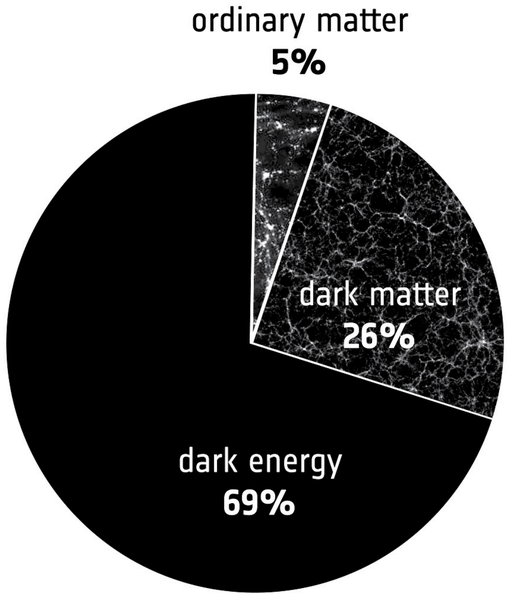
15th International Workshop on the Identification of Dark Matter 2024
8th - 12th of July — L'Aquila (IT)

The quest for dark matter across the photon spectrum

Francesca Calore (CNRS-LAPTh)

Dark matter in the universe

Mounting evidence from kpc-sized galaxies up to cosmological scales suggests that the majority of **pressure-less matter** in the universe is **not baryonic in nature**



Credit: ESA

While the dark matter gravitational impact is well measured, its **nature remains a mystery**

Non-exhaustive list of **open questions** in the dark matter quest:

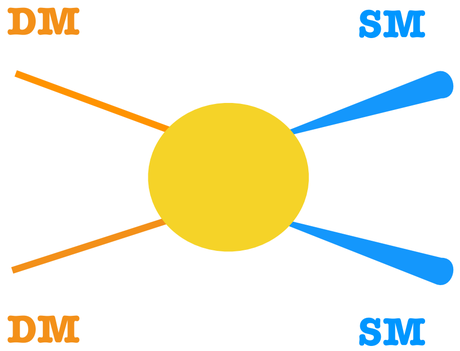
- Is there cosmic evidence to go beyond the cold and *collisionless paradigm*?
- How is dark matter *produced* in the early universe, and how does this connect to late universe observables?
- Is dark matter a particle and fundamentally *wave-like or particle-like*?
- Is there a *dark sector* containing other new particles and/or forces? Does dark matter have important *self-interactions*?

...

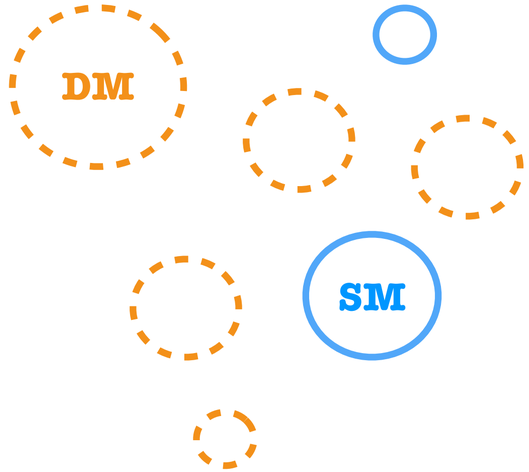
Snowmass Cosmic Frontier; Snowmass Astro&Cosmo Probes of DM; EuCAPT White Paper

Dark matter indirect detection

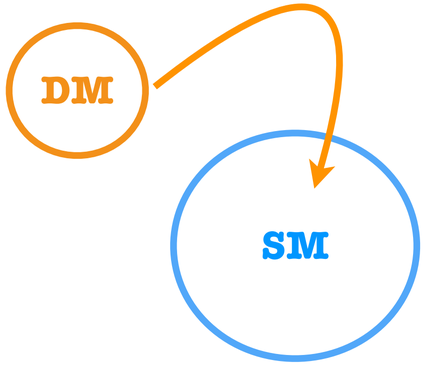
What dark matter does with/to the environment



Energy/particle injection



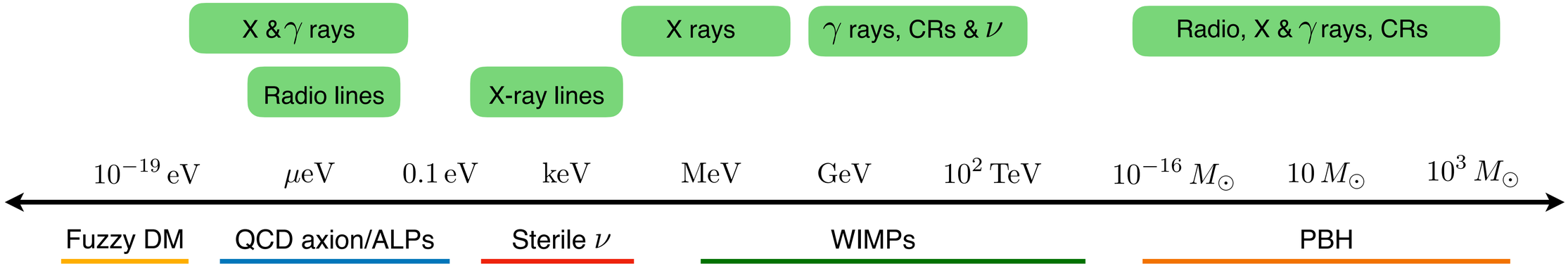
Gravitational interaction



Capture/scattering/accretion in/onto astrophysical objects

A focus on multi-wavelength photons

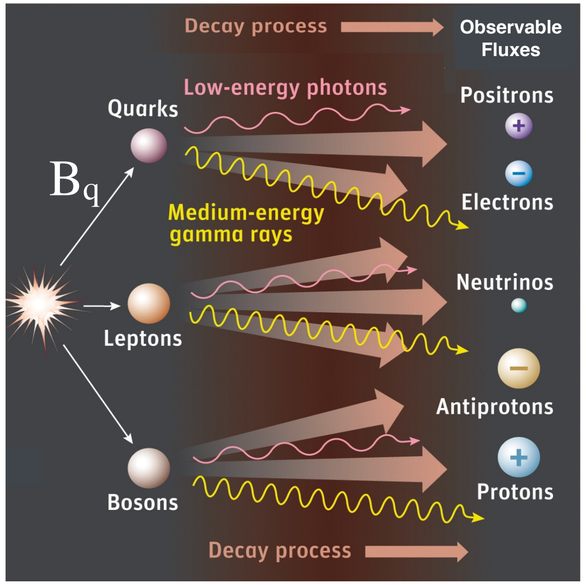
EuCAPT White Paper, arXiv:2110.10074



Indirect searches for dark matter **successfully test different dark matter models** (WIMPs, ALPs, PBHs, etc), probing a large portion of their parameter space

Particle dark matter emission

DM annihilation/decay



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

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

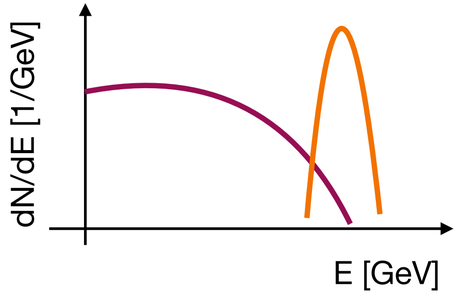
Centre of mass energy $\simeq$ Signal energy

$m_{\rm DM} \lesssim {\rm MeV}$

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

Narrow line signal

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



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

Broader energy distribution

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

M. Di Mauro (Wed)

Particle dark matter emission

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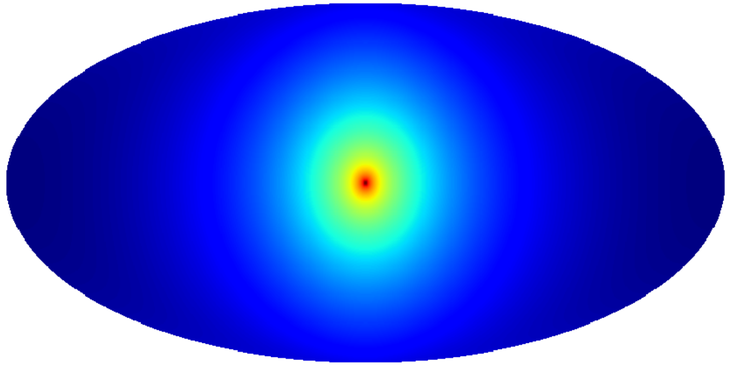
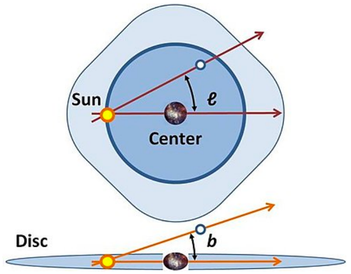


Self-conjugated dark matter annihilation
Differential **gamma-ray** flux

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

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

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



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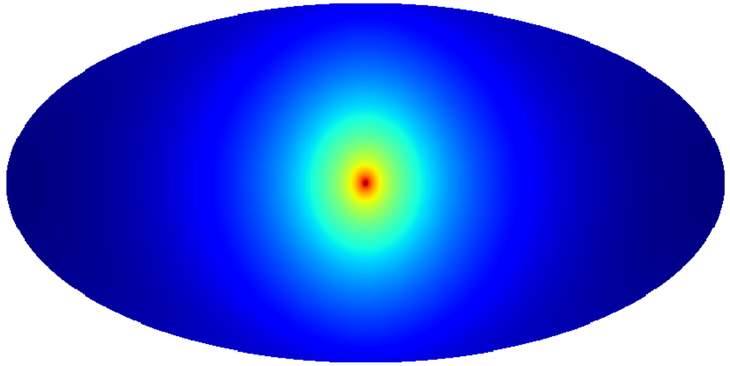

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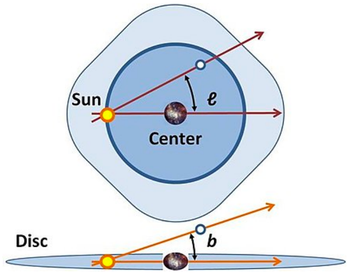
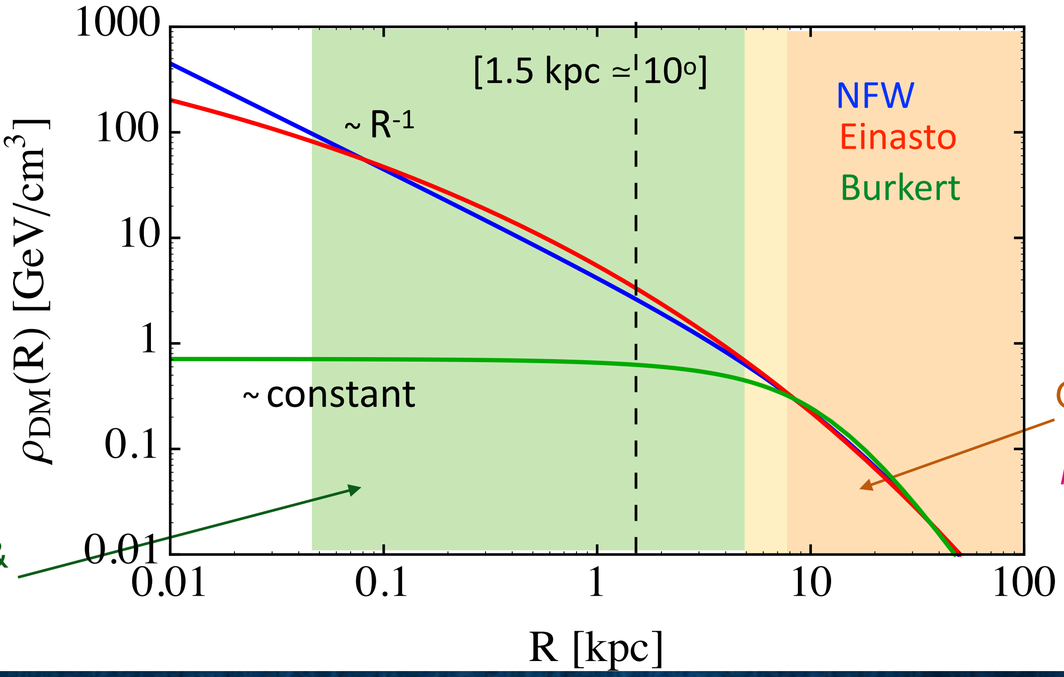


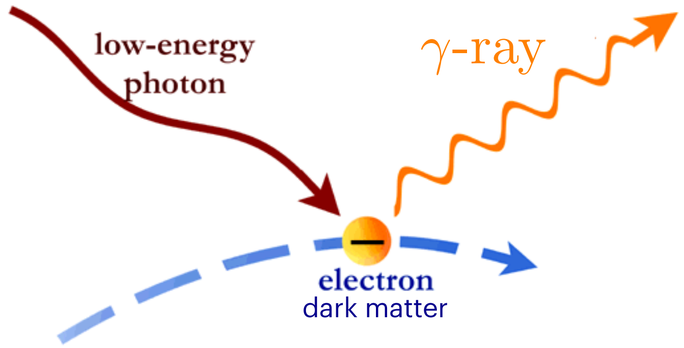


Simulations w/ baryons & semi-analytical models

Galactic rotation curve
Iocco+ Nature Phys.'15

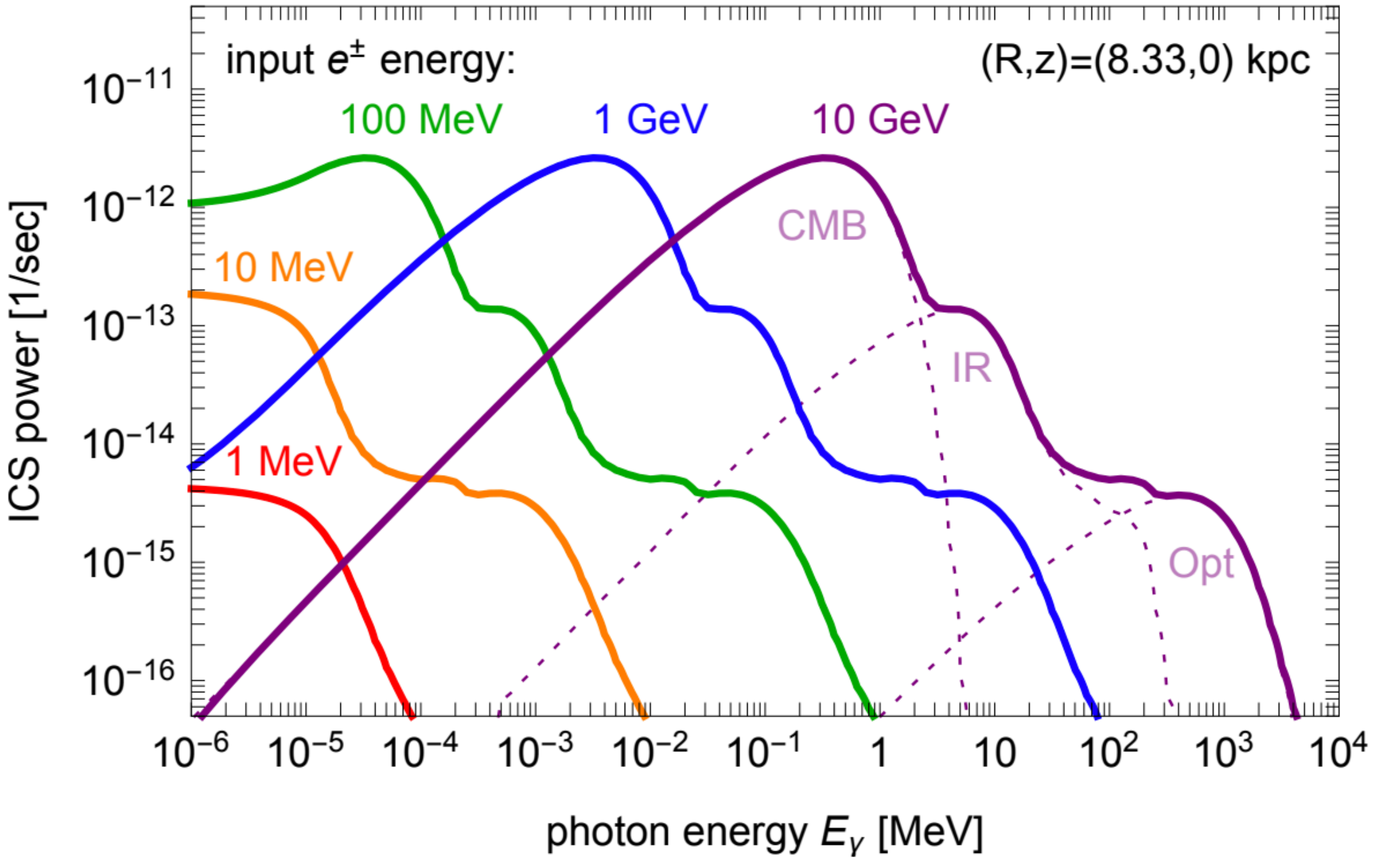
Particle dark matter emission

Inverse Compton scattering



$$\epsilon_f \simeq \gamma^2 \epsilon_i = 30 \left(\frac{\epsilon_i}{\mathrm{eV}}\right) \left(\frac{E_e}{\mathrm{GeV}}\right)^2 \mathrm{MeV}$$

Cirelli+ PRD' 21



Secondary emission processes allow us to probe DM at much higher masses than prompt energy scales

