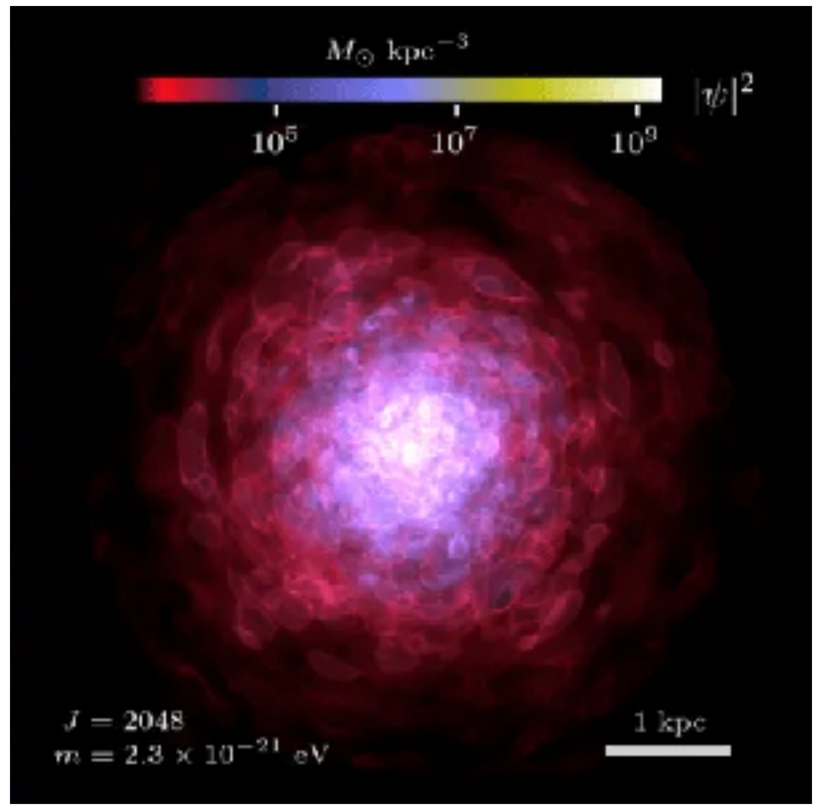
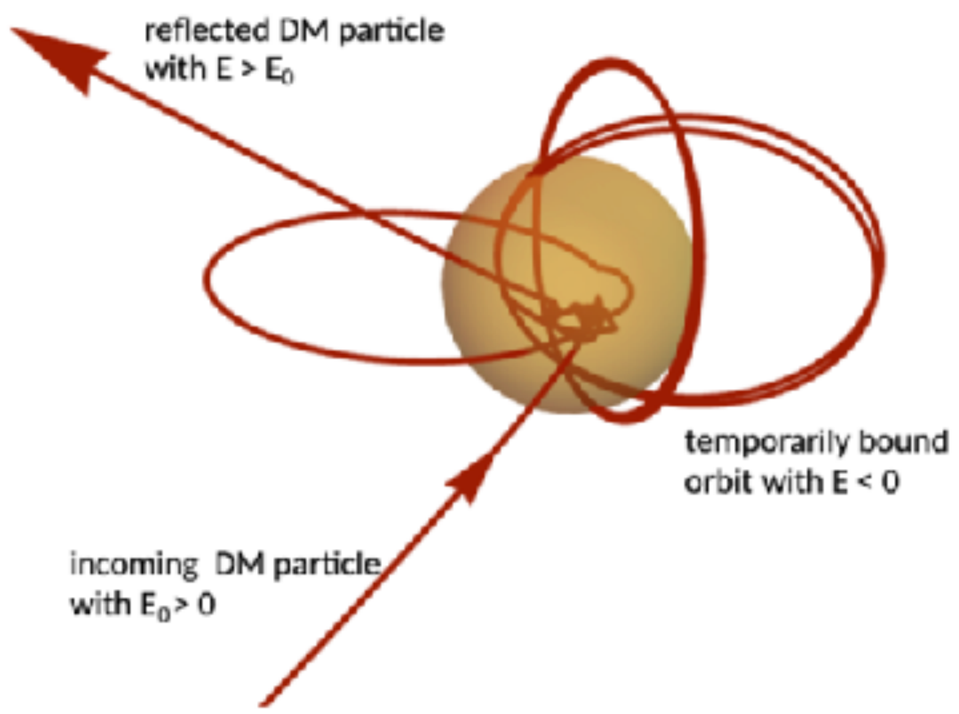
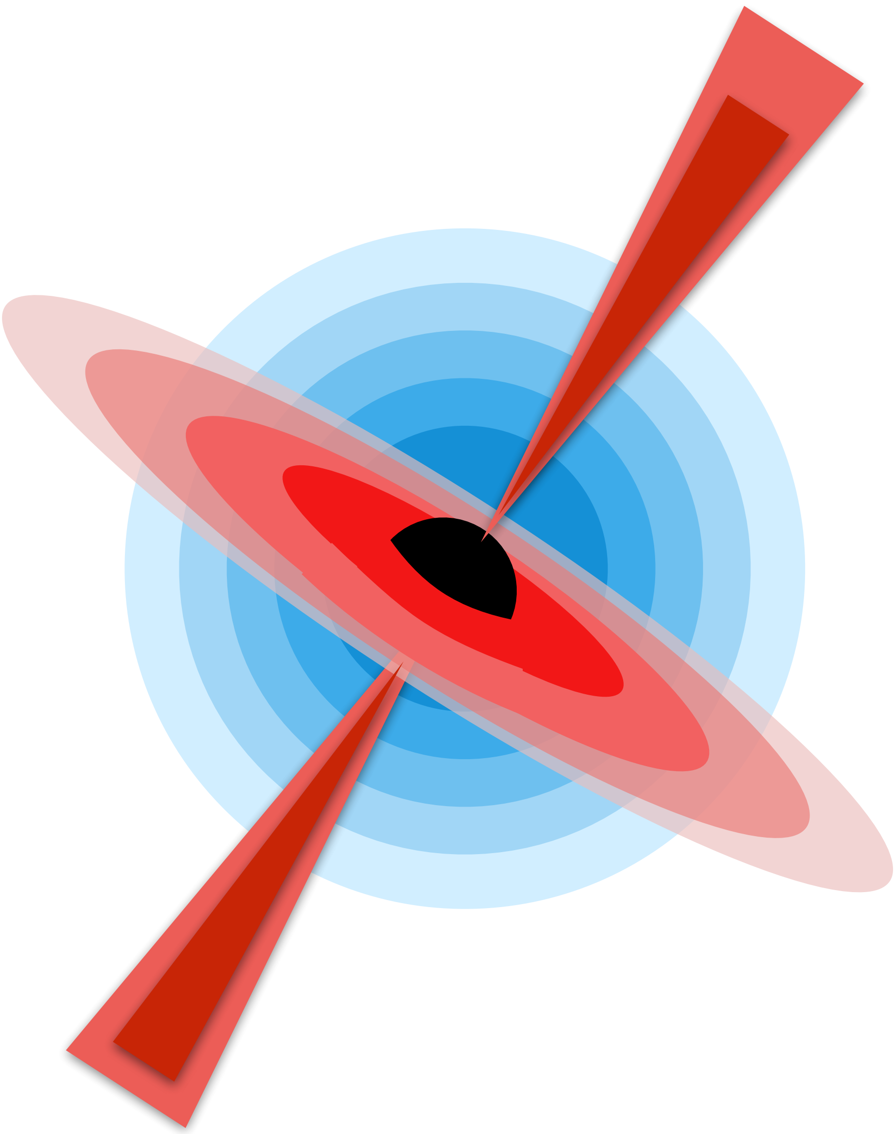
Where should we look for Dark Matter?







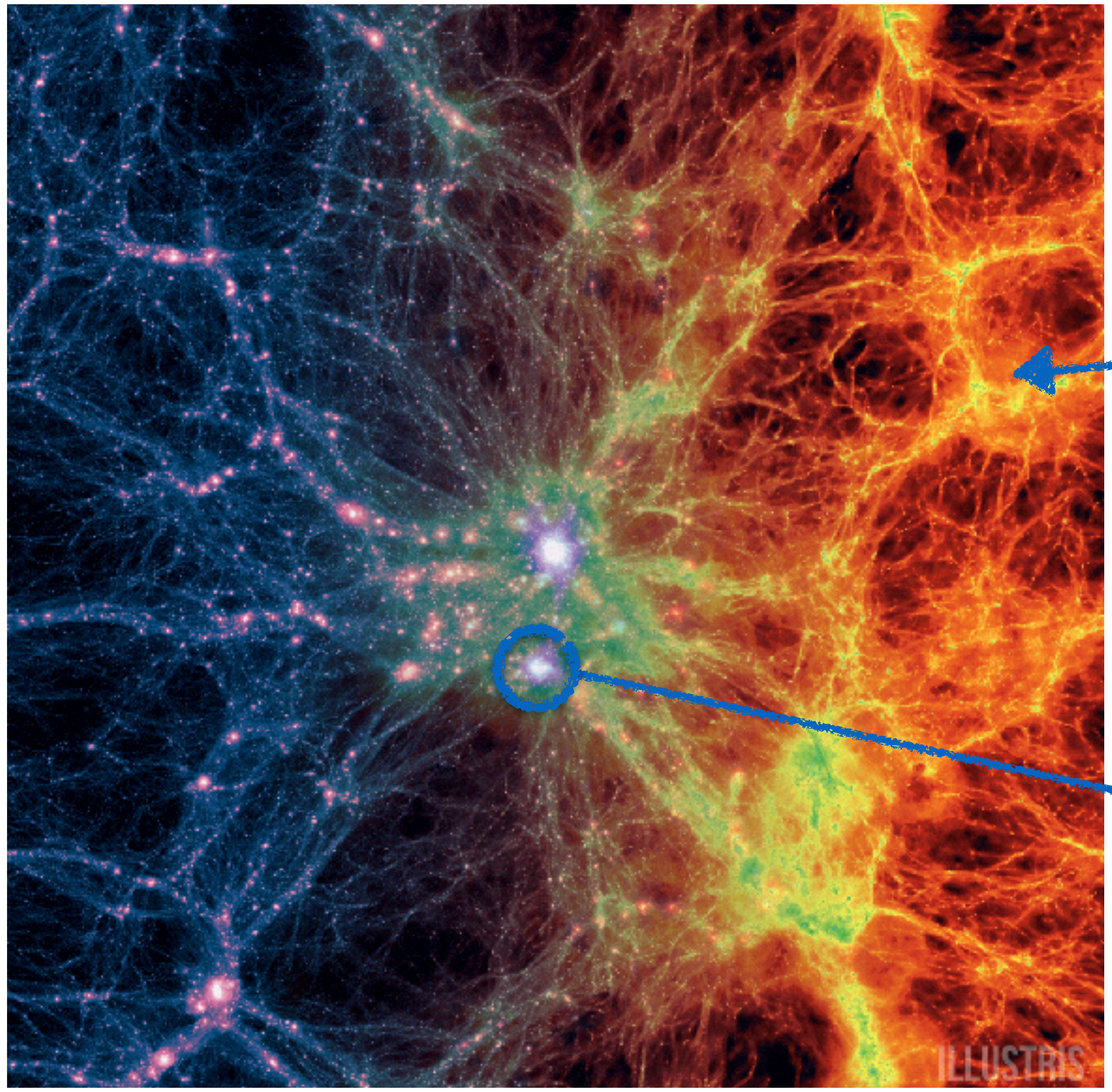
Bradley J Kavanagh [he/him]
Instituto de Fisica de Cantabria (CSIC-UC)
kavanagh@ifca.es

LIII Meeting on Fundamental Physics
Granada, 14th May 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

Dark Matter on all Scales

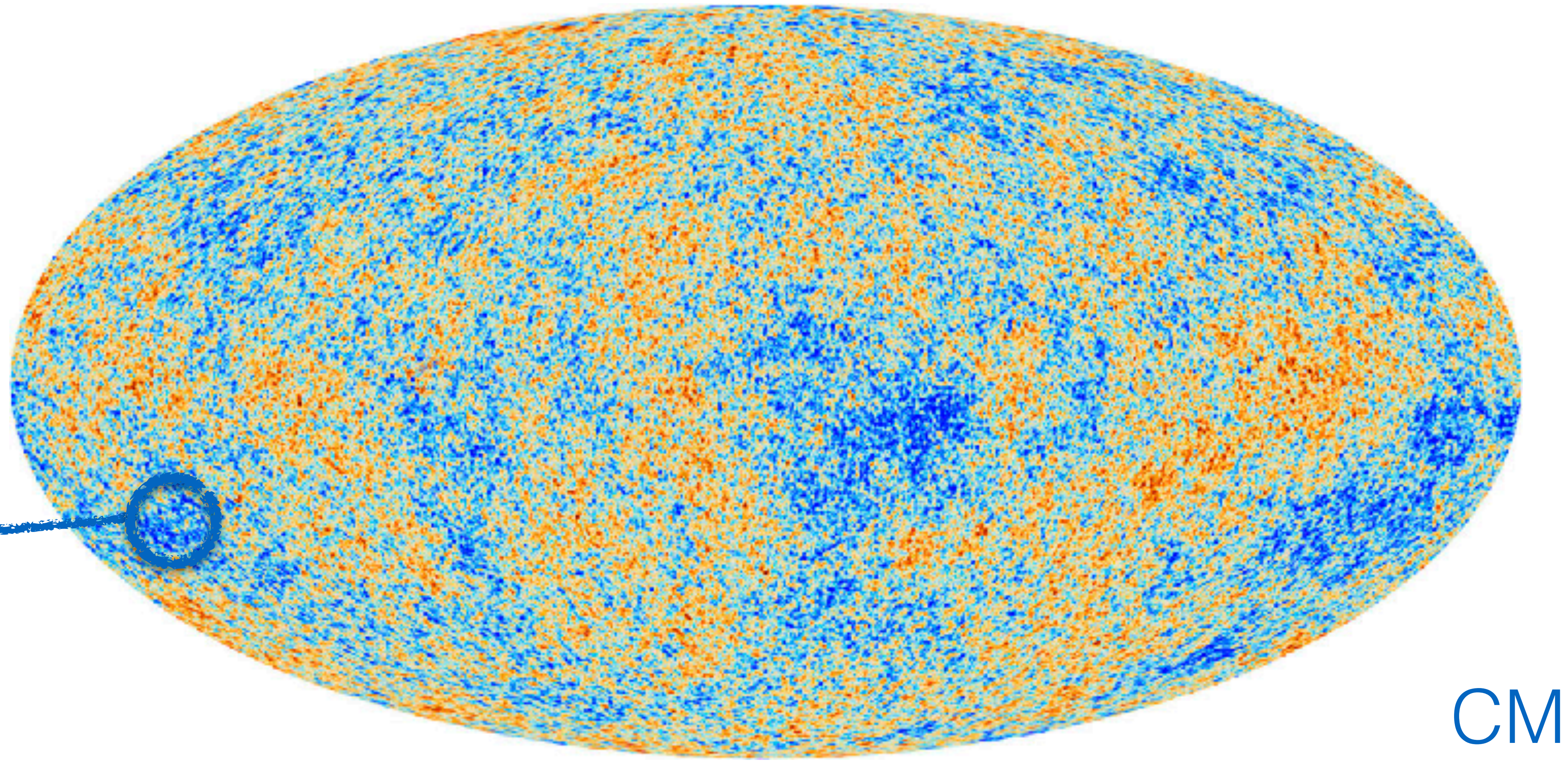
Dark Matter makes up ~85% of the mass of the Universe!



Galaxy clusters

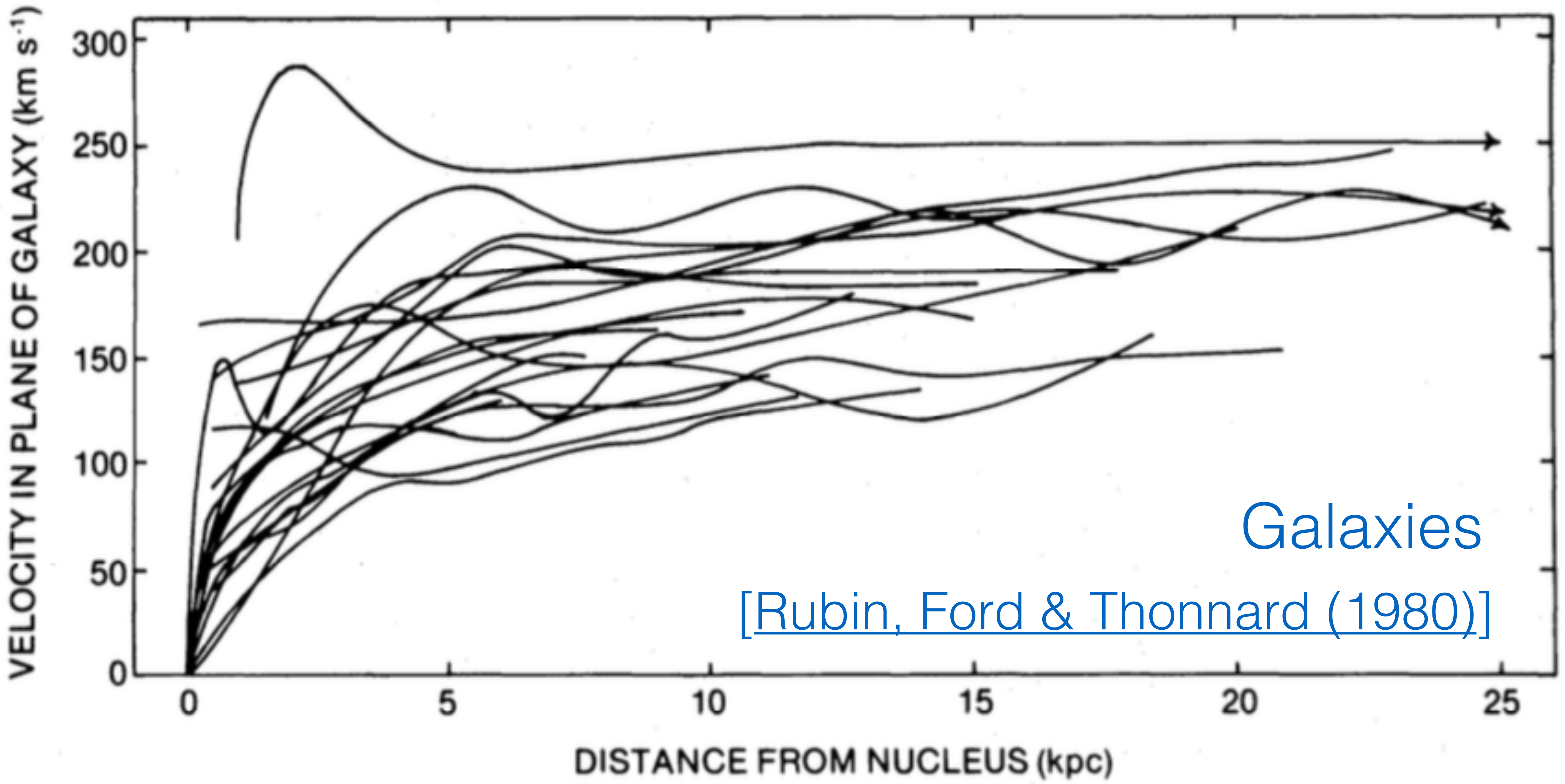
[Illustris, 1405.2921]

[astro-ph/0006397]



CMB

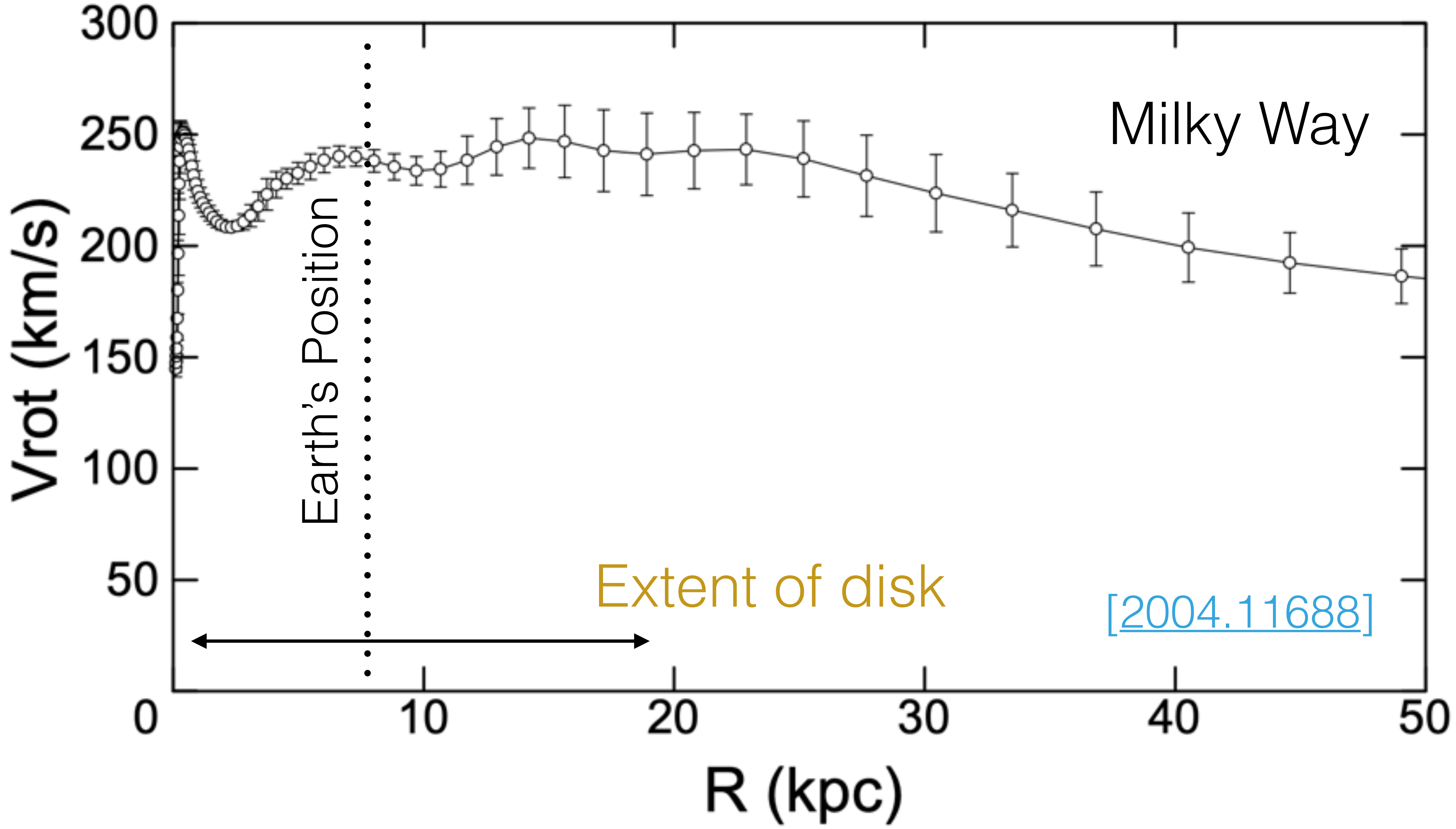
[Planck, 1502.01589]



Galaxies

[Rubin, Ford & Thonnard (1980)]

Local Dark Matter Density



DM density on Earth:

$$\rho_\chi \sim 5 \times 10^{-25}\ \mathrm{g/cm^3}$$
$$\sim 0.3\ \mathrm{GeV/cm^3}$$
$$\sim 0.008\ M_\odot/\mathrm{pc}^3$$

[1404.1938]

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$$\sim 0.3\ \mathrm{GeV/cm^3}$$
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[1404.1938]

Dark Matter collisions with the Human Body

Katherine Freese[1,*] and Christopher Savage[2,†]

[1] *Michigan Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109*

[2] *The Oskar Klein Centre for Cosmopar*

Department of Physics, Stockholm U

AlbaNova, SE-106 91 Stockholm,

(Dated: July 9, 2018)

We investigate the interactions of Weakly Interacting with nuclei in the human body. We are motivated by excellent candidates for the dark matter in the Universe

[1204.1339]

Spontaneous Human Combustion rules out all standard candidates for Dark Matter

Frederic V. Hessman

Institut für Astrophysik und Geophysik, University of Göttingen

J. Craig Wheeler

Dept. of Astronomy, University of Texas at Austin

(Dated: April 1, 2023)

We argue that the reported cases of Spontaneous Human Combustion (SHC) are most likely due to the impact of the human body with an extremely high energy particle like cosmic rays or Dark Matter. Normal and antimatter cosmic rays and classical weakly-interacting massive particles (WIMPs) with energies of GeV to ZeV can be easily ruled out due to their inability to dump

[2304.00319]

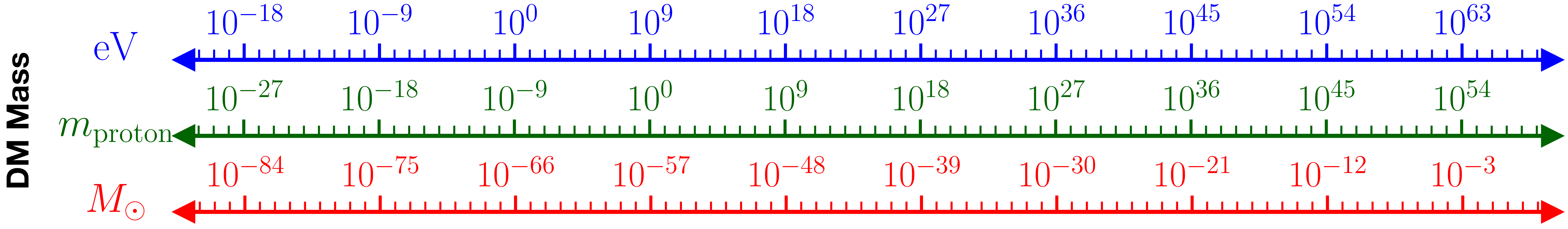
Where should we look for Dark Matter?

Where in *parameter* space? → DM mass scales and target models

Where in *signal* space? → New signals in light DM searches

Where in *physical* space? → DM in extreme environments (e.g. around black holes)

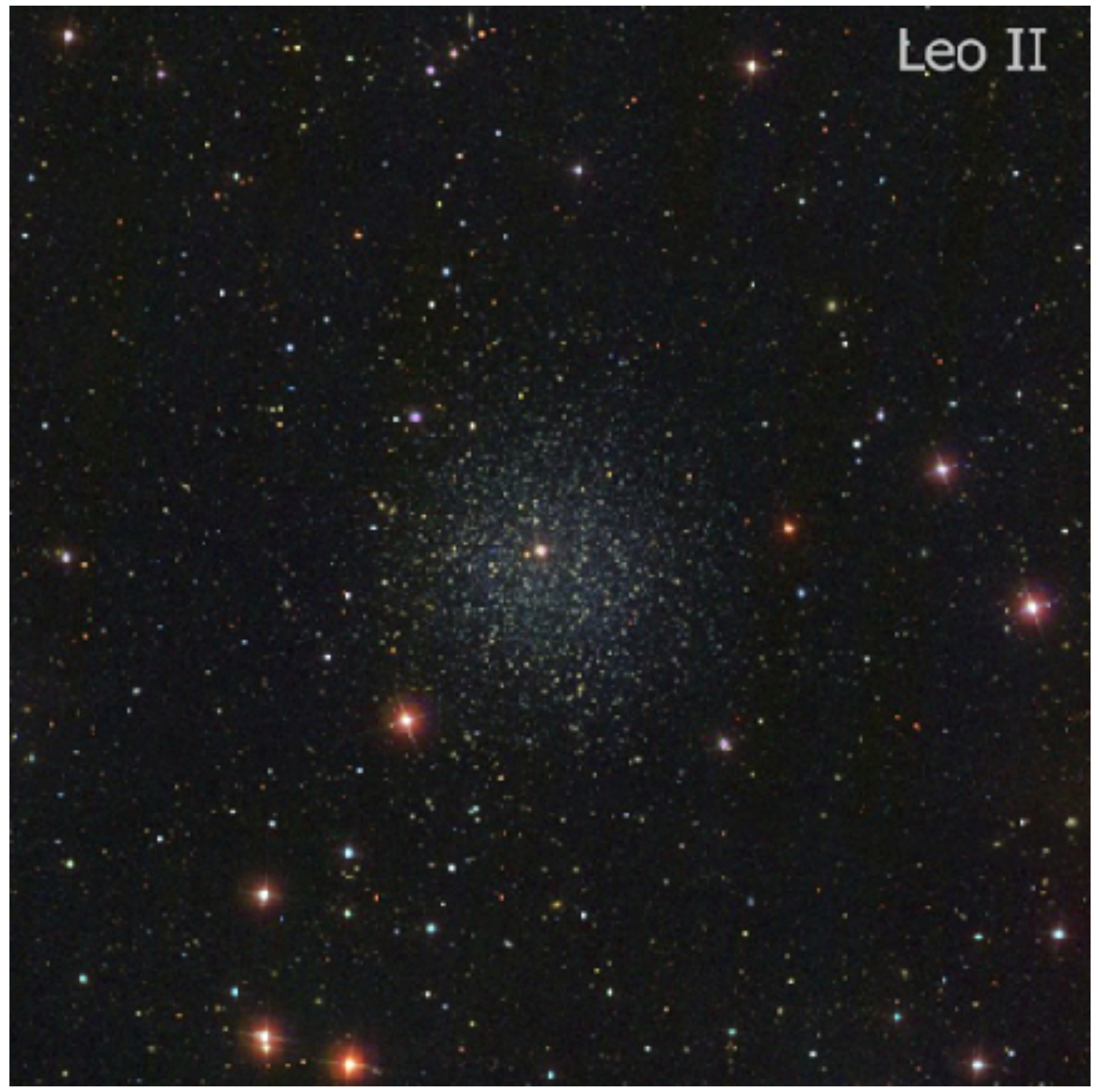
Dark Matter Mass Range



Wave-like (or "Fuzzy") Dark Matter

[Review, 2101.11735]

Very light DM can have $\lambda_{\rm dB} \sim R_{\rm galaxy}$!

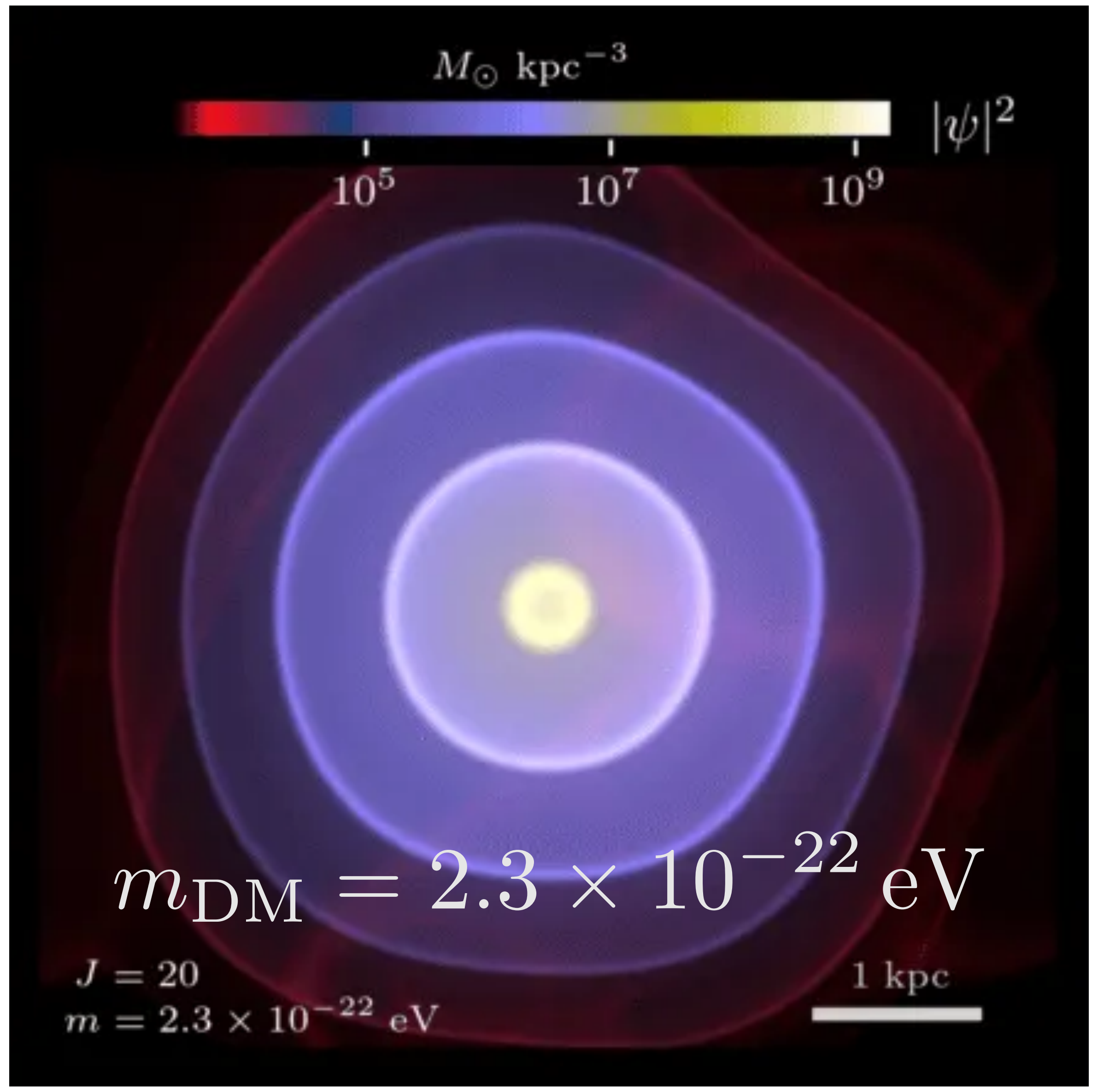


Reconstruct DM density from stellar dynamics in dwarf galaxies

↓

Compare with expected density from wave-like DM (using Schrodinger-Poisson equation)

[Zimmerman et al, 2405.20374]



[King's College London, 2025]

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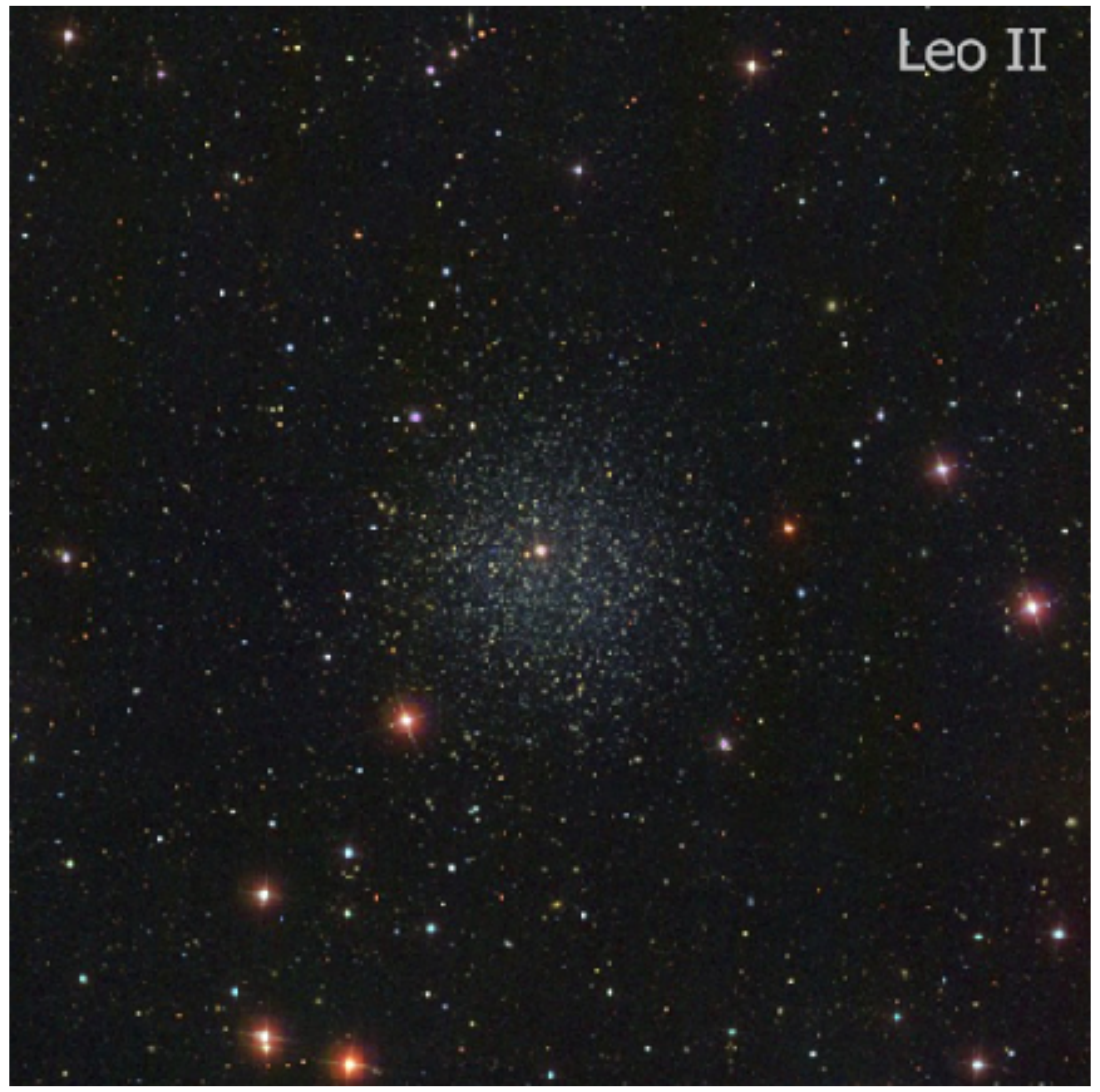

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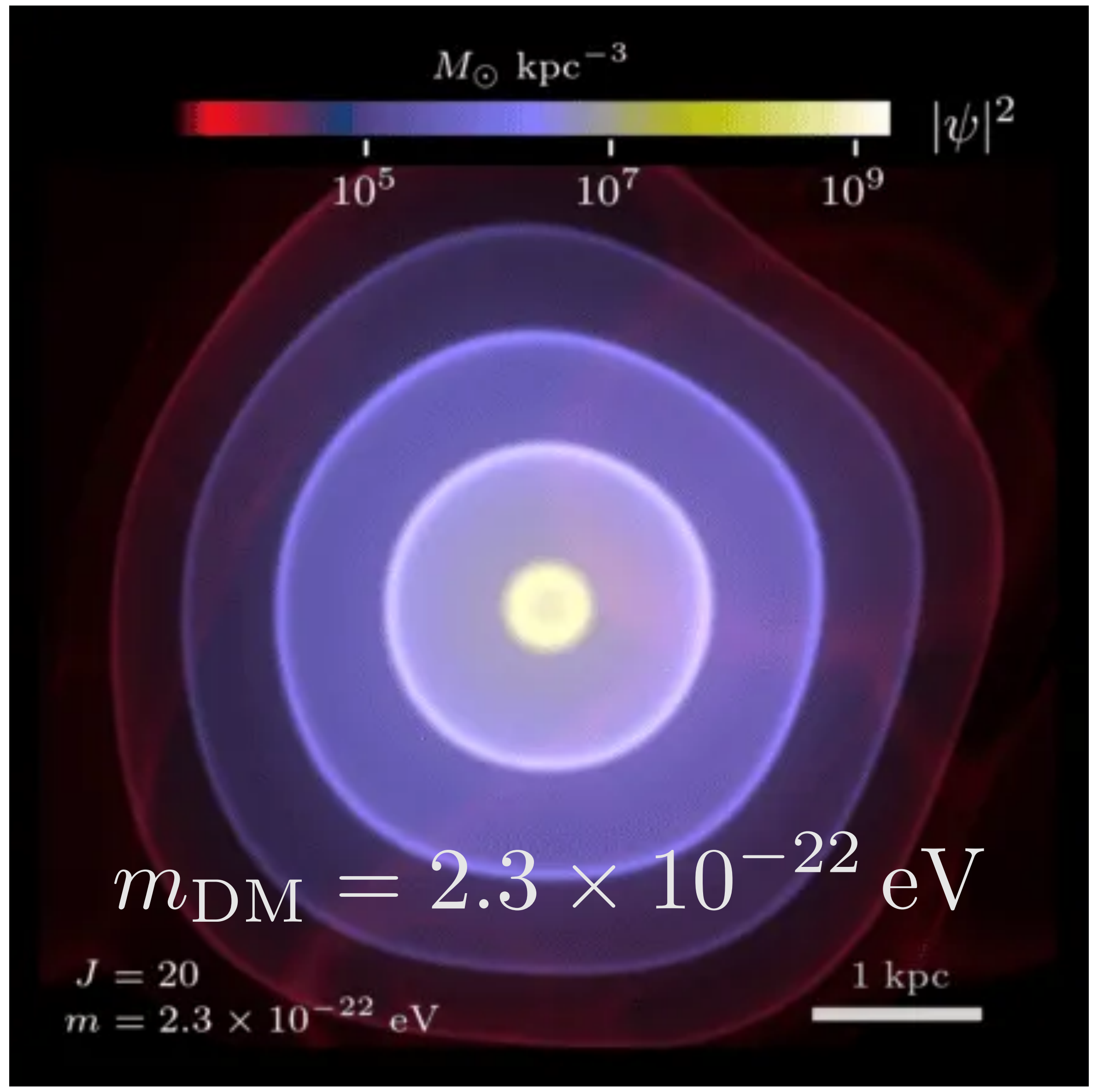

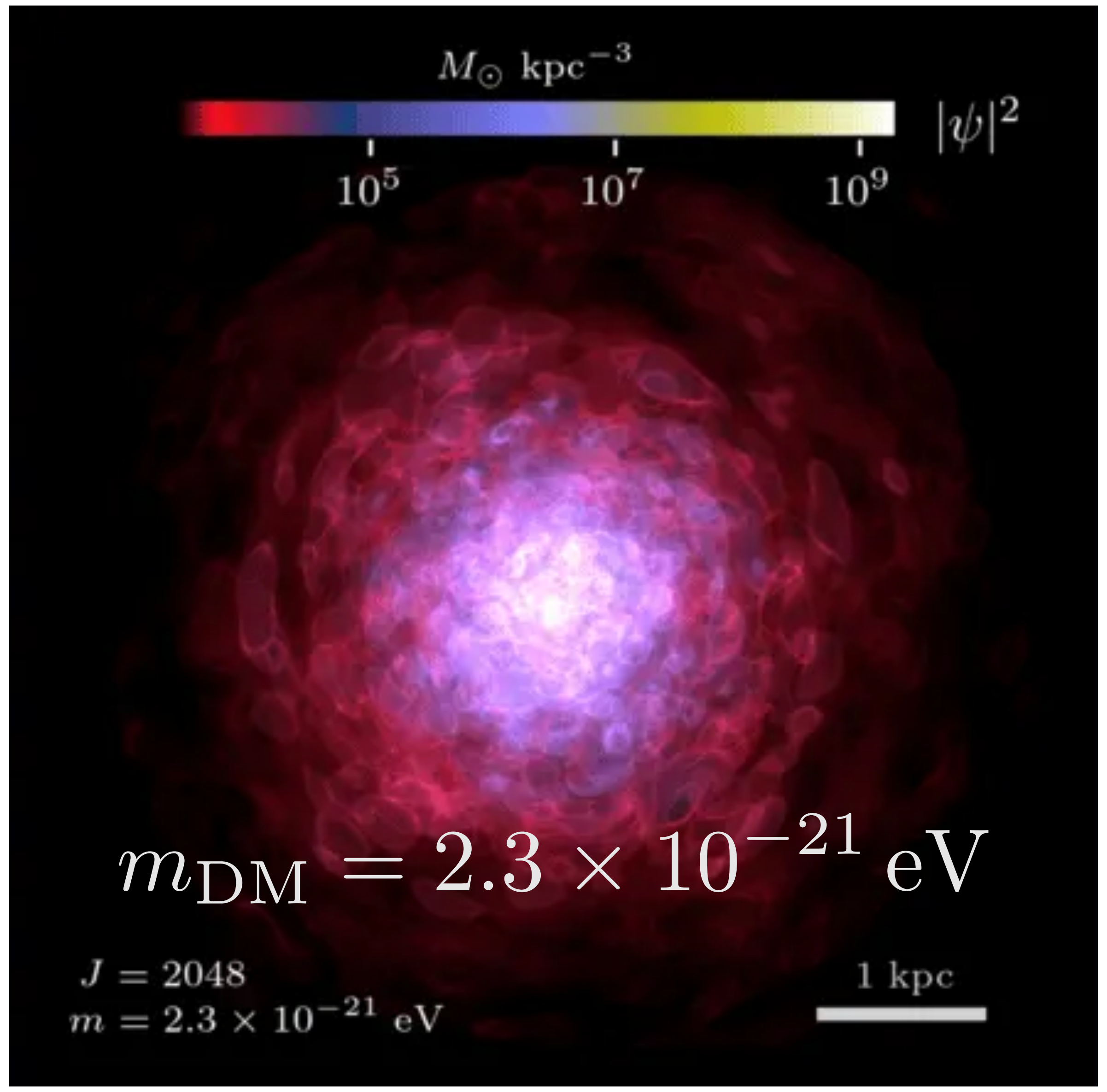

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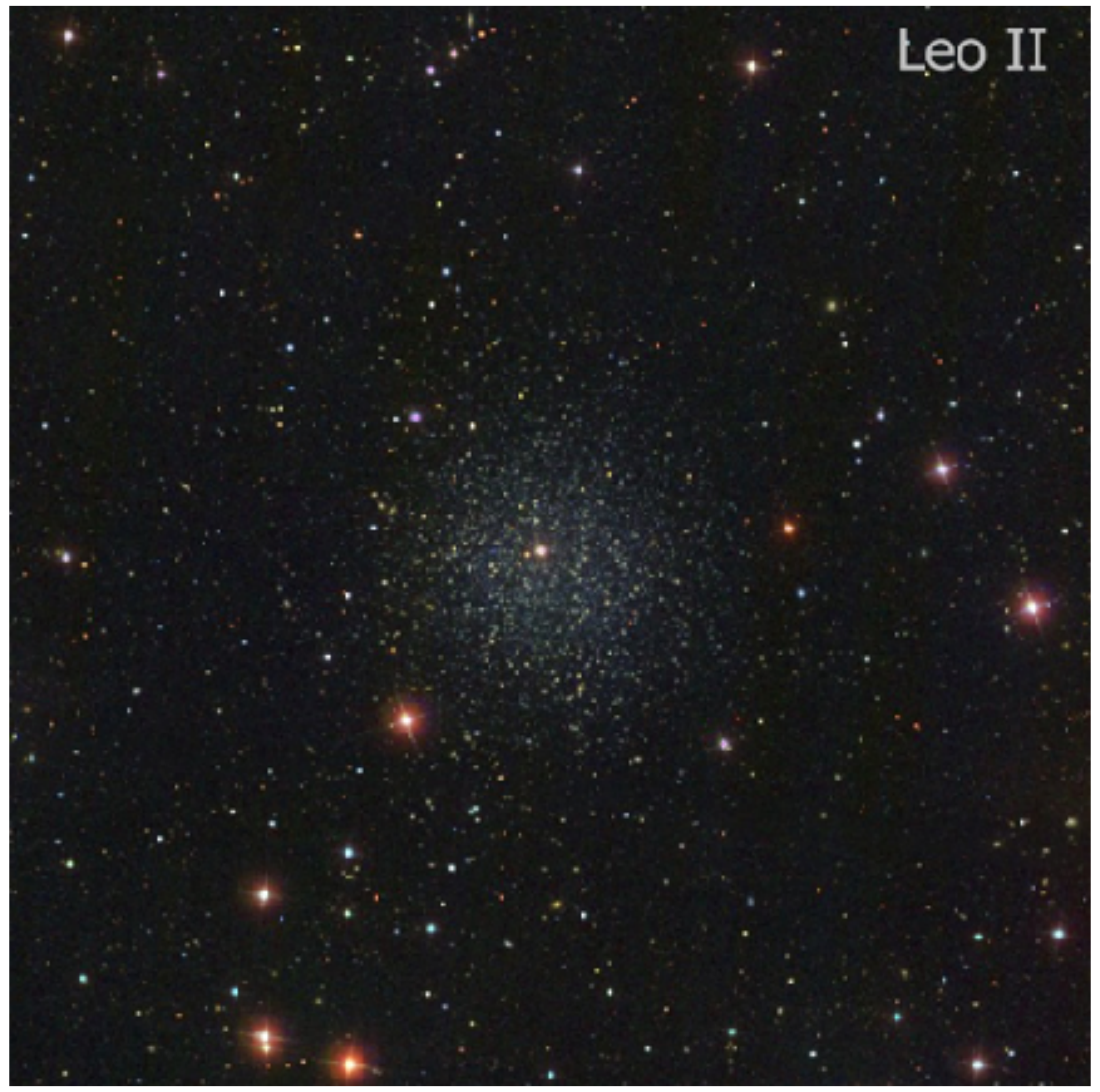

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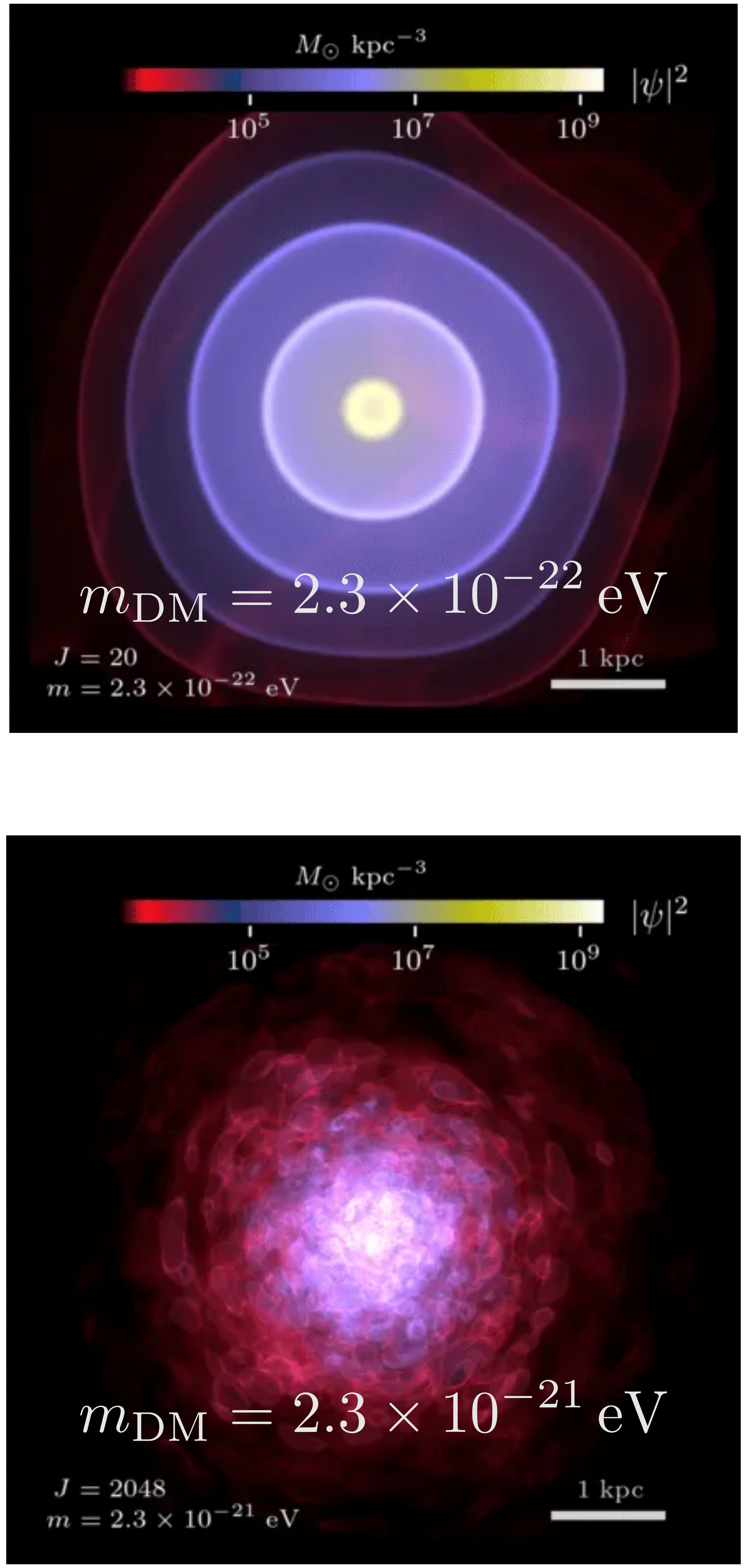


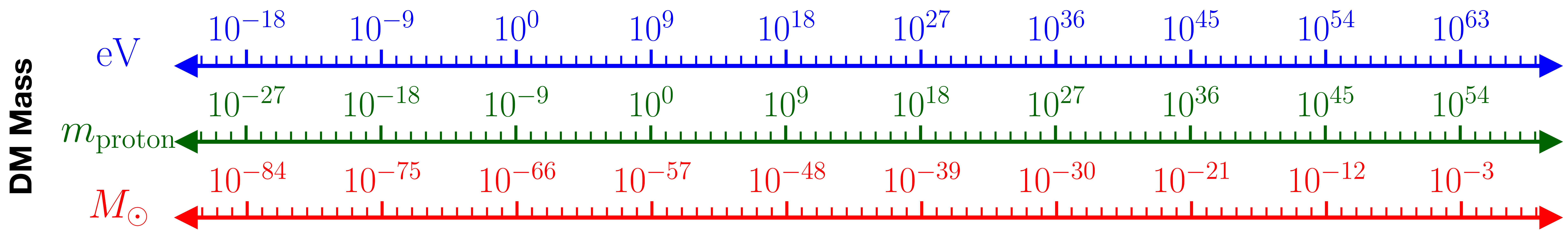
[King's College London, 2025]

Joint analysis of the Milky Way (MW) and Andromeda (M31) satellite galaxies gives an even stronger bound:

$$m_{\rm DM} > 1.74 \times 10^{-20}\,{\rm eV}$$

[Liu, Gong & Liao, 2512.01361]

Dark Matter Mass Range



DM lighter than ~100 eV must be bosonic (fermions cannot be packed to high enough densities in galaxies)

[Tremaine & Gunn (1979)]

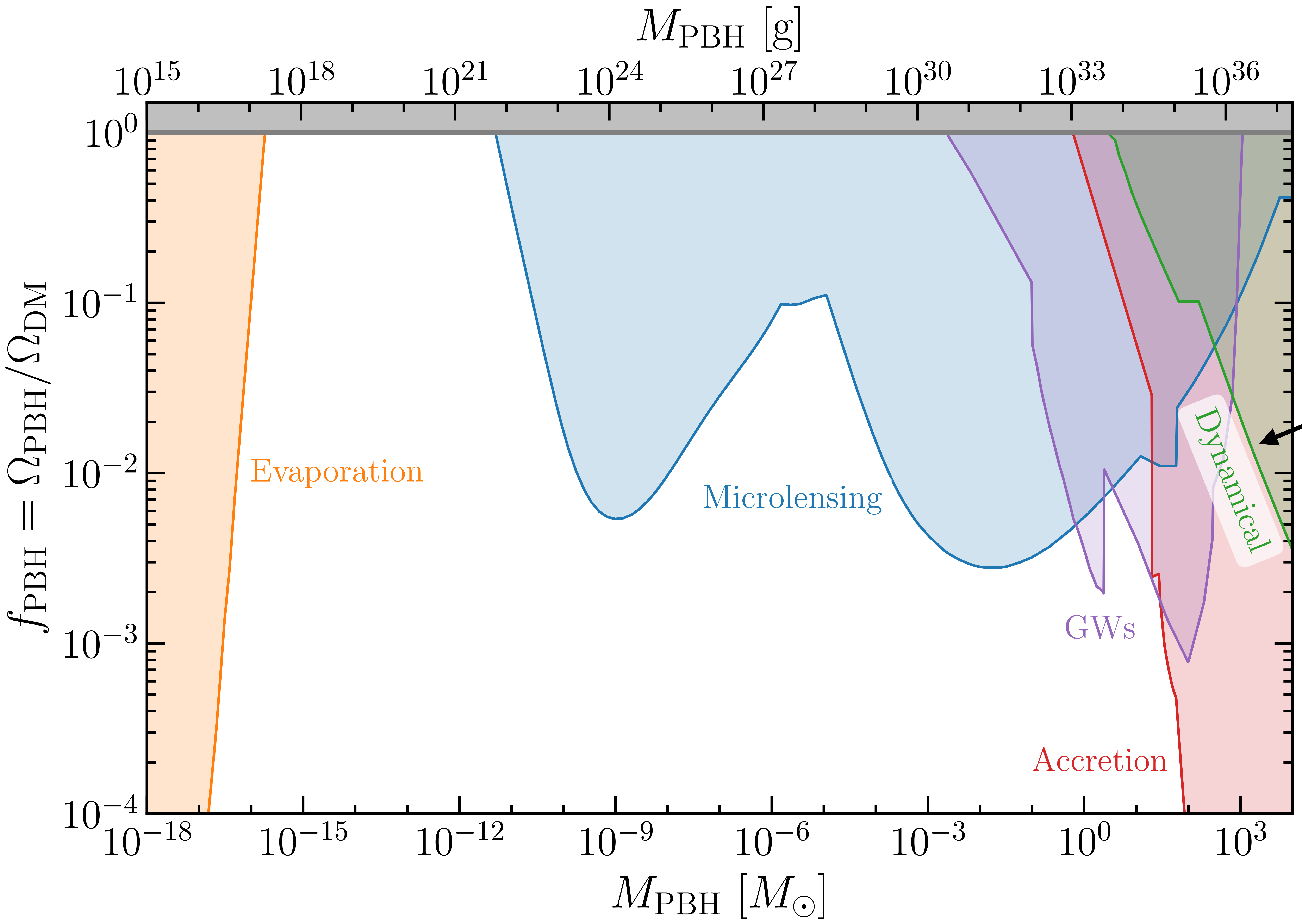
Very light DM ($\lesssim 10^{-22}\,\mathrm{eV}$) has wave-like properties on astrophysical scales, spoiling galactic structure

Compact Object DM

[Green & **BJK**, 2007.10722]

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

Constraints on primordial black hole as DM:

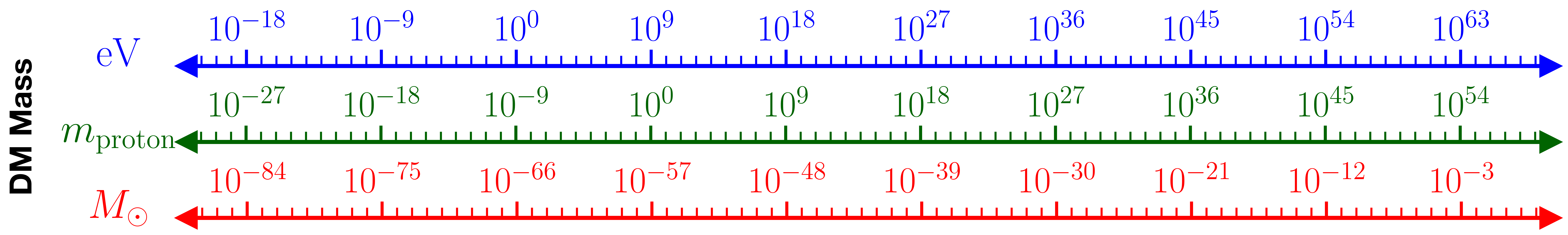


DM in the form of compact objects (e.g. black holes) dynamically heats the stars in dwarf galaxies, disrupting the stellar density profiles

[Stegmann et al., 1910.04793]

[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Dark Matter Mass Range



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Very heavy DM ($\gtrsim 10^3\,M_\odot$) is 'discrete' on astrophysical scales, spoiling galactic structure

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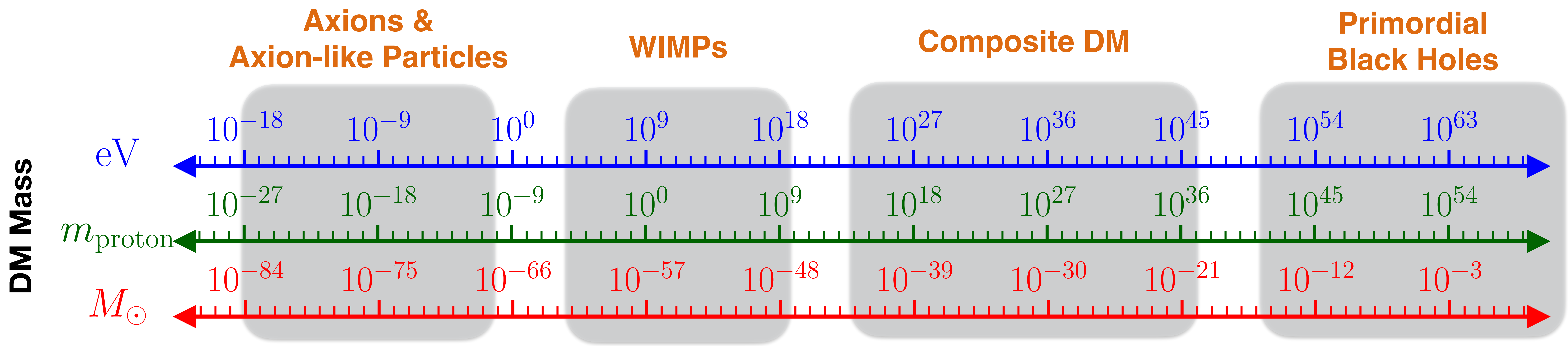

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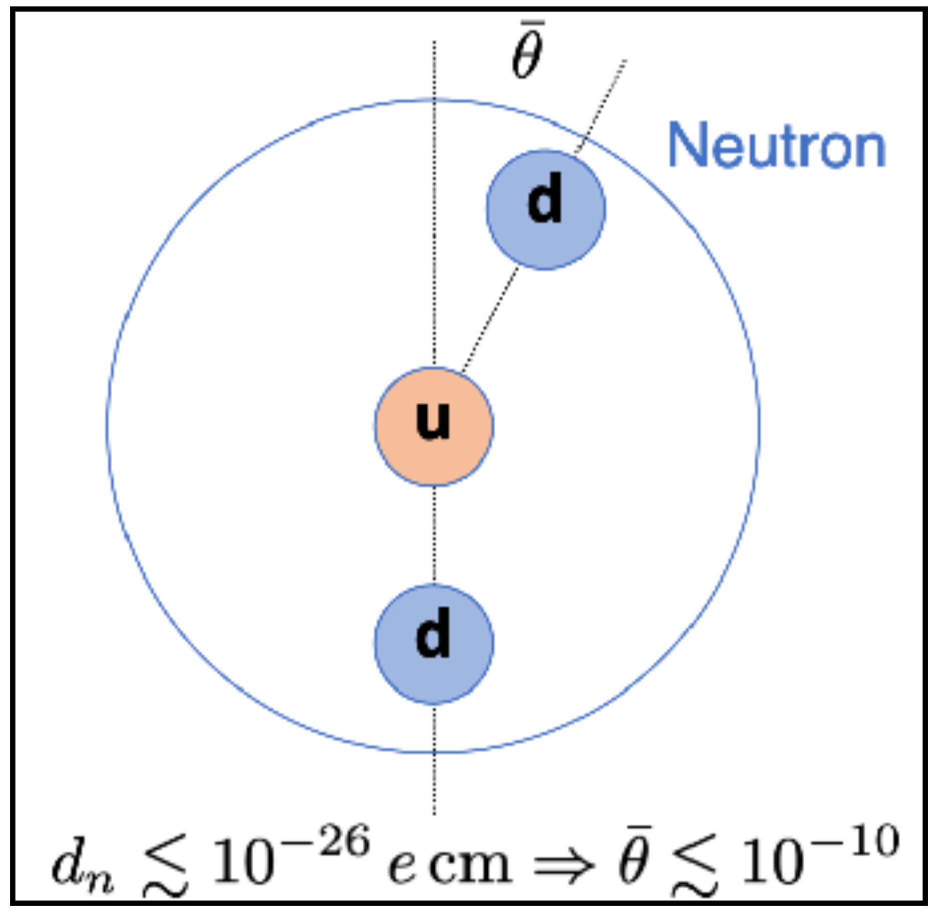
Axion Dark Matter

Quantum Chromodynamics (QCD), the theory of the strong force, could have a large Charge-Parity (CP) violating term:

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta}\,\frac{1}{32\pi^2} G\tilde{G}$$

Gluon field strength

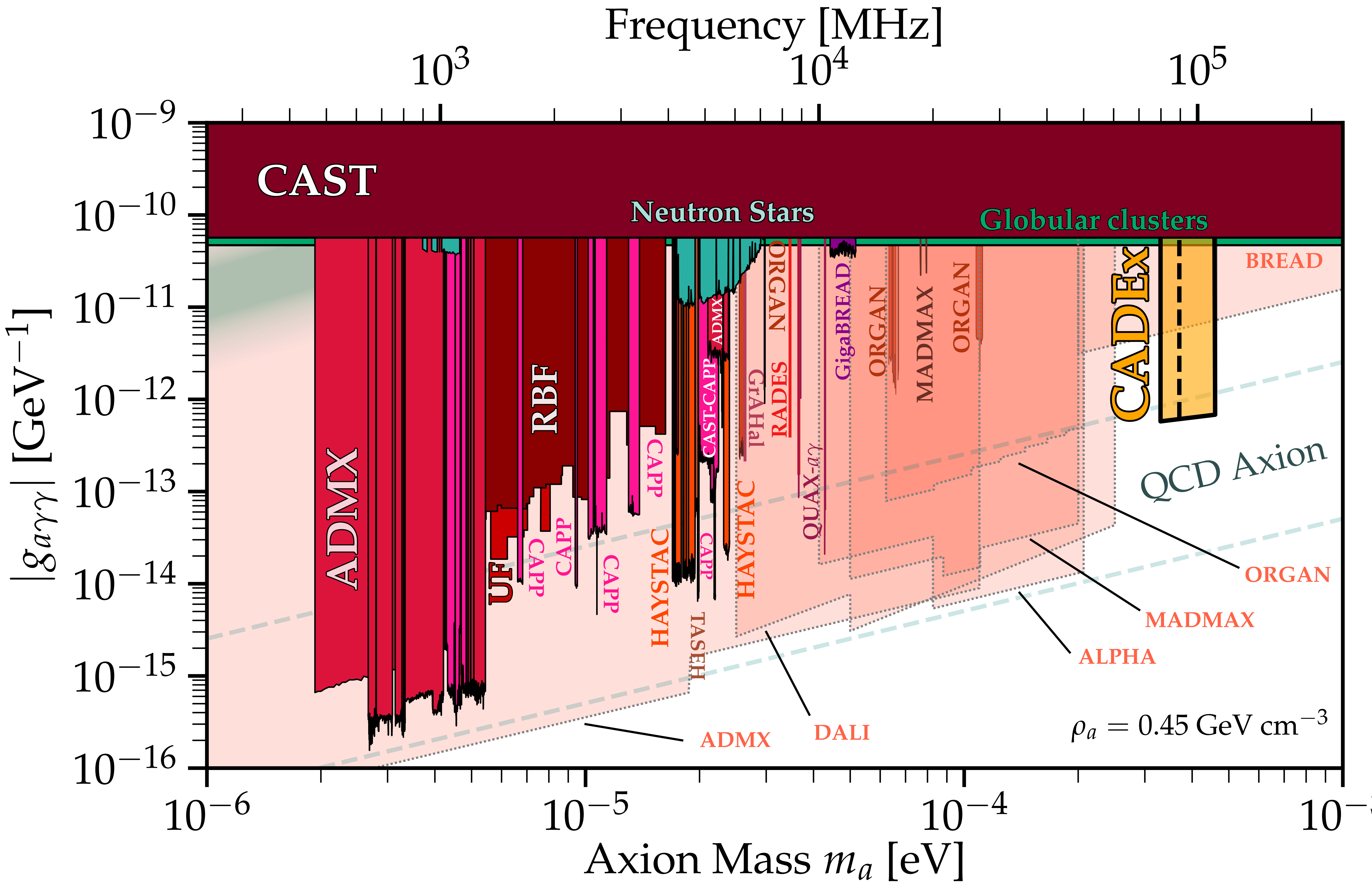


CP violation would give rise to a neutron electric dipole moment $d_n \sim 10^{-16}\,\bar{\theta}\,e\,\mathrm{cm}$.

