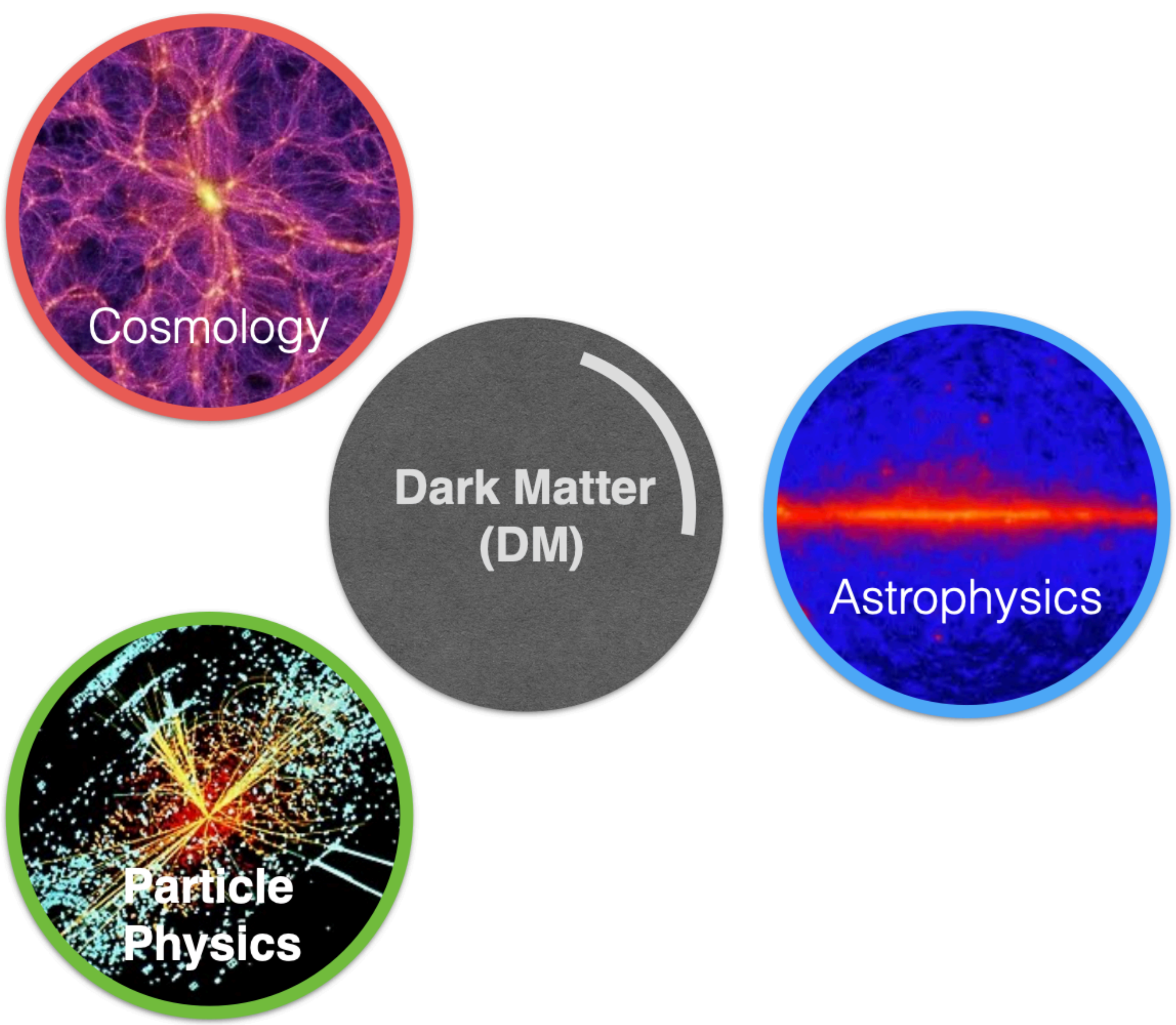
Probing the Nature of Dark Matter with Gamma Rays



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Slovenia

1995 - 2025
UNIVERZA
V NOVI GORICI

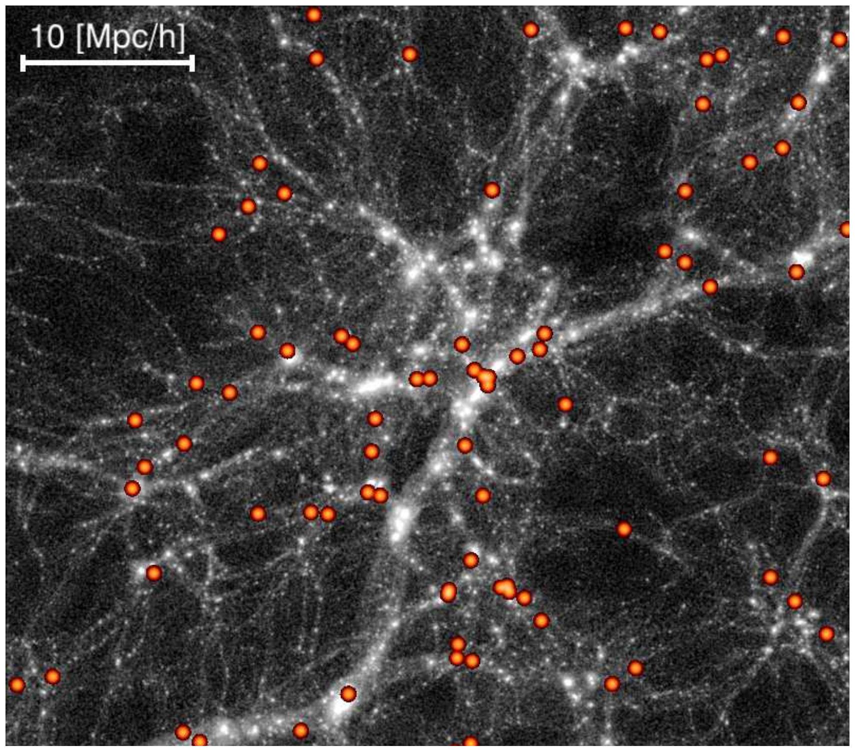
SMASH
machine learning for science and humanities postdoctoral program

Dark matter

an essential building block of the Standard Model of Cosmology

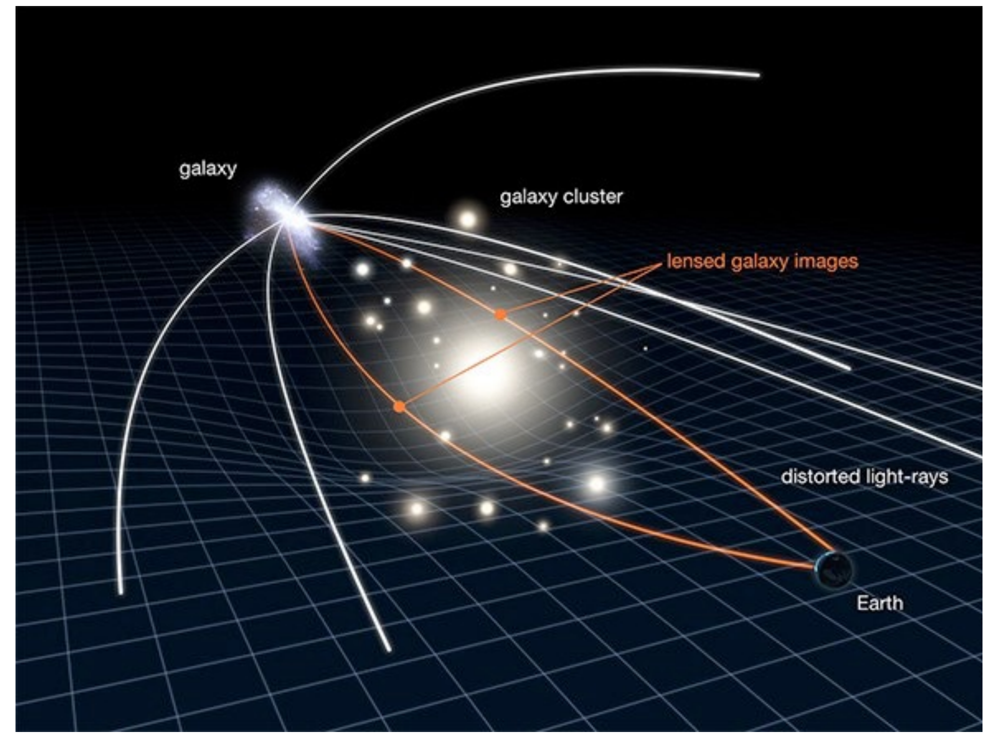
so far only detected through GRAVITY

large scale structures



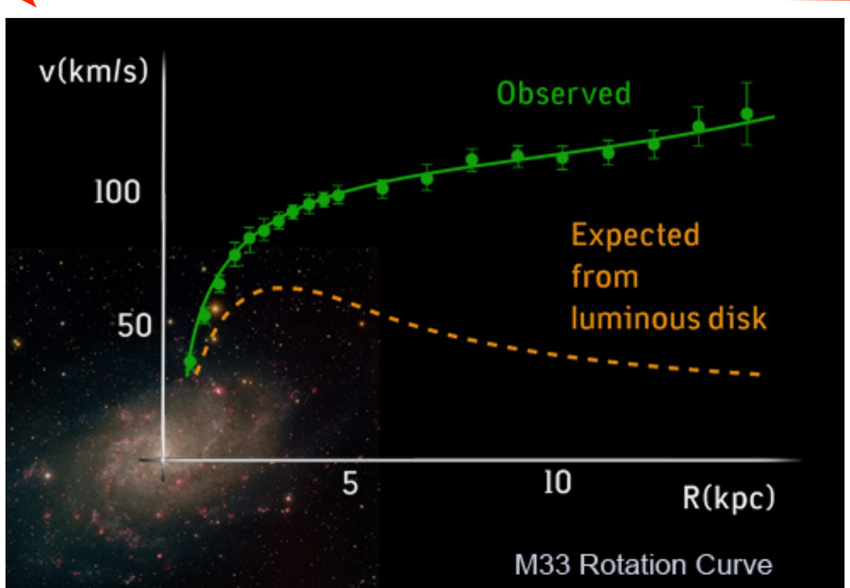
100s Mpc

clusters of galaxies



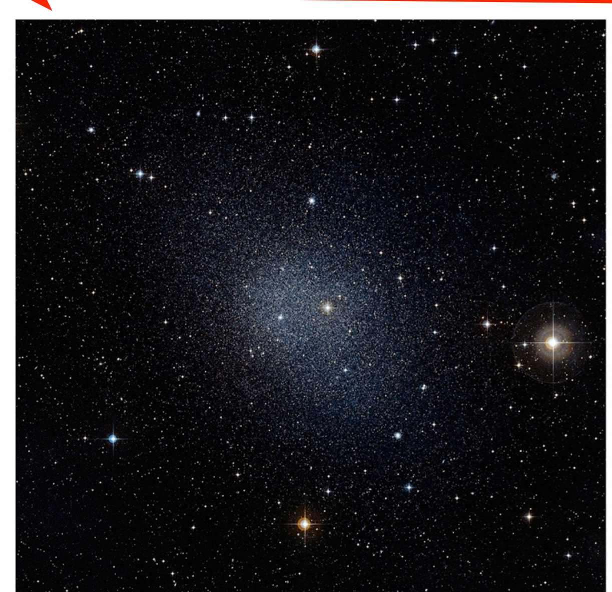
Mpc

Milky Way-size galaxies



100s kpc

dwarf galaxies



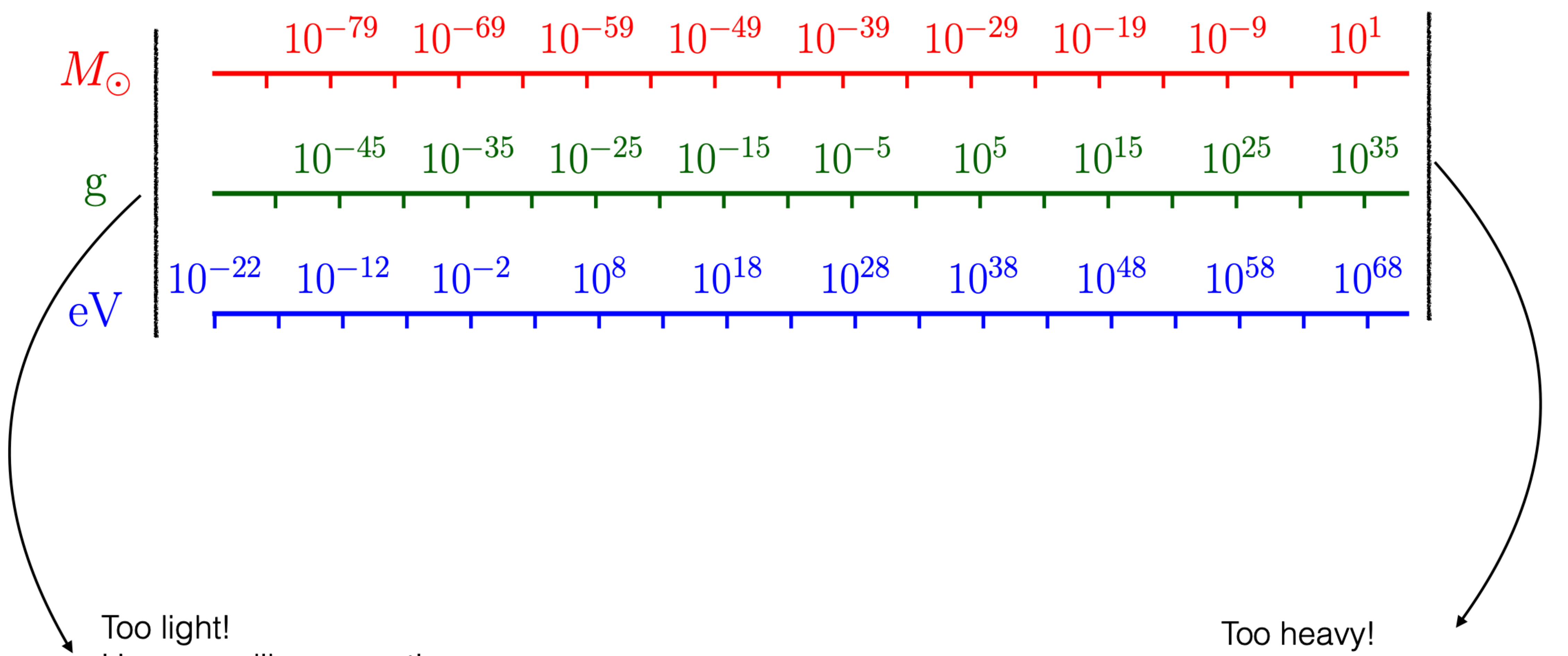
<~ kpc

DM is cold, pressure-less/neutral, stable, Ω_M~0.3

BUT what is its 'nature'?

- Is it a particle?
- How/if does it couple to the Standard Model?
- Composite or elementary?
- 'Maverick' or dark 'sector'?

What do we know so far?

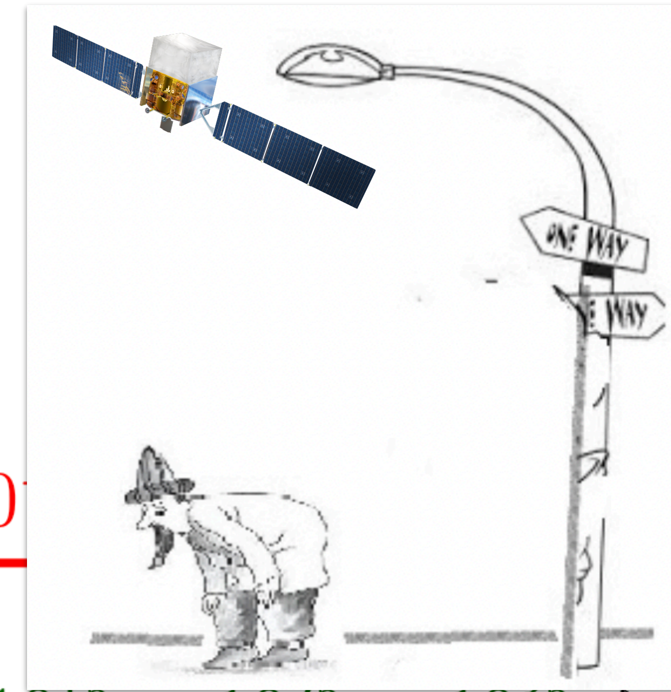


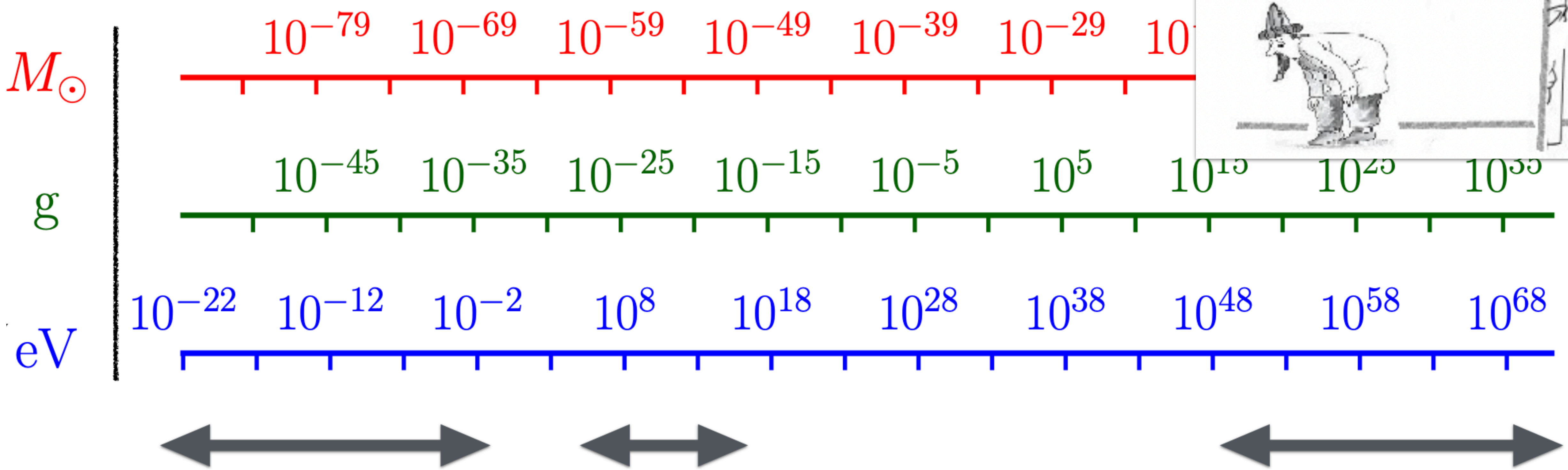
Too light!
Has wave-like properties on galactic scales!

Too heavy!
DM mass comparable to galactic masses!

Candidates

Some clues: **Completion of SM, why stable? Why Ω_M?...**

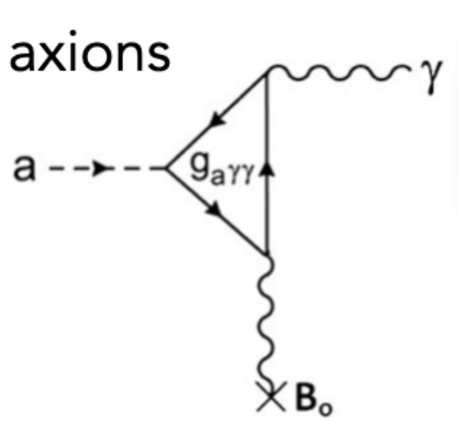


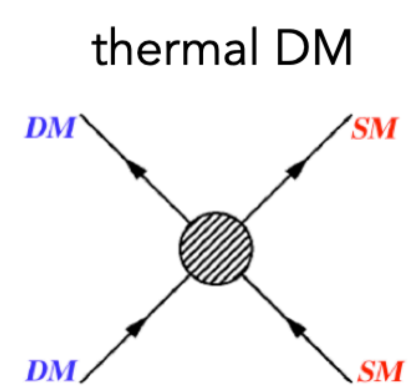


Axion-like particles (**ALPs**)

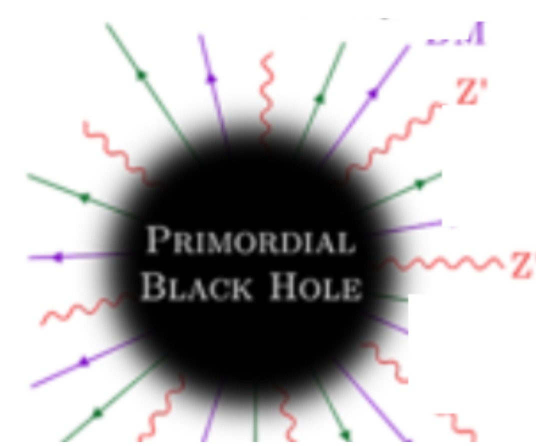
Weakly interacting massive particles

Primordial Black Holes (**PBHs**)



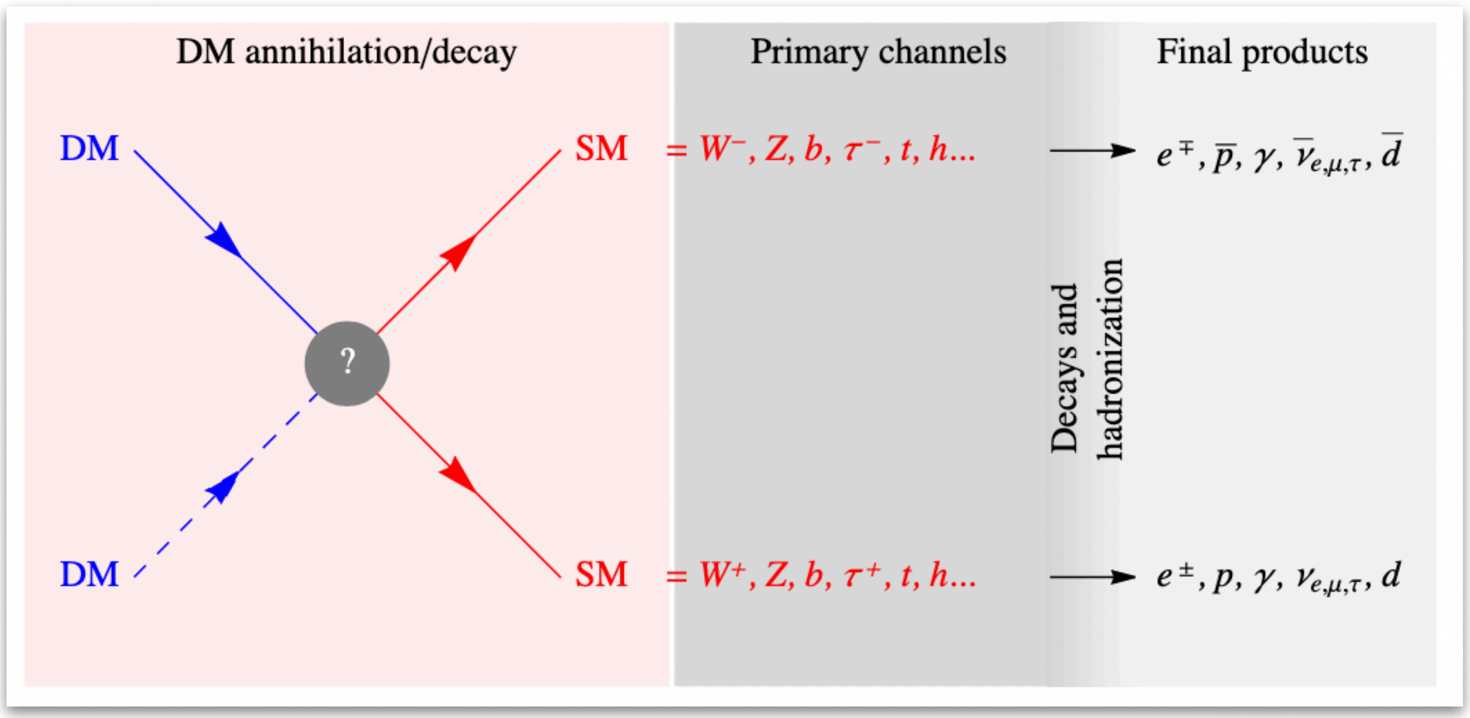


→ γ, ν, $e^{\pm}$, $p^{\pm}$ D-



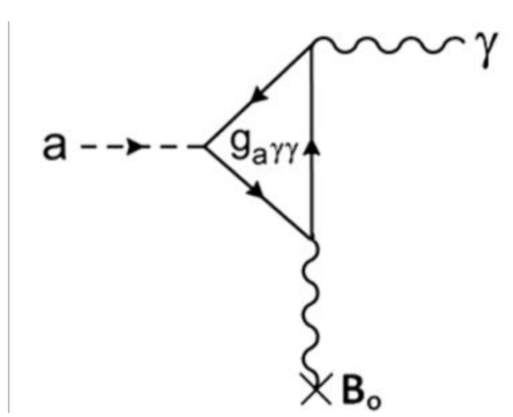
Strategies

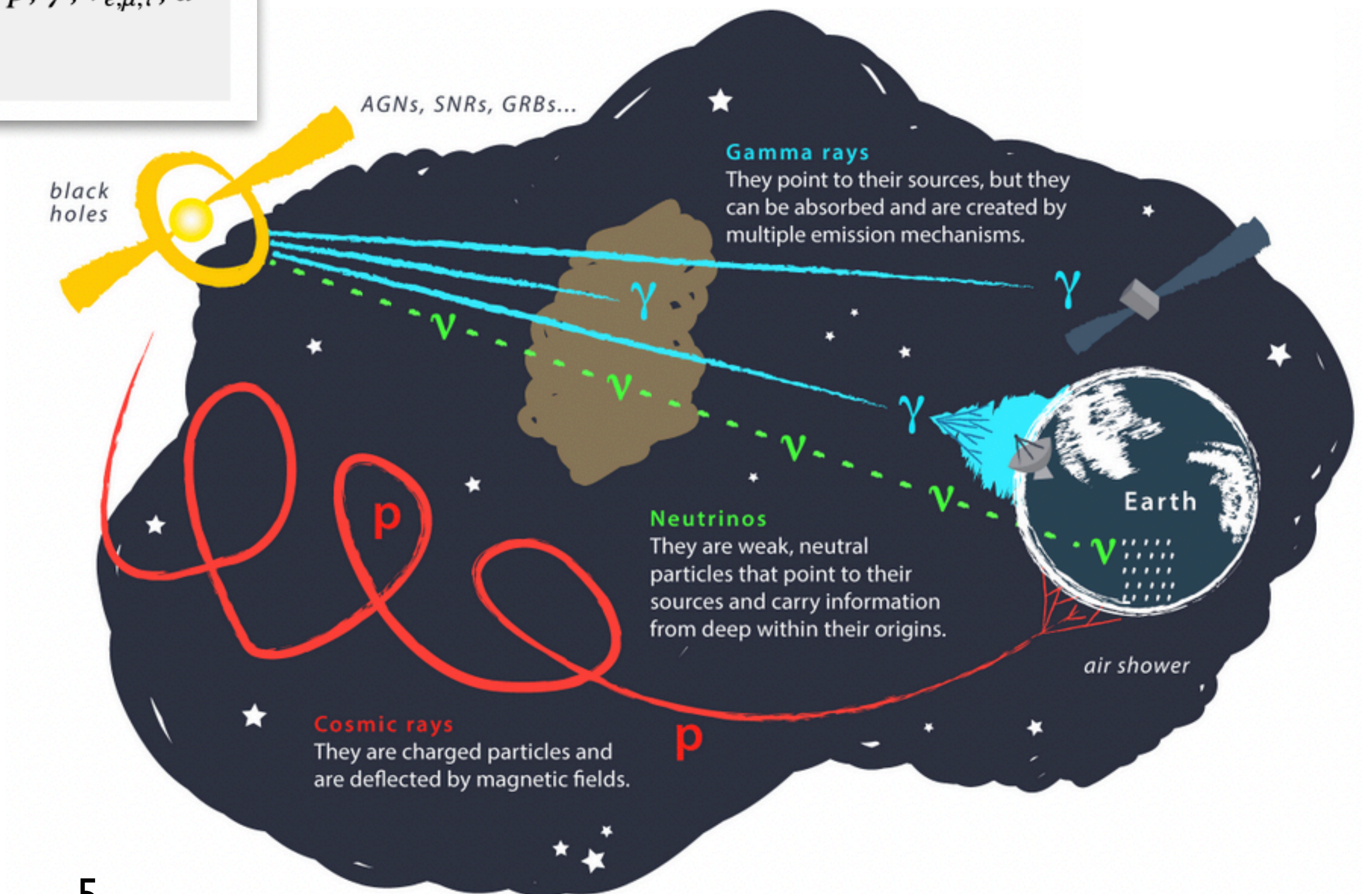
— Thermal (WIMP) DM - look in **cosmic ray data for** DMDM induced ***SM particle injection***



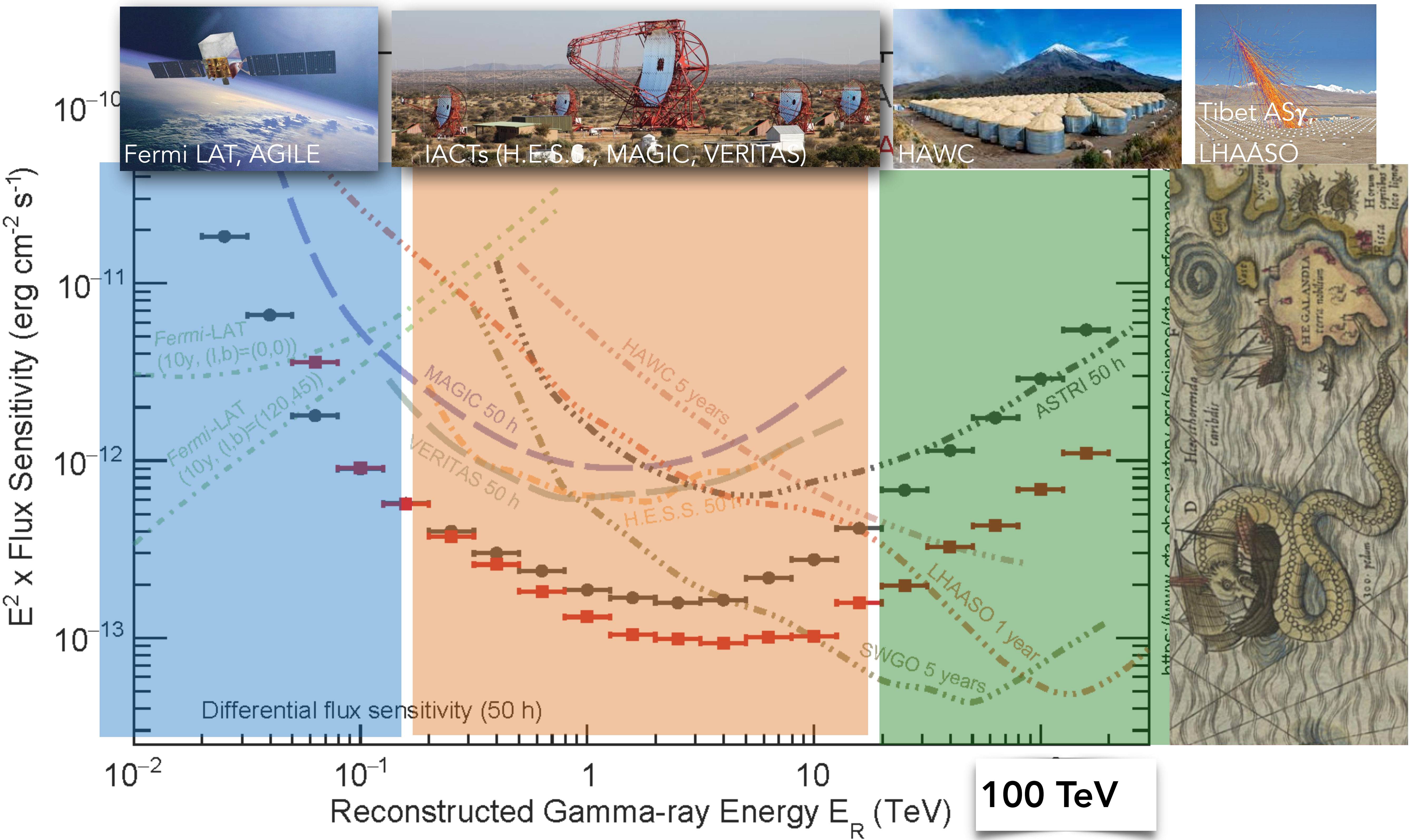
Look at places with high DM density!
In **thermal freeze-out** scenarios - **directly probe of the annihilation process that sets DM abundance**

