CTAO and fundamental physics with gamma rays

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2nd CTA Symposium 2024

SMASH machine learning for science and humanities postdoctoral program

Univerza v Ljubljani

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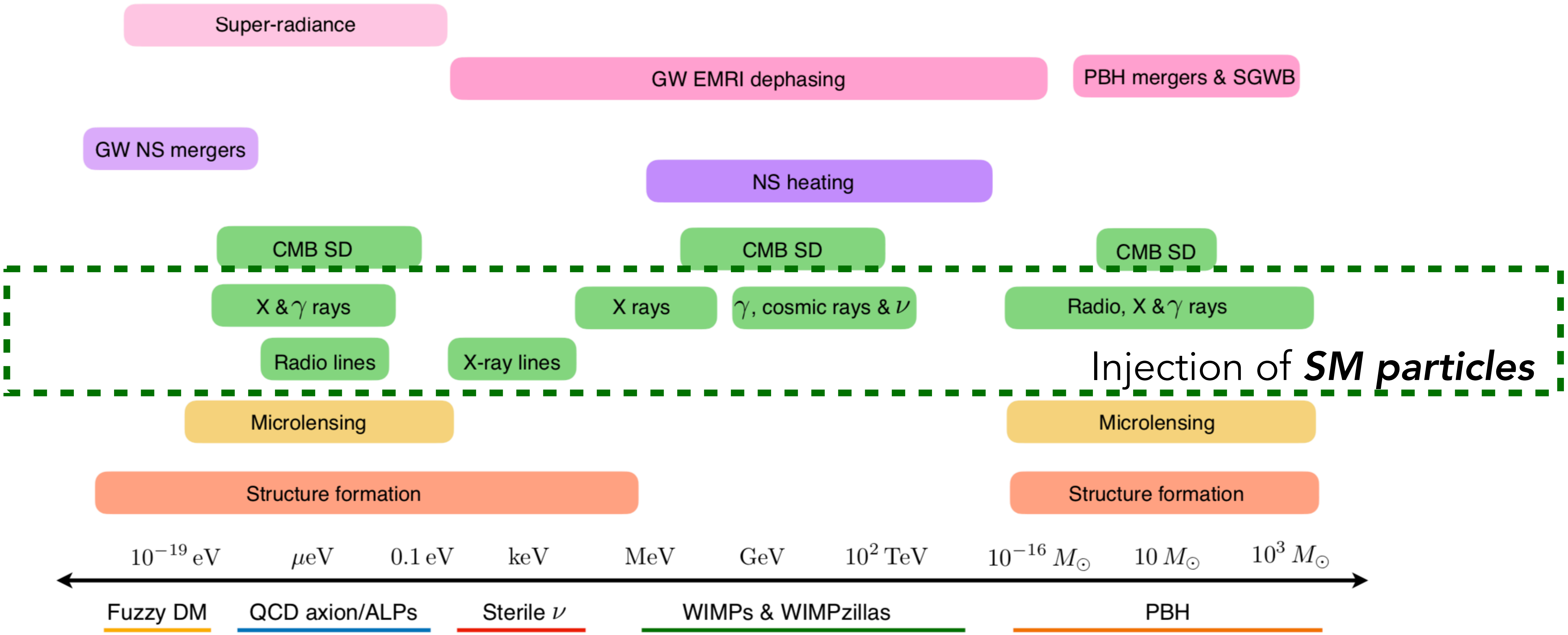
IZUM Institute of Information Science Maribor

REPUBLIC OF SLOVENIA MINISTRY OF THE ENVIRONMENT AND SPATIAL PLANNING SLOVENIAN ENVIRONMENT AGENCY

Co-funded by The European Union

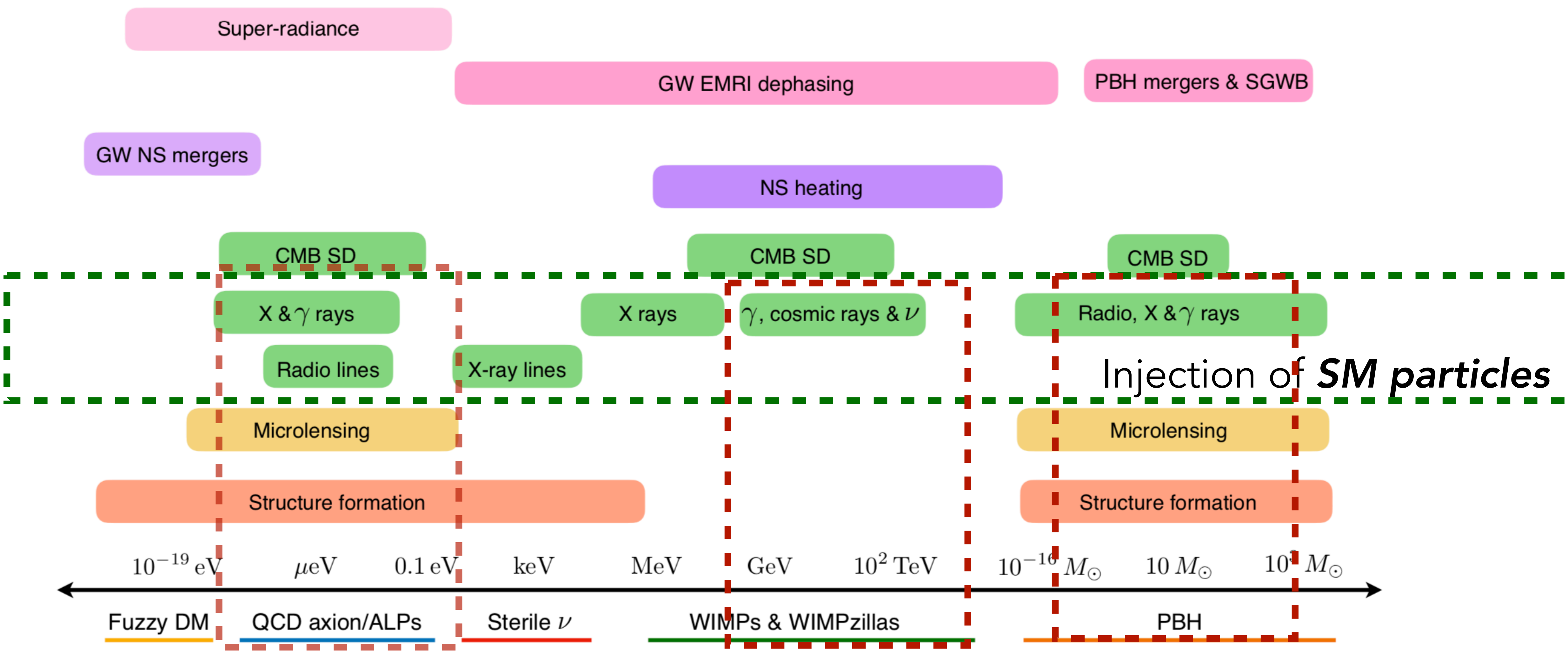
Detection strategies per mass range

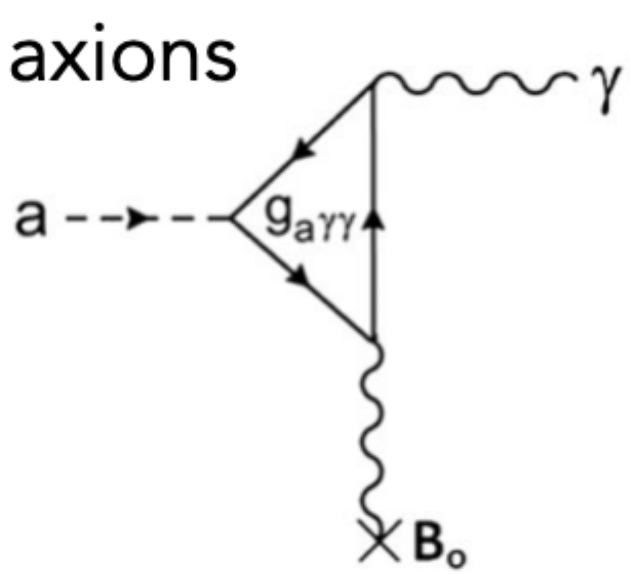


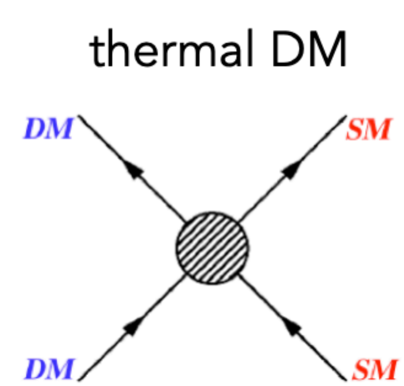
[EuCAPT white paper, 2110.10074]

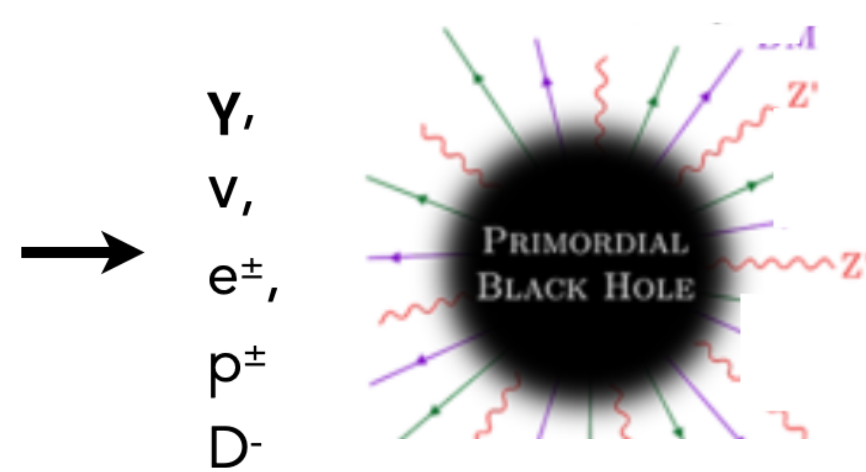
Detection strategies per mass range

THIS TALK: Focus on γ rays



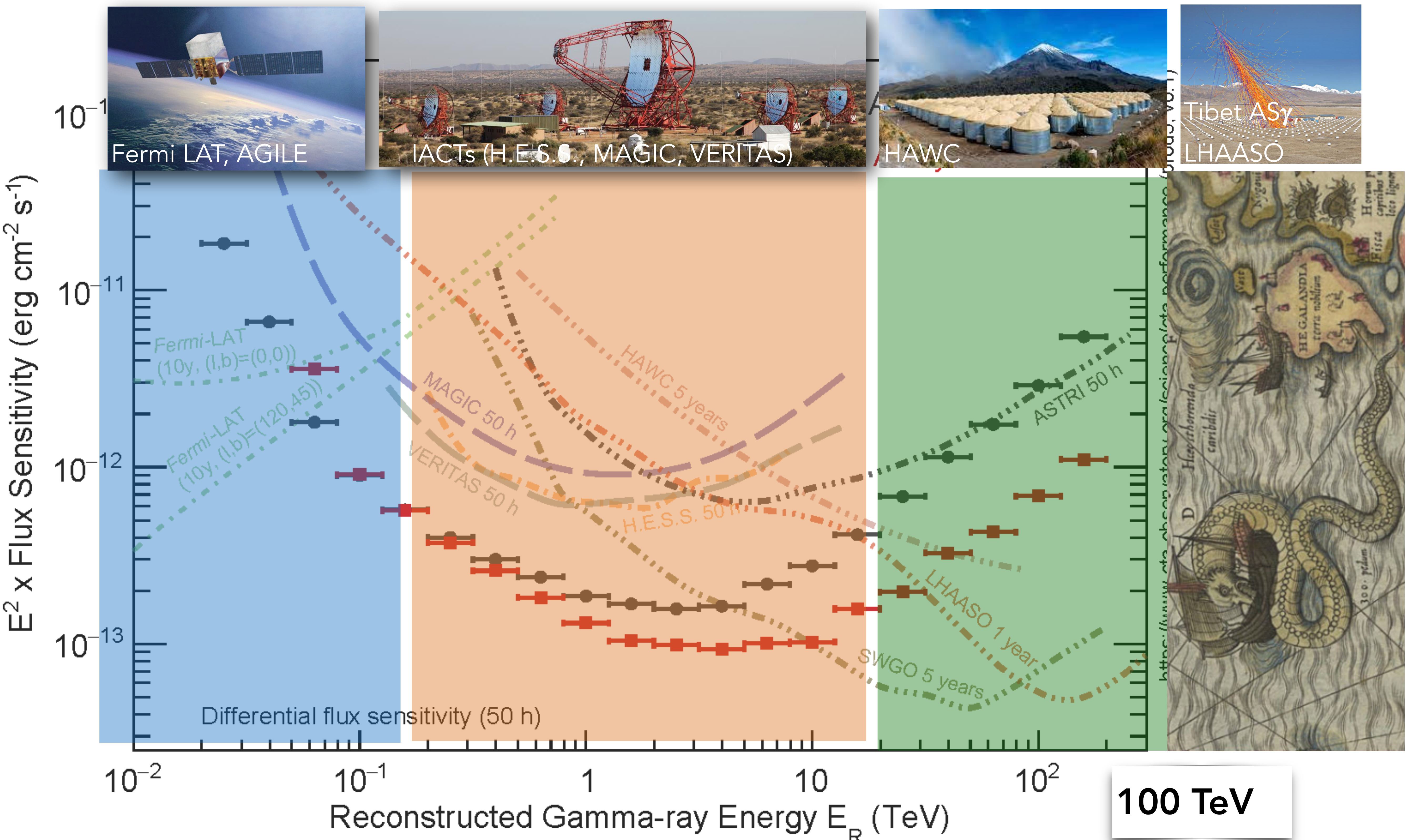




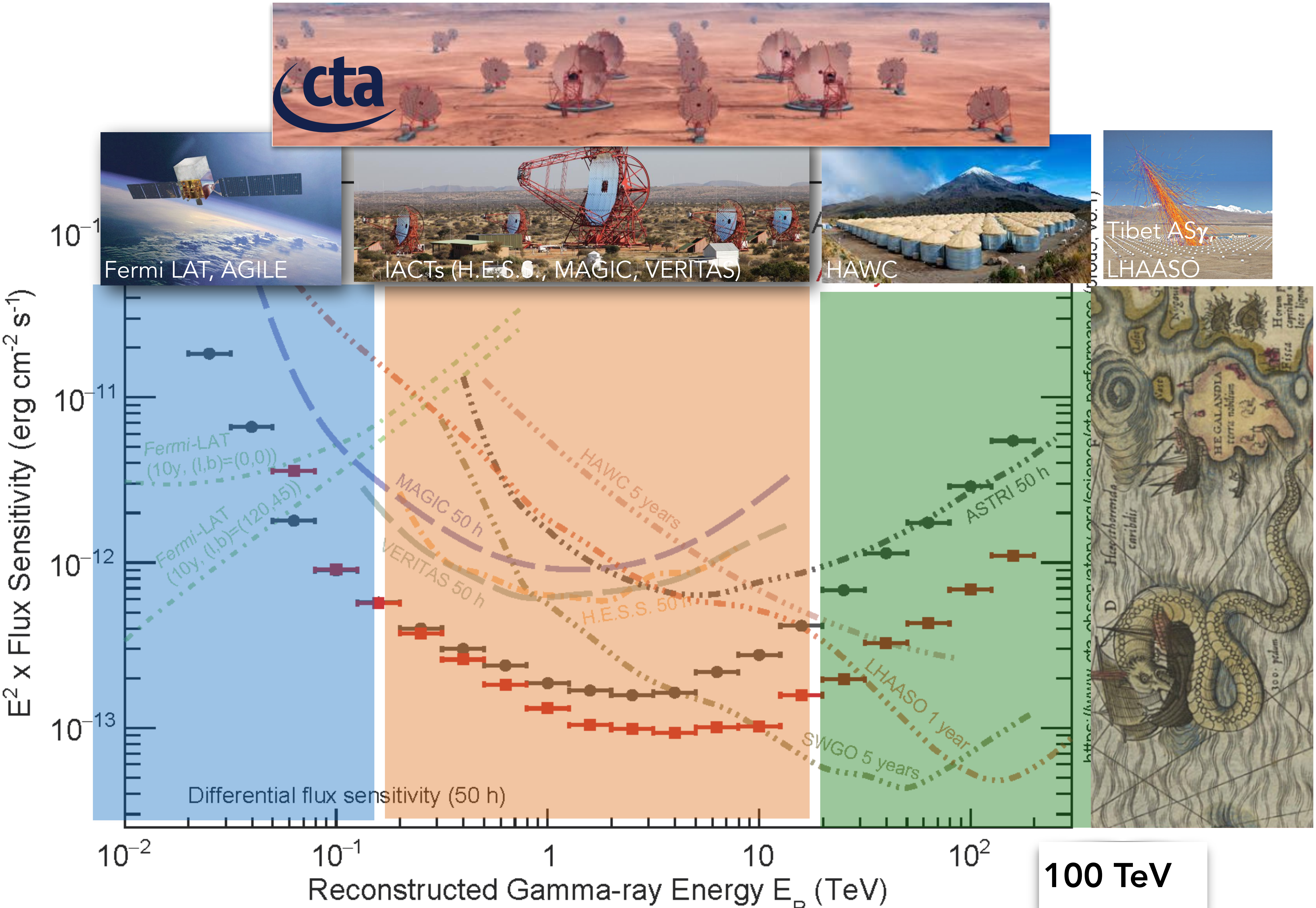


[EuCAPT white paper, 2110.10074]

What tools?


Fermi LAT, AGILE
IACTs (H.E.S.S., MAGIC, VERITAS)
HAWC
Tibet ASγ,
LHAASO
Fermi-LAT
(10y, (l,b)=(0,0))
Fermi-LAT
(10y, (l,b)=(120,45))
MAGIC 50 h
VERITAS 50 h
H.E.S.S. 50 h
HAWC 5 years
ASTRI 50 h
LHAASO 1 year
SWGO 5 years
Differential flux sensitivity (50 h)
E² x Flux Sensitivity (erg cm⁻² s⁻¹)
Reconstructed Gamma-ray Energy E_R (TeV)
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻²
10⁻¹
1
10
10²
100 TeV

What tools?


cta
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H.E.S.S. 50 h
HAWC 5 years
LHAASO 1 year
SWGO 5 years
ASTRI 50 h
Differential flux sensitivity (50 h)
100 TeV

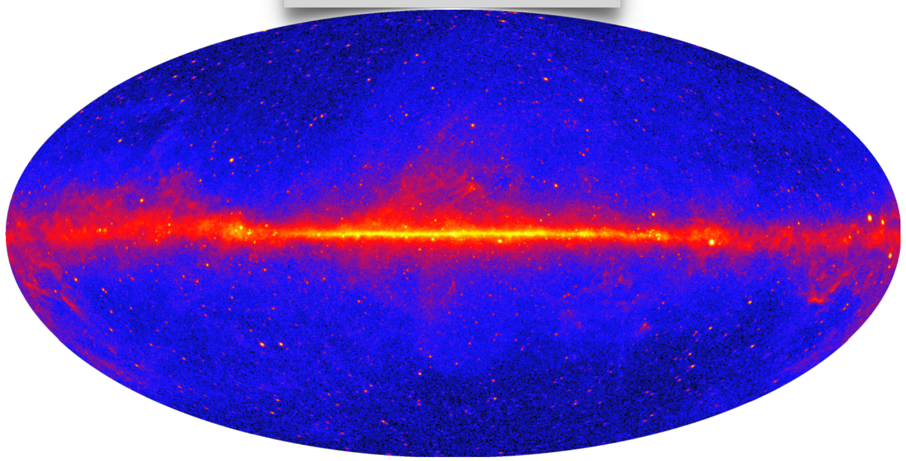
GeV - TeV sky

IACTs

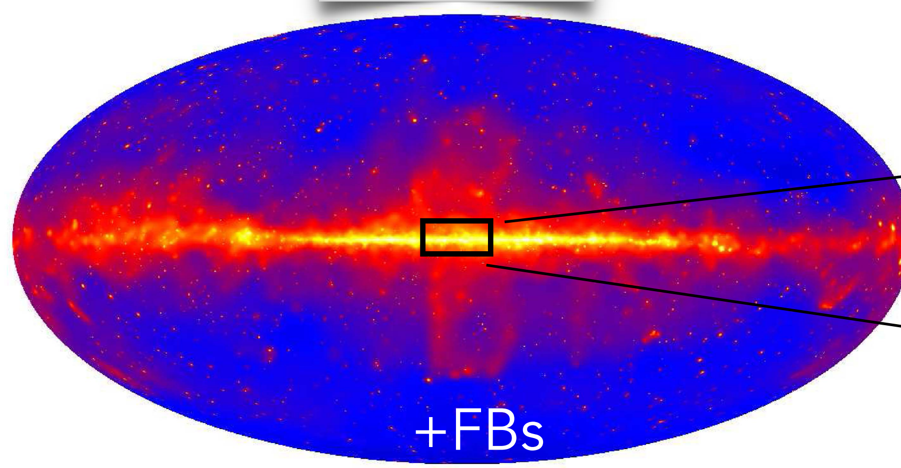
Significant CR contamination

+ limited FoV

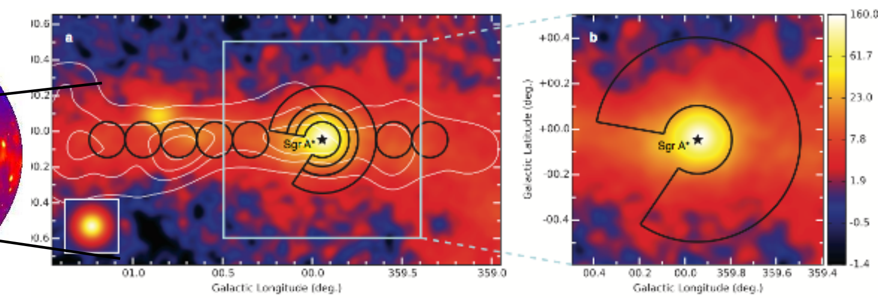
>300 MeV



>10 GeV

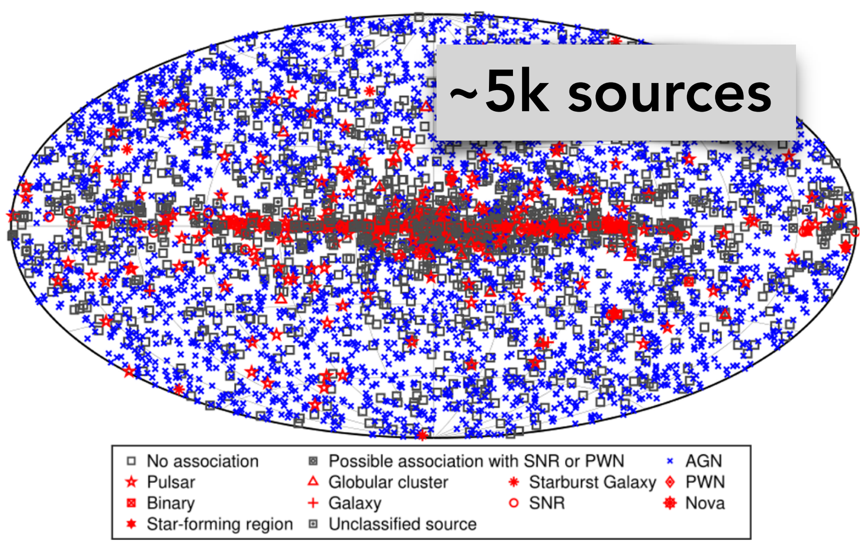


>~100 GeV



HESS, Galactic center Ridge

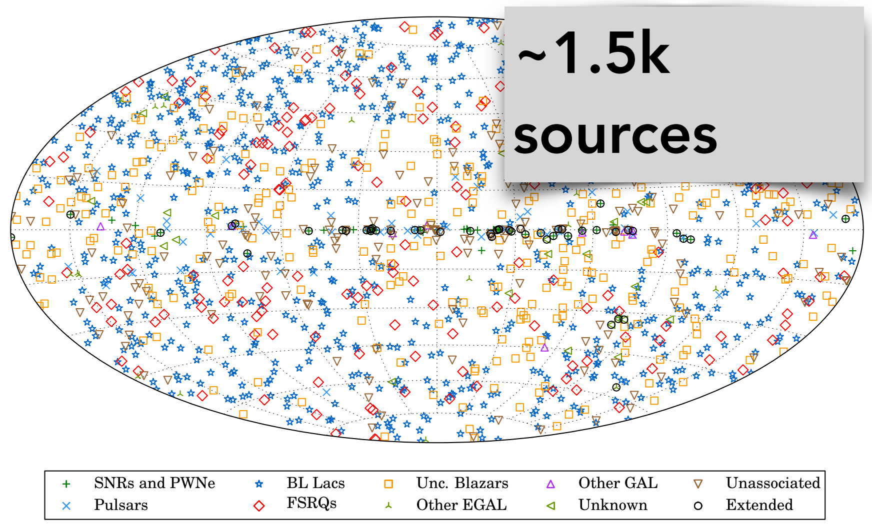
~5k sources



LAT source catalogue,

>300 MeV (4FGL)

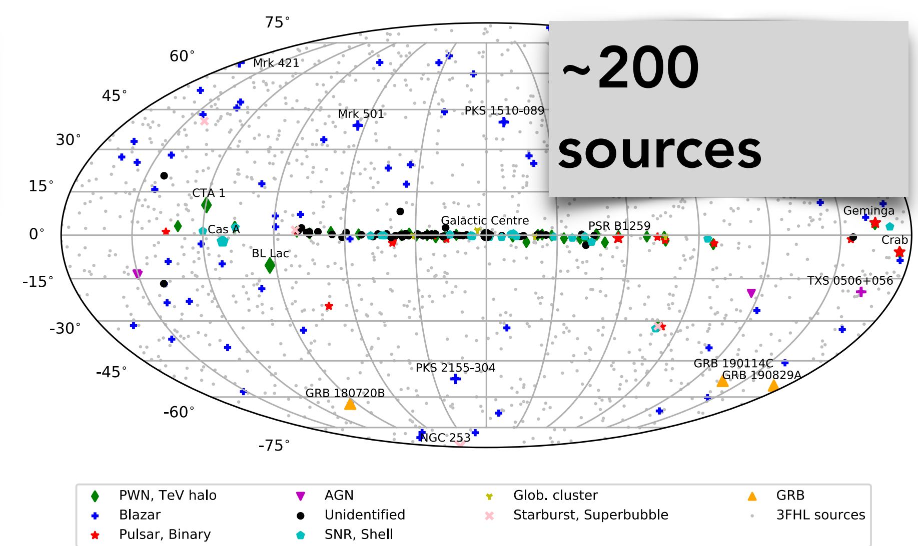
~1.5k sources



LAT source catalogue,

>10 GeV (3FHL)

~200 sources



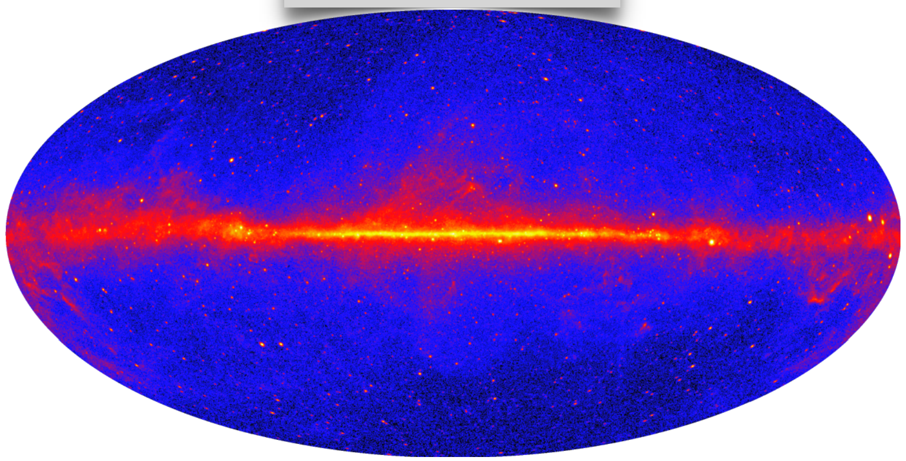
TeVCat,

+90 sources in the 1st LHAASO catalogue [Cao+,AjS 271 (2024) 25]

