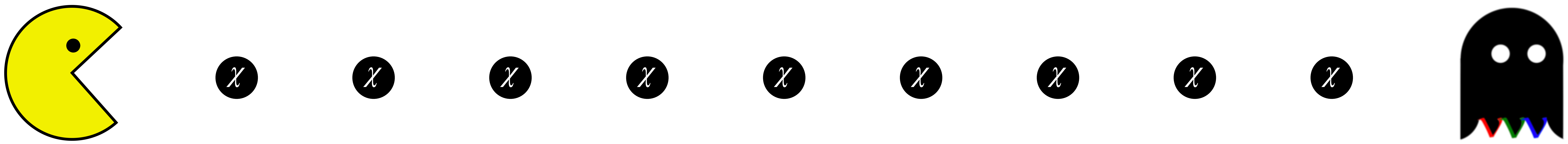


Future Dark Matter Searches

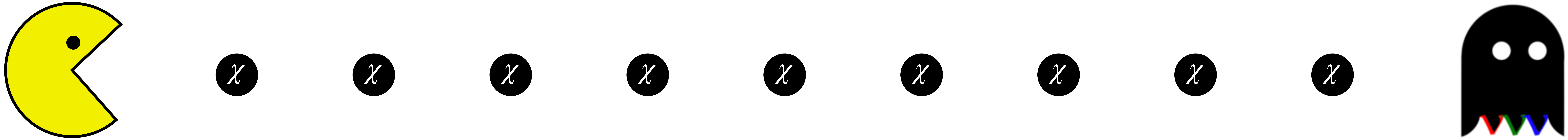
Bradley J. Kavanagh
IFCA (UC-CSIC), Santander

3rd Dark Ghosts Workshop
1st April 2022

[SNOWMASS: Dark Matter In Extreme Astrophysical Environments, 2203.07984]

IFCA Instituto de Física de Cantabria
CSIC Consejo Superior de Investigaciones Científicas
UC Universidad de Cantabria
Excelencia María de Maeztu

kavanagh@ifca.unican.es
@BradleyKavanagh



Dark Matter in Extreme Environments

Bradley J. Kavanagh
IFCA (UC-CSIC), Santander

3rd Dark Ghosts Workshop
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[SNOWMASS: Dark Matter In Extreme Astrophysical Environments, 2203.07984]

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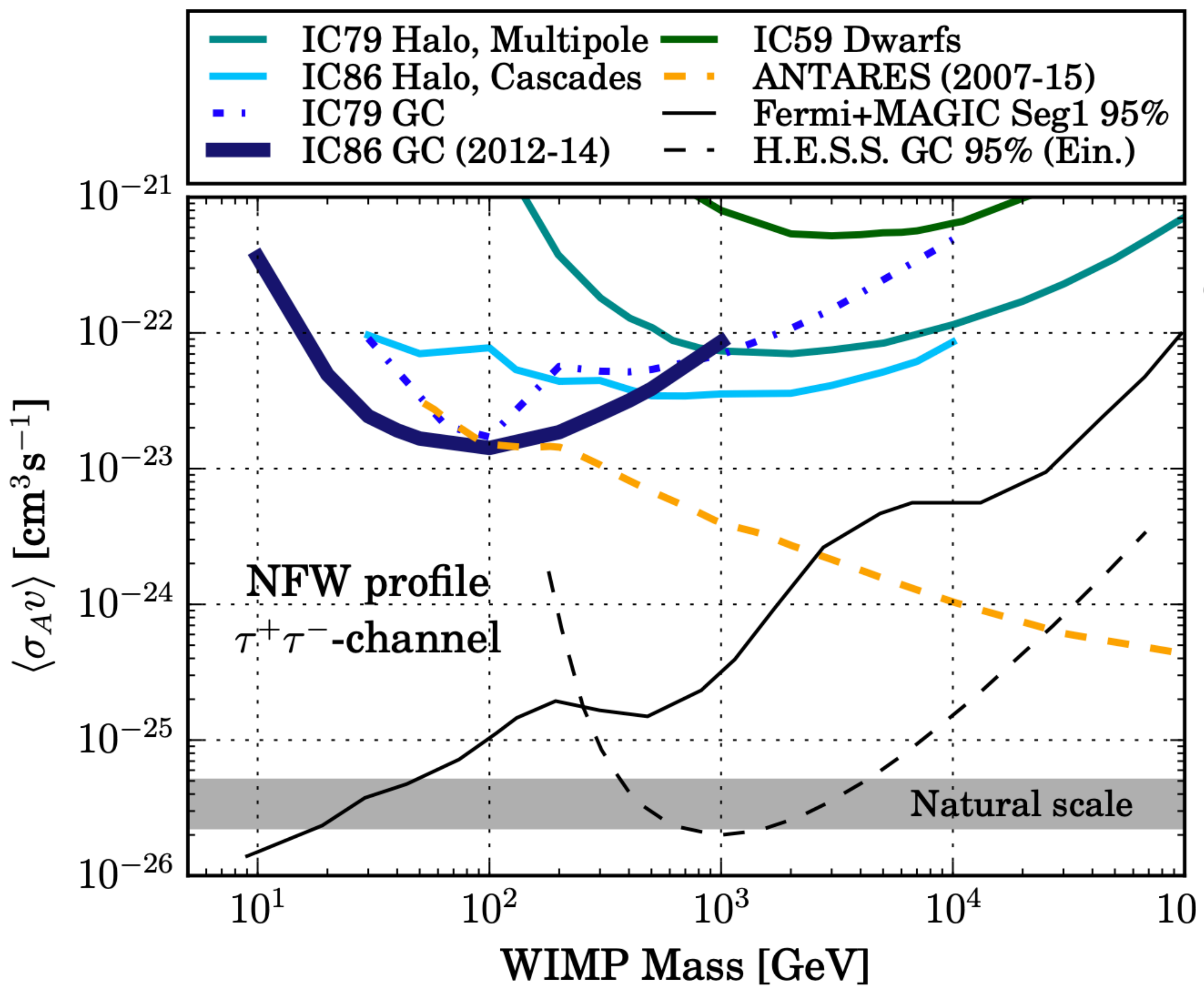
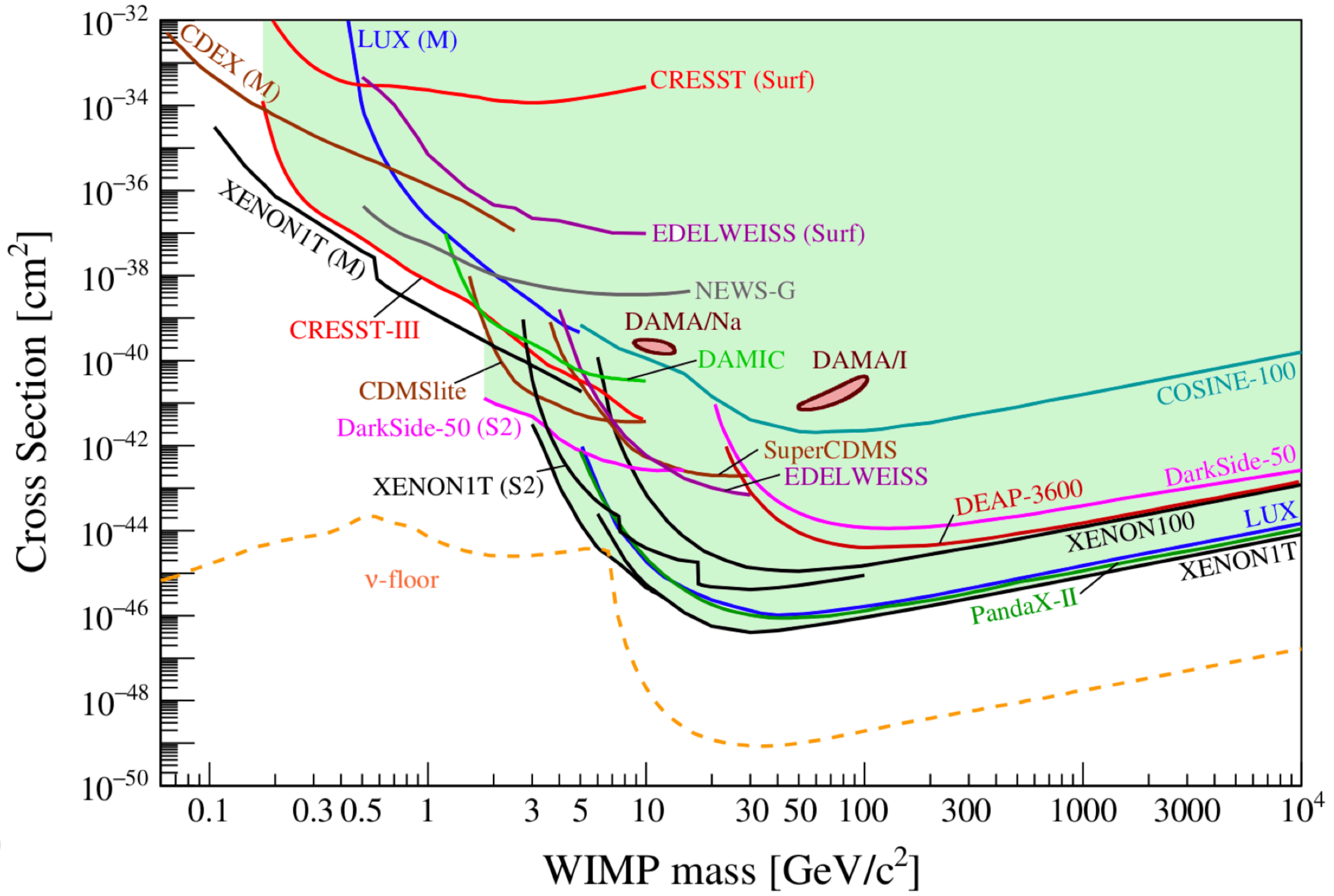
The Dark Matter Landscape

Indirect searches



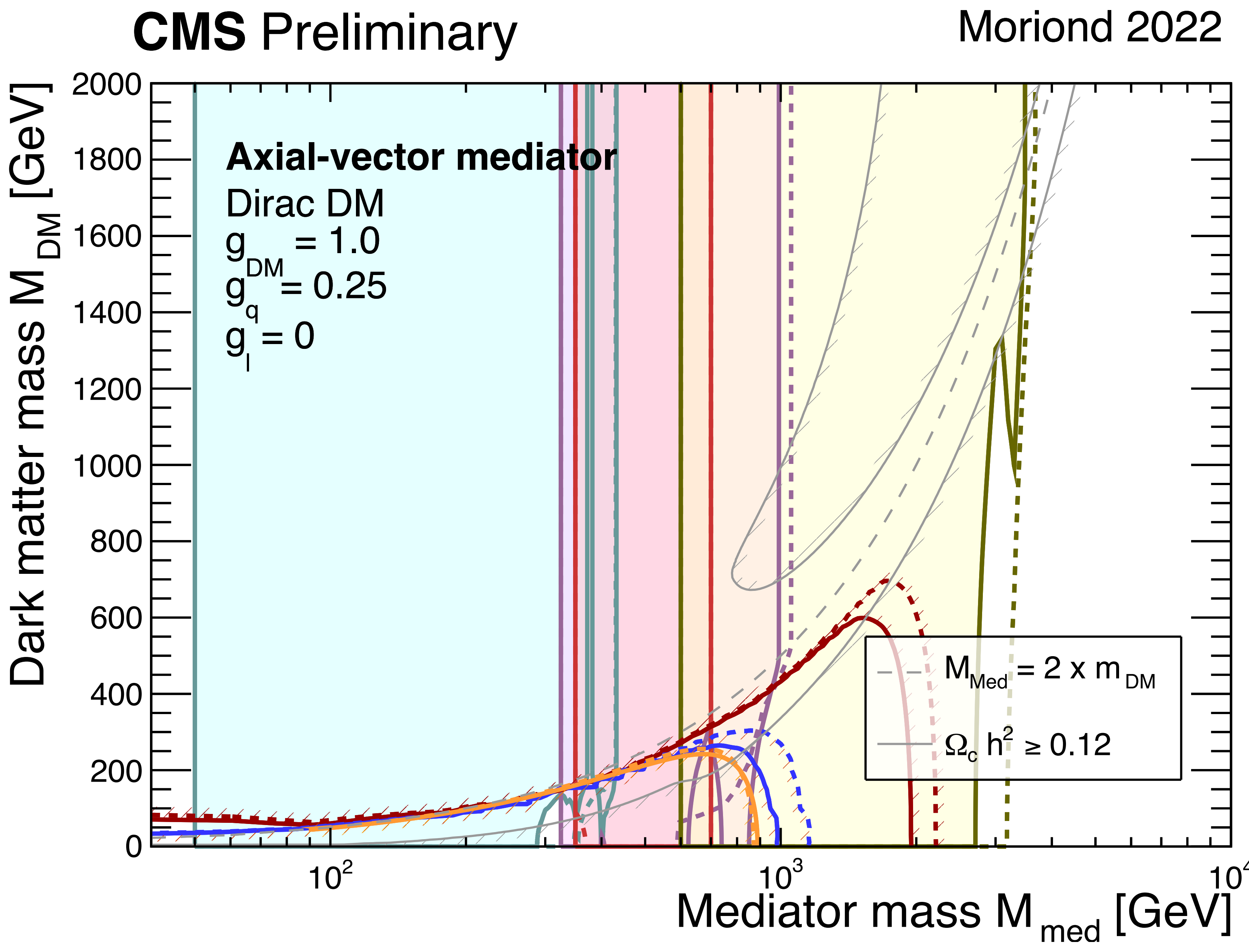
[IceCube, 1705.08103]

Direct Searches



[APPEC, 2104.07634]

Collider Searches



[CMS, DM Summary Plots]

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

The Dark Matter Landscape

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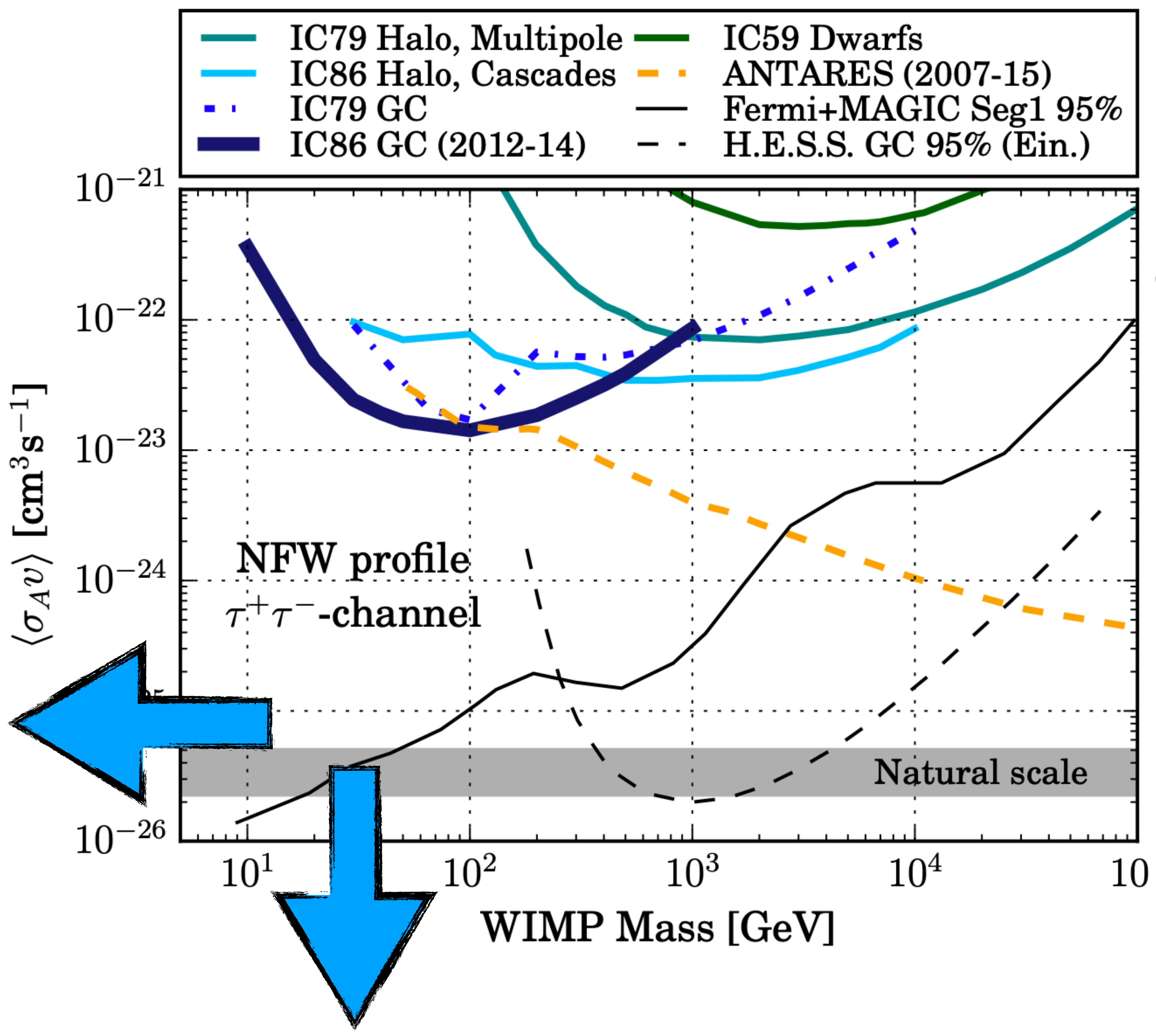
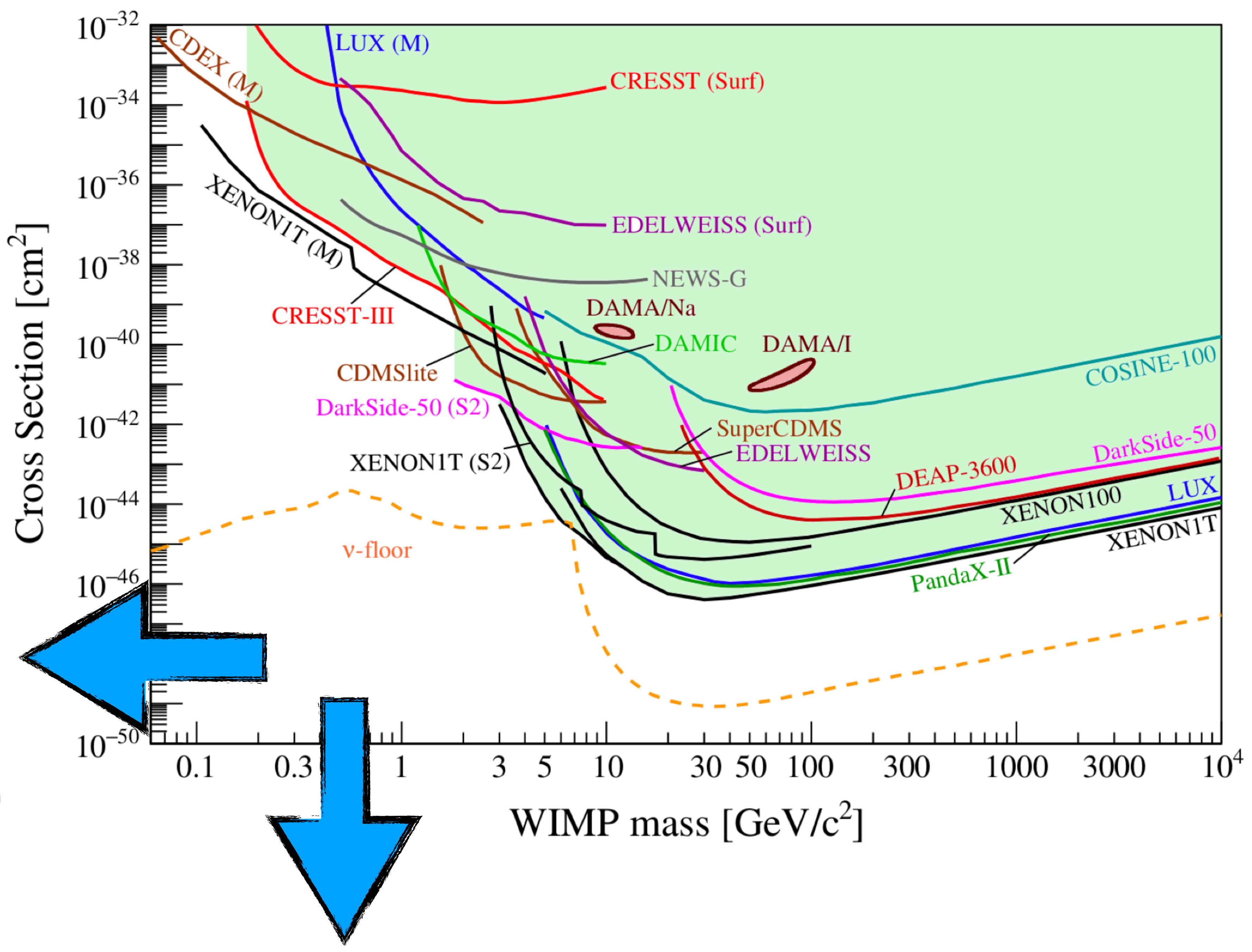


