Indirect detection of dark matter

34th Rencontres de Blois 2023

Francesca Calore

Credit: Ville de Blois

The dark matter landscape

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

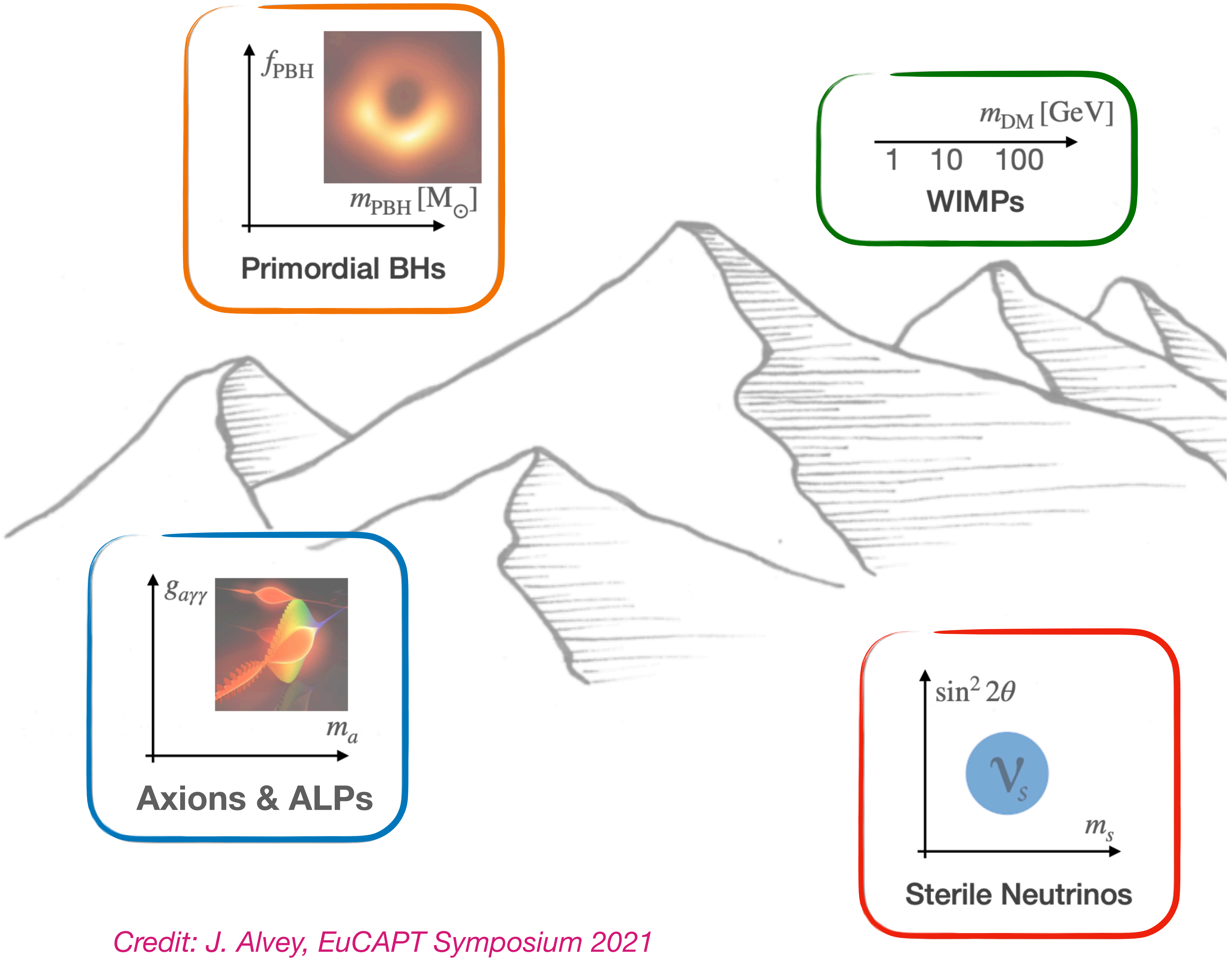
Vast parameter space in mass and interaction strength

K. Boddy (Tue)

The dark matter landscape

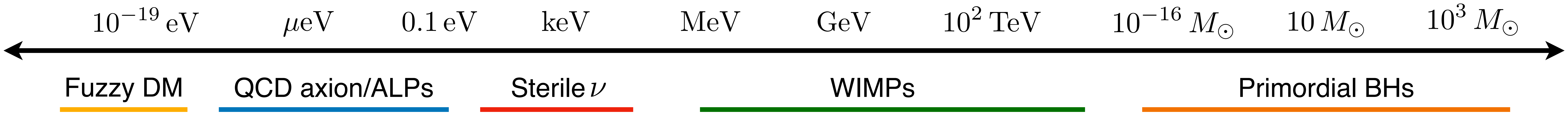
10^{-19} eV | μeV | 0.1 eV | keV | MeV | GeV | 10^2 TeV | $10^{-16}\, M_\odot$ | $10\, M_\odot$ | $10^3\, M_\odot$

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

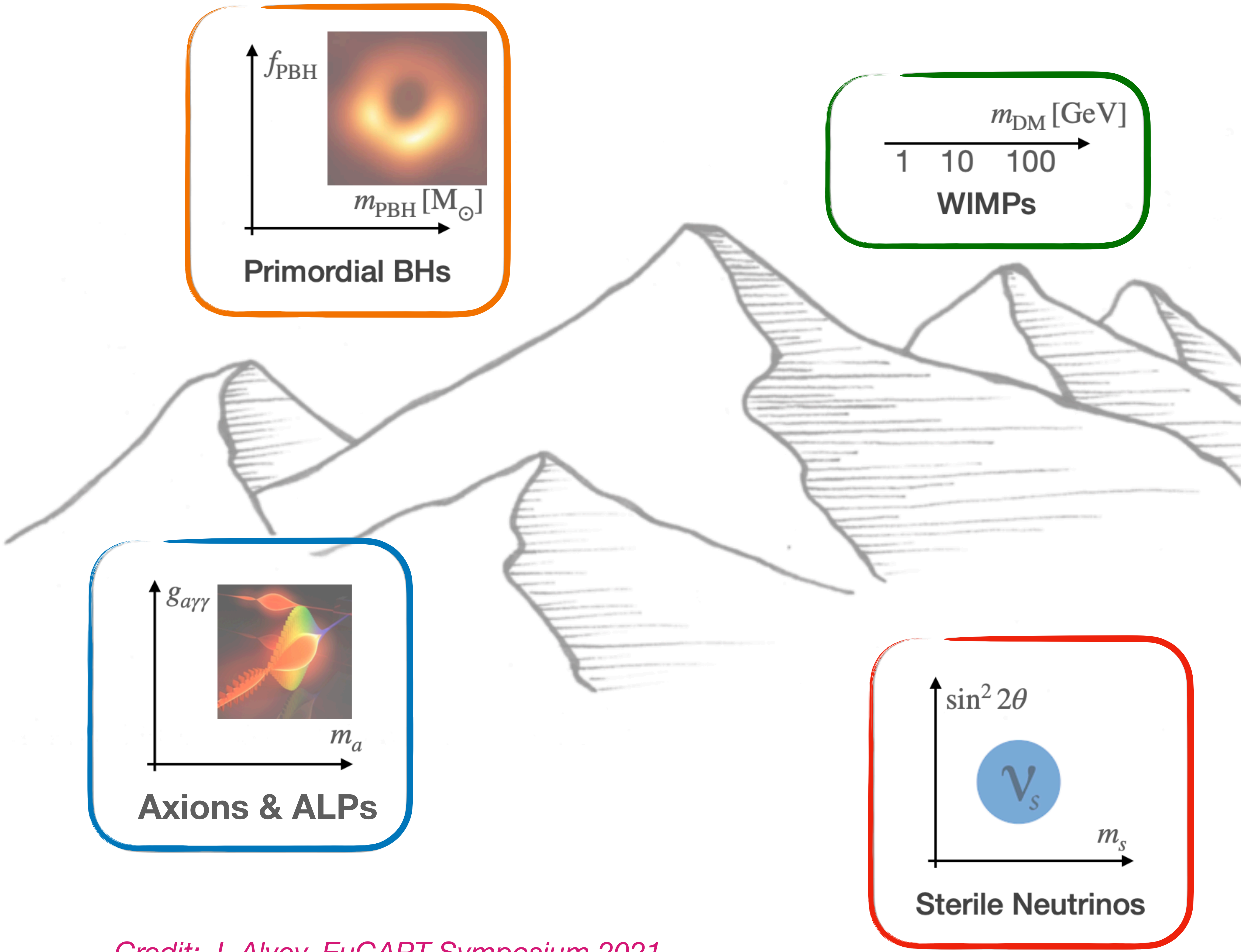


Credit: J. Alvey, EuCAPT Symposium 2021

The dark matter landscape



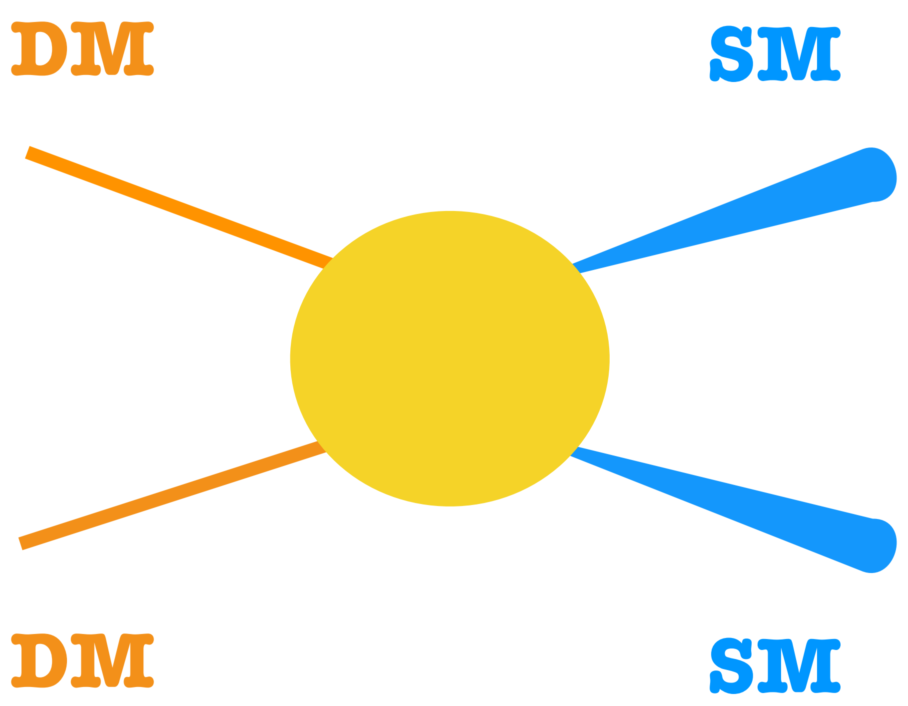
- Identification strategies are necessarily (more or less) **model dependent**
- The **theoretical prejudice** in dark matter searches is also set by what we can probe with available data
- You always need some sort of signature of your model!



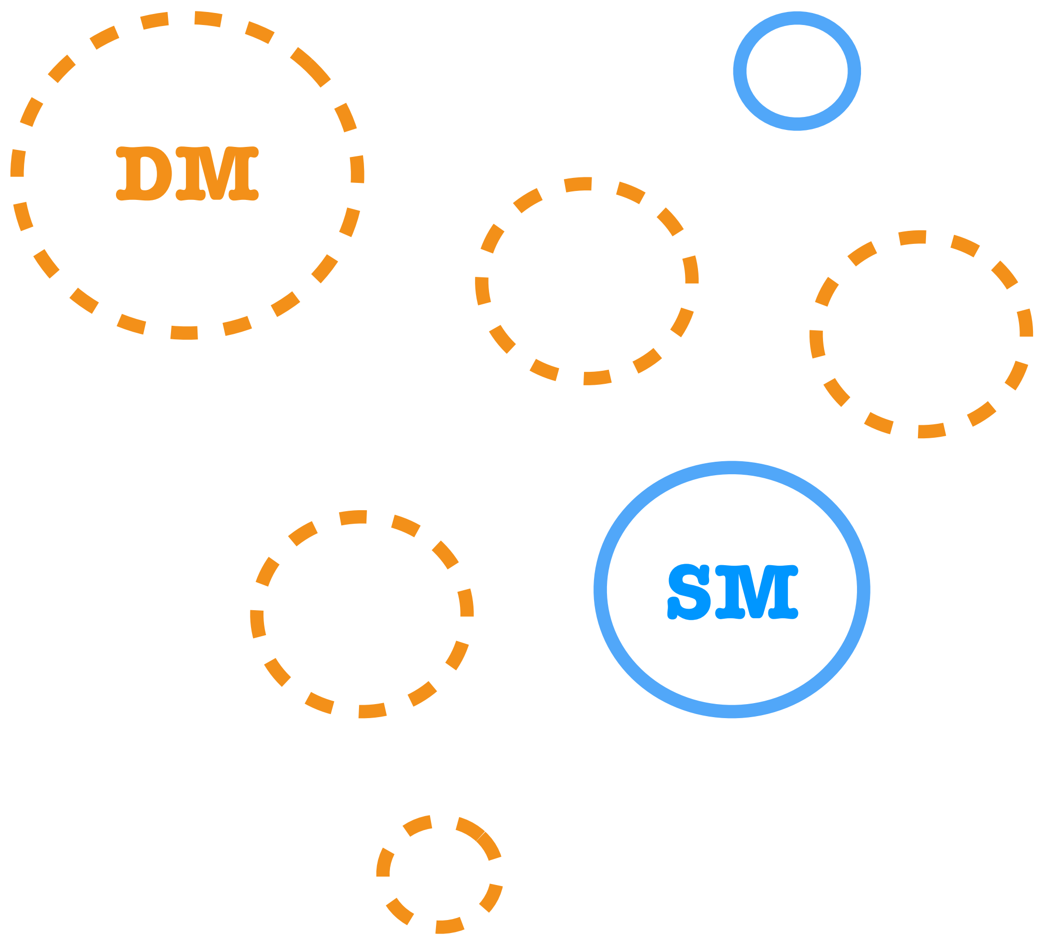
Credit: J. Alvey, EuCAPT Symposium 2021

Dark matter indirect detection

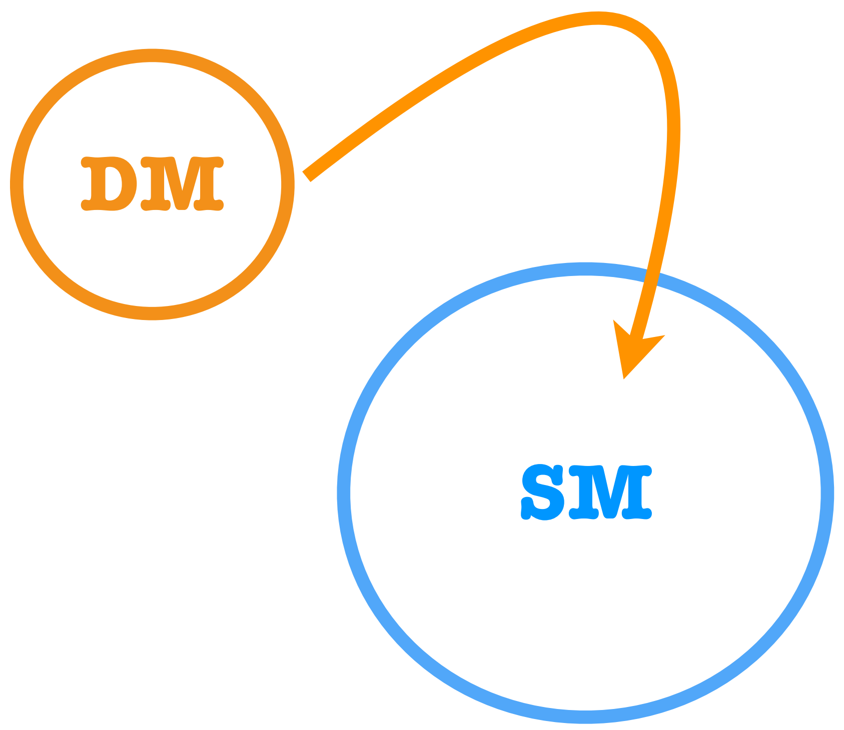
What dark matter does with/to the environment



Energy/particle injection



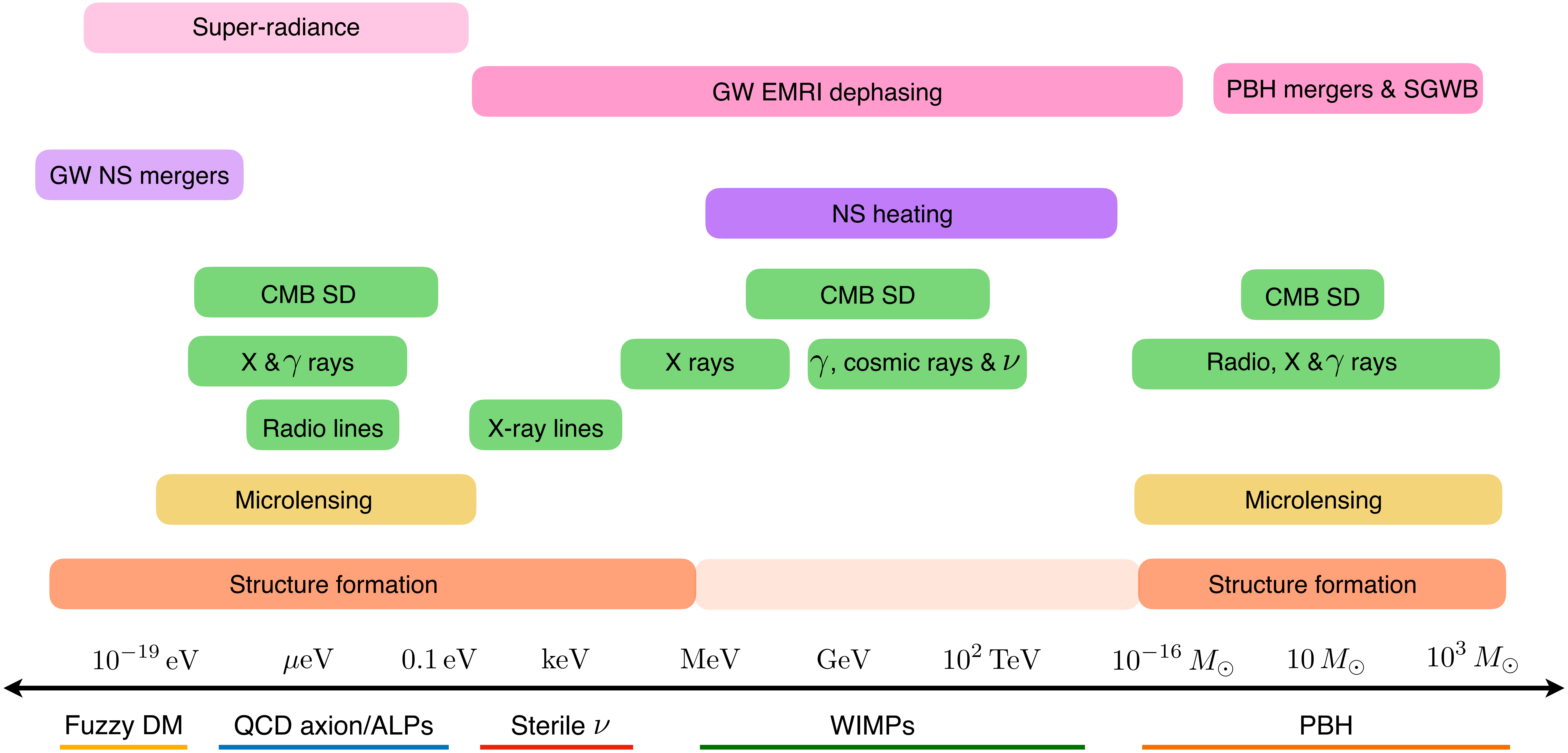
Gravitational interaction



Capture/scattering/accretion in/onto astrophysical objects

Astroparticle observables for dark matter

EuCAPT White Paper, arXiv:2110.10074



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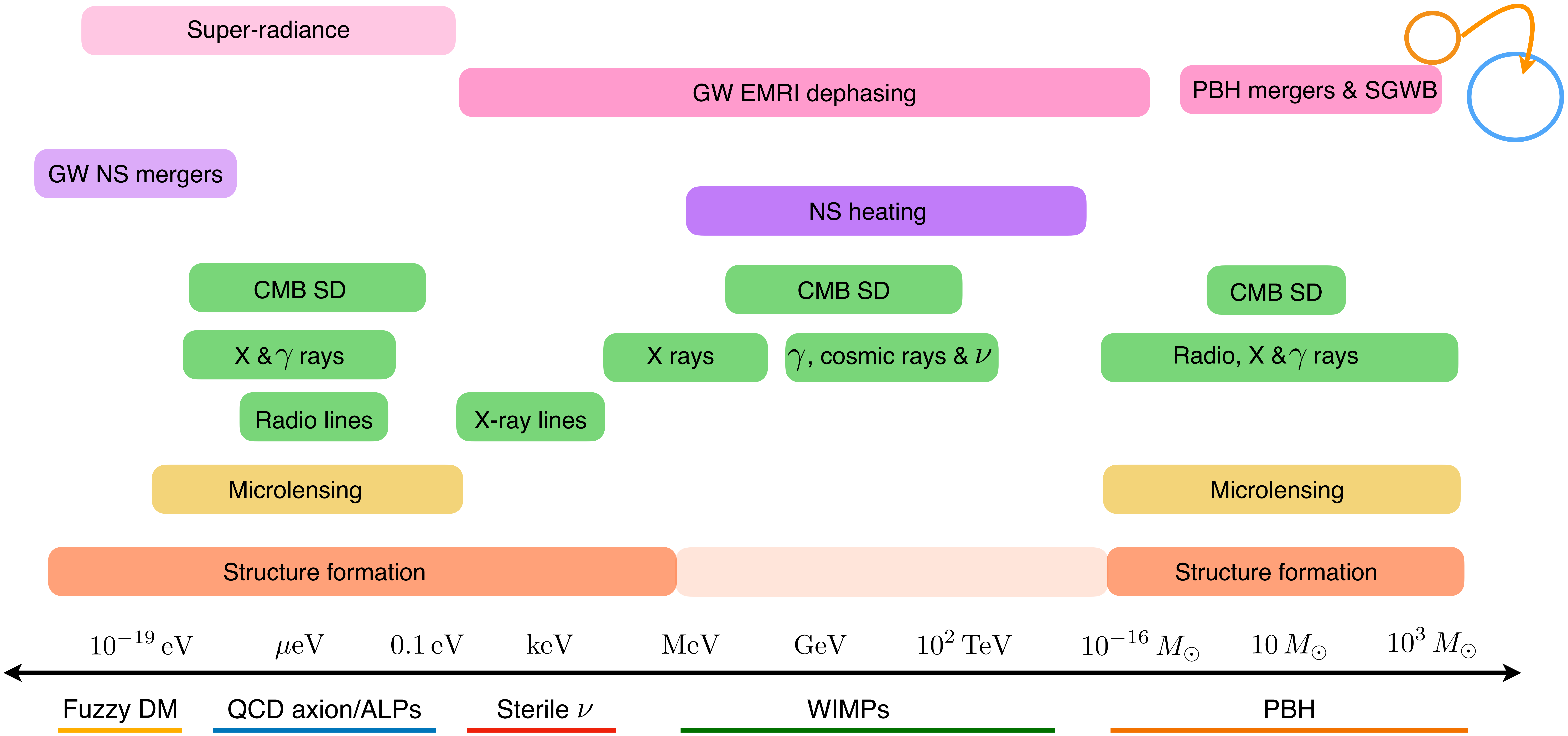

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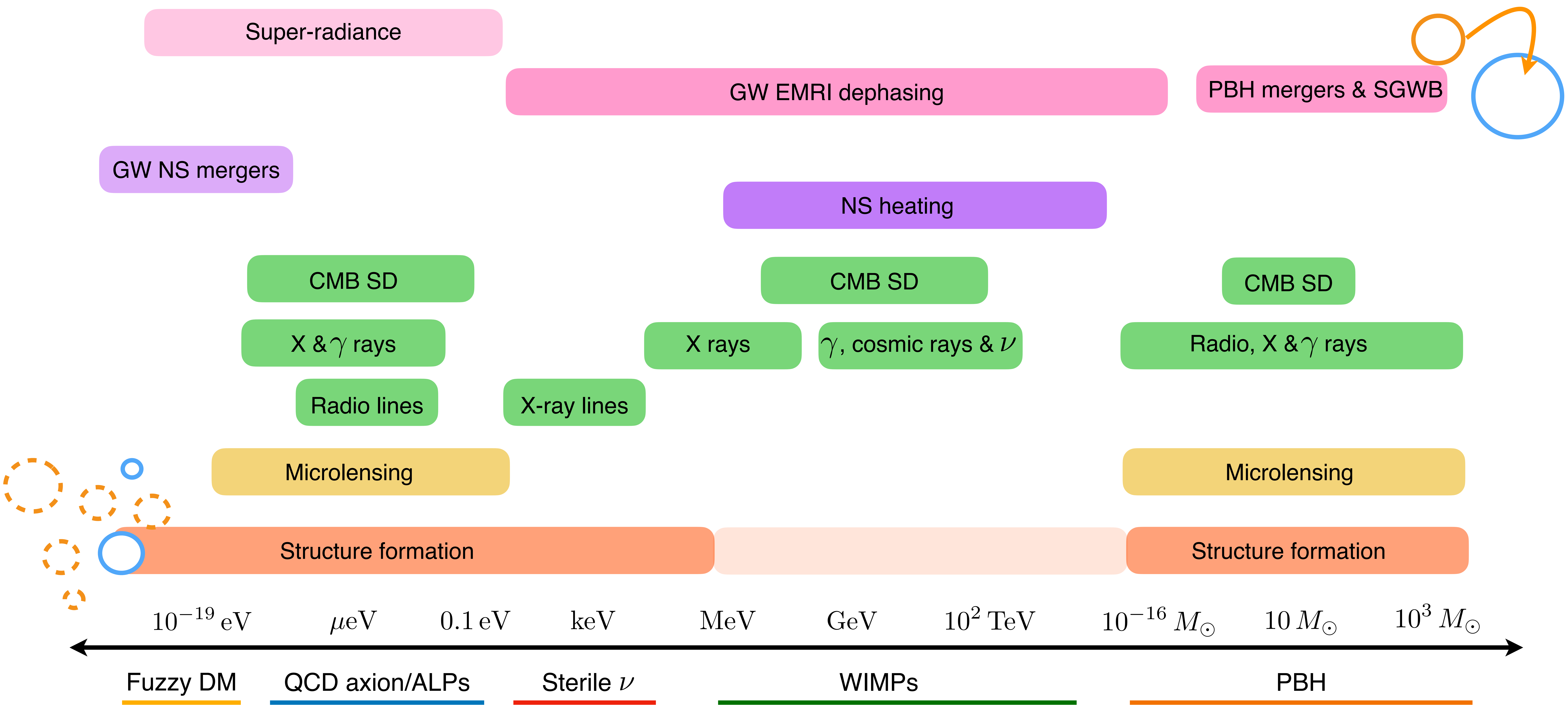

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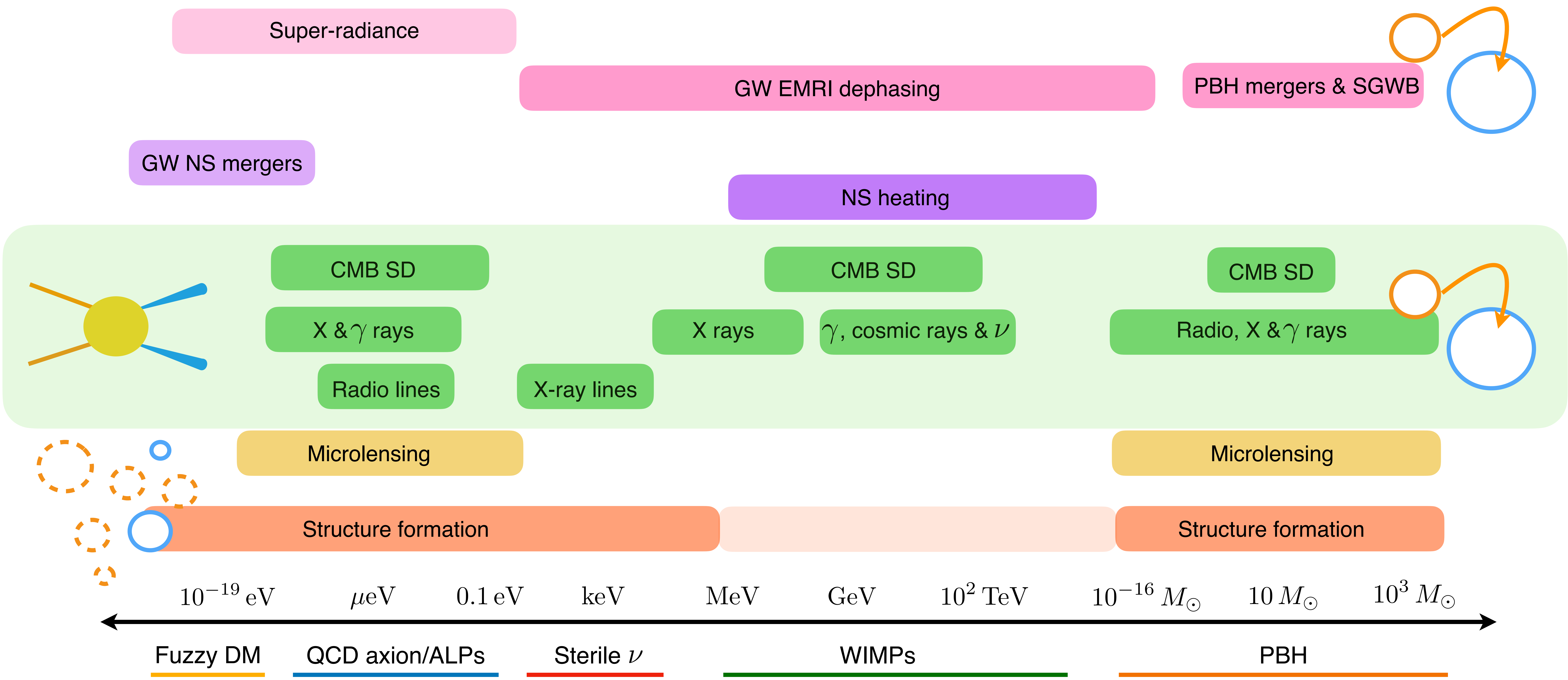
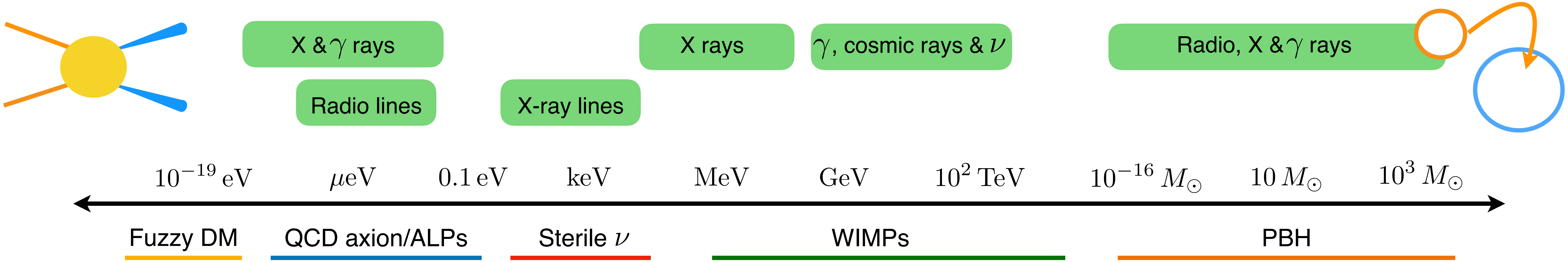


Cosmic messengers

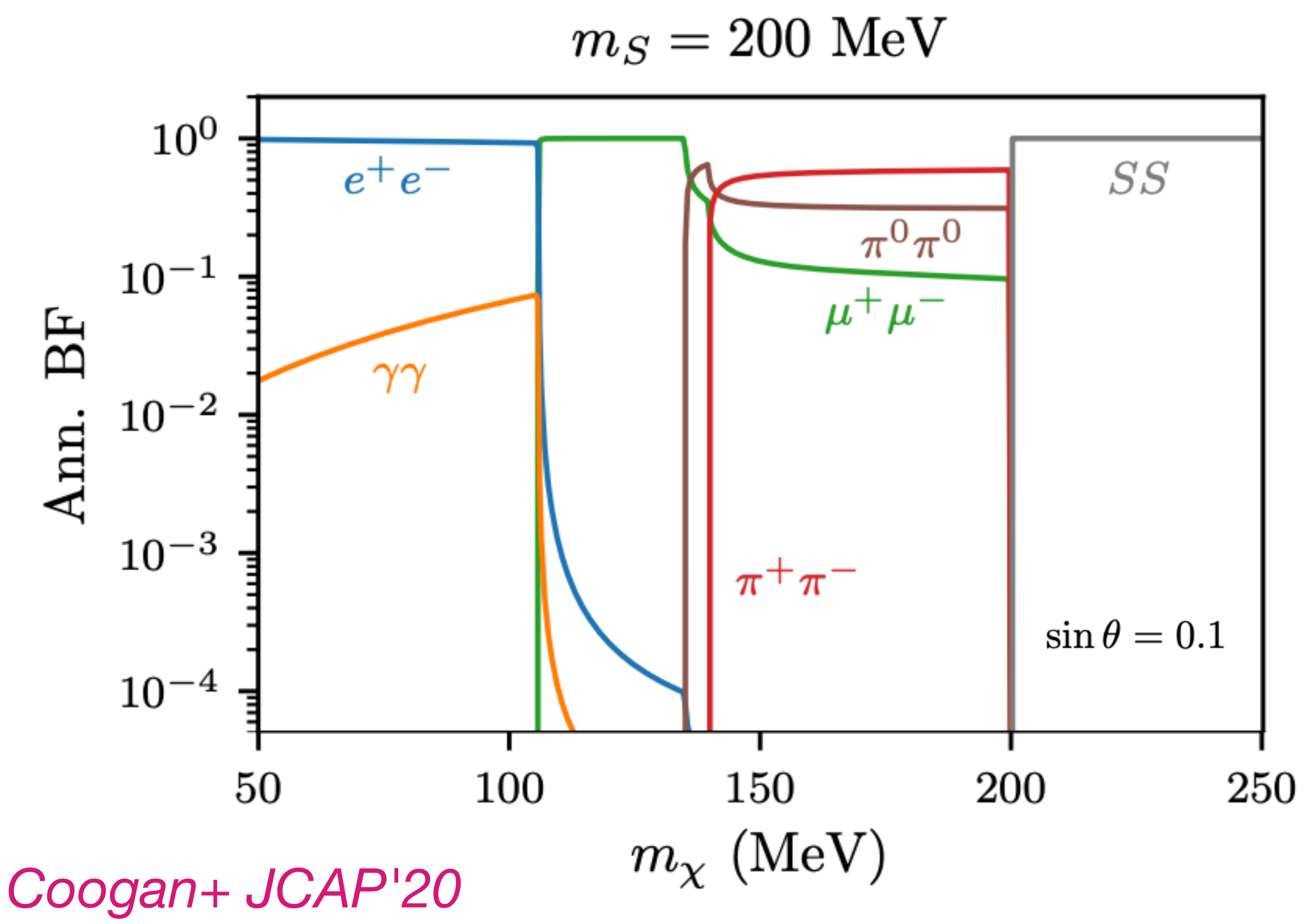


Particle dark matter emission**

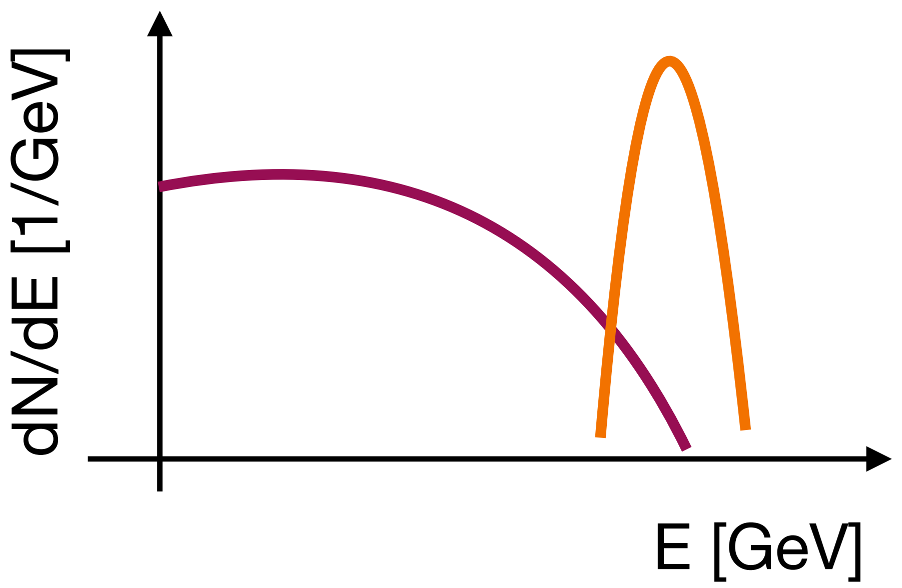
$$(DM)\, DM \to SM\, SM$$

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

Centre of mass energy ≃ Signal energy



Coogan+ JCAP'20



$m_{\rm DM} \lesssim$ MeV

$$E_\gamma = \frac{N m_{\rm DM}}{2}$$

Narrow line signal

$$\frac{dN_\gamma}{dE} = 2\delta\left(E - \frac{N m_{\rm DM}}{2}\right)$$

$m_{\rm DM} \gtrsim$ MeV

Broader energy distribution

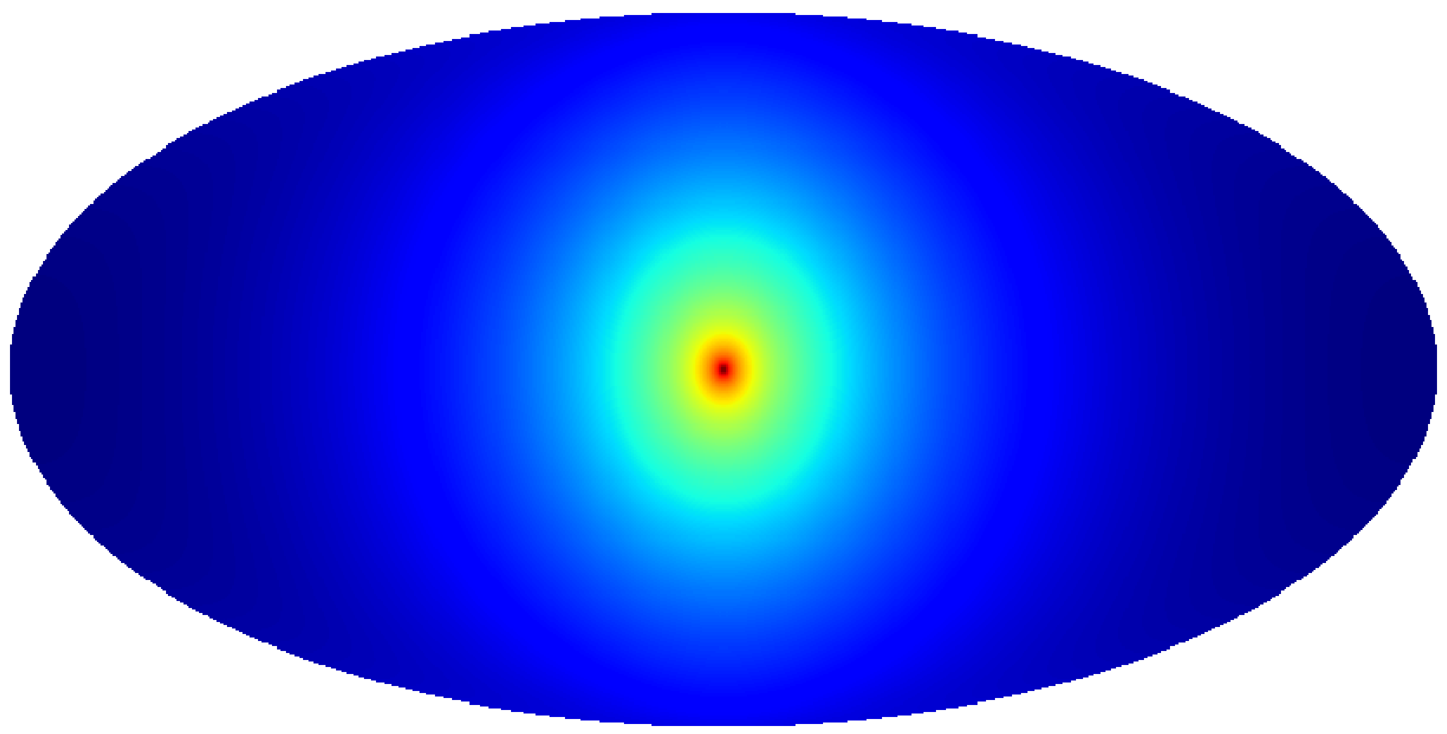
$$\frac{dN_\gamma}{dE} = \left(\frac{dN_\gamma}{dE}\right)_{\gamma\gamma} + \left(\frac{dN_\gamma}{dE}\right)_{\rm sec} + \left(\frac{dN_\gamma}{dE}\right)_{\rm FSR}$$

