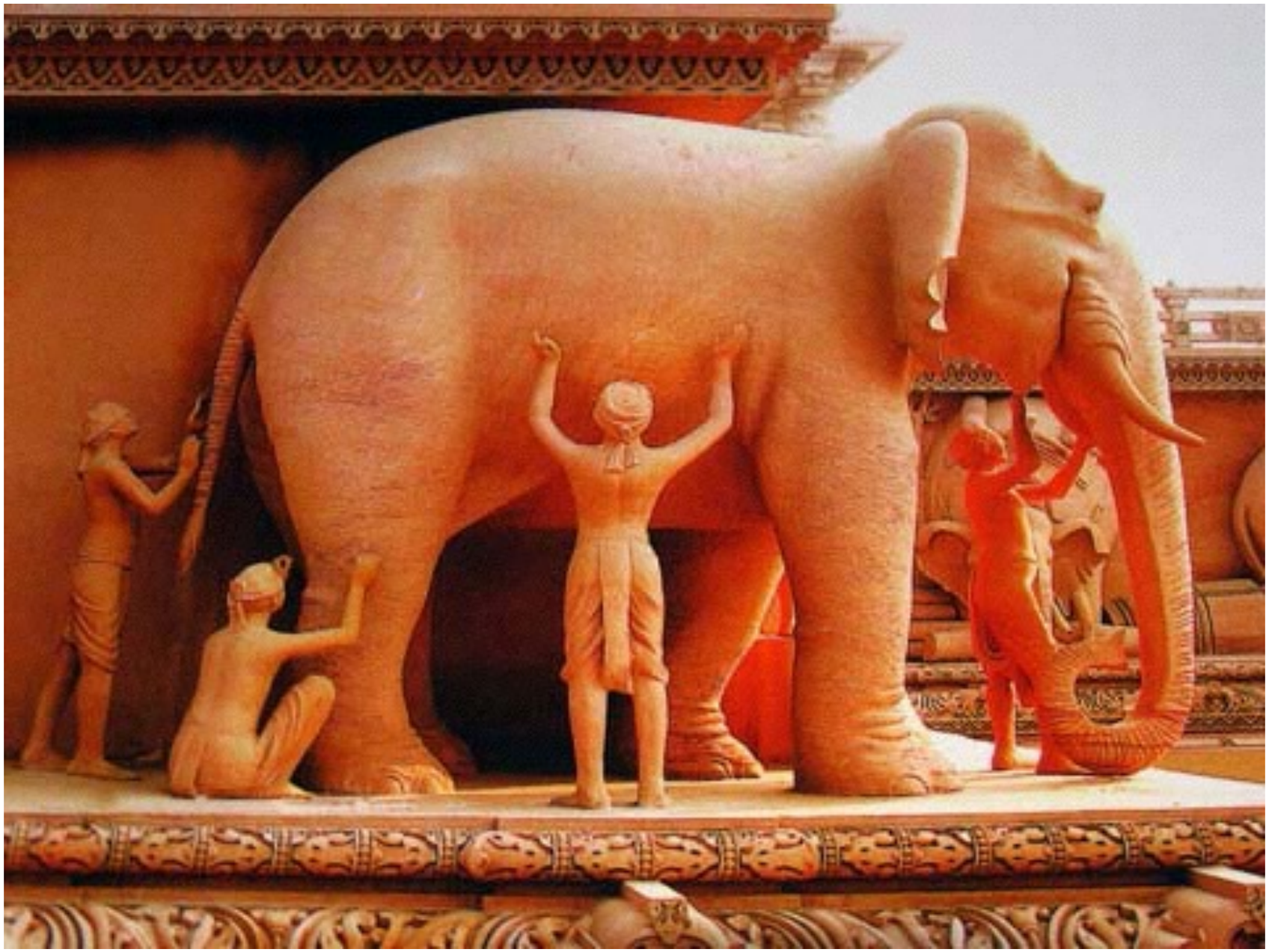
Status of indirect dark ~~matter~~ searches

(circa 2016)

WIMP



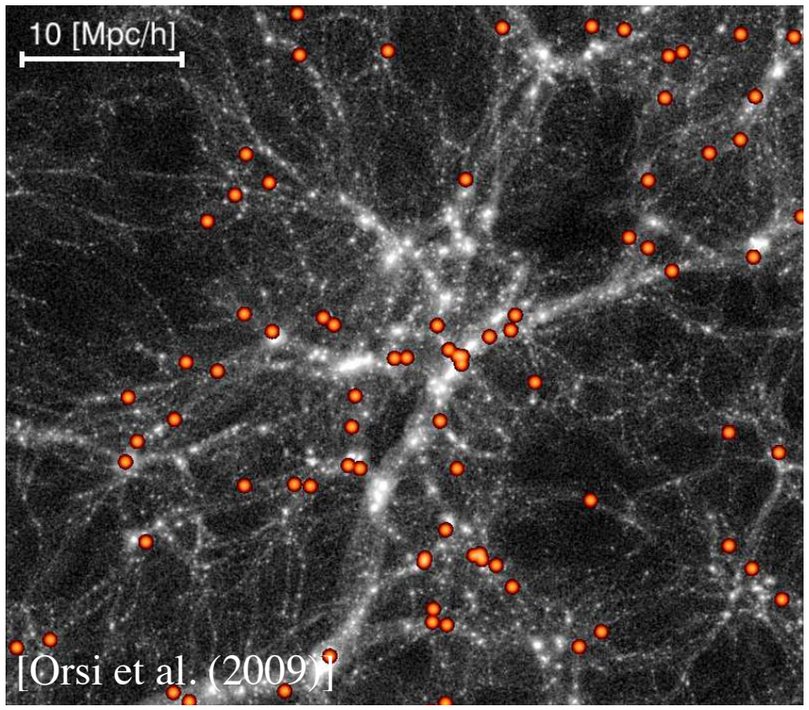
Gabrijela Zaharijas

University of Nova Gorica, Slovenia

Dark matter is out there!

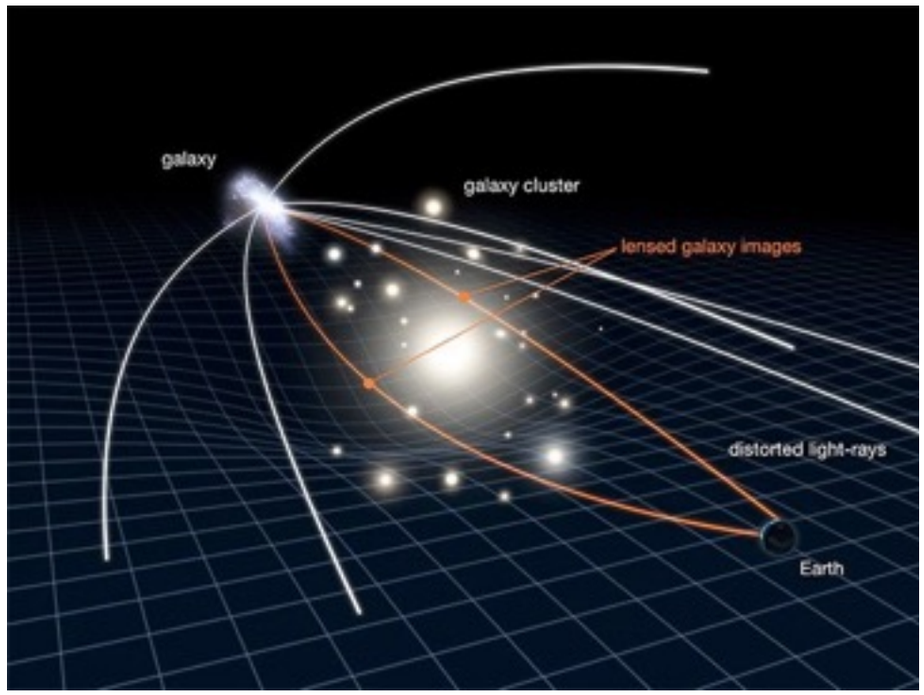
an essential building block of the Standard Model of Cosmology

large scale structures



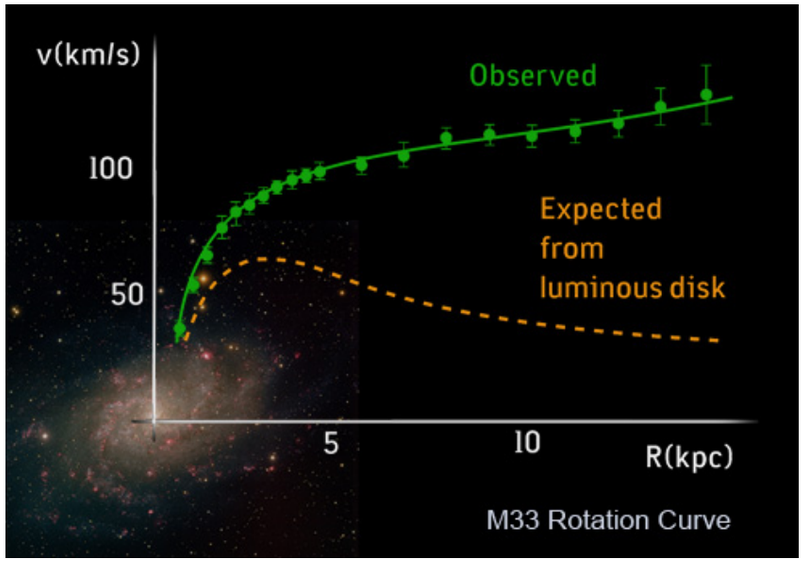
10s Mpc

clusters of galaxies



Mpc

Milky Way-sized galaxies



10s kpc

dwarf galaxies

<~ kpc

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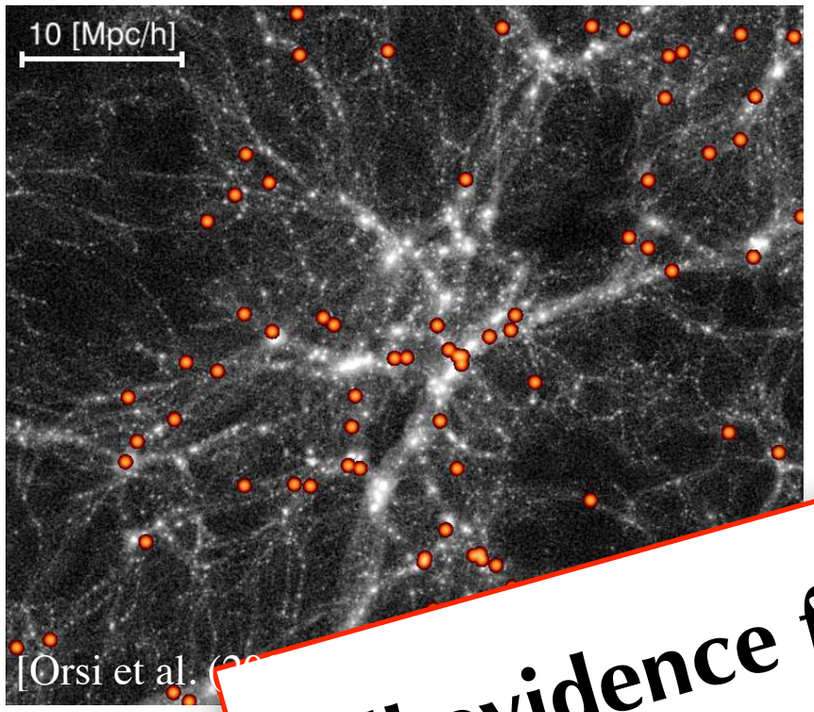
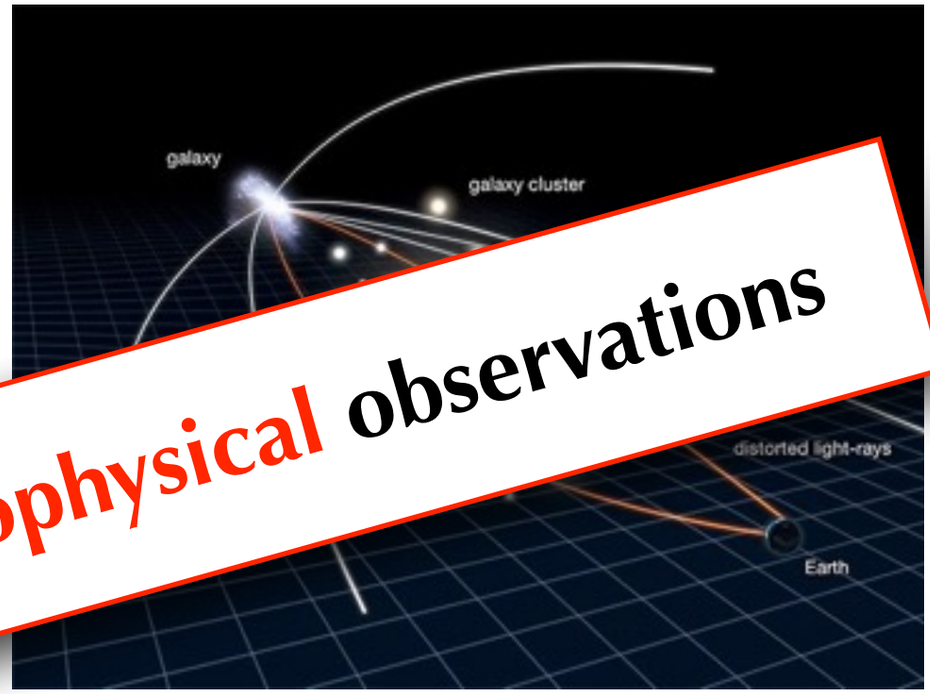


10s Mpc



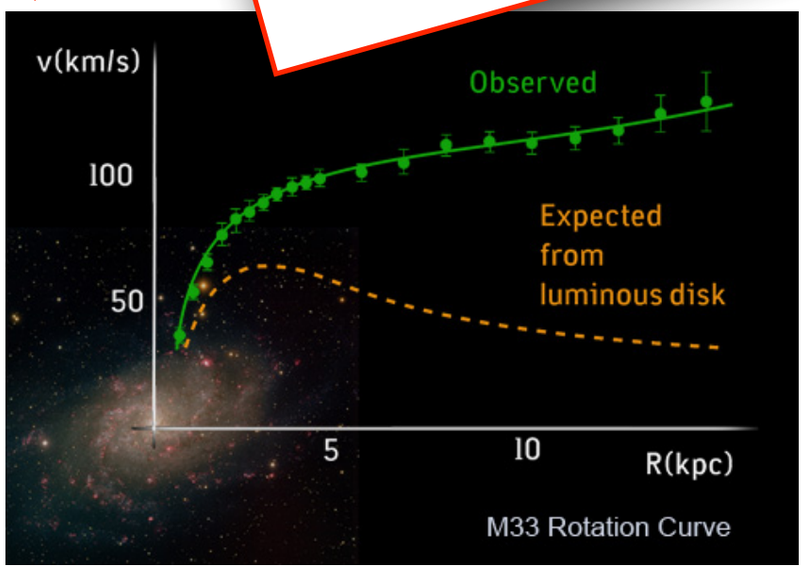
Mpc

[Orsi et al. (2

All evidence from astrophysical observations

Milky W

dwarf galaxies



10s kpc

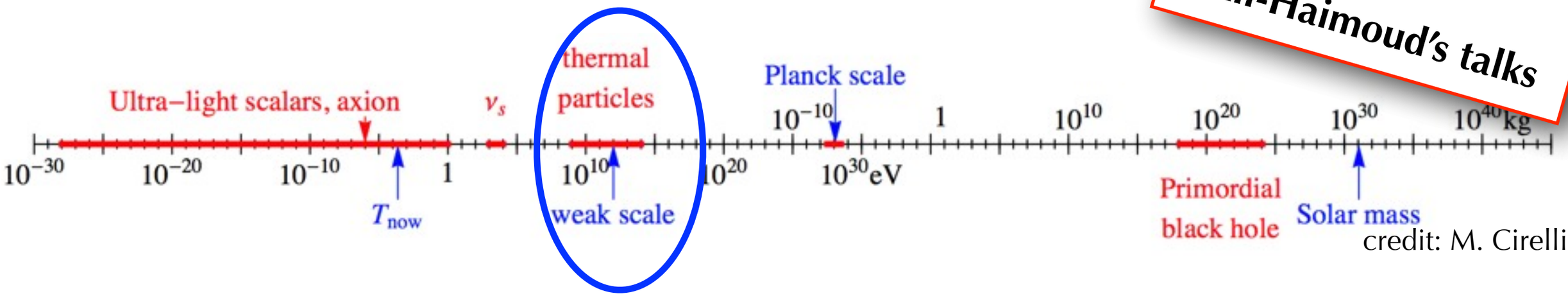
<~ kpc

Dark matter particle nature?

Artwork by Sandbox Studio, Chicago

Dark matter particle nature?

J. Biteau's & Y. Ali-Haimoud's talks



credit: M. Cirelli

WIMPs: *weak-scale mass (~M_Z) + weak interactions (~G_F)*

→ cold

→ many candidates in theories which attempt to explain the origin of EW mass

→ **predictive!**

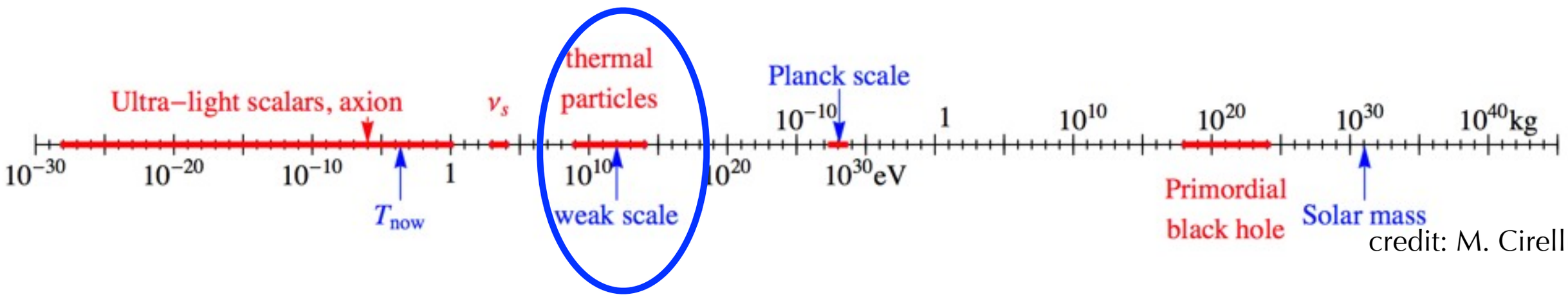
Dark Matter Abundance from Thermal Production

$$\Omega_{dm} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

Cosmological Measurement

Weak Scale Physics

Dark matter particle nature?