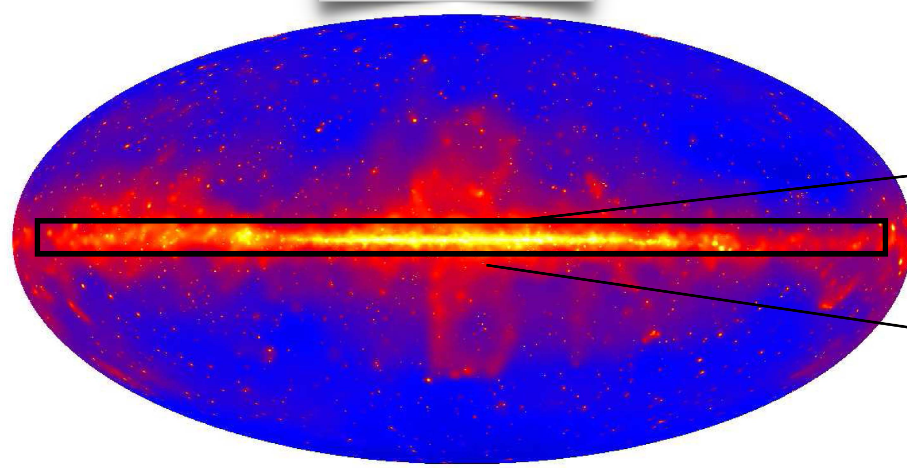
GeV - TeV sky

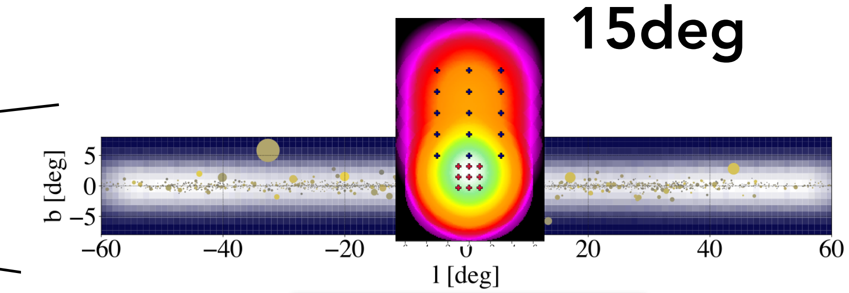
Coming up - **CTAO surveys**

>300 MeV



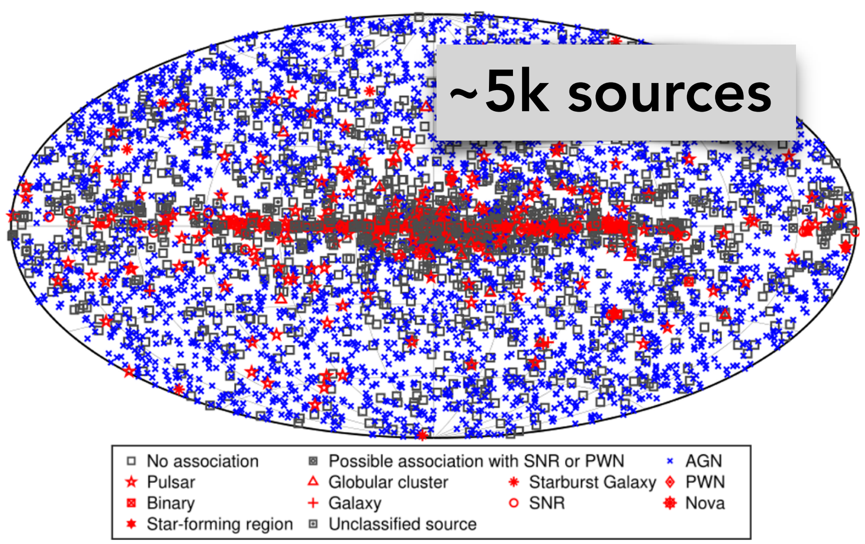
>10 GeV



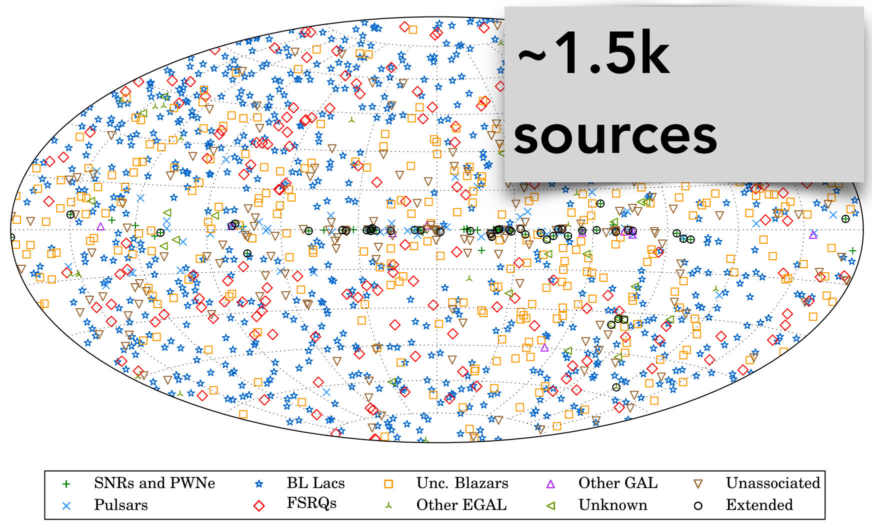


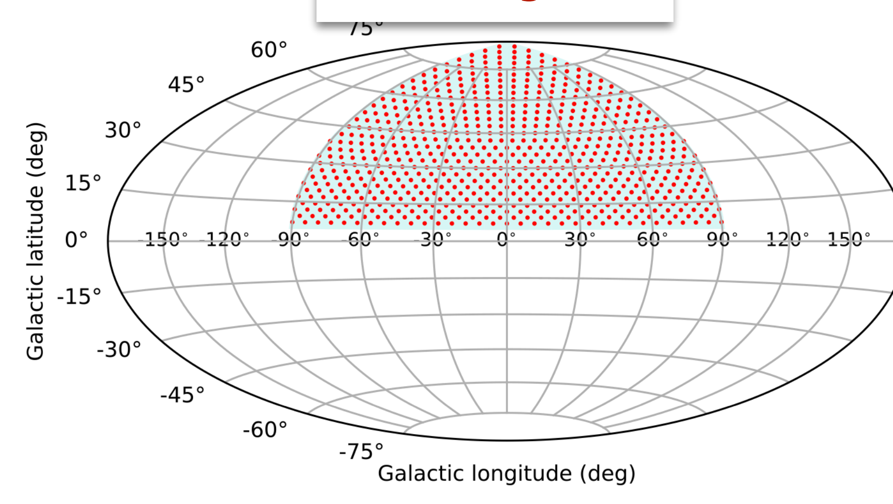
GP + GC surveys

~5k sources



~1.5k sources



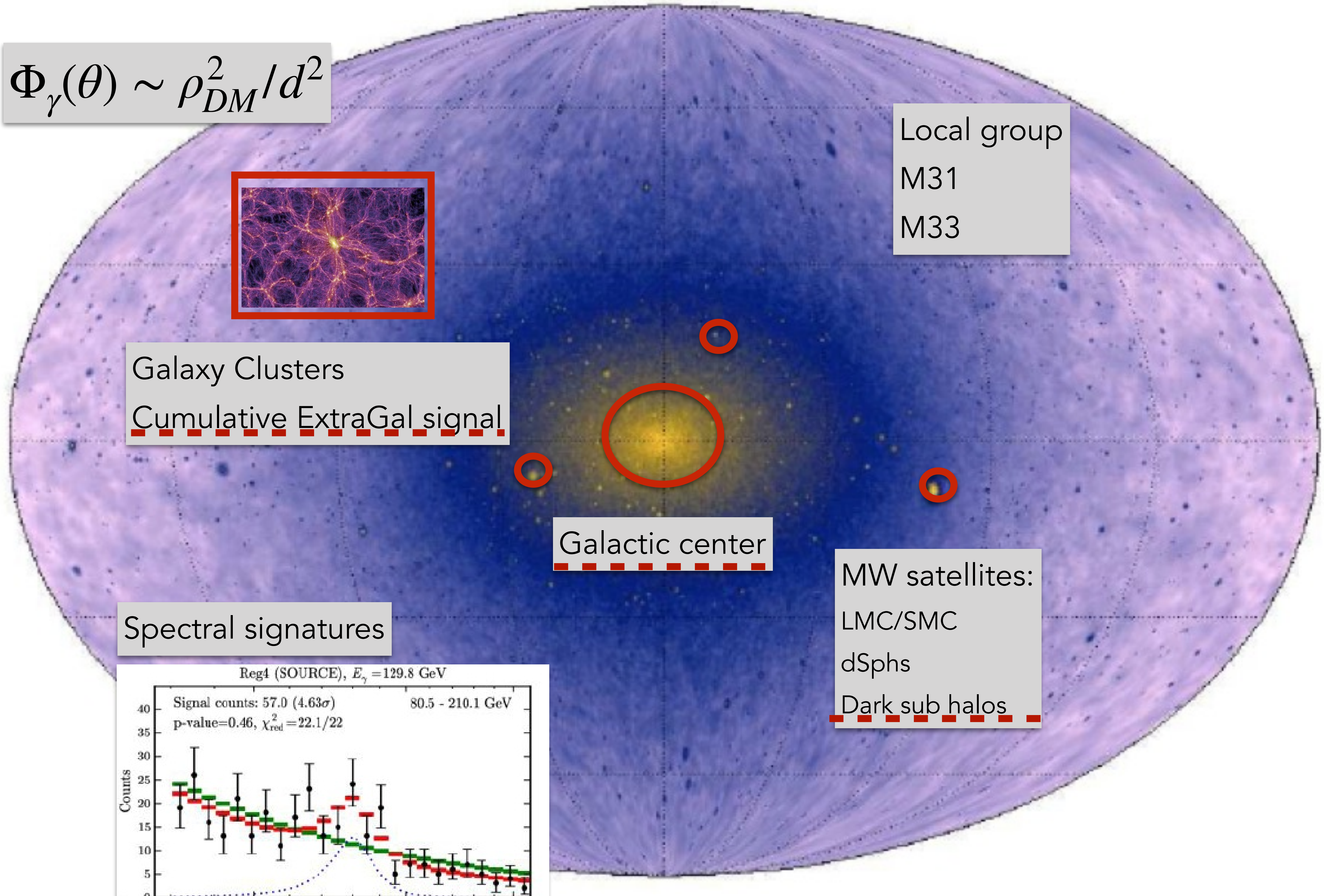


LAT source catalogue, >300 MeV (4FGL)

LAT source catalogue, **>10 GeV** (3FHL)

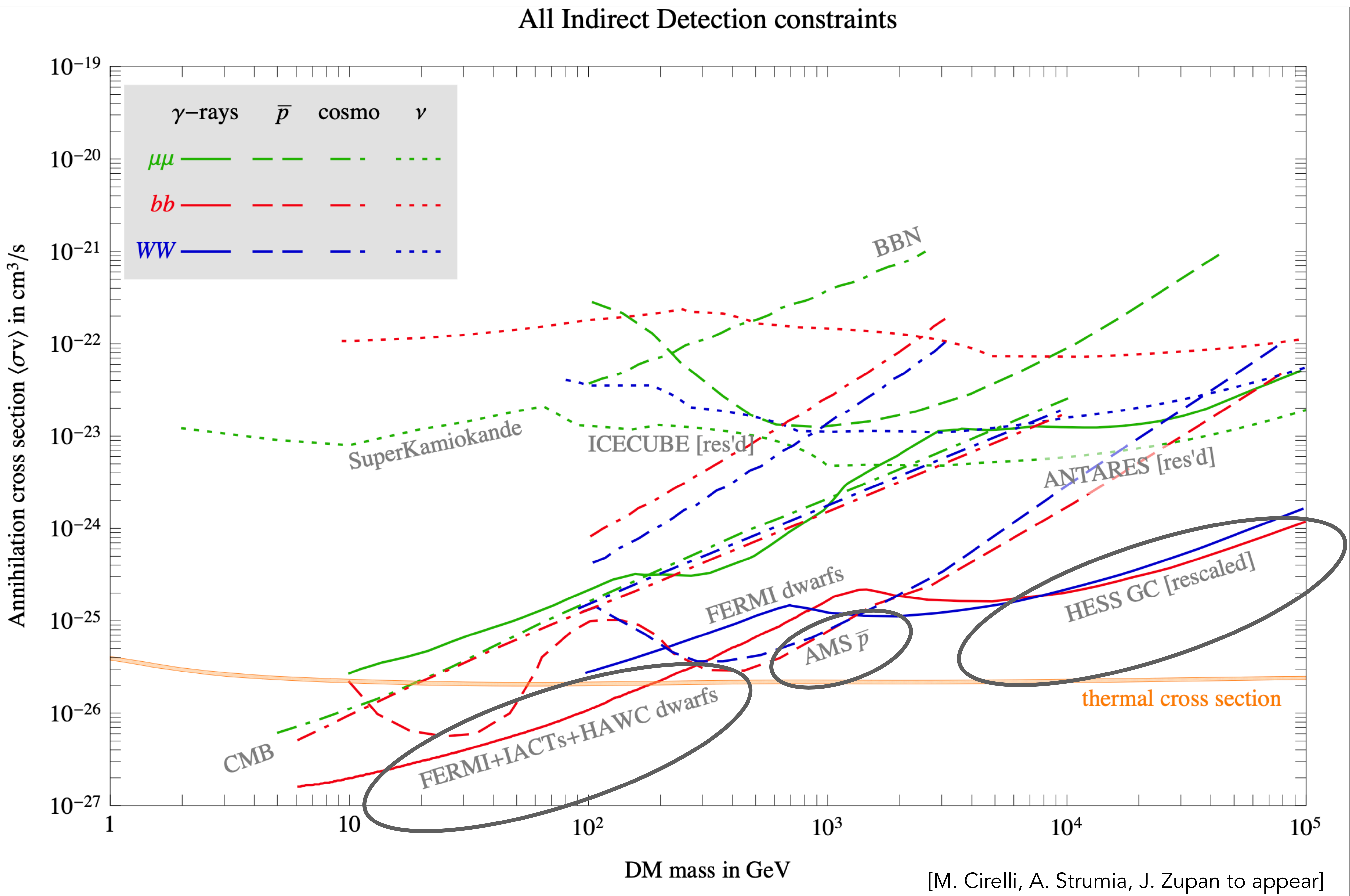
Extra gal **survey**

Part 1: thermal DM



- - - - - Larger sky coverage needed

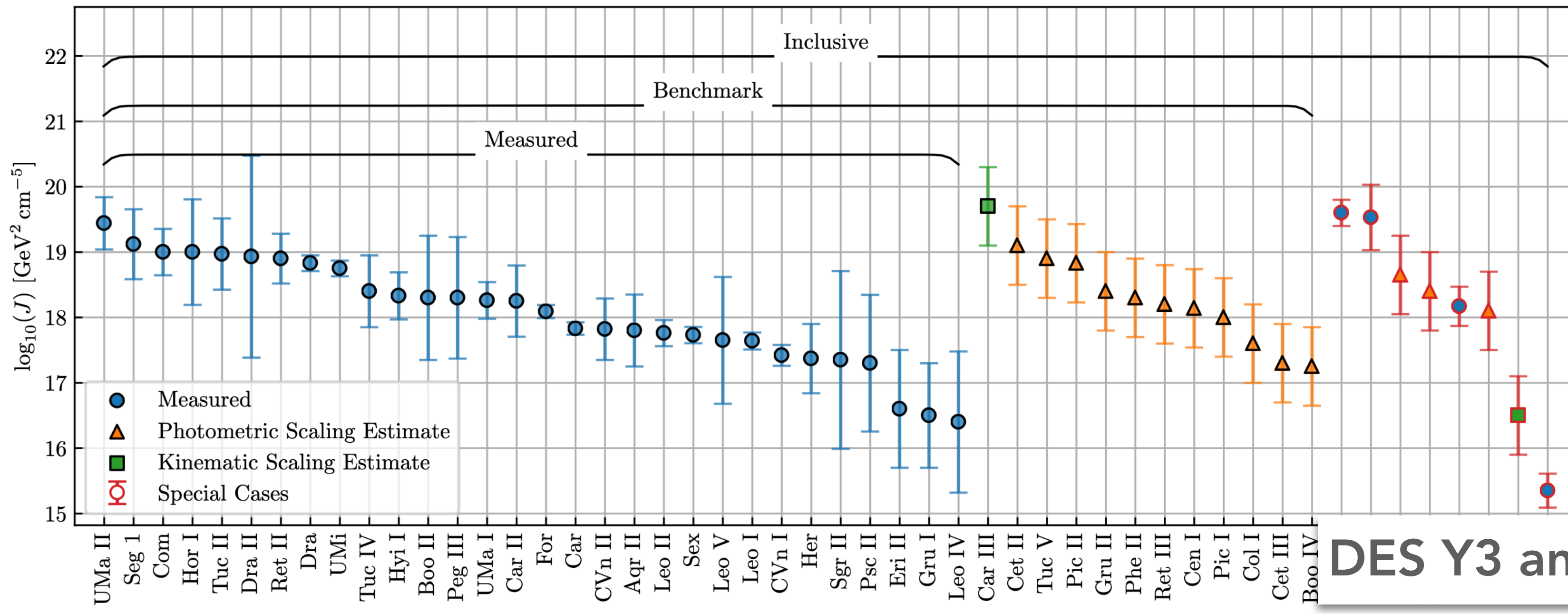
State-of-the-art constraints



[M. Cirelli, A. Strumia, J. Zupan to appear]

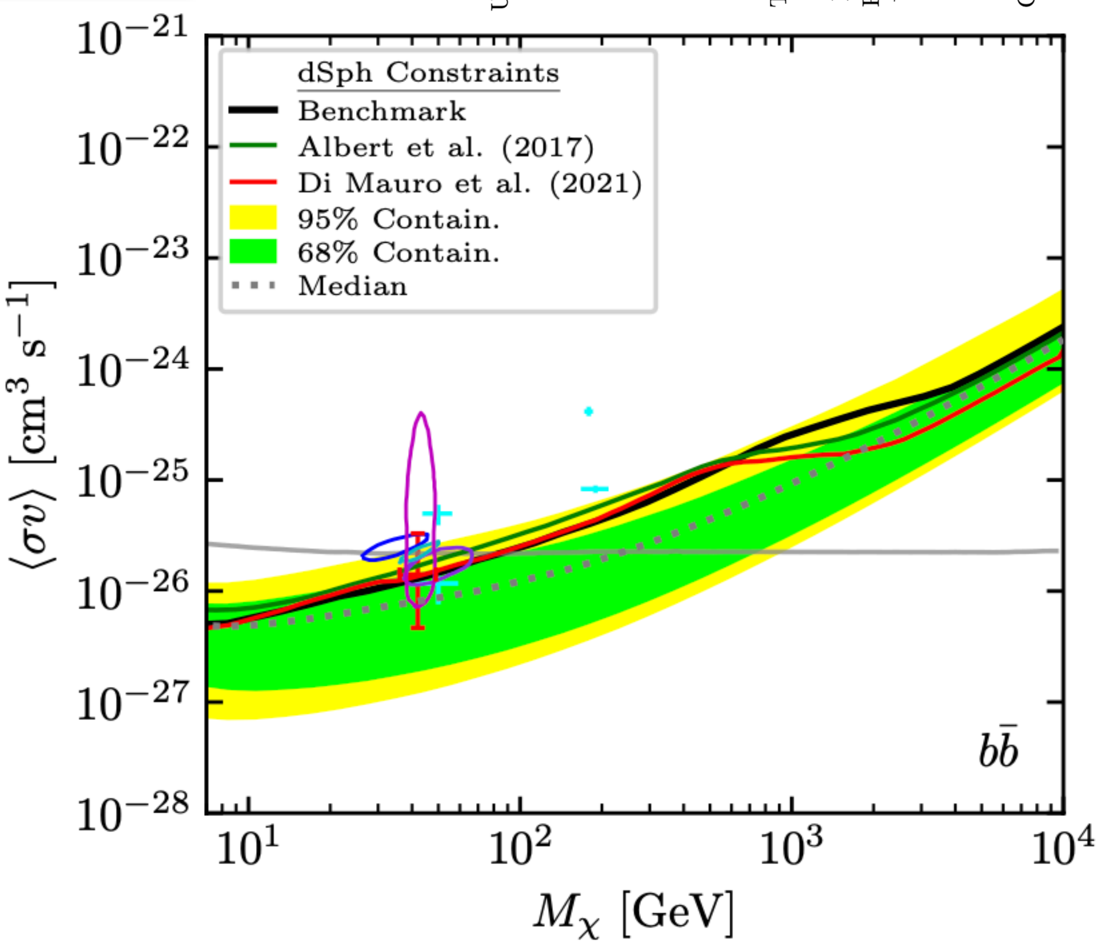
State-of-the-art constraints

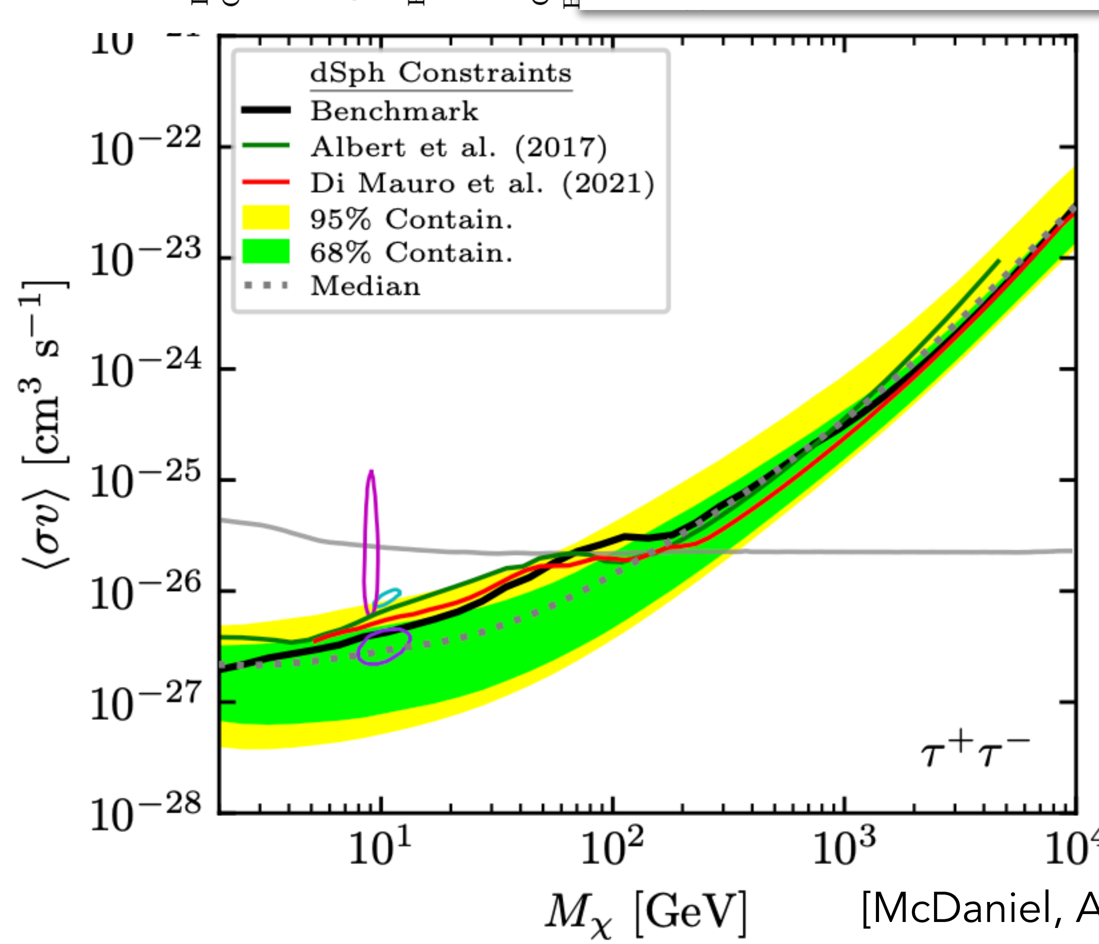
Latest: Legacy Analysis of Dark Matter Annihilation from the Milky Way Dwarf Spheroidal Galaxies with 14 Years of Fermi-LAT Data (30-50 dSphs)



Fermi LAT

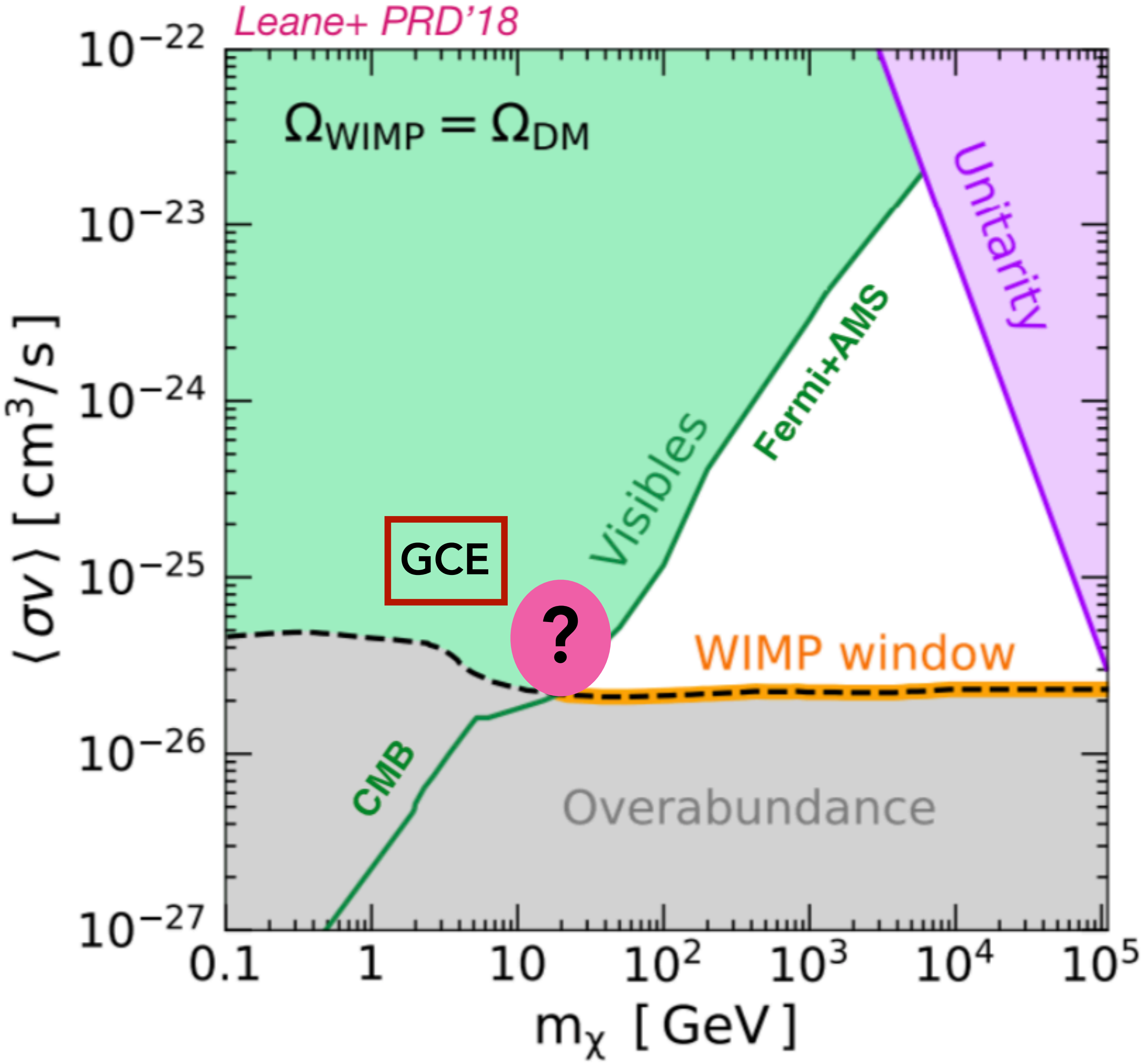
DES Y3 and Pan-STARRS DR1



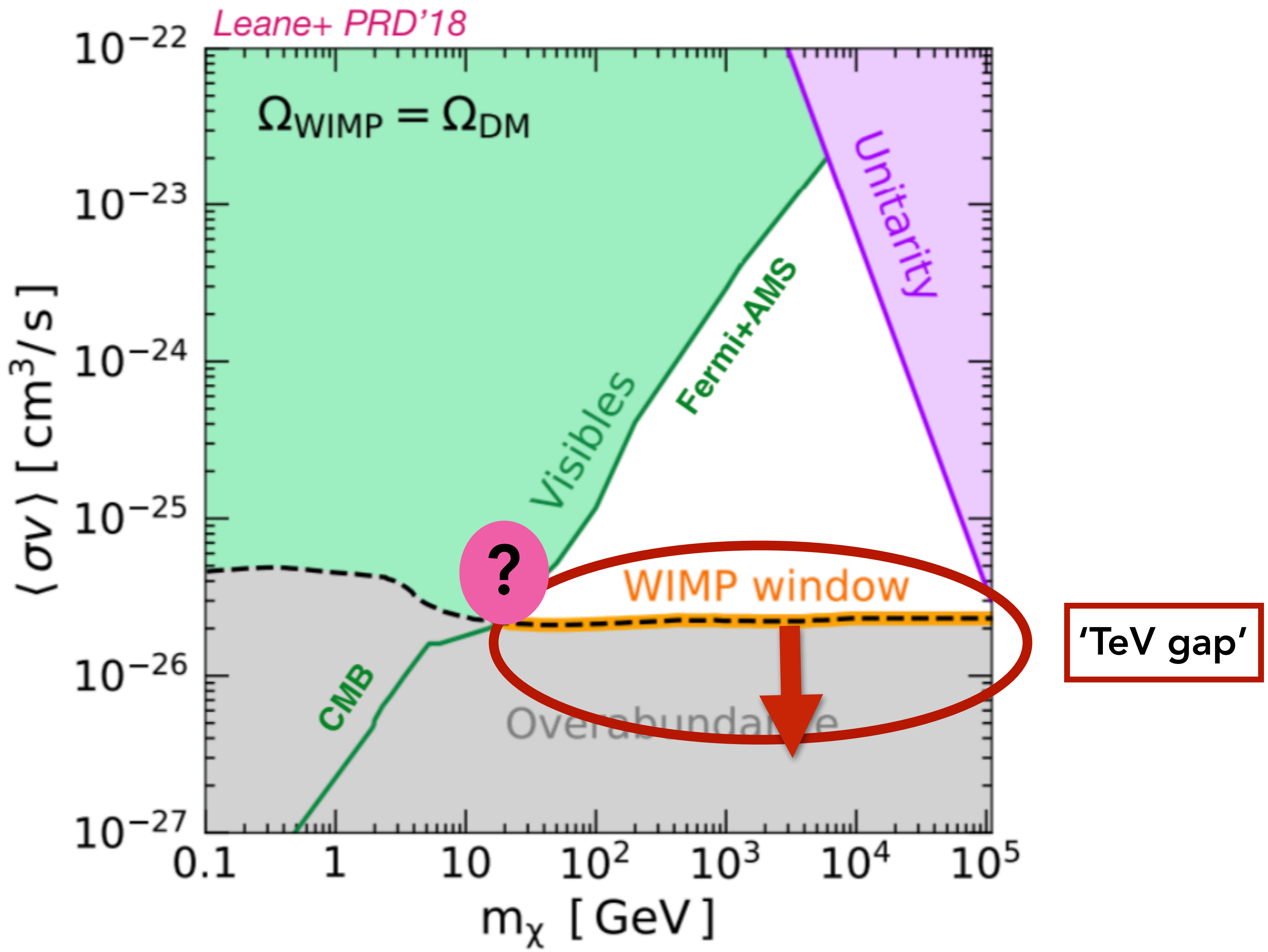


[McDaniel, A.+, 2311.04982]

