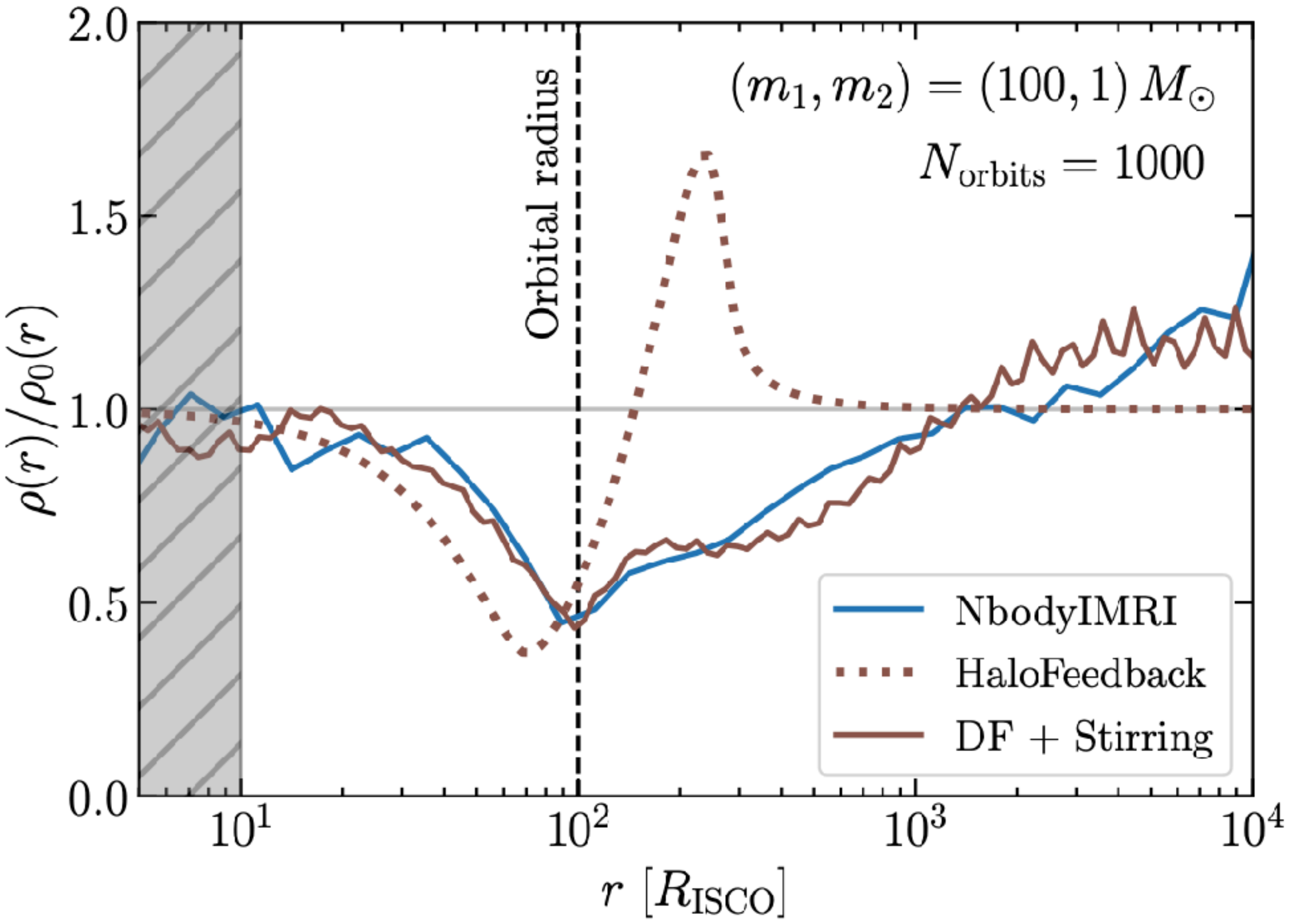
[**BJK** et al., 2402.13762]

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

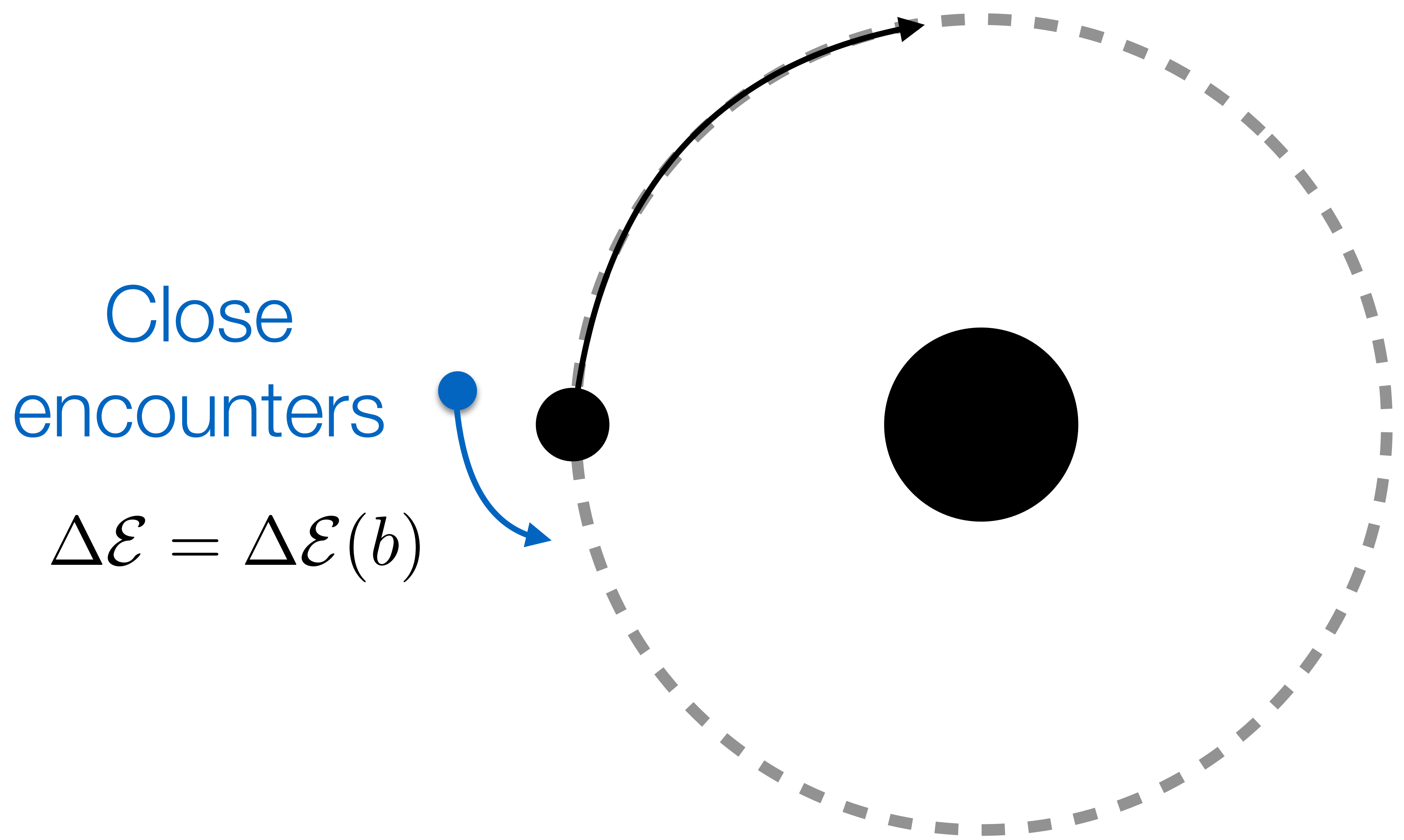
[See also Mukherjee et al., 2312.02275]

N-body Simulations

N-body simulations revealed an additional feedback effect…



But N-body simulations are VERY slow!



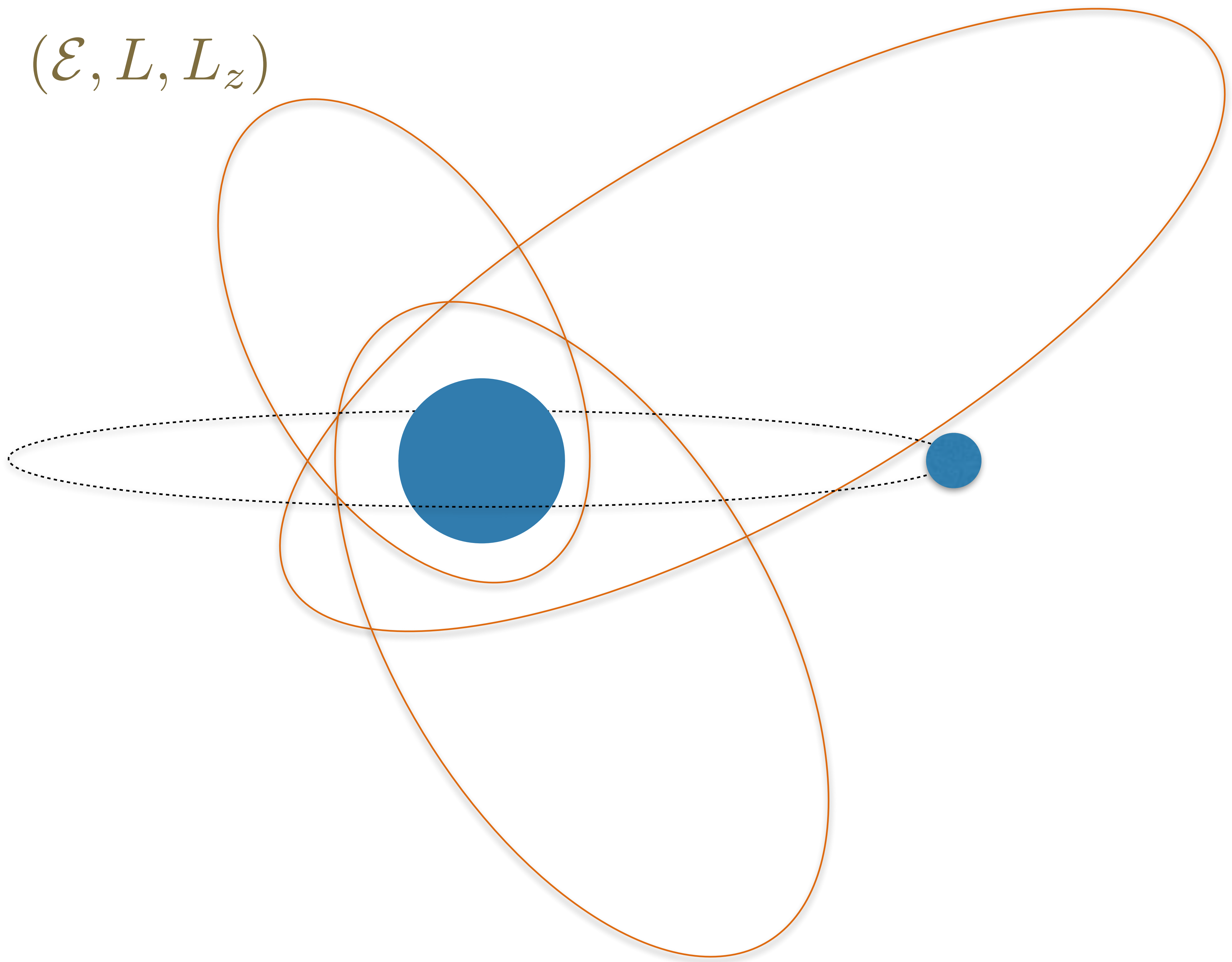
- 3-body 'stirring'

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

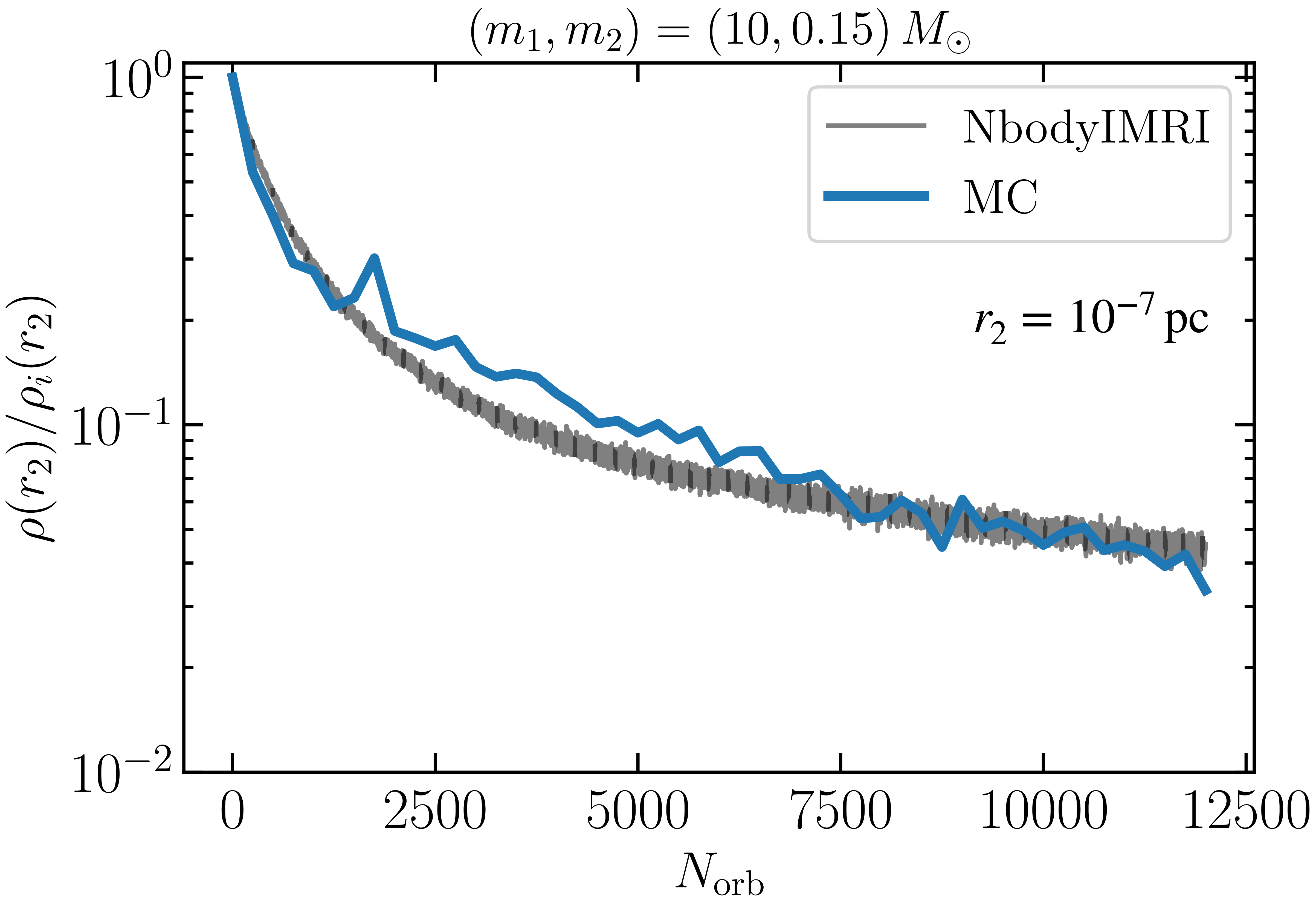
Monte Carlo Simulations

[Scarcella & BJK, 2510.11635, and in prep.]

Phase-space Monte Carlo simulations, in which we track integrals of motion of DM particles $(\mathscr{E}, L, L_z)$.



At each orbit of the binary, we apply a kick $(\Delta\mathscr{E}, \Delta L, \Delta L_z)$ due to close encounters ('dynamical friction') and due to 3-body effects ('stirring').