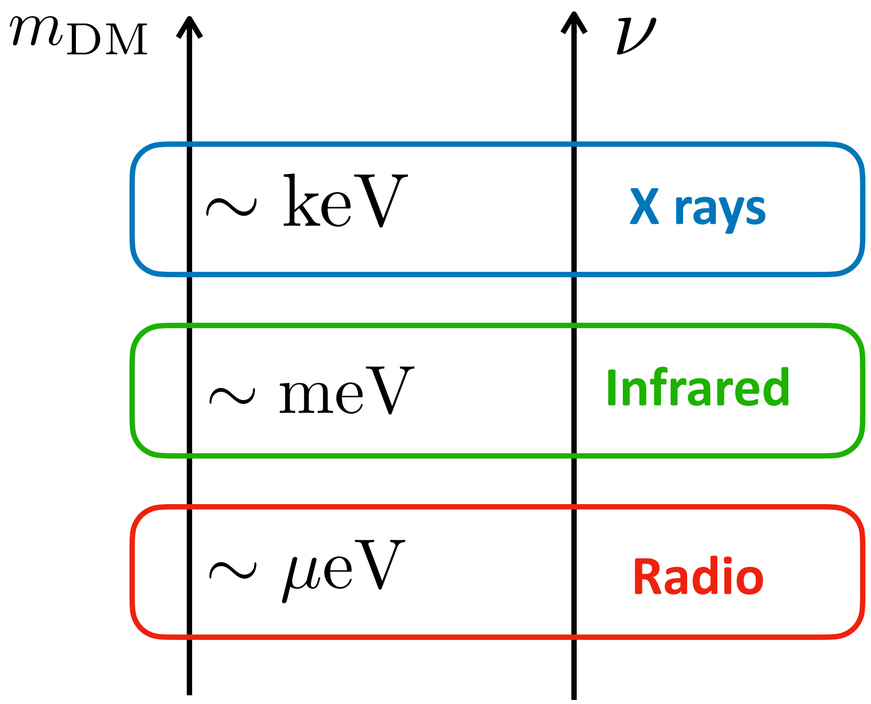
Light dark matter decay: lines

$$m_{\rm DM} \lesssim {\rm MeV}$$

Only allowed final state is into photons emitted back-to-back

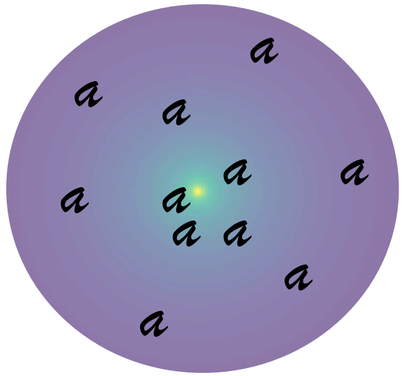
$$E_\gamma = \frac{m_{\rm DM}}{2}$$

Narrow line signal @ energy scale of the DM mass



[Contribution from all galaxies in the universe: redshifted line and integral over star-formation history => contribution to **extragalactic backgrounds**]

ALPs dark matter decay

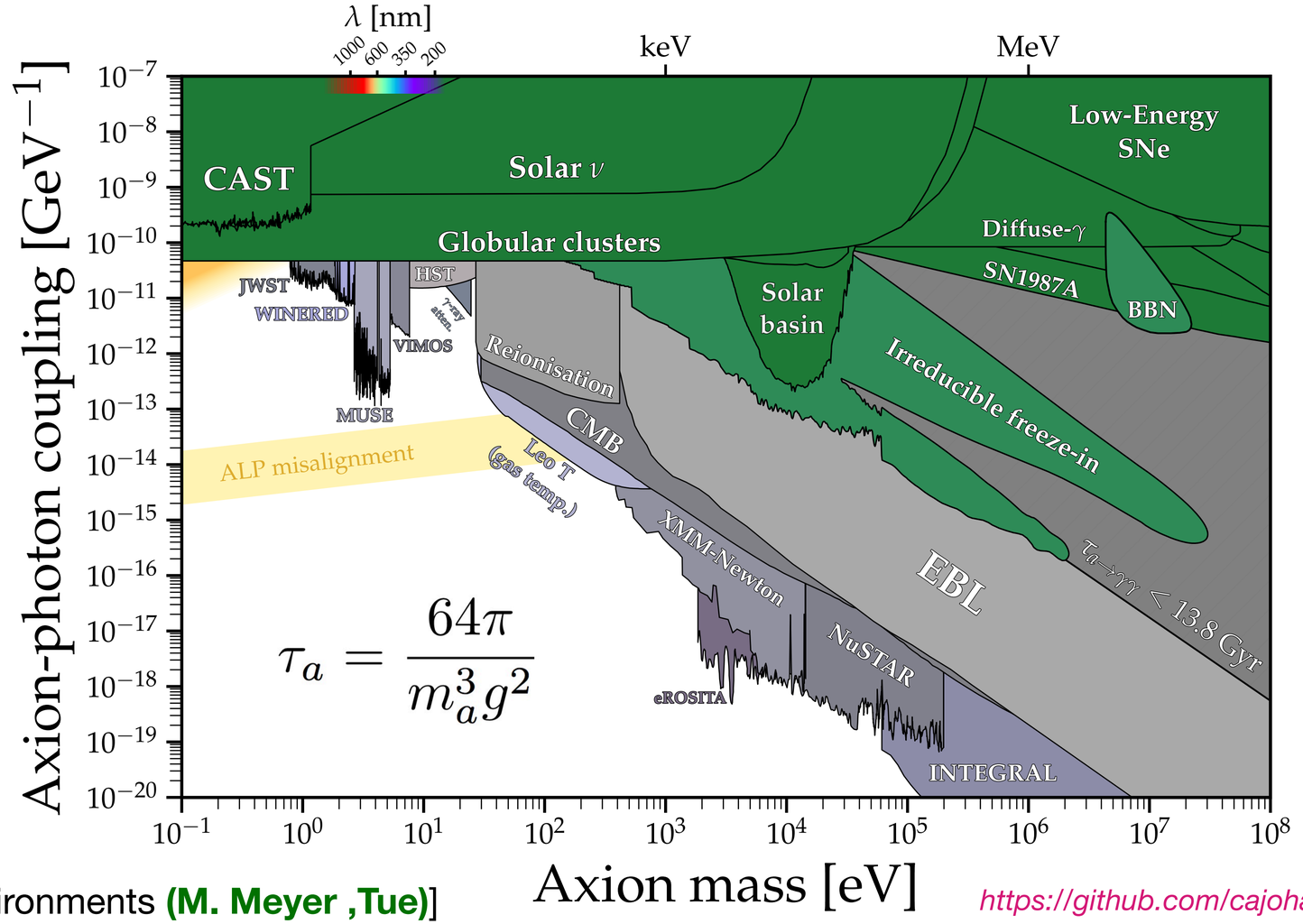


- If DM, ALPs distributed in galaxies according standard DM density distributions (e.g. NFW)
- Search for narrow lines in DM-rich environments

M. Taoso (Wed)

- ALPs can be viable DM candidates in some portions of the parameter space

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



[Lighter ALPs can be probed in HE astro environments **(M. Meyer ,Tue)**]

https://github.com/cajohare/AxionLimits

(…) ALPs dark matter resonant conversion

Monochromatic radio emission (MHz - GHz) from **DM axion/ALP-photon conversion**:

- *Resonant* conversion from highly magnetised neutron stars (NSs), or white dwarf stars

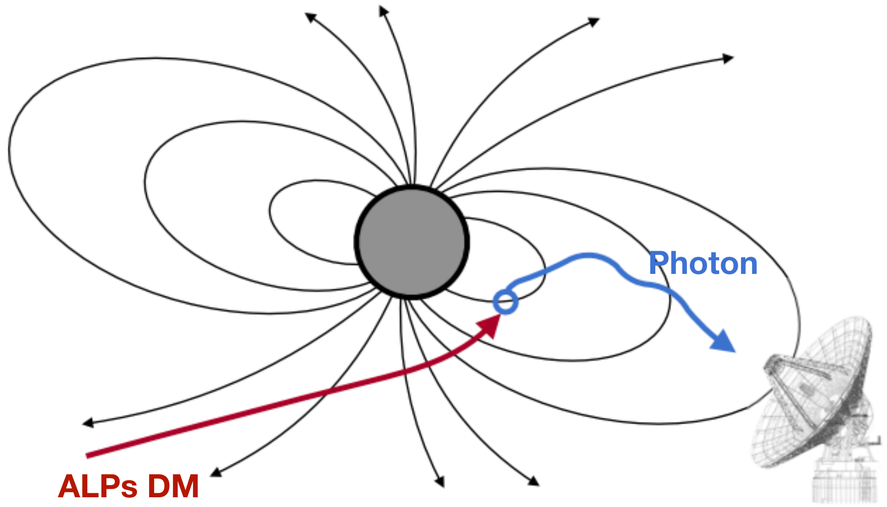
  Pshirkov JETP'09; Huang+2018; Hook+PRL'18

- *Non-resonant* transitions in the Galactic center and/or of discrete astrophysical objects

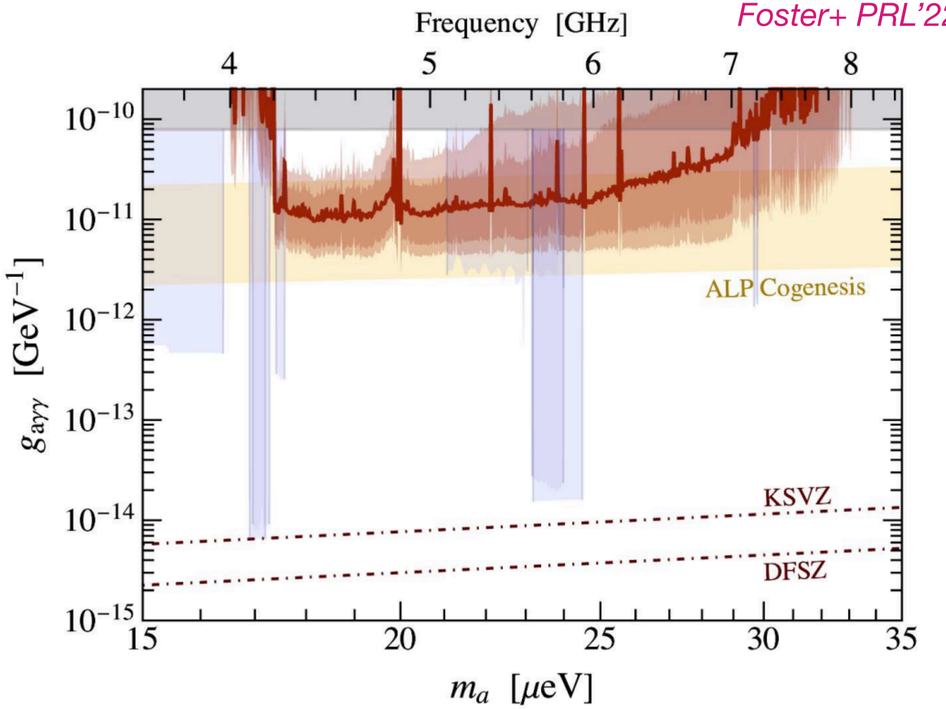
  Kelley&Quinn ApJ'17; Sigl PRD'17

- Still large **limitations** in **model predictions**

  Leroy+ PRD'20; Witte+ PRD'21; Battye+ JHEP'21; Millar+JCAP'21

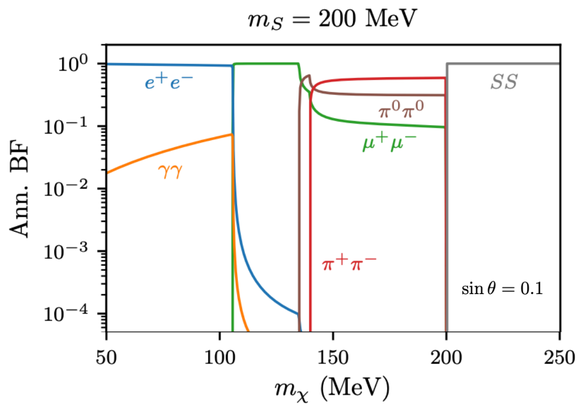


Foster+ PRL'22



L. Visinelli (Wed)

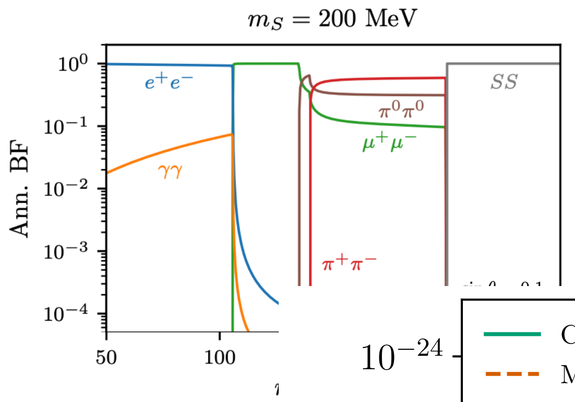
Sub-GeV dark matter limits



Coogan+ JCAP'20

- Simple thermal freeze-out scenario for s-wave annihilation generically ruled out
- But p-wave models (many of the portals) still viable

Sub-GeV dark matter limits



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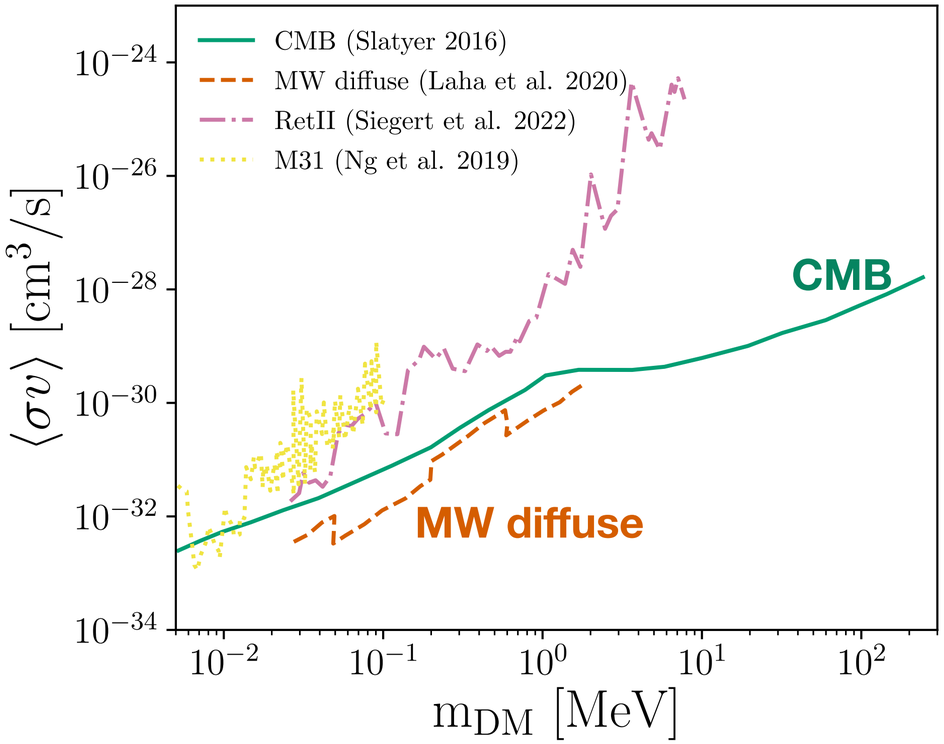
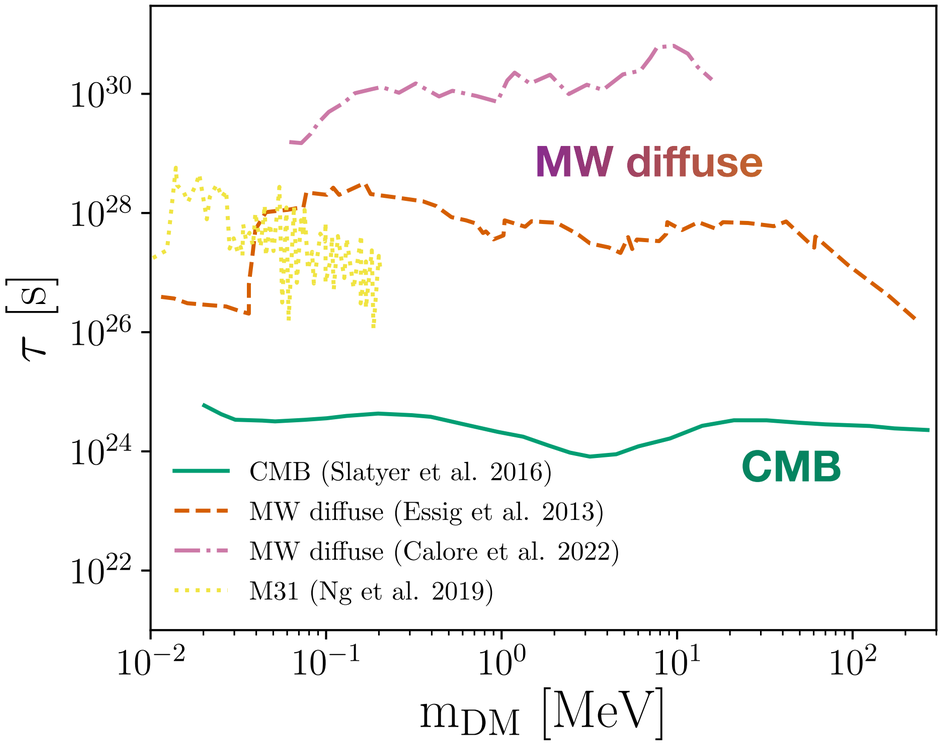
FC FIPs2022 Proceedings