**Weakly interacting massive particles

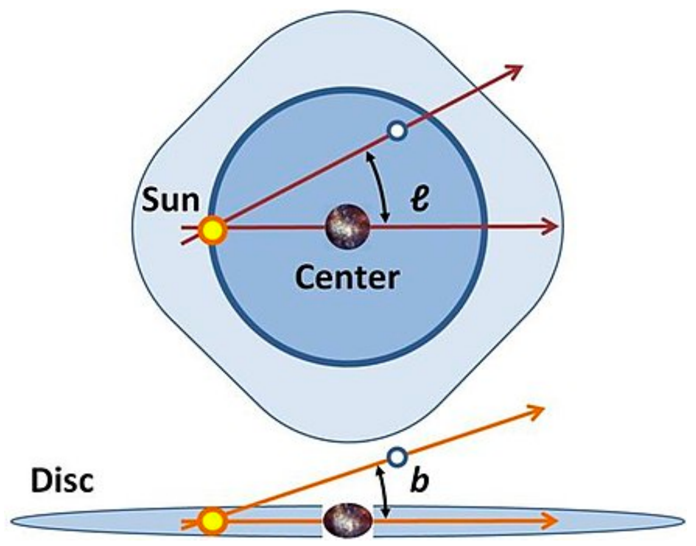
Particle dark matter emission

$$(DM)\,DM \to SM\,SM$$

$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1 \text{ (decay)}, 2 \text{ (annih)}$ Centre of mass energy $\simeq$ Signal energy



Self-conjugated dark matter annihilation
Differential **gamma-ray** flux



$$\frac{d\Phi_\gamma}{dE}(\ell, b) = \mathcal{A}(\theta_{\rm DM}) \times \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} \rho^N_{\rm DM}(s, \ell, b)ds$$

$\theta_{\rm DM} = \{\Gamma_\gamma, m_{\rm DM}\}$ *Decay*

$\theta_{\rm DM} = \{\langle \sigma v \rangle, m^2_{\rm DM}\}$ *Annihilation*

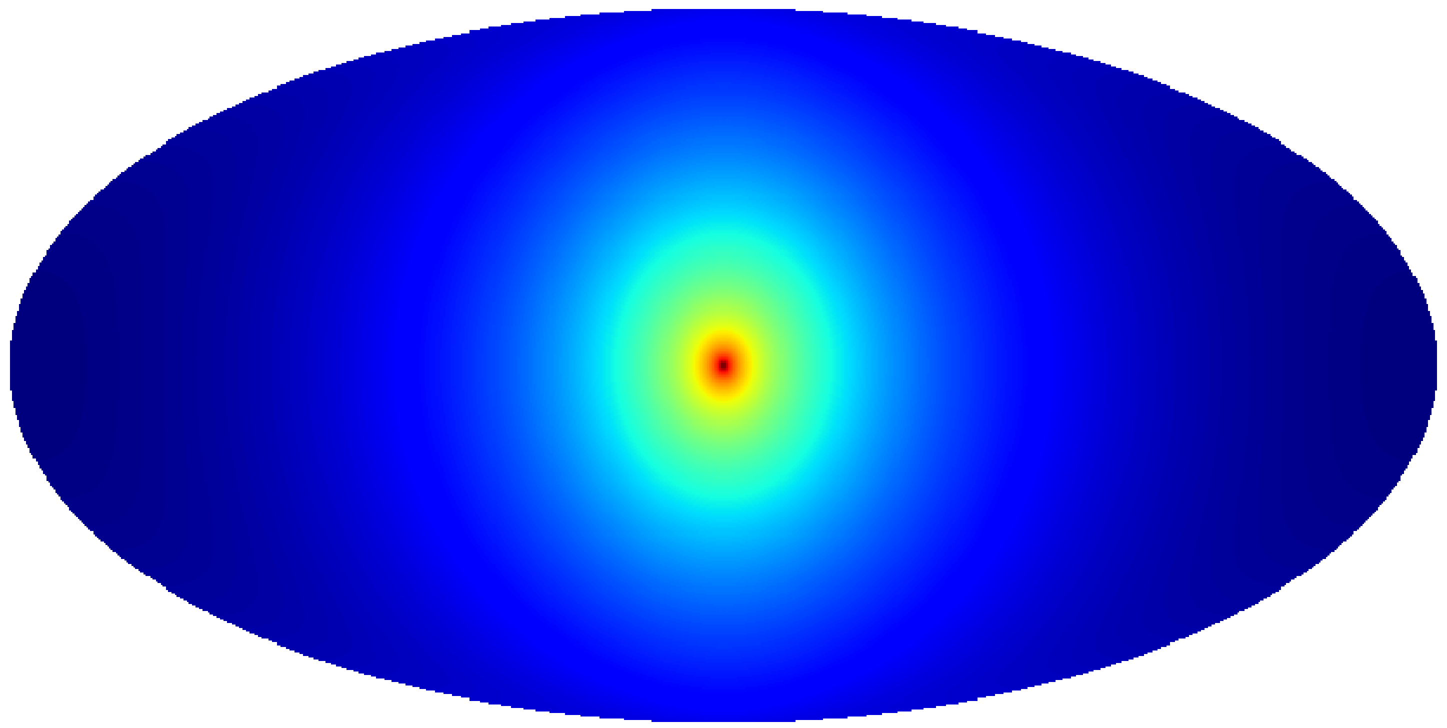
Particle dark matter emission

$$(DM)\,DM \rightarrow SM\,SM$$

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

Centre of mass energy ≃ Signal energy

$$\frac{d\Phi_\gamma}{dE}(\ell, b) = \mathcal{A}(\theta_{\rm DM}) \times \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} \rho^N_{\rm DM}(s, \ell, b)\, ds$$



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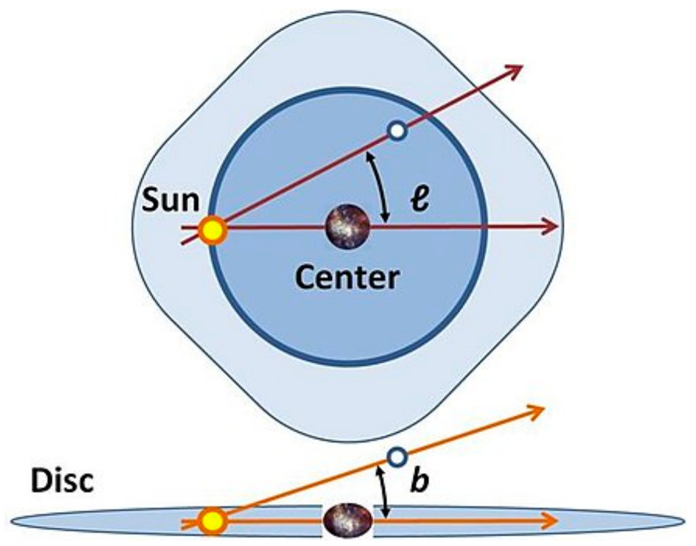
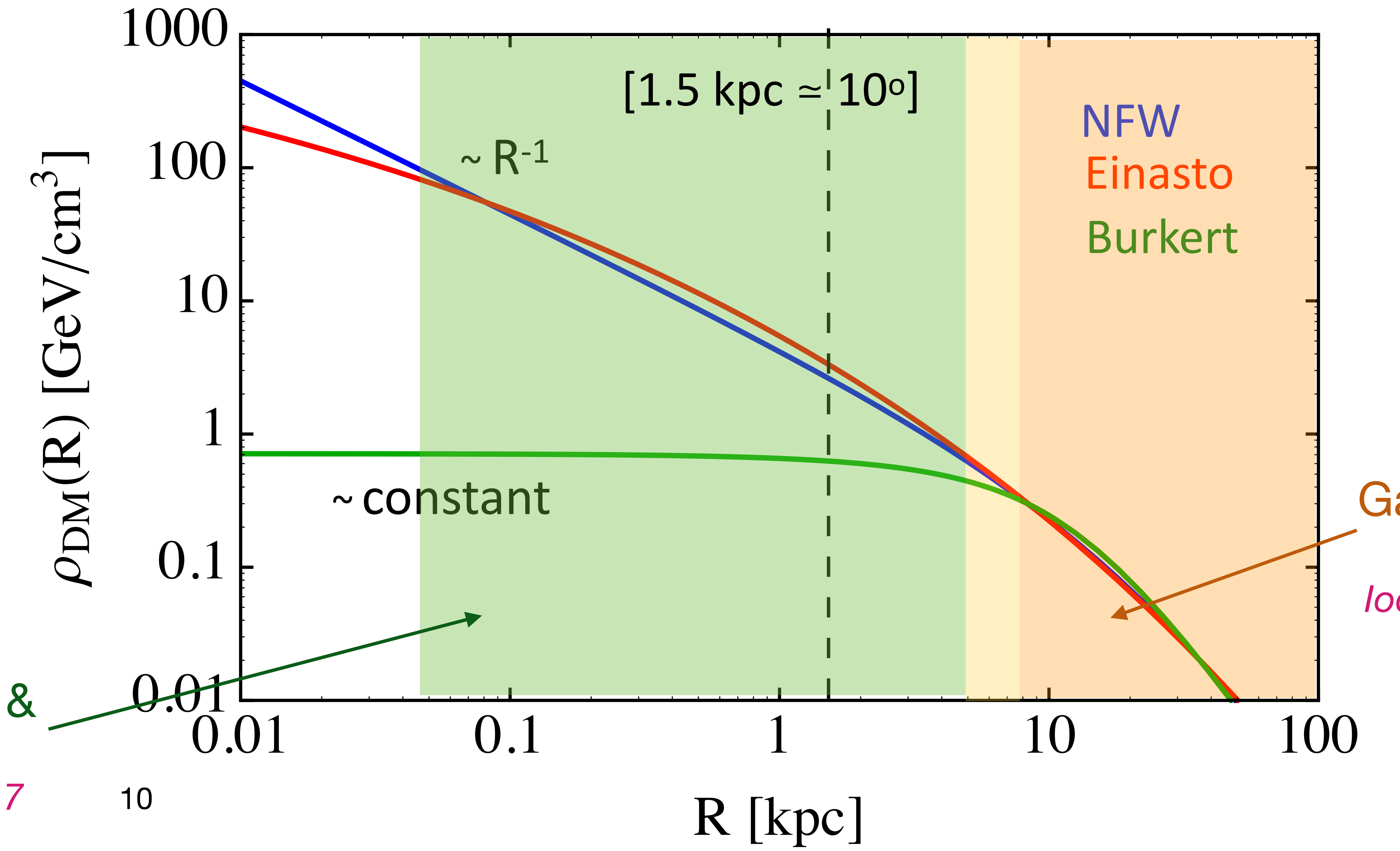




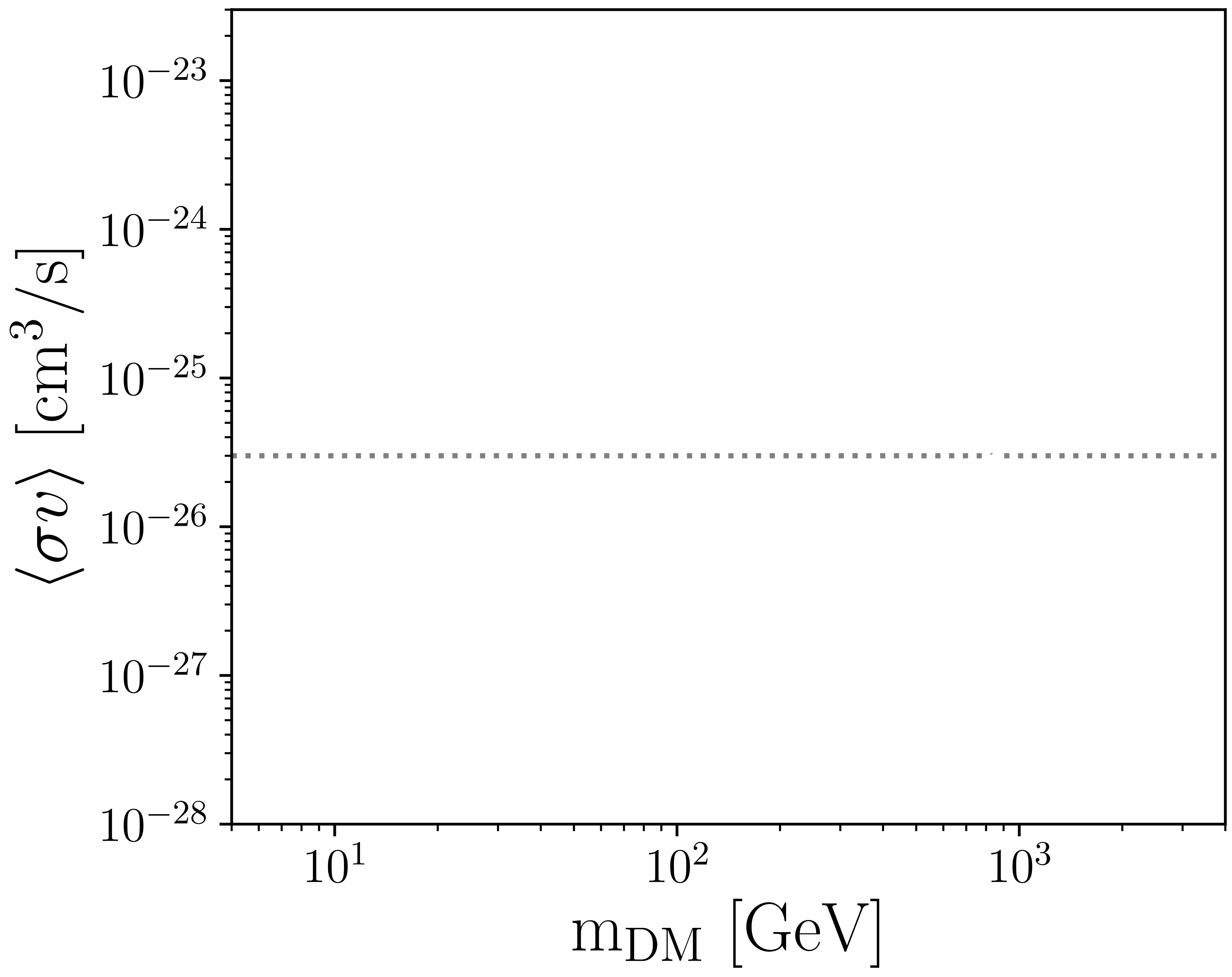
Galactic rotation curve
Iocco+ Nature Phys.'15

Simulations w/ baryons & semi-analytical models
FC+JCAP'15; Stref & Lavalle PRD'17

Limits on annihilating WIMPs

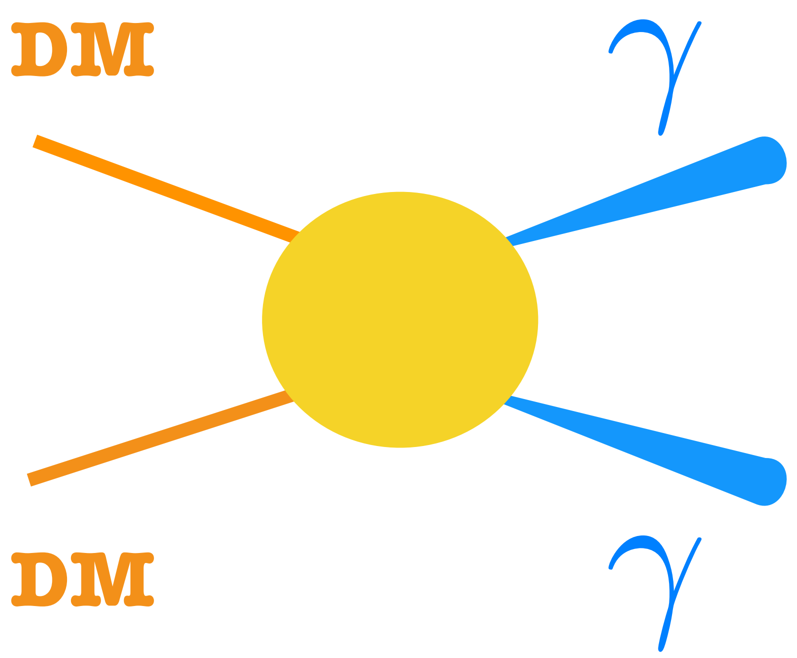
Summary of multi-targets and MW constraints

~ a few GeV — few TeV



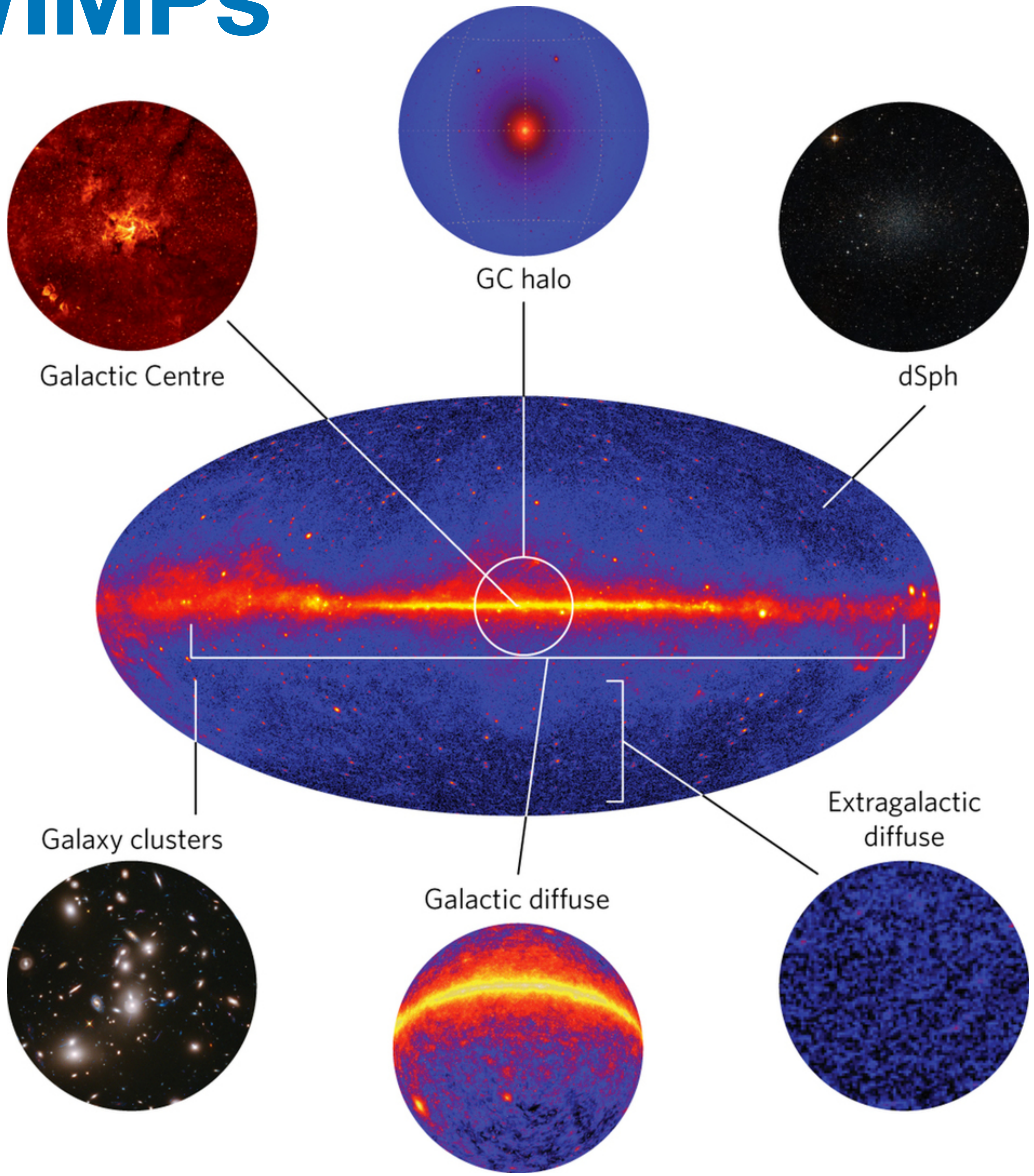
Limits on annihilating WIMPs

Gamma rays



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

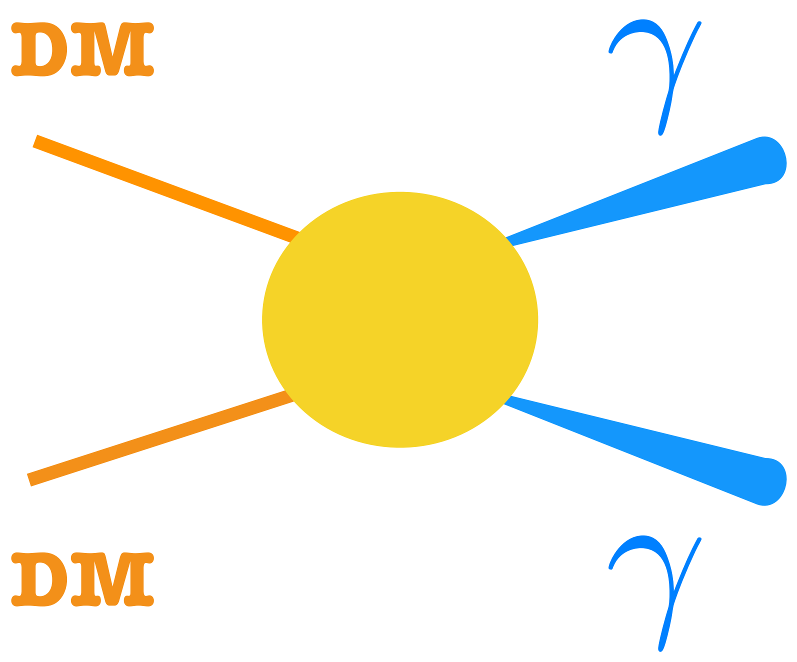
+ dedicated searches for gamma-ray lines
+ similar targets for radio searches (synchrotron)



Conrad & Reimer Nature Phys. 13 (2017)

Limits on annihilating WIMPs

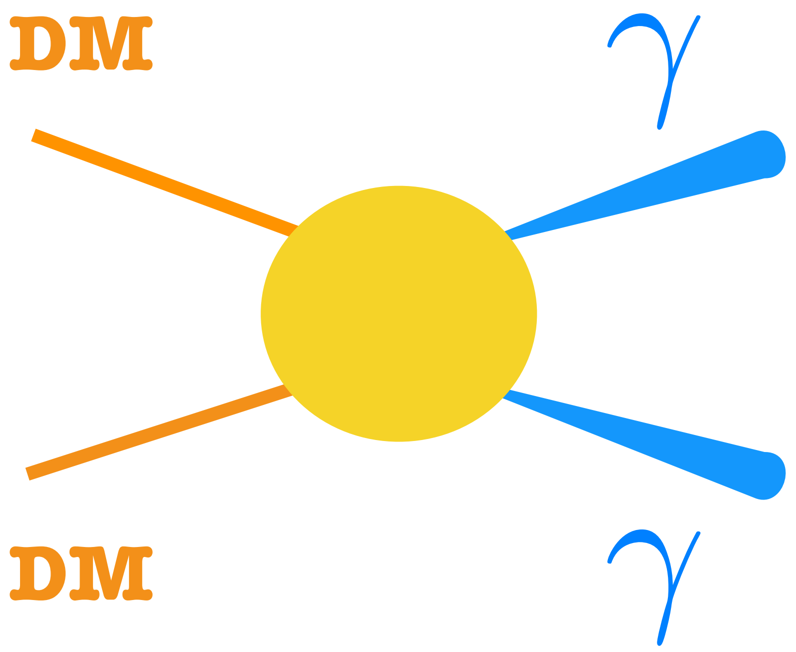
Gamma rays: Dwarf spheroidal galaxies



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

Limits on annihilating WIMPs

Gamma rays: Dwarf spheroidal galaxies



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Limits on annihilating WIMPs

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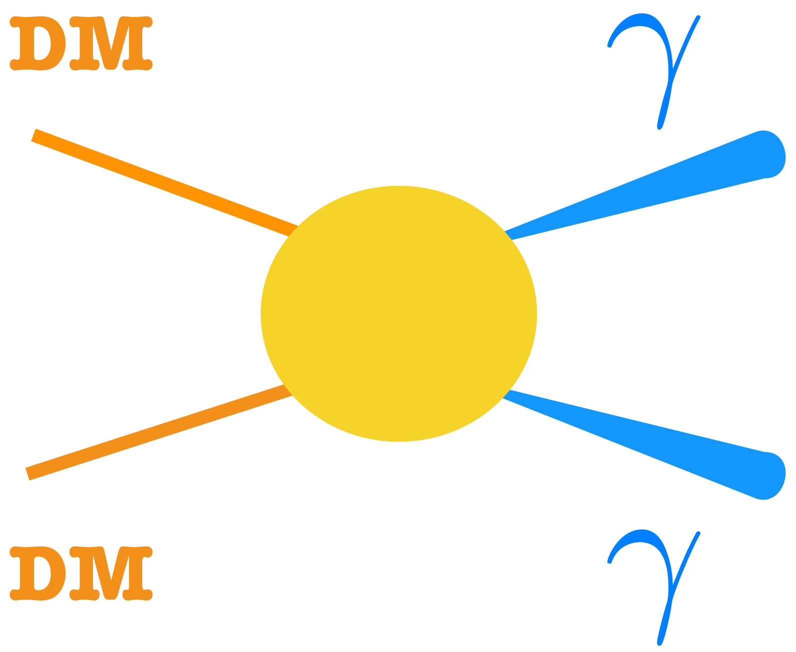

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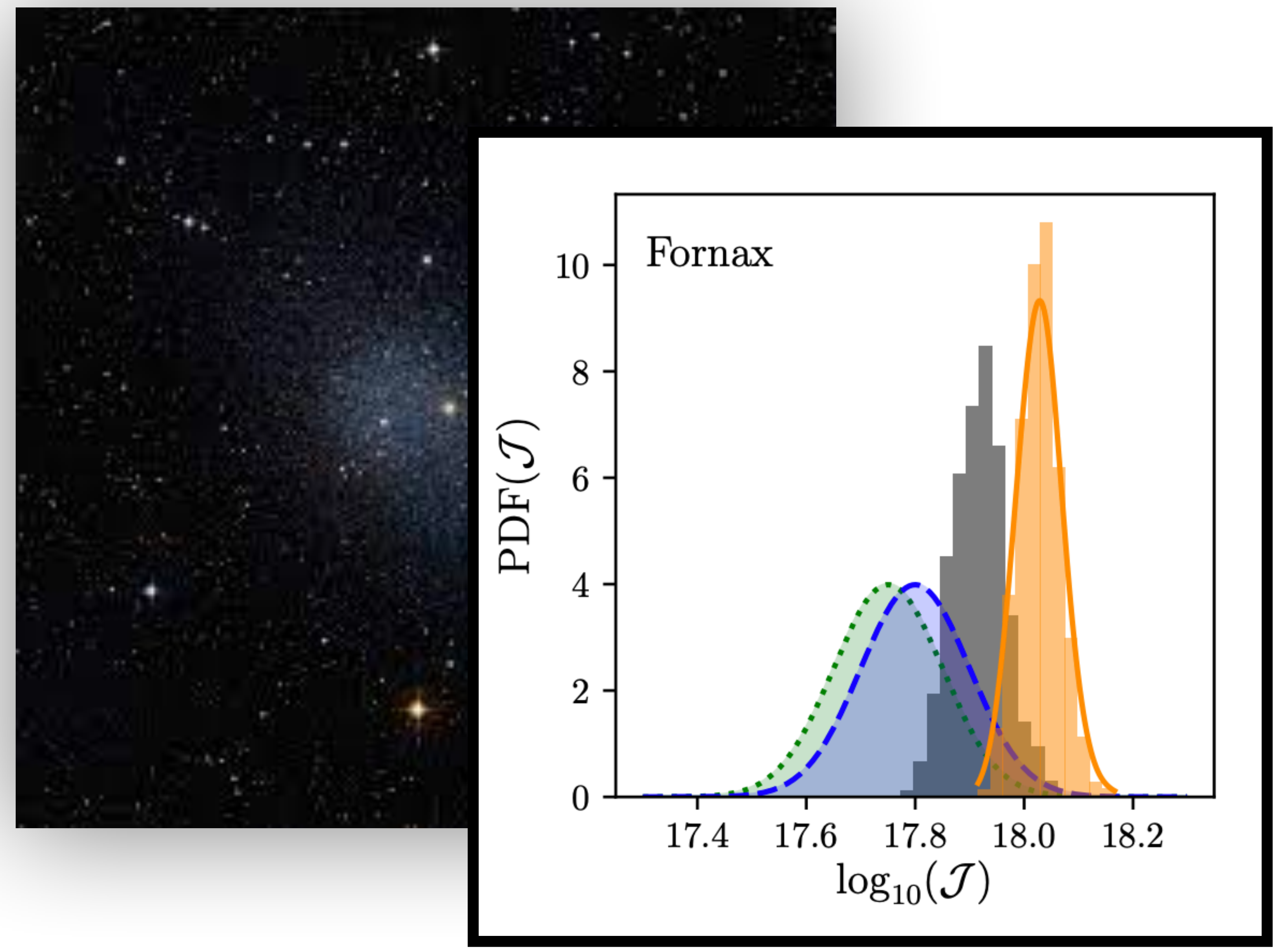
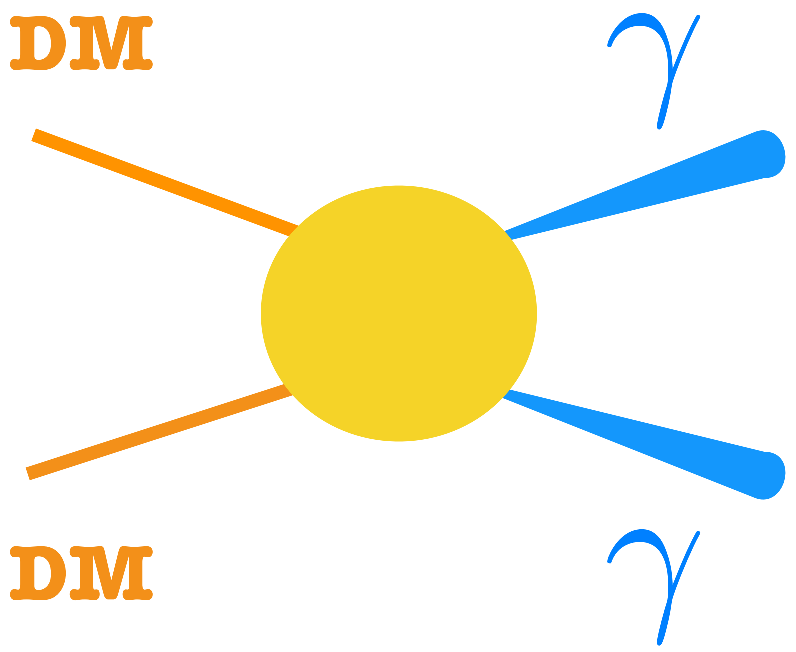


Limits on annihilating WIMPs

Gamma rays: Dwarf spheroidal galaxies



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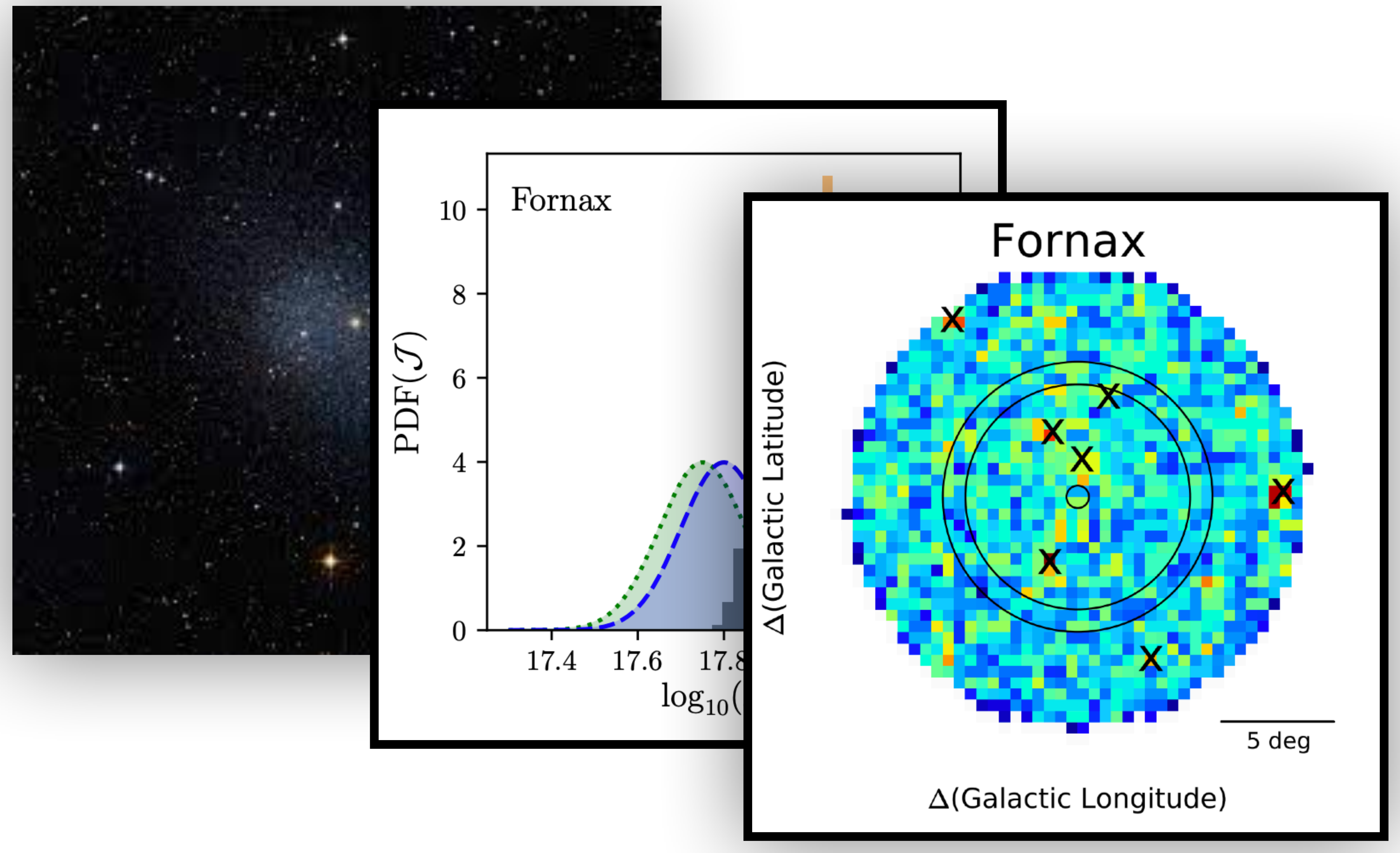
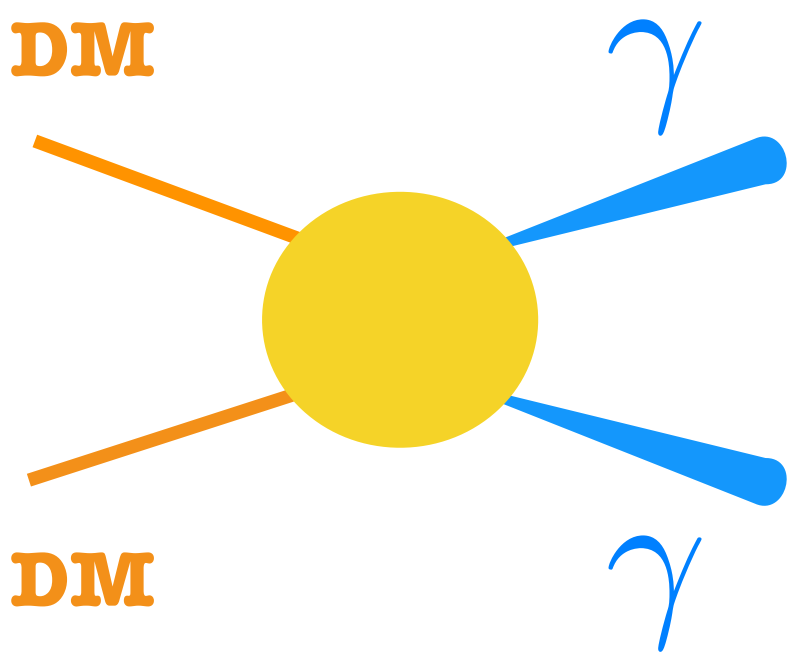