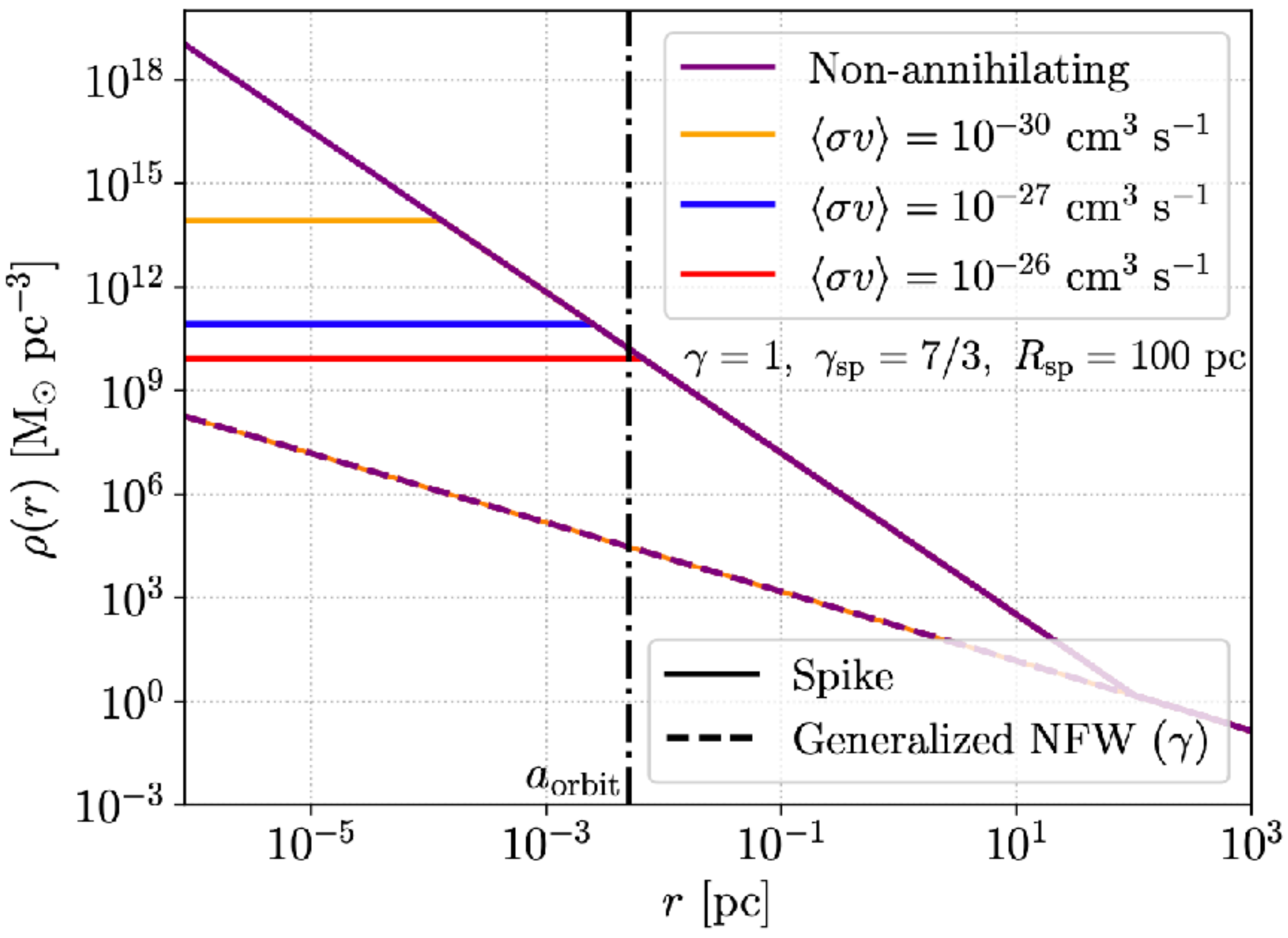


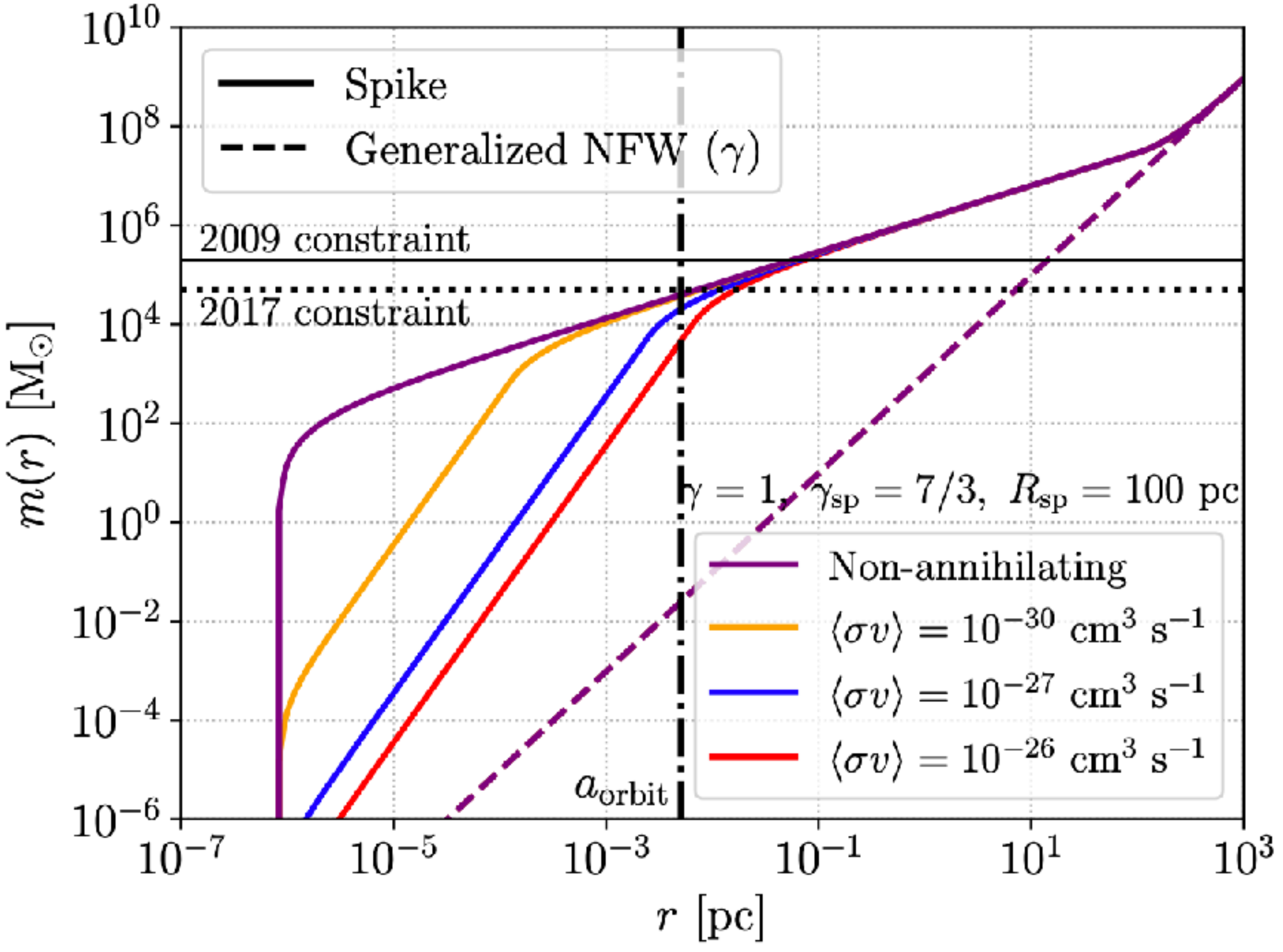
Can now self-consistent track the DM spike evolution!

*Can also be adapted to study feedback from Dark Drag!

The Death of Dark Matter Spikes?

Density around Sgr A*



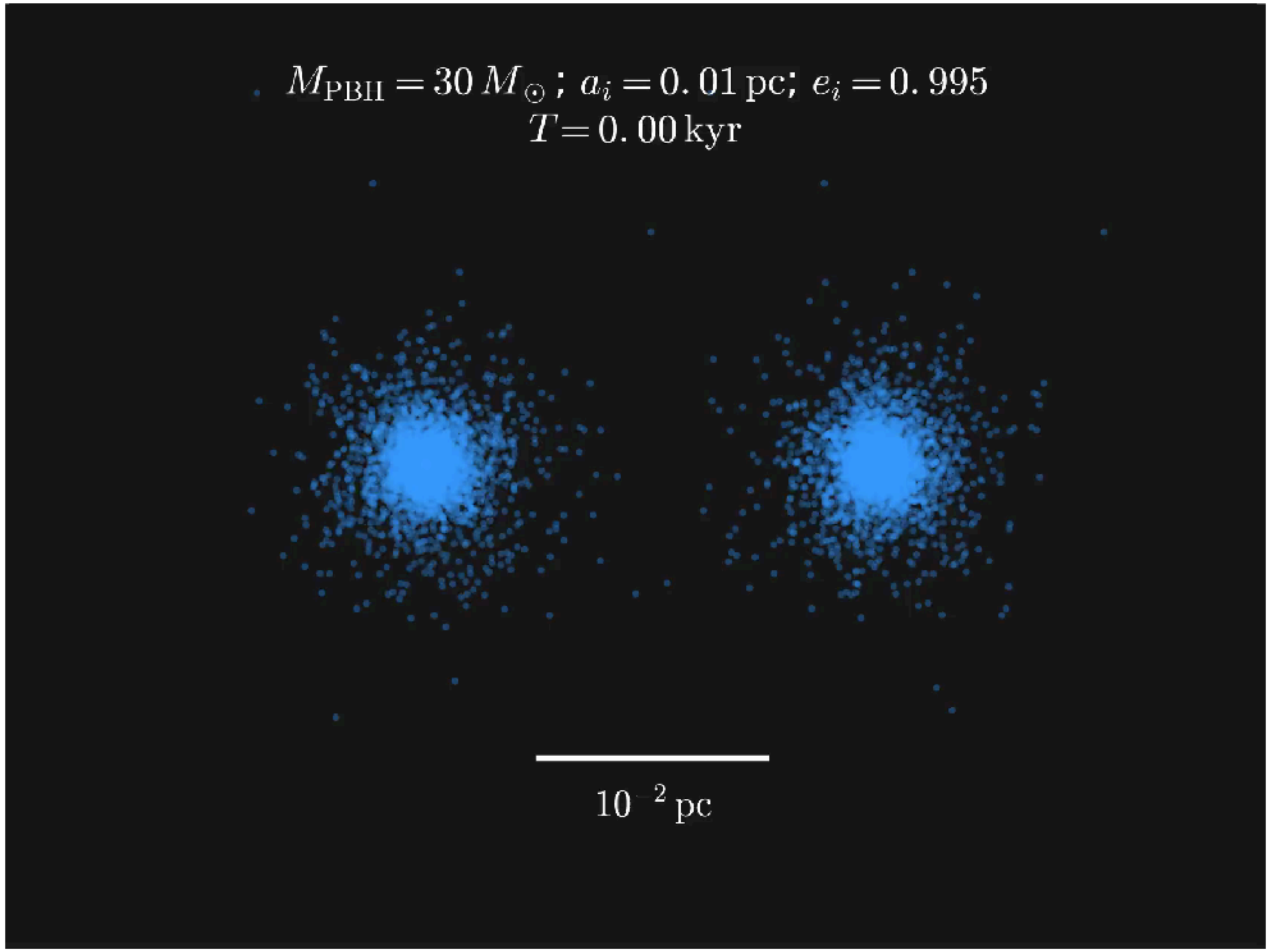


[Lacroix, 1801.01308]

Major Mergers?

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

Roughly equal mass mergers *could* completely disrupt the DM spikes…

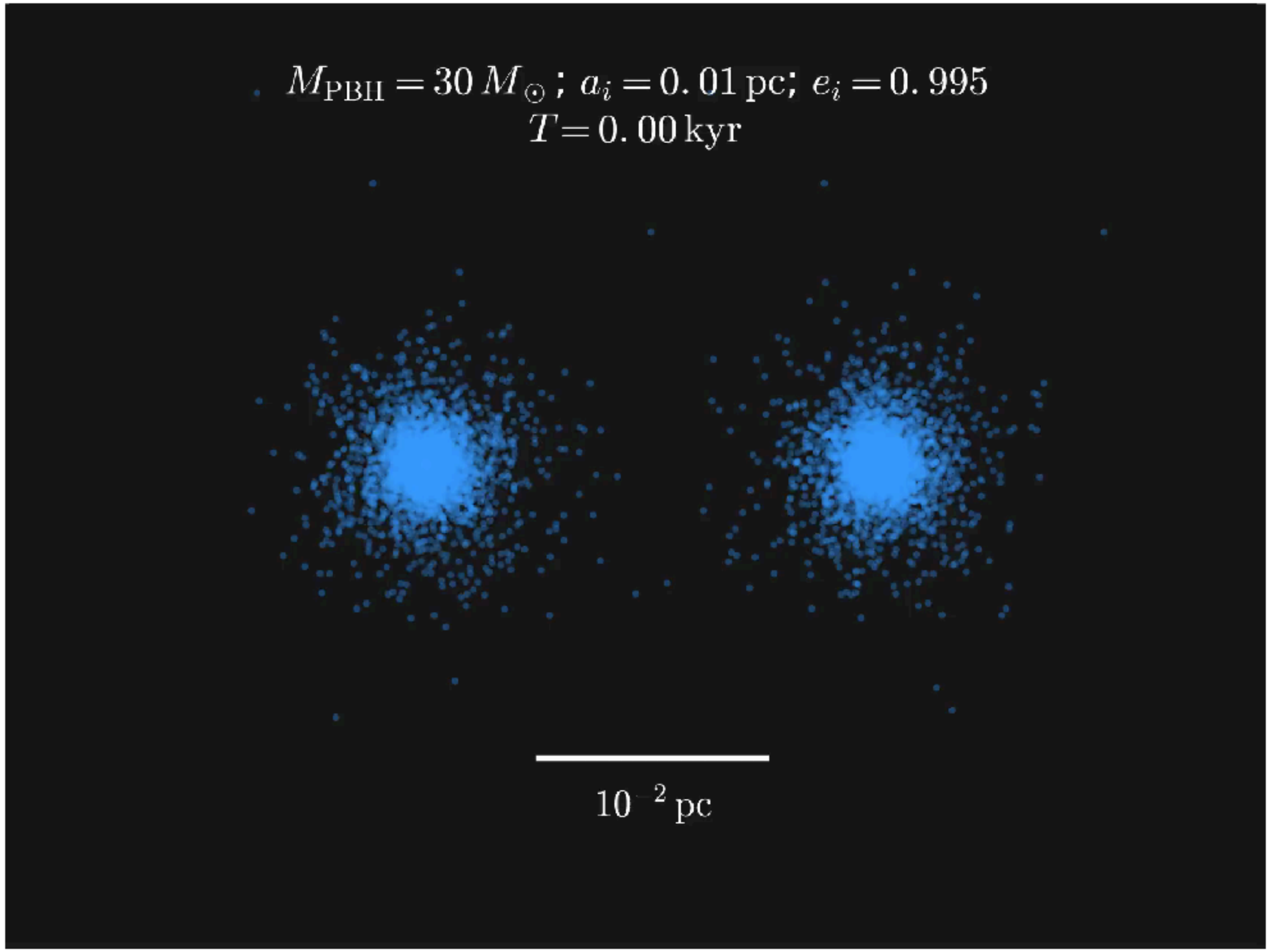


But major (galaxy) mergers could replenish gas, leading to spike re-growth…

Major Mergers?

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

Roughly equal mass mergers *could* completely disrupt the DM spikes…



But major (galaxy) mergers could replenish gas, leading to spike re-growth…

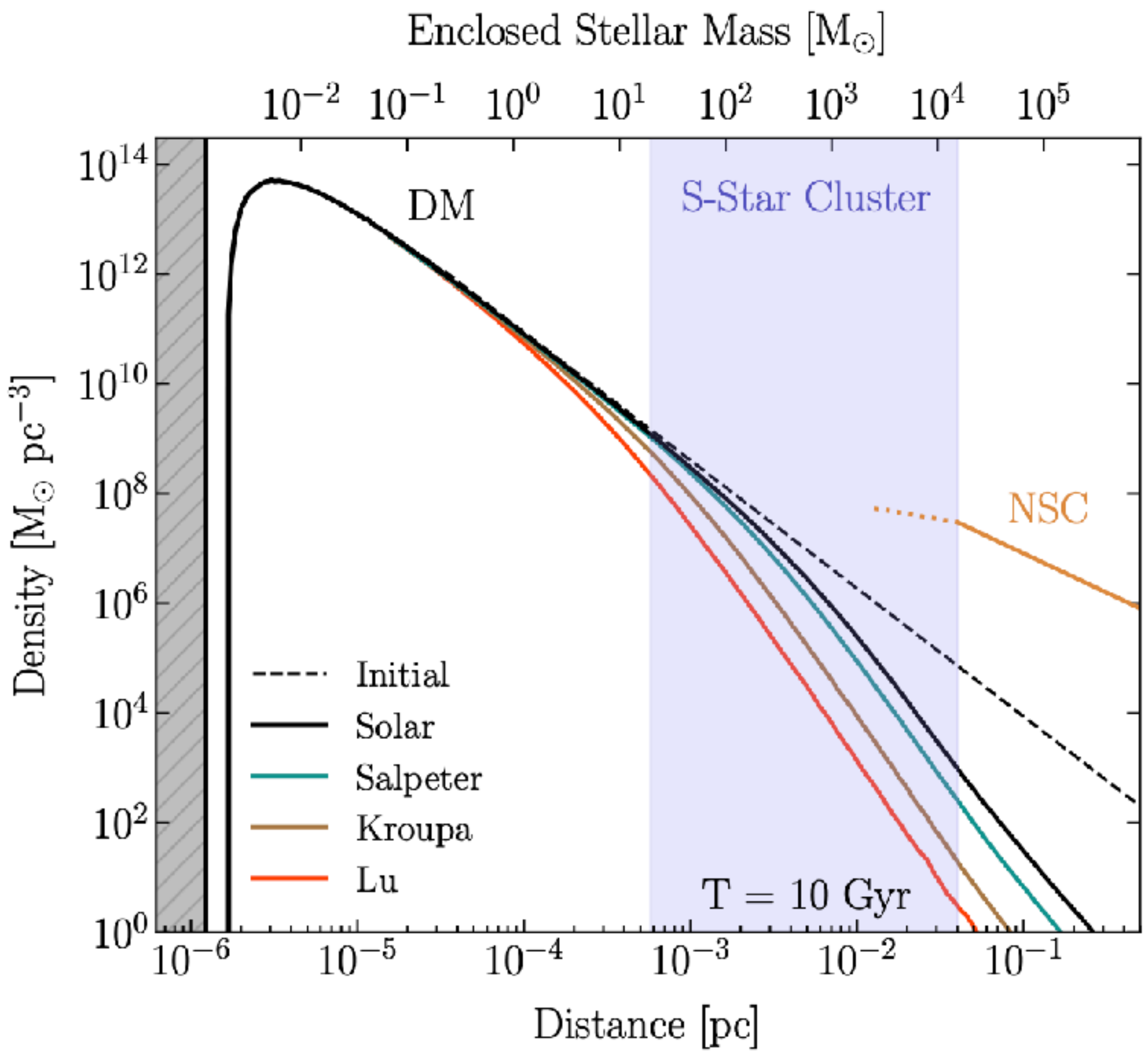
Stellar Depletion

[See also Sharpe et al., 2603.28866, Herrera et al., 2605.01023]

The motion of stars is well-known to dynamically ‘heat’ the DM distribution.

