Dark Matter in Extreme Environments

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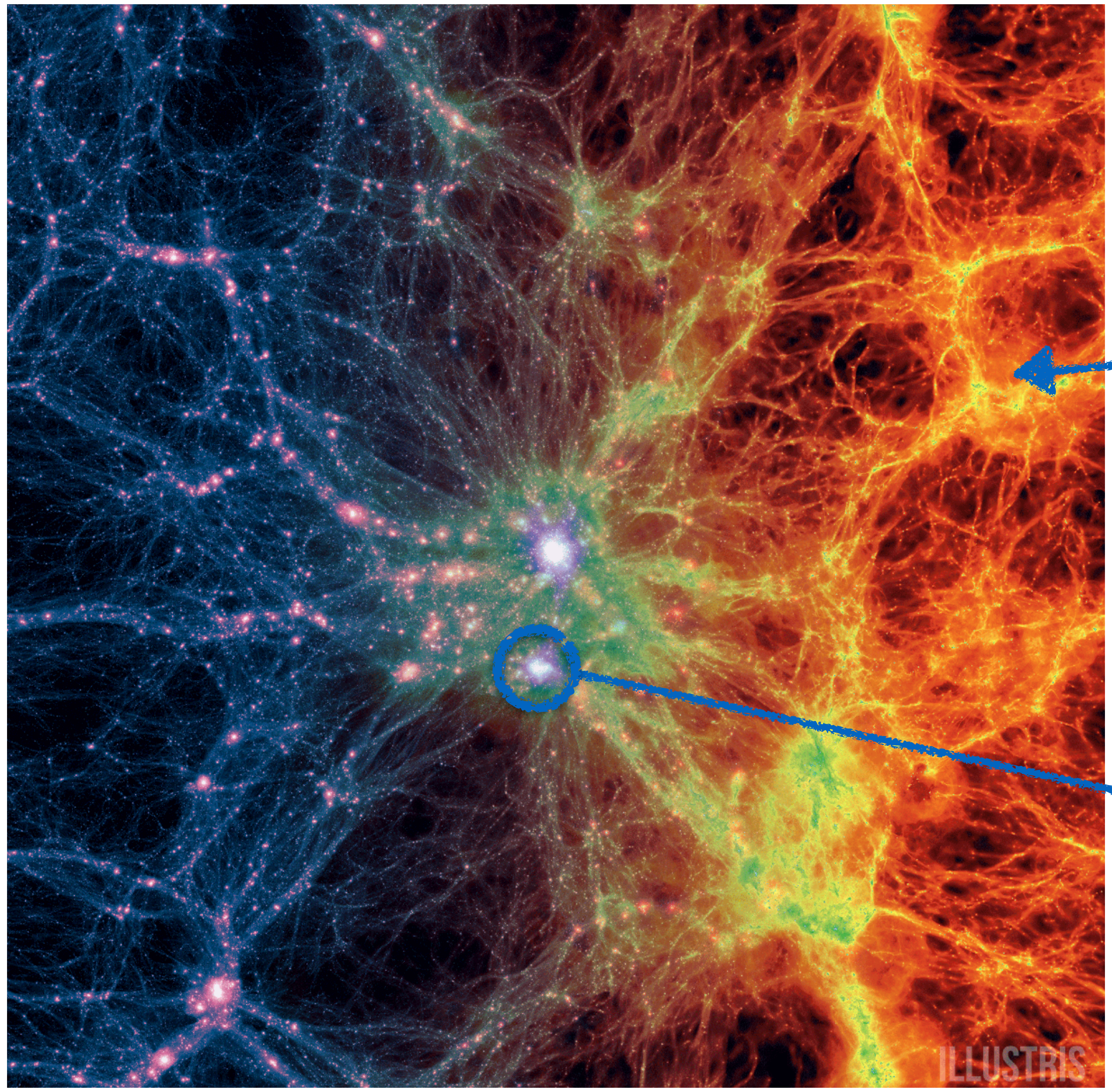
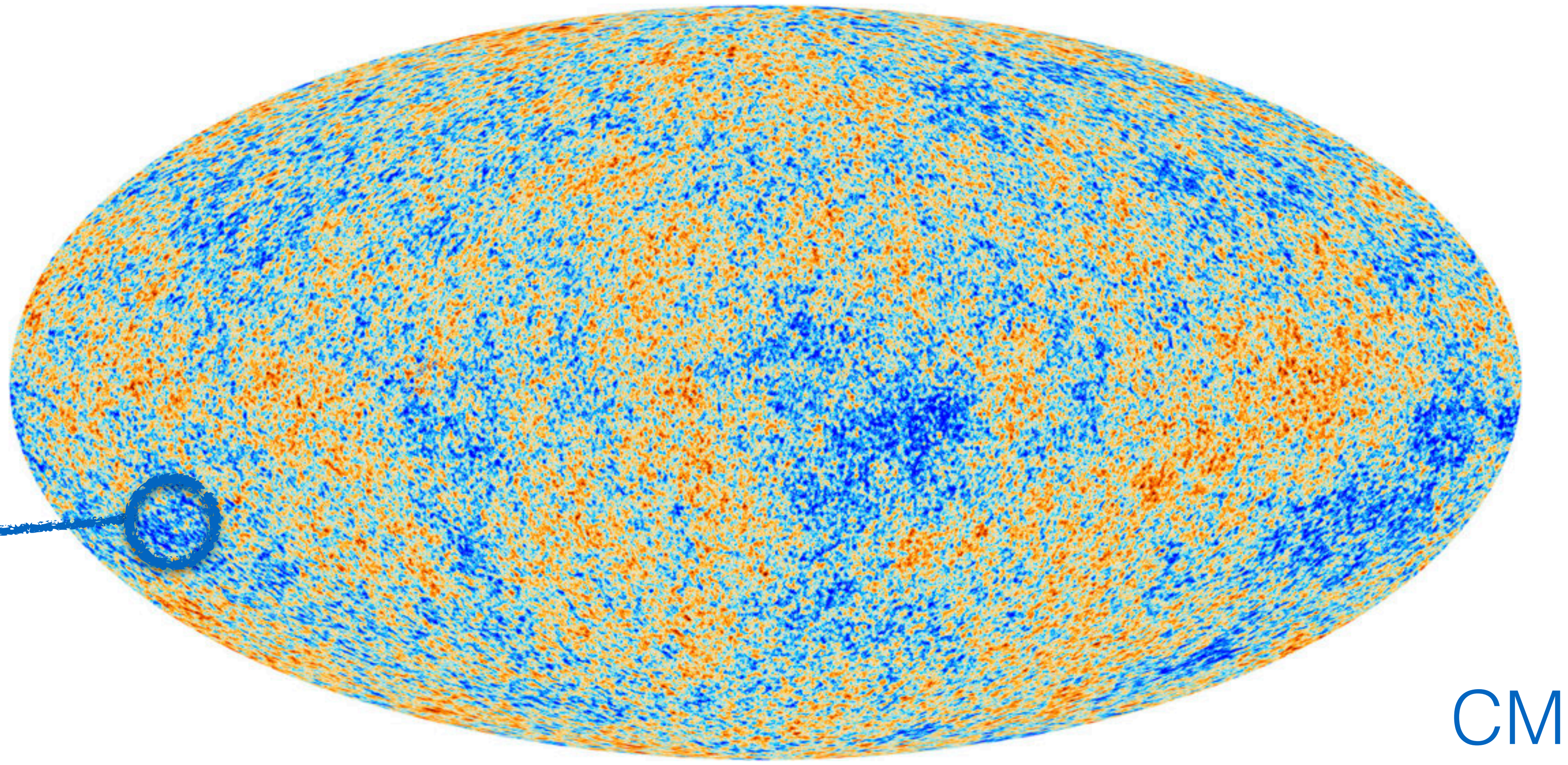
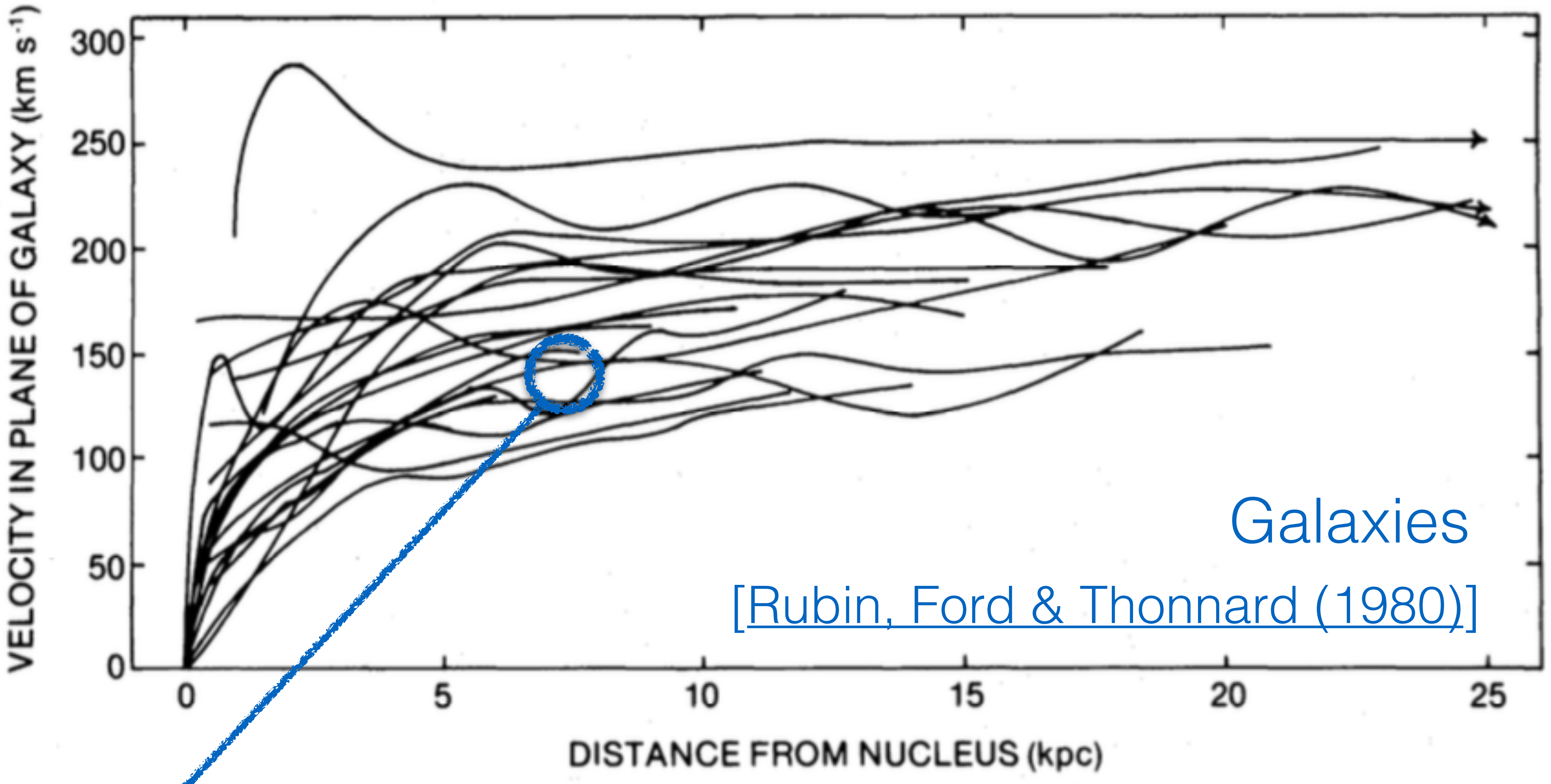
Evidence for Dark Matter



Galaxy clusters
[Illustris, 1405.2921]
[astro-ph/0006397]



CMB
[Planck, 1502.01589]

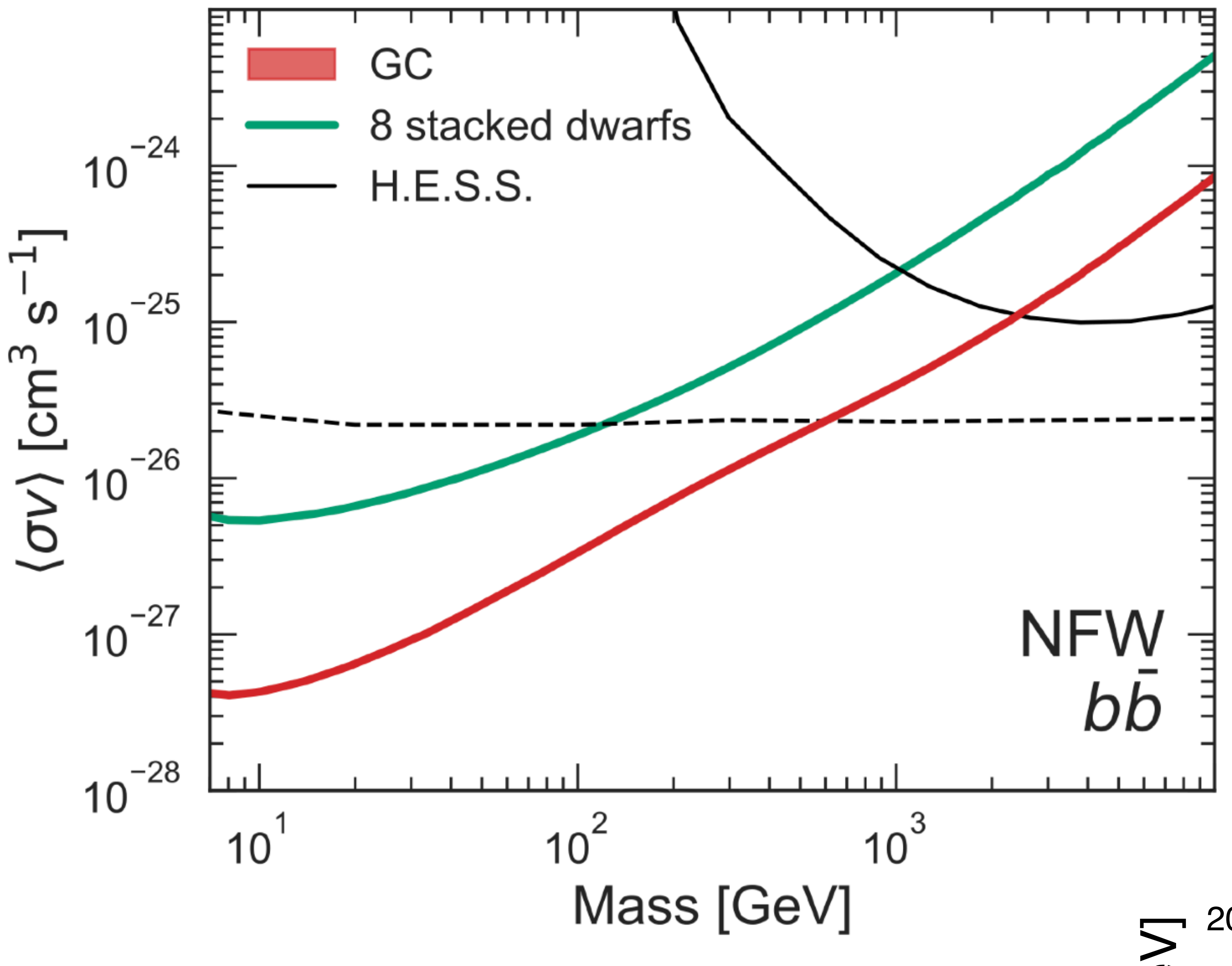


Galaxies
[Rubin, Ford & Thonnard (1980)]

The Dark Matter Landscape

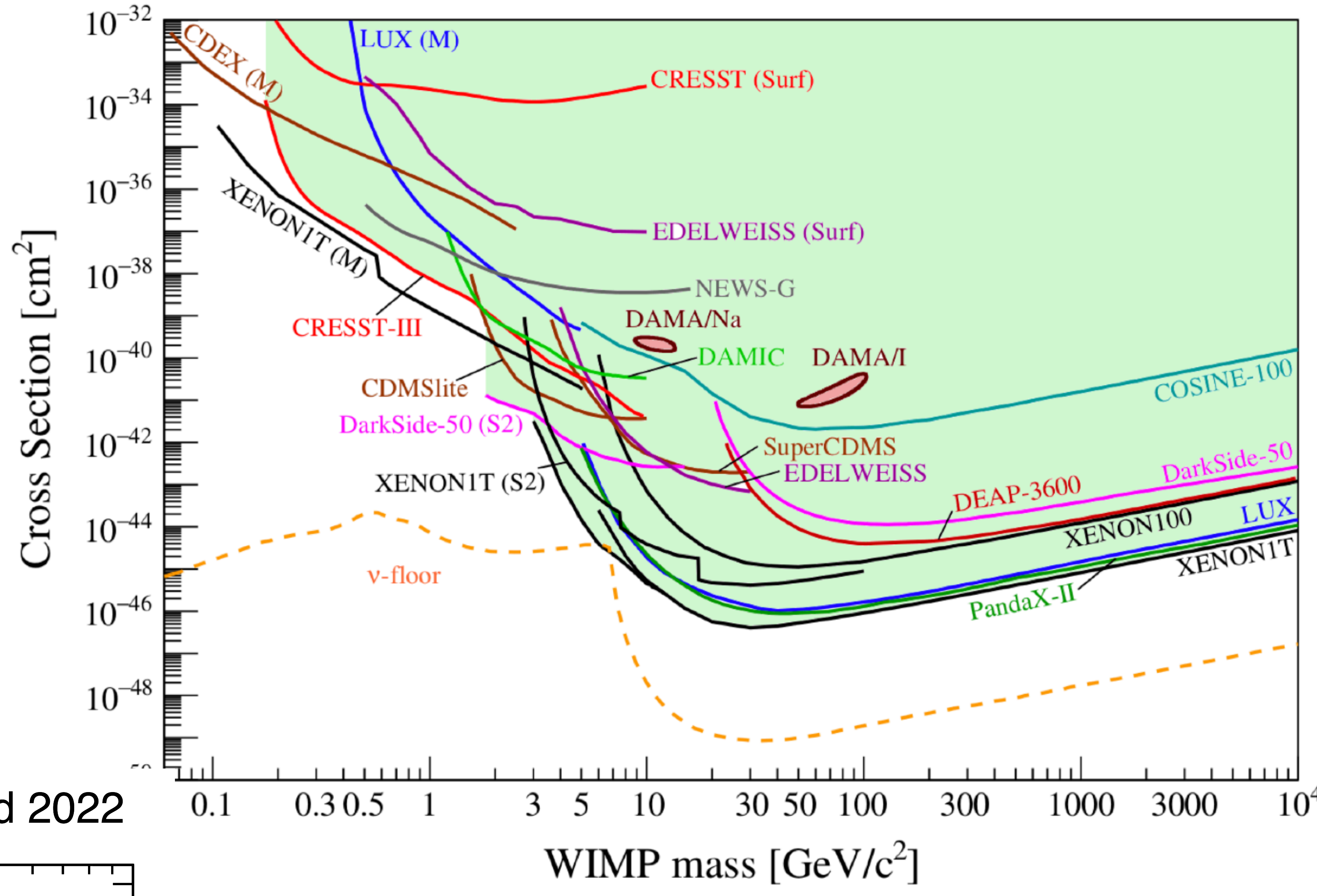
Indirect searches

[Abazajian et al., 2003.10416]



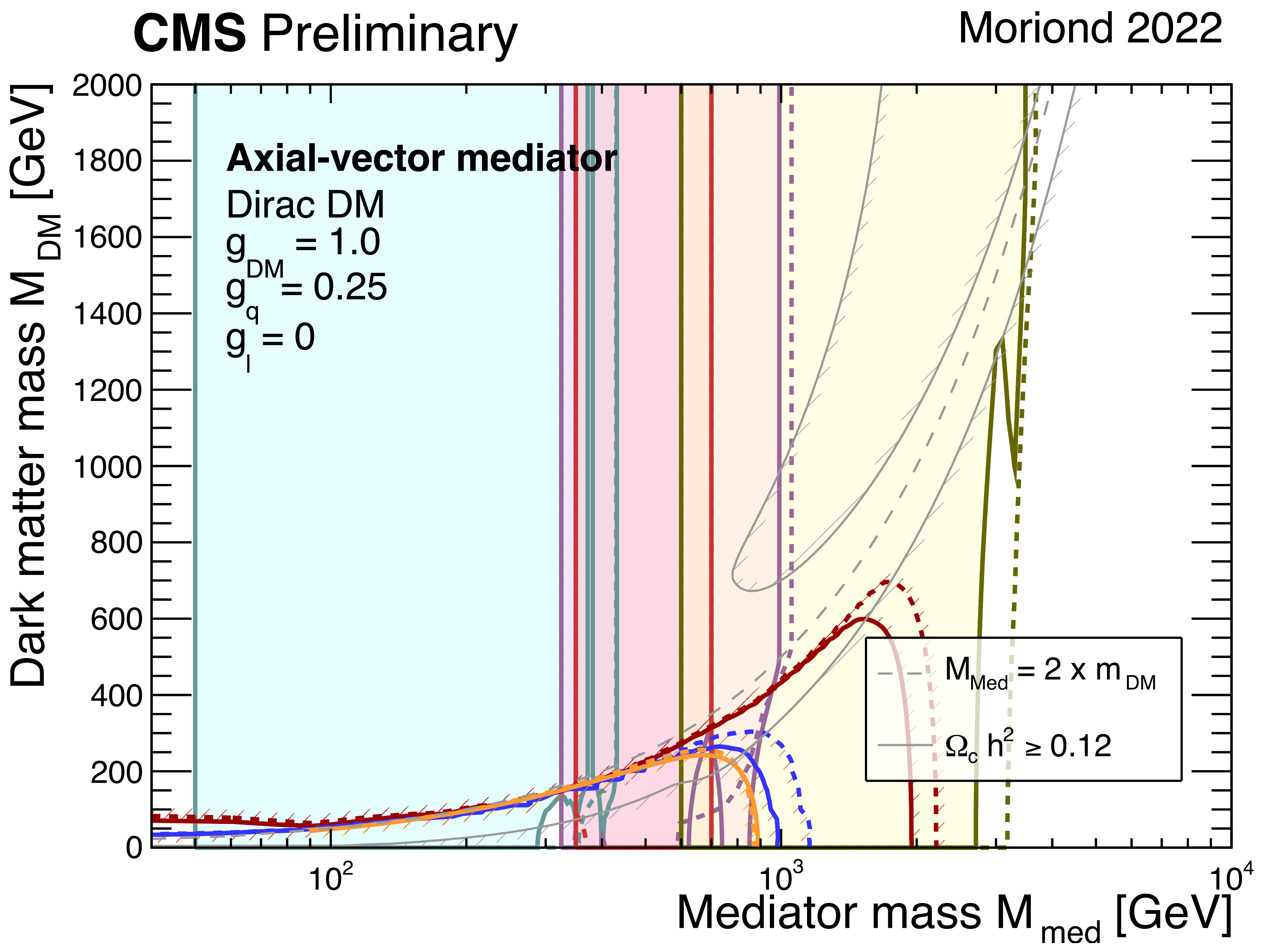
Direct Searches

[APPEC, 2104.07634]



Collider Searches

[CMS, DM Summary Plots]



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

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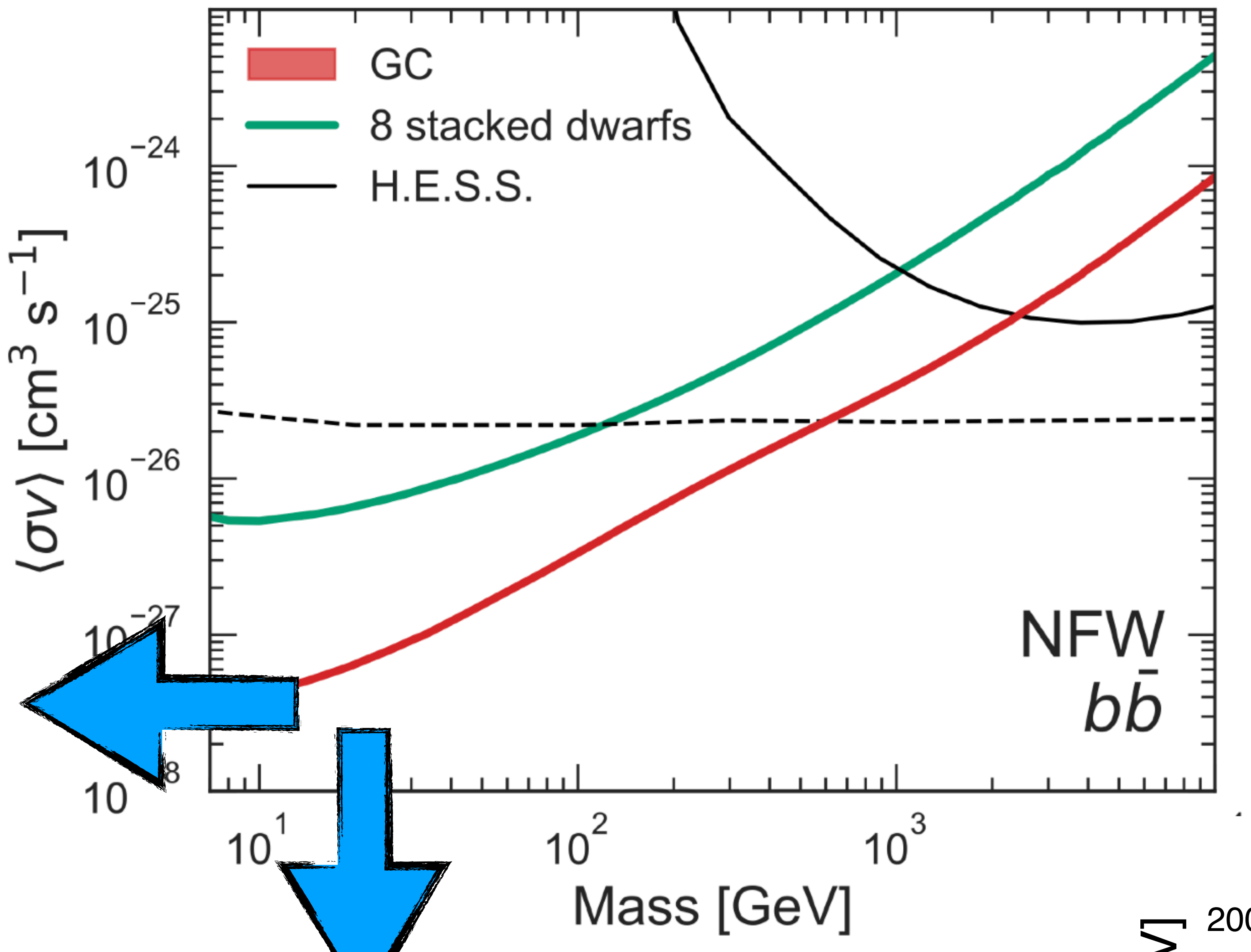
[Abazajian et al., 2003.10416]



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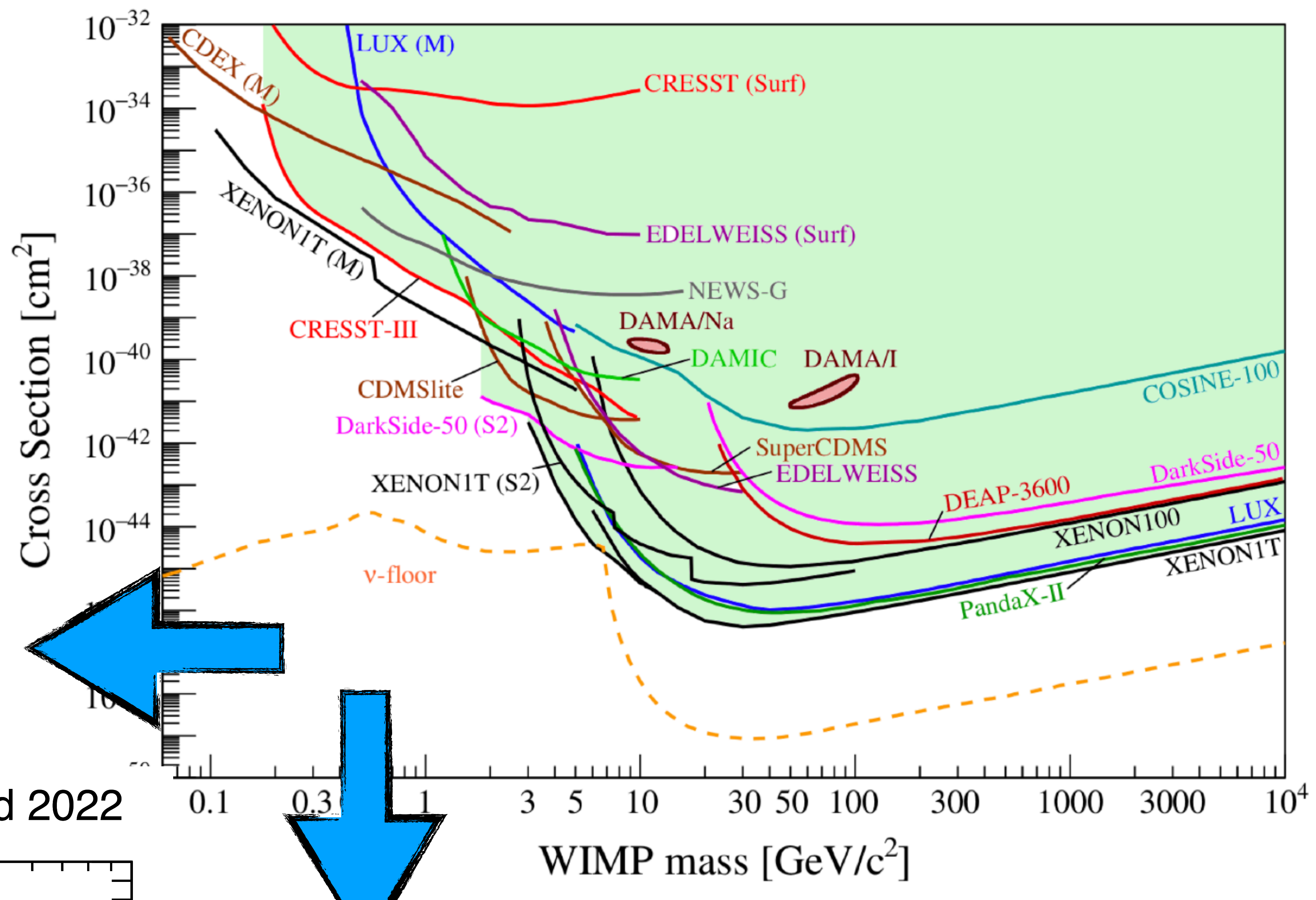

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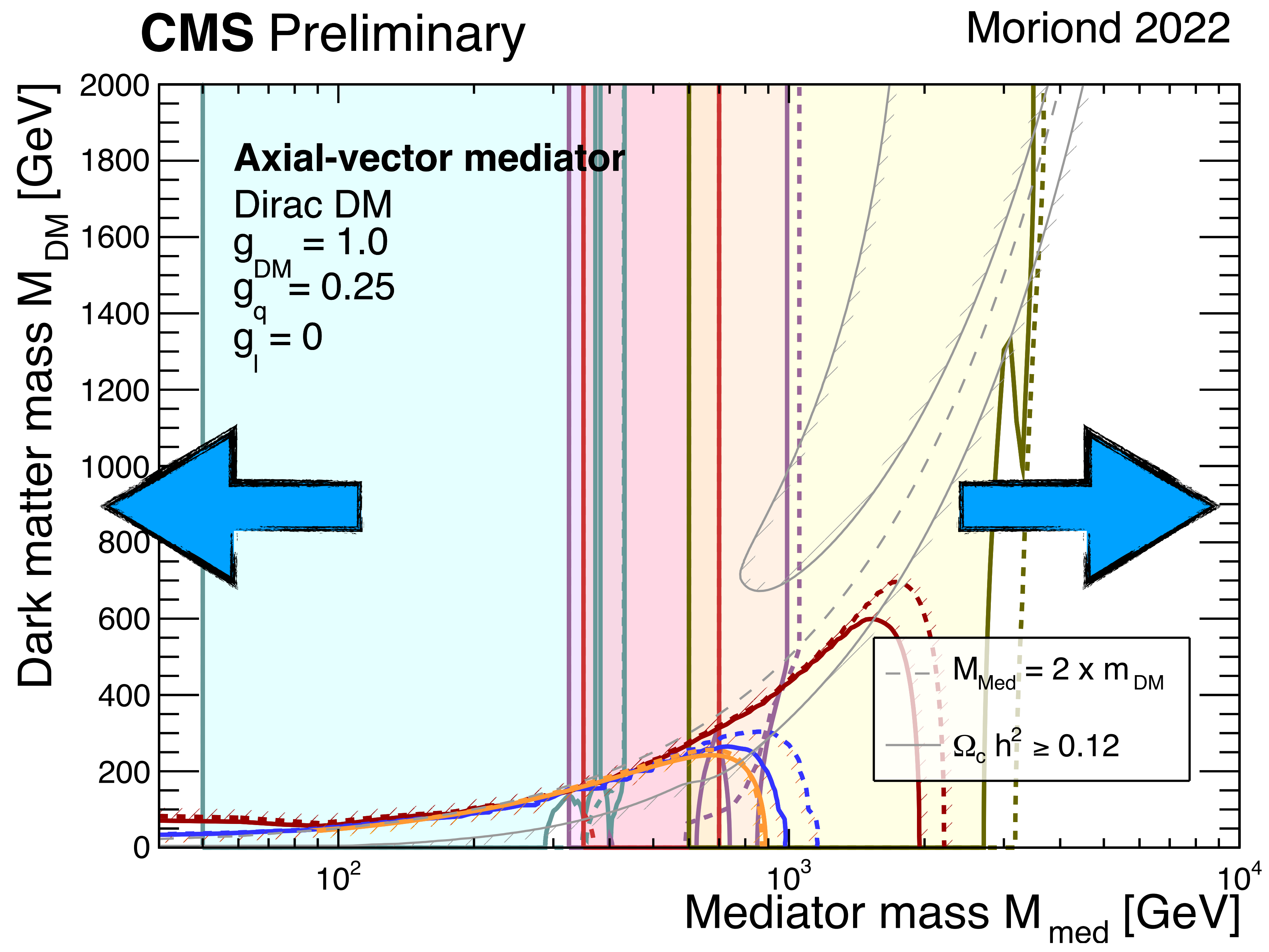

