12th IDPASC School, Granada

Astrophysics and Dark Matter

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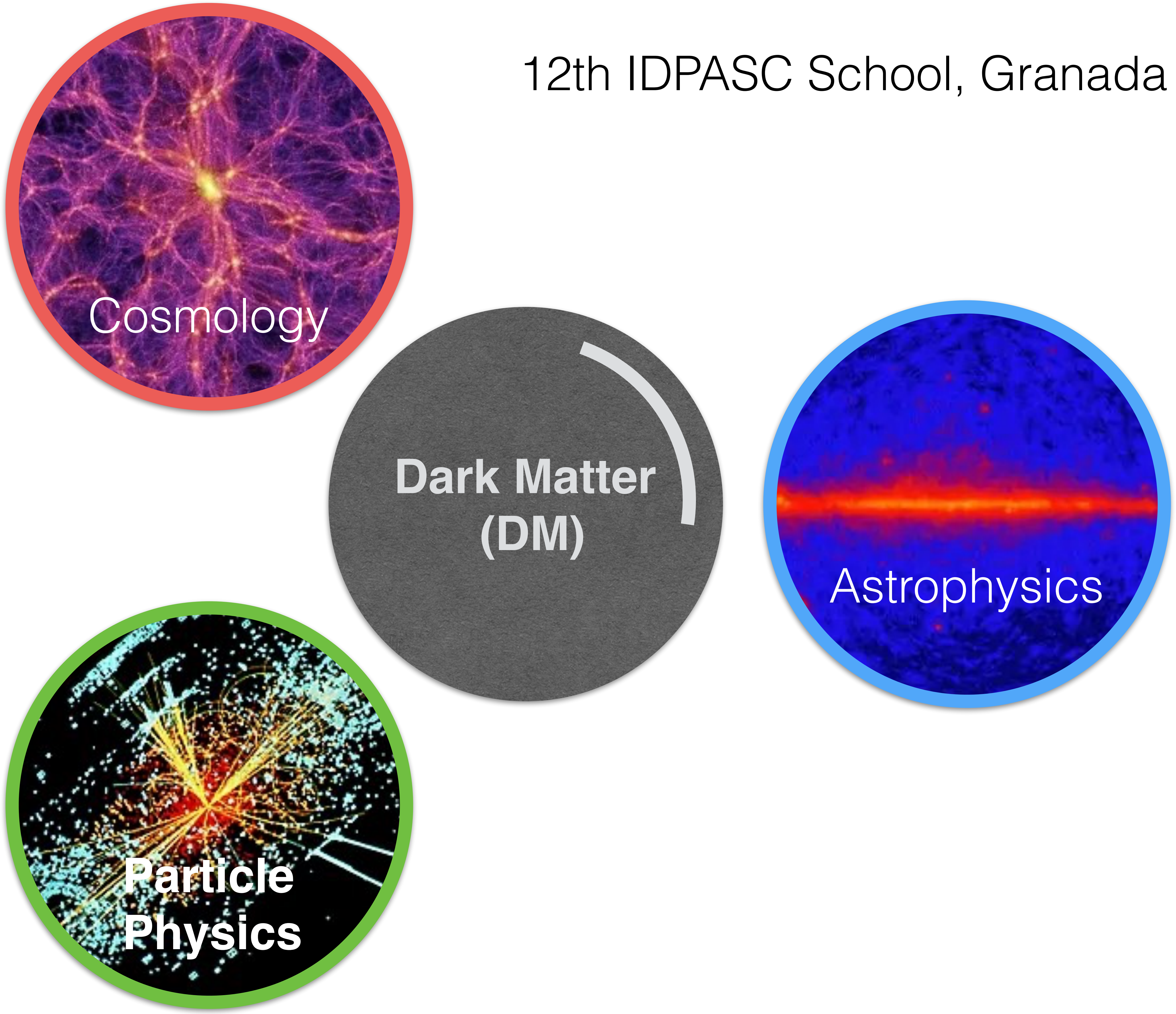


What do the properties of Galaxies tell us about the nature of Dark Matter?

What do astrophysical observations tell us about the nature of Dark Matter?

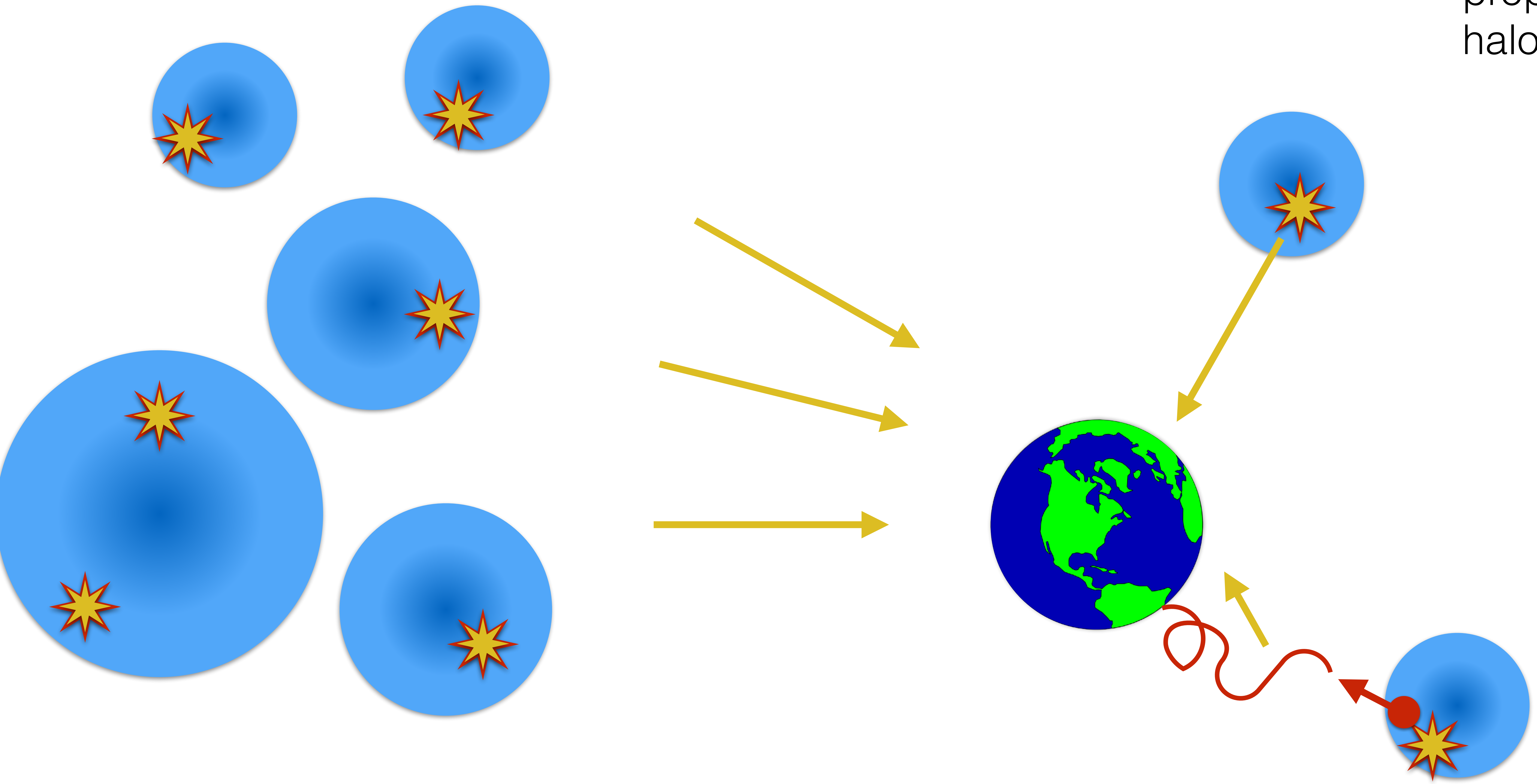
Lecture 1
Dark Matter evidence, properties, and hints from astrophysics of galaxies

Lecture 2
“Indirect detection” of Dark Matter: formalism and signals

Lecture 3
Constraints and anomalies in indirect searches: gamma rays, cosmic rays, neutrinos, and more…

Annihilation Signals

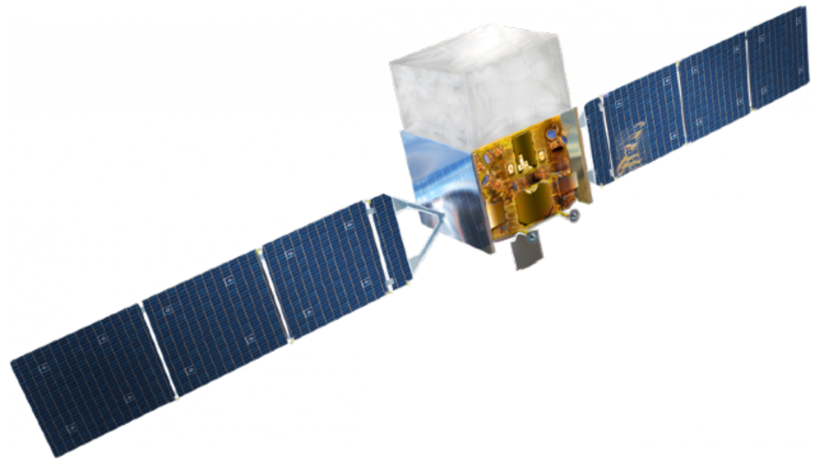
1 **Prompt:** look for primary annihilation products (photons, neutrinos) which propagate directly to us from DM halos in the local Universe



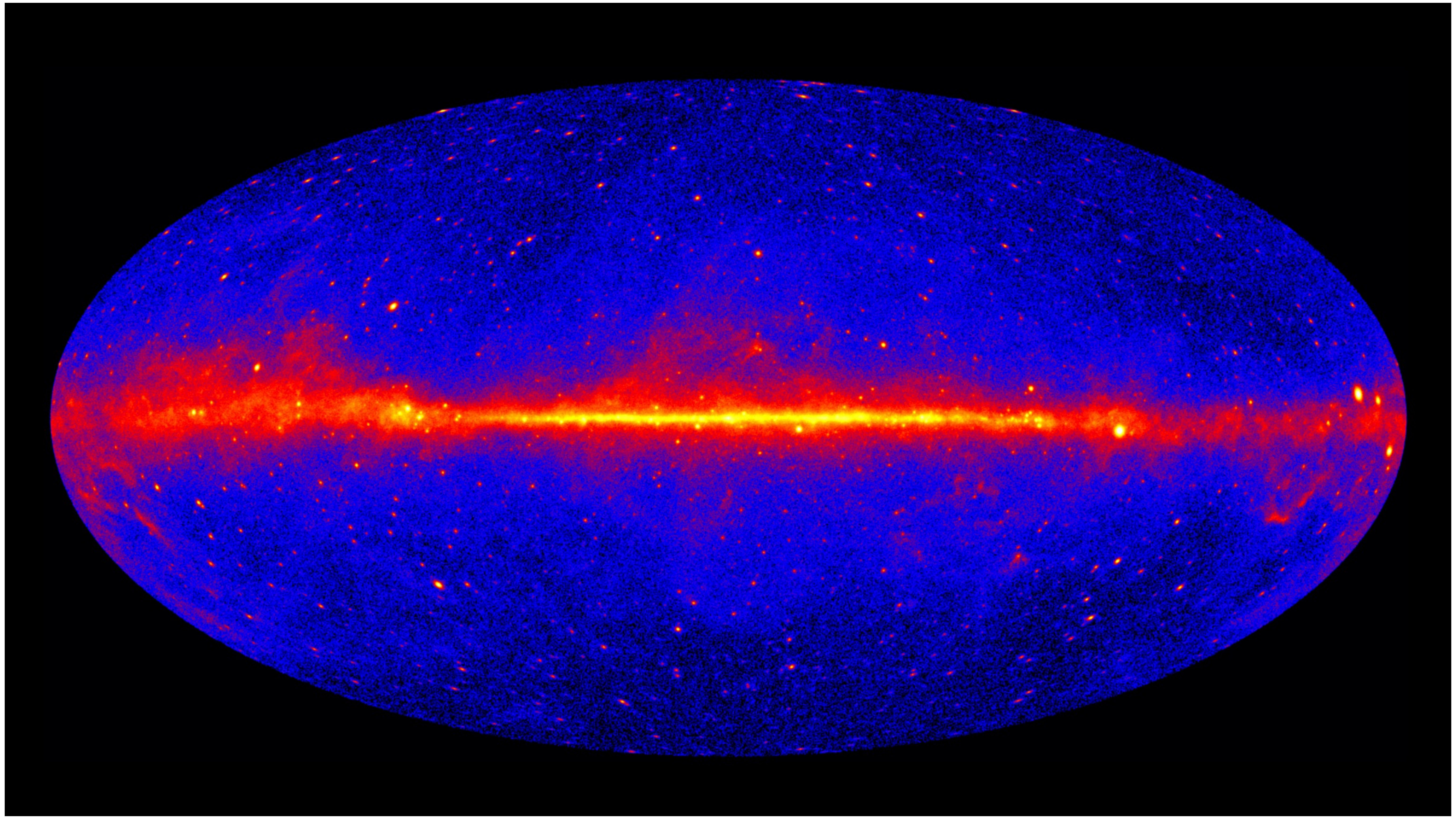
2 **Extragalactic:** look for photons and neutrinos coming from cumulative annihilation of DM across cosmic time

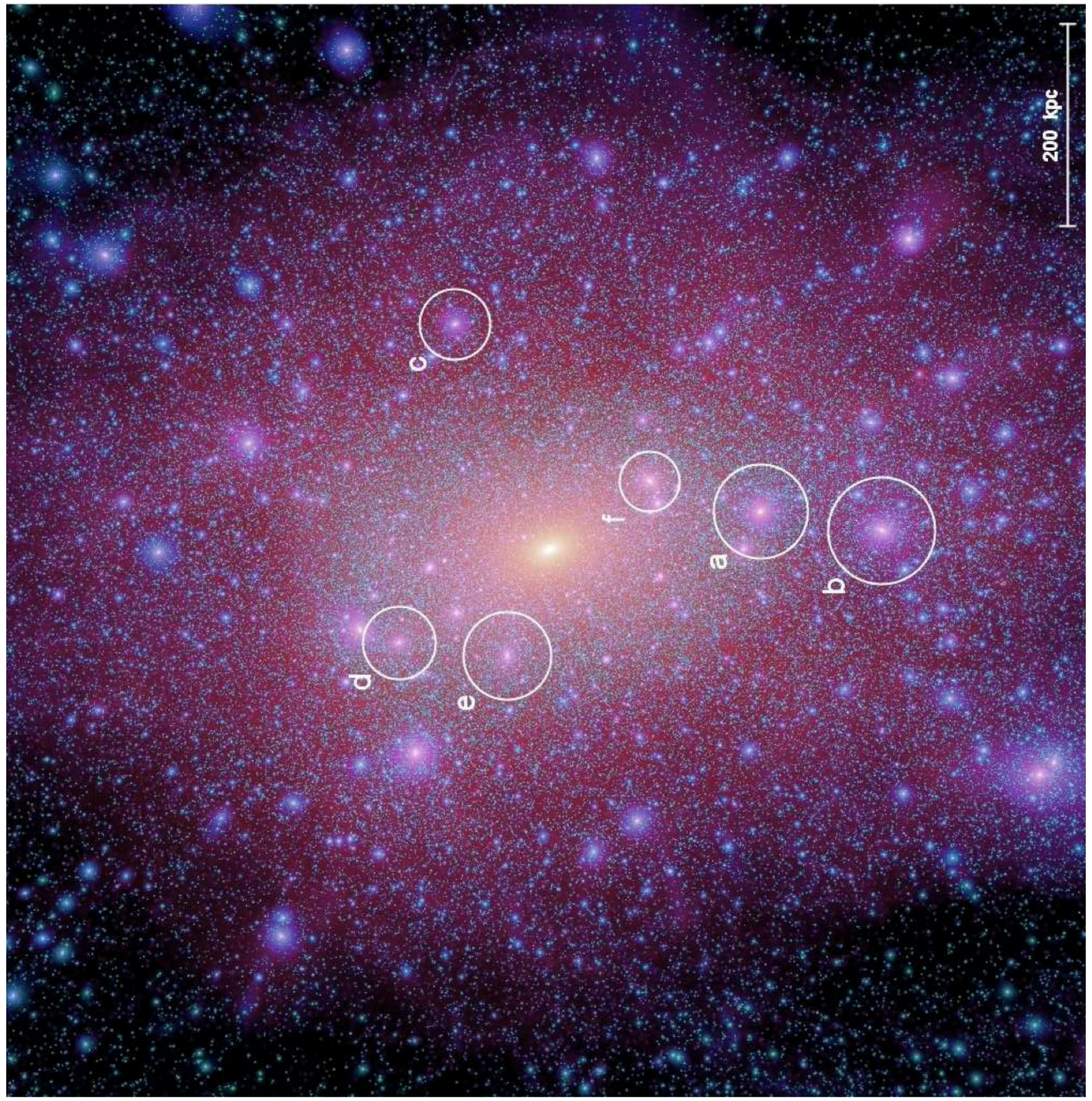
3 **Secondary:** look for annihilation products from the local Universe which undergo secondary effects such as scattering, diffusion,…

Prompt Gamma-ray searches



Gamma-ray Sky above 1 GeV, according to Fermi:



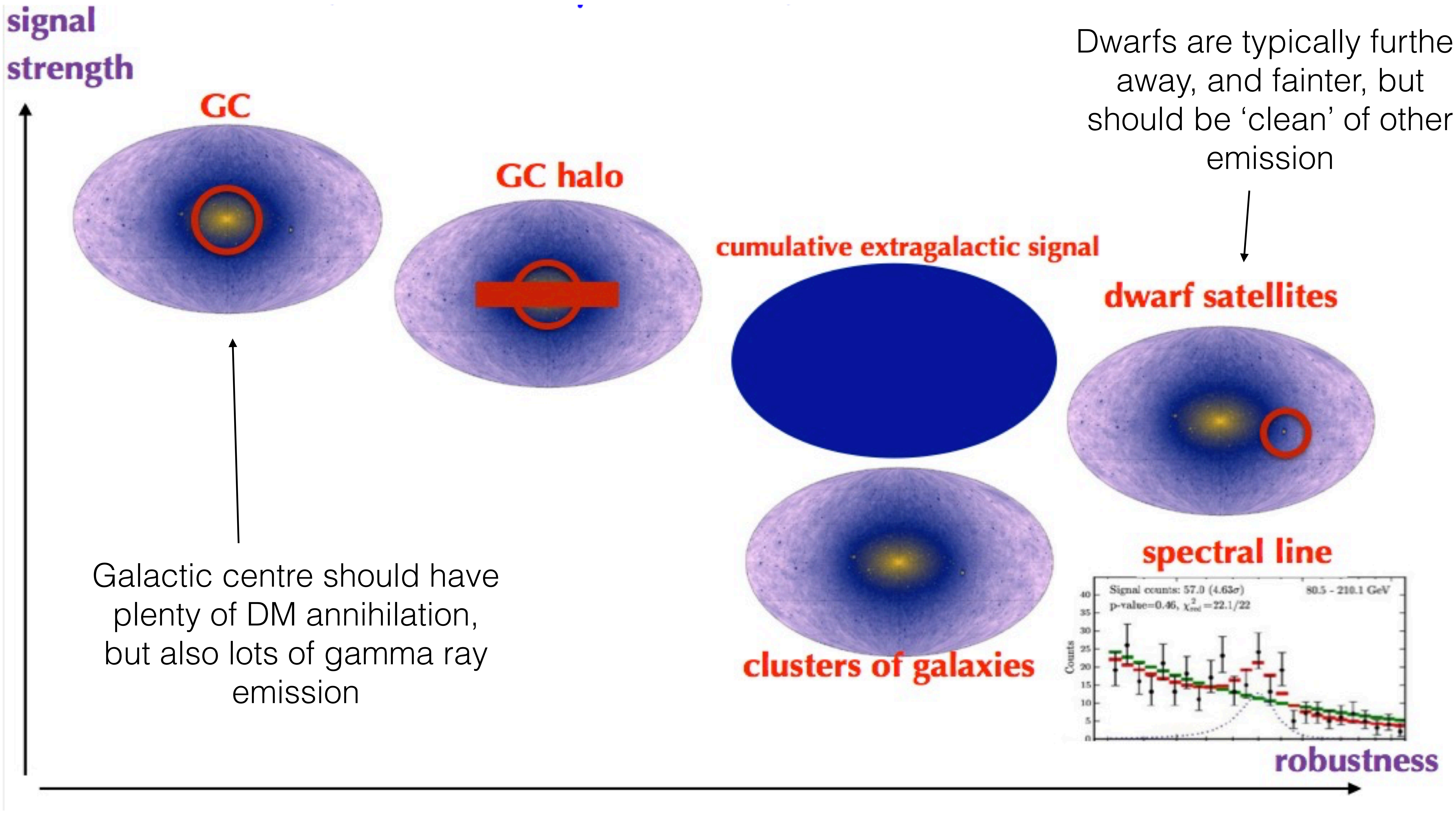


Credit: [NASA/DOE/Fermi LAT Collaboration]

Look in regions of high DM density (i.e. high J-factor) and low gamma-ray emission

Choice of Targets

[Slide by Aldo Morselli]



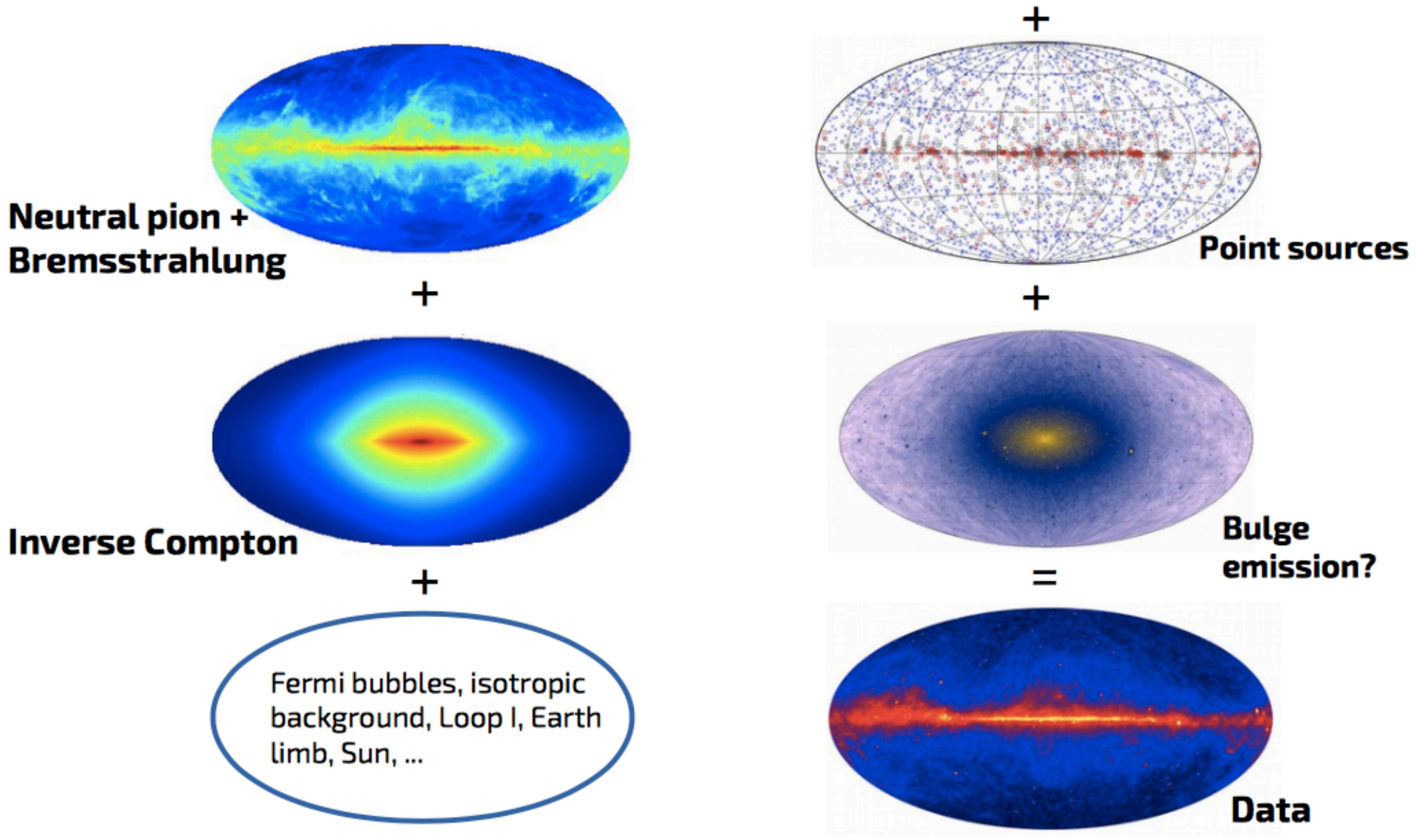
Dwarfs are typically further away, and fainter, but should be ‘clean’ of other emission

Galactic centre should have plenty of DM annihilation, but also lots of gamma ray emission

Mapping the Gamma-ray Sky

See Astroparticle physics Lecture 3

Model various contributions to the gamma-ray sky and look for a possible contribution from Dark Matter annihilation!