But, formalism cannot be trivially extended to $r \to 0$, as number of enclosed stars drops below $\mathcal{O}(1)$!

Smoothly cut off stellar density at low r, and allow DM to diffuse in both $(\mathcal{E}, L)$ - inner density is preserved!



Further in, the depletion due to individual stars can be treated using HaloFeedback. Find minimal depletion:

$$\frac{\Delta\rho}{\rho_0} \approx 2.2 \times 10^{-5} \left(\frac{t}{\mathrm{Myr}}\right)$$

[Karydas et al. (including **BJK**), 2606.13761]

Past EMRIs

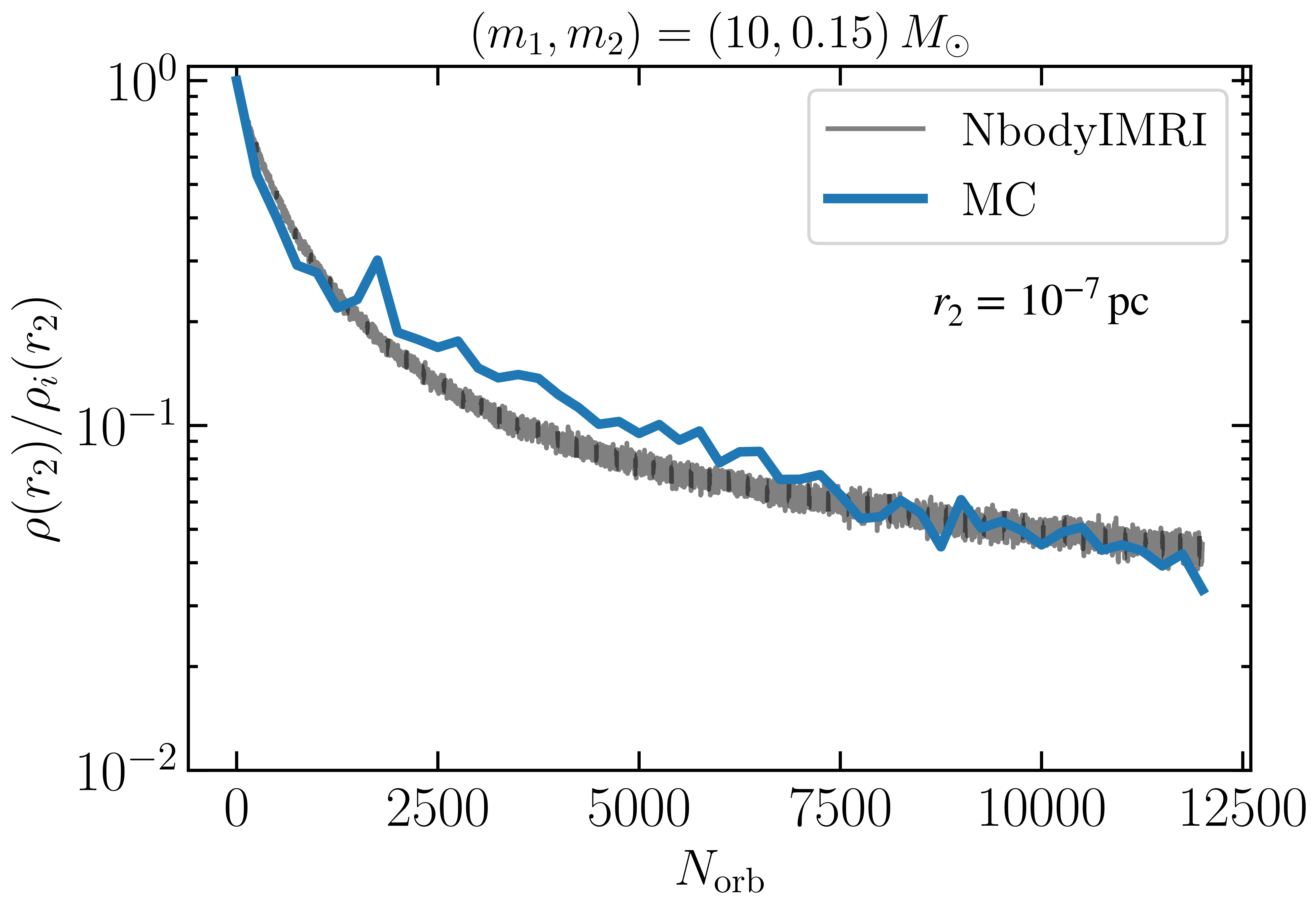
Inner spike may be disrupted by ‘past’ EMRIs. 100s-1000s of mergers of stellar mass BHs with the SMBH. Previous works claim that the density is depleted exponentially, basically to nothing… [Sharpe et al., 2603.28866]

We find only a mild suppression of the spike!

Close encounters with the orbiting object may completely eject DM particles (which would lead to exponential depletion)

But non-ejecting encounters tend to redistribute DM orbits, making them harder to deplete, and ‘refilling’ the depletion earlier in the inspiral.

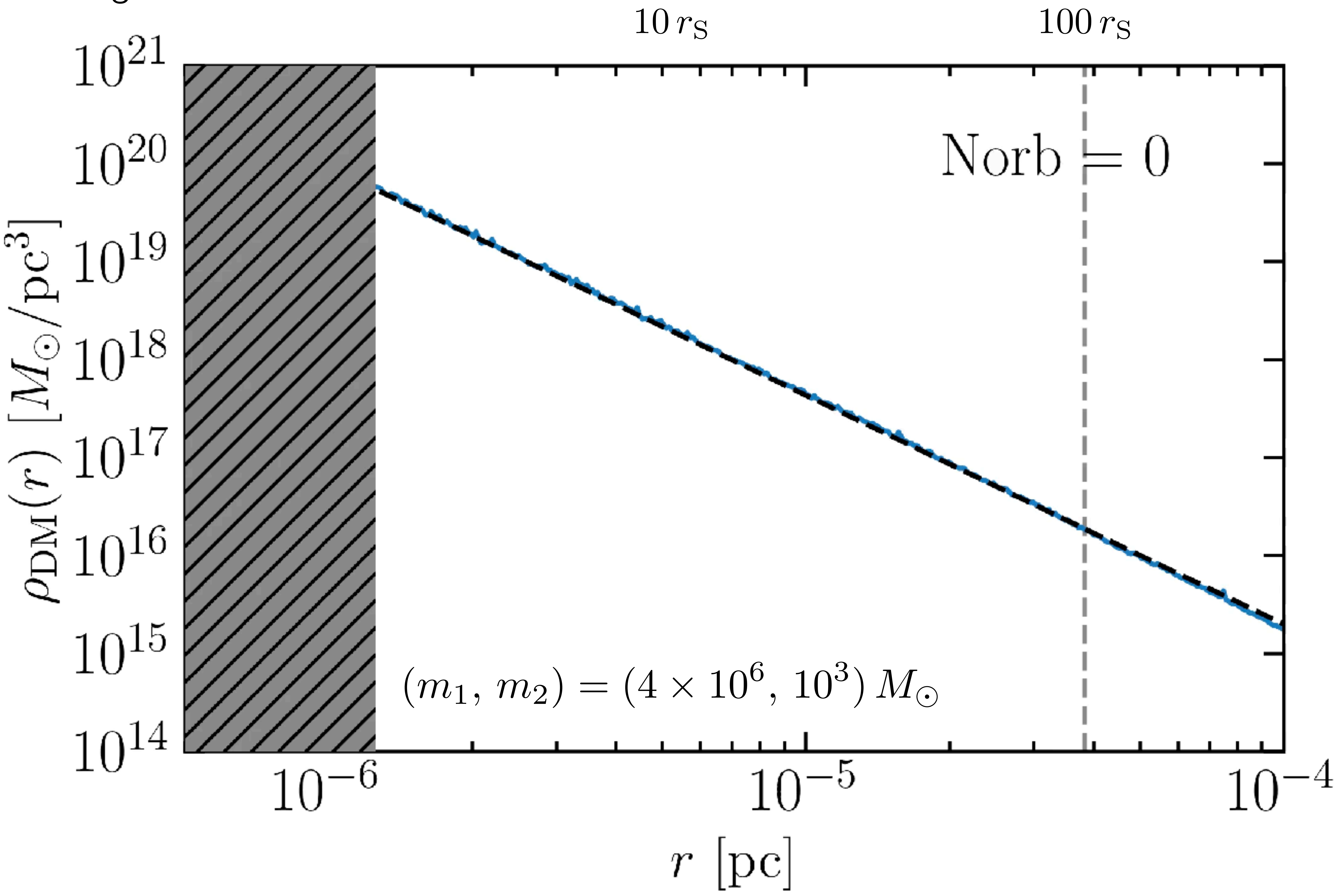
This ‘slower-than-exponential’ depletion is observed in HaloFeedback, in N-body simulations *and* in Monte Carlo simulations!



New and Improved Feedback™

"Strength" of feedback scales roughly as $q^2 = (m_2/m_1)^2$

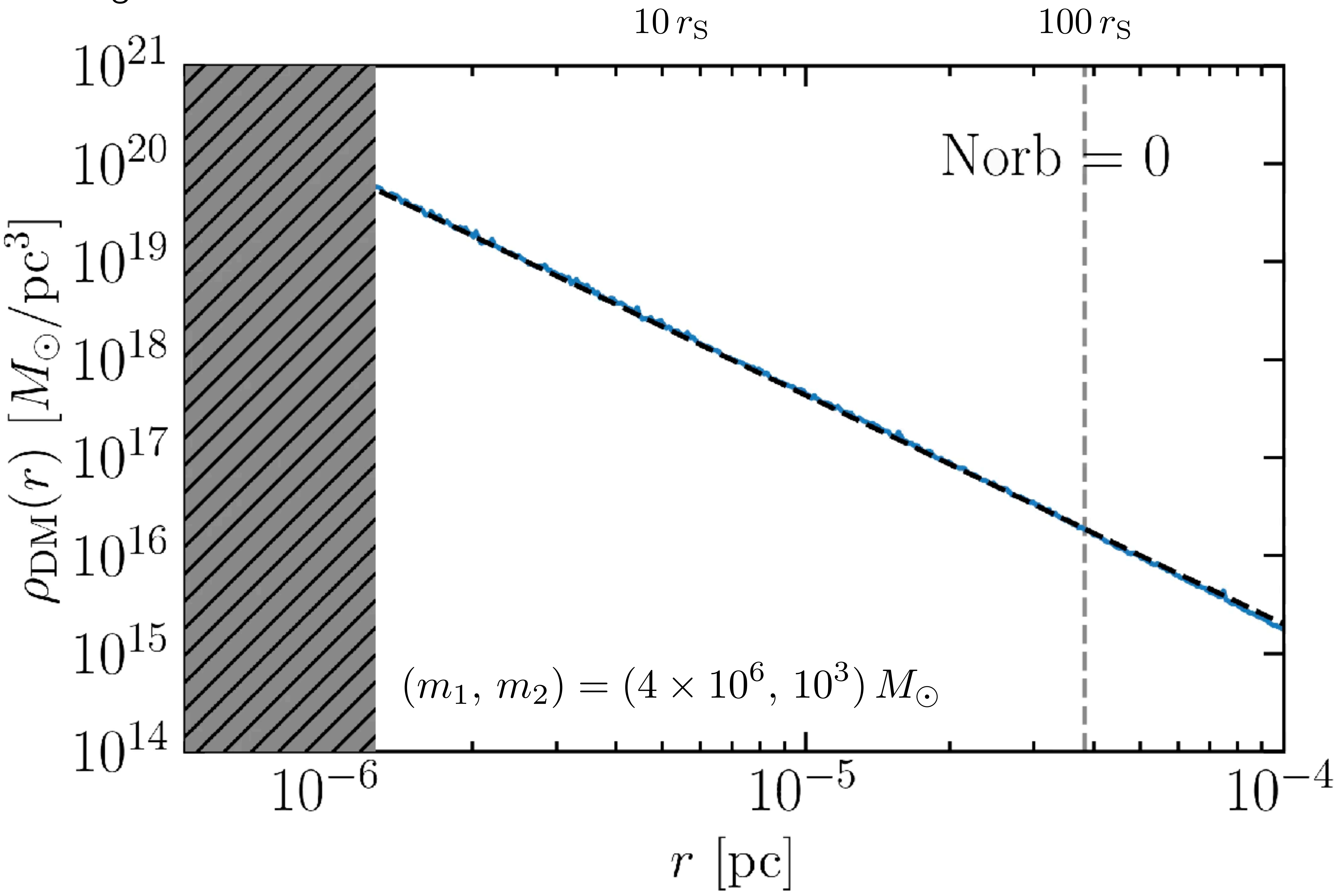
Study feedback using newer MC simulations:



New and Improved Feedback™

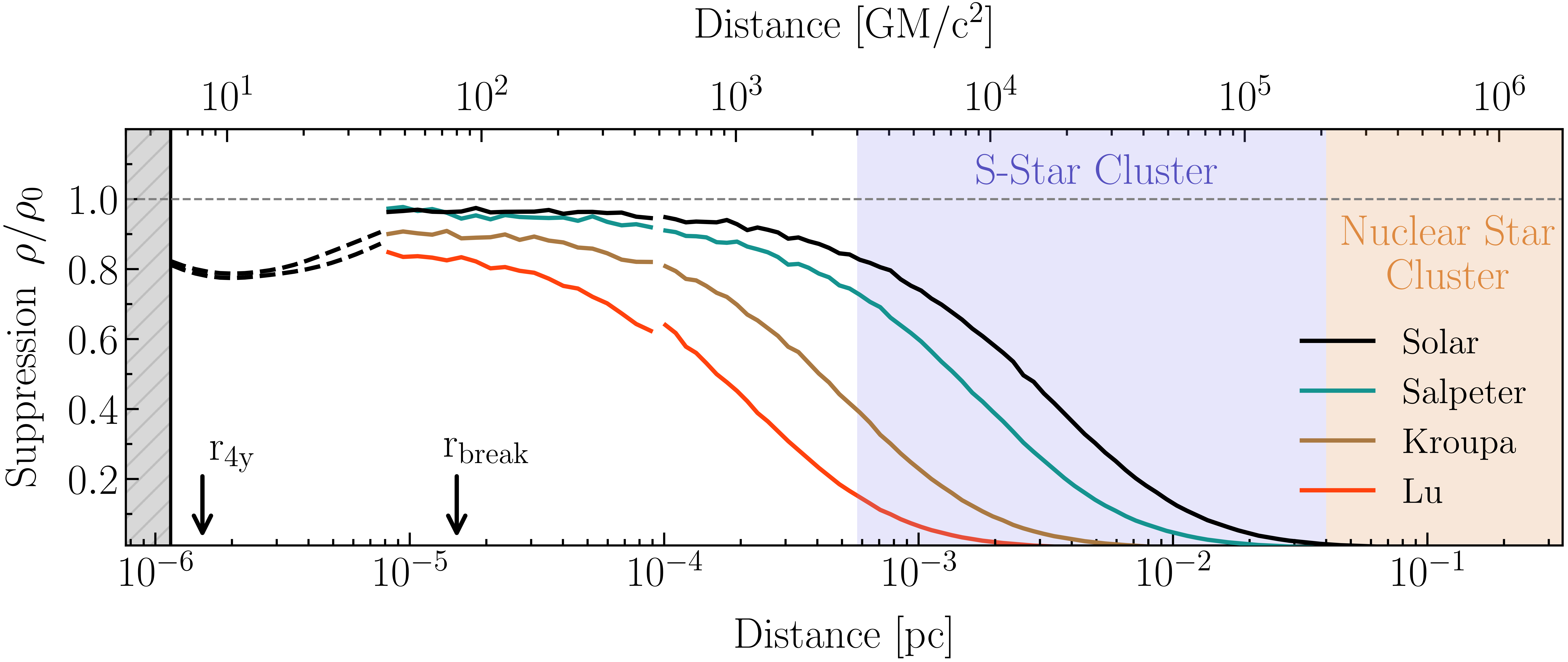
"Strength" of feedback scales roughly as $q^2 = (m_2/m_1)^2$

Study feedback using newer MC simulations:



Dark Matter in the Galactic Center

[Karydas et al. (including **BJK**), 2606.13761]



Similar calculations could be applied to extra-galactic SMBHs.