The big picture

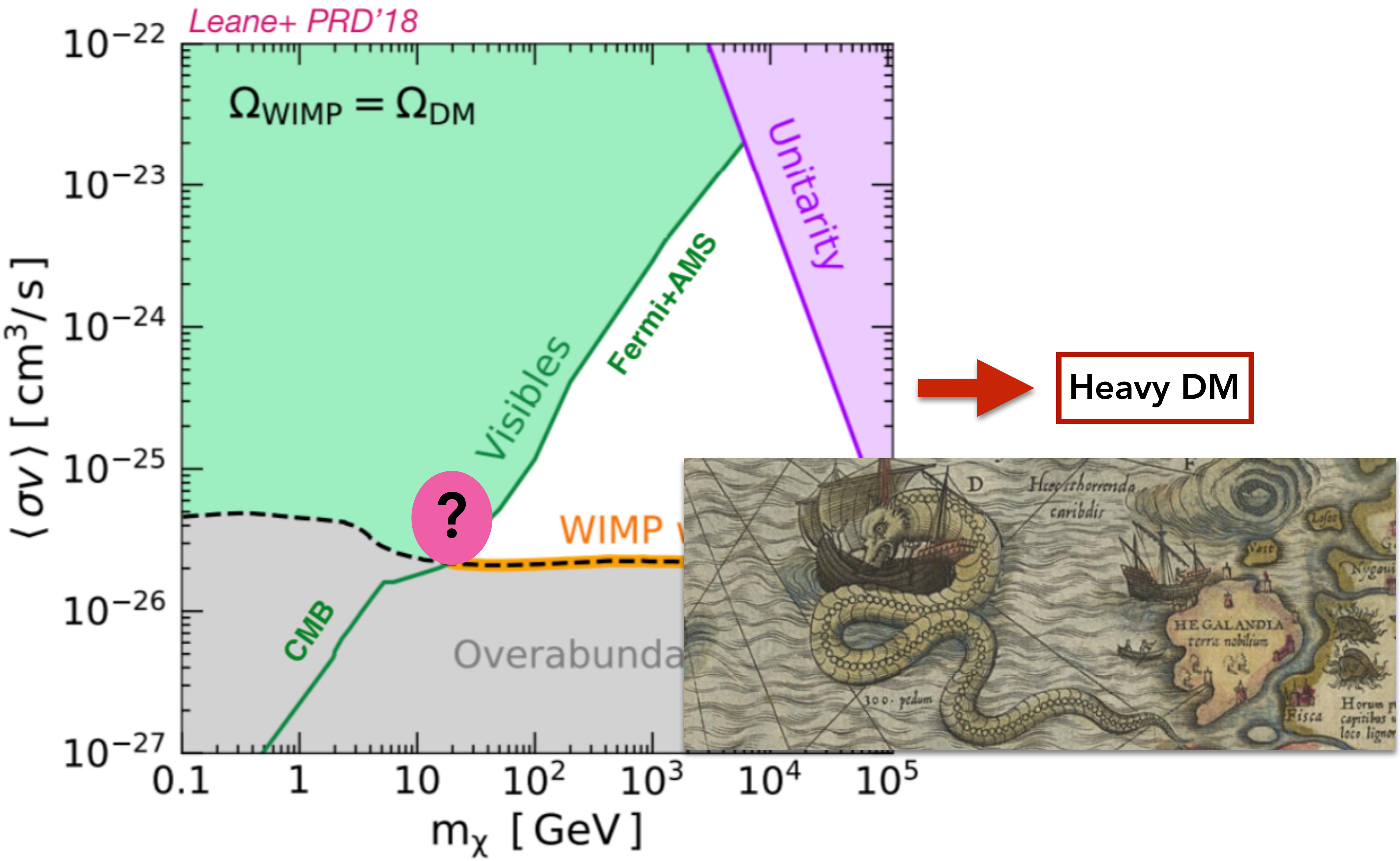


The big picture



1) **CTAO is arguably the only experiment in a position to close the TeV gap.** AMS-02 complementary, systematics due to CR propagation significant.

The big picture

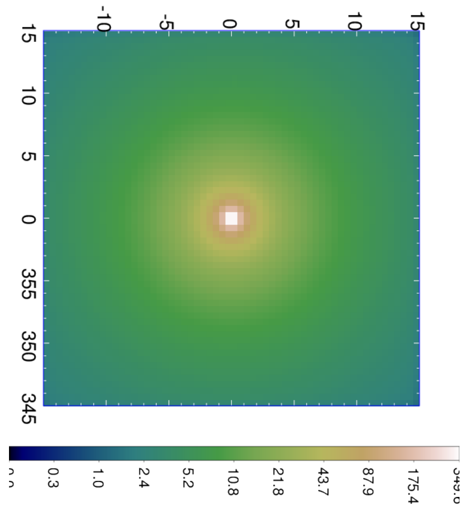


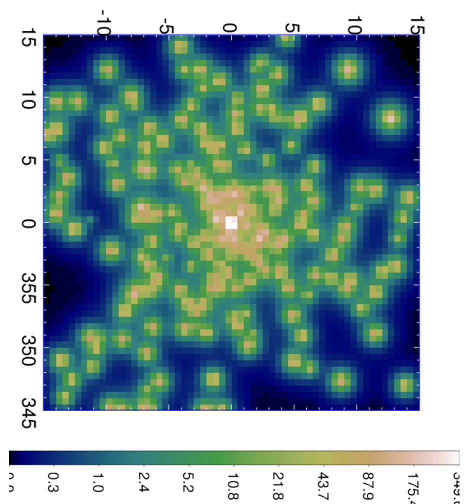
2) CTAO + LHAASO, Ice Cube etc.

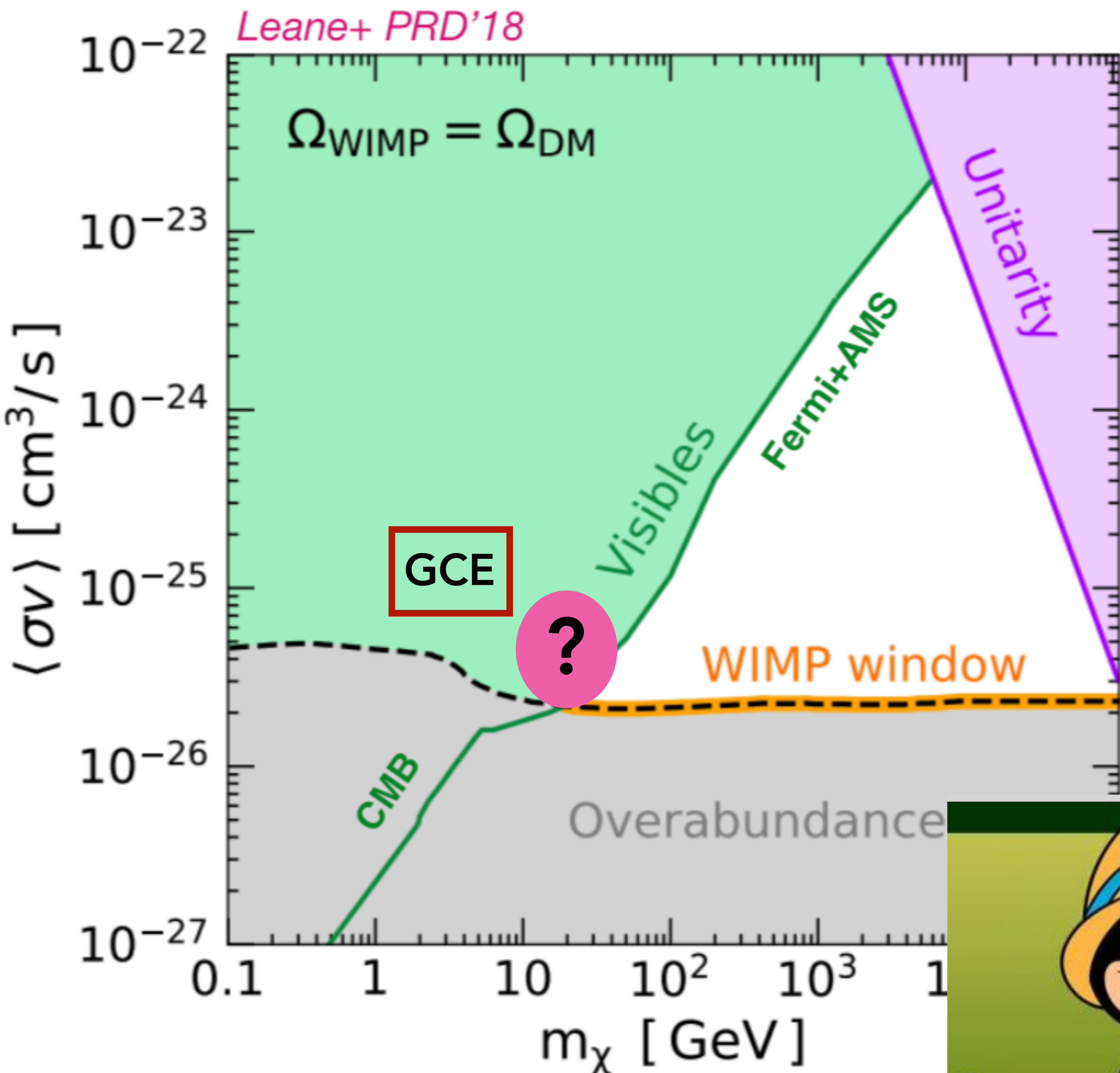
Note: **TeV+ DM mass range - theoretical dragon-land**

- at mDM ≳ few TeV expect **long-range behavior** with **bound states** playing a role
- there is **no model-independent unitarity limit** on mass of thermal relic DM
- **σvrel** ∝ **1/vrel** and rich resonance structure expected

The big picture





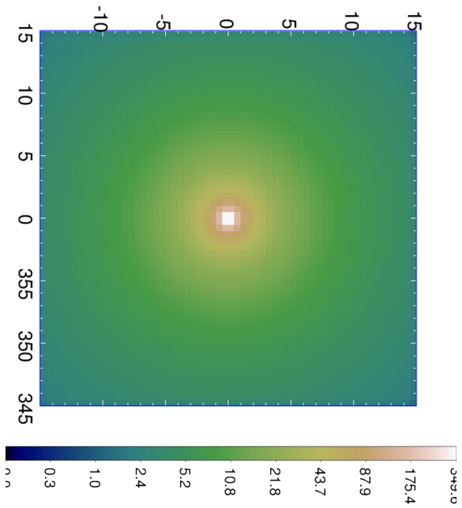


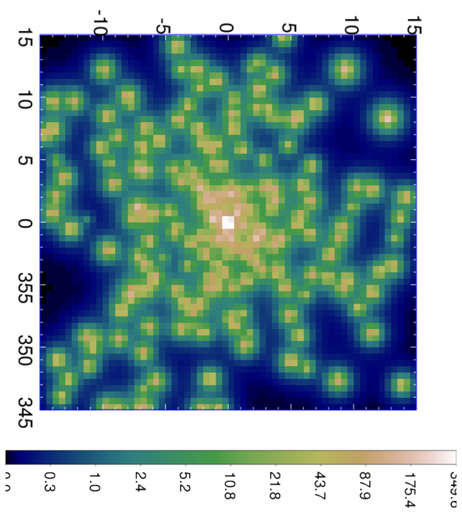
Few words about the GCE:

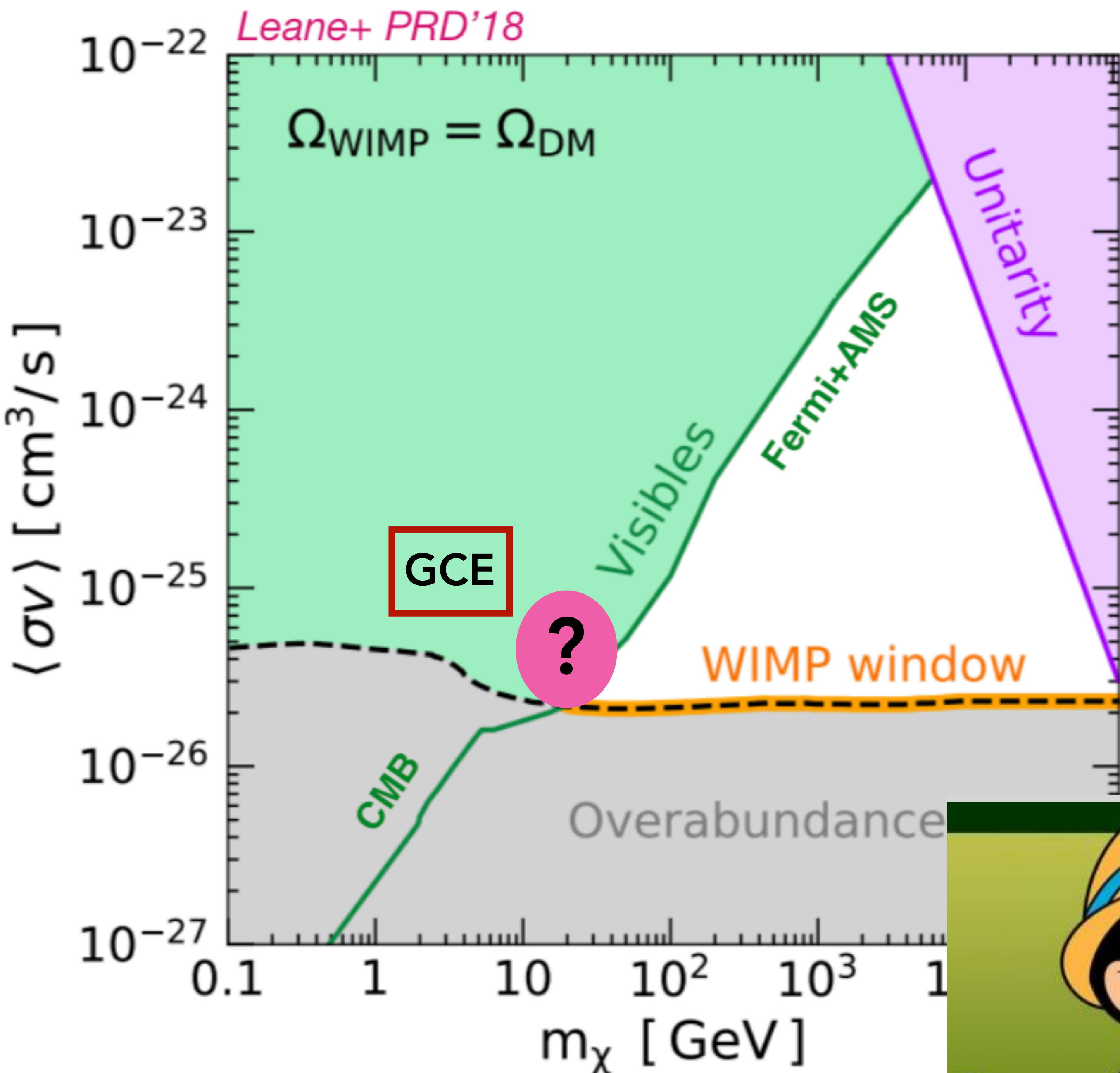
Mind the gap: the fact that reality is not part of the (background) model is a limiting factor of many (all?) current works. **Which current results trustable?**

ML (Deep SVDDs) offer a possibility to test severity of the reality gap [Caron+, JCAP 06 (2023) 013]

The big picture







Multi-wavelength measurements essential:

- **SKA** (pulsars in radio) [Calore+, Astrophys.J. 827 (2016)]
- **CTA** (IC from electrons injected by pulsars) [Manconi+, 2402.04733, etc]

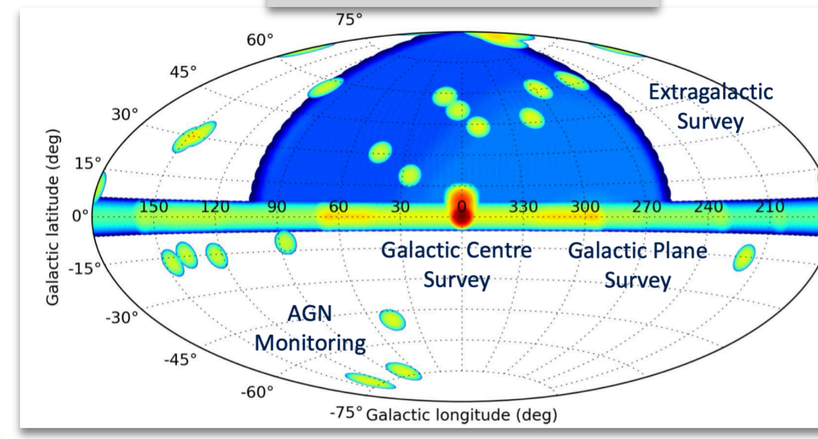
M… background) model is a limiting factor of

m… **table?**

ML (Deep SVDDs) offer a possibility to test severity of the reality gap [Caron+, JCAP 06 (2023) 013]

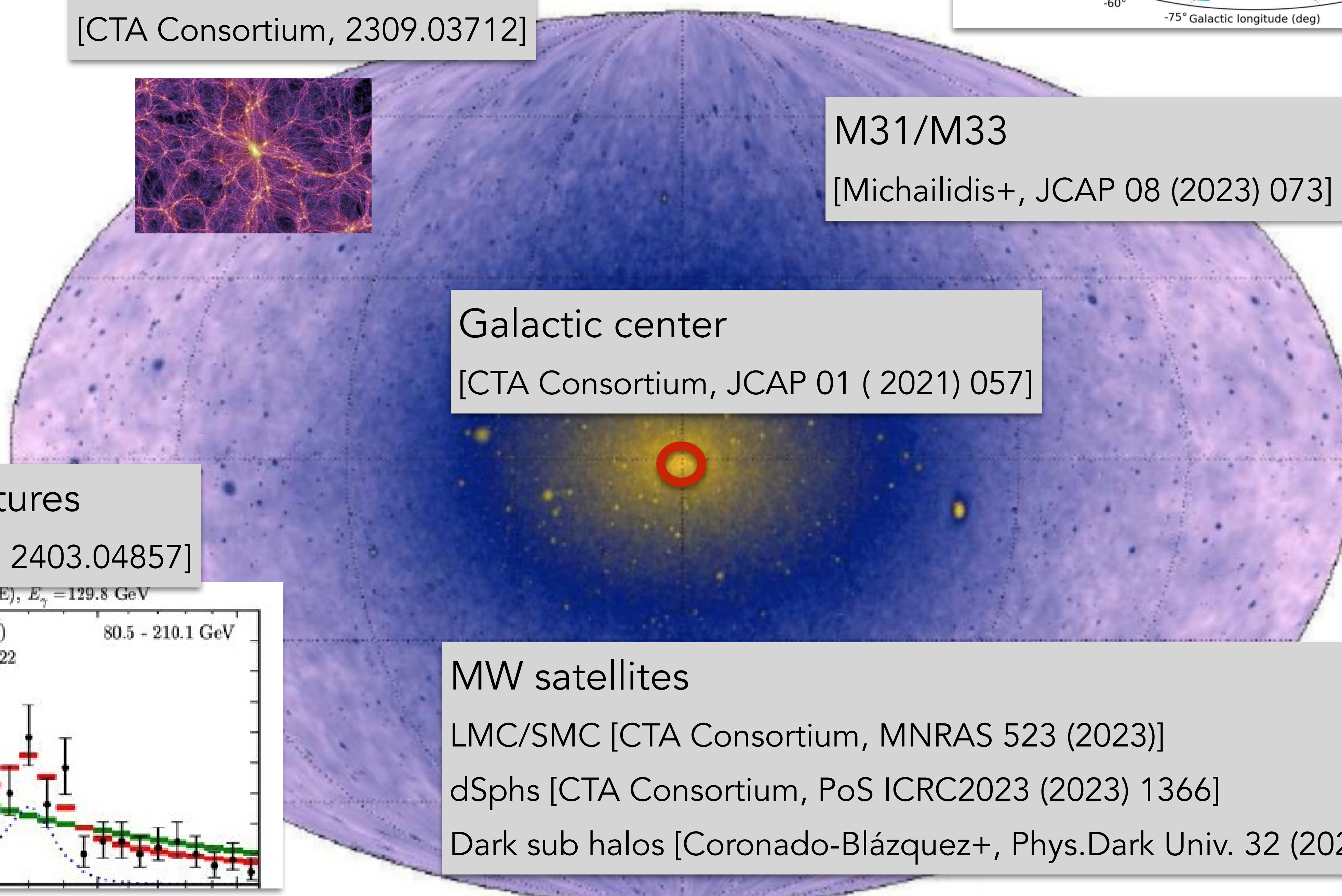
CTAOs sensitivity to thermal DM

CTA exposure



Galaxy Clusters

[CTA Consortium, 2309.03712]



M31/M33

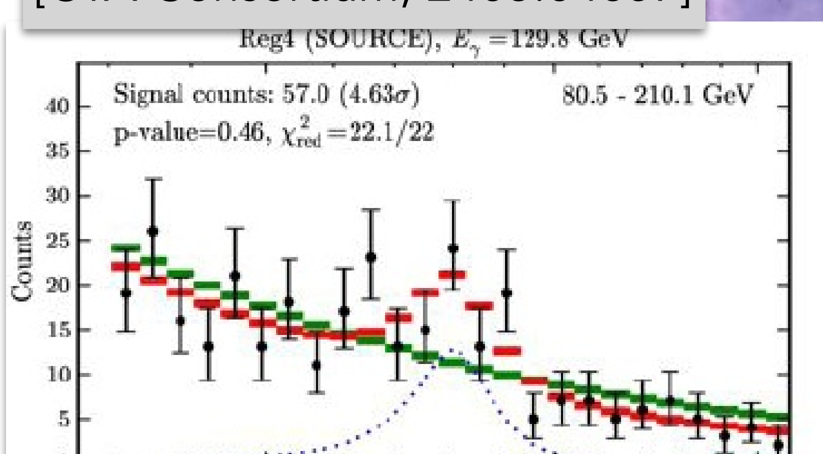
[Michailidis+, JCAP 08 (2023) 073]

Galactic center

[CTA Consortium, JCAP 01 (2021) 057]

Spectral signatures

[CTA Consortium, 2403.04857]



MW satellites

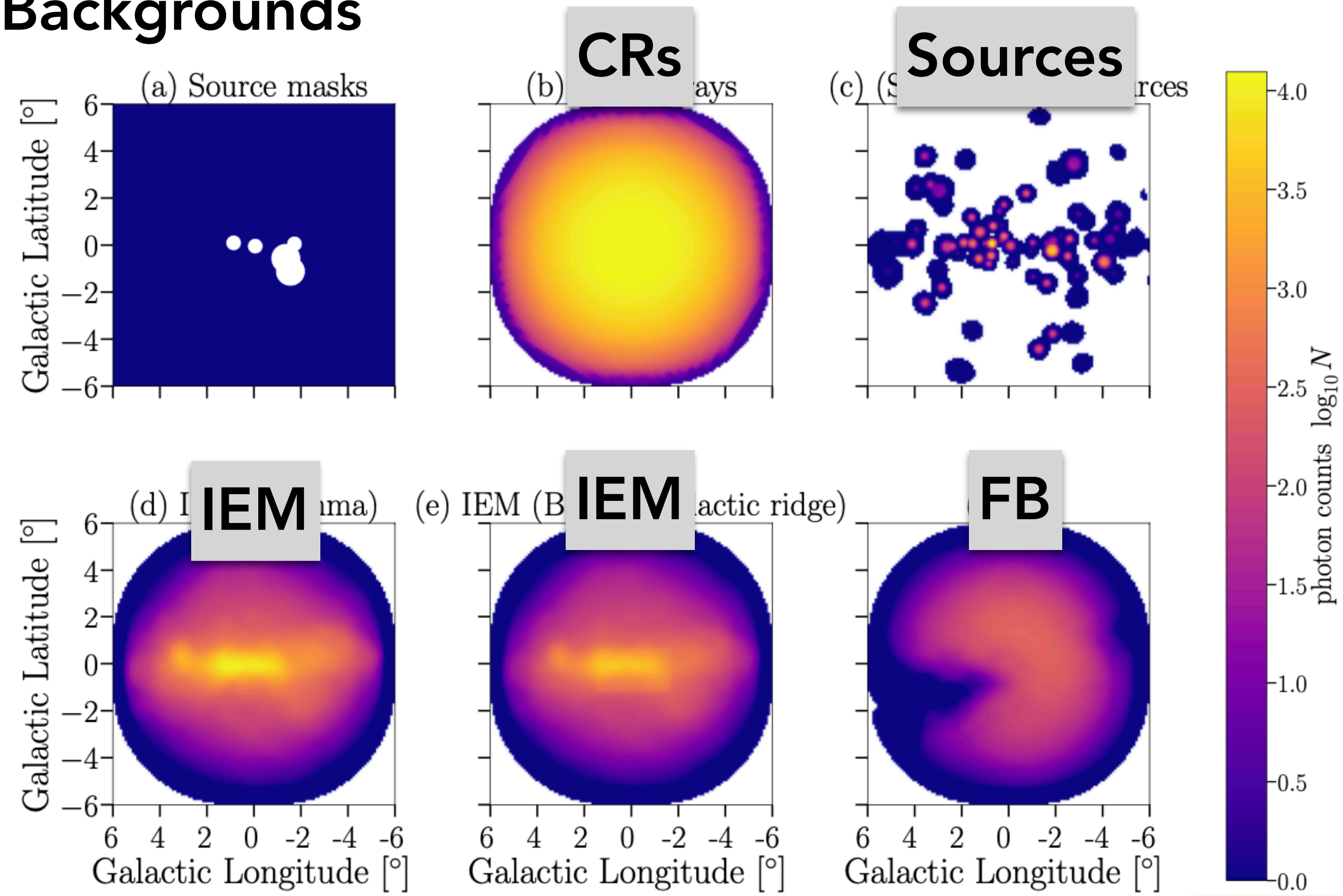
LMC/SMC [CTA Consortium, MNRAS 523 (2023)]

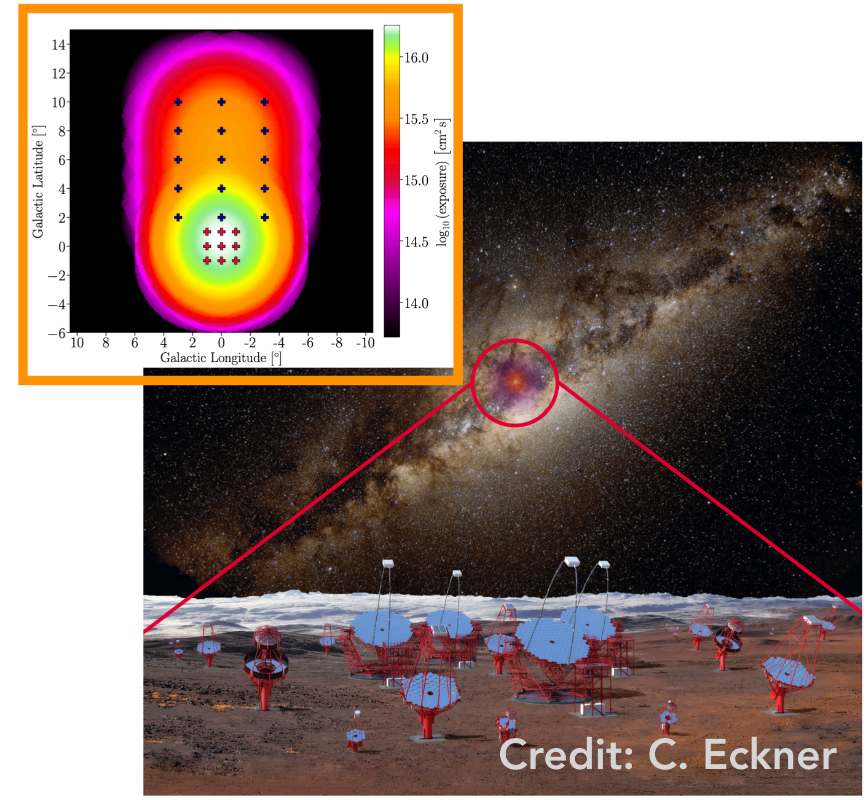
dSphs [CTA Consortium, PoS ICRC2023 (2023) 1366]

