Dark Matter searches with astrophysical probes

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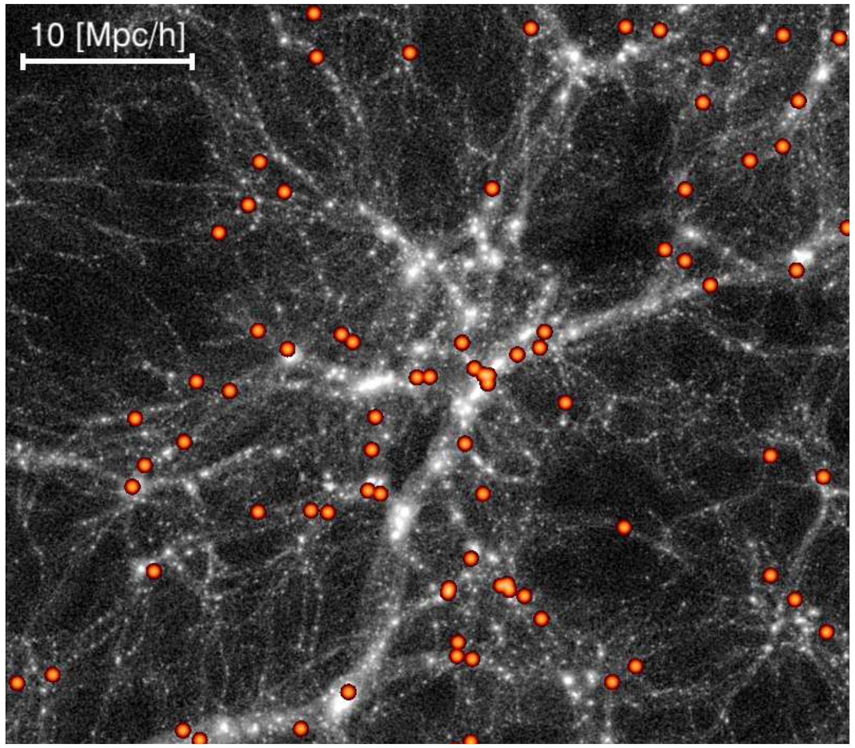
The 27th European Cosmic Ray Symposium 2022

Dark matter

an essential building block of the Standard Model of Cosmology

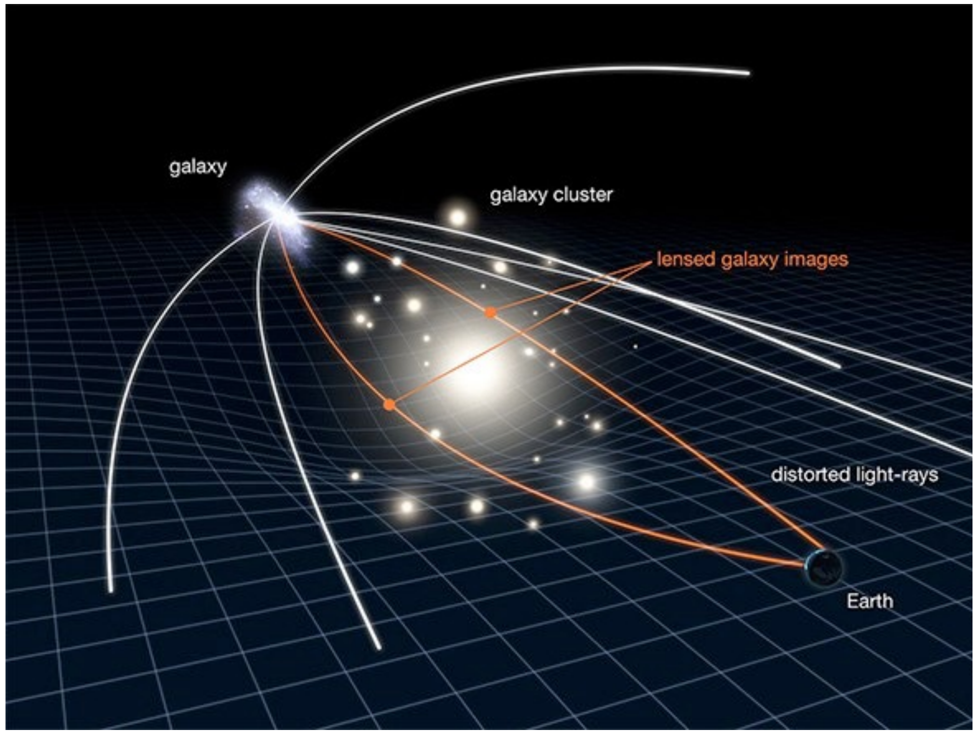
large scale structures

100s Mpc



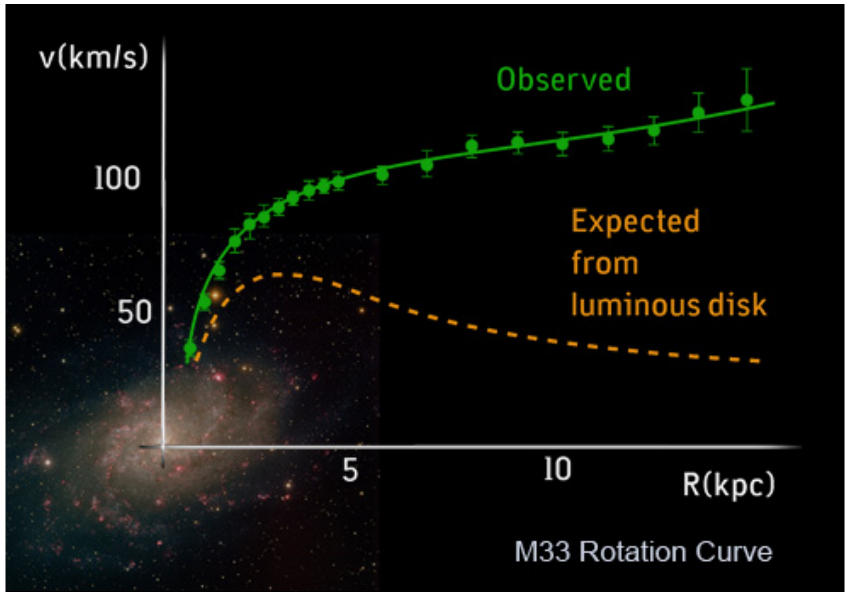
clusters of galaxies

Mpc



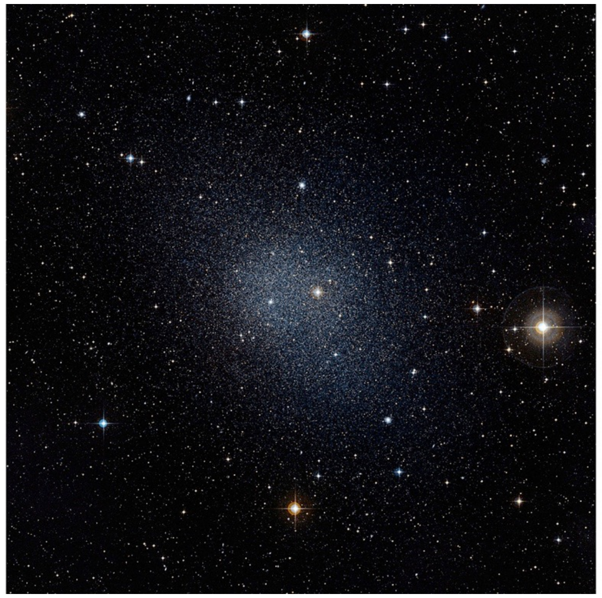
Milky Way-size galaxies

100s kpc



dwarf galaxies

<~ kpc



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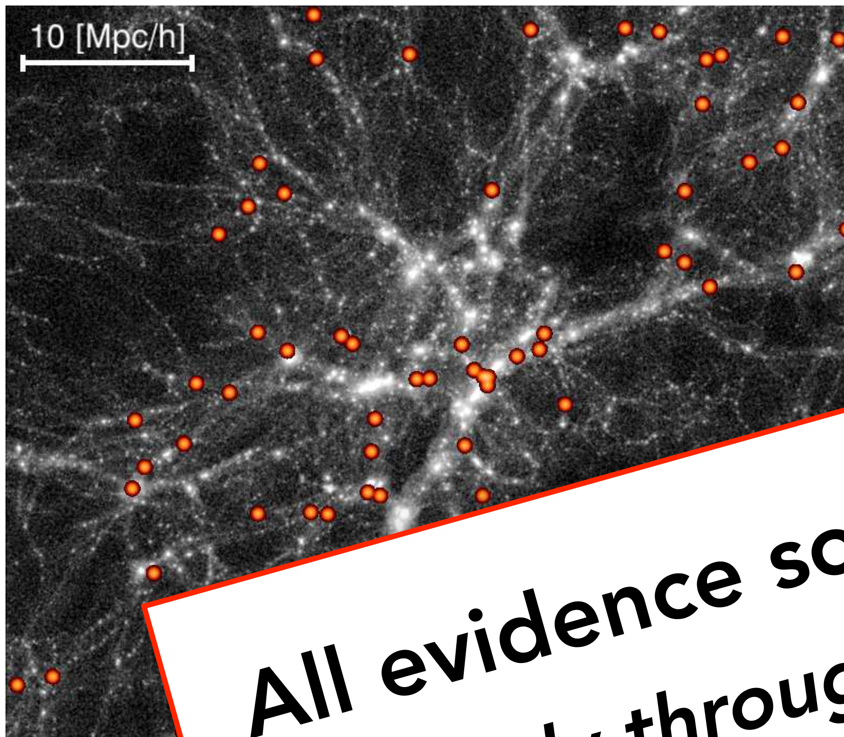
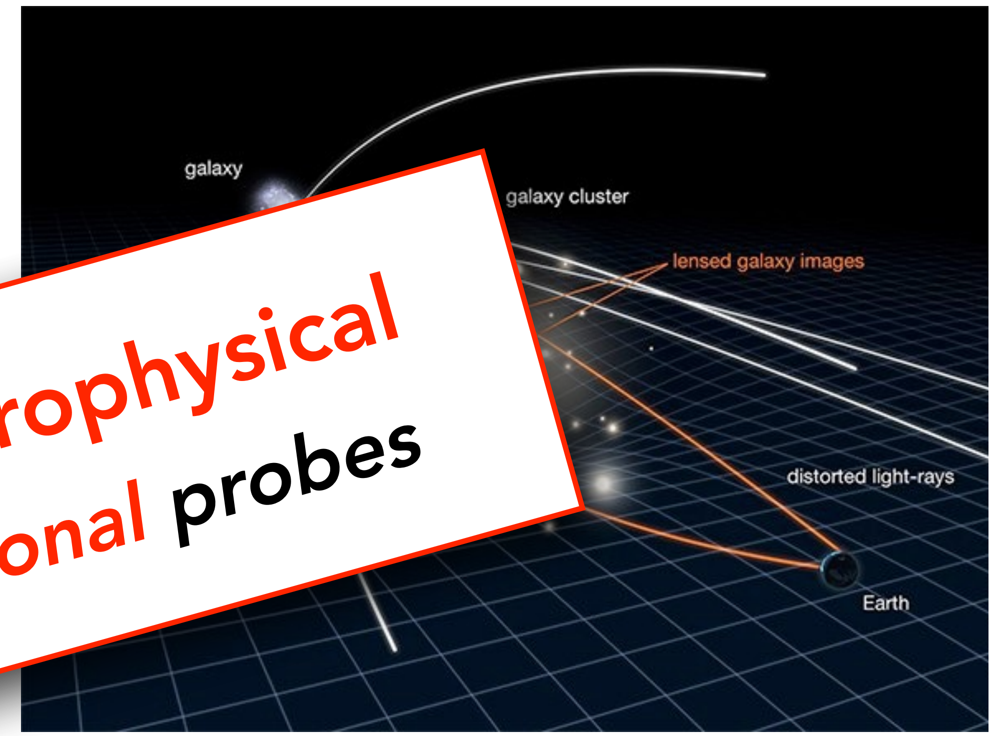


clusters of galaxies

Mpc

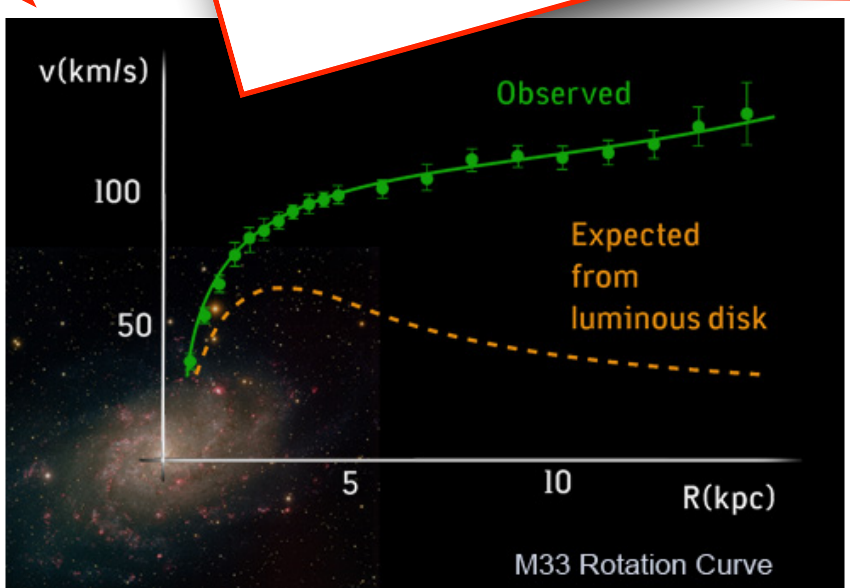


All evidence so far is astrophysical

And only through gravitational probes

Milky

100s kpc



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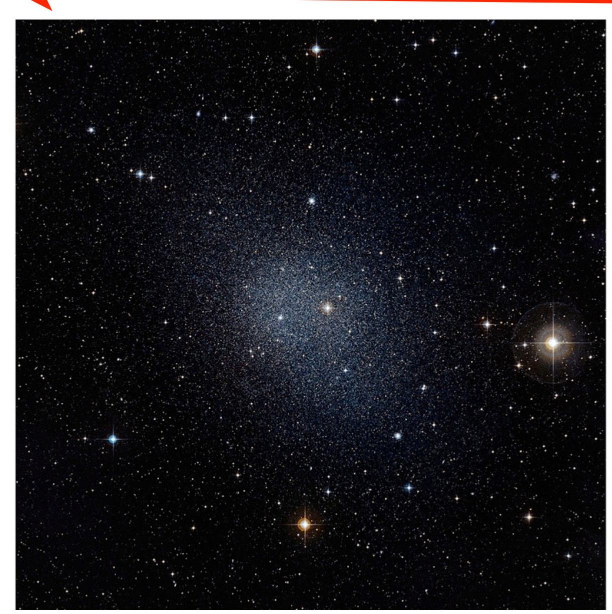
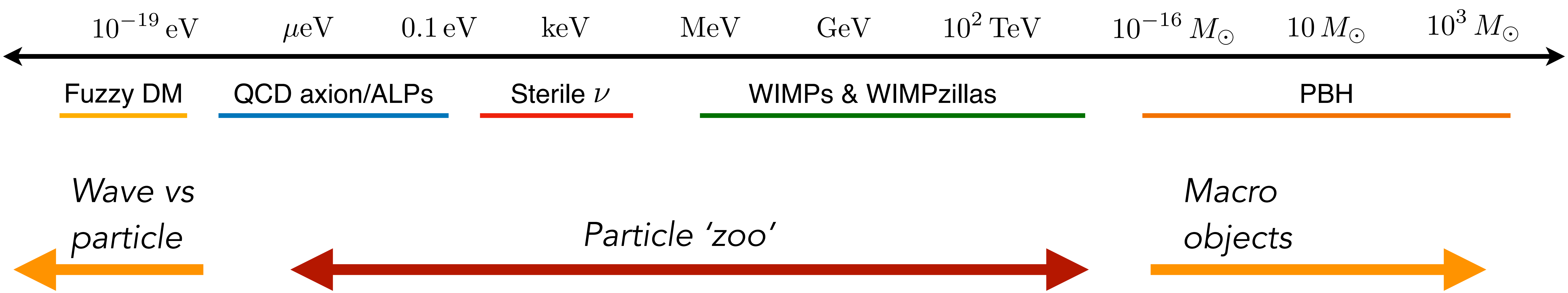
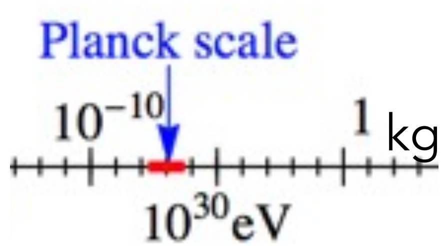


What are the options?



EuCAPT white paper,
arXiv: 2110.10074

Quick conversion :)



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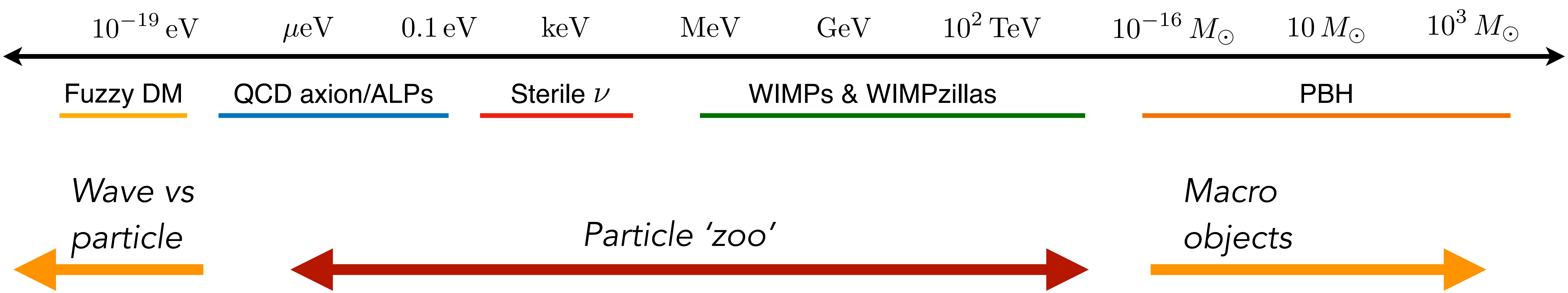


Astrophysical probes of the nature of DM

PROs

— remotely, in places where we have evidence for DM presence

— plenty of astro data available ('*golden age*')

CONs

— learning backgrounds (astrophysics!) and searching for new signals *at the same time*

— *all searches model dependent*

Search under 'theory' lamppost

What are the options?

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

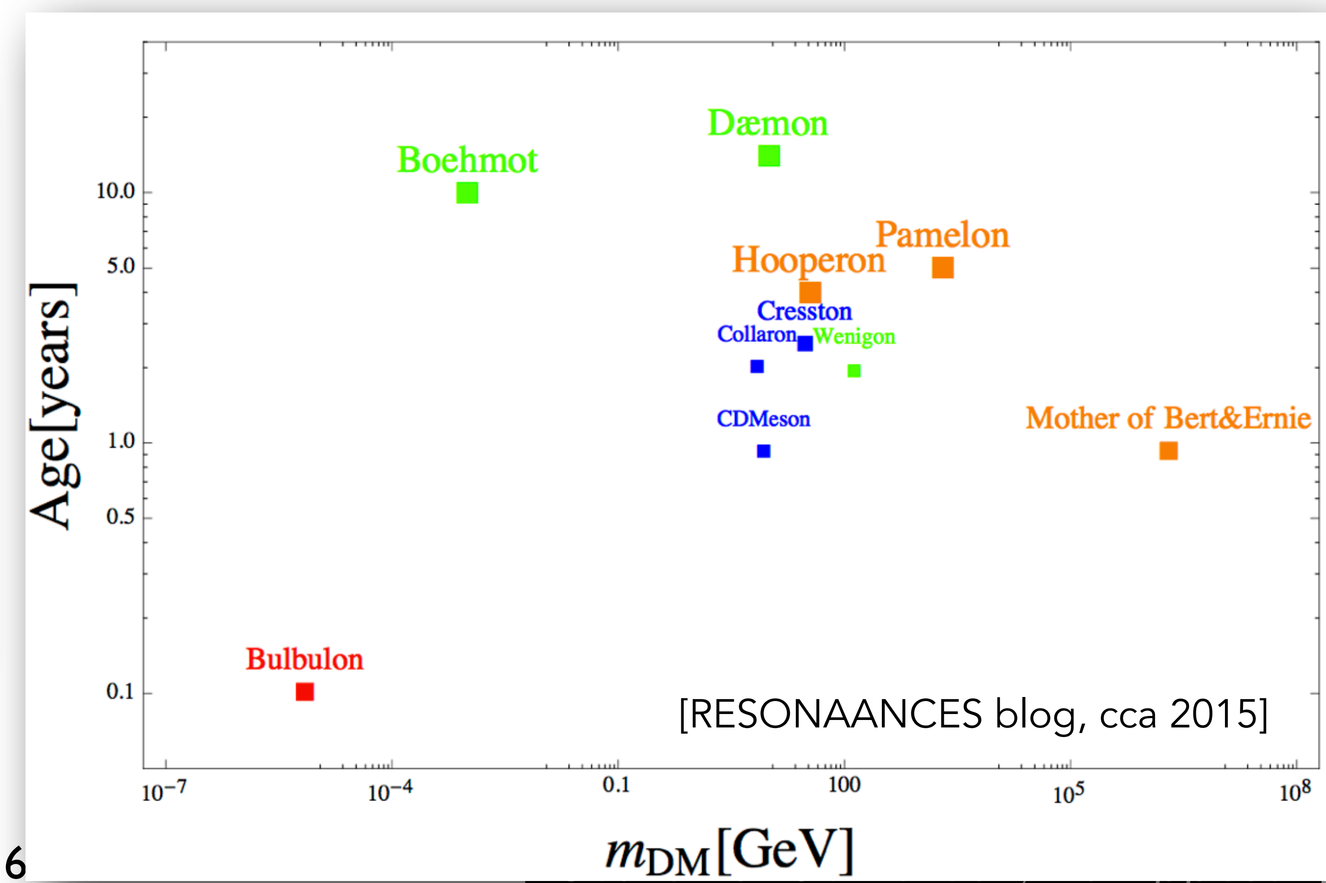
Fuzzy DM | QCD axion/ALPs | Sterile ν | WIMPs & WIMPzillas | PBH

Wave vs particle ← | *Particle 'zoo'* ↔ | → *Macro objects*

Astrophysical probes of the nature of DM

Warning!

Given the complexity of astrophysical phenomena and experimental challenges it happens to stumble upon curious signal hints.



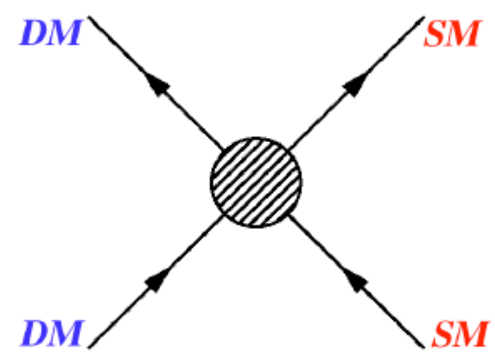
Searches in astrophysical/cosmological data *(DM's 'natural habitat')*

What are the signatures?

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

- In DM DM interactions

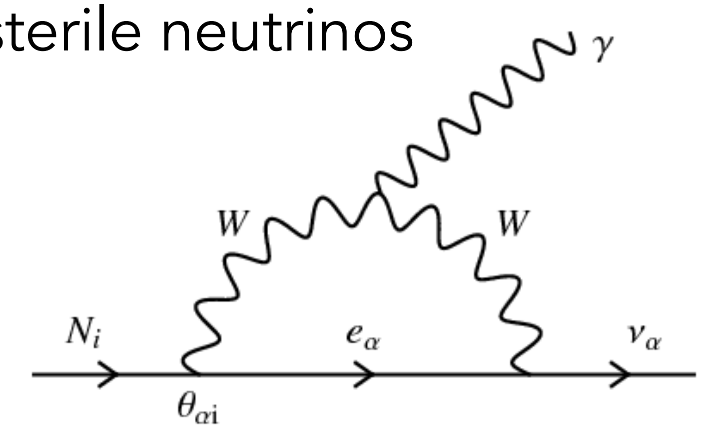
thermal DM



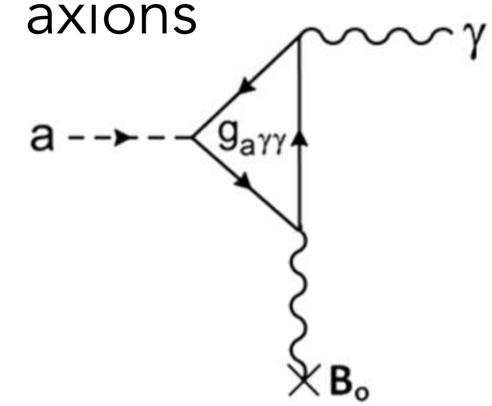
→ γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}

- In DM conversions/decays

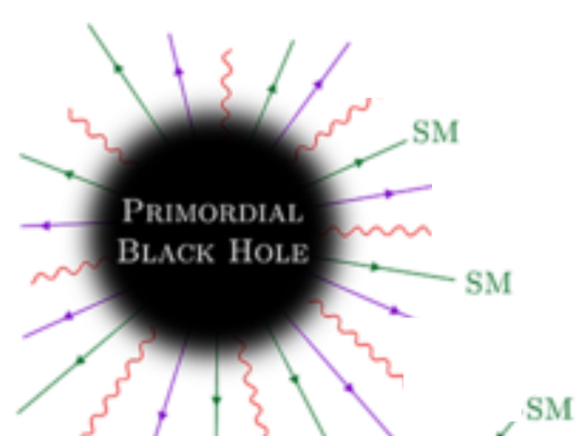
sterile neutrinos



axions



- PBH evaporation…



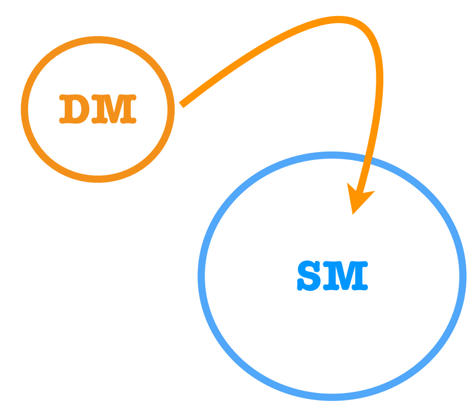
Searches in astrophysical/cosmological data *(DM's 'natural habitat')*

What are the signatures?

2. Altering of behaviour of astrophysical systems

- capture by stars (altering stellar evolution) or planets (altering internal heat production)

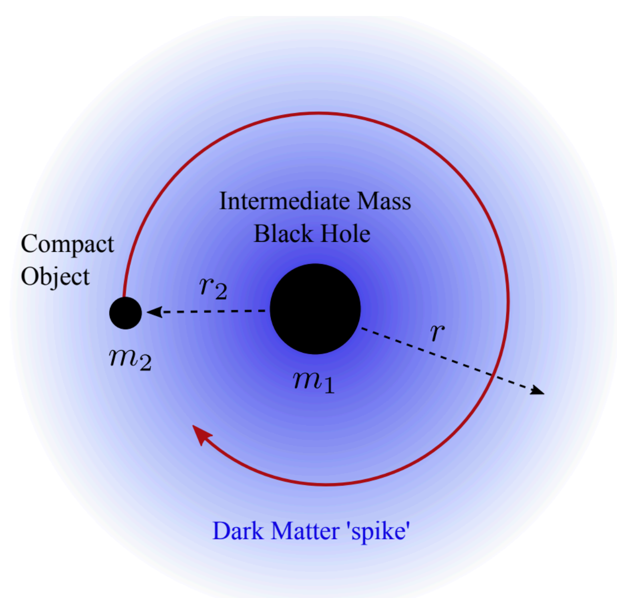
- cooling of stars via DM channel

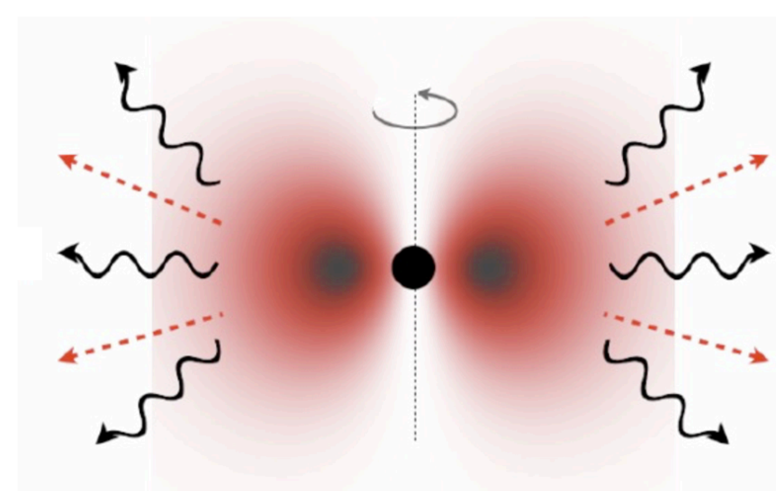


Asymmetric DM

Axions…

- affecting GW emission …





Ultra-ligt bosons

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 *(DM's 'natural habitat')*

What are the signatures?