Limits on annihilating WIMPs

Gamma rays: Dwarf spheroidal galaxies



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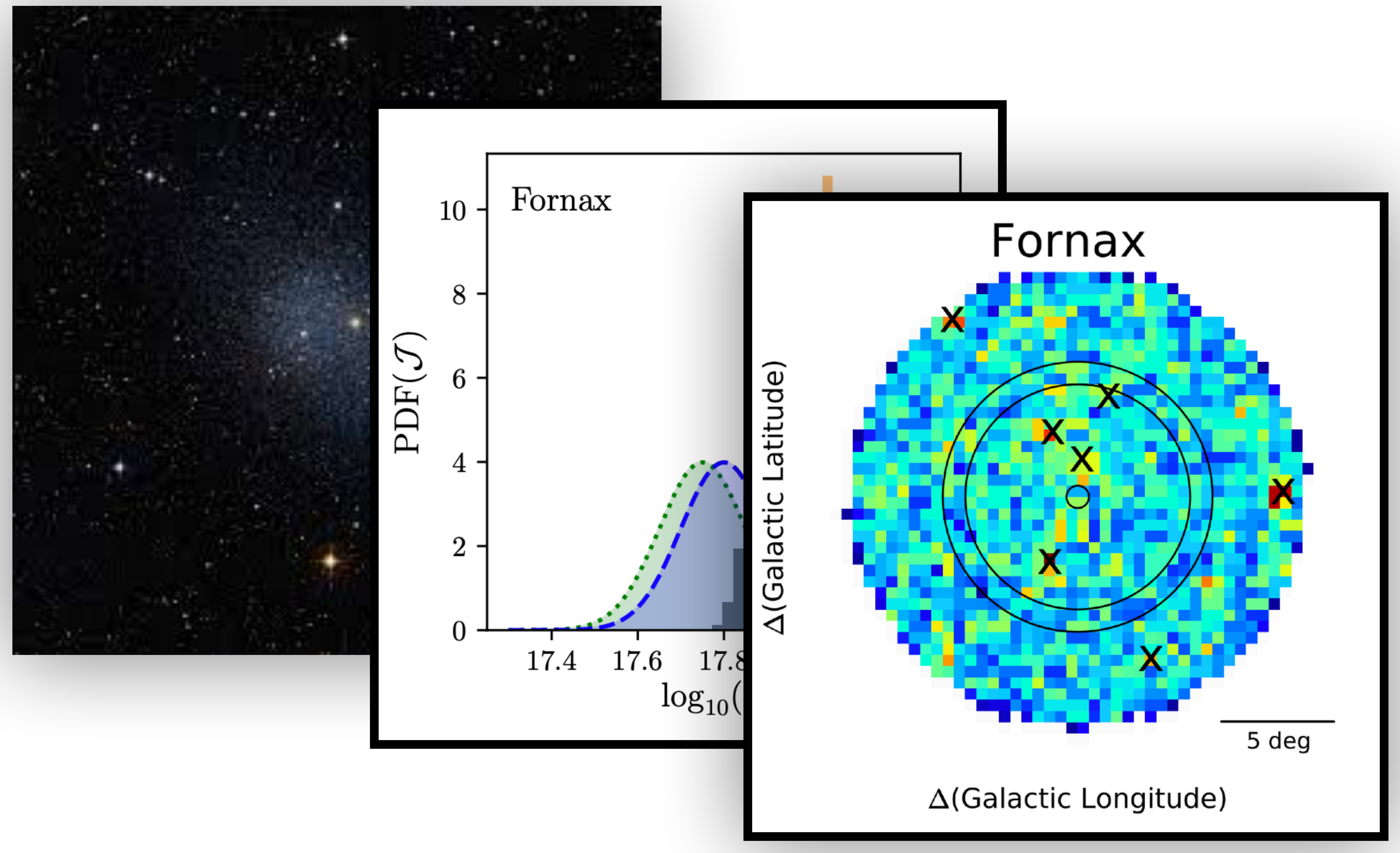


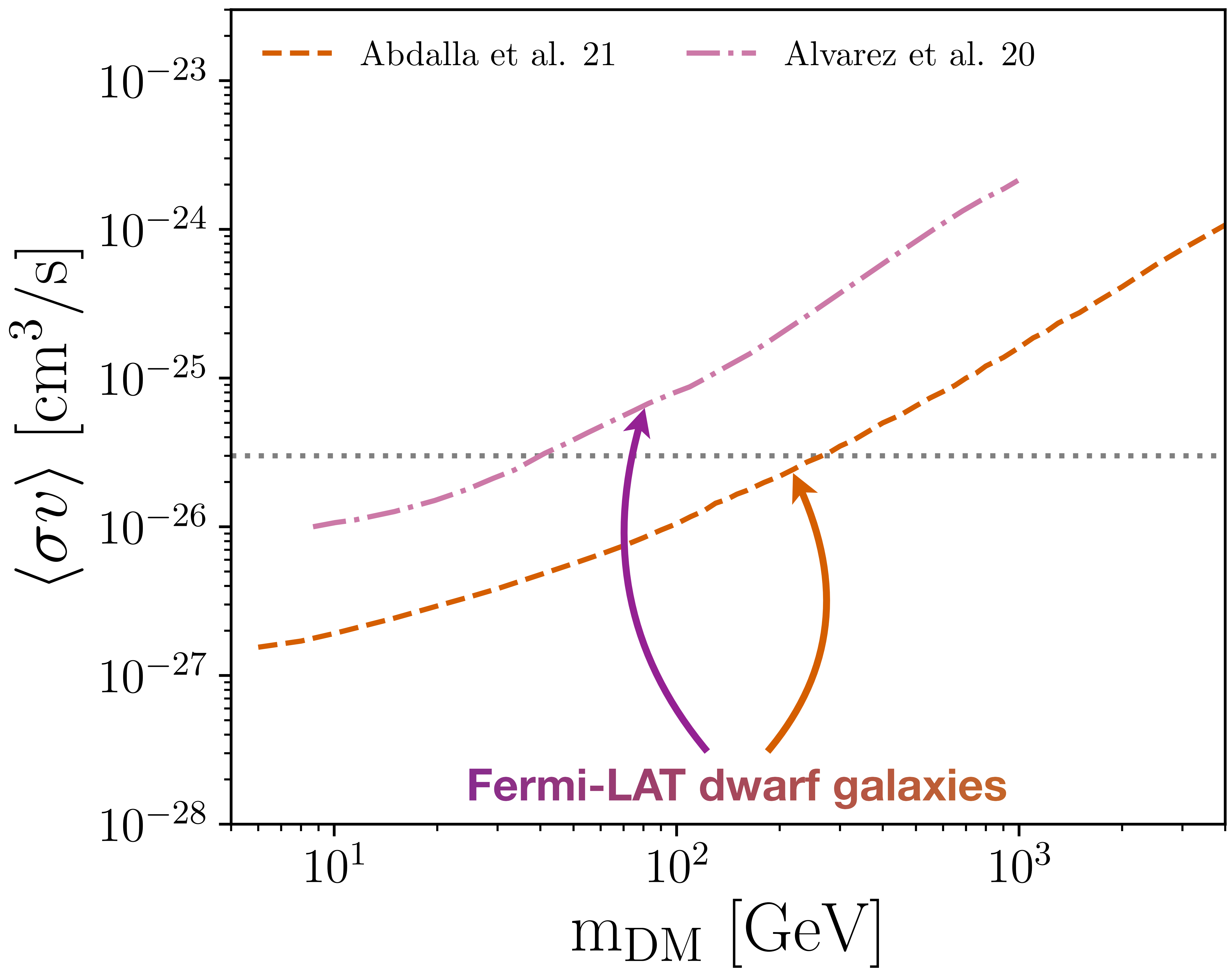
Evidence for additional **DM signal**?

$$\frac{d\Phi_\gamma}{dE}(\ell, b) = \left(\frac{d\Phi_\gamma}{dE}\right)_{\text{diffuse}} + \left(\frac{d\Phi_\gamma}{dE}\right)_{\text{PS}} + \left(\frac{d\Phi_\gamma}{dE}\right)_{\text{DM signal}}$$

Limits on annihilating WIMPs

Gamma rays: Dwarf spheroidal galaxies

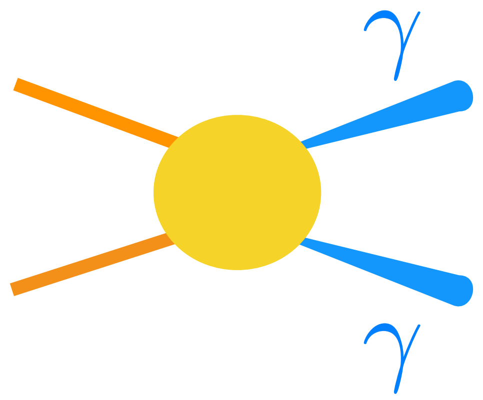
~ a few GeV — few TeV



- Exclude thermal cross section below 30 - 300 GeV
- **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*

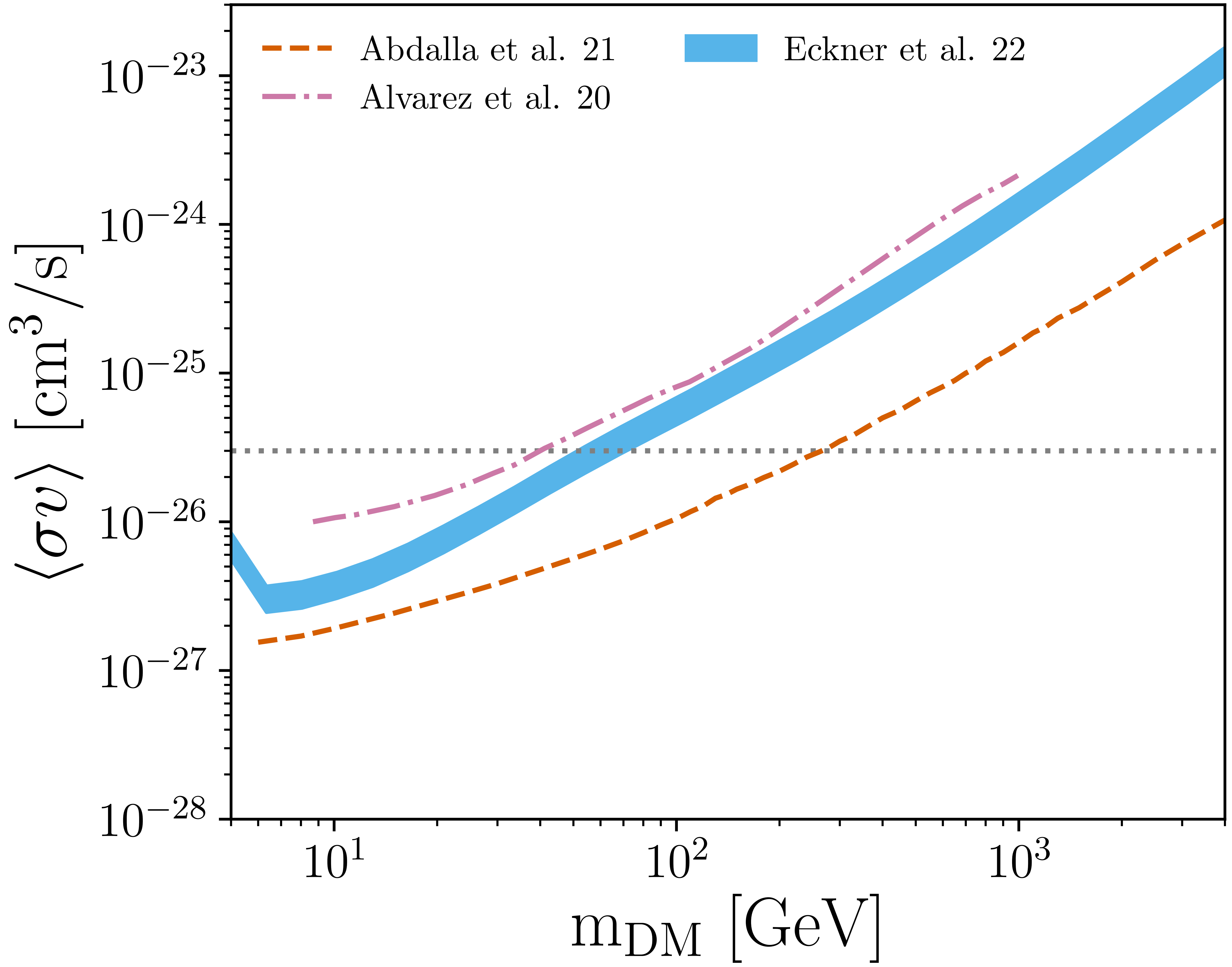
TAKE AWAY: Typically strong probes but keep in mind systematics

Limits on annihilating WIMPs



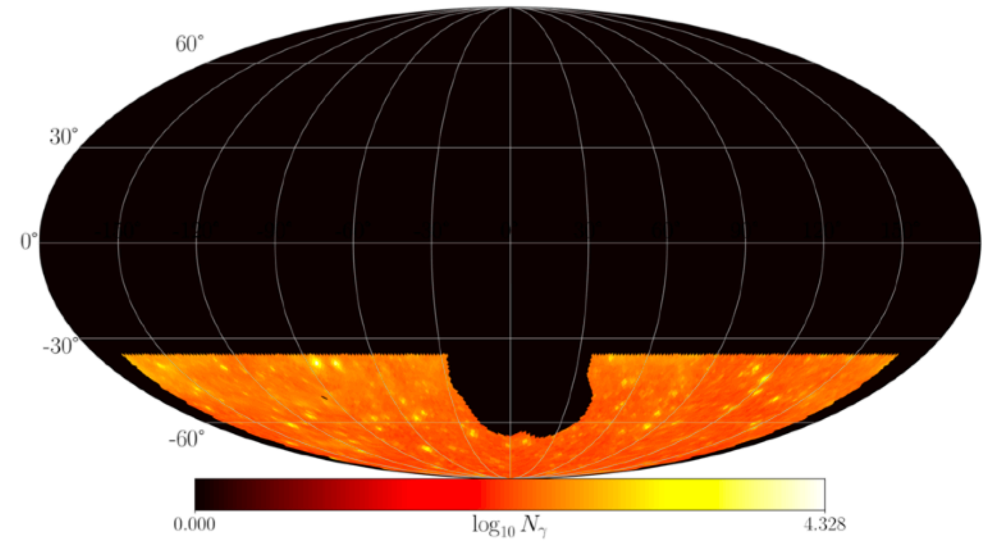
Gamma rays: High-latitude MW halo

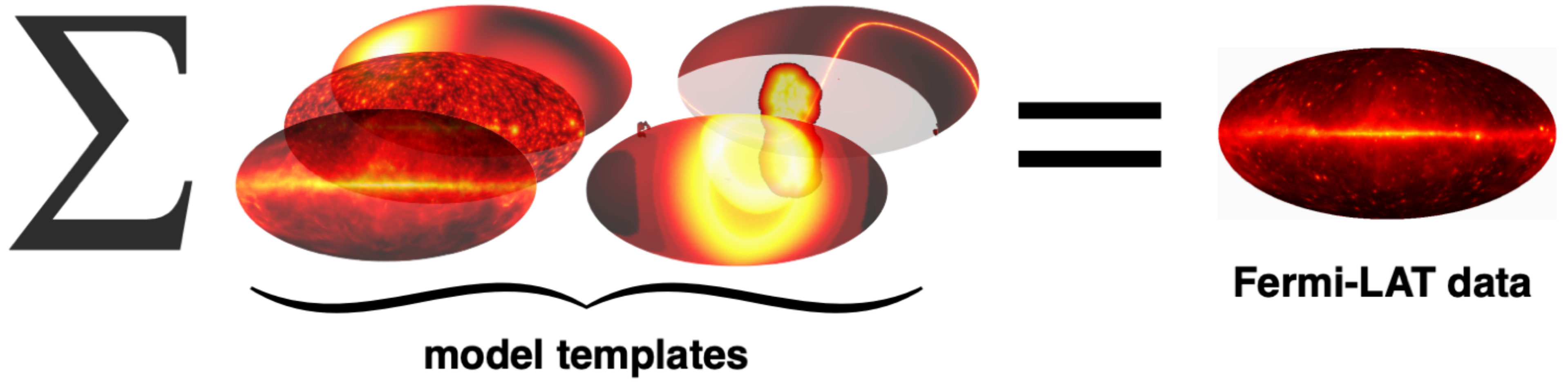
~ a few GeV — few TeV



High-latitude Fermi-LAT sky

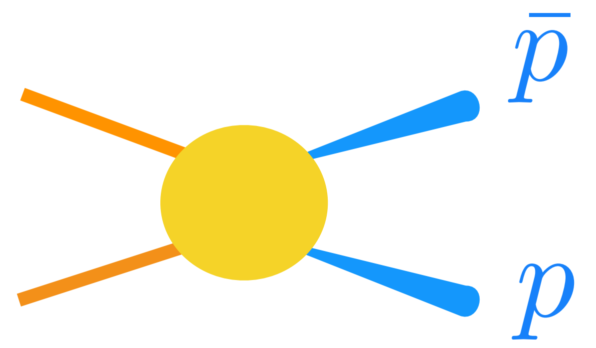
Eckner, FC+ MNRAS'22
Zechlin+ PRD'18
Chang+ PRD'18



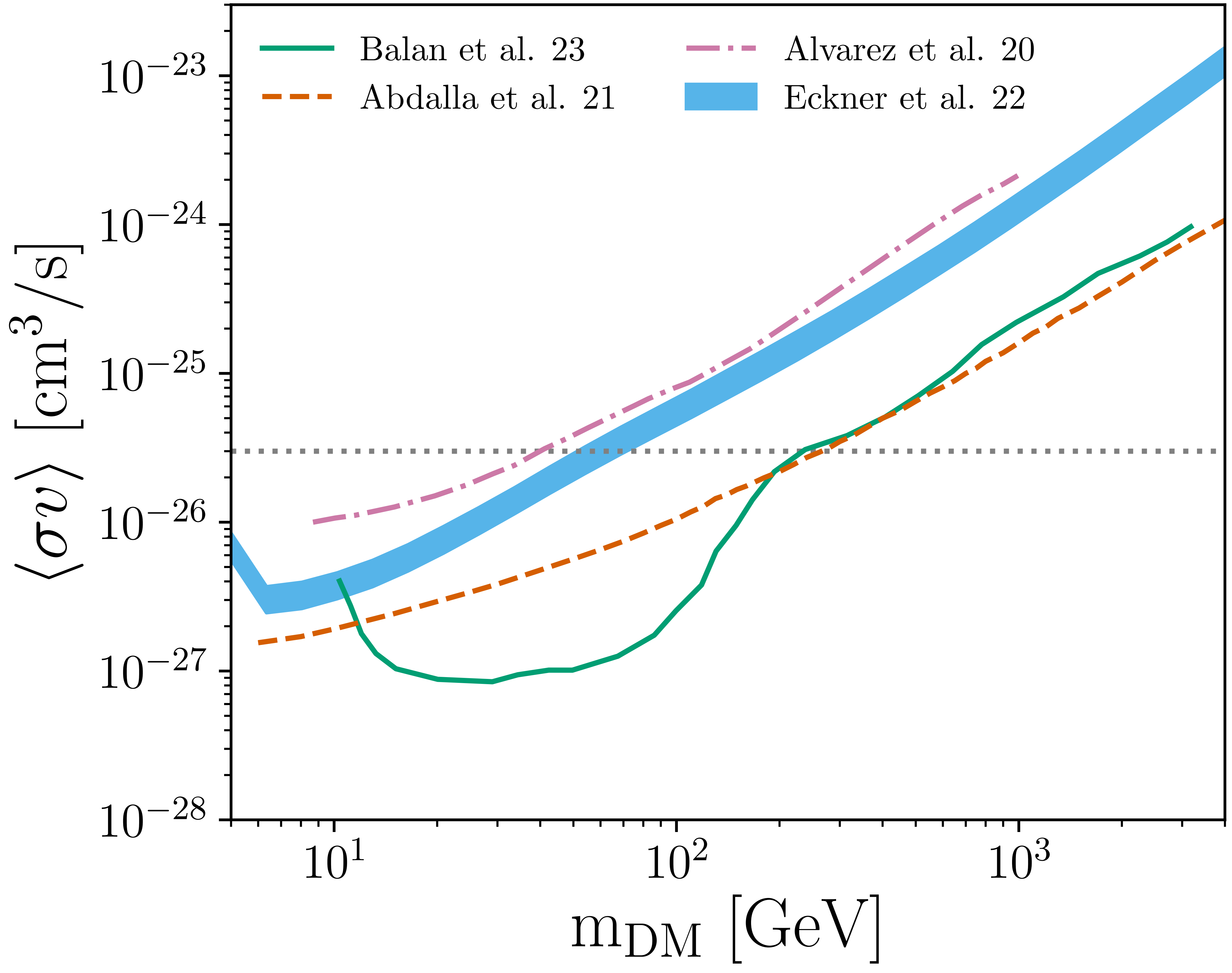


Limits on annihilating WIMPs

Anti-protons flux from the MW

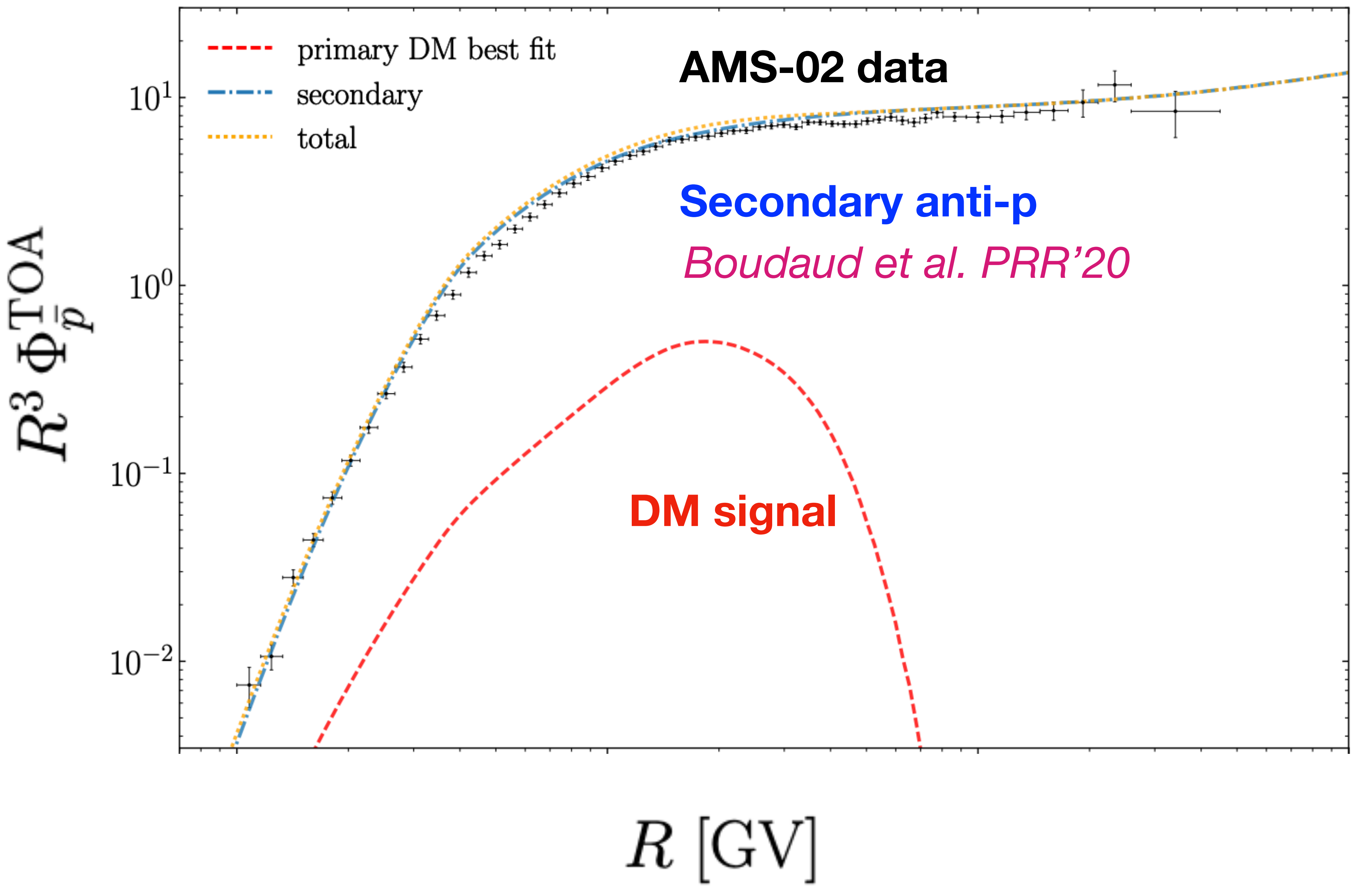


~ a few GeV — few TeV



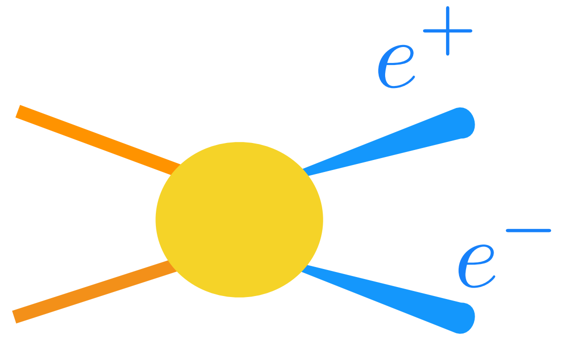
Anti-protons

Balan+ arXiv:2303.07362
Di Mauro+ PRD'21,
FC+ SciPost'22

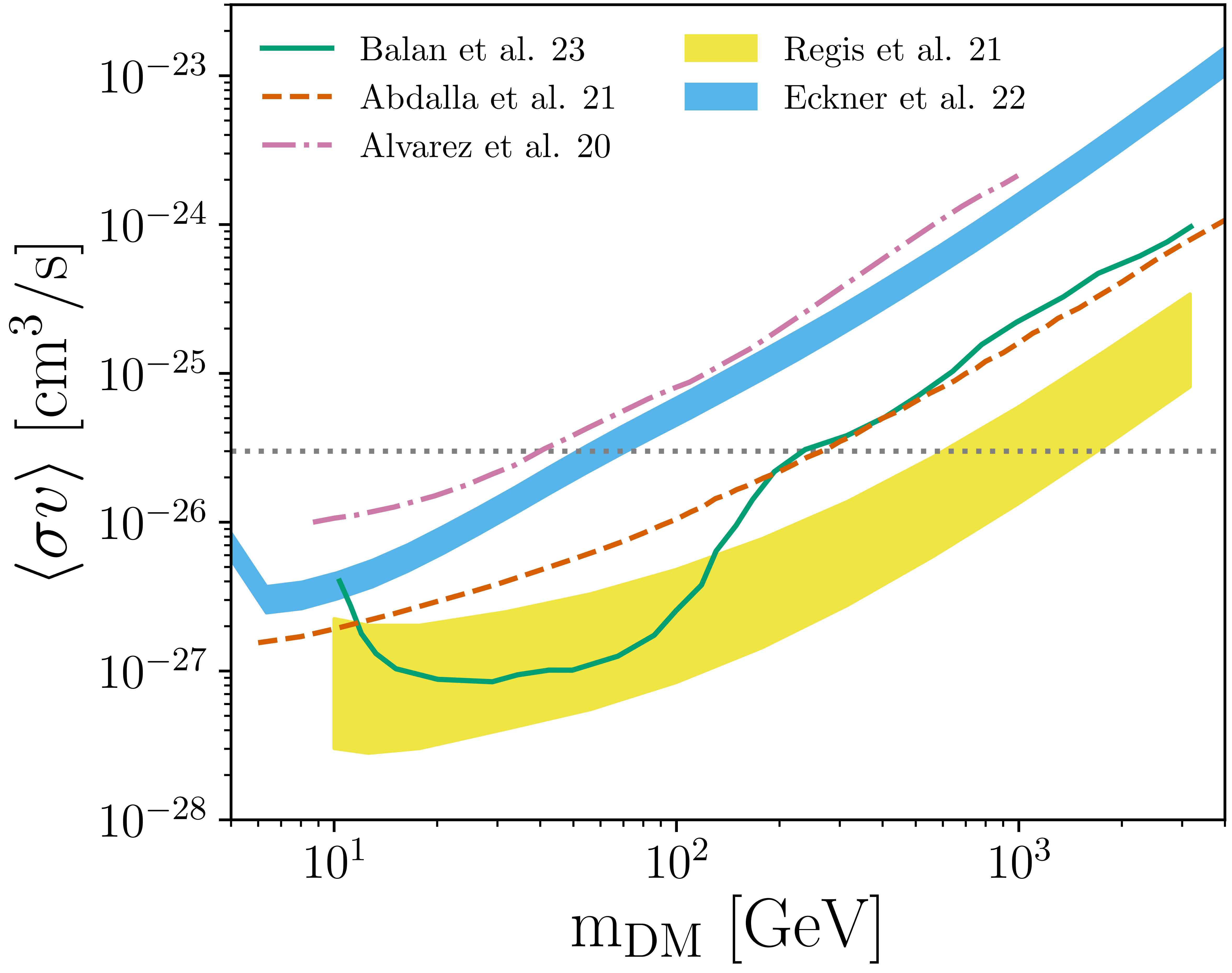


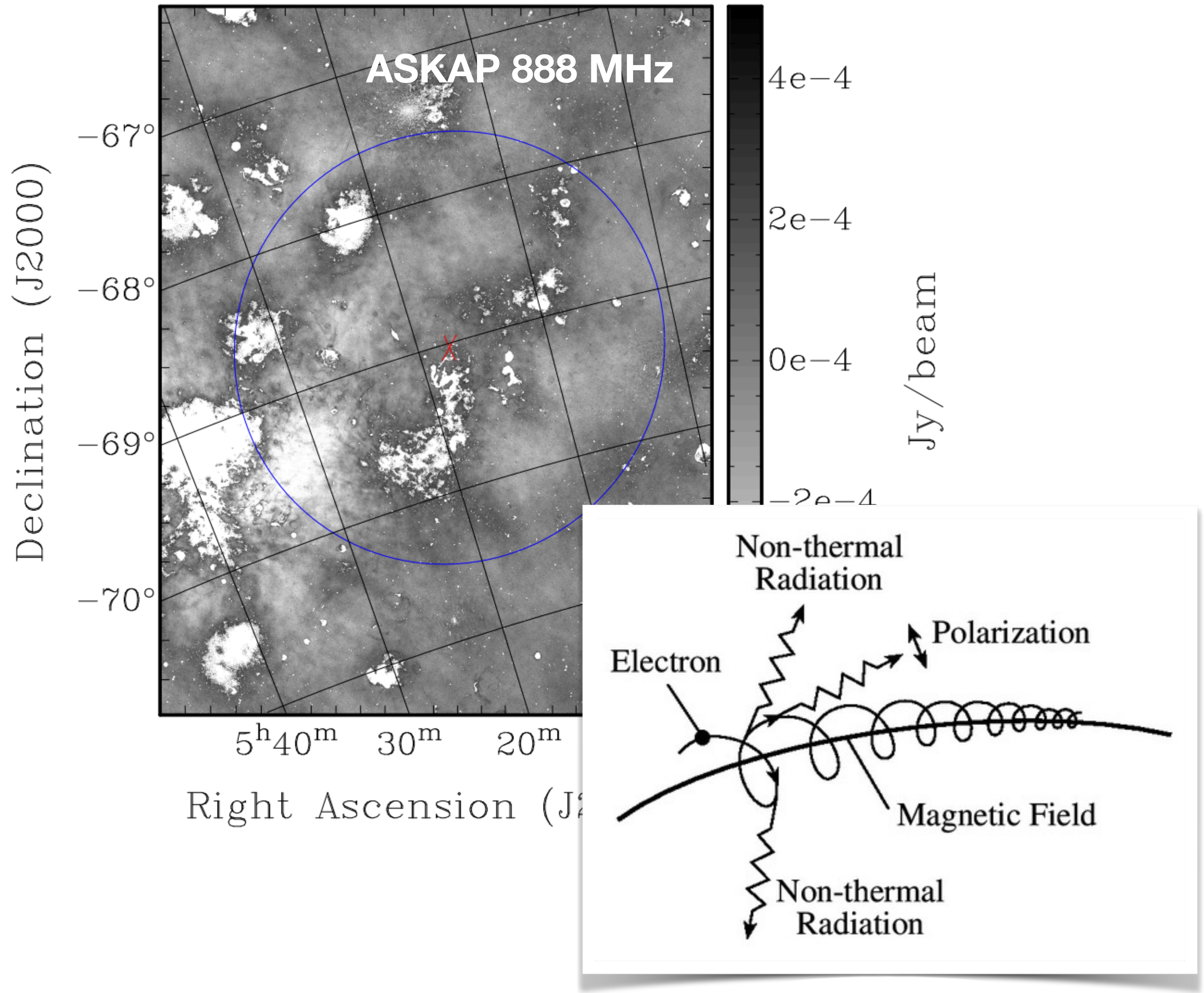
Limits on annihilating WIMPs

Synchrotron emission in the Large Magellanic Cloud



~ a few GeV — few TeV





Radio LMC

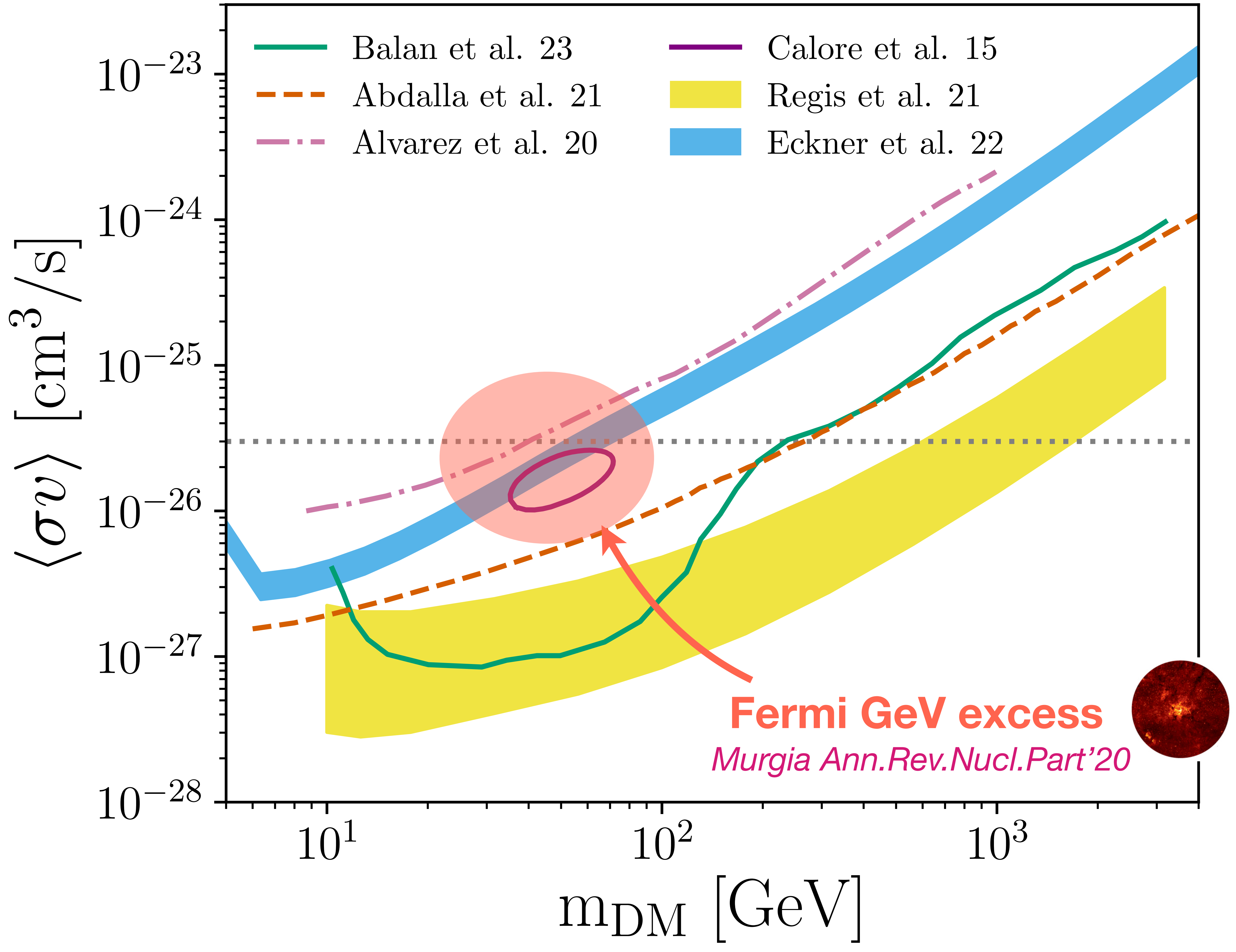
Regis+ JCAP'21

S. Manconi (Tue)

Limits on annihilating WIMPs

Summary of multi-targets and MW constraints

~ a few GeV — few TeV



- Partial **stellar origin** of the excess confirmed by evidence for sub-threshold gamma-ray point sources and stellar bulge morphology

Buschmann+PRD'20; FC+ PRL'21; List+ PRL'21
Macias+ Nat. A'18; Macias+ JCAP'19

- Complementary techniques and **multi-wavelength searches** to test the excess nature

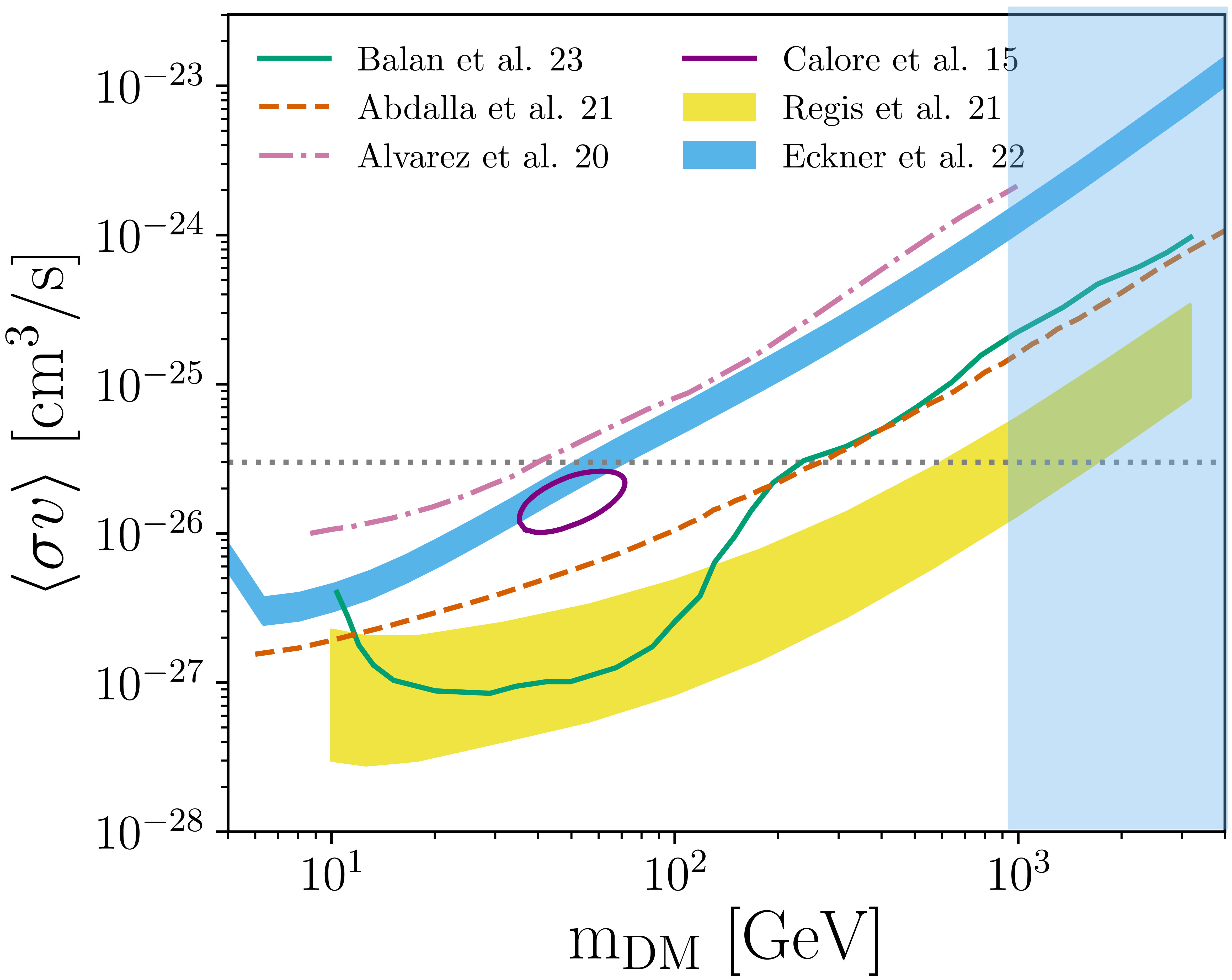
FC+ApJ'16; FC+PRL'19; Berteaud, FC+ PRD'21
Macias+ MNRAS'21

