Dark Matter in Extreme Environments

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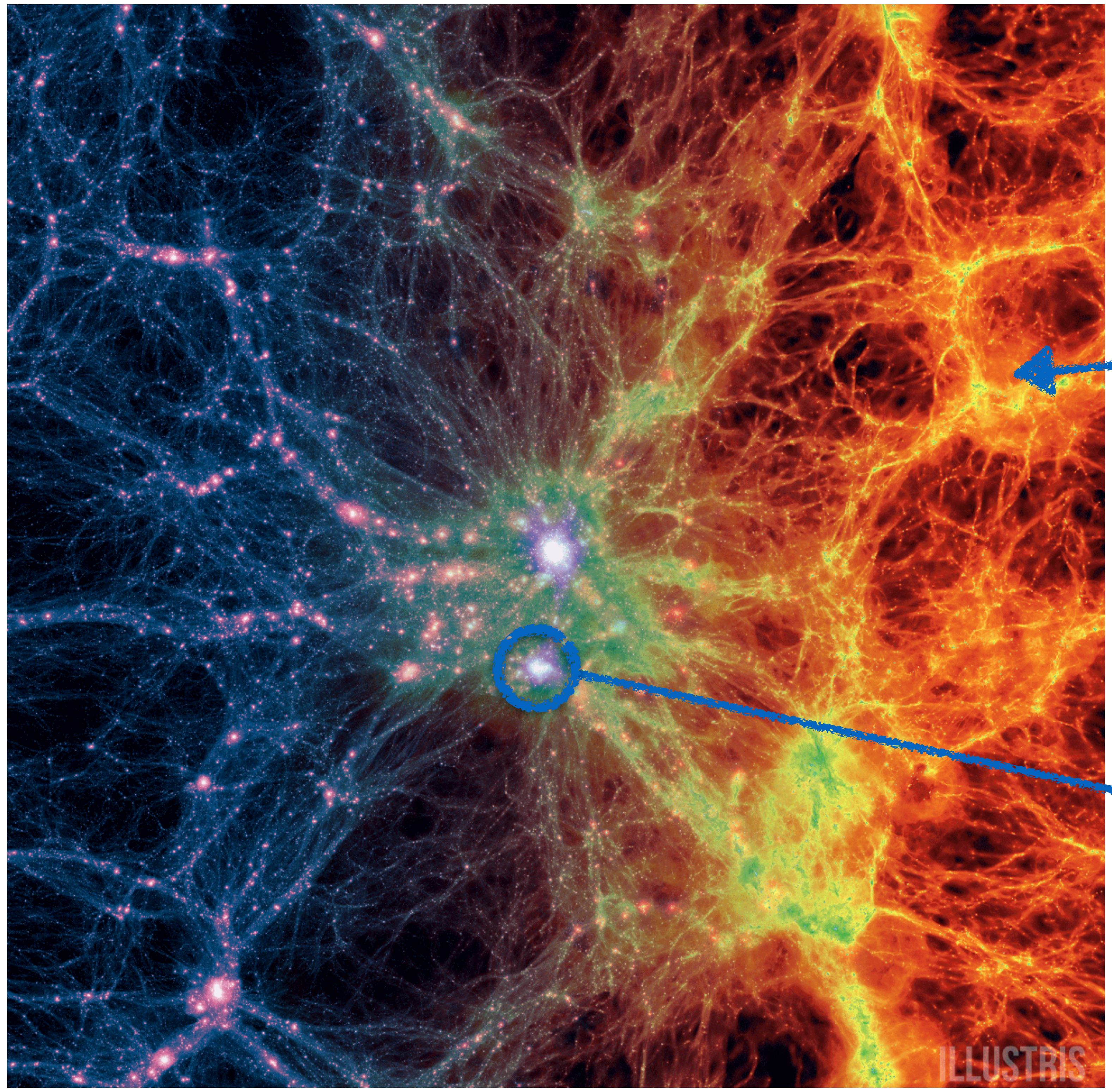
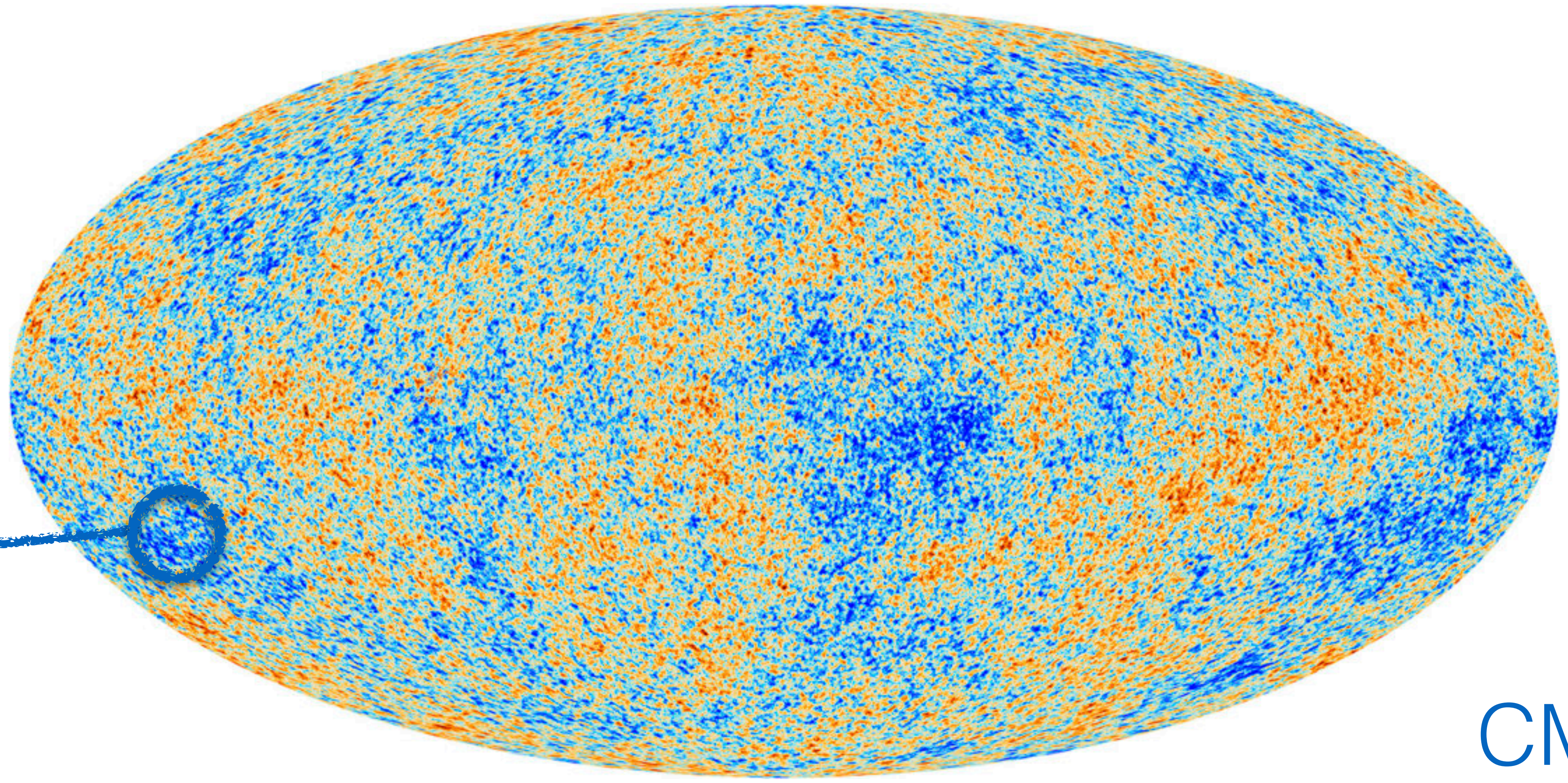
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN
IFCA Instituto de Física de Cantabria
CSIC Consejo Superior de Investigaciones Científicas
50 UC Universidad de Cantabria



Galaxy clusters

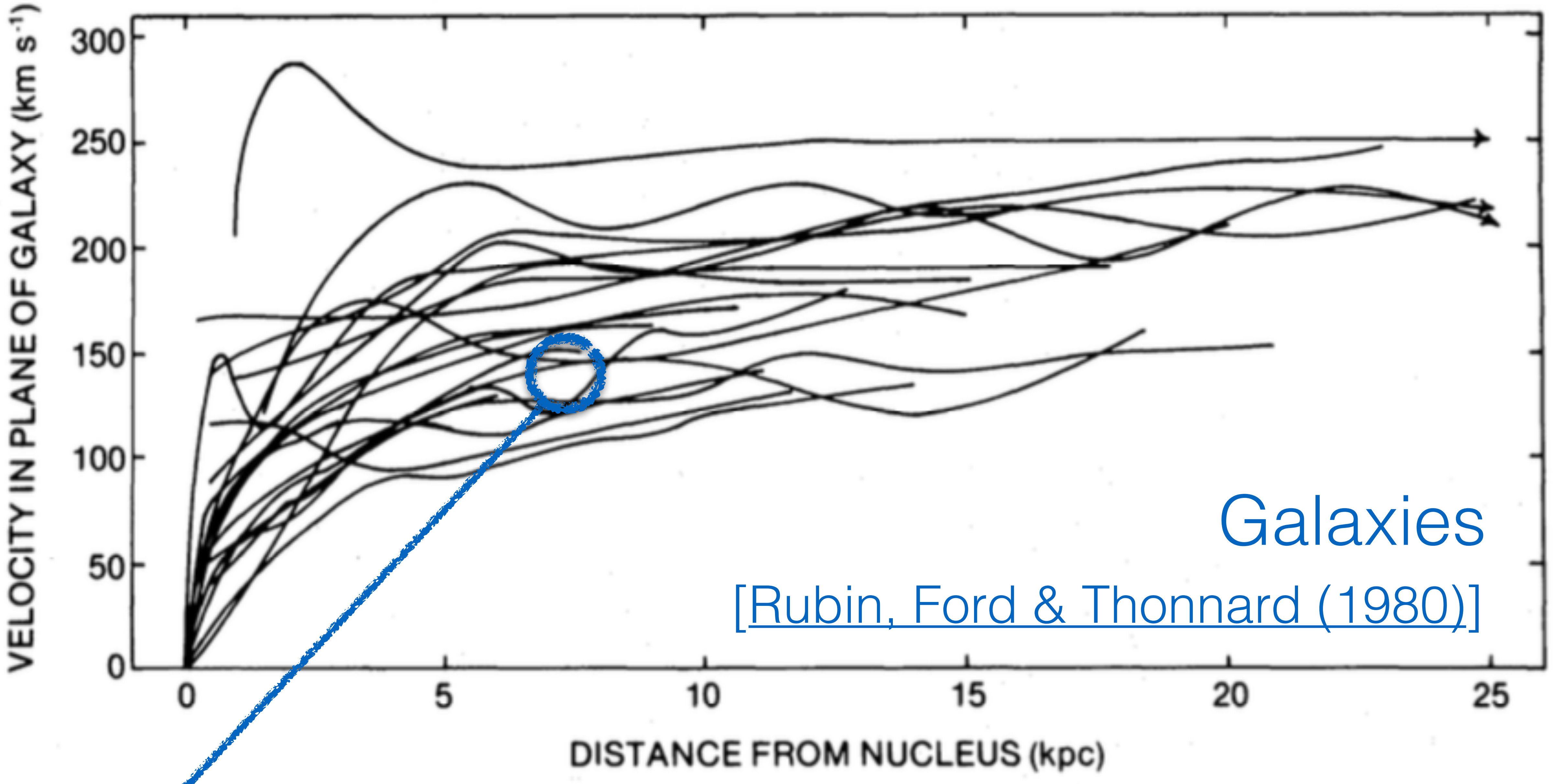
[Illustris, 1405.2921]

[astro-ph/0006397]



CMB

[Planck, 1502.01589]



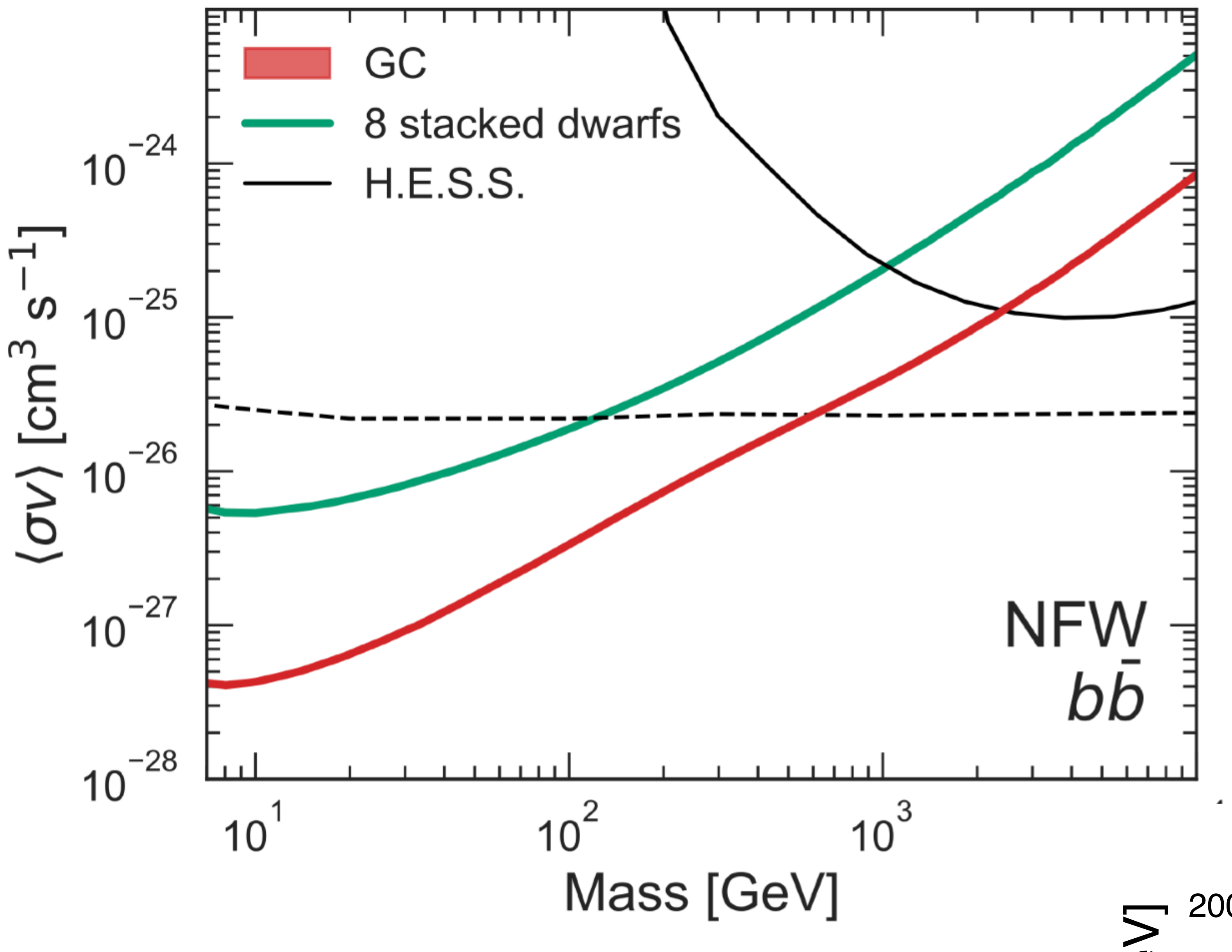
Galaxies

[Rubin, Ford & Thonnard (1980)]

The Dark Matter Landscape

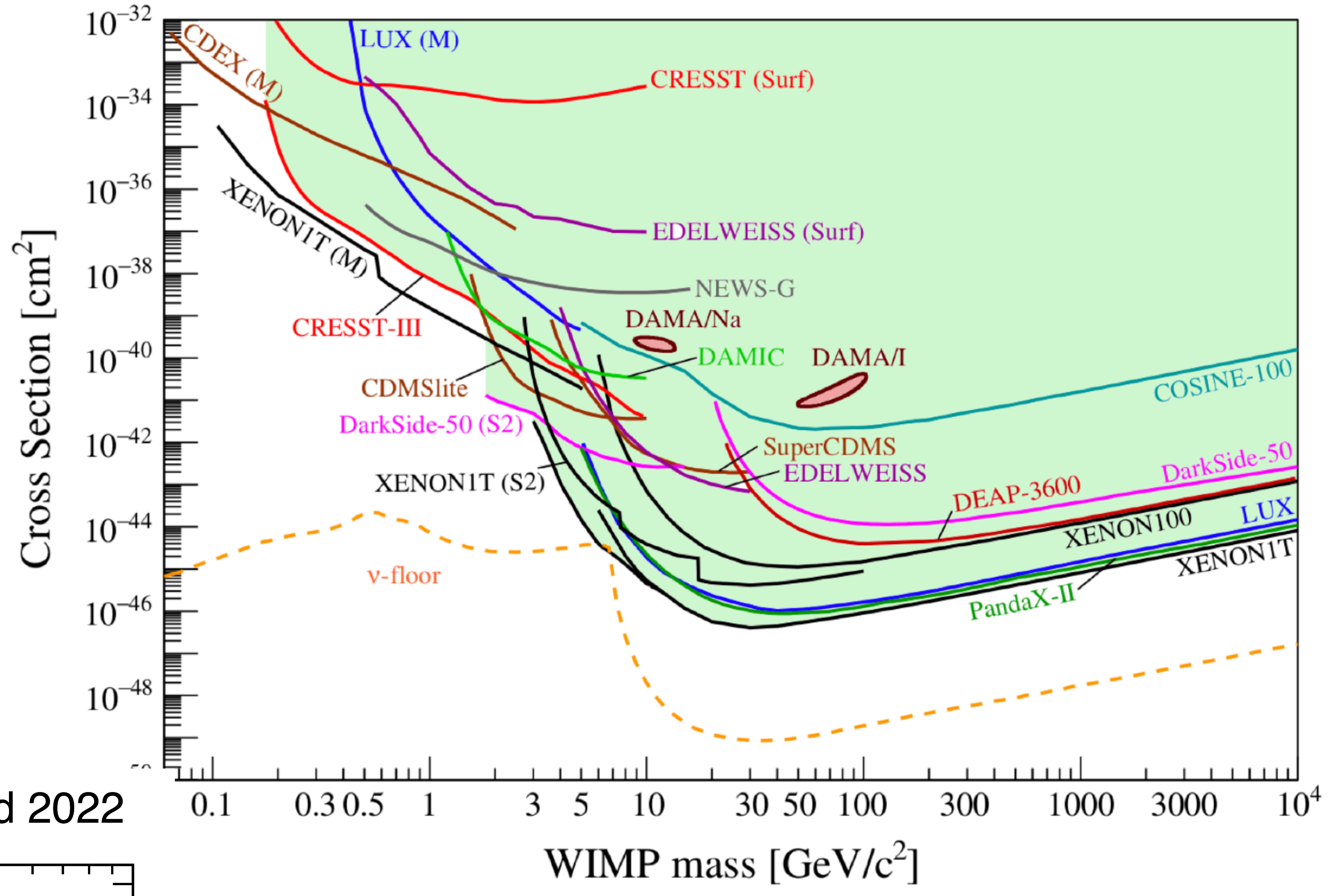
Indirect searches

[Abazajian et al., 2003.10416]



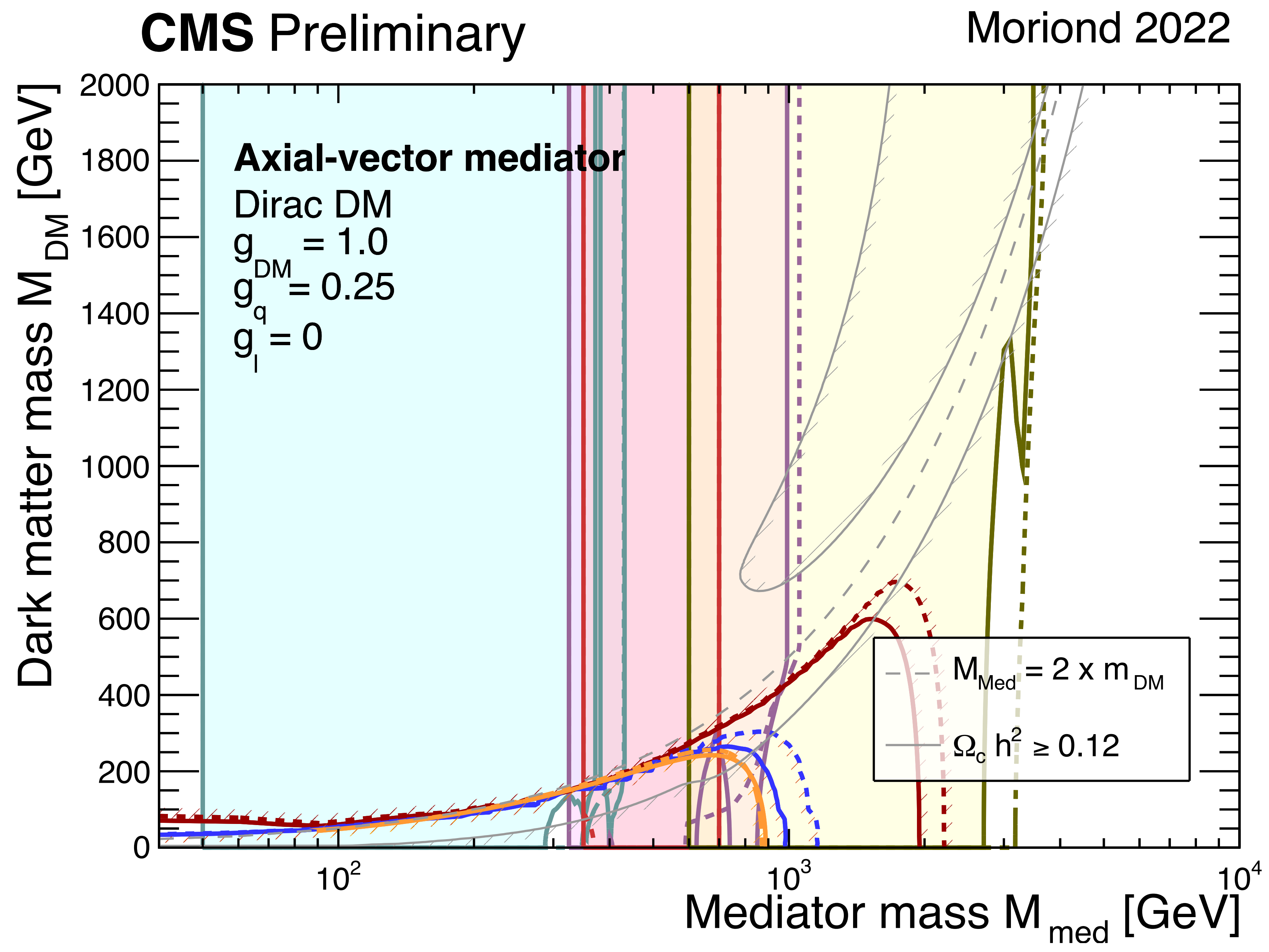
Direct Searches

[APPEC, 2104.07634]



Collider Searches

[CMS, DM Summary Plots]

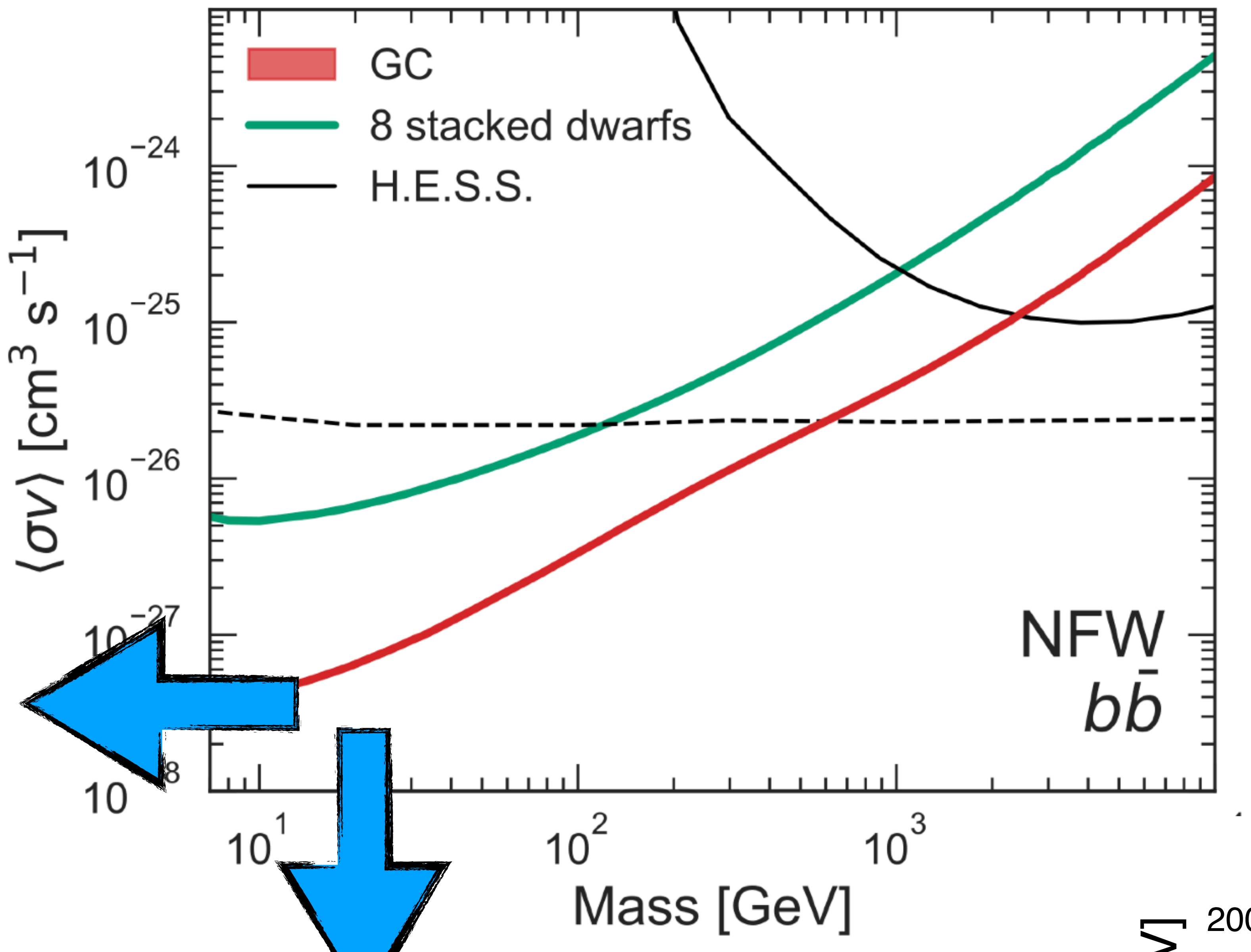


New technologies, lower thresholds, larger exposures, higher energies…

The Dark Matter Landscape

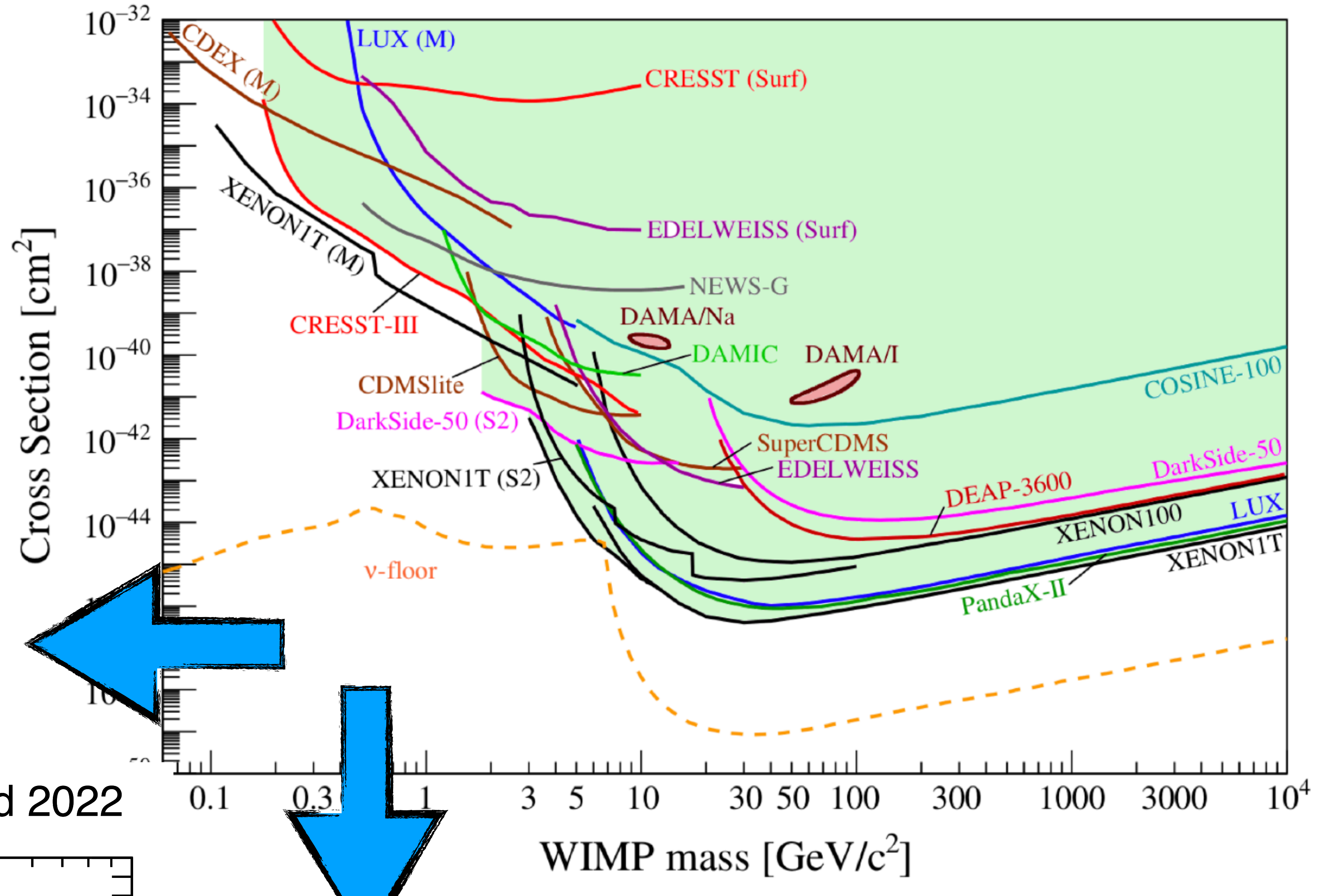
Indirect searches

[Abazajian et al., 2003.10416]



Direct Searches

[APPEC, 2104.07634]



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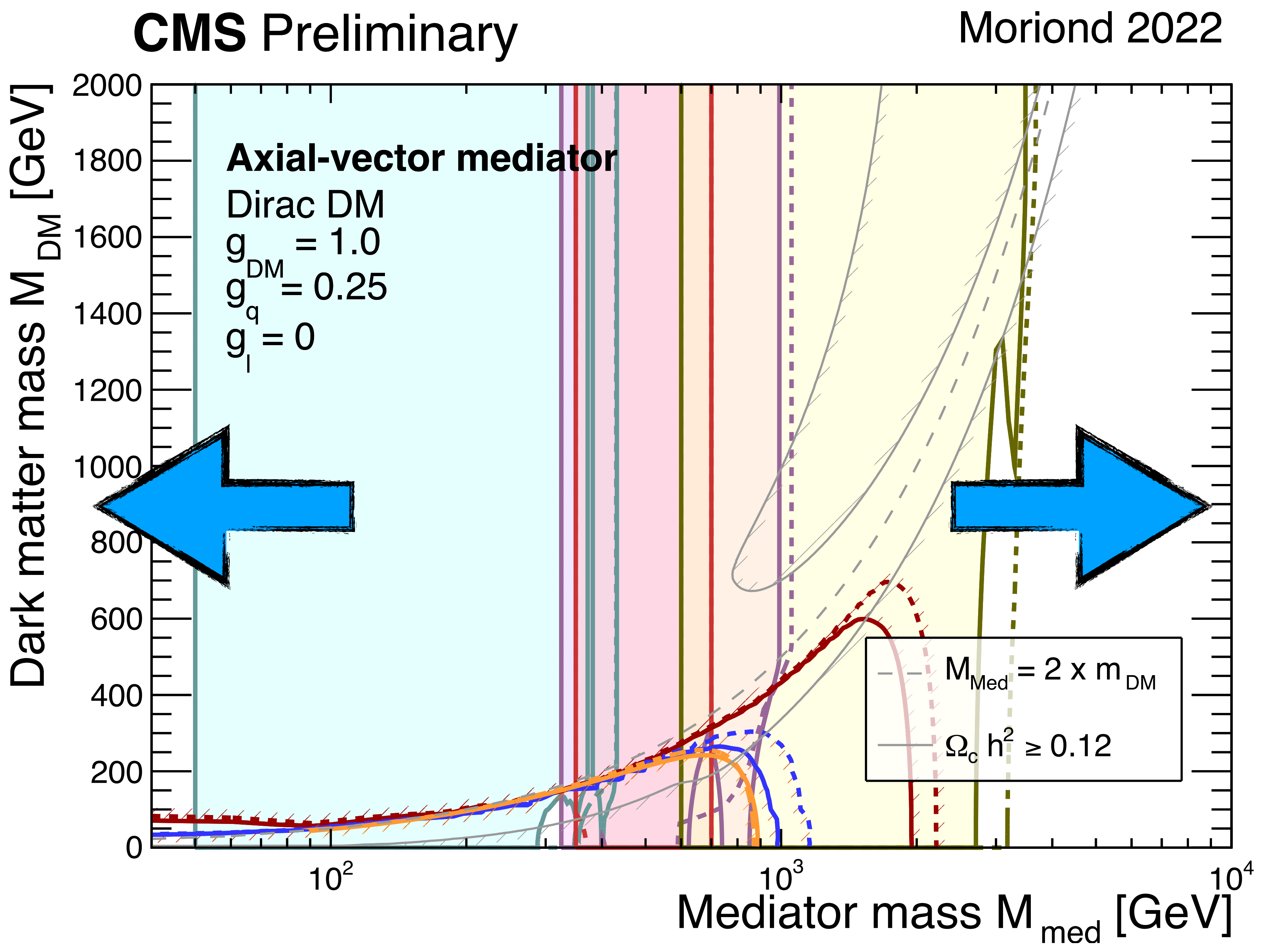


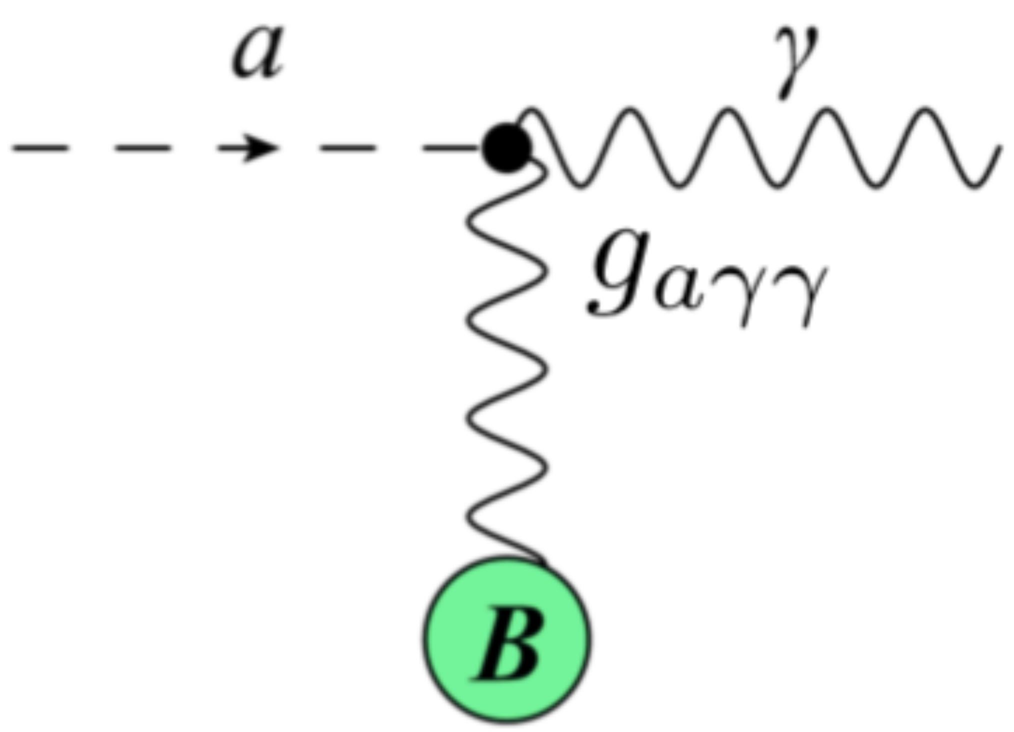
New technologies, lower thresholds, larger exposures, higher energies…

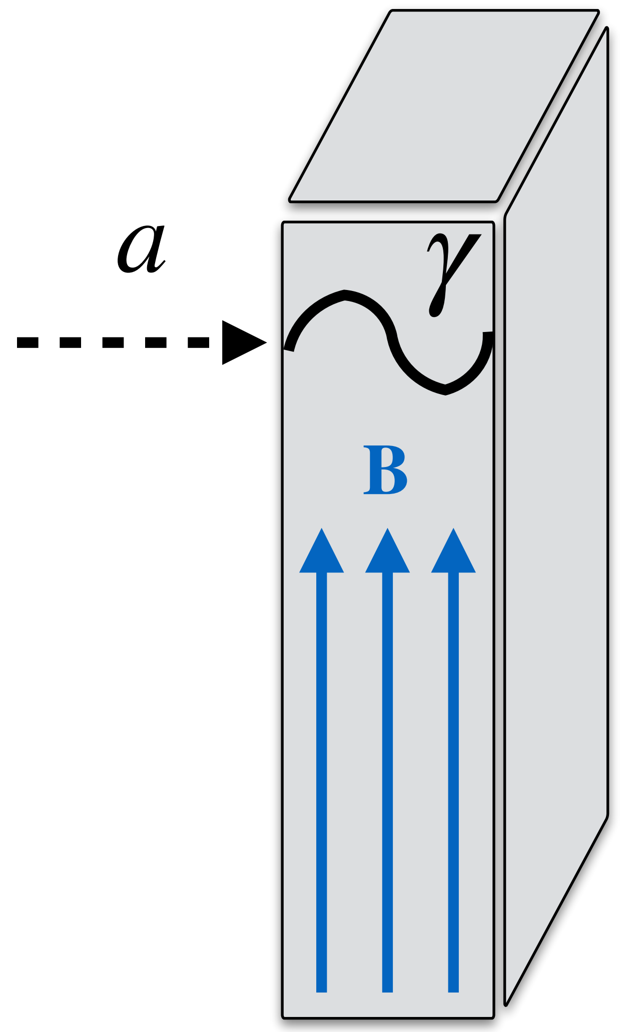
Example: Axion Dark Matter

Dark Matter could be in the form of light **pseudo-scalar 'axions'**, which may arise as psuedo-Goldstone bosons of a spontaneously broken Peccei-Quinn symmetry $U(1)_{\rm PQ}$.