PROs: worked so far…

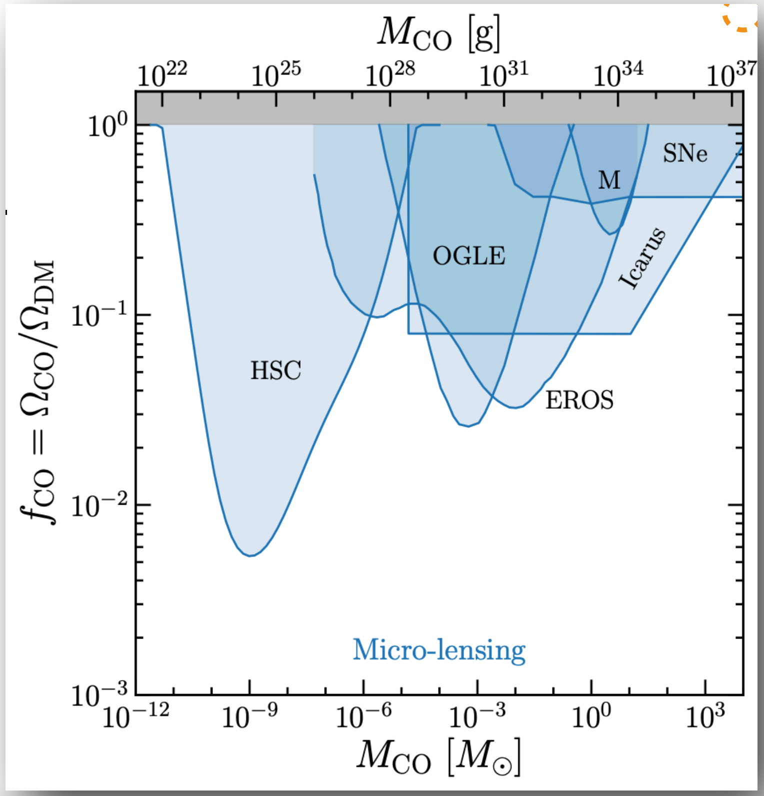
CONs: does not give a handle on other/new forces

3. Purely gravitational interactions with visible matter

- gravitational lensing

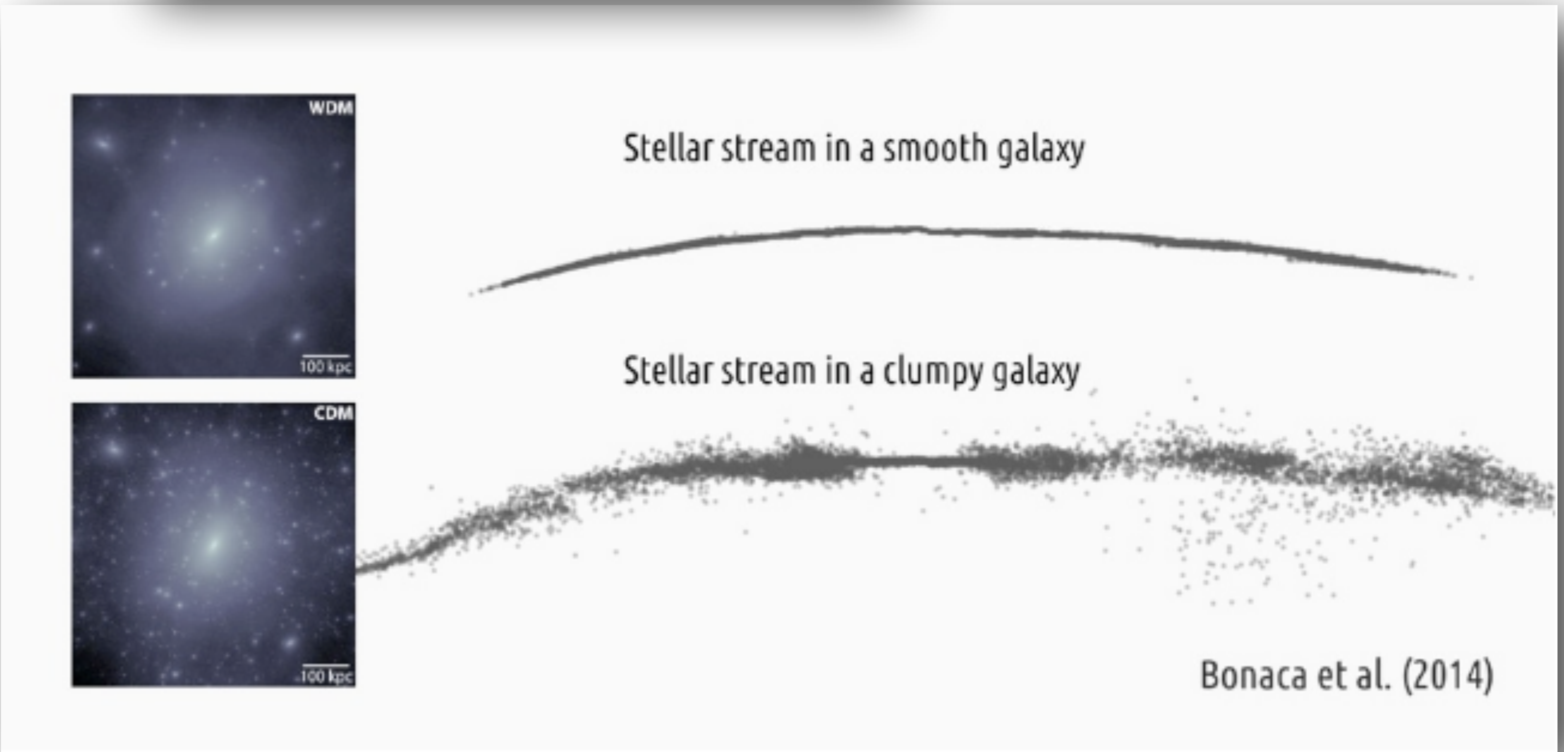
Micro lensing (asteroid to solar masses)

Galaxy-galaxy lensing



- stellar tidal stream disruptions

- stellar wakes…



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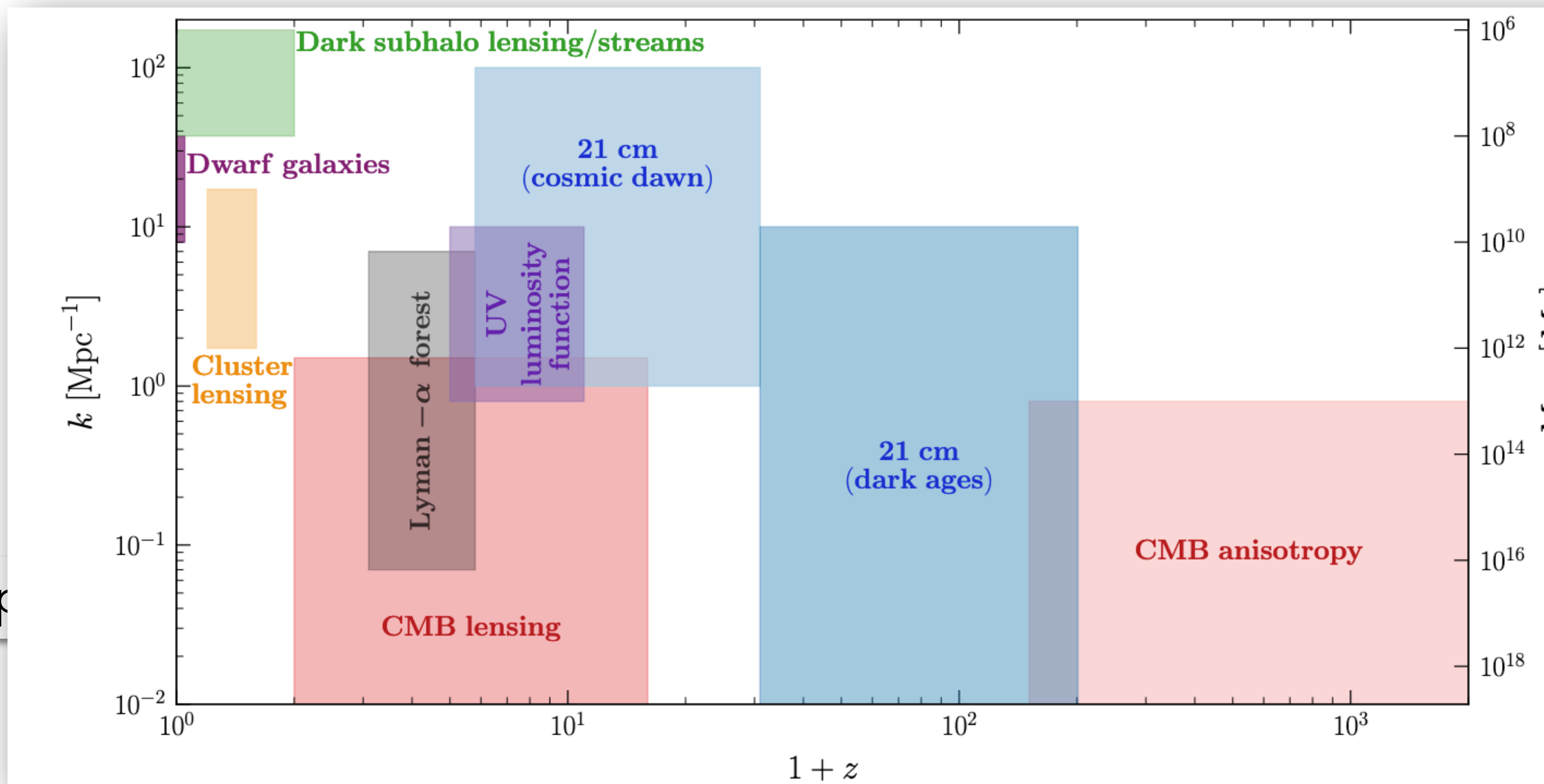

- stellar tidal stream disrup

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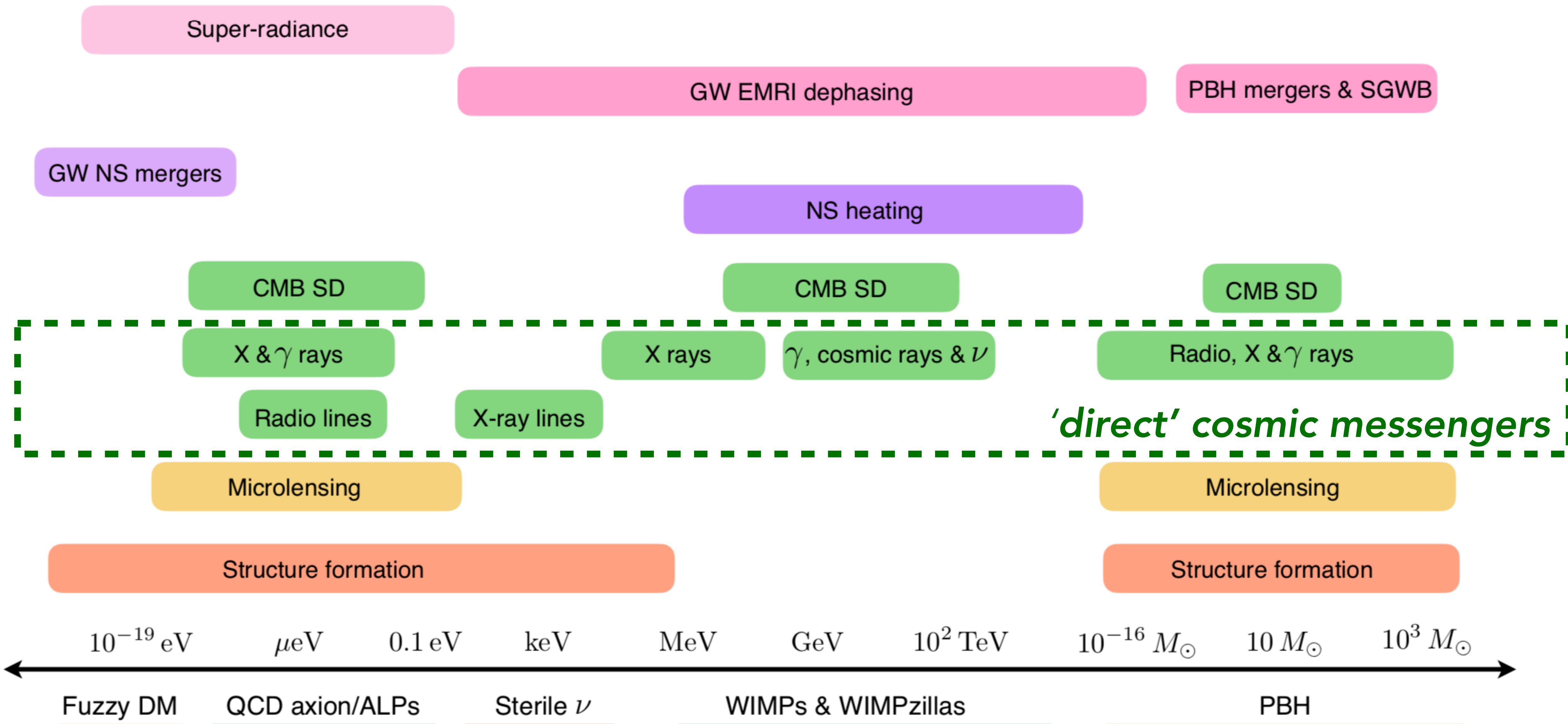
In terms of detection strategies:



EuCAPT white paper,
arXiv: 2110.10074

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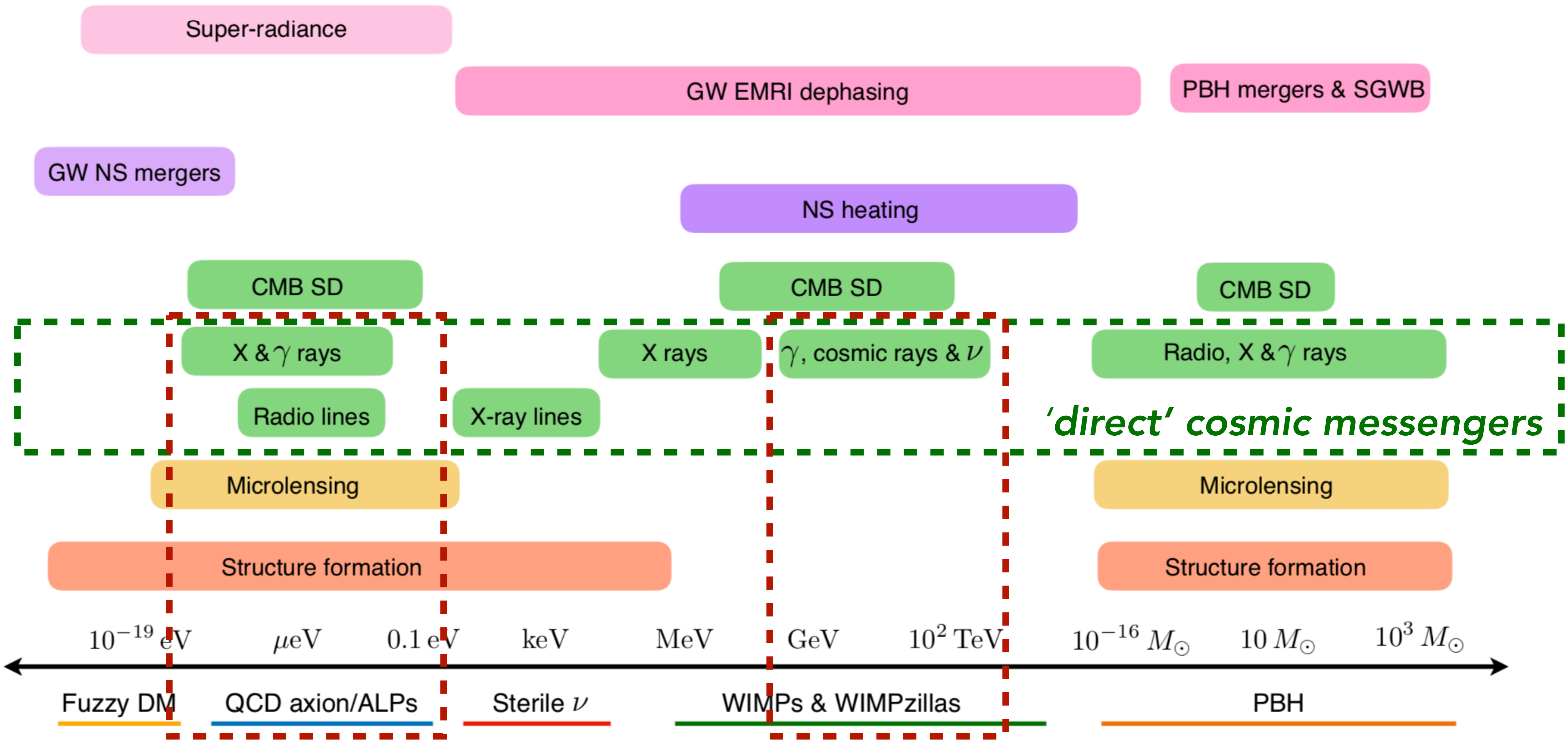

EuCAPT white paper,
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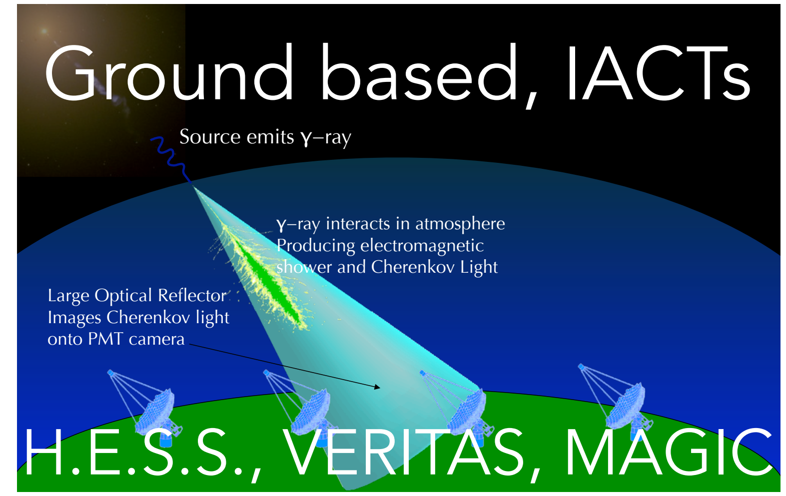
How to look?

γ



Powerful tools covering

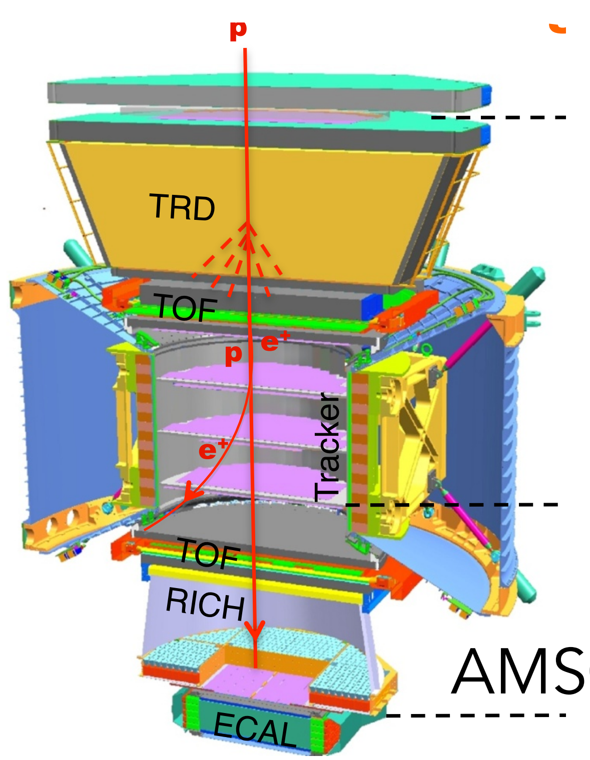
>~$10^{2\pm2}$ GeV range

ν

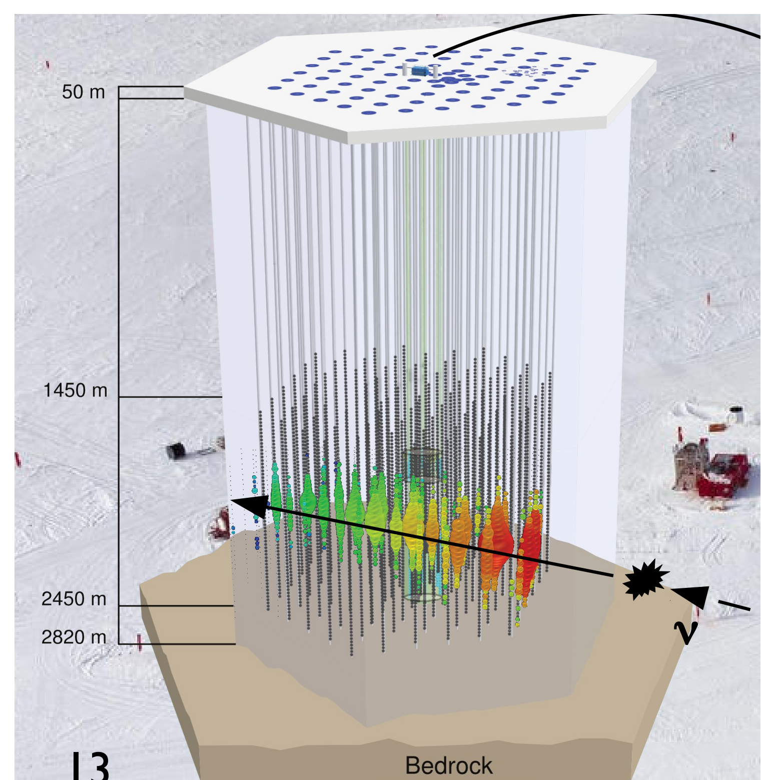
$e^{\pm}$, $p^{\pm}$, D^{-}

PAMELA

DAMPE



AMS02

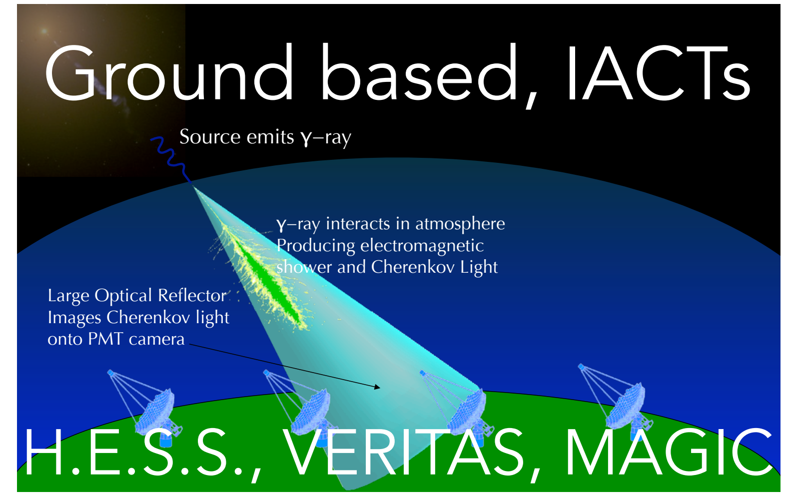


IceCube,

ANTARES

How to look?

γ

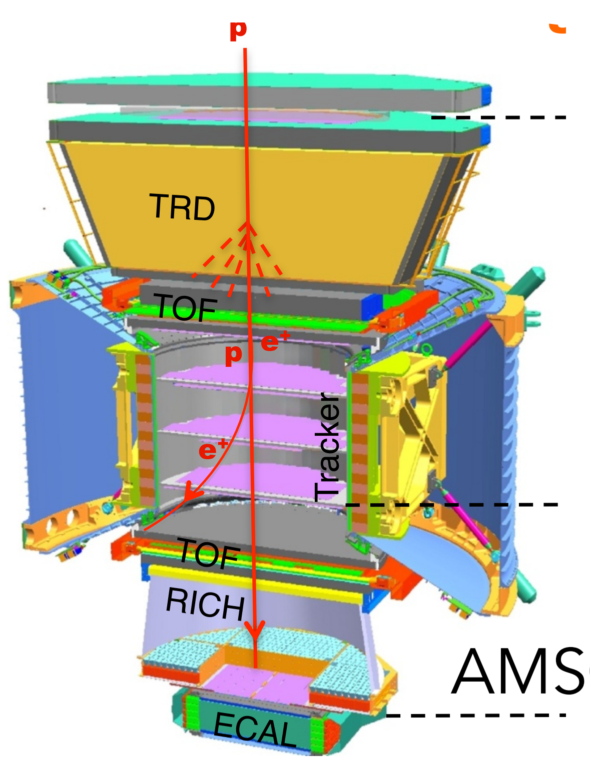


Powerful tools covering
$>\sim 10^{2\pm2}$ GeV range

ν

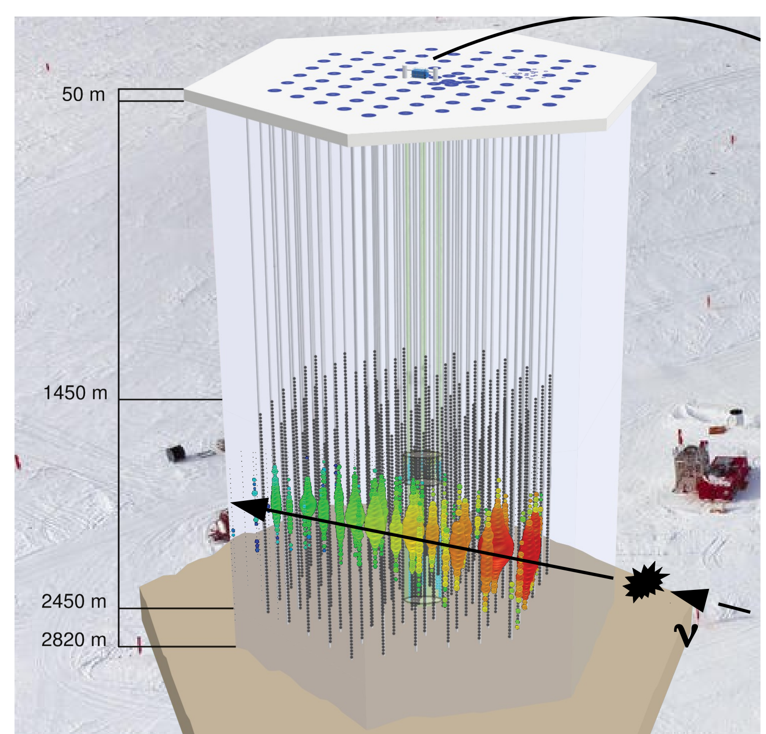
Note: radio, X-rays
(lines) very relevant too

$e^{\pm}$, $p^{\pm}$, D^{-}



DAMPE

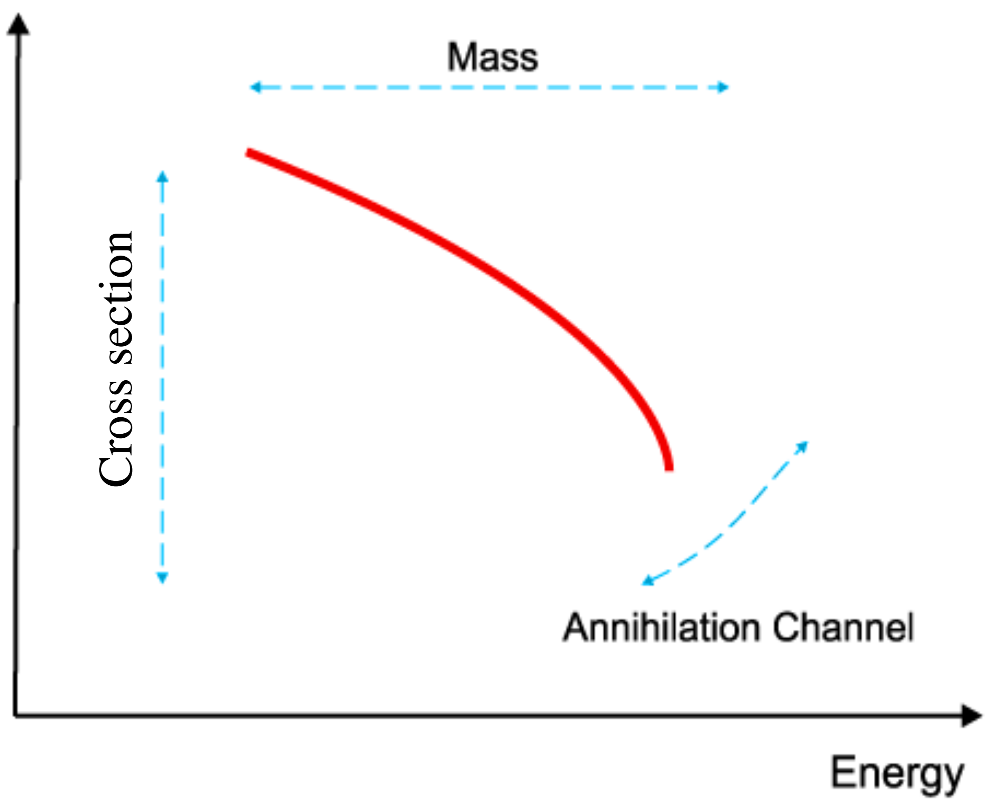
AMS02



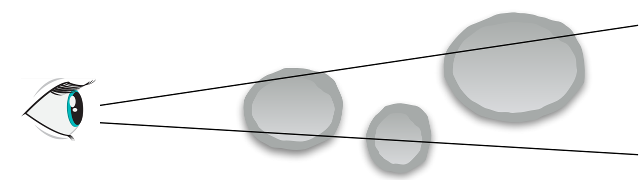
IceCube,
ANTARES

What is the expected DM signal? - γ's and ν's travel in straight lines!