— **axion lik particles**

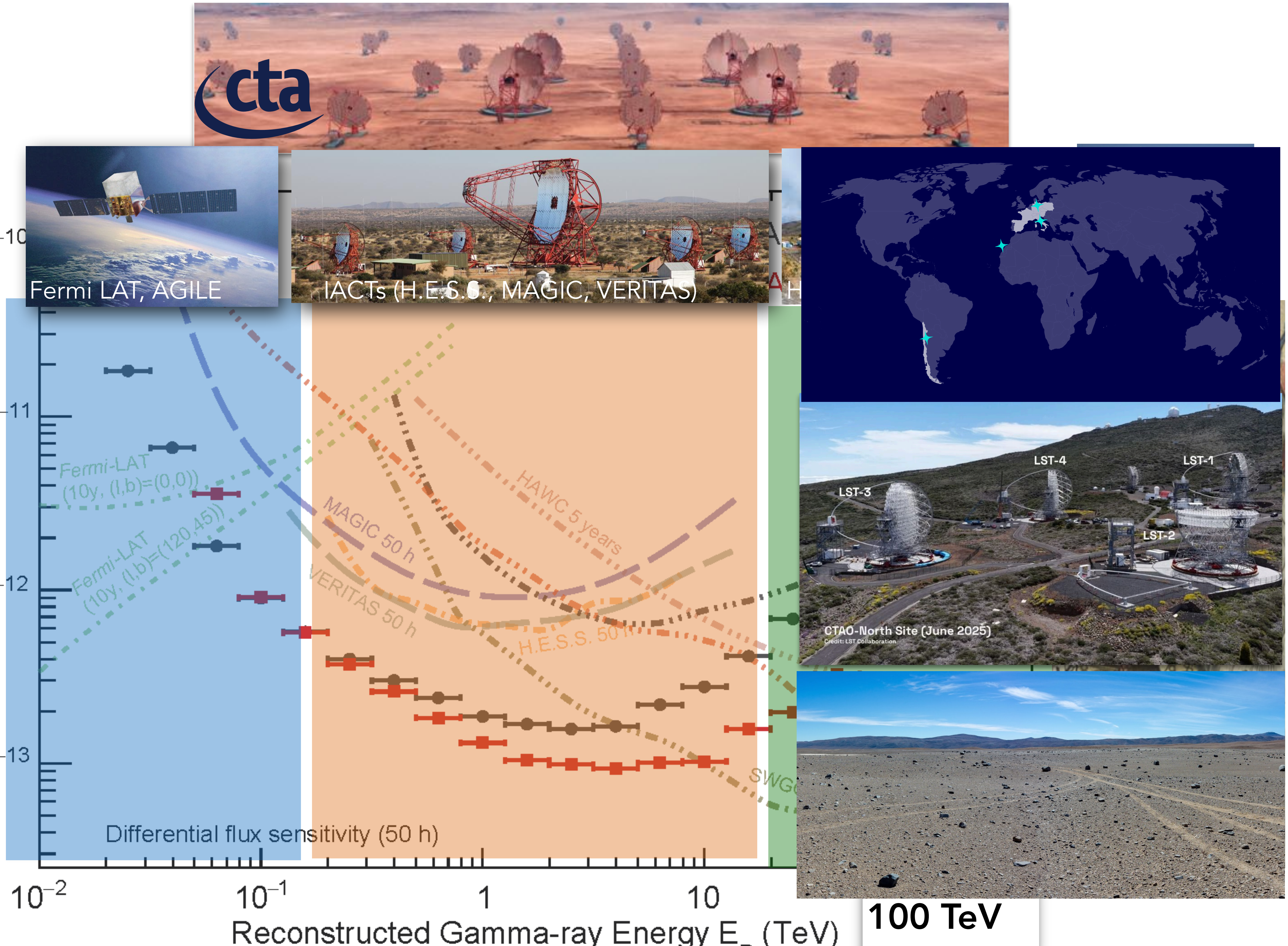




What tools?


Fermi LAT, AGILE
IACTs (H.E.S.S., MAGIC, VERITAS)
HAWC
Tibet ASγ,
LHAASO
10^{-10}
10^{-11}
10^{-12}
10^{-13}
E^2 x Flux Sensitivity (erg cm^{-2} s^{-1})
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)
10^{-2}
10^{-1}
1
10
Reconstructed Gamma-ray Energy E_R (TeV)
100 TeV

What tools?



cta
Fermi LAT, AGILE
IACTs (H.E.S.S., MAGIC, VERITAS)
CTAO-North Site (June 2025)
Credit: LST Collaboration
LST-1
LST-2
LST-3
LST-4
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
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Differential flux sensitivity (50 h)
E^2 x Flux Sensitivity (erg cm^{-2} s^{-1})
10^{-10}
10^{-11}
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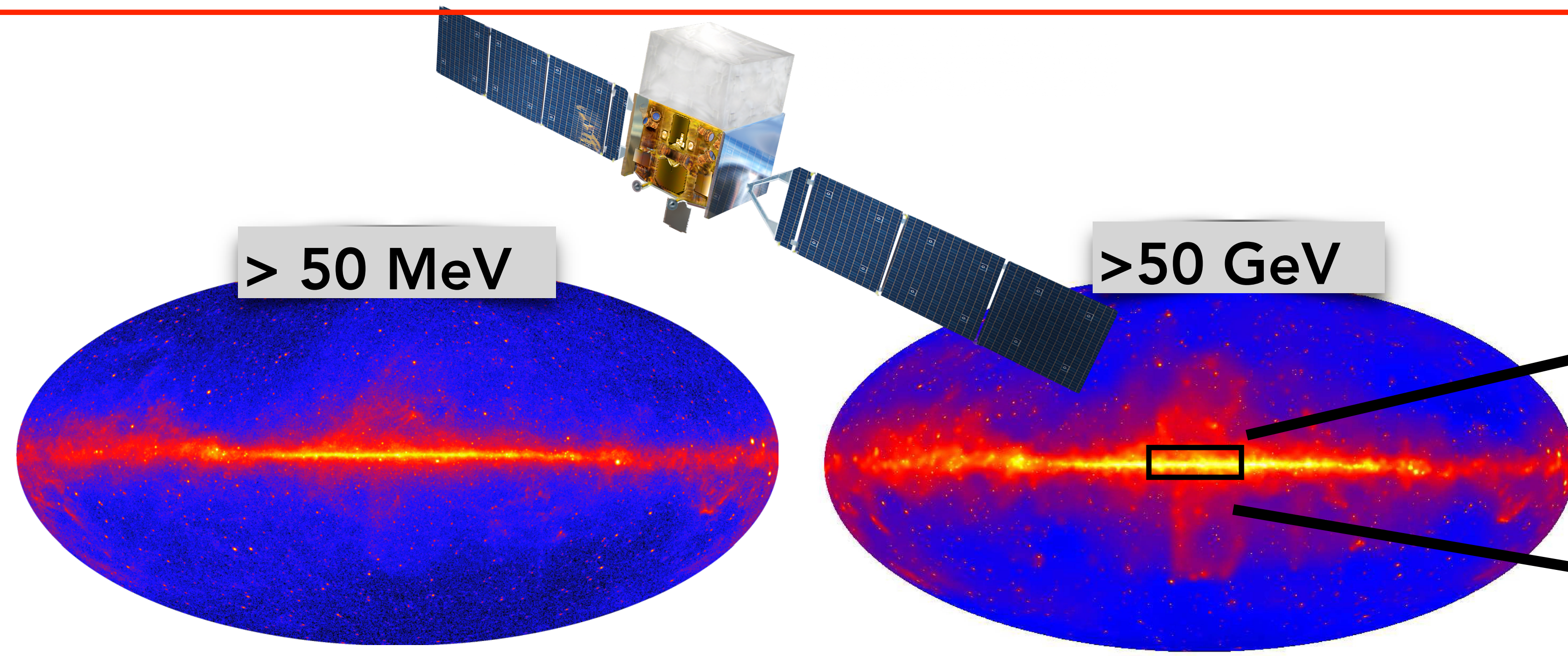
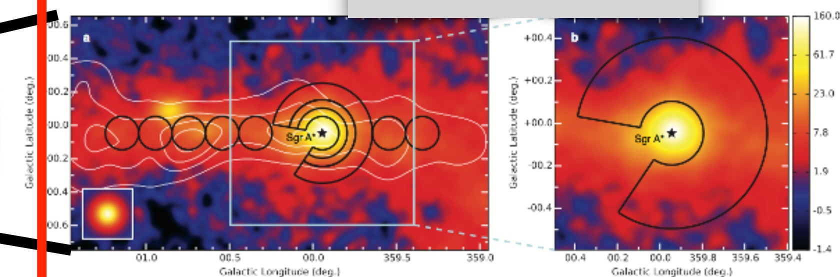
10^{-13}
10^{-2}
10^{-1}
1
10
Reconstructed Gamma-ray Energy E_R (TeV)
100 TeV

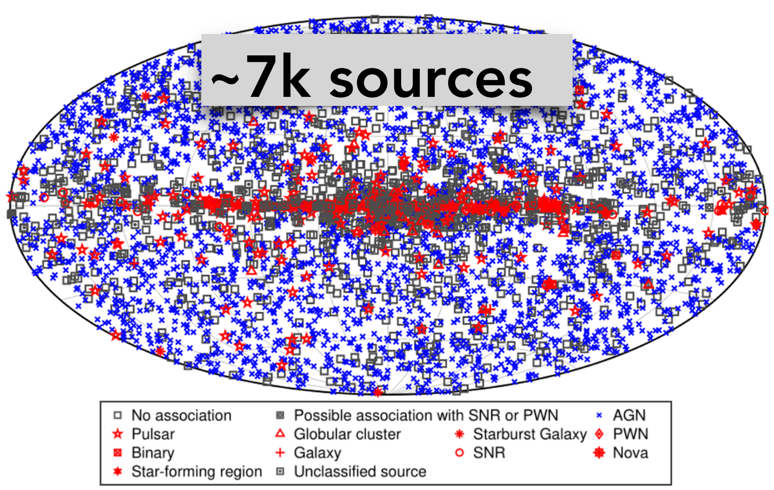
GeV - TeV sky

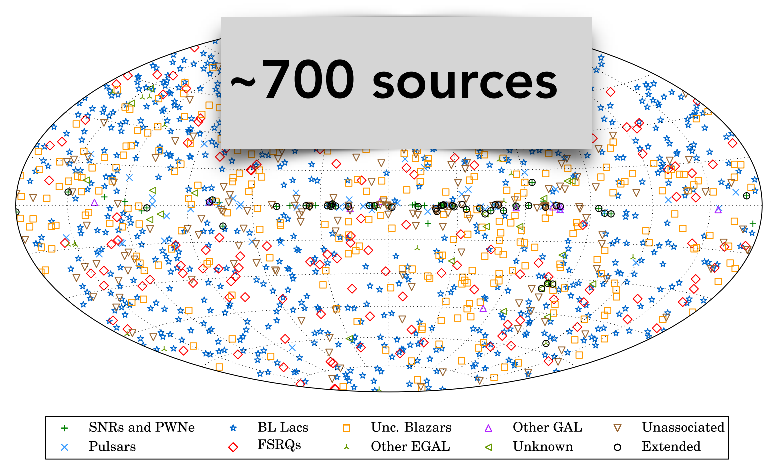
IACTs
Significant CR contamination
+ limited FoV

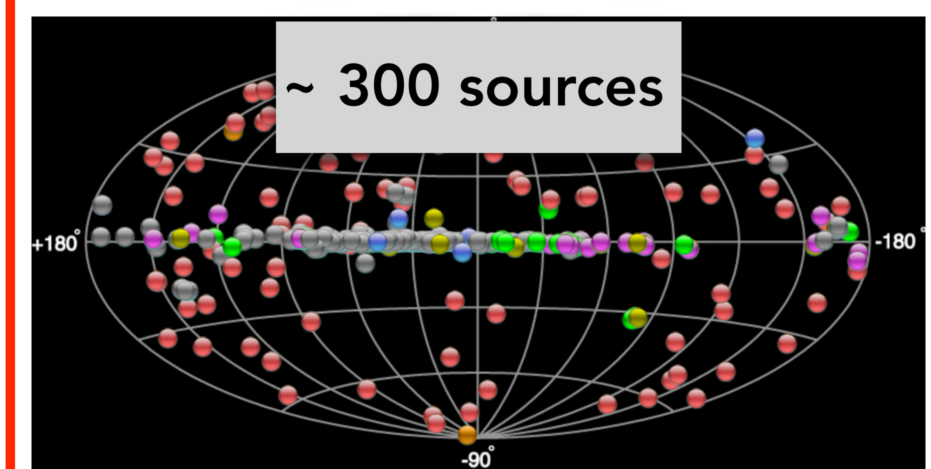




HESS, Galactic center Ridge







LAT source catalogues, >50 MeV (**4FGL - DR4**)

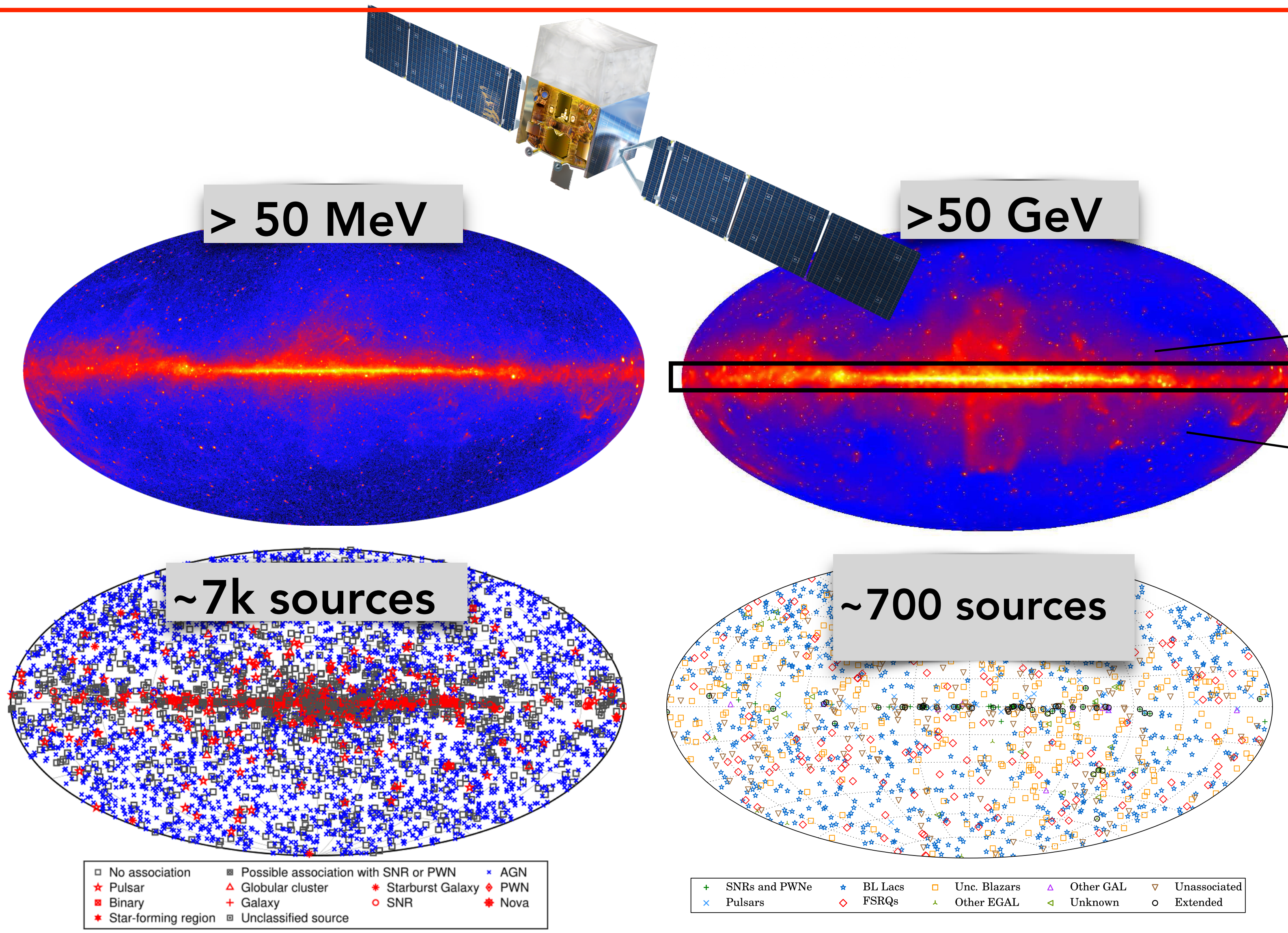
LAT source catalogue, **>50 GeV** (4FHL)

TeVCat

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

GeV - TeV sky

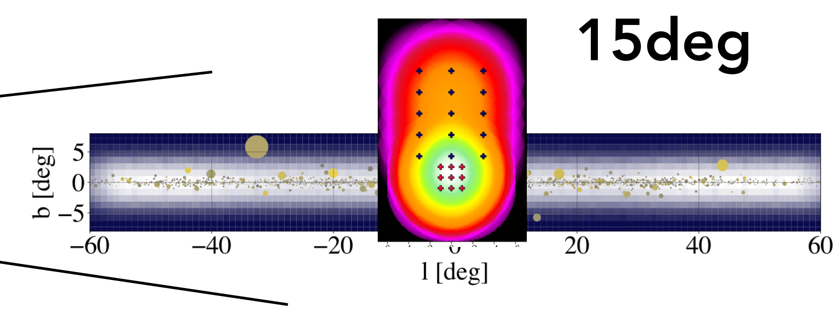
Coming up -
CTAO surveys



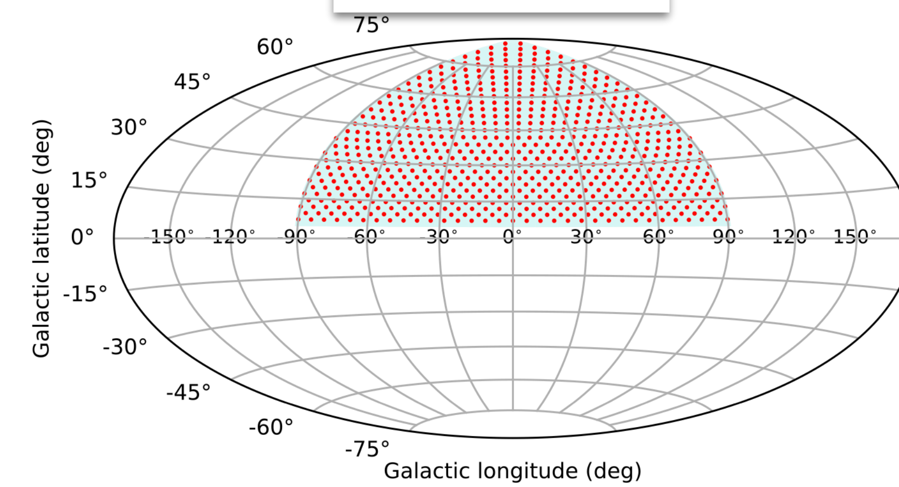
LAT source catalogues,
>50 MeV (**4FGL - DR4**)

LAT source catalogue,
>50 GeV (4FHL)

GP + GC surveys

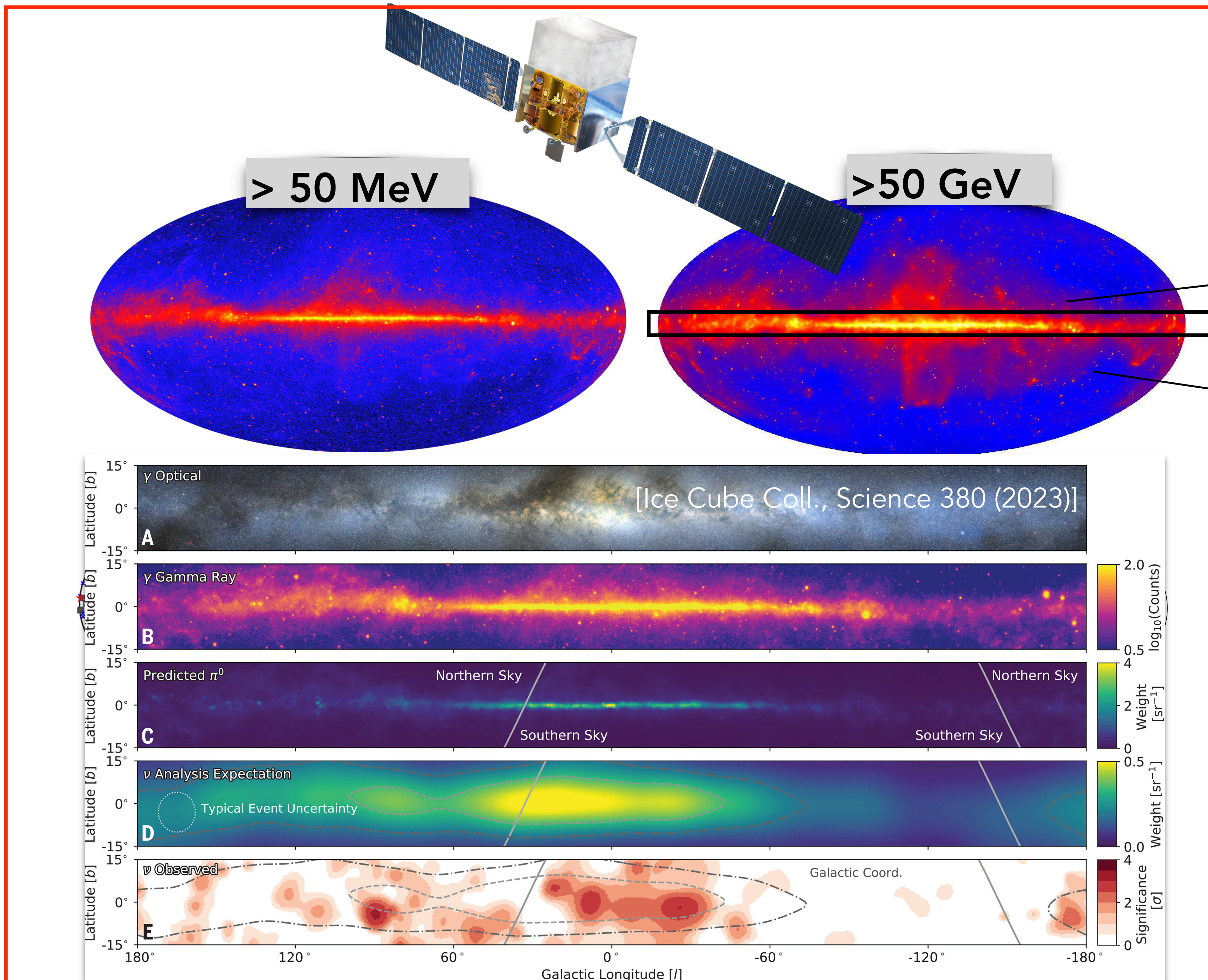


Extra gal
survey



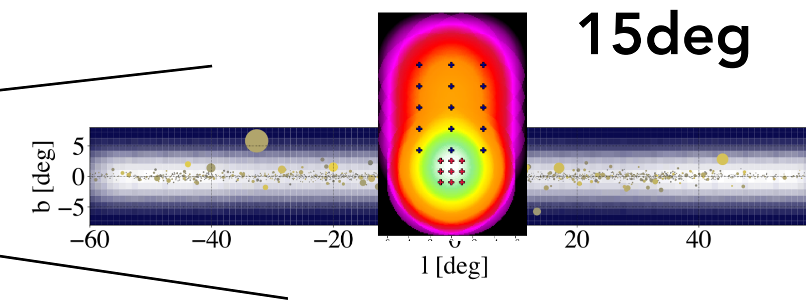
GeV - TeV sky

Impact from other experiments

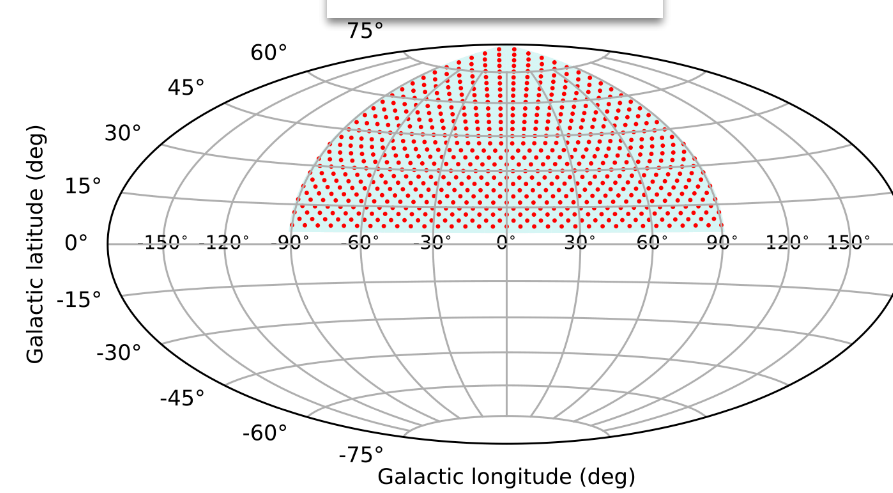


Coming up - **CTAO surveys**

GP + GC surveys



Extra gal **survey**

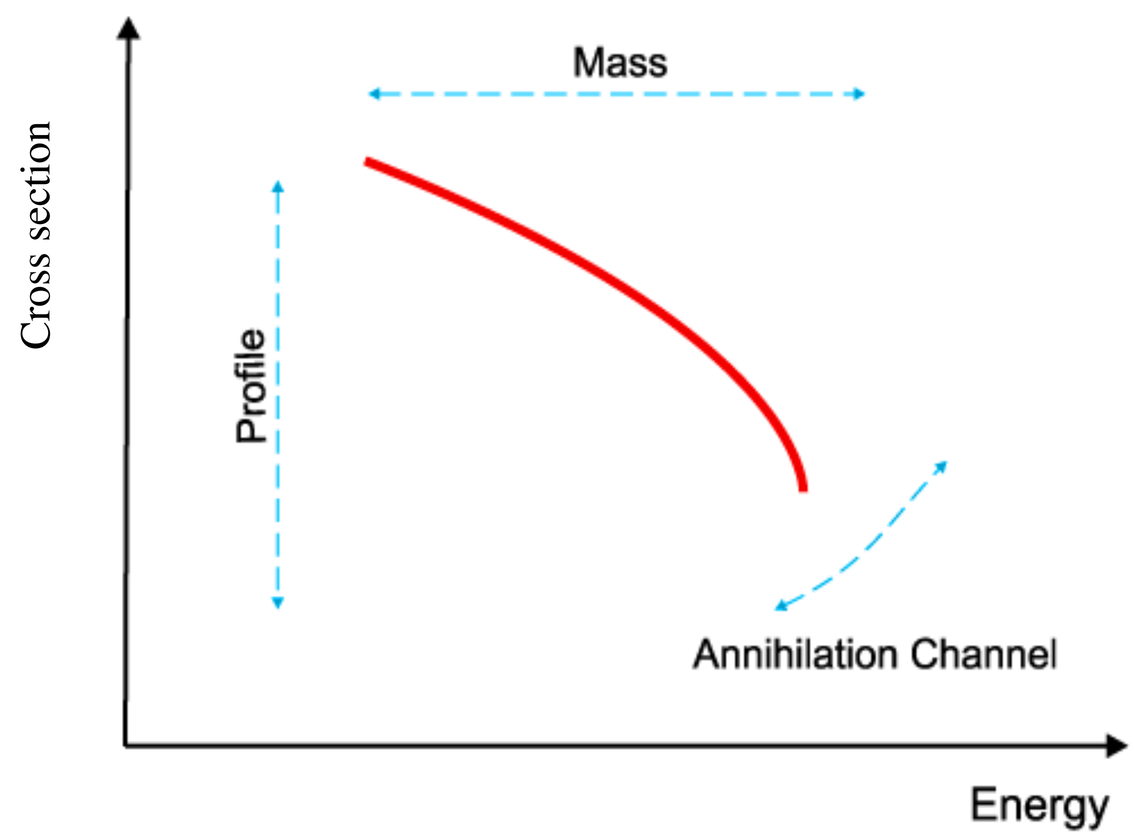


Part 1: thermal DM

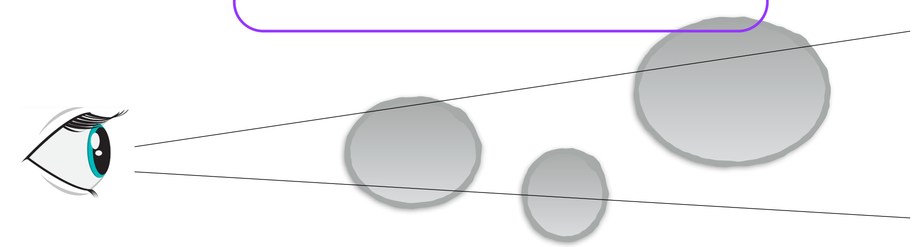
$\chi + \chi \rightarrow \mathrm{SM} + \mathrm{SM}$

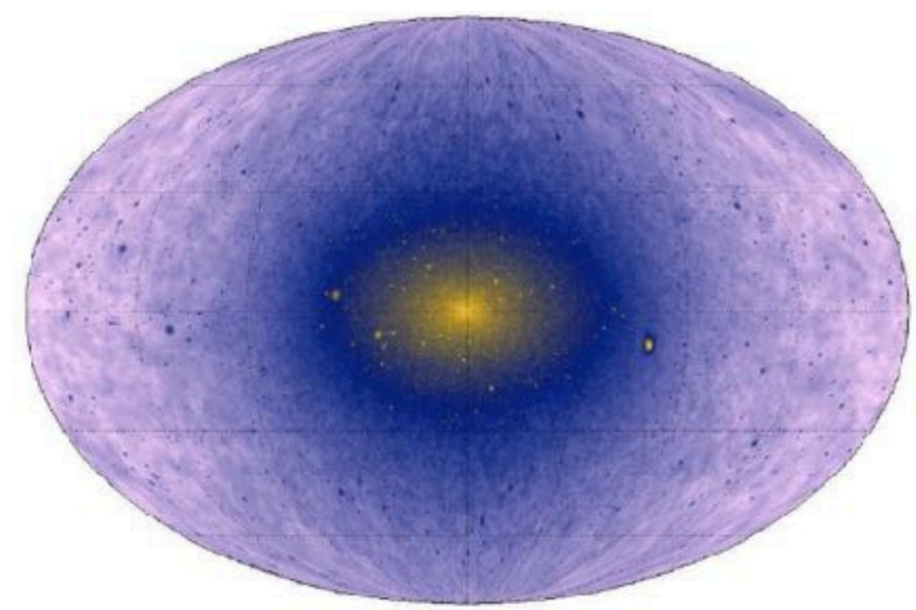
The signal?