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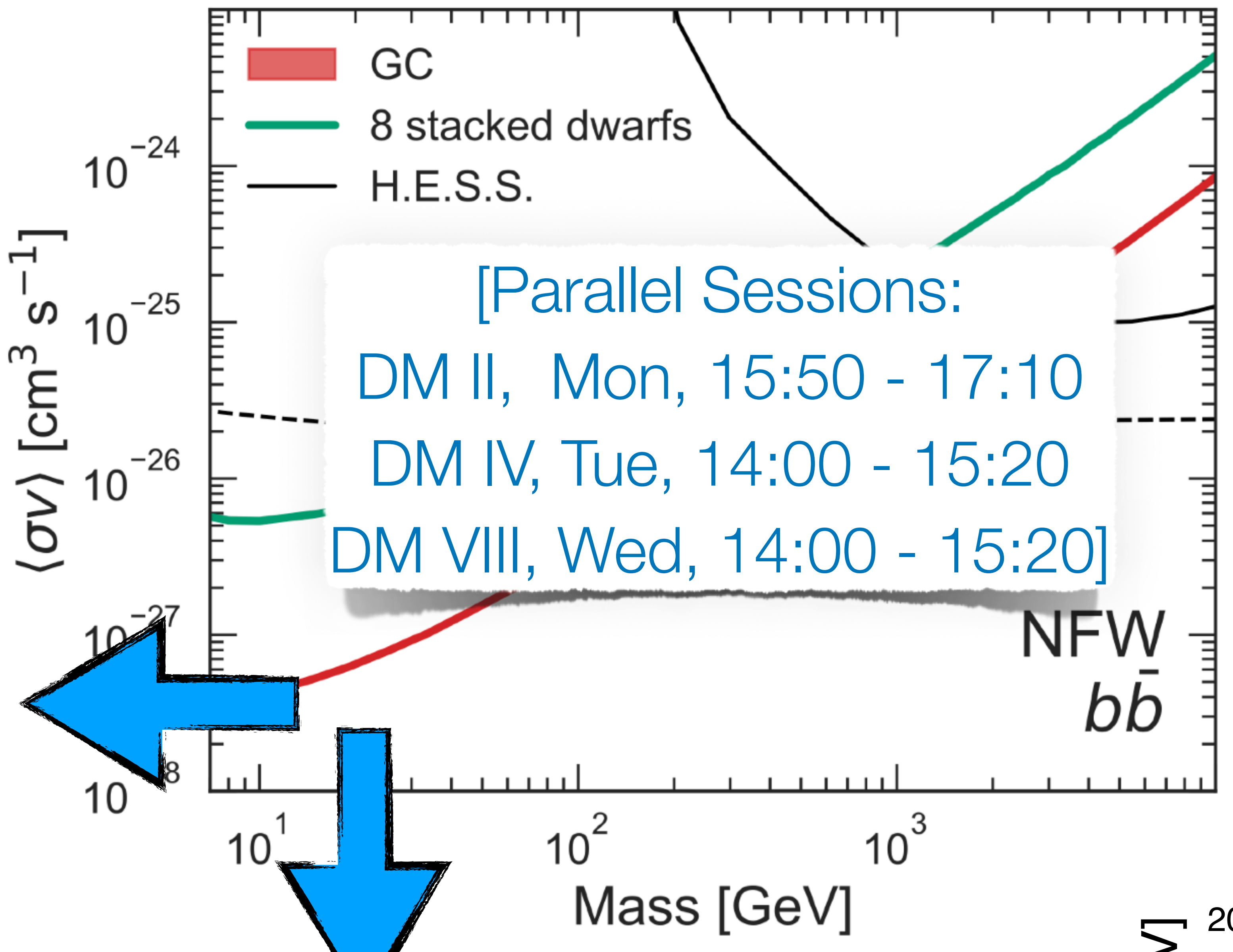
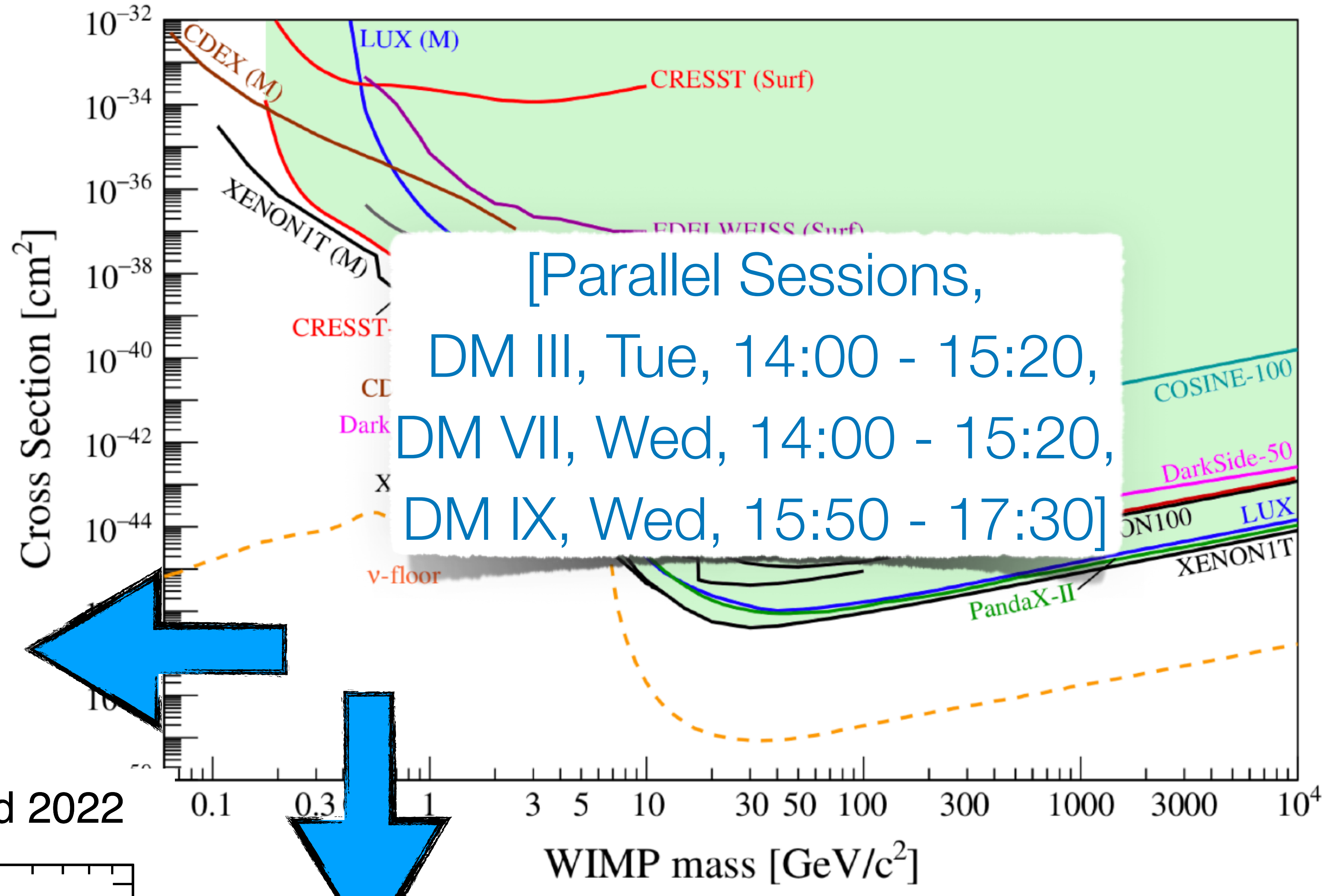


[Parallel Sessions:
DM II, Mon, 15:50 - 17:10
DM IV, Tue, 14:00 - 15:20
DM VIII, Wed, 14:00 - 15:20]

Direct Searches

[APPEC, 2104.07634]



[Parallel Sessions,
DM III, Tue, 14:00 - 15:20,
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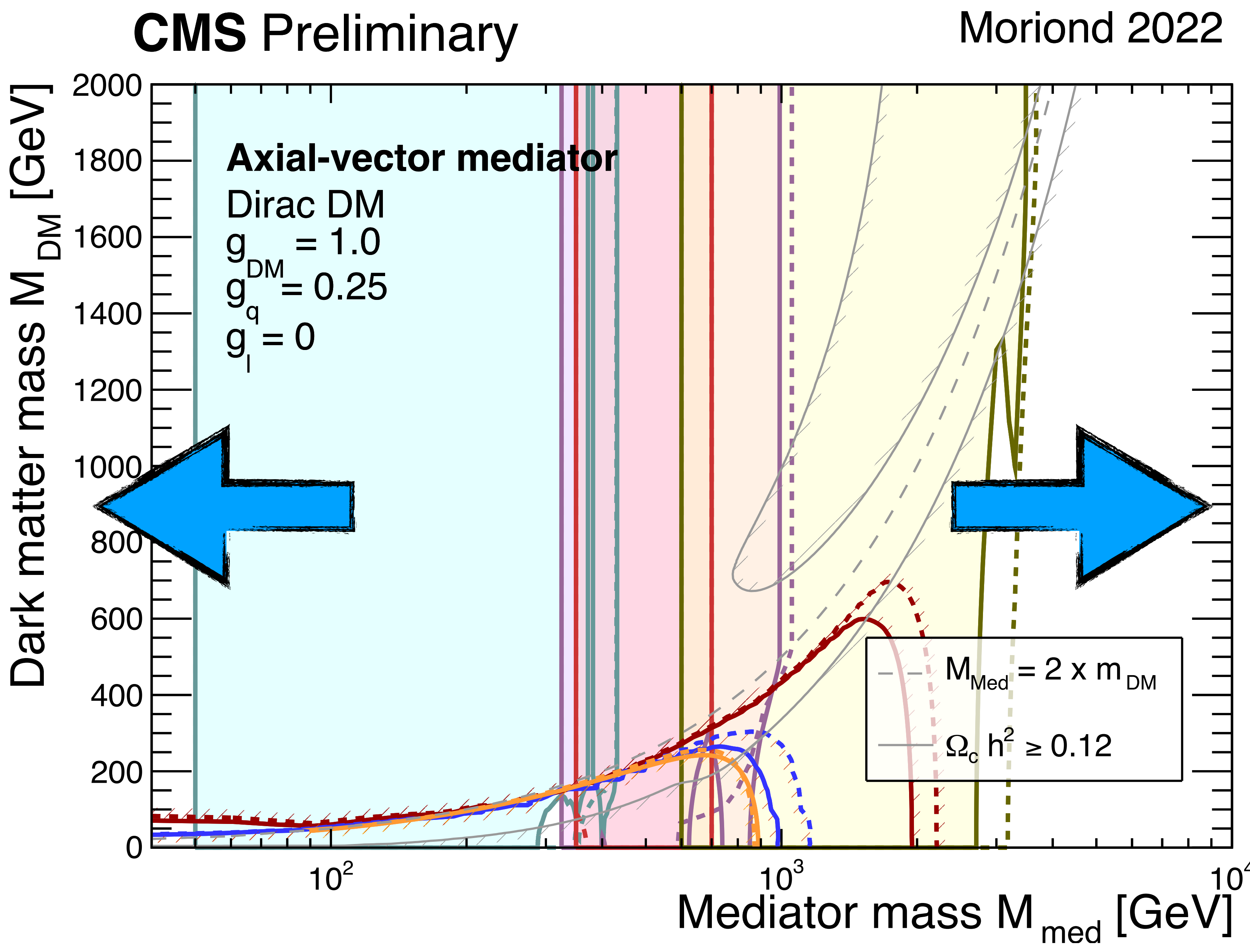
DM IX, Wed, 15:50 - 17:30]

Collider Searches

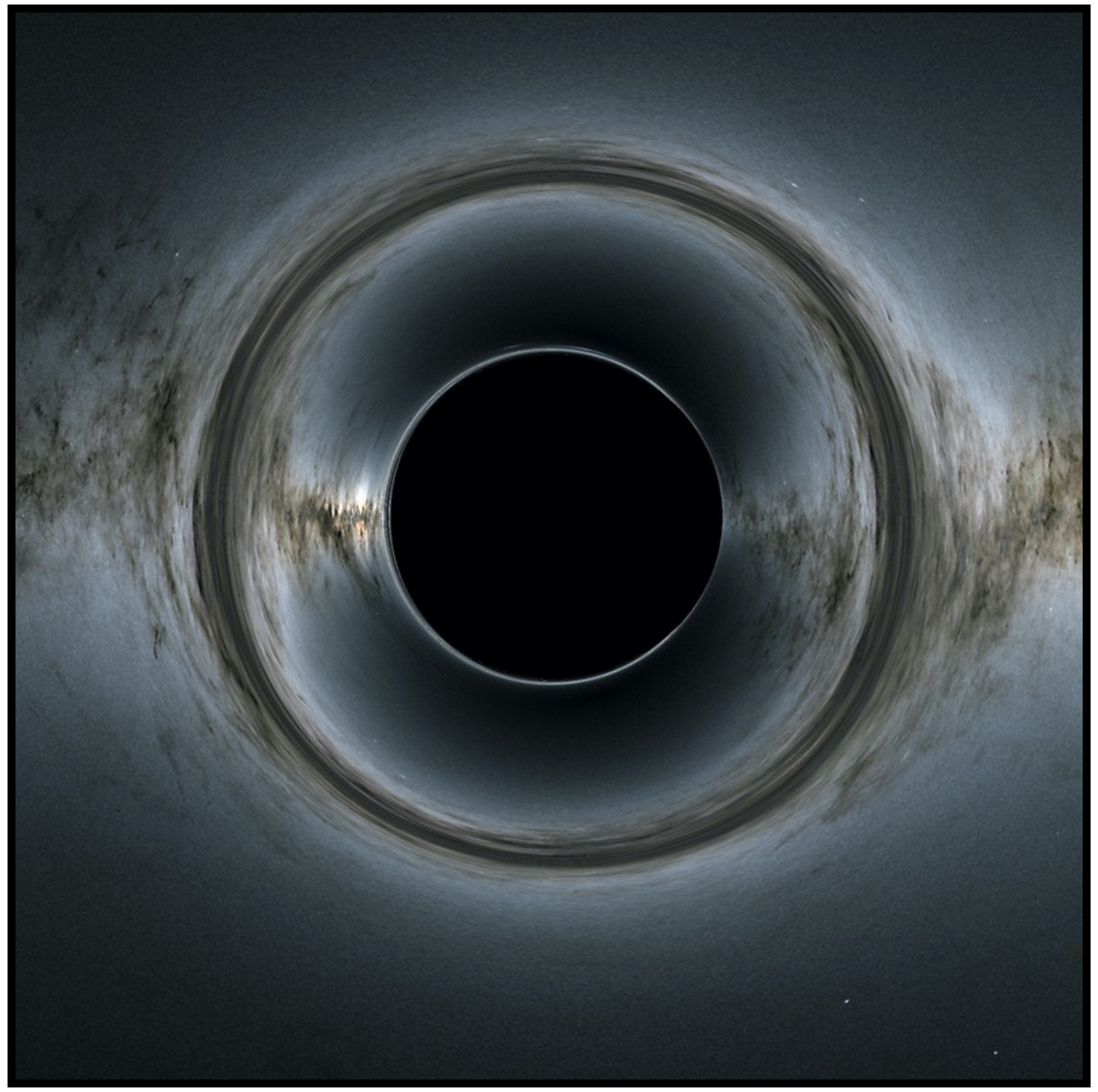
[CMS, DM Summary Plots]



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

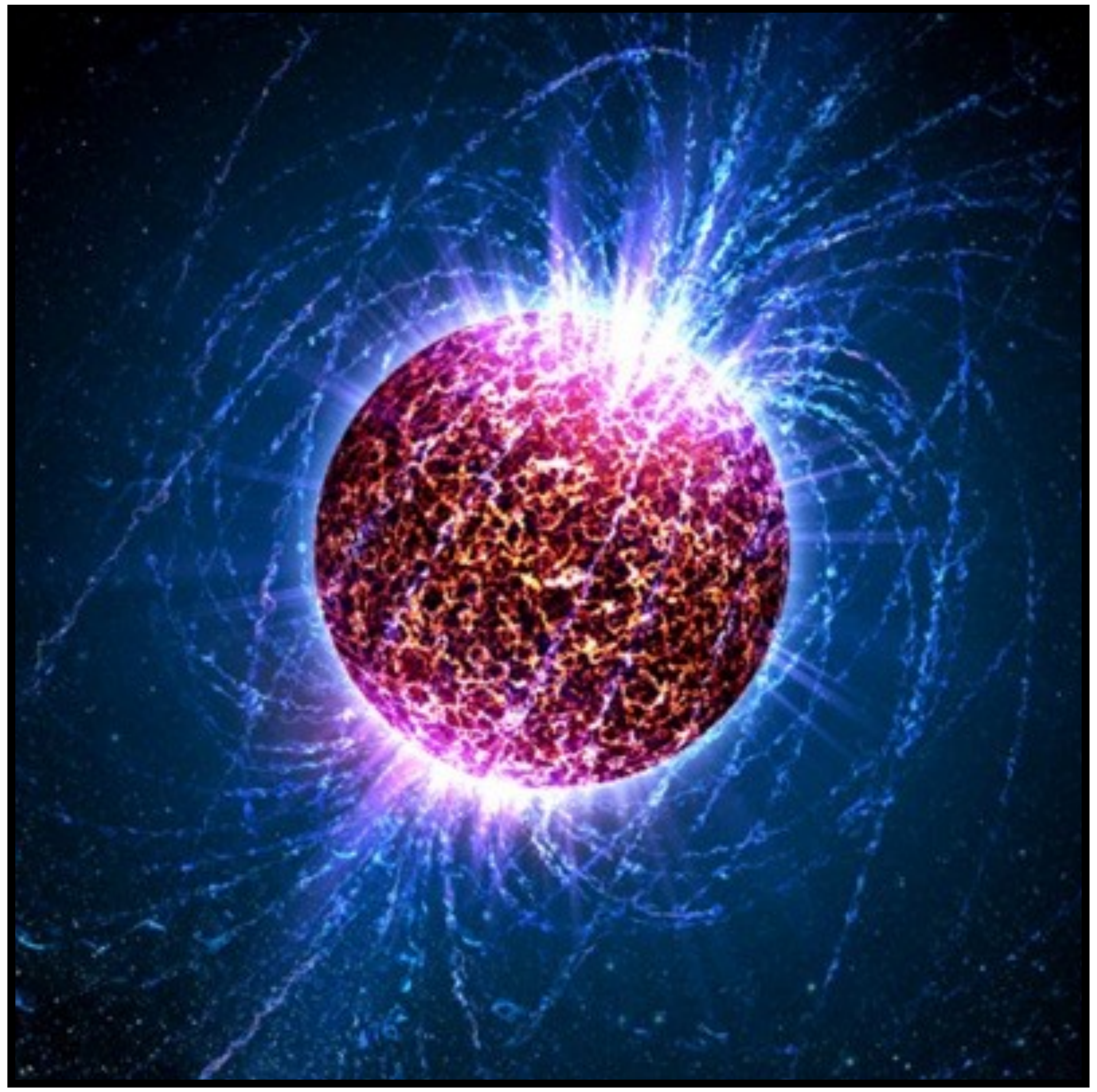
["Dark Matter in Extreme Astrophysical Environments", Baryakhtar et al., 2203.07984]

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

Dark Matter Spikes

'**Spikes**' or '**dresses**' of cold, particle-like DM may form BHs:*

From the slow ('adiabatic') growth of a BH at the centre of a DM halo

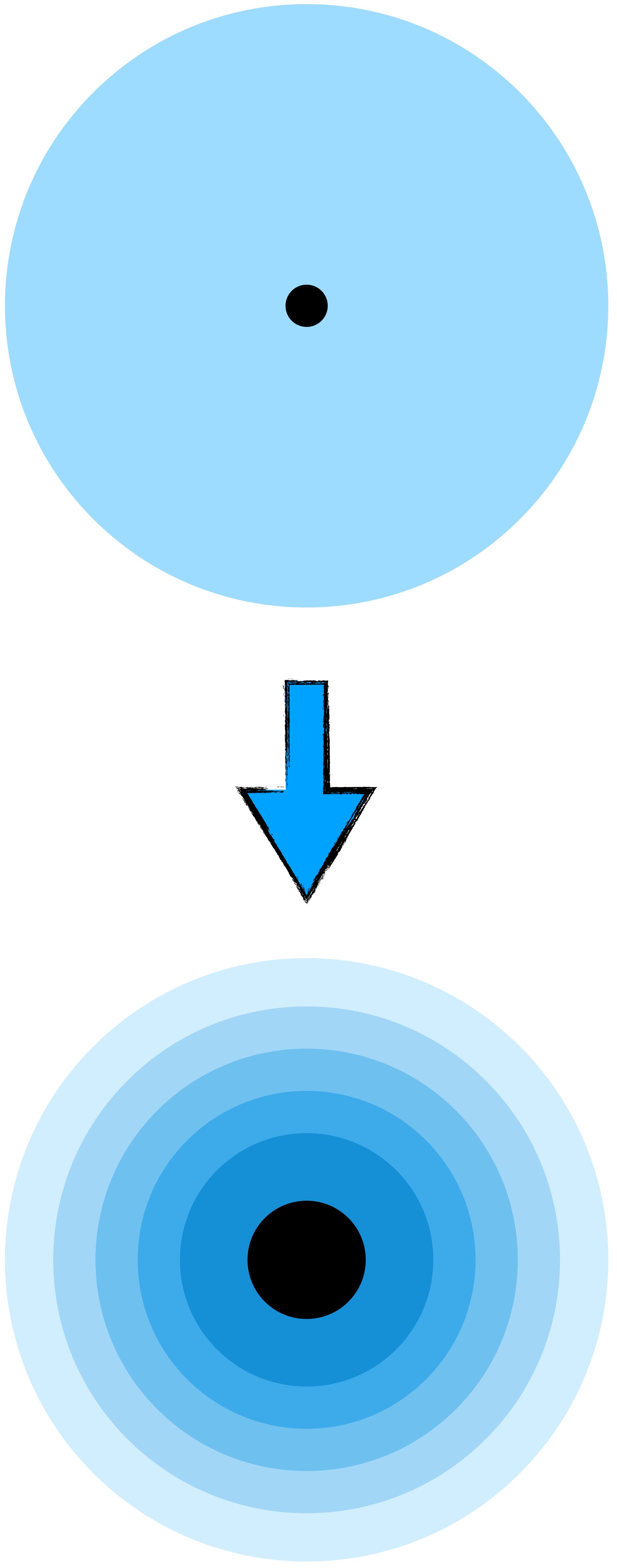
"Astrophysical scenario"

[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"

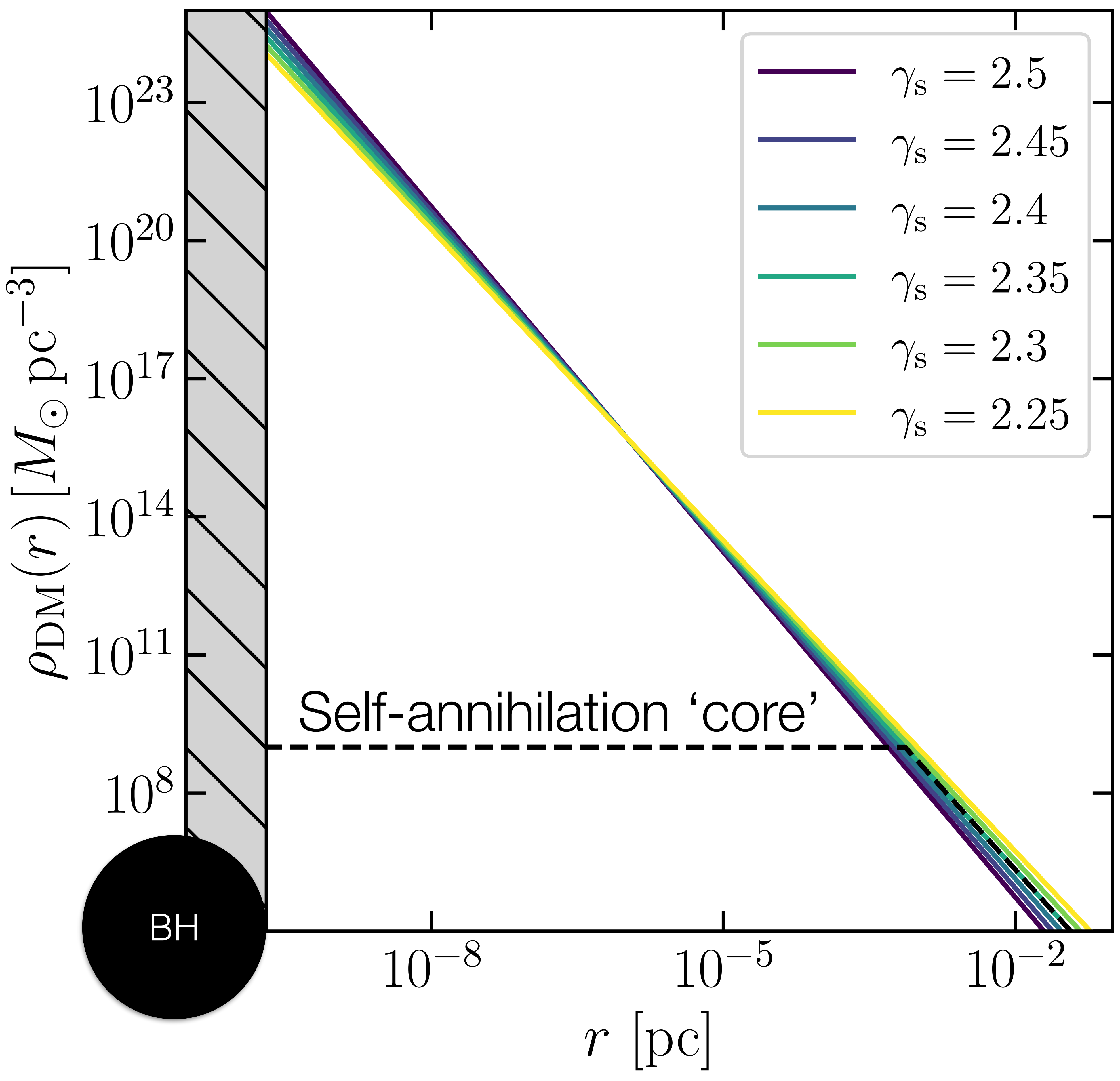
[Bertschinger (1985), astro-ph/0608642, 1901.08528, …]



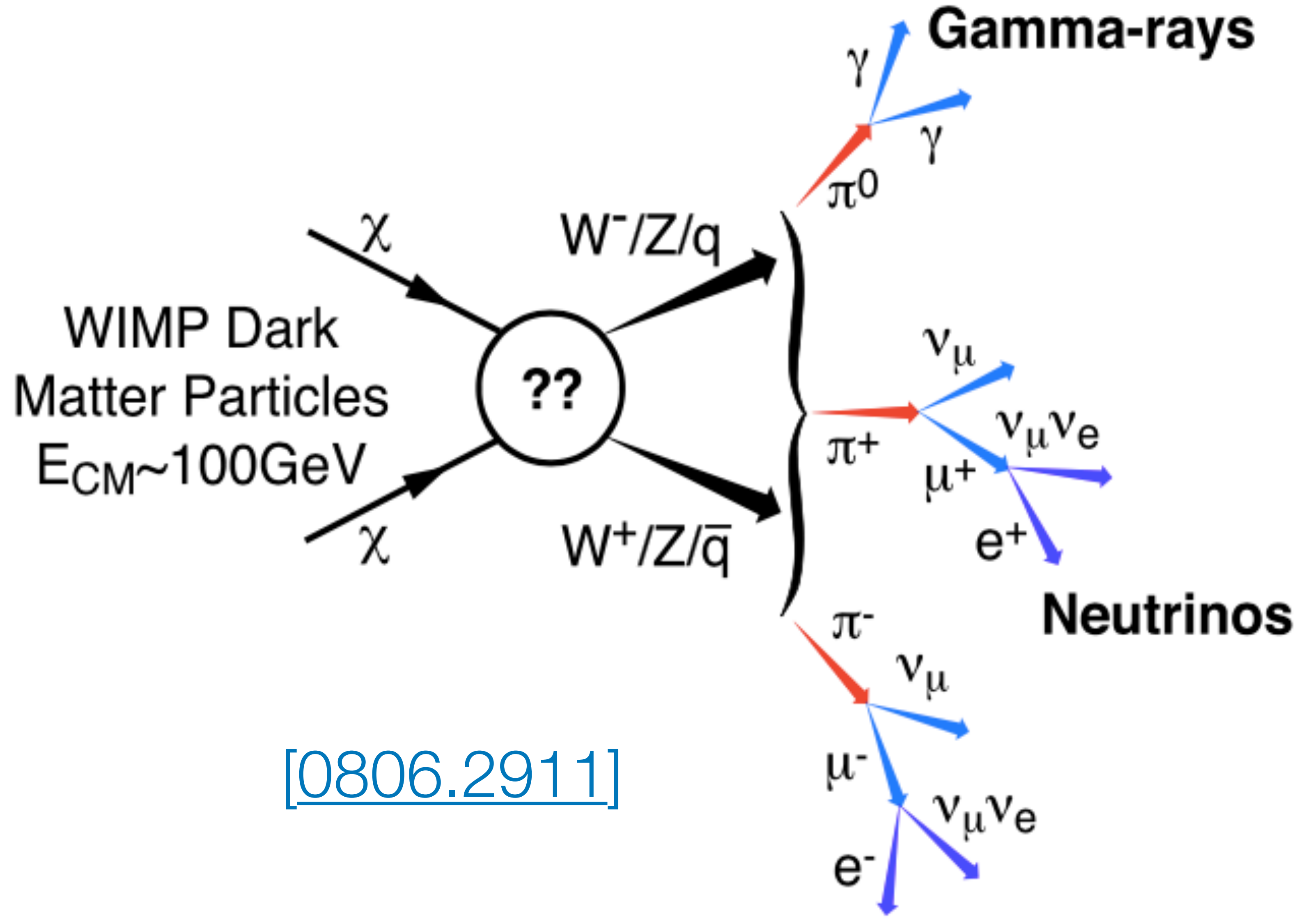
*not to be confused with ultralight boson clouds

DM annihilation?