Flux (γ, ν) = particle physics X cosmology



Bertone 2007



How is DM distributed

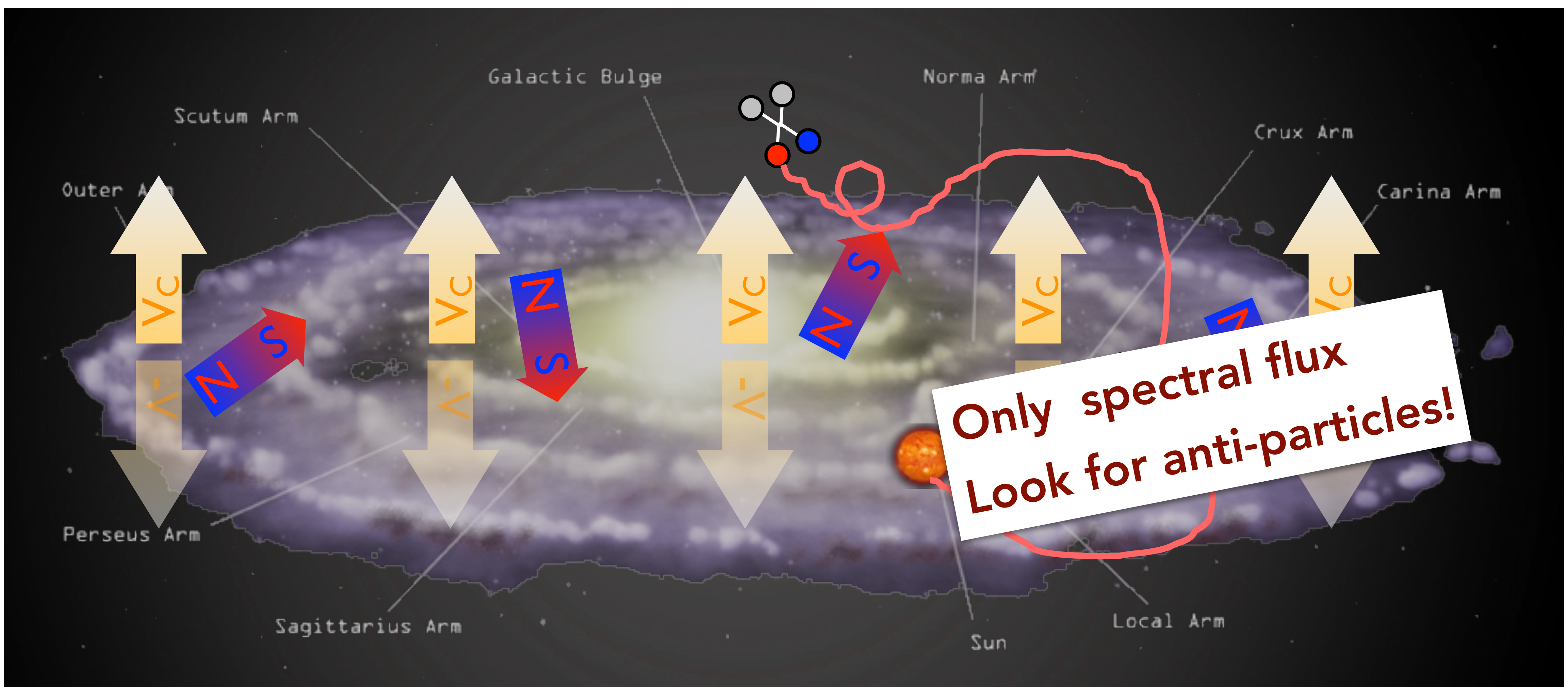
WIMP example

$$\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{(\sigma_{\mathrm{ann}} v)}{2\,m_\chi^2} \;\mathrm{X}\; \sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma} \;\mathrm{X}\; \int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\,\rho^2(s,\Omega)$$

What is the expected DM signal? - charged particles

Flux (CRs) = (**particle physics** X **cosmology**)

astrophysics



Talk Outline

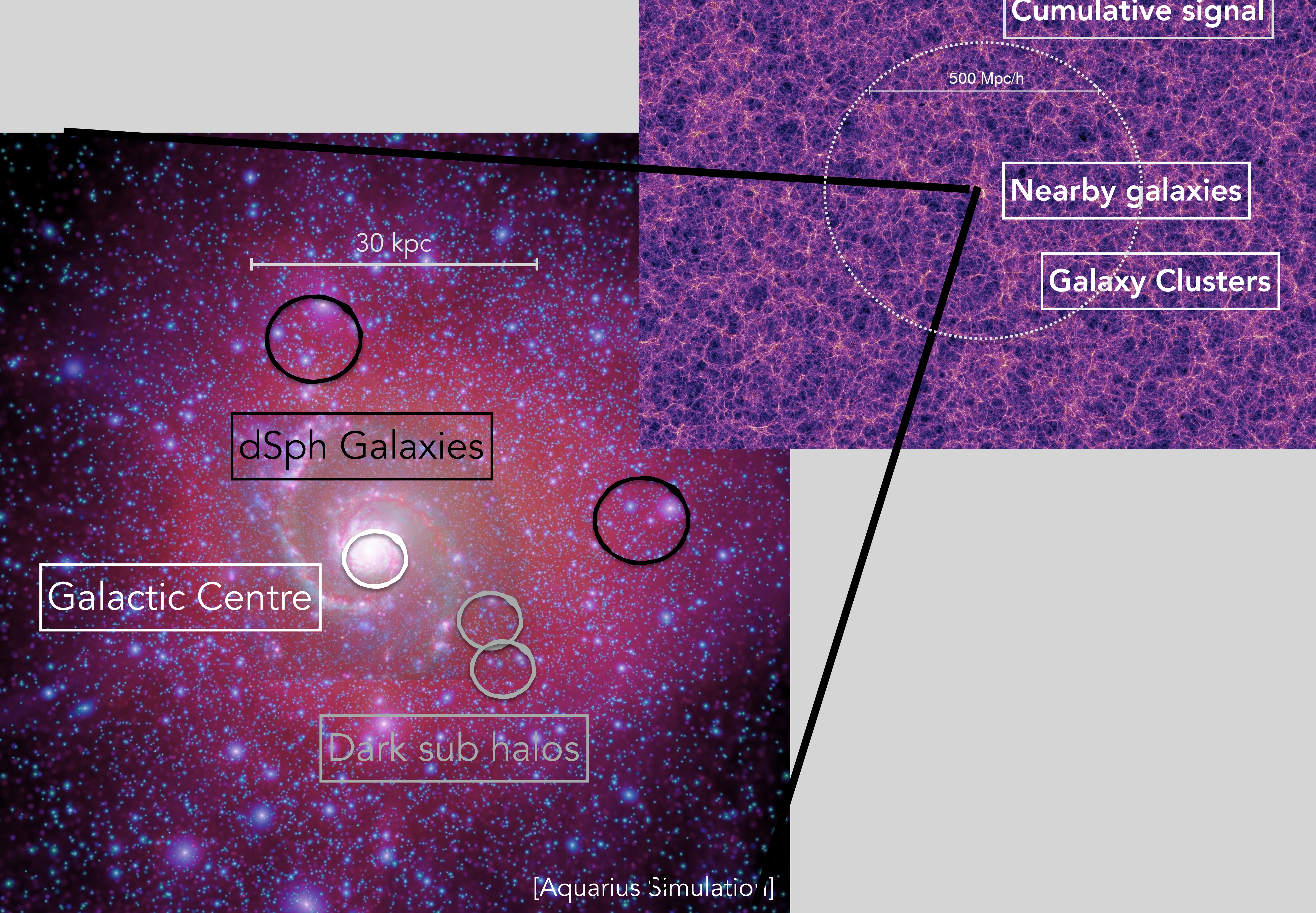
1) **Focus on DM search via gamma-rays (WIMPs, ALPs,** PBHs**…)**

- Where to look/DM distribution
- What (gamma-ray) tools do we have
- What strategies to adopt (WIMPs vs ALPs)
- Future

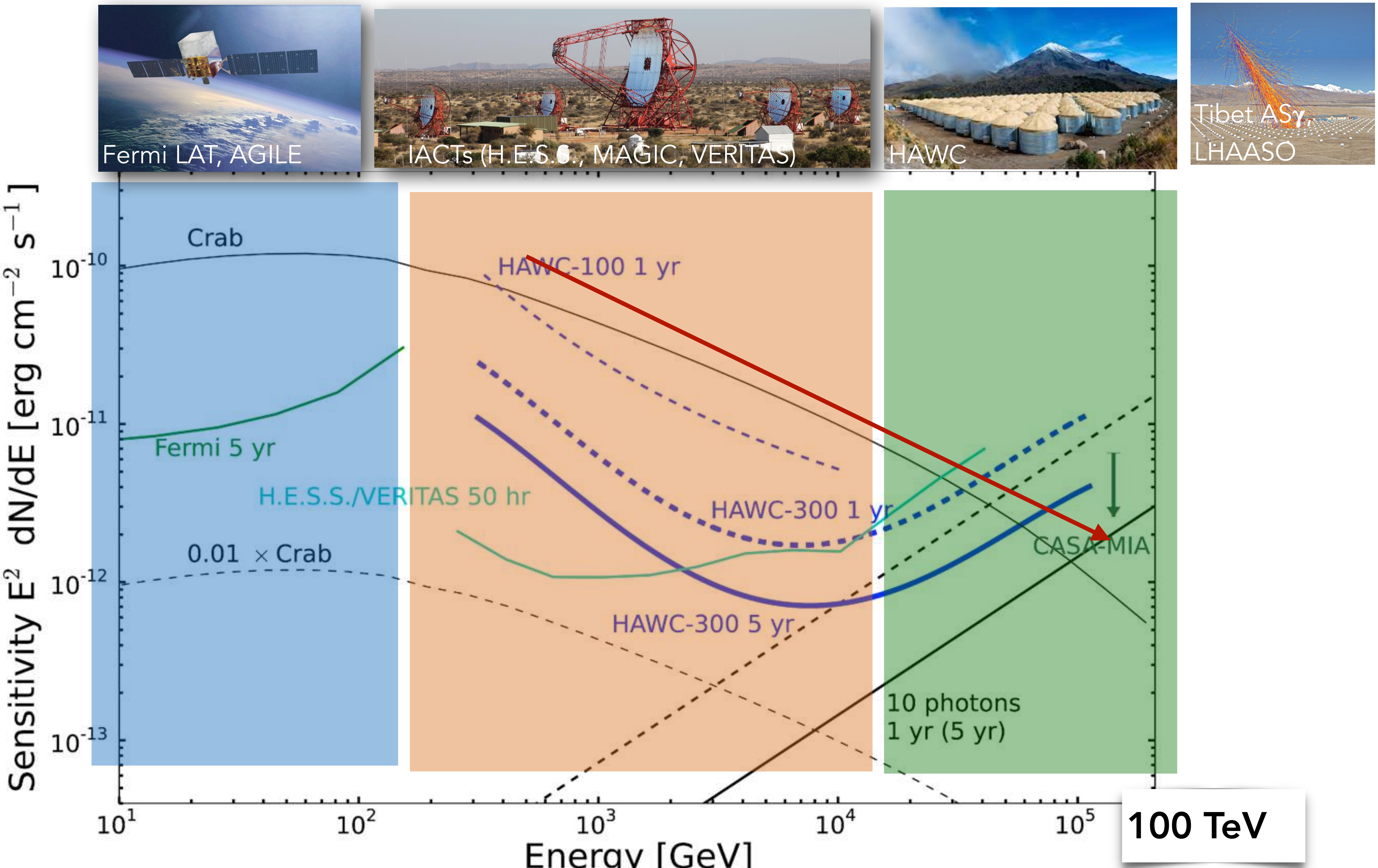
Gamma rays travel in straight line - so carry directional information (morphology)
+ Higher statistics than neutrinos

2) **Some words on DM search via cosmic rays (anti-protons) and neutrinos**

Where to look?

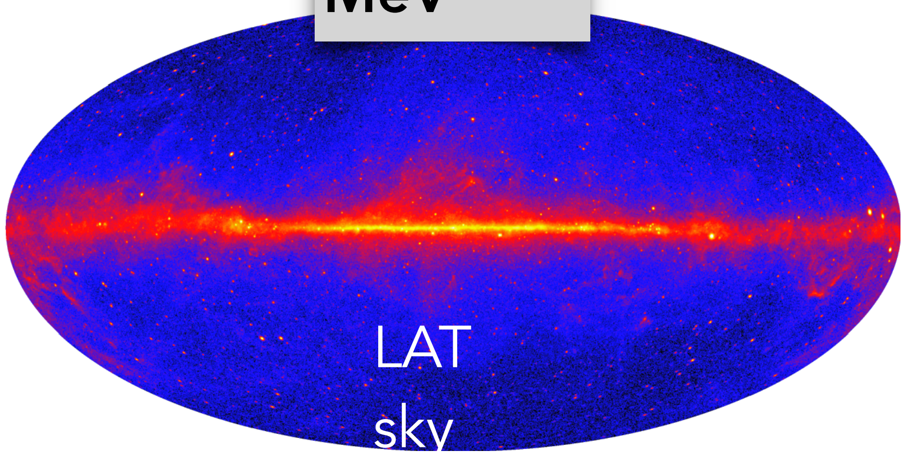


What tools?

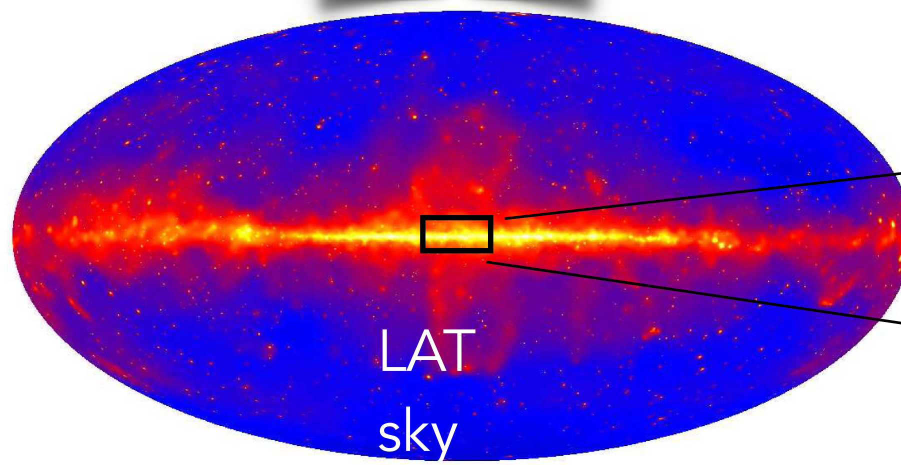

Fermi LAT, AGILE
IACTs (H.E.S.S., MAGIC, VERITAS)
HAWC
Tibet ASγ,
LHAASO
Crab
HAWC-100 1 yr
Fermi 5 yr
H.E.S.S./VERITAS 50 hr
HAWC-300 1 yr
0.01 × Crab
CASA-MIA
HAWC-300 5 yr
10 photons
1 yr (5 yr)
Sensitivity E² dN/dE [erg cm⁻² s⁻¹]
Energy [GeV]
100 TeV

GeV vs TeV

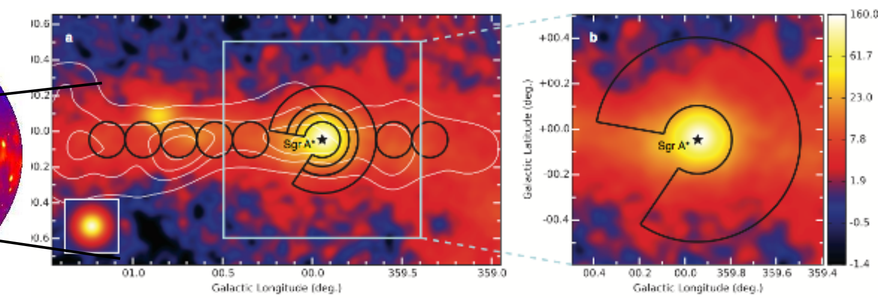
>300 MeV



>10 GeV

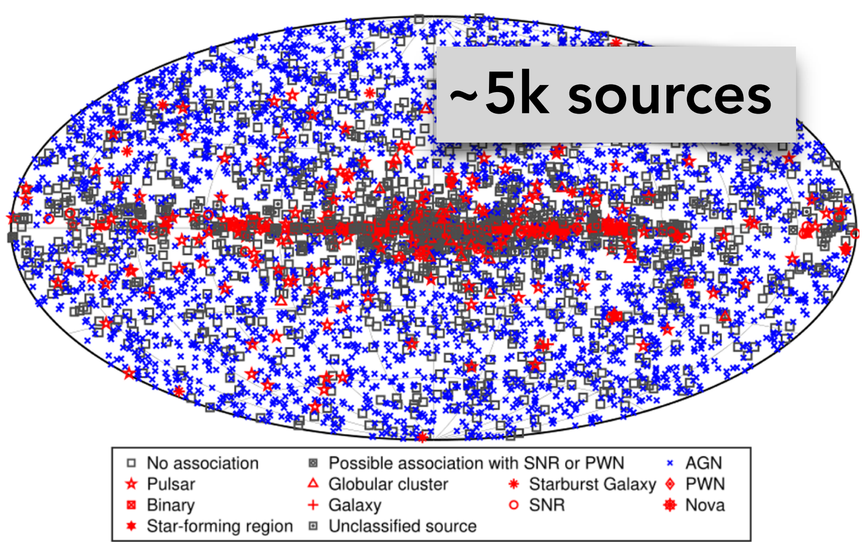


>~100 GeV

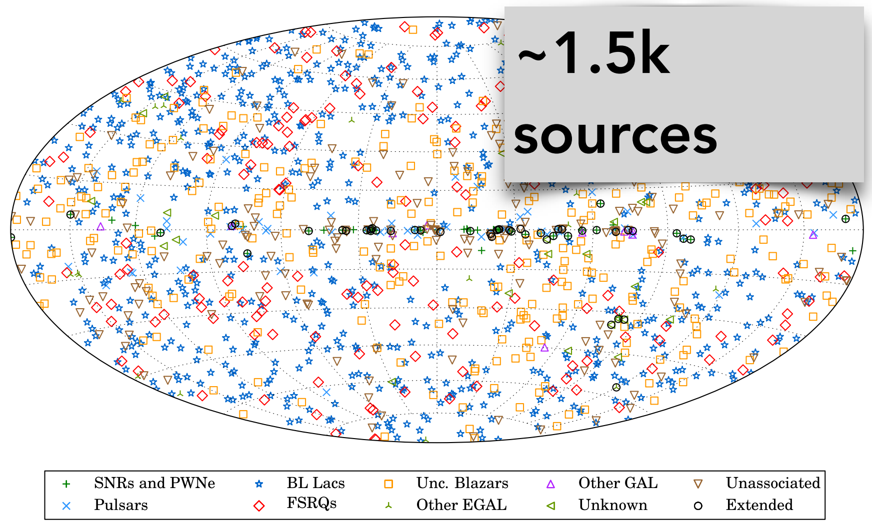


HESS, Galactic center Ridge

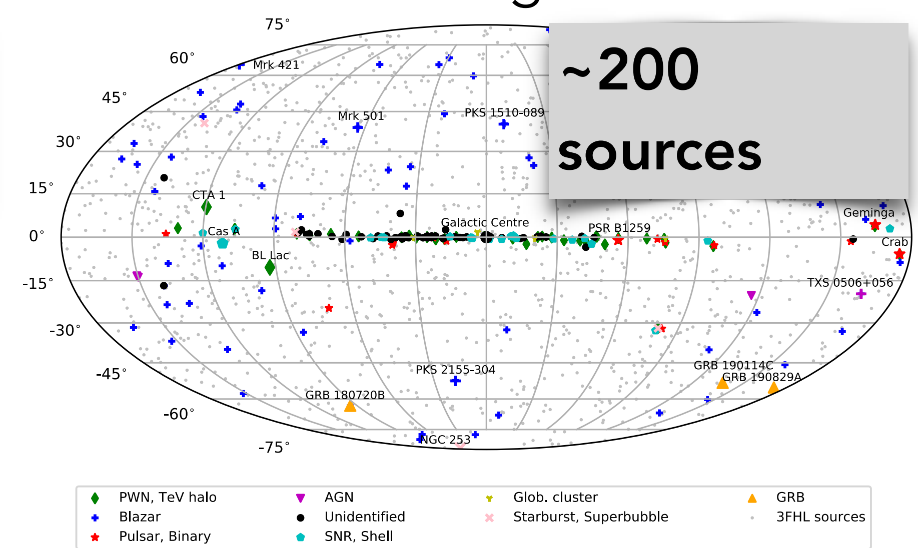
~5k sources



~1.5k sources



~200 sources



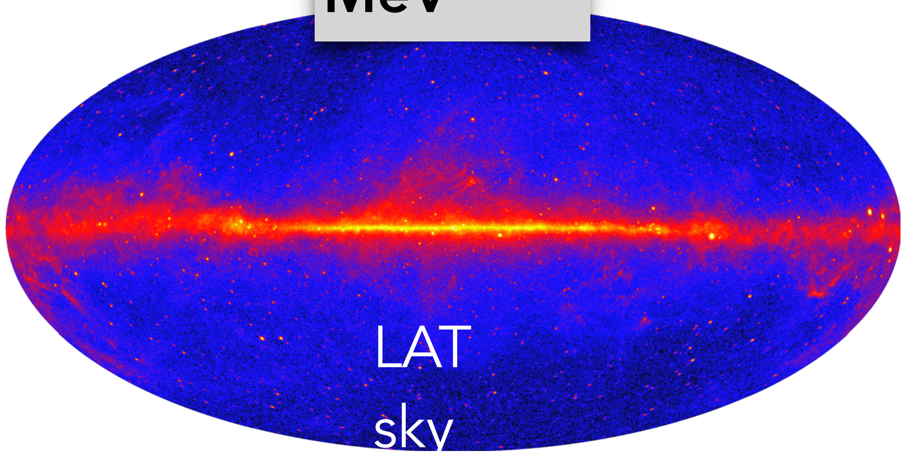
LAT source catalogue, >300 MeV (4FGL)

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

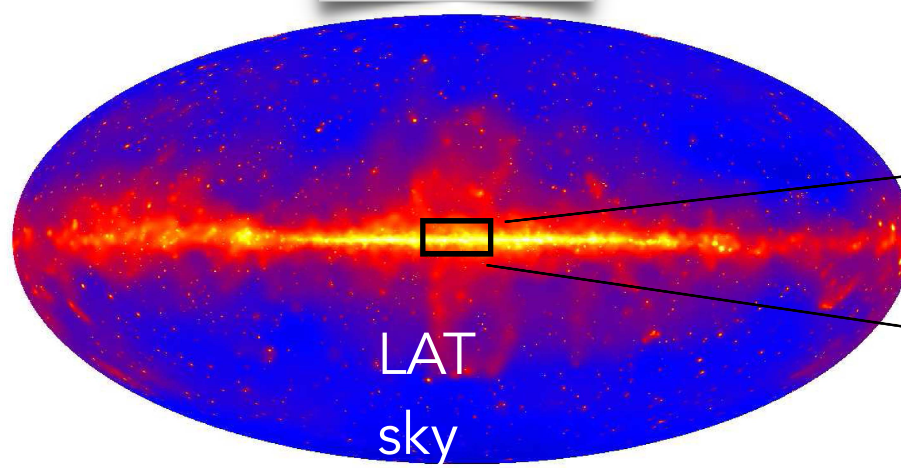
TeVCat, 2019

GeV vs TeV

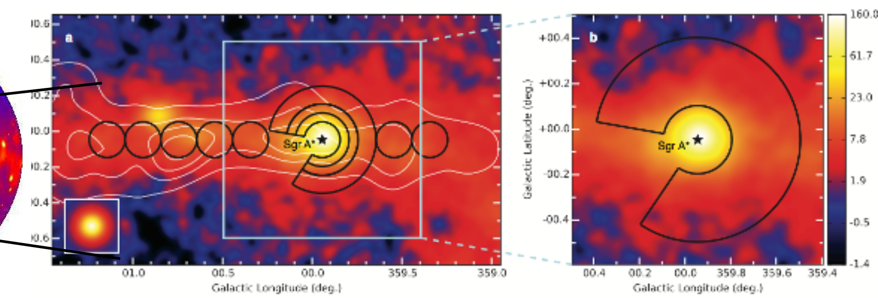
>300 MeV



>10 GeV



>~100 GeV



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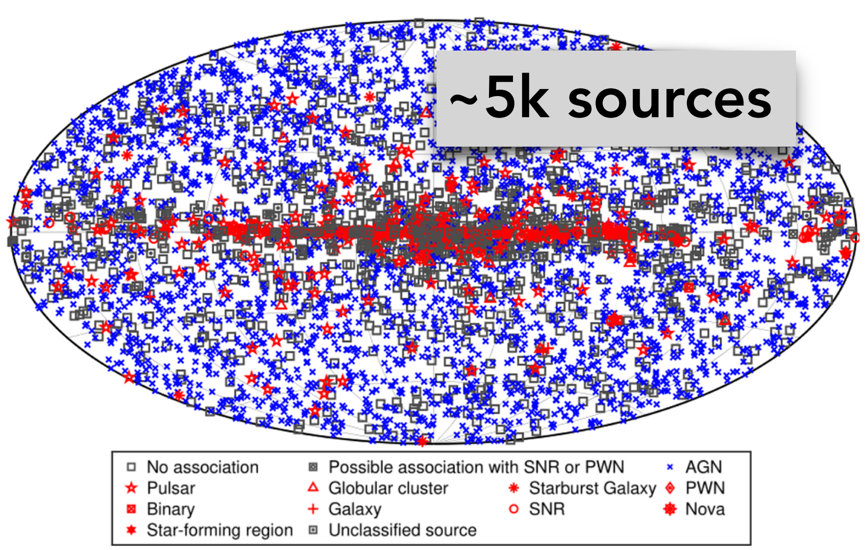
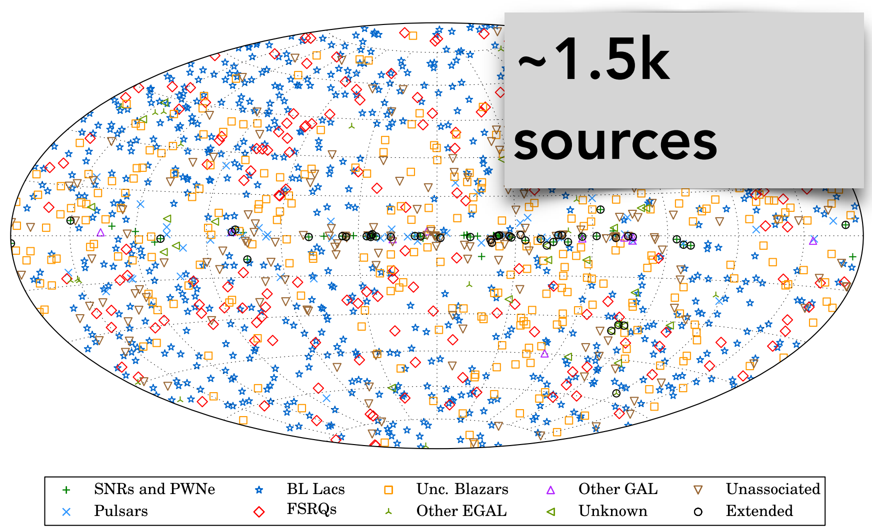


~1.5k sources



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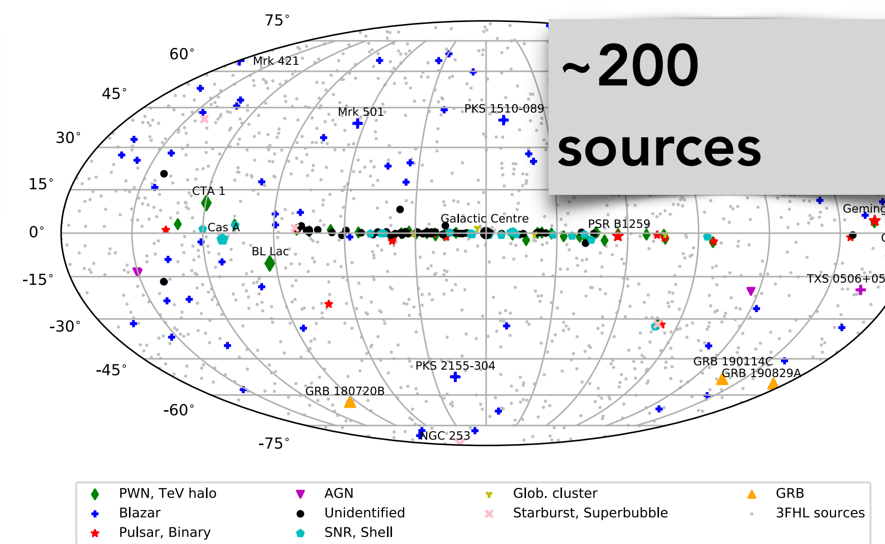


LAT source catalogue, >300 MeV (4FGL)

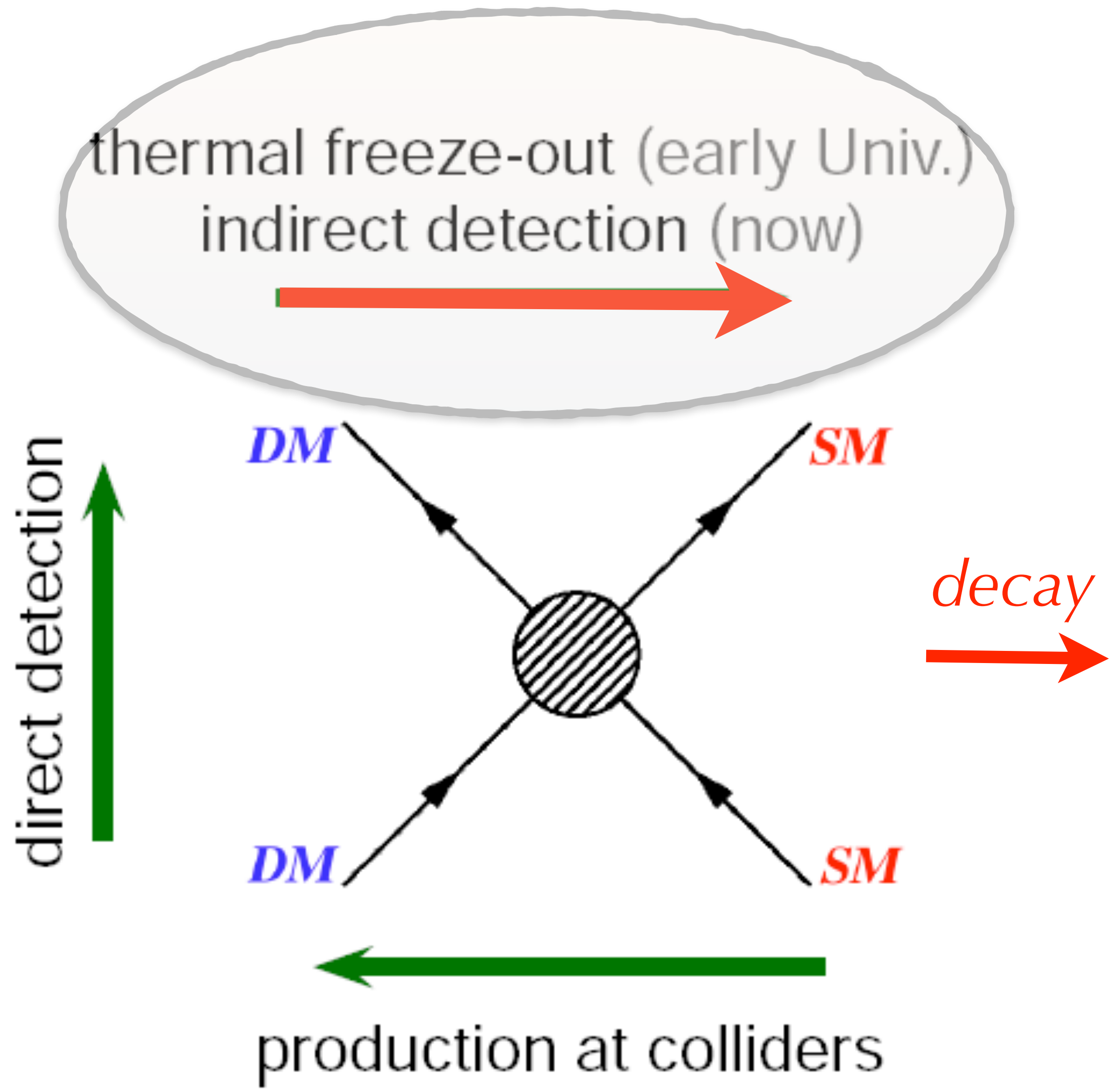
LAT source catalogue, **>10 GeV** (3FHL)

TeVCat,

+12 sources >0.1 PeV (LHAASO) & HAWC, Tibet AS candidates

What strategies (**WIMPs** & ALPs)?