Isotropic Background

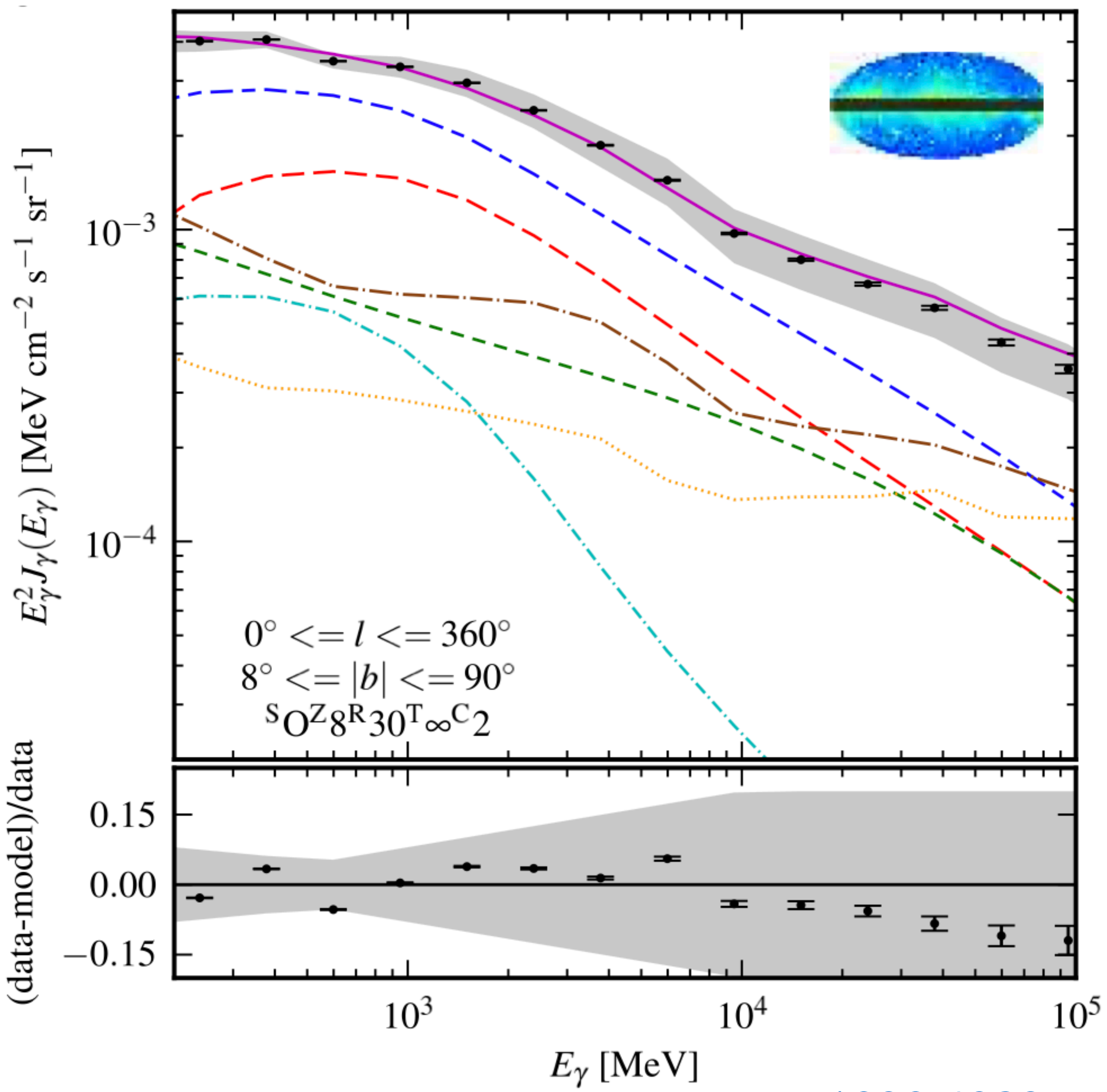
π^0 decay

Bremsstrahlung

Inverse Compton

Total Galactic

Point sources

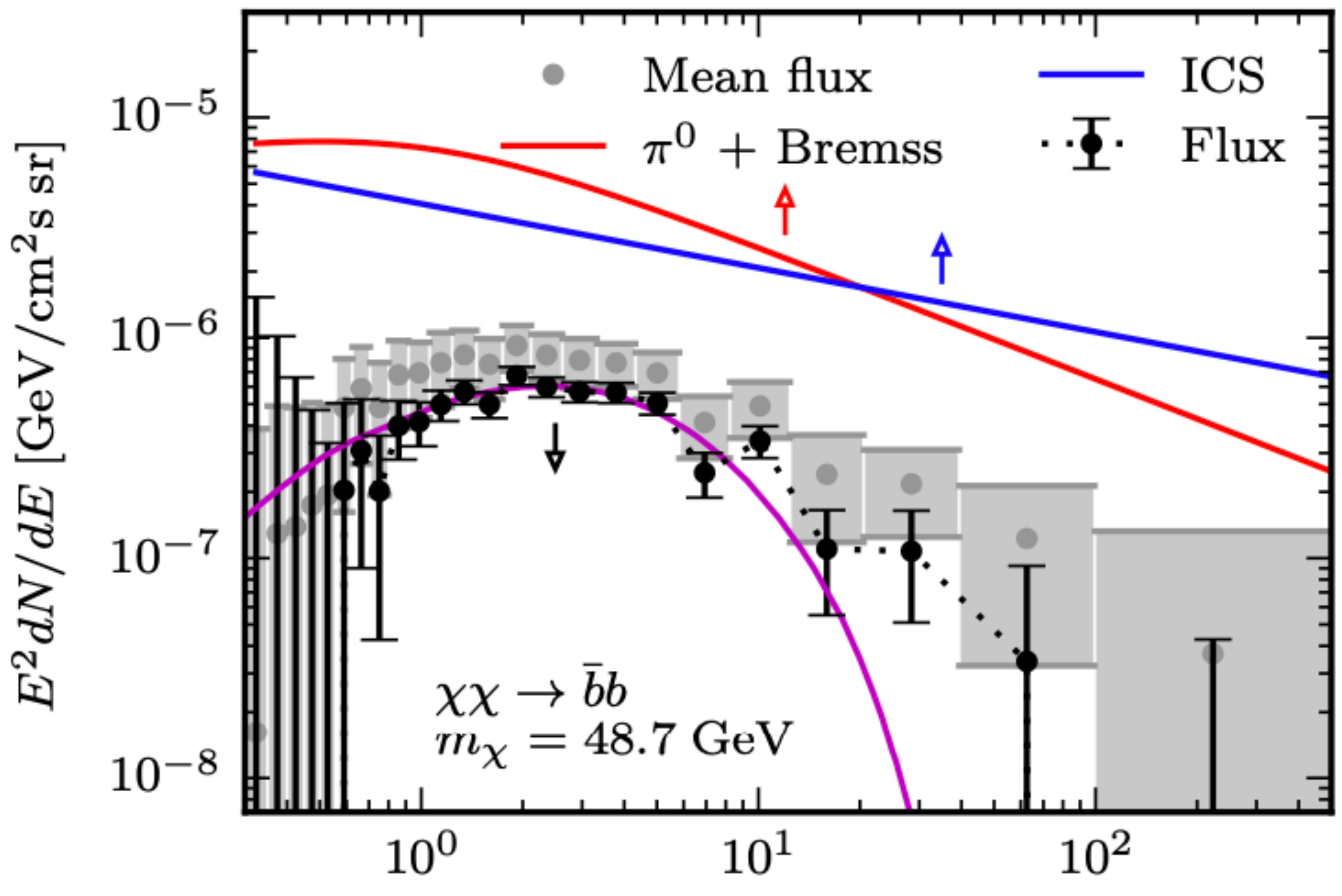


1202.4039

[Slide Credit: Christoph Weniger]

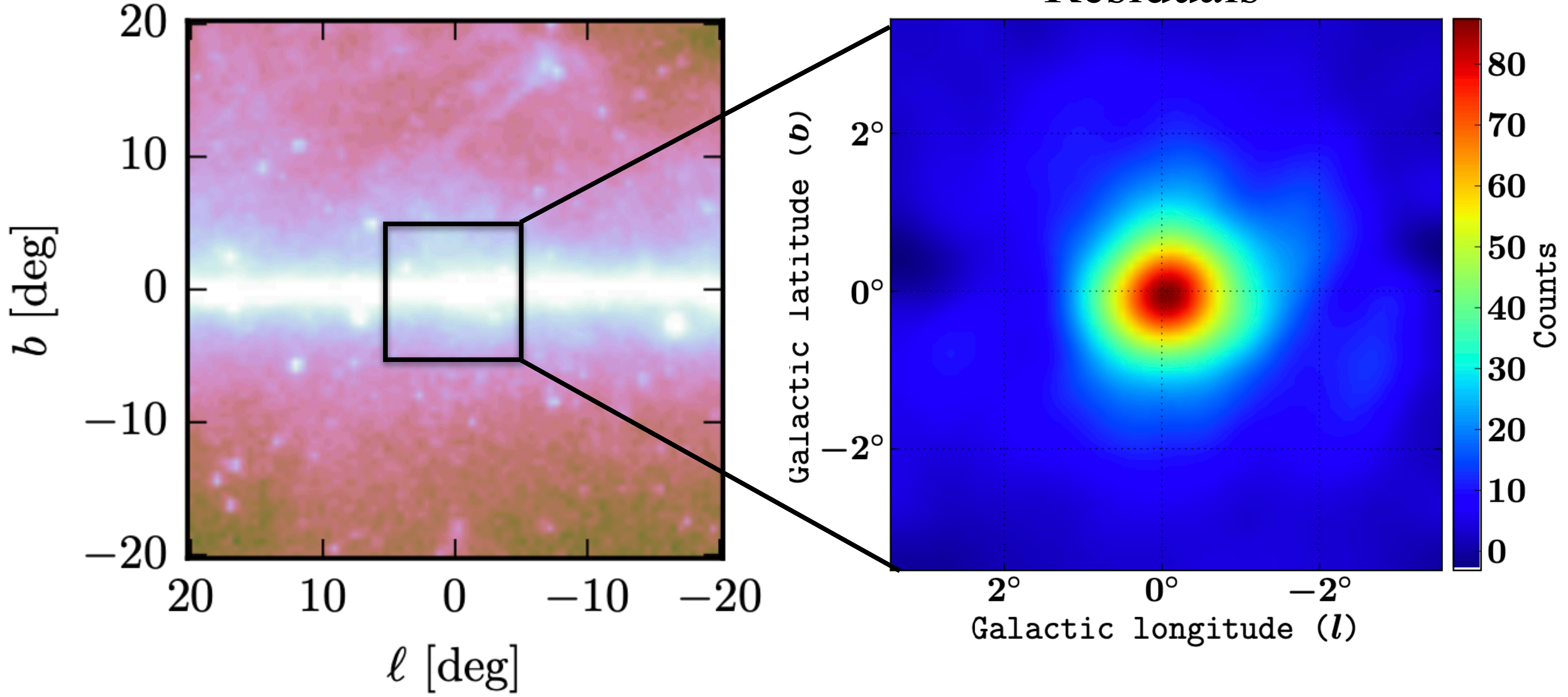
Galactic Centre Excess

1411.4647



Data [1711.04778]

Residuals [1306.5725]



Known since 2009, there is an excess of gamma-rays from the centre of the Milky Way (after subtracting known sources):

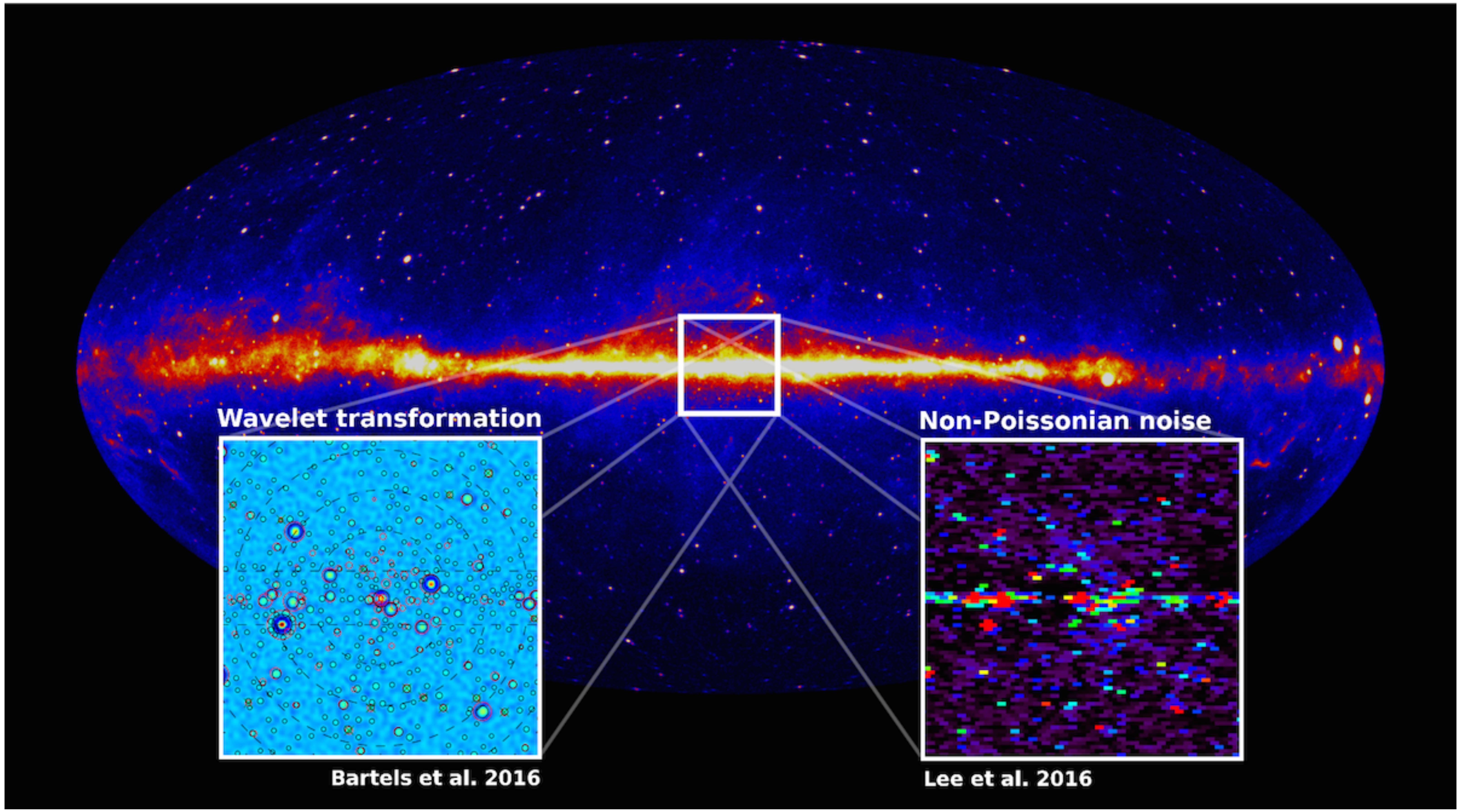
- Shape seems to trace the NFW profile (squared) expected for DM (*inferred from MW rotation curve*)
- Energy spectrum seems to match that expected for DM annihilation to $b\bar{b}$
- Cross section is close to the value required for thermal freeze-out!

[0910.2998]

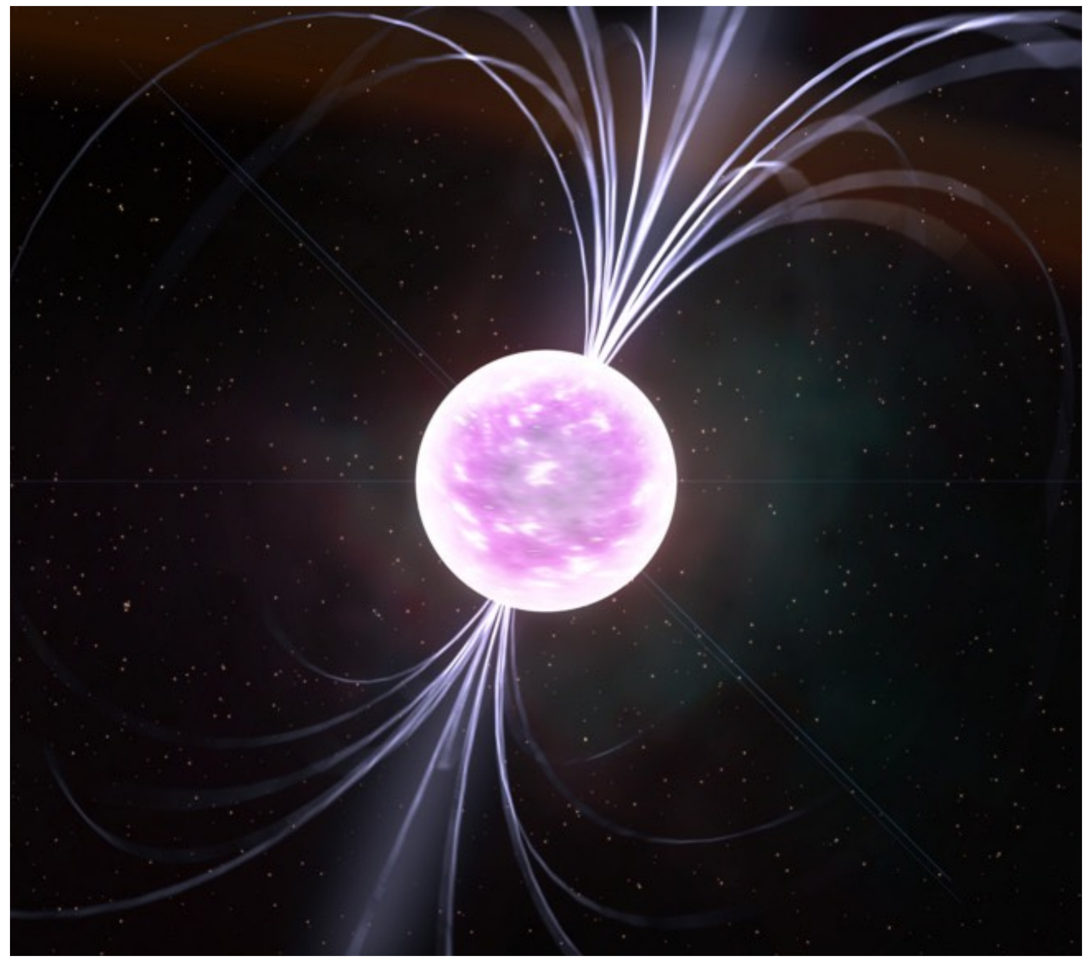
Point sources in the Galactic Centre

See Astroparticle physics Lecture 3

Galactic Centre excess could be due to a population of unresolved point sources (millisecond pulsars?)



[Credit: Christoph Weniger, UvA , © UvA/Princeton]



[Credit: Kevin Gill / Flickr]

Looking at the flux on very small scales, there seems to be some substructure (point sources?)

Flux also seems to trace stellar bulge in the GC

[1506.05104, 1711.04778]

Choice of Targets

[Slide by Aldo Morselli]

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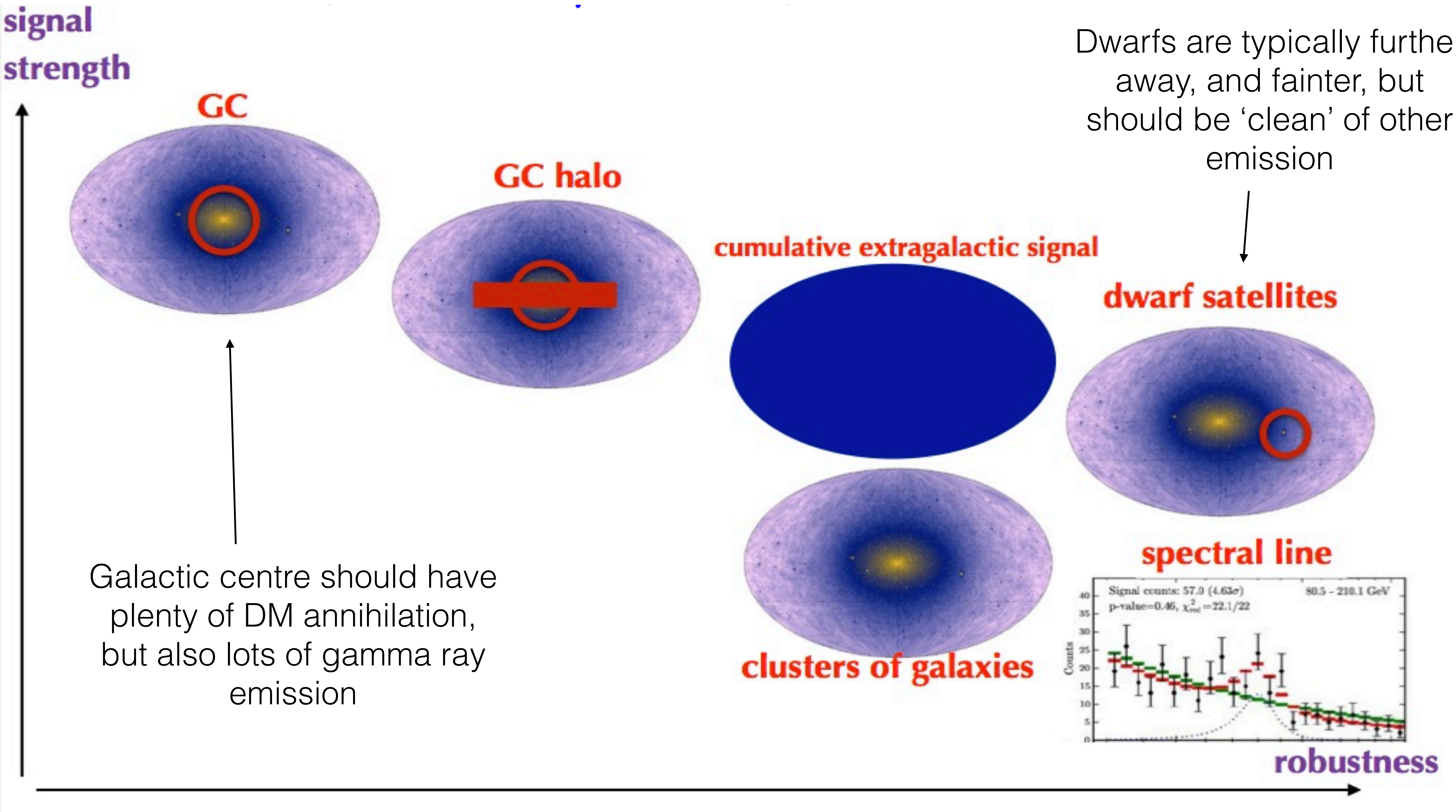
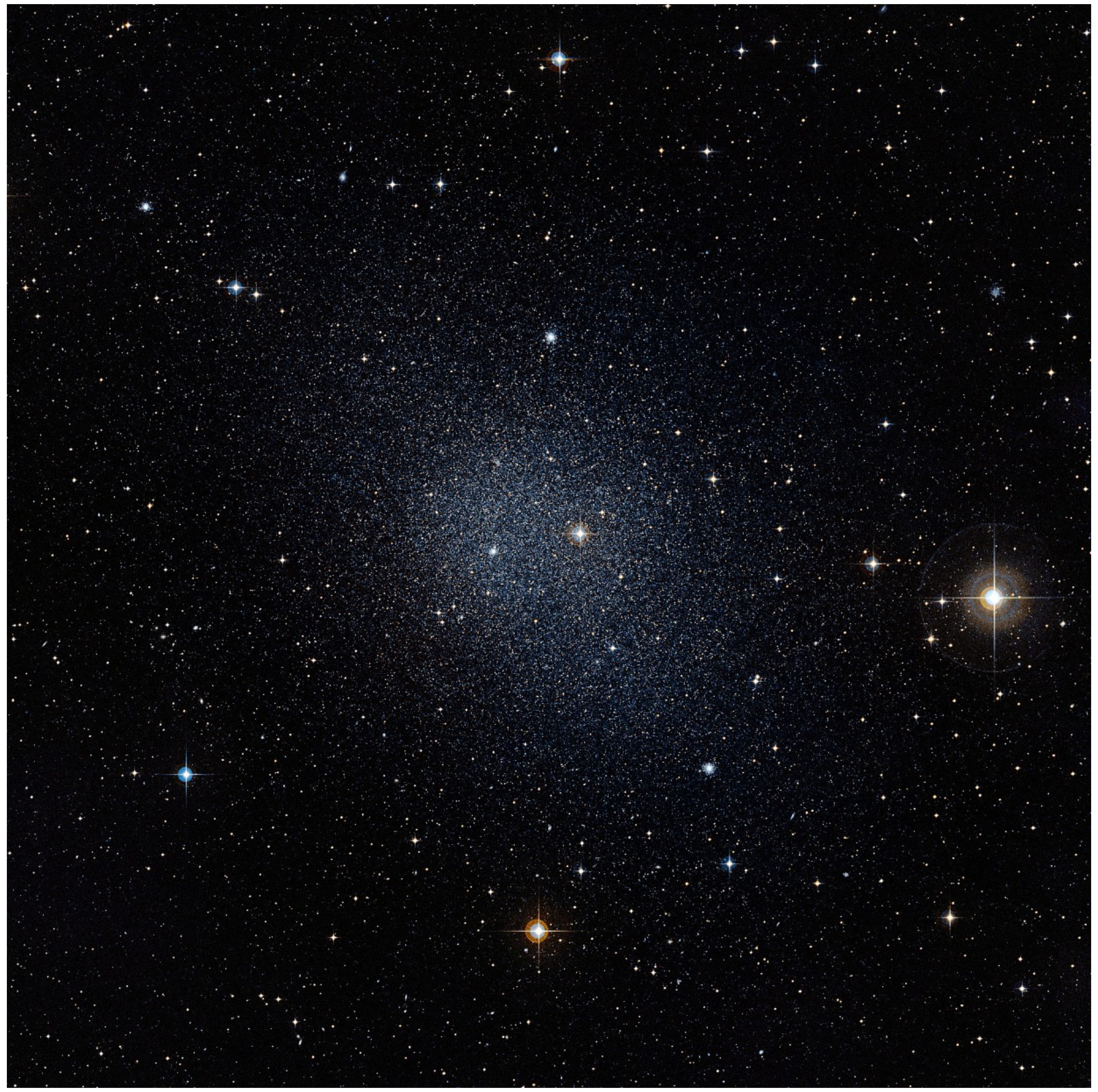


Galactic centre should have plenty of DM annihilation, but also lots of gamma ray emission

DM Density in Dwarf Galaxies

Fornax Dwarf Galaxy
(Satellite of the Milky Way)



[Credit: ESO/Digitized Sky Survey 2]

Dwarf galaxies are DM dominated and have a low gamma-ray flux, meaning that the signal-to-noise ratio for a DM search should be large.

But we first need to infer how much DM there is in these satellite galaxies. The stars are not rotating in a disk but have a distribution of orbital velocities.

Let's write the Collisionless Boltzmann Equation for the distribution function $f(\mathbf{r}, \mathbf{v})$ of stars in the Dwarf:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

with the stellar number density: $n(\mathbf{r}) = \int f(\mathbf{r})\, \mathrm{d}^3\mathbf{v}$

If I know the distribution function of a bunch of tracers (i.e. stars), then I can infer the gravitational potential (and therefore the DM distribution)!

But need to simplify a little..

The Jeans Equation*

*NB: There are lots of "Jeans Equations". James Jeans was a busy guy.

Assuming that the system is in equilibrium, we can set $\partial f / \partial t = 0$.

Let's focus on spherically symmetric systems and transform to spherical coordinates:

Effective potential

Depends only on radial gradient

$$v_r \frac{\partial f}{\partial r} + \left[\frac{2v_\theta^2}{r} - \frac{\partial \Phi}{\partial r}\right]\frac{\partial f}{\partial v_r} - \frac{2v_r v_\theta}{r}\frac{\partial f}{\partial v_\theta} = 0$$

In practice, its hard to measure/estimate the distribution function (its a 6-dimensional function of $\mathbf{r}, \mathbf{v}$). More convenient to work with **moments** of the distribution function. Multiply by v_r and integrate over all velocities:

$$\int v_r^2 \frac{\partial f}{\partial r} \mathrm{d}^3\mathbf{v} + \int \left[\frac{2v_\theta^2}{r} - \frac{\partial \Phi}{\partial r}\right] v_r \frac{\partial f}{\partial v_r}\, \mathrm{d}^3\mathbf{v} - \int \frac{2v_r^2}{r} v_\theta \frac{\partial f}{\partial v_\theta}\, \mathrm{d}^3\mathbf{v} = 0$$

Integrating the last two terms by parts (assuming $f \rightarrow 0$ as $v \rightarrow \infty$), and assuming no net inflow of stars $\langle v_r \rangle = 0$, we obtain:

Radial Jeans Equation: $$\frac{\partial(n\sigma_r^2)}{\partial r} + \left[\frac{2\sigma_r^2 \beta(r)}{r} + \frac{\partial \Phi}{\partial r}\right] n = 0$$

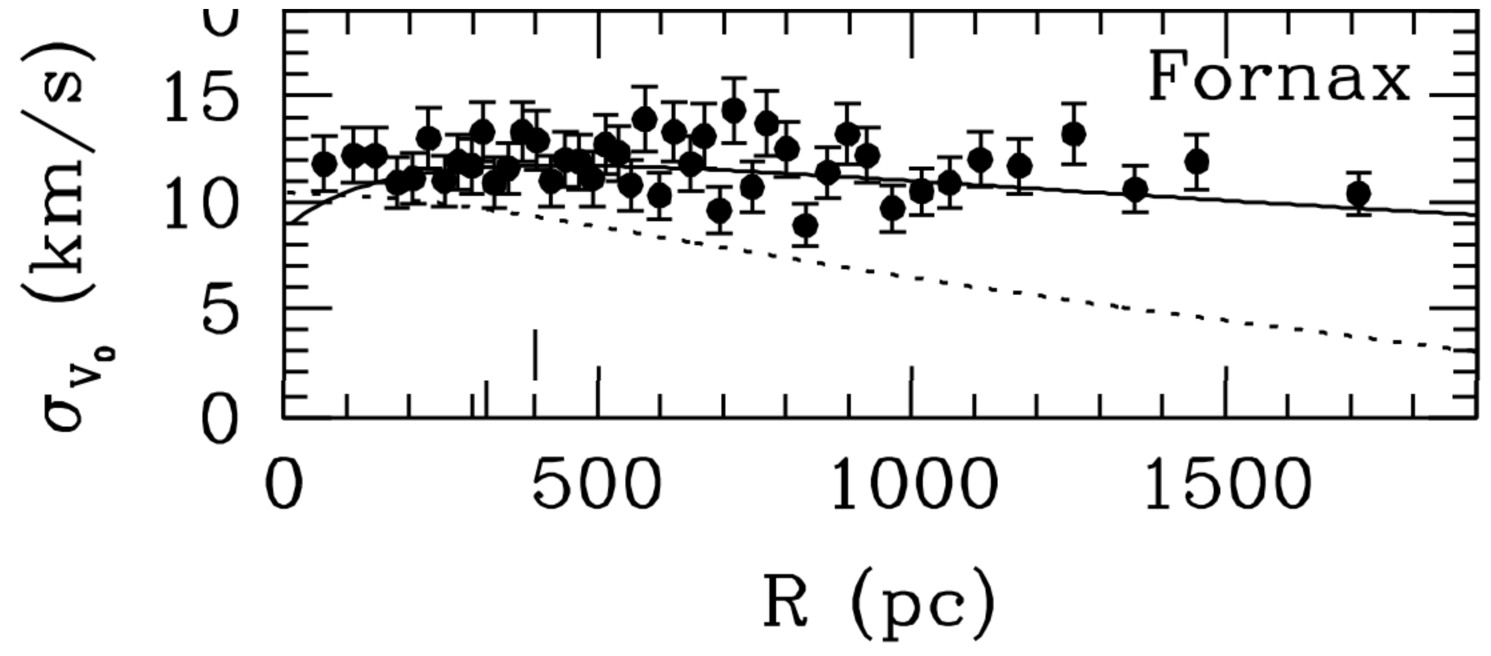
Anisotropy parameter
$\beta(r) = 1 - \sigma_\theta^2/\sigma_r^2$

where σ_r and σ_θ are the velocity dispersions in the radial and tangential directions respectively.