However, there is **no evidence of CP violation in Strong interactions.**

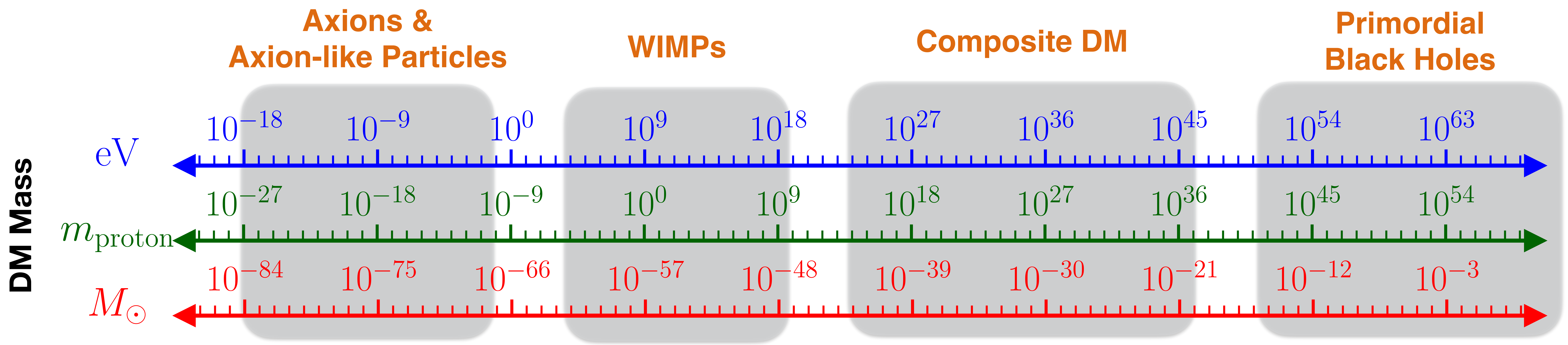
Axions provide a dynamical solution to the Strong CP Problem (why $\bar{\theta} \sim 0$)!

Can be good DM candidates in the **(rough) mass range** $m_a \approx 1 - 1000\,\mu\mathrm{eV}$



https://cajohare.github.io/AxionLimits/

Dark Matter Mass Range



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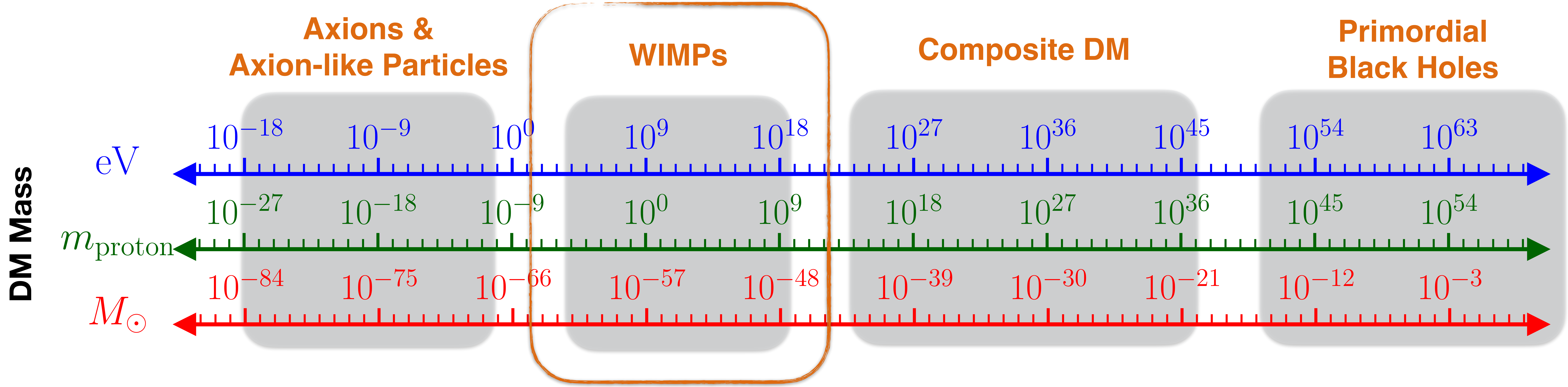

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WIMP-like Dark Matter, χ

Can be produced with the correct abundance in the early Universe, through contact with the Standard Model ("Thermal" DM)

DM with $m \lesssim \mathrm{MeV}$ will be relativistic during Big Bang Nucleosynthesis (BBN), spoiling the yields of light elements

[E.g. Sabti et al., 1910.01649]

DM with $m \gtrsim 100\,\mathrm{TeV}$ would be overproduced in the early Universe ("Unitarity Bound")

[Griest & Kamionkowski, PRL, 1990]

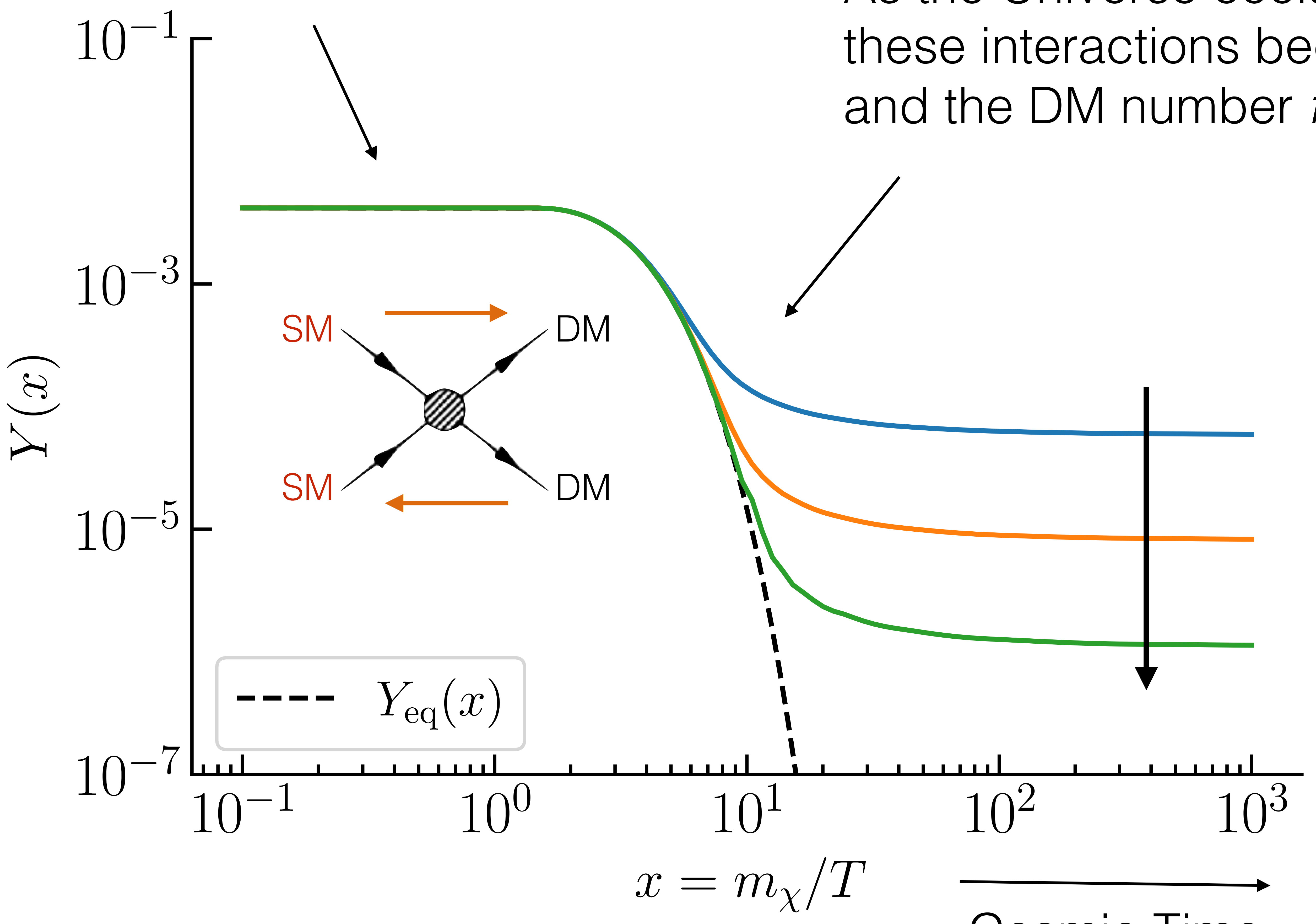
[Inspired by slides from Gordon Krnjaic]

Freeze-out

If DM-SM interactions are strong enough,
DM is initially in thermal equilibrium

As the Universe cools and expands,
these interactions become ineffective
and the DM number *freezes out*

Dark Matter ‘Yield’
(~ total DM number)

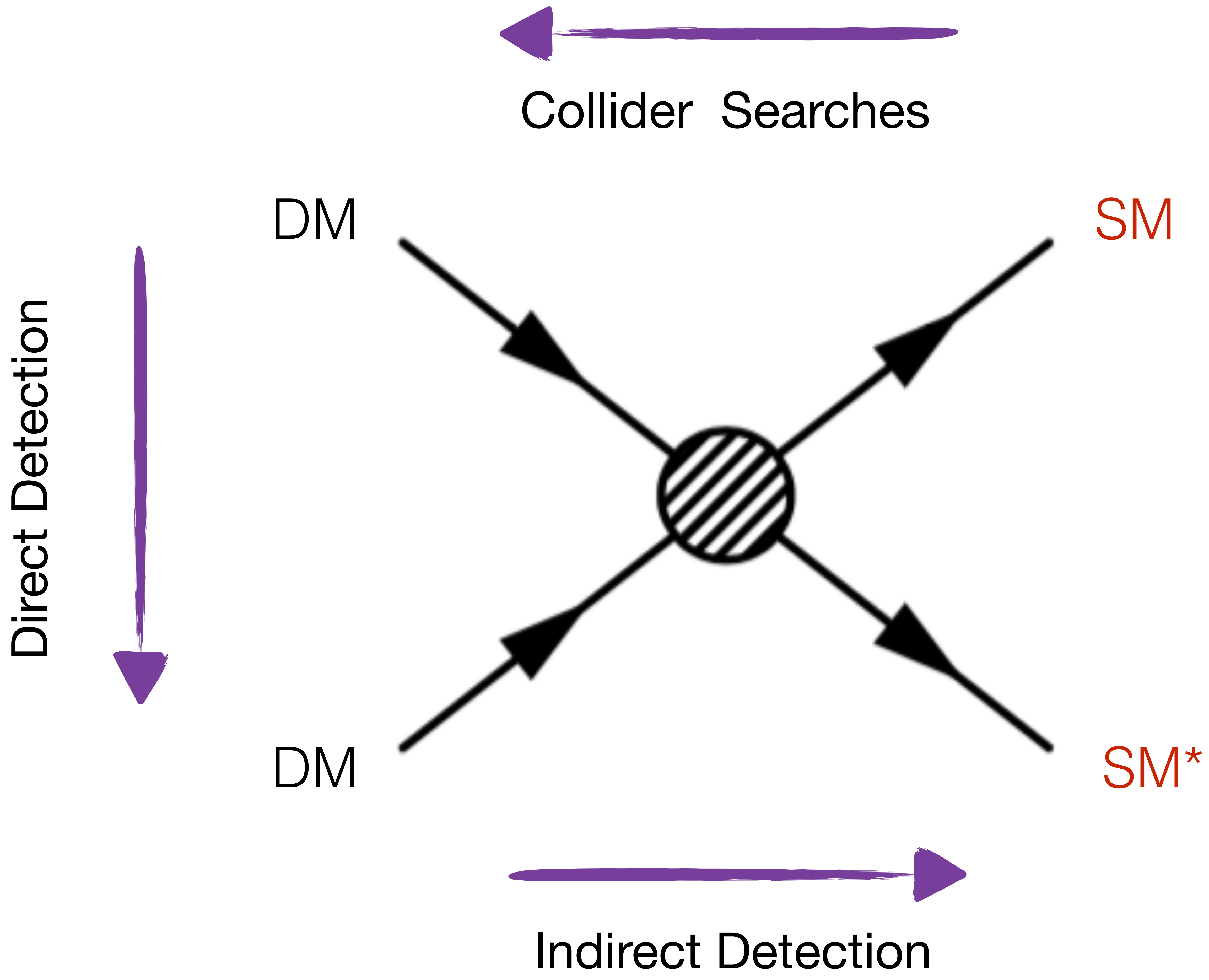


Cosmic Time

Increasing DM annihilation cross-section, *reduces* DM abundance

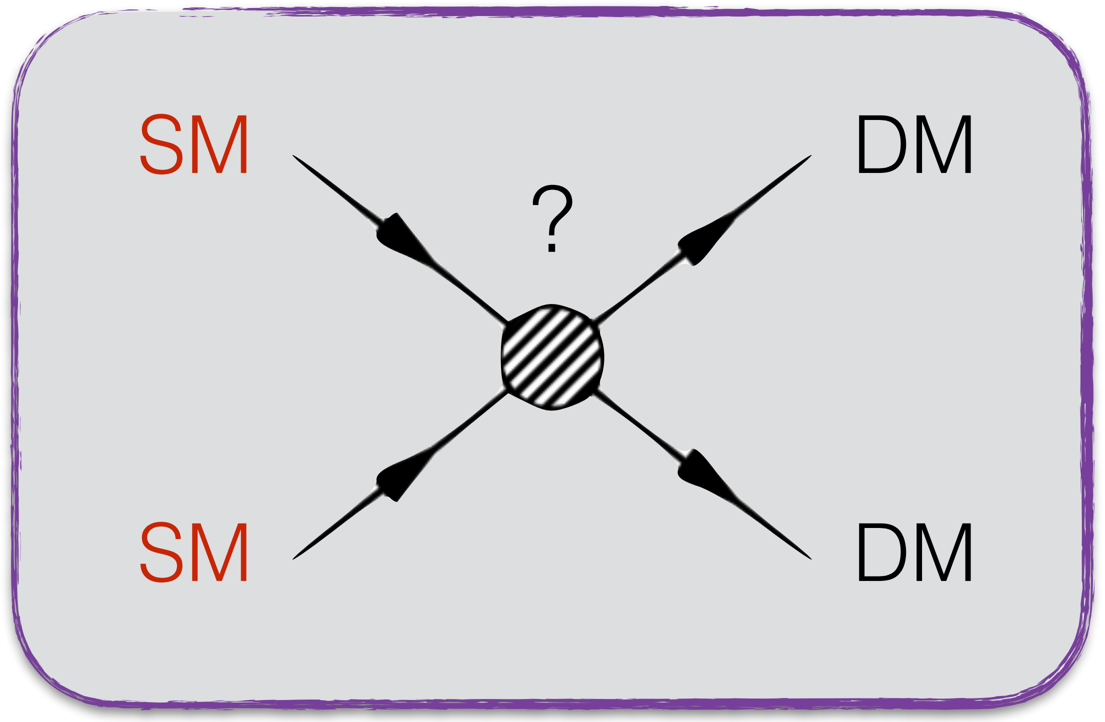
Correct DM abundance achieved for $\langle \sigma v \rangle \approx 3 \times 10^{-26}\,\mathrm{cm^2\,s^{-1}}$ → roughly Weak scale masses and couplings

Where in *signal space*?



*Standard Model
(quarks, electrons, photons etc)

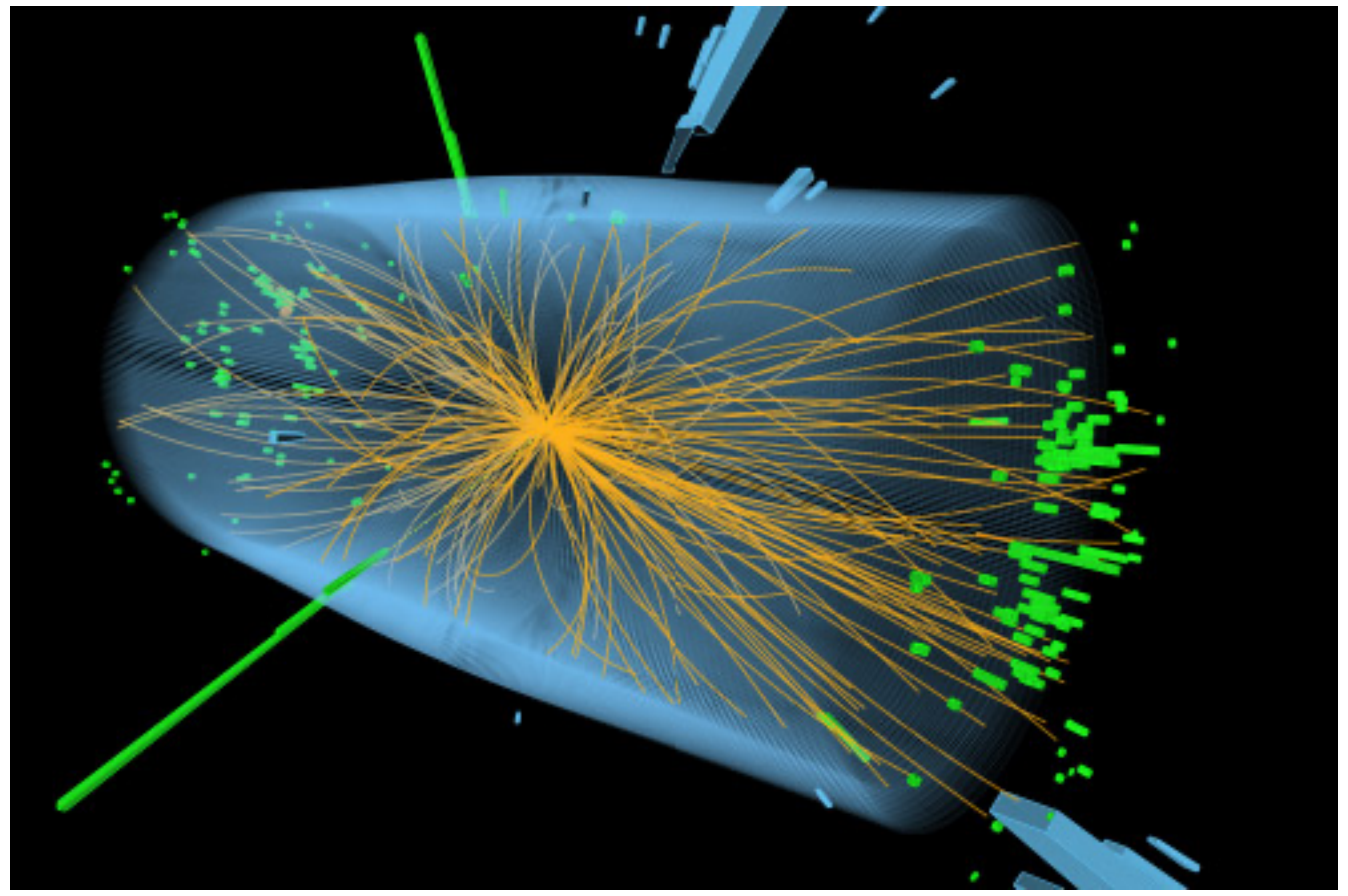
Collider Searches for WIMPs



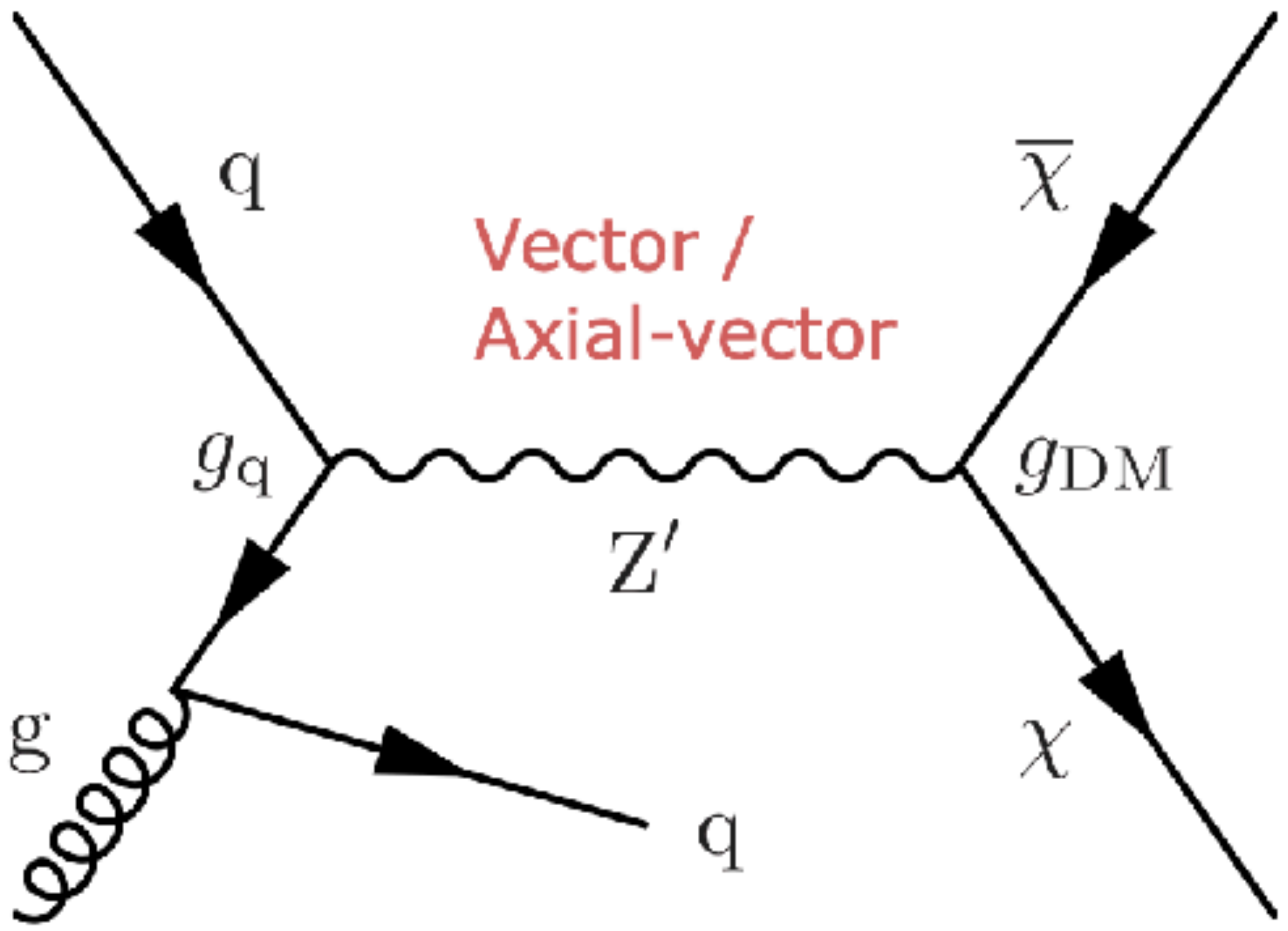
The same interactions which produce DM early in the Universe can be used to search for DM in colliders (e.g. proton-proton collisions):

[See talks on Tuesday by Alberto Escalante del Valle and Tamara Vázquez Schröder]

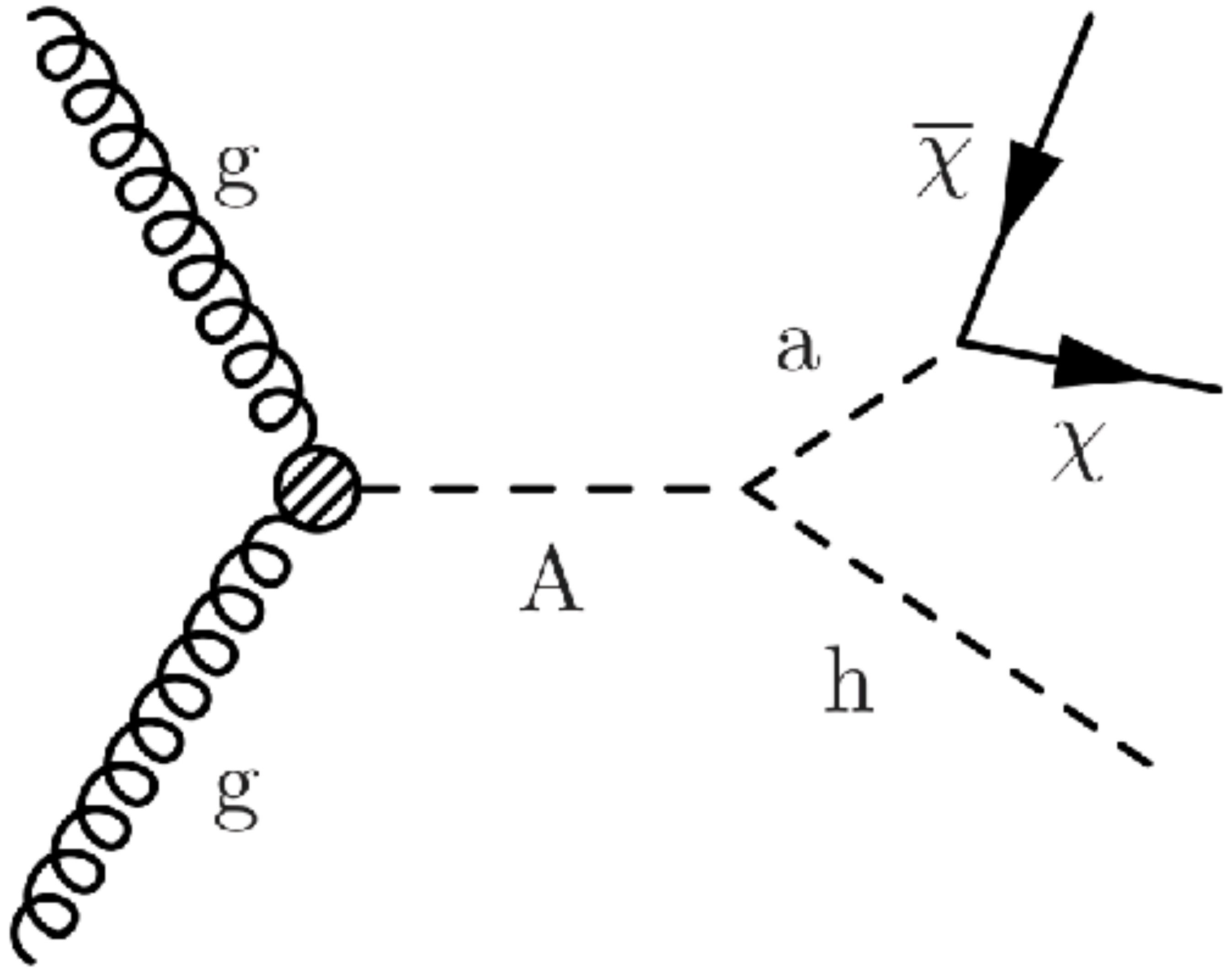
[Credit: CMS/CERN]



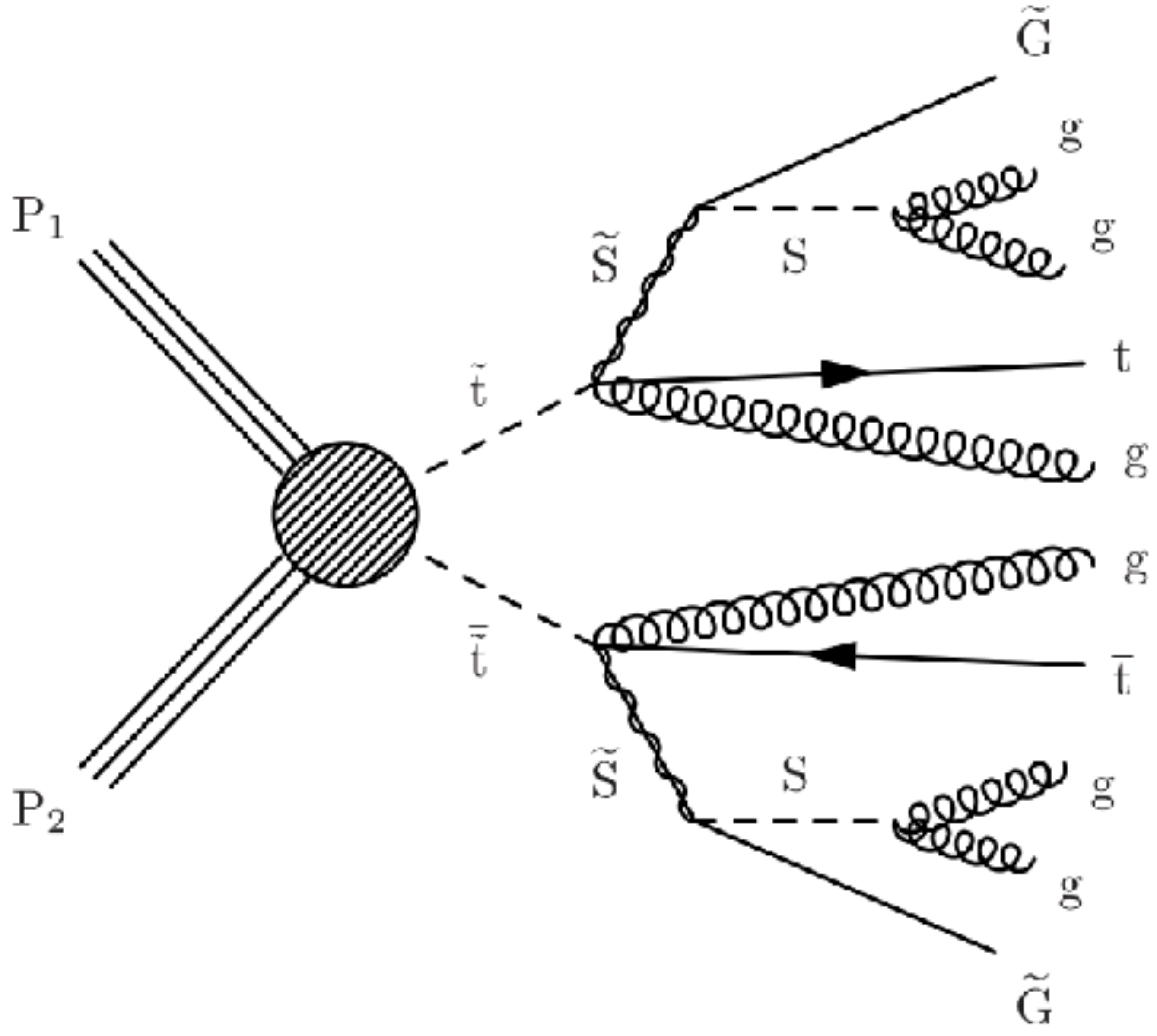
Spin-1 Portal



2HDM+a



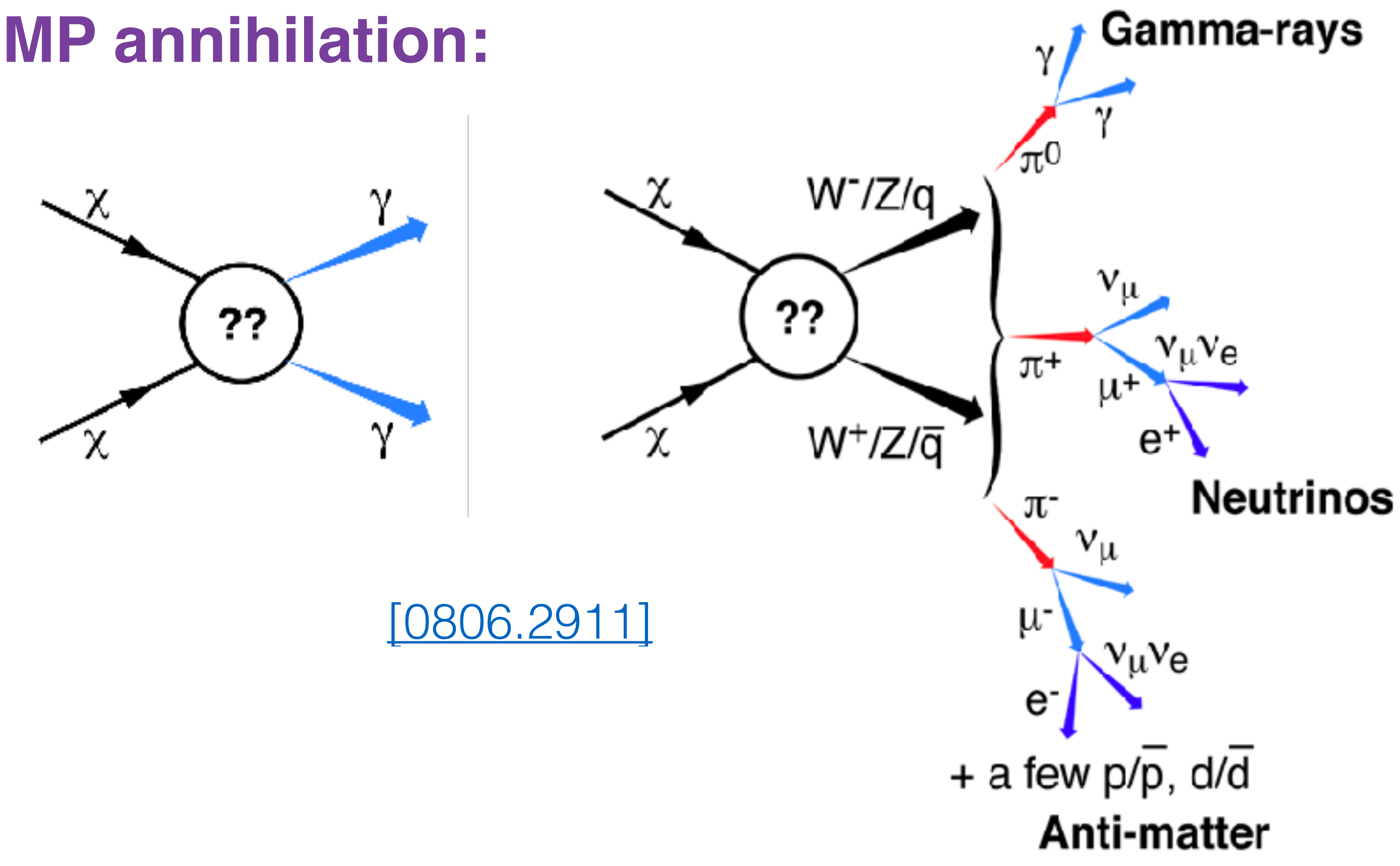
Stealth SUSY



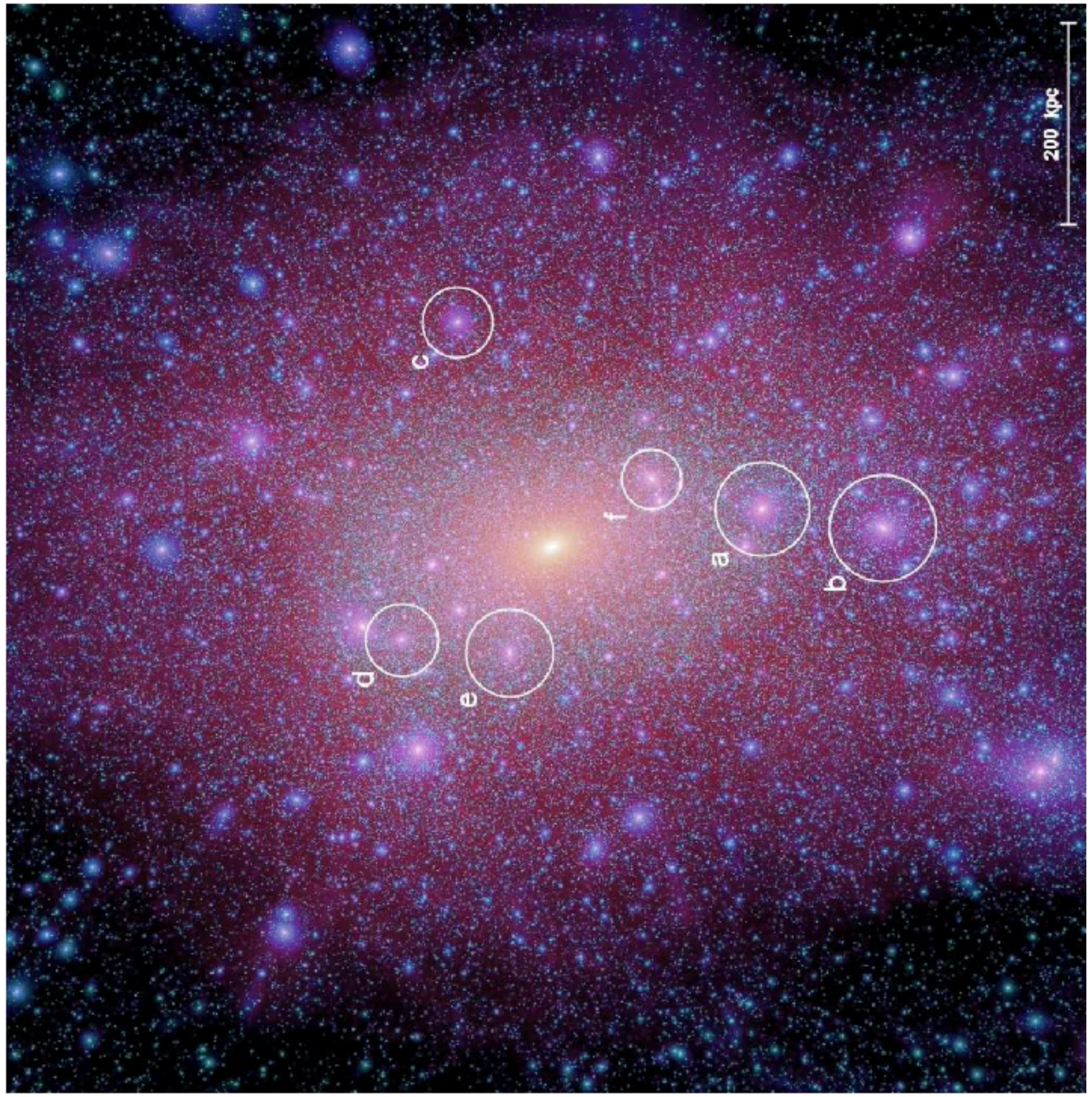
Indirect detection of Dark Matter

Look for signals of Dark Matter annihilation in regions of large DM density!

WIMP annihilation:



[0806.2911]



Aquarius simulation - 0809.0898

Annihilation cross section (particle physics)

DM density distribution (astrophysics)

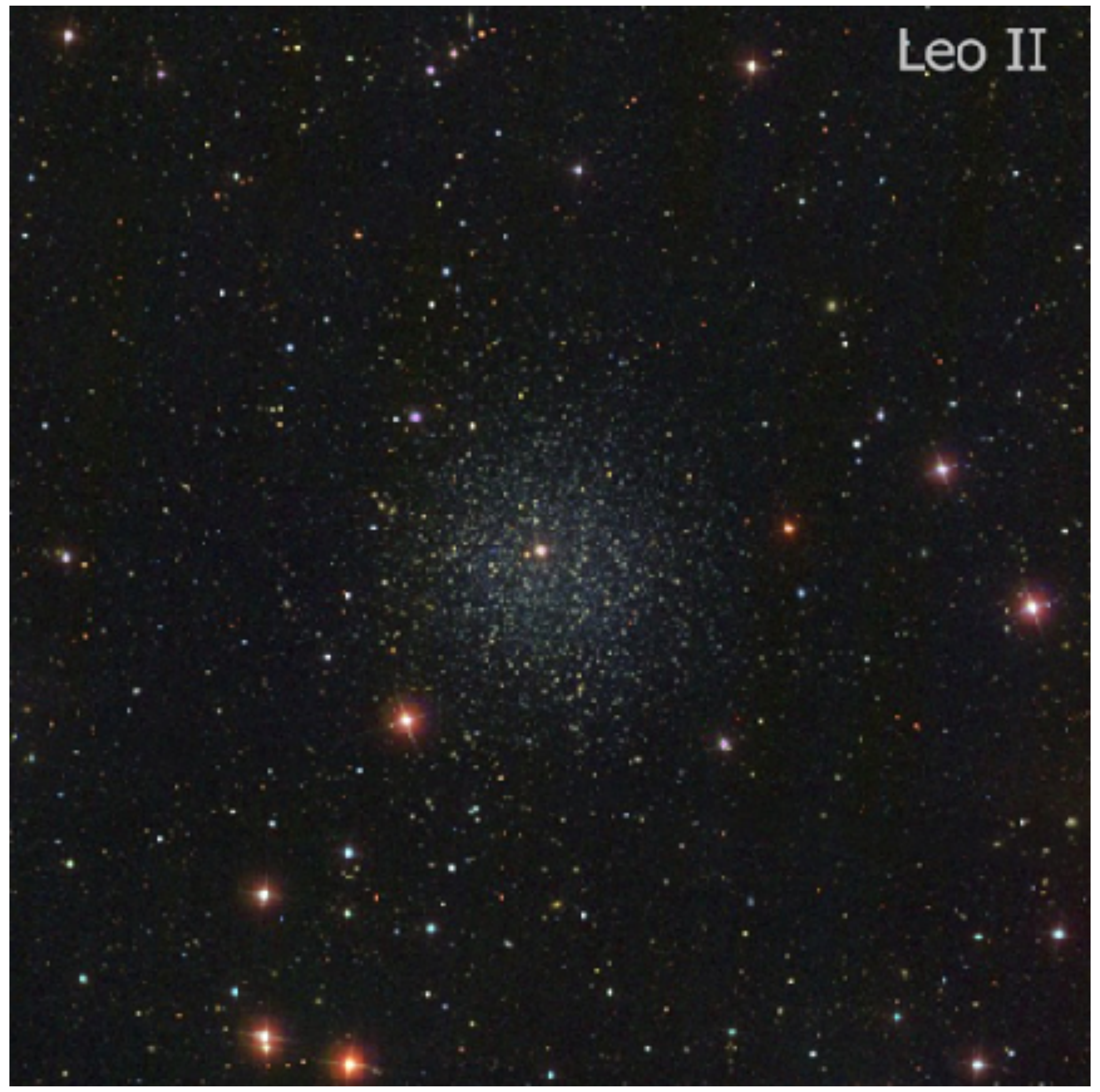
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma} \times \int_{d\Omega} d\Omega' \int_{los} \rho^2 dl\,(r,\theta')$$

Gamma-ray spectrum (annihilation channel)

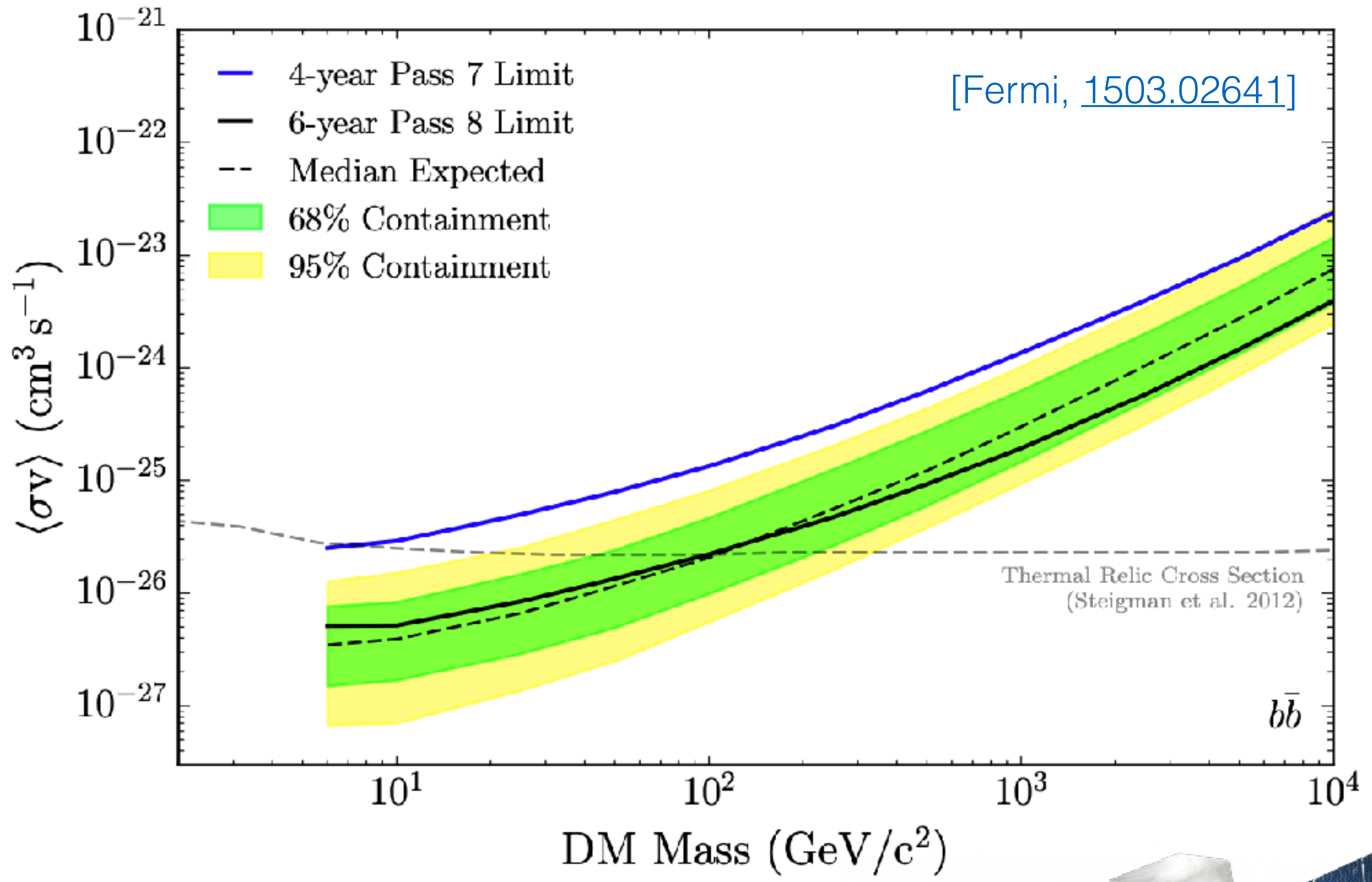
1012.4515

Gamma-ray constraints

Leo II Dwarf Galaxy
(Satellite of the Milky Way)



Fermi constraints from 15 Dwarf Spheroidal Galaxies:

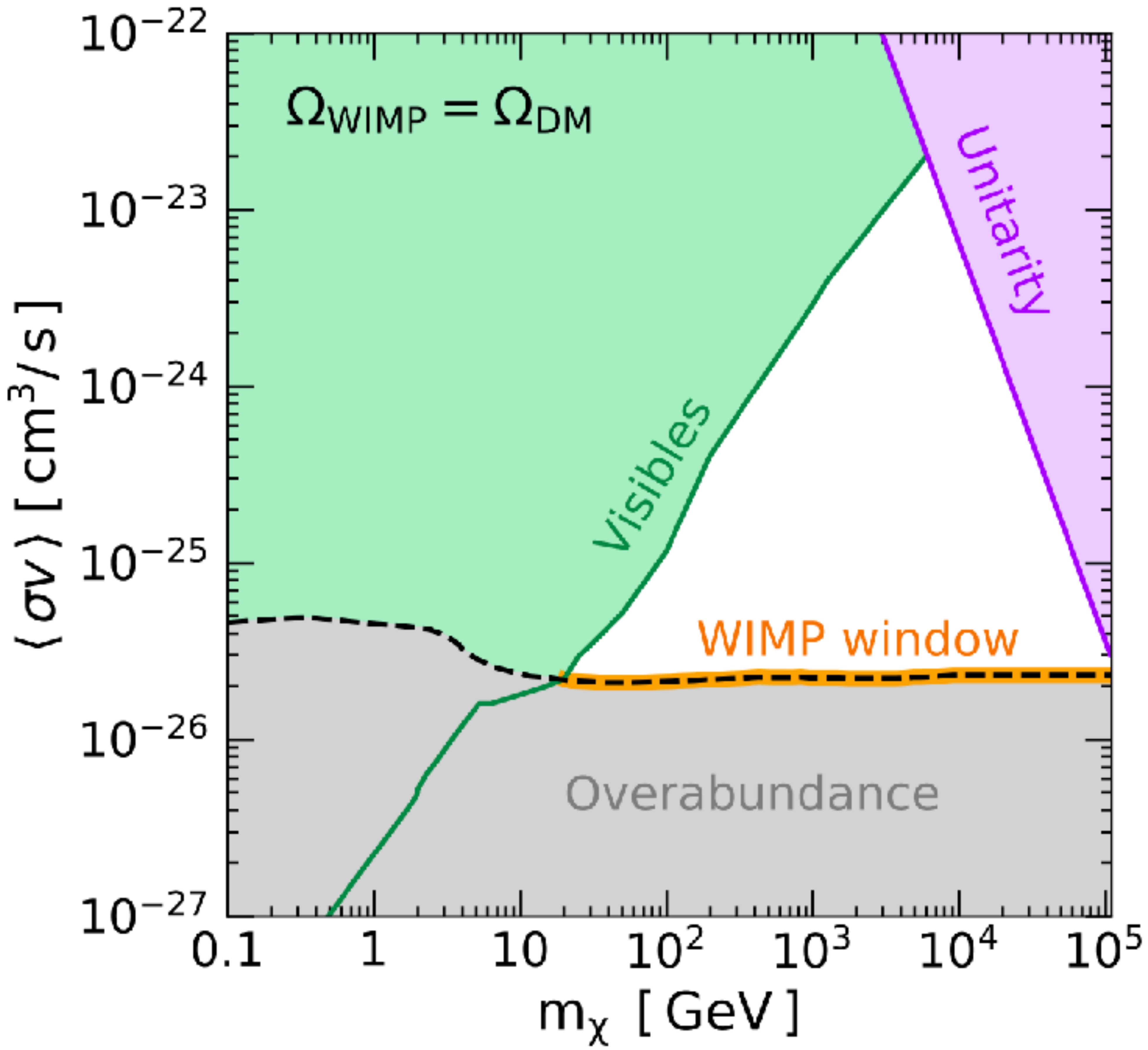


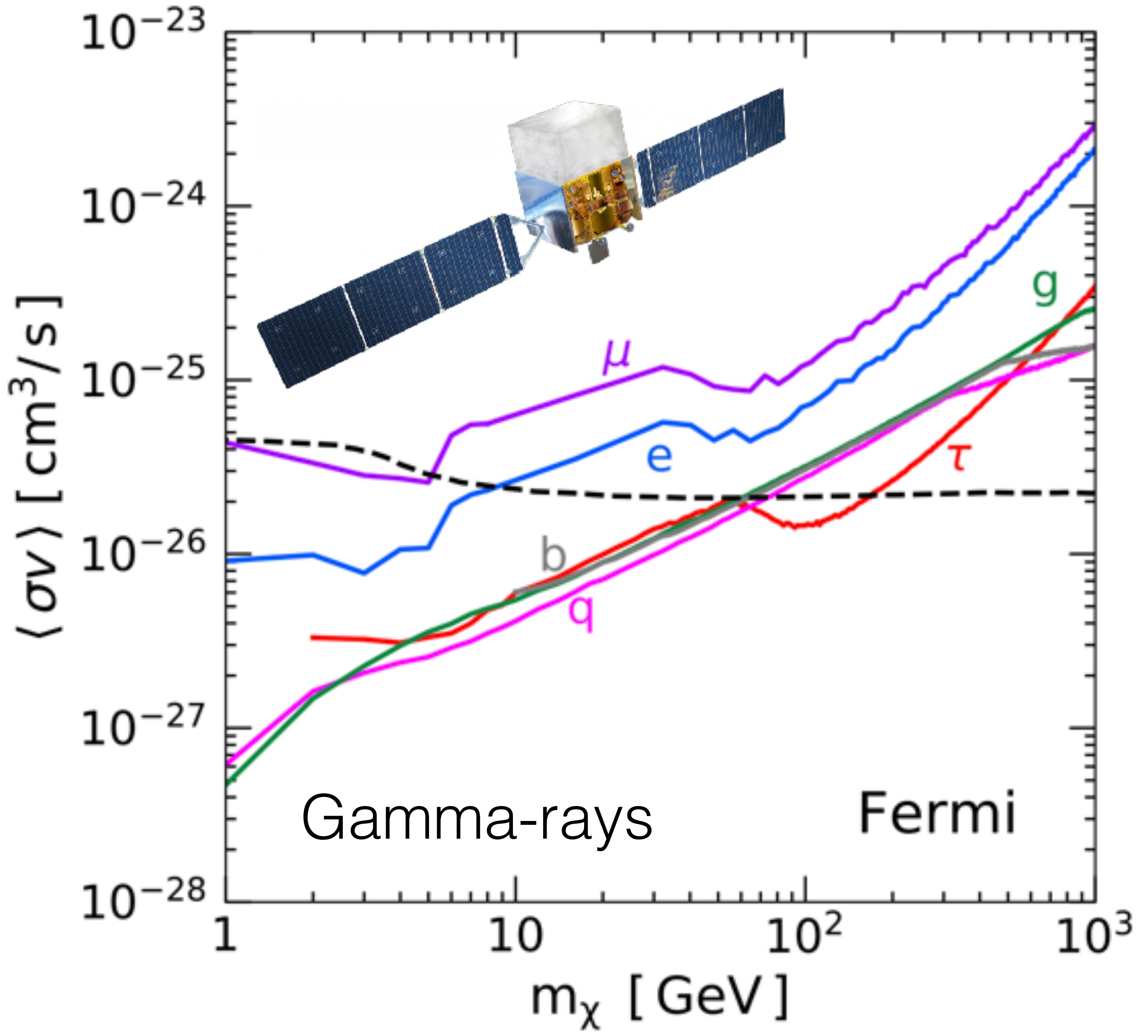
Exact constraints depend on annihilation channel
($\chi\chi \to b\bar{b}, \chi\chi \to W^+W^-, \chi\chi \to e^+e^-$, etc.)

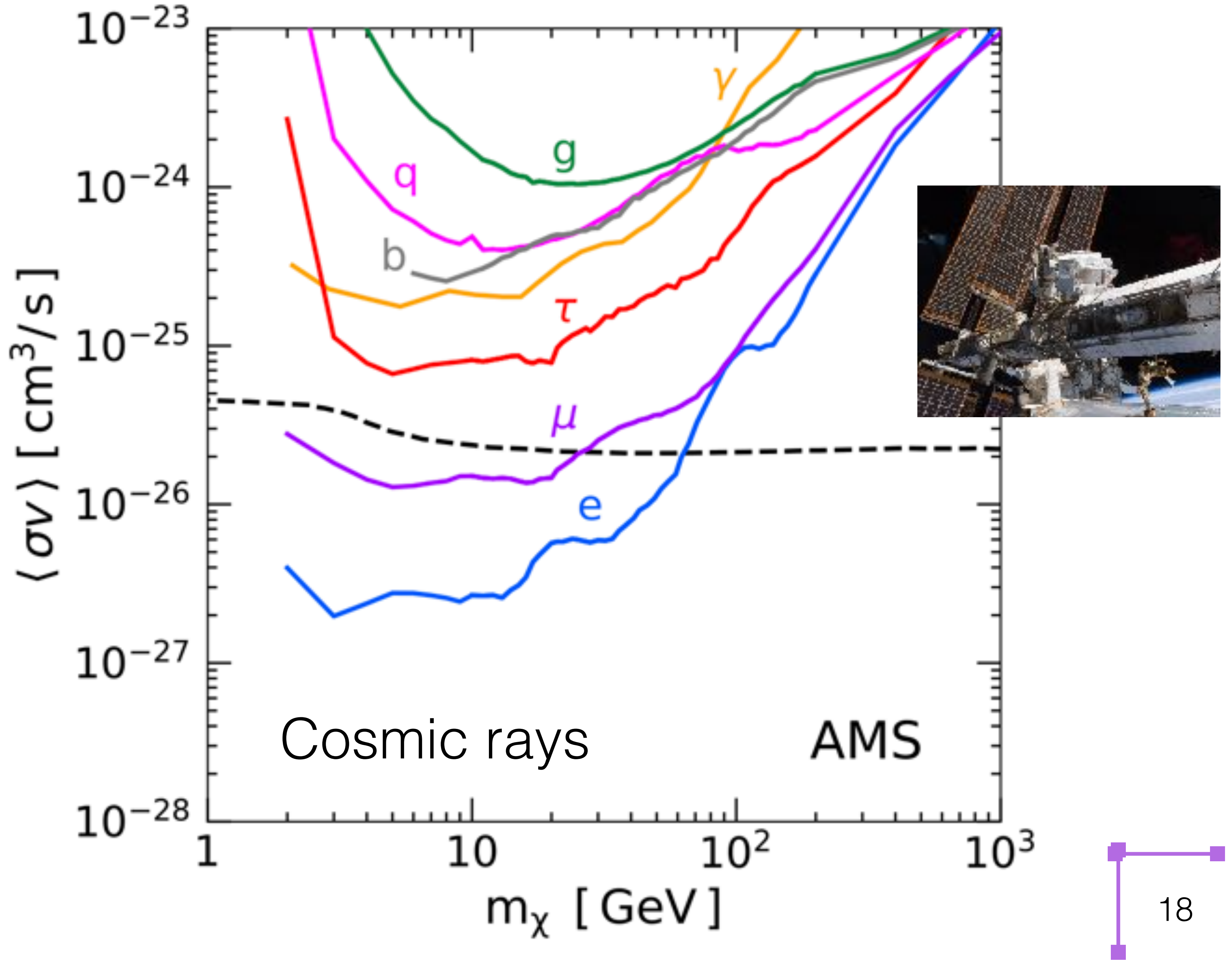
[See also the talk by
Javier Rico this afternoon]

Long live the WIMP

Take the weakest constraint from Fermi and AMS to find the region ruled out by DM annihilation to visible SM particles:





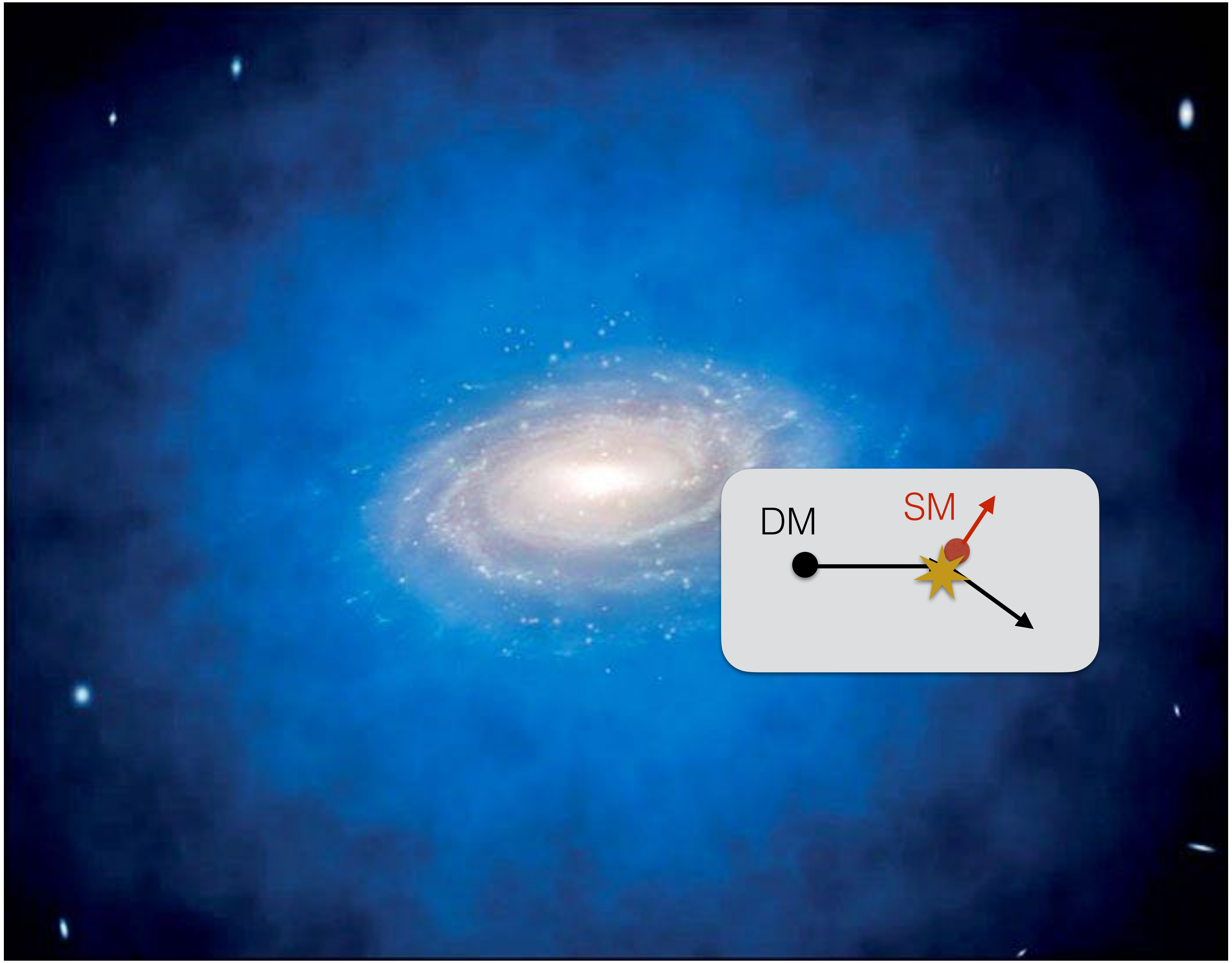


The 'classical' WIMP is alive and well.