Dark sub halos [Coronado-Blázquez+, Phys.Dark Univ. 32 (2021) 100845]

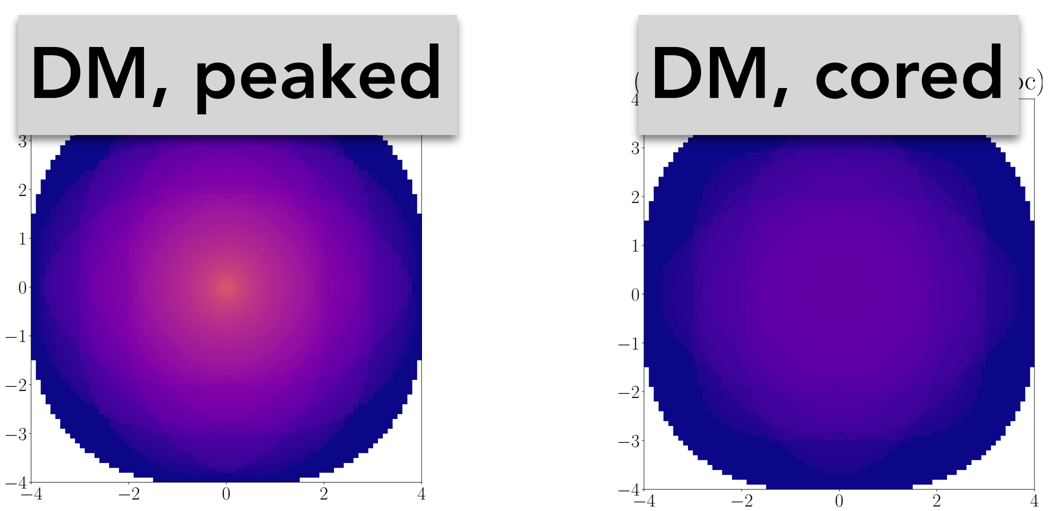
Target 1: Galactic Center, smooth spectra

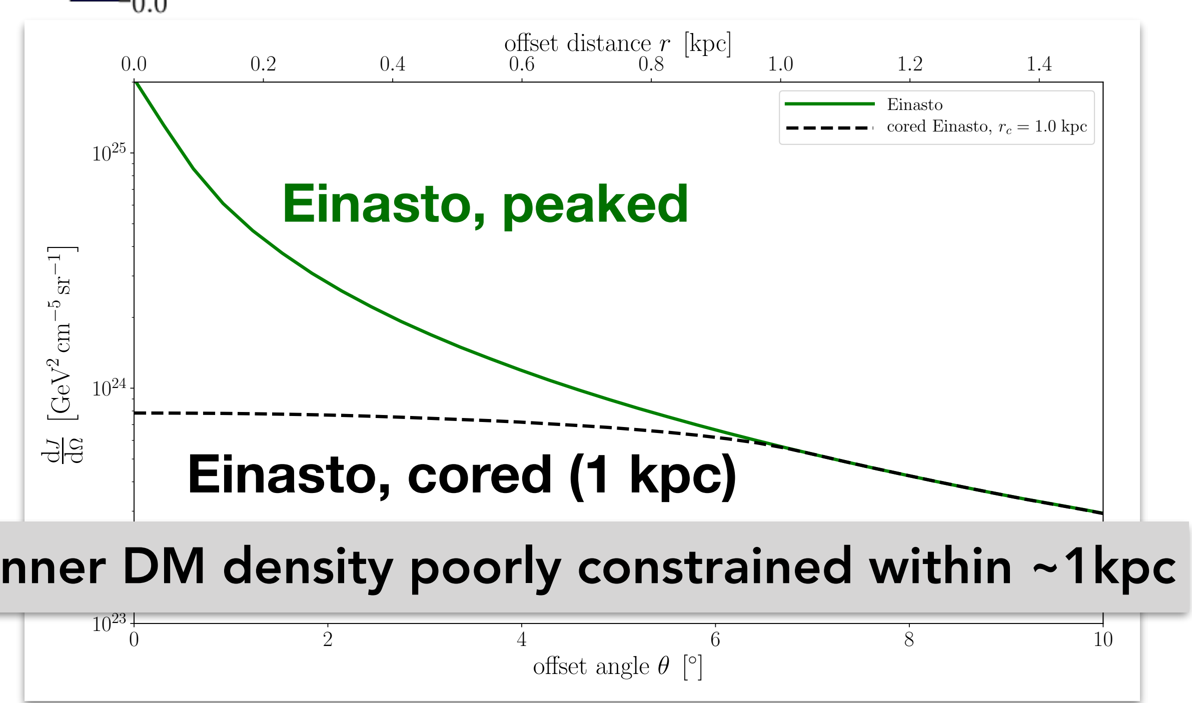
Backgrounds





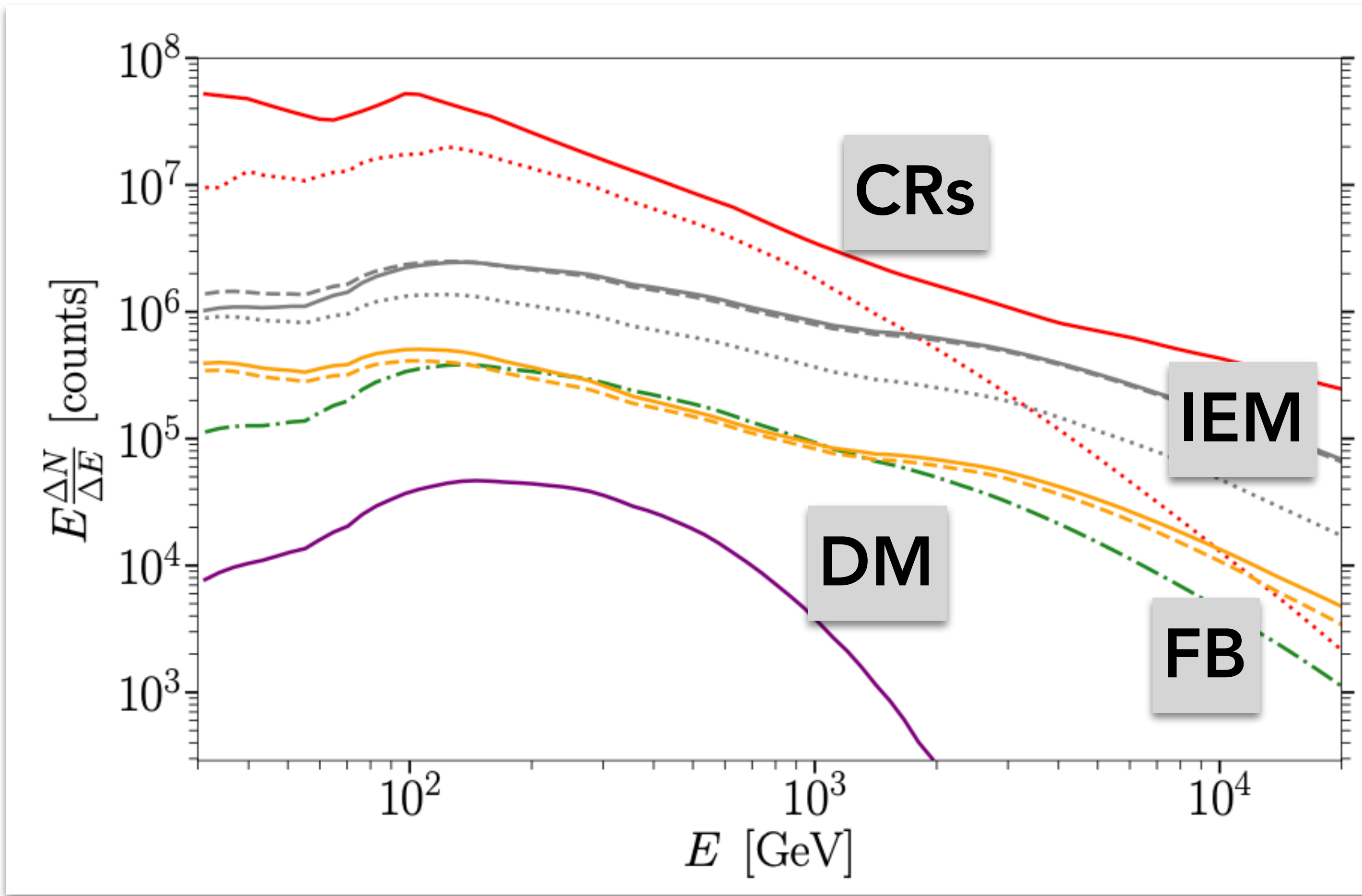
Signal





Target 1: Galactic Center, smooth spectra

Spectra



Analysis

Likelihood (template fitting):

$$\mathcal{L}(\boldsymbol{\mu}|\boldsymbol{n}) = \prod_{k=1}^{\mathcal{N}} \frac{\mu_k^{n_k}}{(n_k)!} e^{-\mu_k}$$

+ systematic uncertainty

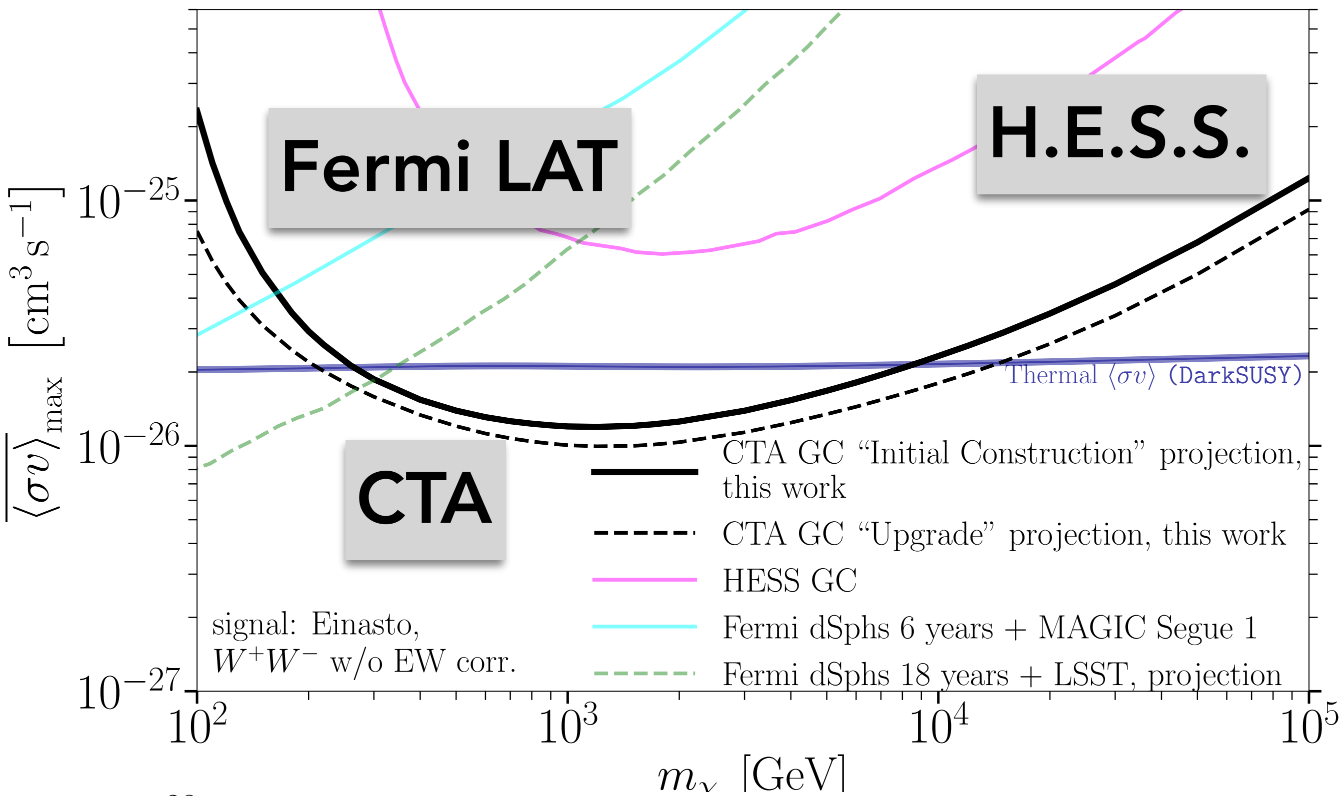
$$\times \exp\left[-\frac{1}{2}\Delta B_k \sum_{l=1}^{\mathcal{N}} \left(K^{-1}\right)_{kl} \Delta B_l\right]$$

CTA likelihood tables for smoothDM spectra available at zenodo.org (https://doi.org/10.5281/zenodo.4057987)

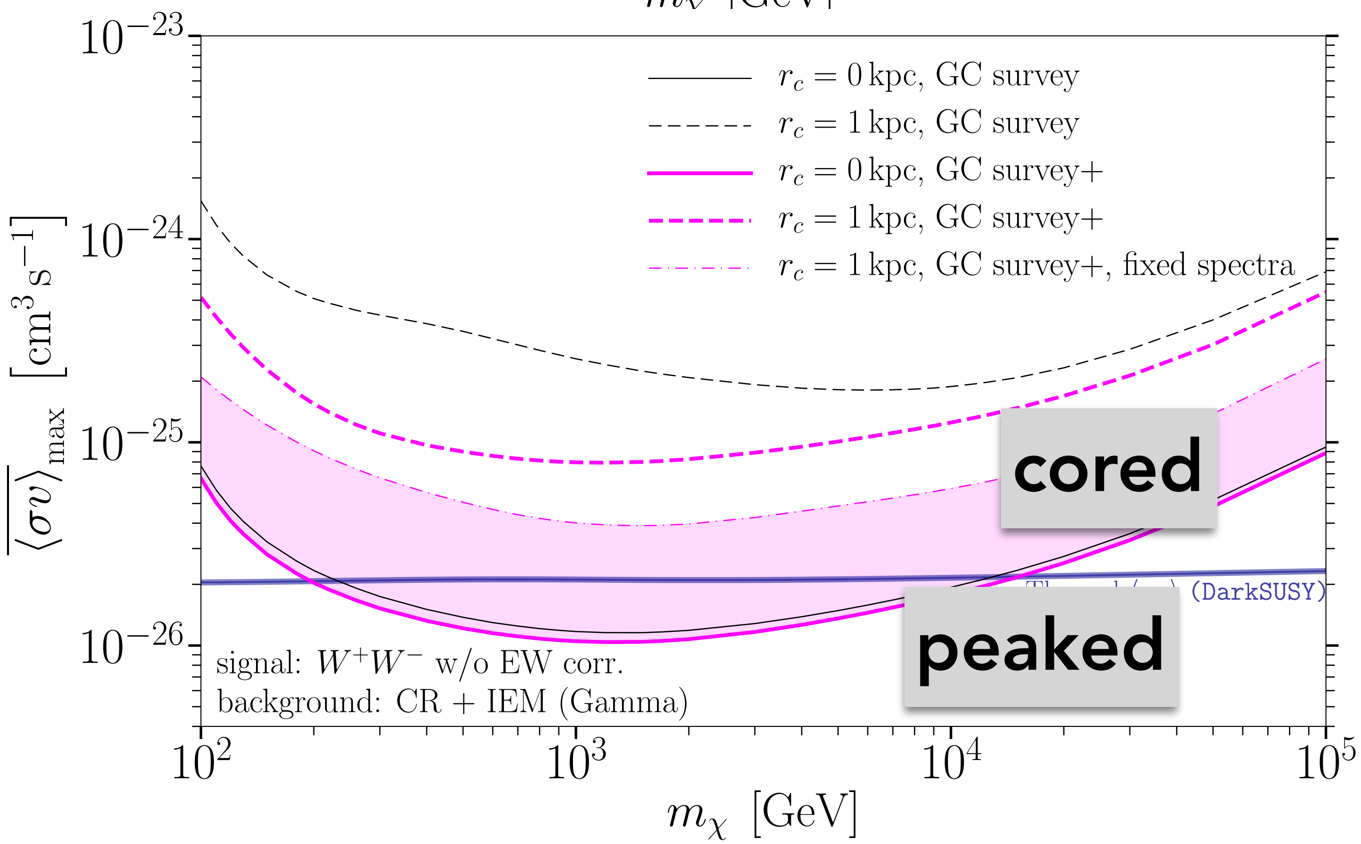
Target 1: Galactic Center, smooth spectra

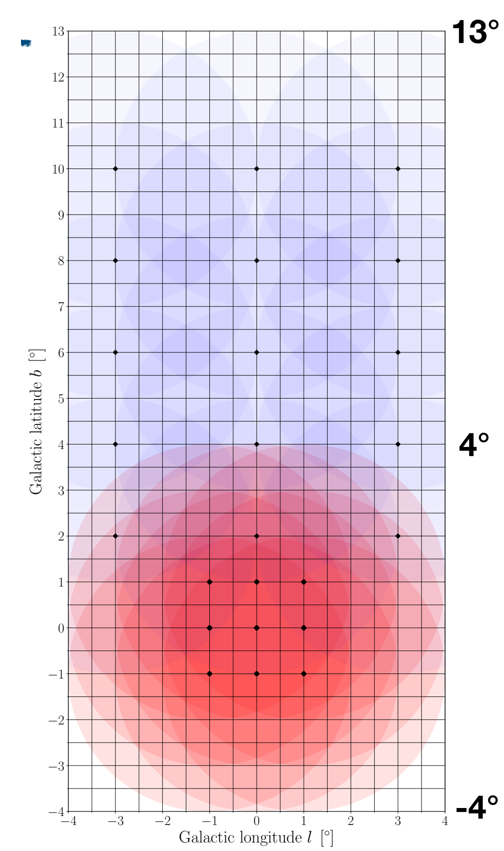
Results

[The CTA Consortium, JCAP 01 (2021) 057]



CTA will be able to probe thermal cross section with the GC survey data





The additional extended GC survey significantly improves the prospects regarding cored profiles.

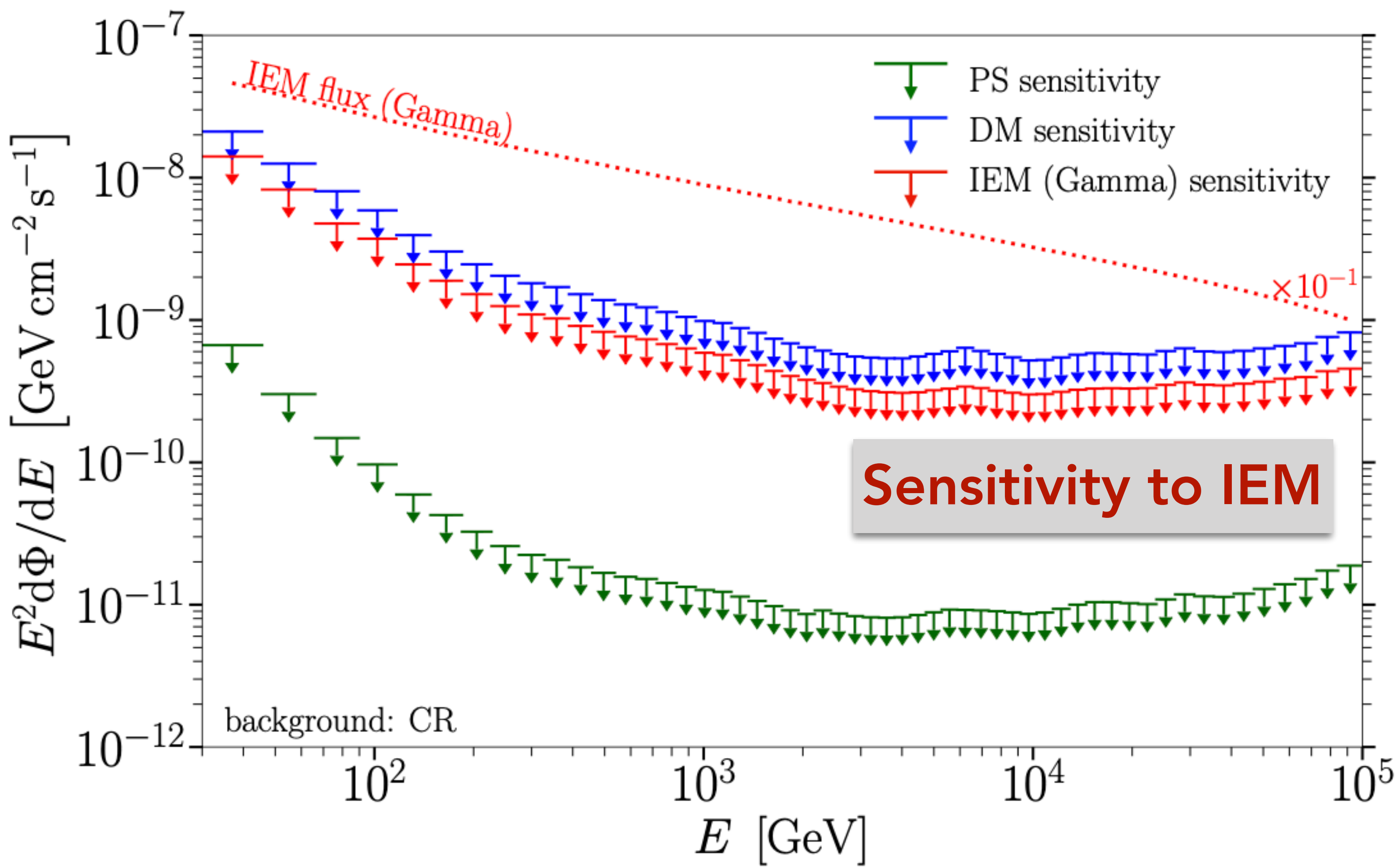
Target 1: Galactic Center, smooth spectra

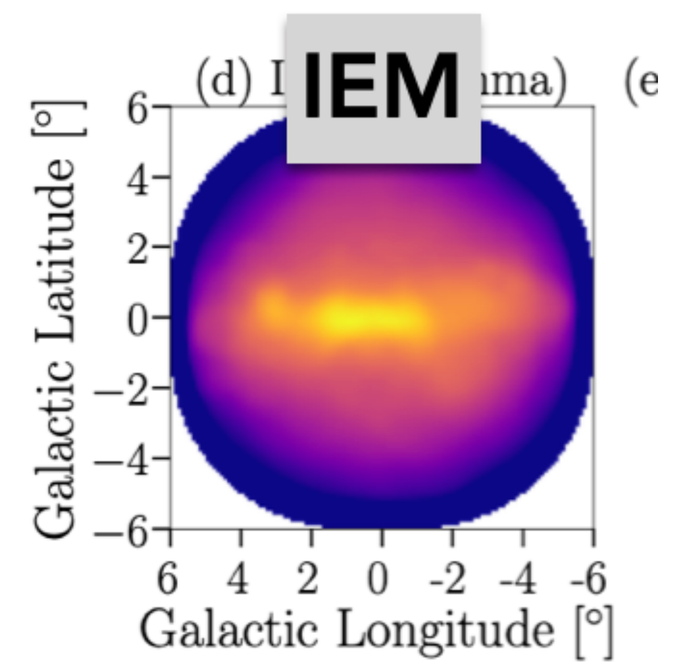
Results

Know thy 'backgrounds'

- diffuse emission (IC in particular) - the most important background for DM search at the GC
- Determination of **IC —> GCE**

[The CTA Consortium, JCAP 01 (2021) 057]





Target 1: Galactic Center, spectral features

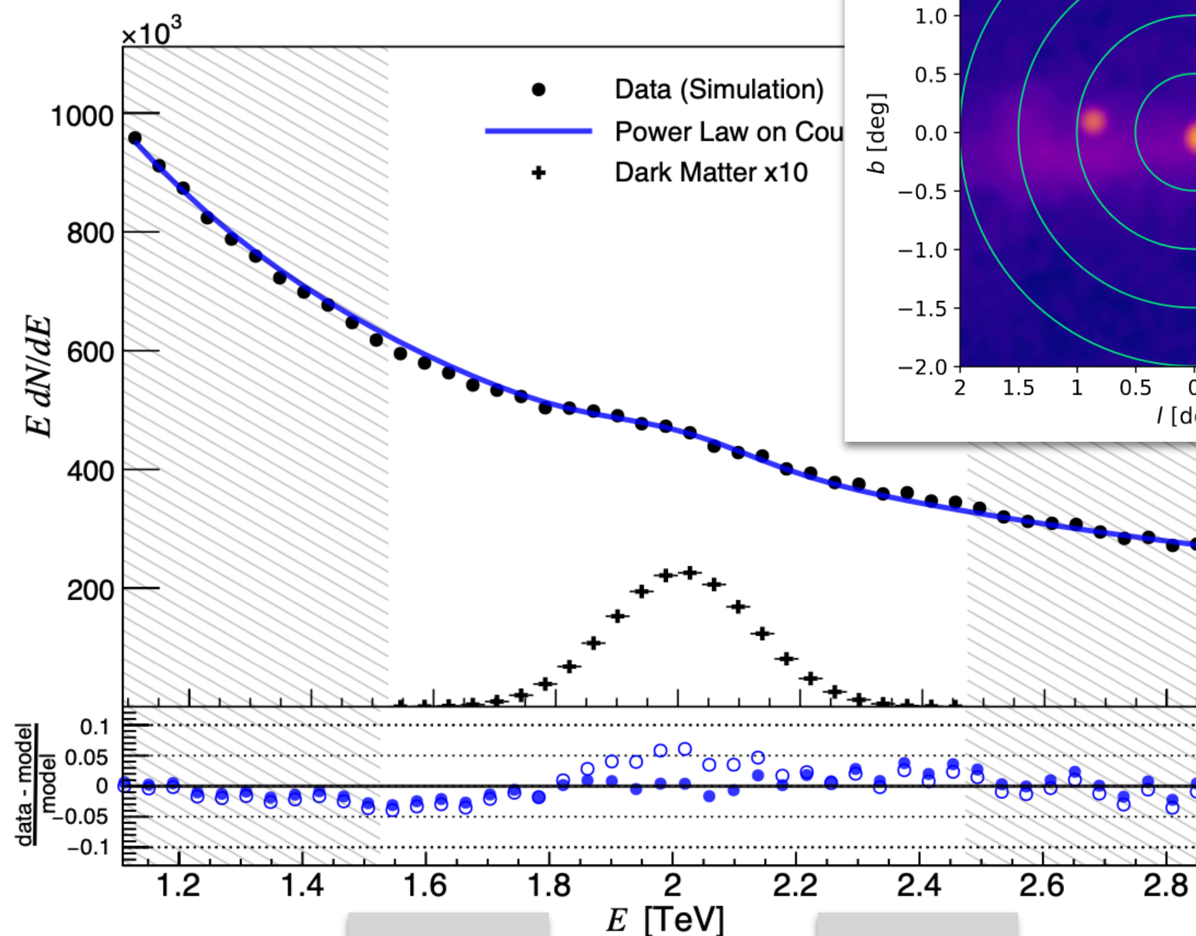
excellent energy resolution of CTA $\Delta E/E \sim 5-8\,\%$ (E >1 TeV)

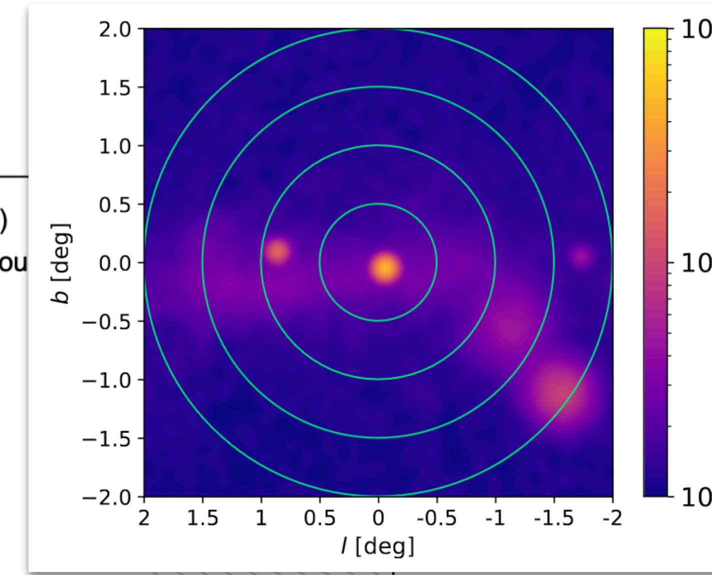
Studies of:

— annihilation (loop suppressed)