Two-photons annihilation

Siegert, FC+ MNRAS'24



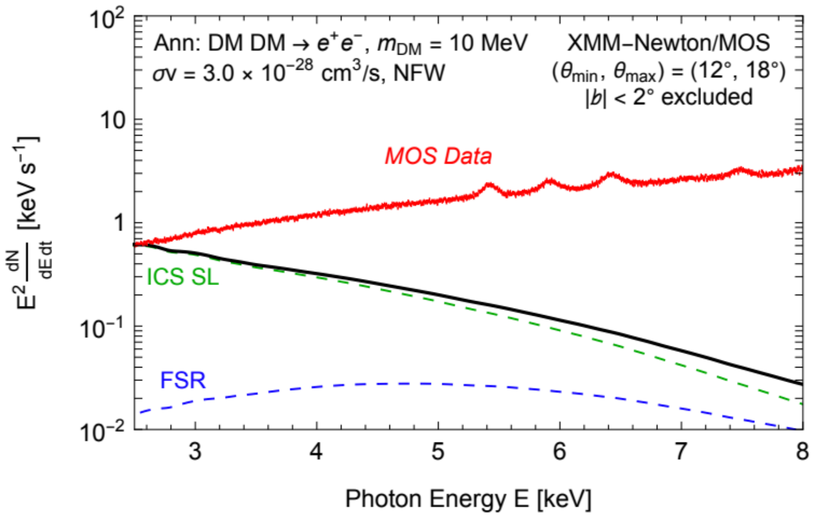
Two-photons decay

FC+ MNRAS'23

https://zenodo.org/record/7984451

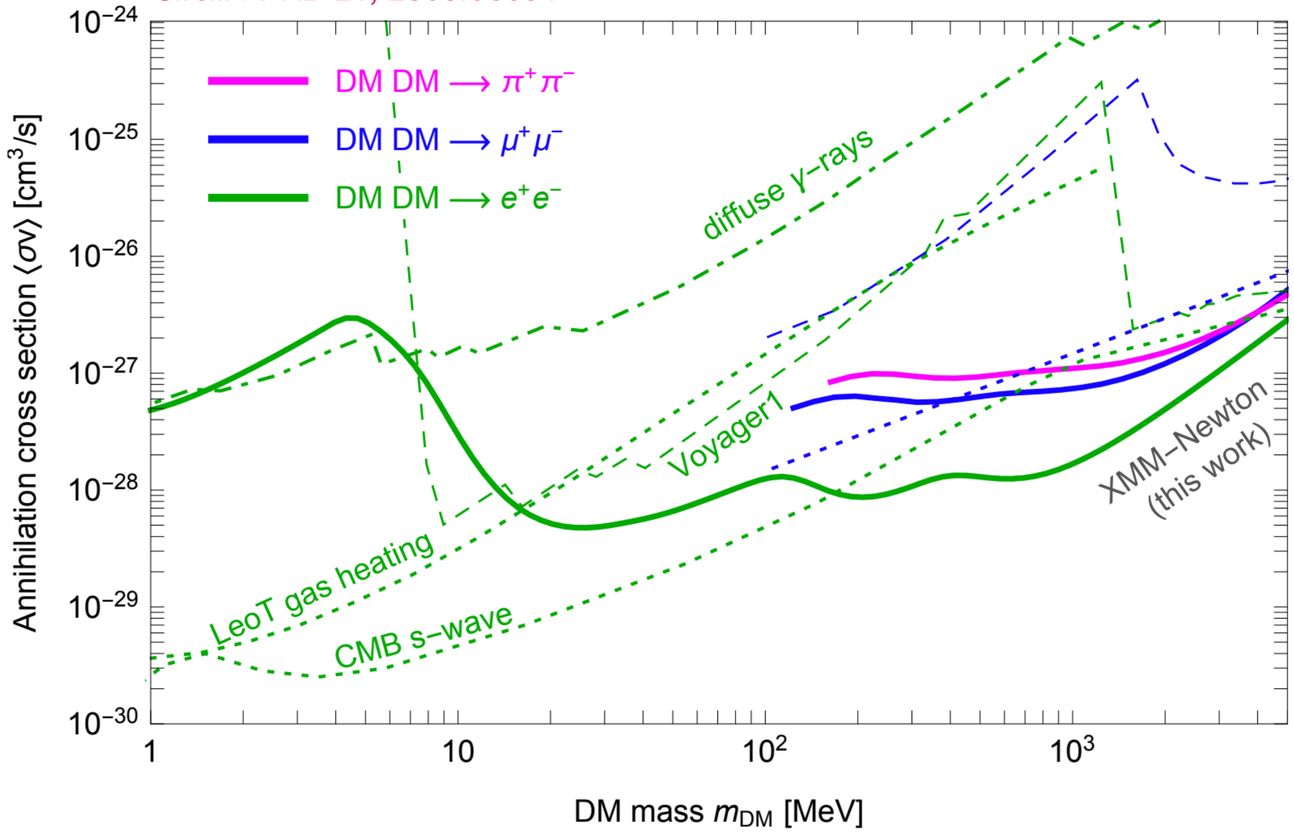
Sub-GeV dark matter limits

The power of inverse Compton emission



Limits on inverse Compton induced gamma-ray emission from **XMM-Newton blank-sky observations**

Cirelli+ PRD'21; 2303.08854



[Strong constraints also from 511 keV line: *De La Torre Luque+ 2312.04907, 2307.13728*]

S. Balaj (Thu)

(…) Strong constraints on PBHs

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

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

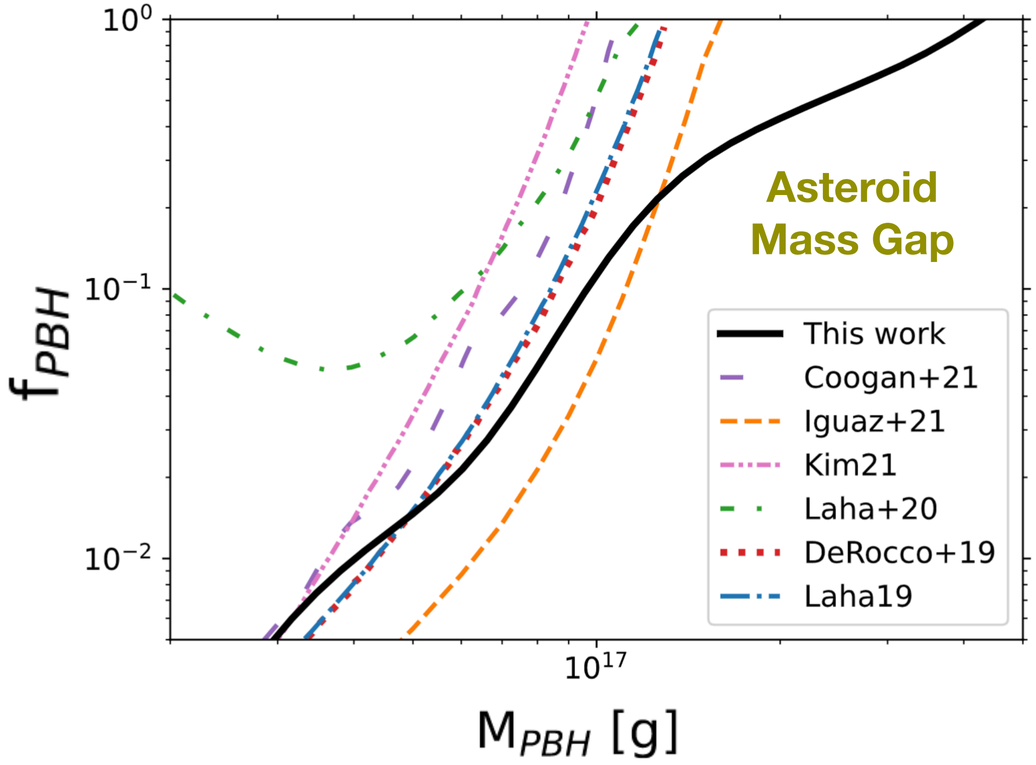
Page & Hawking ApJ'76; Carr & MacGibbon Phys. Rep.'98

- 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

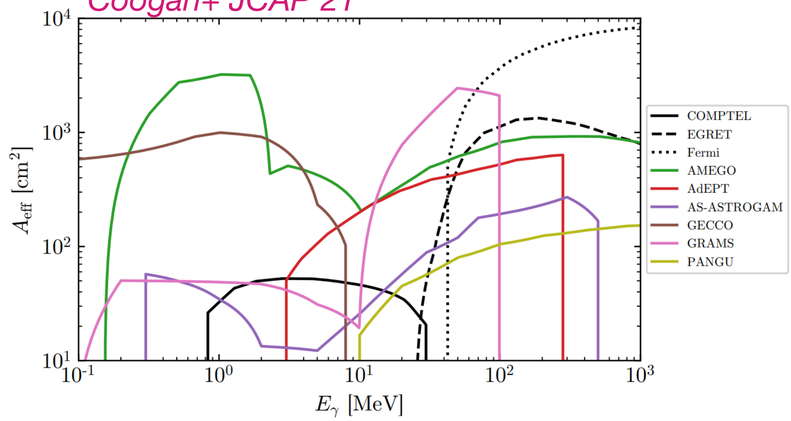
Berteaud, FC+ PRD'22

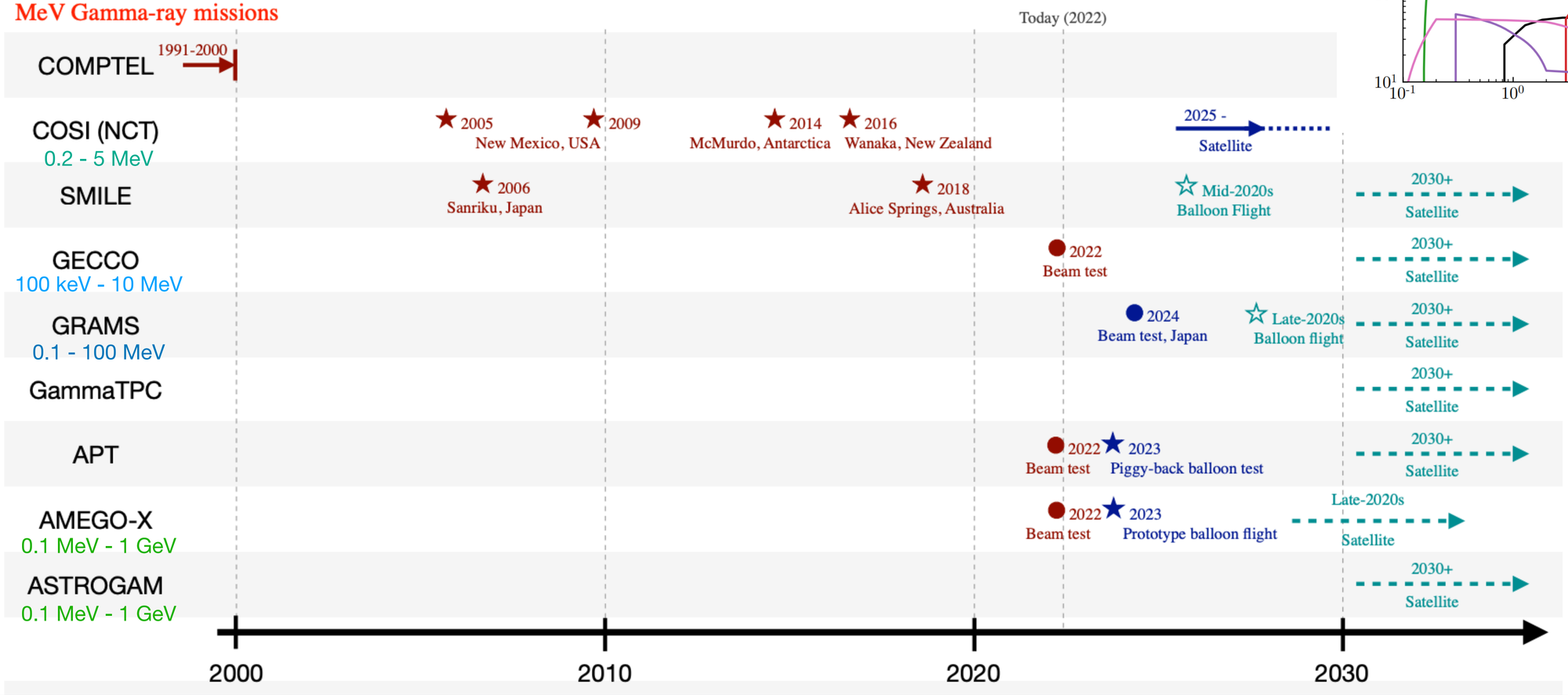


[Strong constraints also from 511 keV line: *De La Torre Luque+ 2406.11949*]

Future: Covering the MeV sensitivity gap

Coogan+ JCAP'21





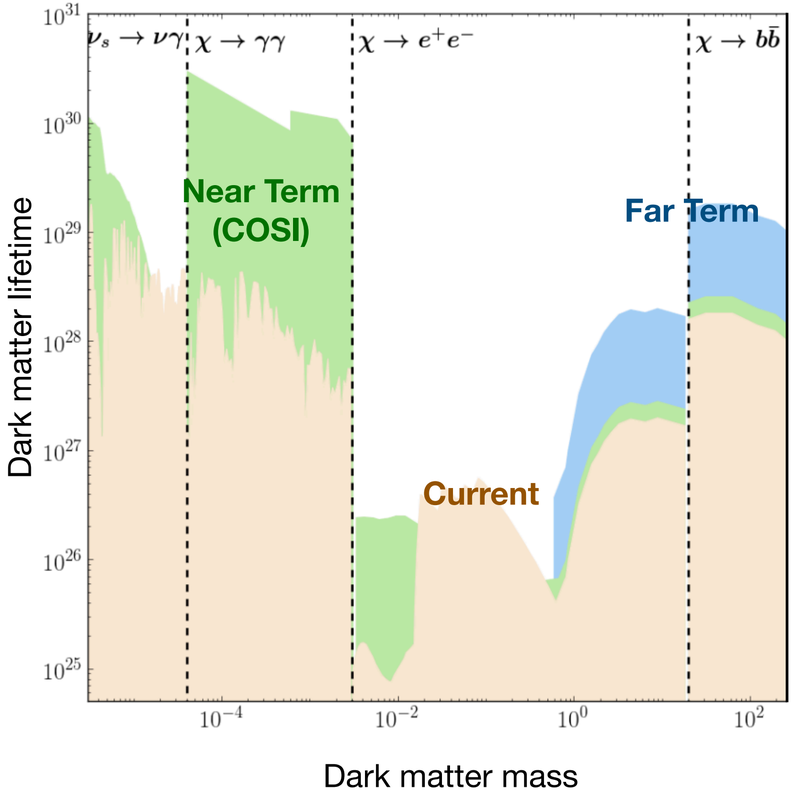
$$N_\gamma = T_{\rm obs} \int_{E_{\rm min}}^{E_{\rm max}} {\rm d}E \, A_{\rm eff} \, \frac{{\rm d}\Phi}{{\rm d}E_\gamma}$$

Aramaki+ Snowmass'21 CF

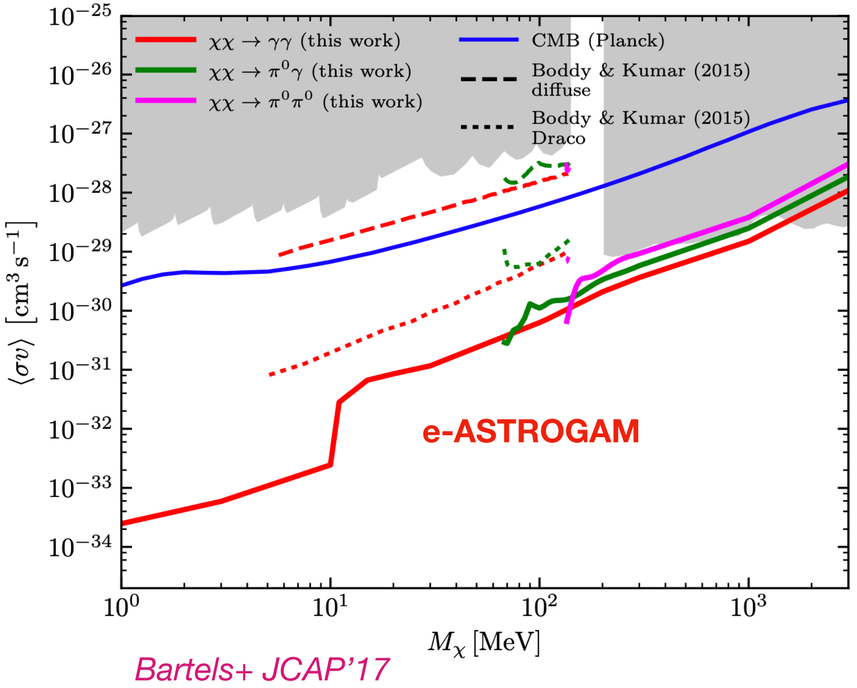
Future: Covering the MeV sensitivity gap