Open Questions/Caveats

Birth - there exists a feasible mechanism to produce DM spikes

- Are spikes guaranteed to form? What fraction of SMBHs host spikes?
- What is the population of DM spikes in the Universe? A *statistical approach*
- How much does growth/regrowth affect the DM spike profile?

Life - DM spikes produce detectable effects in GWs, boosted DM, etc

- How can we search for these effects?
- How much does feedback play a role?
- Can particle-like interactions with DM deplete the spike?

Death - mergers and dynamical effects may (partially) disrupt the spike

- How do major mergers deplete the spike? How common are they? *A statistical approach*
- How do accretion disks and jets affect the stability of the spike?
- Can we develop more detailed feedback formalisms, to understand stellar feedback, EMRIs, etc.

A collective effort

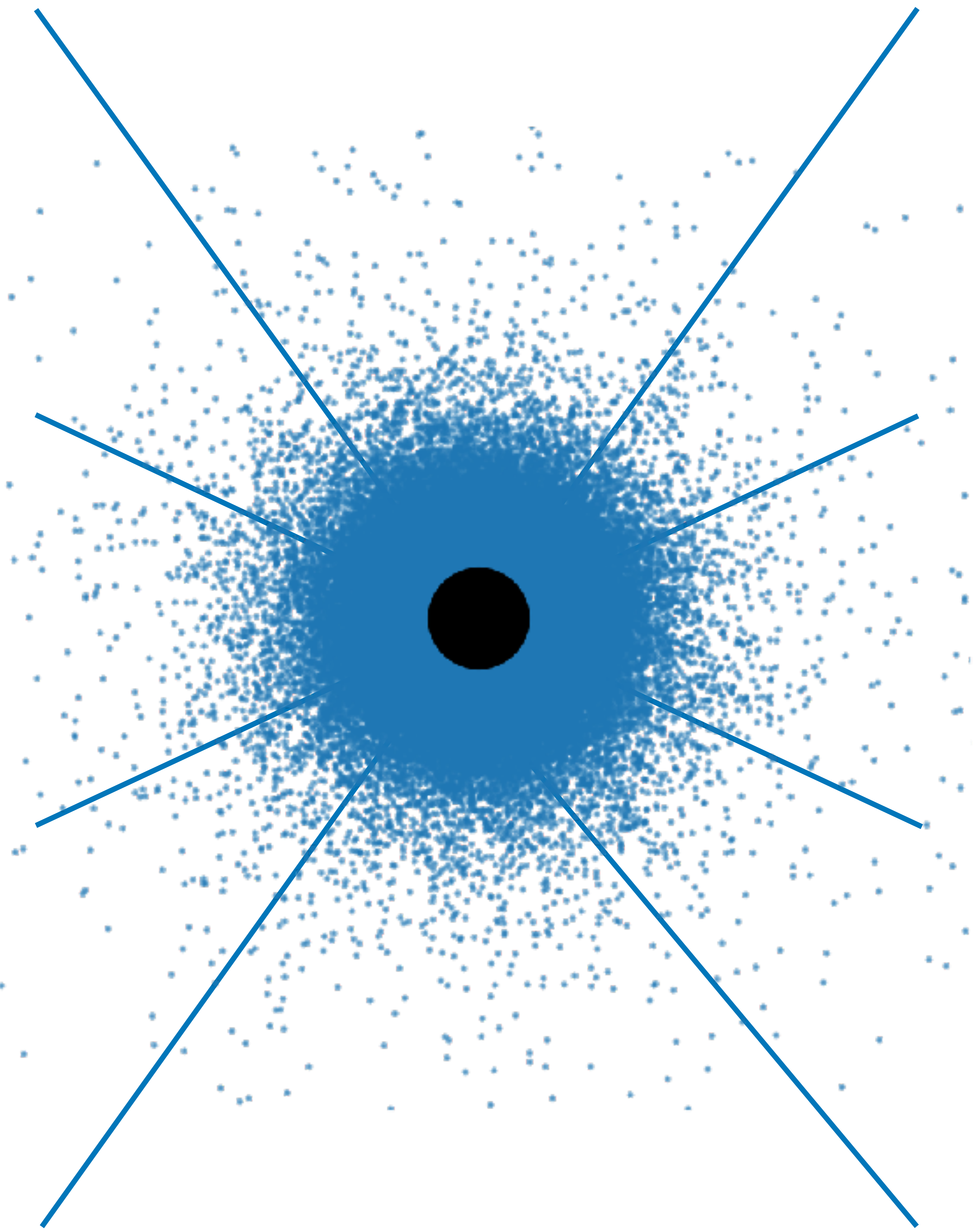
Gianfranco Bertone
(GRAPPA, Amsterdam)

Pippa Cole
(Queen Mary, London)

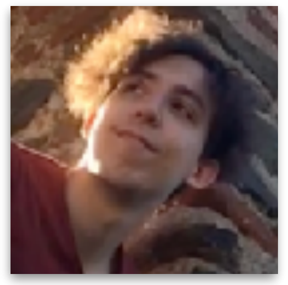
Pierfrancesco di Cintio
(Florence)

Pratika Dayal
(Groningen University)

Daniele Gaggero
(INFN, Pisa)



Francesca Scarcella
(IFCA, Santander)



Theophanes Karydas
(GRAPPA, Amsterdam)

Roberto Caiozzo
(SISSA, Trieste)

Abram Perez Herrero
(IFCA, Santander)

Pratibha Jangra
(IFCA, Santander)

…and others.

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

A collective effort

Thank you!

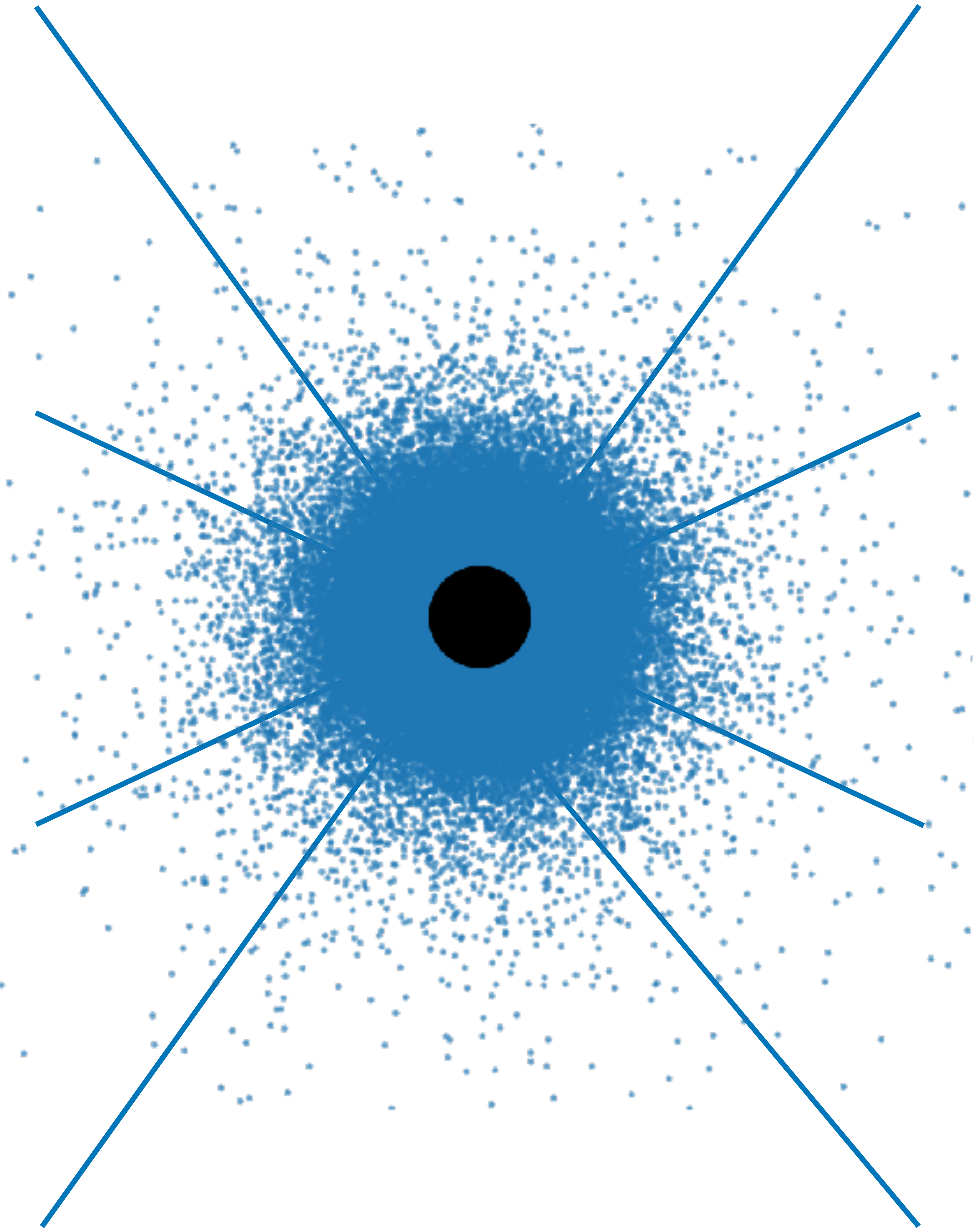
Gianfranco Bertone
(GRAPPA, Amsterdam)

Pippa Cole
(Queen Mary, London)

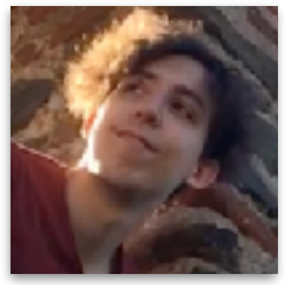
Pierfrancesco di Cintio
(Florence)

Pratika Dayal
(Groningen University)

Daniele Gaggero
(INFN, Pisa)



Francesca Scarcella
(IFCA, Santander)



Theophanes Karydas
(GRAPPA, Amsterdam)

Roberto Caiozzo
(SISSA, Trieste)

Abram Perez Herrero
(IFCA, Santander)

Pratibha Jangra
(IFCA, Santander)

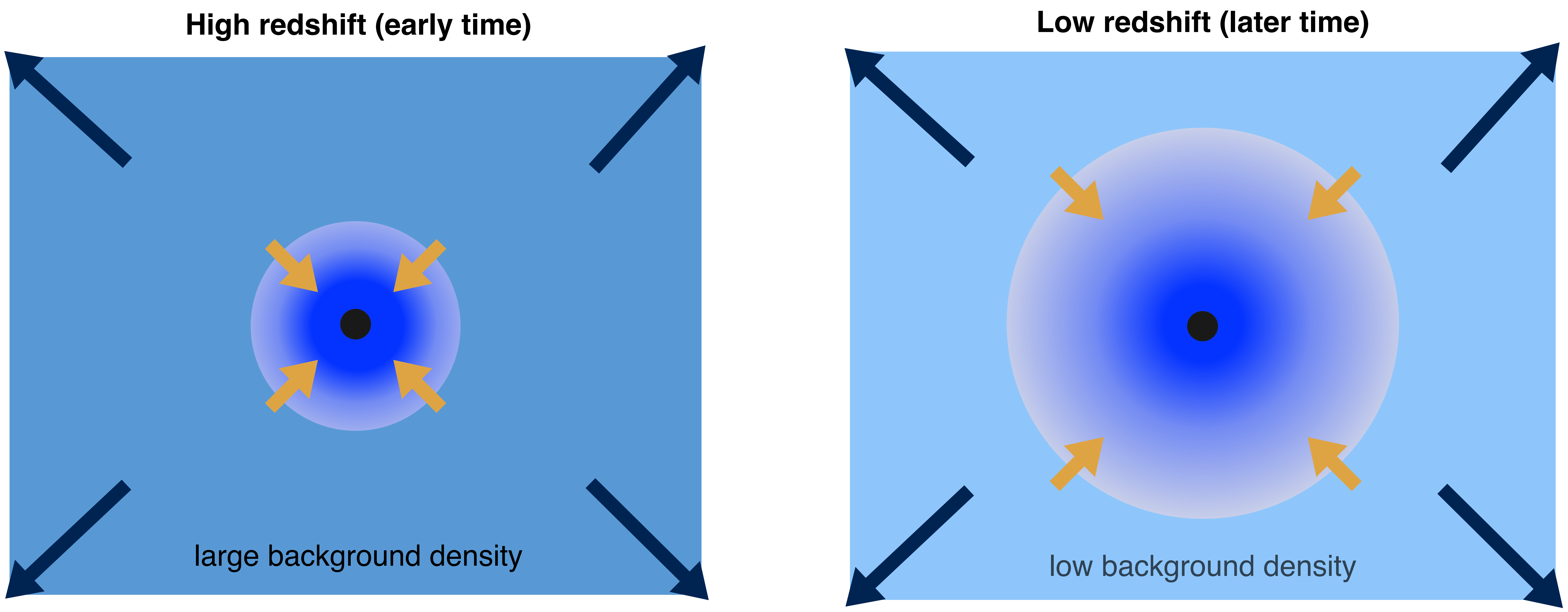
…and others.

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

Backup Slides

PBH Spikes

Primordial Black Holes (PBHs) seed the formation of DM spikes:

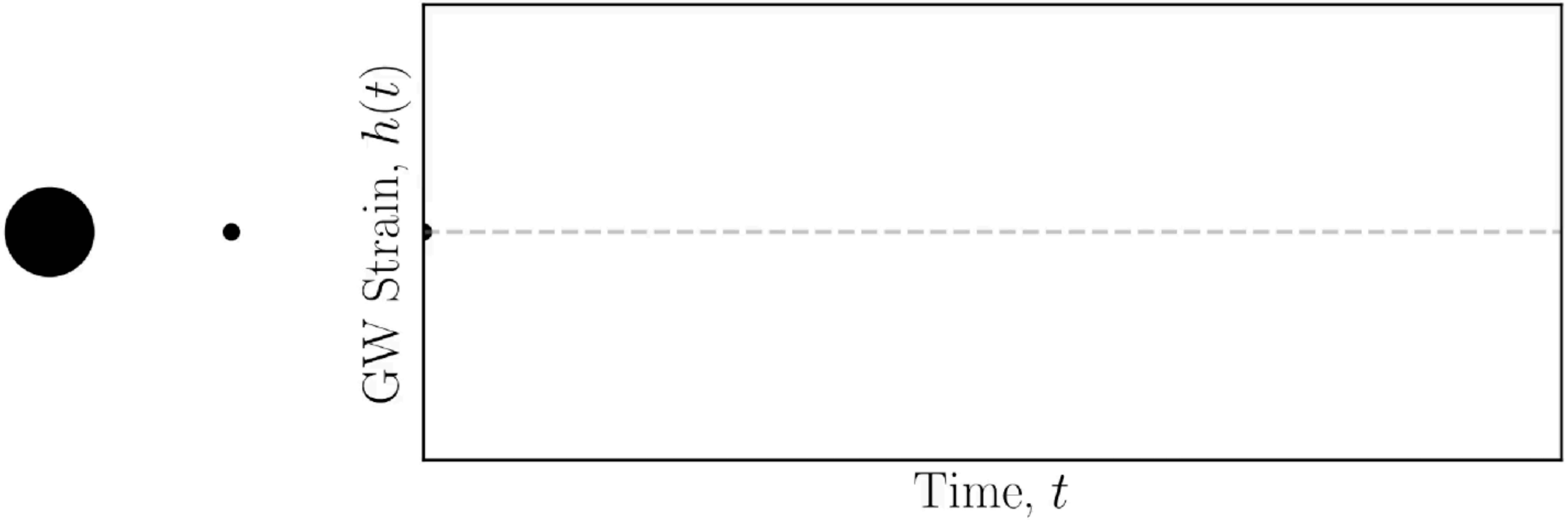


$$r_{\rm sp}(z) = 0.0063 \left(\frac{M_{\rm PBH}}{M_\odot}\right)\left(\frac{1+z_{\rm eq}}{1+z}\right) \,\mathrm{pc} \qquad \rho(r) \propto r^{-9/4}$$

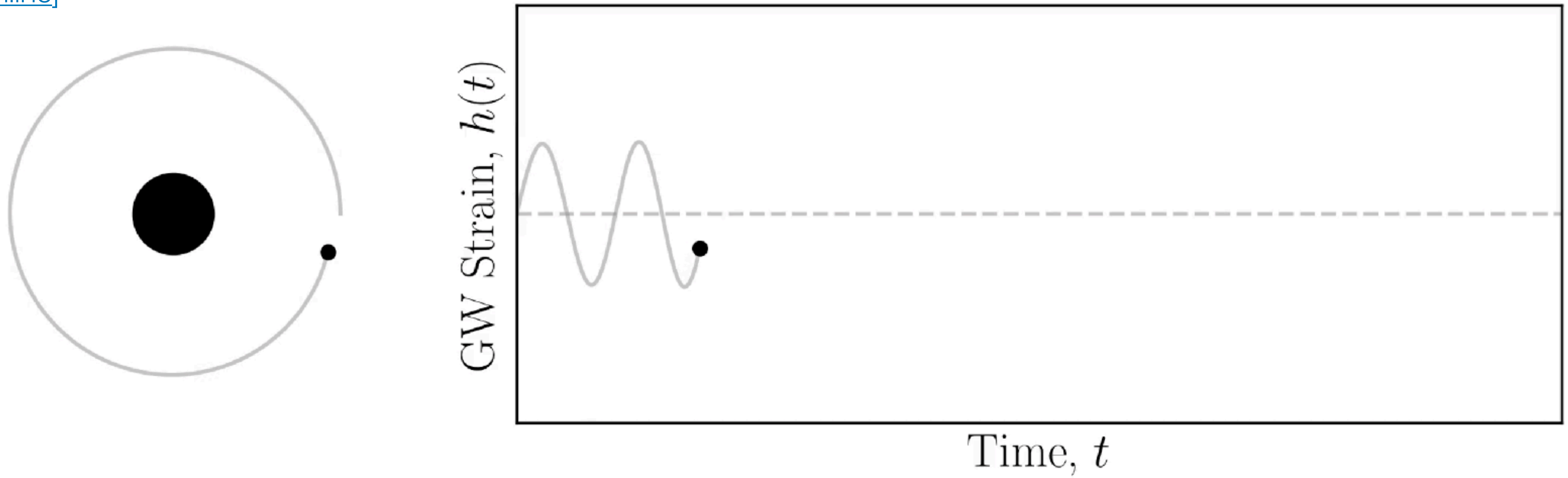
By matter-radiation equality, $M_{\rm spike} \sim M_{\rm PBH}$