[1805.10305]

Direct Detection of Dark Matter

$$\text{Rate} \sim \rho_{\rm DM} \times v_{\rm DM} \times \sigma \times N_{\rm target}$$



$$\rho_{\rm DM} \sim 0.3\,{\rm GeV/cm^3}$$

$$\langle v_{\rm DM} \rangle \sim 300\,{\rm km/s} \sim 10^{-3}\,c$$

Aim to constrain (detect?) DM scattering cross section σ

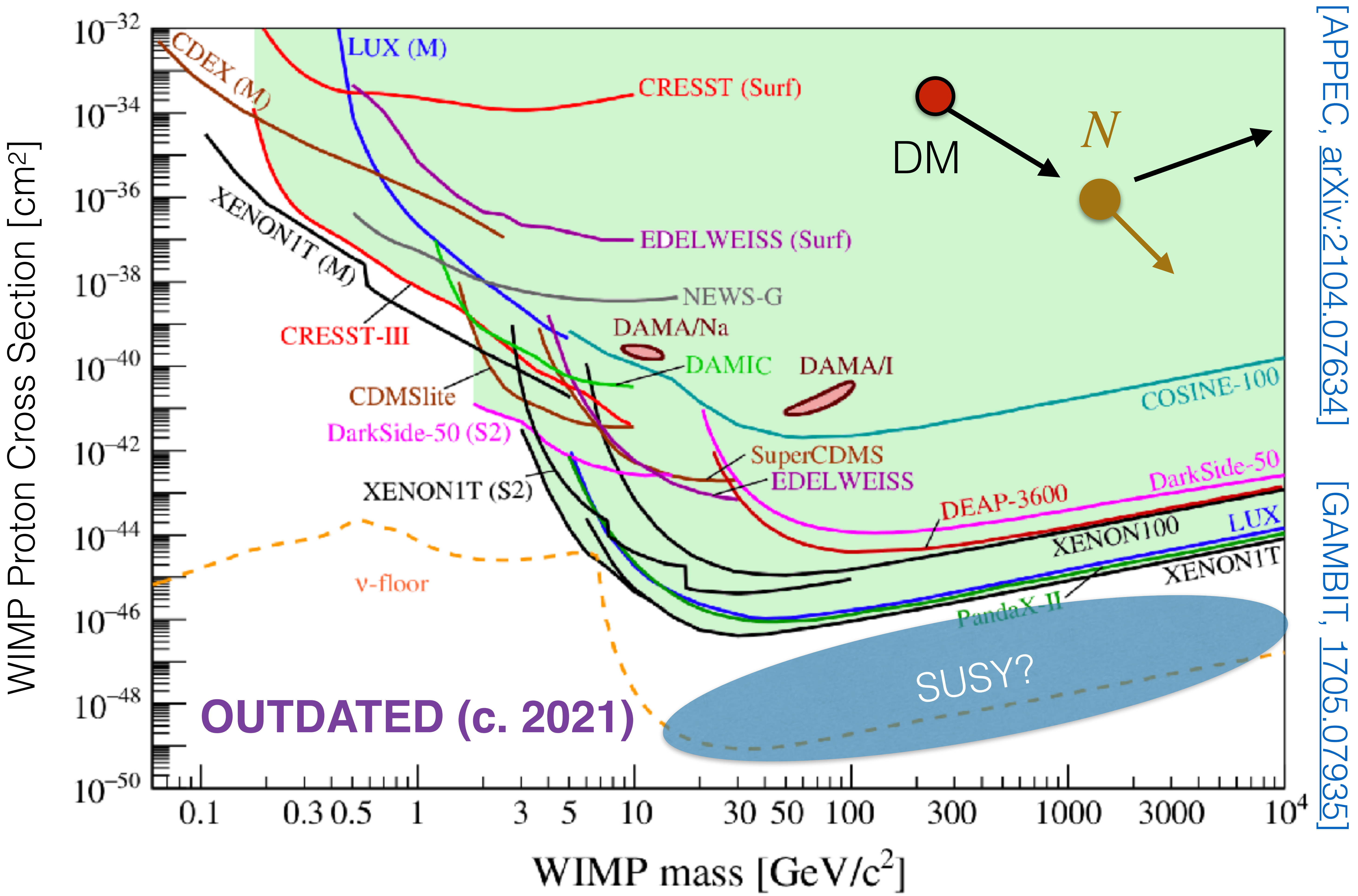
Key detector requirements:

- Low energy threshold
- Low backgrounds
- Large target mass ($N_{\rm target} \uparrow$)

Direct Detection Landscape

[See also the talk by Maria Martinez next]

We typically don't worry too much about obtaining the correct relic density, as long as the DM is Weak Scale.



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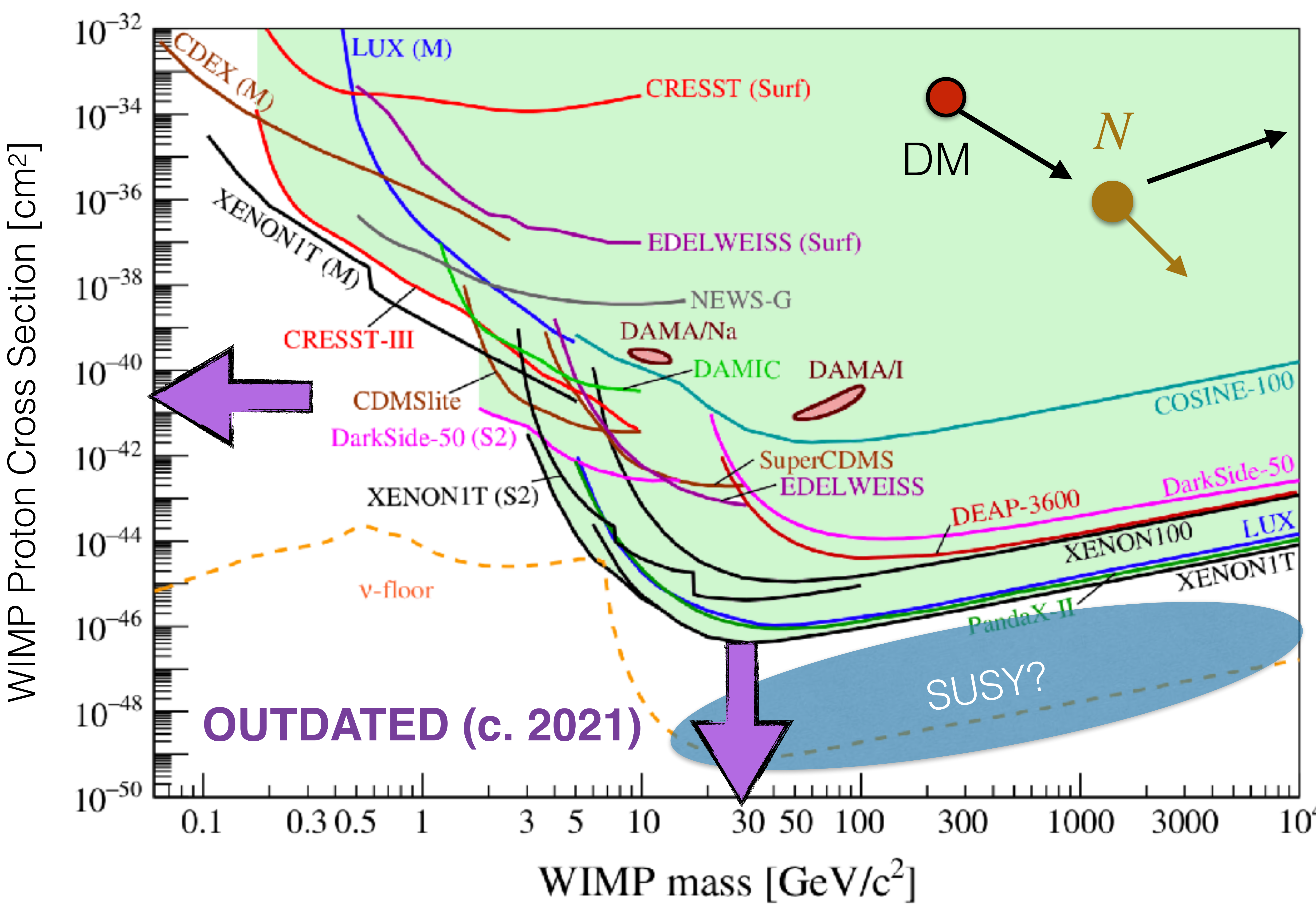

[APPEC, arXiv:2104.07634] [GAMBIT, 1705.07935]

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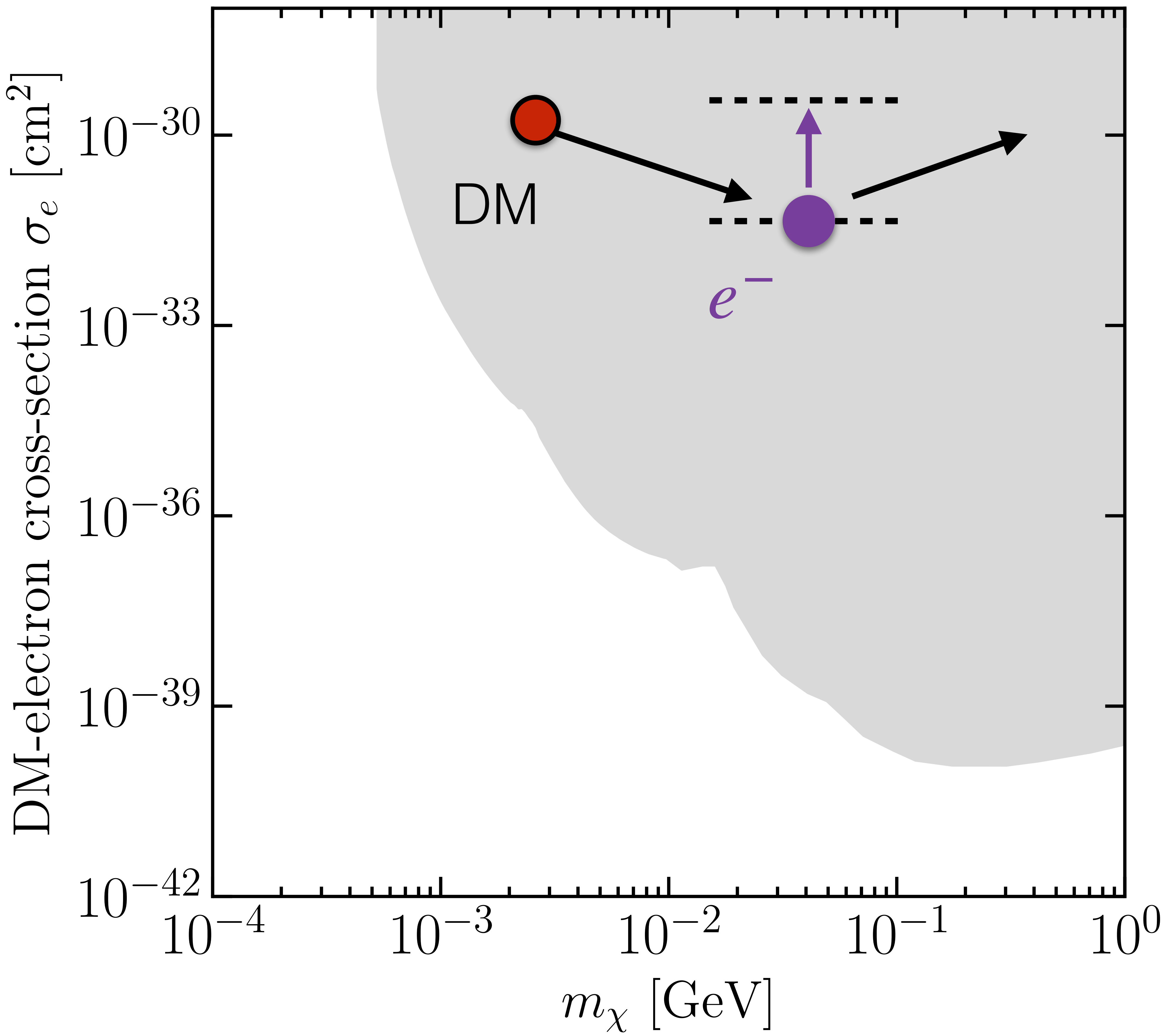
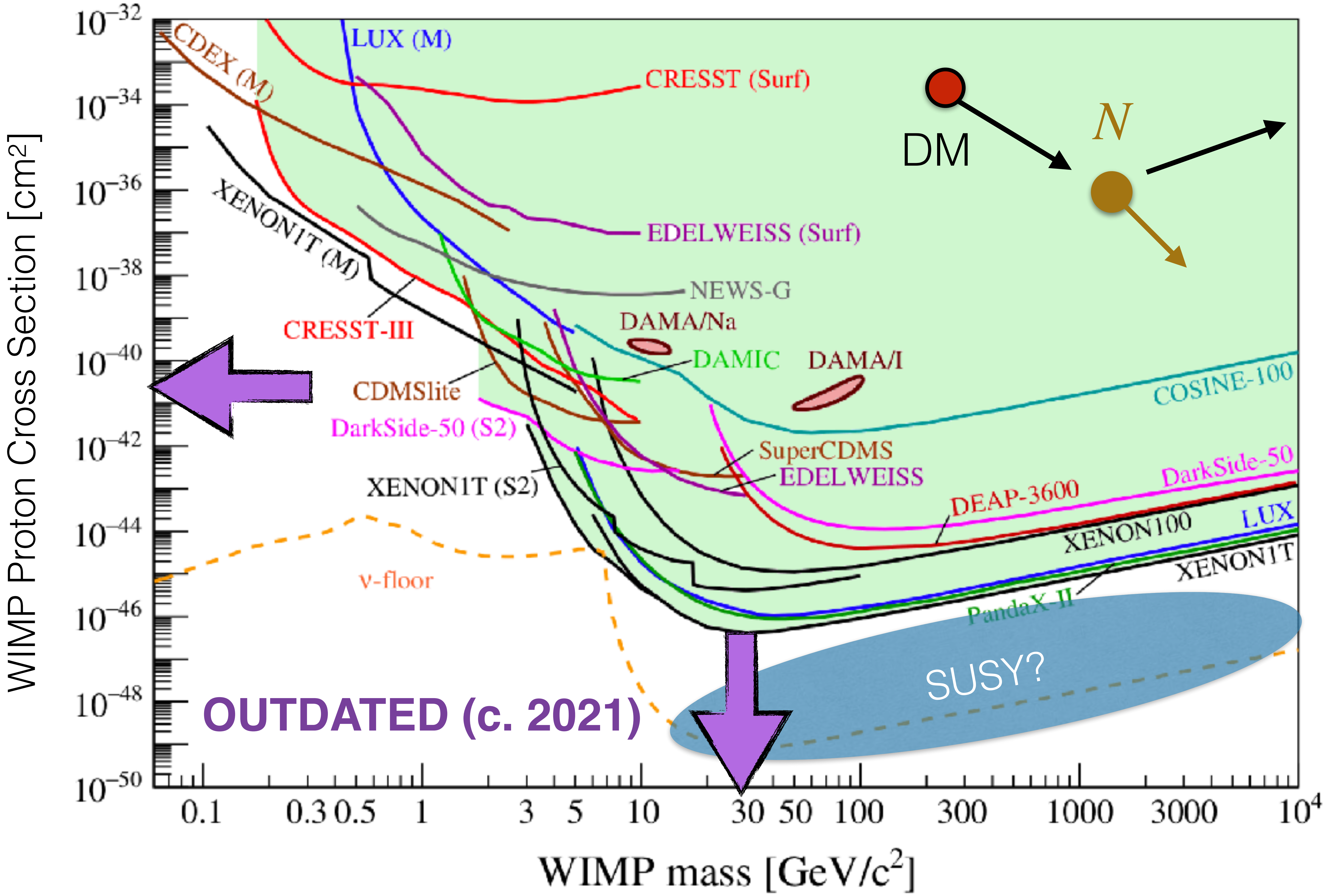




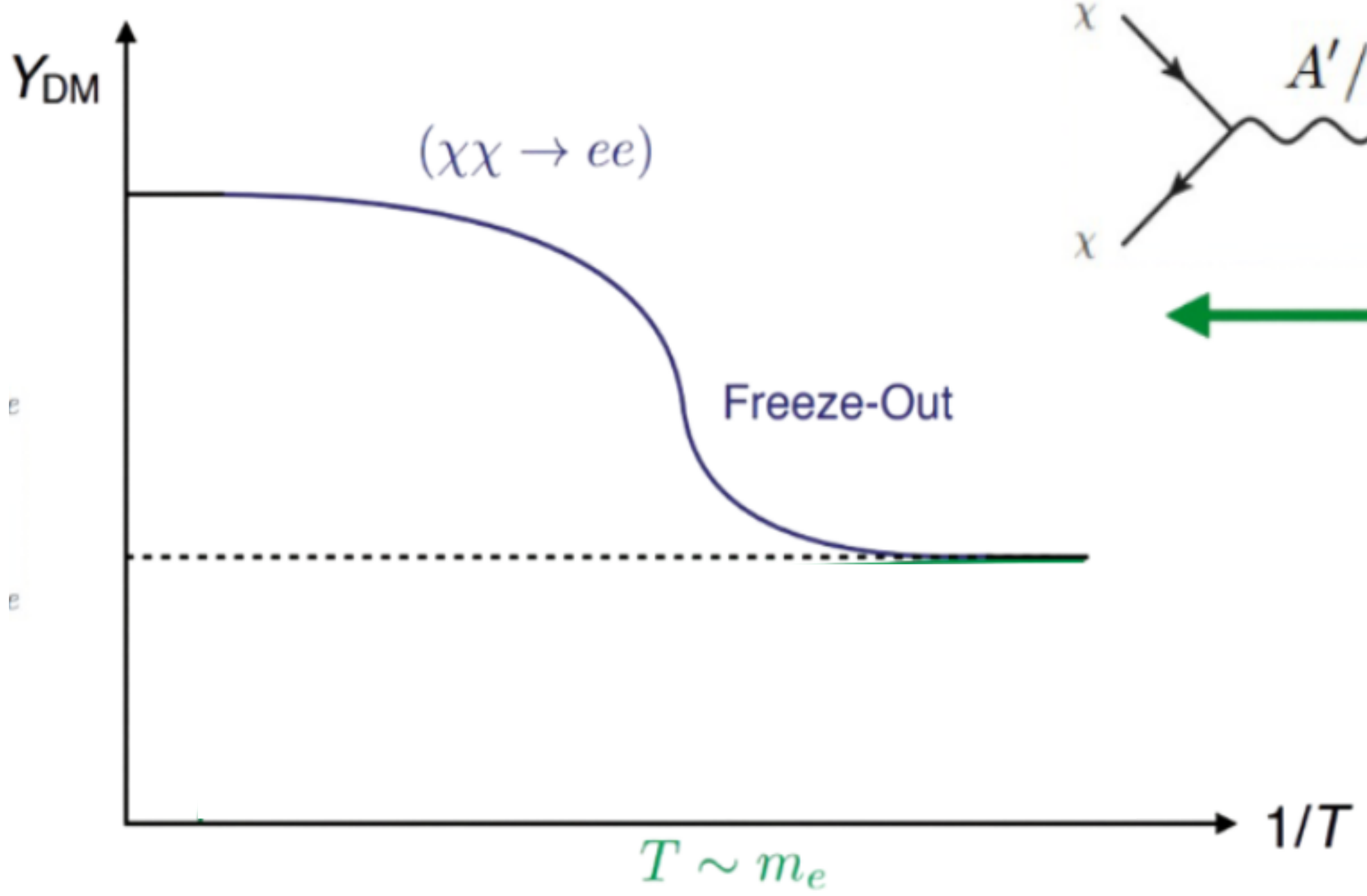
[APPEC, arXiv:2104.07634] [GAMBIT, 1705.07935]

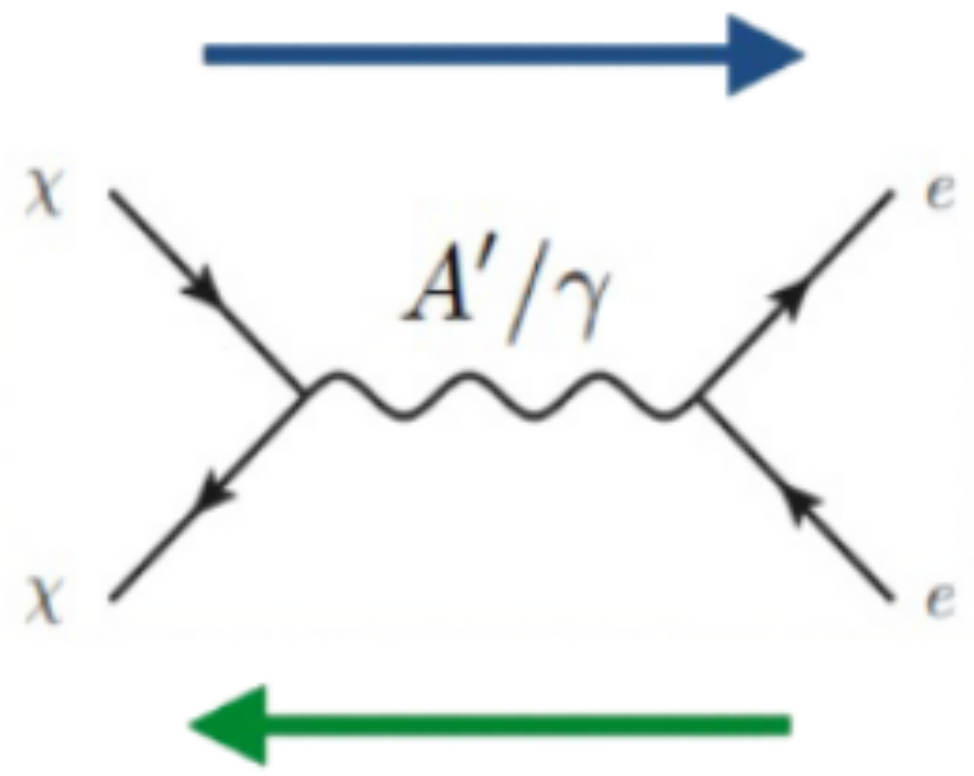
For sub-GeV DM, we want to come up with viable models for DM-electron scattering…

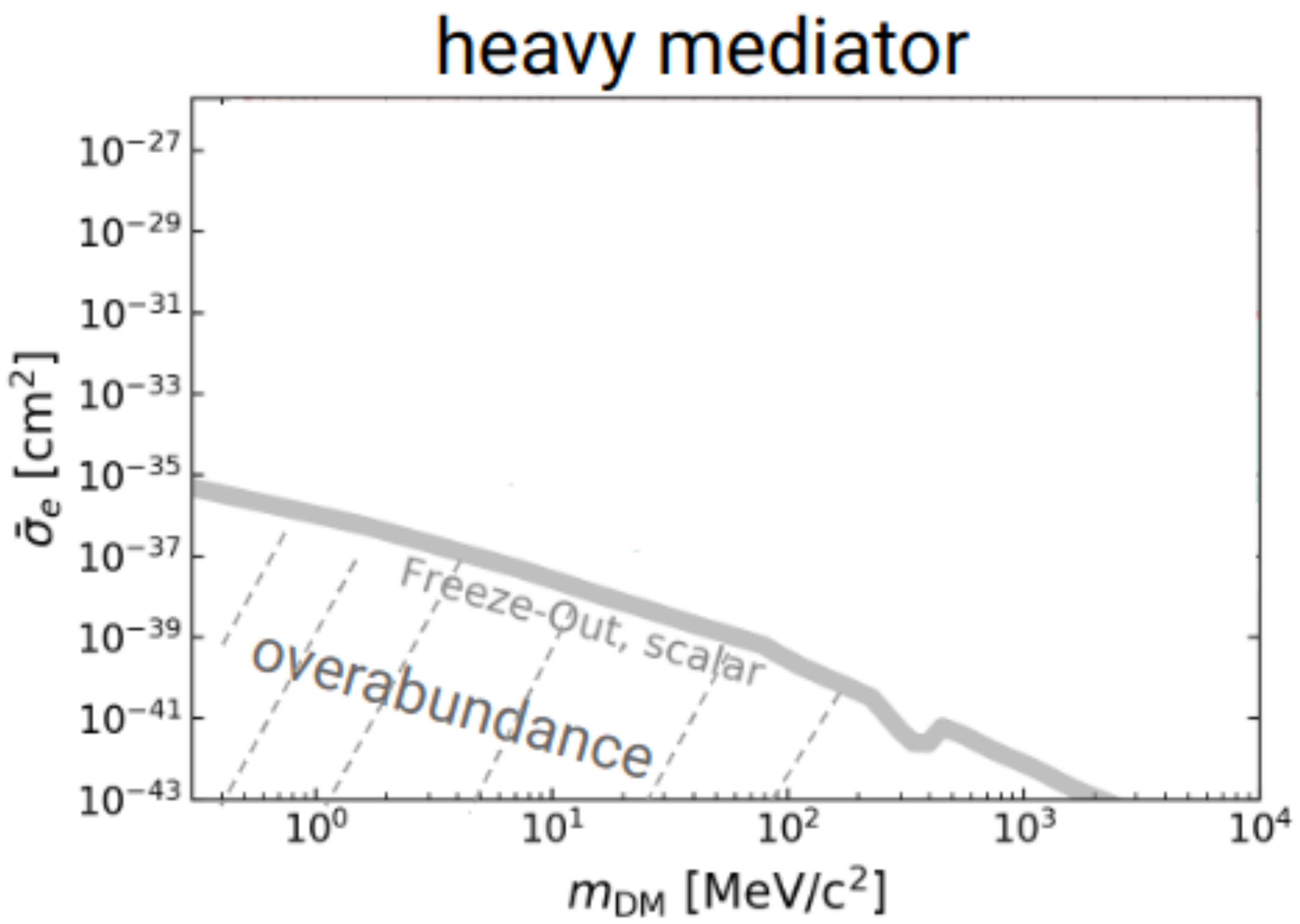
Benchmark Models in Parameter Space

Dark Photon Mediator: Add a dark photon (A') that mixes with the ordinary photon. This acts as a portal between the hidden sector and the SM, coupling to both protons and electrons

$$\mathcal{L}_{int} \sim A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{EM})$$







[Slides inspired by Núria Castello-Mor]

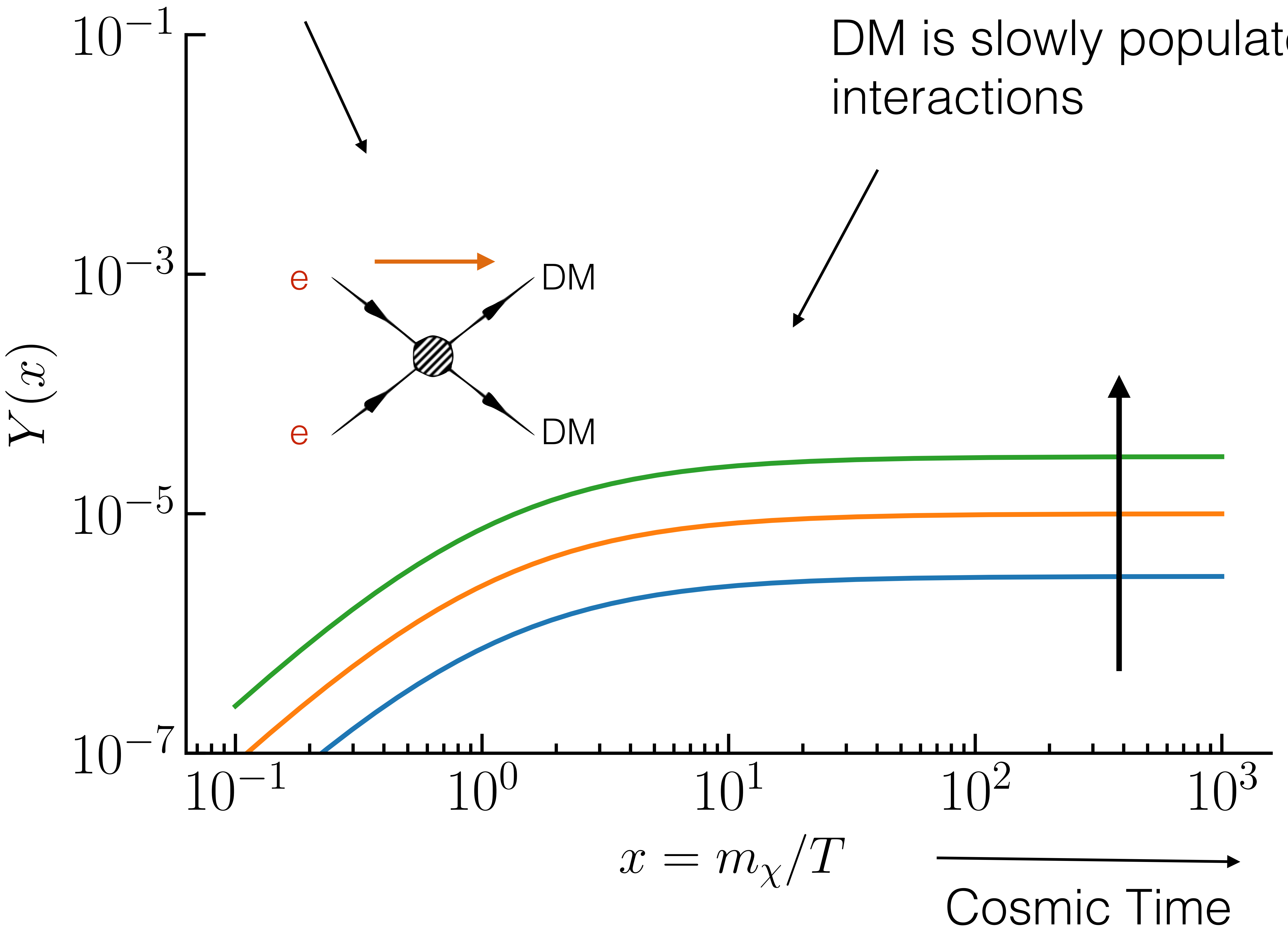
Freeze-in

[Hall et al., 0911.1120]

If DM-SM interactions are *very weak*,
DM never reaches thermal equilibrium

DM is slowly populated by SM interactions

Dark Matter 'Yield'
(~ total DM number)



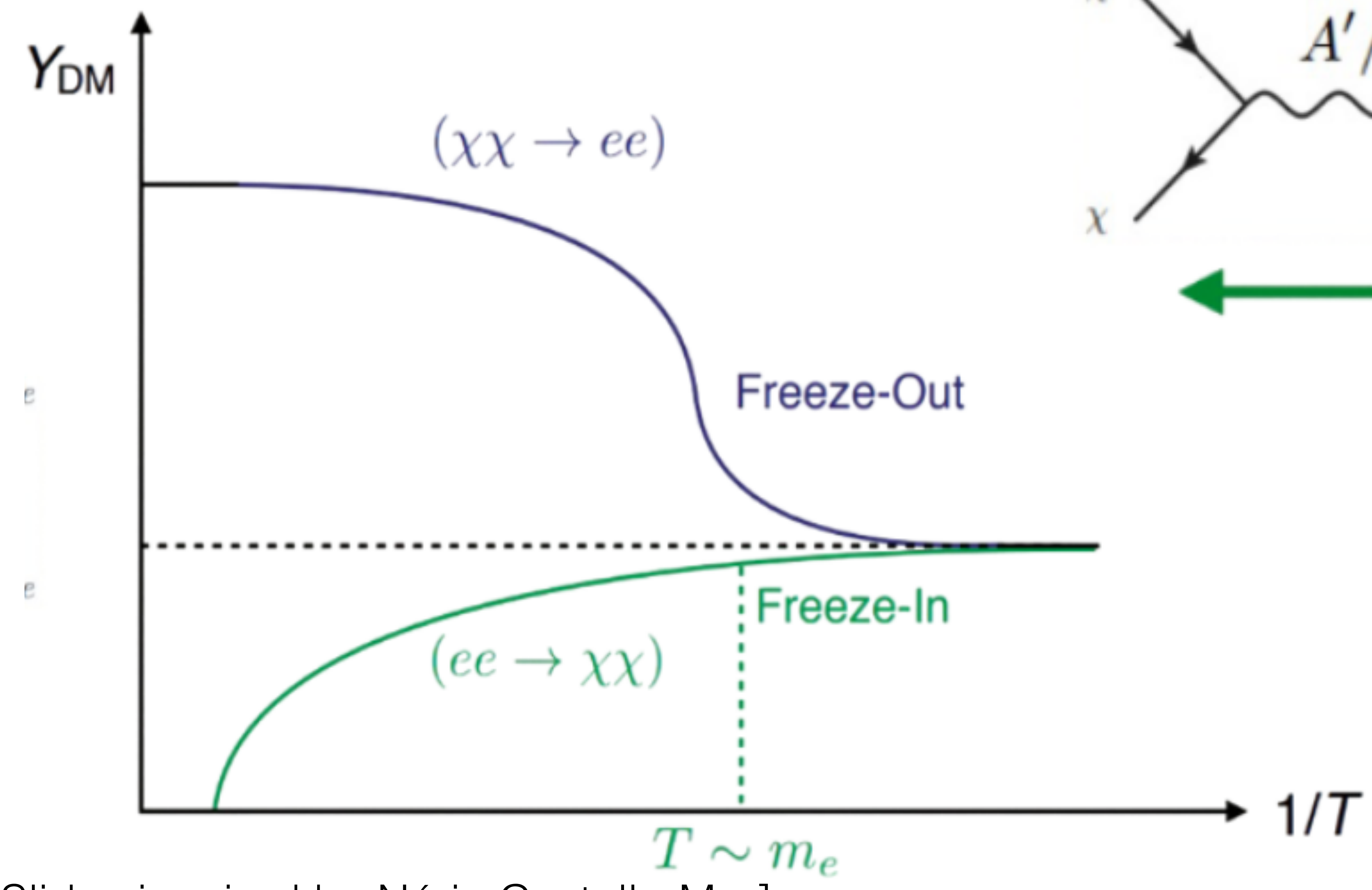
Increasing DM annihilation cross-section, *increases* DM abundance

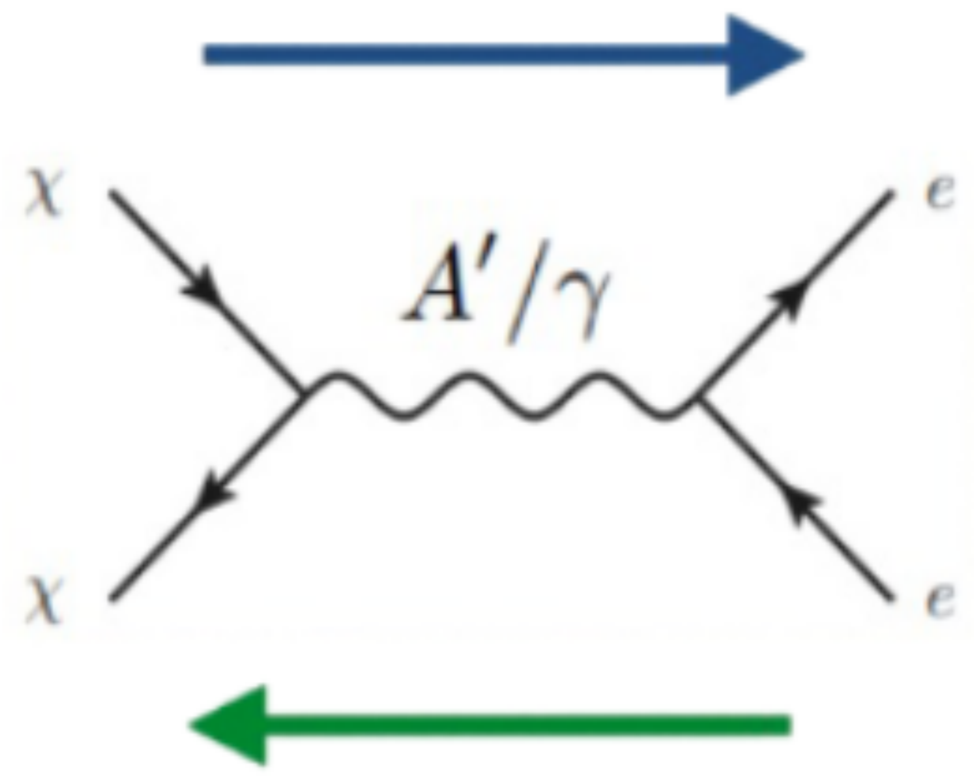
These models are typically hard to probe experimentally, but a light mediator can enhance direct detection cross section…

Benchmark Models in Parameter Space

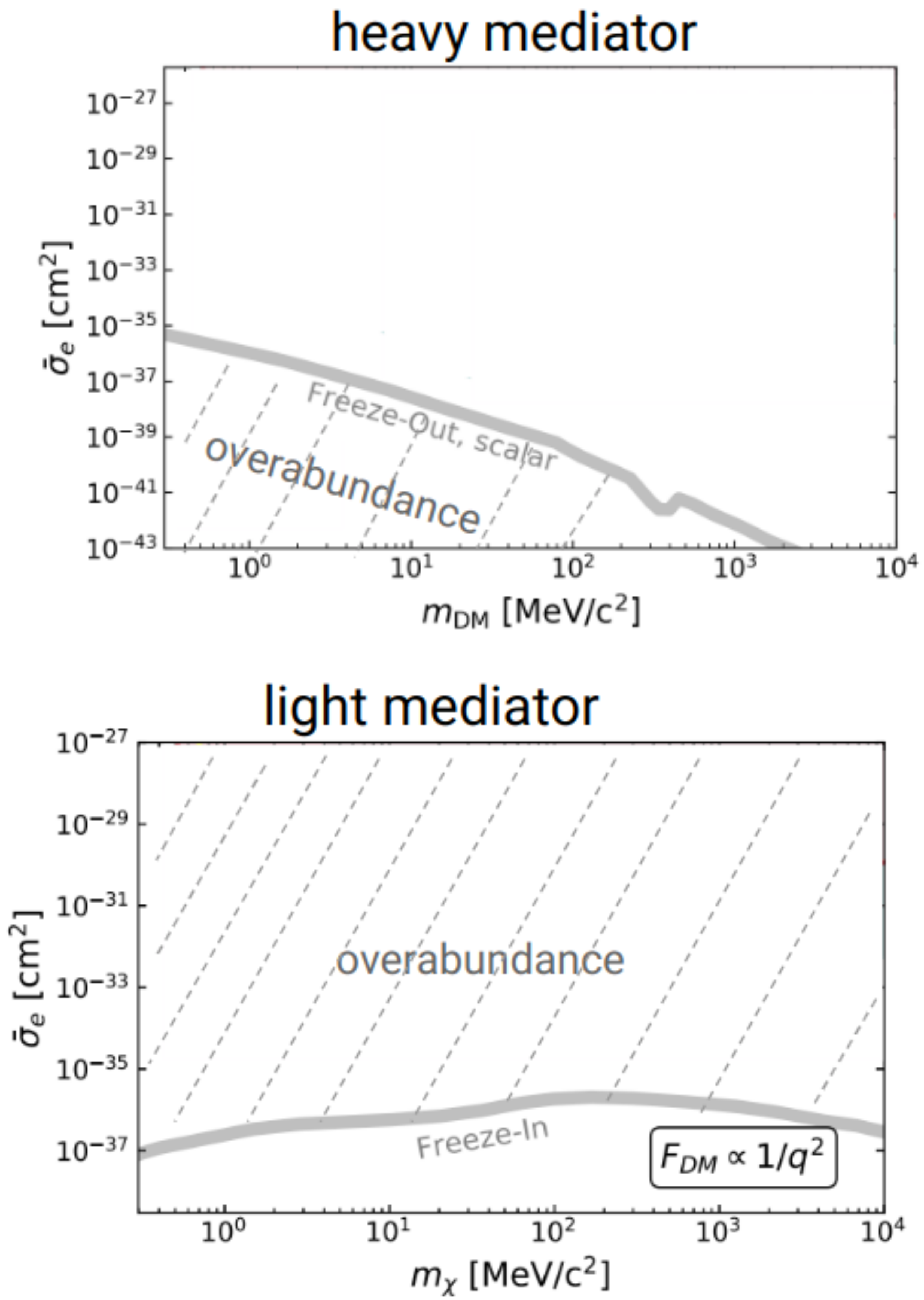
Dark Photon Mediator: Add a dark photon (A') that mixes with the ordinary photon. This acts as a portal between the hidden sector and the SM, coupling to both protons and electrons

$$\mathcal{L}_{int} \sim A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{EM})$$





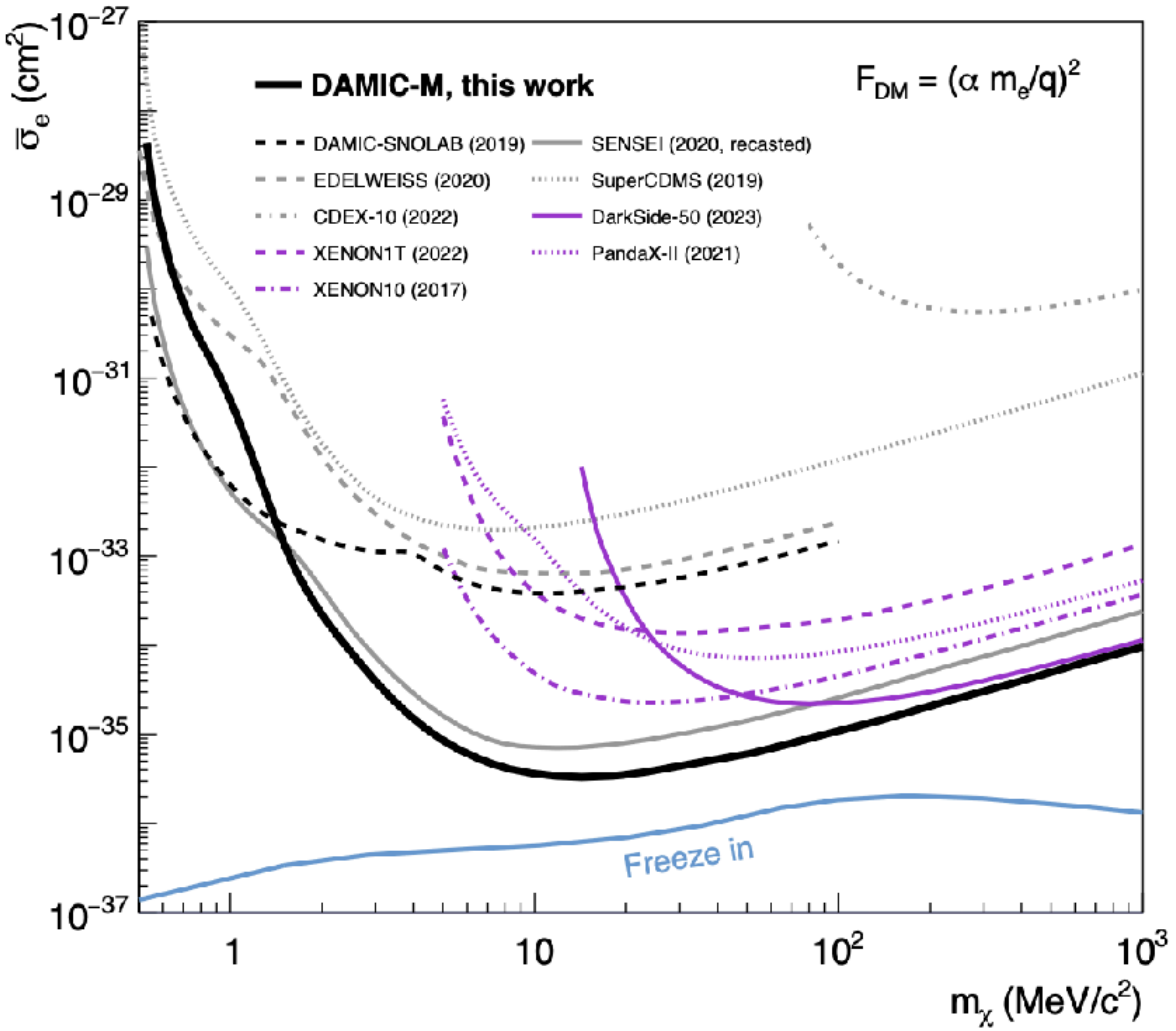
Relevant mechanism depends on dark photon mass

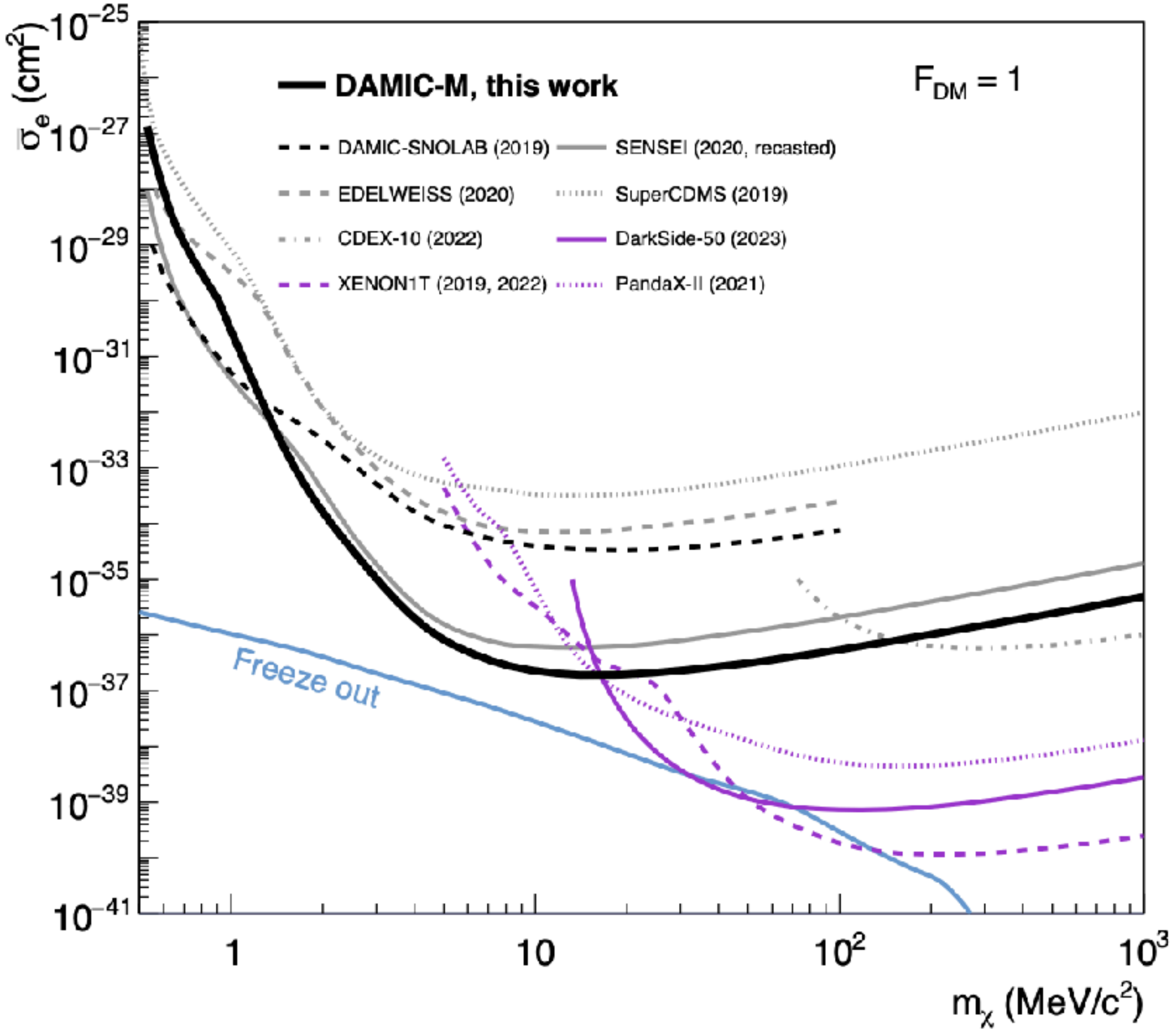


[Slides inspired by Núria Castello-Mor]

Benchmark Models in Parameter Space

OUTDATED (c. 2023)

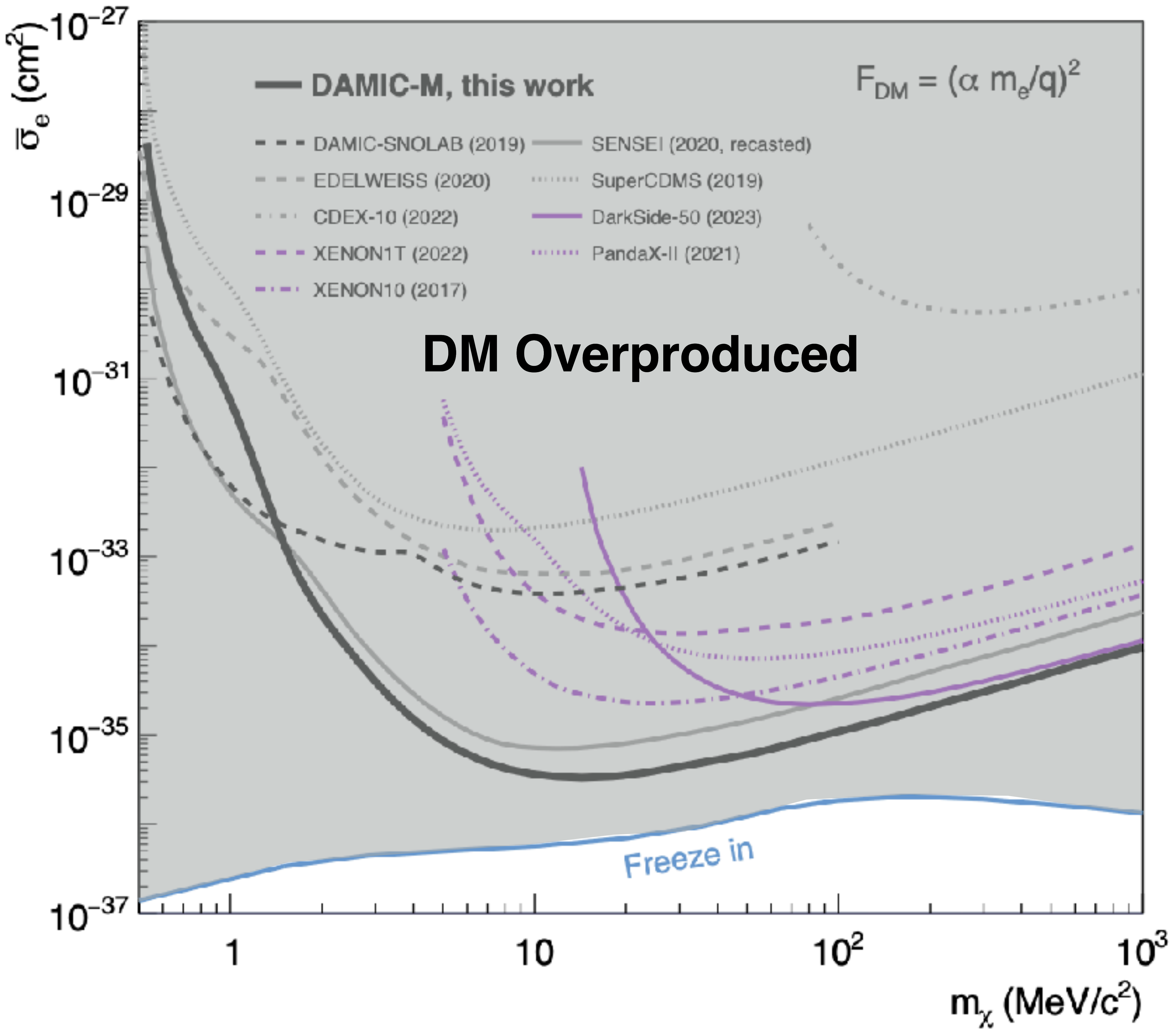


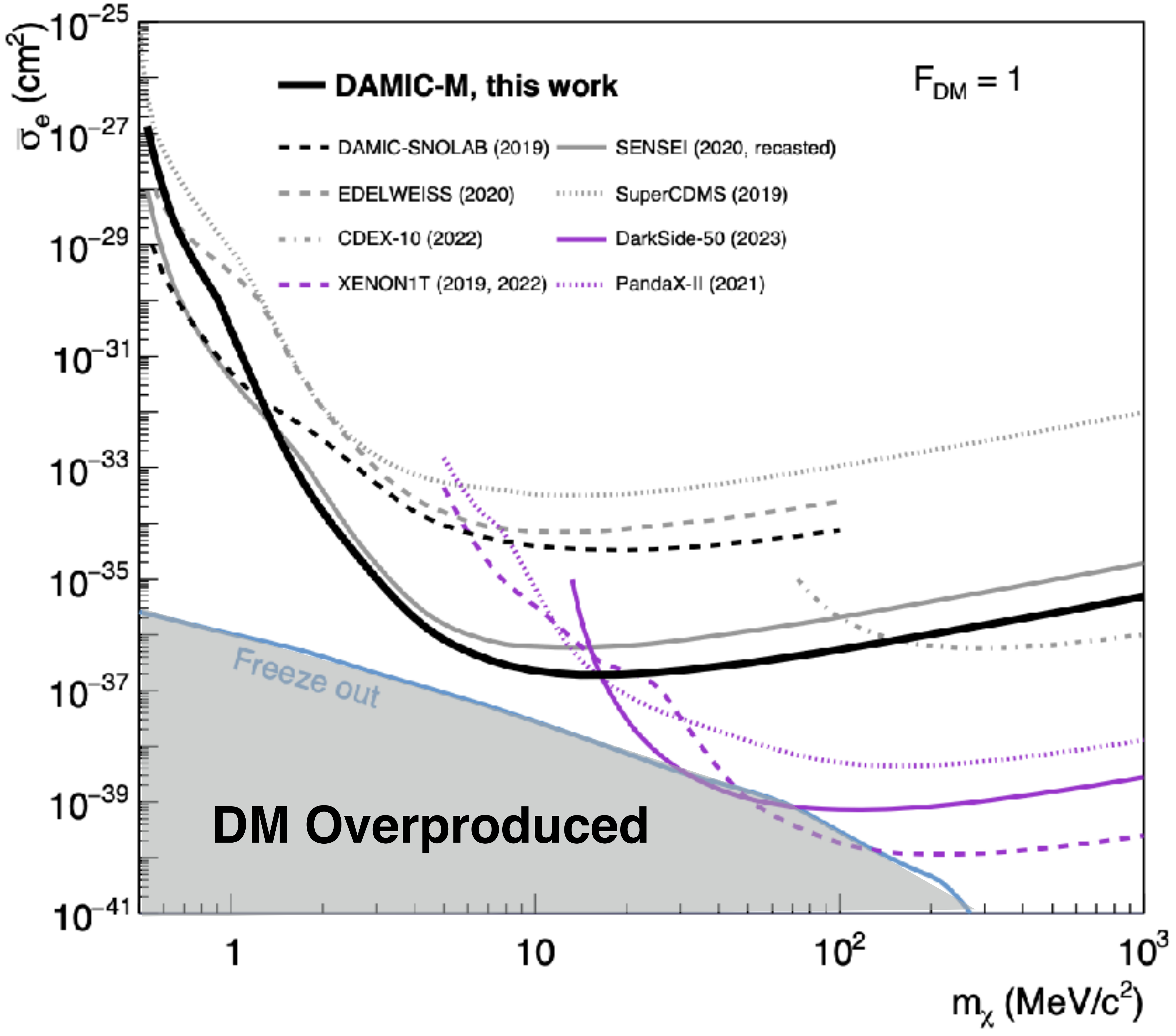


[DAMIC-M Collaboration, 2302.02372]

Benchmark Models in Parameter Space

OUTDATED (c. 2023)



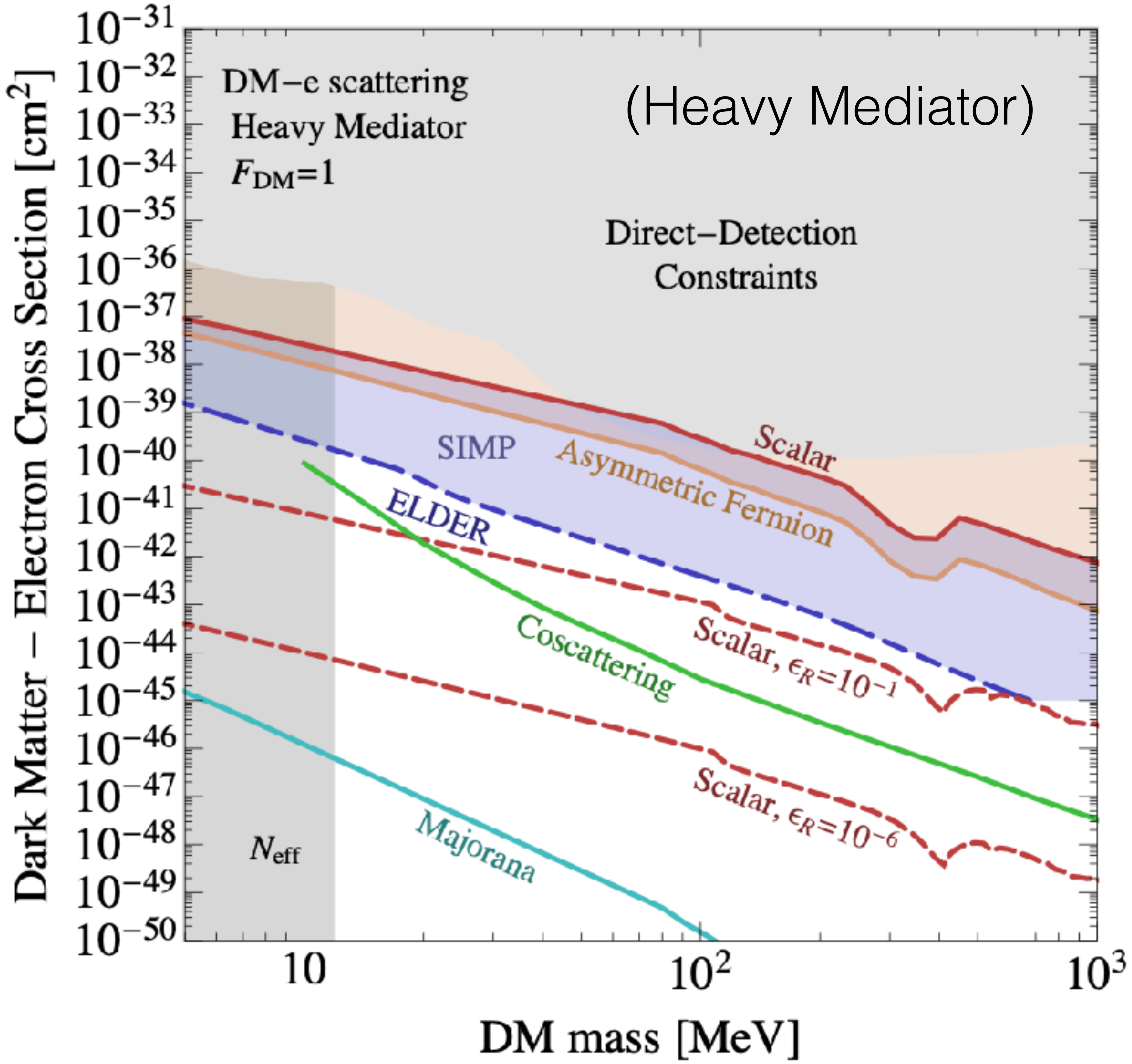


[DAMIC-M Collaboration, 2302.02372]

Beyond Benchmark Models

[See also e.g. 2507.15956, 2603.16863, 2603.03444]

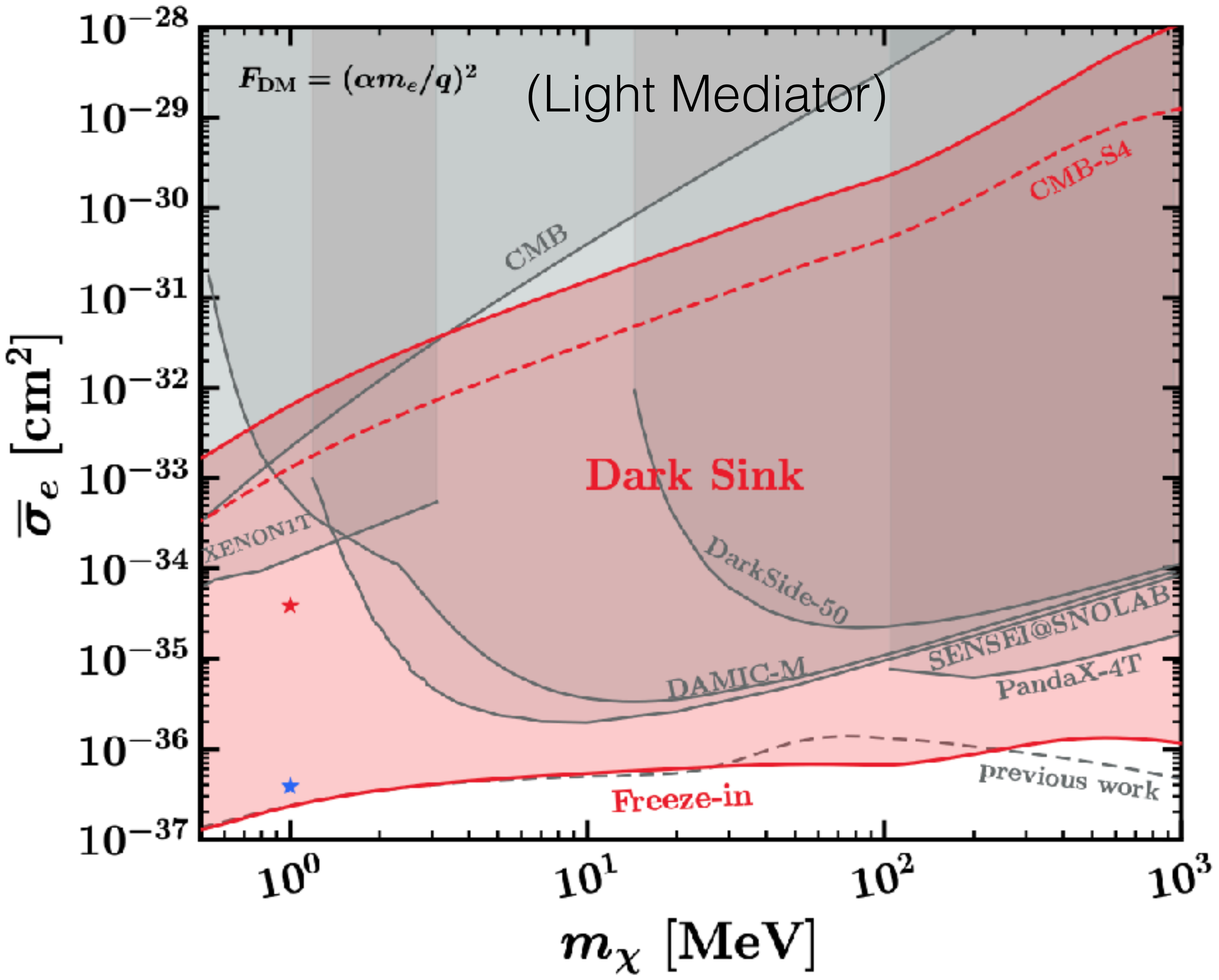
Different DM spins and mediators



[SNOWMASS 2021, 2203.08297]

More complicated Dark Sector

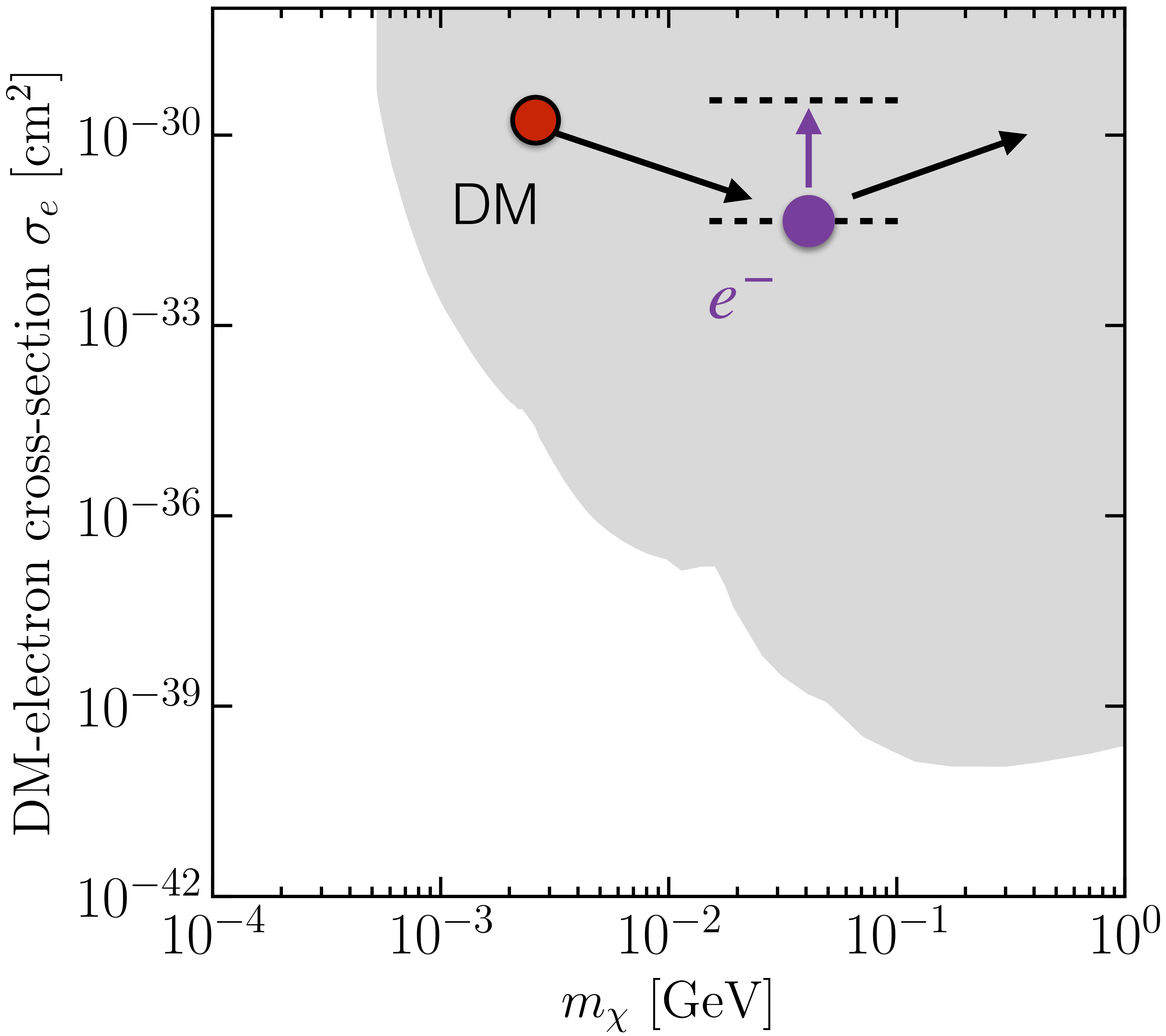
$$\text{SM}\,\text{SM} \to \chi\chi \longleftrightarrow \psi\psi$$

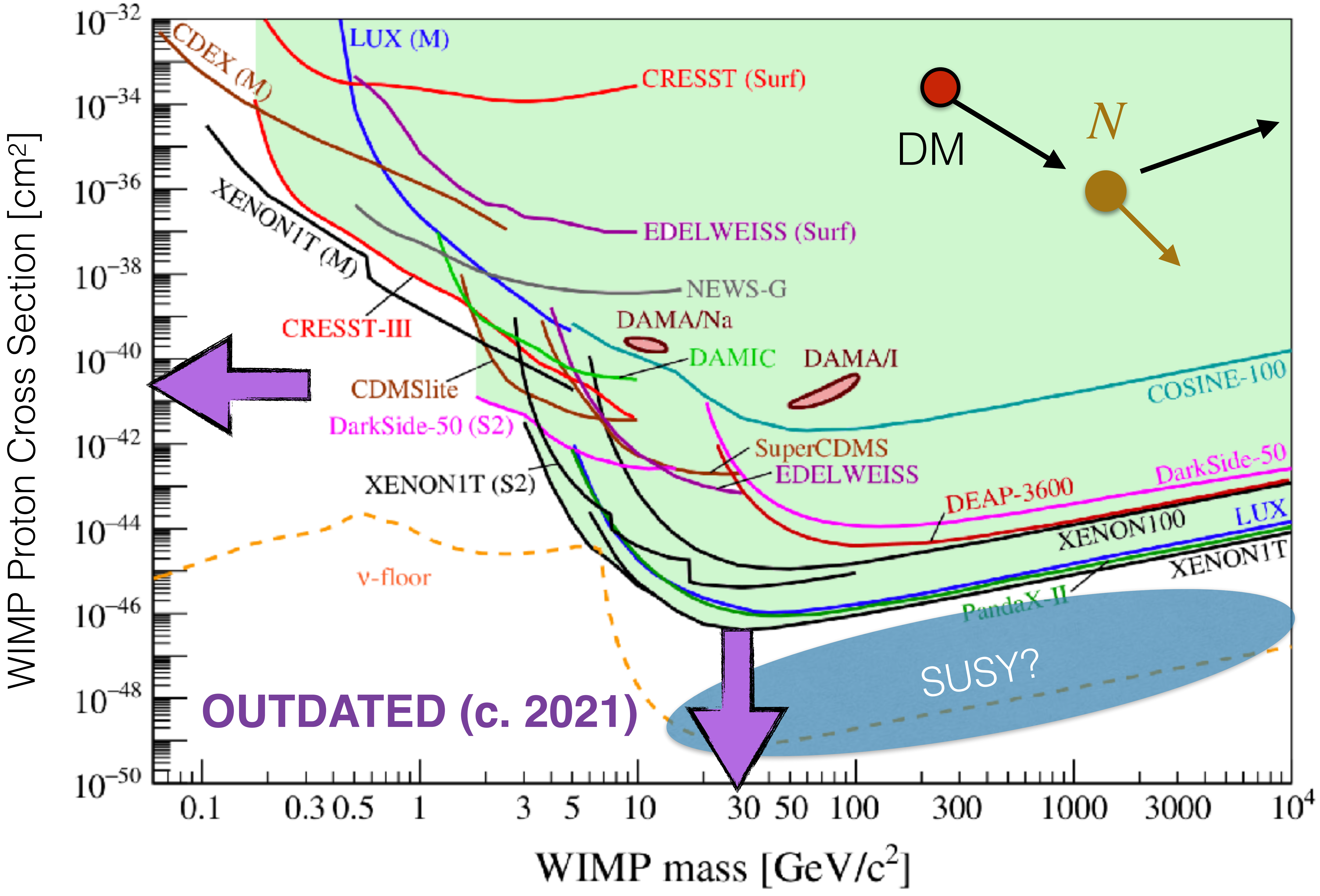


[Bhattiprolu et al., 2312.14152]

New directions in Signal Space

We typically don't worry too much about obtaining the correct relic density, as long as the DM is Weak Scale.

