Dark matter:
Status and prospects

XLIX International Meeting of Fundamental Physics
Benasque, 07/09/2022

Francesca Calore (CNRS/LAPTh)

Dark matter: *indirect probes*
Status and prospects

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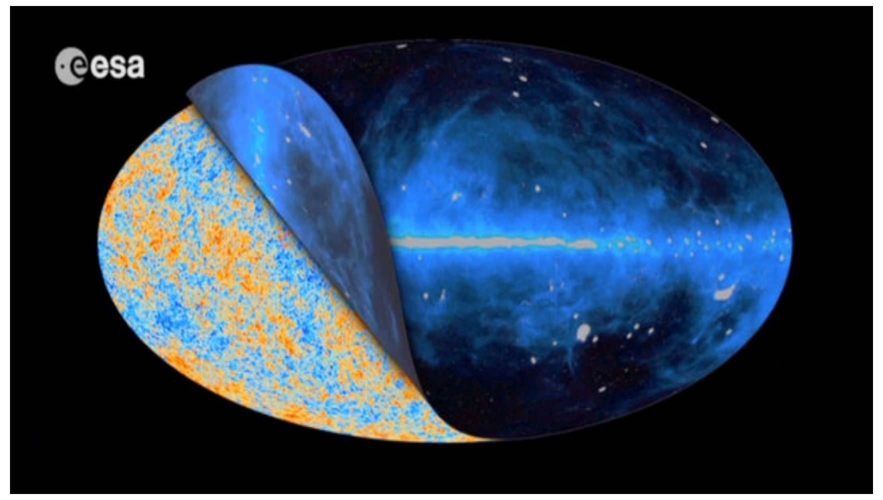
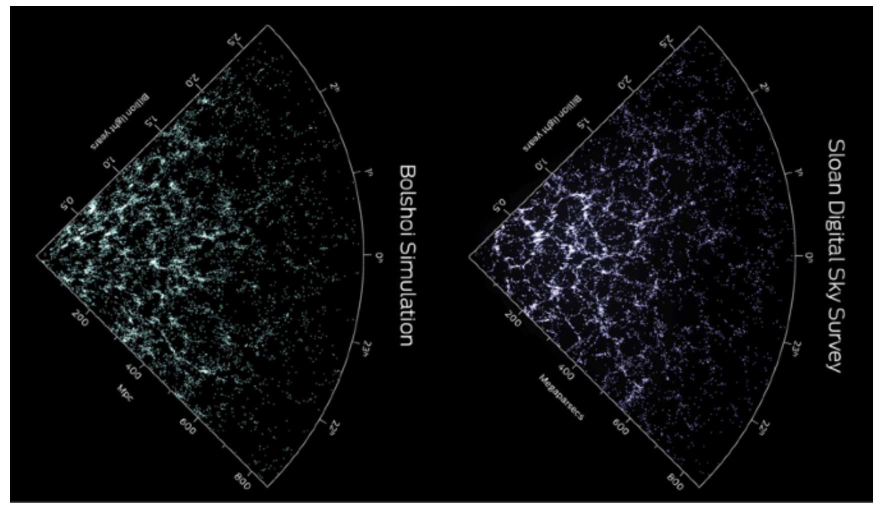
Dark matter gravitational evidence

Cosmic microwave background



Large Scale Structures



Galaxy clusters

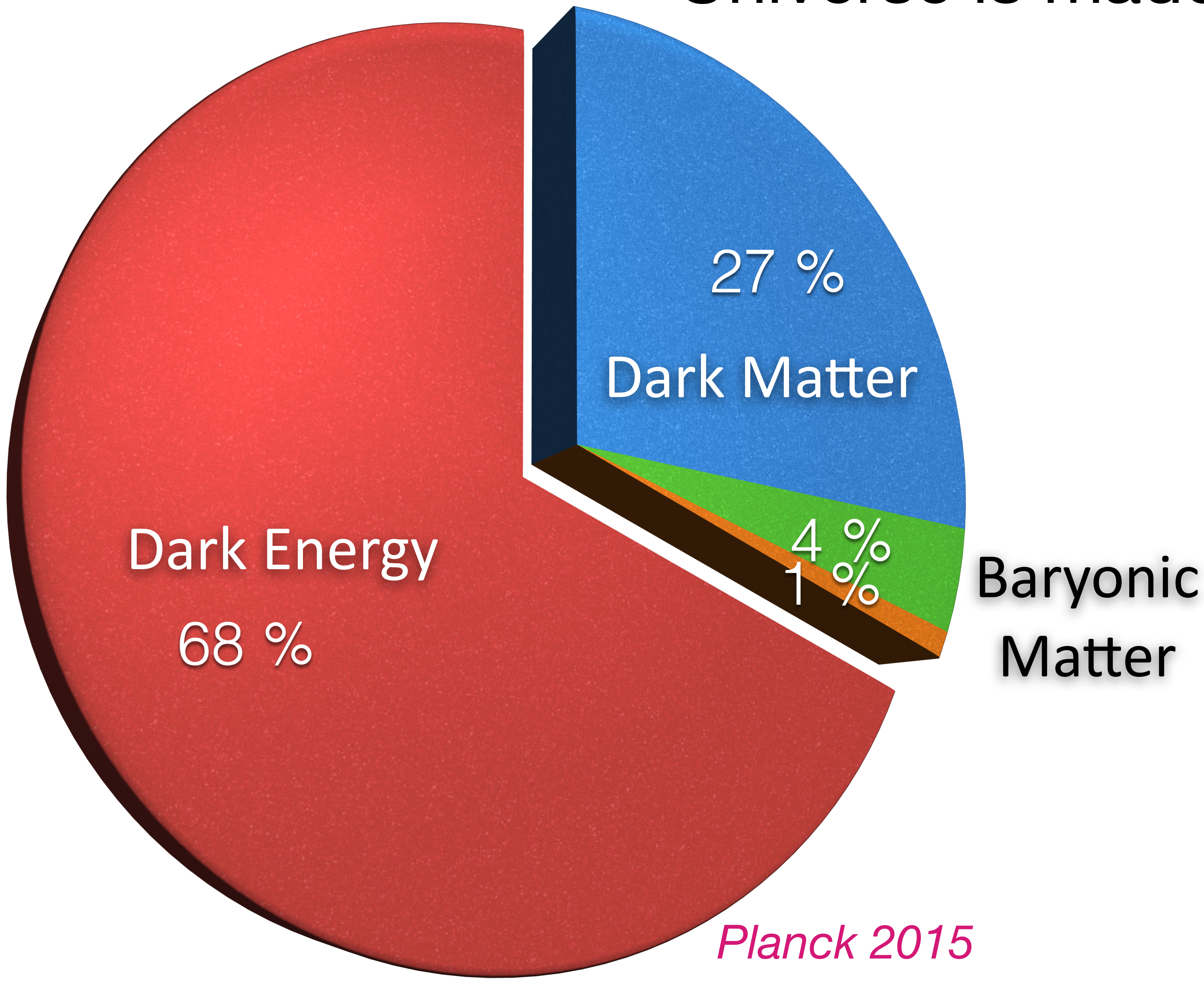
Galaxies

~Gpc

~Mpc

~kpc (10^{19} m)

We do not know what most of the Universe is made of!

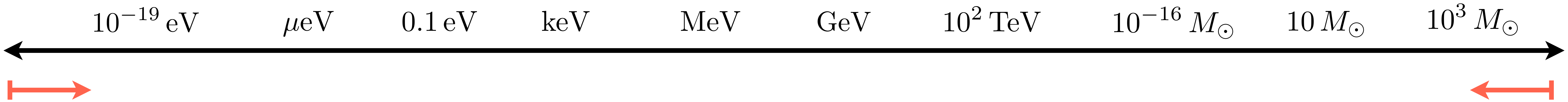


We add one (or more?) extra-ingredient, which interacts only gravitationally

The dark matter landscape

Vast parameter space in mass and interaction strength

The dark matter landscape



Dark matter behaves “classically"

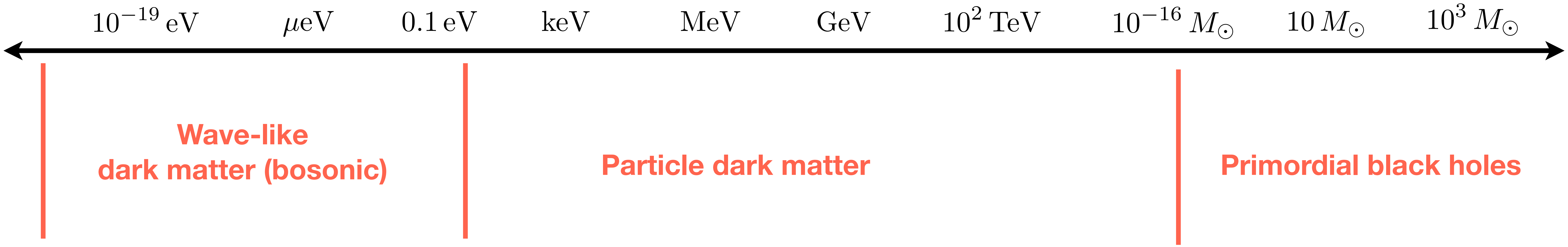
$$m \gtrsim 10^{-22}\,\mathrm{eV}$$

If bosonic, from confinement in dwarf galaxies

Dark matter “lighter” than halo mass

Vast parameter space in mass and interaction strength

The dark matter landscape



The dark matter landscape

$10^{-19}\,\mathrm{eV}$ — $\mu\mathrm{eV}$ — $0.1\,\mathrm{eV}$ — keV — MeV — GeV — $10^{2}\,\mathrm{TeV}$ — $10^{-16}\,M_\odot$ — $10\,M_\odot$ — $10^{3}\,M_\odot$

Wave-like
dark matter (bosonic)

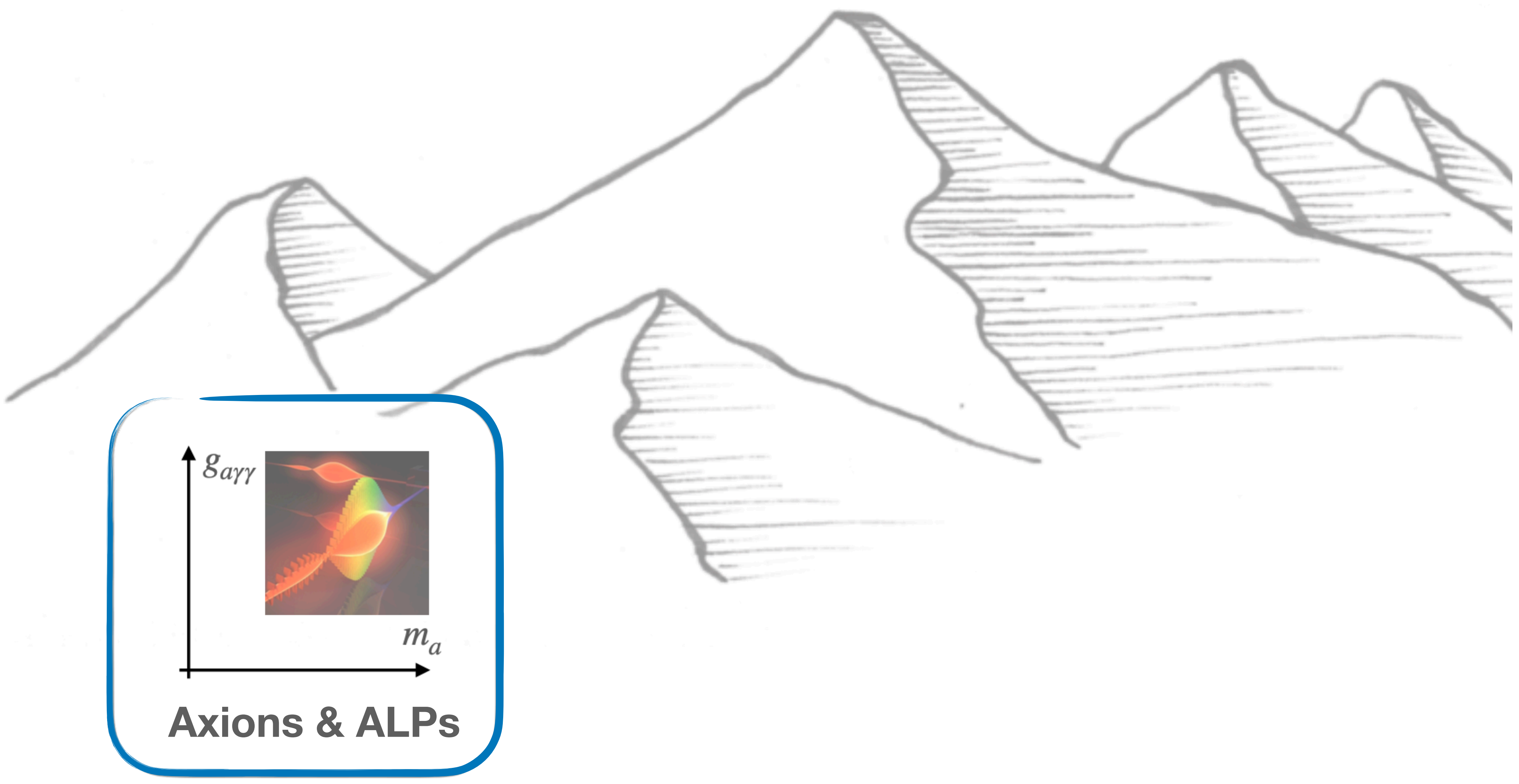
Axion-like particles

- Very light pseudo-scalar bosons predicted by multiple extensions of the Standard Model

Chang+ PRD 2000; Turok PRL 1996; Arvanitaki+ PRD'10

- They represent weakly interacting slim (ultralight) particles (**WISPs**)
- They can be cold dark matter candidates for certain values of mass and coupling

Preskill+ PLB 1983; Sikivie International Journal of Modern Physics '10



Redondo's talk

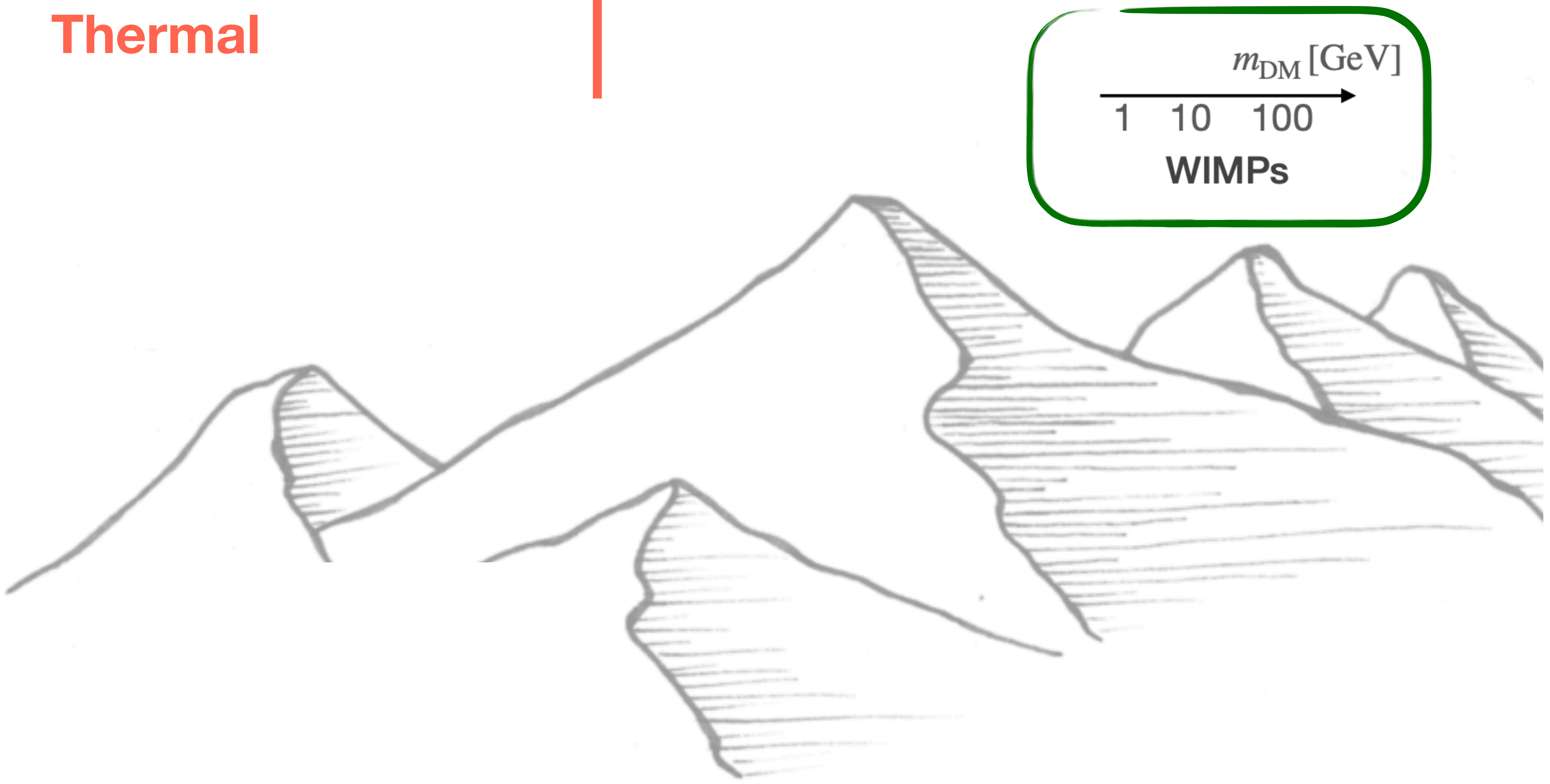
Credit: J. Alvey, EuCAPT Symposium 2021

The dark matter landscape

$10^{-19}\,\mathrm{eV}$ — $\mu\mathrm{eV}$ — $0.1\,\mathrm{eV}$ — keV — MeV — GeV — $10^2\,\mathrm{TeV}$ — $10^{-16}\,M_\odot$ — $10\,M_\odot$ — $10^3\,M_\odot$

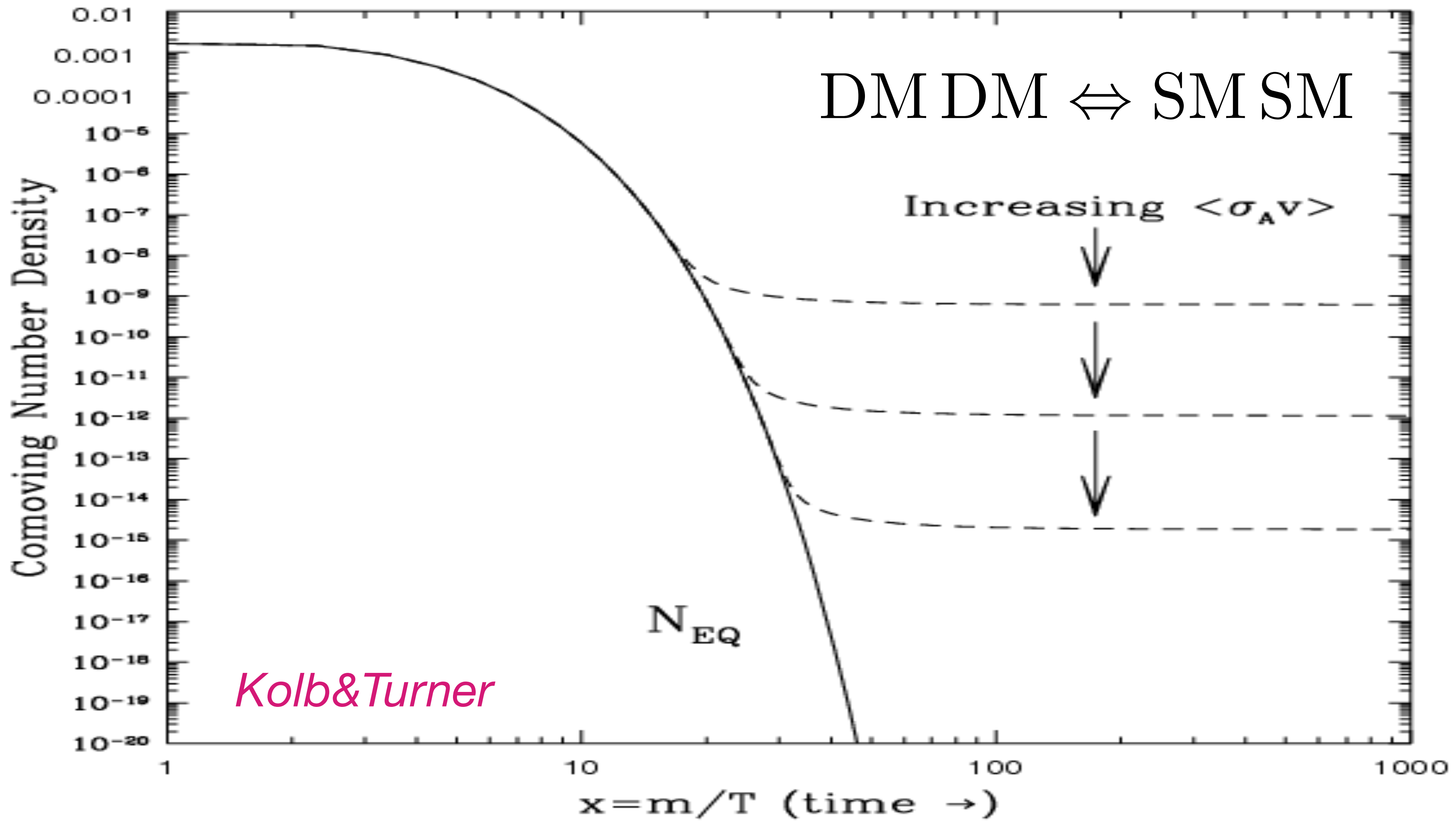
Particle dark matter

Thermal



Weakly interacting massive particles (WIMPs)

- Freeze-out production mechanism



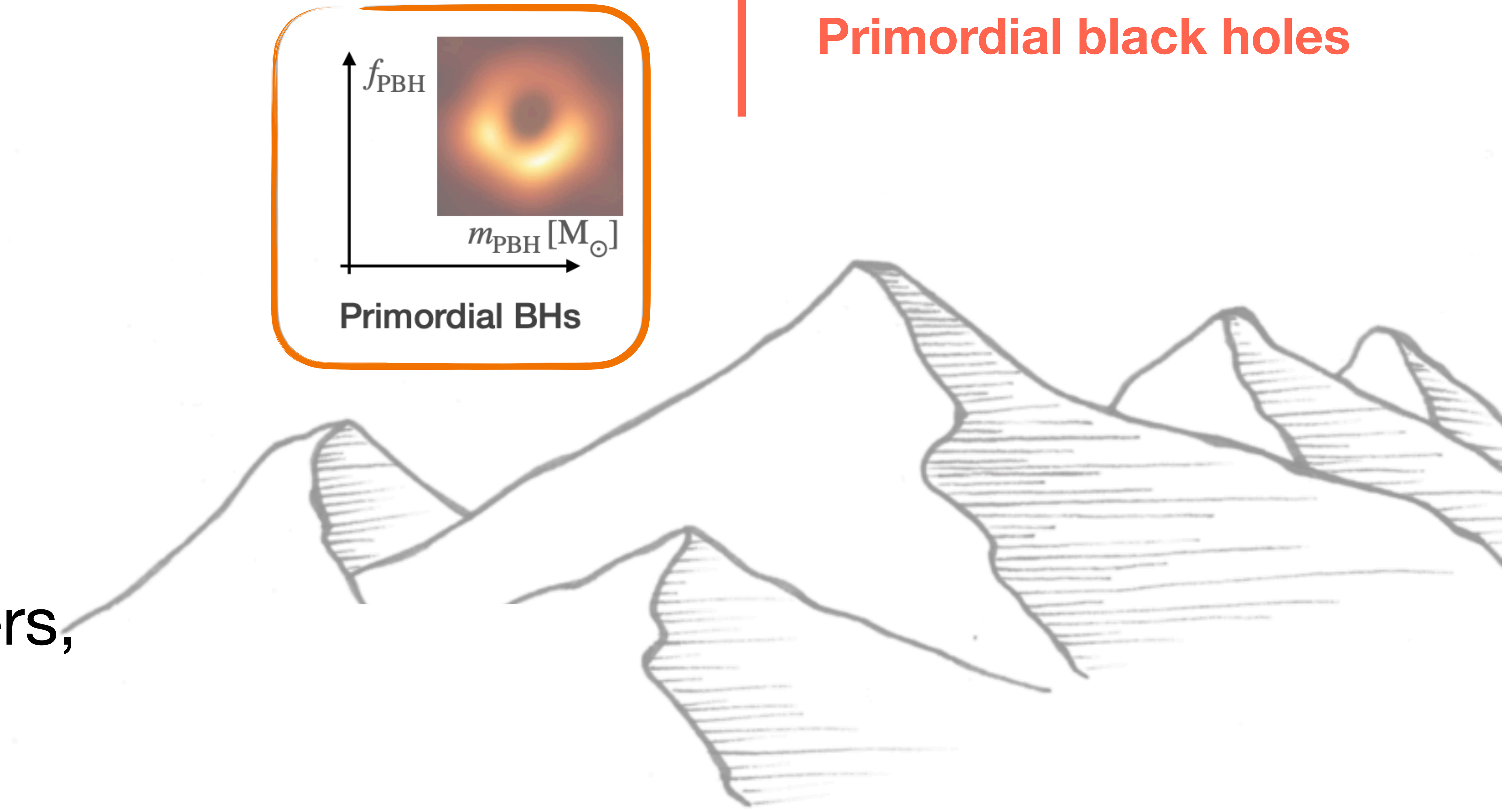
$$\Omega_{\mathrm{DM}} h^2 \sim \frac{10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle \sigma(\mathrm{DM\,DM} \to \mathrm{SM\,SM})\mathrm{v}\rangle}$$

Credit: J. Alvey, EuCAPT Symposium 2021

The dark matter landscape

$10^{-19}\,\mathrm{eV}$ $\mu\mathrm{eV}$ $0.1\,\mathrm{eV}$ keV MeV GeV $10^2\,\mathrm{TeV}$ $10^{-16}\,M_\odot$ $10\,M_\odot$ $10^3\,M_\odot$

Primordial black holes



Primordial black holes (PBH)

- Different possible production mechanism, e.g. primordial fluctuations
- Allowed fraction of PBH dark matter strongly constrained by CMB, dynamics of stellar clusters, X-ray and radio observations

Review & Refs in Carr+PRD'16, Green & Kavanagh J. Phys. G'21

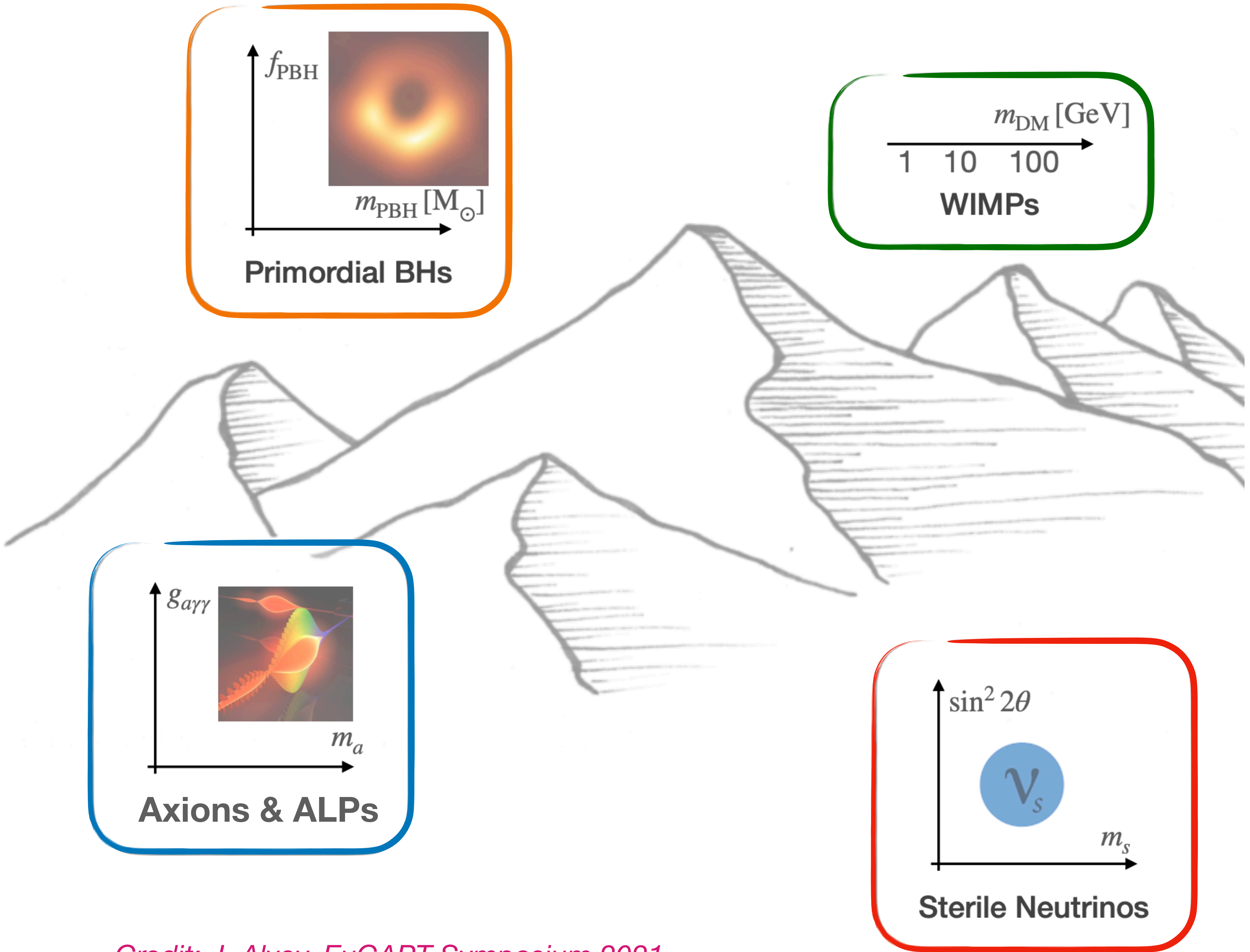
Garcia-Bellido's talk

Credit: J. Alvey, EuCAPT Symposium 2021

The dark matter landscape

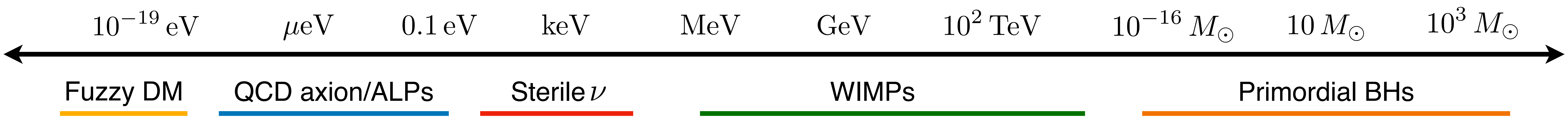
10^{-19} eV — μeV — 0.1 eV — keV — MeV — GeV — 10^2 TeV — $10^{-16}\, M_\odot$ — $10\, M_\odot$ — $10^3\, M_\odot$

Fuzzy DM | QCD axion/ALPs | Sterile ν | WIMPs | Primordial BHs

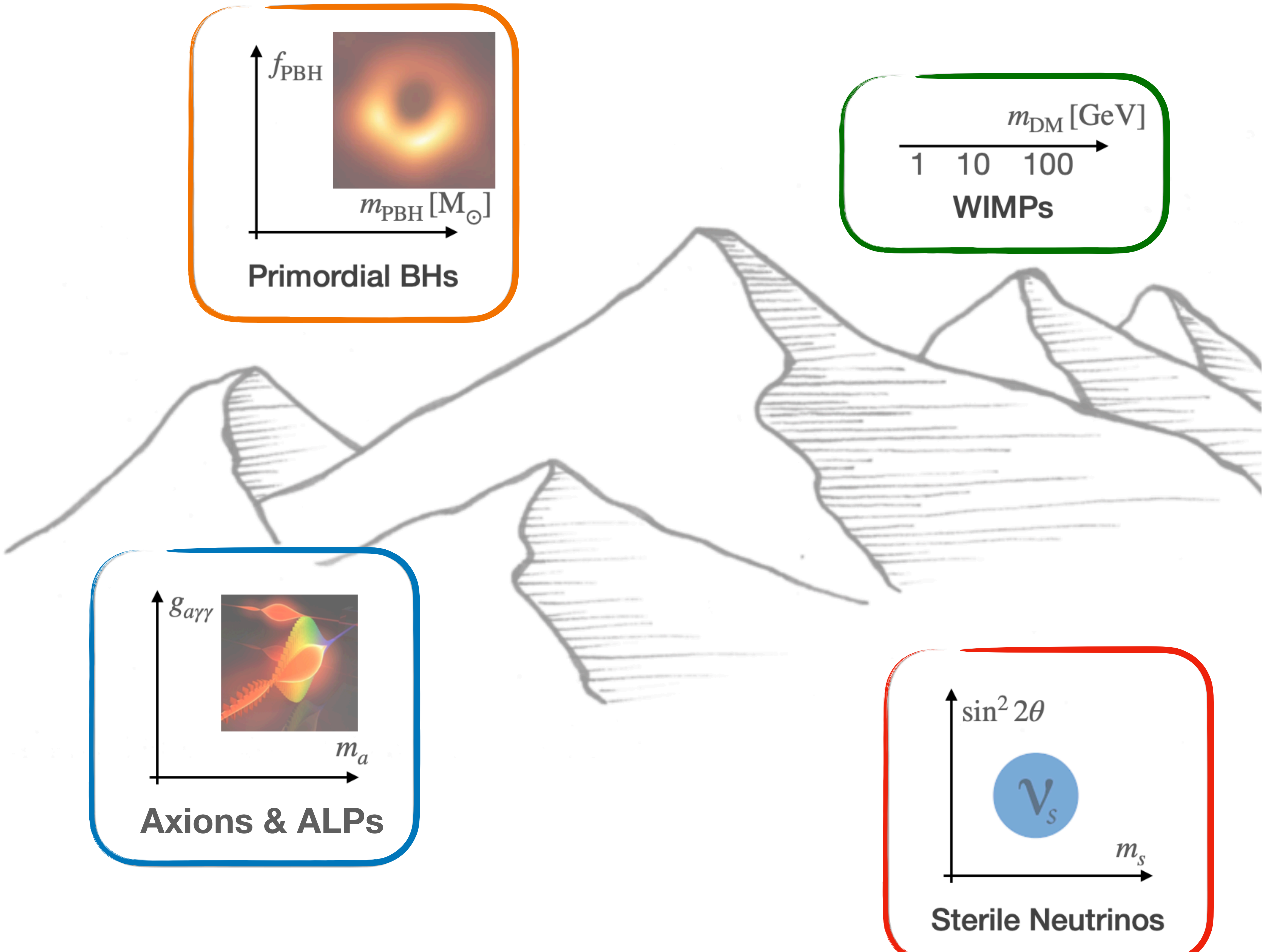


Credit: J. Alvey, EuCAPT Symposium 2021

The dark matter landscape



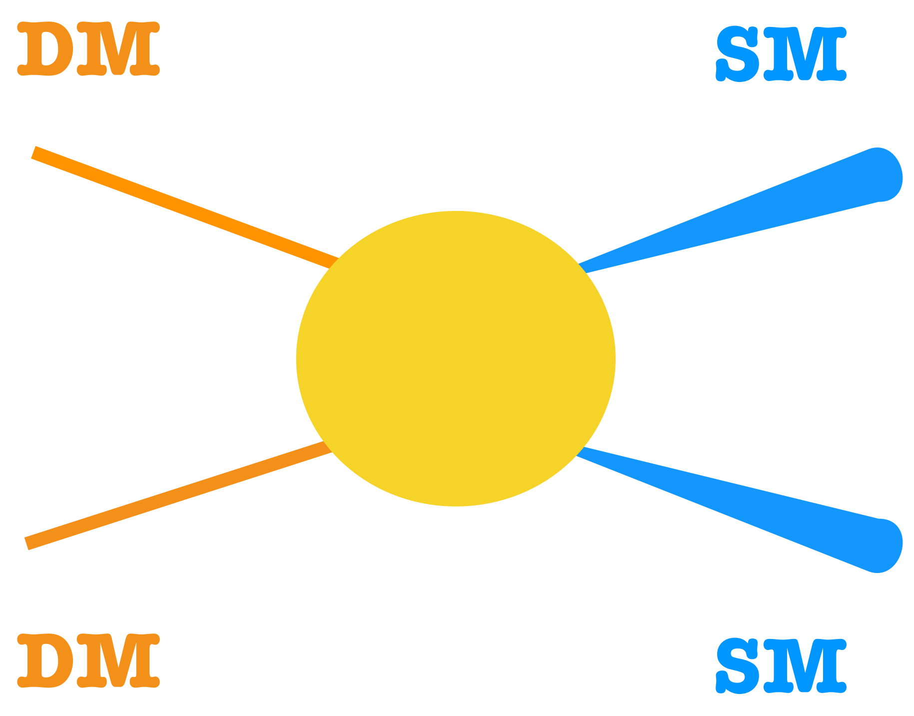
- Identification strategies are necessarily (more or less) **model dependent**
- The **theoretical prejudice** in dark matter searches is also set by what we can probe with available data
- You always need some sort of signature of your model!