[Bertschinger (1985)]
[0706.0864, 1901.08528]

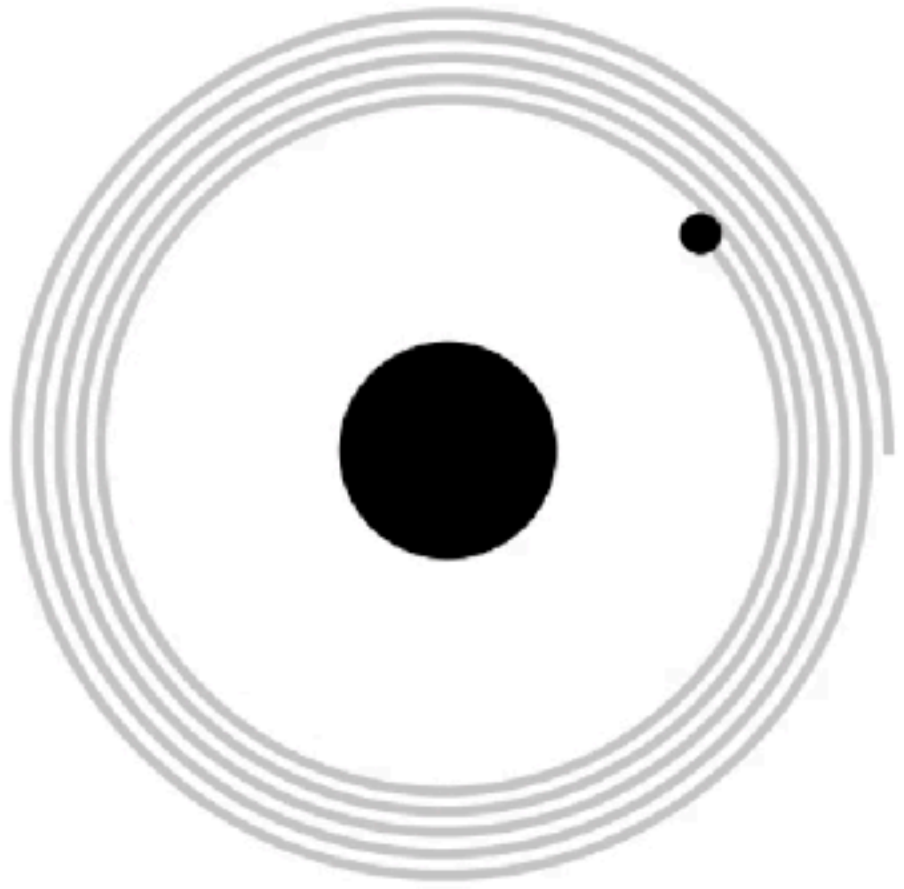
[Animations online]

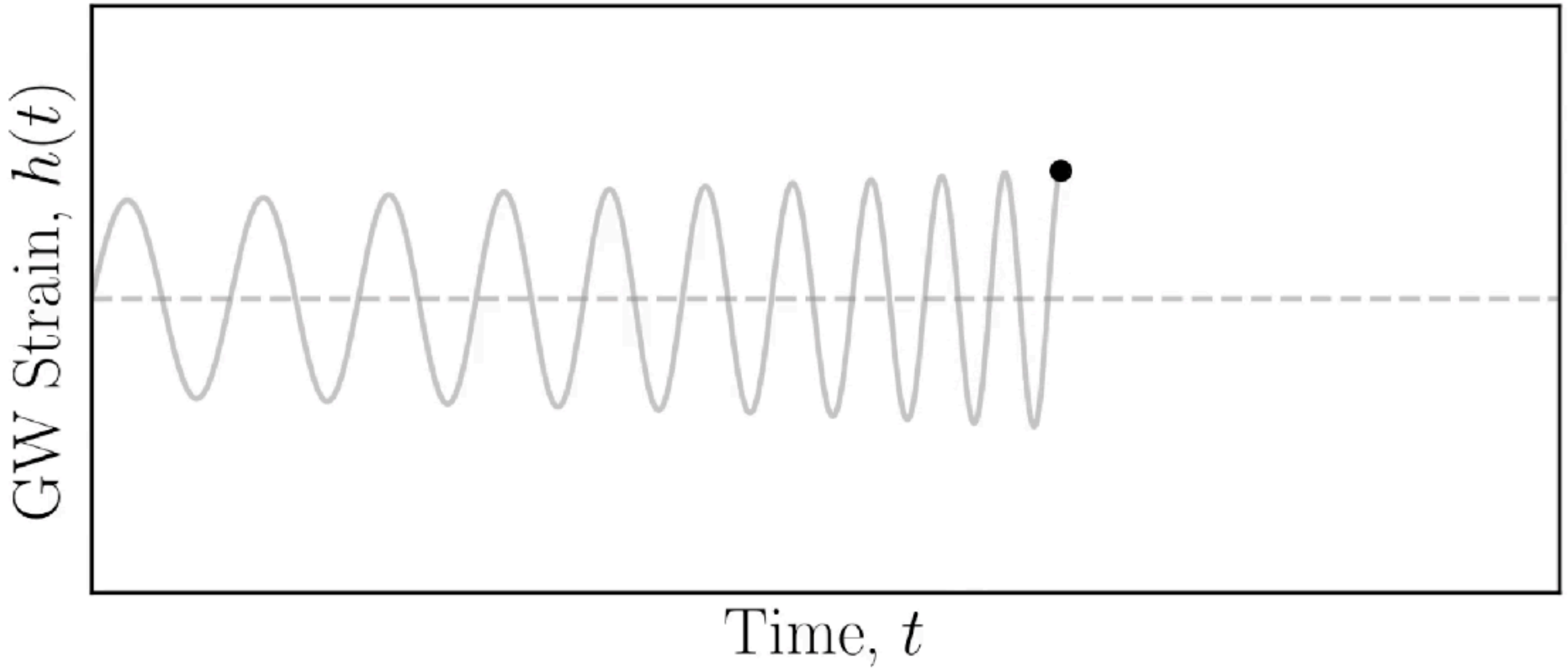


[Animations online]

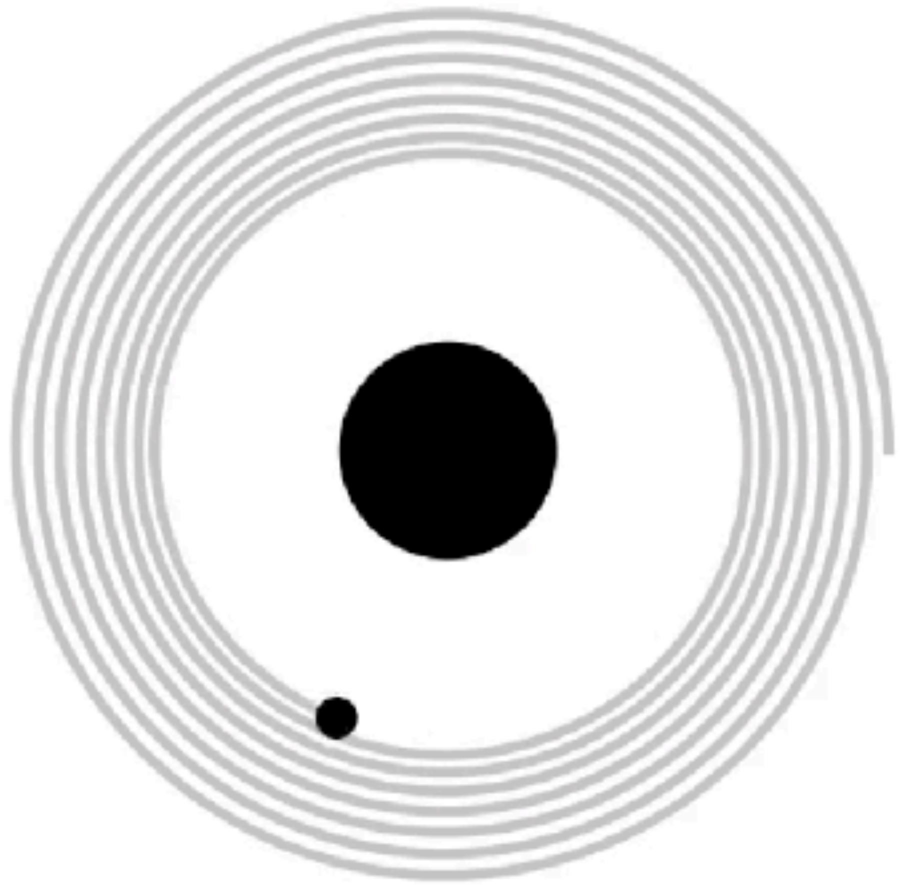


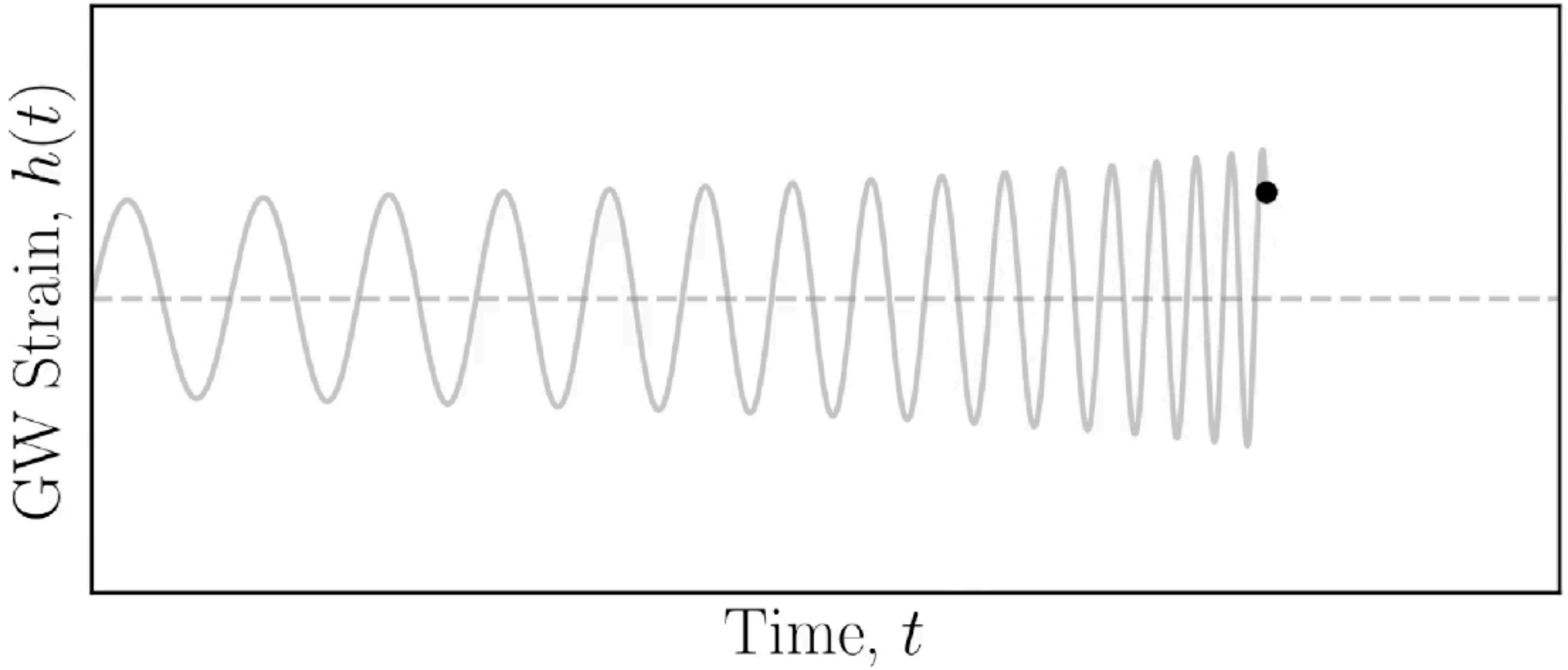
[Animations online]



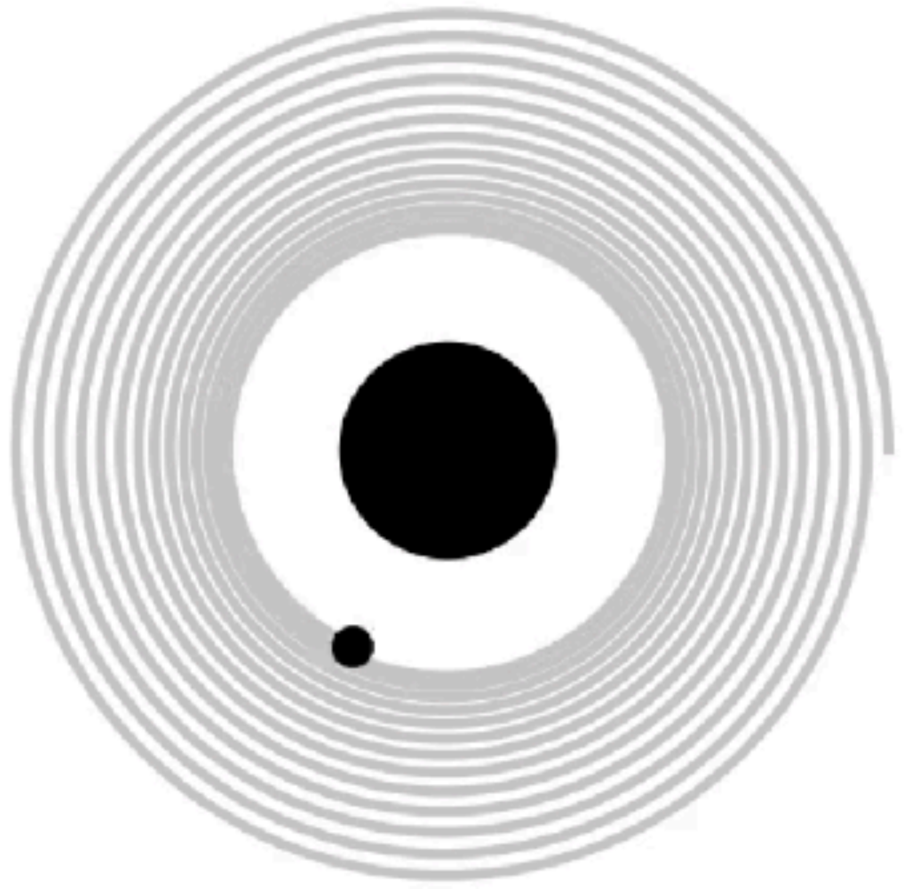


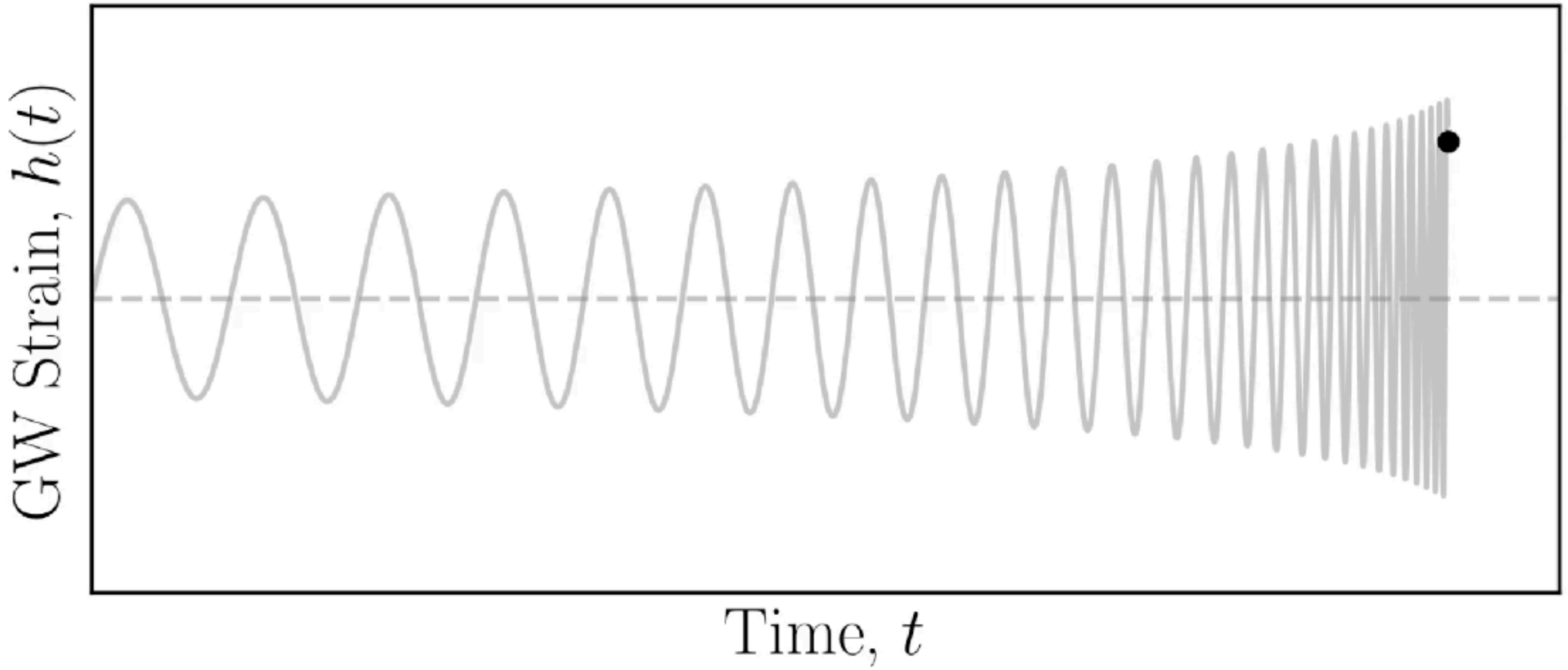
[Animations online]