Sensitivity to dark matter

Cooley+ Snowmass'21 CF1 Report

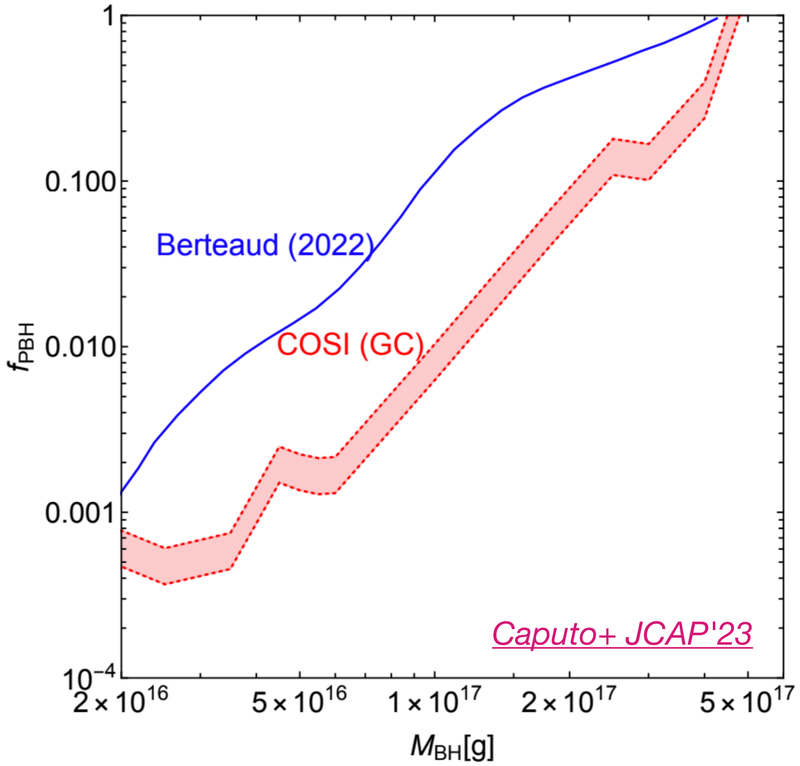


Decay



Bartels+ JCAP'17

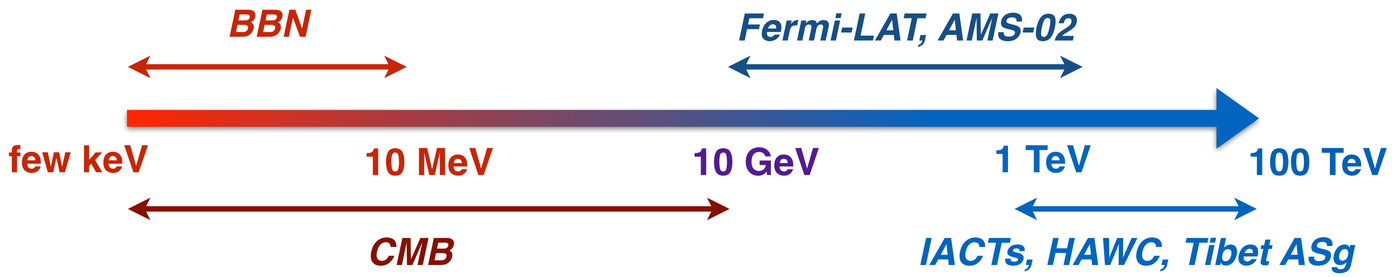
Annihilation

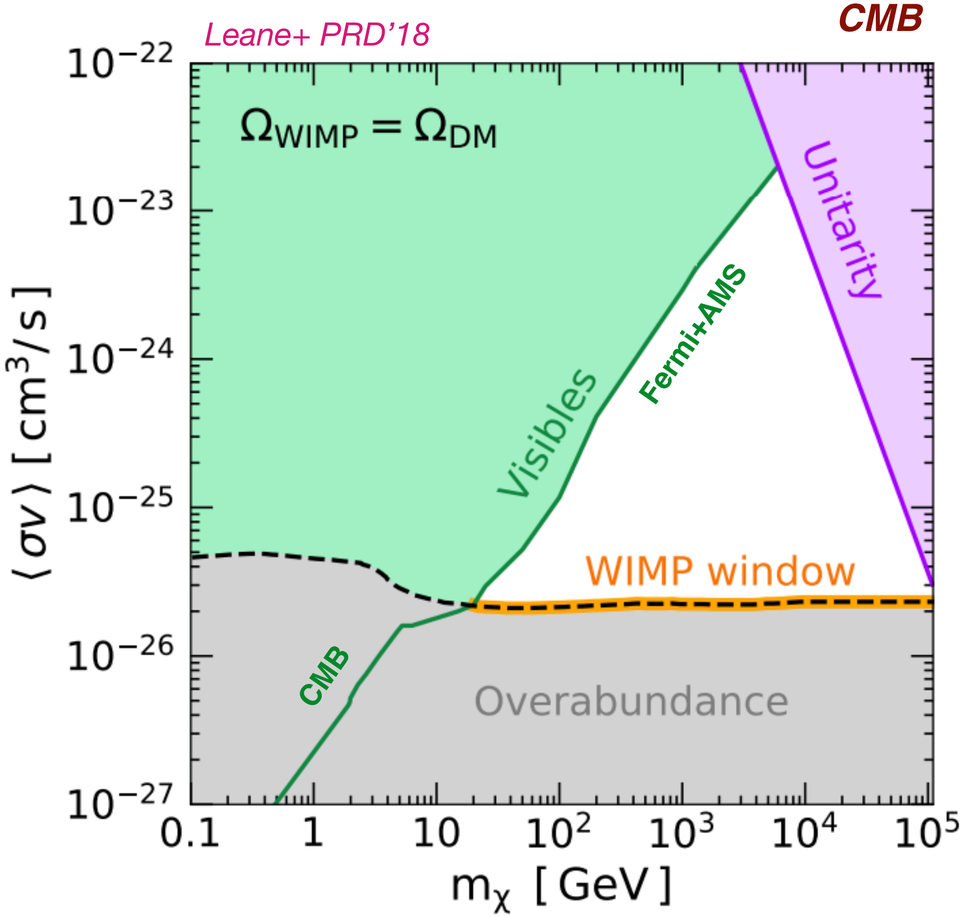


Caputo+ JCAP'23

PBH evaporation

WIMP annihilation window



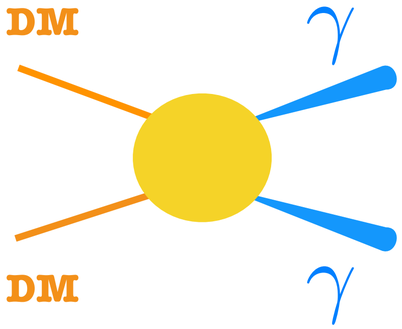


- **Total cross-section** sets **relic abundance**
- **Indirect detection** provides model-independent UL on annihilation **cross-section for a given final state**

→ 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*]

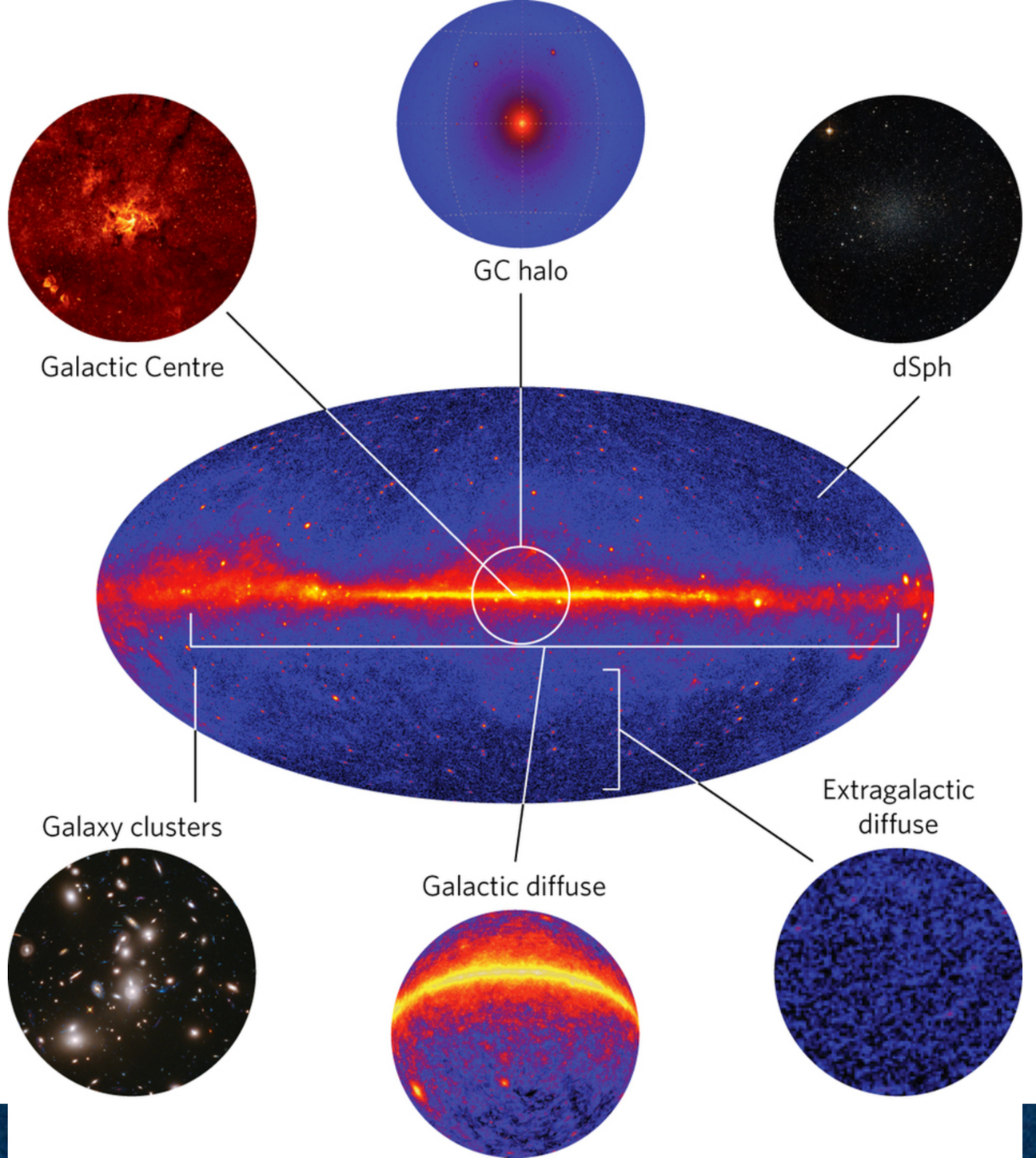
Targets for WIMP gamma-ray searches



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

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

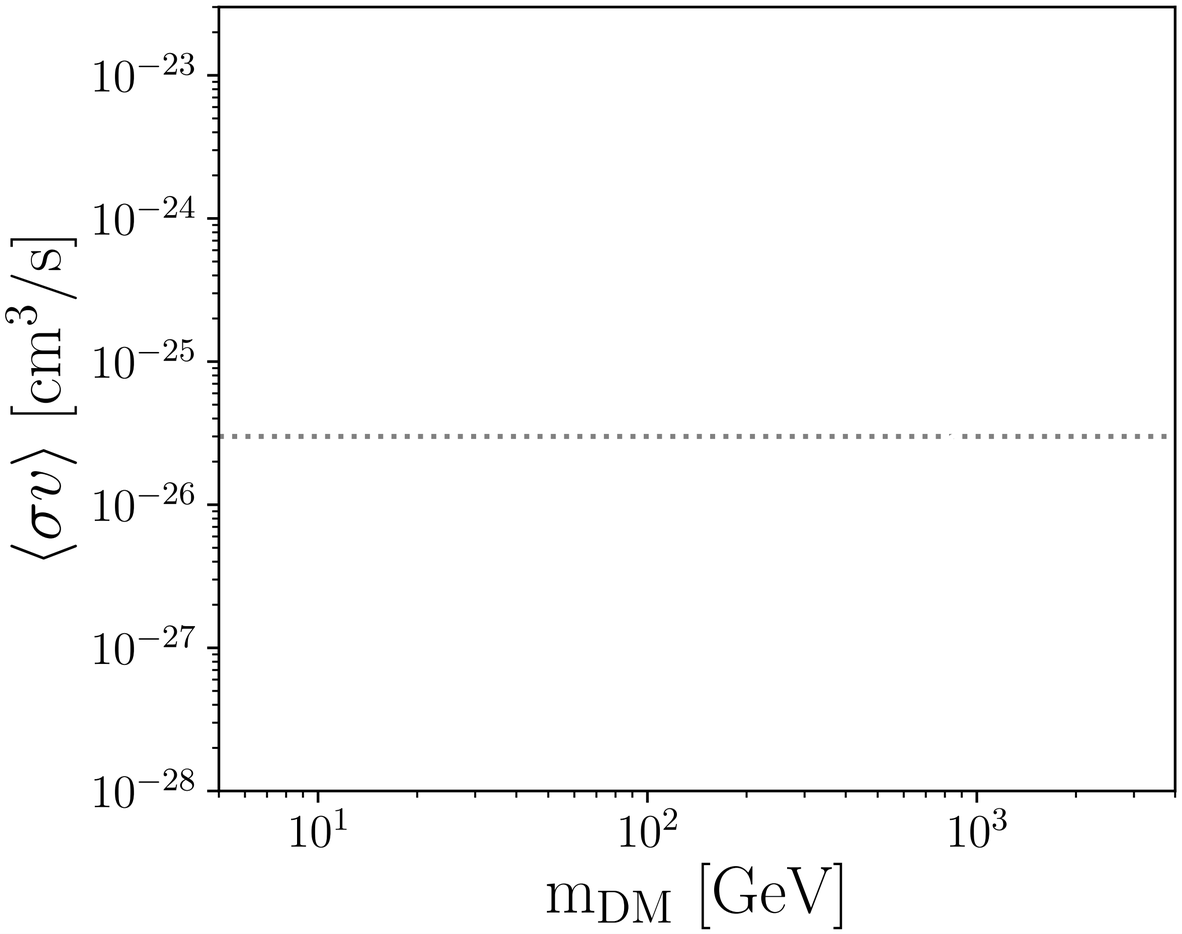
Conrad & Reimer Nature Phys. 13 (2017)



Limits on annihilating WIMPs

Summary of multi-targets and MW constraints

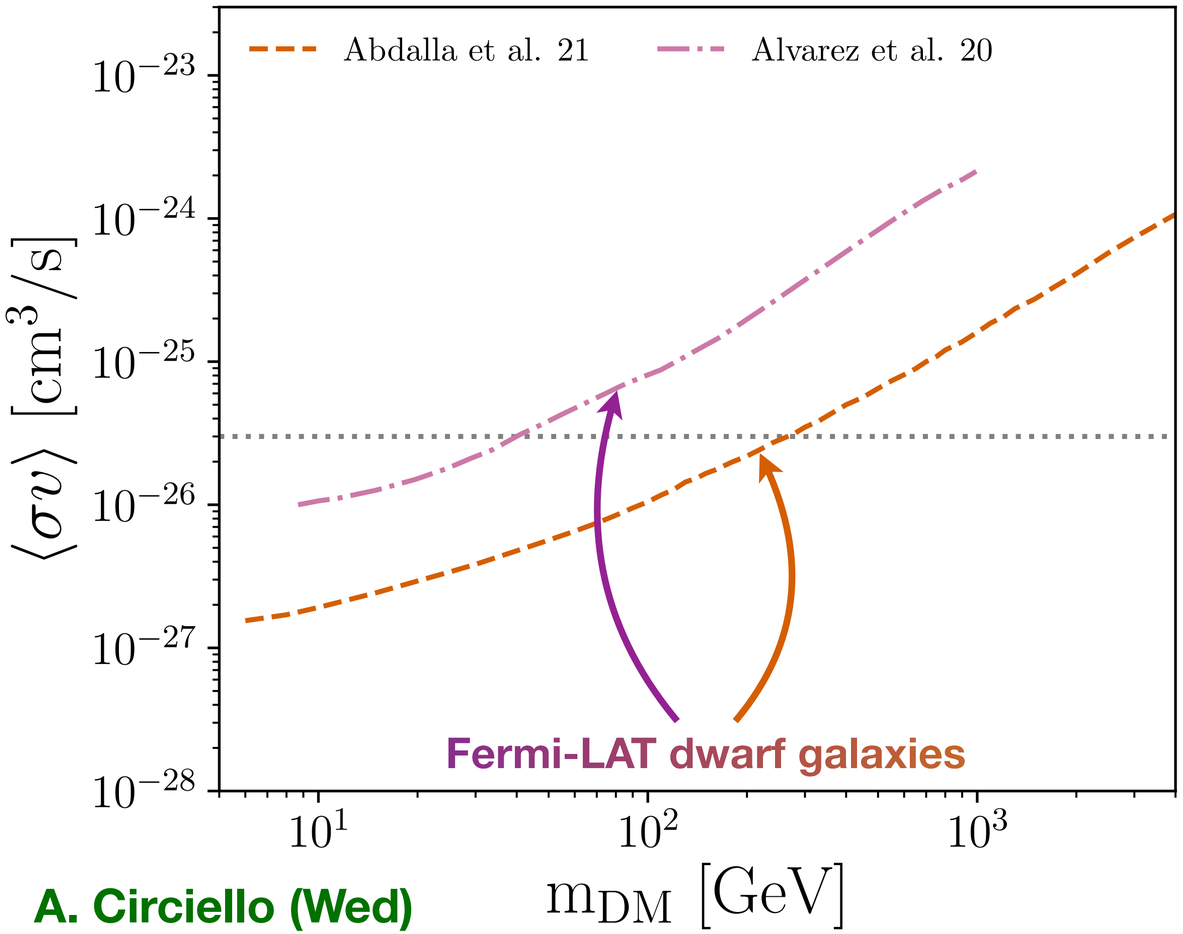
~ a few GeV — few TeV



Limits on annihilating WIMPs

Gamma rays: Dwarf spheroidal galaxies

~ a few GeV — few TeV



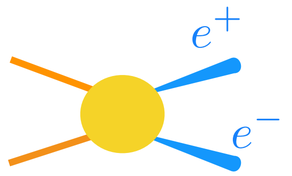
A. Circiello (Wed)

- Exclude thermal cross section below 30 - 300 GeV; multi-instrument
  Kerzberg+, PoS ICRC2023 (2023)
- **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

Synchrotron emission in the Large Magellanic Cloud



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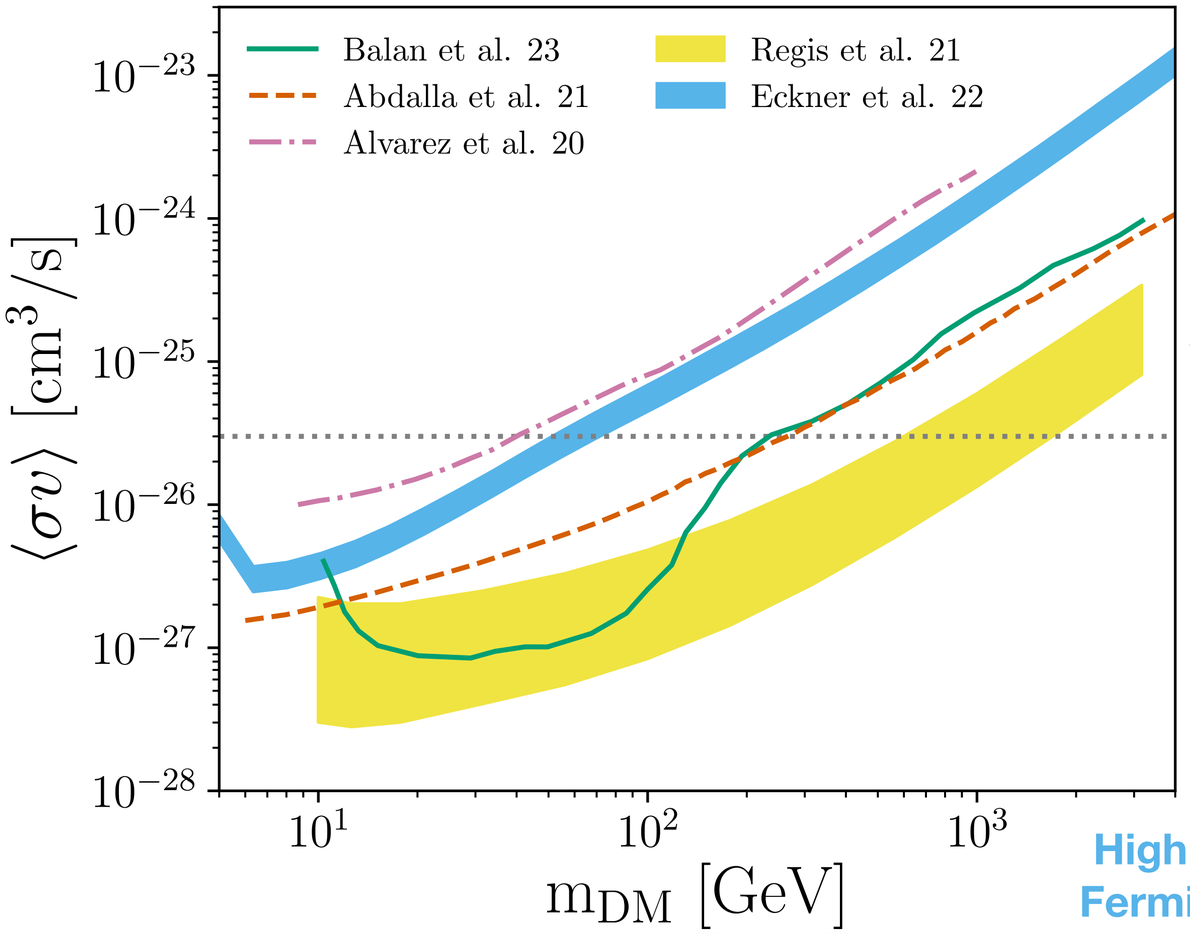
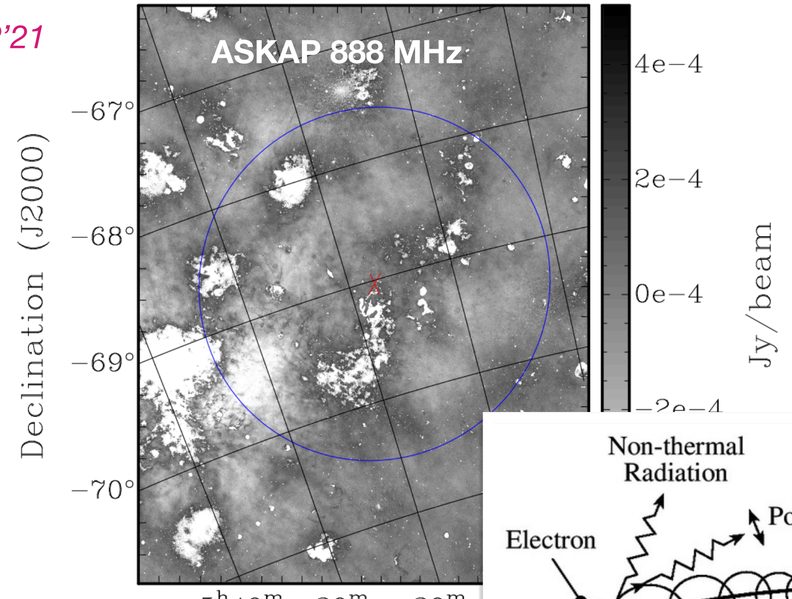