WIMPs: prime example of thermal DM

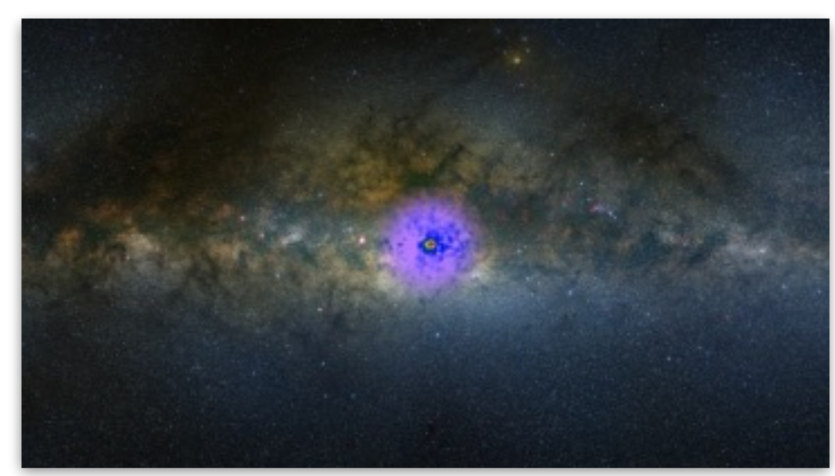


γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}

@ $\mathcal{O}(M_Z)$

In the Early Universe: DM kept in equilibrium w SM by self-annihilations $\langle \sigma v \rangle_{thermal}$.

Today, *DM expected to annihilate with the same* $\langle \sigma v \rangle_{thermal}$, *in places where its **density is enhanced**!*



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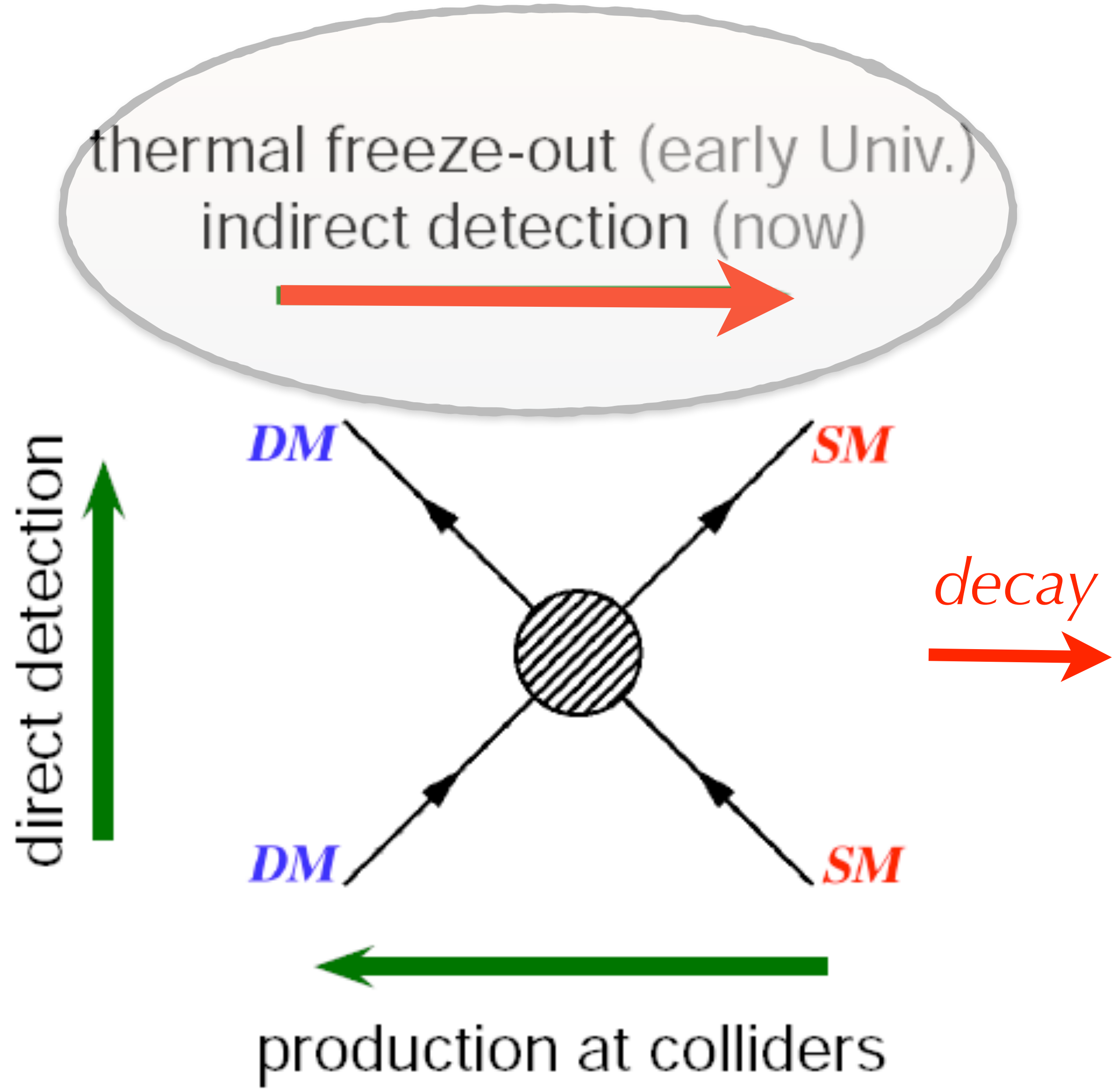

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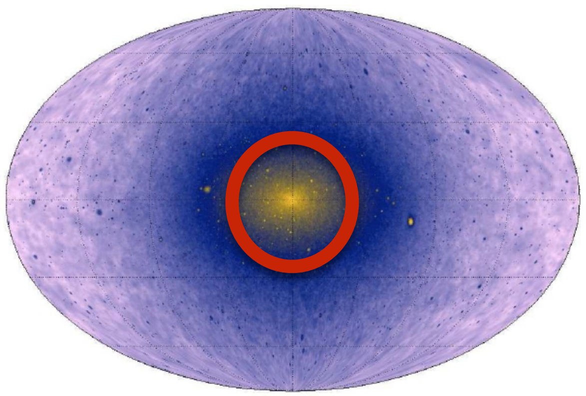
Predictive:

TeV scale & $\langle \sigma v \rangle_{thermal}$

What strategies (**WIMPs** & ALPs)?

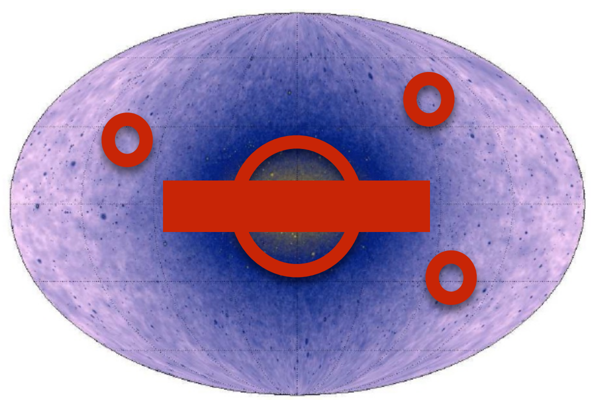
signal strength

GC



[Archaryya et al. JCAP 2020.]

dark subhalos

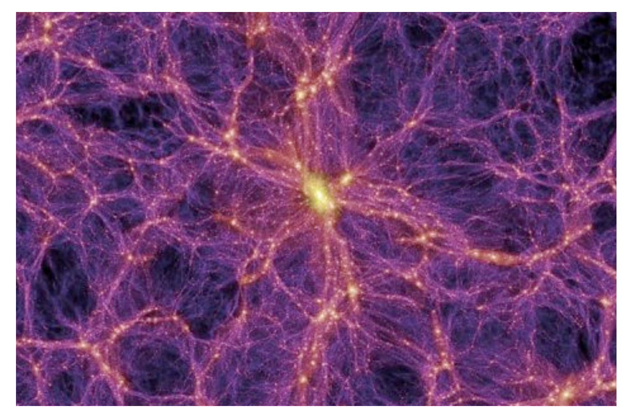


GC halo

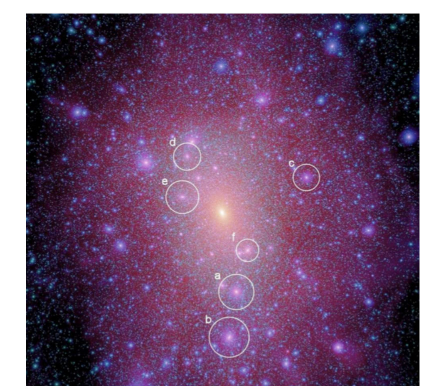
[J. C-B. + Phys.Dark Univ. 32 (2021)]

Extragalactic sources:

- clusters of galaxies
- other galaxies (M31, M33, LMC, SMC)



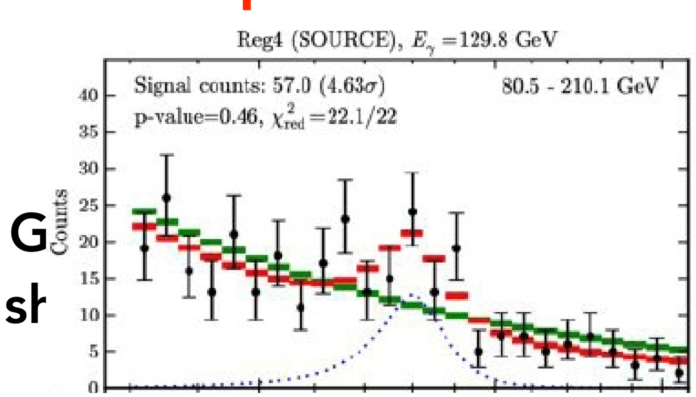
dwarf satellites



Cosmological signal/UEBG:

- Spectral flux
- Auto-correlations
- Cross-correlations w G
  catalogs and cosmic sh

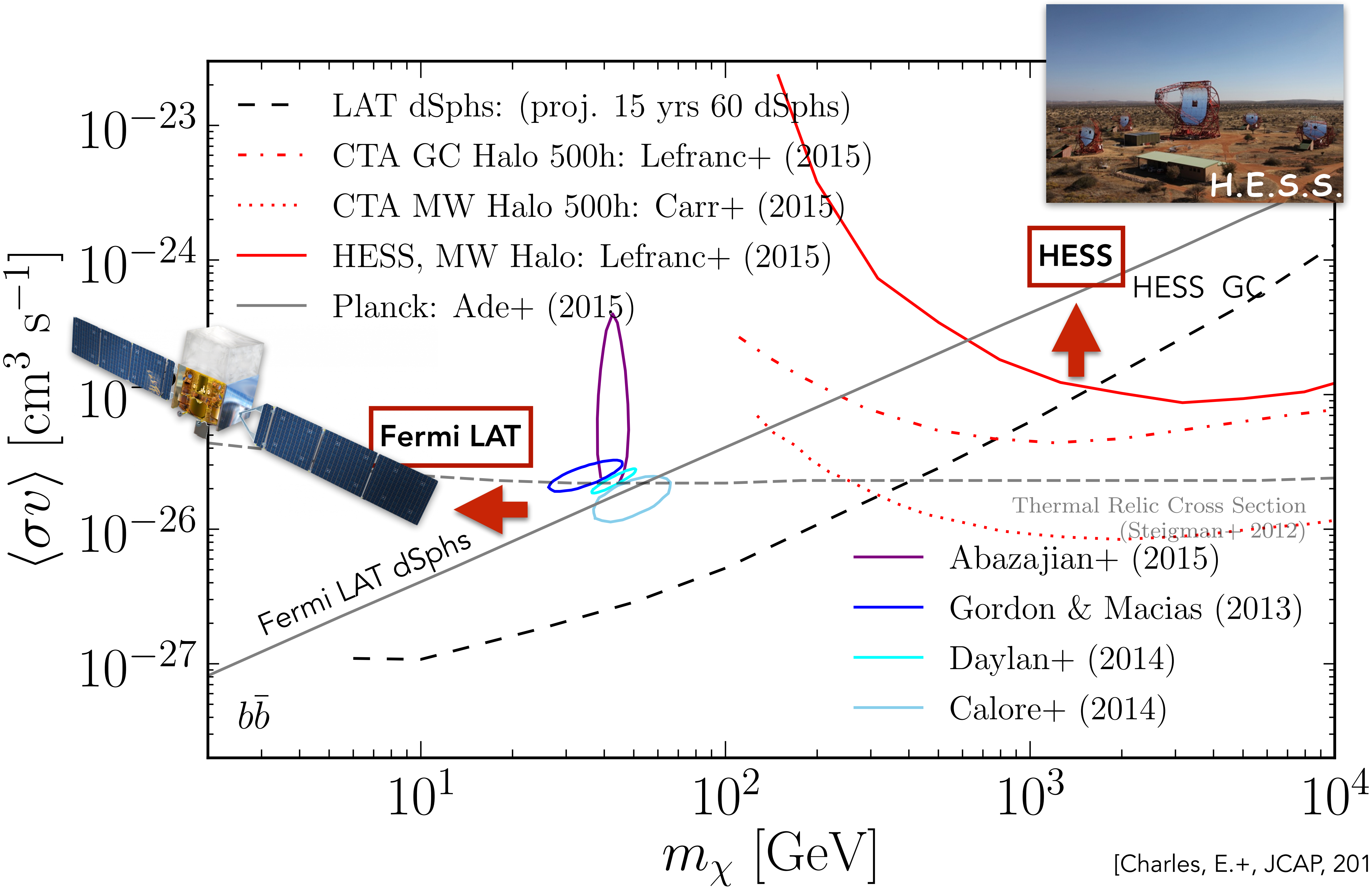
spectral line



robustness

[adapted from: H.-S. Zechlin]

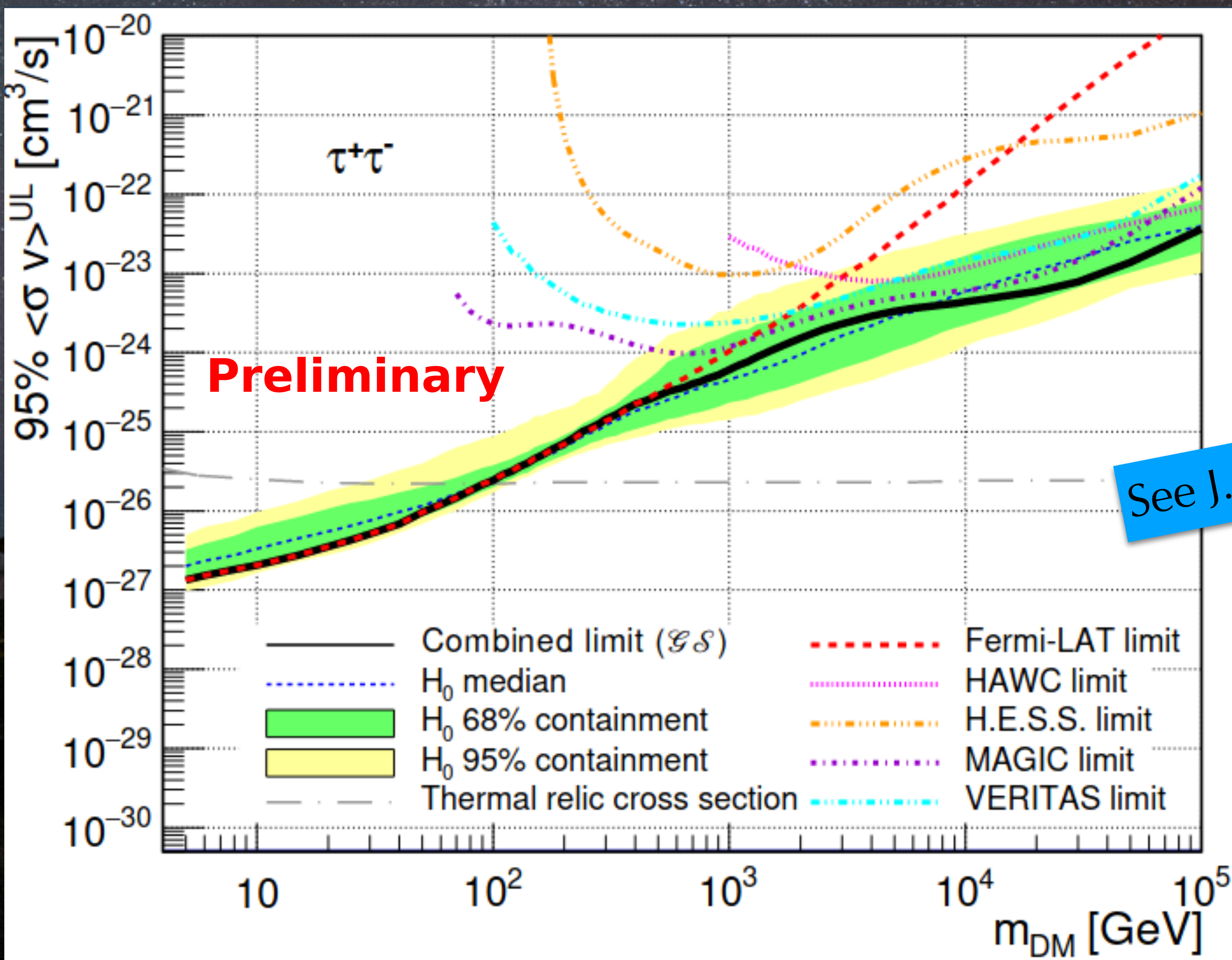
State-of-the-art



[Charles, E.+, JCAP, 2016]

State-of-the-art

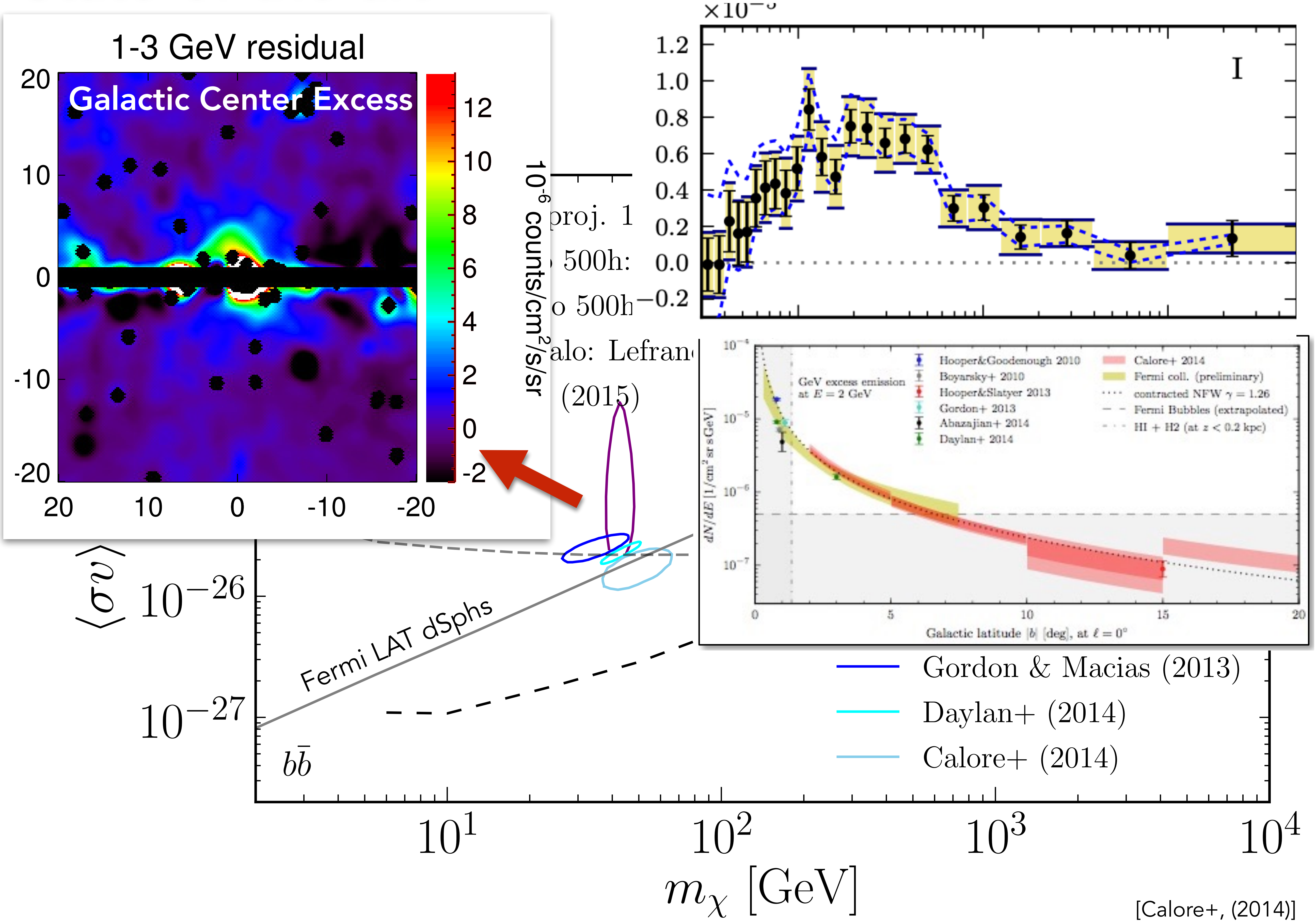
★ Stack likelihood functions of 20 dwarf satellite galaxies by 5 gamma-ray telescopes (Fermi-LAT, MAGIC, HESS, VERITAS, HAWC)



Kerszberg et al. Gamma 2022 conference

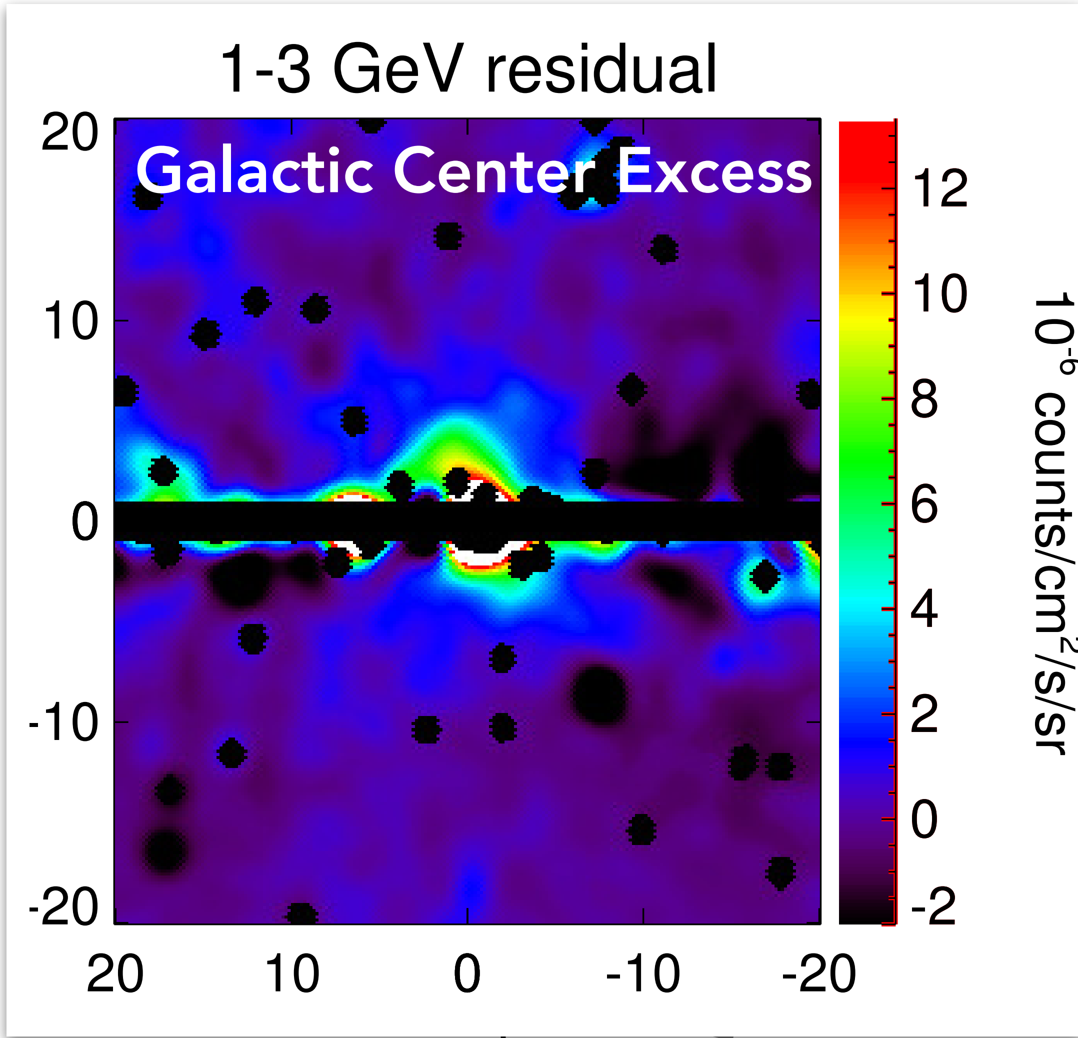
See J. Rico's talk

State-of-the-art

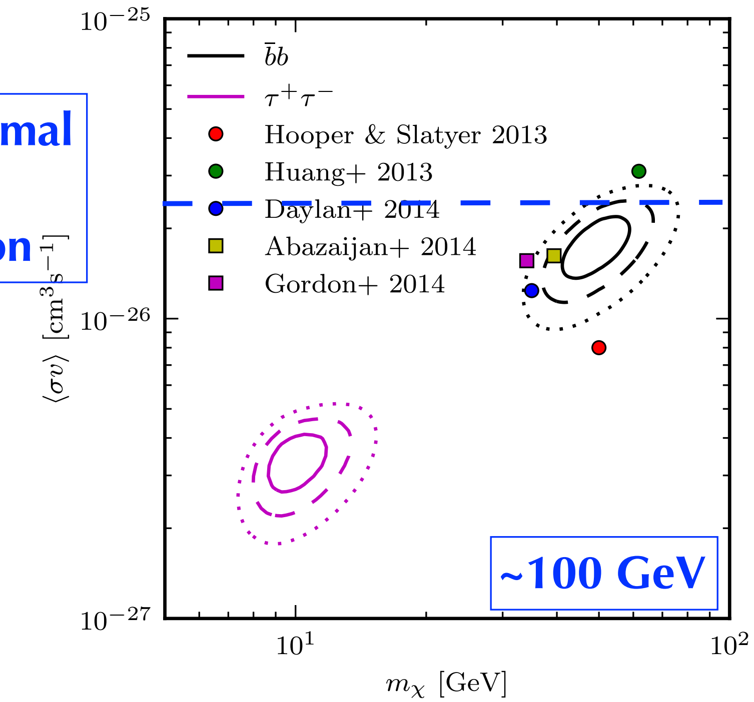


[Calore+, (2014)]

State-of-the-art



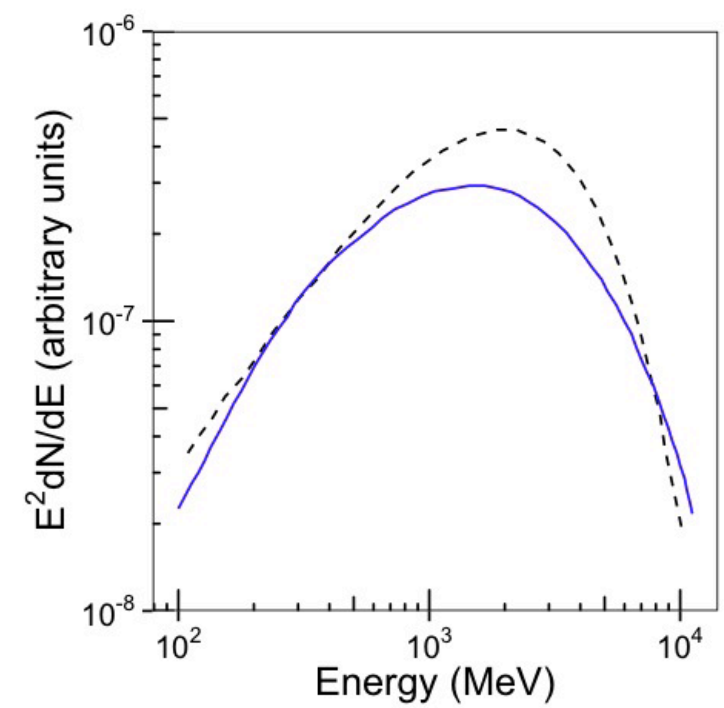
Right on the spot where WIMP DM is supposed to be!