[IceCube, 1705.08103]

Direct Searches



[APPEC, 2104.07634]

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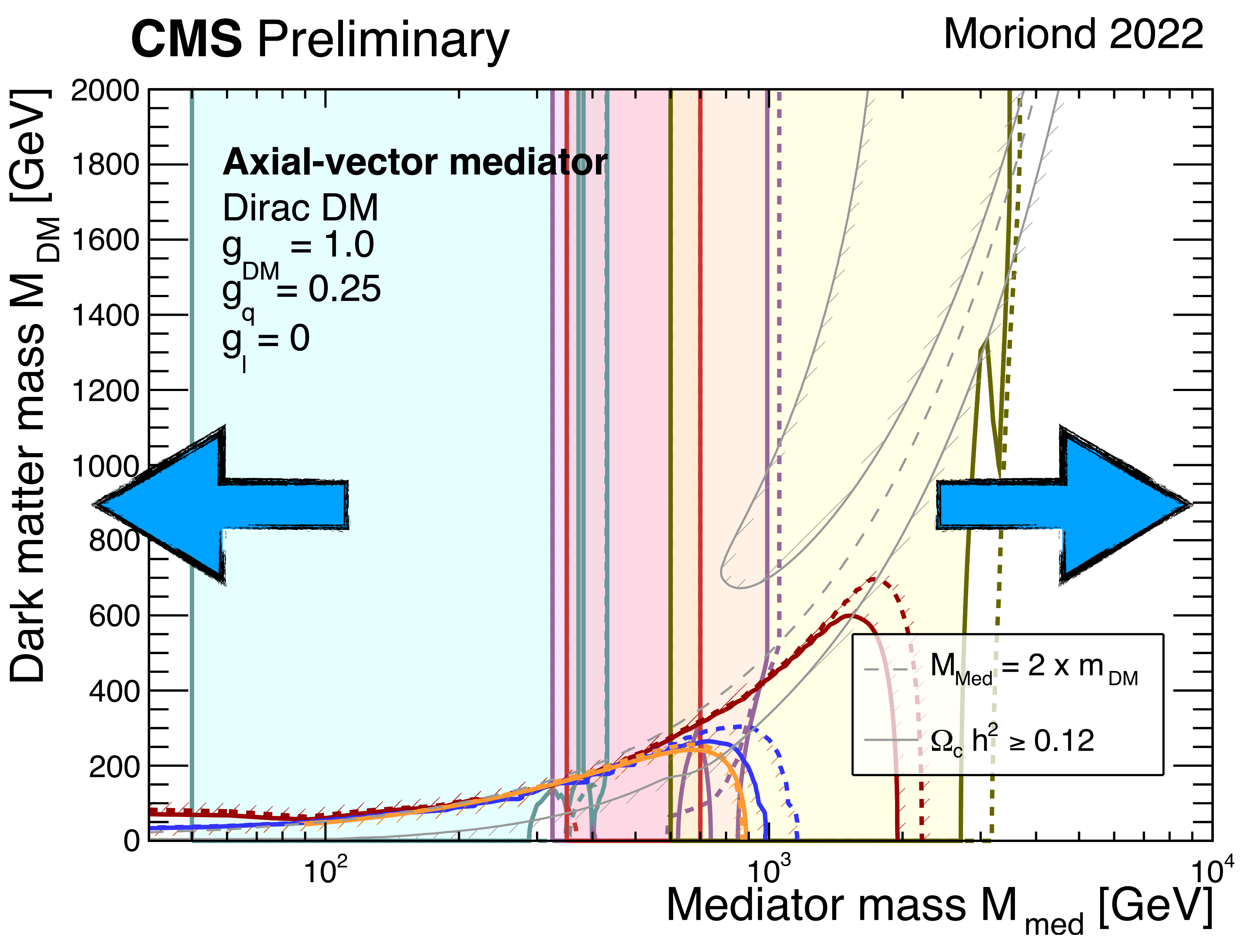
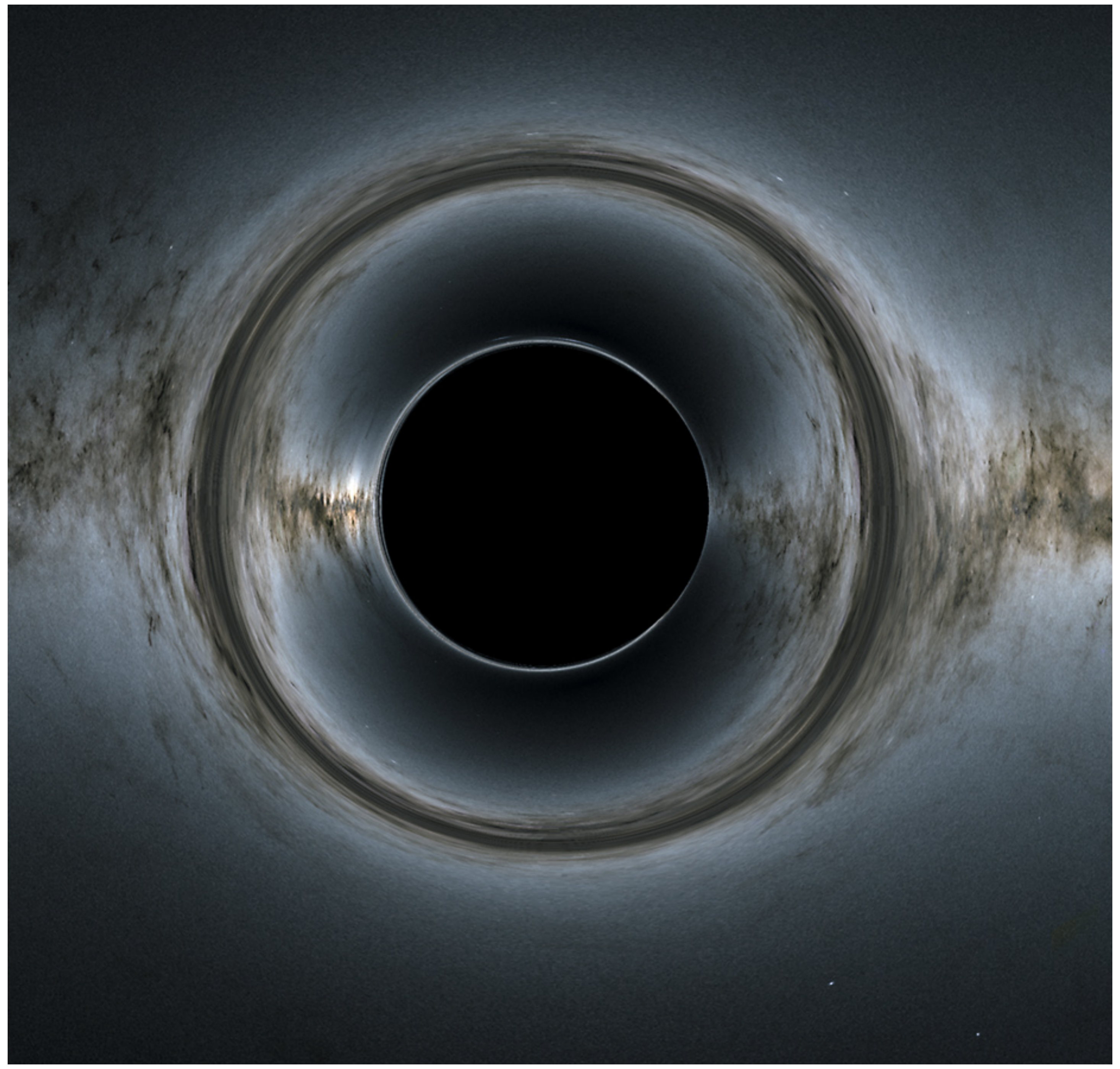


[CMS, DM Summary Plots]

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

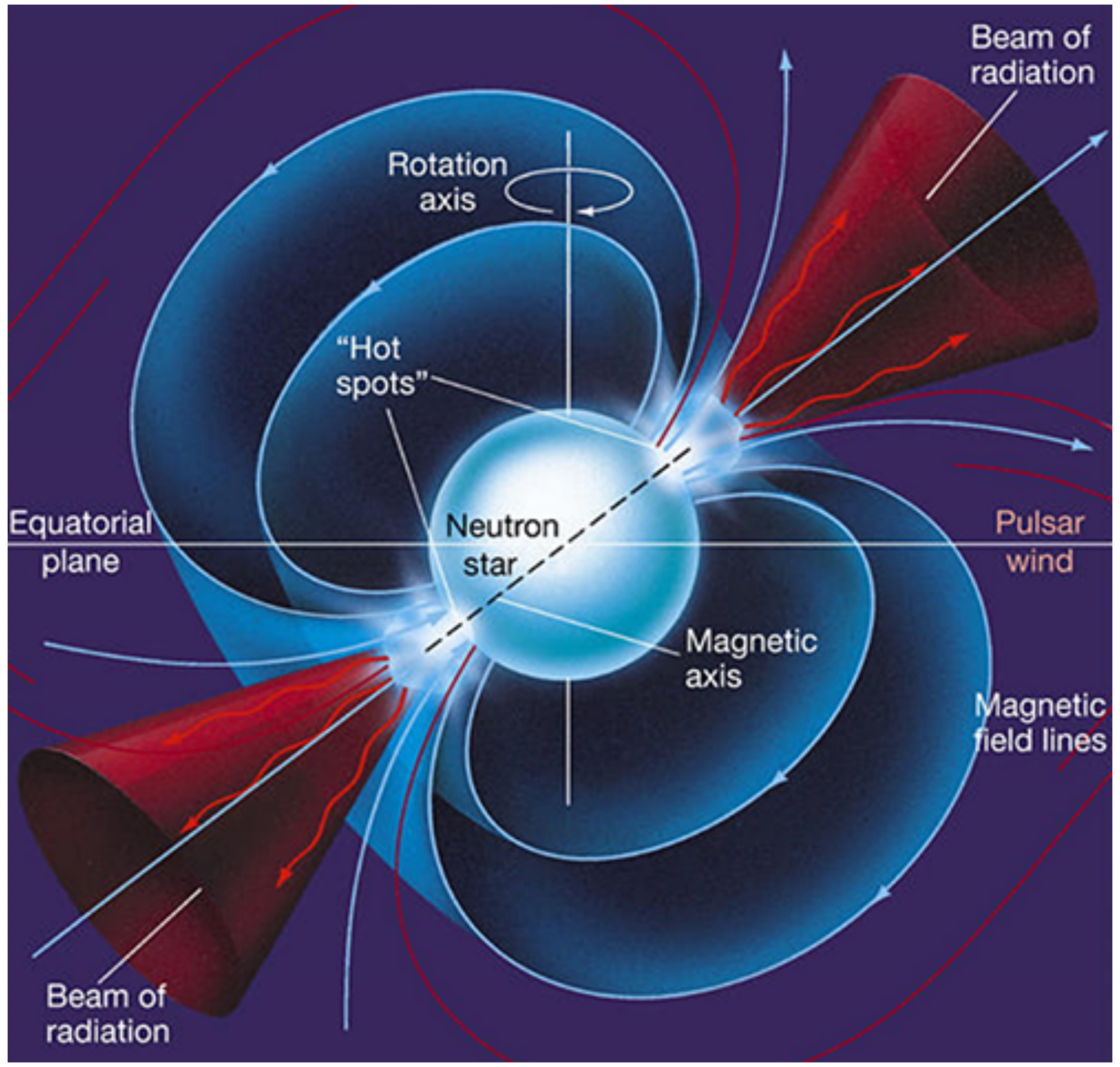
DM in Extreme Environments

Black Holes



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

Neutron Stars

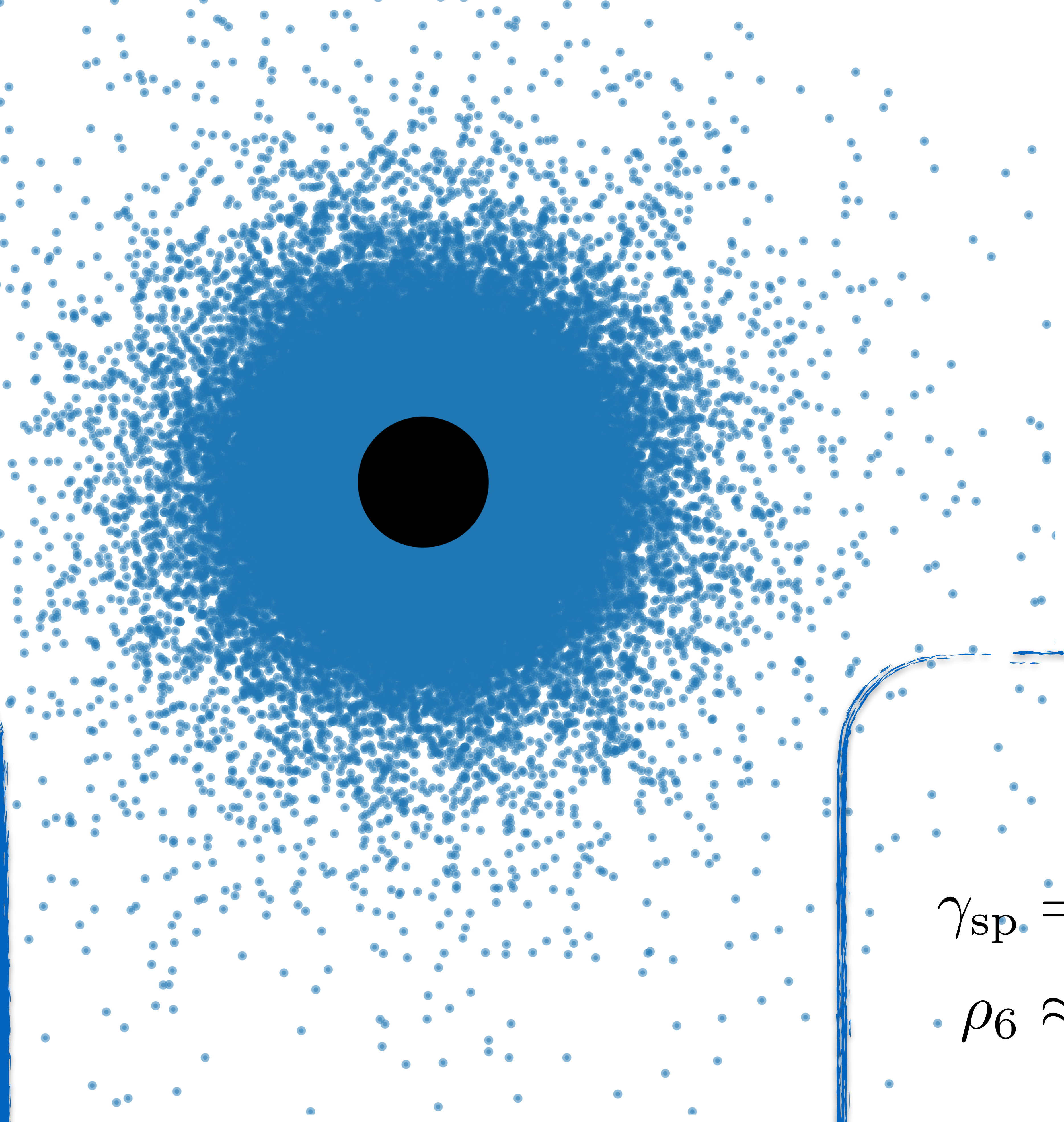


Higher densities, larger magnetic fields, longer timescales…

Black Holes and DM Spikes

Consider a cold **DM** ‘**spike**’ or ‘**dress**’ around an intermediate mass black hole (IMBH)*