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



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



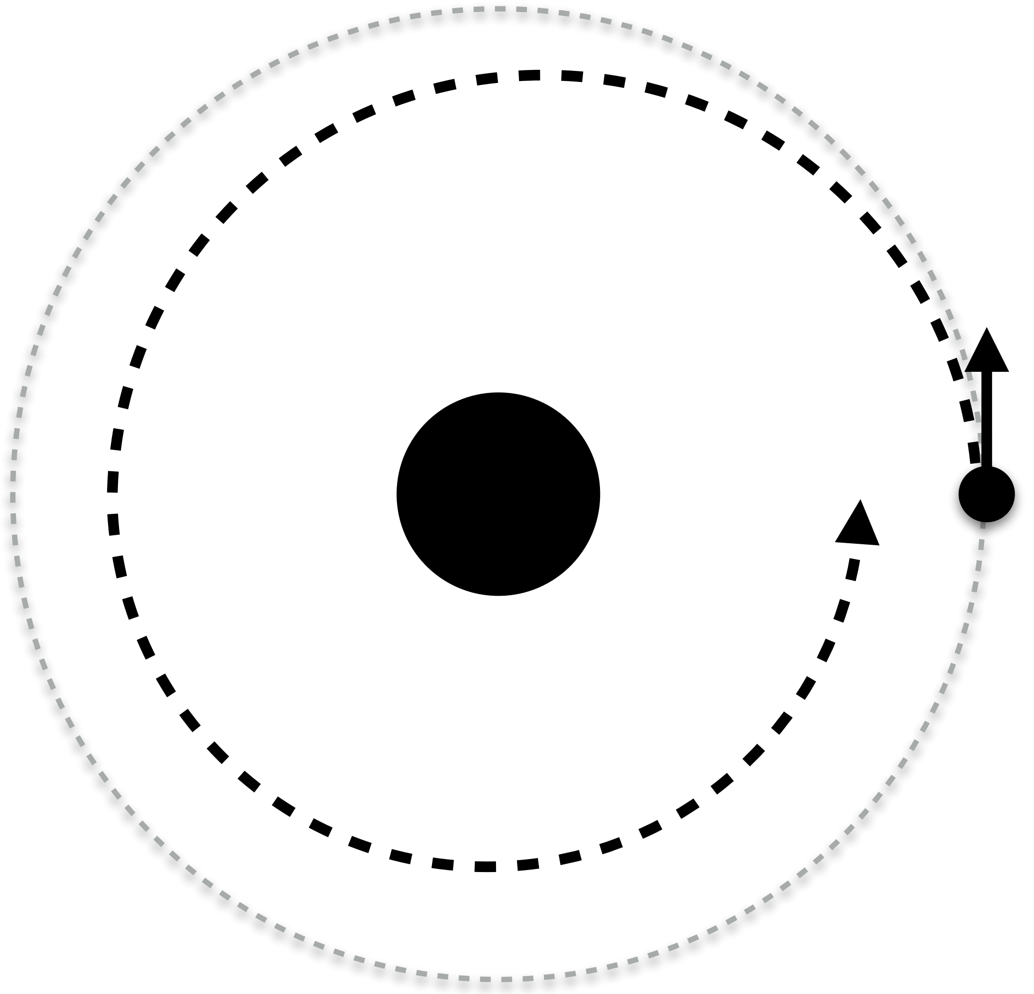
[0806.2911]

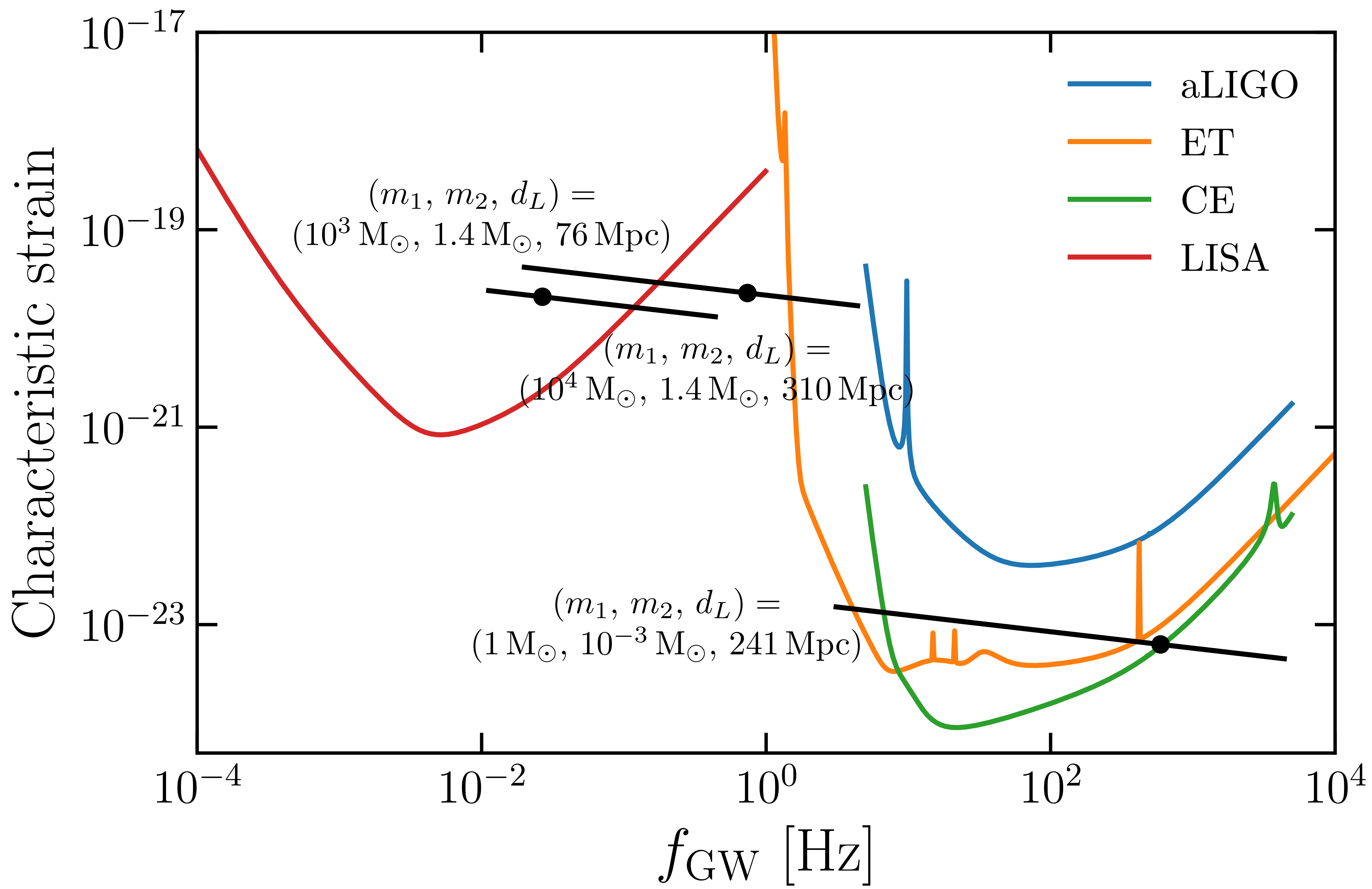
DM self-annihilation can suppress the spike density, but can still lead to large (diffuse and point source) fluxes of gamma-rays and neutrinos

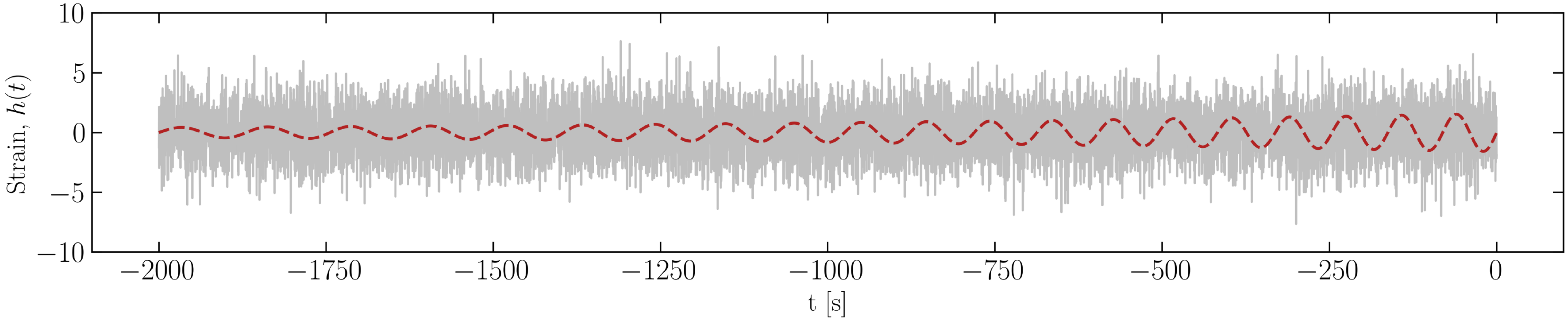
[E.g. Lacroix & Silk, 1712.00452, Bertone et al., 1905.01238, Freese et al., 2202.01126]

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

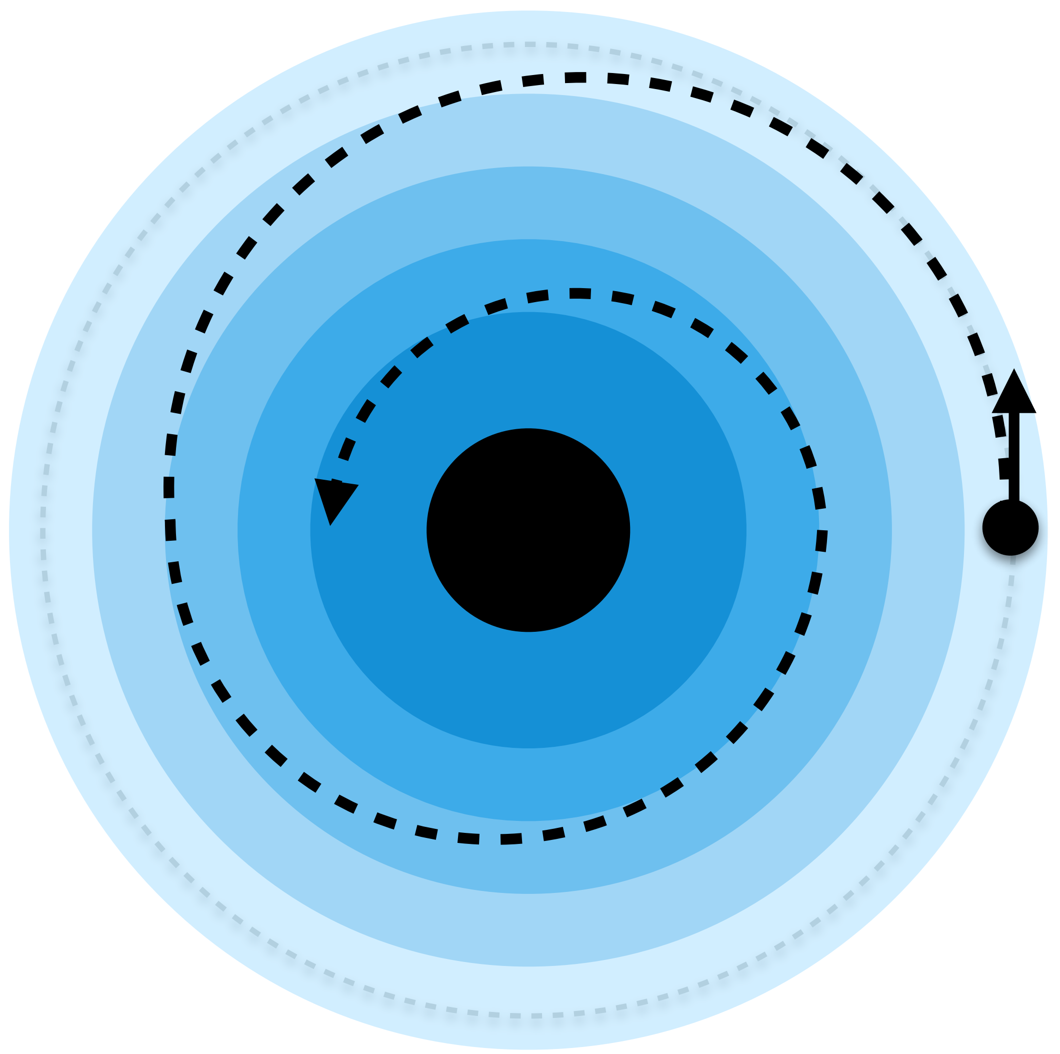
Intermediate Mass Ratio Inspirals (IMRIs)

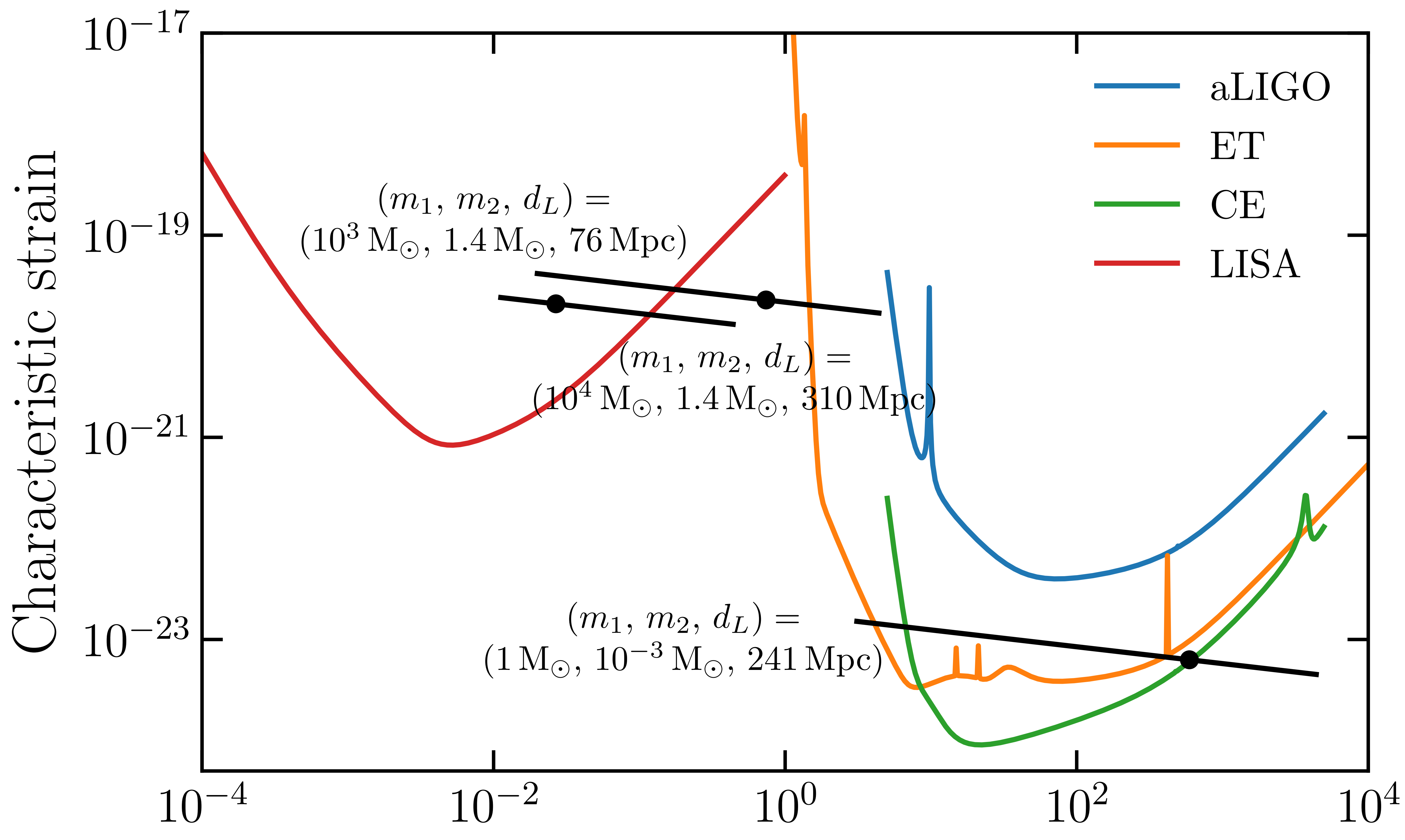






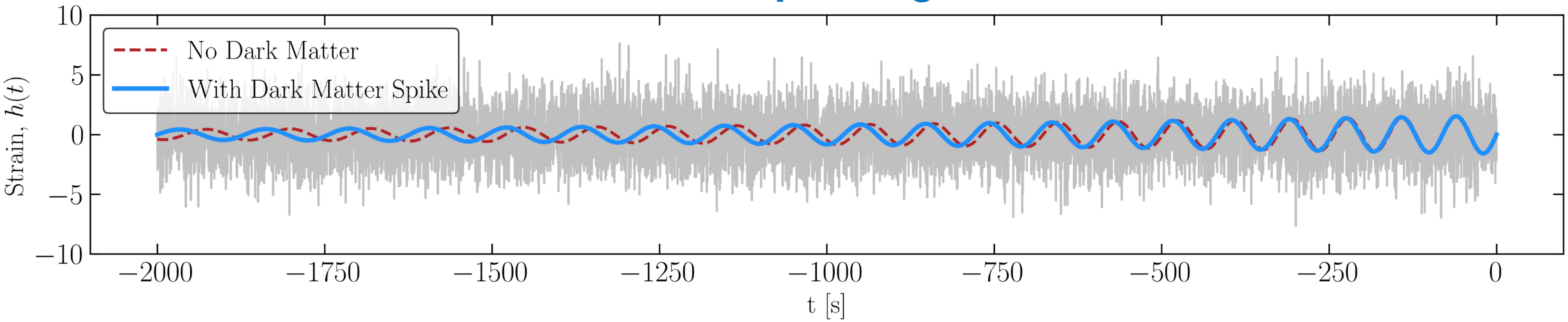
Dephasing of 'Dressed' IMRIs





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

"Dephasing"

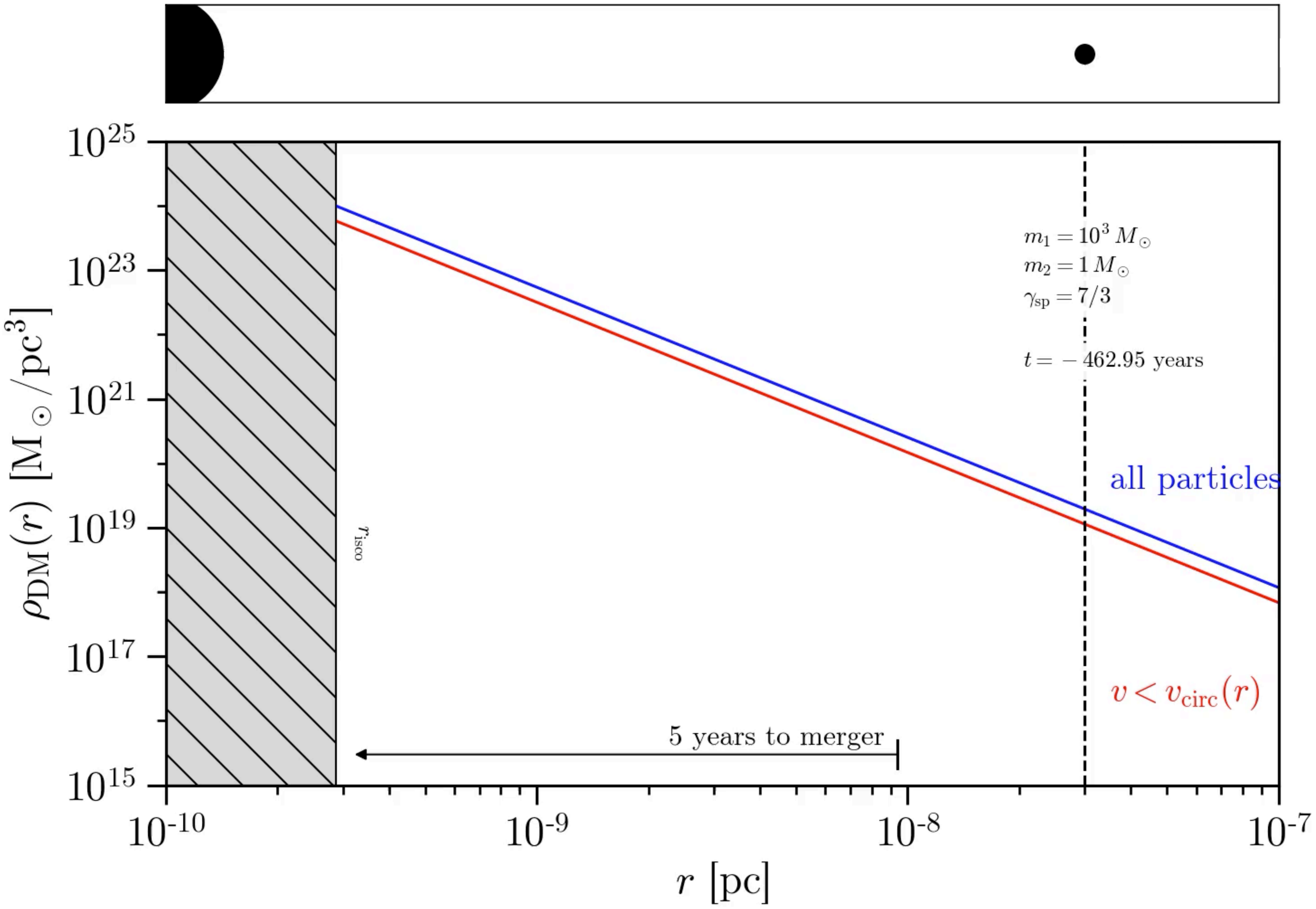


[See e.g. Eda et al. 1301.5971, 1408.3534, Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Co-evolution

Newtonian motion of the binary, taking into account:

- GW emission
- Dynamical Friction
- DM Halo Feedback



Density of the DM spike is depleted (and replenished.

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

[Movies: tinyurl.com/GW4DM]

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

[Code: github.com/bradkav/HaloFeedback]

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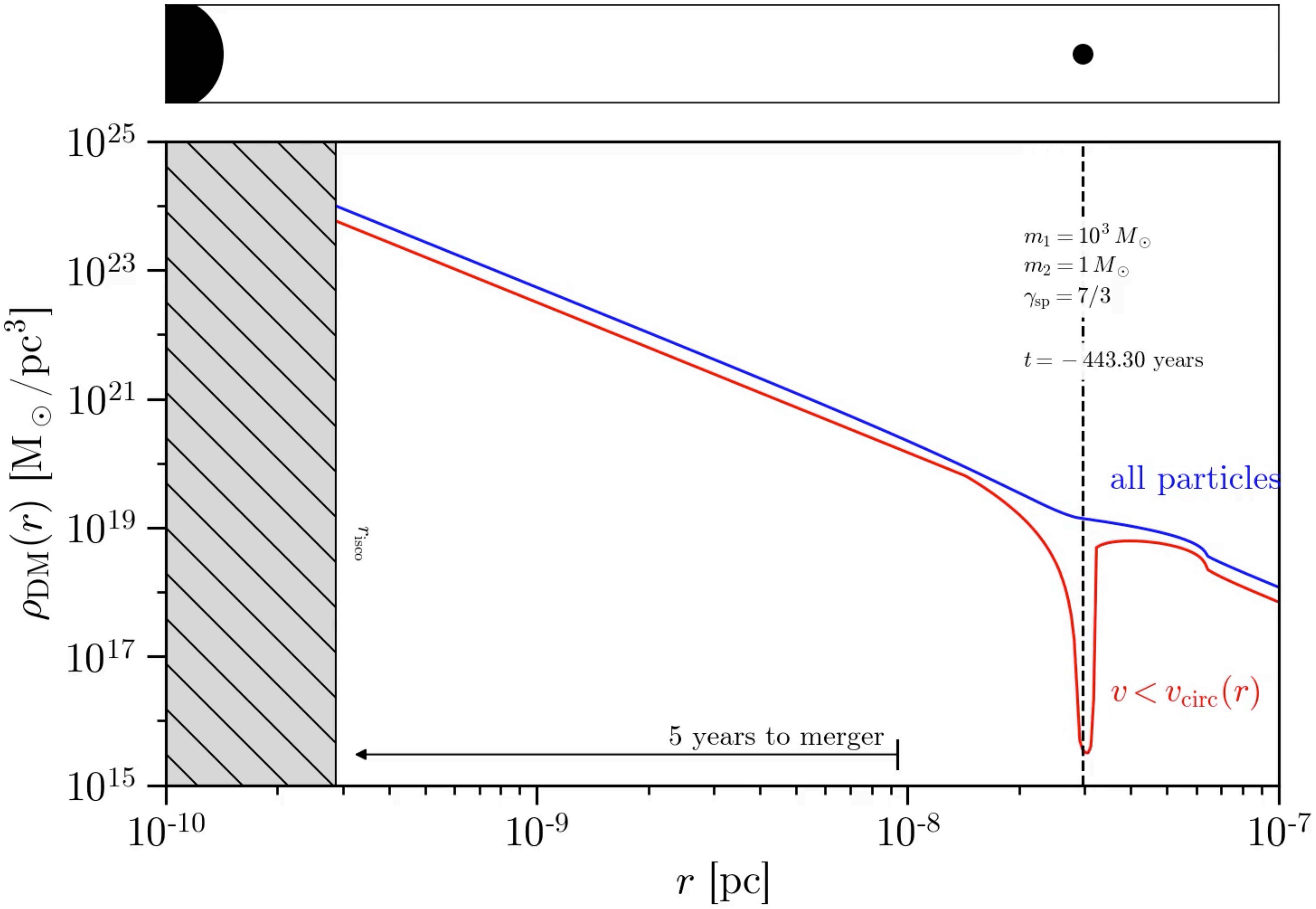

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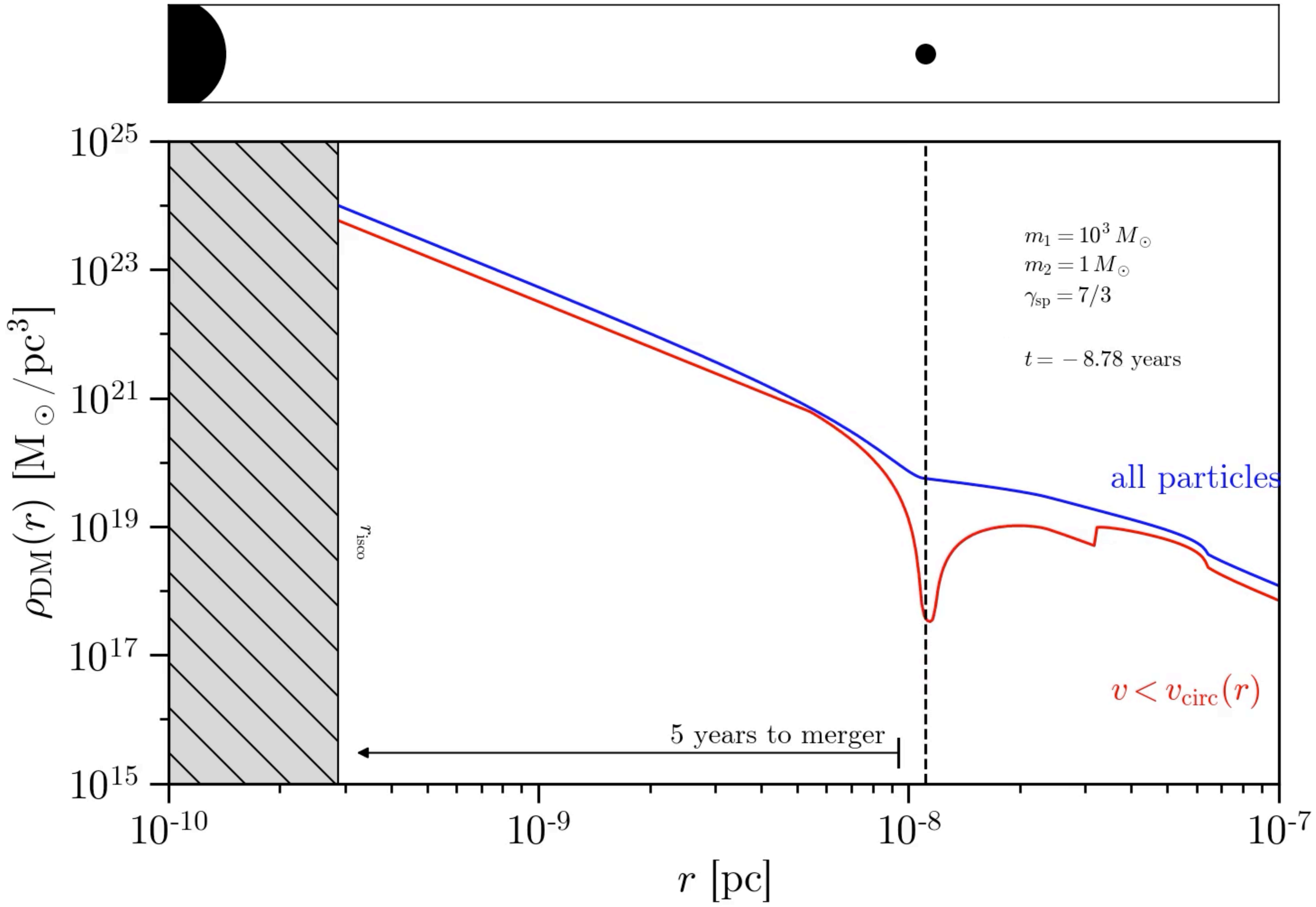

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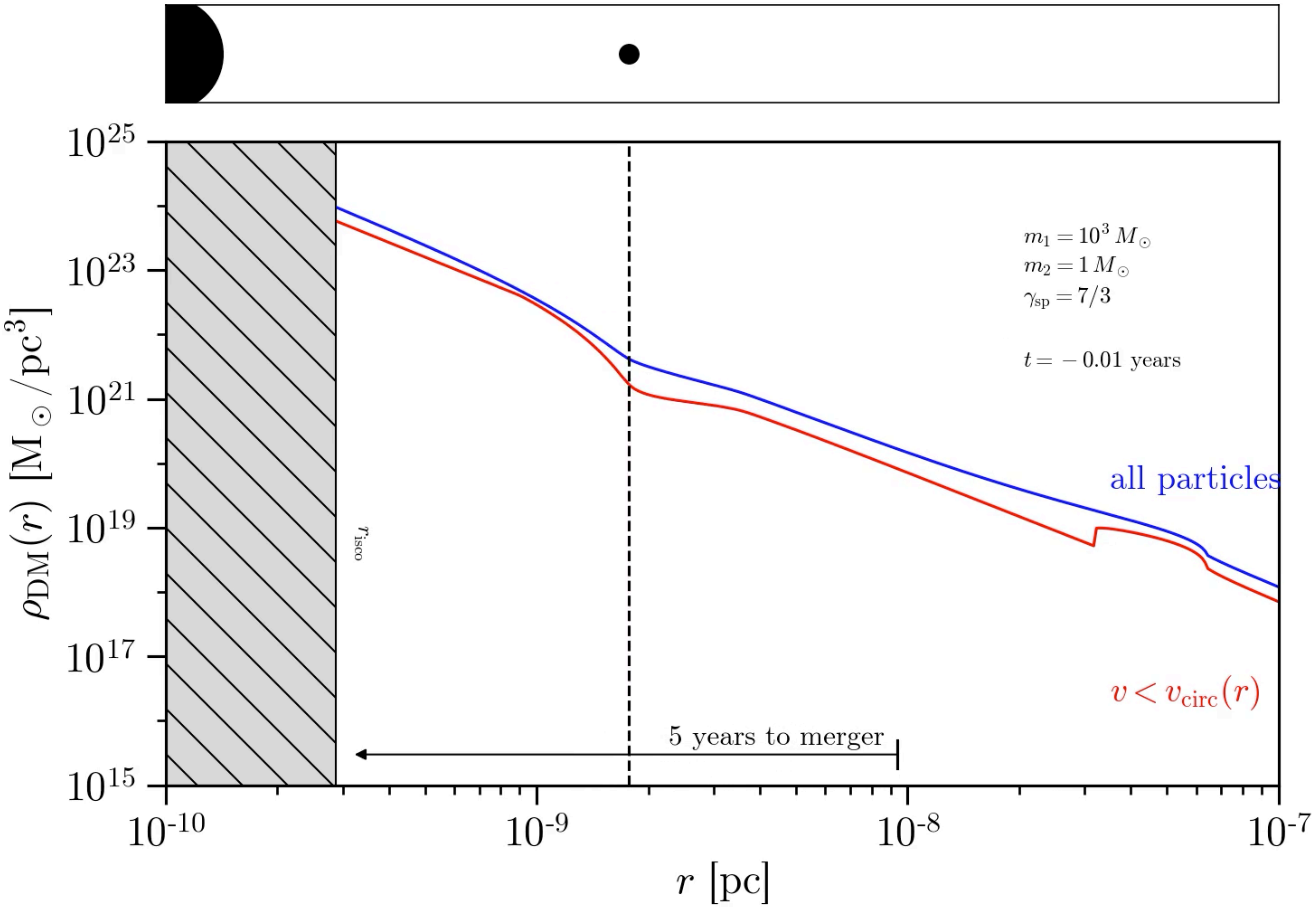

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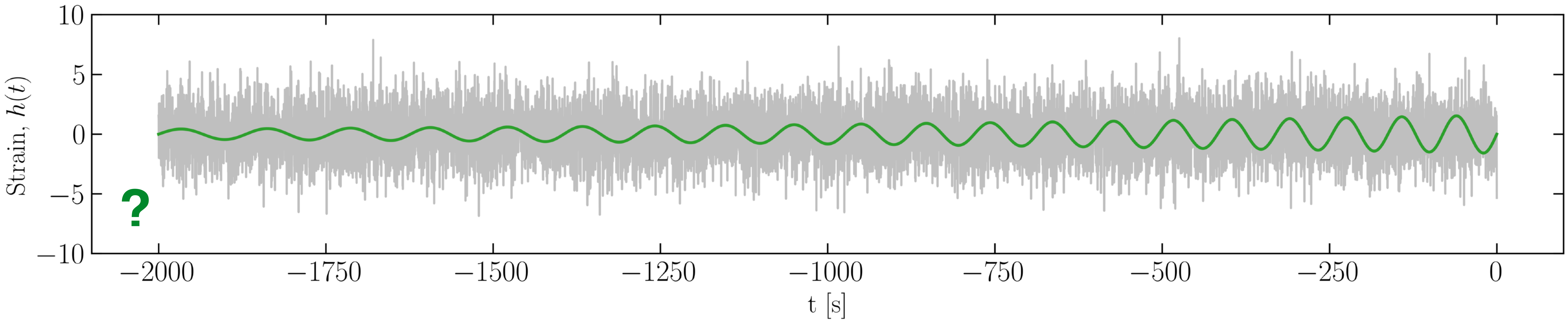
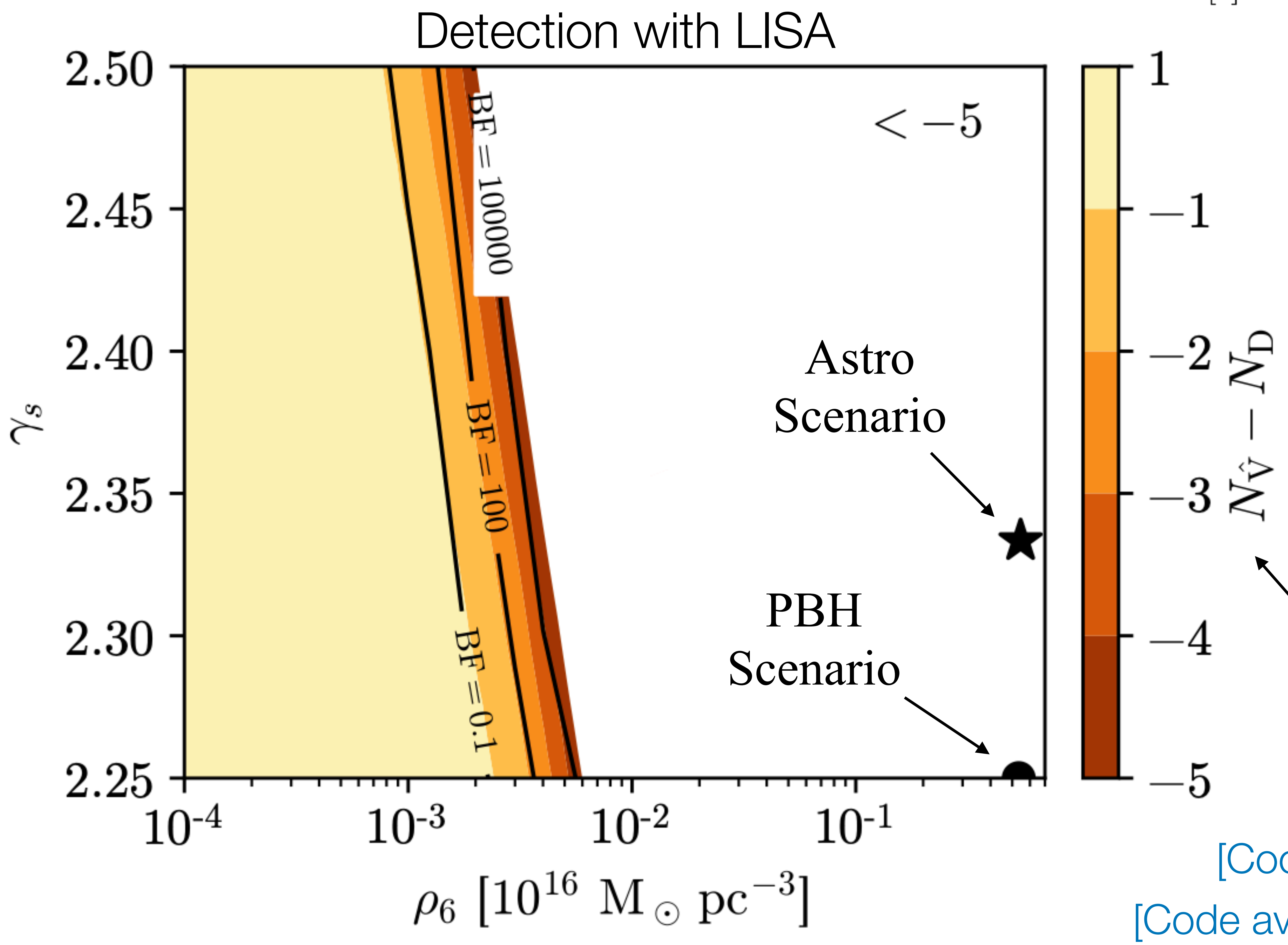
Discoverability





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.