Limits on annihilating WIMPs

Summary of multi-targets and MW constraints

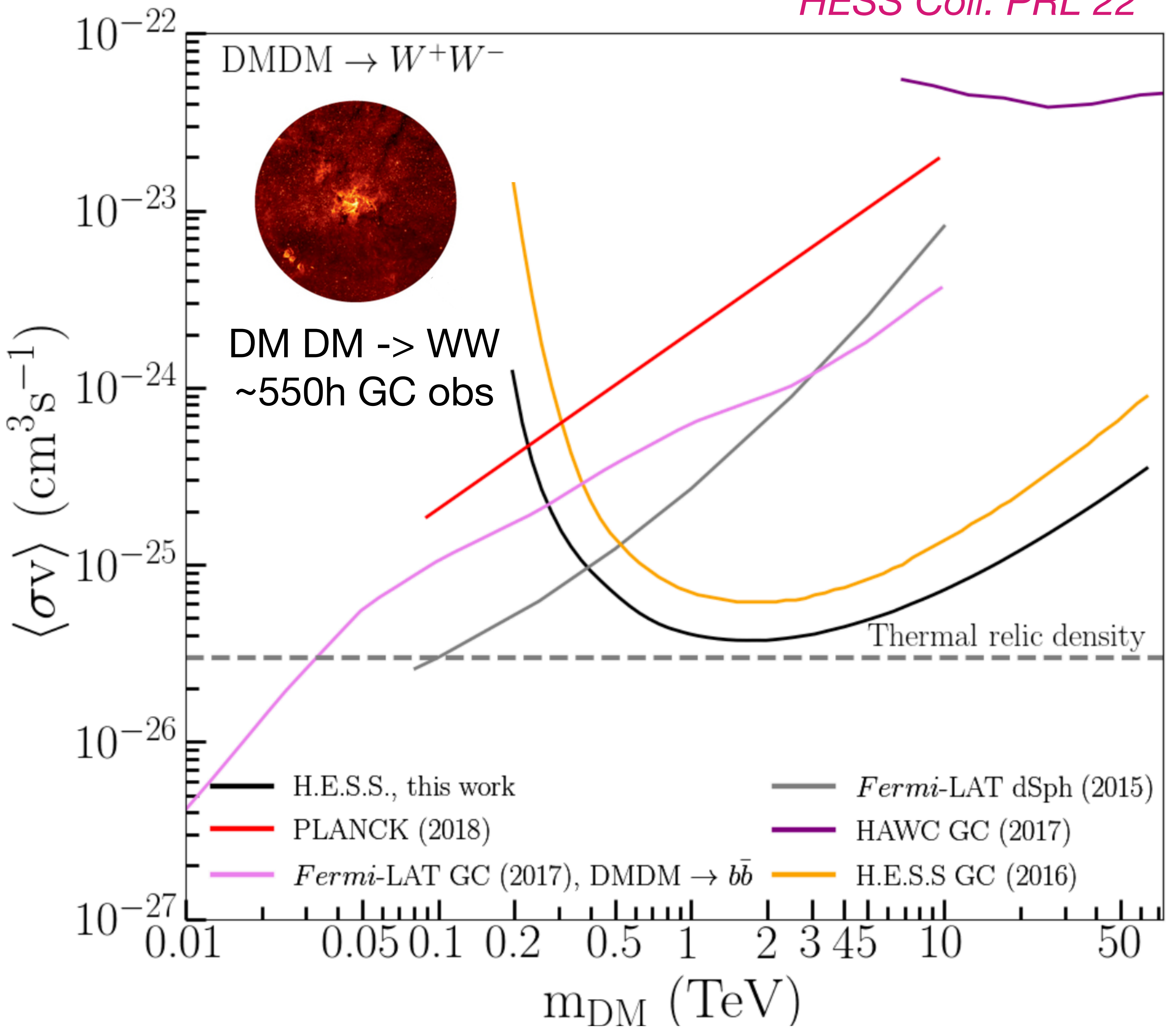
A. Montanari (Tue)
V. Vitale (Wed)

~ a few GeV — few TeV



0.2 TeV — 50 TeV

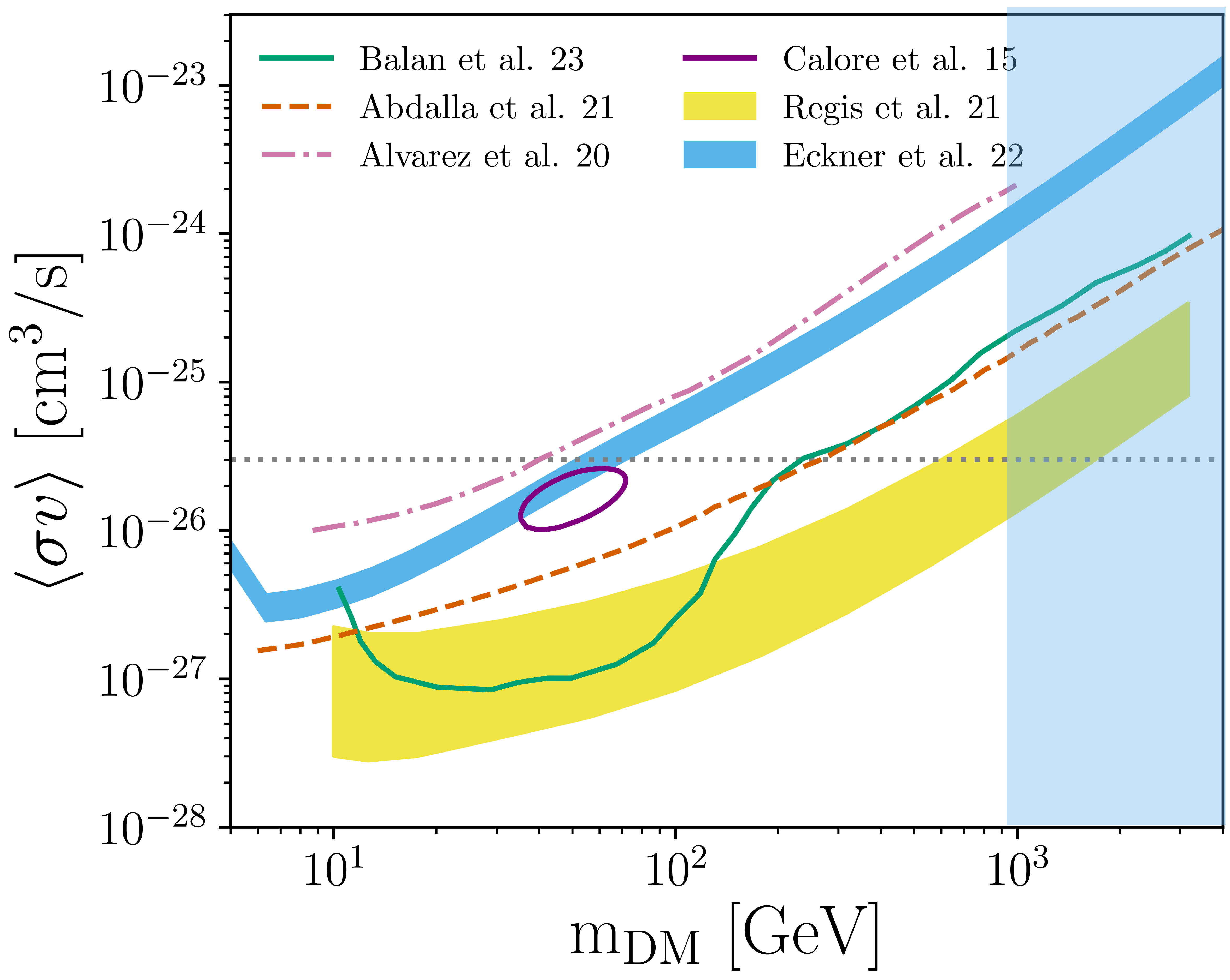
HESS Coll. PRL'22



Prospects and opportunities

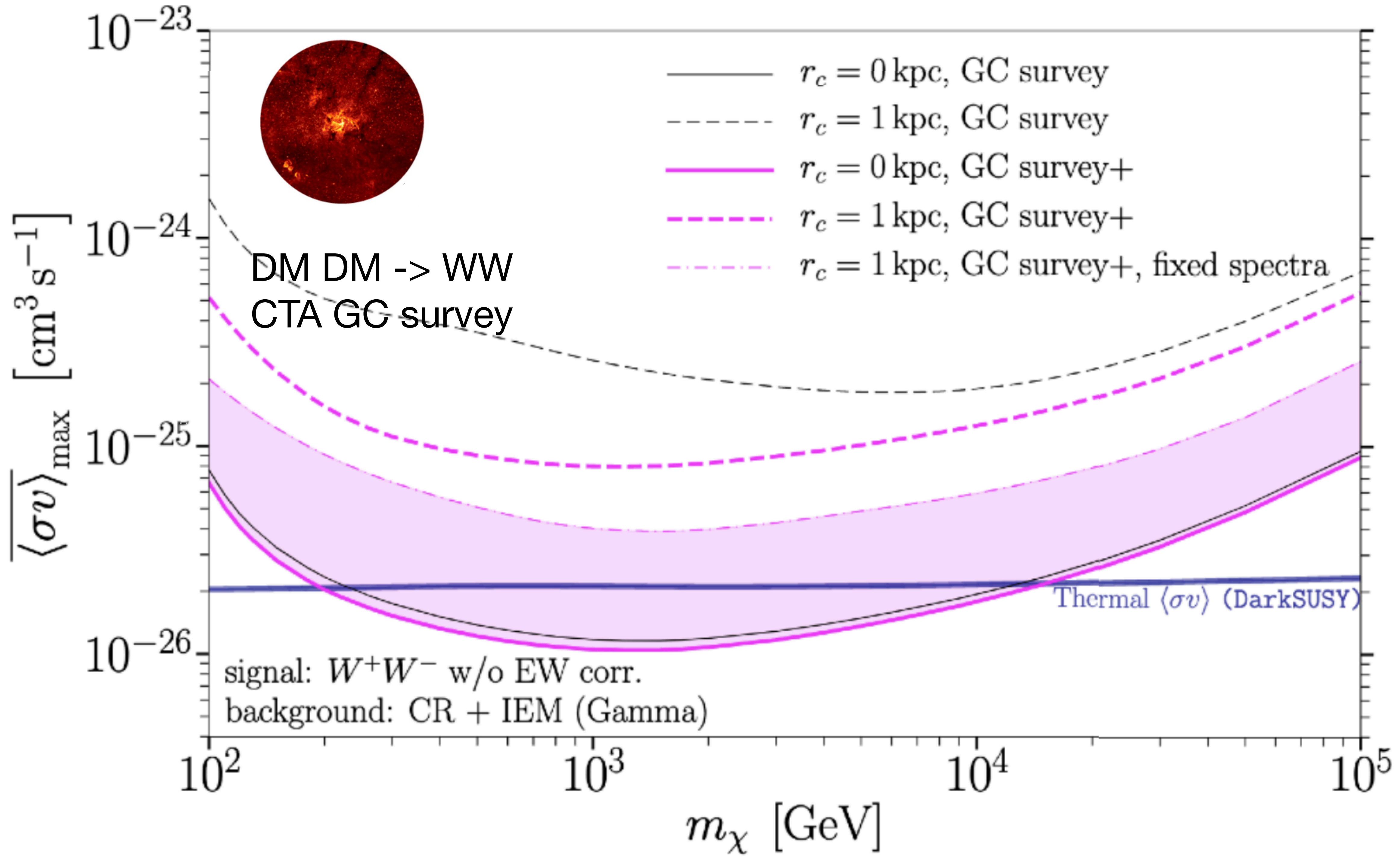
Extending the energy/mass scale

~ a few GeV — few TeV



TeV frontier

HAWC, CTA, SWGO



N. Hiroshima (Tue)

Prospects and opportunities

O. Deligny (Tue)

Extending the energy/mass scale

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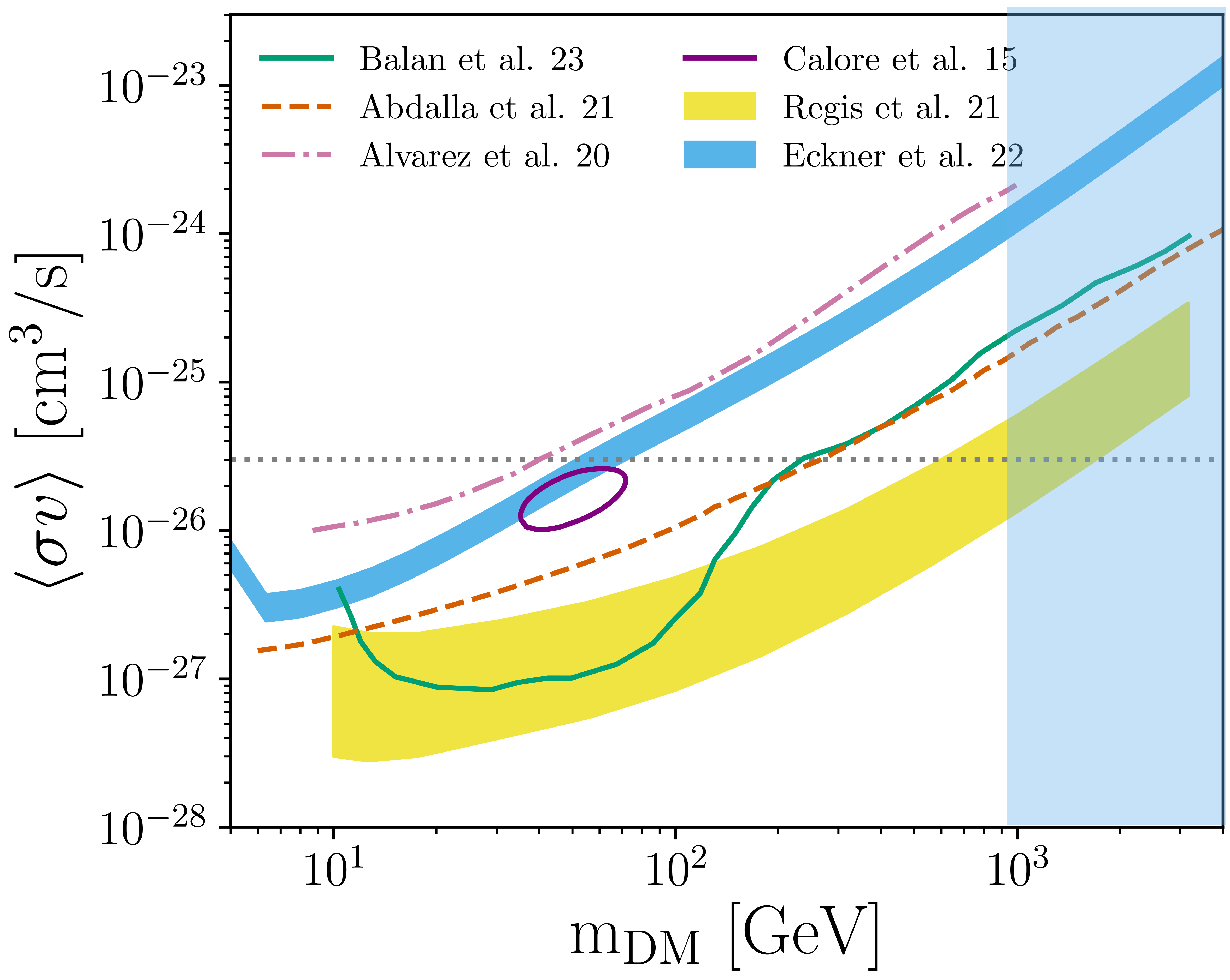

Sub-PeV frontier
LHAASO,Tibet ASg

- 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

Prospects and opportunities

Extending the energy/mass scale

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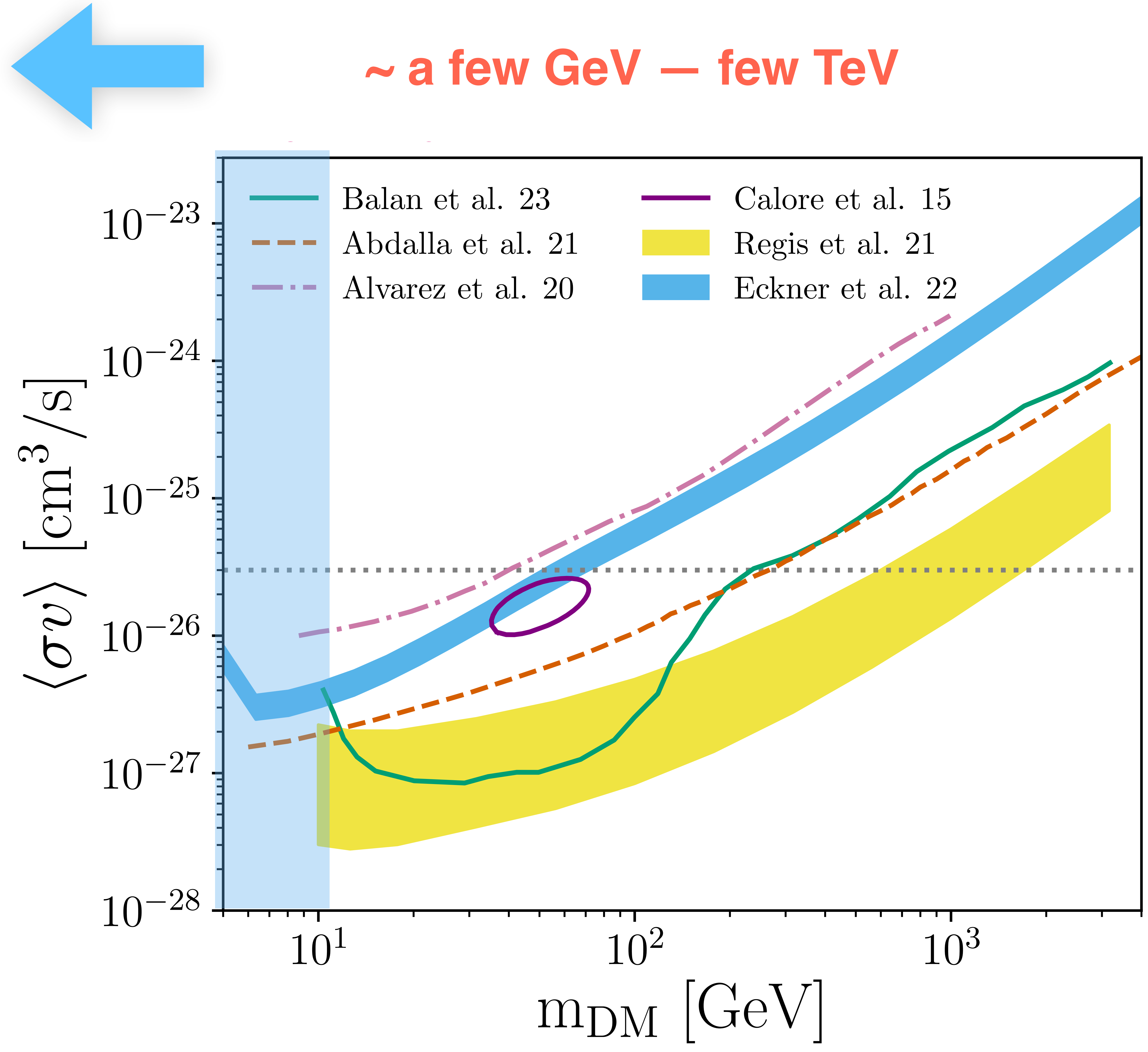

Prospects and opportunities

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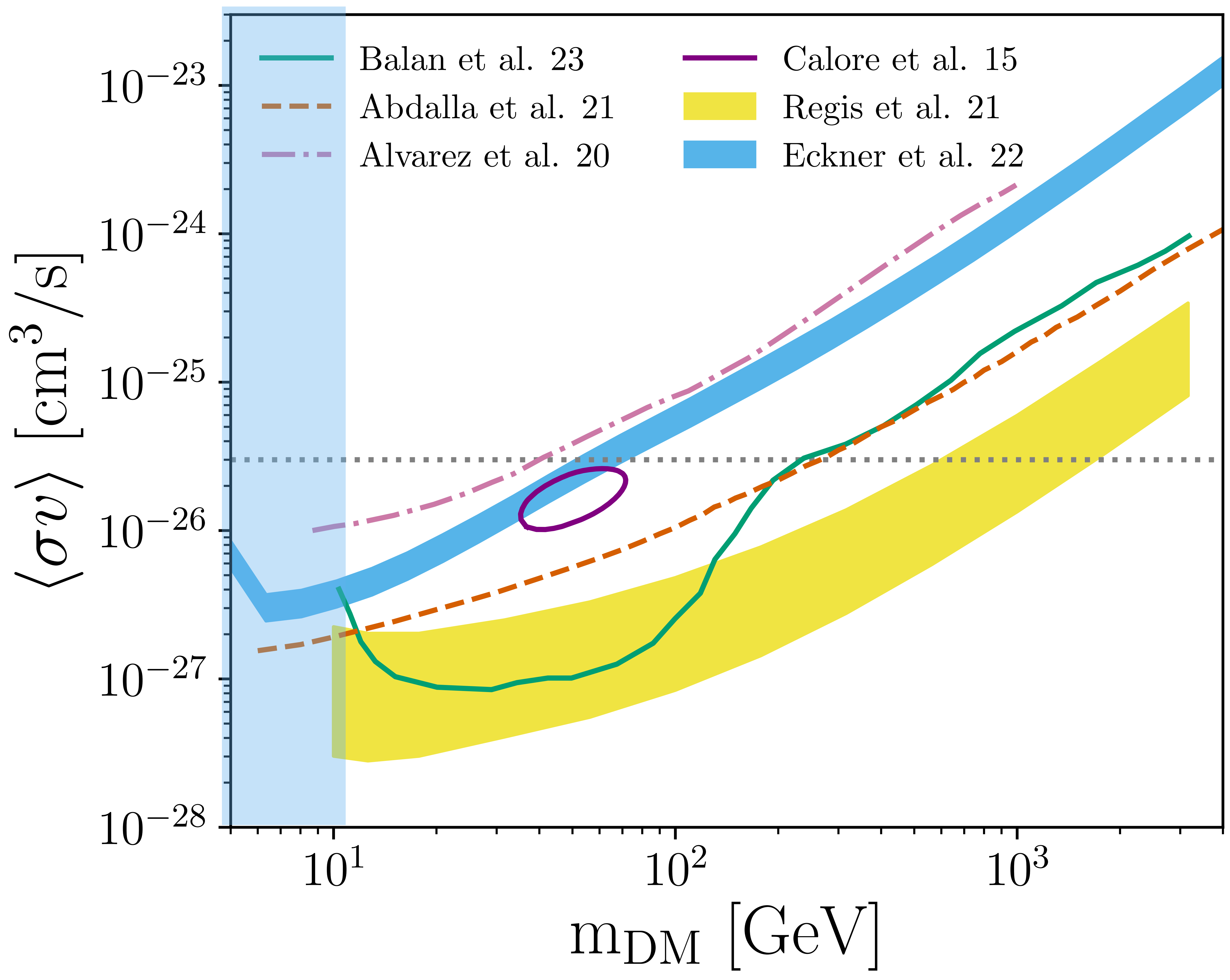
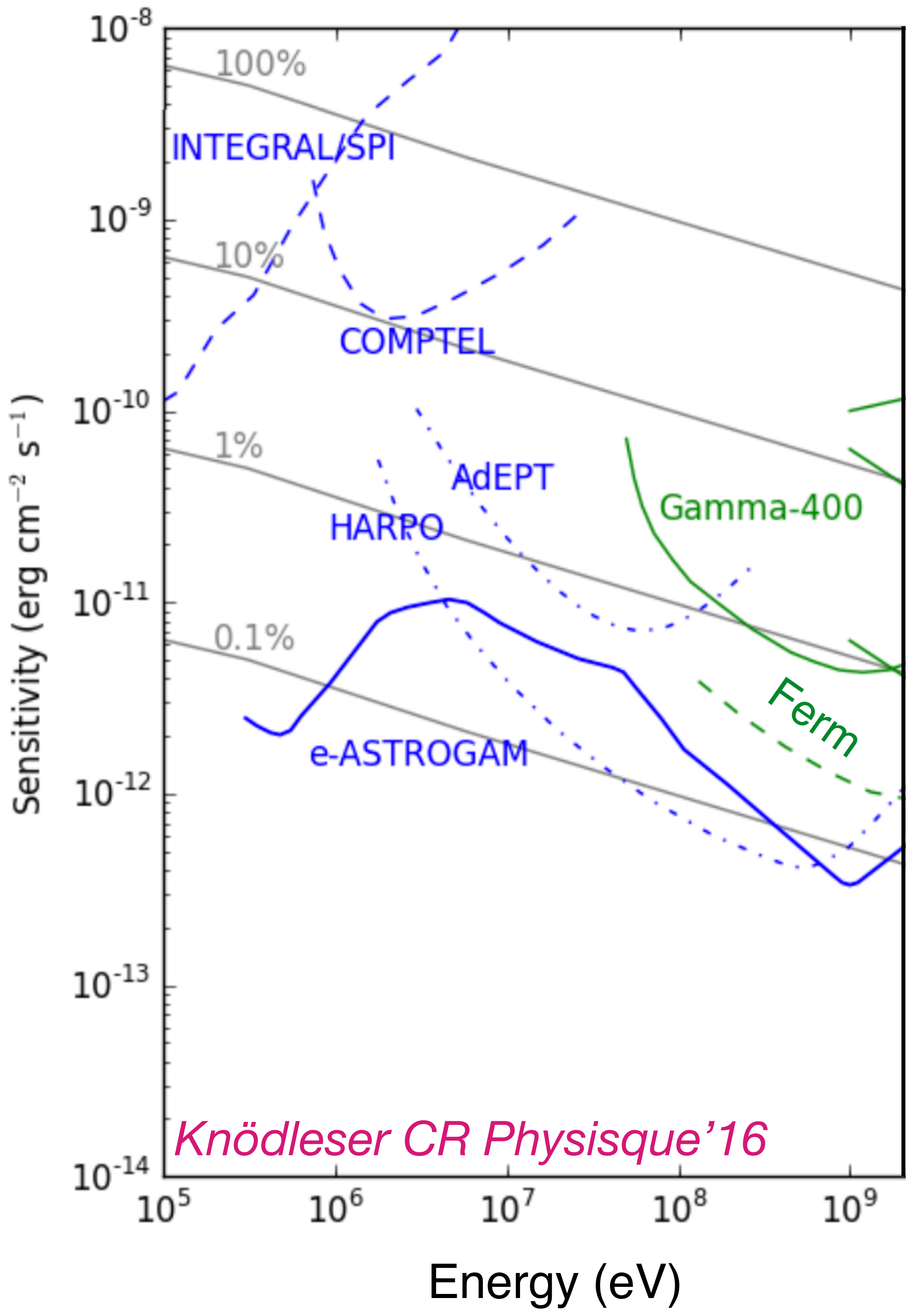


MeV sensitivity gap

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



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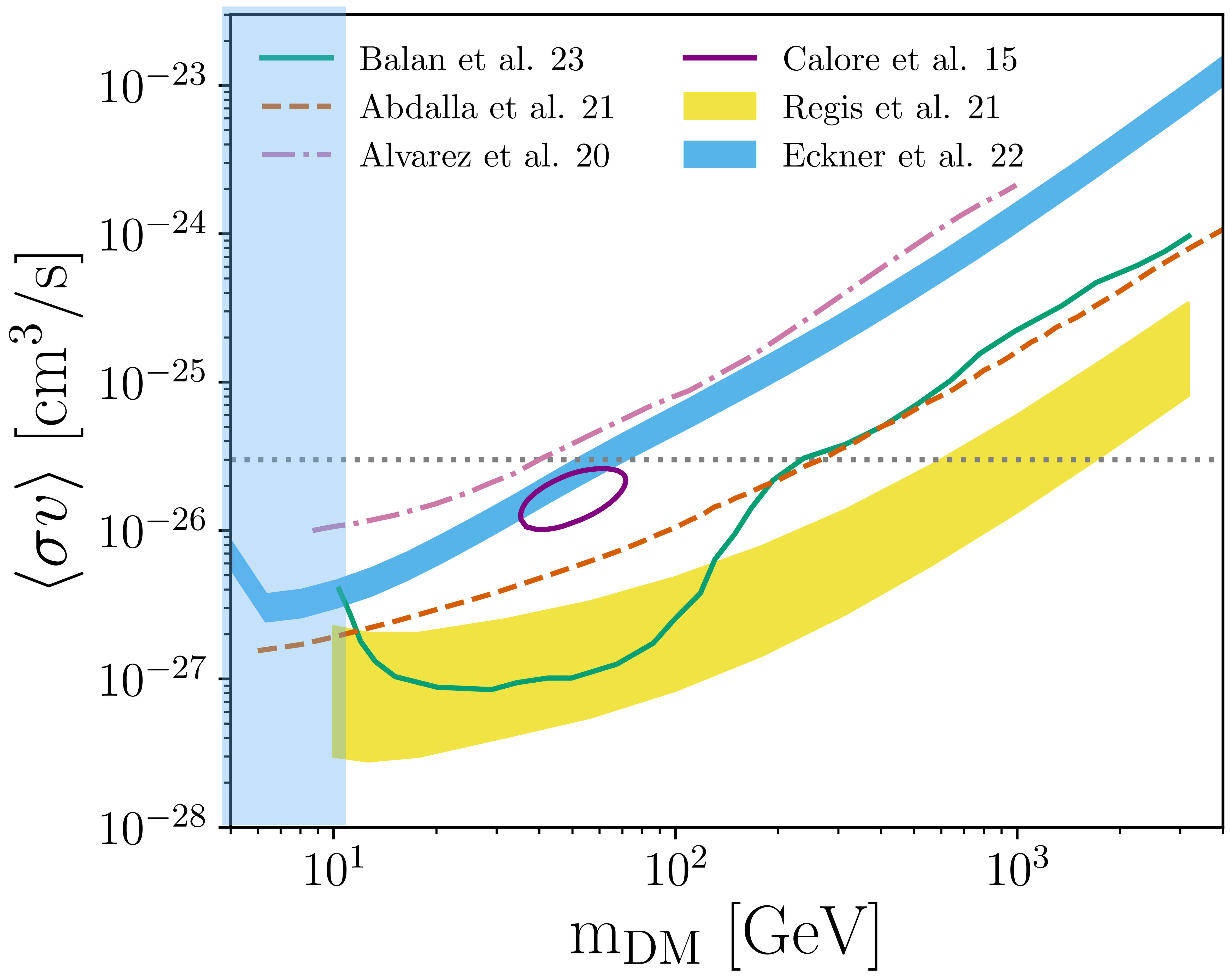

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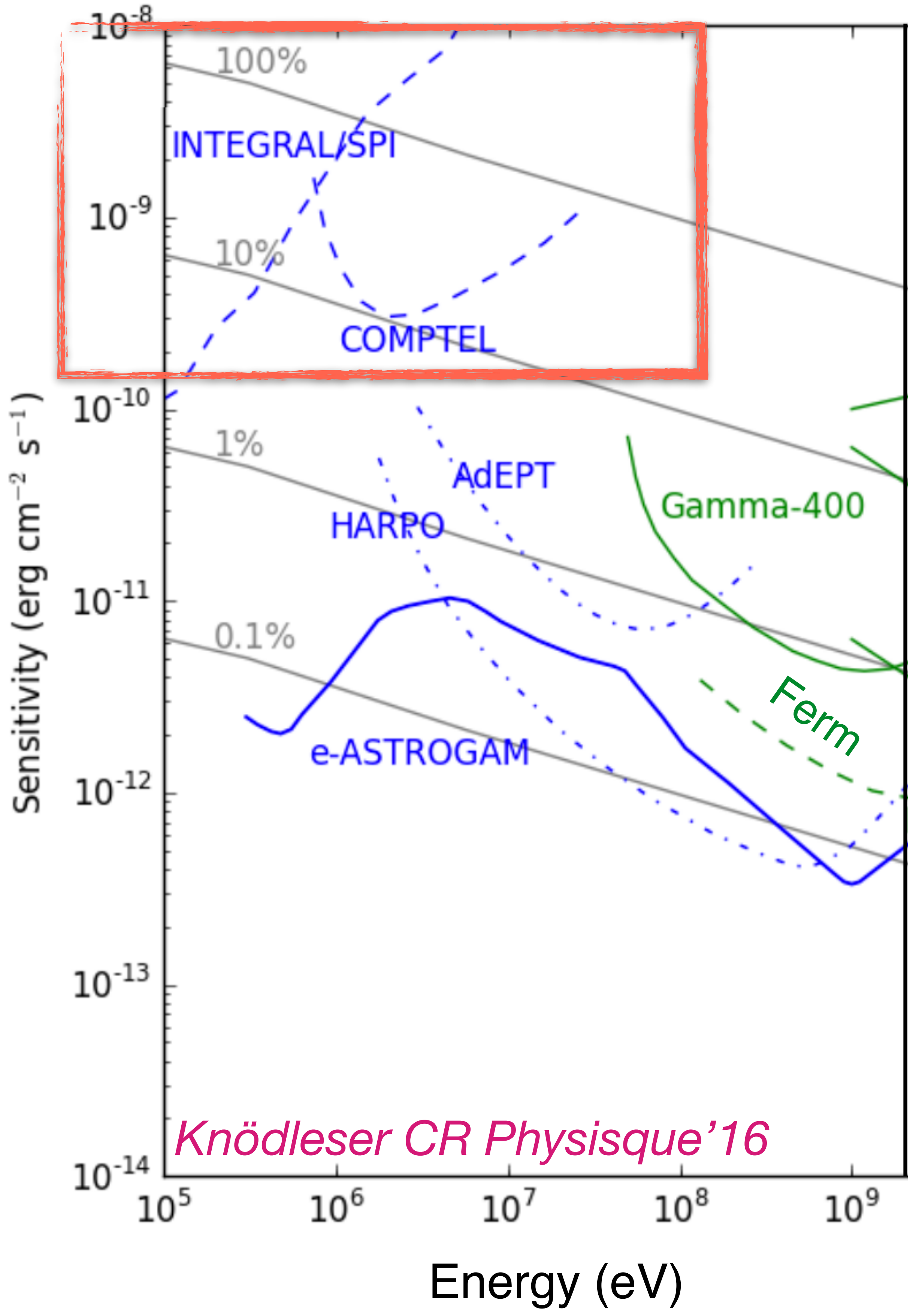
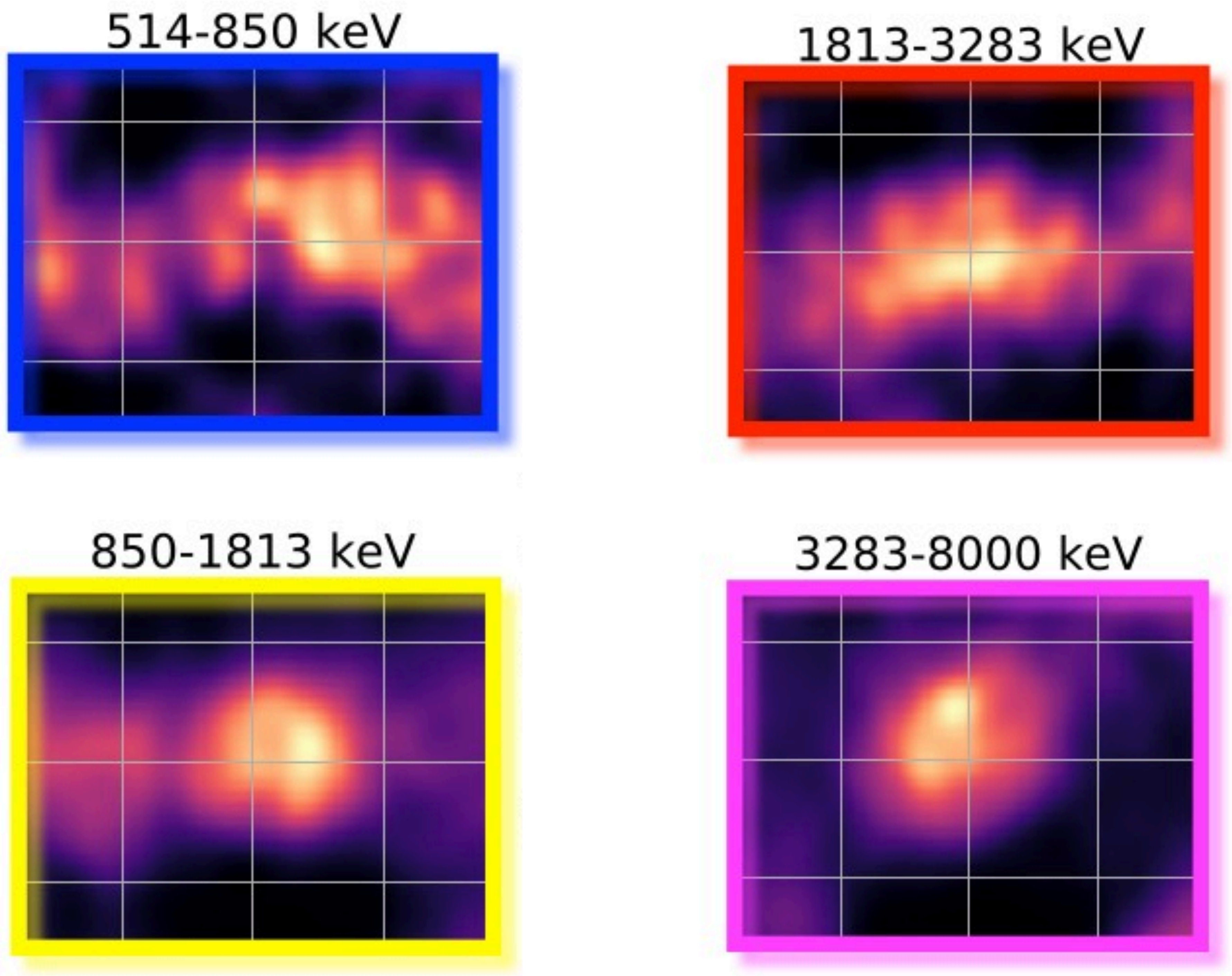


An old instrument, a new analysis

MeV Galactic diffuse emission with INTEGRAL/SPI

Modeled **spatial templates**

- **Inverse Compton scattering** of electrons off the interstellar radiation field $e^{\pm}_{CR} + \gamma \longrightarrow e^{\pm} + \gamma_{MeV}$
- Unresolved sources
- Nuclear lines
- Positronium annihilation line