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Cosmological Measurement

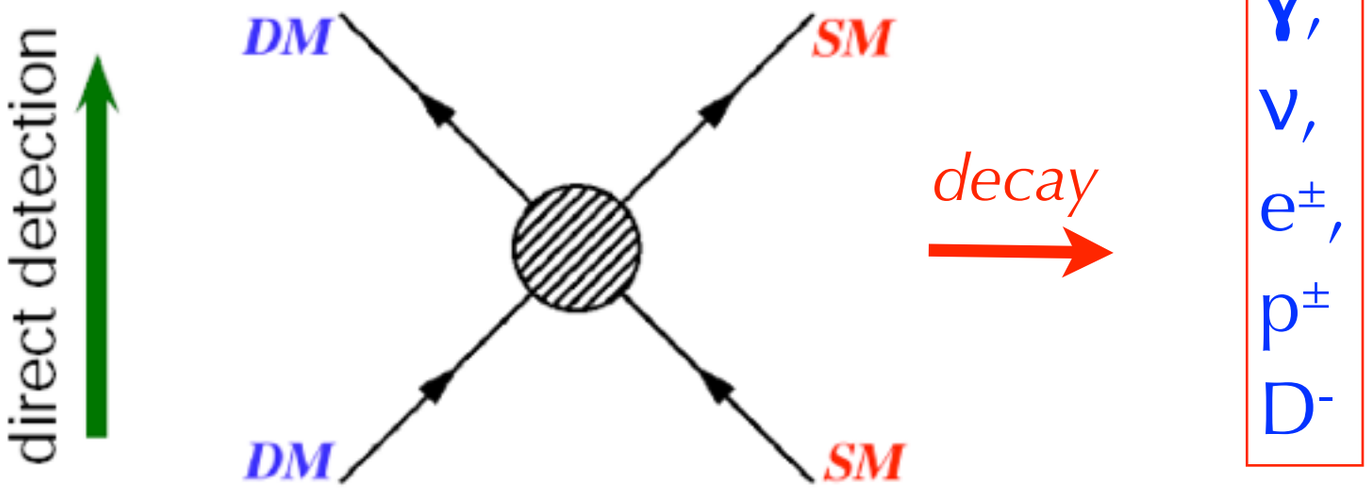
Weak Scale Physics

postmodern view *"Like all tyrannies, there is a single yoke of control: the one thing we know about WIMPs is their relic abundance. We've lived with this tyranny for a long time. It's provided all of us with jobs... and some of us with tenure."*
– Neal Weiner, **on the 'tyranny' of the WIMP Miracle paradigm** *(F. Tanedo, DMNotes)*

- WIMP hypothesis is **predictive**:

thermal freeze-out (early Univ.)

indirect detection (now)



production at colliders

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

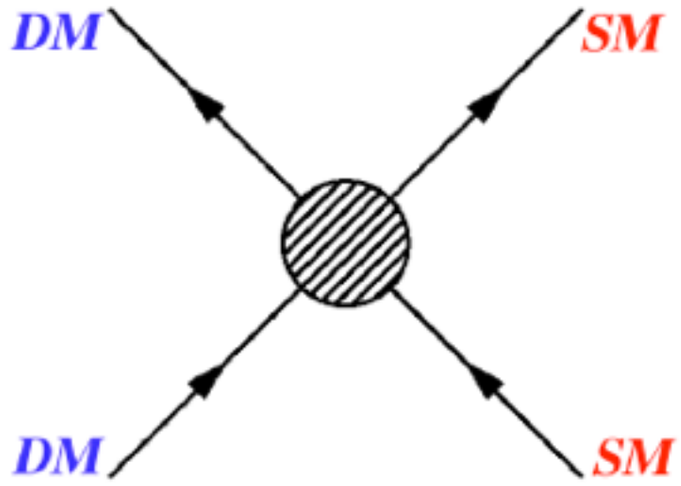
Today, *DM expected to annihilate with the same* $\langle \sigma v \rangle_{thermal}$, *in places where its* **density is enhanced**!

@ $\mathcal{O}(M_Z)$

in astrophysical systems - *remotely*

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

direct detection



decay

γ,
ν,
$e^{\pm}$,
$p^{\pm}$
D^{-}

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

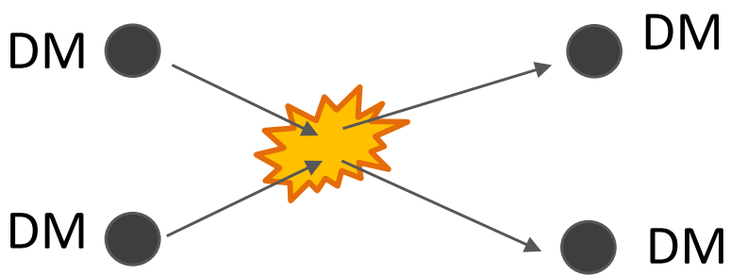
***Today**, DM expected to annihilate with the same $\langle \sigma v \rangle_{thermal}$, in places where its* **density is enhanced**!

production at colliders

@ $\mathcal{O}(M_Z)$

structure formation

Self-interactions

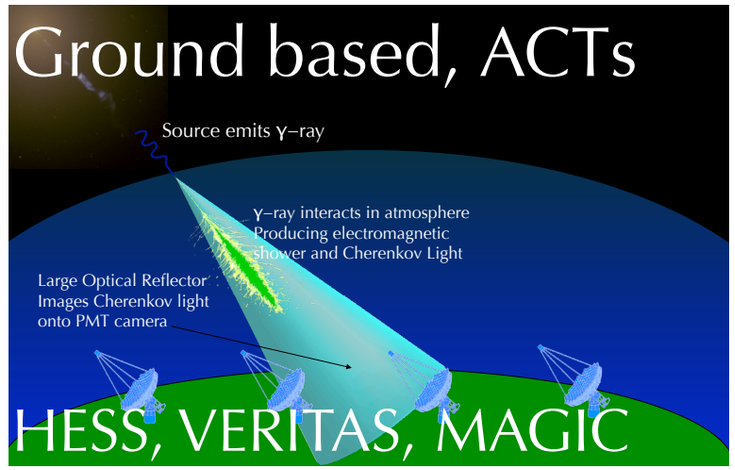


Credit: S. Tulin

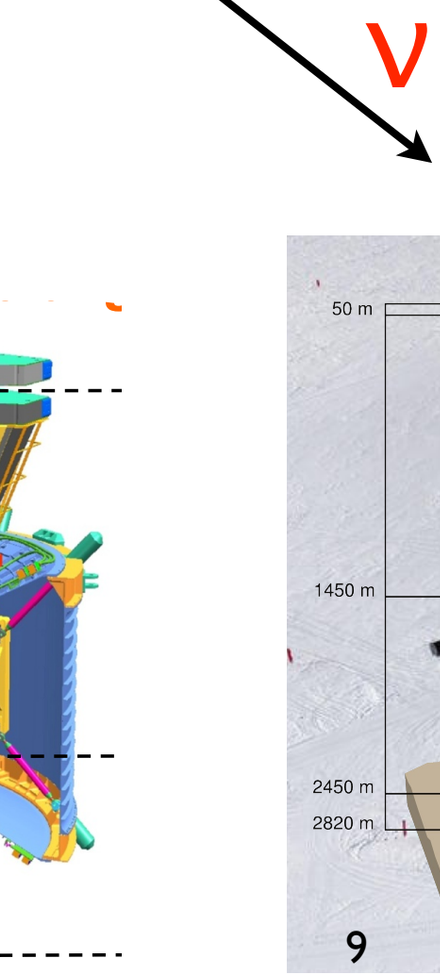
in astrophysical systems - *remotely*

and now we have powerful tools

@ $\mathcal{O}(M_Z)$

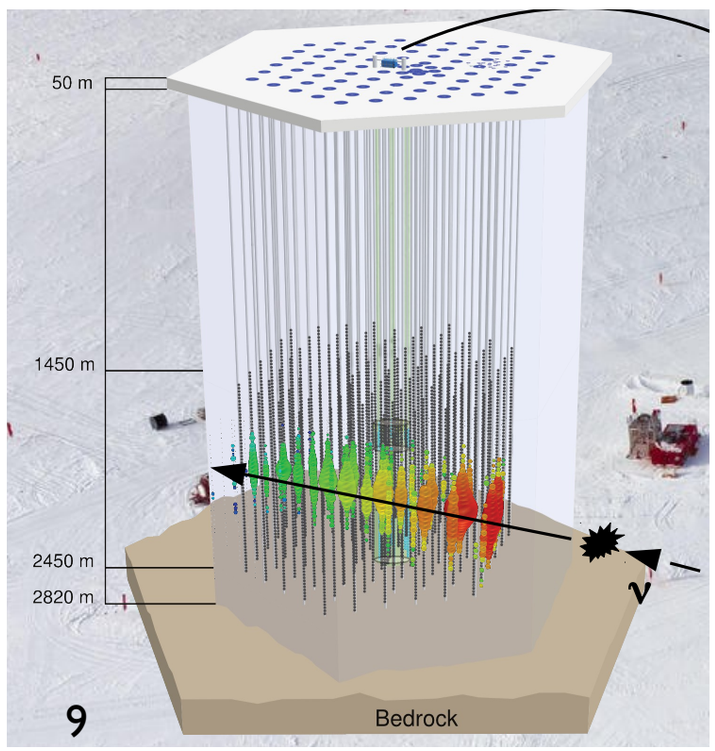


$e^{\pm}$, $p^{\pm}$, D^{-}



PAMELA, AMS02

ν



Ice Cube, ANTARES

and now we have powerful tools

@ $\mathcal{O}(M_Z)$

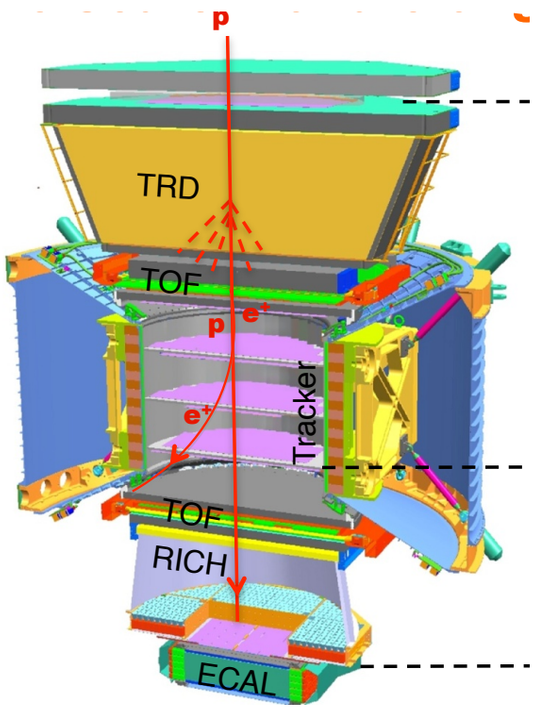
γ

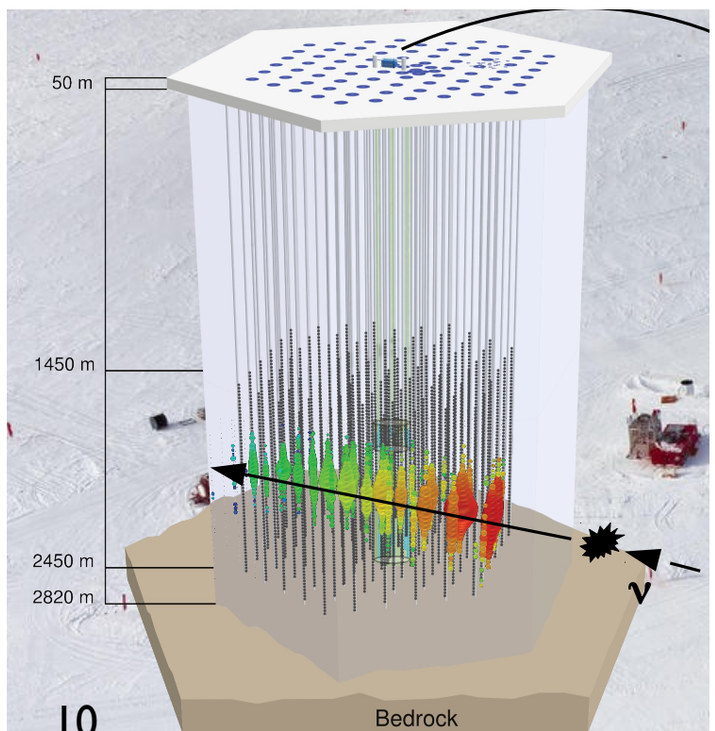
γs & νs point back to their source!

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

ν

PAMELA, AMS02

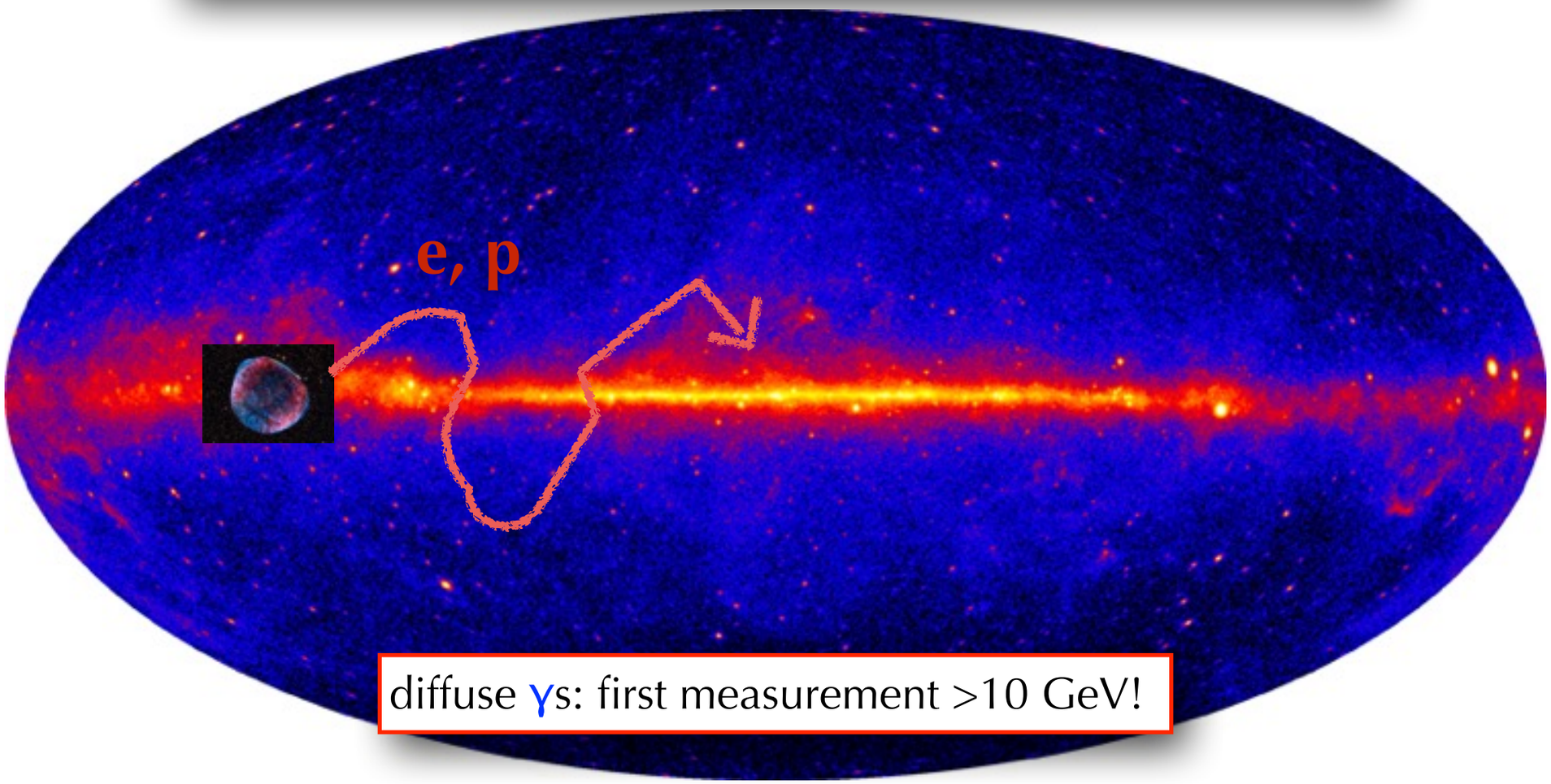




Ice Cube, ANTARES

Astrophysical experiments: multipurpose experiments w rich scientific program → discovering the sky @>~Mz energies!

Fermi LAT: launched 2008,
energy range: 30 MeV->300GeV, whole sky coverage



diffuse γs: first measurement >10 GeV!

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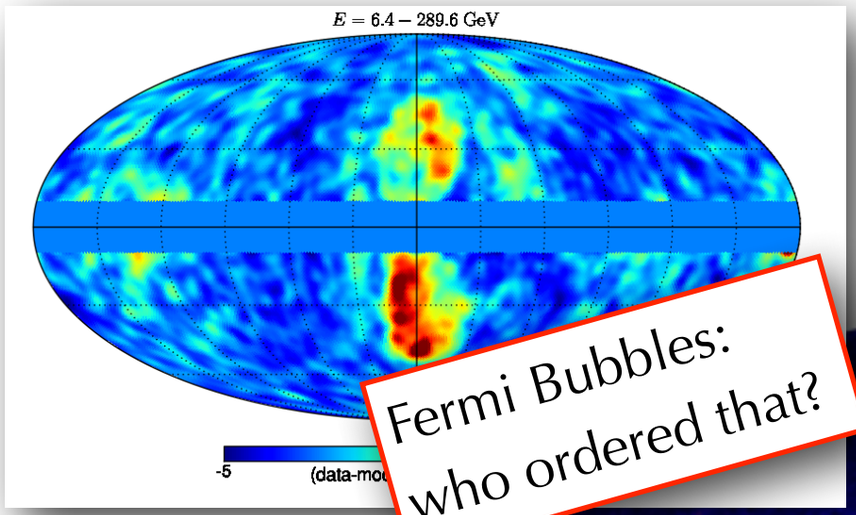

Fermi Bubbles: who ordered that?