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

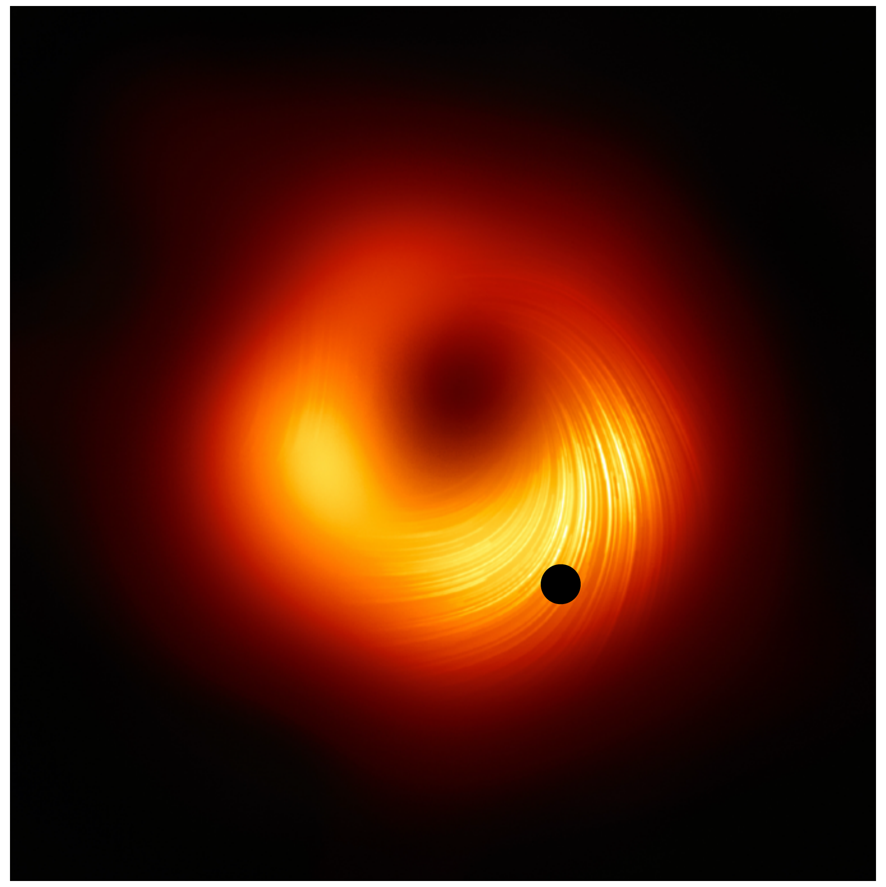
[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]

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

Other environmental effects

[Work in progress, lead by Pippa Cole]

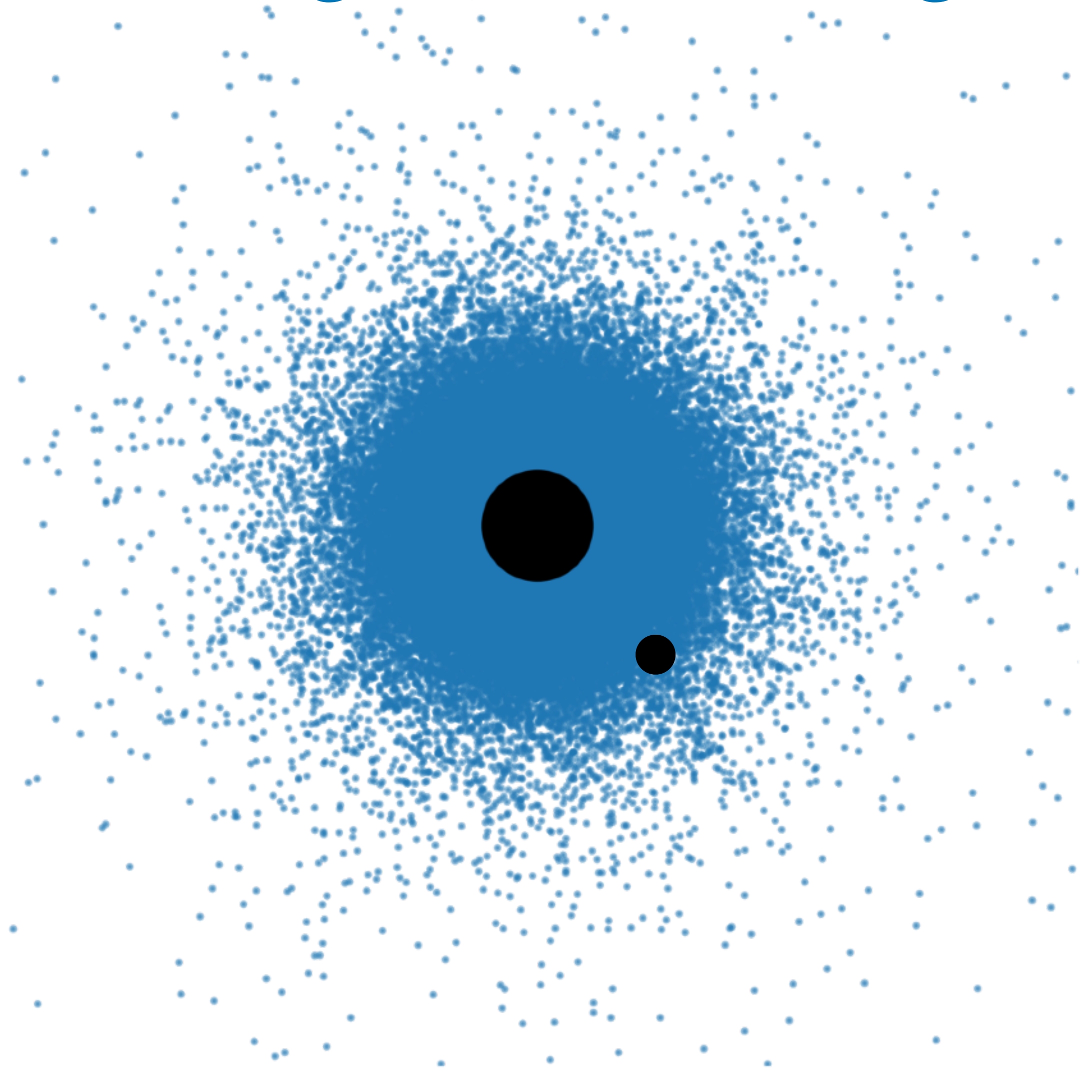
Generate waveform assuming:



[Event Horizon Telescope]

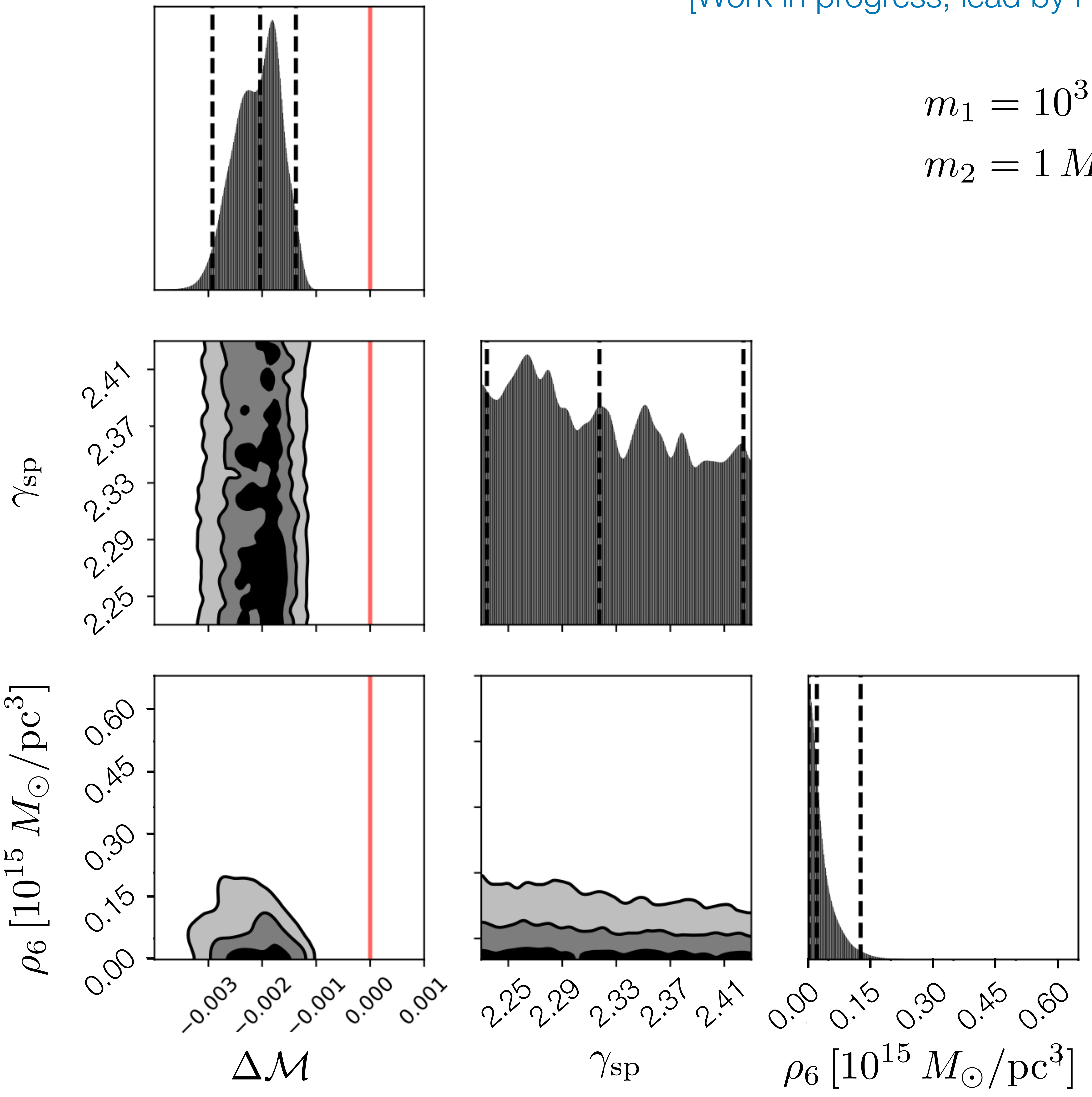
$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1/2}$$

Fit signal assuming:



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

$m_2 = 1\, M_\odot$



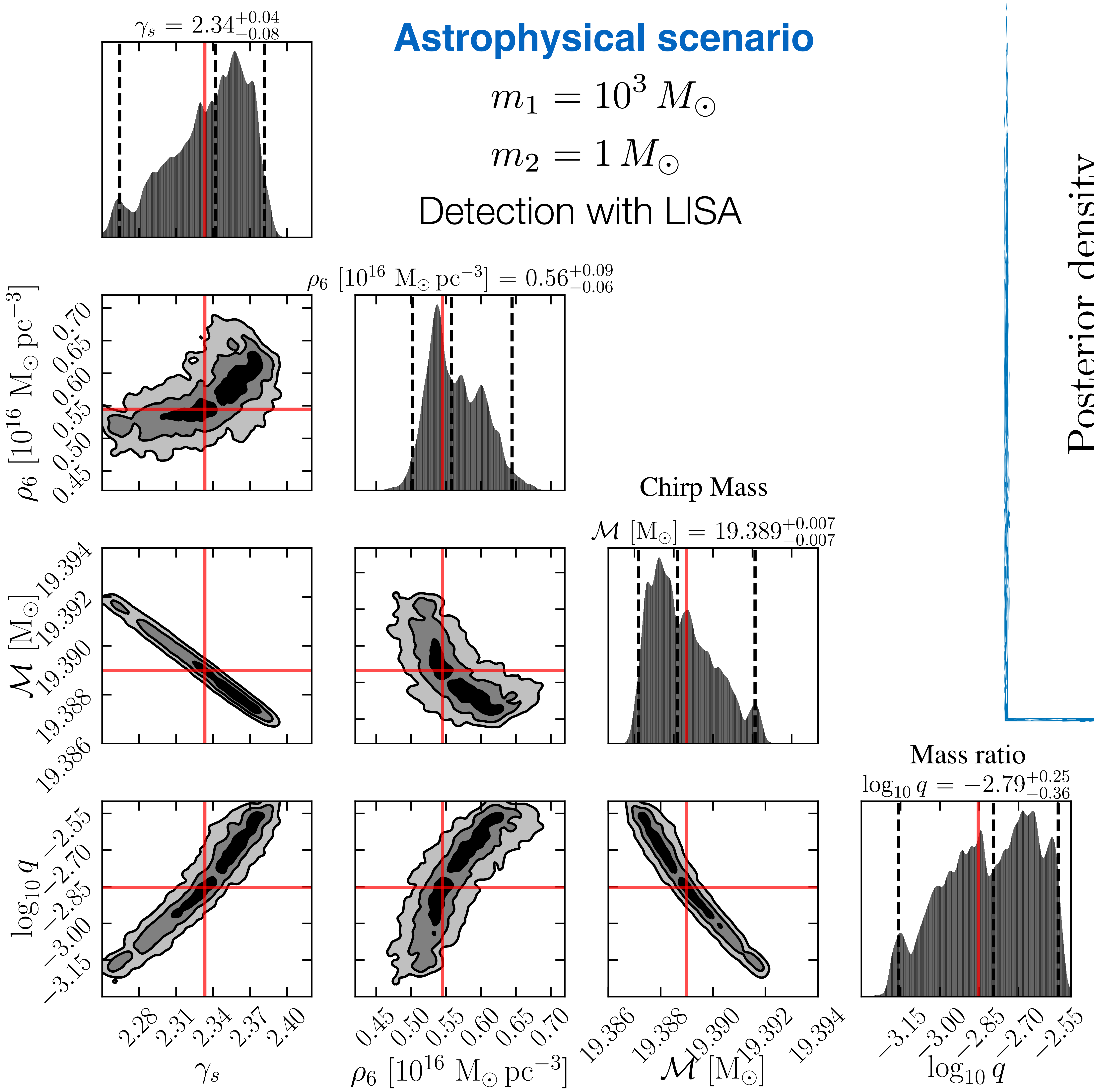
Measurability

Astrophysical scenario

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

$m_2 = 1\, M_\odot$

Detection with LISA



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

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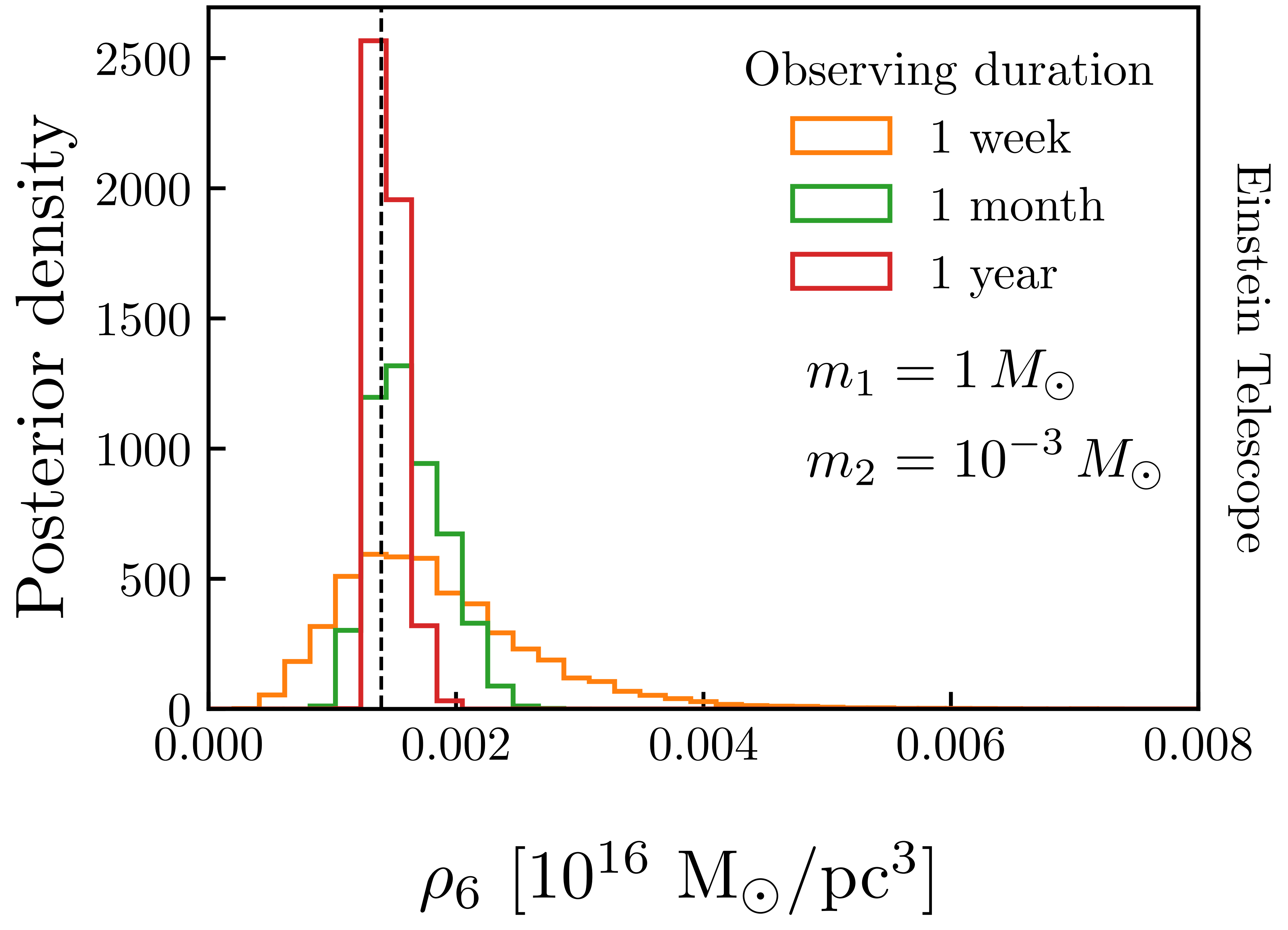
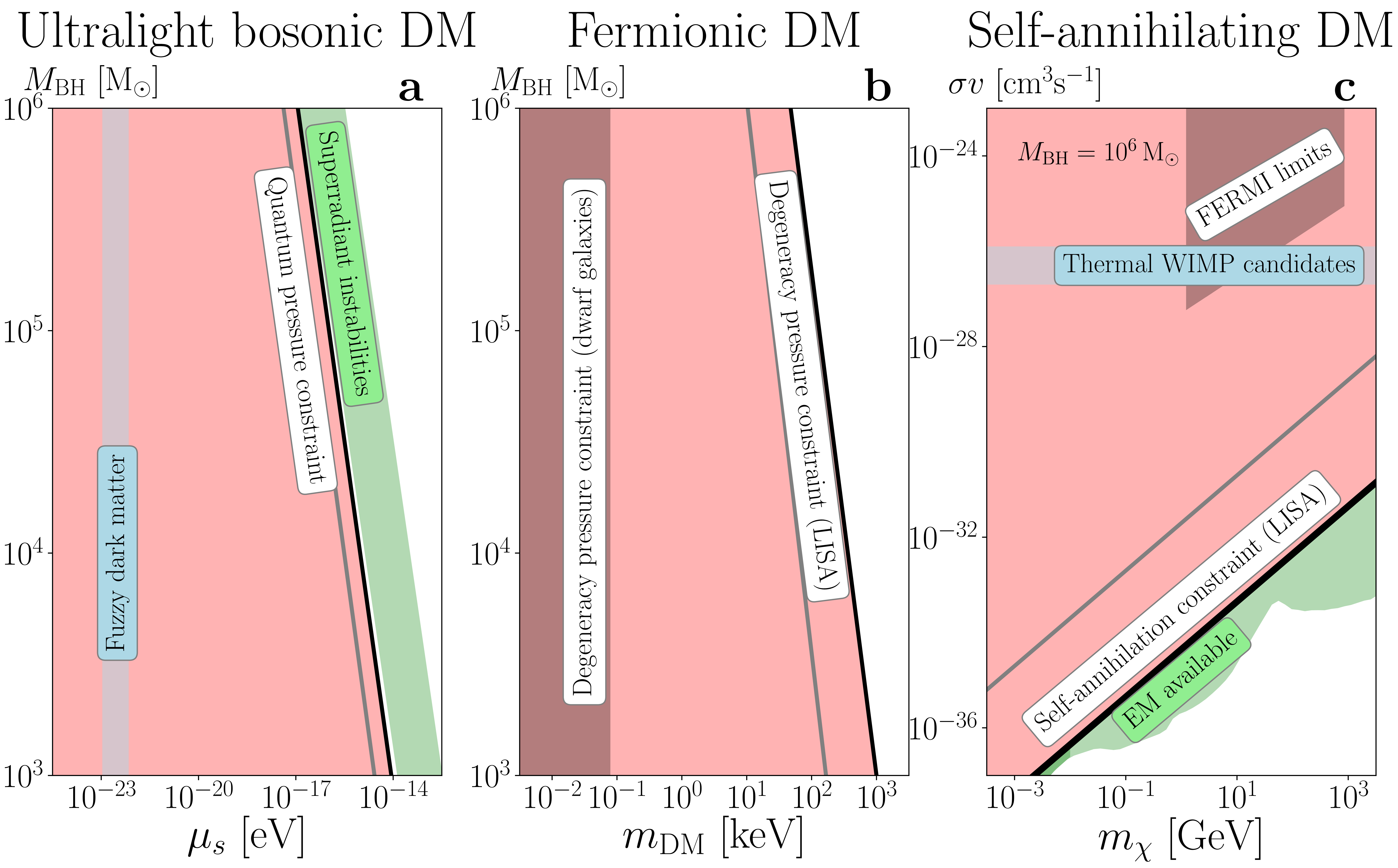
PBH scenario



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

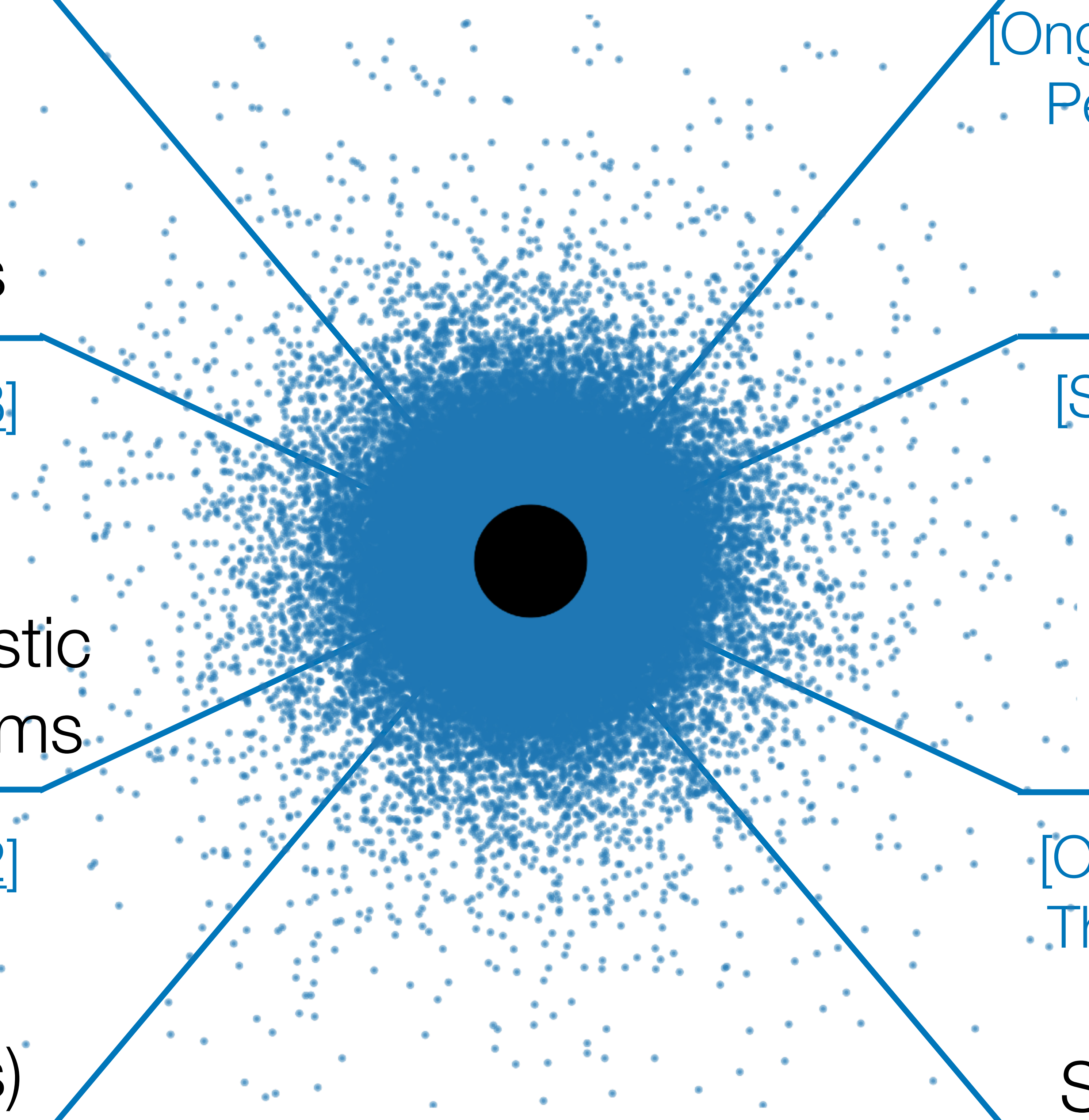
Red regions would be ruled out by observation of a DM spike!

[1906.11845]



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

Towards better DM spikes



Confusion with other environmental effects

[Ongoing work lead by Pippa Cole]

Relativistic effects

[See e.g. 2204.12508]

Integration with realistic IMRI/EMRI waveforms

[See e.g. 2104.04582]

Accretion (for BHs)

Realistic spike formation scenarios

[Ongoing work with Abram Perez & Pratika Dayal]

Eccentric orbits

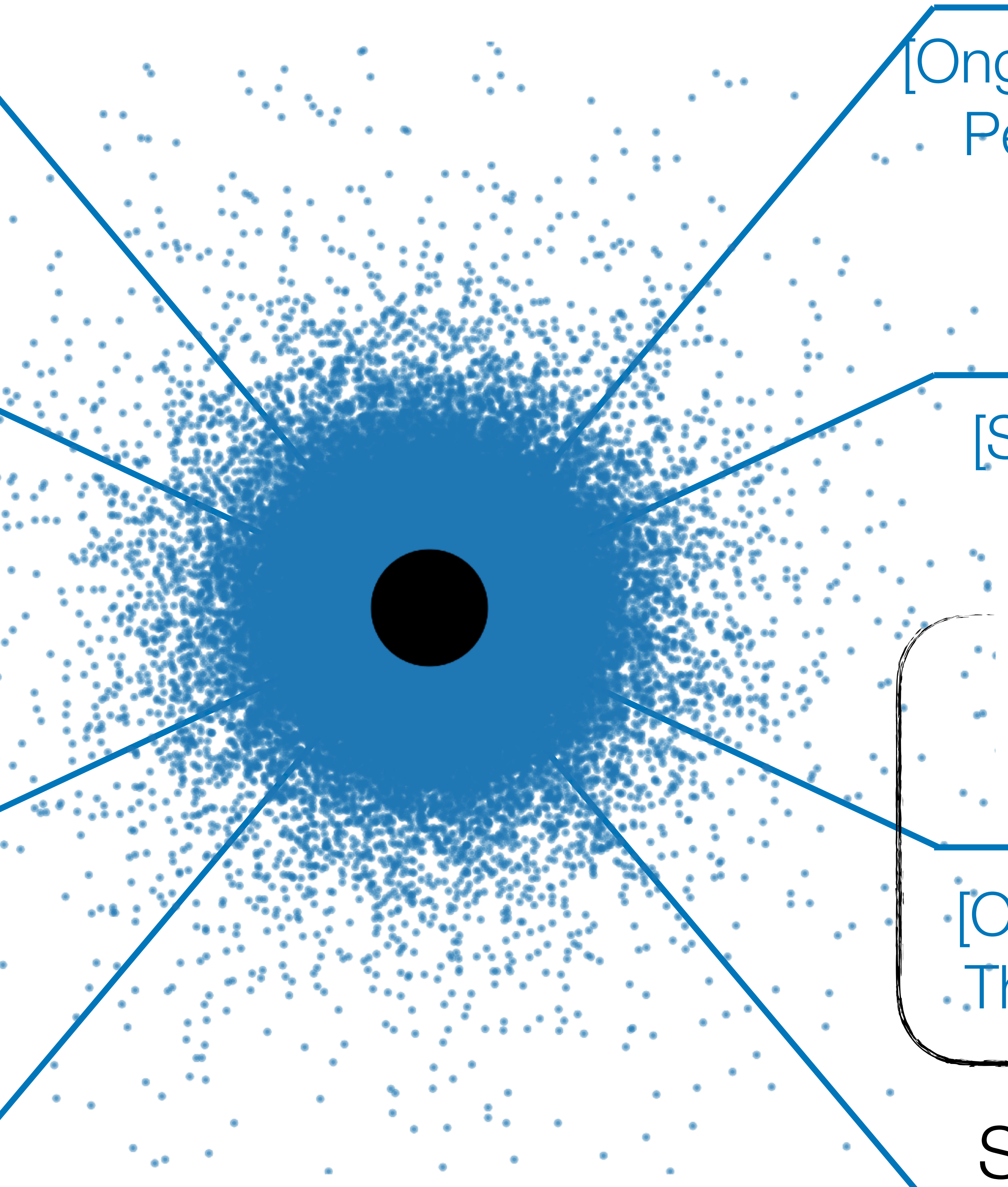
[See e.g. Becker et al., 2112.09586]

More realistic feedback

[Ongoing work lead by Theophanes Karydas]

