Astrophysical probes of the **dark matter** particle properties

A 'biased' overview

Gabrijela Zaharijas

Centre for Astrophysics and Cosmology,

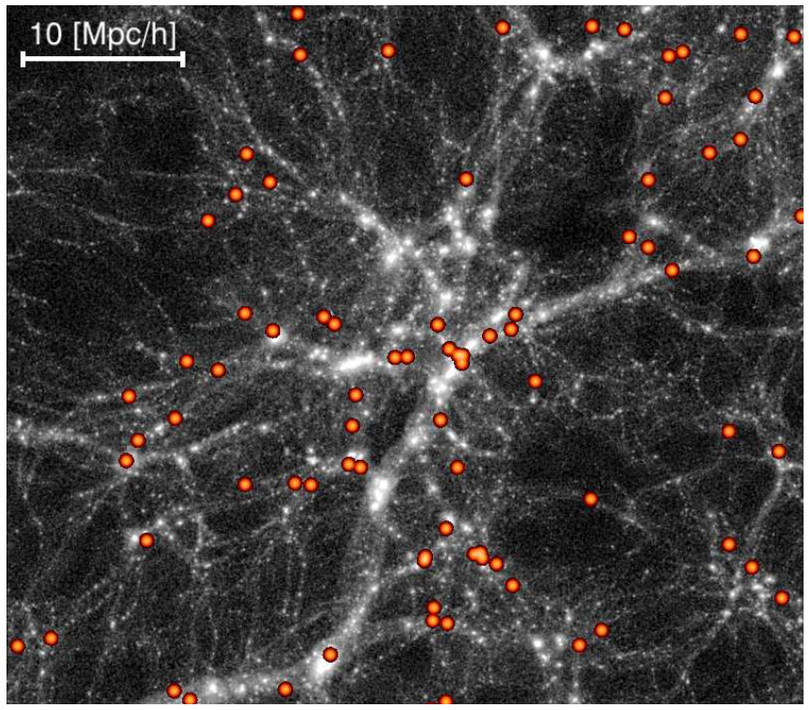
University of Nova Gorica, Slovenia

Portorož 2019: Precision era in HEP

Dark matter

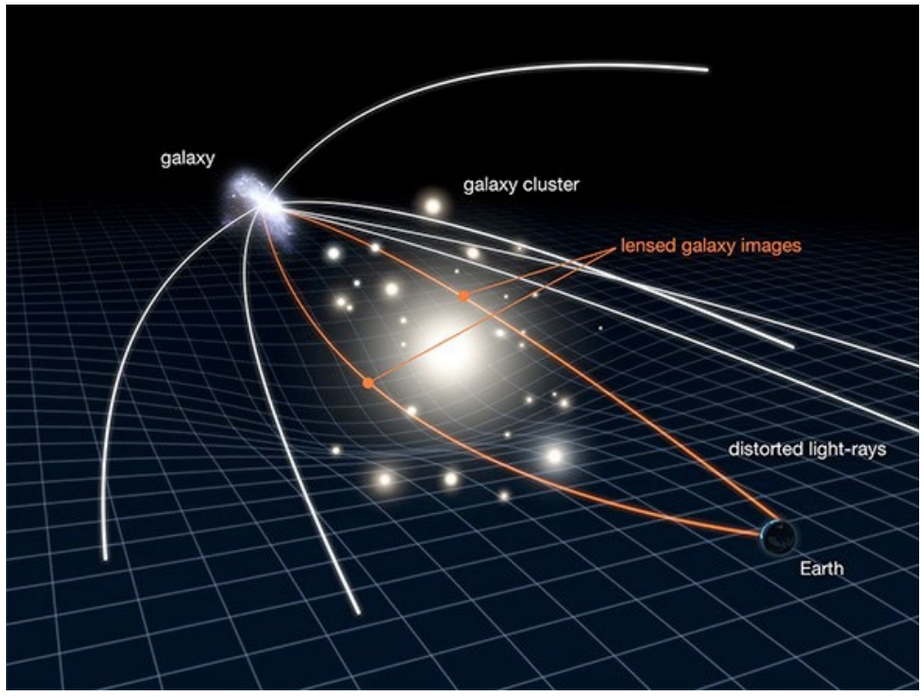
an essential building block of the Standard Model of Cosmology

large scale structures



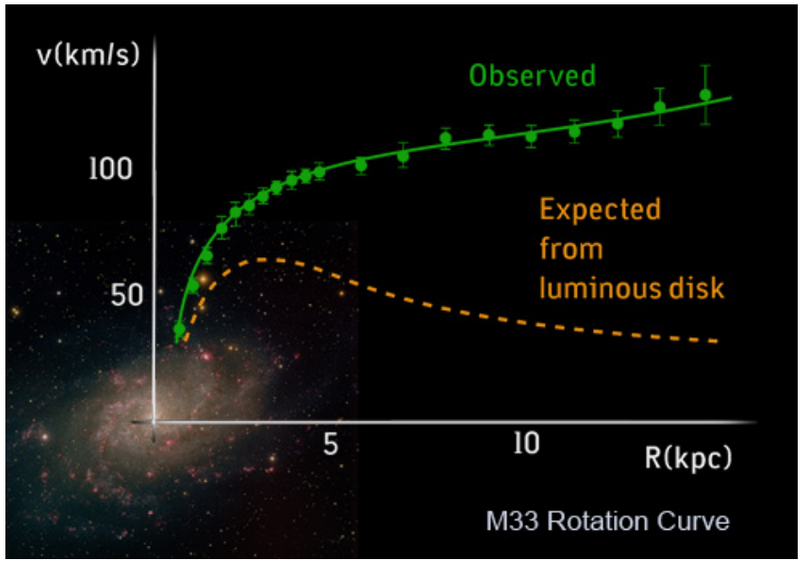
100s Mpc

clusters of galaxies



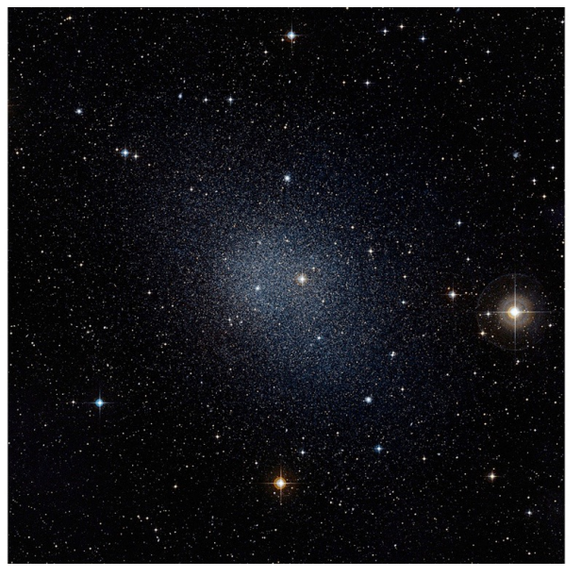
Mpc

Milky Way-size galaxies



100s kpc

dwarf galaxies



<~ kpc

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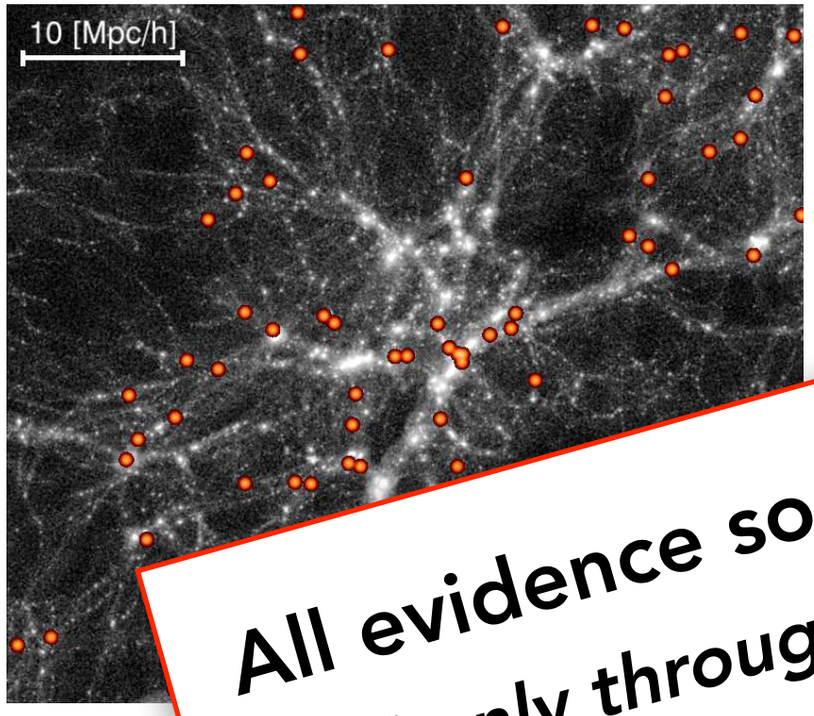

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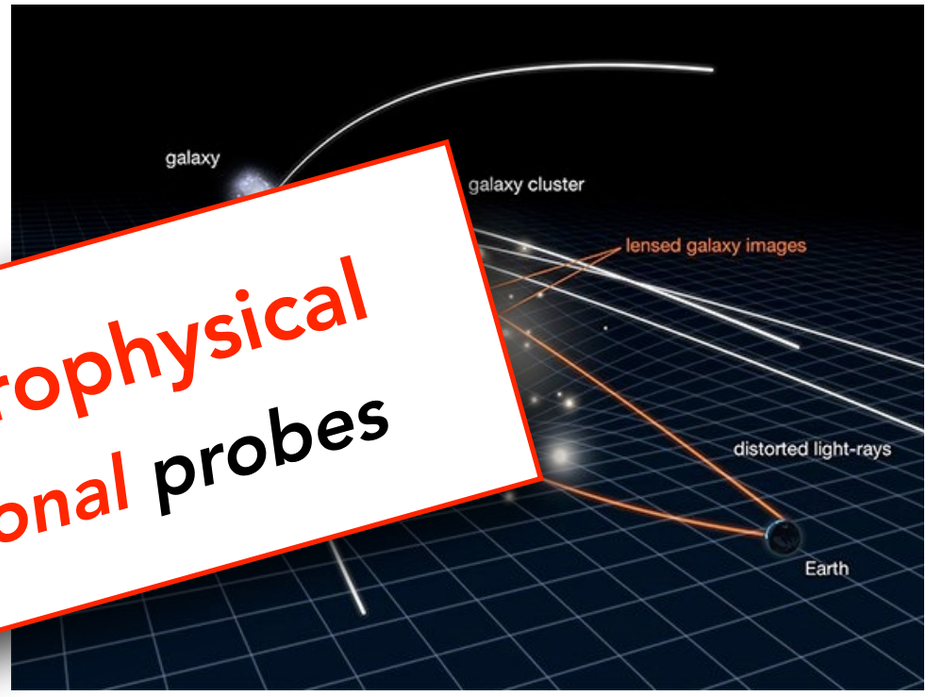
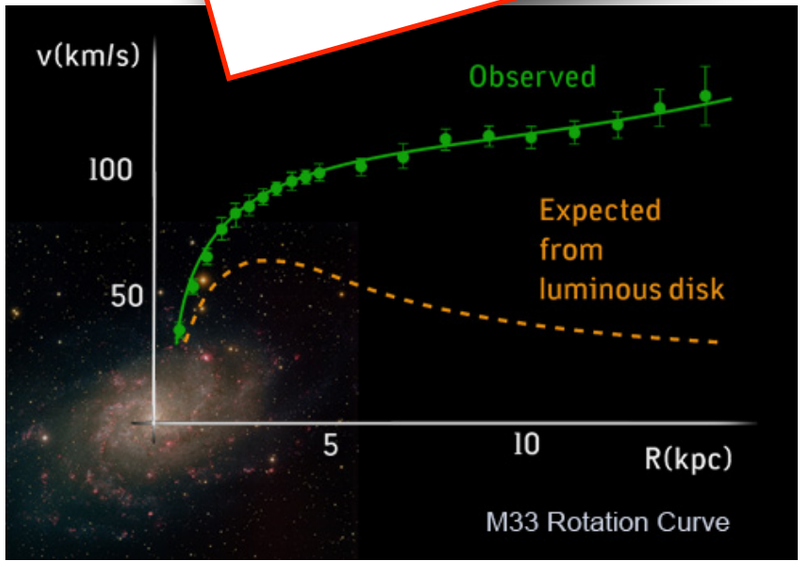


Mpc

All evidence so far is astrophysical
And only through gravitational probes

Milky



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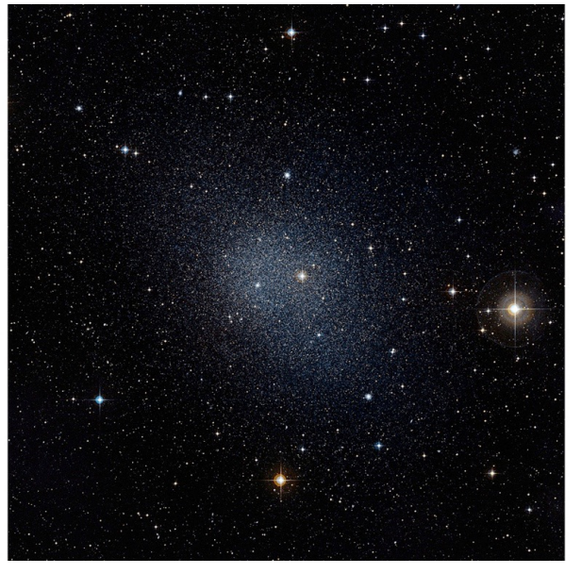
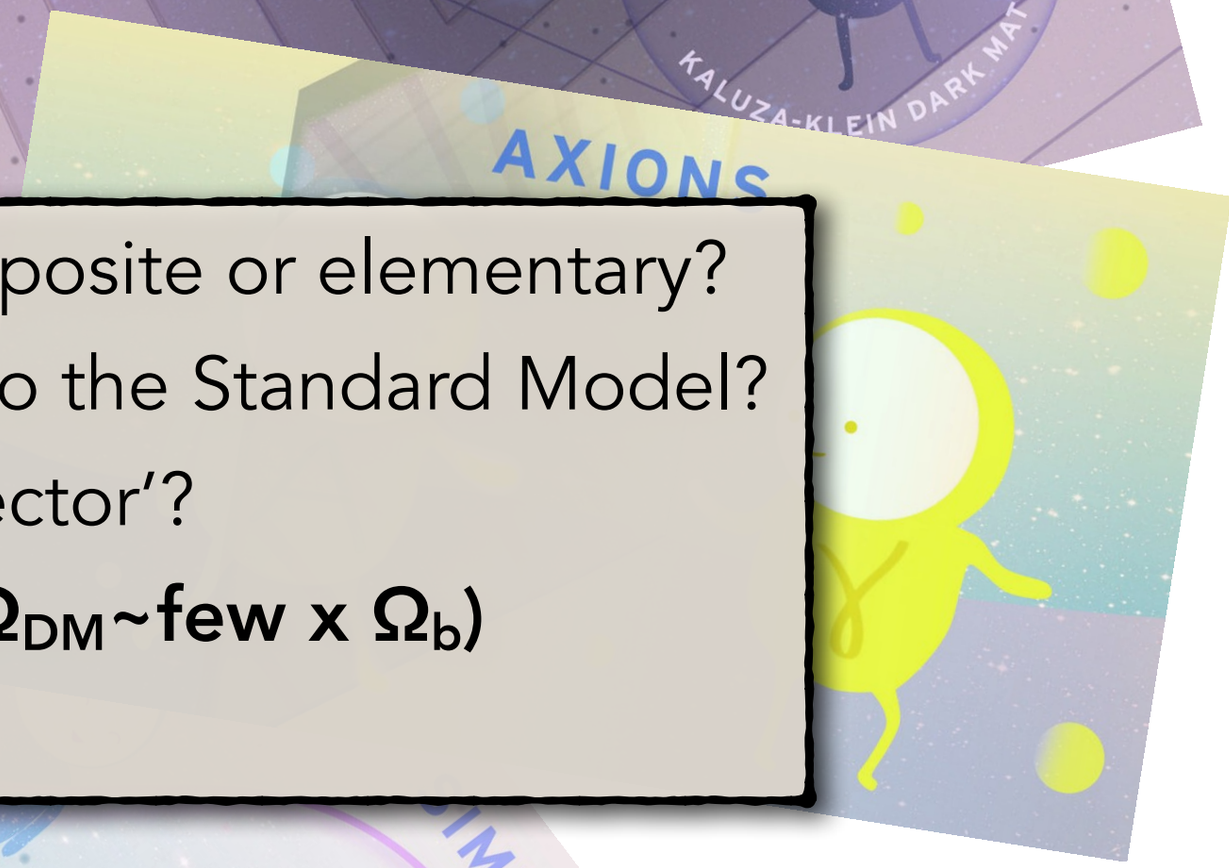
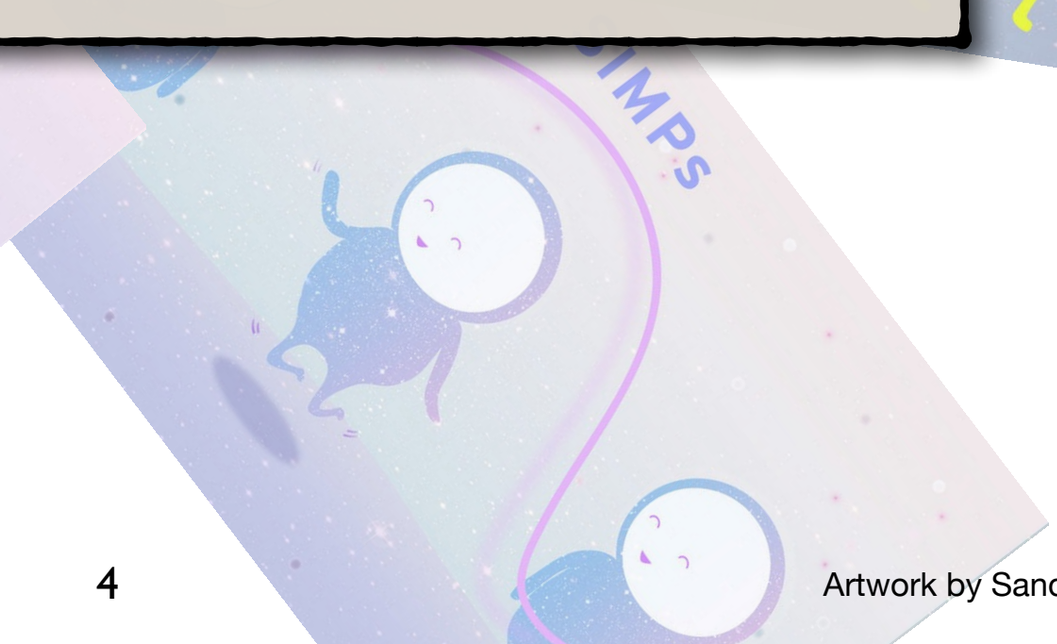


<~ kpc

The challenge

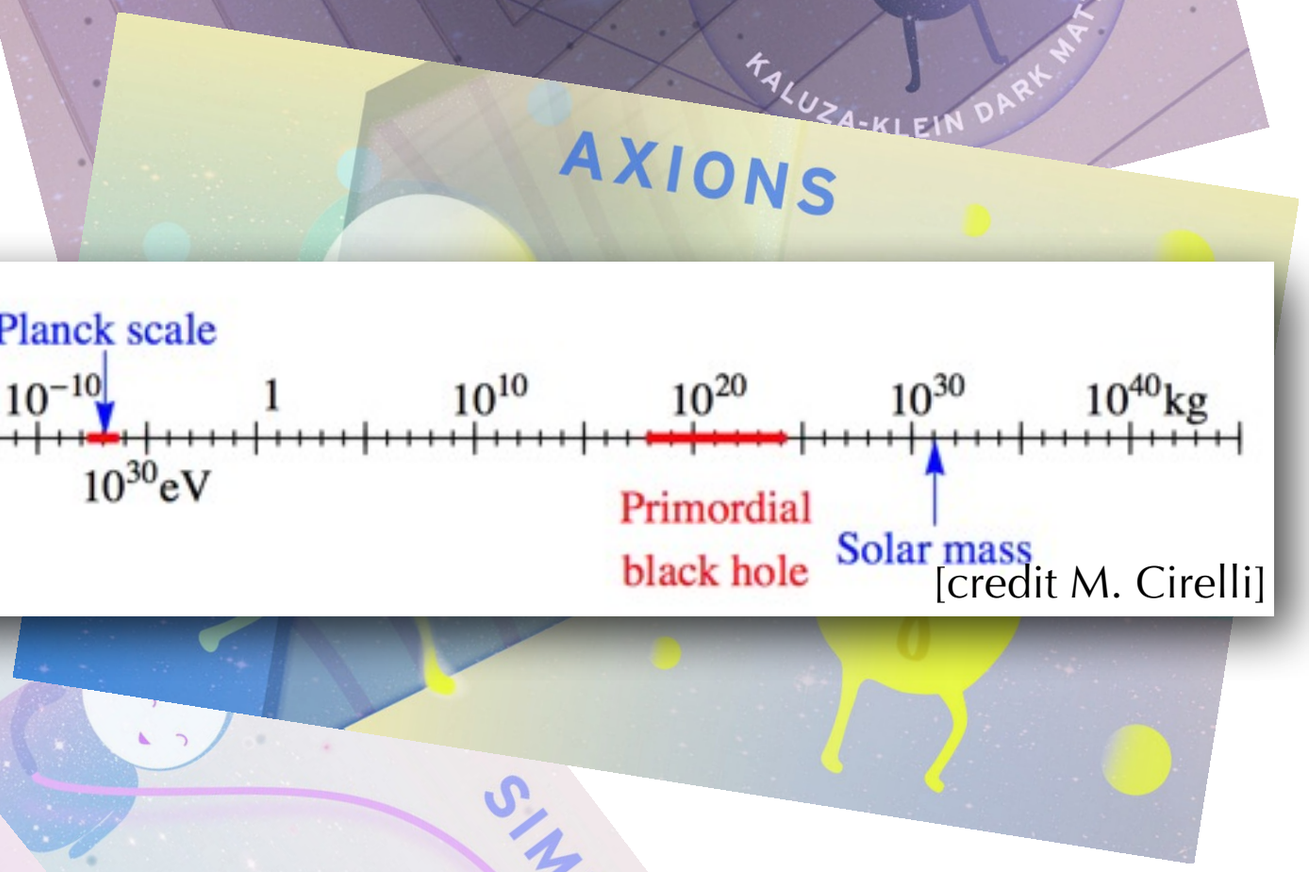




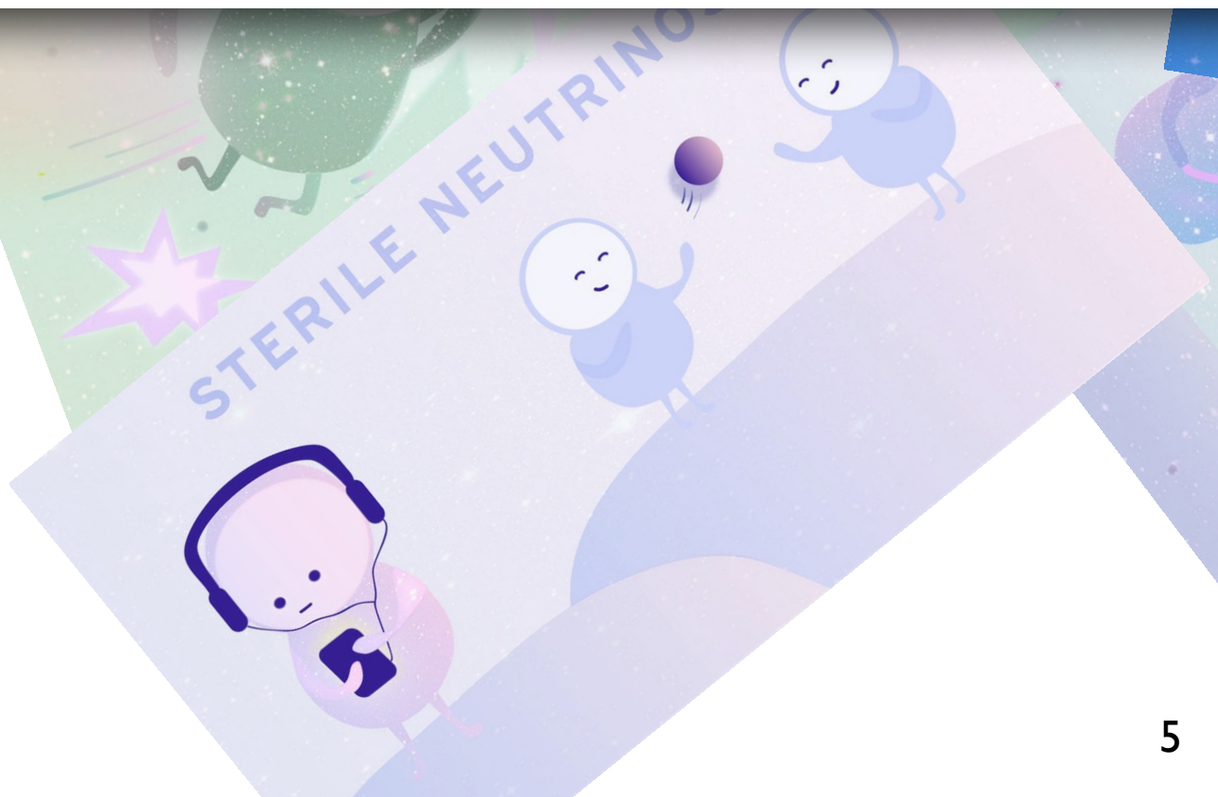
- A new particle? Composite or elementary?
- How does it couple to the Standard Model?
- ‘Maverick’ or dark ‘sector’?
- Why so abundant? (Ω_{DM}~**few x** Ω_b)
- Why stable?

Artwork by Sandbox Studio, Chicago

What are the options?

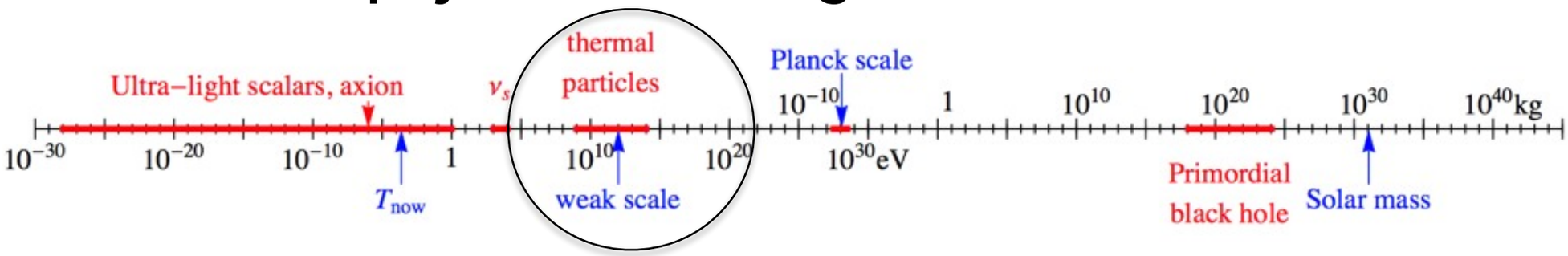


[credit M. Cirelli]

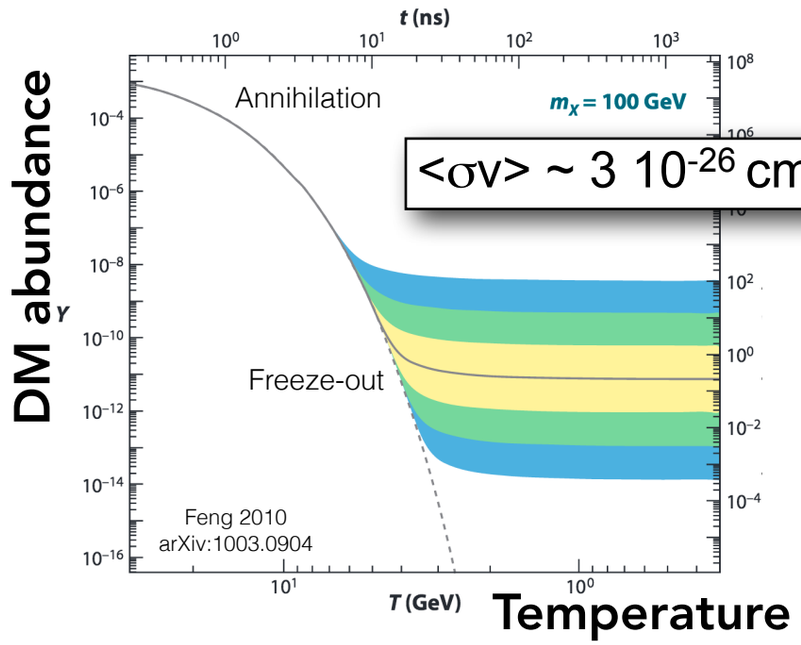


Artwork by Sandbox Studio, Chicago

Searches in astrophysical/cosmological data - i.e. in the DM's '*natural habitat*'

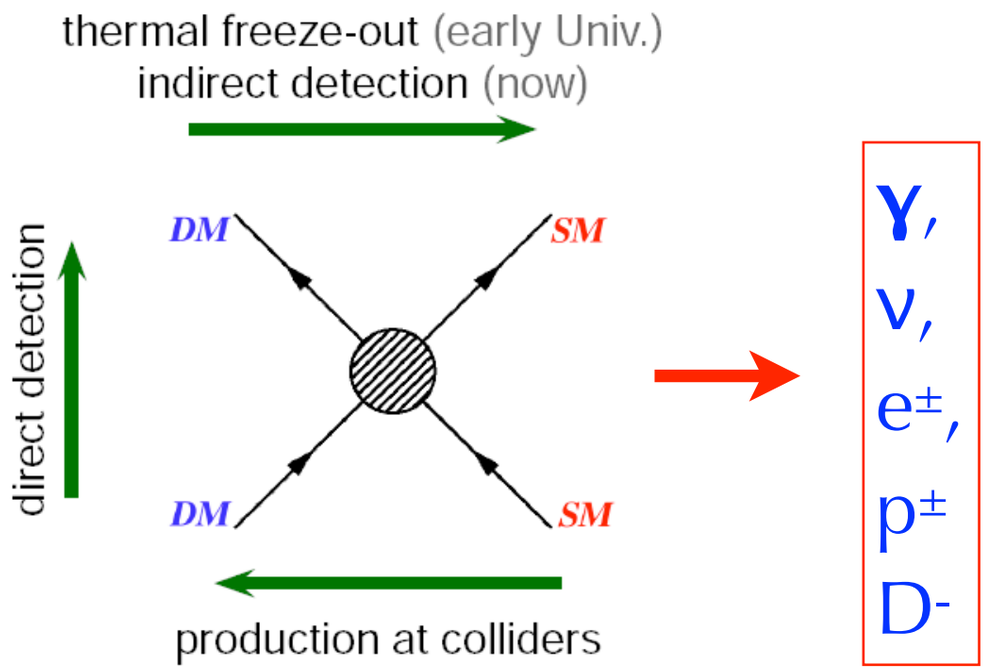


1. Look for ***thermal*** *DM* (*WIMPs*)



$\langle\sigma v\rangle \sim 3\ 10^{-26}\ cm^3 s^{-1}$

Predictive!



+ connection with Early Universe physics

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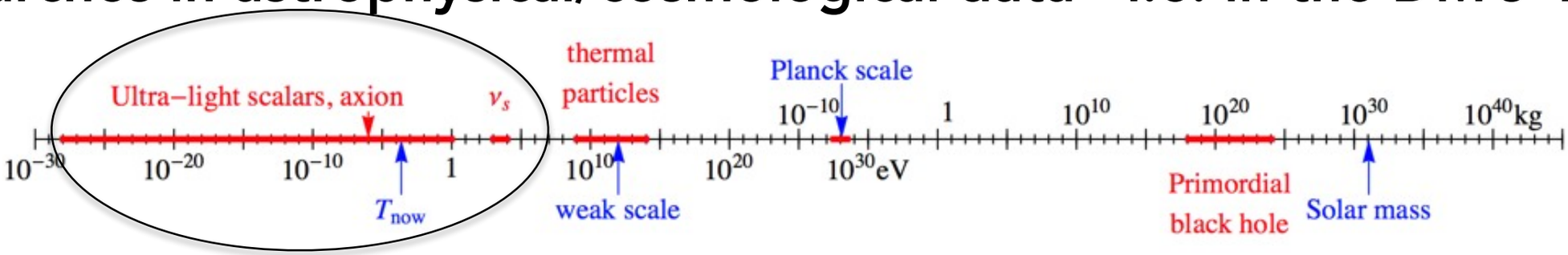

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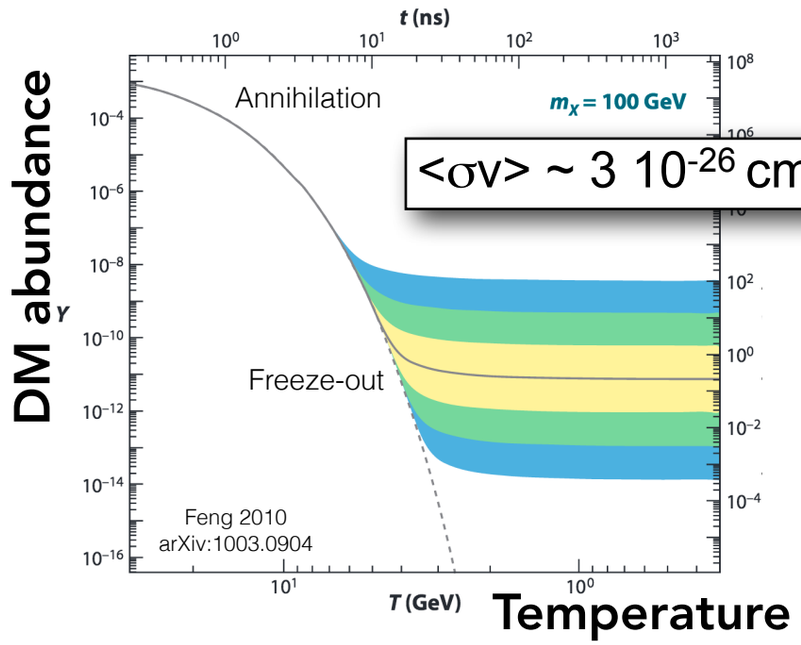

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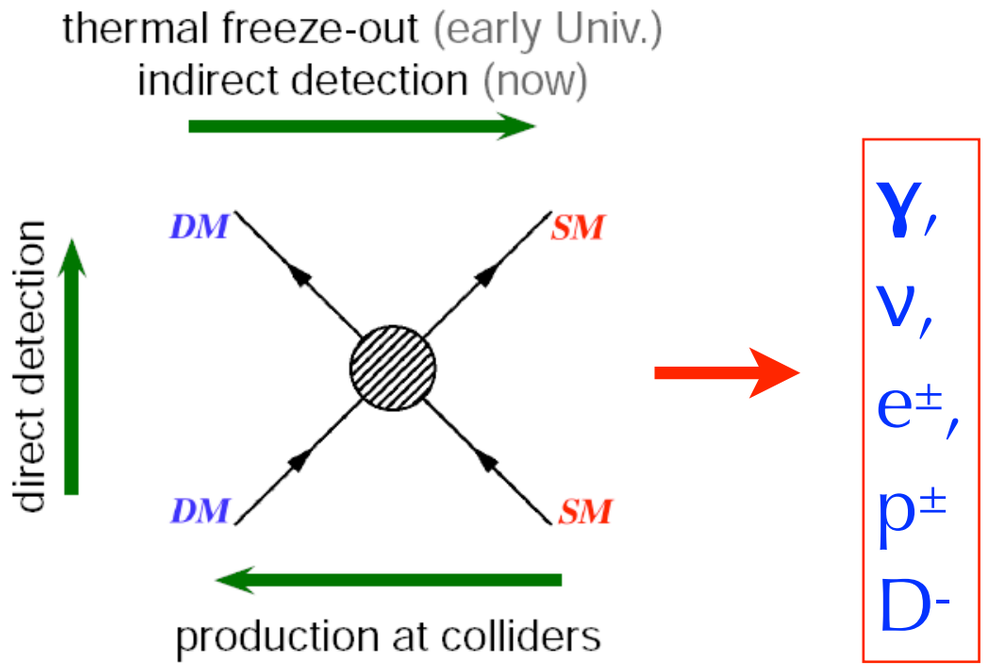

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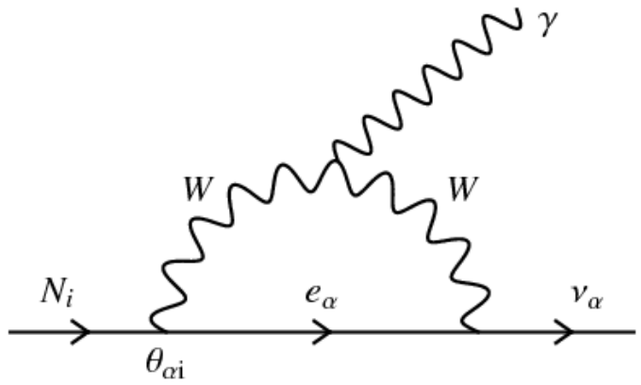

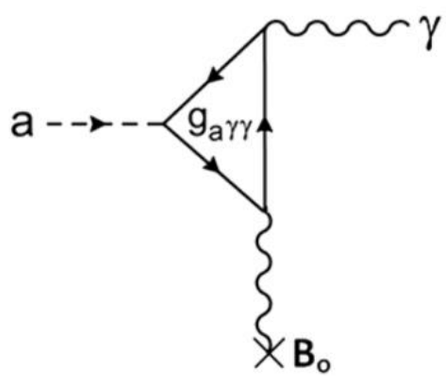

γ, ν

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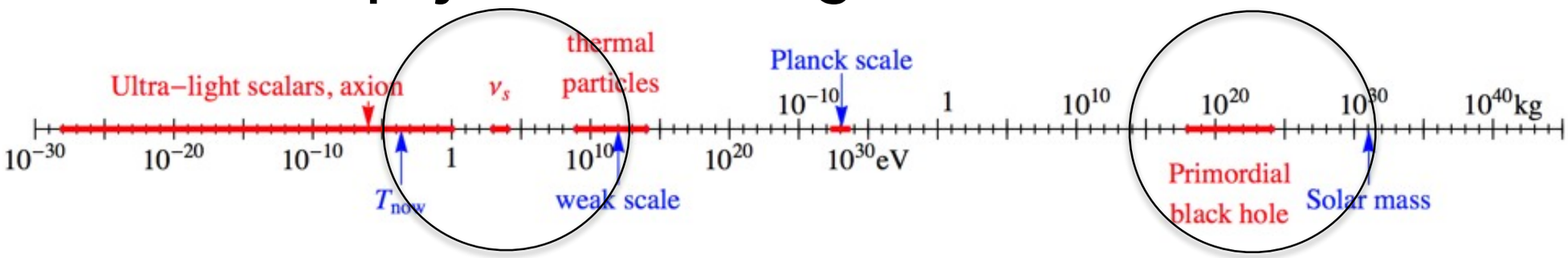

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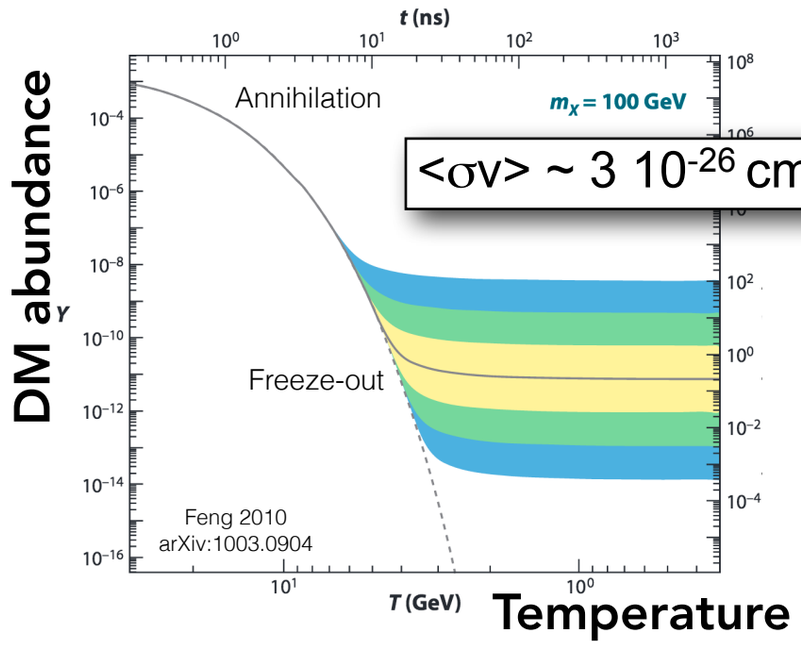

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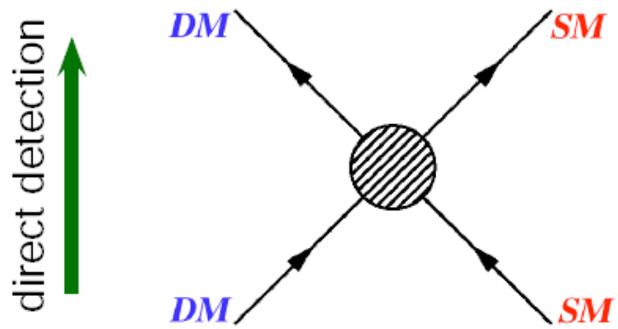
Predictive!

thermal freeze-out (early Univ.)
indirect detection (now)



γ, ν, $e^{\pm}$, $p^{\pm}$ D-

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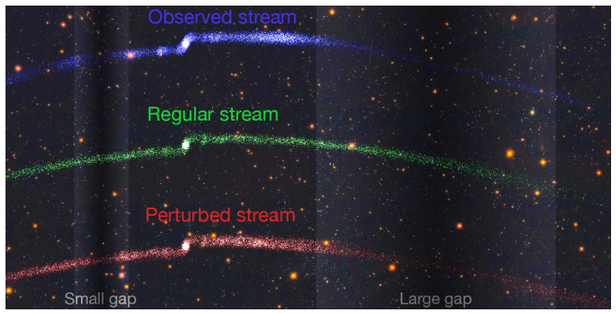
γ, ν

3. Look for DM particle properties via its **clustering on small scales**

Gravitational probes

(***worked so far***…)



e.g. from stellar tidal stream disruptions, stellar wakes, etc

warm dark matter, PBHs…

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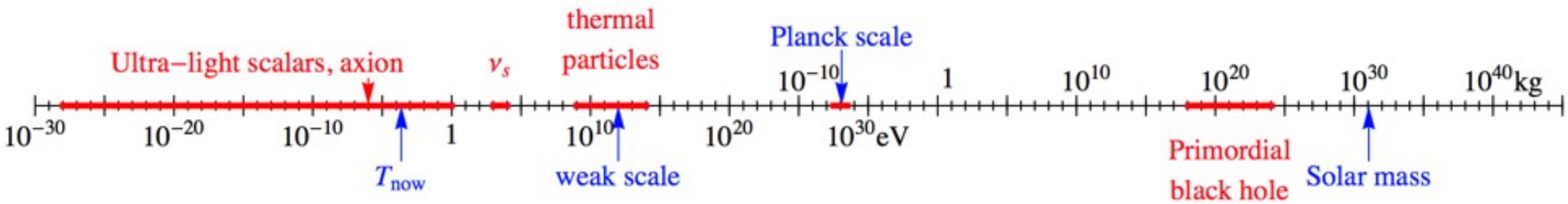

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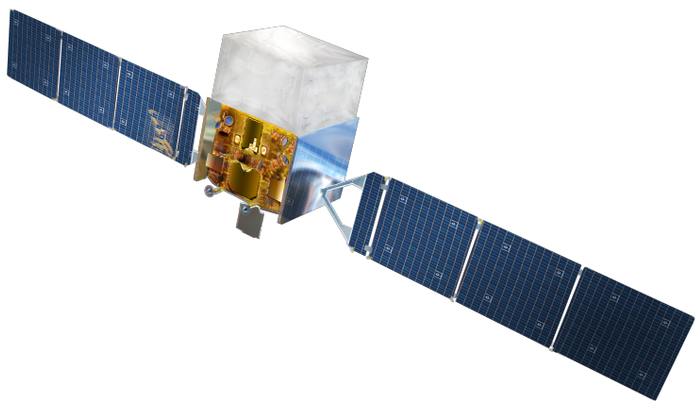

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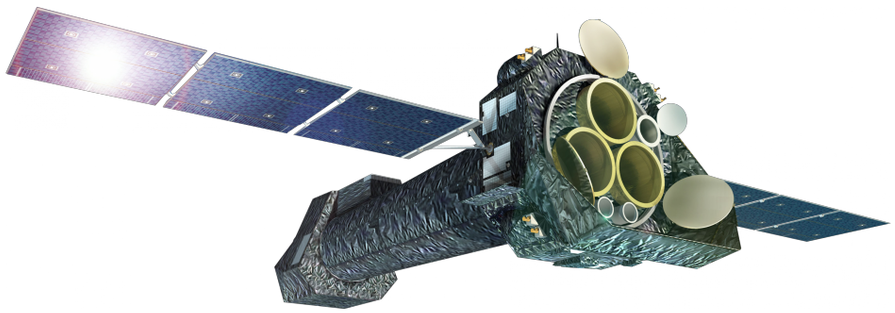