Inferring Dwarf Galaxy J-factors

In practice, it's complicated:

- Only measure line of sight velocities (not radial/tangential velocities)
- System may deviate from equilibrium or spherical symmetry
- Isotropy parameter $\beta(r)$ not known *a priori* and must be fit to data



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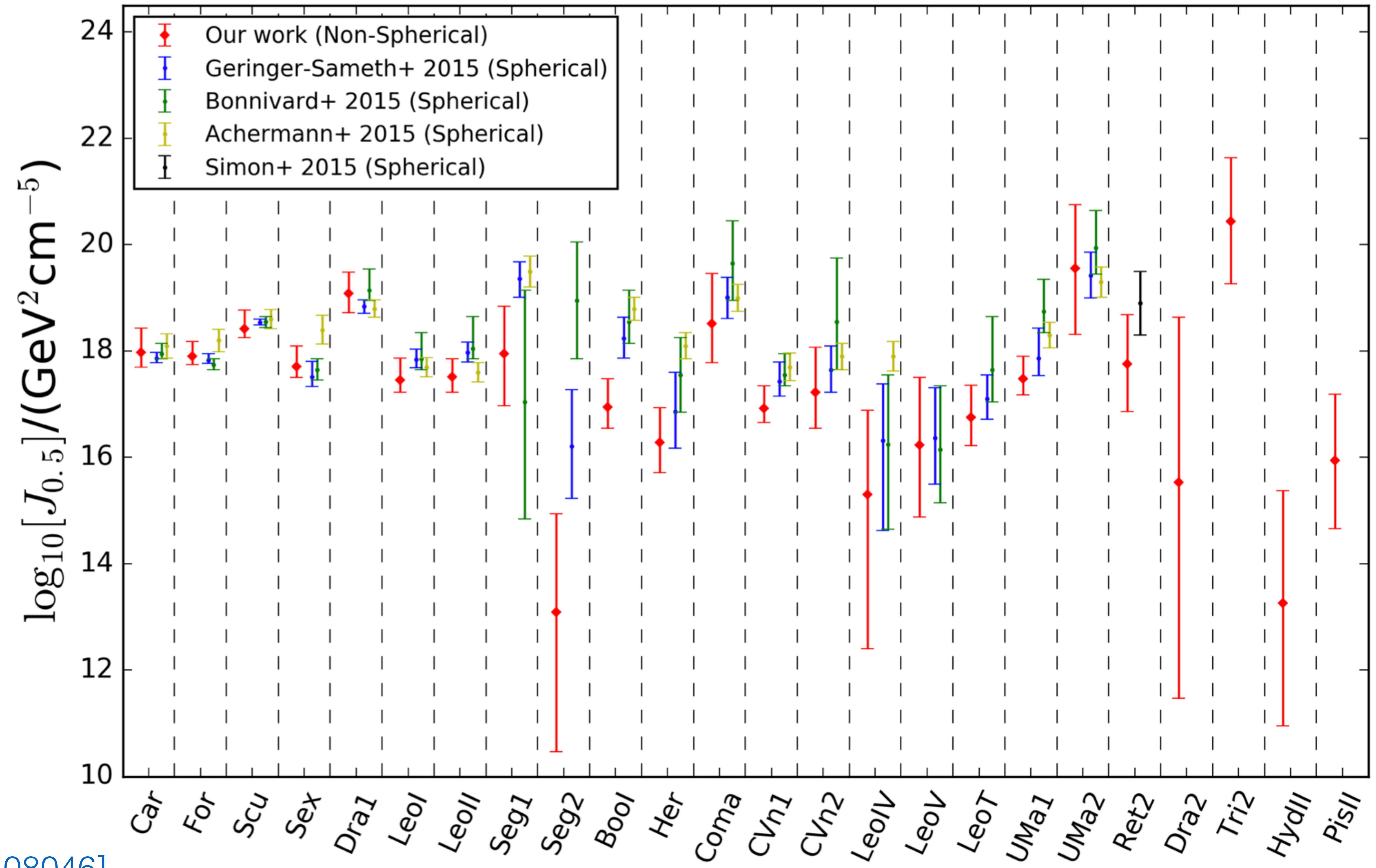


In many cases, the J-factors are large (which is good) but the uncertainties can be large (which is bad, because ideally we would like to know the expected flux as precisely as possible in order to constrain the cross-section).

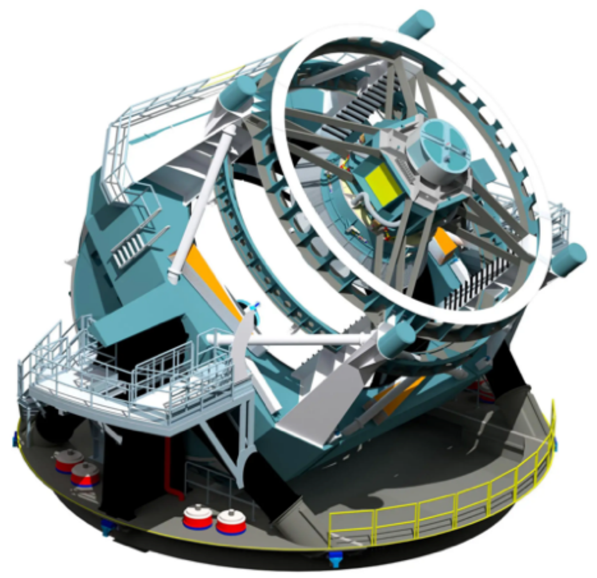
[1603.08046]

Dwarf Galaxy Constraints

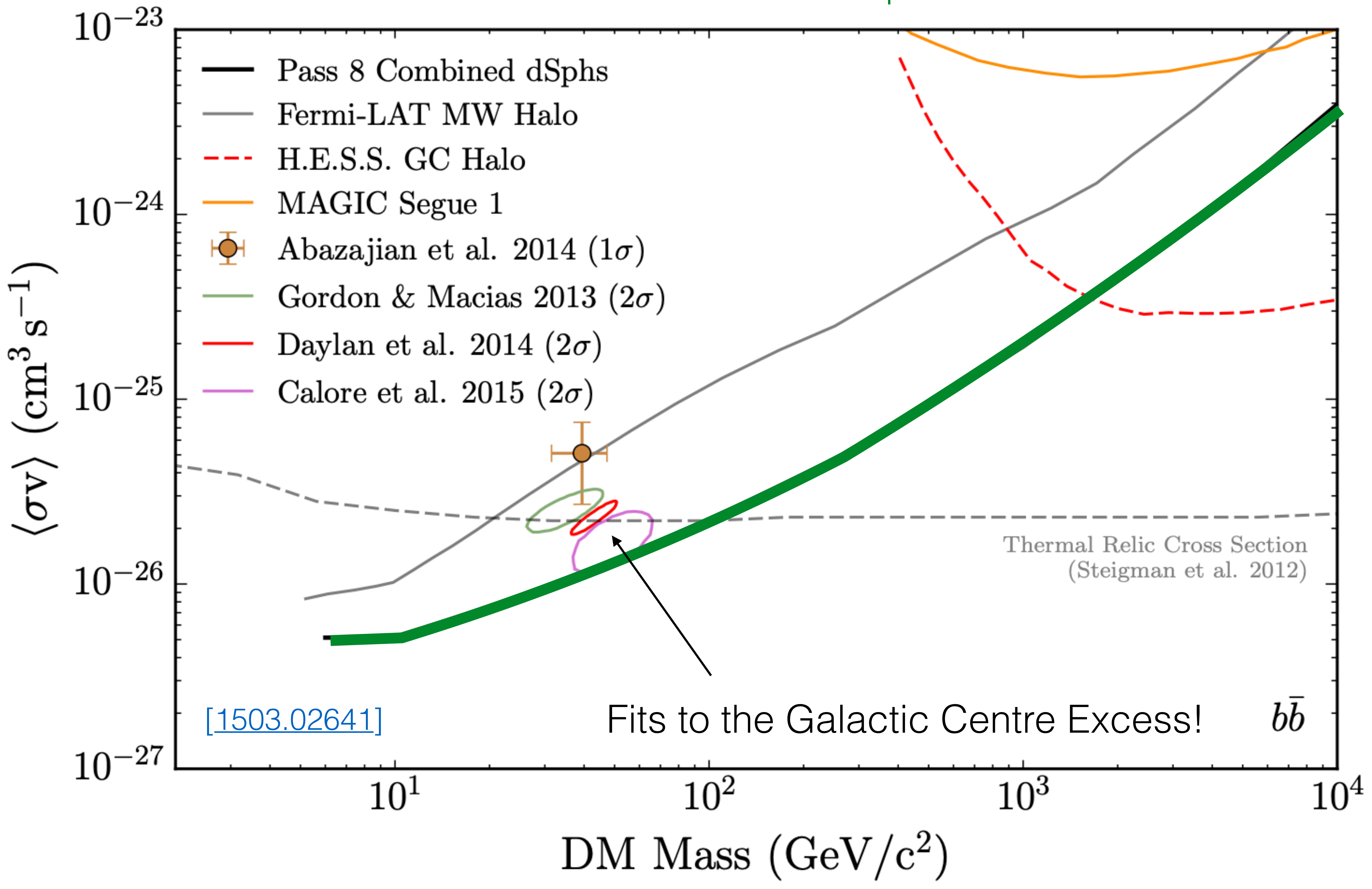
MW Dwarf Galaxies give the most stringent constraints on prompt gamma-ray emission

There seems to be tension with a DM interpretation of the Galactic Centre Excess.

Future optical surveys (e.g. LSST) should find new ultra-faint dwarfs, so constraints will strengthen!



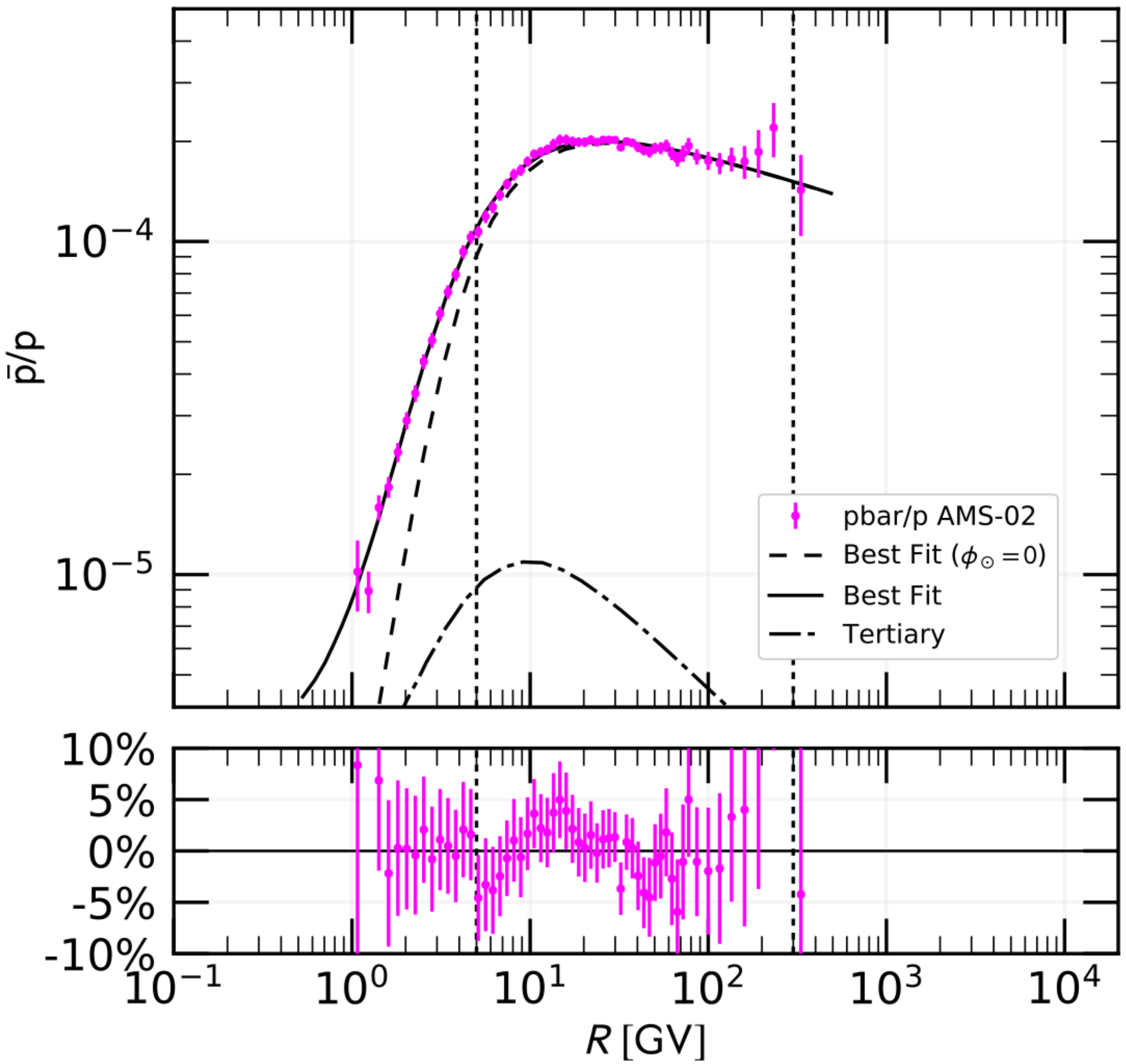
Fermi constraints from 15 Dwarf Spheroidal Galaxies:

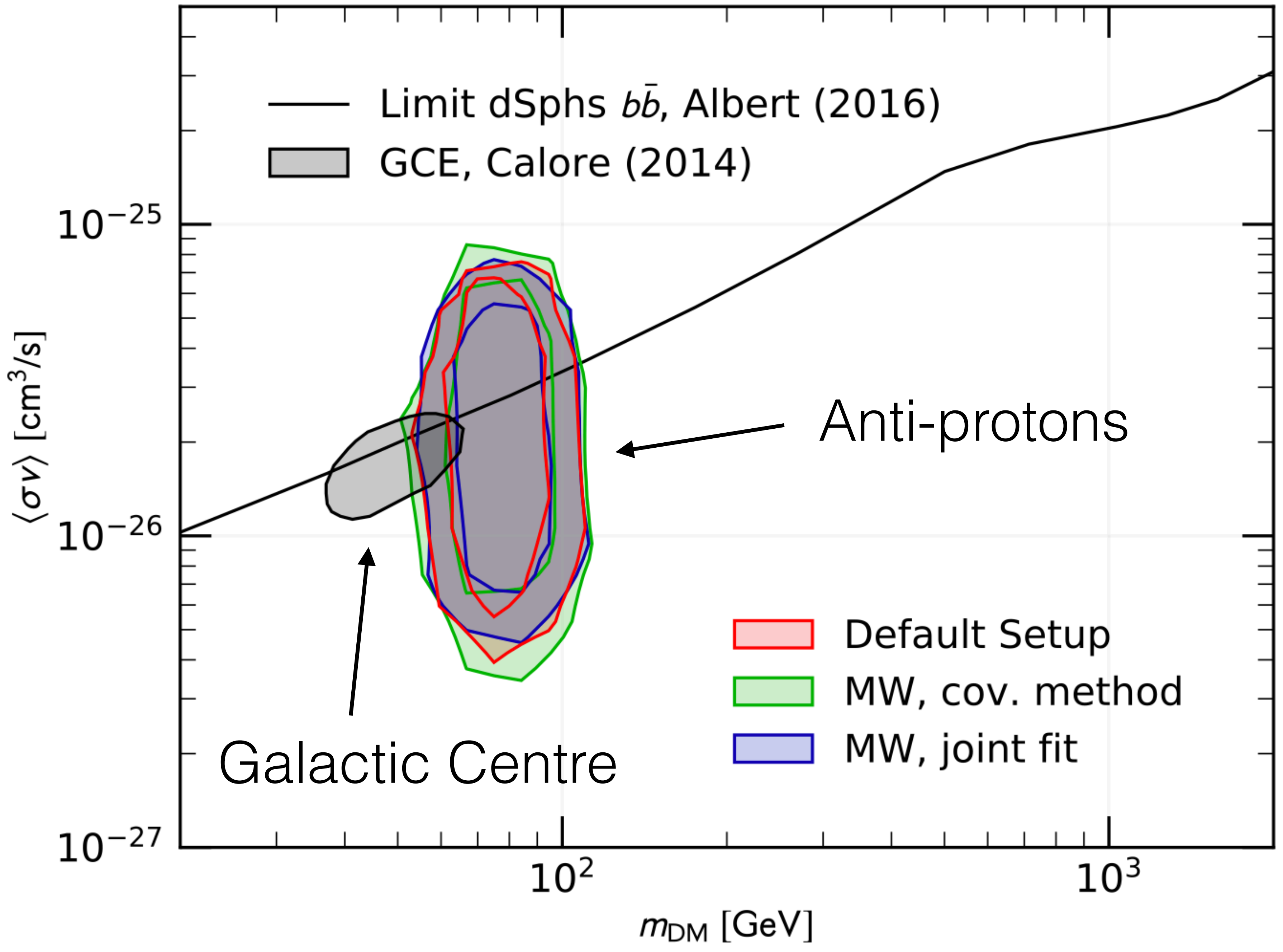


NB: Exact constraints depend on annihilation channel.

Anti-proton excess

Anti-protons are an excellent probe of DM annihilation - they're hard to make!





But modelling cosmic ray propagation (and anti-proton production) is complicated.

[1504.04276, 1610.03071, 1903.01472]

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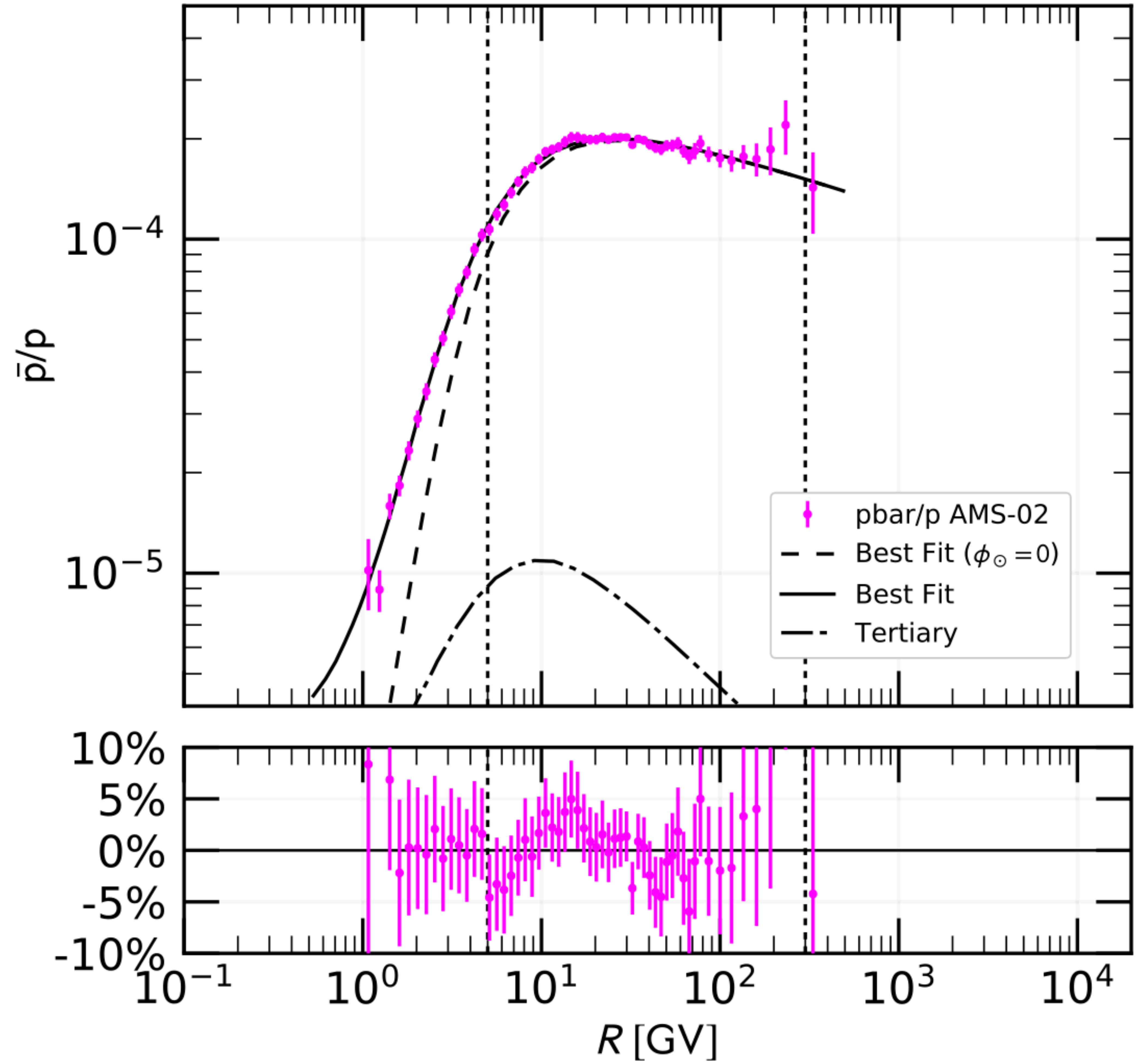
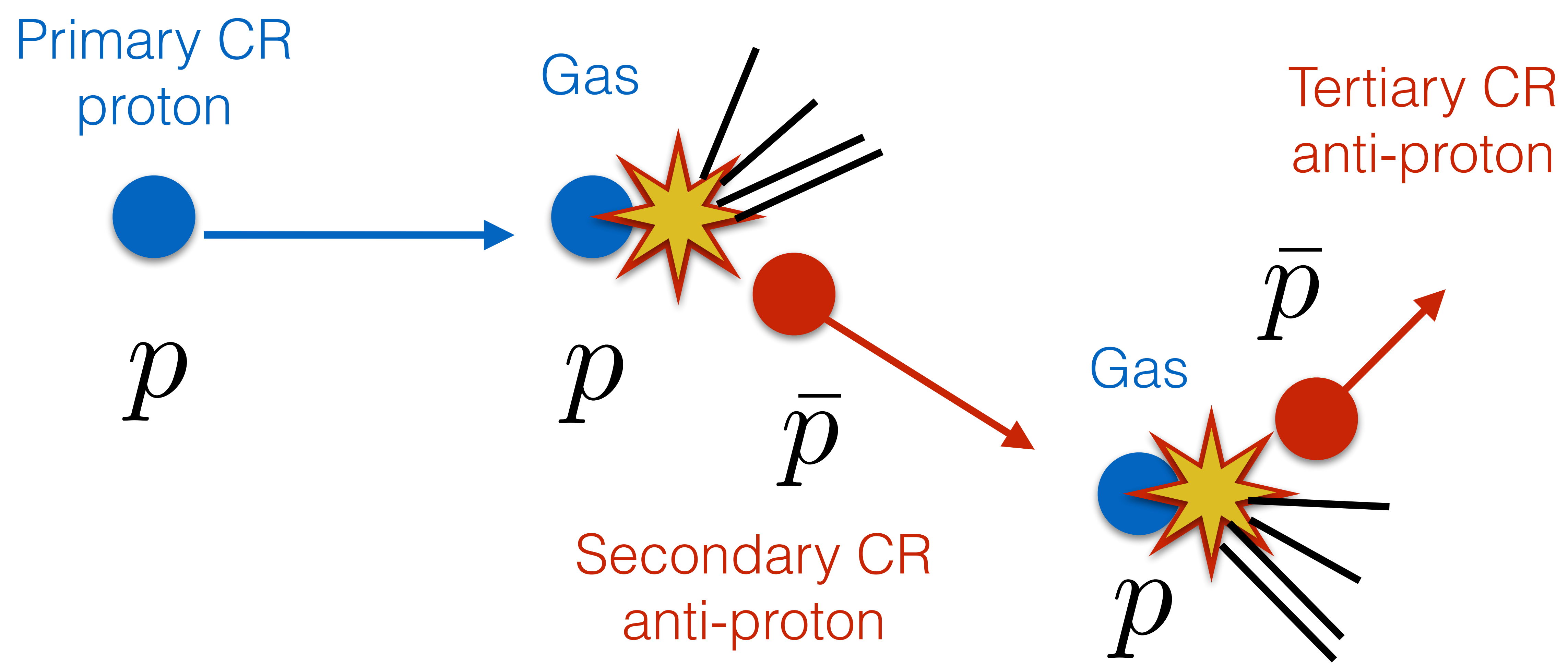


But modelling cosmic ray propagation (and anti-proton production) is complicated.

Need to account for e.g. tertiary anti-proton production

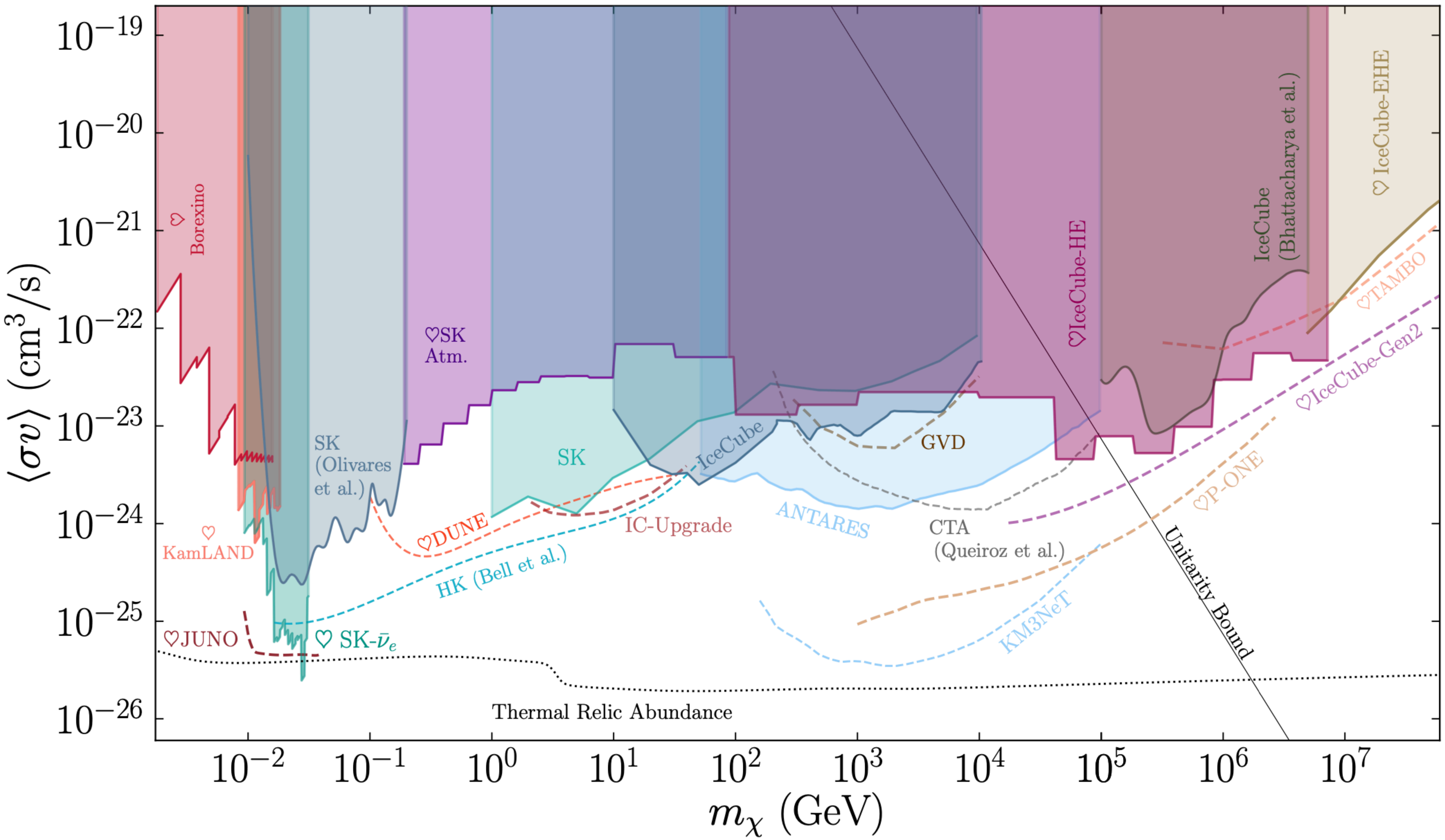


[1504.04276, 1610.03071, 1903.01472]

Annihilation to Neutrinos

[1912.09486]

Can also search for annihilation to neutrinos. But neutrinos are hard to detect, so it's hard to reach the thermal freeze-out cross section.