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



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

Astrophysical scenario

$$\gamma_{\rm sp} = 7/3 \approx 2.3333\ldots$$

$$\rho_6 \approx 5.45 \times 10^{15}\,M_\odot\,{\rm pc}^{-3}$$

…depending on a number of environmental factors…

[astro-ph/9906391, astro-ph/0509565, 1305.2619, …]

PBH scenario

$$\gamma_{\rm sp} = 9/4 \approx 2.25$$

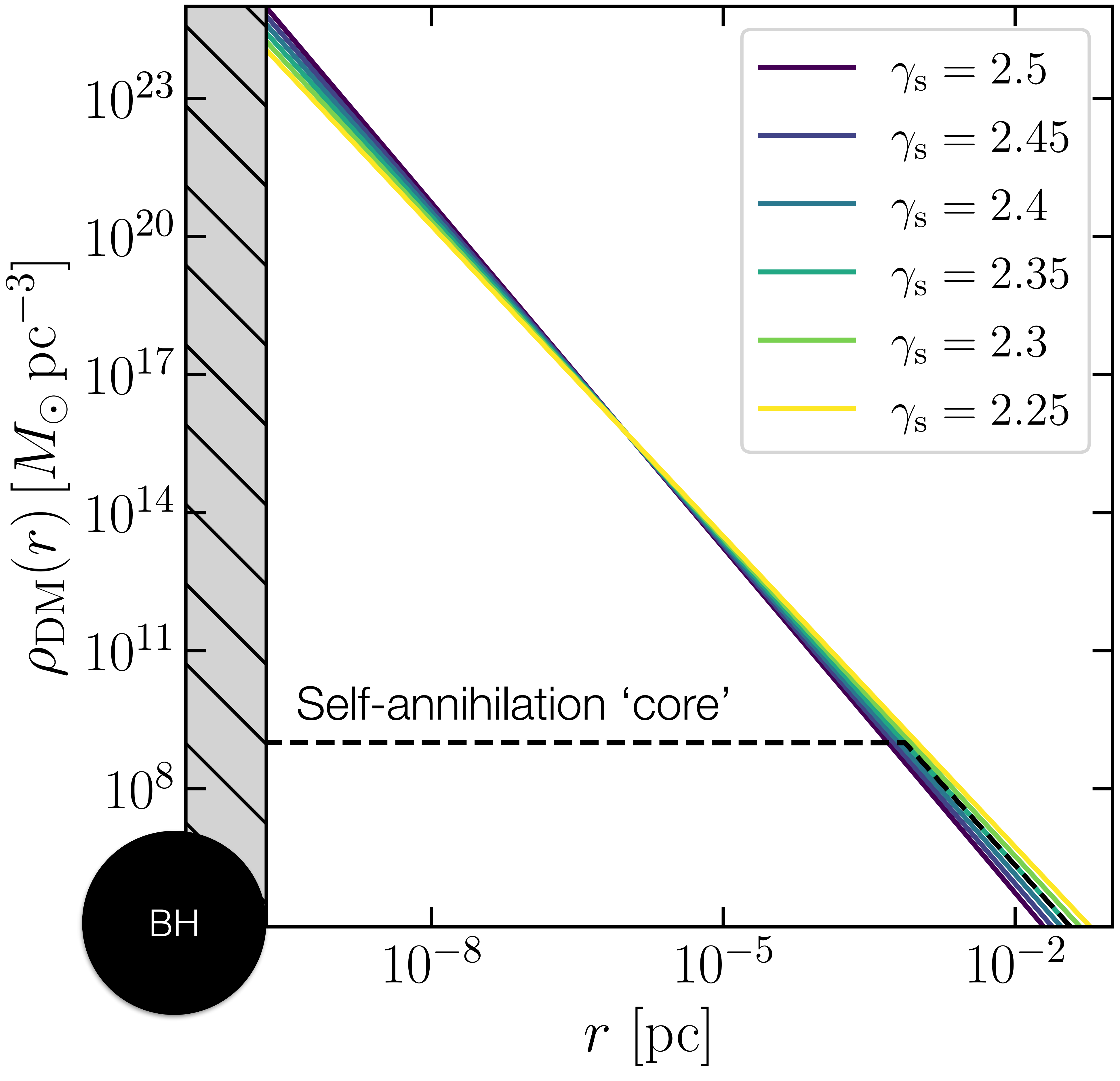
$$\rho_6 \approx 5.35 \times 10^{15}\,M_\odot\,{\rm pc}^{-3}$$

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

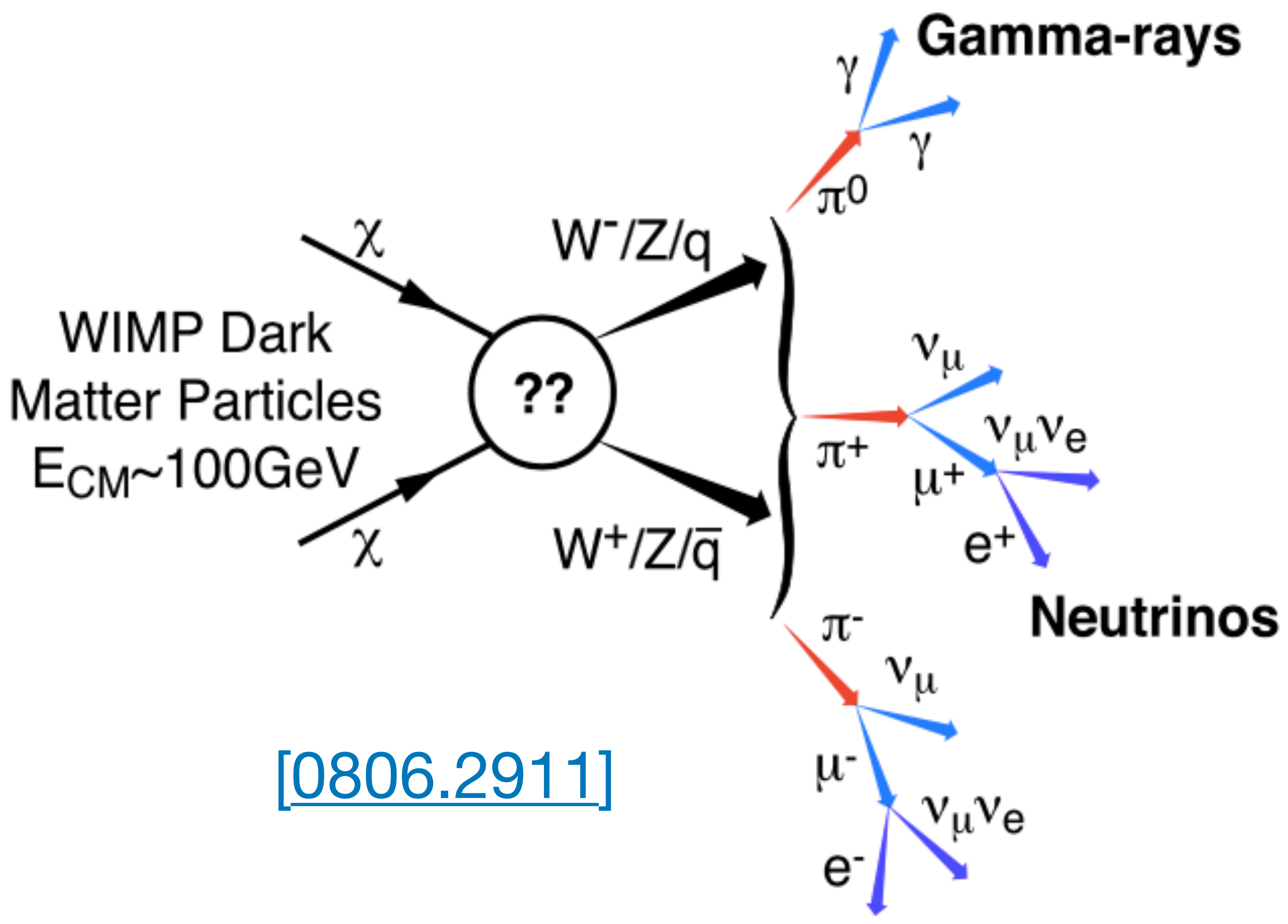
*not to be confused with an ultralight boson cloud

DM annihilation?

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



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



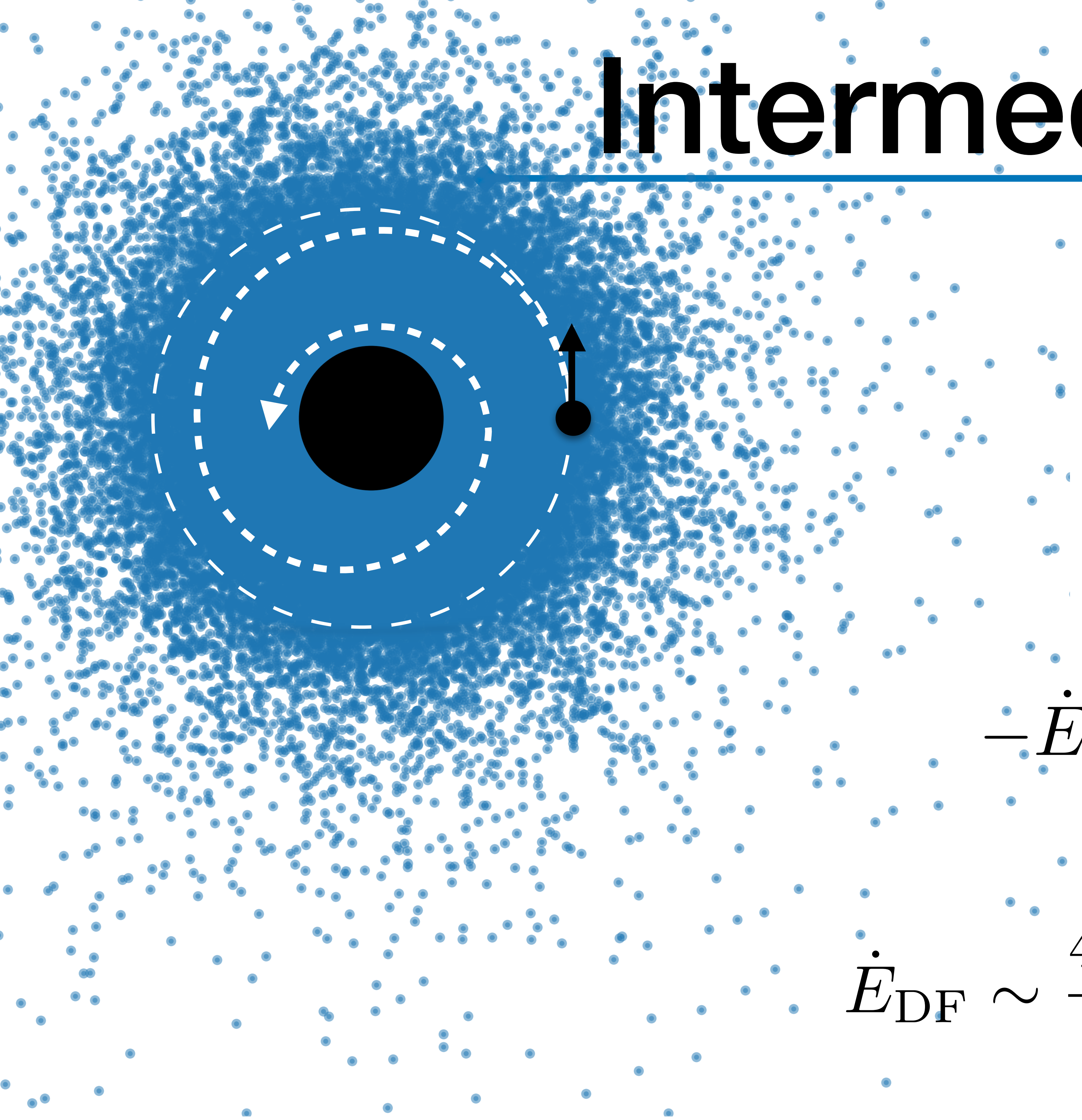
[0806.2911]

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

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

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

Intermediate mass-ratio inspirals

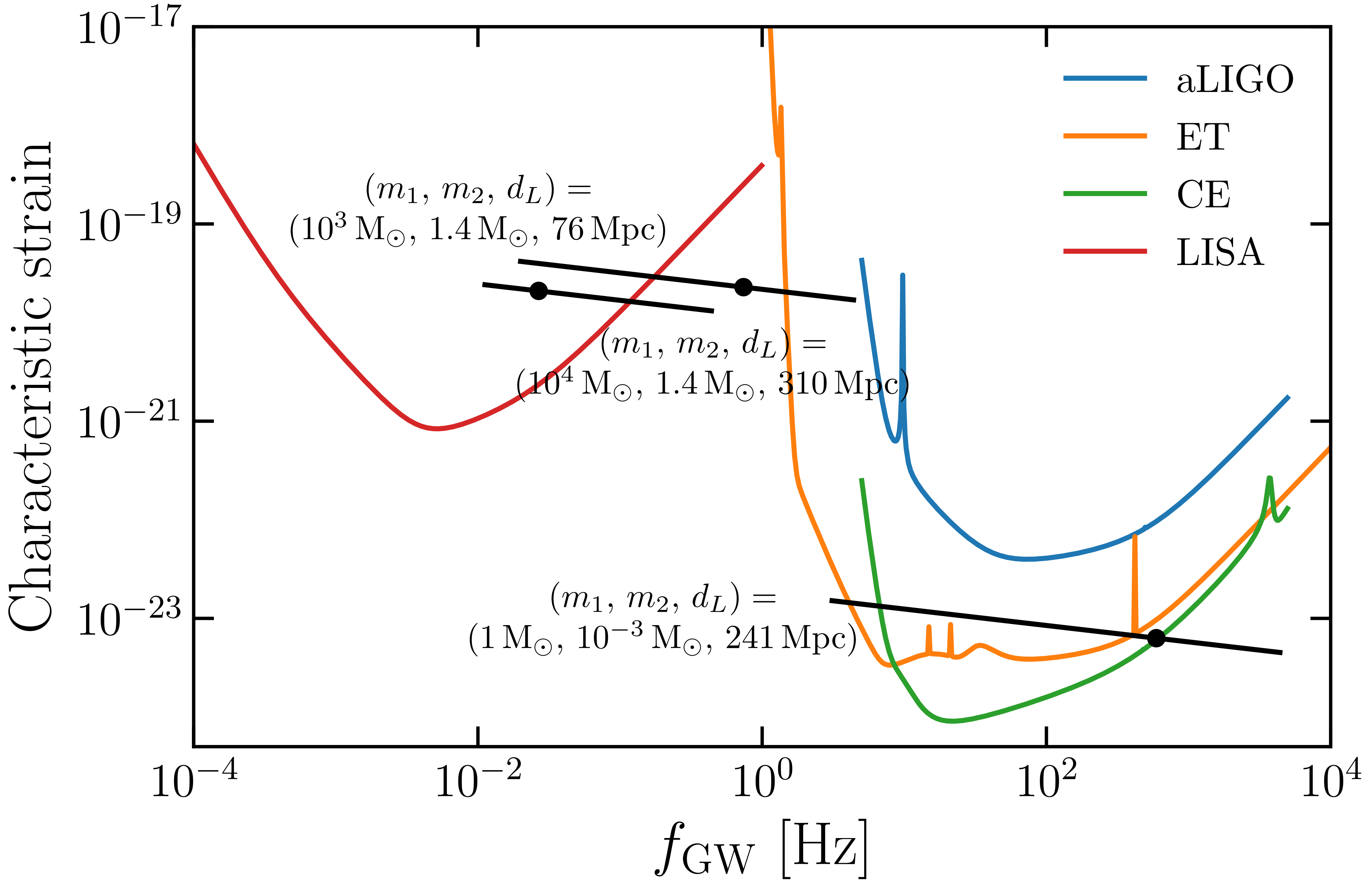


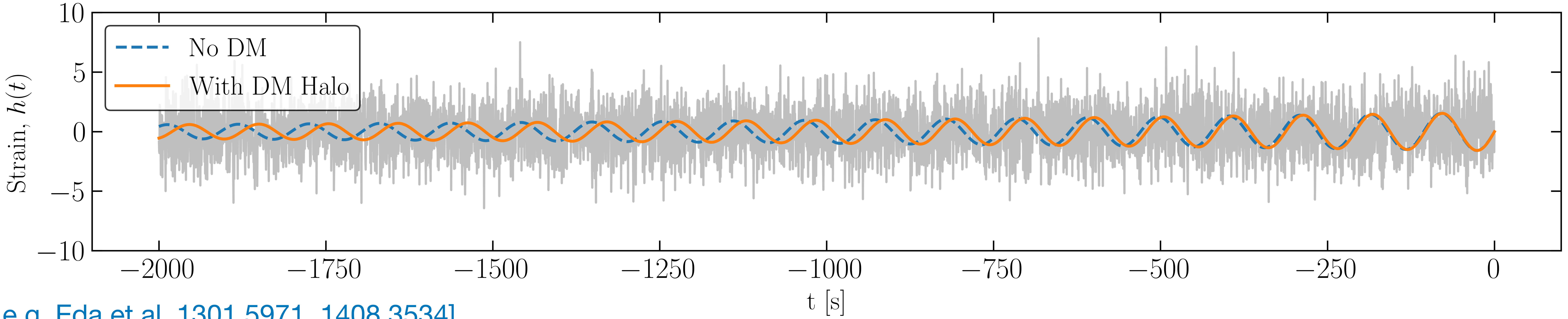
$$m_1 = 10^3\, M_\odot$$
$$m_2 = 1\, M_\odot$$

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

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

[Chandrasekhar, 1943]