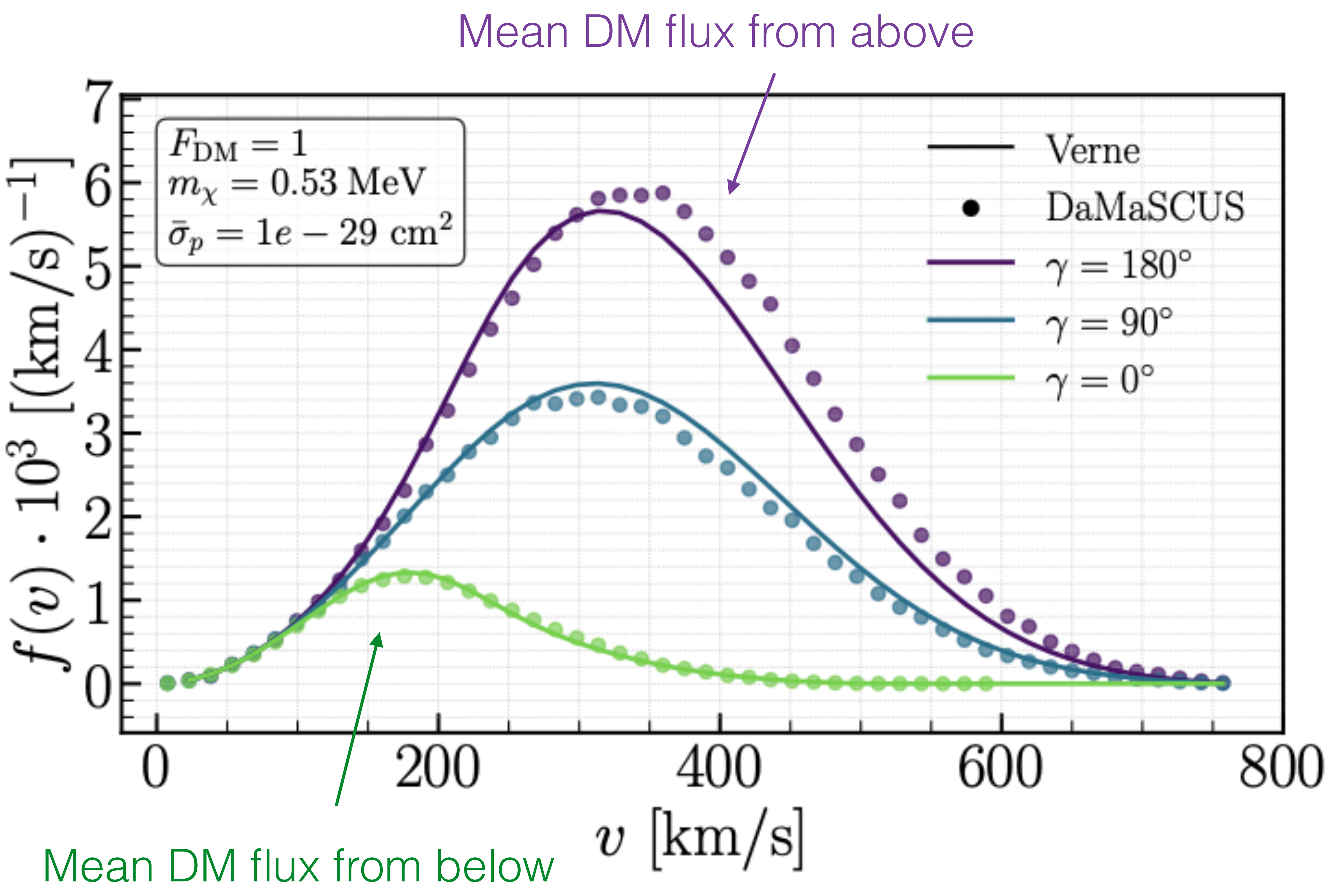


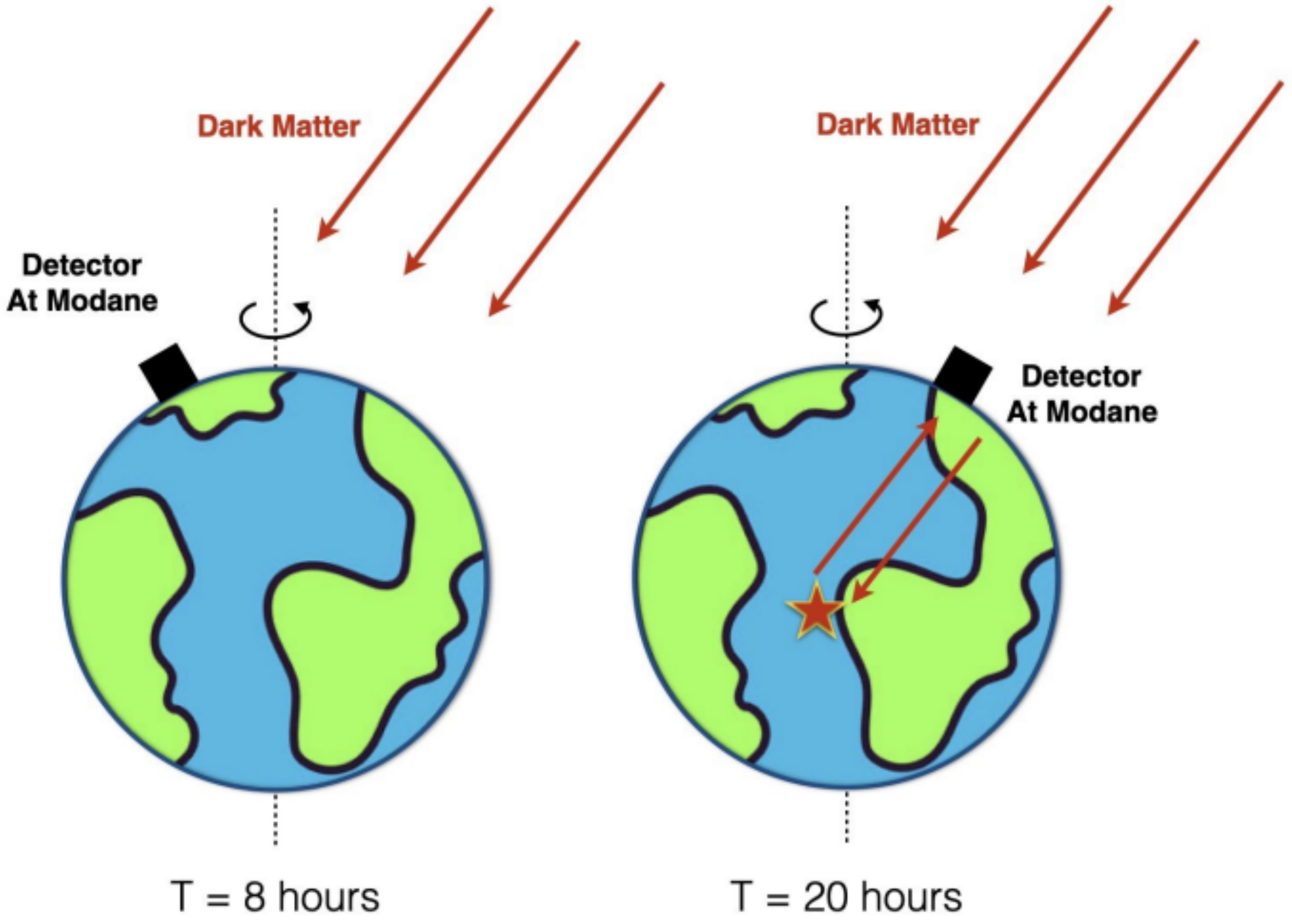


[APPEC, arXiv:2104.07634] [GAMBIT, 1705.07935]

Daily Modulation

If DM has a moderately large scattering cross-section, it may scatter before reaching the detector, distorting the flux [Collar & Avignone, PLB 275, 1992]





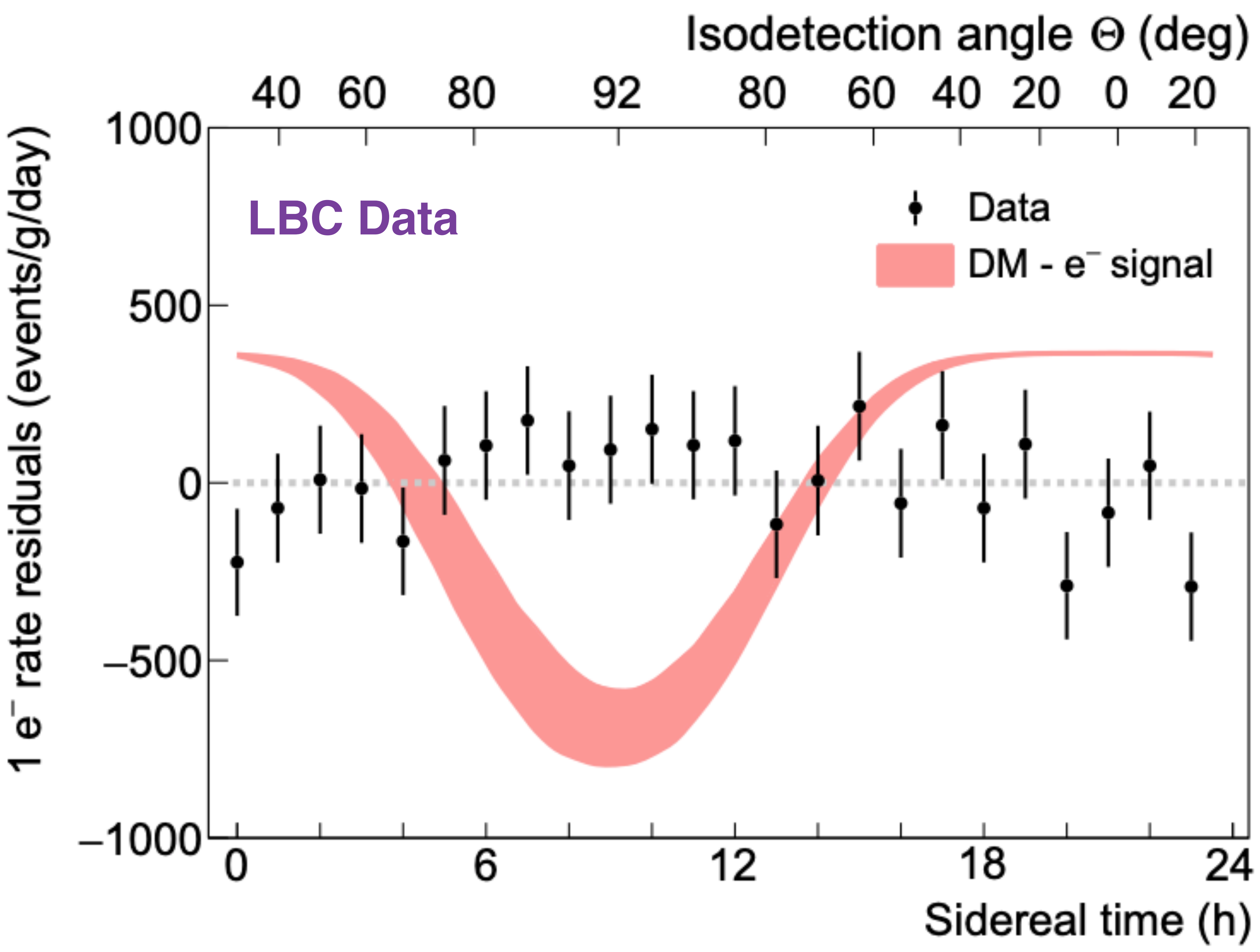
Flux at the detector can be solved using full Monte Carlos simulations of DM trajectories

[DaMaSCUS by Emken & Kouvaris, 1706.02249]

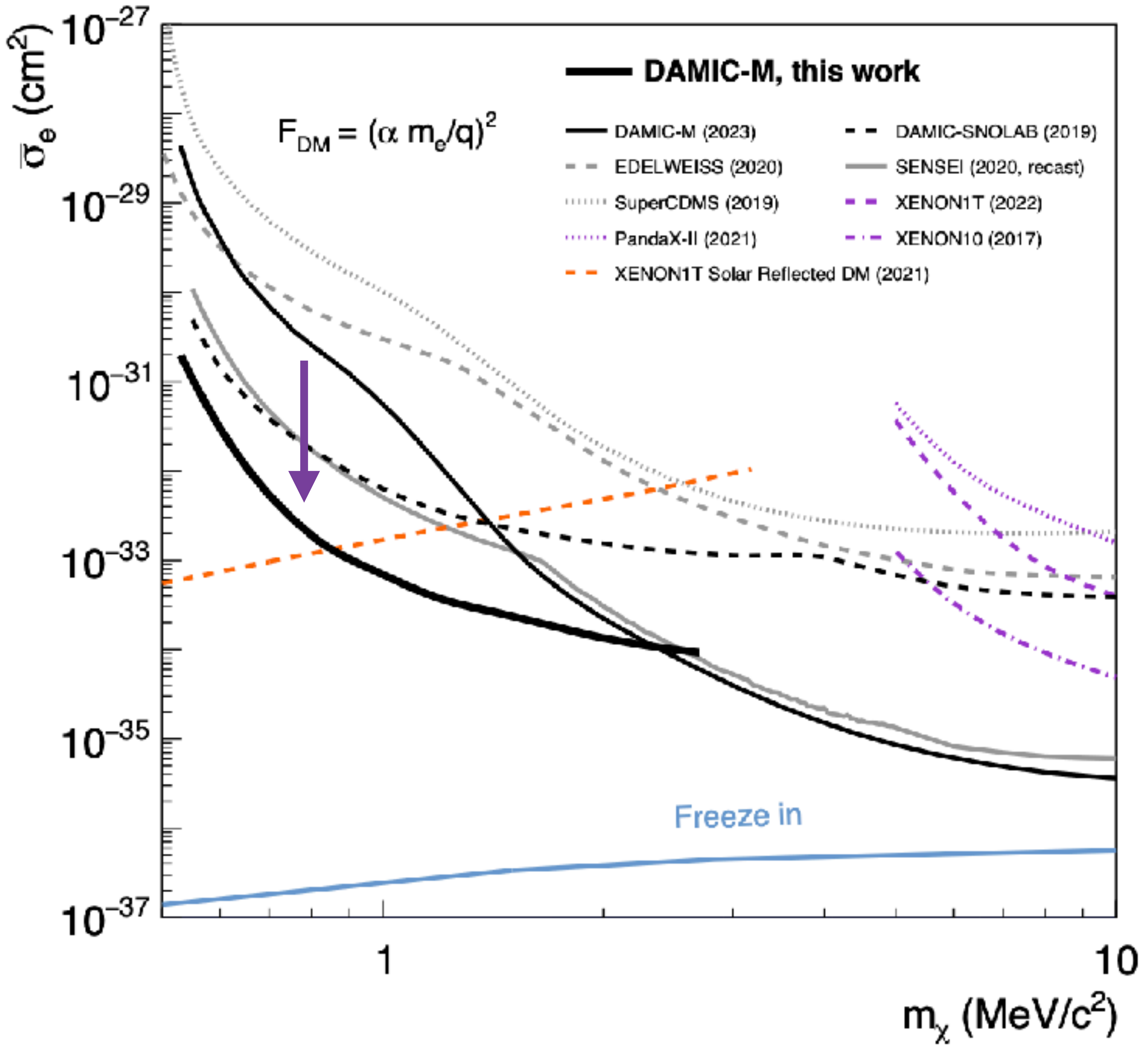
Recent progress in fast semi-analytic estimates of the signal [**BJK** et al., 1611.05453, 1712.04901, 2511.10589]

Daily Modulation Searches

This daily modulated signal allows you to beat an otherwise irreducible (time-independent) background:



[DAMIC-M Collaboration (including **BJK**), 2307.07251]

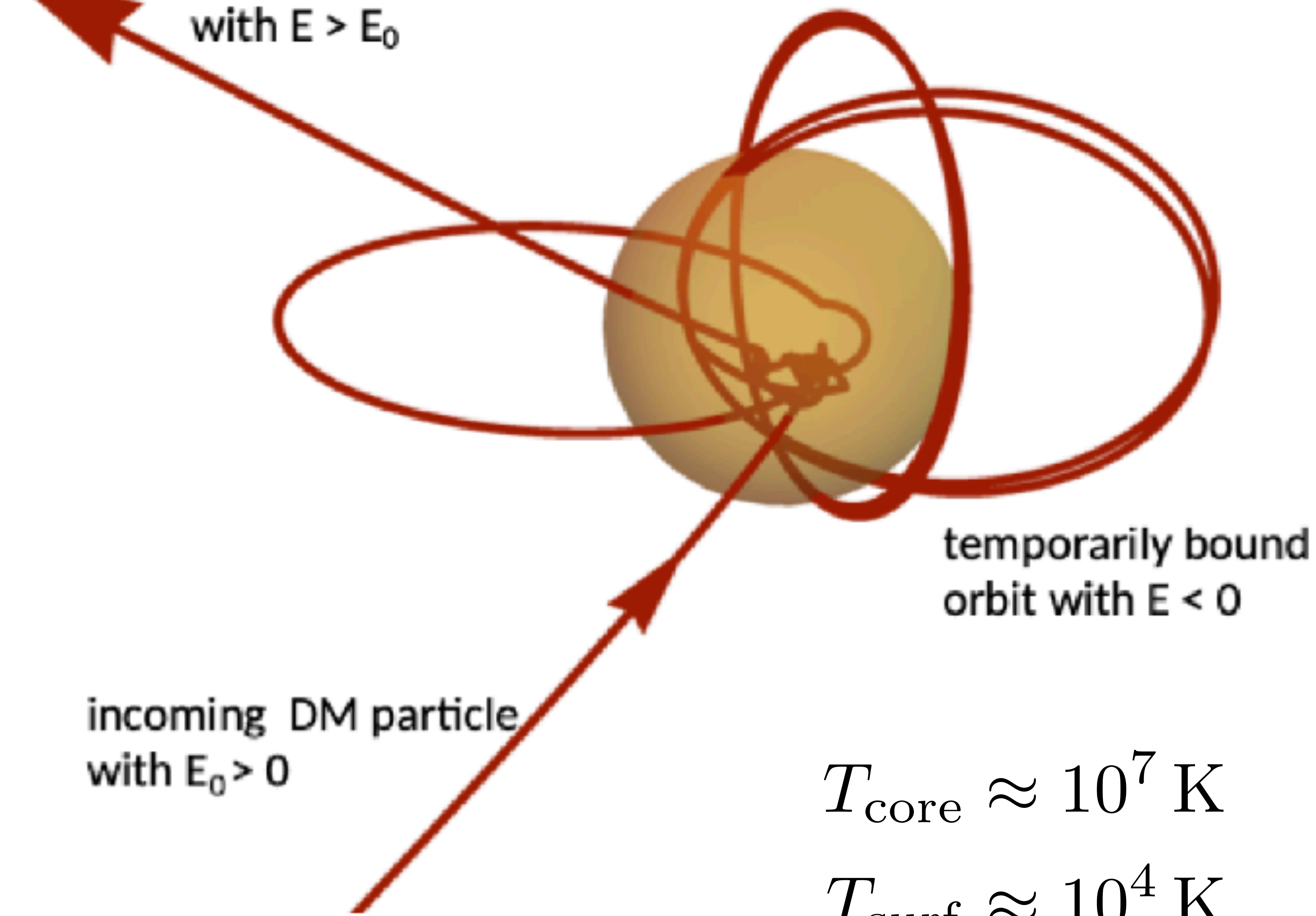


[See also SENSEI Collaboration, 2510.20889]

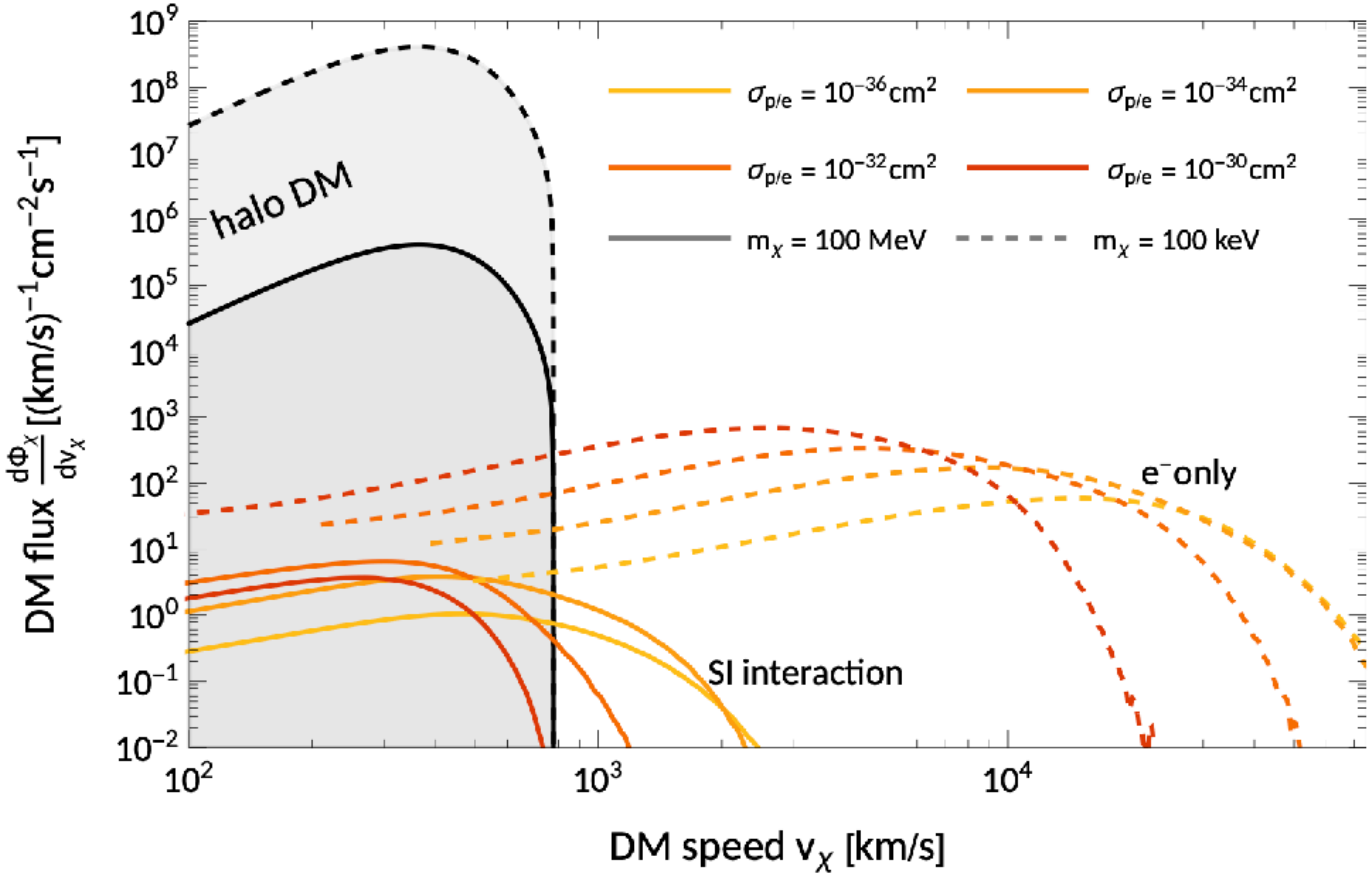
Solar Reflected DM

[An et al., 2108.10332]

Dark Matter may also scatter in the Sun off hot protons and electrons and be reflected towards us.



$$T_{\rm core} \approx 10^7\,{\rm K}$$
$$T_{\rm surf} \approx 10^4\,{\rm K}$$



Detailed Monte Carlo simulations show complicated mass+cross section dependence (depends on whether the DM can penetrate into the hotter centre of the Sun, or scattered in the cool outer layers).

[Emken et al., 2102.12483, 2404.10066]

Solar Reflected DM Searches

[An et al., 2108.10332]

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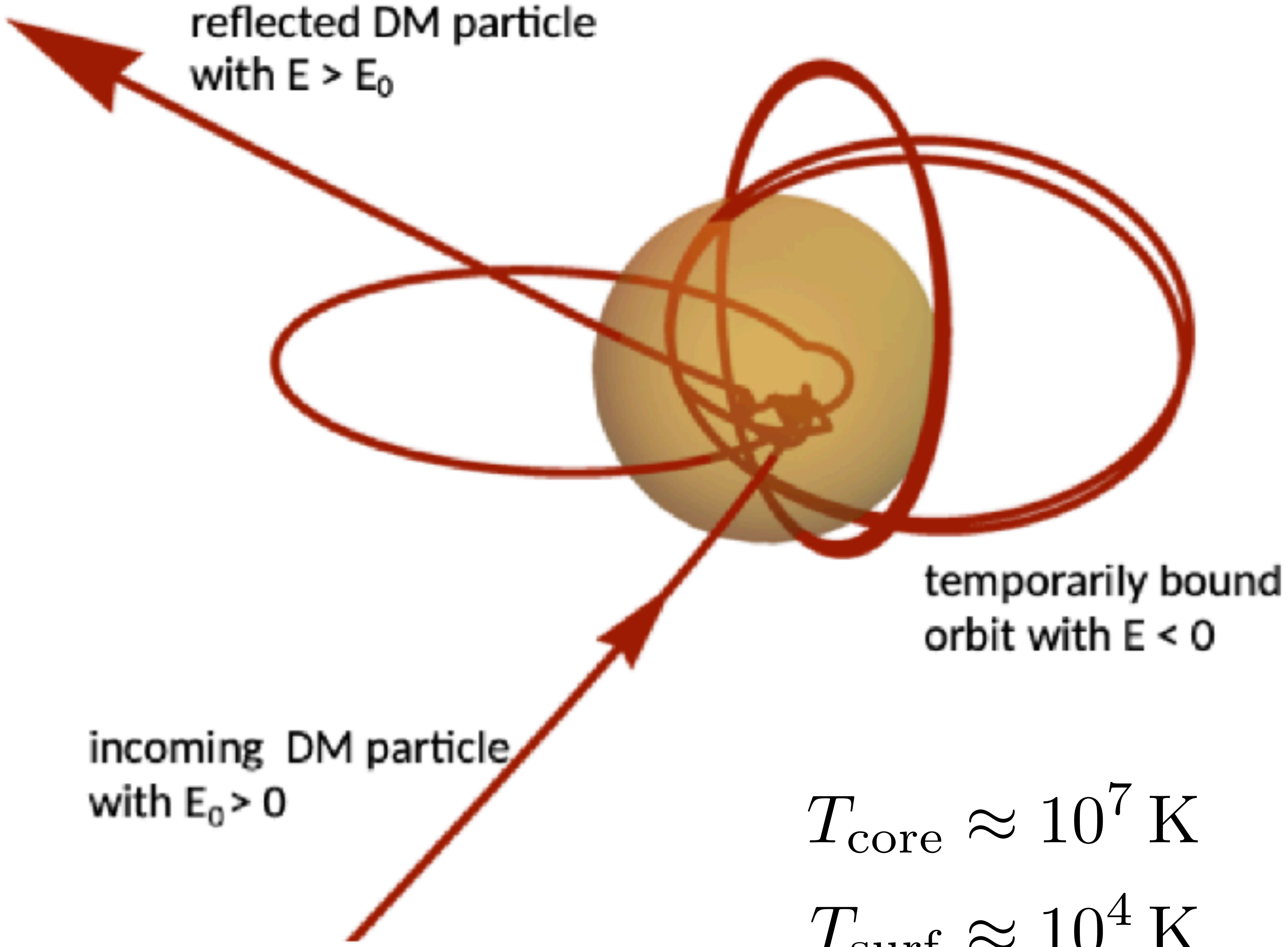

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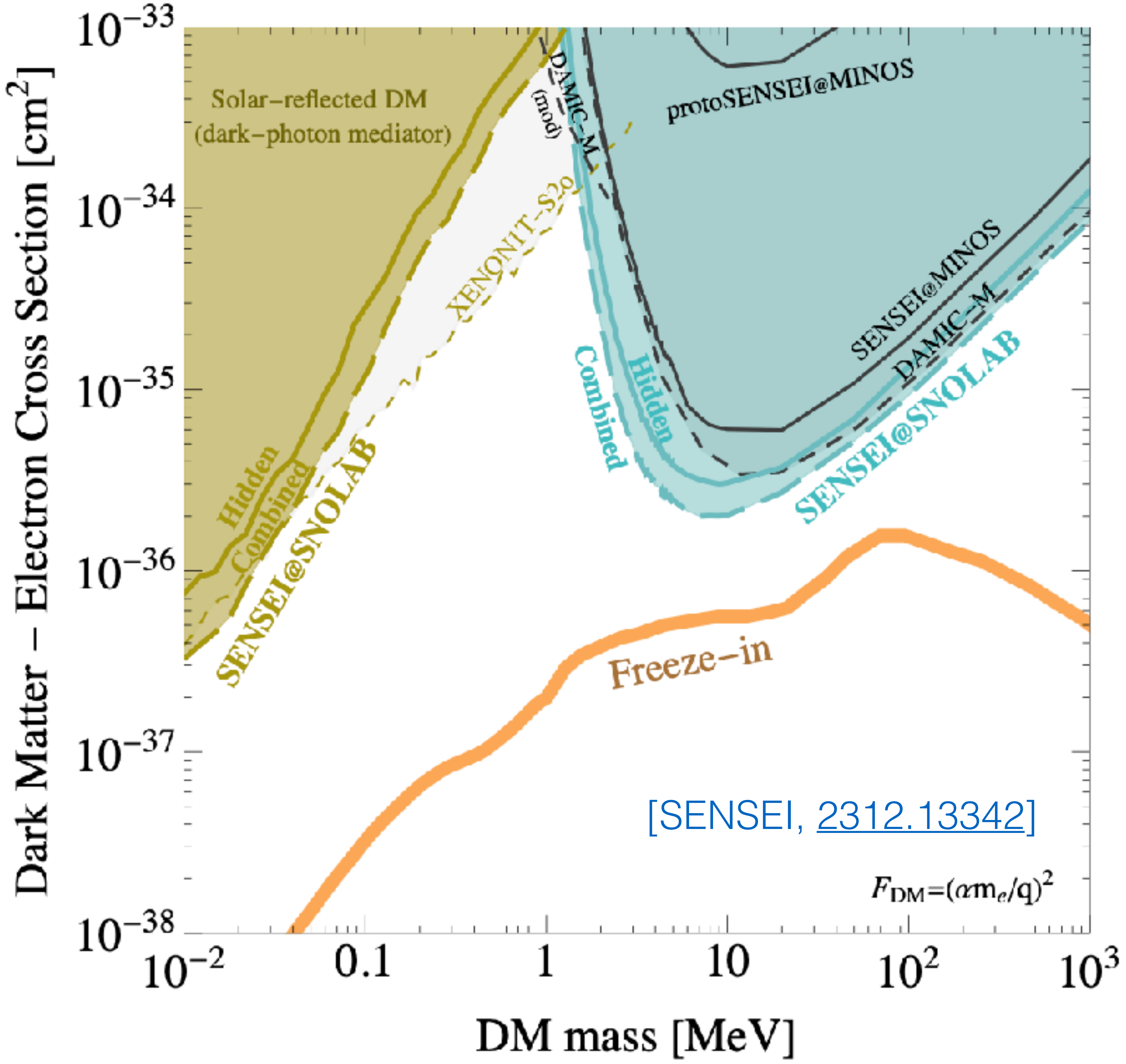
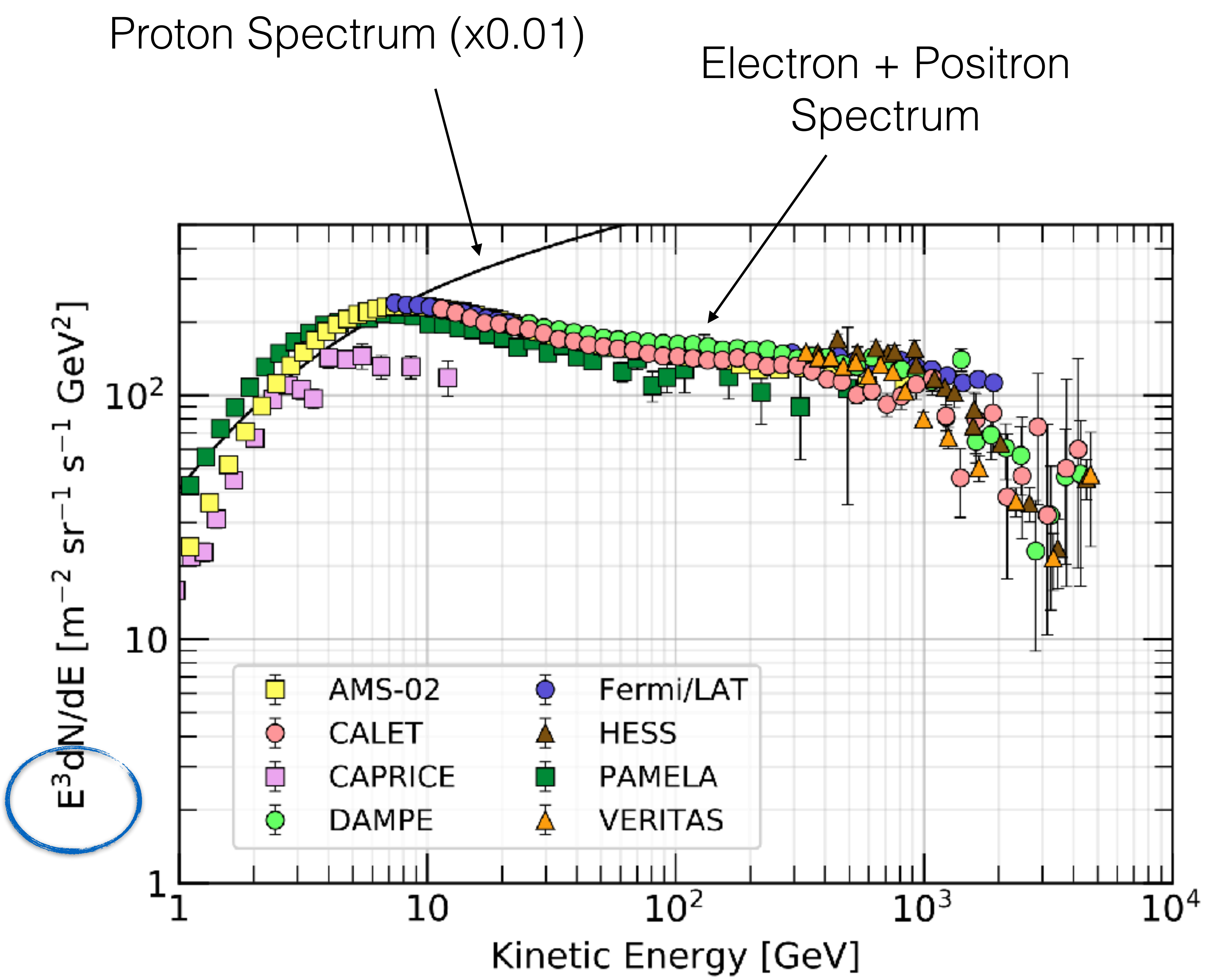


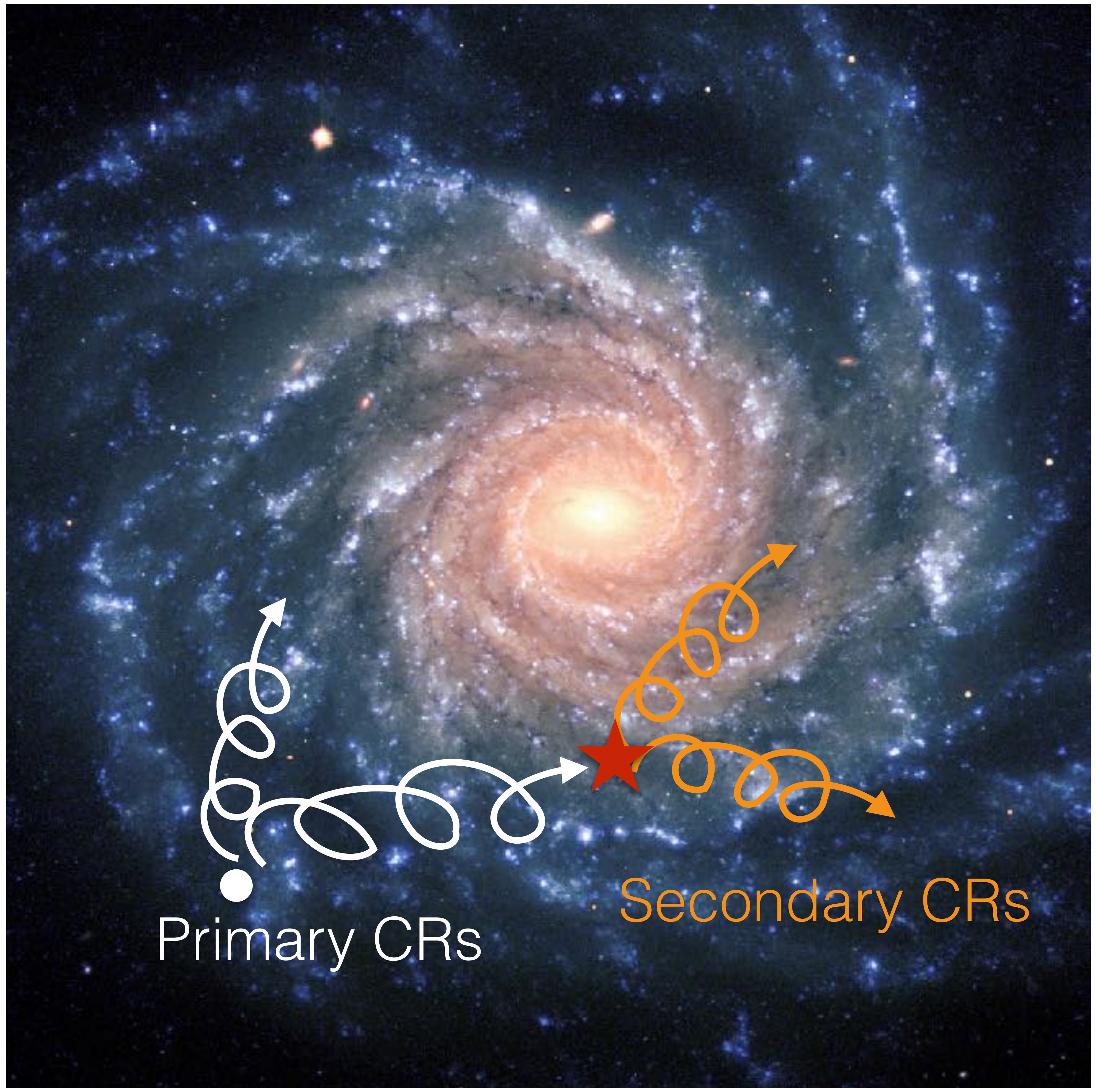
[SENSEI, 2312.13342]

[Emken et al., 2102.12483, 2404.10066]

Cosmic Ray Upscattered DM



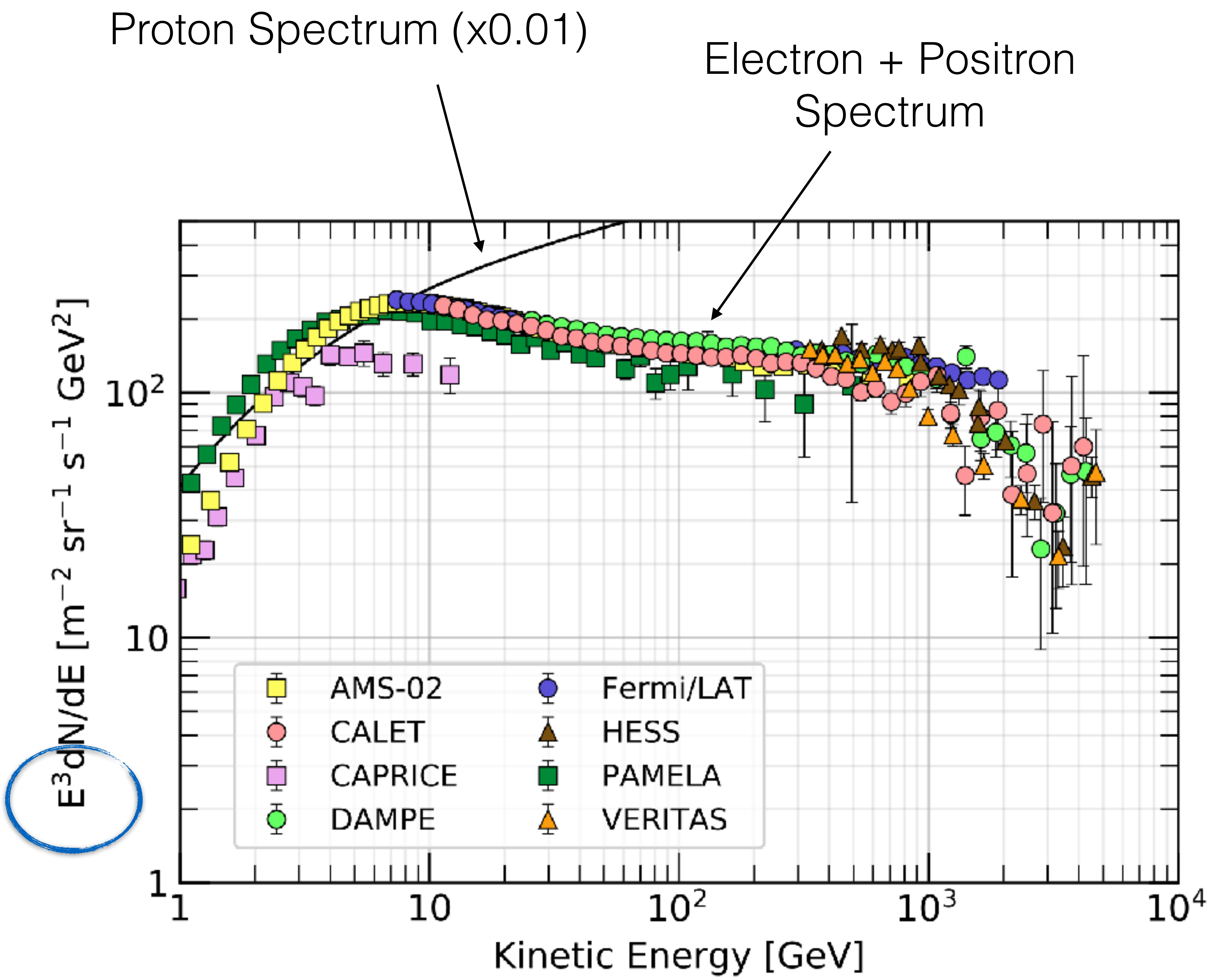
Credit: Particle Data Group (2020)



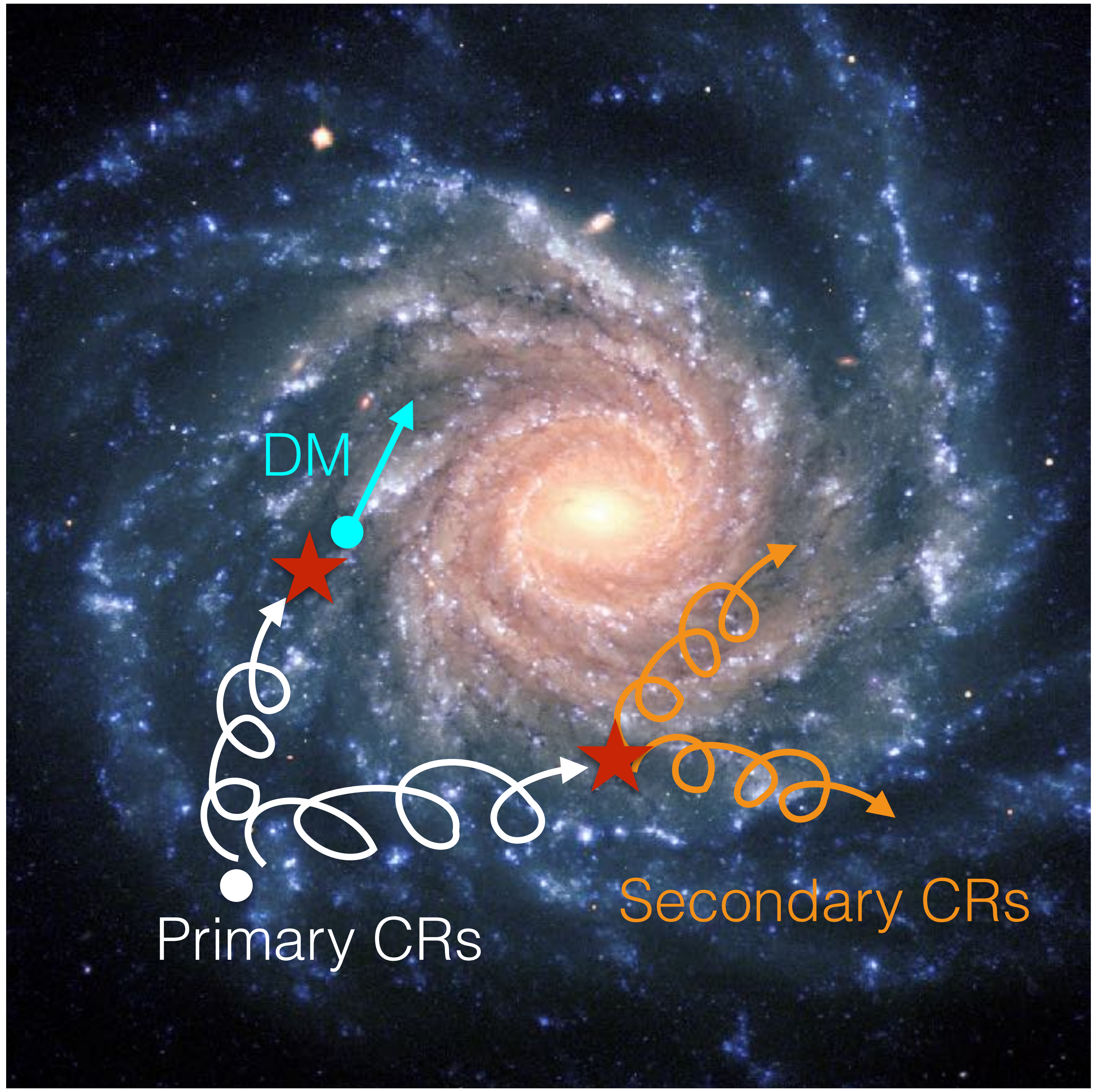
[Bringmann & Pospelov, 1810.10543]

[Ema et al., 1811.00520]

Cosmic Ray Upscattered DM



Credit: Particle Data Group (2020)



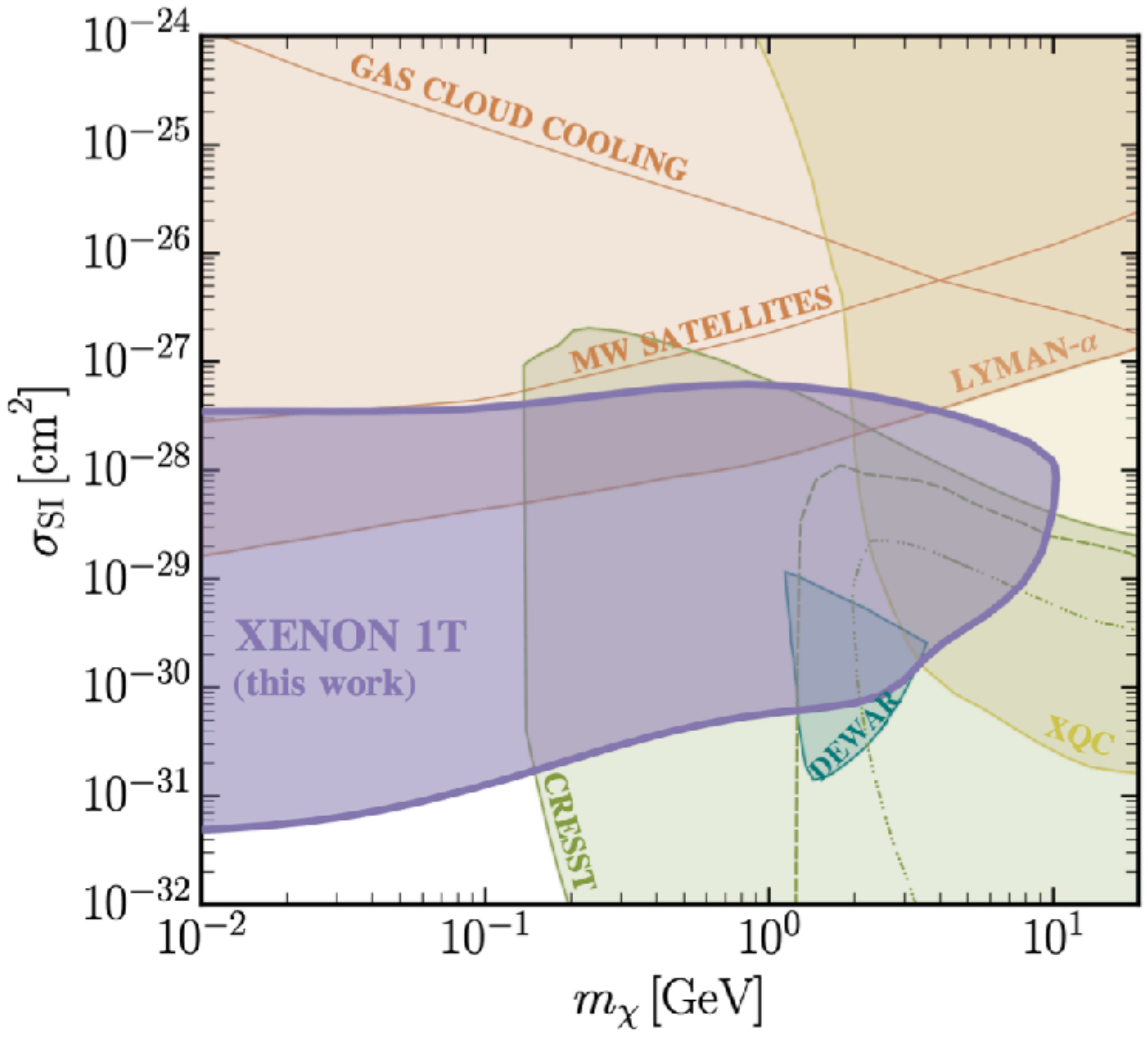
[Bringmann & Pospelov, 1810.10543]

[Ema et al., 1811.00520]

Cosmic Ray Upscattered DM

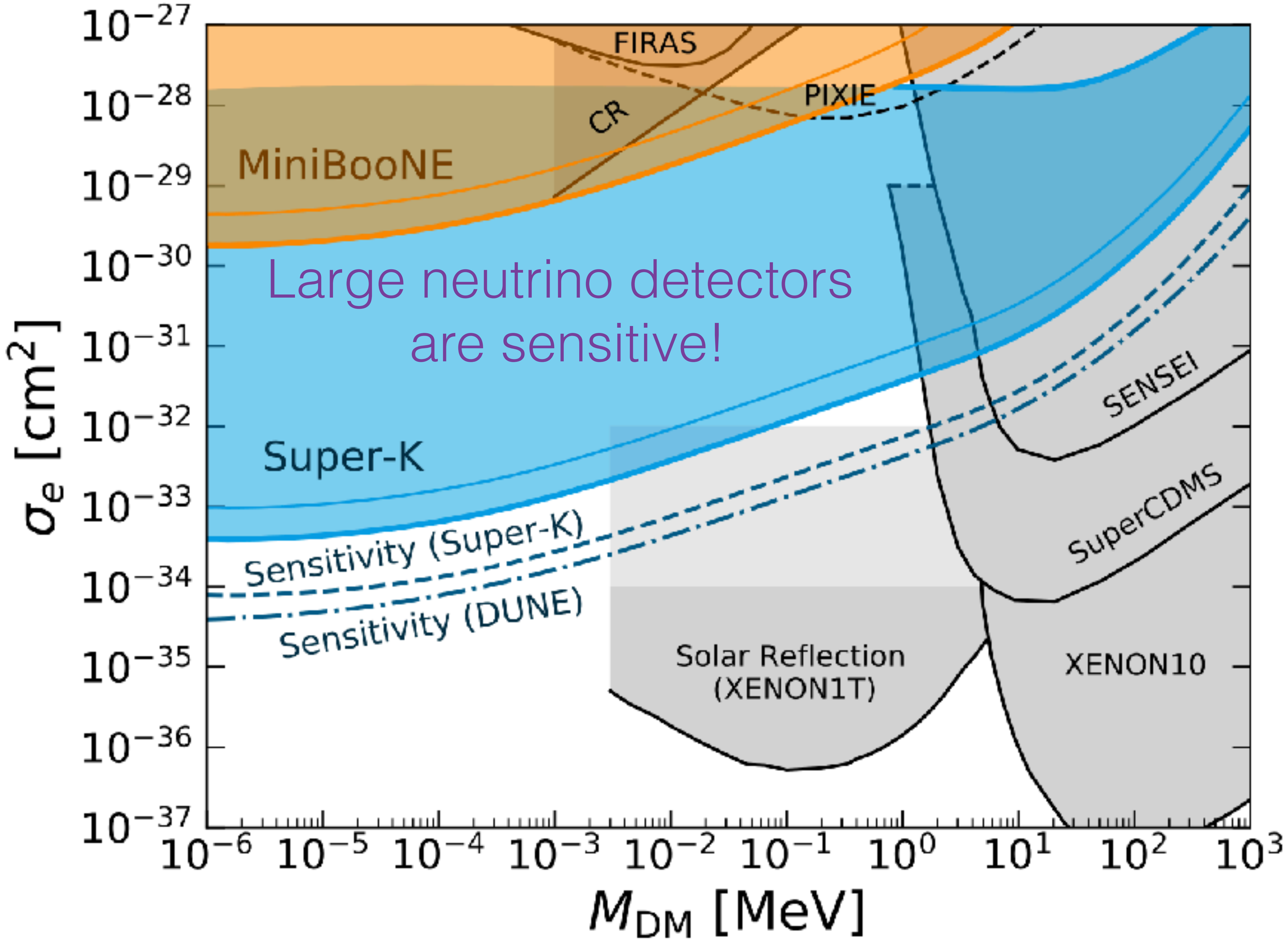
DM can be upscattered to relativistic speeds ($E \sim \mathrm{GeV}$)

DM-proton scattering



[Alvey et al., 2209.03360]

DM-electron scattering

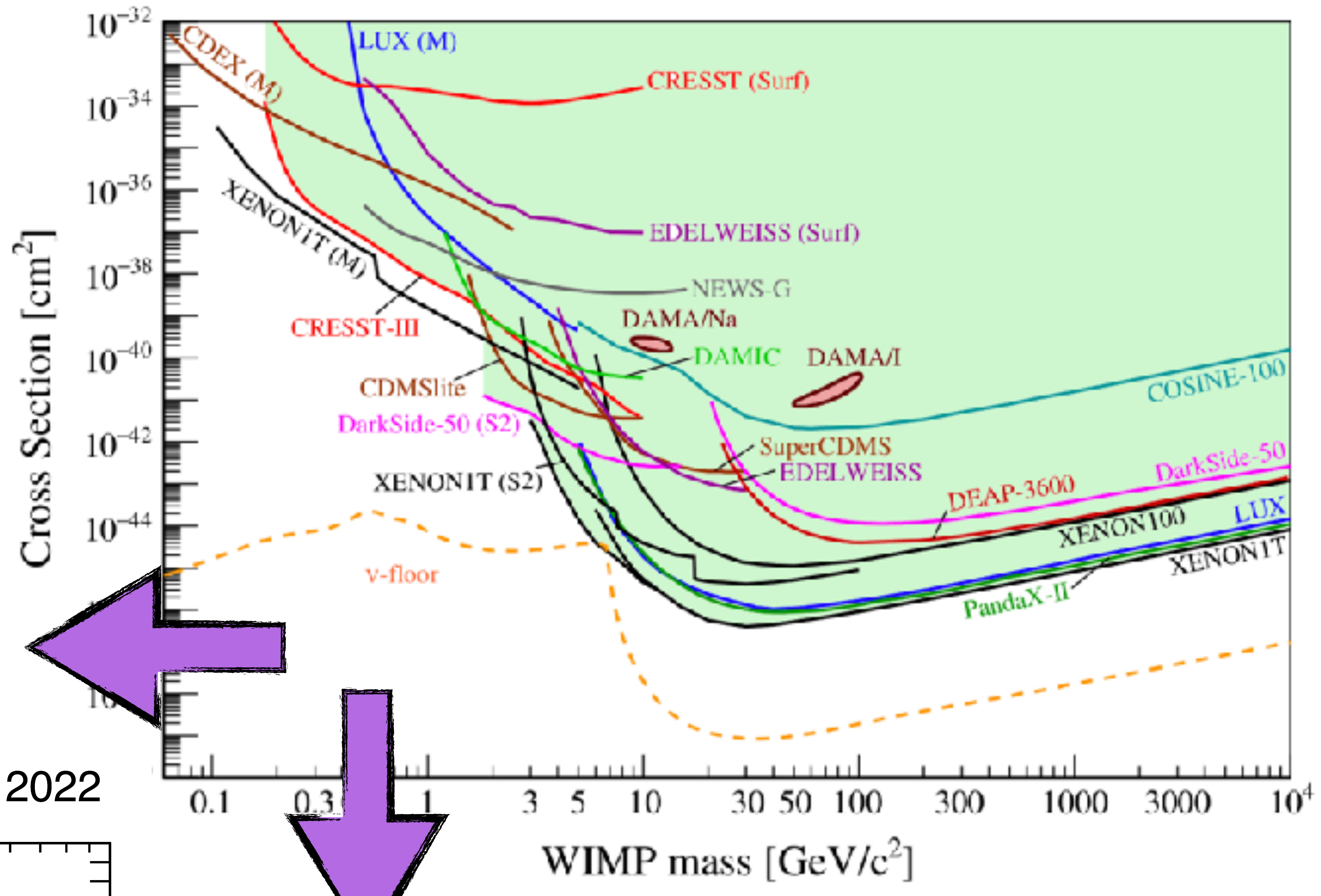


[Ema et al., 1811.00520]