Siegert, FC+ A&A'22

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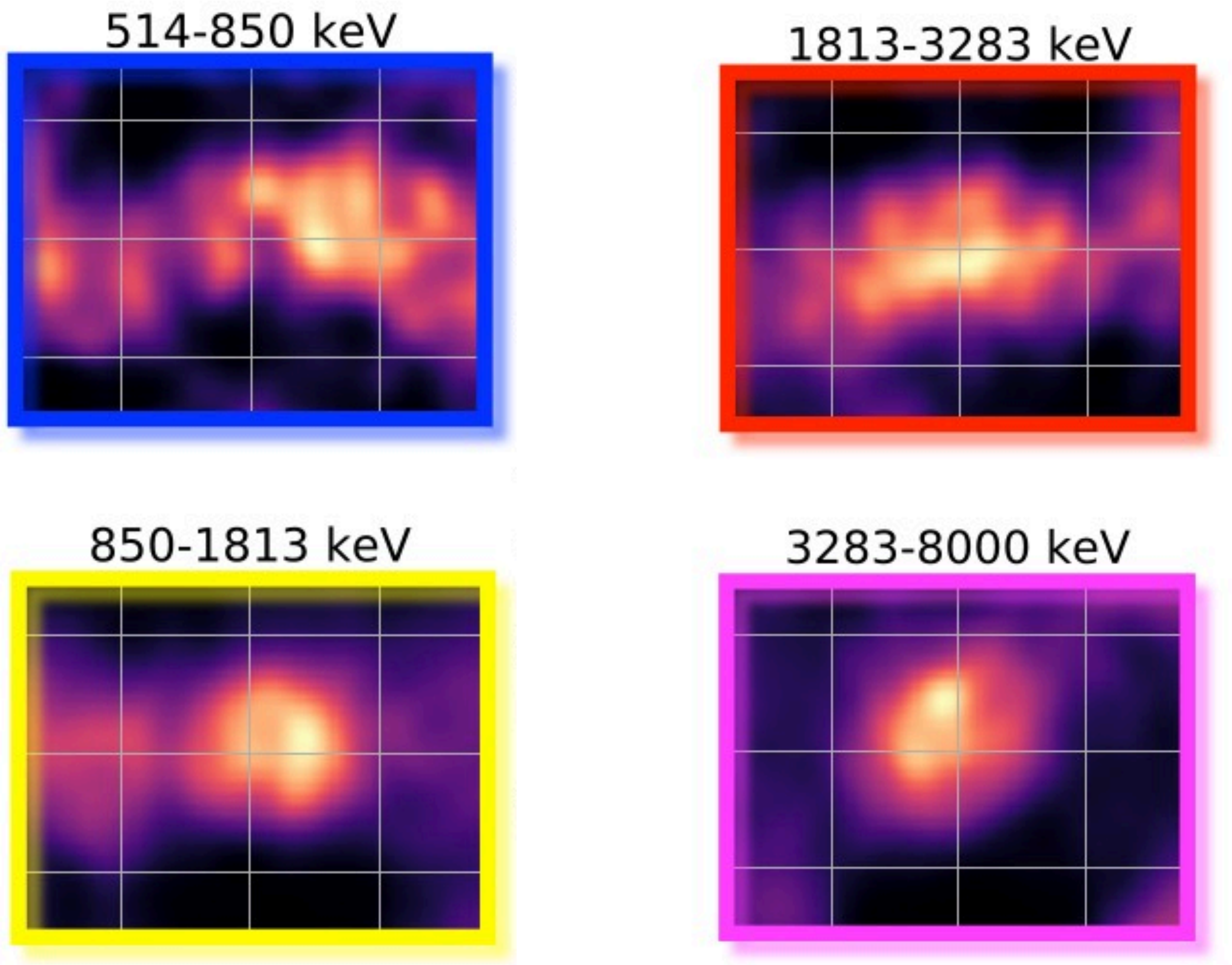


Constraints on **cosmic-ray transport** at MeV energy but also on **exotic emission mechanisms**: particle and non-particle dark matter

Siegert, FC+ A&A'22

An old instrument, a new analysis

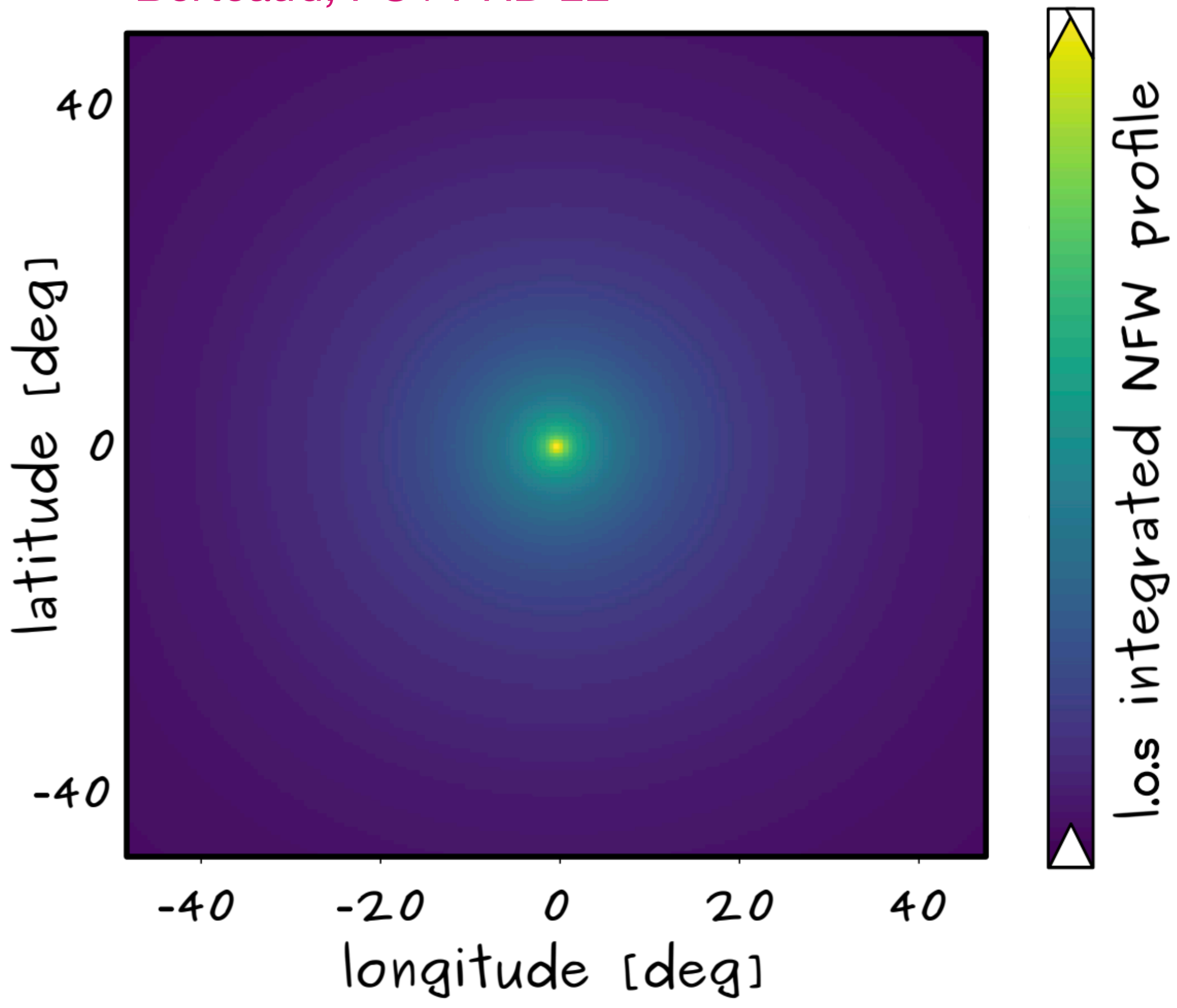
Is there evidence for an additional dark matter component?

Modeled **spatial templates**

- **Inverse Compton scattering** of electrons off the interstellar radiation field $\mathrm{e}^{\pm}_{\mathrm{CR}} + \gamma \longrightarrow \mathrm{e}^{\pm} + \gamma_{\mathrm{MeV}}$
- Unresolved sources
- Nuclear lines
- Positronium annihilation line
- **Decaying dark matter ?**

$$\frac{d\Phi_\gamma}{dE}(\ell, b) = \mathcal{A}(\theta_{\mathrm{DM}}) \times \frac{dN_\gamma}{dE} \times \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}(s, \ell, b) ds$$

Berteaud, FC+ PRD'22

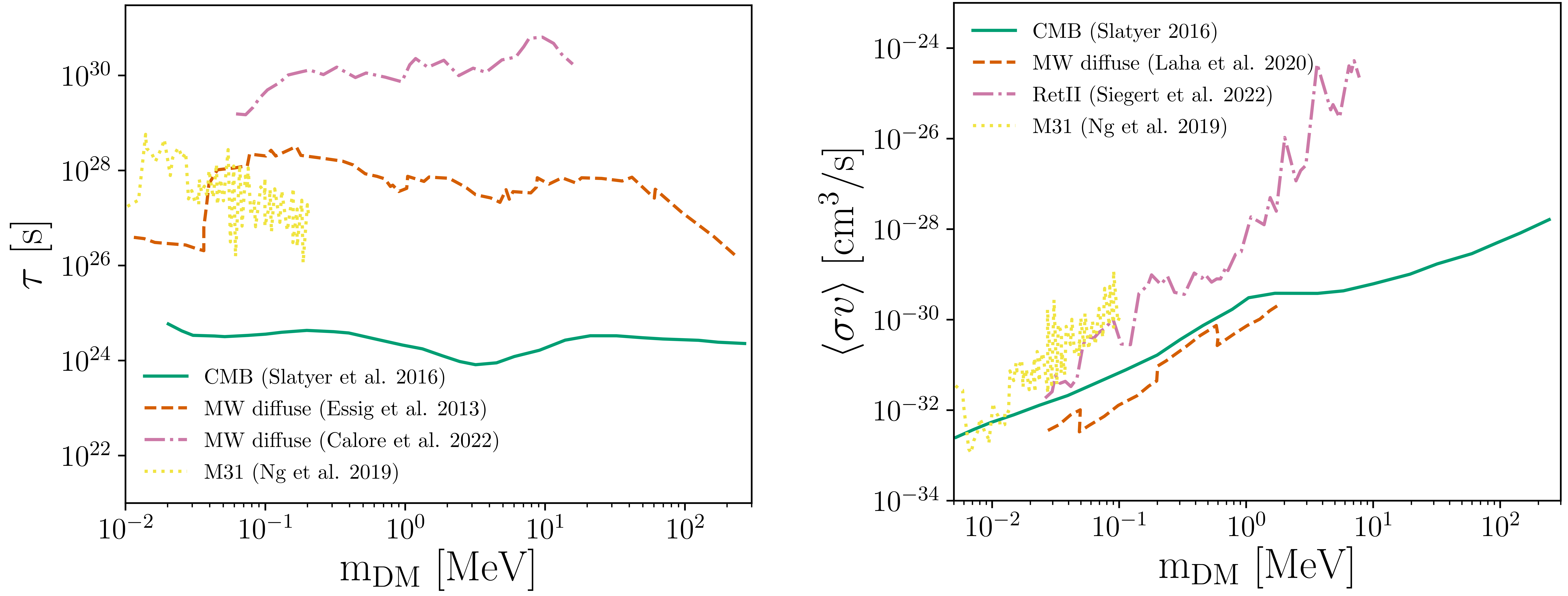


Observables for sub-GeV DM

J. Koechler (Wed)

Decaying and annihilating DM into 2 photons

FC FIPs2022 Workshop report, arXiv:2305.01715



[For e+e- channel, very relevant limits from Vogayer 1 data *Boudaud+ PRL'17*]

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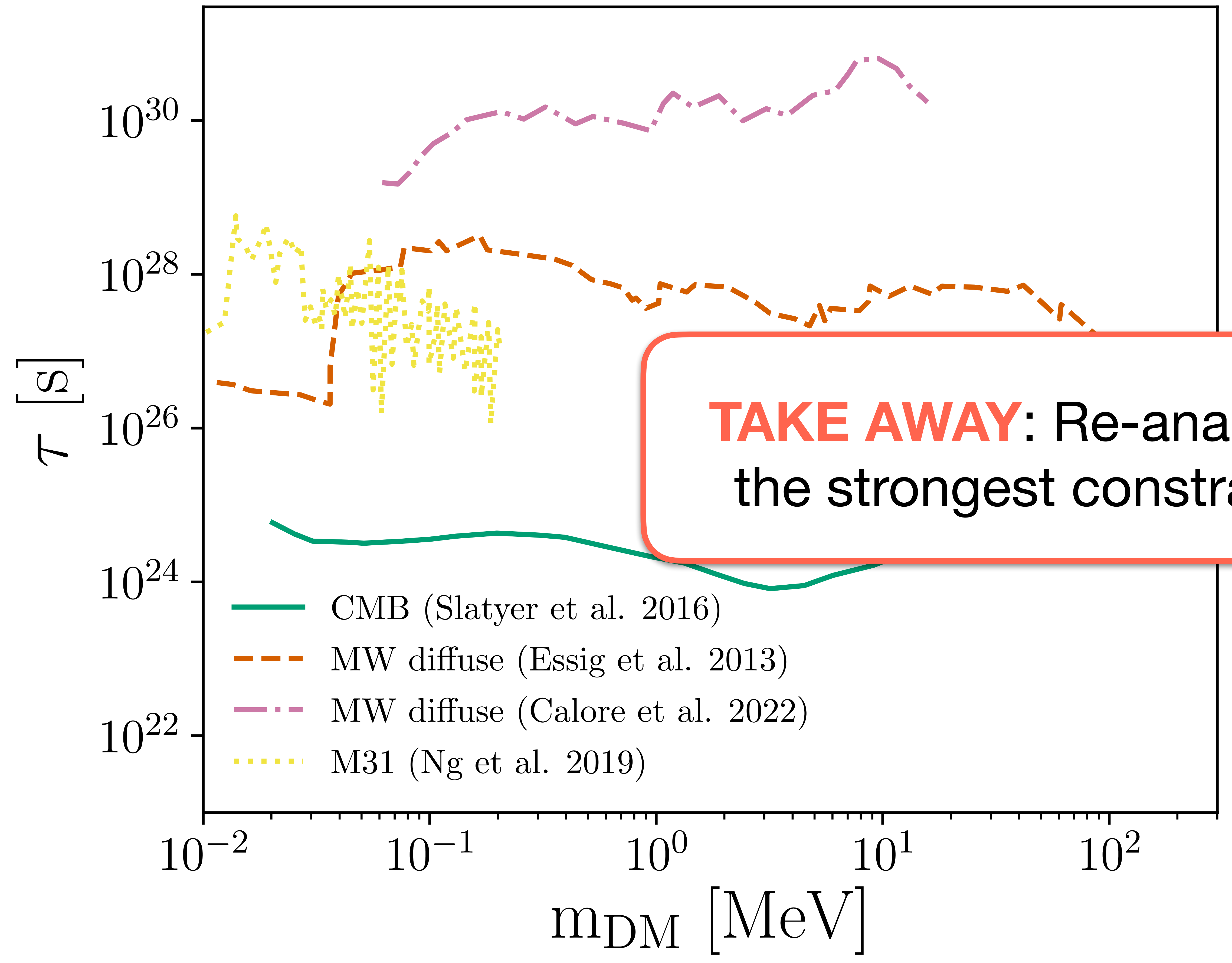
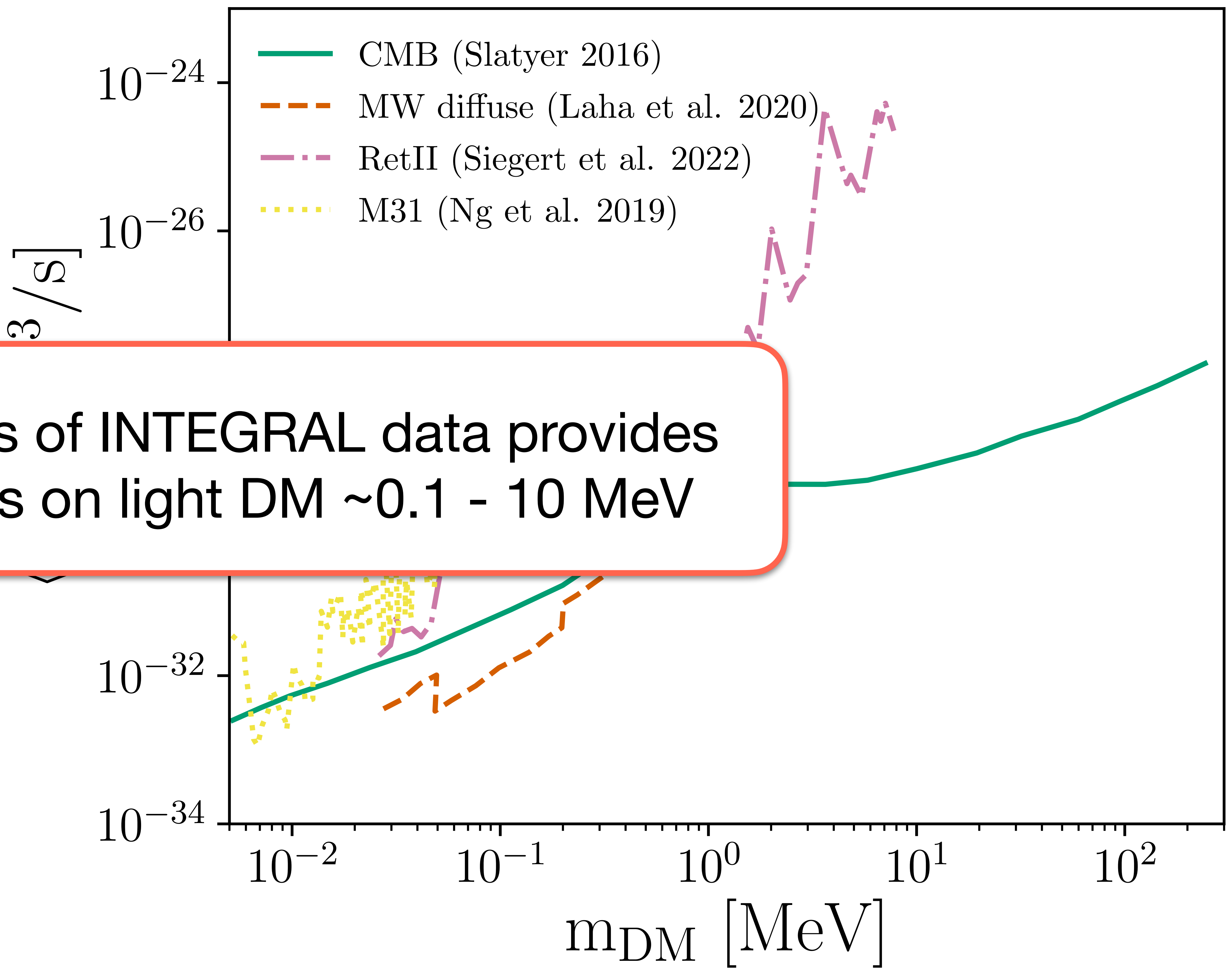




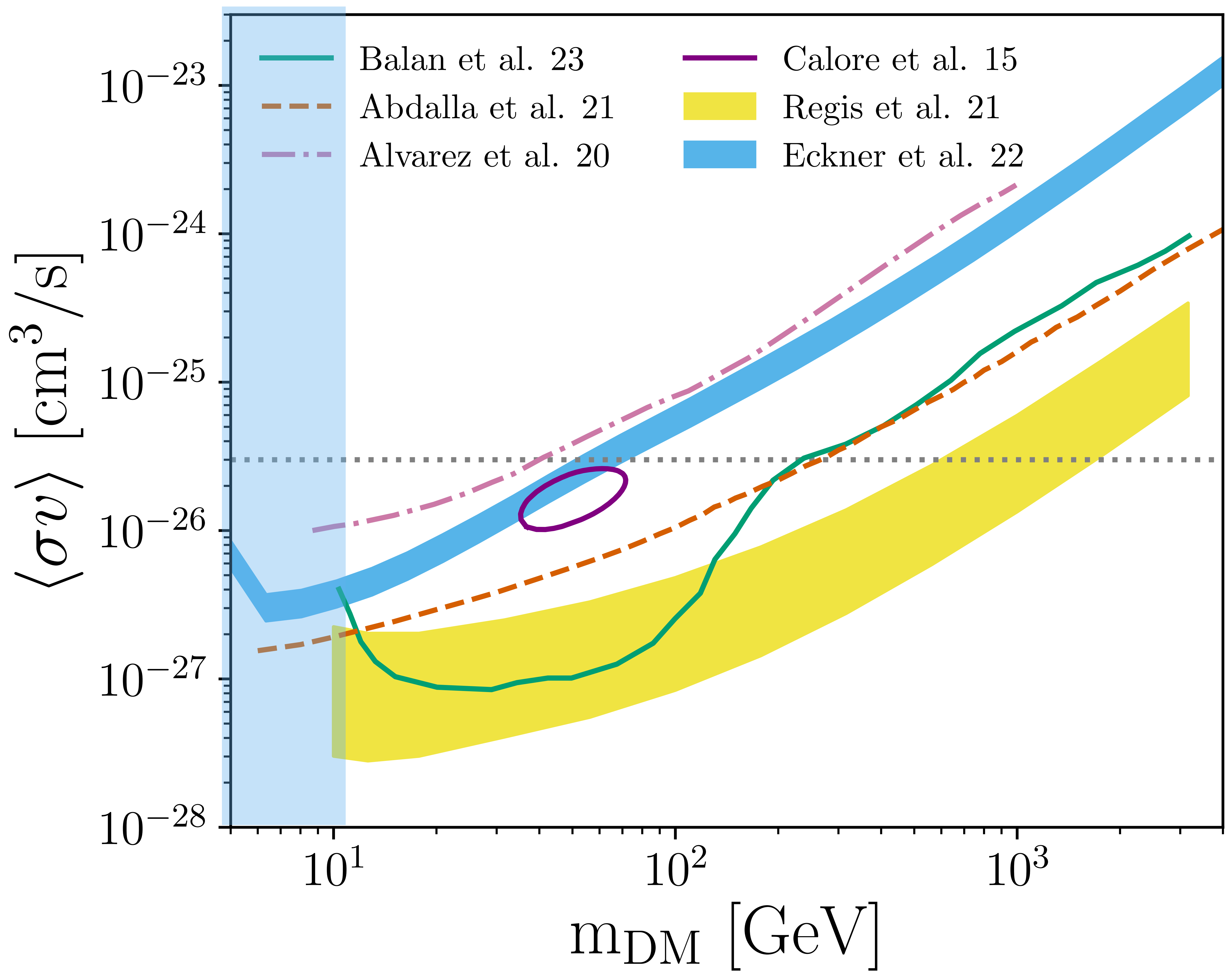
TAKE AWAY: Re-analysis of INTEGRAL data provides the strongest constraints on light DM ~0.1 - 10 MeV

[For e+e- channel, very relevant limits from Vogayer 1 data *Boudaud+ PRL'17*]

Prospects and opportunities

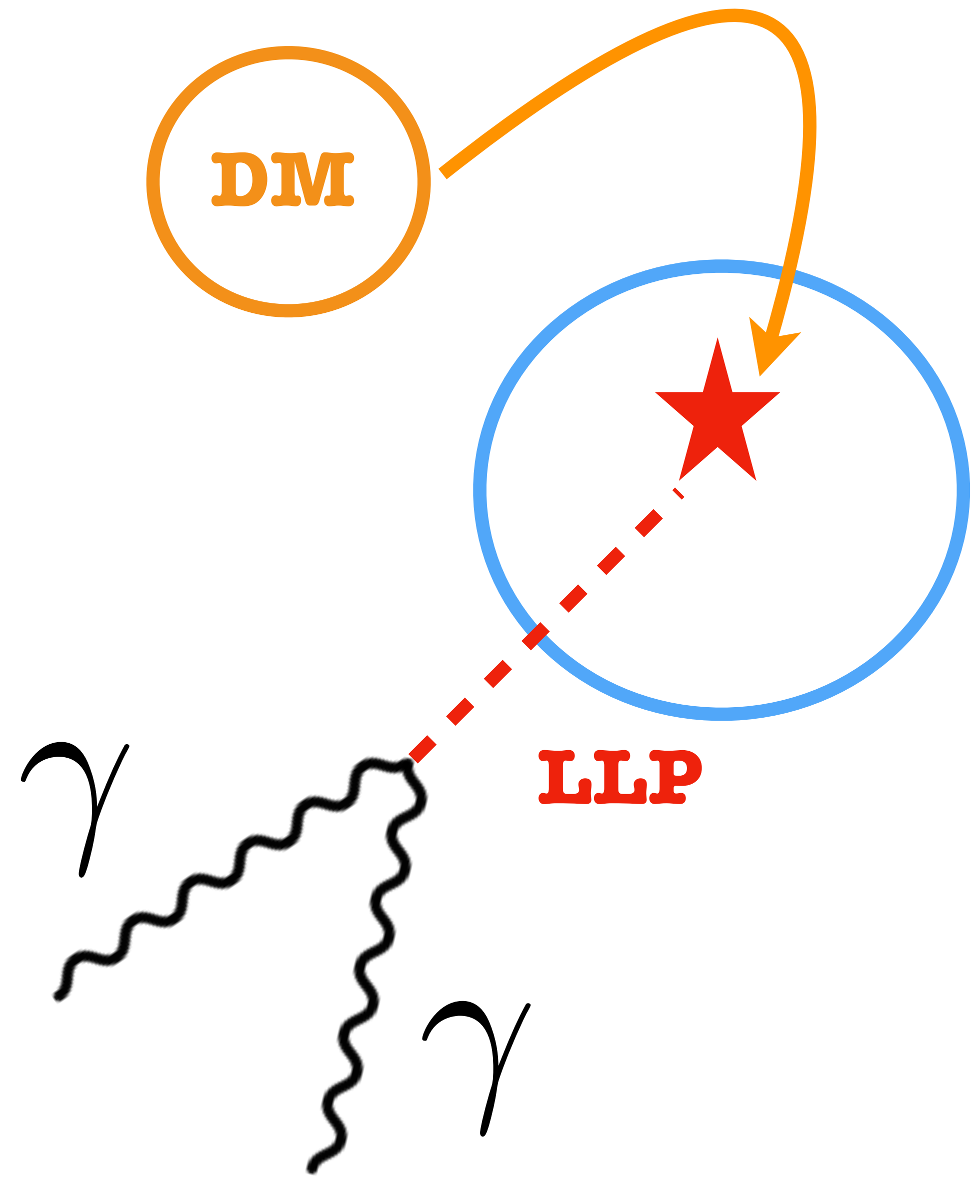
Extending the energy/mass scale

~ a few GeV — few TeV



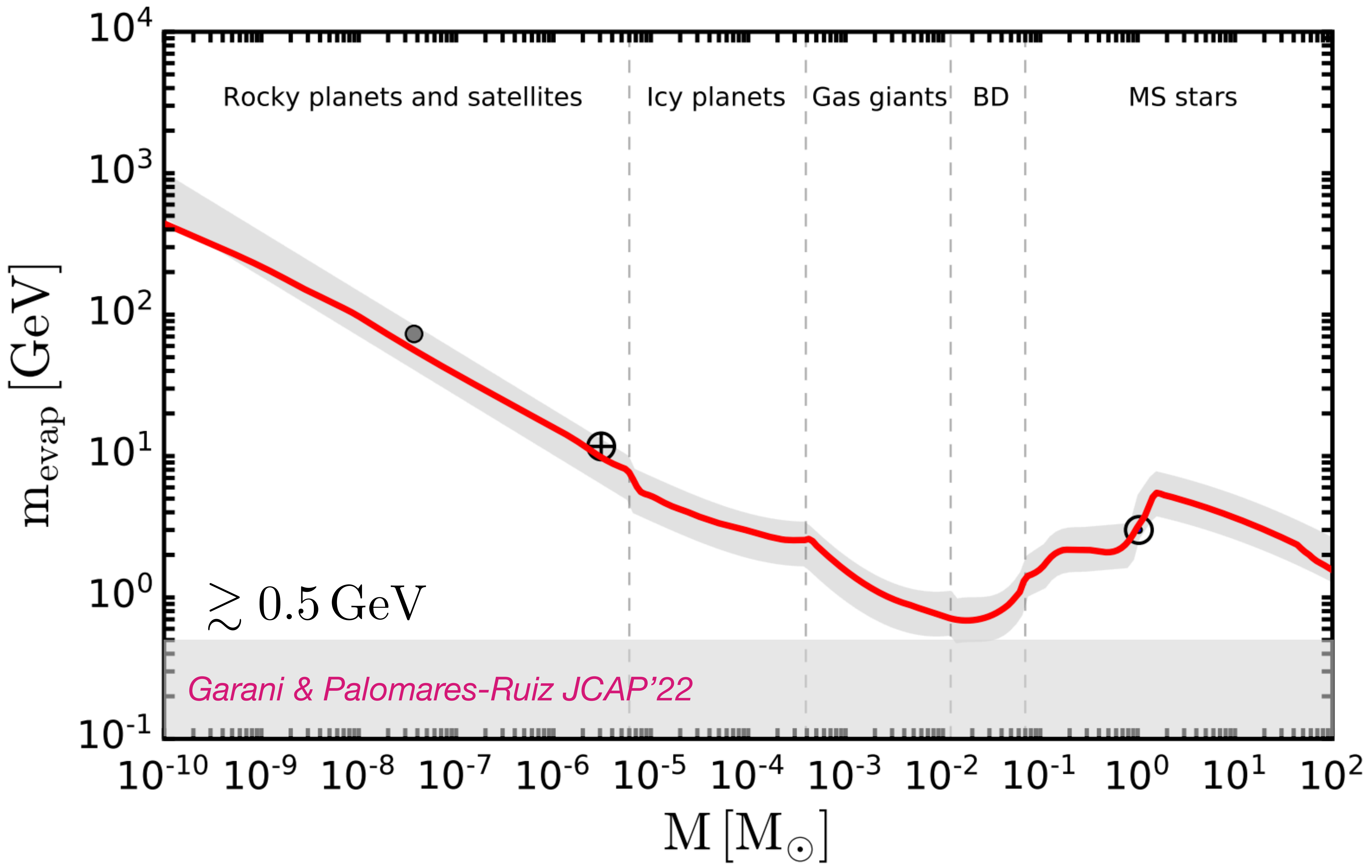
Change the model and targets

Long-lived mediators trapped in stars or celestial bodies



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

DM capture in celestial bodies



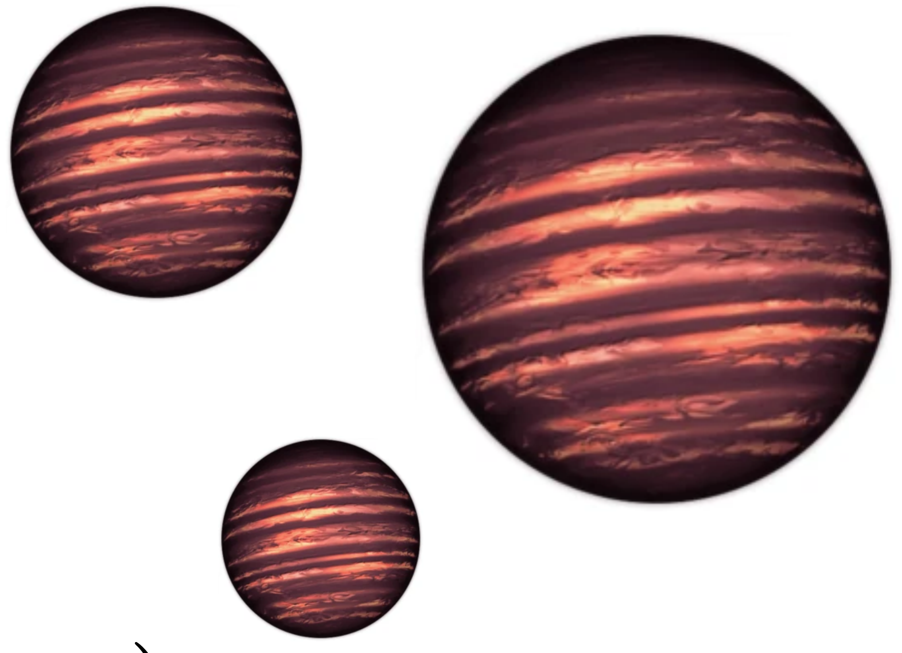
Brown dwarfs (BDs):

Big, Cold, Dense!

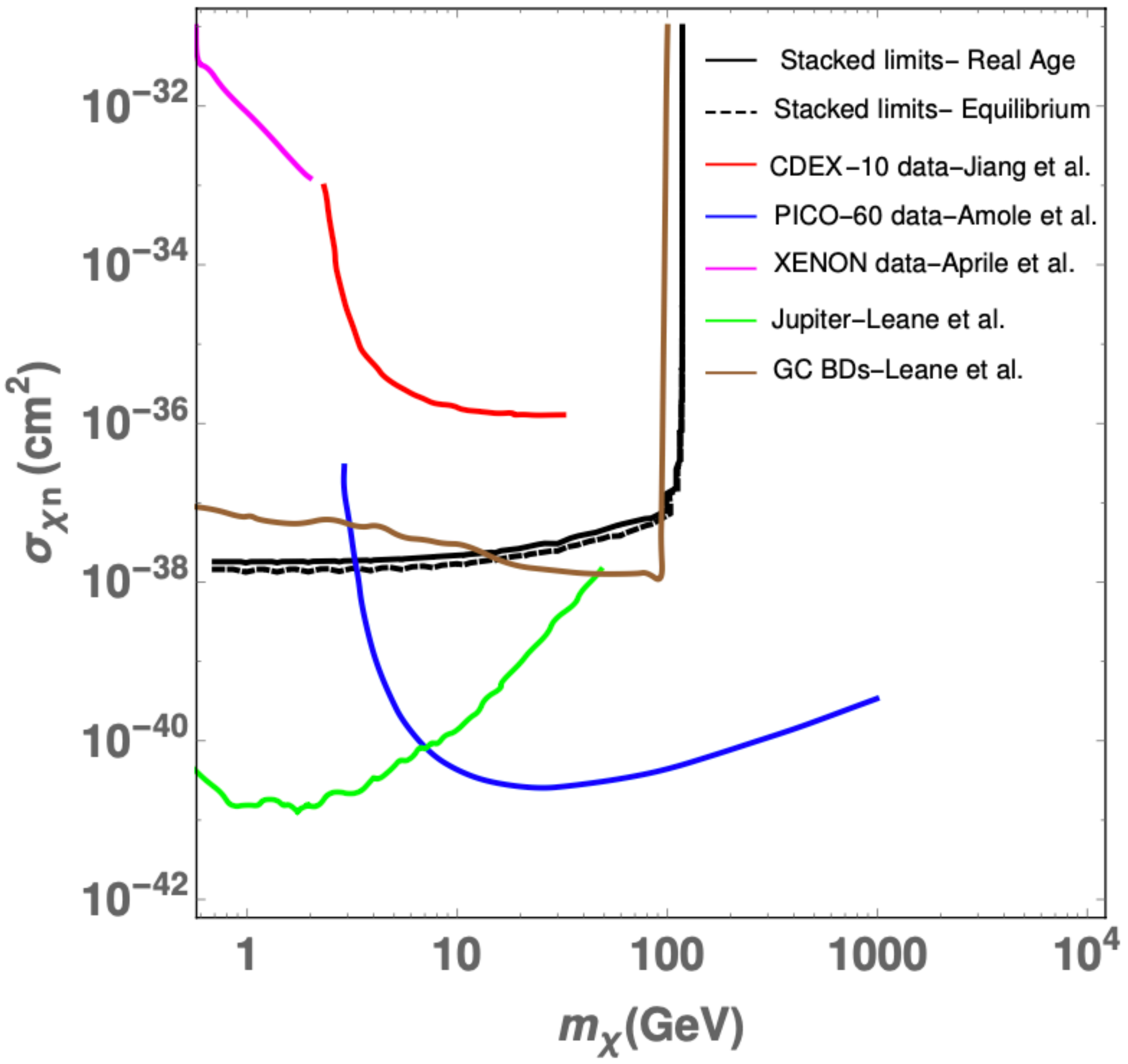
+ Large statistics (> 800 objects within 100 pc)
+ Very nearby (closest at 2 pc)
+ Up to 10^9 objects expected in the GC