Search strategies

Towards better DM spikes



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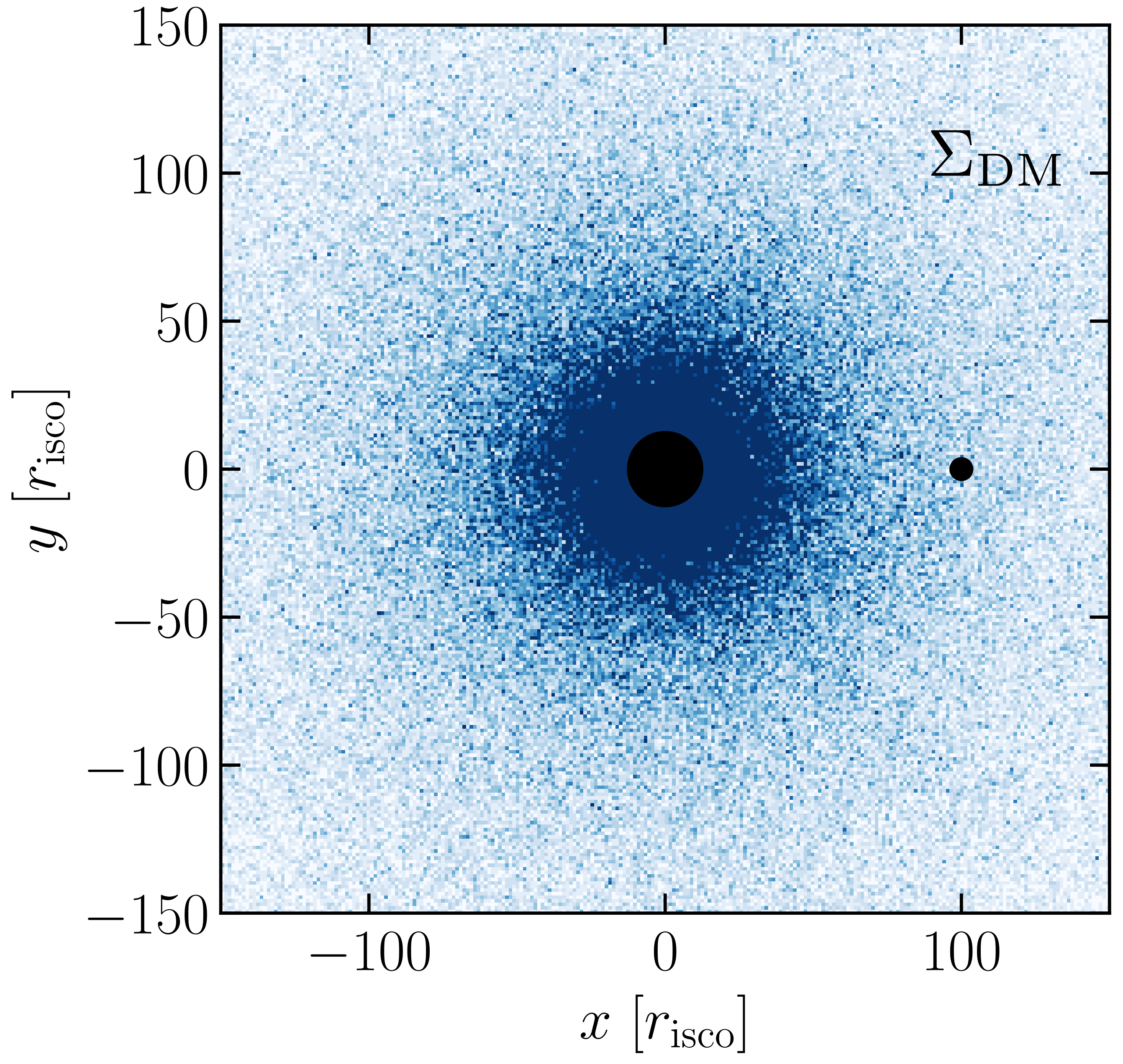
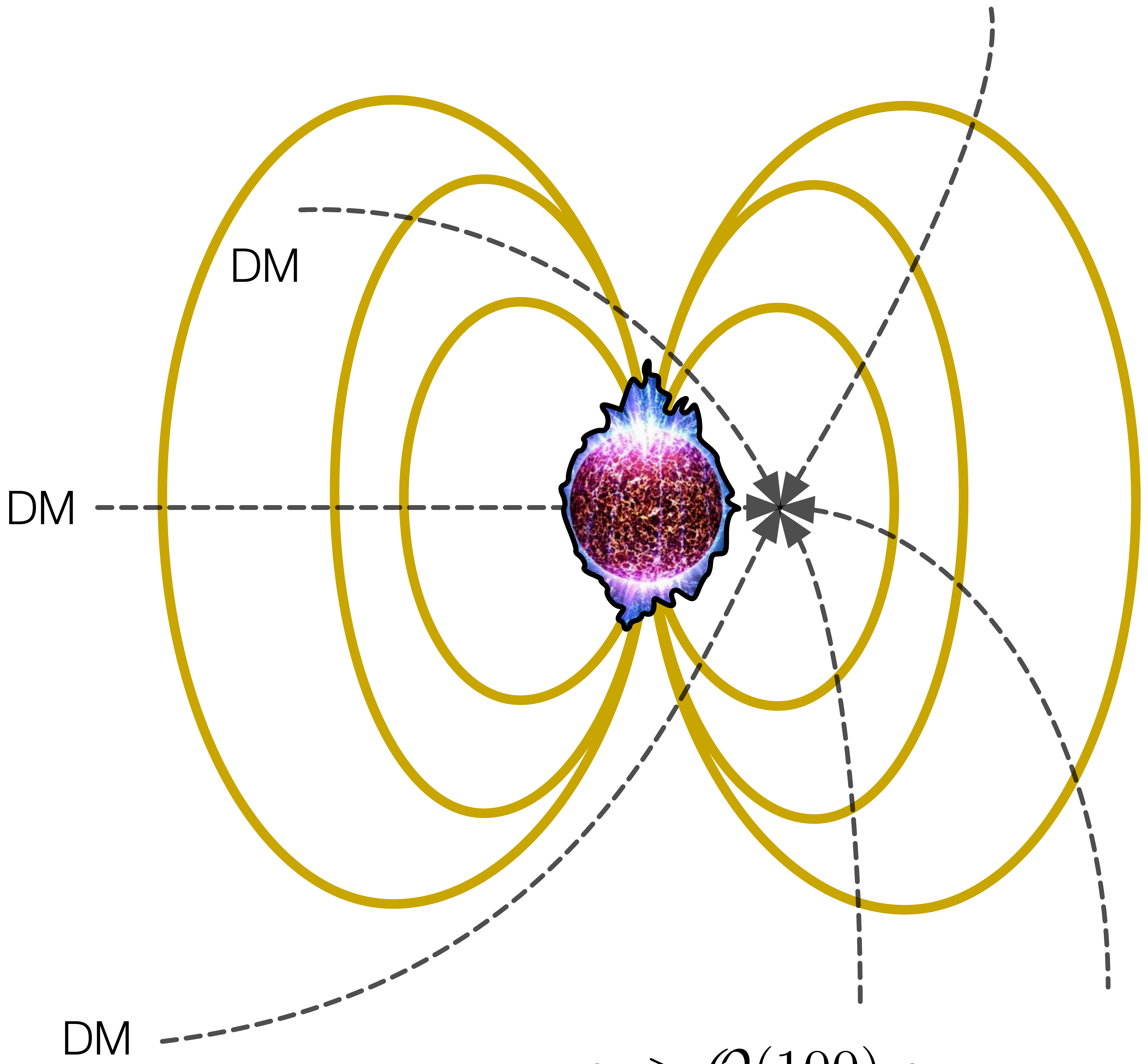
[Code here: github.com/bradkav/NbodyIMRI]



Part 2:
Neutron Stars

Neutron Stars (NSs)



$$\rho_c > \mathcal{O}(100)\,\rho_\infty$$

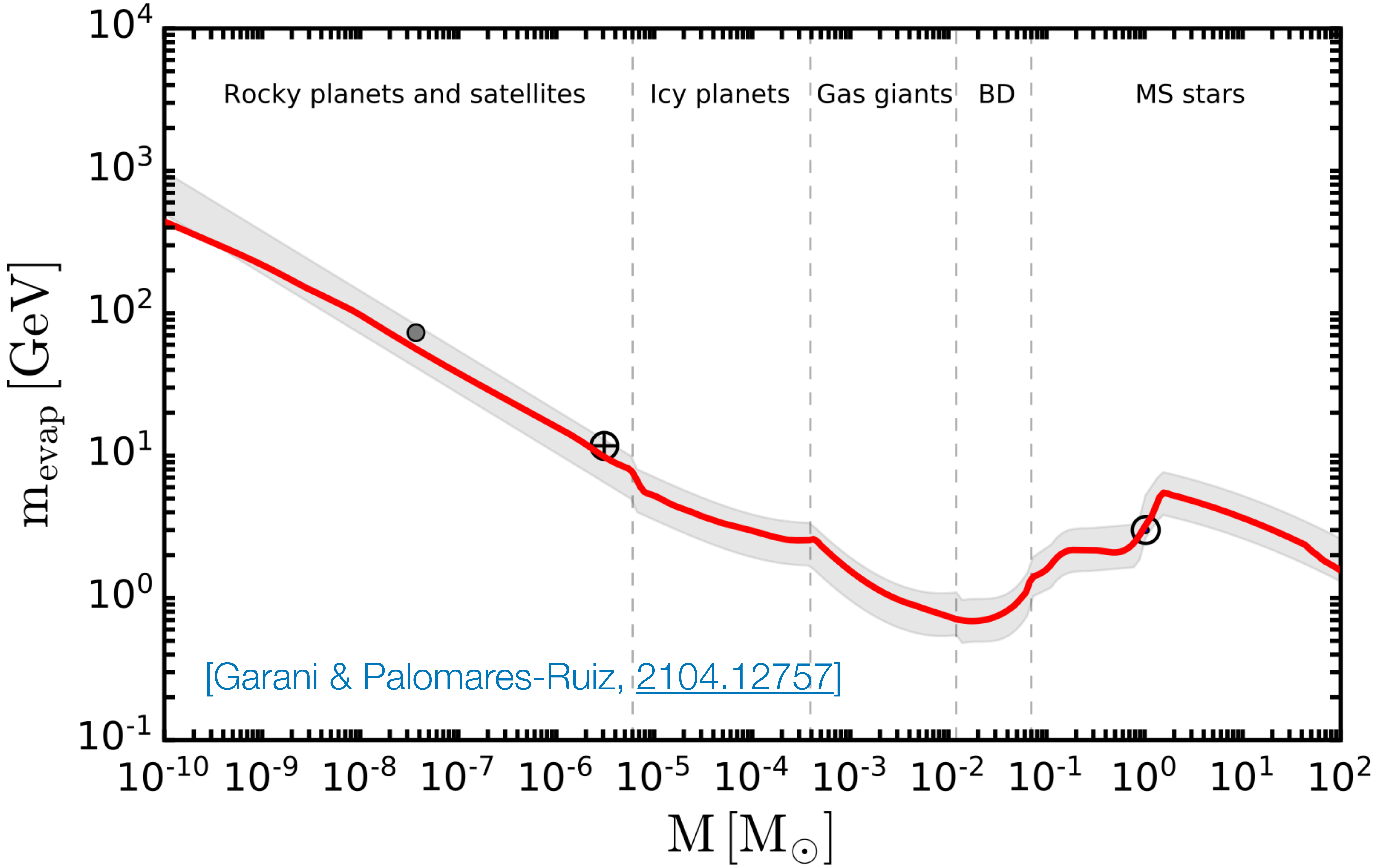
Strong gravitational field compresses DM phase space, enhancing DM density near NS surface

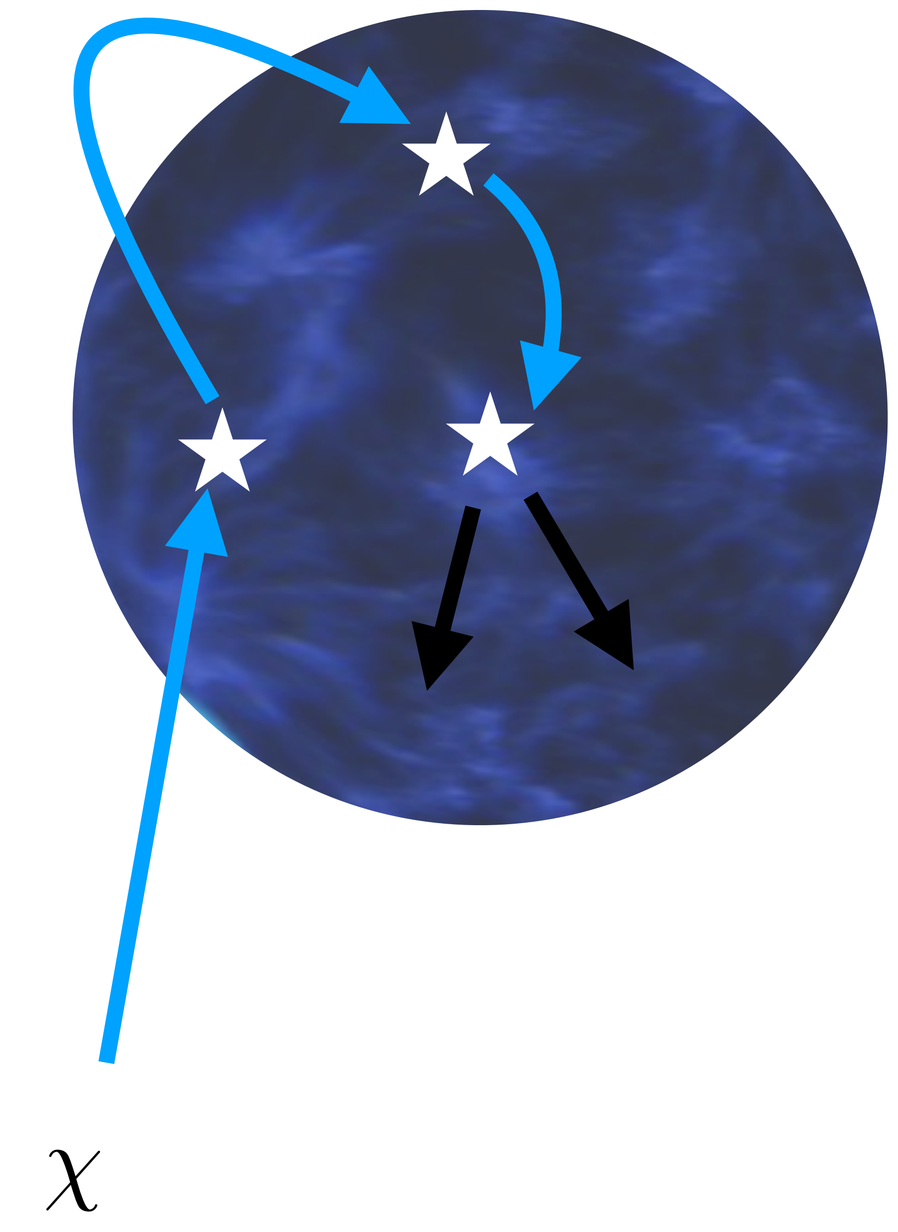
High 'target' densities means high opacity to DM-nucleon scattering:

$$\rho > 4.2 \times 10^{11}\ \mathrm{g/cm^3}$$

Young neutron stars can have **extremely high magnetic fields** ($B_0 = 10^{12} - 10^{15}\ G$), relevant for axion DM

DM Capture (and evaporation)





Capture of DM in NSs is possible down to keV masses and can lead to distinctive signatures:

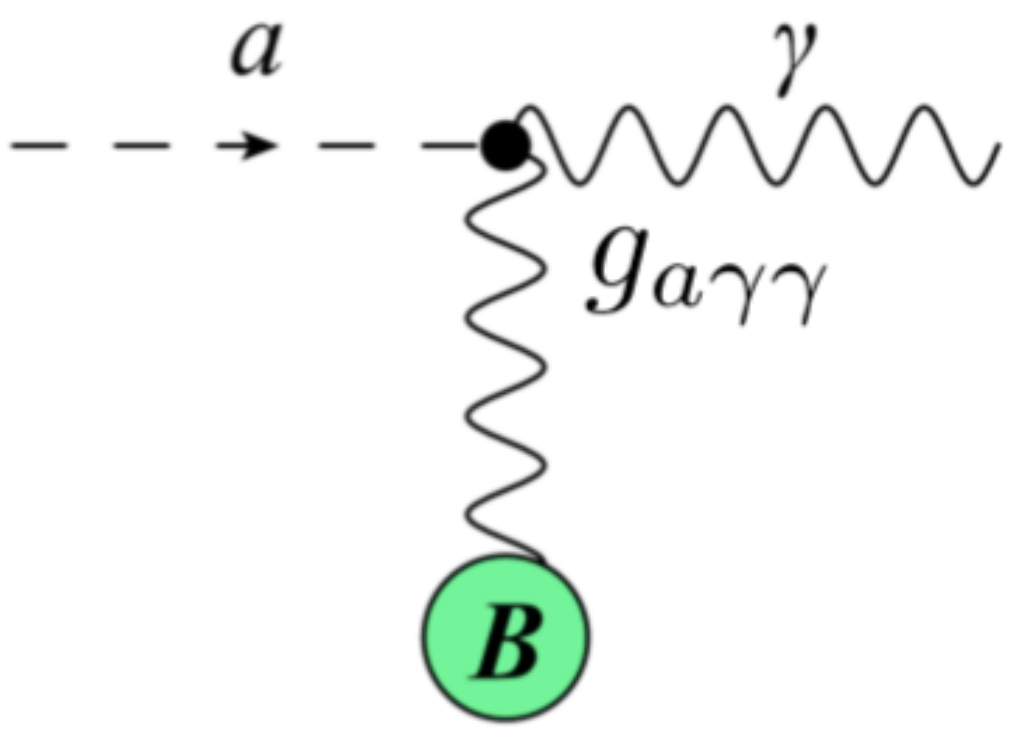
- Impact on NS equation of state (possible GW signatures?) [E.g. Cermeño et al., 1710.06866]
- Neutron star heating (possible optical, X-ray emission) [E.g. Baryakhtar et al., 1704.01577]
- Transient NS heating (for clumpy DM) [E.g. Bramante, **BJK**, Raj, 2109.04582]

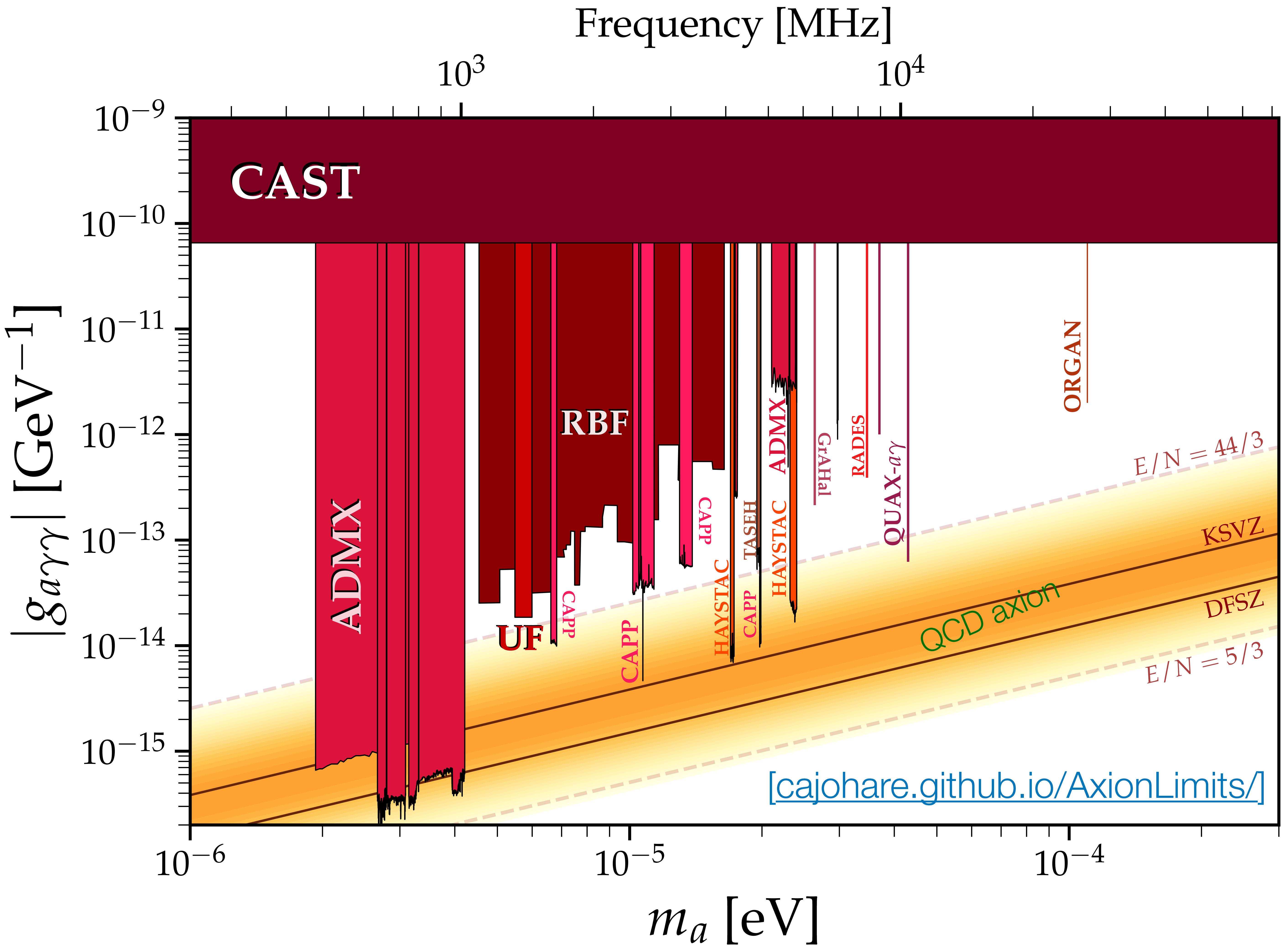
[See parallel talks by Nirmal Raj, Joshua Ziegler and Shiuli Chatterjee on Thursday afternoon]

Axion-photon conversion

Dark Matter could be in the form of light **pseudo-scalar 'axions', which may convert to photons** (and vice versa) in an external magnetic field:

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

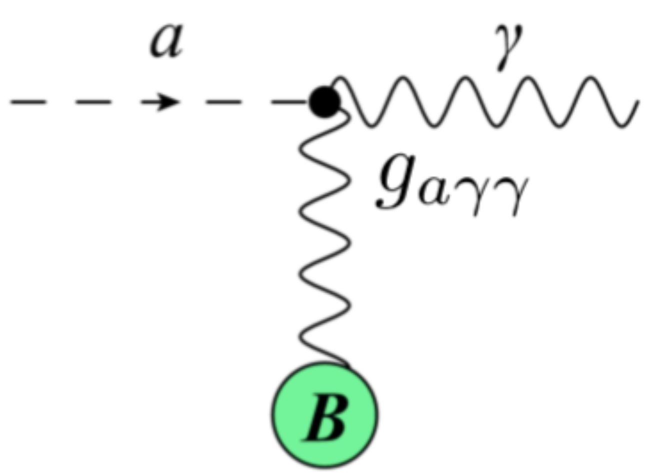




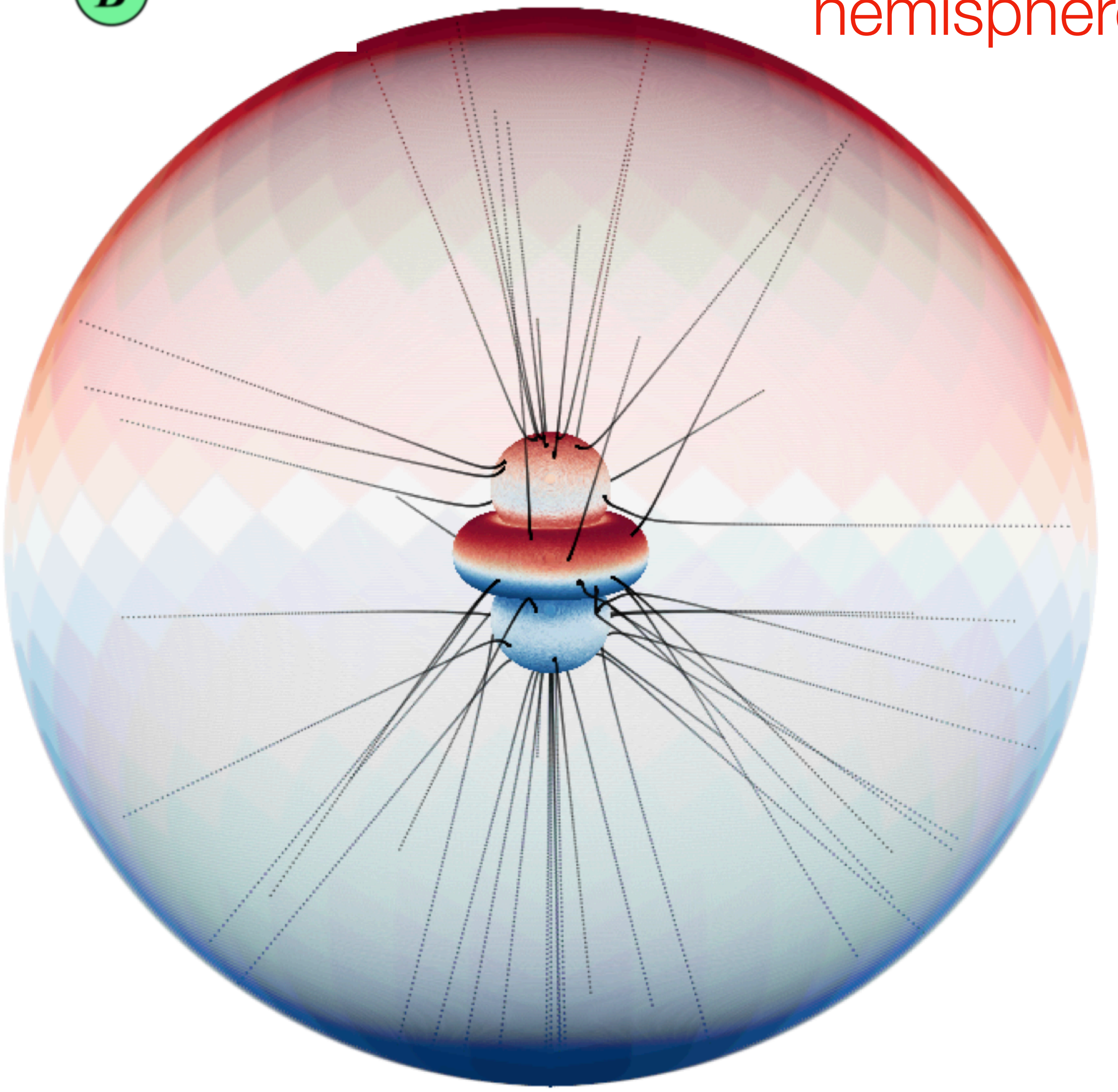
[See also parallel session, DM X, Wed, 15:50 - 17:30]

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

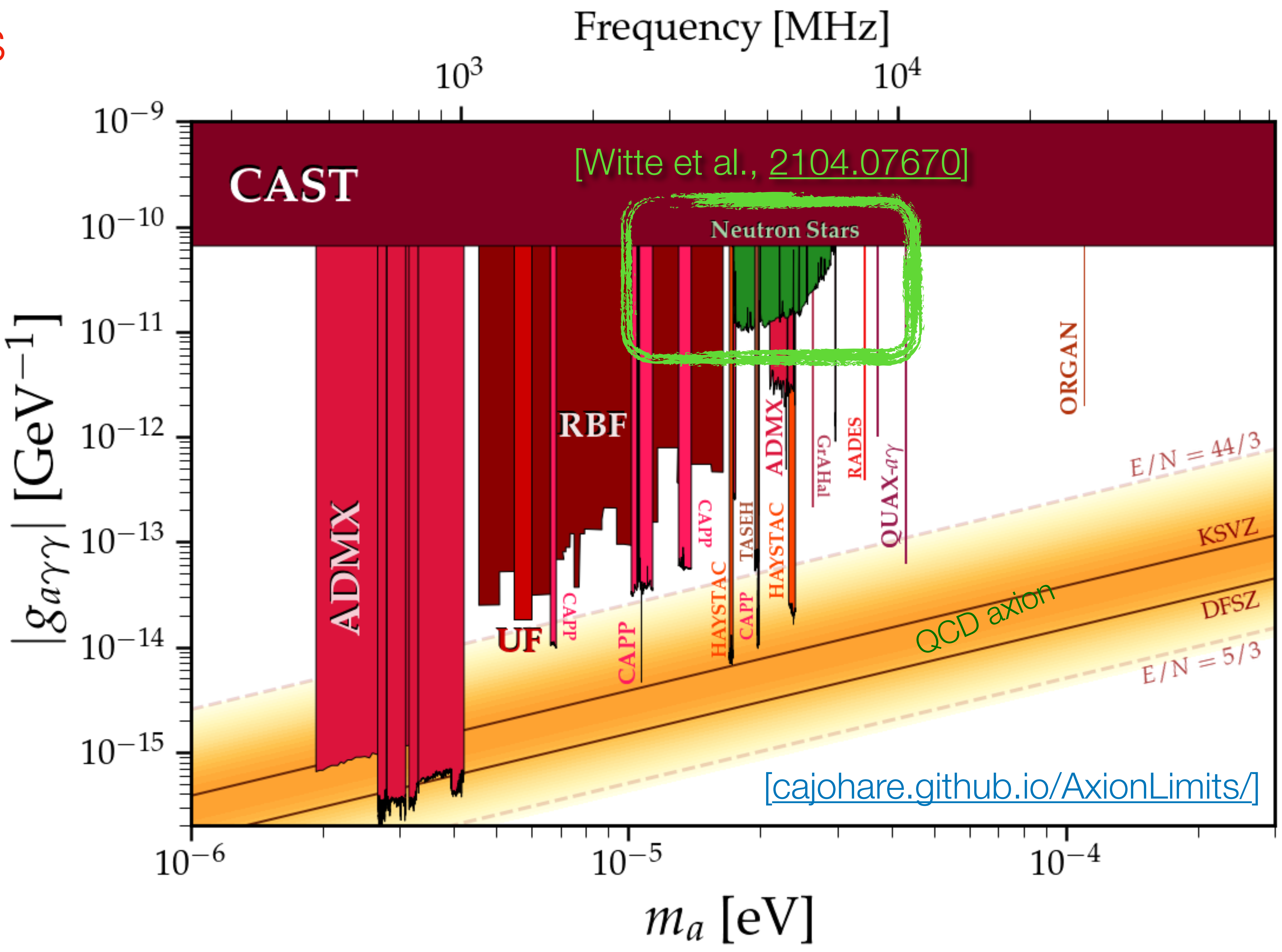
[1803.08230, 1804.03145, 1811.01020]