Flux (γ, ν) = particle physics X cosmology



Bertone 2007





Part 1: thermal DM

$\chi + \chi \rightarrow \mathrm{SM} + \mathrm{SM}$

potential impact on other fields

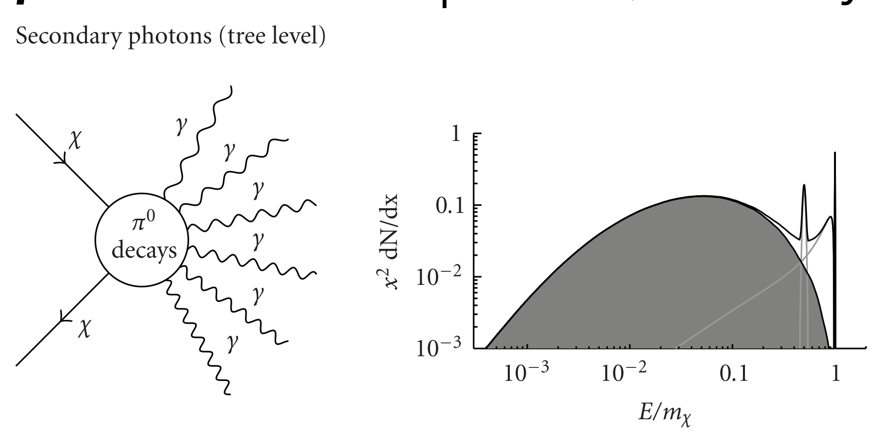
The signal?

particle physics

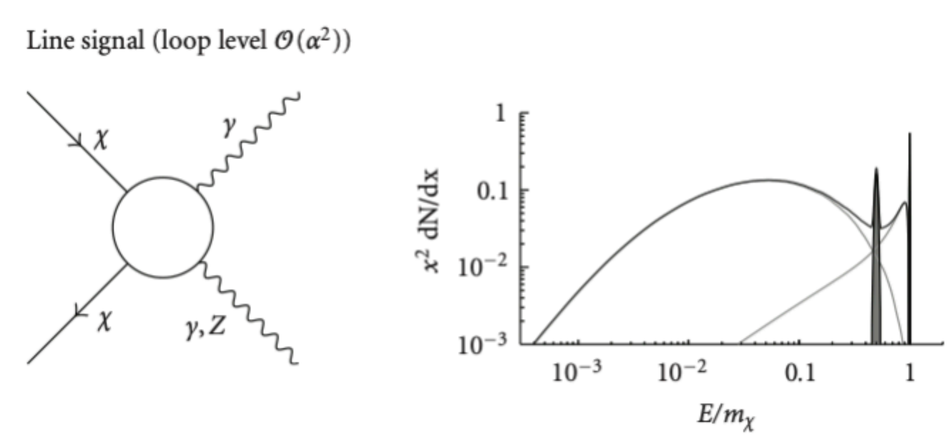
$$\text{Flux } (\gamma, \nu) = \frac{1}{4\pi} \frac{(\sigma_{\rm ann} v)}{2\, m_\chi^2} \times \sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma} \times \text{cosmology}$$

flux of SM particles per DM annihilation

quasi-universal **spectra (π^0 decays)**



Spectral features



Part 1: thermal DM

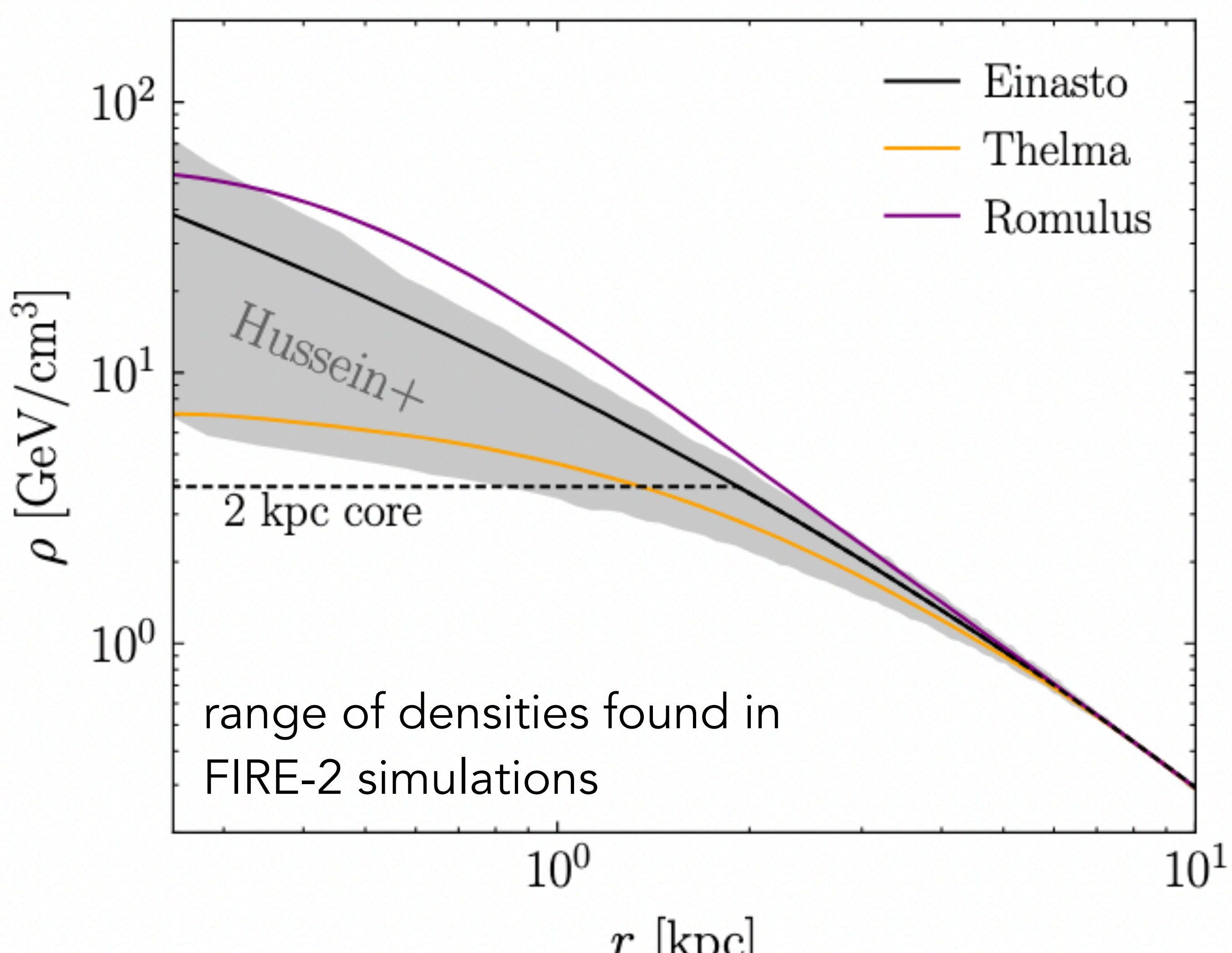
$\chi + \chi \rightarrow \mathrm{SM} + \mathrm{SM}$

potential impact on other fields

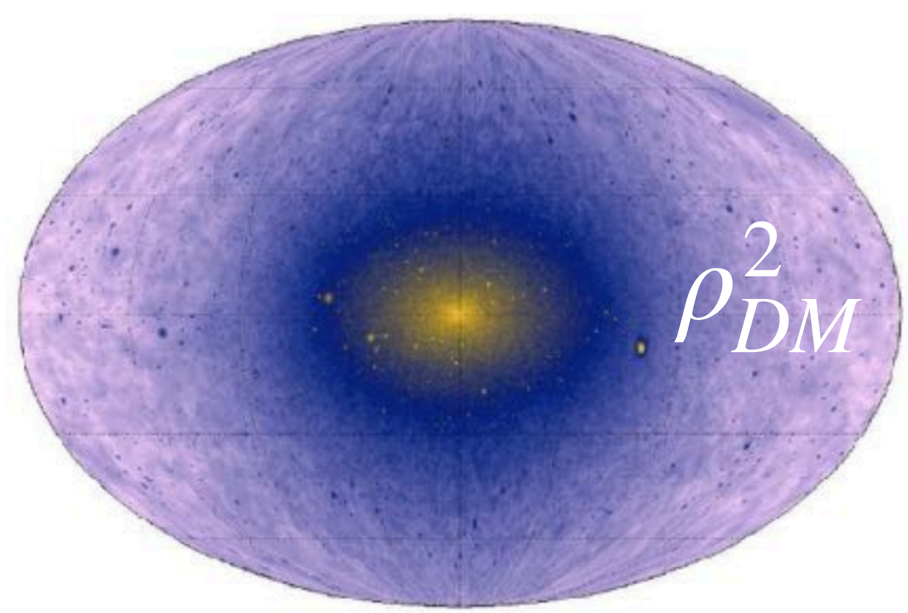
The signal?

cosmology

Flux (γ, ν) = particle physics X $\int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\, \rho^2(s, \Omega)$



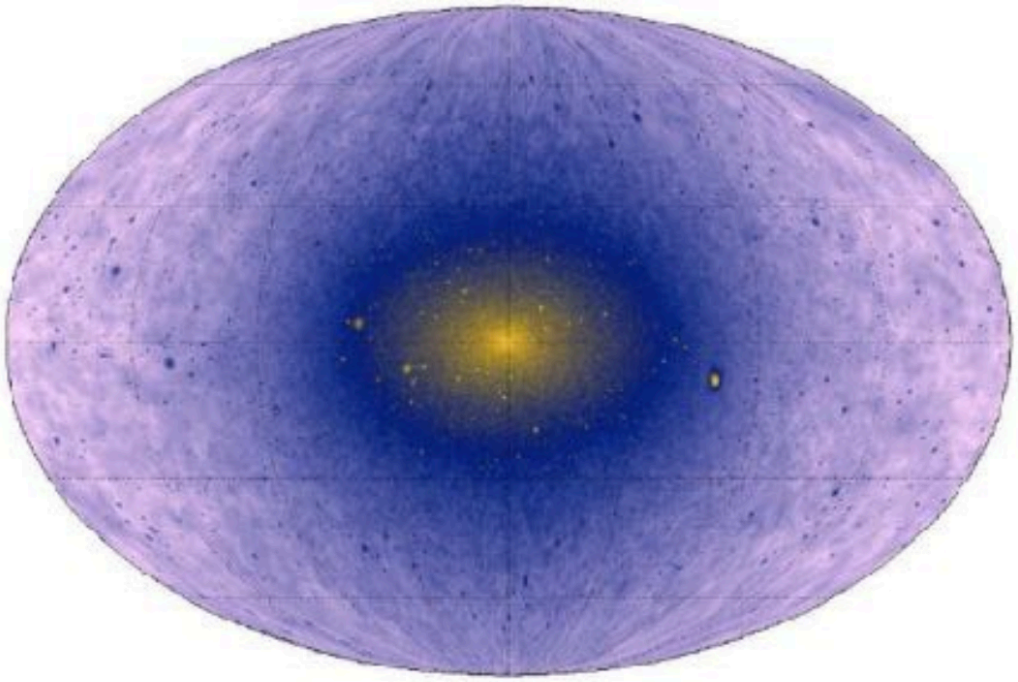
range of densities found in FIRE-2 simulations

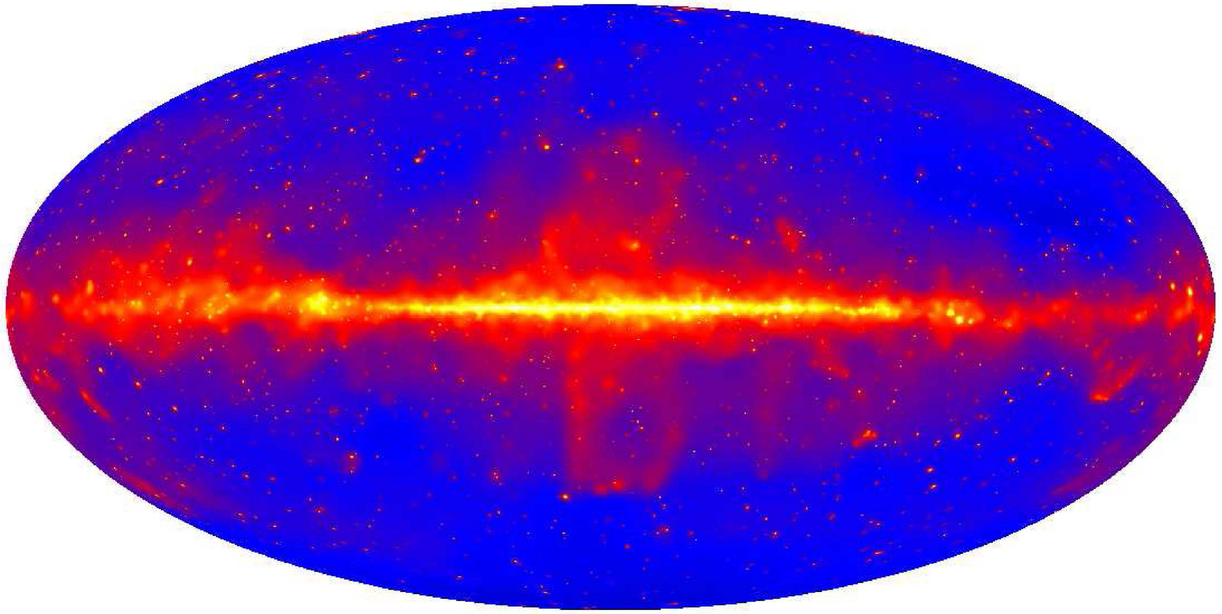


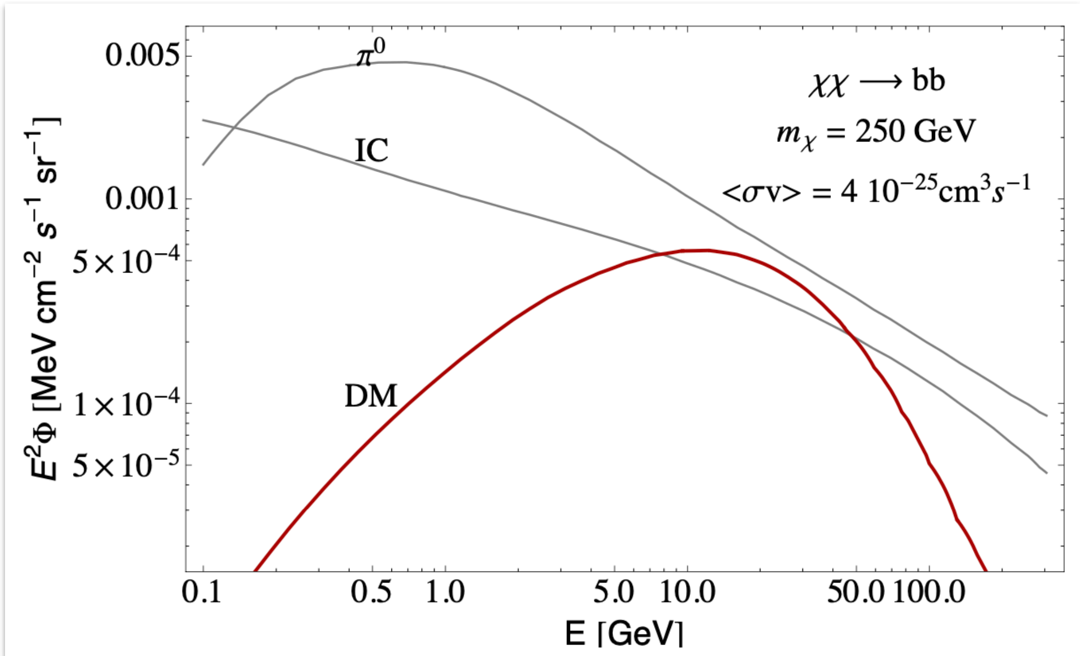
Significant uncertainties on small scales!
(where bulk of the signal comes from)

Part 1: thermal DM

The challenge in a nutshell



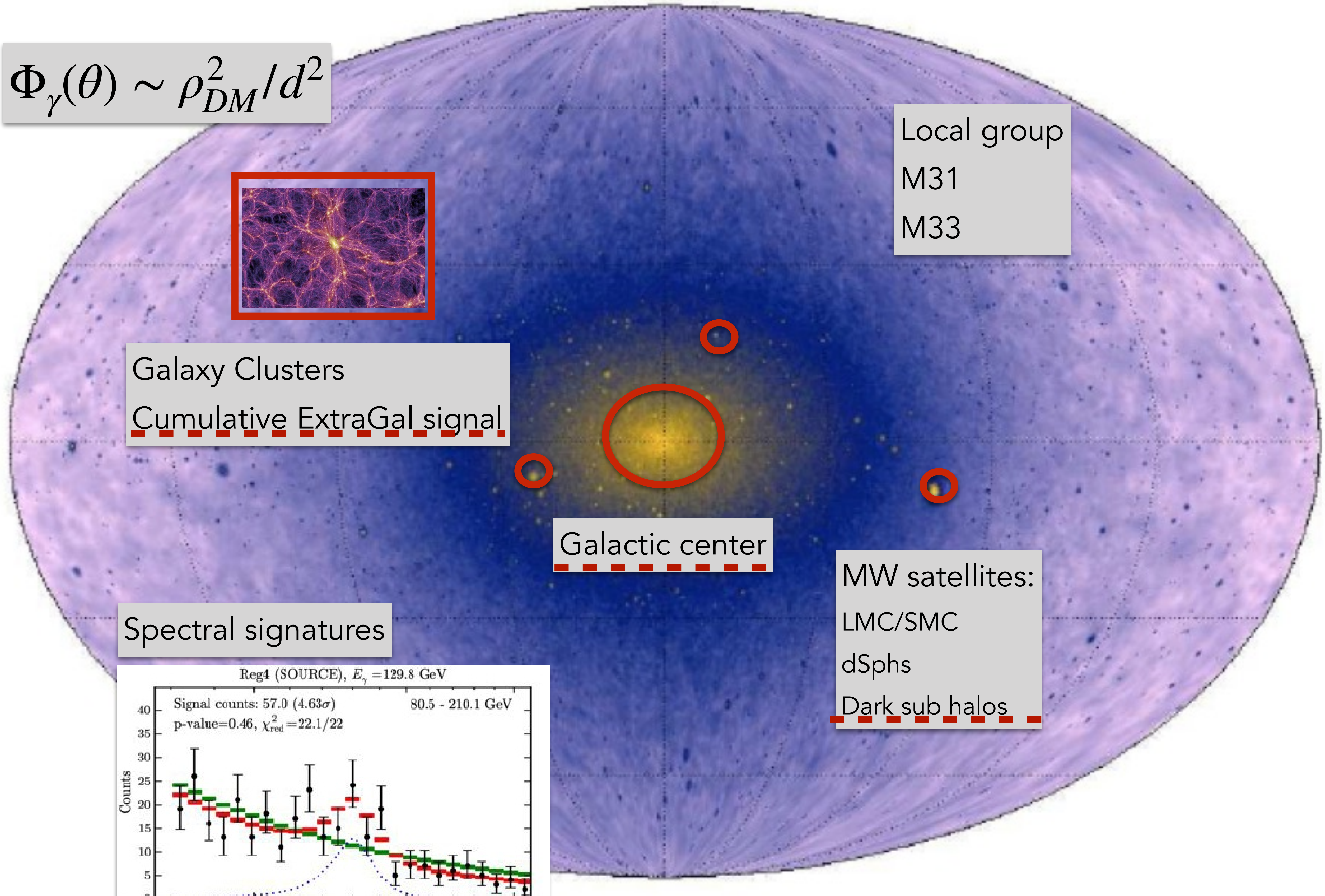




Analysis methods:

- template likelihood
- machine learning (CNNs, SBI)

Part 1: thermal DM



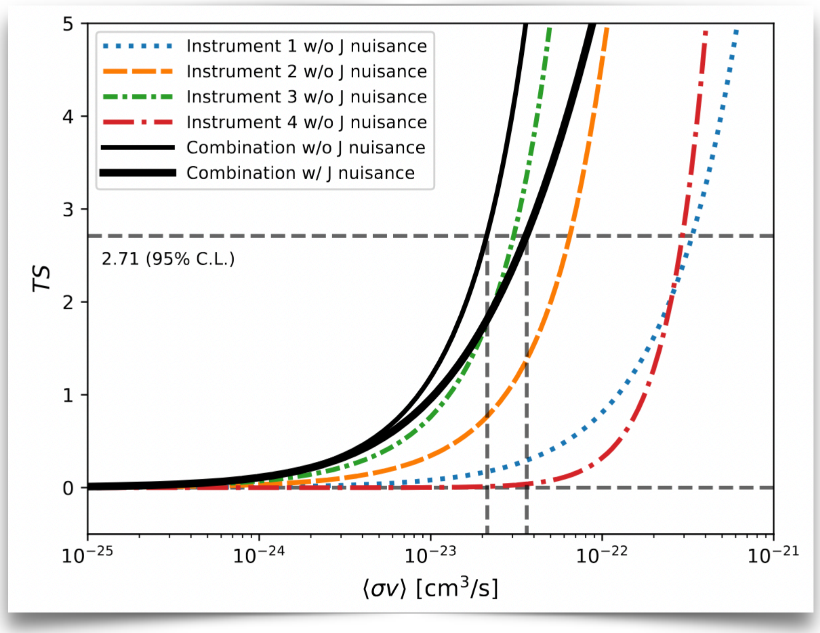
- - - - - Larger sky coverage needed

Part 1: thermal DM - highlights

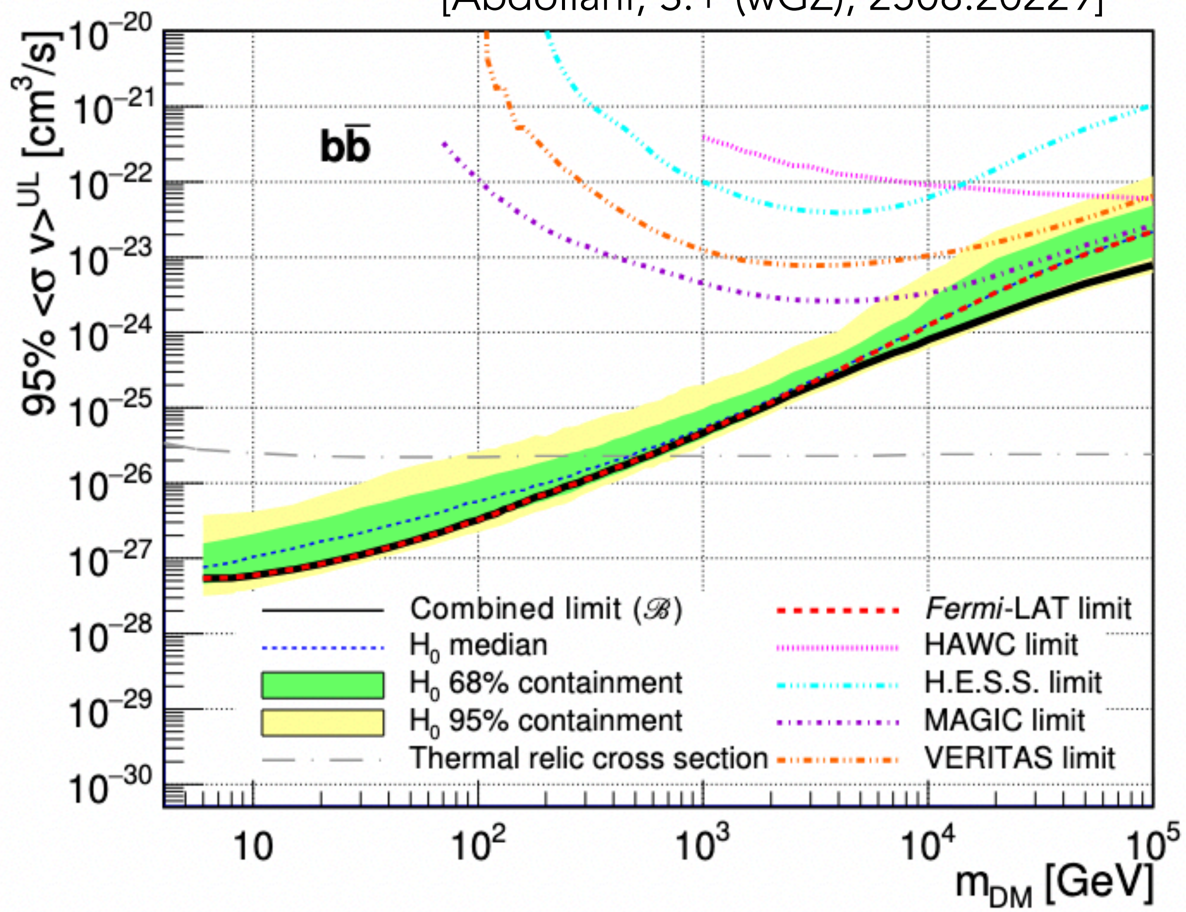
(NON) Observation of **dSPhs** one of the **most stringent and robust** limits:

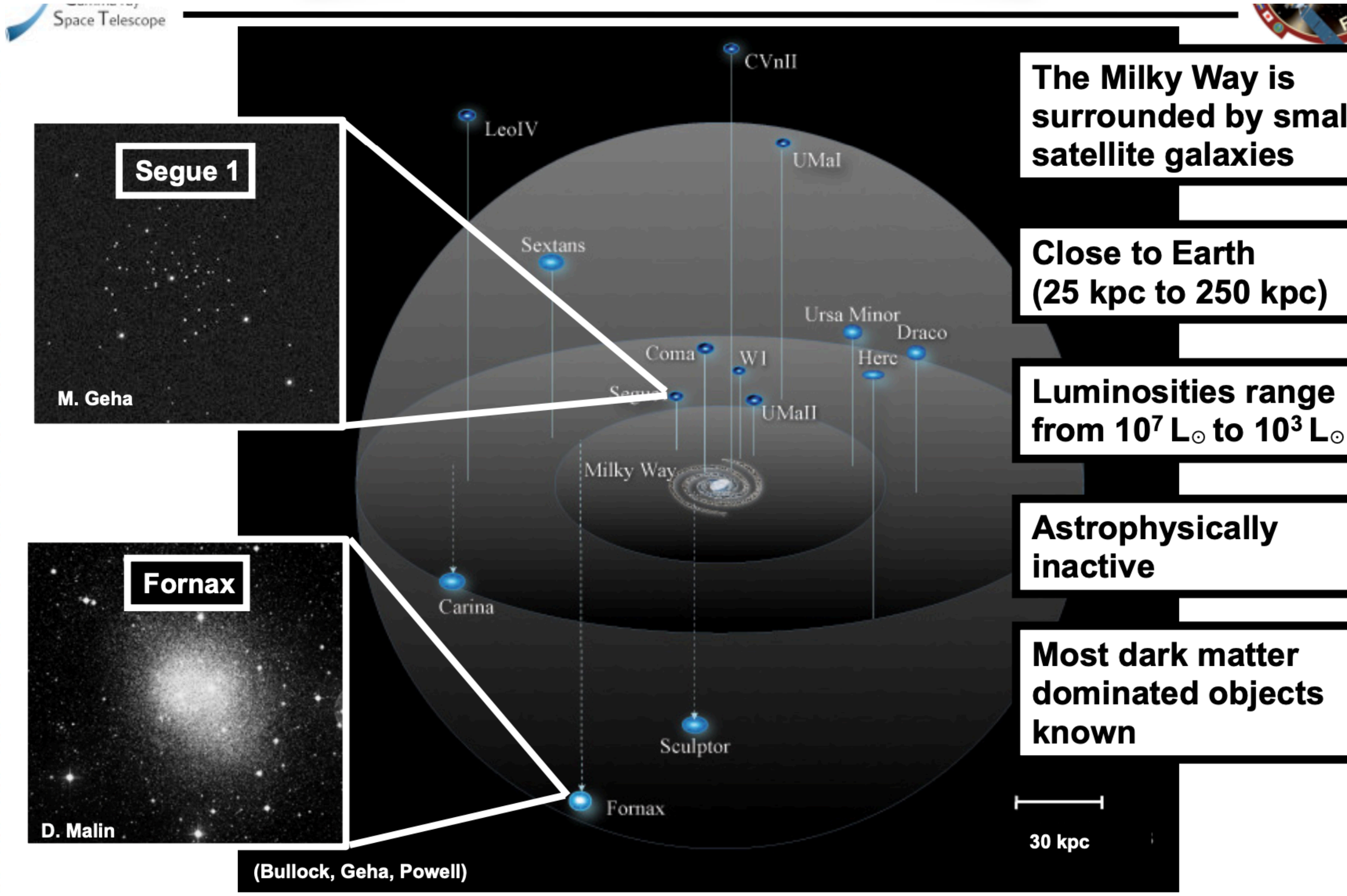
— joint likelihood analysis of **20 dSphs** using observations by 5 gamma-ray telescopes

(**Fermi LAT, MAGIC, HESS, VERITAS, HAWC**)



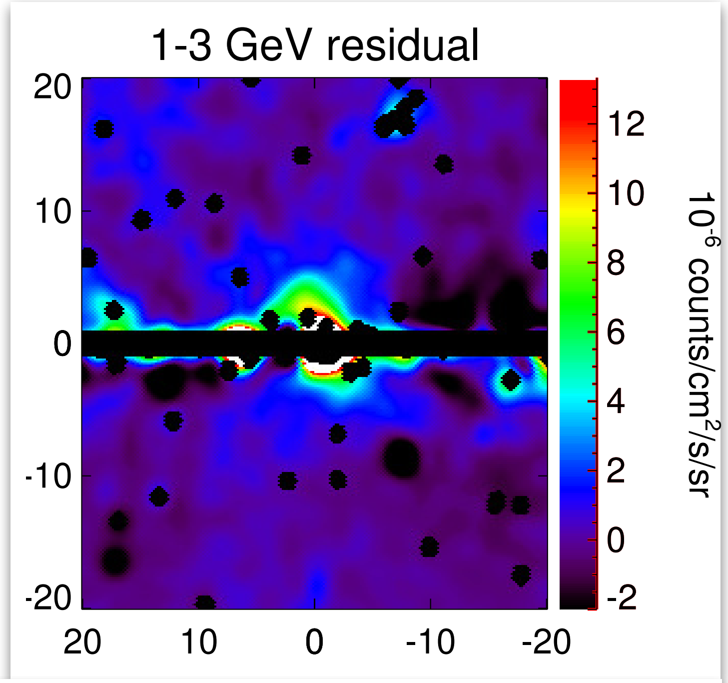
[Abdollahi, S.+ (wGZ), 2508.20229]



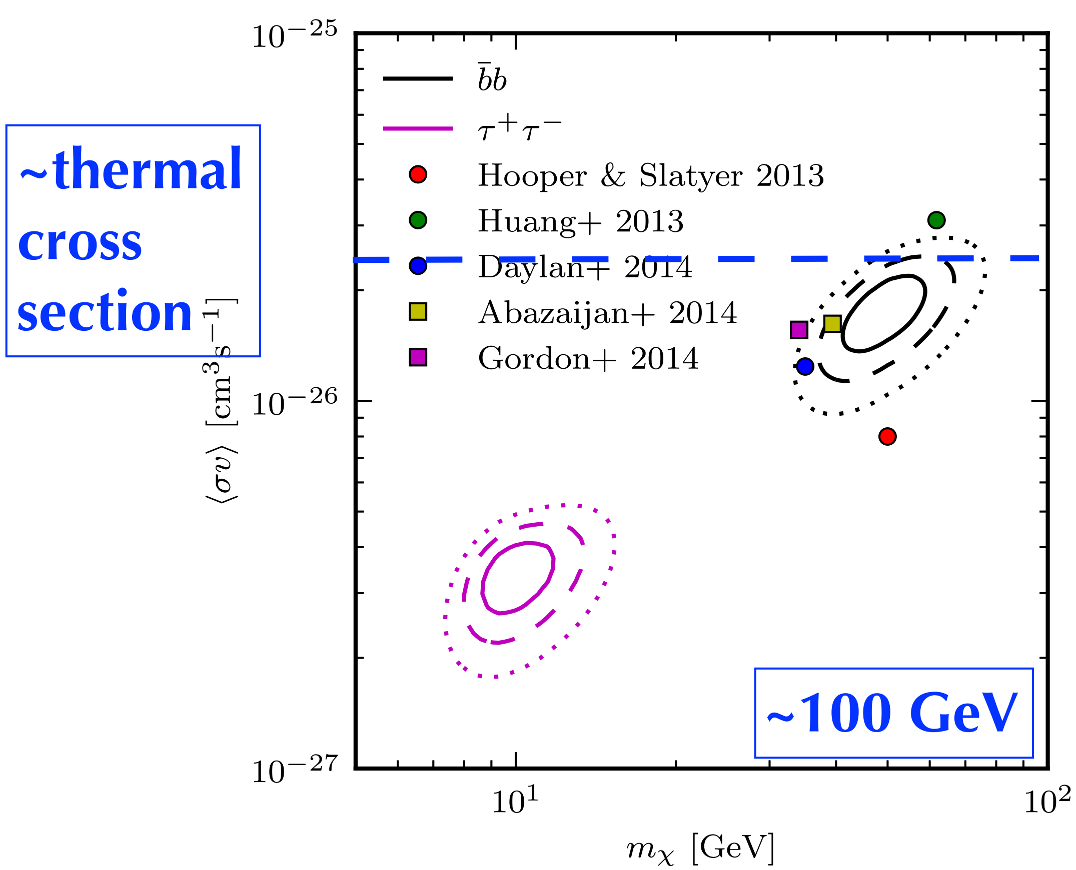


Part 1: thermal DM - highlights

The curious case of the
Galactic center excess



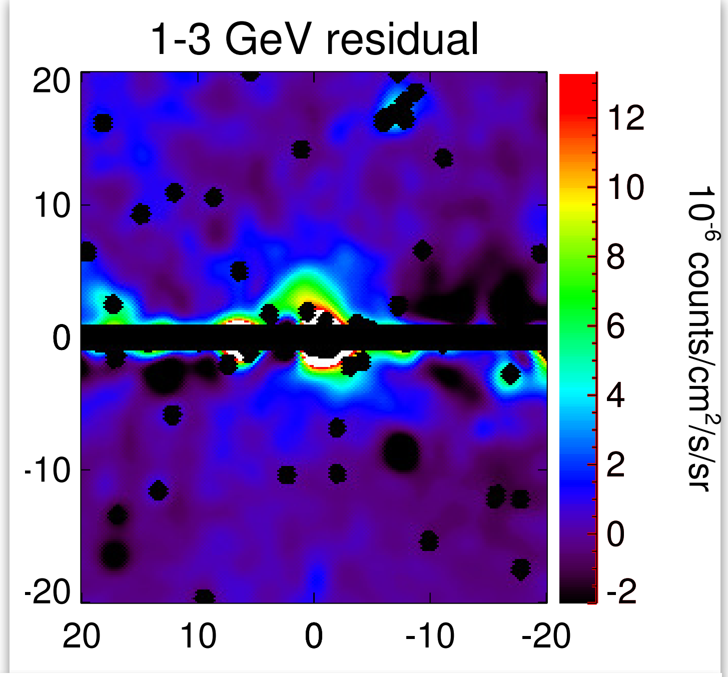
Right on the spot where WIMP DM is supposed to be!