Leane+ PRD'21

Limits on sub-GeV DM from BDs



$\chi\chi \to \phi\phi$ $\phi \to \gamma\gamma$

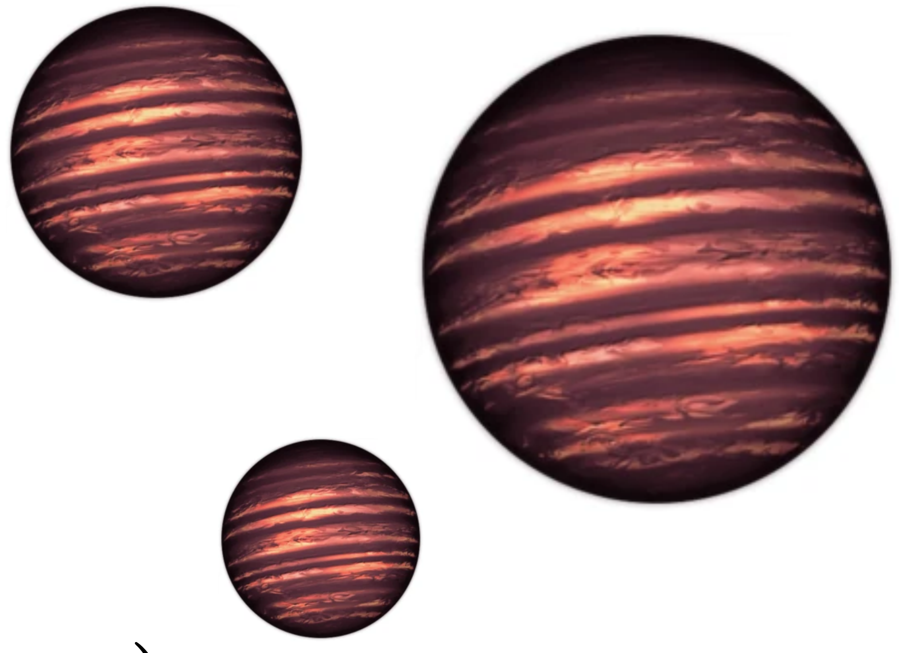


$$N_\chi \simeq \mathcal{C}\,\tau_{\rm eq} = \sqrt{\mathcal{C}/\mathcal{A}}$$

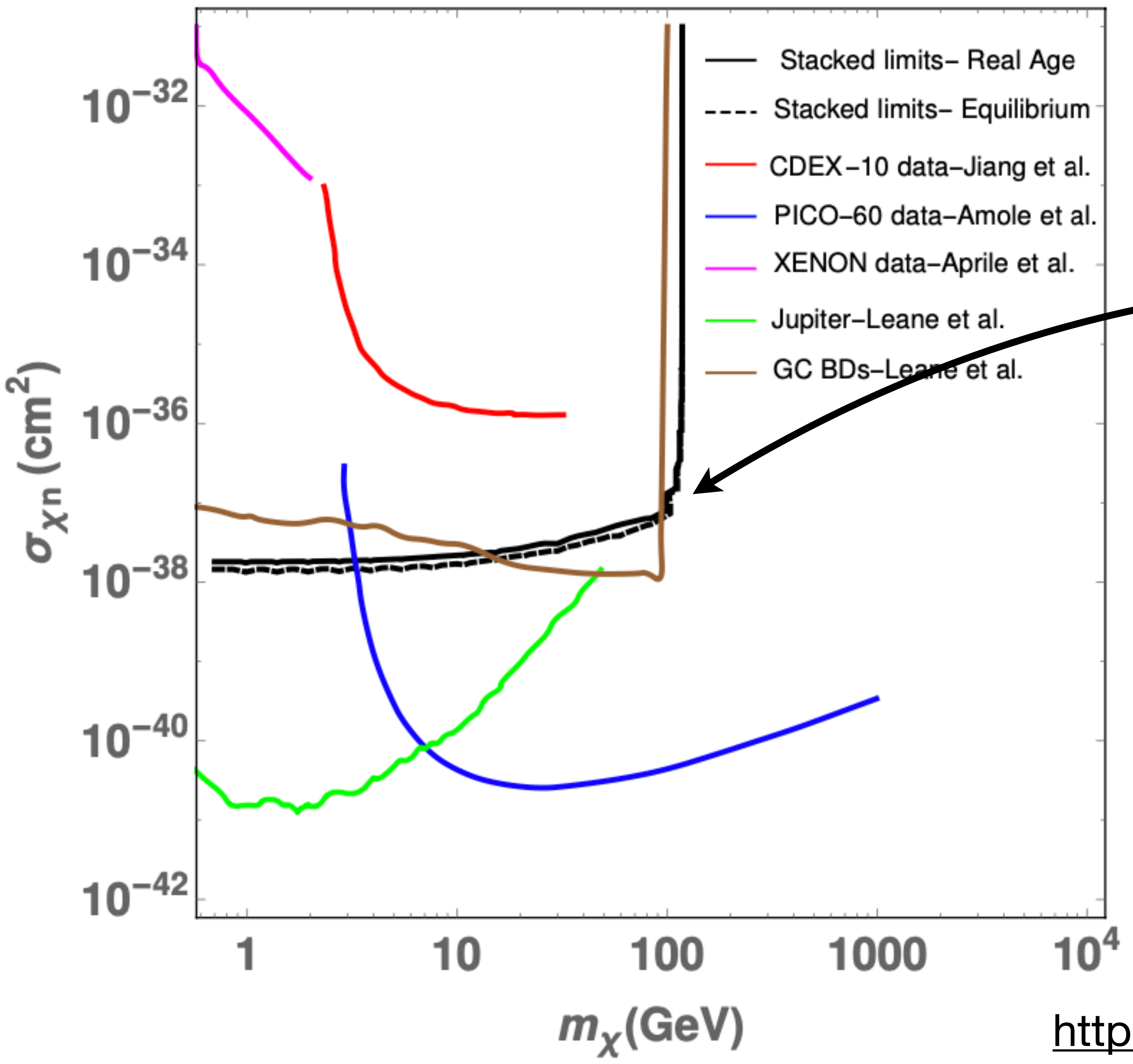
$$\mathcal{C} = f(M_\star, R_\star, d_{\rm GC}, \rho_{\rm DM}, \sigma_{\chi N})$$

E. Figueroa-Feliciano (Tue)

Limits on sub-GeV DM from BDs



$$\chi\chi \to \phi\phi \qquad \phi \to \gamma\gamma$$



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Nearby BDs

Bhattacharjee, FC & Serpico PRD'23

* Selection of **9 nearby** (< 10pc), **massive, cold BDs**, and **old (> 2 Gyr)**
* Search for gamma-ray point-like excesses in *Fermi*-LAT data

Dark Matter Test Science Project

ESCAPE
European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

EOSC Future

https://gitlab.in2p3.fr/escape2020/virtual-environment/brown-dwarfs-gamma

E. Figueroa-Feliciano (Tue)

Limits on sub-GeV DM from BDs

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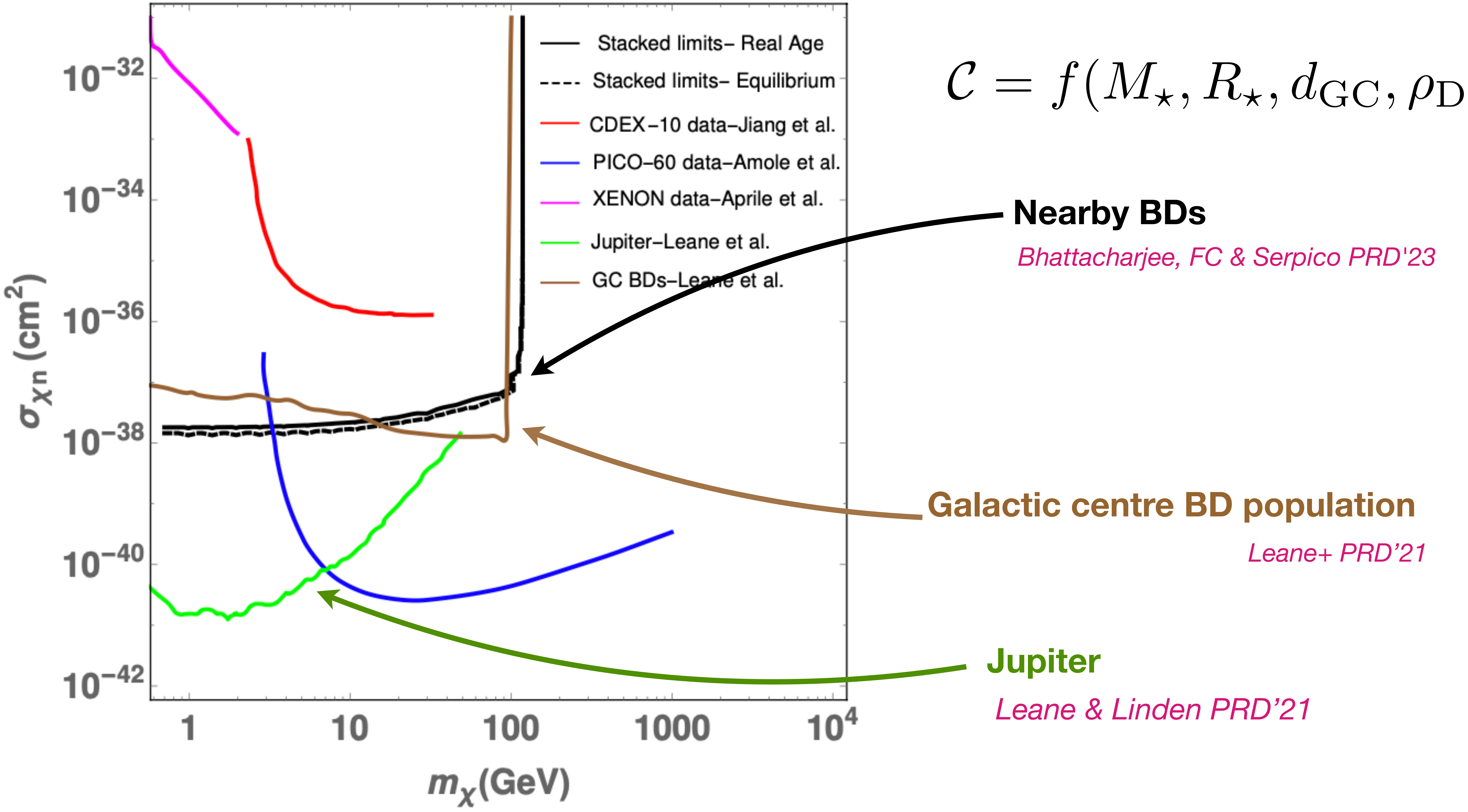

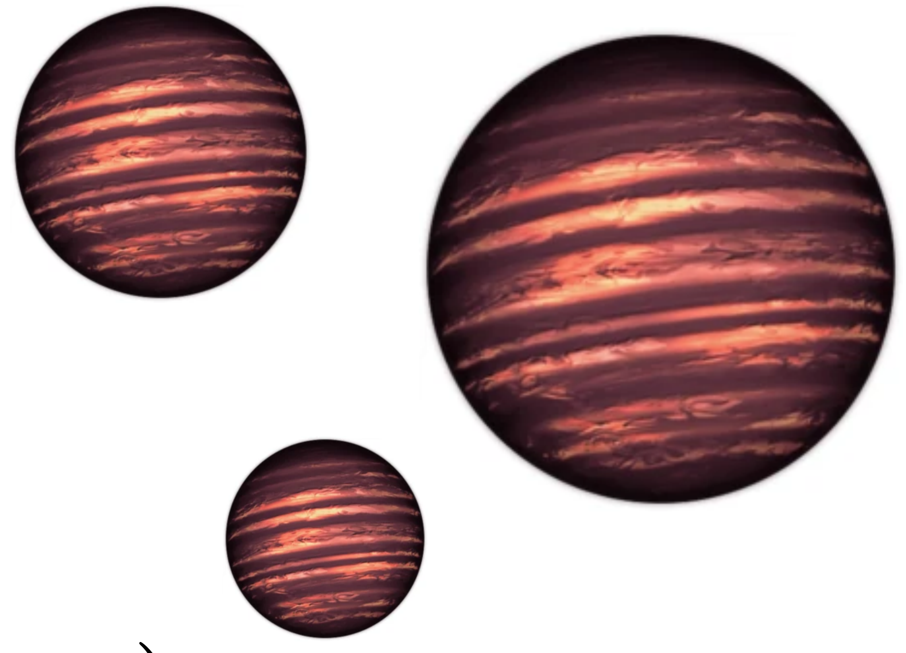

E. Figueroa-Feliciano (Tue)

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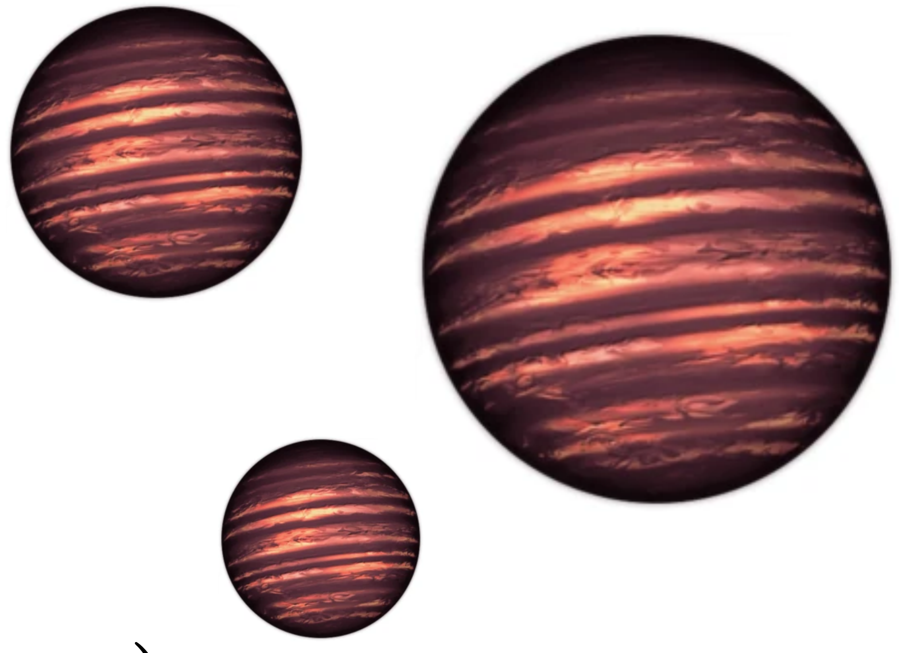

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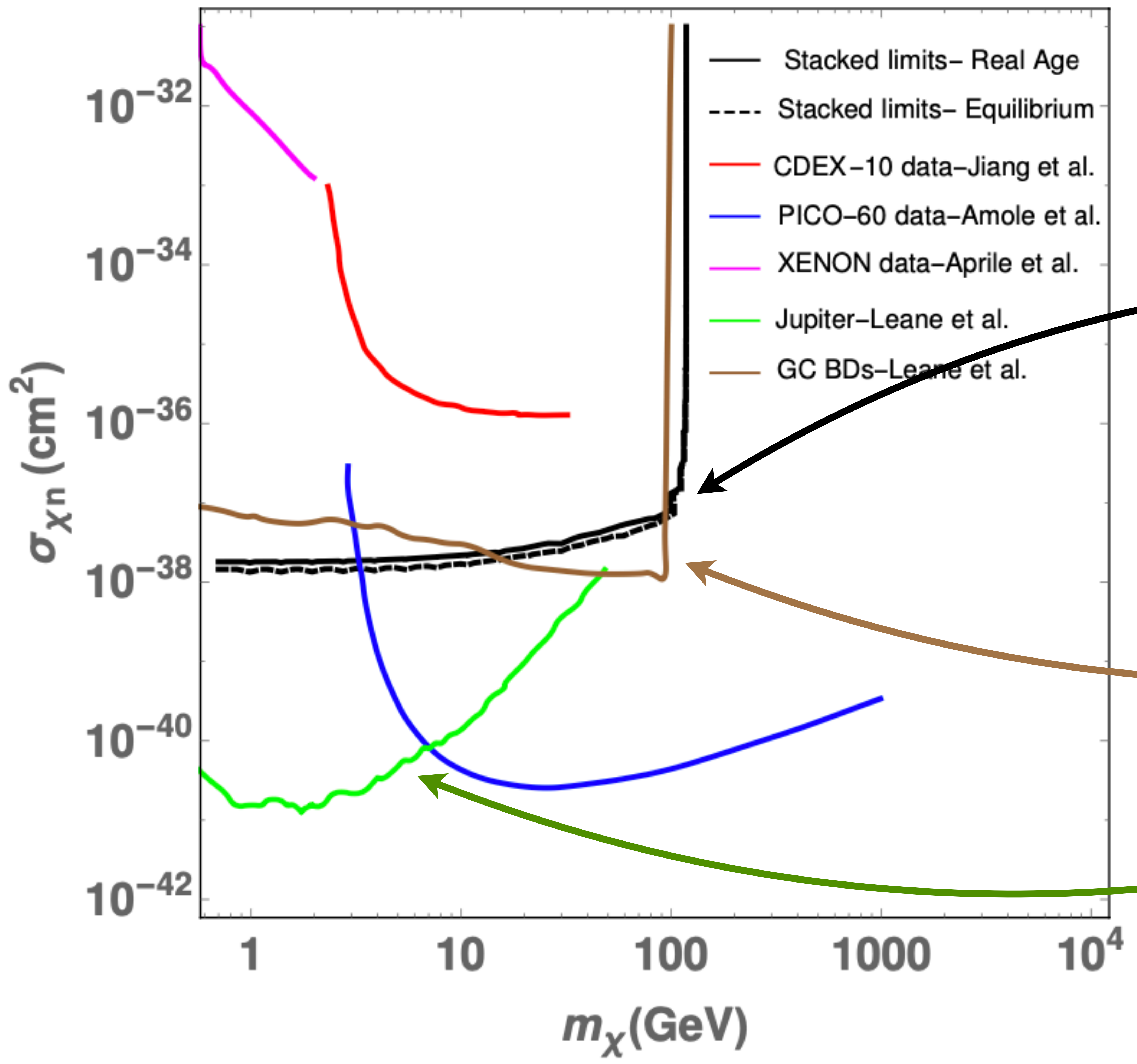

Nearby BDs

Bhattacharjee, FC & Serpico PRD'23

Galactic centre BD population

Leane+ PRD'21

TAKE AWAY: Celestial body capture provides comparable bounds to DM direct detection in sub-GeV mass range.

E. Figueroa-Feliciano (Tue)

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 (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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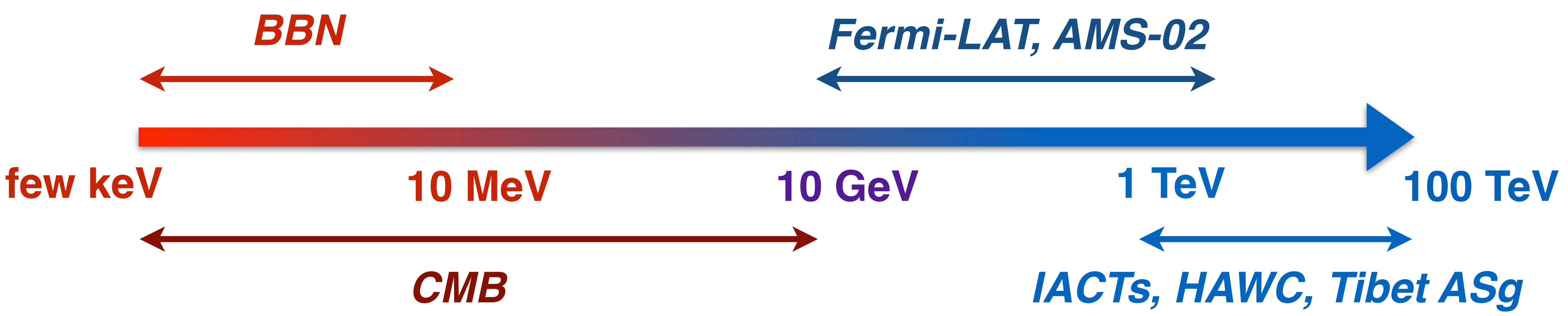
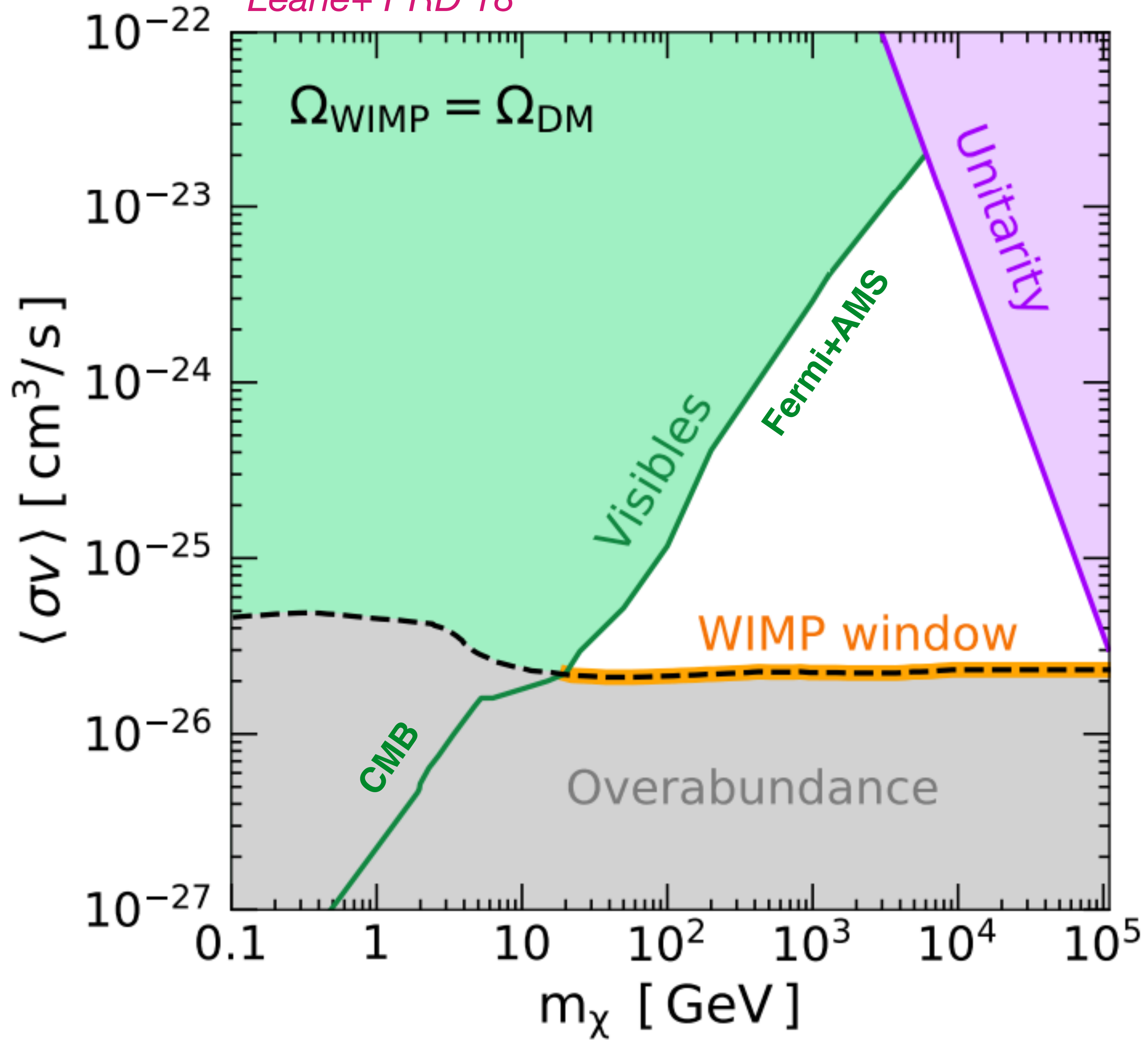
Thank you for the attention

Backup

WIMP annihilation window



Leane+ PRD'18



- **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

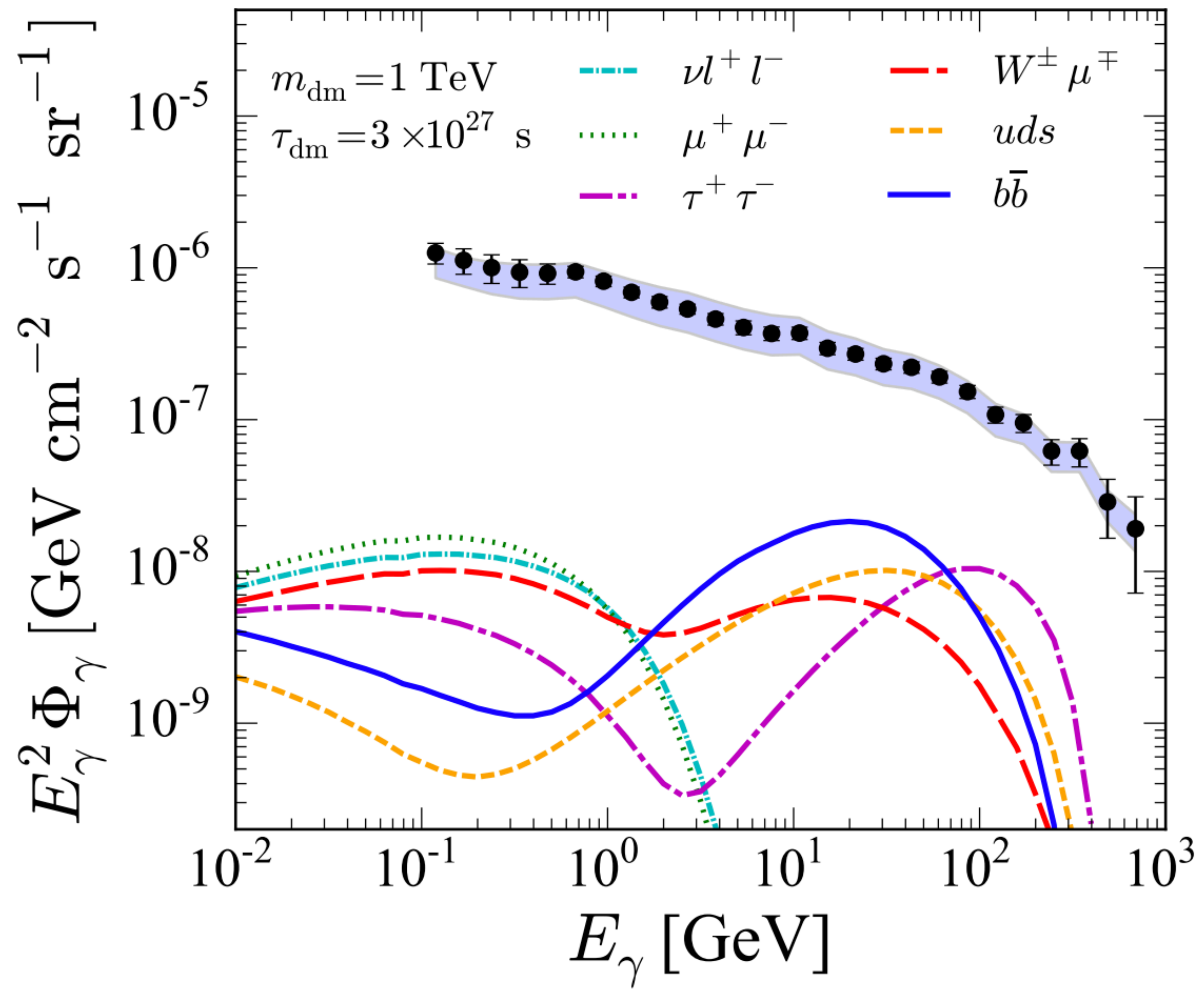
TAKE AWAY: Window of opportunity still open for thermal WIMP DM

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

Decaying WIMP dark matter

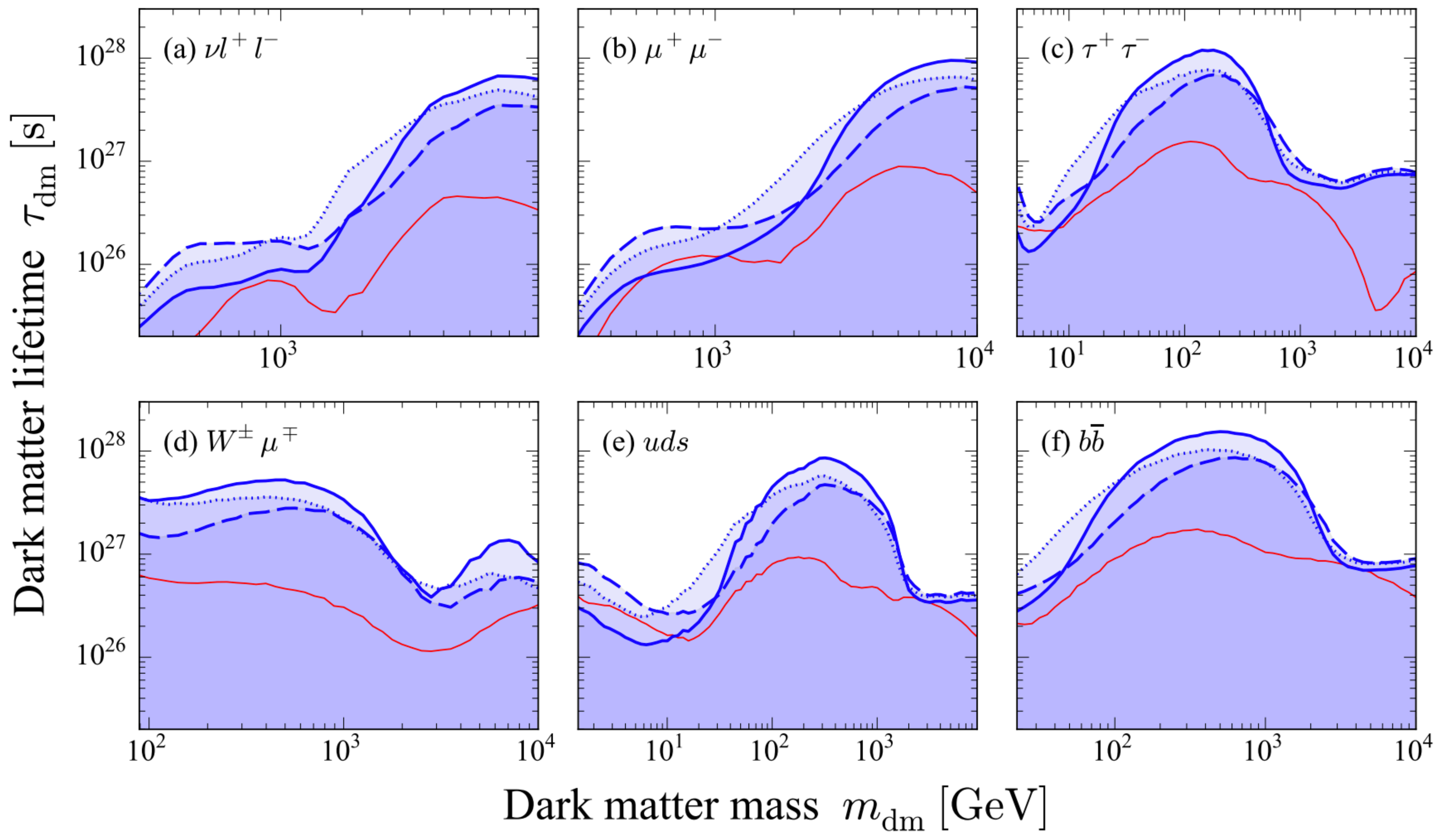
DM models: gravitino and axino in RPV models; or leptophilic models (positron fraction)

$$m_{\rm dm}\,,\ \tau_{\rm dm}\,,\ \frac{dN_I}{dE}\quad (I=\gamma,\, e^{\pm},\cdots)$$



Extragalactic signal
Considering prompt and IC emission
Modelling astrophysical bkg EGRB

Ando & Ishiwata, JCAP 05 (2015) 024 [1502.02007]



[For a review see *Ibarra+ Int.J.Mod.Phys. A28 (2013) 1330040*]

Dark Matter test science project

Open Science Projects bring together different ESCAPE services.

- ESCAPE is an EU-funded project to bring together different research infrastructures.
- Improve productivity of researchers.
- Gain new insights and innovation across disciplines.
- Two science projects being developed.

The Dark Matter Science Project provides the community with tools to do all these tasks and allows access to data and software on the EOSC through ESCAPE infrastructure

To maximise each experiment's science outputs is imperative to:

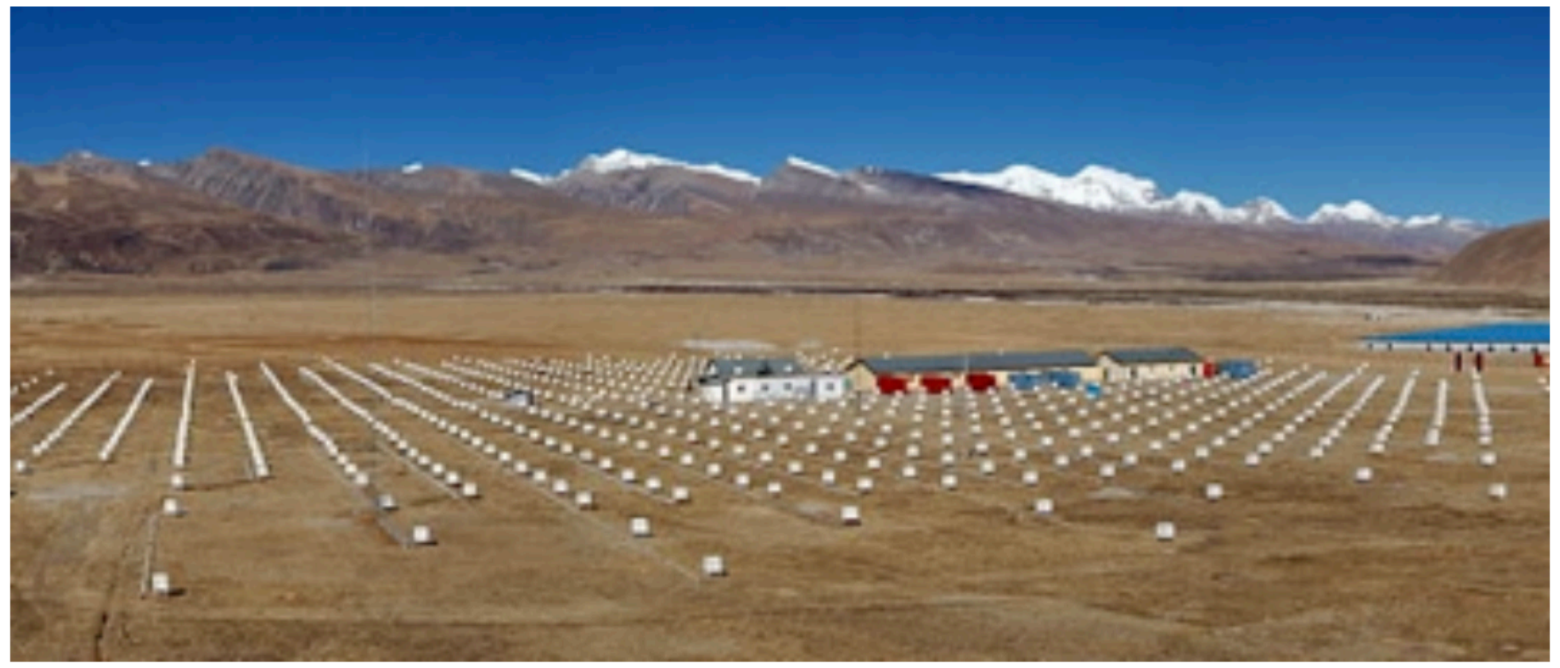
- **create** and store new analyses, datasets and results
- **combine** multiple results studying the same question
- **reinterpret** existing studies for new questions

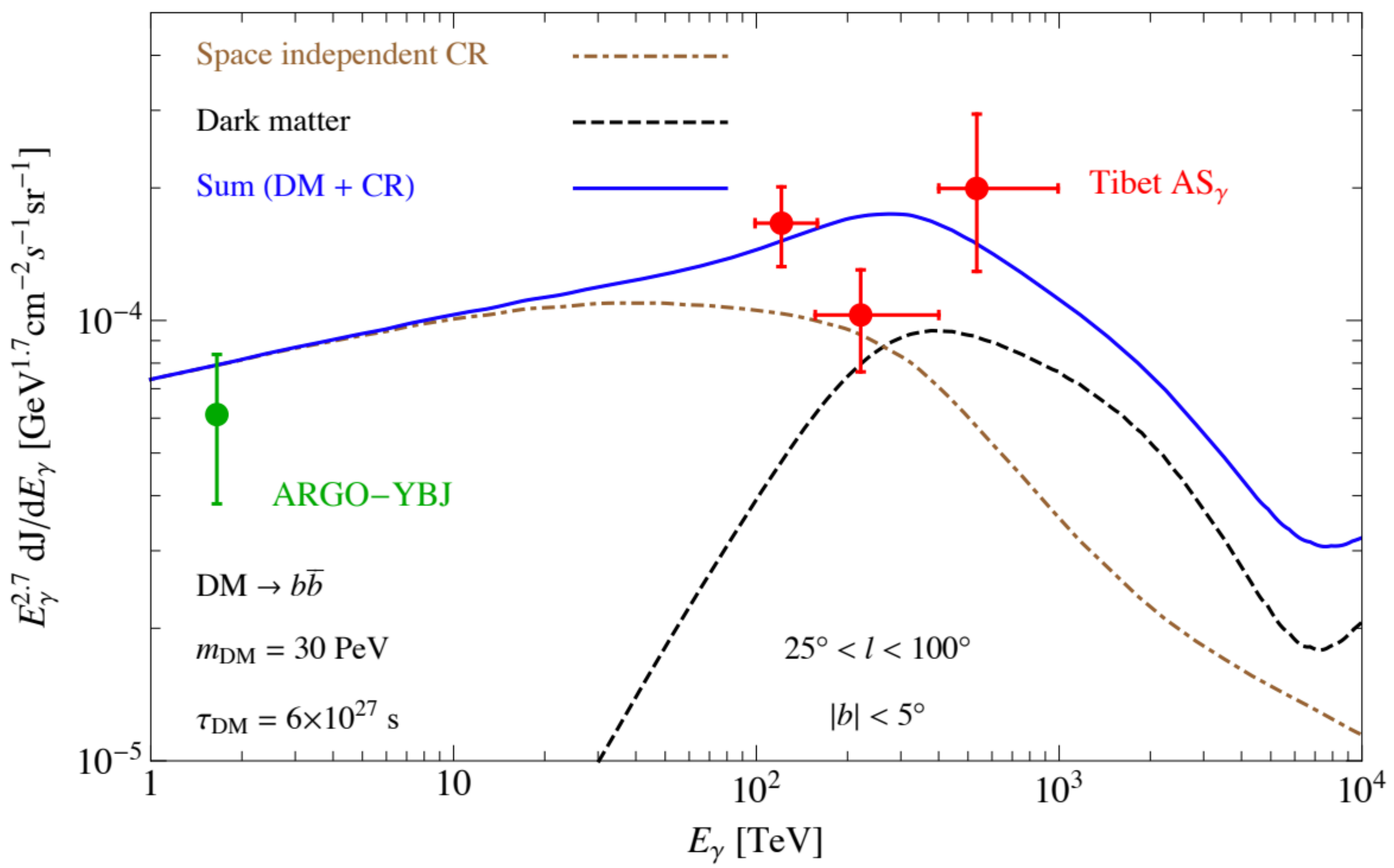
VHE gamma rays: PeV dark matter

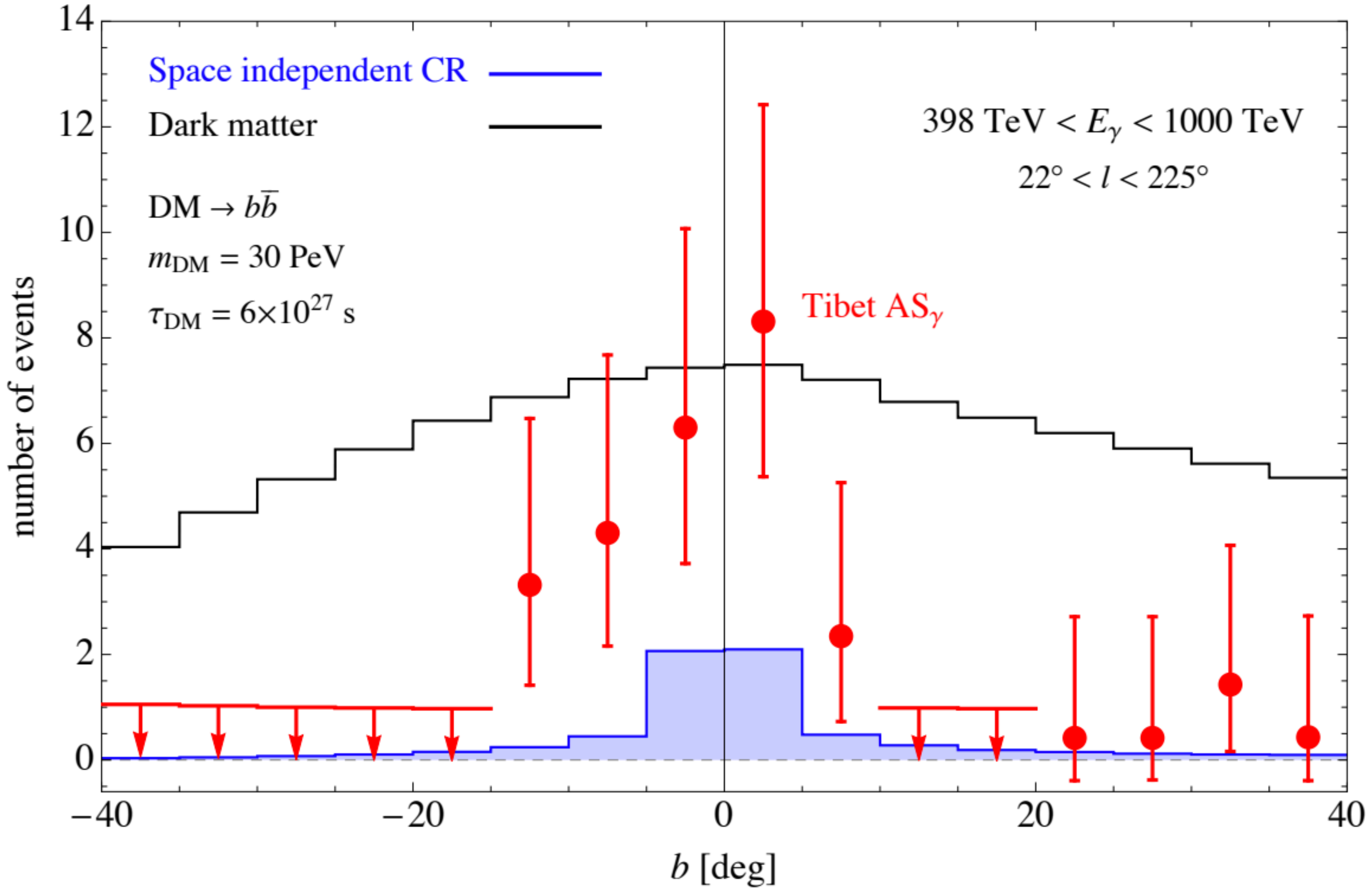
First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies

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: PeV dark matter

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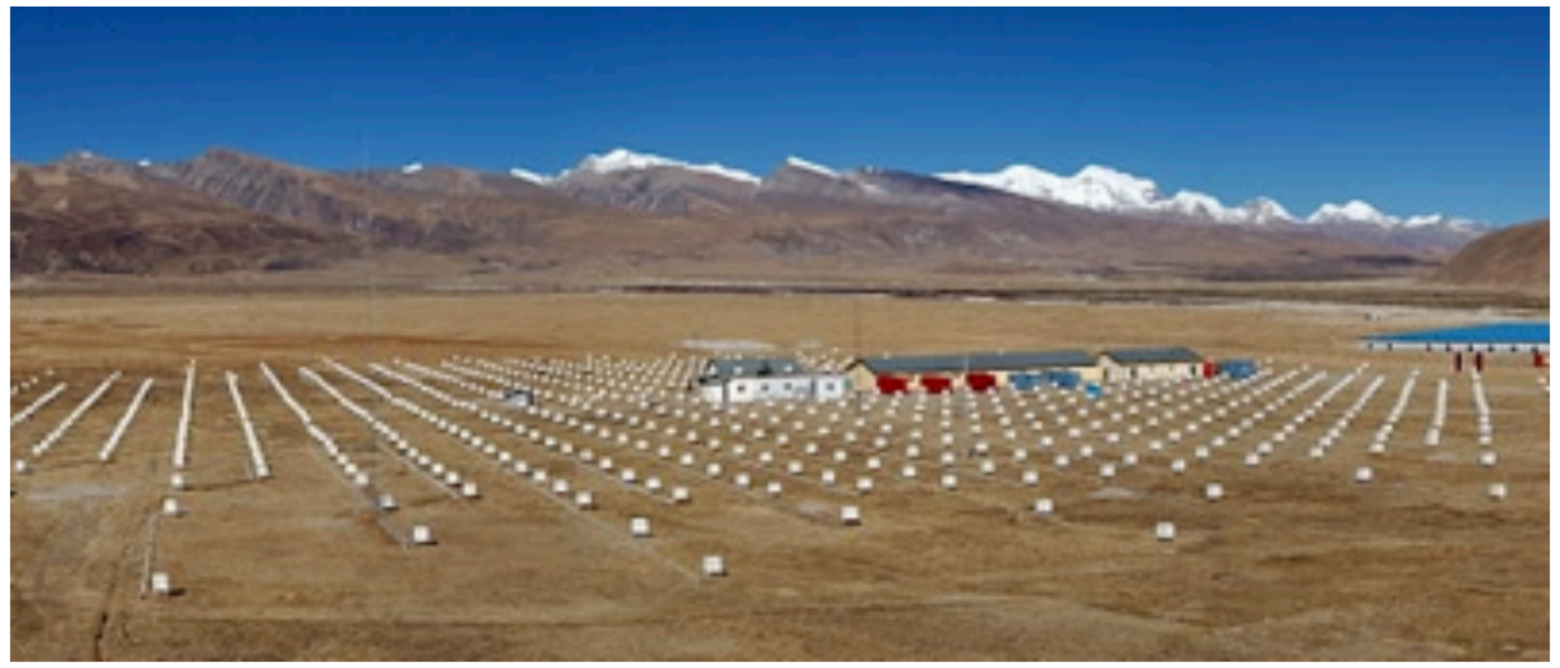
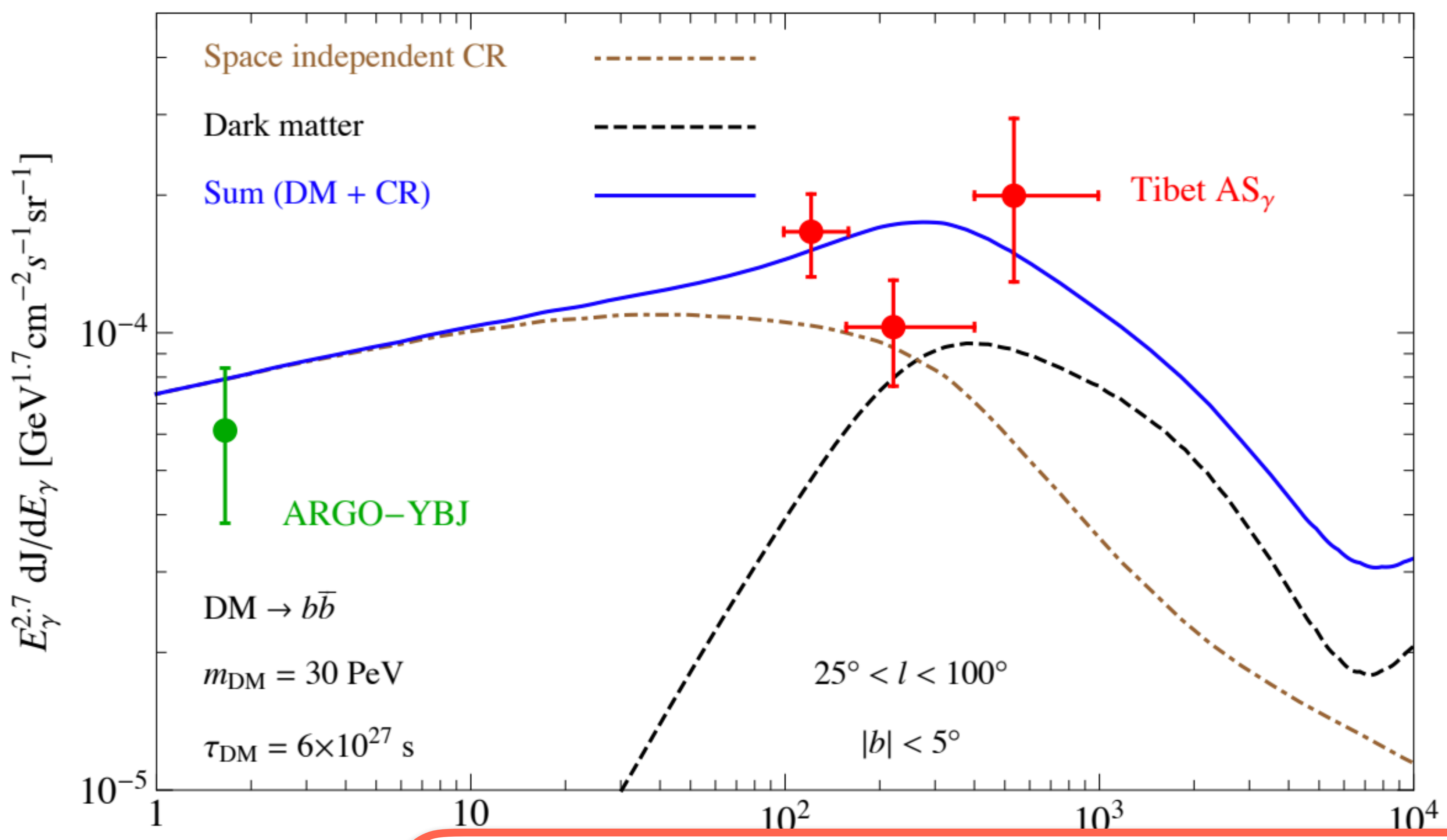
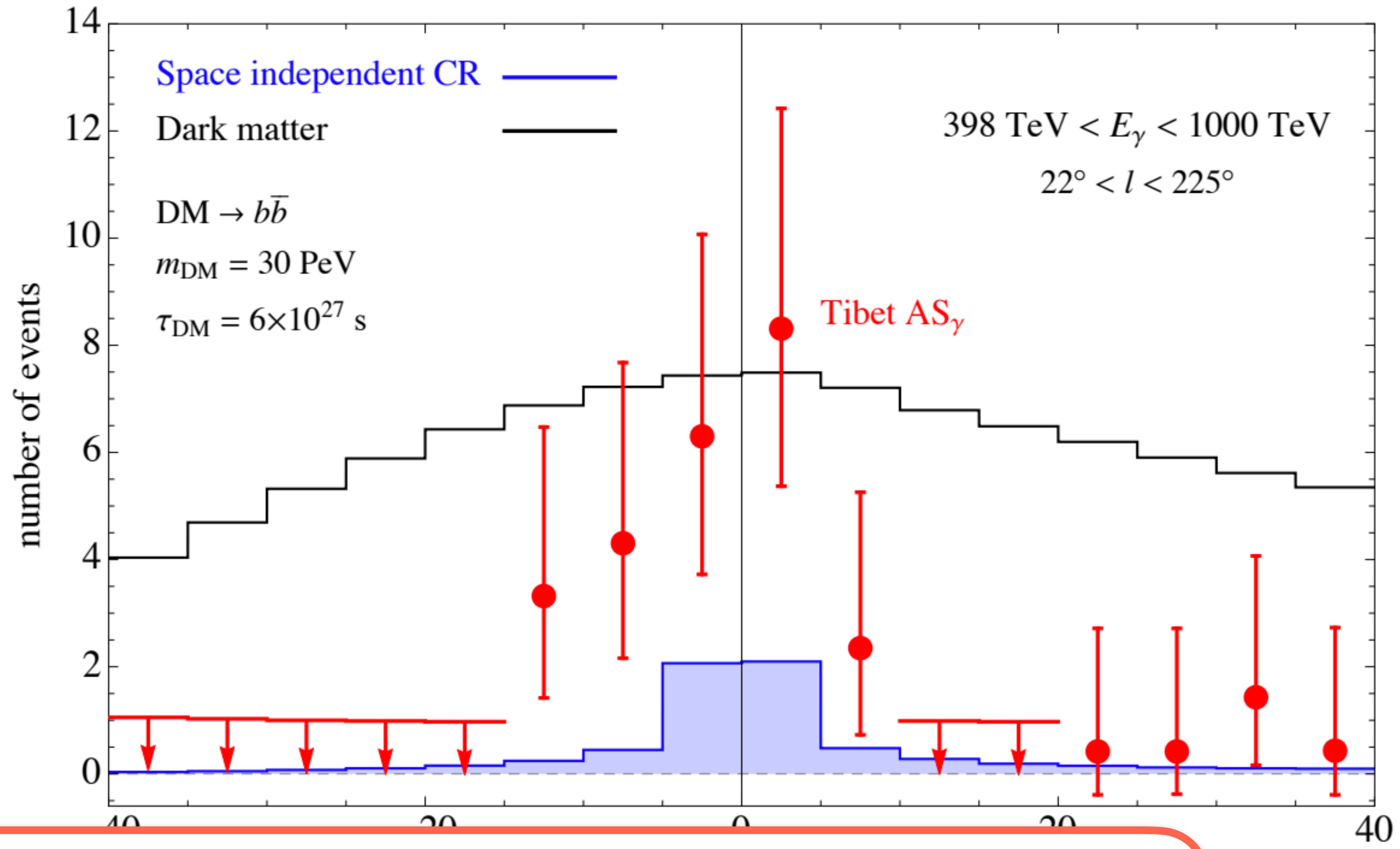




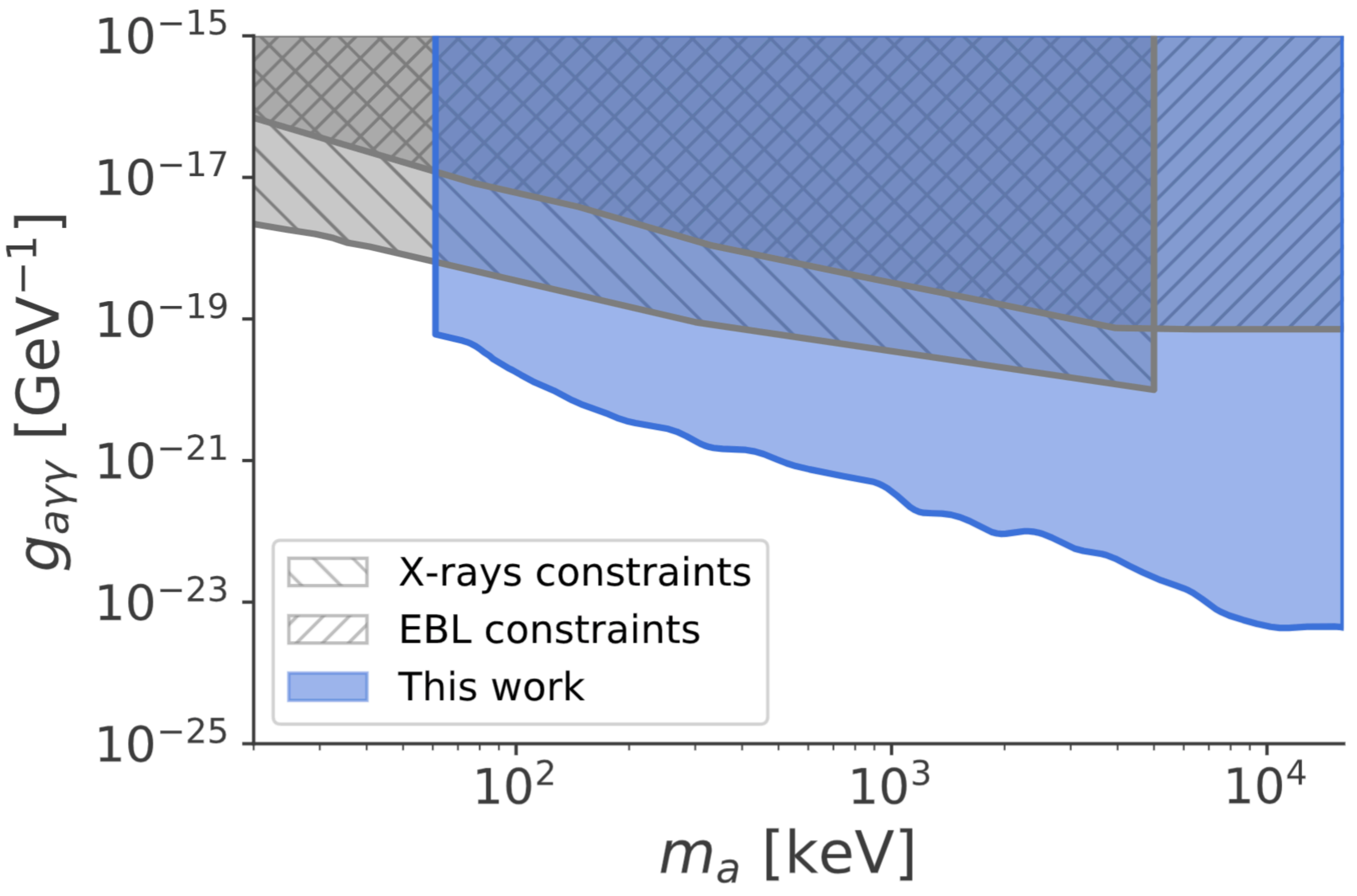


TAKE AWAY: Strong potential of VHE gamma rays (LHAASO, TibetAS-g, HAWC)

Limits on feebly interacting particles

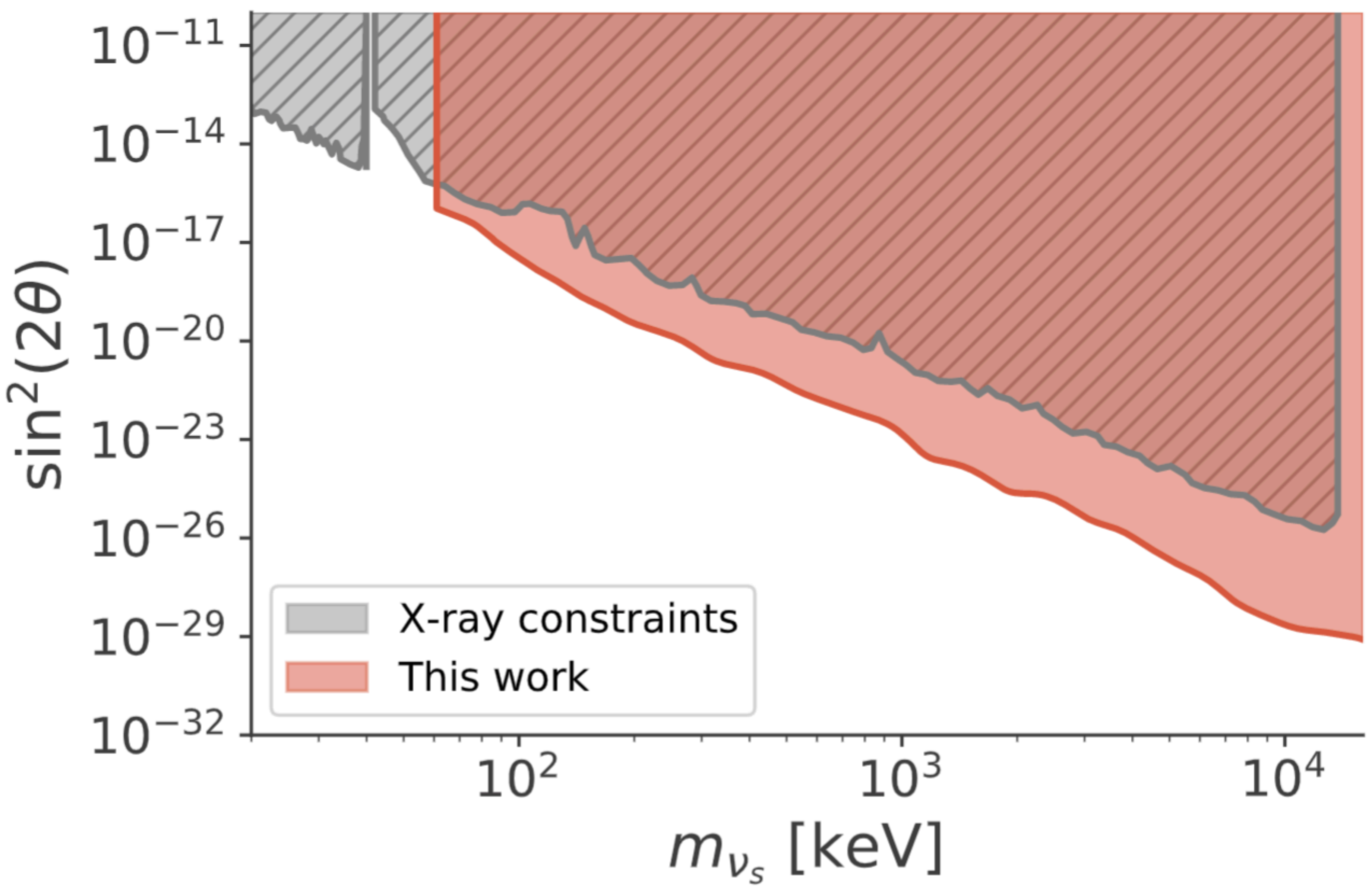
Axion-like particles

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



Sterile neutrinos

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



Dekker, FC+'22 arXiv:2209.06299

What is the origin of the GeV excess?

Possible interpretations

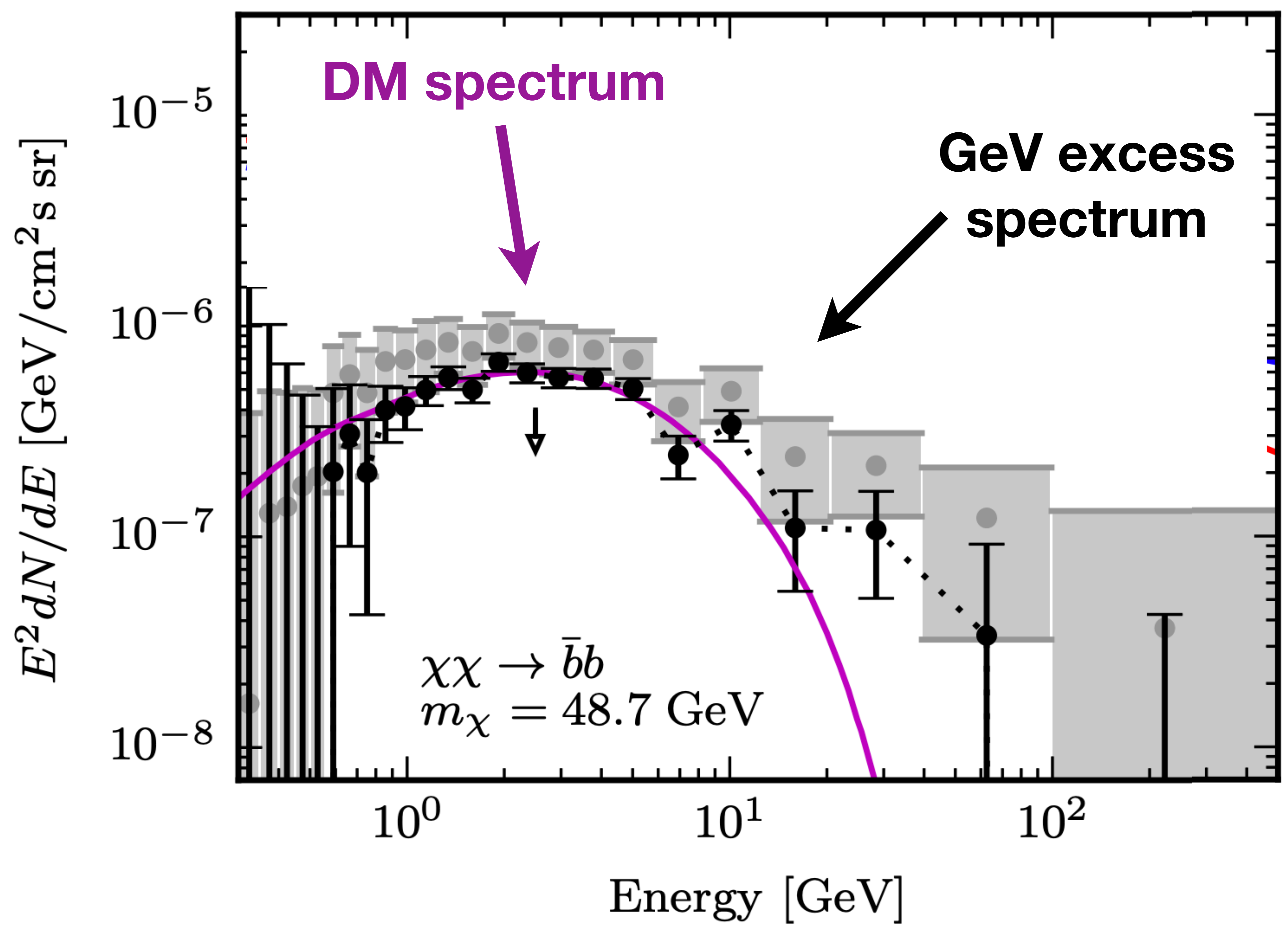
I. **Dark matter annihilation**: large freedom in channel/masses thanks to systematic uncertainties

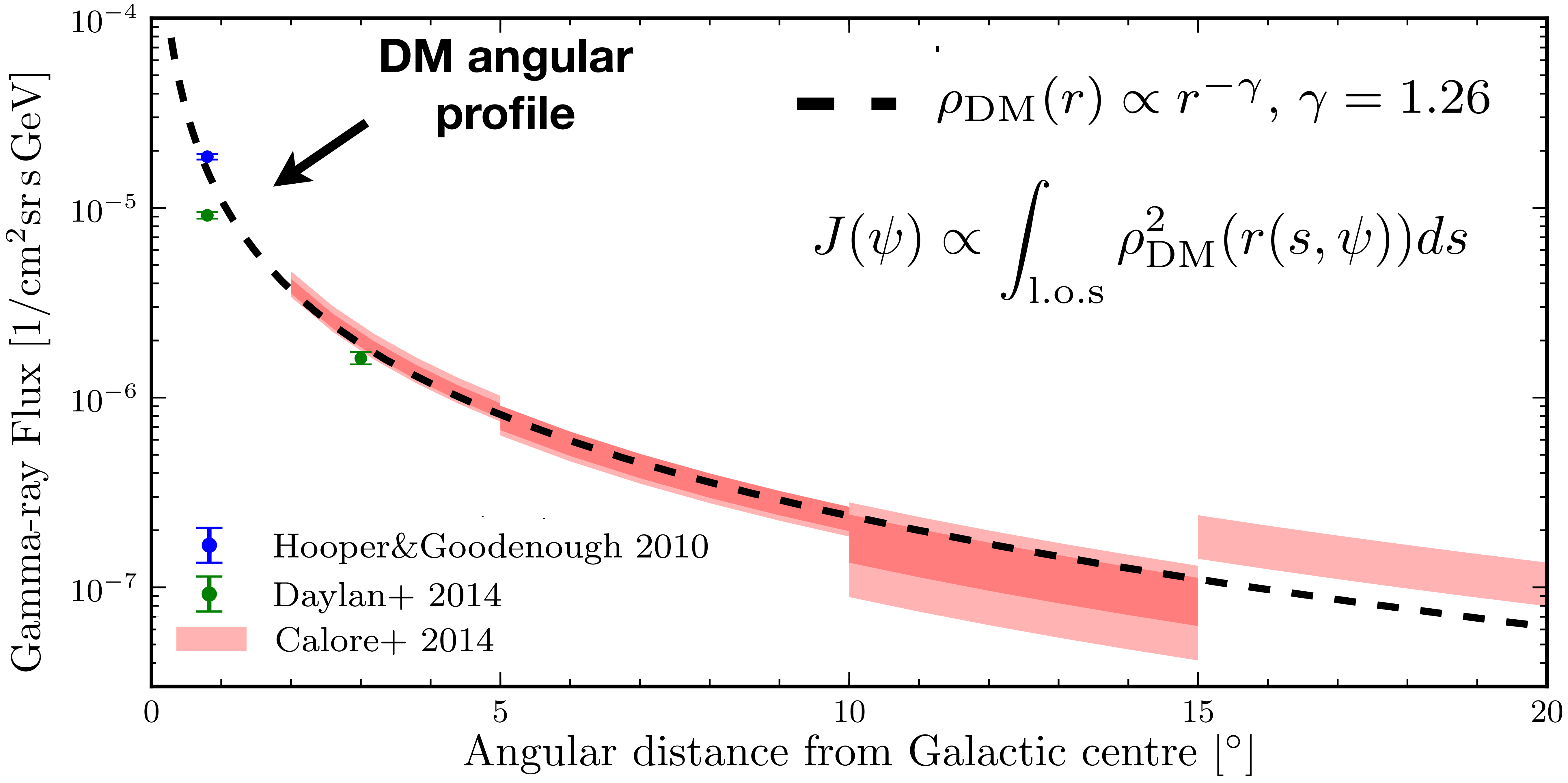
Agrawal+JCAP'15; Achterberg+JCAP'15; Bertone, FC+ JCAP'15; Liem, FC+ JCAP'16; O(>100) papers

II. Diffuse emission from electrons/positrons at the Galactic centre (**enhanced SF or activity GC**)

Gaggero+JCAP'15; Carlson+ PRD'16, PRL'16; Petrovic+ JCAP'14; Cholis, FC+ JCAP'15

III. **Cumulative emission** from **point sources** below LAT detection threshold (**unresolved sources**)

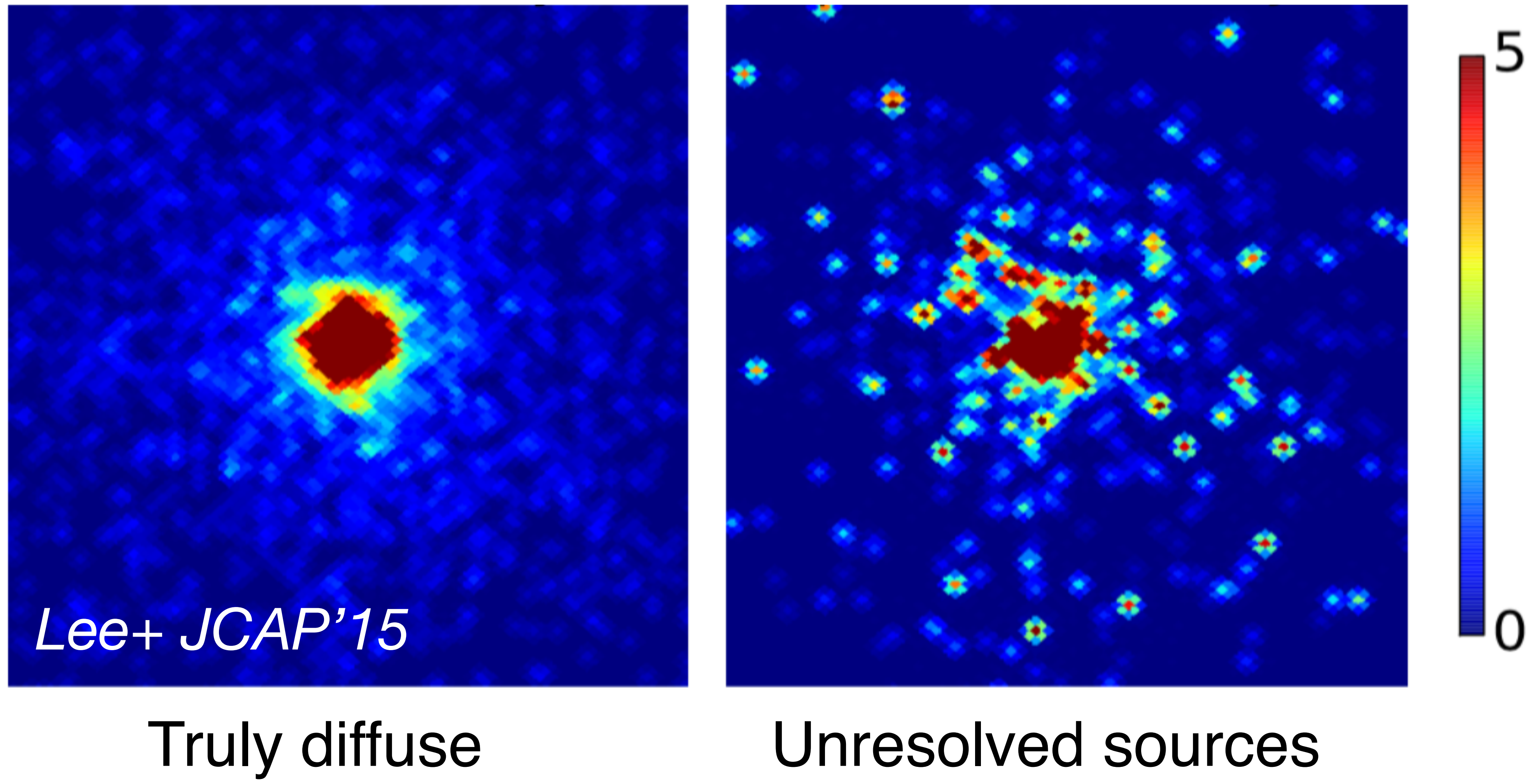


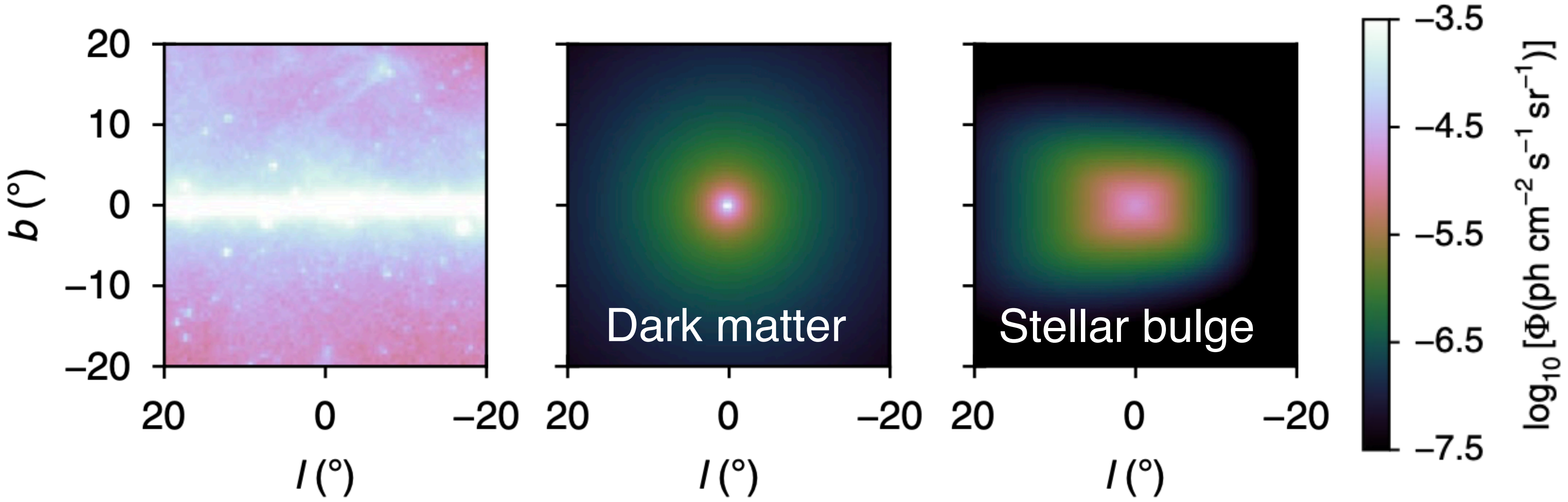


FC+PRD'15

The GeV excess nature

The gamma-ray perspective





- Difference in **statistics of photon counts** can be quantified and used for model comparison

Bartels+ PRL'16; Lee+PRL'16

- **Strong bias** from mis-modelling of foreground diffuse emission and controversial results

Zhong+PRL'19; Leane&Slatyer PRL'20, PRD'20; Chang+ PRD'20, Buschmann+PRD'20

- Nonetheless: **evidence for unresolved point sources** is there with different, independent, methods

Buschmann+PRD'20; FC+ 2102.12497; List+ 2107.09070

- **Stellar bulge morphology preferred over DM** also when modelling faint point sources

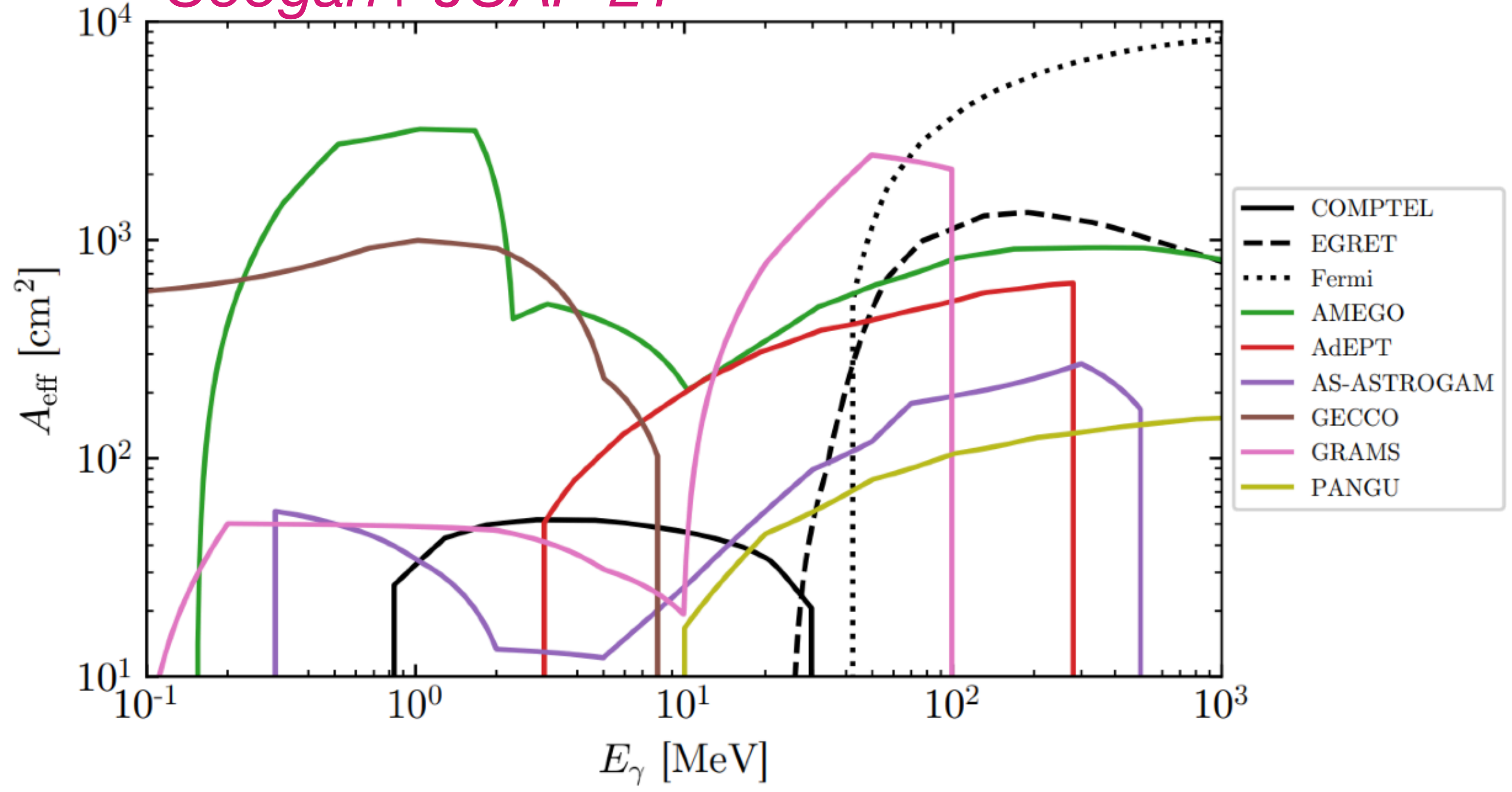
FC+ PRL' 21

Macias+ Nature Astronomy'18; Macias+ JCAP'19

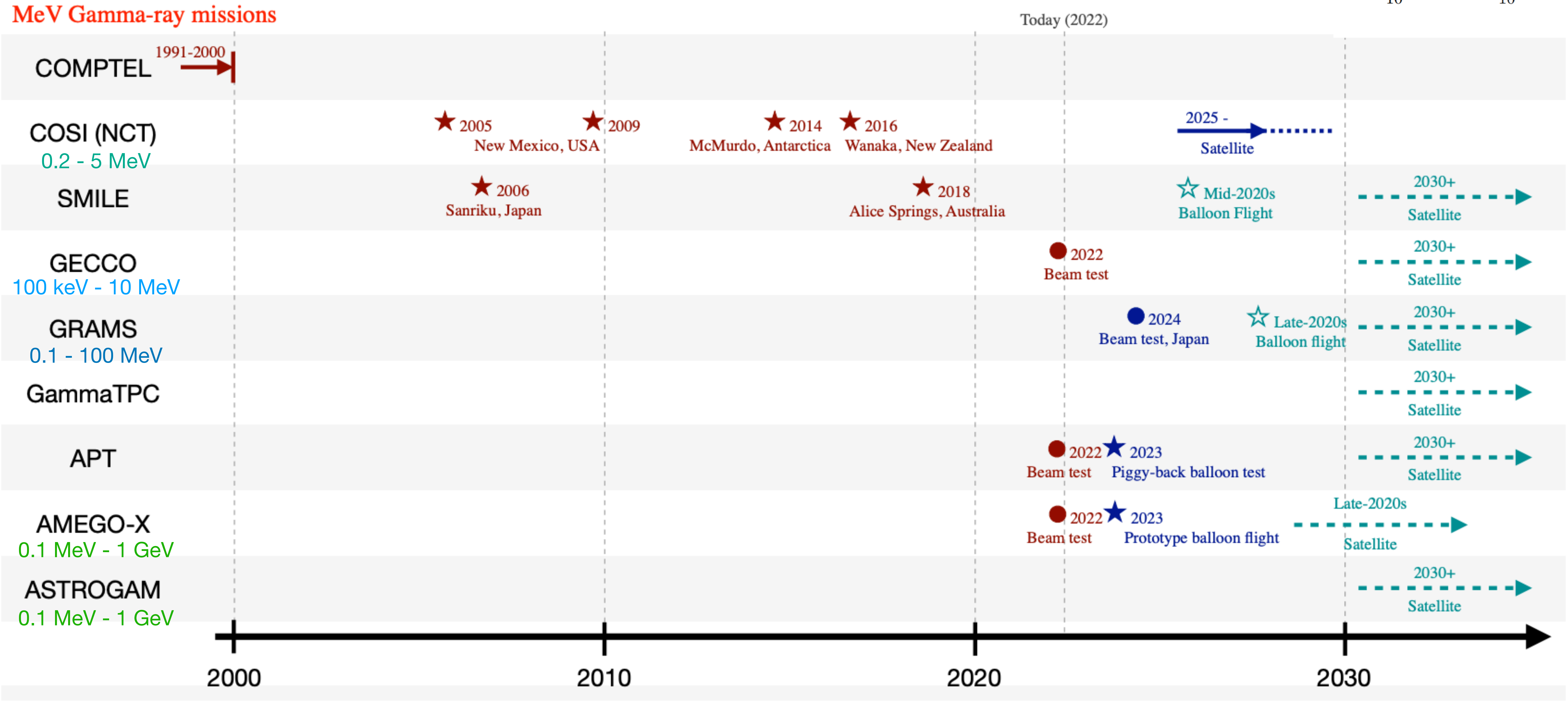
An (at least) partial **stellar origin of the GeV excess** seems to be confirmed