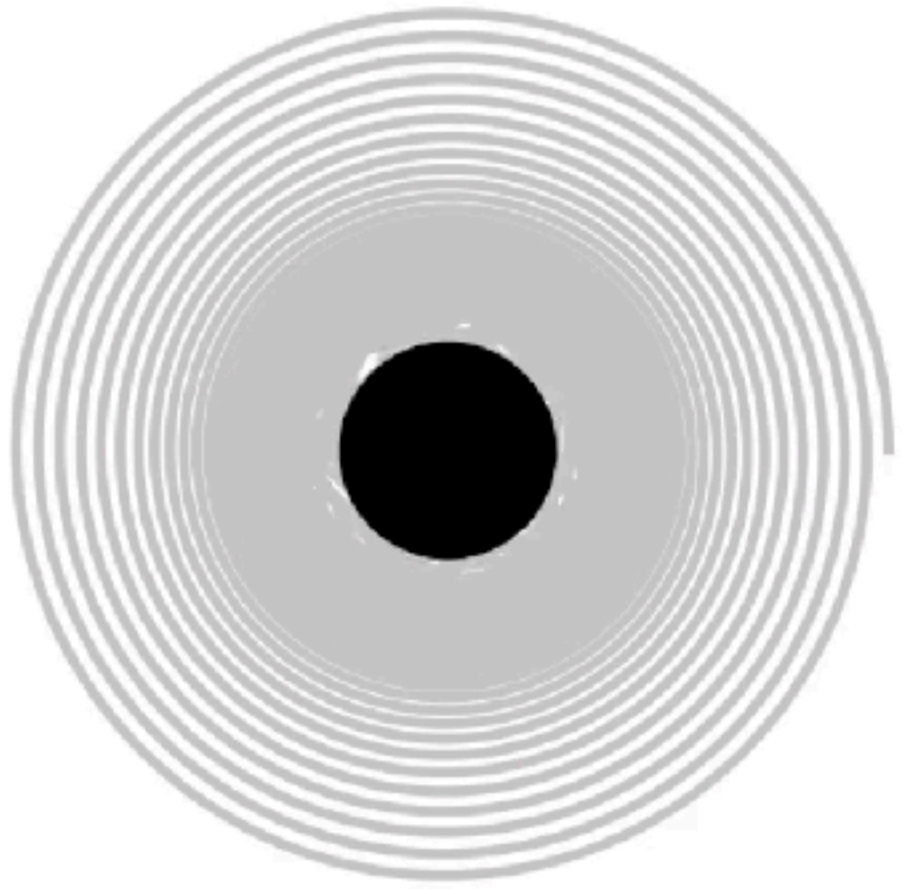


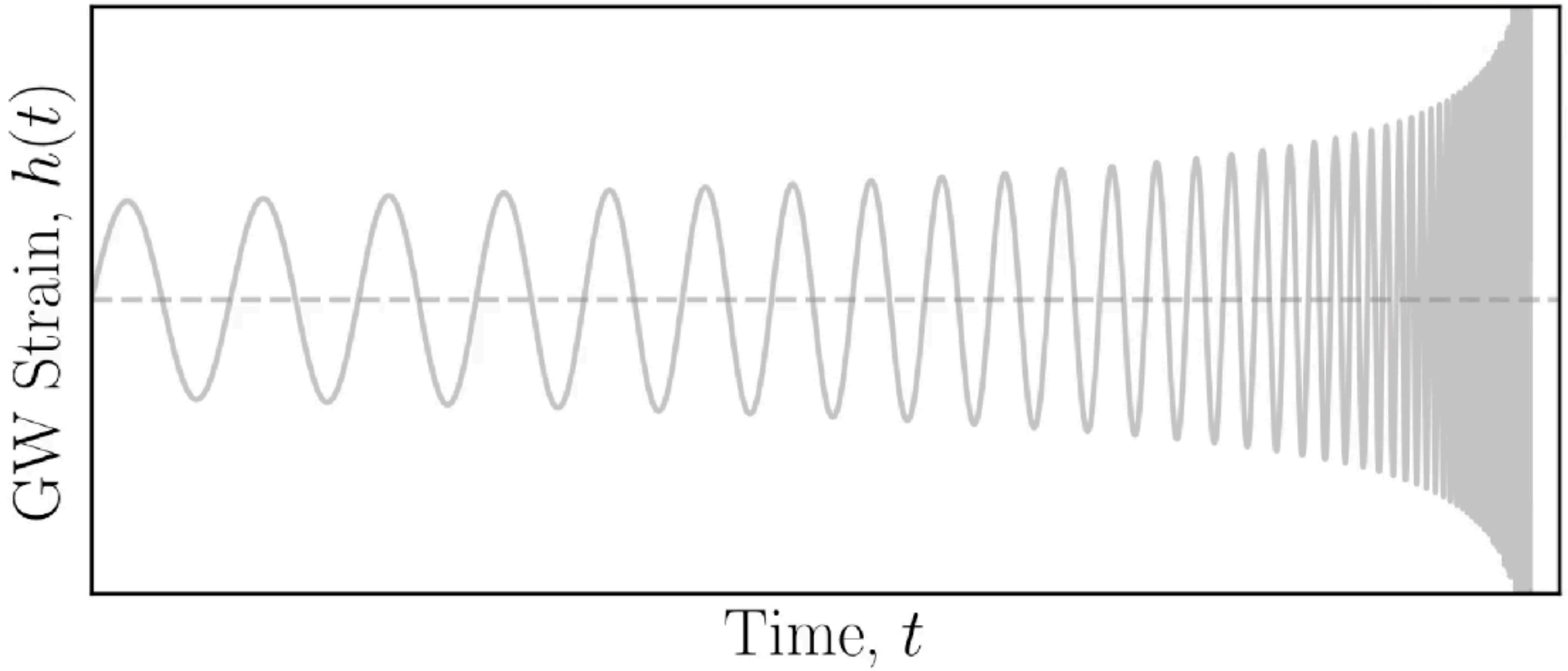
[Animations online]



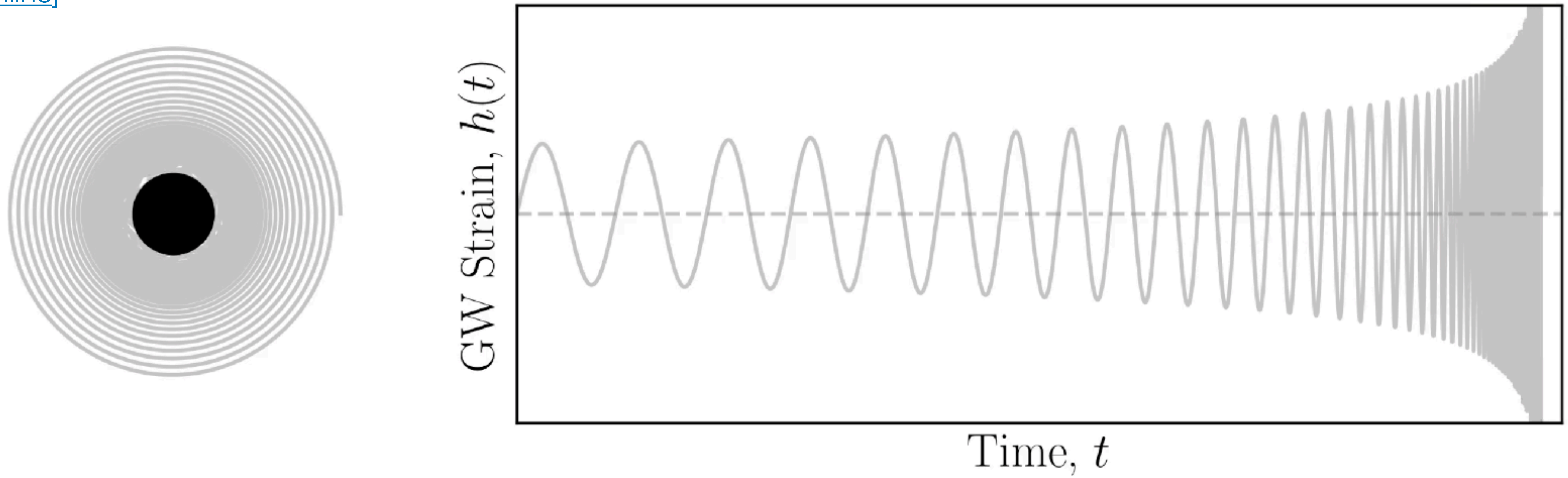


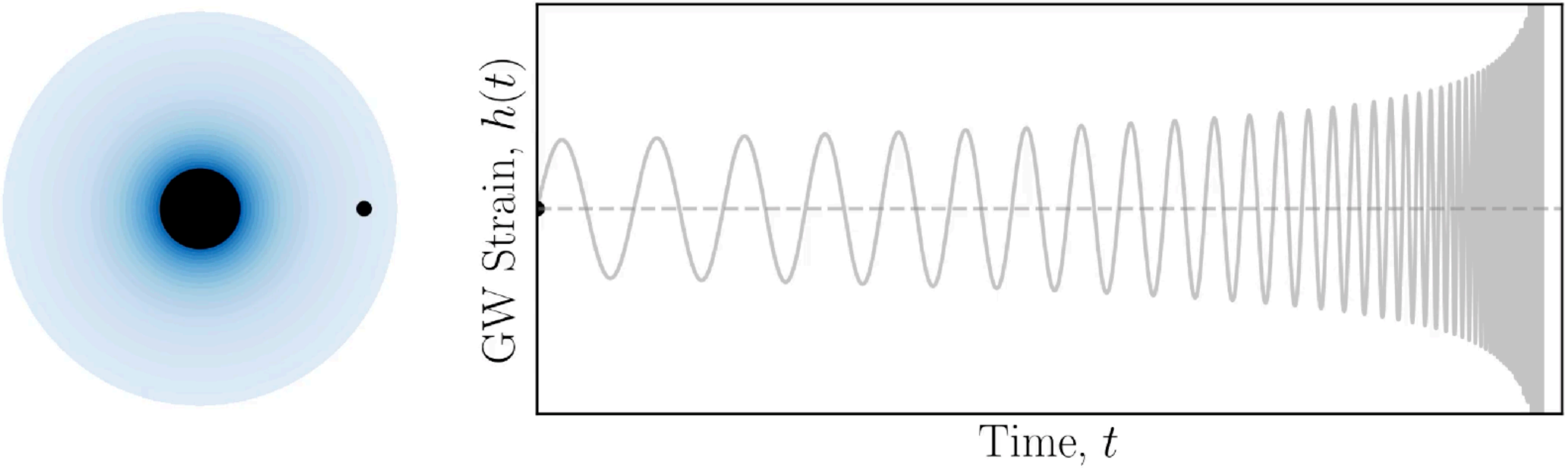
[Animations online]



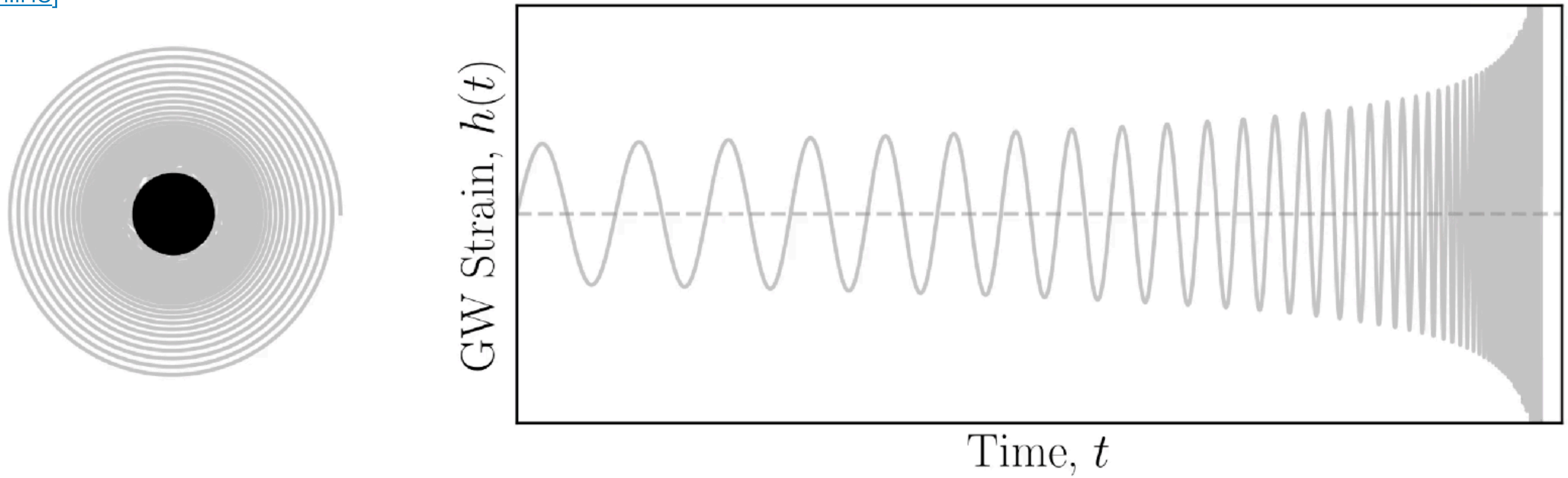


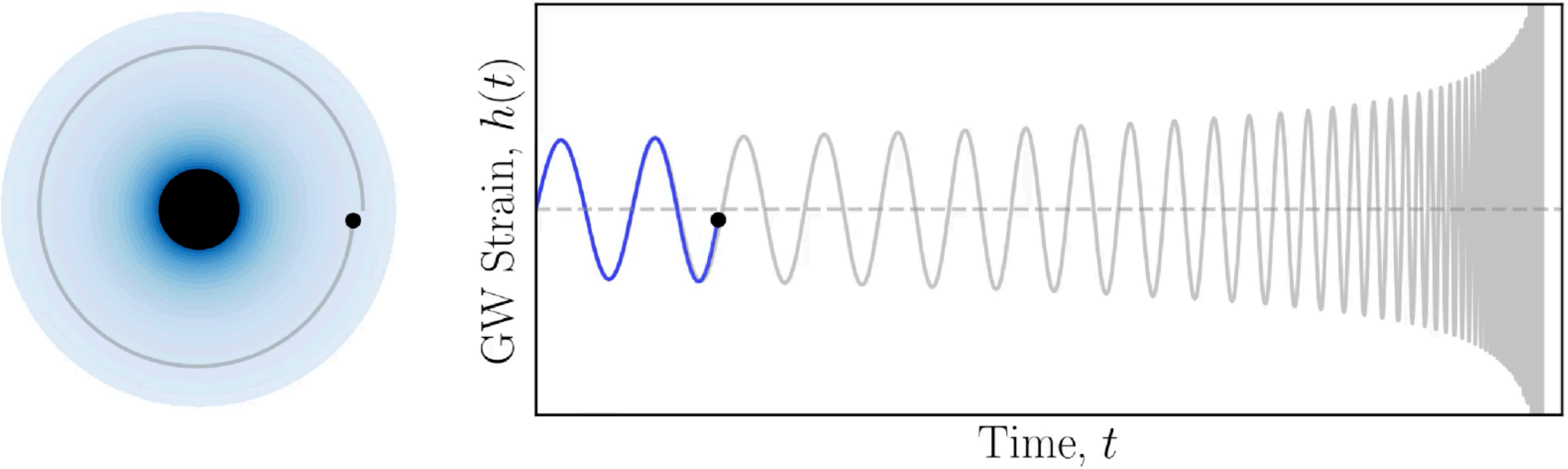
[Animations online]