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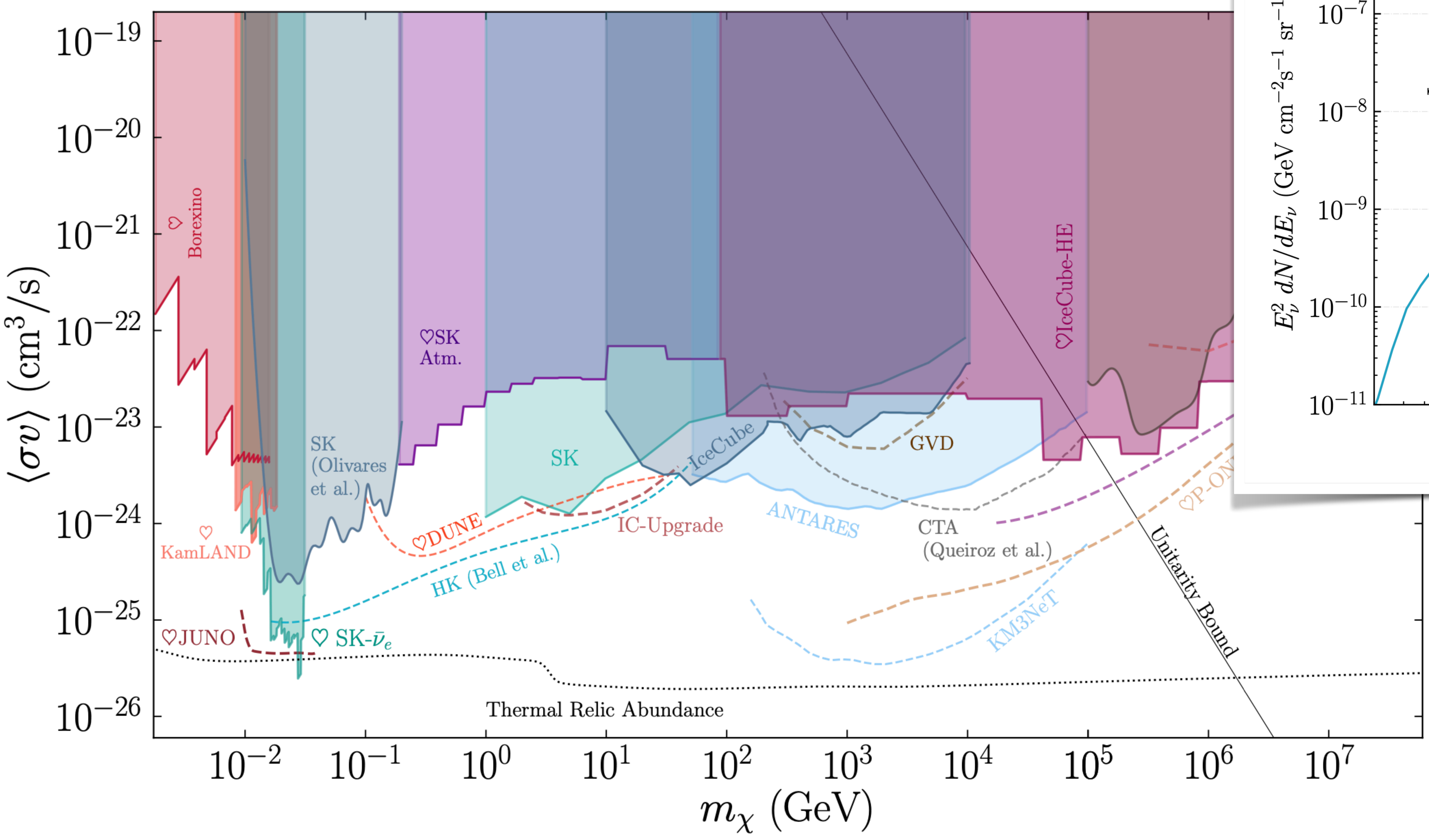
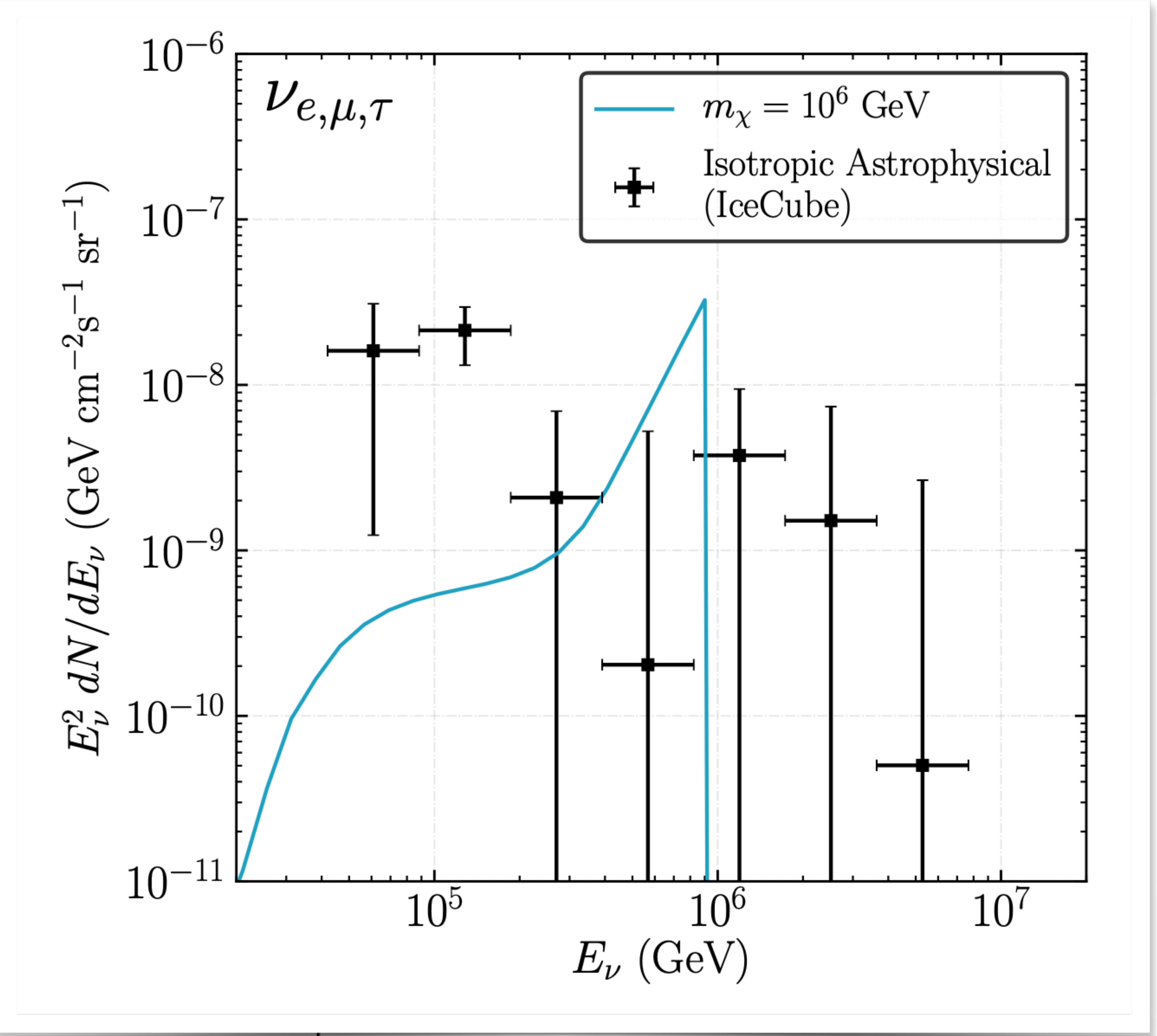




Hints of very heavy (PeV) DM annihilating/decaying to neutrinos?

Model-independent constraints

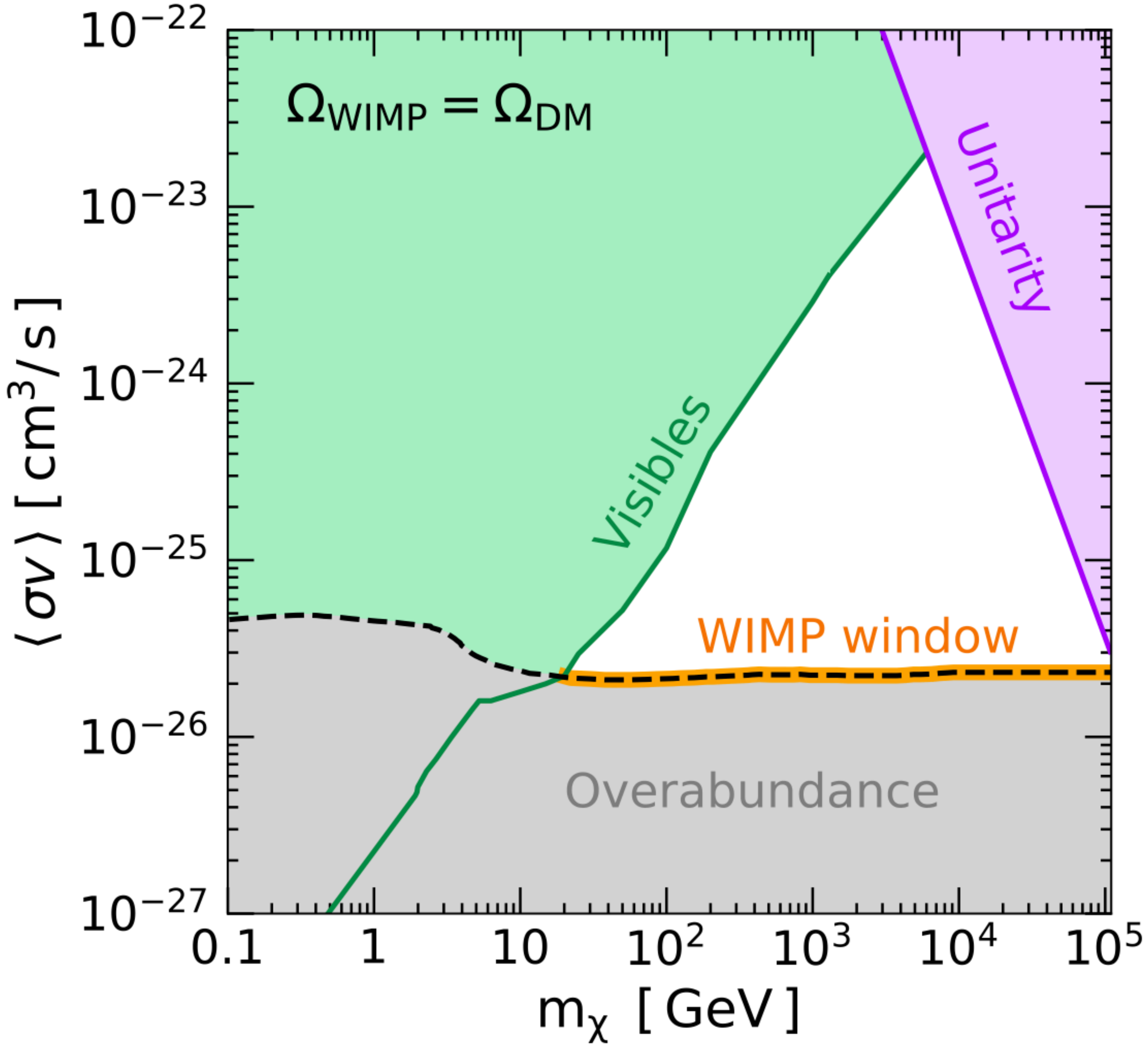
Have we detected WIMP annihilation products in gamma-rays and/or cosmic rays? It's not clear. Set constraints instead…

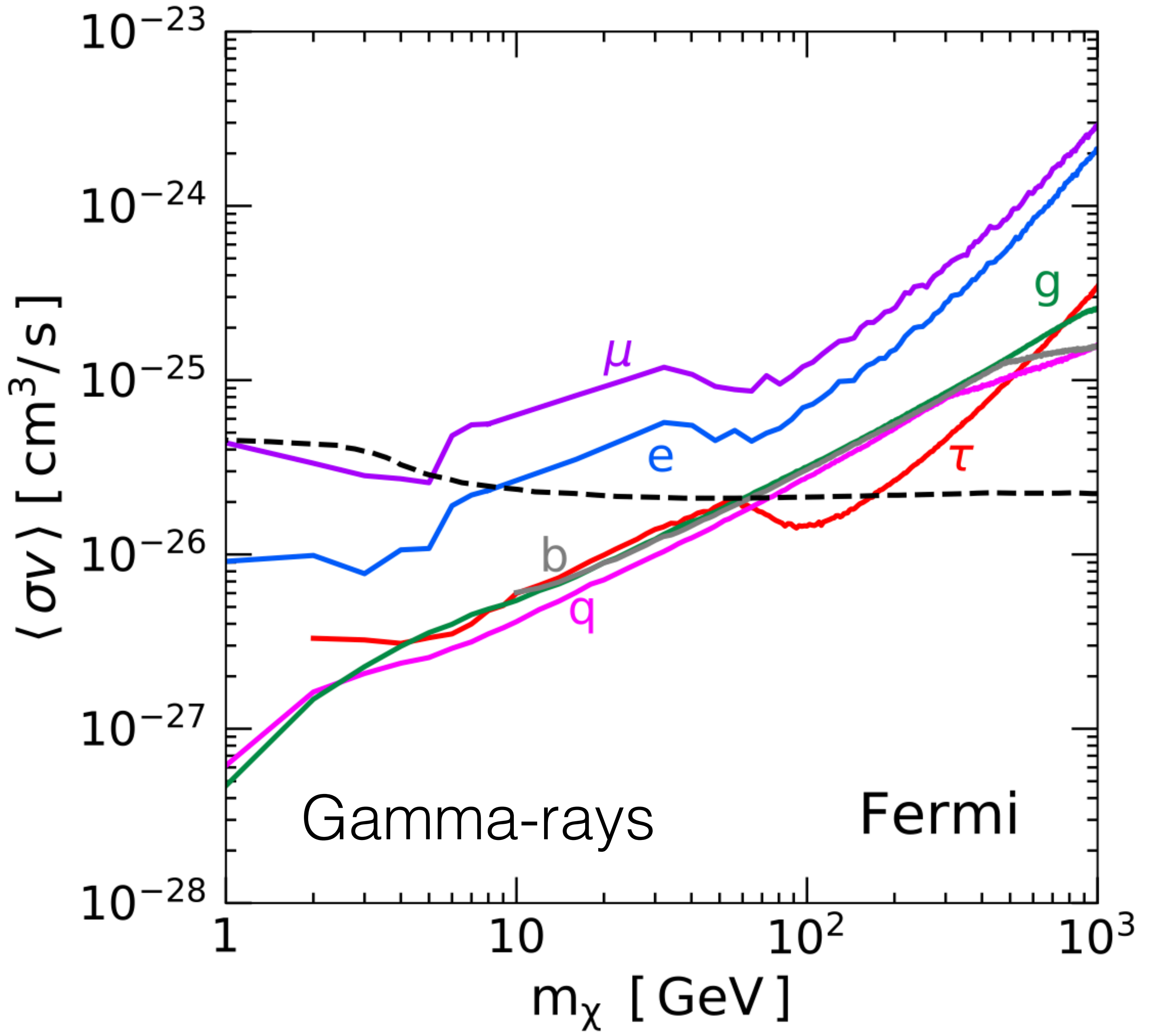
Freeze-out sets the total cross section, but not the branching ratios: $\Omega_{\rm DM} h^2 \approx 3 \times 10^{-27}\ \mathrm{cm^3\ s^{-1}} / \langle \sigma v \rangle$

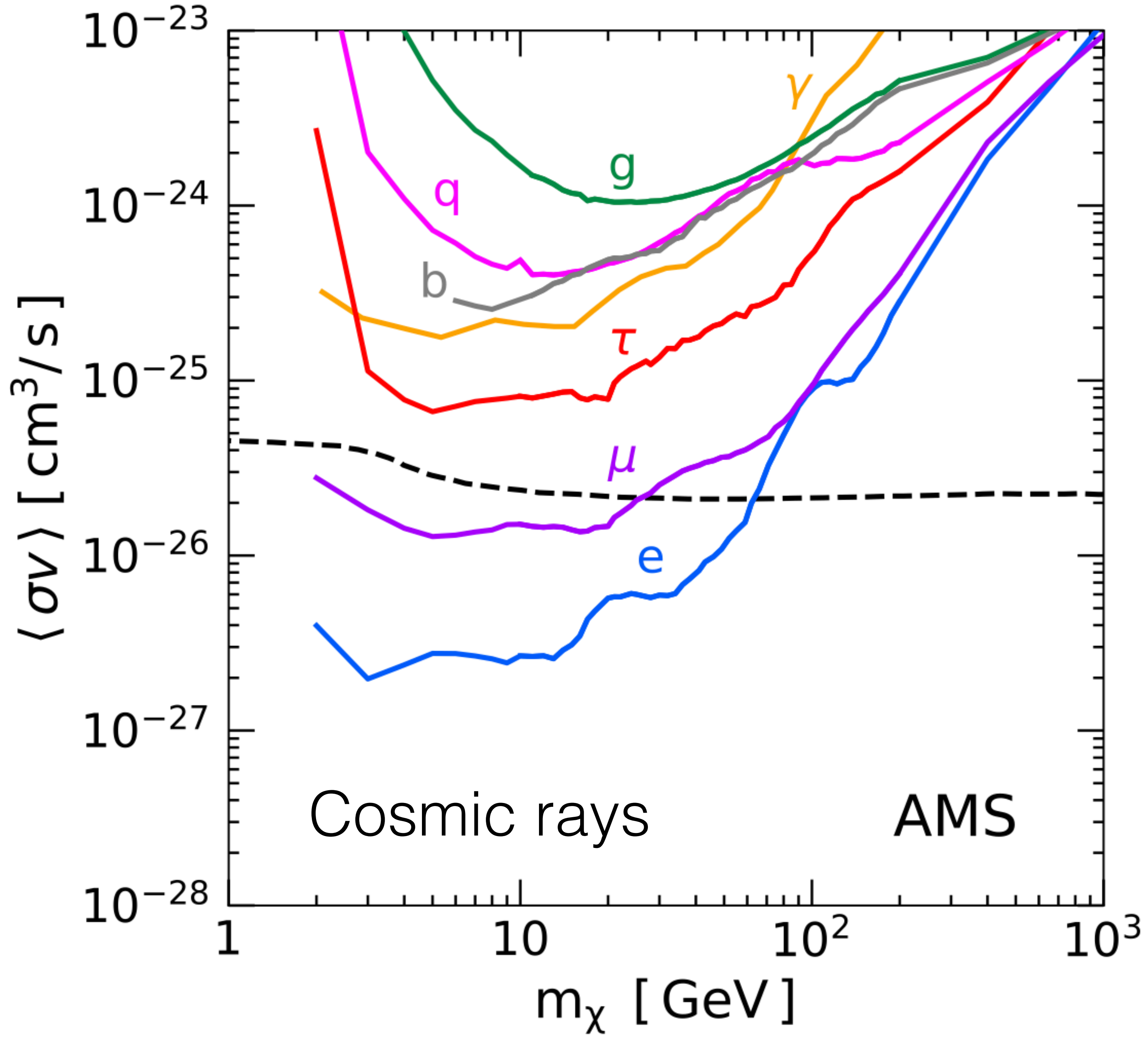
Take the weakest constraint from Fermi and AMS to find the region ruled out by DM annihilation to visible SM particles:

The WIMP is alive and well.

[1805.10305]

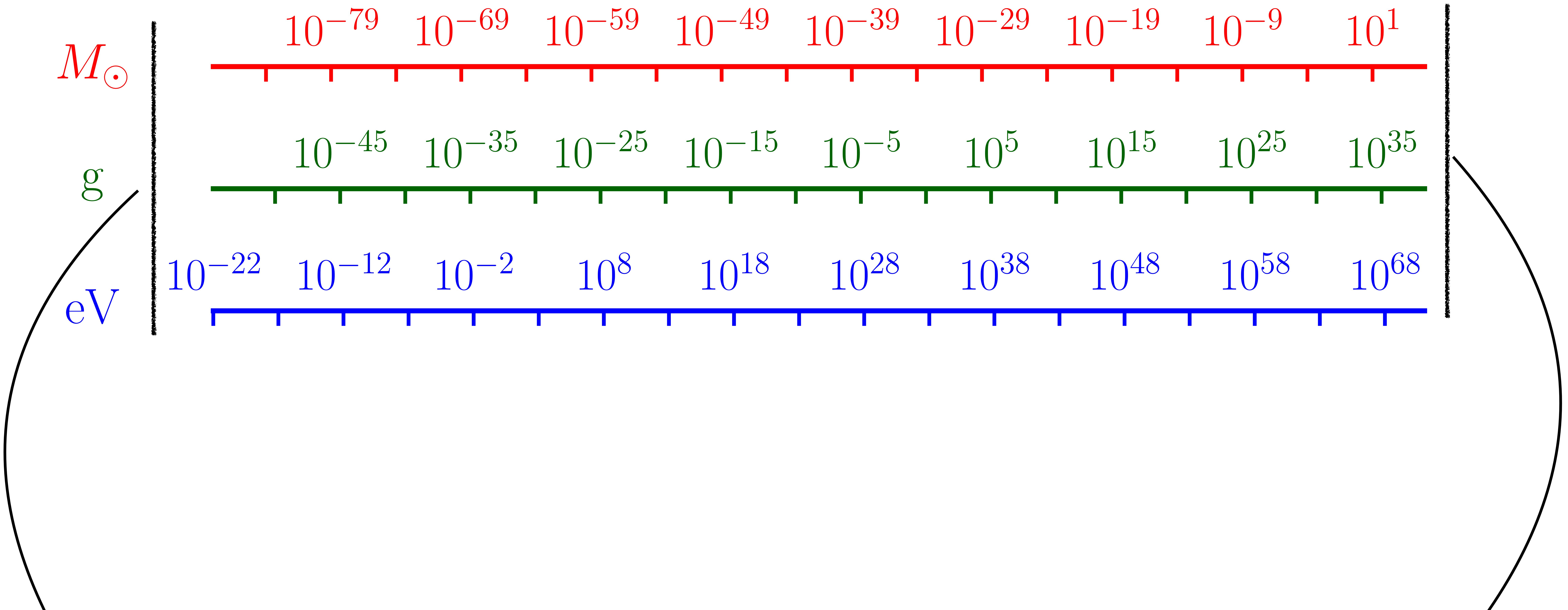






Primordial Black Holes

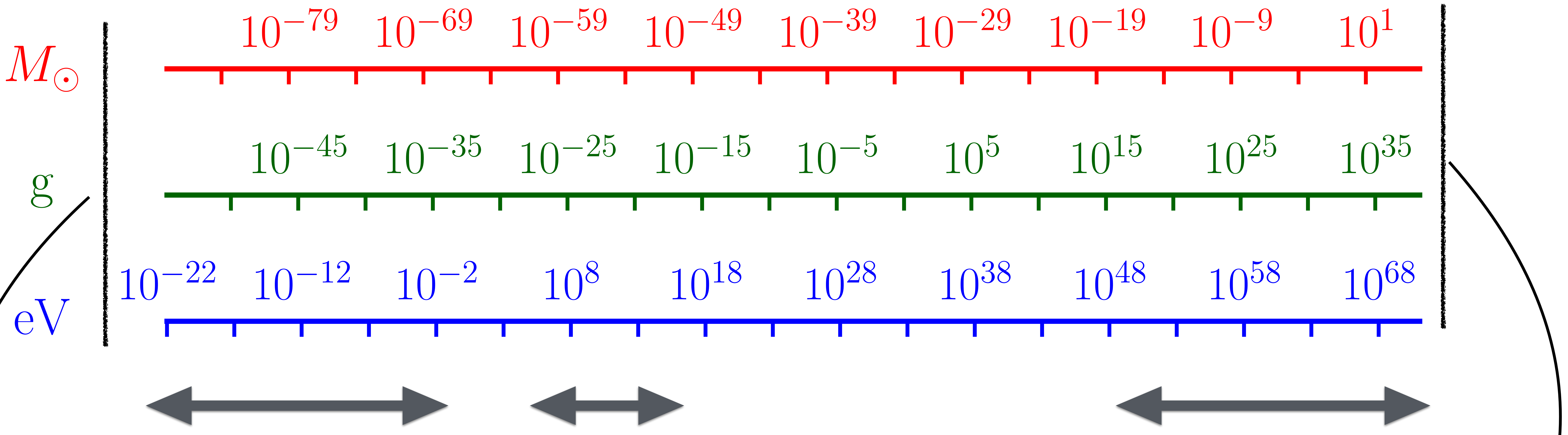
Dark Matter mass range



Too light!
Has wave-like properties on galactic scales!

Too heavy!
DM mass comparable to galactic masses!