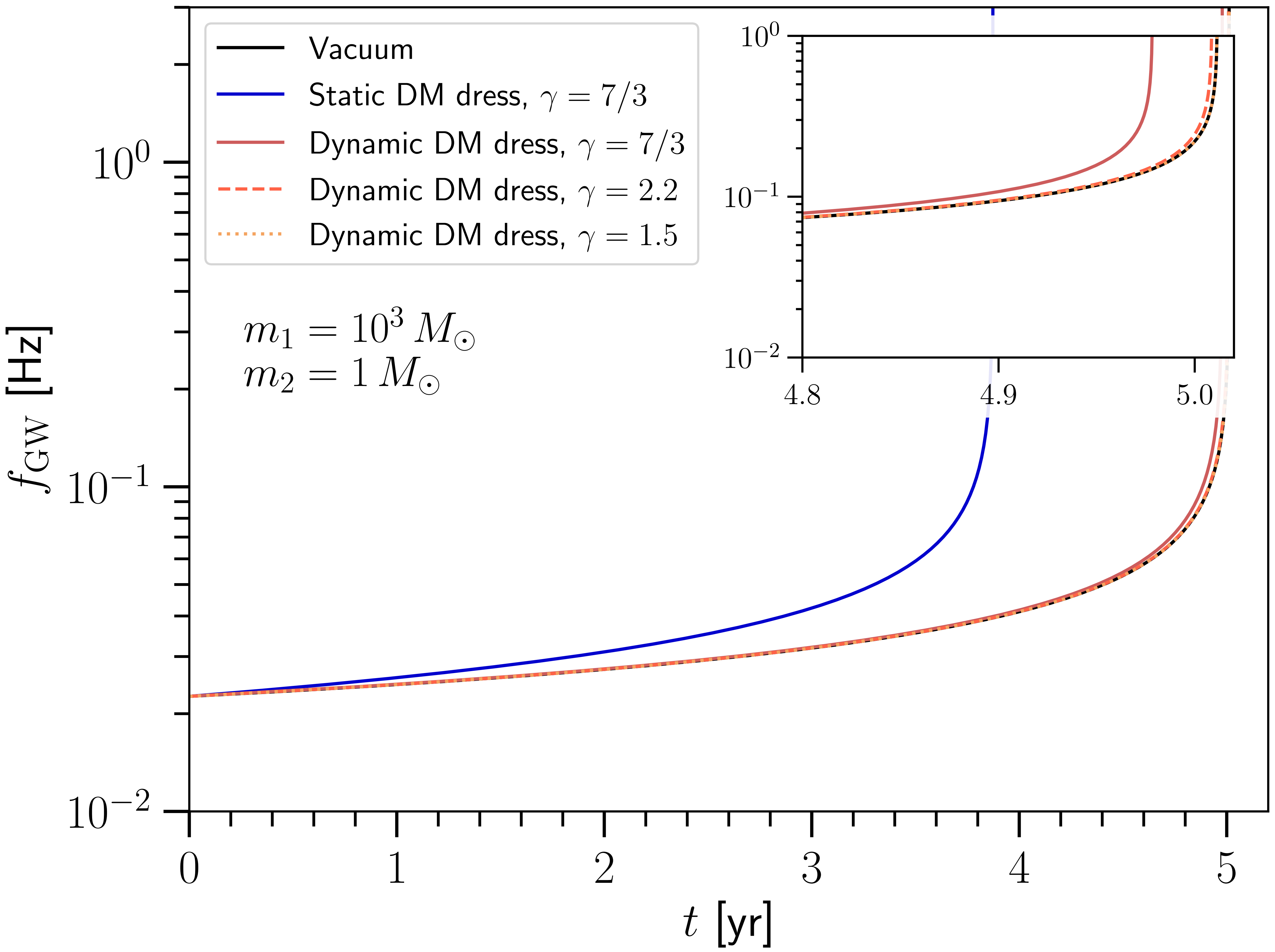


[See e.g. Eda et al. 1301.5971, 1408.3534]

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

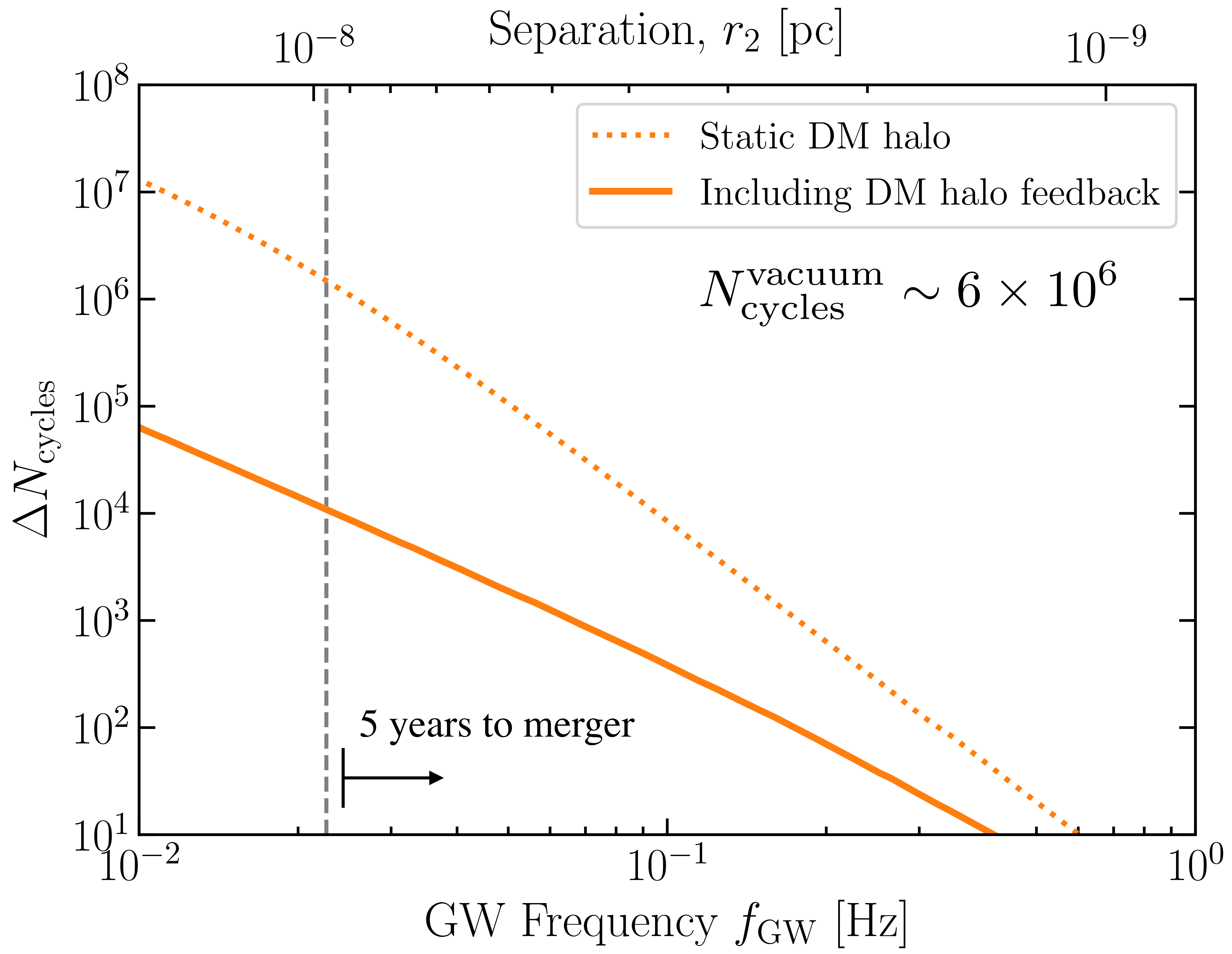
Dephasing

Change in time-frequency evolution of the GW inspiral:



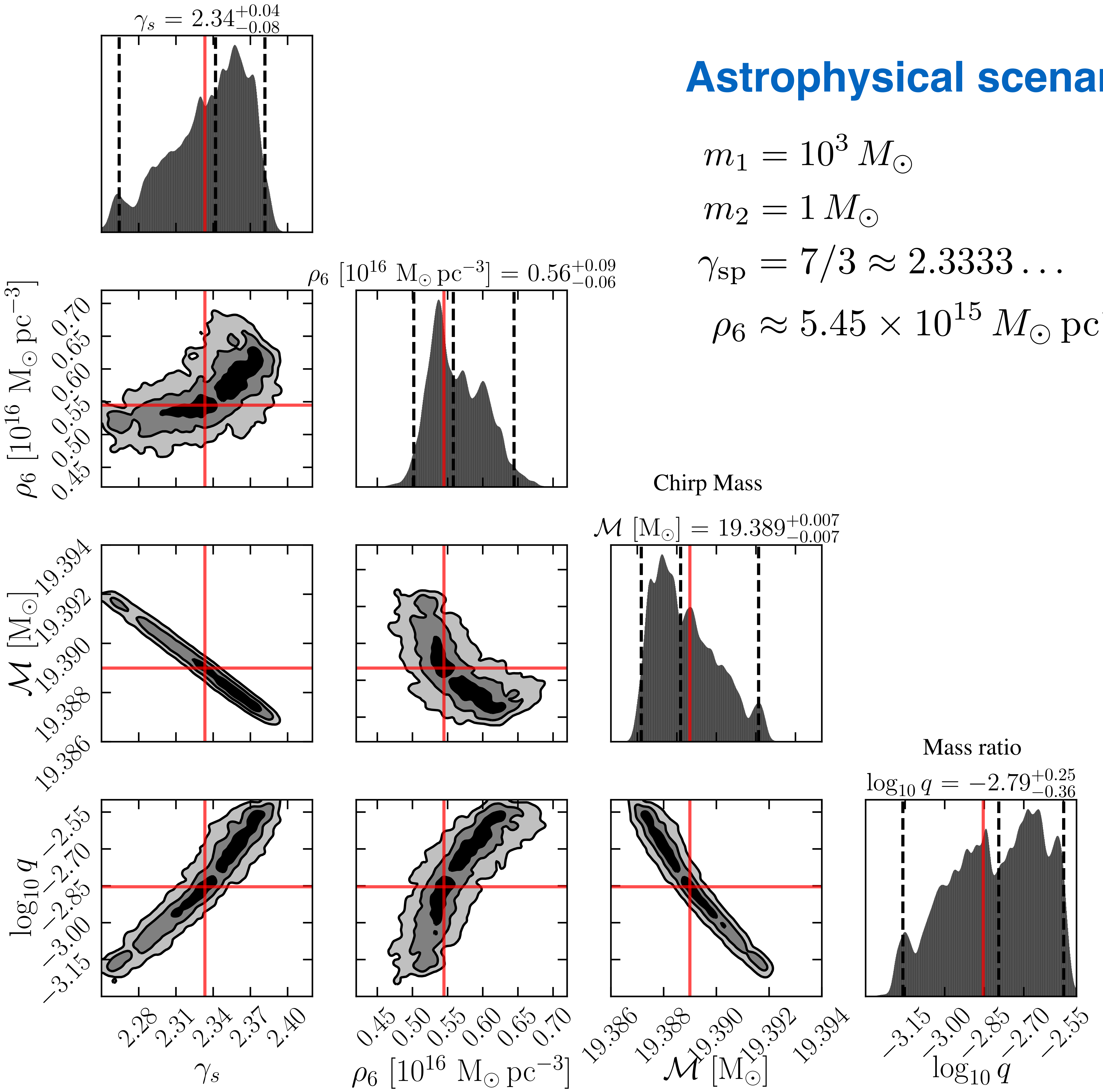
'Dressed' system mergers ~days earlier than 'vacuum' system

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



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

Measurability with LISA



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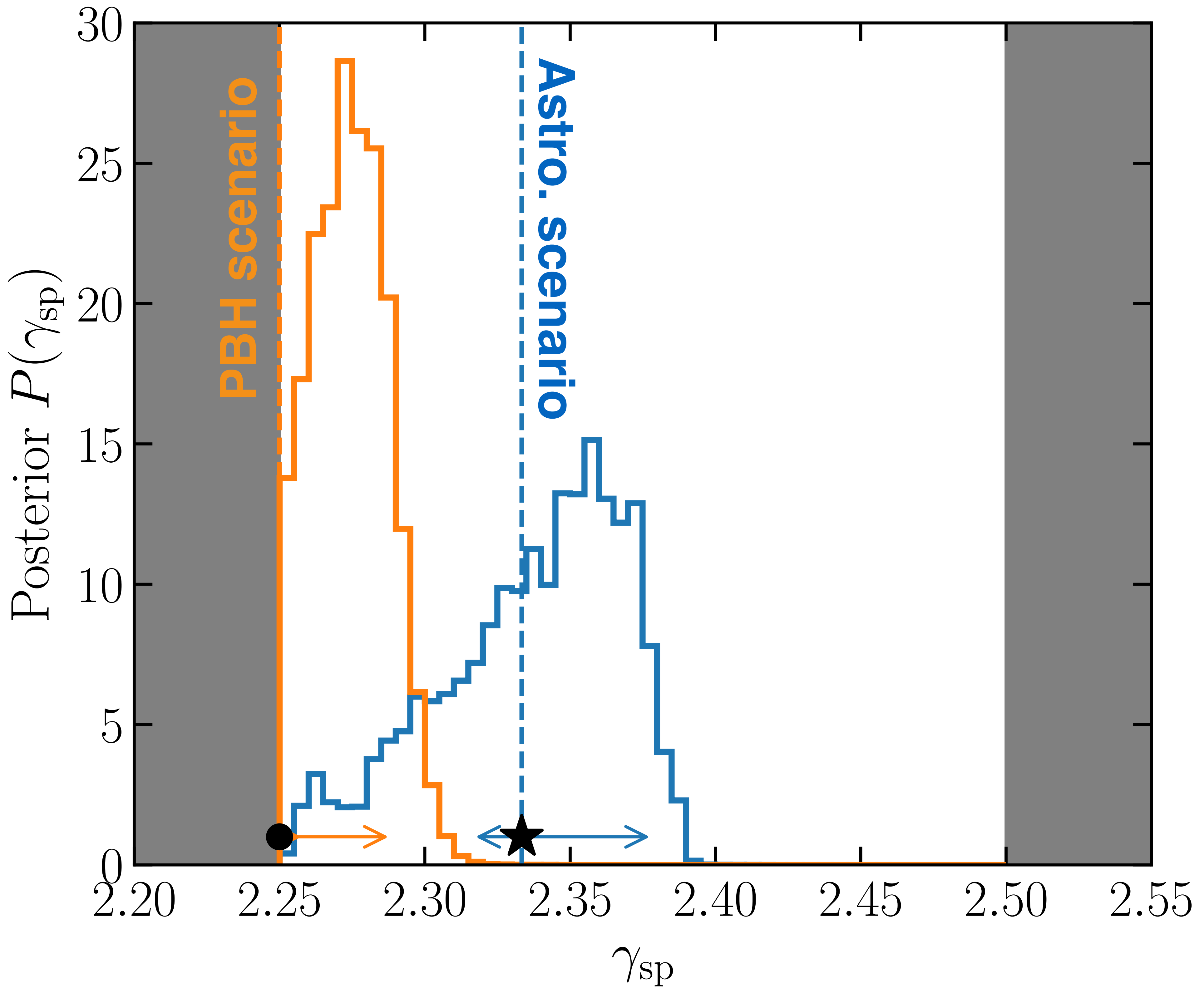
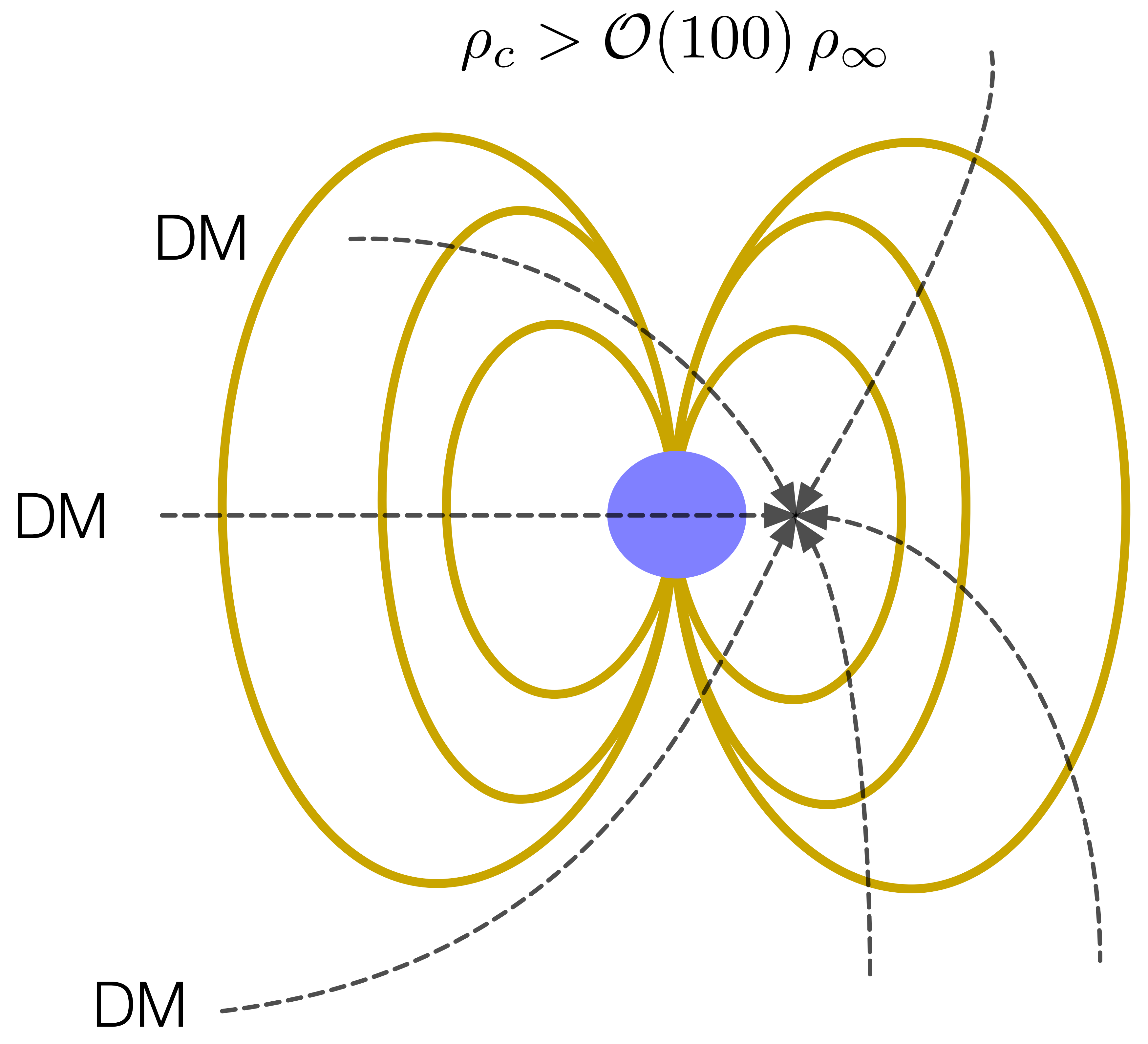


We may be able to distinguish different shapes of spike → Different formation mechanisms and DM models (exclude self-annihilating DM, keV fermions, light boson etc.)!