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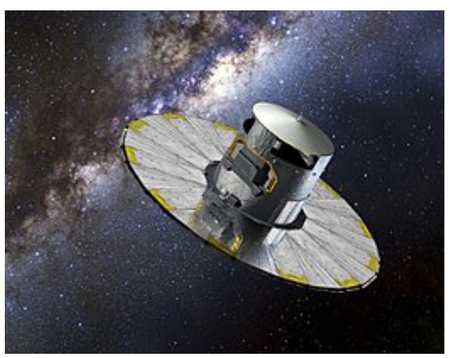

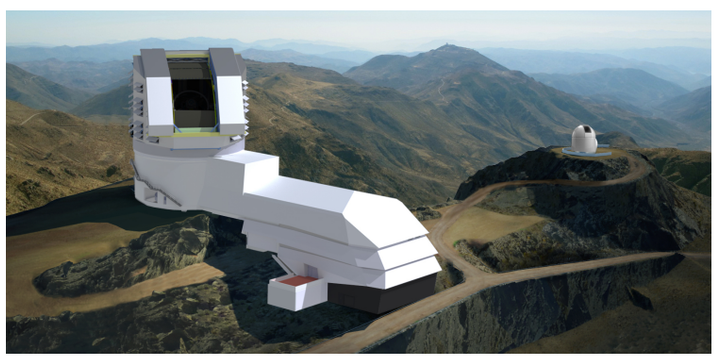

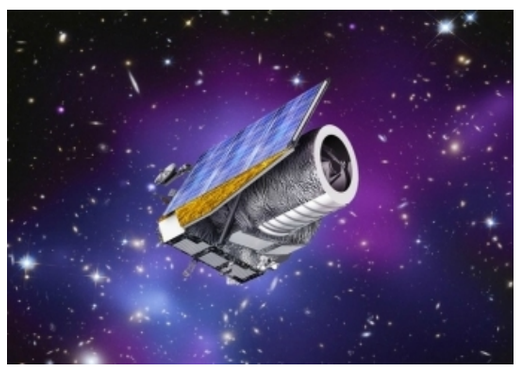

Gravitational probes

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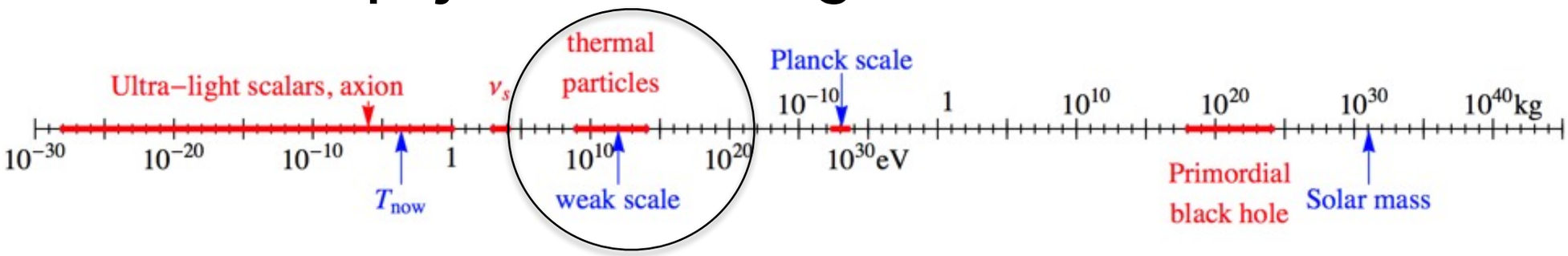

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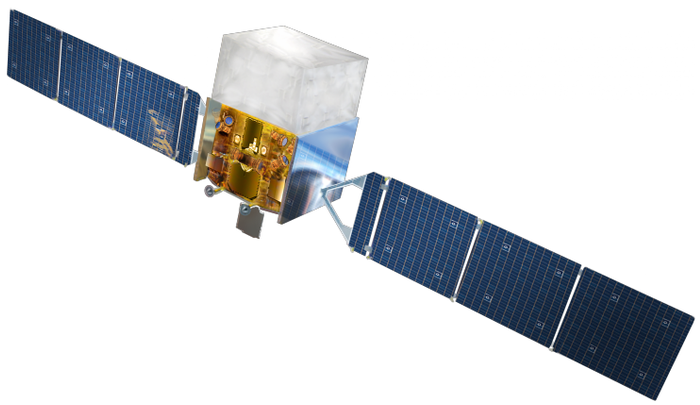

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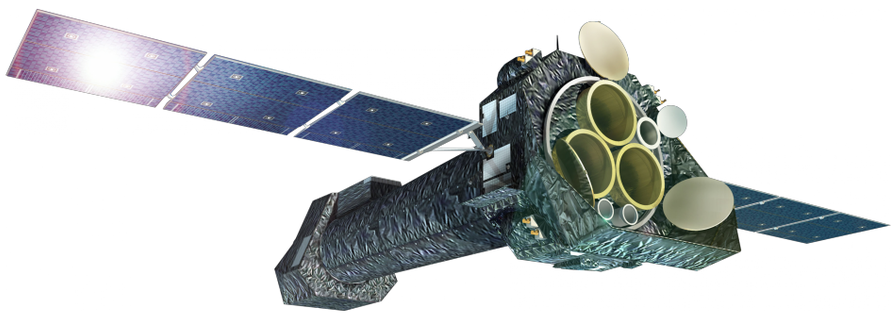

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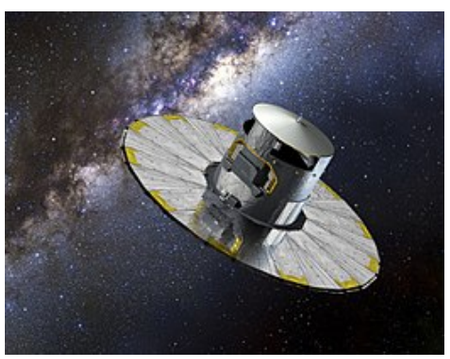
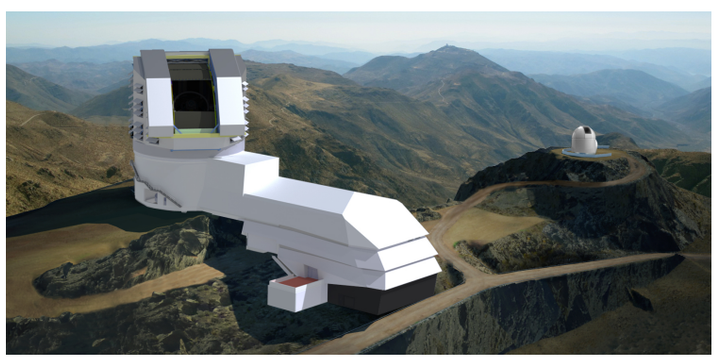
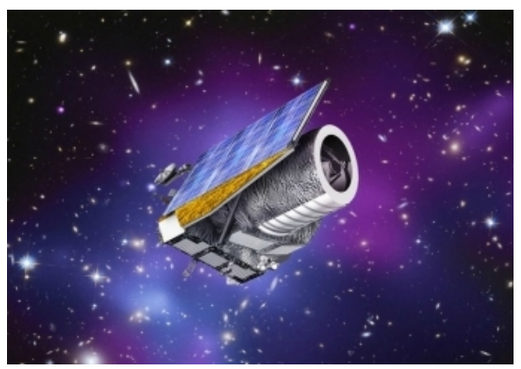






Gravitational probes

Where to look (ν and γ)?

- 'locally'

dSph Galaxies

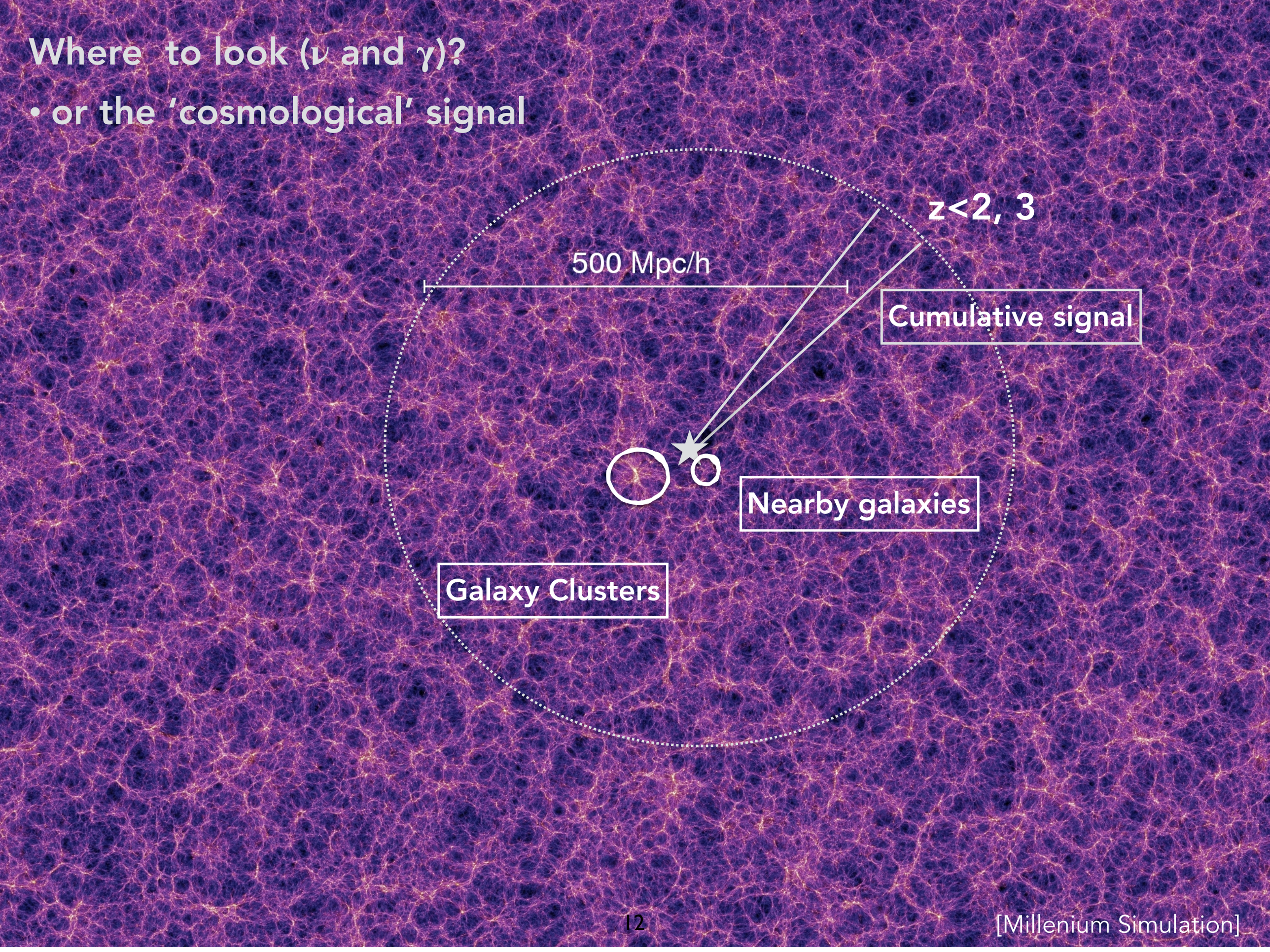
Galactic Centre

Dark sub halos

[Aquarius Simulation]

Where to look (ν and γ)?

- or the 'cosmological' signal

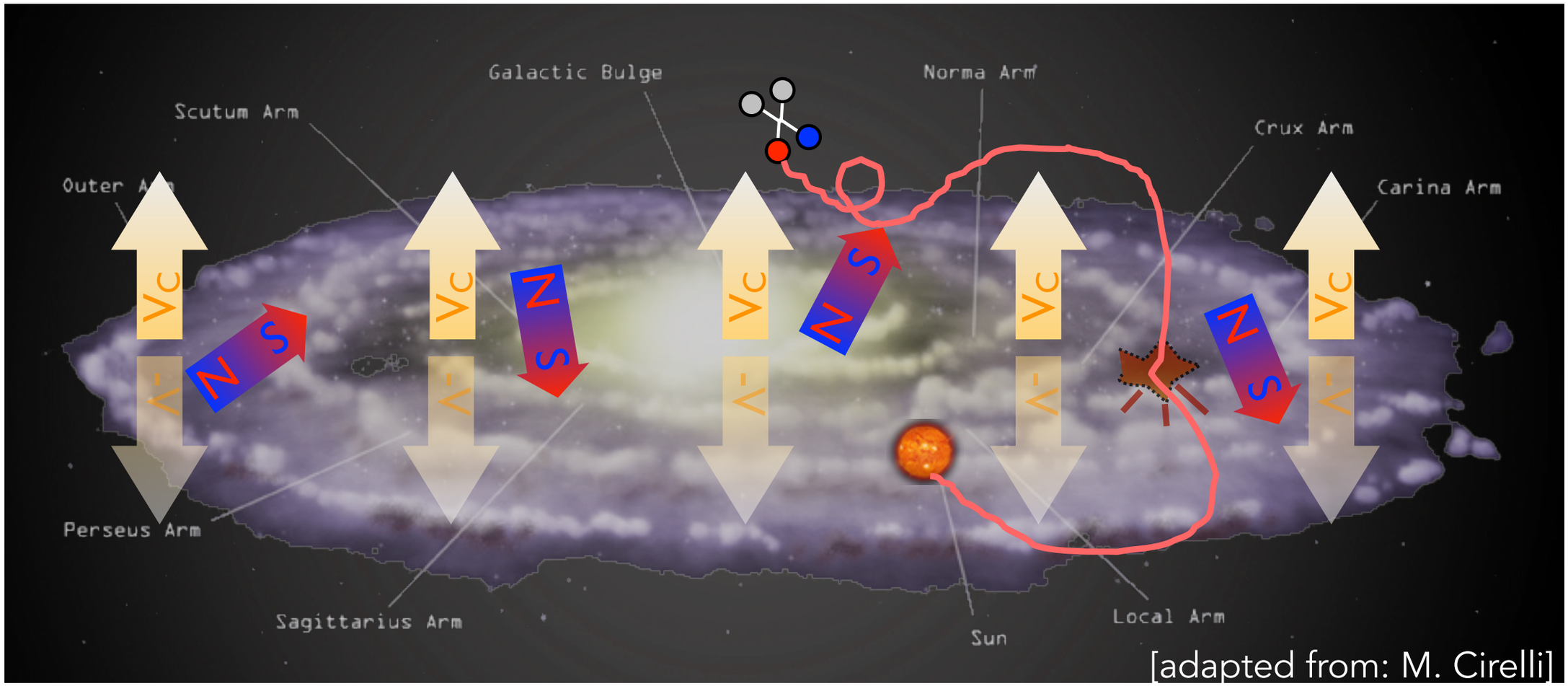


[Millenium Simulation]

Where to look ? - charged particles

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

astrophysics



[adapted from: M. Cirelli]

Charged particles propagate diffusively in galactic B and are affected by energy losses!

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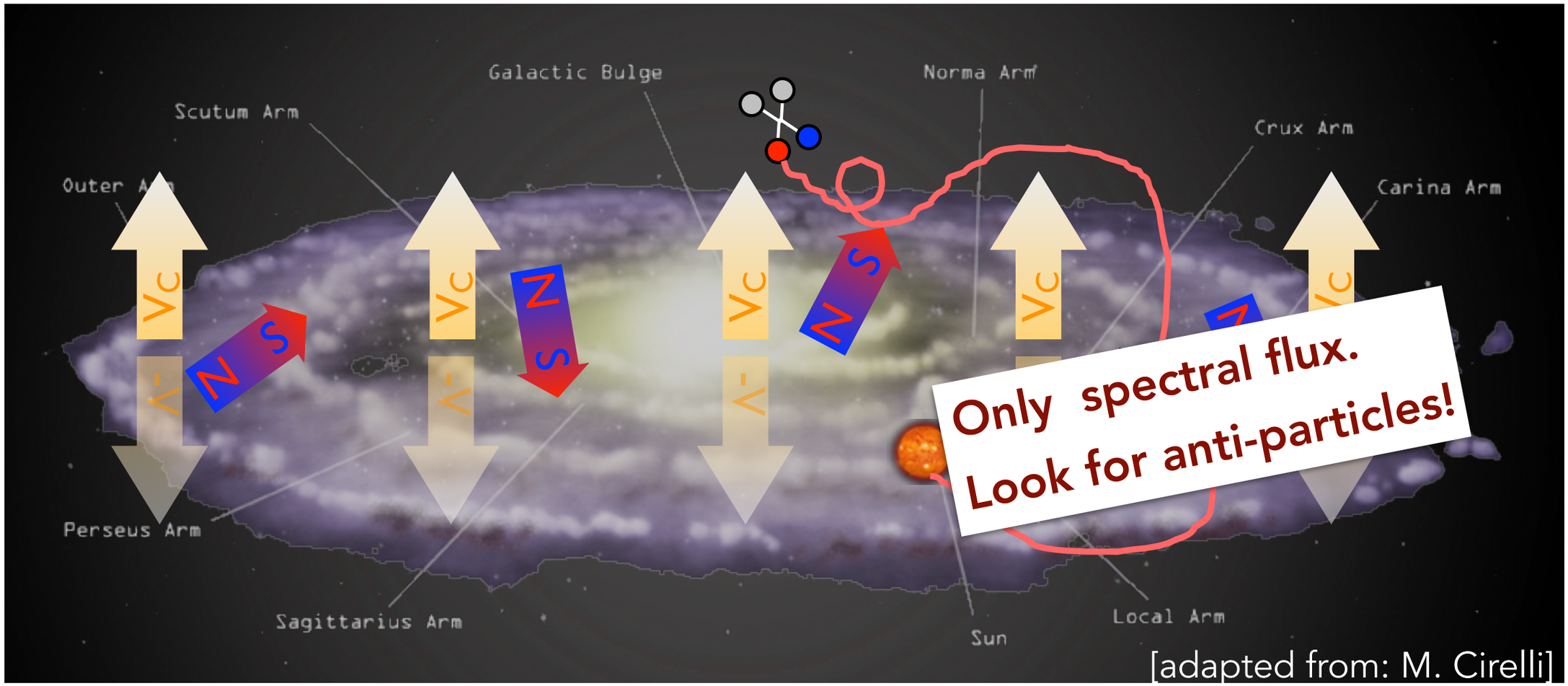
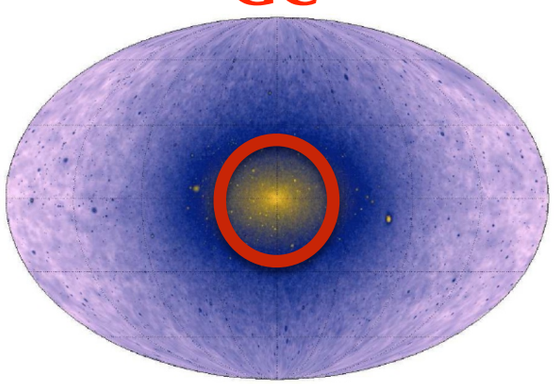


Charged particles propagate diffusively in galactic B and are affected by energy losses!

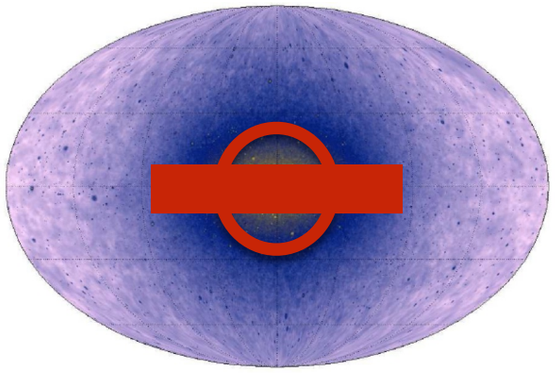
Strategies

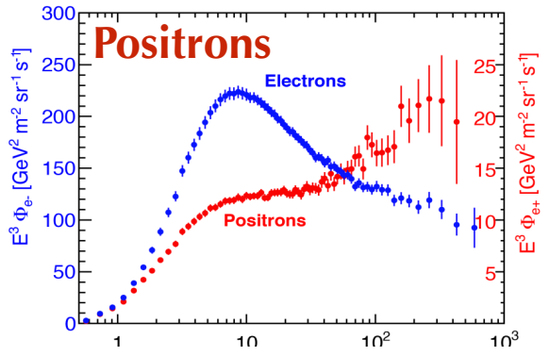
signal strength

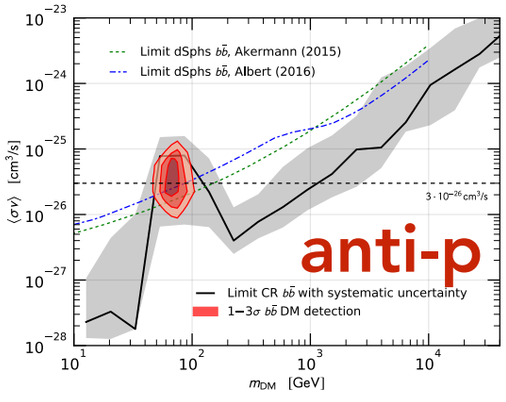
GC



GC halo

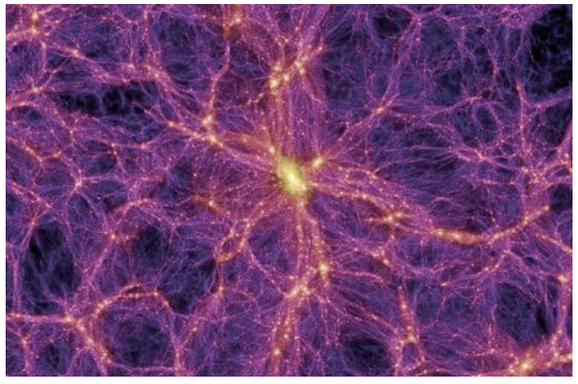




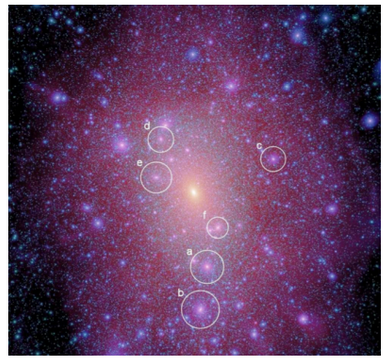


Cosmological signal/UEBG:

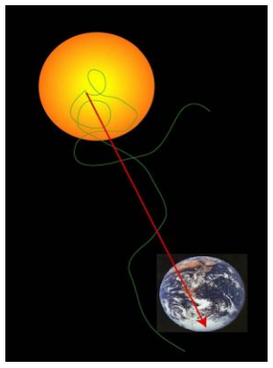
- Spectral flux
- Auto-correlations
- Cross-correlations w Galaxy catalogs and cosmic shear



dwarf satellites



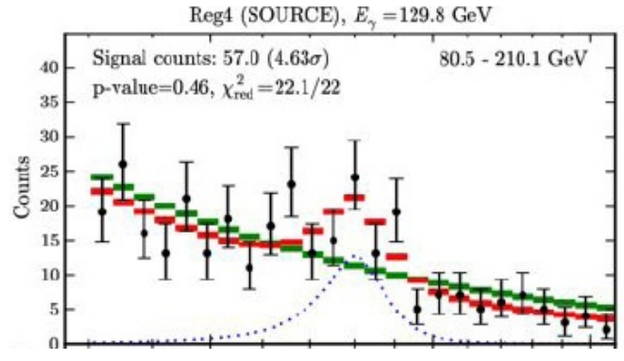
High energy ν from the



Extragalactic sources:

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

spectral line



[adapted from: H.-S. Zechlin]

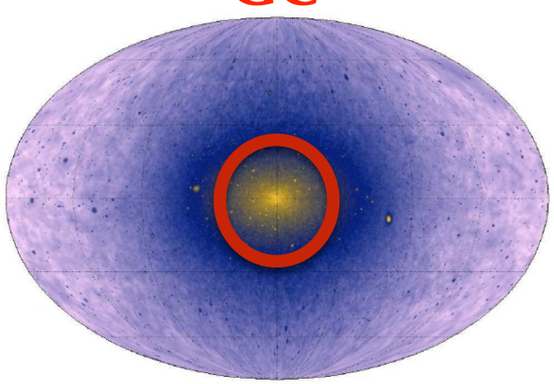
robustness

Strategies

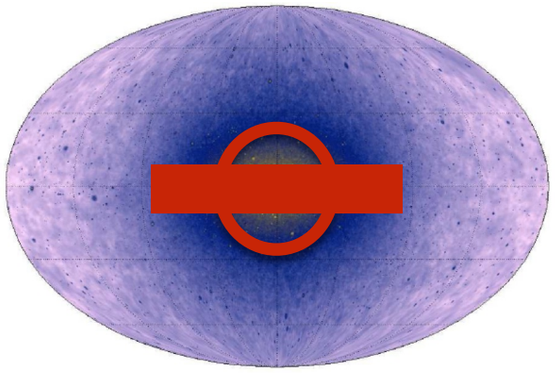
Multi-target & multi -messenger
detections required for confirmation

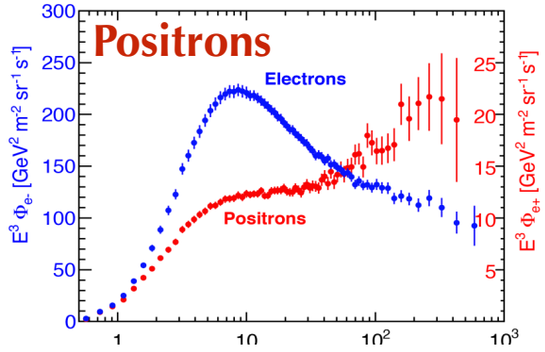
signal strength

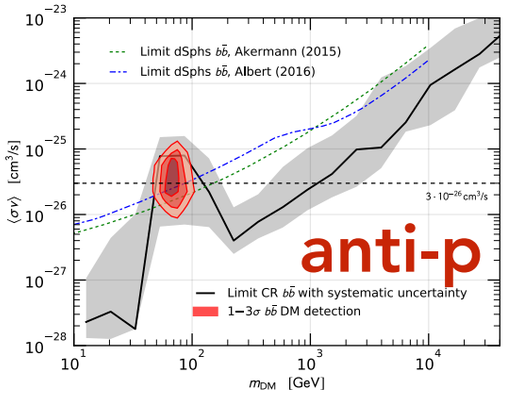
GC



GC halo







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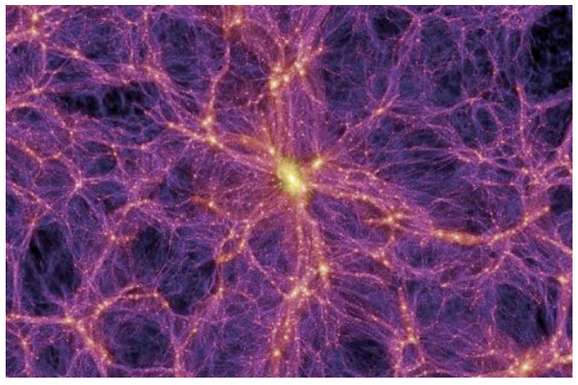
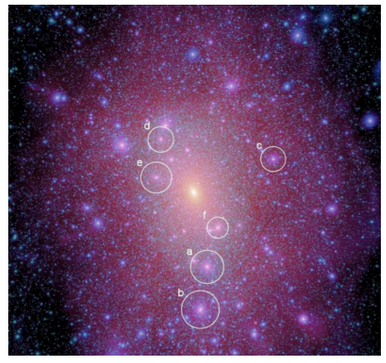
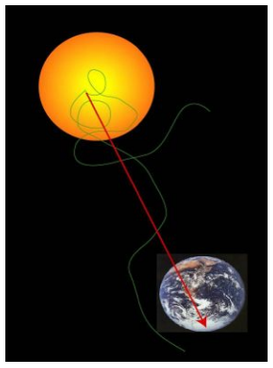


dwarf satellites



High energy ν from the



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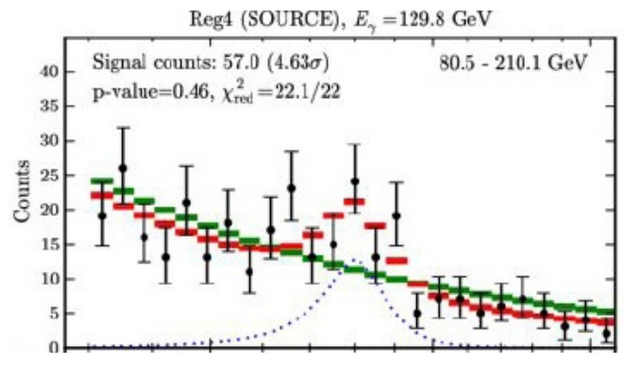
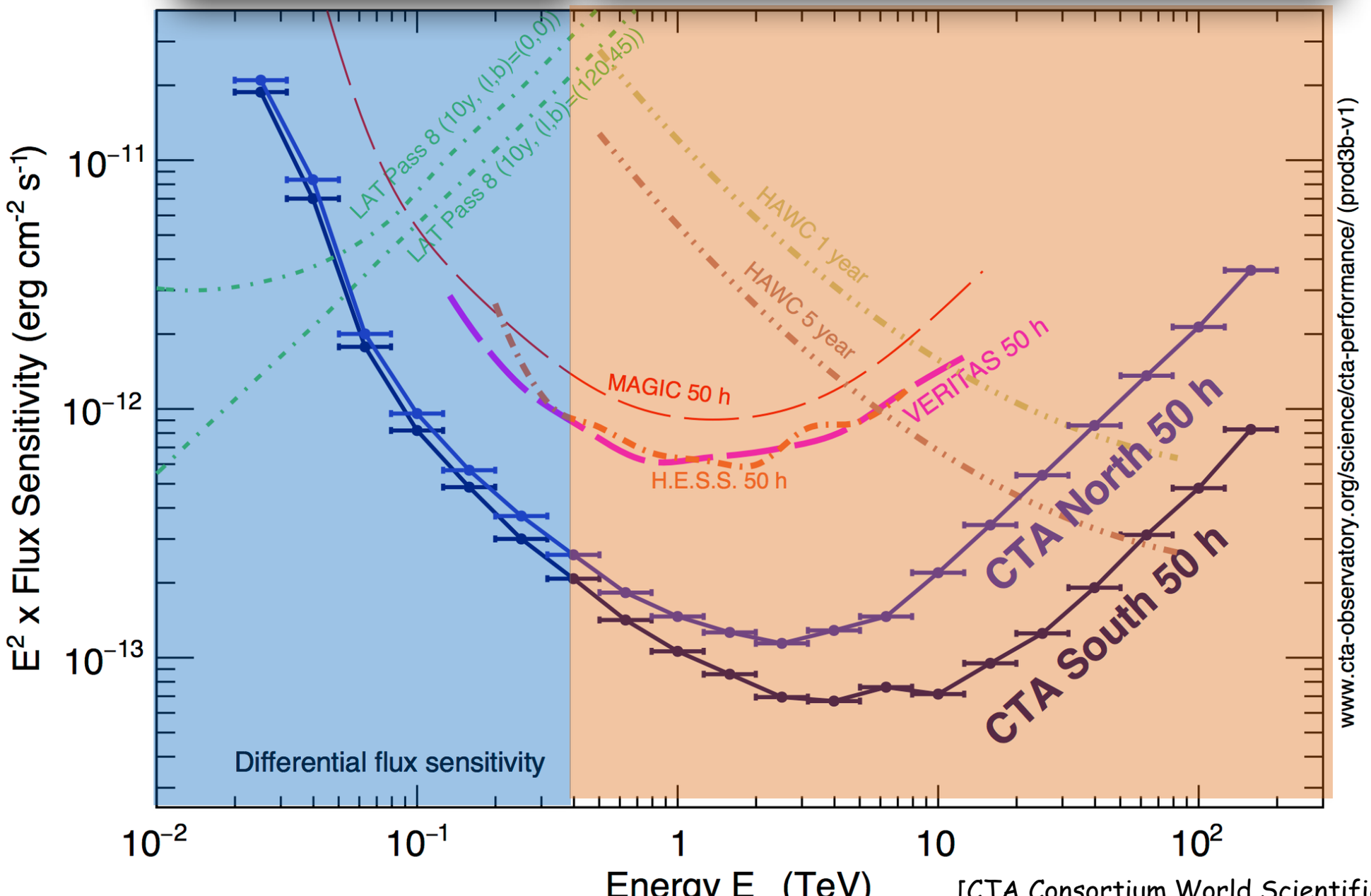


[adapted from: H.-S. Zechlin]

robustness

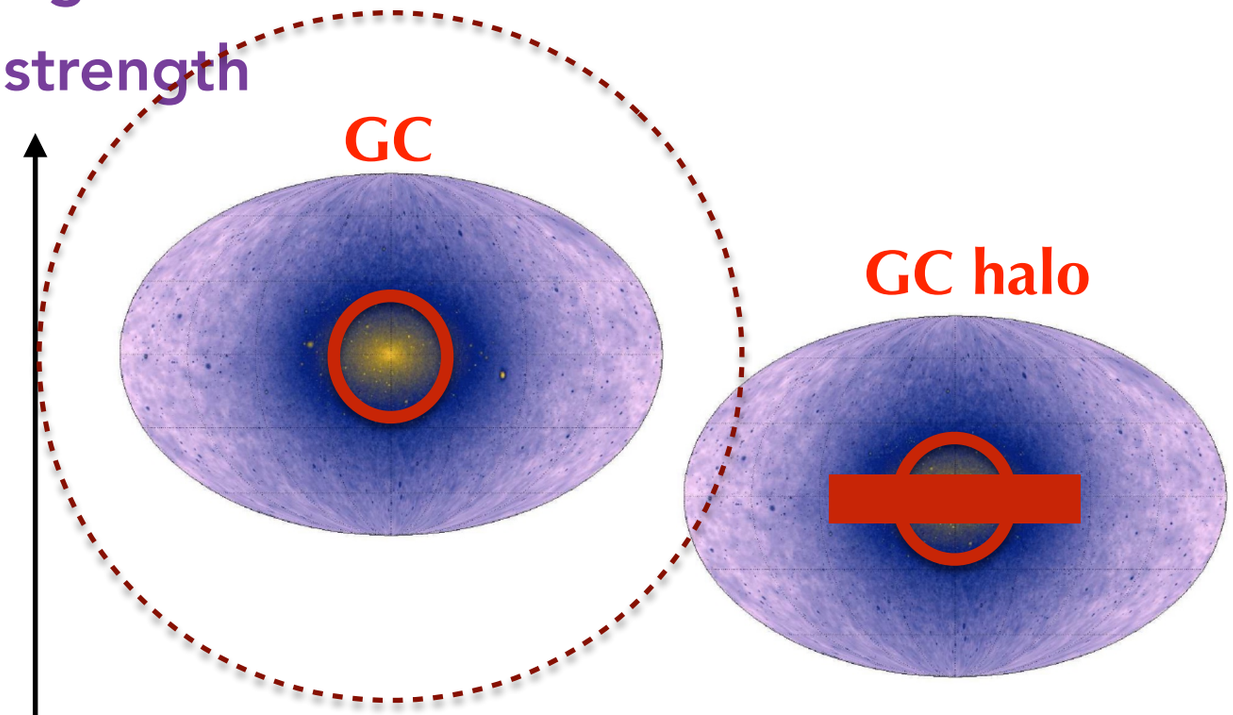
Gamma rays

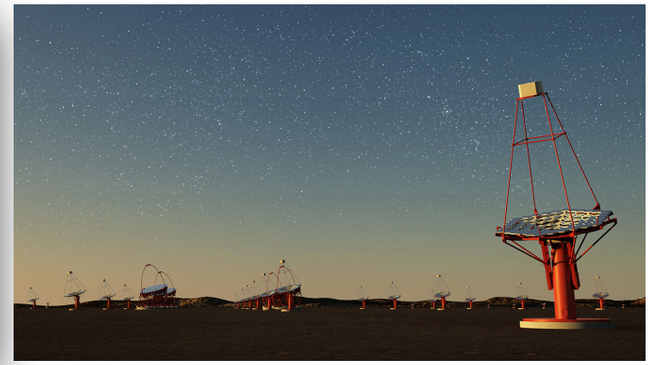


[CTA Consortium, World Scientific (2019), 1709.07997]

Status of the search

signal strength





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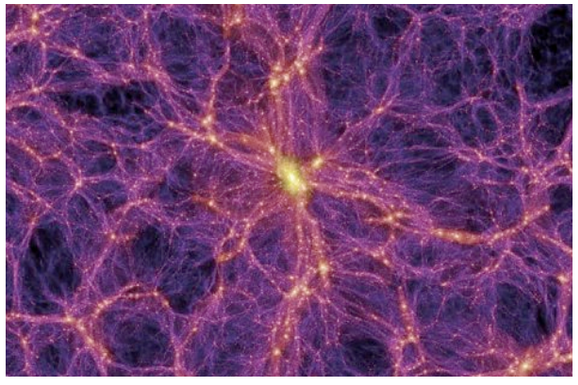
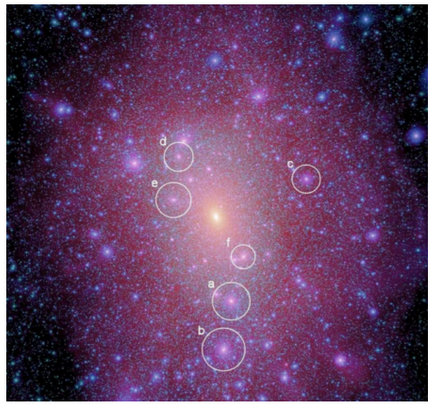


dwarf satellites



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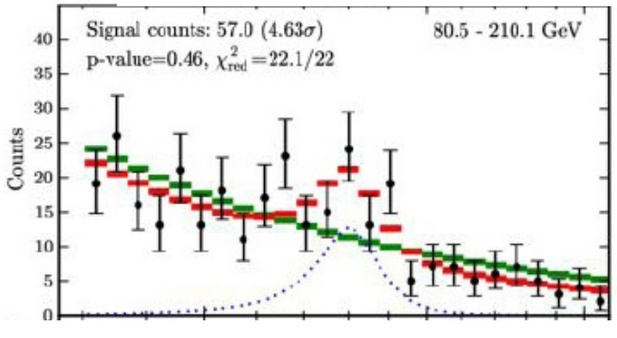

[adapted from: H.-S. Zechlin]

robustness

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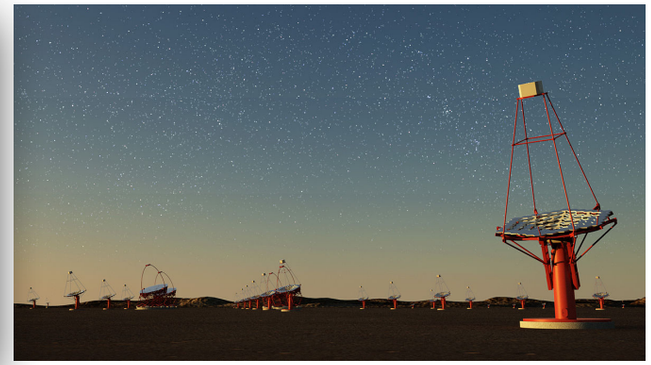
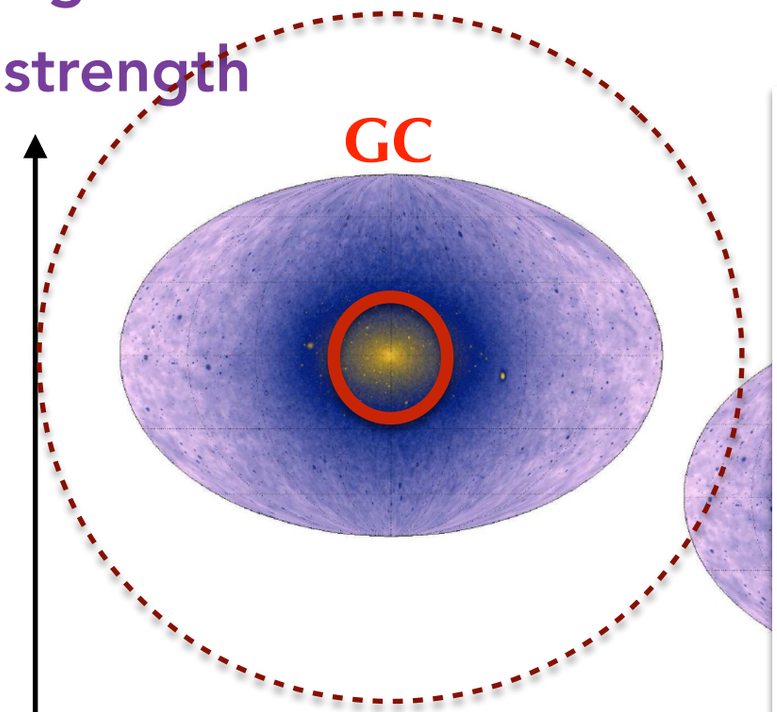
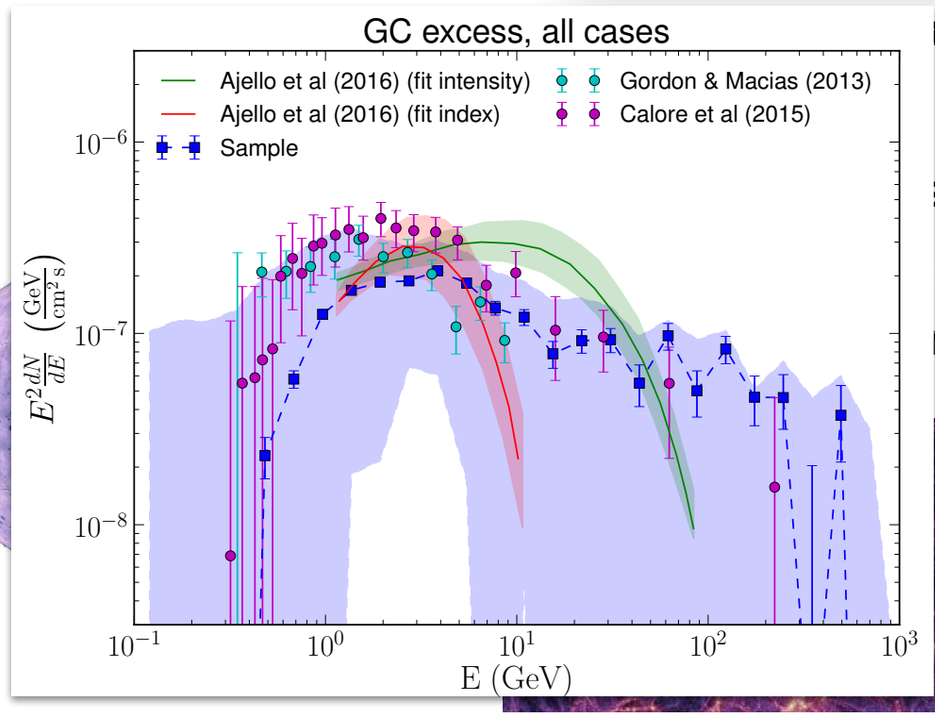


signal strength





Signal spectrally and morphological consistent with thermal DM detected since ~2010s

- Could it be 'it'?