Northern NS hemisphere



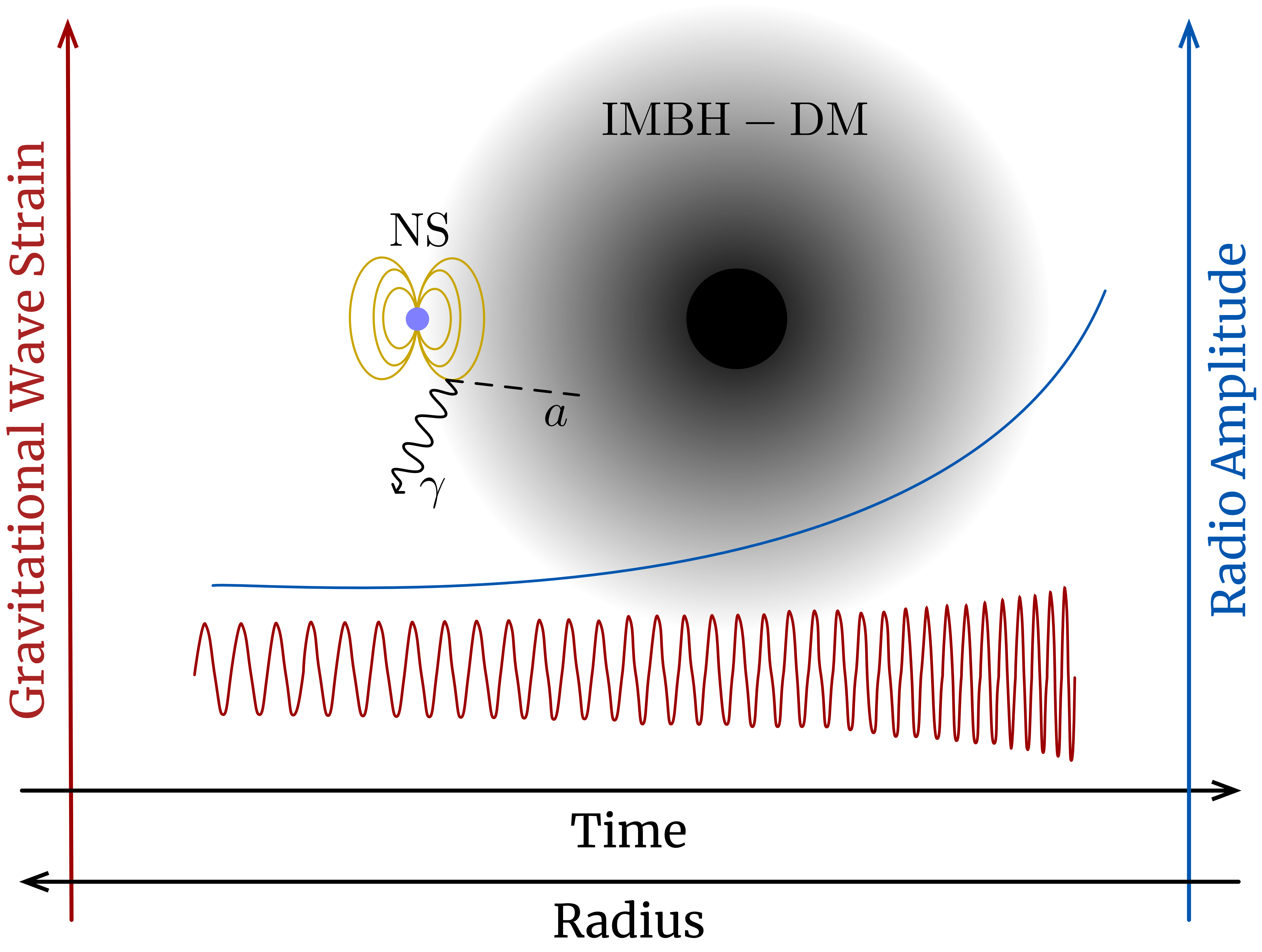
Southern NS hemisphere

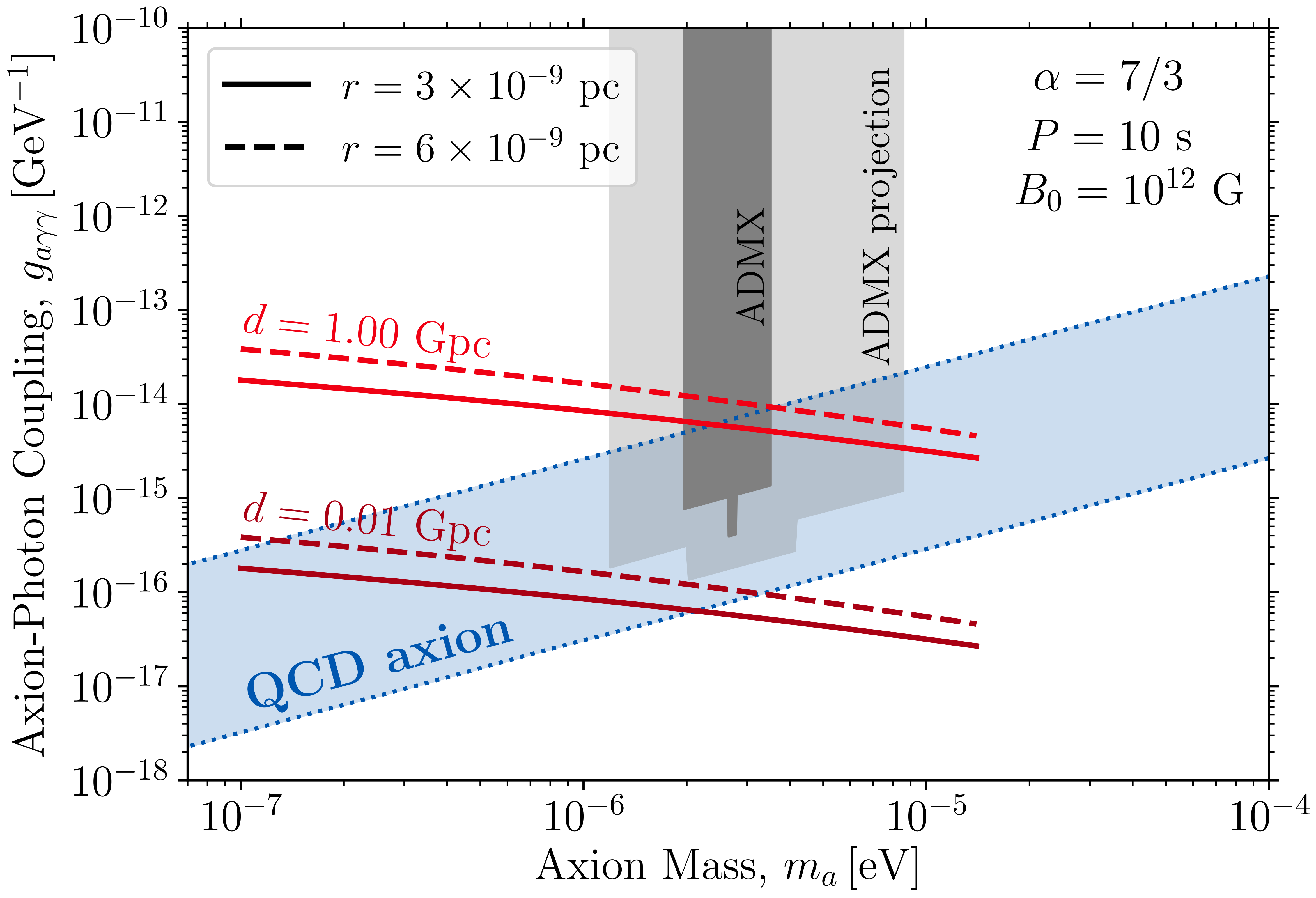


[For recent modeling developments, see also Battye et al., 1910.11907, 2104.08290; Leroy et al., 1912.08815, Foster et al., 2202.08274]

[See also parallel session, DM X, Wed, 15:50 - 17:30]

Multi-messenger Axions





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

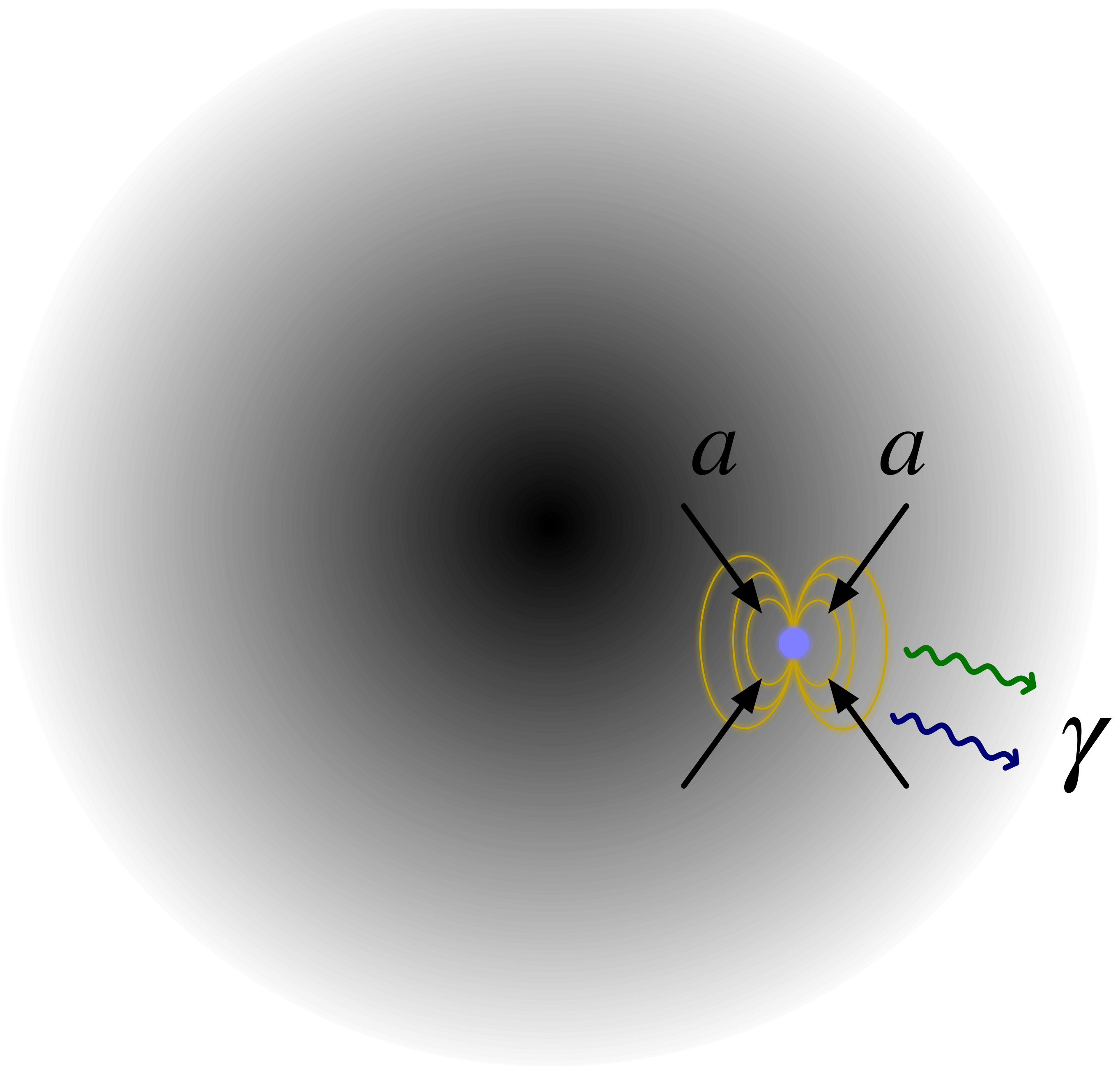
[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

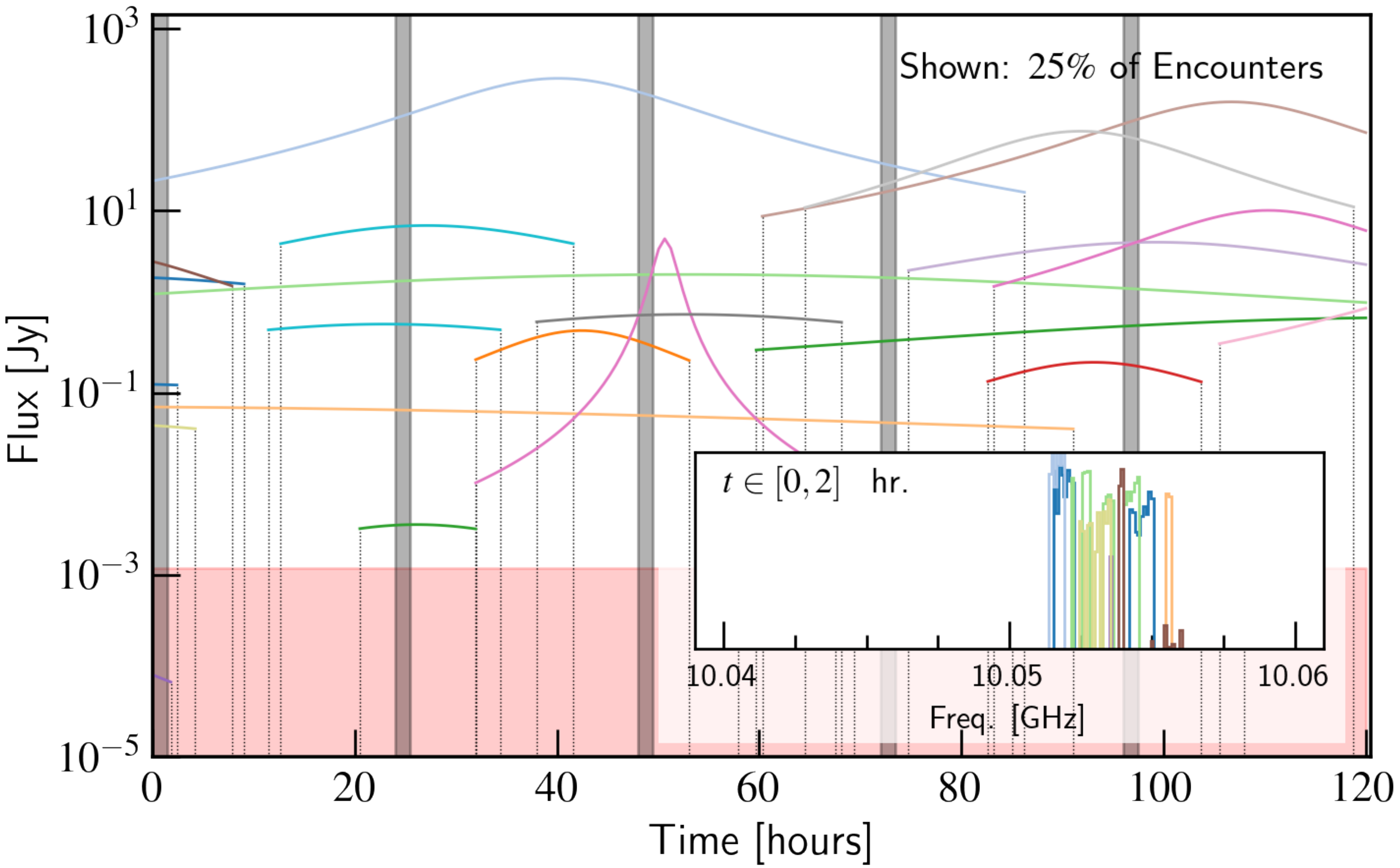
Axion Miniclusters (AMCs)

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

[Hogan & Rees (1988)]

$$M_{\rm AMC} \sim 10^{-14}\,M_\odot$$
$$R_{\rm AMC} \sim 10^{-7}\,{\rm pc}$$





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

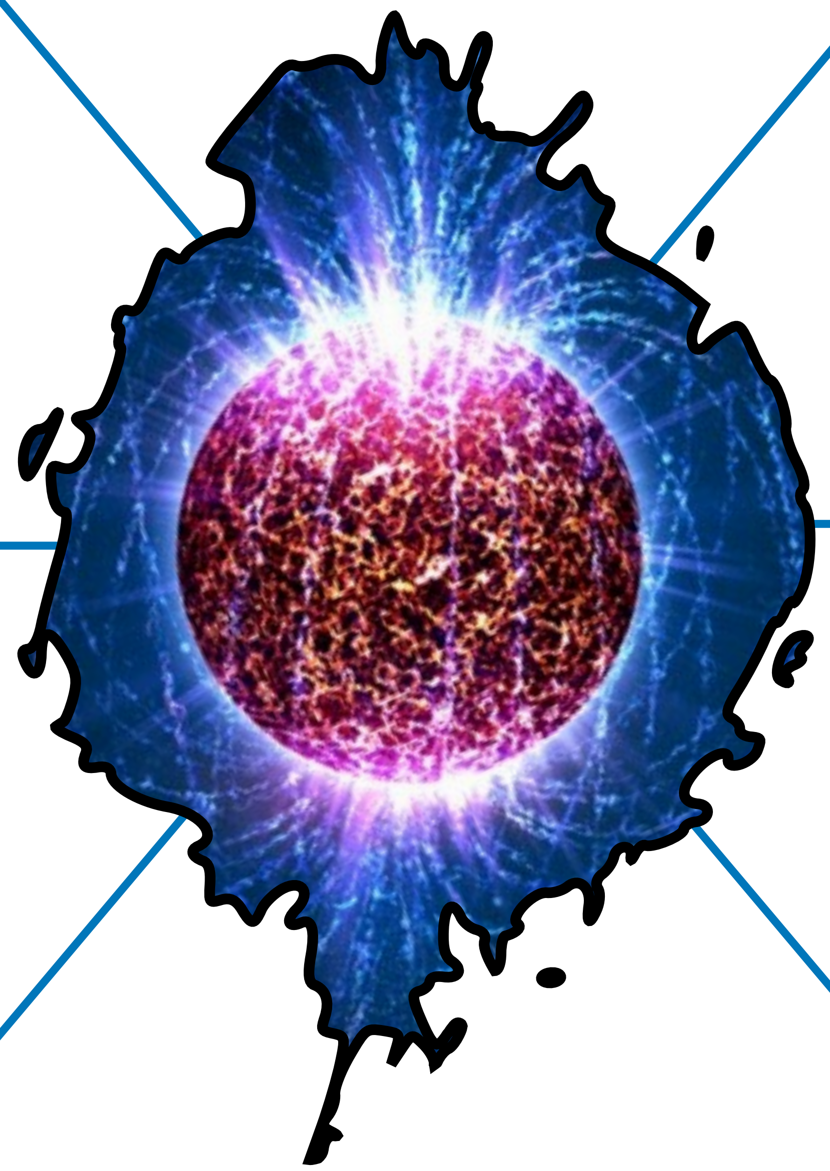
[Code: github.com/bradkav/axion-miniclusters]

Understanding DM signals from NSs

Capture of light DM
(Neutron superfluid?)

NS magnetic field
distributions

[Ongoing work lead
by Sam Witte]



Searches for cold NSs

[See e.g. 2205.05048]

AMC distribution
and evolution

[See e.g. 2206.04619,
2207.11276]

Better modelling of
NS magnetospheres

Search strategies?

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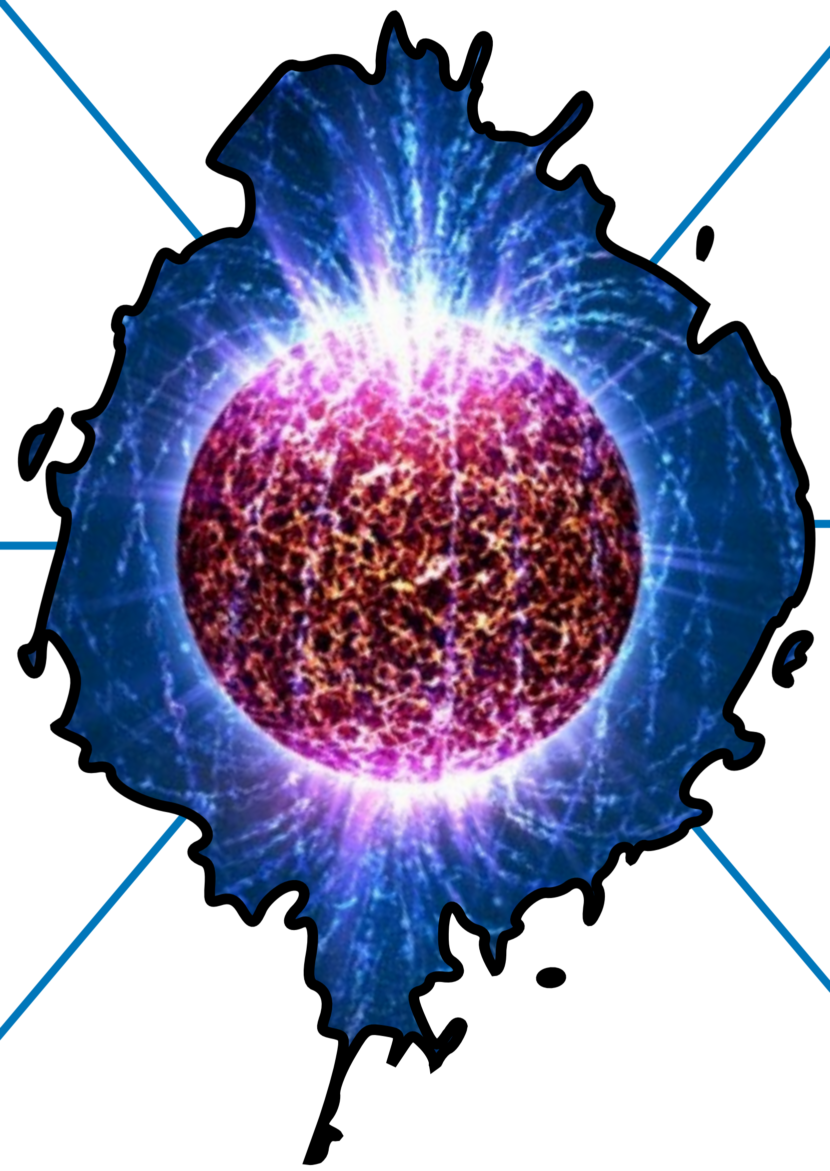

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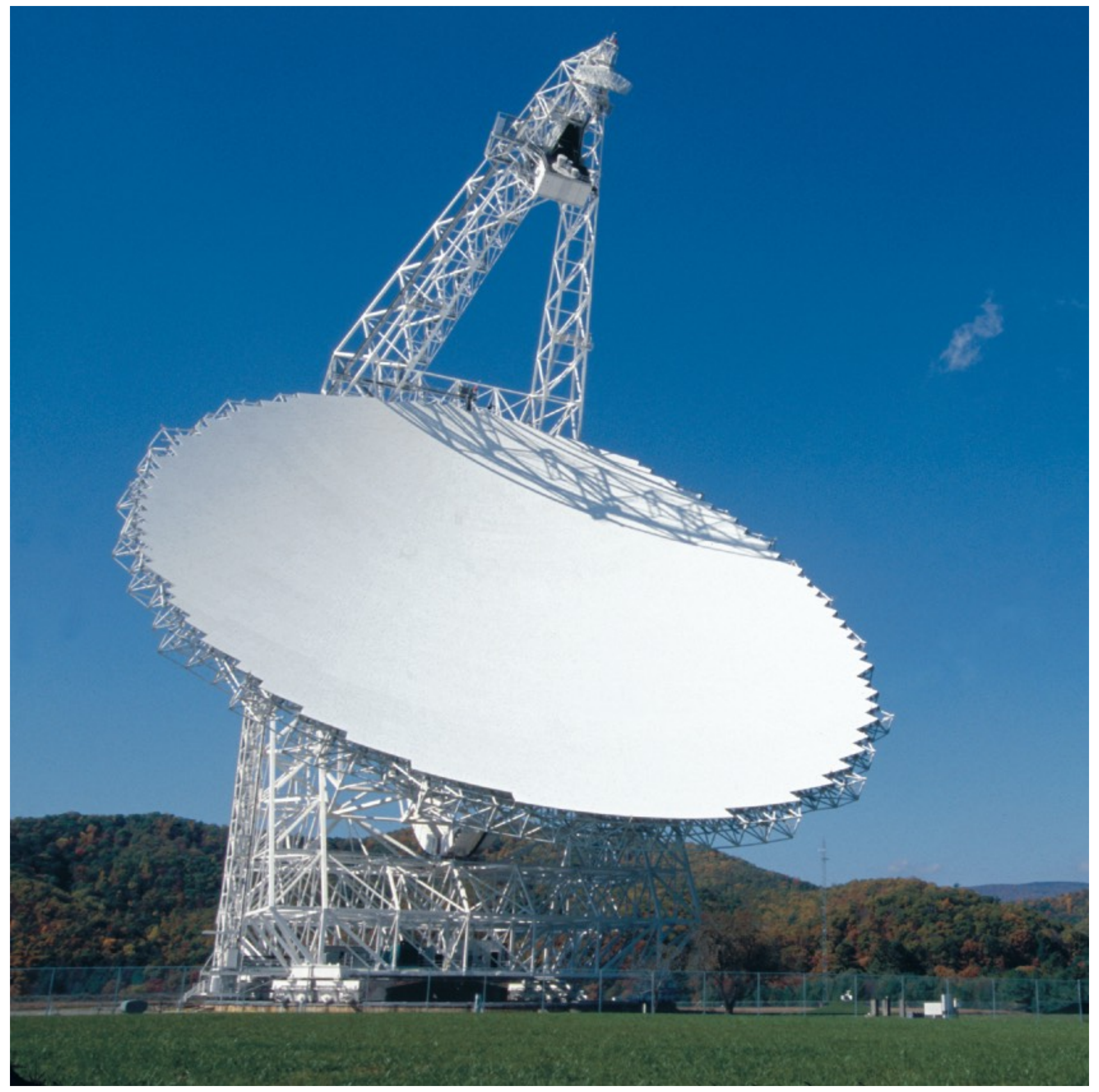


Search currently underway
for radio transients in
Andromeda using the Green
Bank Telescope (GBT)

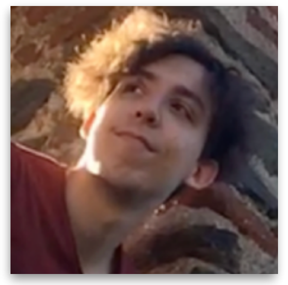
Many thanks to many collaborators

Dark Matter and Black Holes

Gianfranco Bertone
(GRAPPA, Amsterdam)

Pratibha Jangra
(IFCA, Santander)

Pippa Cole
(GRAPPA, Amsterdam)



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(GRAPPA, Amsterdam)

Adam Coogan
(Mila, Montreal)

David Nichols
(U. Virginia)

Pratika Dayal
(Groningen University)

Abram Perez Herrero
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(IFIC, Valencia)

Gimmy Tomaselli
(GRAPPA, Amsterdam)

Dark Matter and Neutron Stars

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(GRAPPA, Amsterdam)

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(Stockholm)

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(U. Virginia)

Liam Walters
(U. Virginia)

Doddy Marsh
(KCL, London)

Jordan Shroyer
(U. Virginia)

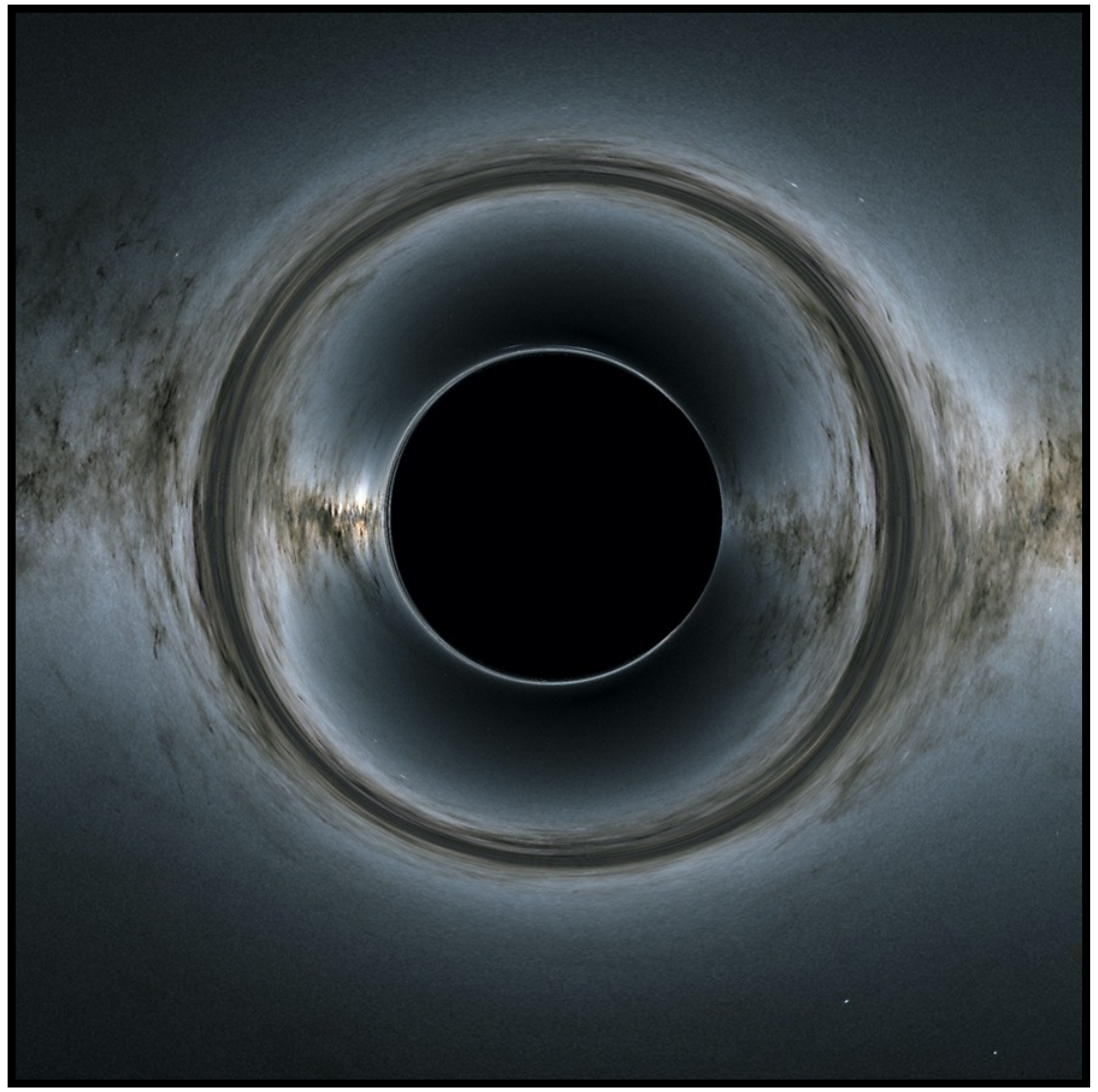
Nirmal Raj
(TRIUMF)

Luca Visinelli
(Shanghai Jiao Tong)

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

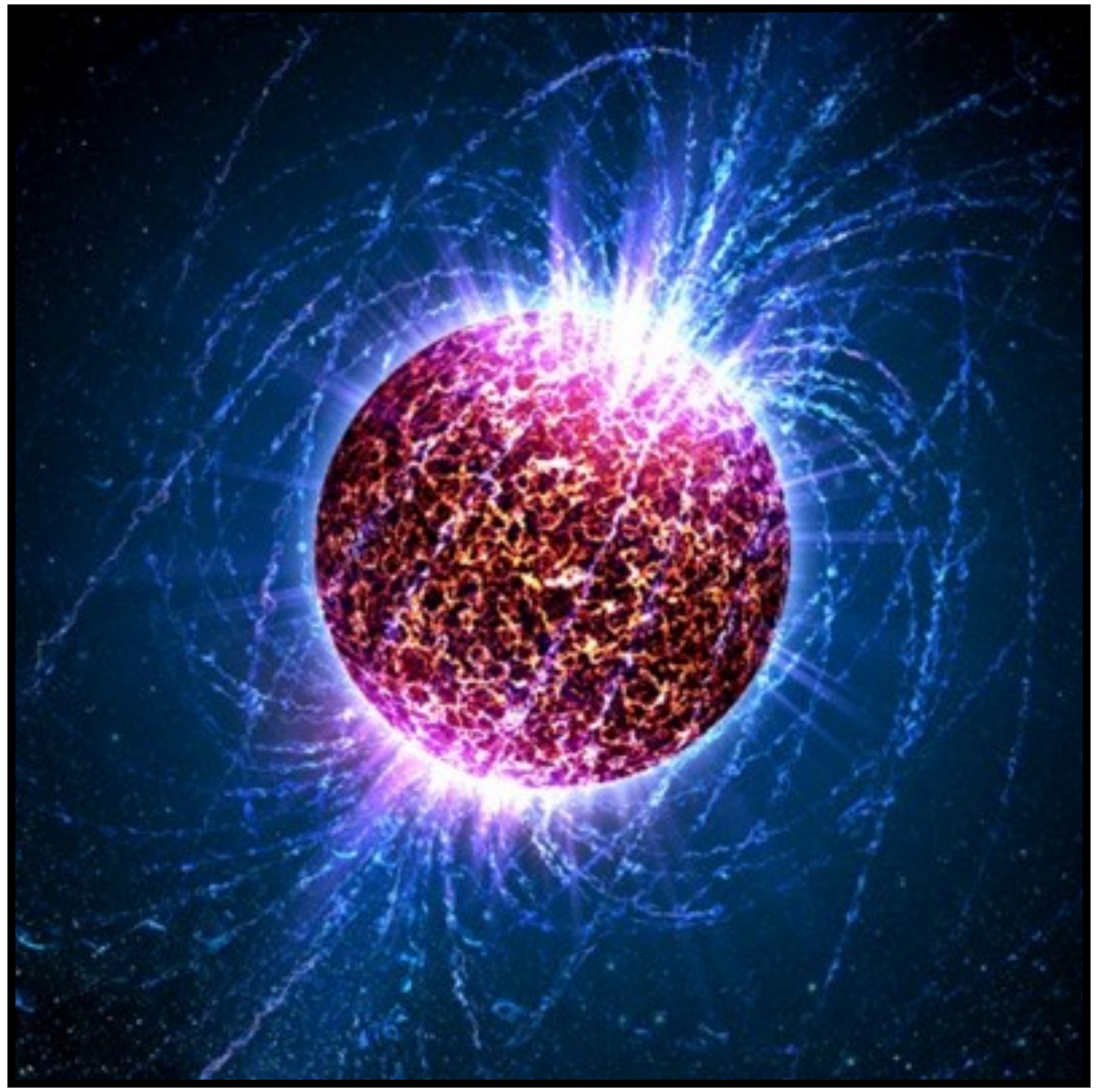
Higher densities, larger magnetic fields, longer timescales…but plenty still to do…

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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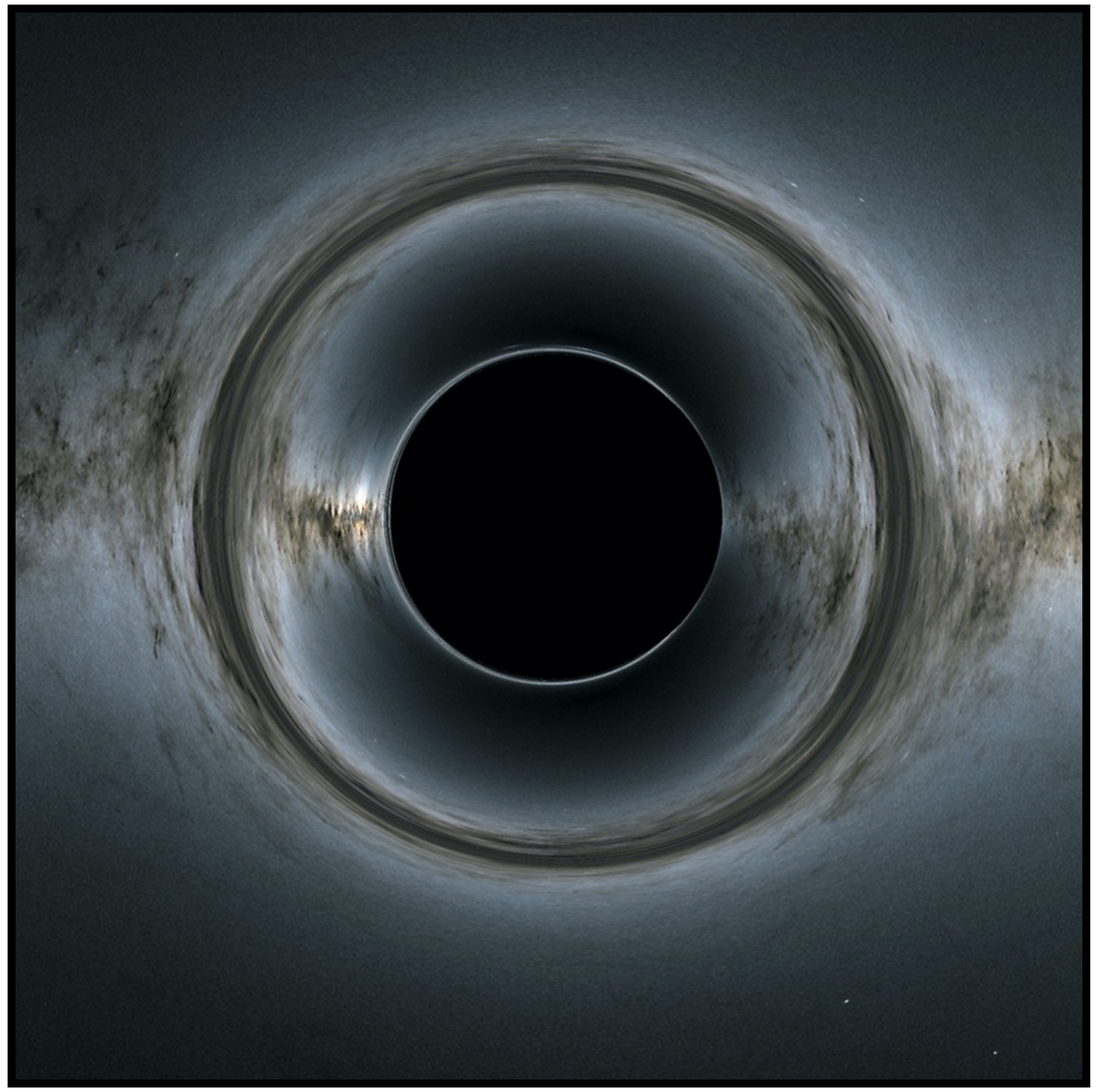
Black Holes