Dark Matter mass range



Axion-like particles (**ALPs**)

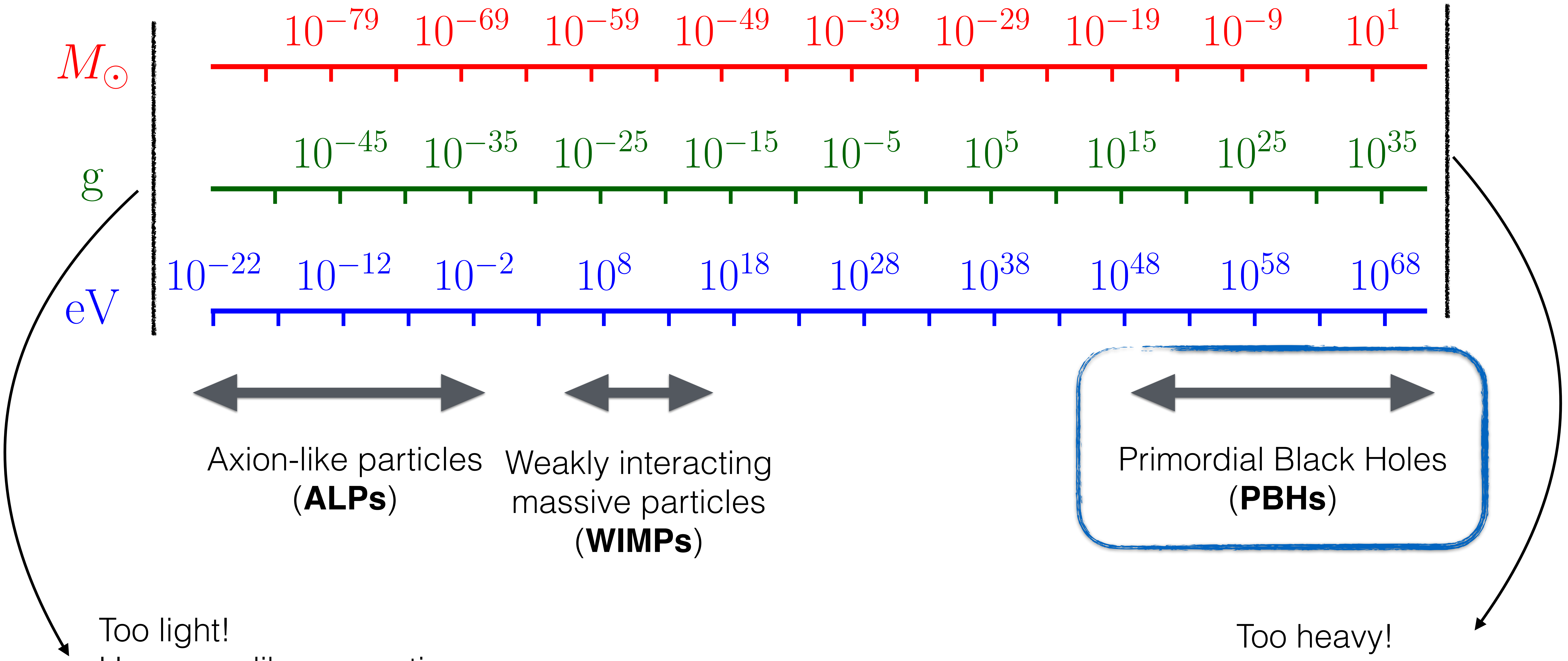
Weakly interacting massive particles (**WIMPs**)

Primordial Black Holes (**PBHs**)

Too light!
Has wave-like properties on galactic scales!

Too heavy!
DM mass comparable to galactic masses!

Dark Matter mass range

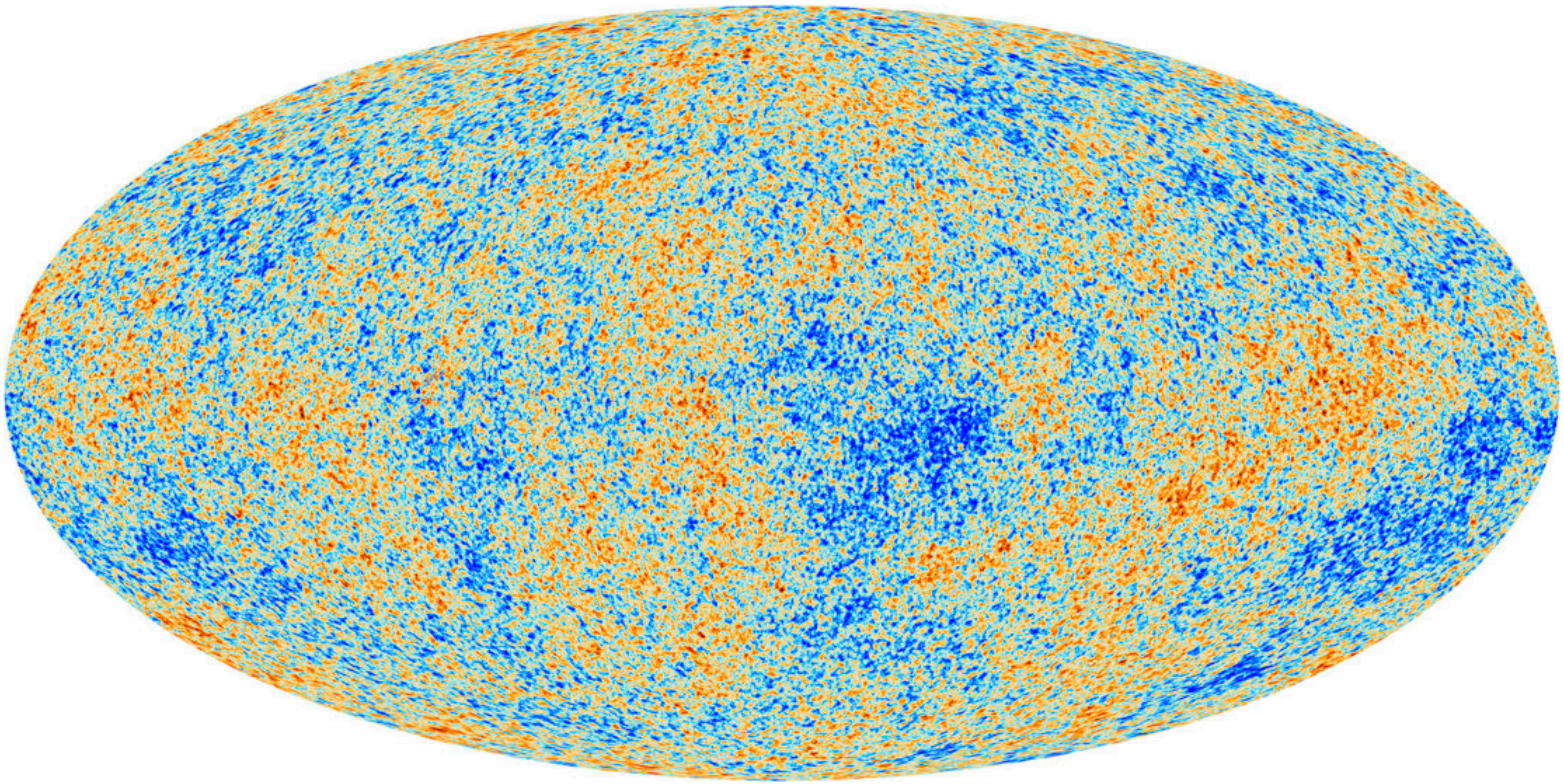


Too light!
Has wave-like properties on galactic scales!

Too heavy!
DM mass comparable to galactic masses!

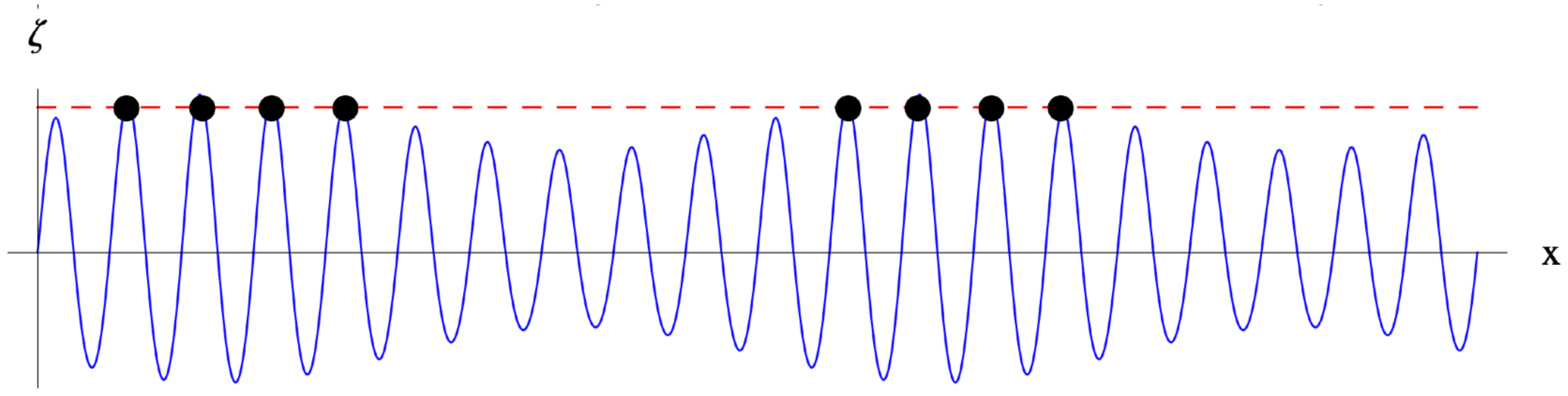
Primordial Fluctuations

The CMB exhibits fluctuations at the level of $\delta\rho/\rho \sim 10^{-5}$, which have grown from even smaller "primordial fluctuations" produced during inflation

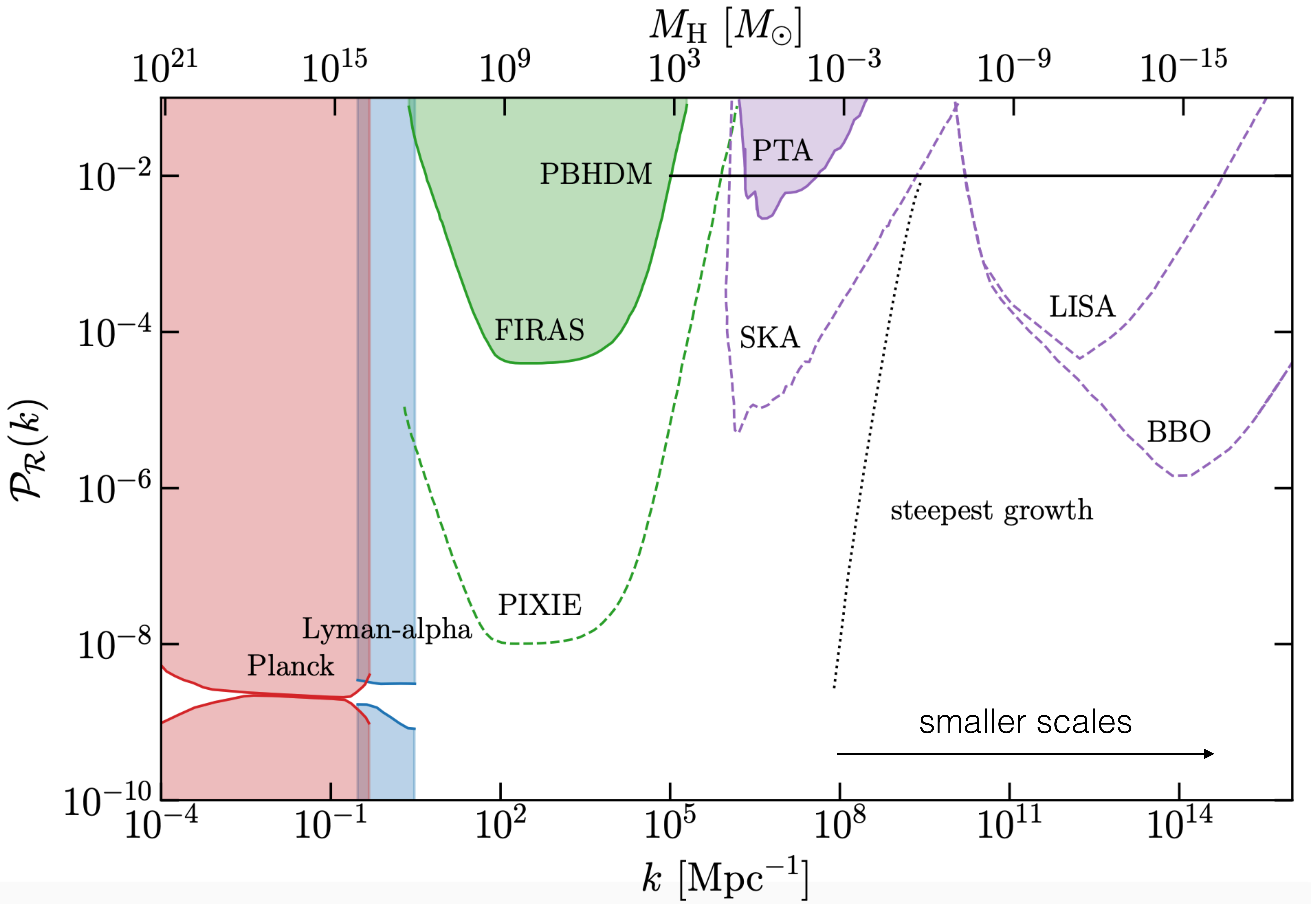


But this only tells us about fluctuations on large scales: $\lambda \sim 10\,\mathrm{Mpc} \longrightarrow k \sim 0.05\,\mathrm{Mpc}^{-1} \longrightarrow M_H \sim 10^{16}\,M_{\odot}$

Primordial Fluctuations



[Young & Byrnes, 1411.4620]



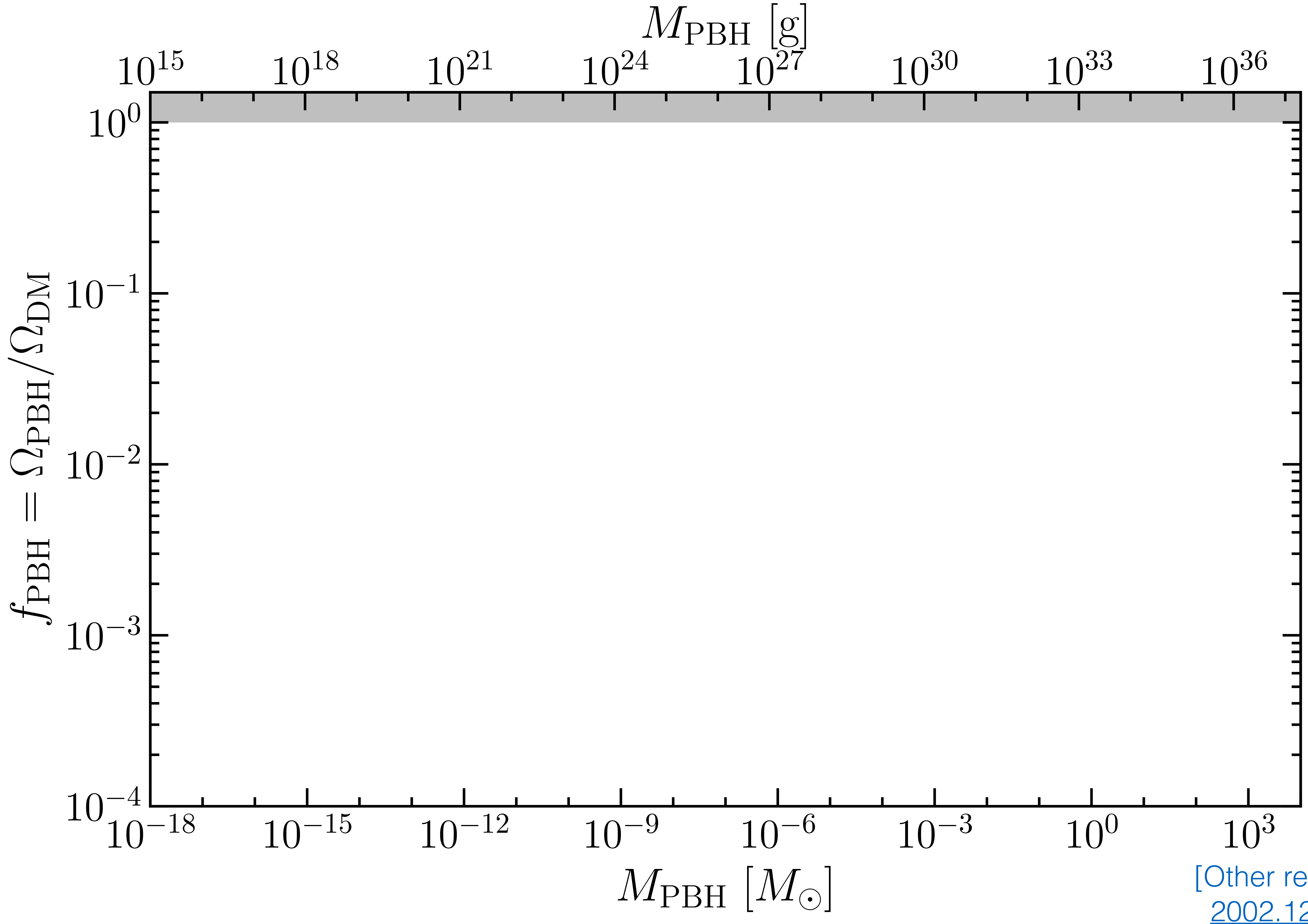
Fluctuations on small scales are poorly constrained! Large enough fluctuations can collapse to form Primordial Black Holes (PBHs).

Note that this would require exotic physics in the early Universe!

PBH Parameter Space

[Green & **BJK**, 2007.10722]

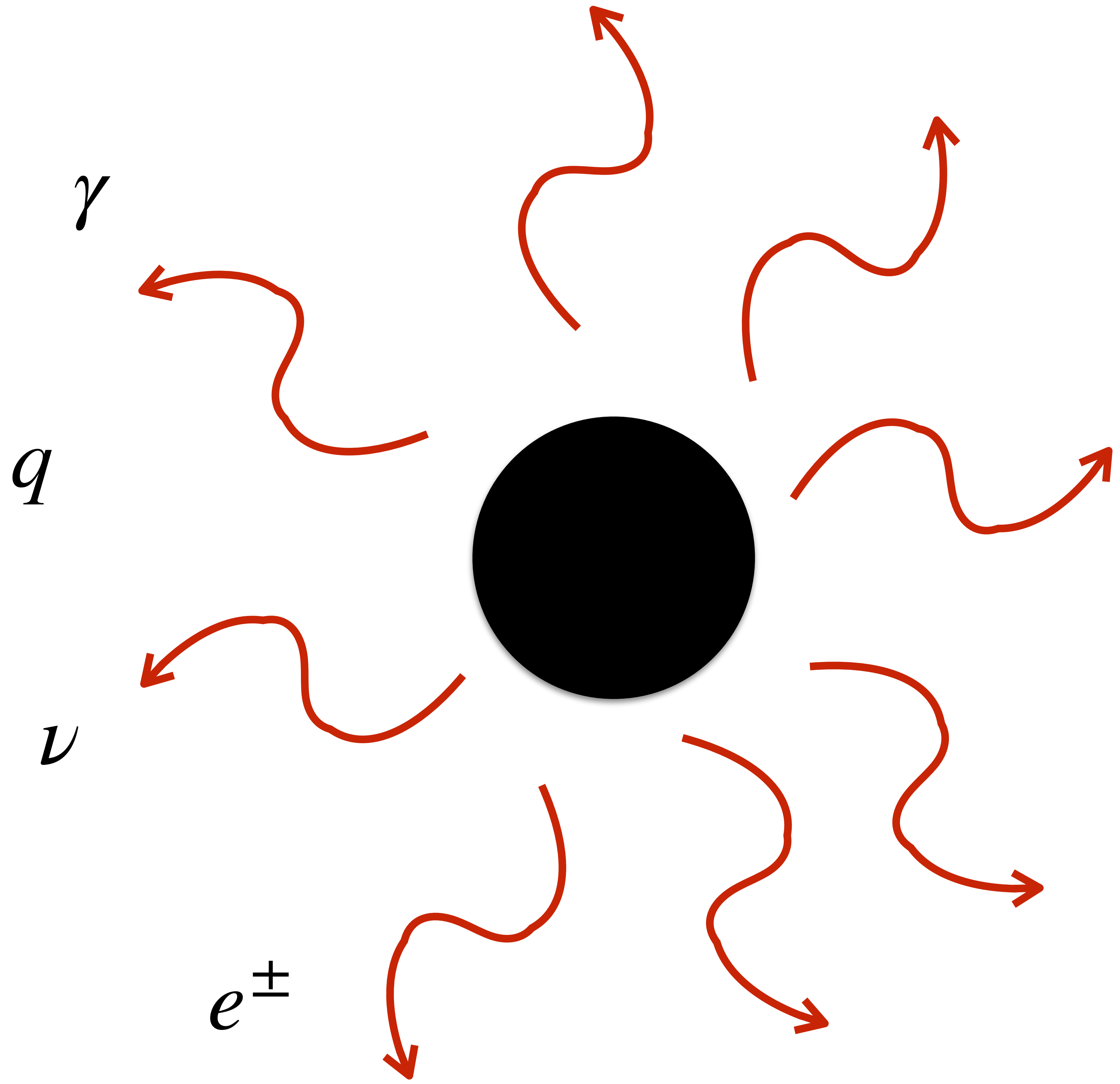
[Code online: github.com/bradkav/PBHbounds]



[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Hawking Evaporation

Black holes *radiate* with a temperature depending on the mass:



$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{\hbar c^4}{G^2}\frac{\alpha}{M^2}$$

BHs lose mass and eventually evaporate with a lifetime:

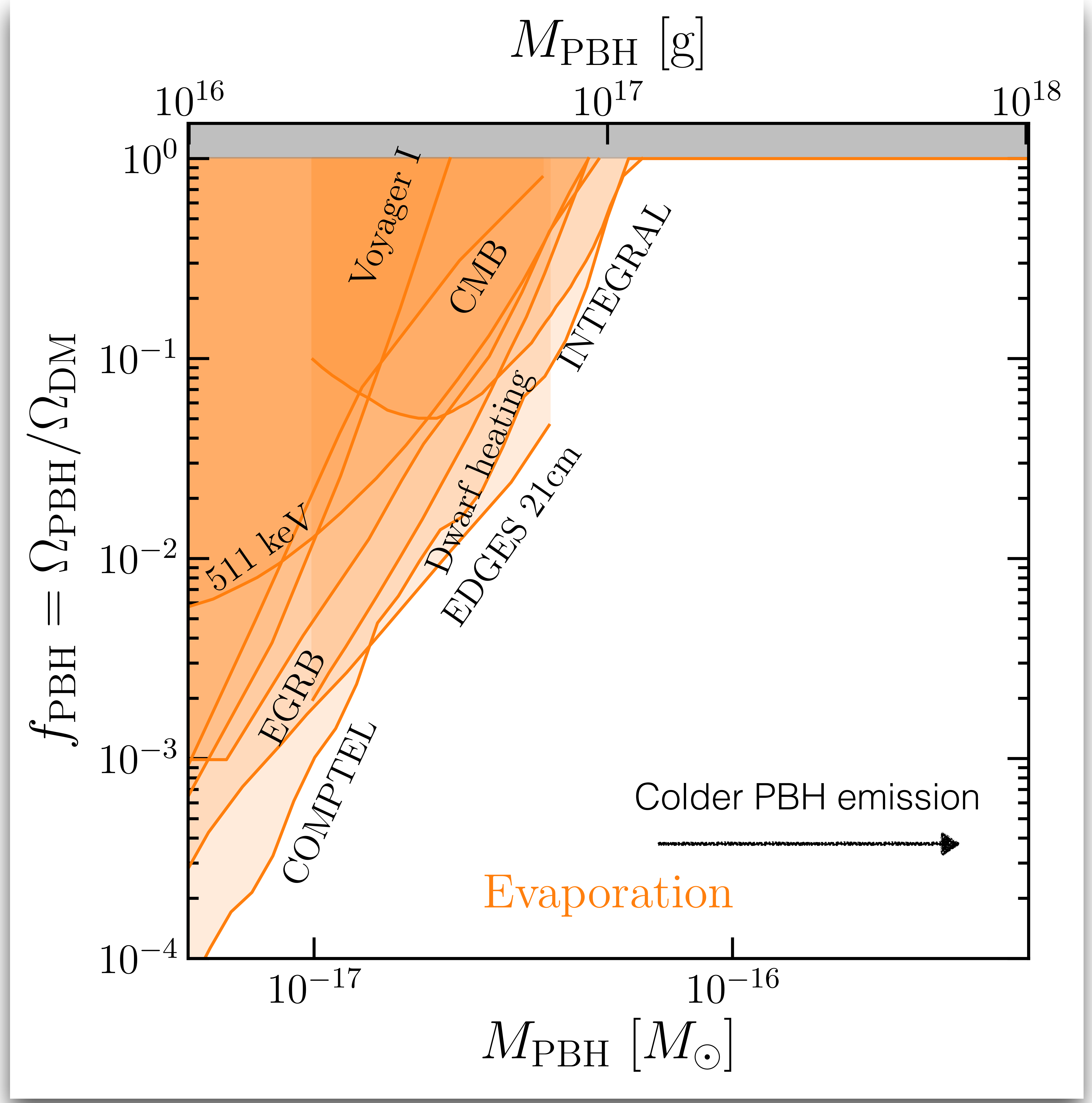
$$\tau(M) \simeq 200\,\tau_U \left(\frac{M}{10^{15}\mathrm{g}}\right)^3$$

Temperature of the Horizon goes as:

$$T_{\mathrm{H}} = \frac{\hbar c^3}{8\pi G k_{\mathrm{B}} M}$$
$$\approx 1\,\mathrm{MeV}\left(\frac{10^{16}\ \mathrm{g}}{M_{\mathrm{PBH}}}\right)$$

[Hawking, Nature (1974);
Carr & Hawking, MNRAS (1974);
Arbey & Auffinger, 1905.04268]

Evaporation Constraints



$$T_{\rm H} = \frac{\hbar c^3}{8\pi G k_{\rm B} M}$$
$$\approx 1\,{\rm MeV}\left(\frac{10^{16}\,{\rm g}}{M_{\rm PBH}}\right)$$

$$\tau(M) \simeq 200\,\tau_U \left(\frac{M}{10^{15}{\rm g}}\right)^3$$

Look for hot PBH emission contributing to X-rays, electron flux and other backgrounds

PBH Parameter Space

[Green & **BJK**, 2007.10722]