— virtual internal Bremsstrahlung

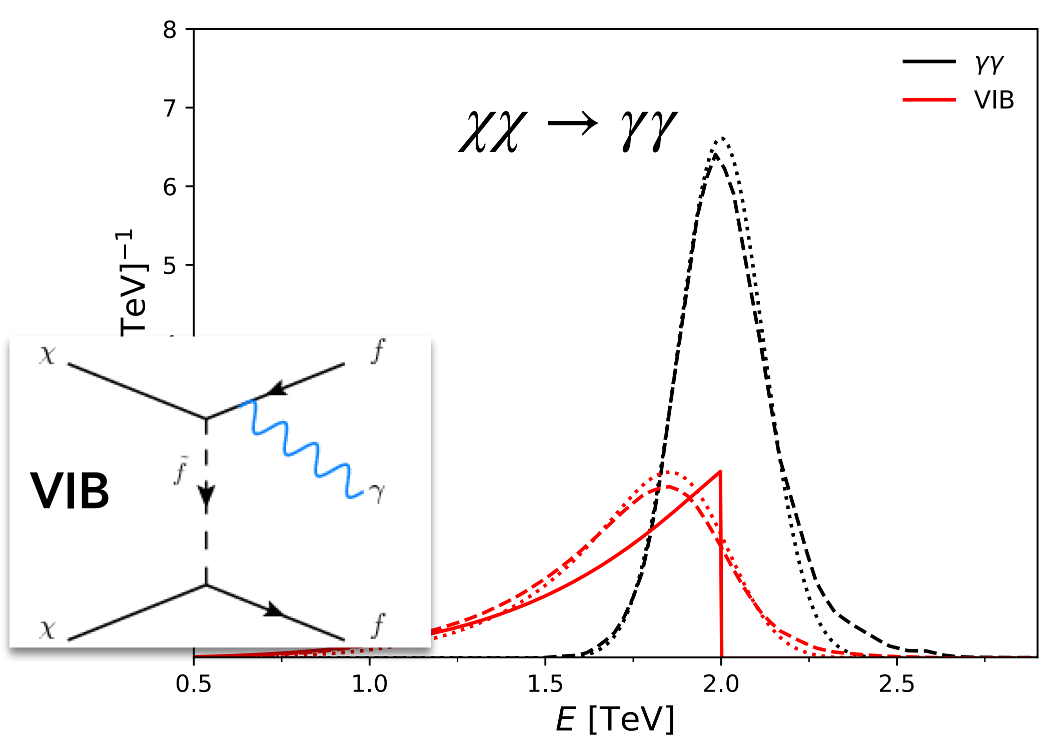
— decay of long-lived mediators (box-shaped)

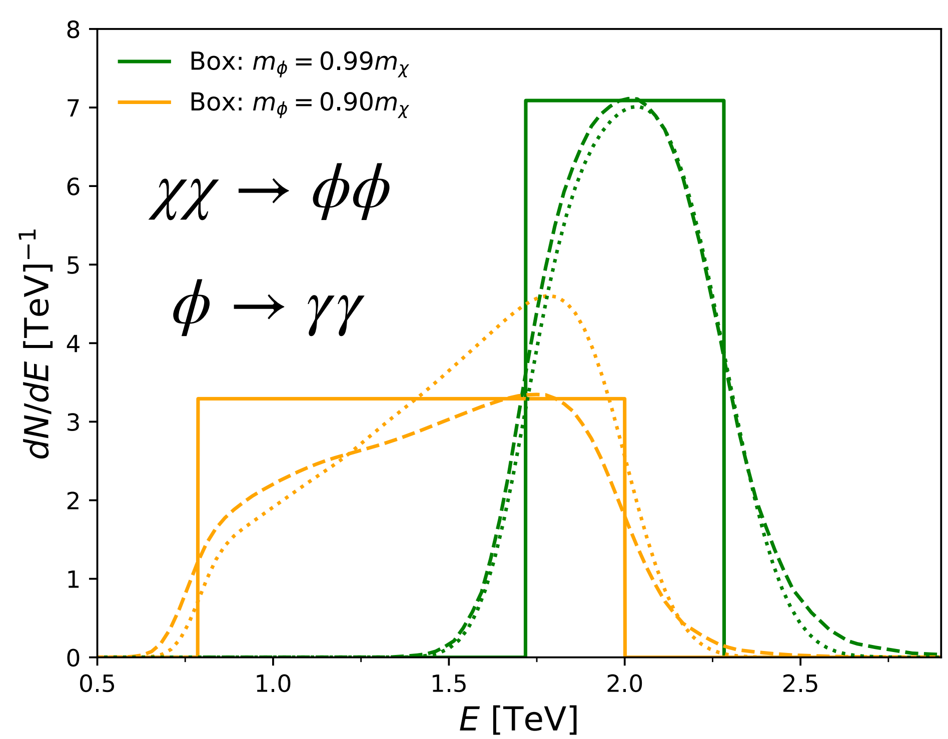




1.6 TeV

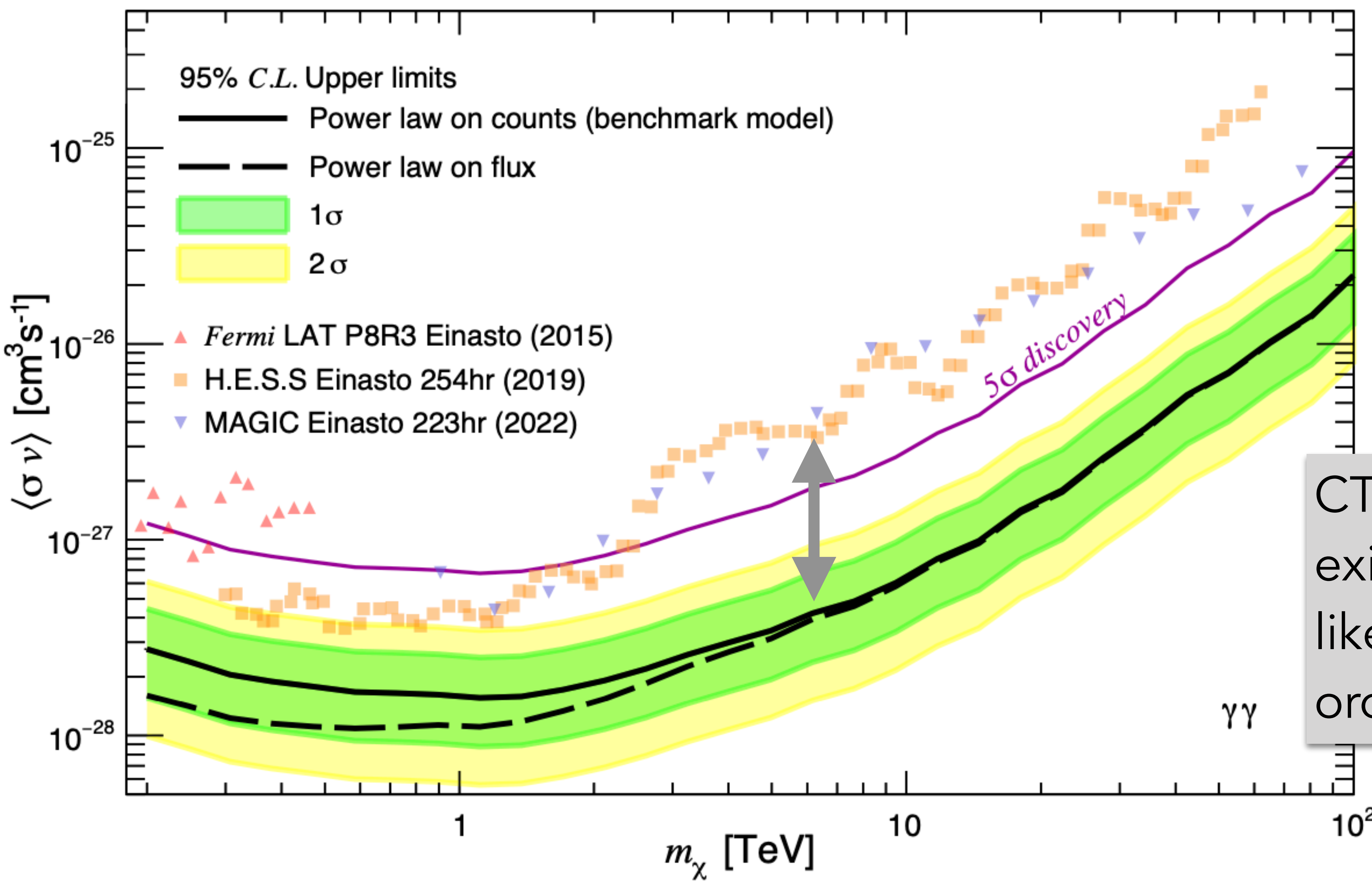
2.4 TeV





Target 1: Galactic Center, spectral features

Results

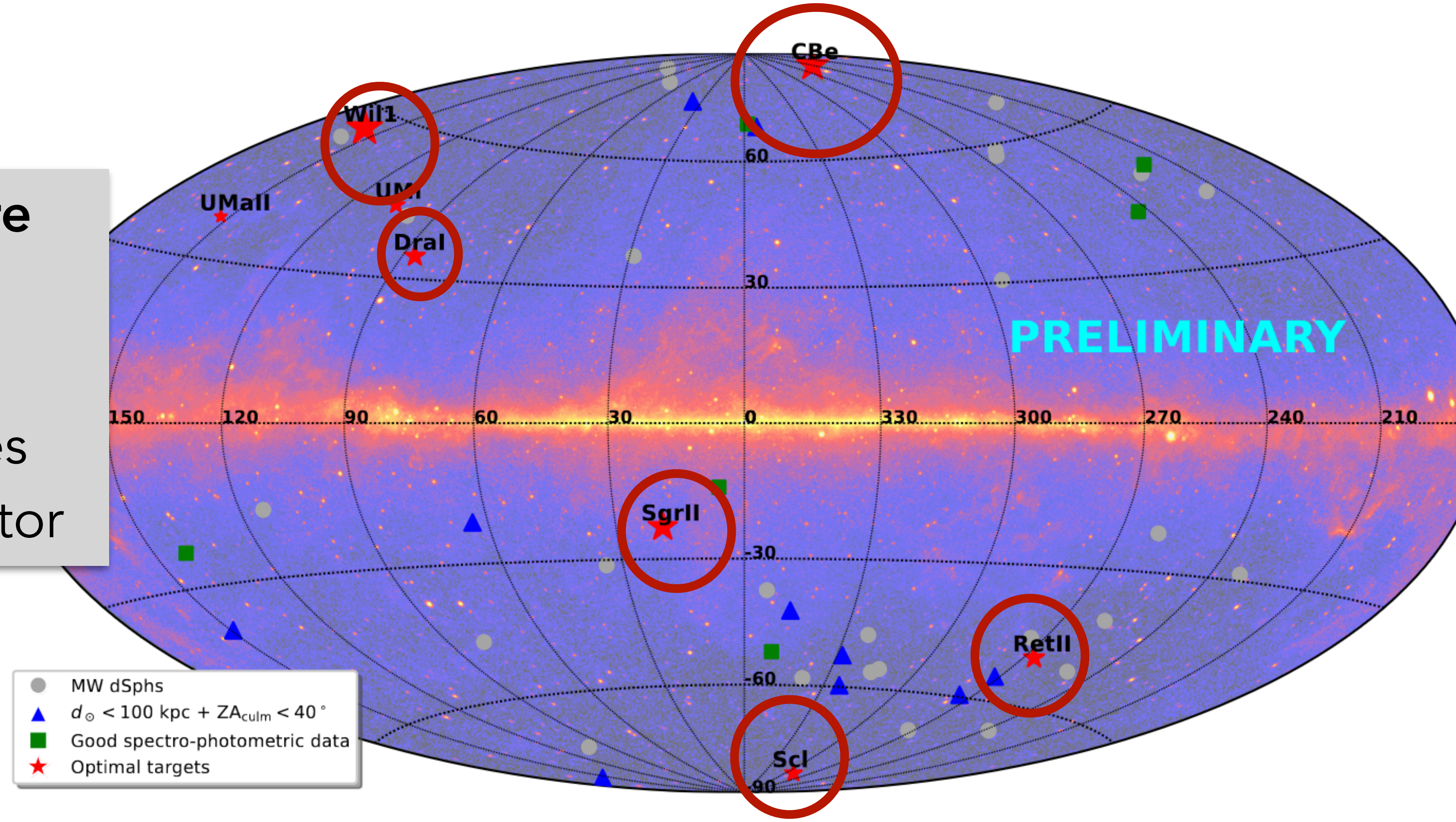


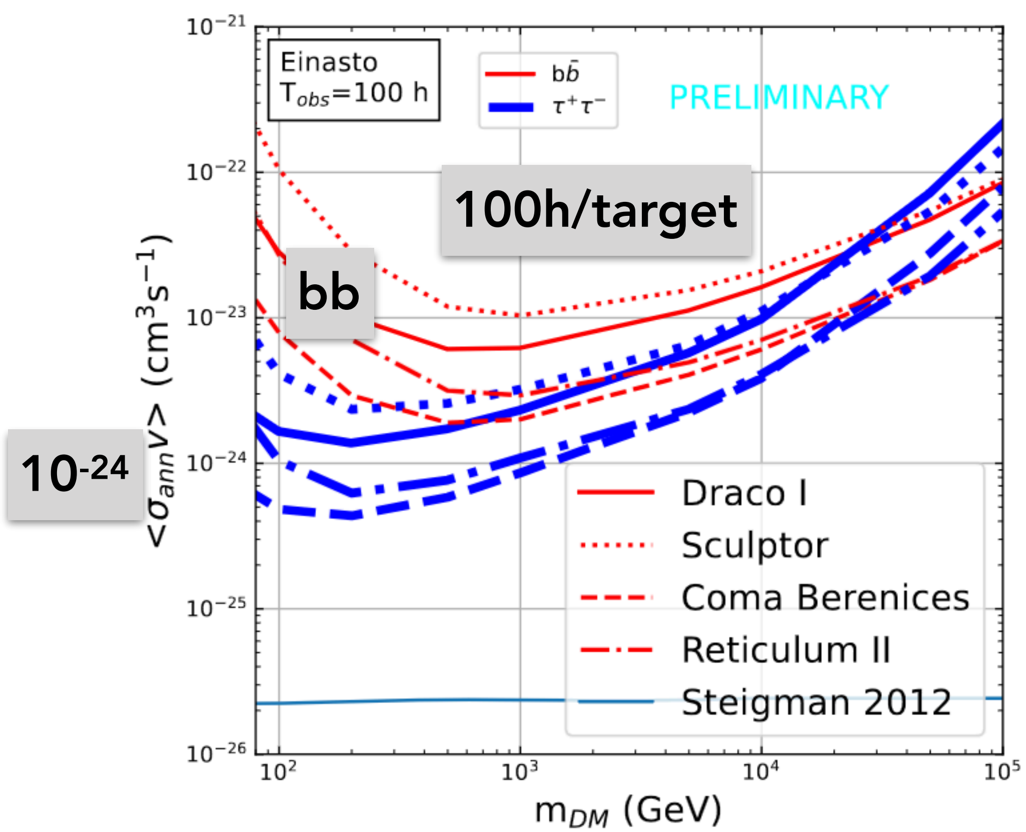
CTA will improve existing limits on line-like searches by an order of magnitude.

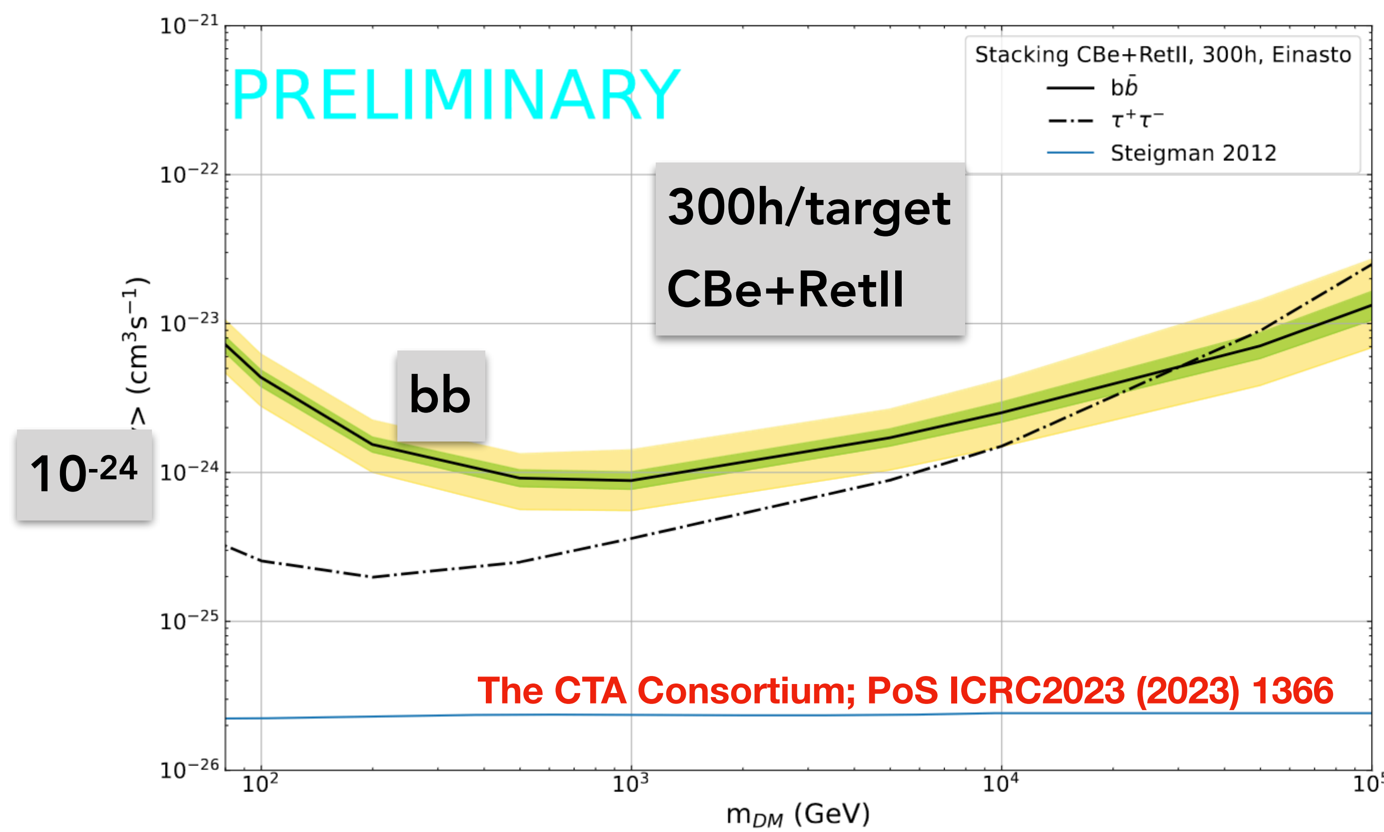
CTA likelihood tables for line-like DM spectra available at zenodo.org (https://doi.org/10.5281/zenodo.10792466)

Target 2: dSphs

Three dSphs per hemisphere
—> have the best trade-off between the expected signal intensity and the uncertainties on the astrophysical *J*ann factor





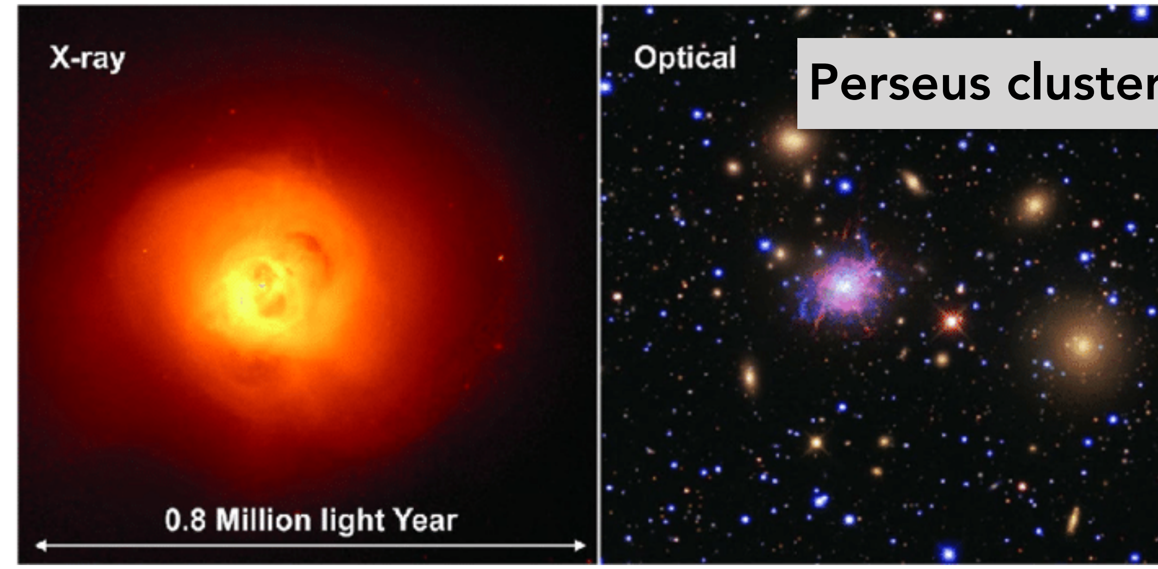


Target 3: Galaxy Clusters

Most massive virialized halos

Large reservoirs of DM but also hot gas and CRs

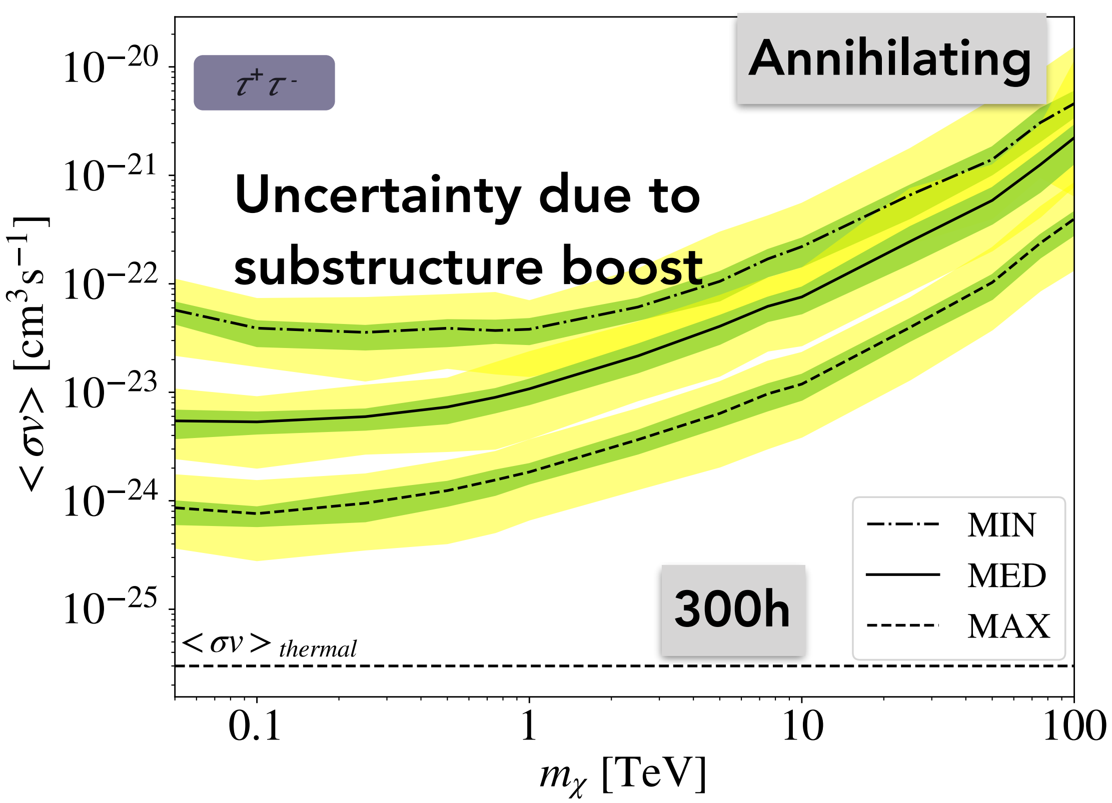
Not yet observed in gamma rays - CTA well positioned for a discovery

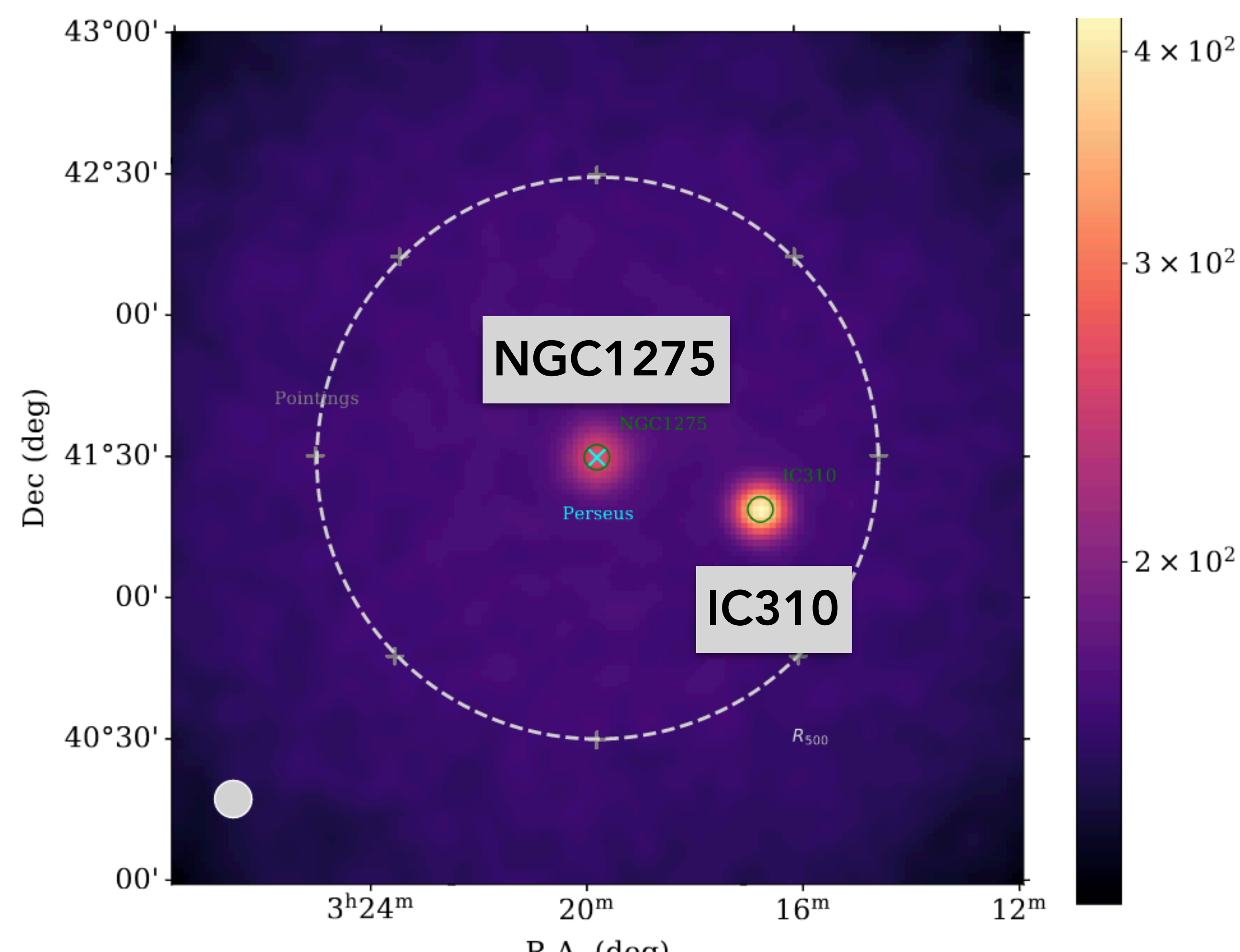


Focus on Perseus Cluster

Likelihood fitting, 8 parameters

$$\vec{\theta} \equiv \left(A_\chi, A_{\rm CR}, A_{\rm PS}^{(1,2)}, \alpha_{\rm PS}^{(1,2)}, A_{\rm bkg}, \alpha_{\rm bkg}\right)$$





[The CTA Consortium; arXiv:2309.03712]