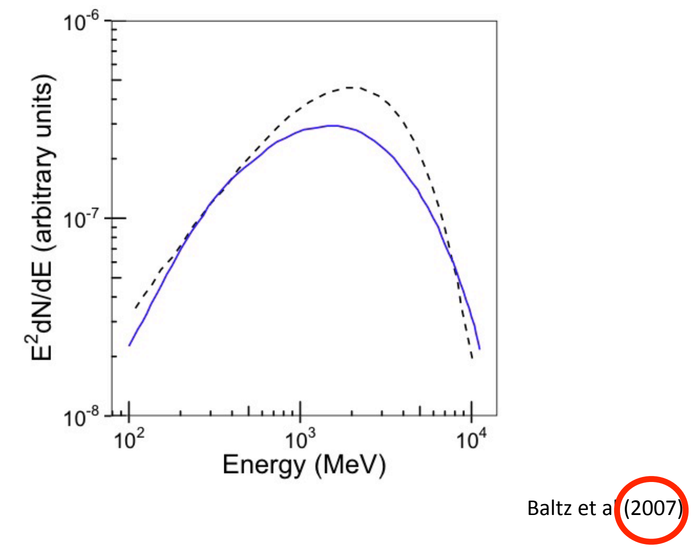
γ

Part 1: thermal DM - highlights

The curious case of the
Galactic center excess



Spectral twins: Pulsar/DM Annihilation
(30 GeV bb channel)



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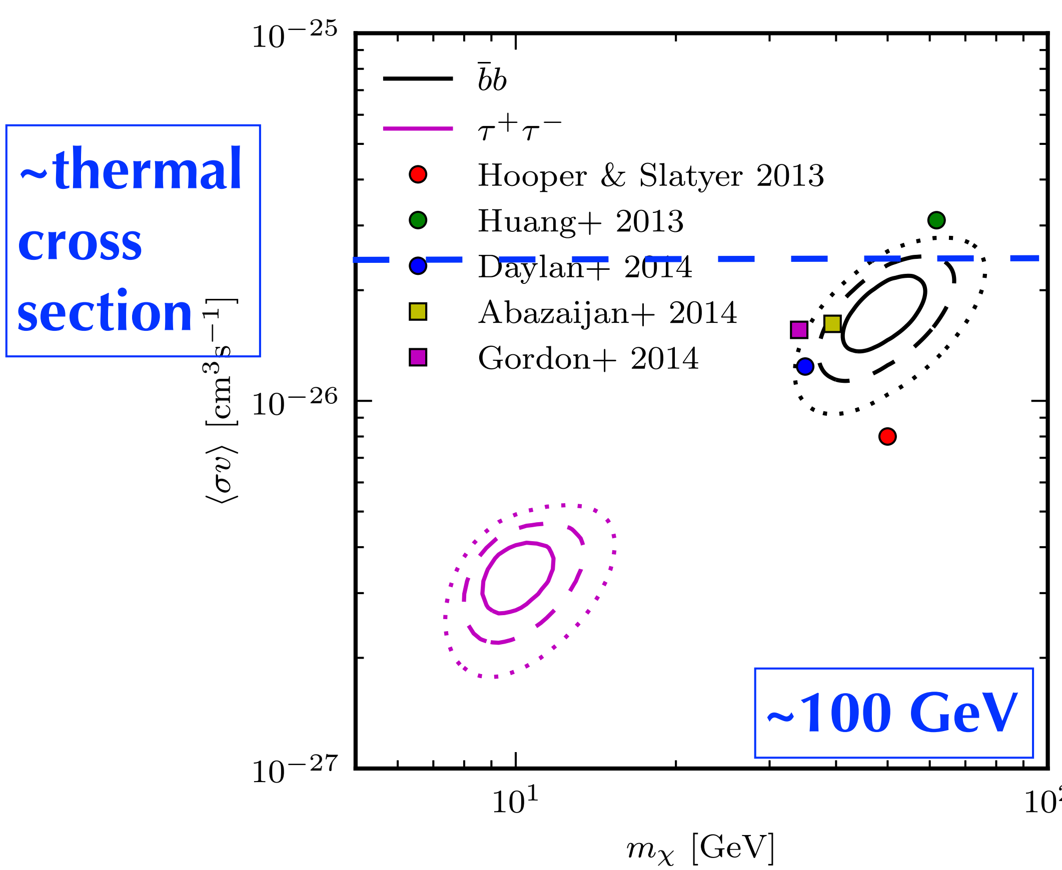
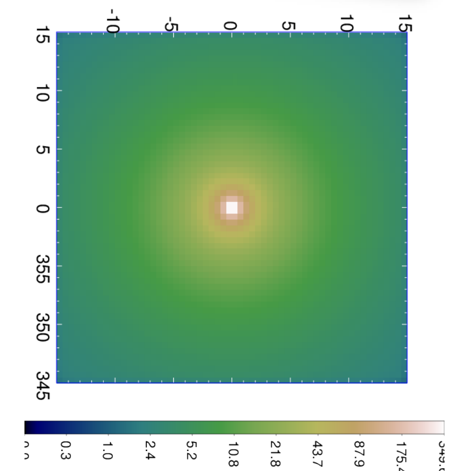
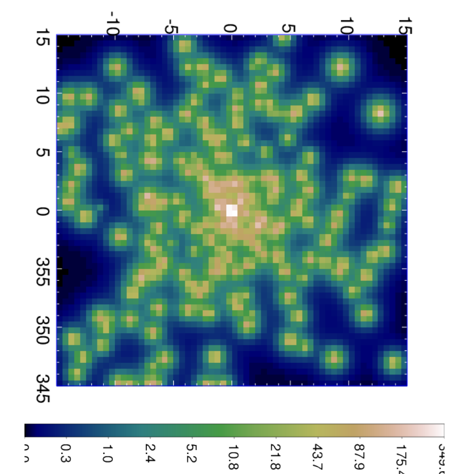


γ

Dark matter

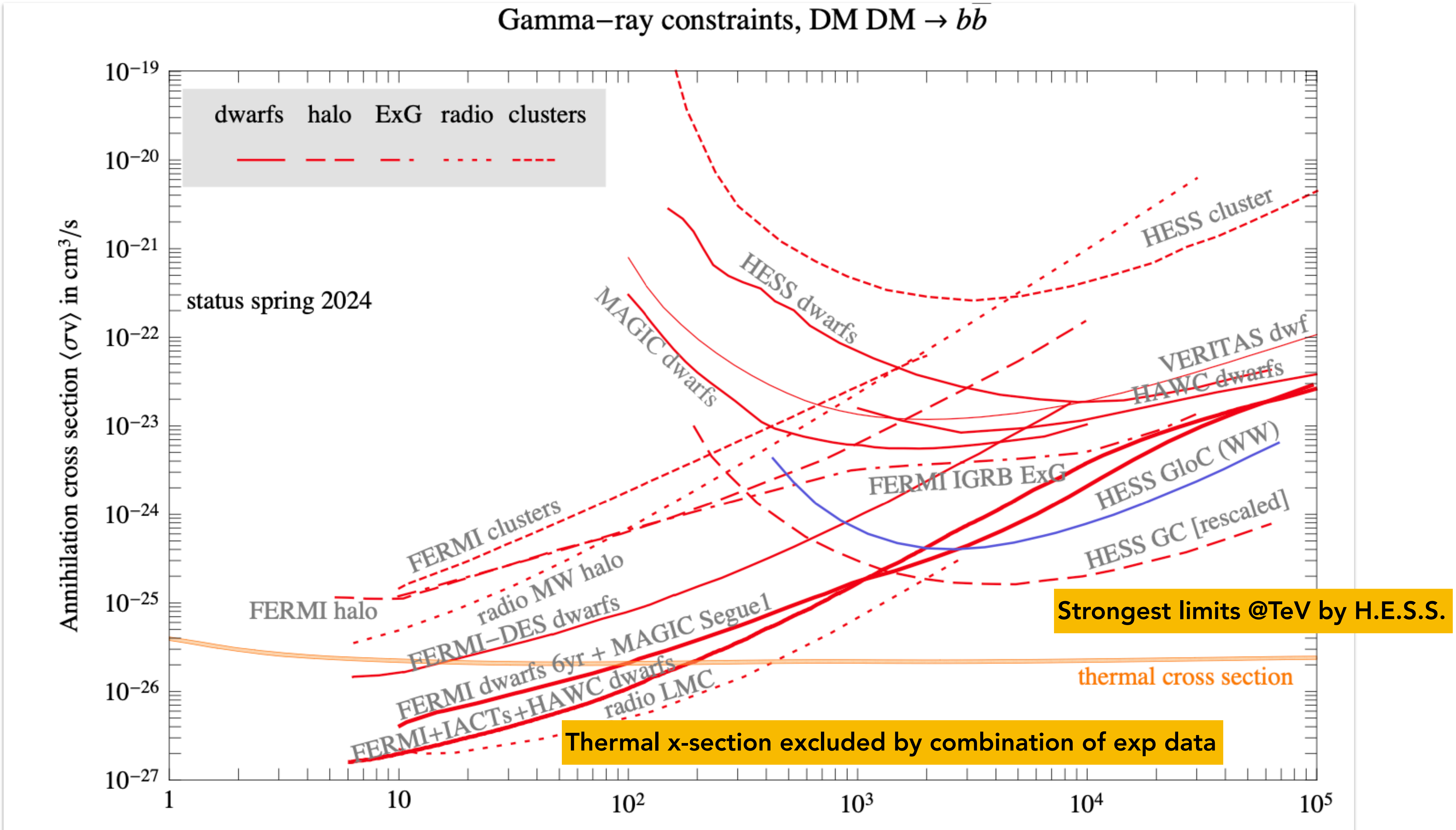


Or unresolved sources?



Part 1: thermal DM

Status cca 2024

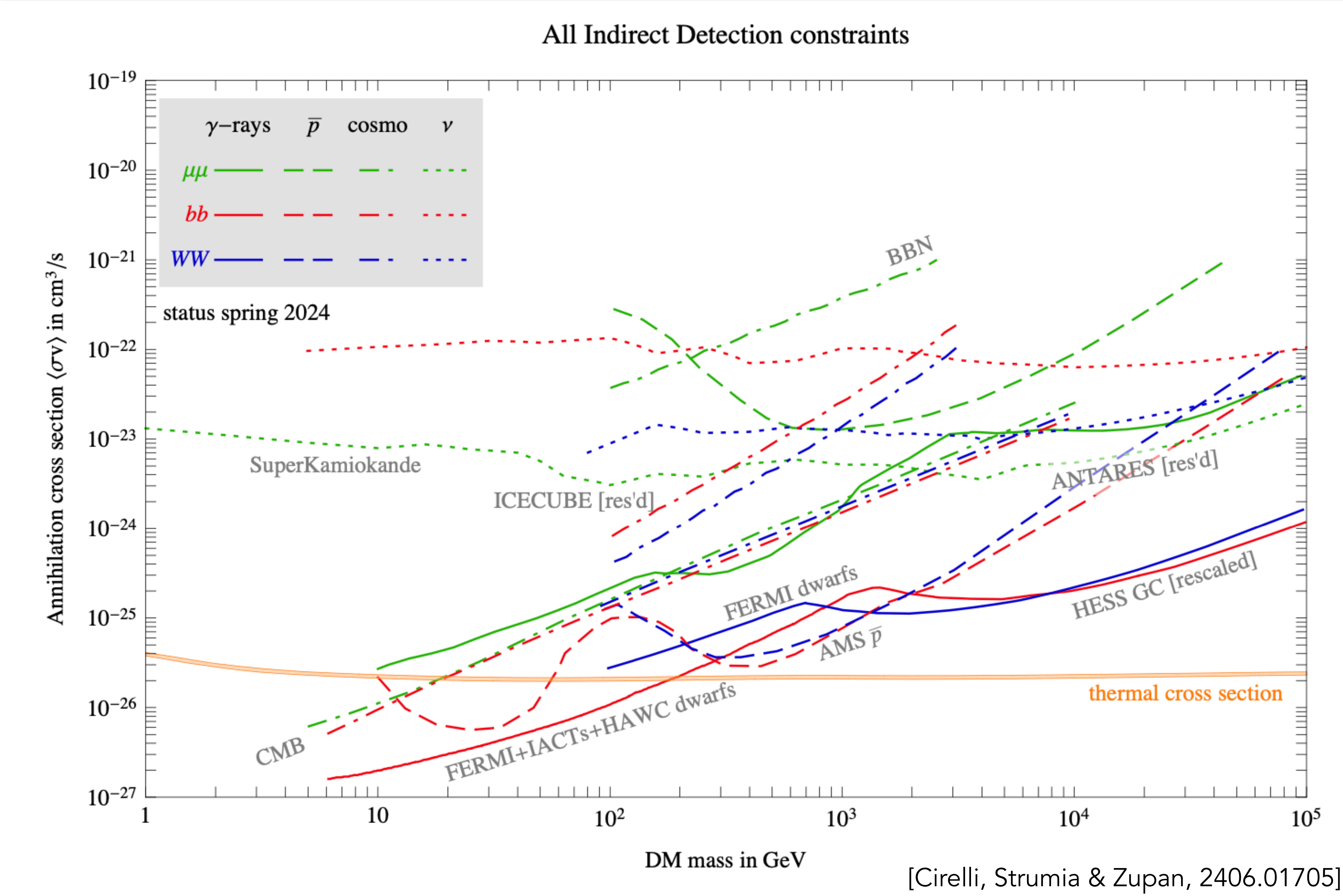


[Cirelli, Strumia & Zupan, 2406.01705]

Part 1: thermal DM

Status cca 2024

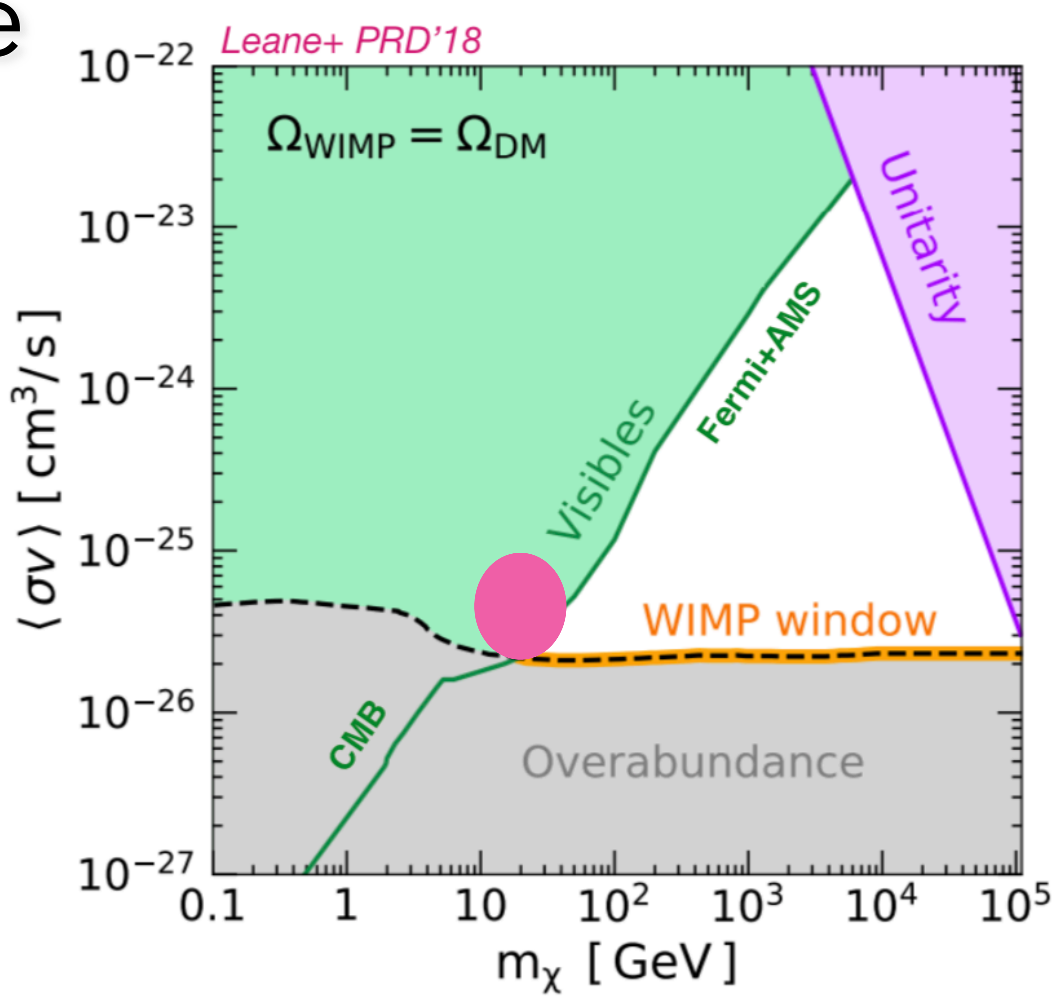
Impact from other experiments



[Cirelli, Strumia & Zupan, 2406.01705]

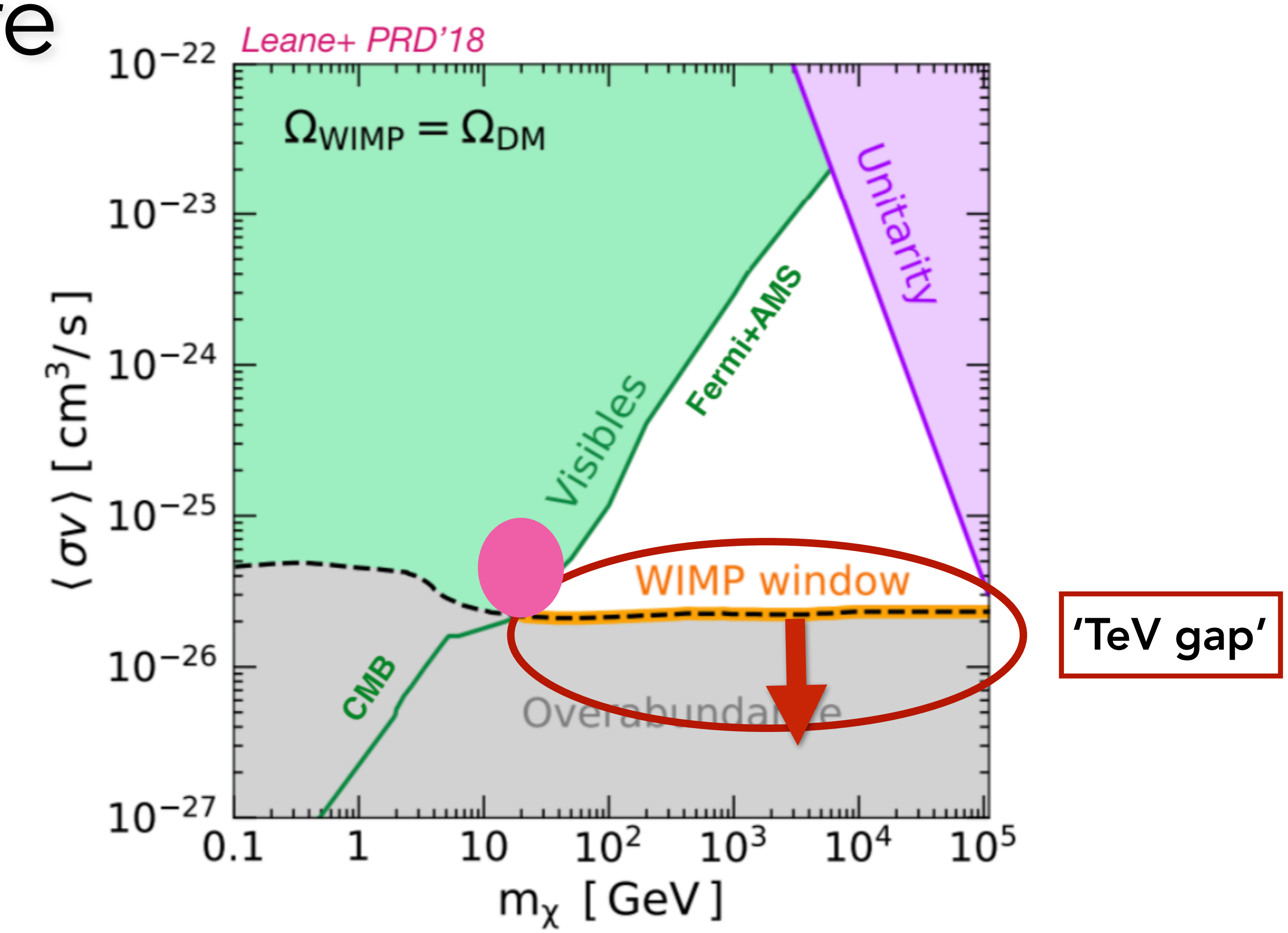
Thermal DM

The big picture



Thermal DM

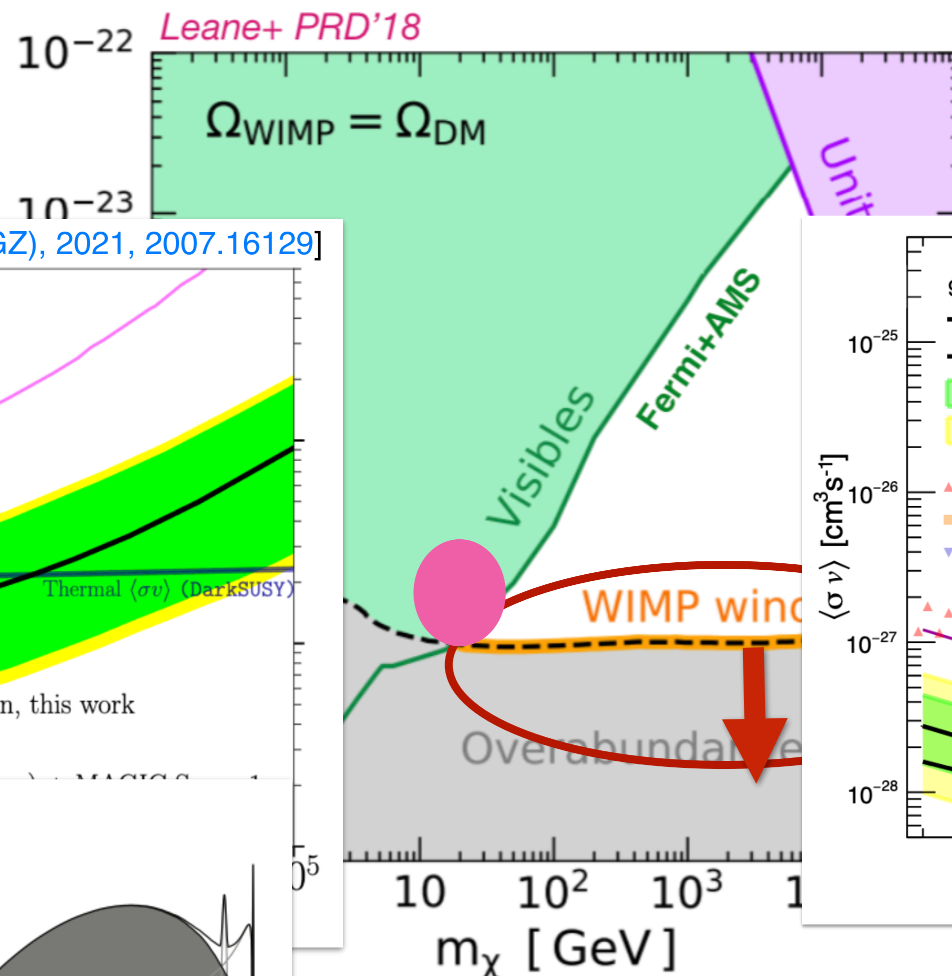
The big picture



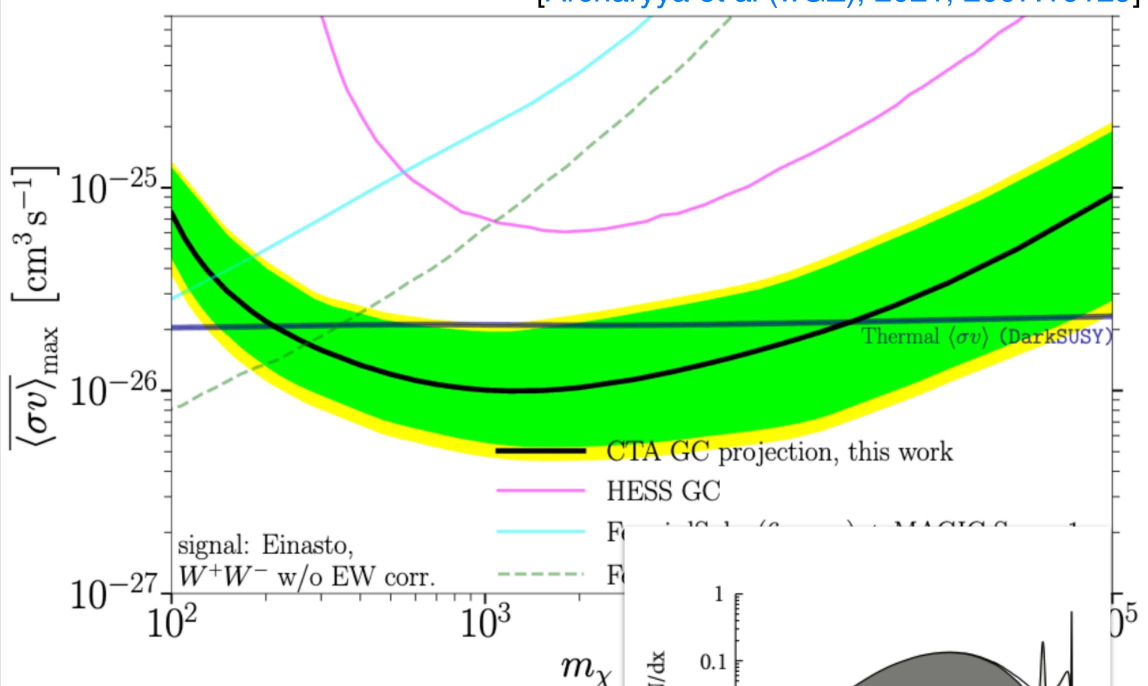
1) **CTAO is arguably the only experiment in a position to close the TeV gap**. AMS-02 complementary, systematics due to CR propagation significant.