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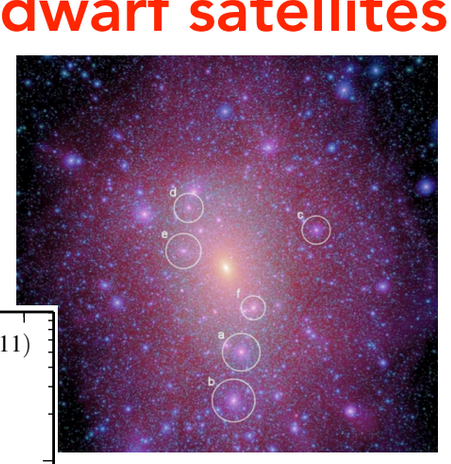

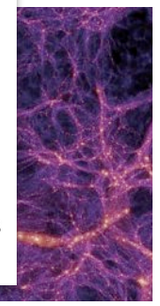

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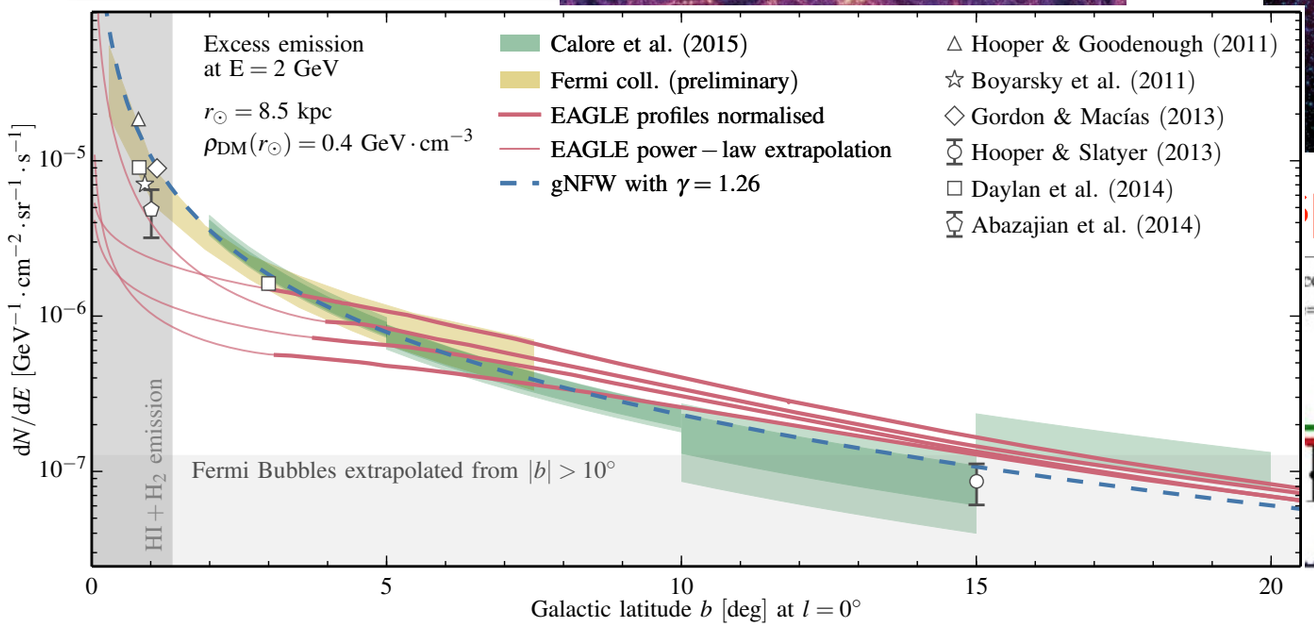
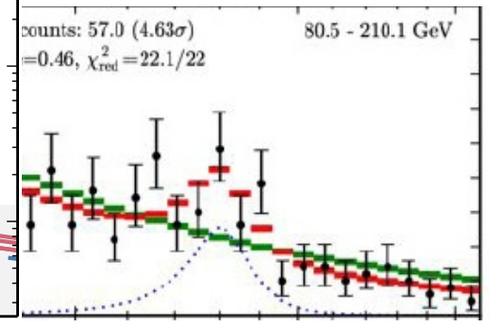
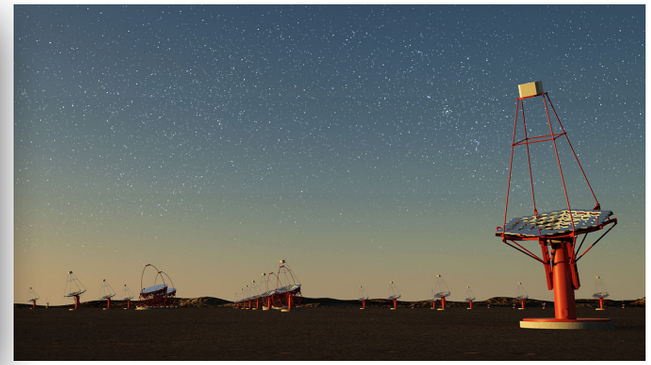




robustness

[adapted from: H.-S. Zechlin]

Status of the search



signal strength

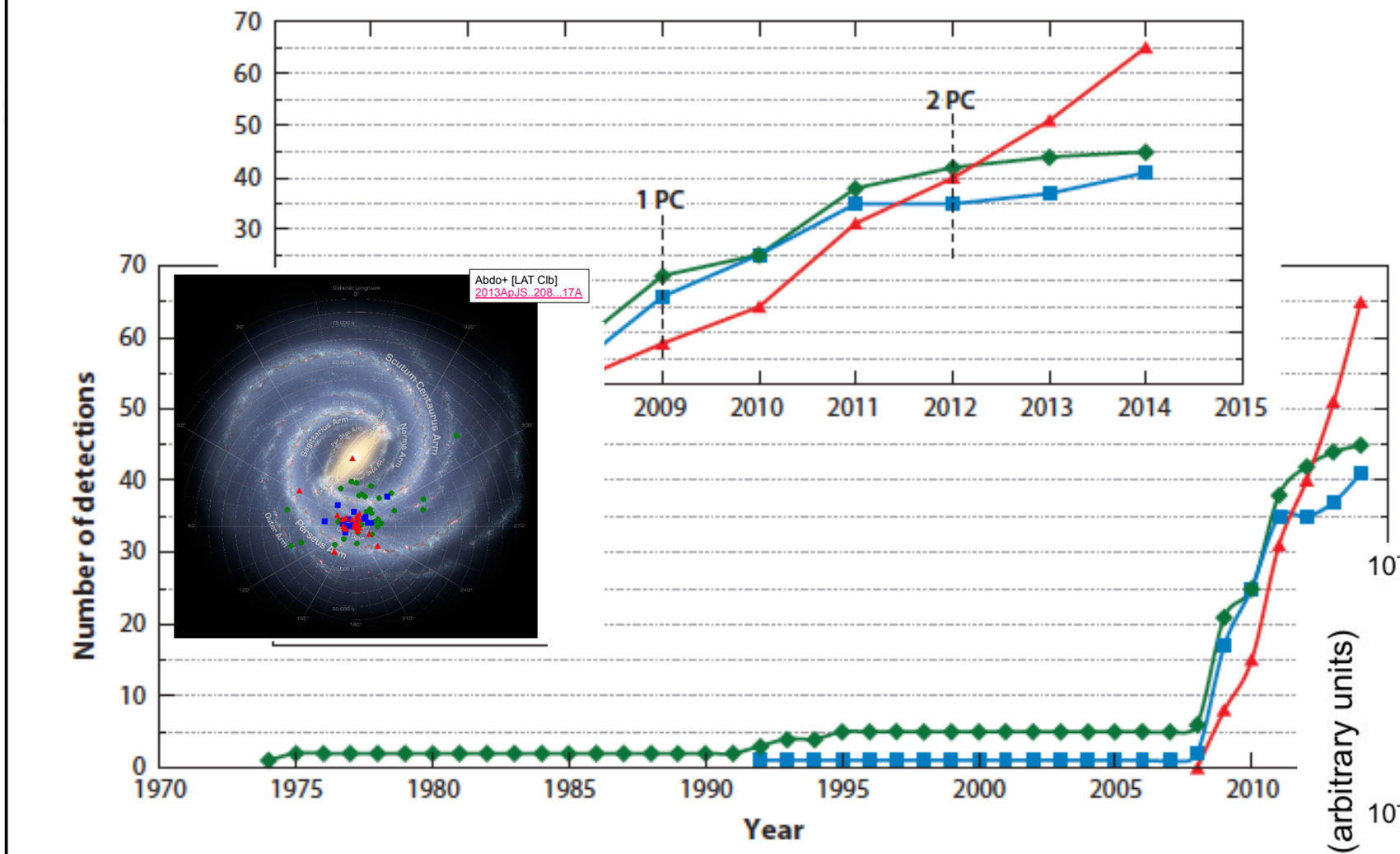
GC

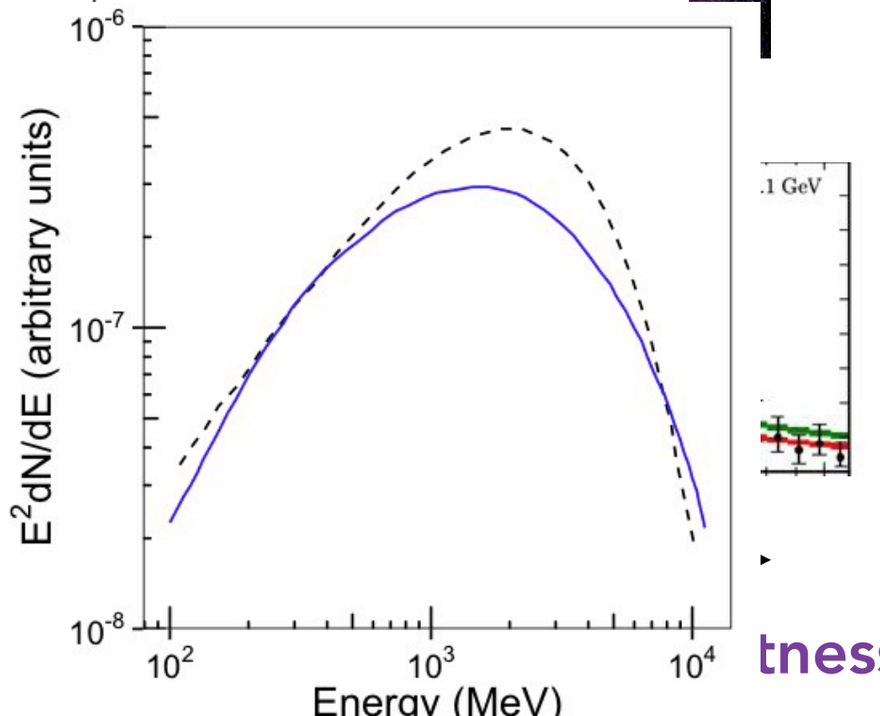
Cosmological signal/U

- Spectral flux

Signal spectrally and morphological consistent with thermal DM detected since ~2010s

- Could it be 'it'?
- 'unexpected' backgrounds - pulsars - only few detected before Fermi, now the most abundant gamma ray source in the galaxy





[adapted from: H.-S. Zechlin]

tness

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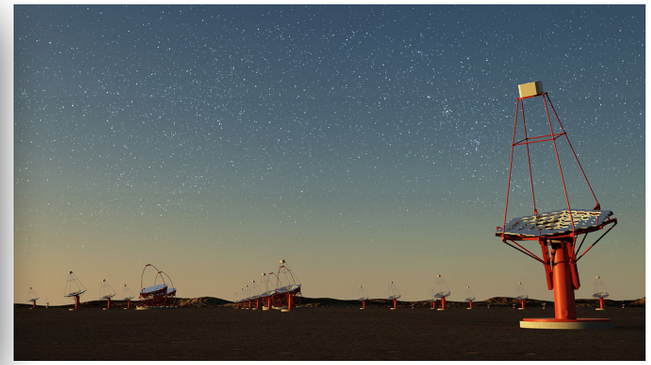

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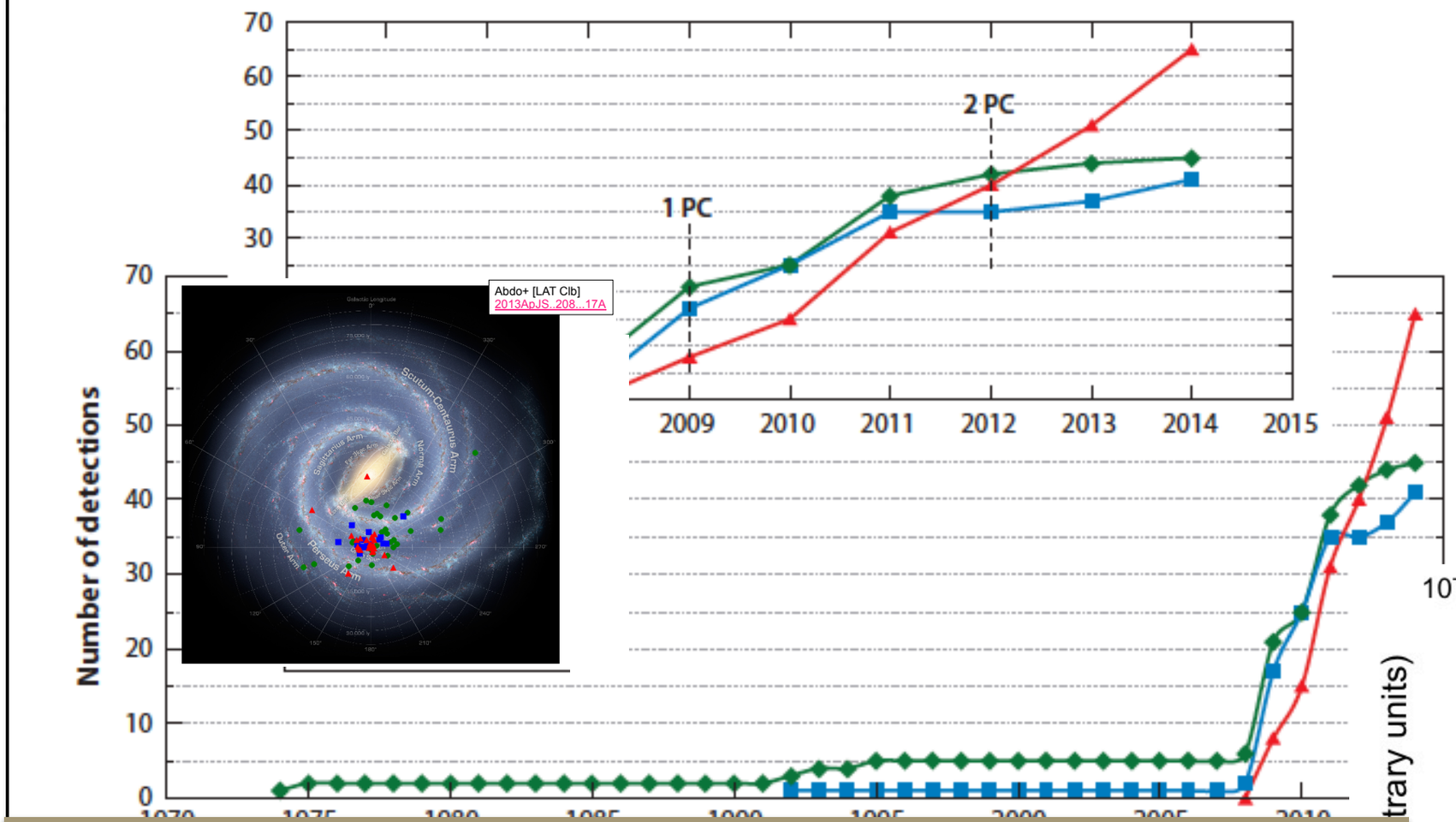
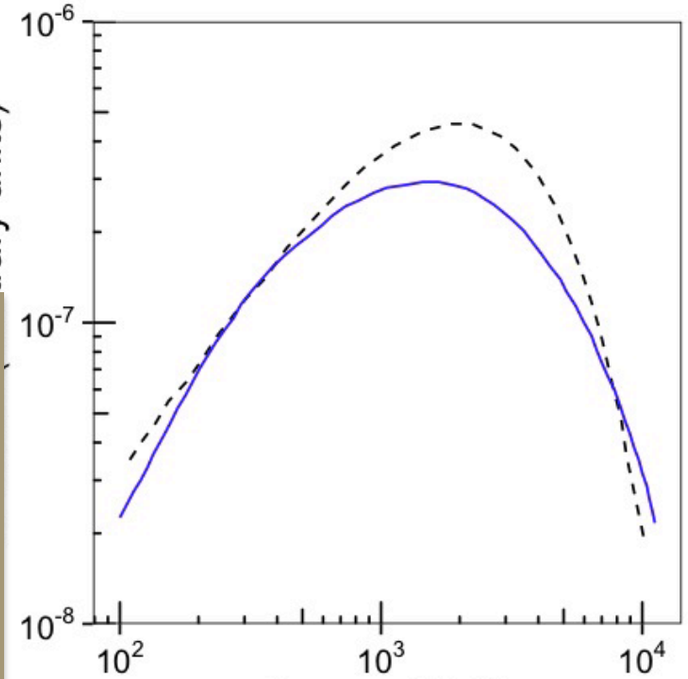




Evidence for pulsars building up (wavelets (Bartels+ (PRL 2016)), 1DPDF (Lee+, PRL 2016)…)

Future tests:

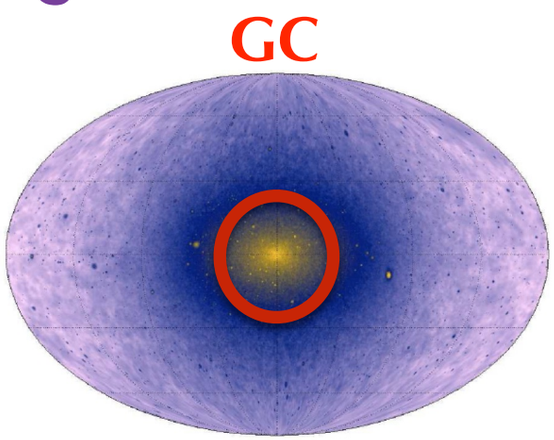
— **SKA** should detect o(100) MSPs (Calore+, ApJ 2016)

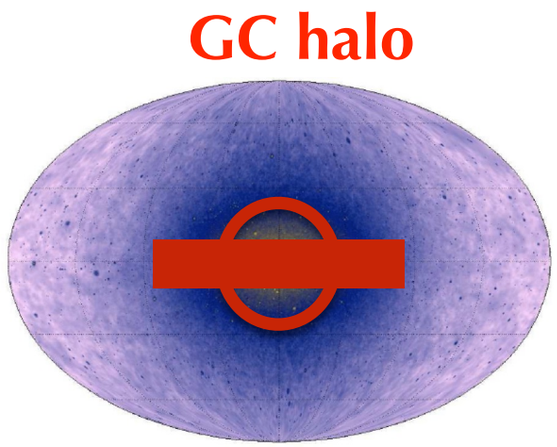
— **GWs** from pulsars should also be observable (Calore+, PRL 2019)

tness

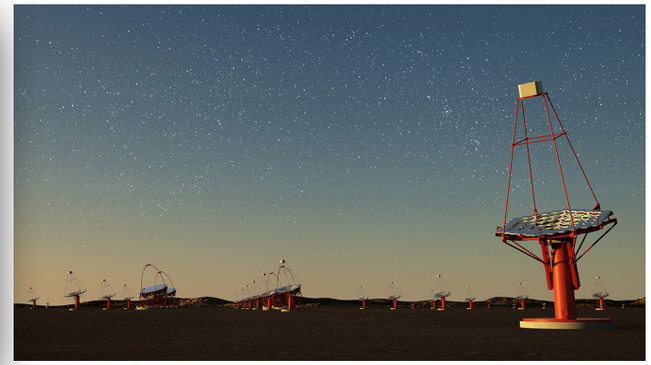
Status of the search

signal strength





For DM interpretation, multi-target tests are essential —> dwarf spheroidal galaxies!



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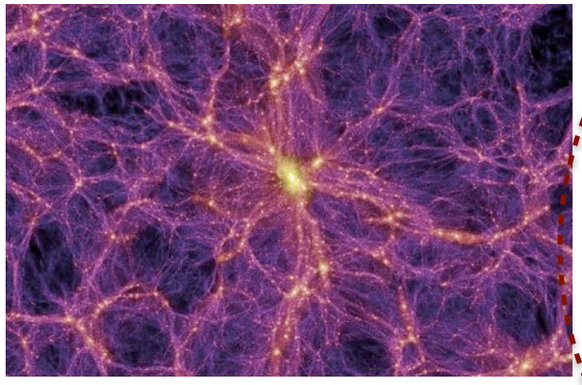

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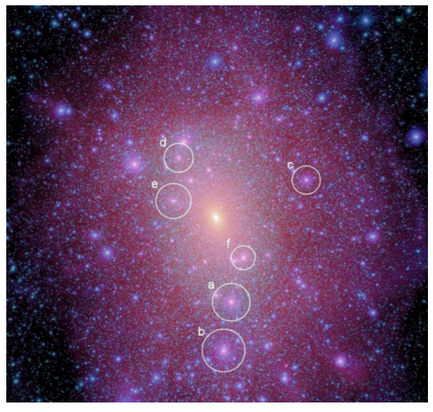
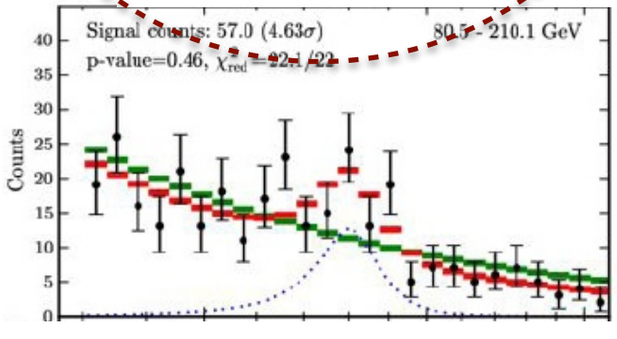


spectral line

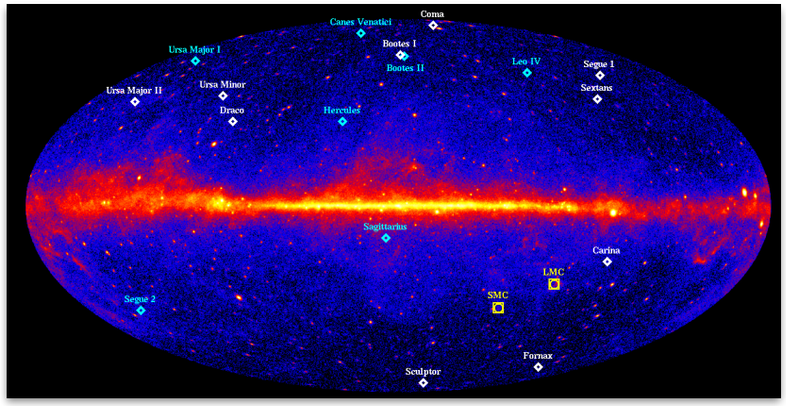


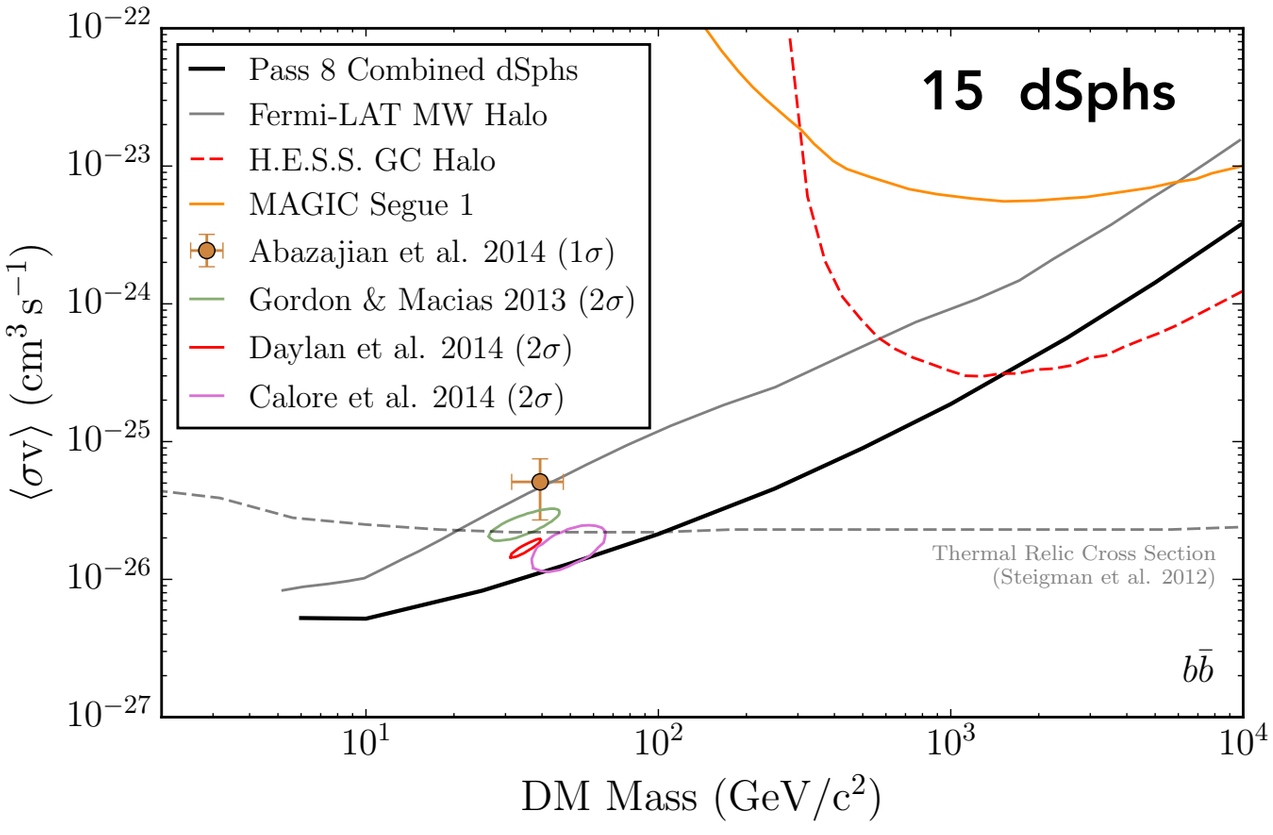
[adapted from: H.-S. Zechlin]

robustness

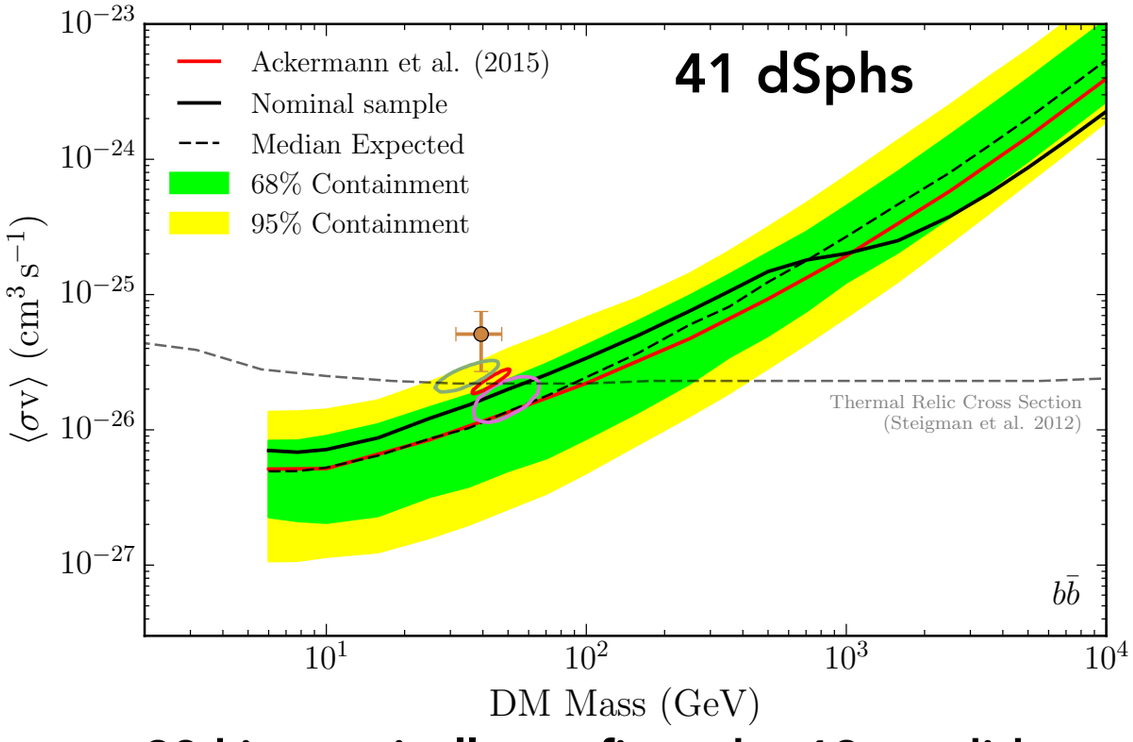
DM search in dSph galaxies

Using the joint likelihood to combine info from **a set of dSphs, taking into account the uncertainties in their DM content —> one of the strongest DM limits to date**





[Ackermann+, PRL,1503.02641]



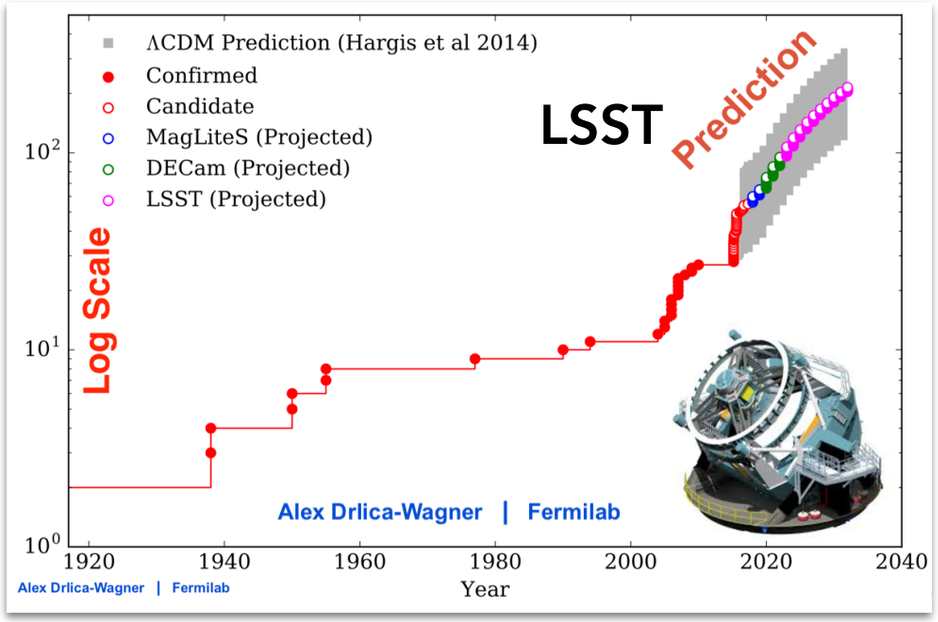
28 kinematically confirmed + 13 candidates

('nominal' sample)

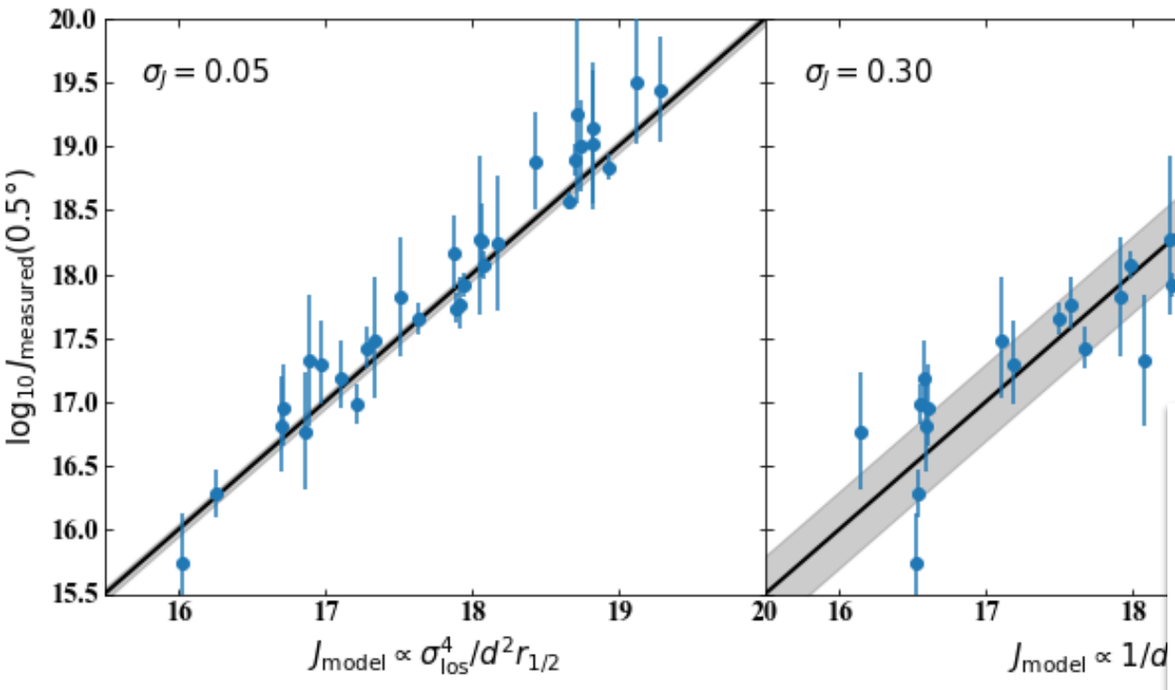
[A. Albert+, ApJ (2017)]

dSphs - next steps

More 'dSPh-candidates', expected **hundreds** of new dSphs with LSST (Hagris+, ApJL (2014))

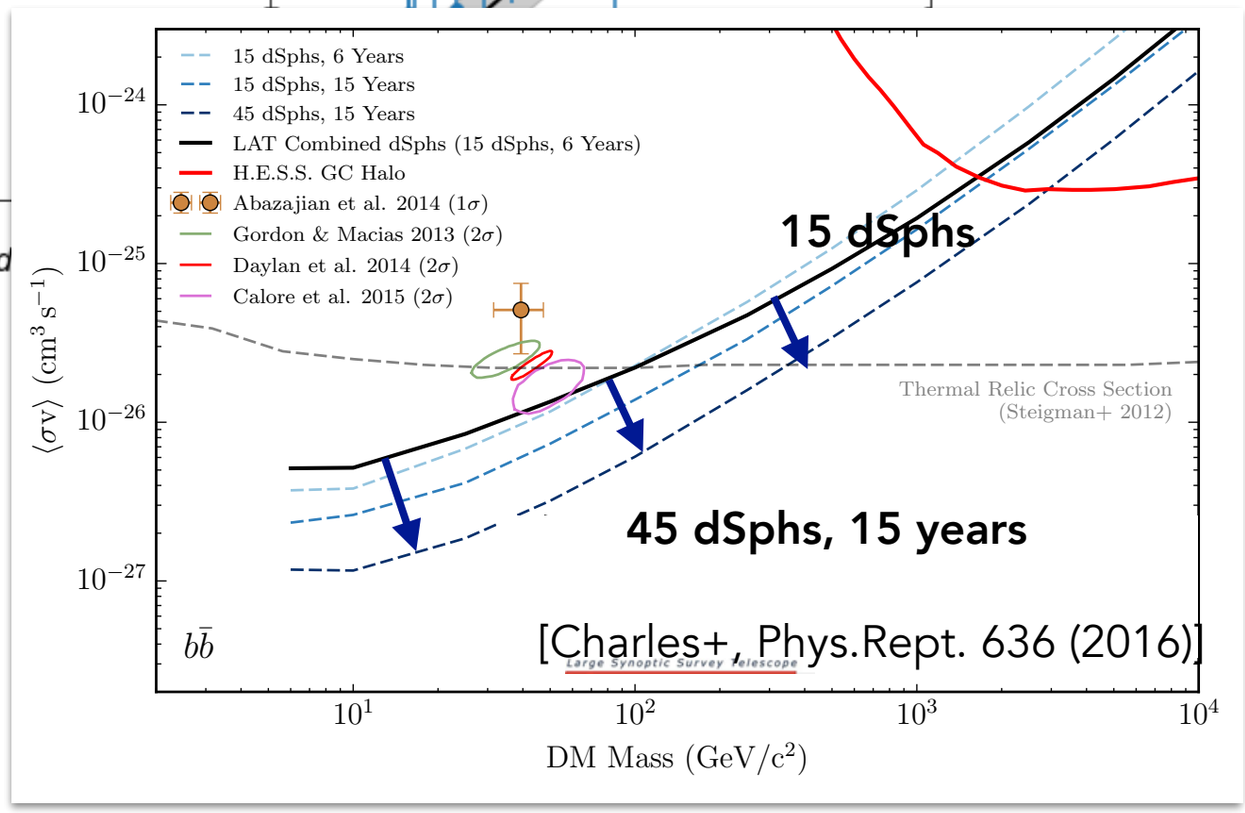


BUT, kinematic follow-ups time-consuming, need to use **scaling relations**



[Pace&Strigari, 1802.06811]

Currently: performing an analysis with >10years of P305 data with the most updated list (~50) of dSphs.



Status of the search

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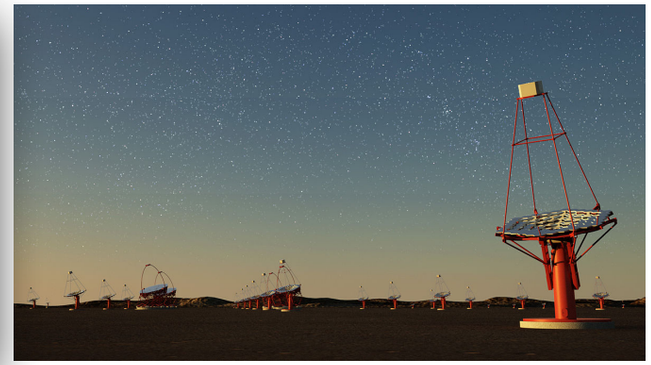
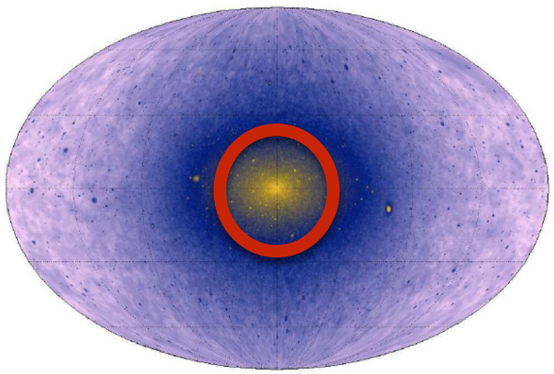
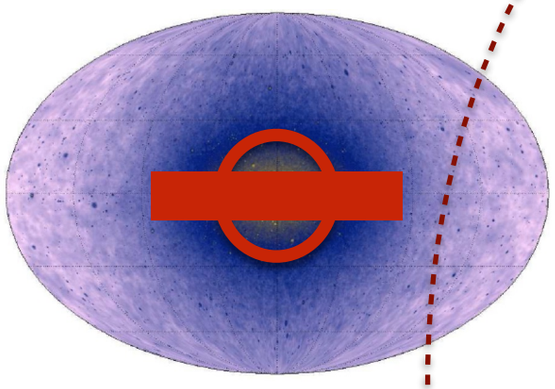


GC



GC halo



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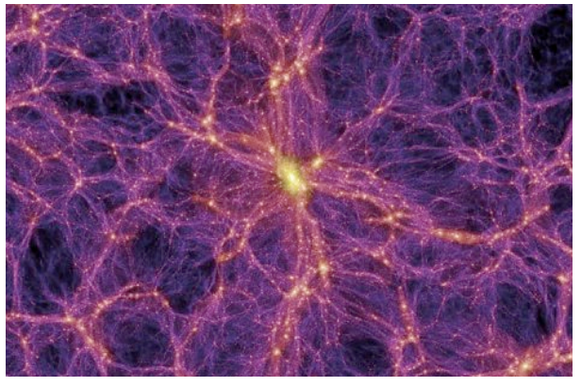

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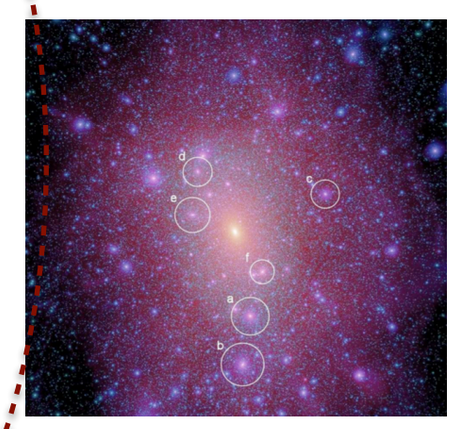

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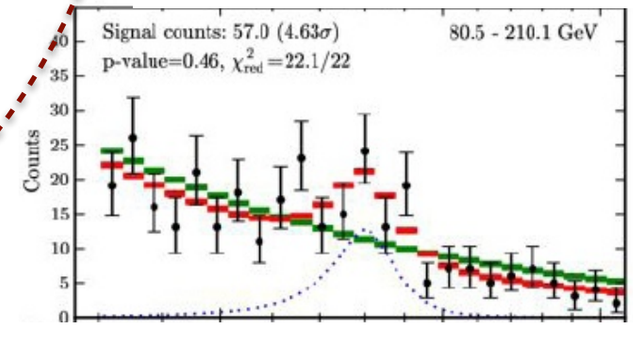
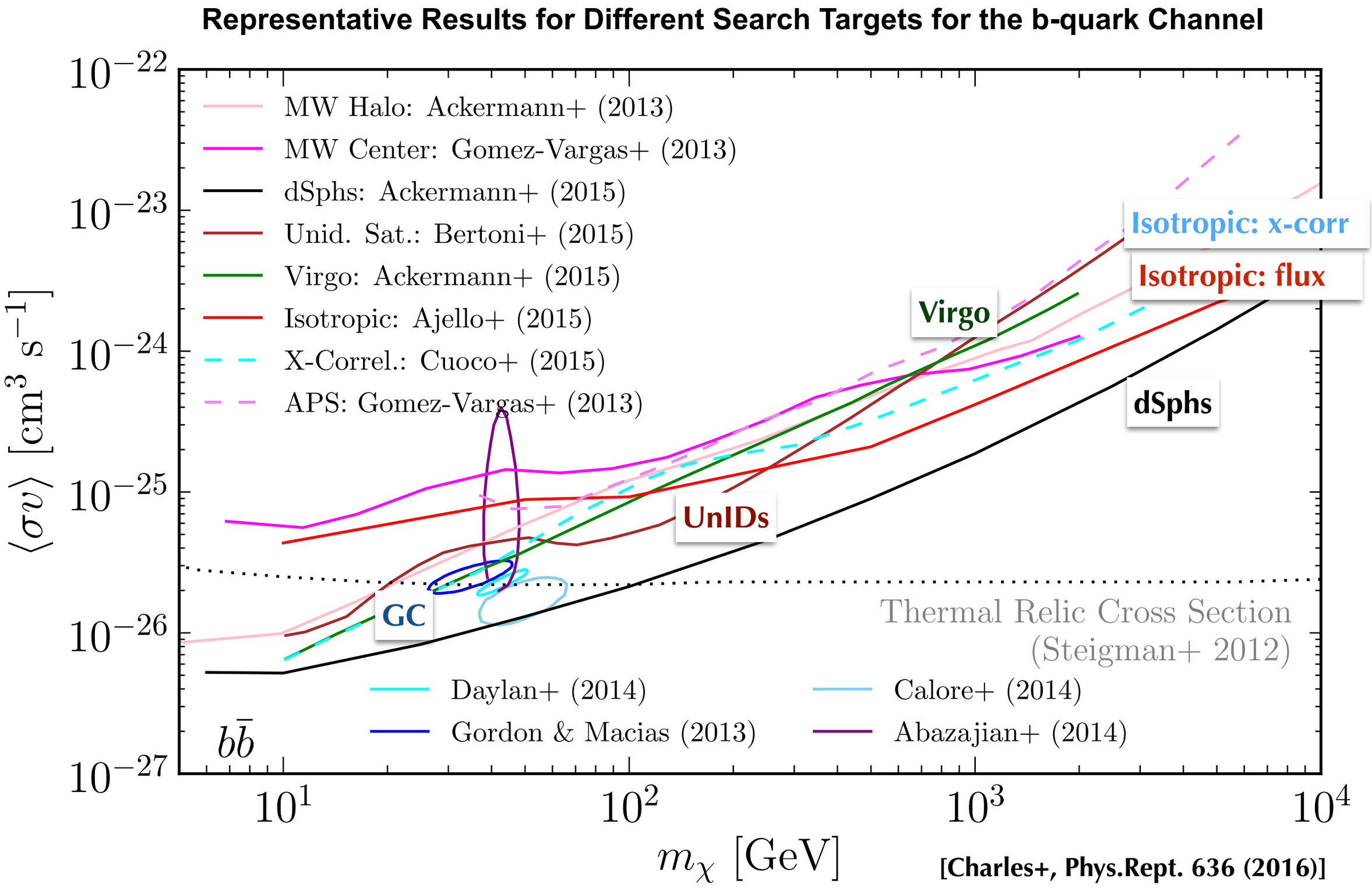


[adapted from: H.-S. Zechlin]

robustness

The status of the LAT WIMP search (cca 2016)



[Charles+, Phys.Rept. 636 (2016)]

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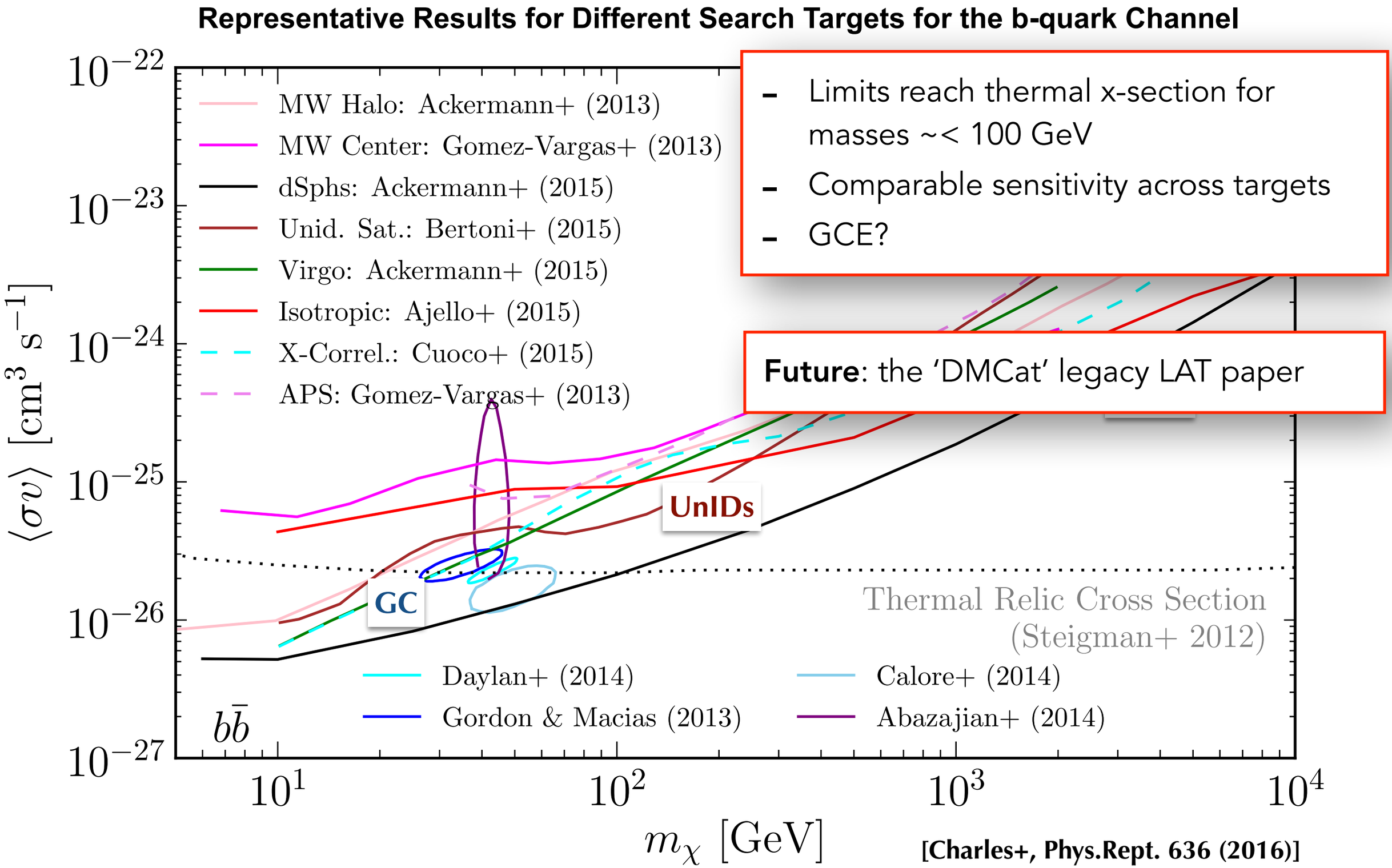


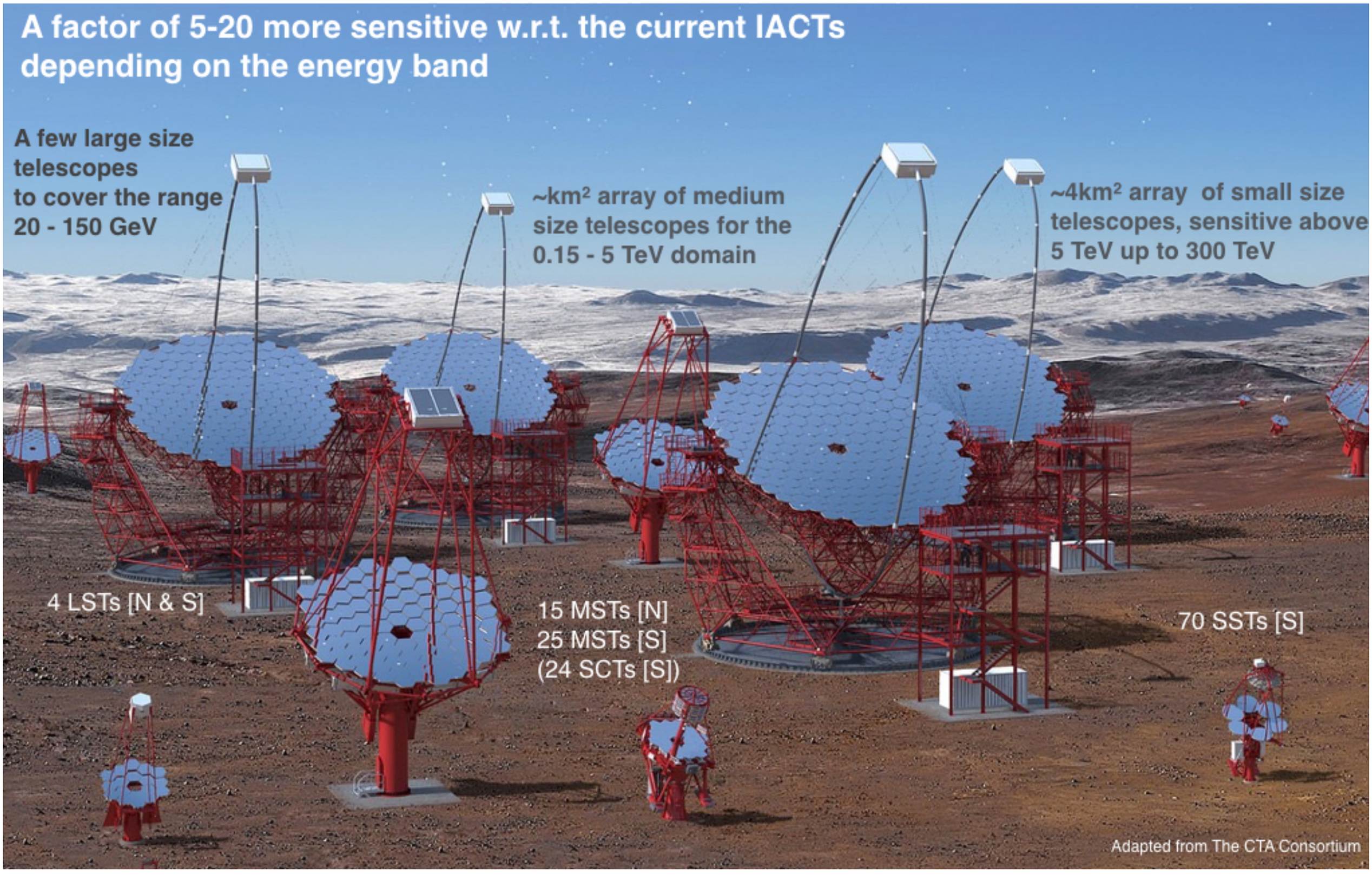
- Limits reach thermal x-section for masses ~< 100 GeV
- Comparable sensitivity across targets
- GCE?