Target 3: Galaxy Clusters

Poster: Pérez-Romero

Perseus cluster

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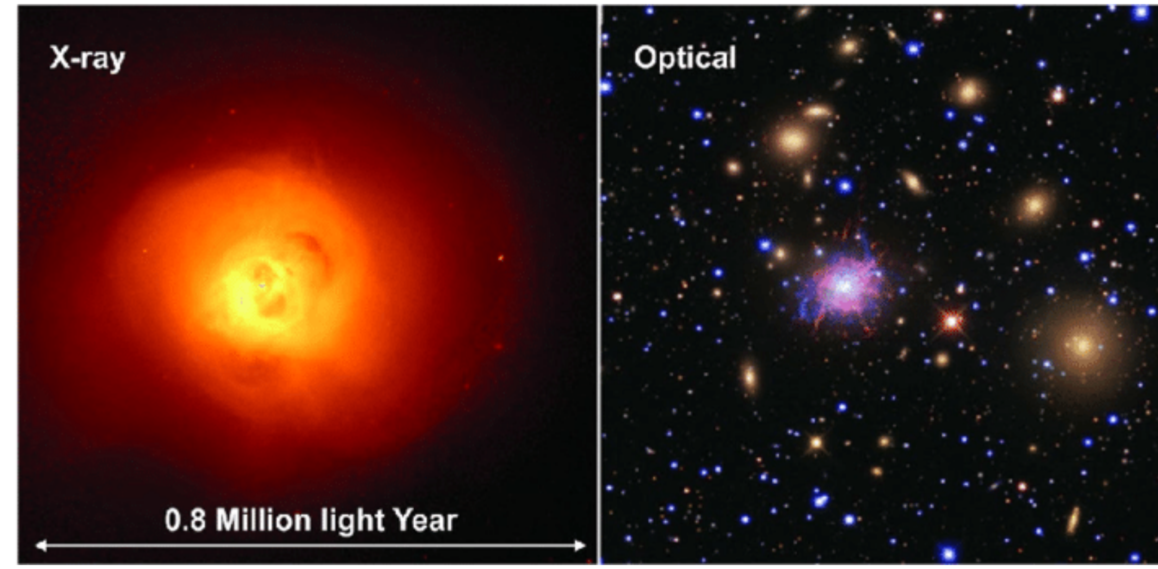
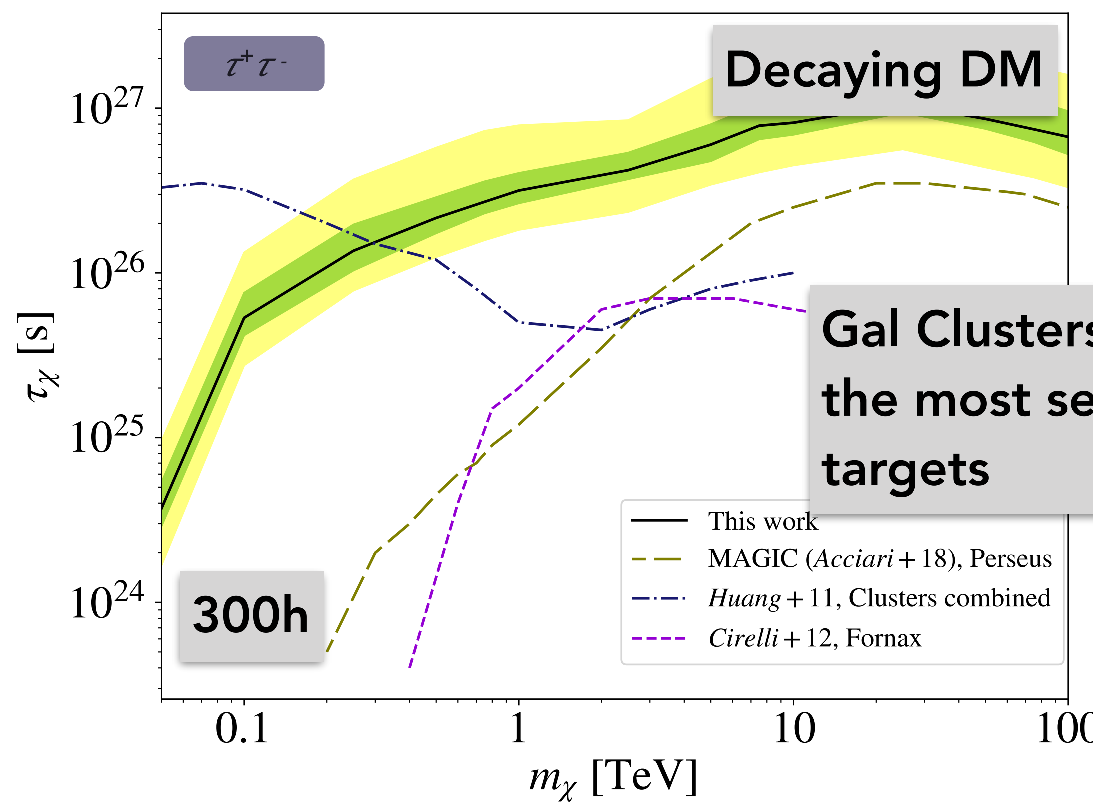
Large reservoirs of DM but also hot gas and CRs

Not yet observed in gamma rays - CTA well positioned for a discovery



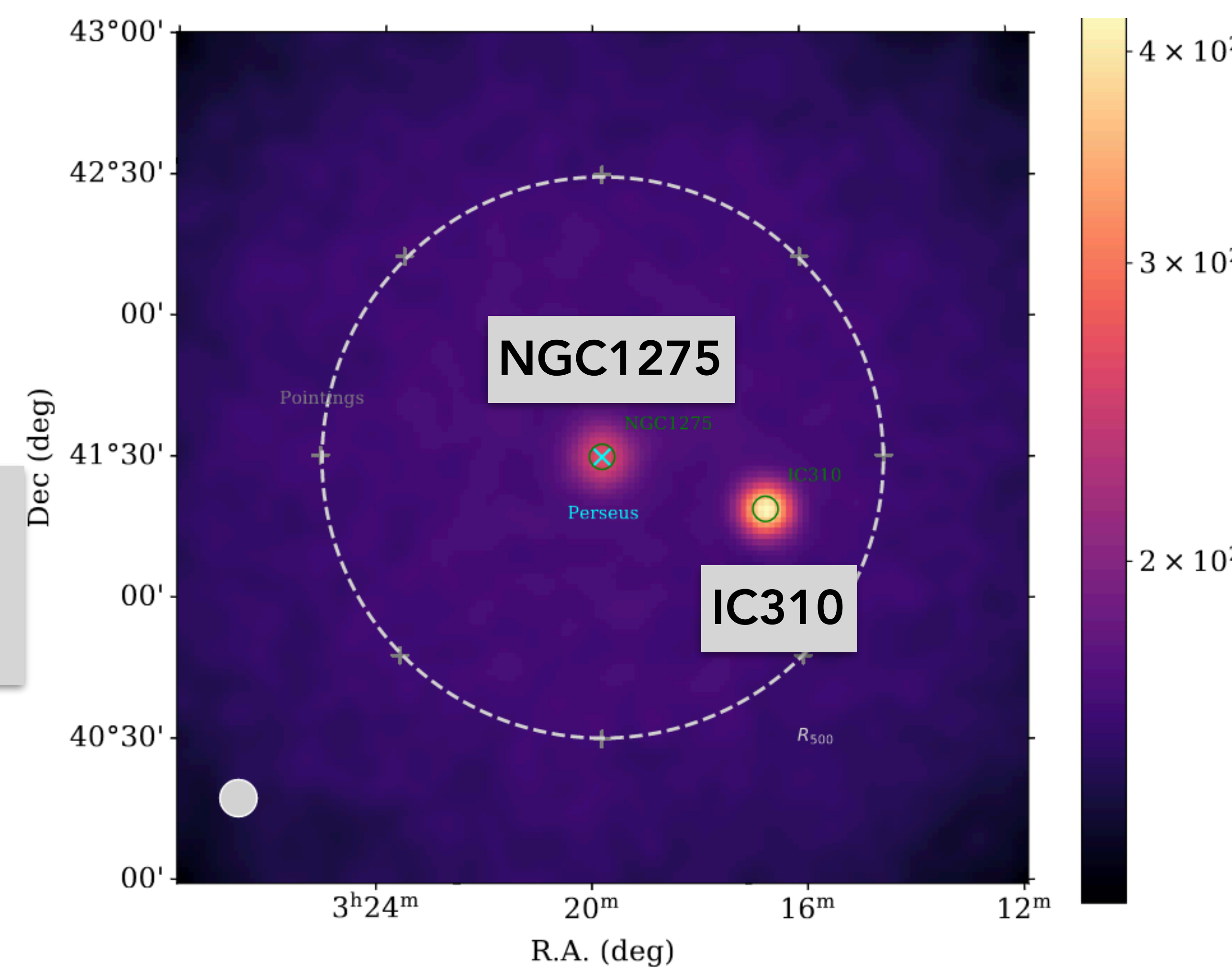
Likelihood fitting, 8 parameters

$$\vec{\theta} \equiv \left(A_\chi, A_{\rm CR}, A_{\rm PS}^{(1,2)}, \alpha_{\rm PS}^{(1,2)}, A_{\rm bkg}, \alpha_{\rm bkg}\right)$$



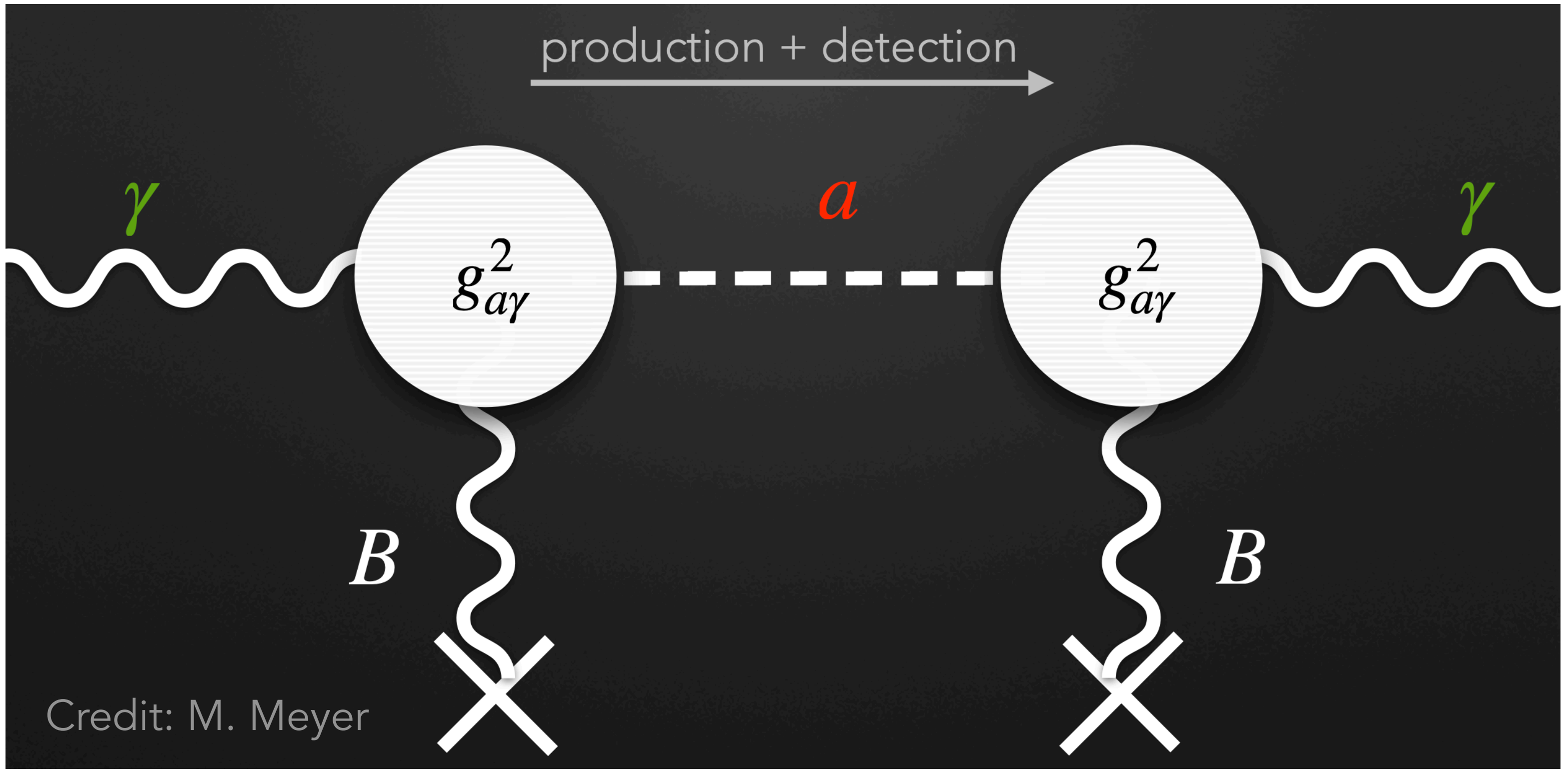
Decaying DM

Gal Clusters among the most sensitive targets



[The CTA Consortium; arXiv:2309.03712]

CTAOs sensitivity to ALPs

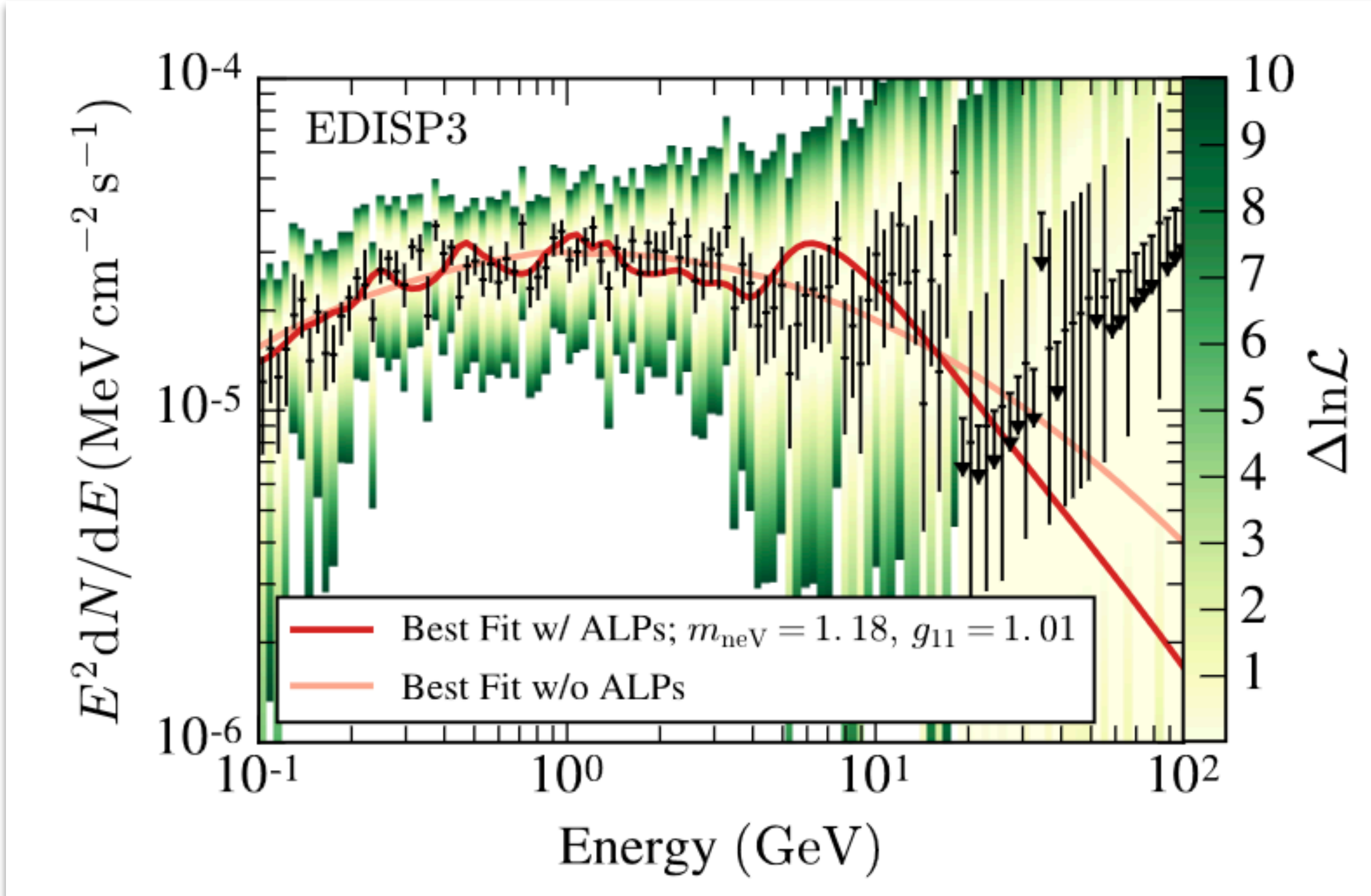


Strong mixing regime:

$$P_{\gamma\gamma}(E, m_a, g_{a\gamma}, \mathbf{B}_j)$$

Where to look?

- strong magnetic fields
- large distances



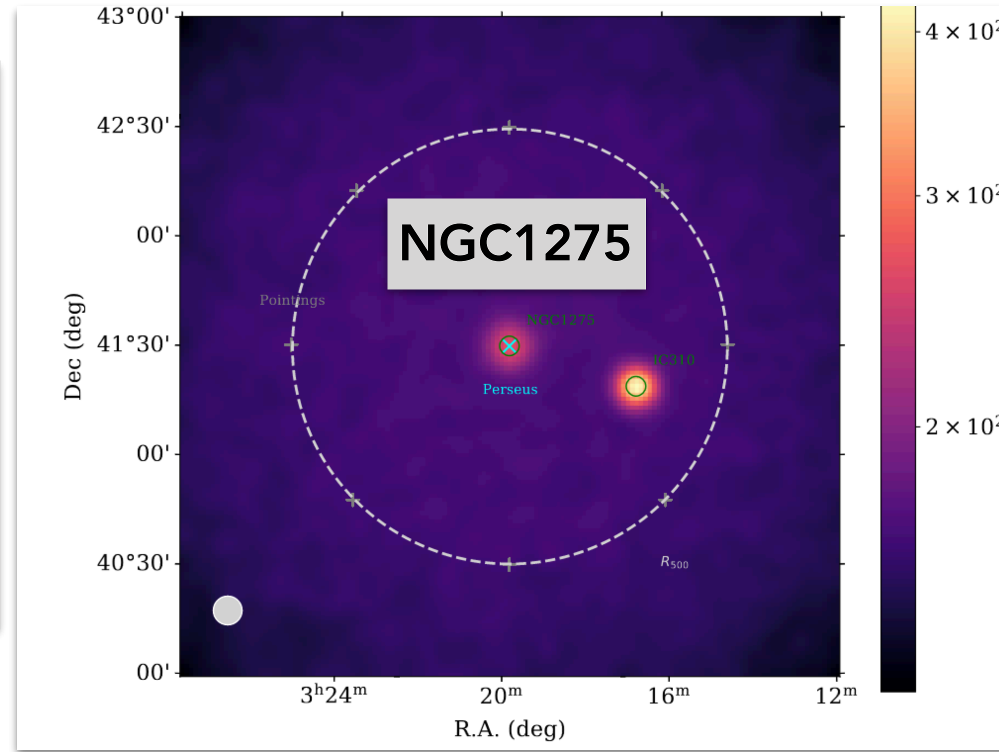
CTAOs sensitivity to ALPs

Galaxy clusters excellent target

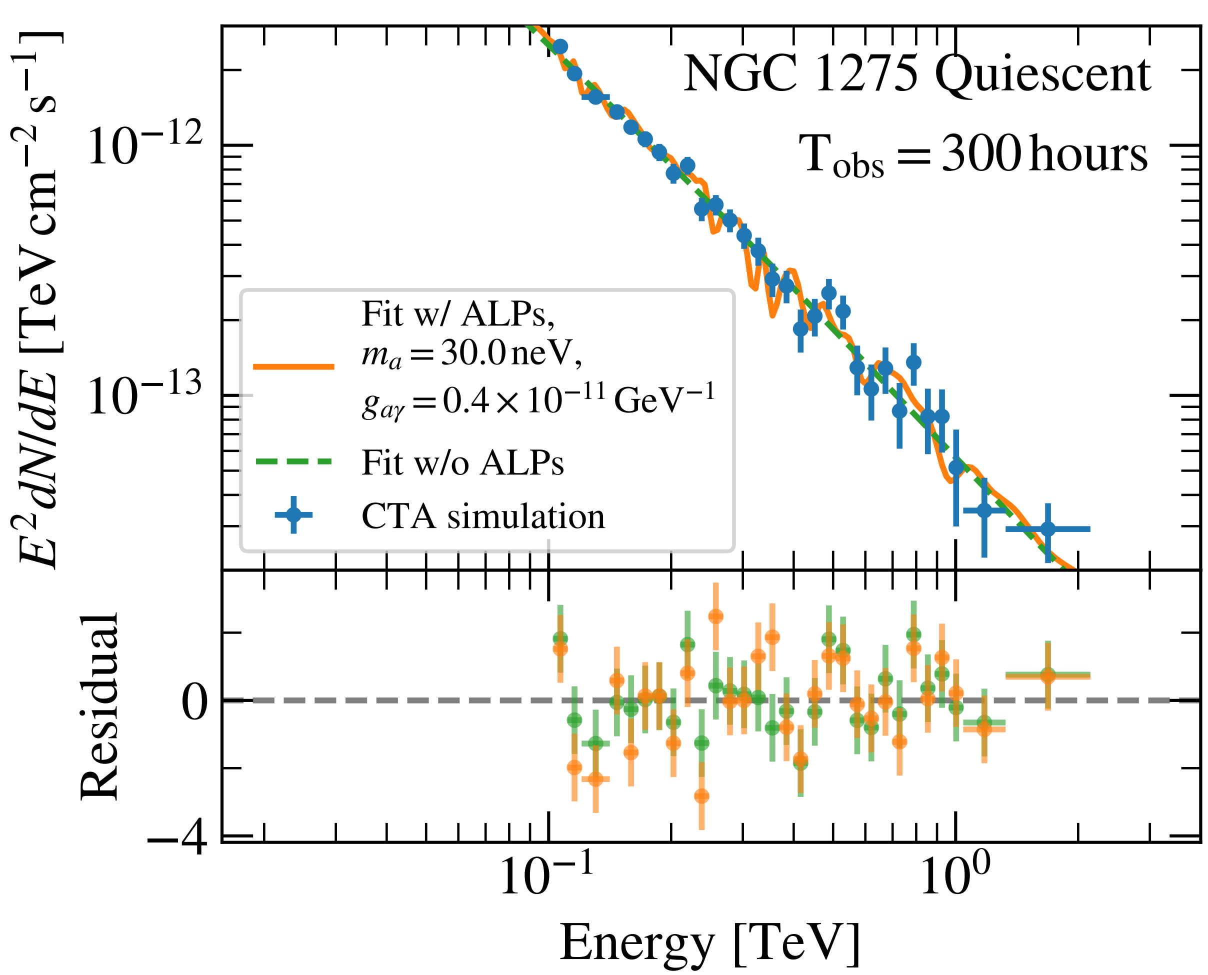
Perseus cluster hosts NGC 1275 AGN at its center and harbours a strong magnetic field, ~25 μG, modeled as a random field with Gaussian turbulence

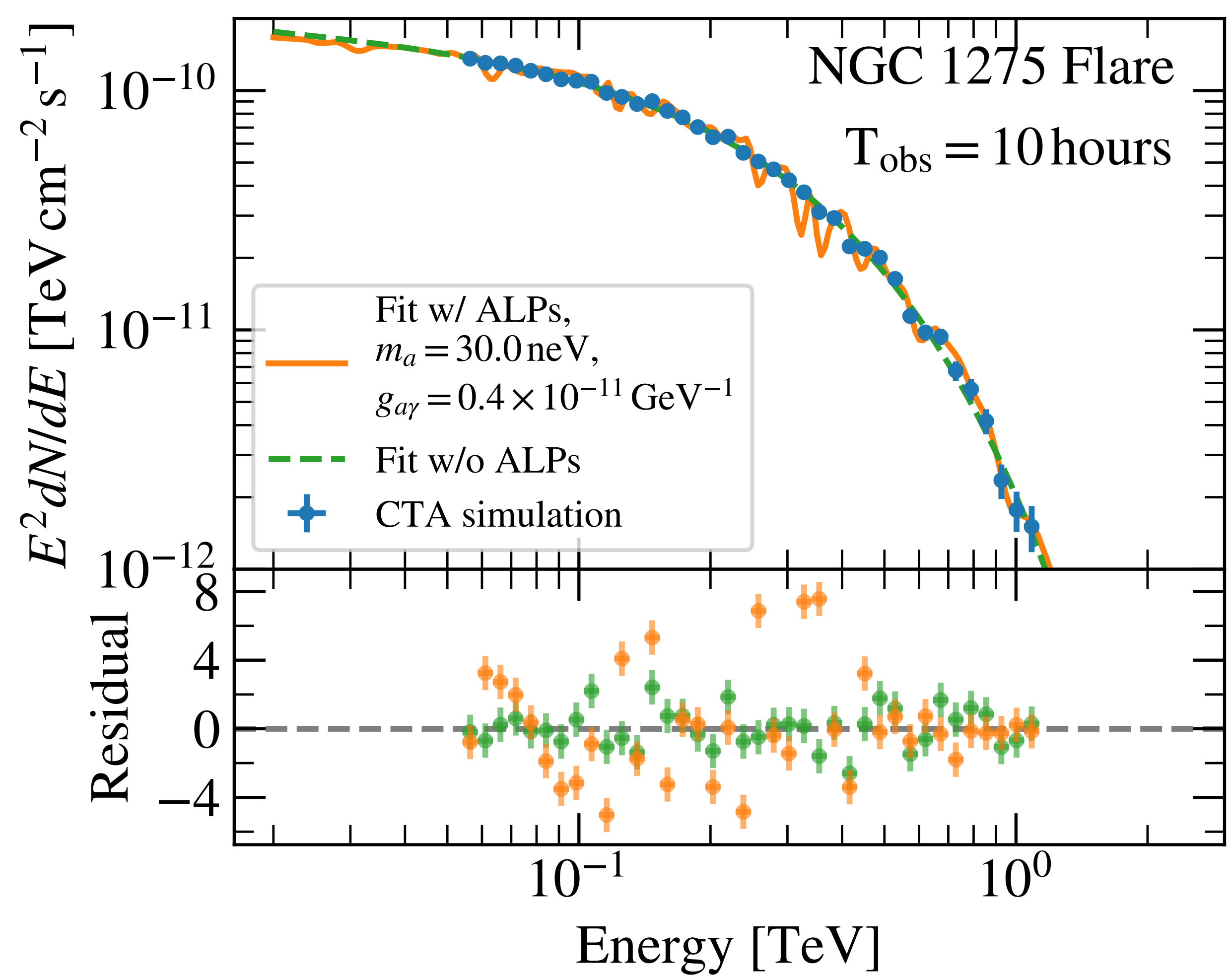
Planned 300h observation

Quiescent or flaring state



[The CTA Consortium; JCAP 02 (2021) 048]