Pulsars are spectral twins of DM + about 300 pulsars discovered in the LAT data (none in the inner GC region)

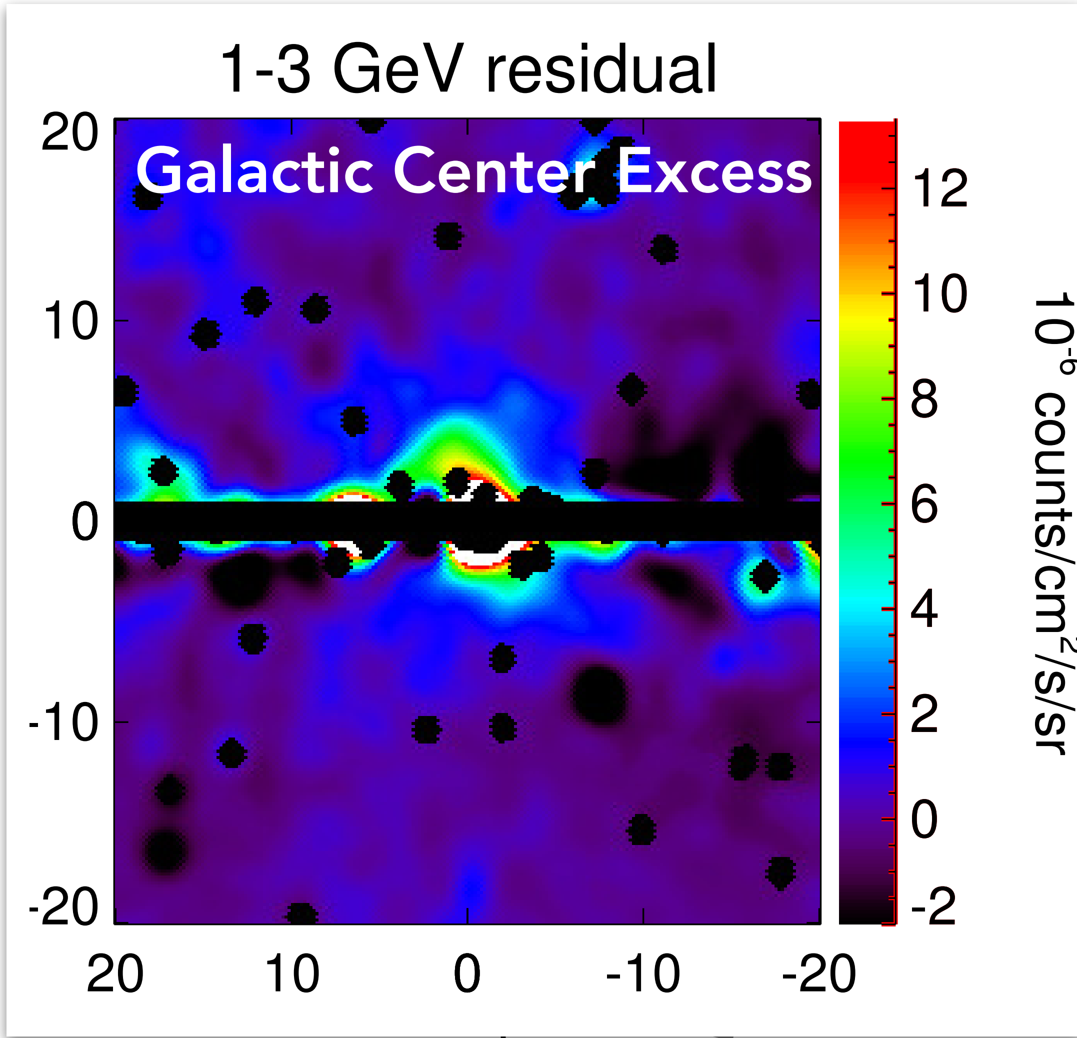
See M. DiMauro's talk

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

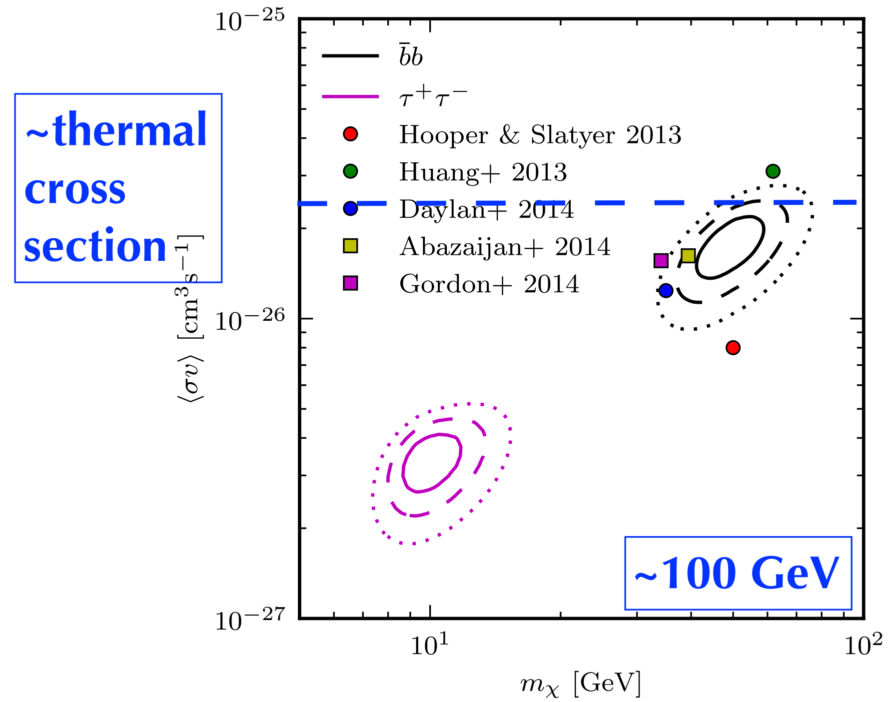


Baltz et al (2007)

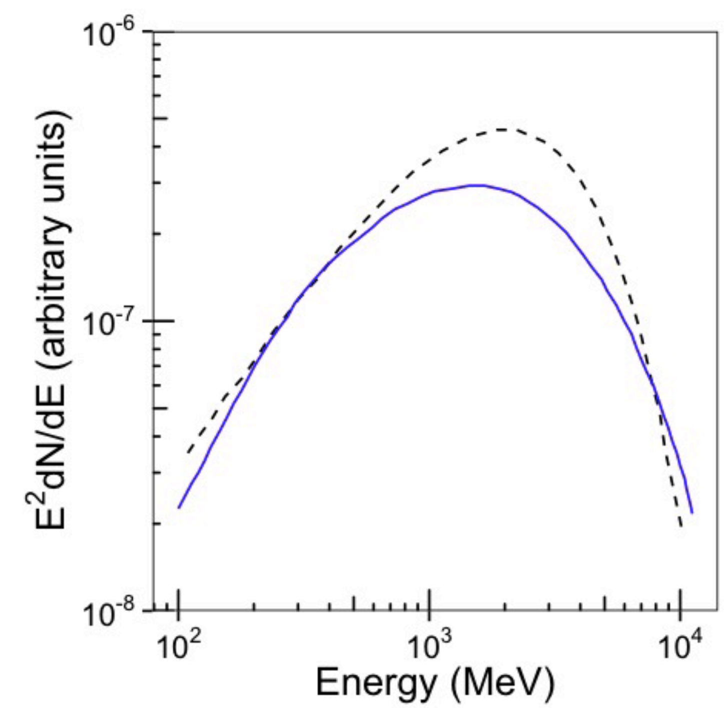
State-of-the-art



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



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



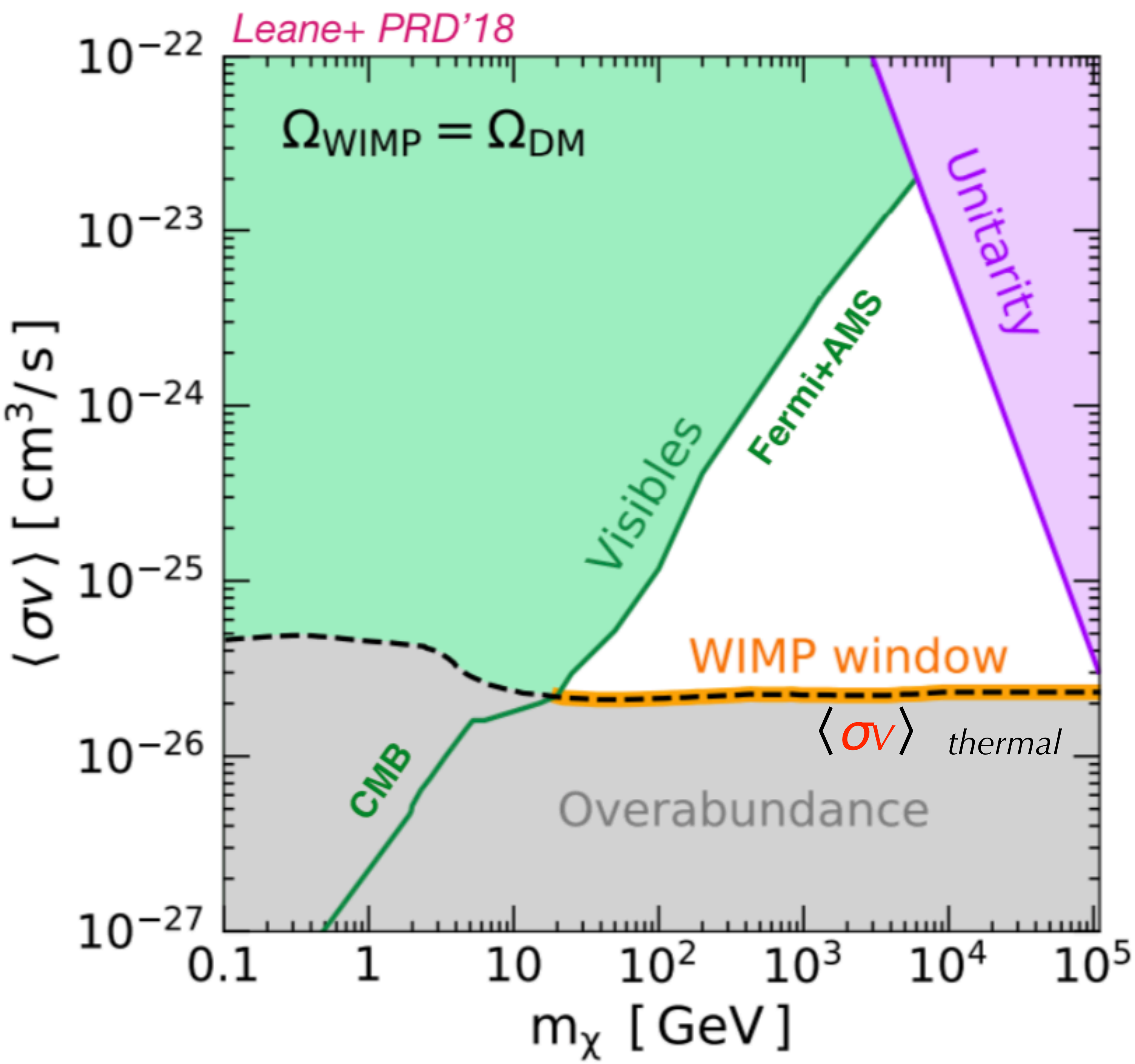
Baltz et al (2007)

Fierce debate ongoing!

Galactic center is a complex fascinating region and GC excess needs to be understood, but at a moment does not represent robust DM discovery

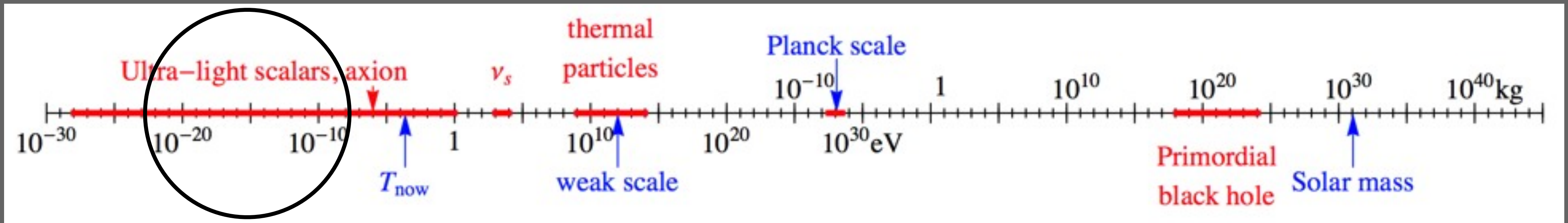
State-of-the-art

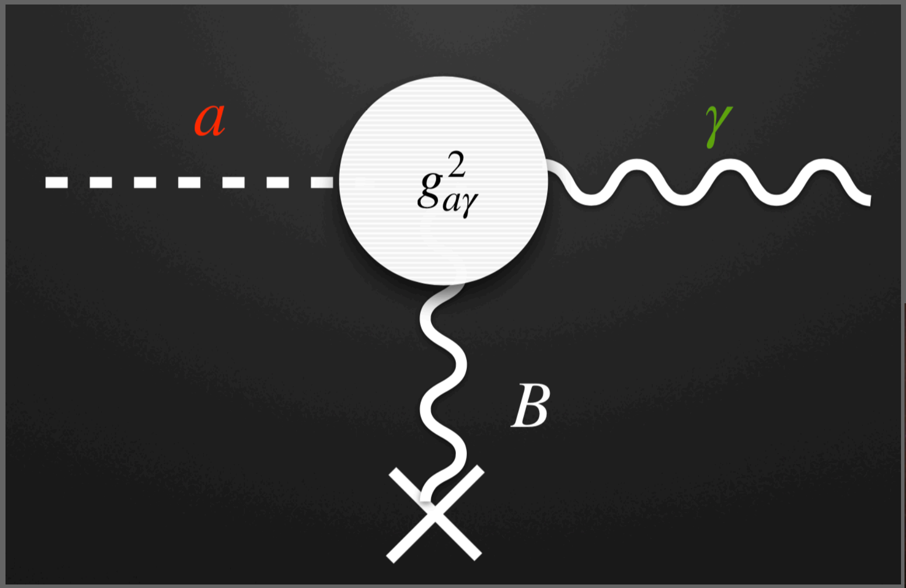
'cornering the WIMP'



The 'TeV window' still remains to be explored

What strategies (WIMPs & **ALPs**)?



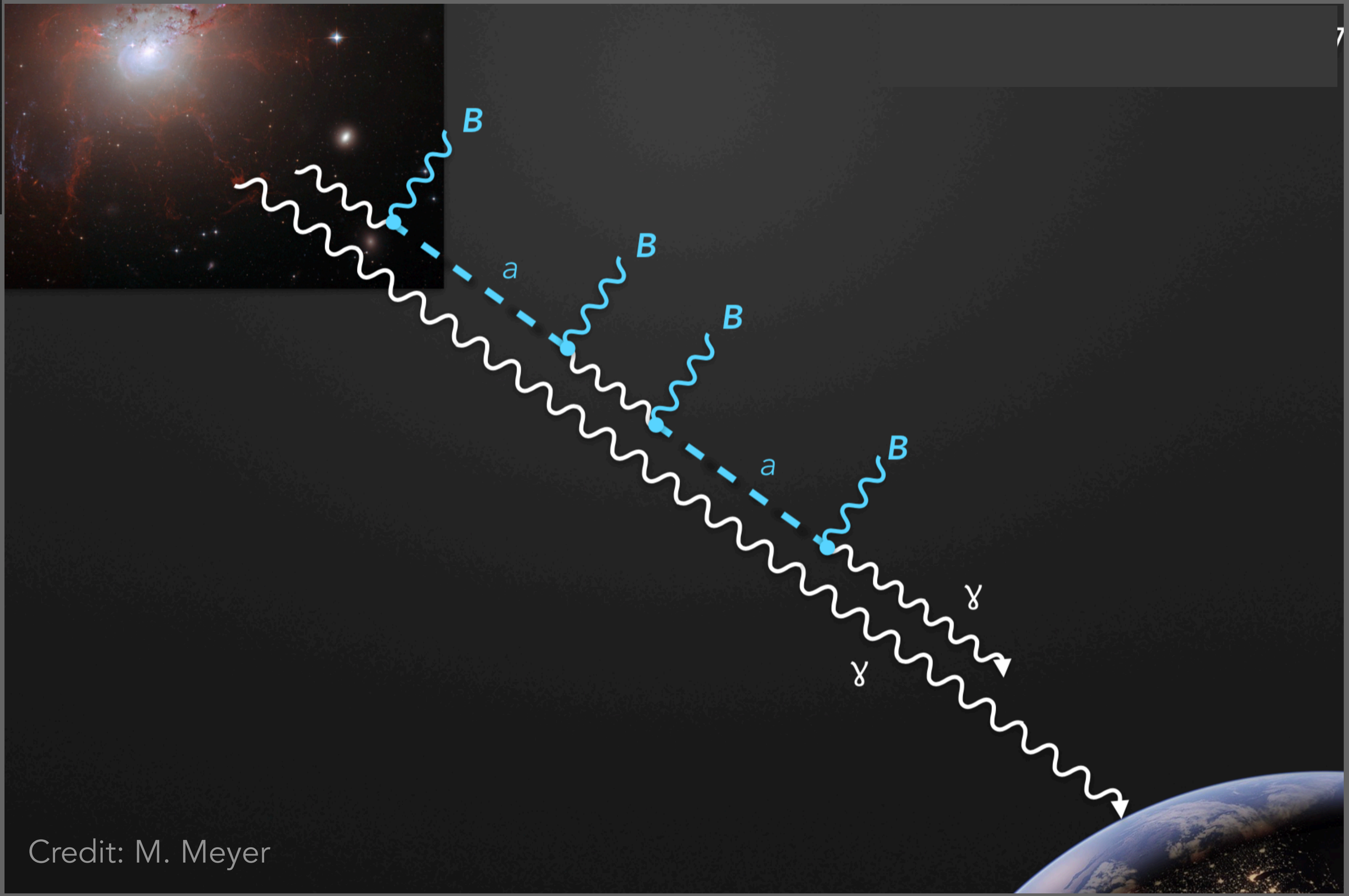


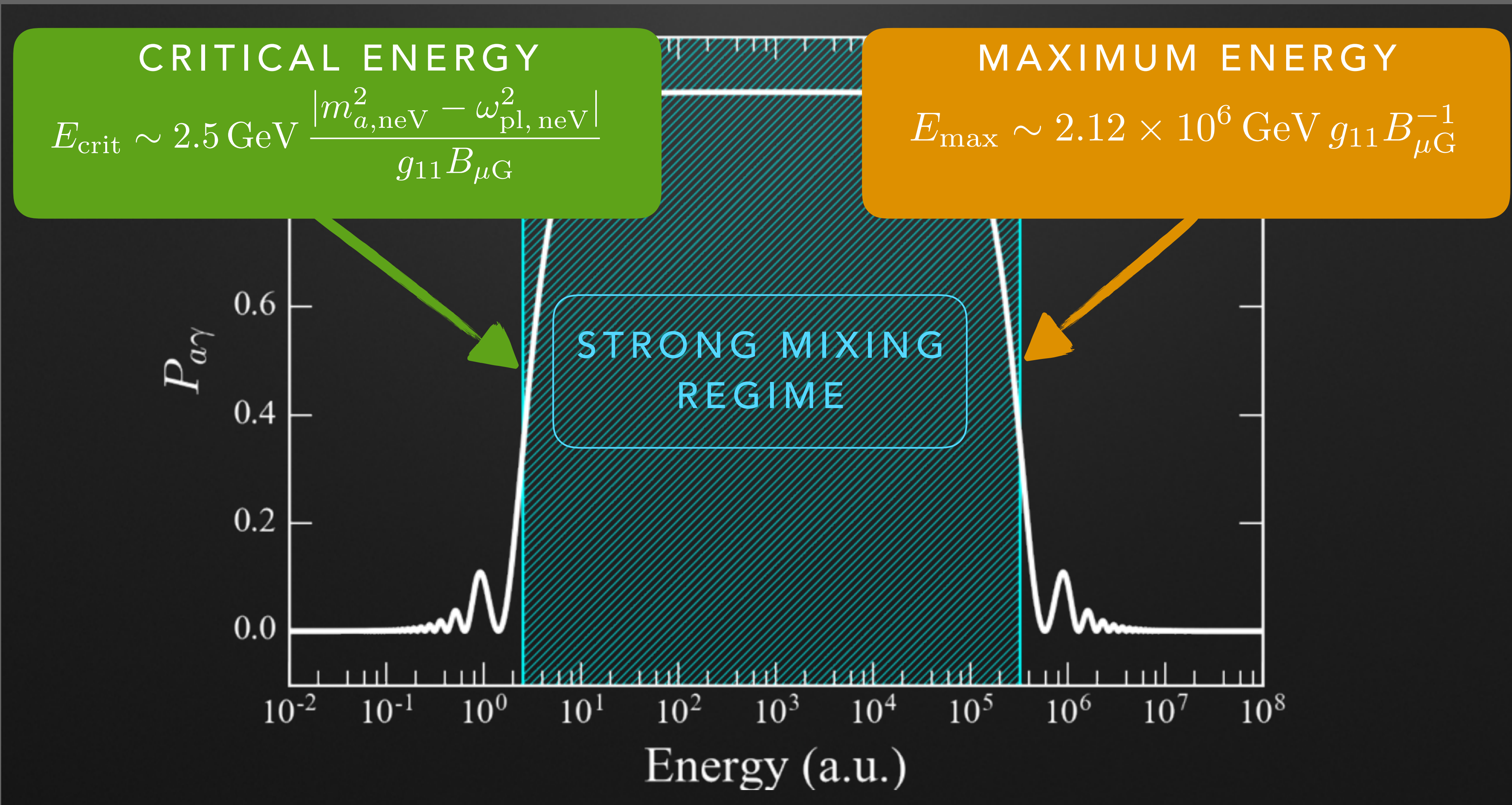
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E}\,\mathbf{B} a$$

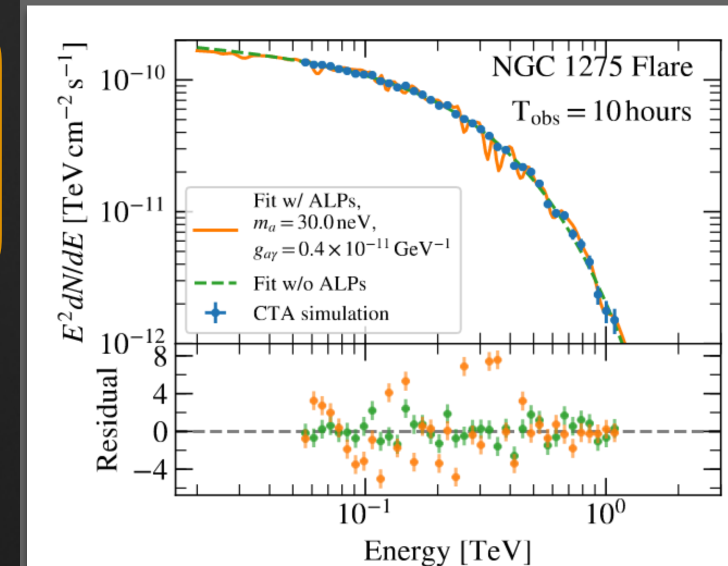
Where to look?

- **strong magnetic fields**
- **large distances**

→ e.g. **galaxy clusters**



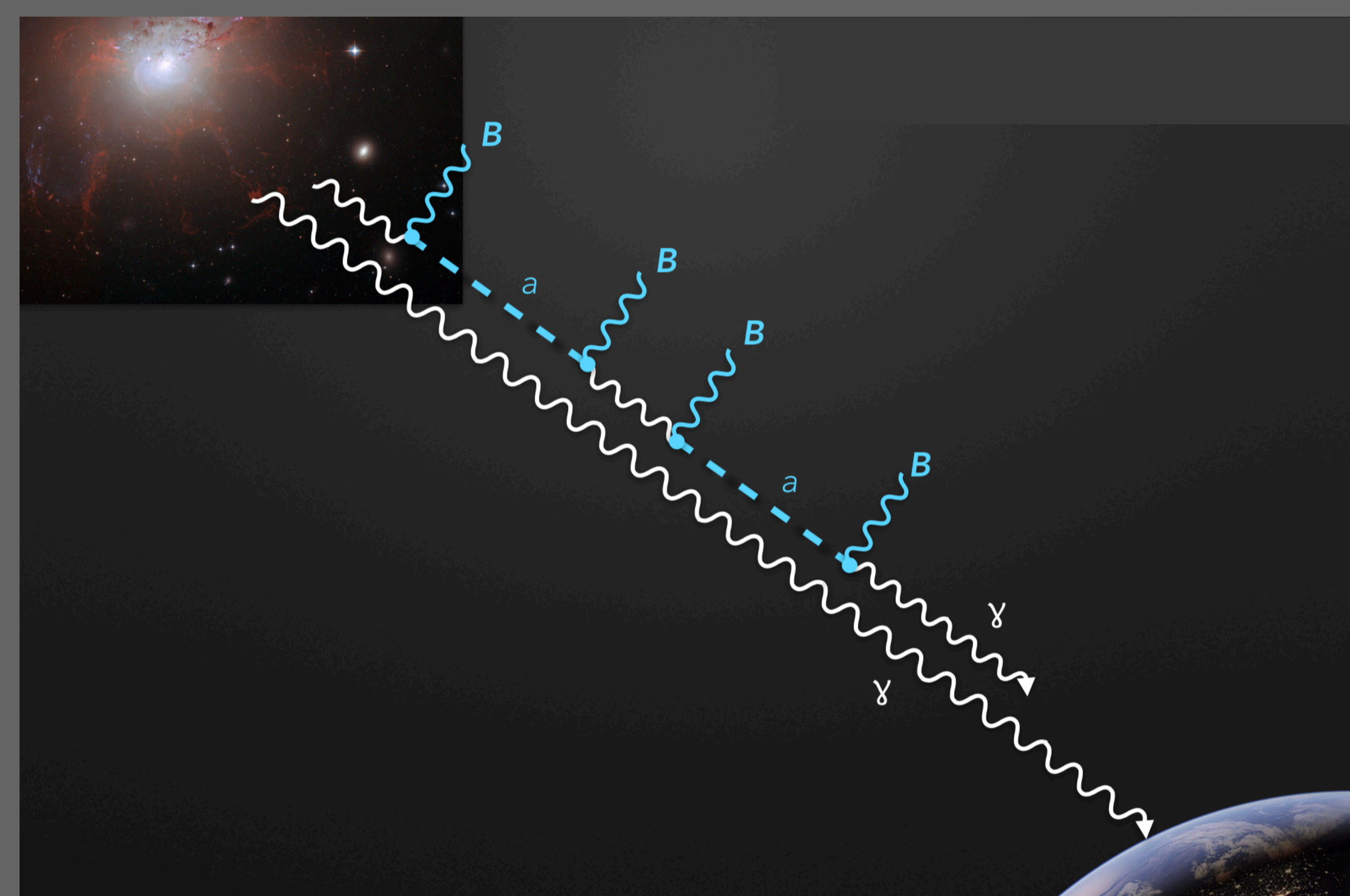




Strategy 1: examine the γ spectra of astro sources and use it to constrain the probability of ALP-γ conversion

— affects gamma ray '**opacity**'

— causes **spectral irregularities**

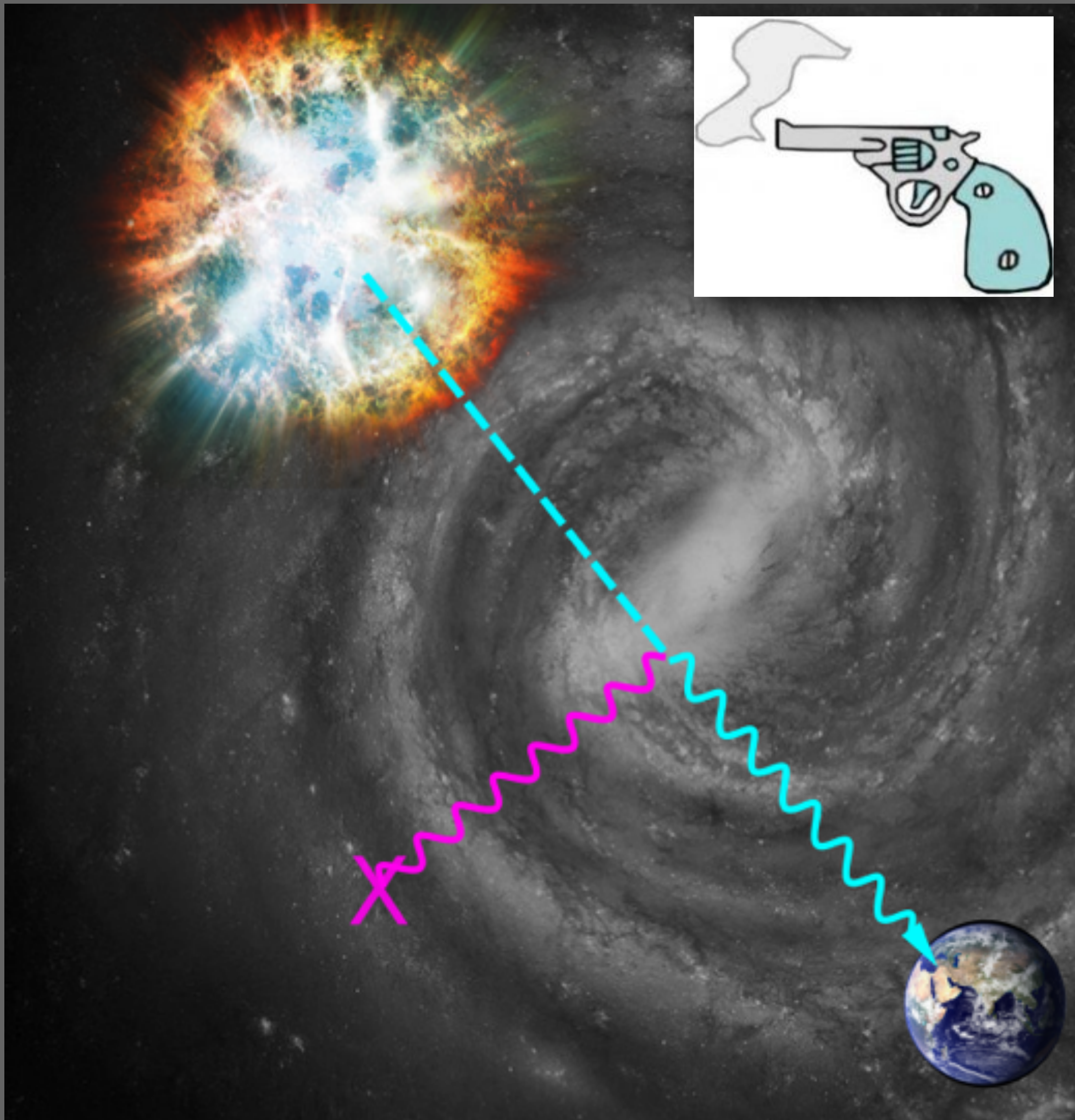


Credit: M. Meyer

What strategies (WIMPs & **ALPs**)?