Future: MeV coverage

Coogan+ JCAP'21



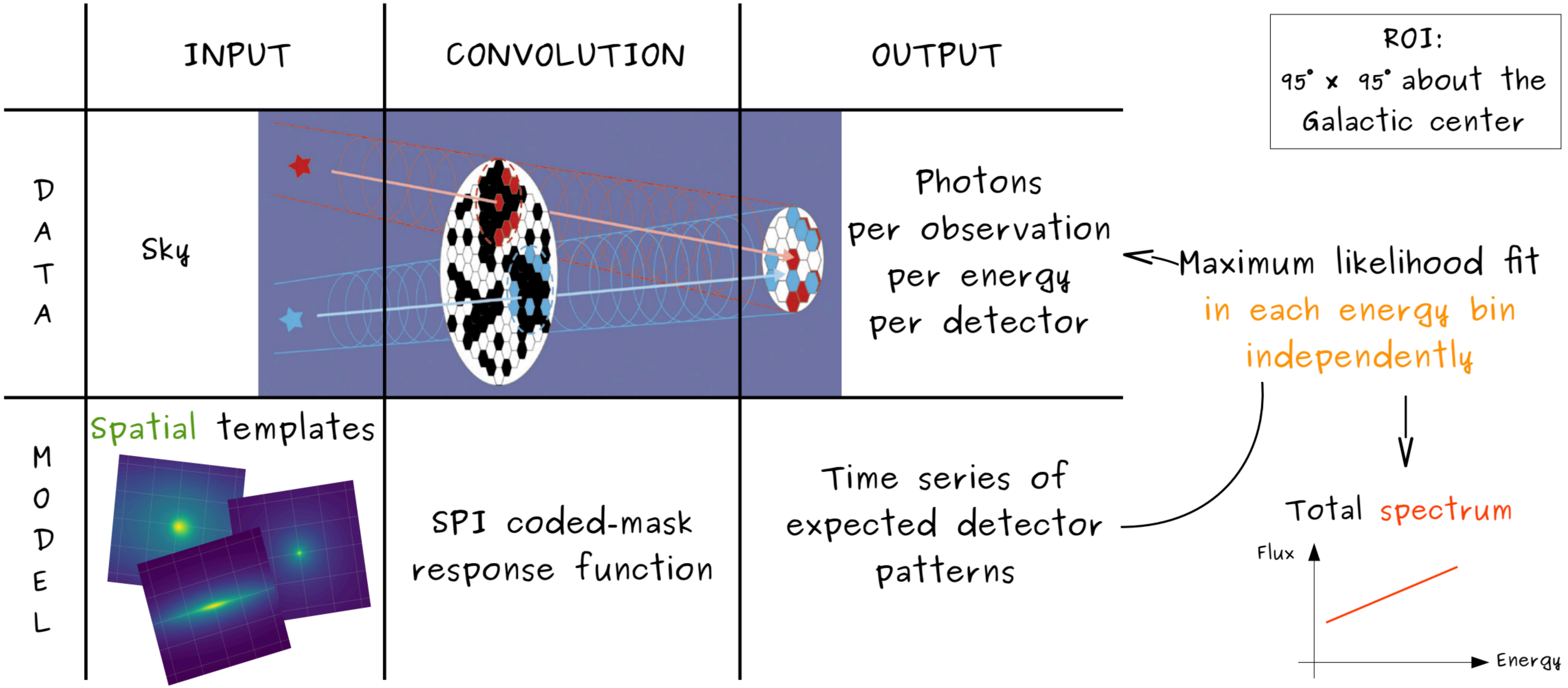
$$N_\gamma = T_{\rm obs} \int_{E_{\rm min}}^{E_{\rm max}} {\rm d}E\, A_{\rm eff} \frac{{\rm d}\Phi}{{\rm d}E_\gamma}$$



Aramaki+ Snowmass'21 CF

An old instrument, a new analysis

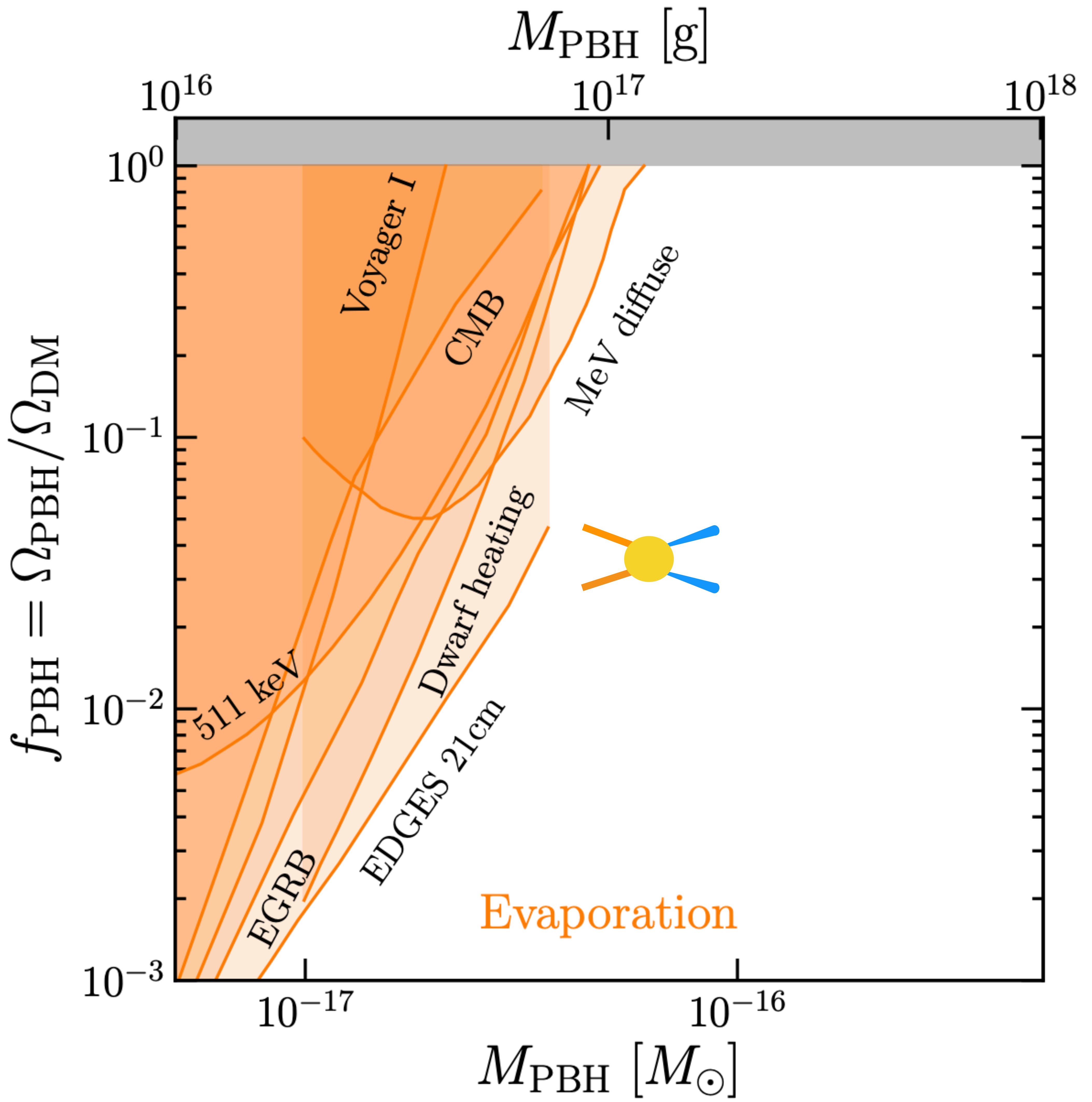
Diffuse Galactic emission spectrum with SPI 16yr data



Credit: J. Berteaud, RICAPP'22

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

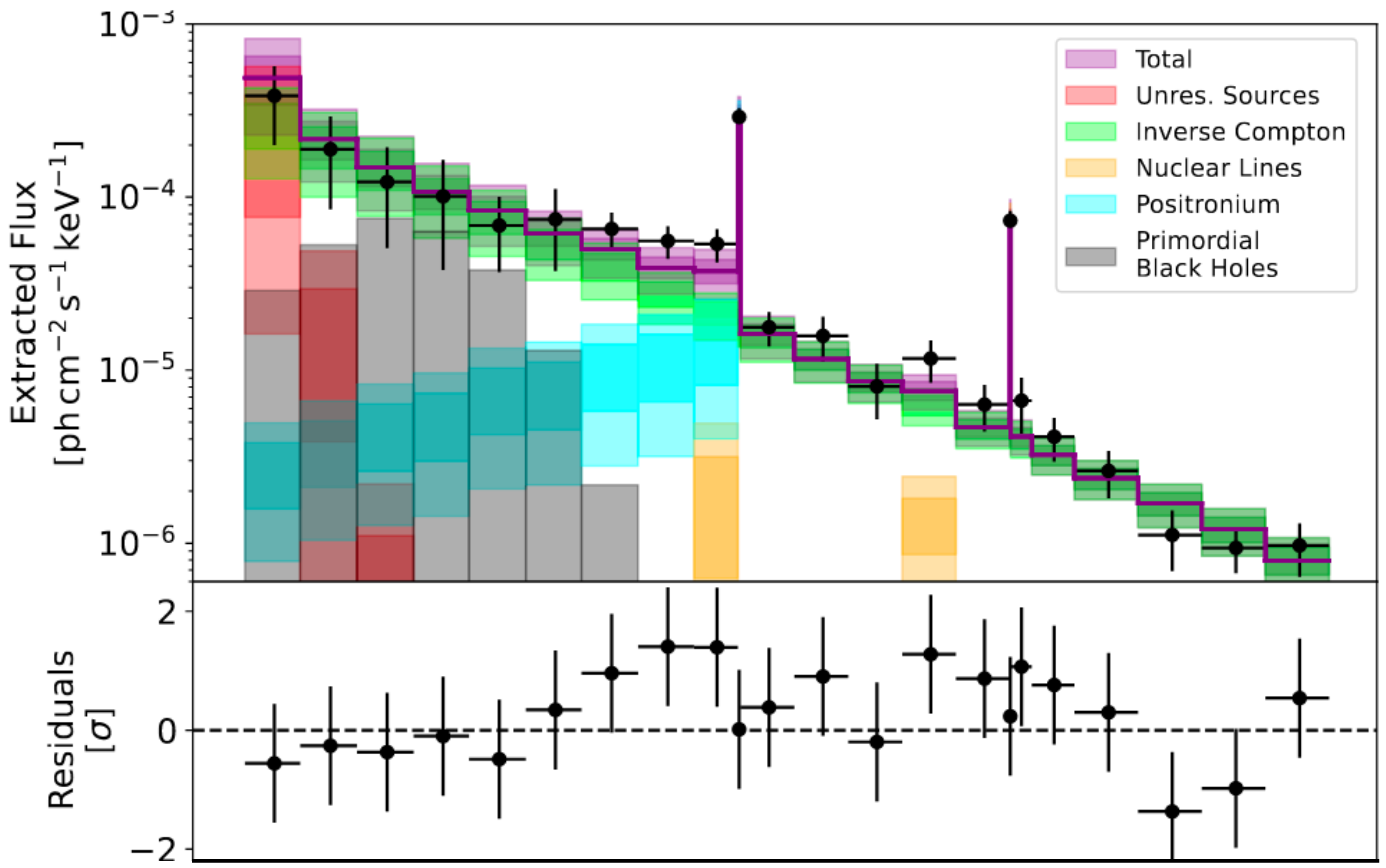
Carr+ PRD'10; Ballesteros+ PLB'20; Iguaz+ PRD'21

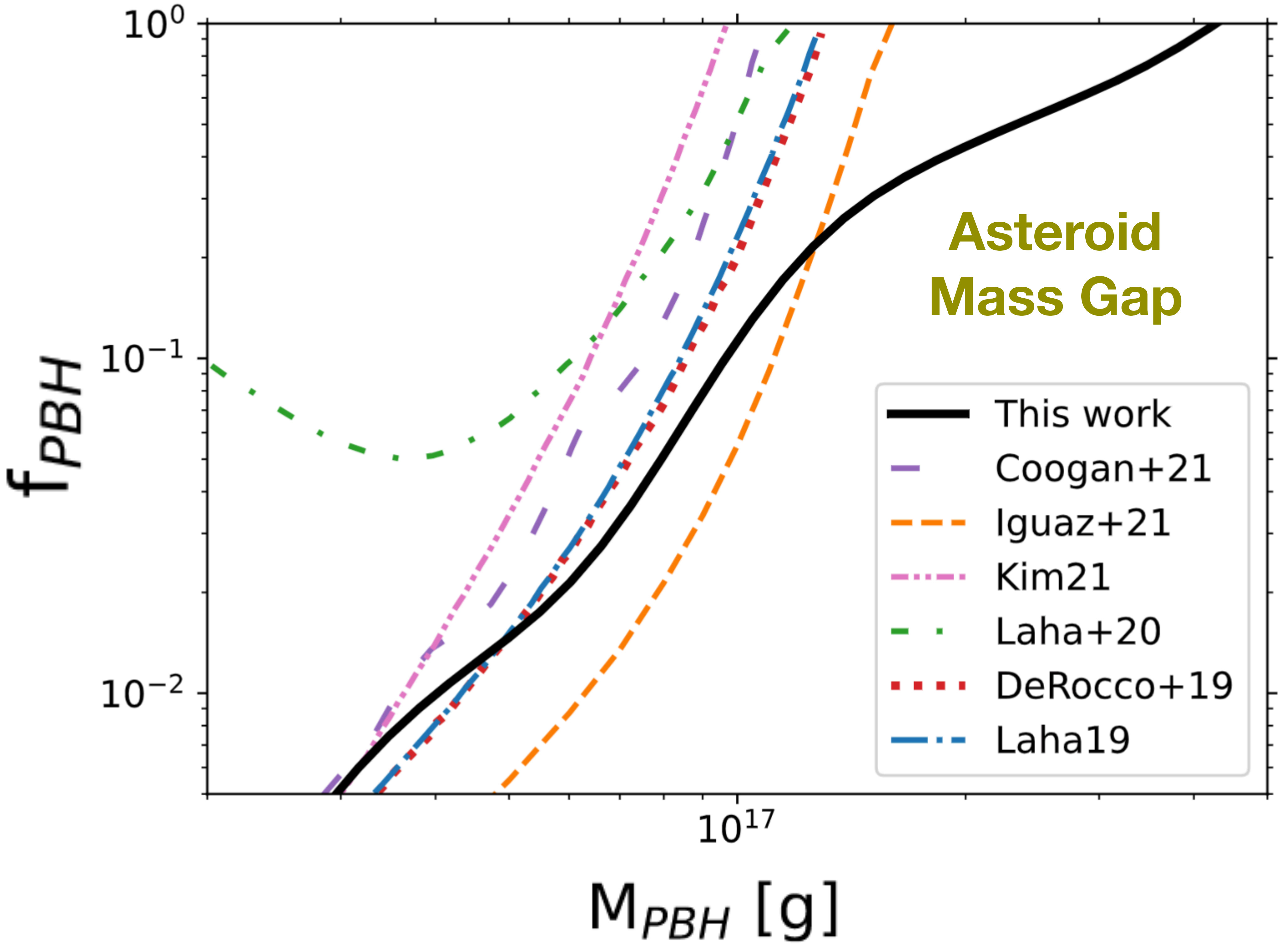
- Unconstrained mass range ~10^{17} — 10^{22} g, the so-called *asteroid mass gap* where f_{PBH} can be 1

Limits on primordial black holes

Evaporation of PBH and Galactic diffuse emission

Berteaud, FC+ PRD'22





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

=> Upper limits on PBH spectrum

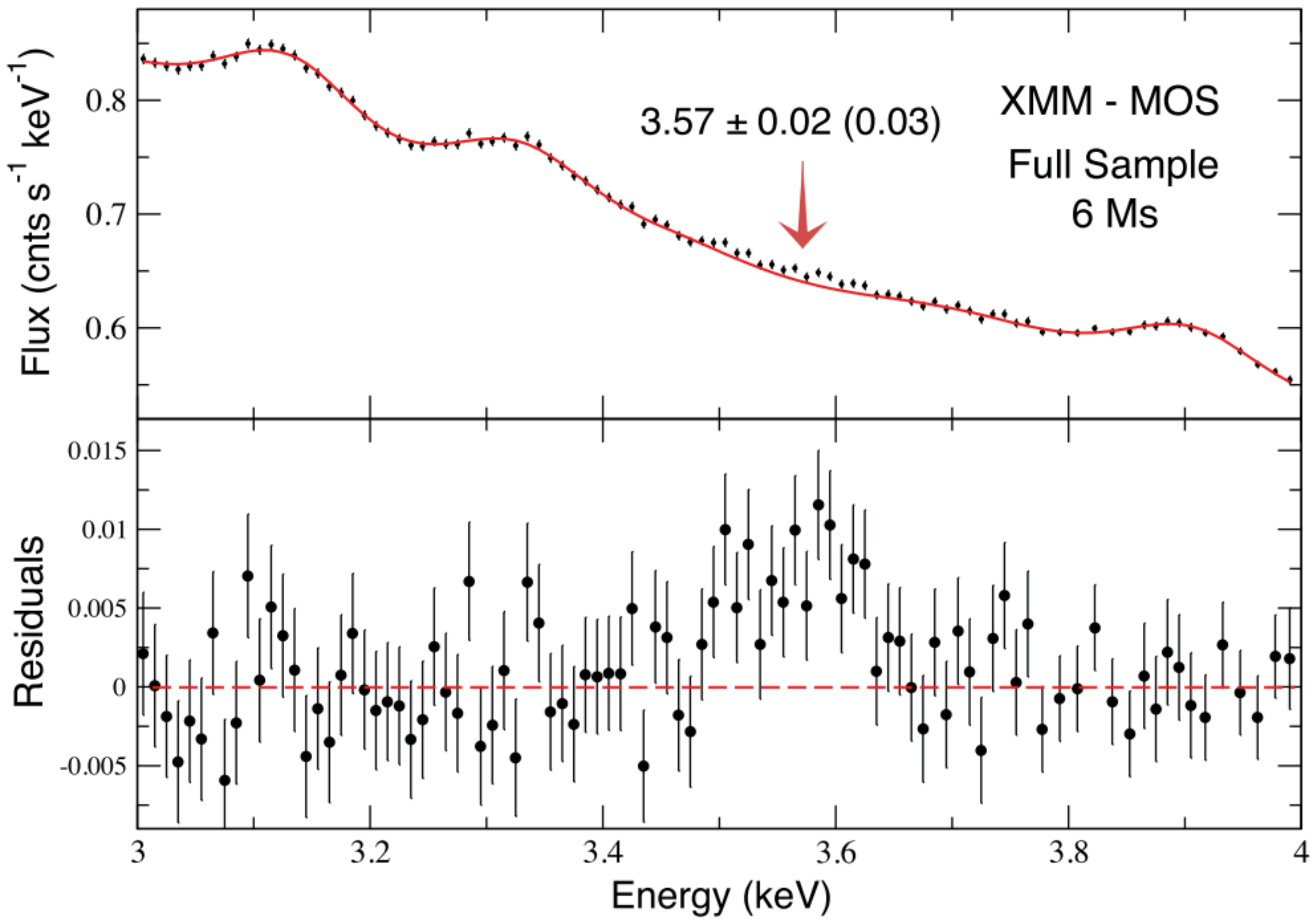
Review: K. N. Abazajian, Phys. Rept. 711-712, 1 (2017)

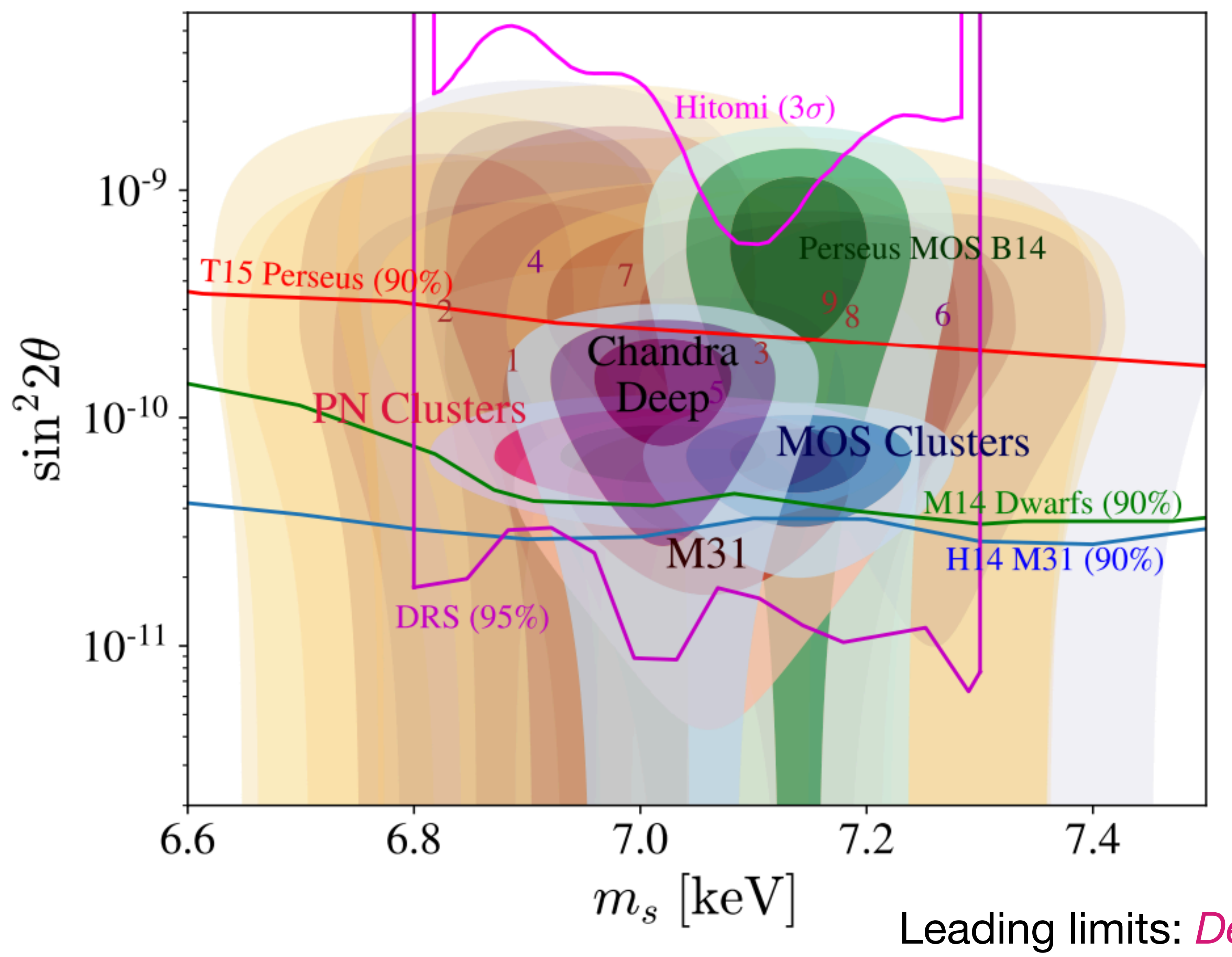
Sterile neutrinos X-ray lines

X-ray telescopes and spectral analysis

Starting from early 2014:

- **Detection** of an unidentified line at **3.5 keV**: XMM-Newton (6 Ms) & *Chandra*, Perseus cluster; XMM-Newton, M31; Suzaku, Perseus; etc
- **Constraints** from *Chandra* M31; XMM-Newton/Chandra 80 galaxies; blank field pointings Chandra and XMM-Newton, etc





Leading limits: *Dessert+ Science' 20*

Constraints on ALP-photon mixing

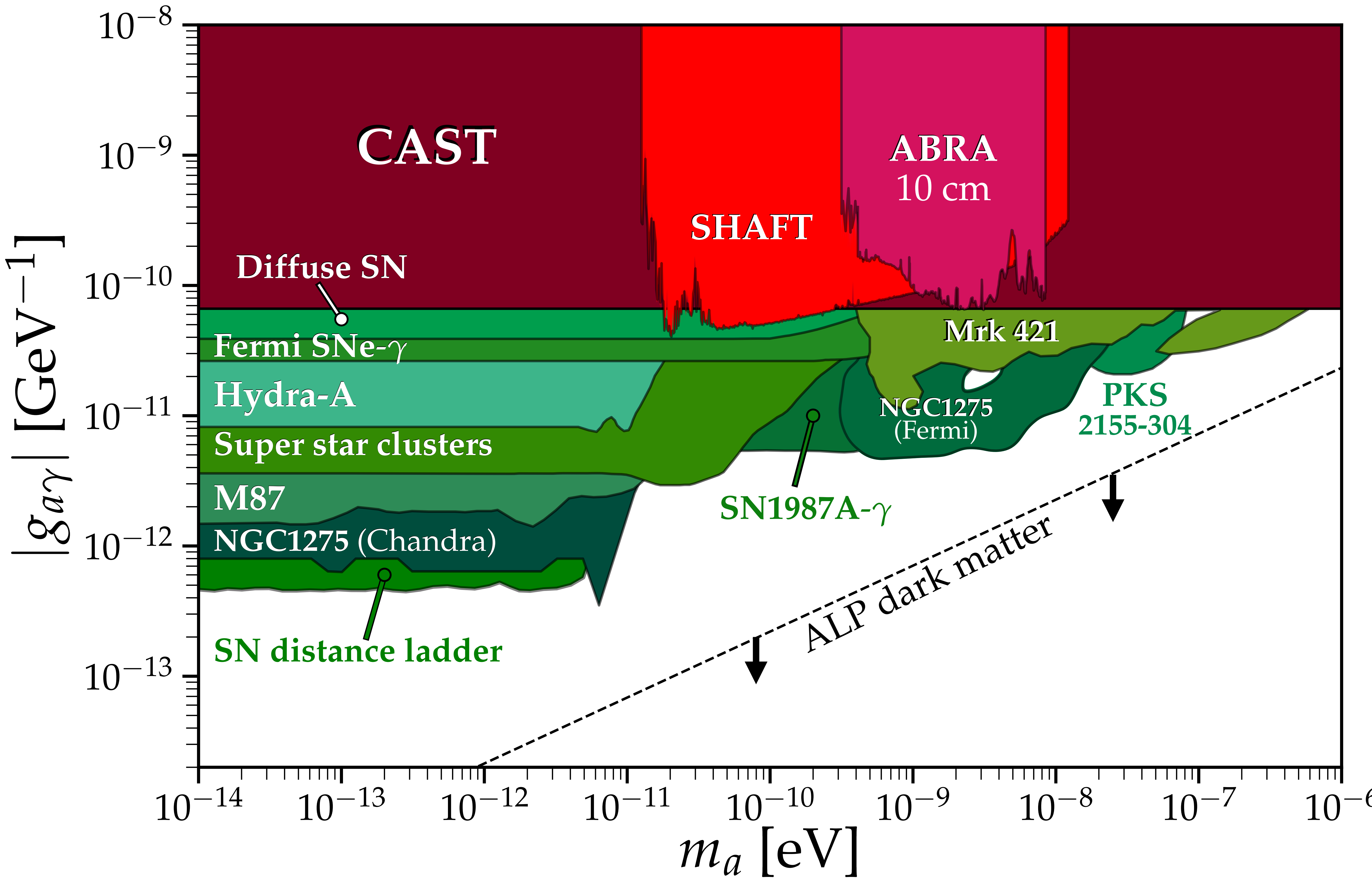
Spectral distorsion

- Spectra of high-energy Galactic and extra-galactic sources from X- to gamma rays
- For extra-gal, large uncertainties in turbulent vs ordered intra-cluster B field

Core-collapse SNe

- Searches for single SNe events or cumulative flux from all past SNe
- MeV to GeV cosmic backgrounds offer a unique window on this production mechanism

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



https://github.com/cajohare/AxionLimits

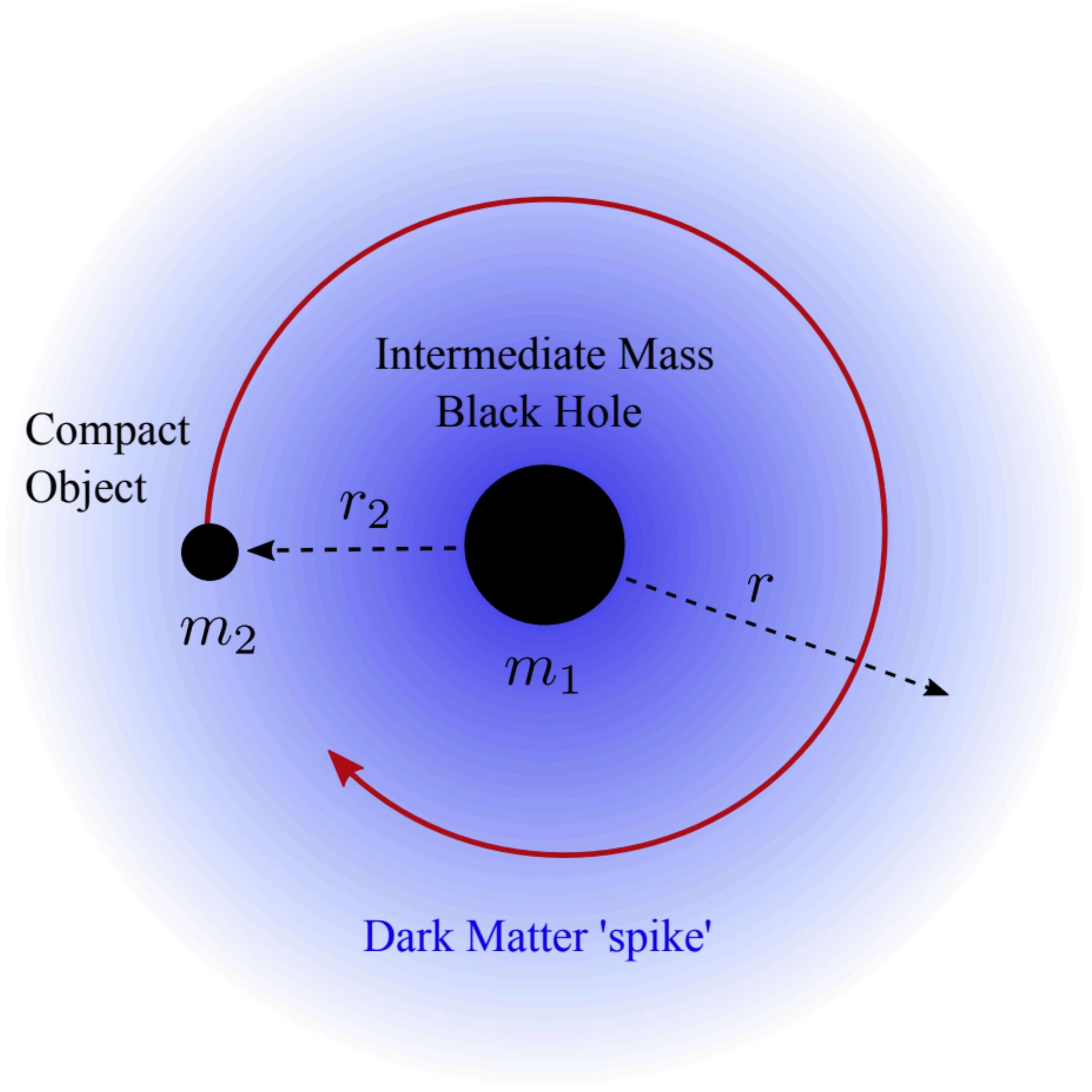
Gravitational wave constraints

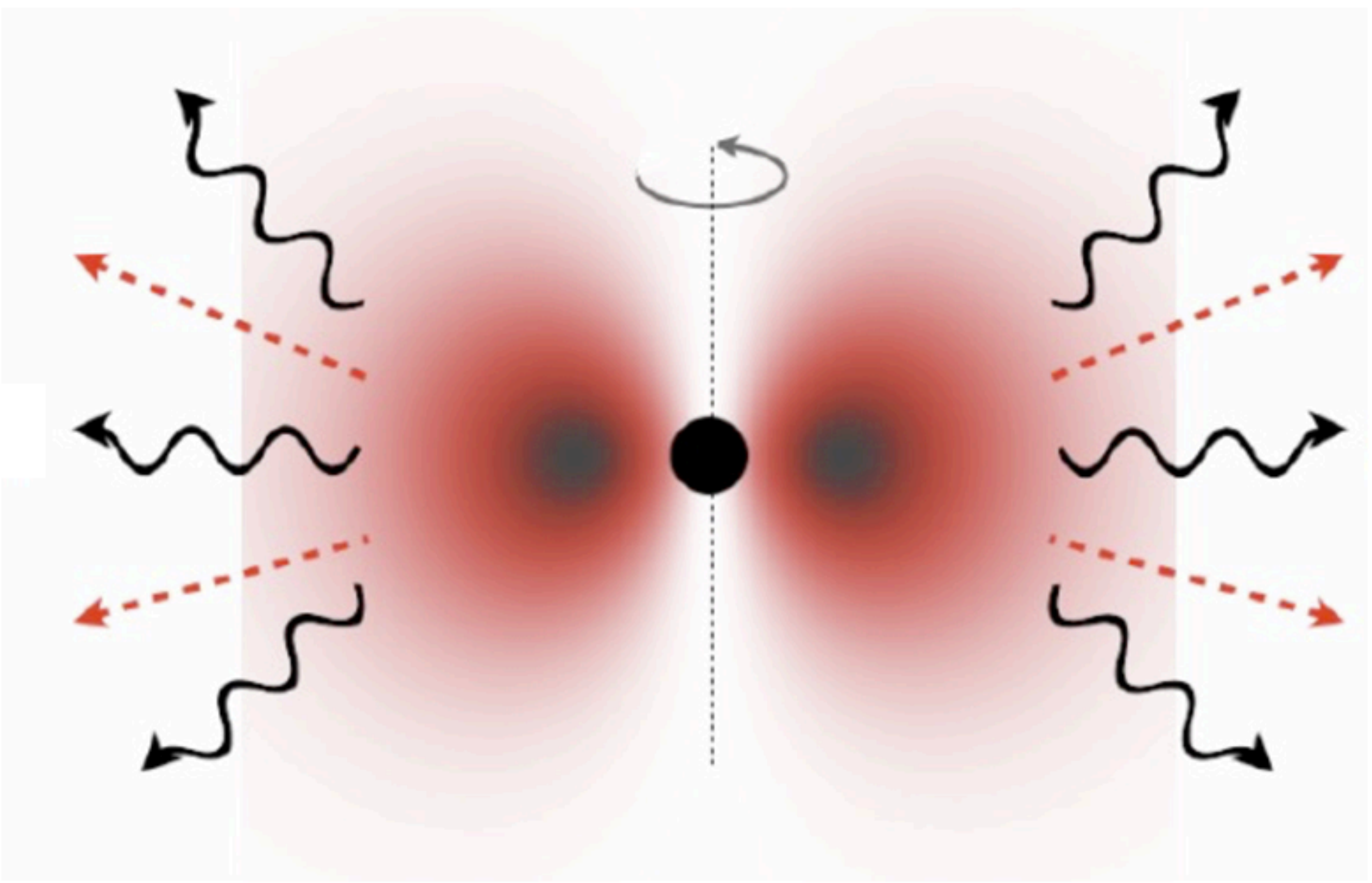
Bertone+ SciPost Phys.Core'20

- **PBHs**: formation scenarios and primordial origin can leave specific imprint in the **stochastic GW background**; smoking-gun signature in LIGO/Virgo band: **nearby mergers of sub-solar mass BHs**
- **Environmental effects**: capture/accretion of DM onto black holes or neutron stars induces specific GW signatures; e.g. de-phasing of GW-forms, spin-down of black holes due to super-radiance
- **Exotic compact objects**: DM may form new binary systems, emitting GW during mergers; e.g. boson stars mergers in the LISA window.
- **Non-pertubative DM dynamics** and **cosmological phase transitions** may leave signatures in the **stochastic GW background**

GW from environmental effects

GW signals generated by local DM (or baryon) environments modifying the GW signal from a merger of two compact objects in a distinctive way





Cold DM "dress" around (P)BHs => de-phasing of GW-form

Gondolo&Silk PRD'99; Zhao&Silk PRD'05; Kavanagh+ PRD'18; Coogan+ arXiv:2108.04154

Light boson fields around BHs => Super-radiance

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