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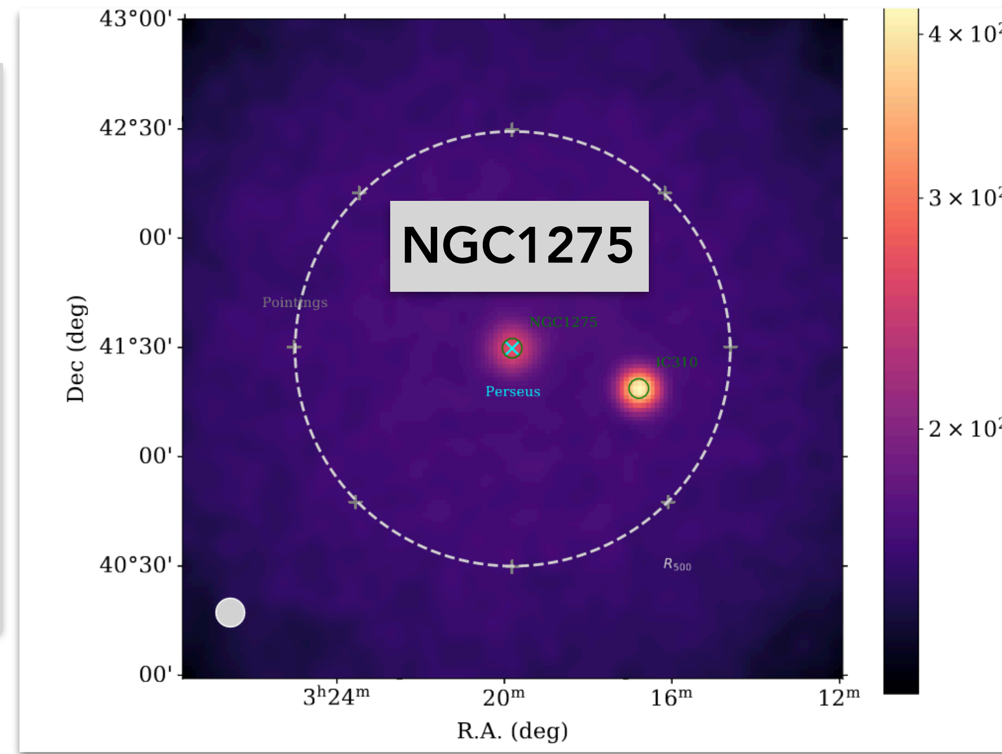
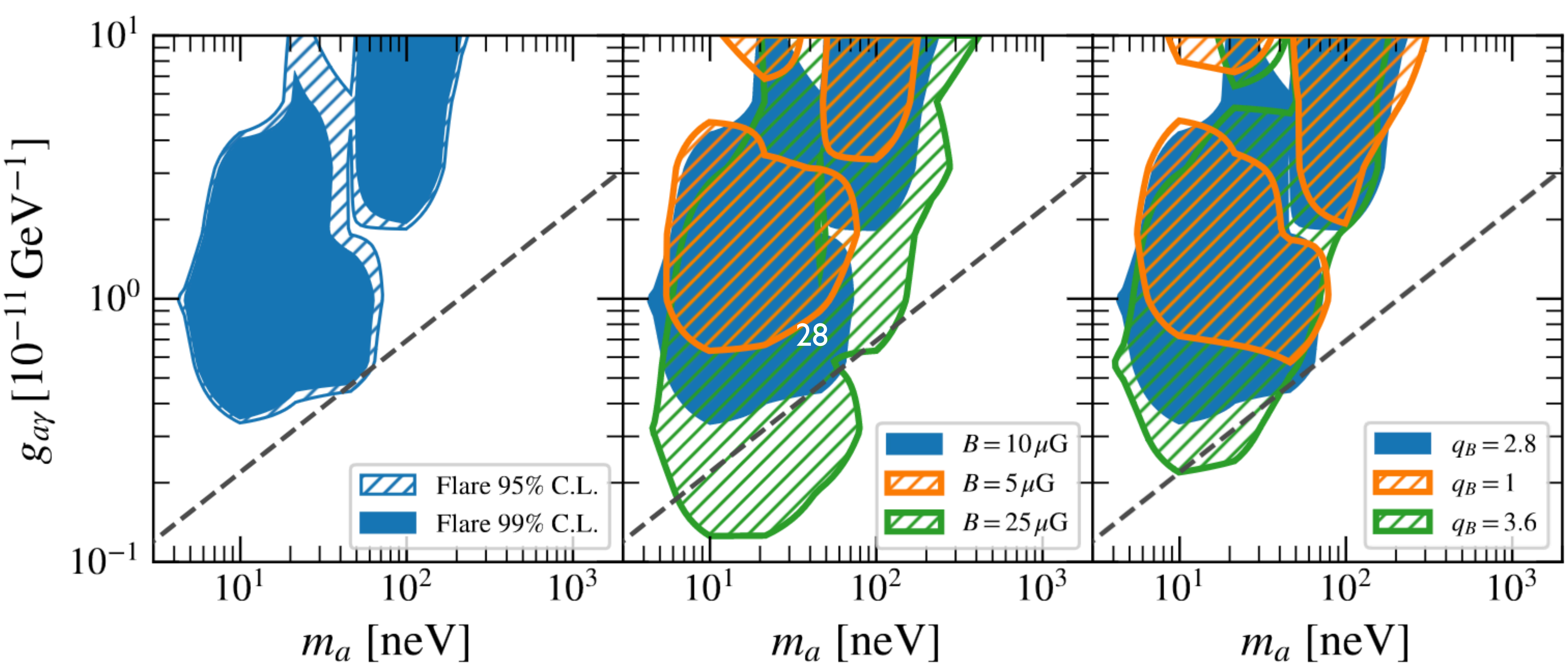
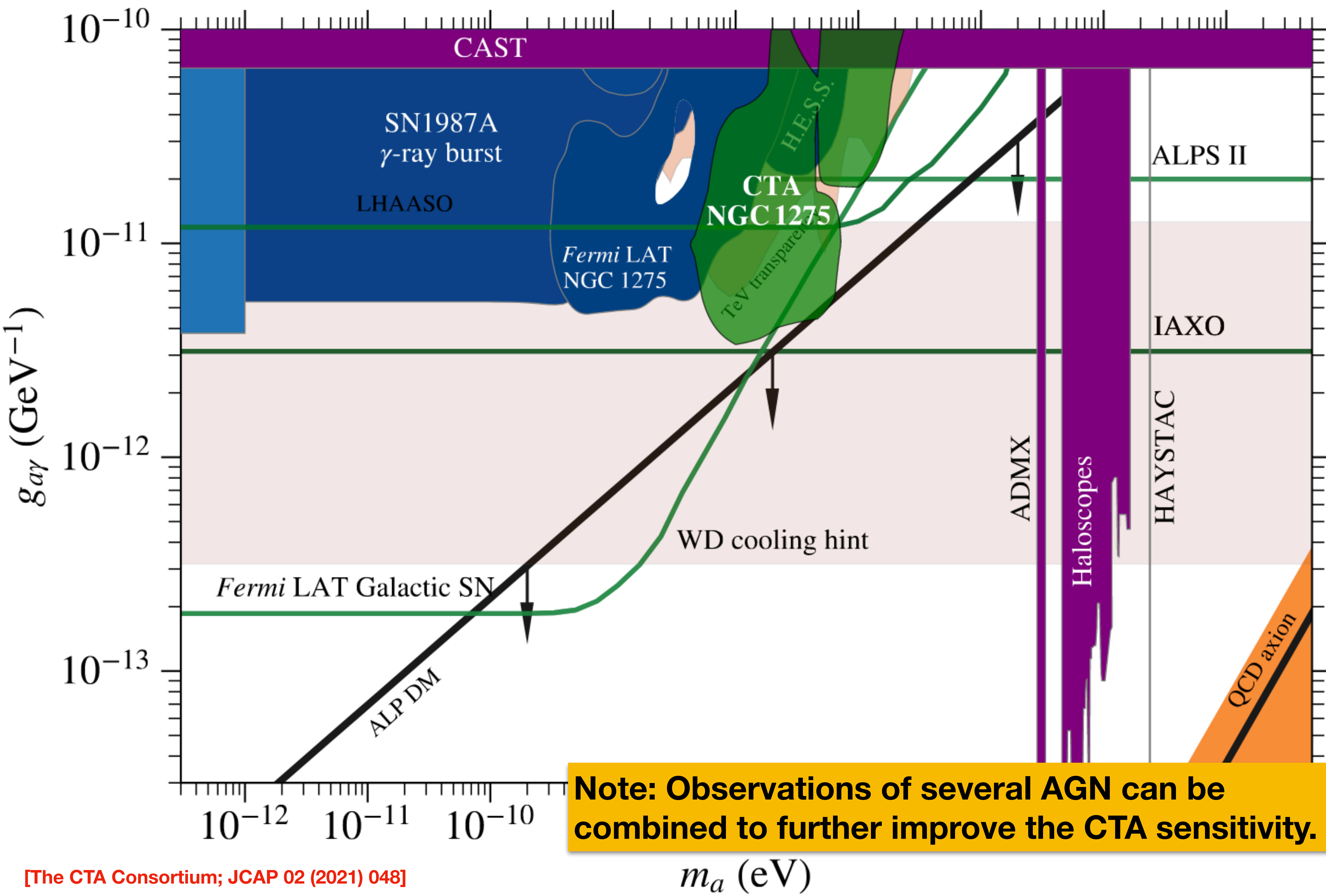


[The CTA Consortium; JCAP 02 (2021) 048]





Note: Observations of several AGN can be combined to further improve the CTA sensitivity.

[The CTA Consortium; JCAP 02 (2021) 048]

Outlook

CTAO will observe the TeV+ sky with unprecedented sensitivity:

- Unique experiment capable of testing thermal DM in TeV range (where PP phenomenology expected to be rich)
  - Excellent sensitivity spectral features
  - Should be able to address the origin of DM signal hints from Fermi LAT
- Promising sensitivity to DM ALP models (and PBHs!)
- Not only DM - tests of LIV together with other HE instruments (LHAASO, Pier Auger…)

Poster: Glicenstein

Poster: Plard

Surprises?

EXTRA SLIDES

Lorenz invariance tests with CTA

Many QG models that lead to a vacuum velocity of light that is energy dependent

$$c^2 p^2 = E_\gamma^2 \sum_\alpha \pm \xi_\alpha (E_\gamma^\alpha / E_{\mathrm{QG}}^\alpha)$$

Dispersion measure

ξ_α - correction factor, with the leading linear ($\alpha = 1$) and quadratic ($\alpha = 2$) terms

For measuring dispersion due to LIV there are three criteria that an ideal probe should meet:

- emit very high energy photons (>10 TeV, SSTs!)
- be very distant,
- exhibit variability with good statistics

—> energy-dependent time delay AGNs, GRBs, …

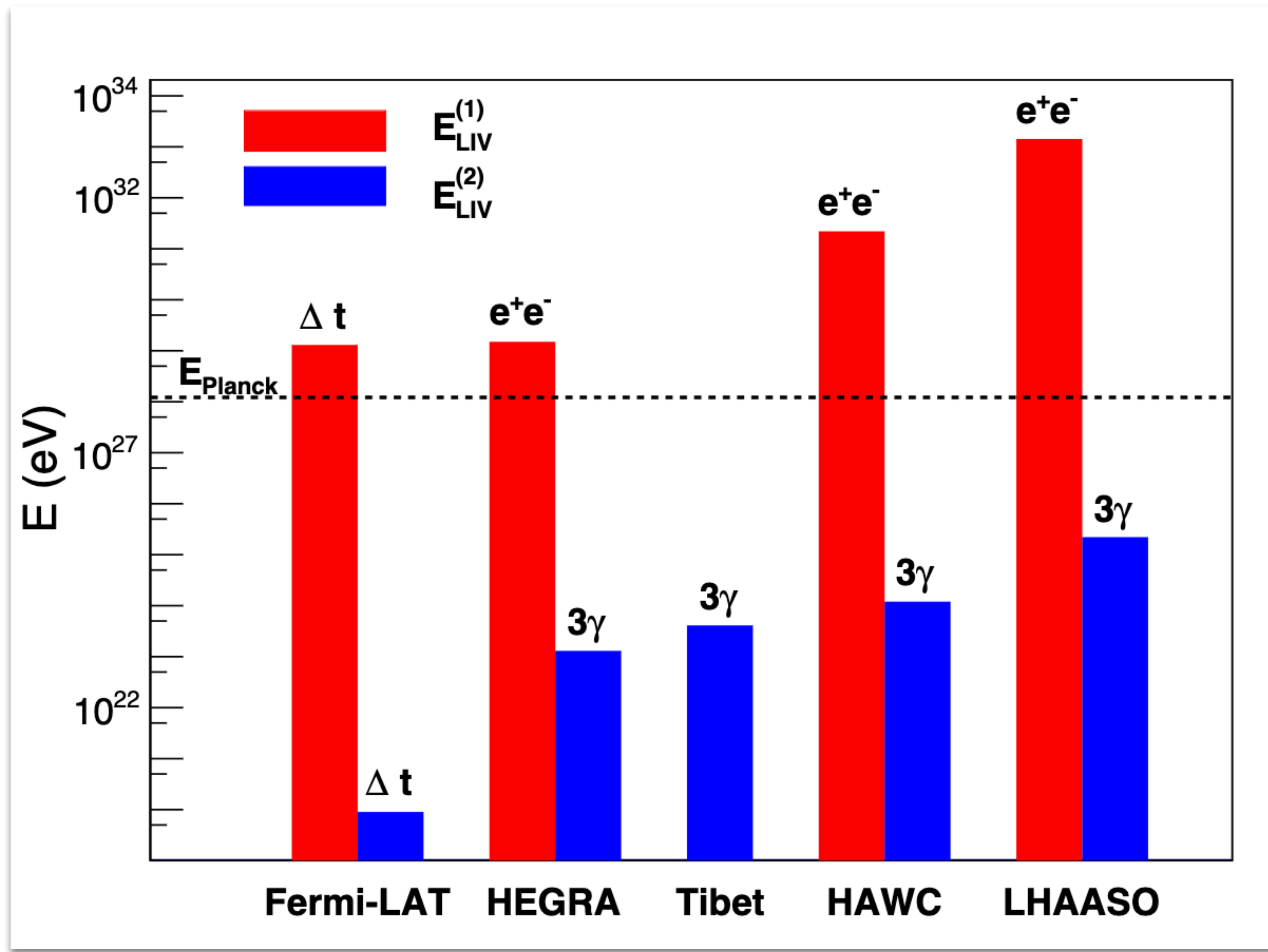
Lorenz invariance tests with CTA

LHAASO, Phys.Rev.Lett. 128 (2022) 5, 051102

Consider LHAASO J0534+2202 and LHAASO J2032+4102 - two sources with the highest energy γ-like events up to PeV energies. The ultra-high-energy γ events are used to constrain the LIV effect, which is predicted to give hard cutoff to the energy spectra of γ-ray sources due to the MDR-induced photon decay or splitting.

the superluminal LIV case:

- photons can decay into a pair of electron and positron, $\gamma \rightarrow e^- e^+$, as long as the threshold condition is satisfied - leads to a sharp cutoff in the γ-ray spectrum
- photon splitting into multiple photons, $\gamma \rightarrow N\gamma$ (3γ), also results in a hard cutoff



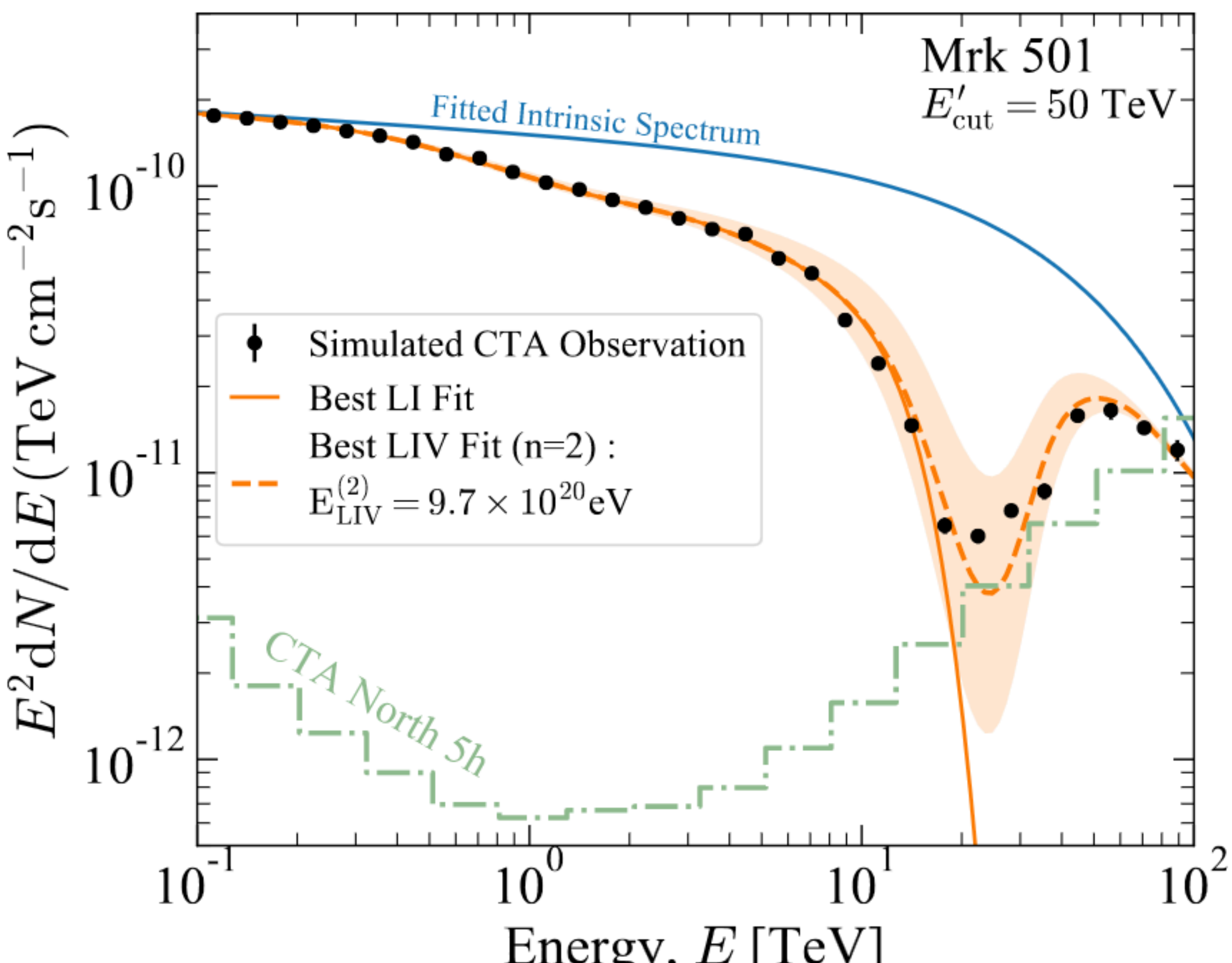
Lorenz invariance tests with CTA

[The CTA Consortium; JCAP 02 (2021) 048]

potential of CTA to detect or constrain LIV with two blazars, Mrk 501 and 1ES 0229+200

flaring state of Mrk 501 and a long-term observation of 1ES 0229+200 are simulated for 10 hours and 50 hours

CTA potential to test LIV-induced modifications of the pair-production threshold in γ-ray interactions with the EBL.



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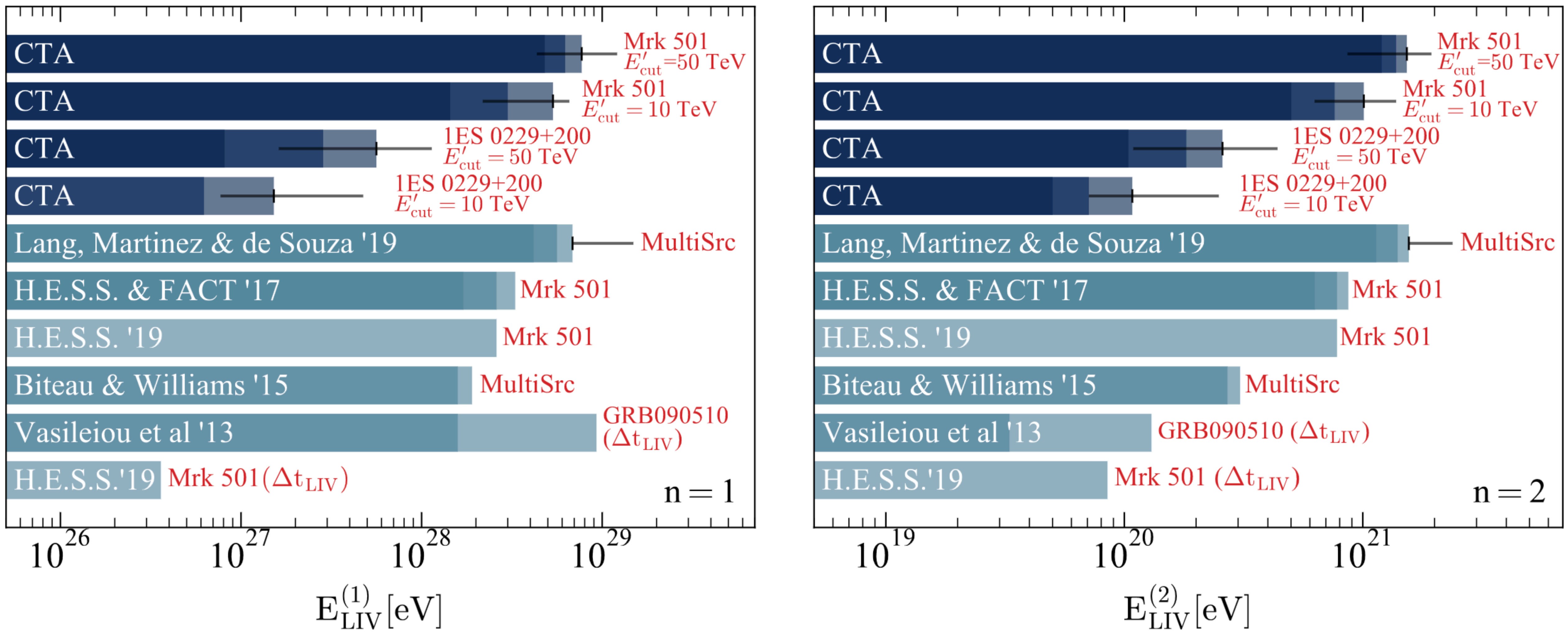

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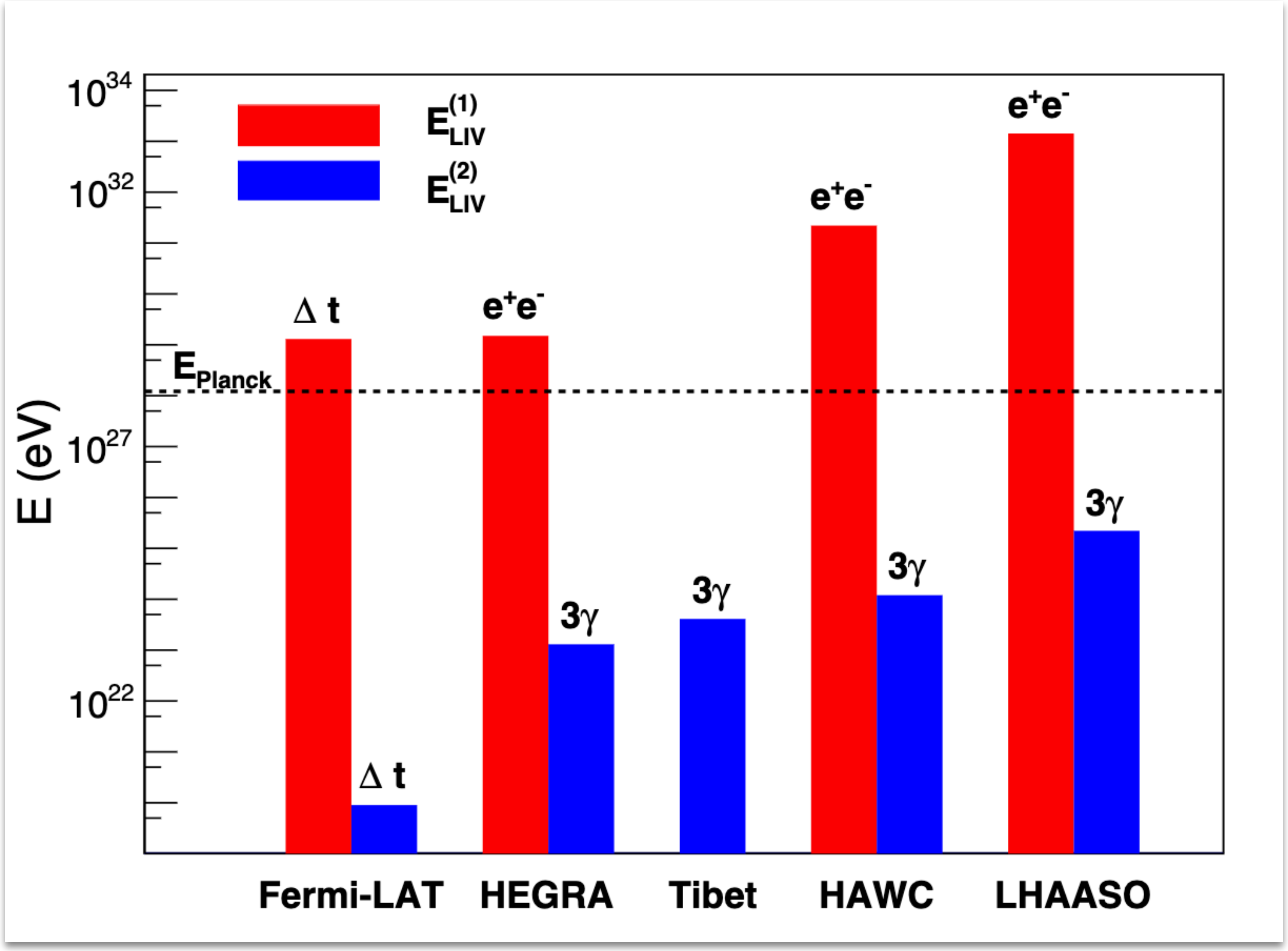
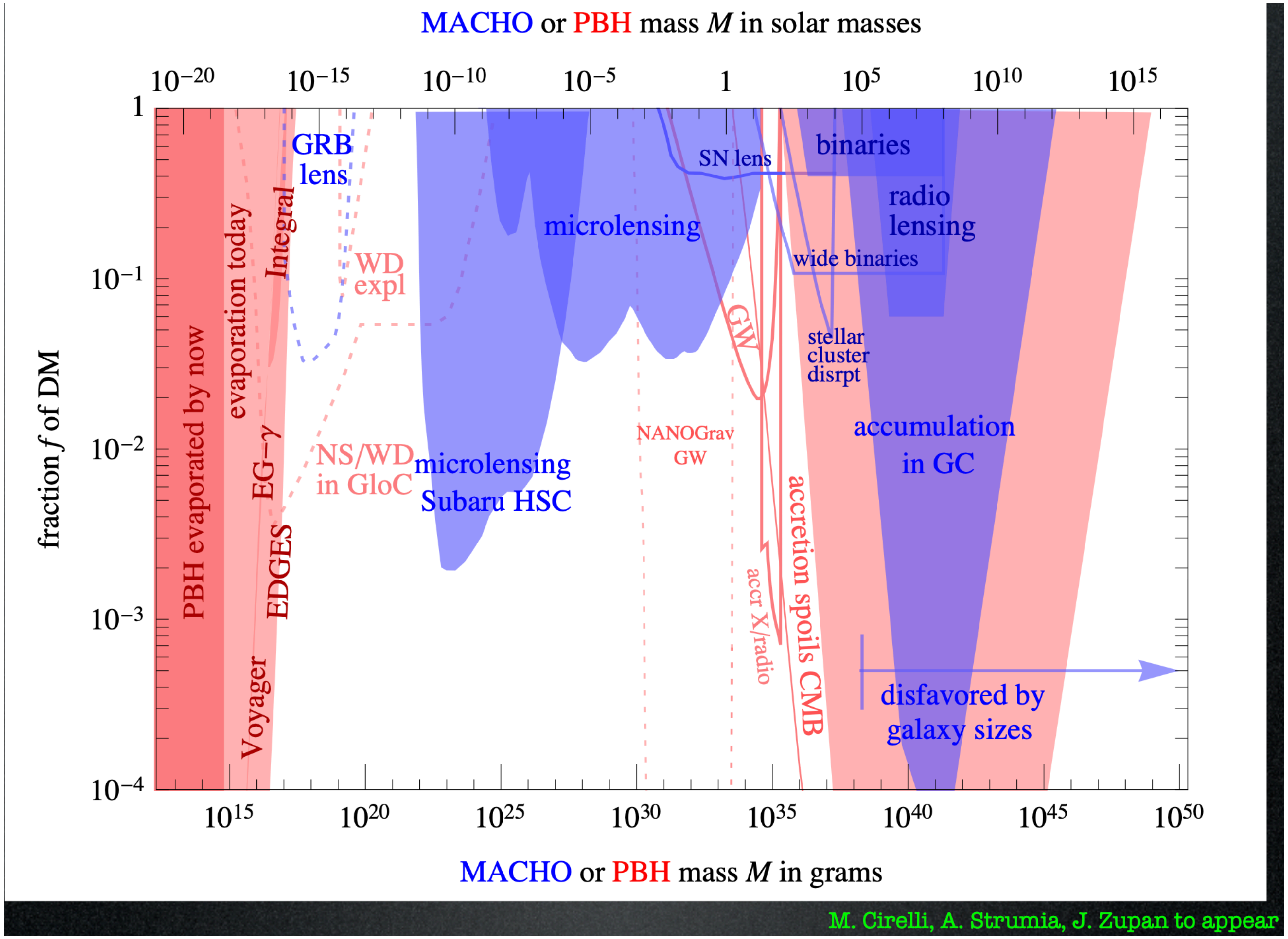
The first-order LIV energy-scale is constrained to be higher than 105 Mpl, and the second-order LIV energy-scale should exceed 10−3 Mpl.

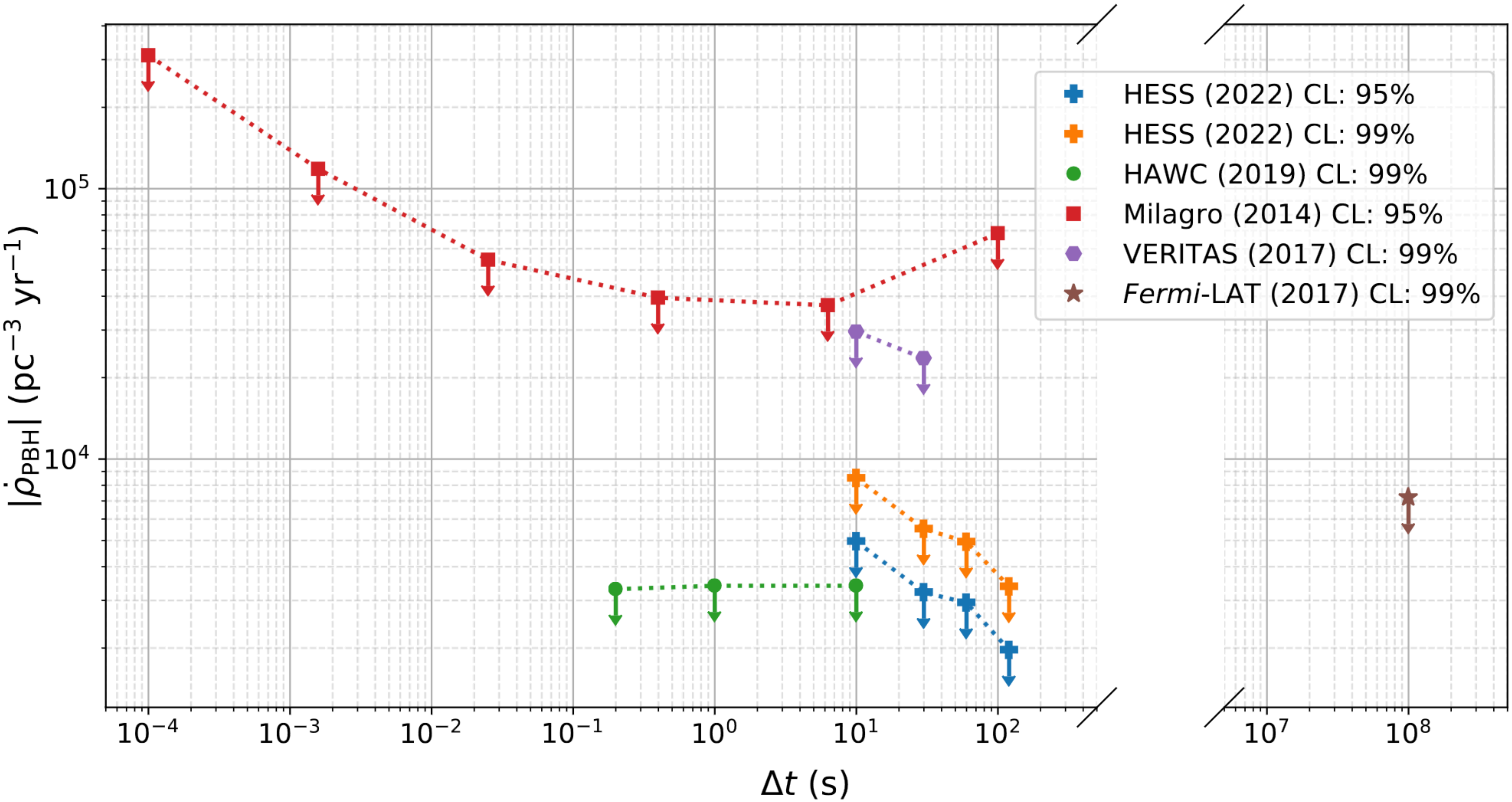


PBHs



[HESS, JCAP 04 (2023) 040]

PBHs



Search for TeV gamma-ray bursts with a timescale of a few seconds to a few minutes, as expected from the final stage of PBHs evaporation $Q \simeq 40\ \mathrm{TeV}(1\ \mathrm{s}/\Delta t)^{1/3}$

H.E.S.S. is sensitive to PBH evaporations up to distances of order r0 = 0.1 pc

[HESS, JCAP 04 (2023) 040]

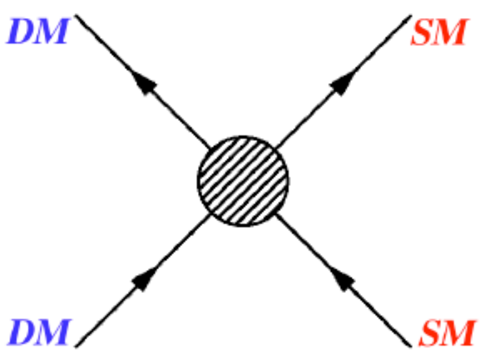
Searches in astrophysical/cosmological data

Signatures?