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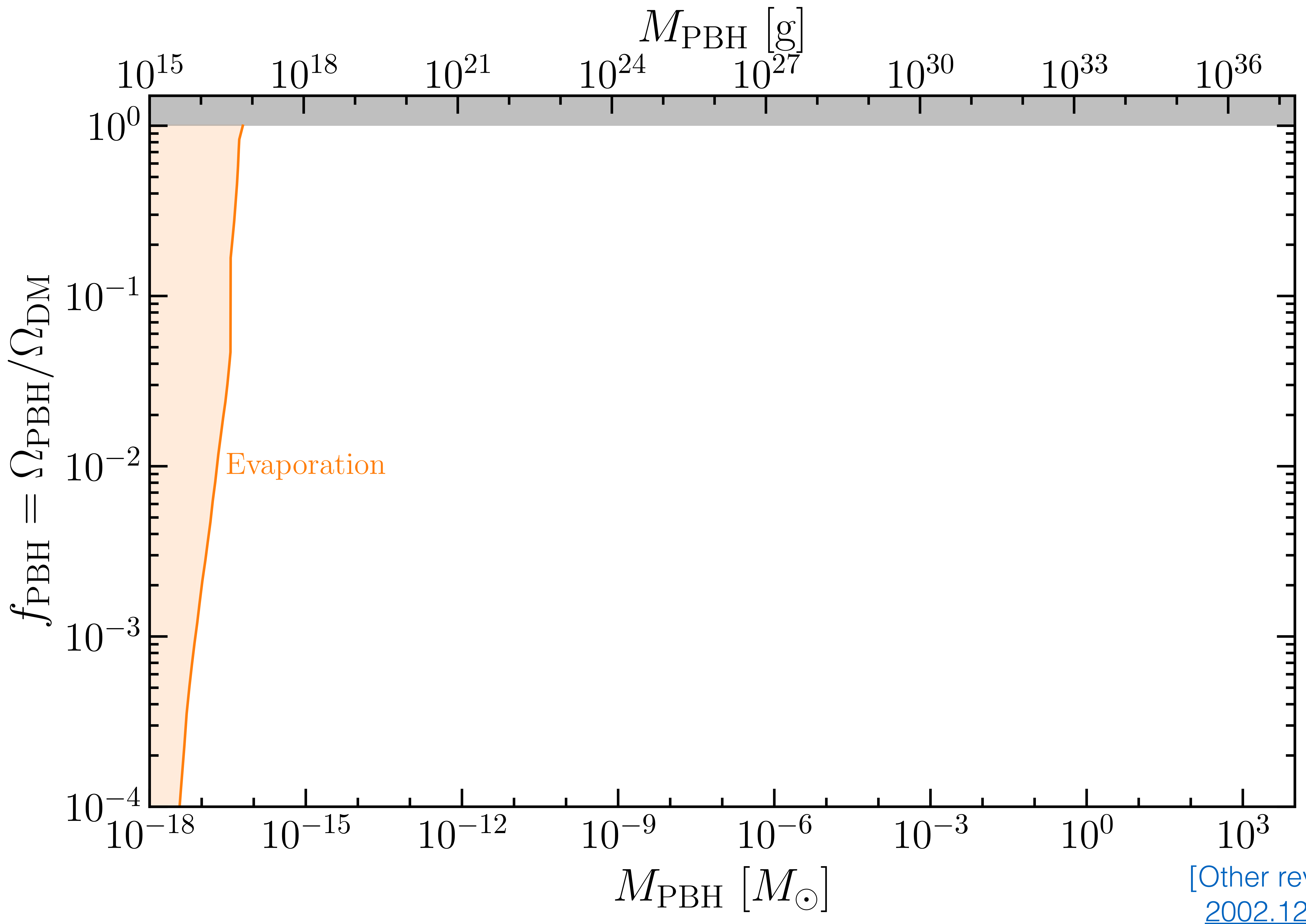
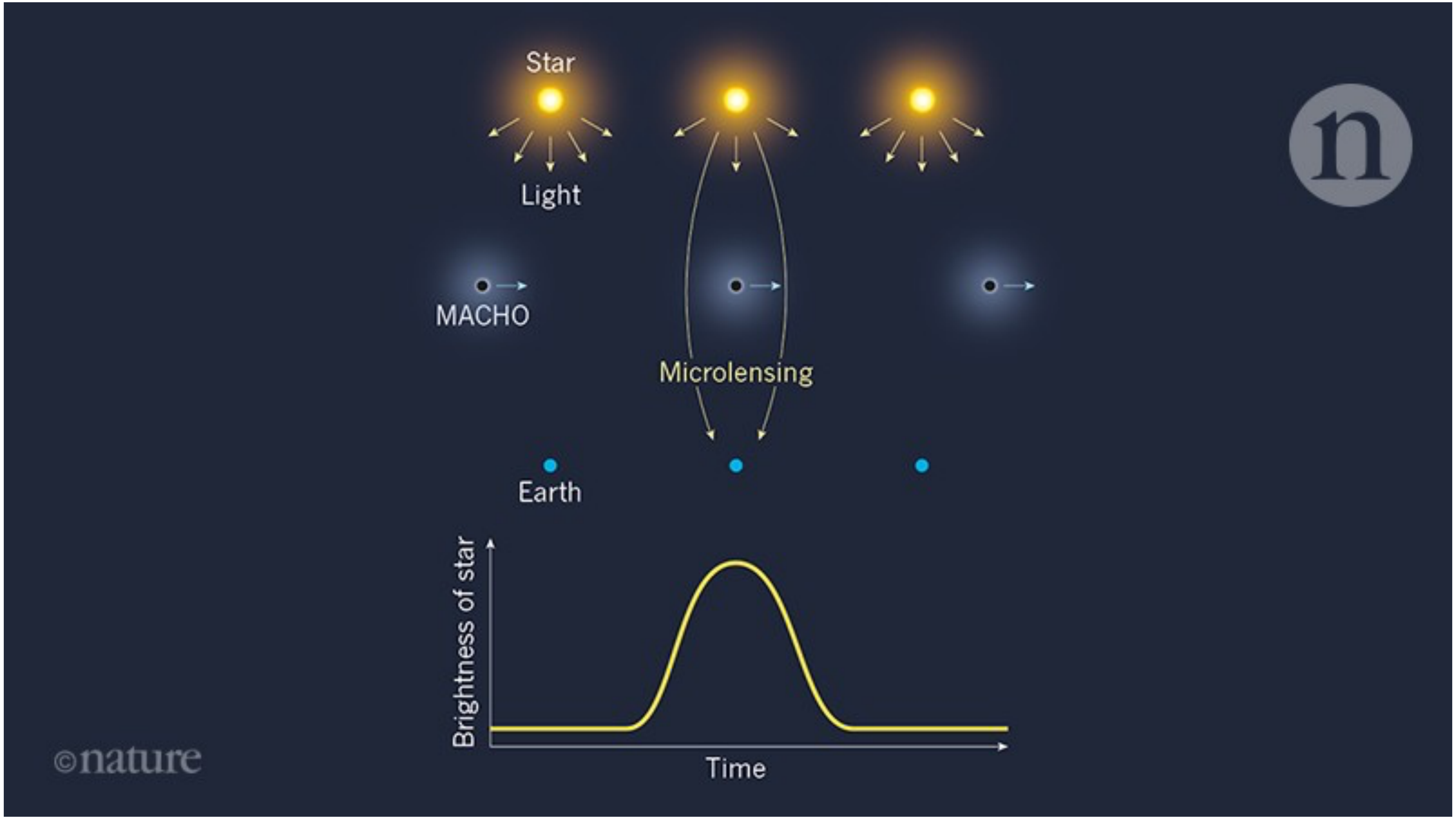


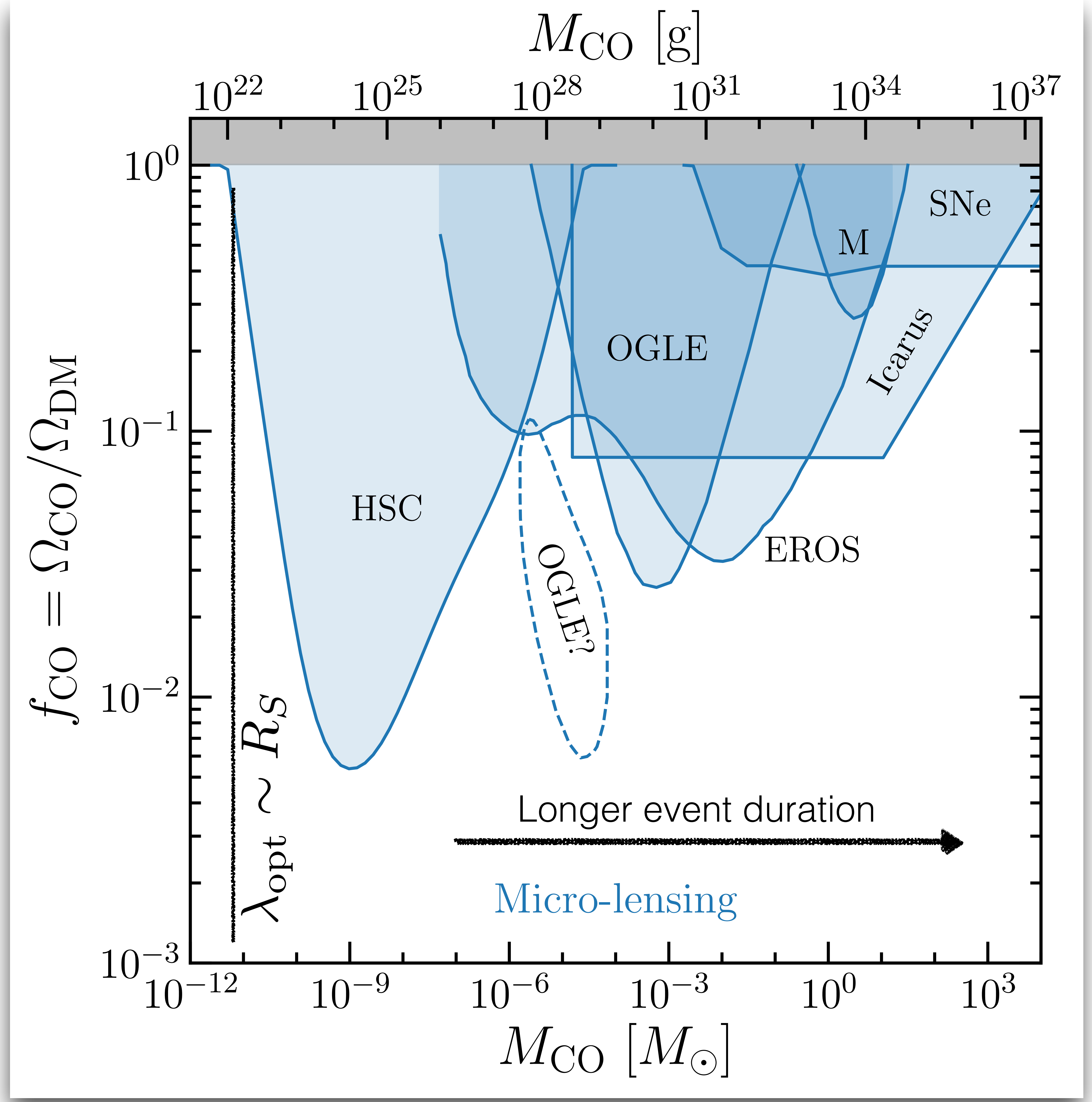
[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Microlensing



$$t_{\rm E} \simeq 44 \text{ days} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{d_{\rm L} d_{\rm LS}/d_{\rm S}}{4\text{kpc}}\right)^{1/2}$$

Microlensing Constraints



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Recently updated at the low mass end

[Smyth et al., 1910.01285, Croon et al., 2007.12697]

Hint from 6 ultra-short events? (t ~ 0.1-0.3 days)

[OGLE, 1901.07120]

ICARUS! A star at z ~ 1.5

[Kelly et al., 1706.10279, Oguri et al., 1710.00148]

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[Green & **BJK**, 2007.10722]

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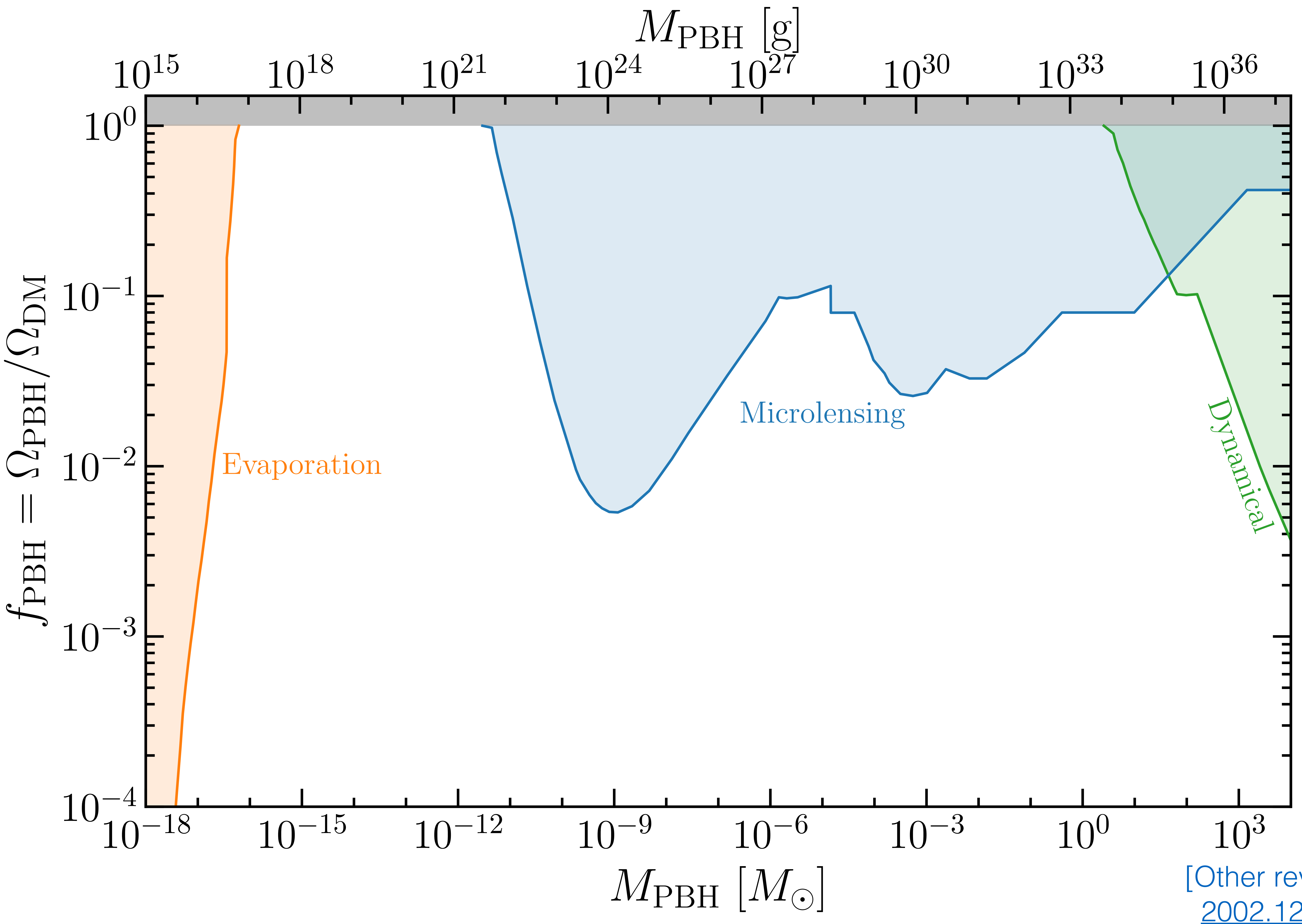
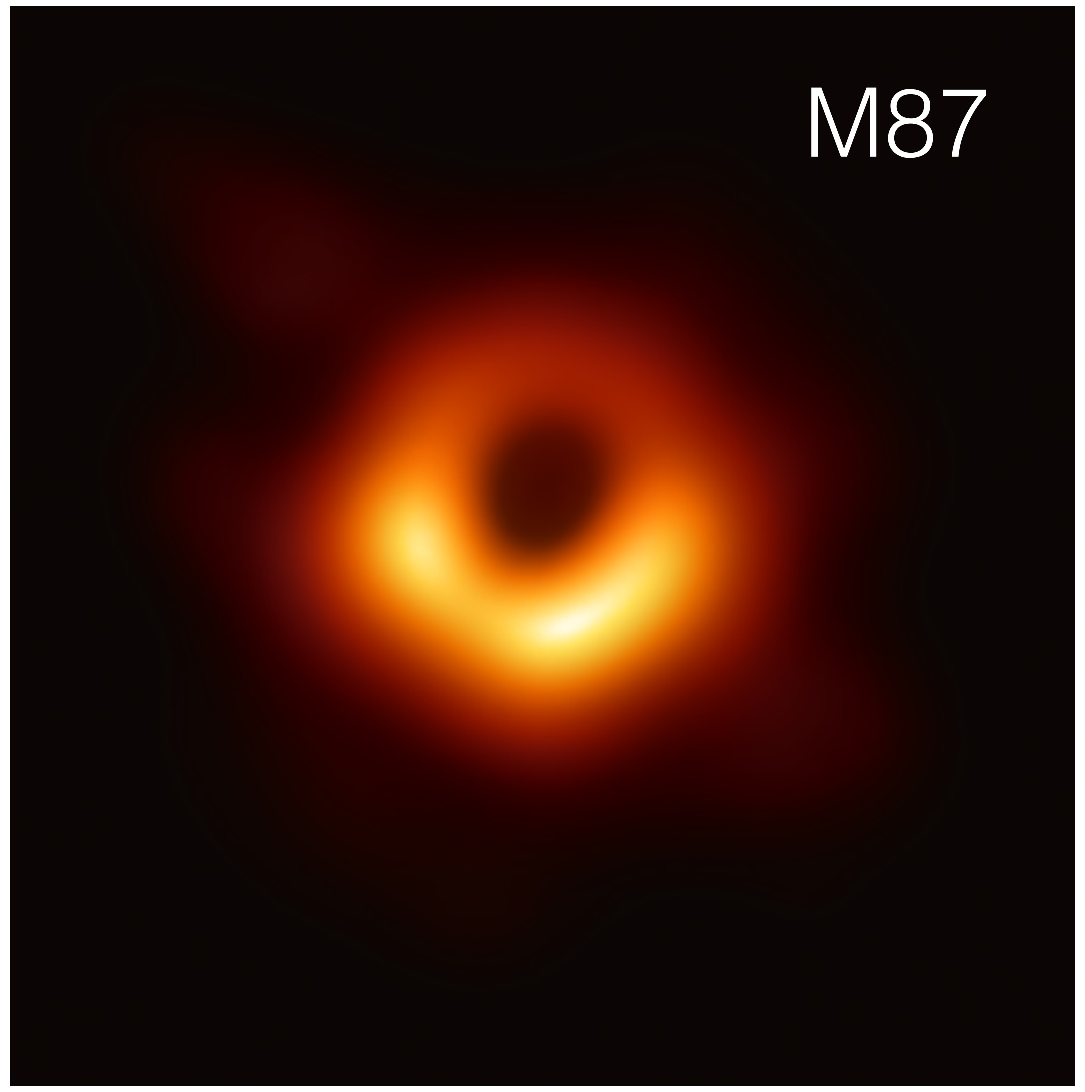


[Other reviews: 1801.05235, 2002.12778, 2006.02838]

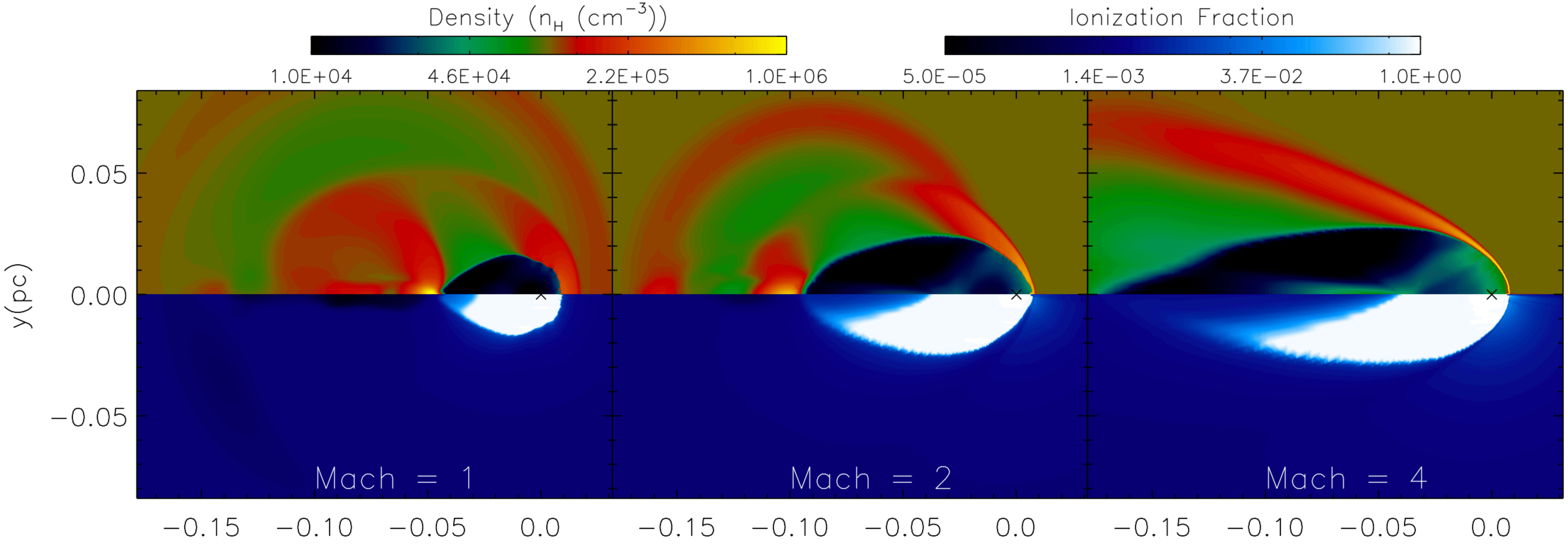
Accretion

Primordial Black Holes can accrete surrounding gas,
forming an accretion disk which heats up and emits radiation

$$\dot{M} \equiv 4\pi \left(G M_{\mathrm{BH}}\right)^2 \rho \left(v^2 + c_{\mathrm{s}}^2\right)^{-3/2}$$

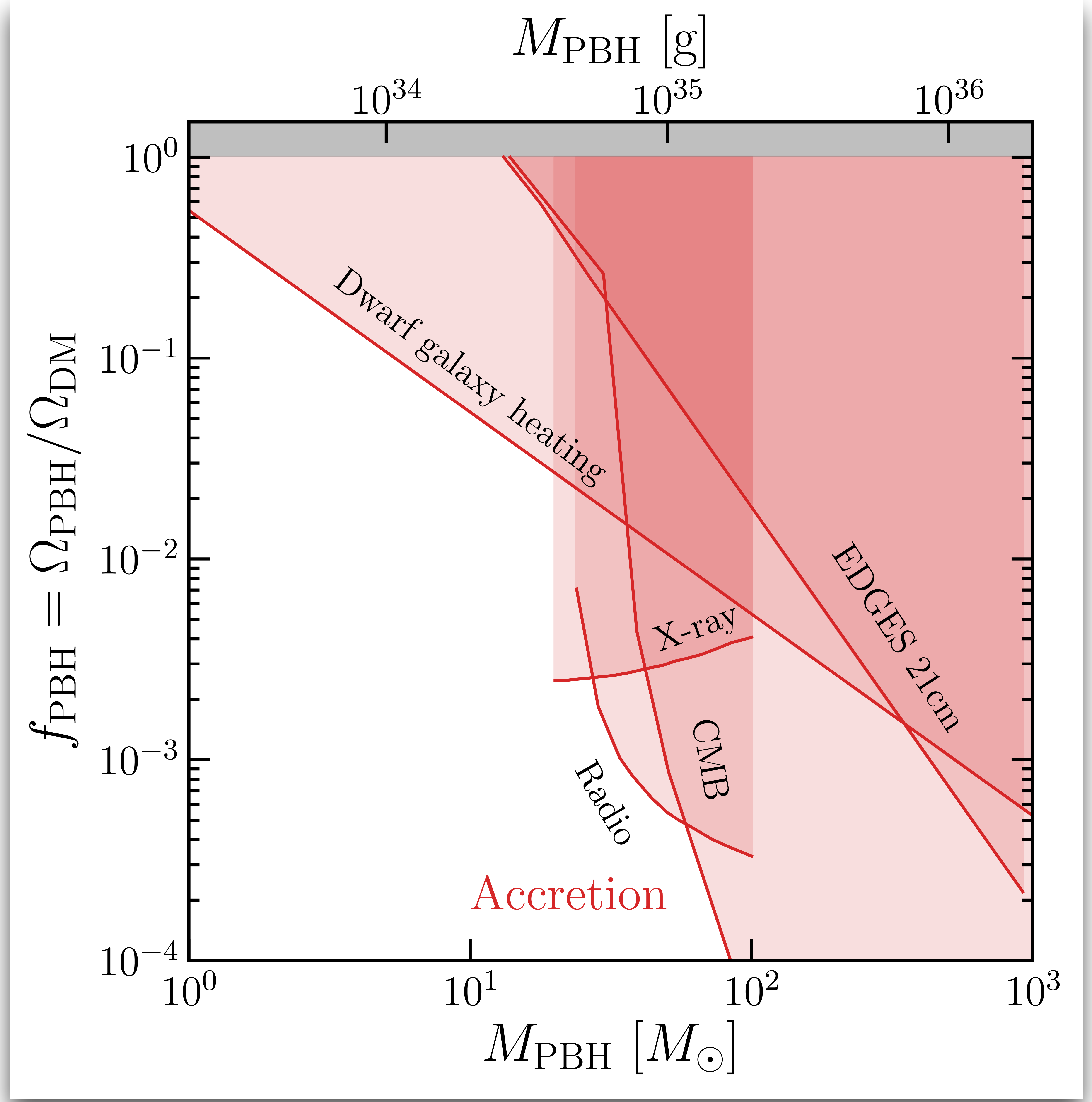


[Event Horizon Telescope, 1906.11241]



[Park & Ricotti, 1211.0542]

Accretion Constraints



Emission due to accretion can be relevant at early and late times

Large uncertainties due to accretion model

[E.g. Manshanden et al., 1812.07967]

CMB bounds now on solid ground (and getting stronger)

[Serpico et al., 2002.10771]

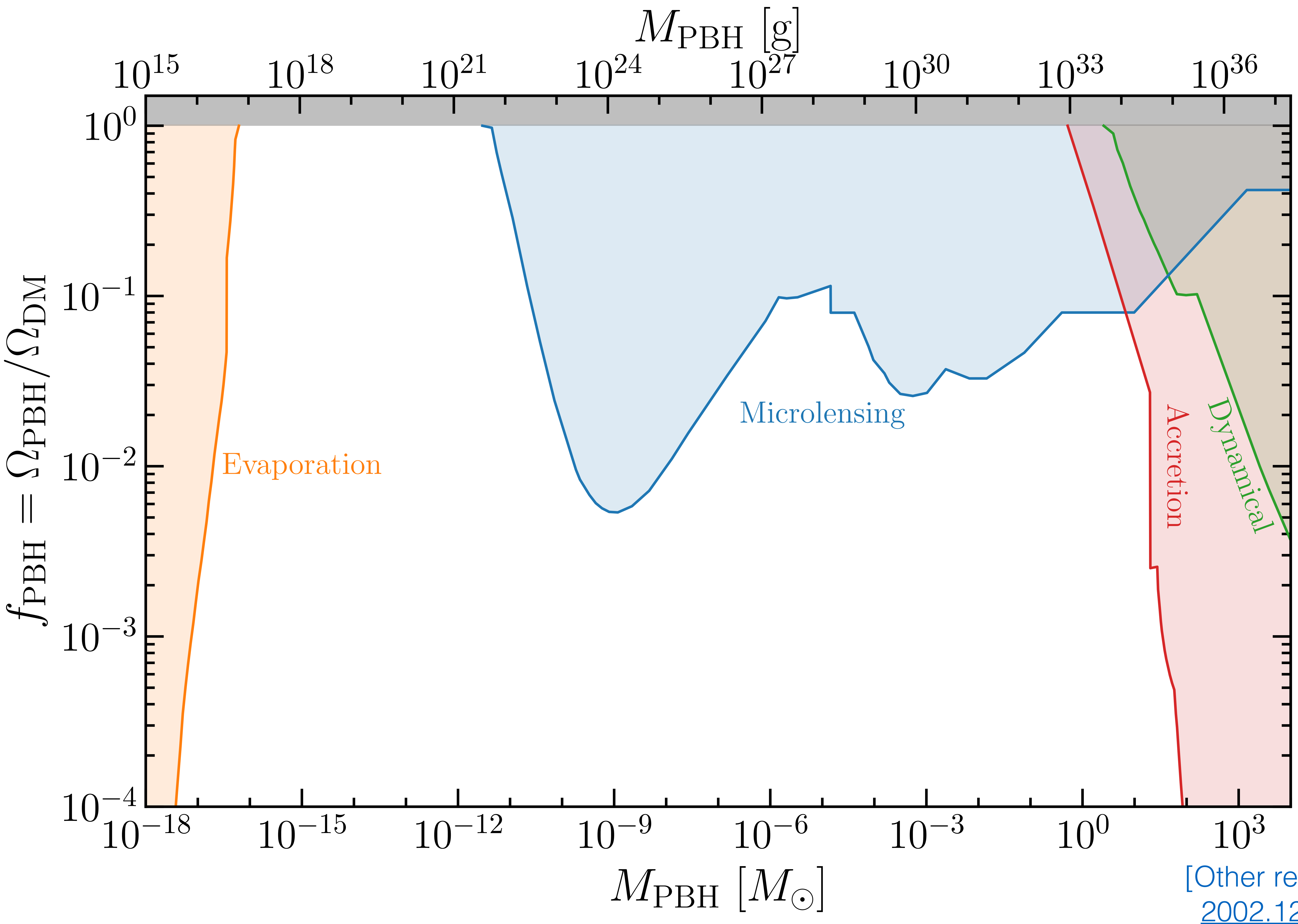
New bounds from gas heating in Leo T dwarf

[Lu et al., 2007.02213]