Axions can **convert to photons** (and vice versa) in an external magnetic field:

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$= -\frac{1}{4} g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$





$$\omega = m_a$$

$$\text{Power} \sim g_{a\gamma}^2 \frac{\rho_a}{m_a} B^2 Q_0 V$$

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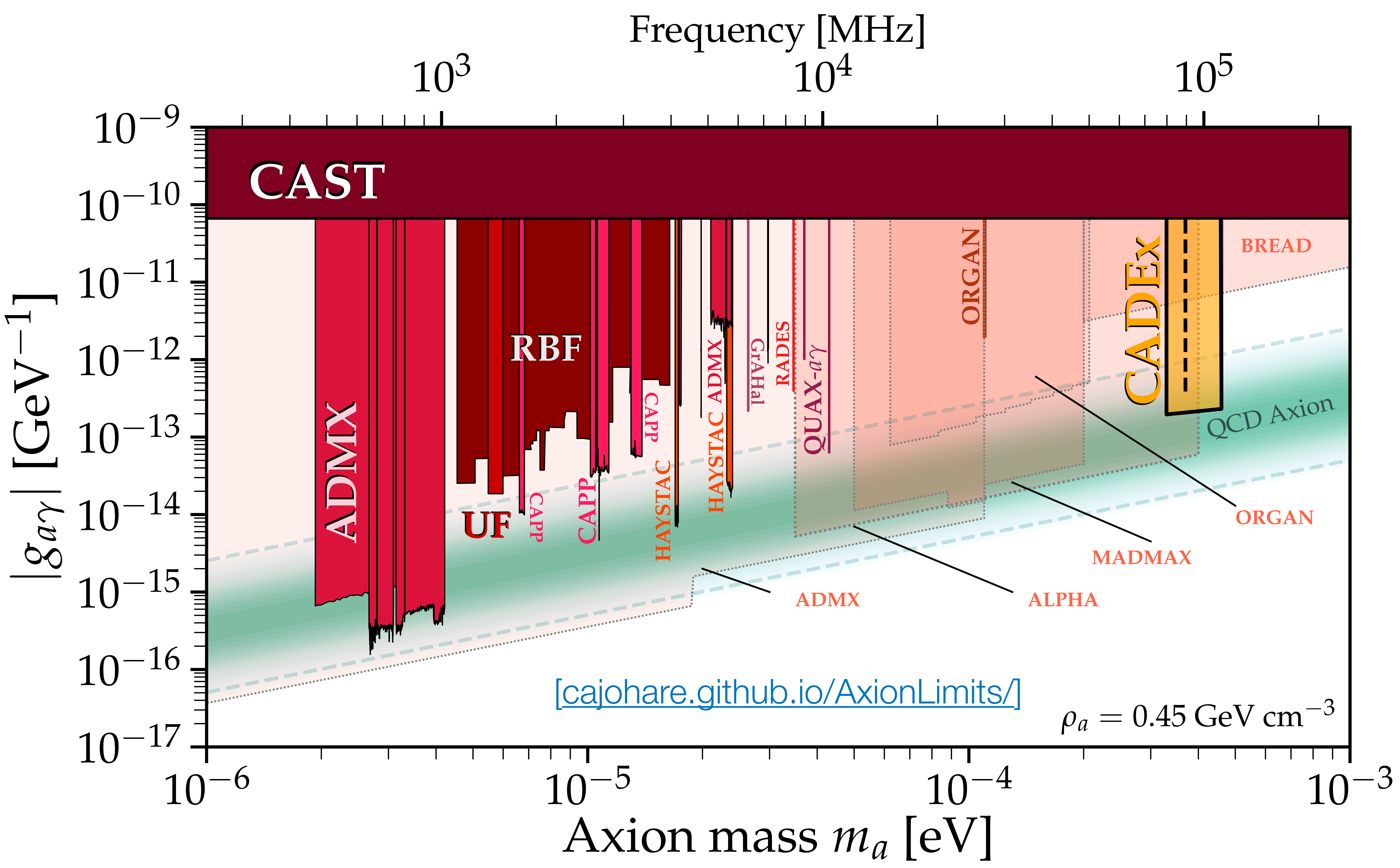
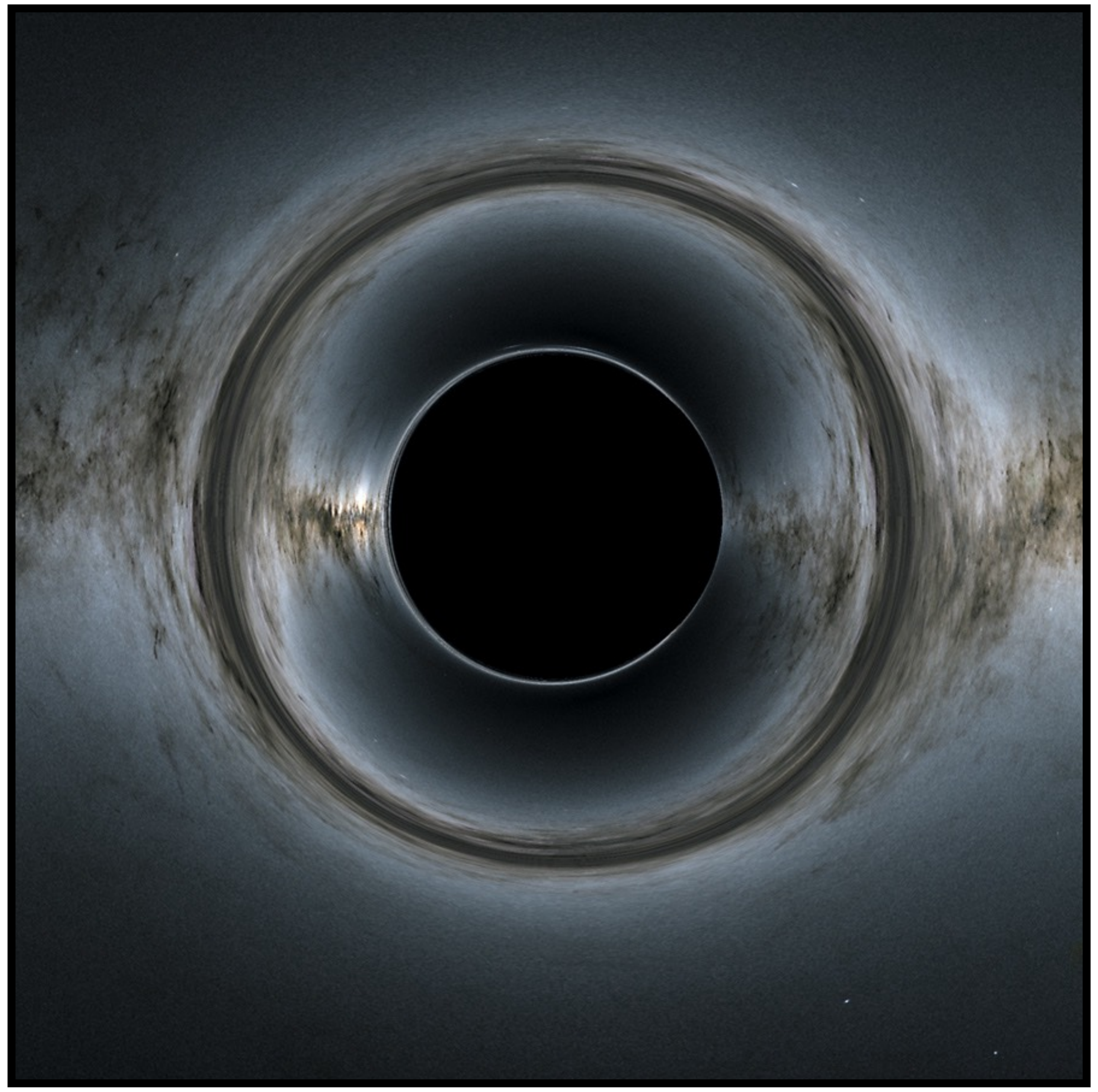


[CADEx Collaboration, including **BJK**, arXiv:2206.02980]

DM in extreme environments

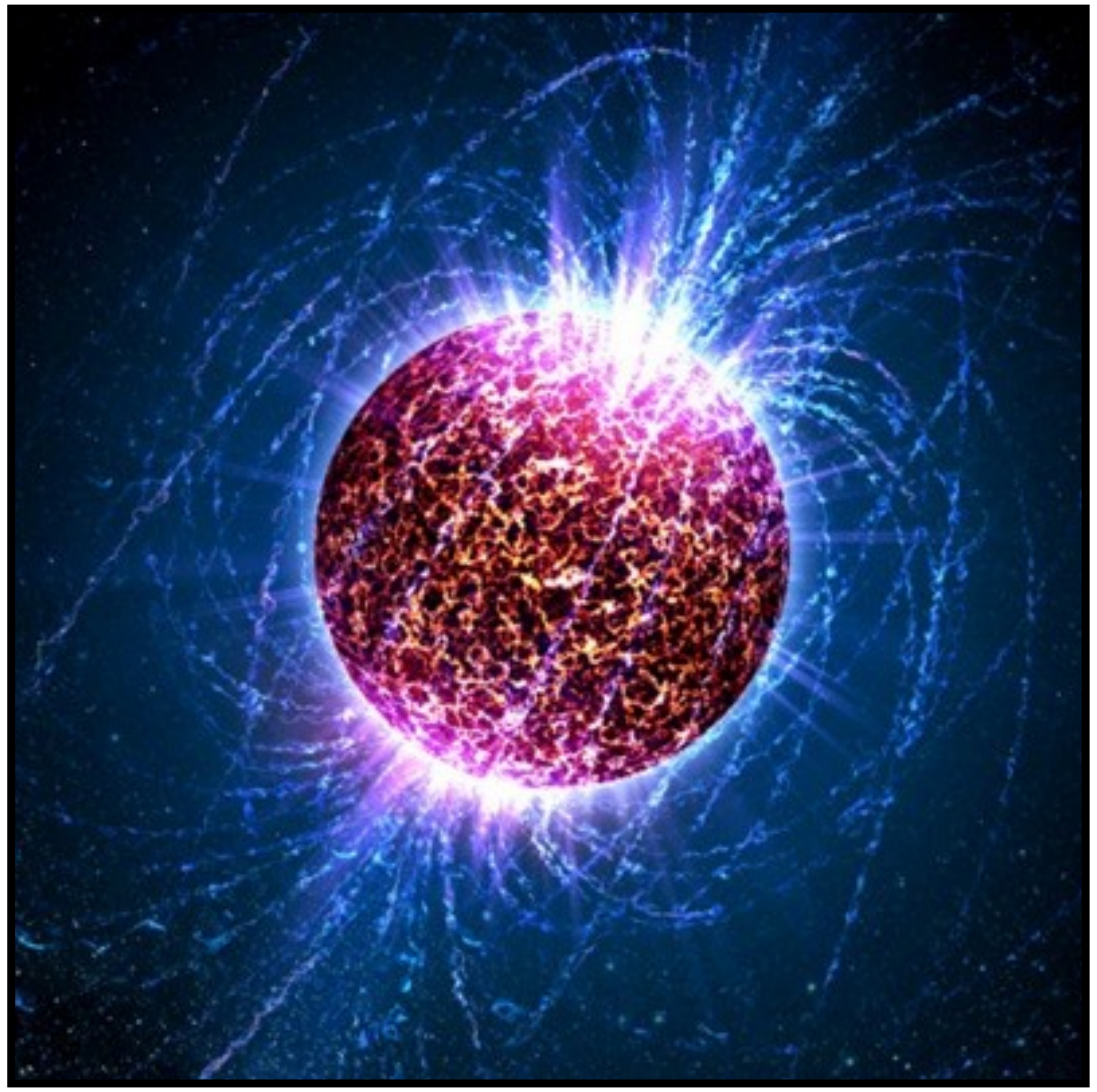
["Dark Matter in Extreme Astrophysical Environments", Baryakhtar et al., 2203.07984]

Black Holes



[Credit: NASA's Goddard Space Flight Center; background, ESA/Gaia/DPAC]

Neutron Stars

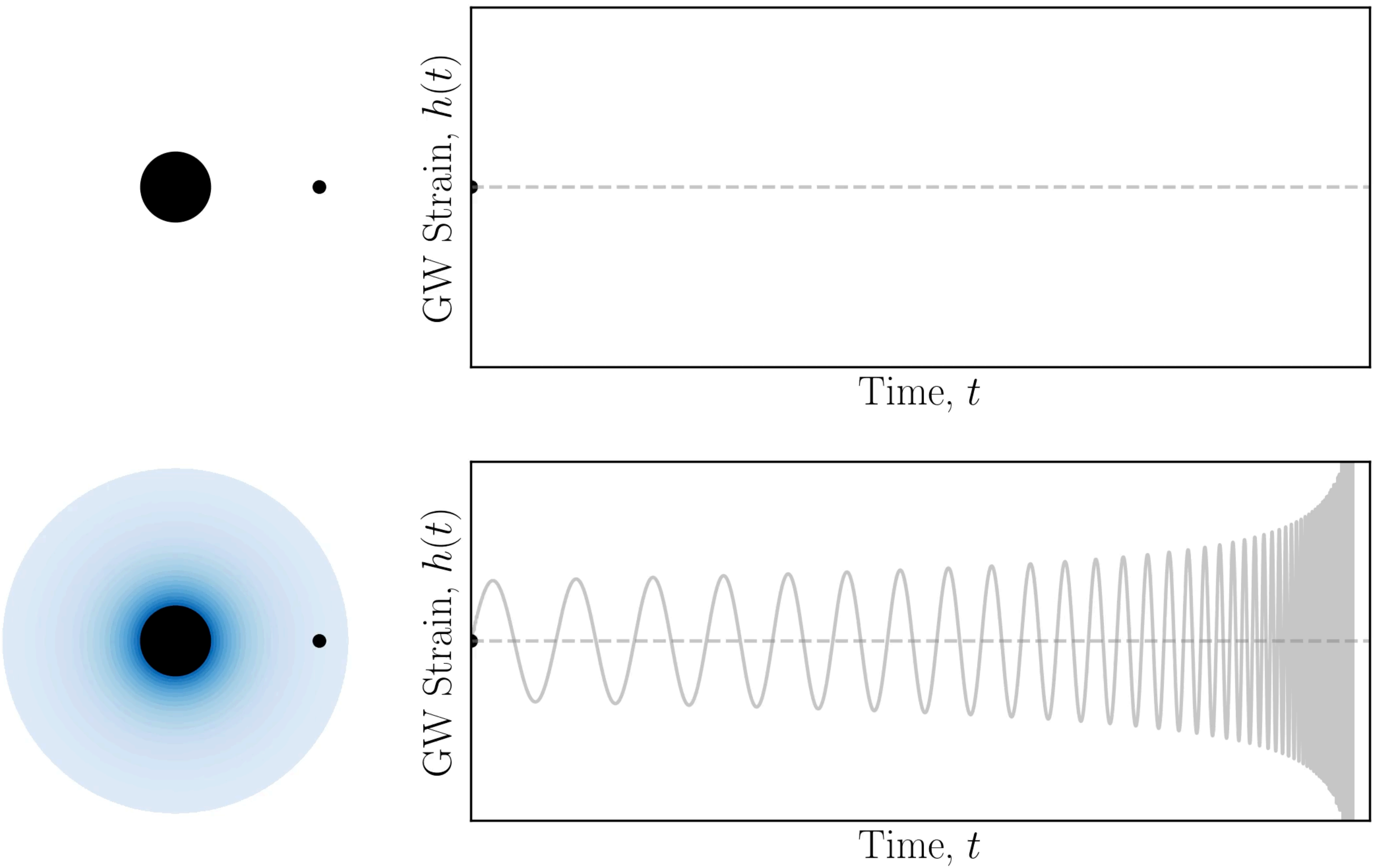


[Credit: Casey Reed (Penn State University), Wikimedia Commons]

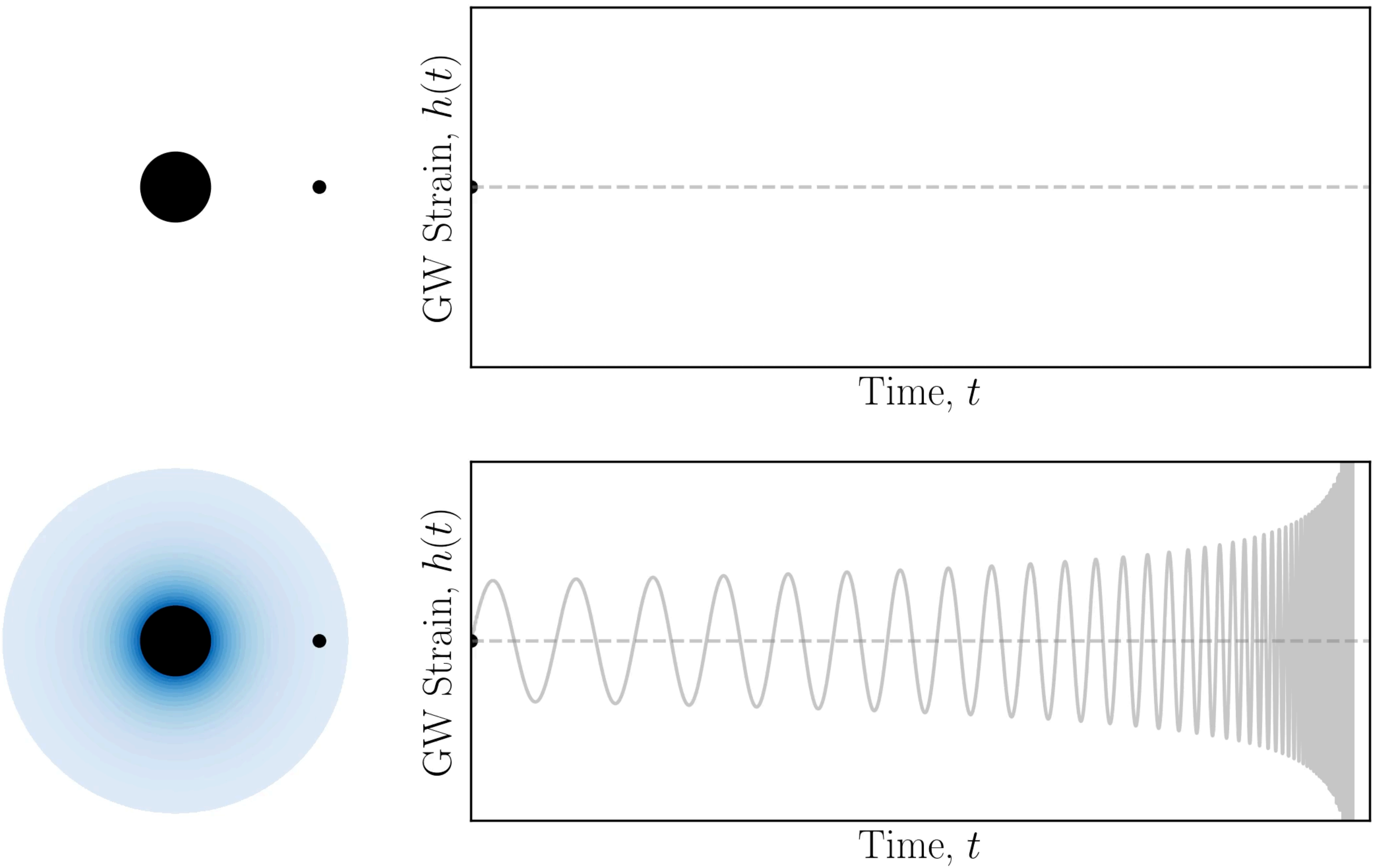
Higher densities, larger magnetic fields, longer timescales…

Part 1:
Black Holes

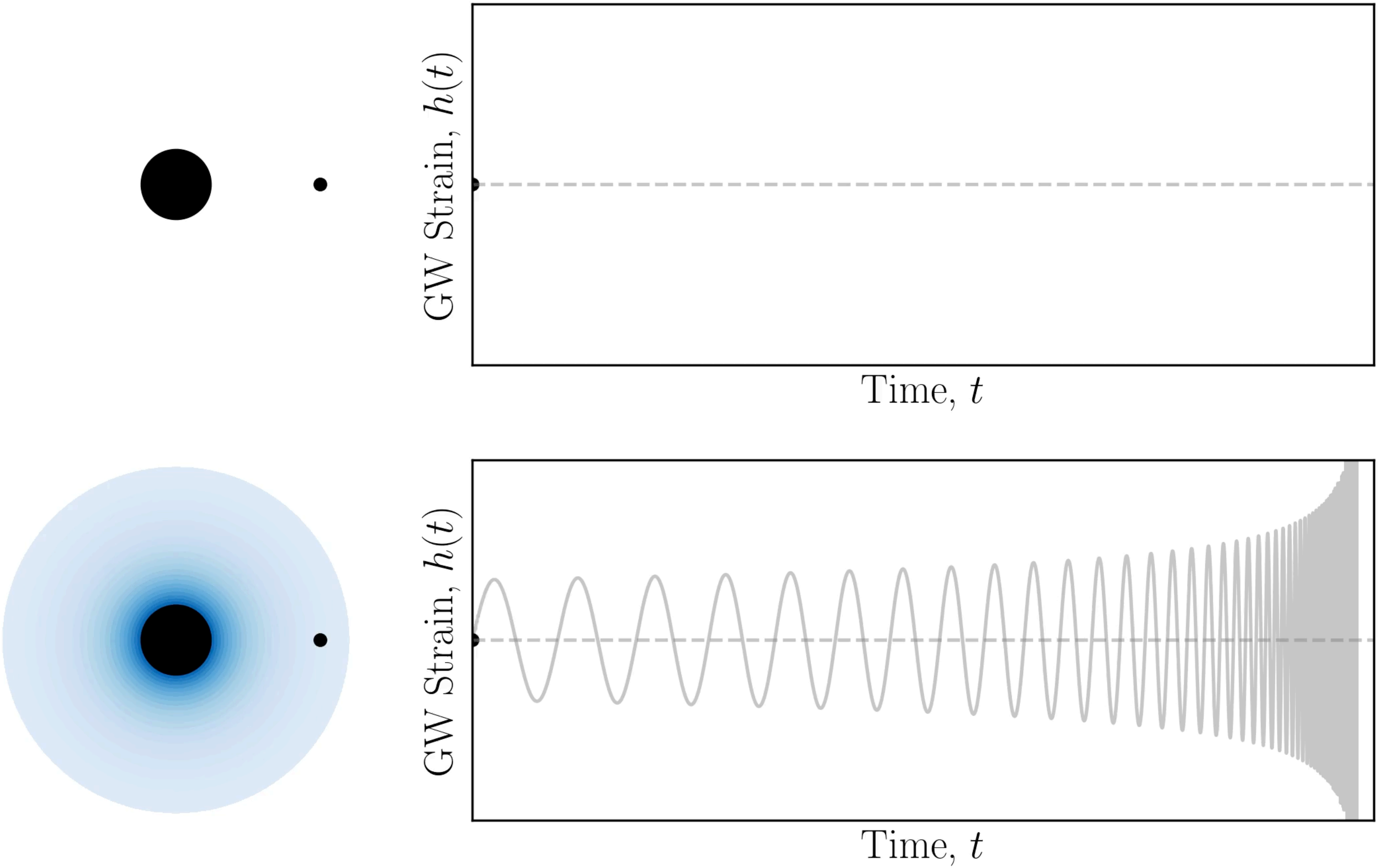
Gravitational Wave Dephasing



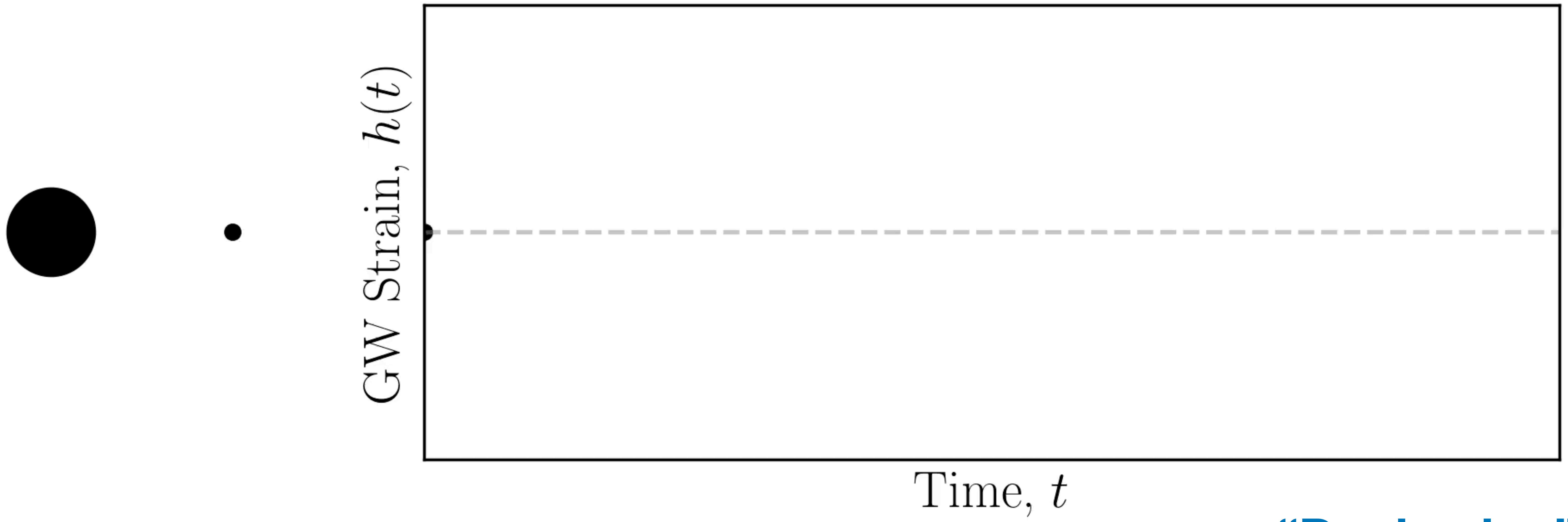
Gravitational Wave Dephasing



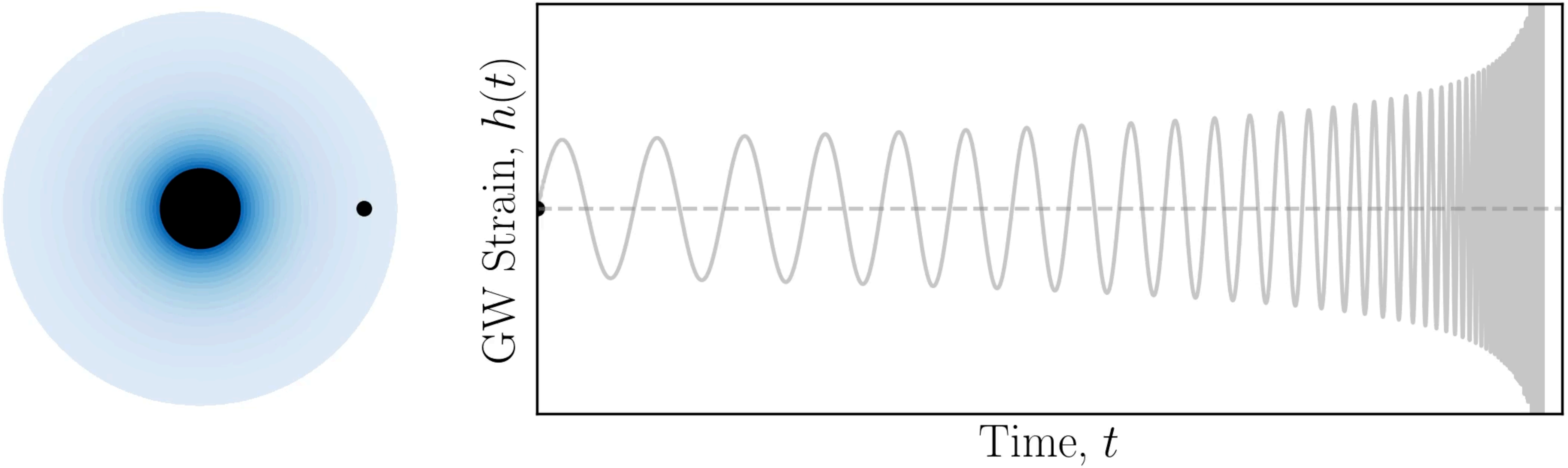
Gravitational Wave Dephasing



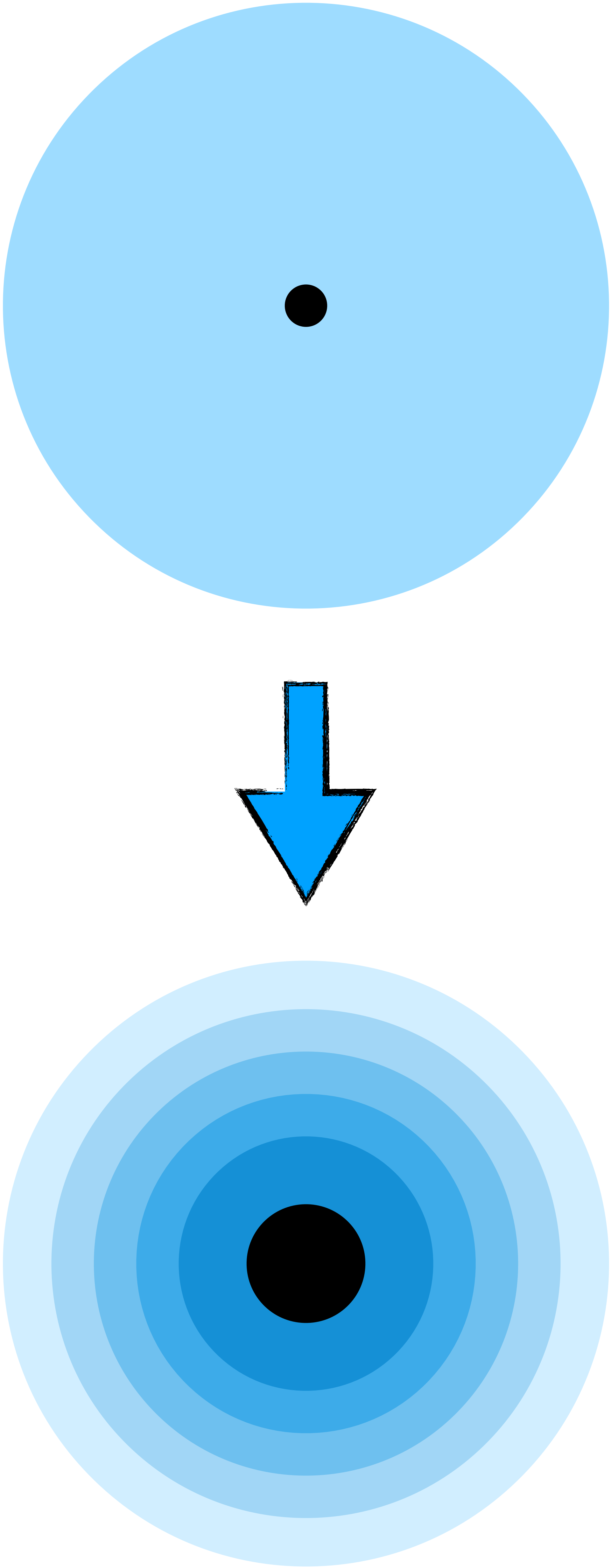
Gravitational Wave Dephasing



"Dephasing"



Dark Matter Spikes



‘**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

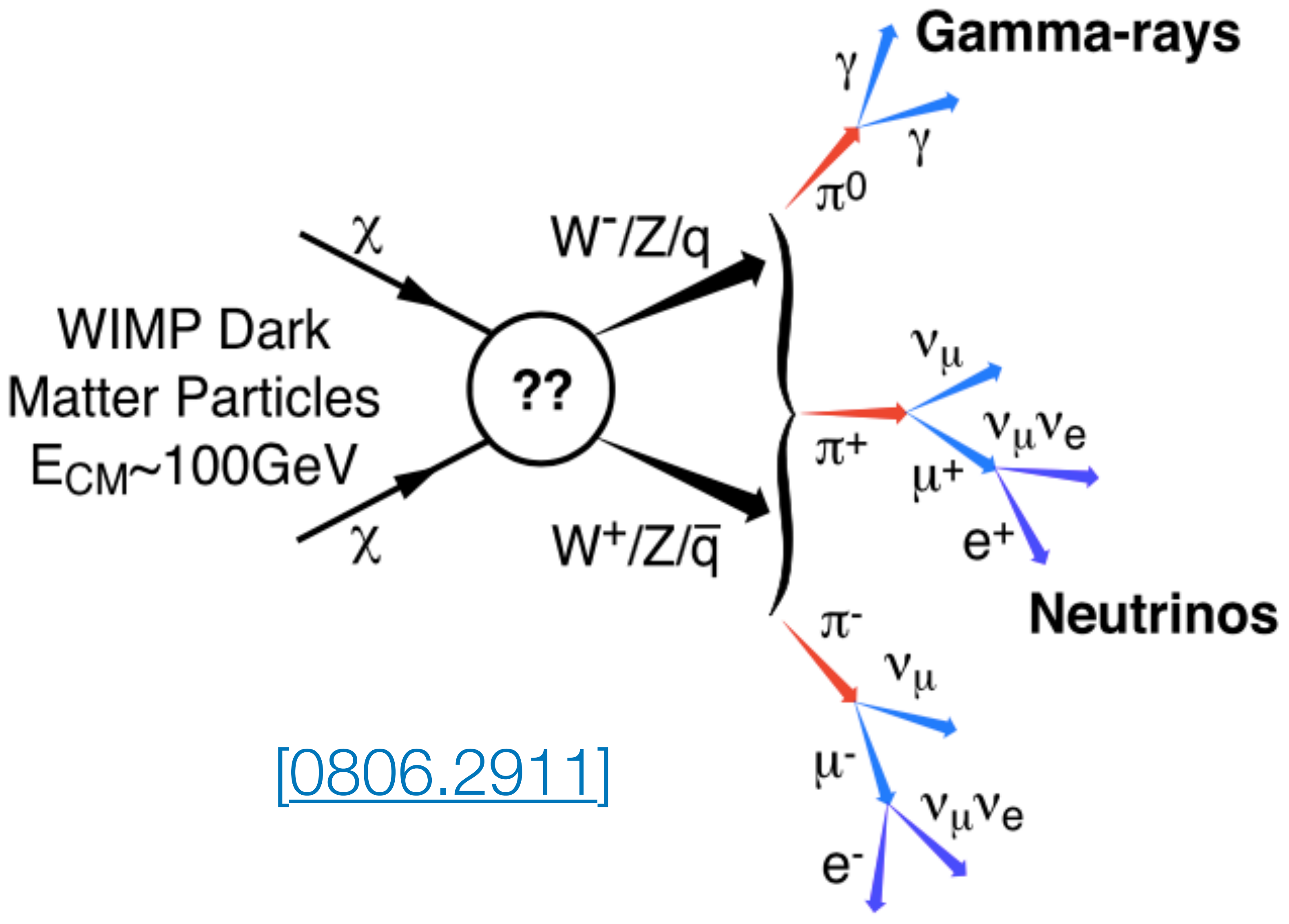
“Astrophysical scenario”

[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, …]



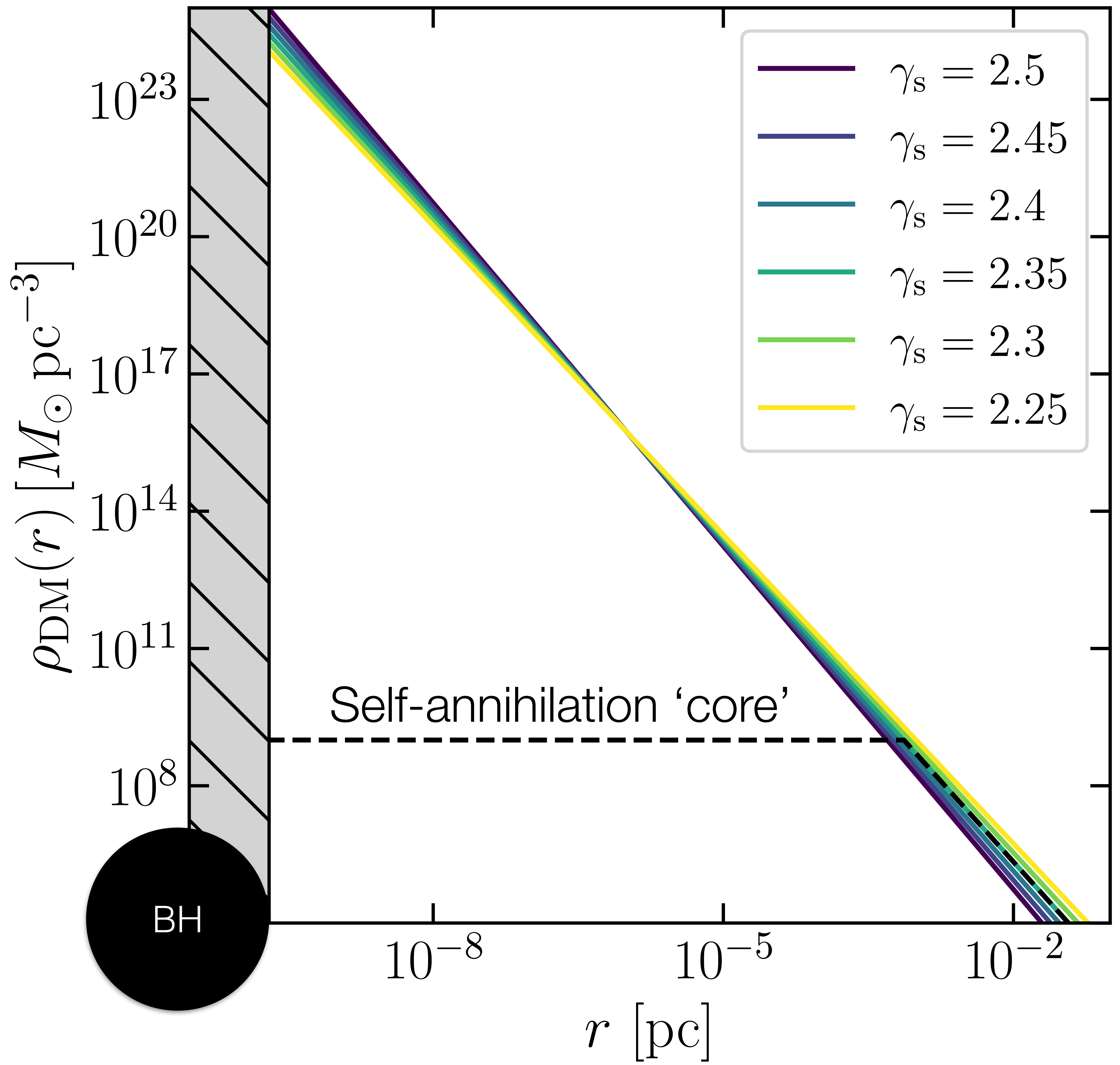
[0806.2911]

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]