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

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

Neutron Stars



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

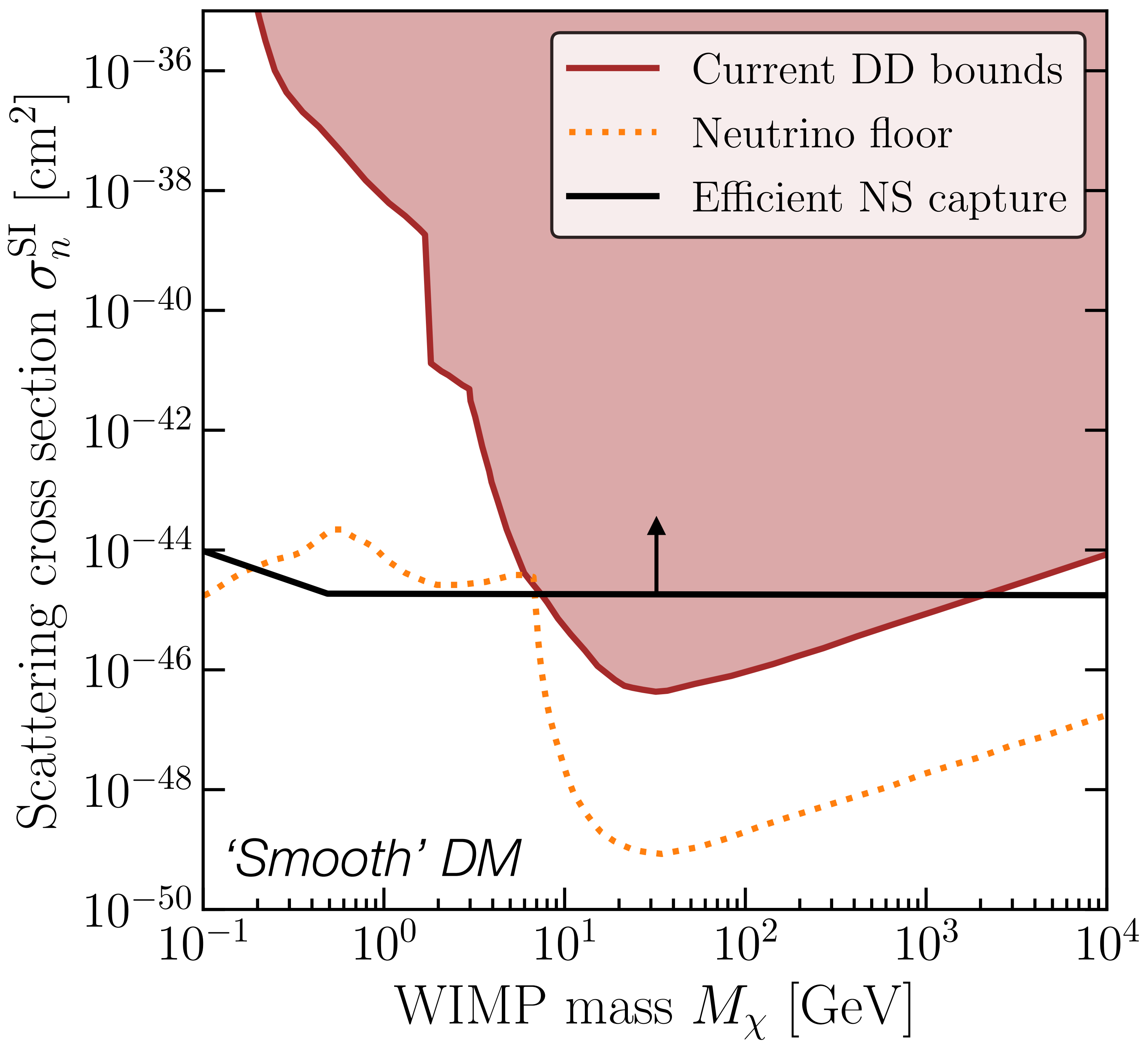
High 'target' densities means high opacity to DM-nucleon scattering:

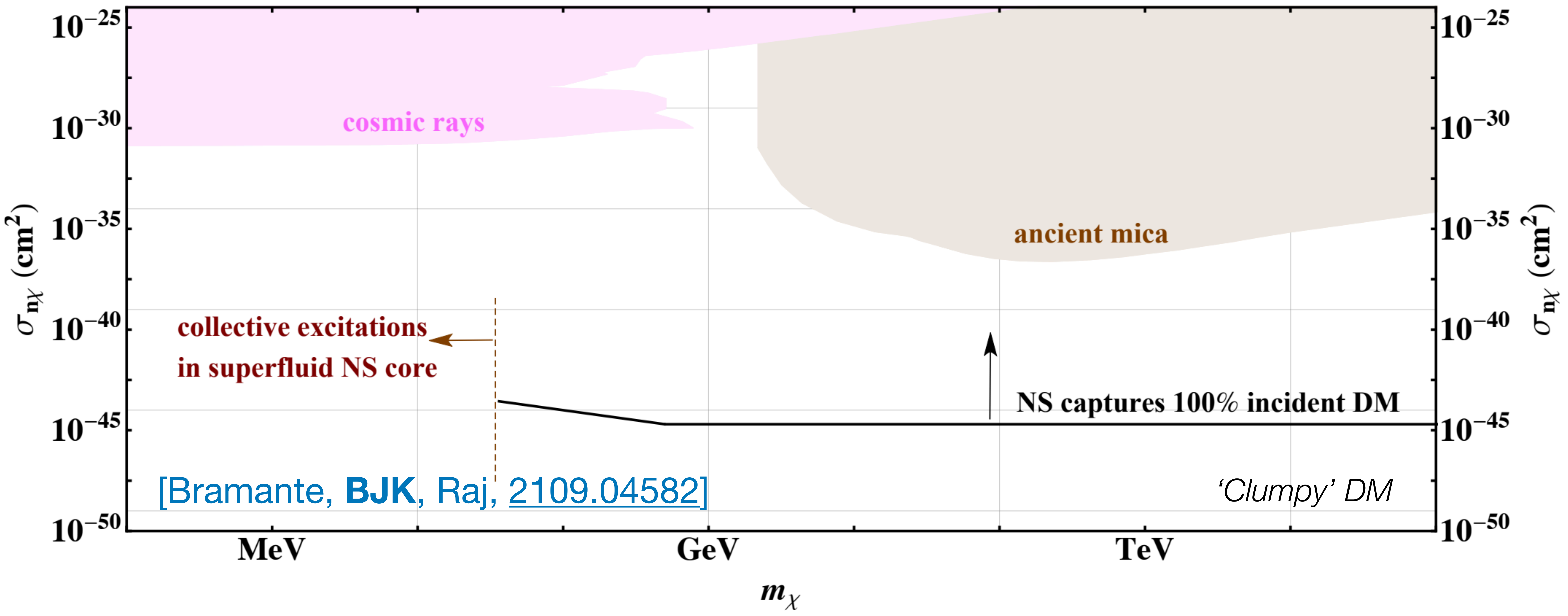
$$\rho > 4.2 \times 10^{11}\ \mathrm{g/cm^3}$$

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

Caveat: still lots to learn about Neutron Star internal properties and populations…

DM Capture in NSs



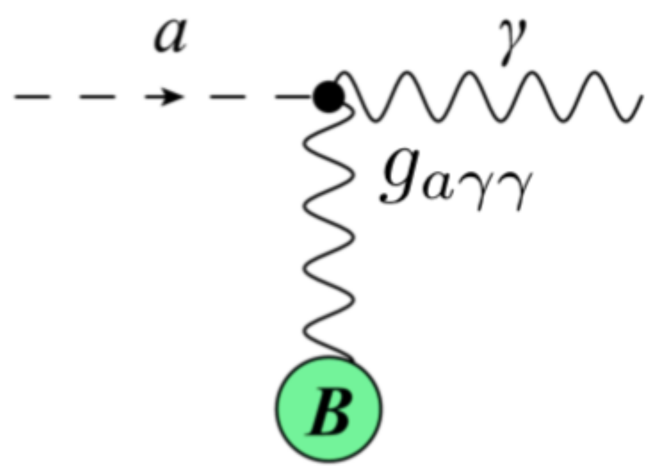


Capture of GeV-scale DM in NSs can lead to distinctive signatures:

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

[See also yesterday's talk by Sergio Palomares-Ruiz]

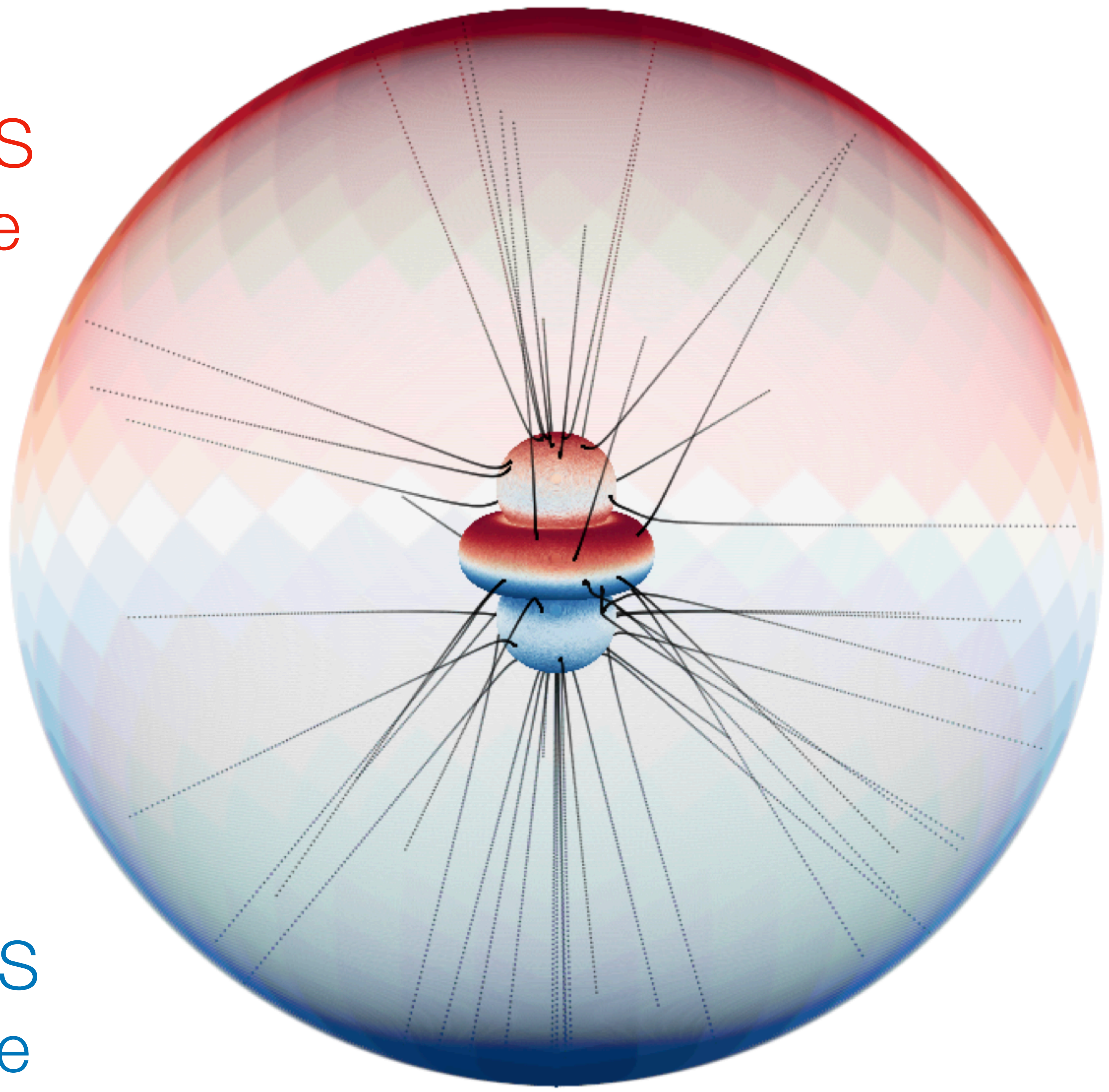
Axion-photon conversion



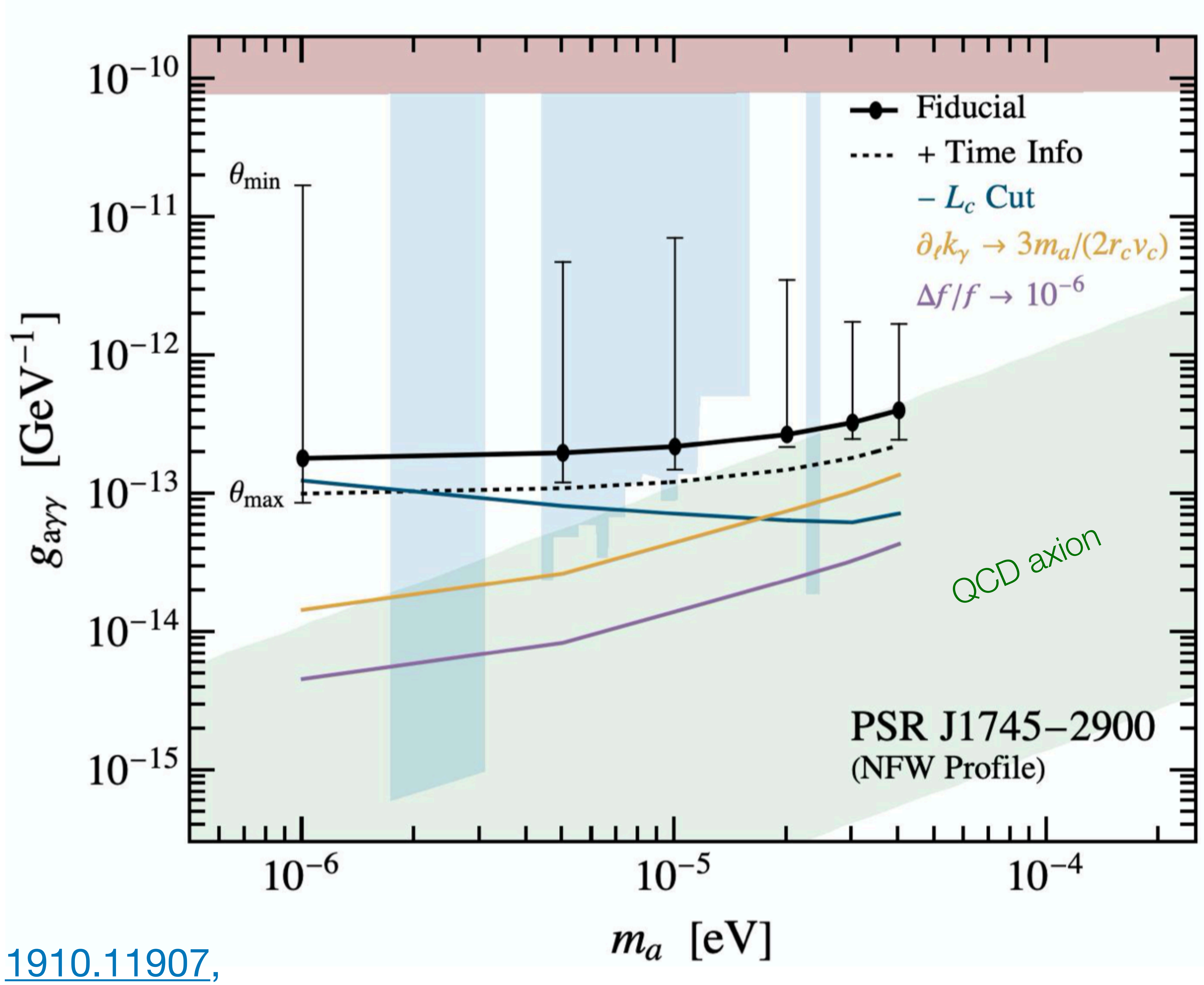
NS surrounded by a dense plasma which allows 'resonant' conversion, when axion mass matches plasma mass: $\omega_p(B_0, P) = m_a/2\pi$

[1803.08230, 1804.03145, 1811.01020, 1910.11907]