Fermi LAT

e, p

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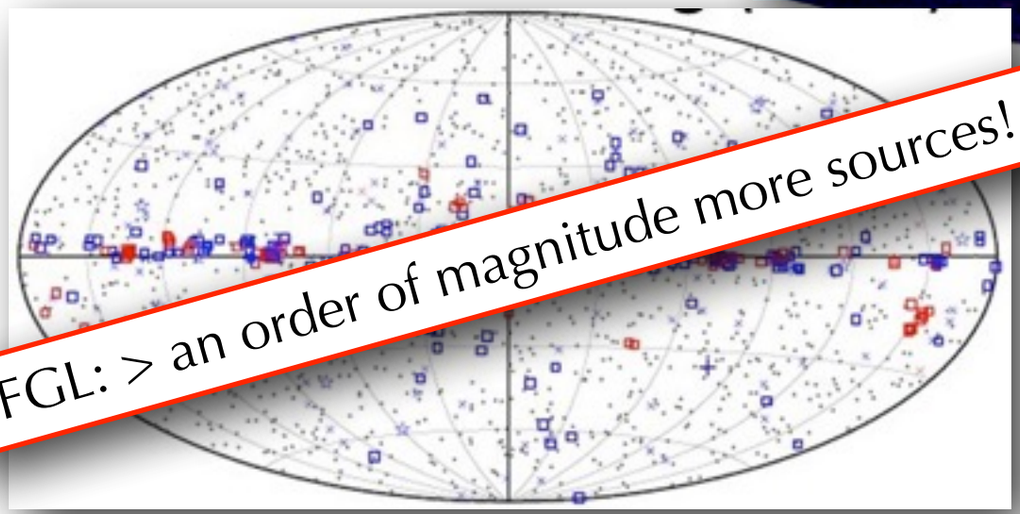
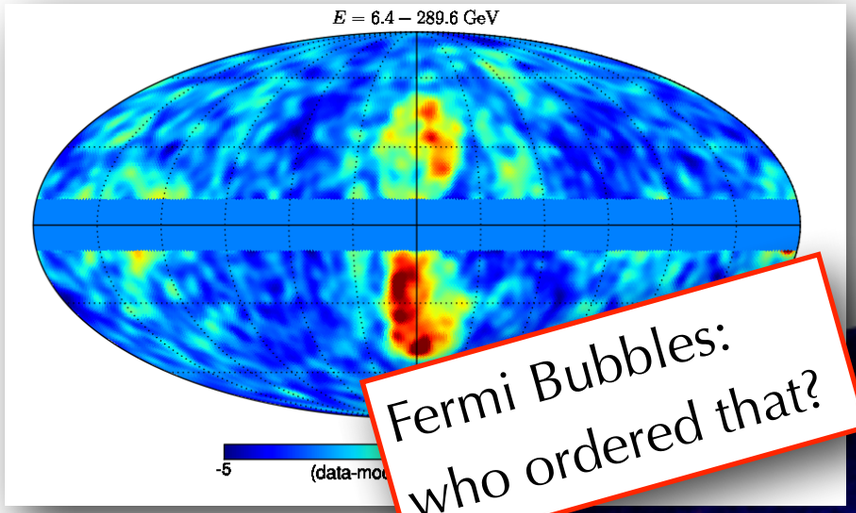


3FGL: > an order of magnitude more sources!

Astrophysical experiments: multipurpose experiments w rich scientific program → discovering the sky @>~Mz energies!



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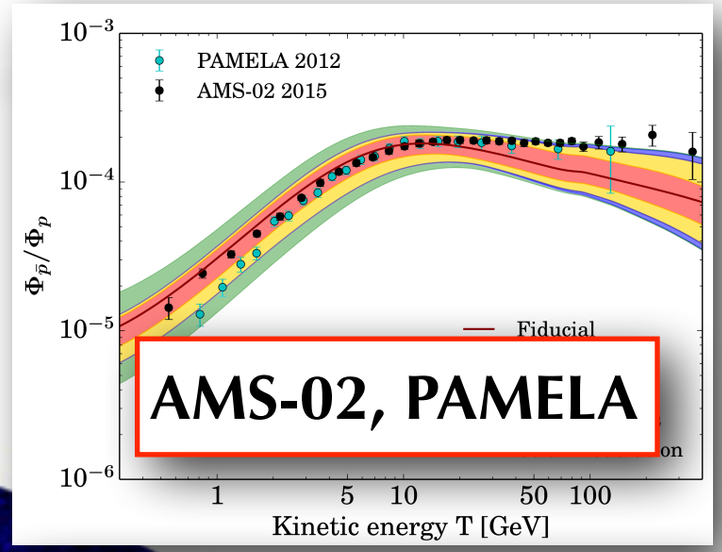
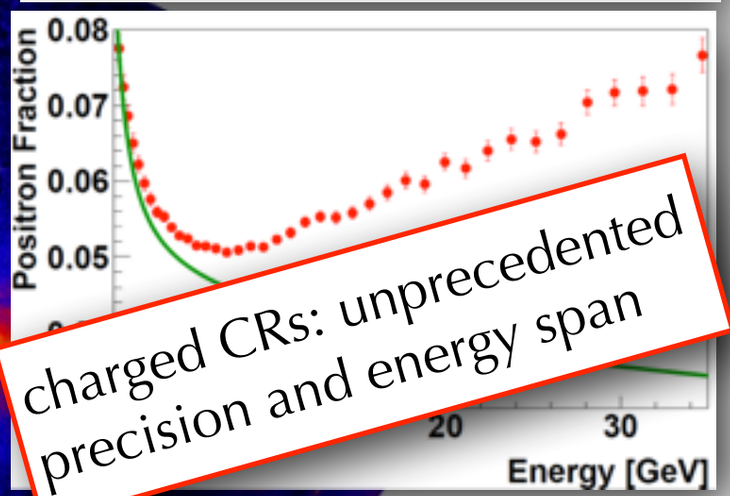


AMS-02, PAMELA

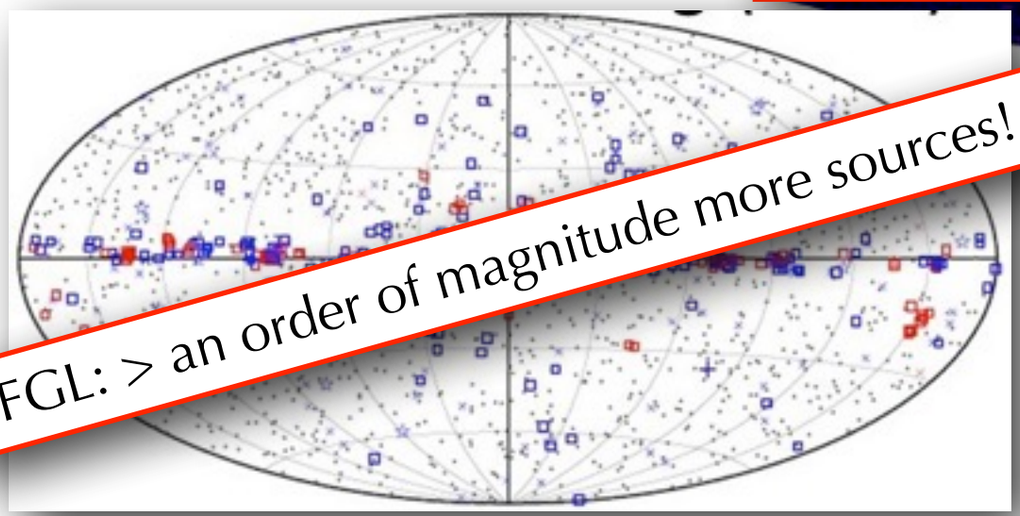
Fermi LAT

e, p



charged CRs: unprecedented precision and energy span

diffuse γs: first measurement >10 GeV!



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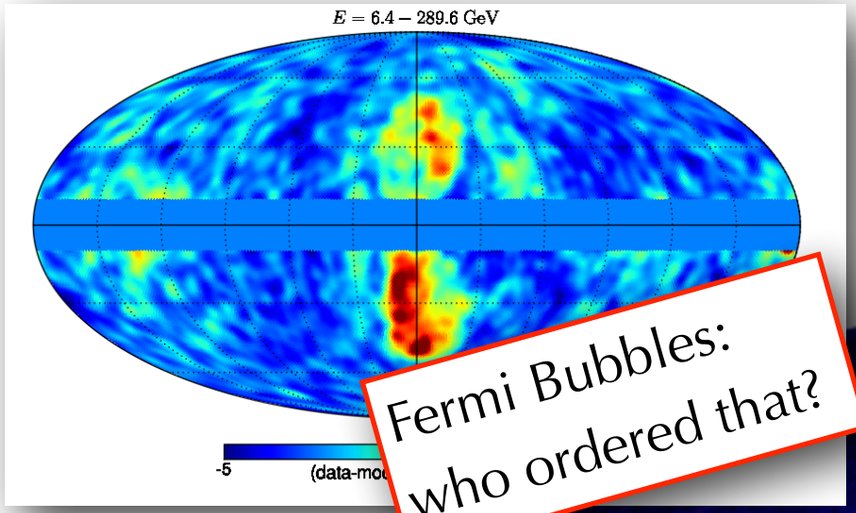

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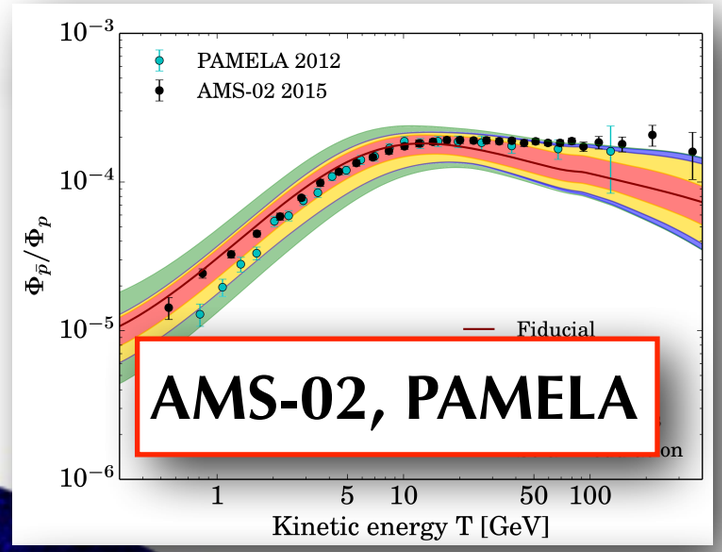

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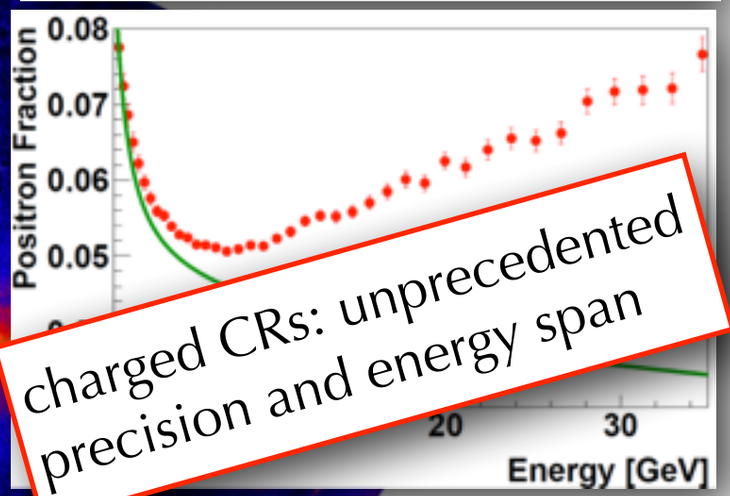

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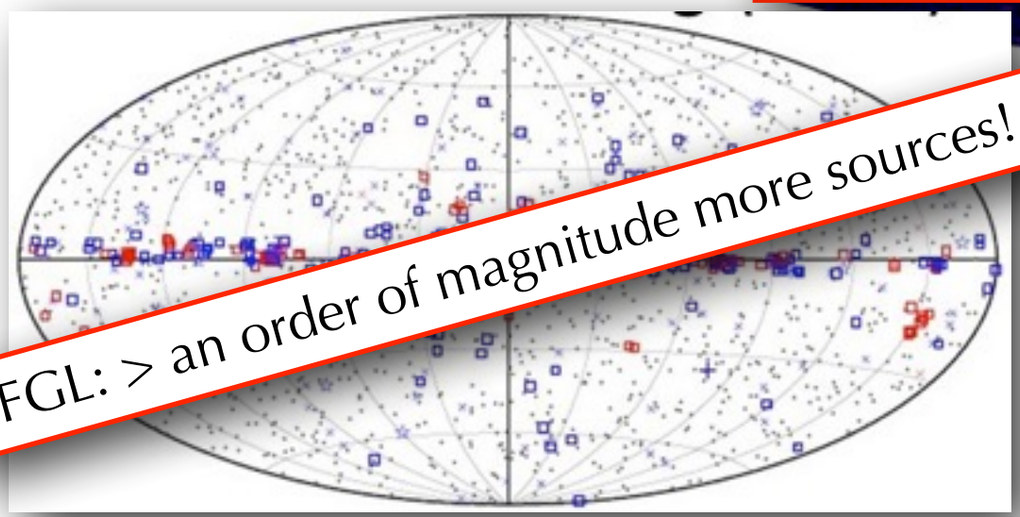

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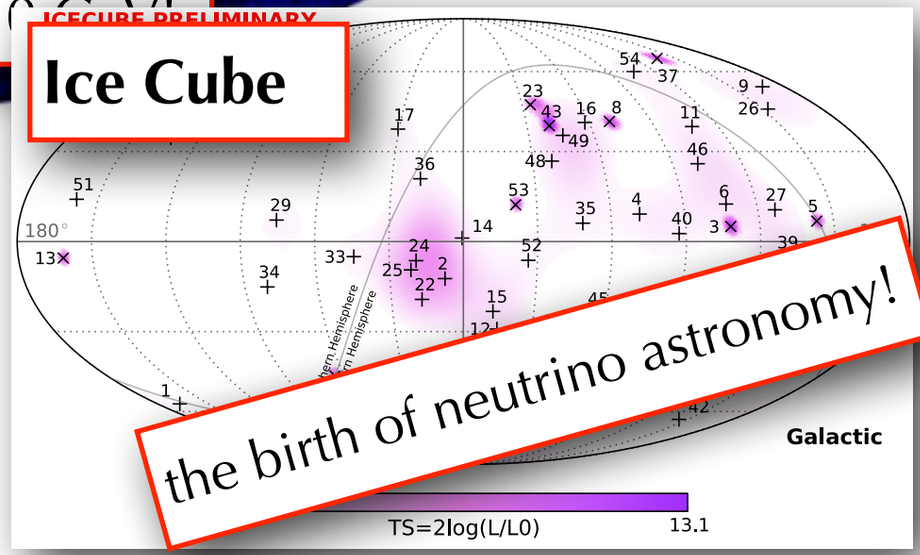
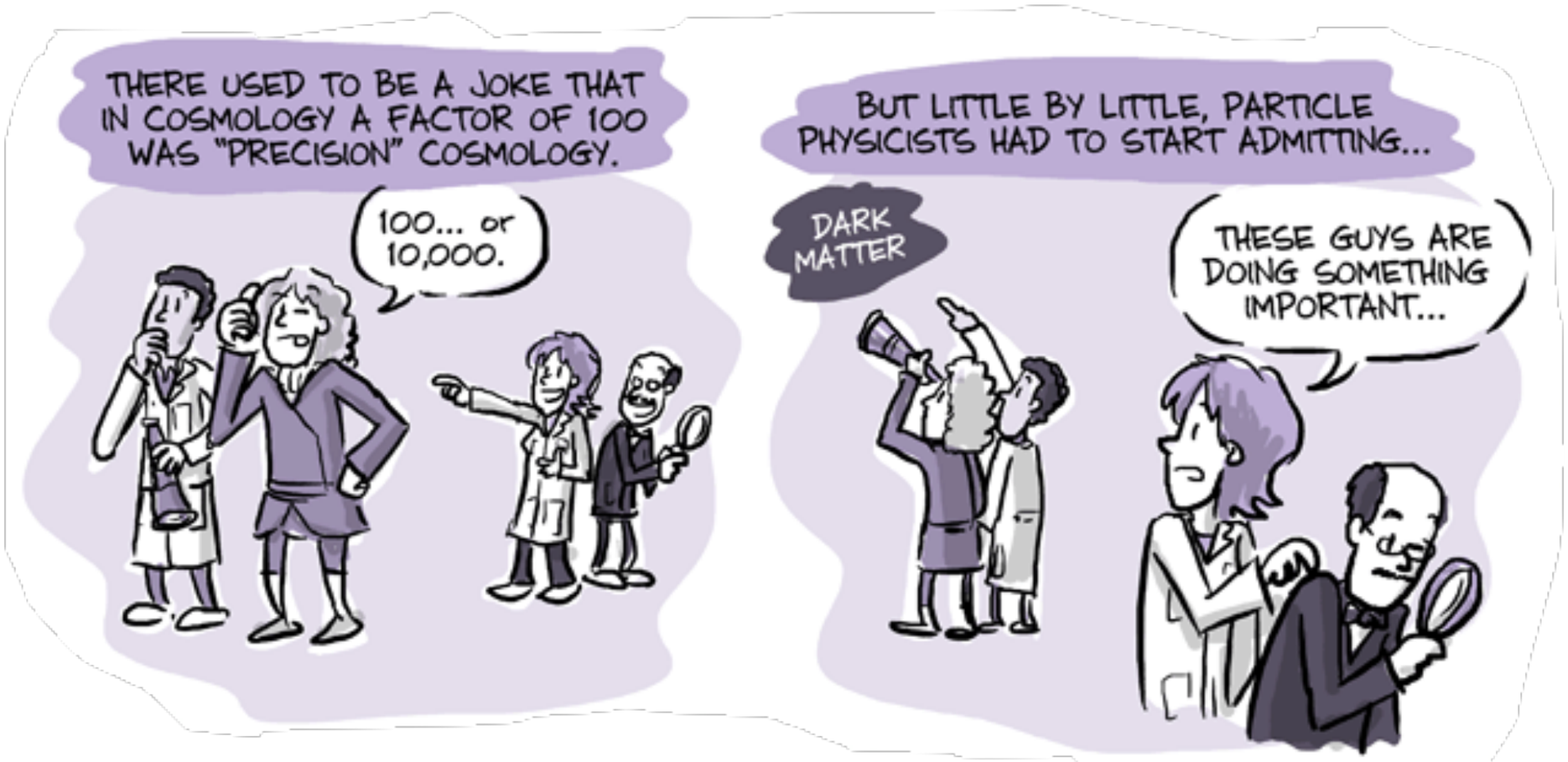


Ice Cube

the birth of neutrino astronomy!