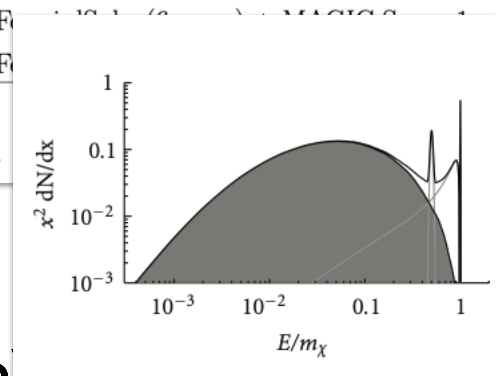
Thermal DM

The big picture

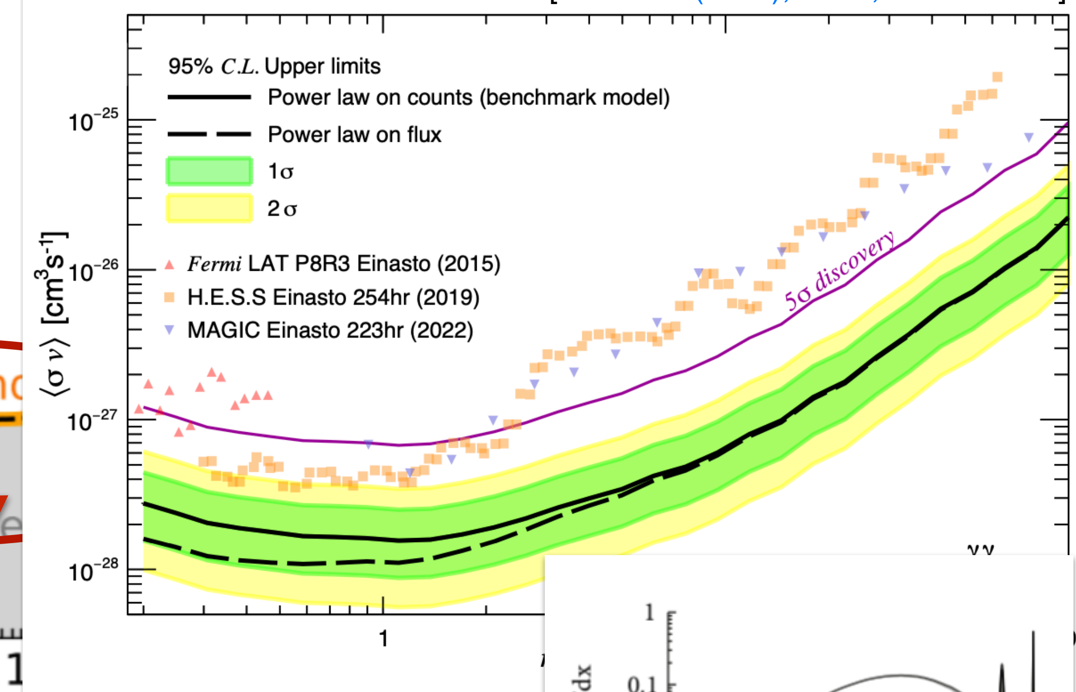


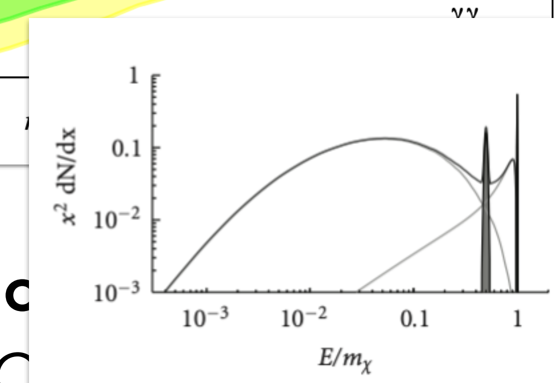
[Archaryya et al (wGZ), 2021, 2007.16129]





[Abe et al (wGZ), 2024, 2403.04857]



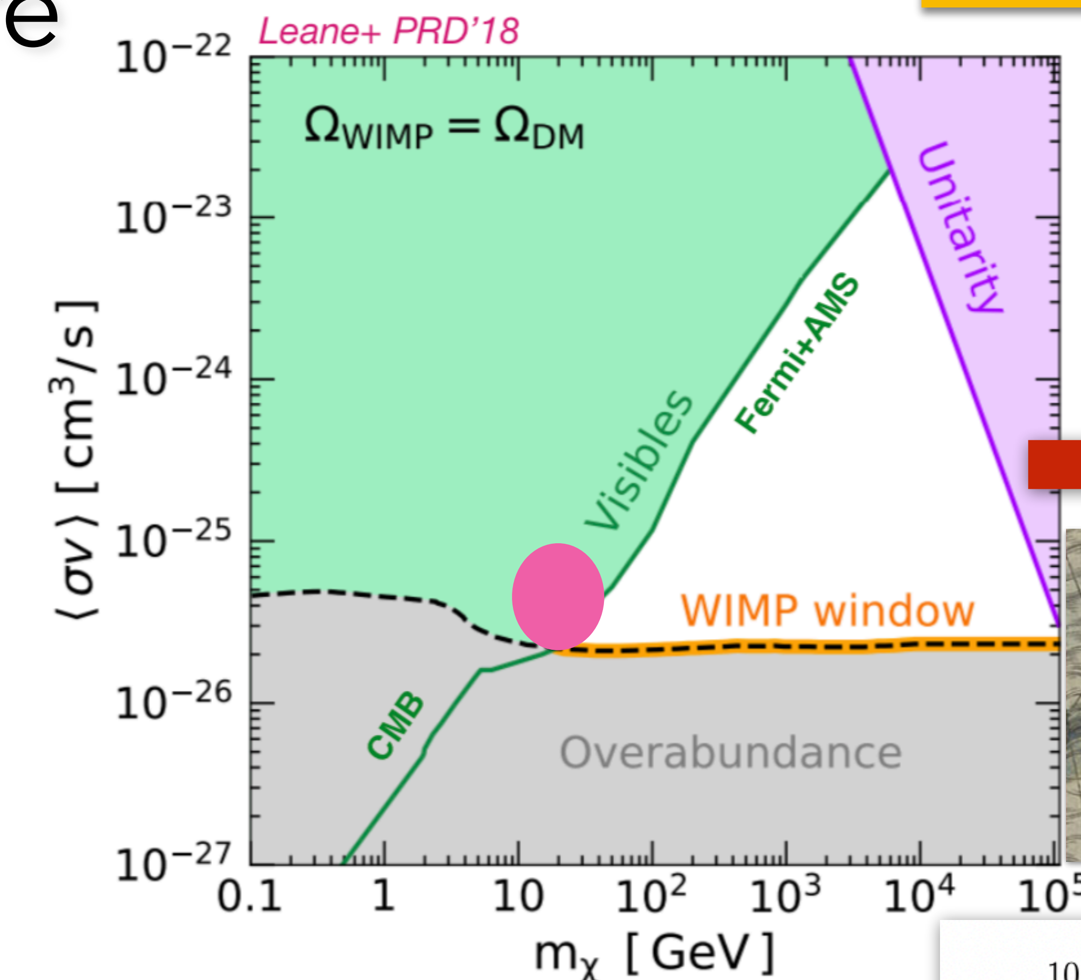


1) **CTAO** … **only experiment in a position to clo…**
the Te… gap. … complementary, systematics due to C…
propagation significant.

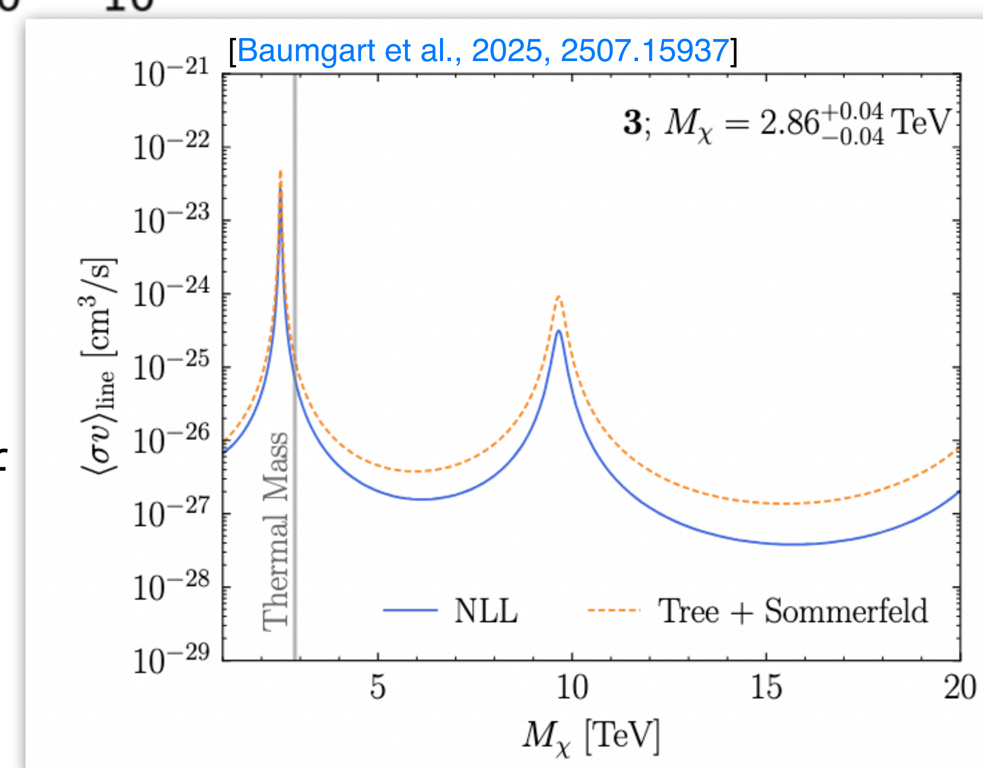
Thermal DM

The big picture

Impact from PP community (NLO)



Heavy DM



2) **New phenomenology at >TeV DM mass range**

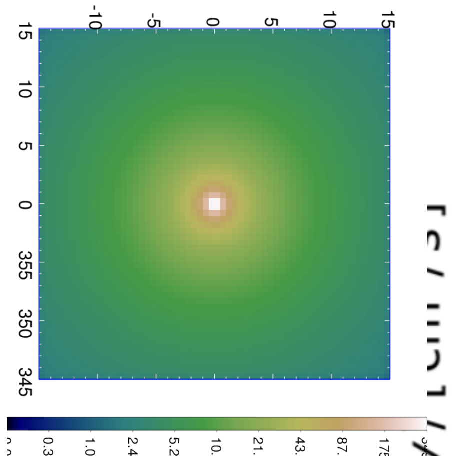
- at mDM ≳ few TeV expect **long-range behavior** with **bound states** playing a role
- there is **no model-independent unitarity limit** on mass of thermal relic DM
- **σvrel ∝ 1/vrel** and rich resonance structure expected

Thermal DM

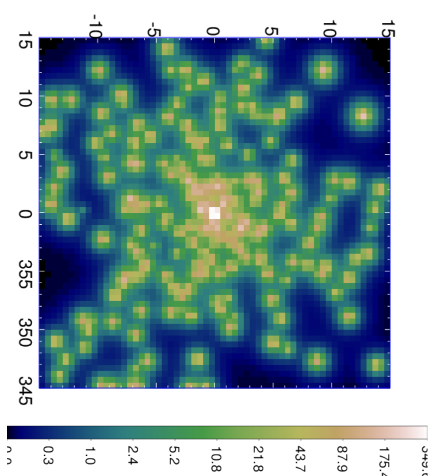
Impact from other experiments

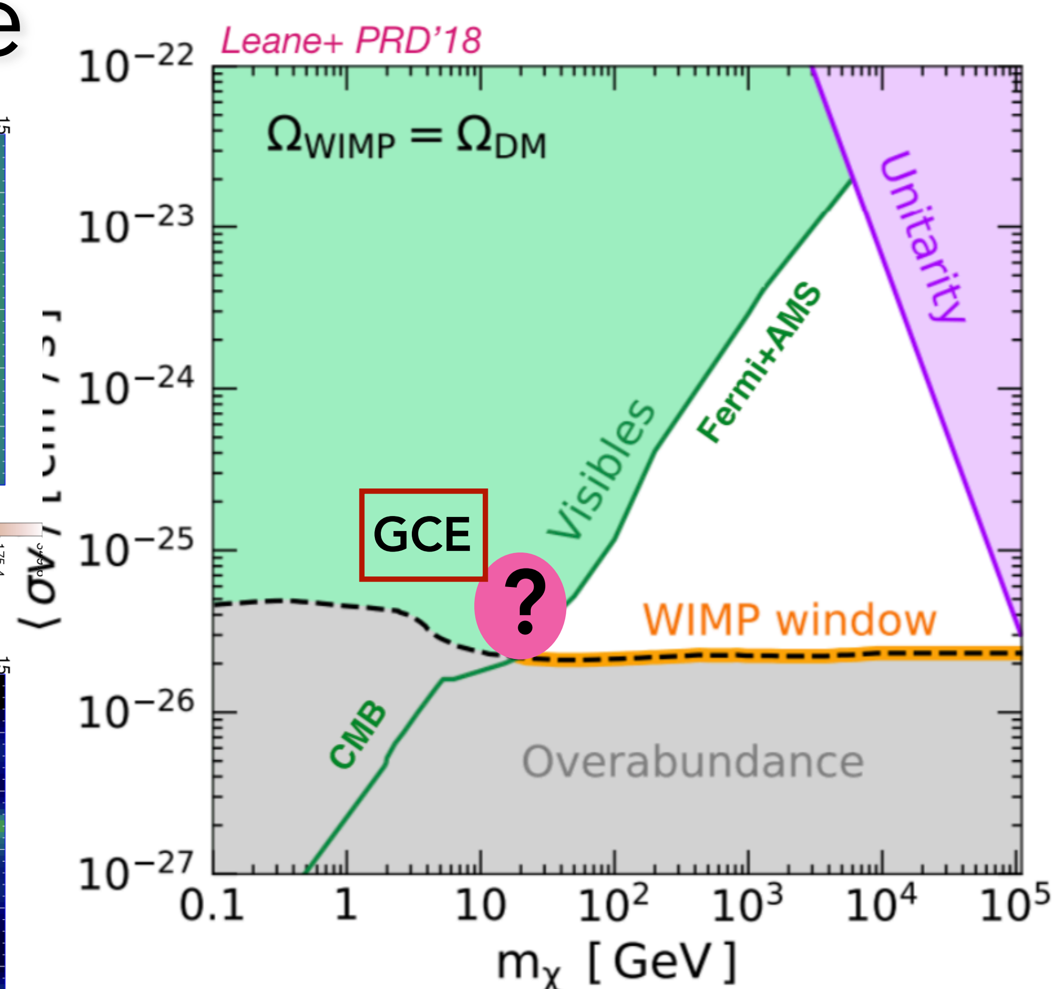
The big picture

Dark matter



Or unresolved sources?





Multi-wavelength measurements essential:

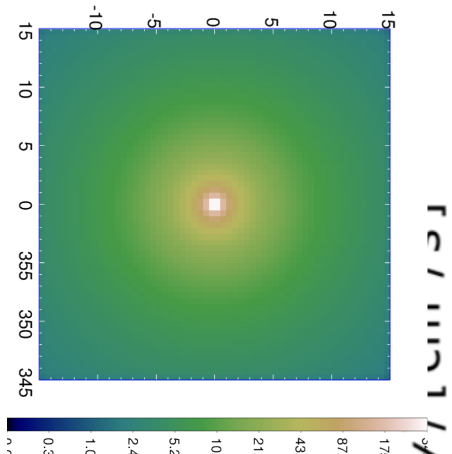
- **SKA** (pulsars in radio) [Calore+, Astrophys.J. 827 (2016)]
- **CTA** (IC from electrons injected by pulsars) [Manconi+, 2402.04733, etc]

Thermal DM

'General purpose' ML/AI methods

The big picture

Dark matter



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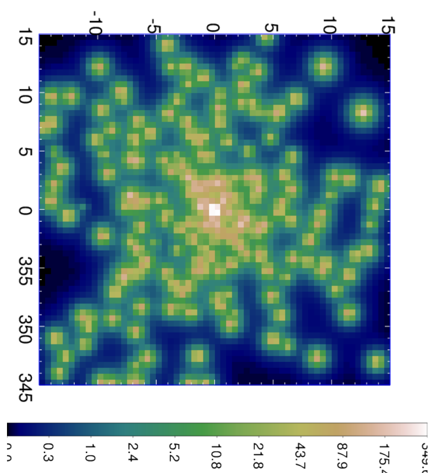
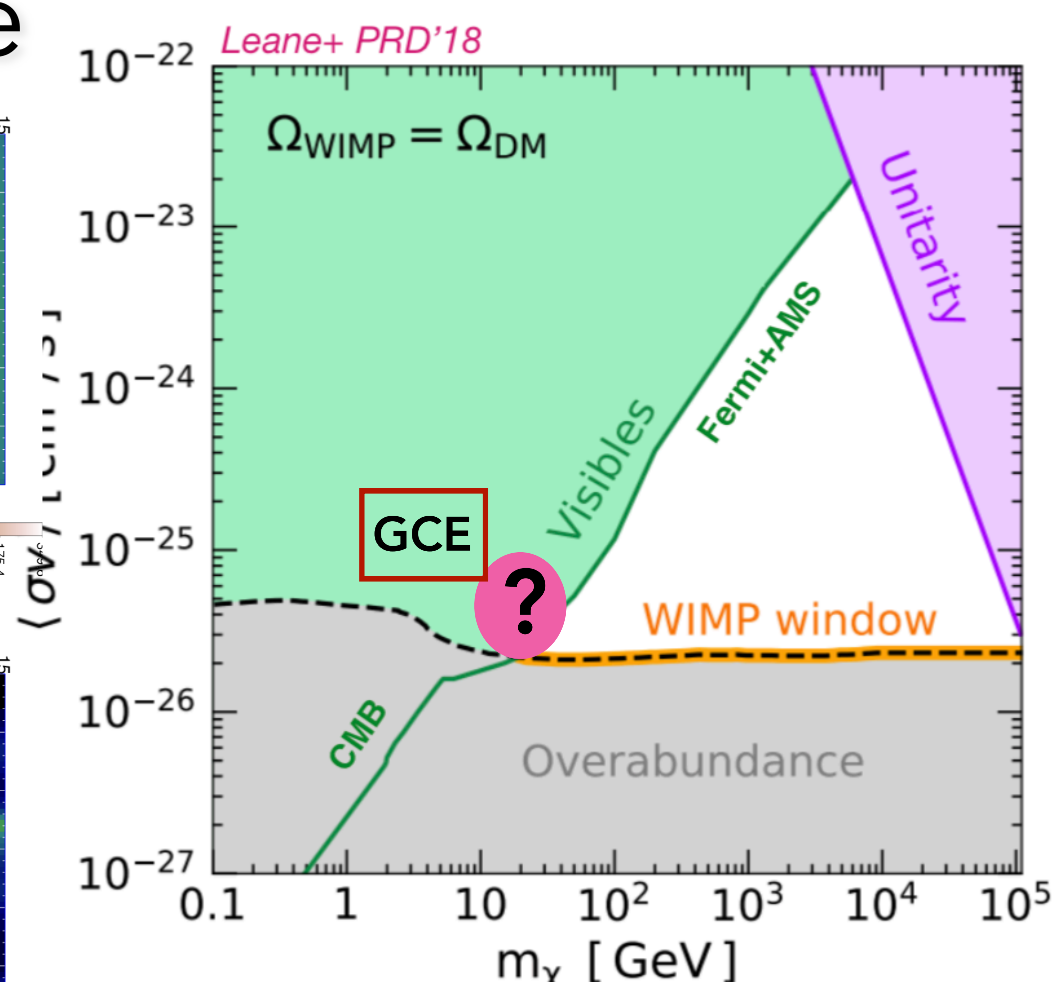
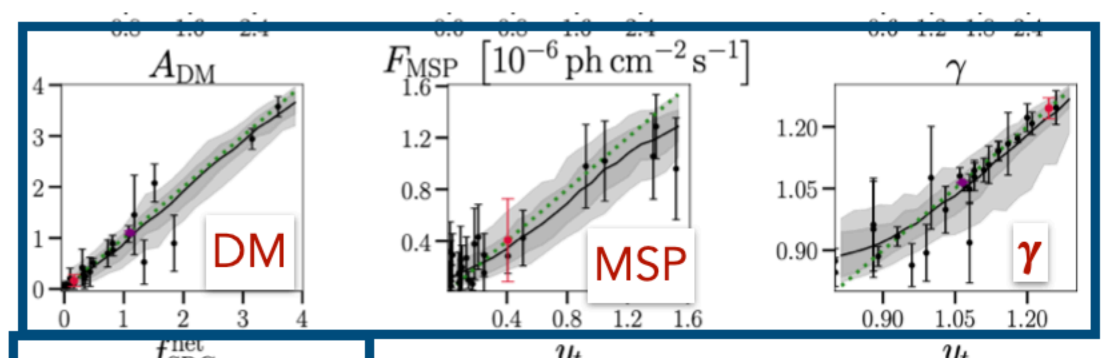
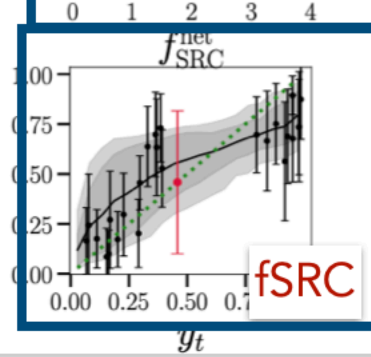




Many analyses, including **ML approach with CNNs**

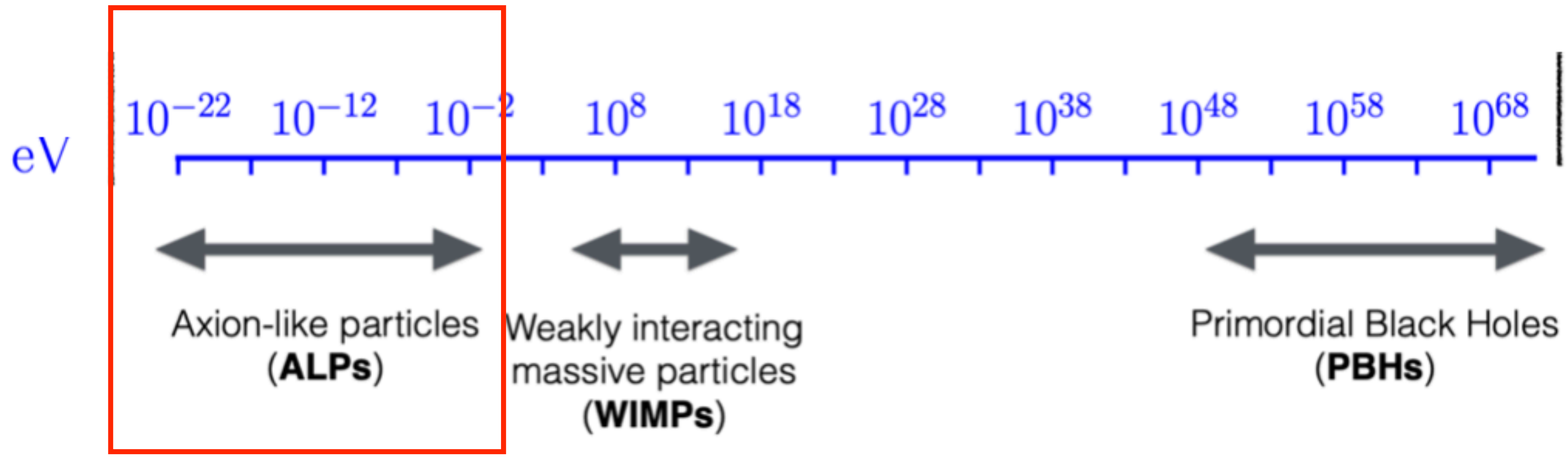




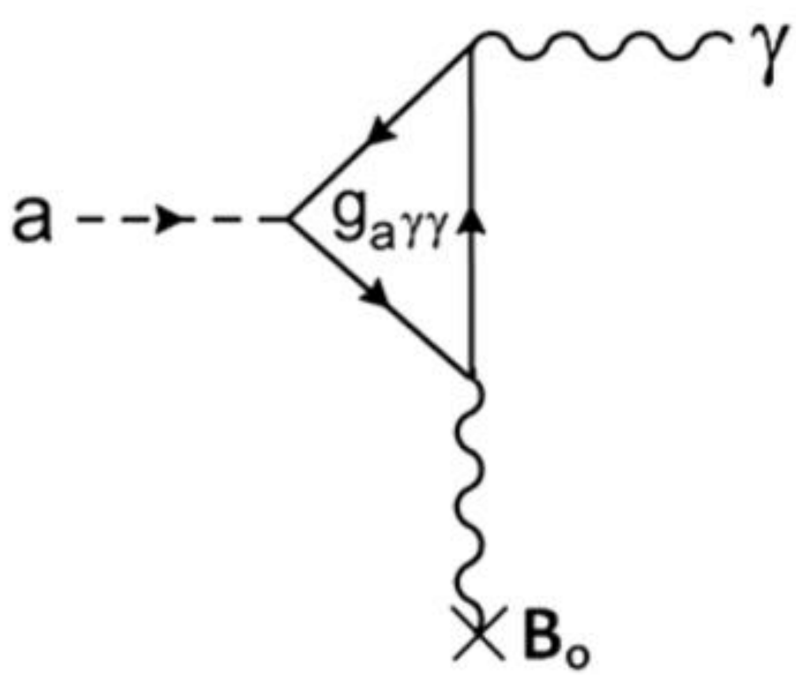
—> 'reality gap' the main limitation

[Caron+ (wGZ), 2211.09796]

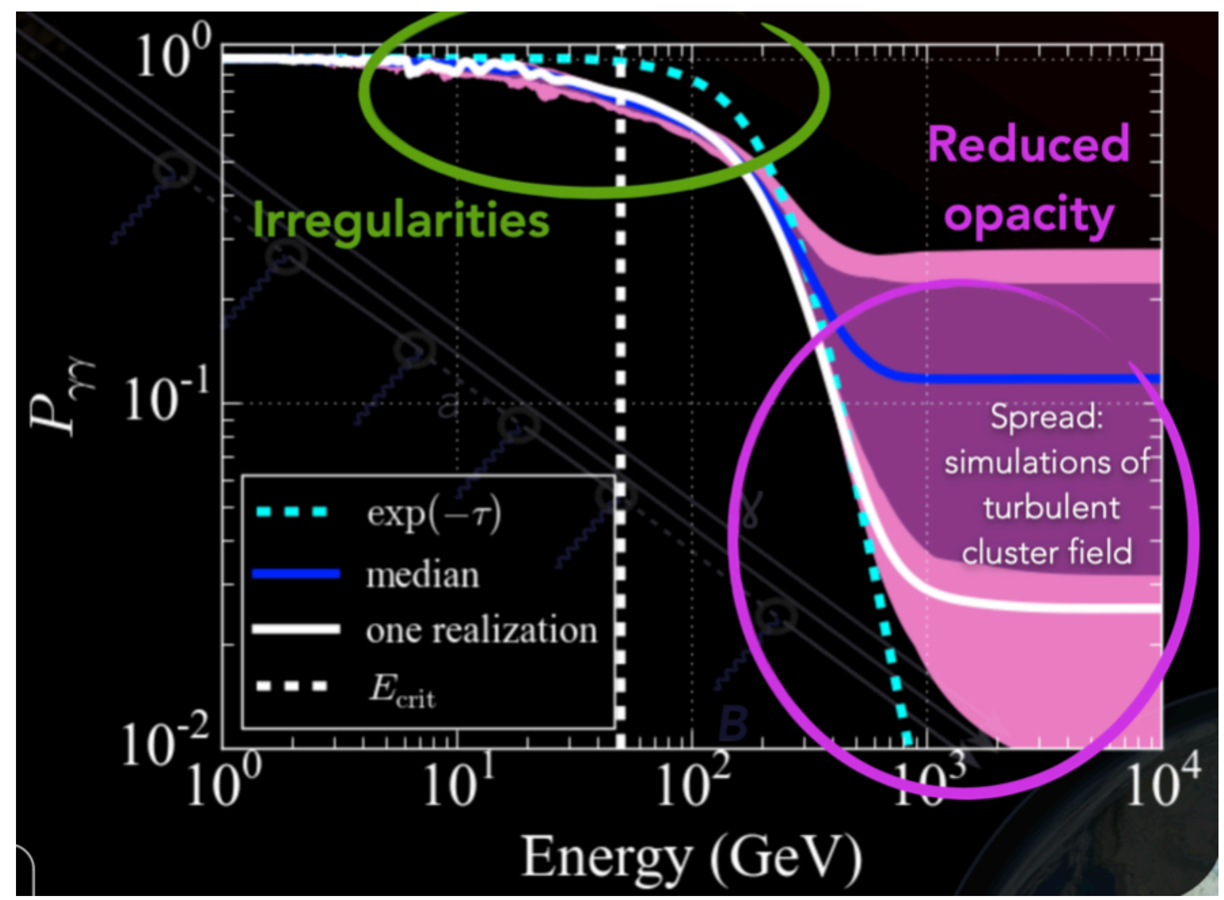
Part 2: ALPs



eV
10^{-22} 10^{-12} 10^{-2} 10^{8} 10^{18} 10^{28} 10^{38} 10^{48} 10^{58} 10^{68}
Axion-like particles (**ALPs**)
Weakly interacting massive particles (**WIMPs**)
Primordial Black Holes (**PBHs**)

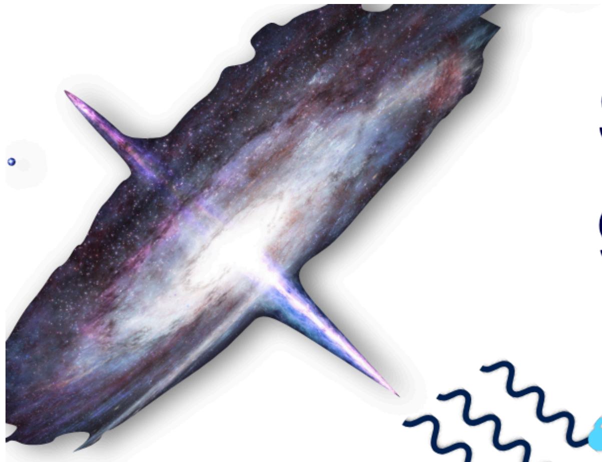


a
$g_{a\gamma\gamma}$
γ
B_o



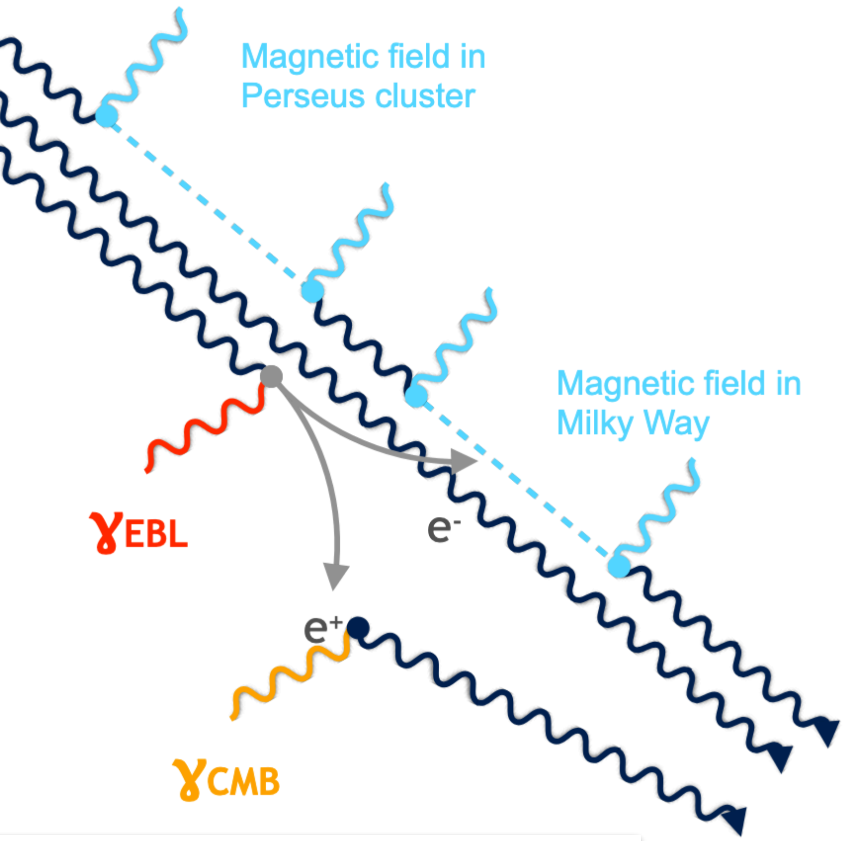
Irregularities
Reduced opacity
Spread: simulations of turbulent cluster field
exp(−τ)
median
one realization
E_{crit}
$P_{\gamma\gamma}$
Energy (GeV)