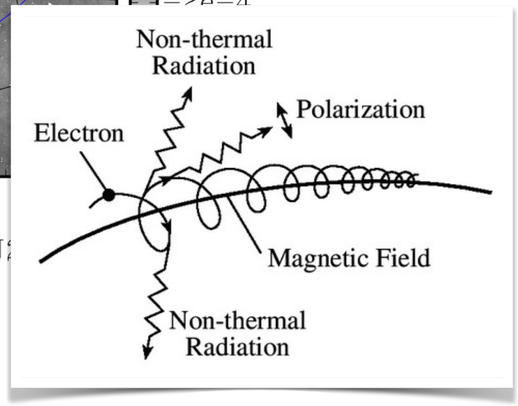
High-latitude Fermi-LAT sky

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

Radio LMC

Regis+ JCAP'21





Anti-protons

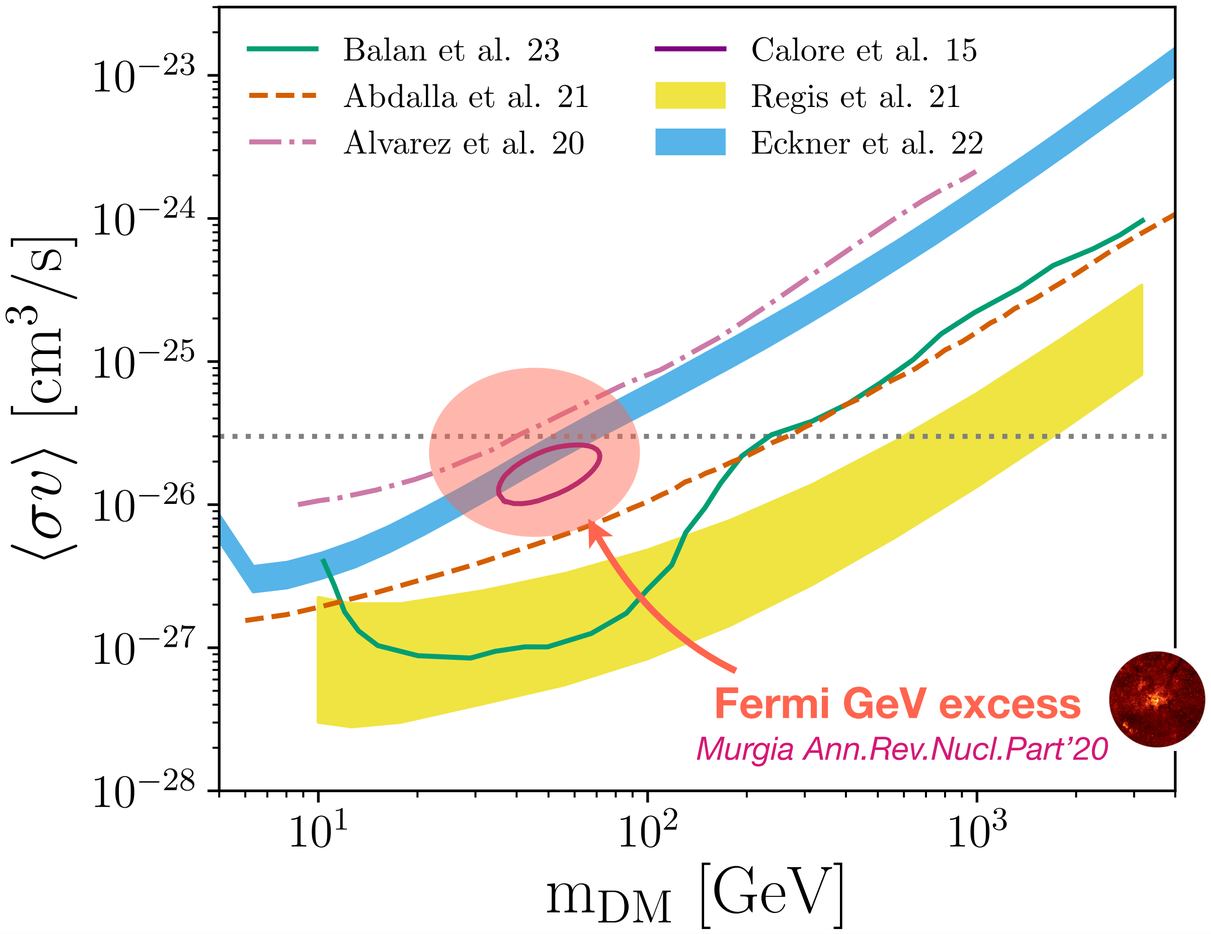
Balan+ arXiv:2303.07362
Di Mauro+ PRD'21,
FC+ SciPost'22

Limits on annihilating WIMPs

Summary of multi-targets and MW constraints

D. Hooper (Wed)
J. Kumar (Thu)
C. Gordon (Thu)

~ a few GeV — few TeV



- **Evidence** for excess emission is **established**
- **Advanced statistical techniques** developed to scrutinise diffuse emission properties and photon-count statistics
- An, at least, **partial stellar origin** of the excess seems confirmed

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

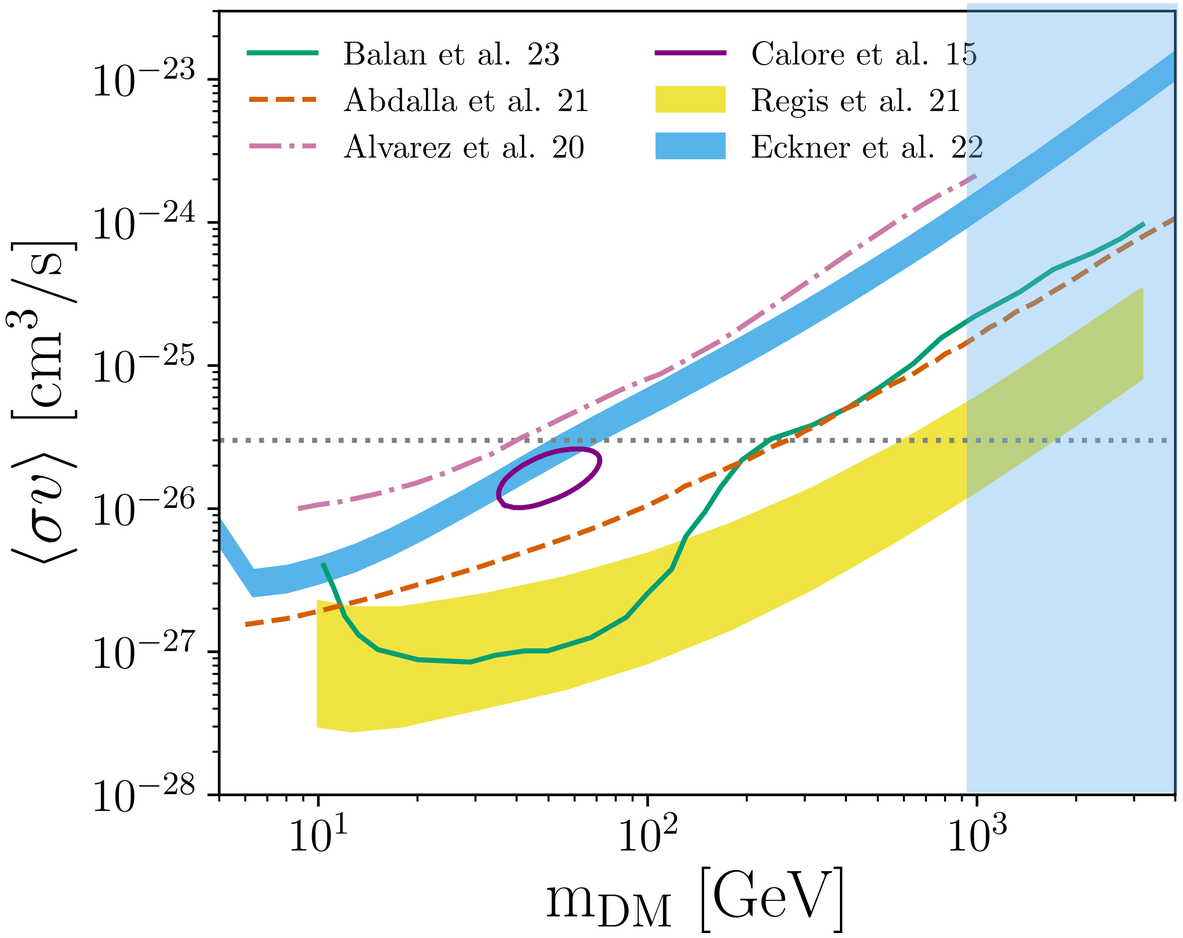
- Complementary and **multi-wavelength searches** to test the excess nature are on-going

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

Limits on annihilating WIMPs

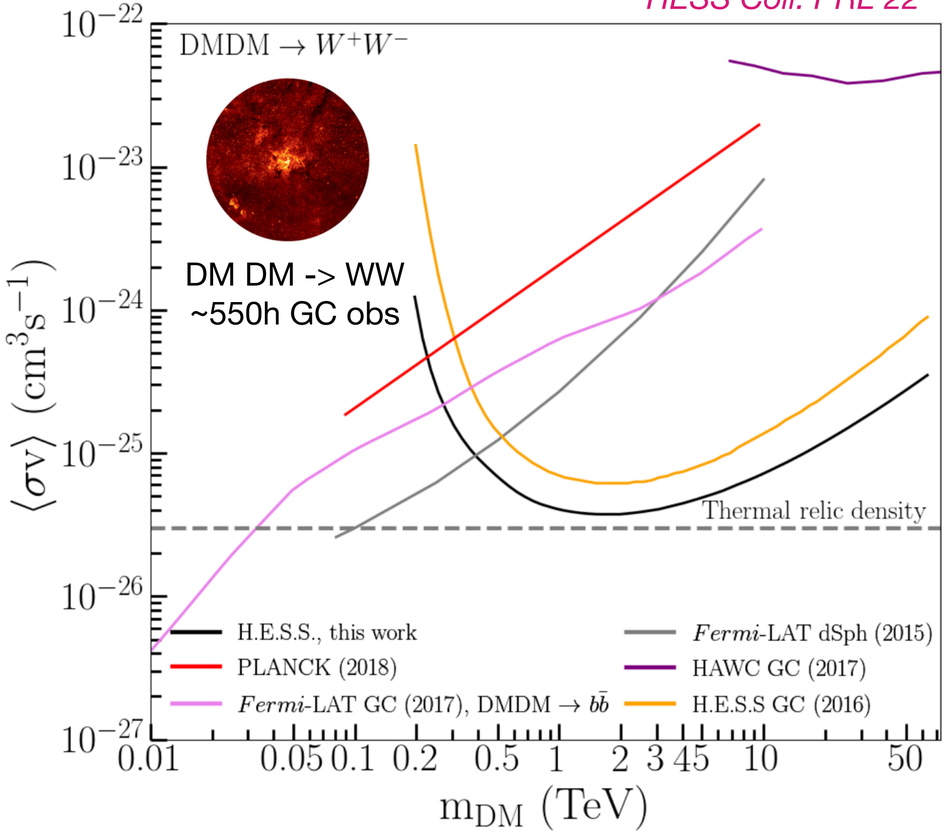
Summary of multi-targets and MW constraints

~ a few GeV — few TeV



0.2 TeV — 50 TeV

HESS Coll. PRL'22

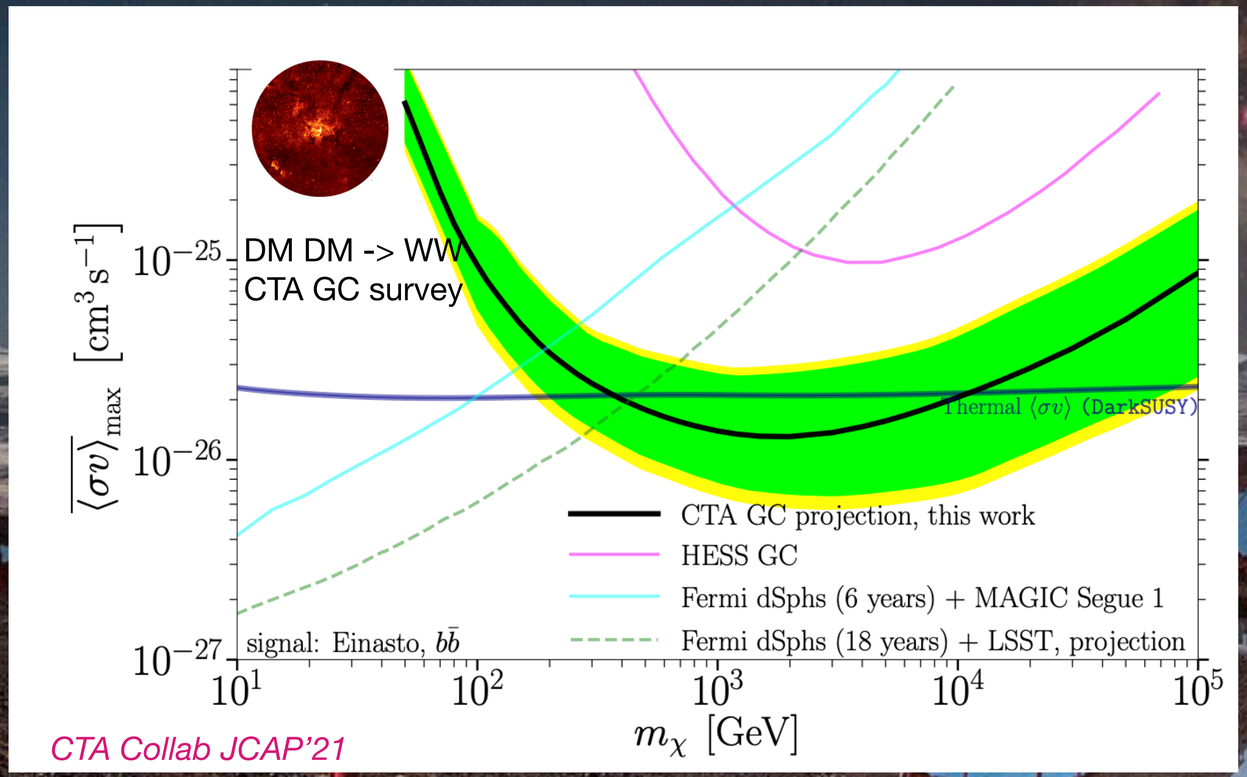


See also: *Rodd+ 2405.13104*

Future: The Cherenkov Telescope Array

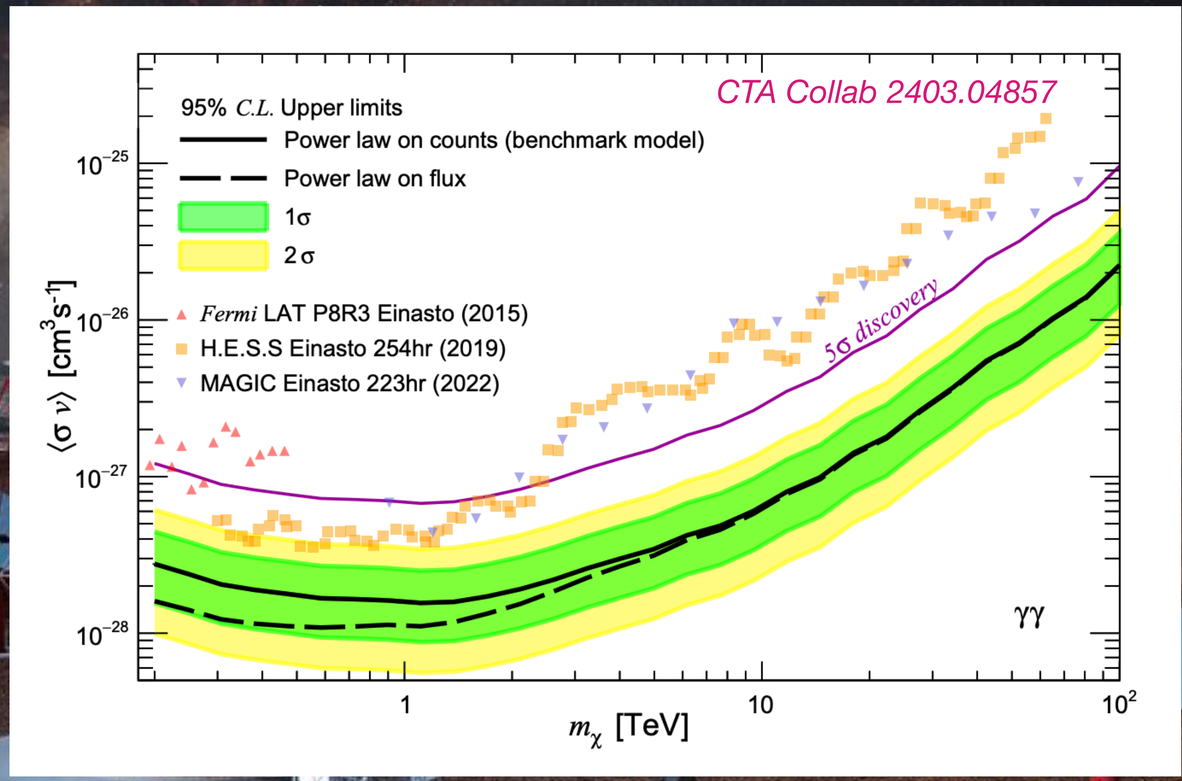
C. Eckner (Thu)
J. Perez-Romero (Thu)