PBH Parameter Space

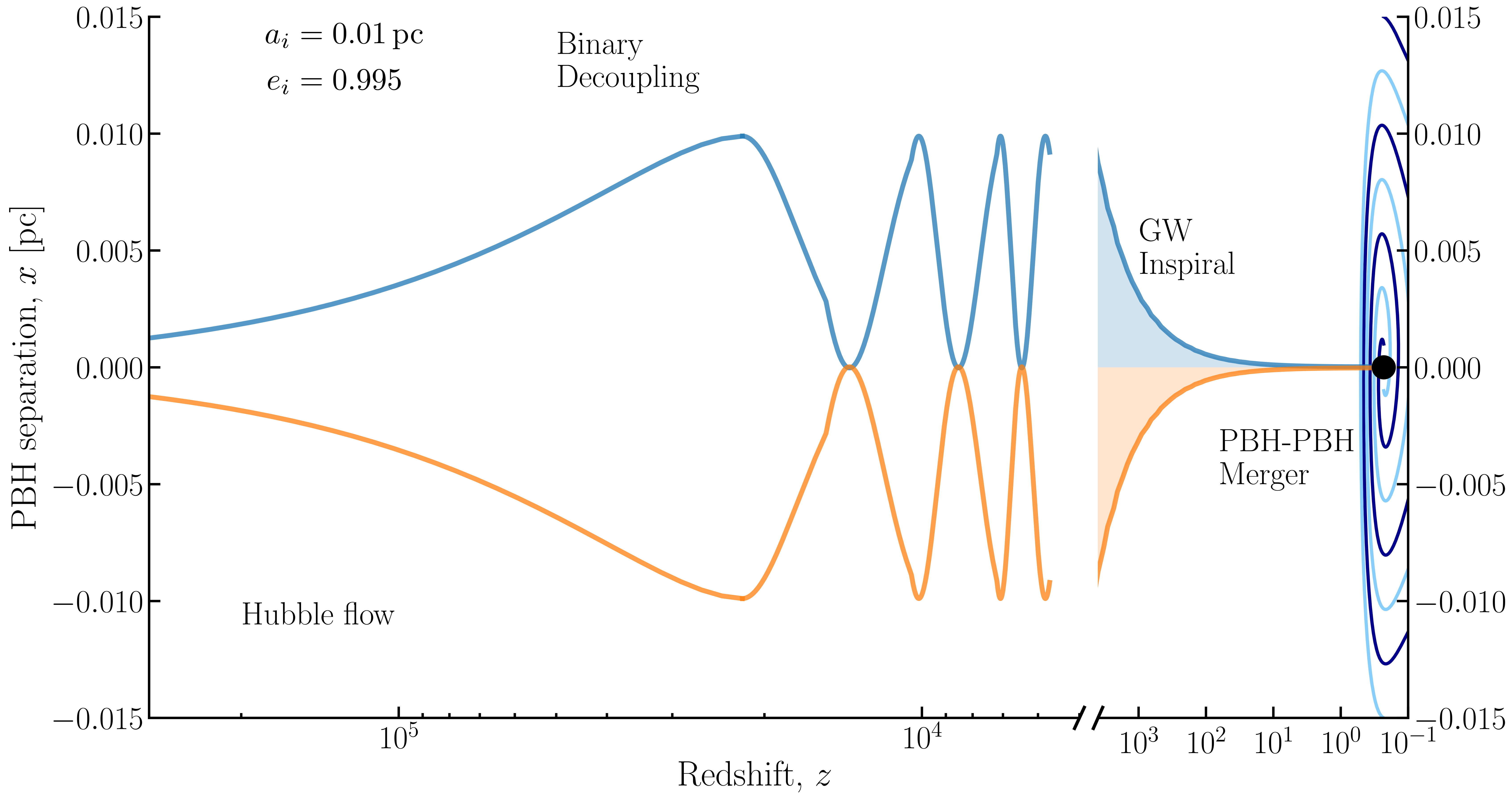
[Green & **BJK**, 2007.10722]

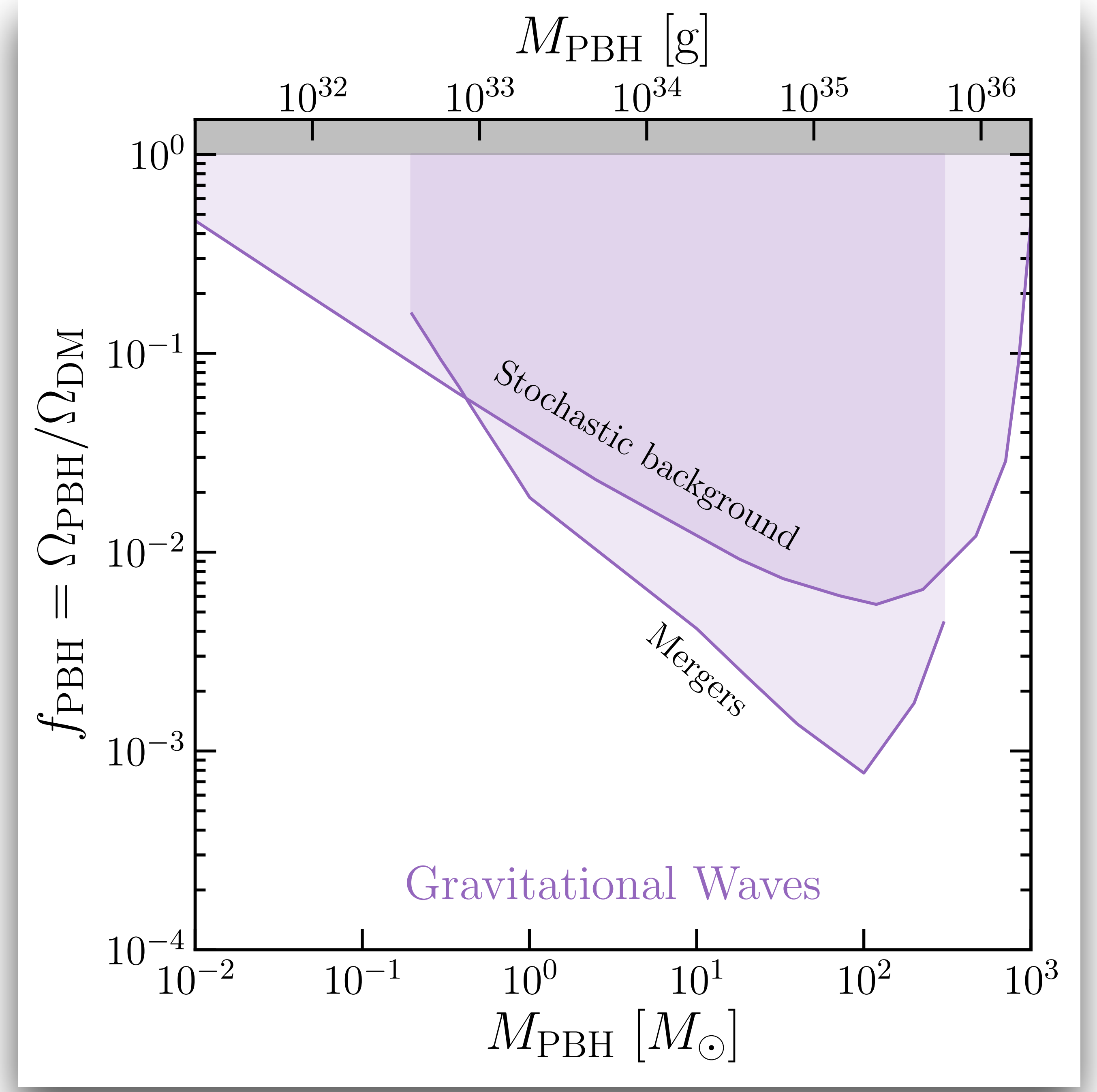
[Code online: github.com/bradkav/PBHbounds]



[Other reviews: 1801.05235, 2002.12778, 2006.02838]

PBHs and Gravitational Waves





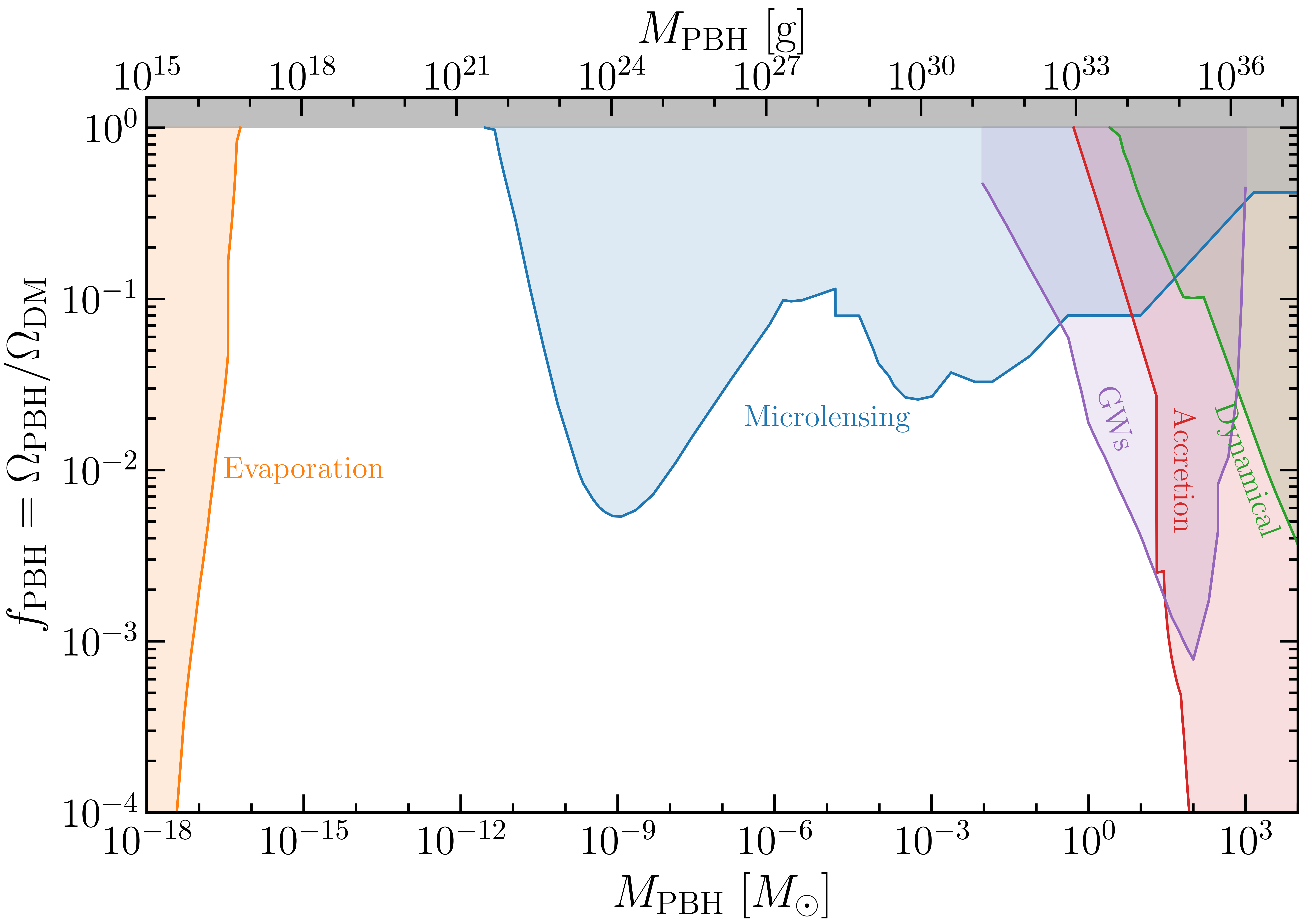
Could PBHs contribute to the population of BHs seen by LIGO?

See Gravitational Wave Lectures

Primordial Black Holes

2007.10722

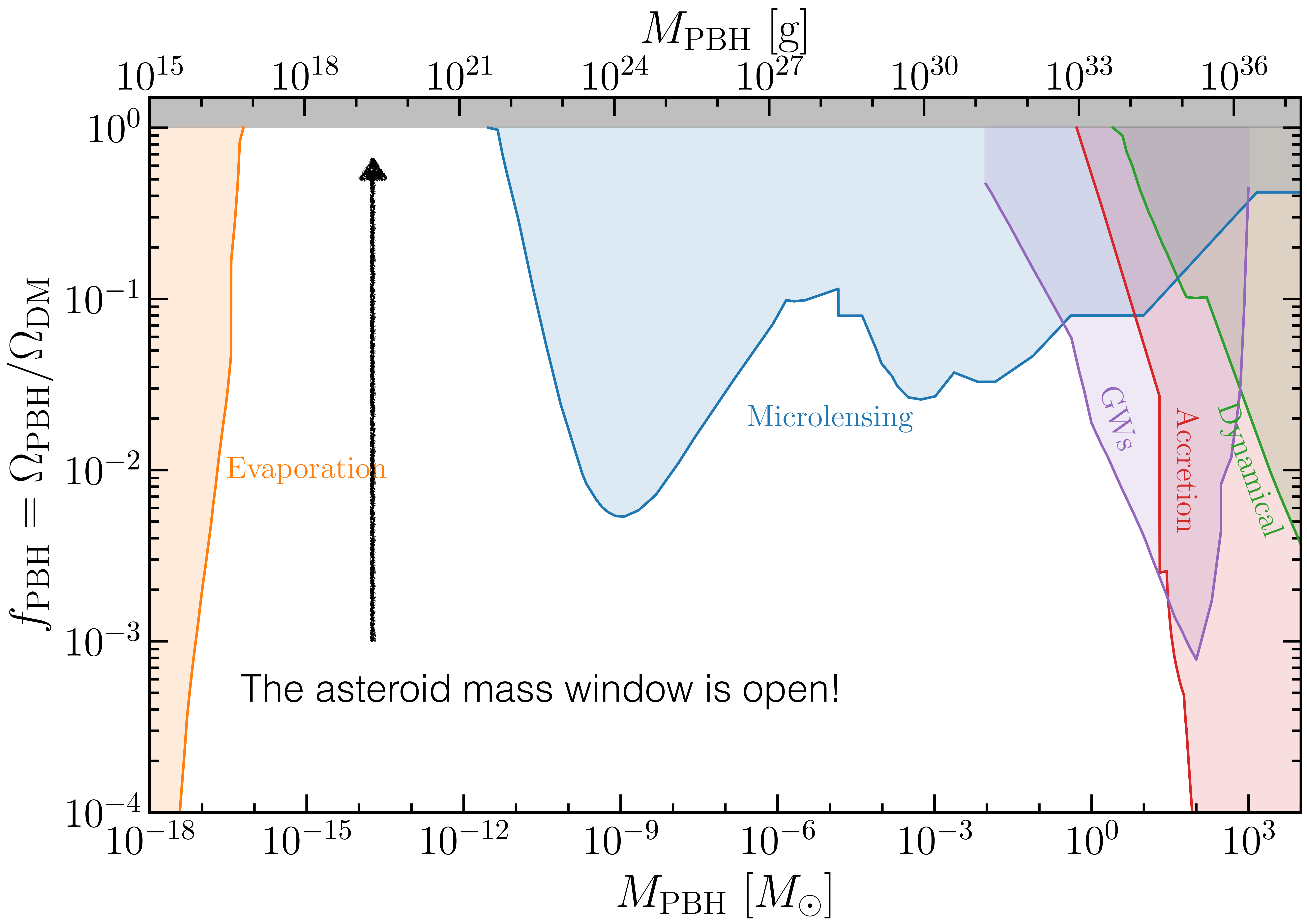
Bounds online



Primordial Black Holes

[2007.10722](2007.10722)

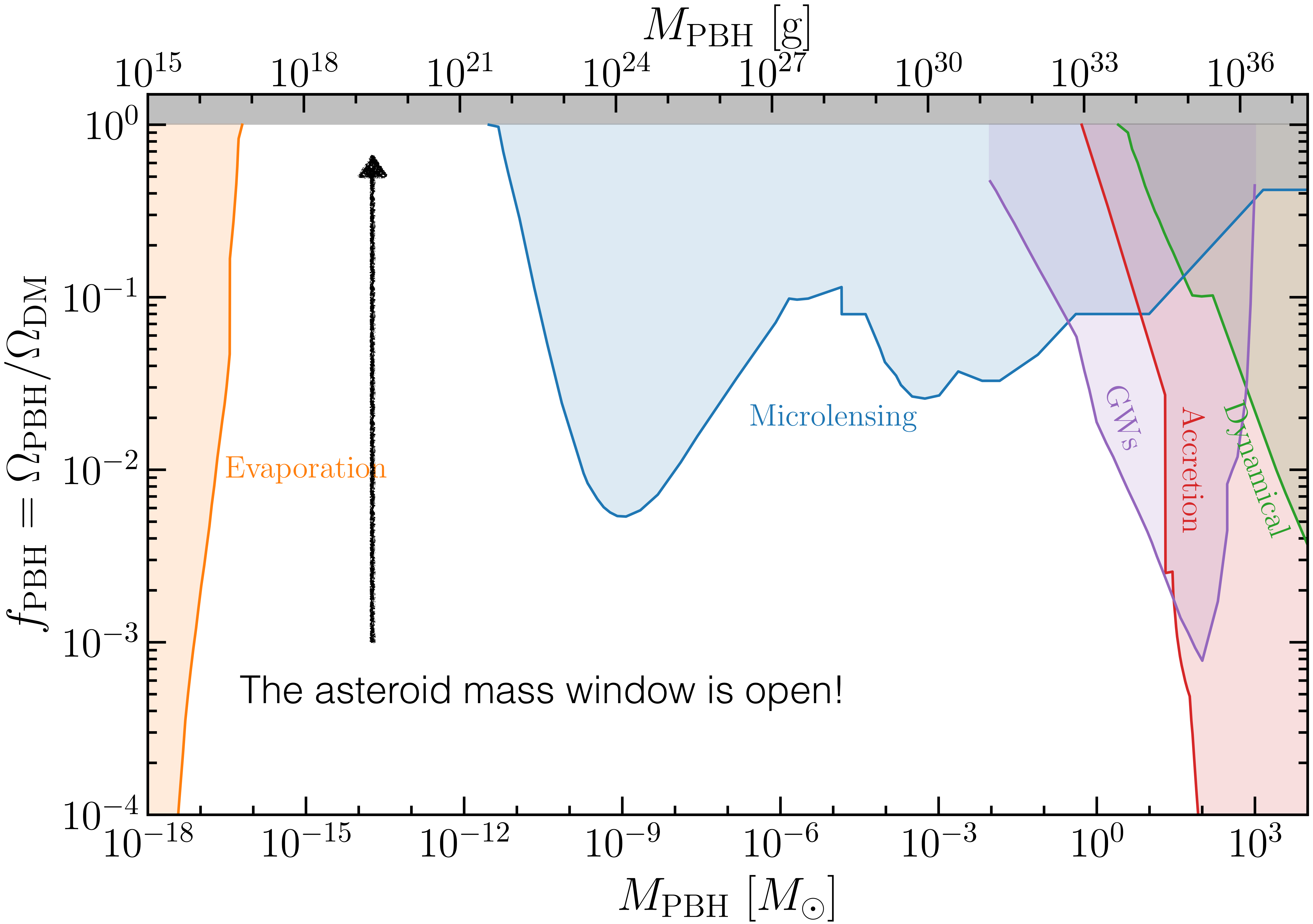
Bounds online



Primordial Black Holes

2007.10722

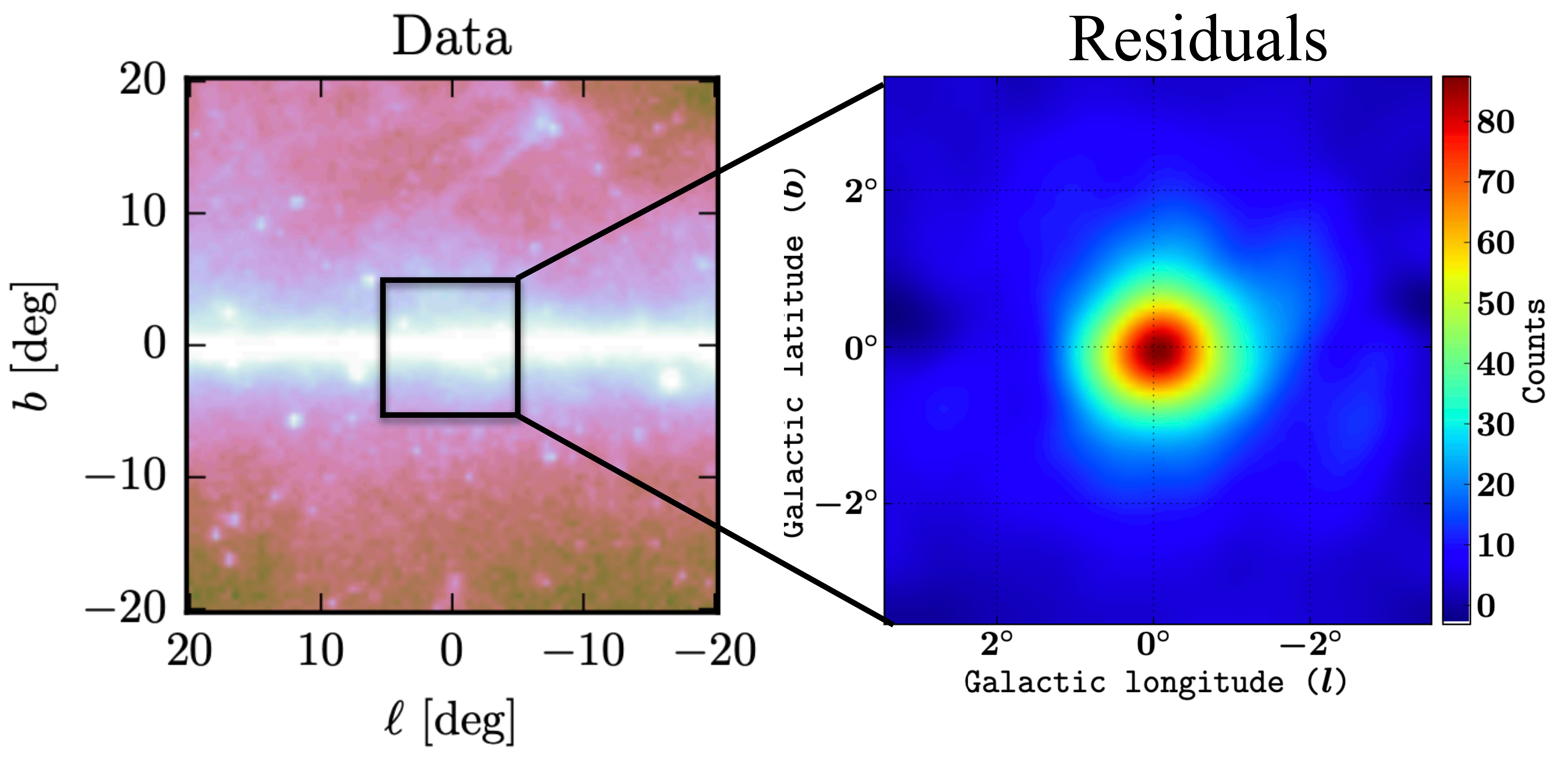
Bounds online



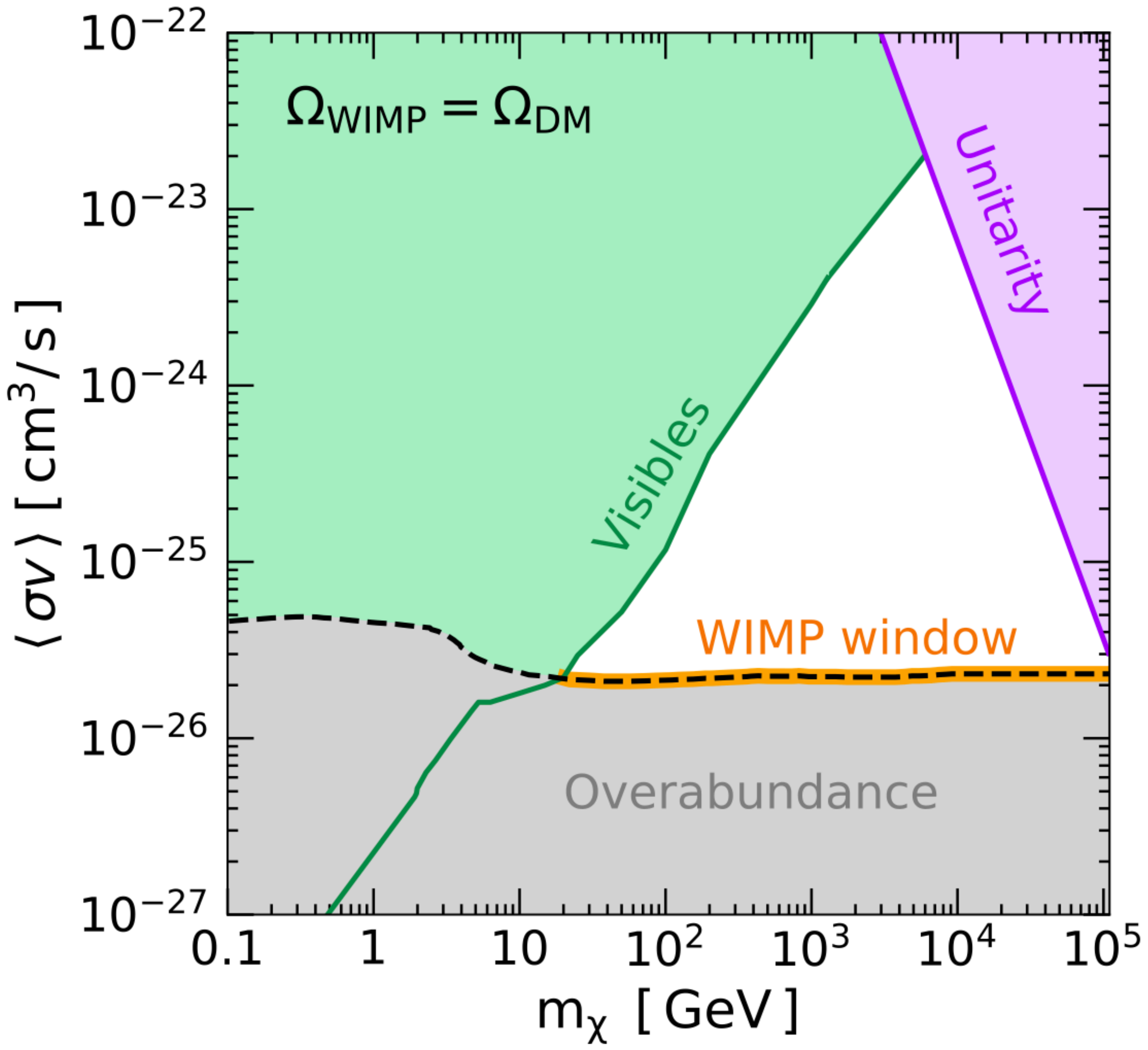
PBHs are alive and well!

Summary

Excesses in Gamma rays and cosmic rays perhaps point towards a 50-60 GeV WIMP. But these are ‘messy’ channels with complicated backgrounds.