Part 2: ALPs

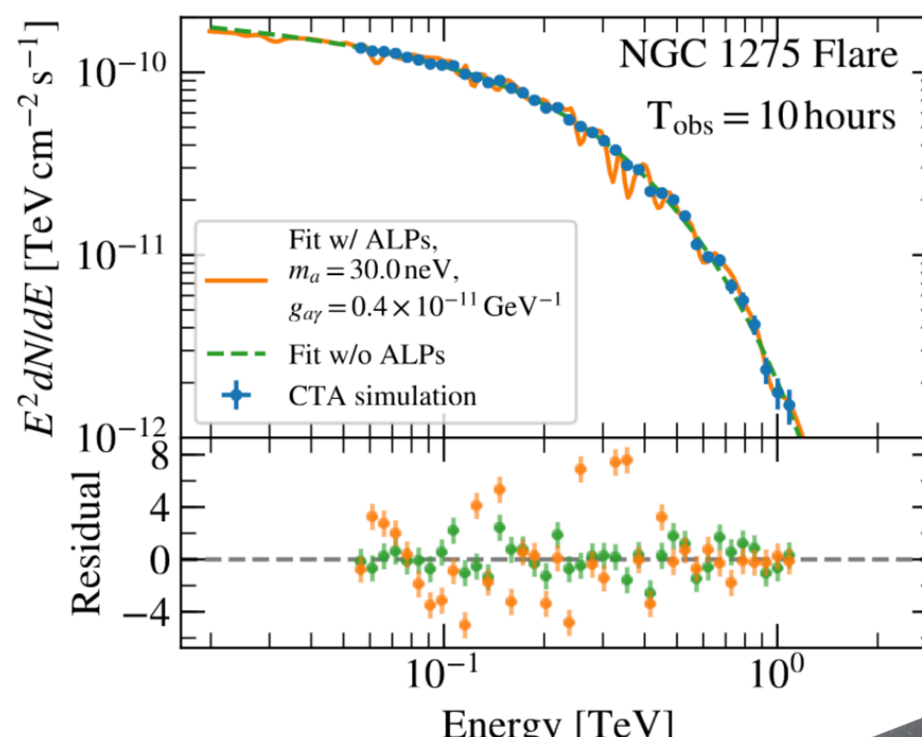


Searching for oscillations between gamma rays and axion-like particles

CTAO



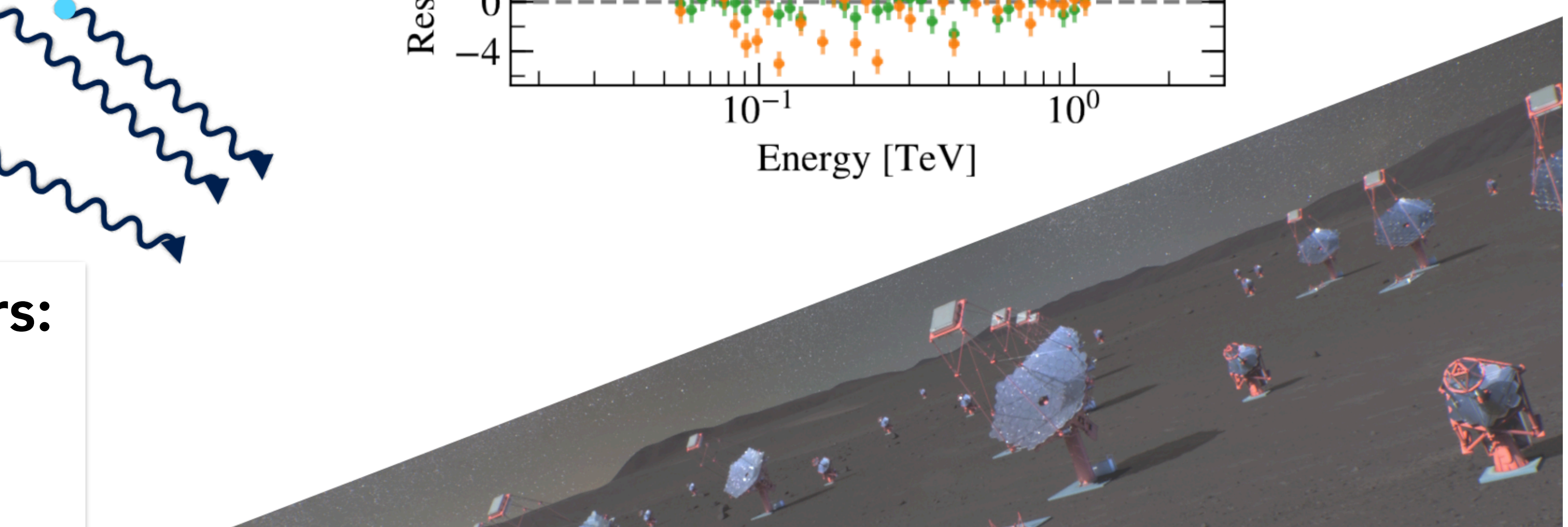
Photon-ALP oscillations could lead to a reduced gamma-ray opacity or oscillation features in gamma-ray spectra



AGNs in centres of Galaxy clusters:

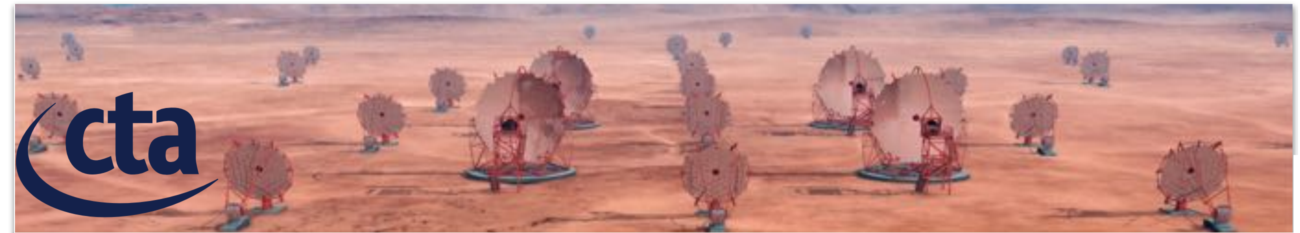
Strong magnetic fields

Long distances

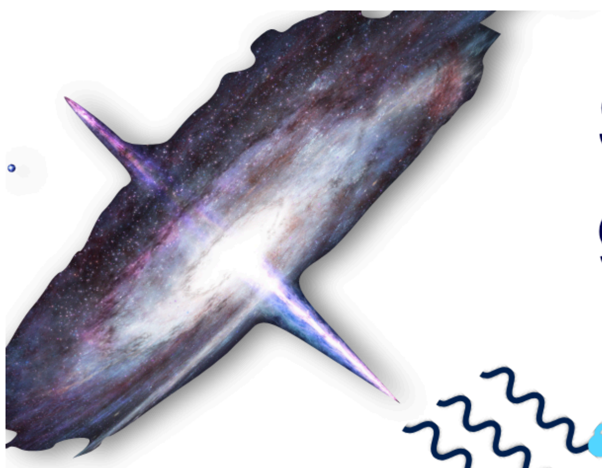


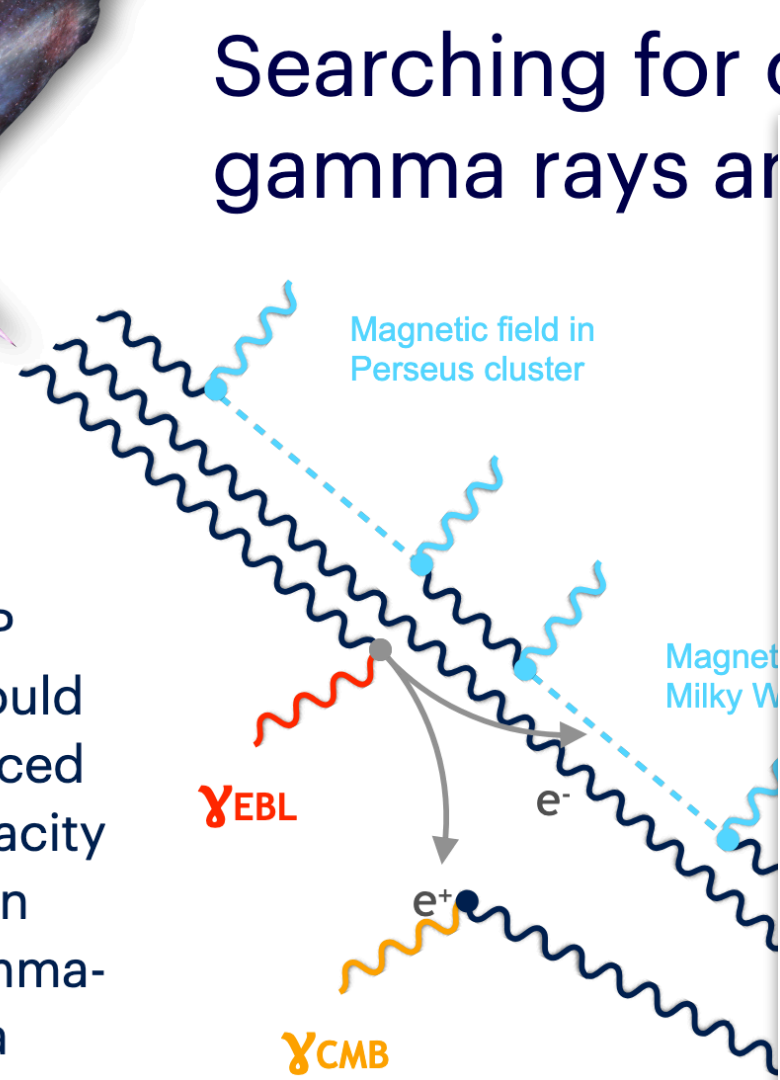
[Credit: Manuel Meyer, TeVPA2024]

Part 2: ALPs



CTA will be very sensitive probe due to an improved sensitivity and energy resolution !





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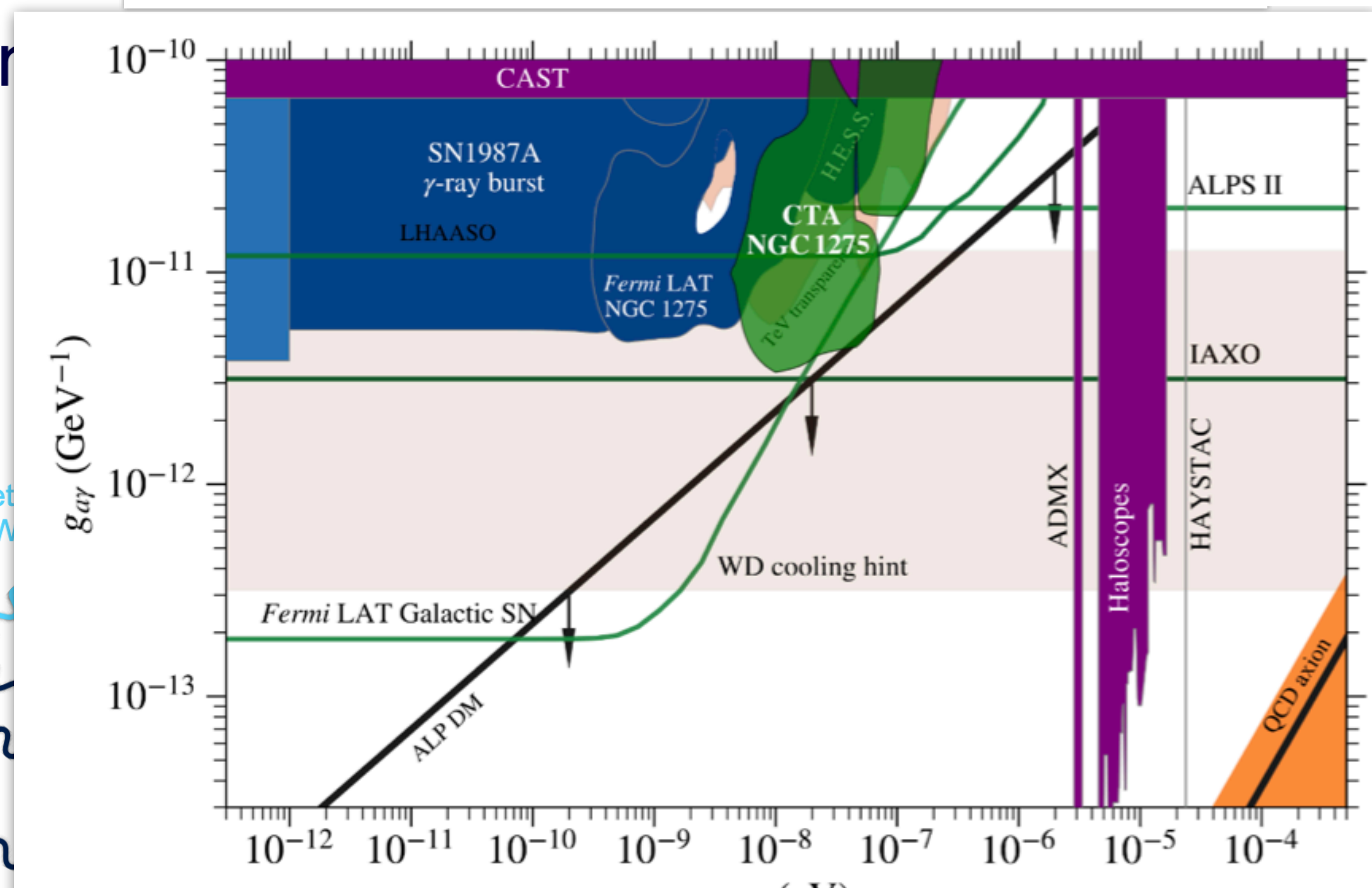
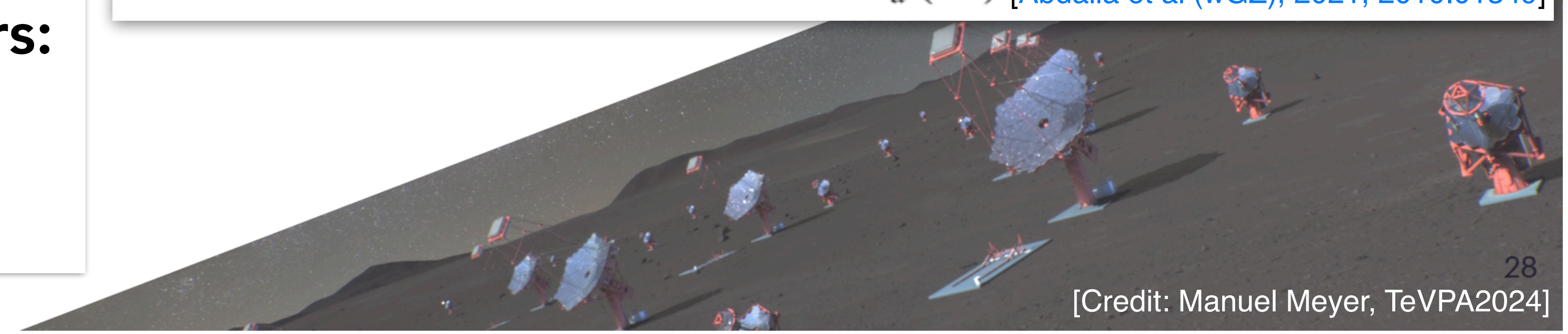


[Abdalla et al (wGZ), 2021, 2010.01349]

AGNs in centres of Galaxy clusters:

Strong magnetic fields

Long distances



[Credit: Manuel Meyer, TeVPA2024]

Part 2: ALPs

'General purpose' ML/AI methods

Application of machine learning highly motivated for this problem:

Many parameter problem, so cannot do inference without neglecting uncertainties

—> Simulation Based Inference (SBI) **great alternative approach to Bayesian inference**

- ALP mass, m
- ALP coupling to photons, g

} Parameters of interest

- NGC1275 intrinsic spectrum amplitude
- NGC1275 intrinsic spectral index
- NGC1275 intrinsic cut-off energy
- Magnetic field strength of NGC1275
- Magnetic field configuration
- Extension of Perseus cluster
- 7 electron density-related parameters
- 3 turbulence-related parameters

} ~15 Nuisance parameters

[Credit: Gert Kluge, TeVPA2024]

SBI "likelihood-free" or "implicit likelihood" inference — the notion that **"running your simulator" is the same as sampling from the (simulated-)data likelihood p(x|θ)**.

Truncated Marginal Neural Ratio Estimation (TMNRE), implemented within the framework of **swyft**.

A binary classification task – it asks the question given a pair (x,θ), did θ generate x?
The relative precision of the posterior distribution reflects how difficult it is to discriminate between joint and marginal samples.

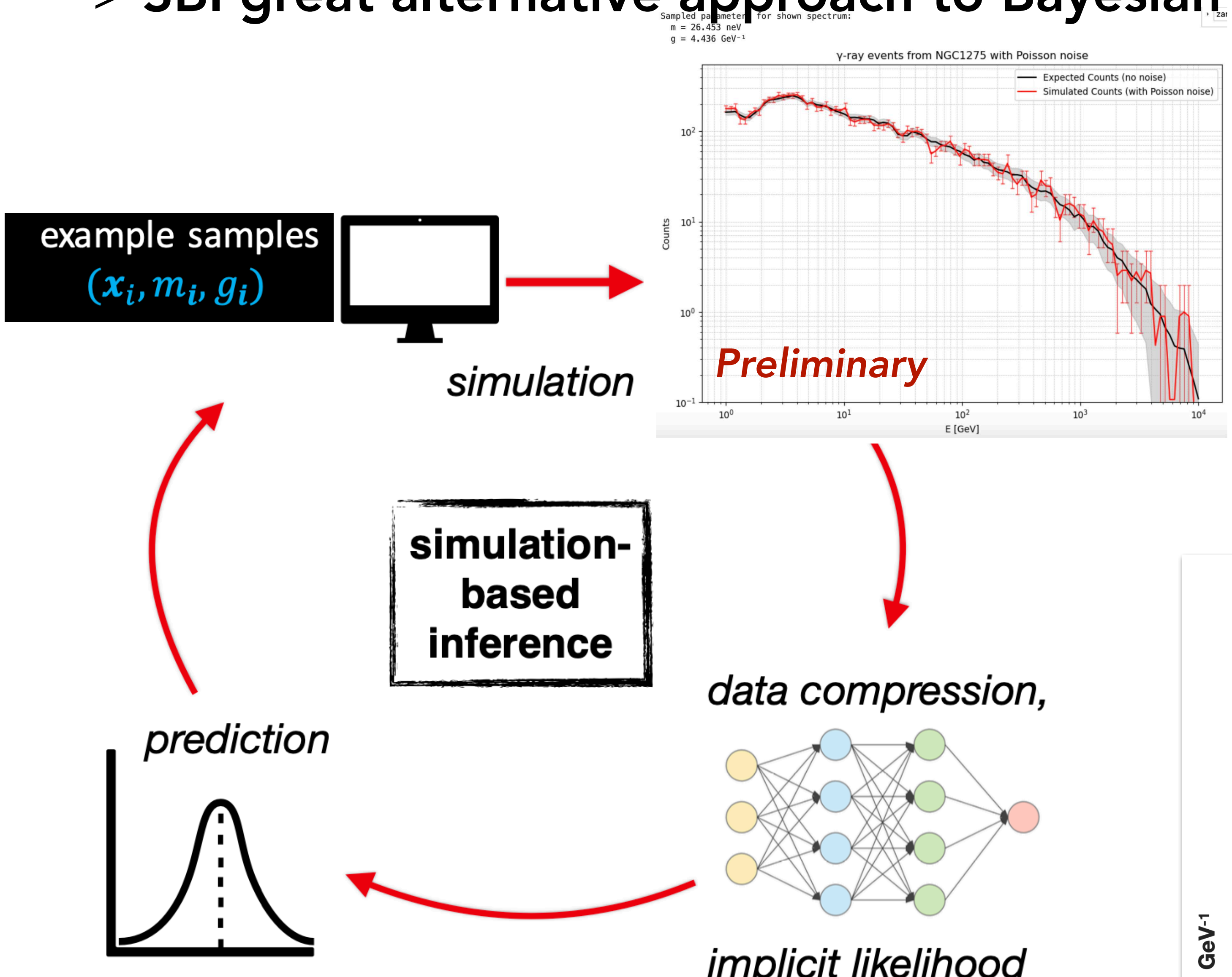
Part 2: ALPs

'General purpose' ML/AI methods

Application of ML highly motivated:

Many parameter problem, so cannot do inference without neglecting uncertainties

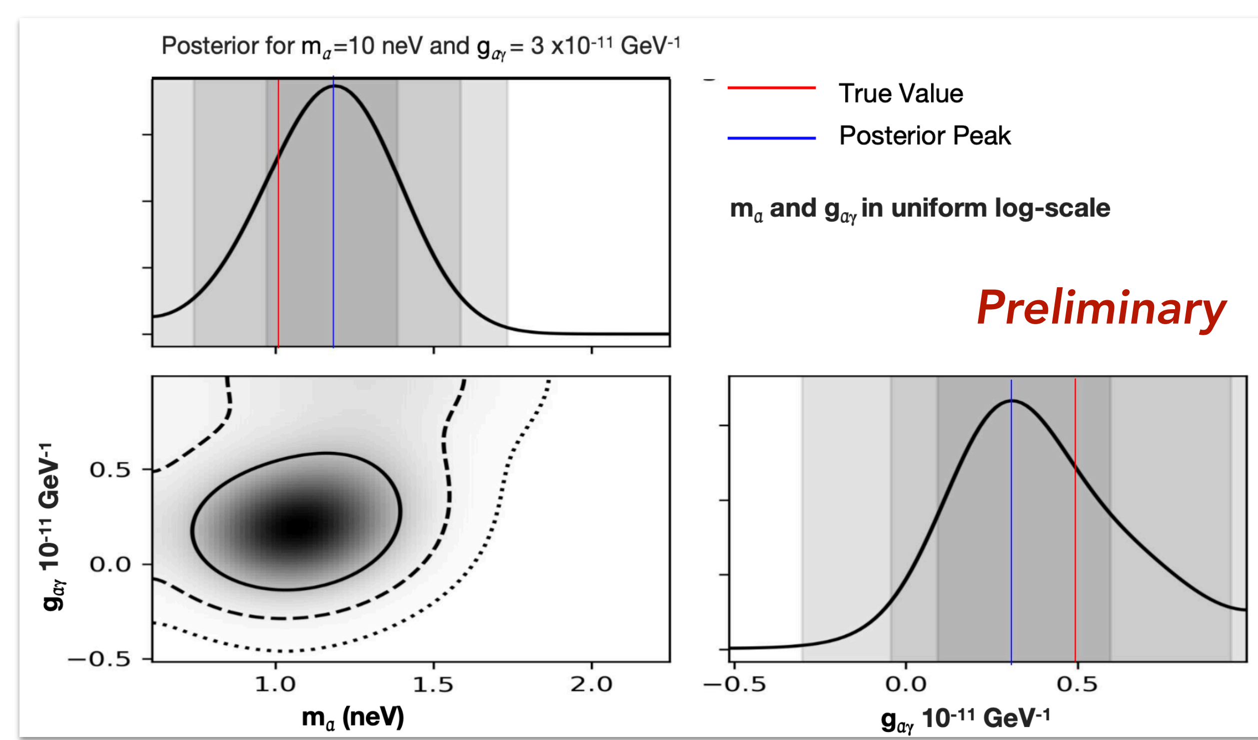
—> SBI great alternative approach to Bayesian inference



[Credit: C. Eckner, ICRC2025]

Ongoing work with SMASH fellows

Pooja Bhattacharjee and Christopher Eckner



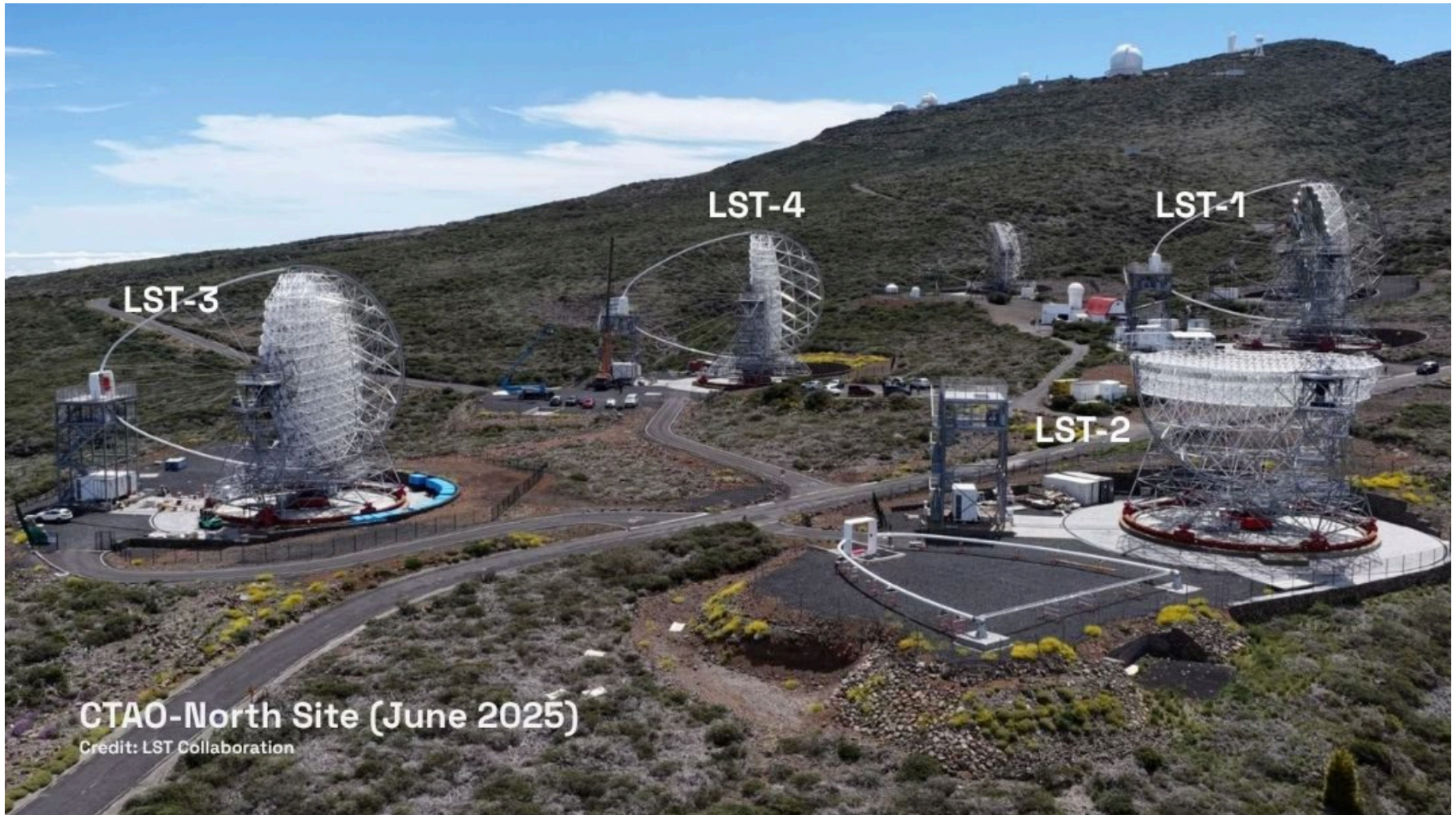
Summary

Just a flavour of a vast field that is DM search in astrophysical data

Amazing new experiments just got online or will do shortly

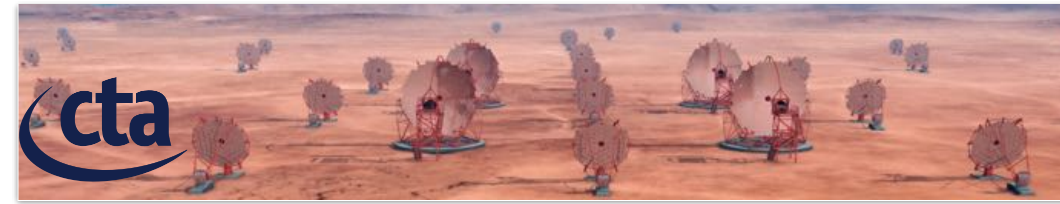
New techniques (ML) are also there, getting ready to be applied widely

Collaboration across fields: theory (heavy DM), methods (ML/AI), experiments necessary!