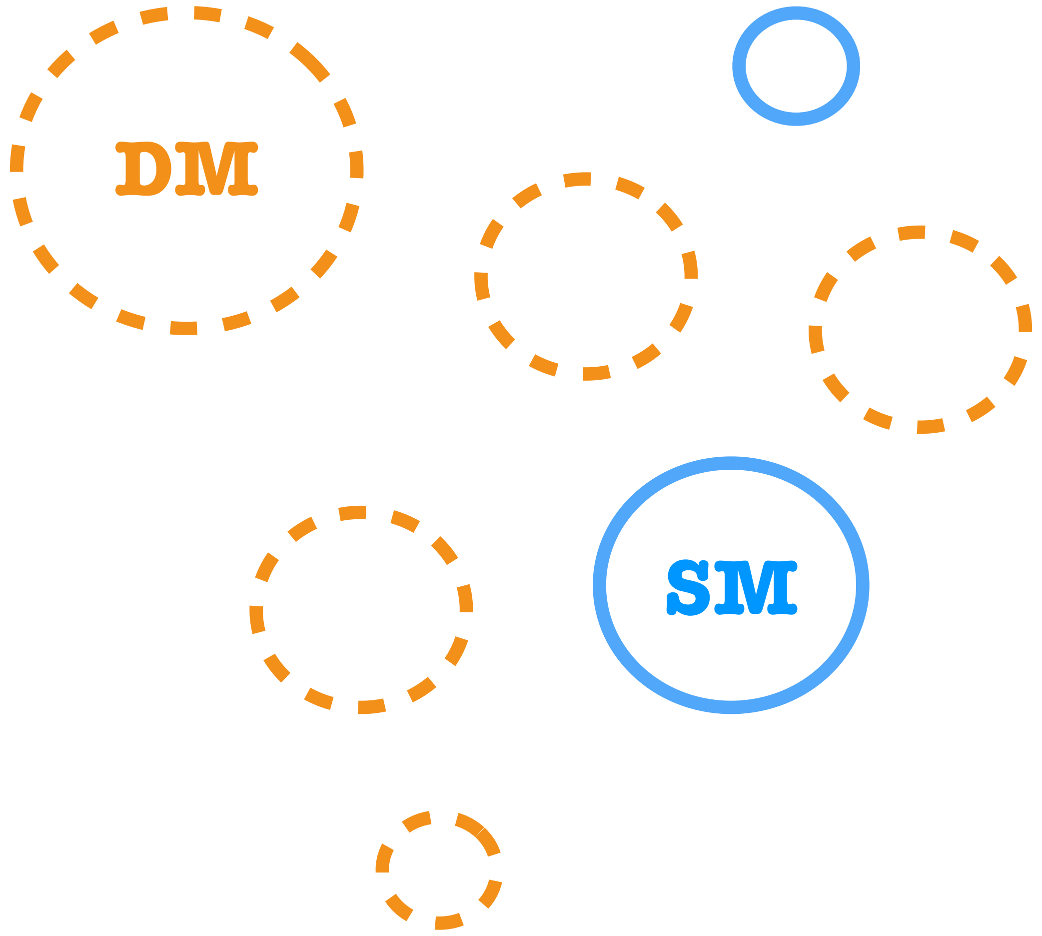
Credit: J. Alvey, EuCAPT Symposium 2021

Dark matter indirect detection

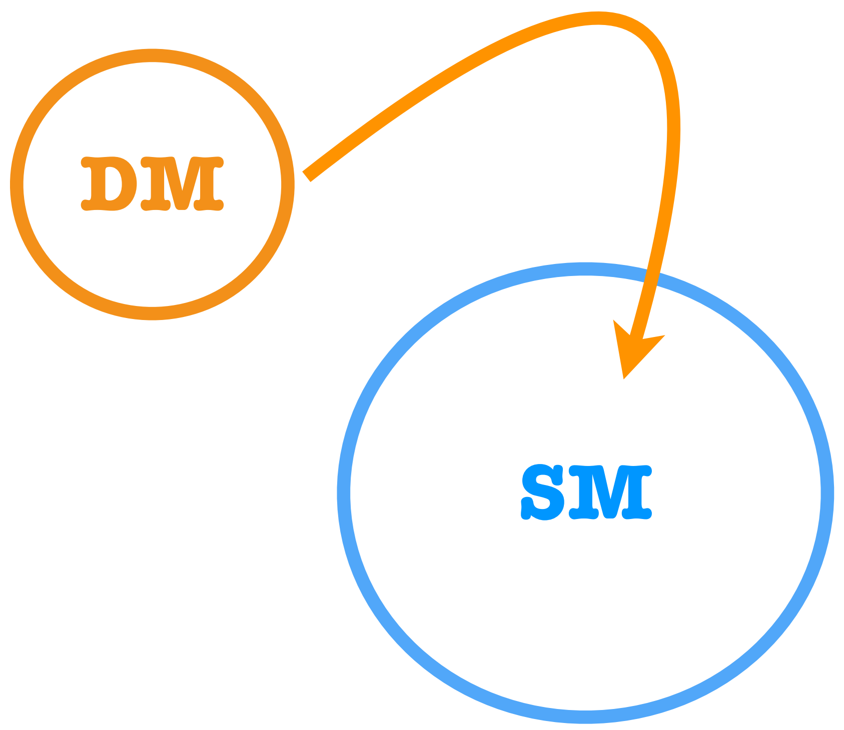
What dark matter does



Energy/particle injection



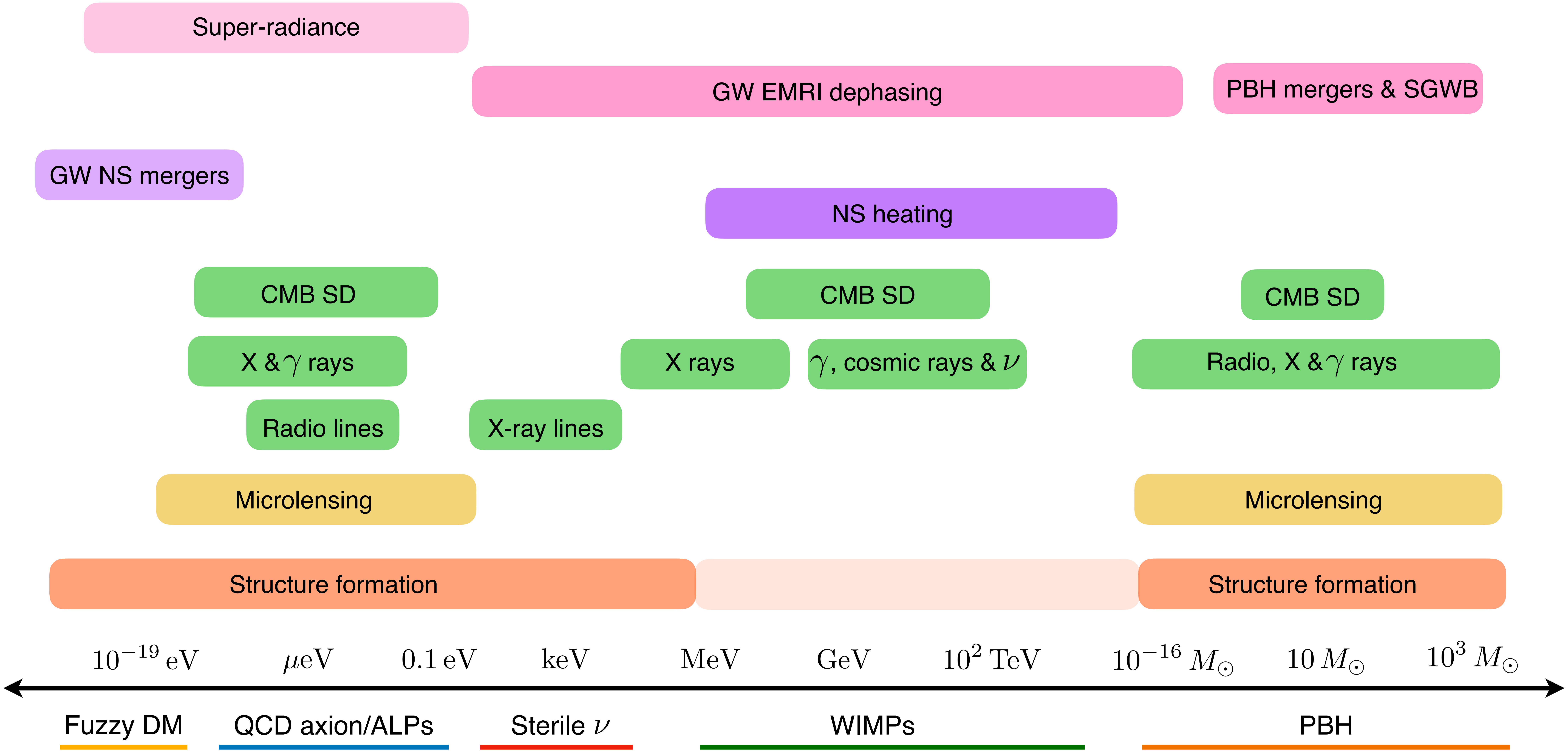
Gravitational interaction



Capture/scattering/accretion in/onto astrophysical objects

Astroparticle observables for dark matter

EuCAPT White Paper, arXiv:2110.10074



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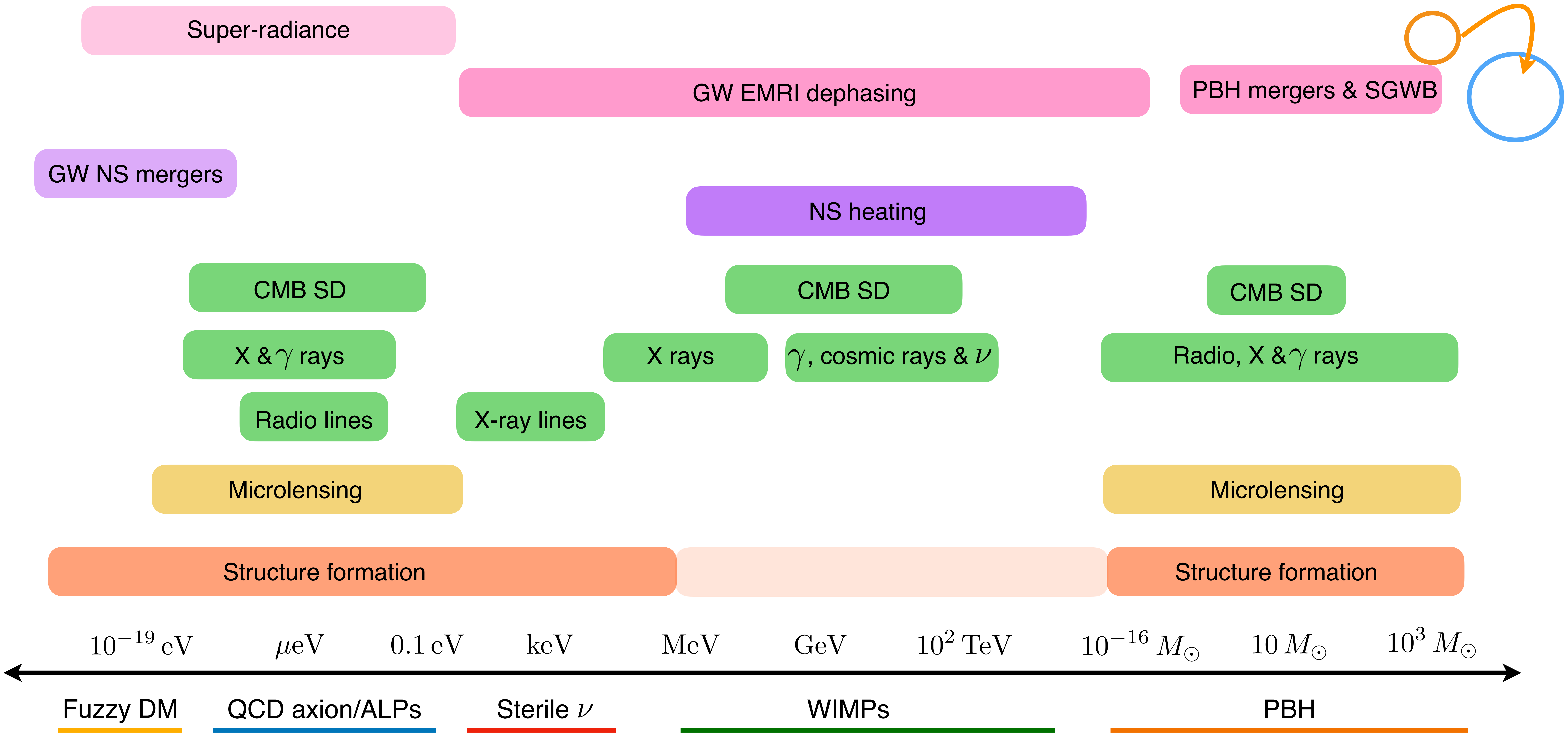

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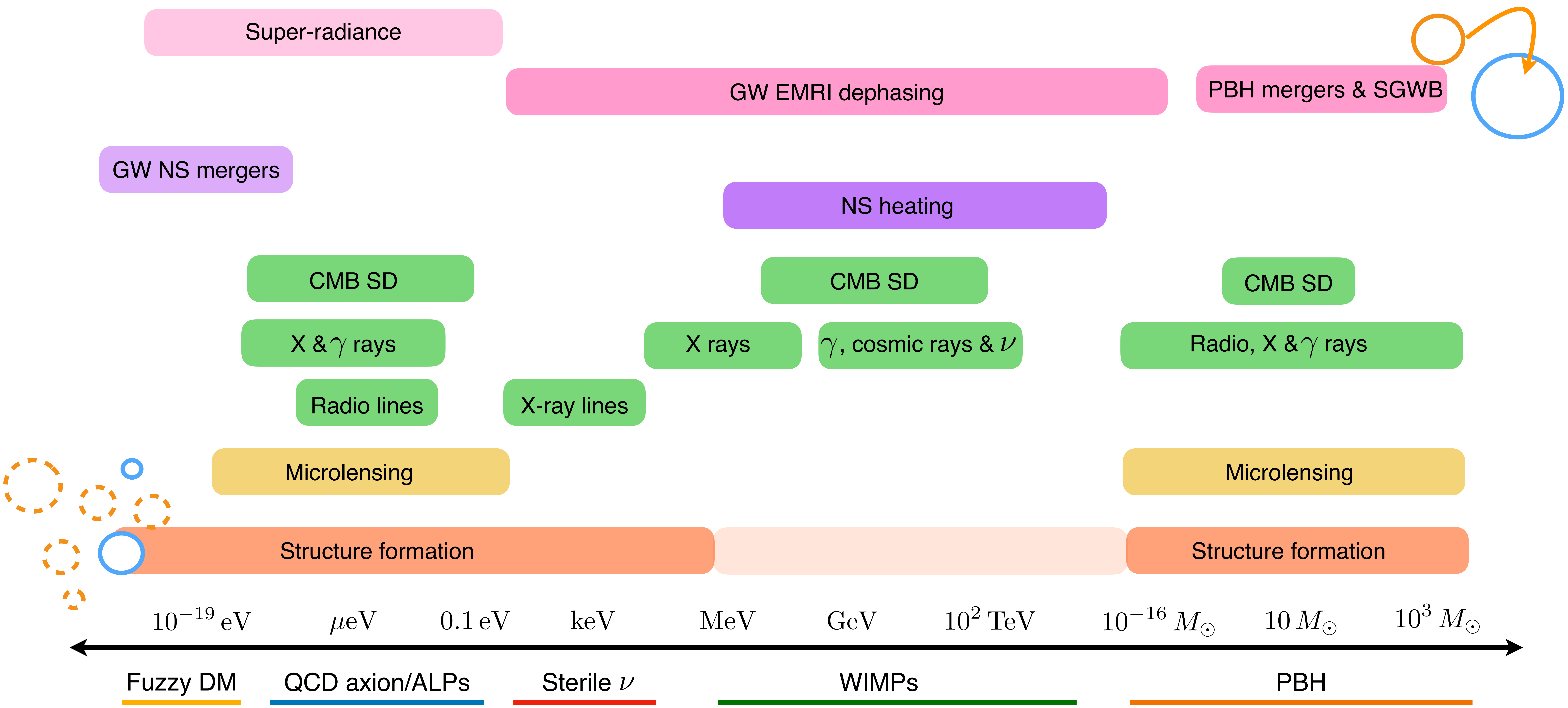

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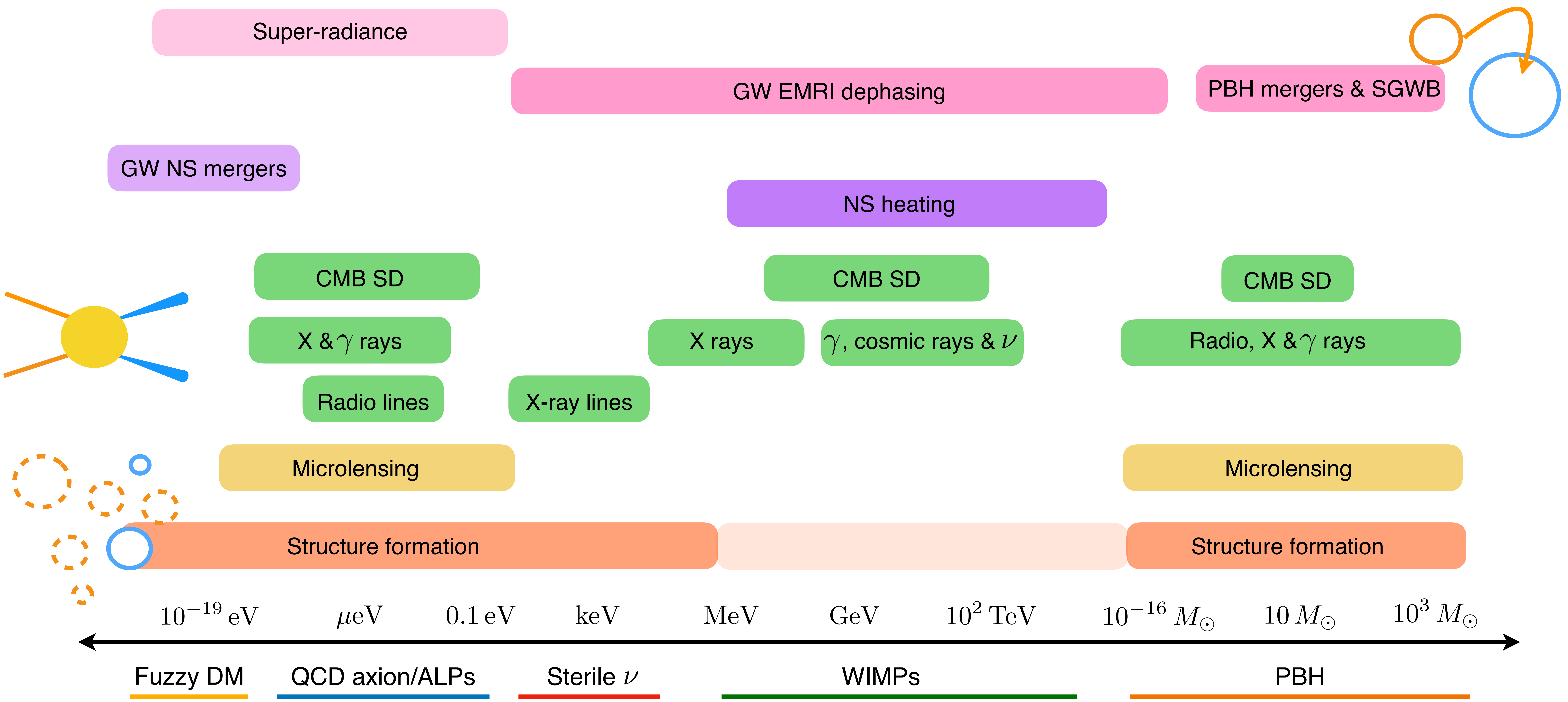
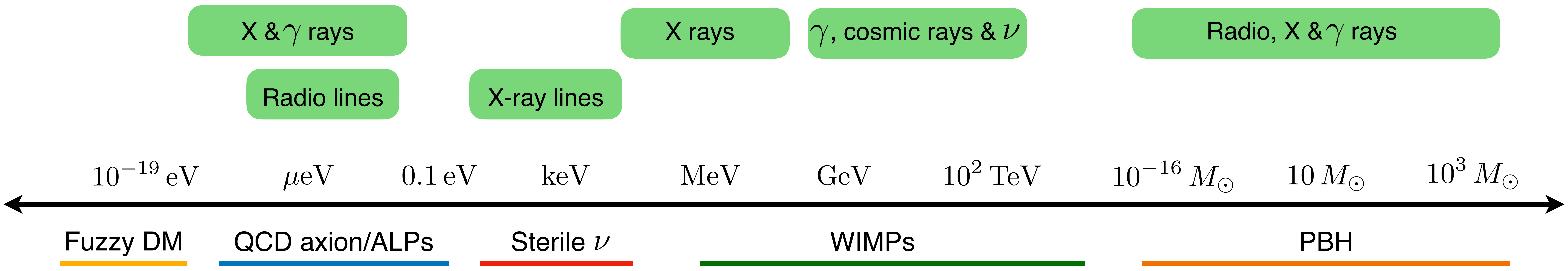
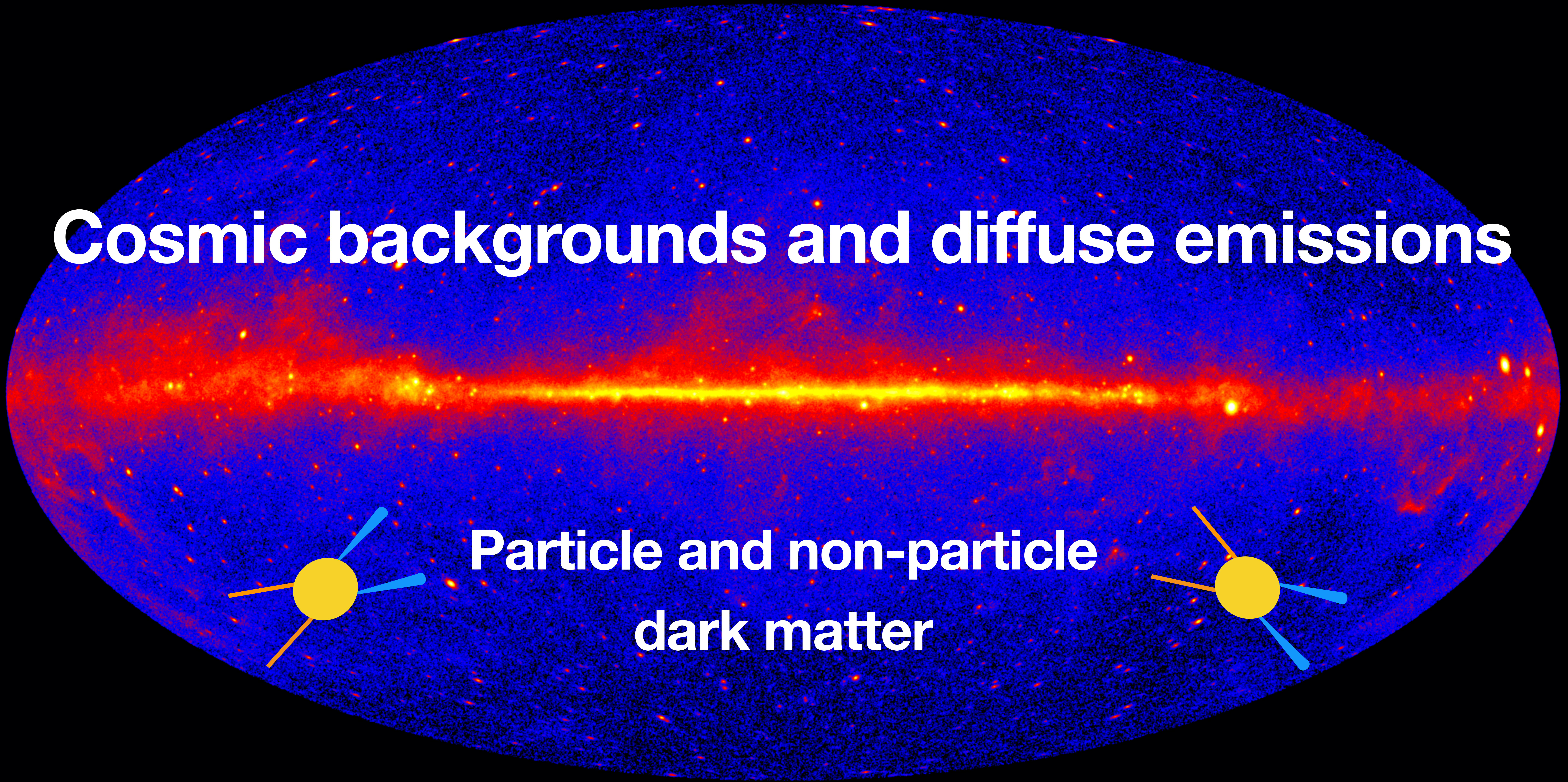


Travelling messengers




Cosmic backgrounds and diffuse emissions
Particle and non-particle
dark matter

Particle dark matter emission*

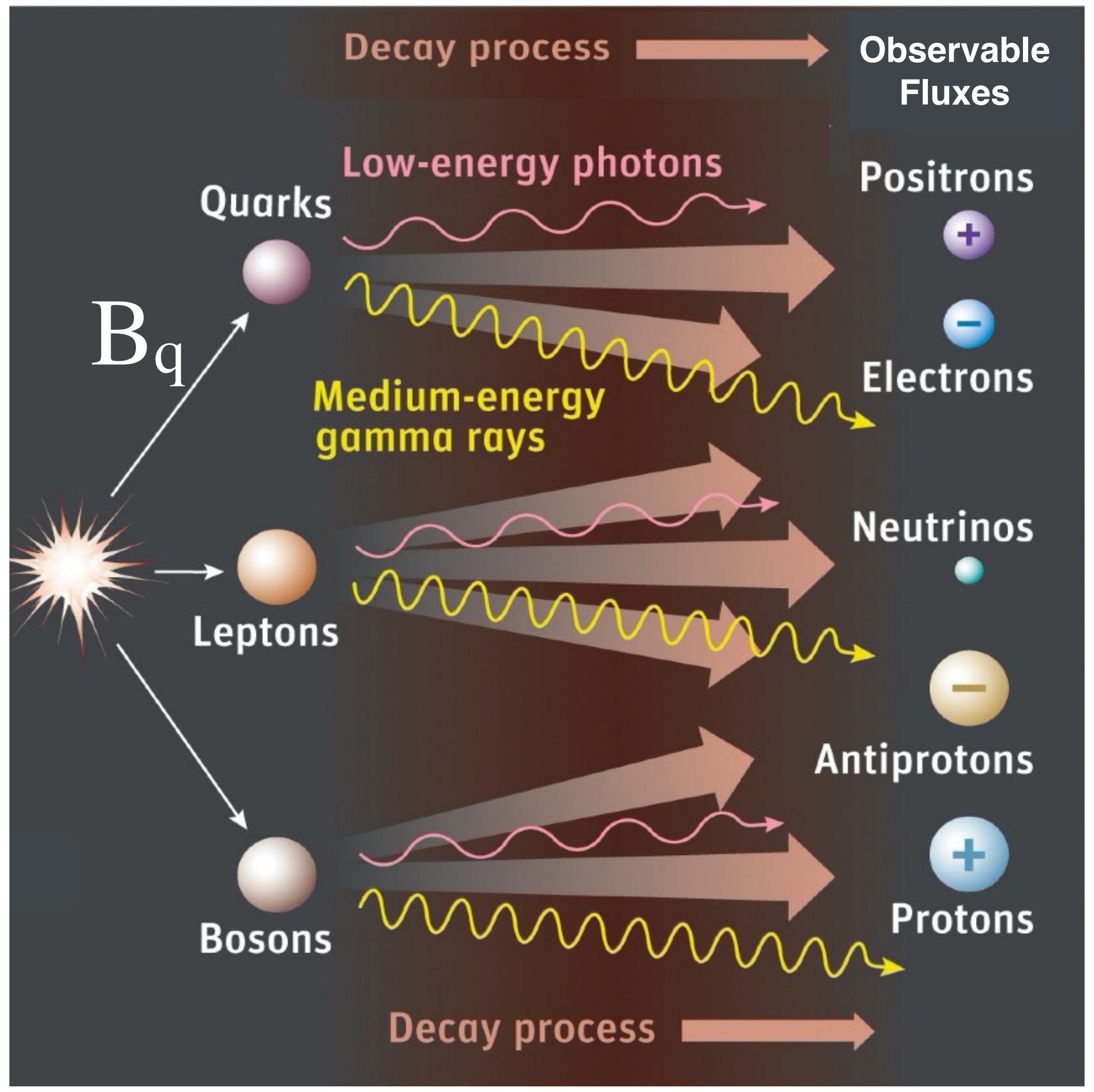
From radio to TeV gamma rays

$$E_{\mathrm{CM}} = N\, m_{\mathrm{DM}}\,, \qquad N = 1\ (\mathrm{decay}),\ 2\ (\mathrm{annih})$$

Centre of mass energy $\simeq$ Signal energy

$$m_{\mathrm{DM}} \gtrsim \mathrm{MeV}$$

DM annihilation/decay



[*Dark matter = Weakly interacting massive particles, **WIMPs**]

Particle dark matter emission

From radio to TeV gamma rays

$$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1\ ({\rm decay}),\ 2\ ({\rm annih})$$

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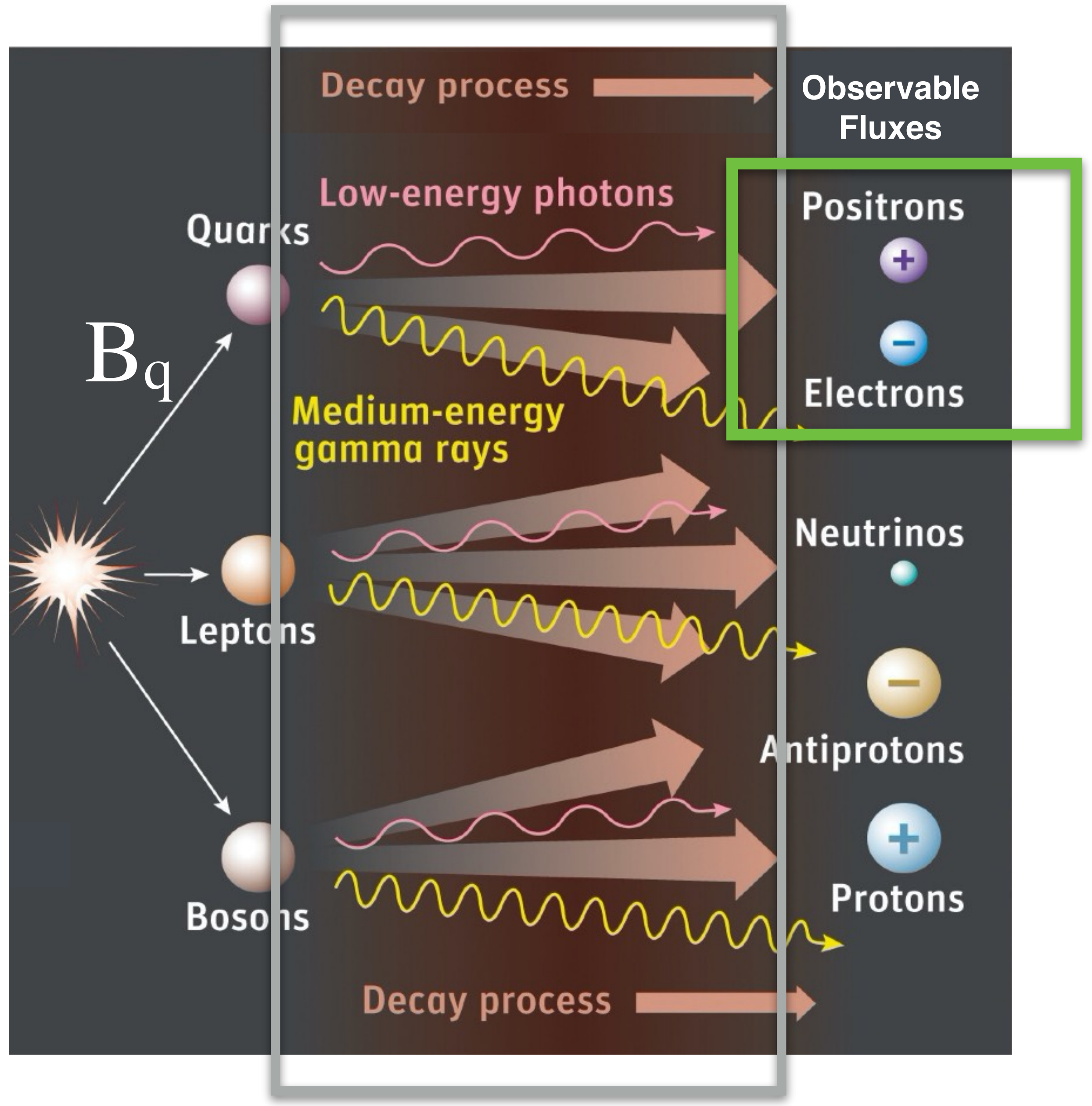

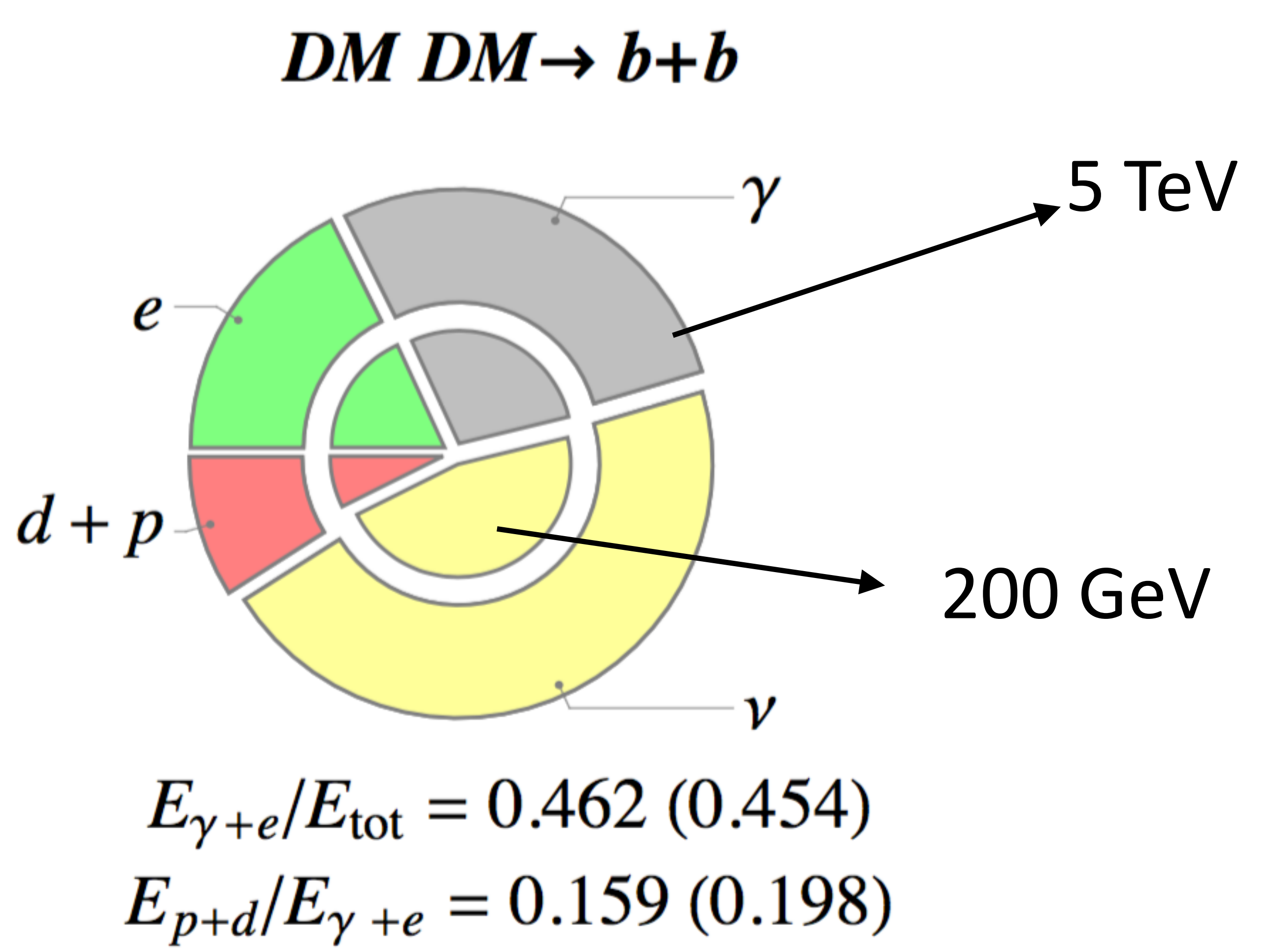

Prompt emission of observable particles *i*

$$\sum_f B_f \frac{dN_i^f}{dE}(E)$$

Particle dark matter emission

From radio to TeV gamma rays

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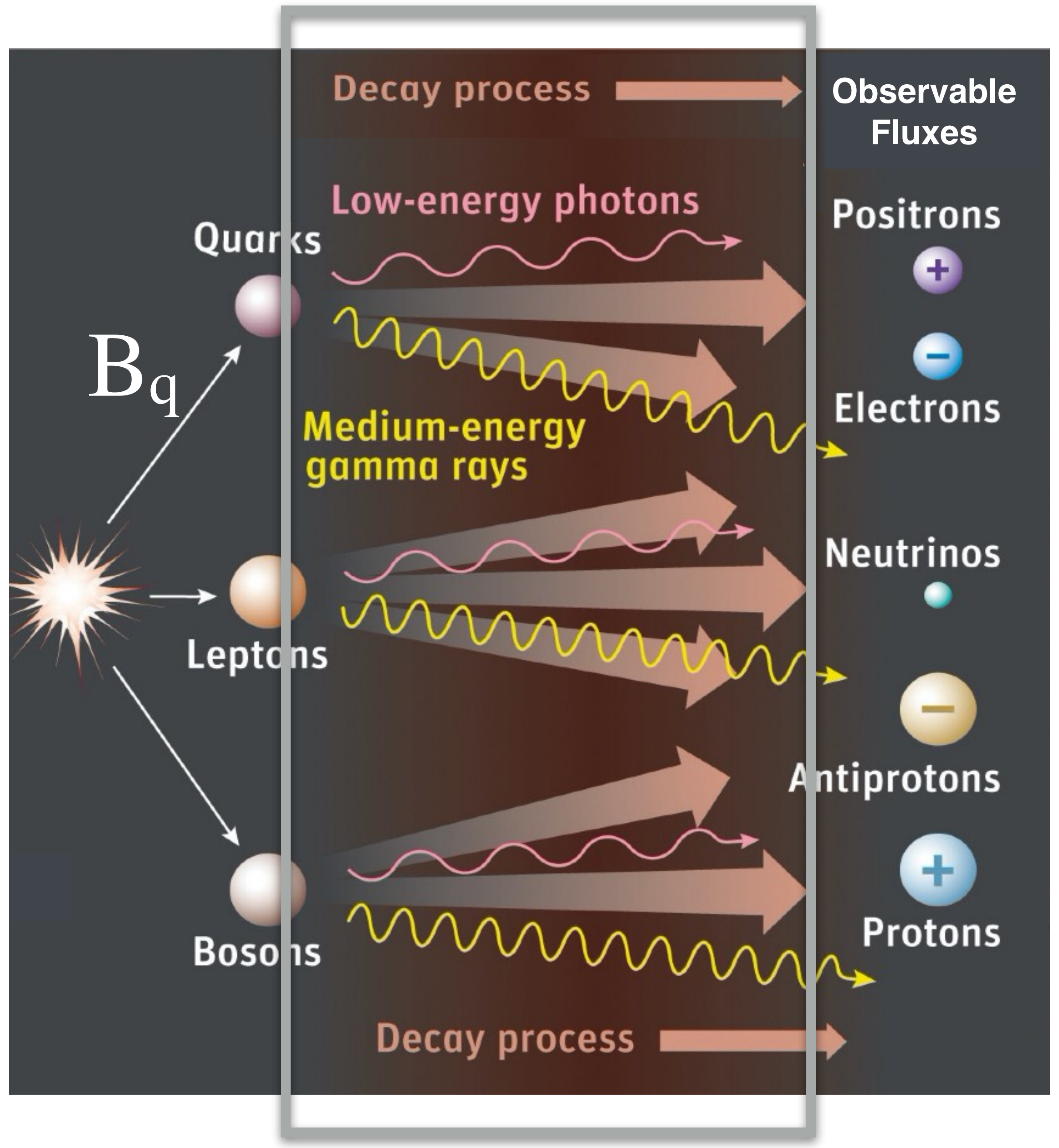
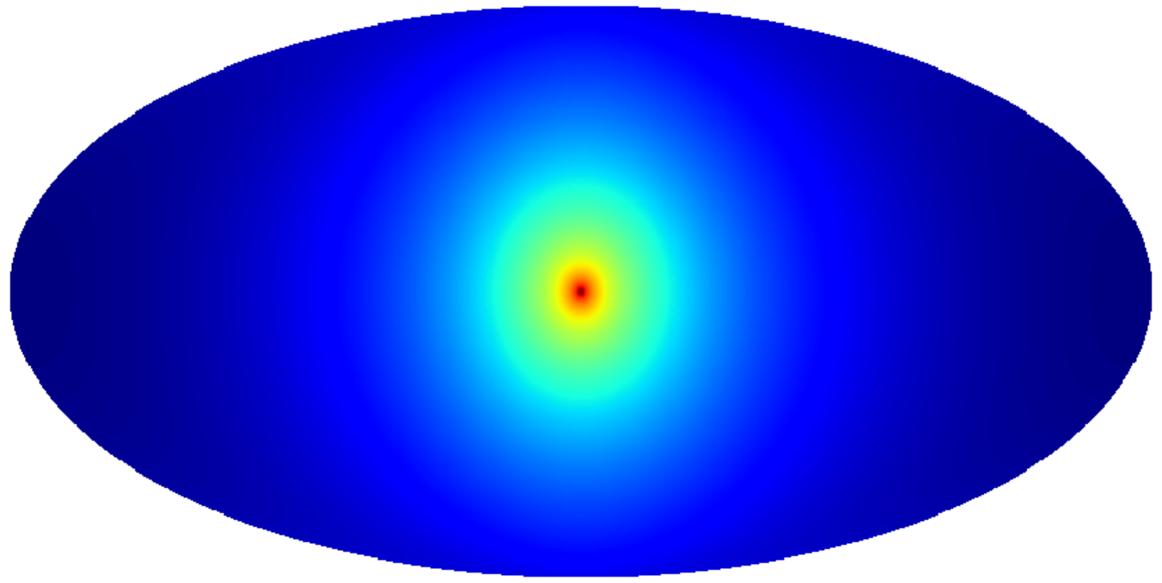
DM annihilation/decay

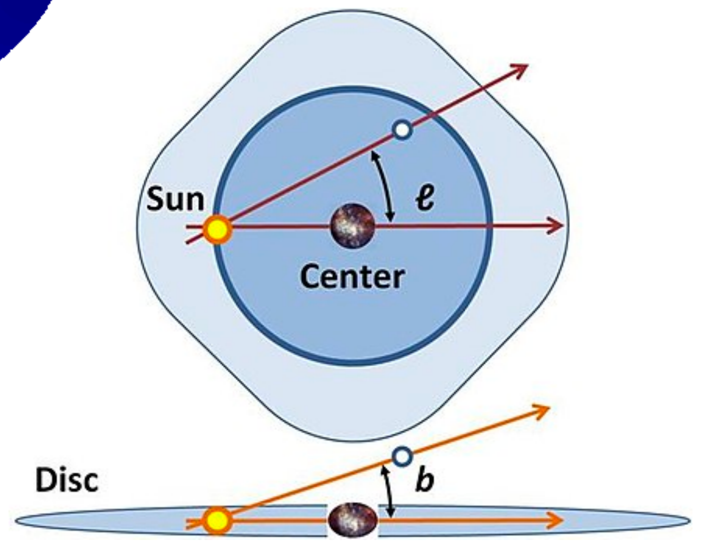


Example: Self-conjugated dark matter annihilation

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, s, \Delta\Omega) = \frac{\langle \sigma v \rangle}{2 m_{\rm DM}^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} \rho_{\rm DM}^2(s) ds$$