Future: the 'DMCat' legacy LAT paper

[Charles+, Phys.Rept. 636 (2016)]

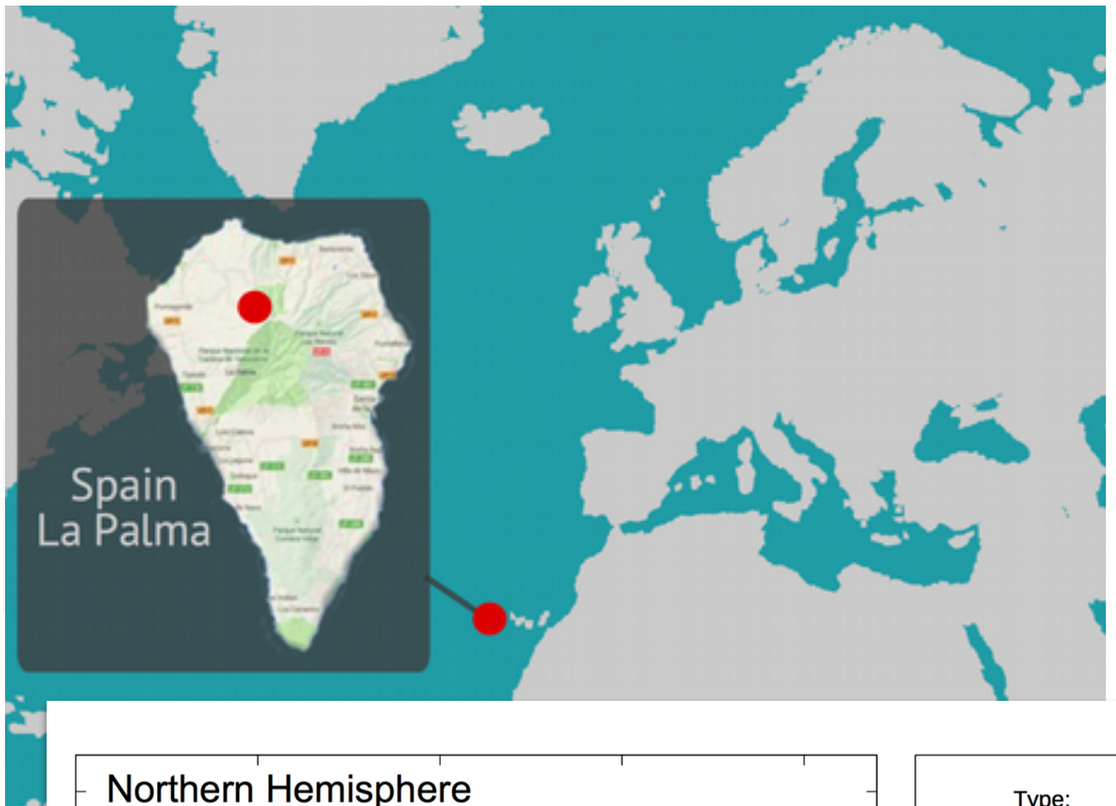
The future? CTA - Cherenkov Telescope Array

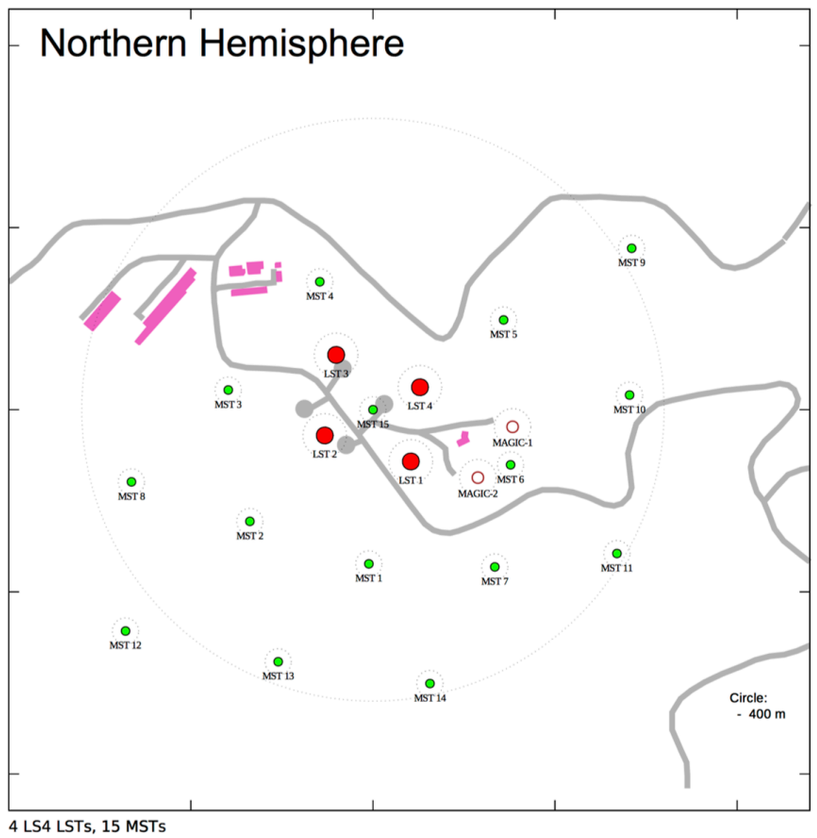
one of the biggest projects in high energy astrophysics

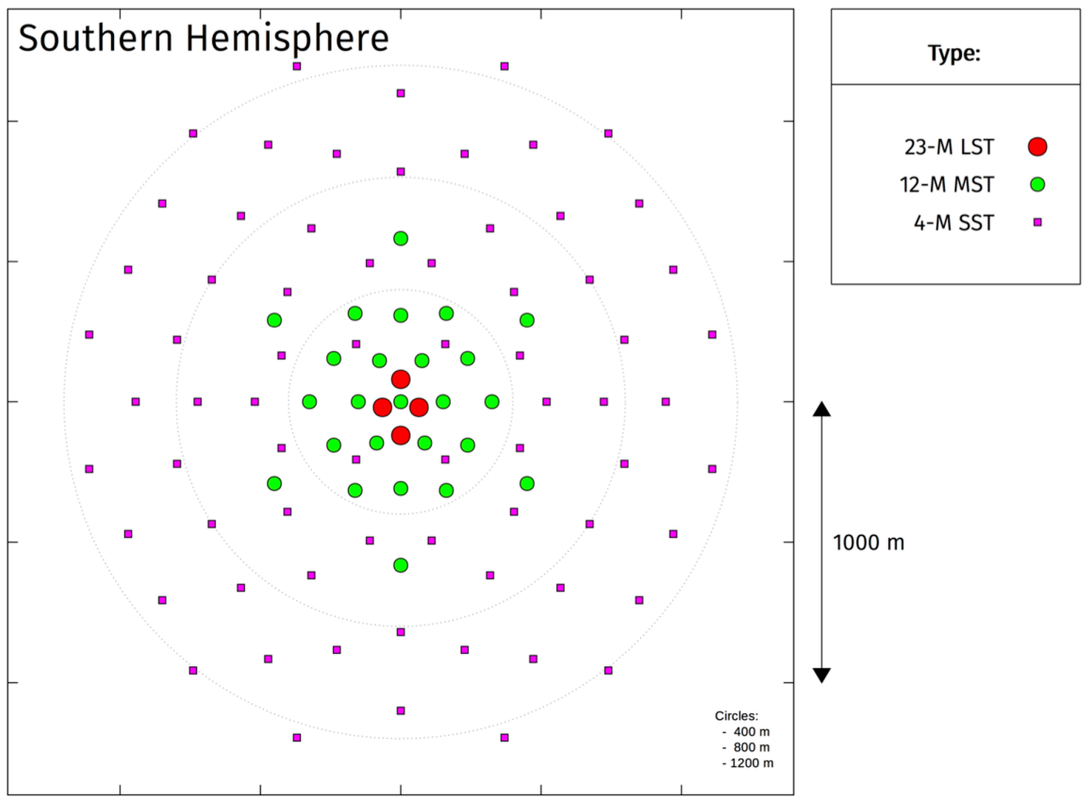


CTA

sites and example telescope layouts



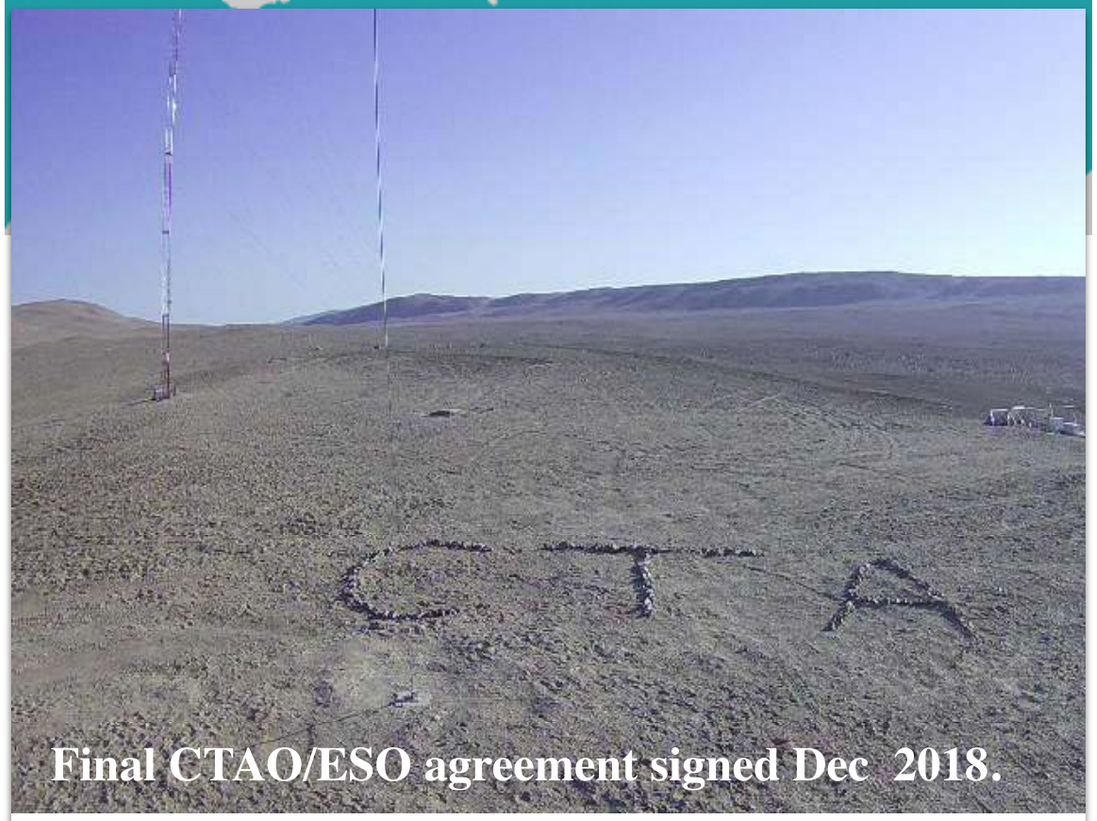




[www.cta-observatory.org]

CTA

sites and example telescope layouts

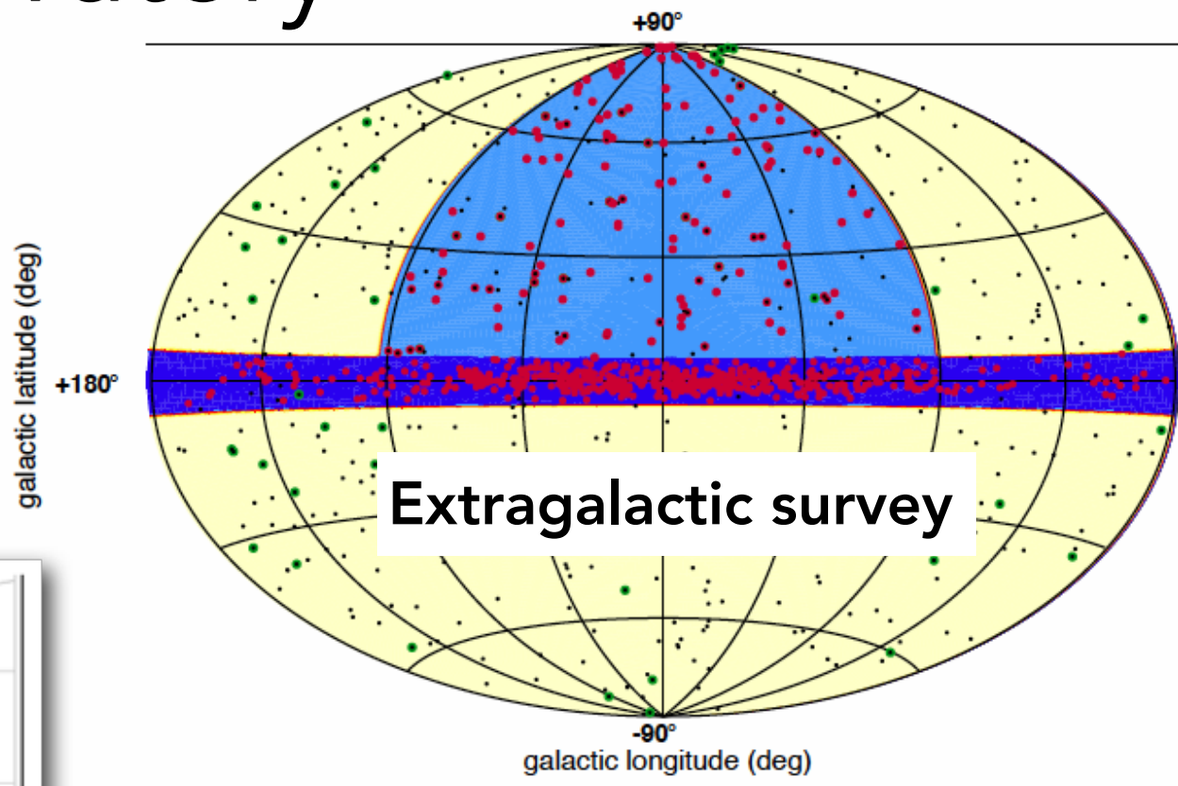


CTA-S location (Paranal)

CTA as a whole-sky observatory

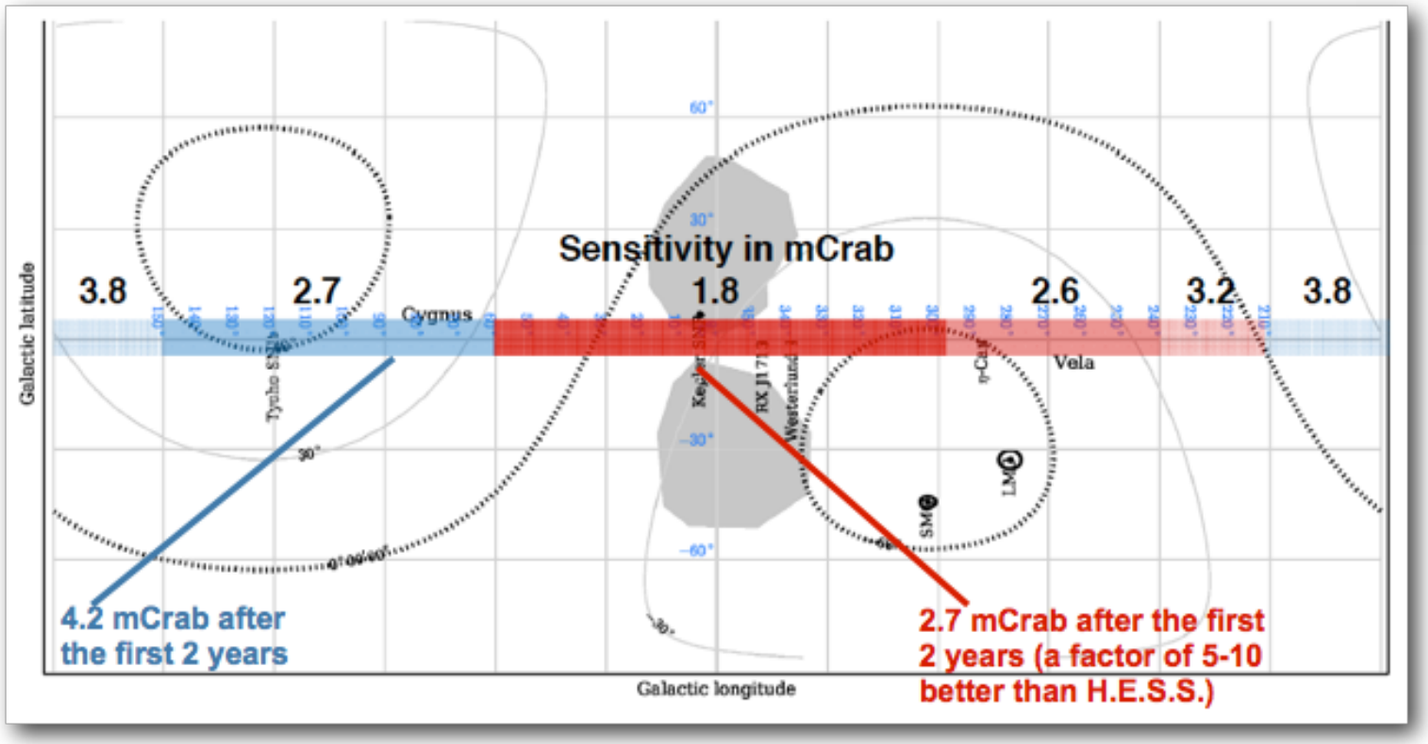
Novel observational strategy: **sky surveys**

(thanks to a large number of CTA telescopes)



1/4 of the sky (~10^4 deg^2) Limiting flux ~ 5 mCrab

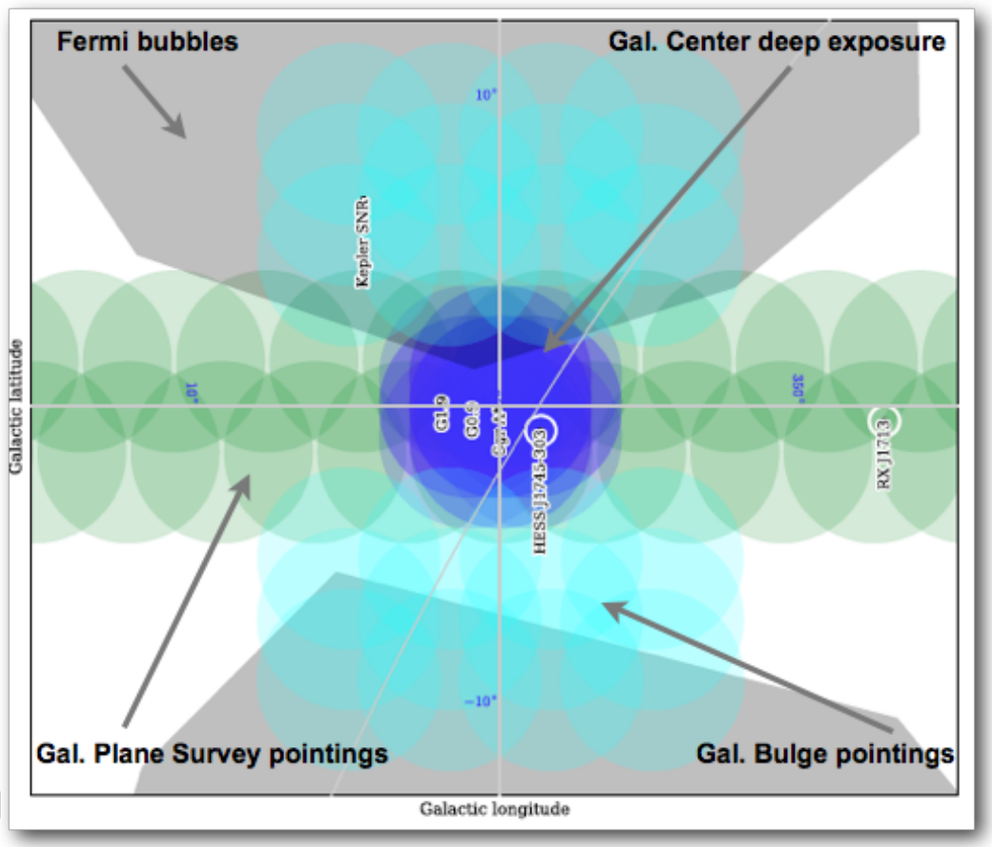
Galactic plane survey



Galactic centre

525 h deep exposure to uniformly cover the central 5 deg

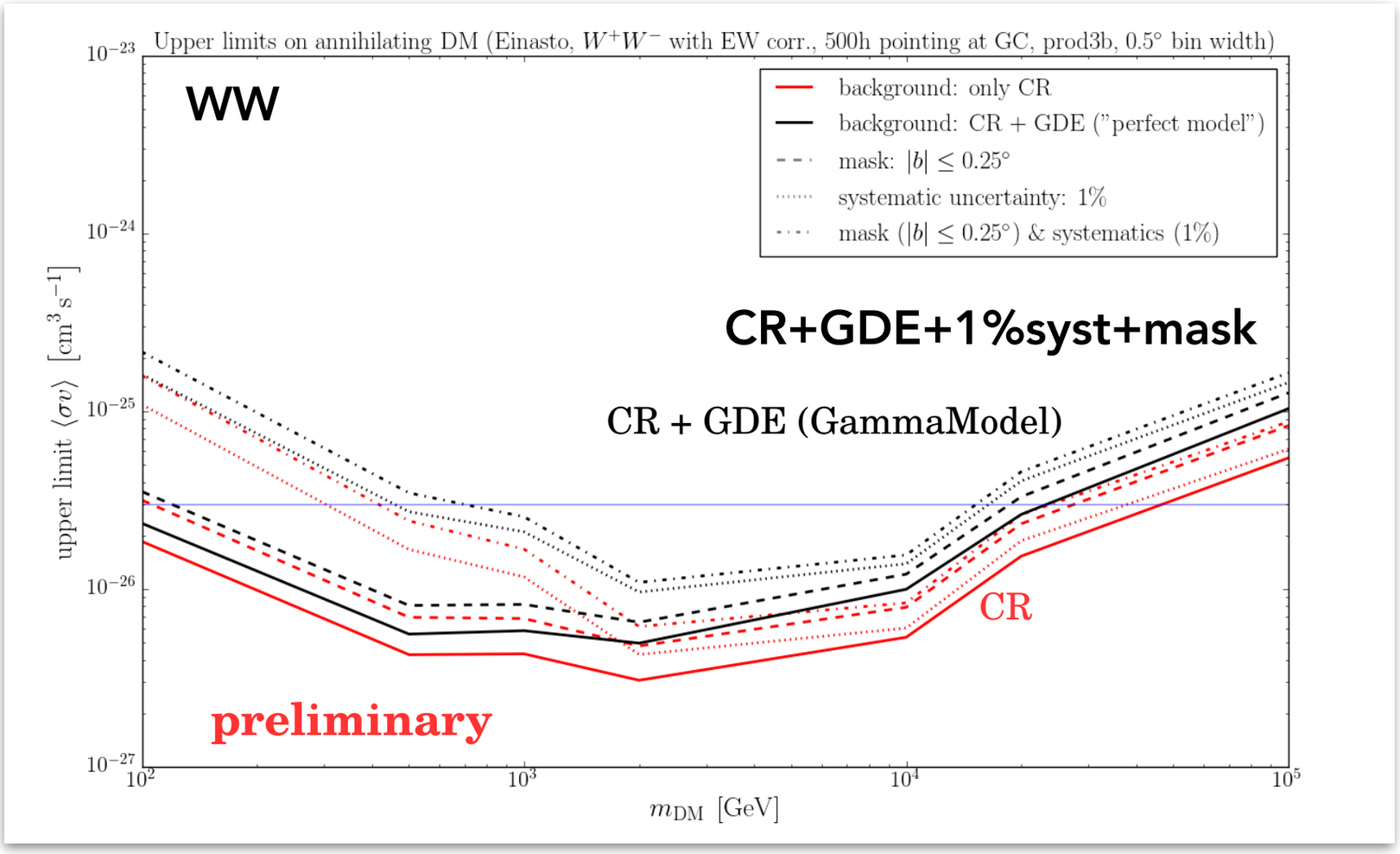
+ 300 h extended survey,10x10 deg

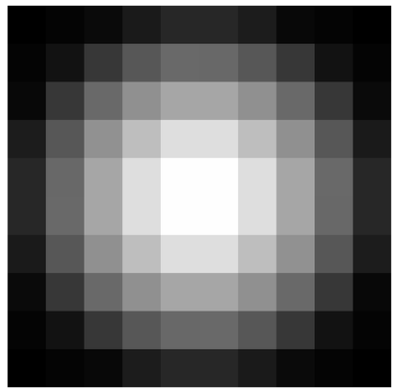


CTA DM sensitivity

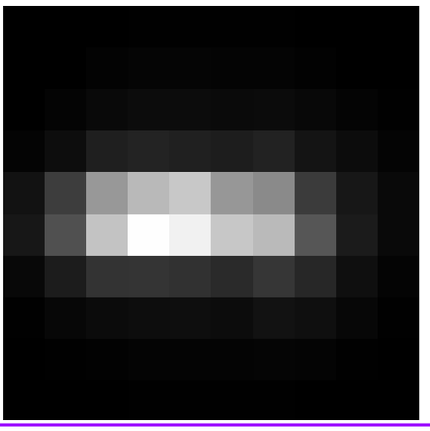
Some results:

→ Galactic center

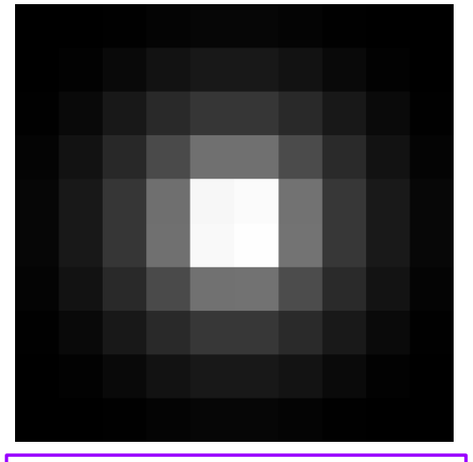




Cosmic Ray (CR) background



Galactic Diffuse Emission (GDE)



Dark Matter (DM) Signal

Consortium publication in prep:

- **'template' fitting *a la* Fermi**
- **astrophysical backgrounds from Fermi LAT + HESS**

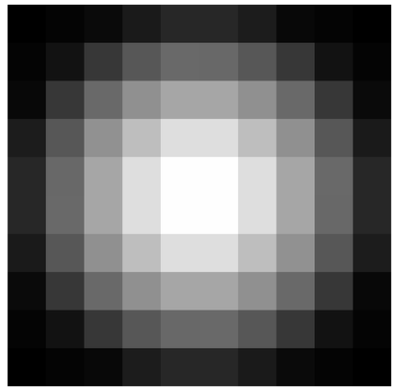
CTA DM sensitivity

Some results:

→ Galactic center

Description of all Key Science projects

In-depth analyses ongoing!



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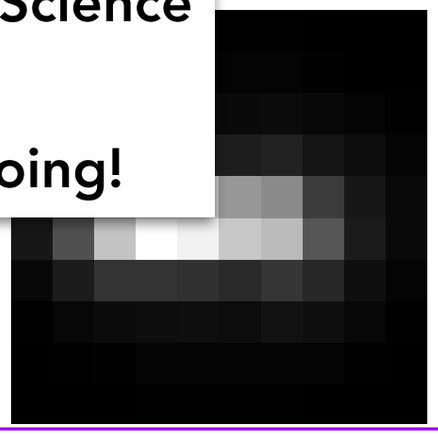

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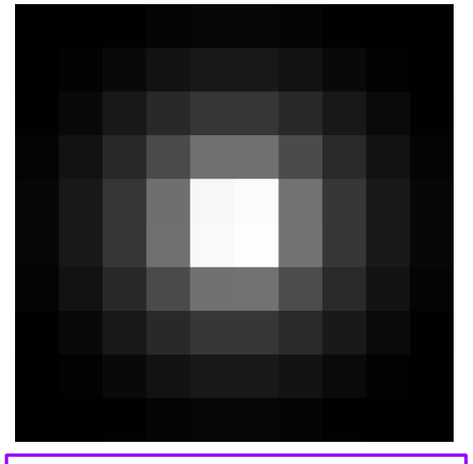


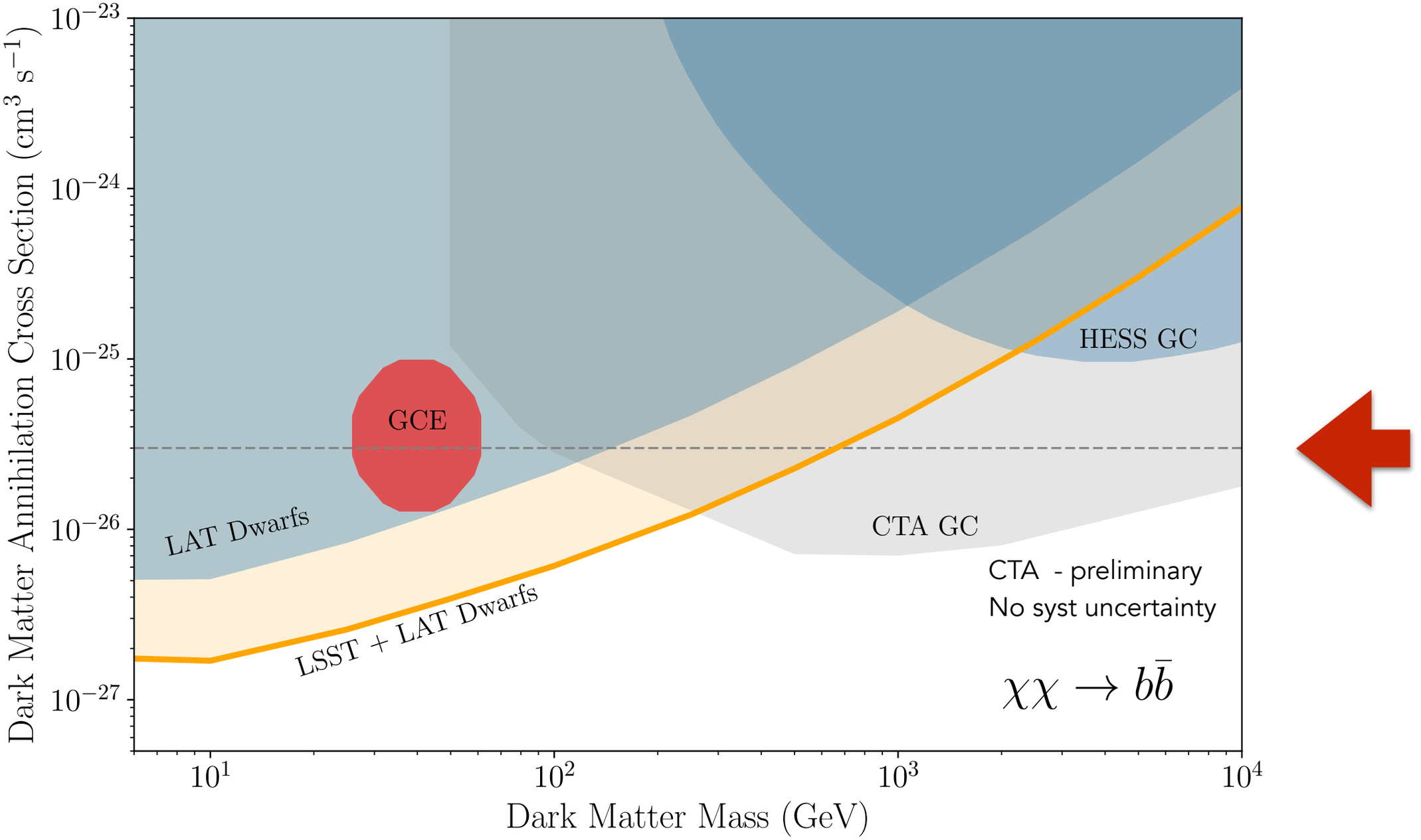
Dark Matter (DM) Signal

+ dSphs, + LMC, etc

Future?

LAT + CTA + complementary probes (LSST, Euclid, +…)

will test **vanilla thermal DM over the whole range 10 GeV- ~>10 TeV**



[Probing the Fundamental Nature of Dark Matter with the LSST, Drlica-Wagner+, 2019]

Charged cosmic rays - the precision era

DM limits:

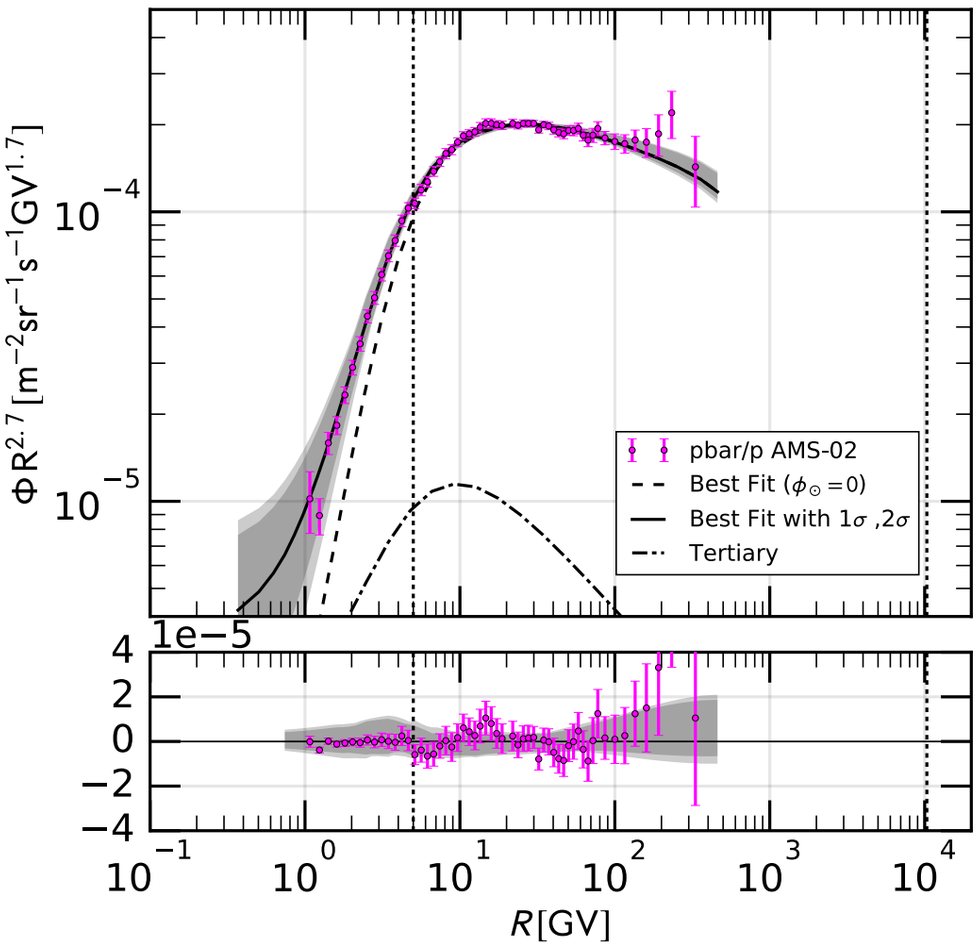
Antiprotons - one of the most sensitive probes of new physics

— p spectra measured exquisitely well

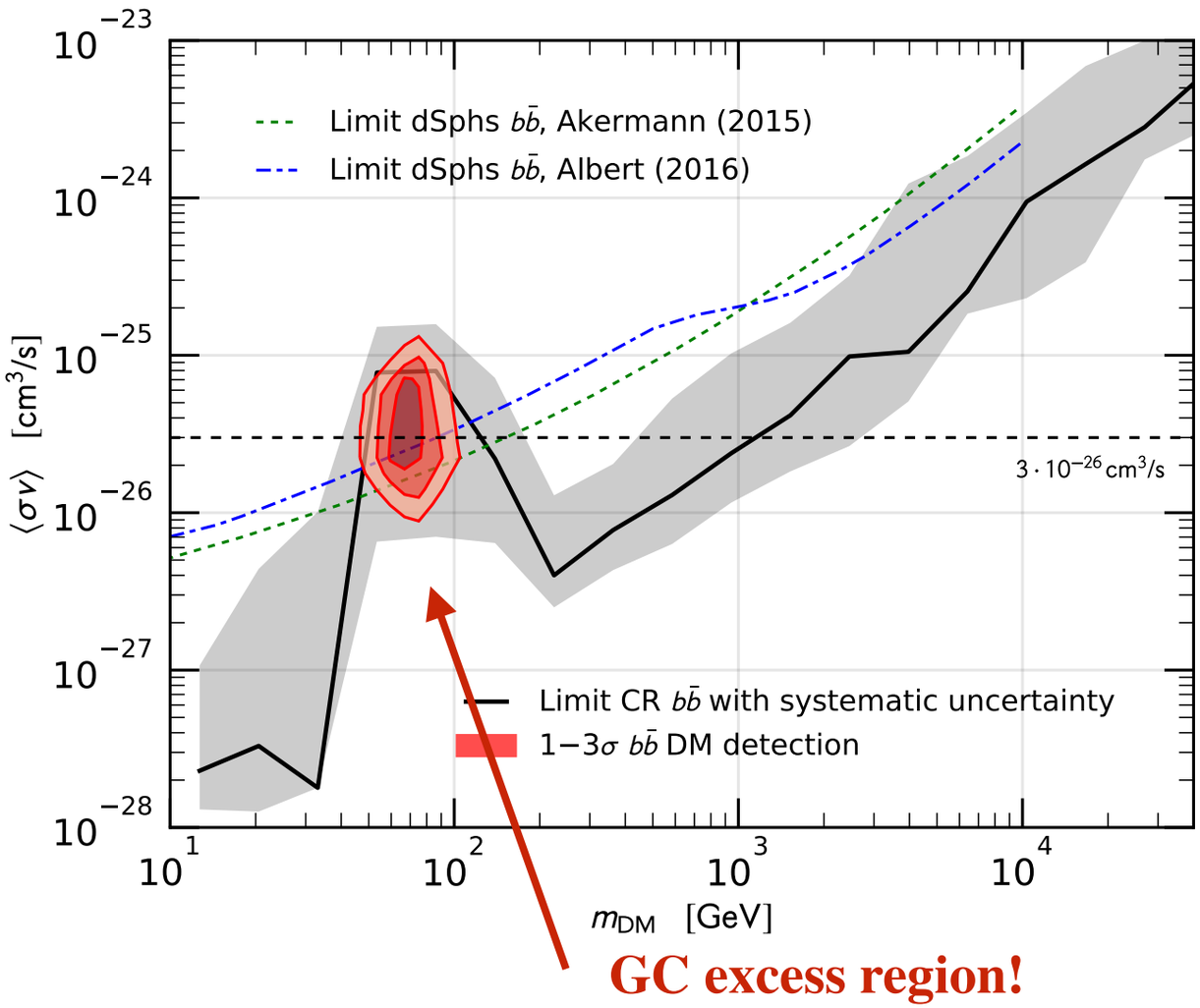
— anti-p produced as secondaries, with the proton spectra as the source term