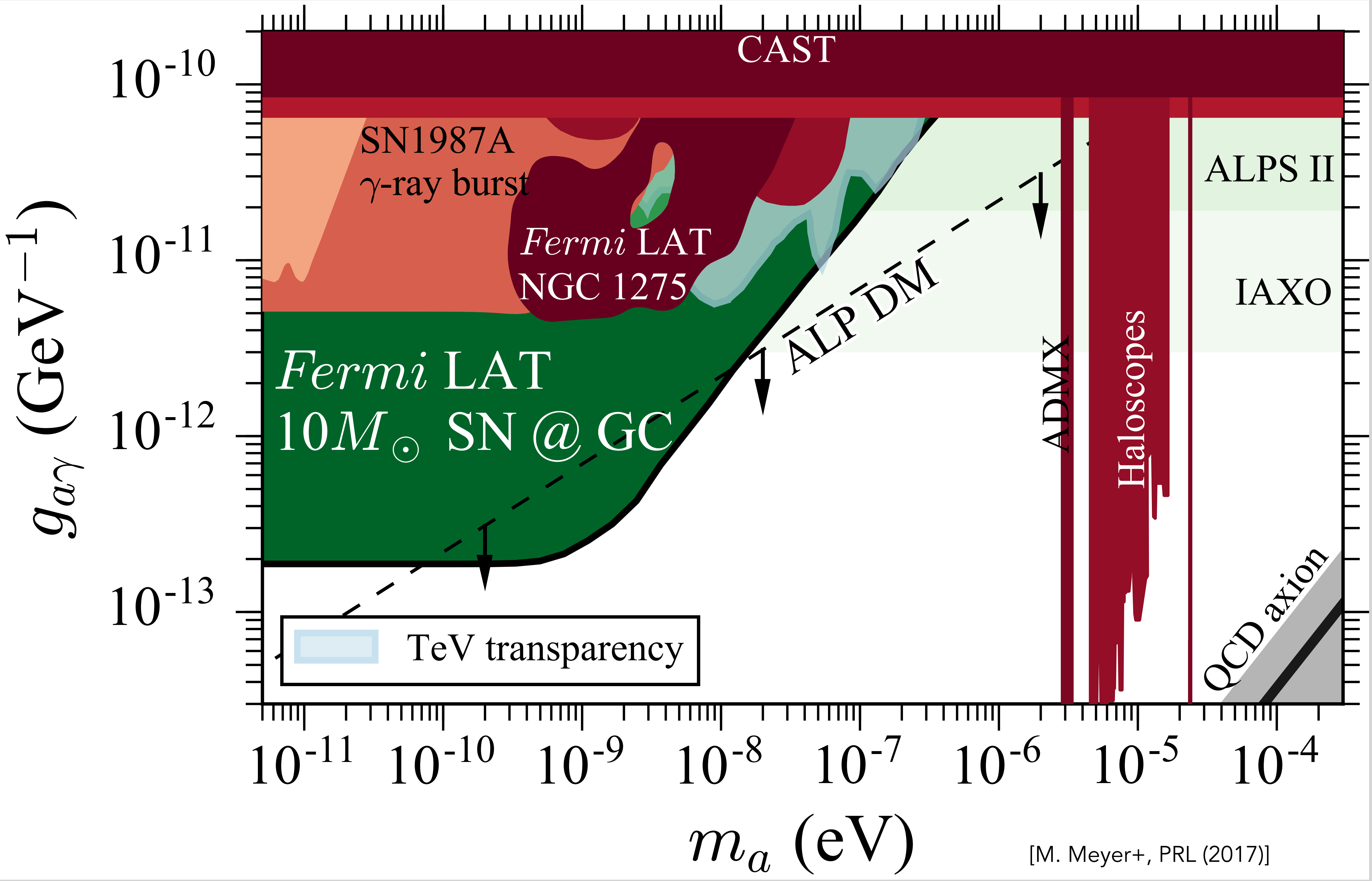
Strategy 2: ALPs would be produced in a core-collapse SN explosion via Primakoff process

Smoking gun! Gamma rays would arrive contemporary with neutrinos.

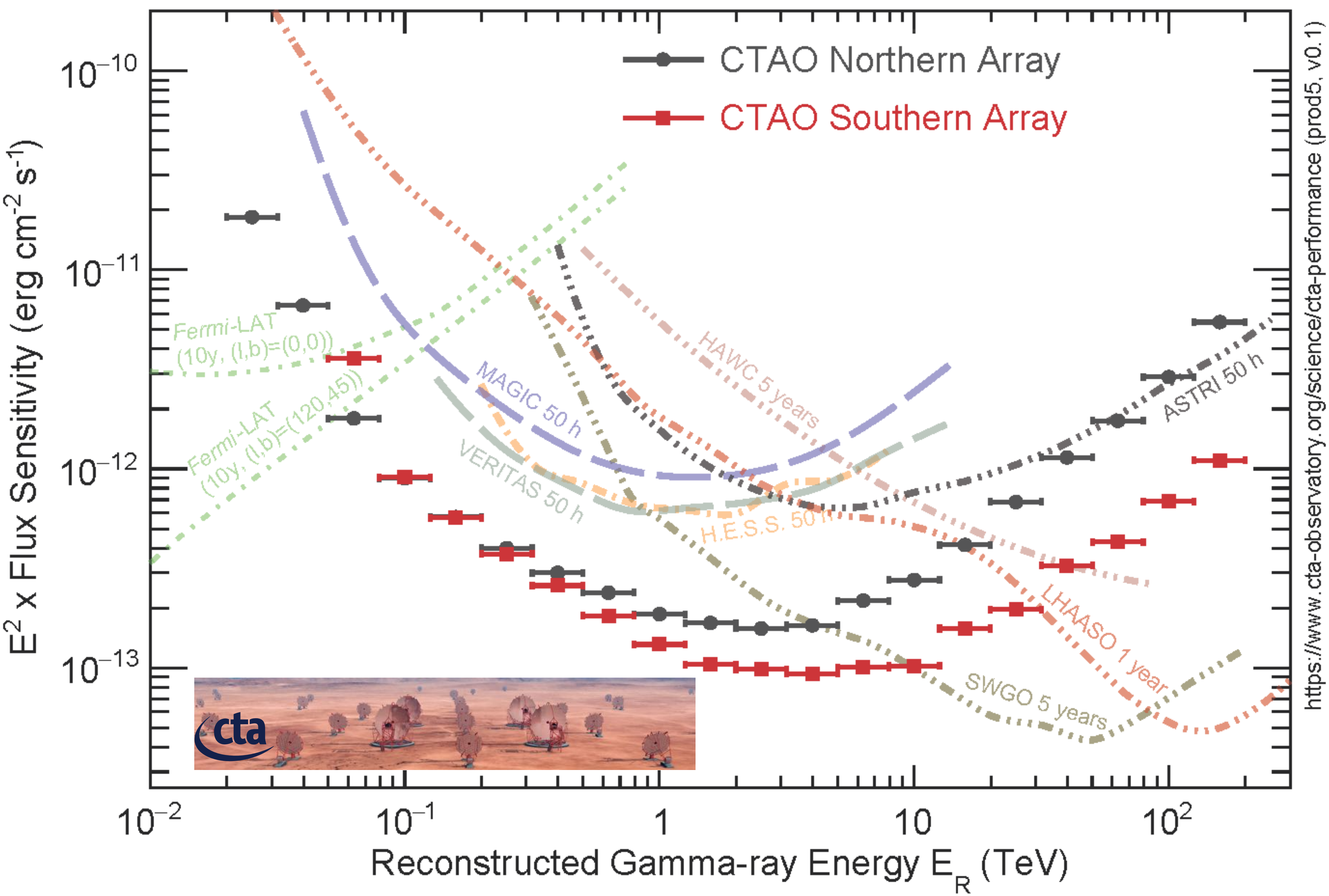


Credit: M. Meyer

State-of-the-art



Future?



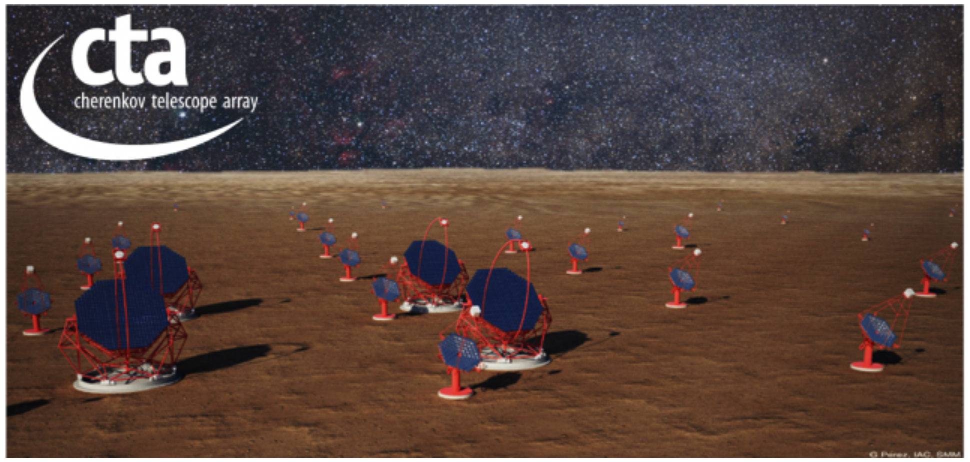
CTAO Northern Array
CTAO Southern Array
Fermi-LAT (10y, (l,b)=(0,0))
Fermi-LAT (10y, (l,b)=(120,45))
MAGIC 50 h
VERITAS 50 h
H.E.S.S. 50 h
HAWC 5 years
LHAASO 1 year
SWGO 5 years
ASTRI 50 h
cta
E^2 x Flux Sensitivity (erg cm^{-2} s^{-1})
Reconstructed Gamma-ray Energy E$_R$ (TeV)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-2}
10^{-1}
1
10
10^2
https://www.cta-observatory.org/science/cta-performance (prod5, v0.1)

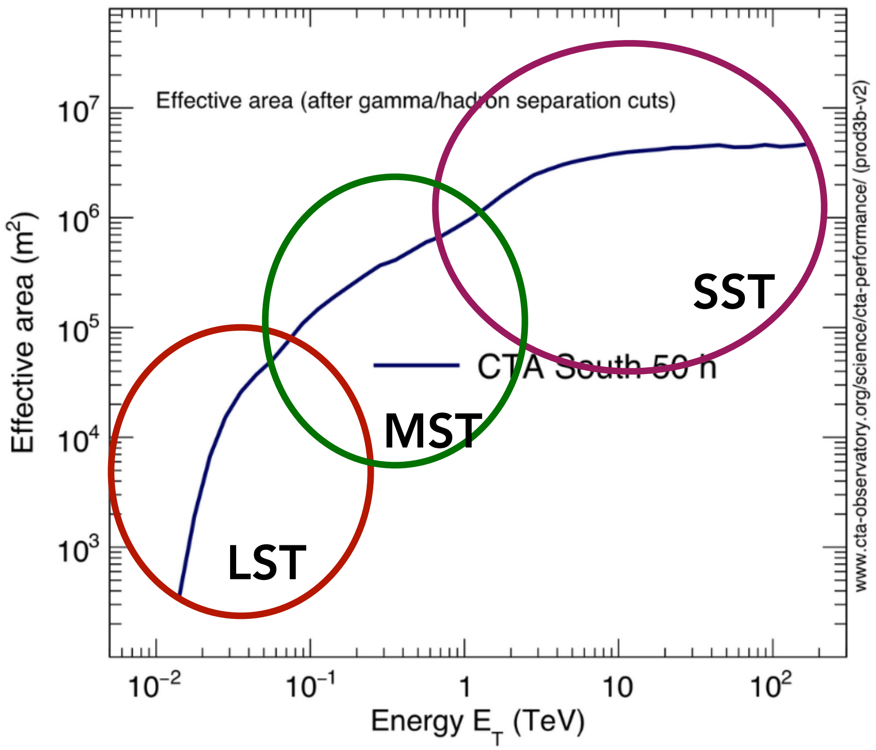
CTA

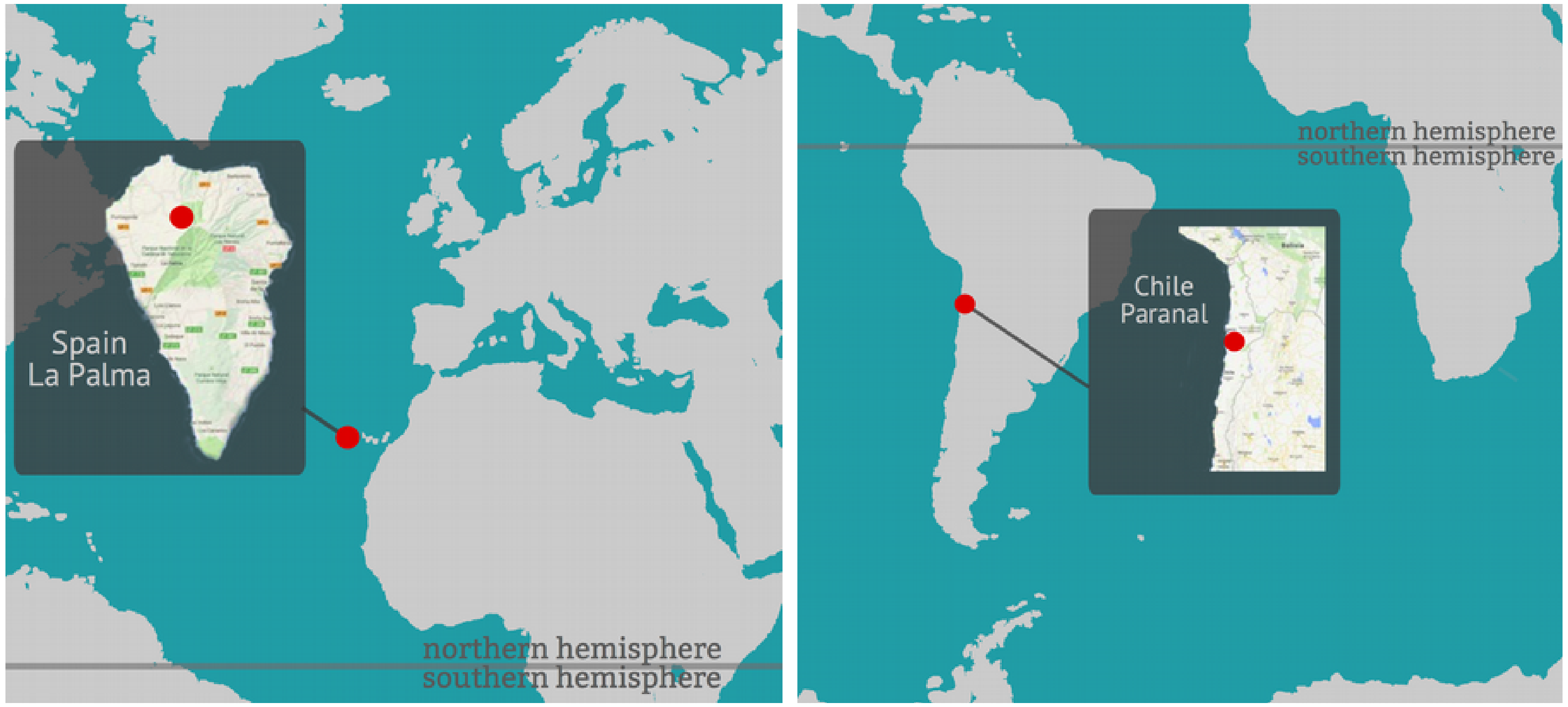
Wide energy coverage ~>20 GeV -200 TeV (three kinds of telescopes)

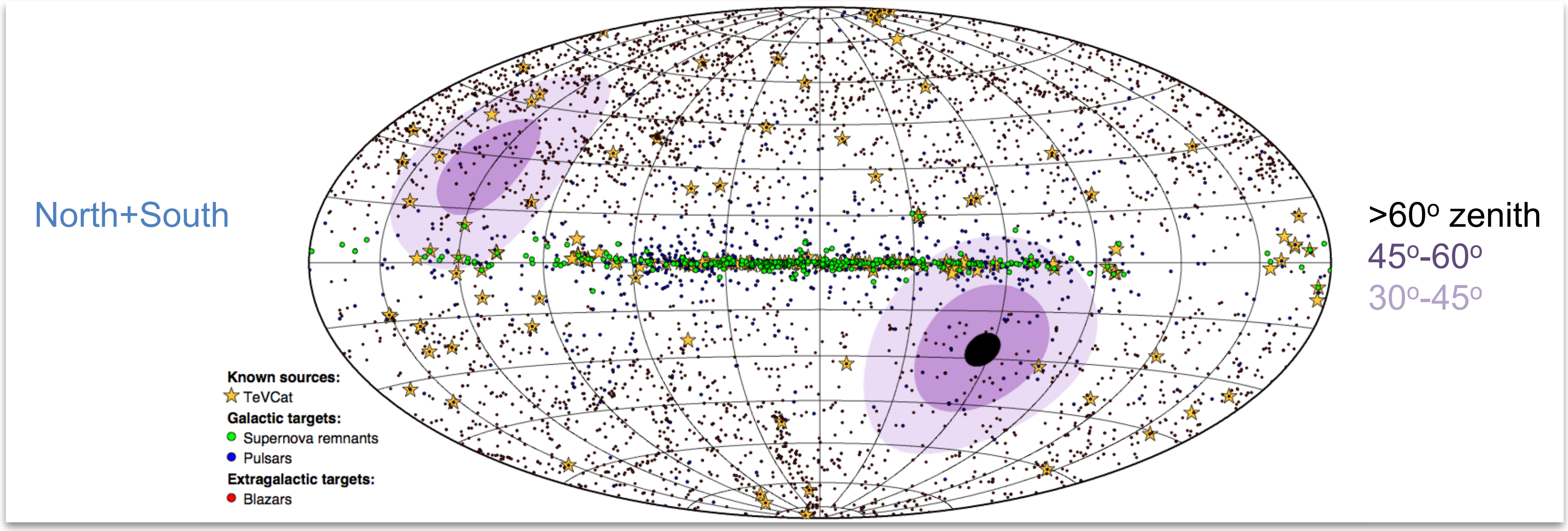
Full sky (two sites)

High sensitivity (>60 telescopes)









[www.cta-observatory.org]

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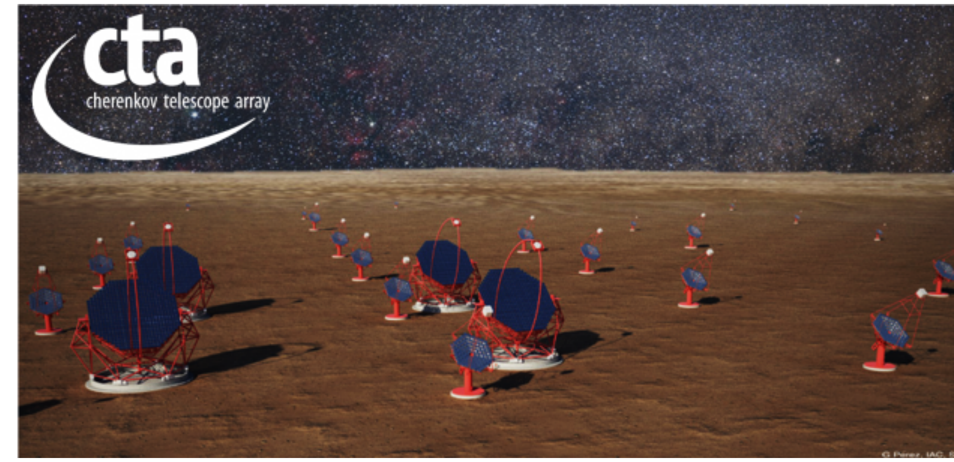
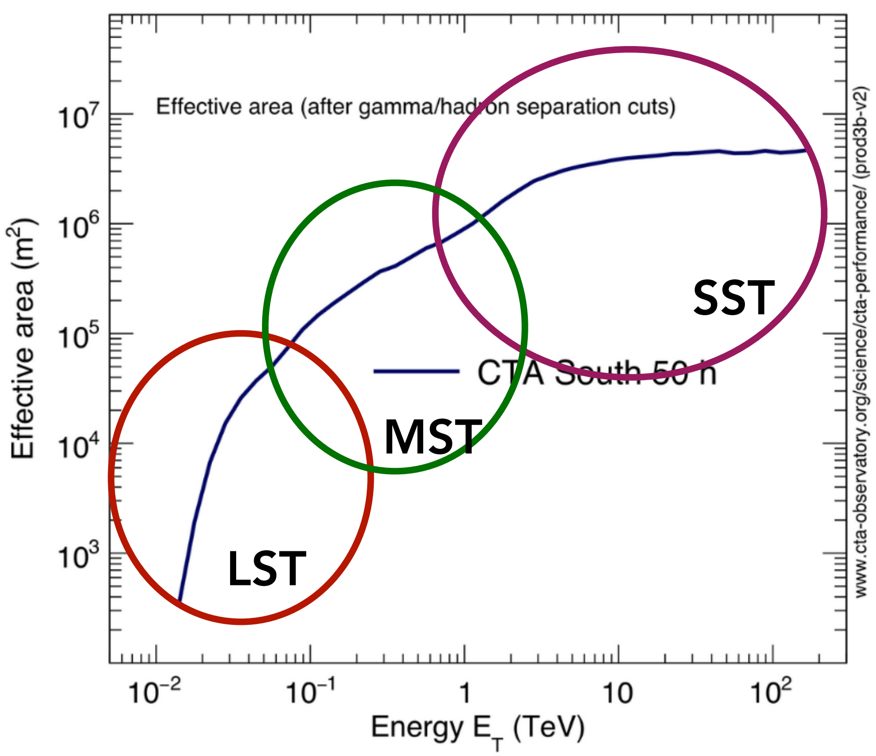
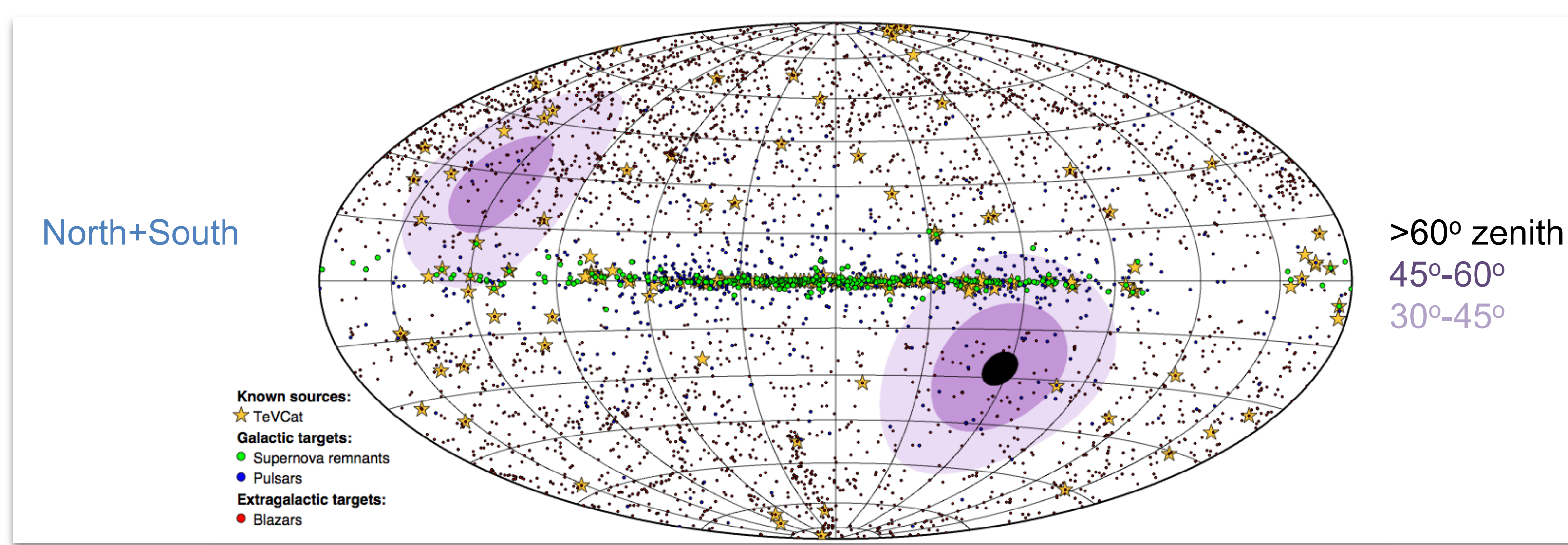




STATUS:

LST-1 installed in la Palma in 2018 (in commissioning phase)

Construction: the next 3-5 years.

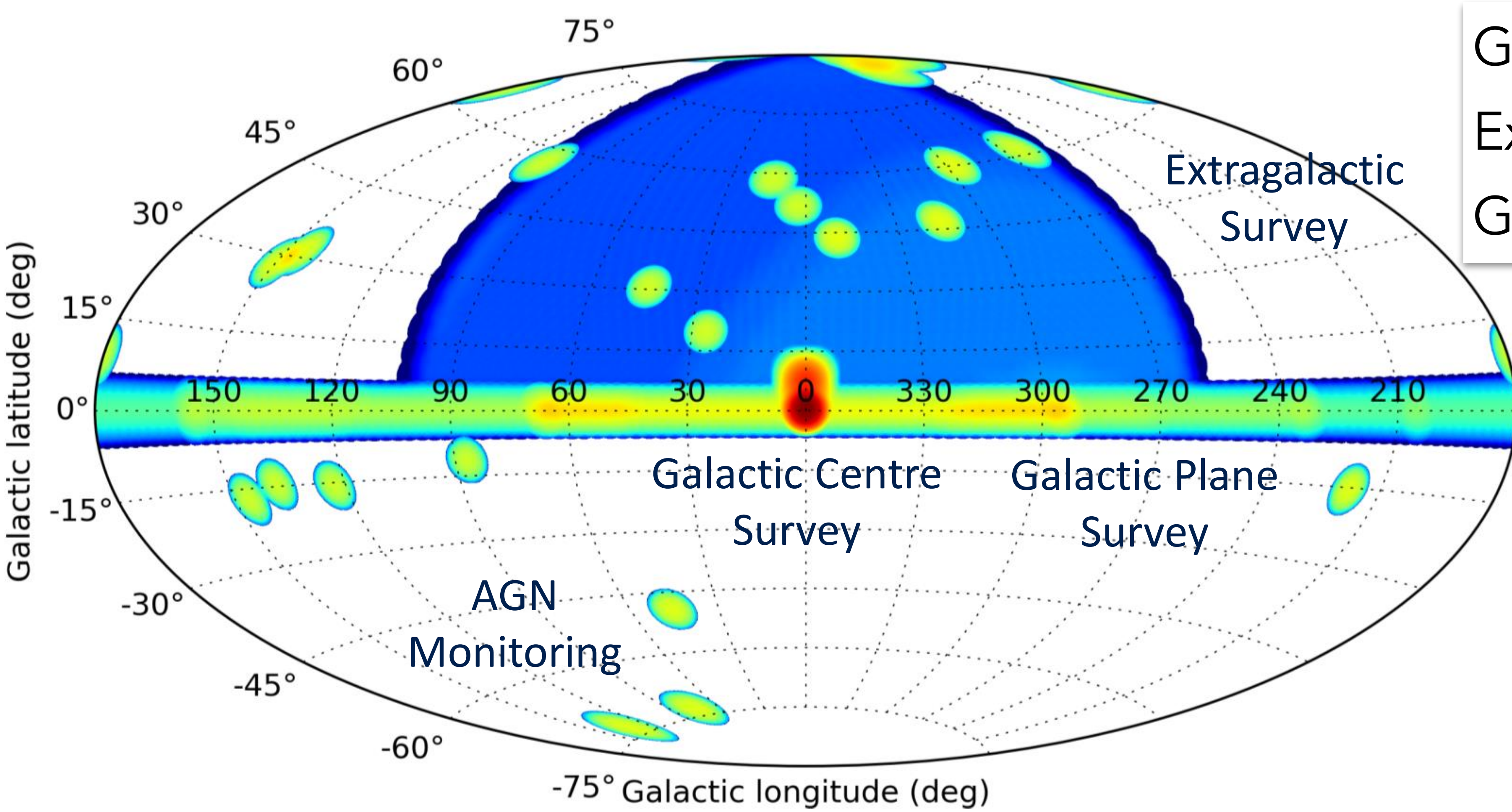


[www.cta-observatory.org]

CTA

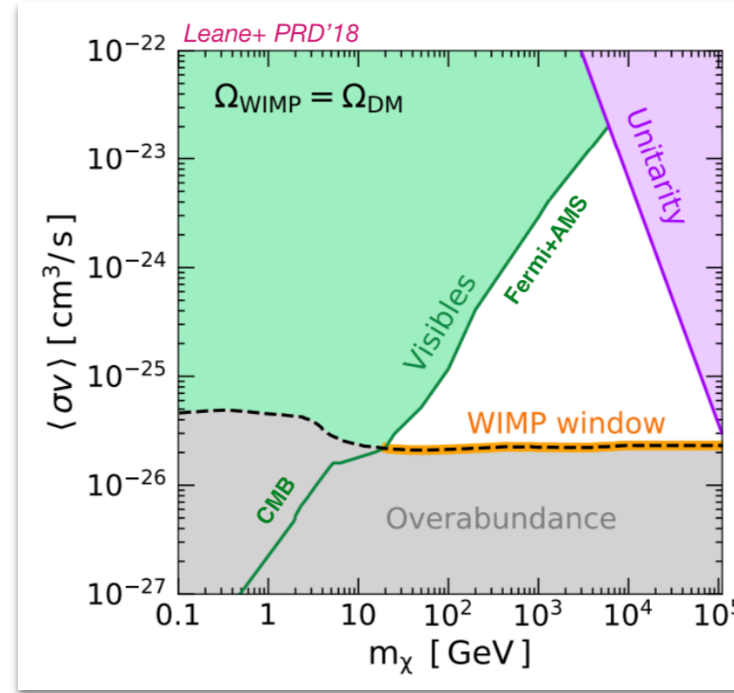
Dedicated observational strategy: **sky surveys**

- **Unbiased view** of the sky
- Bridging the differences with **satellite data**