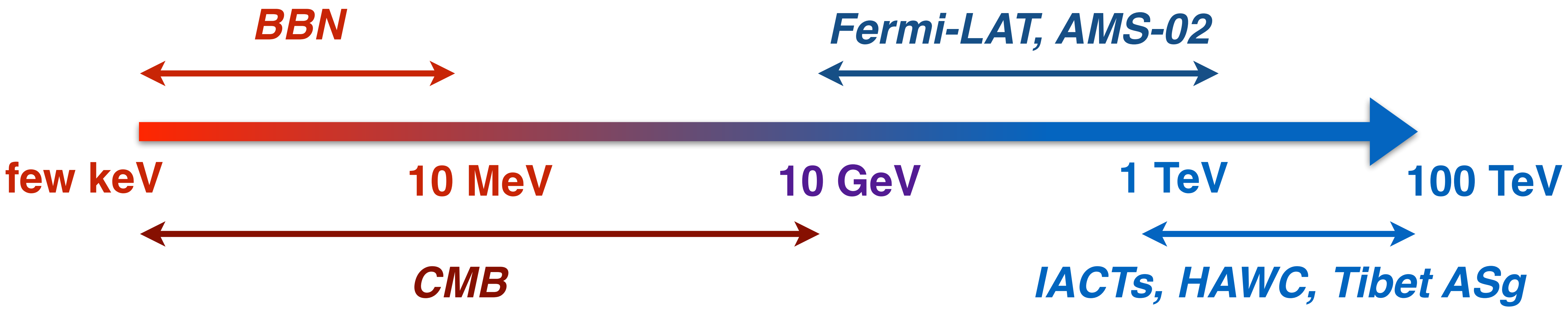
Differential **gamma-ray** flux

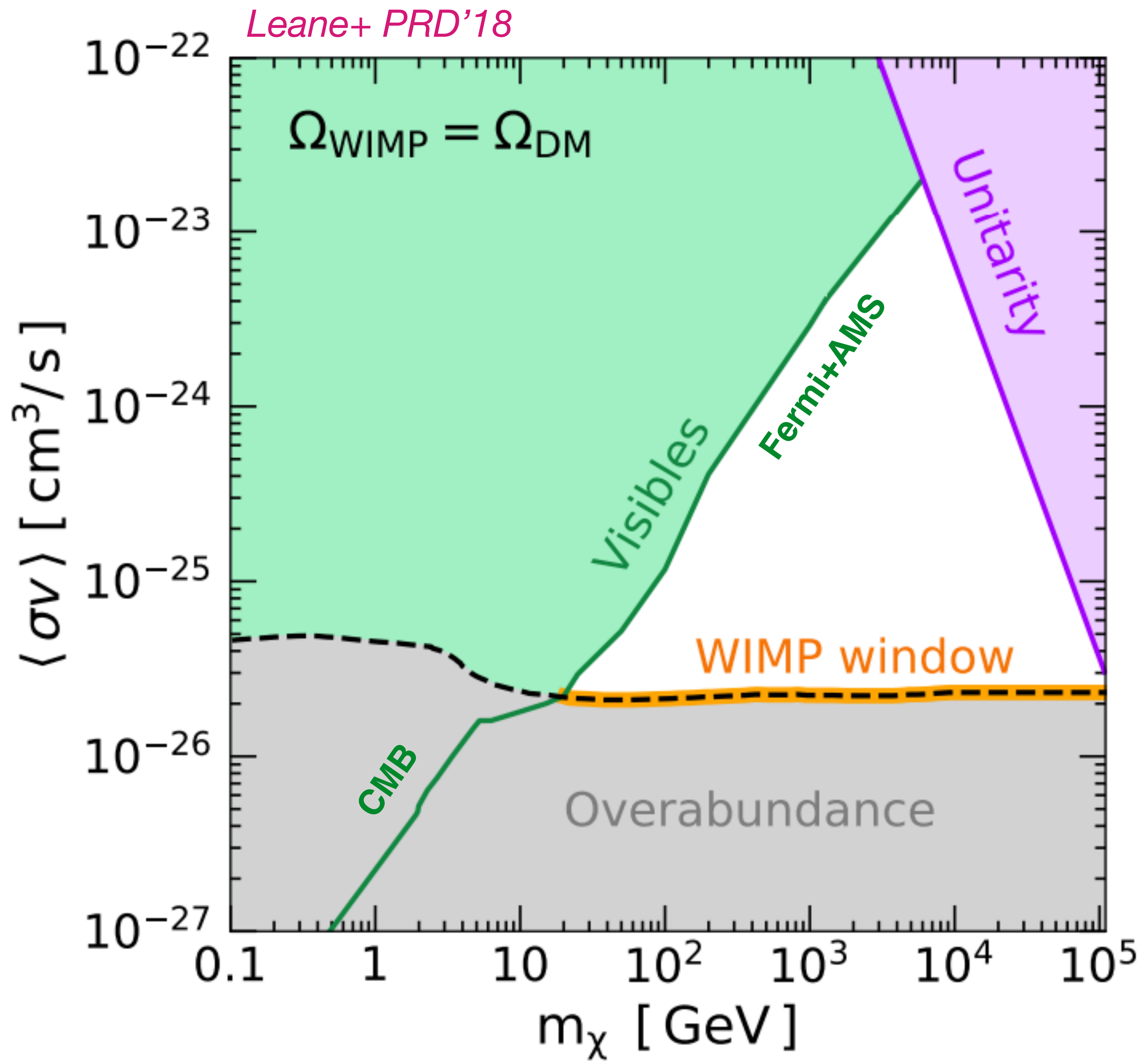




[Gamma-ray lines typically suppressed at loop level for generic WIMP models]

WIMP annihilation window



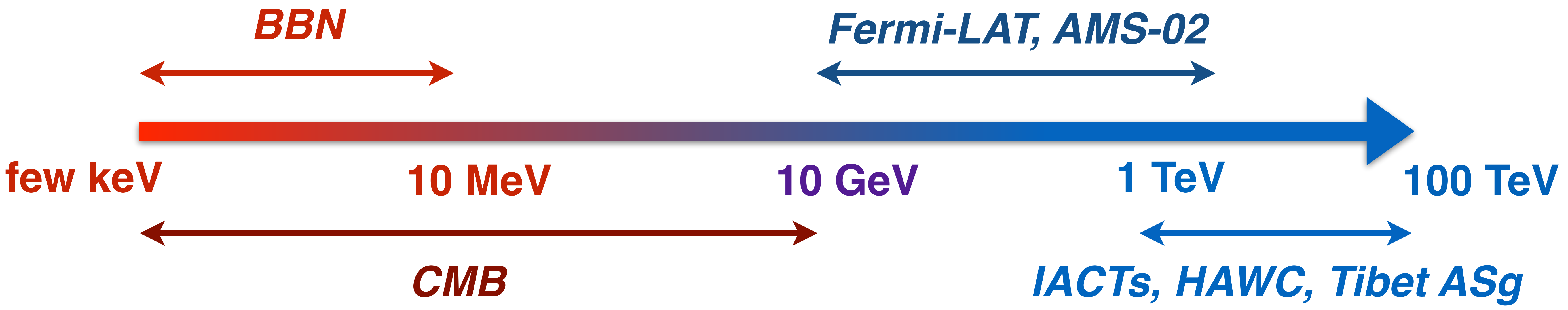


- **Total cross-section** sets **relic abundance**
- **Indirect detection** provides model-independent UL on annihilation **cross-section for a given final state**

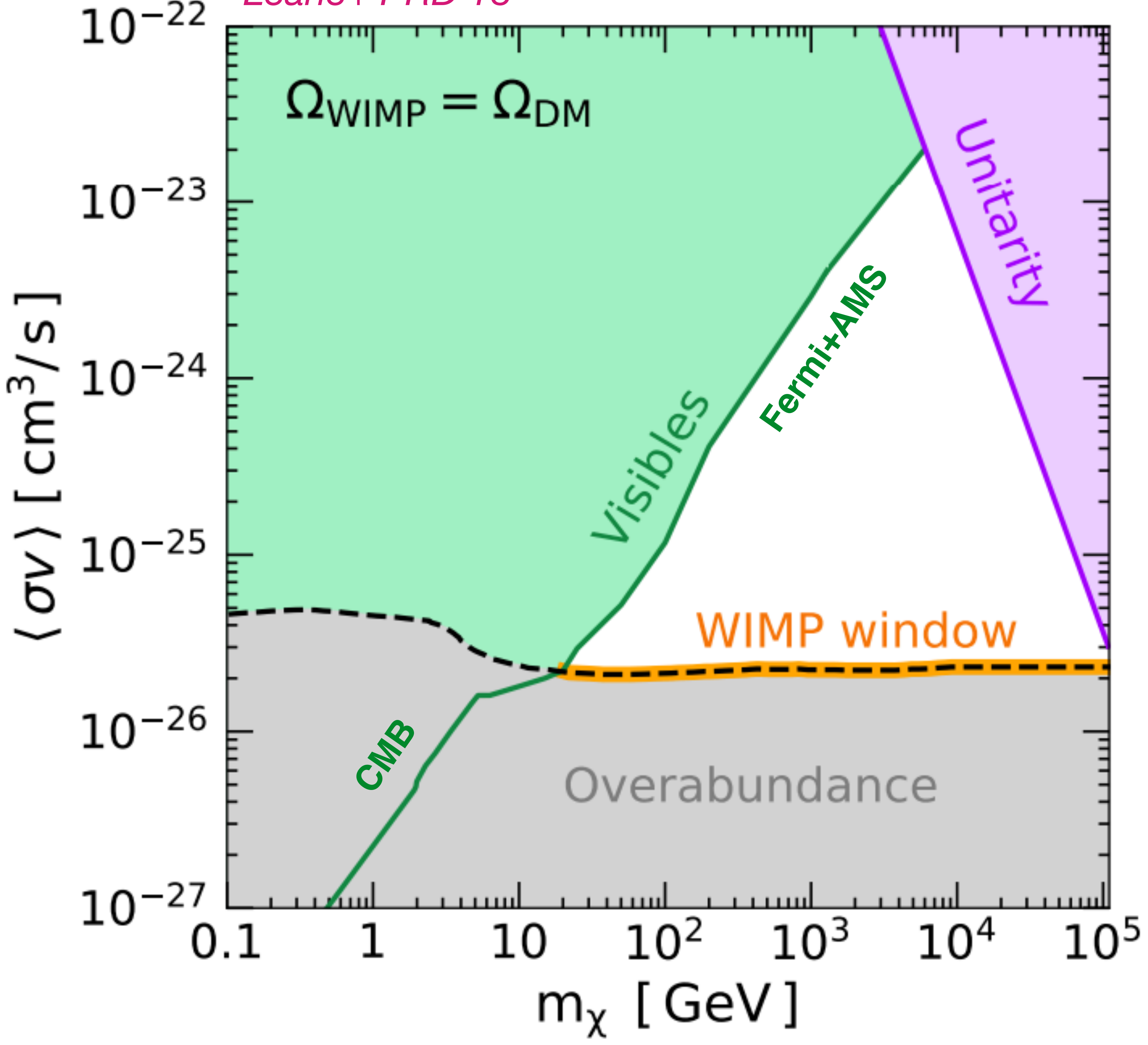
→ Consistent and conservative interpretation of the data in the context of the generic thermal WIMP

[Low DM masses constrained by energy injection at early times and CMB observations *Slatyer & Wu, PRD'17*]

WIMP annihilation window



Leane+ PRD'18



- **Total cross-section** sets **relic abundance**
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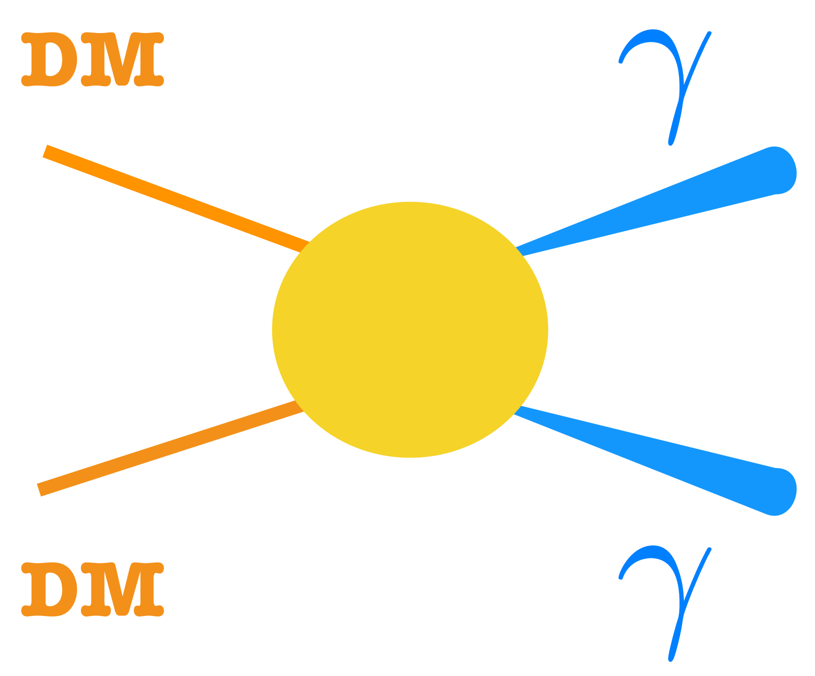
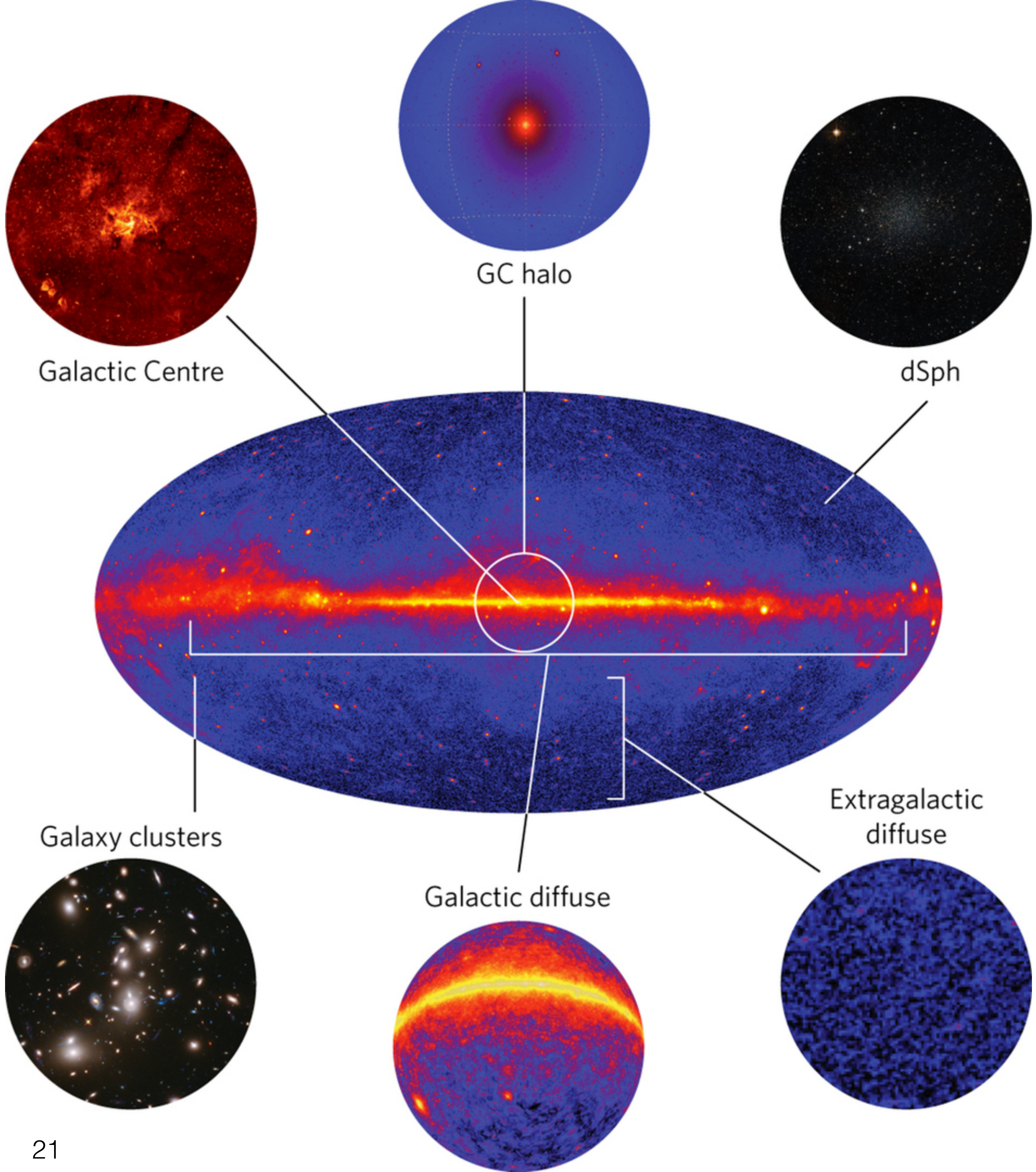
TAKE AWAY: Window of opportunity still open for thermal WIMP DM

[Low DM masses constrained by energy injection at early times and CMB observations *Slatyer & Wu, PRD'17*]

Targets for WIMP gamma-ray searches



$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi)\right]^2$$



+ dedicated searches for gamma-ray lines
+ similar targets for radio searches (synchrotron)

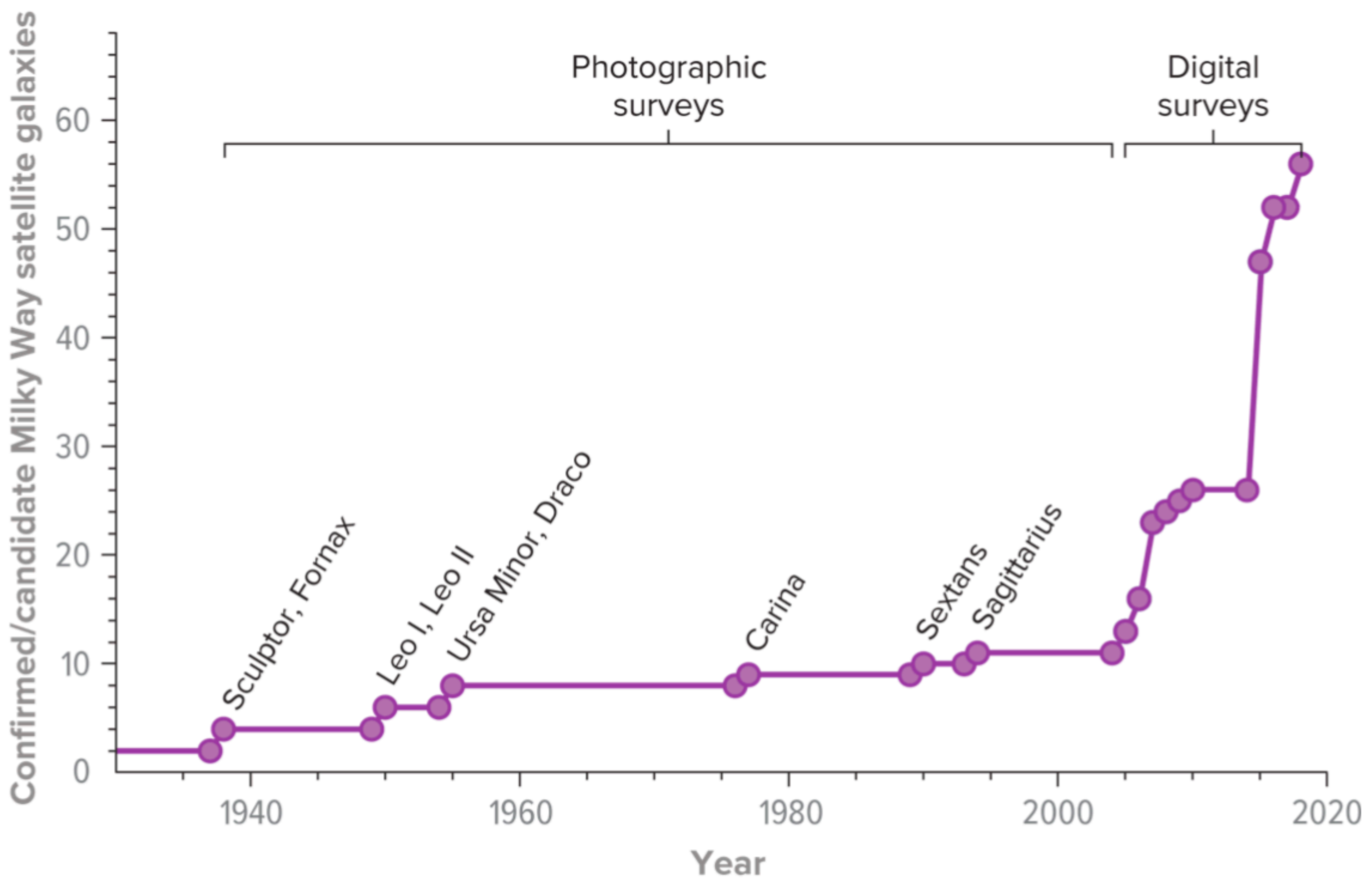
Conrad & Reimer Nature Phys. 13 (2017)

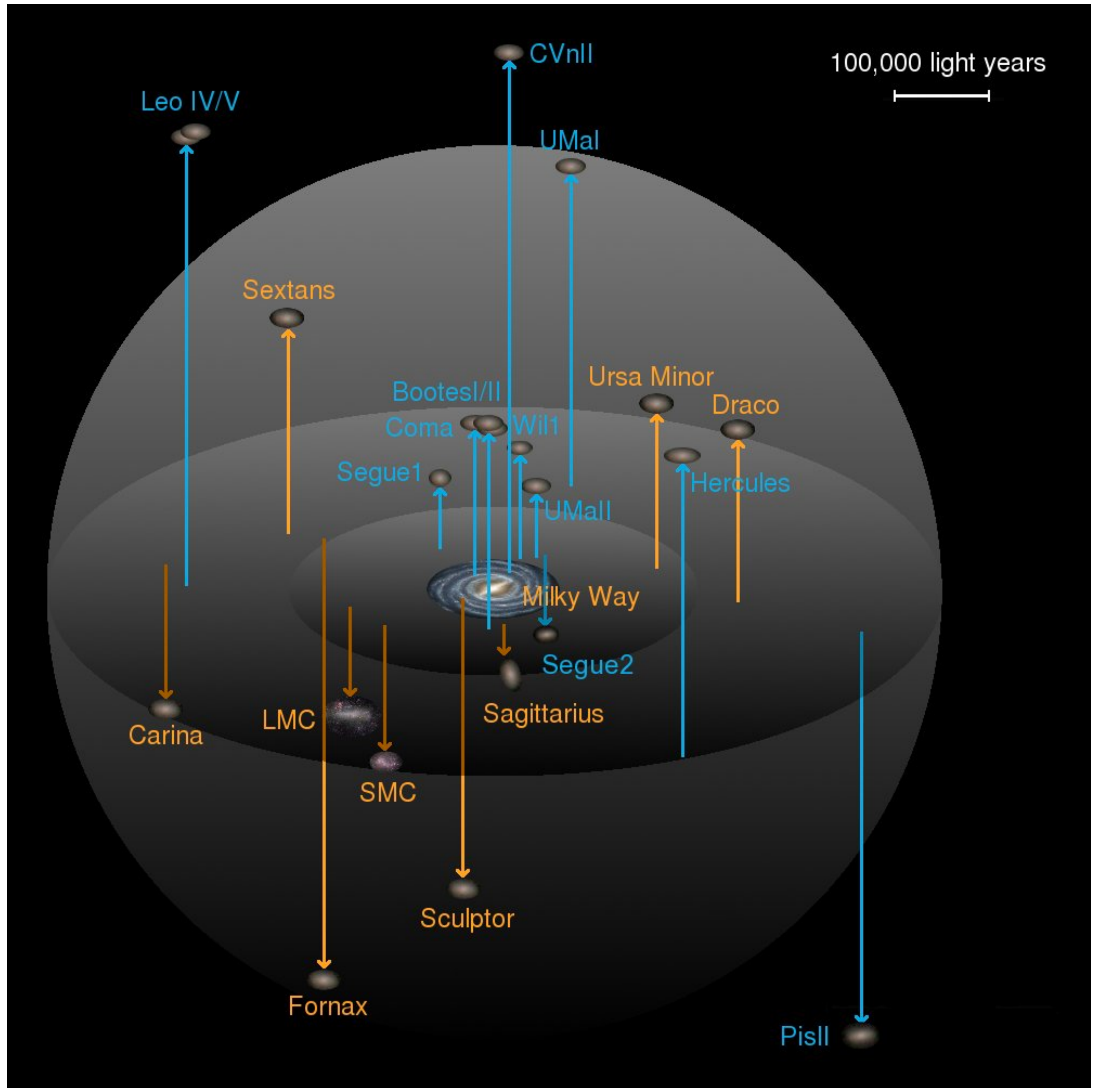
Dwarf spheroidal galaxies

Known satellites of the Milky Way at ~100 kpc from Earth

“Clean” target for DM searches, high mass-to-light ratio and little astrophysical emission

Winter+ ApJ’16

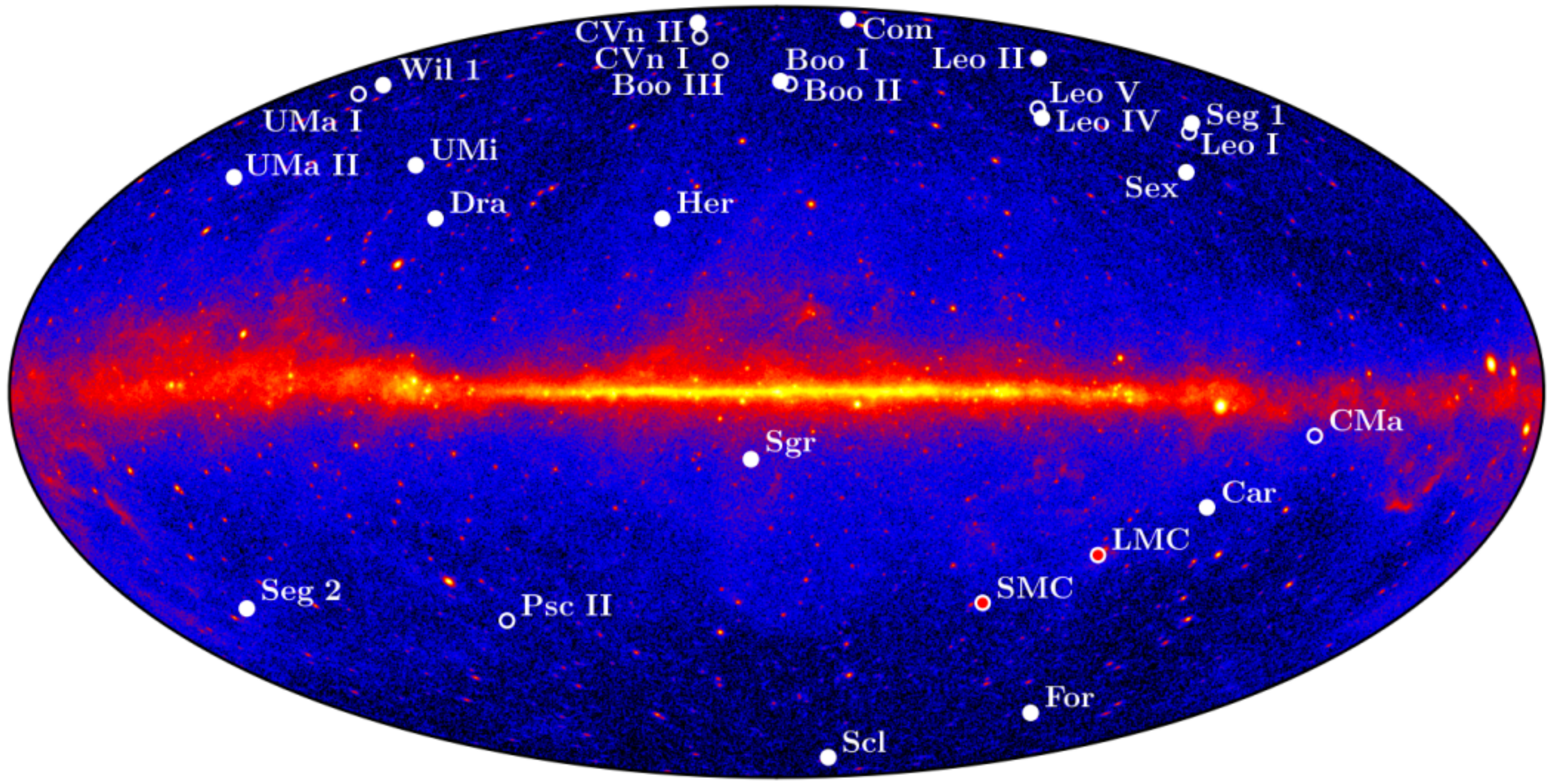




A growing Galactic crowd
> 50 satellites
(SDSS, PanSTARRS, DES)

Credit: J.D. Simon / AR Astronomy and Astrophysics

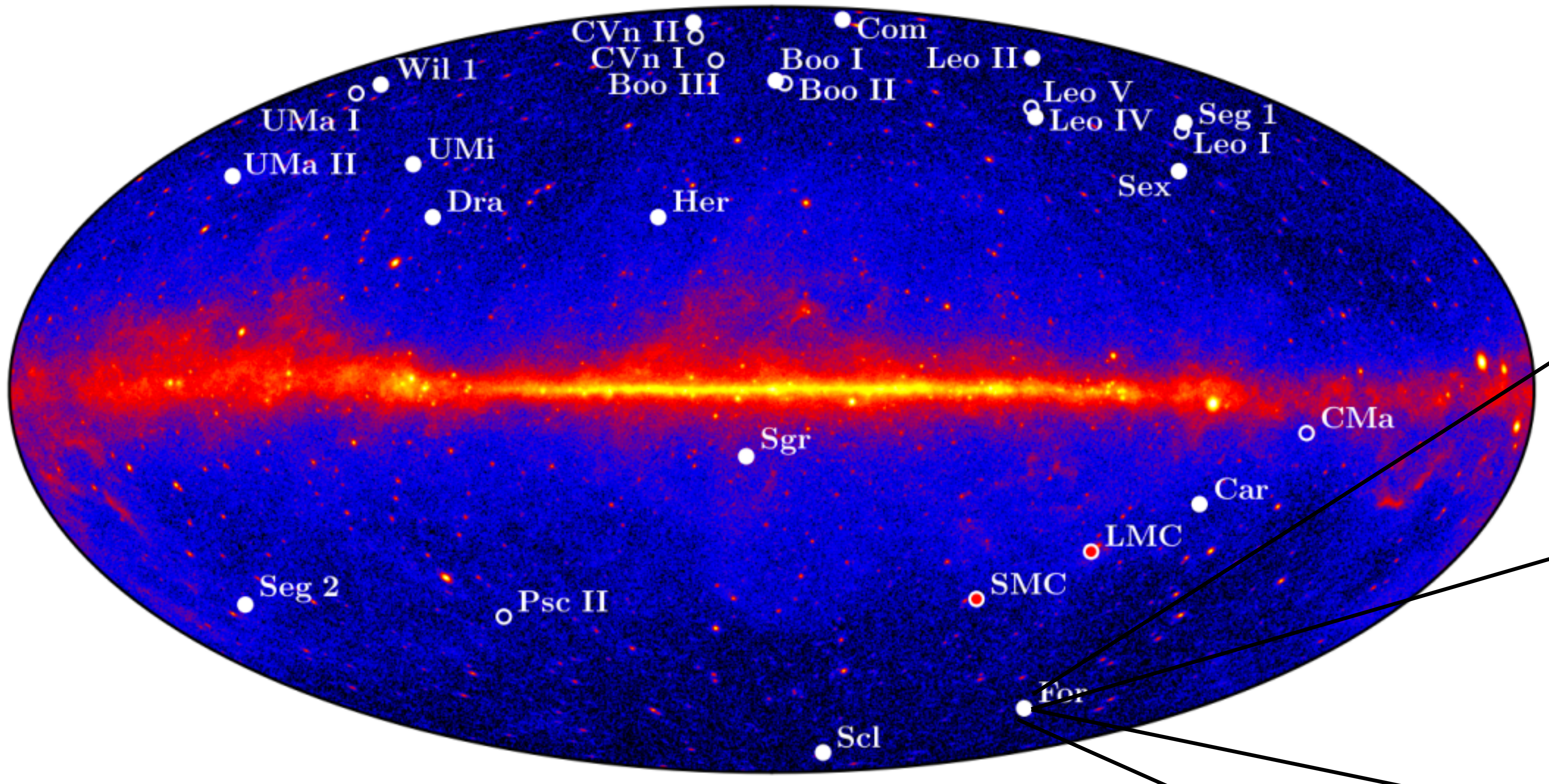
Limits from dwarf spheroidal galaxies



$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell,\psi)\right]^2$$

Fermi-LAT Collaboration, PRL'11

Limits from dwarf spheroidal galaxies



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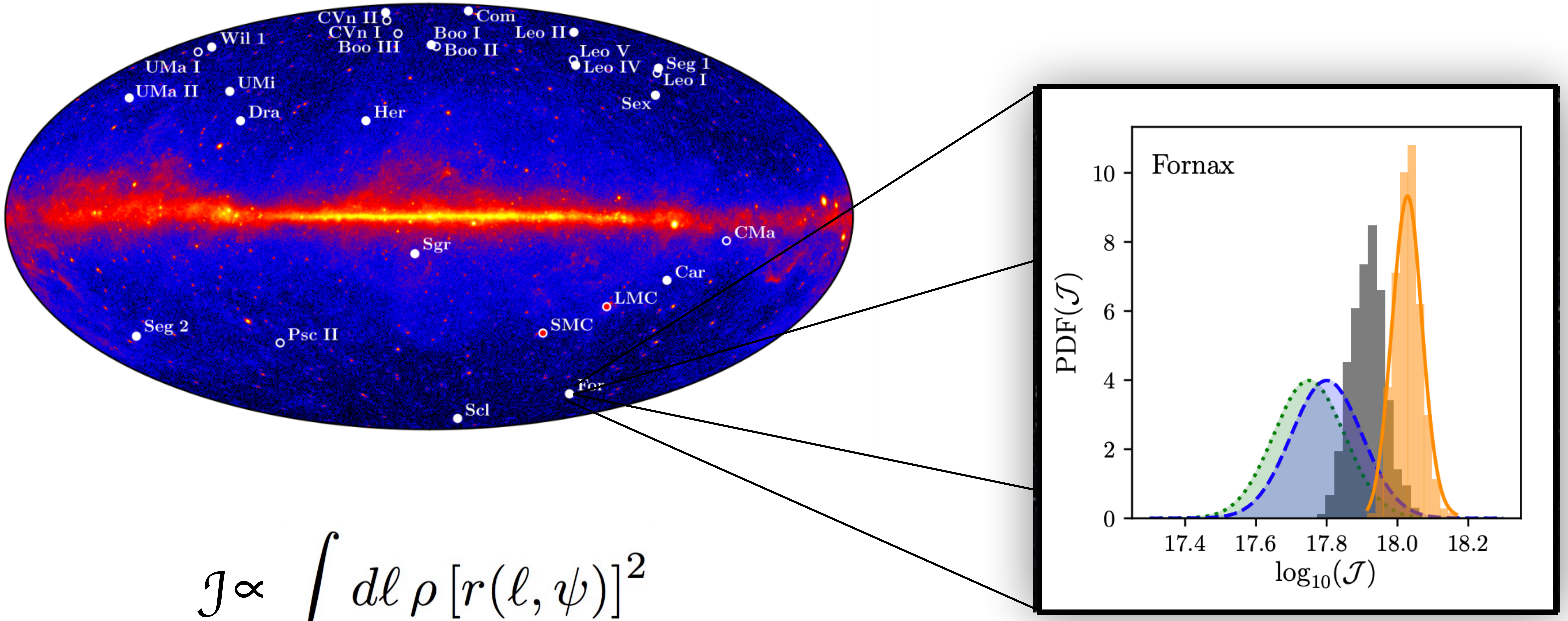
Fermi-LAT Collaboration, PRL'11

Credit: ESO/Fornax galaxy

Limits from dwarf spheroidal galaxies



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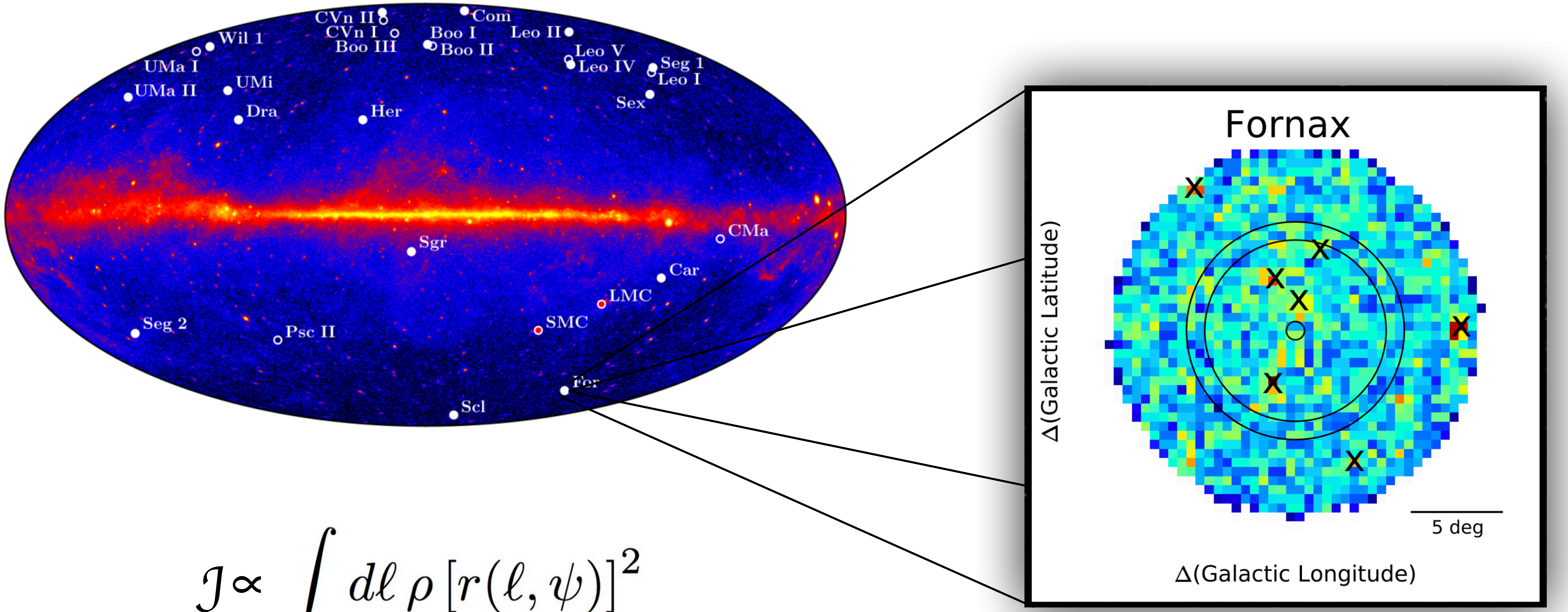
Fermi-LAT Collaboration, PRL'11

GRAVSPHERE
Alvarez, FC+ JCAP'20

Limits from dwarf spheroidal galaxies



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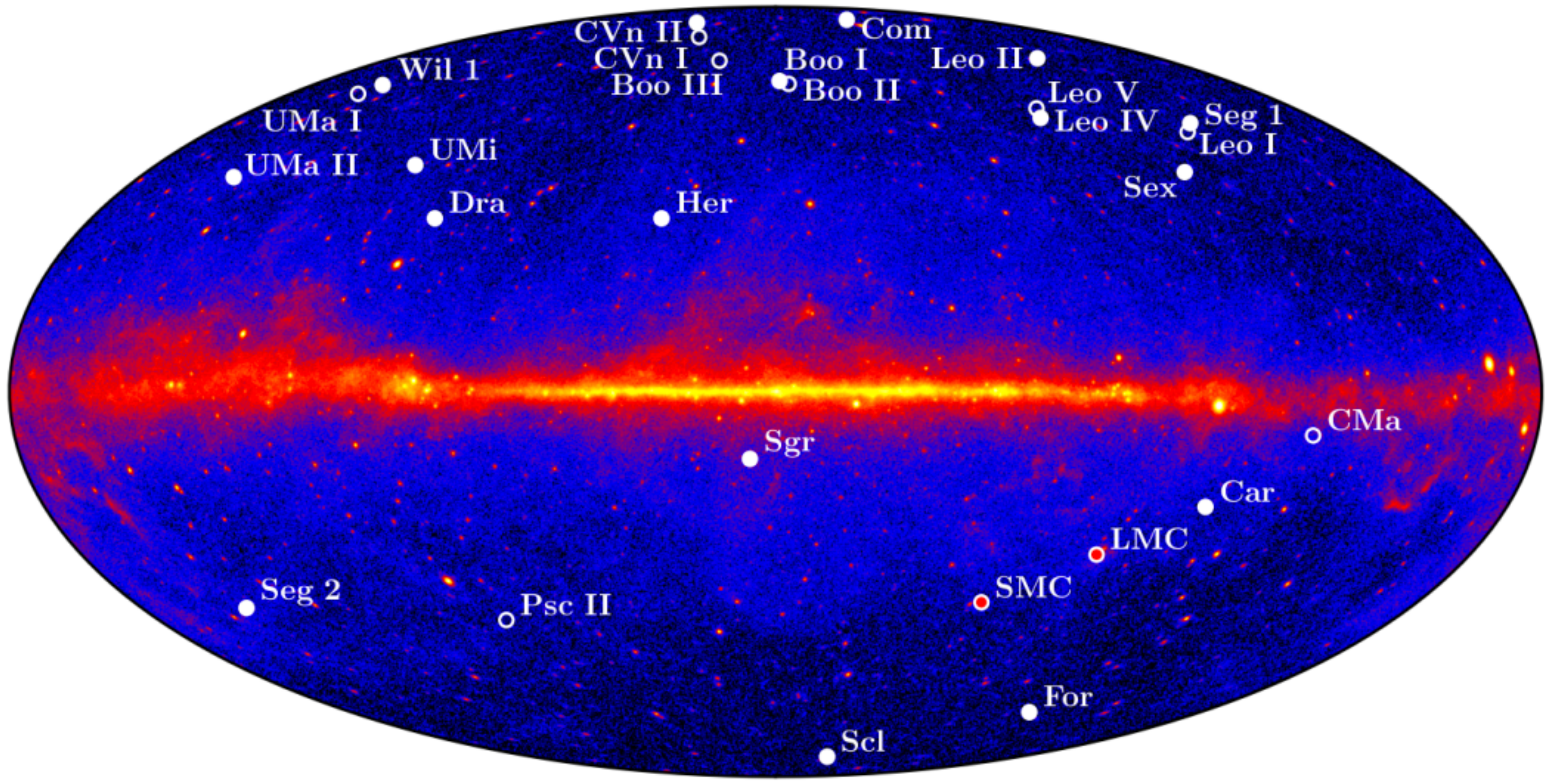
Fermi-LAT Collaboration, PRL'11