Gamma-ray continuum



CTA Collab JCAP'21

Gamma-ray lines

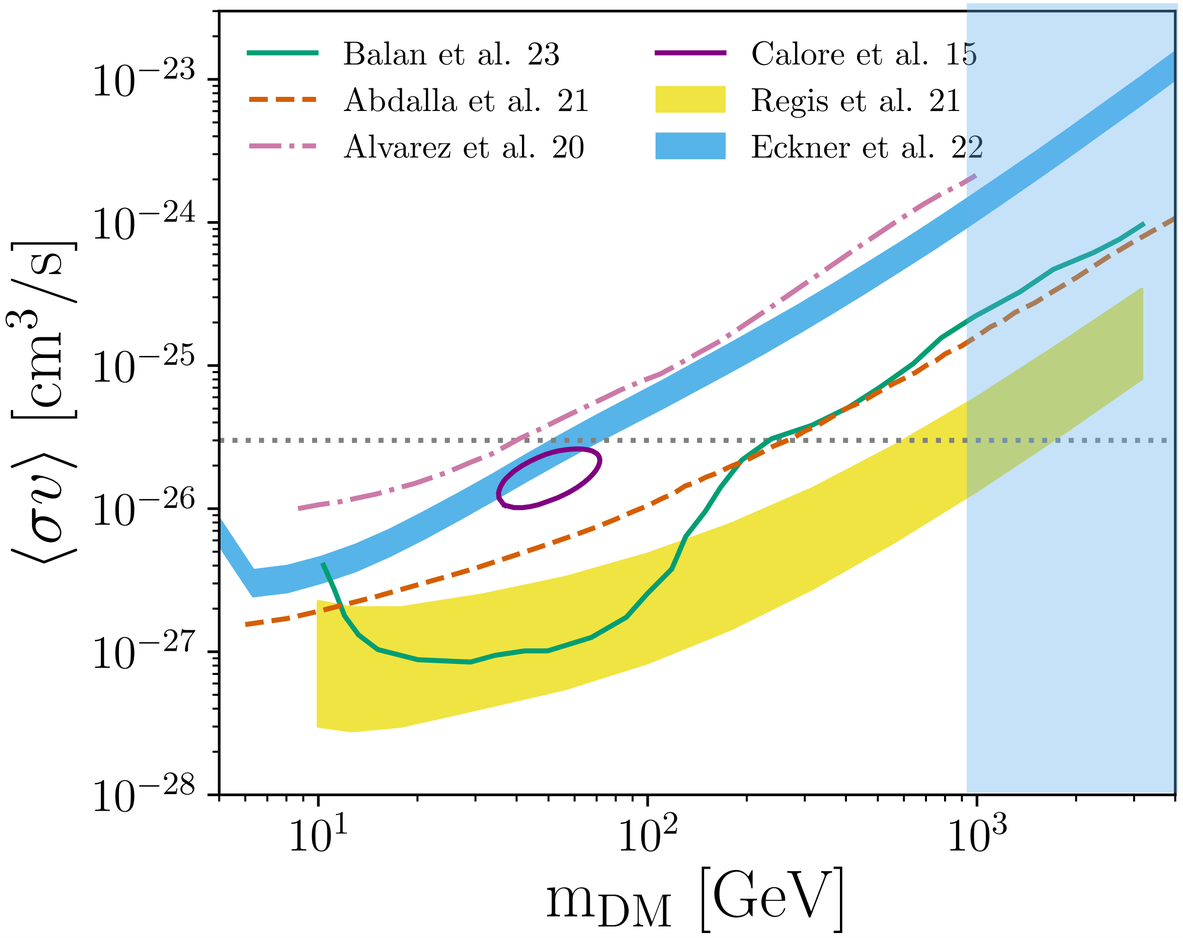


Wino and Hggsino dark matter in the reach of CTA

Rodd+ 2405.13104; Montanari+ PRD'22; Rinchiuso+ PRD'21

Dark matter at PeV energies

~ a few GeV — few TeV



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*

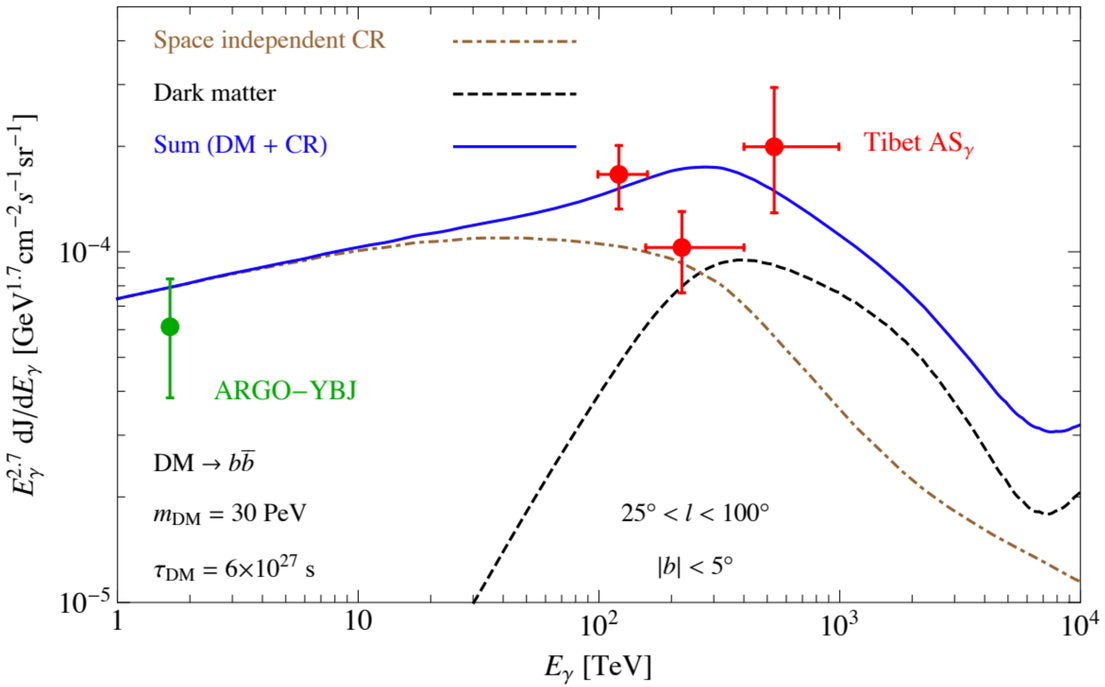
→ These data often provide *best bounds* to heavy DM lifetime

Esmaili & Serpico, PRD'21; *Chianese+ arXiv:2108.01678*

Dark matter at PeV energies

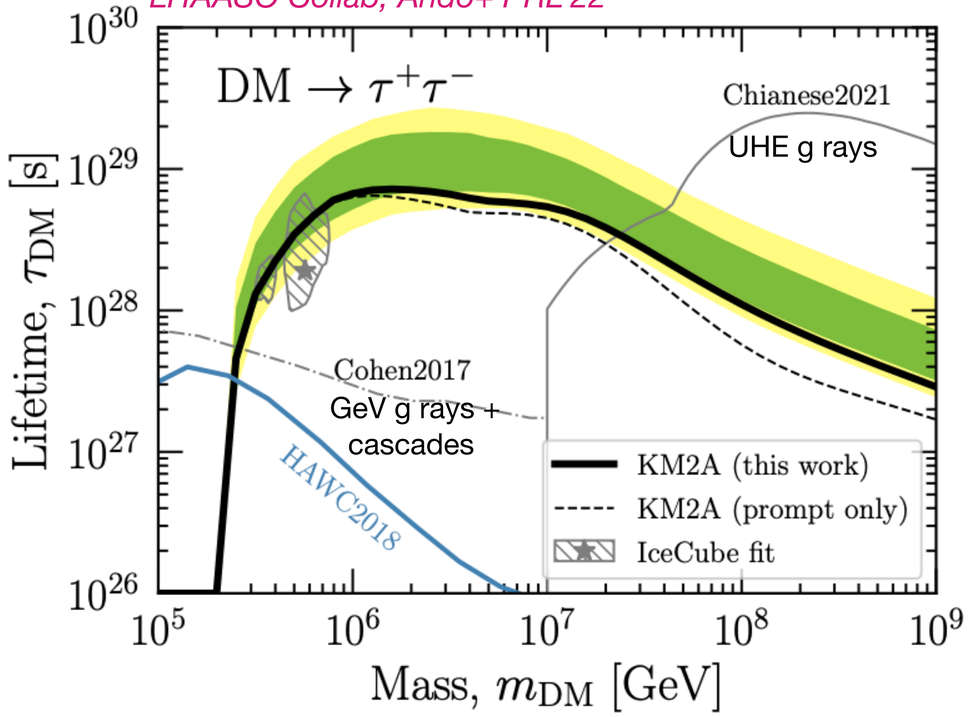
R. Aloisio (Thu)
A. Dubey (Thu)

Esmaili & Serpico, PRD Letters'21; Tarak+ PRD'21



Important degeneracies broken by **angular distribution of arrival photon directions**

LHAASO Collab, Ando+ PRL'22



Dedicated LHAASO DM **search** at slightly higher latitudes ⟶ Strongest constraints on PeV DM

Challenges: 1. Production and propagation of UHE gamma rays; 2. DM spectra at production for $E_{CM} >> E_{LHC}$

Bauer+ JHEP'21

Take away: Strong potential from VHE gamma rays

Conclusions and outlook

- ✓ Dark matter evidence requires new BSM physics, however the **landscape for particle and non-particle models is broad and diverse**
- ✓ **Indirect searches** for dark matter **successfully test different dark matter models** (WIMPs, ALPs, PBHs, etc), probing a large portion of their parameter space
- ✓ 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 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

Supplemental material

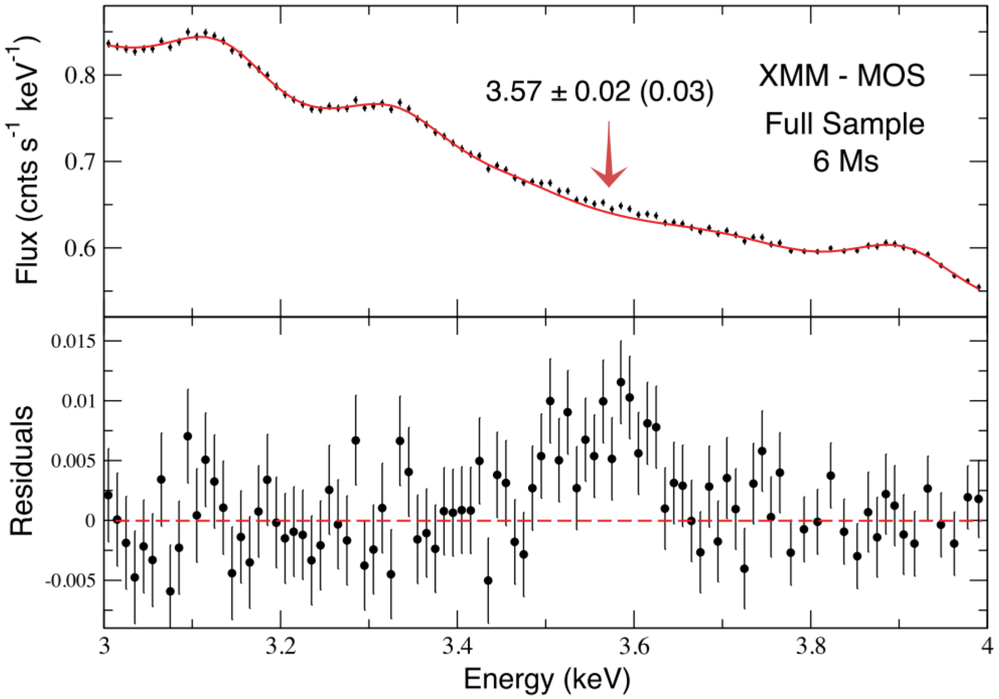
Review: *K. N. Abazajian, Phys. Rept. 711-712, 1 (2017)*

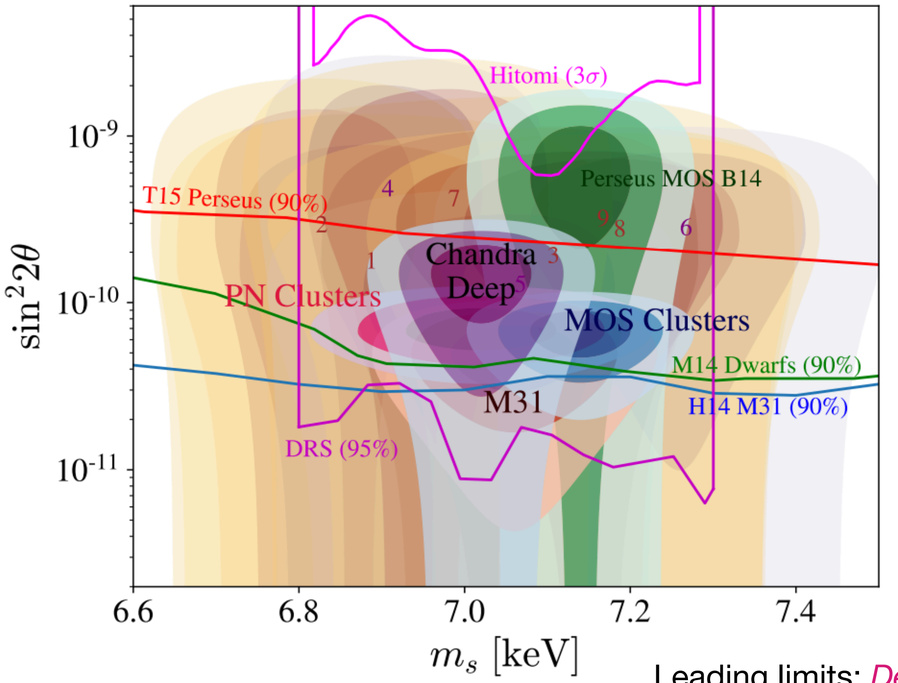
Sterile neutrinos X-ray lines

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 eV ALPs

IR - optical wavelengths

Search for **narrow lines** in IR and optical data

- **MUSE**: search in the direction of 5 known dwarf galaxies

Todarello+ JCAP'24

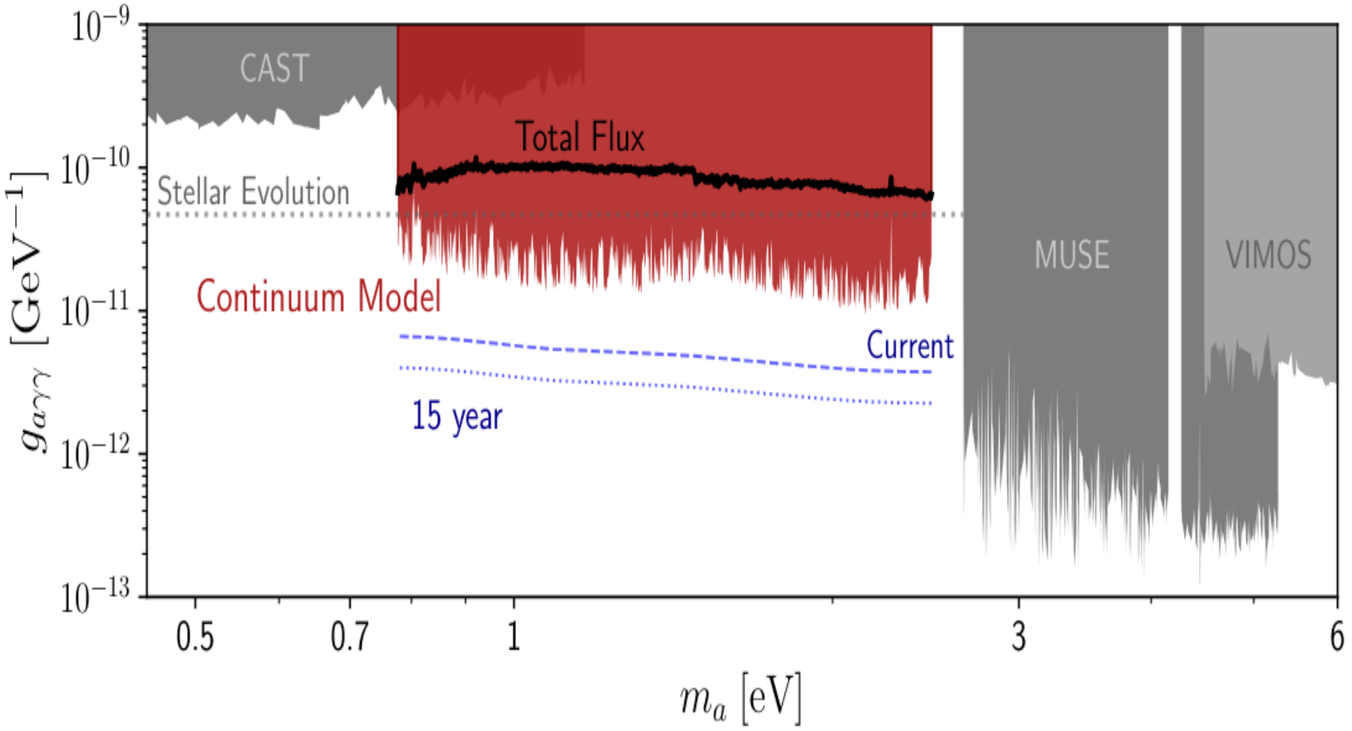
- **VIMOS (Visible Multi-Object Spectrograph)**: galaxy clusters Abell 2667 and 2390