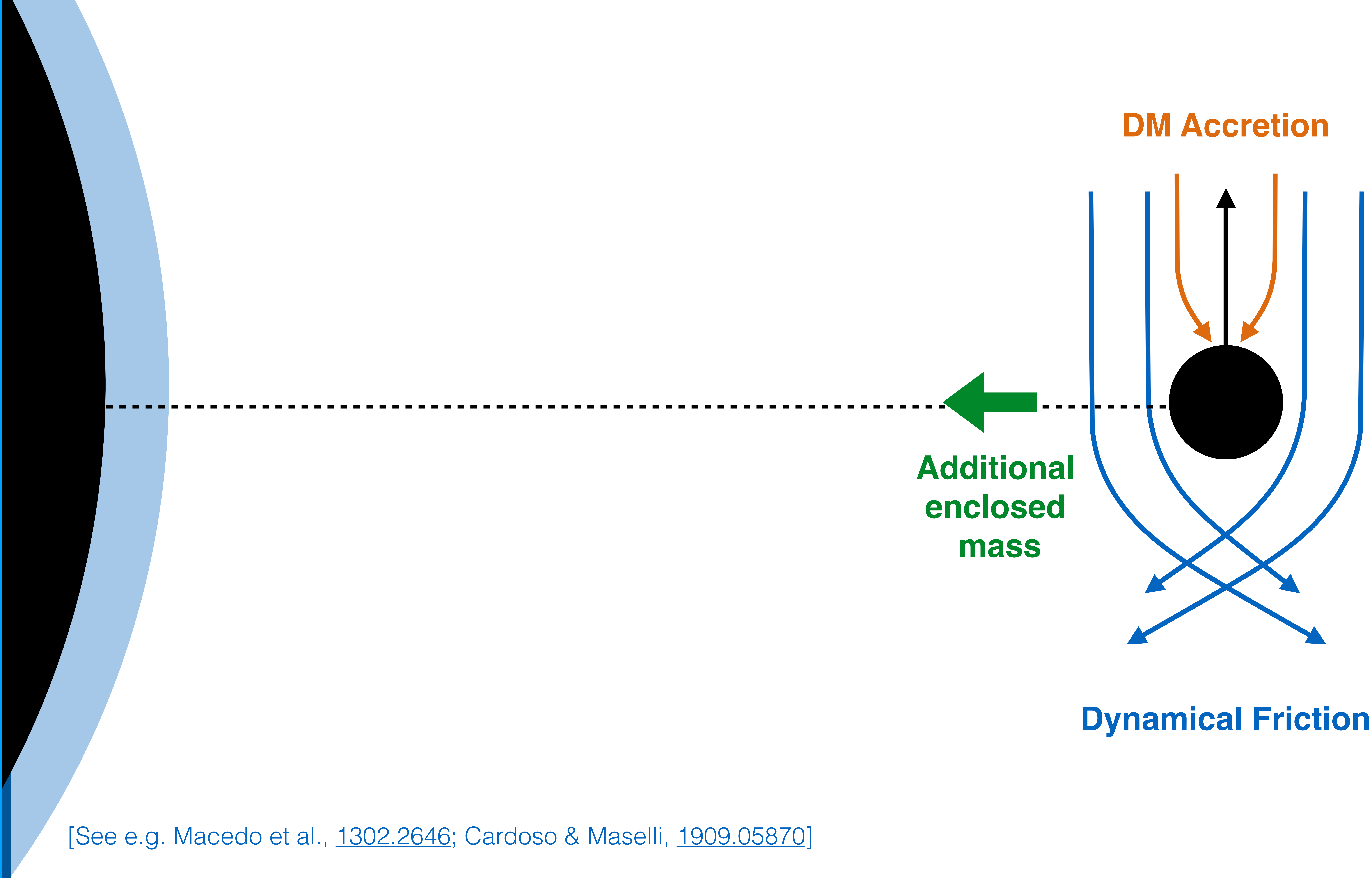
What about ***non-annihilating DM****?*

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



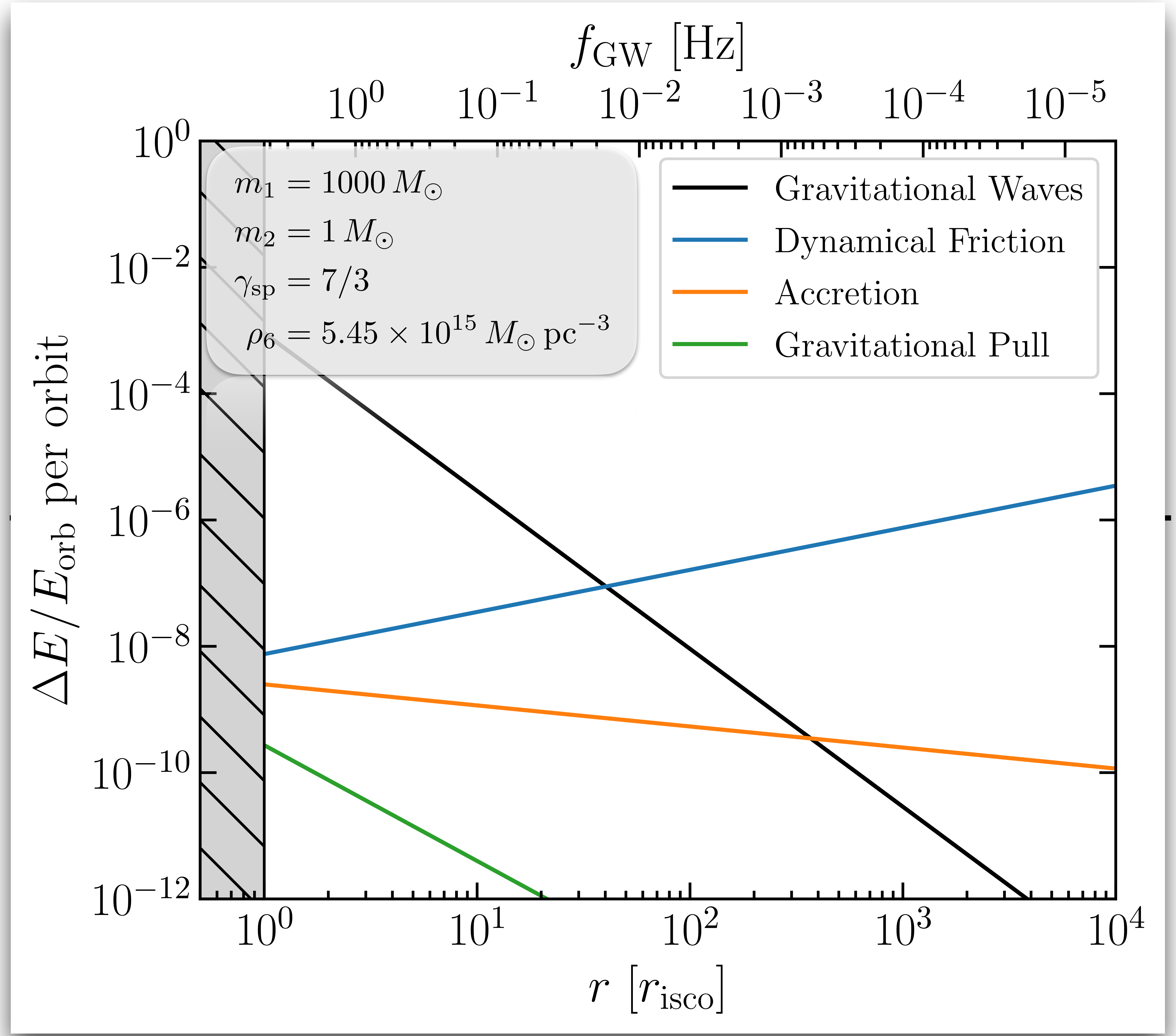
$$\rho_{\rm DM,\,local} \sim 10^{-2}\,M_\odot/{\rm pc}^3$$

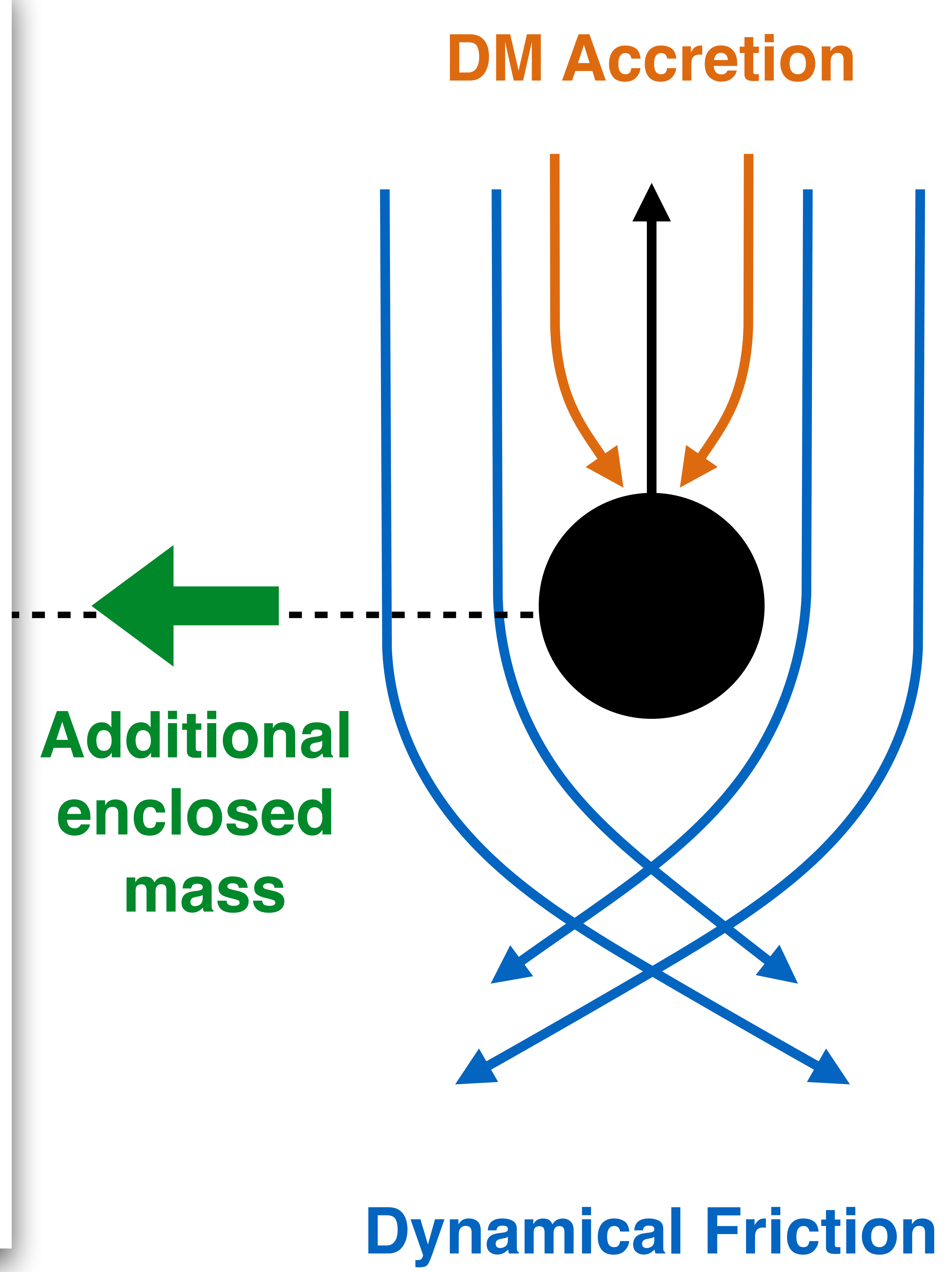
Impact of DM Spikes



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

Impact of DM Spikes





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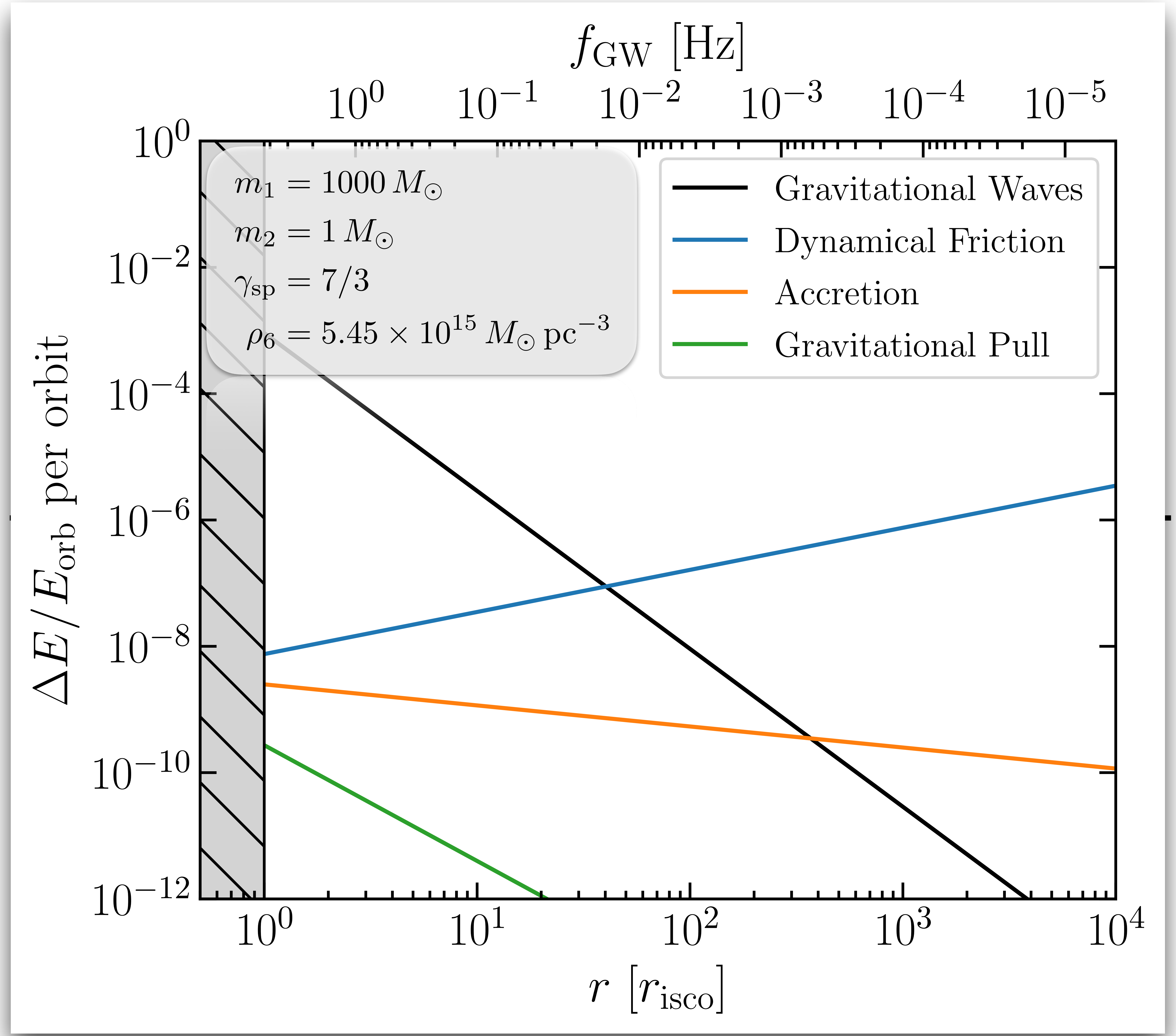
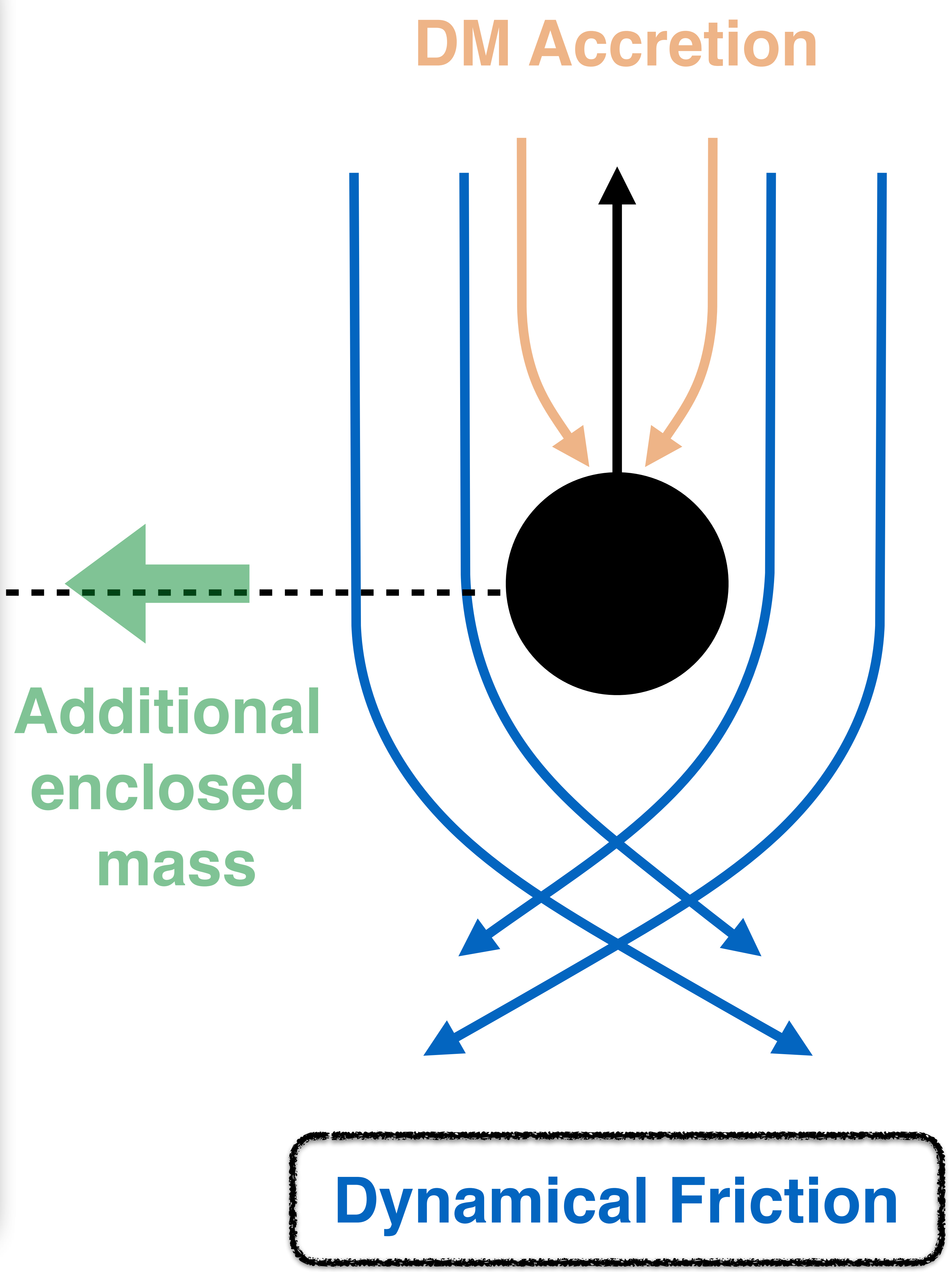
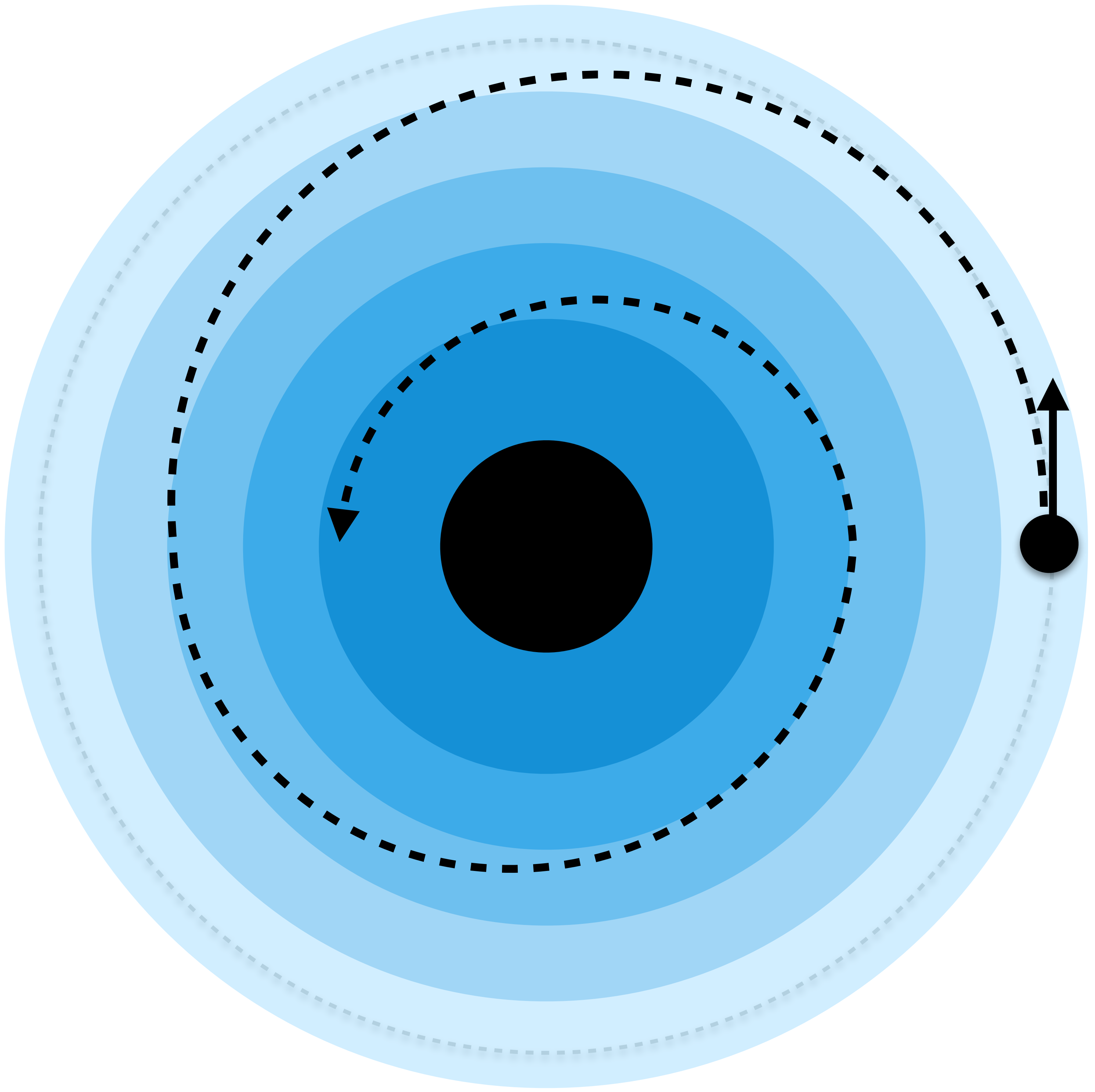




$$\dot{E}_{DF} \sim \frac{4\pi G^2 m_2^2 \rho_{DM}(r)\xi(v)}{v} \ln\Lambda$$

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

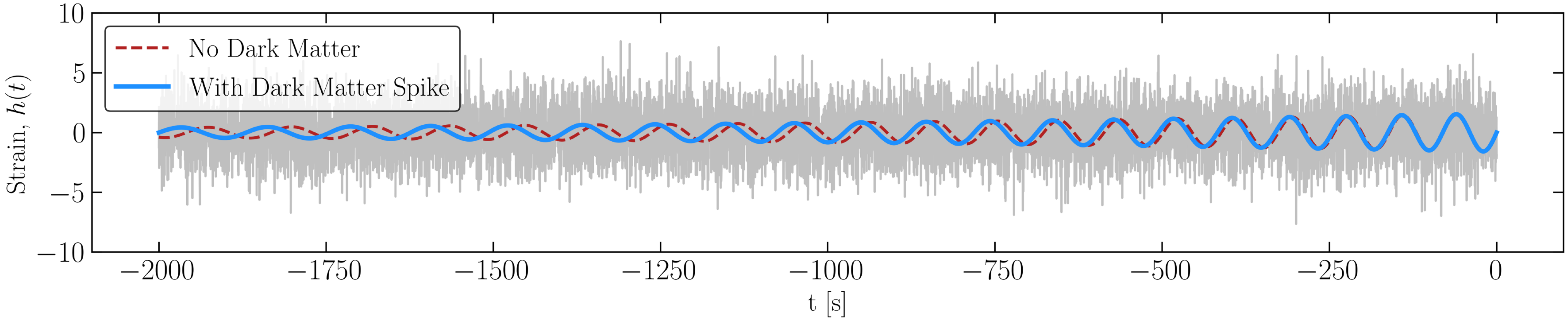
Dephasing of 'Dressed' IMRIs



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

Solve for Newtonian motion of the binary, taking into account:

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



[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:

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

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

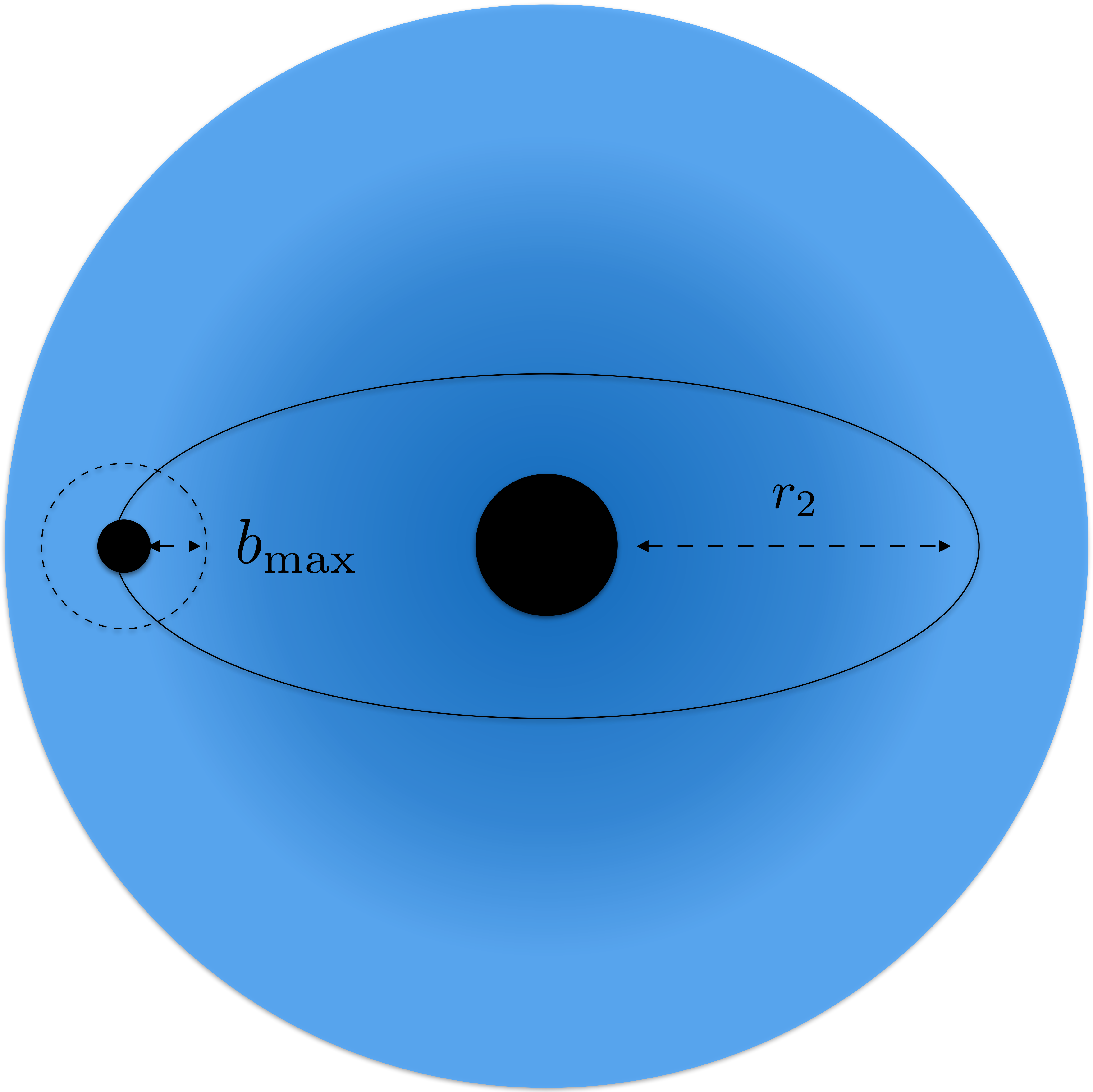
Each particle receives a 'kick' through gravitational scattering

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

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]

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' $\Delta\mathcal{E}$

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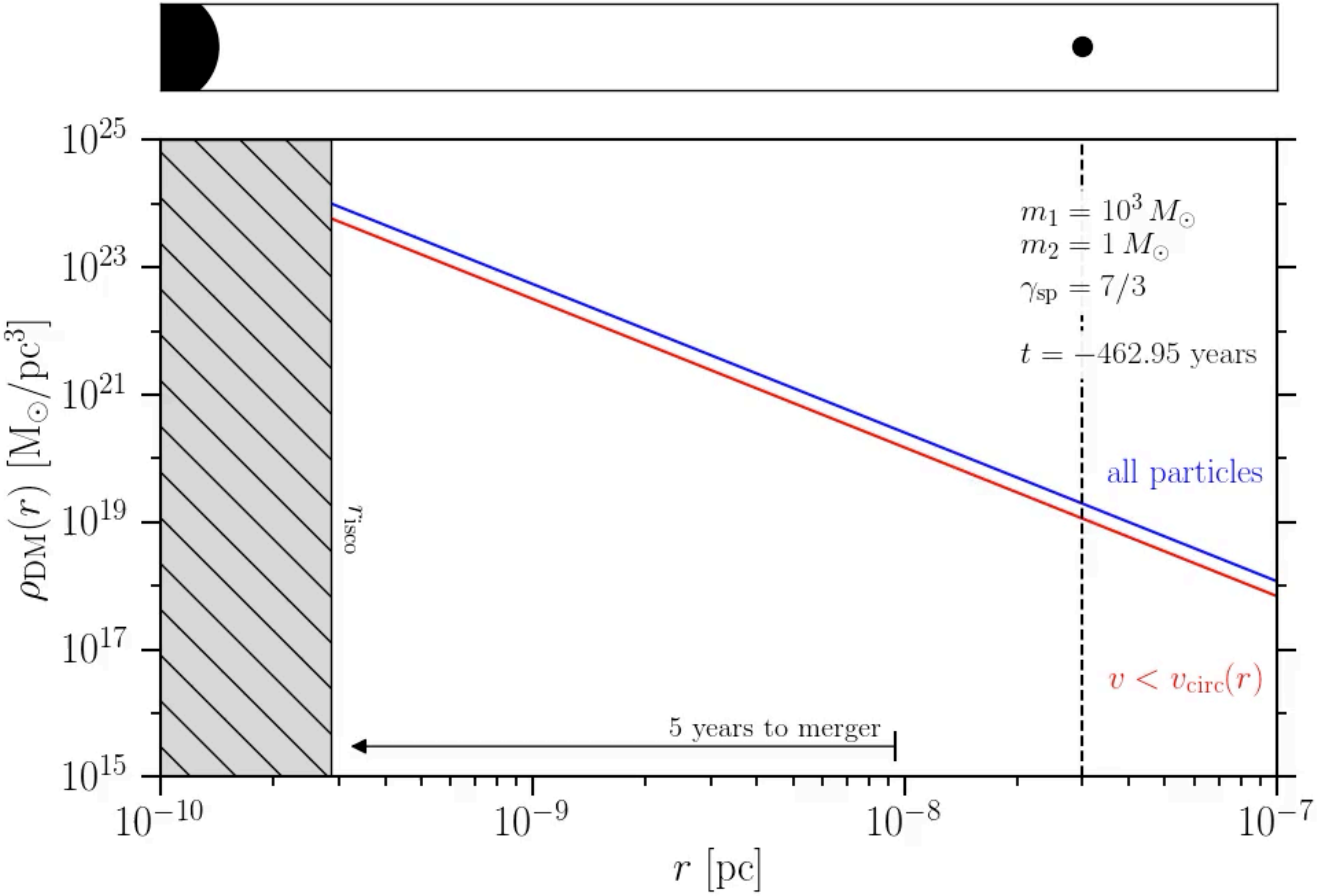
[**BJK**, Nichols, Gaggero, Bertone, 2002.12811] [Code available online: github.com/bradkav/HaloFeedback]

Co-evolution

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]

[Code: github.com/bradkav/HaloFeedback]

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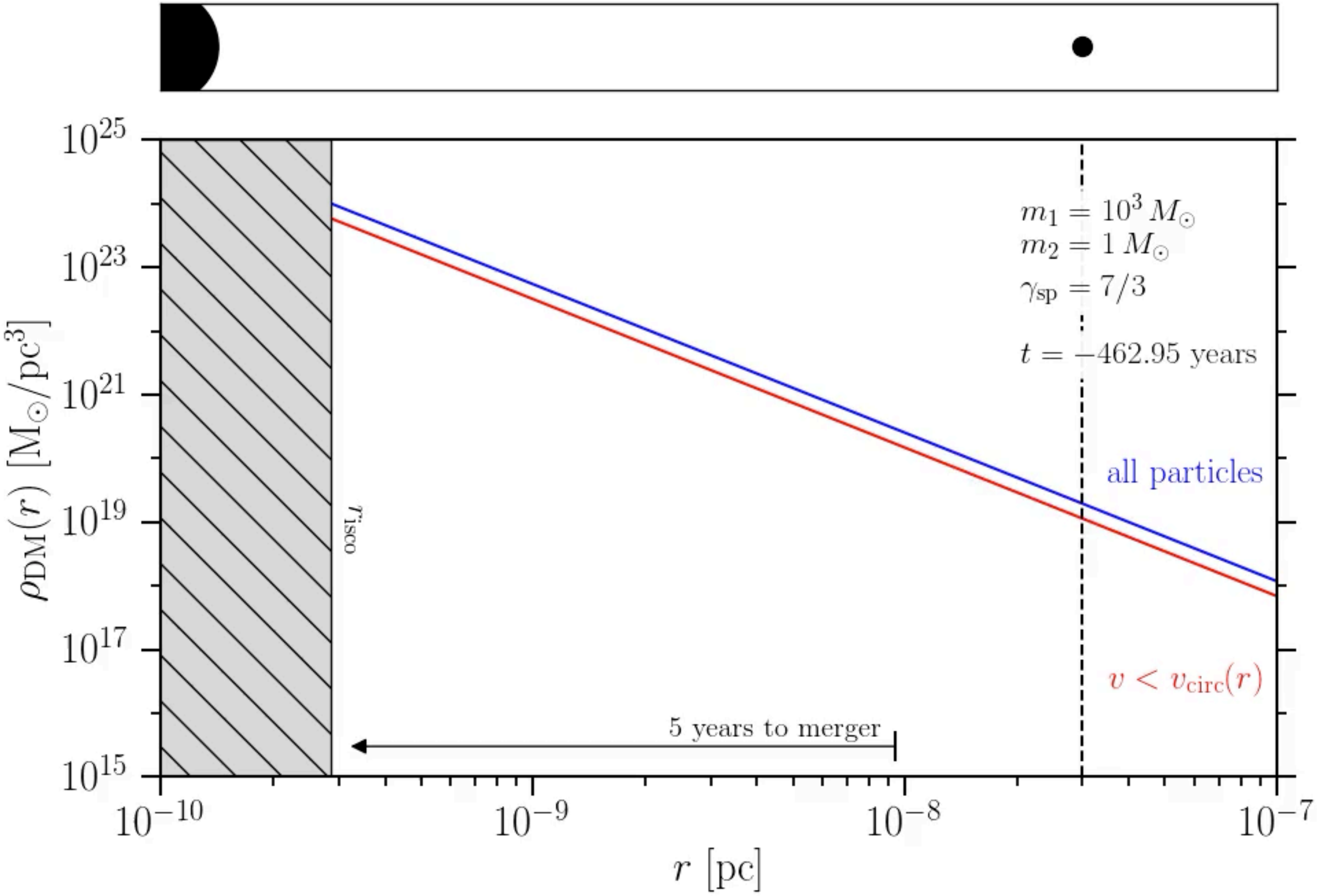