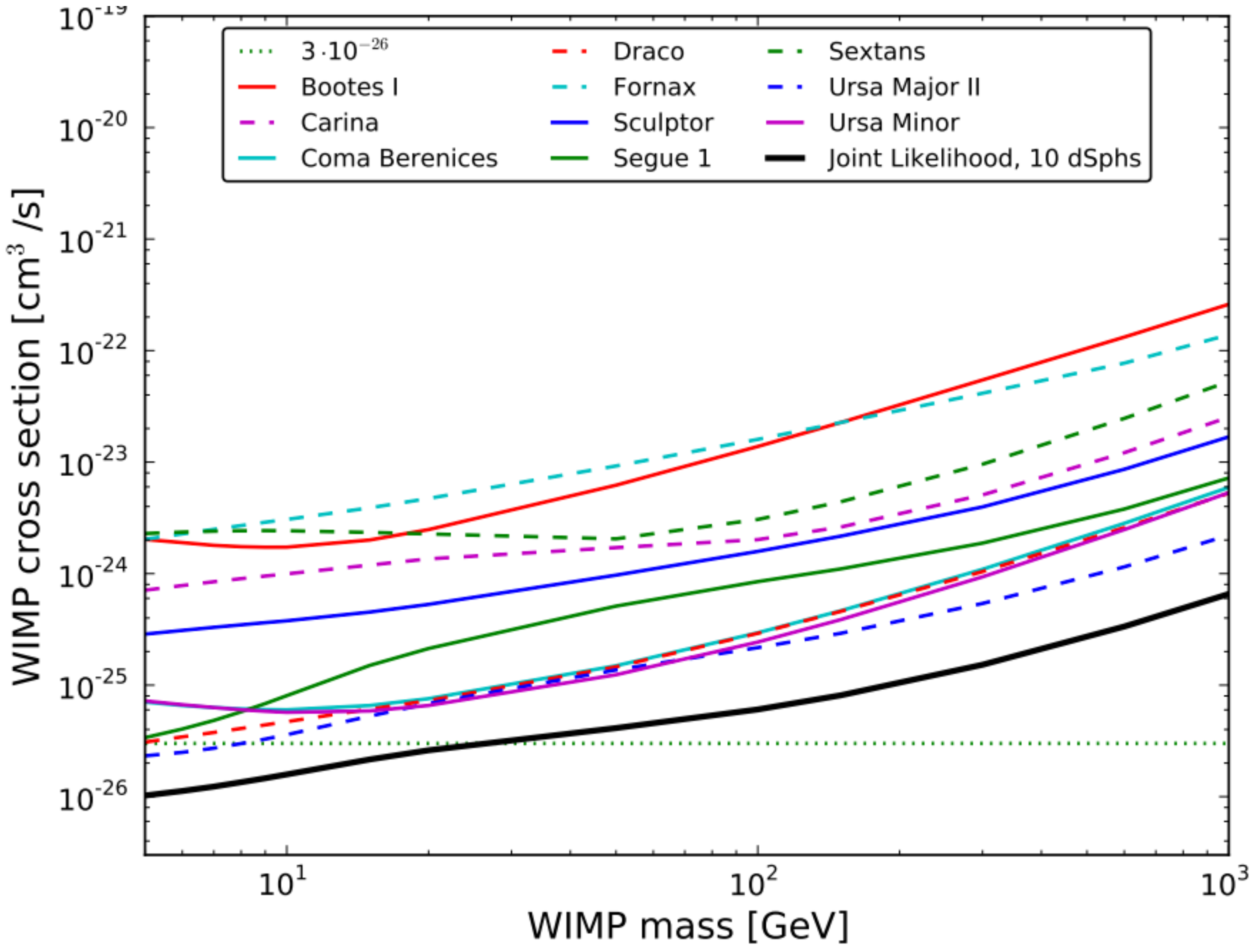
Mazziotta+Astrop. Phys.'12

Limits from dwarf spheroidal galaxies



$$L(D|\mathbf{pw},\{\mathbf{p}\}_i) = \prod_i L_i^{\mathrm{LAT}}(D|\mathbf{pw},\mathbf{p}_i)$$

$$\times \frac{1}{\ln(10)\, J_i\sqrt{2\pi}\sigma_i} e^{-\left[\log_{10}(J_i)-\overline{\log_{10}(J_i)}\right]^2/2\sigma_i^2}$$



Analysing dSphs as a group results in sensitivity competitive with other targets => **Stacking technique**

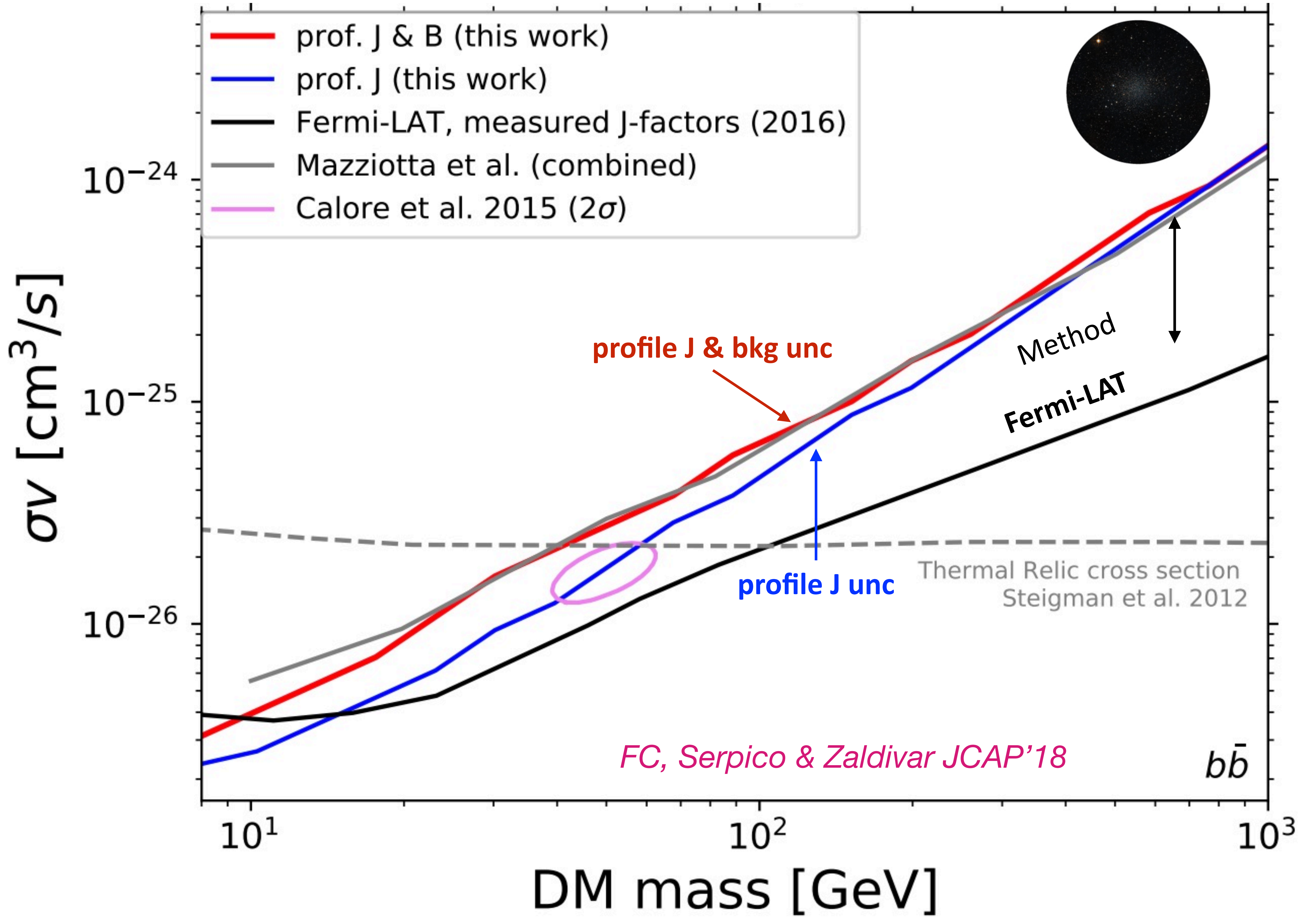
Fermi-LAT Collaboration, PRL'11

$$\mathcal{J} \propto \int d\ell\, \rho\left[r(\ell,\psi)\right]^2$$

Limits from dwarf spheroidal galaxies

Current status

- Exclude thermal cross section below 100 GeV (16 dSphs stacking, 6 yr of data)
  Albert+ ApJ'17
- Syst unc J-factor determination for ultra-faint dSphs (tri-axiality, contamination, velocity anisotropy)
  Ullio&Valli JCAP'16; Hayashi+ MNRAS'16; Klop+ PRD'17; Ando+PRD'20
- Syst unc background mis-modelling are important (3x weaker limits)
  FC, Serpico & Zaldivar JCAP'18; Alvarez, FC+ JCAP'20
- Improved sensitivity by combining data from ~20 targets taken by 5 instruments (Fermi-LAT, MAGIC, HESS, VERITAS, HAWC)
  Armand ICRC21



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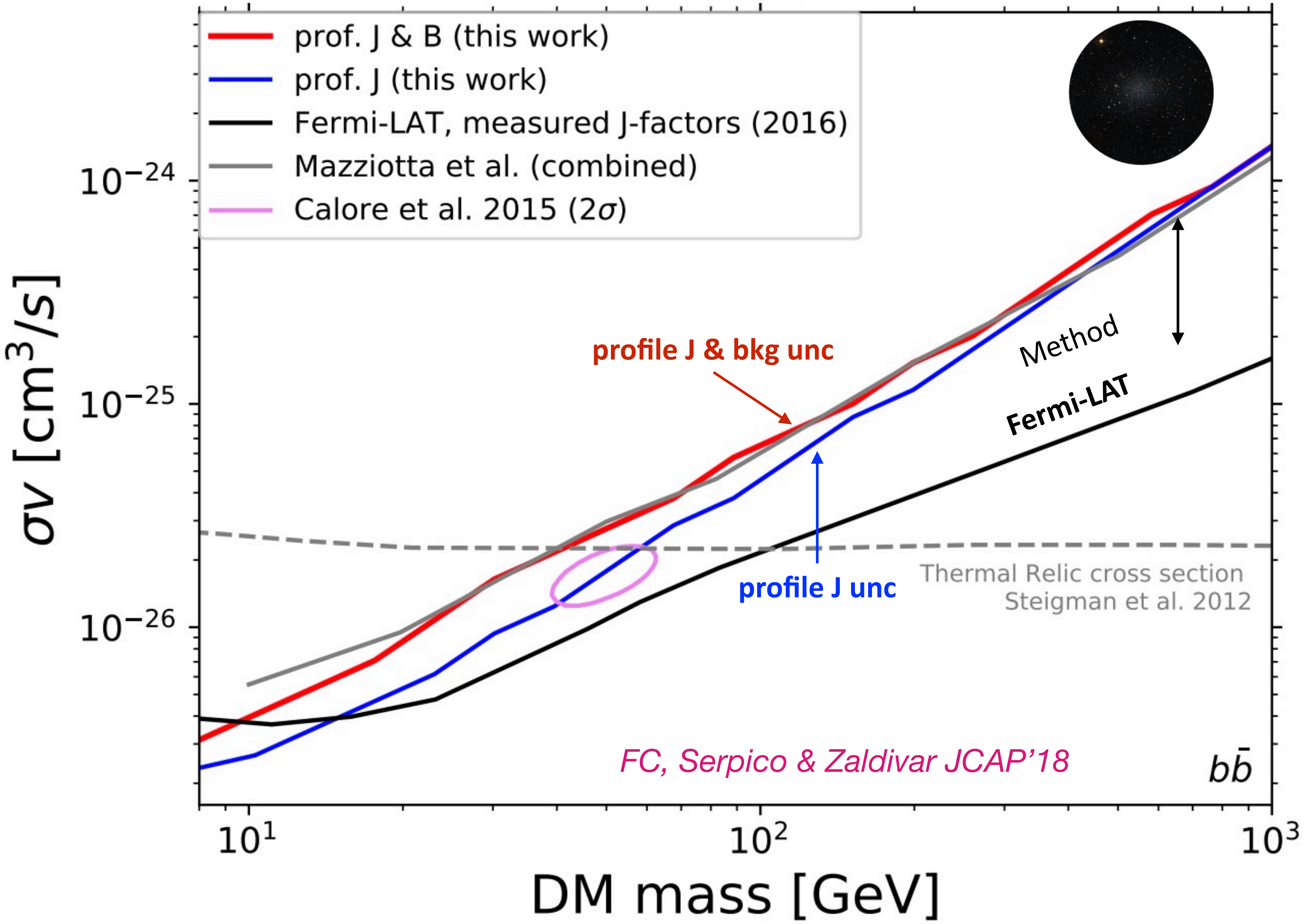


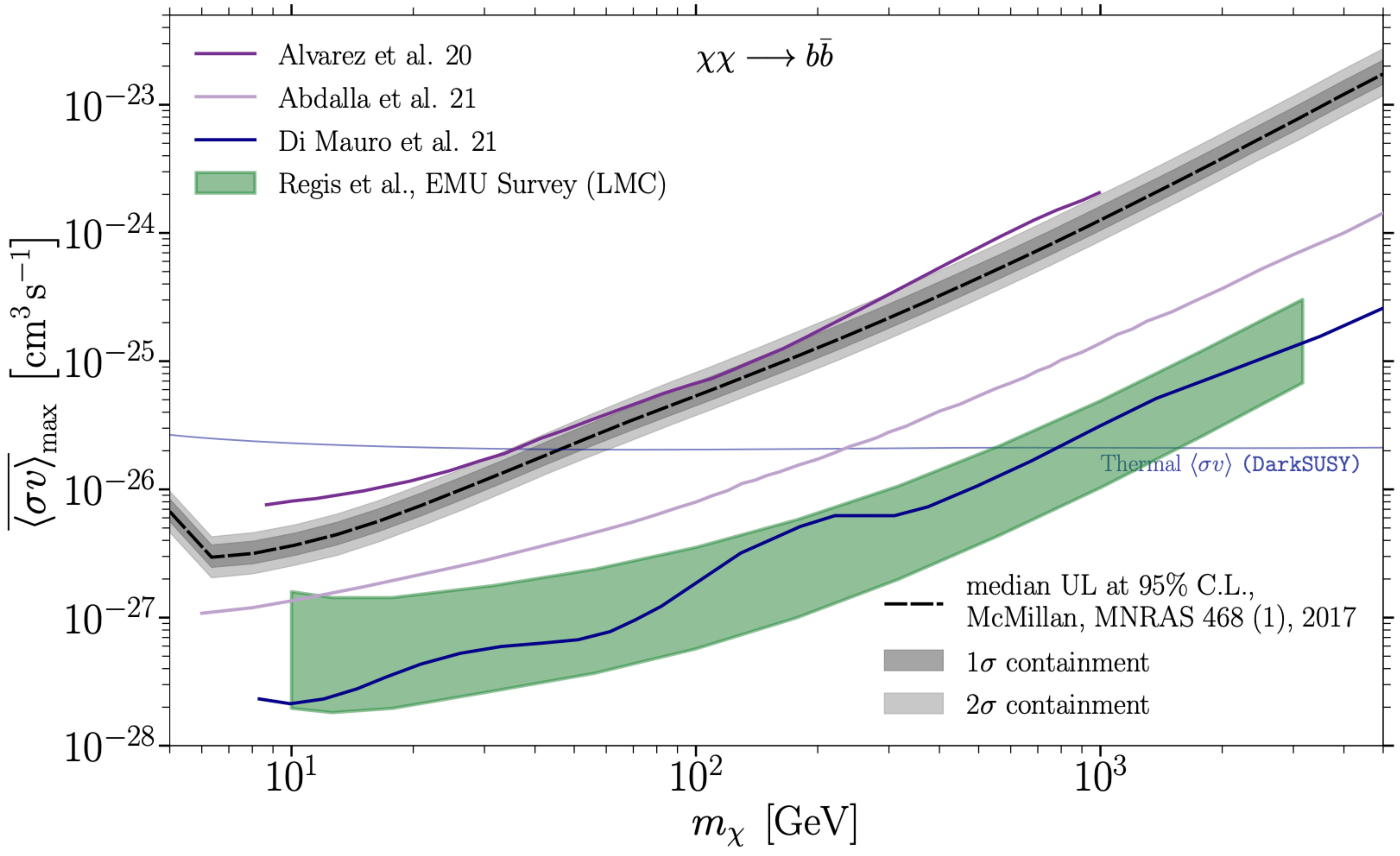
TAKE AWAY: Typically strong probes but keep in mind systematics

Limits on annihilating WIMPs

Summary of multi-targets and MW constraints

~ a few GeV — few TeV

Eckner, FC+ 2208.03312



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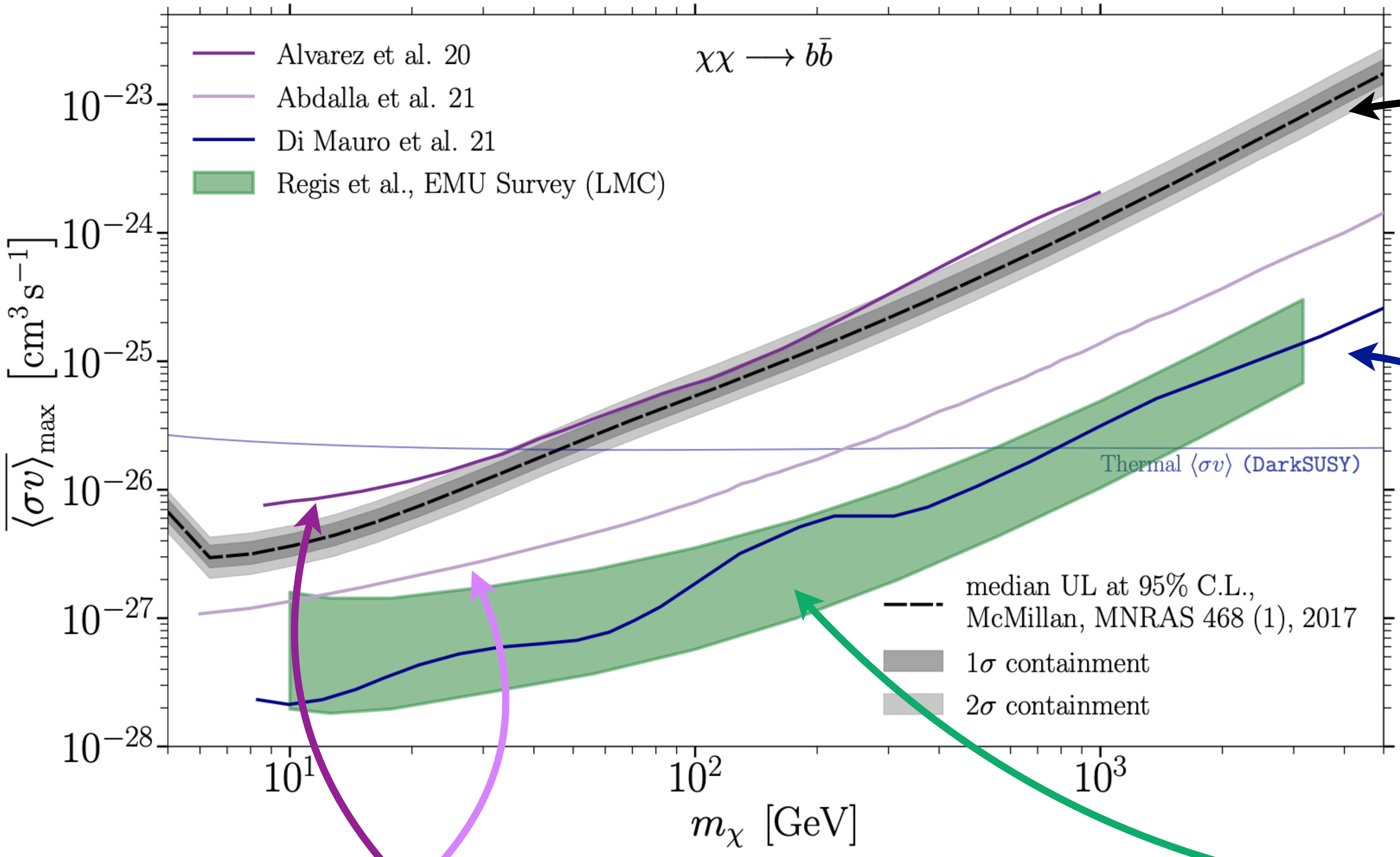
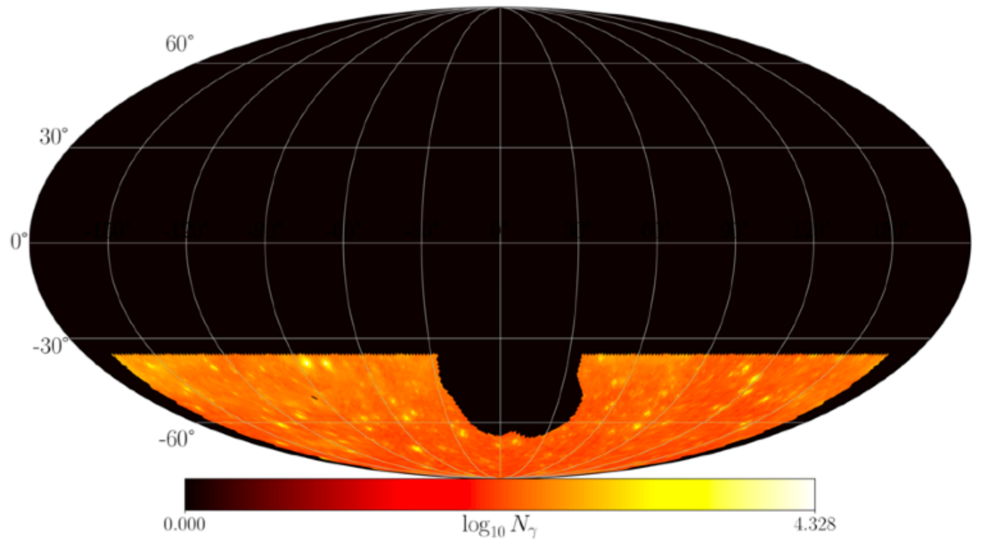


High-latitude Fermi-LAT sky

Eckner, FC+ In preparation



Anti-protons

Di Mauro+ PRD'21, Calore+ SciPost'22

Fermi-LAT dwarf galaxies

Alvarez, FC+ JCAP'20; Addalla+ PoS'21

Radio LMC

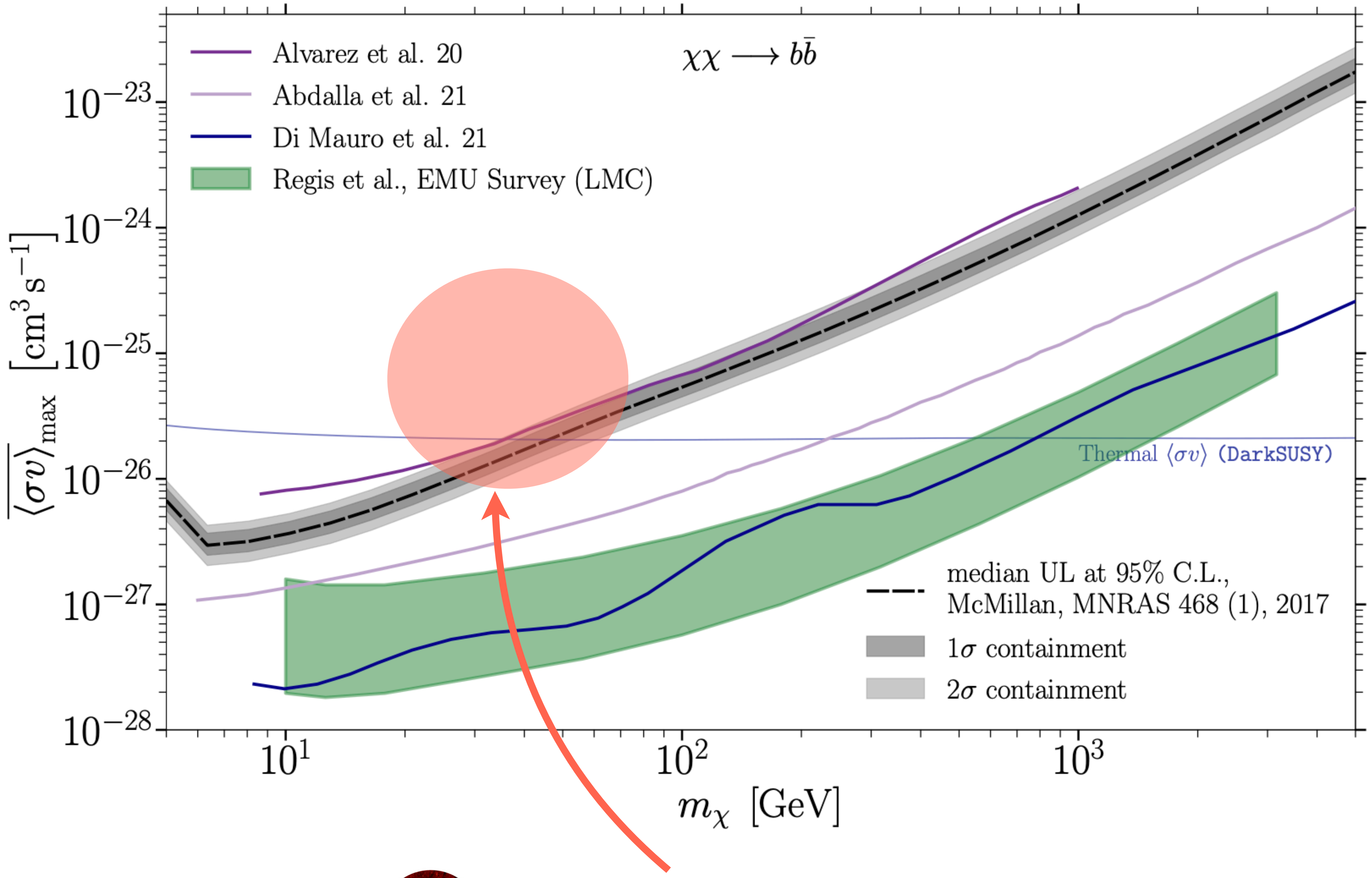
Regis+ JCAP'21

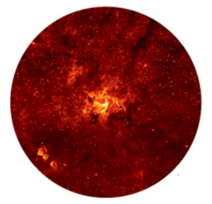
Limits on annihilating WIMPs

Summary of multi-targets and MW constraints

~ a few GeV — few TeV

Eckner, FC+ 2208.03312





Fermi GeV excess

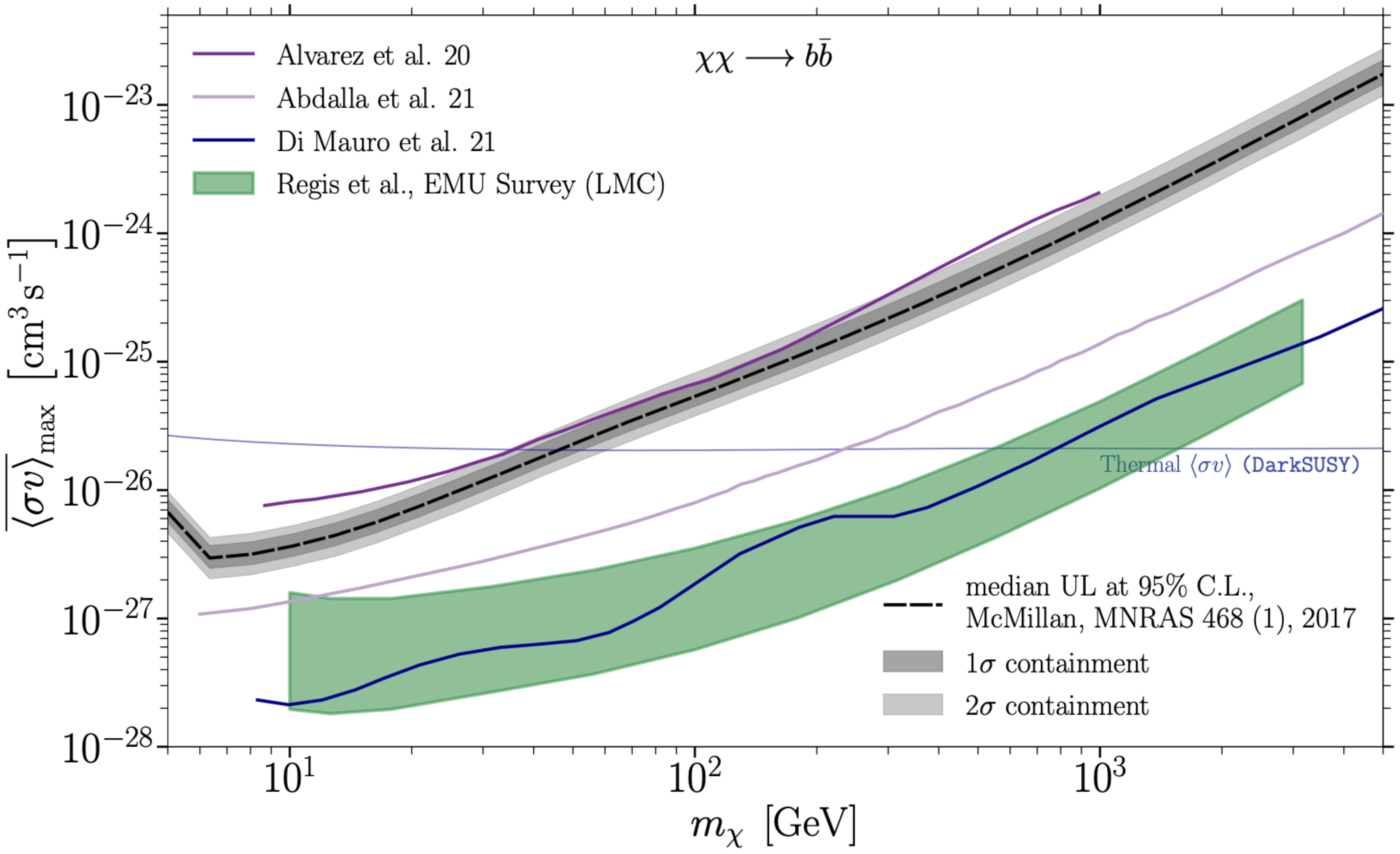
Murgia Ann.Rev.Nucl.Part'20

Limits on annihilating WIMPs

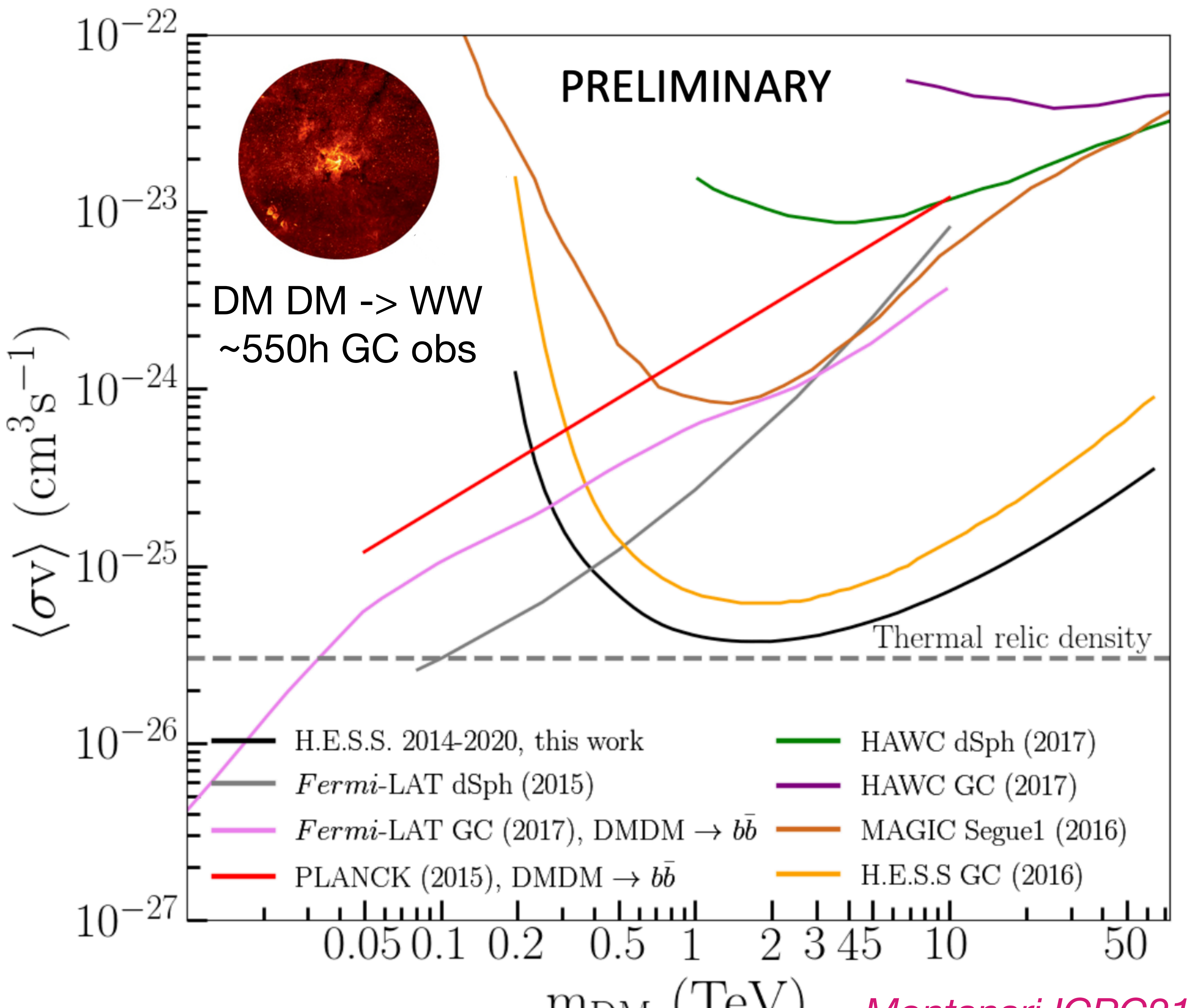
Summary of multi-targets and MW constraints