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

An excess of~10-20 GeV cosmic-ray antiprotons



[Cuoco+, PRL 118(2016),
Gielsen+, JCAP1509 (2015), …
Cholis+ (2019) - significance 3.3σ-4.7σ]



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

Charged cosmic rays - the precision era

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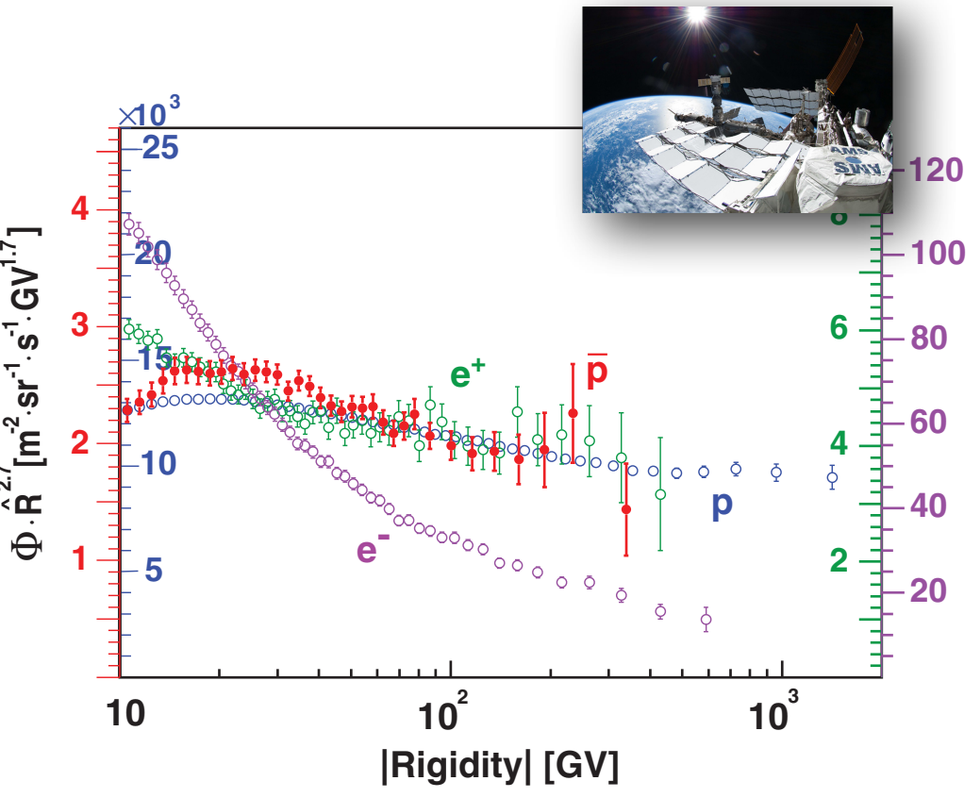
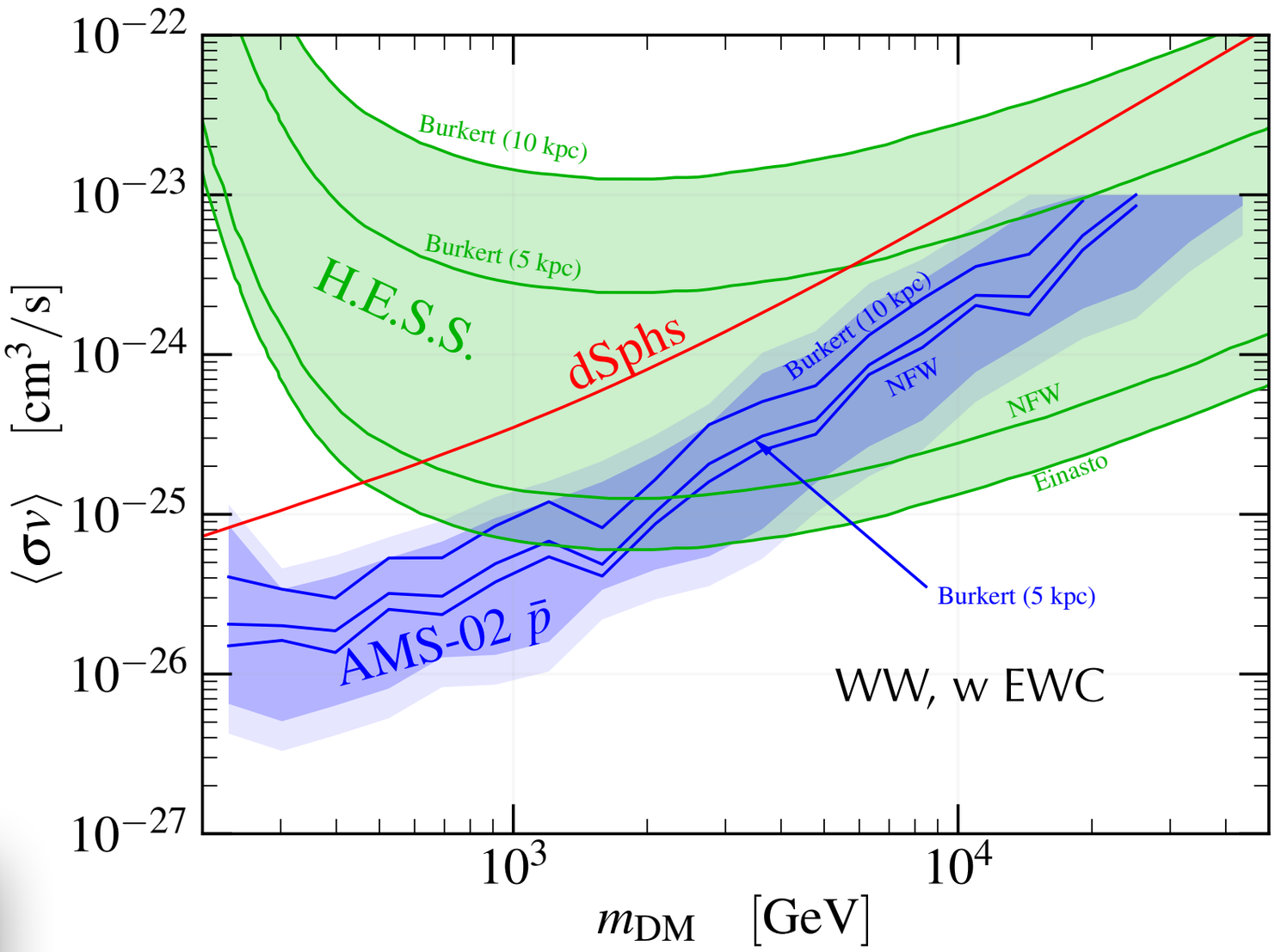


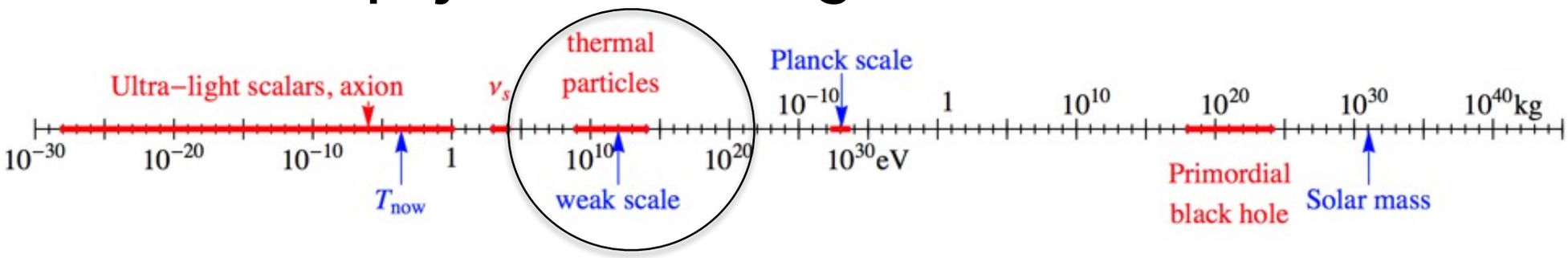
[Aguilar+, PRL117 (2014)]

Note strong limits at high >~100 GeV masses



[Cuoco+, JCAP1804 (2018)]

Searches in astrophysical/cosmological data - i.e. in the DM's 'natural habitat'



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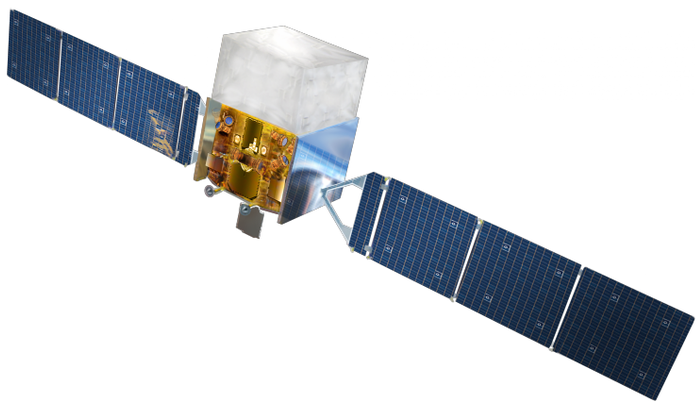

γ, ν, $e^{\pm}$, $p^{\pm}$ D^{-}

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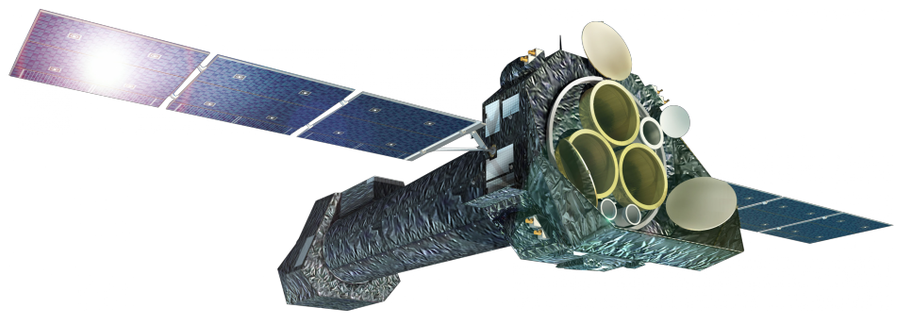

γ, ν

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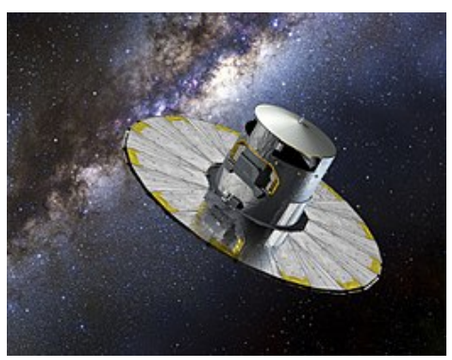
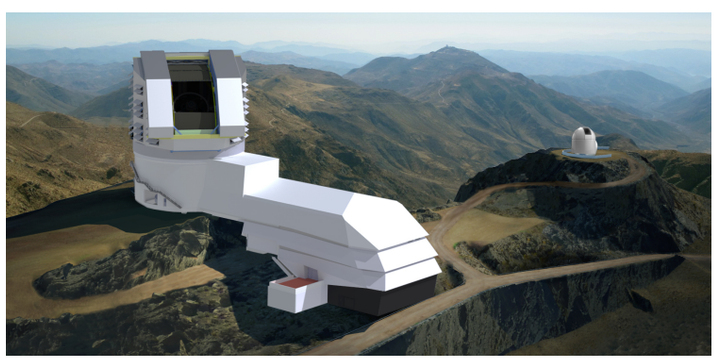
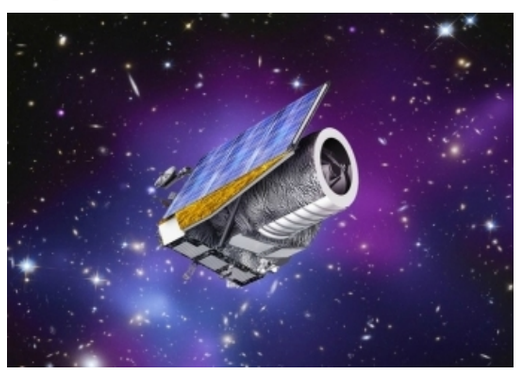
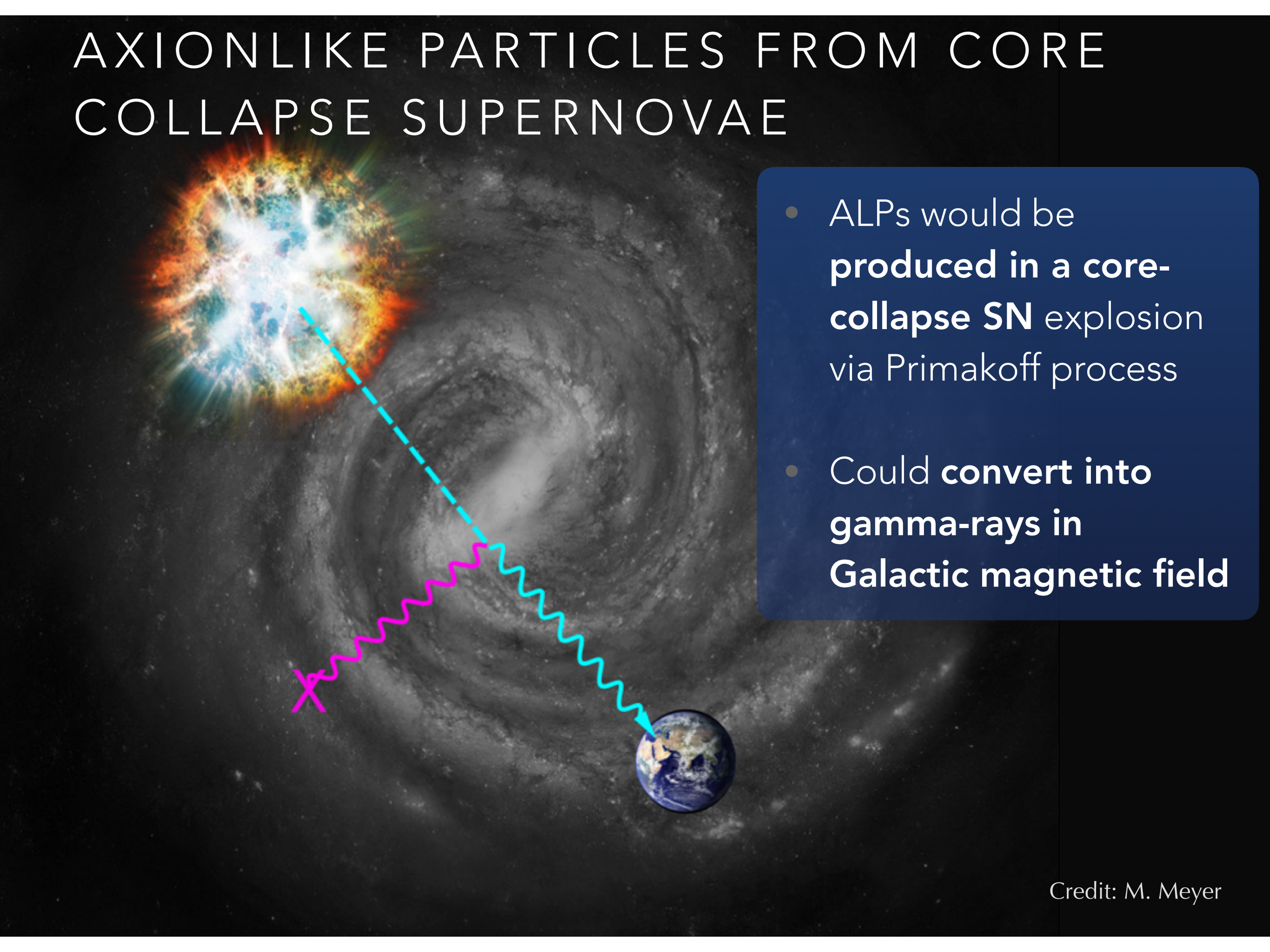






Gravitational probes

AXIONLIKE PARTICLES FROM CORE COLLAPSE SUPERNOVAE



- ALPs would be **produced in a core-collapse SN** explosion via Primakoff process
- Could **convert into gamma-rays in Galactic magnetic field**

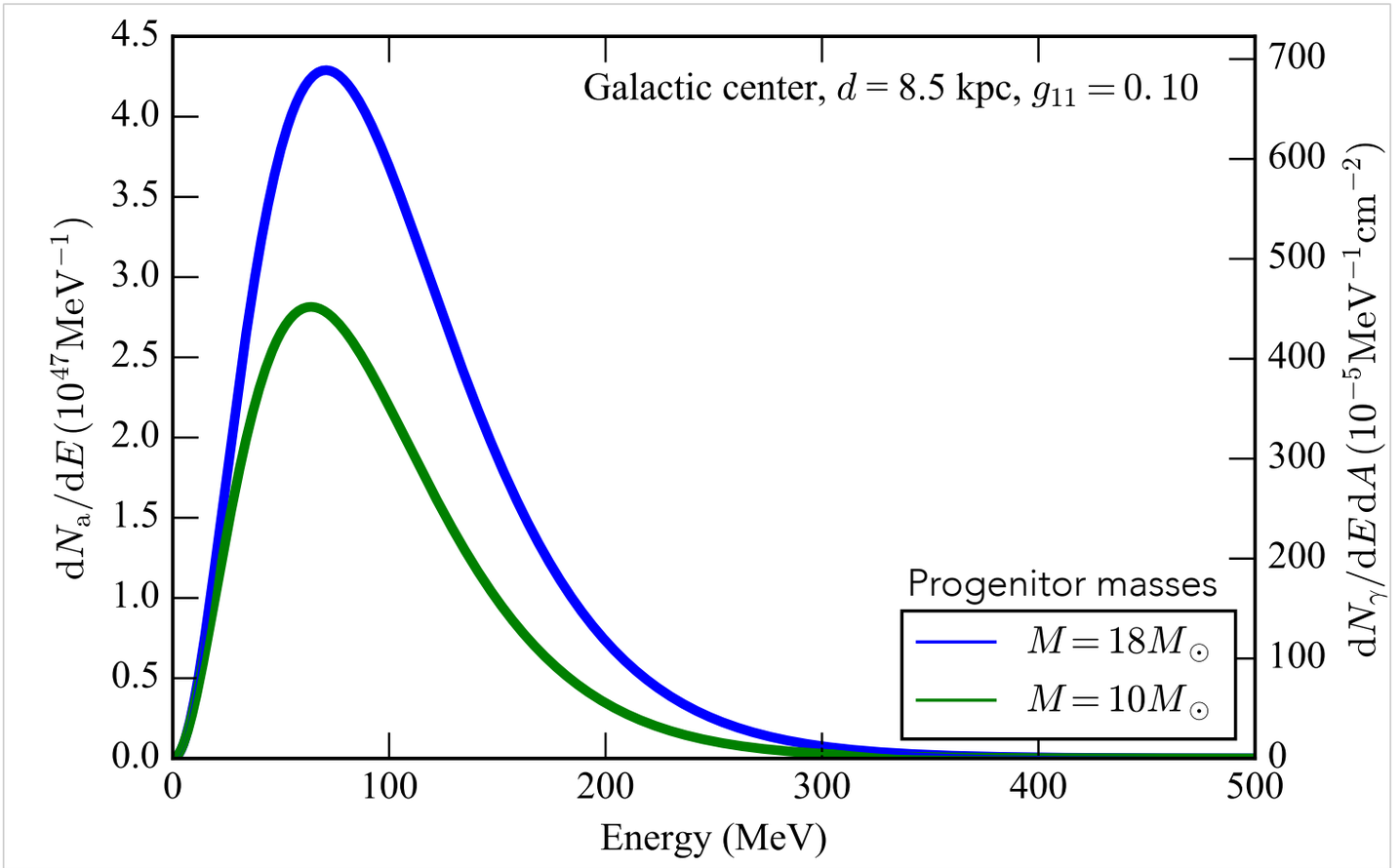
Credit: M. Meyer

EXPECTED ALP SIGNAL

- ALPs produced in SN core within ~10 s after explosion and escape core ➜ **short burst**
- **Spectrum** has thermal-like shape, **peaks at ~50 MeV**
- **Gamma rays would arrive co-incident with SN neutrinos** (provides time tag)

Credit: M. Meyer

ALP / ɣ-ray flux integrated over explosion time

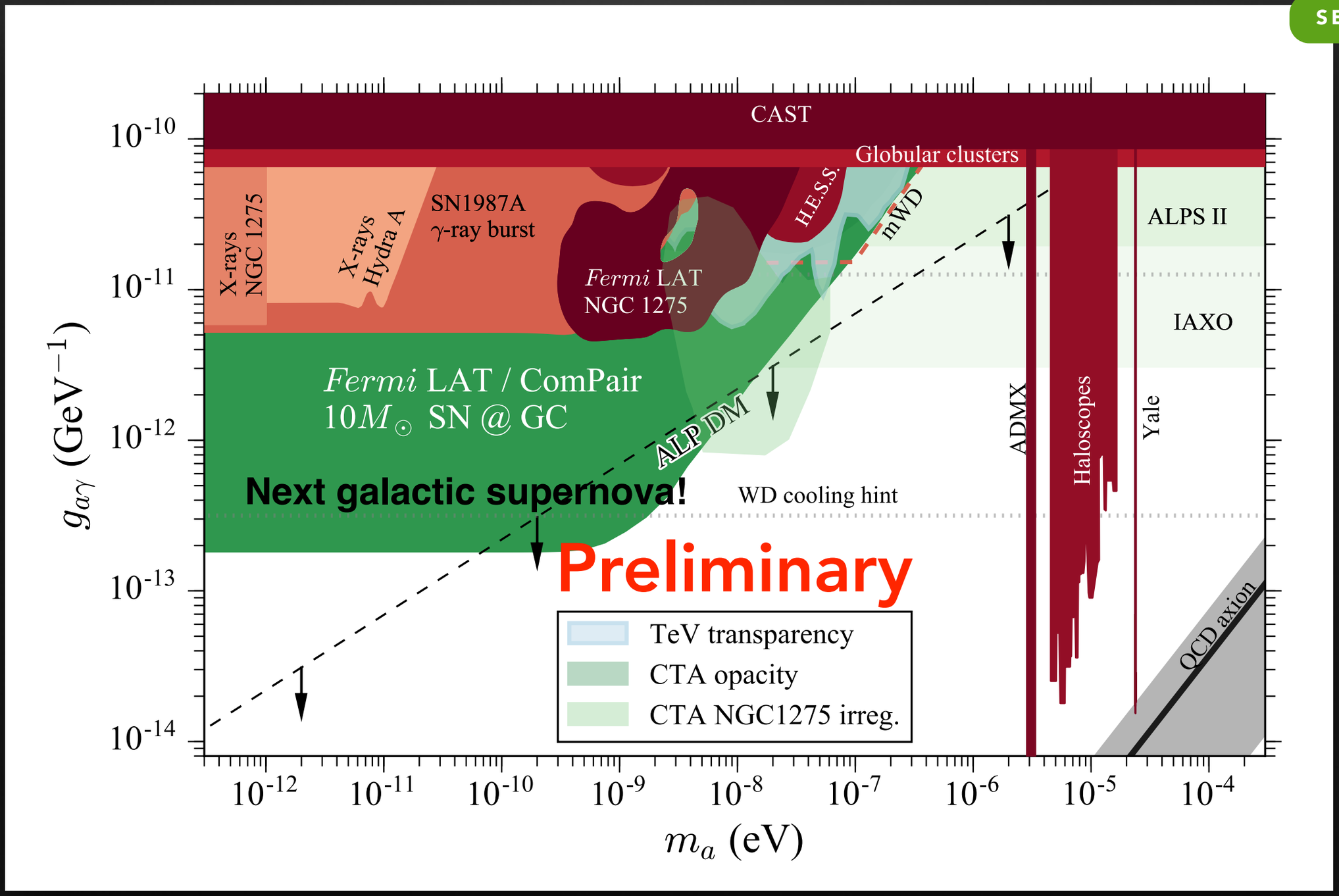


Better **gamma-ray sensitivity and large FoV** of *Fermi* LAT promise **unparalleled sensitivity** for ALPs in case of a Galactic core-collapse SN within *Fermi*-LAT lifetime and FoV

CONSTRAINTS & SENSITIVITIES

LIMITS

SENSITIVITIES



Credit: M. Meyer

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde, accepted in PRL. ArXiv:1609.02350]

CONSTRAINTS & SENSITIVITIES

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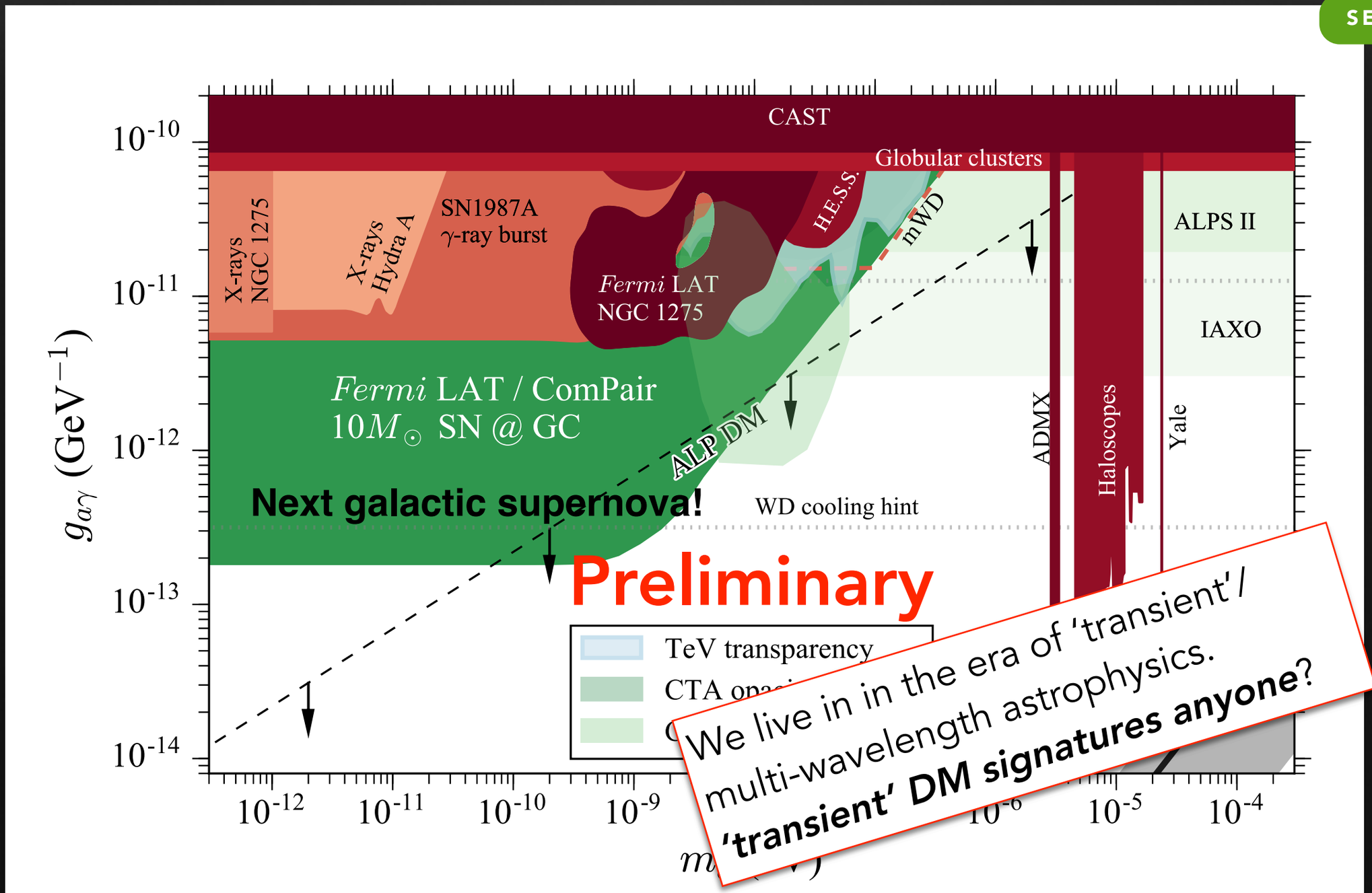

We live in in the era of 'transient'/ multi-wavelength astrophysics.
'transient' DM signatures anyone?

Credit: M. Meyer

[MM; M. Giannotti, A. Mirizzi, J. Conrad; M. Sanchez-Conde, accepted in PRL. ArXiv:1609.02350]

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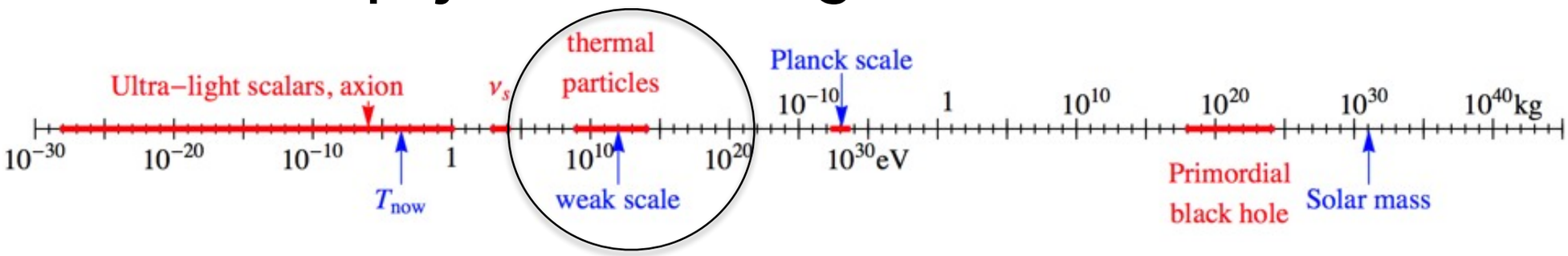

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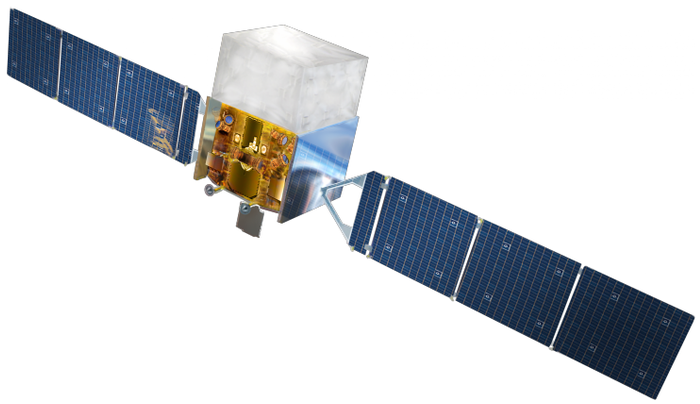

γ, ν, $e^{\pm}$, $p^{\pm}$ D-

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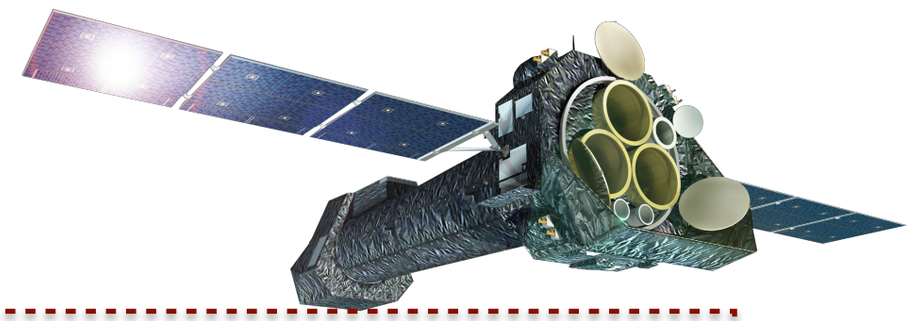

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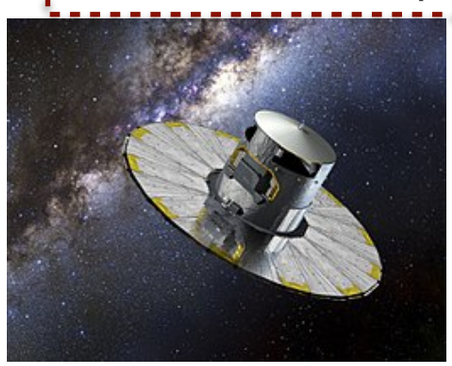
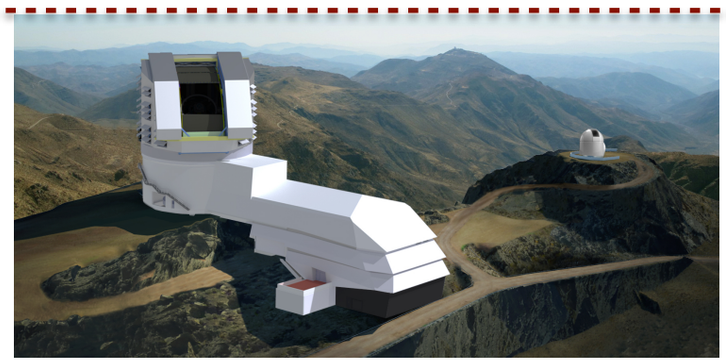
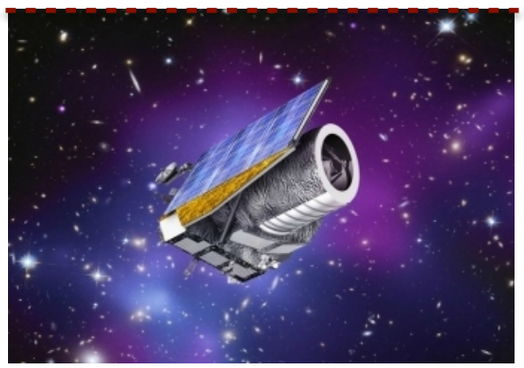


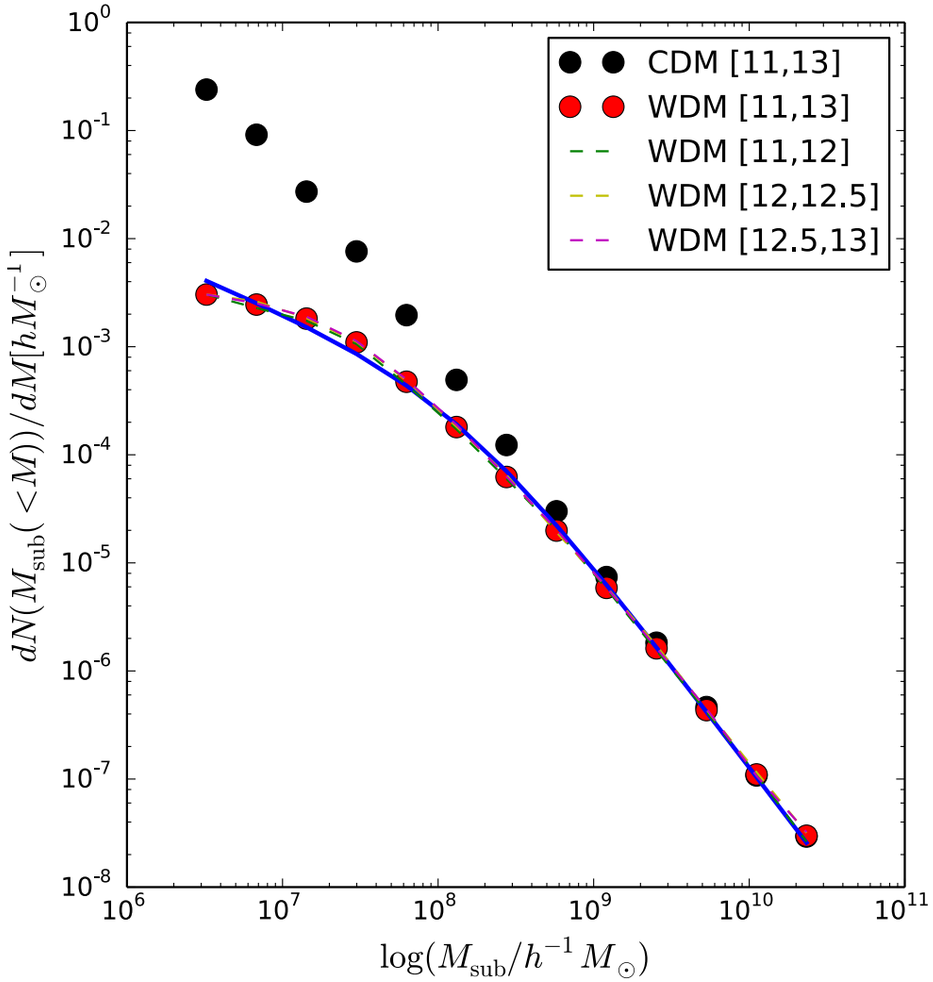


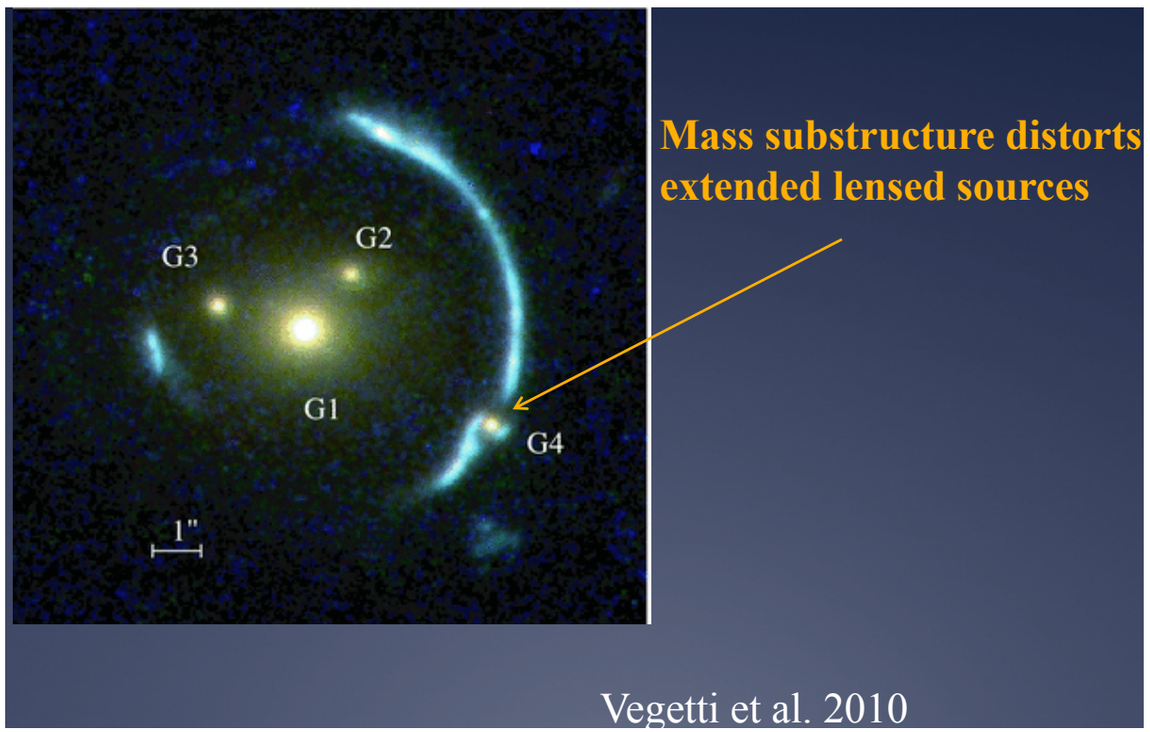


Gravitational probes

How does DM cluster at smallest scales, can we e.g. probe the **free streaming length (→ DM mass for thermal particles)**?

Can we detect 10^7 M_{sol} subhalos?





1) **Strong lensing - sub halo perturbations**

Current limit is **10^8 M_{sol}** (Vegetti et al. 2012, 2014)
With Next Generation Adaptive Optics and then TMT we should reach 107 solar masses and below, where the discrepancy with theory is strongest

[Banik, Bertone, Bovy, Bozorgnia , 1804.04384]

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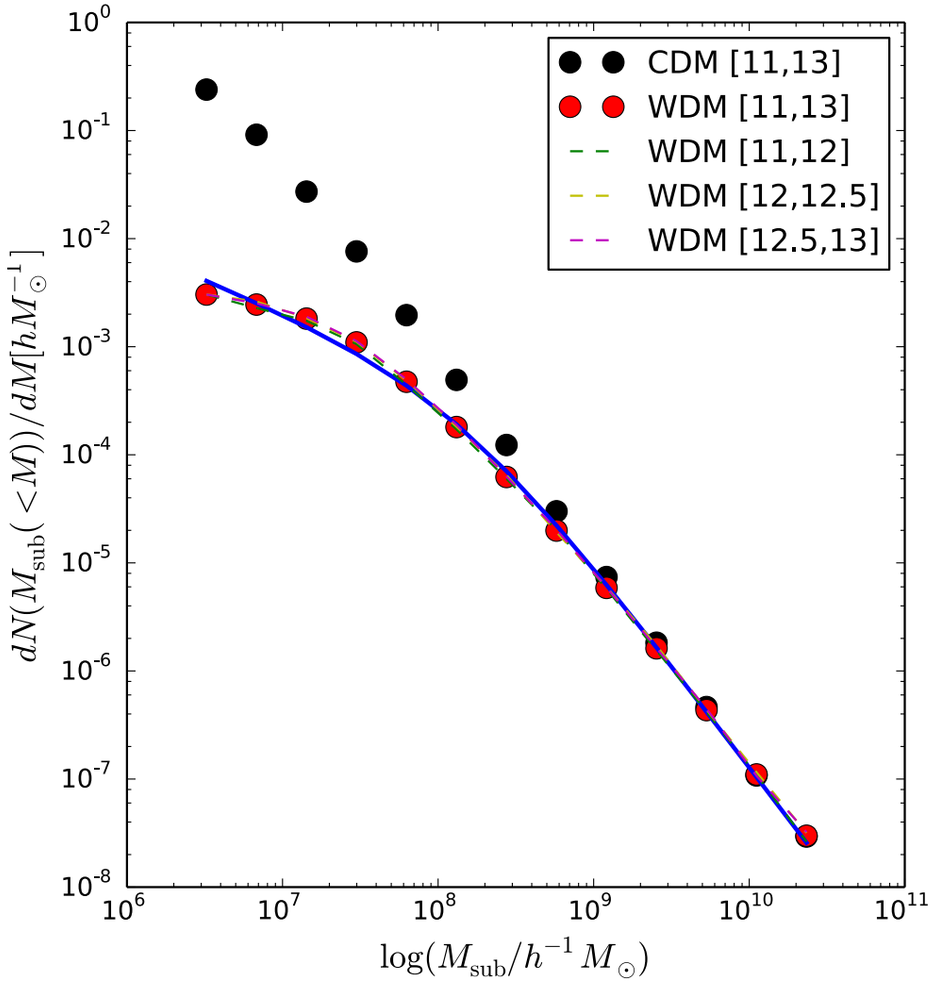
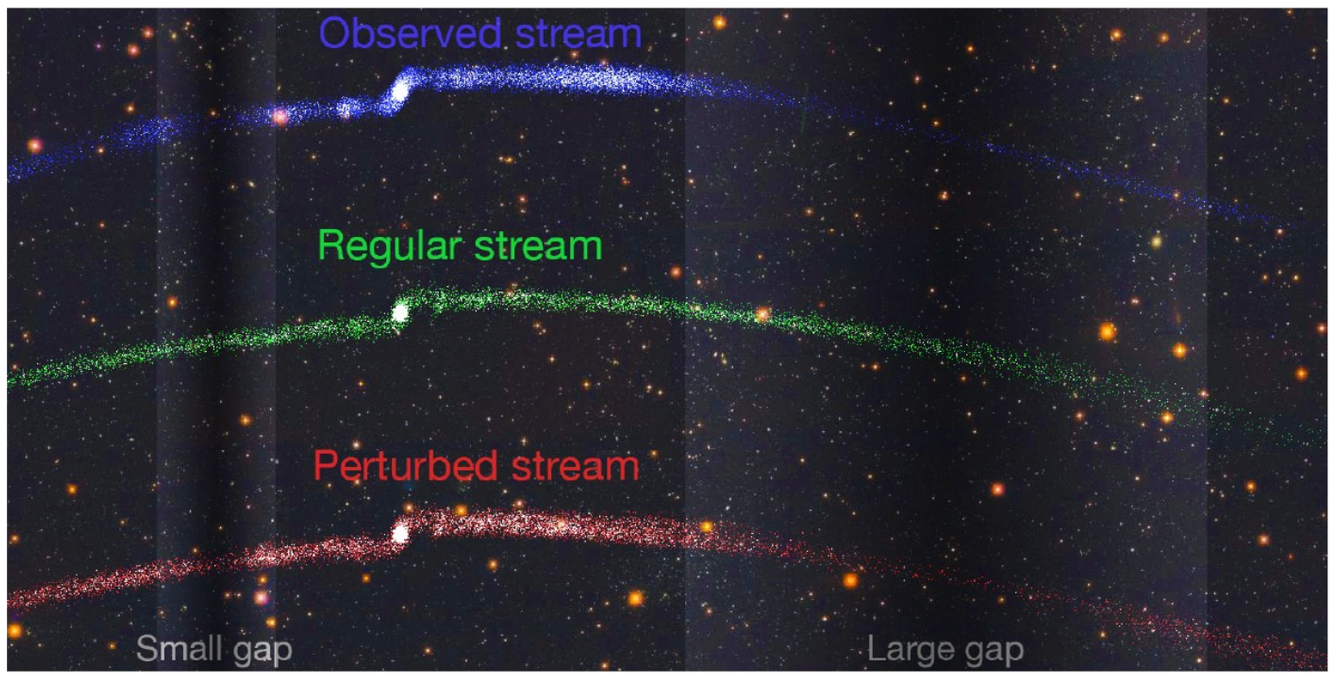
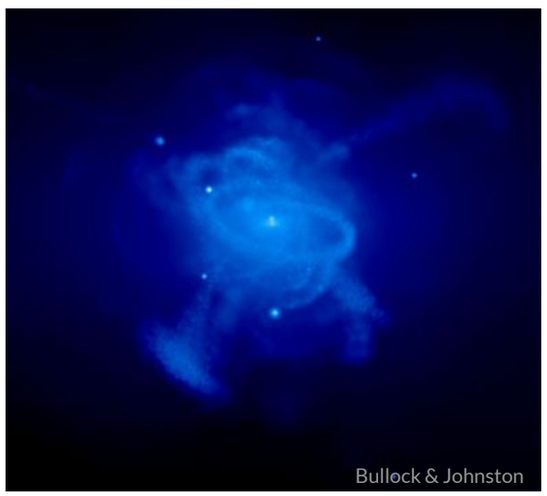


MW Stellar Stream perturbation



2) **Tidal stellar streams**, produced by dissolving globular clusters



Sensitive to encounters with dark haloes, which would produce stellar gaps.