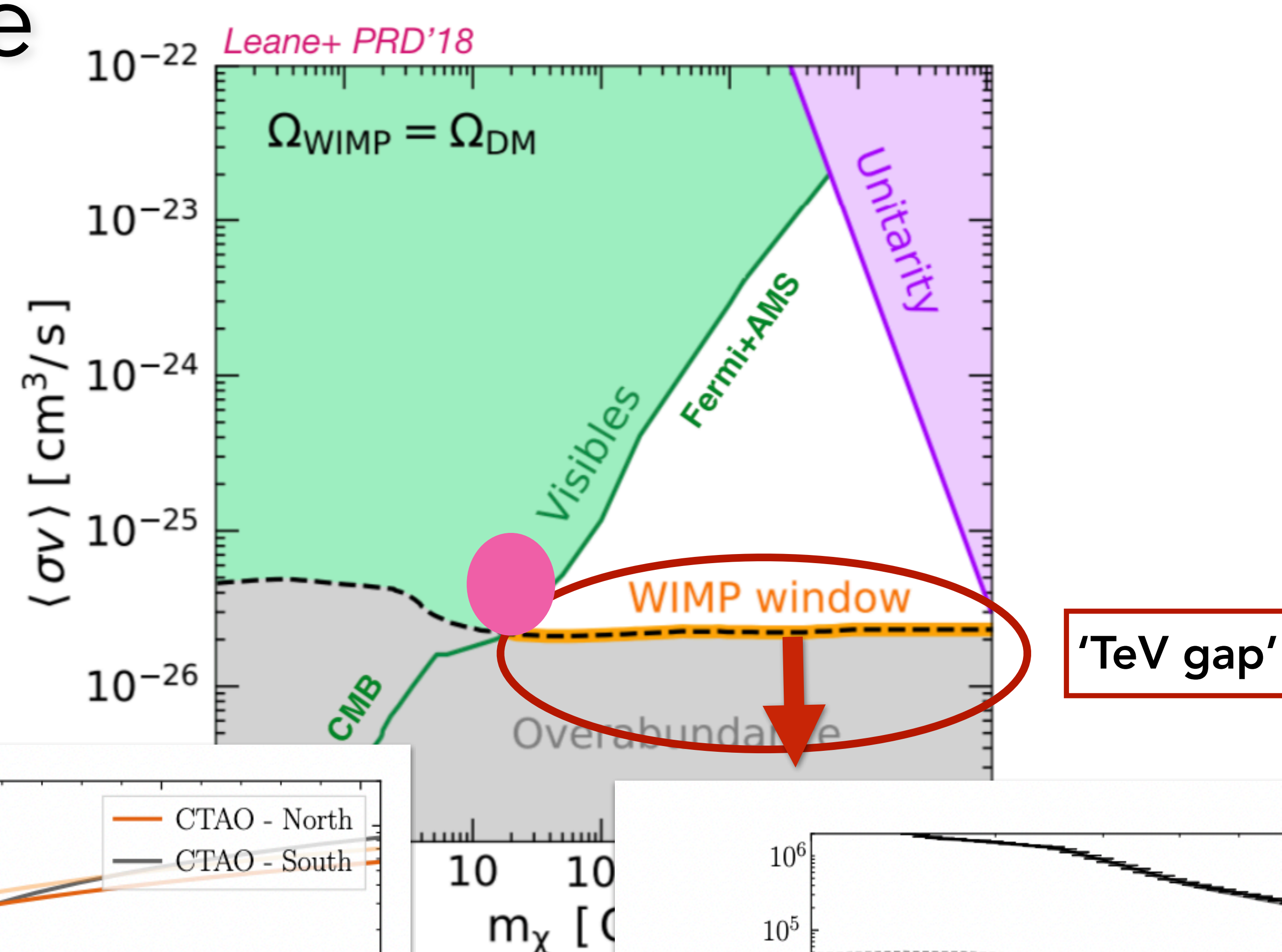
EXTRA SLIDES

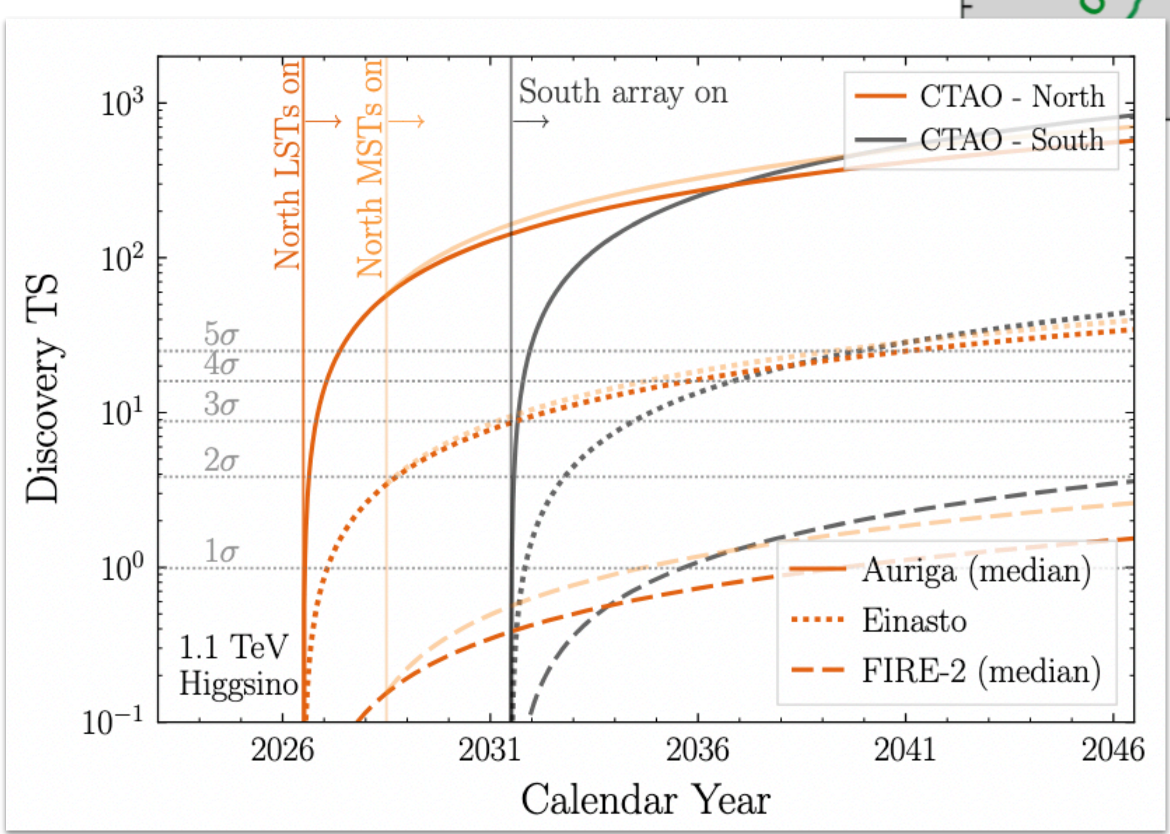
Thermal DM

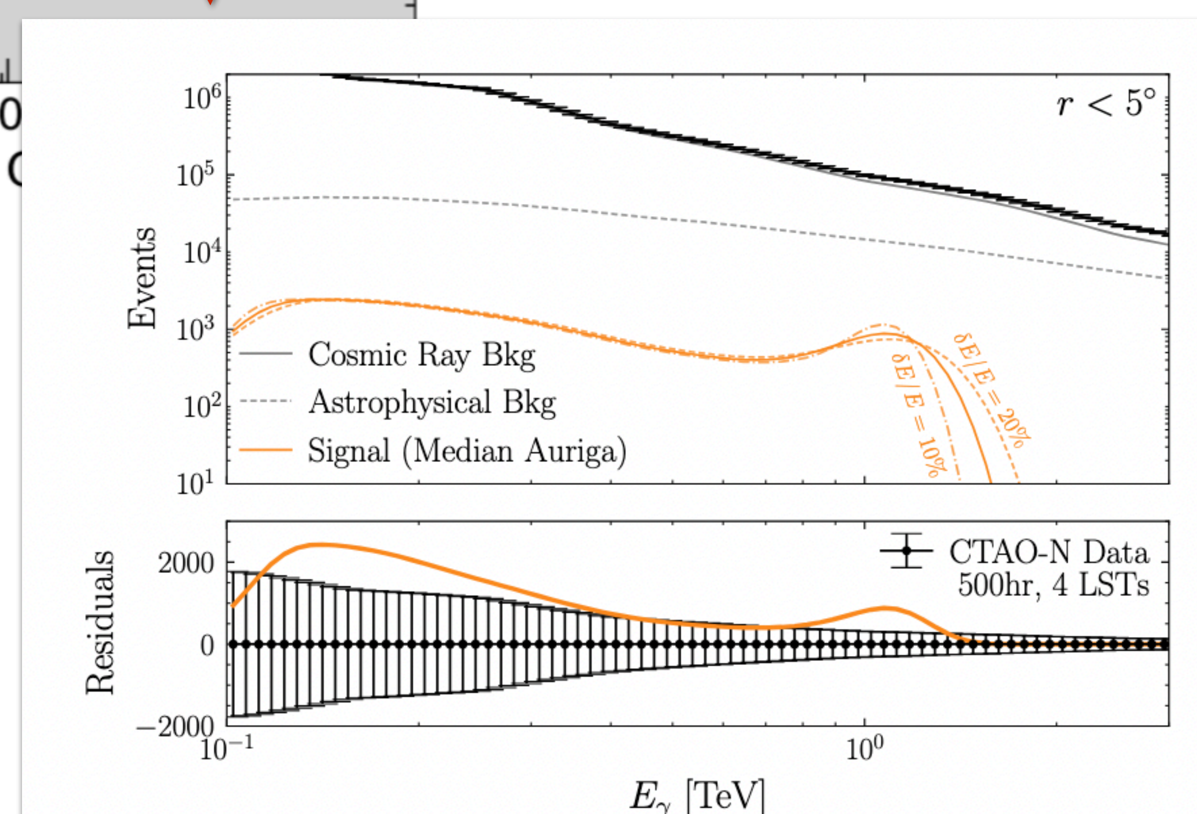


The big picture

For 1.1 TeV thermal higgsino





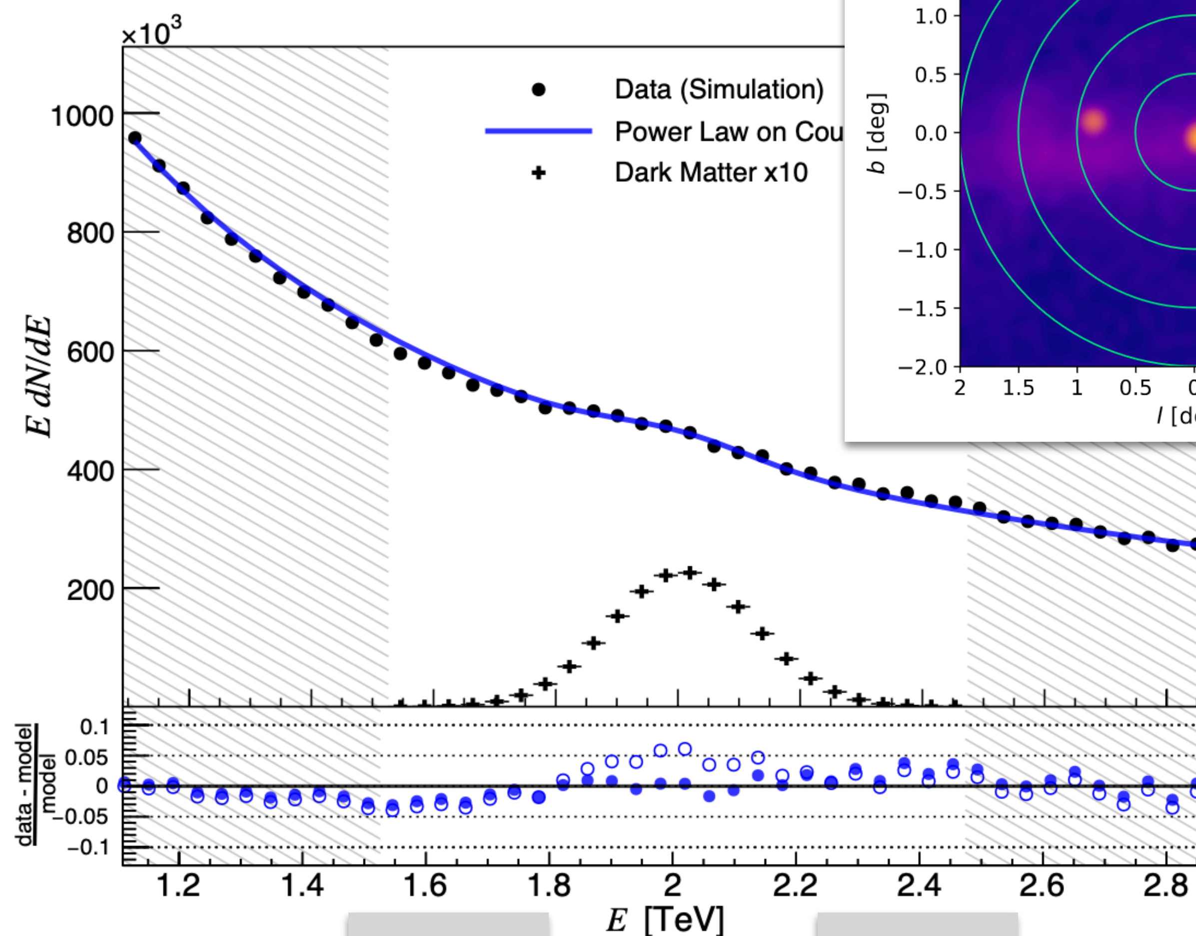


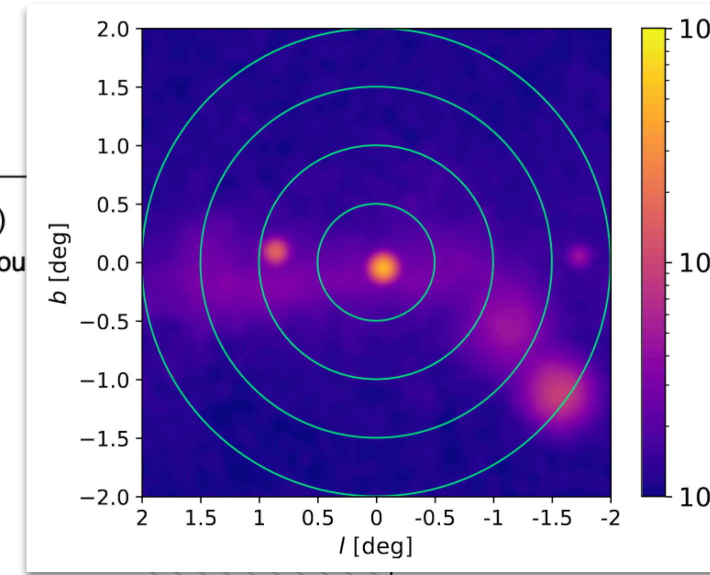
[Abe et al, "Discovering the Higgsino at CTAO-North within the Decade" 2506.08084]

Target 1: Galactic Center, spectral features

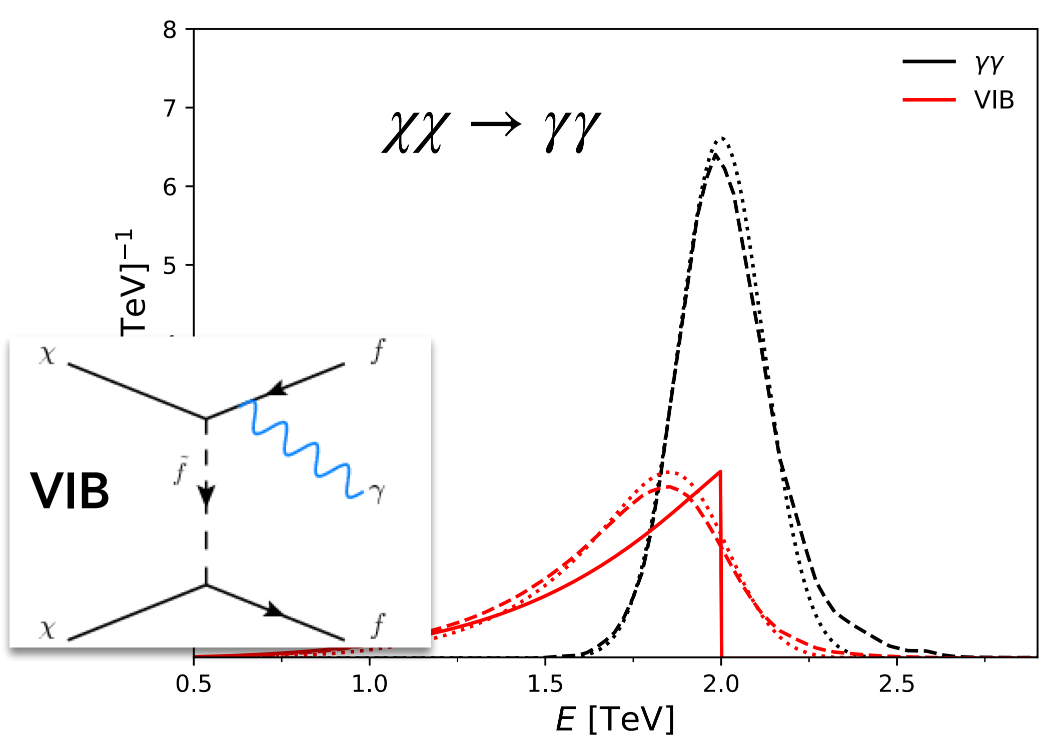
excellent energy resolution of CTA $\Delta E/E \sim 5-8\,\%$ (E >1 TeV)

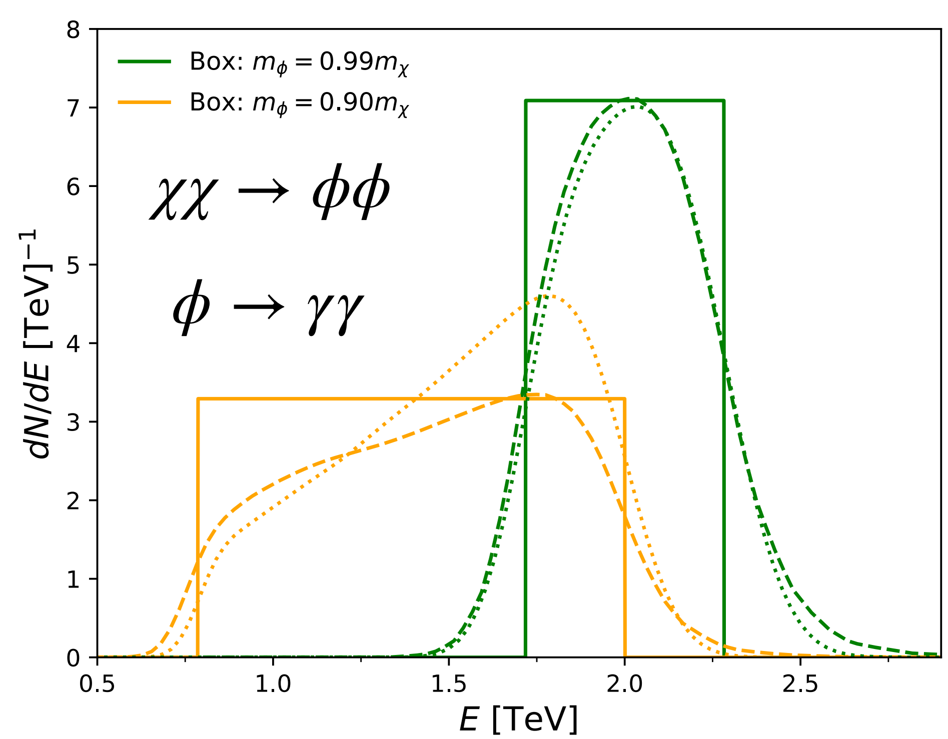
Studies of:
— annihilation (loop suppressed)
— virtual internal Bremsstrahlung
— decay of long-lived mediators (box-shaped)





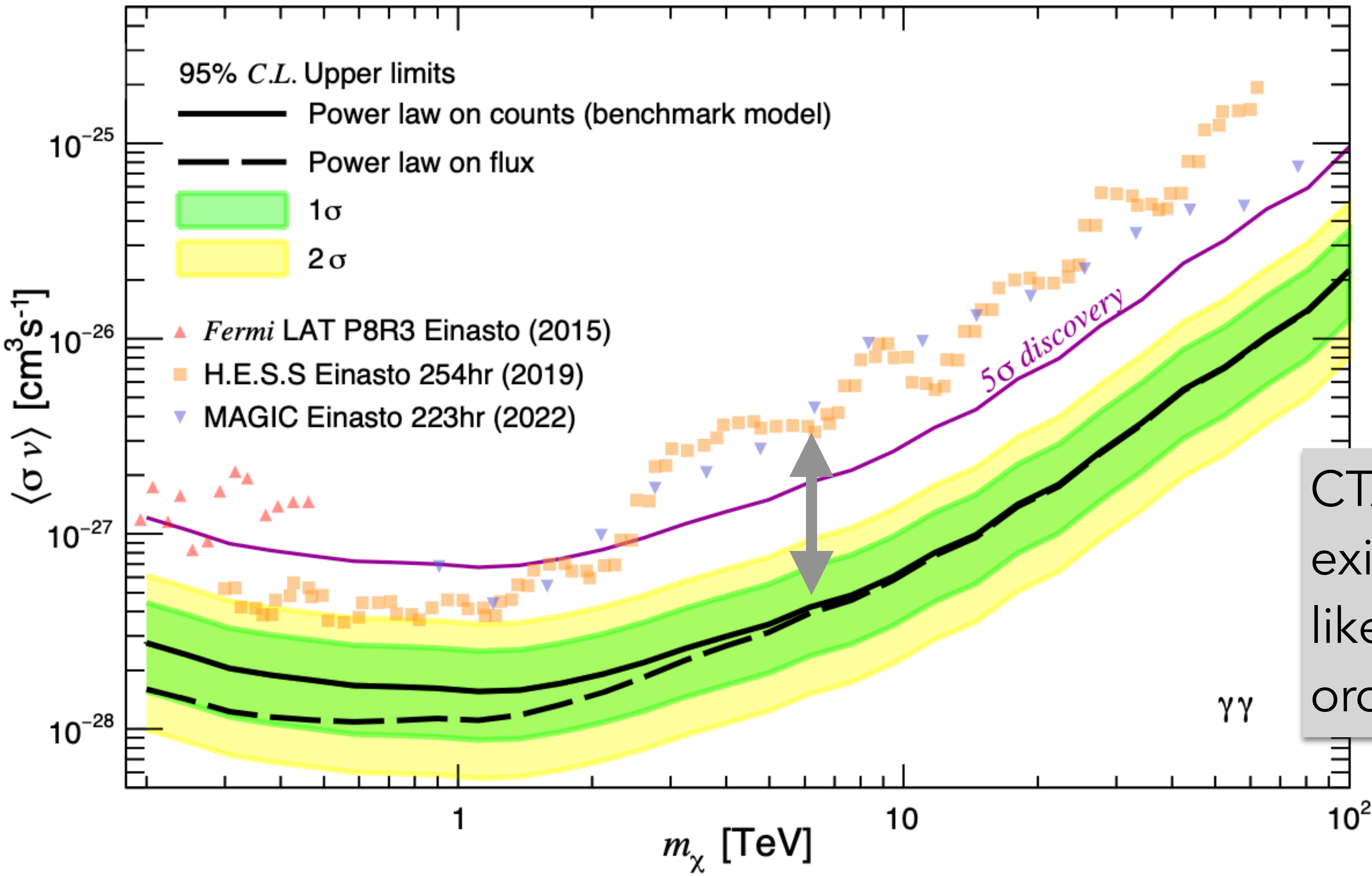
1.6 TeV **2.4 TeV**





Target 1: Galactic Center, spectral features

Results



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

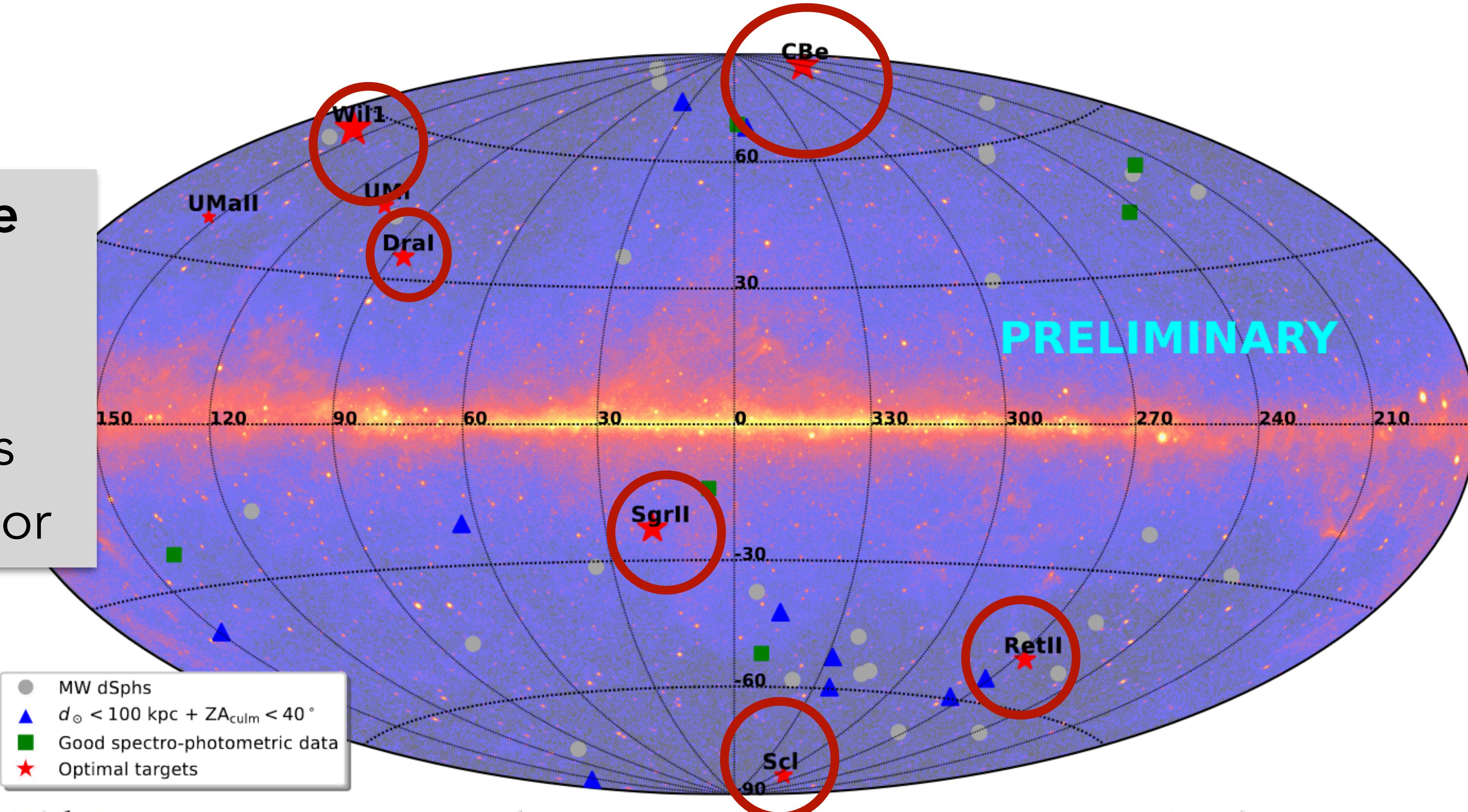
CTA likelihood tables for line-like DM spectra available at zenodo.org (https://doi.org/10.5281/zenodo.10792466)

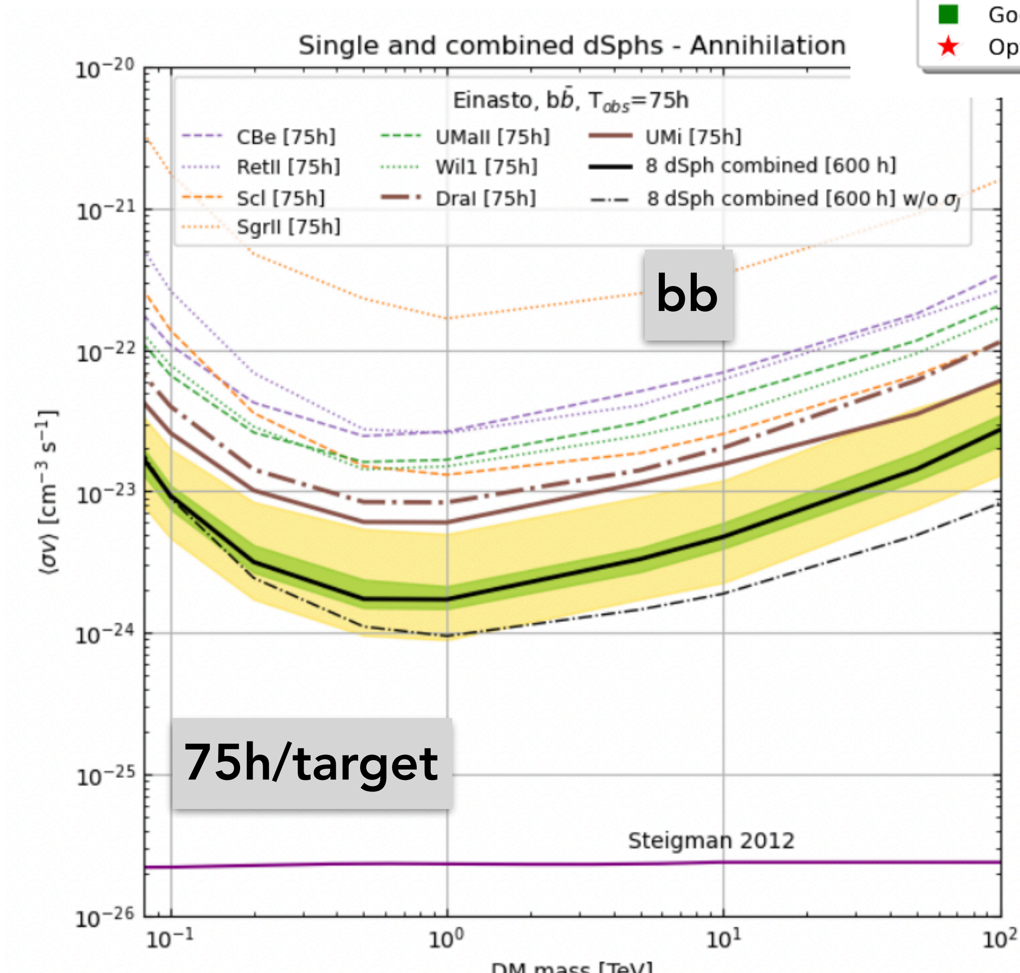
Target 2: dSphs

[Abe et al, 2508.19120]

Three dSphs per hemisphere

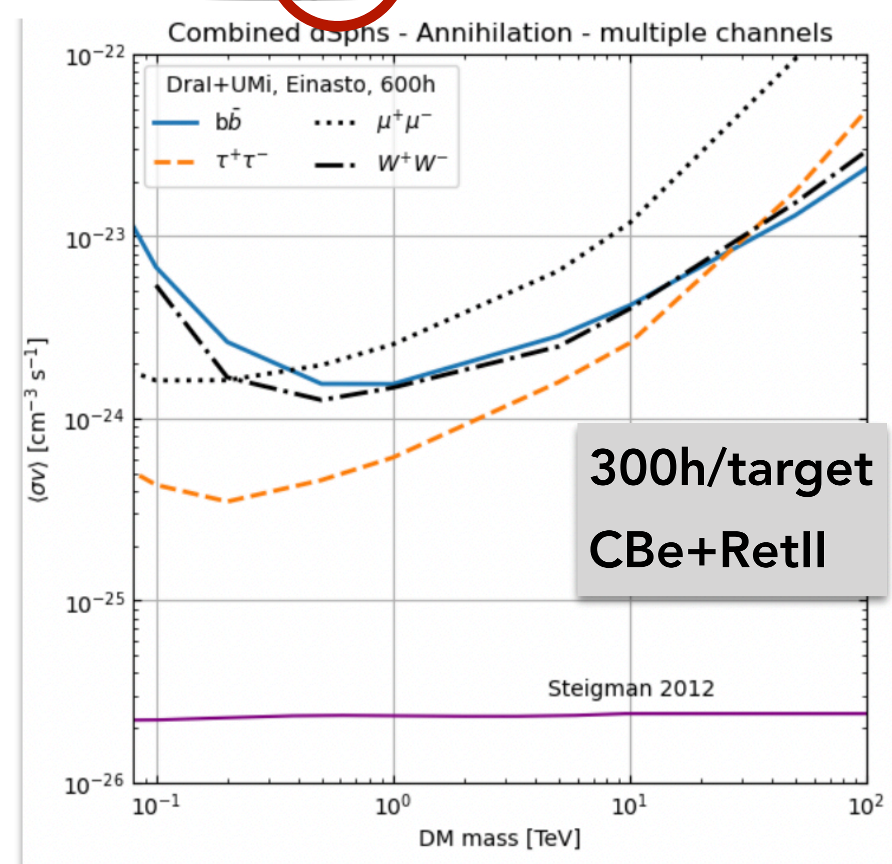
—> have the best trade-off between the expected signal intensity and the uncertainties on the astrophysical *J*ann factor