~ a few GeV — few TeV

Eckner, FC+ 2208.03312



0.2 TeV — 50 TeV



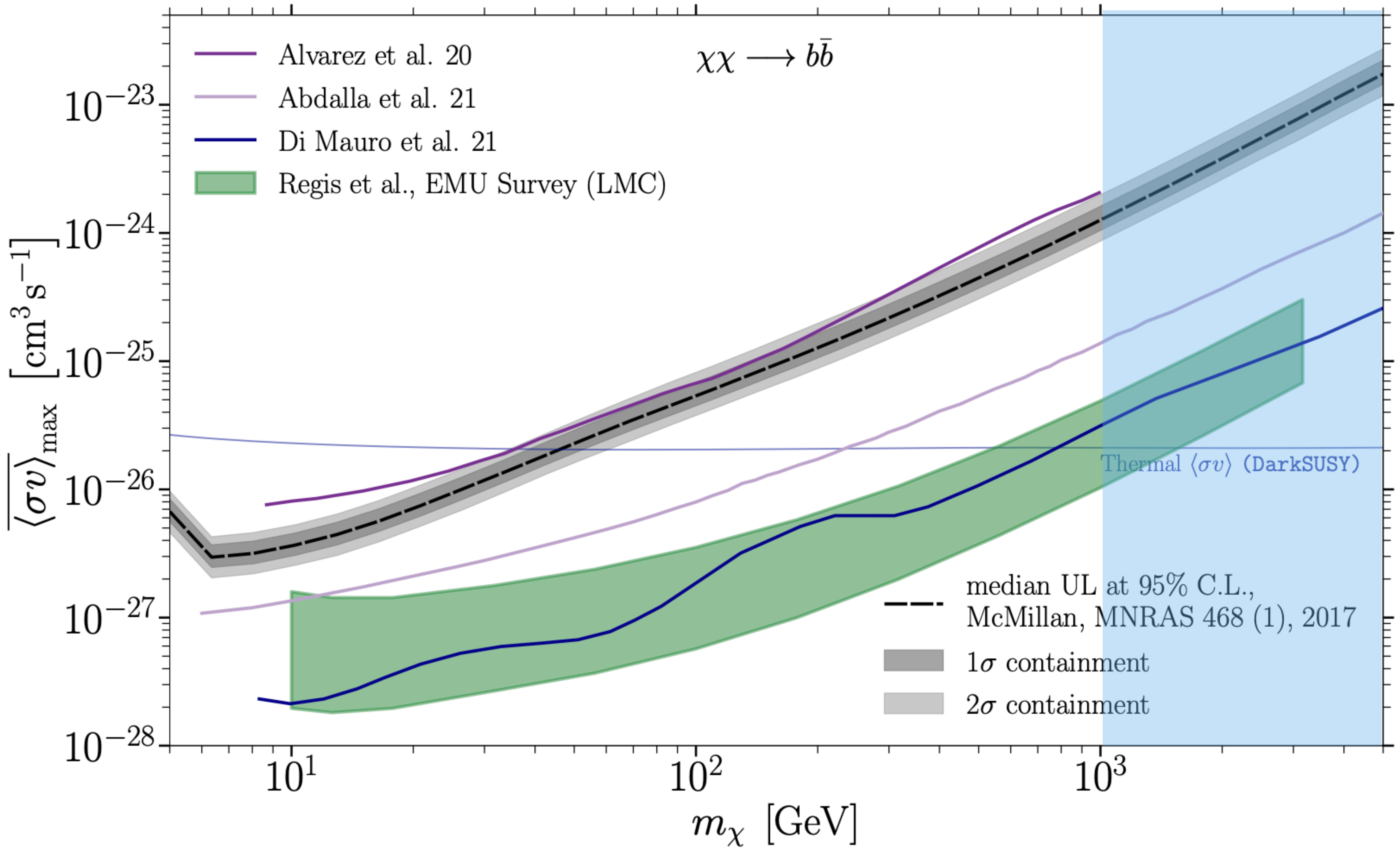
Montanari ICRC21

Prospects and opportunities

Extending the energy/mass scale

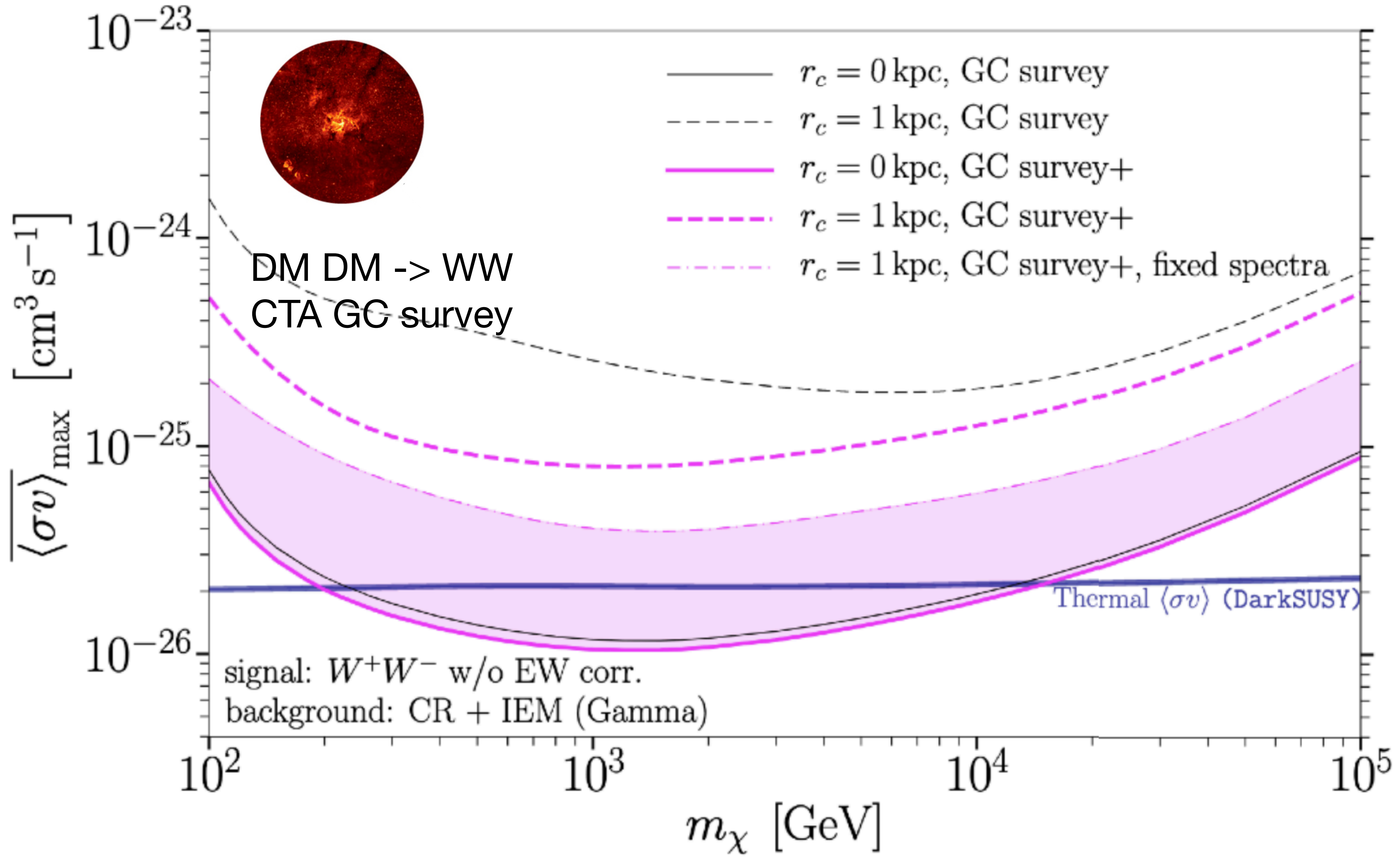
~ a few GeV — few TeV

Eckner, FC+ 2208.03312



TeV frontier

HAWC, CTA, SWGO



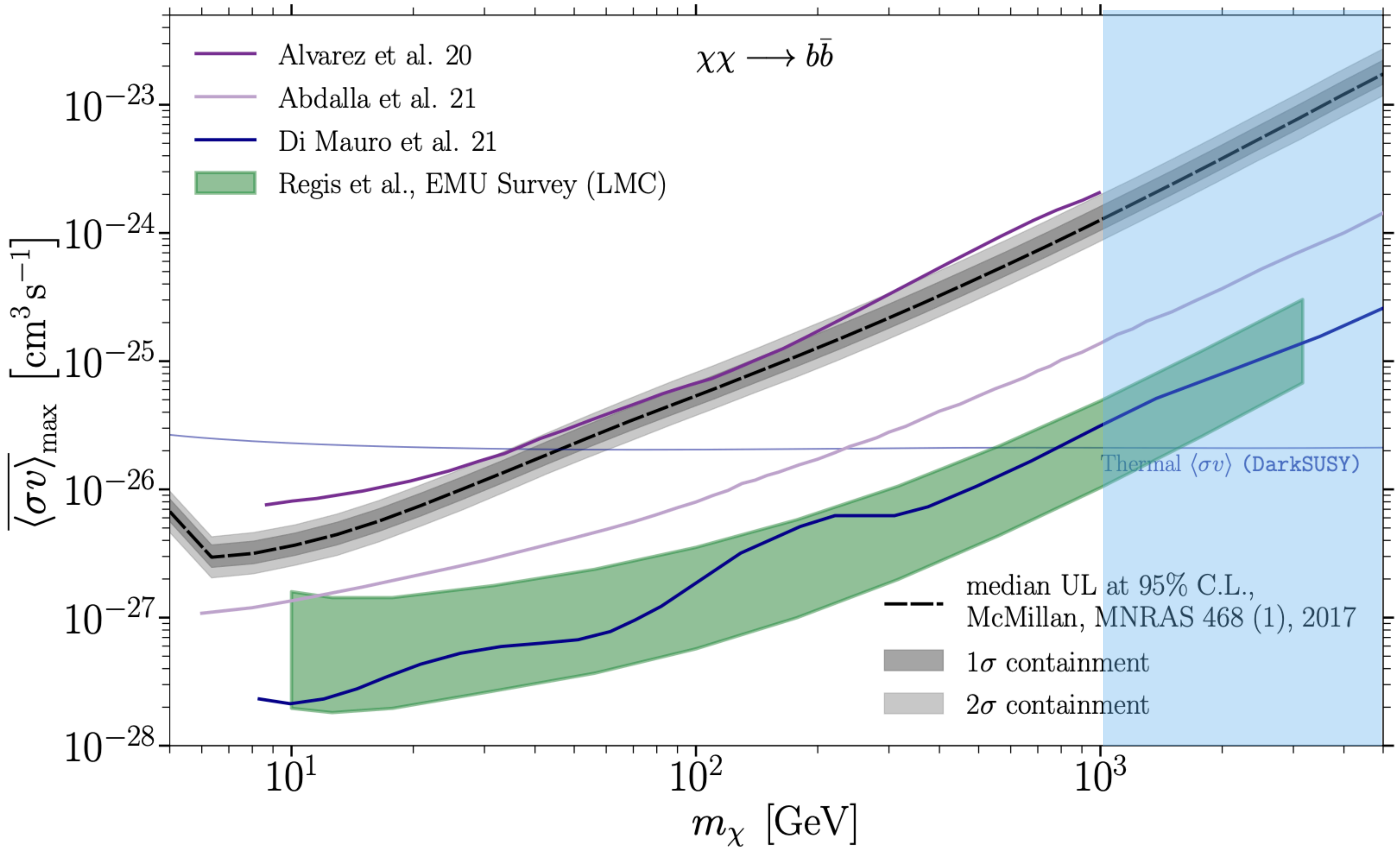
[Good prospects for decaying dark matter, together with HE neutrinos, e.g. *Esmaili & Serpico, PRD'21*; *Chianese+ arXiv:2108.01678*]

Prospects and opportunities

Extending the energy/mass scale

~ a few GeV — few TeV

Eckner, FC+ 2208.03312



Sub-PeV frontier

LHAASO,Tibet ASg

- Cannot be thermally produced (WIMpy) DM, since you hit the unitarity bound

Griest & Kamiomkowski, PRD' 90

- Viable production mechanisms for PeV DM exist, e.g. inflation decay in low-scale reheating scenarios

Harigaya+ 1402.2846

- The signal should come through decay and should appear in neutrino fluxes even before gamma rays

Feldstein+ PRD'13; Esmaili & Serpico, JCAP'13;
Chianese+ arXiv:2108.01678

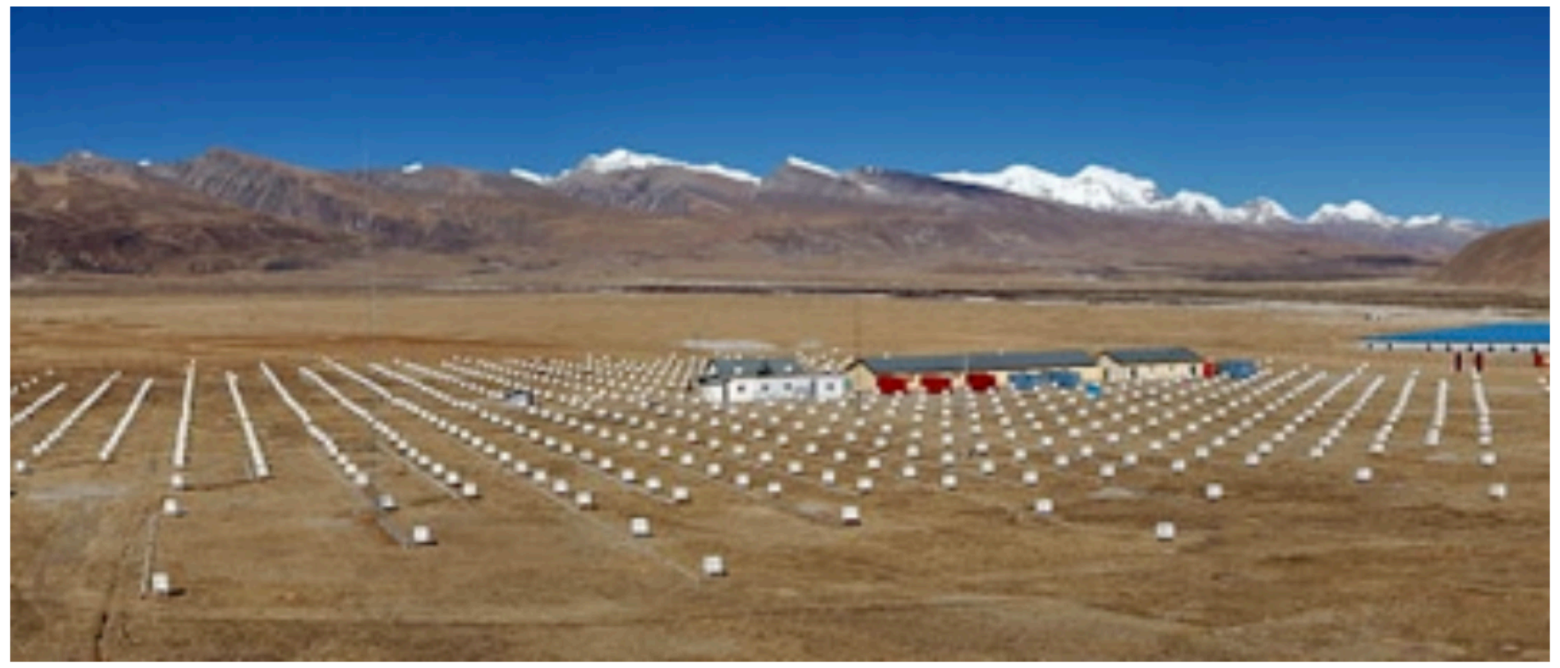
→ These data often provide *best bounds* to heavy DM lifetime

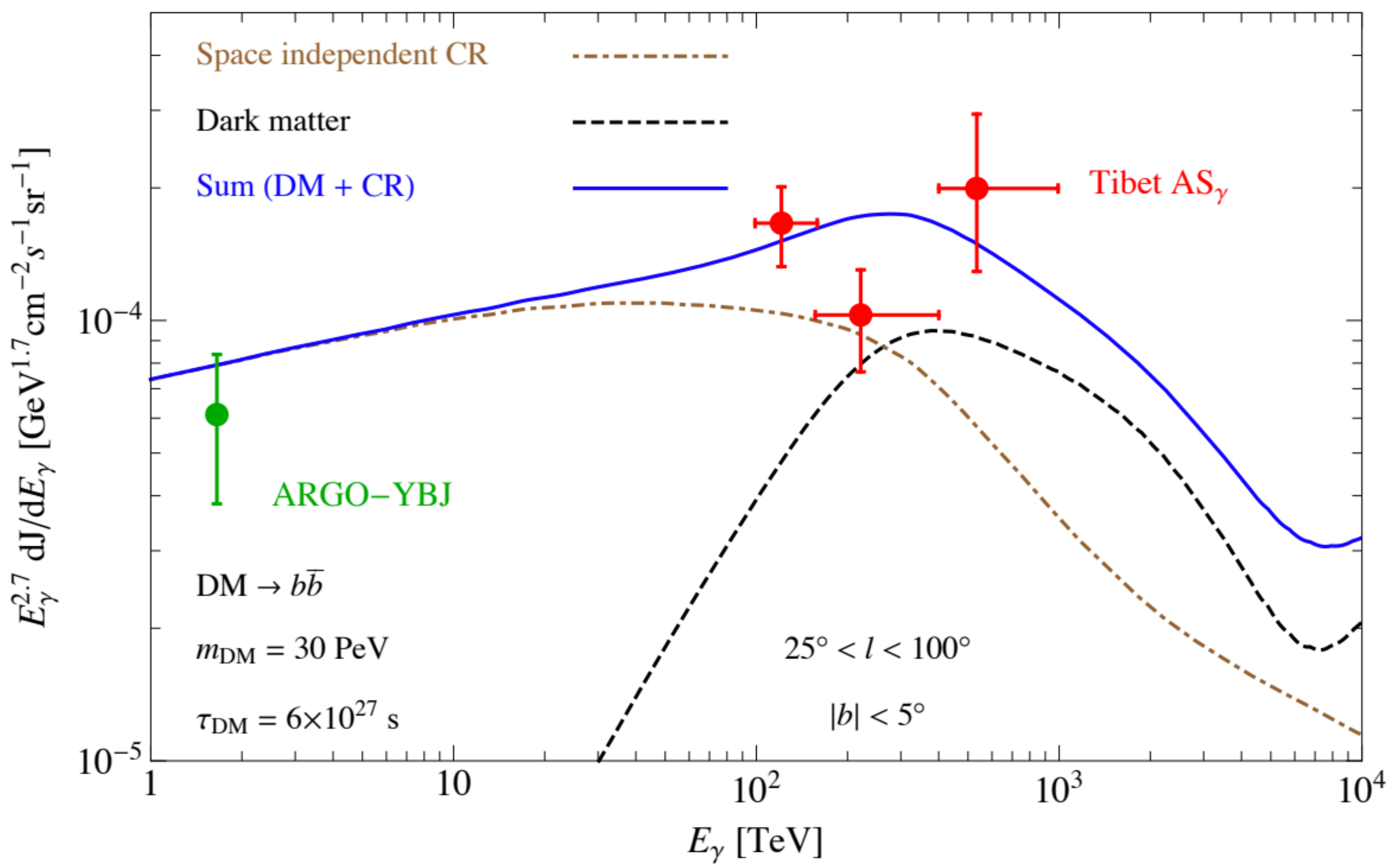
VHE gamma rays: sub-PeV dark matter

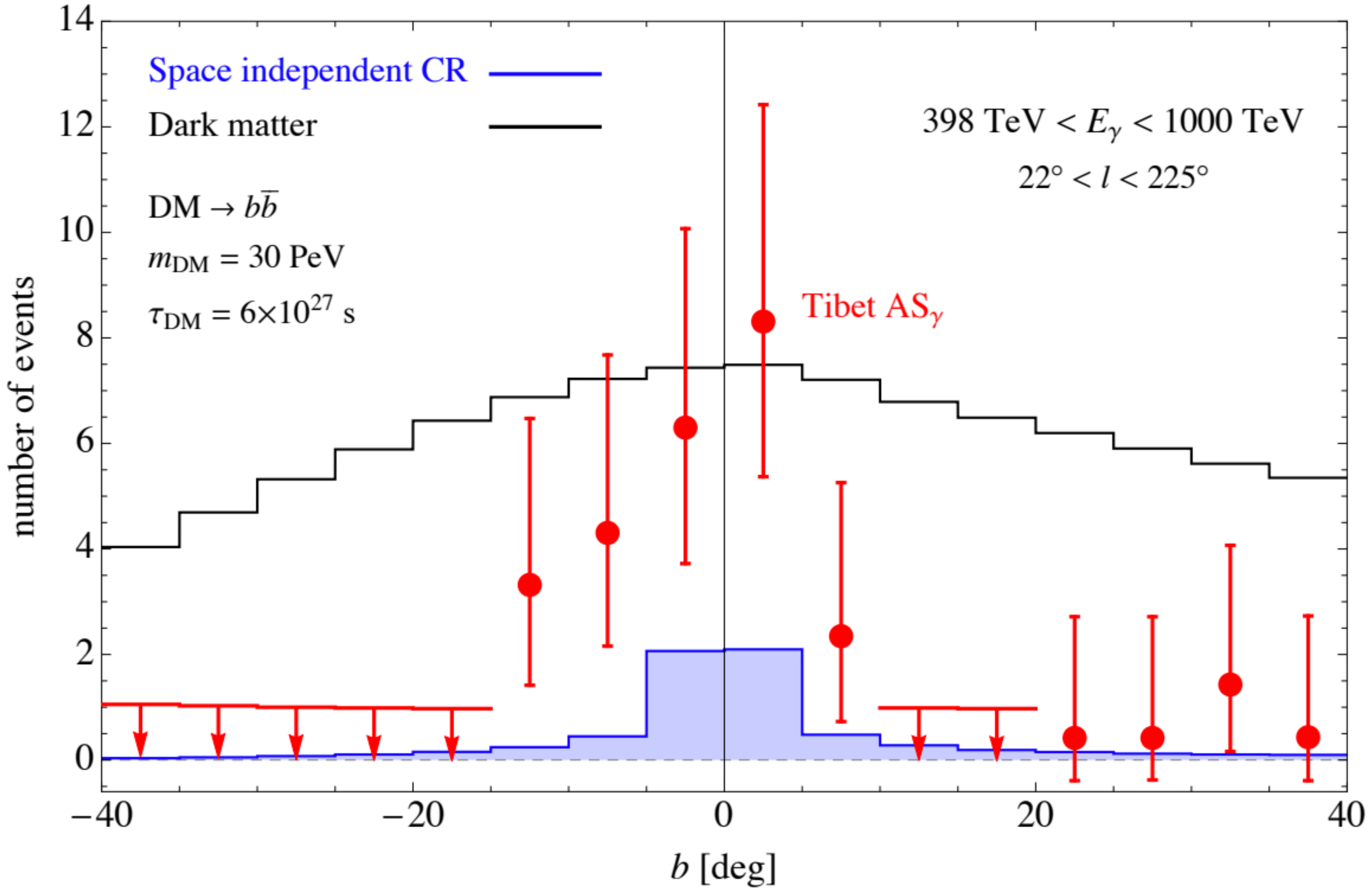
First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies

M. Amenomori *et al.* (Tibet AS_γ Collaboration)

Phys. Rev. Lett. **126**, 141101 – Published 5 April 2021





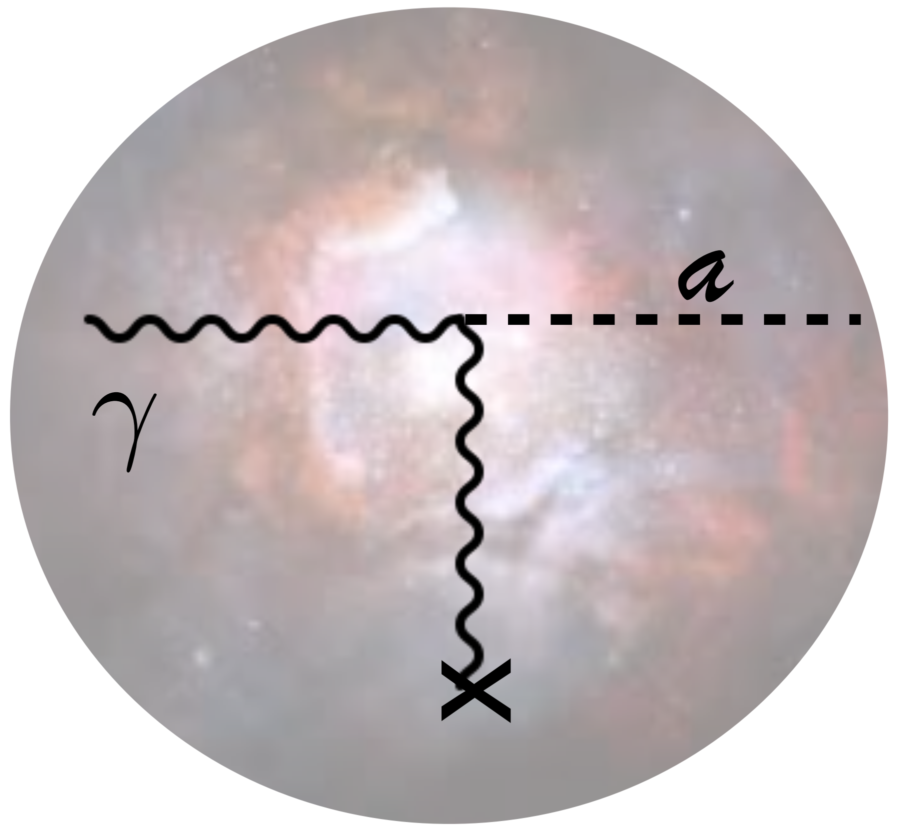


DM spectrum ok, but unacceptable angular distribution of photons

Esmaili & Serpico, PRD Letters'21

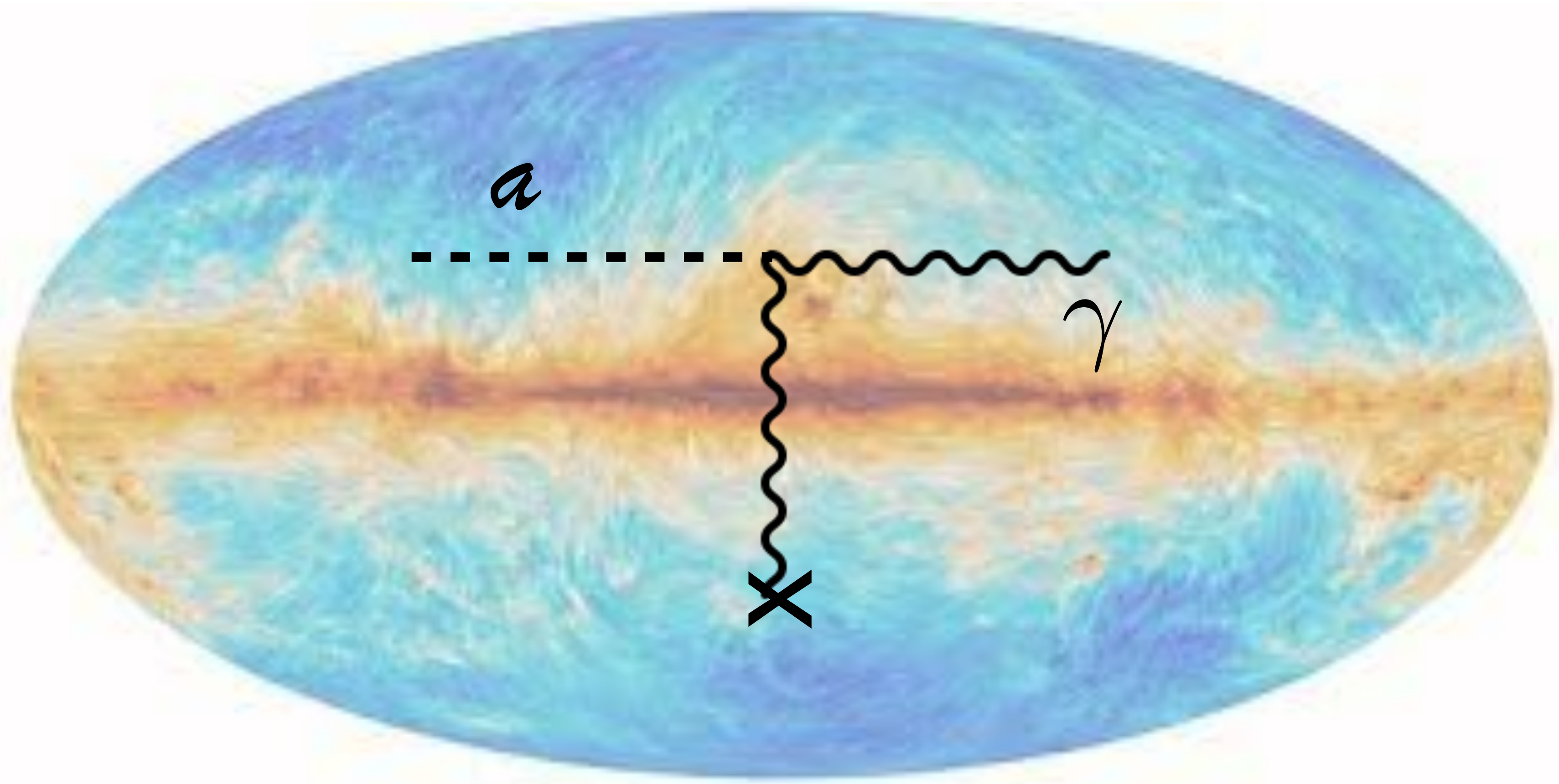
VHE gamma rays: ALPs

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

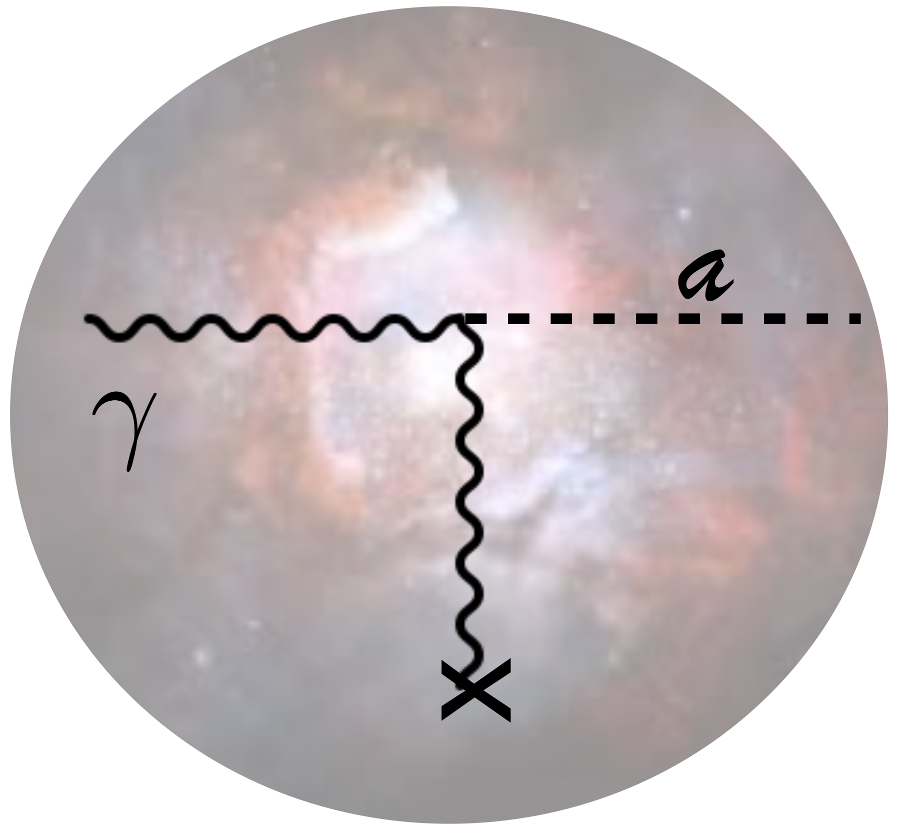


Photons produced by some sources convert into ALPs in the presence of external B-field

ALPs travel unimpeded through IGM and reach the Galaxy, where they reconvert back to photons



VHE gamma rays: ALPs

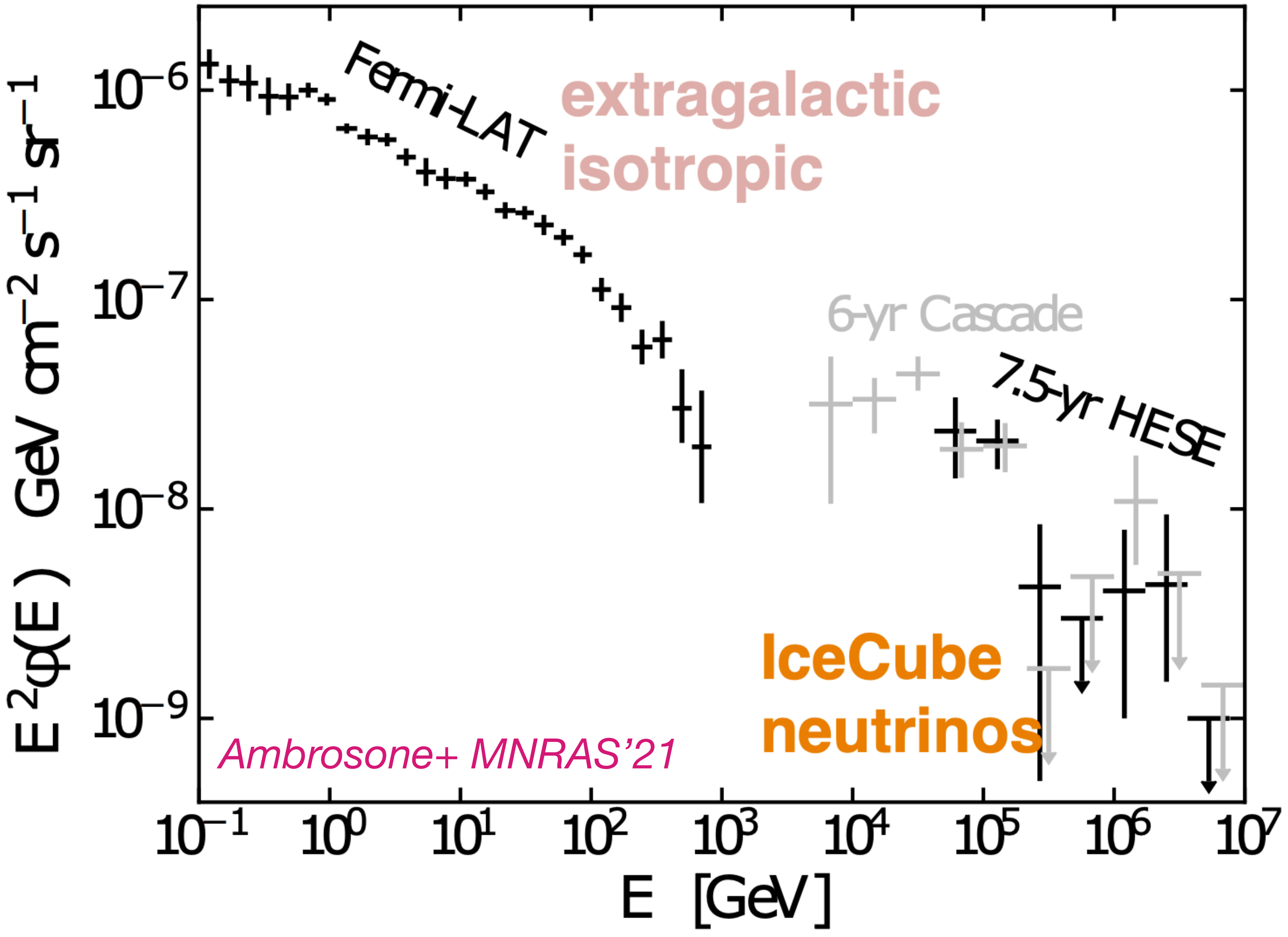


High-energy neutrinos can be produced in pp and pγ interactions from all galaxies in the universe

$$E_\nu^2 \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\left(E_\nu = \frac{E_\gamma}{2}\right) = \frac{3}{2} E_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}$$

In-situ photon spectrum, calibrated on the neutrino one

In-situ conversion into ALPs
* Interstellar medium
* Intergalactic radiation fields
* Magnetic field strength and coherence length



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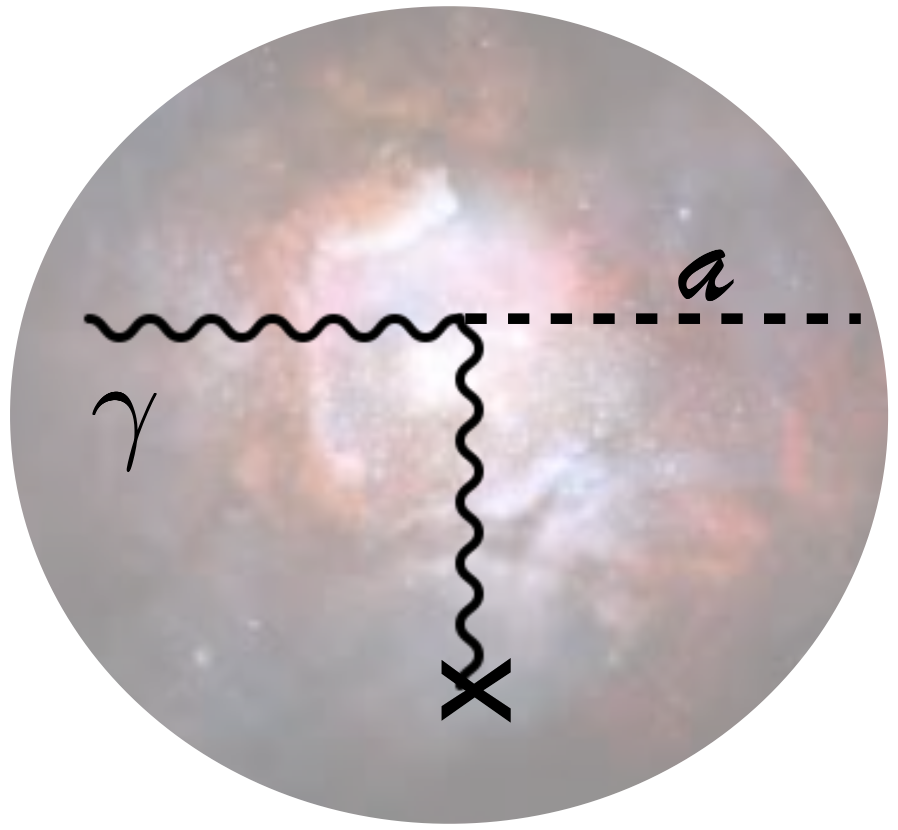

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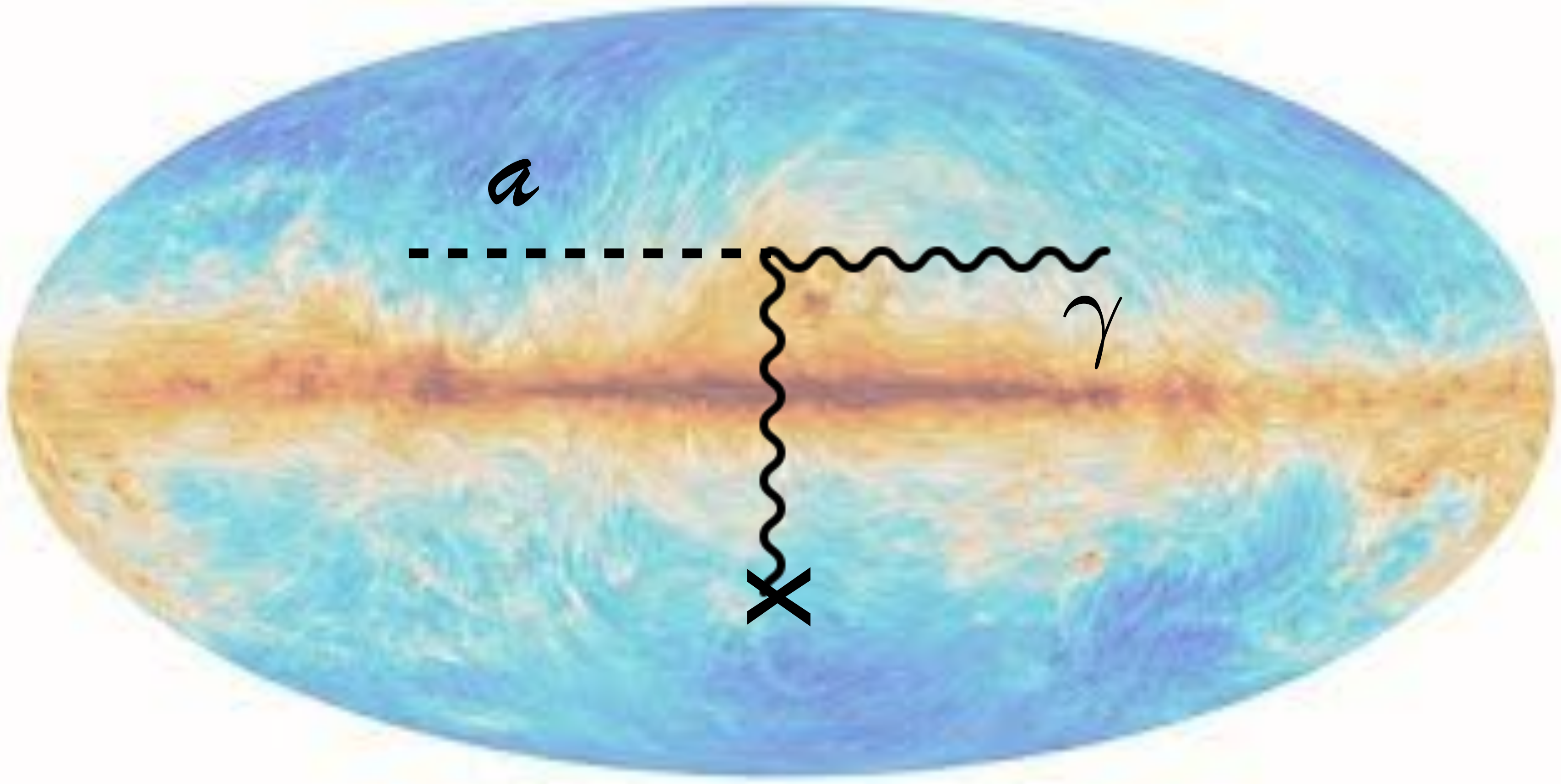

In-situ conversion into ALPs
* Interstellar medium
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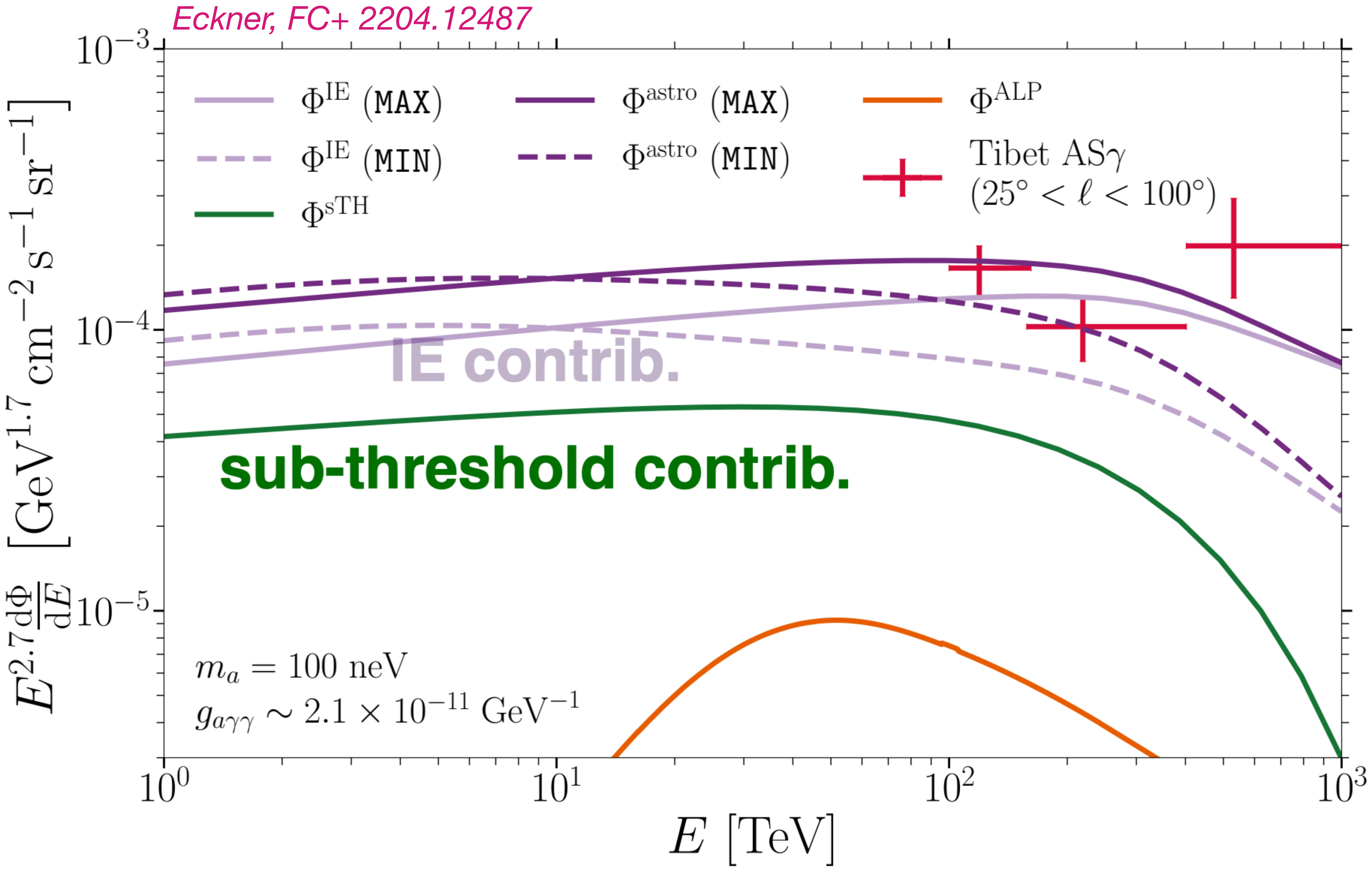
Photons from ALPs produced in sources of astro neutrinos reach Earth with **sub-PeV energies**!