- **Why indirect searches?**
  - direct detection and collider searches are cleaner environments with 'controlled' backgrounds
- Important:
  - to detect/measure DM ***remotely/in places where it was discovered***
  - direct ***link to early universe physics***
  - ideally: detect it in the Lab AND astrophysical objects. ***Multiple handle*** on its properties.



Gamma rays (&neutrinos)

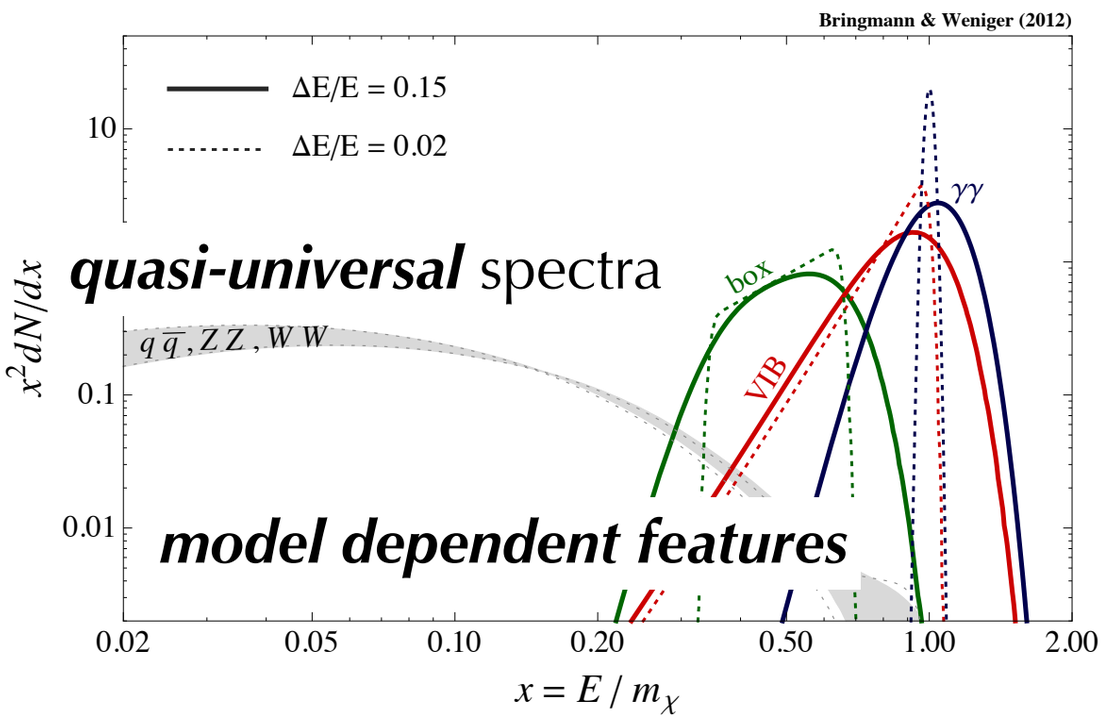
particle physics

structure formation

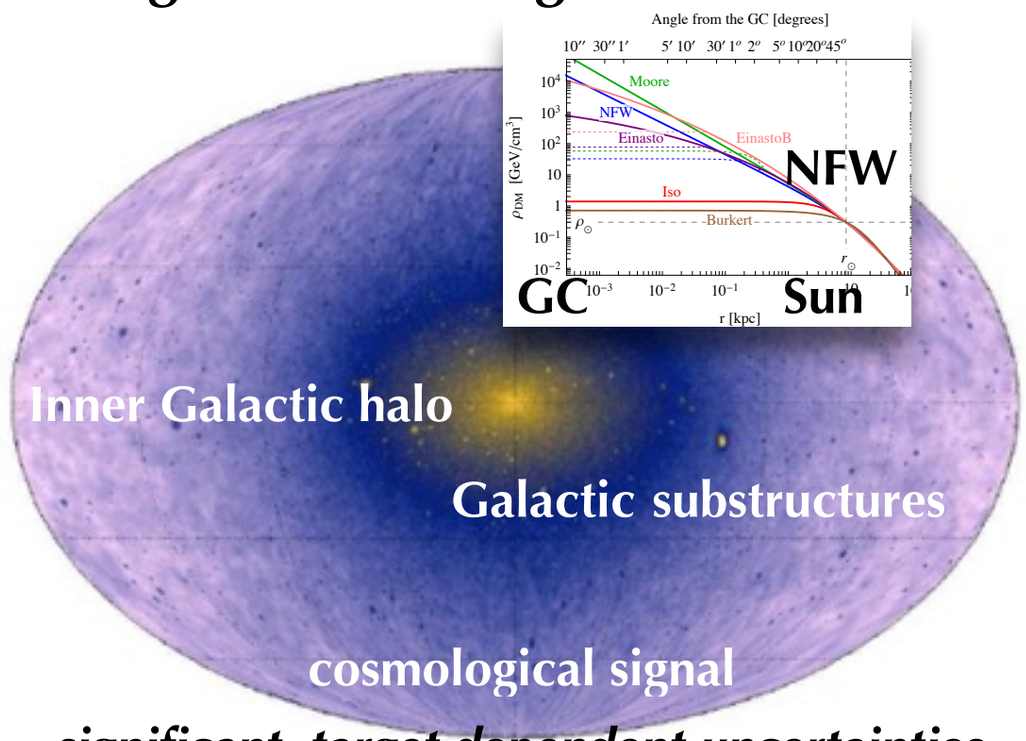
$$\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\frac{(\sigma_{\rm ann} v)}{2\, m_\chi^2} \times \sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{\rm los} \mathrm{d}s\, \rho^2(s,\Omega)$$

this is what we are after!

flux of SM particles per DM annihilation: two-body final states



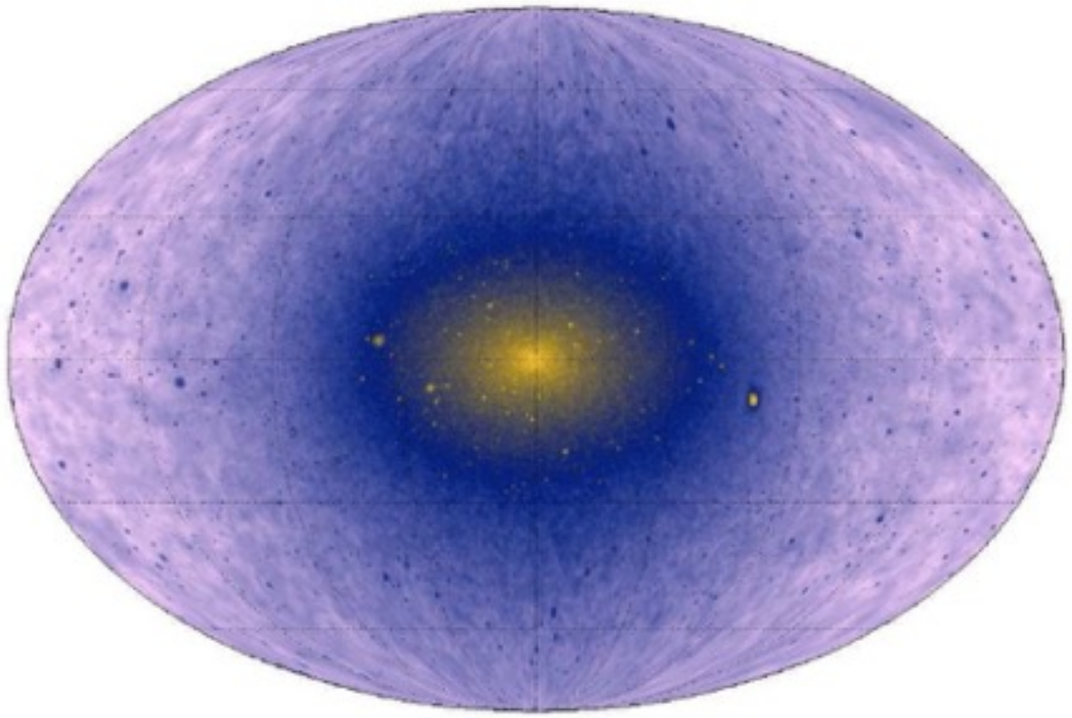
integrated DM density squared along the line of sight



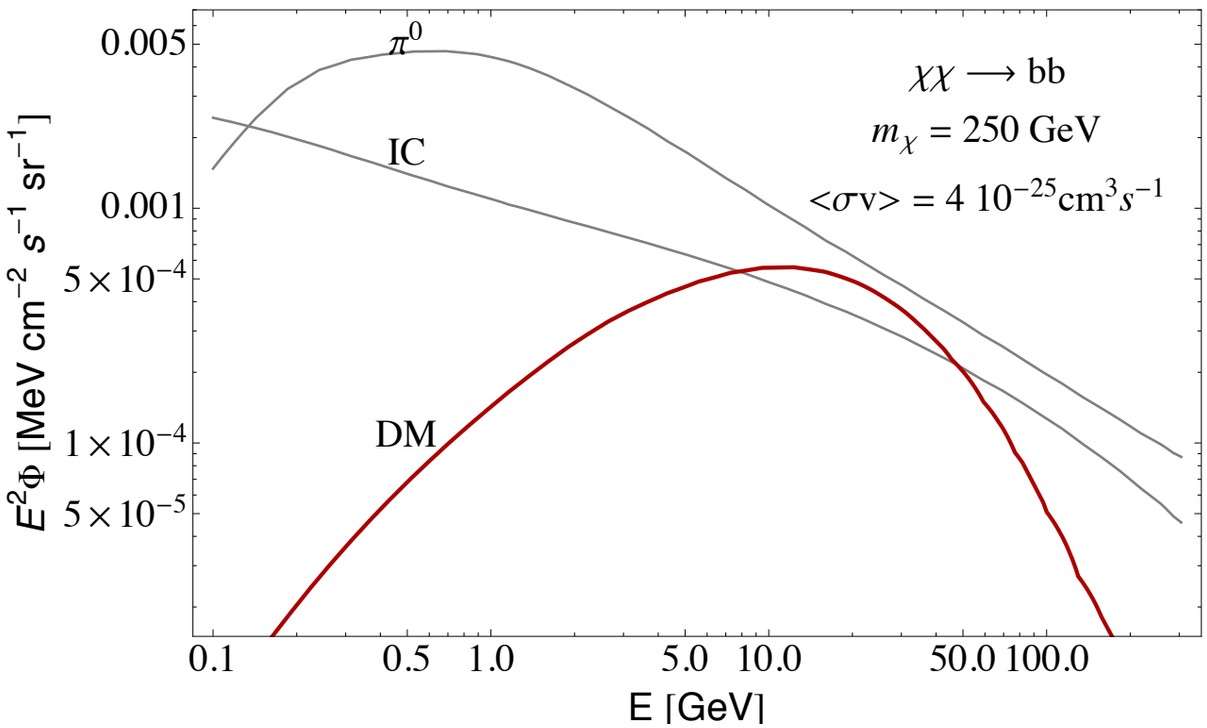
significant, target dependent uncertainties