Northern NS hemisphere

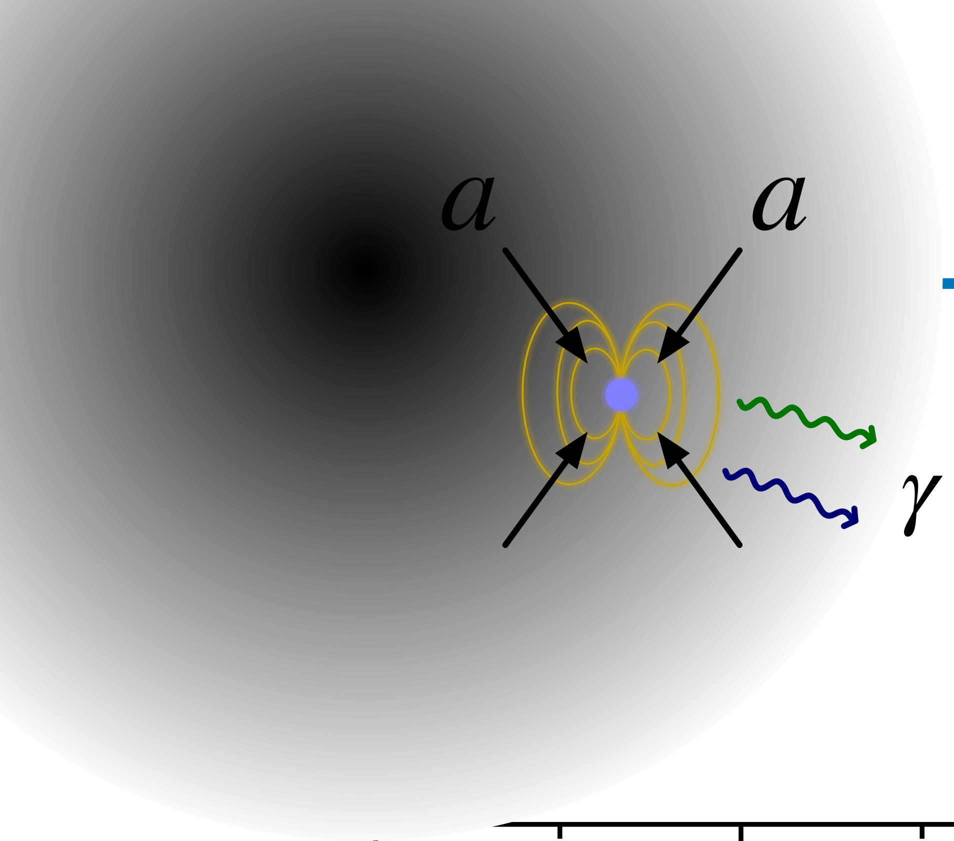


Southern NS hemisphere



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

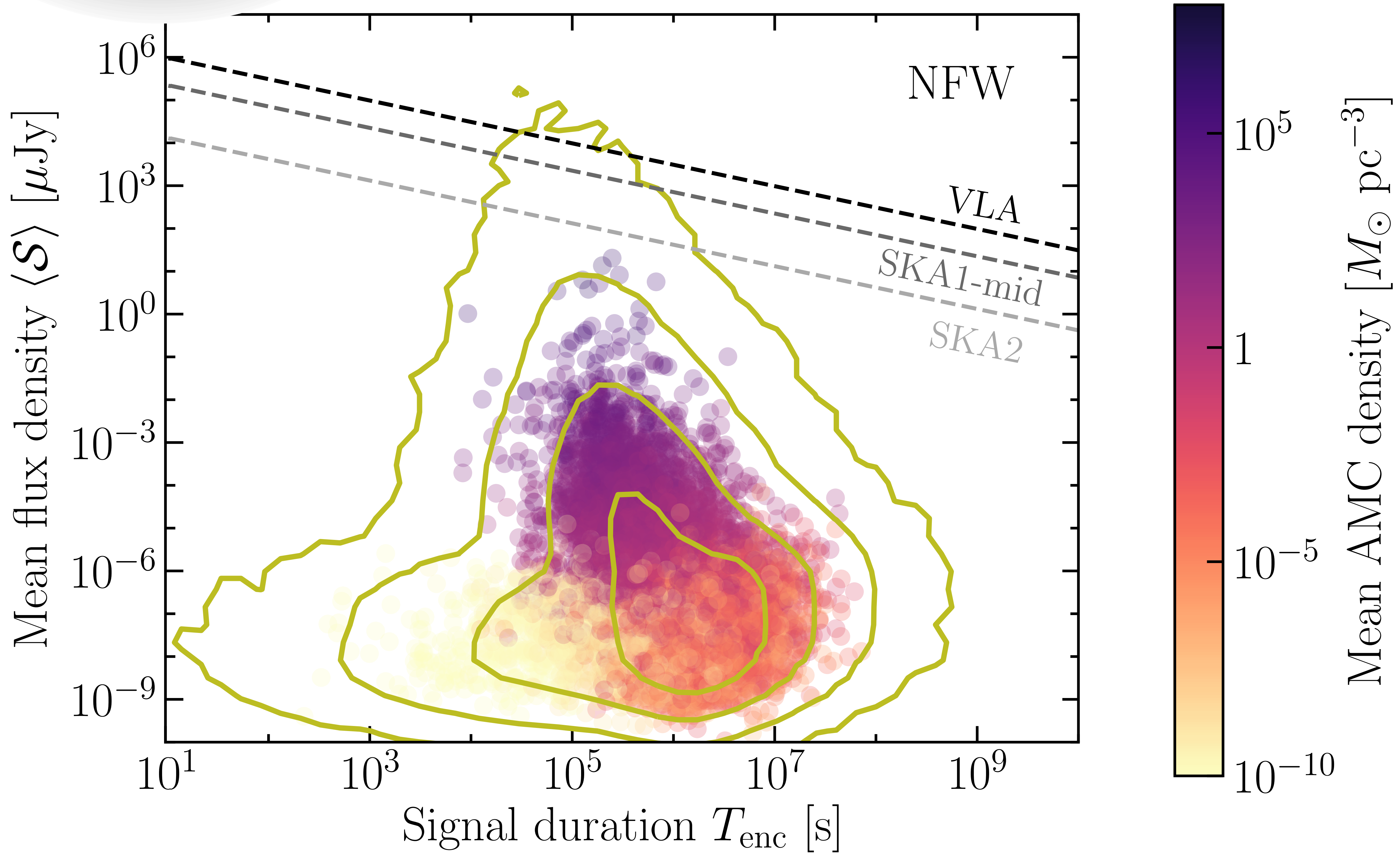
[Witte et al., 2104.07670]

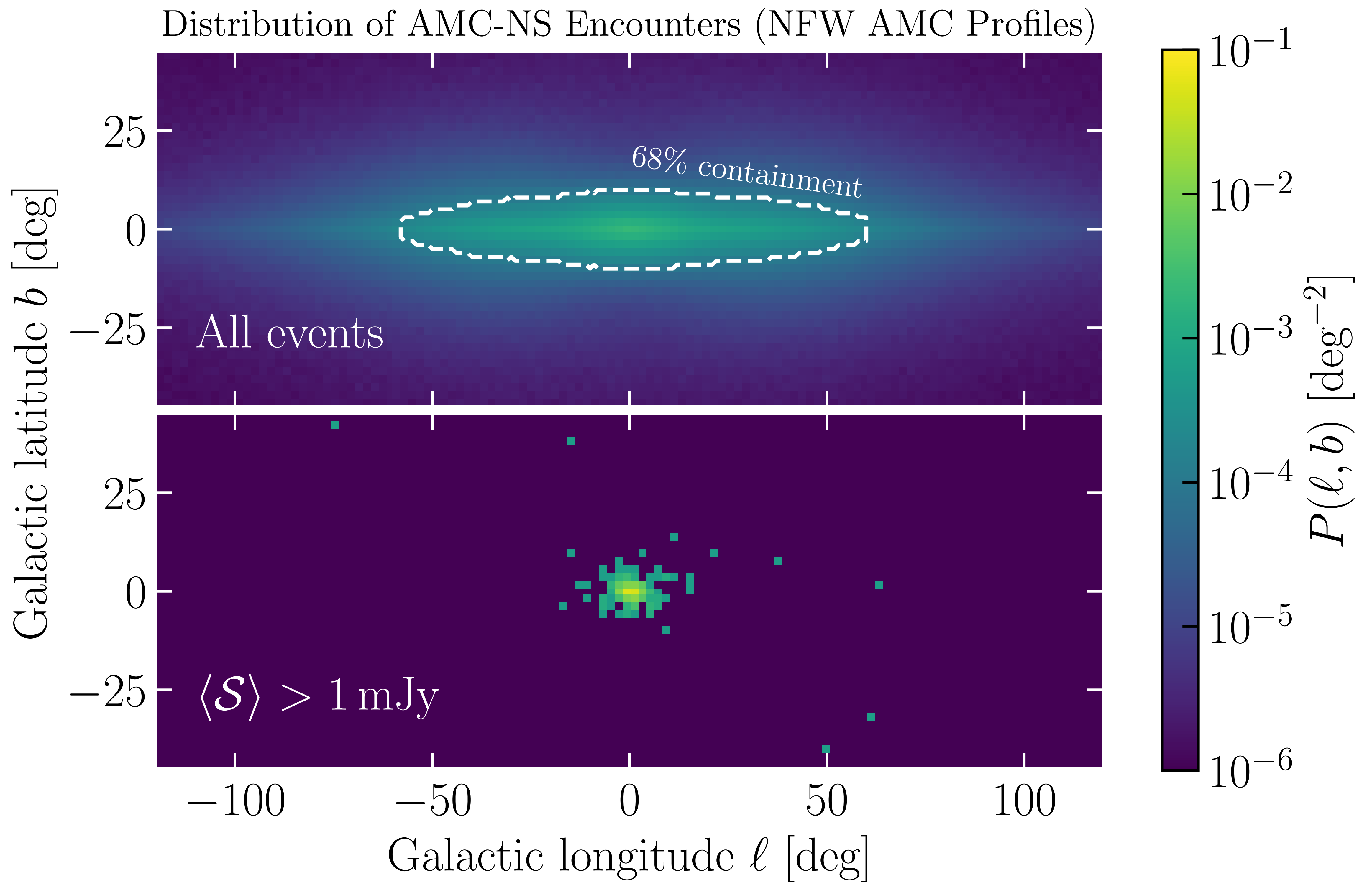


Axion Miniclusters (AMCs)

[Hogan & Rees (1988)]

Clumps of axion DM ('miniclusters') crossing NSs could lead to bright radio transients towards the GC:



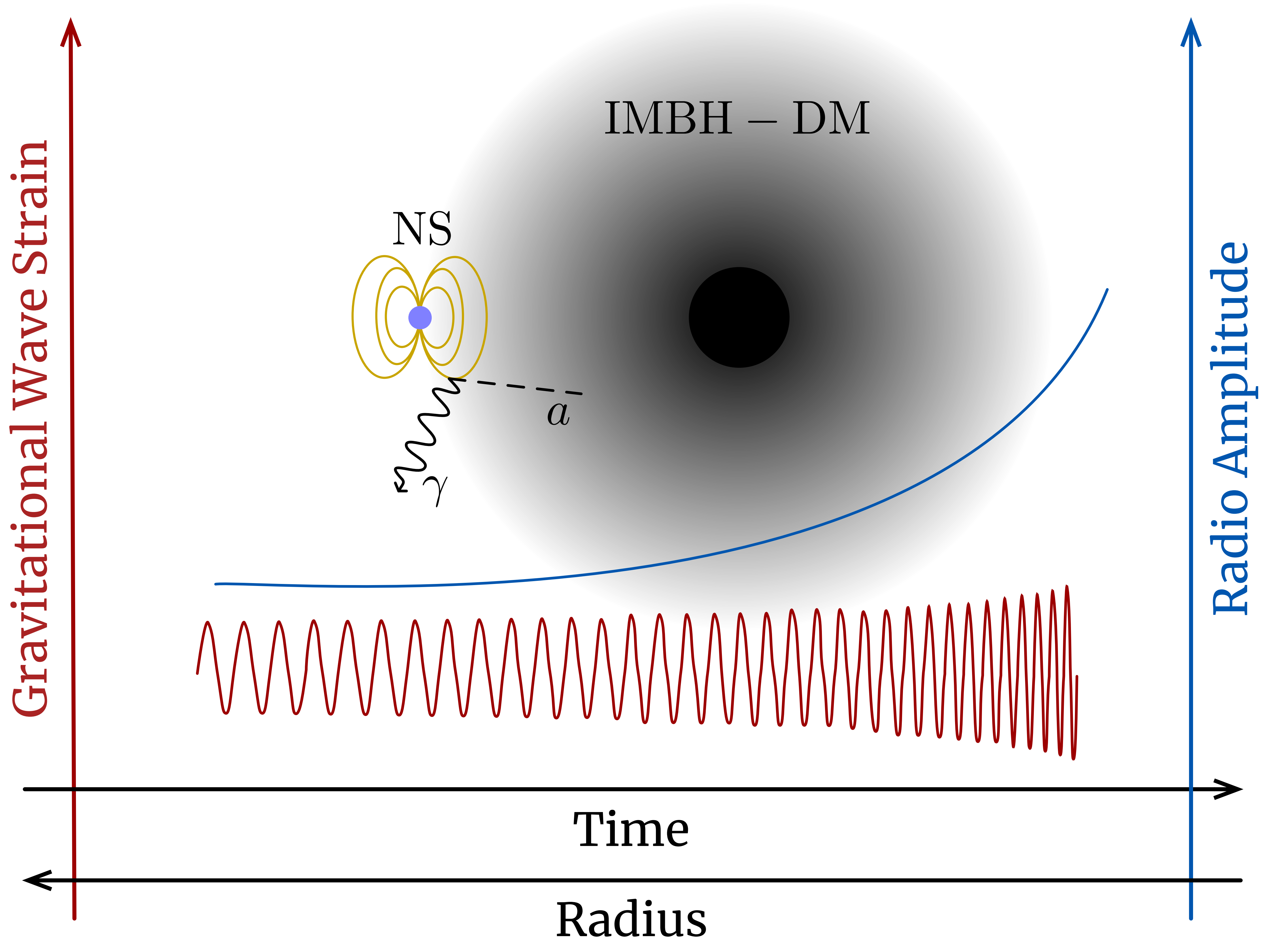


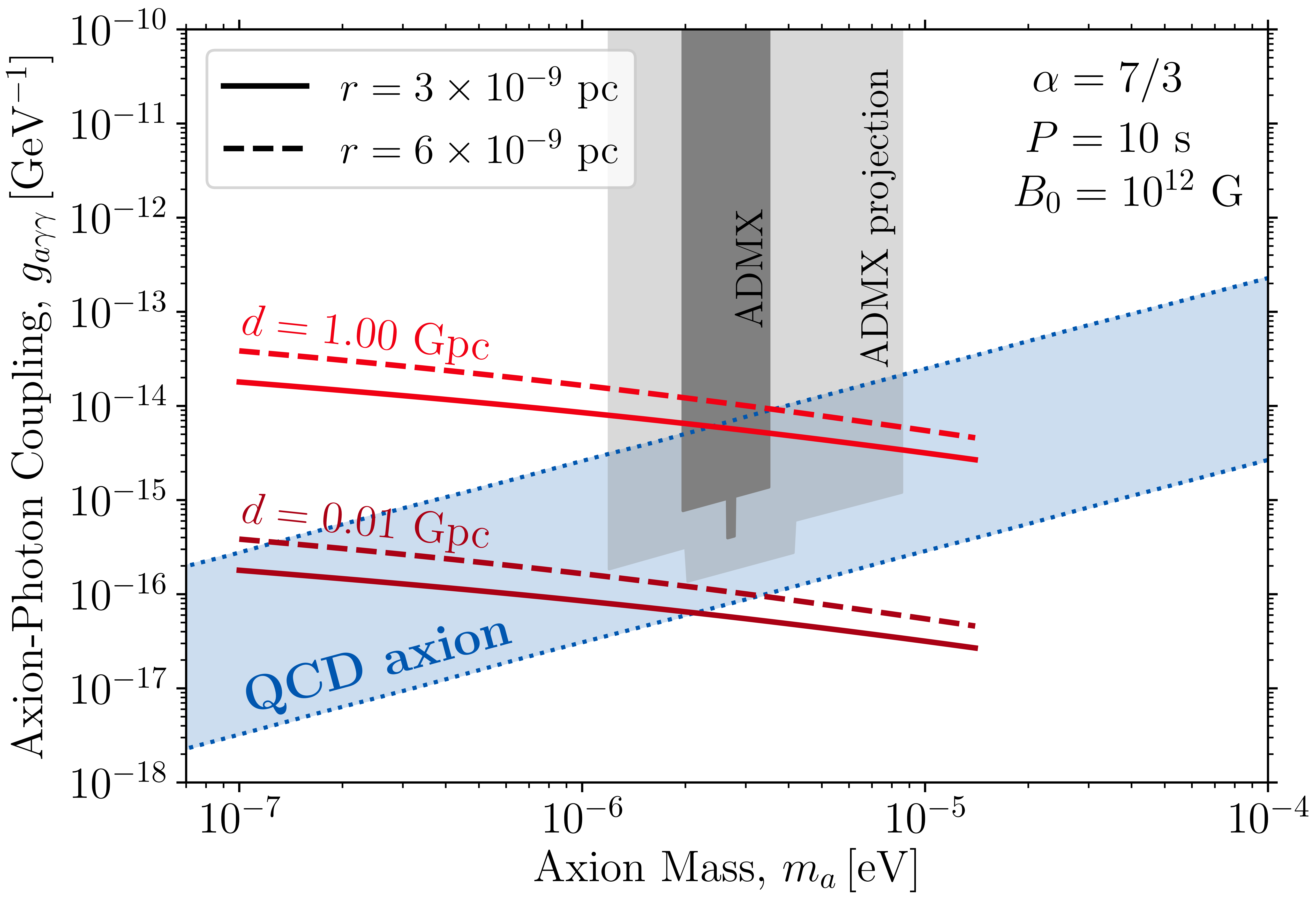
Search currently underway for radio transients in Andromeda using the Green Bank Telescope (GBT)

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

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

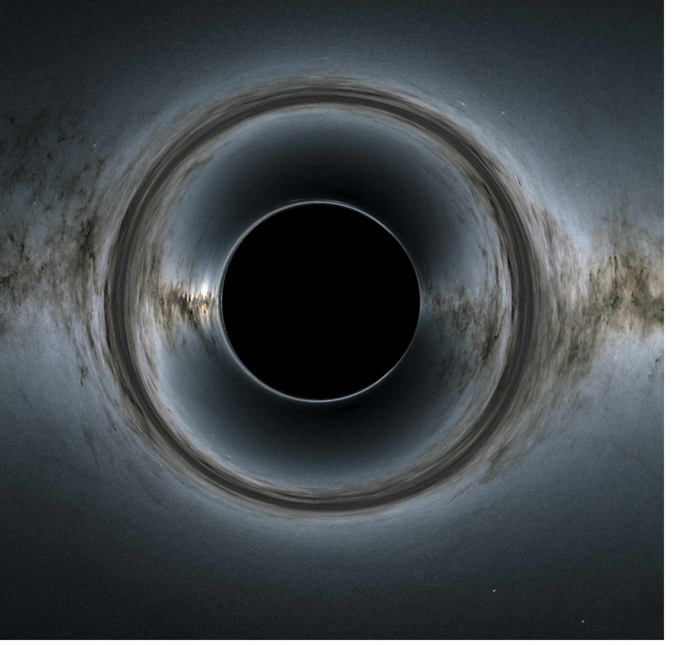
Multi-messenger Axions



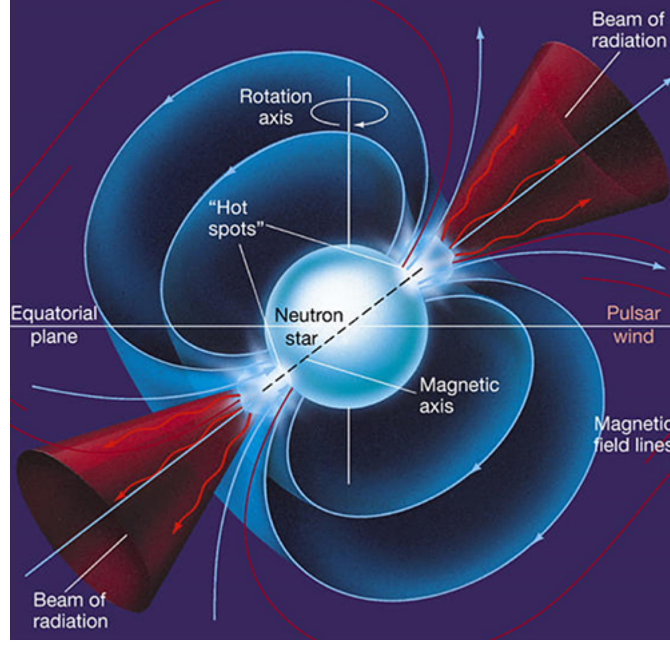


Future radio observations should be able to probe QCD axion DM in the range $10^{-7} - 10^{-5}$ eV, while LISA would constrain the DM density close to the IMBH!