Grin+ PRD'06

- **JWST**: public blank sky observations from the NIRSpec IFU

Janish & Pinetti 2310.15395

Janish & Pinetti 2310.15395



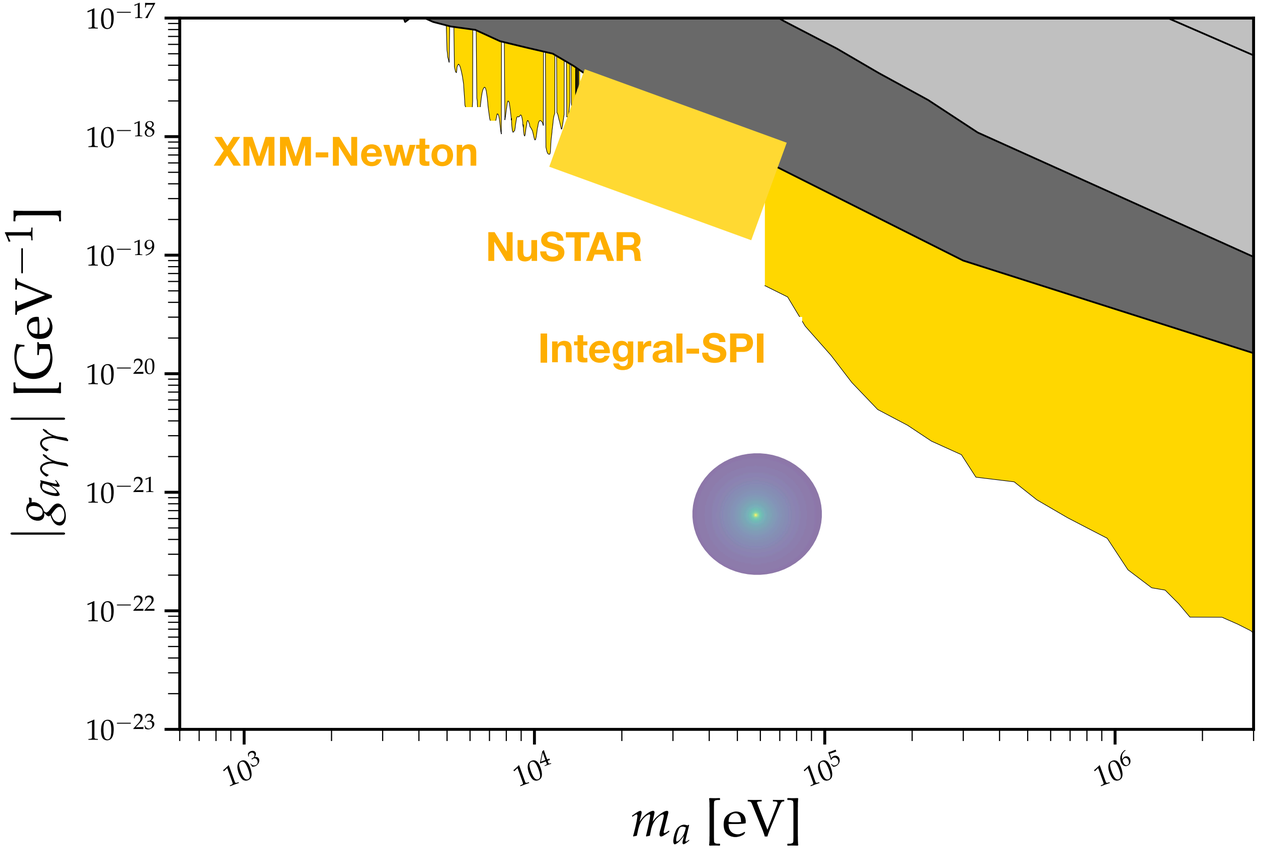
Constraints on keV - MeV ALPs

X-ray and soft gamma rays energies

Heavy ALPs DM decay

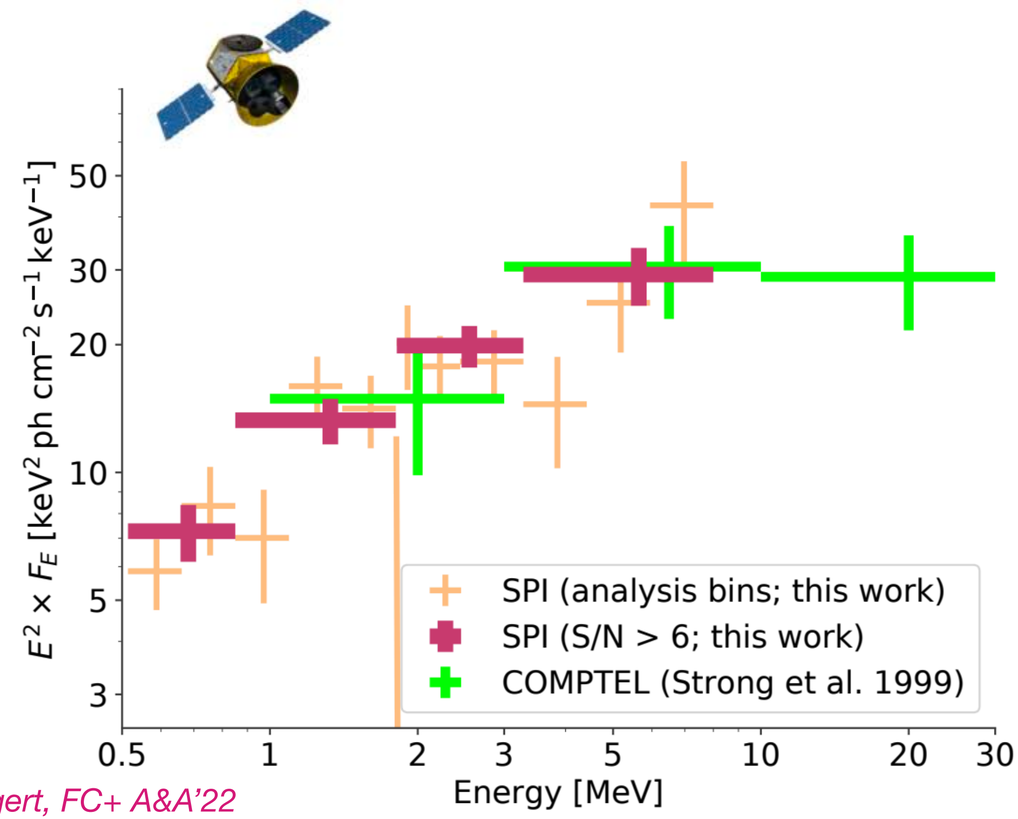
Search for **narrow lines** in X and gamma-ray data

- **XMM-Newton**: 5-16 keV, archival data => No evidence found for unassociated X-ray lines *Foster+ PRL'21*
- **NuSTAR**: 7-Ms/detector deep blank-sky exposures *Roach+ PRD'23*
- **Integral-SPI**: new analysis of 16yr data with dedicated search for DM component in continuum Galactic emission *Berteaud, FC+PRD'22; FC+ MNRAS'23*



https://github.com/cajohare/AxionLimits

Soft gamma rays with Integral/SPI



Siegert, FC+ A&A'22

New analysis of 16yr-data from SPI
30 keV — 8 MeV

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

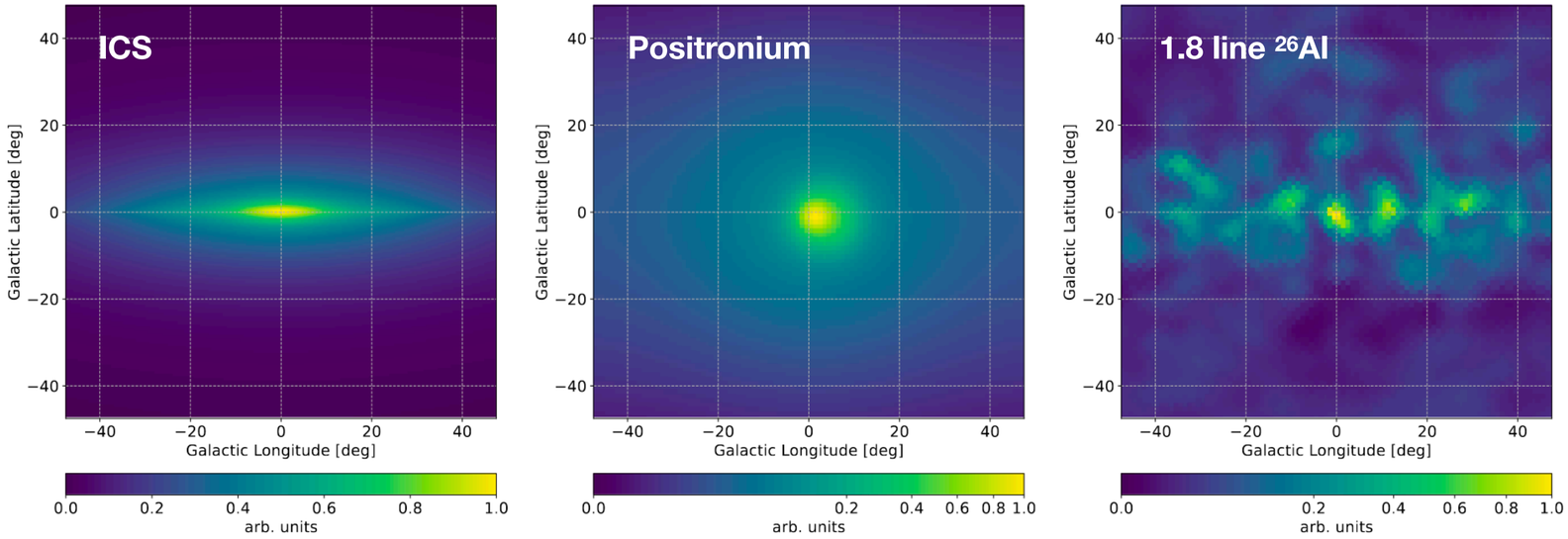
Berteaud, FC+ PRD'22 ; FC+ MNRAS'23

Soft gamma rays with Integral/SPI

Astrophysical contributions

Modelled **spatial templates** (30 keV — 8 MeV)

- **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 (<100 keV)
- Nuclear lines
- Positronium annihilation line+continuum



Berteaud, FC+ PRD'22

Soft gamma rays with Integral/SPI

Dark matter contribution?

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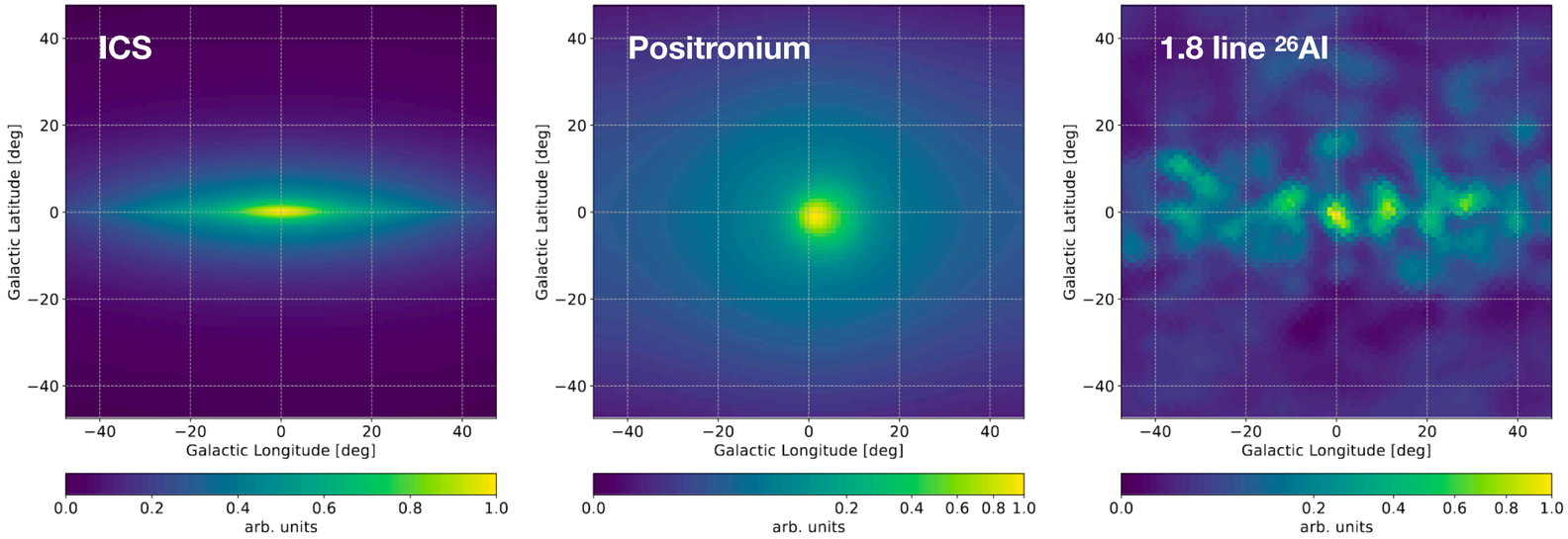
- Additional **DM signal**?

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



Berteaud, FC+ PRD'22

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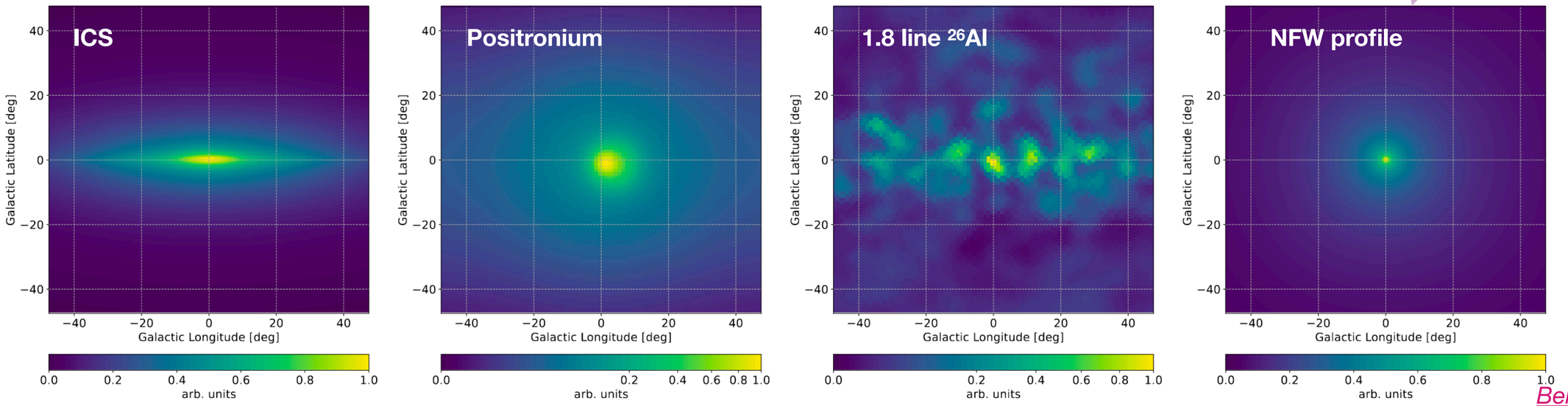
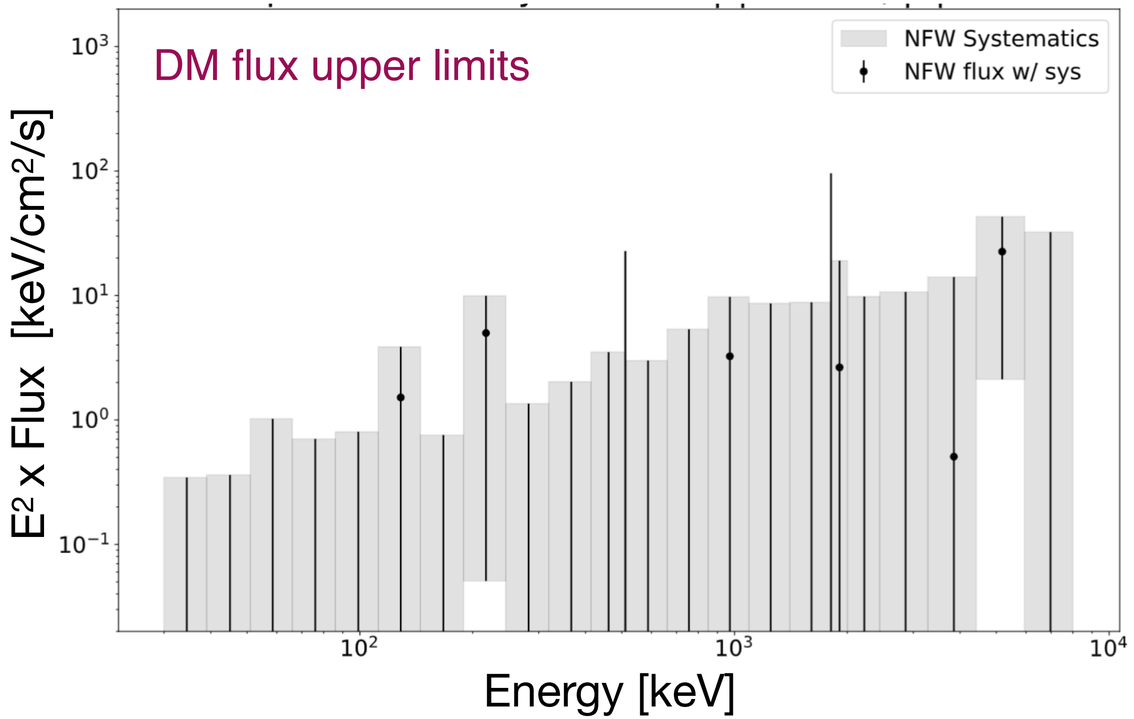