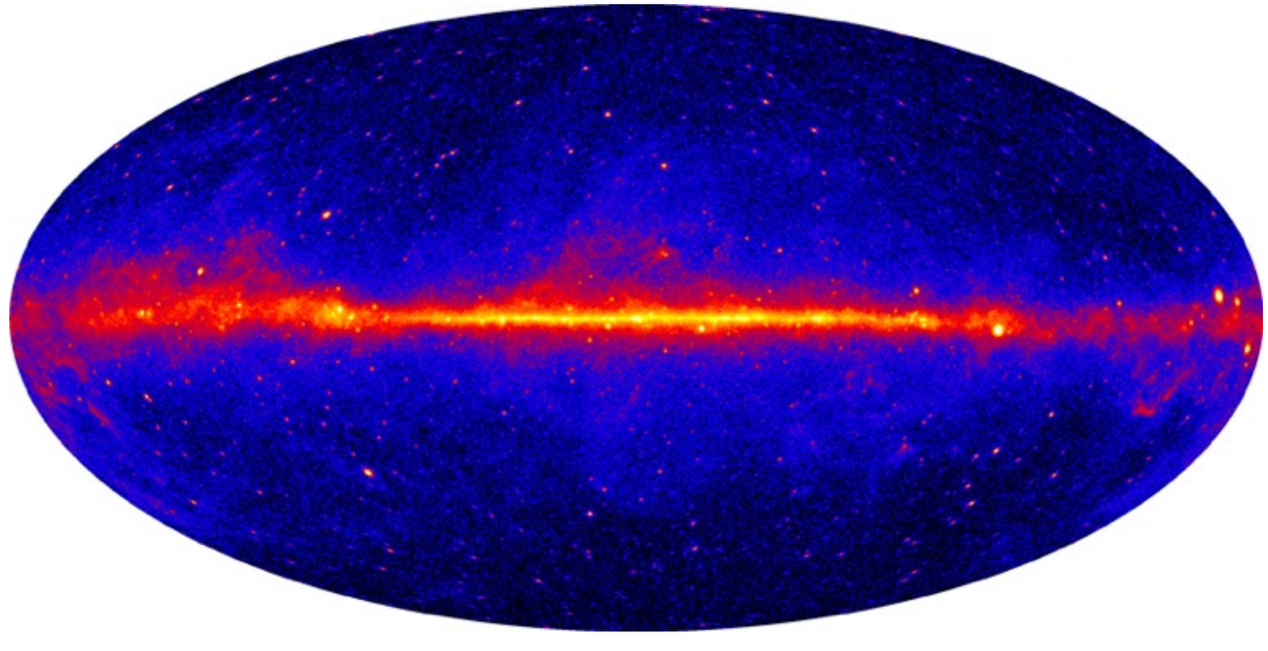
DM search - the challenge

look for an uncertain signal hidden in uncertain backgrounds



WIMPs gamma ray signals, as (expected to be) seen from the Earth



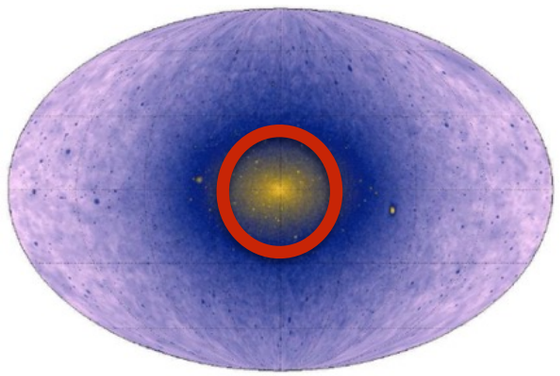


gamma ray sky, >1 GeV, 5yr Fermi LAT

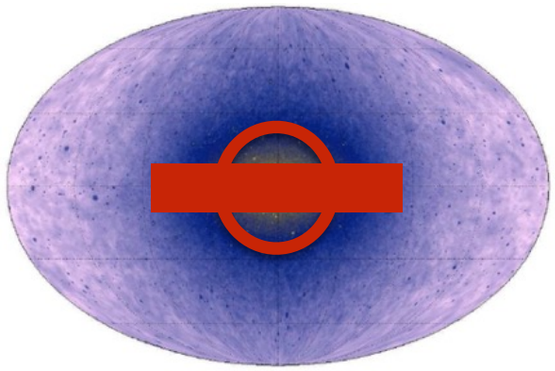
Strategies

signal strength

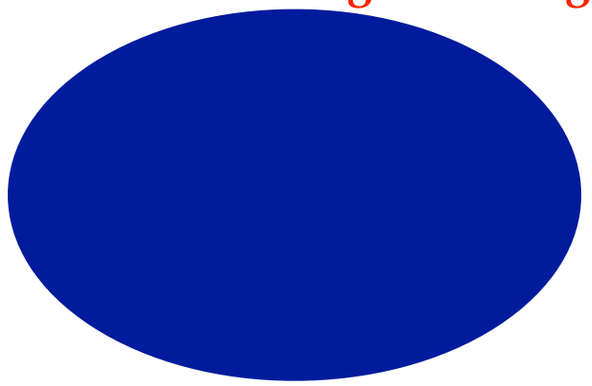
GC



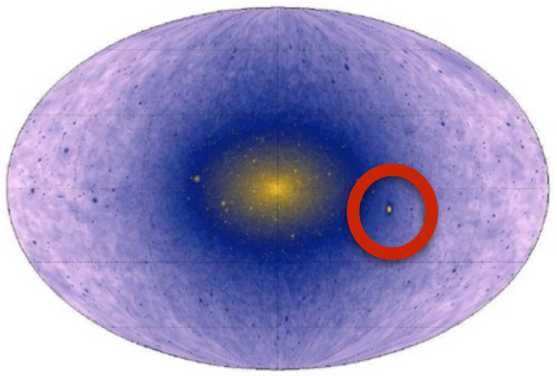
GC halo



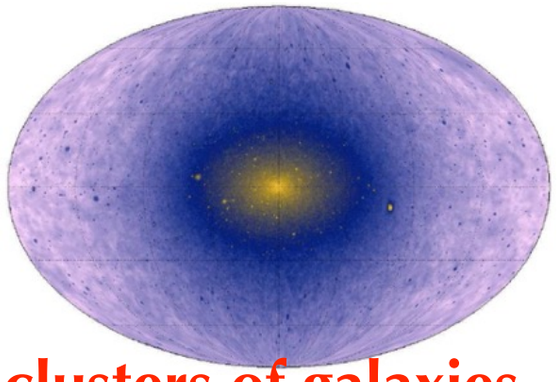
cumulative extragalactic signal



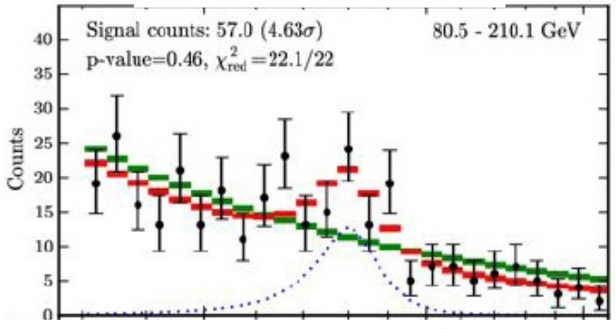
dwarf satellites



clusters of galaxies



spectral line

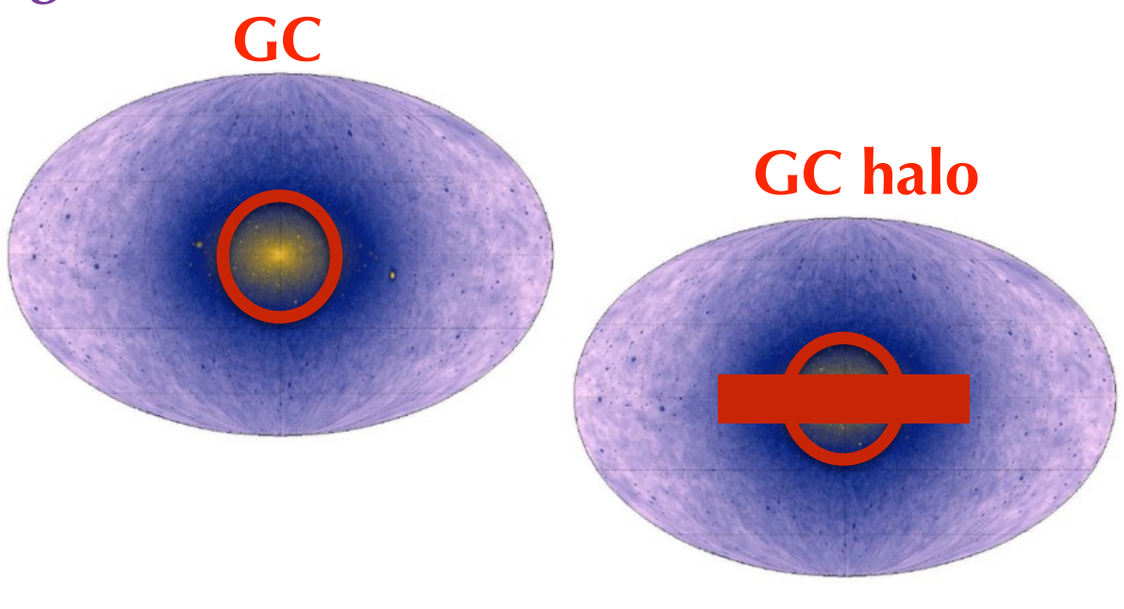


robustness

[adapted from: H.-S. Zechlin]

Strategies

signal strength



1) search for generic WIMP signatures
and use rich astrophysical data to model (or measure) the backgrounds

current experimental sensitivity in the right ballpark for vanilla models
confirmation across wavelengths/messengers/targets necessary!

robustness

[adapted from: H.-S. Zechlin]

Strategies

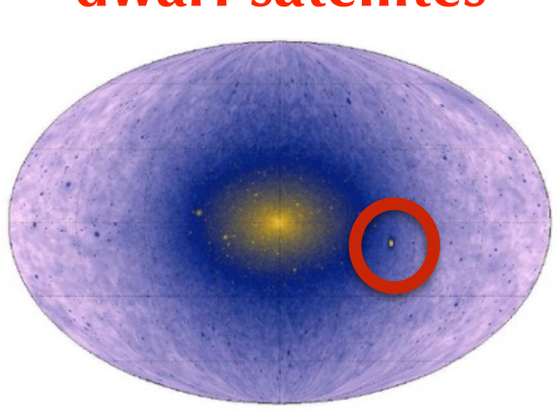
signal strength

or, look for the 'smoking guns'

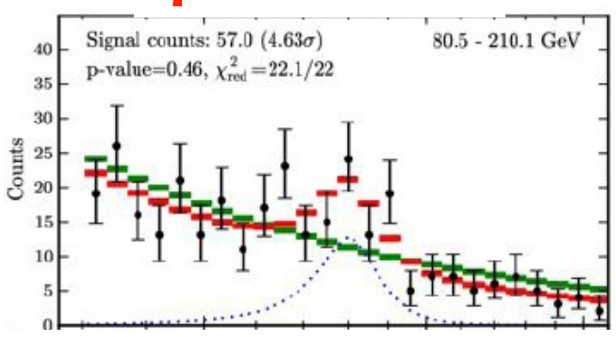
'zero' astro backgrounds, but expected signals (for vanilla DM) low

need luck, or optimised analysis techniques

dwarf satellites



spectral line



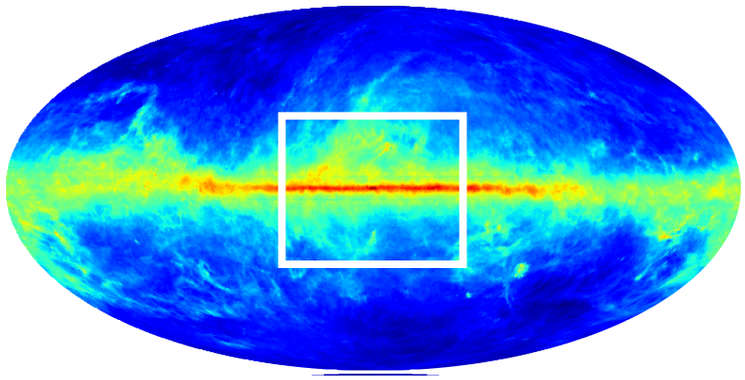
robustness

[adapted from: H.-S. Zechlin]

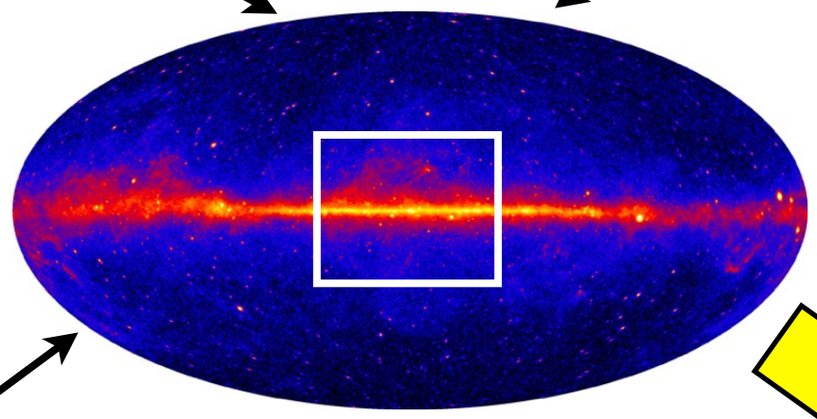
DM search in the inner Galaxy

general approach

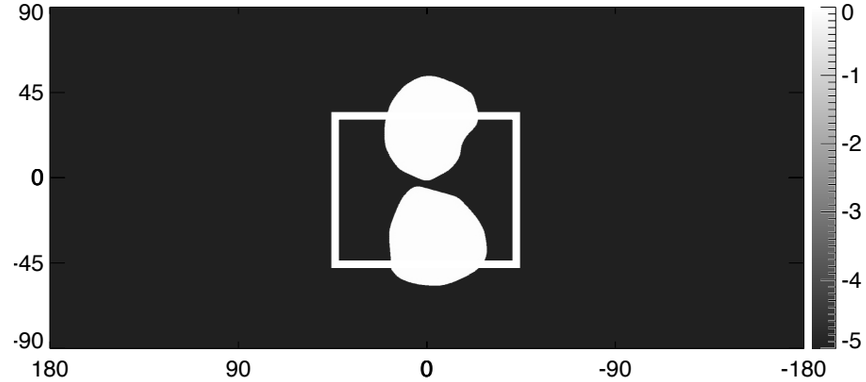
apply ***template fitting*** procedure to the inner ~<20 deg with addition of the FBs



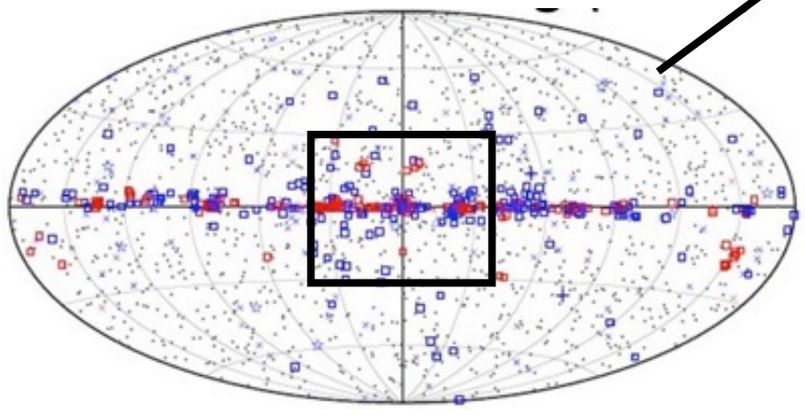
model(s) of the diffuse emission



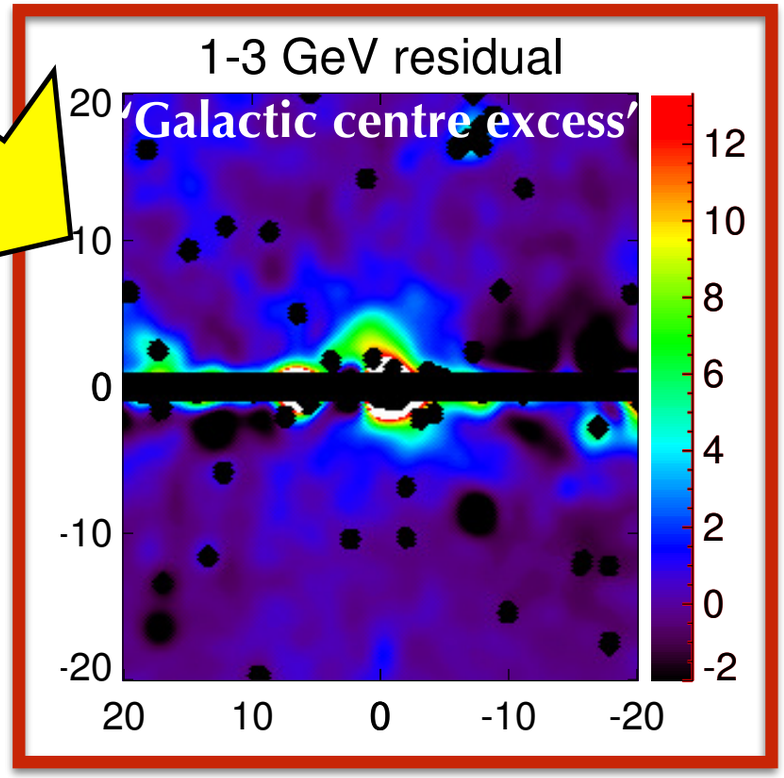
LAT data



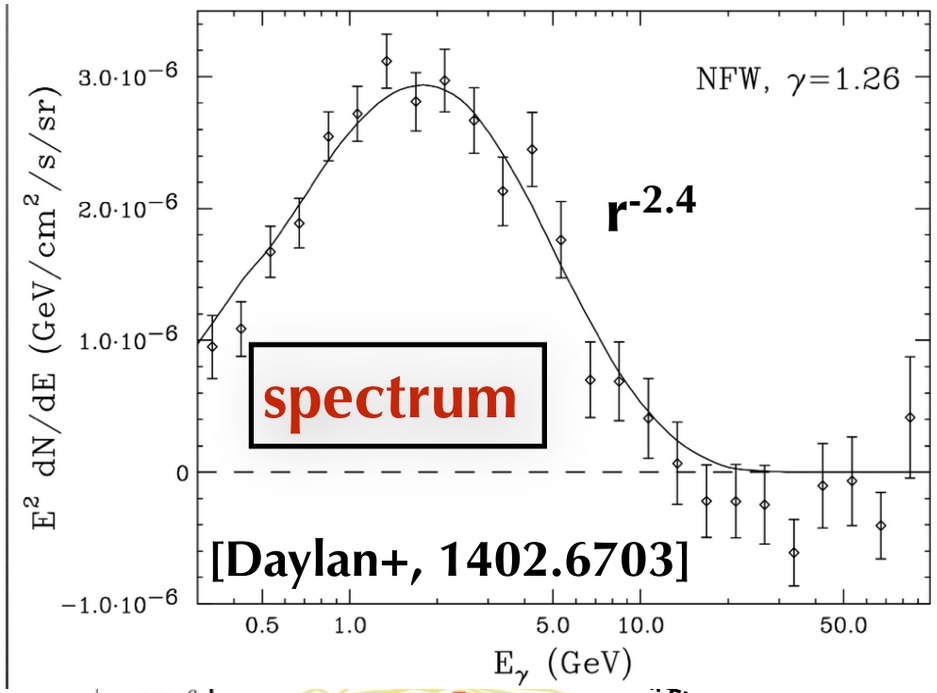
uniform-brightness template for the Fermi Bubbles