Broadening the search

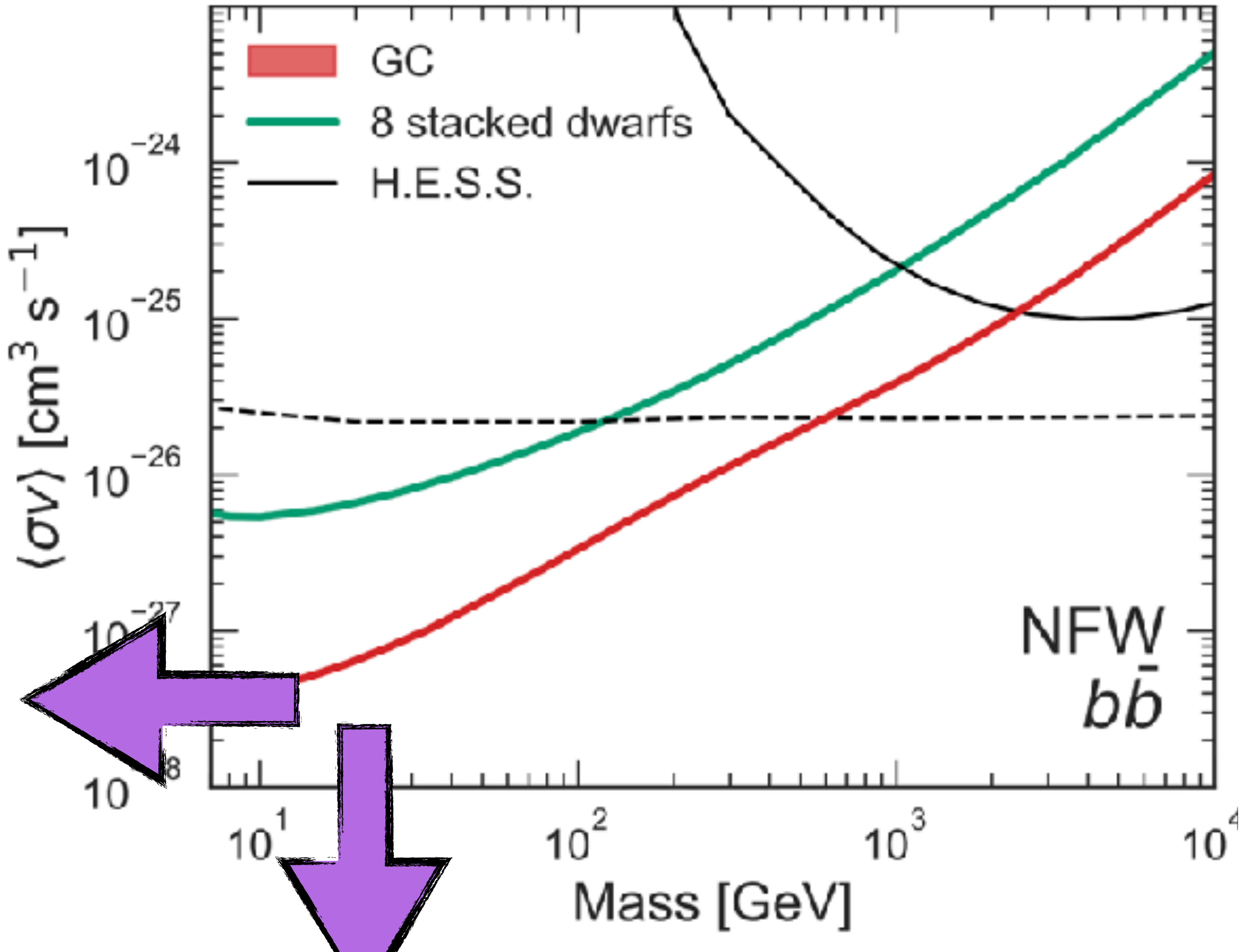
Direct Searches

[APPEC, 2104.07634]



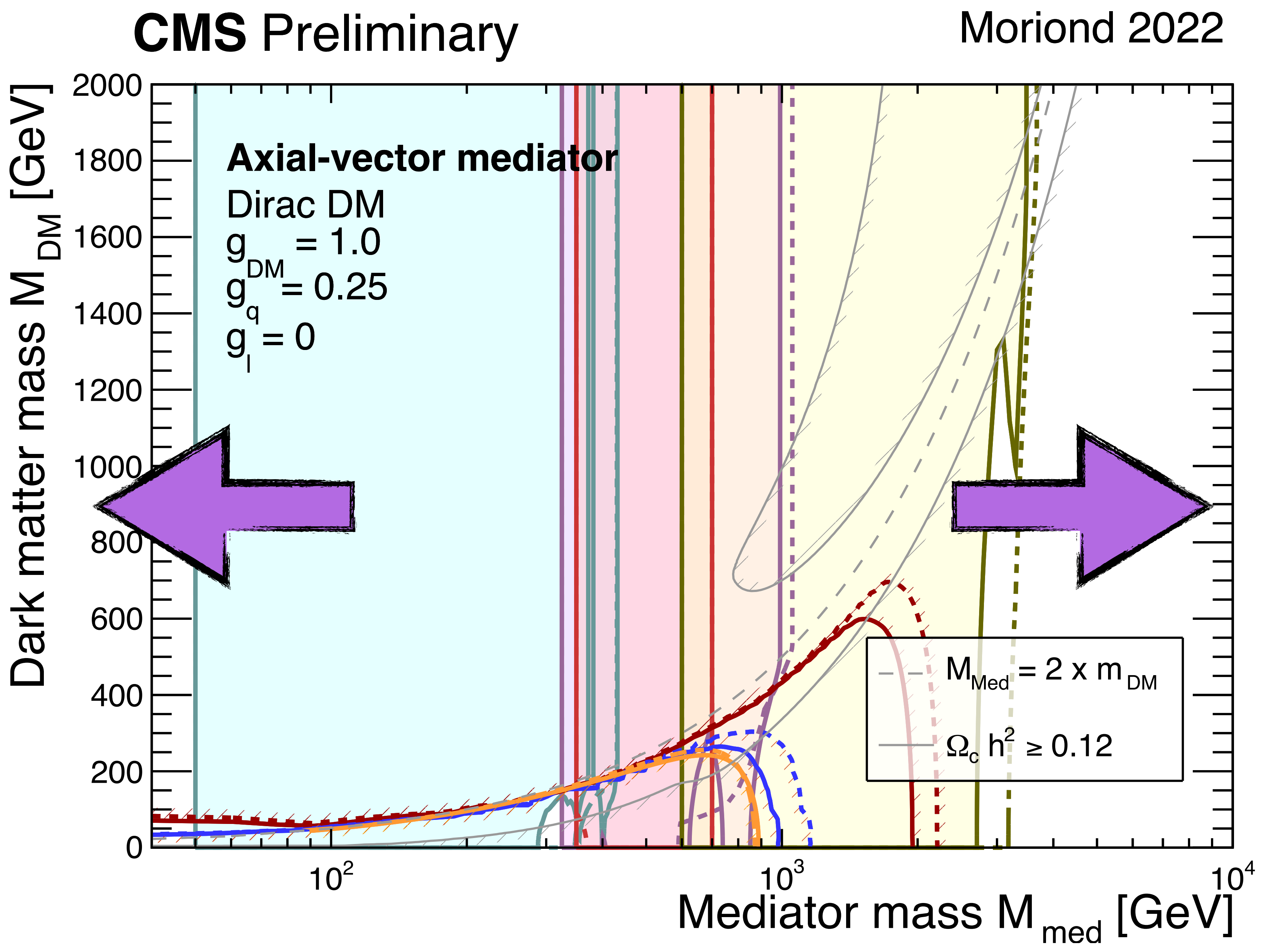
Indirect searches

[Abazajian et al., 2003.10416]



Collider Searches

[CMS, DM Summary Plots]



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

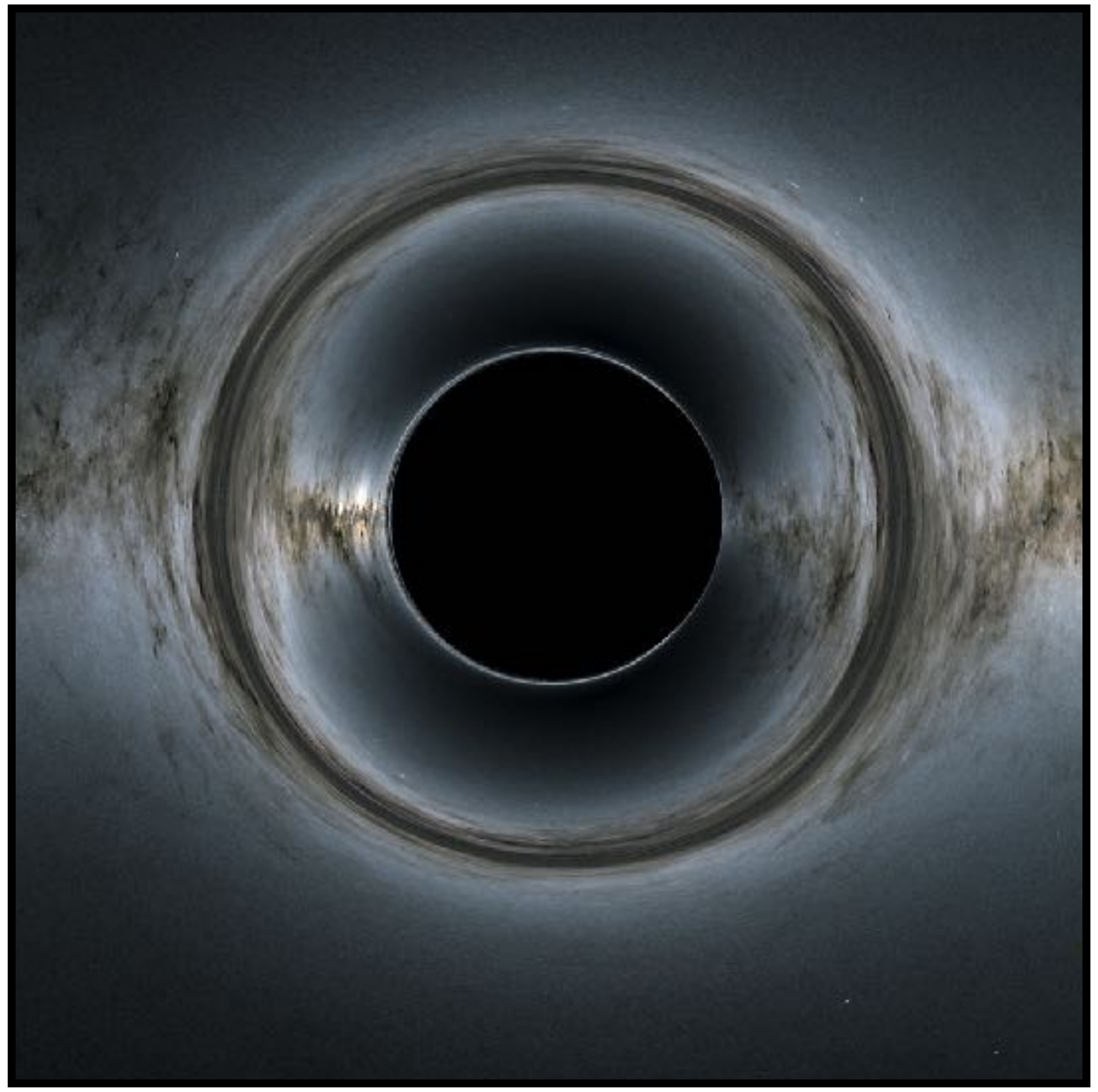
Where in *physical space*?

Where in *physical space*?

[Baryakhtar et al. (including **BJK**), 2203.07984]

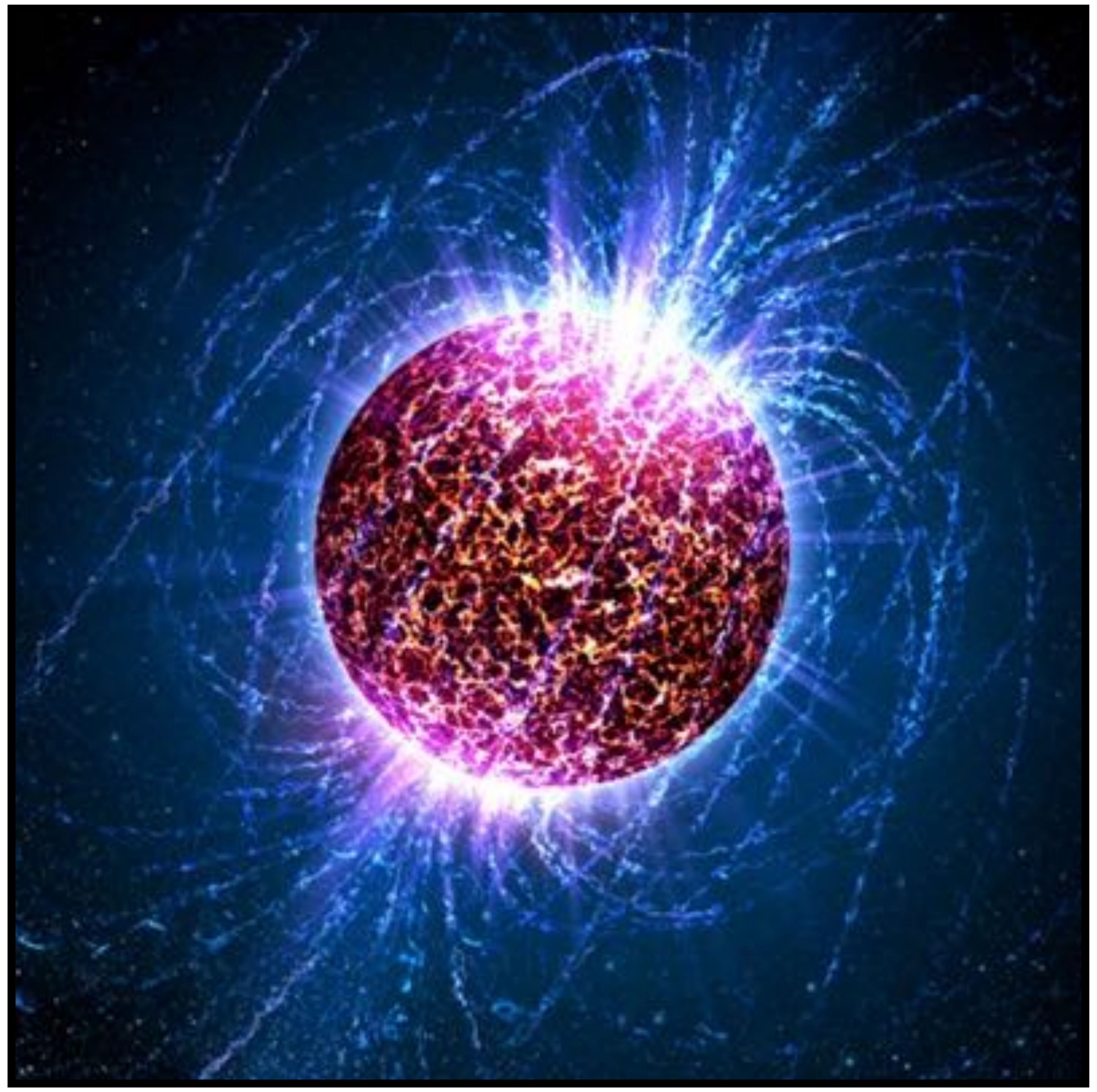
Dark Matter in extreme astrophysical environments:

Black Holes



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

Neutron Stars



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

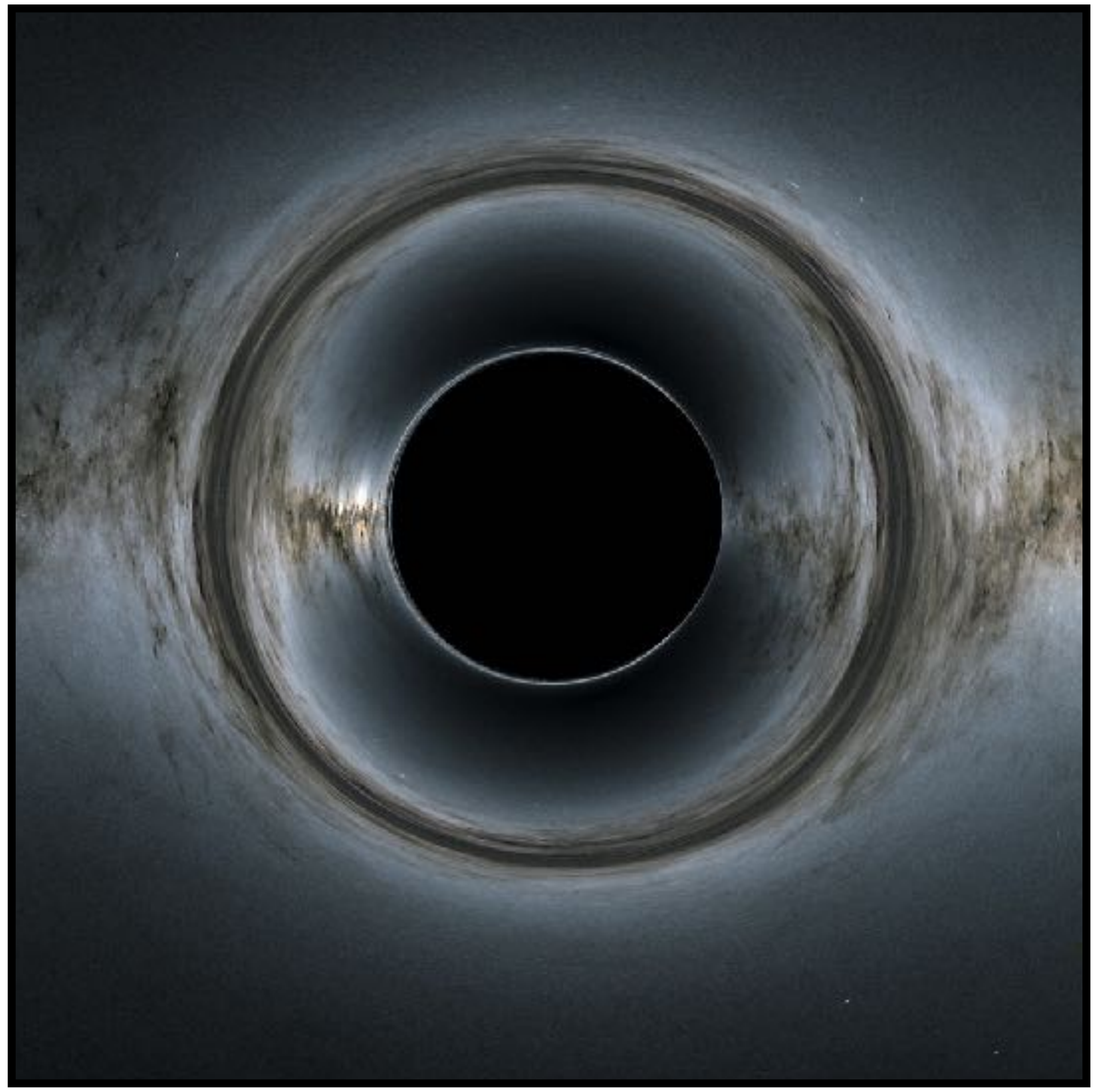
Higher densities, larger magnetic fields, longer timescales…

Where in *physical space*?

[Baryakhtar et al. (including **BJK**), 2203.07984]

Dark Matter in extreme astrophysical environments:

Black Holes



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

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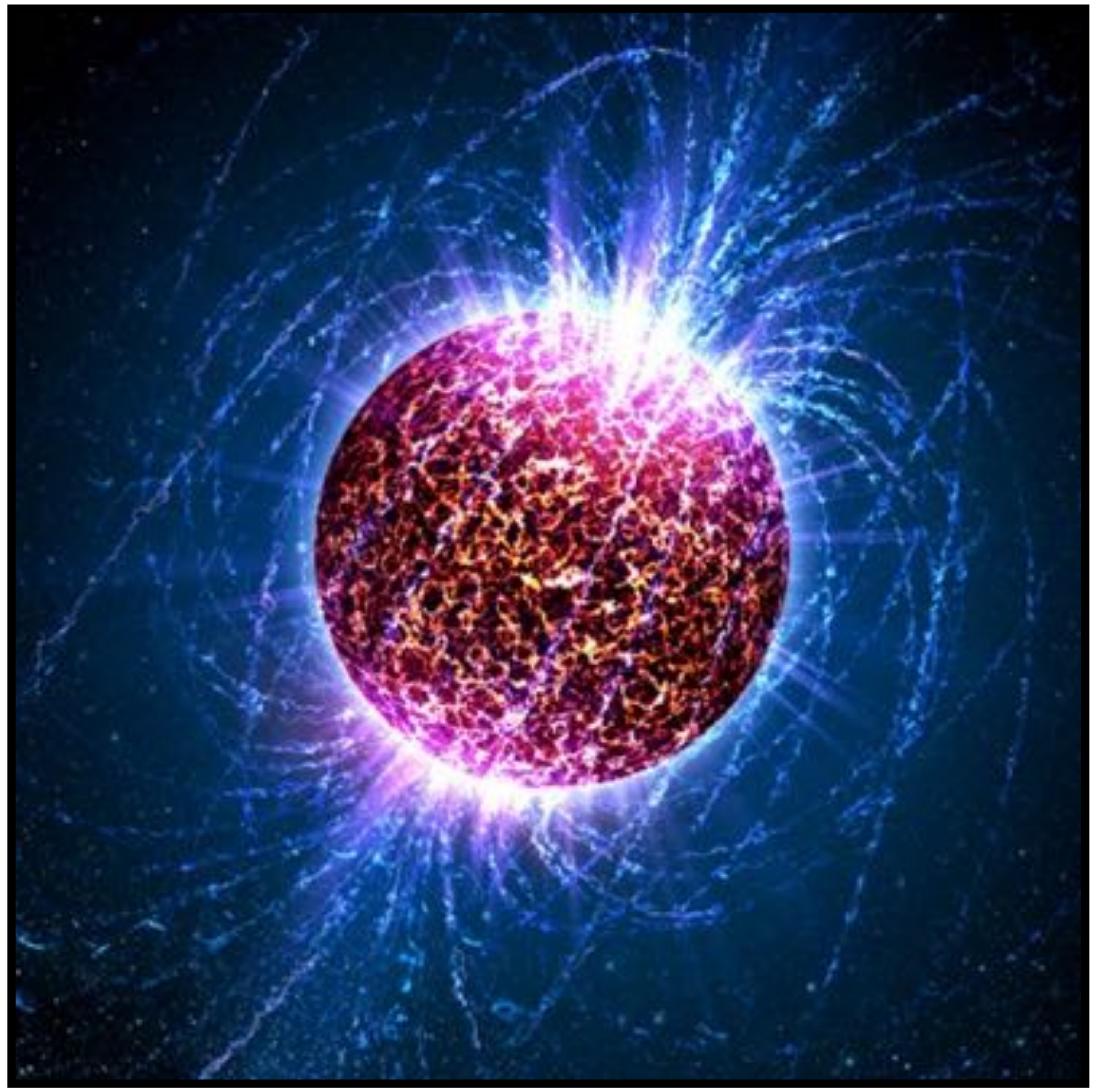
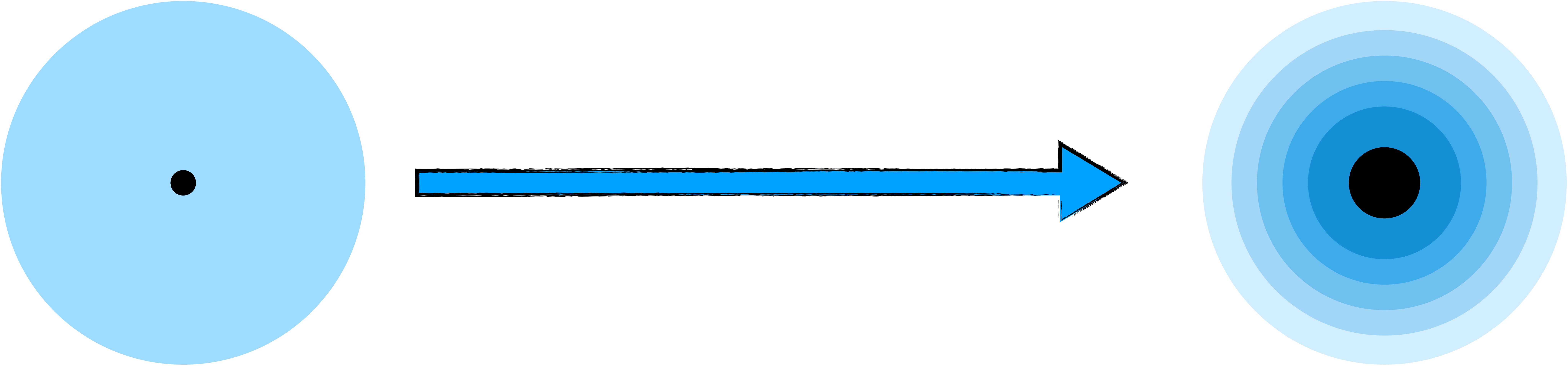


[Credit: Casey Reed (Penn State University), Wikimedia Commons]

Higher densities, larger magnetic fields, longer timescales…

Dark Matter Spikes



Dense '**spikes**' of DM may form from the slow ('adiabatic') growth of a BH at the centre of a DM halo

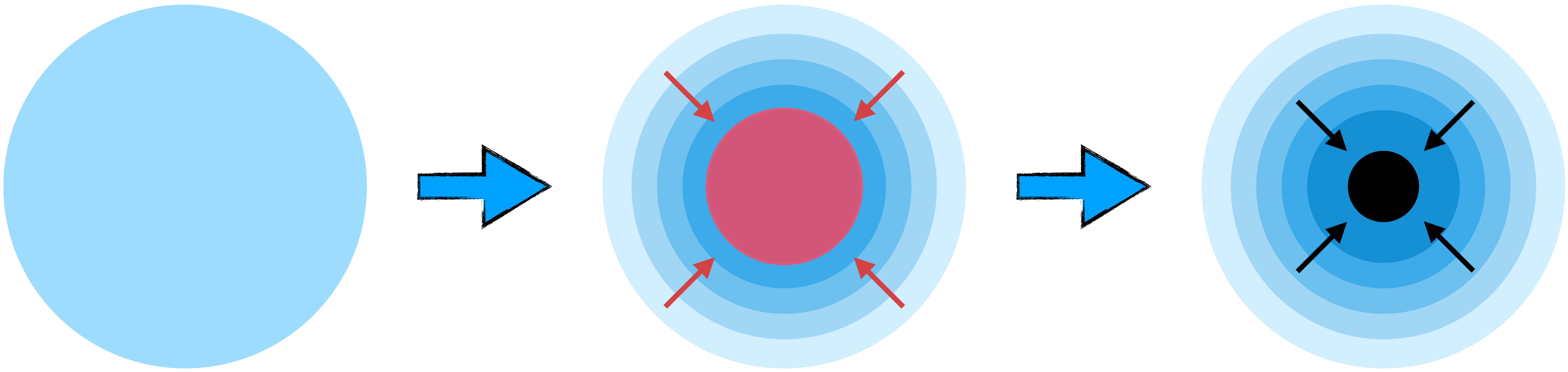
[astro-ph/9906391, astro-ph/0509565, 1305.2619, …]

*Also possible around BHs which form from large density fluctuations in the early Universe (i.e. Primordial Black Holes)

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

Dark Matter Mounds

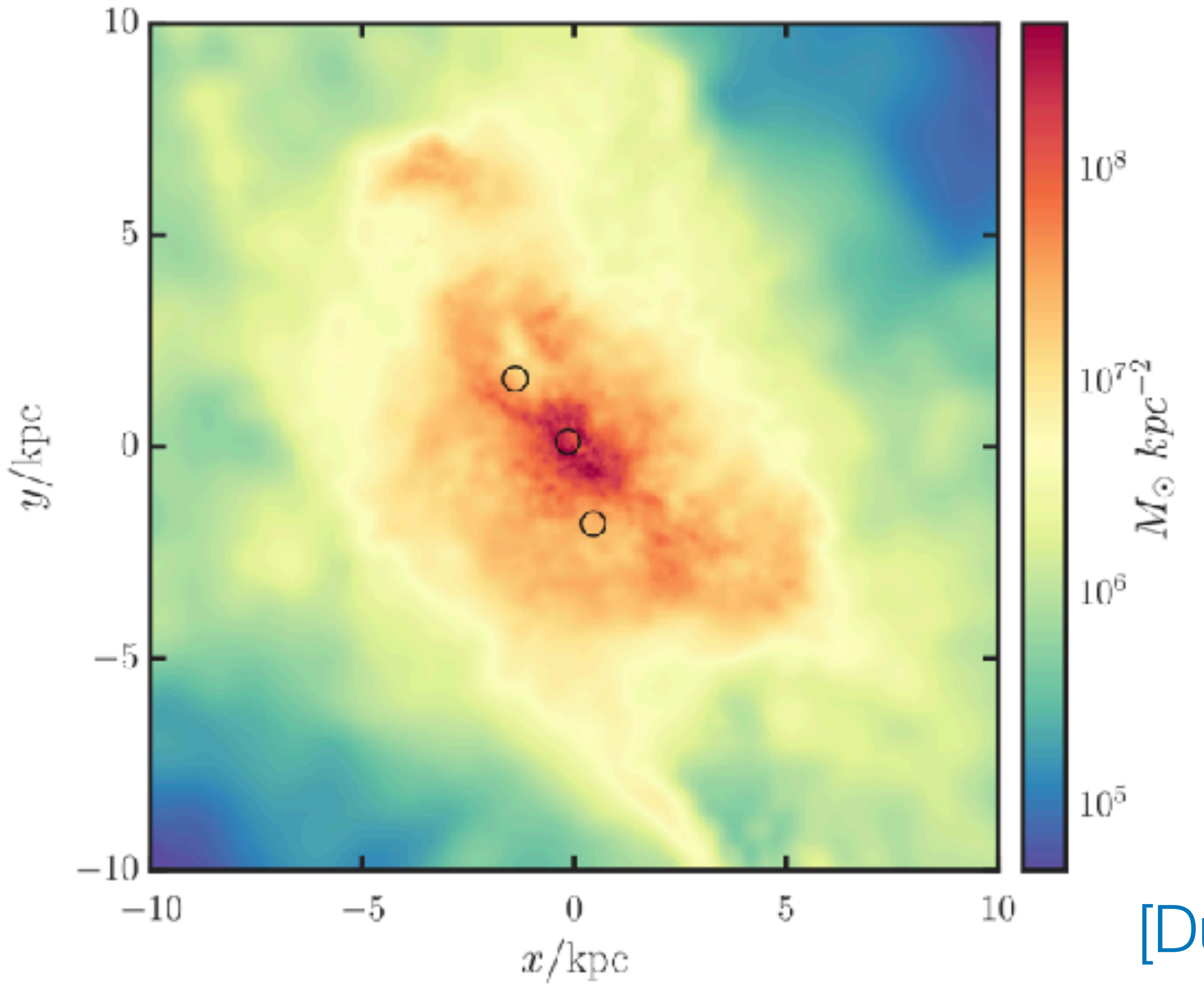
*Precise details of formation affect slope and density of DM very close to BH



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

Supermassive 'star'

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



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

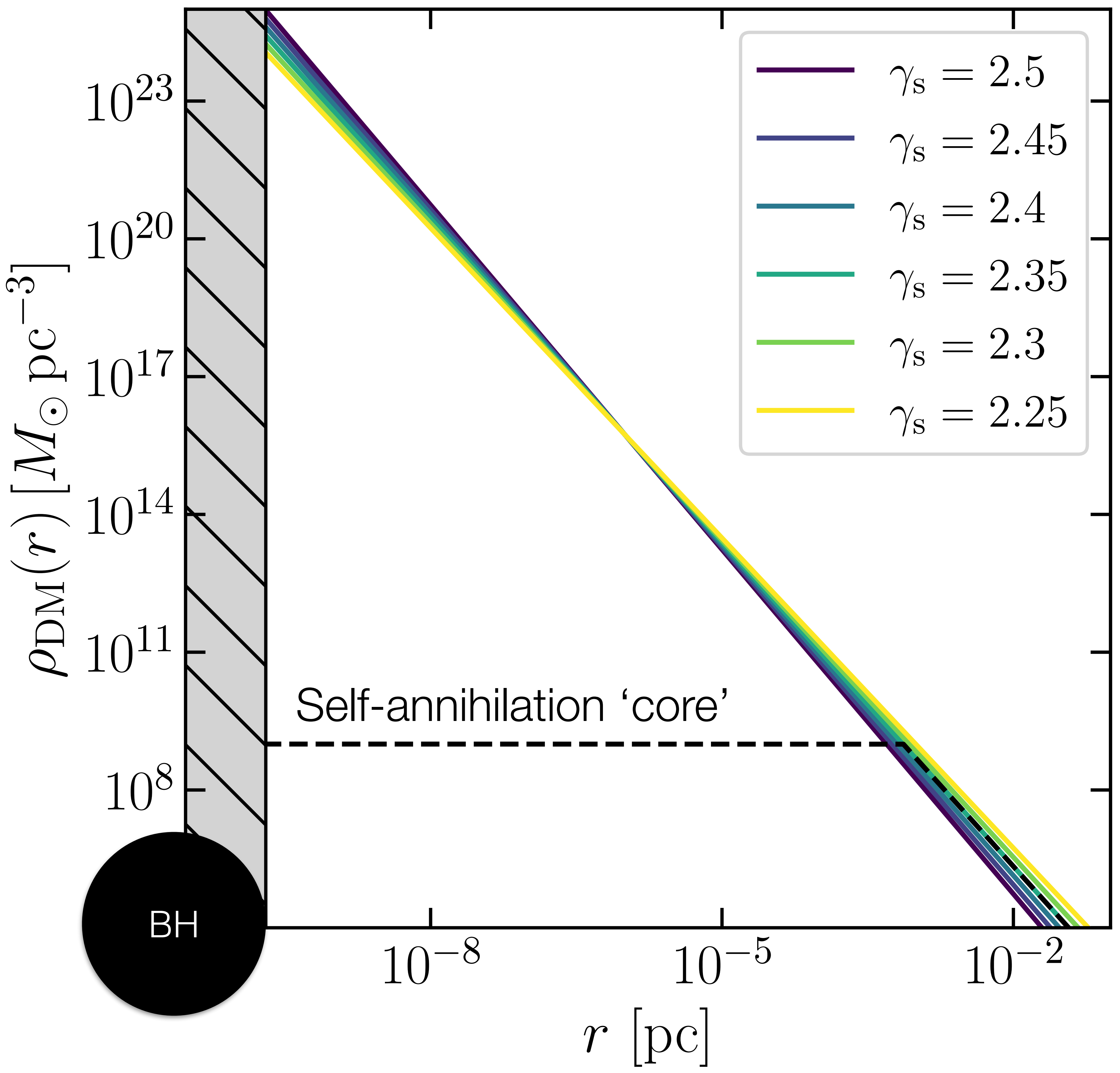
The BH may experience subsequent growth to become supermassive

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

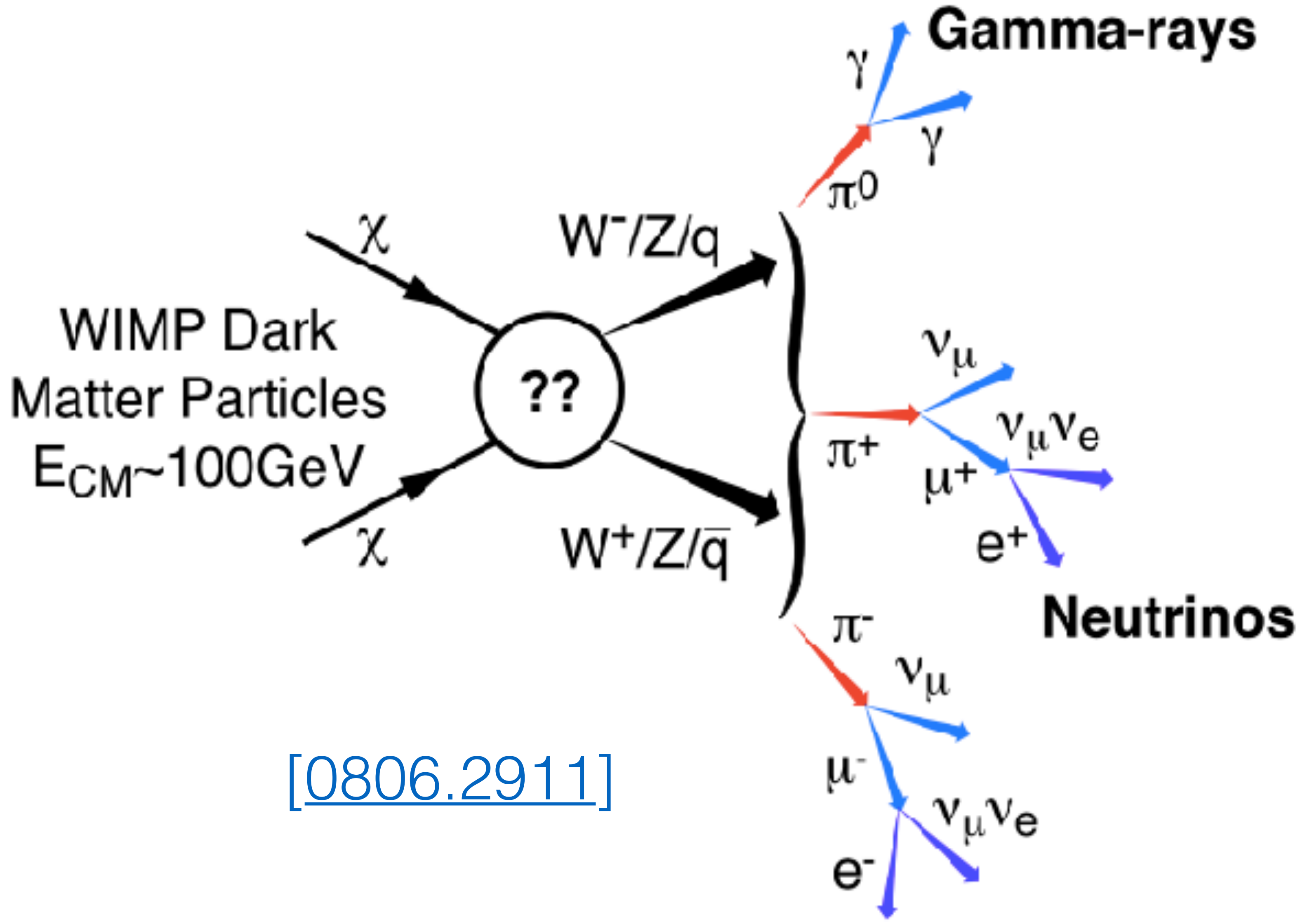
[Dunn et al., 1803.01007]

DM Annihilation Signals

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



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



[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

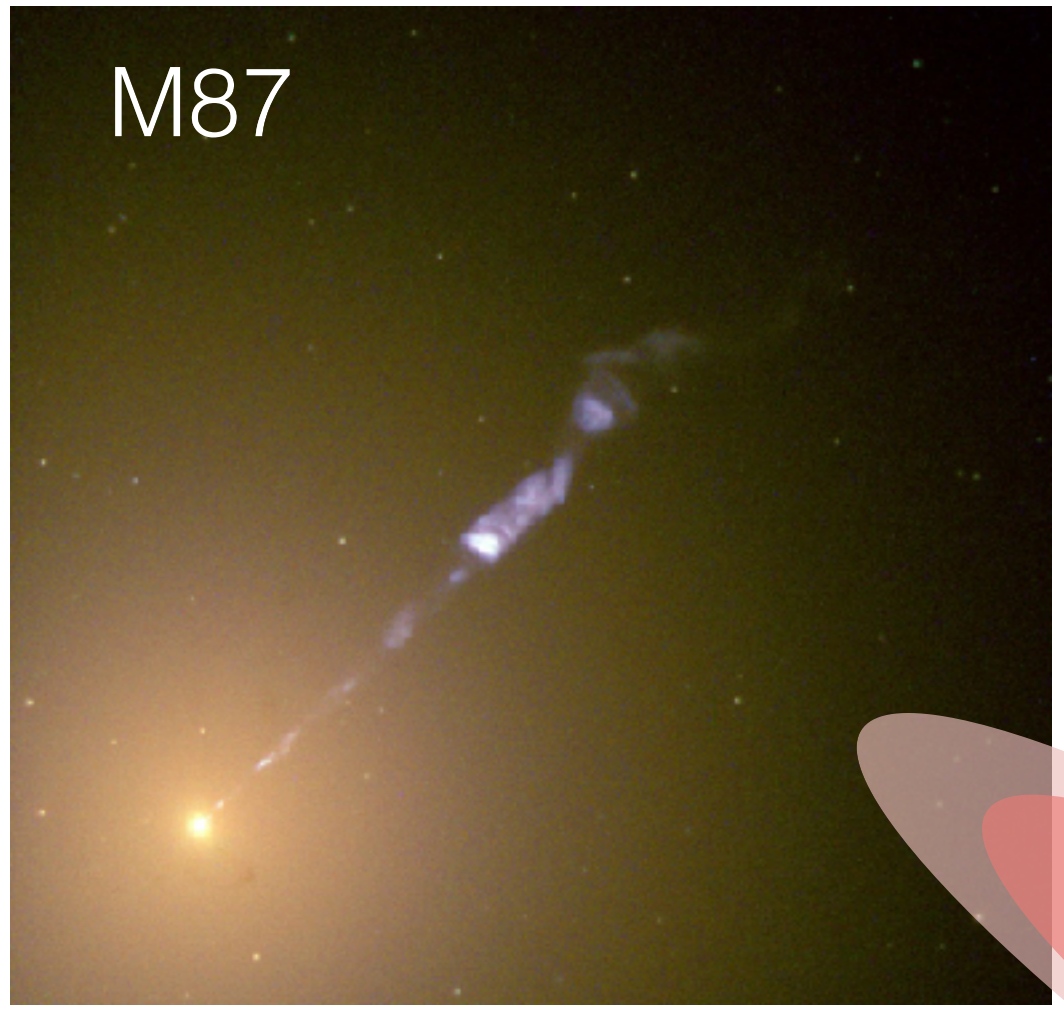
Could be used to constrain DM annihilation around SMBHs and IMBHs in the Milky Way (but there are still many uncertainties)

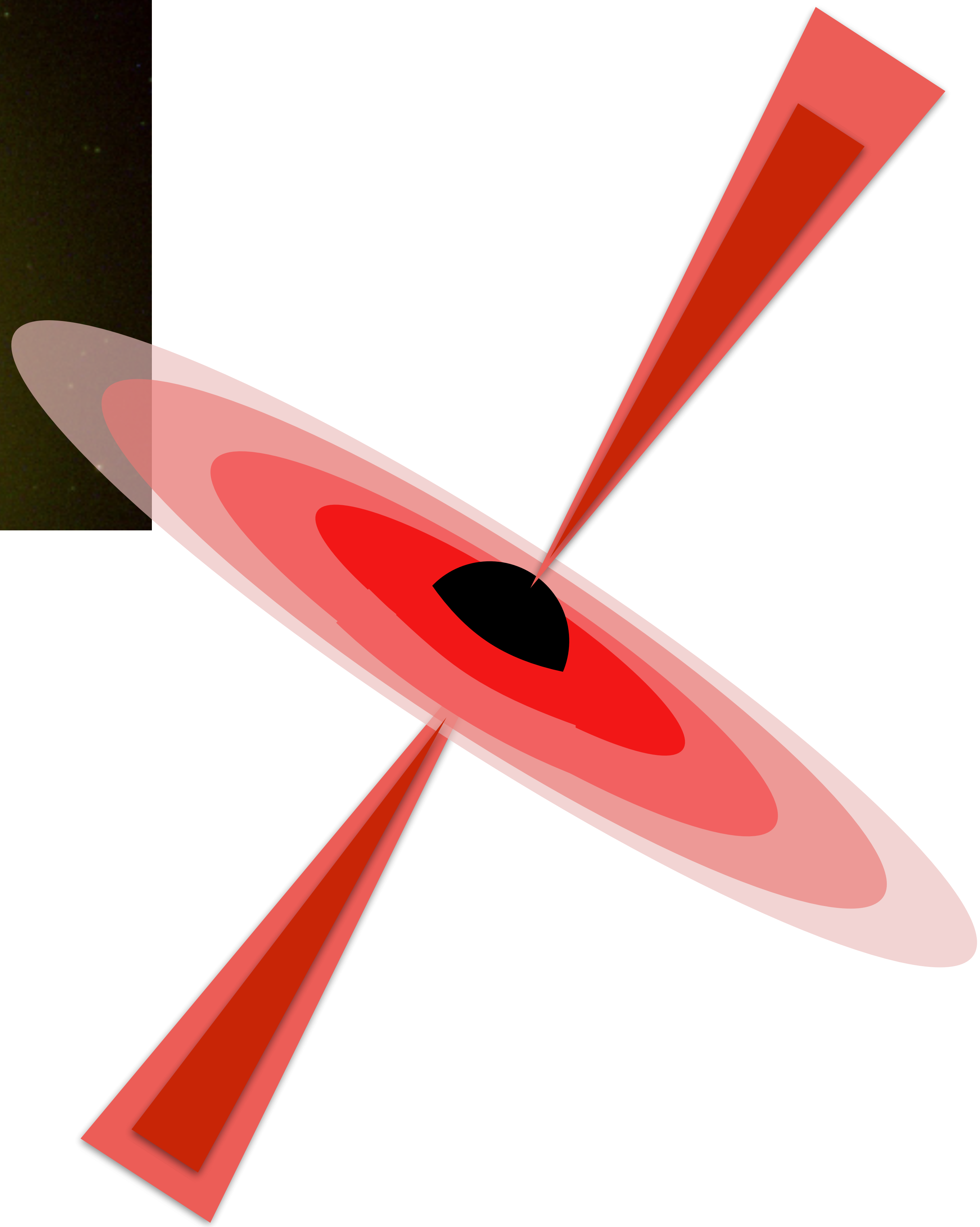
[E.g. Lacroix & Silk, 1712.00452, Freese et al., 2202.01126, Balaji et al., 2303.12107]

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

Blazar-boosted DM

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





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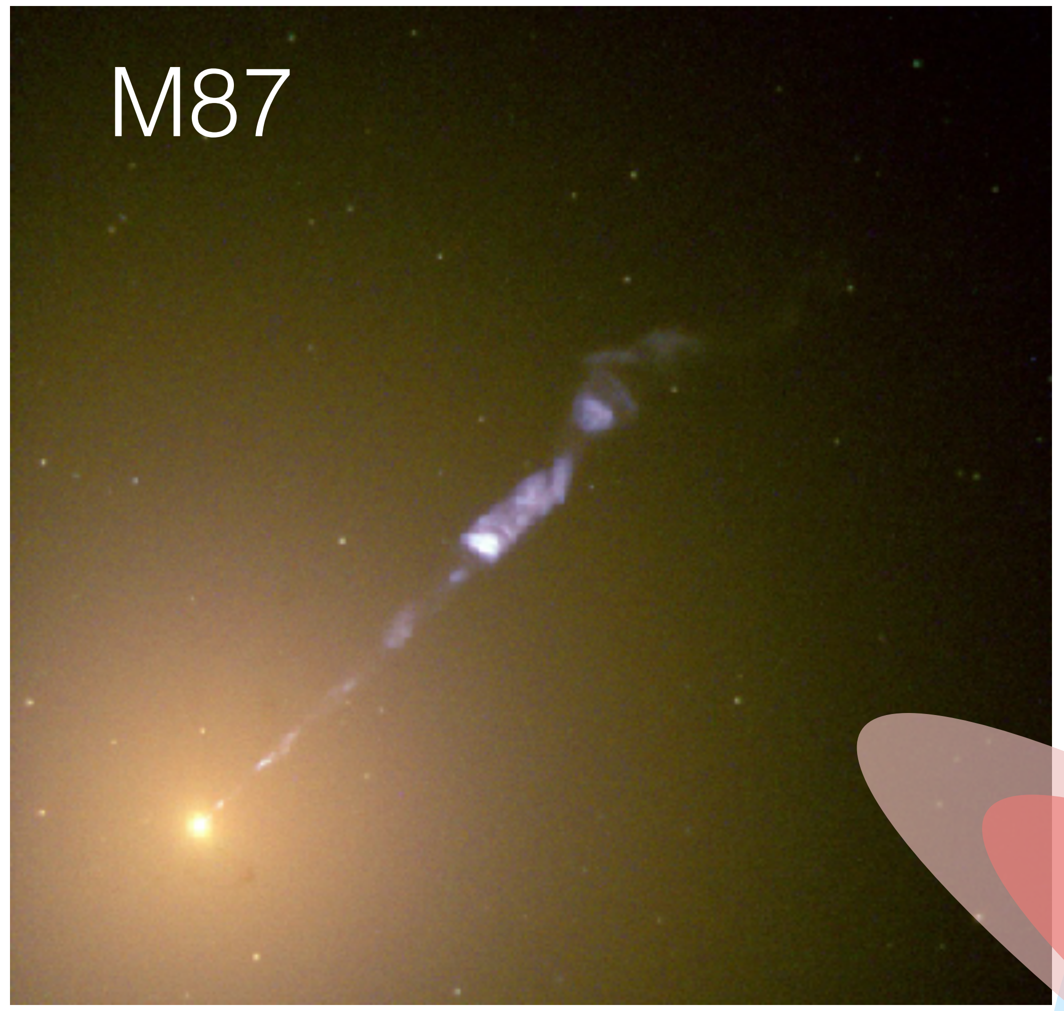
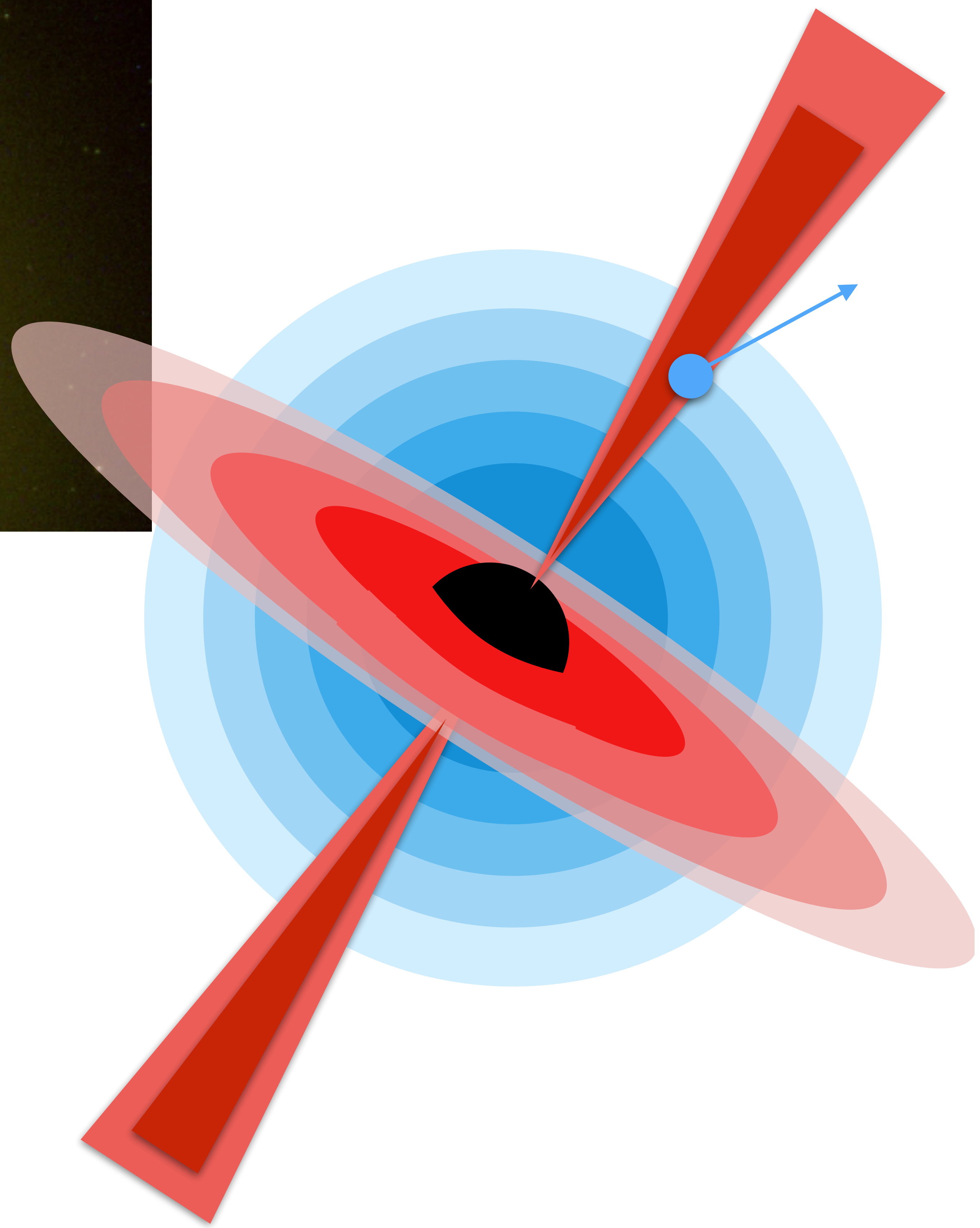
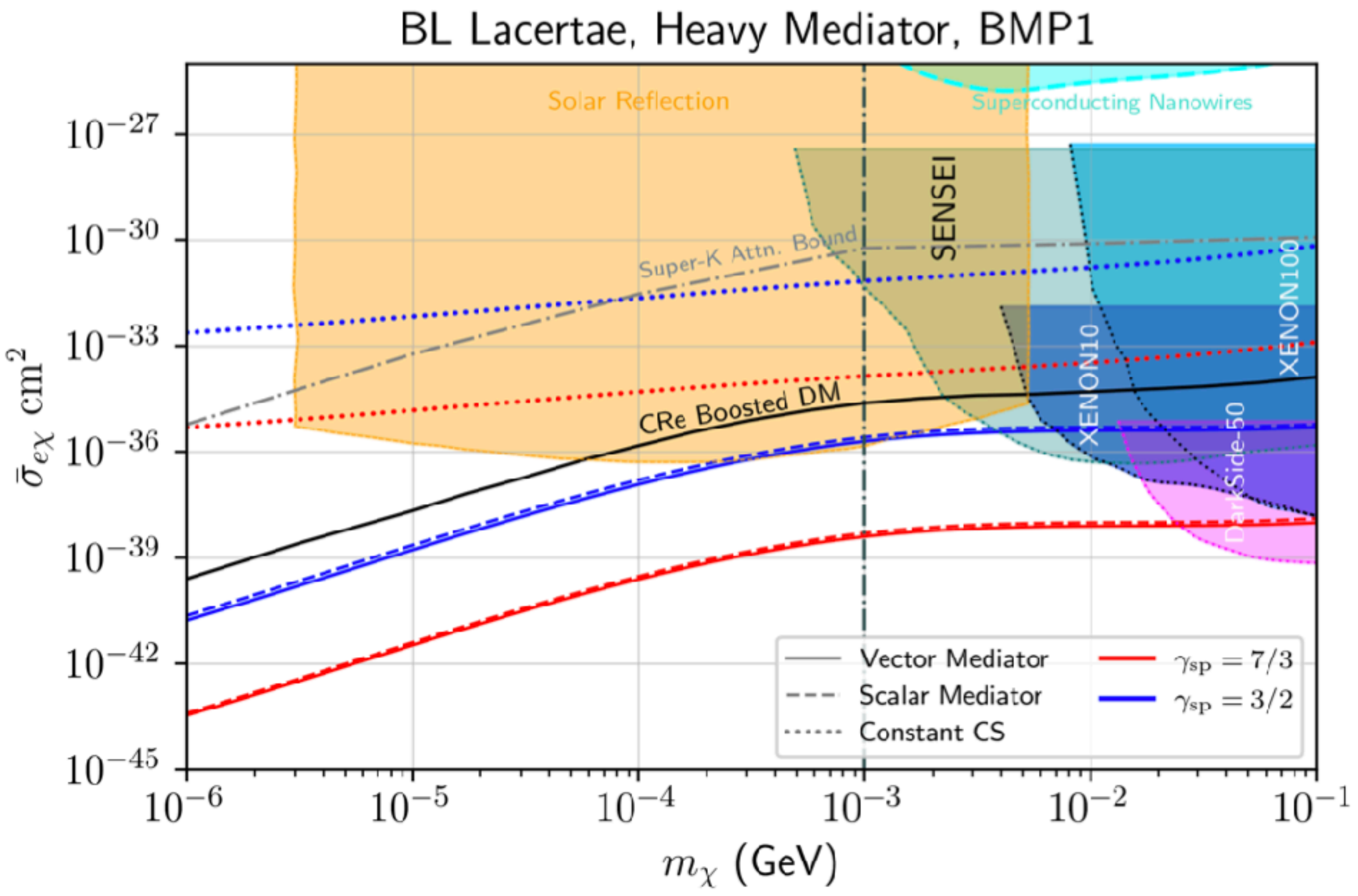




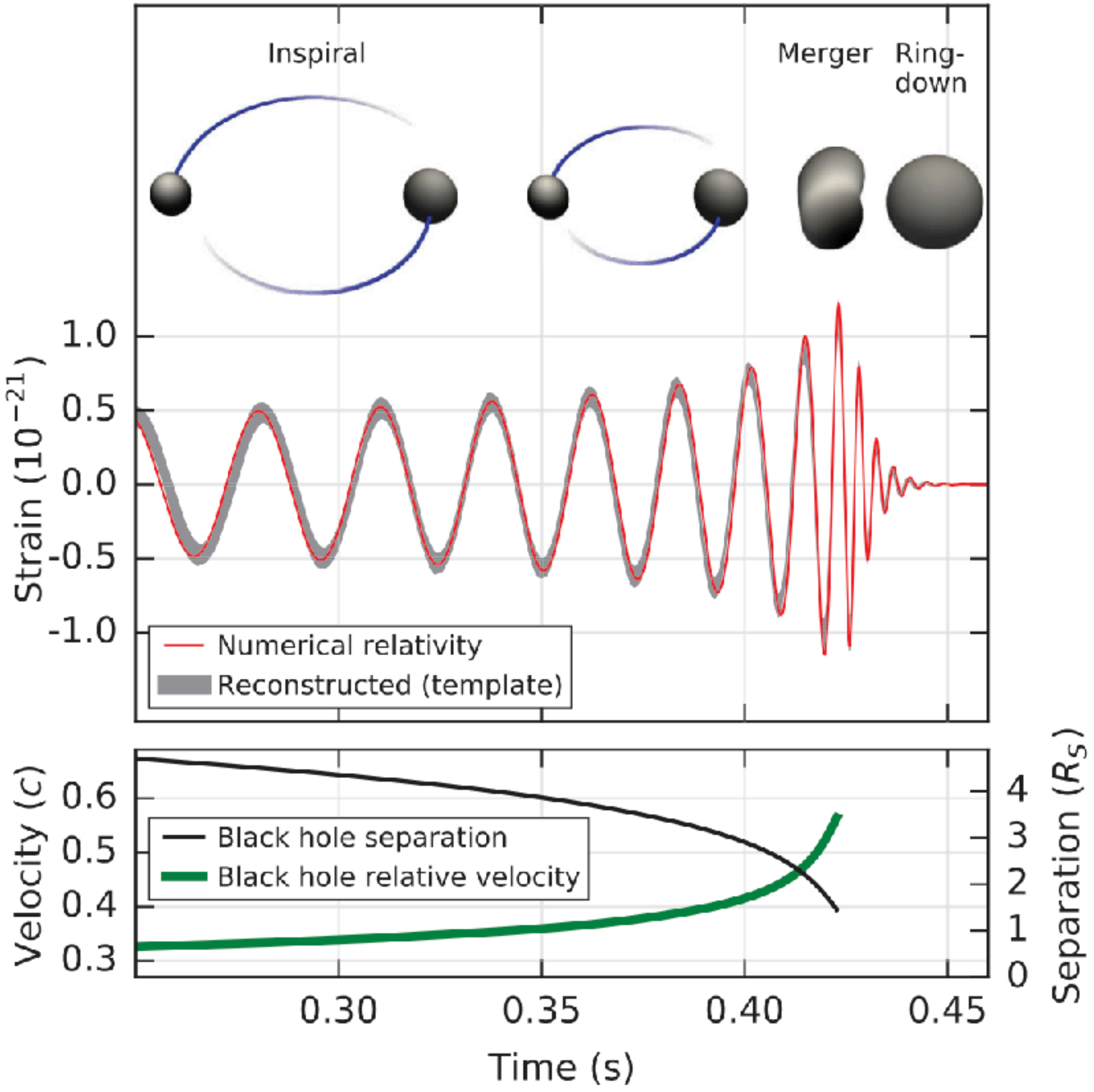


[E.g. Bhowmick et al., 2301.00209; Barillier et al., 2509.07265]

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

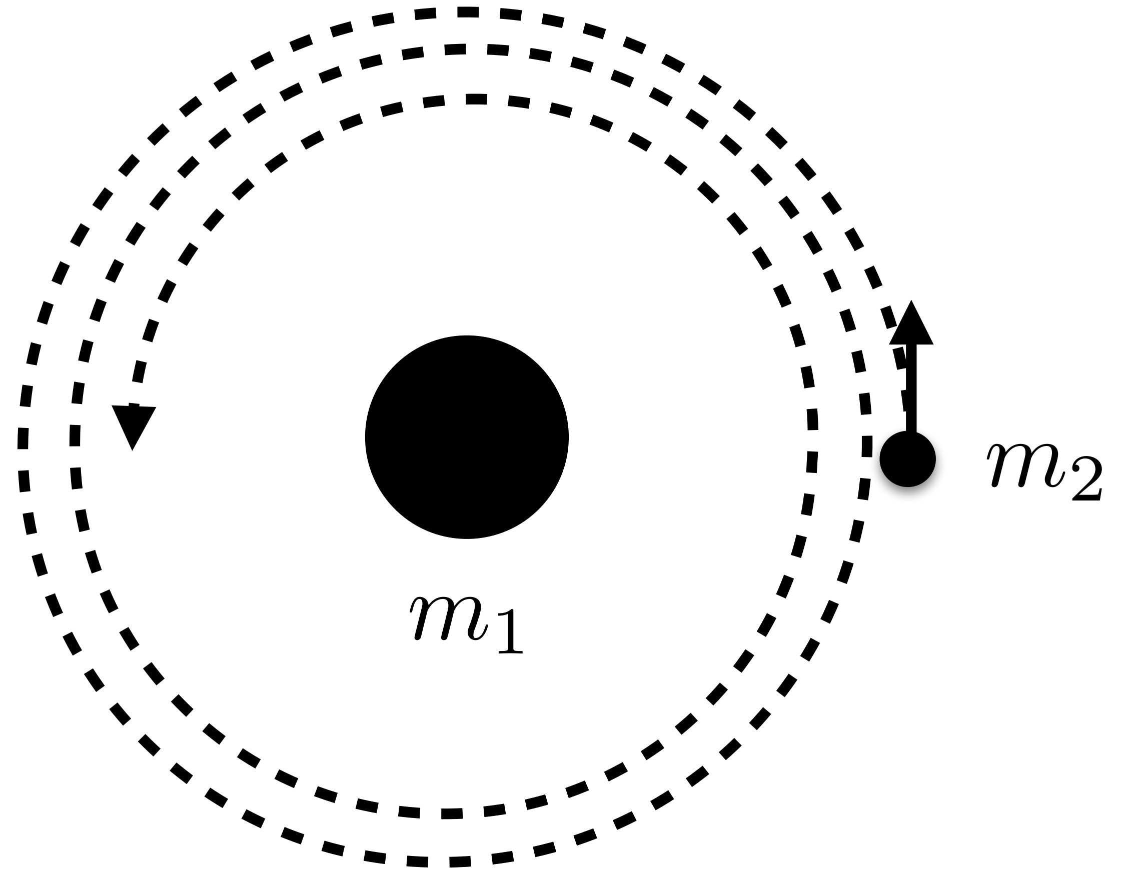
Gravitational Waves (GW)