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



DM in Extreme Environments



Black Holes

GW dephasing from cold DM spikes*

Still to do:

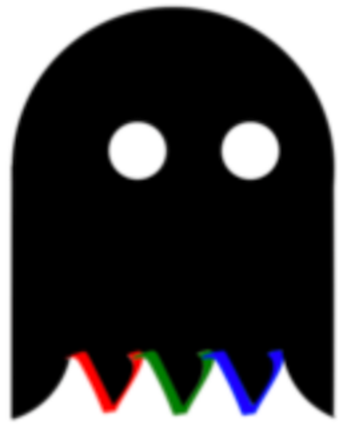
- Understanding population of DM spikes in the Universe (formation? survival?)
- Extending formalism to eccentric orbits, post-Newtonian corrections, etc.
- Exploring possible signals in (Hz-kHz frequency) ground based detectors (e.g. from solar and sub-solar PBH binaries)
- Realistic search strategies!

Neutron Stars

WIMP capture or Axion conversion

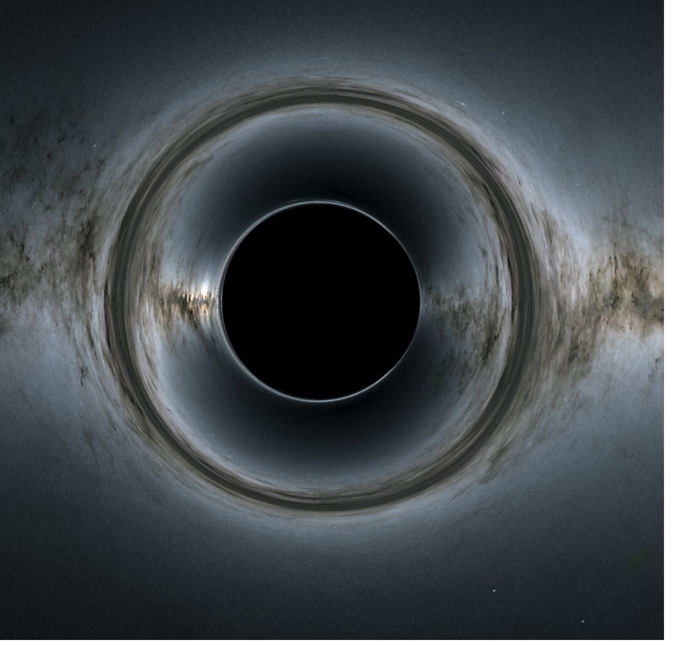
Still to do:

- Neutron Star population modeling in the Milky Way (and other galaxies)
- Careful modeling of axion-photon conversion in realistic NS magnetospheres
- Understanding axion minicluster formation, evolution and disruption in the Early Universe and today.



Black Holes and Neutron Stars provide extreme (and extremely promising) environments for testing Dark Matter with GW and EM observations. But there's plenty of modelling to do before we can explore their full potential!

*and possible annihilation signatures



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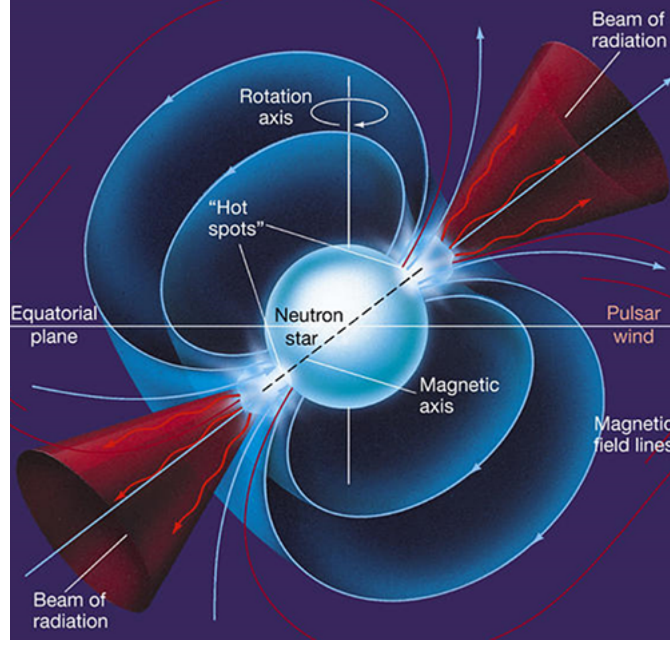

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Black Holes and Neutron Stars provide extreme (and extremely promising) environments for testing Dark Matter with GW and EM observations. But there's plenty of modelling to do before we can explore their full potential!

Thank you!

*and possible annihilation signatures

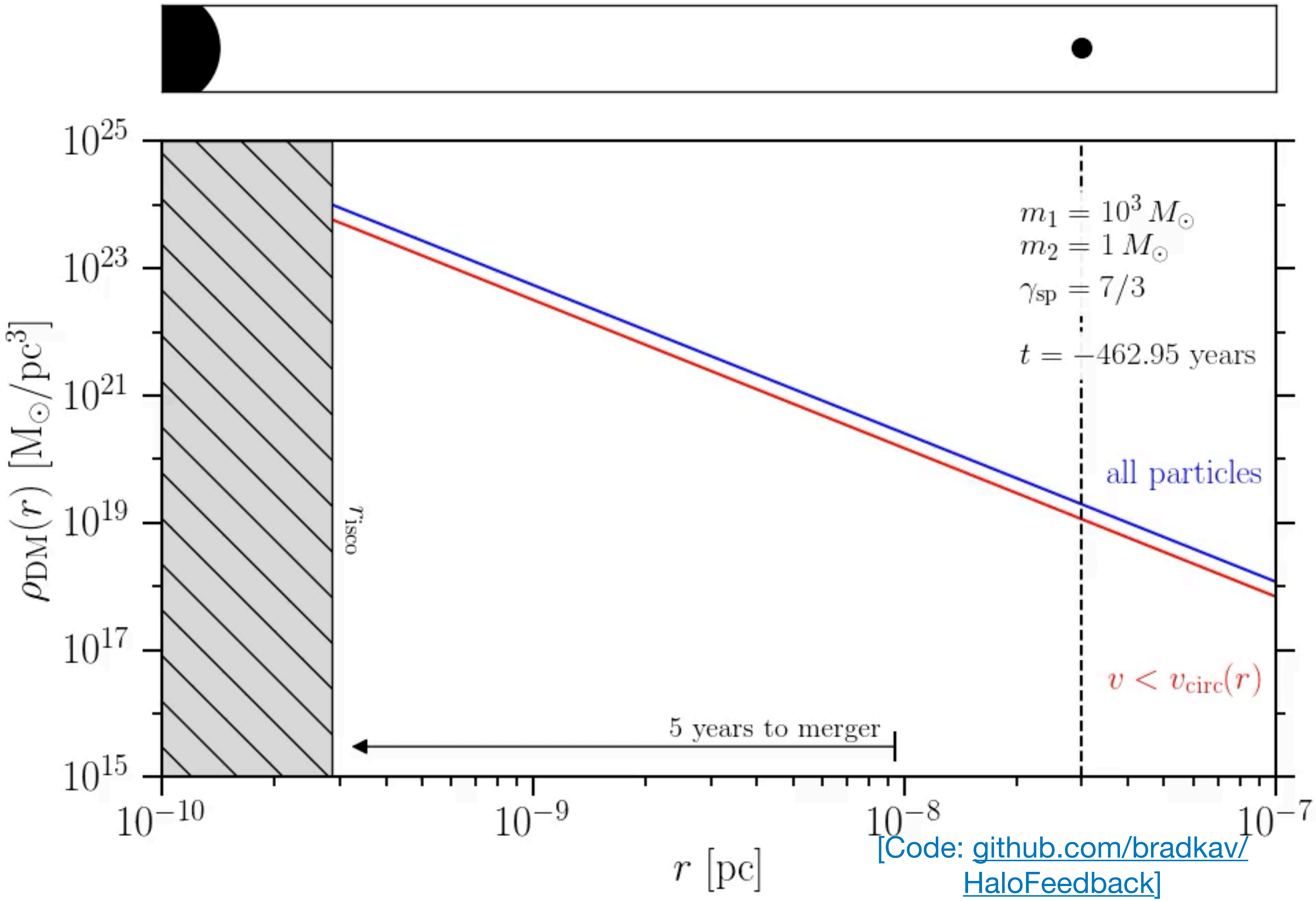
Backup Slides

Co-evolution

[BJK, Nichols, Gaggero, Bertone, 2002.12811]
[Movies: tinyurl.com/GW4DM]

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…

[Code: github.com/bradkav/HaloFeedback]

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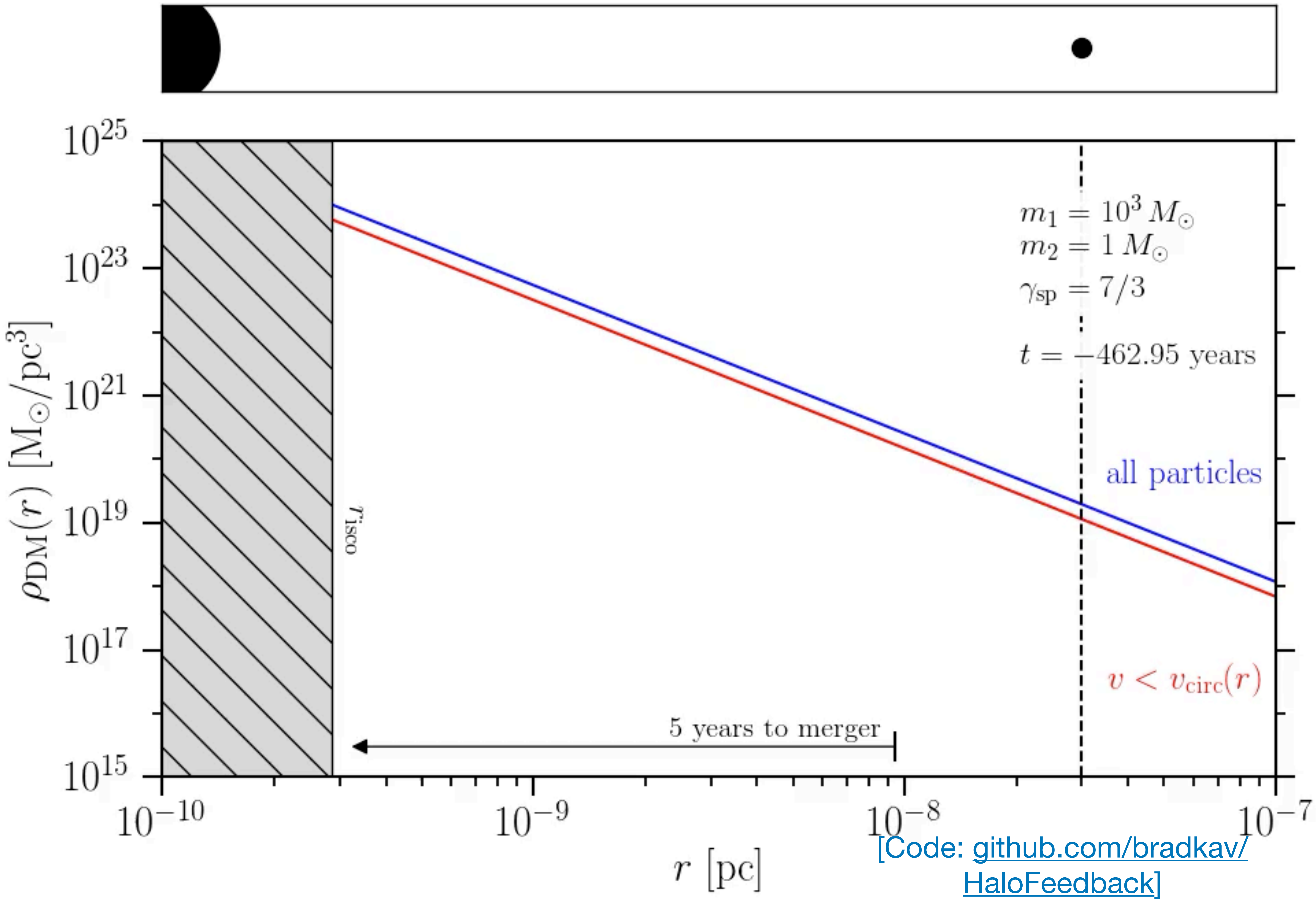

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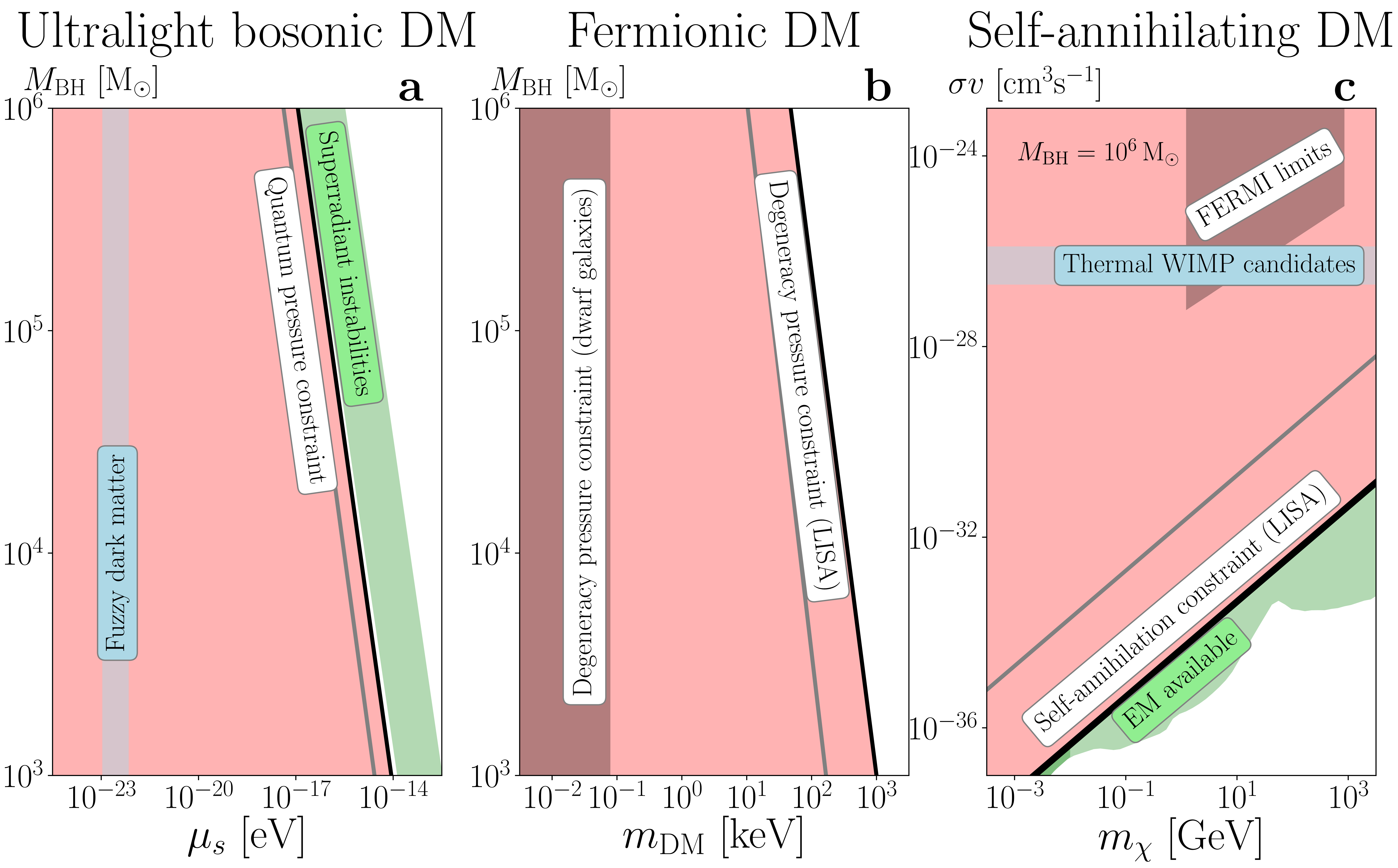
[Code: github.com/bradkav/HaloFeedback]

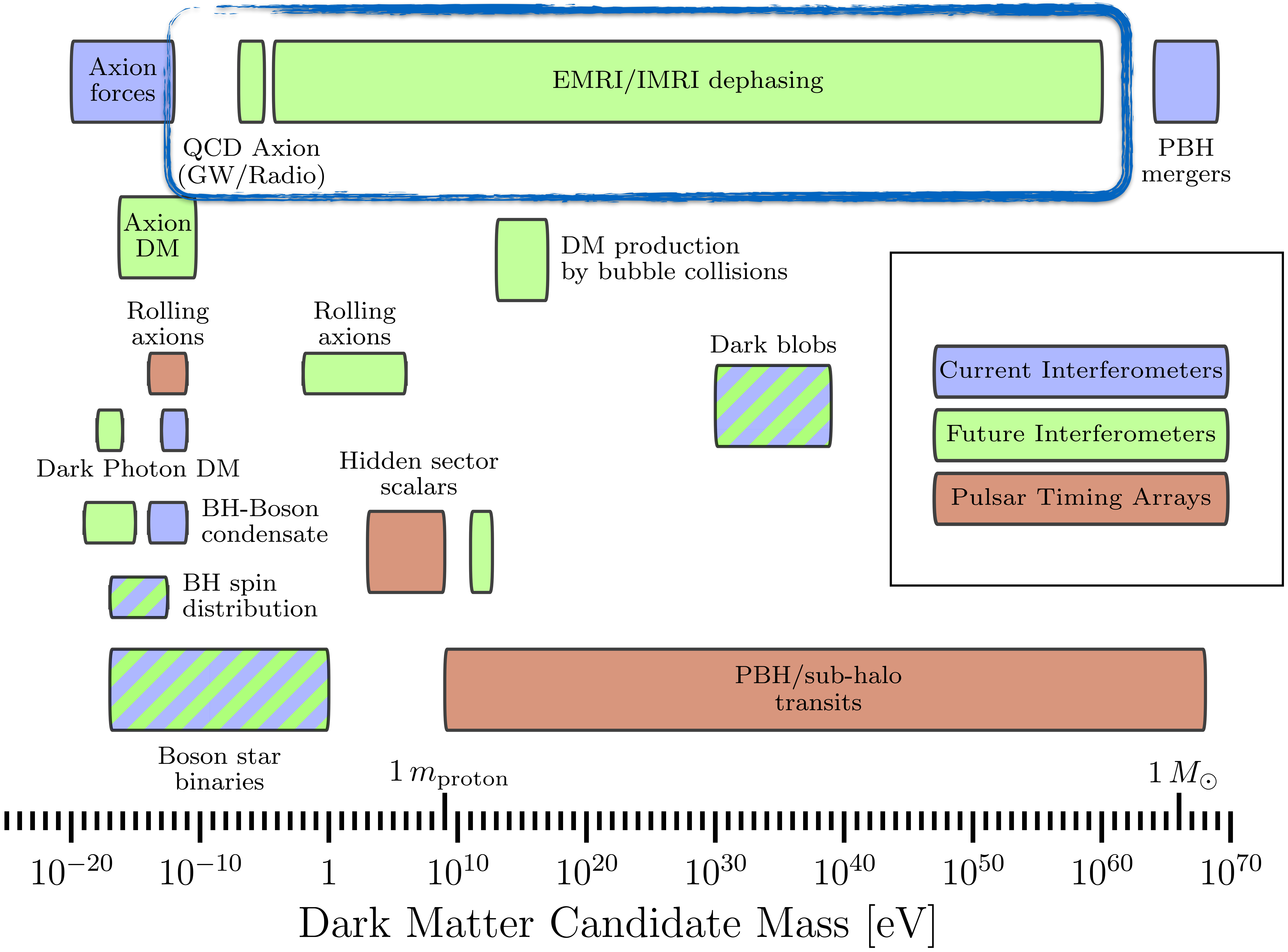
Nature of Dark Matter

Red regions would be ruled out by observation of a DM spike! [1906.11845]



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

GW Probes of DM



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

DM 'dephasing' of GWs is sensitive over a huge range of DM masses and particle physics interaction.