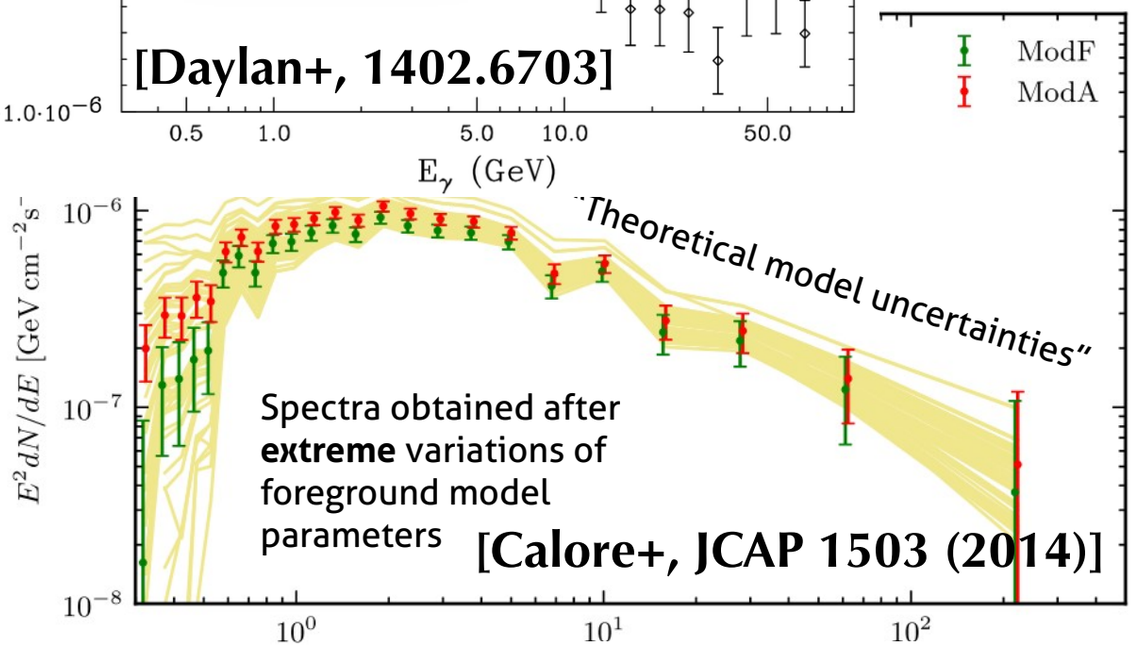


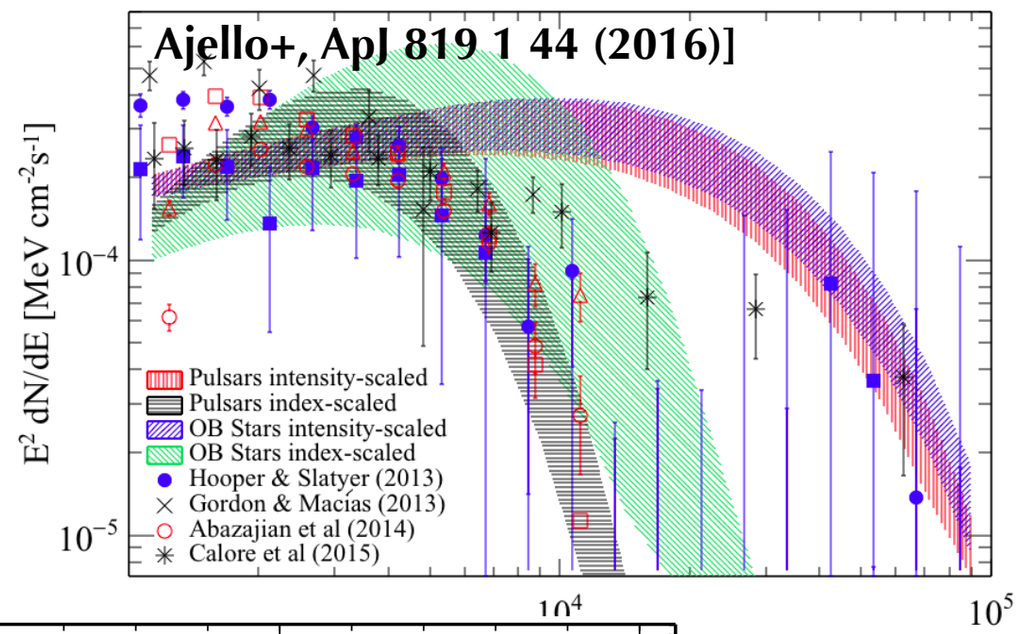
point sources from the catalog

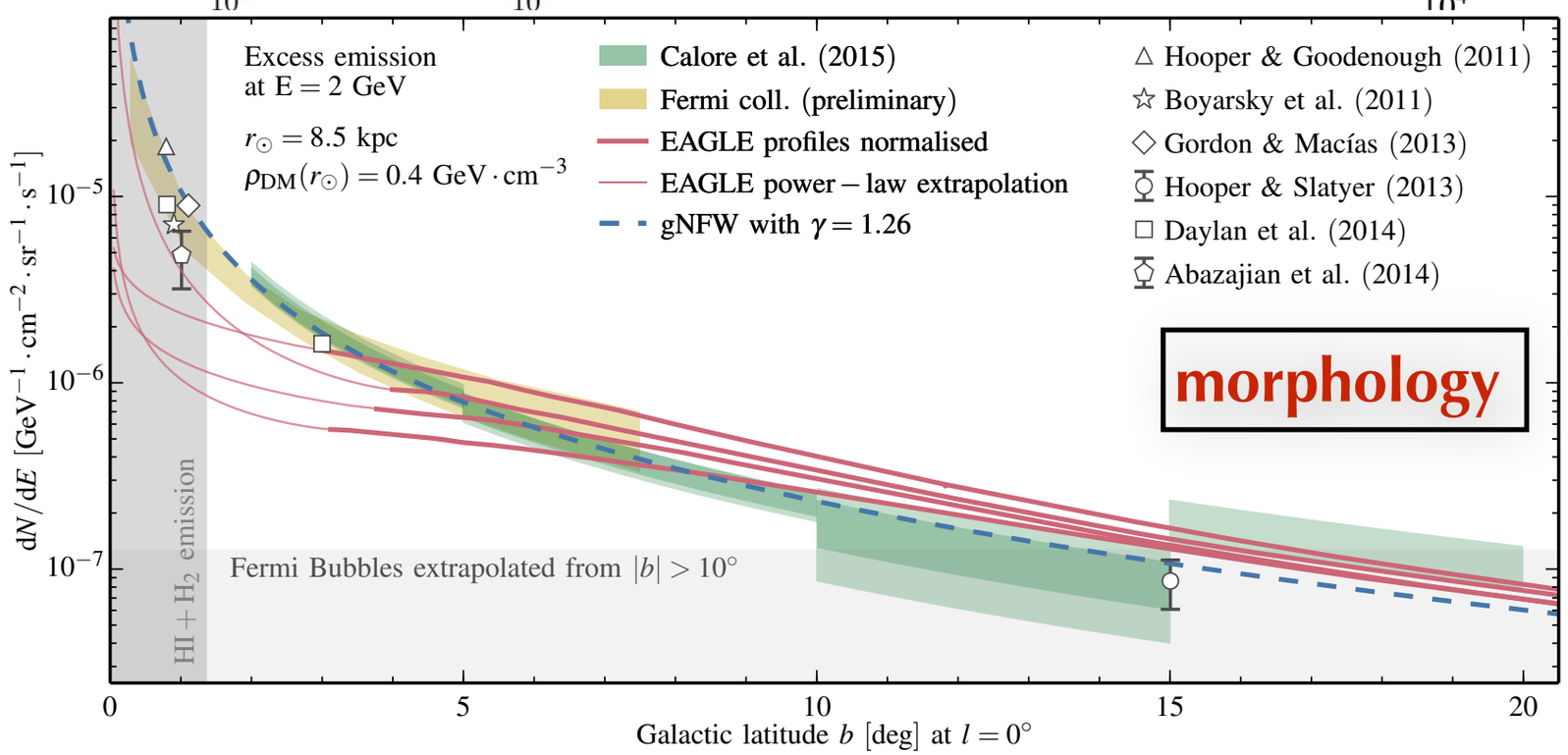


Many works reaching similar results: Vitale & Morseli (**2009**), Goodenough & Hooper (2009), Hooper & Goodenough (2011, PLB 697 412), Hooper & Linden (2011, PRD 84 12), Abazajian & Kaplinghat (2012, PRD 86 8), 1207.6047, Hooper & Slatyer (2013, PDU 2 118), 1302.6589 Gordon & Macias (2013, PRD 88 8) 1306.5725 Macias & Gordon (2014, PRD 89 6) 1312.6671, Abazajian et al. (2014, PRD 90 2) 1402.4090, Daylan et al. (2014) 1402.6703, 1407.5583 1407.5625 1410.1527



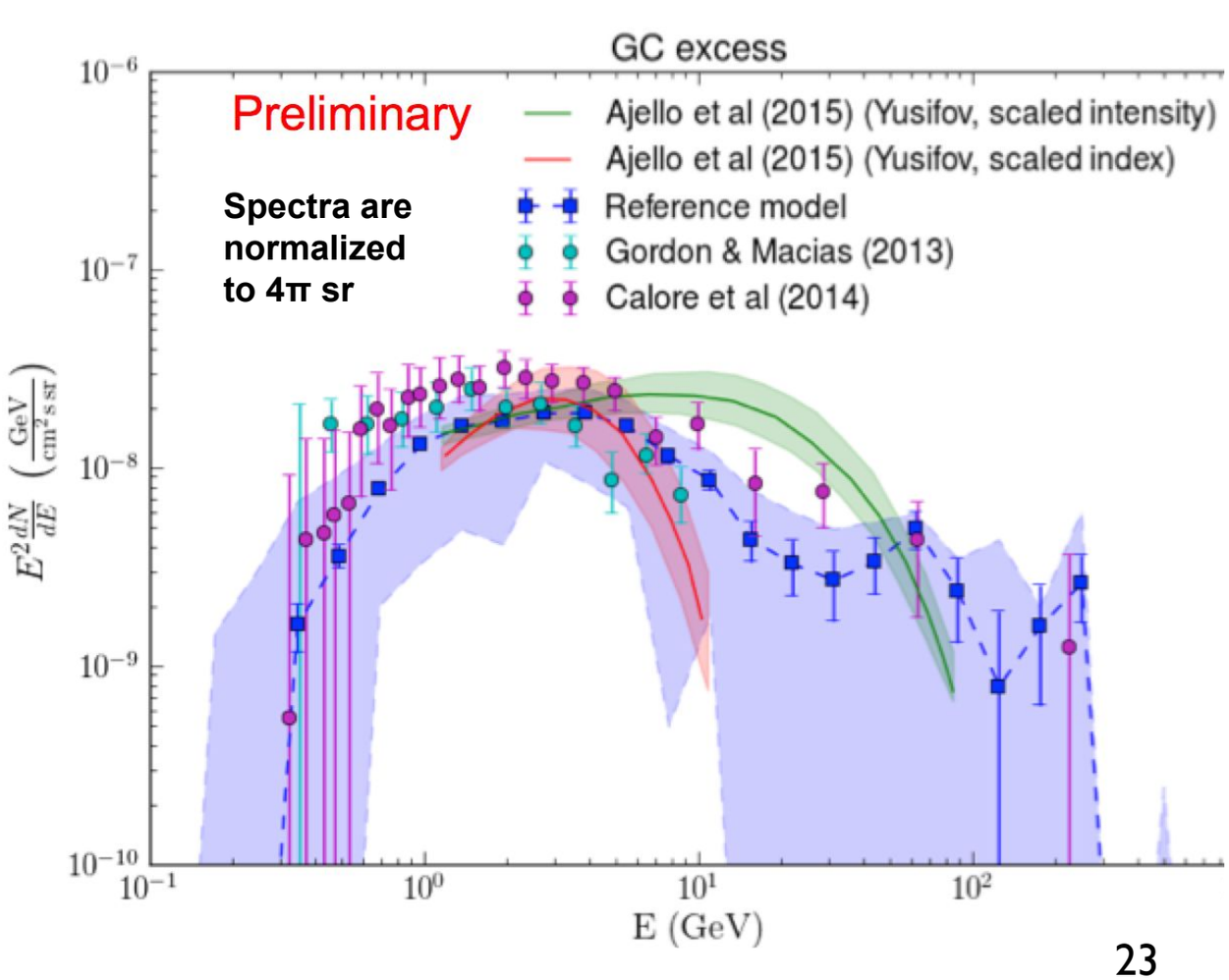






Updated Fermi LAT analysis (preliminary)

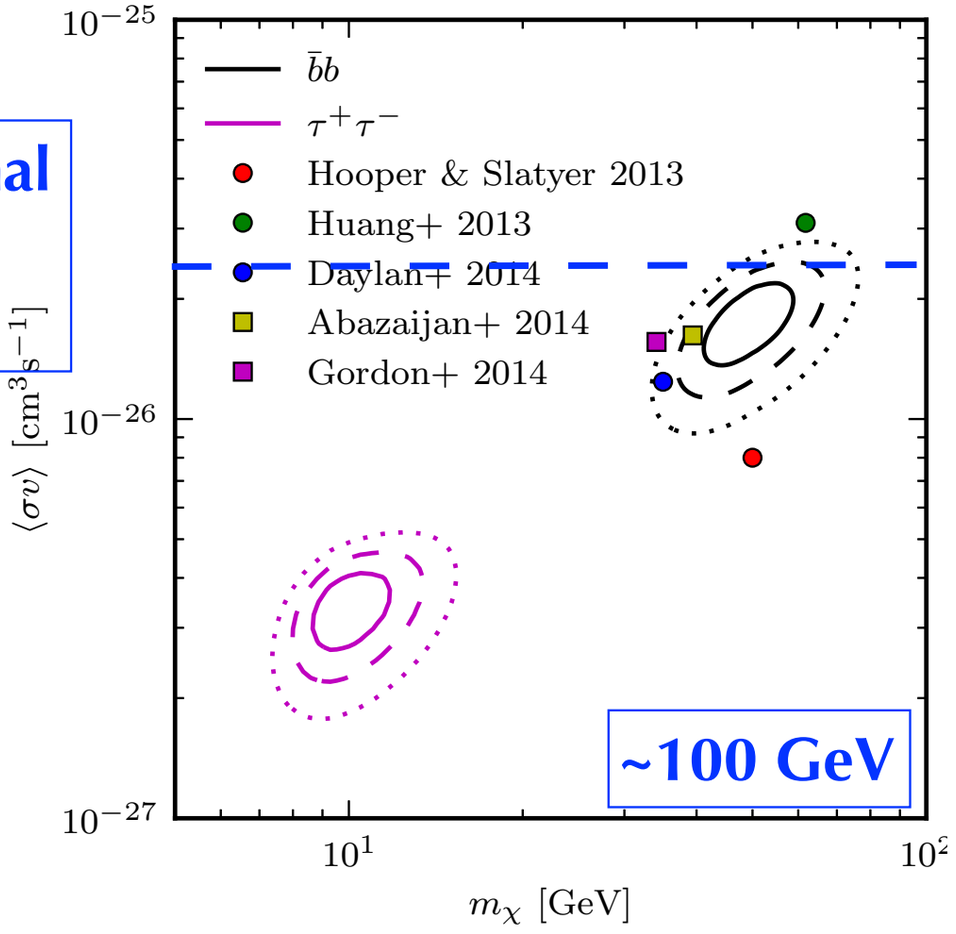
- uses more data (**80m)**
- uses improved event selection: **pass 8 (**improved angular and energy resolution, increased effective area at the high- and low-energy ends)
- checks additional systematic uncertainties:
  - GALPROP model parameters variations
  - **Alternative gas maps** (softer GCE spectrum < 1GeV)
  - Include additional sources of **CR electrons near the GC** (Gaggero+2015, Carlson+2015 ; GCE reduced)
  - add **data driven template of the Fermi Bubbles** (excess >10 GeV gone)



New emission component in the Galactic centre appears robust to various checks of the systematic uncertainty
its exact spectral features are model dependent

[A. Albert, APS 2016 meeting]

Origin of the excess?



~thermal cross section

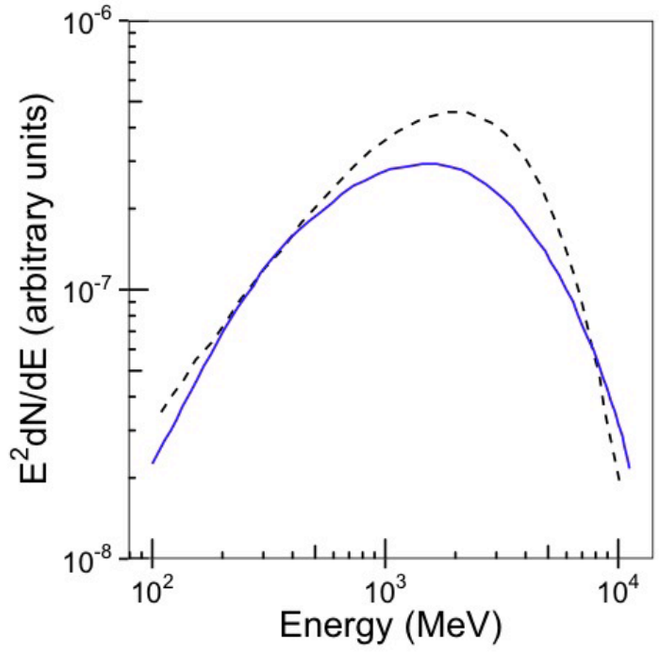
~100 GeV

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

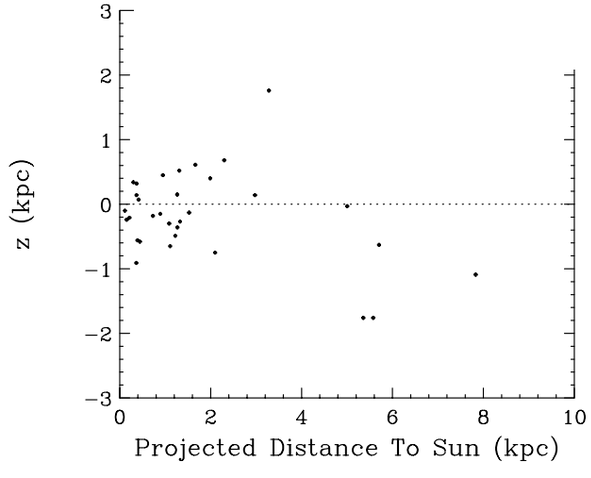
i) Individually unresolved point sources?

pulsars?

- spectral twins of ~50 GeV DM



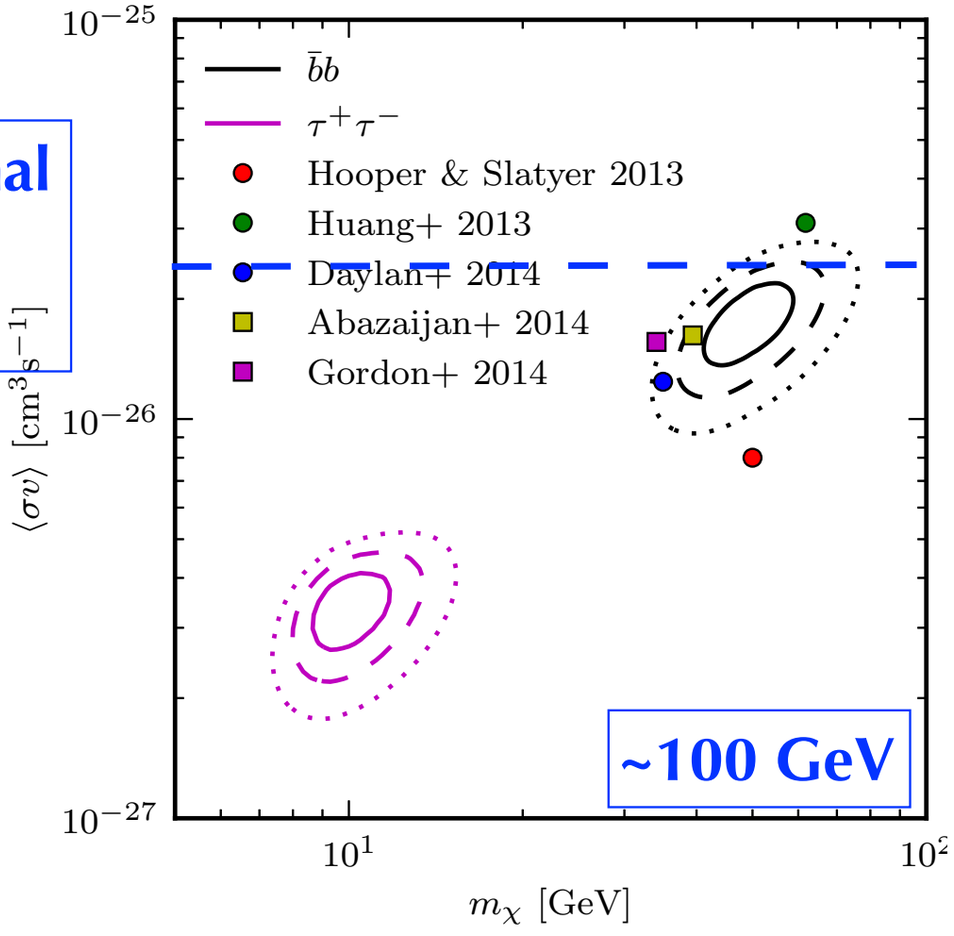
Baltz et al (2007)



- Fermi LAT discovered 100+ of these objects in the Galaxy

[Abazajian, 2012, Mirabal, 2014; Macias, 2014, Petrovic +, 2015, Brandt+2015, Lee+, 2015, Bartels+, 2015…]

Origin of the excess?