10^{-24}

10^{-24}

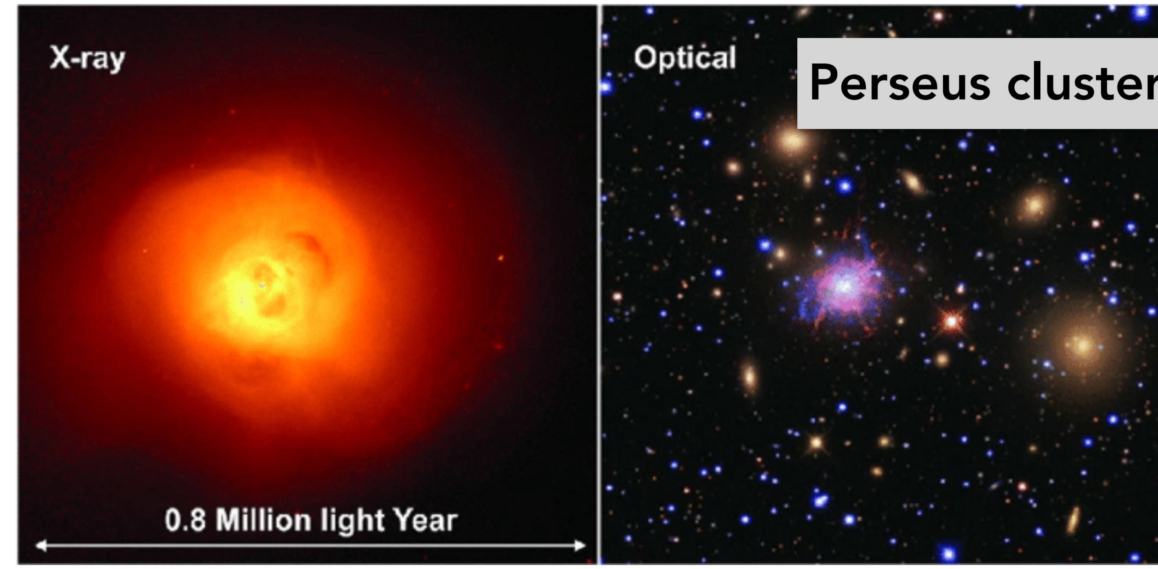


Target 3: Galaxy Clusters

Most massive virialized halos

Large reservoirs of DM but also hot gas and CRs

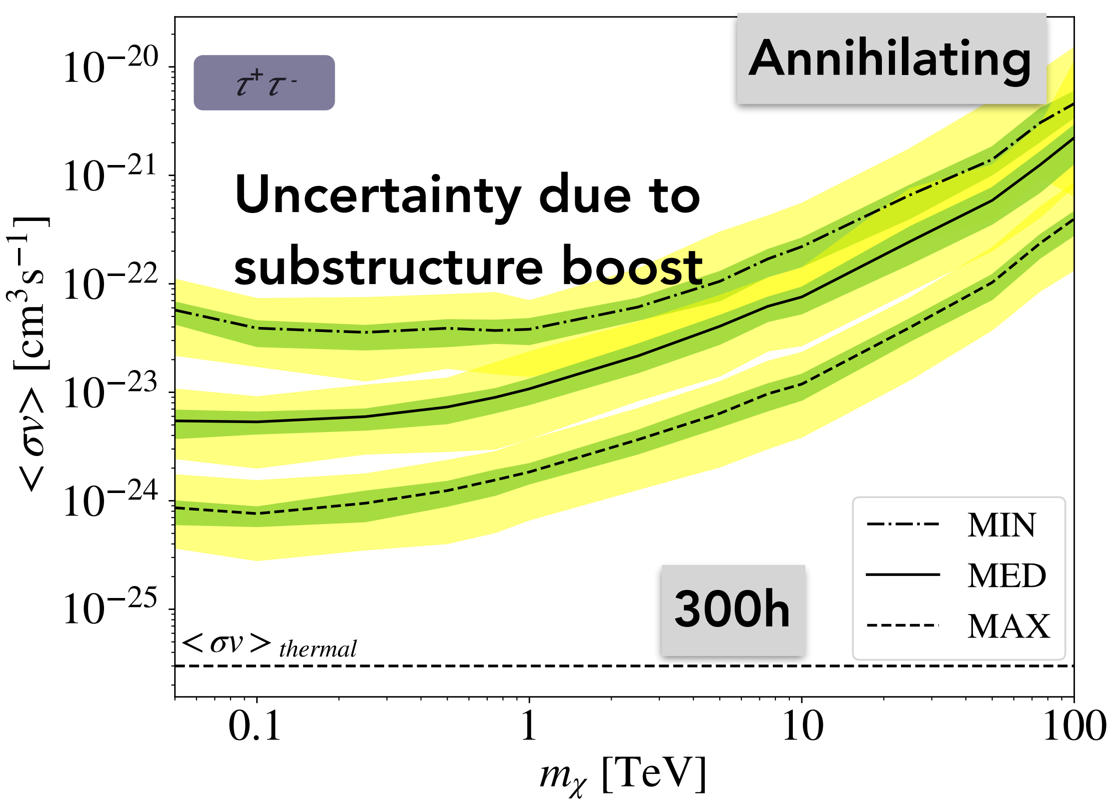
Not yet observed in gamma rays - CTA well positioned for a discovery

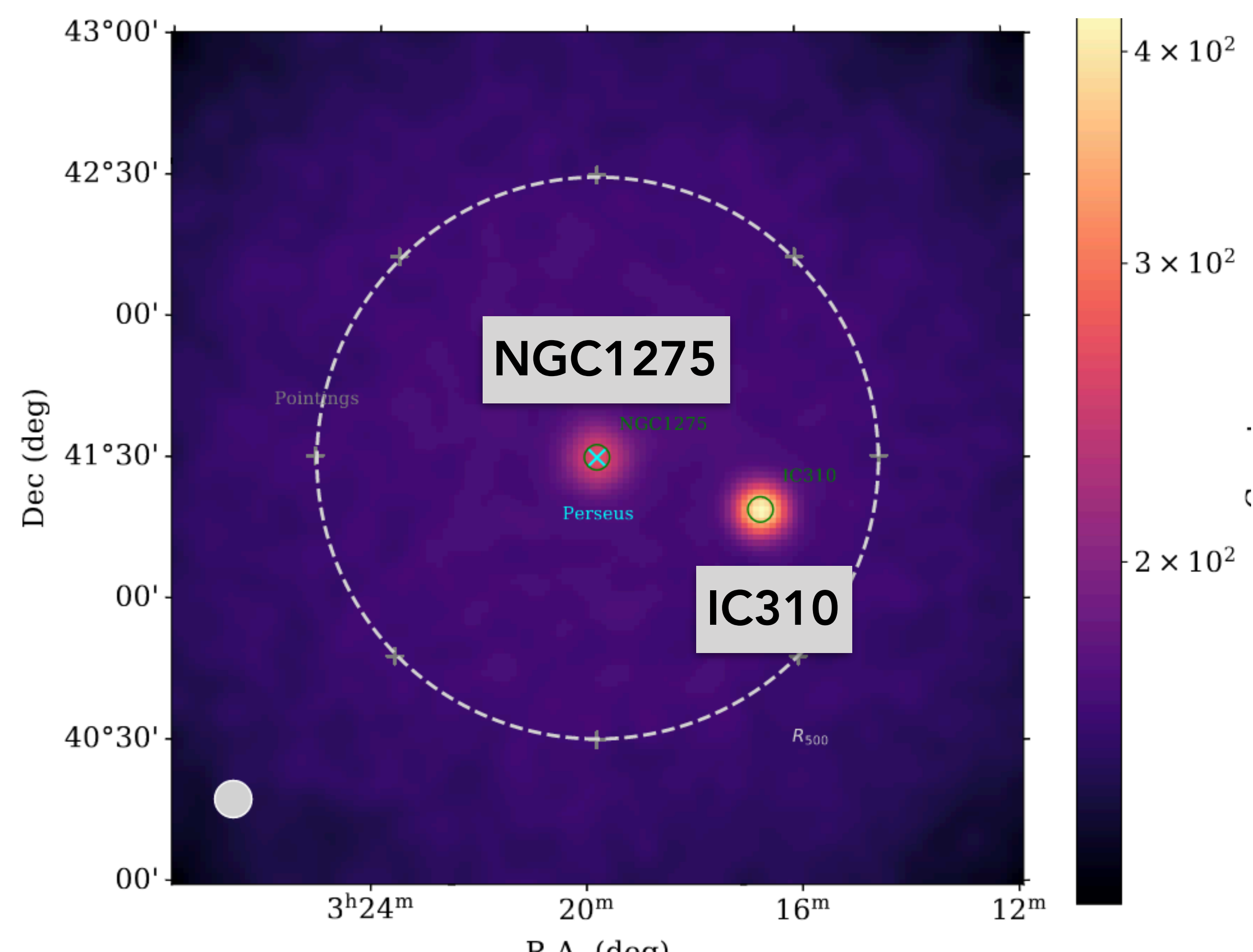


Focus on Perseus Cluster

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]

Lorenz invariance tests with CTA

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

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

Dispersion measure

ξ_α - correction factor, with the leading linear (α = 1) and quadratic (α = 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, …

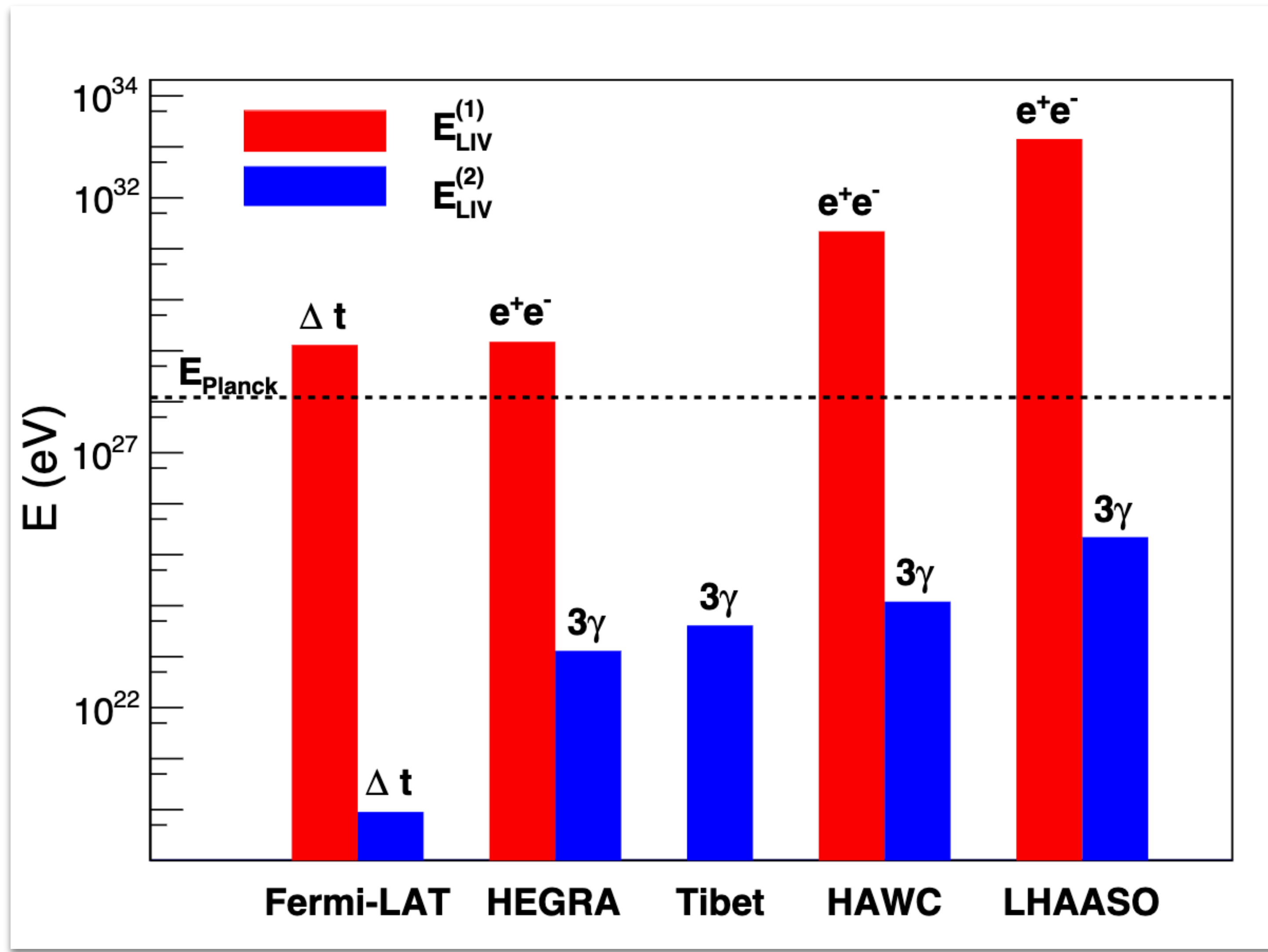
Lorenz invariance tests with CTA

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



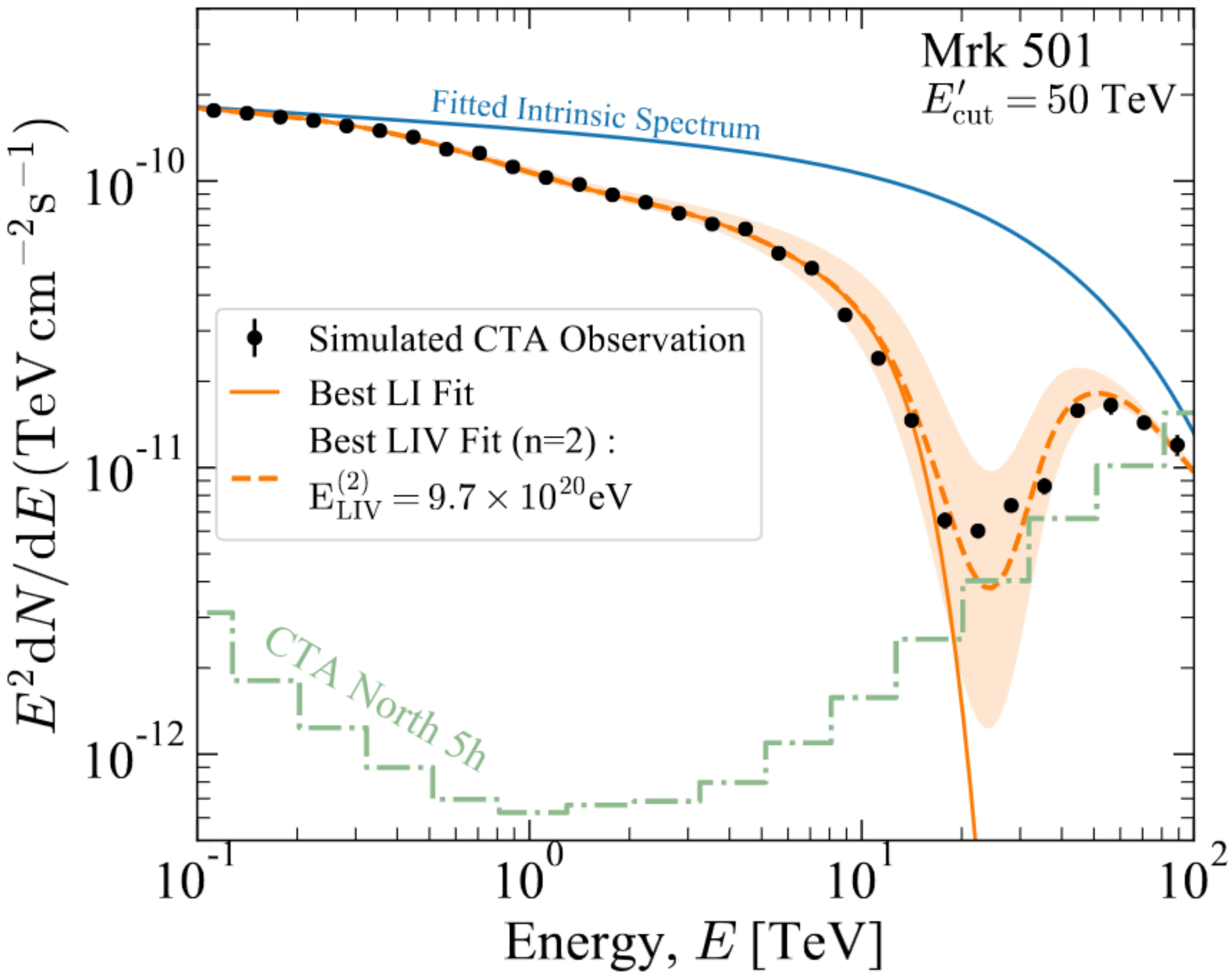
Lorenz invariance tests with CTA

[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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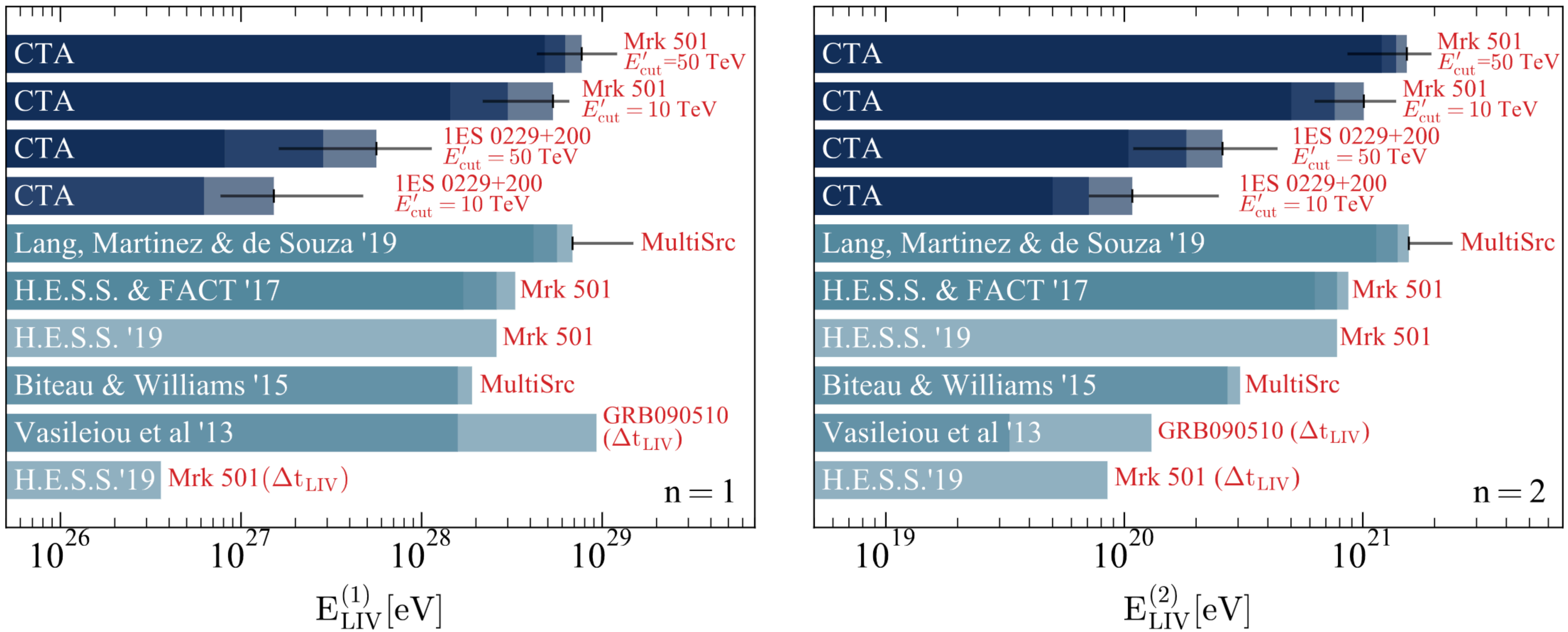

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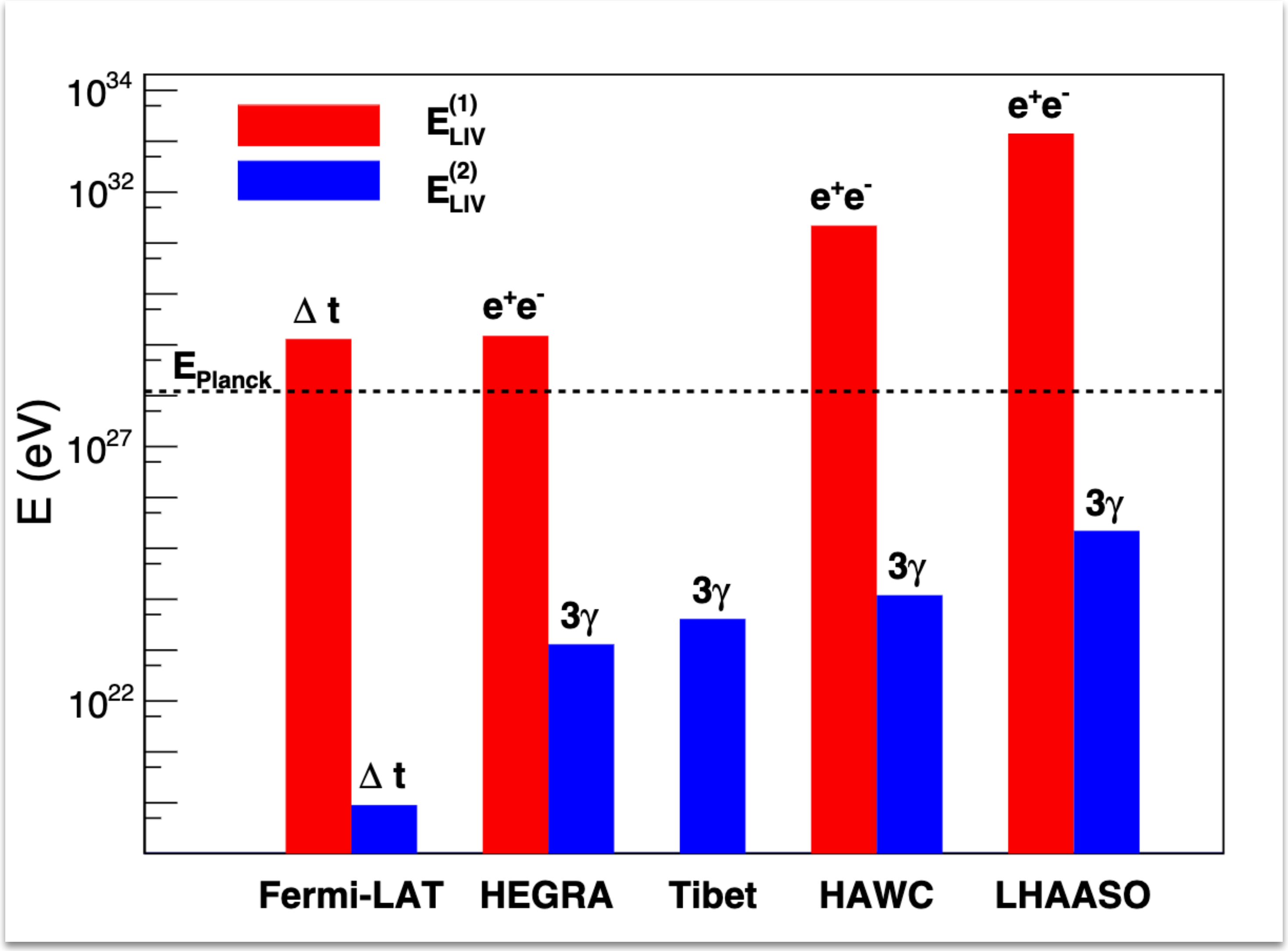
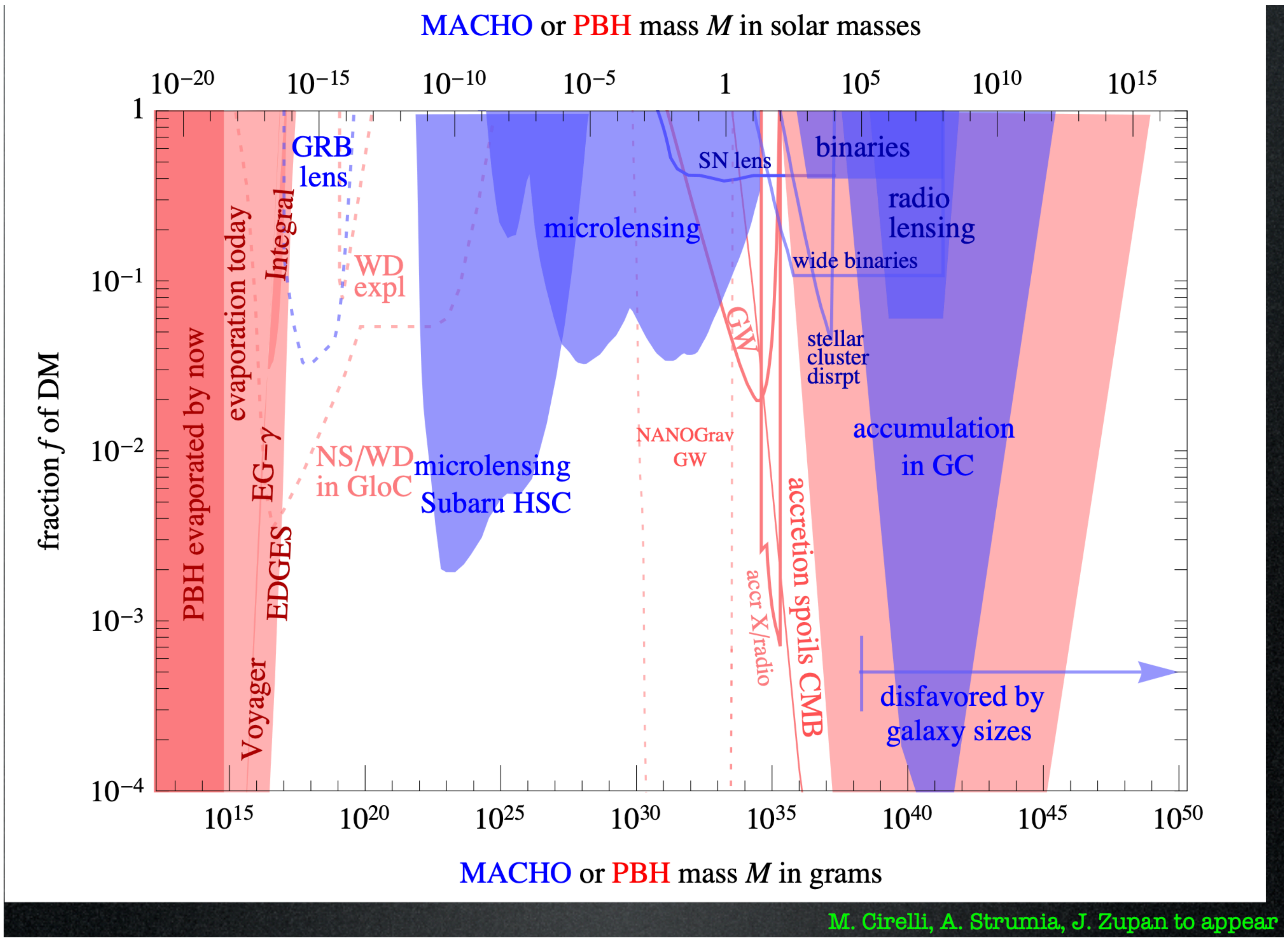
The first-order LIV energy-scale is constrained to be higher than 105 Mpl, and the second-order LIV energy-scale should exceed 10−3 Mpl.

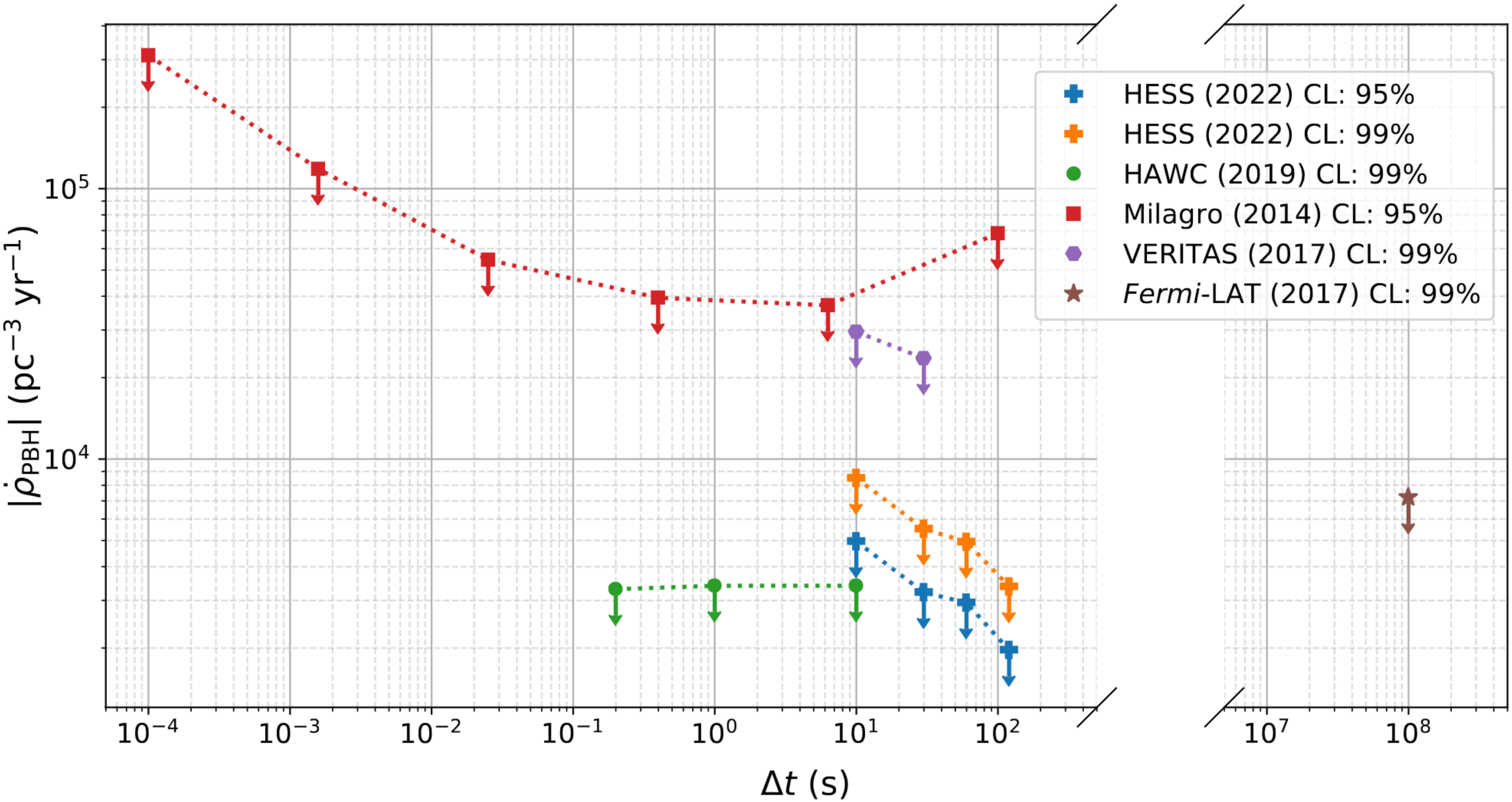


PBHs



[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]