VHE gamma rays: ALPs



IE contrib: diffuse emission from CR interactions with gas and ambient fields

De la Torre Luque+ 203.15759

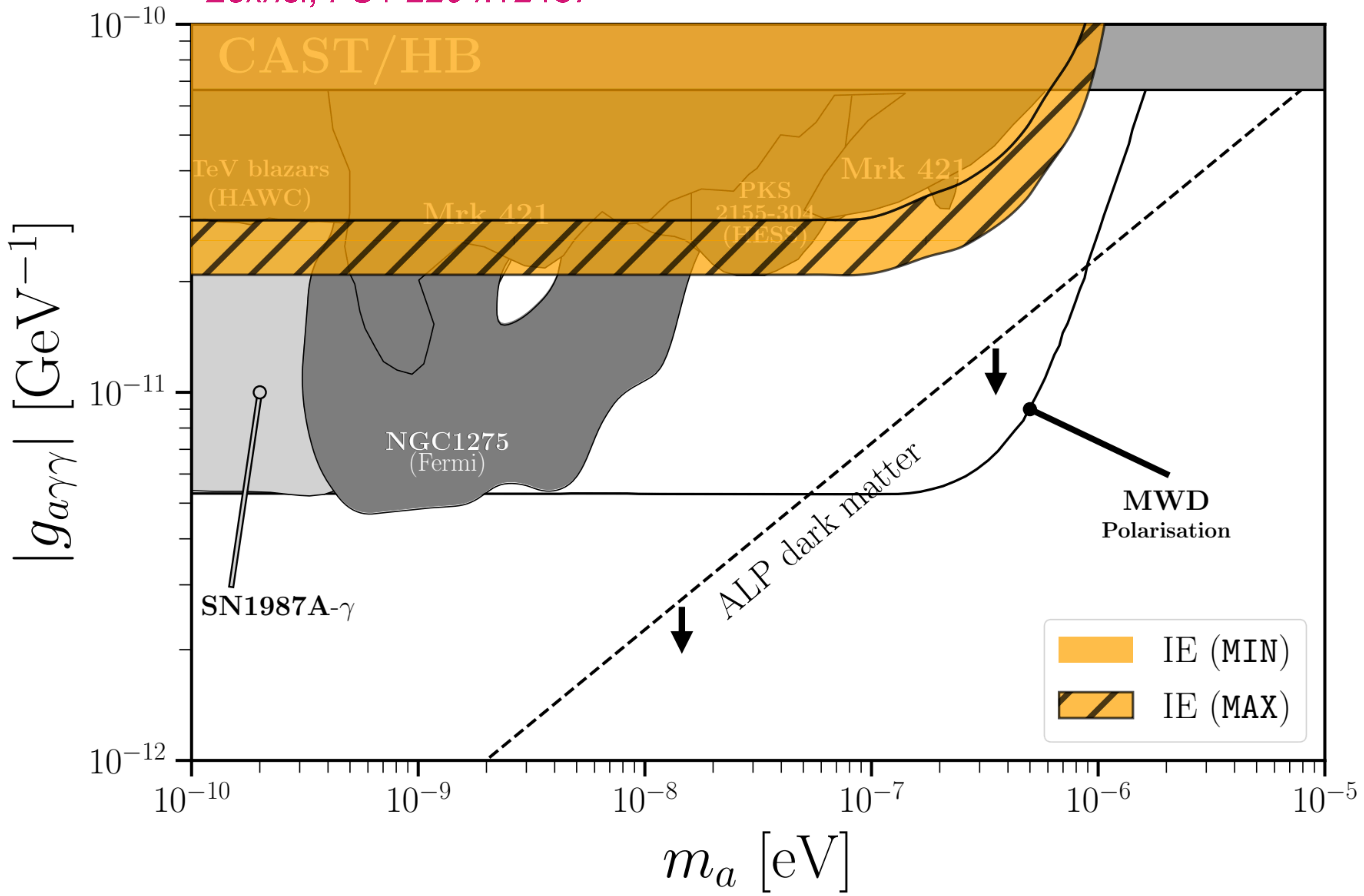
Sub-threshold contrib: sources emitting below instrument detection threshold

Vecchiotti+ 2107.14584

ALPs signal: from star-forming galaxies associated to astro neutrinos

VHE gamma rays: ALPs

Eckner, FC+ 2204.12487



- Uncertainty between minimal and maximal IE around a factor of 1.5
- Even in minimal scenario, competitive constraints
- ALPs-only constraints worse by a factor of 3
- Factor of 1.5 deterioration if B-field does not evolve with reshift

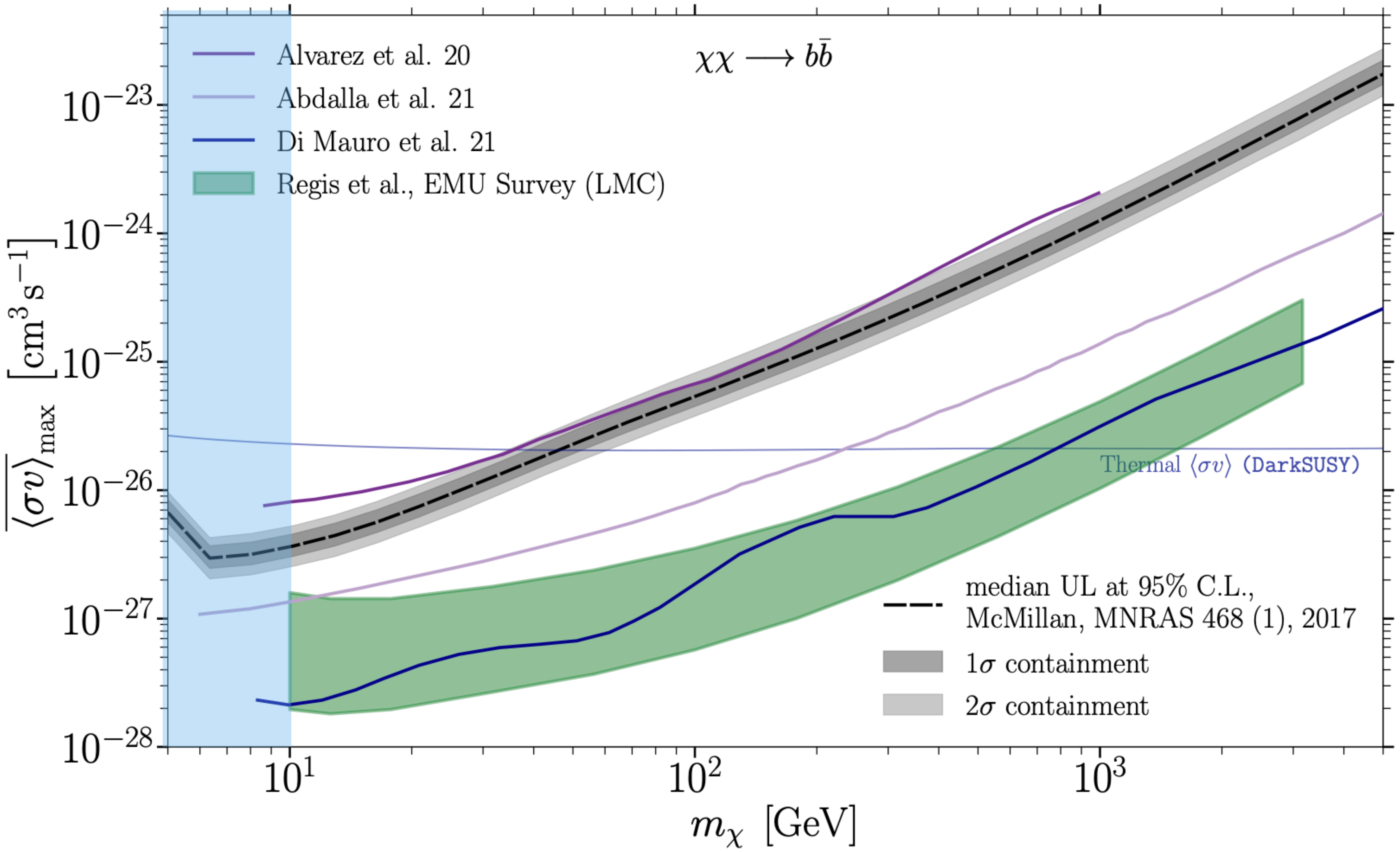
TAKE AWAY: Strong potential of VHE gamma rays (LHAASO, TibetAS-g, HAWC)

Prospects and opportunities

Extending the energy/mass scale

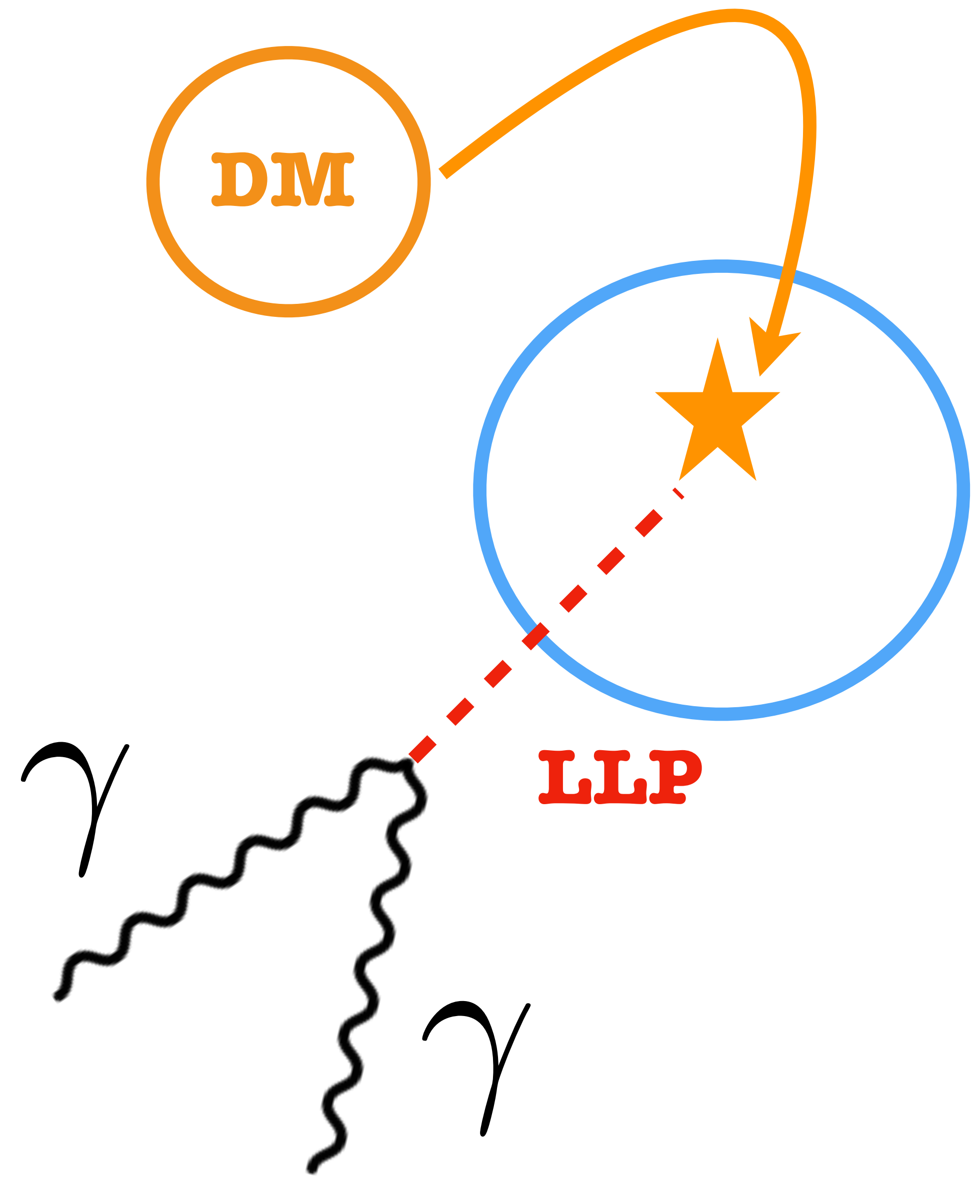
~ a few GeV — few TeV

Eckner, FC+ 2208.03312

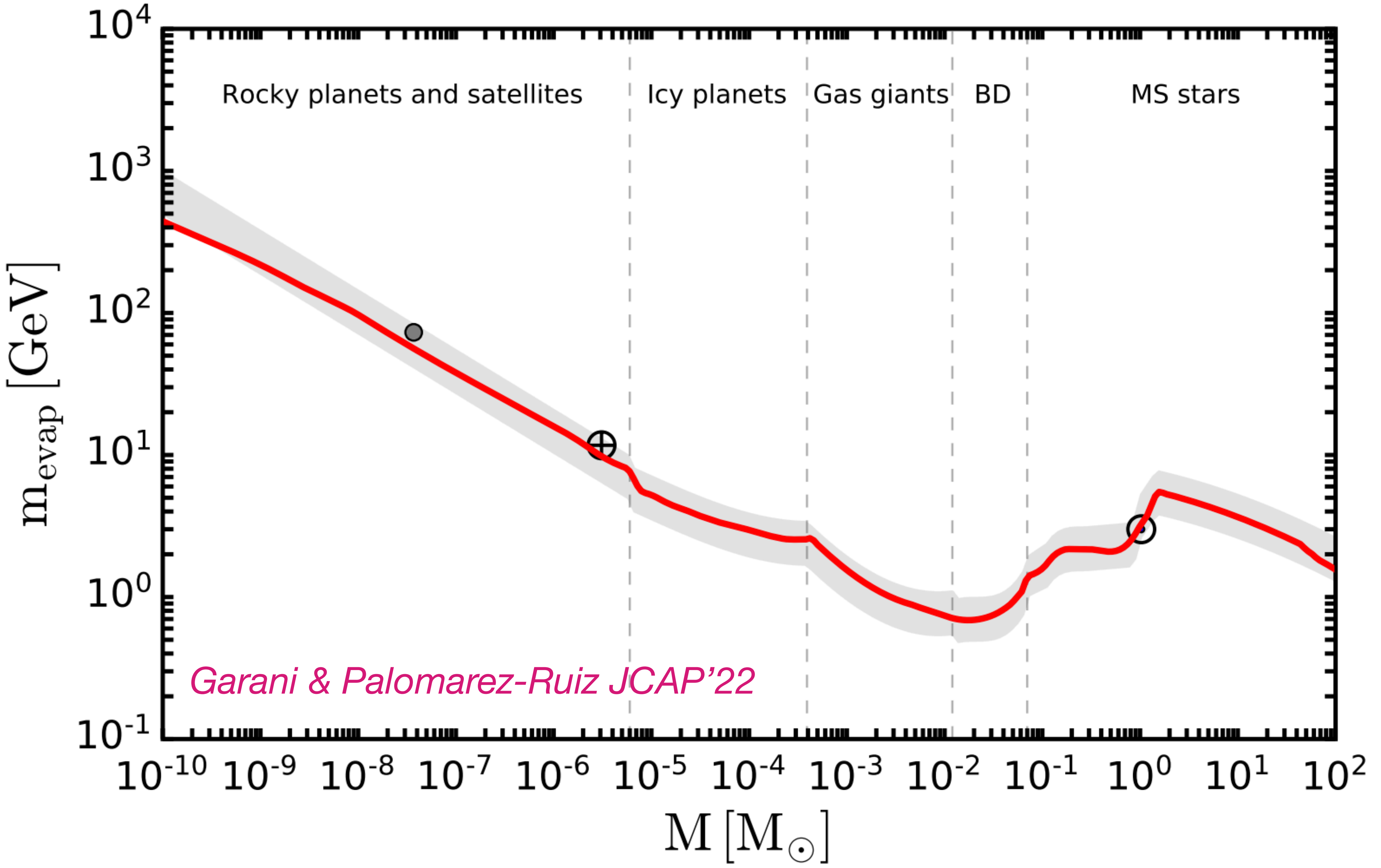


Change the model and targets

Long-lived mediators trapped in stars or celestial bodies



DM capture in celestial bodies



$$\frac{dN_\chi(t)}{dt} = \mathcal{C} - \mathcal{A}\, N_\chi^2(t) - \mathcal{E}\, N_\chi(t)$$

If evaporation not efficient and object old enough

$$N_\chi \simeq \mathcal{C}\, \tau_{eq} = \sqrt{\mathcal{C}/\mathcal{A}}$$

Optimal targets?

* Large radius => More DM captured
* High density => Easier to trap DM
* Cold temperature => Low kinetic energy to DM particles

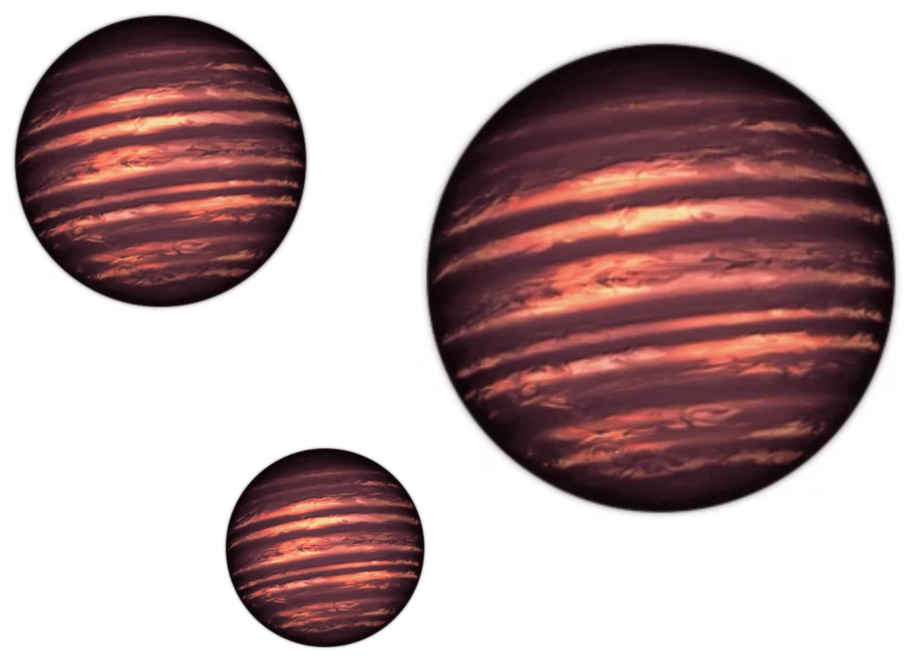
Brown dwarfs (BDs):
Big, Cold, Dense!

+ Large statistics (> 800 objects within 100 pc)
+ Very nearby (closest at 2 pc)
+ Up to 10^9 objects expected in the GC

Leane+ PRD'21

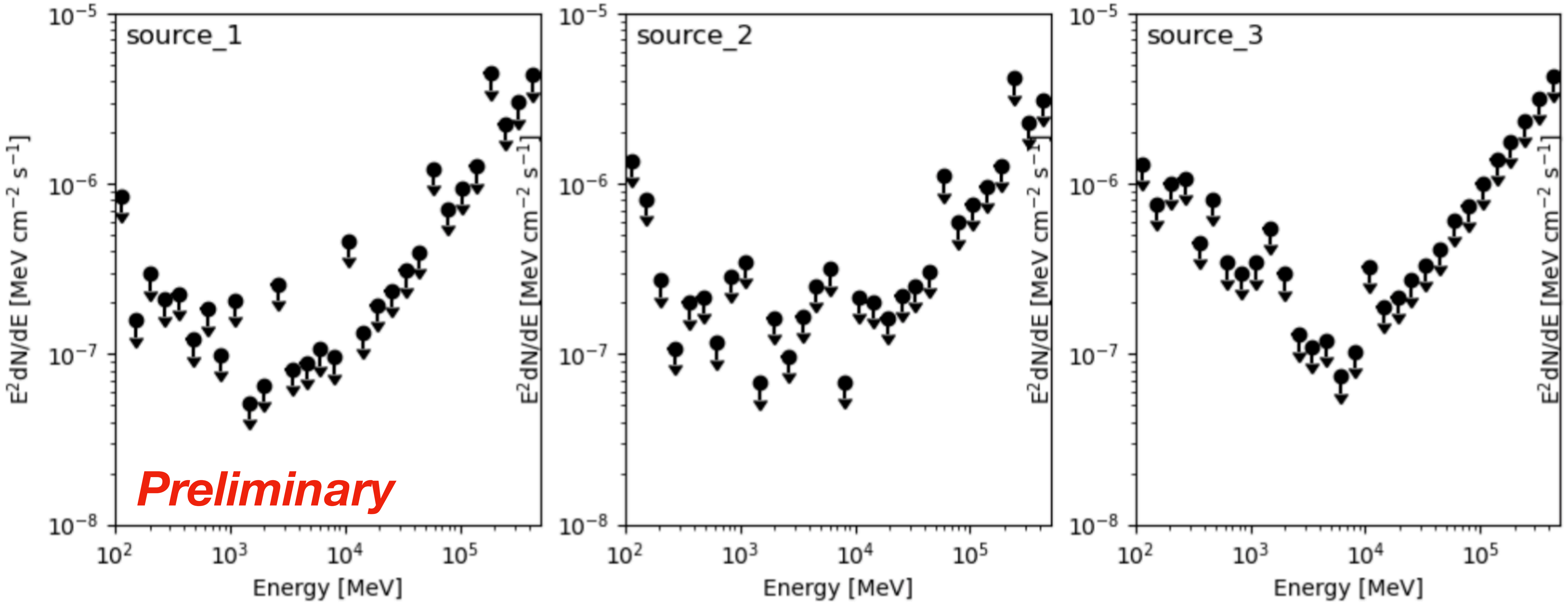
Sun (*Leane+ PRD'17, 18*) and Jupiter (*Leane & Linden PRD'21*)

Gamma-ray signals from know BDs



Bhattacharjee, FC & Serpico, In prep

- Selection of about 30 nearby (< 20pc), massive, cold and old BDs
- Search for gamma-ray point-like excesses in *Fermi*-LAT data
- No excess found => Upper limits on photon flux



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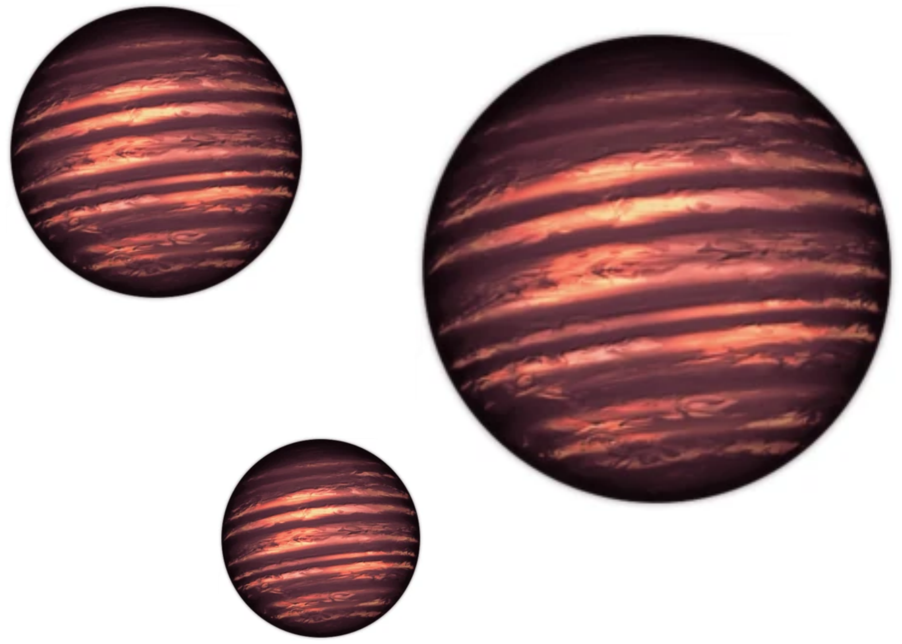

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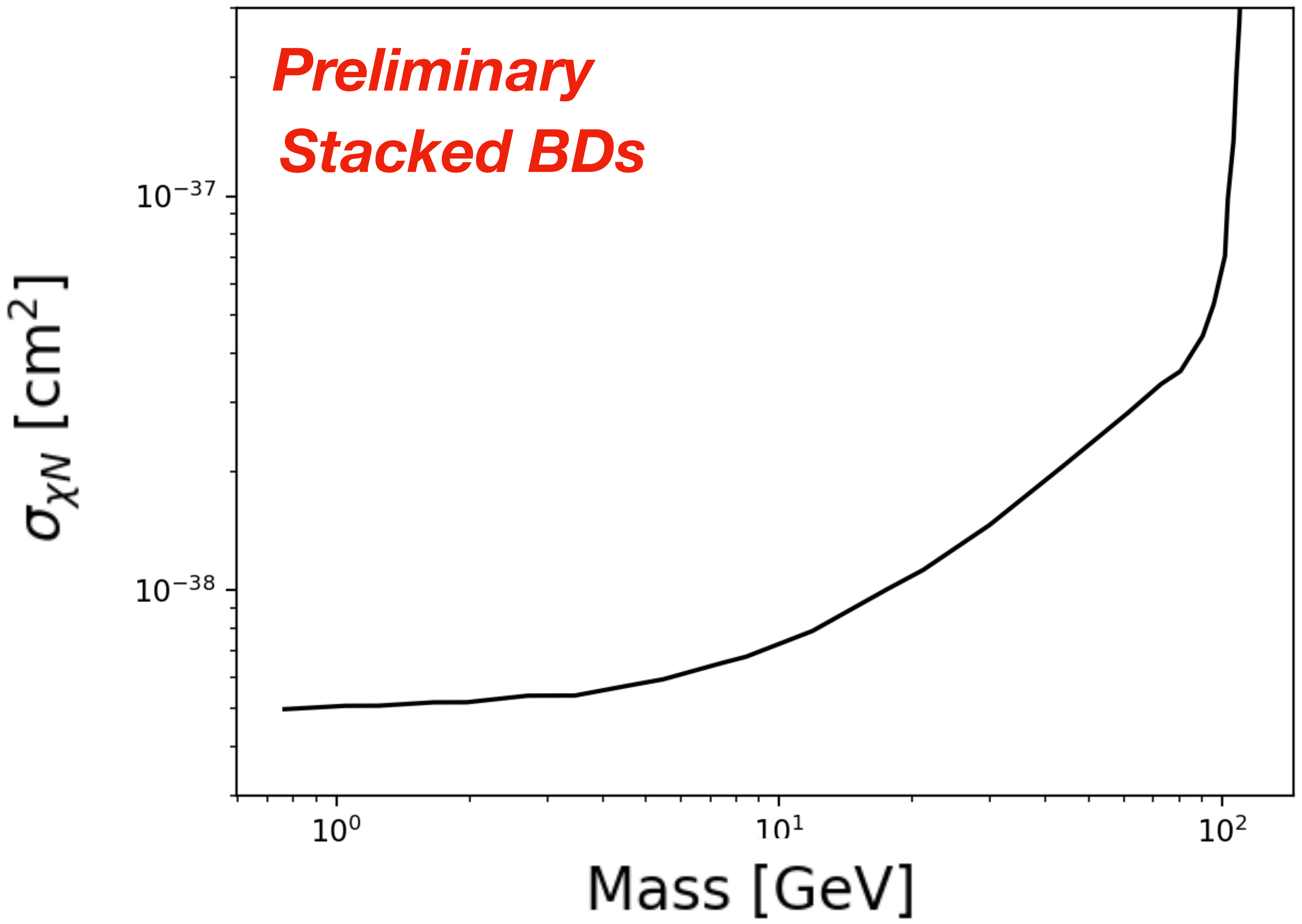
* We consider decay of the light mediators into photons
* Point-like signal search imposes a limit on mediator decay length
* Box-shaped gamma-ray spectrum

$$\chi\chi \to \phi\phi \qquad m_\phi \ll m_\chi$$

$$10^8\,\mathrm{m} \simeq R_\star \lesssim L \lesssim d_\star\,\theta_{68\%} \simeq 10^{14}\,\mathrm{m}$$

$$E^2 \frac{\mathrm{d}\Phi}{\mathrm{d}E} \propto \frac{\mathcal{C}}{4\pi d_\star^2} \times E^2 \frac{\mathrm{d}N}{\mathrm{d}E}$$

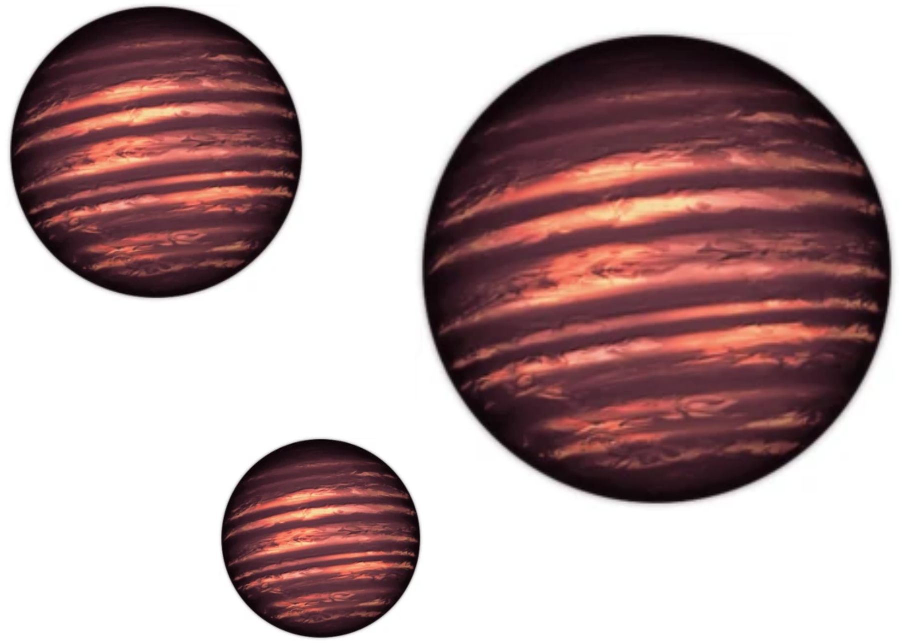
$$\mathcal{C} = f(M_\star, R_\star, d_{\mathrm{GC}}, \rho_{\mathrm{DM}}, \sigma_{\chi N})$$



Lower evaporation mass for *neutron stars* and *white dwarfs* but larger uncertainties on system T and density

Gamma-ray signals from know BDs

Bhattacharjee, FC & Serpico, In prep



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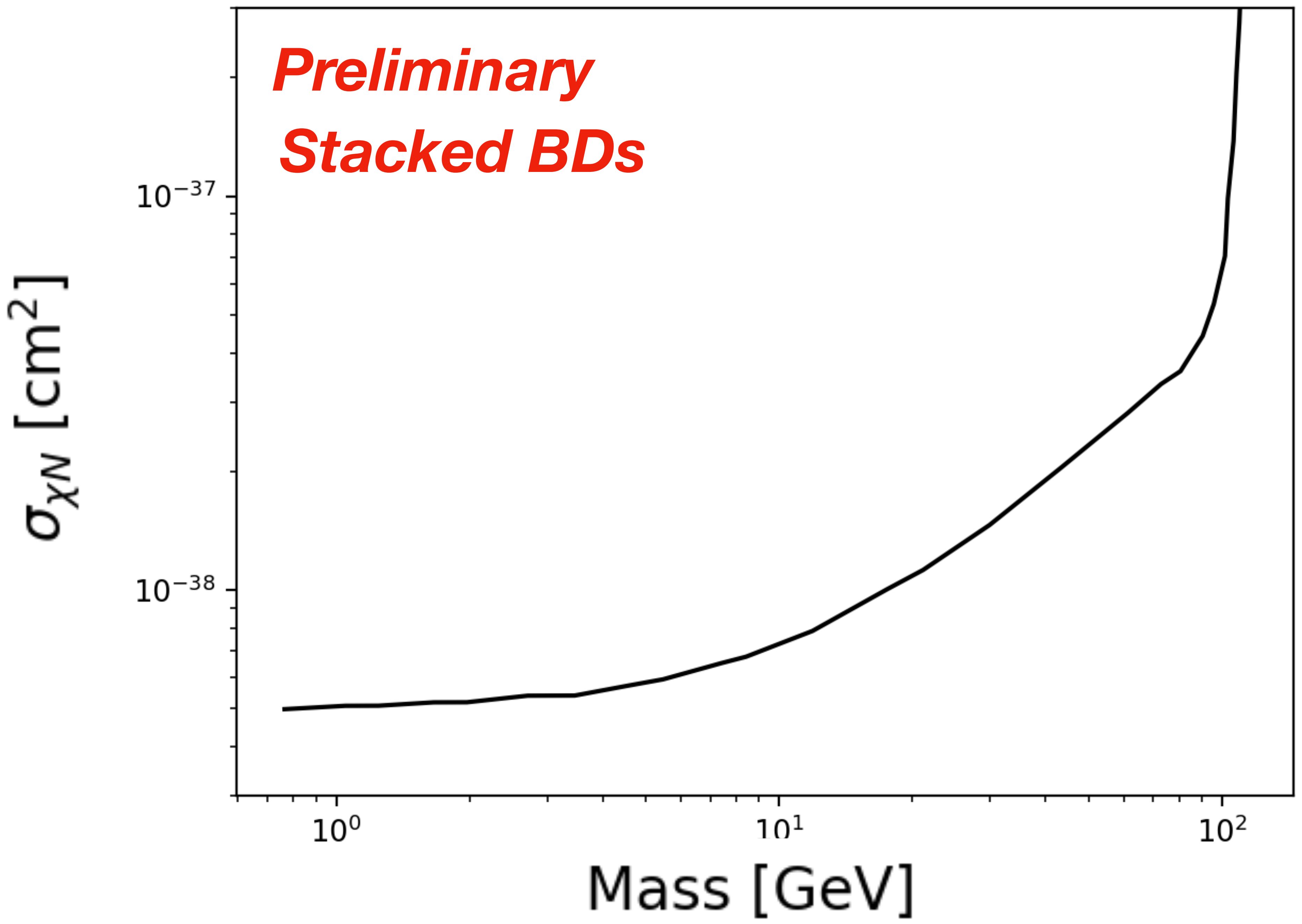


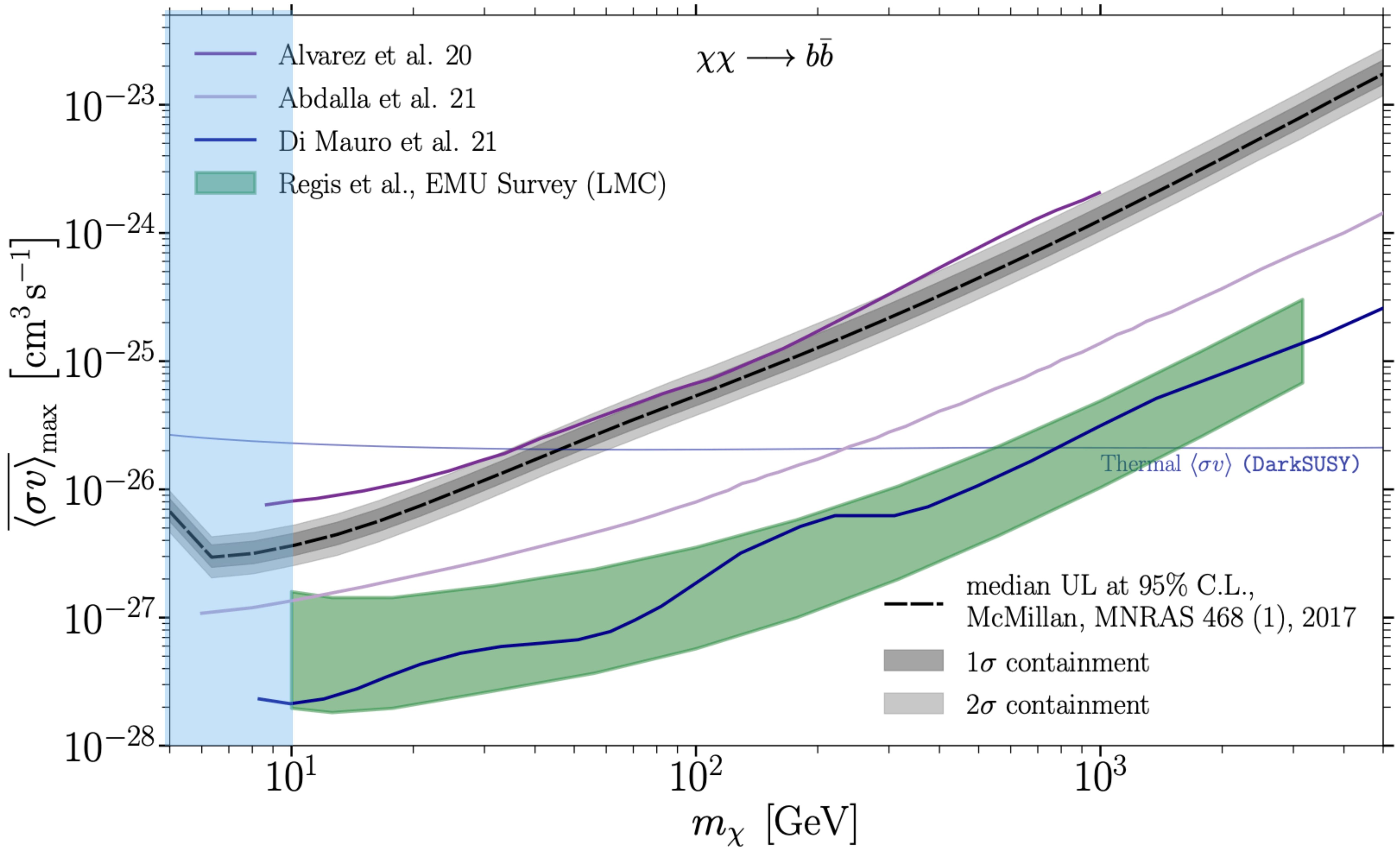
TAKE AWAY: Celestial body capture provides comparable bounds to DM direct detection in ~GeV mass range. Many more systems to be discovered with JWST!