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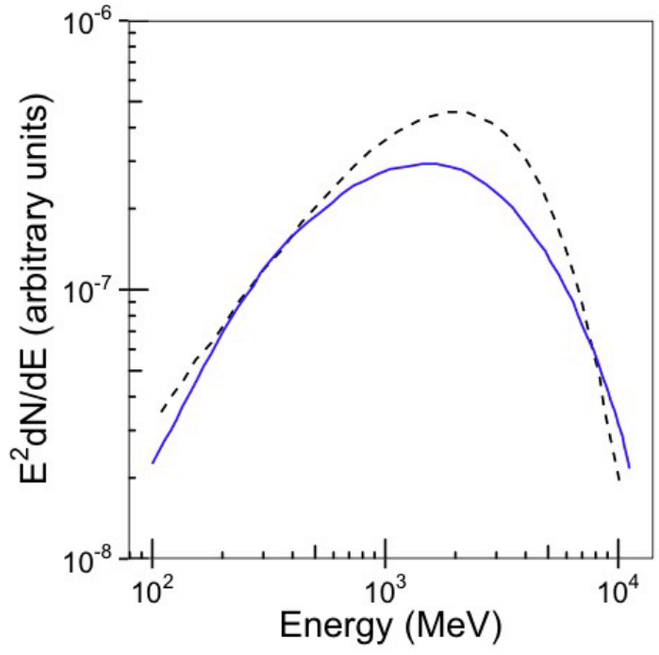

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[Abazajian, 2012, Mirabal, 2014; Macias, 2014, Petrovic +, 2015, Brandt+2015, Lee+, 2015, Bartels+, 2015…]

ii) Transient at the GC: inverse Compton emission from electrons injected during an energetic burst event ~Myr ago

[Petrovic+, 2015; Carlson+, 2015, Cholis+, 2016]

iii) steady-state electron source at the GC

[Carlson+, 2016; Gaggero+, 2015]]

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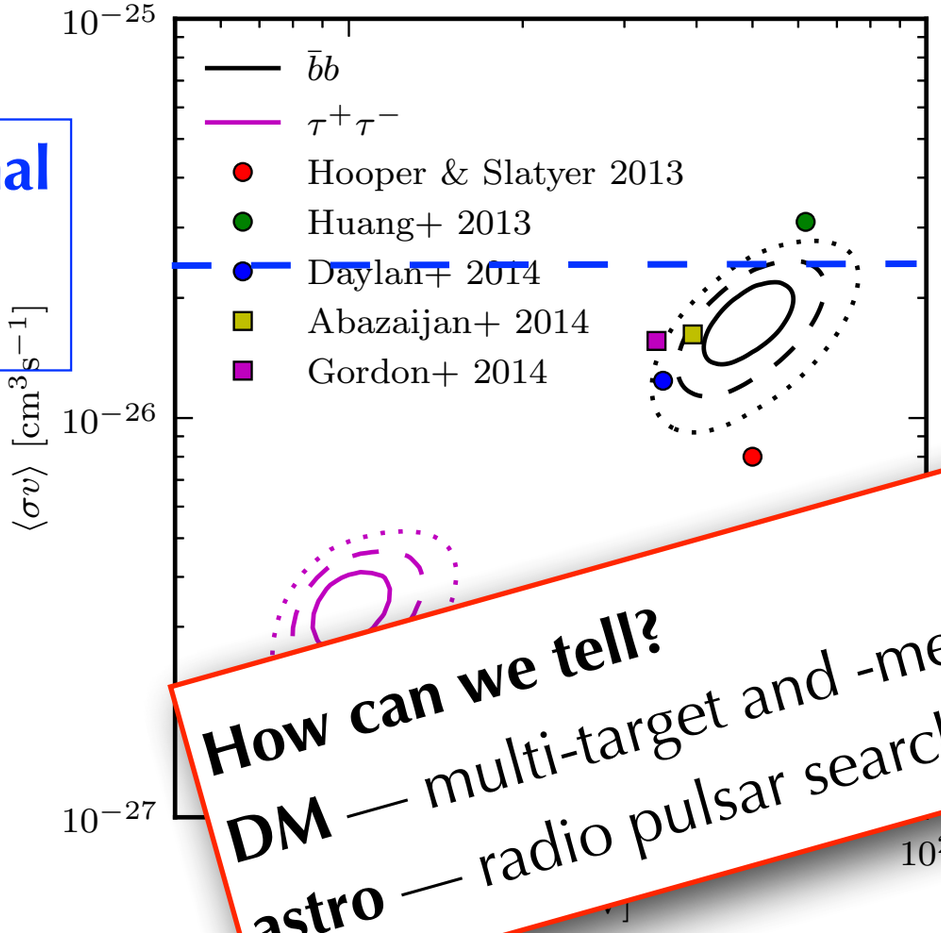


~thermal cross section

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

How can we tell?

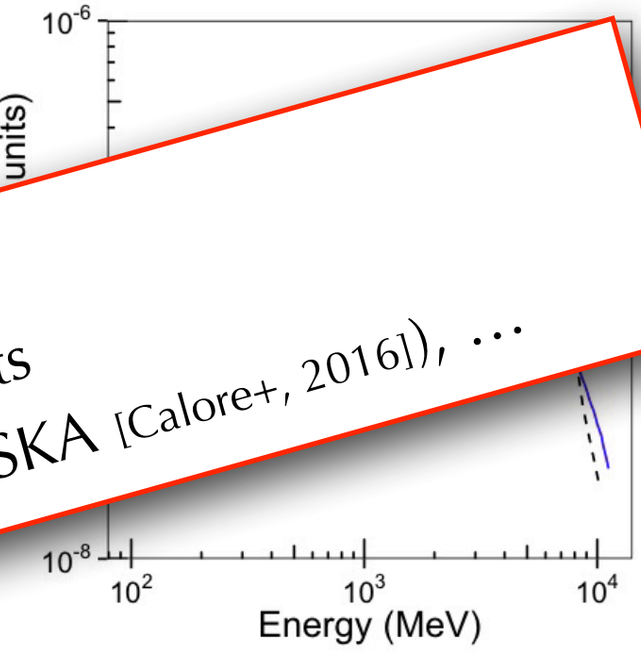
DM — multi-target and -messenger tests

astro — radio pulsar searches (e.g. w SKA [Calore+, 2016]), …

i) Individually unresolved point sources?

pulsars?

- spectral twins of ~50 GeV DM



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[Abazajian, 2012, Mirabal, 2014; Macias, 2014, Petrovic +, 2015, Brandt+2015, Lee+, 2015, Bartels+, 2015…]

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[Petrovic+, 2015; Carlson+, 2015, Cholis+, 2016]

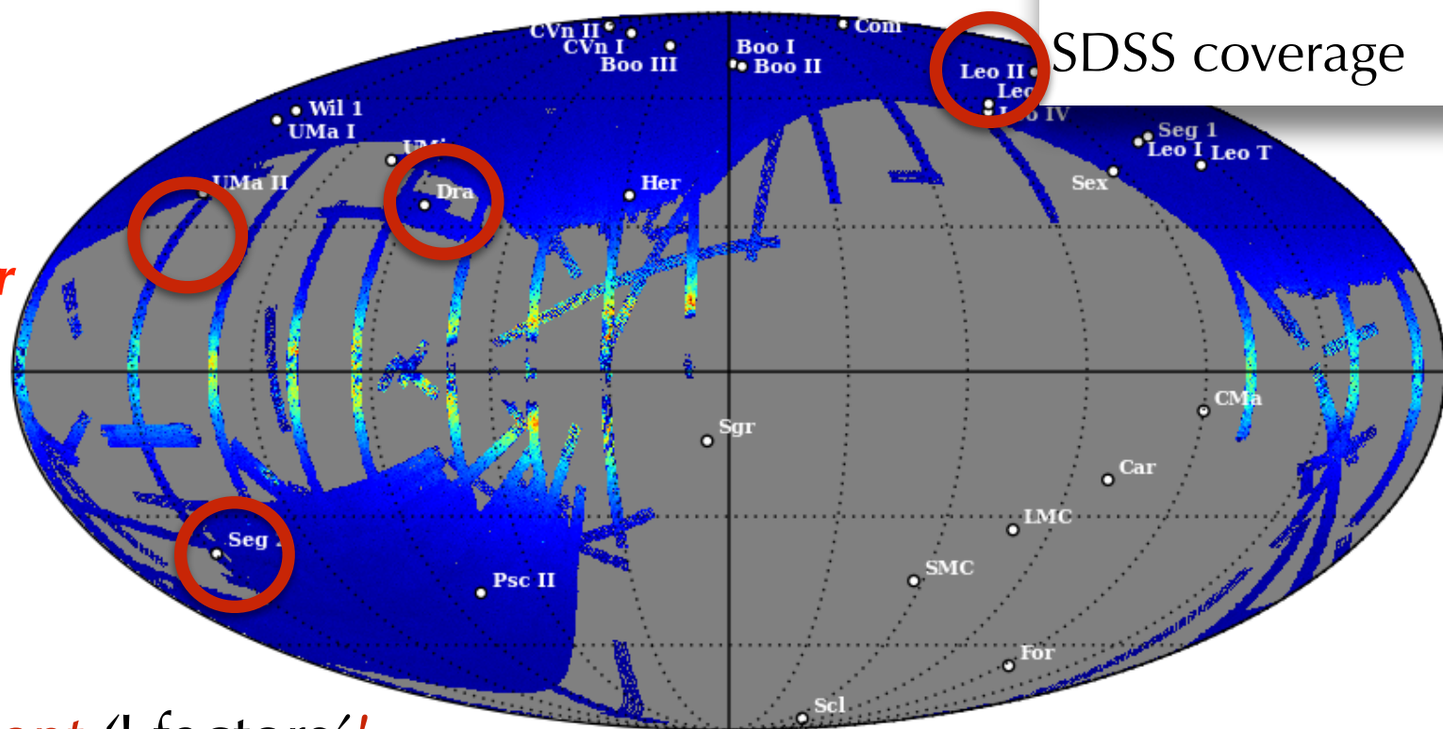
iii) steady-state electron source at the GC

[Carlson+, 2016; Gaggero+, 2015]]

DM search in dwarf galaxies

Dwarf spheroidal galaxies are ***the cleanest targets*** for DM search

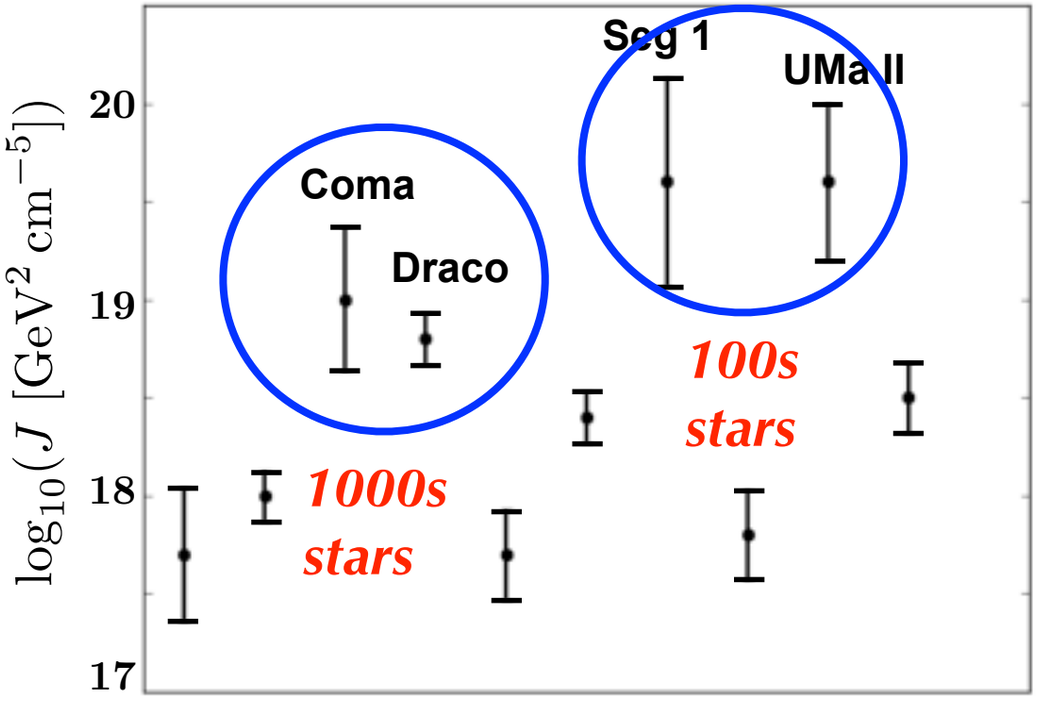
- ***old stars -> no high energy emission***
- ***100+ times more dark than visible matter***
- ***located in quiet regions of the sky***



LAT data within SDSS coverage

The biggest uncertainty: dark matter content 'J factors'*!*

Determined from stellar velocity dispersion



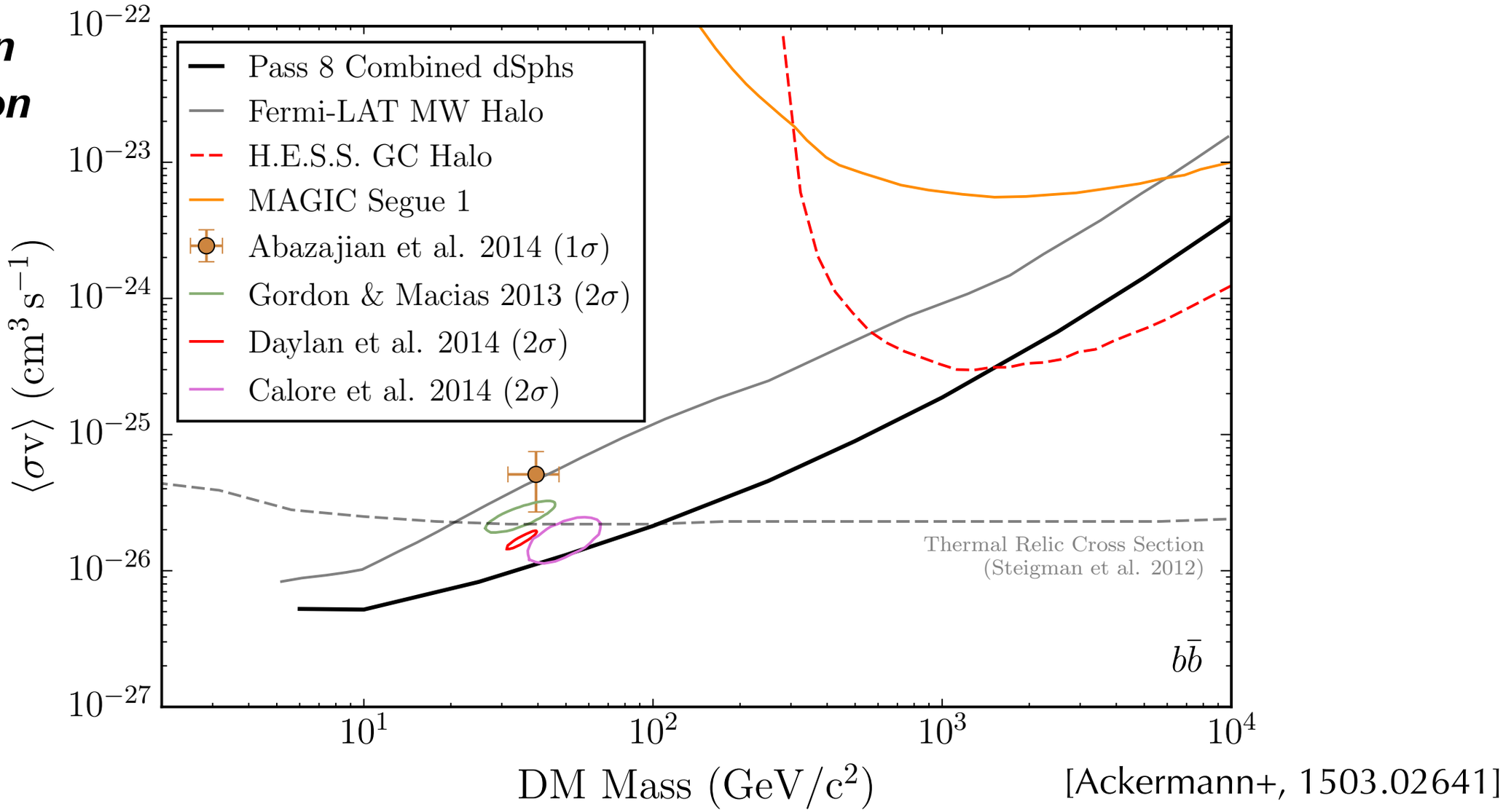
Fermi LAT analysis method:

- construct the **joint likelihood**, combining info from:

- *15 dSphs*
- *photon angular resolution information*
- *J factor uncertainties (caveat Ullio+, 1603.07721)*

DM search in dwarf galaxies

annihilation cross section



[Ackermann+, 1503.02641]