An ~equal mass inspiral: GW150914



[LIGO/Virgo, arXiv:1602.03837]

Intermediate and extreme mass ratio inspirals:

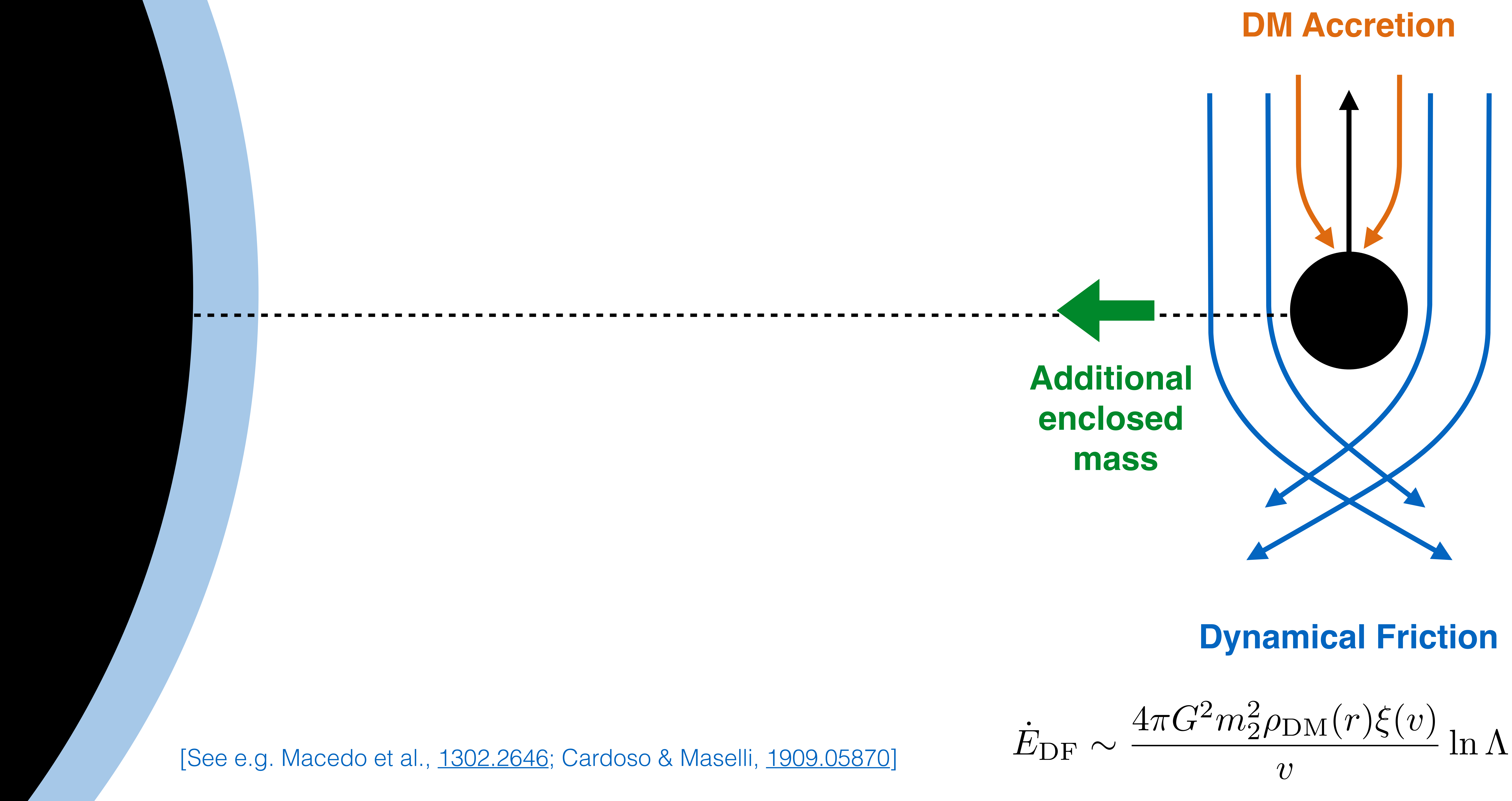


$m_2/m_1 \ll 1$

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

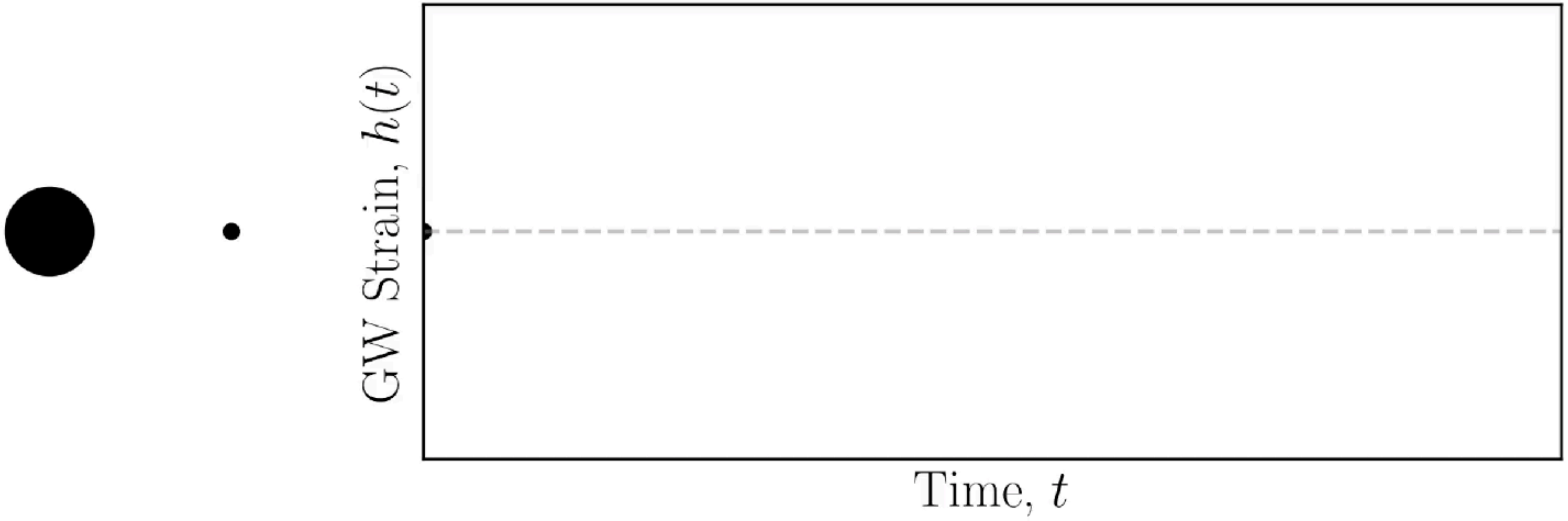
Text



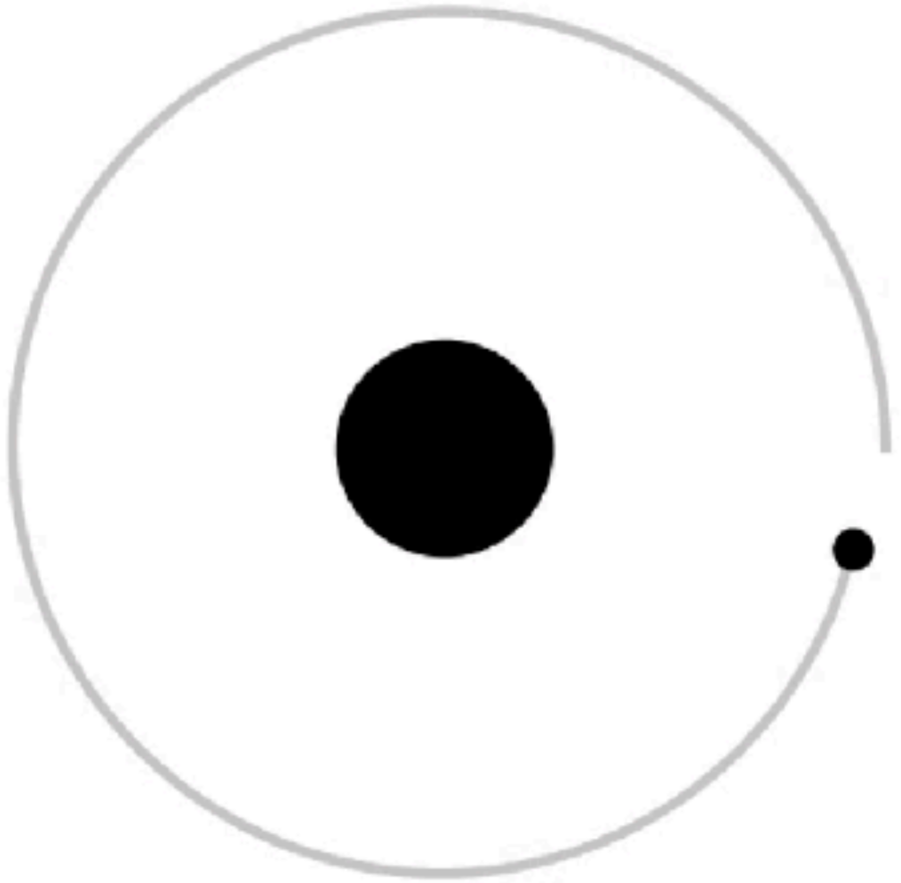
$$\dot{E}_{\rm DF} \sim \frac{4\pi G^2 m_2^2 \rho_{\rm DM}(r)\xi(v)}{v} \ln\Lambda$$

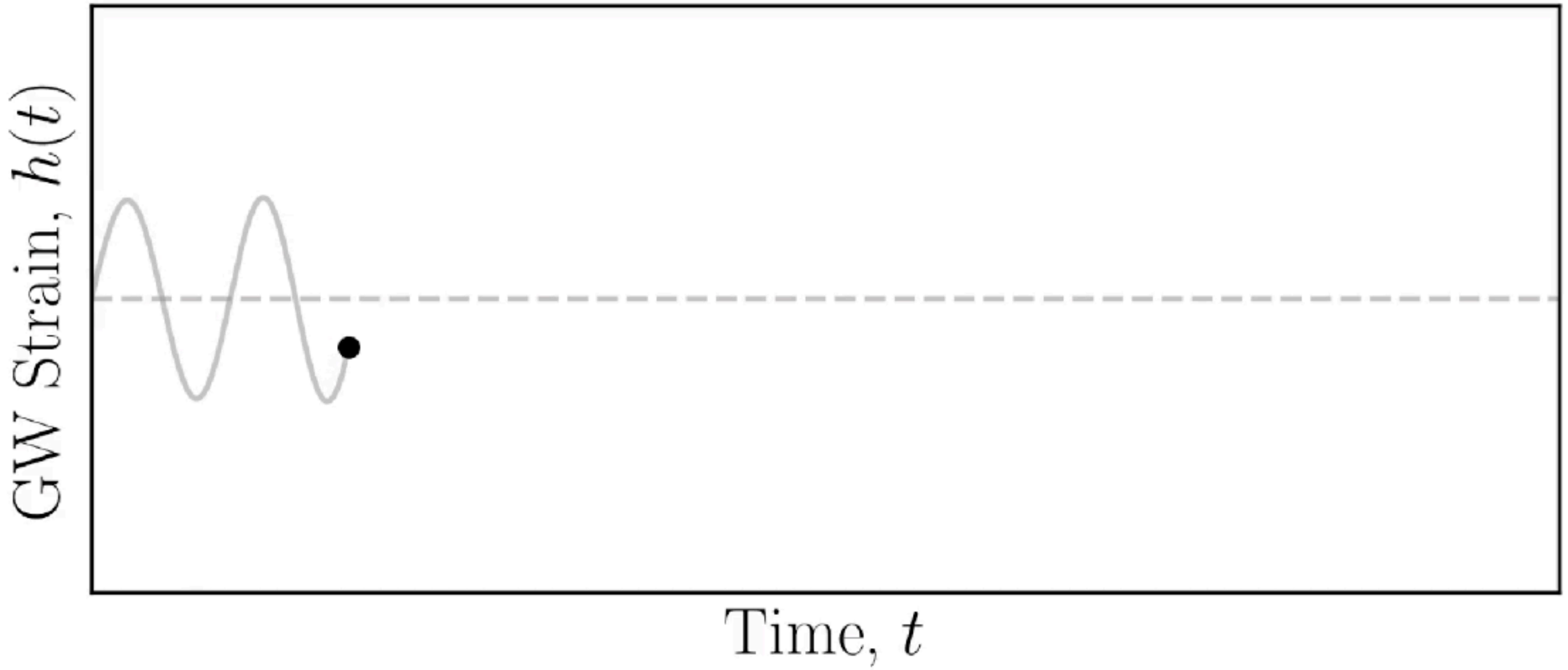
[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

[Animations online]

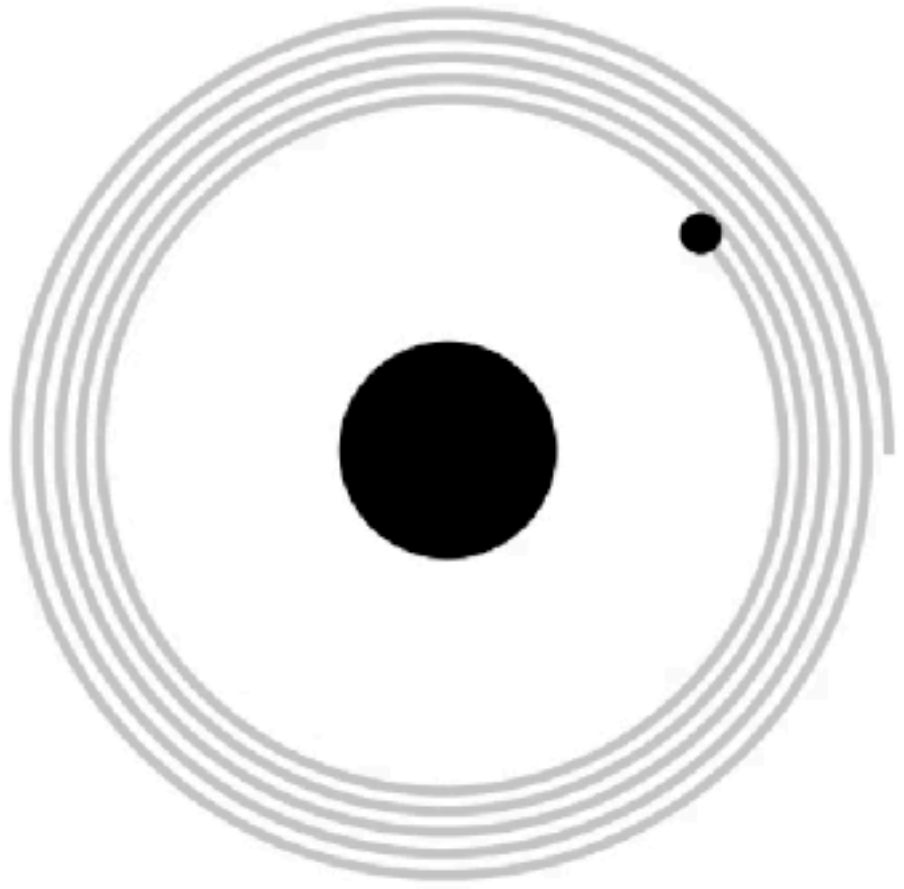


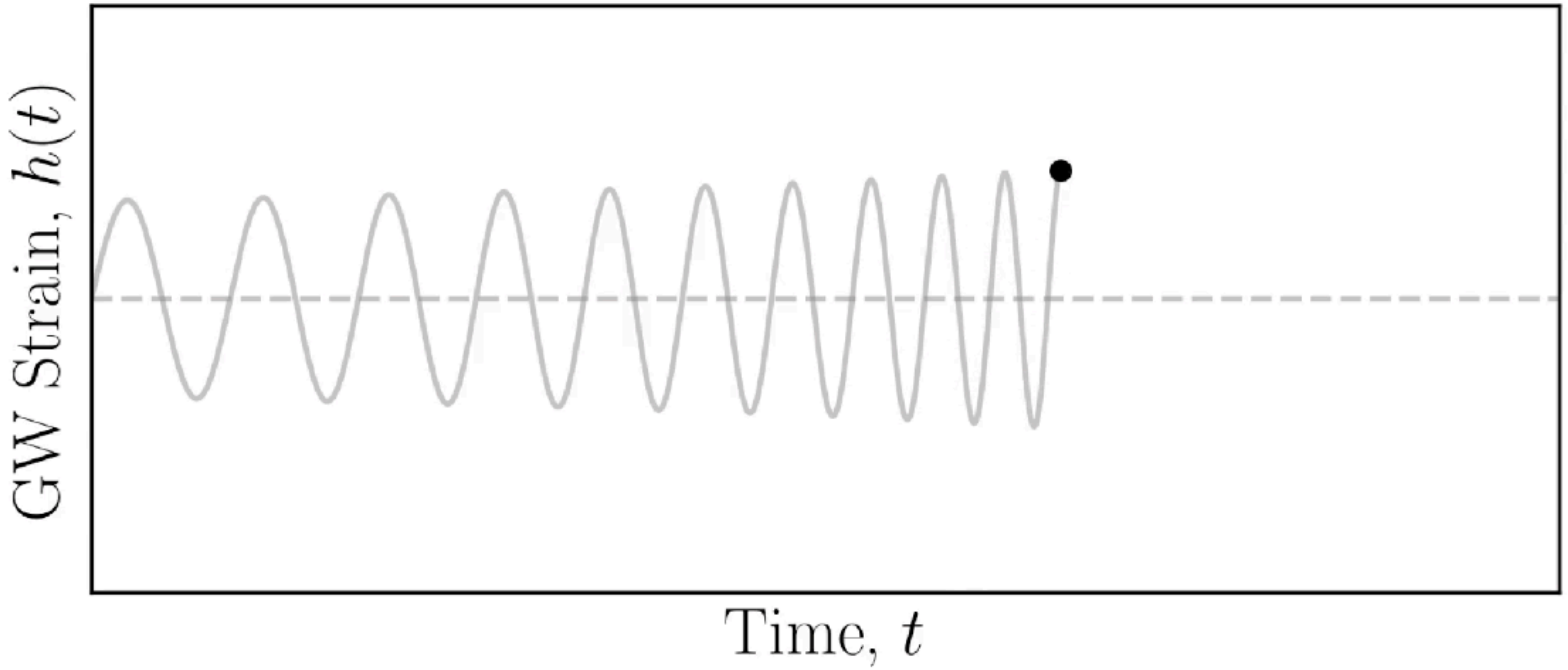
[Animations online]



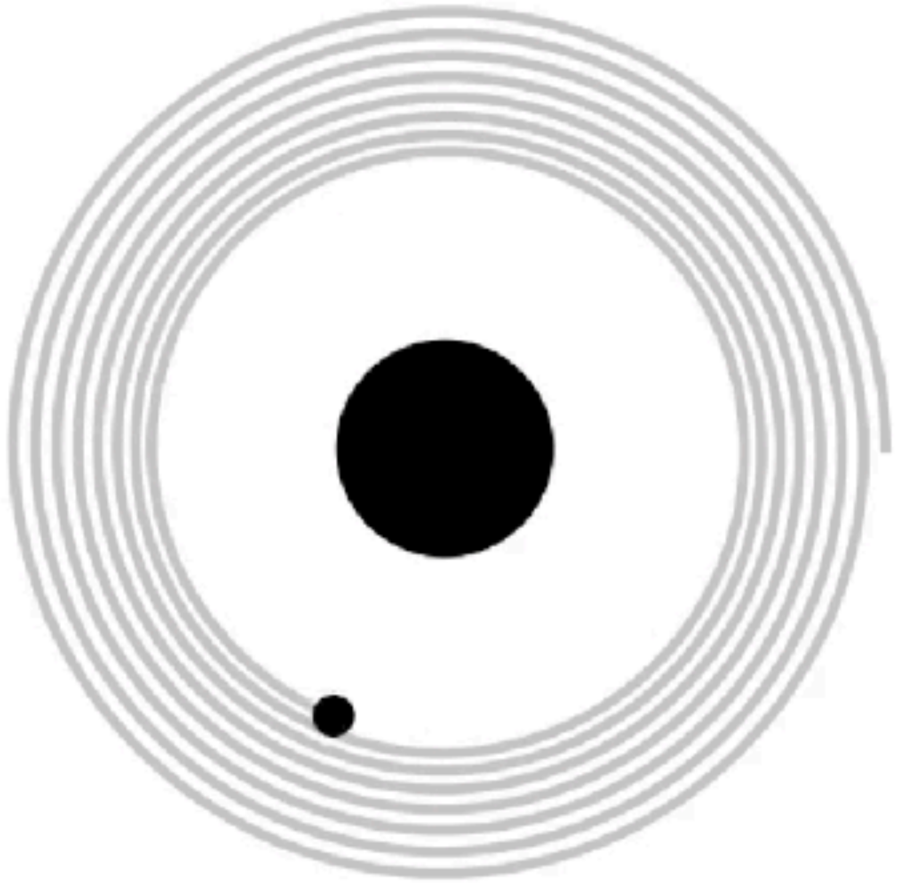


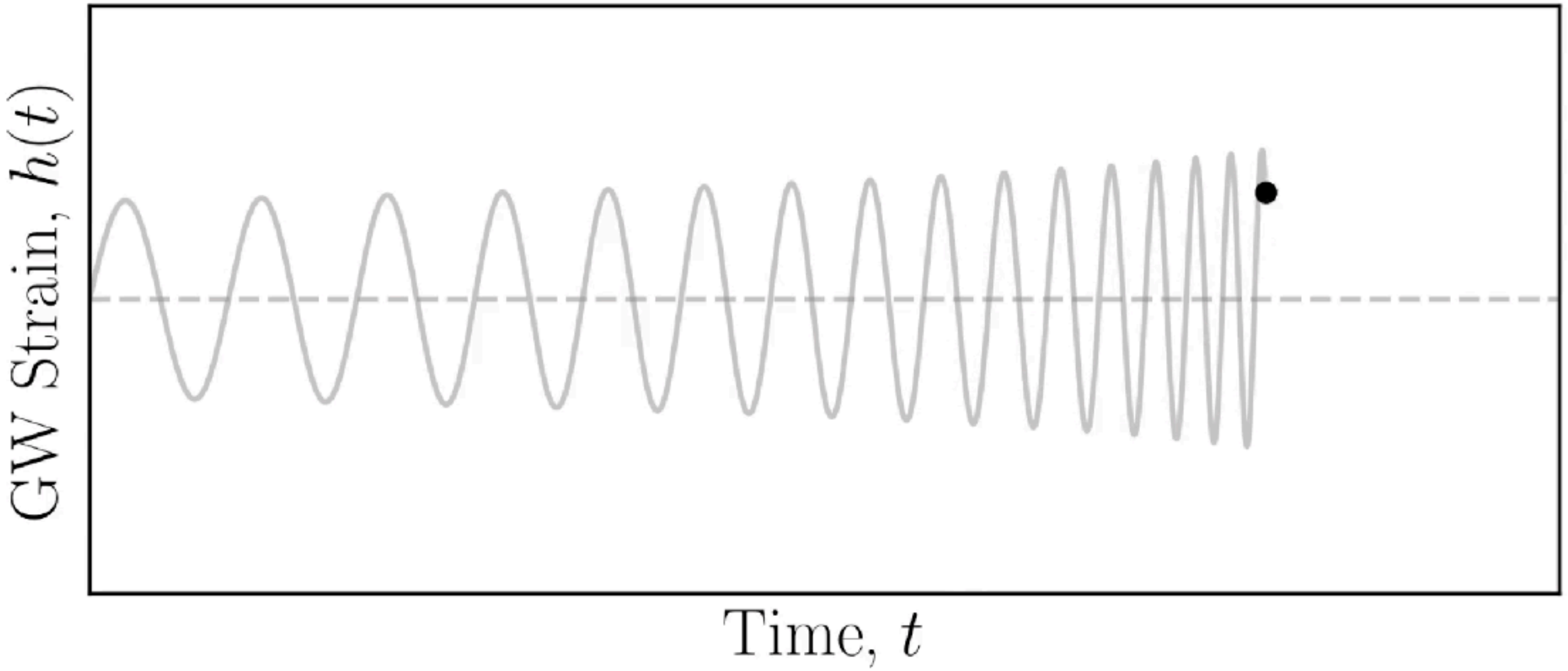
[Animations online]



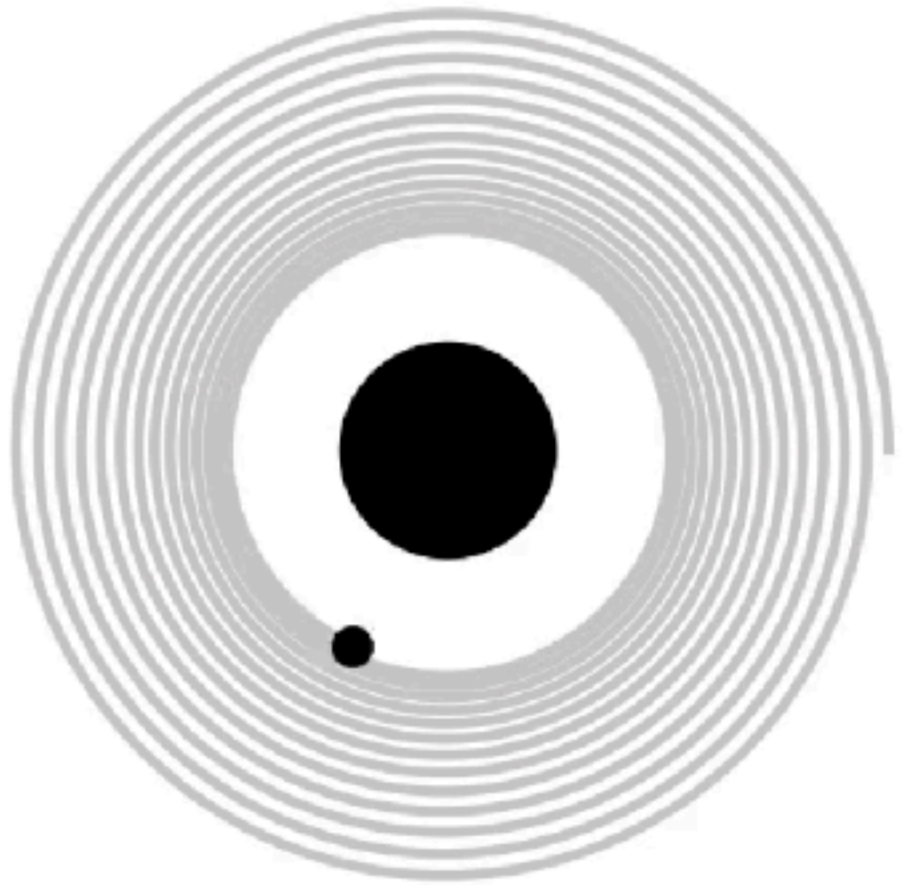


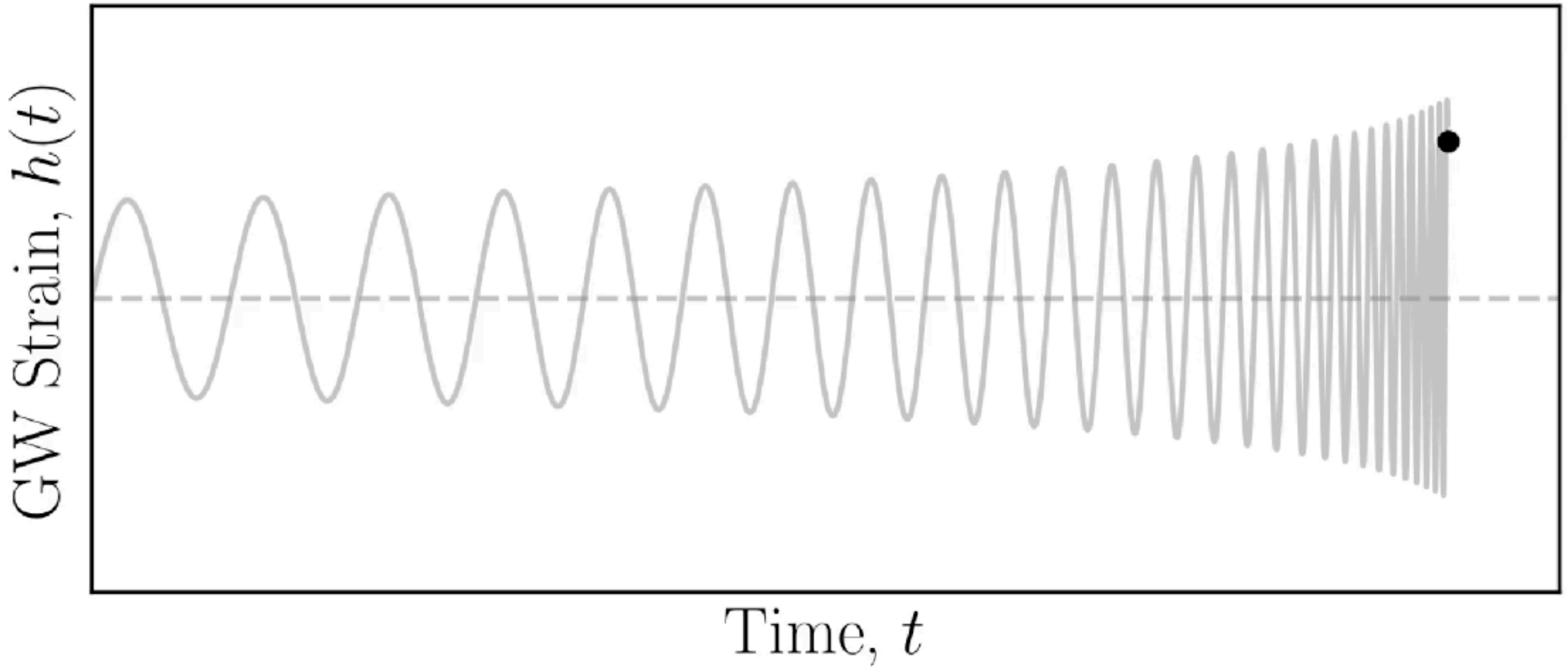
[Animations online]



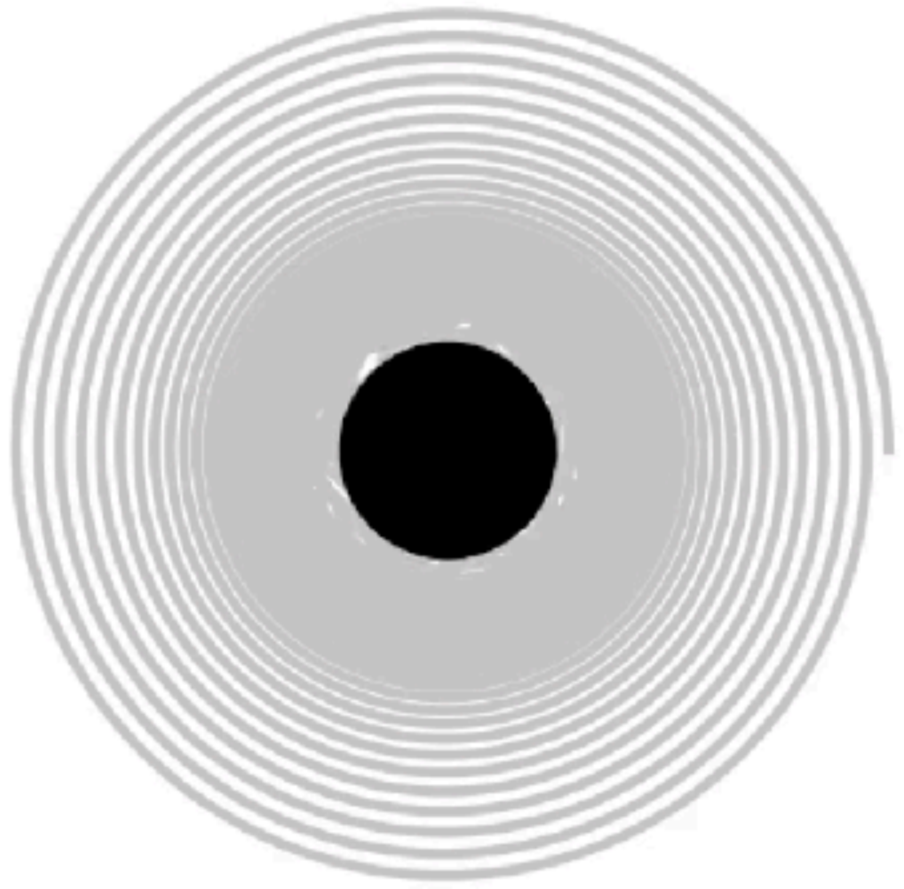


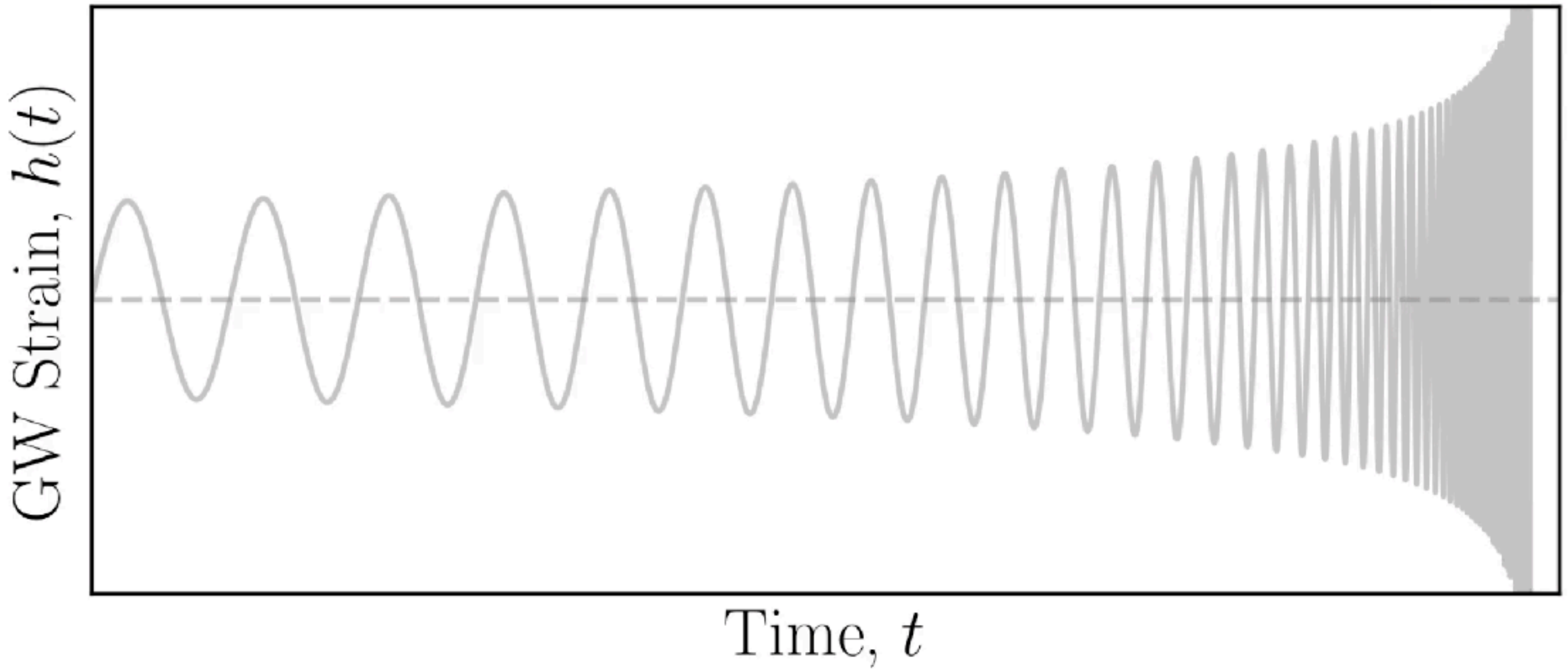
[Animations online]



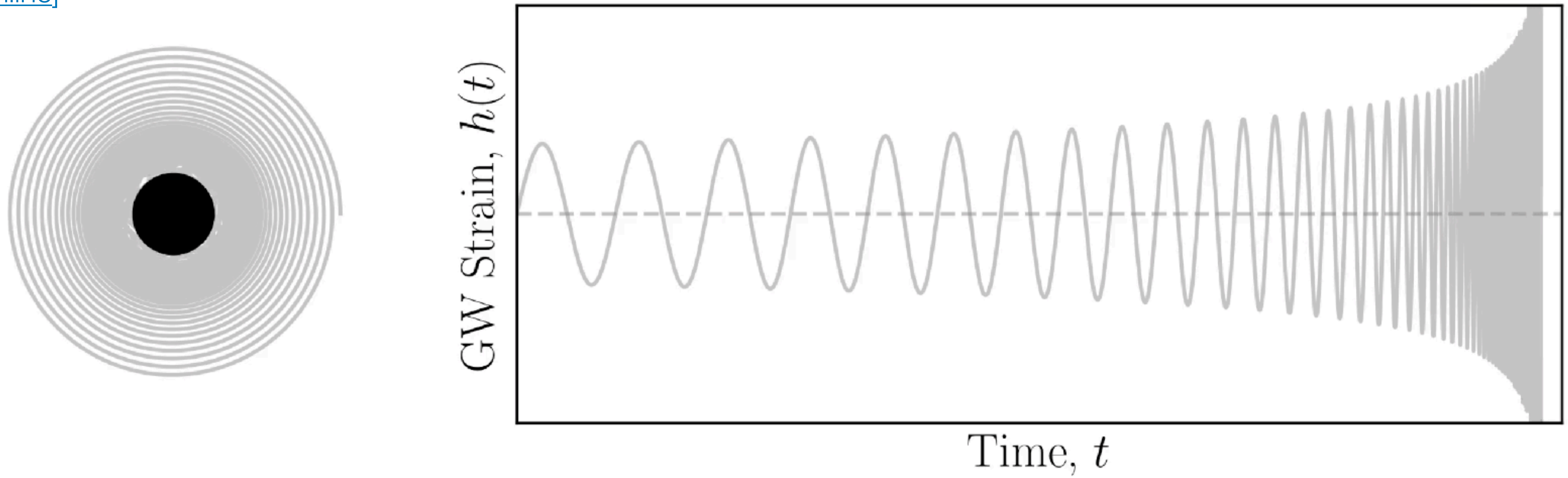


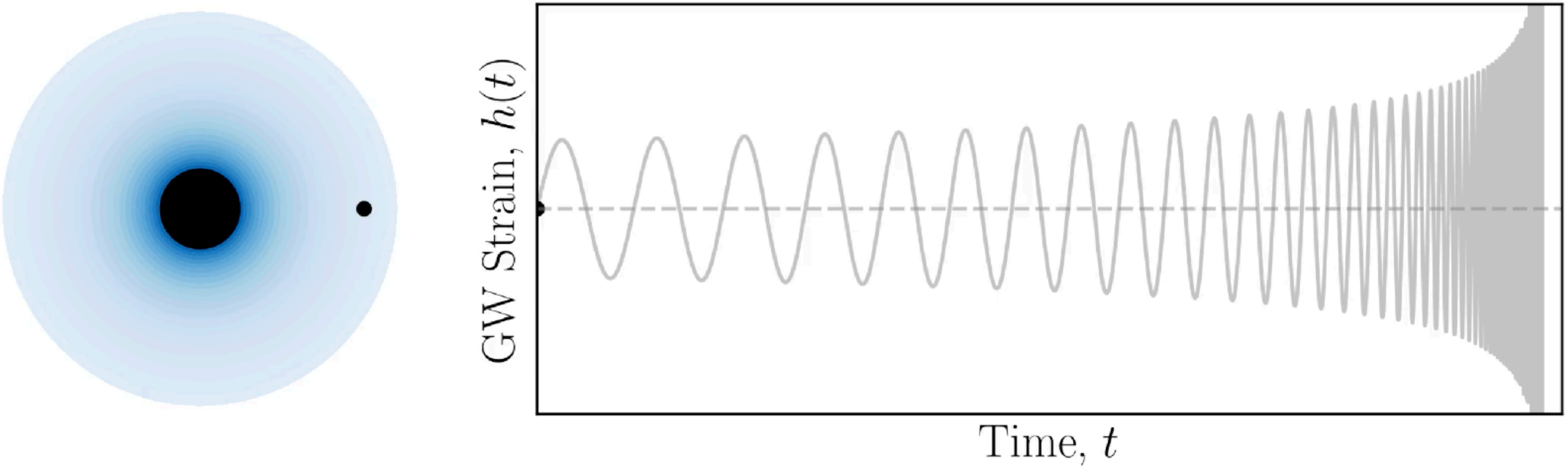
[Animations online]



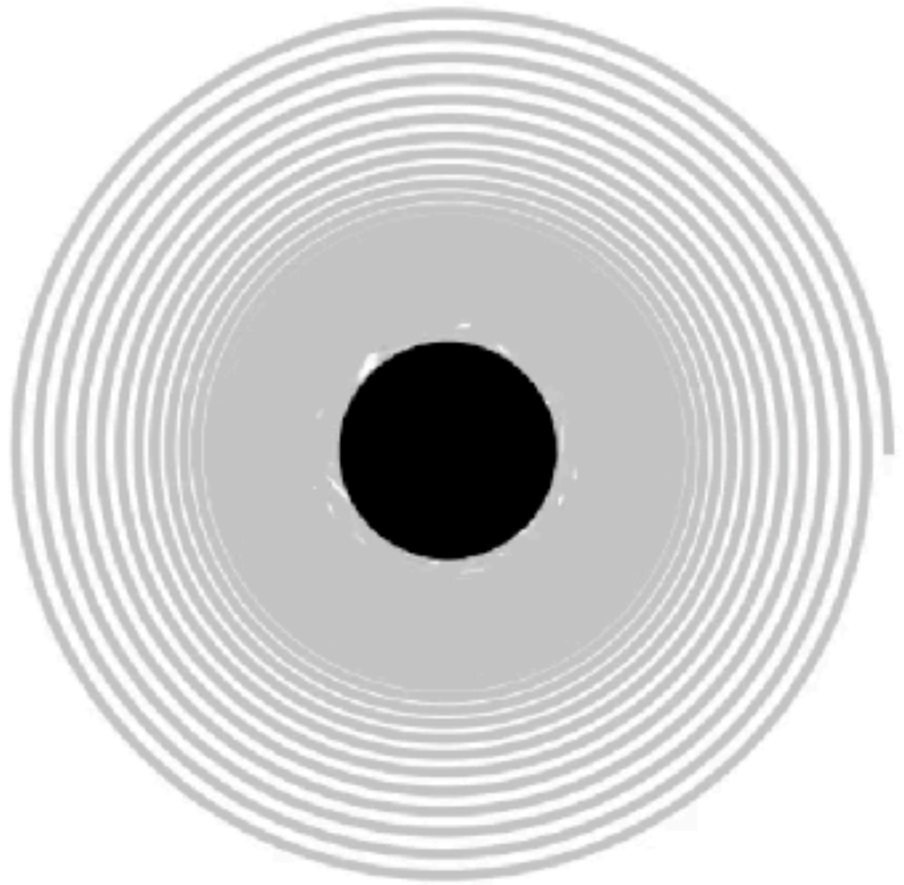


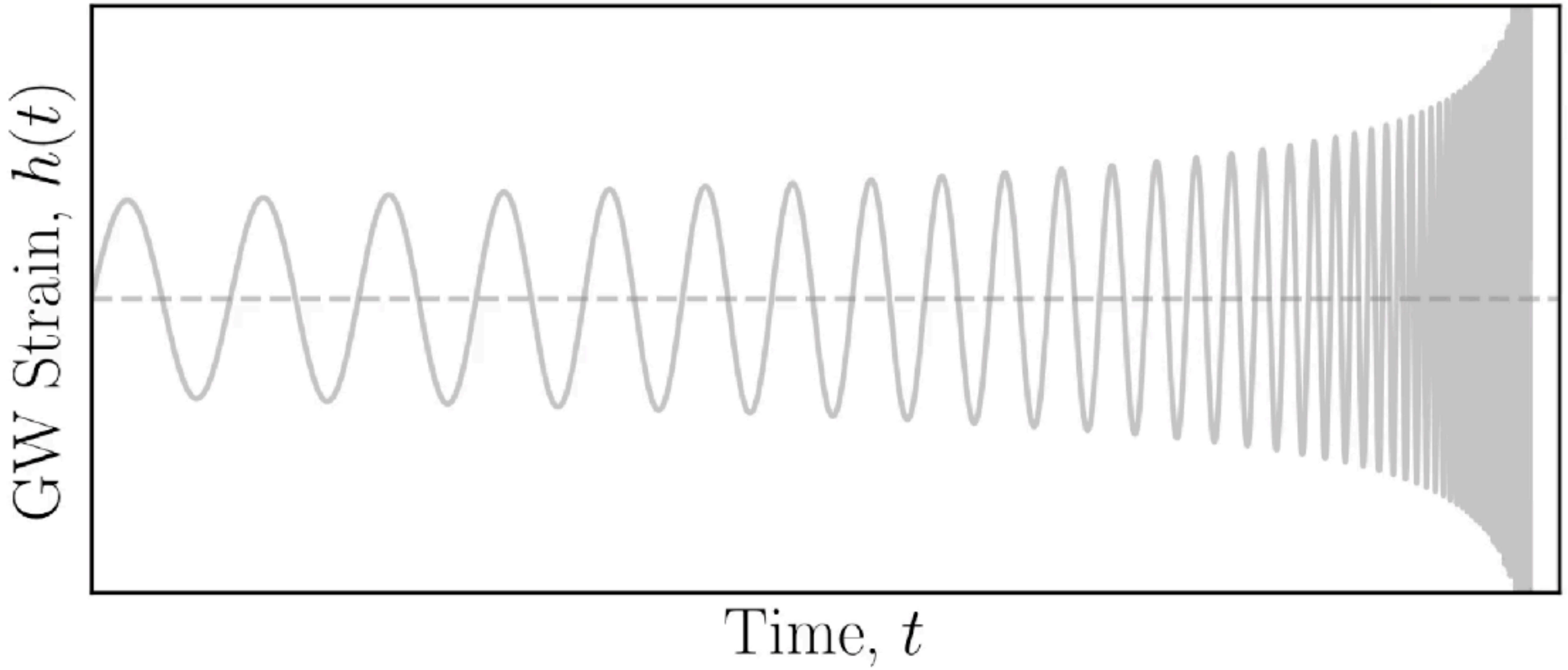
[Animations online]

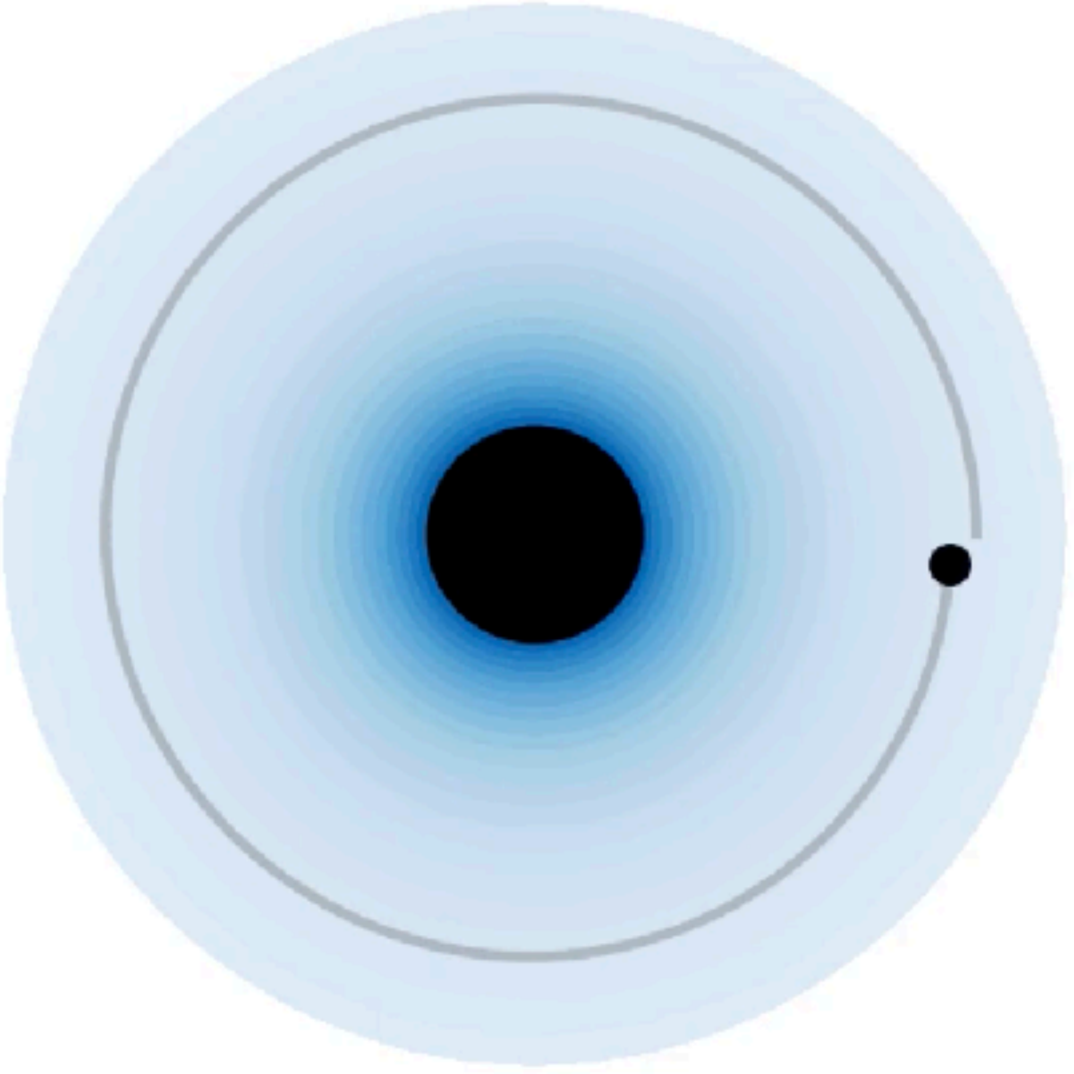


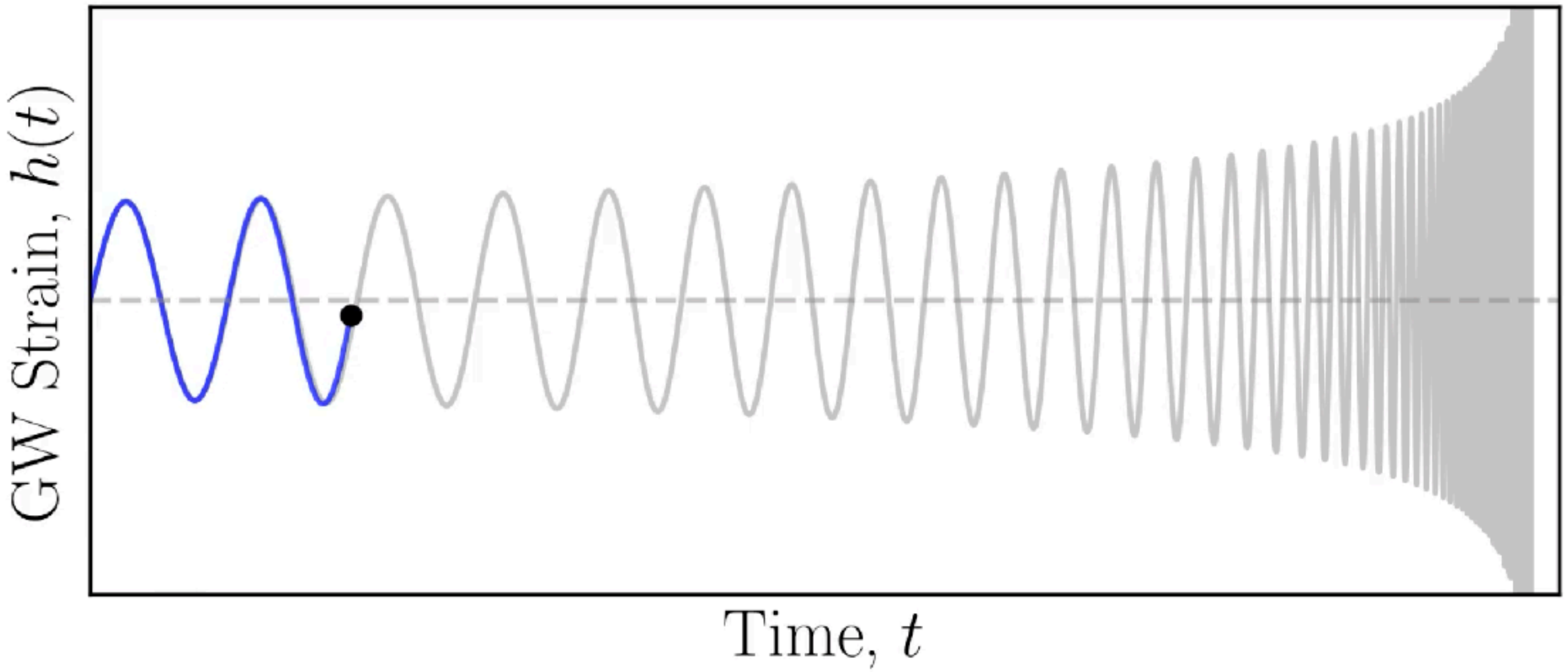


[Animations online]









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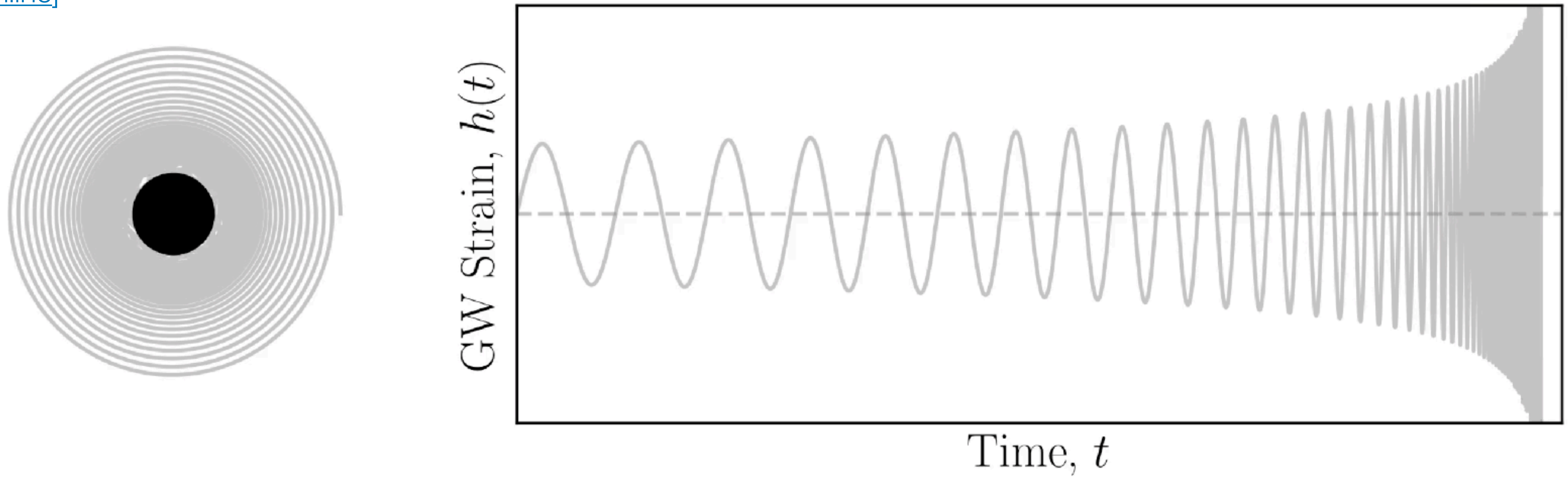

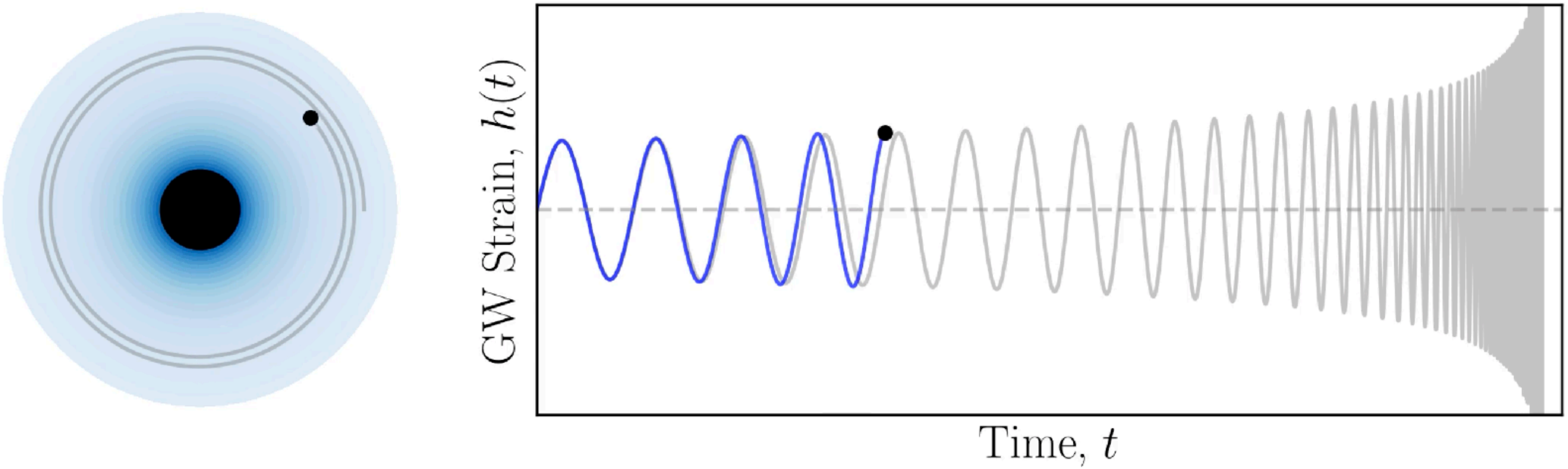

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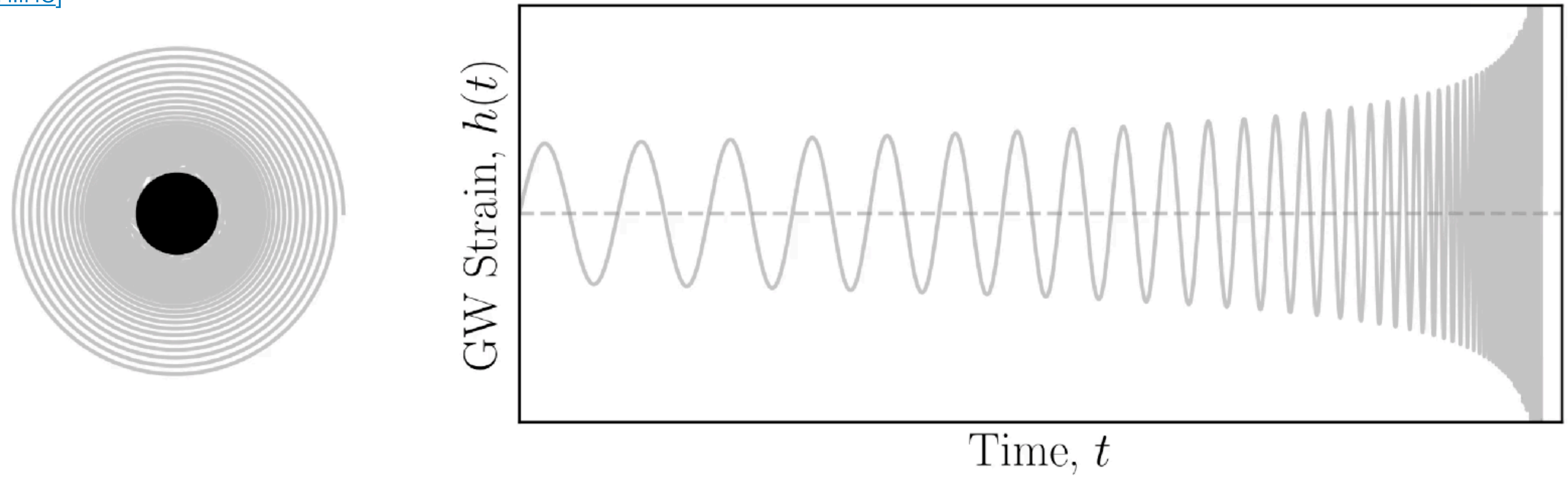
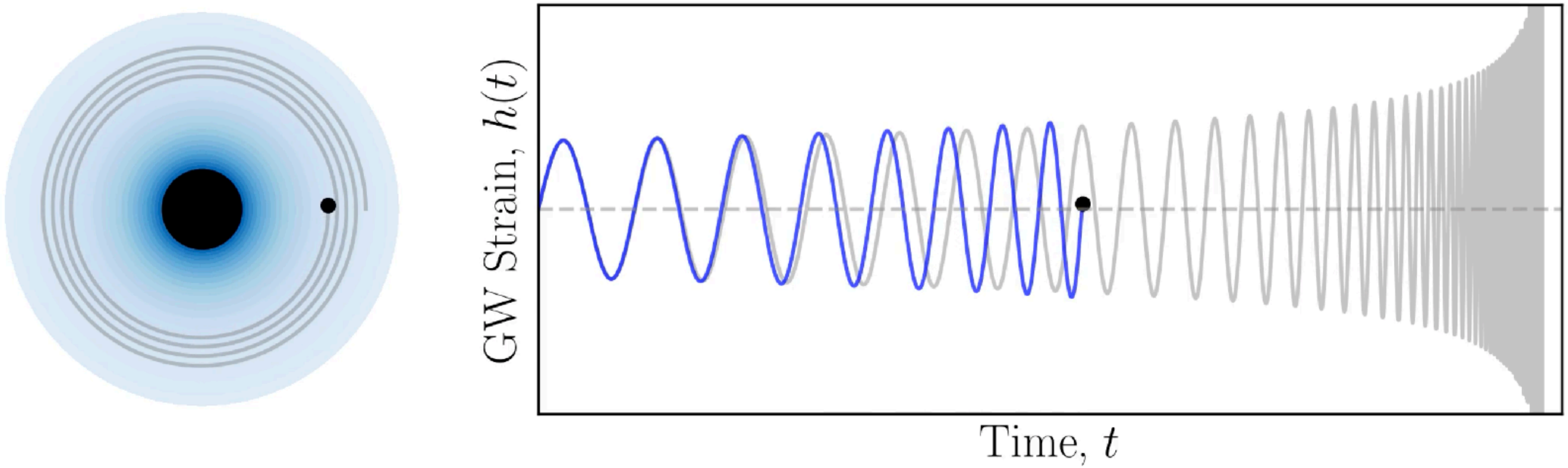
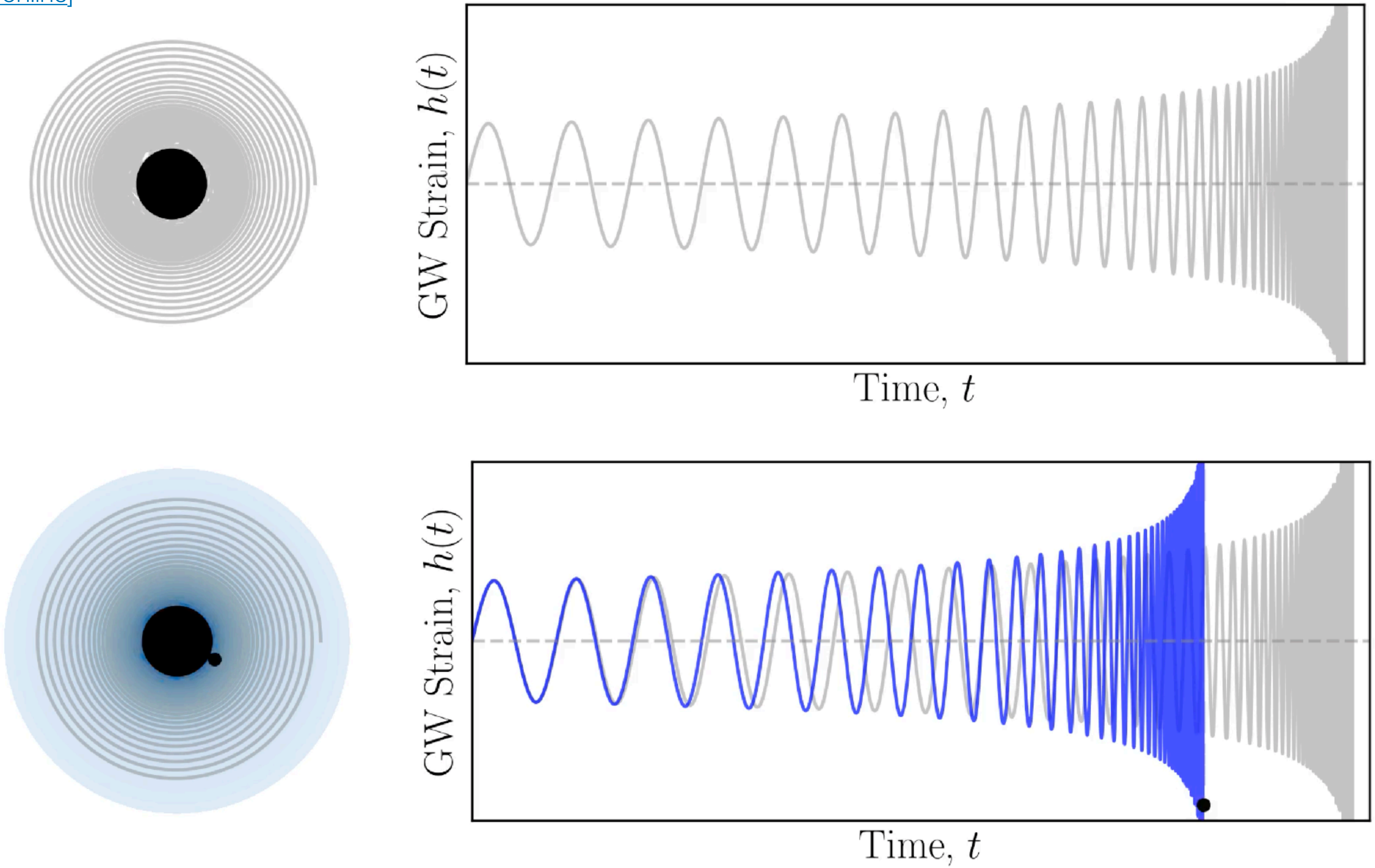
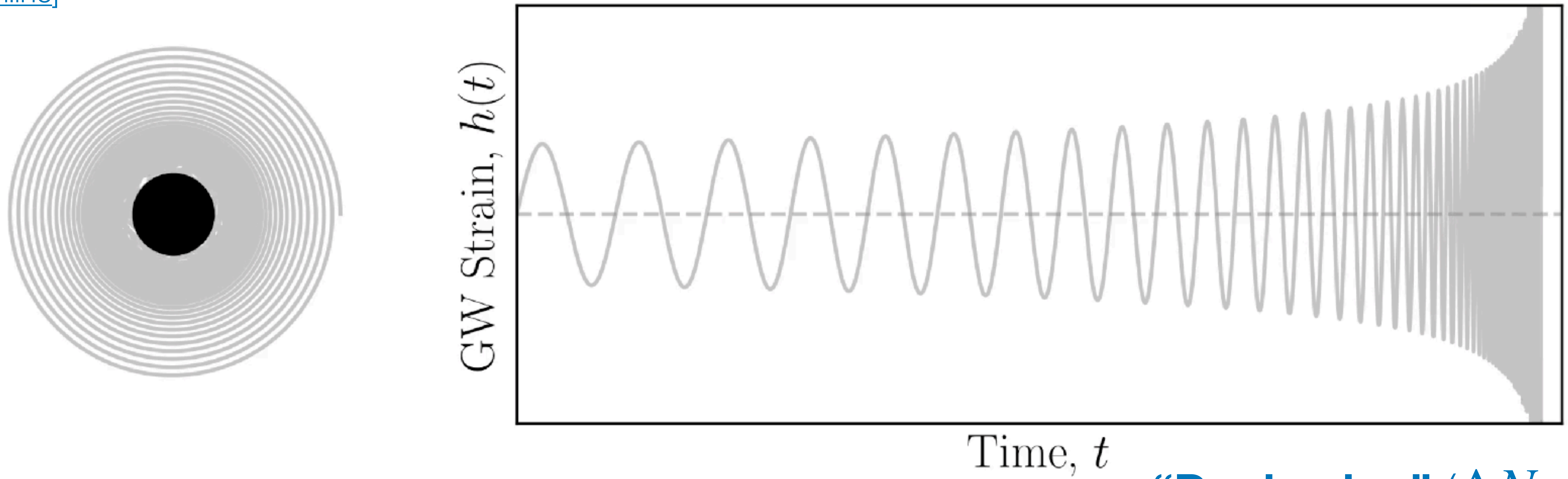