Prospects and opportunities

Extending the energy/mass scale

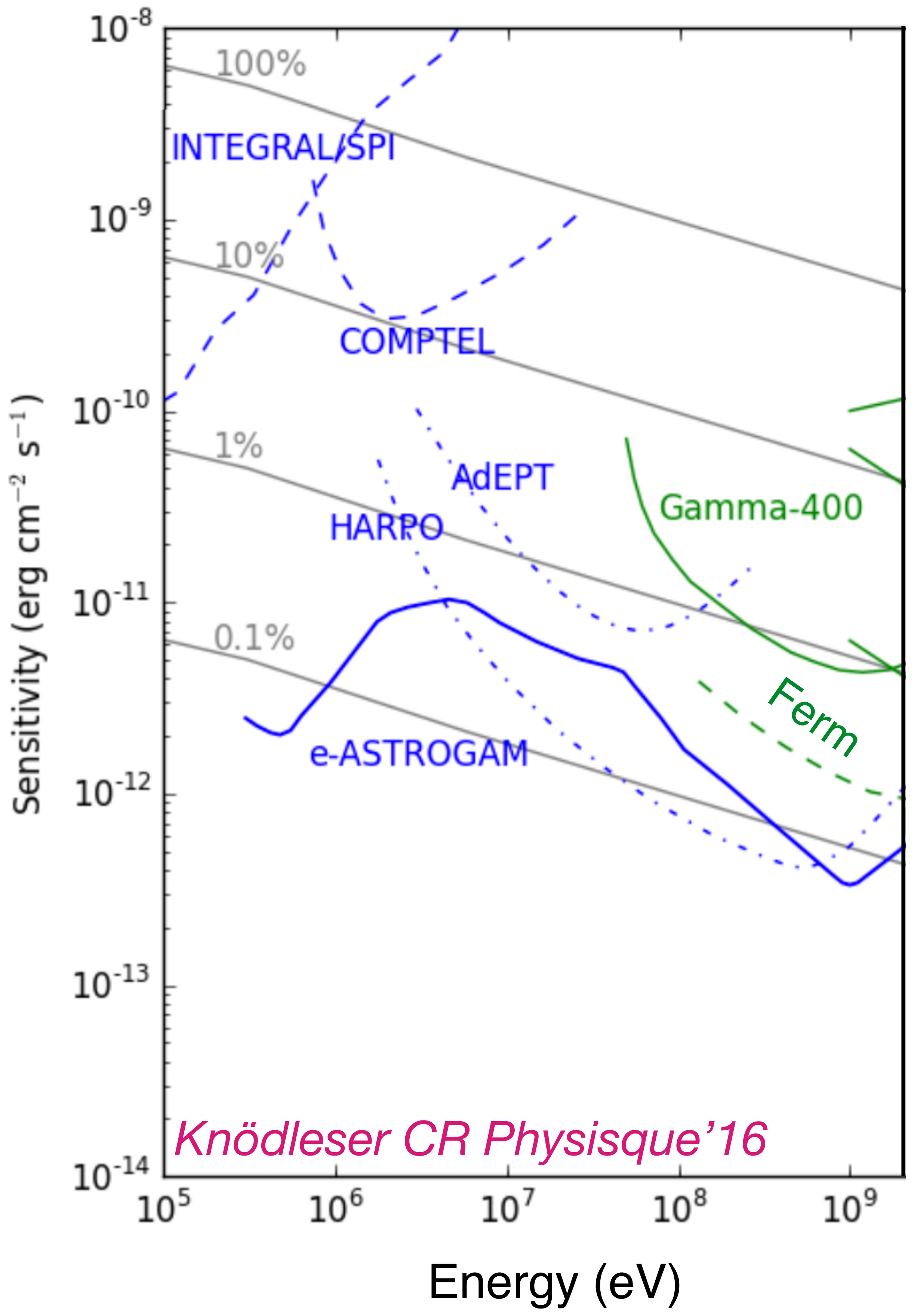
~ a few GeV — few TeV

Eckner, FC+ In preparation



MeV sensitivity gap

Amego, e-ASTROGAM, GECCO, GRAMS, COSI, MeVCube, etc



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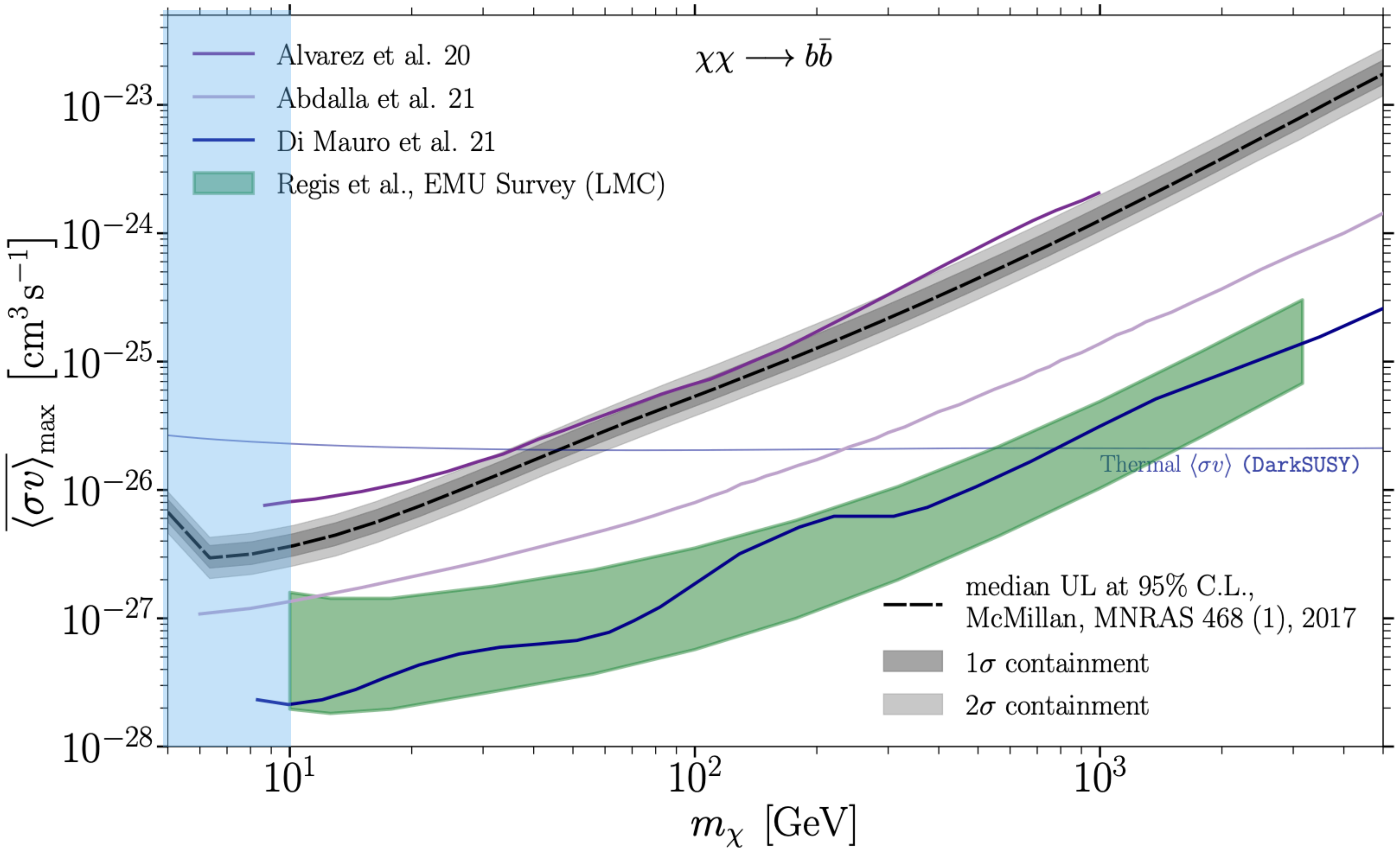

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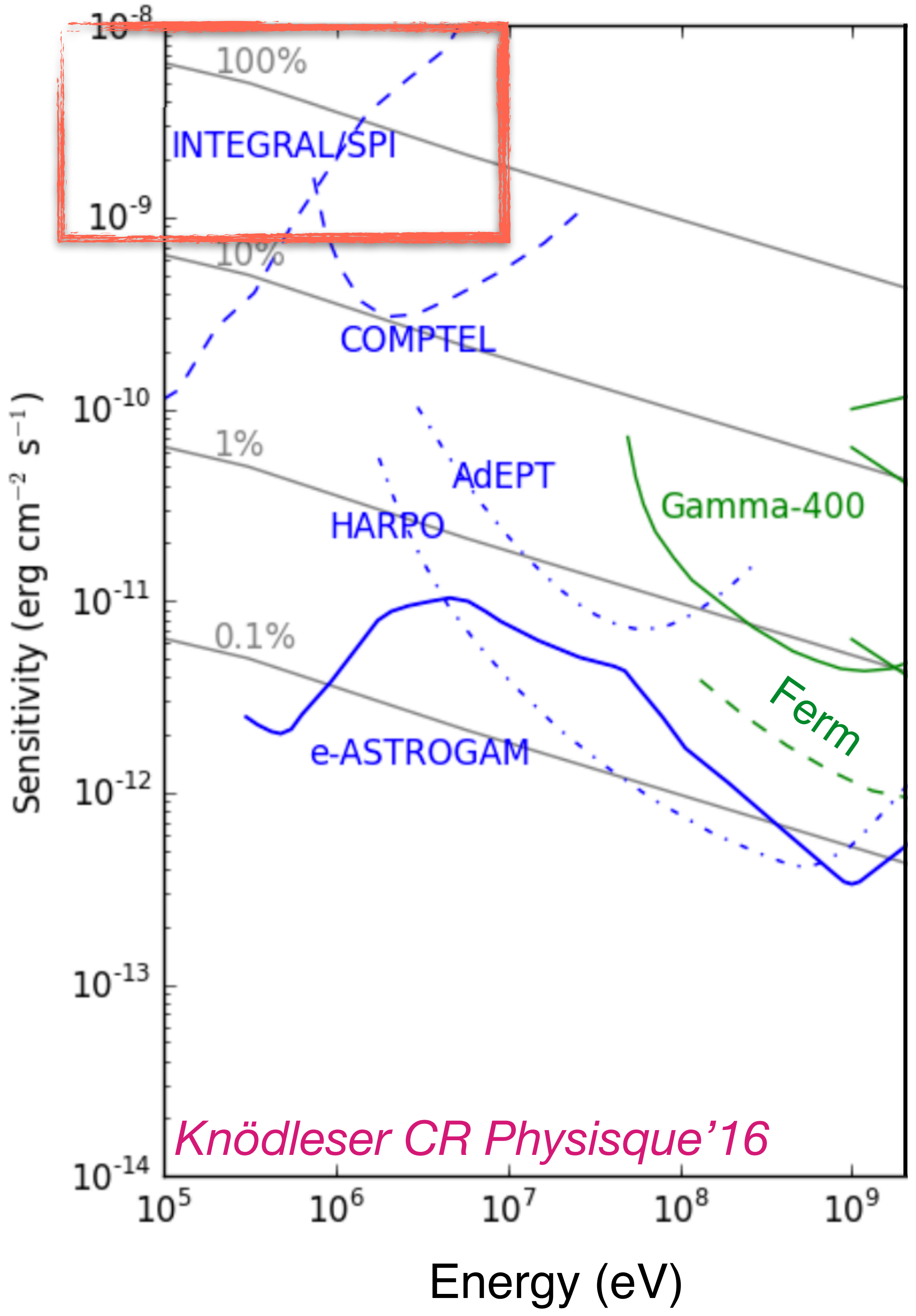
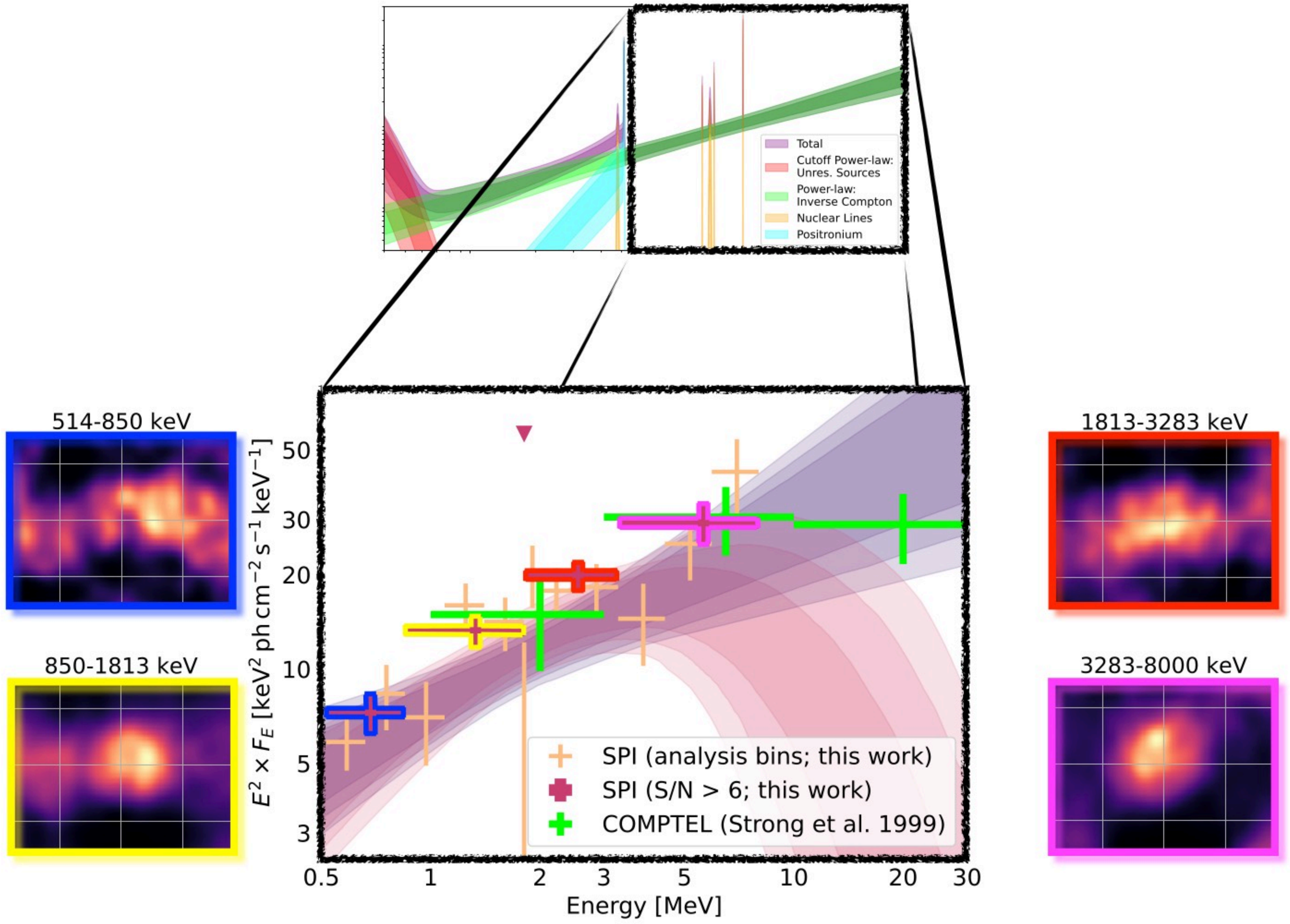


An old instrument, a new analysis

Diffuse Galactic emission spectrum between 0.5 and 8.0 MeV



Integral picture of the month, March 2022

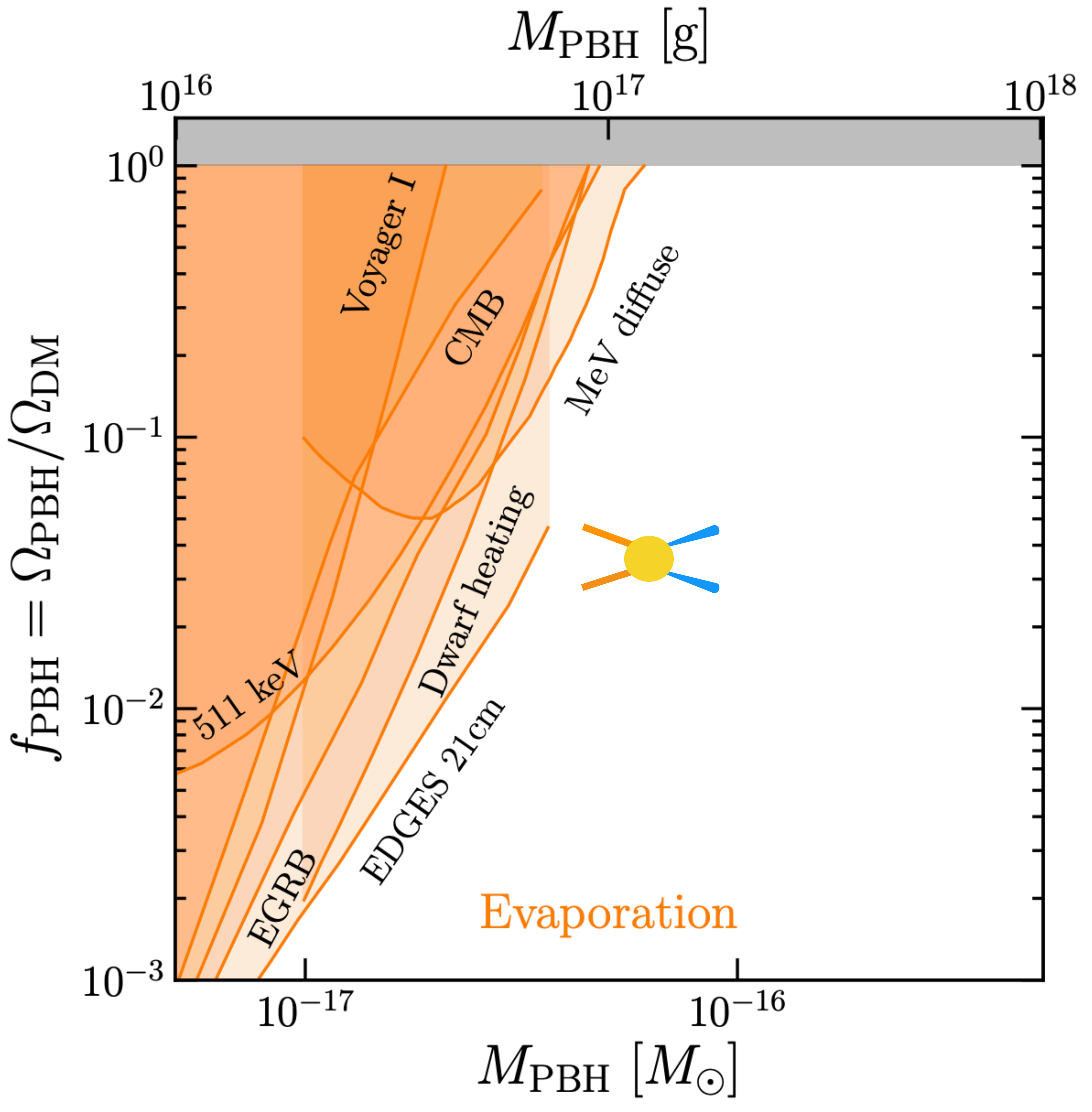
Siegert, FC+ A&A'22

- INTEGRAL SPI supersedes 20yr-old COMPTEL data in the measurement of the **Galactic diffuse MeV emission**
- Emission dominated by **Inverse Compton scattering** of electrons off the interstellar radiation field, producing a smooth power-law spectrum
- Constraints on cosmic-ray transport at MeV energy but also on exotic emission mechanisms: particle and non-particle dark matter

Berteaud, FC+ PRD'22
Dekker, FC+'22 In preparation

Limits on primordial black holes

Evaporation of PBH and cosmic backgrounds



Green & Kavanagh J. Phys. G'19

- PBH can emit **charged cosmic rays** and **photons** via Hawking radiation => Almost-black (grey) body emission

$$T_{\rm PBH} \simeq \frac{10^{13}{\rm g}}{M_{\rm PBH}}\,{\rm GeV}$$

Page & Hawking ApJ'76; Carr & MacGibbon Phys. Rep.'98

- Sufficient emission from $M_{PBH} > 10^{14}$ g to set limits on their evaporation products today
- Photon contribution to the extragalactic gamma-ray and X-ray backgrounds

Carr+ PRD'10; Ballesteros+ PLB'20; Iguaz+ PRD'21

- Unconstrained mass range ~10^{17} — 10^{22} g, the so-called *asteroid mass gap* where f_{PBH} can be 1

Limits on primordial black holes

Evaporation of PBH and Galactic diffuse emission

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E}(l,b) = \frac{f_{\mathrm{PBH}}}{4\pi M_{\mathrm{PBH}}}\frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\mathrm{d}t}\int_{\mathrm{l.o.s.}} \mathrm{d}s\,\rho(r(s,l,b))$$

Berteaud, FC+ PRD'22

Limits on primordial black holes

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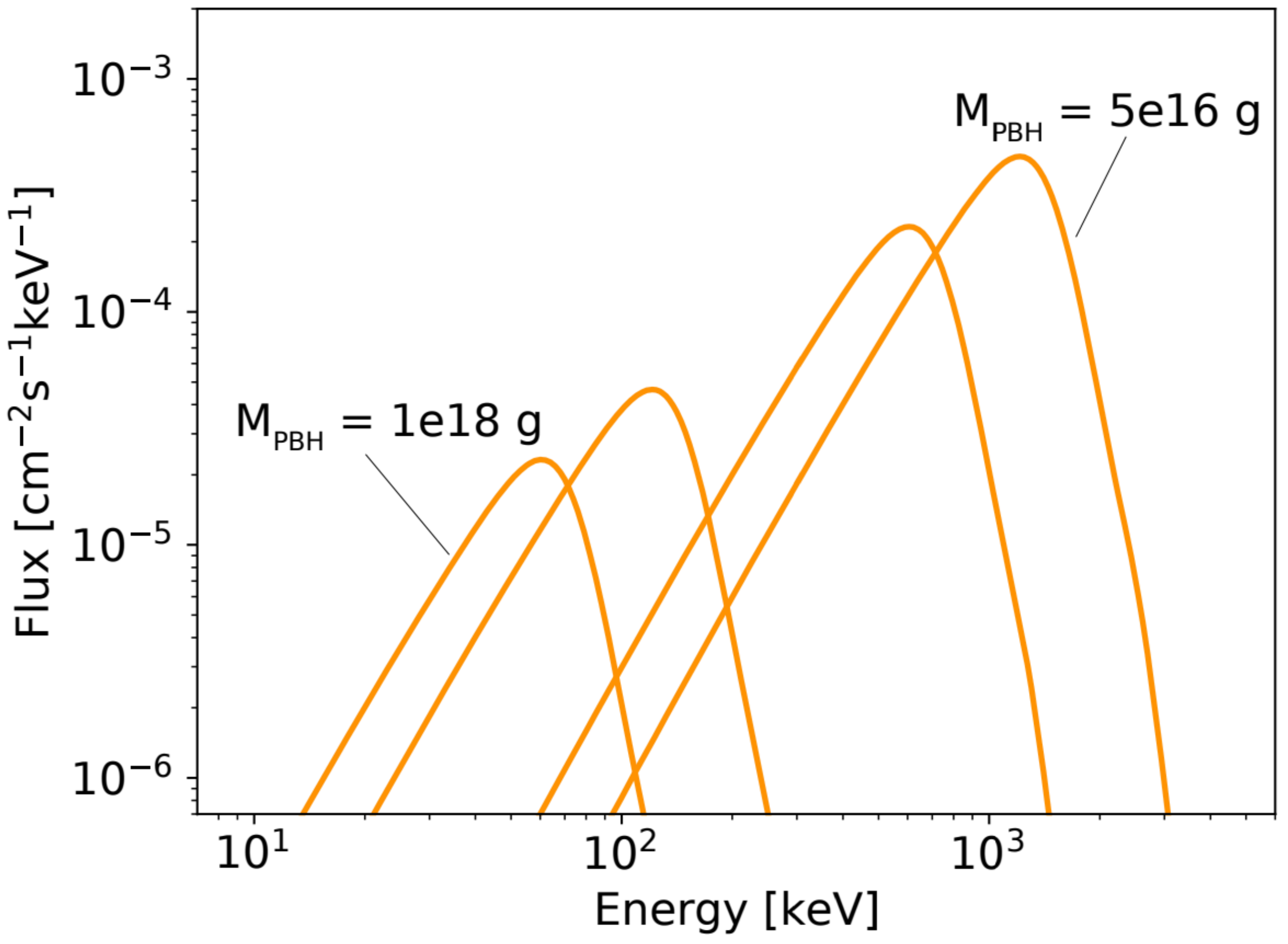

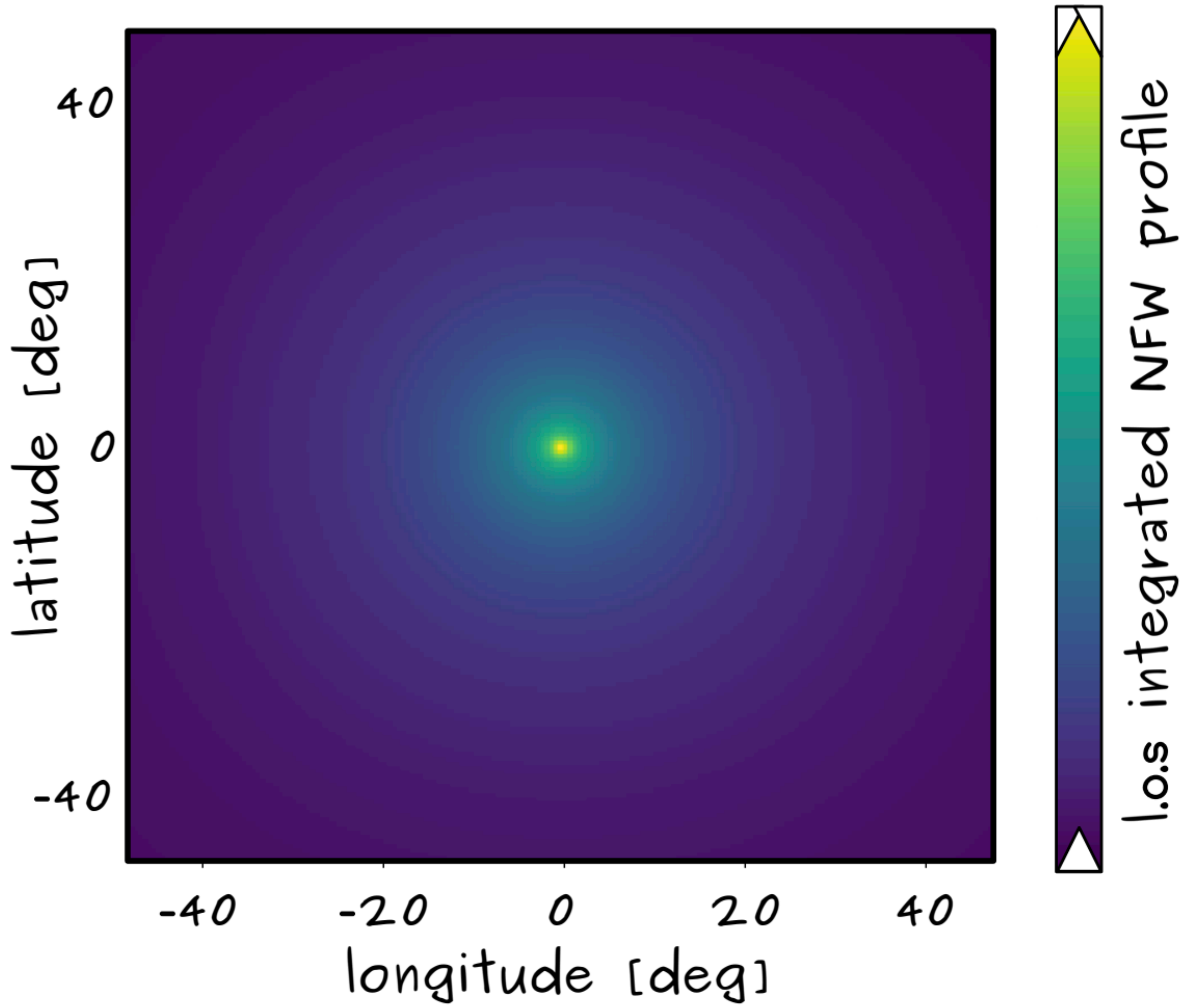

Berteaud, FC+ PRD'22

Limits on primordial black holes

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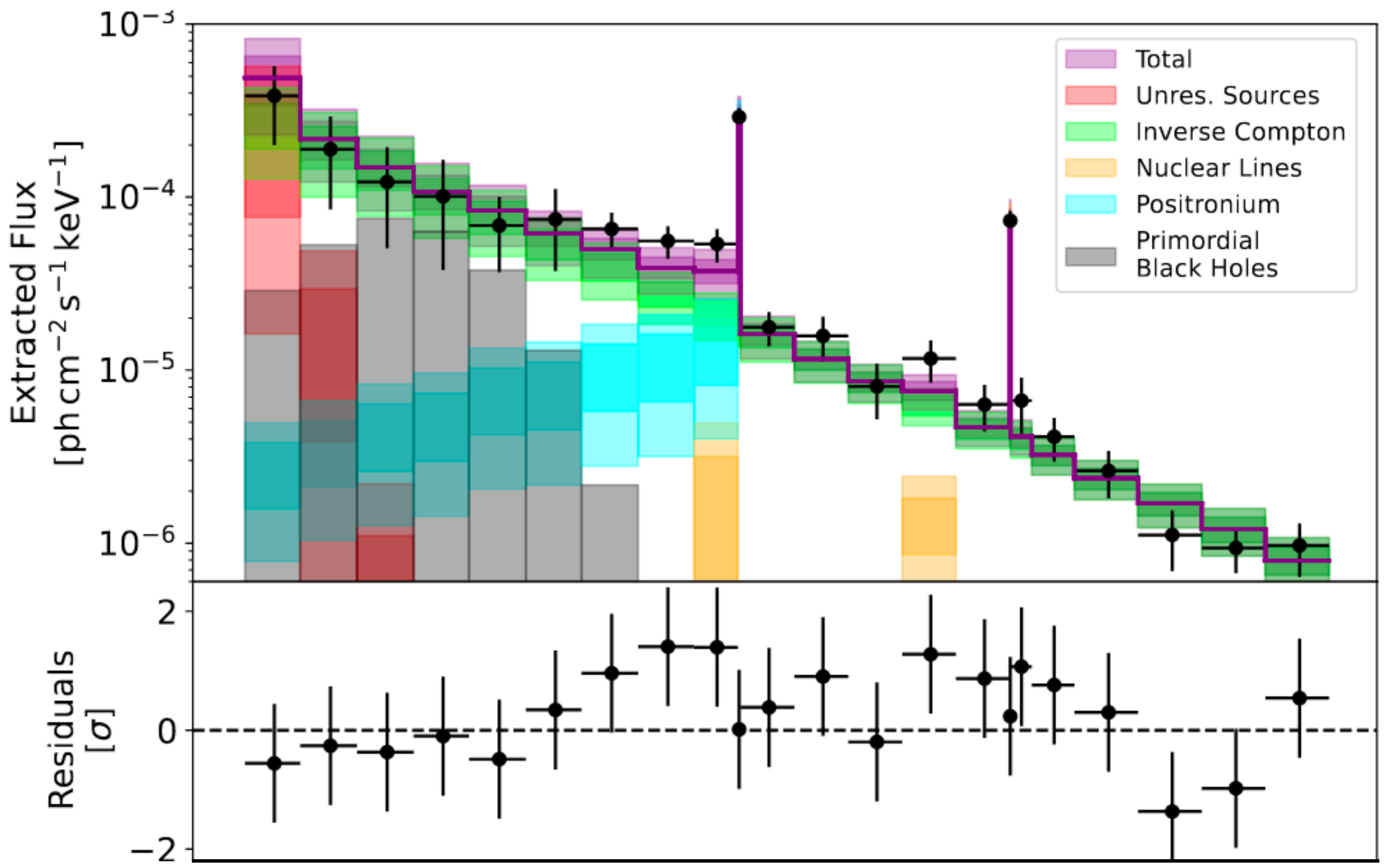
Berteaud, FC+ PRD'22

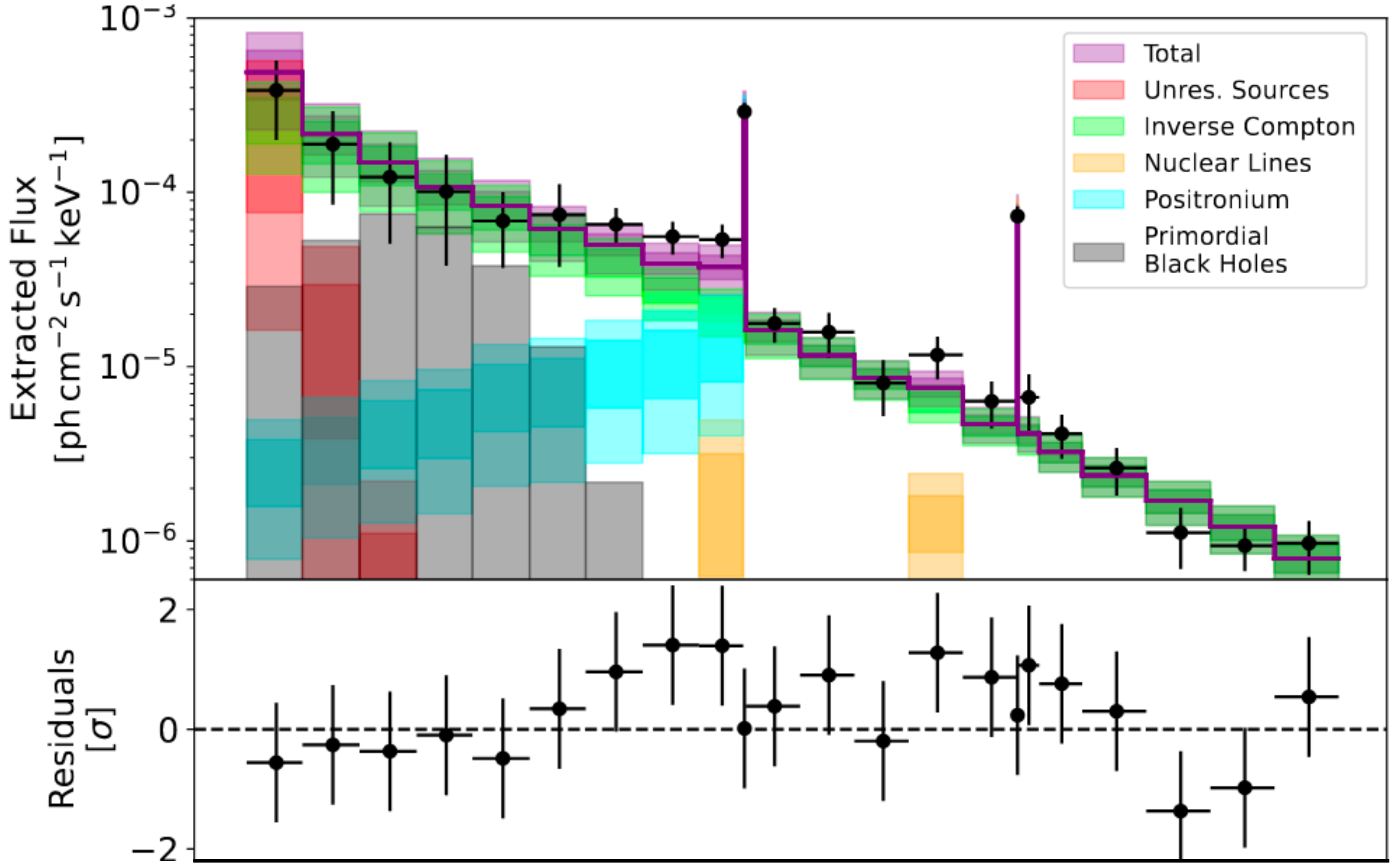


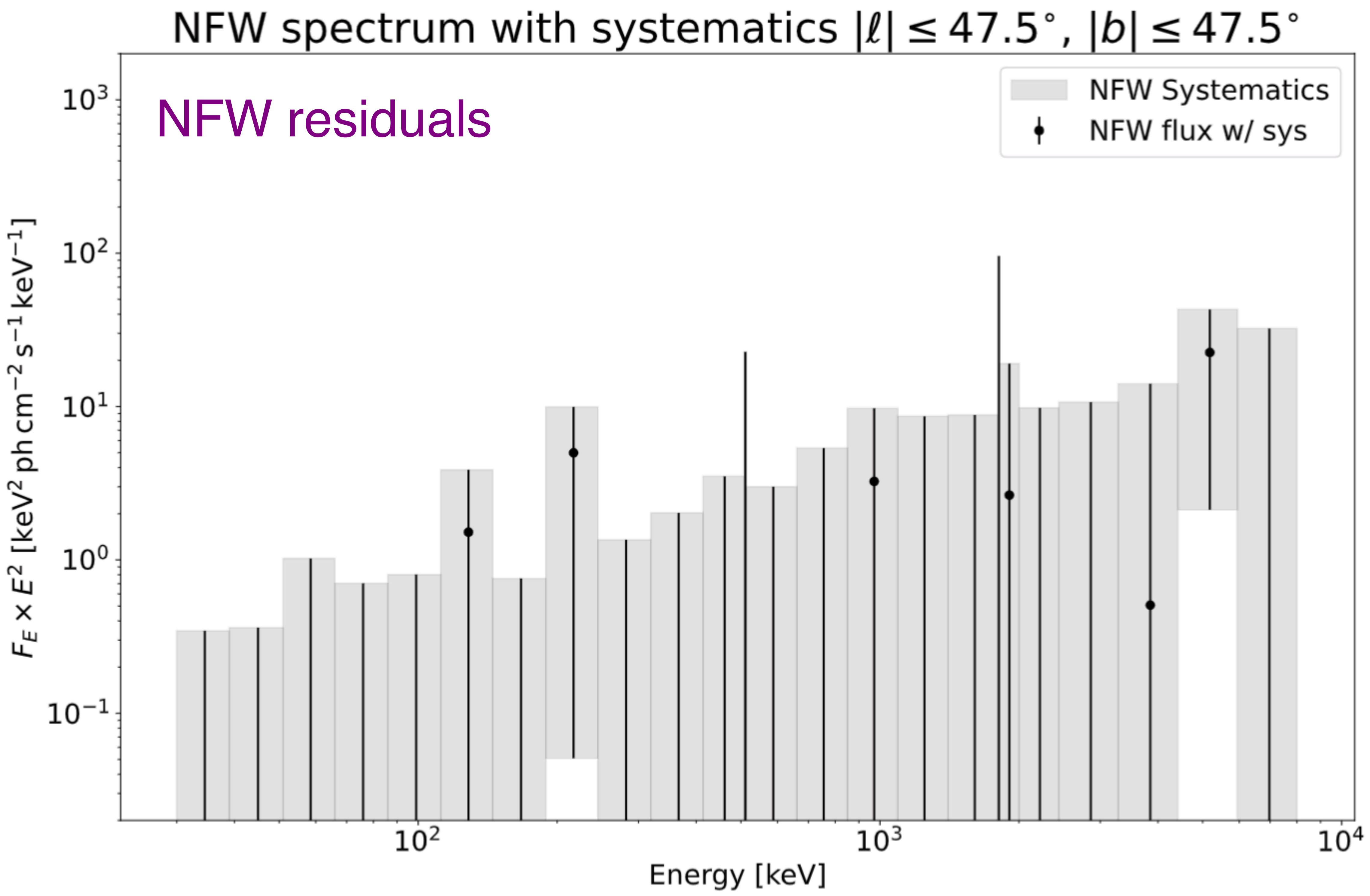
- We look for MeV diffuse emission from NFW distribution decay
- No signal detected