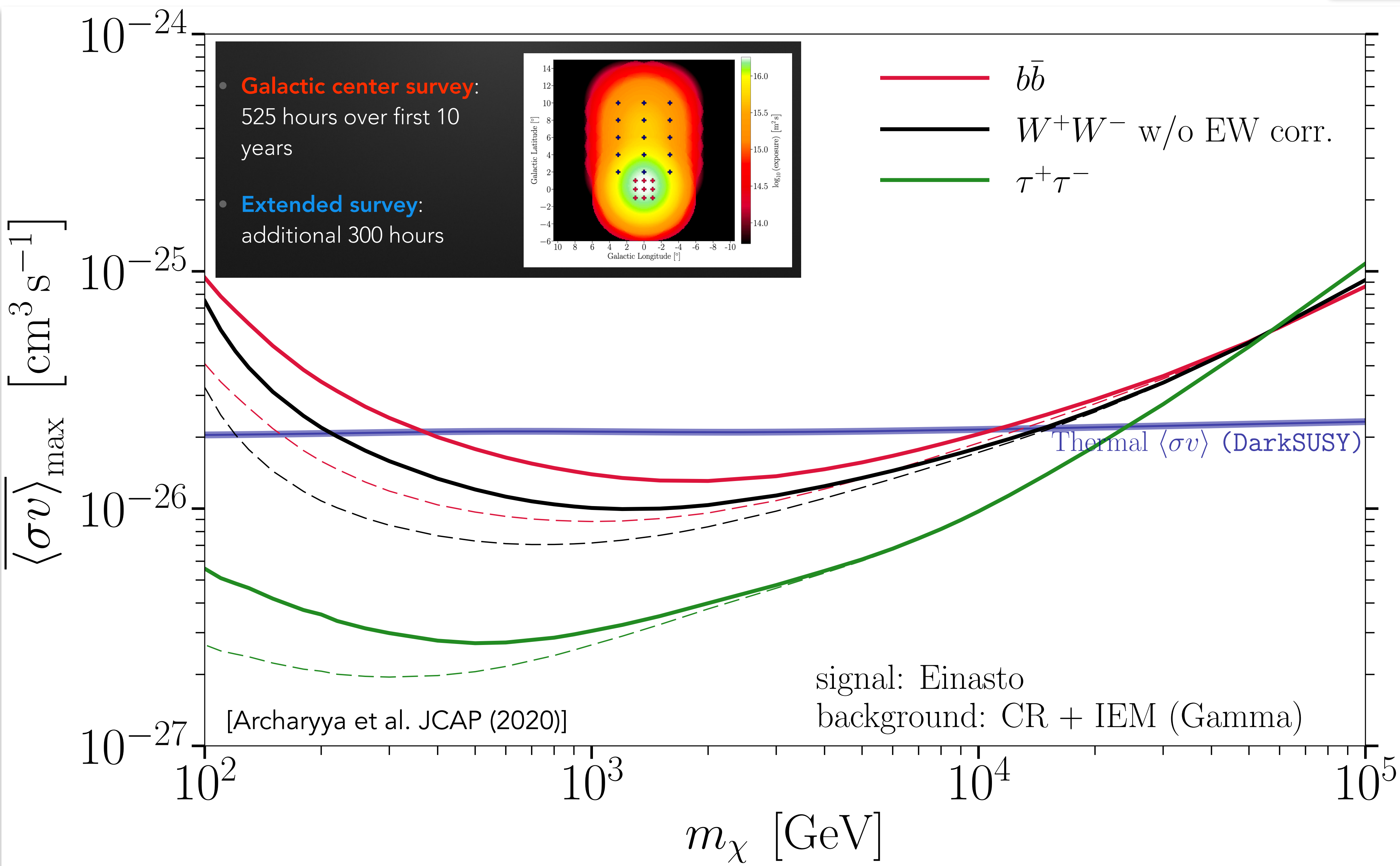
Galactic Plane survey
Extragalactic survey
Galactic center survey

CTA: WIMPs@ GC



DM sensitivity in a range of targets being explored

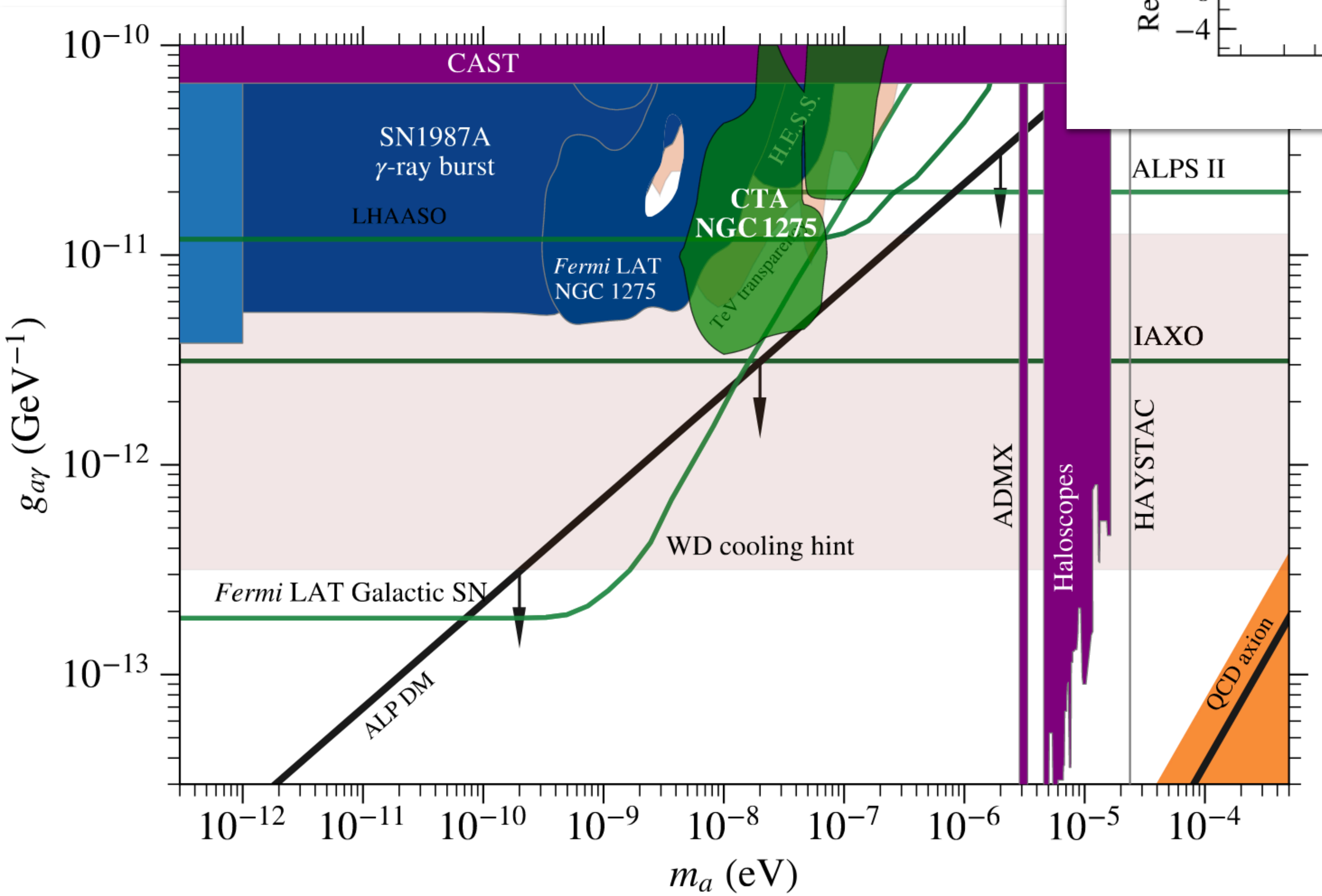
The observation of the GC has the potential to close the WIMP TeV window

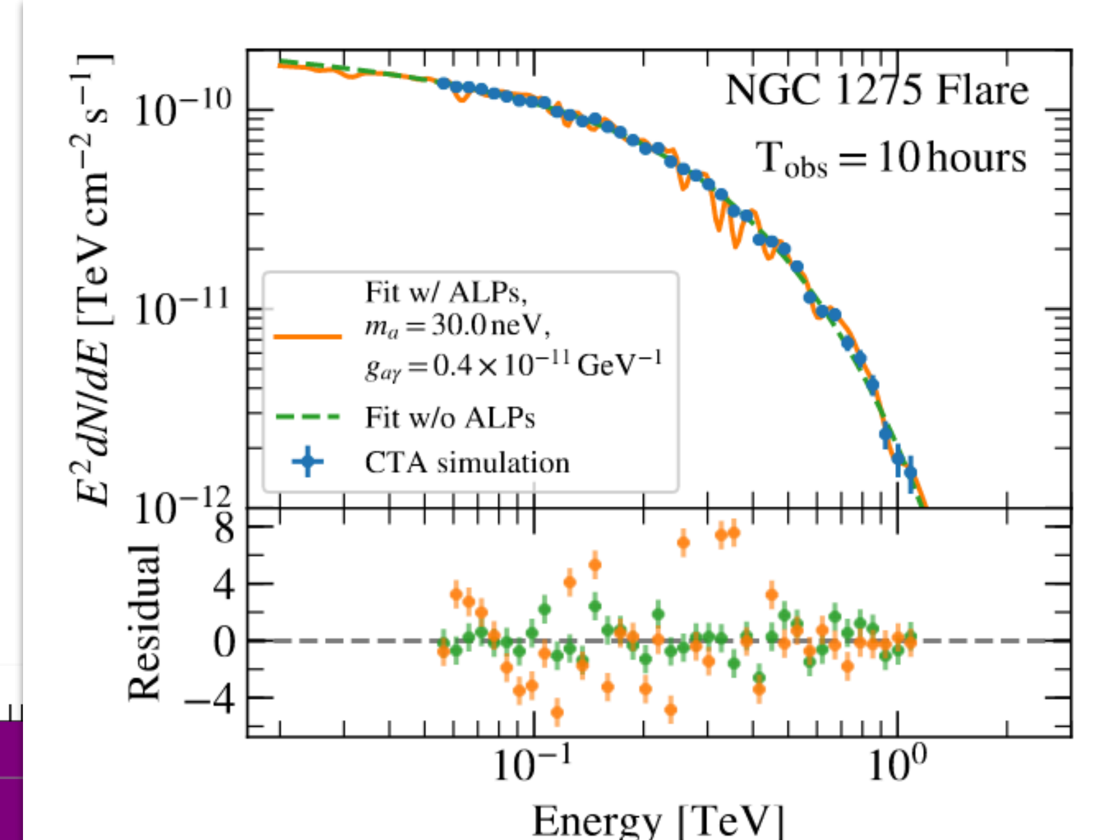


CTA
ALPs@ NGC1275

NGC 1275 is the central galaxy of the Perseus cluster, at a distance of ~ 75 Mpc.

Perseus cluster harbors a strong magnetic field, ~25 μG.



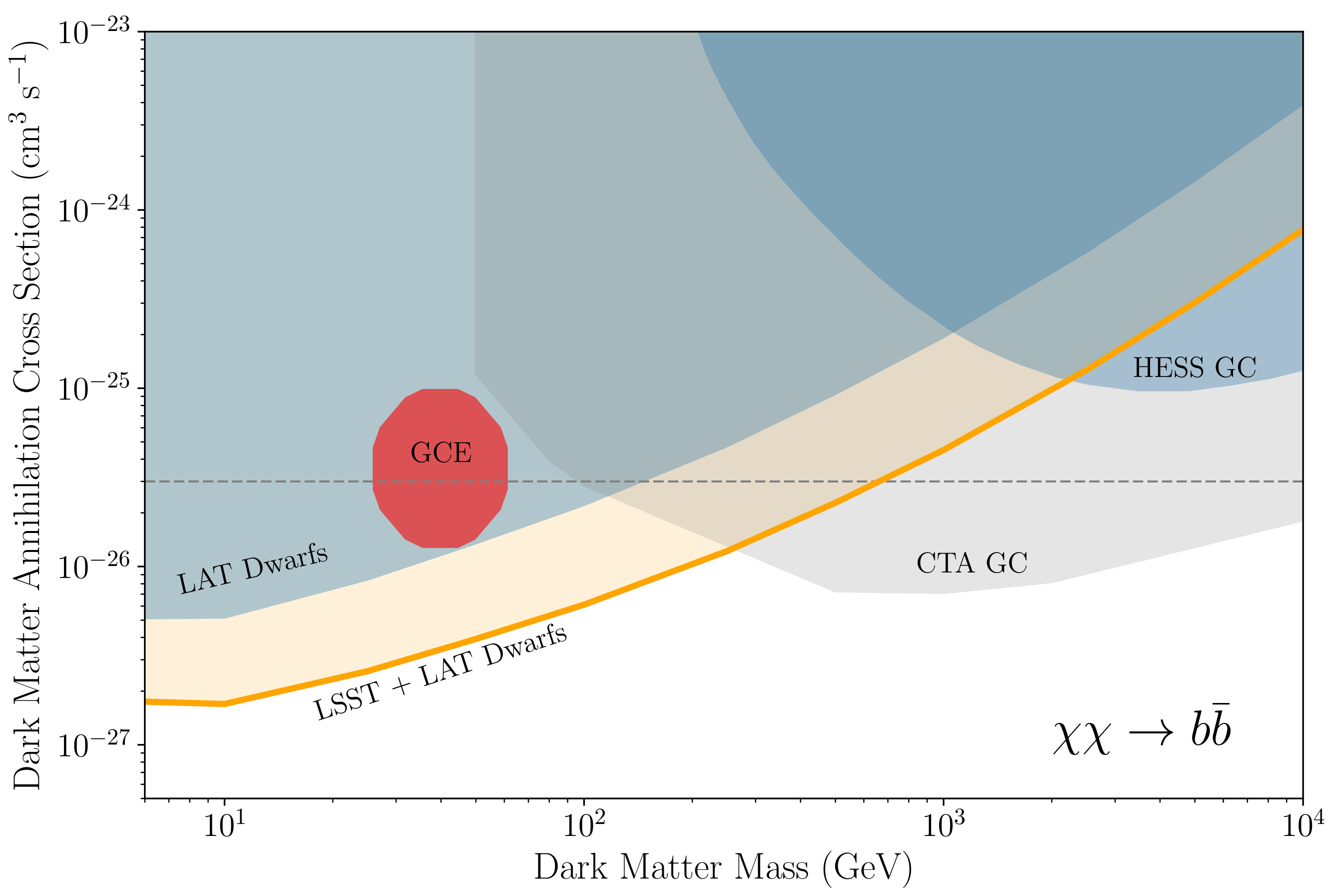


[Archaryya et al. JCAP 2021.]

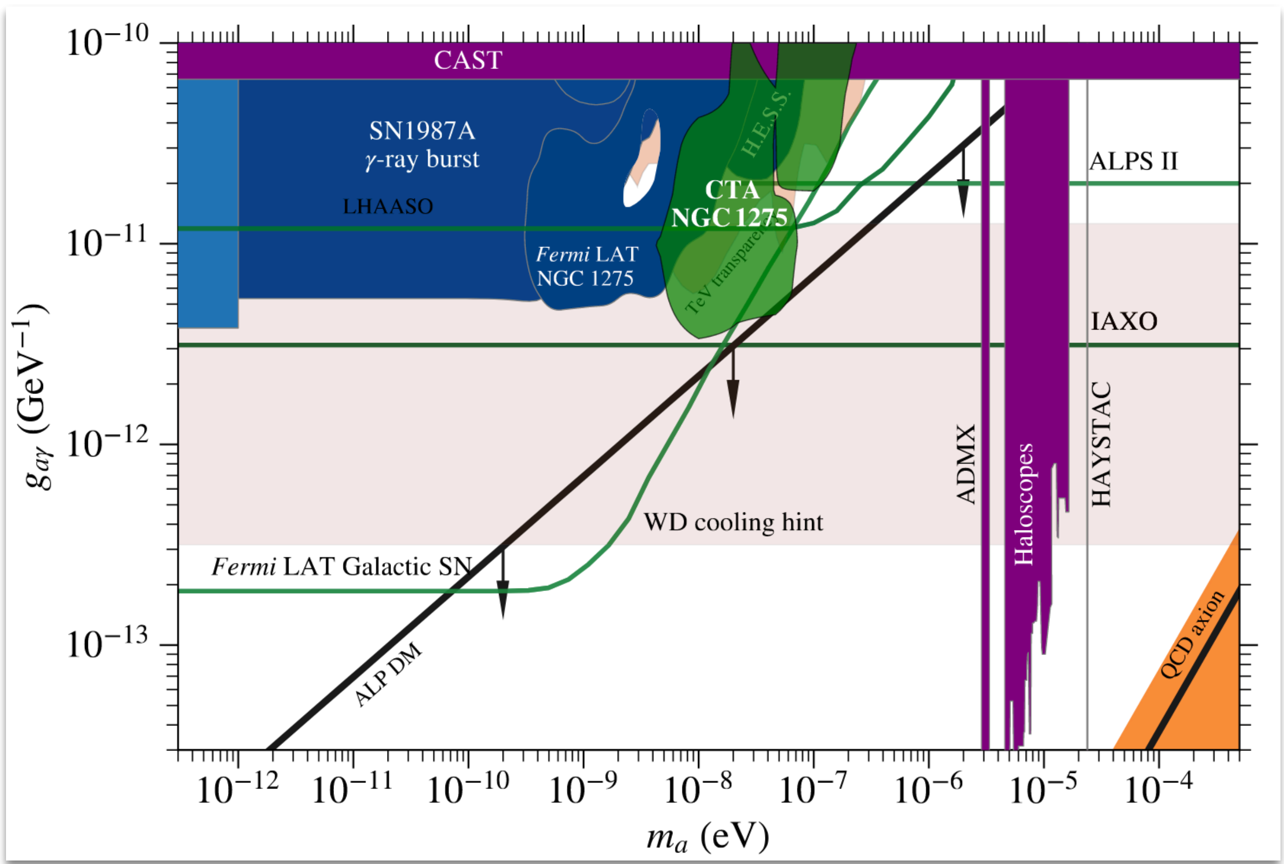
Gamma-ray DM search summary

The 'vanilla' WIMP parameter space already largely constrained and the remaining TeV window will be probed by the CTA

Fermi LAT and CTA data (will be) able to constrain chunks of the ALP DM parameter space



[Drlica-Wagner+, 2019]



[Archaryya et al. JCAP 2021]

DM search with charged MRs

DM limits:

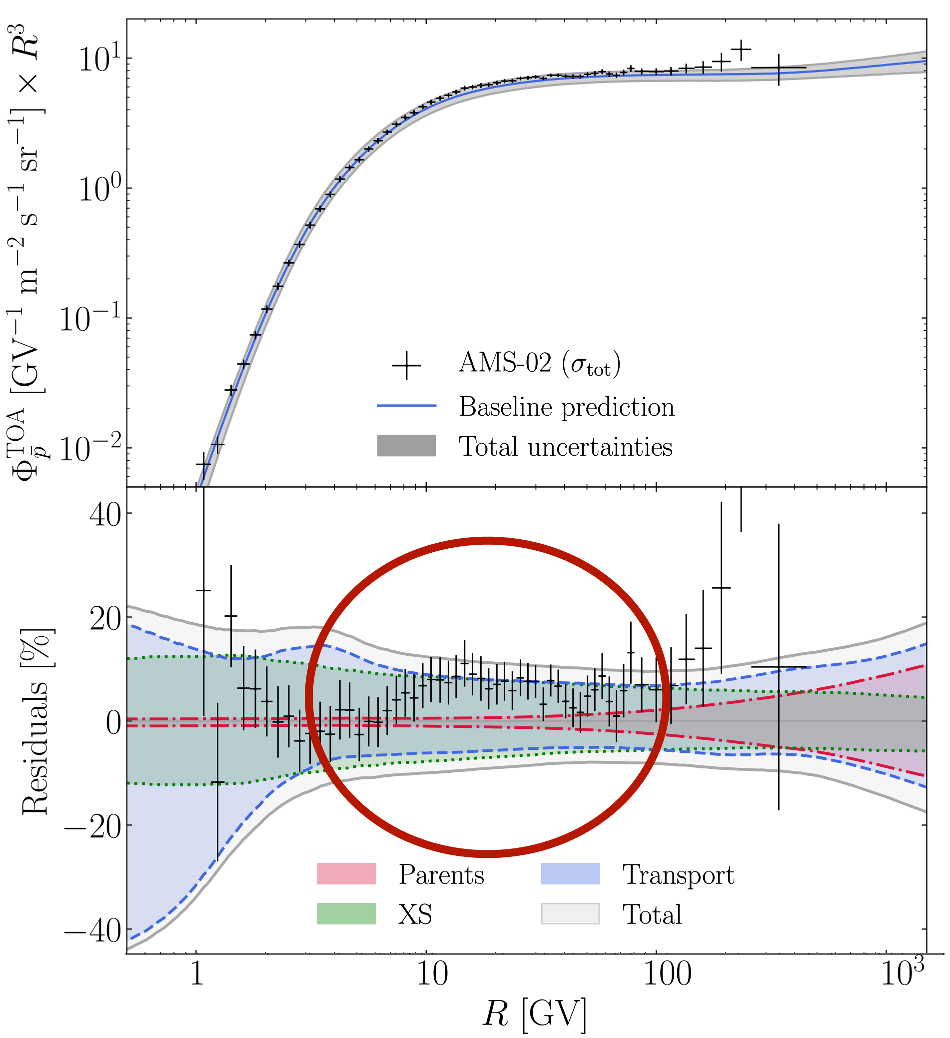
Antiprotons - one of the most sensitive probes of new physics

— p spectra measured exquisitely well

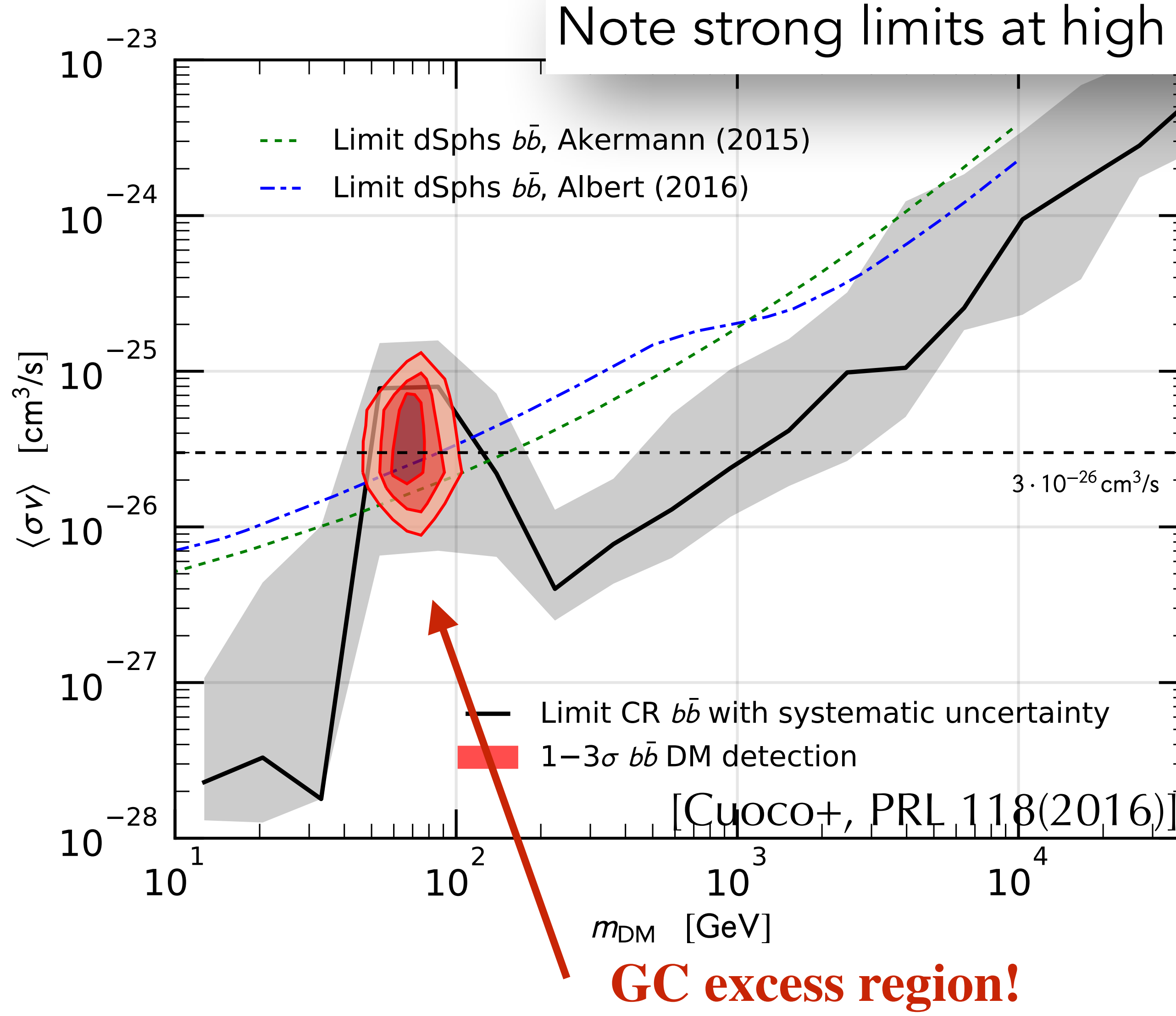
— anti-p produced as secondaries, with the proton spectra as the source term

Simultaneous fit to p and He spectra (constrain propagation parameters) + DM component

Boudaud+[1906.07119]



Note strong limits at high masses

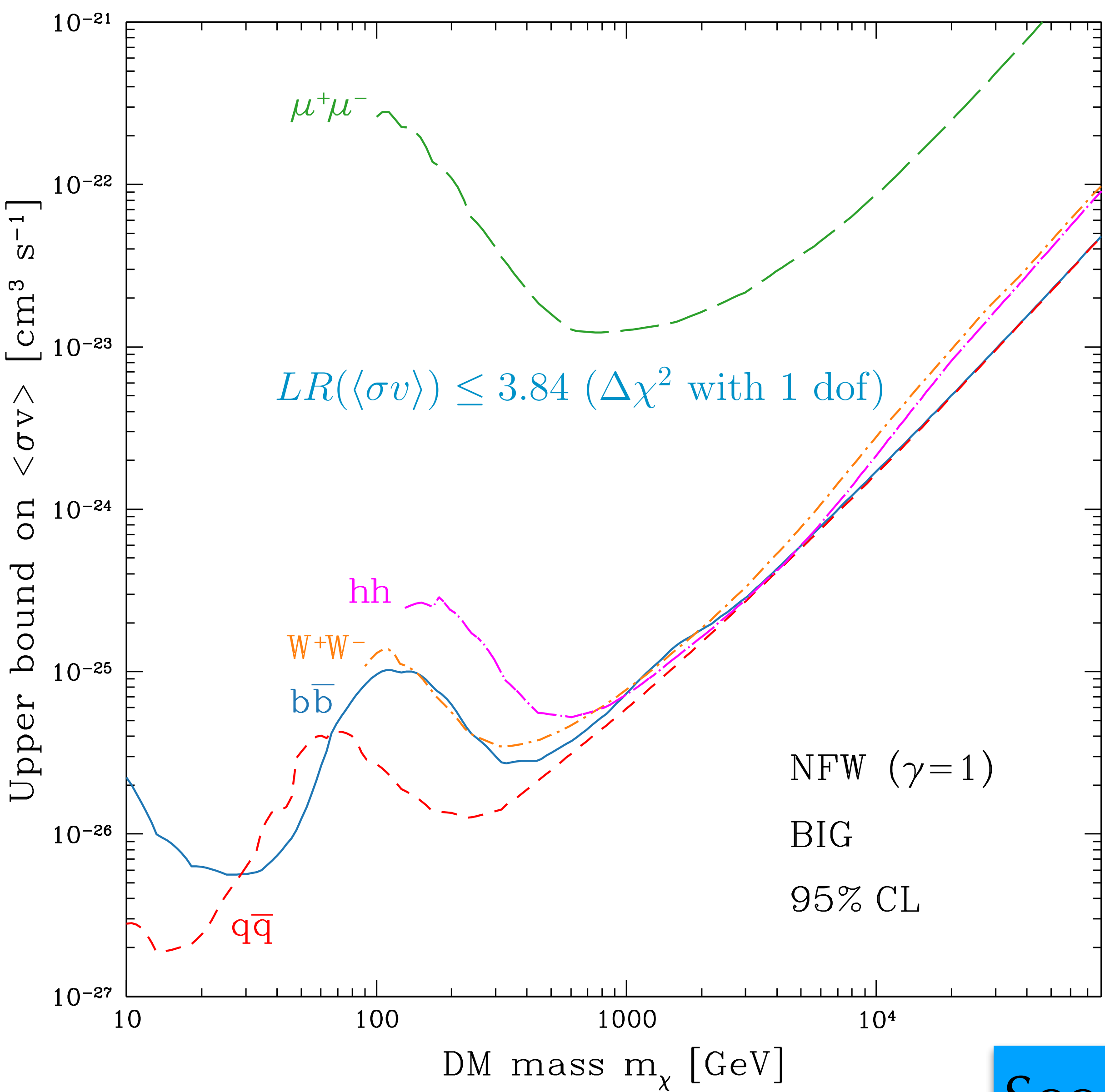


However, uncertainty in solar modulation, pp x-section, …

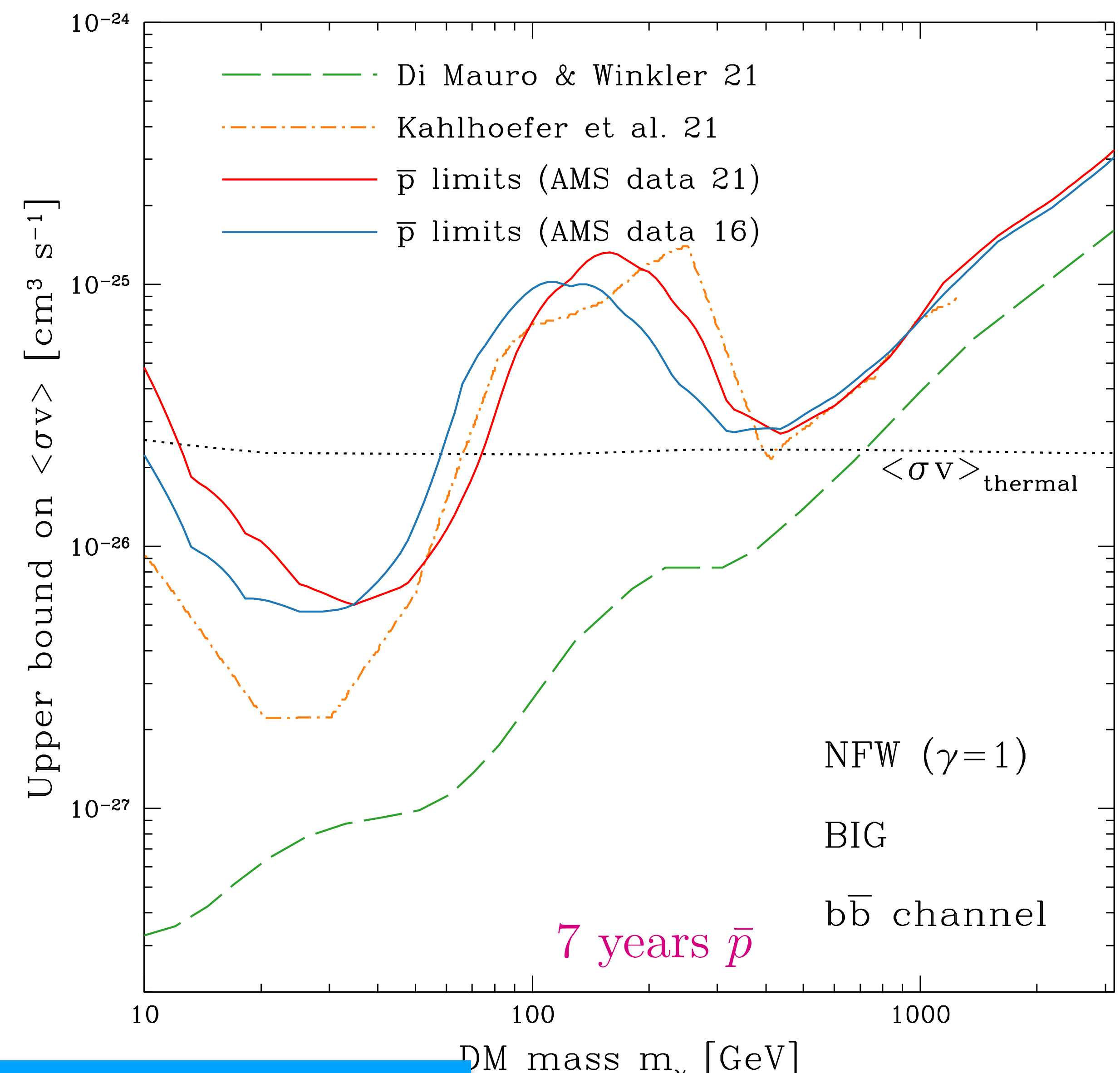
Charged cosmic rays - the precision era

DM limits: Antiprotons

New results that take systematics uncertainties (via covariance matrices) into account