But formation and properties of the spike *are* sensitive to DM properties.

Detection of a spike would exclude ultra-light bosons, sub-keV fermions, self-annihilating DM, compact object DM (all of which do not form spikes)!

[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238; Hannuksela et al., 1906.11845]

Gravitational Atoms

Compton wavelength of a light scalar field:

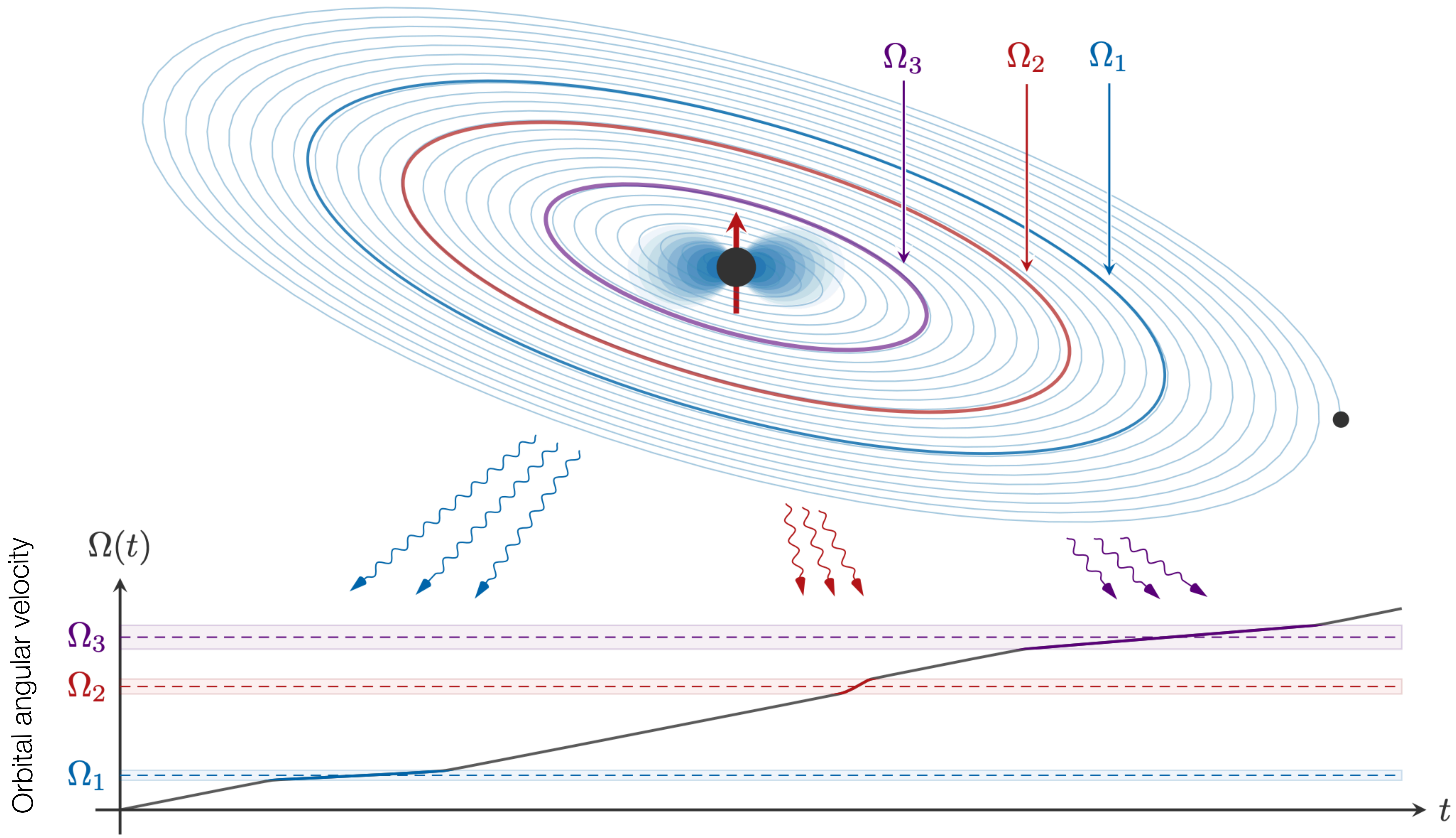
$$\lambda_c \simeq 2\,\mathrm{km}\left(\frac{10^{-10}\,\mathrm{eV}}{\mu}\right)$$

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]



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

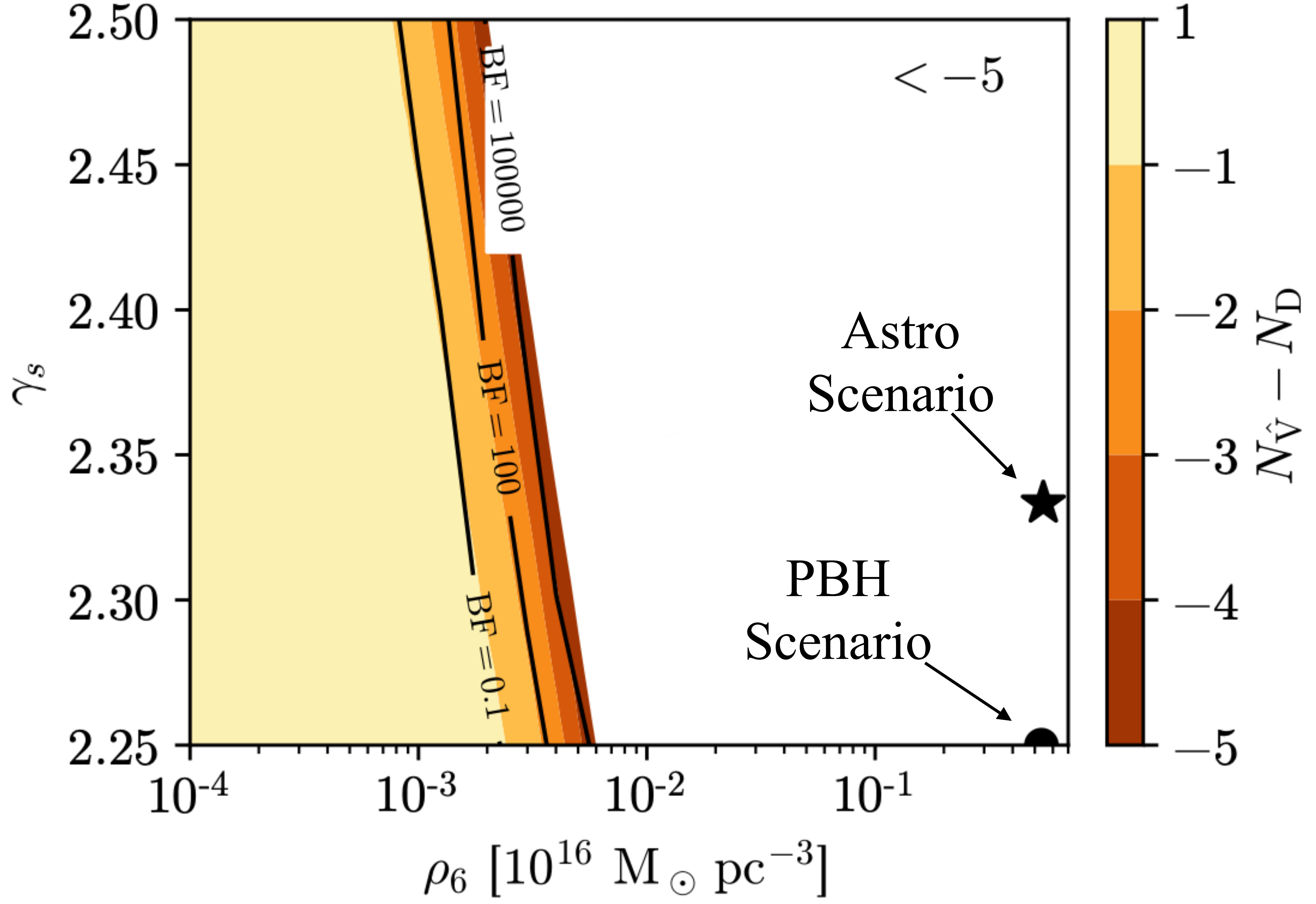
DM Spike Discoverability

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

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

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

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



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

Likelihood

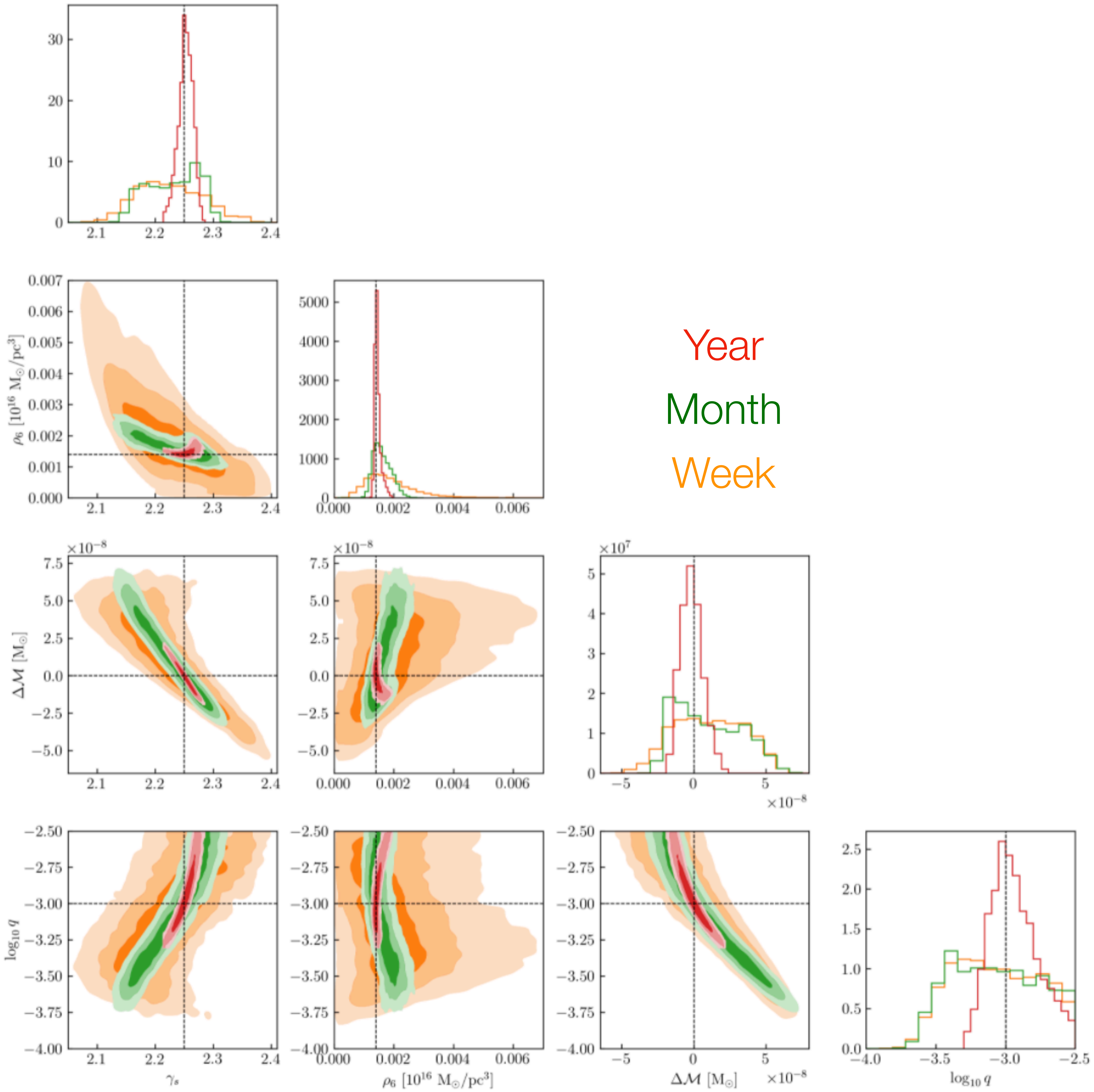
Prior

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

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

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

PBH binaries with Einstein Telescope



$$m_1 = 1\, M_\odot$$

$$m_2 = 10^{-3}\, M_\odot$$

PRELIMINARY

Axion miniclusters

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

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

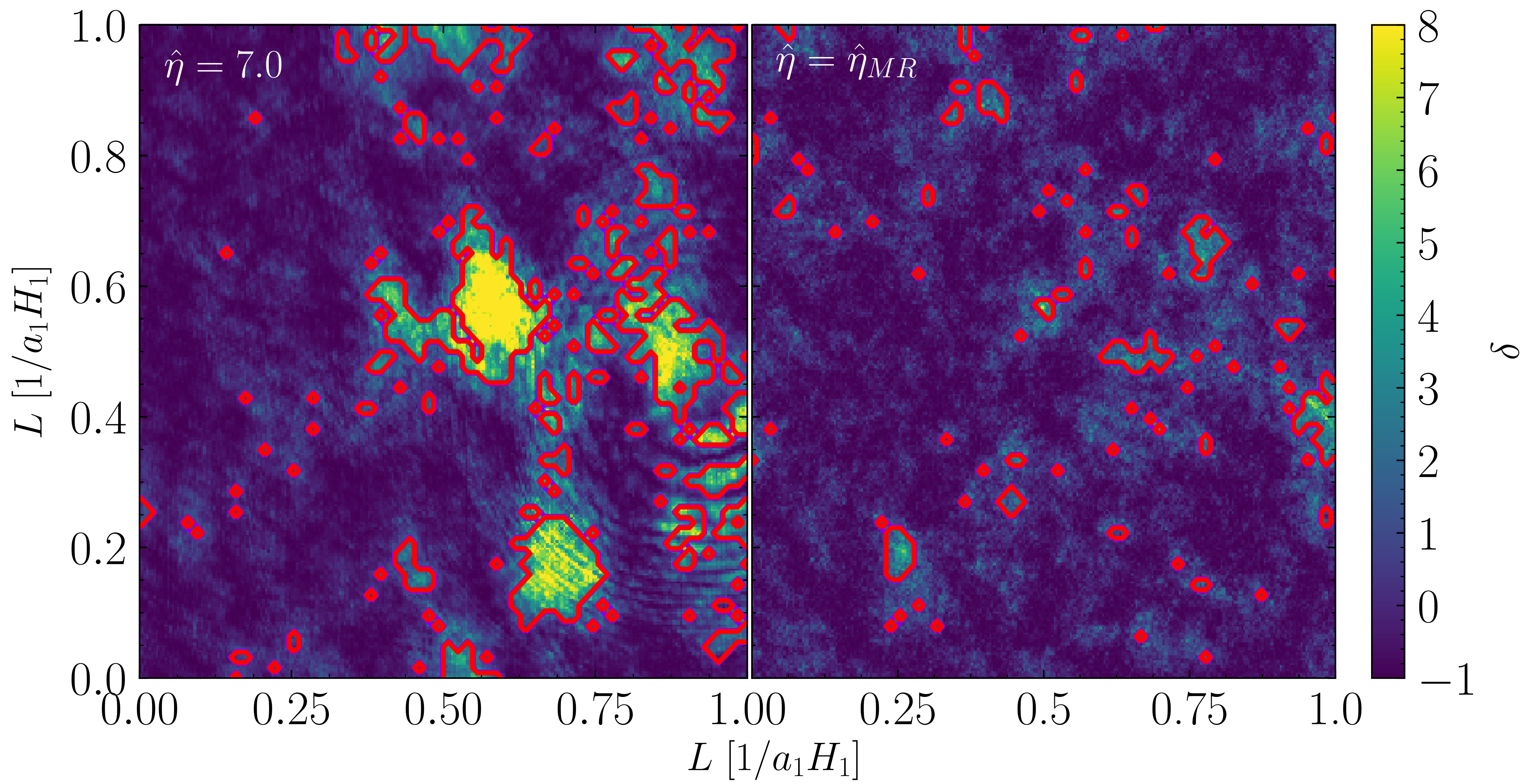
$$\rho_{\mathrm{AMC}}(\delta) = 140(1+\delta)\delta^3 \rho_{\mathrm{eq}}$$

[Kolb & Tkachev, astro-ph/9403011]

Not to be confused with Axion Stars

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

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



[Buschmann et al., 1906.00967]