LSST, should be able to provide at least comparable constraints to Lyman-α.

[Banik, Bertone, Bovy, Bozorgnia , 1804.04384]

Summary

So far, tons of astro data and many searches for DM signals across a large span of candidates!

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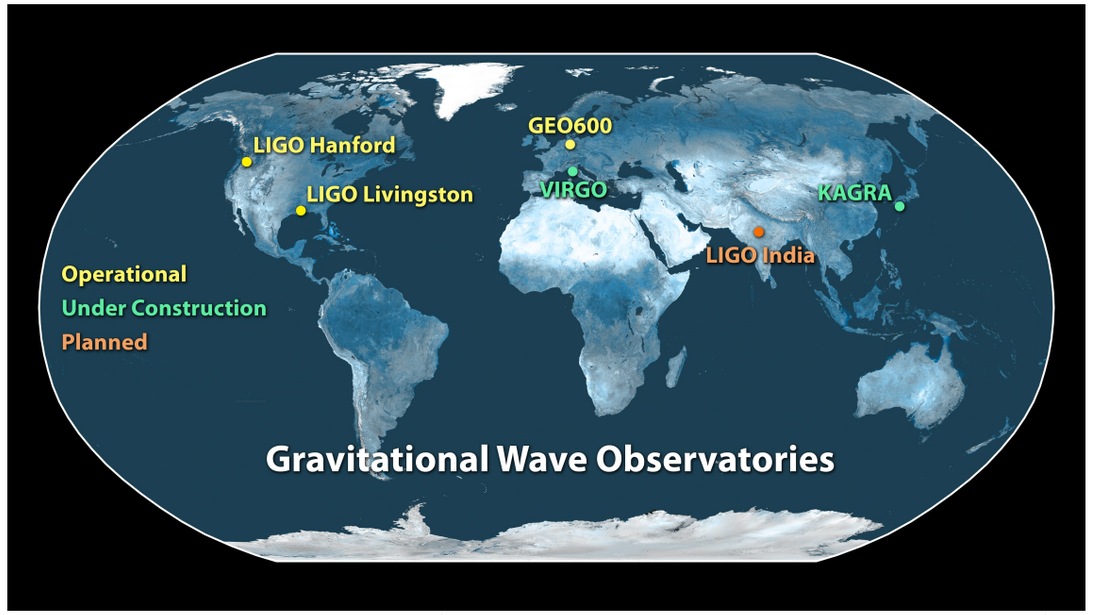
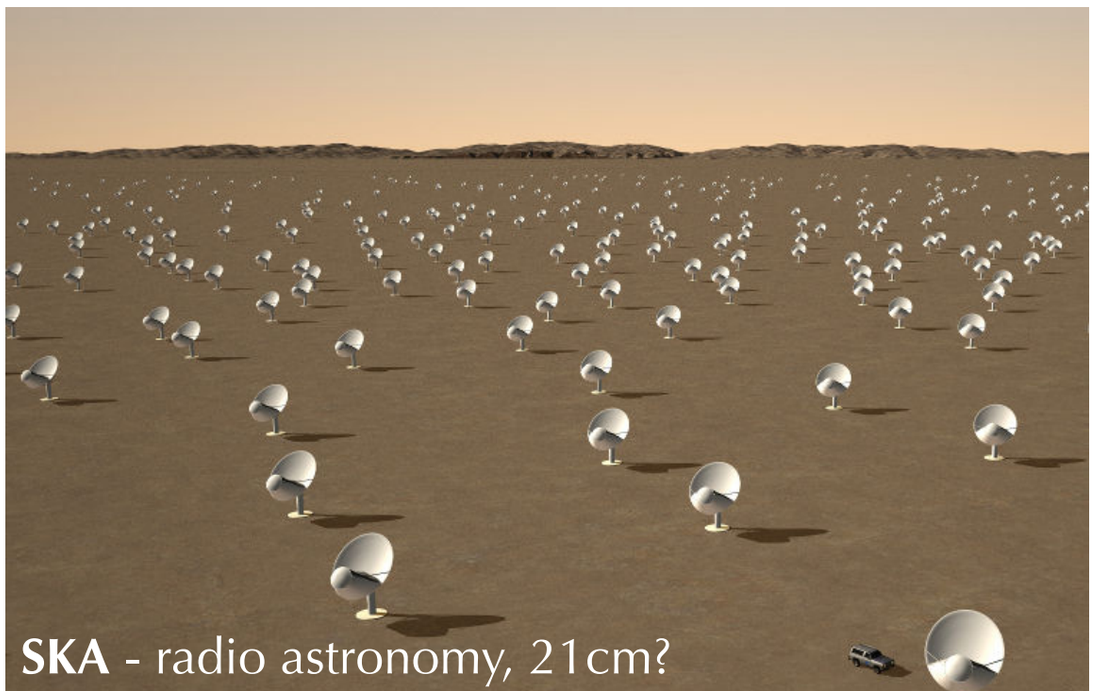
So far, tons of astro data and many searches for DM signals across a large span of candidates!

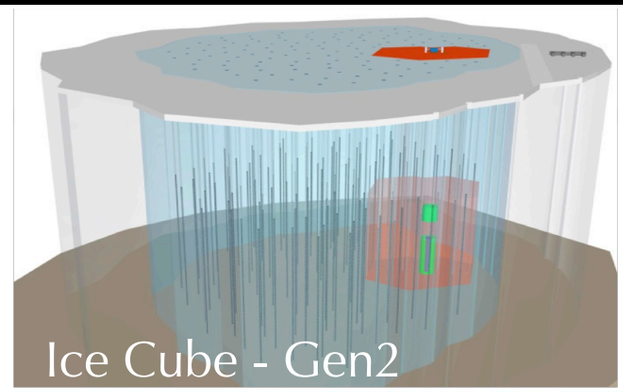
And **many relevant experiments just around the corner.**

LSST - more dSphs; stellar tidal streams…

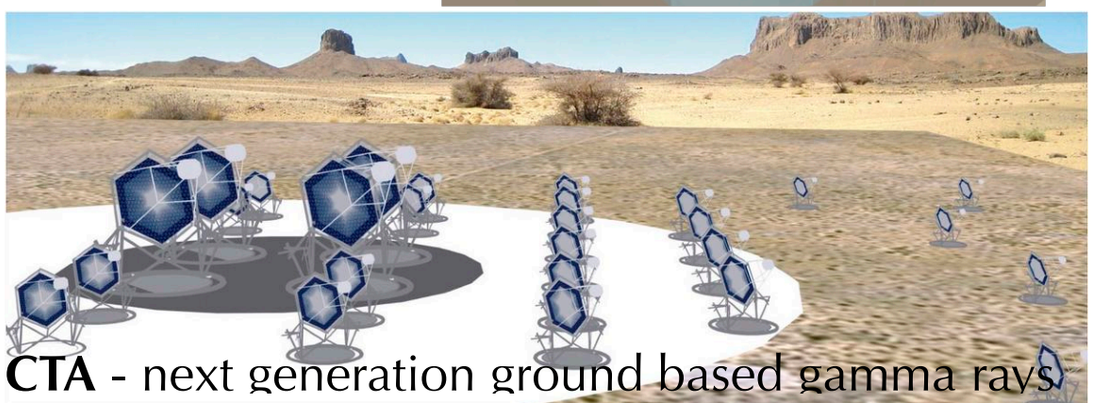




SKA - radio astronomy, 21cm?



Ice Cube - Gen2



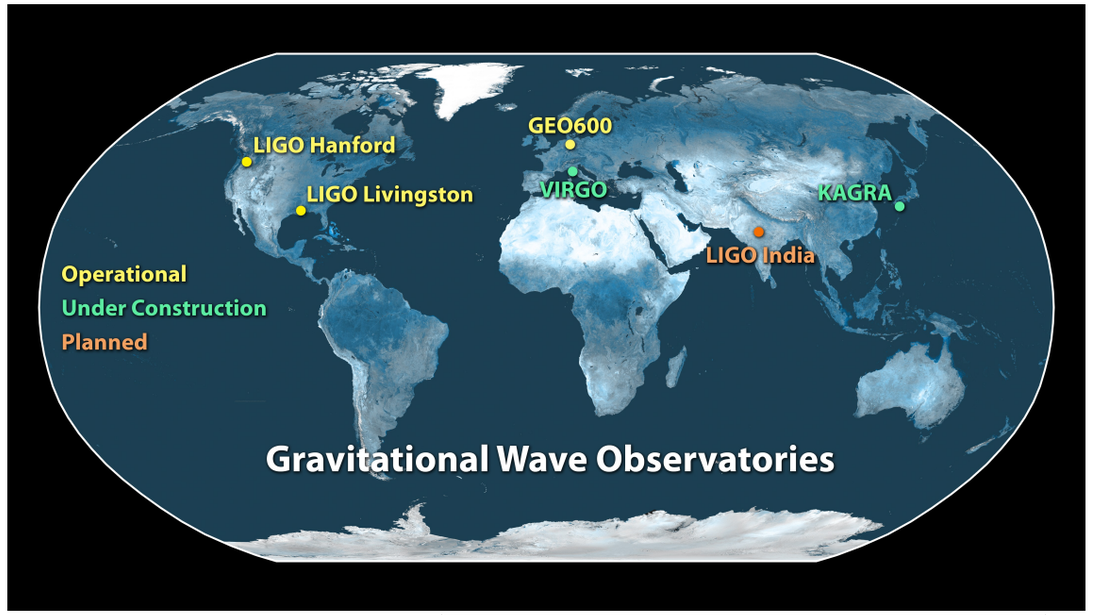
CTA - next generation ground based gamma rays

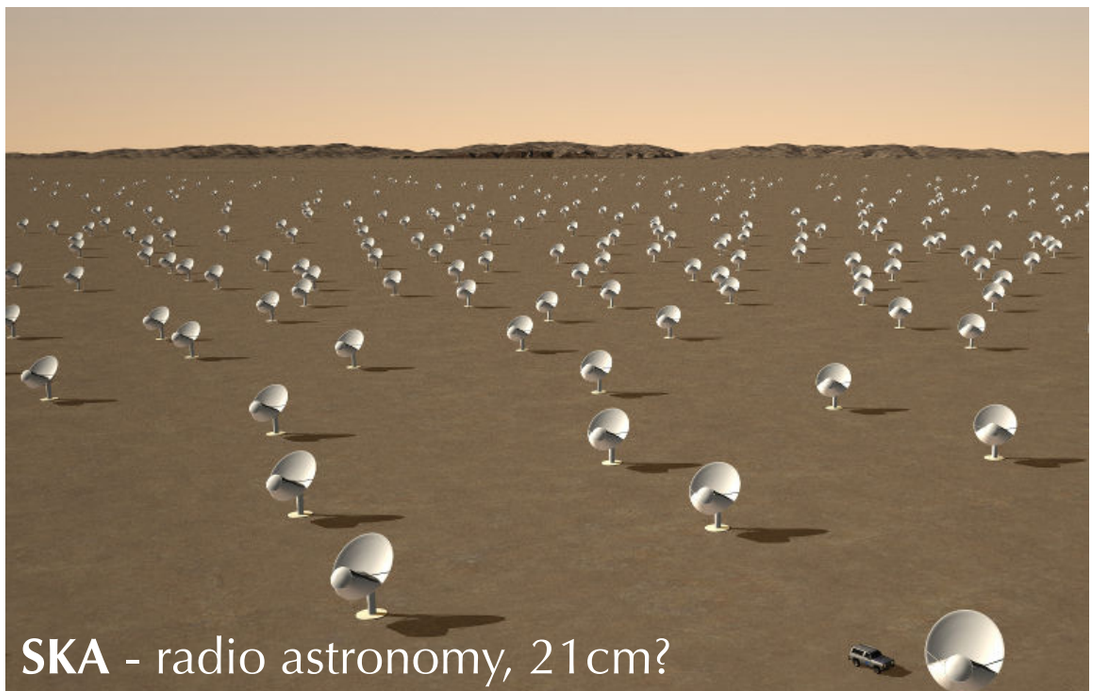
Summary

New ideas?

New data analysis tools?

LSST - more dSphs; stellar tidal streams…





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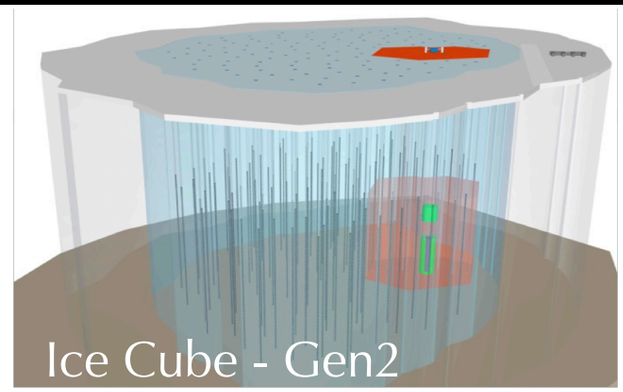

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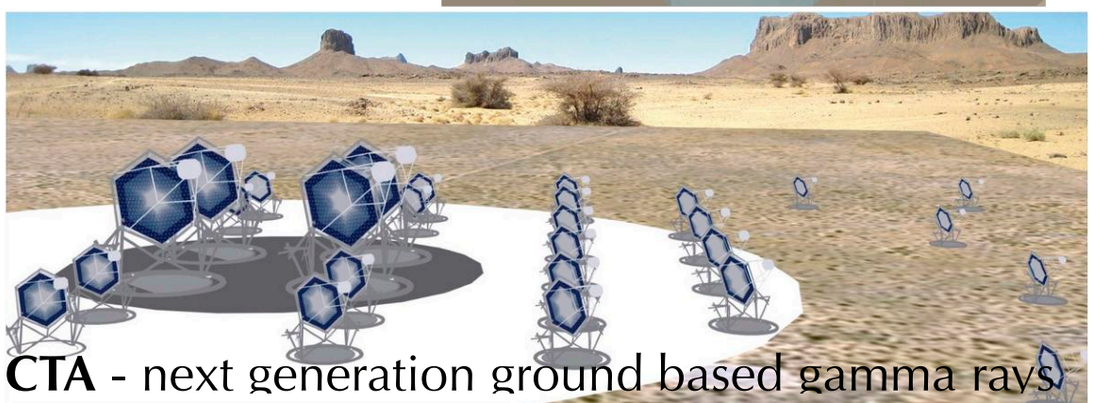

CTA - next generation ground based gamma rays

Summary

New ideas?

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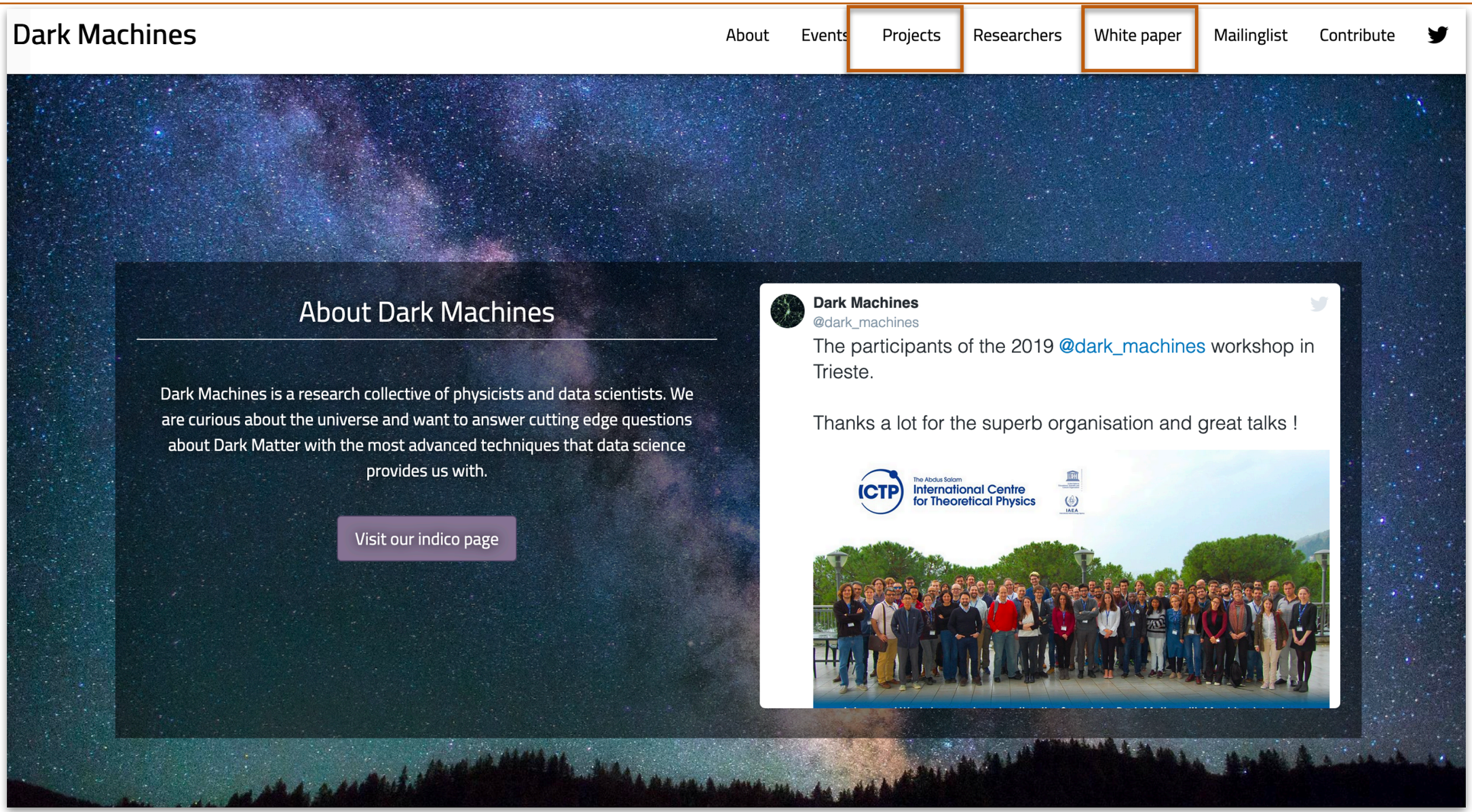
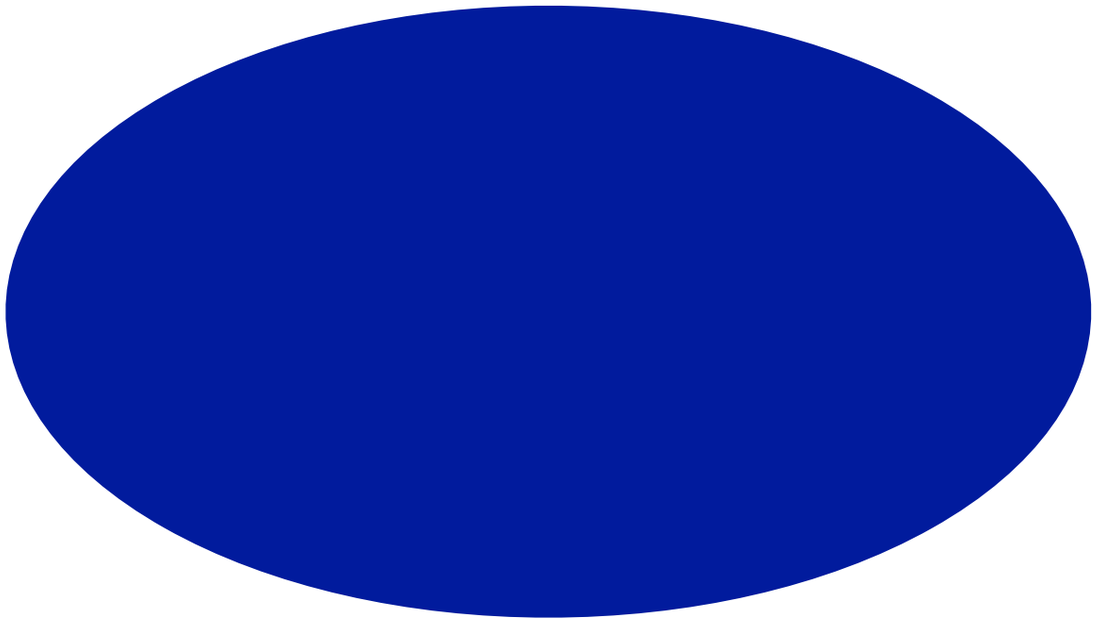
'***Accelerating the Search for Dark Matter with Machine Learning***' series of workshops (Leiden 2018, Trieste 2019) under the umbrella of the ***darkmachines.org community***

Join the challenges on ***collider*** and various ***astro DM searches*** - white paper in preparation

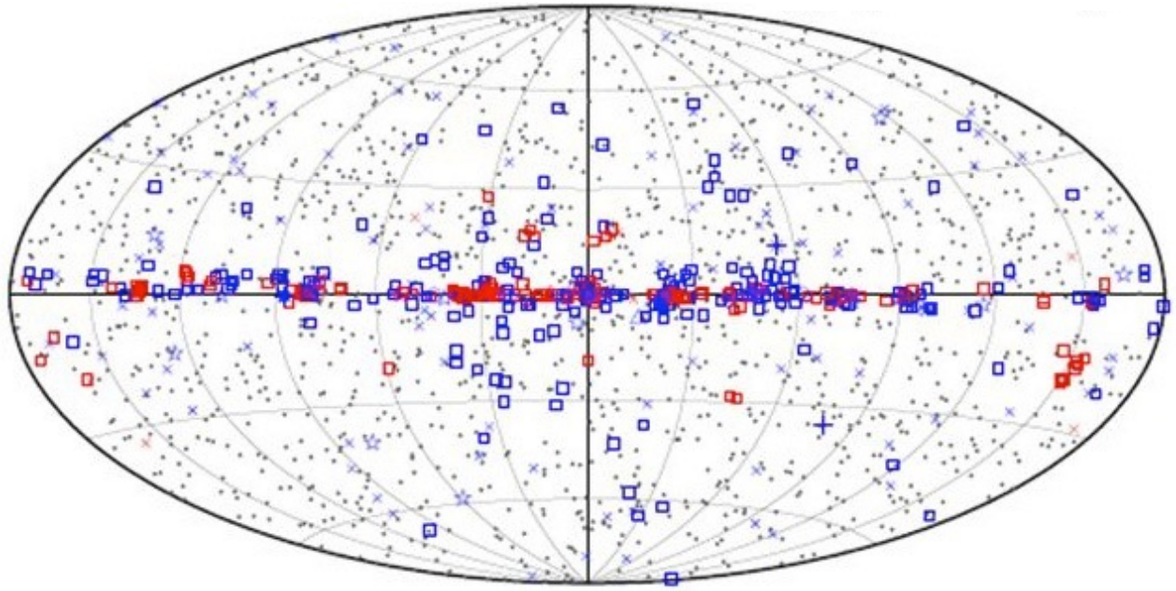


Extra Slides

Isotropic gamma ray emission



- Made up of **individually unresolved gamma-ray point sources**
- Or **truly diffuse** emission (DM?)



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Intensity flux: Abdo, JCAP (2010), Ajello+, ApJ (2015), …

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Pixel count fluctuations (1pPDF): Zechlin+2015, Feyereisen+ JCAP 2015, …

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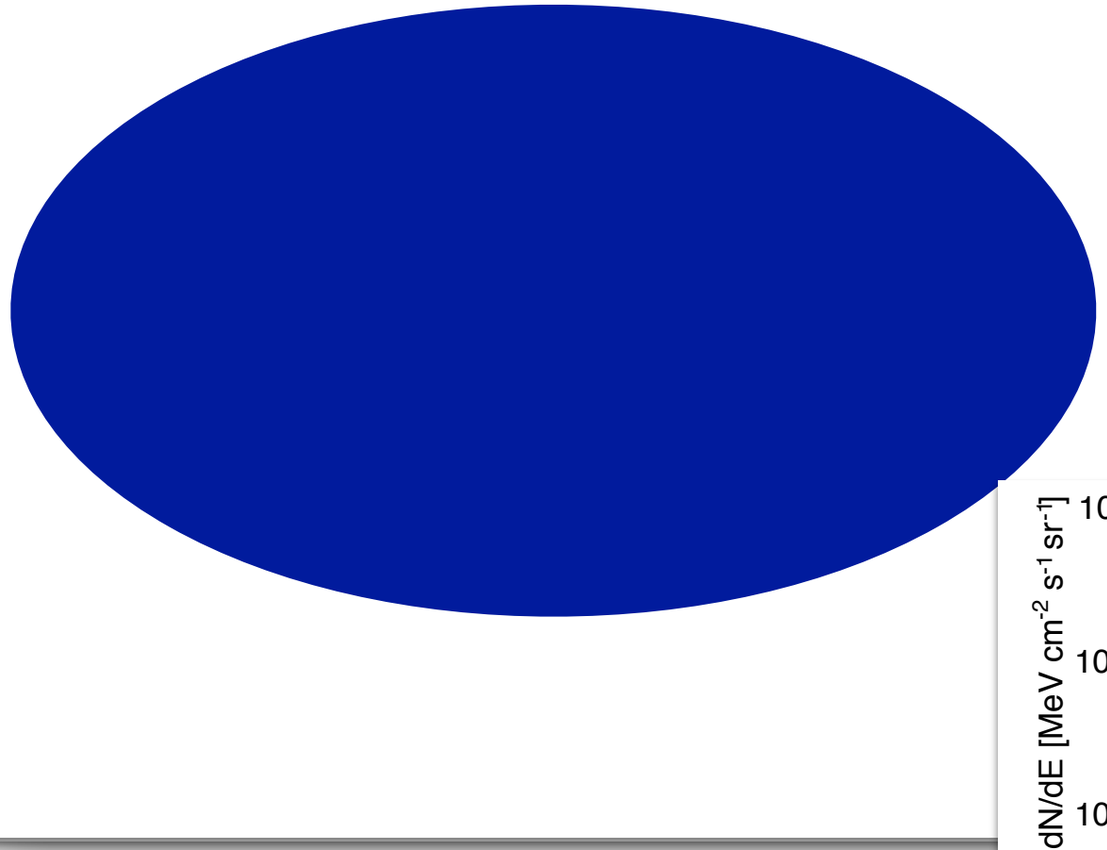
Isotropic gamma ray emission



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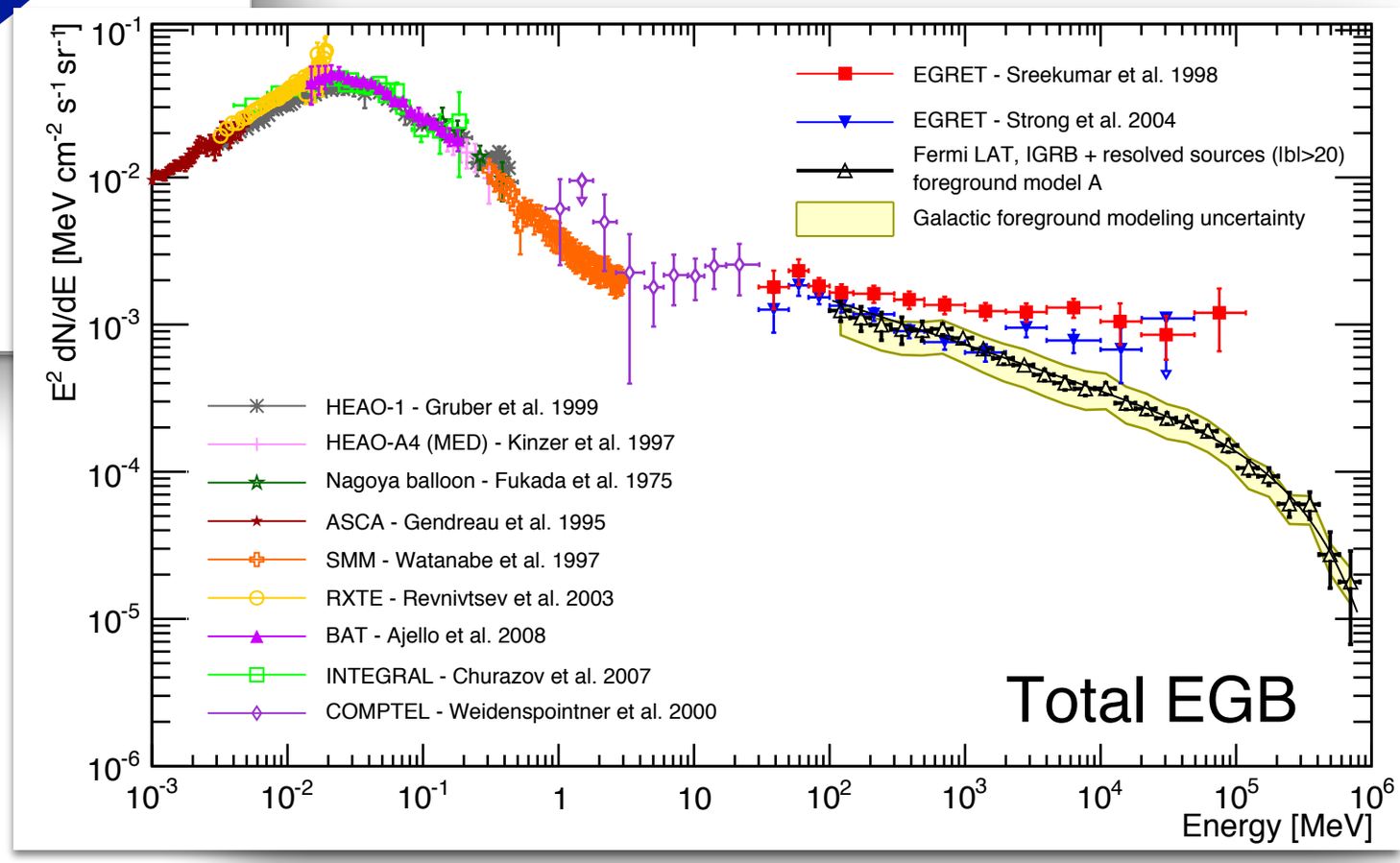

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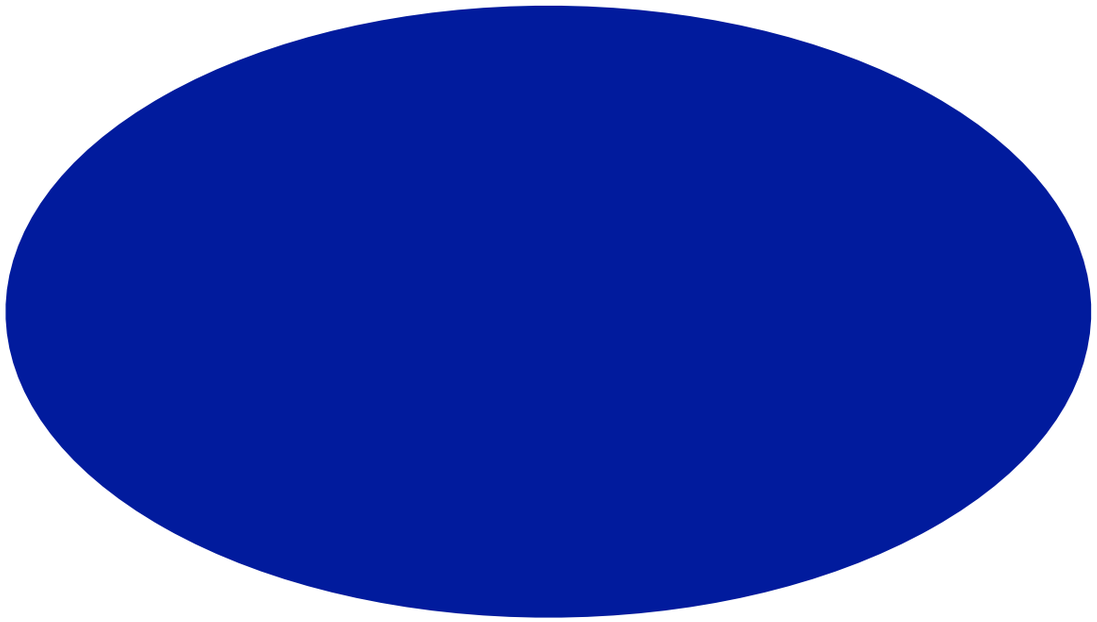

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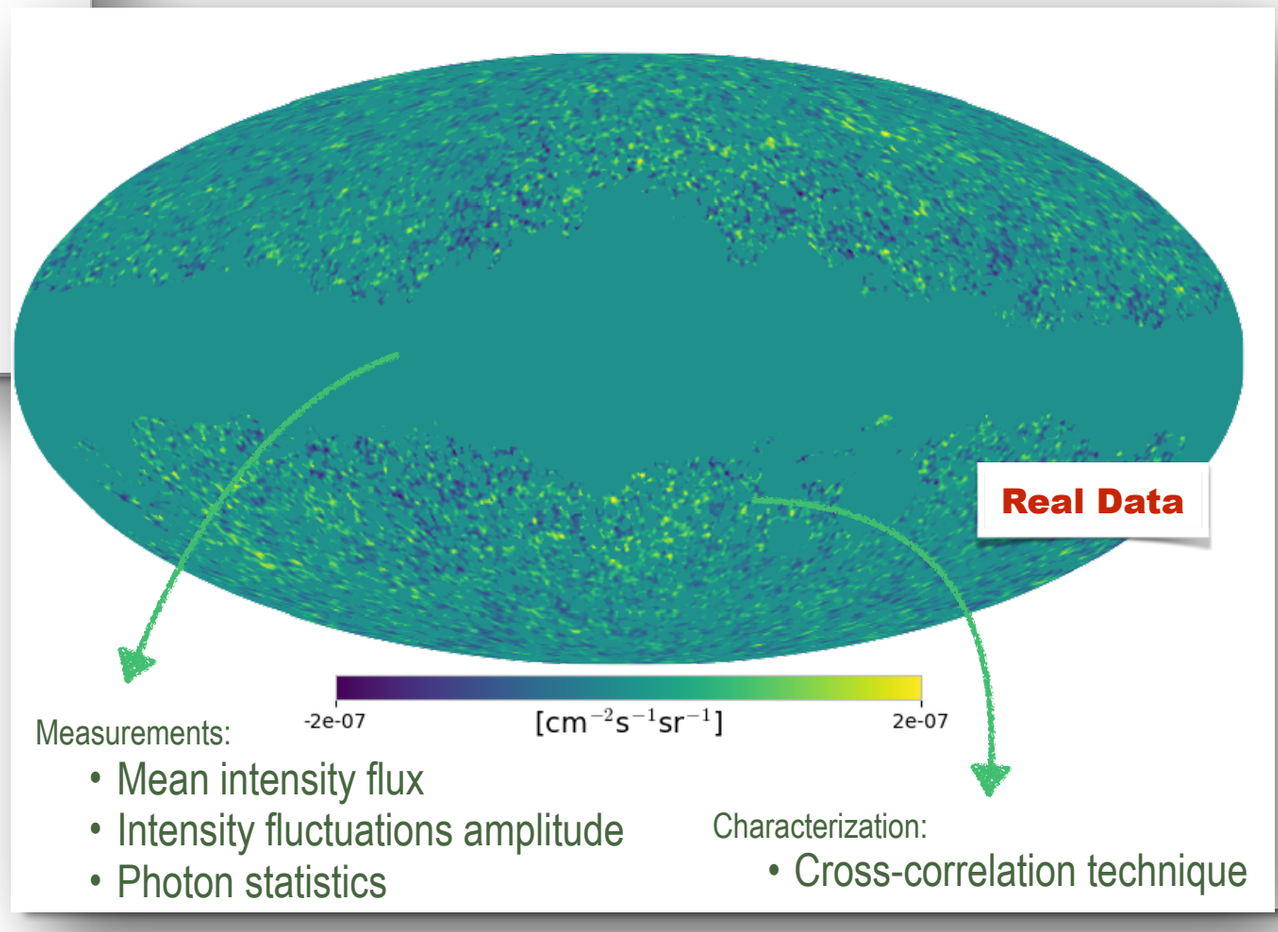

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Intensity flux: Abdo, JCAP (2010), Ajello+, ApJ (2015), …

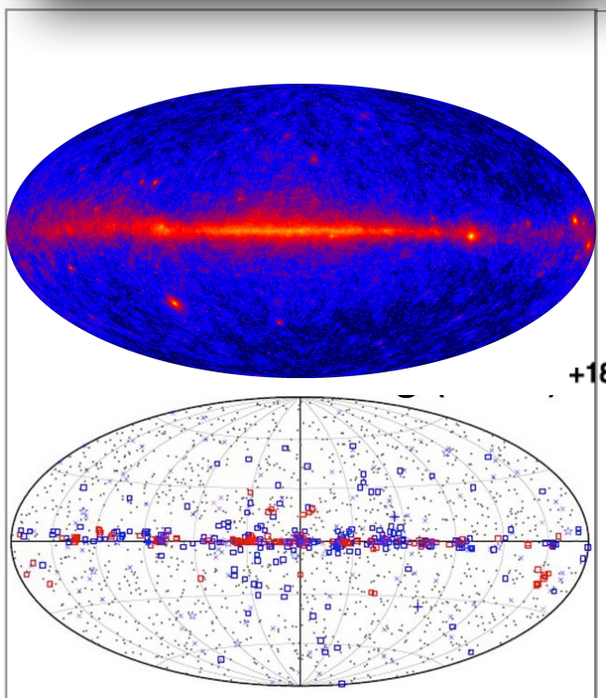
Anisotropy energy spectrum: Gomez-Vargas+ (2013), Fornasa+, PRD (2016), …

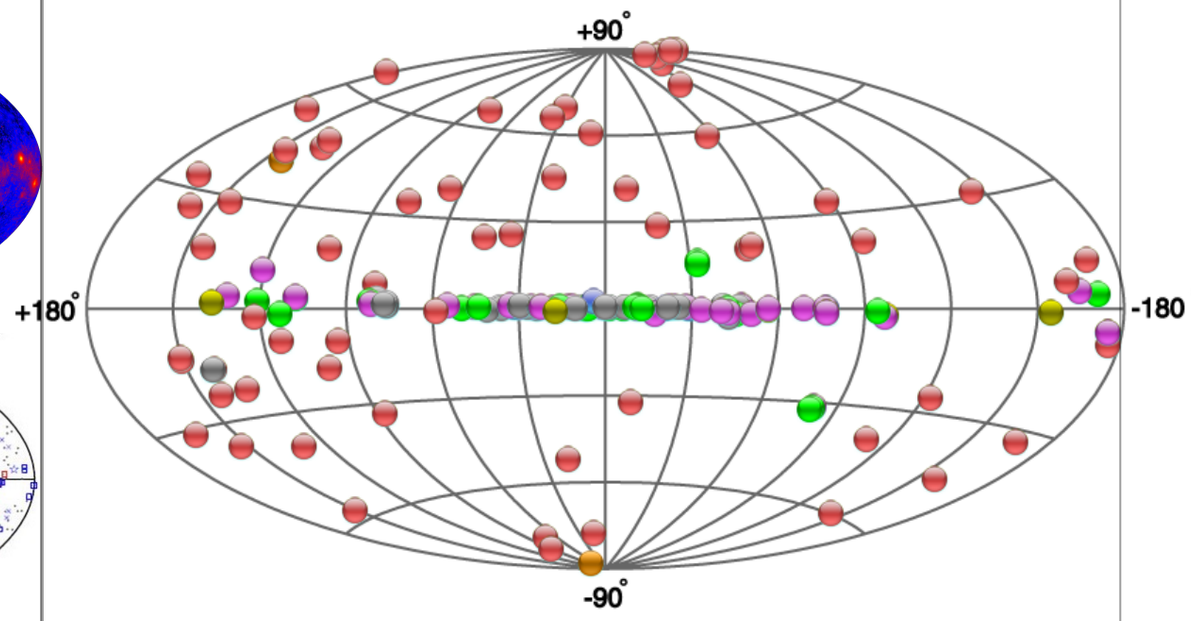
Pixel count fluctuations (1pPDF): Zechlin+2015, Feyereisen+ JCAP 2015, …

x-correlations: Ando, JCAP (2014), Fornengo & Regis (2014), Xia+, ApJS (2015), Cuoco+, ApJS (2015)…

Credit: M. Negro, VHEPU2018

What tools?