1. Injection of ***SM particles/Cosmic rays***

- In DM DM interactions

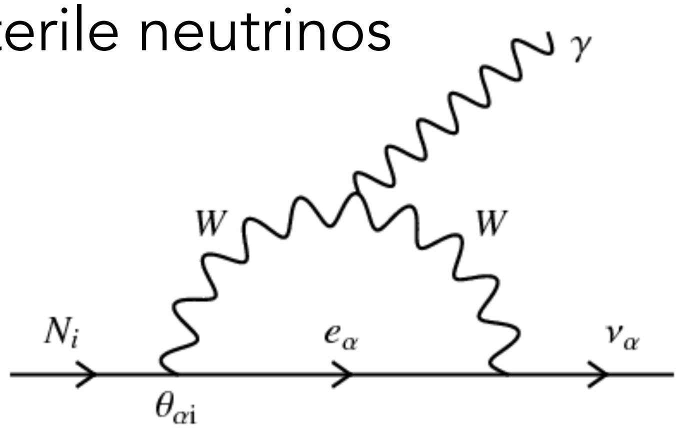
thermal DM



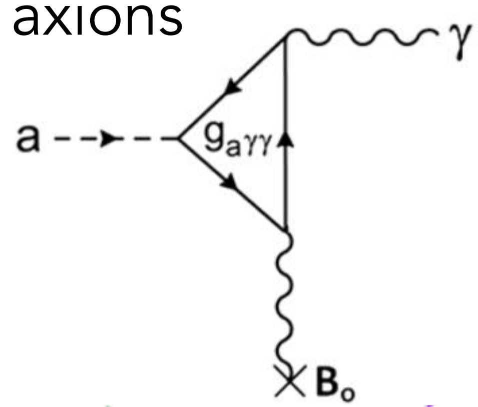
→ γ, ν, $e^{\pm}$, $p^{\pm}$ D-

- In DM conversions/decays

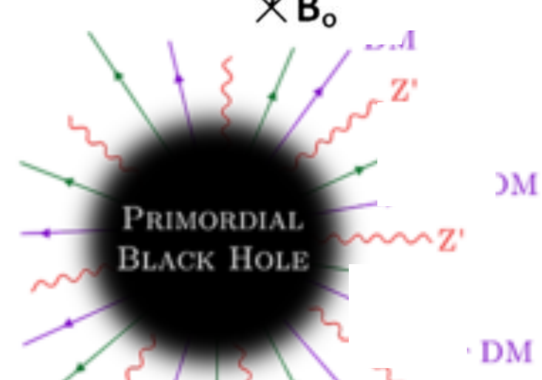
sterile neutrinos



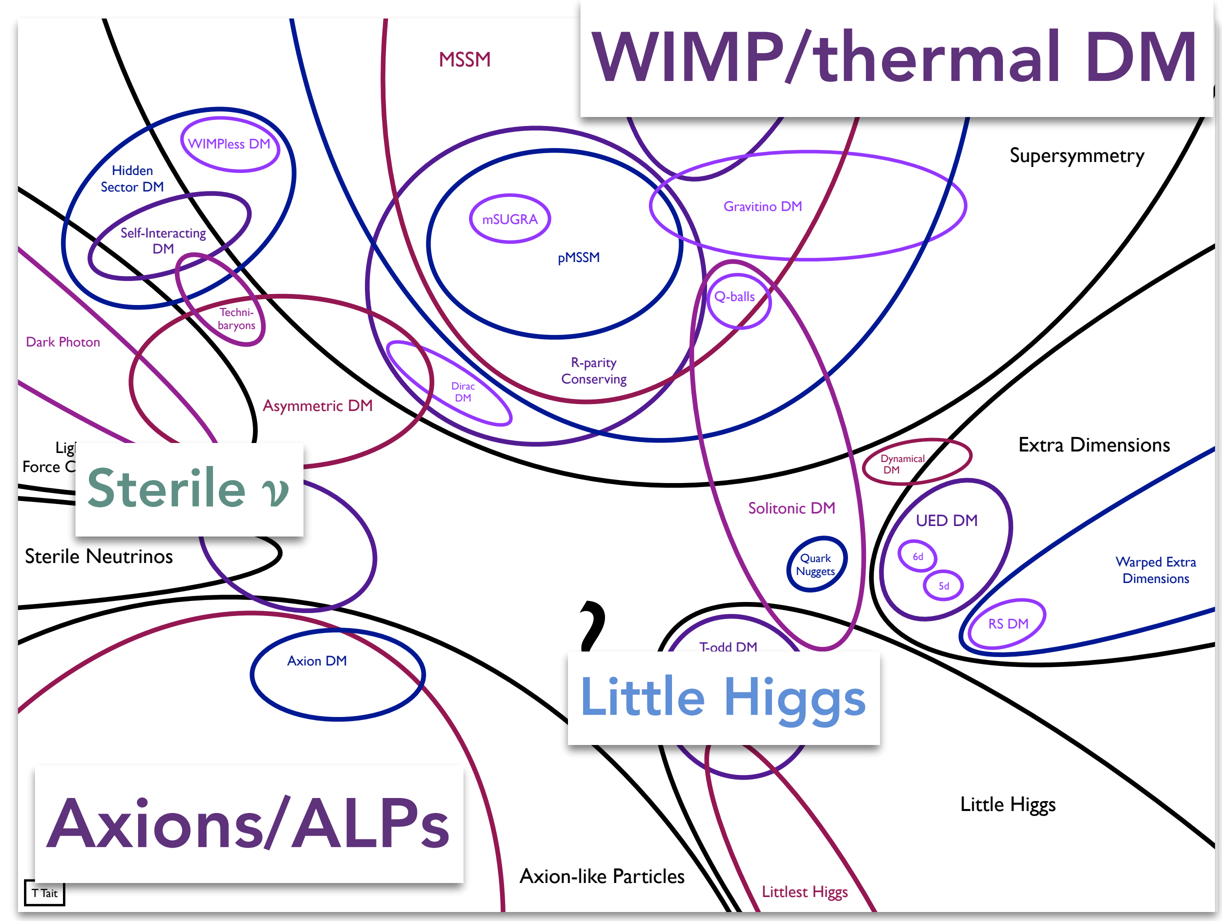
axions

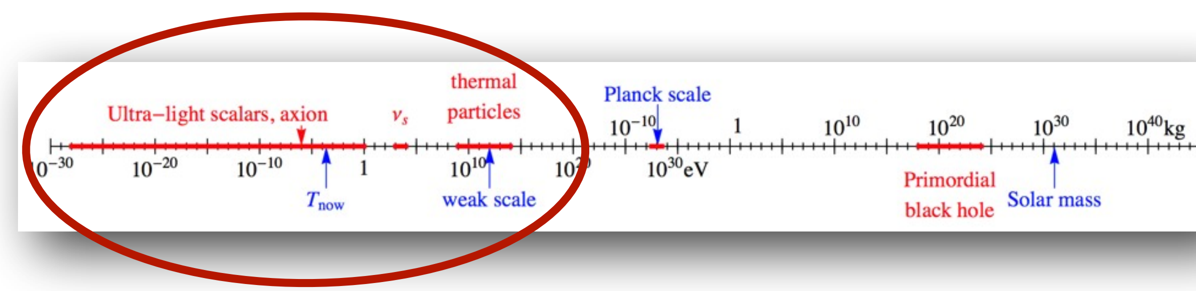


- PBH evaporation…



Particle DM ('Tait') landscape





Searches in astrophysical/cosmological data

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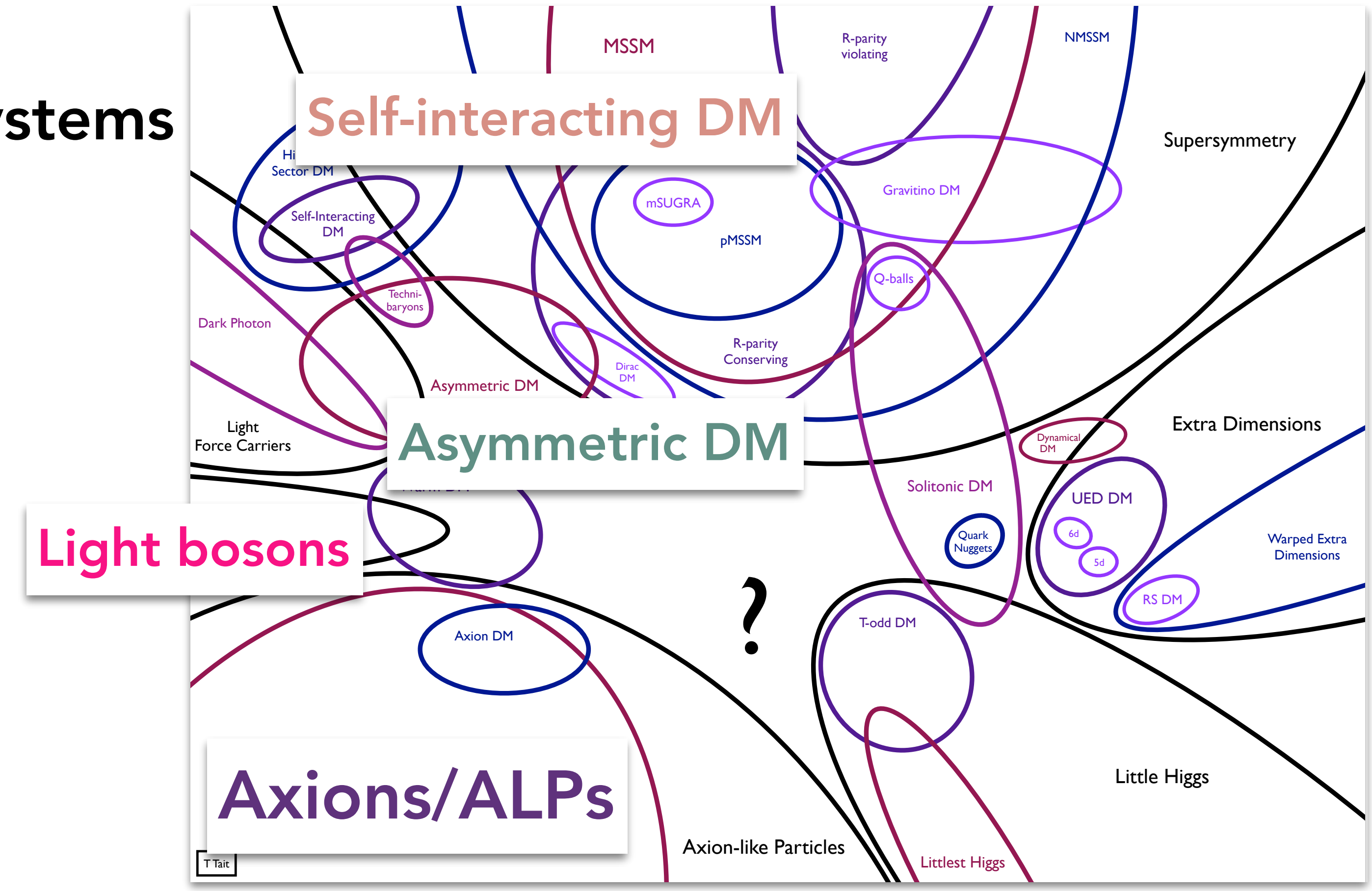
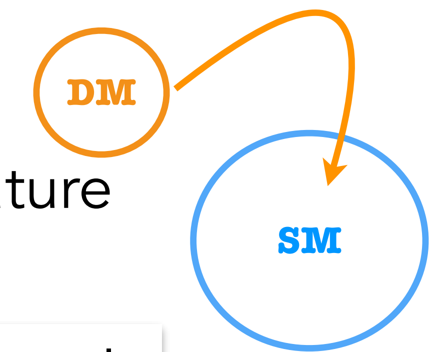


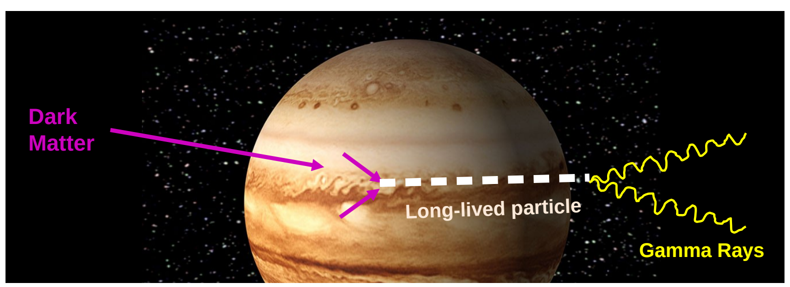
2. Altering of behaviour of astrophysical systems

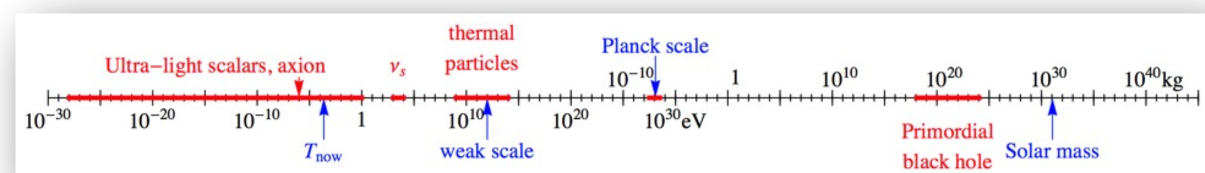
- capture by stars or planets

- changes in stellar evolution
- or (planet) internal temperature

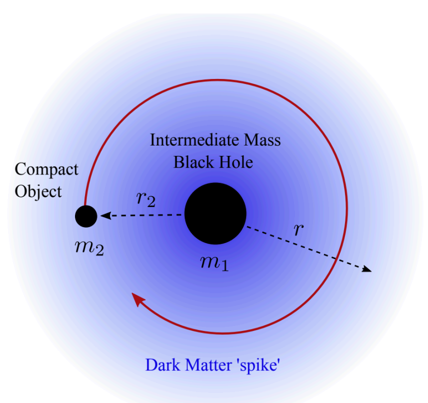


- cooling of stars via DM channel



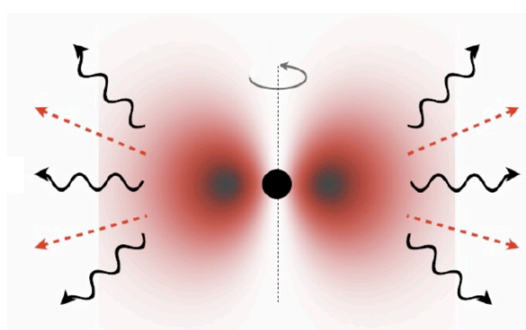


- affecting GW emission …



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

Brito+ Lect. Notes Phys.'15

Searches in astrophysical/cosmological data

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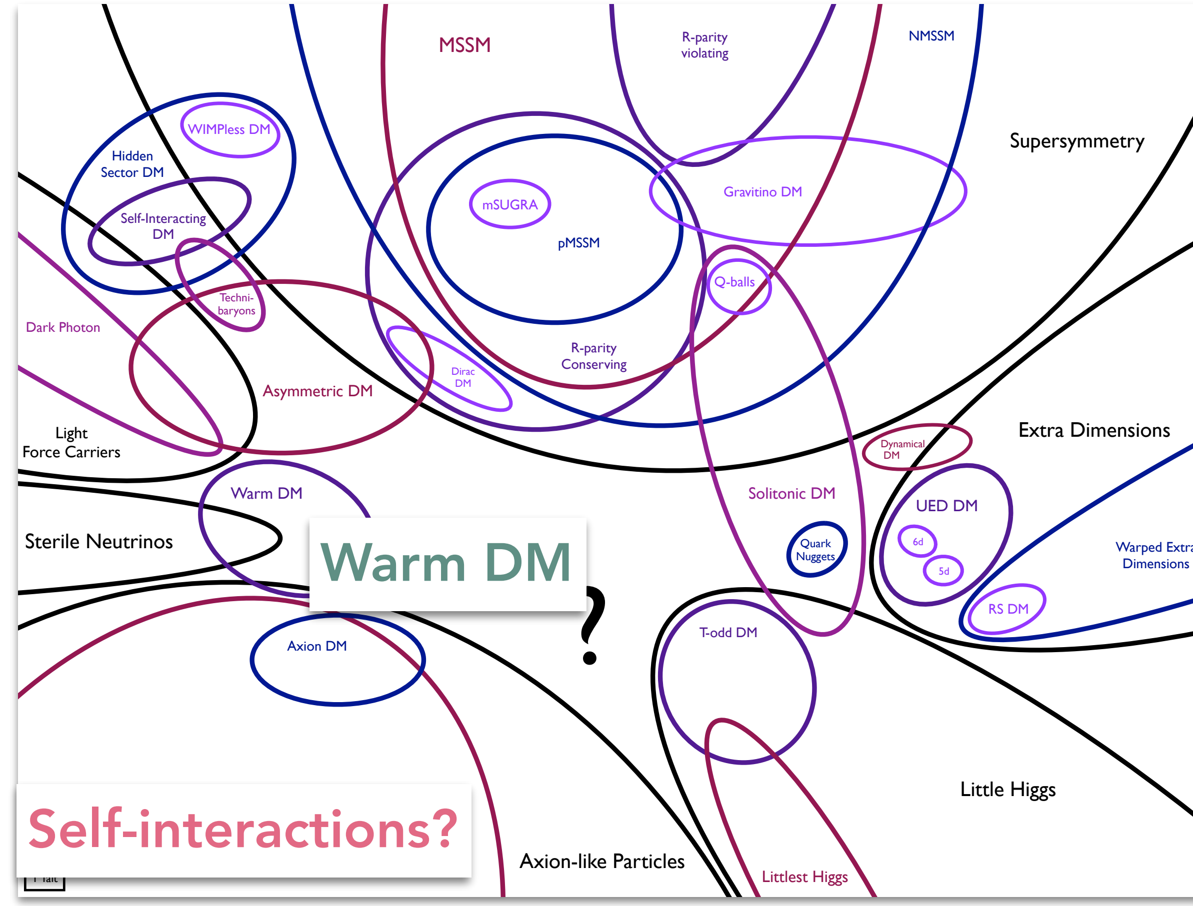


Warm DM ?

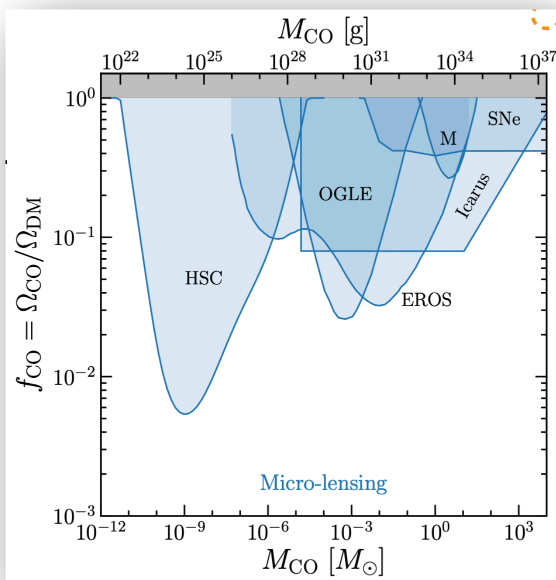
Self-interactions?

3. Purely gravitational interactions with visible matter

- gravitational lensing

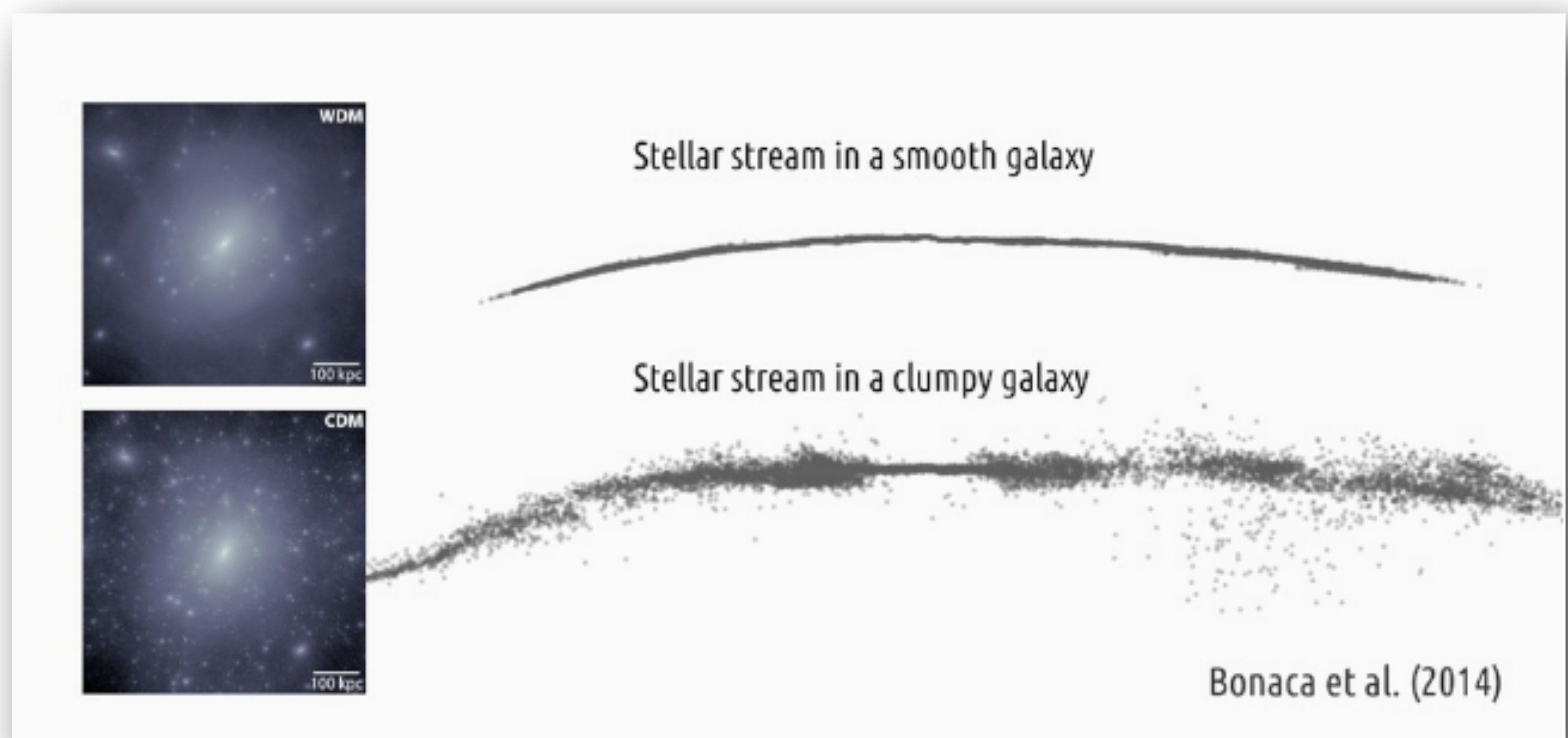
Micro lensing (asteroid to solar masses)

Galaxy-galaxy lensing

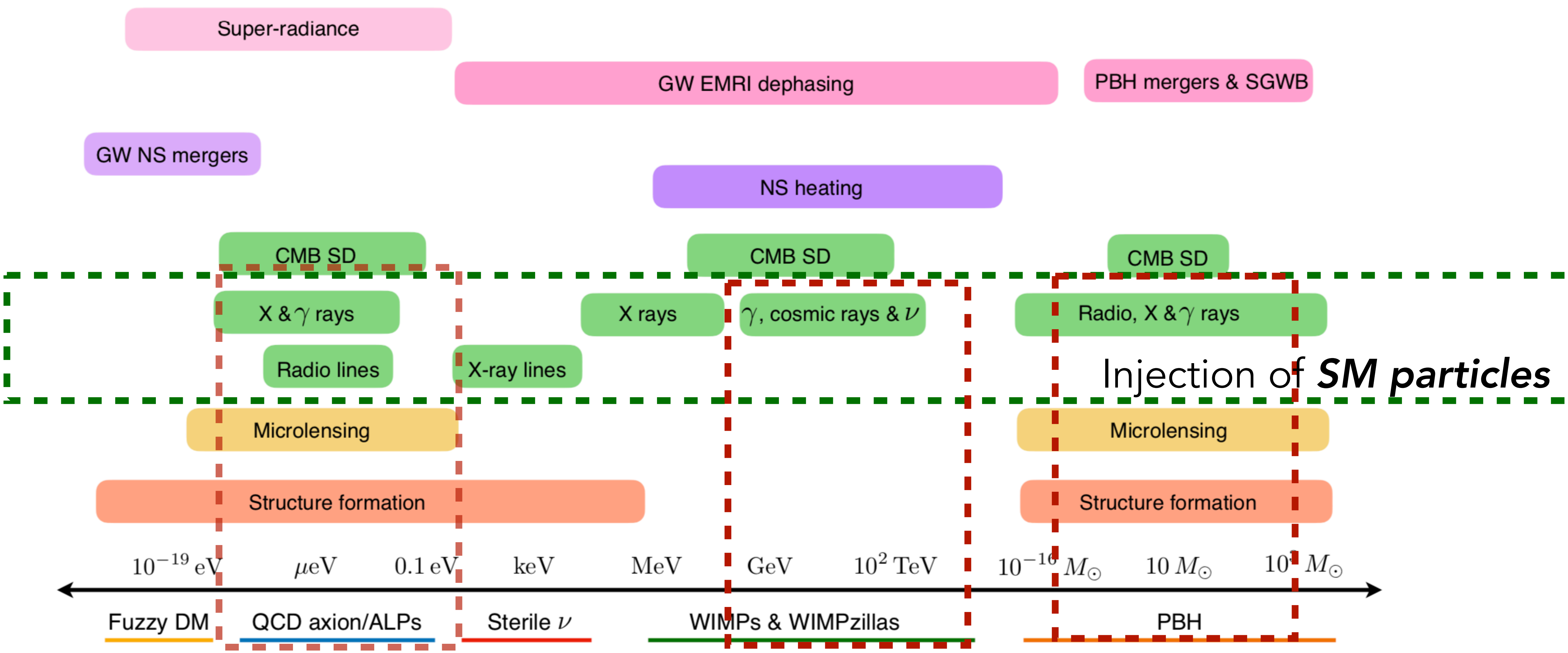


- stellar tidal stream disruptions

- stellar wakes…



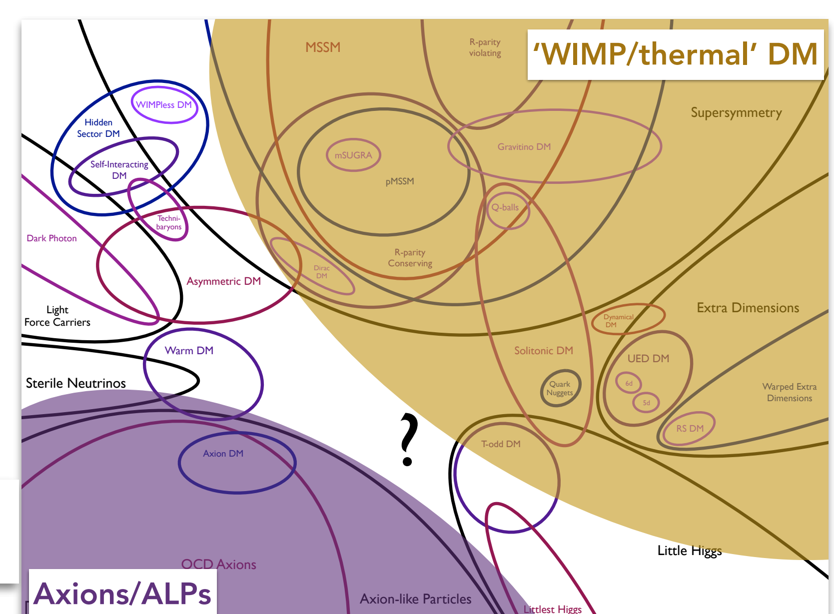
Detection strategies per mass range



γ rays - straight lines, high statistics

ν - straight lines, lower statistics but catching up

CRs - complex diffusion and energy loss processes



THIS TALK: Focus on γ rays -> WIMP and ALPs (PBHs)