Berteaud, FC+ PRD'22

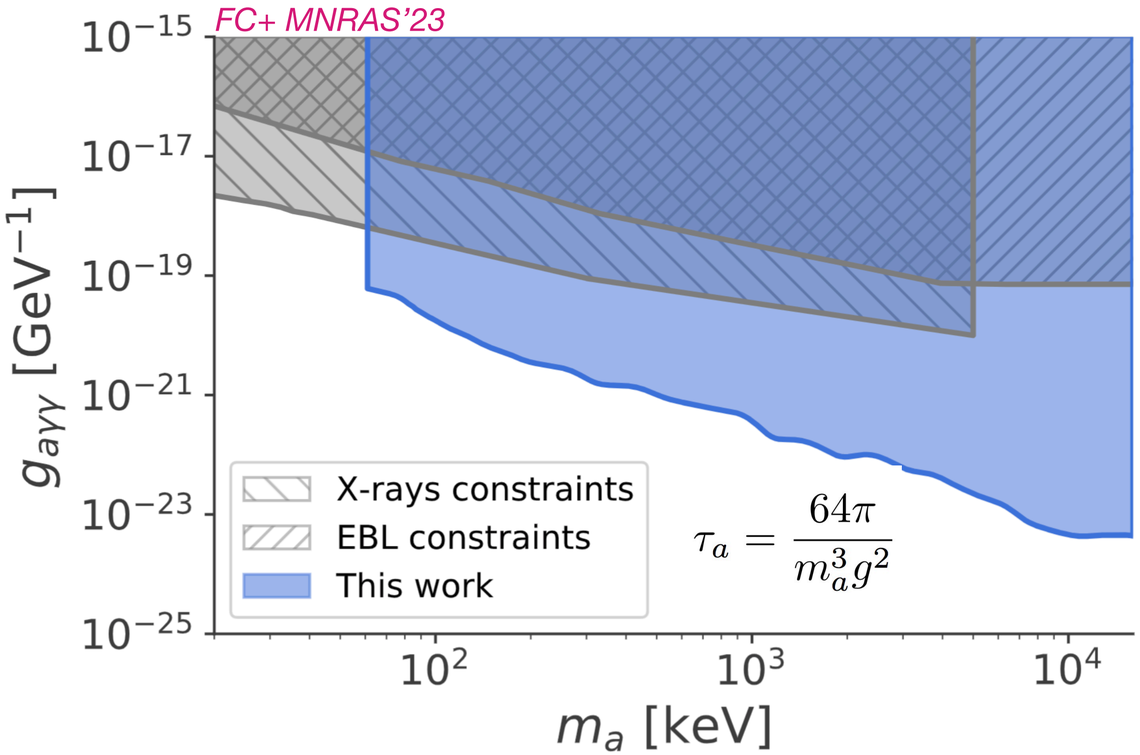
Soft gamma rays with Integral/SPI

Constraints on decaying dark matter

No signal detected



⟶ Upper limits on **light particle decay**



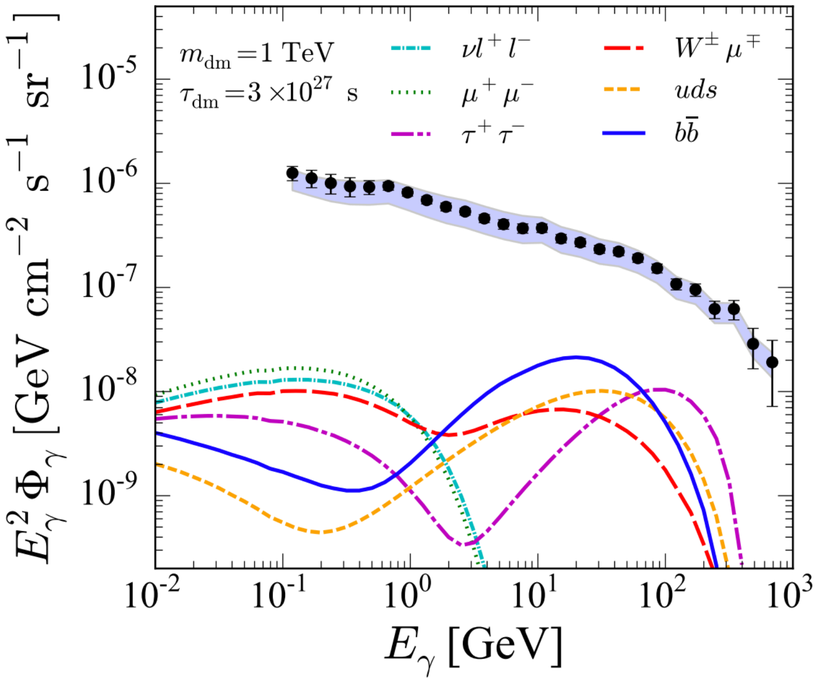
Re-analysis of Integral/SPI data provides the **strongest constraints** on (light) particle and non-particle DM PBHs

https://zenodo.org/record/7984451

Decaying WIMP dark matter

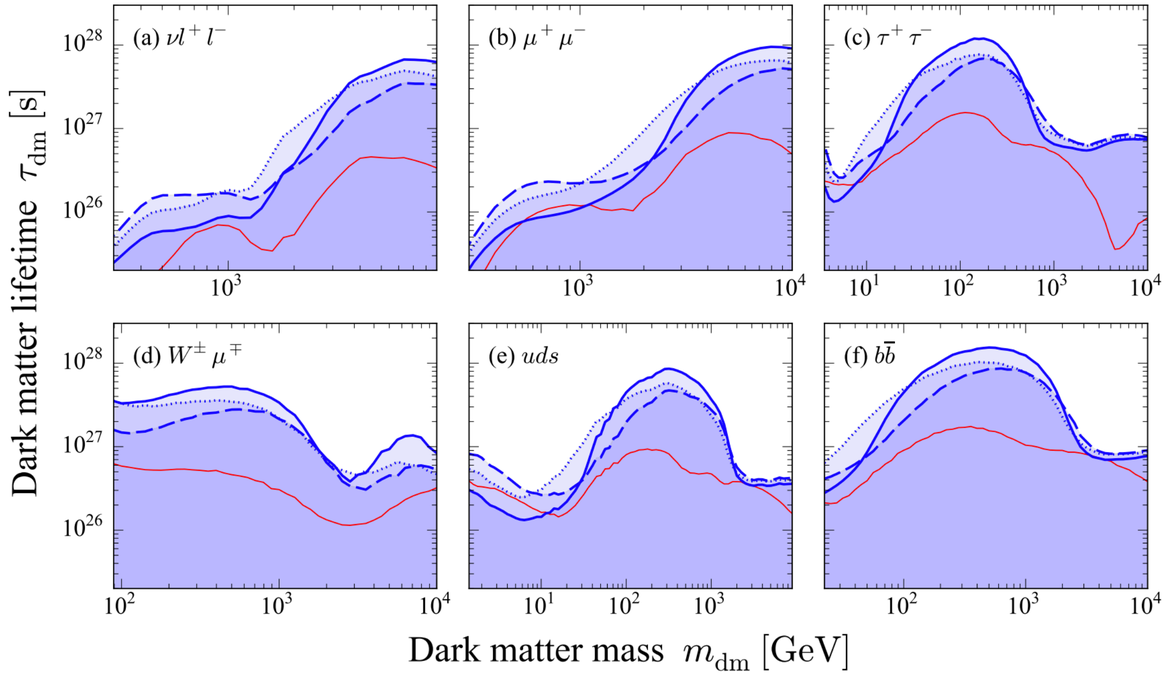
DM models: gravitino and axino in RPV models; or leptophilic models (positron fraction)

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



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*]

What is the origin of the GeV excess?

Possible interpretations

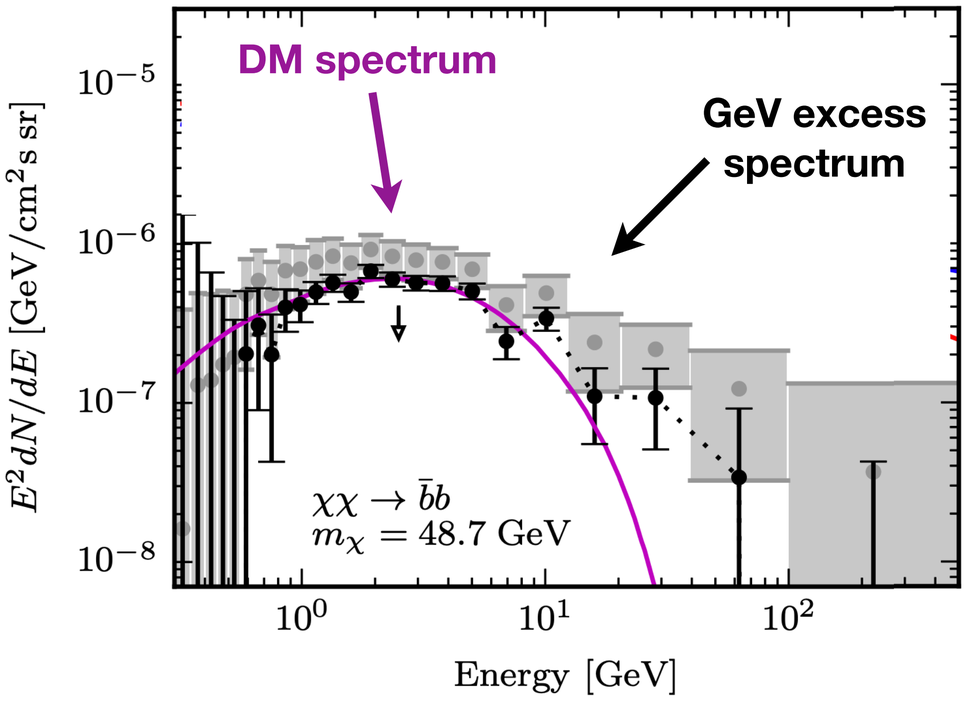
I. **Dark matter annihilation**: large freedom in channel/masses thanks to systematic uncertainties

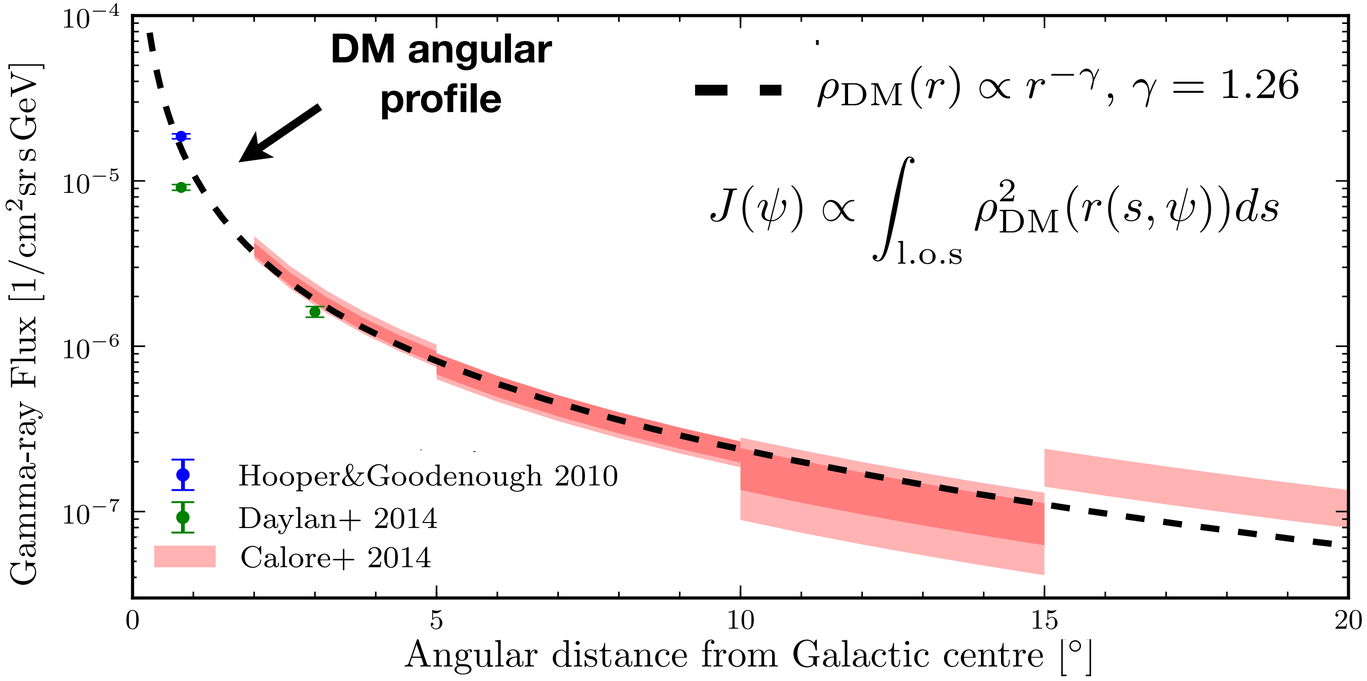
Agrawal+JCAP'15; Achterberg+JCAP'15; Bertone, FC+ JCAP'15; Liem, FC+ JCAP'16; O(>100) papers

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**)

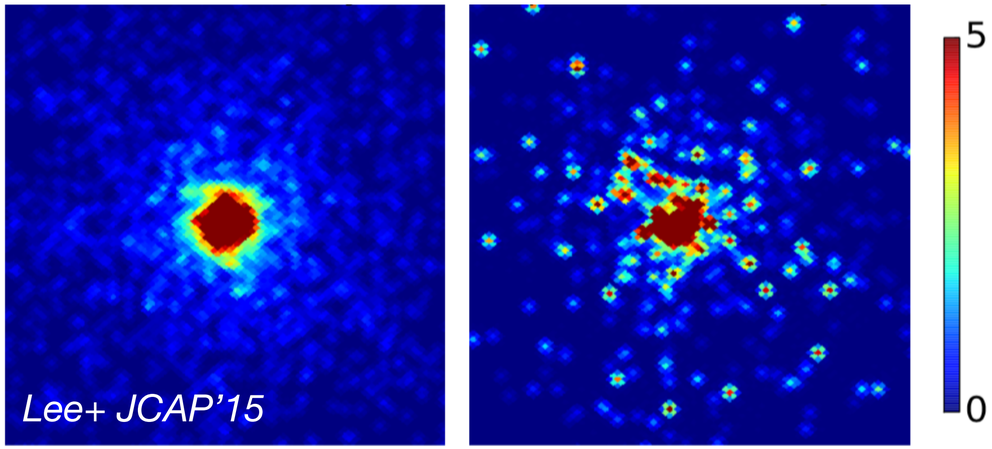




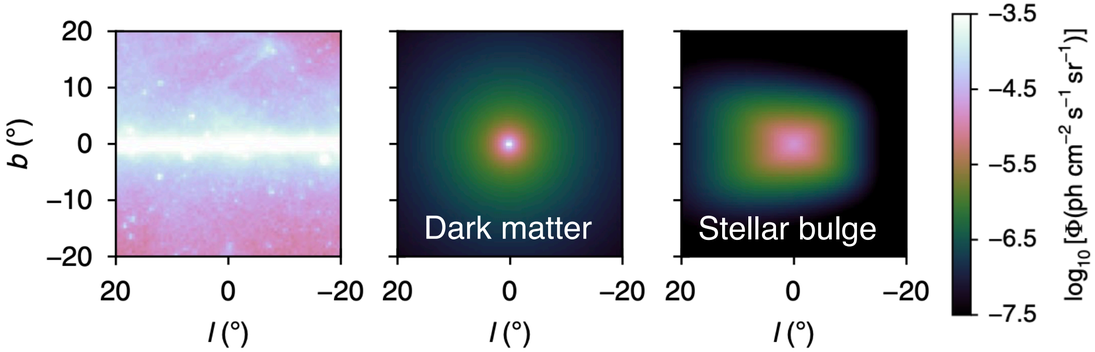
FC+PRD'15

The GeV excess nature

The gamma-ray perspective



Truly diffuse Unresolved sources



- 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

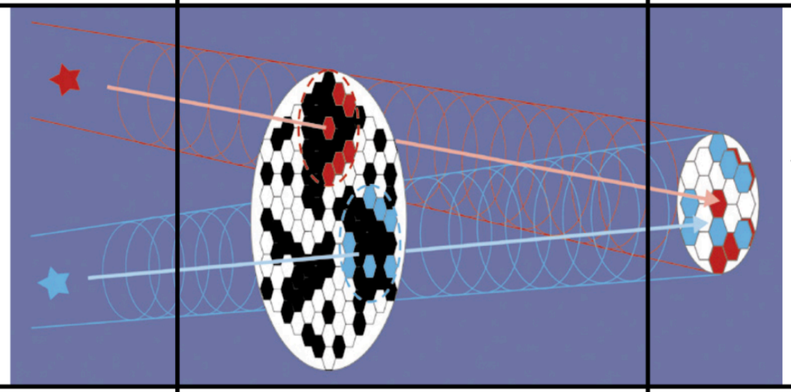
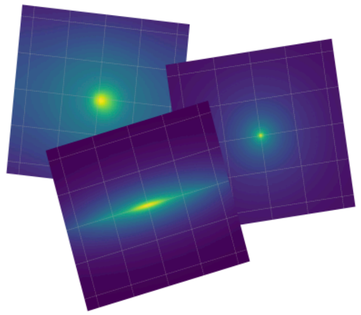
  FC+ PRL' 21

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

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

An old instrument, a new analysis

Diffuse Galactic emission spectrum with SPI 16yr data

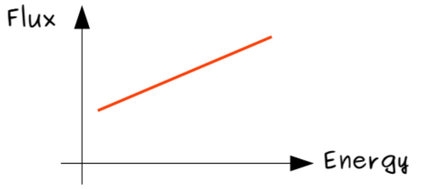
	INPUT	CONVOLUTION	OUTPUT
DATA	Sky		Photons per observation per energy per detector
MODEL	Spatial templates 	SPI coded-mask response function	Time series of expected detector patterns

ROI:
95° x 95° about the Galactic center

← Maximum likelihood fit in each energy bin independently

↓

Total spectrum



Credit: J. Berteaud, RICAPP'22