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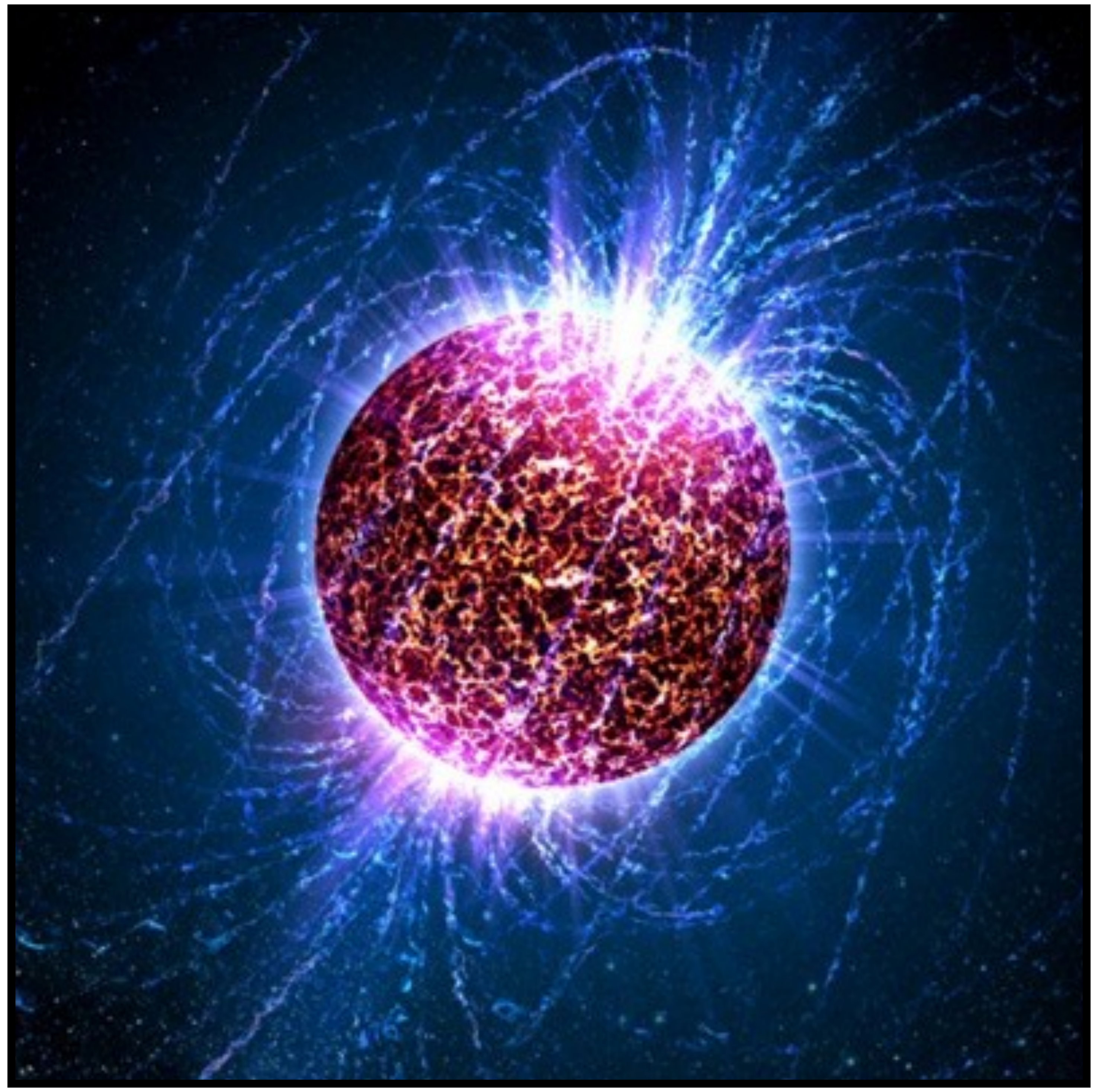
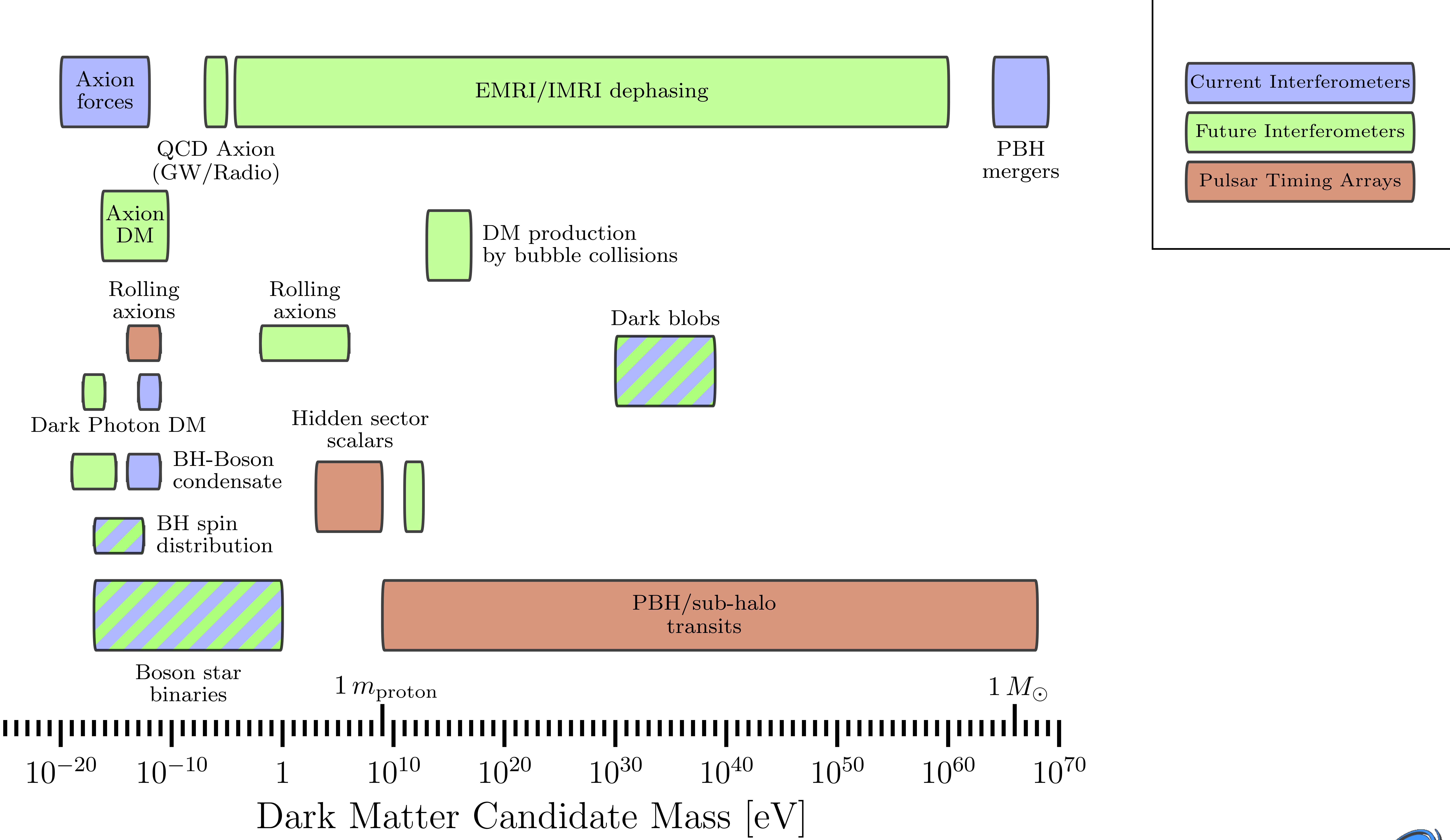


[Credit: Casey Reed (Penn State University), Wikimedia Commons]

Thank you TeVPA!

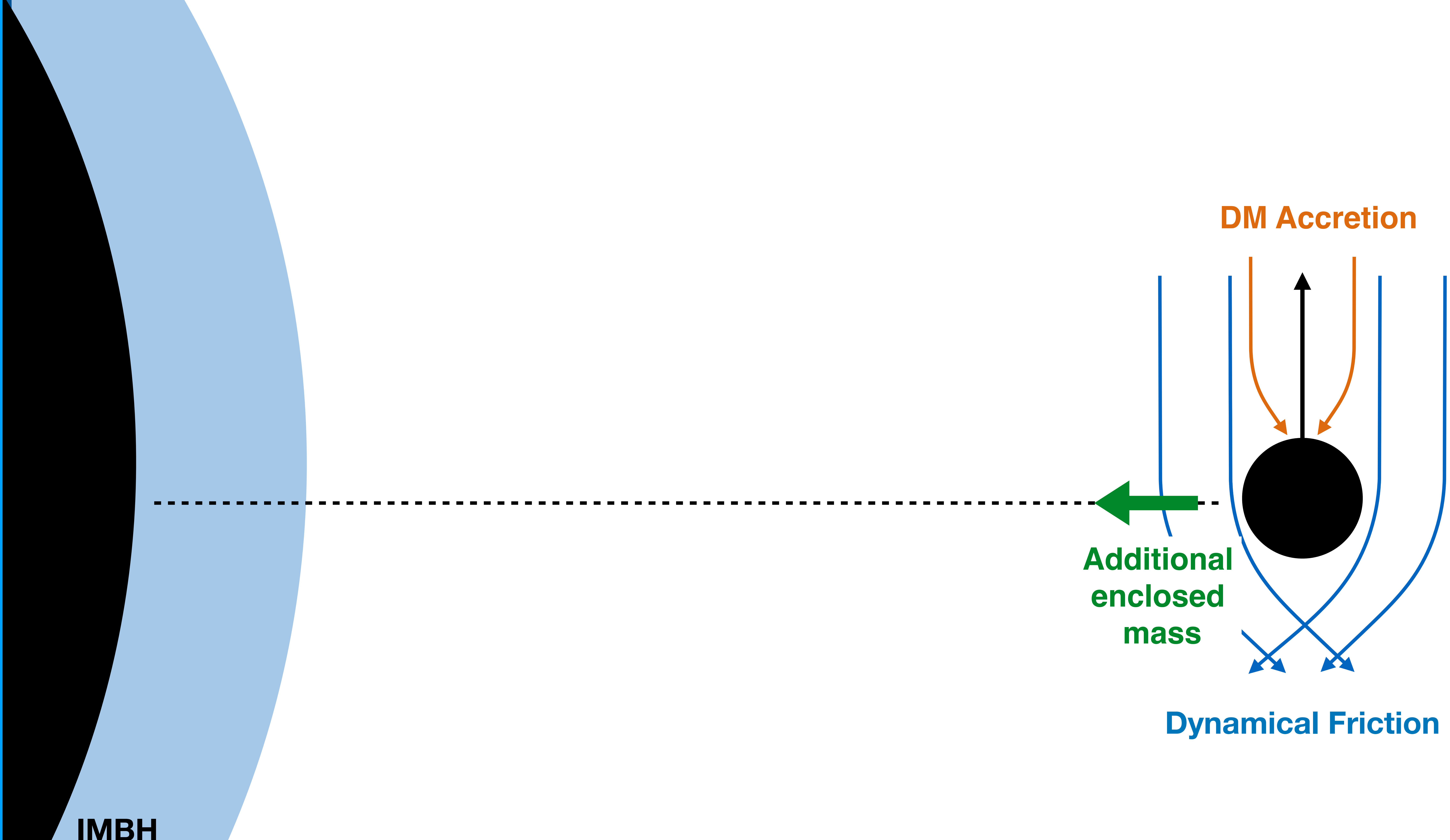
Backup Slides

GW Probes



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

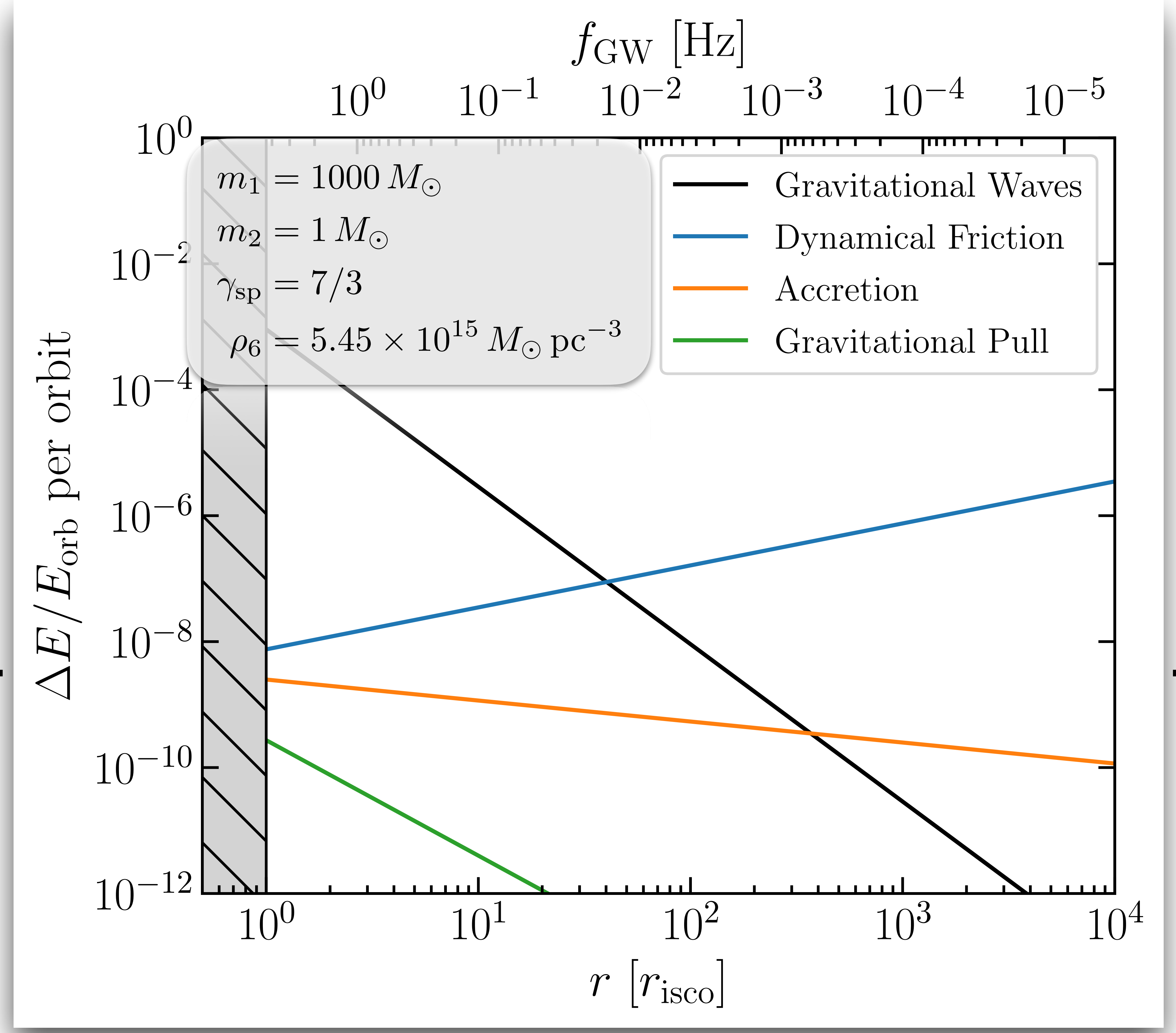
Impact of Dark Matter Spikes

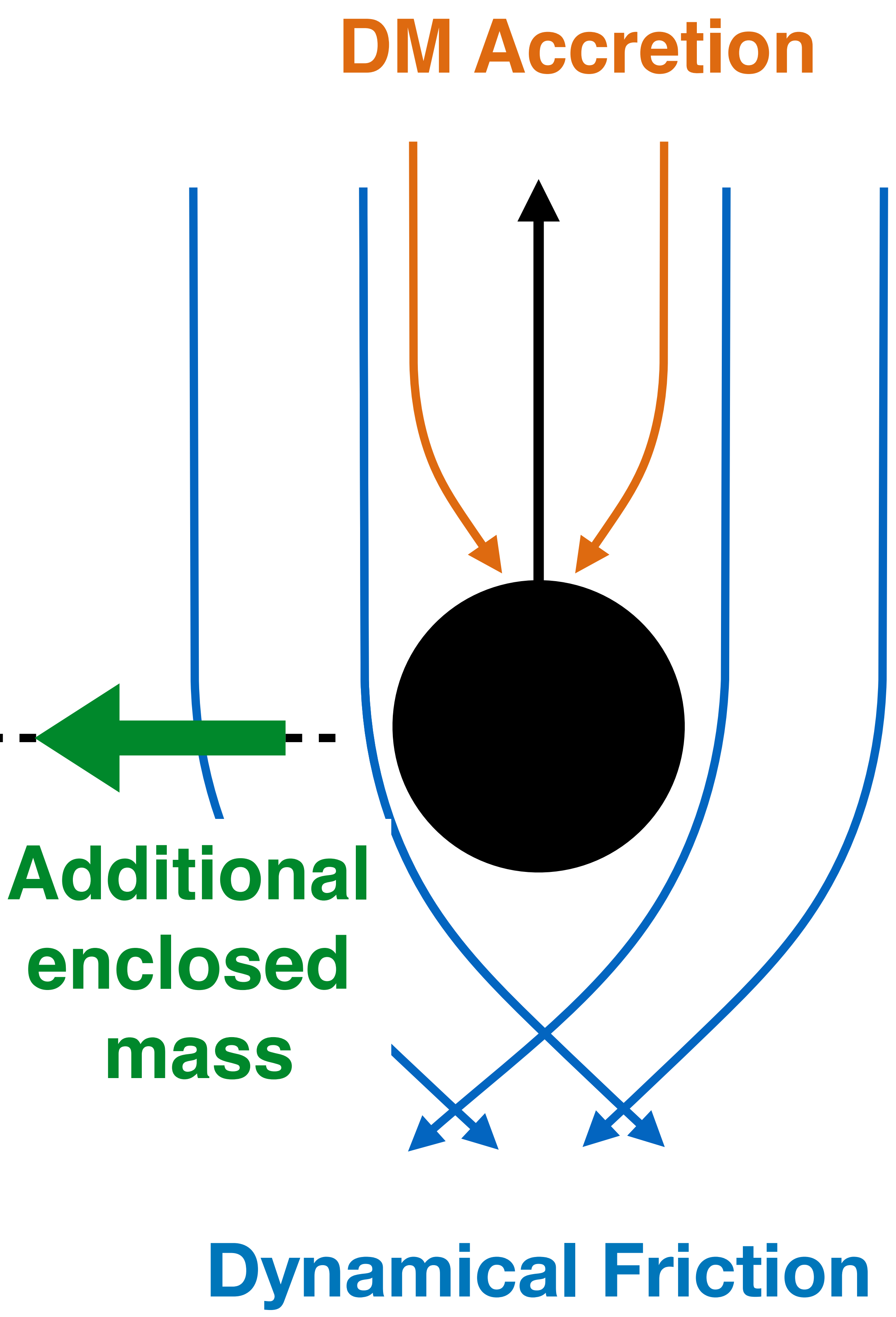


[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Impact of Dark Matter Spikes

IMBH





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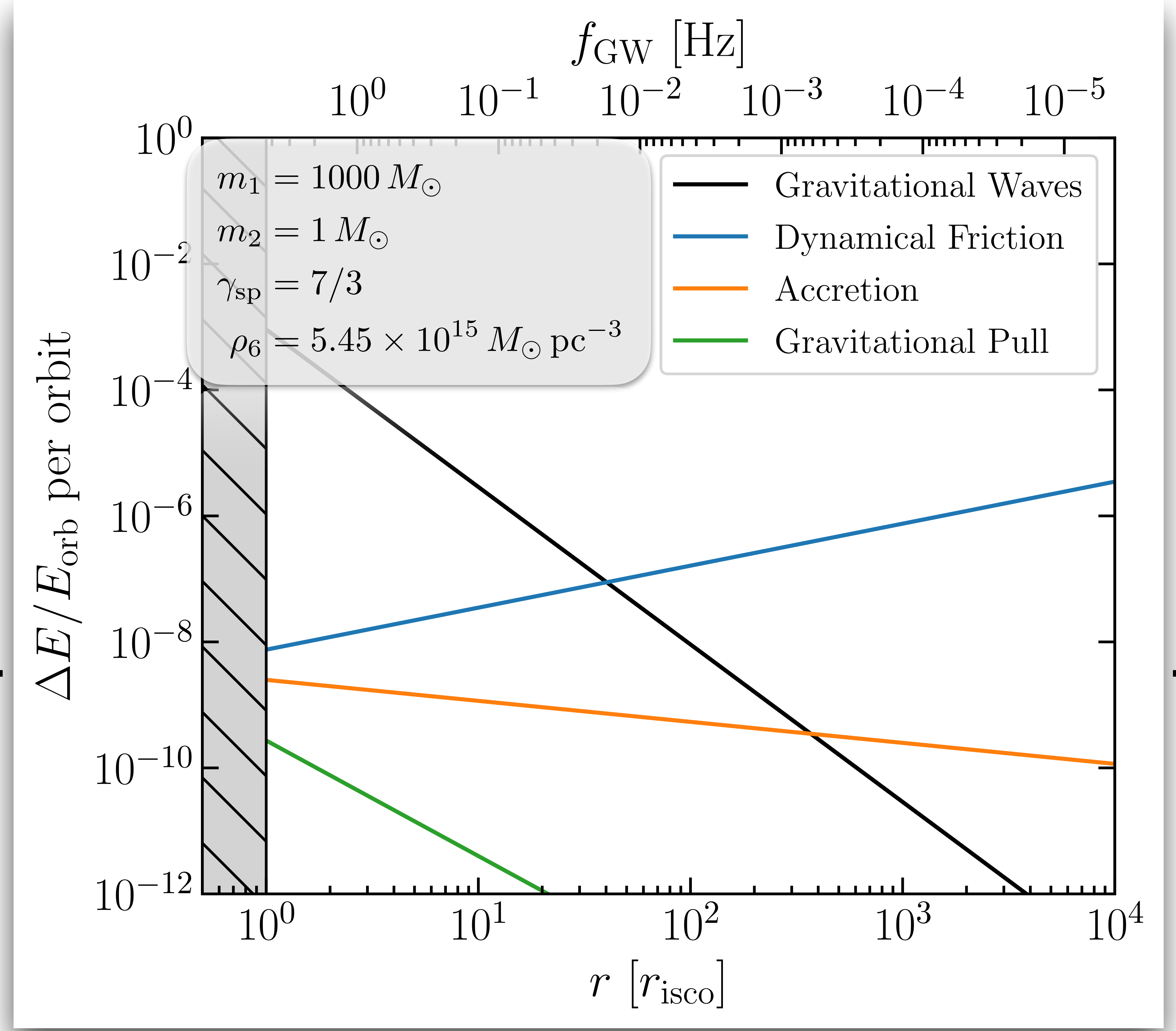
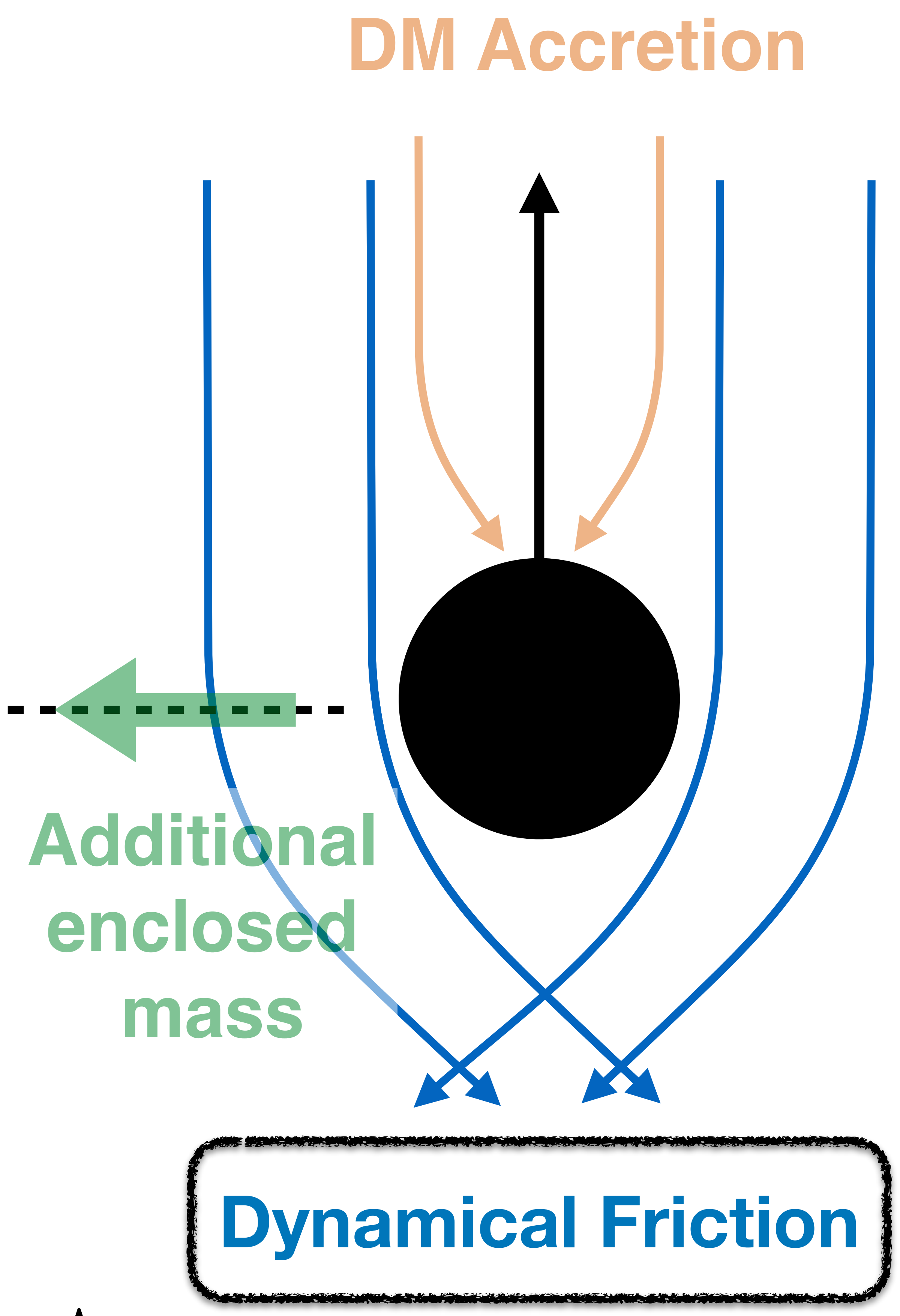
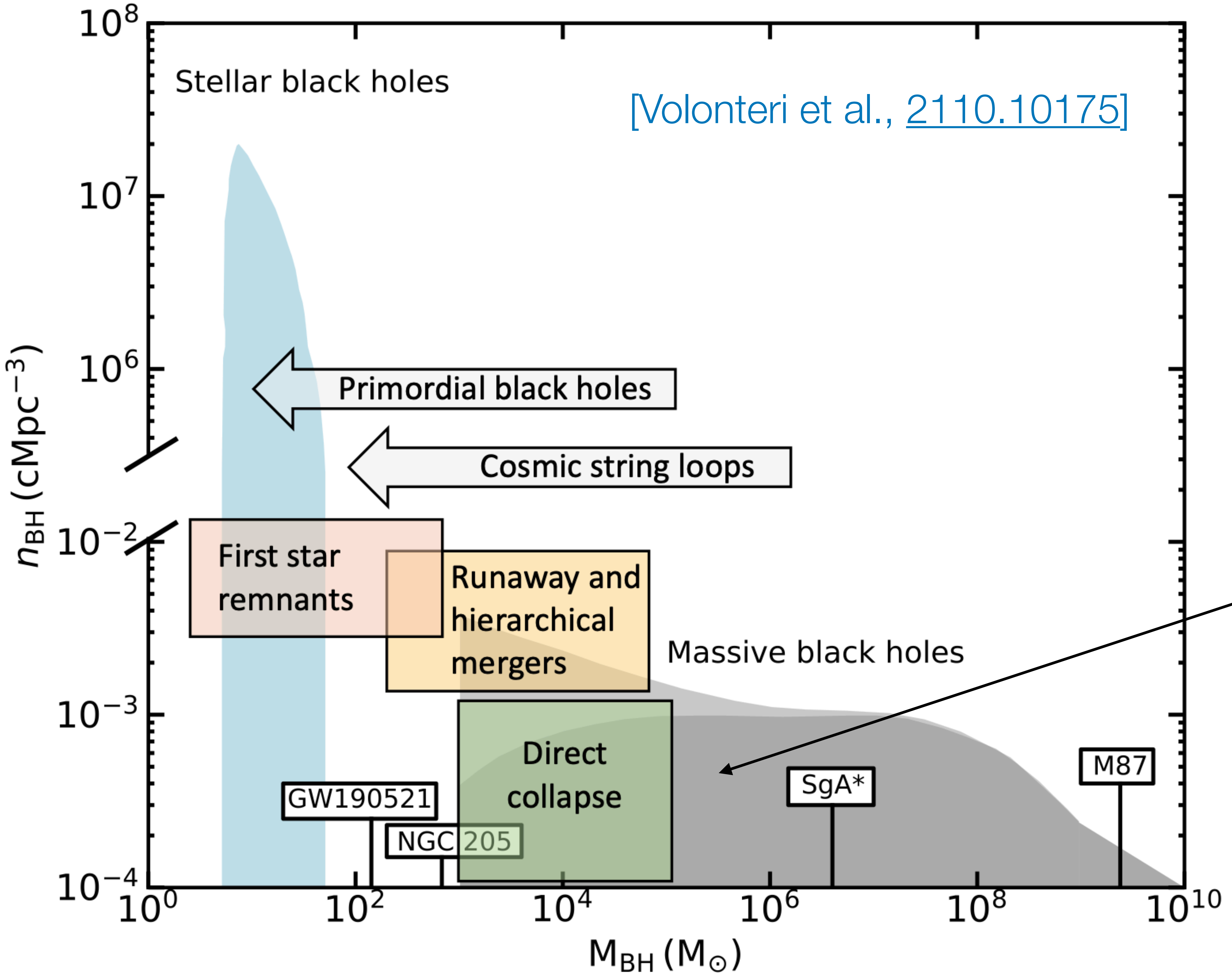