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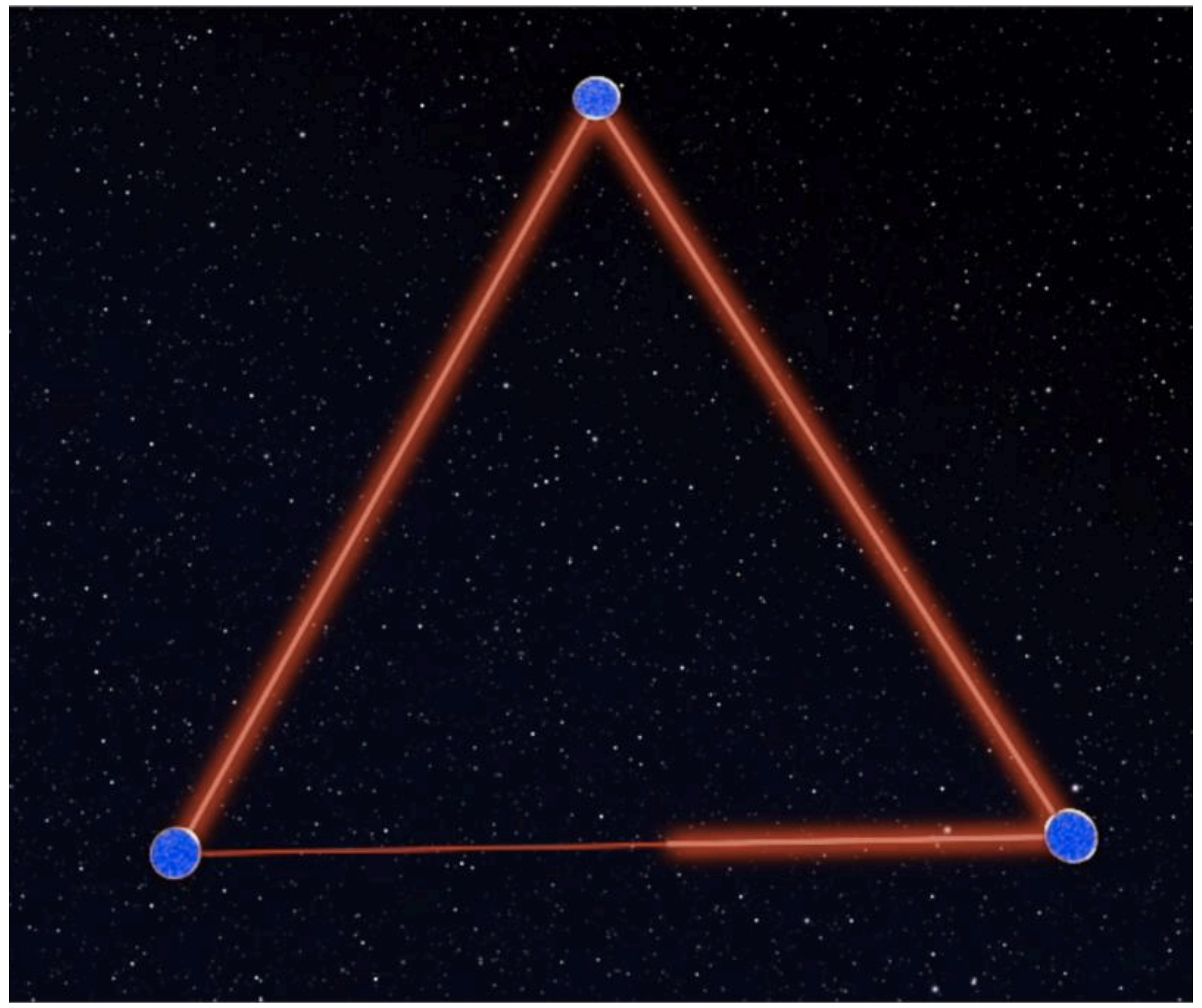
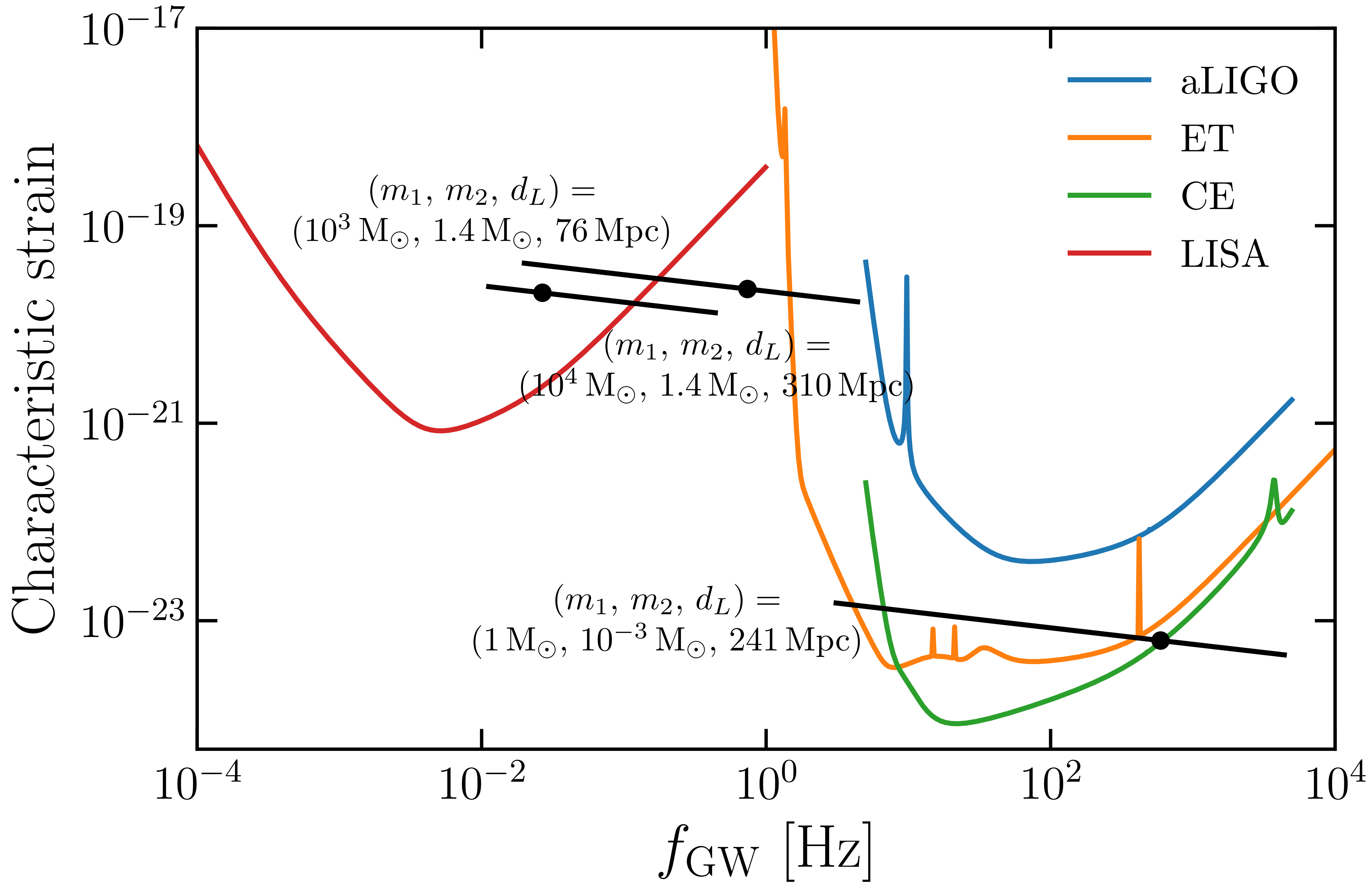
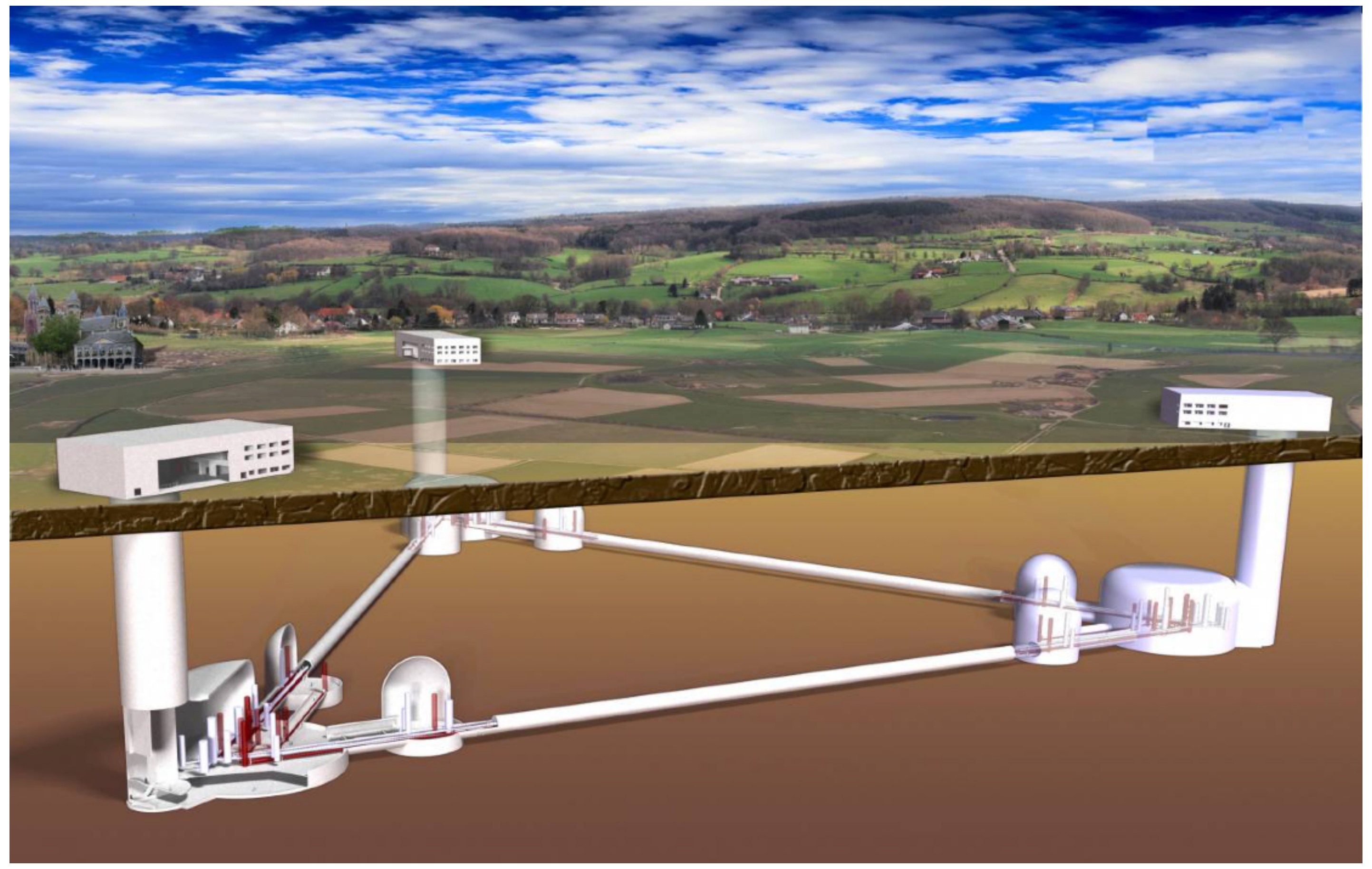


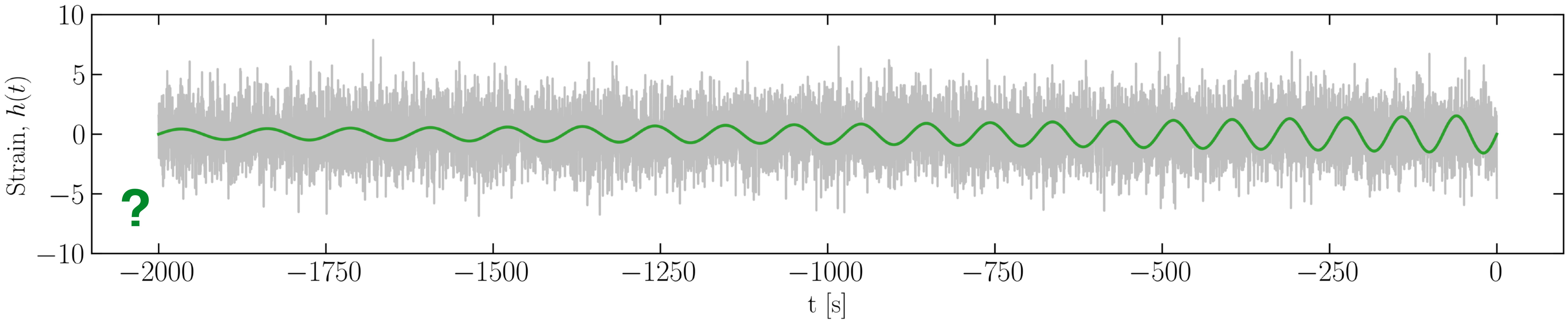
Laser **I**nterferometer **S**pace **A**ntenna
(planned for the 2030s)
[1907.06482]

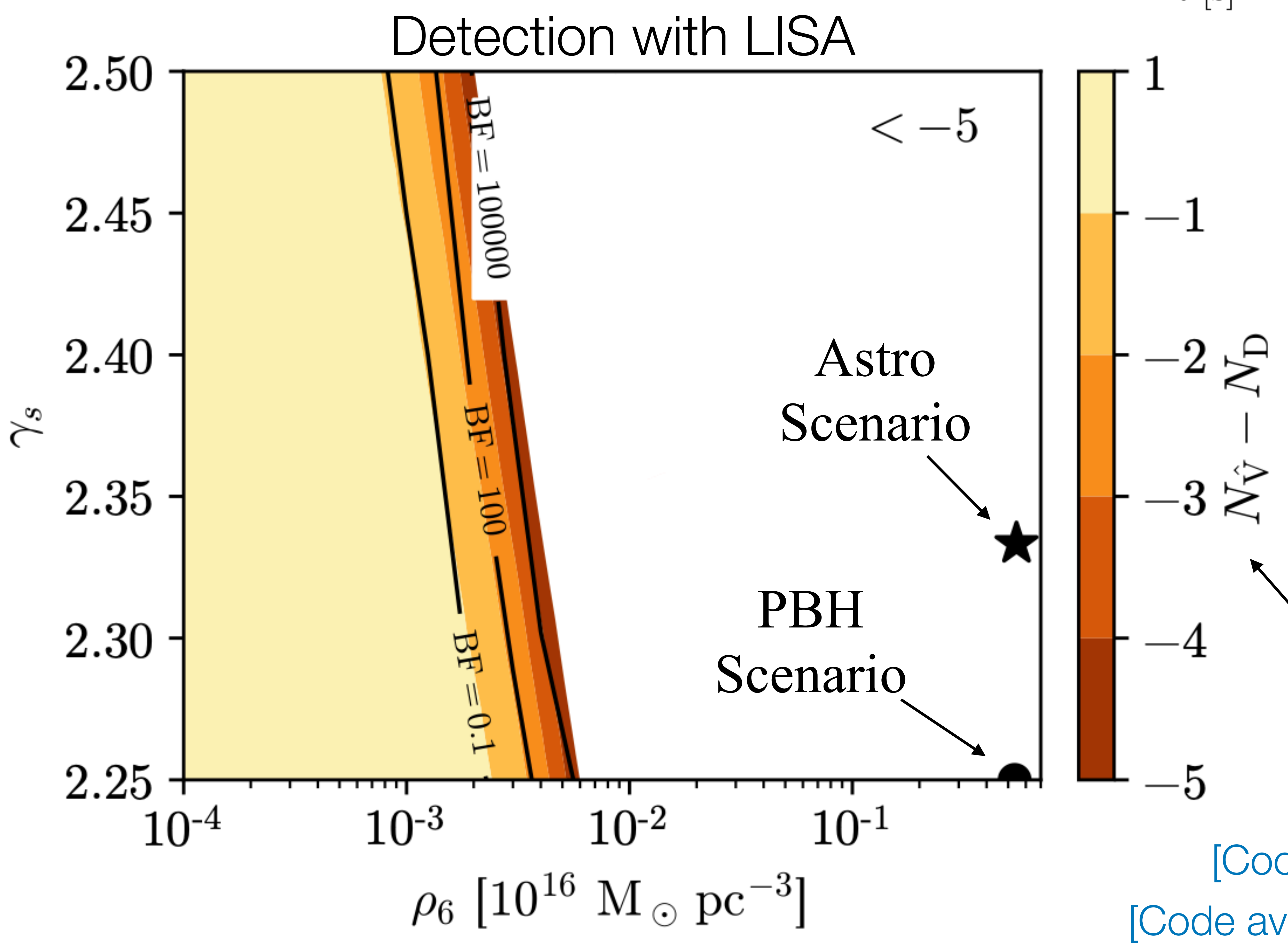


Einstein **T**elescope
[1912.02622]



Discoverability





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

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

vs.

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

Number of GW cycles of dephasing

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

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

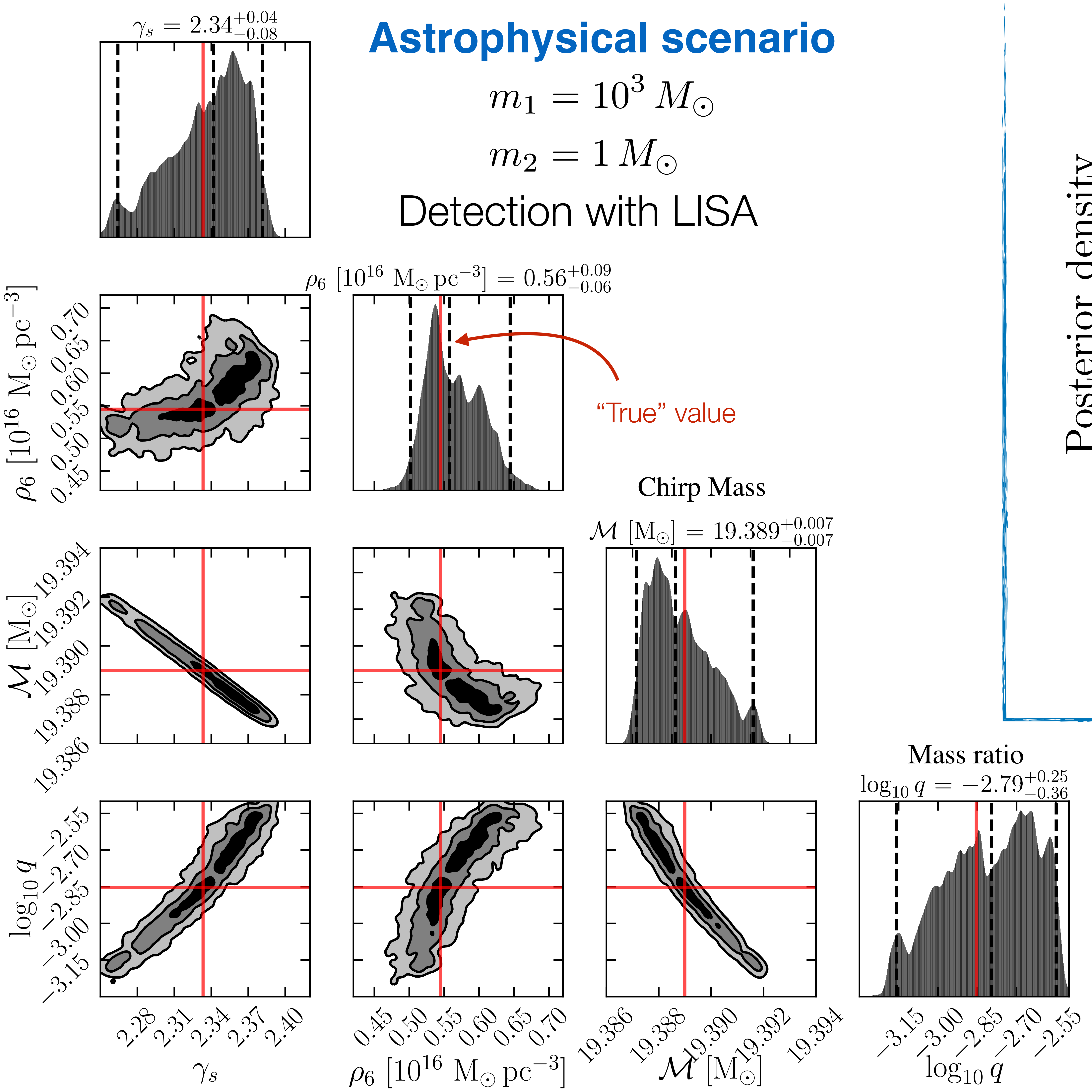
Measurability

Astrophysical scenario

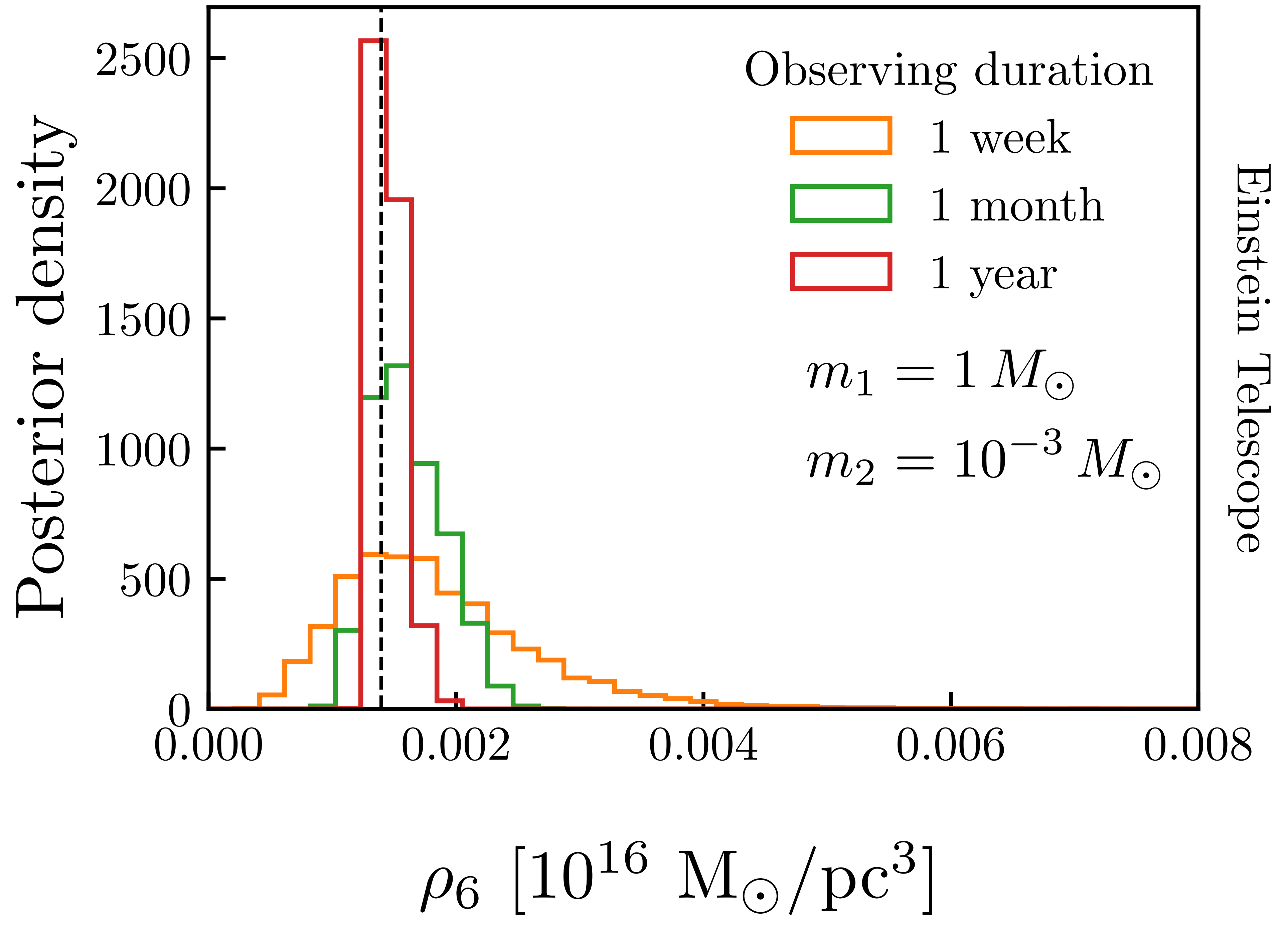
$m_1 = 10^3\, M_\odot$

$m_2 = 1\, M_\odot$

Detection with LISA



PBH scenario



Detection with Einstein Telescope

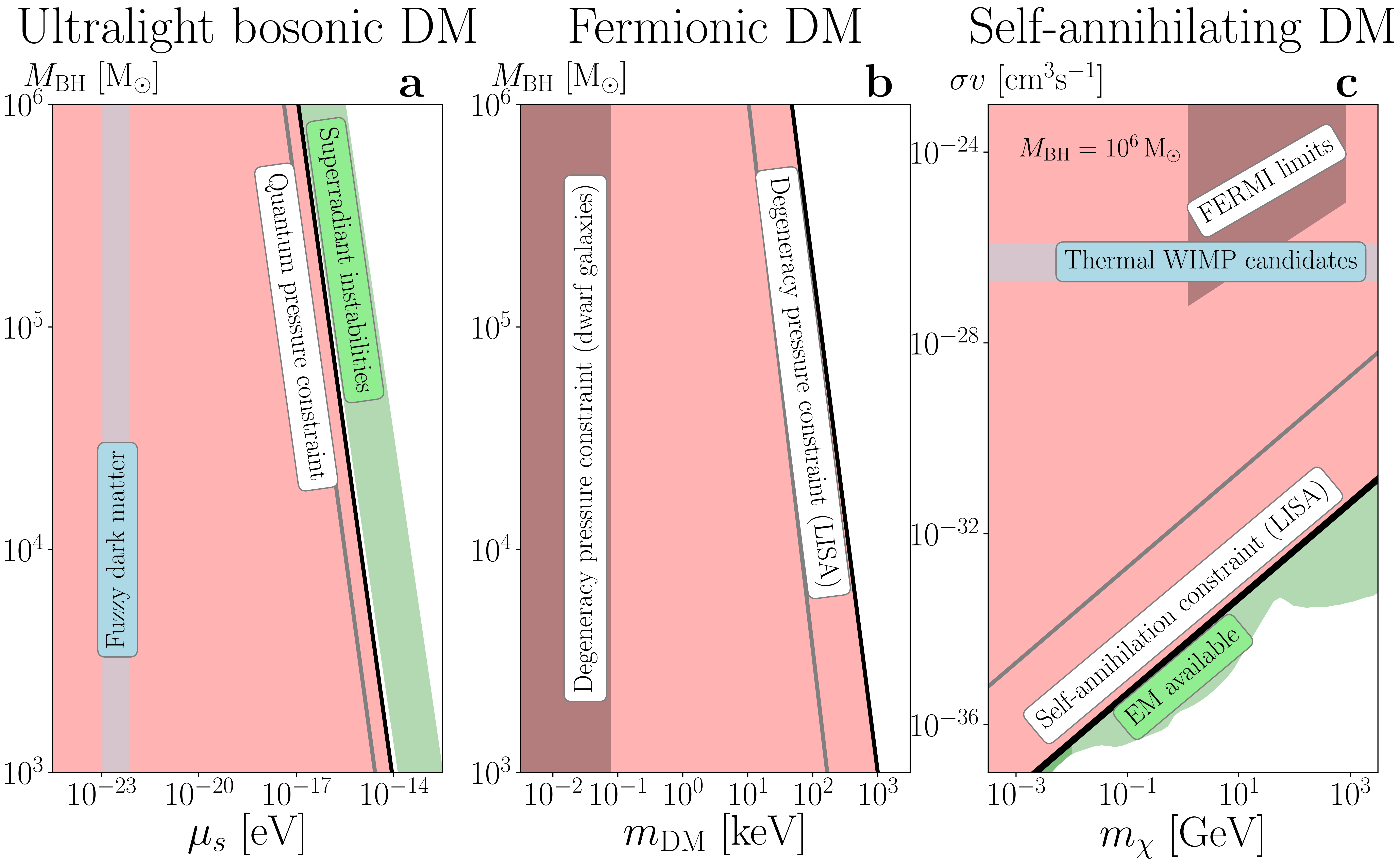
[Cole, Coogan, **BJK**, Bertone, 2207.07576]

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

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

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

[1906.11845]



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

Towards better DM spikes

Confusion with other environmental effects

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

Relativistic effects

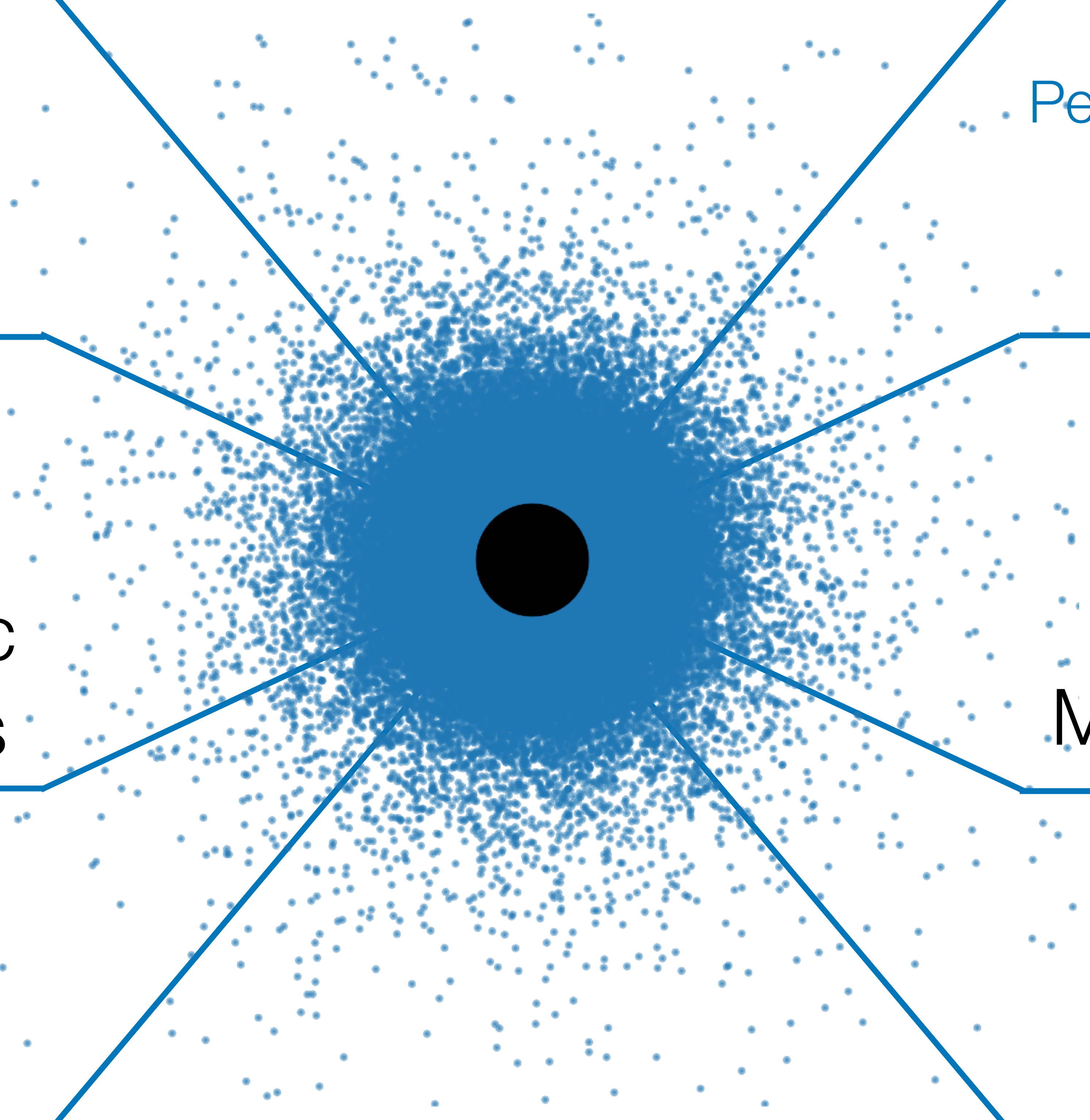
[See e.g. 2204.12508]

Integration with realistic IMRI/EMRI waveforms

[See e.g. 2104.04582]

Accretion (for BHs)

[See e.g. Nichols et al. 2309.06498]



Realistic spike formation scenarios

[Ongoing work with Abram Perez, Pratika Dayal, and others]

Eccentric orbits

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

More realistic feedback

[Ongoing work led by Theophanes Karydas]

Search strategies

Towards better DM spikes

Confusion with other environmental effects

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

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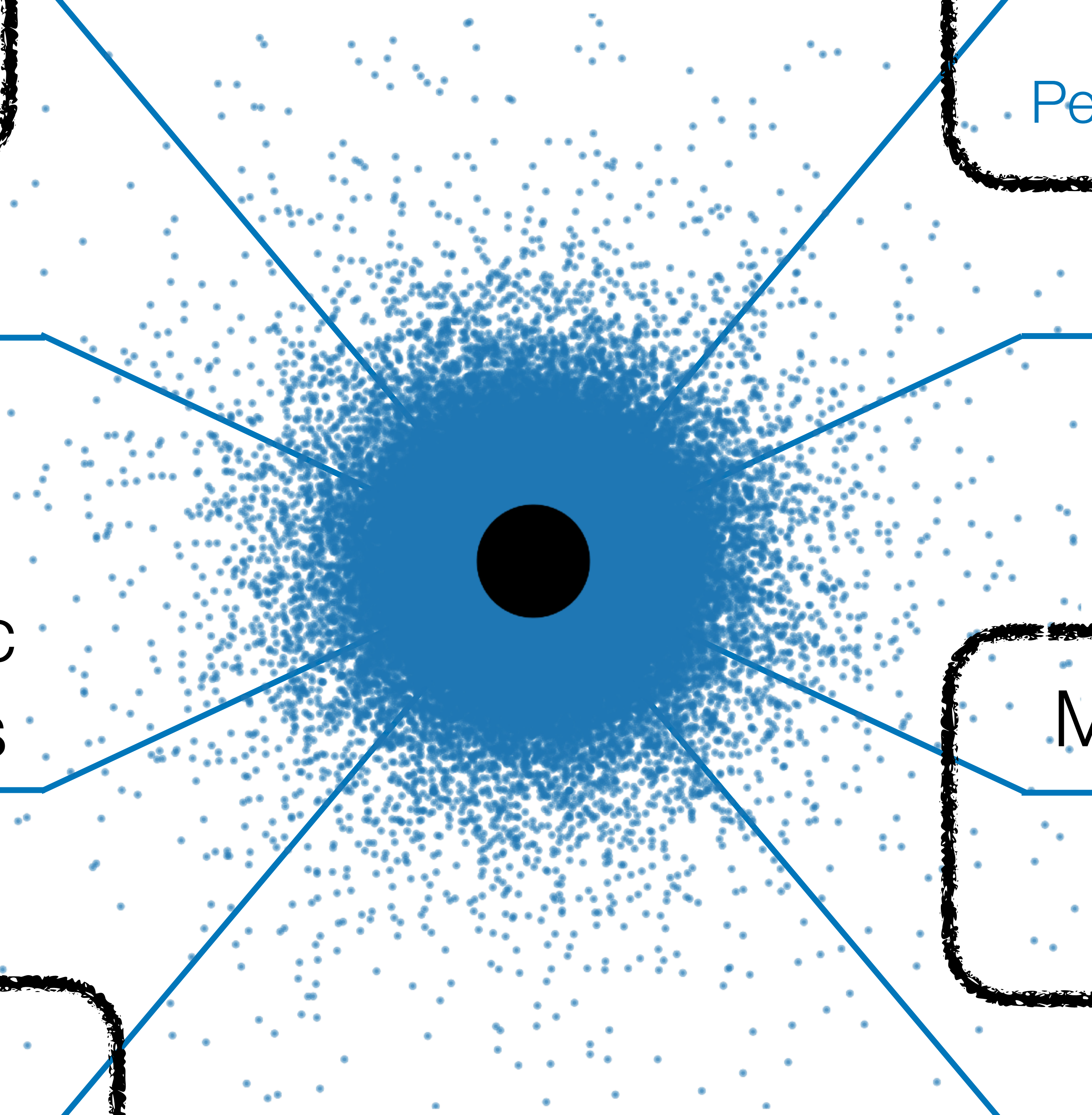

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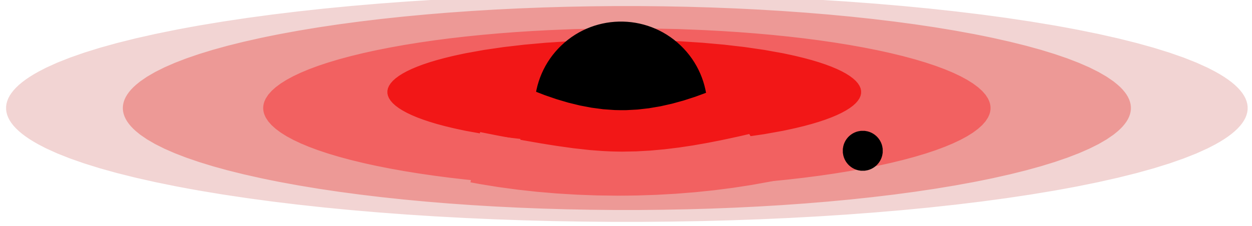
Search strategies

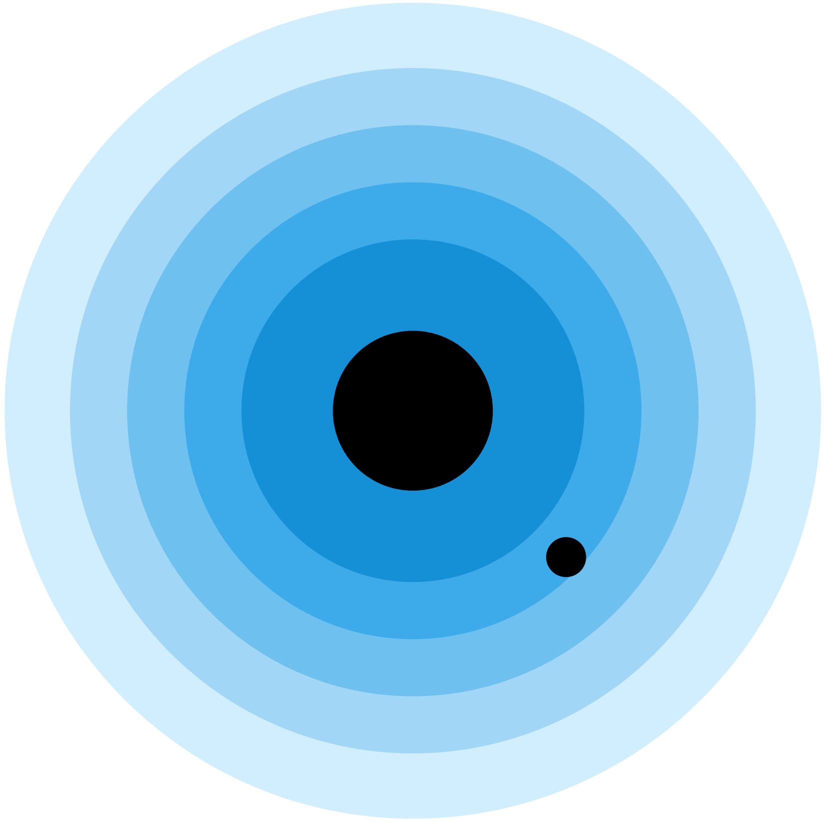
Environmental confusion?