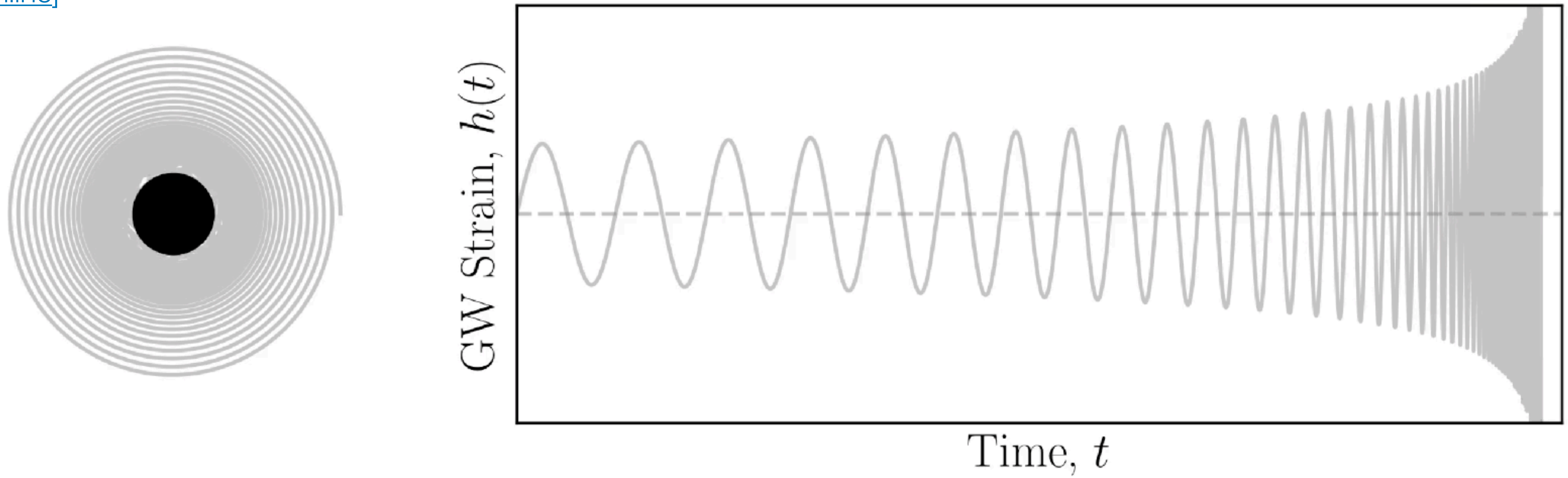


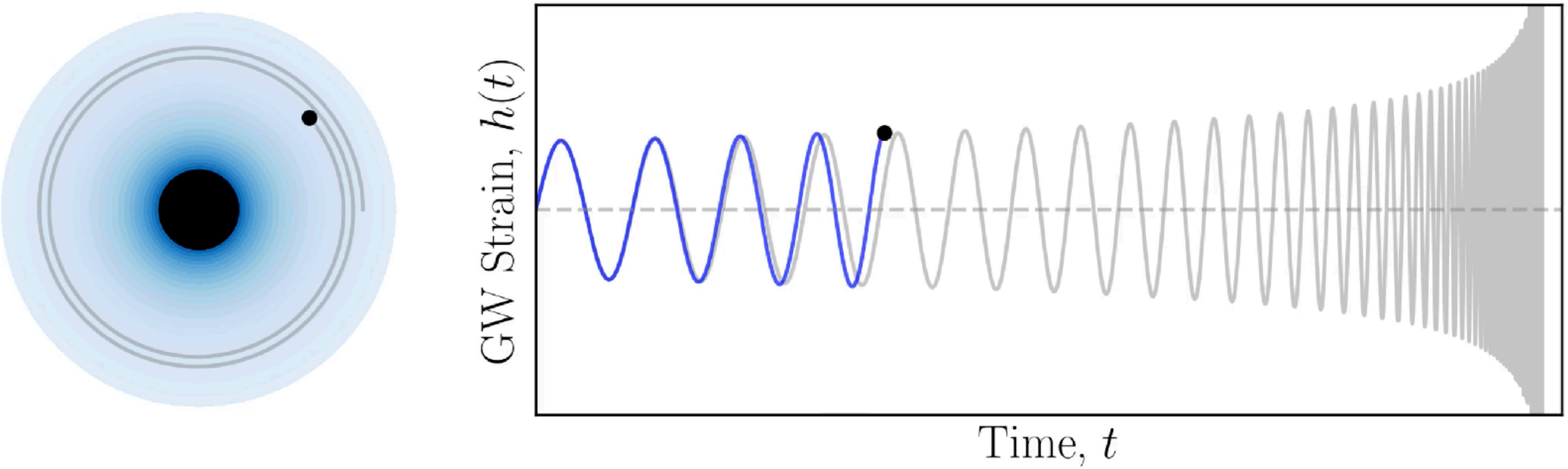
[Animations online]



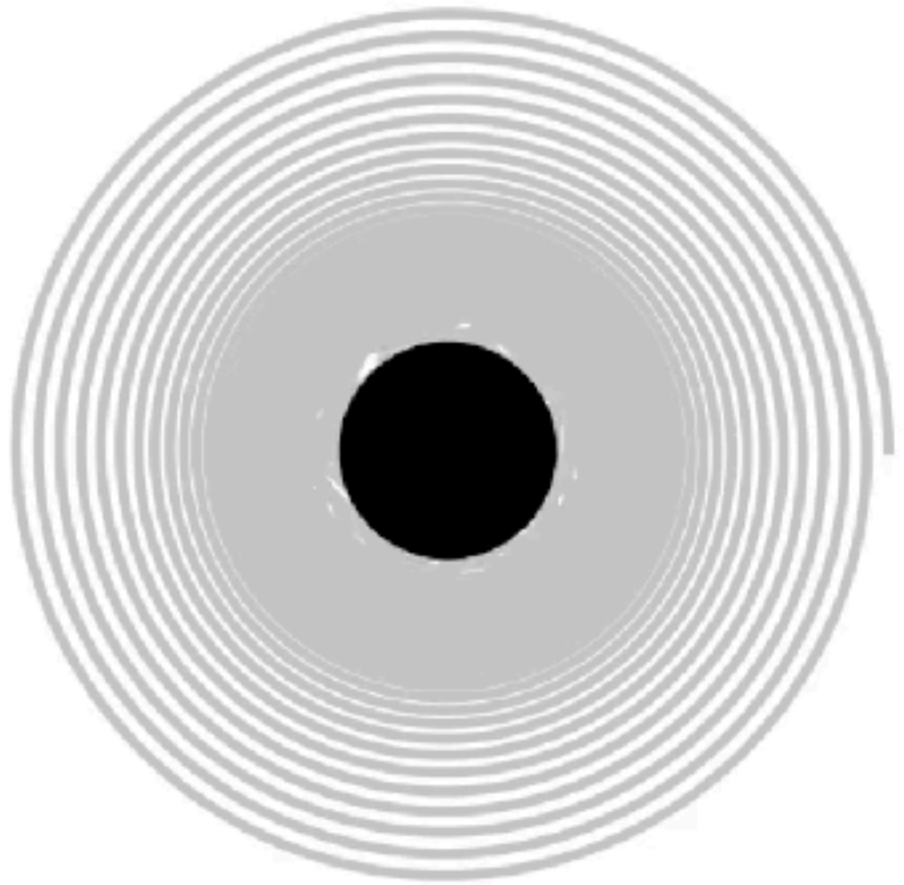


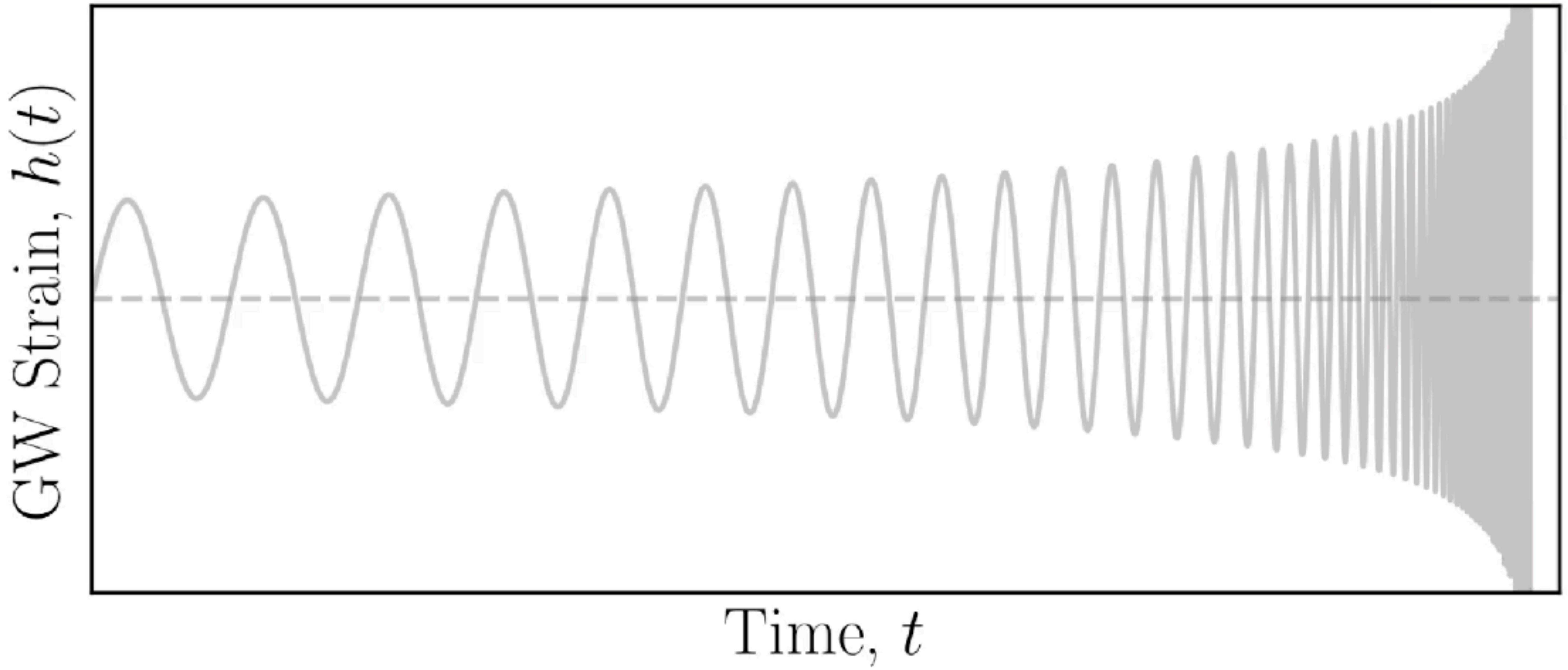
[Animations online]

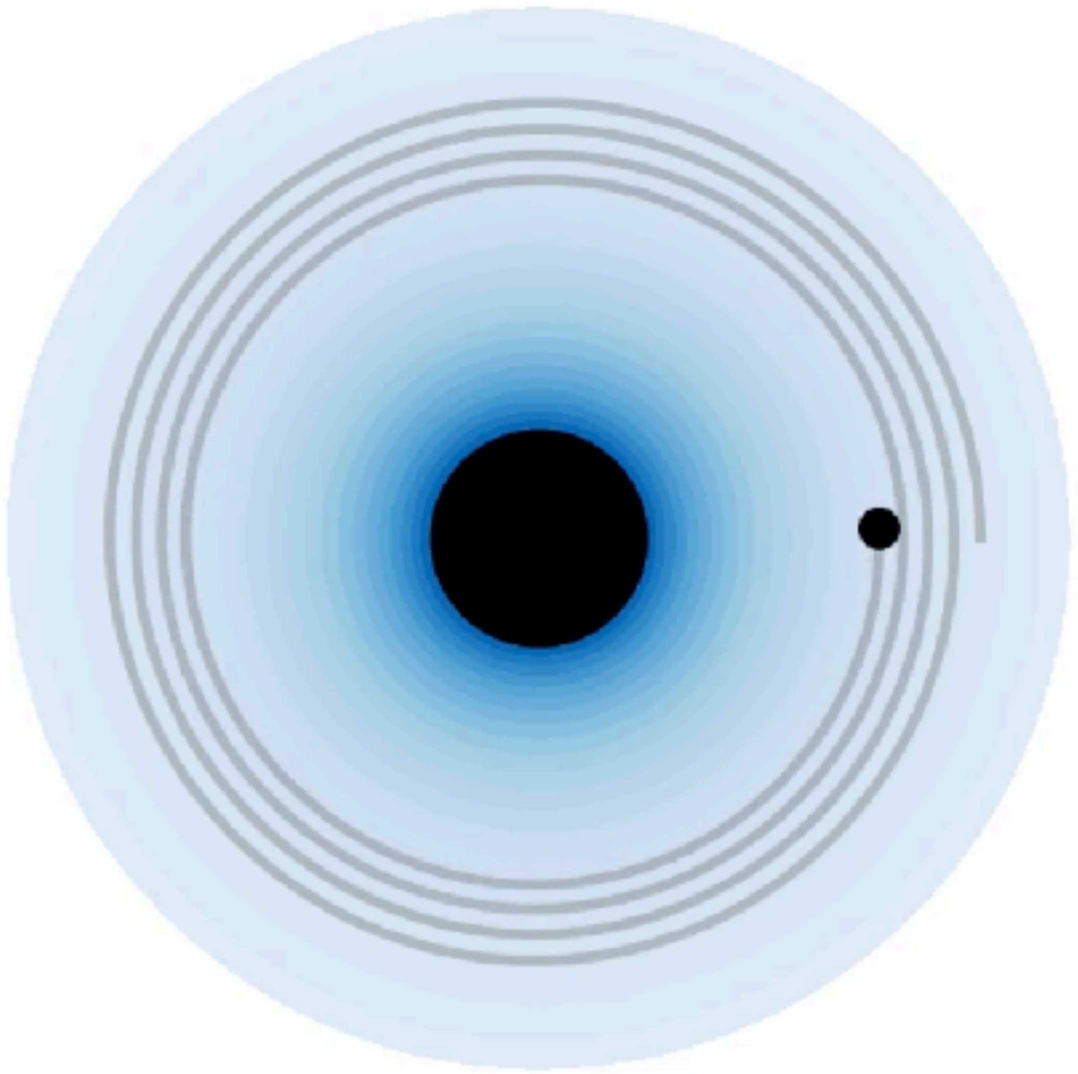


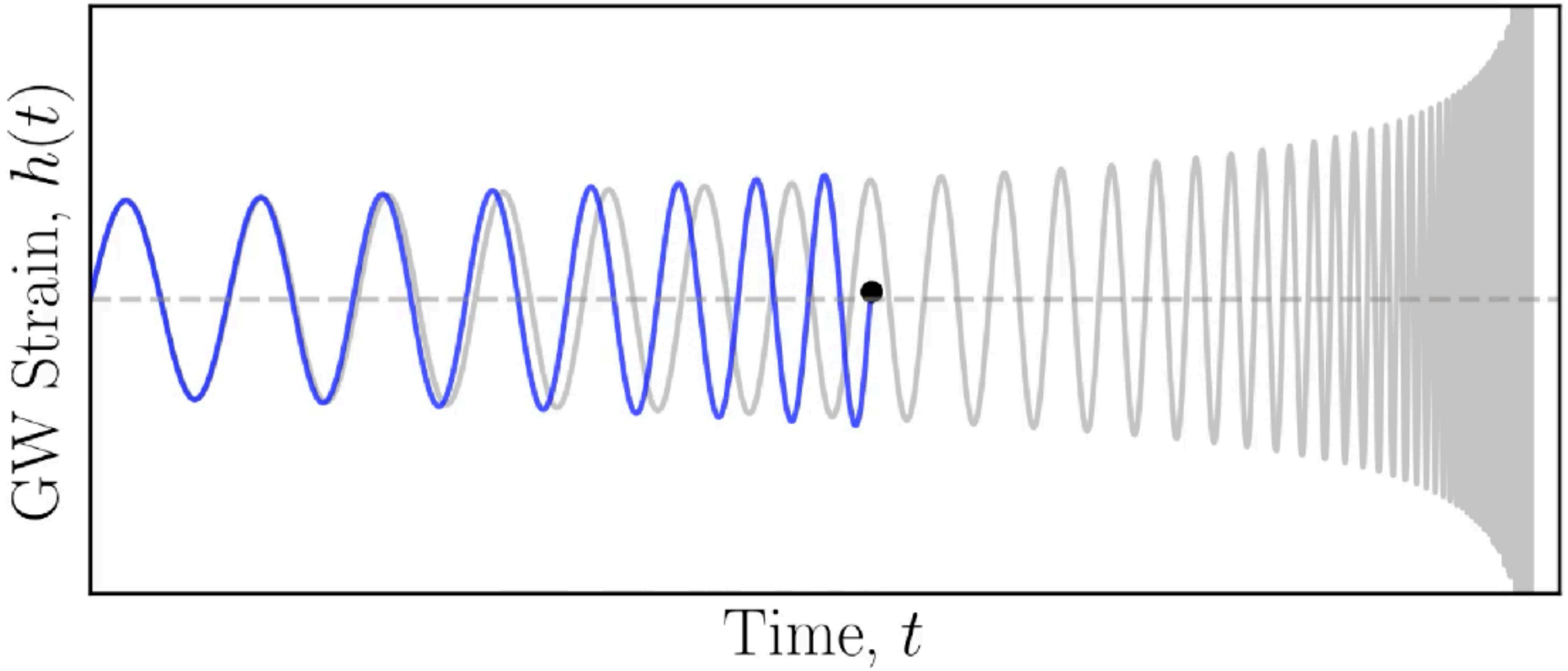


[Animations online]