Tension with constraints from ‘clean’ searches in Dwarf Galaxies. **We continue to narrow down the parameter space of the thermal WIMP.**

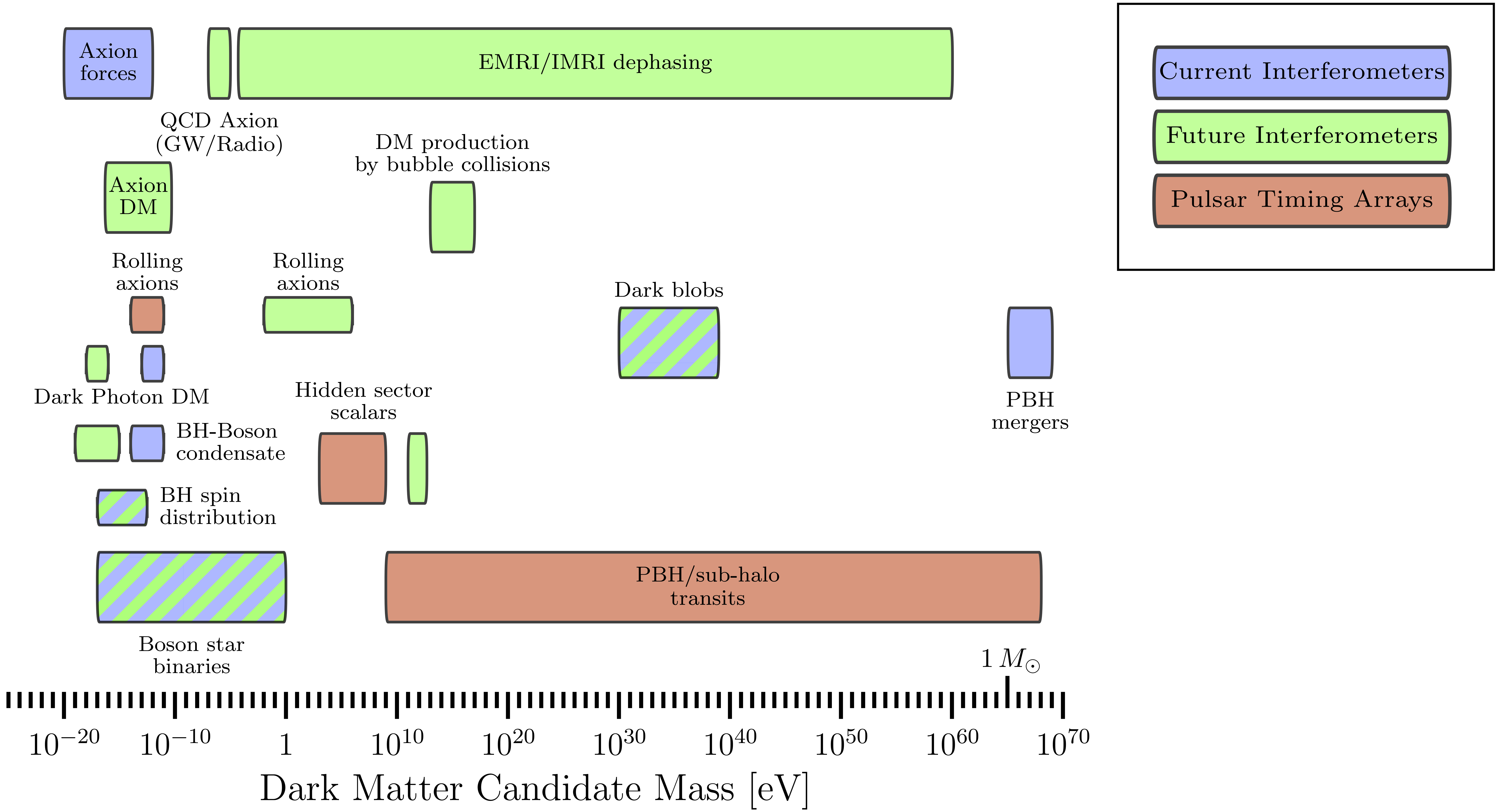


Ultimately, clear connection between production mechanisms (e.g. Freeze-out) and DM annihilation is a strength of indirect DM searches. But astrophysics is **hard**.

We’ve only scratched the surface! Looking out at the early and late Universe tells us about the properties of a huge number of DM candidates: Primordial Black Holes, axions, sterile neutrinos, …

Additional Slides

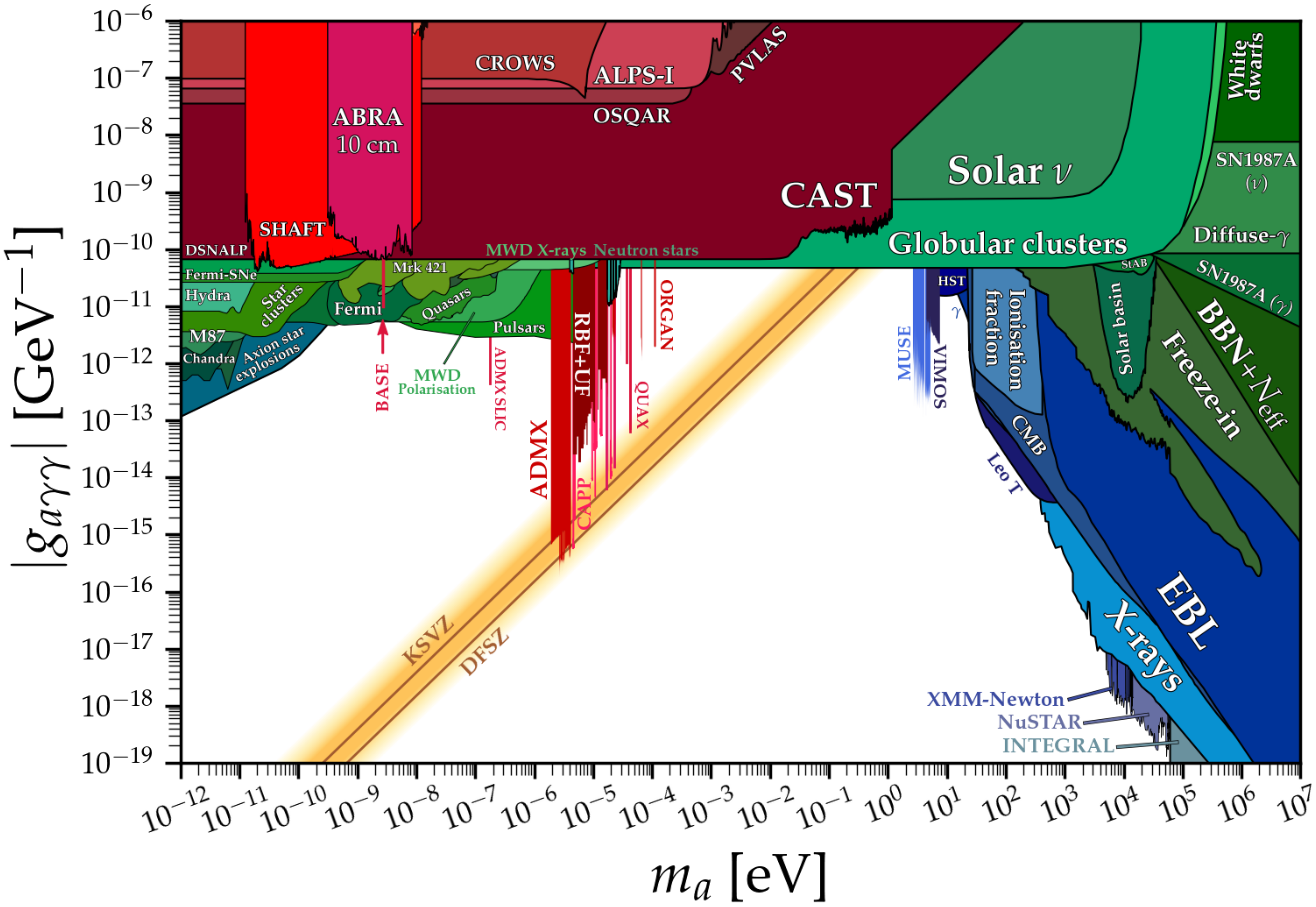
Gravitational Waves and Dark Matter



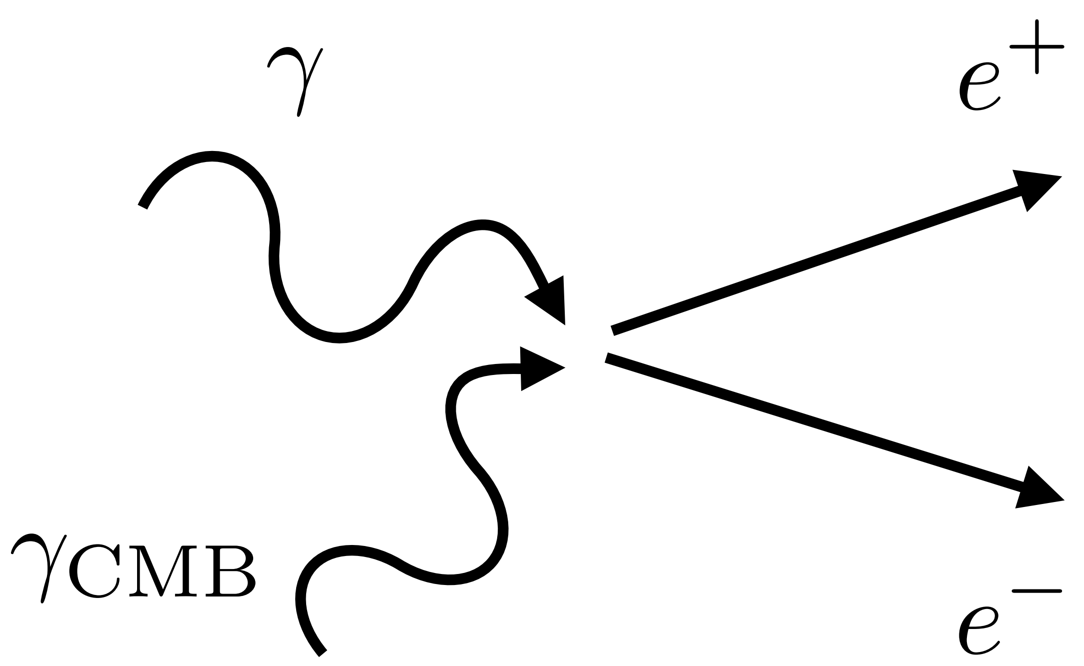
For more information about probing Dark Matter with Gravitational Waves, see 1907.10610

Constraints on the Axions

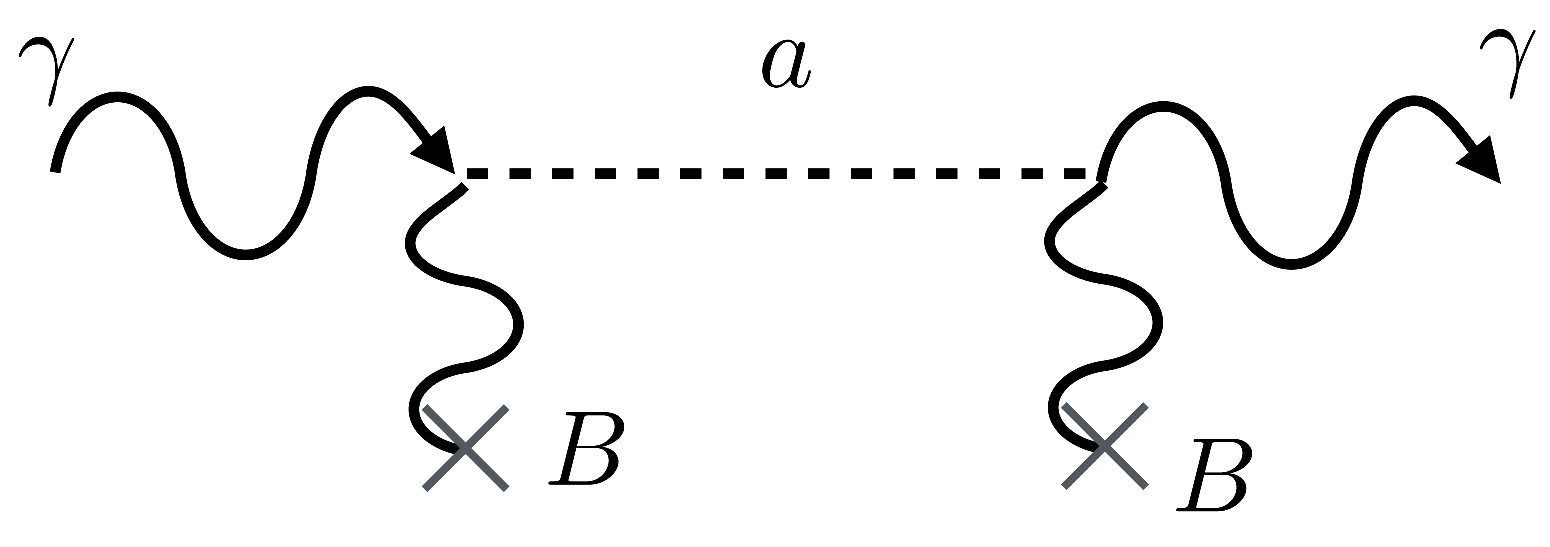
[https://cajohare.github.io/]

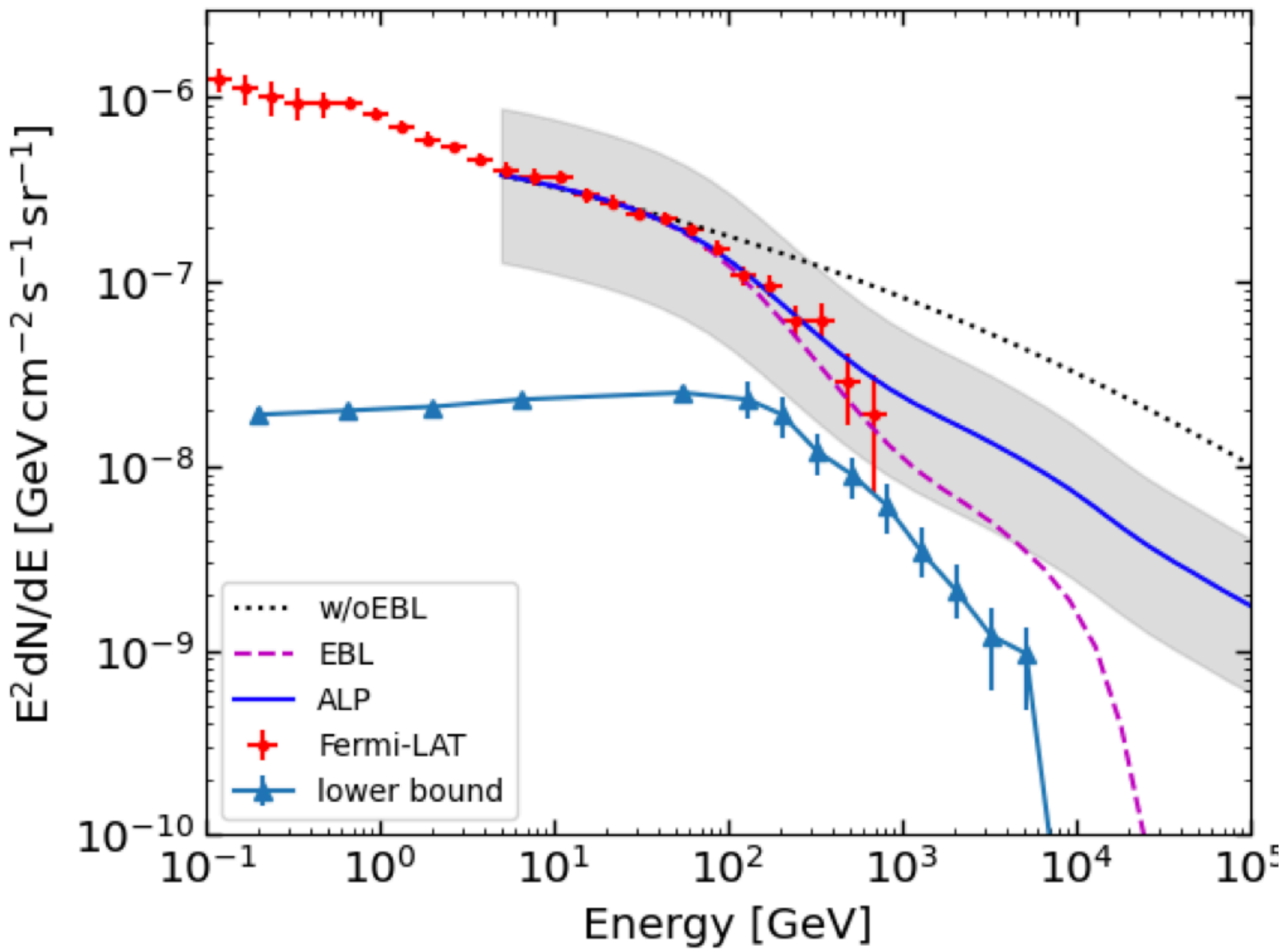


Gamma-ray transparency and axions

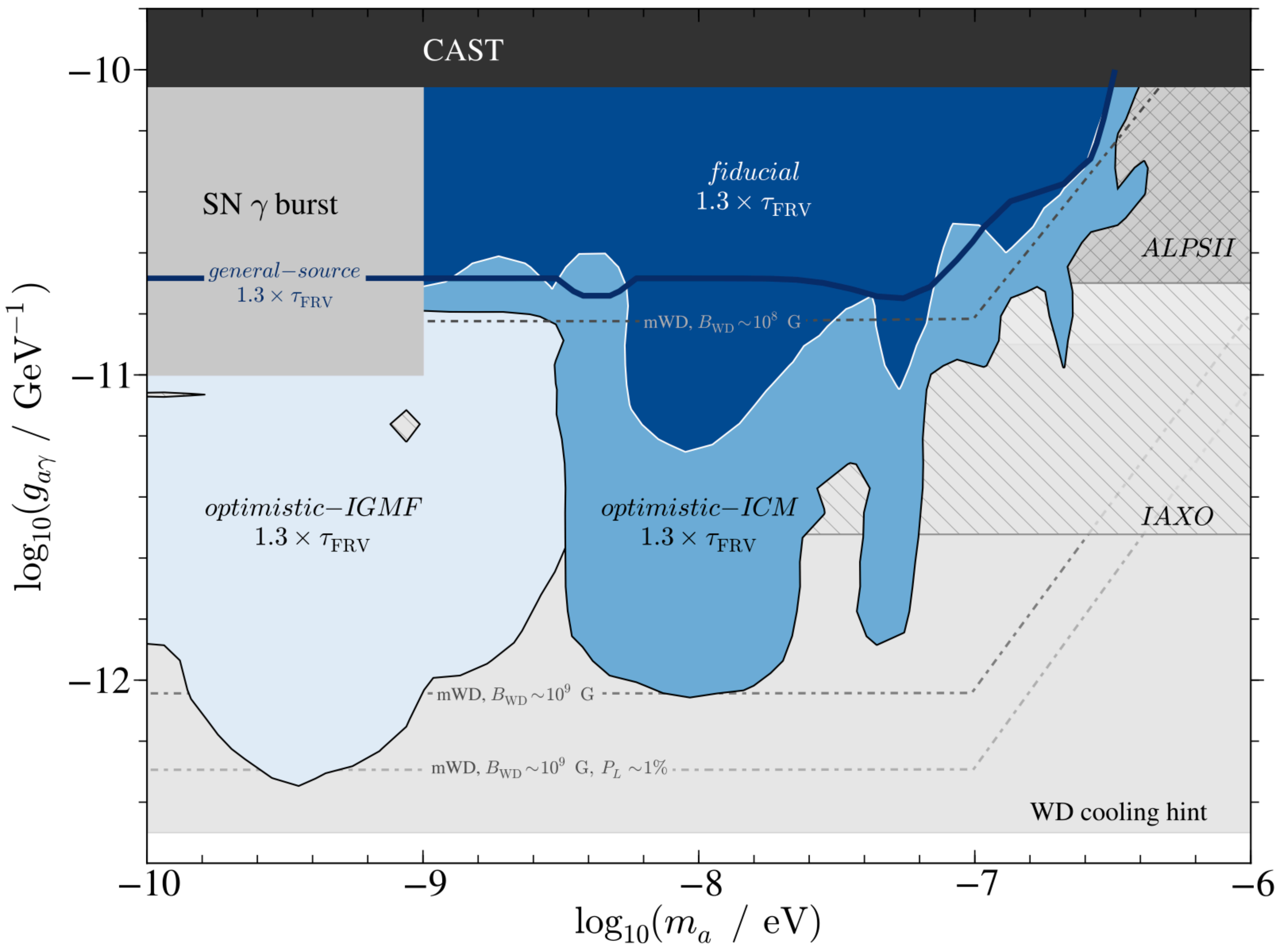


Axion-like particle:





[2012.15513](2012.15513)

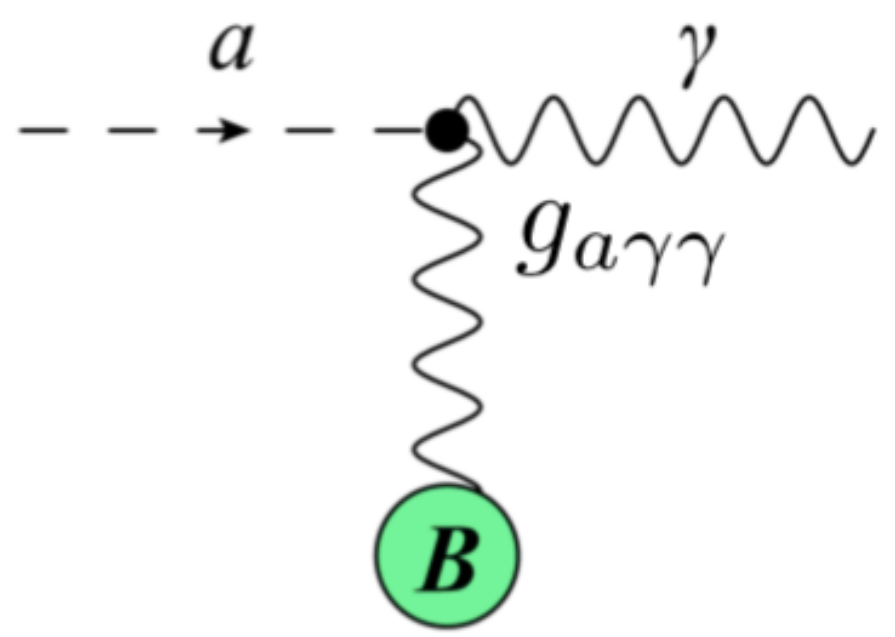


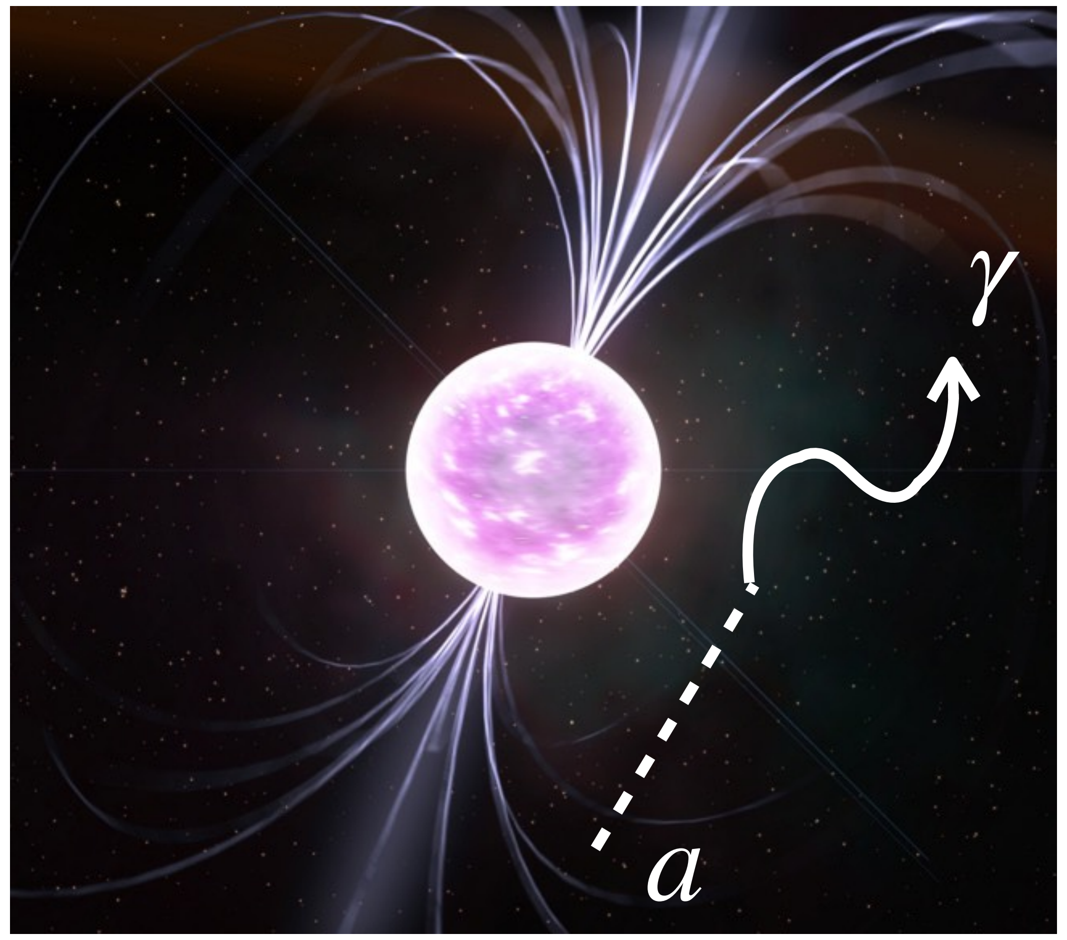
[1302.1208](1302.1208)

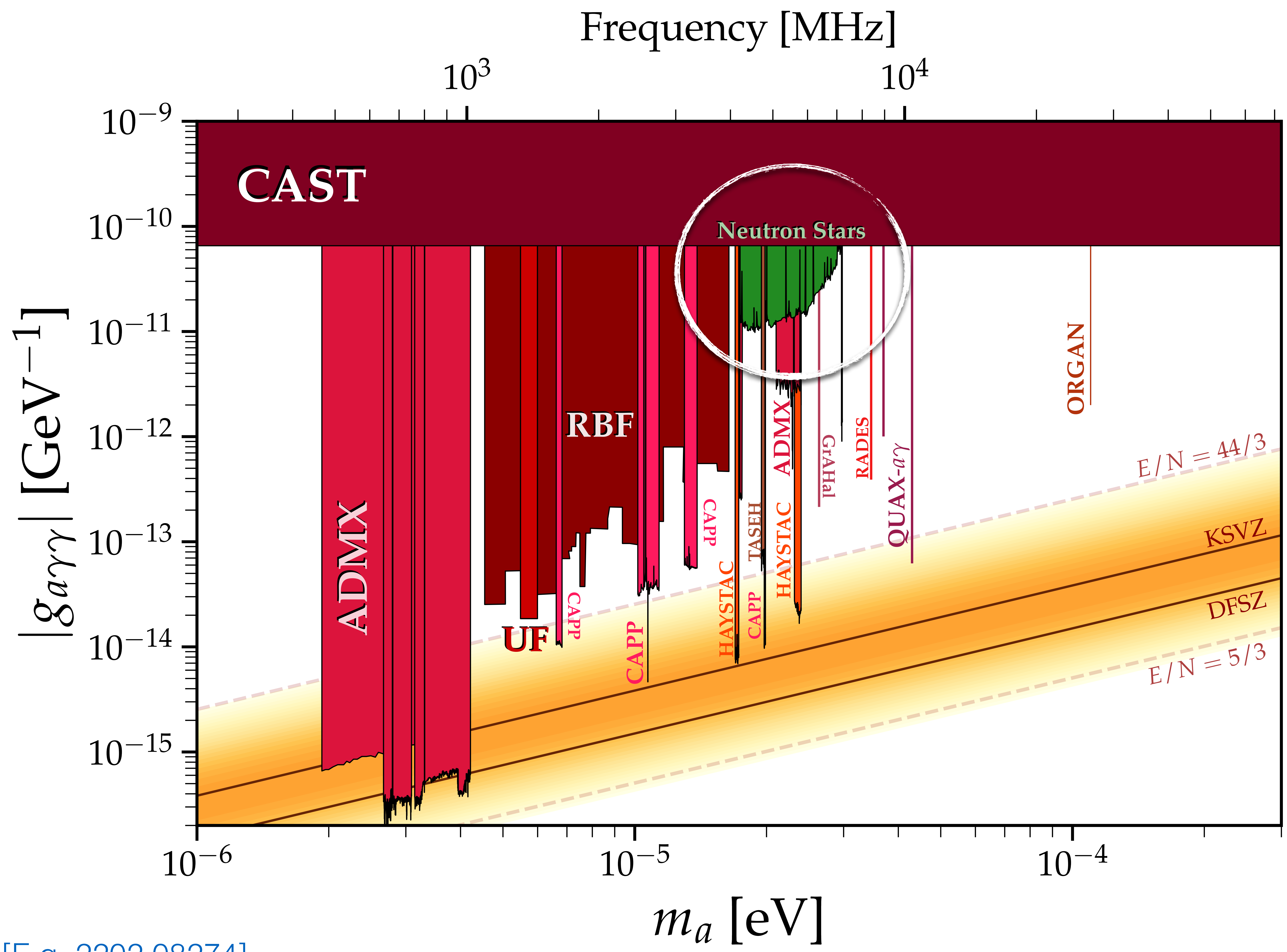
Axion searches and Neutron Stars

Axions: light pseudoscalar particles, a

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







[E.g. 2202.08274]

Credit: Ciaran O'Hare, AxionLimits