Limits on primordial black holes

Evaporation of PBH and Galactic diffuse emission

Berteaud, FC+ PRD'22





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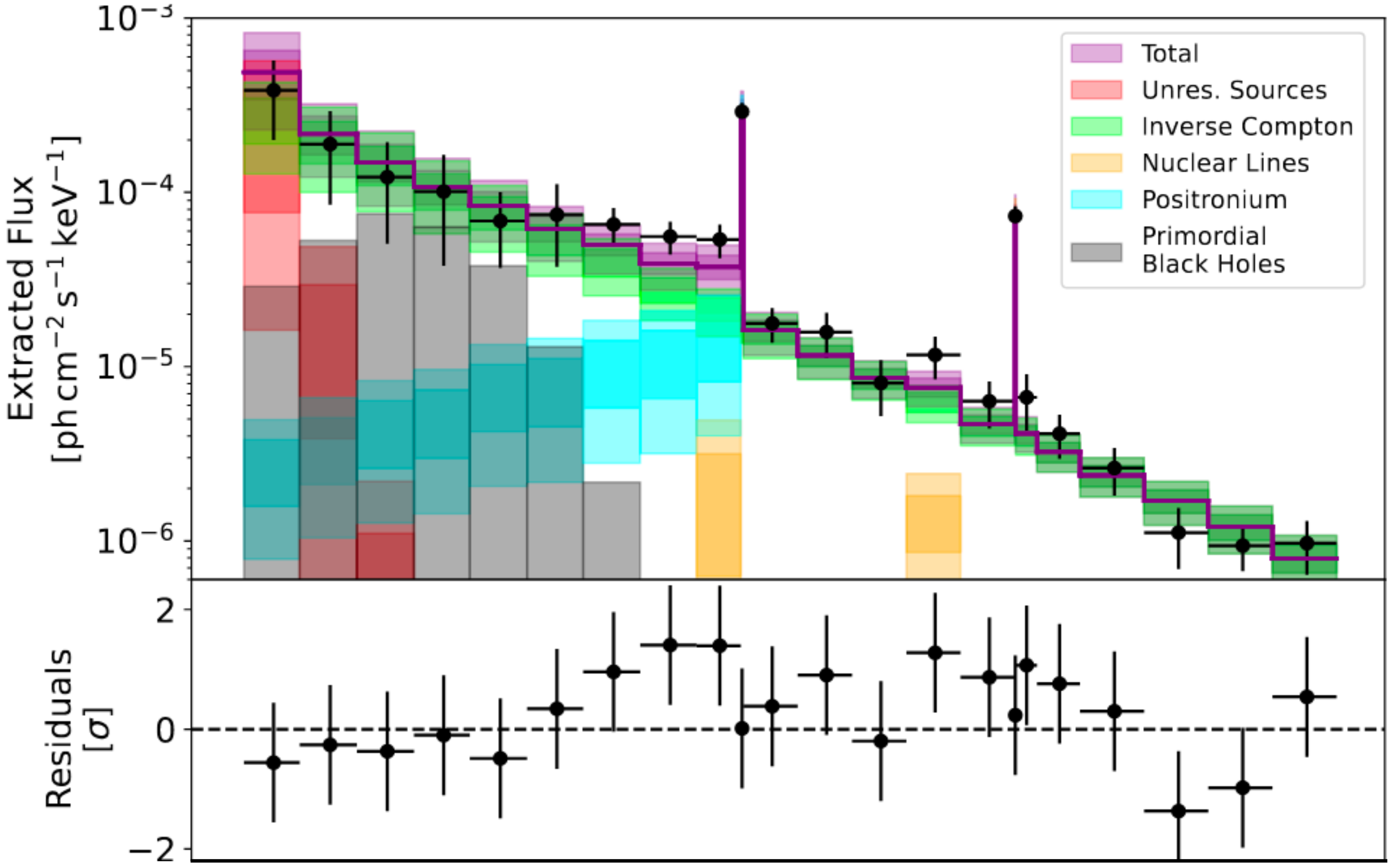
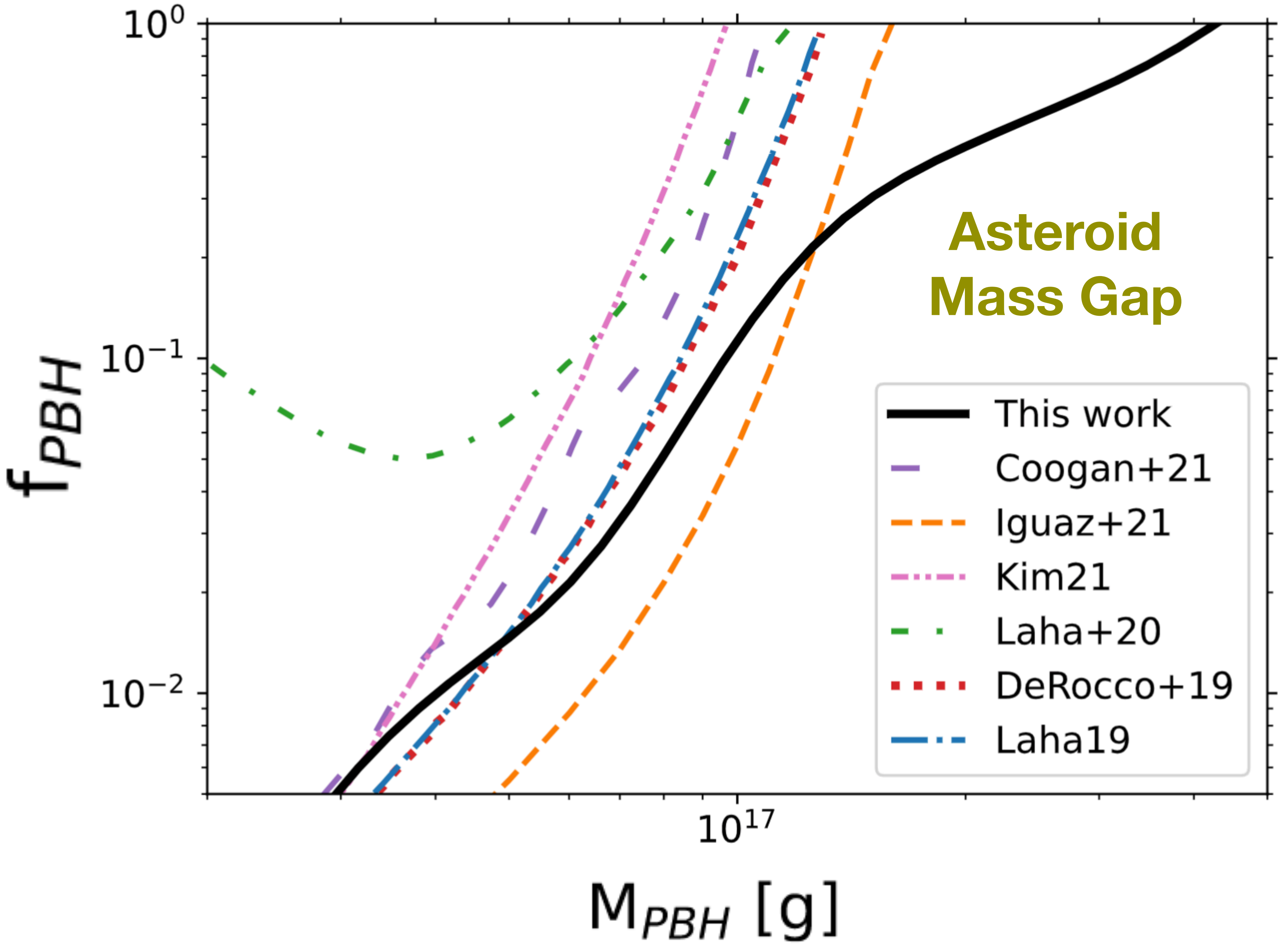
=> Upper limits on NFW decay flux

Limits on primordial black holes

Evaporation of PBH and Galactic diffuse emission

Berteaud, FC+ PRD'22





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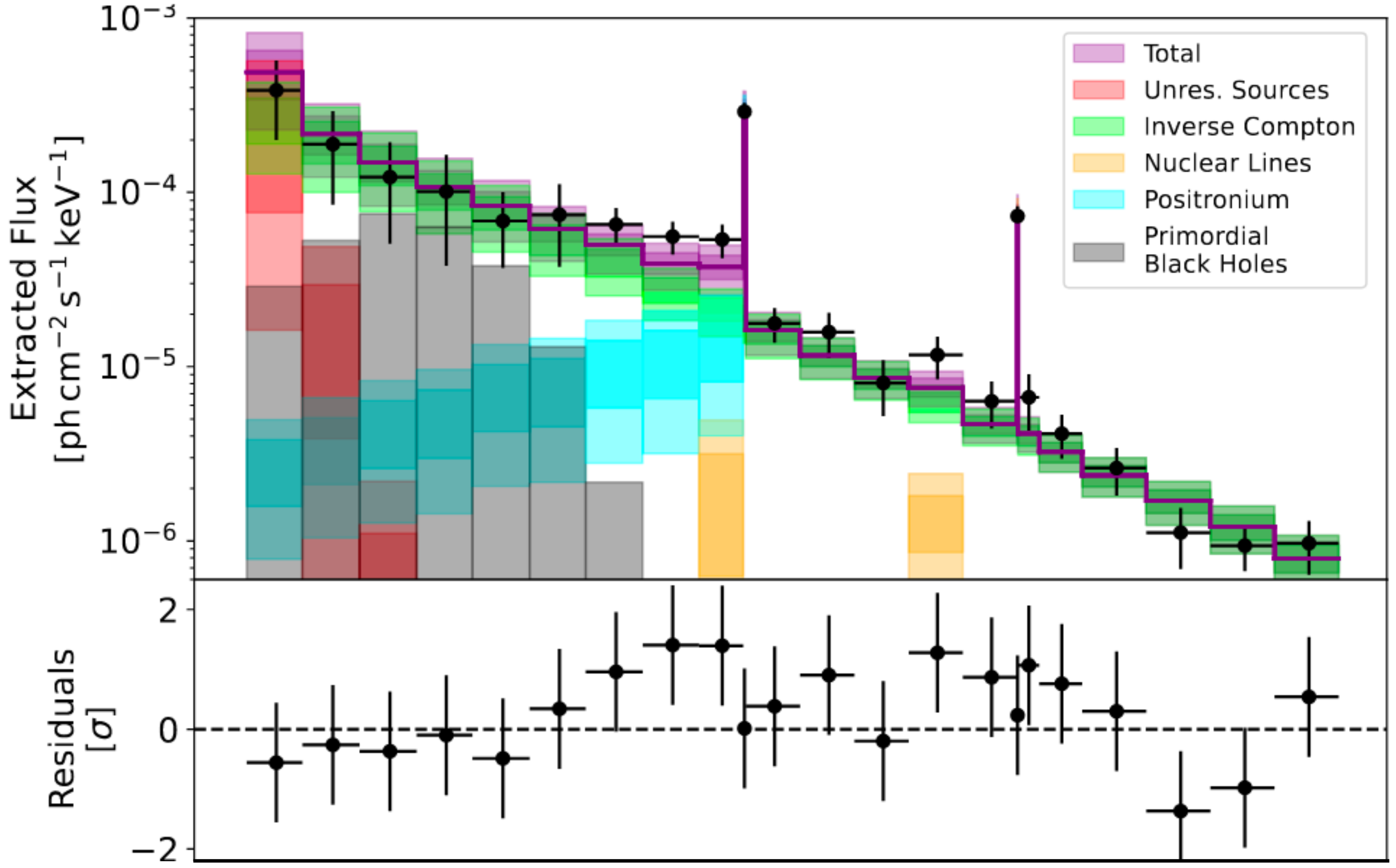
=> Upper limits on PBH spectrum

Limits on primordial black holes

Evaporation of PBH and Galactic diffuse emission

Berteaud, FC+ PRD'22



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➡ **Future** e-ASTROGAM and ASTRO-H will allow a more precise measurement of the isotropic gamma-ray and X-ray backgrounds => Improved constraints in the **10^{16}–10^{18} g mass window**

AMEGO: https://arxiv.org/abs/2102.06714

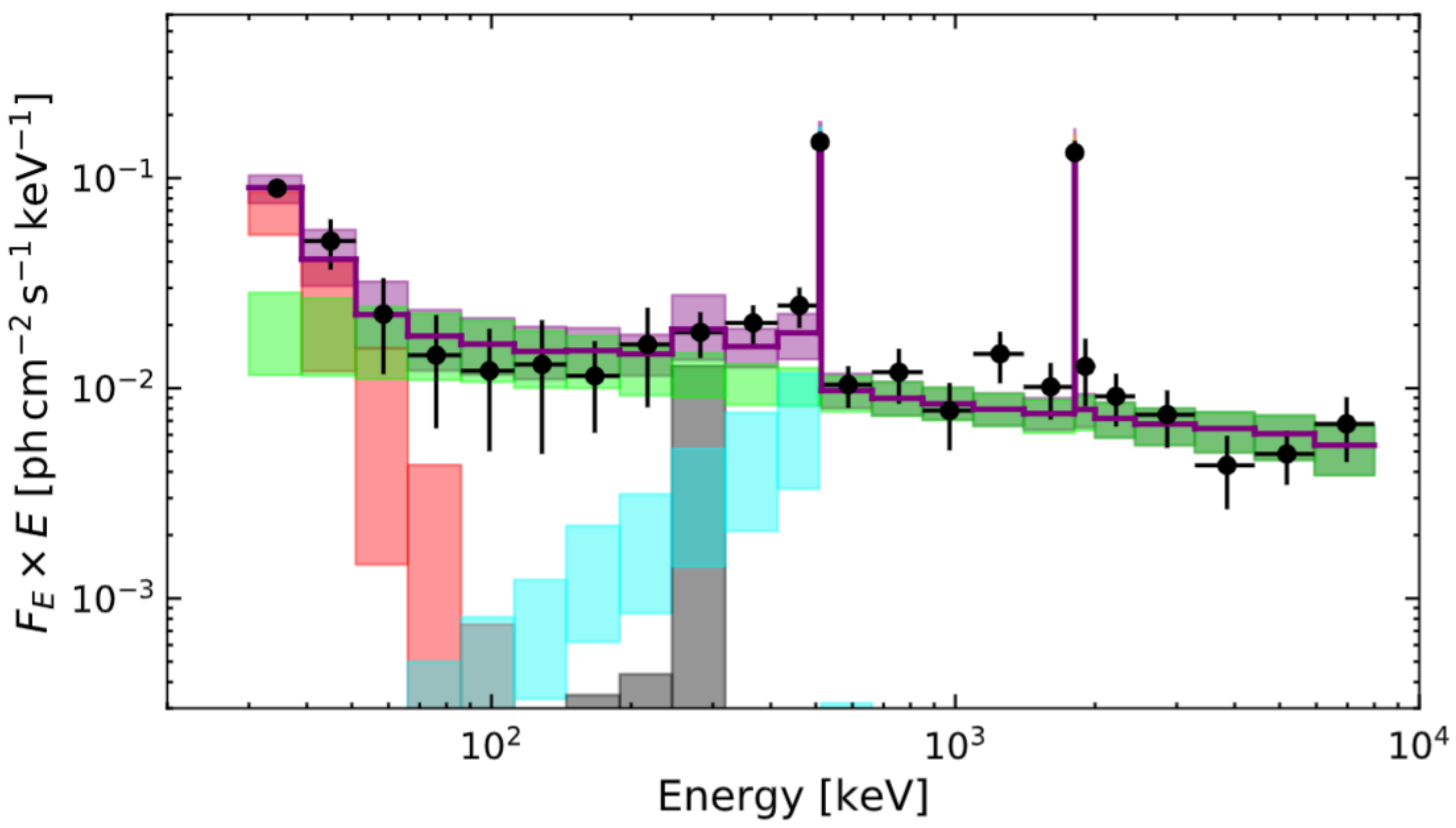
➡ Precise **micro-lensing surveys** with Roman Space Telescope, Euclid and the Vera C. Rubin Observatory

Green & Kavanagh J. Phys. G'19

Limits on feebly interacting particles

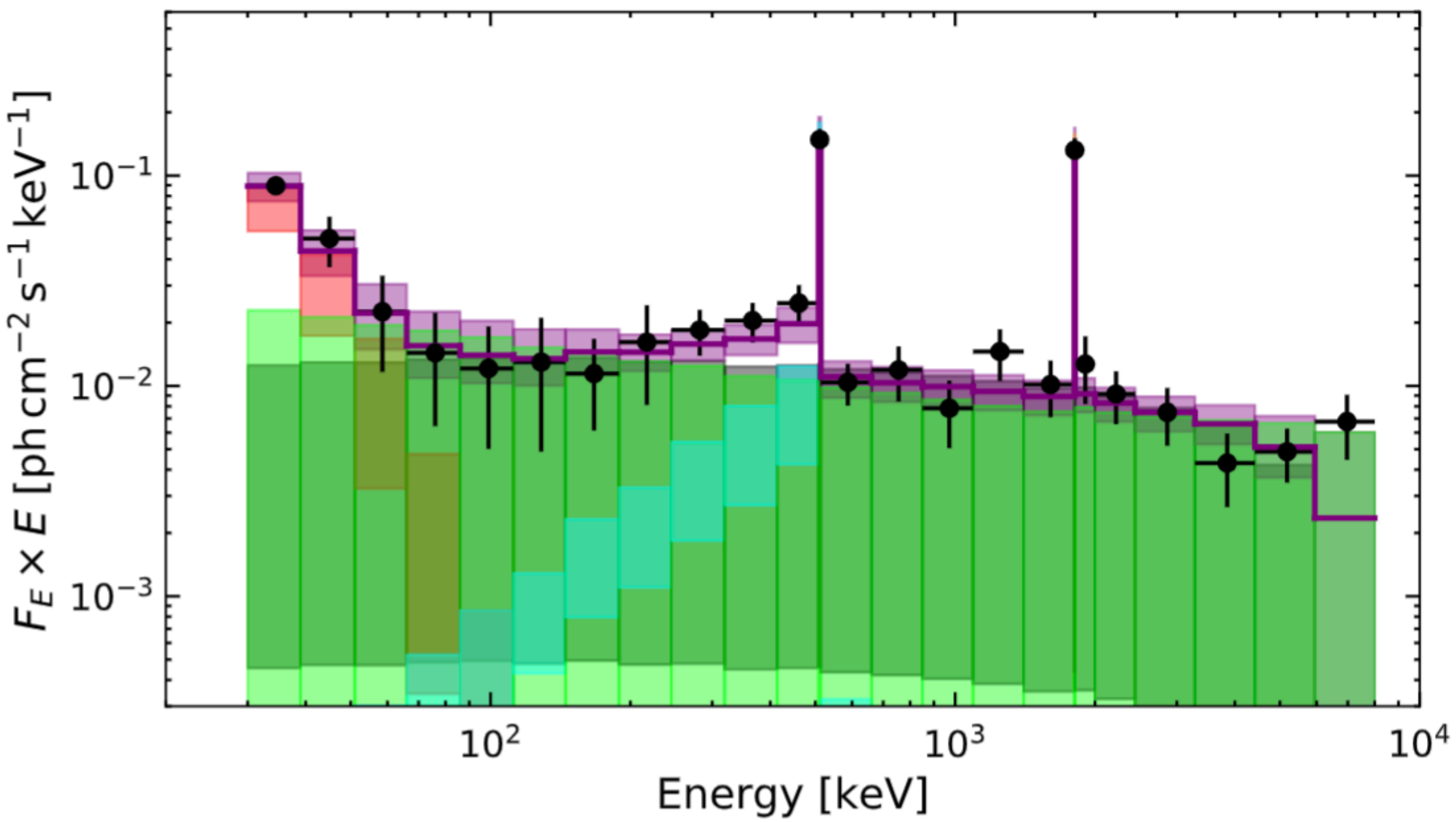
Dekker, FC+'22 In preparation

$$\mathrm{DM} \to \gamma + \gamma$$



$$\frac{\mathrm{d}N_{\mathrm{decay}}}{\mathrm{d}E} = 2\delta\left(E - \frac{m_{\mathrm{DM}}}{2}\right)$$

$$\mathrm{DM} \to e^+ + e^- + \gamma$$



$$\frac{\mathrm{d}N_{\mathrm{decay}}}{\mathrm{d}E} \simeq \frac{\alpha}{2\pi}\left[\frac{m_{\mathrm{DM}}^2 + (m_{\mathrm{DM}} - 2E)^2}{m_{\mathrm{DM}}^2 E} \ln\left(\frac{m_{\mathrm{DM}}(m_{\mathrm{DM}} - 2E)}{m_e^2}\right)\right]$$

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Dekker, FC+'22 In preparation

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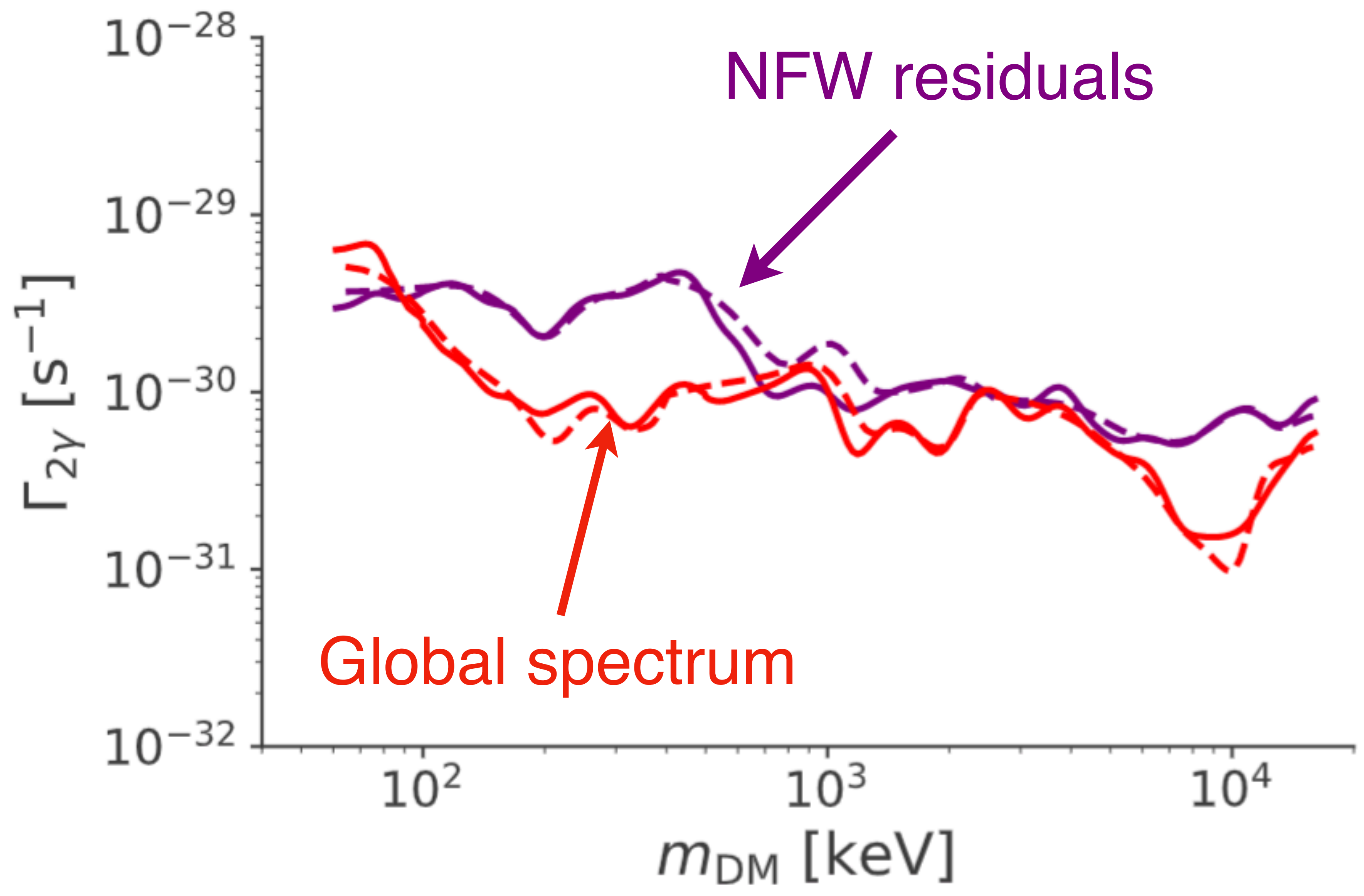

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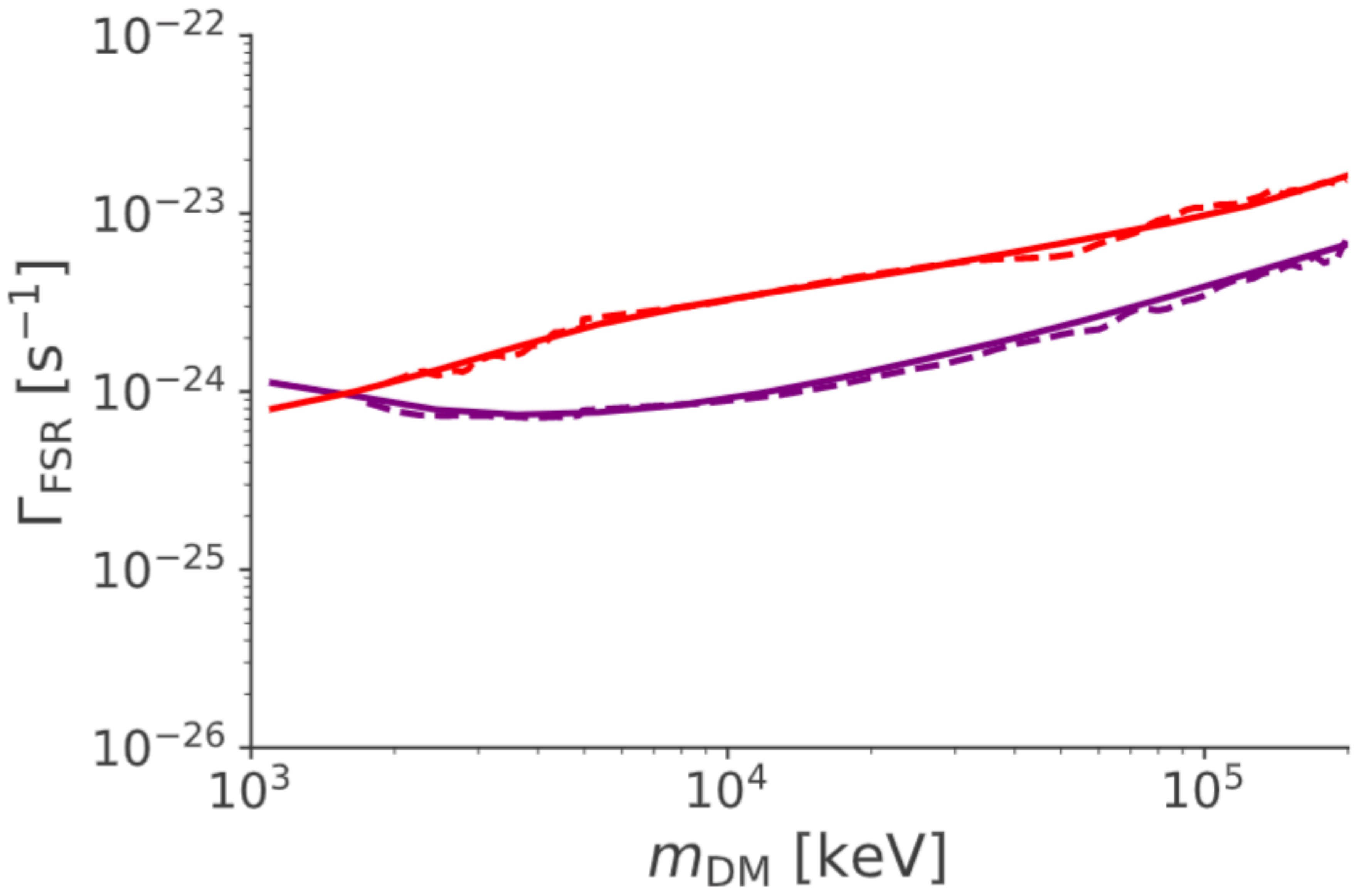

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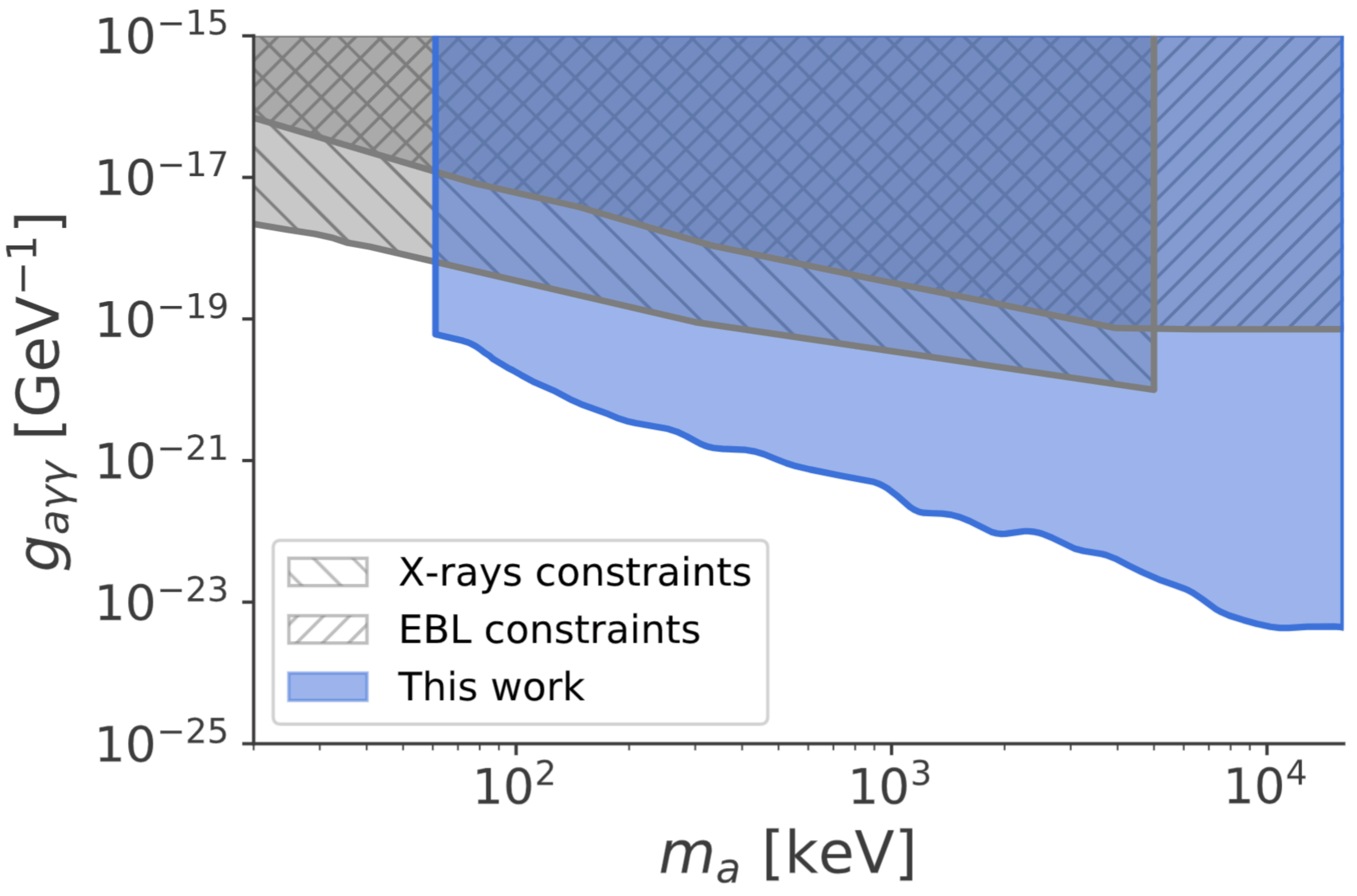
Limits on feebly interacting particles

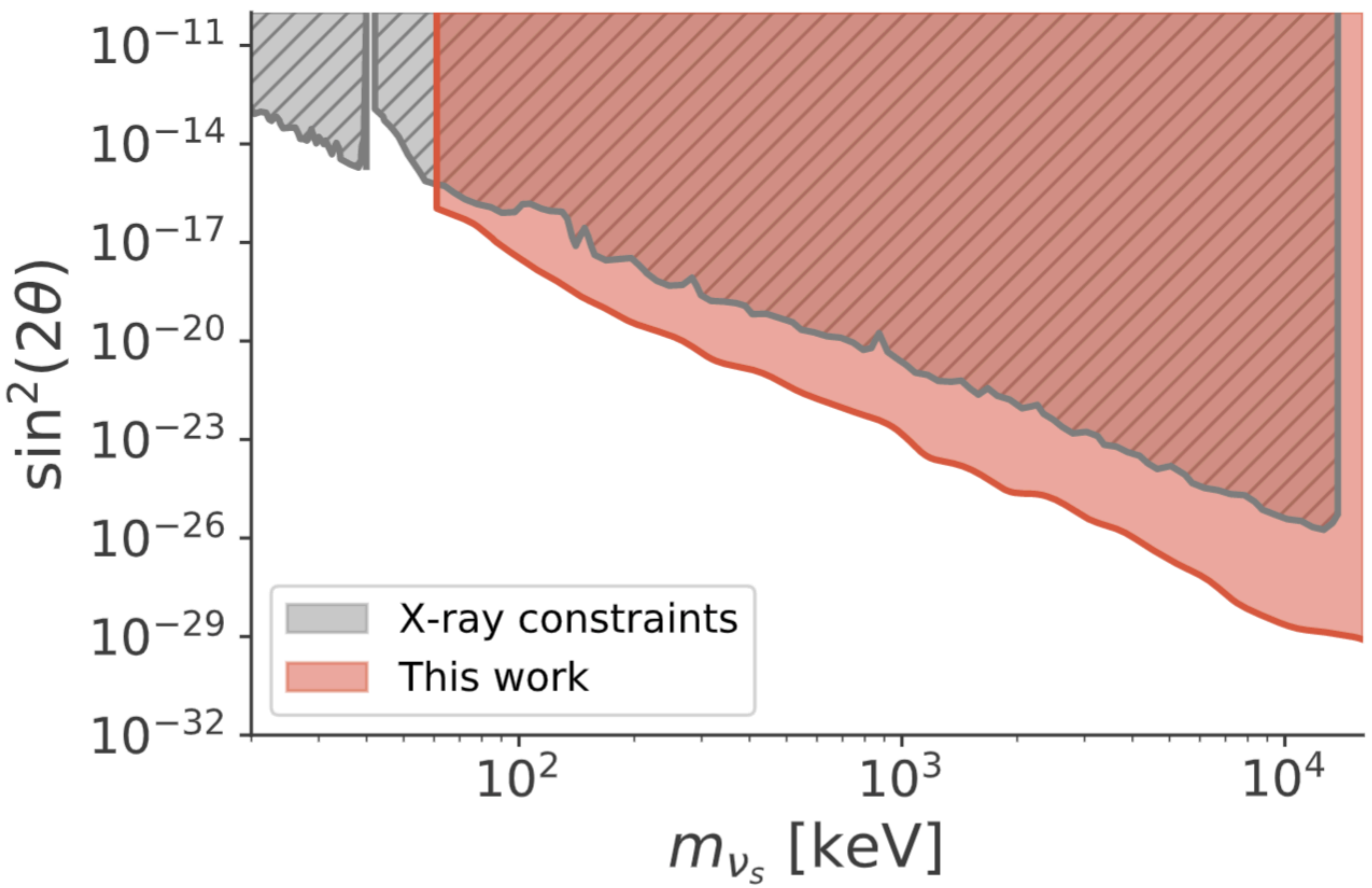
Axion-like particles

$$\Gamma_{2\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 0.755 \times 10^{-30} \left(\frac{g_{a\gamma\gamma}}{10^{-20}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_a}{100\,\mathrm{keV}}\right)^3 \mathrm{s}^{-1}$$



Sterile neutrinos

$$\Gamma_{\nu\gamma} \simeq \frac{9\alpha G_F^2 m_s^5 \sin^2(2\theta)}{1024\pi^4} \simeq 1.36 \times 10^{-29}\ \mathrm{s}^{-1} \left[\frac{\sin^2(2\theta)}{10^{-7}}\right] \left(\frac{m_{\nu_s}}{1\ \mathrm{keV}}\right)^5$$



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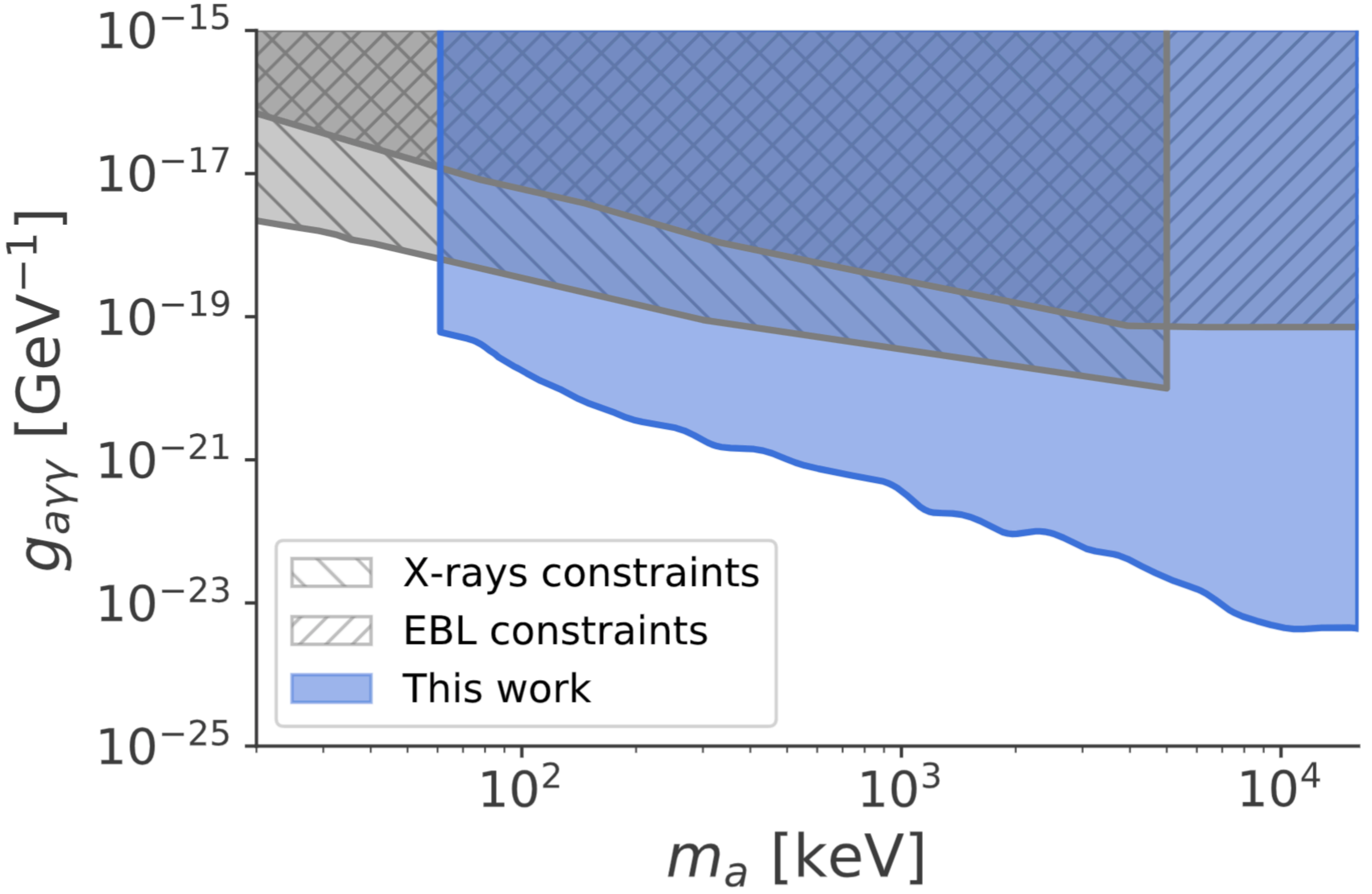

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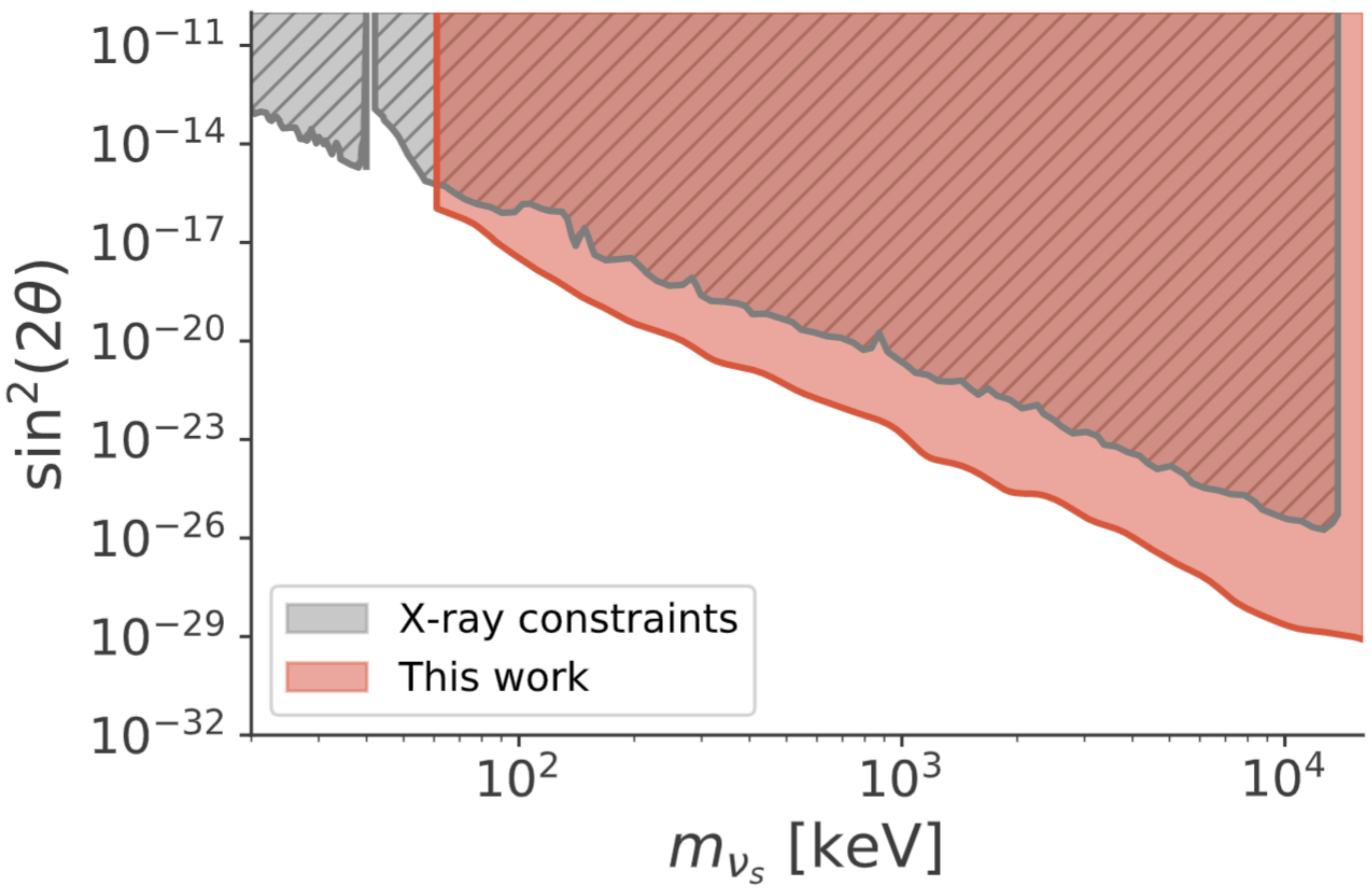

TAKE AWAY: Re-analysis of INTEGRAL data provides the strongest constraints on particle DM ~100 keV and PBH ~10^{17} g

Conclusions & Outlook

- ✓ **Indirect searches** for dark matter **successfully test different dark matter models** (WIMPs, ALPs, PBHs, etc), probing a large portion of their parameter space
- ✓ **Diversified program** to tackle dark matter over a wide spectrum of models and signatures
- ✓ Nowadays from indirect detection we can get **strong constraints but assessing their robustness is crucial** especially when cross-checking signal hints
- ✓ Great experimental progress at multiple wavelengths/messengers (LOFAR, SKA, Athena, CTA, GW detectors, etc) will provide **access to yet uncharted portions of the DM parameter space** and **new windows of opportunity for DM detection**!

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Thank you for the attention