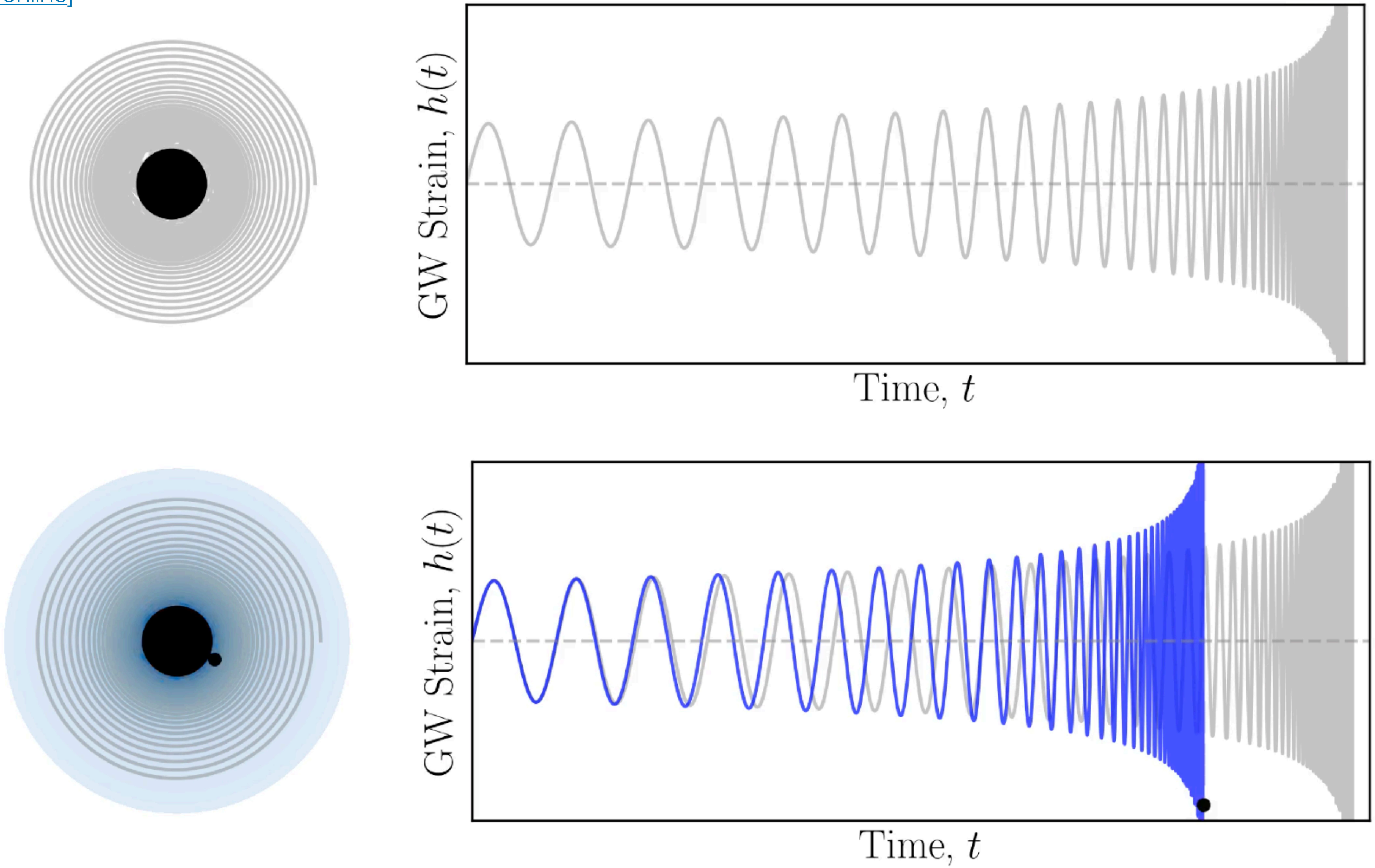




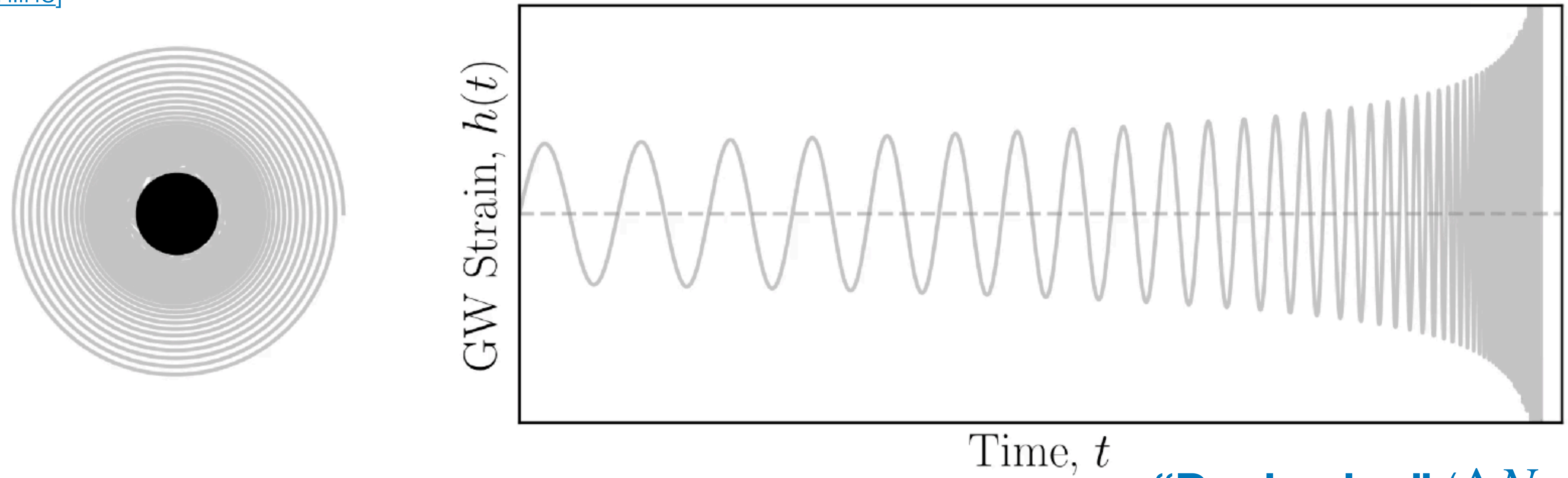




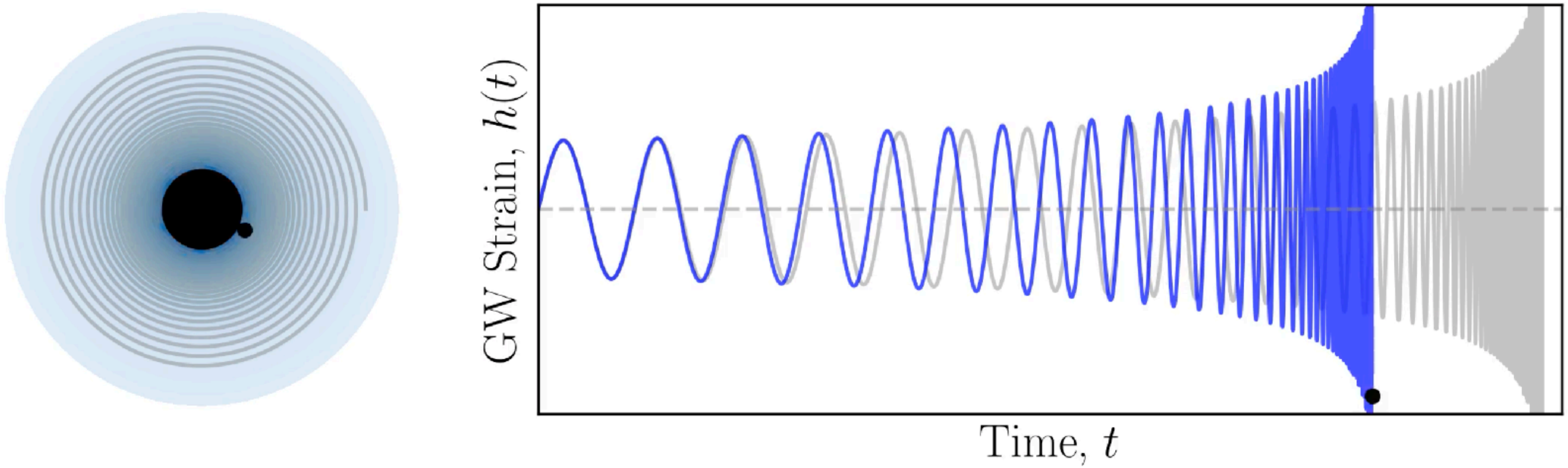
[Animations online]



[Animations online]

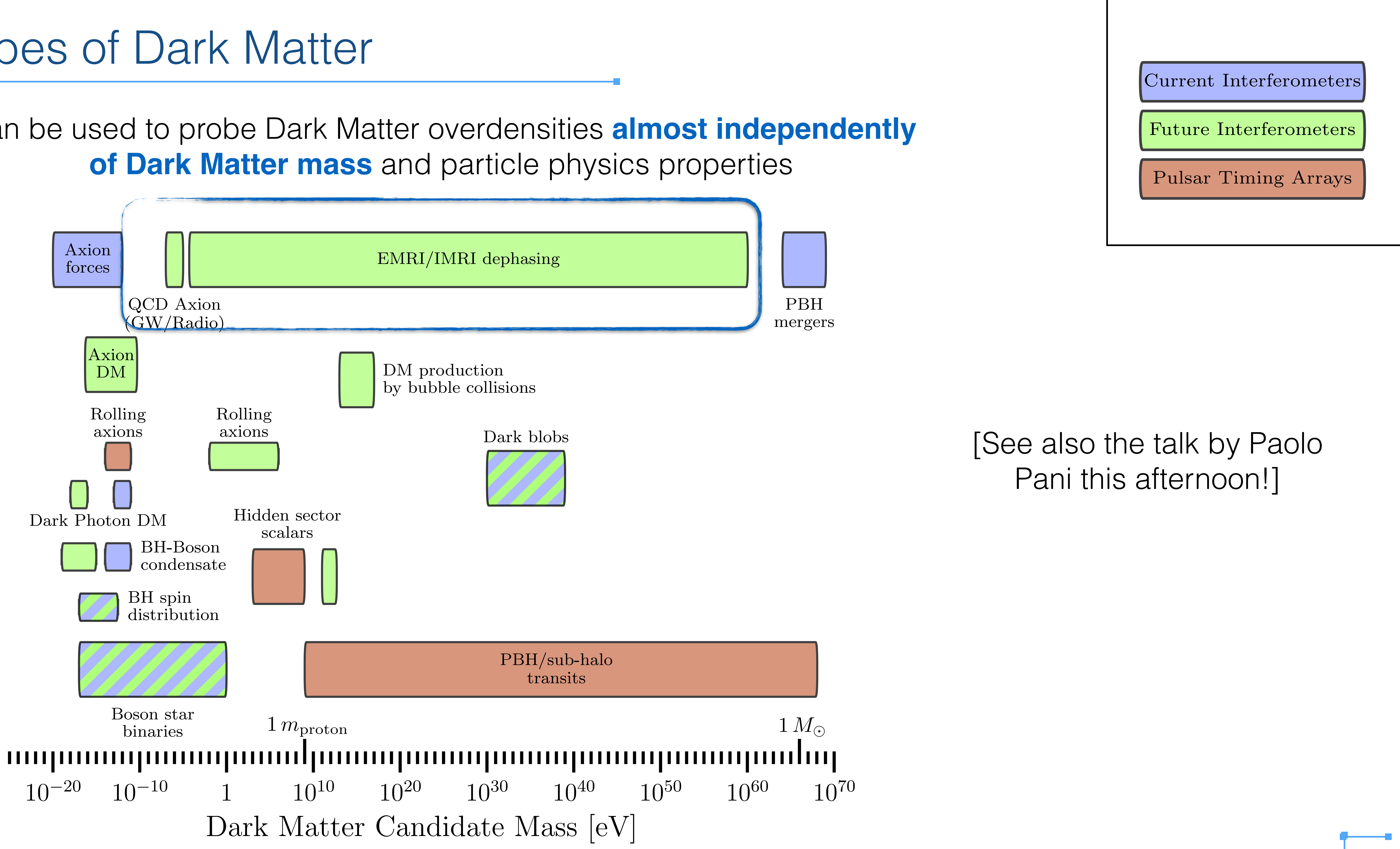


"Dephasing" $(\Delta N_{\rm GW})$



GW Probes of Dark Matter

Can be used to probe Dark Matter overdensities **almost independently of Dark Matter mass** and particle physics properties



[See also the talk by Paolo Pani this afternoon!]

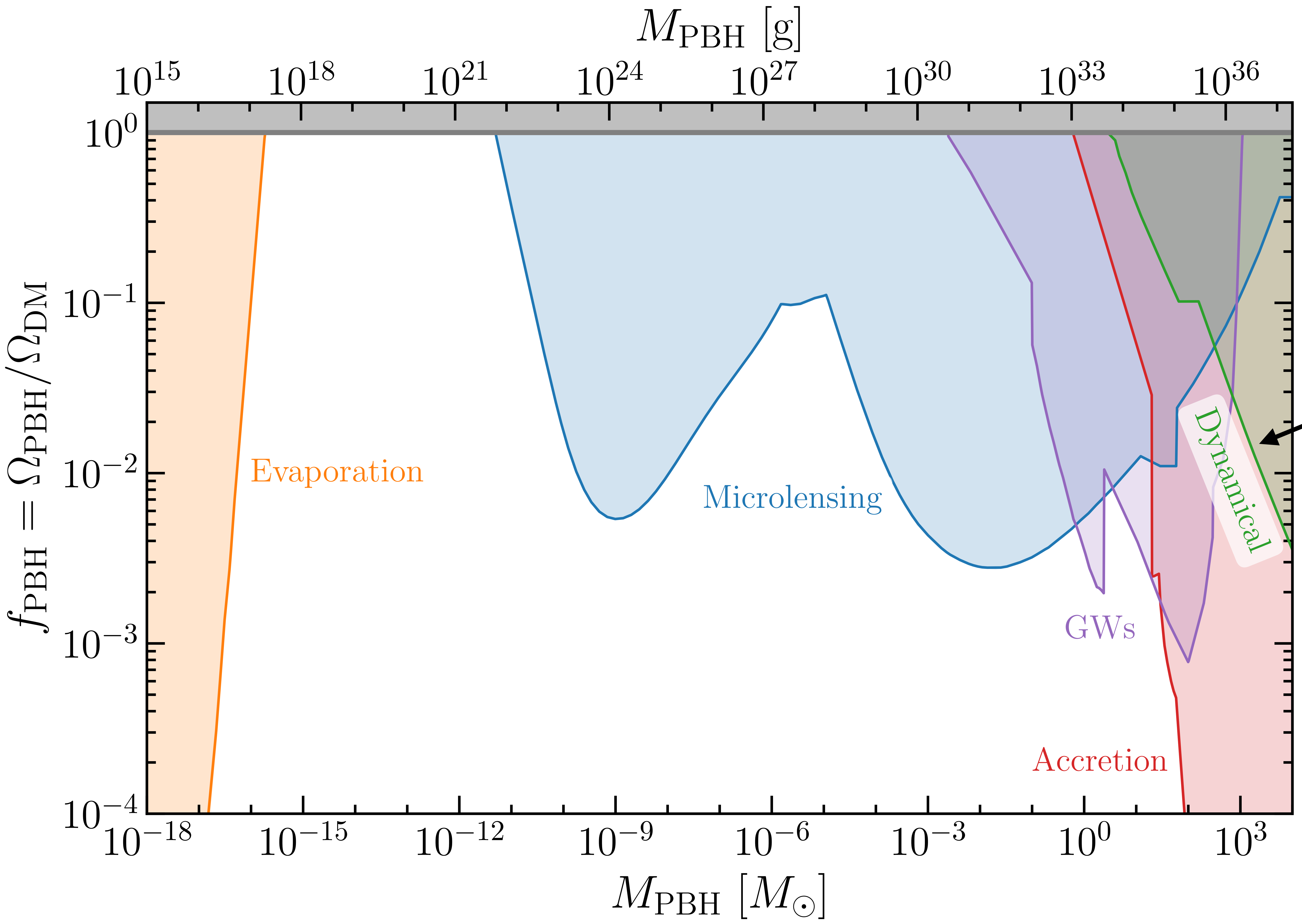
[Bertone, Croon, et al (including **BJK**), 1907.10610]

Compact Object DM

[Green & **BJK**, 2007.10722]

[Code online: github.com/bradkav/PBHbounds]

Constraints on primordial black hole as DM:



DM in the form of compact objects (e.g. black holes) dynamically heats the stars in dwarf galaxies, disrupting the stellar density profiles

[Stegmann et al., 1910.04793]

[Other reviews: 1801.05235, 2002.12778, 2006.02838]