Fermi LAT:

- **Large FoV (whole sky)**
- **Negligible CR**

IACTs are pointing telescopes:

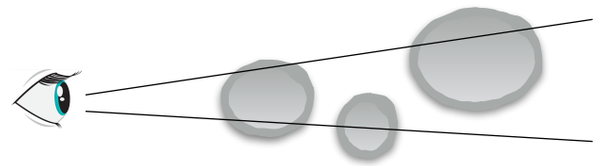
- **Small FoV**
- **Significant CR contamination**
- **Reach higher energies…**

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

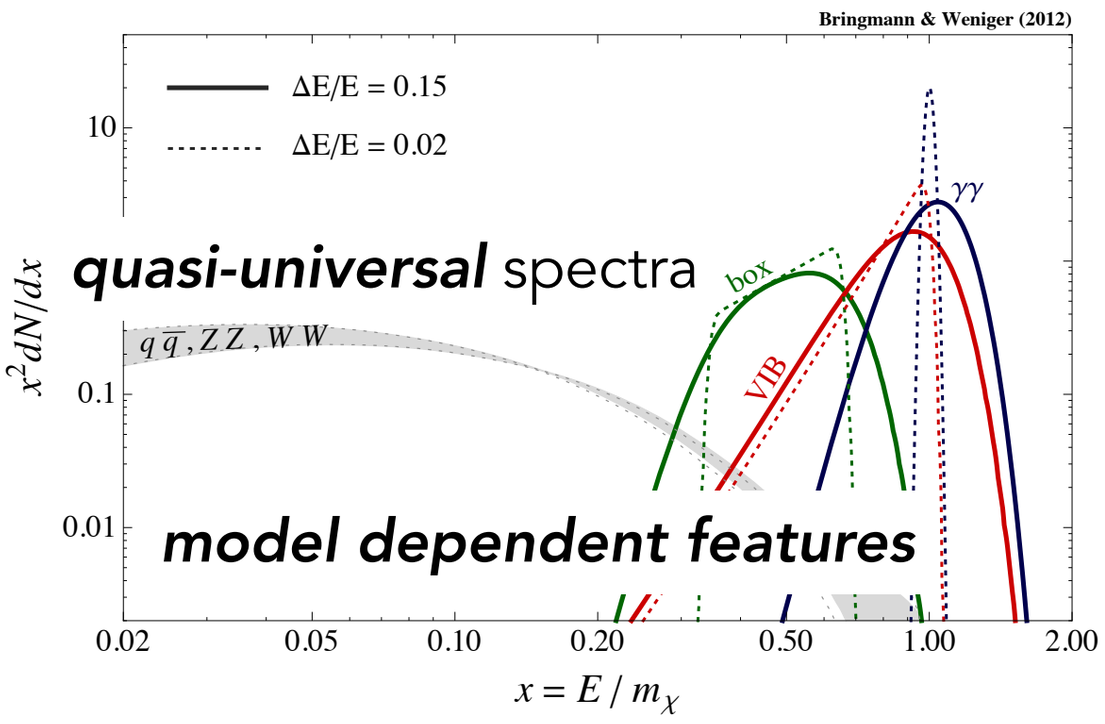
particle physics | cosmology

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\frac{(\sigma_{\rm ann} v)}{2\, m_\chi^2} \times \sum_i {\rm BR}_i \frac{dN_\gamma^i}{dE_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)$$

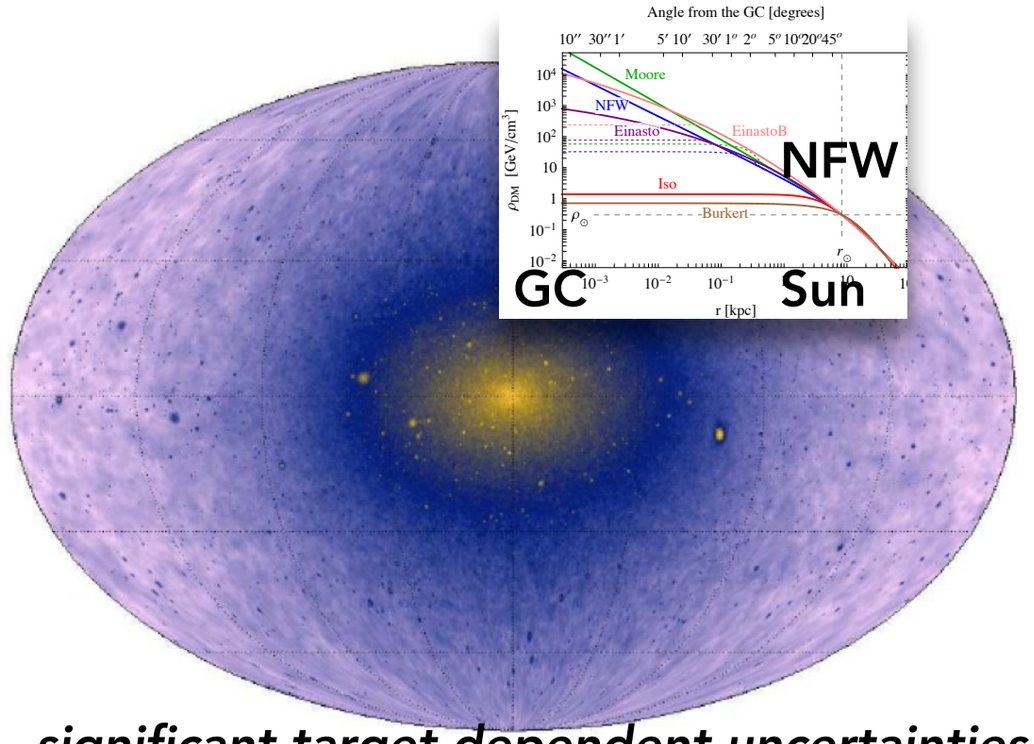
this is what we are after!



flux of SM particles per DM annihilation



integrated DM density squared along the line of sight

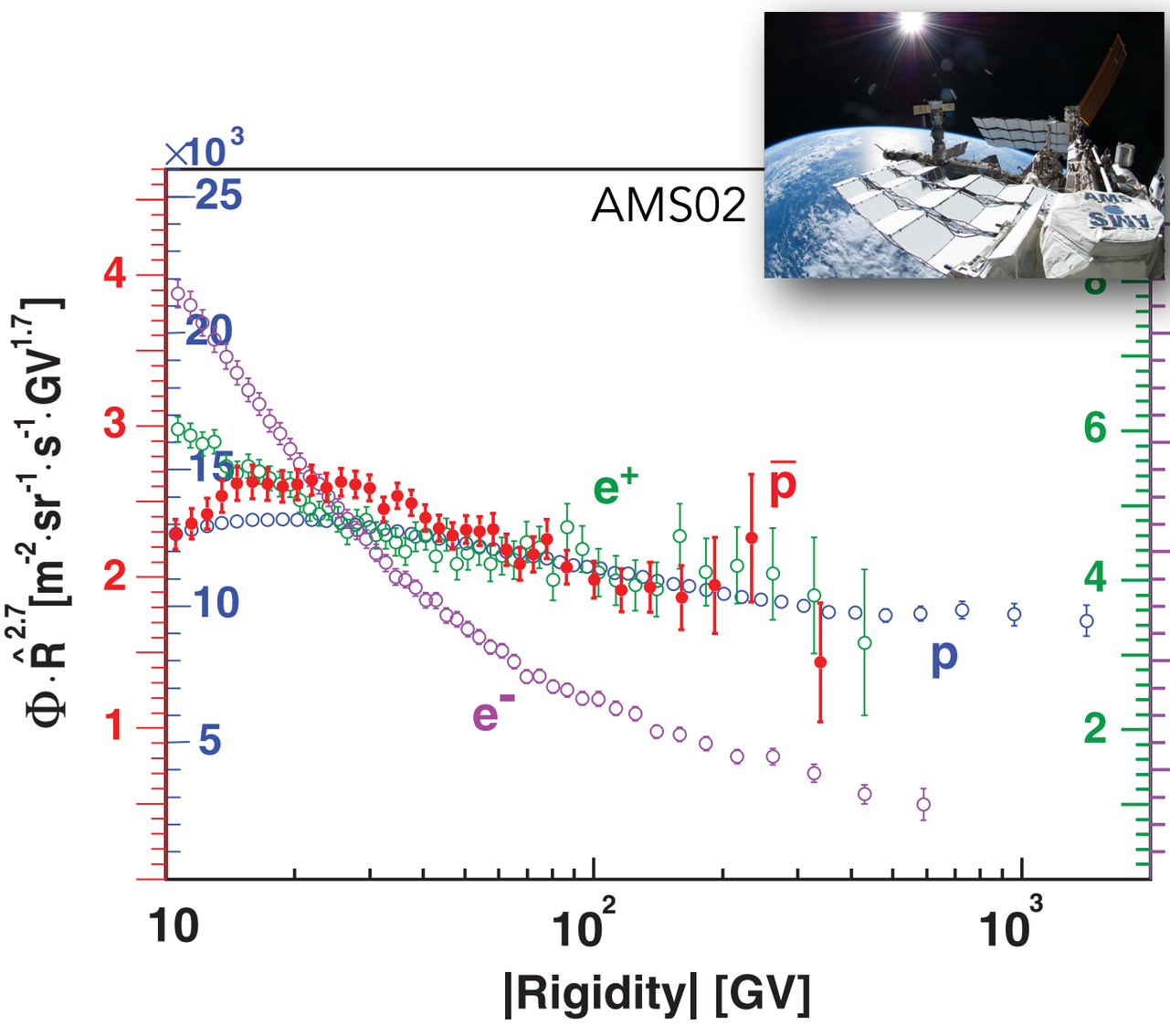


significant target dependent uncertainties

Charged cosmic rays - the precision era

PAMELA, AMS-02, DAMPE… measured CR fluxes with exquisite precision and reaching <~ TeV energies.

Challenge the 'Standard model' of CR propagation in the Galaxy



[Aguilar+, PRL117 (2014)]

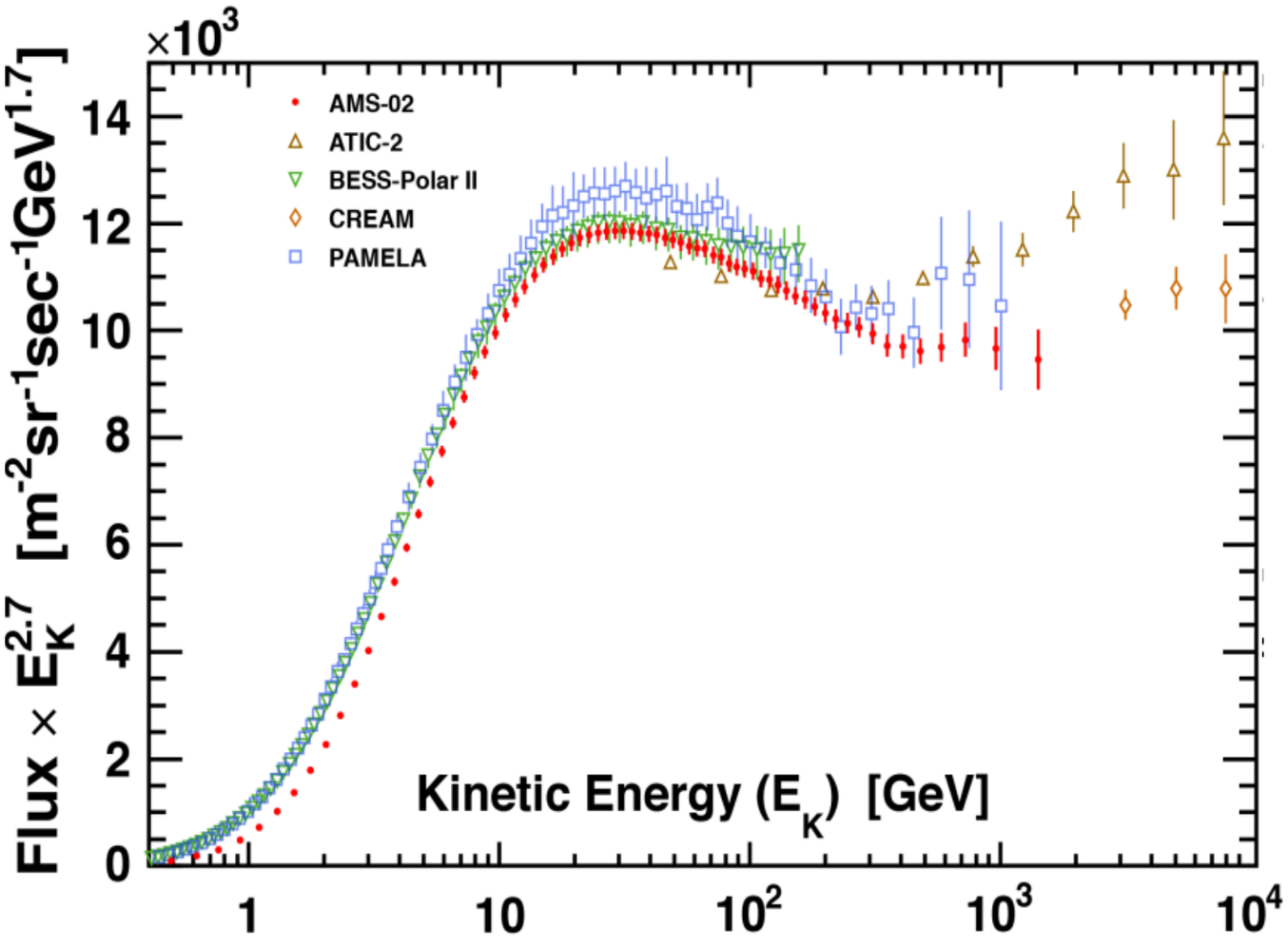
[Ambrosi+, Nature552 (2017)]

Charged cosmic rays - the precision era

Unexpected features:

1. spectra of p and He fluxes are **broken power laws** (PAMELA, AMS-02; NEW measurements: https://mediastream.cern.ch/MediaArchive/Video/Public2/weblecture-player/index.html?year=2018&lecture=729900&ftime=00:06:00#)

AMS-02 H flux measurement:
300 million events



Aguilar+, PRL114 (2014)

The origin of the hardening?

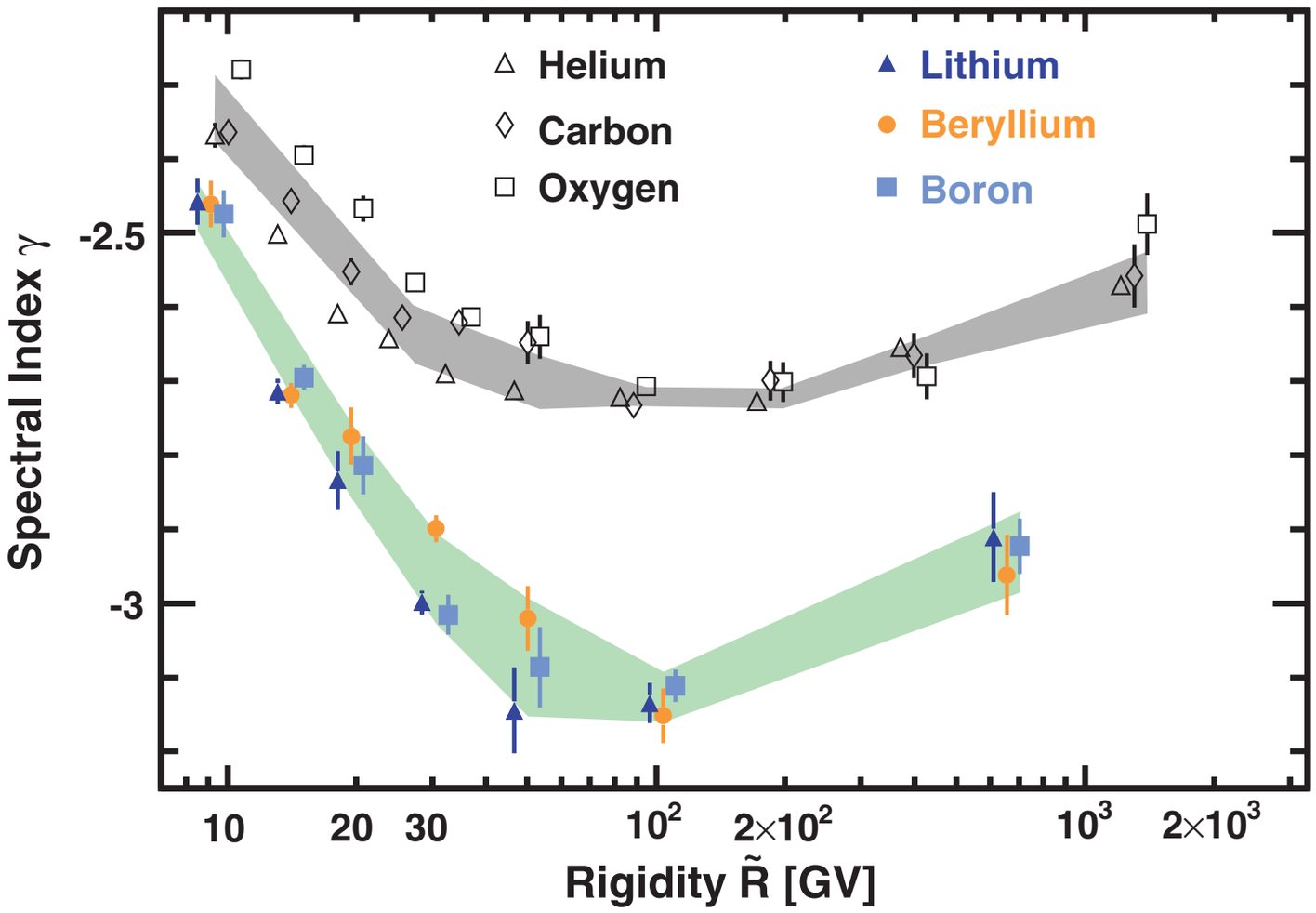
(e.g. see P. Blasi, Braz.J.Phys. 44 (2014) 426)

- At the sources: **multi-populations**, etc.?
- **Propagation effects?** - Break should be present also in B/C ratio. Favoured by B/C [Genolini+, 1706.09812].

Charged cosmic rays - the precision era

Unexpected features:

1. spectra of p and He fluxes are **broken power laws** (PAMELA, AMS-02; NEW measurements: https://mediastream.cern.ch/MediaArchive/Video/Public2/weblecture-player/index.html?year=2018&lecture=729900&ftime=00:06:00#)



[Aguilar+, PRL120 (2018)]

The origin of the hardening?

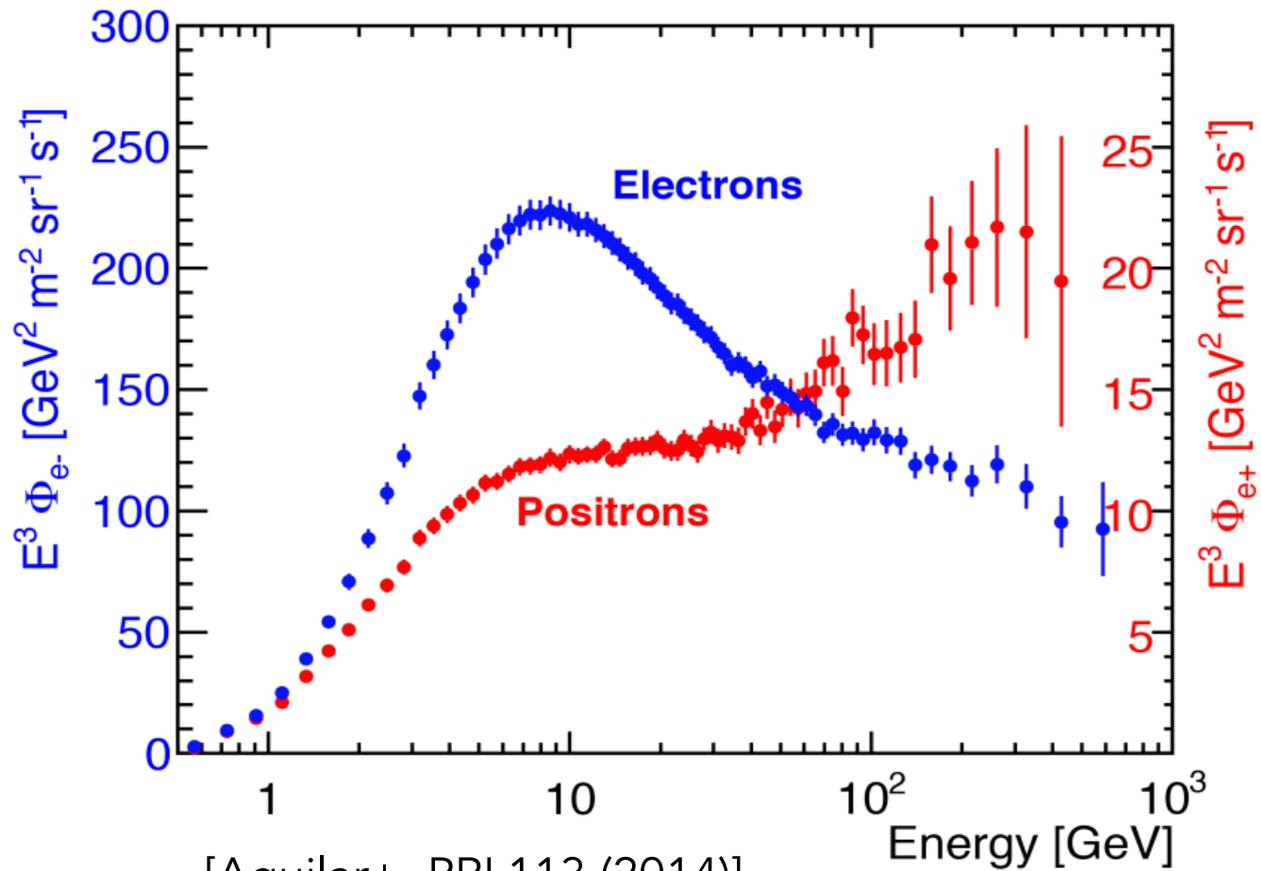
(e.g. see P. Blasi, Braz.J.Phys. 44 (2014) 426)

- At the sources: **multi-populations**, etc.?
- **Propagation effects?** - Break should be present also in B/C ratio. Favoured by B/C [Genolini+, 1706.09812] -> **Observed!**

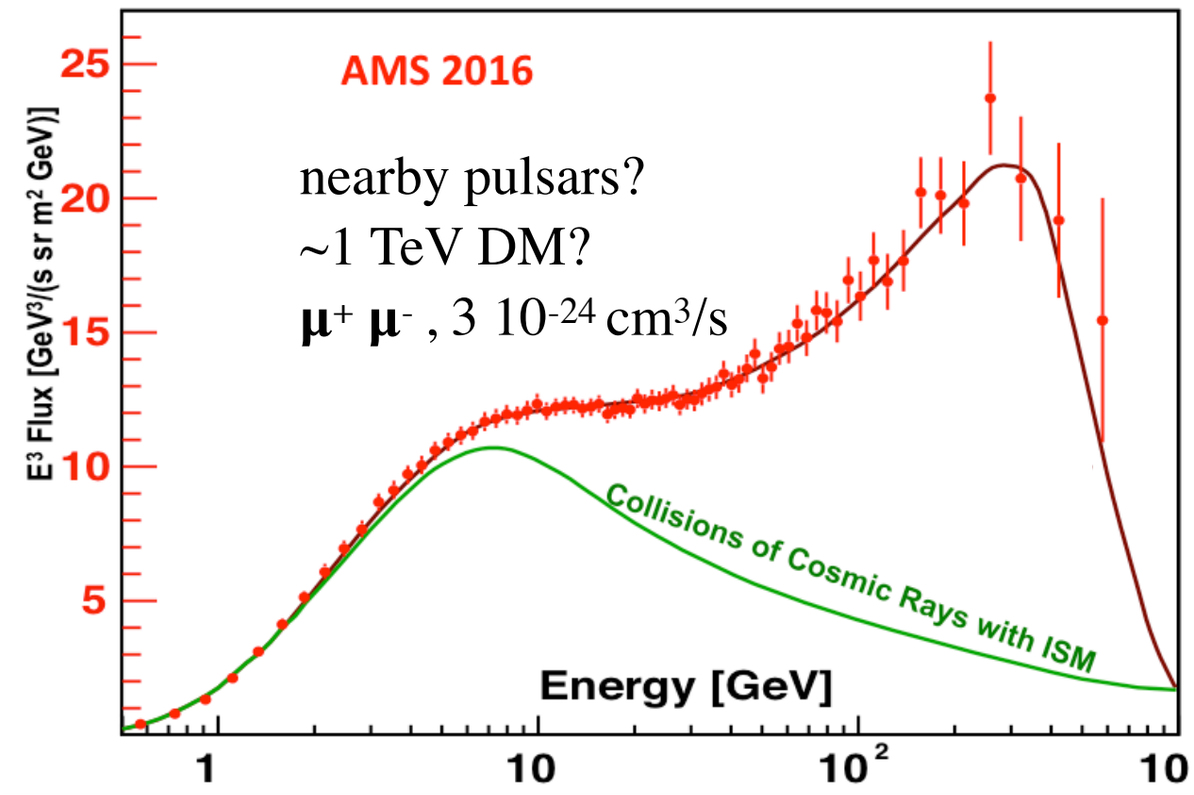
Charged cosmic rays - the precision era

Unexpected features:

1. spectra of p and He fluxes are **broken power laws** (PAMELA, AMS-02; NEW measurements: https://mediastream.cern.ch/MediaArchive/Video/Public2/weblecture-player/index.html?year=2018&lecture=729900&ftime=00:06:00#)
2. raising positron fraction — new source of anti-matter. Seen as a DM channel, but later realised that nearby pulsars (nearby sources) could explain the raise as well.



[Aguilar+, PRL113 (2014)]



[Kopp, PRD88 (2013)]

Charged cosmic rays - the precision era

DM limits:

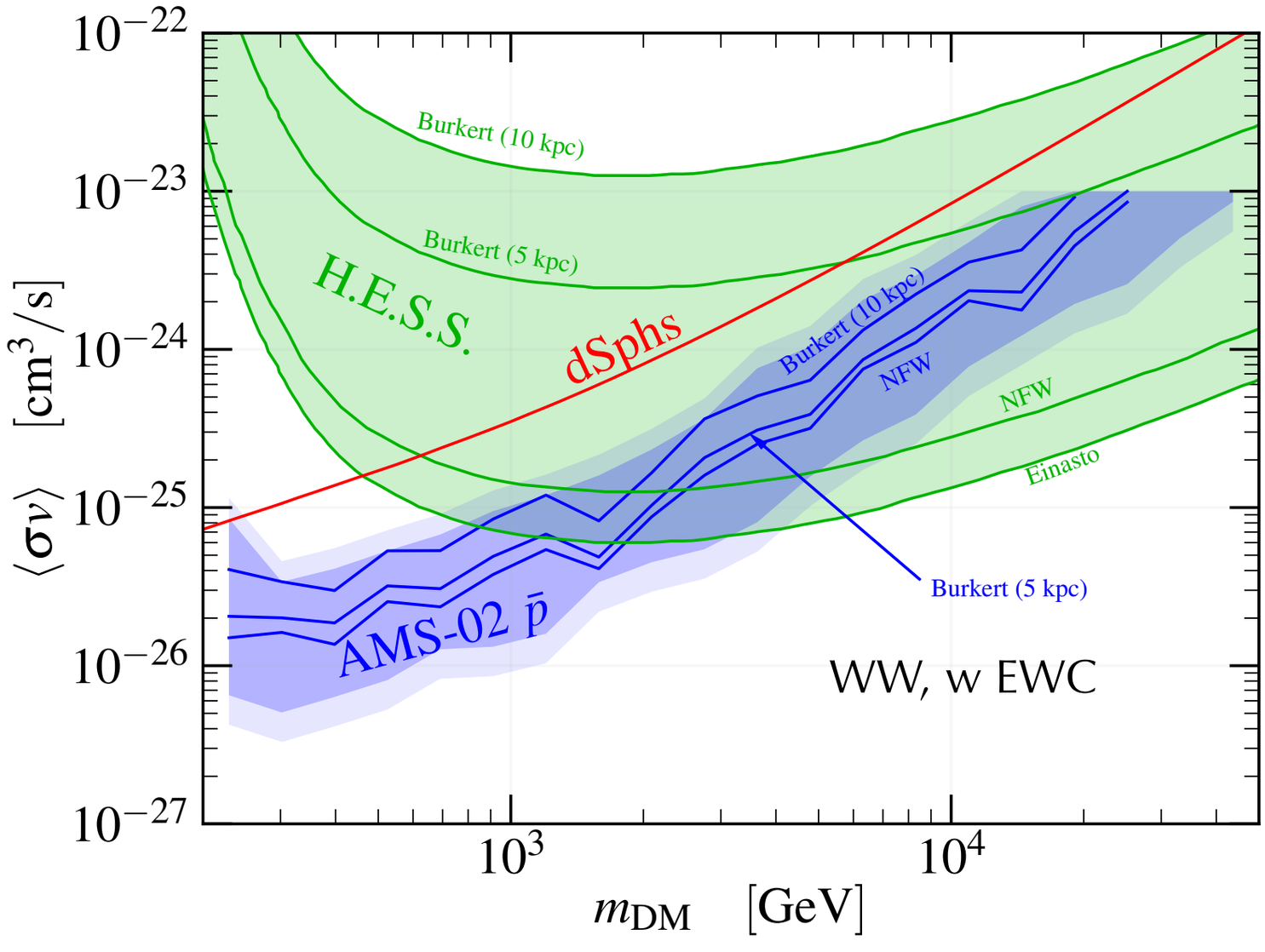
Antiprotons - one of the most sensitive probes of new physics

— 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

Note strong limits at high >~100 GeV masses



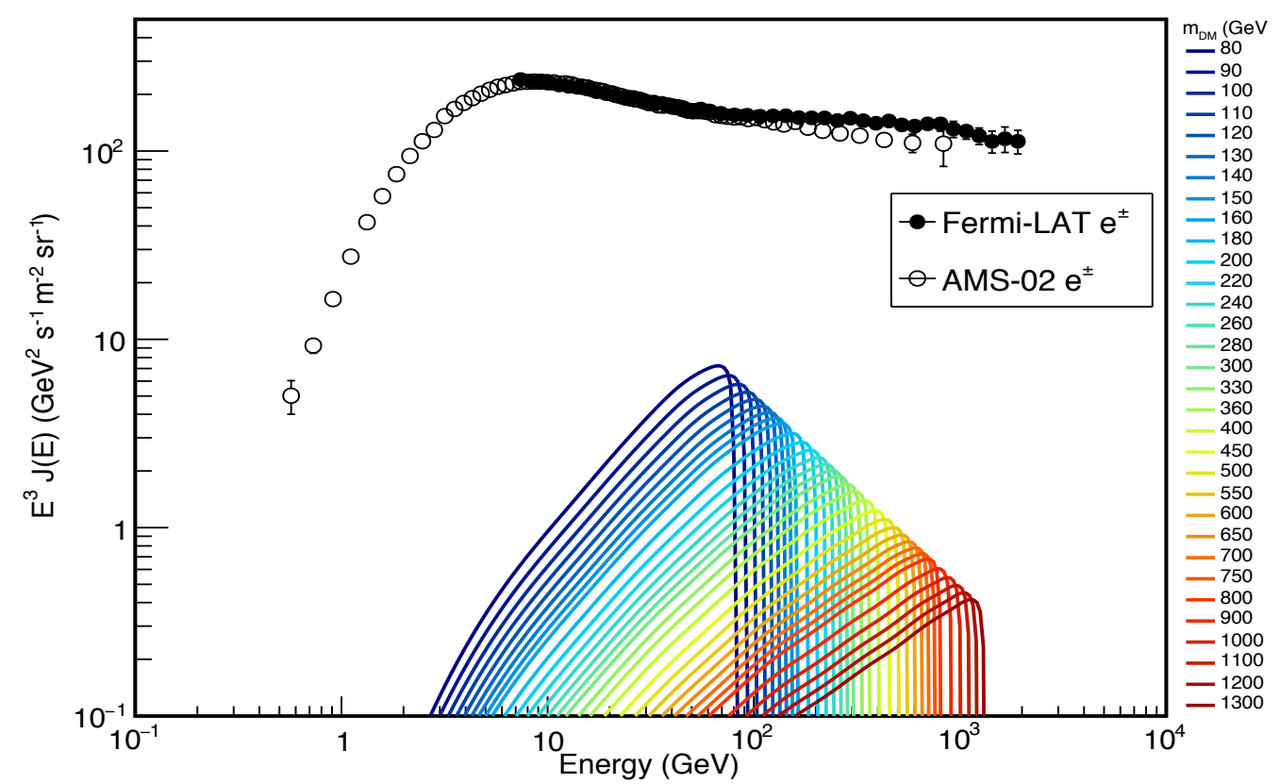
[Cuoco+, JCAP1804 (2018)]

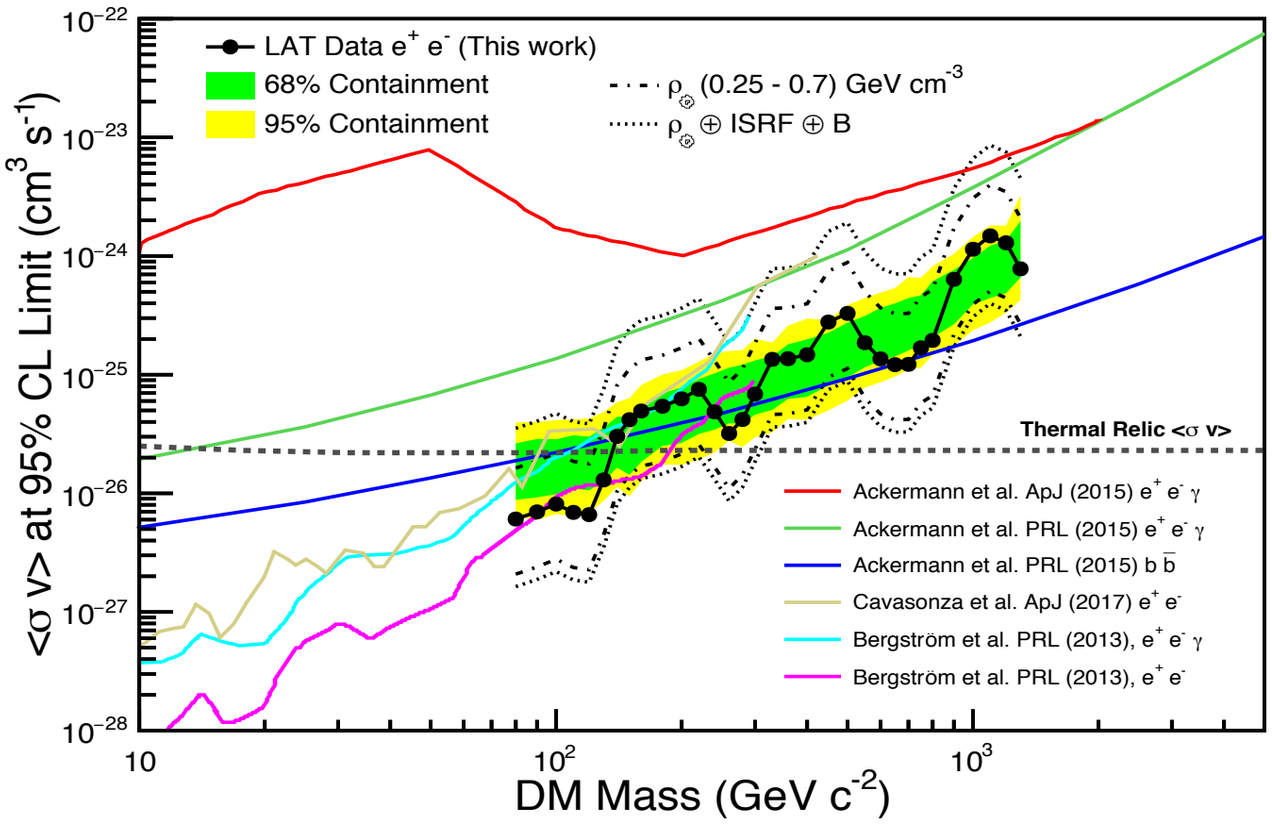
Charged cosmic rays - the precision era

DM limits:

Features in electron&positron spectrum

— e^+e^- line or $e^+e^-\gamma$ hard feature

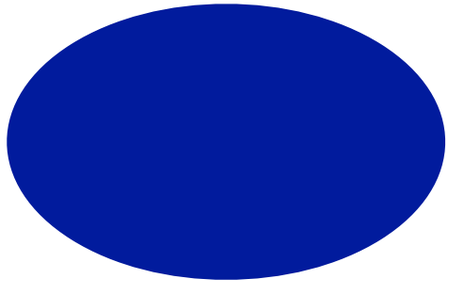




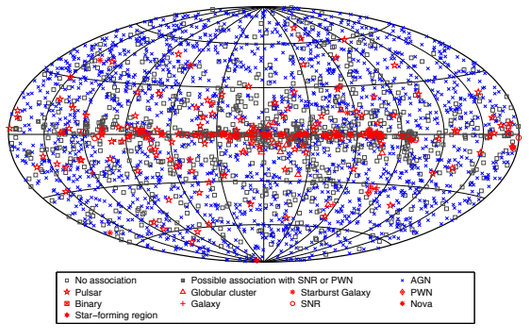
[Mazziotta+, 1712.07005]

DM search in the isotropic emission

In a nutshell…

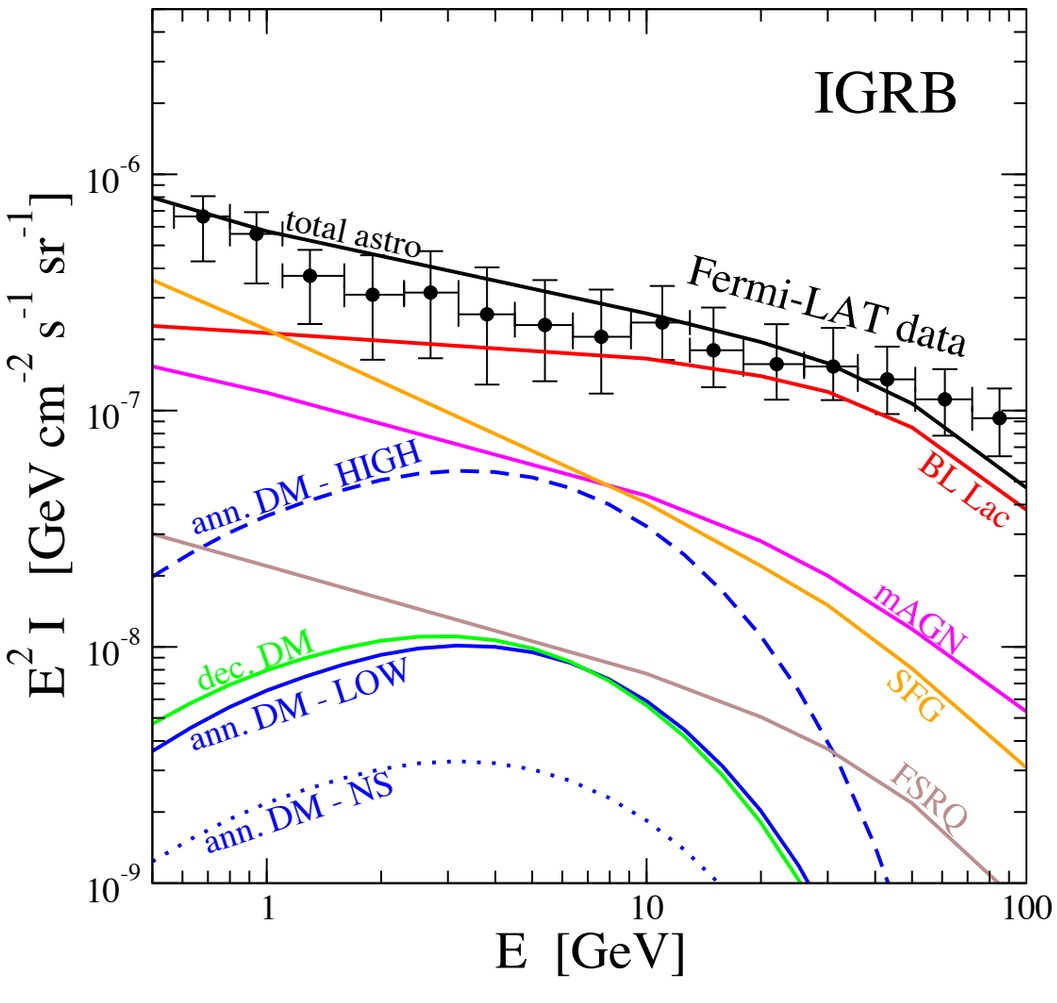


—

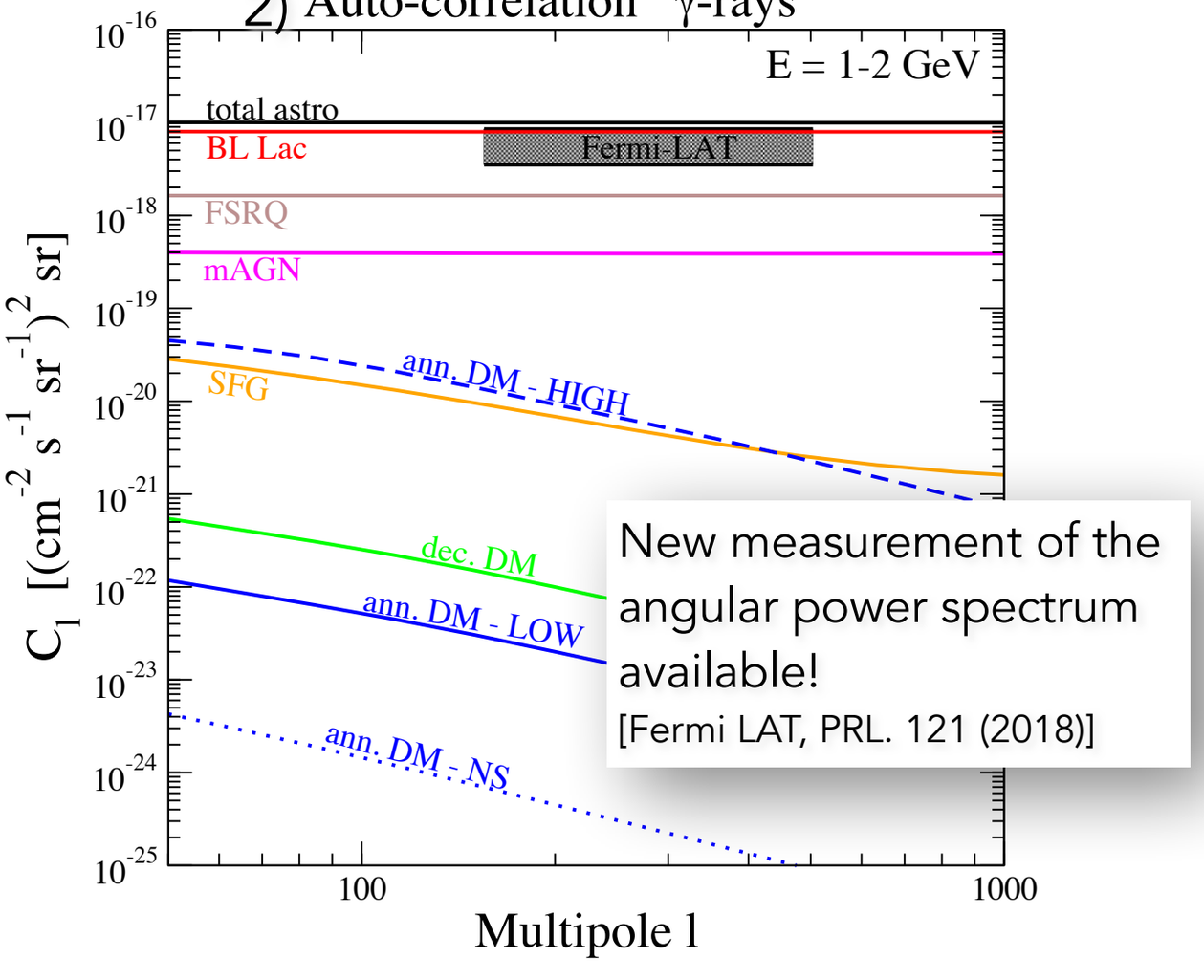


Guaranteed contribution

1) Mean flux



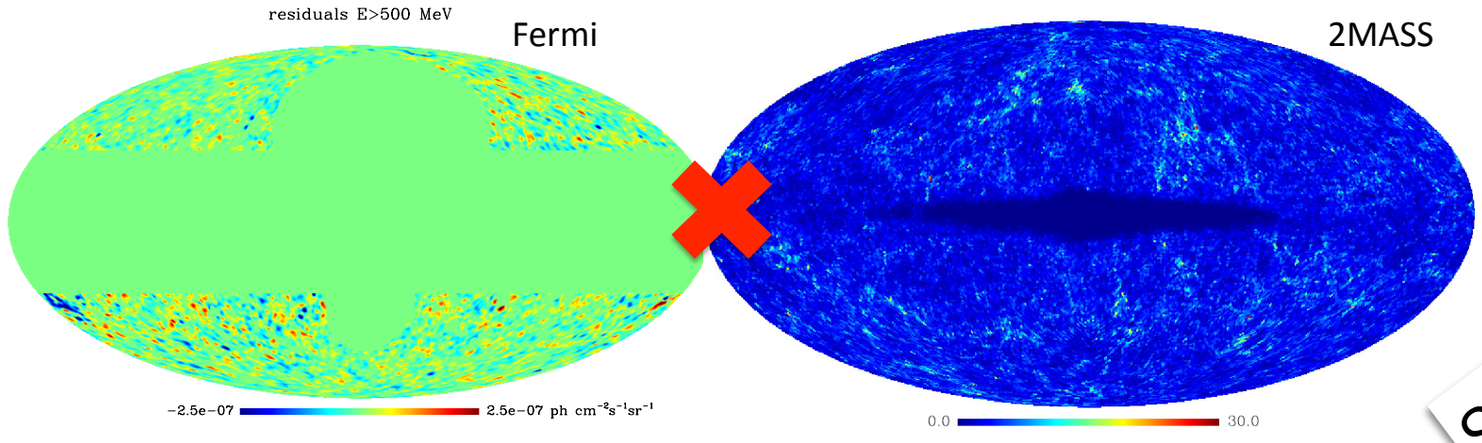
2) Auto-correlation γ-rays



New measurement of the angular power spectrum available!
[Fermi LAT, PRL. 121 (2018)]

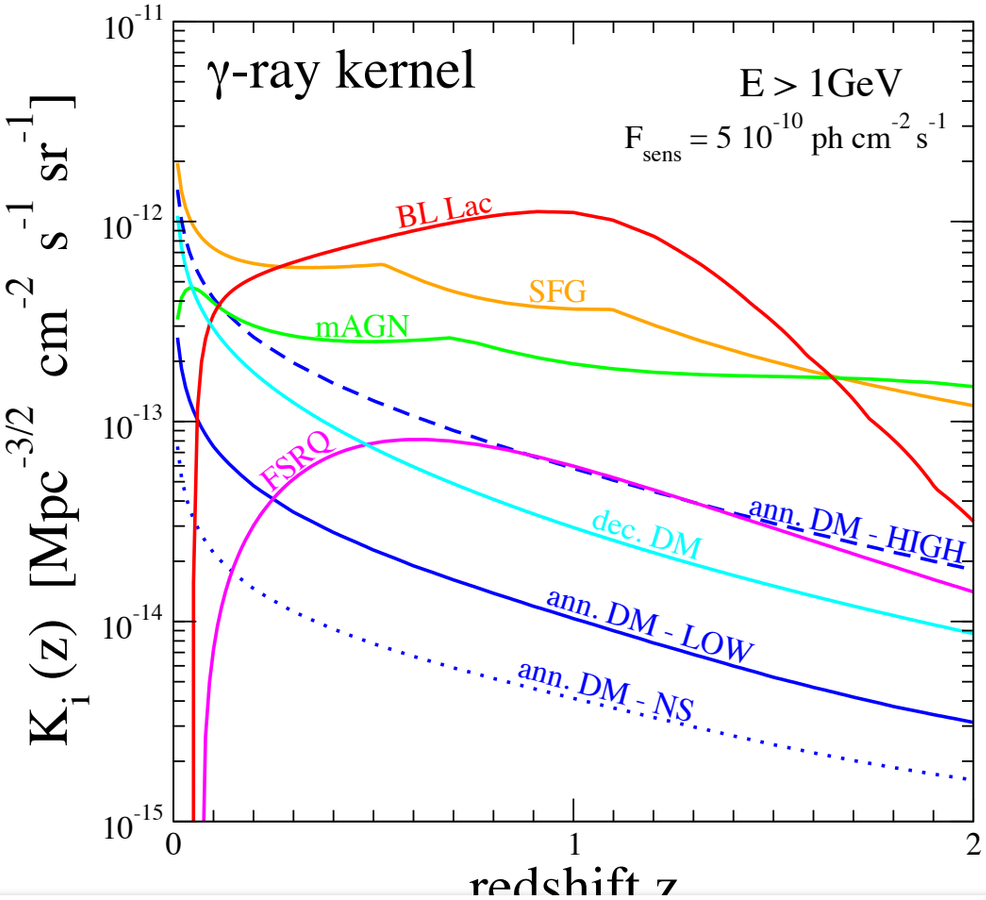
[Cuoco+:, 1506.01030; Reggis+, PRL (2015), 1503.05922]