Generate waveform assuming:

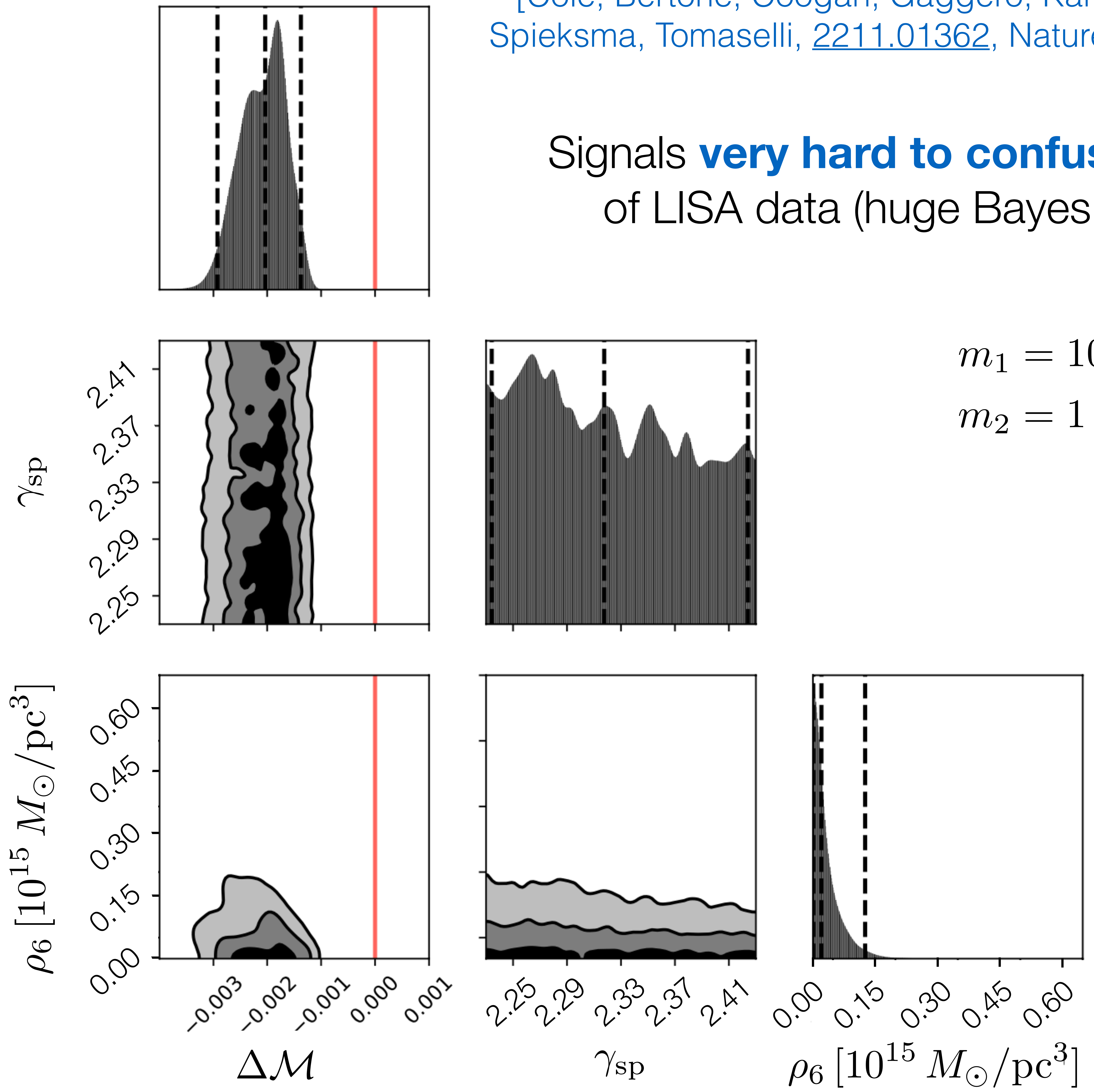


$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1/2}$$

Fit signal assuming:

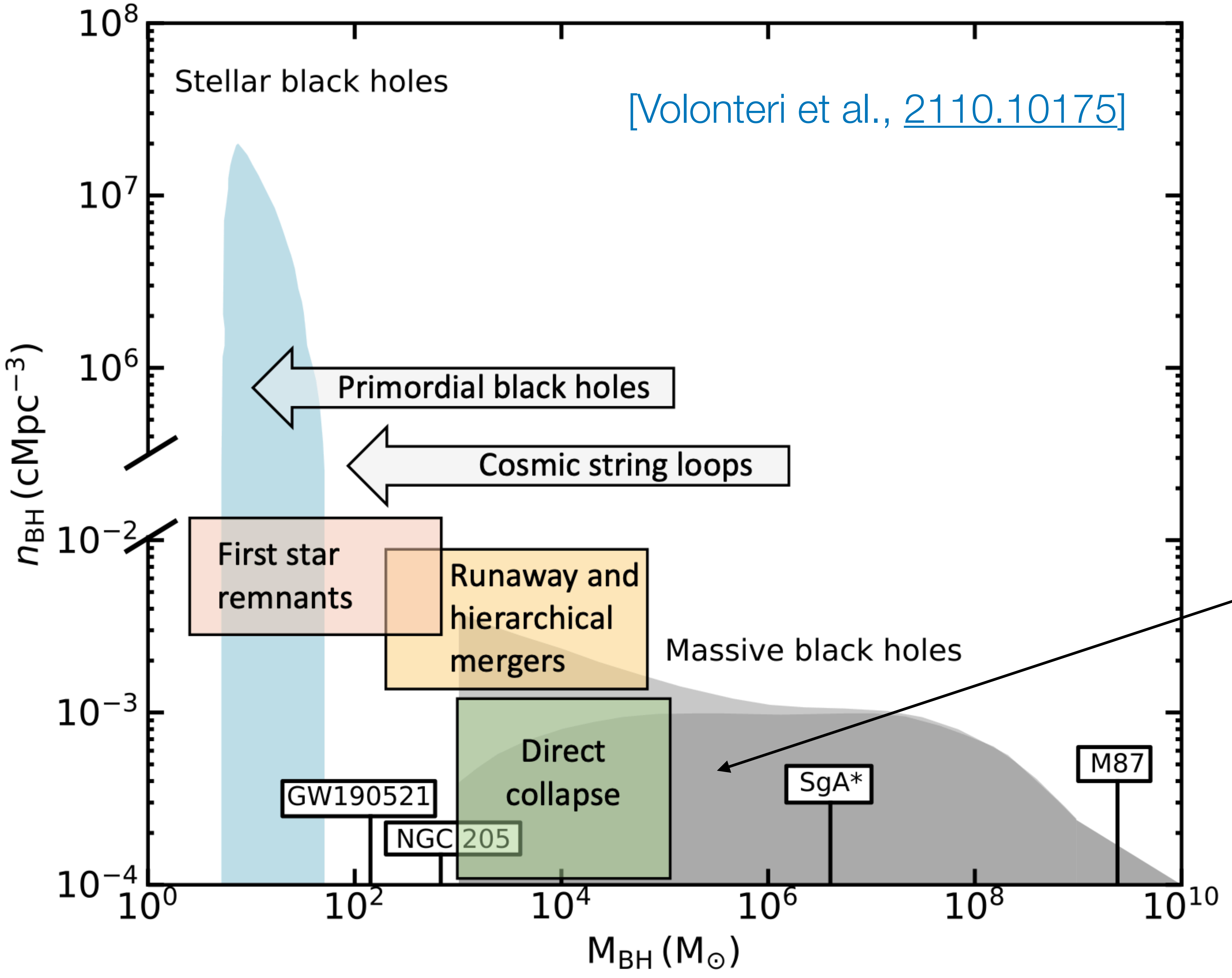


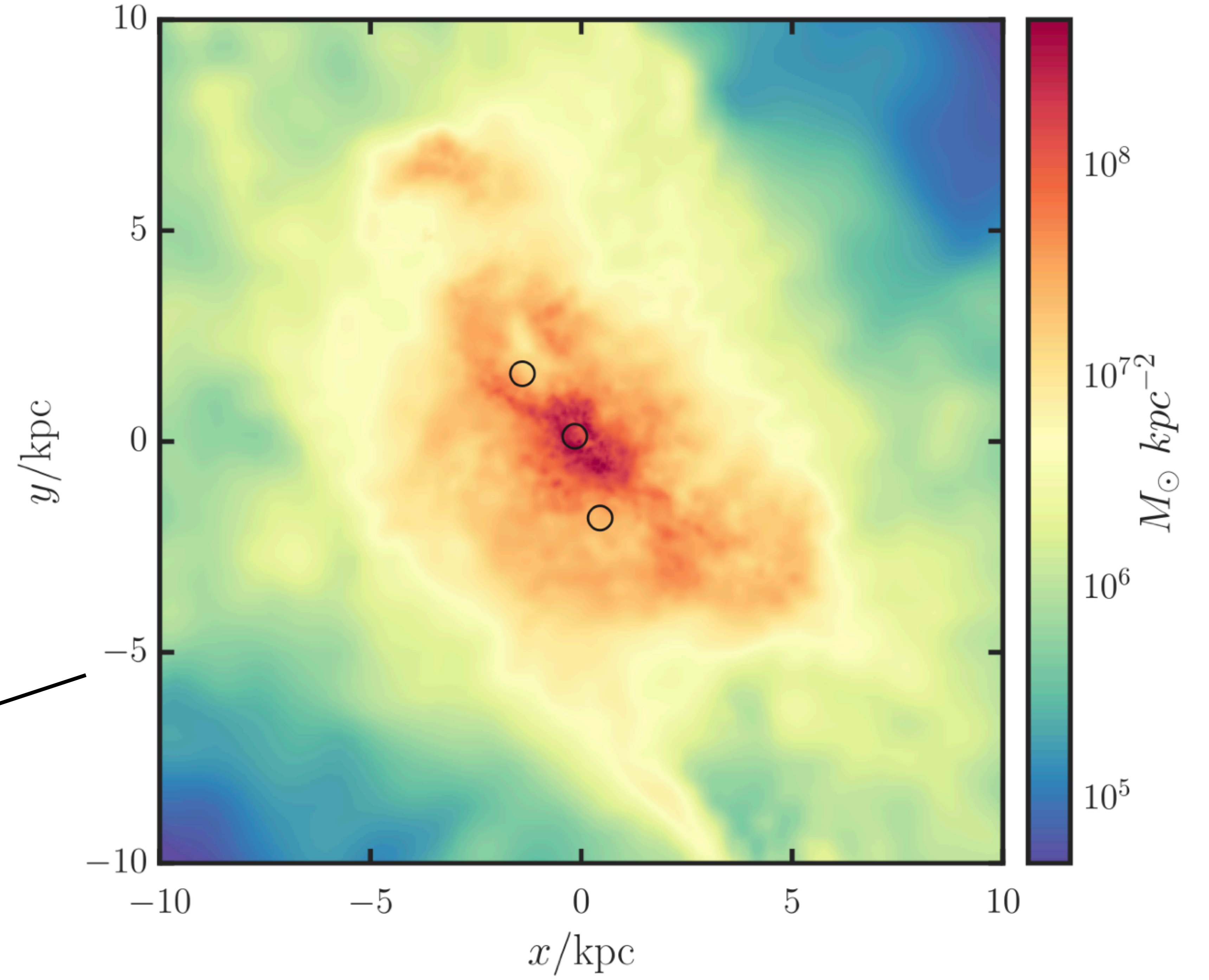
[Cole, Bertone, Coogan, Gaggero, Karydas, **BJK**, Spieksma, Tomaselli, 2211.01362, Nature Astronomy]



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

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





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

Preliminary results suggest that large densities are possible but do these systems survive, and are they common?

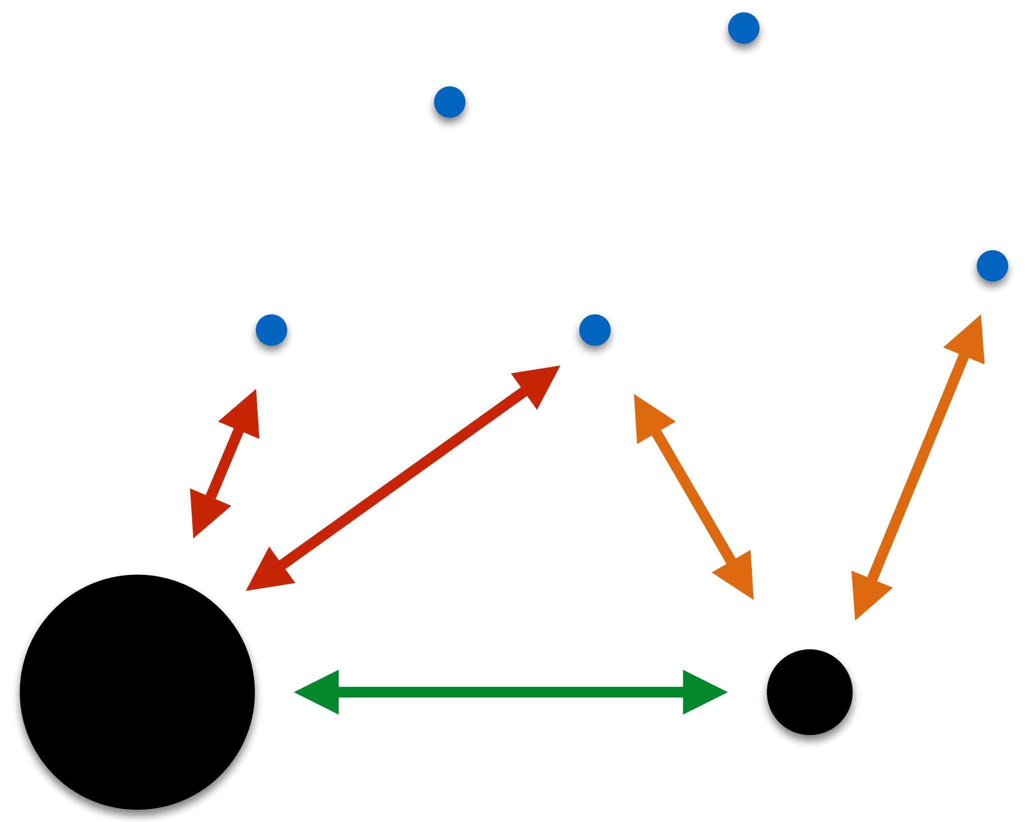
$$\rho_6 \gtrsim 10^{16}\, M_\odot\, \mathrm{pc}^{-3}$$

[Work in progress with Abram Perez and Pratika Dayal, as well as Daniele Gaggero, Renske Wierda & Gianfranco Bertone]

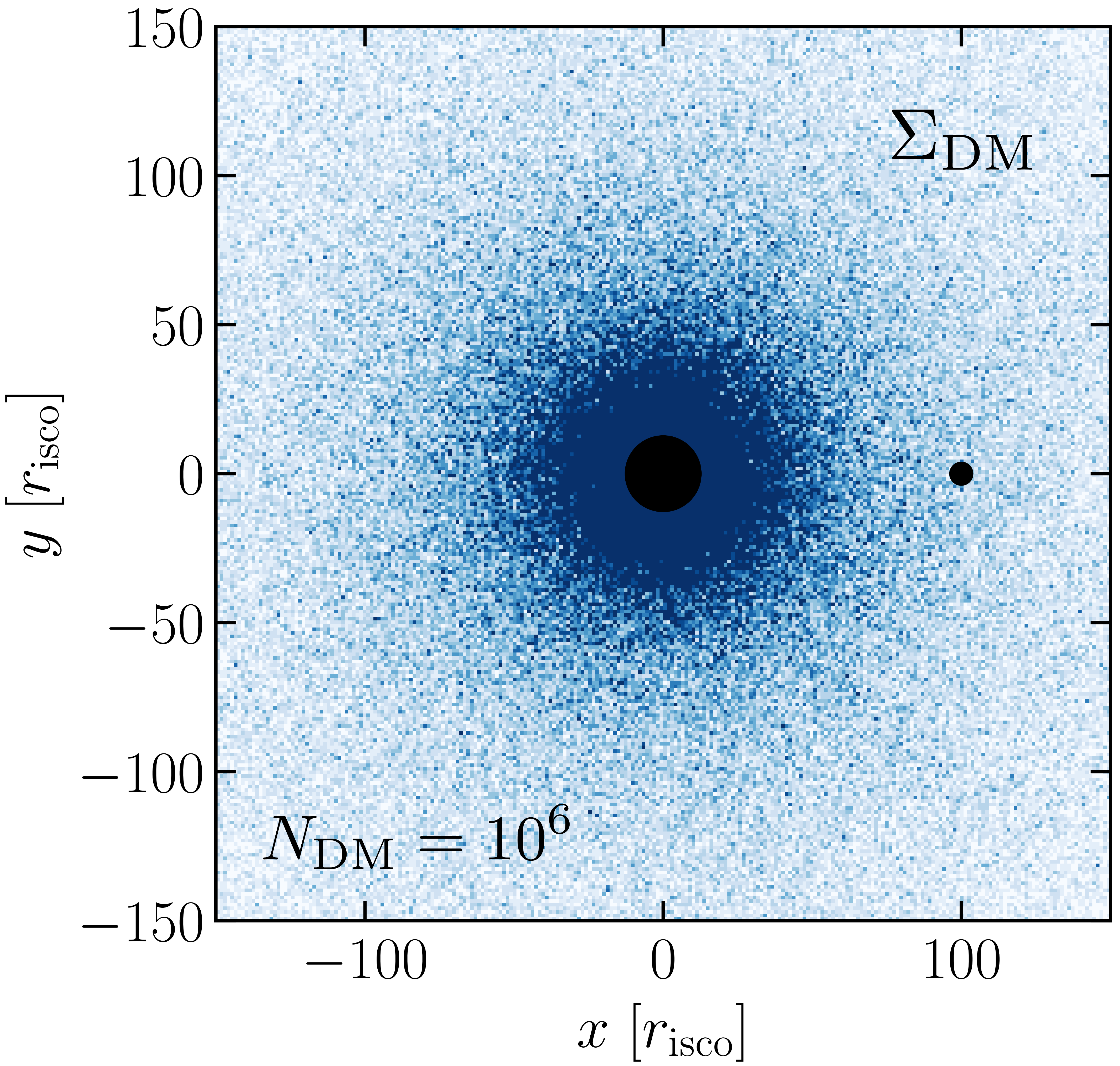
Eventually need to expand and verify our description of dynamical friction and feedback in the DM spike (also include anisotropy, accretion, post-Newtonian corrections…)

NbodyIMRI: N-body solver tailored to DM spikes

No DM-DM interparticle forces



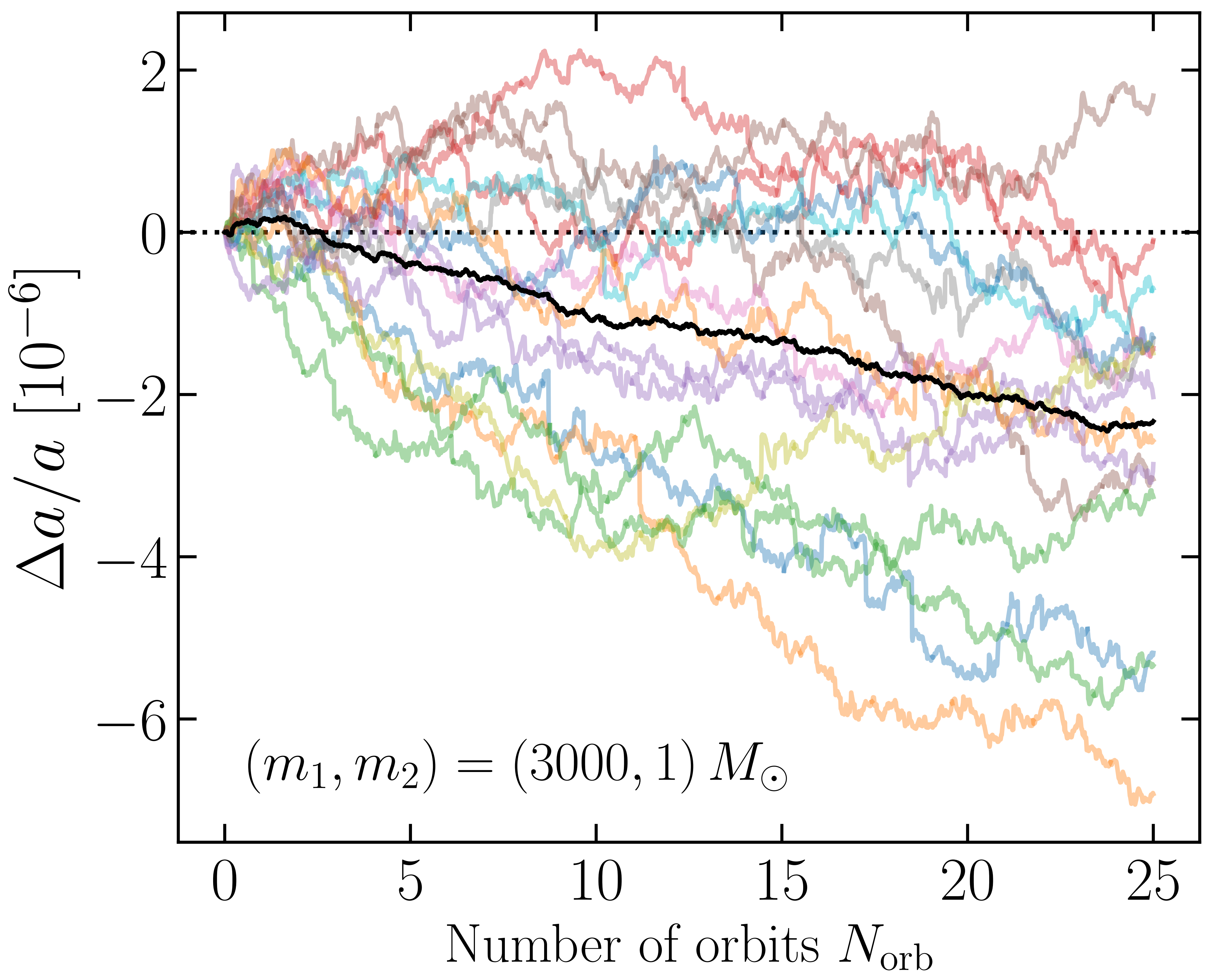
[Code here: github.com/bradkav/NbodyIMRI]



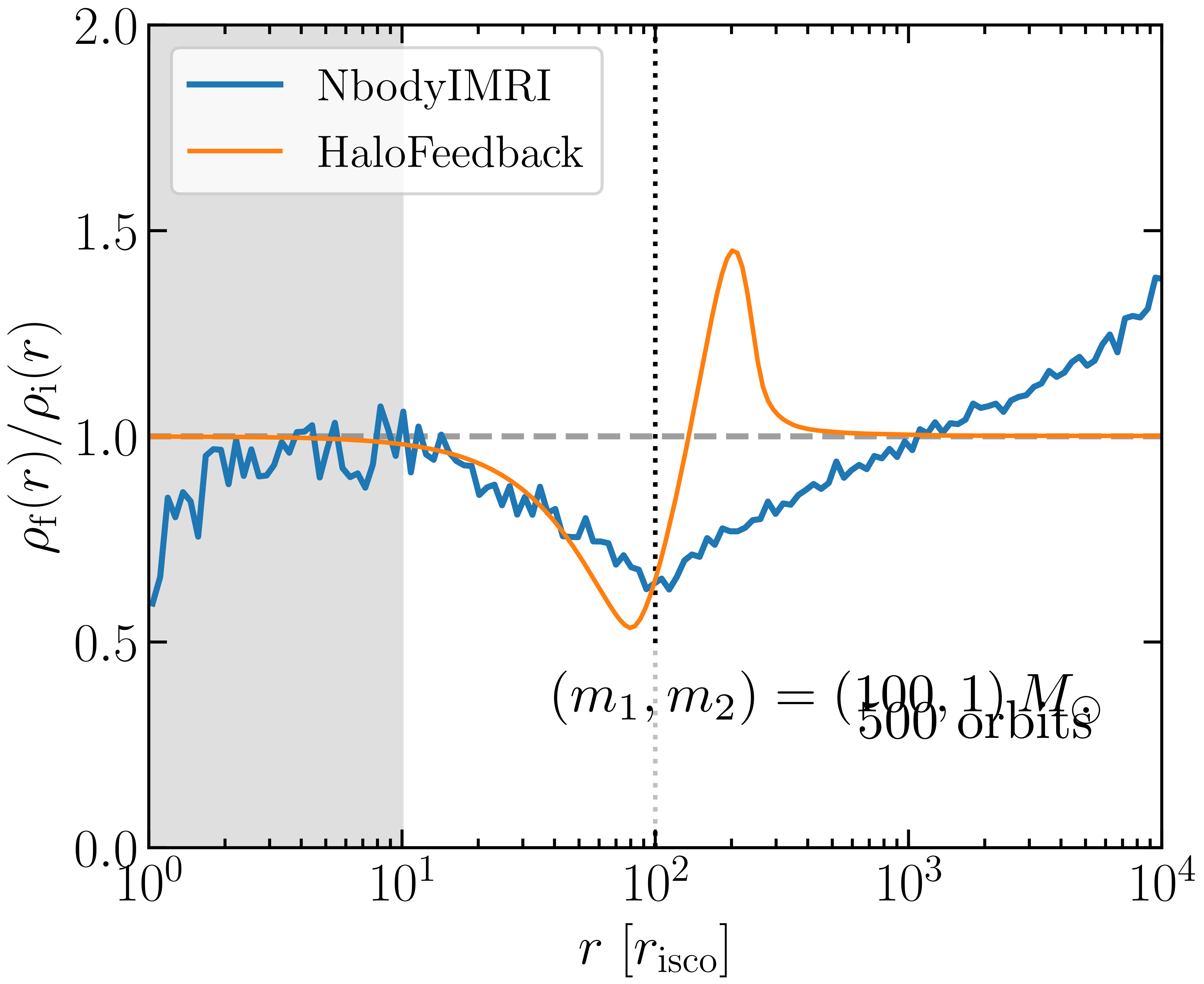
N-body Verification

PRELIMINARY

Verify strength of dynamical friction force:



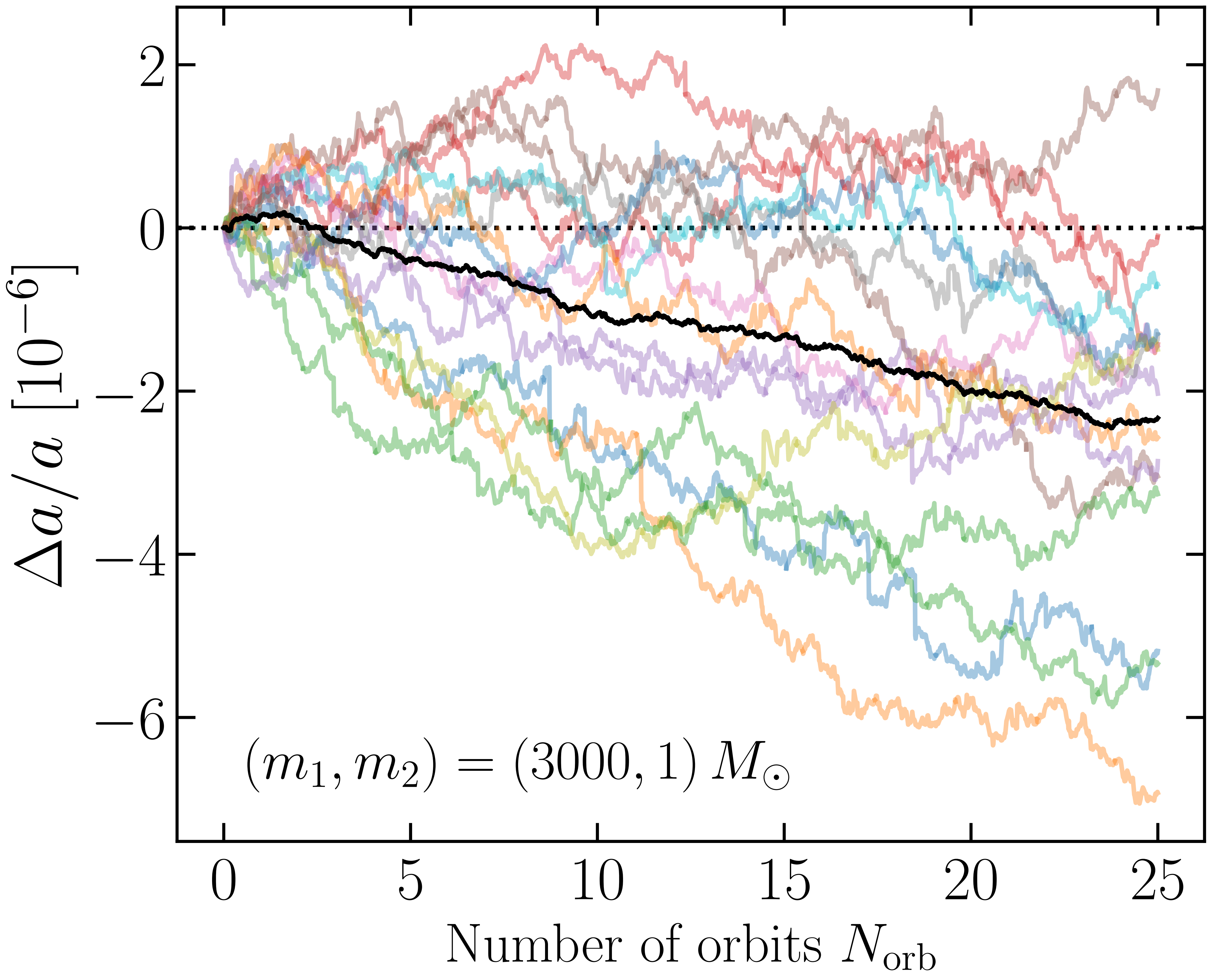
Verify dynamics of the DM halo:



N-body Verification

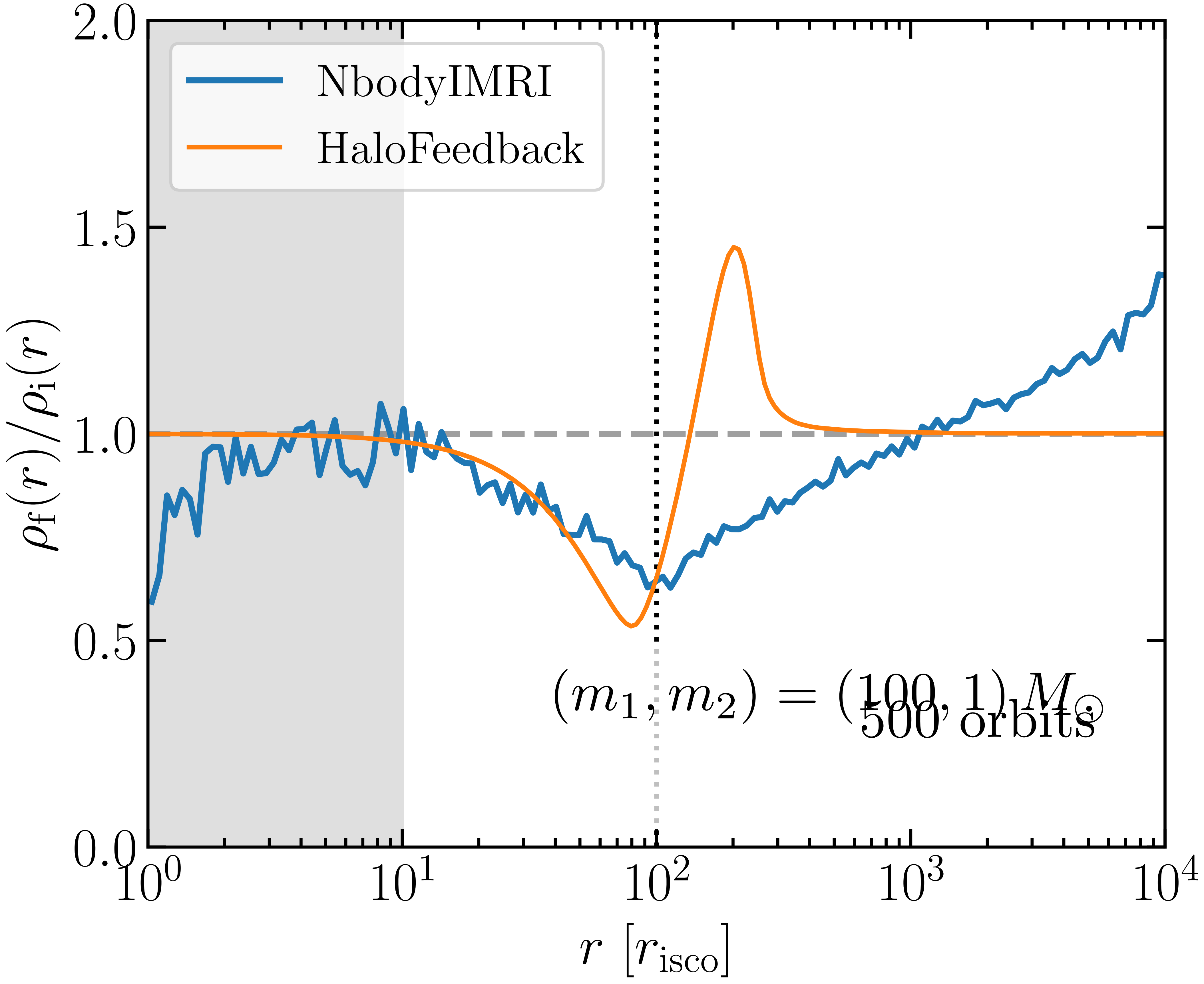
PRELIMINARY

Verify strength of dynamical friction force:



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

Verify dynamics of the DM halo:



DM Accretion

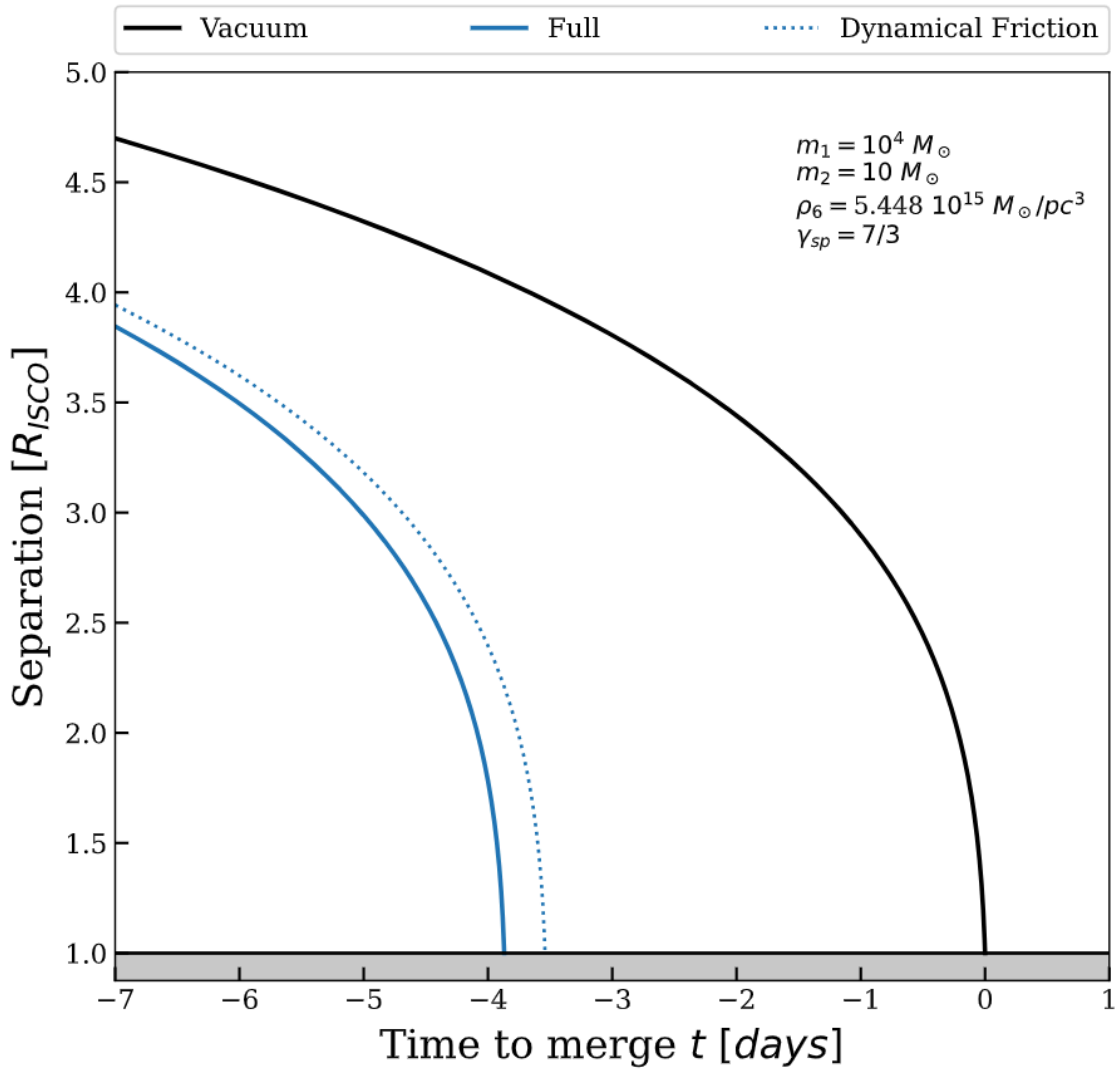
PRELIMINARY

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

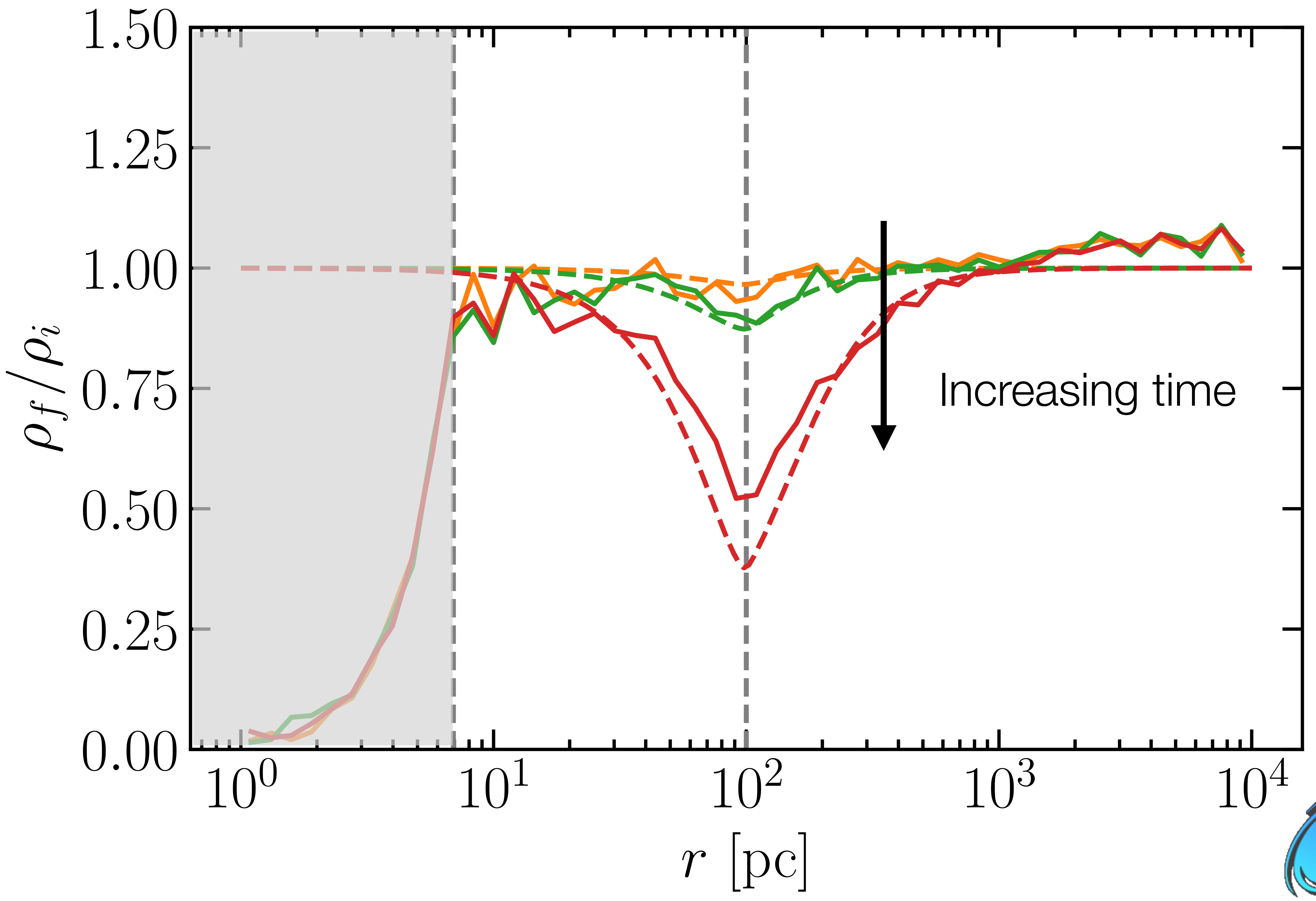
$$F_{\rm acc} = \int \mathrm{d}^3\mathbf{v}\, \pi b_{\rm acc}^2(\mathbf{v}_{\rm rel}) v_{\rm rel}\, \rho_\chi \mathbf{v}_{\rm rel} \qquad \mathbf{v}_{\rm rel} = \mathbf{v}_{\rm orb} - \mathbf{v}$$

[Work in progress with Theophanes Karydas & Gianfranco Bertone]