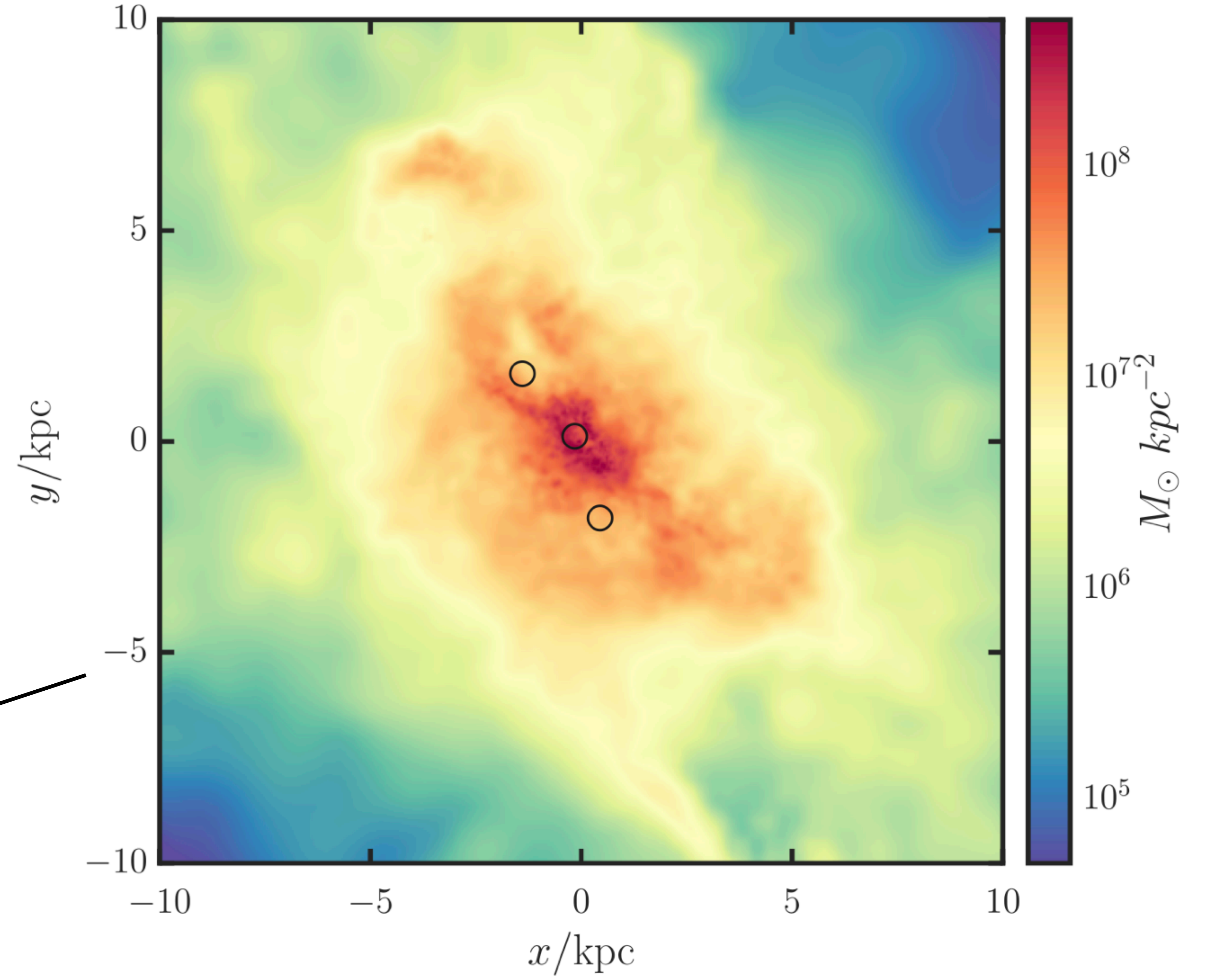
$$\dot{E}_{\rm DF} \sim \frac{4\pi G^2 m_2^2 \rho_{\rm DM}(r)\xi(v)}{v} \ln \Lambda$$

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

Black Holes and Spike Formation



[Dunn et al., 1803.01007]

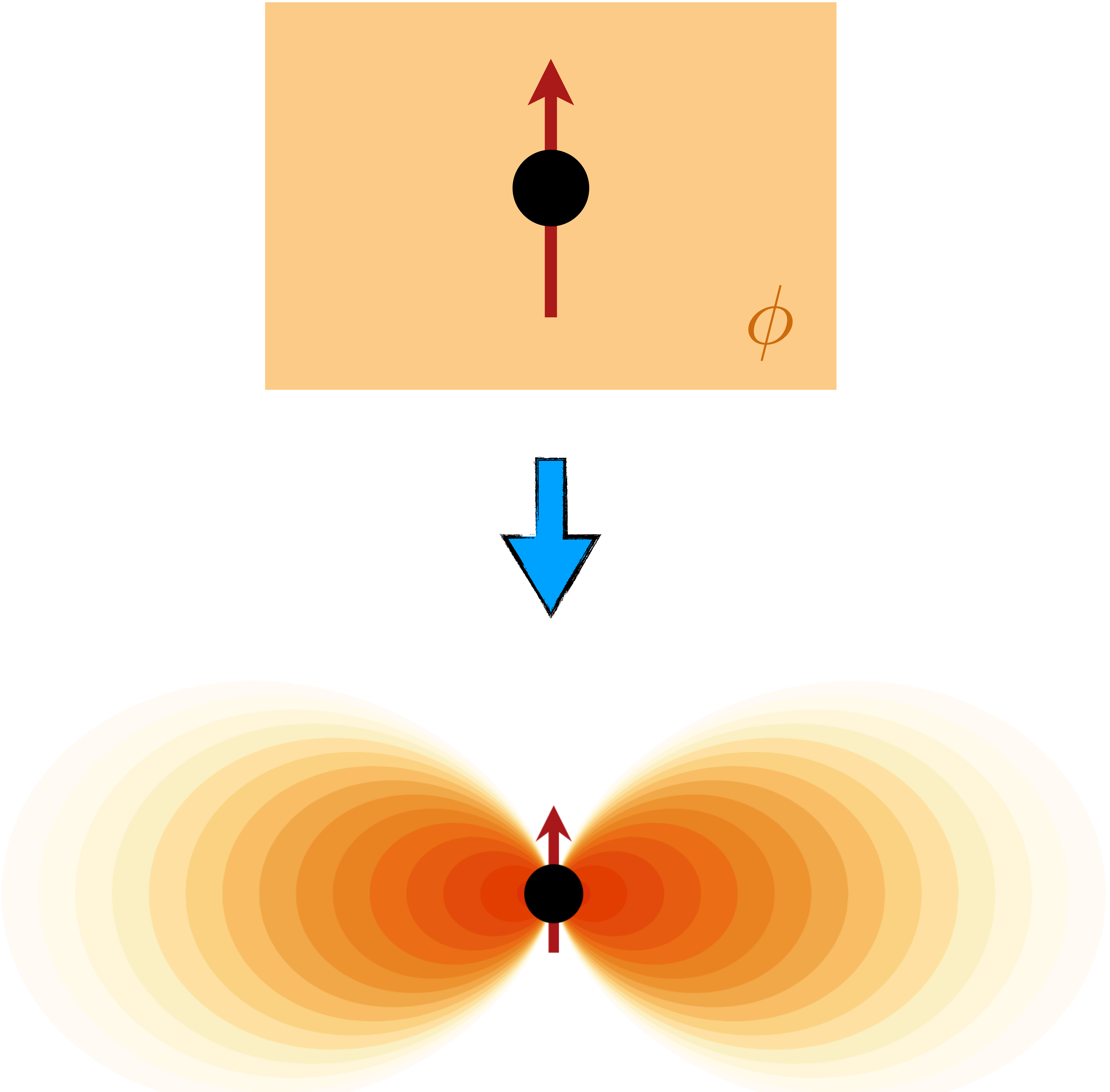


Use semi-analytic galaxy formation models to study the properties of Direct Collapse Black Holes and the halos they form in.

Preliminary results suggest that large densities are possible 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, Pratika Dayal, and others]



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:

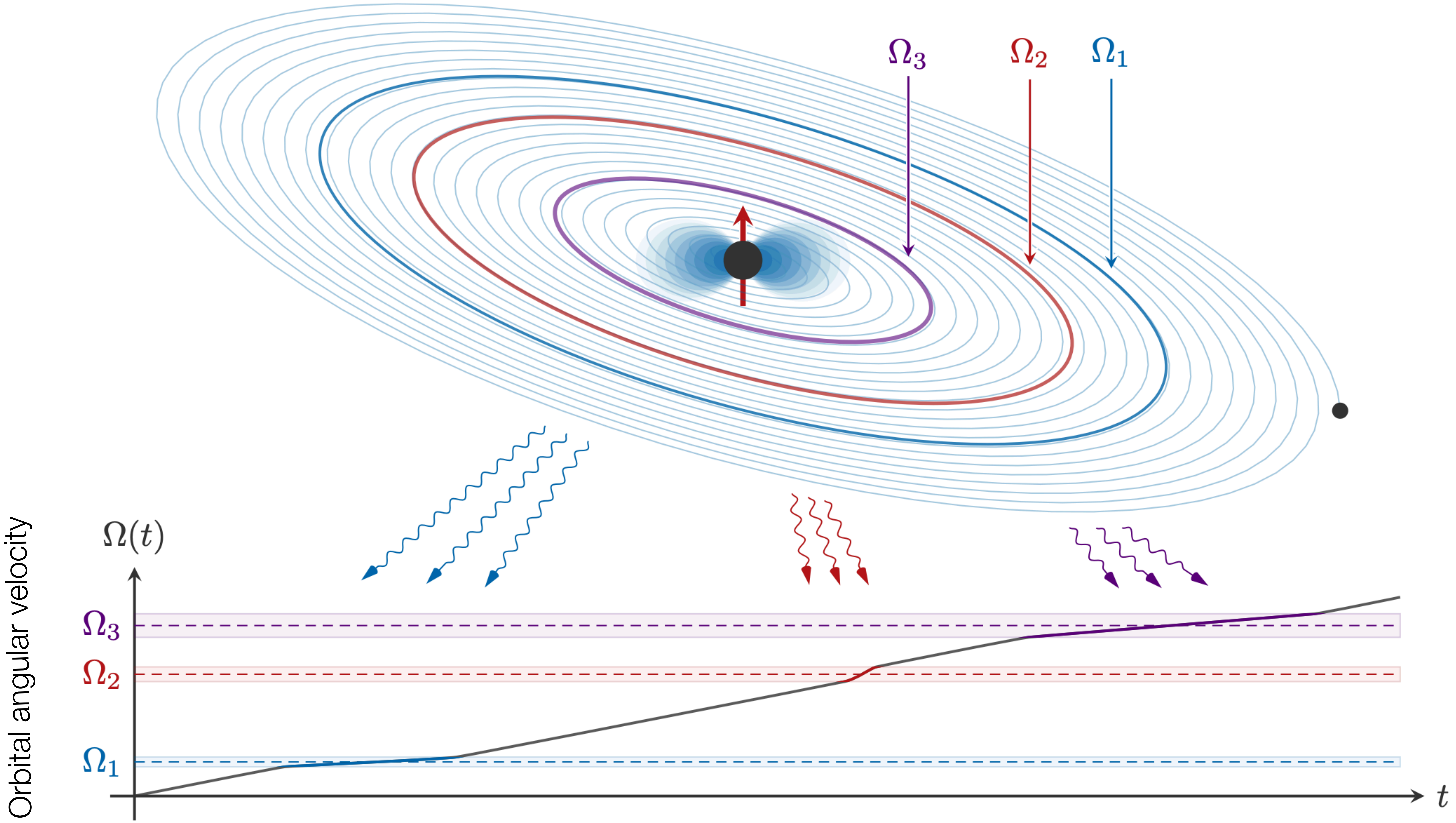
$$r_g \sim GM_{\mathrm{BH}}/c^2 < \lambda_c$$

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

[Chia, 2012.09167]

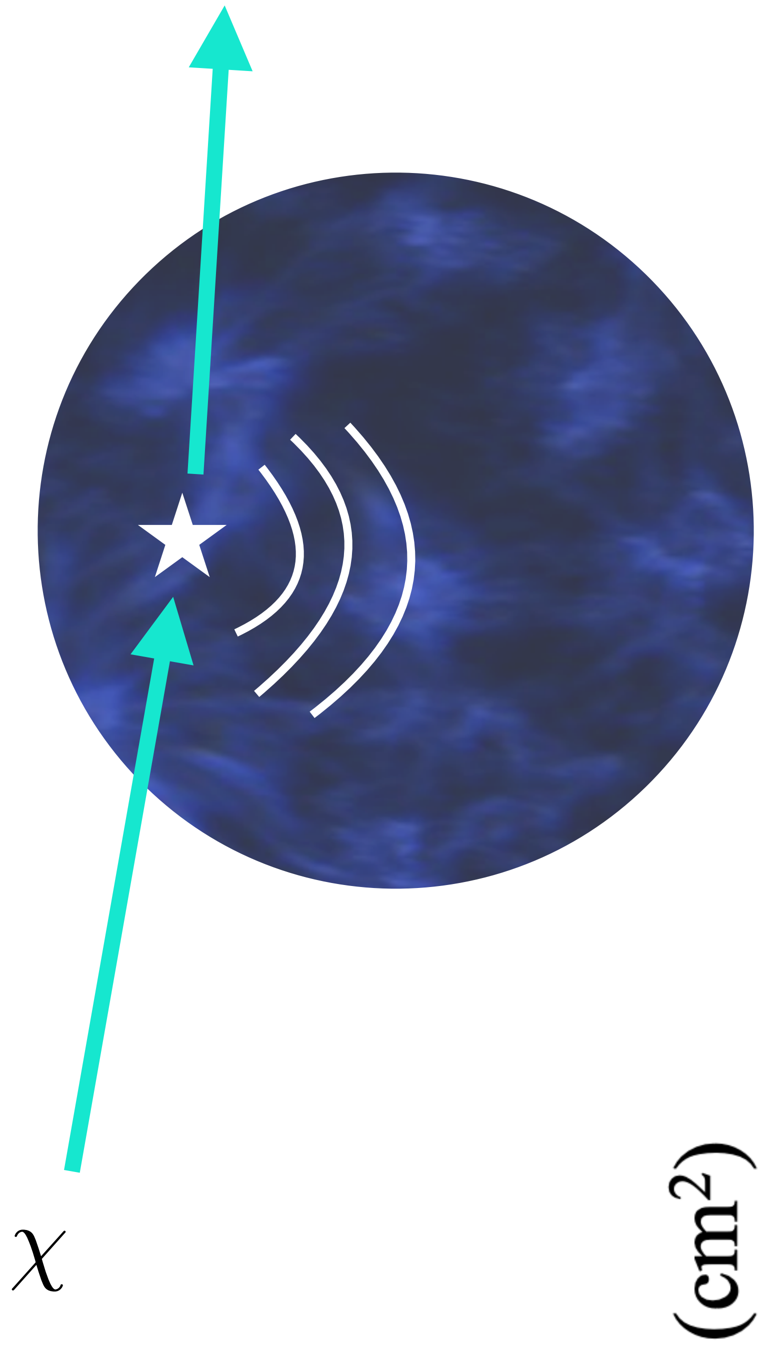
[E.g. Baumann et al., 1804.03208, 1908.10370, 1912.04932, 2112.14777]

Gravitational Atoms

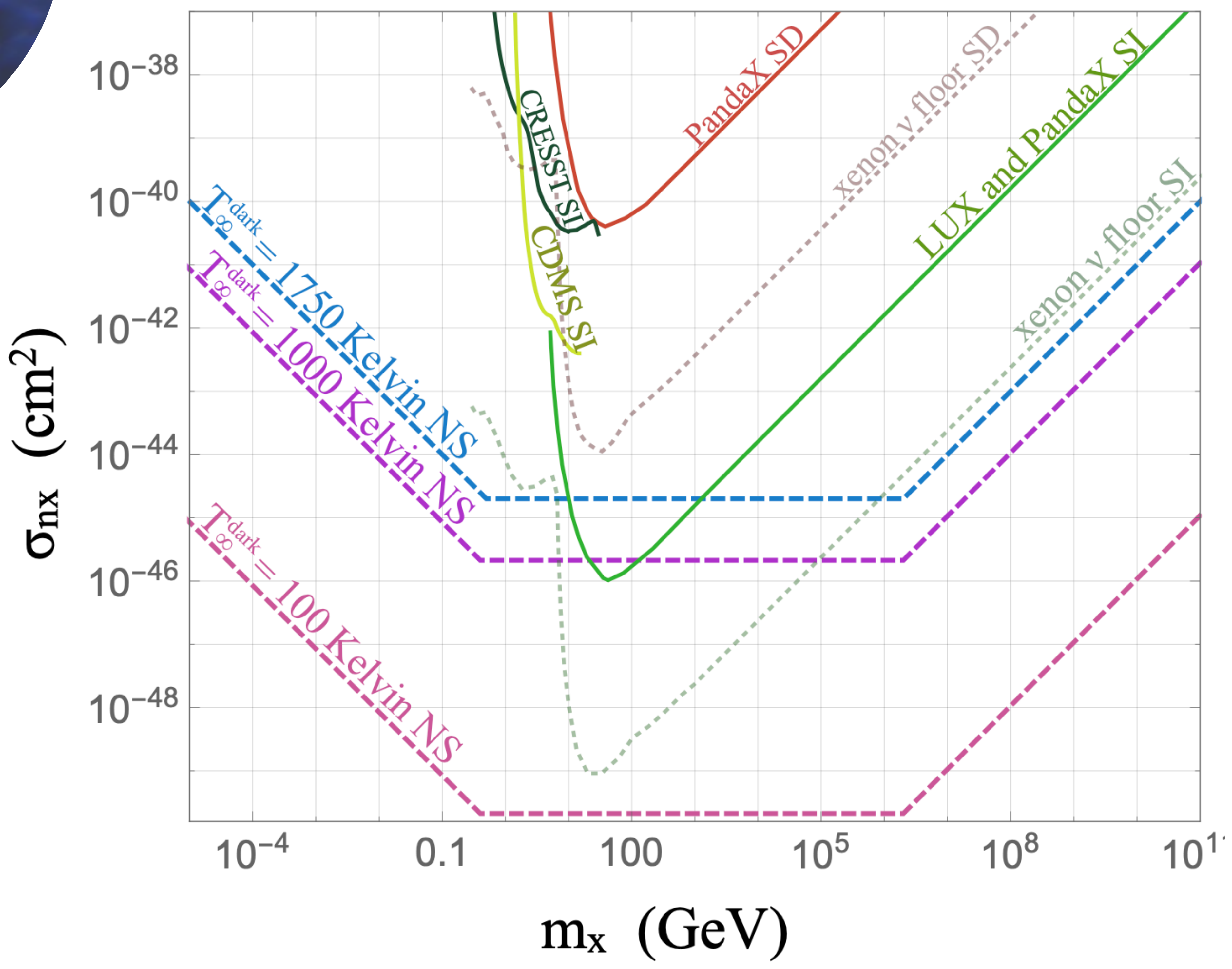


[Baumann et al., 1804.03208, 1908.10370, 1912.04932, 2012.09167, 2112.14777]

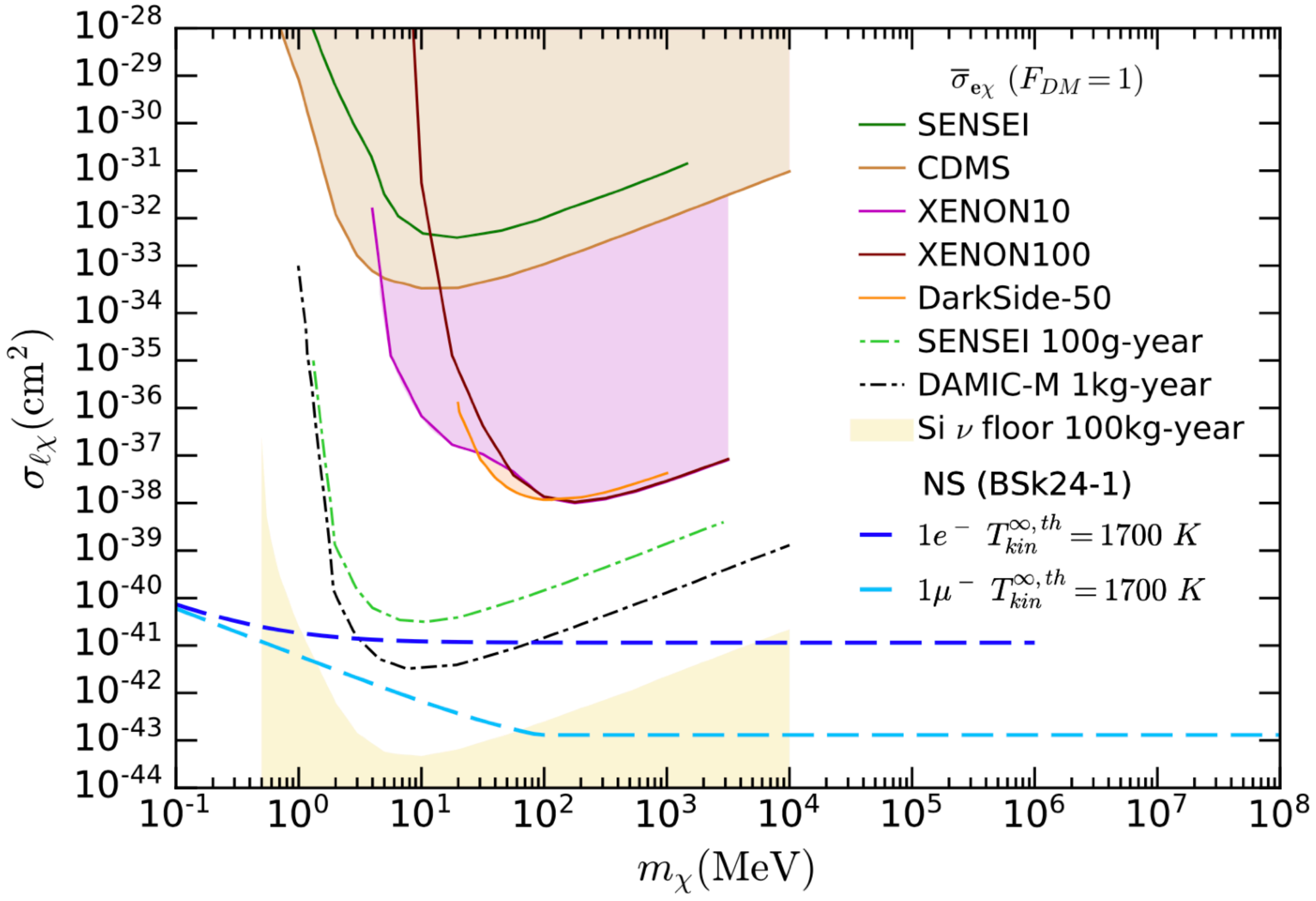
Neutron Star Heating



[Baryakhtar et al., 1704.01577]



[Bell et al., 1904.09803]



NS and WD capture rate becoming more and more refined, but what are the observational prospects?

[Acevedo et al., 1911.06334; Bell et al., 2004.14888, 2104.14367; Dasgupta et al., 2006.10773]

Captured DM may also affect NS equation of state: [Cermeño et al., 1710.06866]

Axion miniclusters

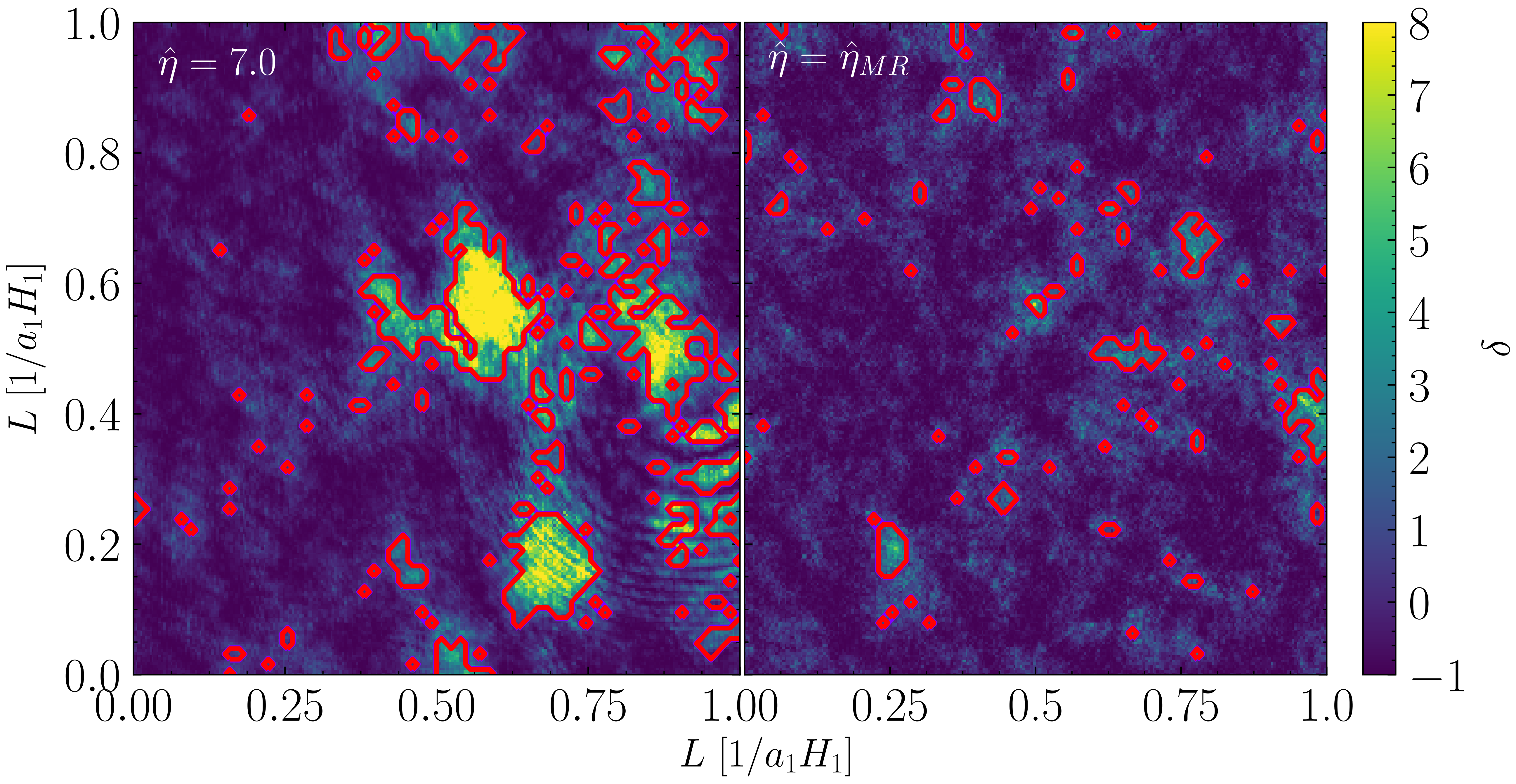
$$\delta = (\rho - \bar{\rho})/\rho$$

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

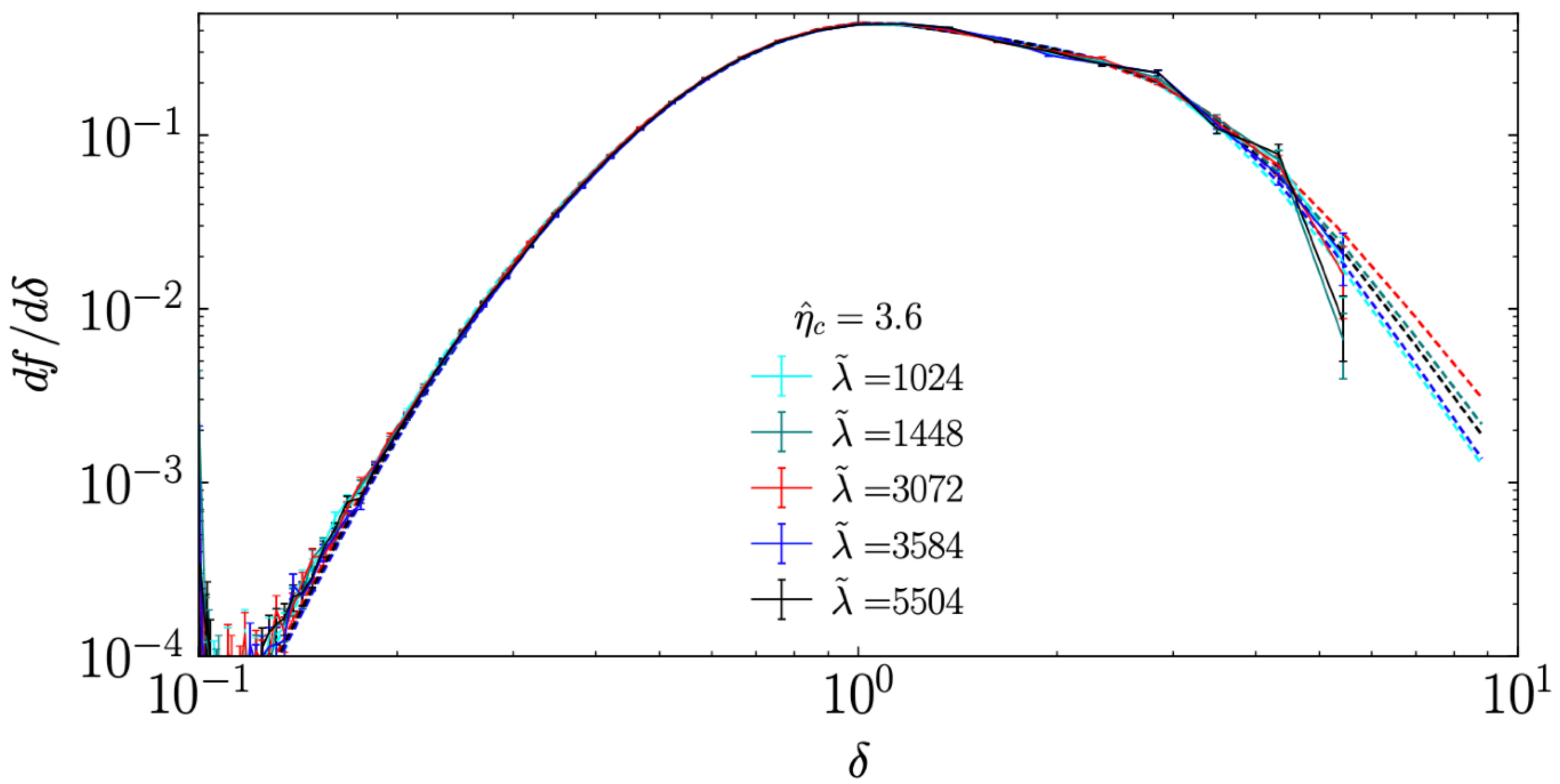
For an overdensity of size $\delta = (\rho - \bar{\rho})/\rho$ the final density is:

$$\rho_{\rm AMC}(\delta) = 140(1+\delta)\delta^3 \rho_{\rm eq}$$

[Kolb & Tkachev, astro-ph/9403011]



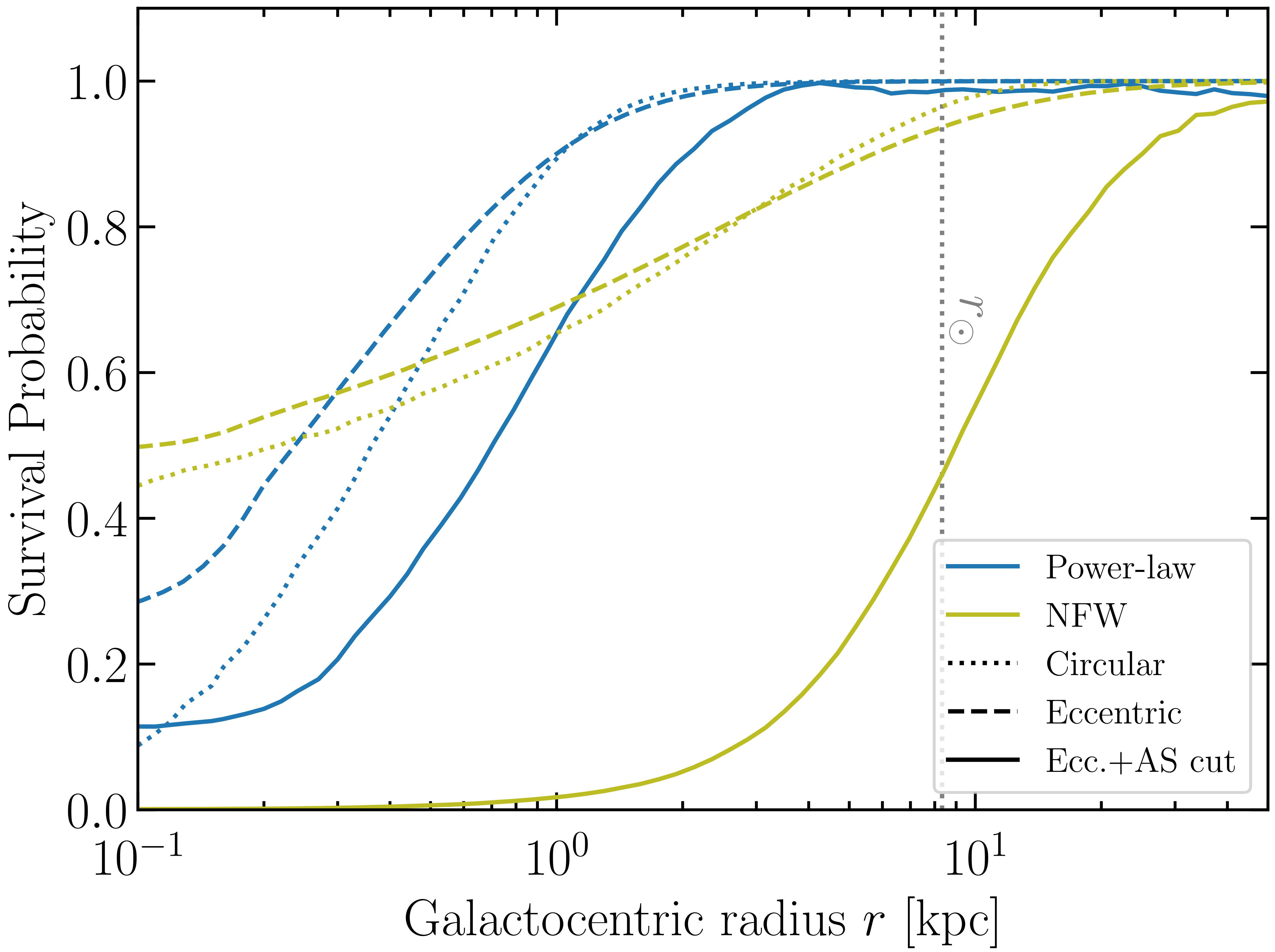
[Buschmann et al., 1906.00967]



Not to be confused with Axion Stars

[Schive et al., 1407.7762, Visinelli et al., 1710.08910]

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]