Calore+[2202.03076]

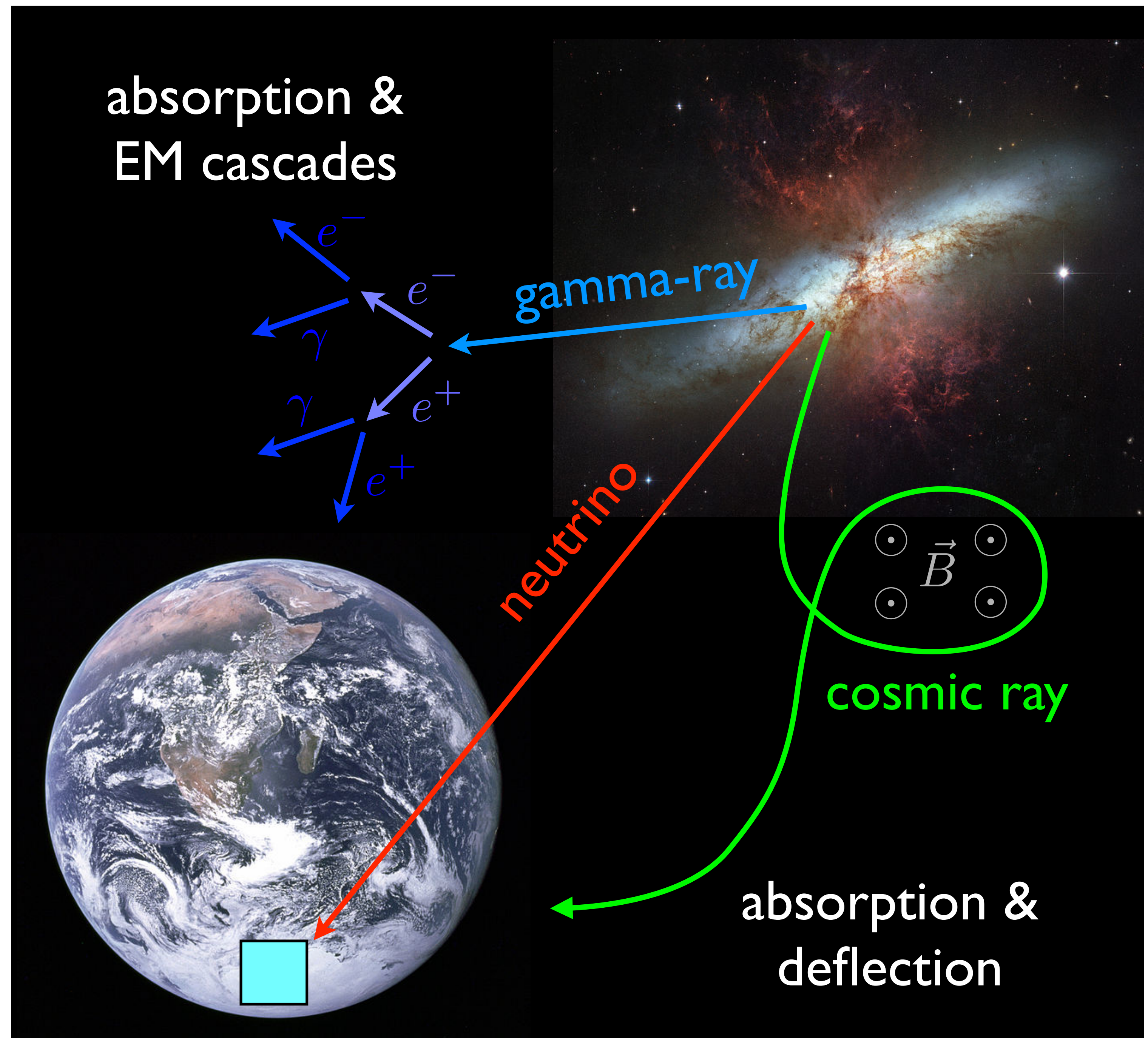


See M. DiMauro's talk

DM search with neutrinos

In the PeV range it is natural to expect a neutrino-first detection! (-> decaying DM!)

Gamma horizon at PeV is only up to Galactic Center distance…



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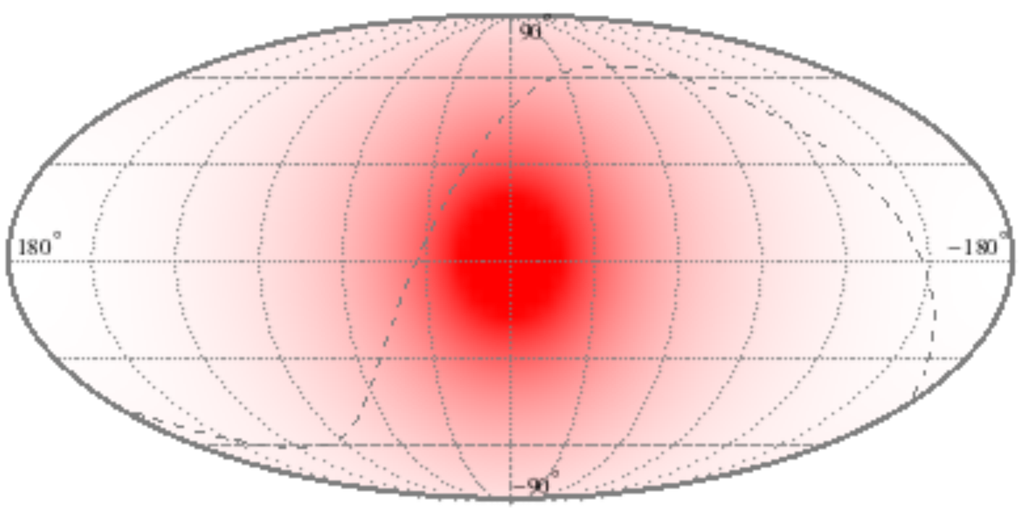
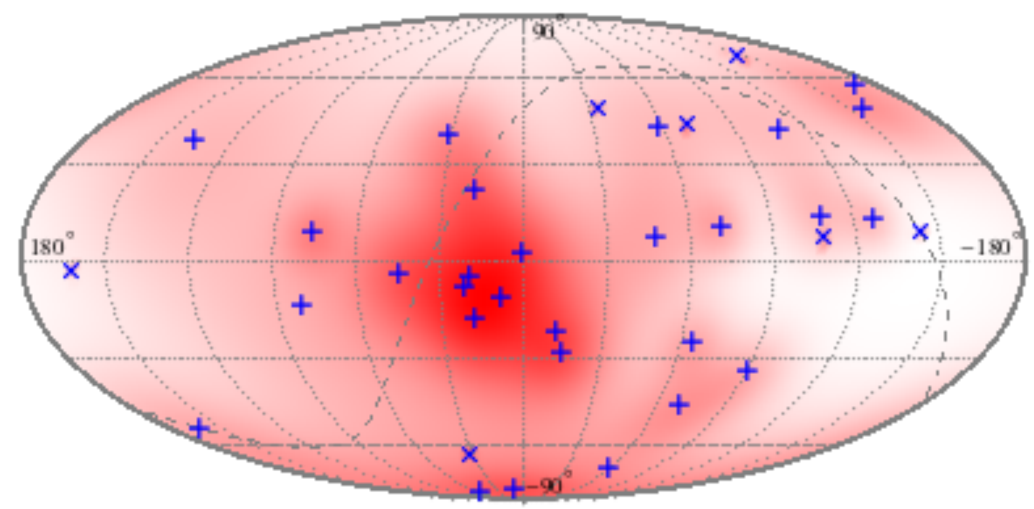




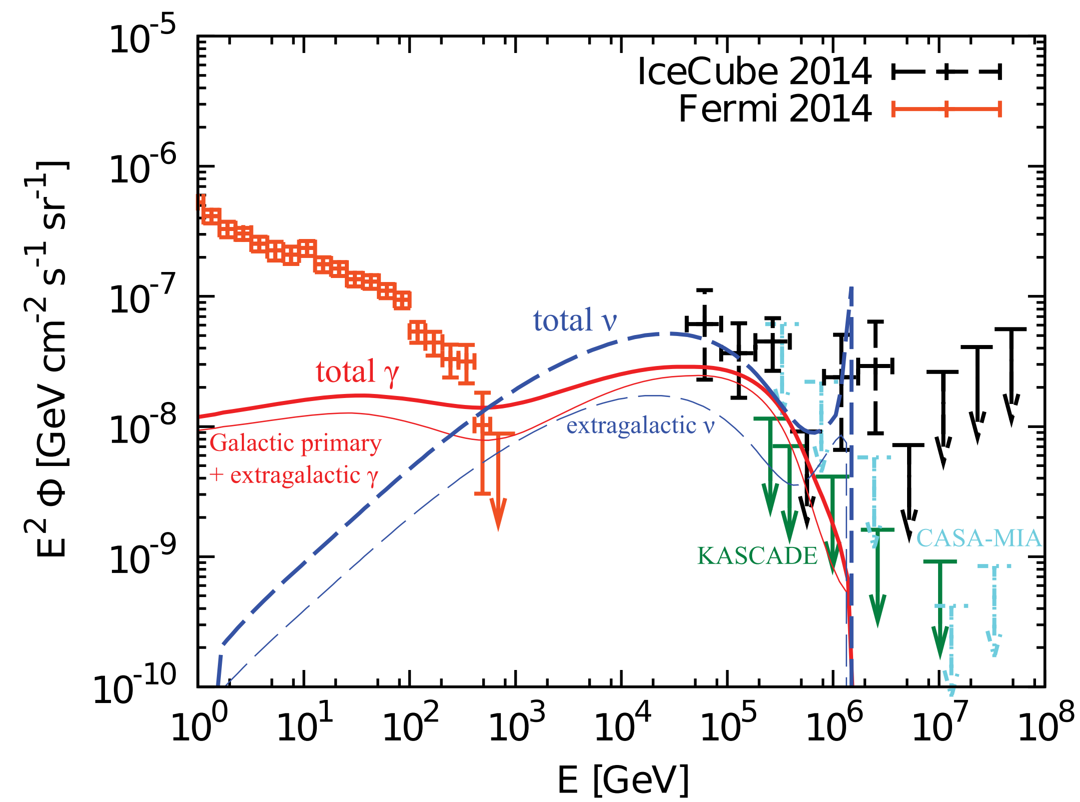
Decaying DM signal (Gal+ExtraGal)

2 PeV DM could provide a good fit!

Murase+ JCAP 1210 (2012)
Esmaili,+ JCAP(2012)
Rott+, PRD92, (2015), …

However, neutrino flux can be described well with a combination of DM and a diffuse astrophysical flux with a power-law energy spectrum, and DM alone is disfavoured **[IceCube, 1804.03848]**

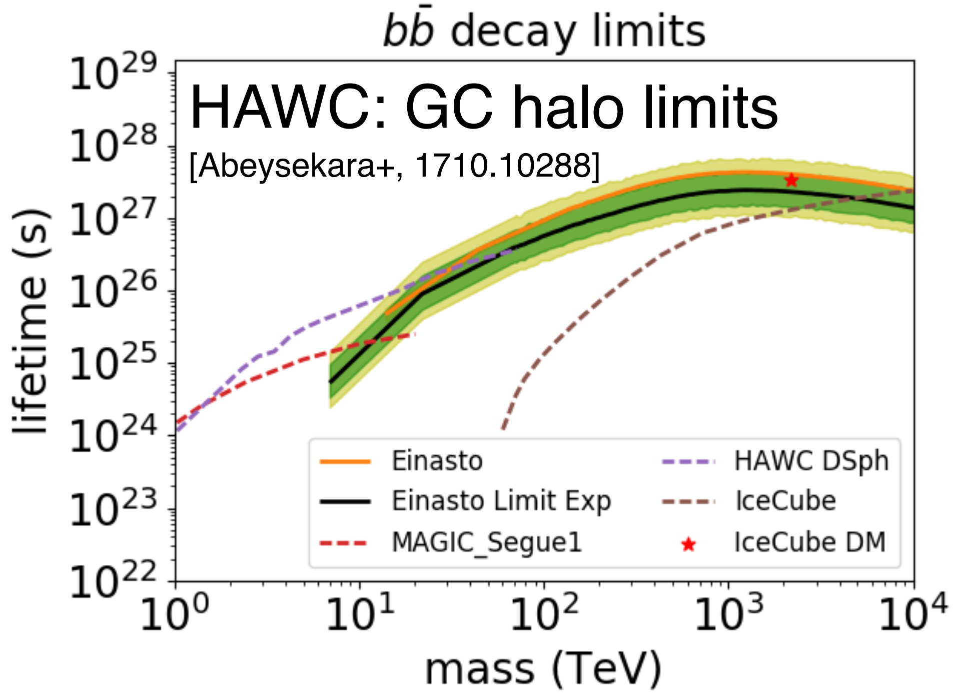
PeV Dark Matter Decay (*e.g.* DM$\to \nu\bar{\nu}/q\bar{q}$)



[*e.g.* Murase, Laha, Ando & MA'15]

DM search with neutrinos

Multi messenger tests!



=> Limits!

Decaying DM limits limits over 6 decades in mass

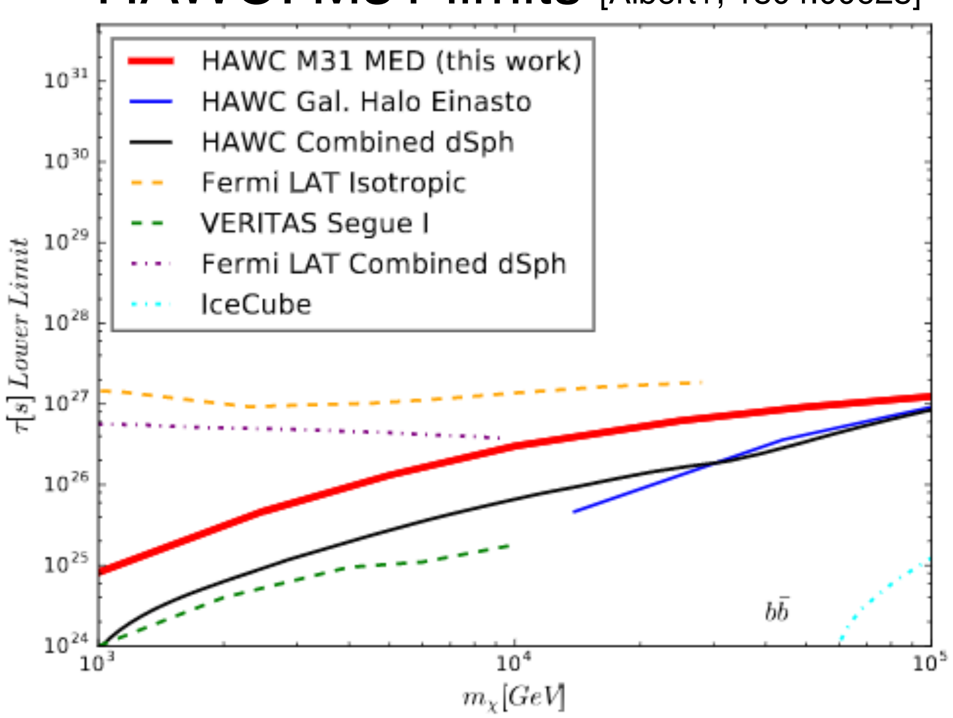
high mass targets most constraining (rather then very dense regions)

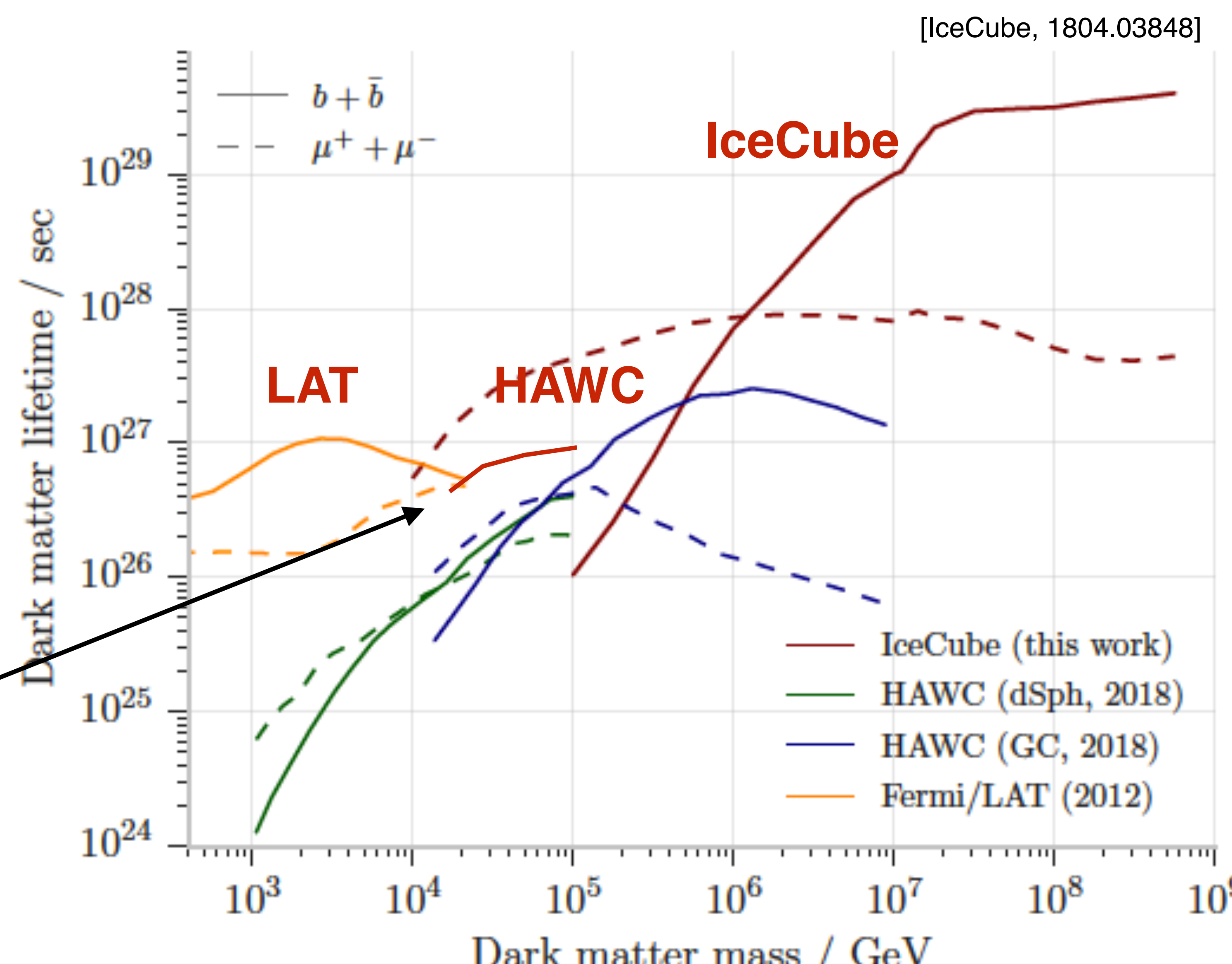
LAT - isotropic - whole sky emission

HAWC: GC halo and Andromeda (huge and close by)

IceCube - whole sky events

HAWC: M31 limits [Albert+, 1804.00628]

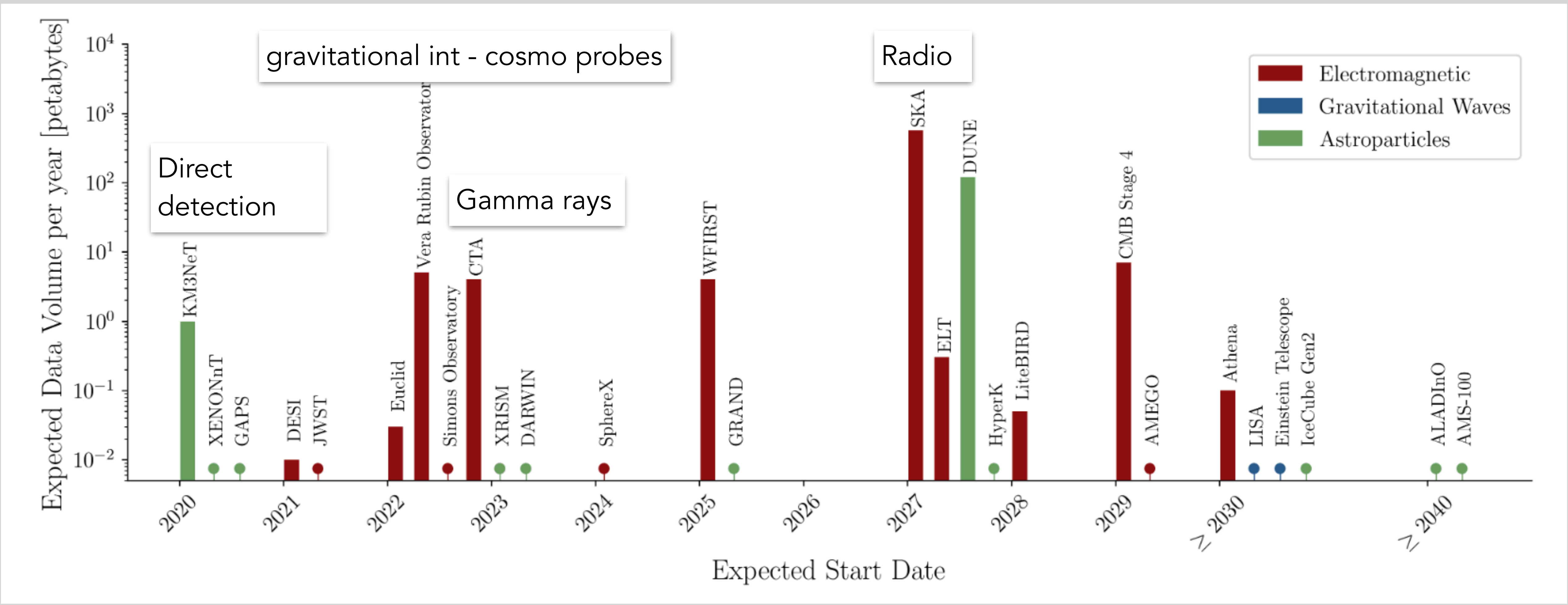




Future? New experiments

More data are coming! (CTA, Vera Rubin, SKA…)

Sheer amounts of (upcoming) data plus the complexity of physics and multiwave/messenger connections are making it increasingly challenging to analyse the data in a comprehensive way via traditional techniques



Future - Machine learning?

Starting slowly in this field

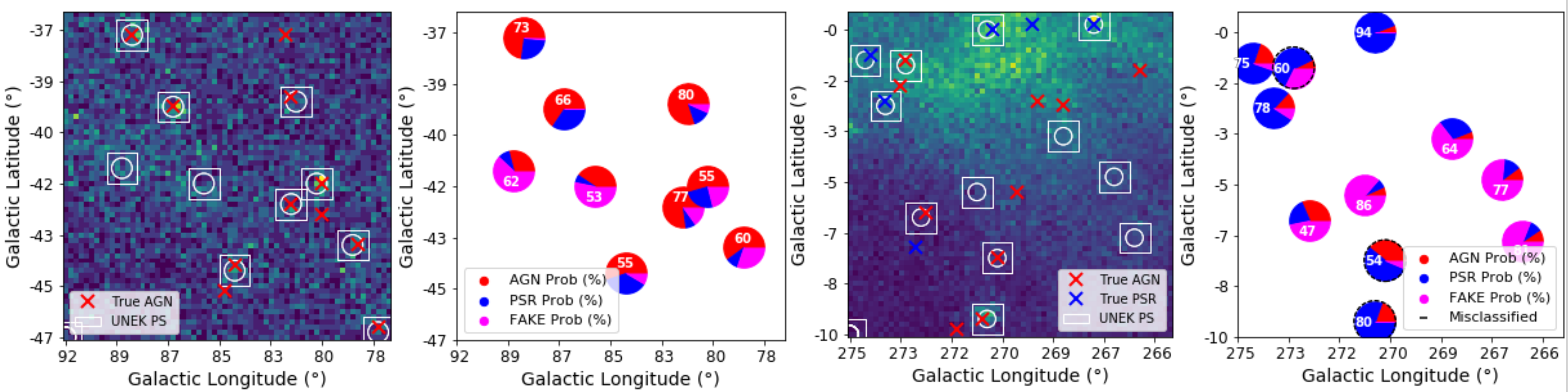
An example, automatic source detection and classification from raw LAT images (AutoSourceID):

— faster, more robust to background model

— extension to multi-wavelength ~natural

Results for High Latitude: $|b| > 20°$

Results for Low Latitude: $|b| < 20°$



Low background emission. Higher accuracy in localization.

Better classification.

Regions closer to galactic plane. Background emission dominates.

Algorithm performance deteriorates.

(www.autosourceid.org, A&A, 2103.11068)

[credit: *Saptashwa Bhattacharyya, TeVPA 2021*]

Outlook

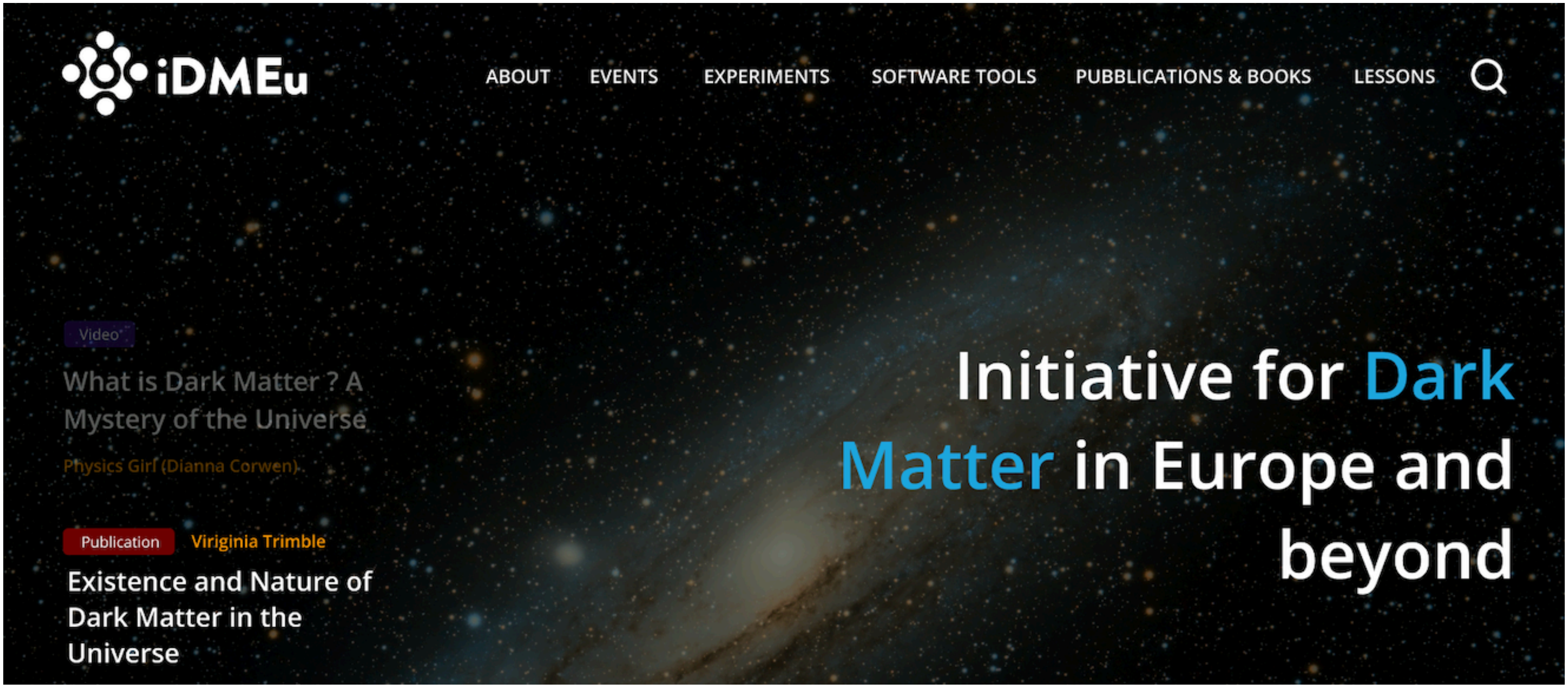
Exciting multi-disciplinary field & lots of data to play with !

Significant progress on probing WIMP models and more to come soon

The search is widening - *It always seems impossible until it's done* :)

Curious to find out more?

http://www.idmeu.org — ***a go-to place for all things dark matter***



A hub for News/Events/Experiments/Models/Tools….