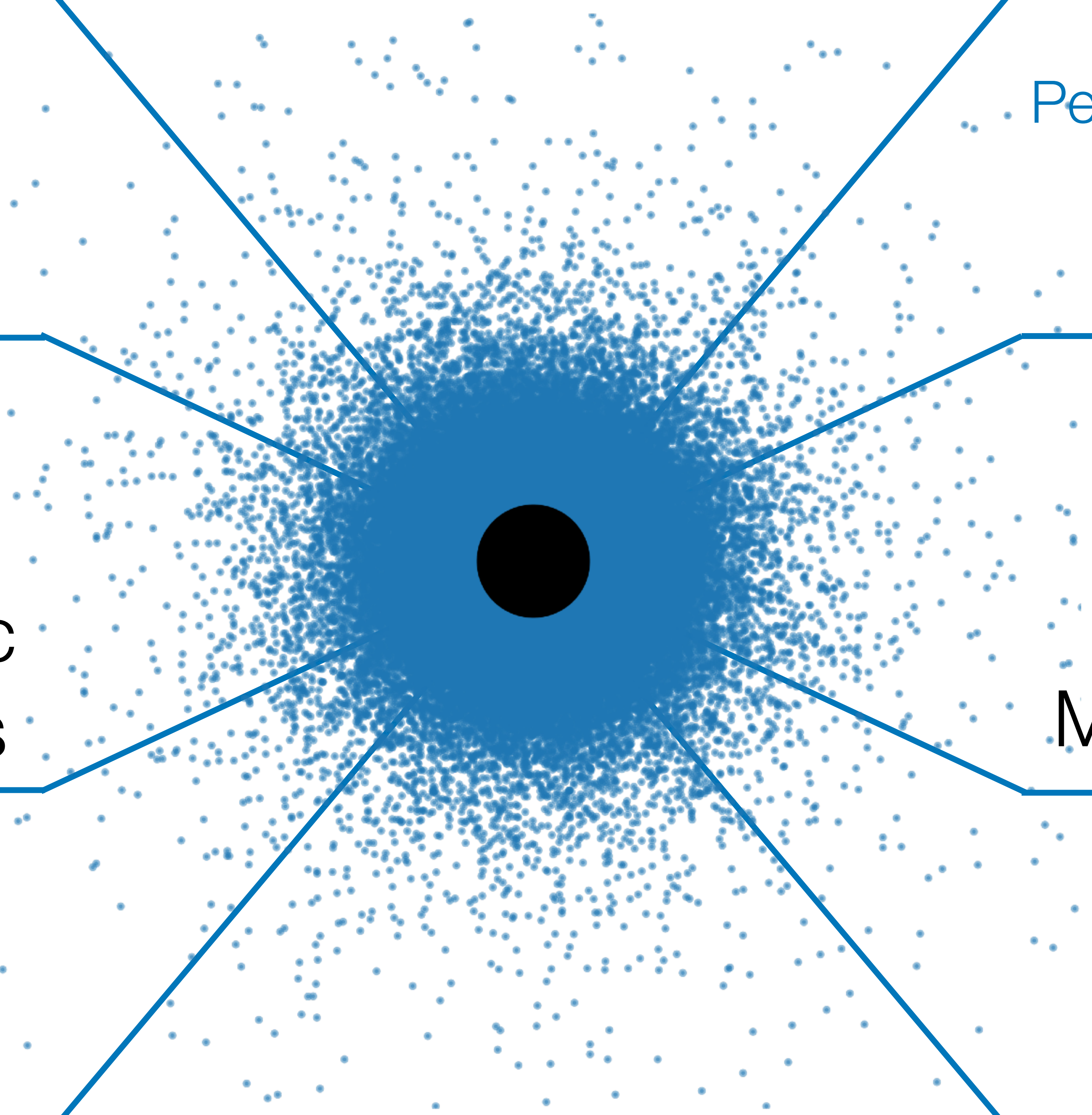
[See also Nichols et al. 2309.06498]



Use simulations to validate accretion force and DM spike depletion:



Towards better DM spikes



Confusion with other environmental effects

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

Relativistic effects

[See e.g. 2204.12508]

Integration with realistic IMRI/EMRI waveforms

[See e.g. 2104.04582]

Accretion (for BHs)

[See e.g. Nichols et al. 2309.06498]

Realistic spike formation scenarios

[Ongoing work with Abram Perez, Pratika Dayal, and others]

Eccentric orbits

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

More realistic feedback

[Ongoing work lead by Theophanes Karydas]

Search strategies

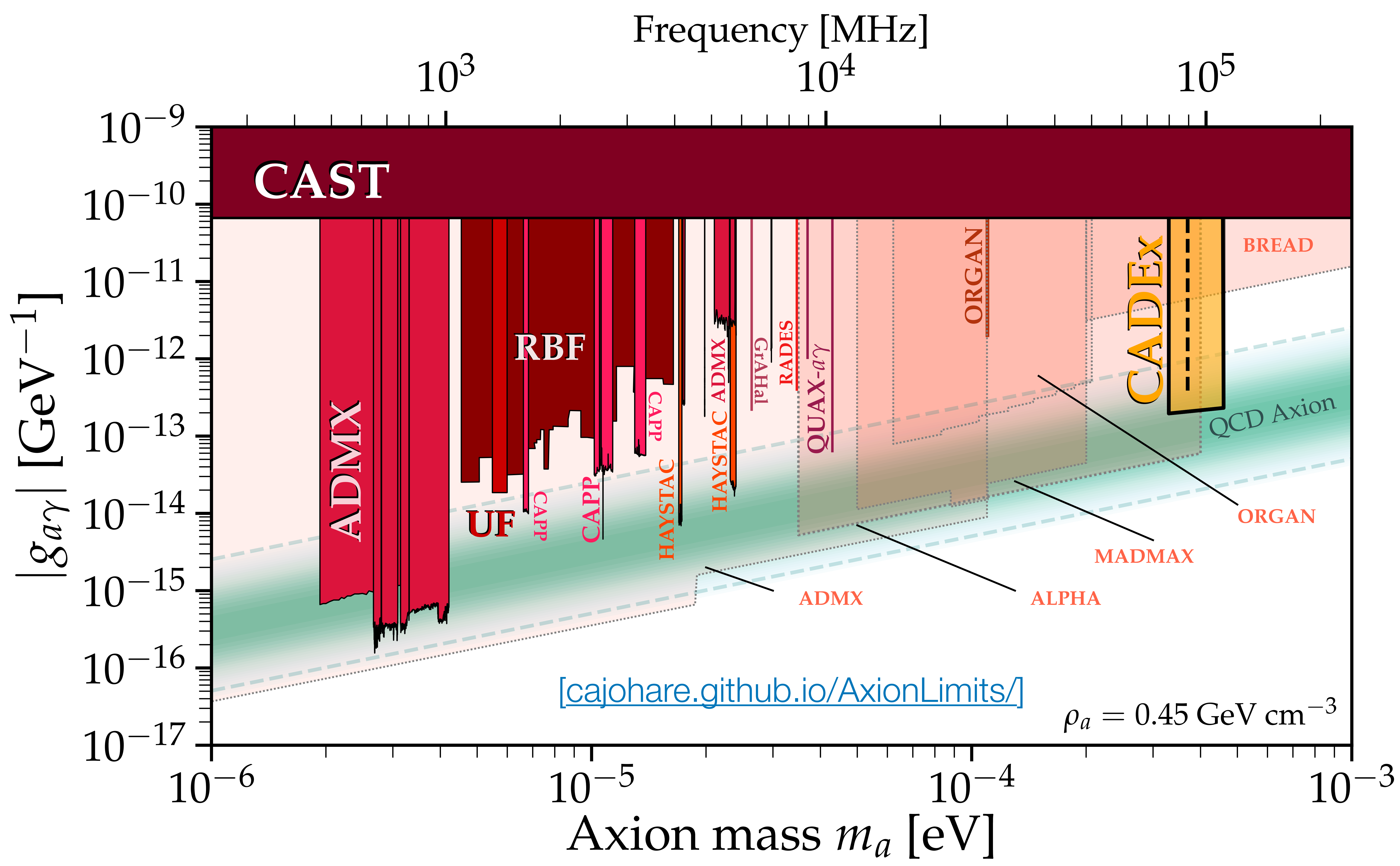
Part 2:
Neutron Stars

Example: Axion Dark Matter

Dark Matter could be in the form of light **pseudo-scalar 'axions'**, which may arise as psuedo-Goldstone bosons of a spontaneously broken Peccei-Quinn symmetry $U(1)_{\rm PQ}$.

Axions can **convert to photons** (and vice versa) in an external magnetic field:

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -\frac{1}{4} g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$



[CADEx Collaboration, including **BJK**, arXiv:2206.02980]

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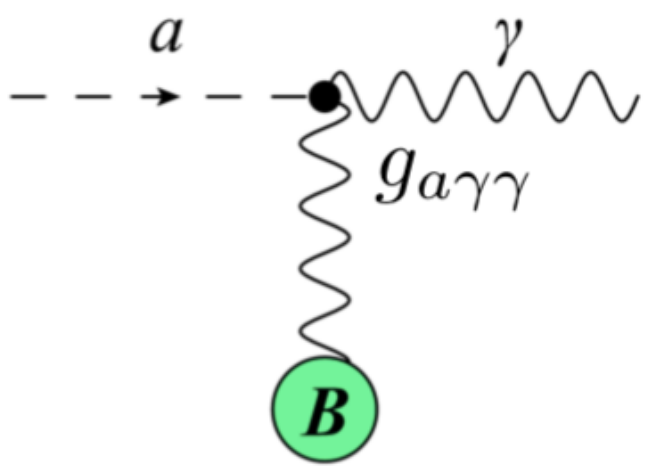
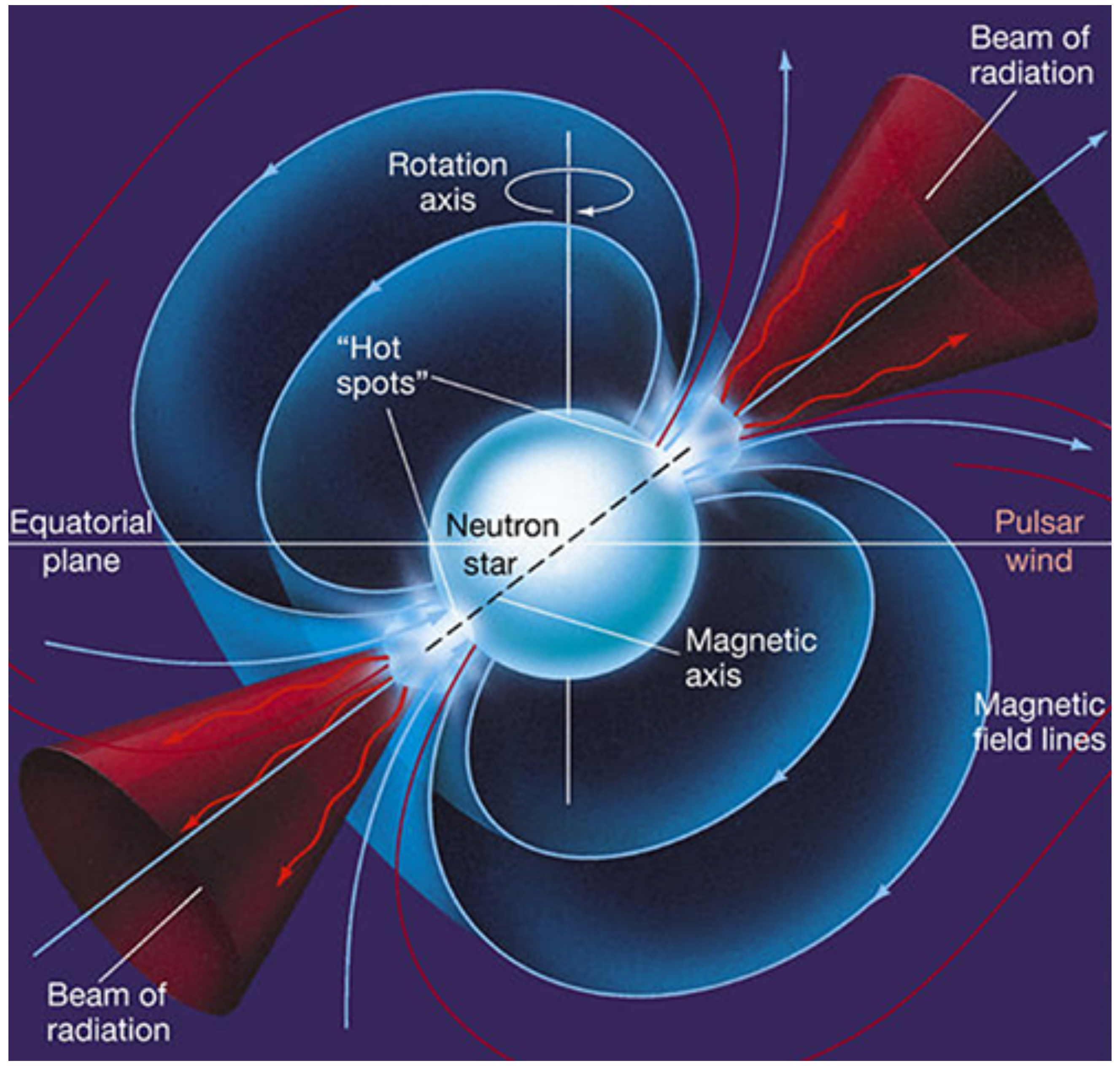




Neutron Star surrounded by a dense plasma which allows 'resonant' conversion, when **axion mass matches plasma mass**: $\omega_p(B_0, P) = m_a/2\pi$

This occurs at the conversion radius r_c, with conversion possible over a distance:

$$L = \sqrt{2\pi r_c v_c / (3m_a)}$$

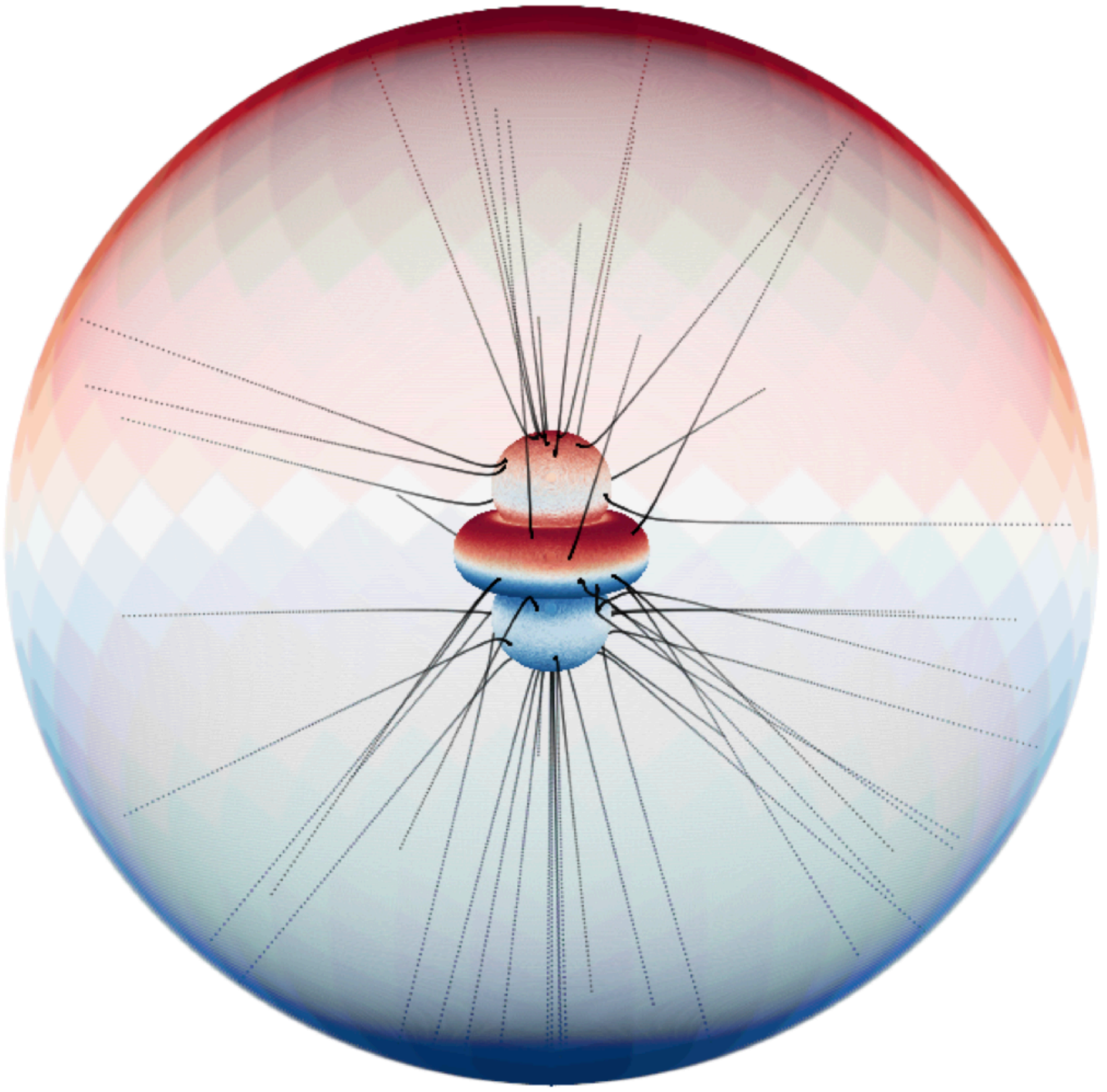
With this, the radiated power is:

$$\frac{\mathrm{d}\mathcal{P}\left(\theta, \theta_m t\right)}{\mathrm{d}\Omega} \approx p_{a\gamma} \rho_{\mathrm{DM}}^{r_c} v_c r_c^2 \approx g_{a\gamma}^2 B(r_c)^2 L^2 \rho_{\mathrm{DM}}^{r_c} r_c^2$$

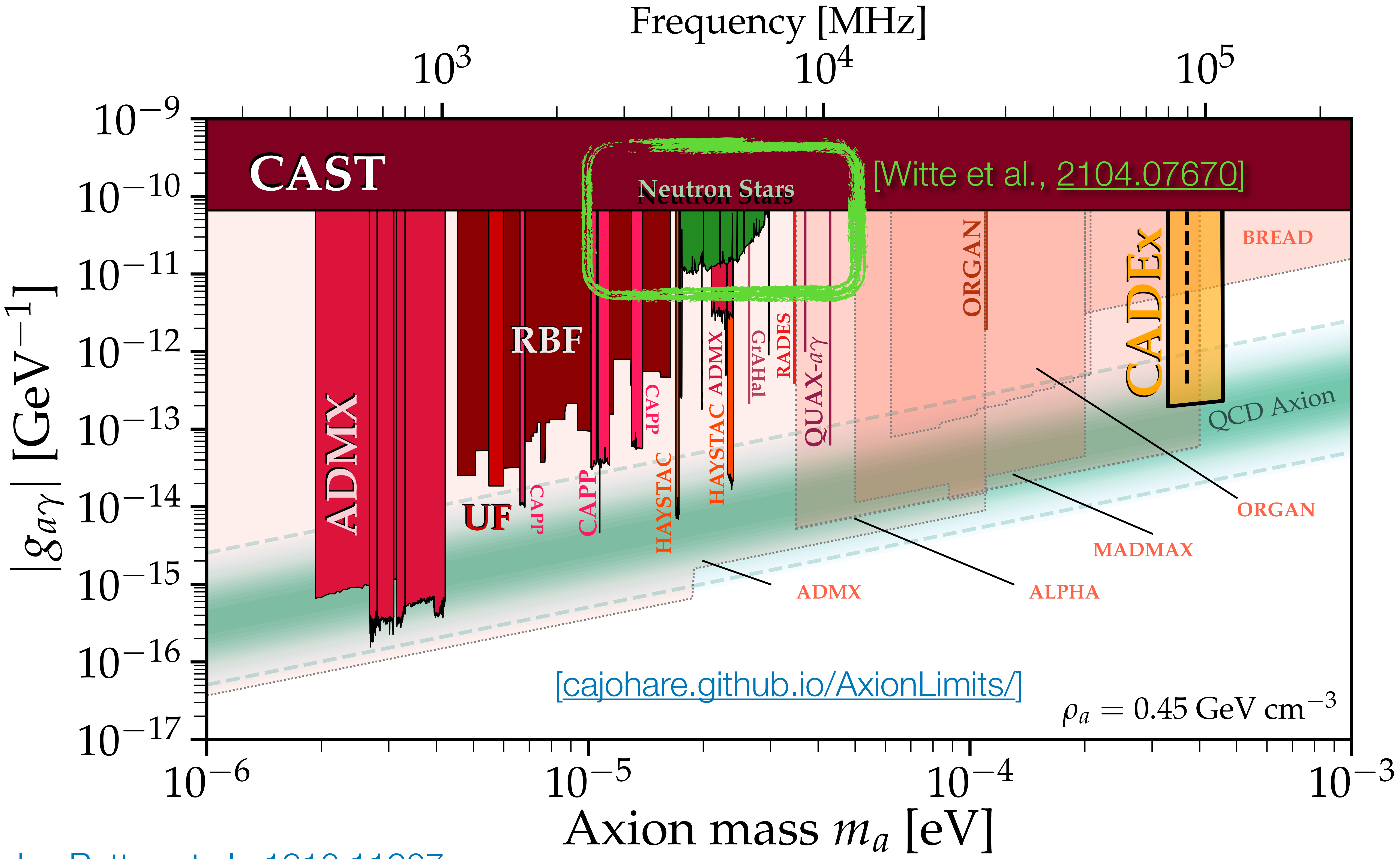
[1803.08230, 1804.03145, 1811.01020]

Dark Matter could be in the form of light **pseudo-scalar 'axions'**, which may arise as psuedo-Goldstone bosons of a spontaneously broken Peccei-Quinn symmetry $U(1)_{\rm PQ}$.

Northern NS hemisphere

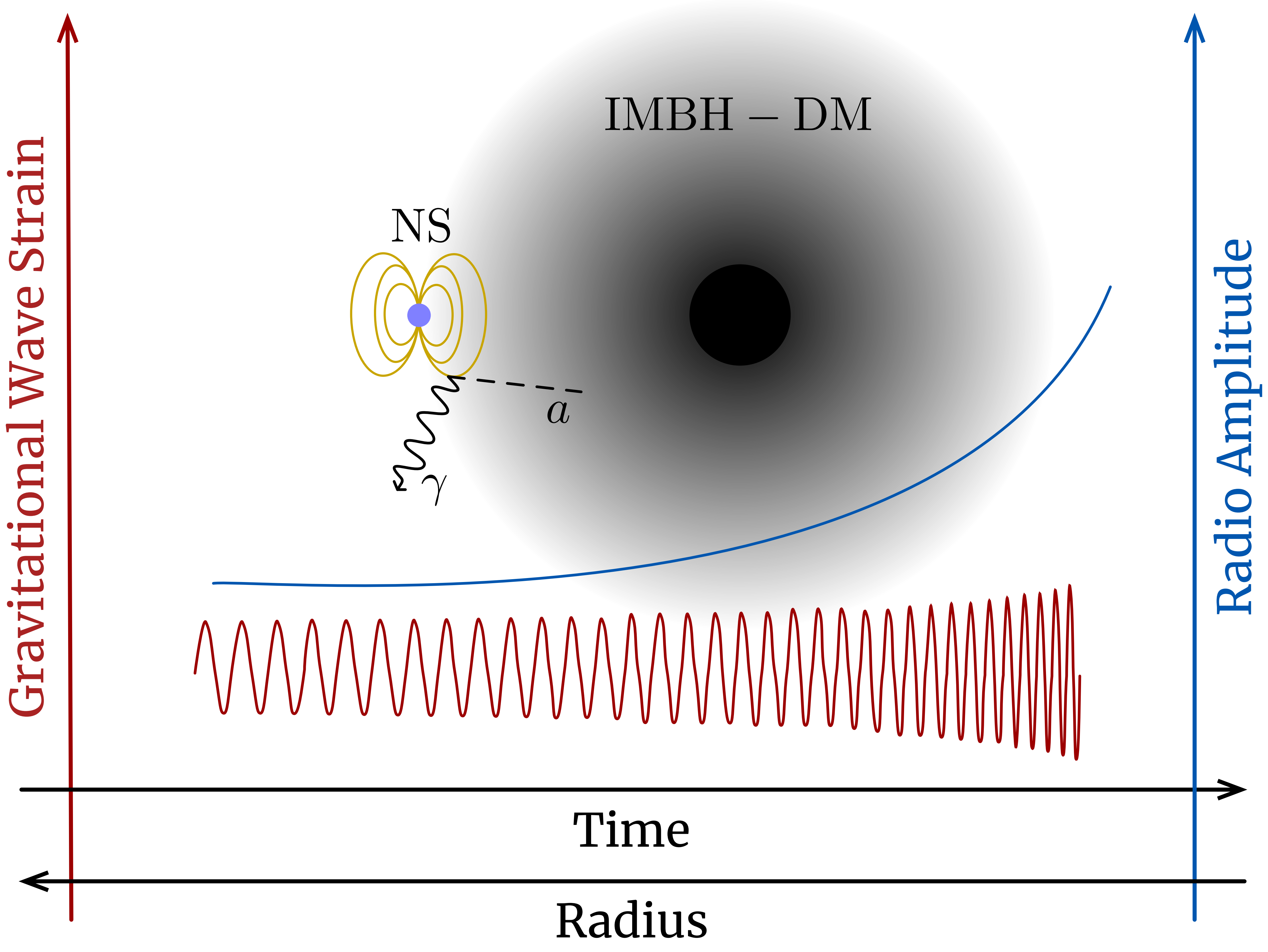


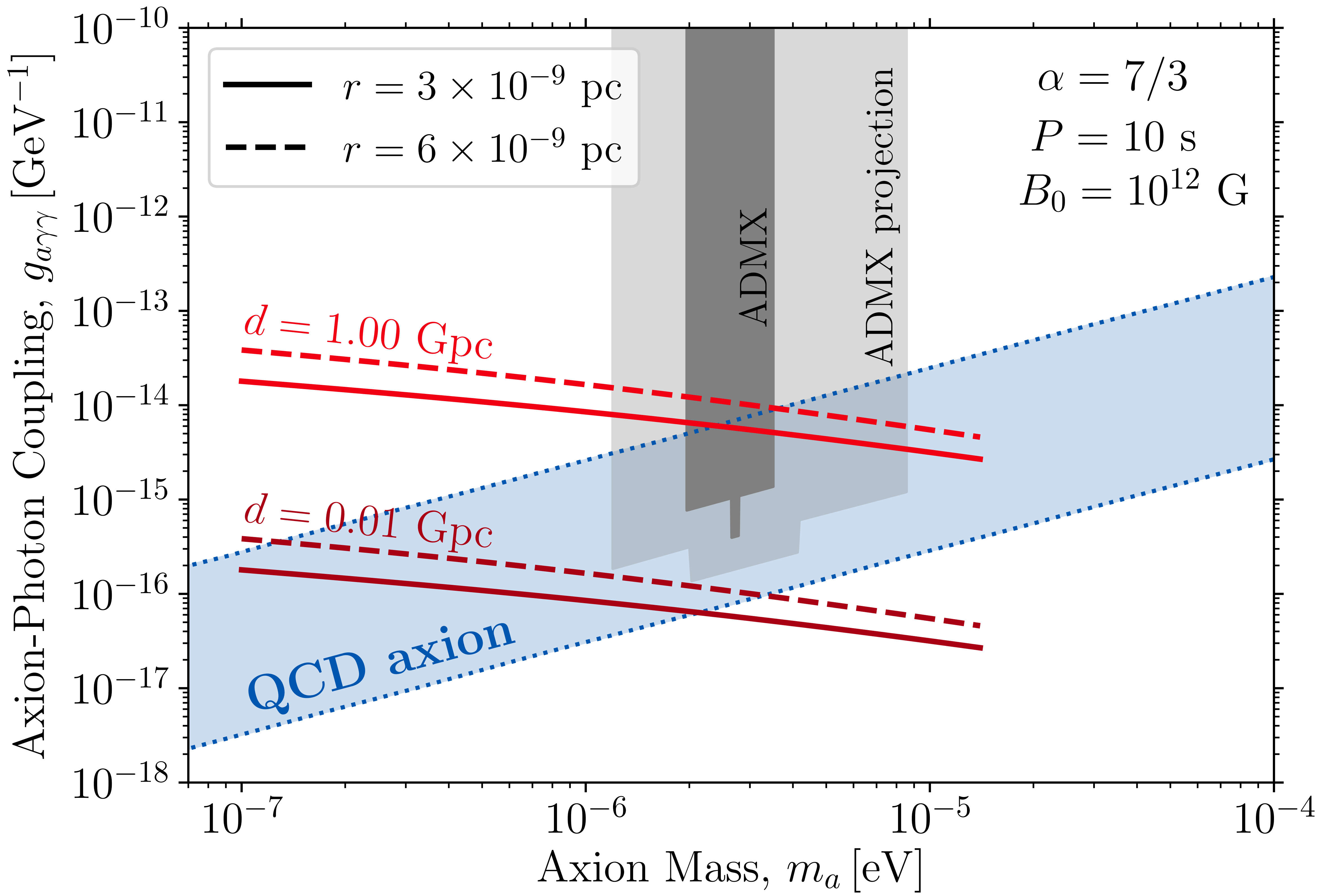
Southern NS hemisphere



[For recent modeling developments, see also Battye et al., 1910.11907, 2104.08290; Leroy et al., 1912.08815, Foster et al., 2202.08274]

Multi-messenger Axions





Future radio observations should be able to probe QCD axion DM in the range $10^{-7} - 10^{-5}\,\mathrm{eV}$, while LISA would constrain the DM density close to the IMBH!

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

Post-inflationary axion production

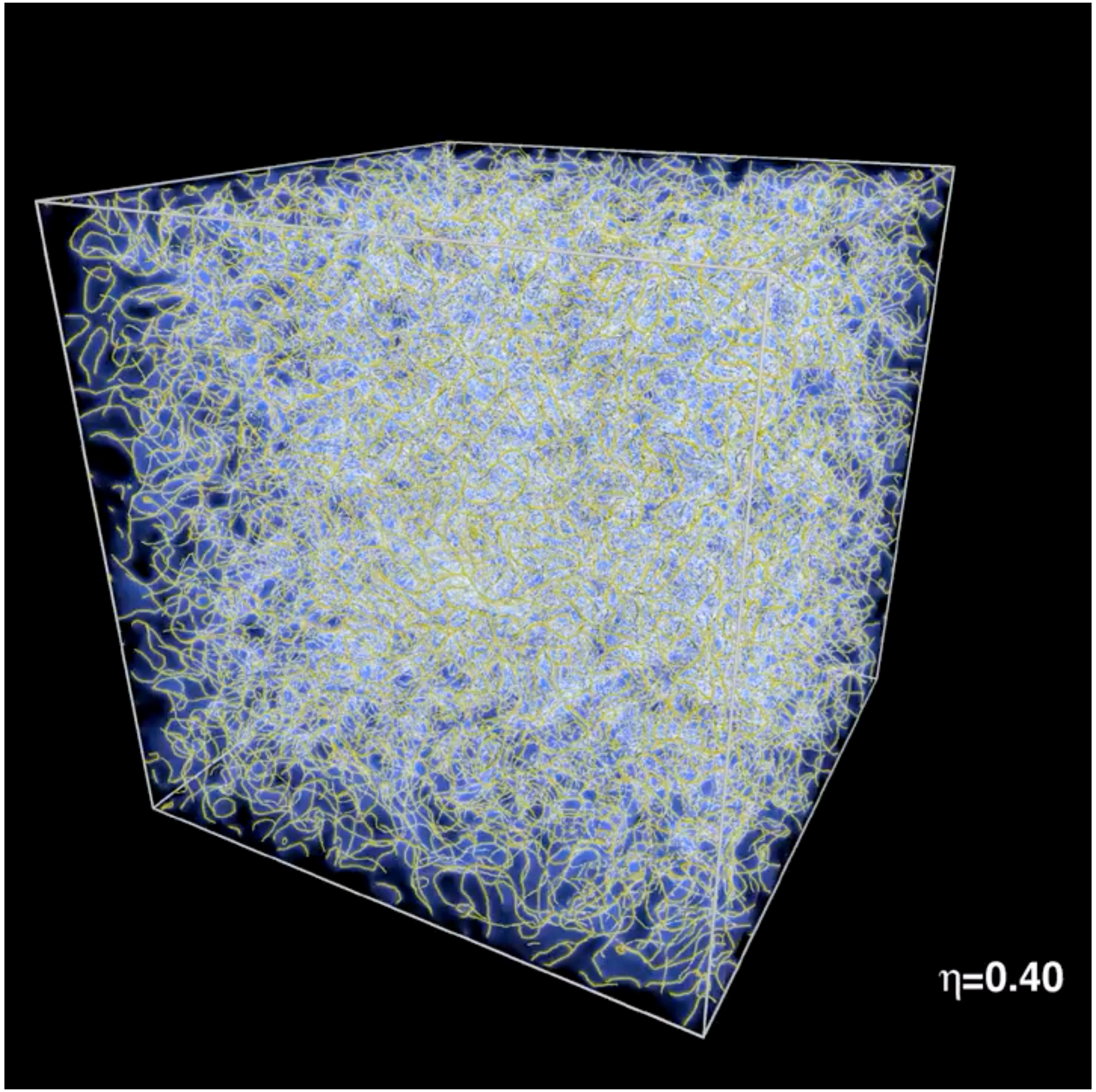
Consider Dark Matter QCD axions, in which the PQ symmetry is broken *after* inflation

Axion field has random initial values in causally disconnected patches

Need to solve complicated dynamics of topological defects (axion walls, strings) in order to determine present-day DM density.

Simulations are tricky, but point to masses above $m_a = 20\mu\text{eV}$.