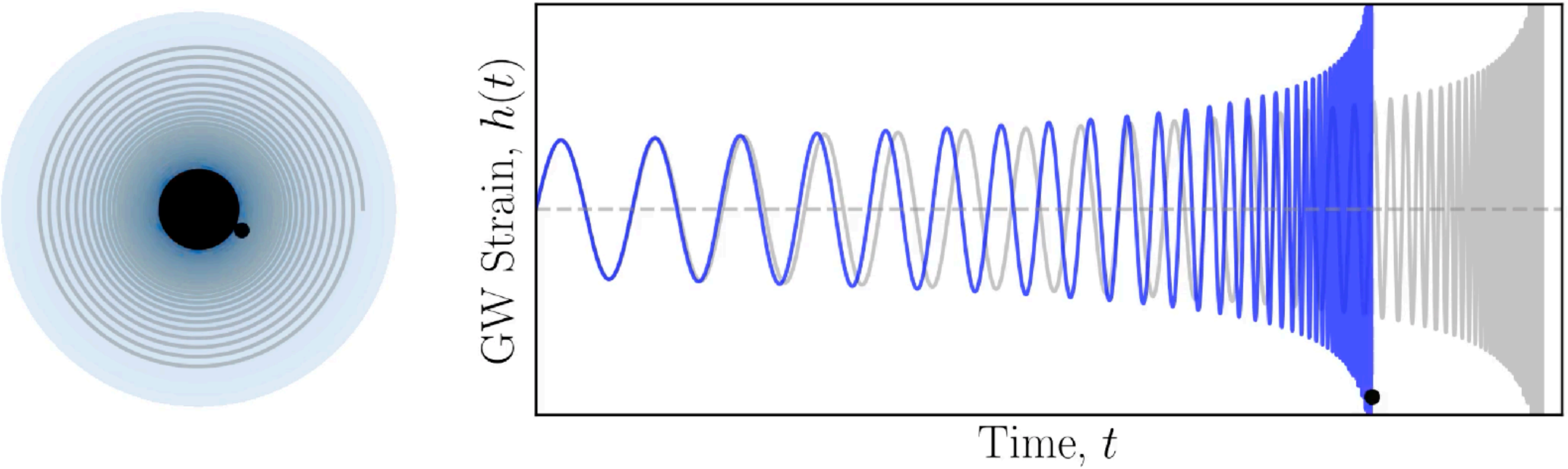
[Animations online]



[Animations online]

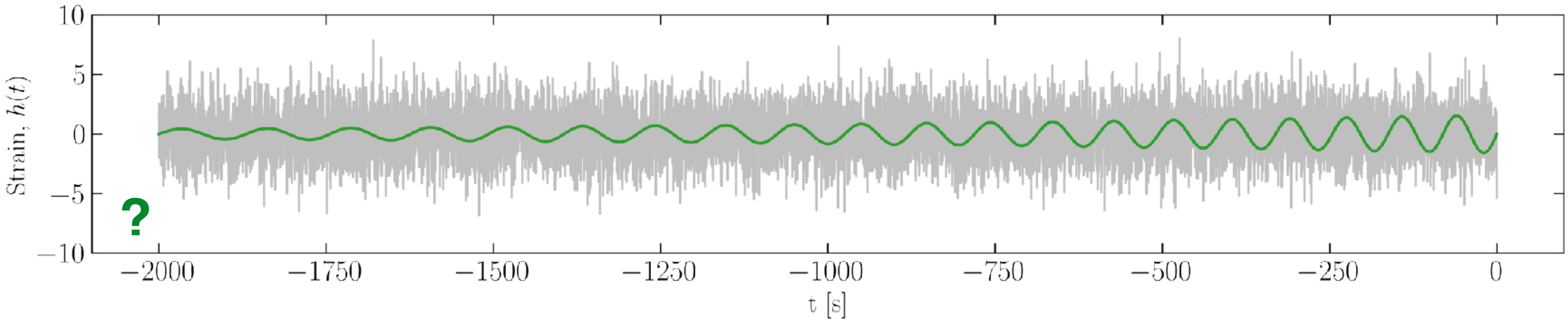


“Dephasing” $(\Delta N_{\rm GW})$



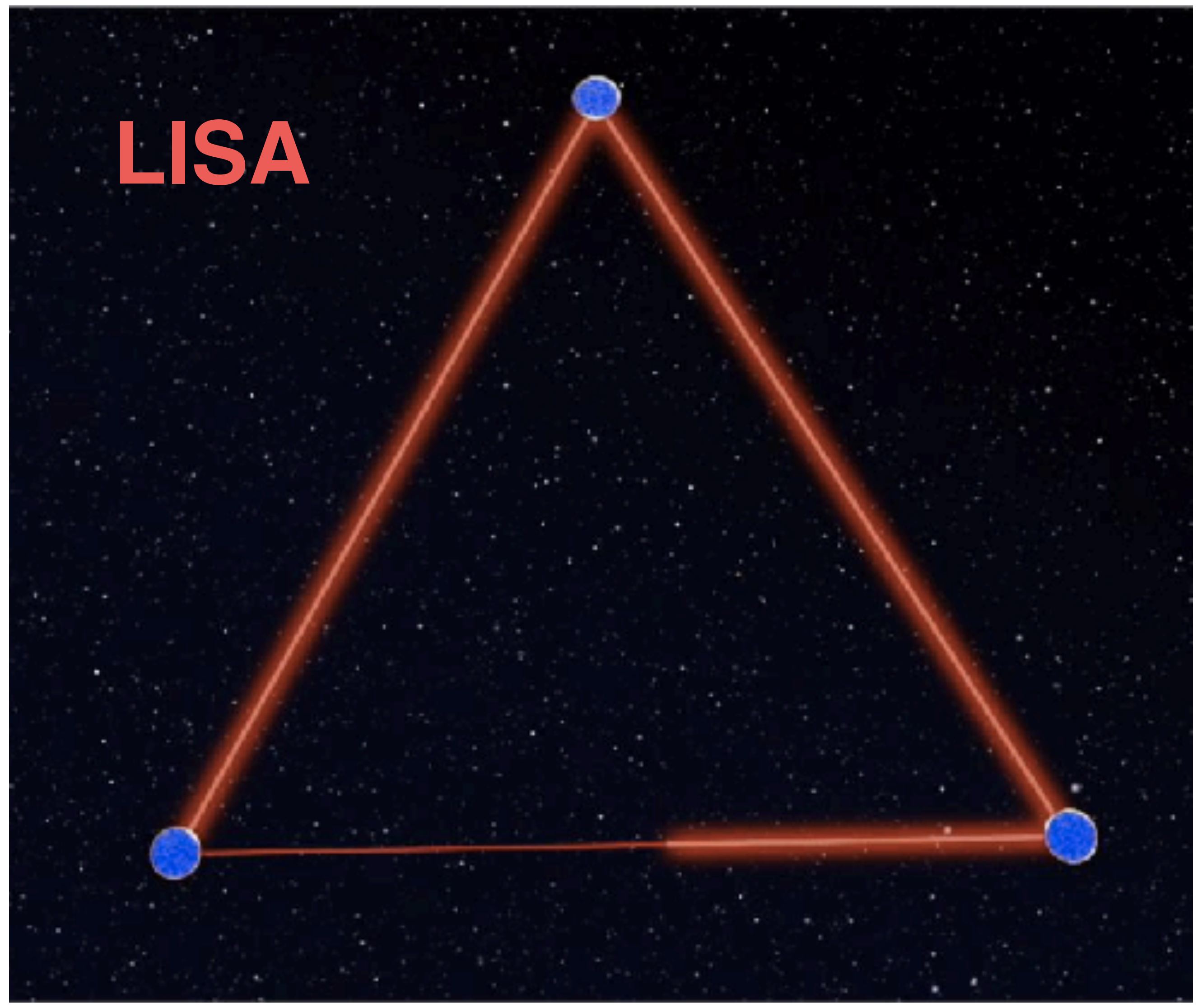
Can we measure this effect?

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



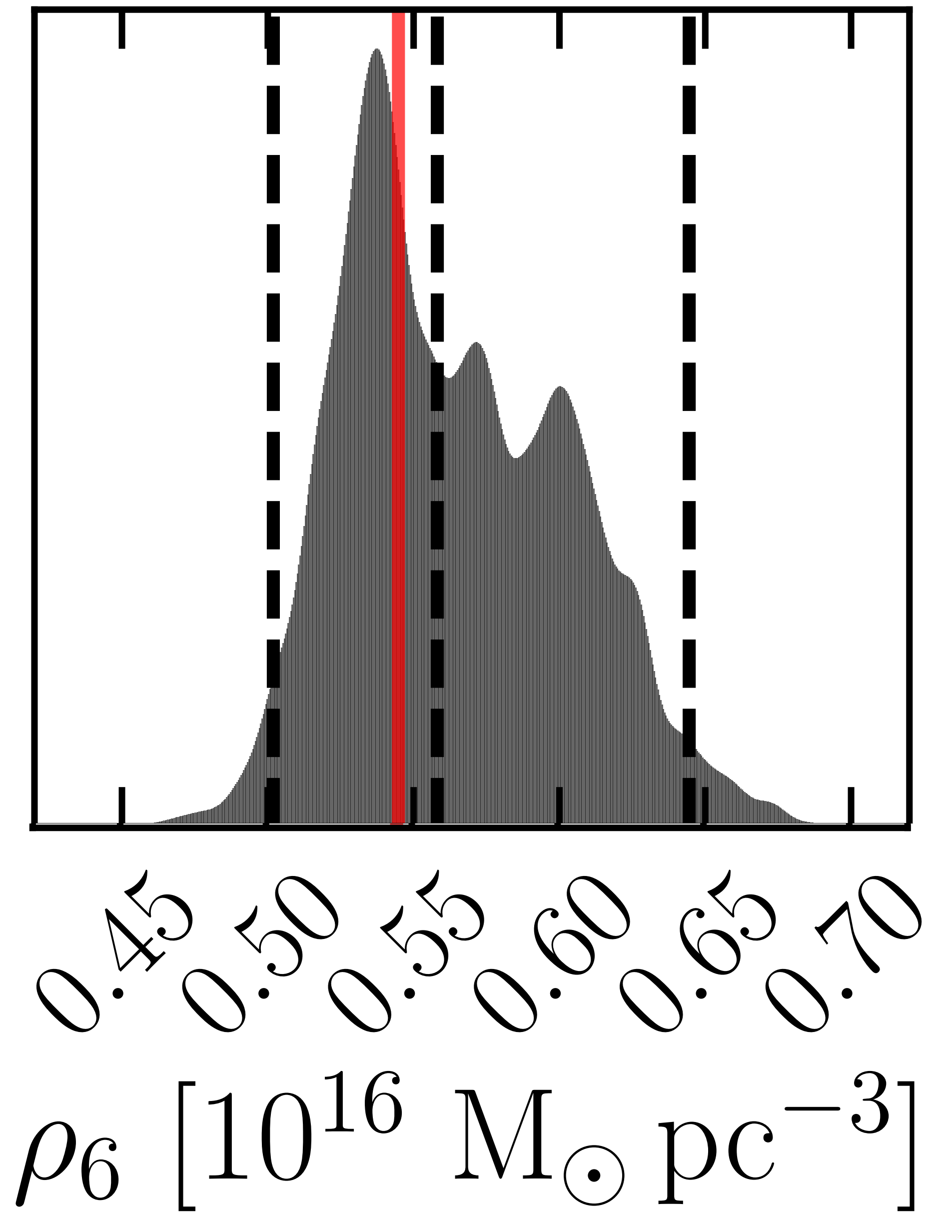
$m_1 = 1000\,M_\odot$
$m_2 = 1\,M_\odot$
$\gamma_{\rm sp} = 7/3$
$\rho_6 = 5.45 \times 10^{15}\,M_\odot\,{\rm pc}^{-3}$

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



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

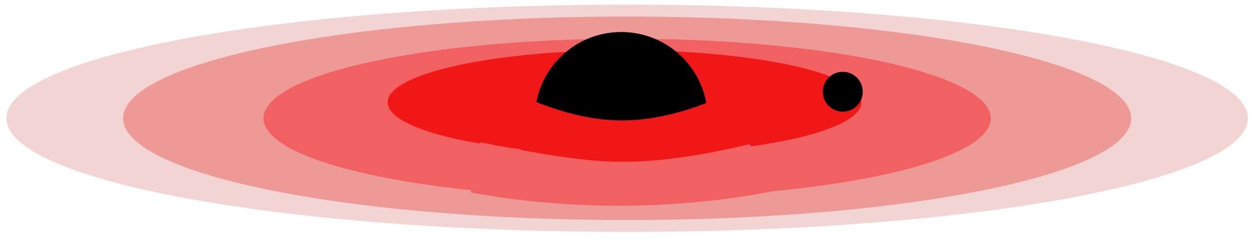
$\rho_6\ [10^{16}\ {\rm M_\odot\,pc^{-3}}] = 0.56^{+0.09}_{-0.06}$



Environmental Confusion

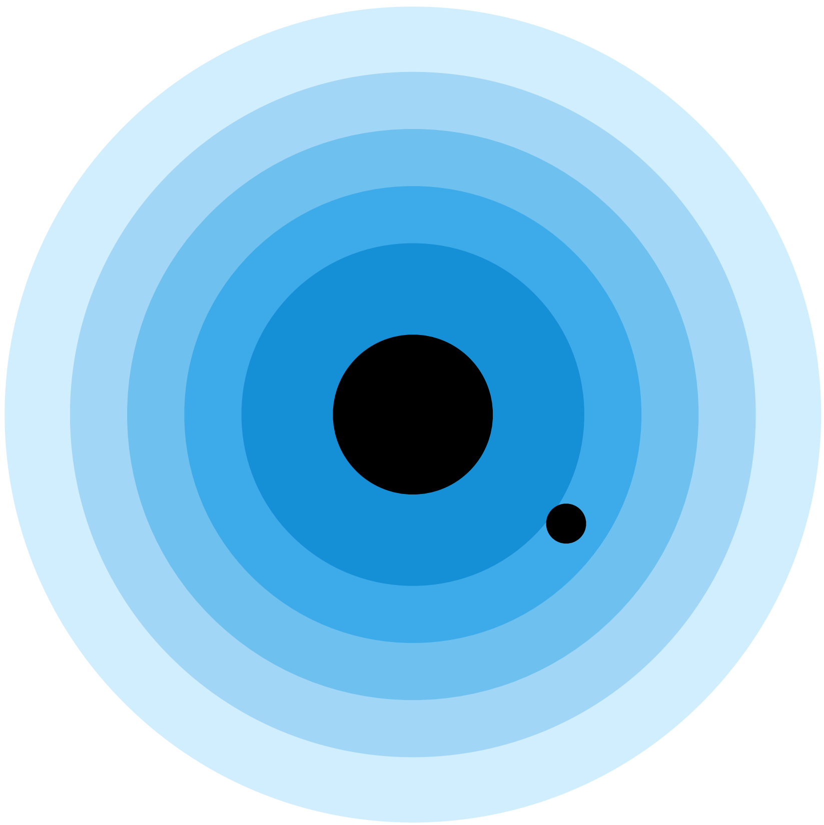
[Cole, Bertone, Coogan, Gaggero, Karydas, **BJK**, Spieksma, Tomaselli, 2211.01362, Nature Astronomy]

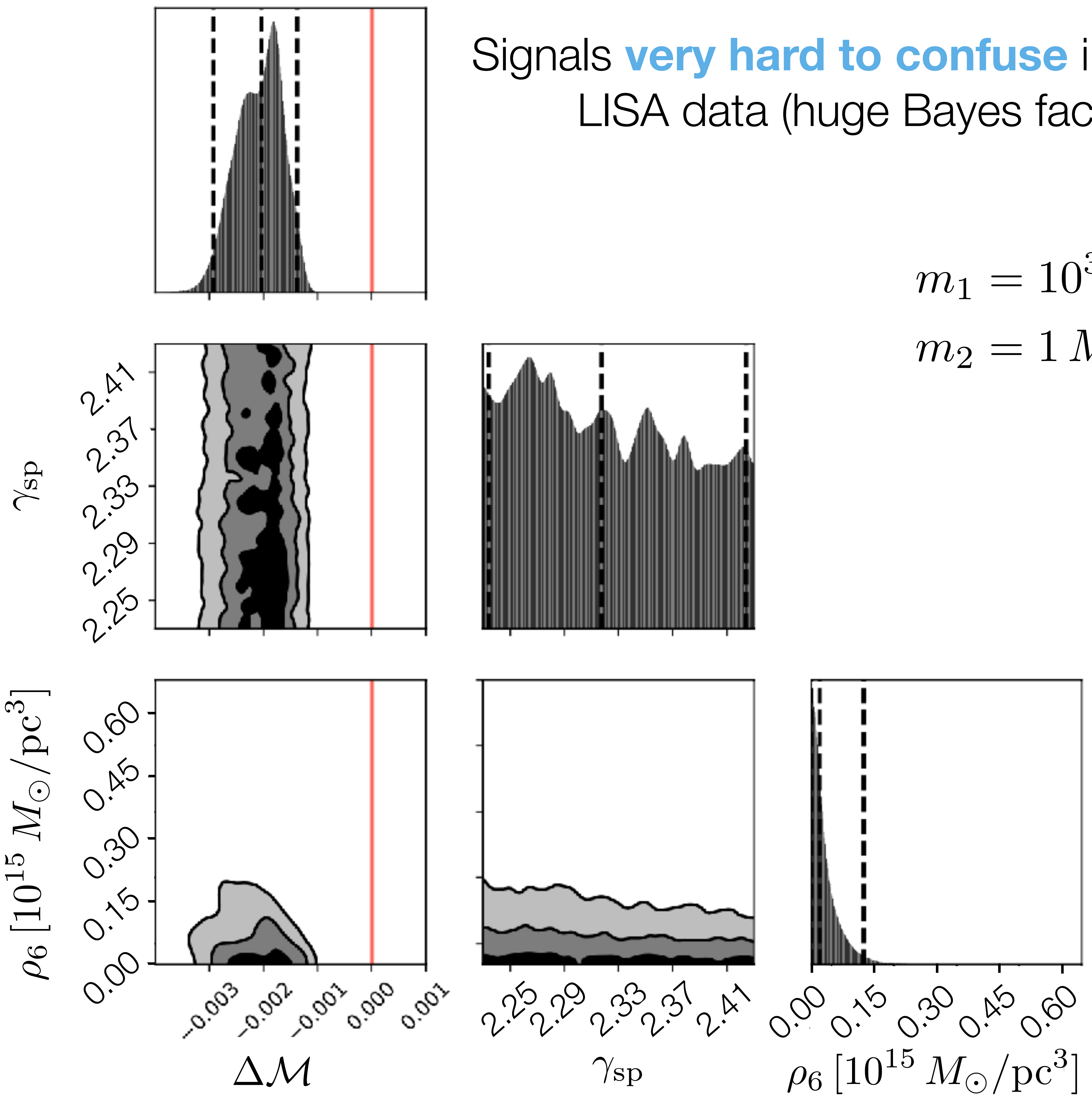
Generate waveform assuming:



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

Fit signal assuming:

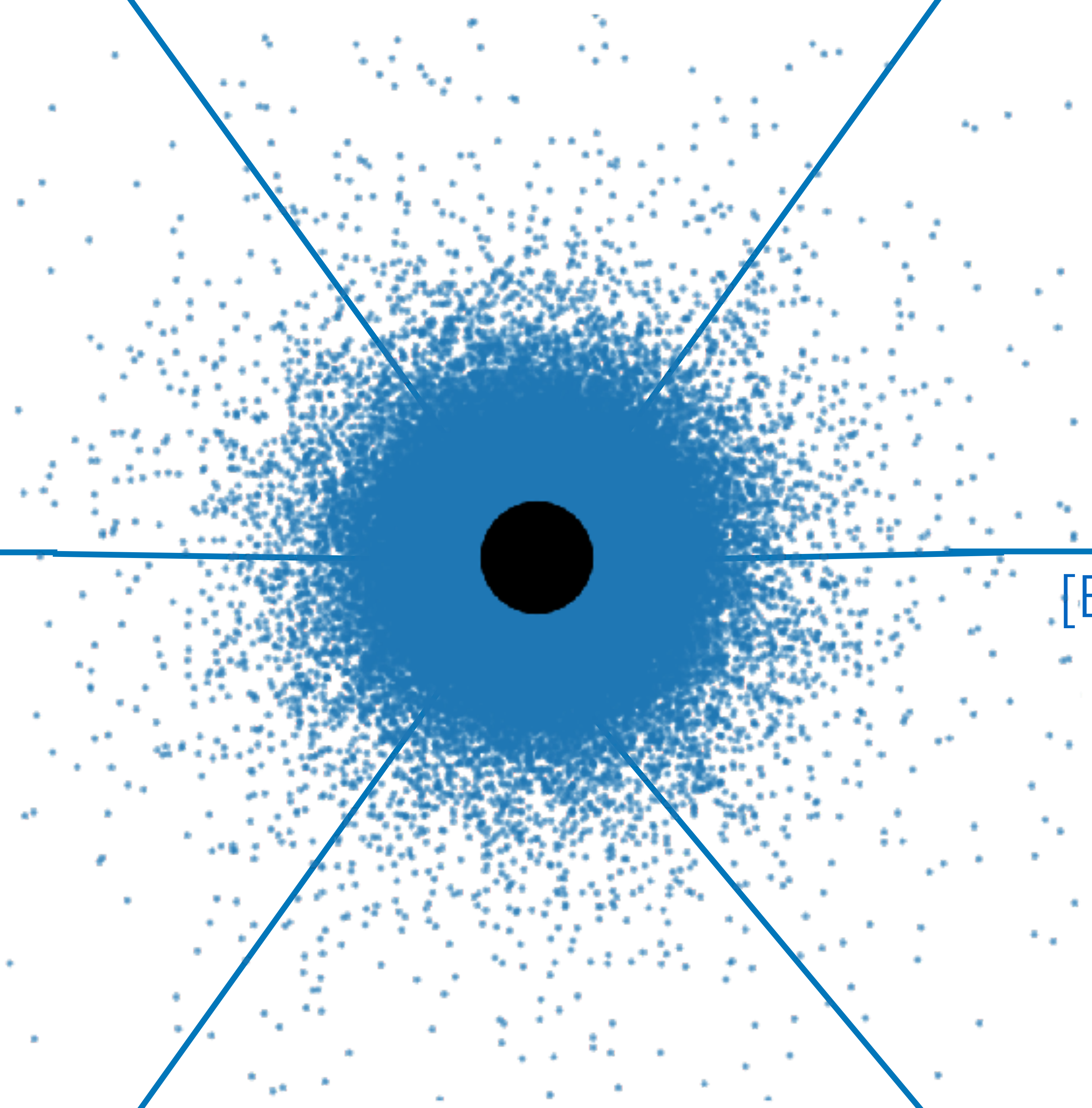




Signals **very hard to confuse** in 1 year of LISA data (huge Bayes factors!)

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

Many nuances and uncertainties



Relativistic effects

[E.g. Speeney et al., 2204.12508; Vicente et al., 2505.09715]

Integration with realistic IMRI/EMRI waveforms

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

Search strategies

Realistic spike formation and abundance

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

Spike survival

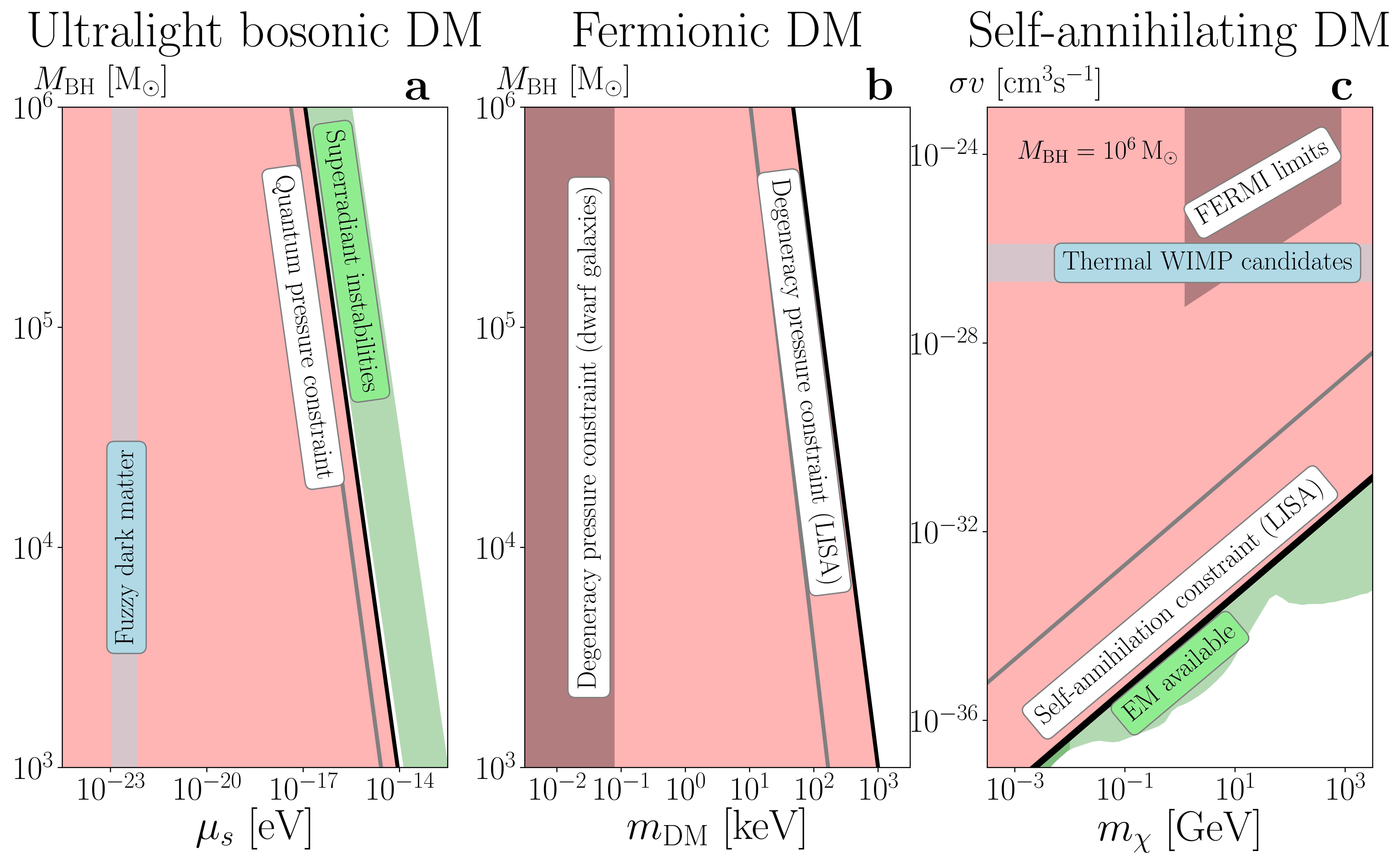
[E.g. Sharpe et al., 2603.28866; Herrera et al., 2605.01023]

Realistic feedback

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

Spikes for particle physics!

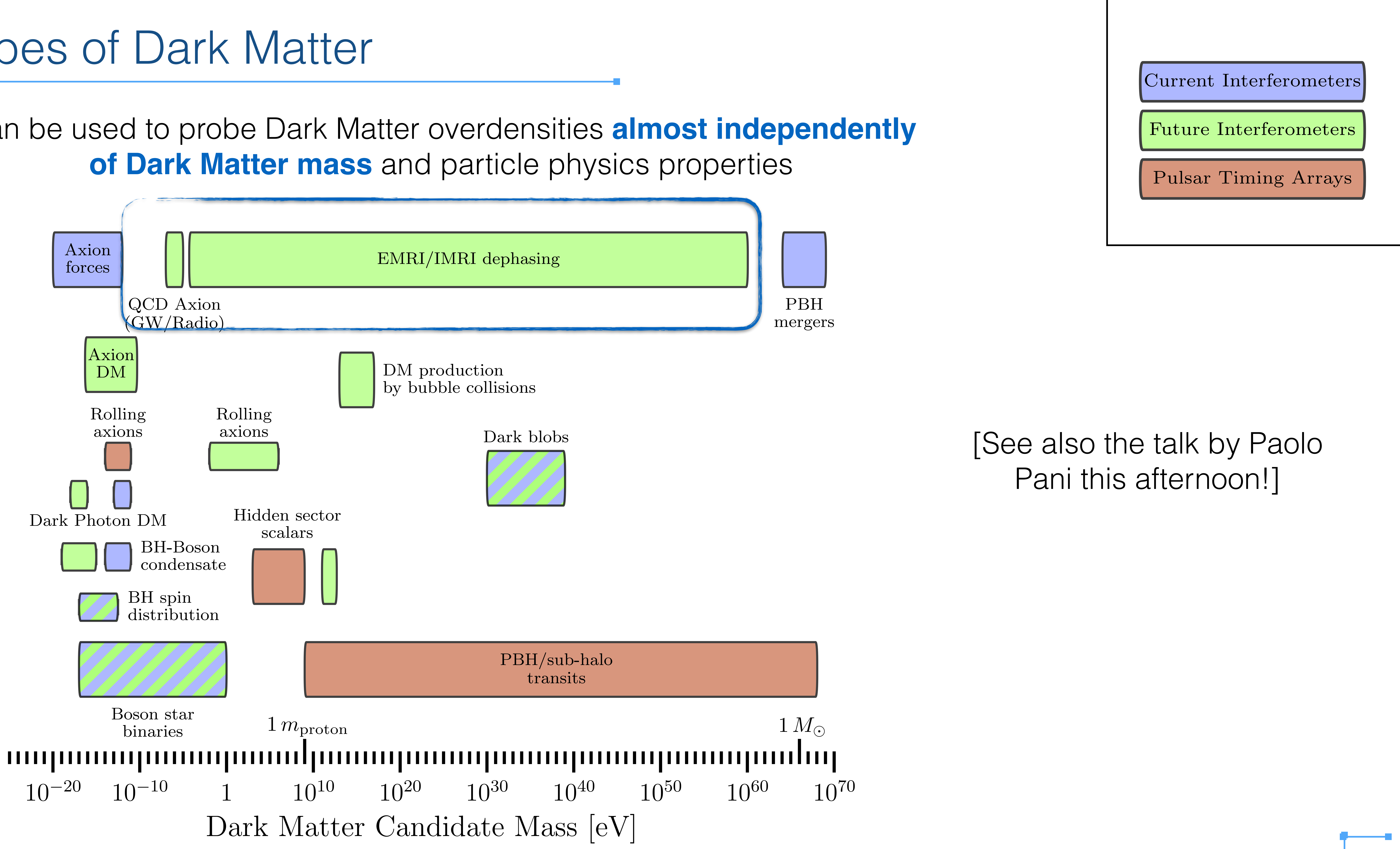
Red regions would be ruled out by observation of a DM spike! [1906.11845]



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

GW Probes of 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]

Where should we look for Dark Matter?

Where in *parameter* space?

Search for self-consistent models (and production mechanisms) for DM.

There are plenty within reach (but we shouldn't stop at benchmarks!)

Where in *signal* space?

As we enter new parameter spaces, we should be aware of new signals.

New interactions, new fluxes, new uses for existing experiments!

Where in *physical* space?

Dark matter is all around us, but we should also look further afield.

Extreme environments provides challenges, but also complementarity and opportunity!

*Many of these ideas also apply e.g. to axion dark matter

Where should we look for Dark Matter?

Thank you!

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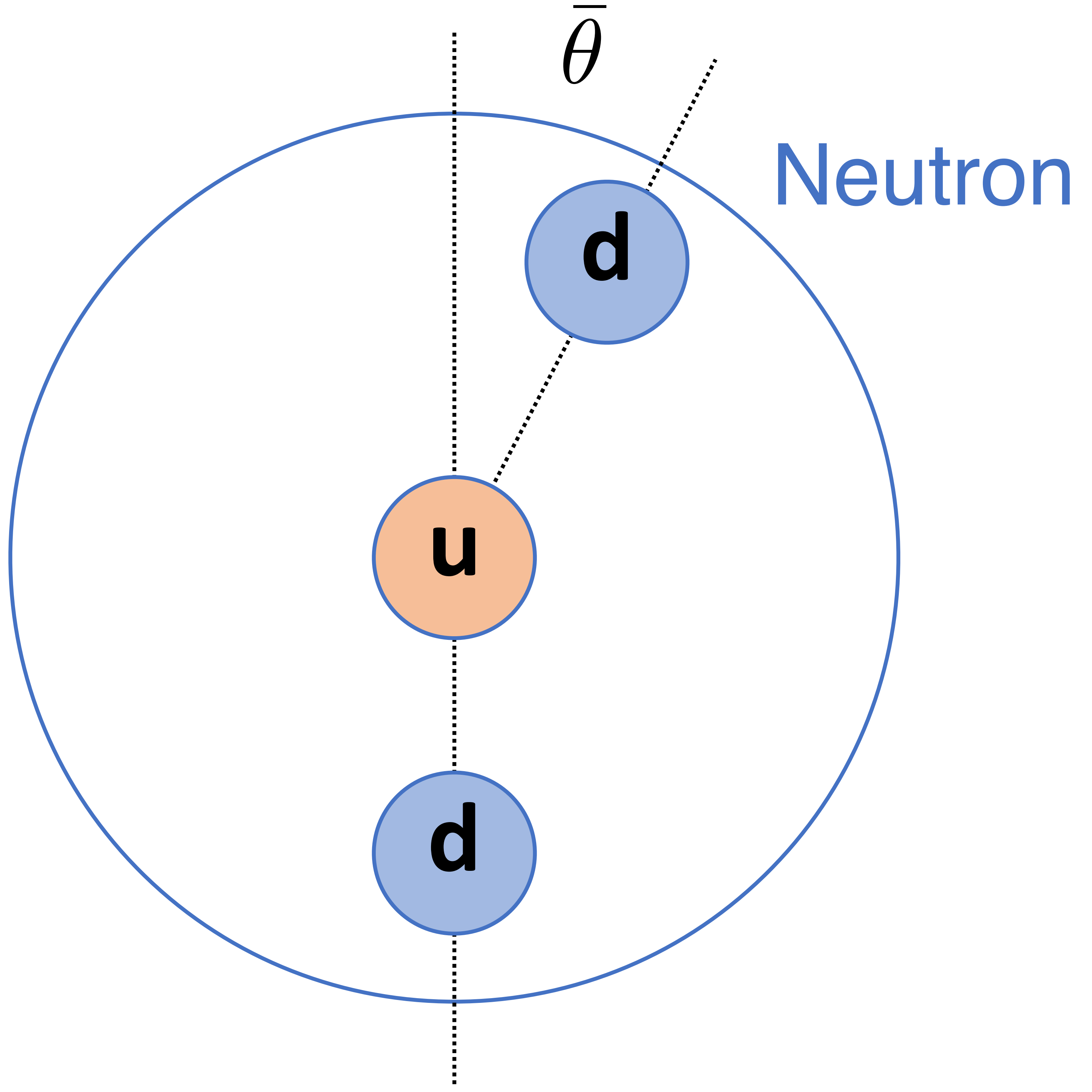
Backup Slides

The Strong CP Problem

Quantum Chromodynamics (QCD), the theory of the strong force, could have a large Charge-Parity (CP) violating term:

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta}\,\frac{1}{32\pi^2} G\tilde{G}$$

Gluon field strength



$d_n \lesssim 10^{-26}\,e\,{\rm cm} \Rightarrow \bar{\theta} \lesssim 10^{-10}$

CP violation would give rise, for example, to a neutron electric dipole moment $d_n \sim 10^{-16}\,\bar{\theta}\,e\,{\rm cm}$. However, there is **no evidence of CP violation in Strong interactions.**

In QCD alone, the value of $\bar{\theta}$ is just a parameter of the theory, $\theta_{\rm QCD}$ - it could in principle be $\mathcal{O}(1)$!

Much worse: the Weak Interactions *do* violate CP and this can be transferred to the Strong sector through non-perturbative effects related to the quark masses: $\theta_{\rm Weak} = {\rm Arg}\,|\mathbf{M}_q| \sim \mathcal{O}(1)$

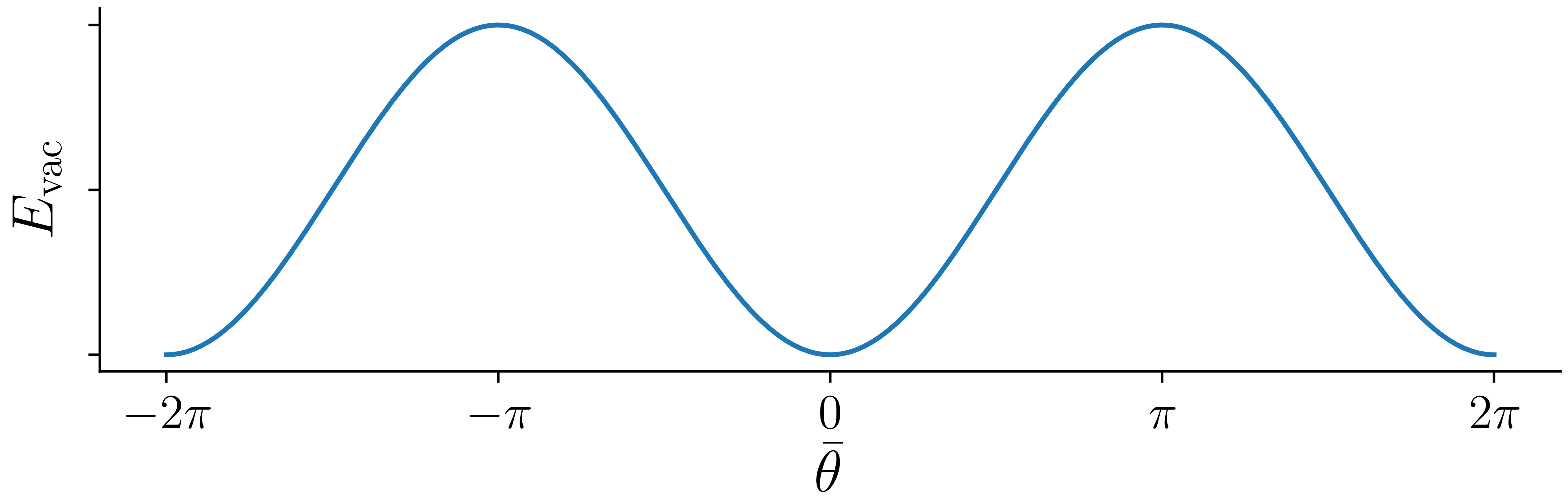
Strong CP Problem: *why is* $\bar{\theta} = \theta_{\rm QCD} + \theta_{\rm Weak}$ *so small?!*

Solving the Strong CP Problem

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta}\,\frac{1}{32\pi^2} G\tilde{G}$$

In fact, this CP violating term has an associated vacuum energy:

$$E_{\rm vac} \sim \cos(\bar{\theta})$$



[Vafa & Witten (1984)]

But the parameter $\bar{\theta}$ is *static* so this doesn't help us… → Make $\bar{\theta}$ dynamical!

Peccei-Quinn (PQ) Mechanism: introduce a new complex scalar field φ, charged under a new global symmetry, $U_{\rm PQ}(1)$ [Peccei & Quinn, 1977]

At low energy, the couplings of φ with the Standard Model introduce a new (dynamical) contribution to the CP violating term:

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta}\,\frac{1}{32\pi^2} G\tilde{G} + \mathcal{C}\theta\,\frac{1}{32\pi^2} G\tilde{G}$$

The `colour anomaly' $\mathcal{C}$ depends on exactly how the Standard Model is coupled to the new PQ symmetry (e.g. KSVZ, DFSZ)

Axions as Dark Matter

Below the QCD phase transition, the axion obtains a mass through its interactions with QCD:

$$m_a \approx f_\pi m_\pi / f_a \approx 5.7 \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mu\mathrm{eV}$$

[1510.07633]

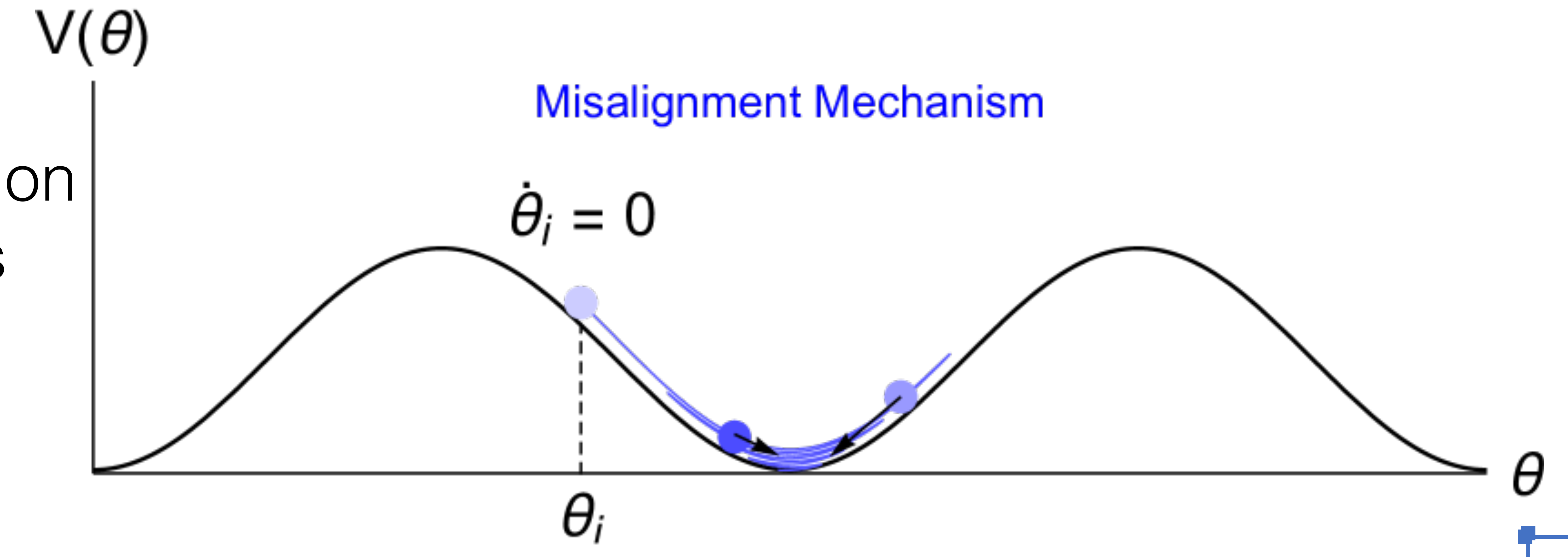
In general, if f_a is very large, then axions are very light, very weakly coupled and very long-lived!

→ **Perfect DM Candidates!**

Below the QCD phase transition, the axion field evolves to give $\theta = a/f_a \to 0$, but the initial **misalignment angle** can take a random value $\theta_i = a/f_a \in [0, 2\pi]$.

The energy density stored in the axion field at this initial value $V(\theta_i)$ is converted into coherent oscillations of the axion field about the minimum — behaves as cold collisionless matter

→ **Misalignment Mechanism**



[1910.14152]

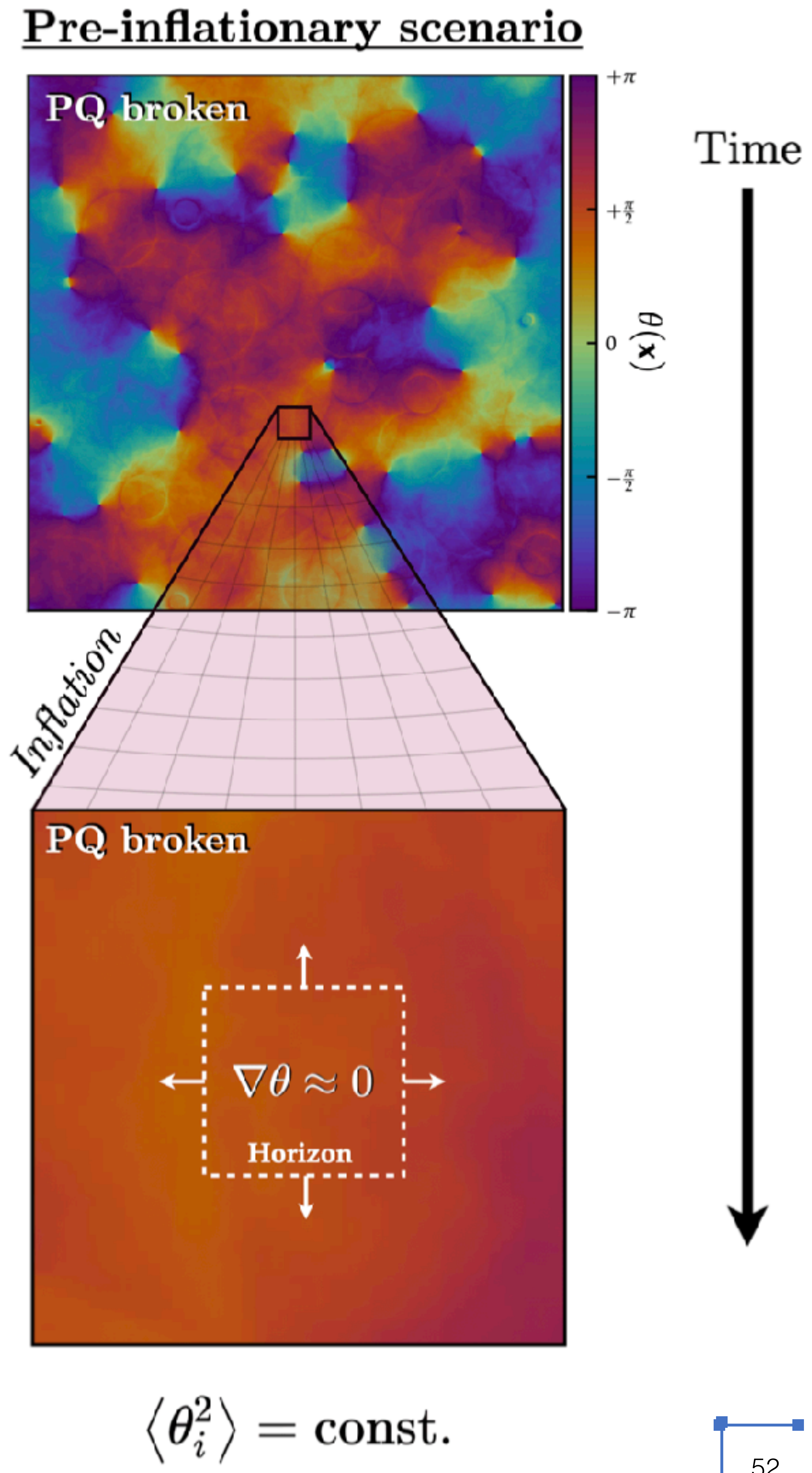
Pre- and post-inflationary axions

If the PQ symmetry is broken **before cosmic inflation**, then a small patch of the Universe with a given θ_i is inflated to become our observable Universe.

The axion abundance can be calculated as:

$$f_{\rm DM} = \rho_a/\rho_{\rm DM} \approx \left(\frac{\theta_i}{2.155}\right)^2 \left(\frac{28\,\mu{\rm eV}}{m_a}\right)^{7/6}$$

…depends on the unknown parameter θ_i



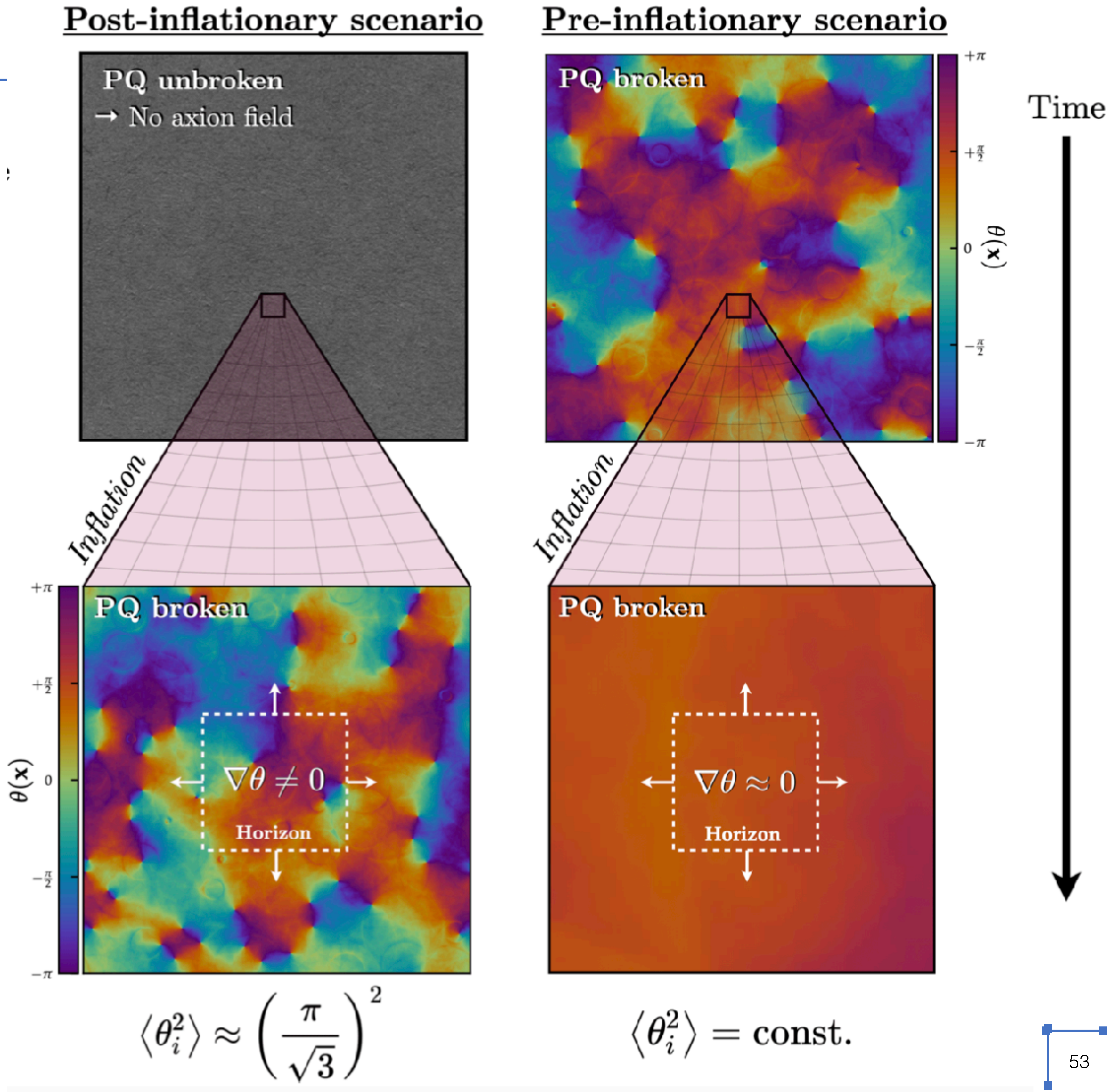
[2403.17697]

Pre- and post-inflationary axions

If the PQ symmetry is broken **after cosmic inflation**, then nearby patches of the Universe will have different initial misalignment angles.

Average misalignment angle $\langle\theta_i^2\rangle$ is known so the axion abundance depends only on the axion mass.

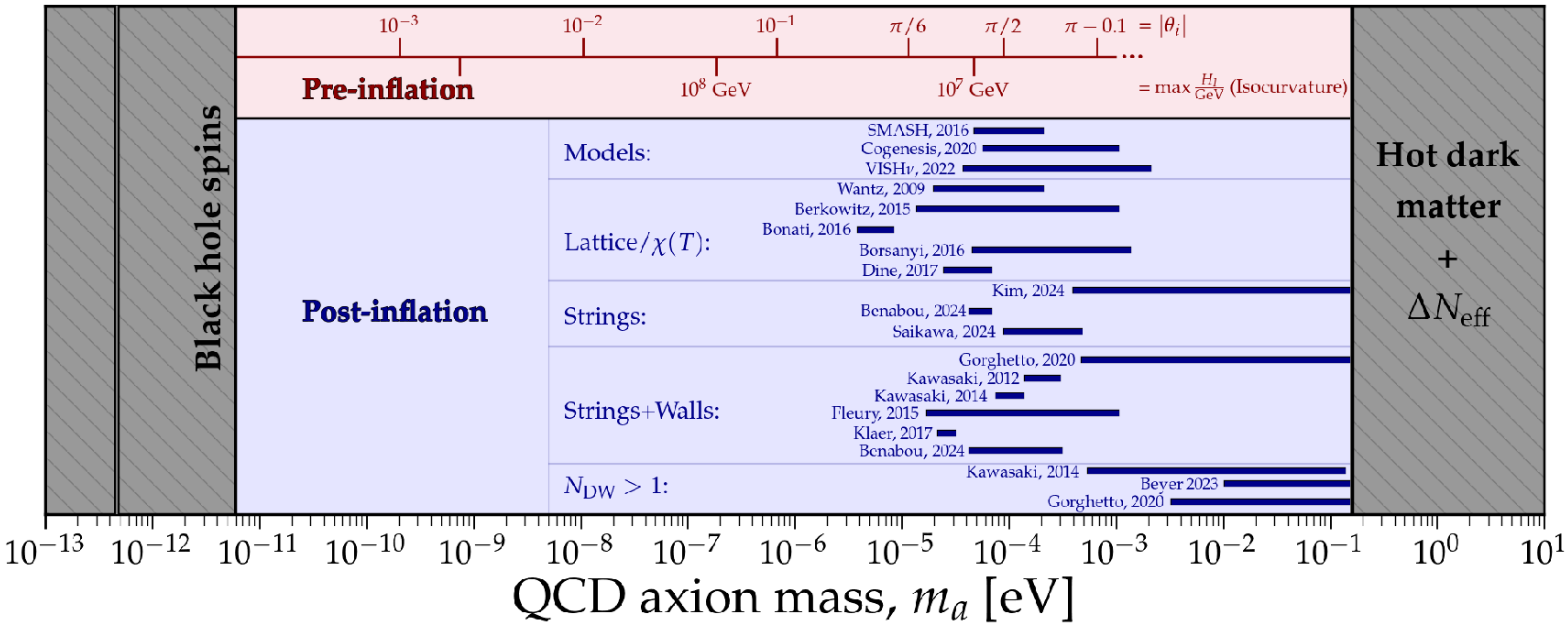
In principle, we can calculate the value of the axion mass required to explain all of the DM!