3) **cross correlations** - cross-correlation analysis between the IGRB and objects that may trace the astrophysical sources of the IGRB

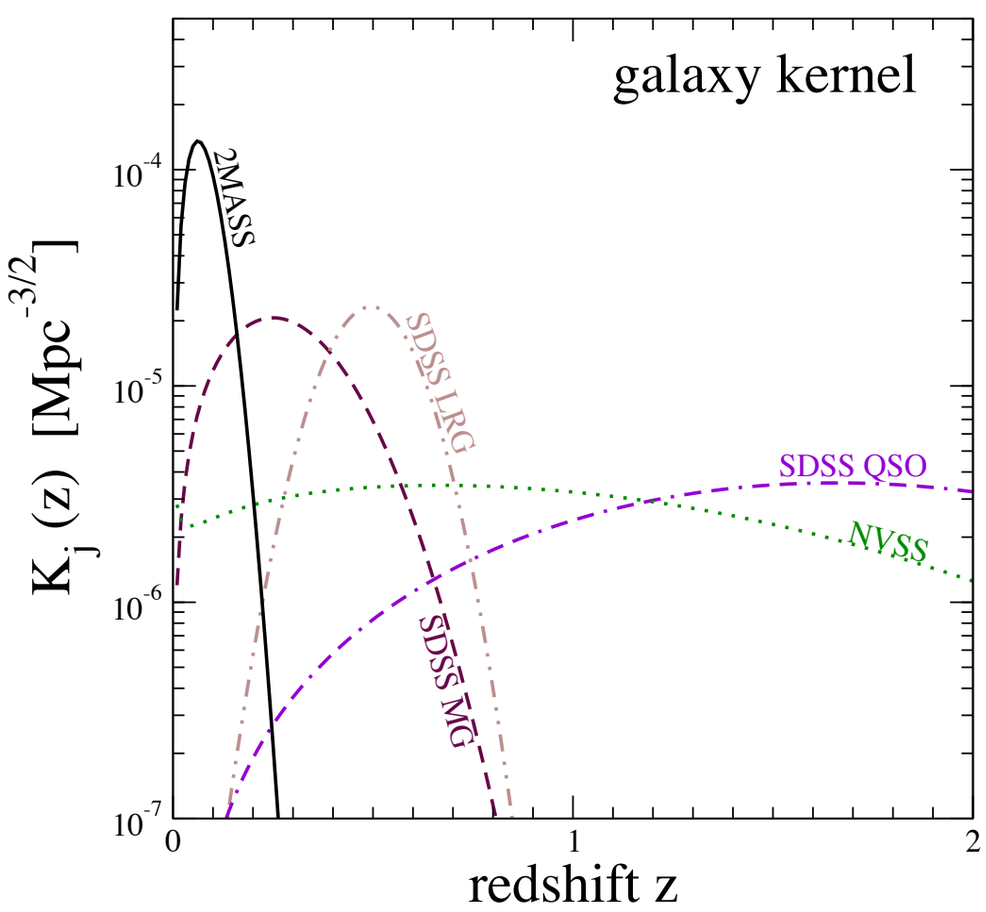


S. Camera's talk

Tomography of the gamma ray sky



A. Cuoco, E. Branchini, S. Camera, M. Viel,....

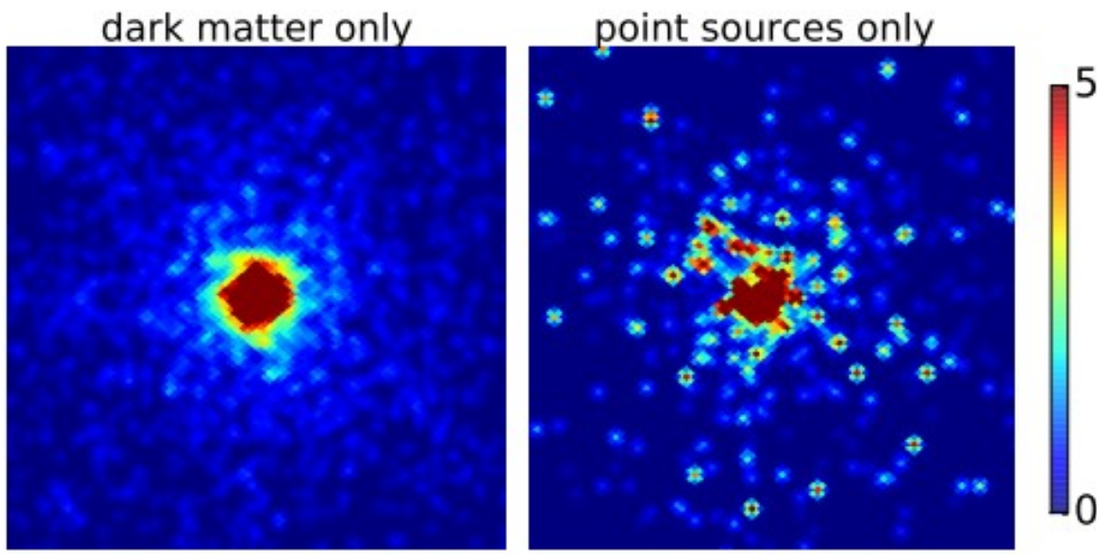


[Cuoco+:, 1506.01030; Reggis+, PRL (2015), 1503.05922]

The origin of the GCE — current status

Point-source origin of the excess?
— **statistical properties of photo counts** suggest that GCE is of a ‘point source’ origin

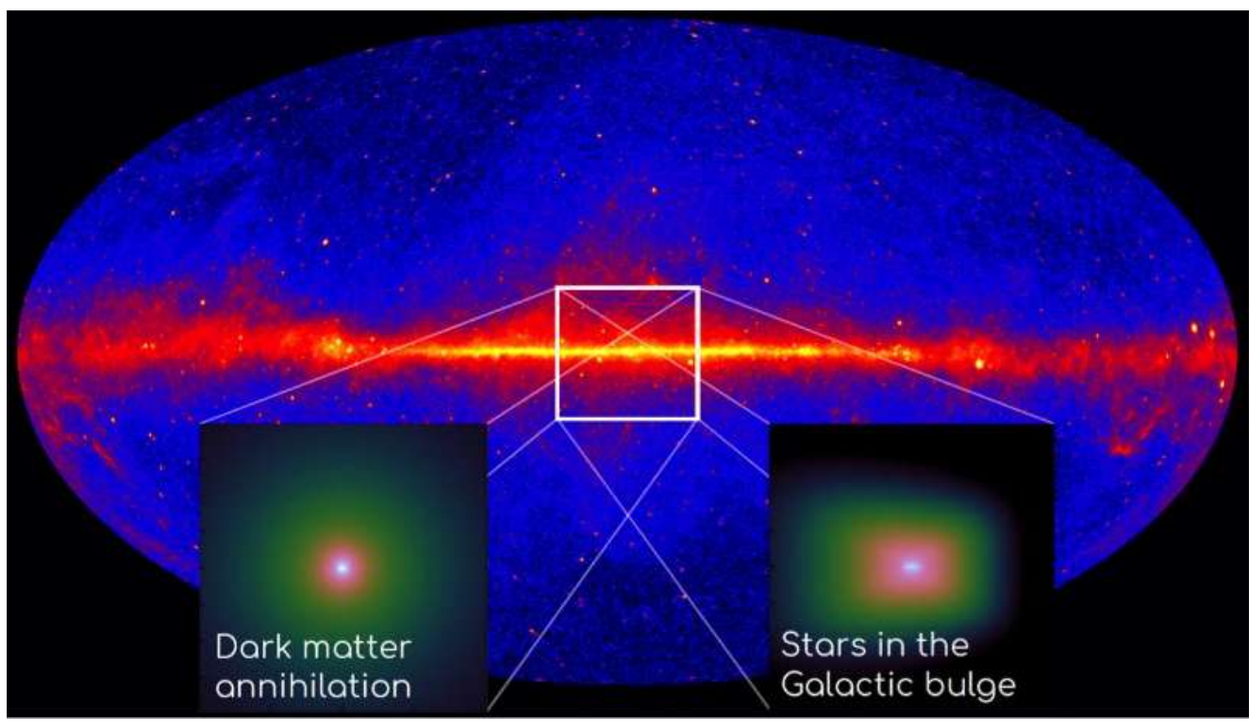
(Bartels+, PRL (2016), Lee+, PRL (2016))



(Credit: Lee+ 2014)

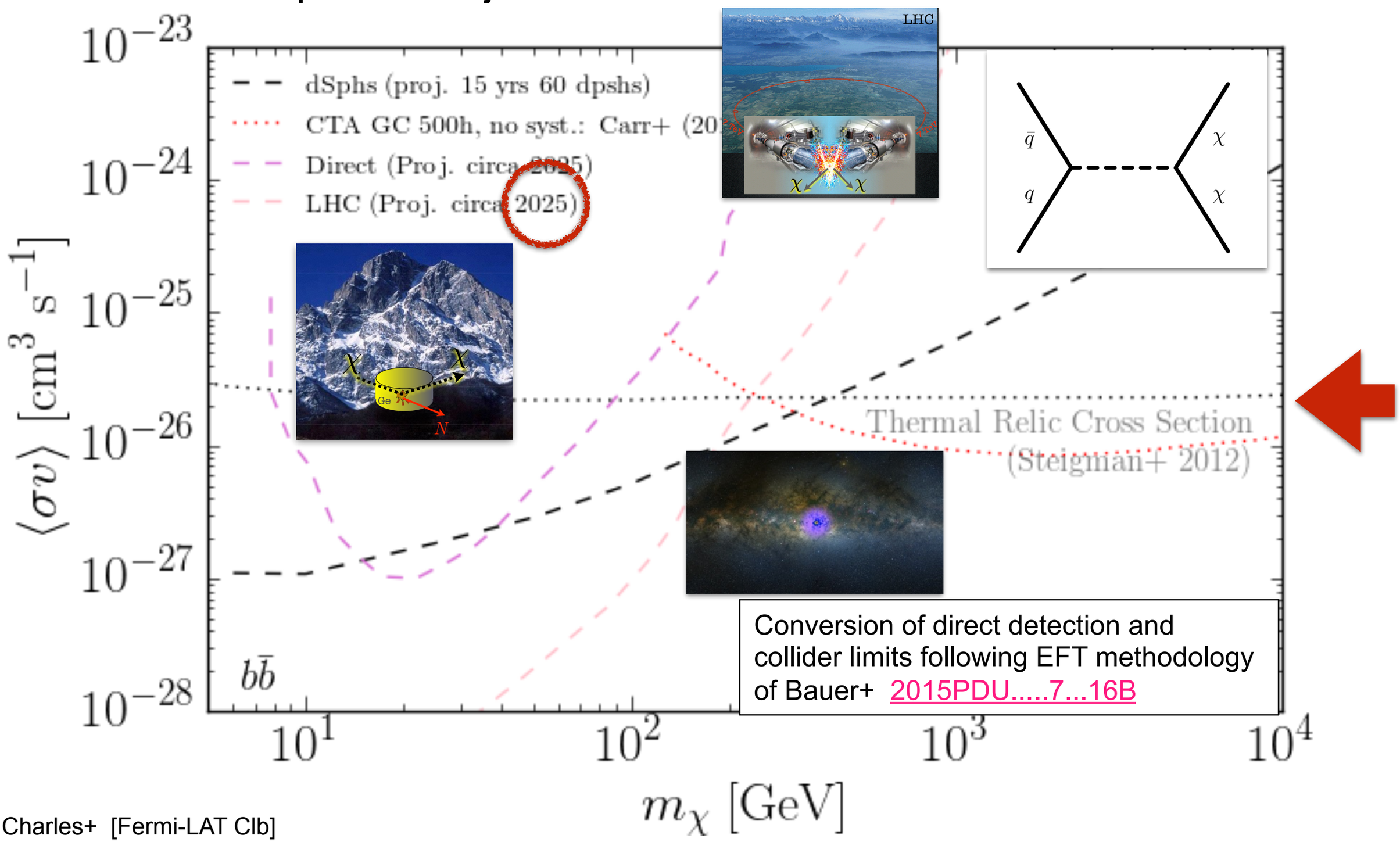
— evidence of **GCE tracing stellar densities**

(Bartels+, Nature Astronomy (2018);
Macias+, Nature Astronomy (2018))



Credit: C. Weniger/FermiLAT

Outlook— cornering the WIMPs

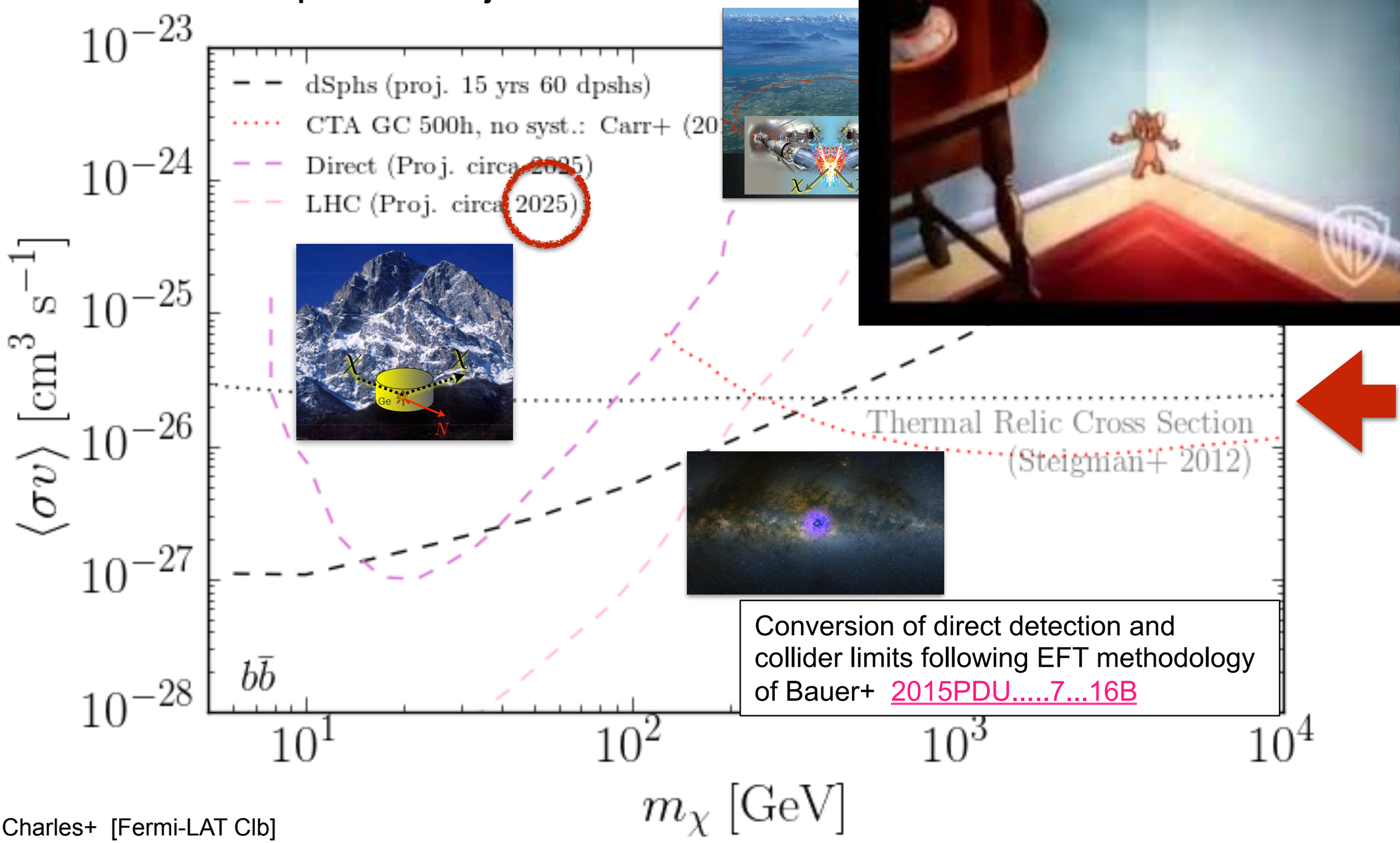


Conversion of direct detection and collider limits following EFT methodology of Bauer+ 2015PDU.....7...16B

Charles+ [Fermi-LAT Clb]
2016PhR...636....1C

Caution: model dependent! EFT assumed here.

Outlook— cornering the WIMPs

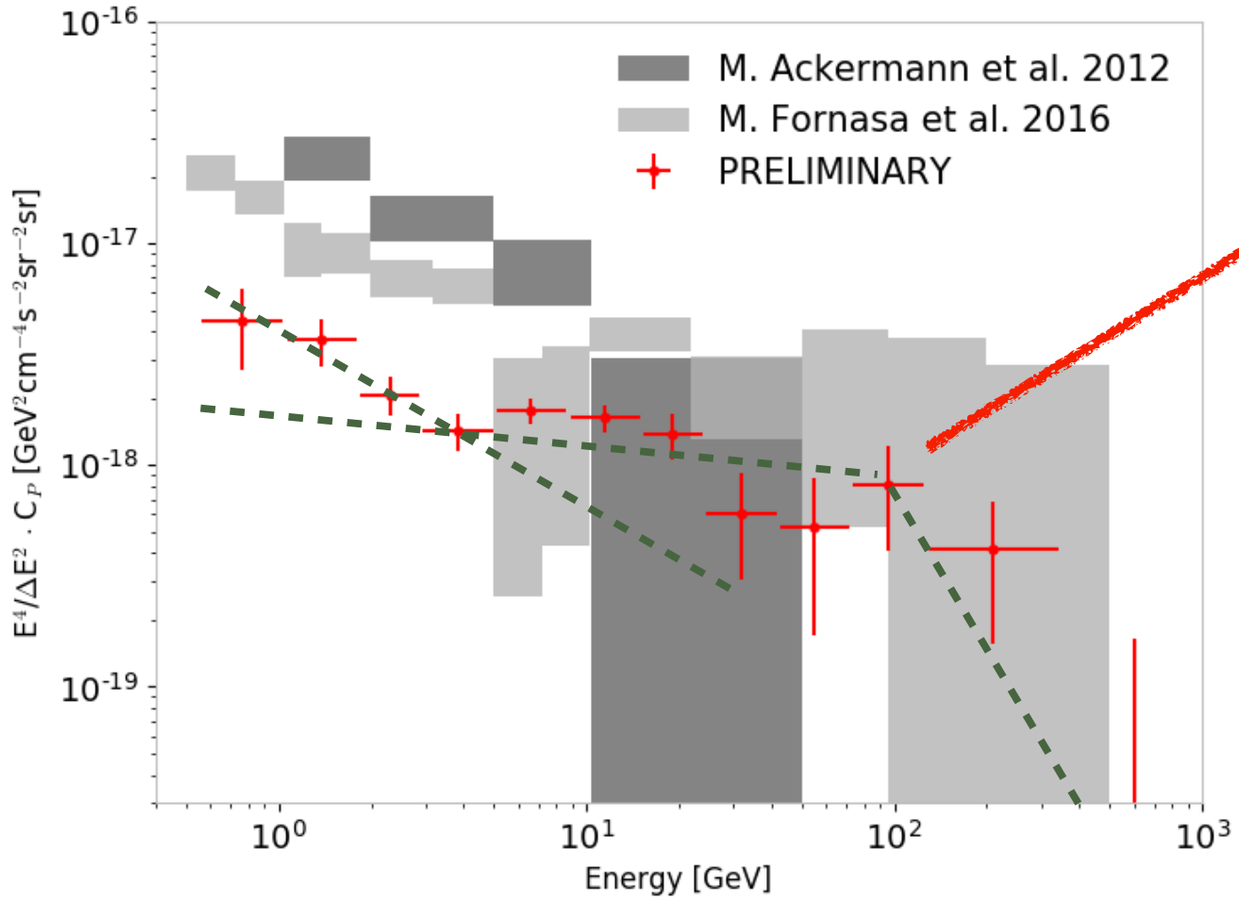


Conversion of direct detection and collider limits following EFT methodology of Bauer+ 2015PDU.....7...16B

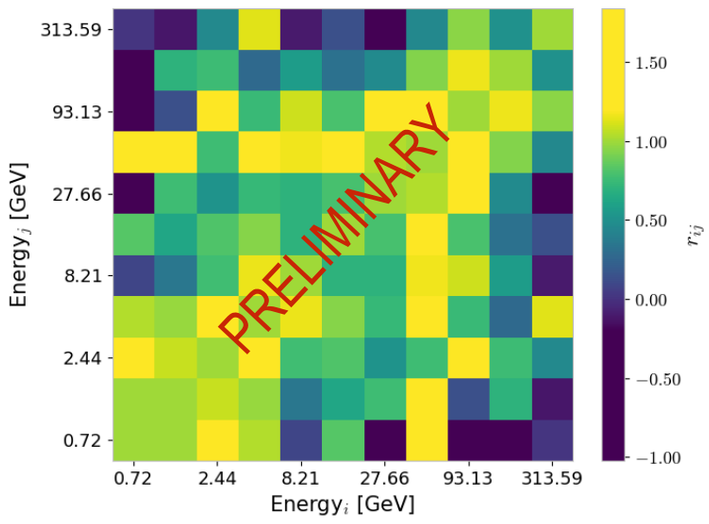
Charles+ [Fermi-LAT Clb]
2016PhR...636....1C

Caution: model dependent! EFT assumed here.

Isotropic emission



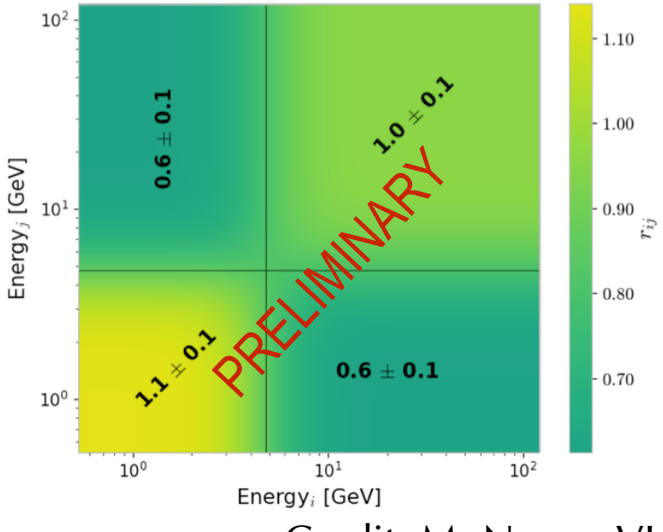
8 years (Pass 8)
0.5-1000 GeV (12 bins)
FL8Y mask (plus GP mask)
$50 < \ell < \ell_{max}$ **(E)**



Two power laws + cutoff: $\alpha = 2.51 \pm 0.16 \quad \beta = 1.82 \pm 0.12$

Low energy component: mAGN / SFG / ?

High energy component: ~100% Blazars



Credit: M. Negro, VHEPU2018

CTA @ spectral lines

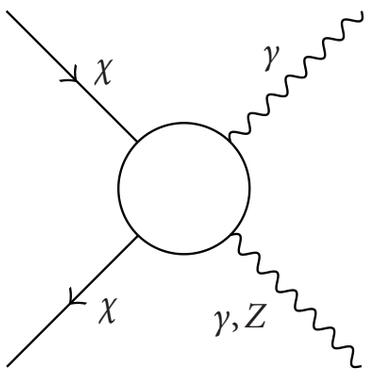
CTA excellent energy resolution — high sensitivity to spectral line search!

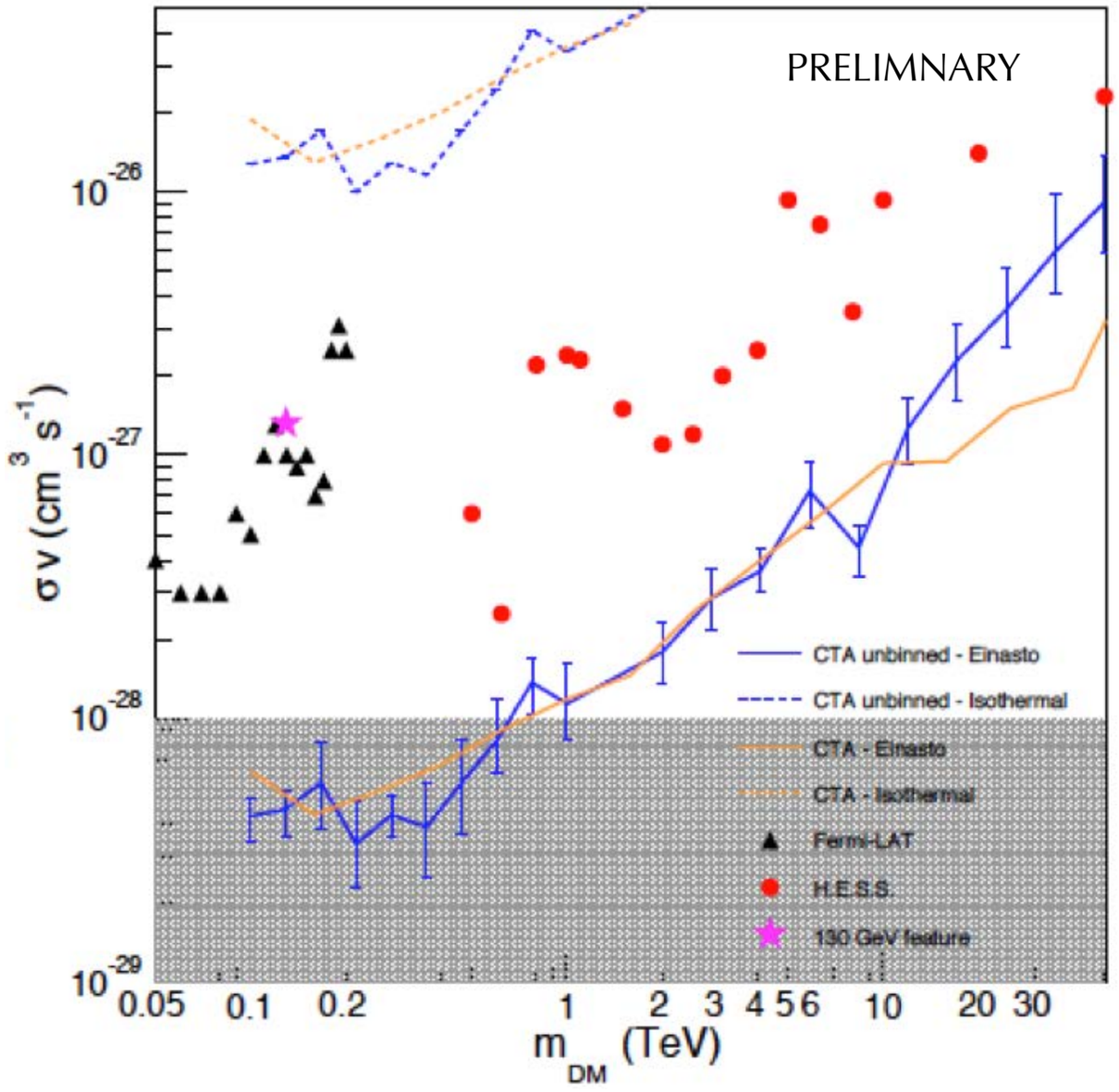
- data within a circle of 1 deg radius around the center

- standard astrophysical emission taken into account as background

- sensitivity improvement by a factor of ~10 expected

Line signal (loop level $\mathcal{O}(\alpha^2)$)

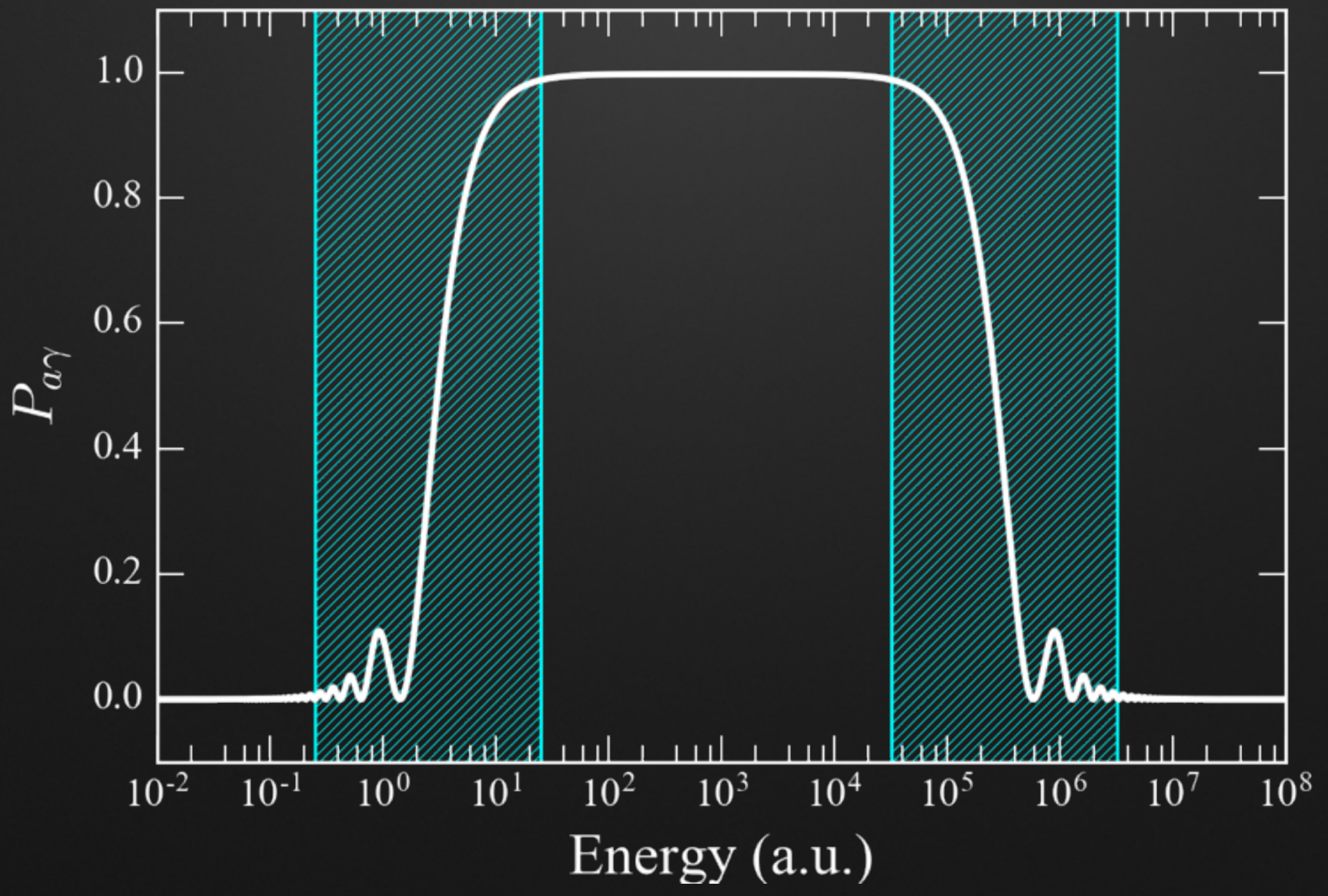




CTA Collaboration, in preparation

PHOTON-AXION/ALP MIXING

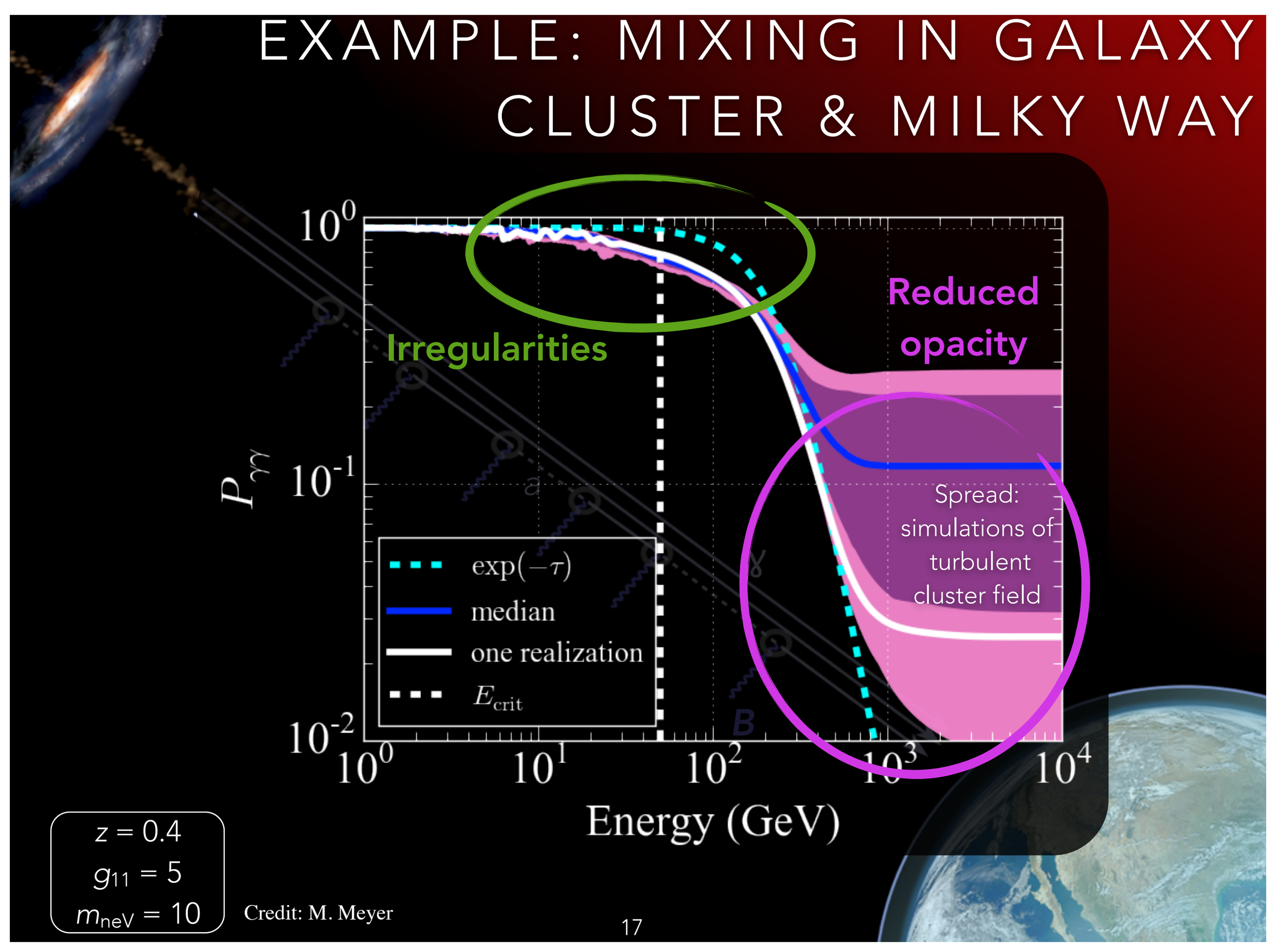
2nd Observable: irregularities in energy spectrum around E_{crit} and E_{max}



Credit: M. Meyer

[Östman & Mörtsell 2005; Hooper & Serpico 2007; Mirizzi et al 2007; Hochmuth & Sigl 2007; De Angelis et al. 2008; Wouters & Brun 2012,2013; Abramowski et al. 2013; Ajello et al. 2016]

EXAMPLE: MIXING IN GALAXY CLUSTER & MILKY WAY



$z = 0.4$

$g_{11} = 5$

$m_{\rm neV} = 10$

Credit: M. Meyer

SEARCH FOR IRREGULARITIES WITH FERMI LAT FROM NGC 1275

- **Radio galaxy NGC 1275**, **bright *Fermi* source** [e.g. Abdo et al. 2009]

- In the center of **cool-core** Perseus cluster

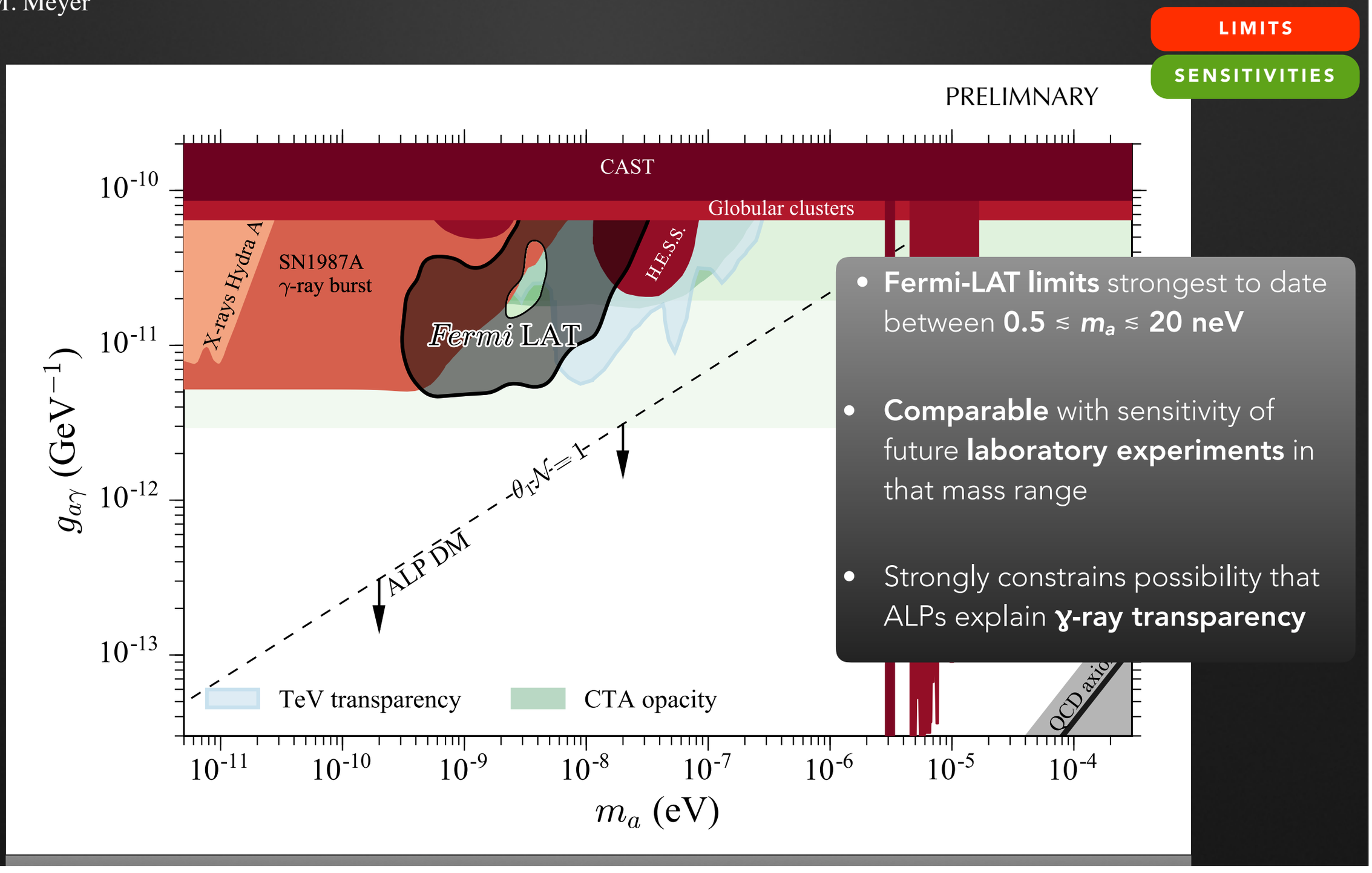
- Rotation measures: **central** B field ~**25μG** [Taylor+ 2006]

- **B ≳ 2 μG from non-observation of γ rays** [Aleksic et al. 2012]

Credit: M. Meyer

QCD Axion: $m_a \approx 0.3\,\mathrm{eV}\,\dfrac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}} = 0.3\,\mathrm{eV}\,g_{10}$

Credit: M. Meyer



- **Fermi-LAT limits** strongest to date between **0.5 ≲ m_a ≲ 20 neV**
- **Comparable** with sensitivity of future **laboratory experiments** in that mass range
- Strongly constrains possibility that ALPs explain **ɣ-ray transparency**

QCD Axion: $m_a \approx 0.3\,\mathrm{eV}\,\dfrac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}} = 0.3\,\mathrm{eV}\,g_{10}$

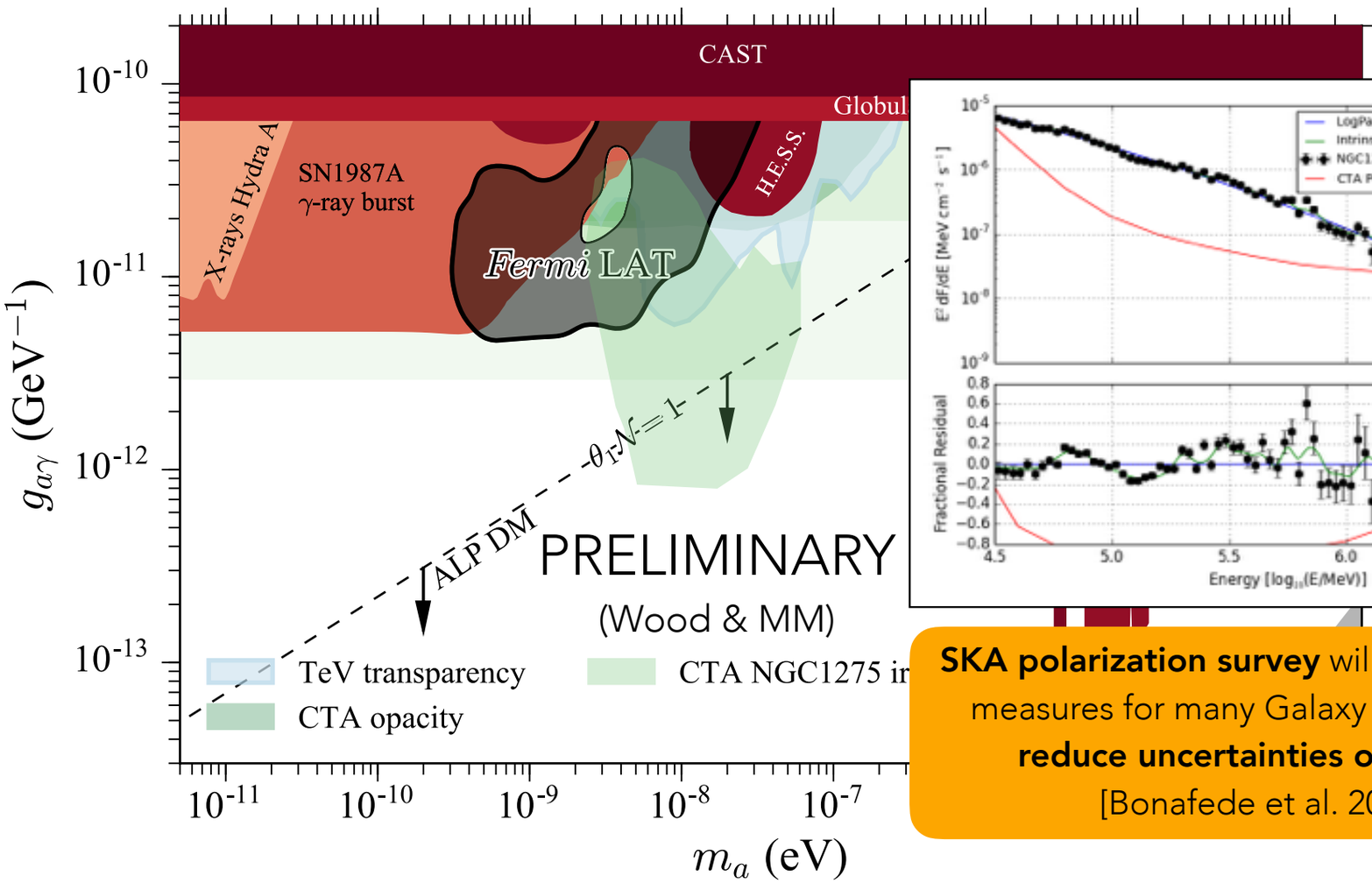
Credit: M. Meyer

CONSTRAINTS & SENSITIVITIES

cta cherenkov telescope array

LIMITS

SENSITIVITIES



SKA polarization survey will yield rotation measures for many Galaxy clusters and **reduce uncertainties on B field** [Bonafede et al. 2015]