[See e.g. Gorghetto et al., 2007.04990]



[Buschmann et al., 1906.00967]

Post-inflationary axion production

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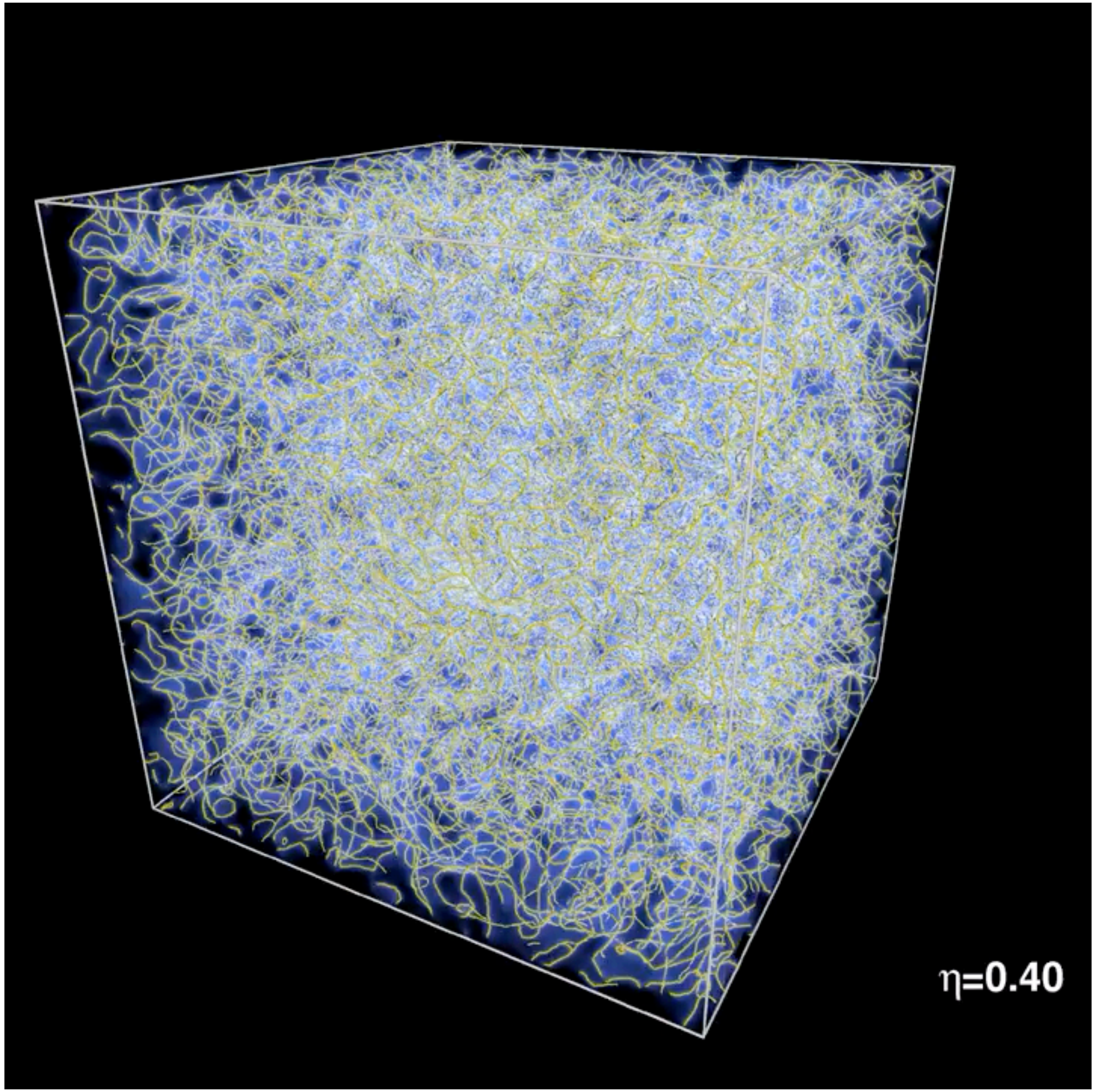
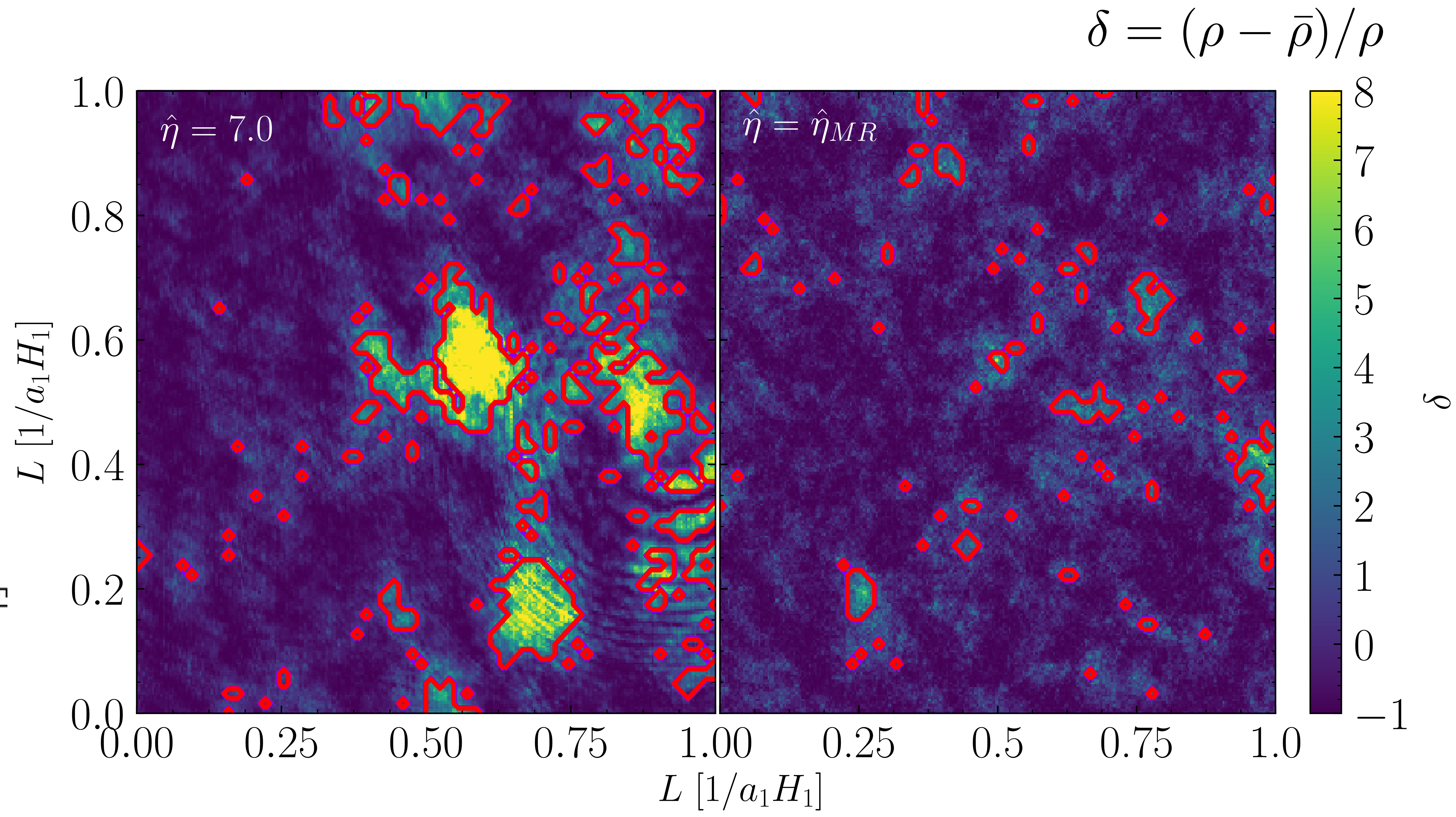


[Buschmann et al., 1906.00967]

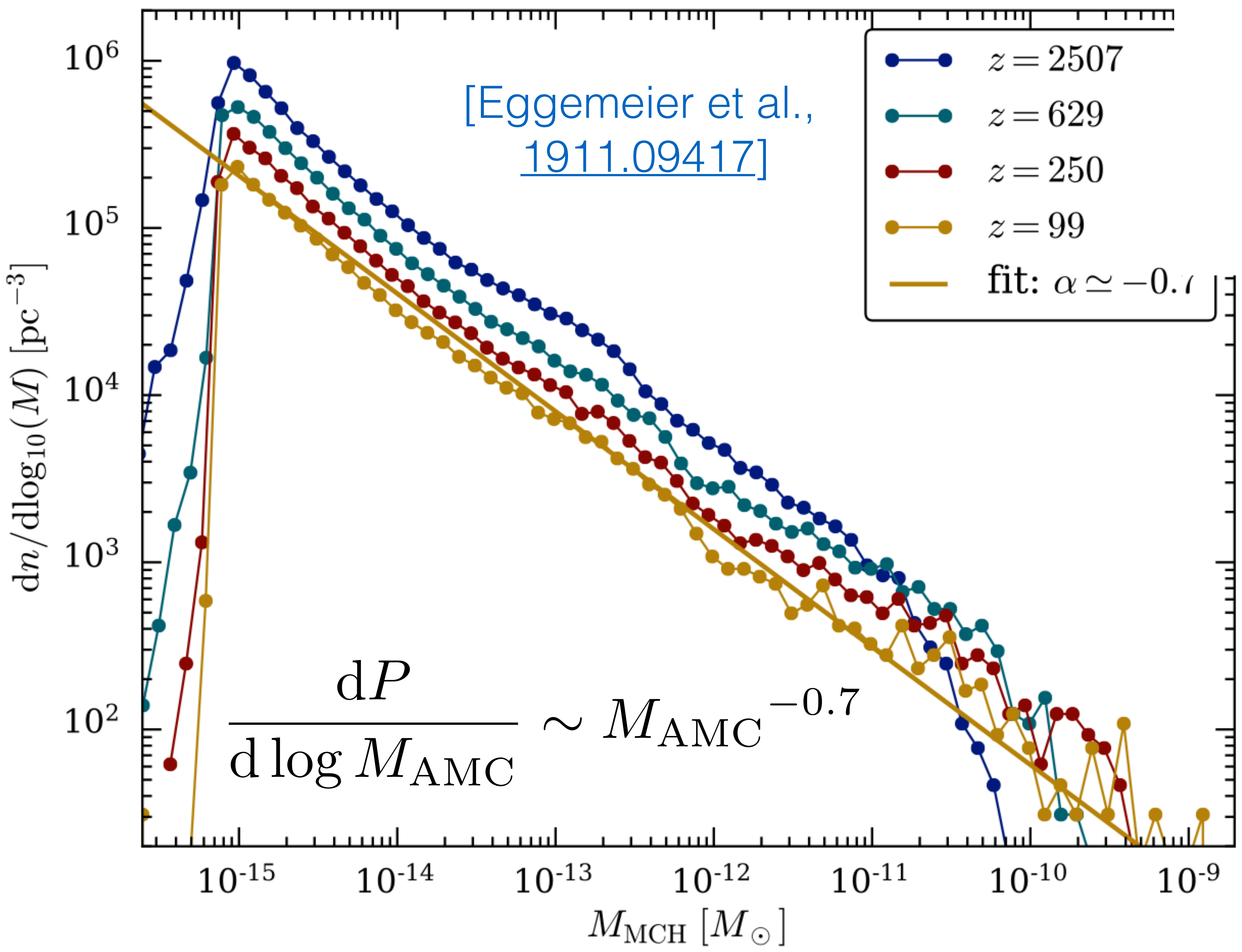
Axion Miniclusters (AMCs)

Overdensities act as ‘seeds' for bound **axion miniclusters (AMCs)**

[Kolb & Tkachev, astro-ph/9403011]



[Buschmann et al., 1906.00967]



Today, expect minicluster masses in the range

$$M_{\mathrm{AMC}} \sim 10^{-19} - 10^{-5}\, M_\odot.$$

But, AMC density profile is uncertain…

[Fairbairn et al., 1707.03310]

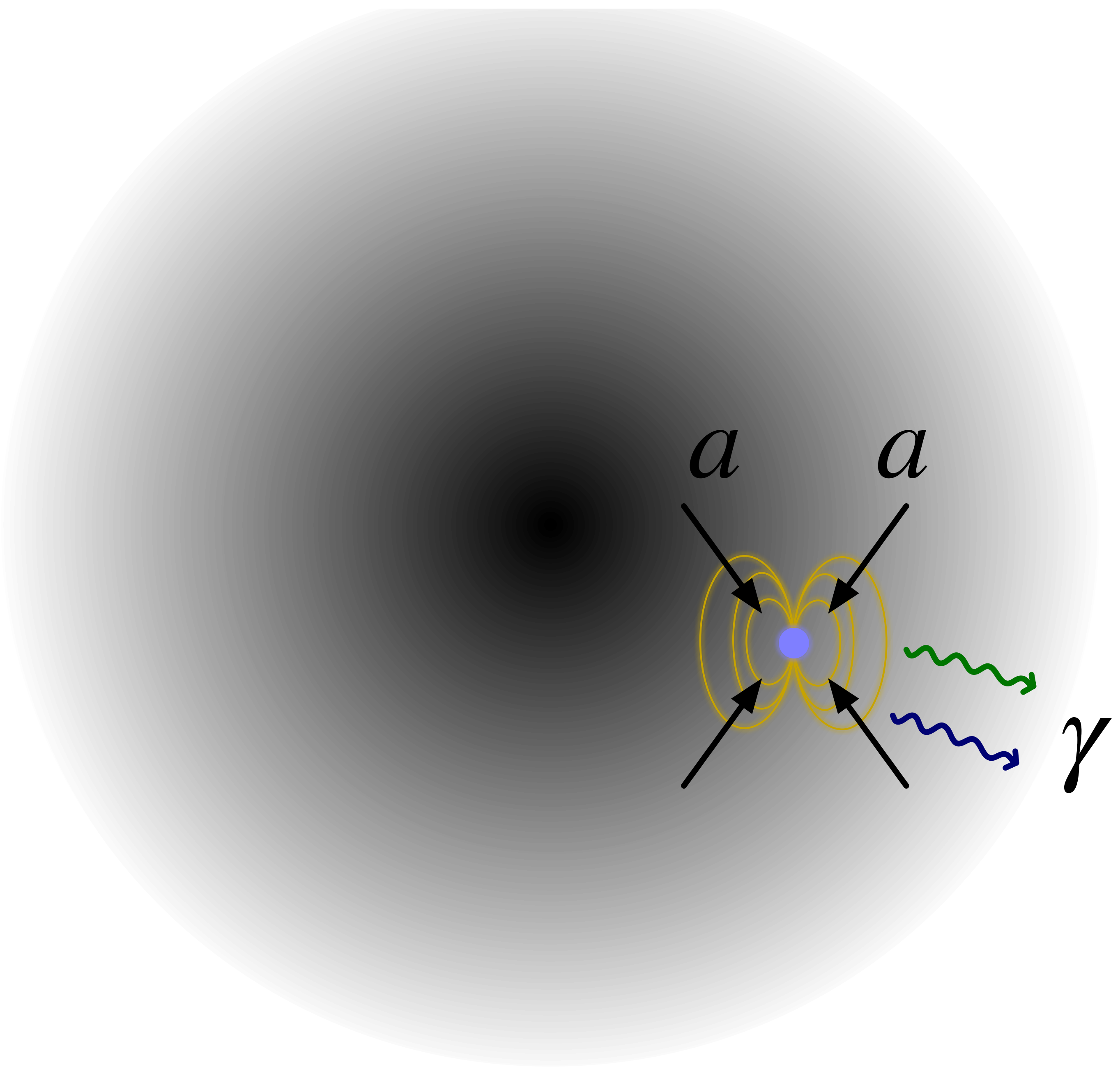
[See also Zurek et al., astro-ph/0607341; Vaquero et al., 1809.09241]

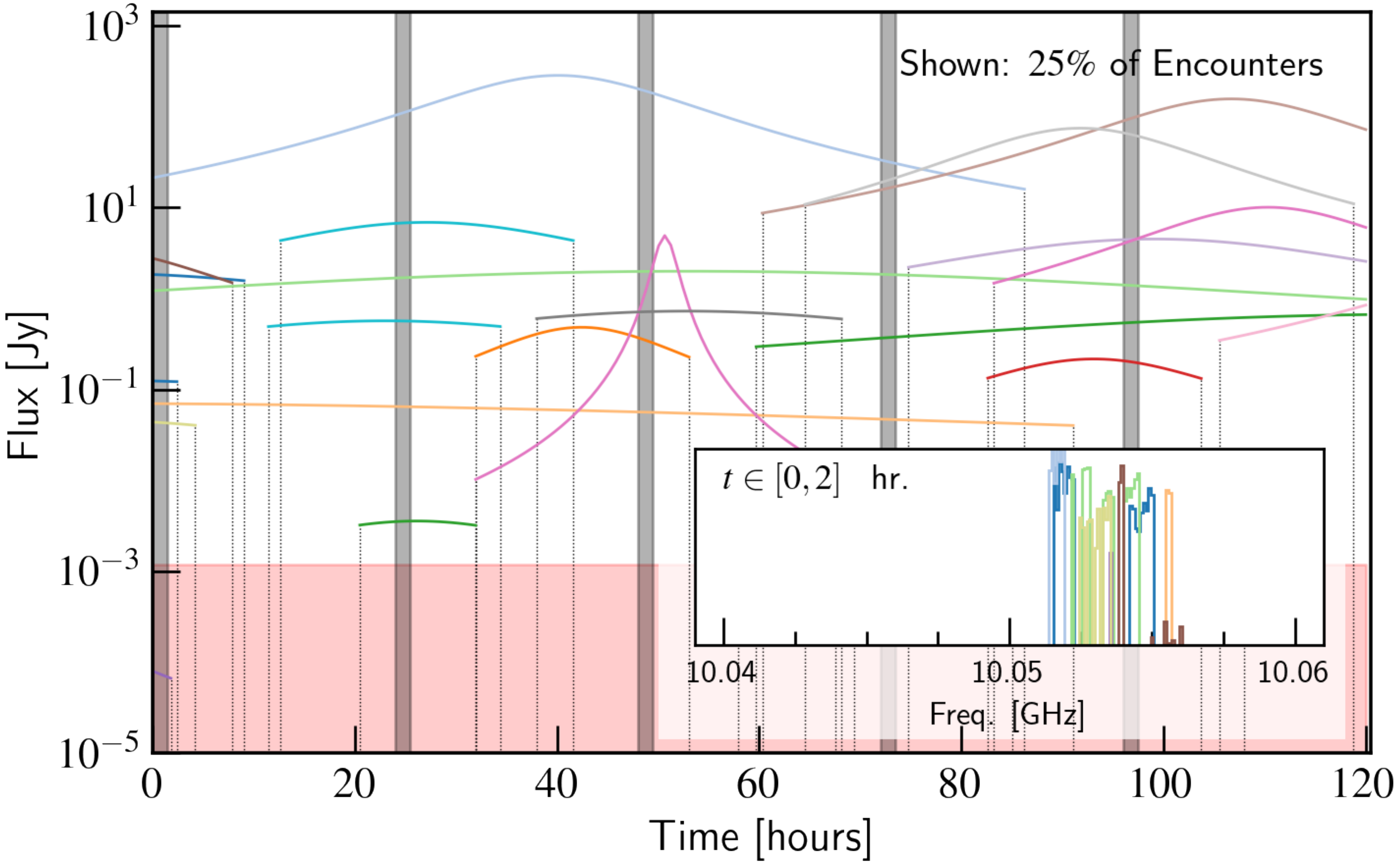
Clumps of axion DM ('**axion miniclusters**' or '**AMCs**') crossing NSs could lead to bright radio transients:

[Hogan & Rees (1988)]

$$M_{\rm AMC} \sim 10^{-14}\, M_\odot$$

$$R_{\rm AMC} \sim 10^{-7}\,{\rm pc} \sim 10^{6}\,{\rm km}$$

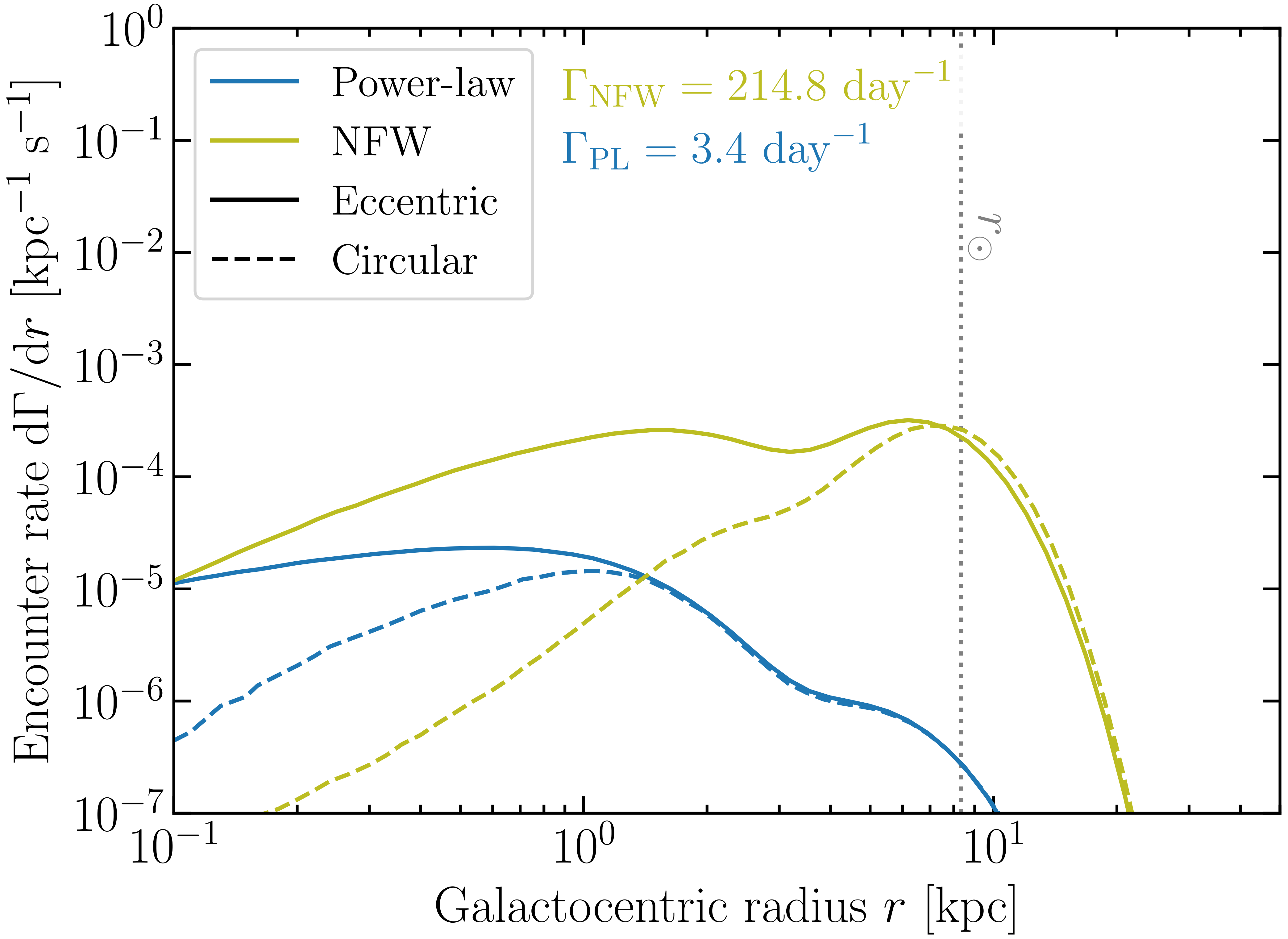


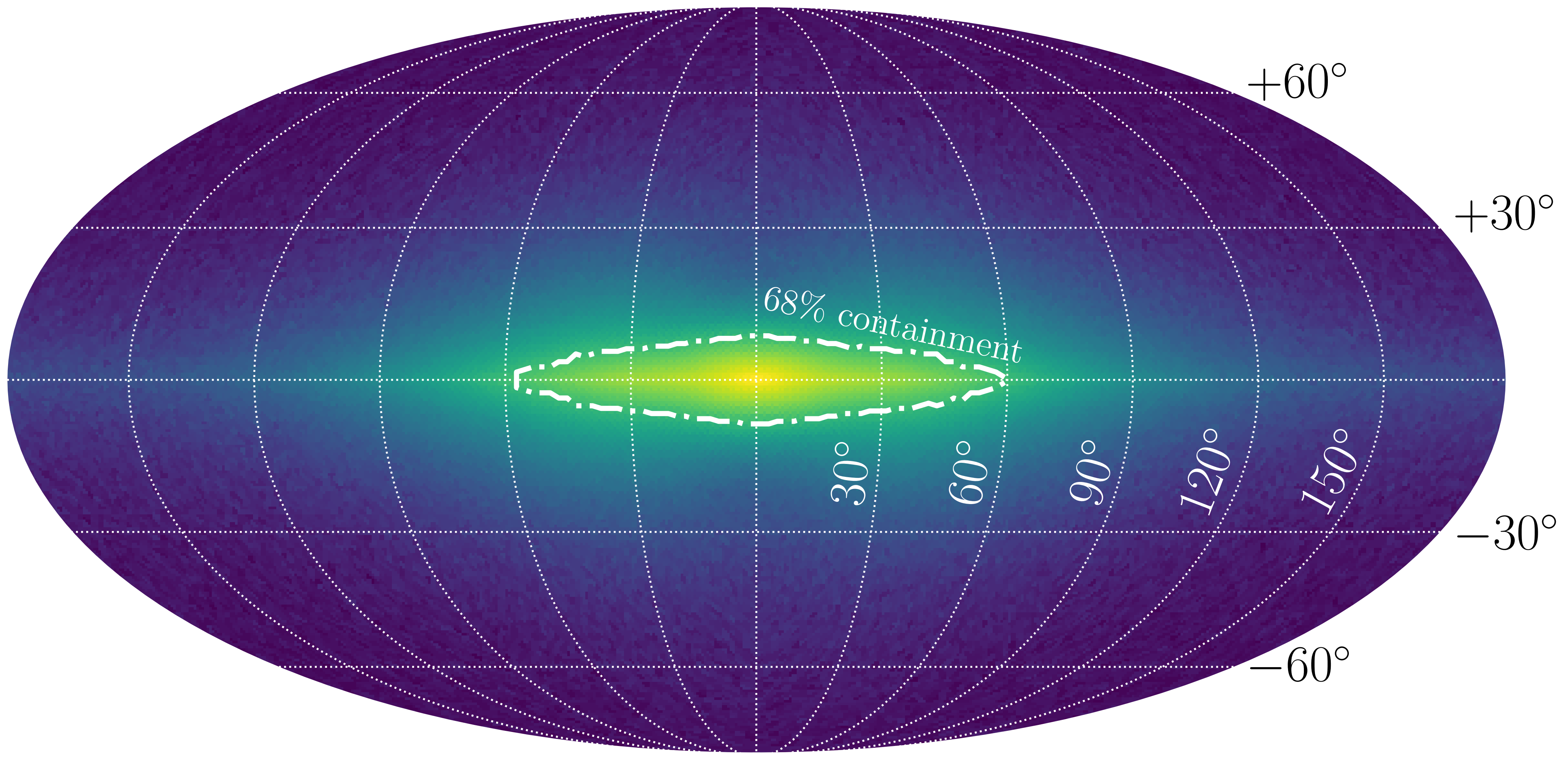


[**BJK**, Edwards, Visinelli & Weniger, 2011.05377; Edwards, **BJK**, Visinelli & Visinelli, 2011.05378; Witte et al., 2212.08079]

[Code: github.com/bradkav/axion-miniclusters]

AMC-NS encounter rate obtained by convolving the surviving AMC distribution and the expected distribution of NSs. For the Milky Way:



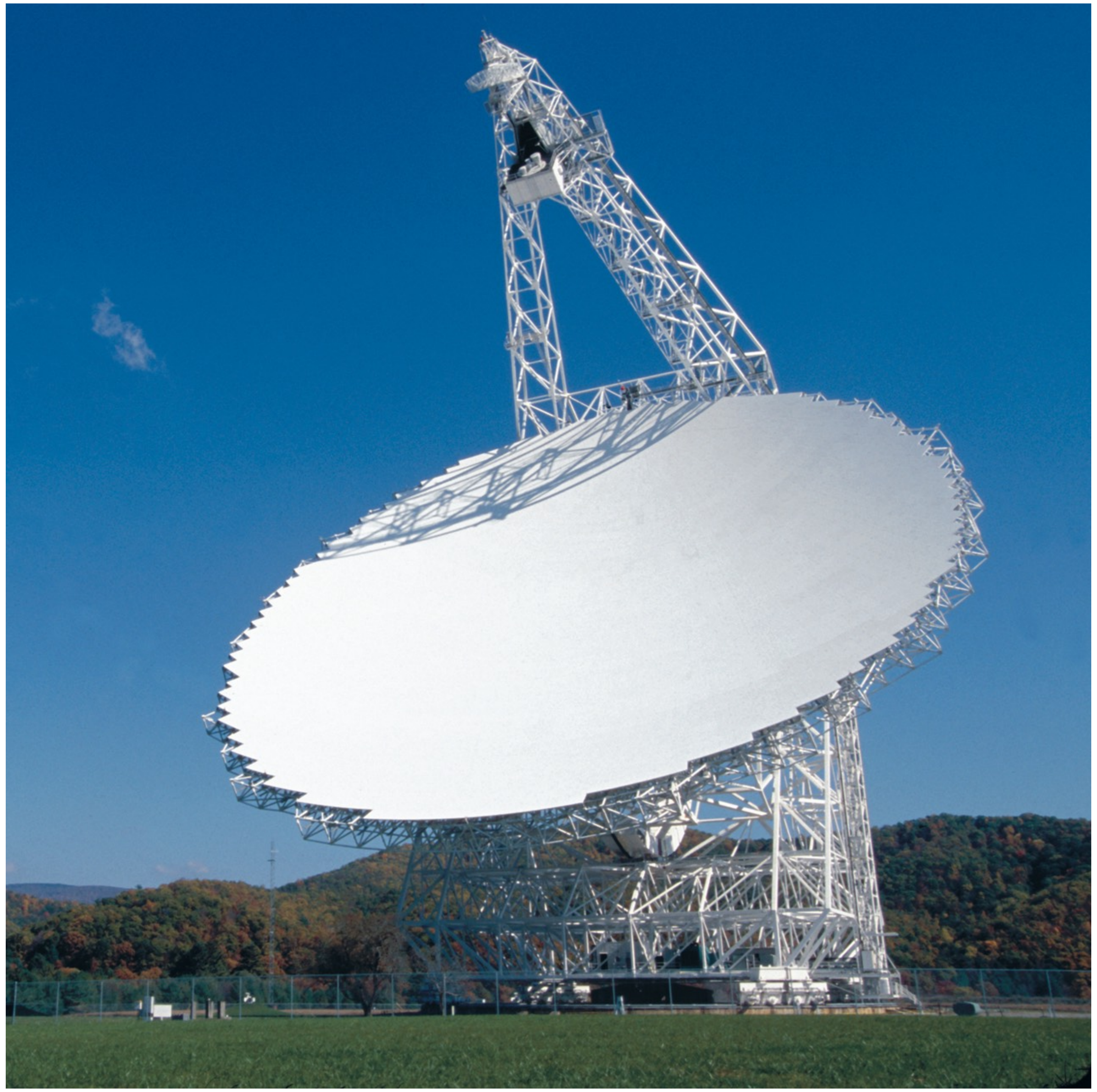


$$\Gamma = \int \mathrm{d}^3\mathbf{r} \int \mathrm{d}R \frac{\mathrm{d}n_{\rm AMC}(r)}{\mathrm{d}R} n_{\rm NS}(\mathbf{r}) \langle \widetilde{\sigma u} \rangle (r)$$

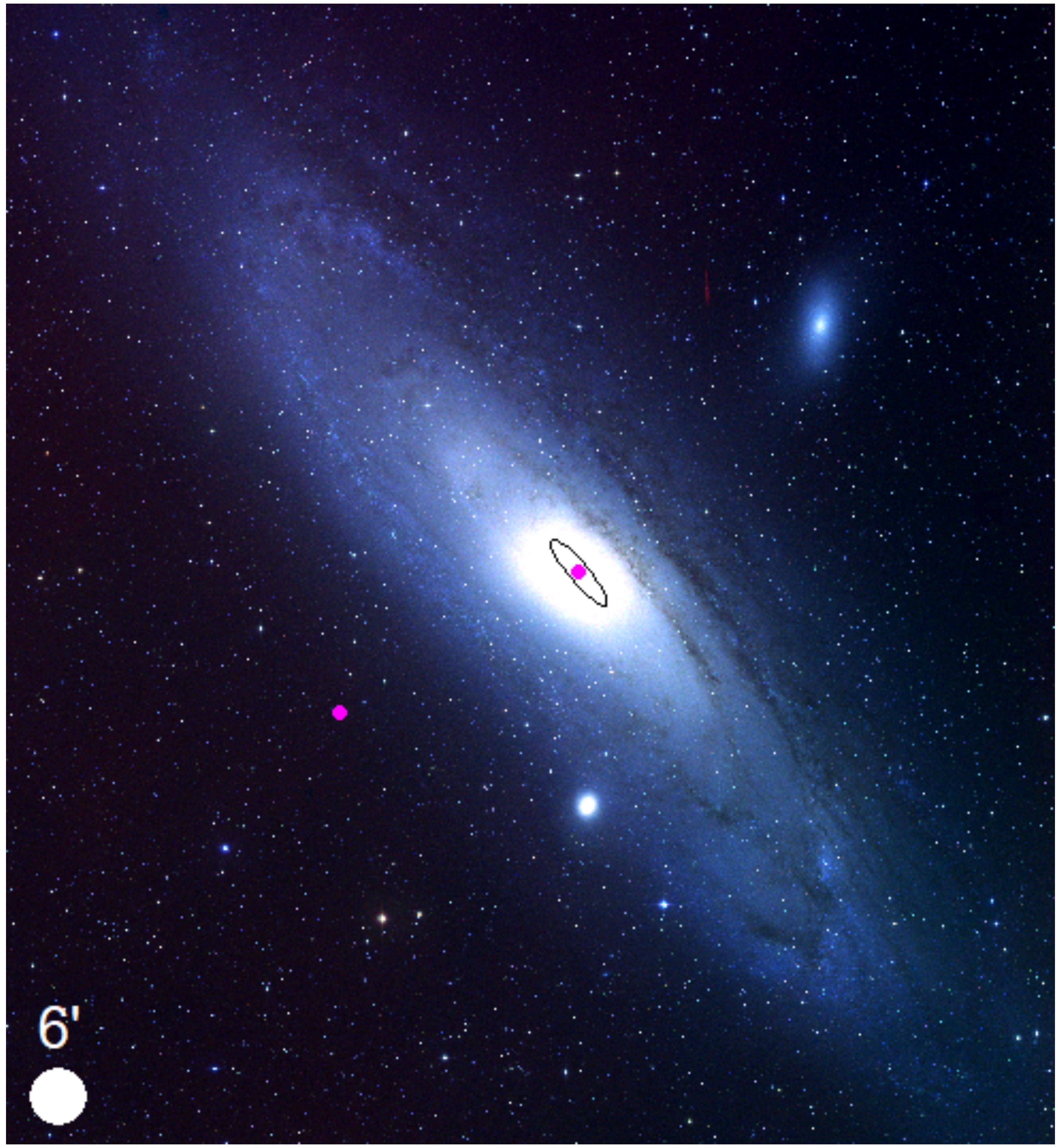
$$\langle \sigma u \rangle (r) \sim \sigma_u R^2$$

Difficult to catch all of the encounters in a single radio beam. Look at nearby galaxies…

Search for AMCs in Andromeda



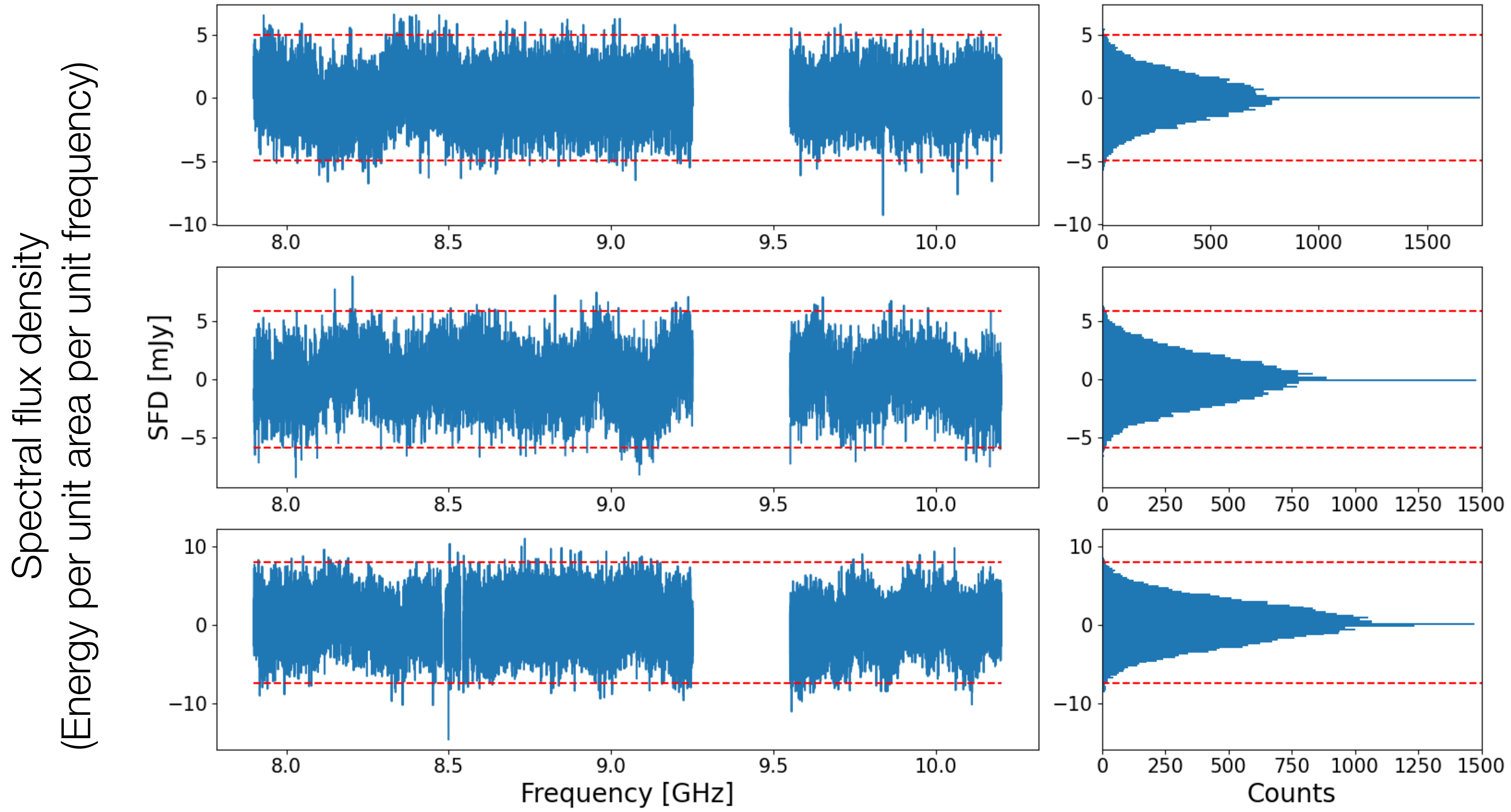
Green Bank Radio Telescope



*in close collaboration with University of Virginia Astronomy Instrumentation Group.

GBT observations after reduction, calibration, RFI removal, and signal filtering

PRELIMINARY



04 Feb 2022

05 Feb 2022

10 Jul 2022

$m_a = 32\,\mu\text{eV}$ $m_a = 48\,\mu\text{eV}$

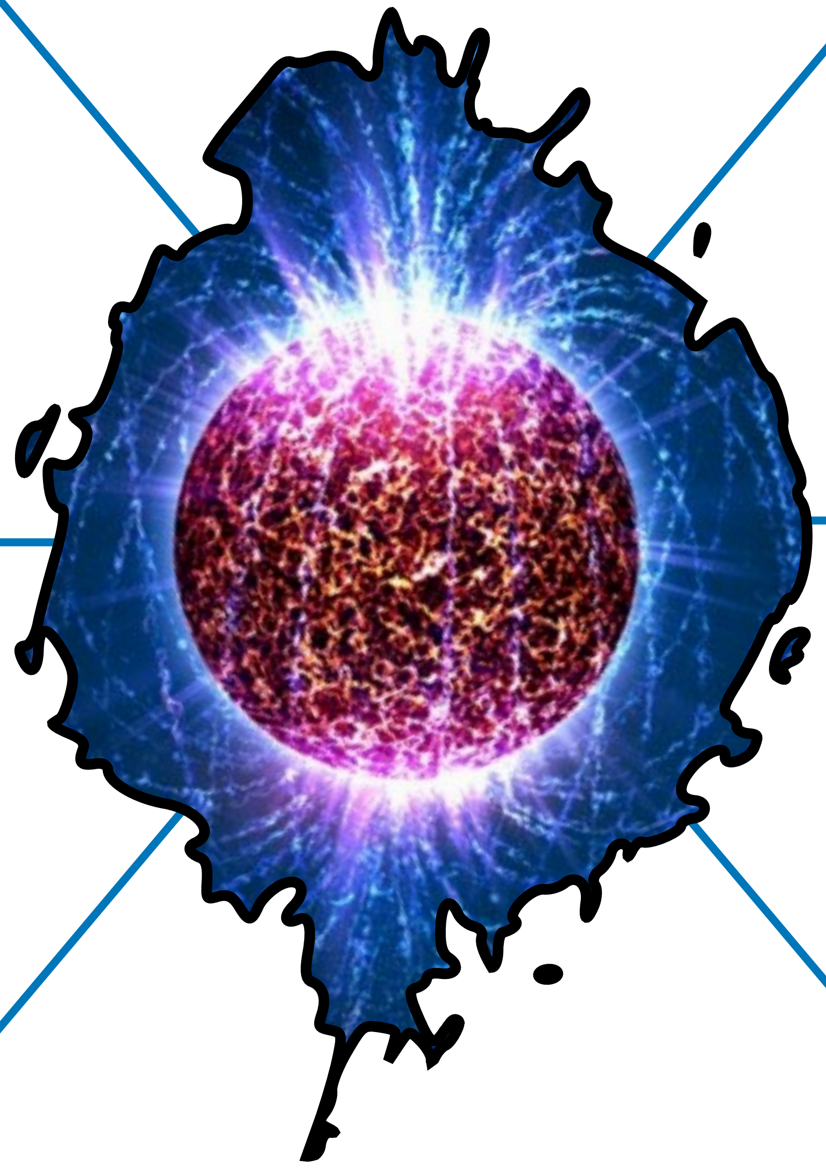
Understanding DM signals from NSs

Development of signal modeling pipeline

[Witte et al., 2212.08079]

NS populations and magnetic field distributions

[Ongoing work lead by Sam Witte]



Searches for NSs

[See e.g. 2205.05048]

AMC distribution and evolution

[See e.g. 2206.04619, 2207.11276]

Better modelling of NS magnetospheres

Search strategies?