[2403.17697]

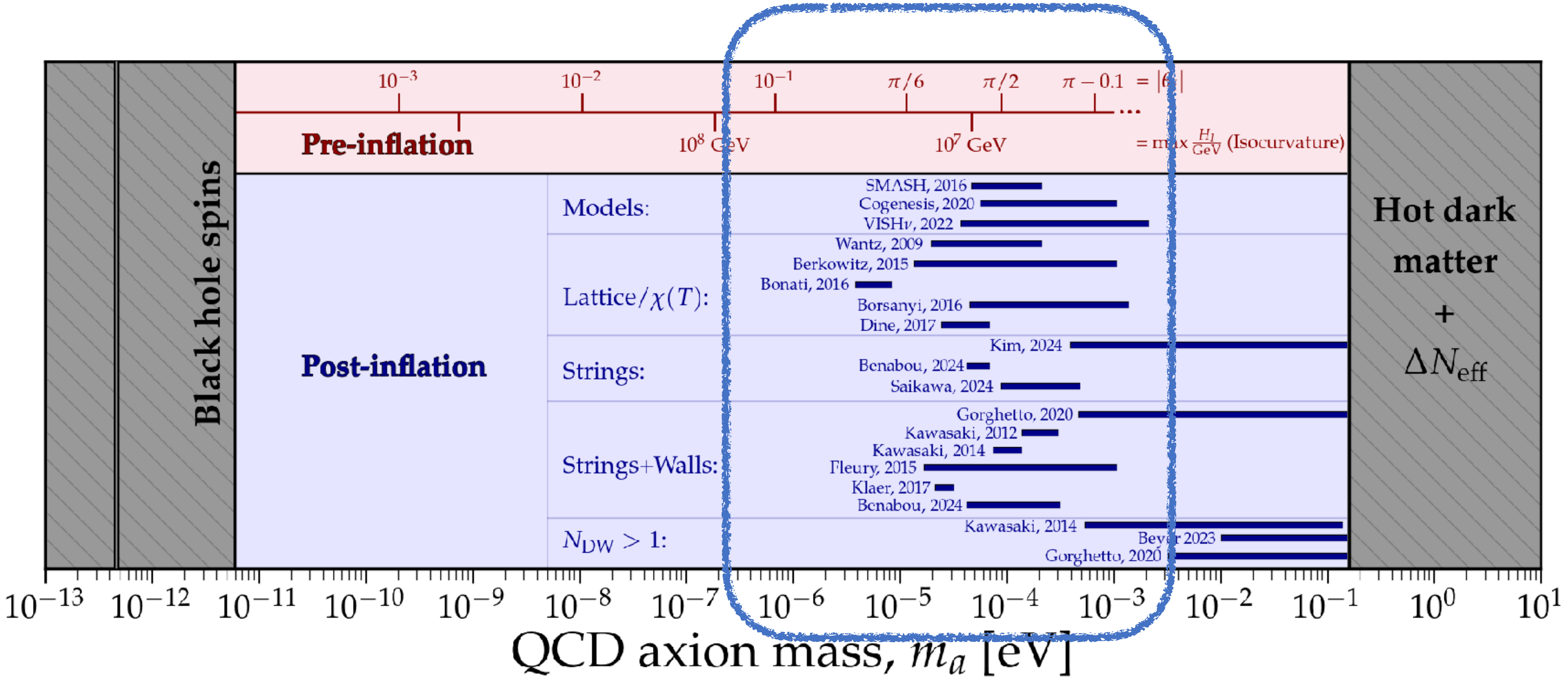
Axion Mass

[cajohare.github.io/AxionLimits/]

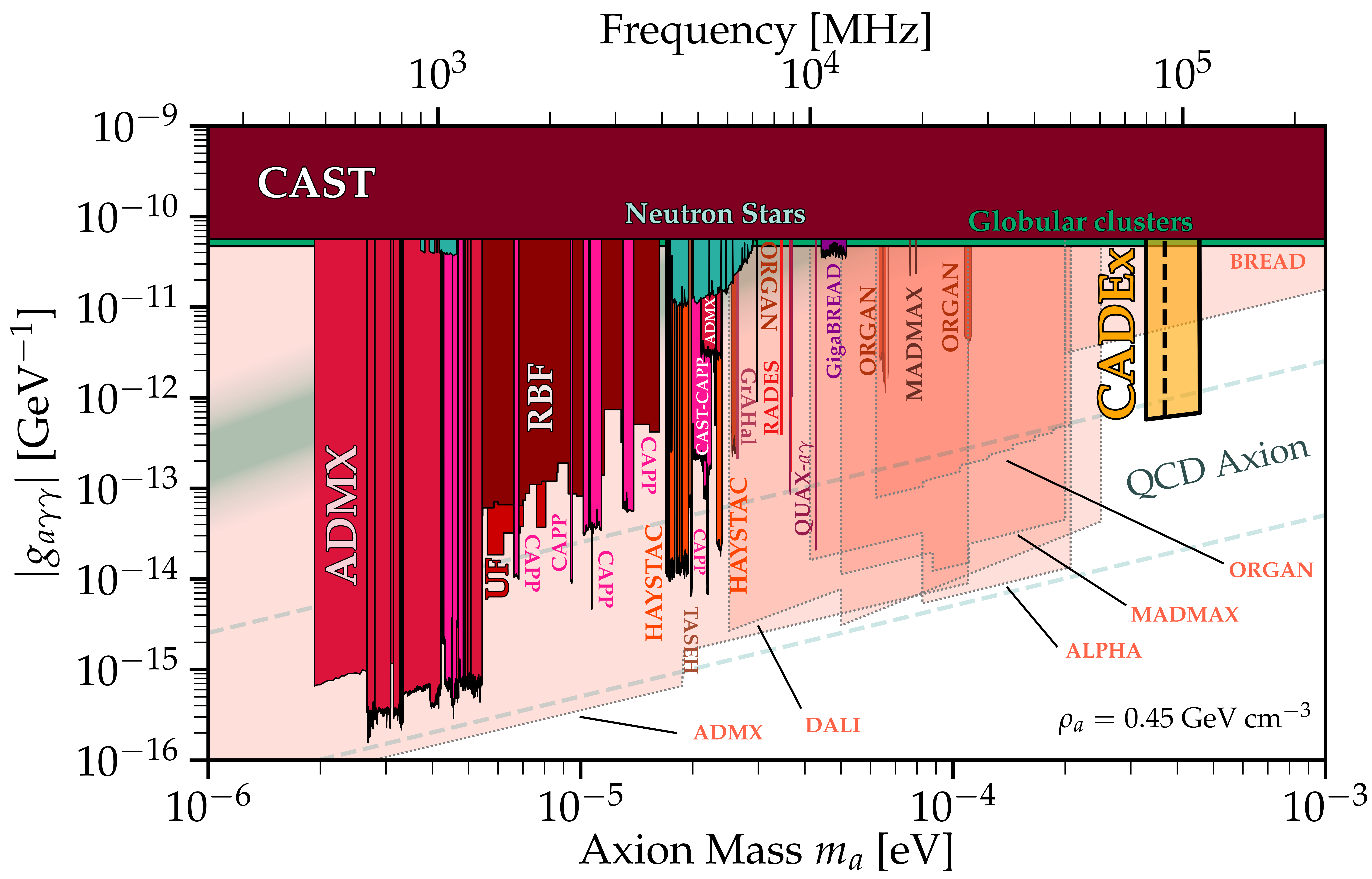


Axion Mass

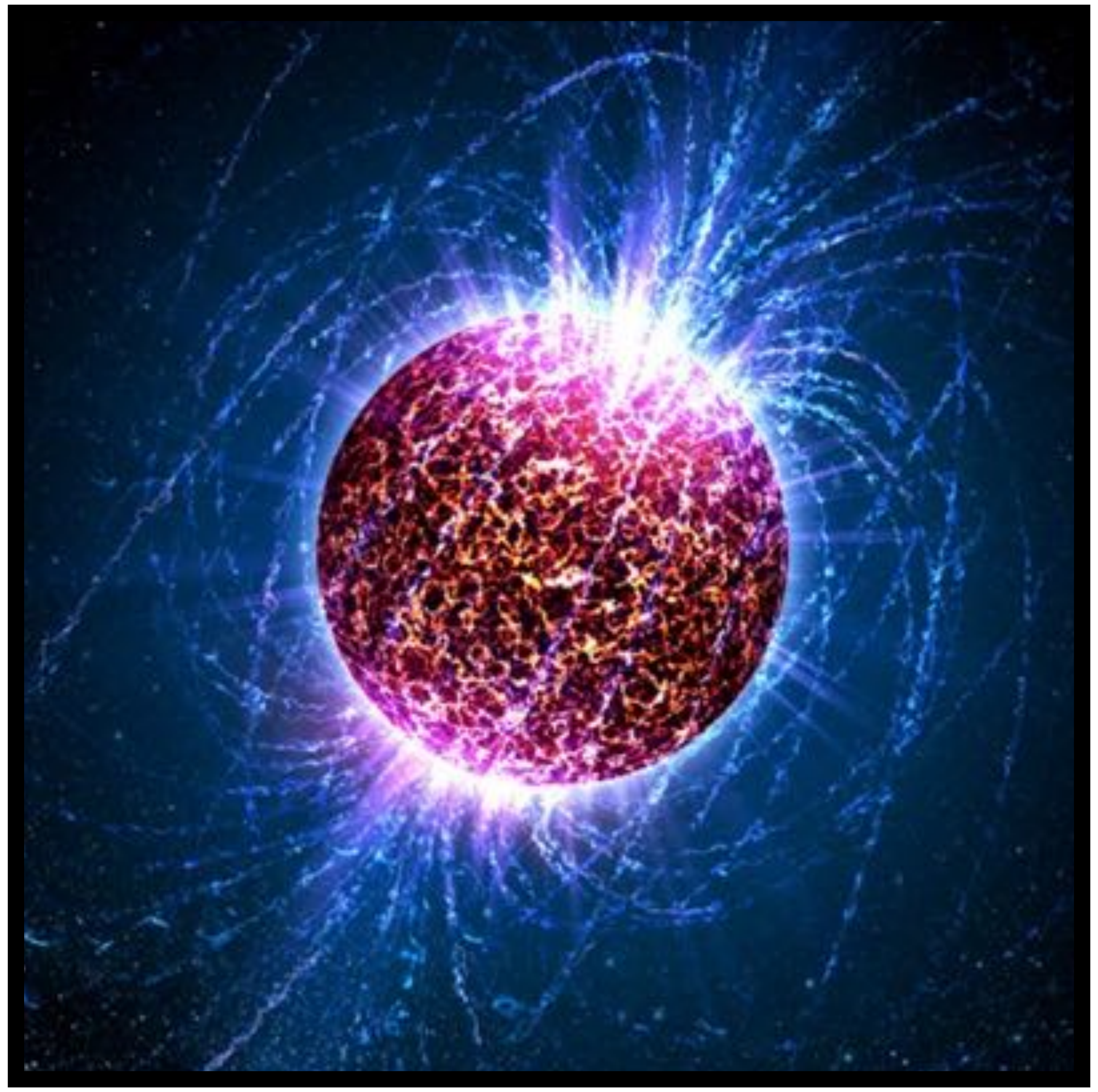
[cajohare.github.io/AxionLimits/]



Axion Landscape



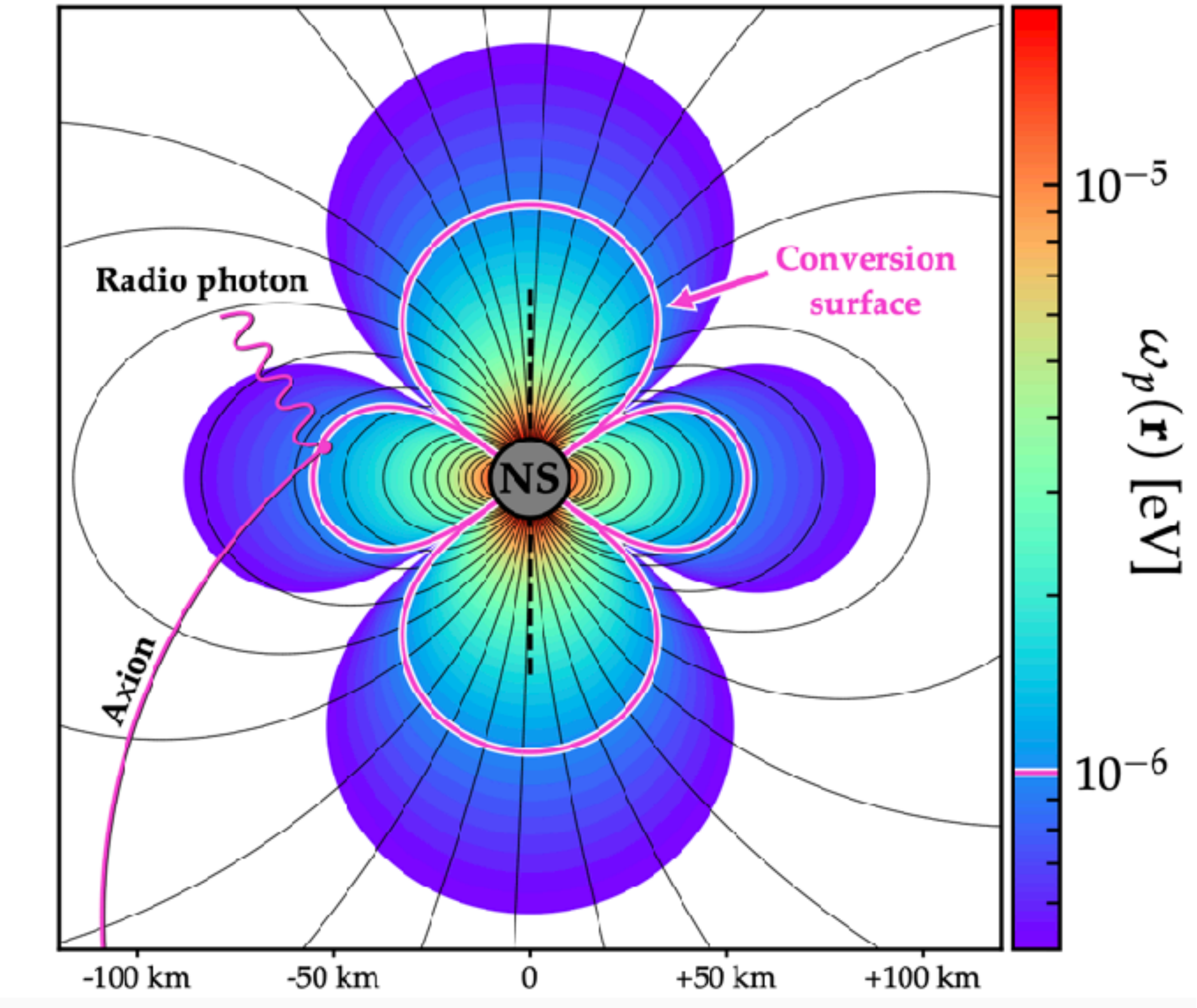
Neutron Stars



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

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

Young neutron stars can have **extremely high magnetic fields**
$\left(B_0 = 10^8 - 10^{11}\,\mathrm{T}\right)$



NS surrounded by a dense plasma which allows 'resonant' conversion, when **axion mass matches plasma mass**:

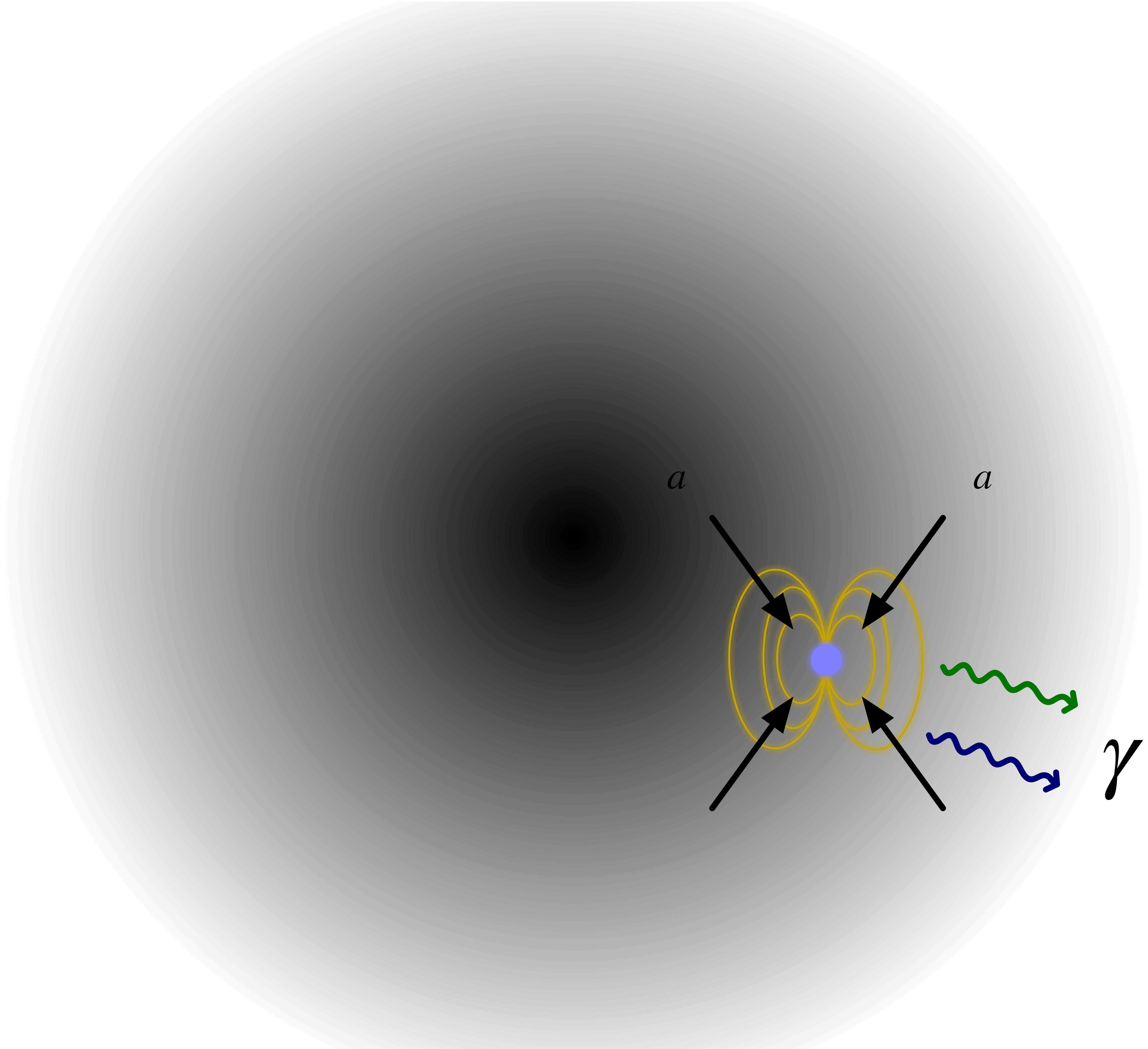
$\omega_p(B_0, P) = m_a/2\pi$

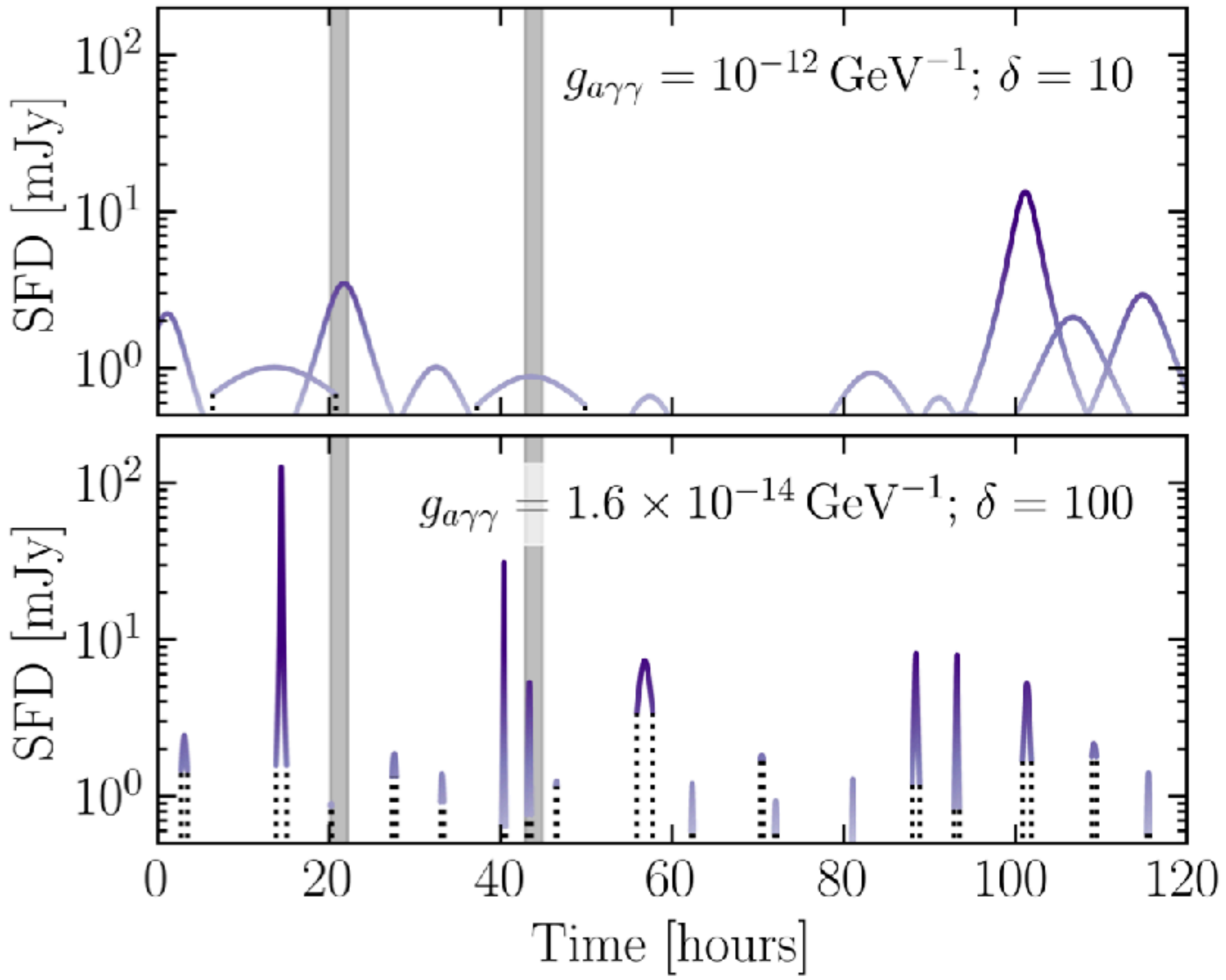
[For recent modeling developments, see also Battye et al., 1910.11907, 2104.08290; Leroy et al., 1912.08815]

[Search in the Galactic Centre, Foster et al., 2202.08274]

Radio Transients

If it turns out that most of the axion density is locked up in axion miniclusters, one promising way to find it would be in **radio transients**.

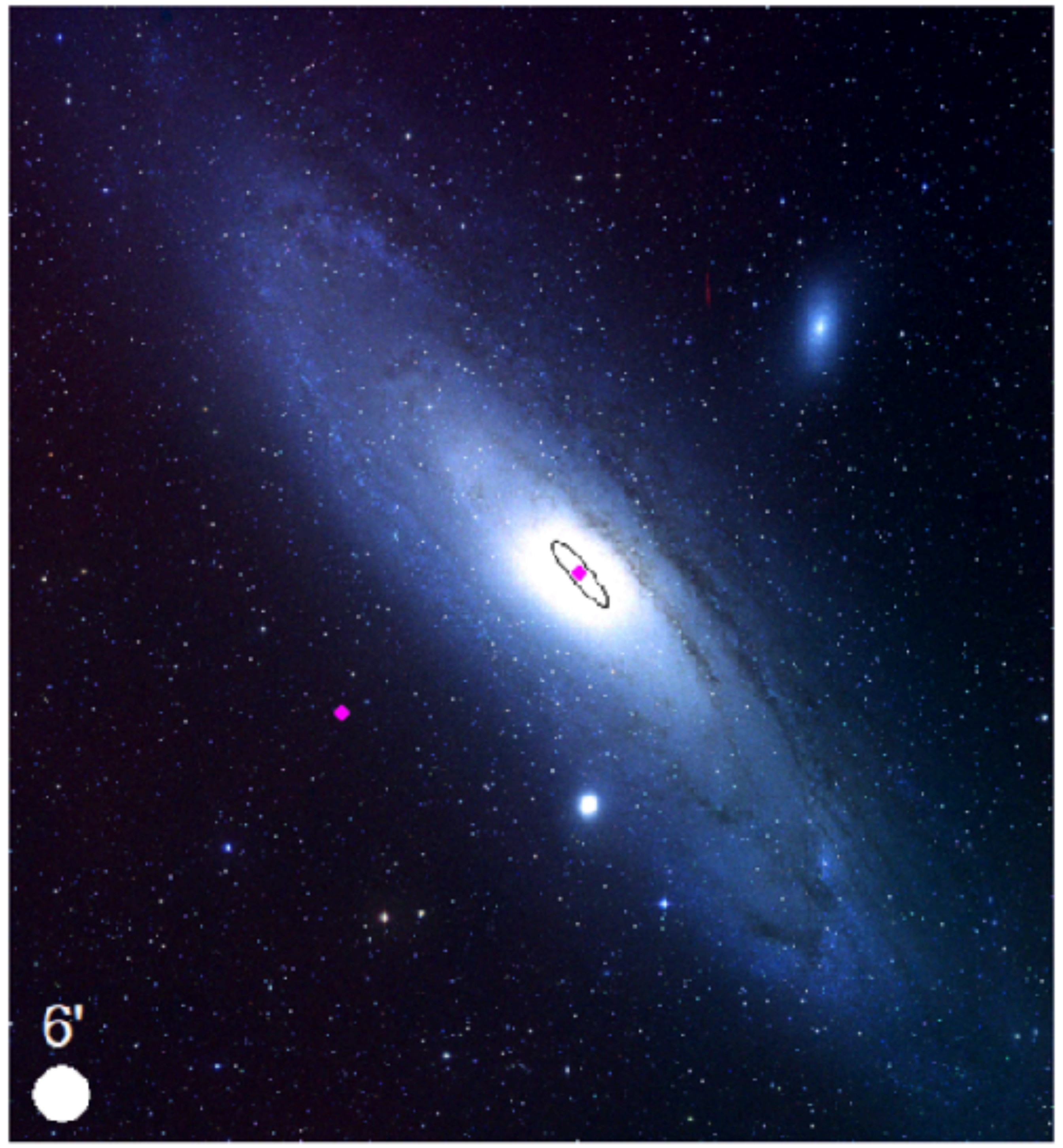




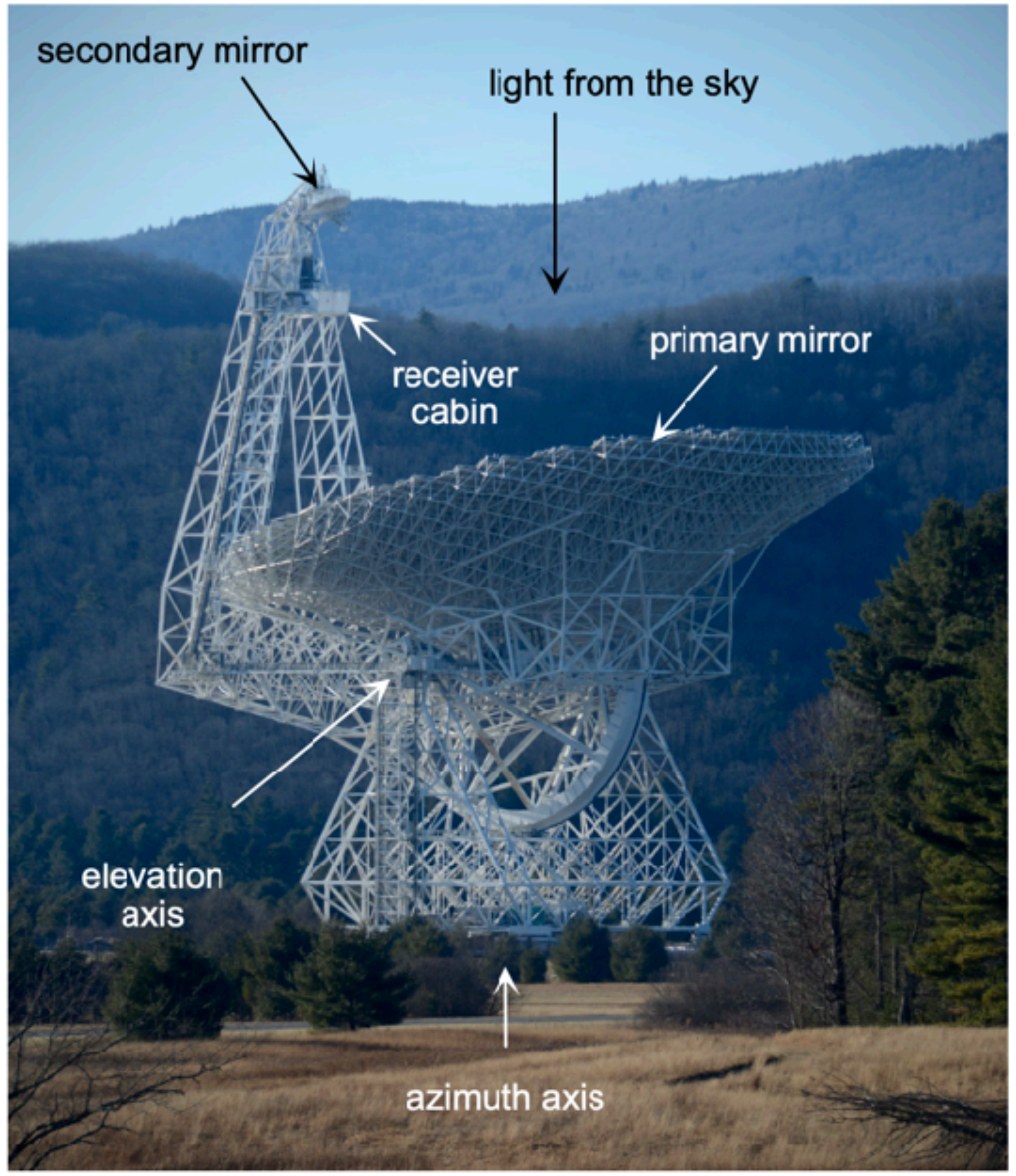
Expect rates of O(1) per day per galaxy

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

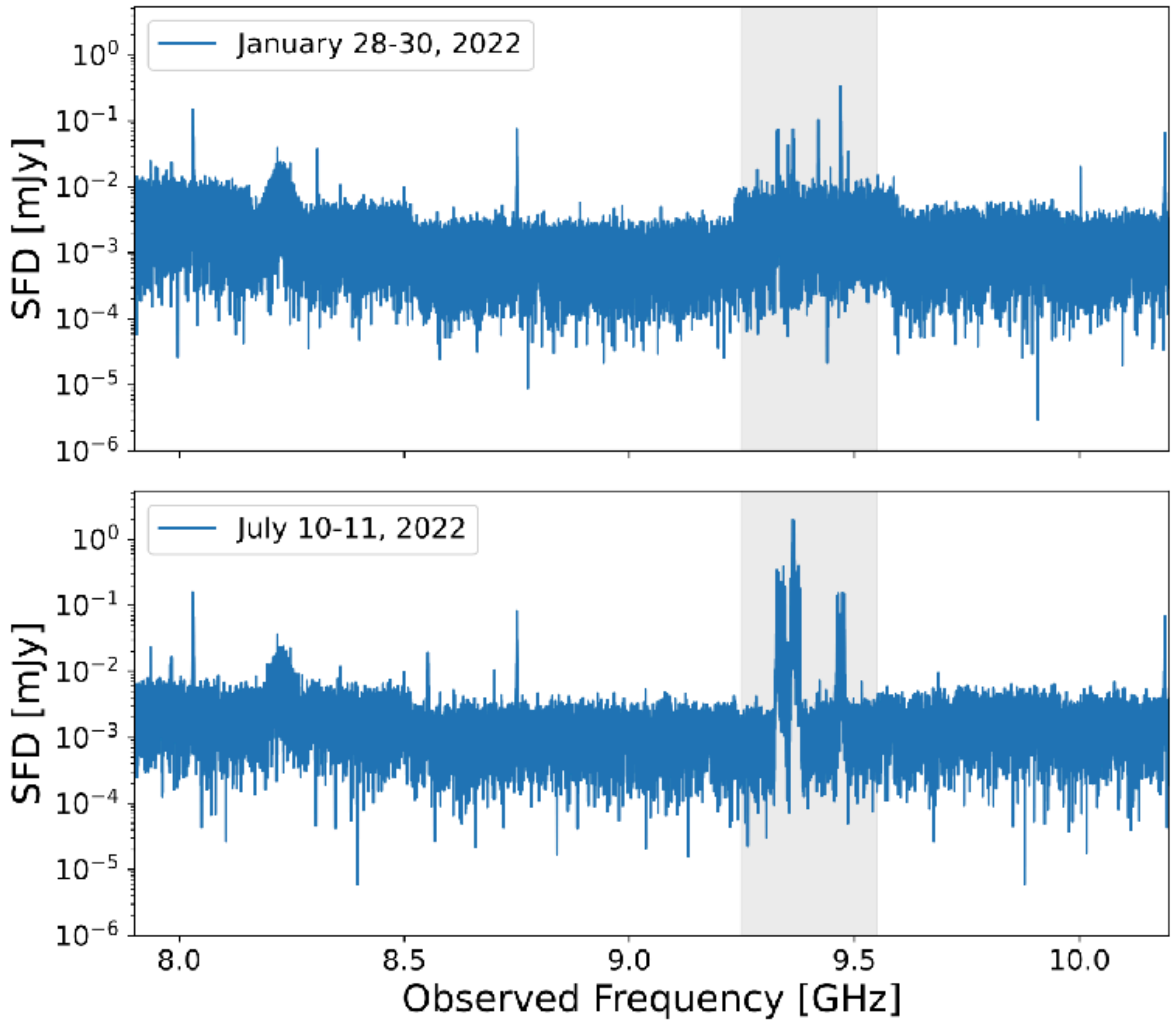
Axions in Andromeda



Andromeda (M31)



Green Bank Telescope (GBT)



No axion-like transients observed in X-band (~8-10 GHz)

[Walters et al. (including **BJK**), 2407.13060]

Strongly Interacting DM Constraints

[Emken et al., 1905.06348]

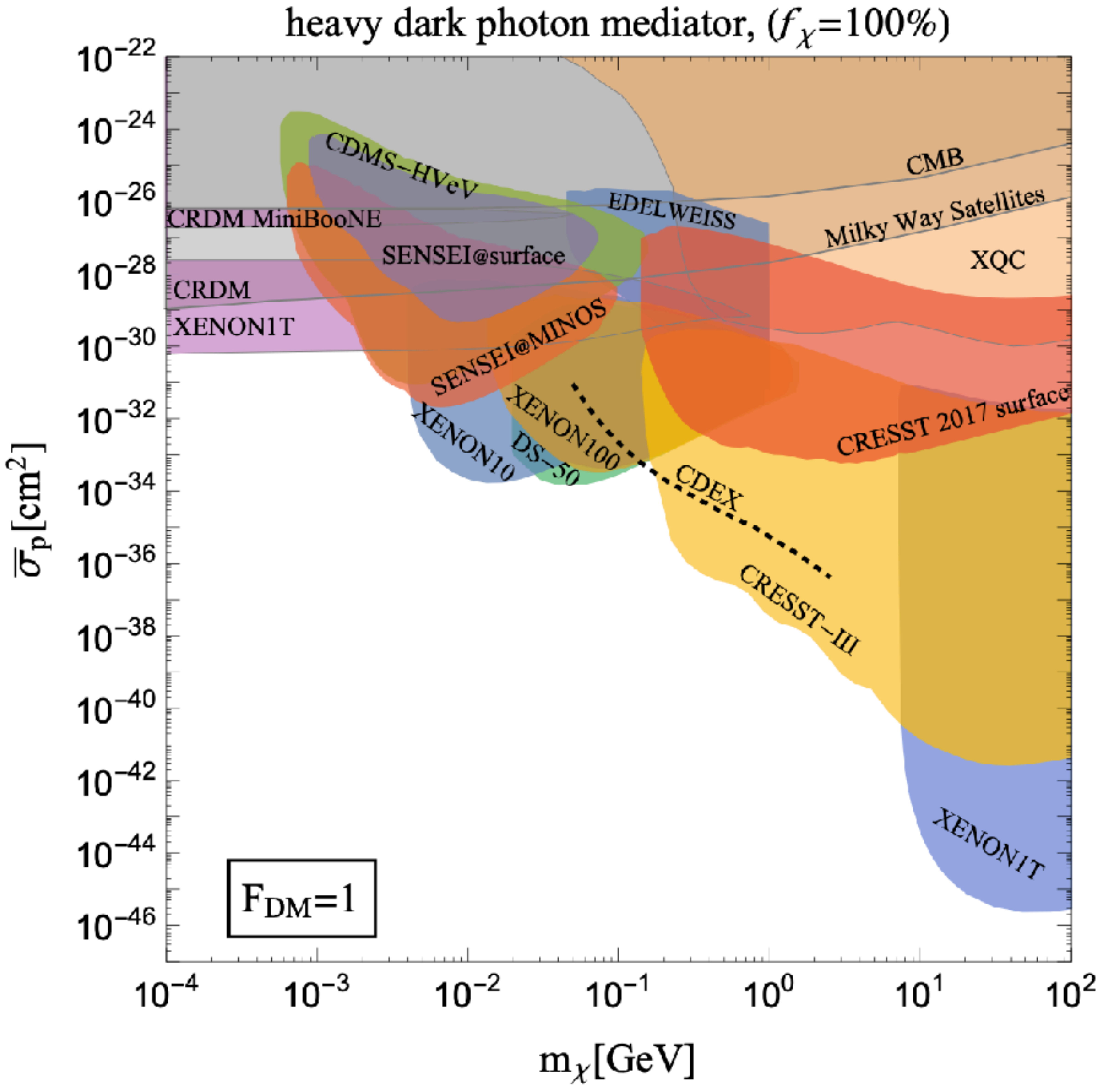
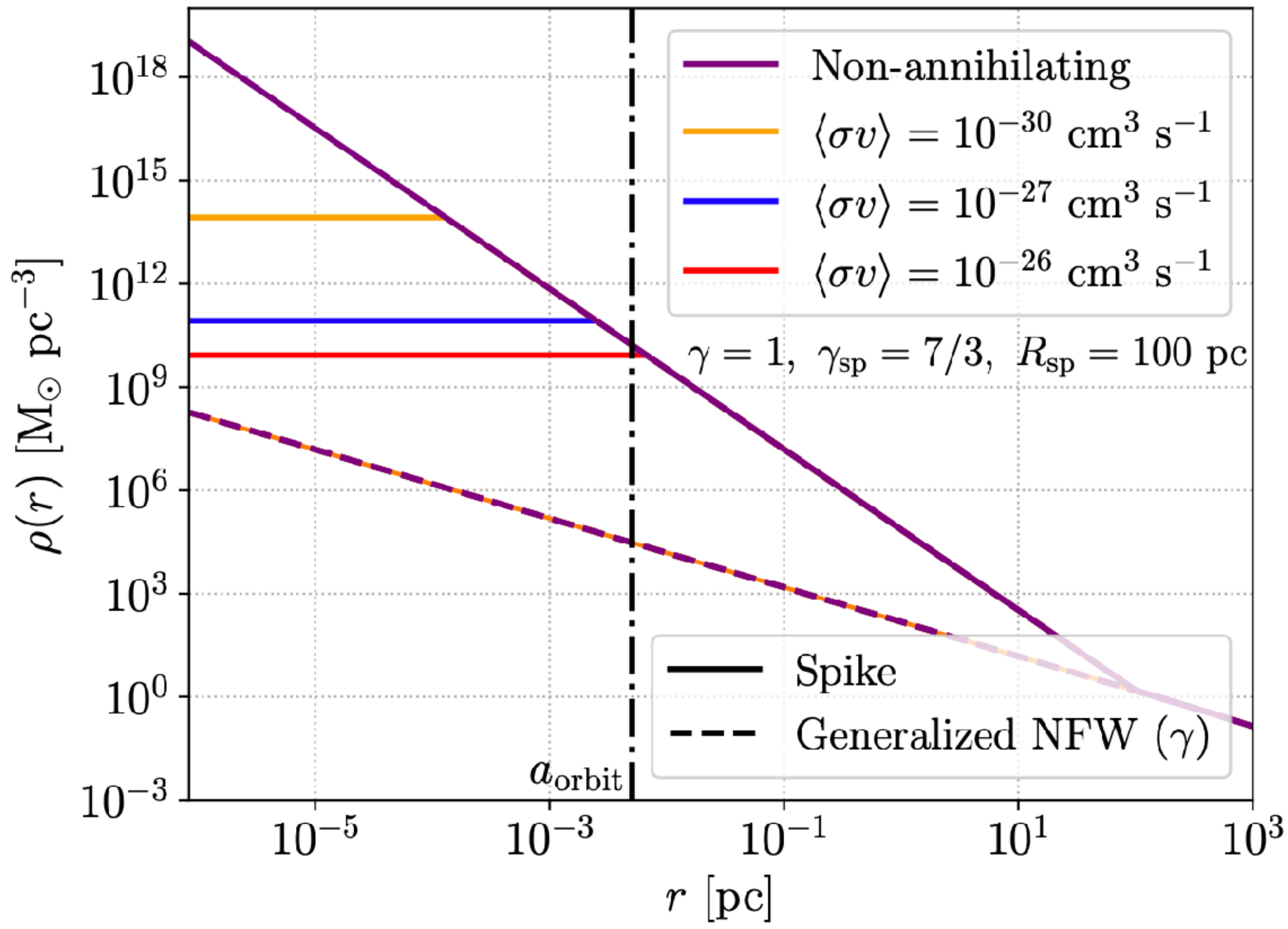


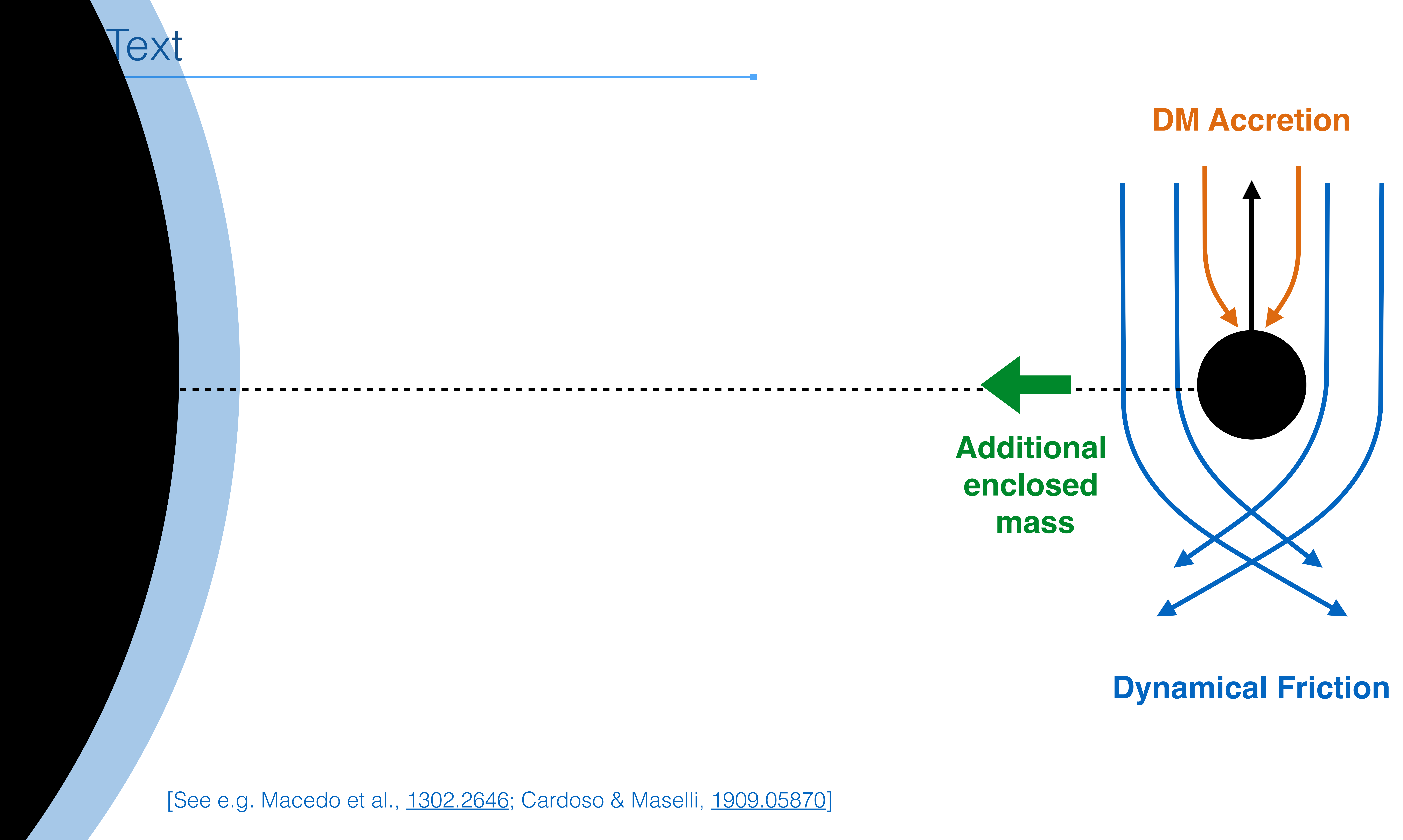
Figure 5: Direct-detection, cosmological, and astrophysical constraints on the DM-proton cross section for contact interactions mediated by a dark photon. In addition to the bounds derived in this paper (see Fig. 4, top left), we also show constraints from nuclear recoil DM-searches by XENON1T [93], CRESST-III [94, 95], the CRESST 2017 surface run [96] as obtained in [53], and Migdal effect based bounds from EDELWEISS [46] and CDEX [97], together with constraints from the X-ray Quantum Calorimeter experiment (XQC) [54], cosmic-rays ("CRDM") [31], CMB [68], and Milky-Way satellites [98]. We do not show collider or beam-dump bounds, but see e.g. [99–101].

Density around Sgr A*



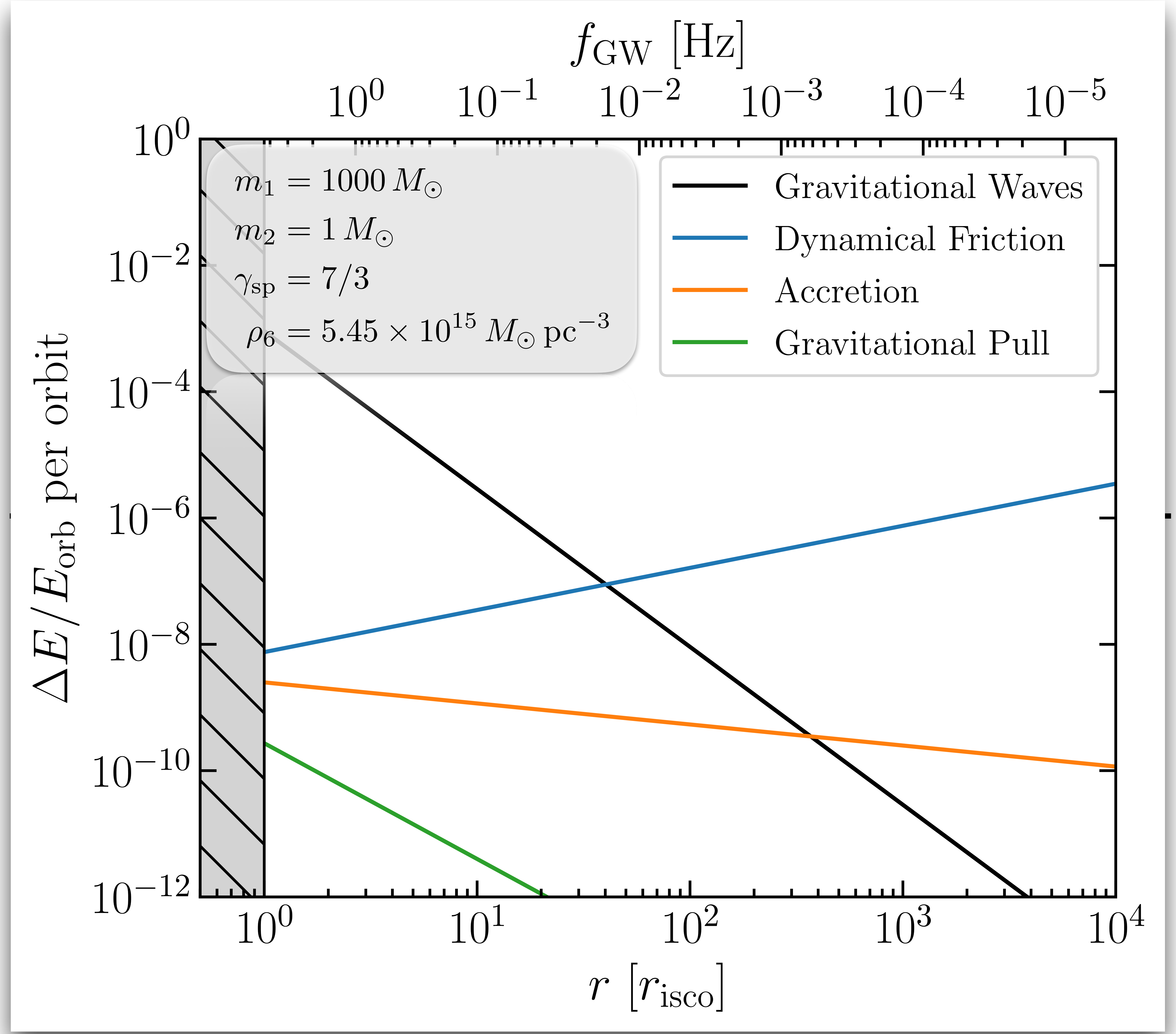
[Lacroix, 1801.01308]

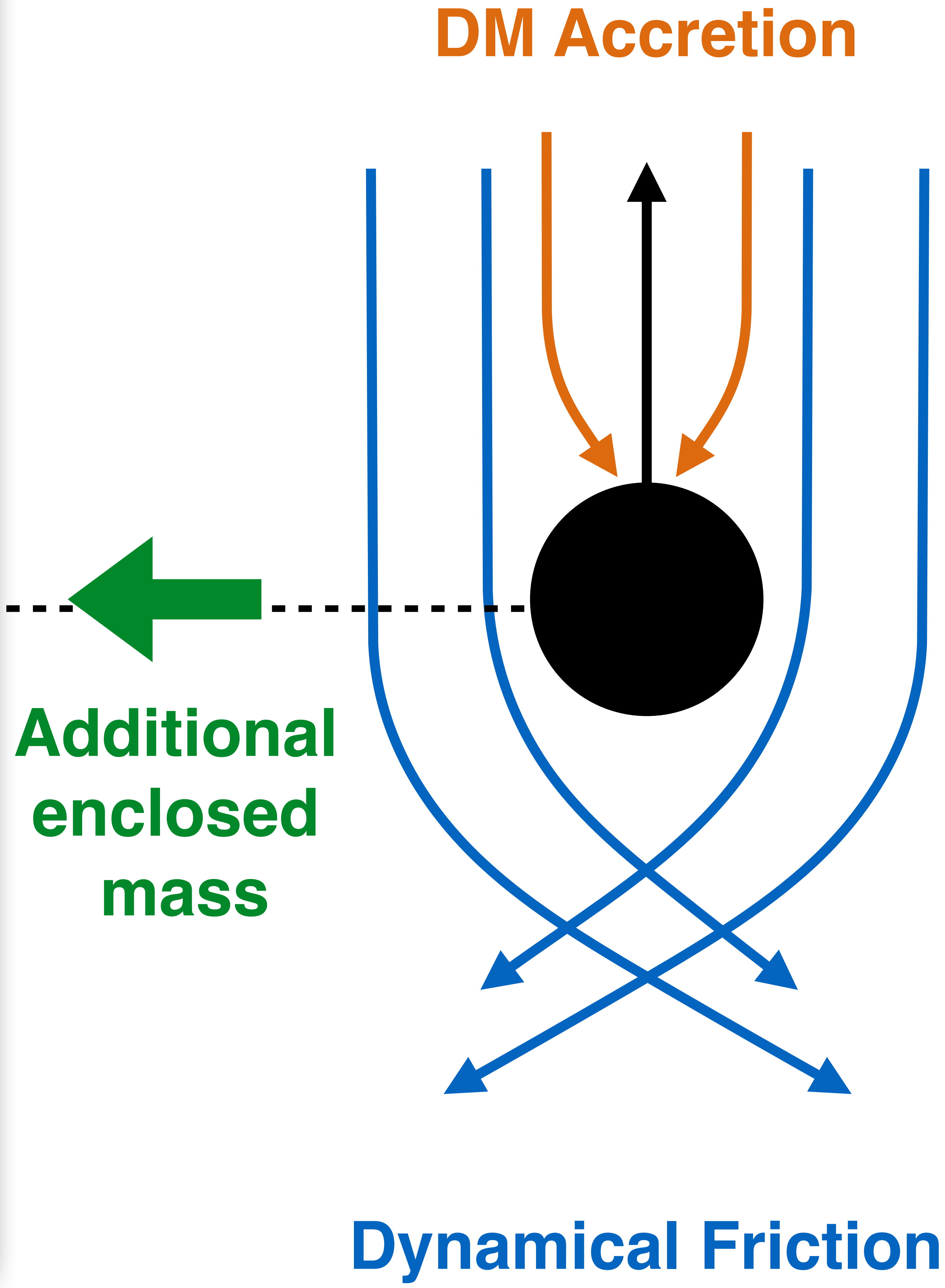
Text



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

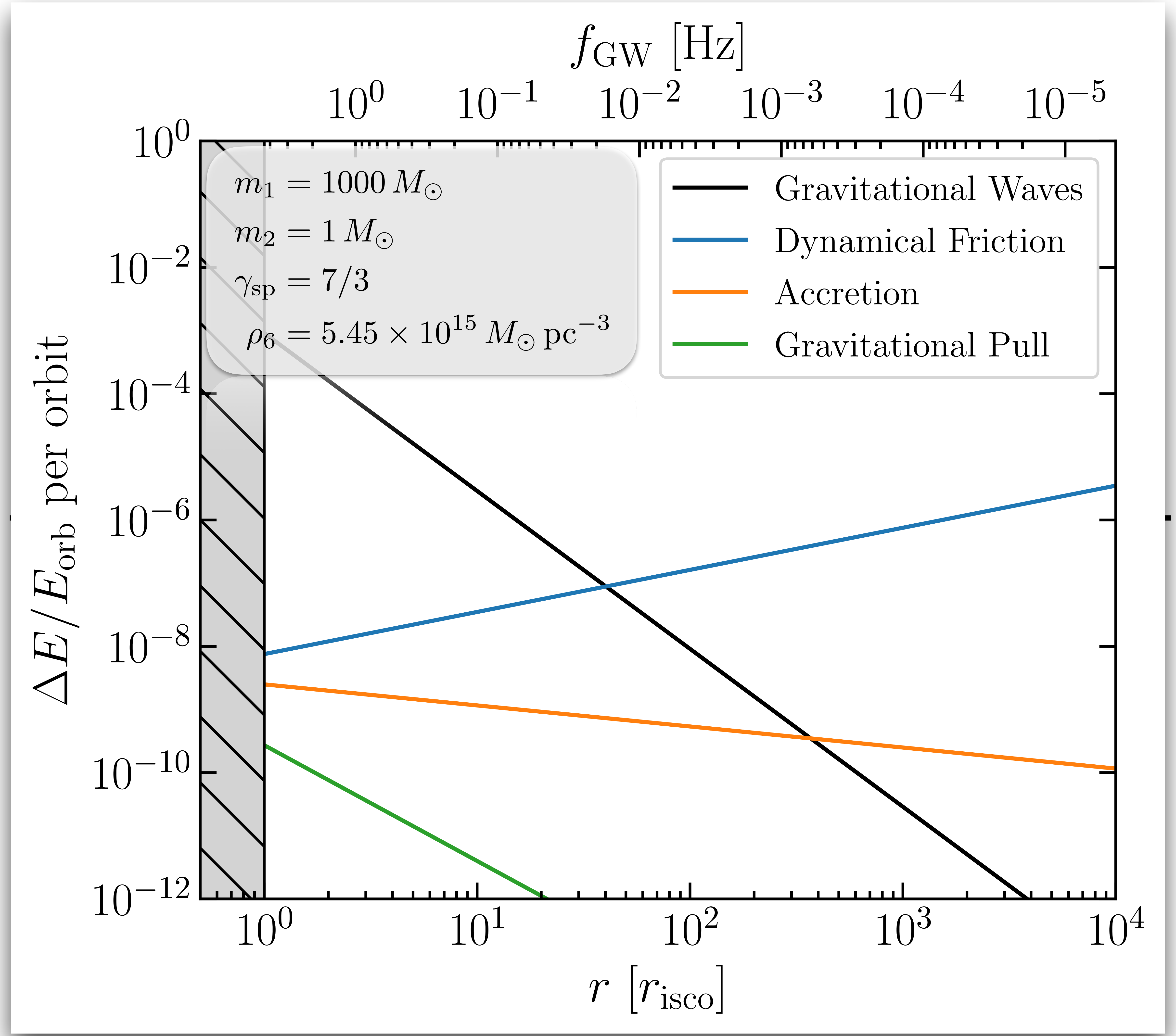
Text

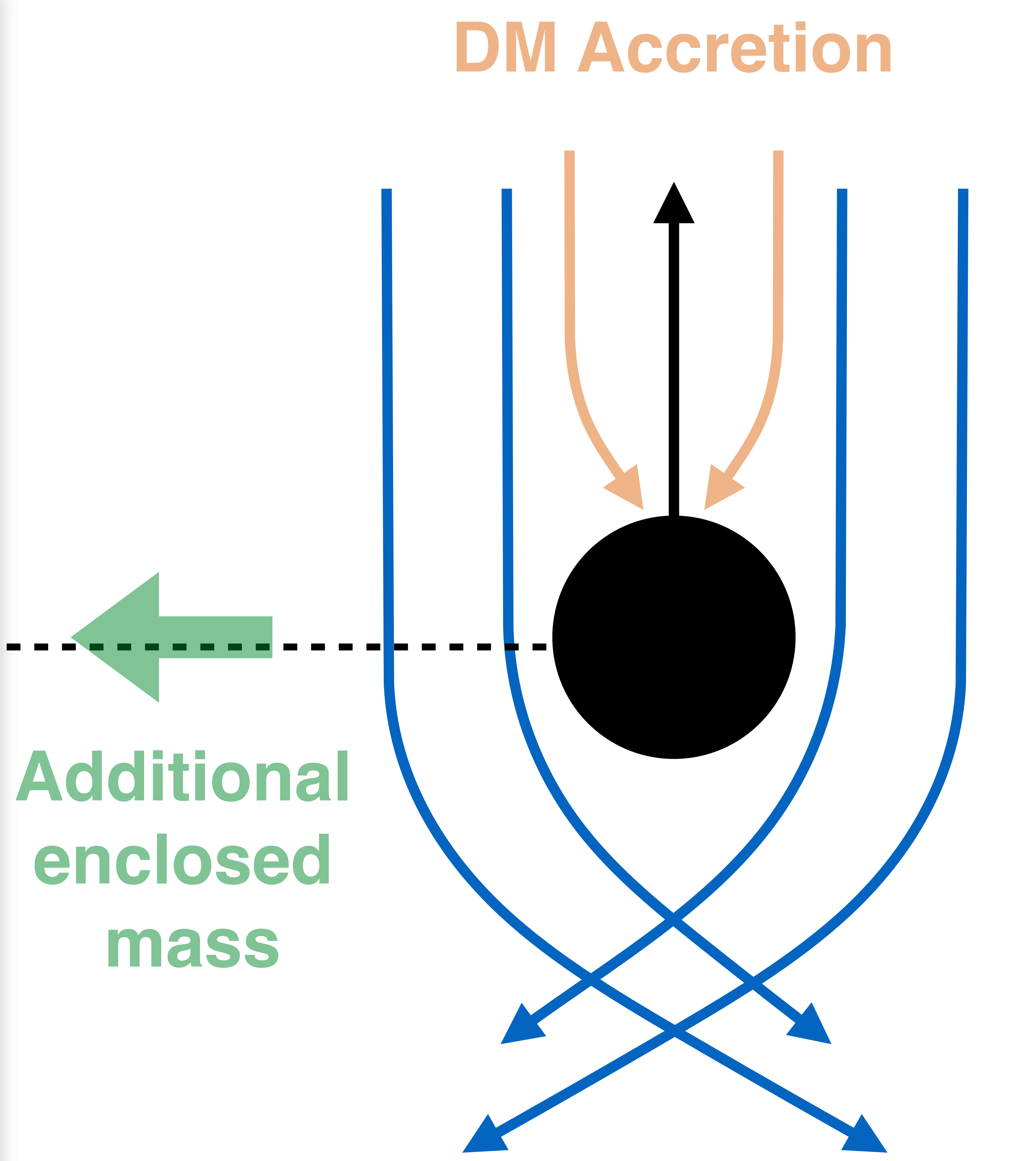




[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Text





Dynamical Friction

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

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

The Gravitational Wave Spectrum

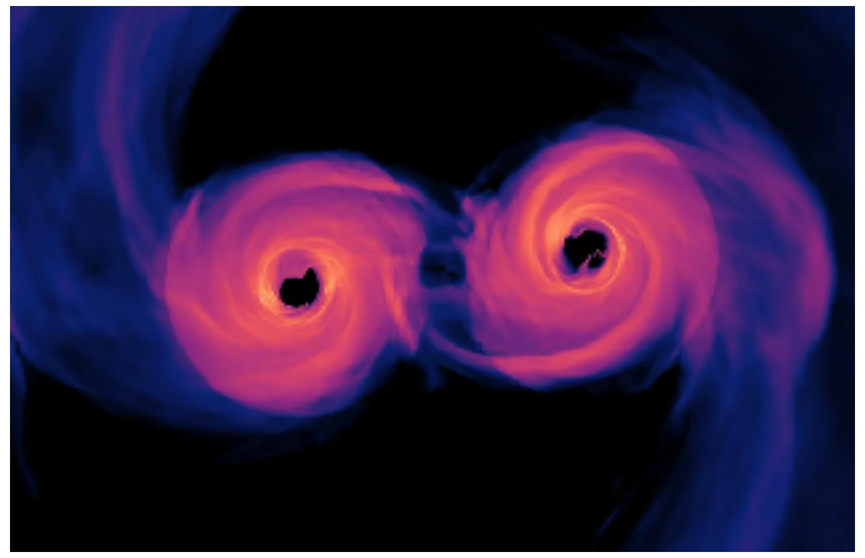
$$c = \lambda_{\rm GW} \cdot f_{\rm GW}$$

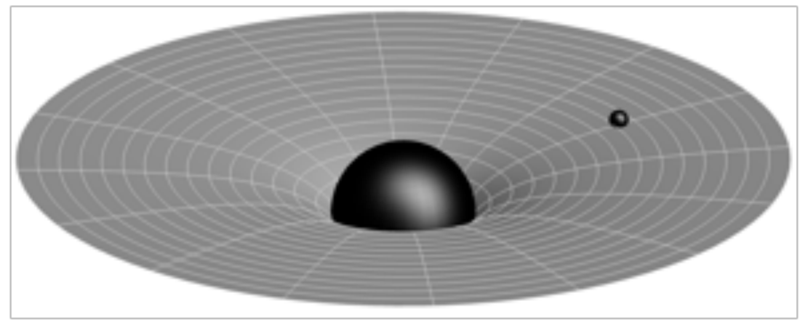
$f_{\rm GW}$: nHz, μHz, mHz, Hz, kHz

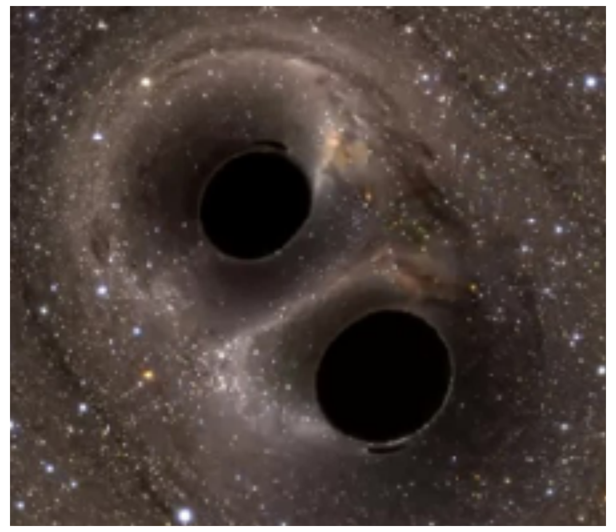
$\lambda_{\rm GW}$: 10^{13} km ~ pc, 10^{11} km, 10^{8} km, 10^{5} km, 100 km

$T_{\rm GW}$: 30 years, 10 days, 15 minutes, 1 second, 1 ms

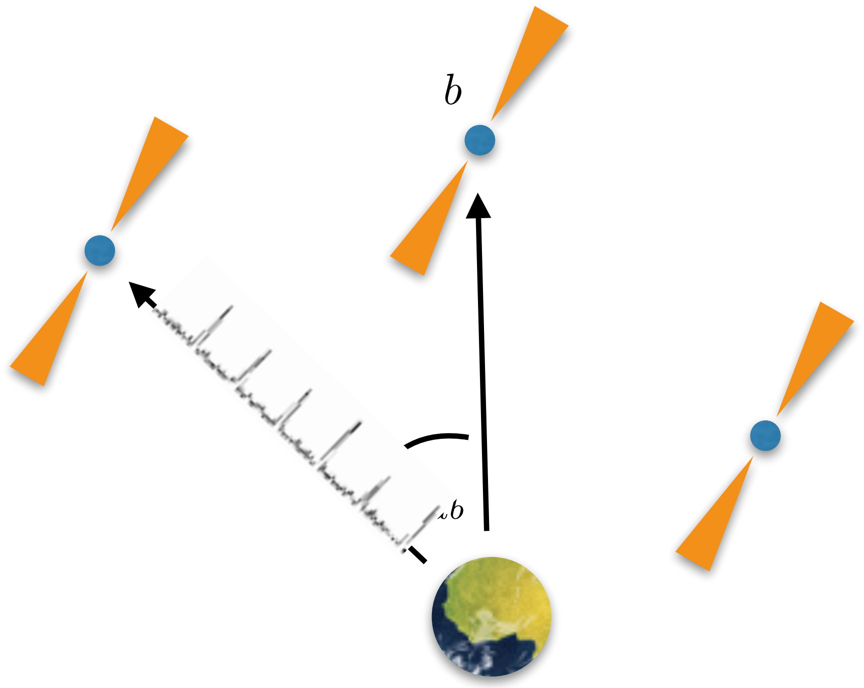
SOURCES

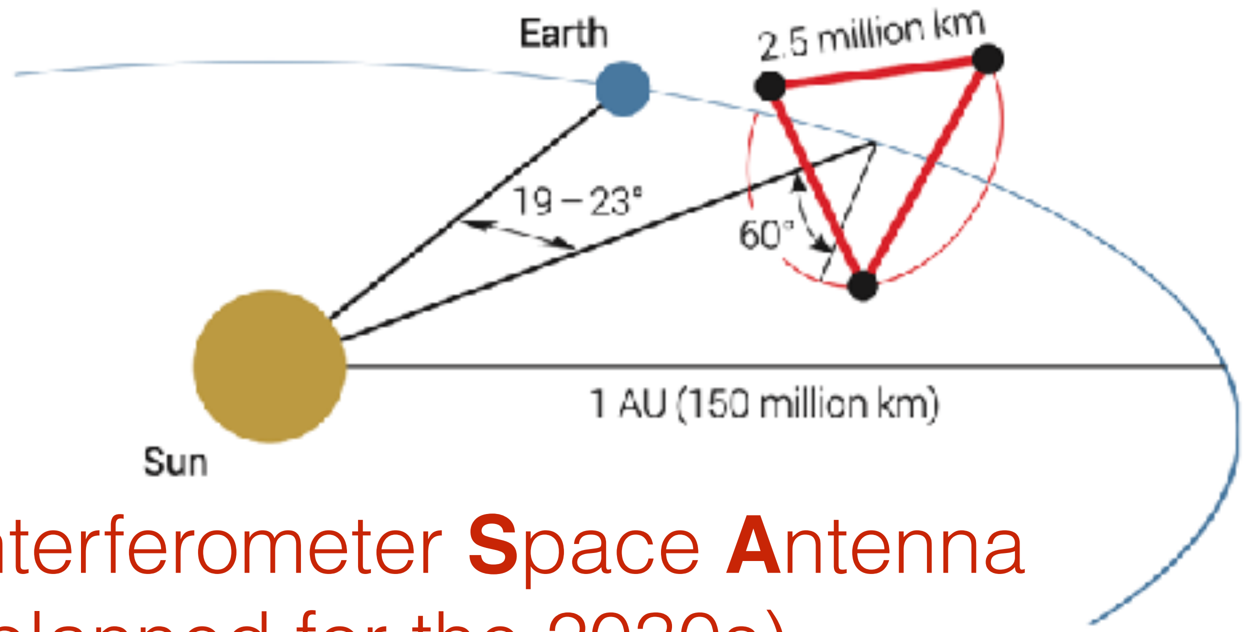






DETECTORS?





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