Many thanks to many collaborators

Dark Matter and Black Holes

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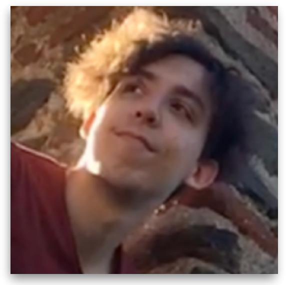
Pratibha Jangra
(IFCA, Santander)

Pippa Cole
(GRAPPA, Amsterdam)


Theophanes Karydas
(GRAPPA, Amsterdam)

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(Mila, Montreal)


David Nichols
(U. Virginia)

Pratika Dayal
(Groningen University)


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(IFCA, Santander)

Jose Maria Diego
(IFCA, Santander)


Francesca Scarcella
(IFT, Madrid)

Daniele Gaggero
(INFN, Pisa)


Gimmy Tomaselli
(GRAPPA, Amsterdam)

Dark Matter and Neutron Stars

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Scott Ransom
(NRAO)

Joe Bramante
(Queen's University)


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(GRAPPA, Amsterdam)

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Liam Walters
(U. Virginia)

Doddy Marsh
(KCL, London)


Jordan Shroyer
(U. Virginia)

Nirmal Raj
(TRIUMF)

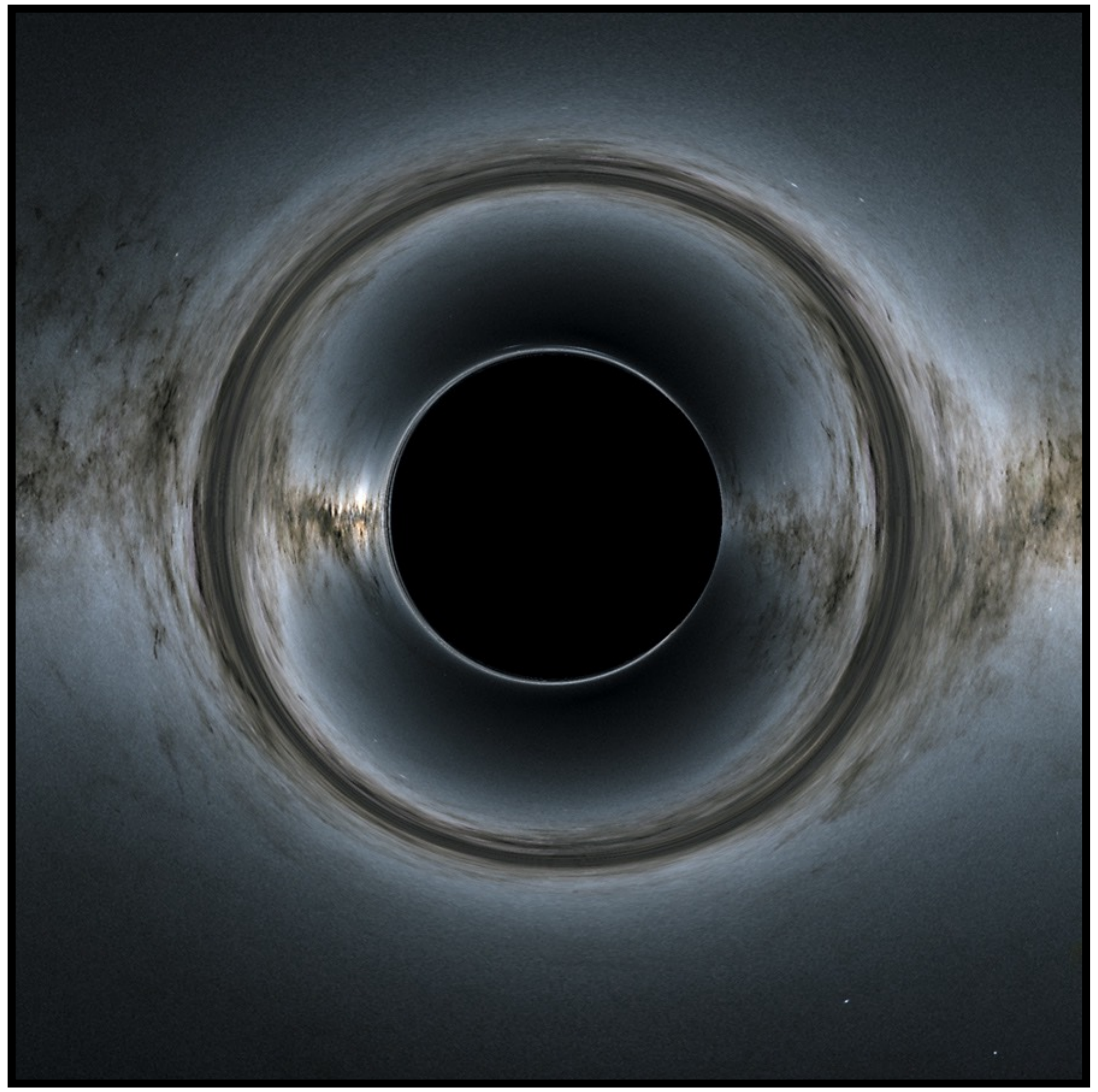

Luca Visinelli
(Shanghai Jiao Tong)

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

DM in extreme environments

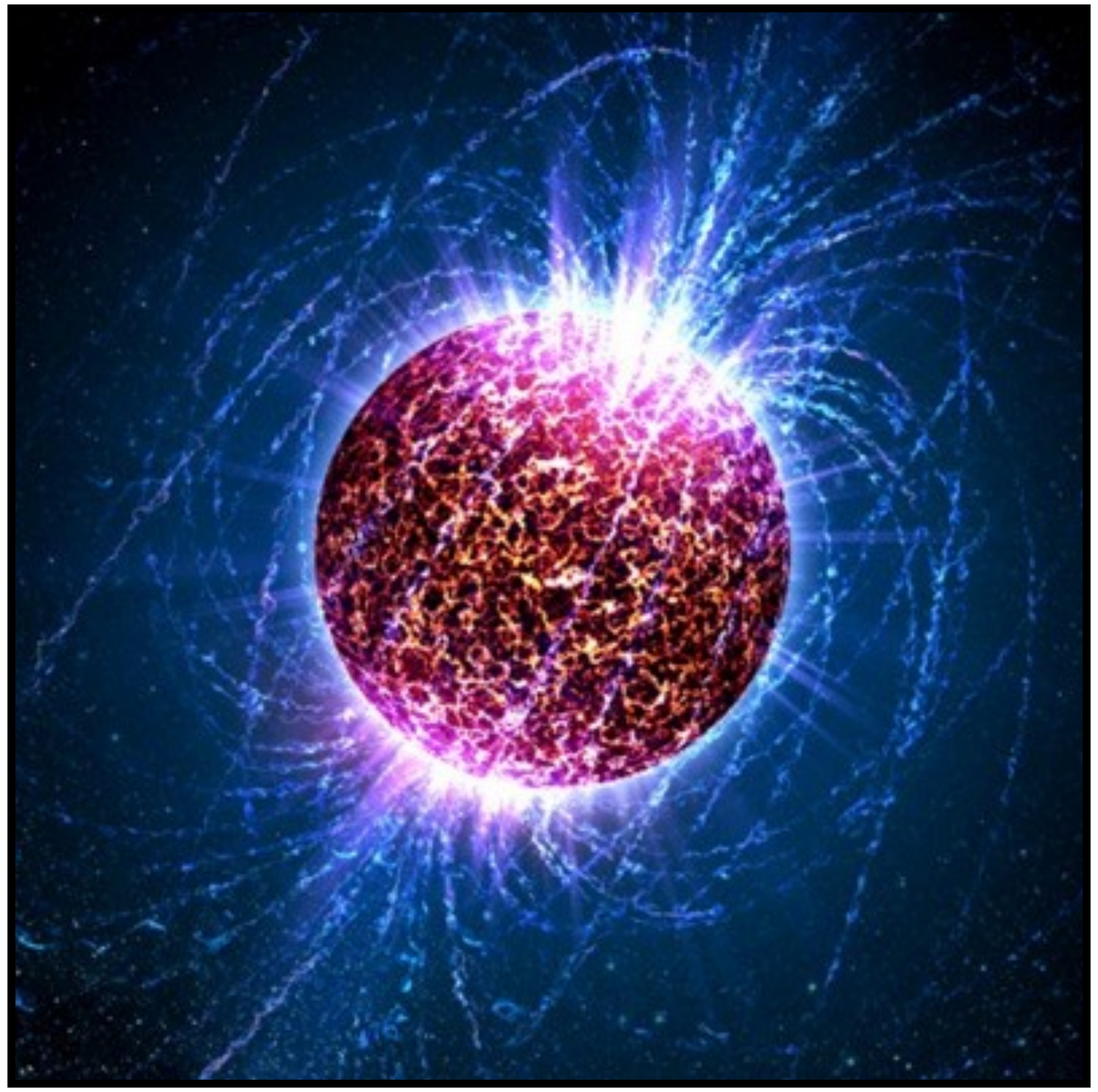
Higher densities, larger magnetic fields, longer timescales…but plenty still to do…

Black Holes



[Credit: NASA's Goddard Space Flight Center; background, ESA/Gaia/DPAC]

Neutron Stars



[Credit: Casey Reed (Penn State University), Wikimedia Commons]

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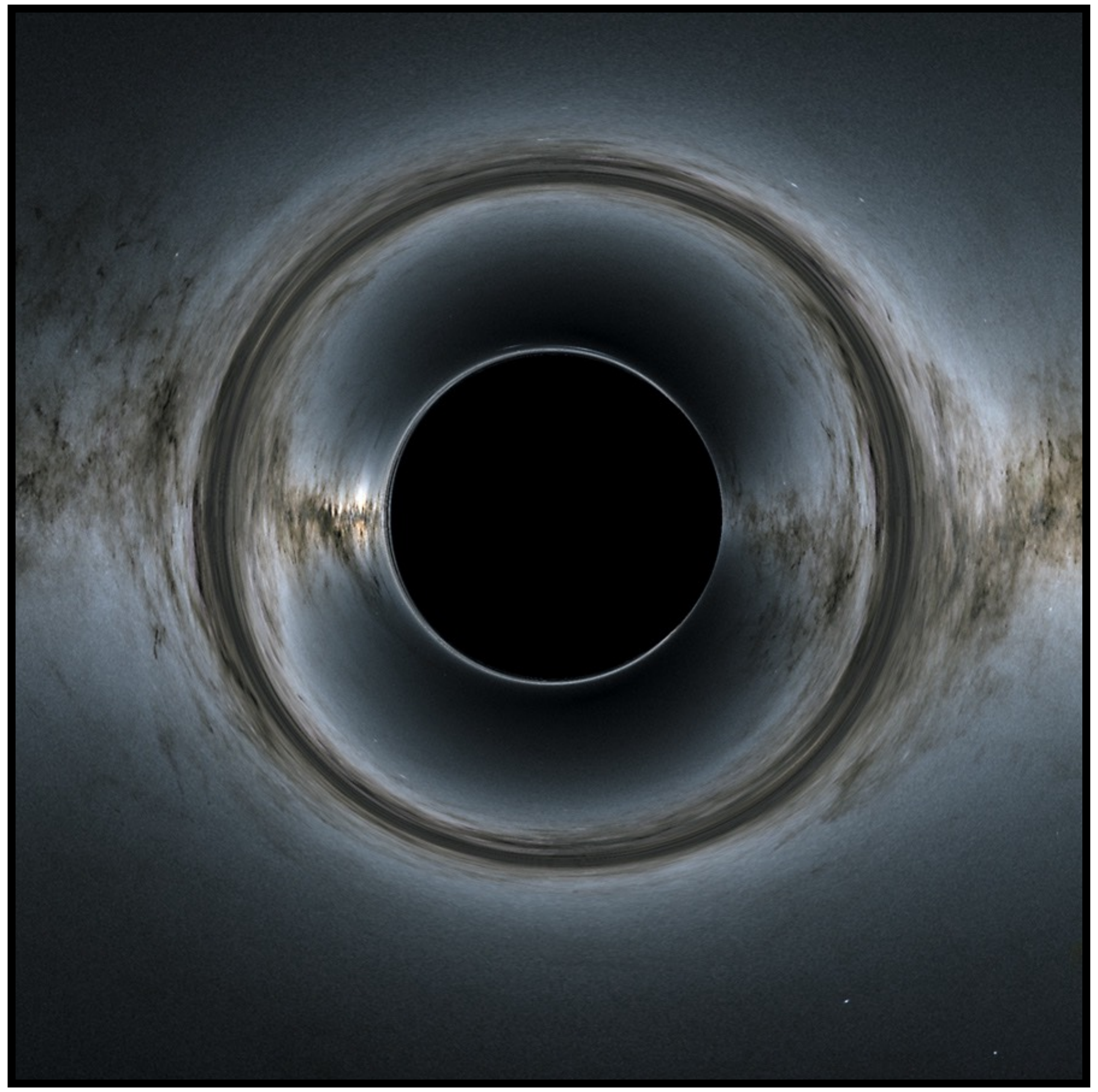
Black Holes



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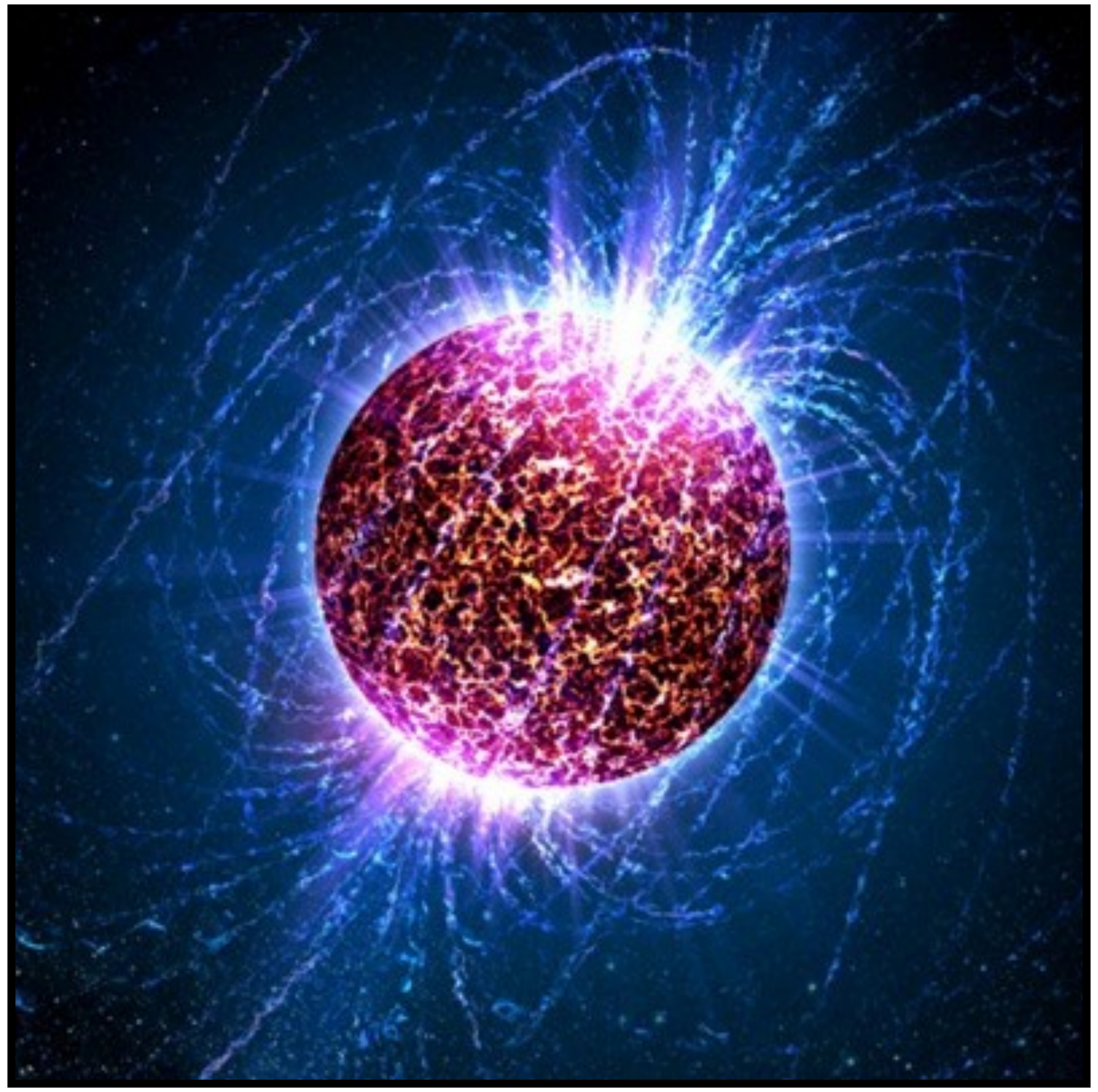
Neutron Stars

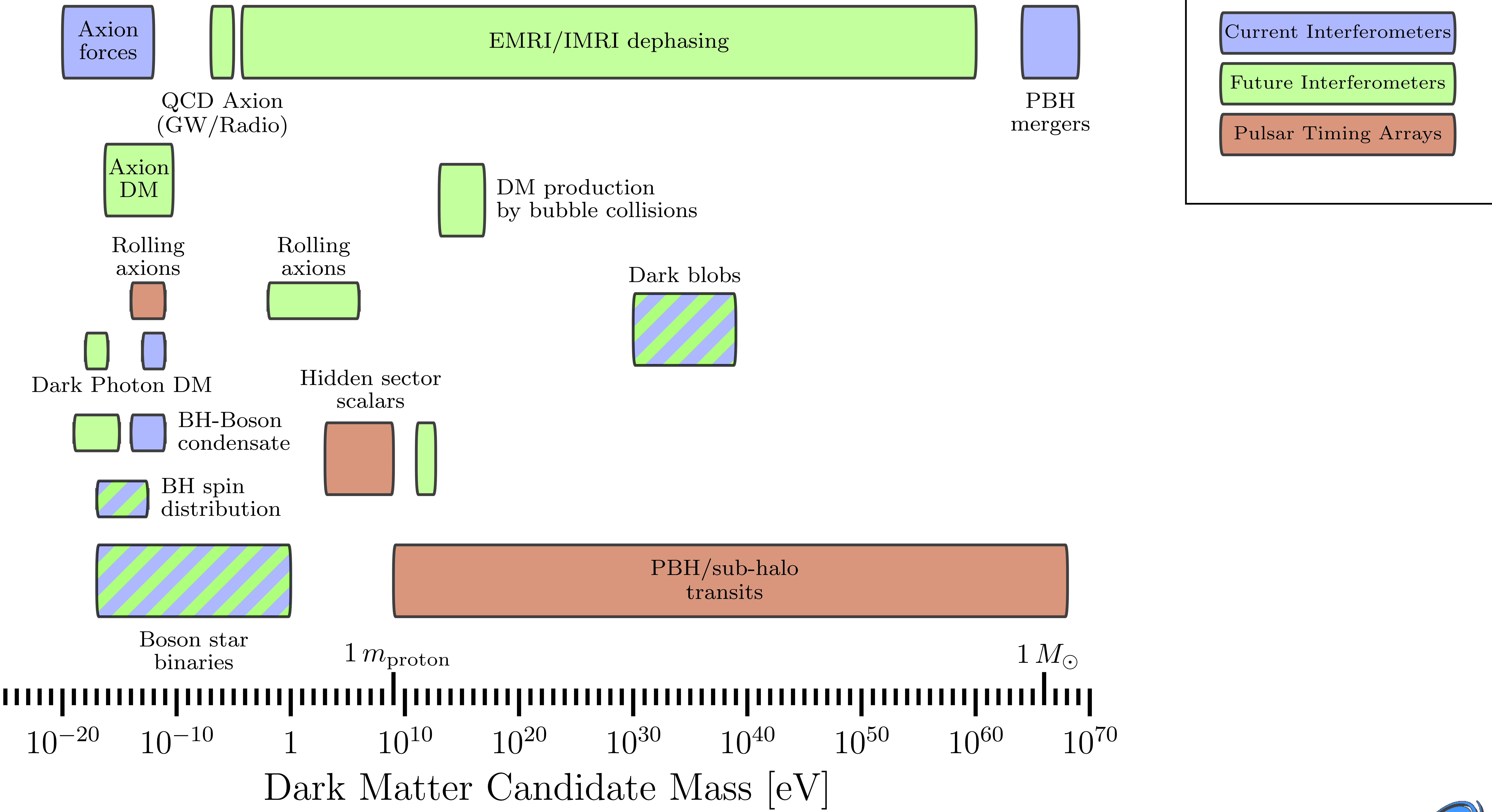


[Credit: Casey Reed (Penn State University), Wikimedia Commons]

Thank you!

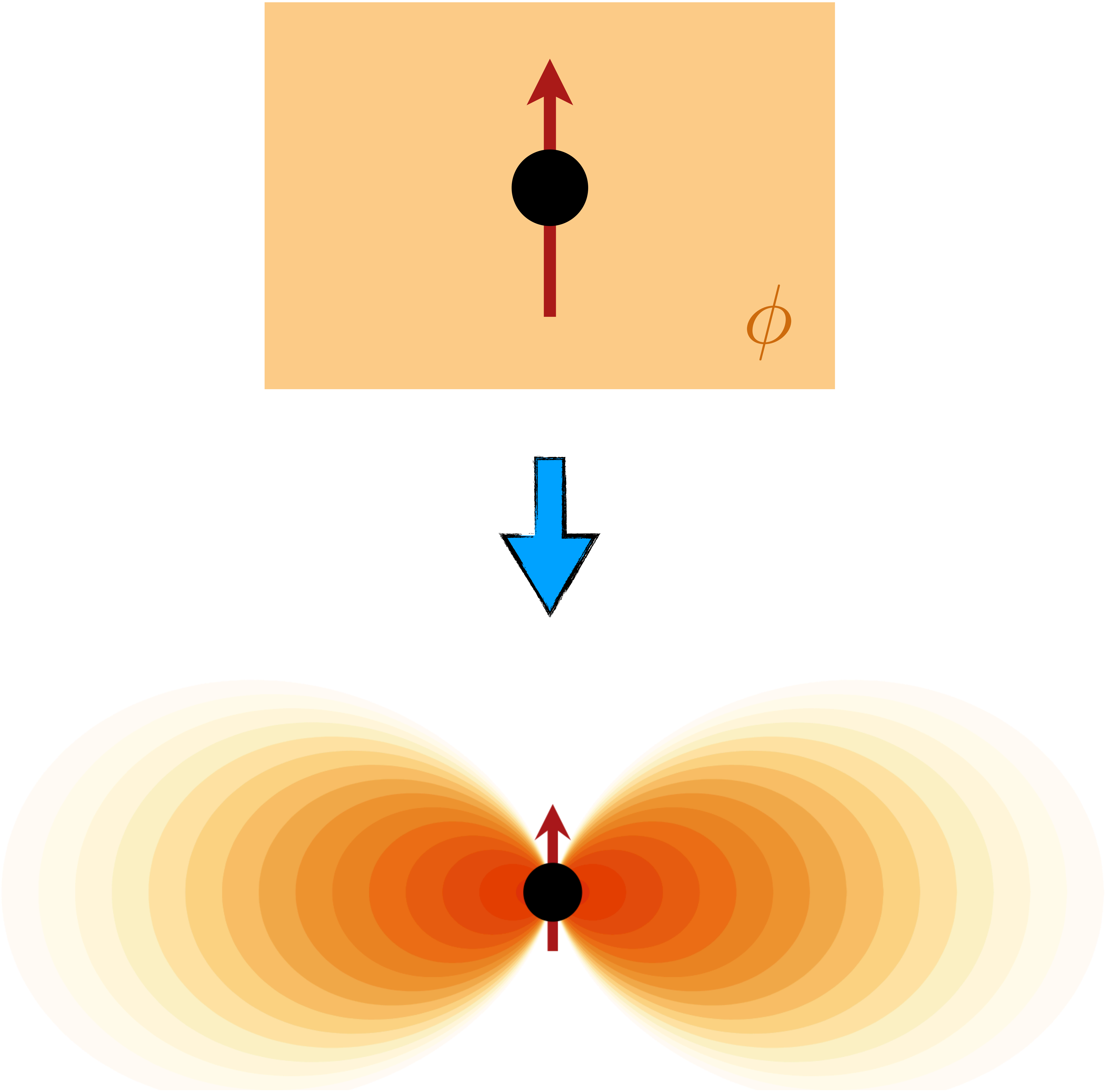
Backup Slides

GW Probes



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

Gravitational Atoms



Compton wavelength of a light scalar field:

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

Super-radiance (and growth of a '**gravitational atom**') when:

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

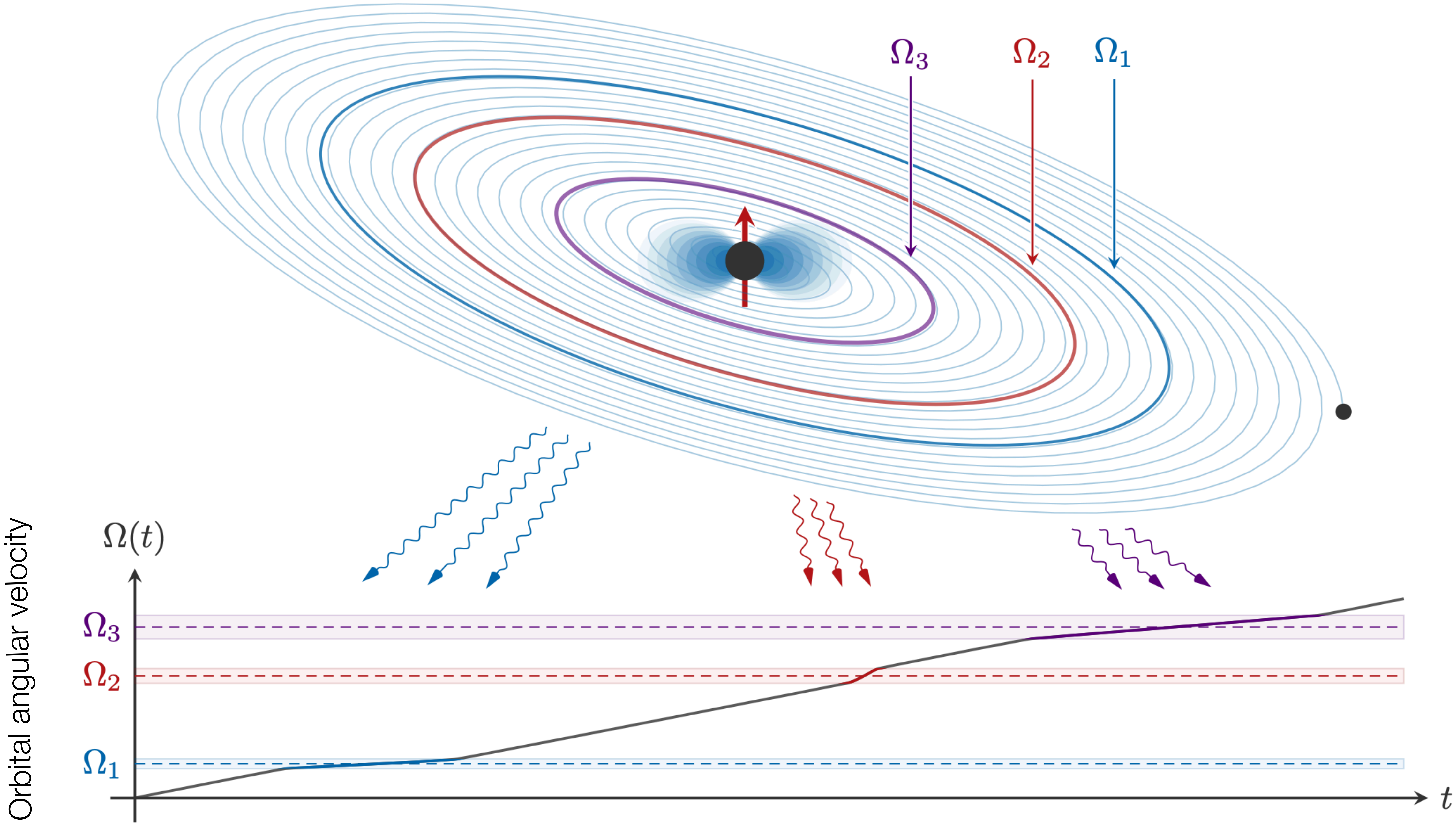
$$M_{\mathrm{BH}} \in [1, 10^{10}]\,M_\odot$$

$$\to m_\phi \in [10^{-20}, 10^{-10}]\,\mathrm{eV}$$

[Chia, 2012.09167]

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

Gravitational Atoms

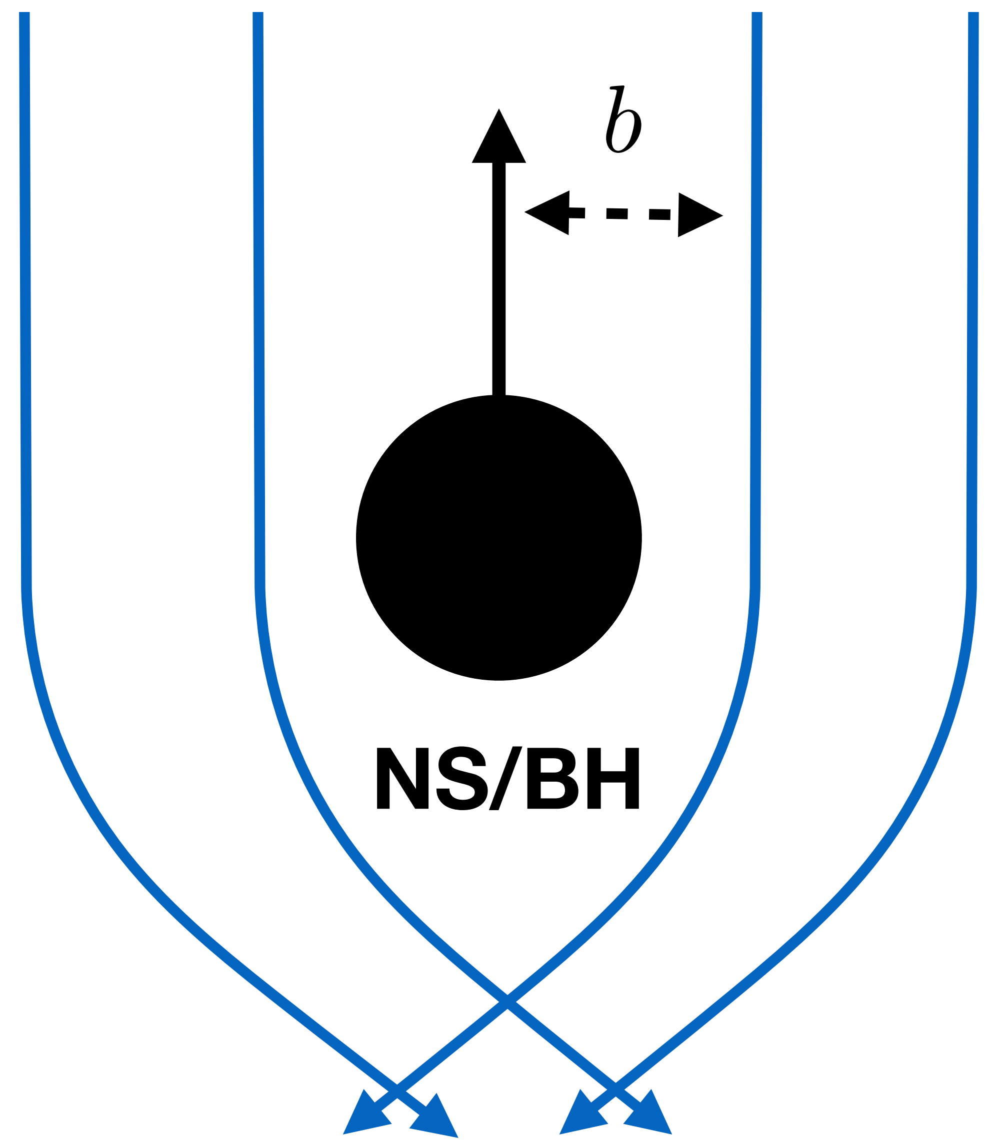


[Baumann et al., 1804.03208, 1908.10370, 1912.04932, 2012.09167, 2112.14777]

DM Gravitational Scattering Probability

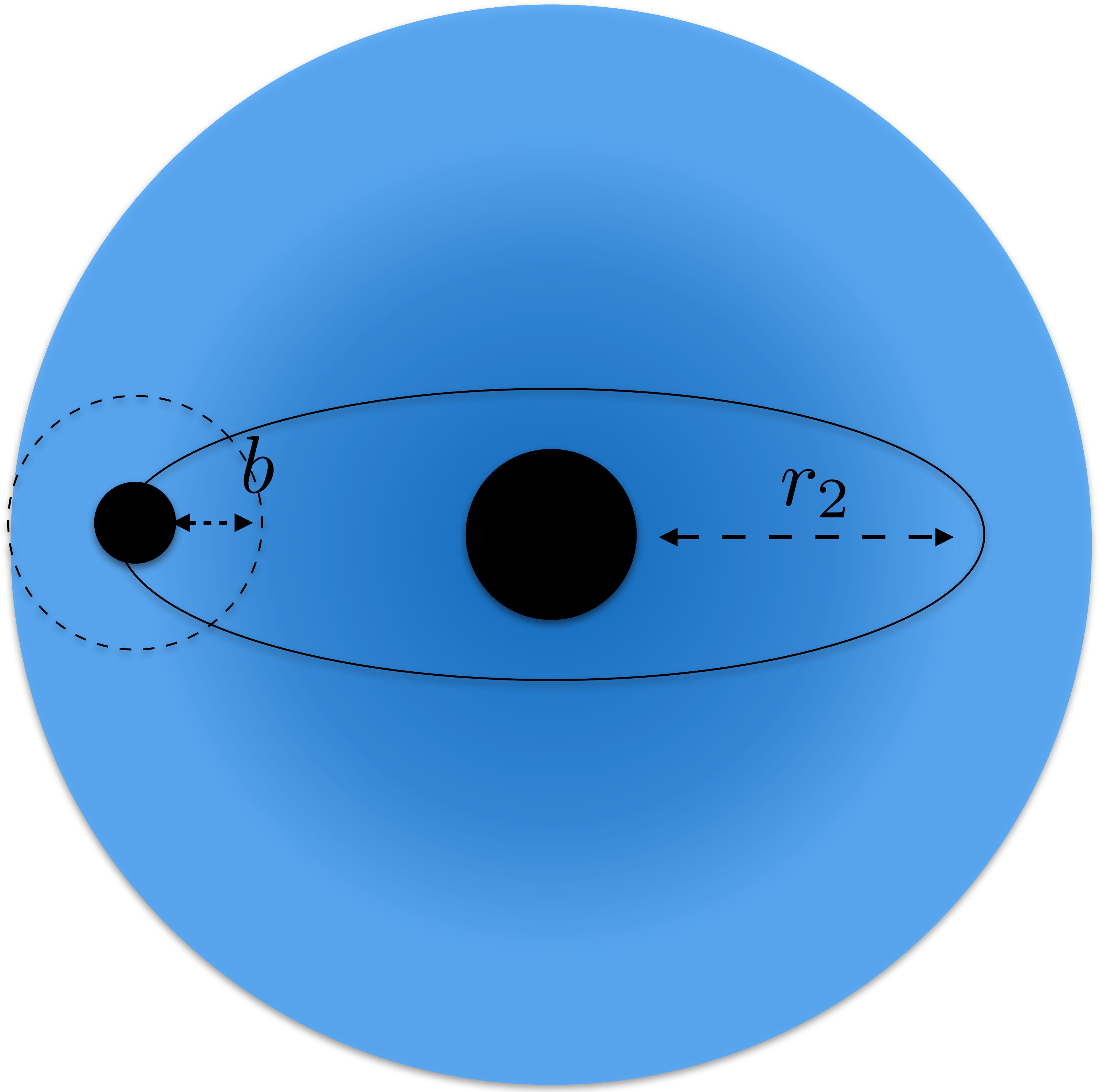
Two body scattering problem relates energy exchange to impact parameter:

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



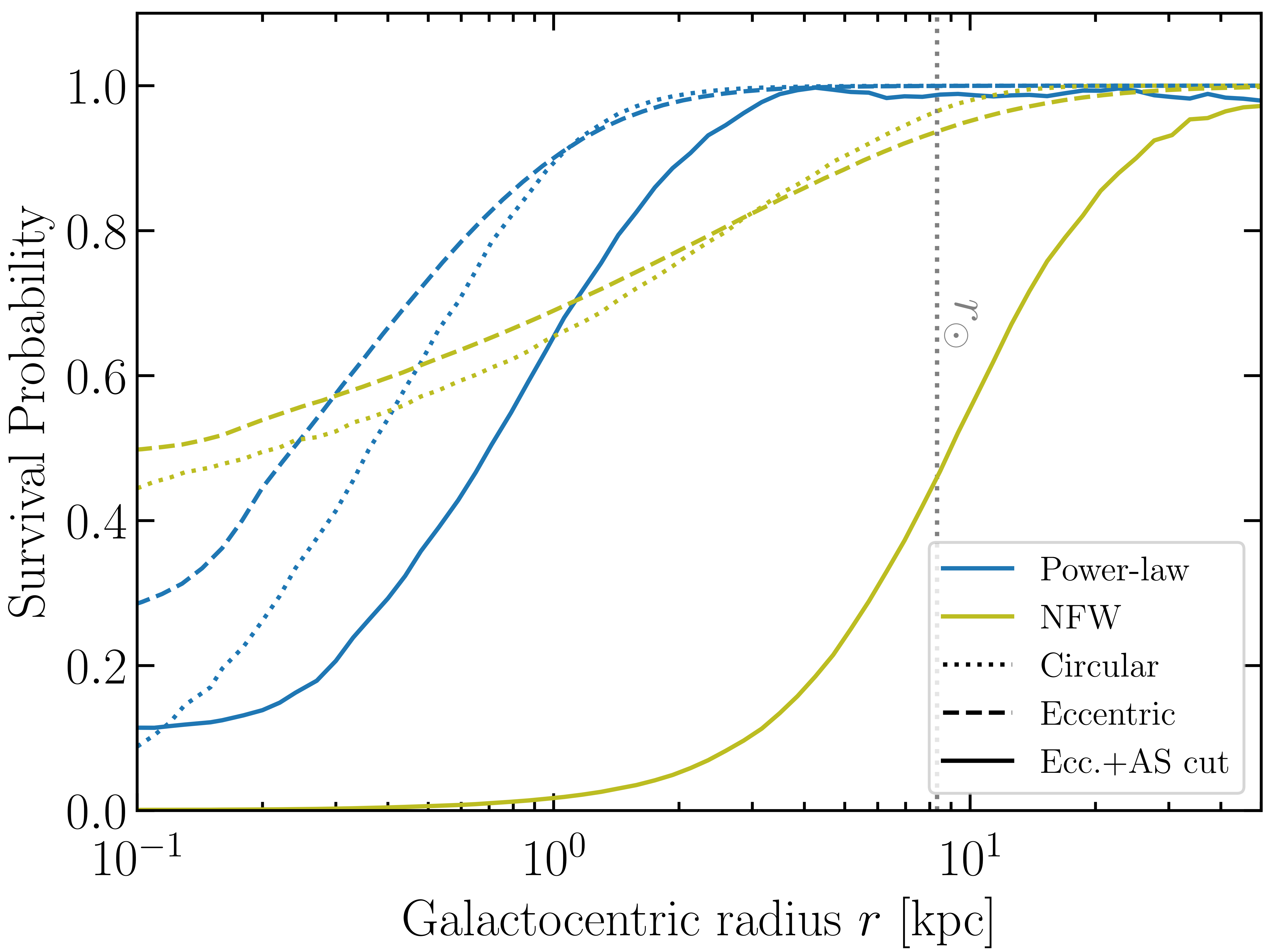
Scattering probability becomes a *geometric* problem:

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



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

AMC Survival in the Milky Way



Survival probability at Solar circle:
$\mathcal{O}(40\%)$ for NFW profiles
$\mathcal{O}(99\%)$ for PL profiles

But remember that even 'surviving' AMCs may be drastically altered.

[**BJK**, Edwards, Visinelli & Weniger, 2011.05377; Edwards, **BJK**, Visinelli & Visinelli, 2011.05378]

[See also previous work, e.g. Tinyakov et al., 1512.02884; Dokuchaev et al., 1710.09586; and more recent work e.g. Dandoy et al., 2206.04619, Shen et al., 2207.11276]