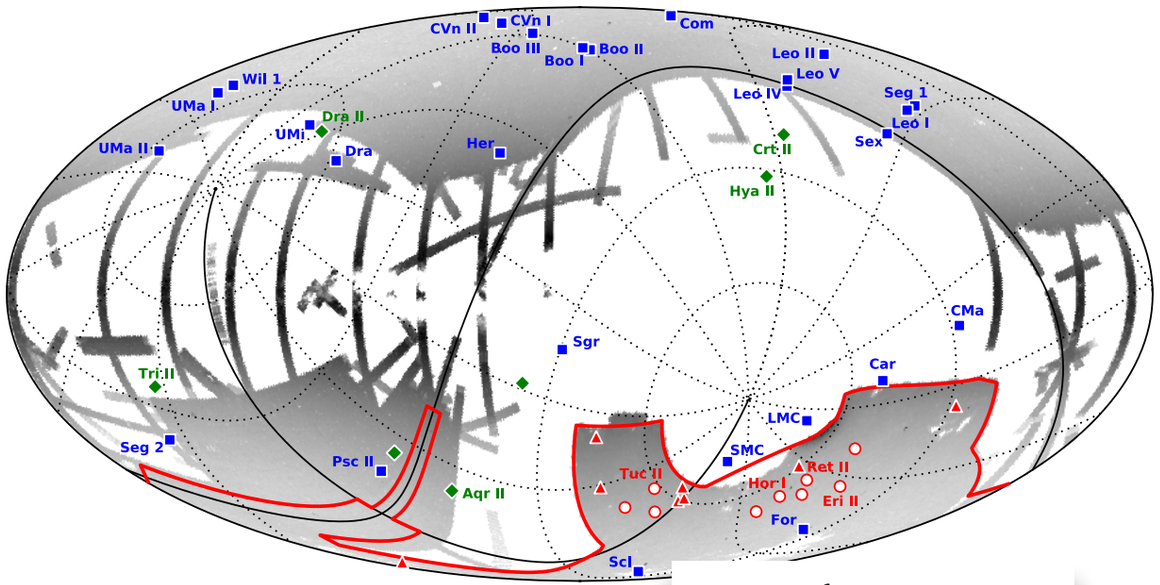
One of the strongest DM limits to date

GCE dark matter origin in tension with complementary gamma ray observations

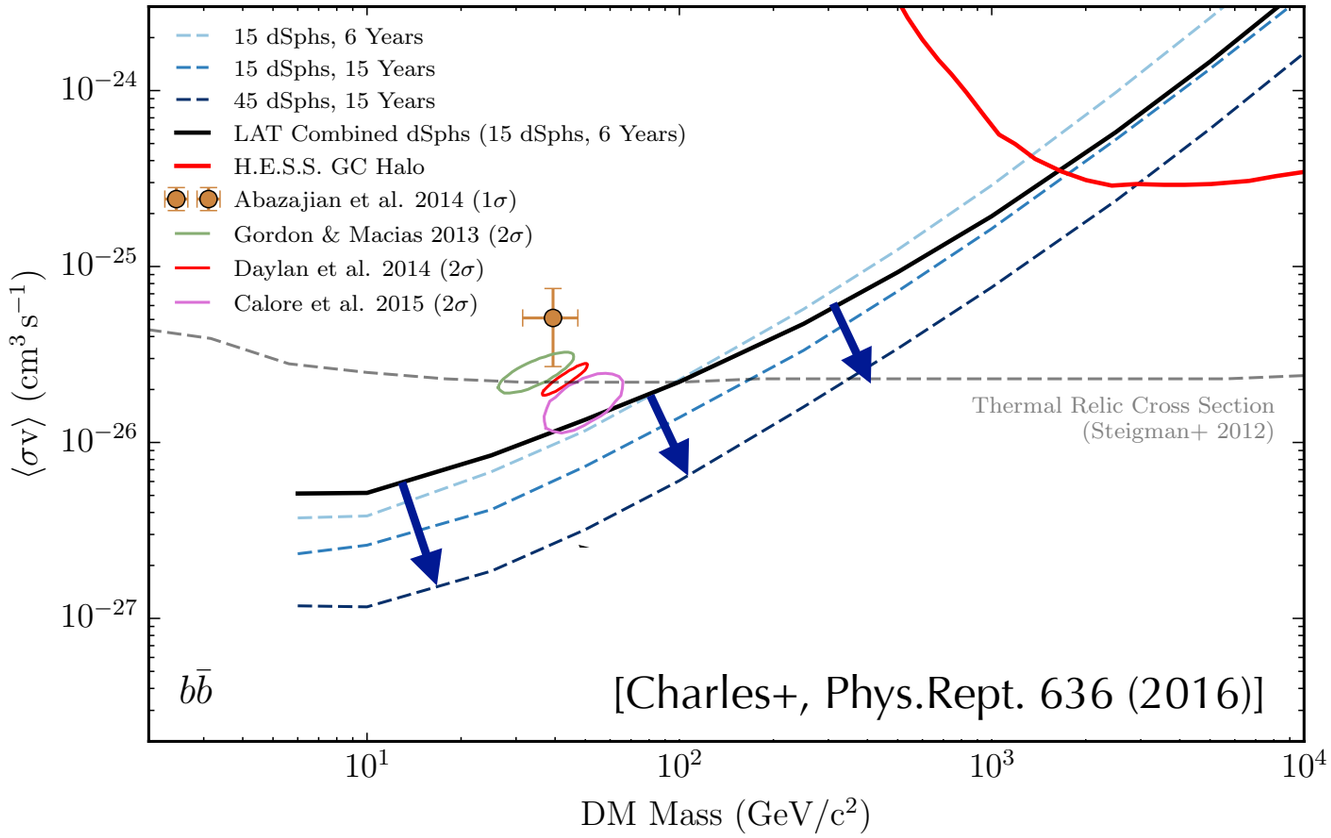
DM search in dwarf galaxies

More targets coming up!

In 2015 discoveries by optical surveys have roughly ***doubled*** the number of candidate dSphs (***DES (2013 -)***, Pan-STARSS (2008-))



DES footprint



- 1st year of DES: **8 new dSphs candidates** No significant gamma ray emission (local significance of 2.4σ for Reticulum II dSph, [Drlica-Wagner, 1503.02632])
- 2nd year DES/LAT paper (submitted): **28 confirmed and 17 dSph candidates**, ***stay tuned!***

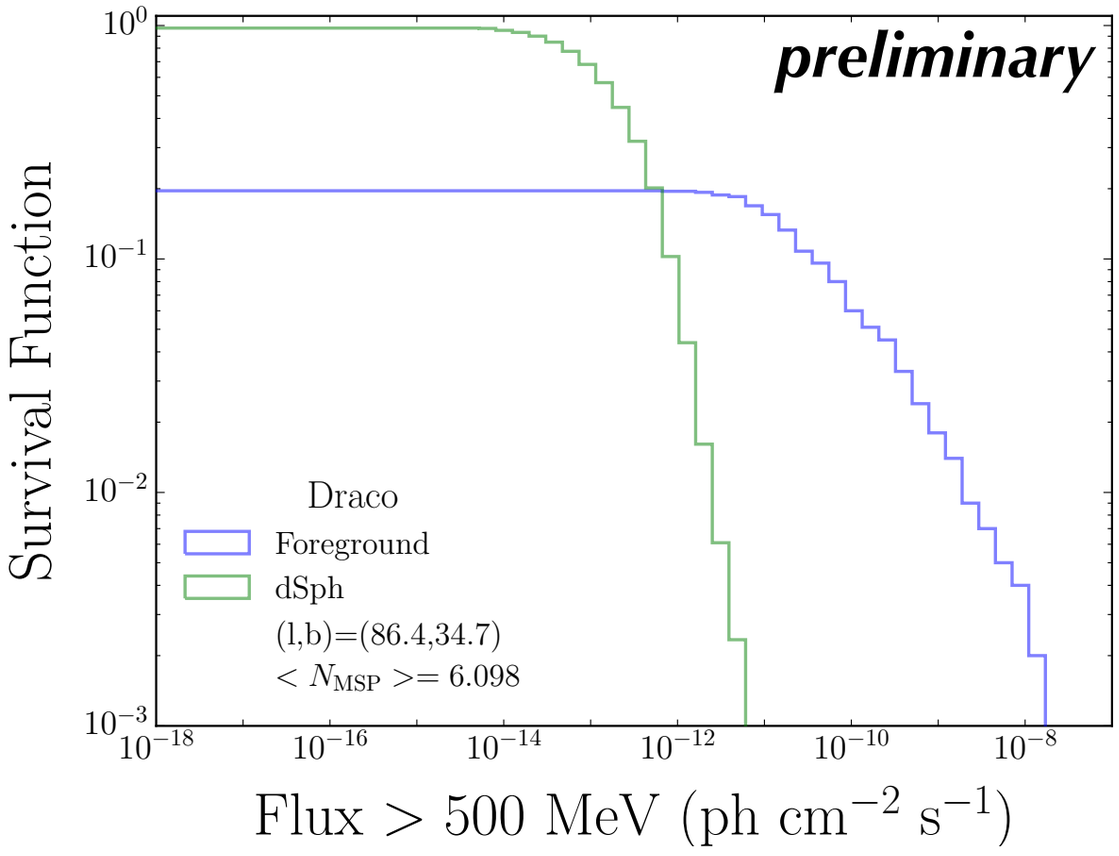
[Bechtol+ 1503.02584, Belokurov+, 1403.3406, Laevens+, 1503.05554]
[Gerringer-Sameth et al. 2015, Hooper & Linden 2015, Li et al. 2016]

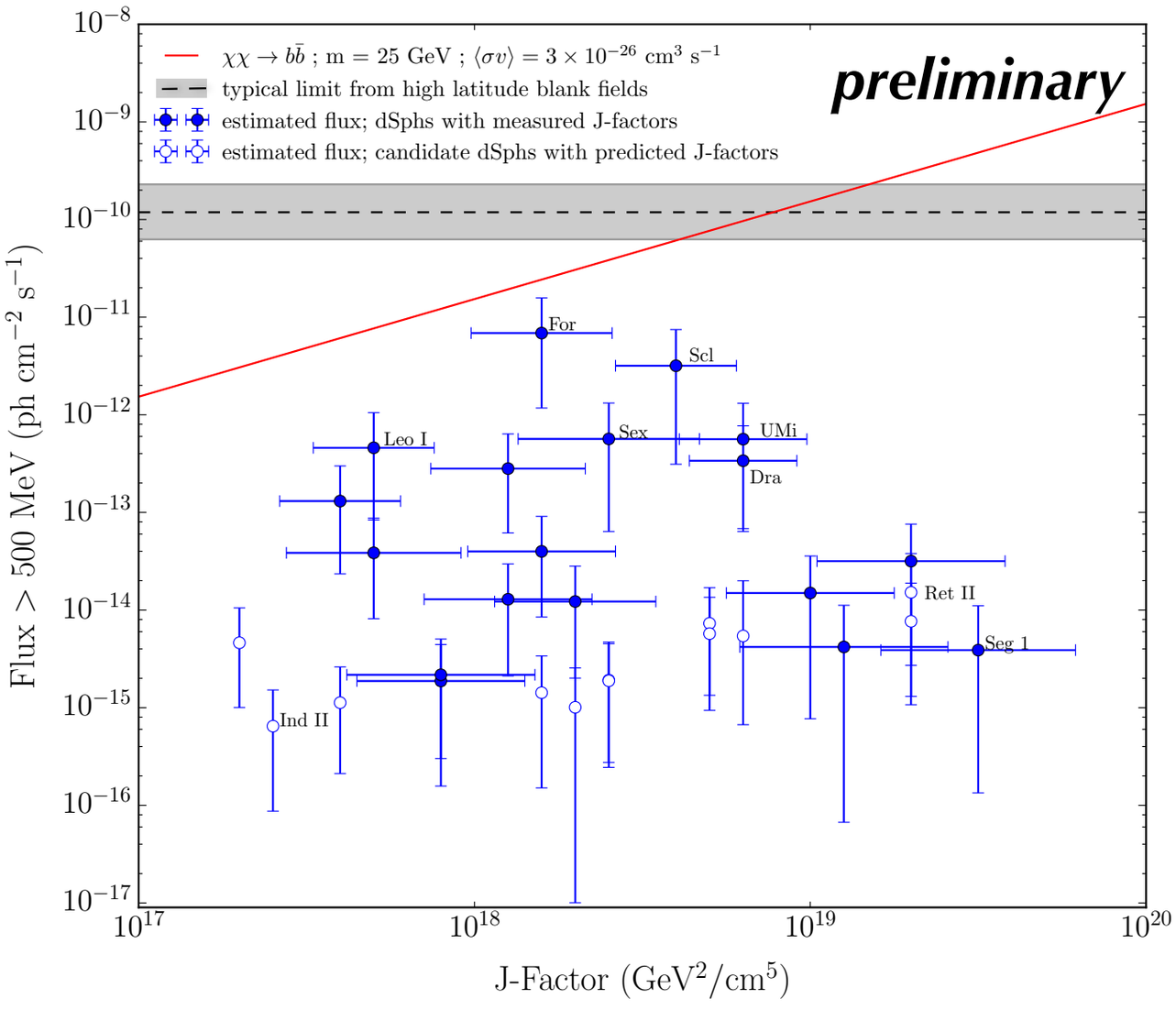
DM search in dwarf galaxies

More targets coming up!

Food for thought: Pulsars present **irreducible** background to WIMP search

As we find more dSphs, could they ultimately show up also in that 'smoking gun' target?



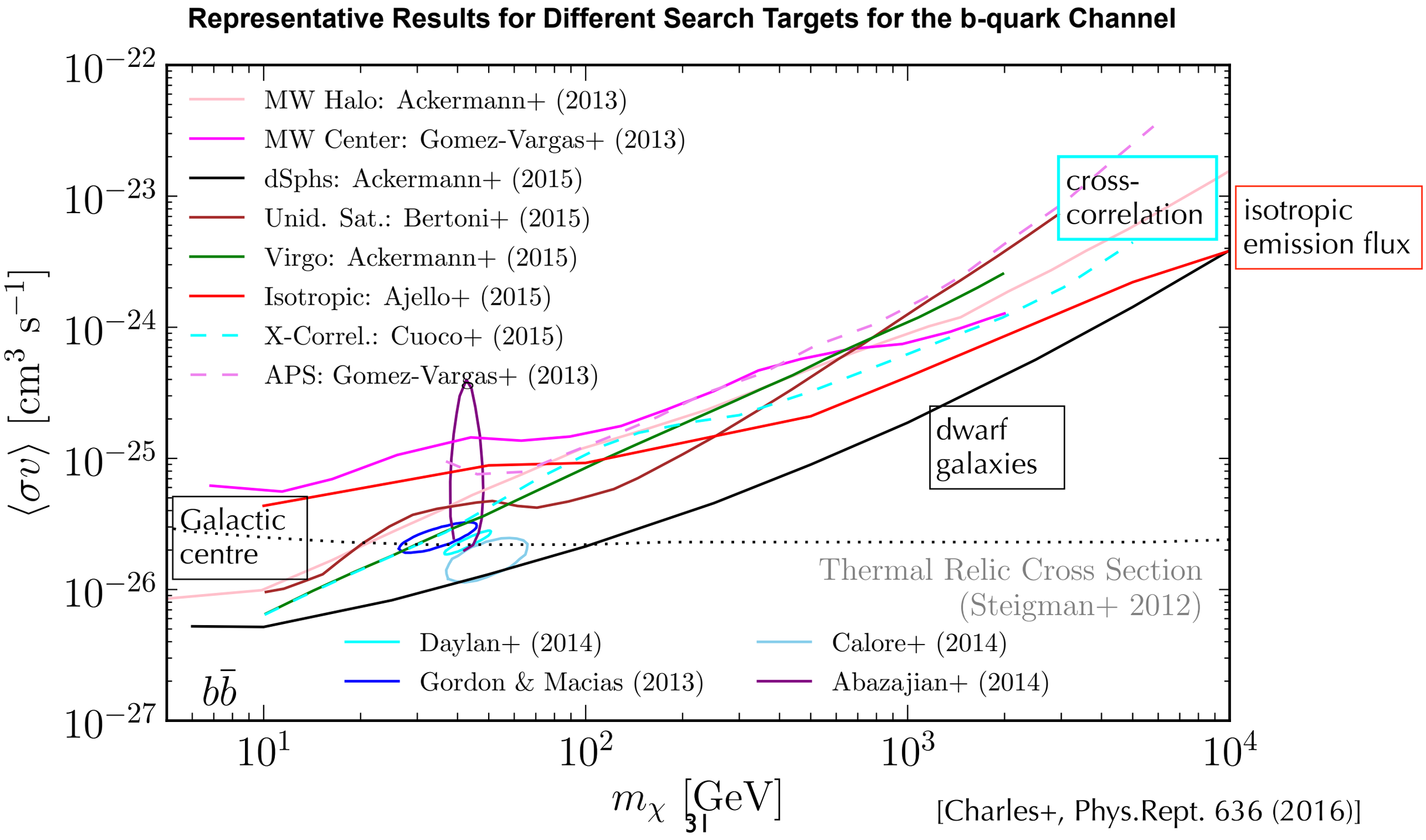


[Winter, GZ, Bechtol, Vandenbroucke, 1607.06390]

dSphs are "safe" for DM searches in GeV gamma rays (in the immediate future),
except for possibly the highest stellar mass "classical" dSphs

Outlook - LAT looks at many DM targets!

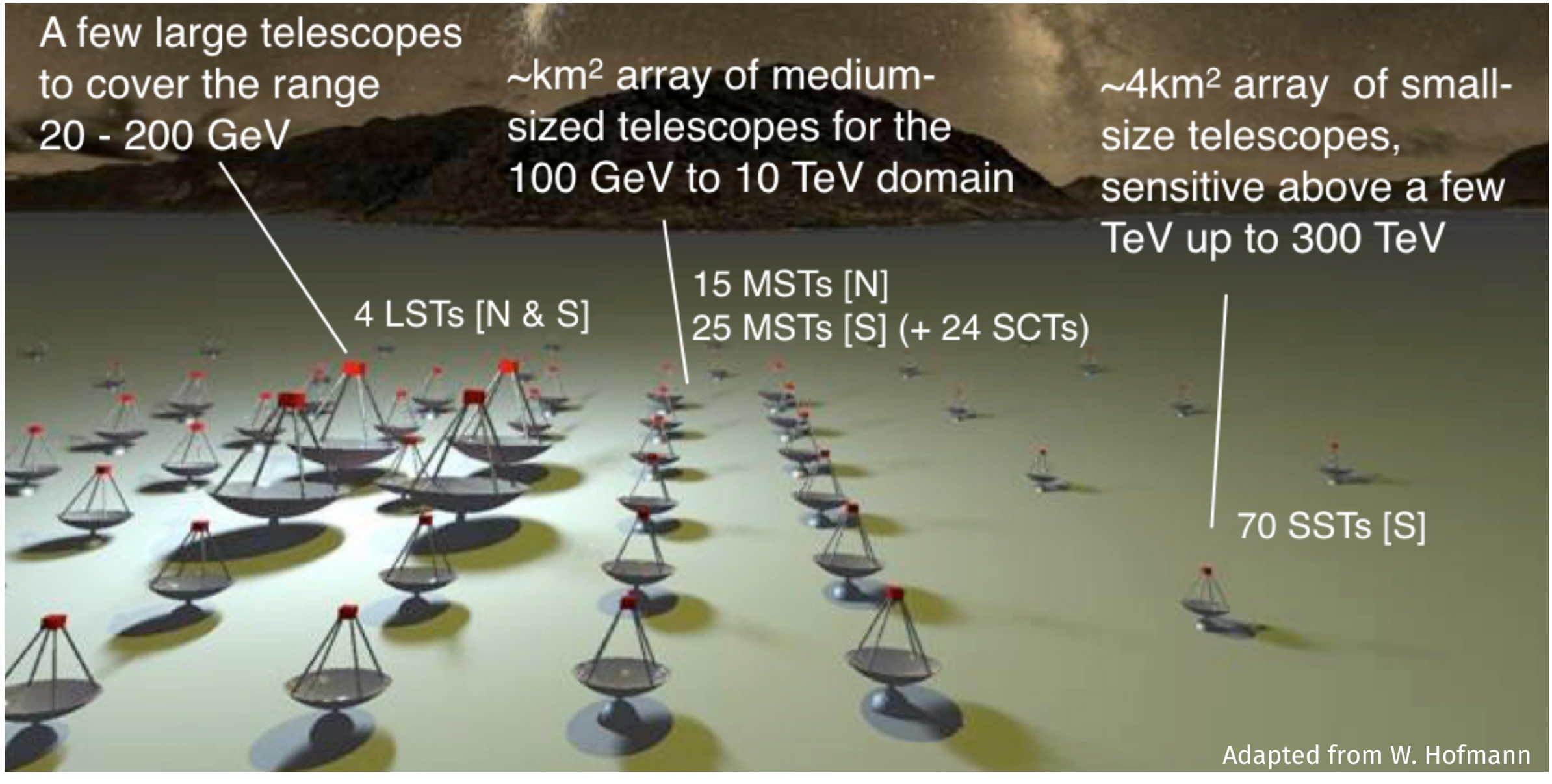
Many interesting analysis approaches, increasingly competitive constraints



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

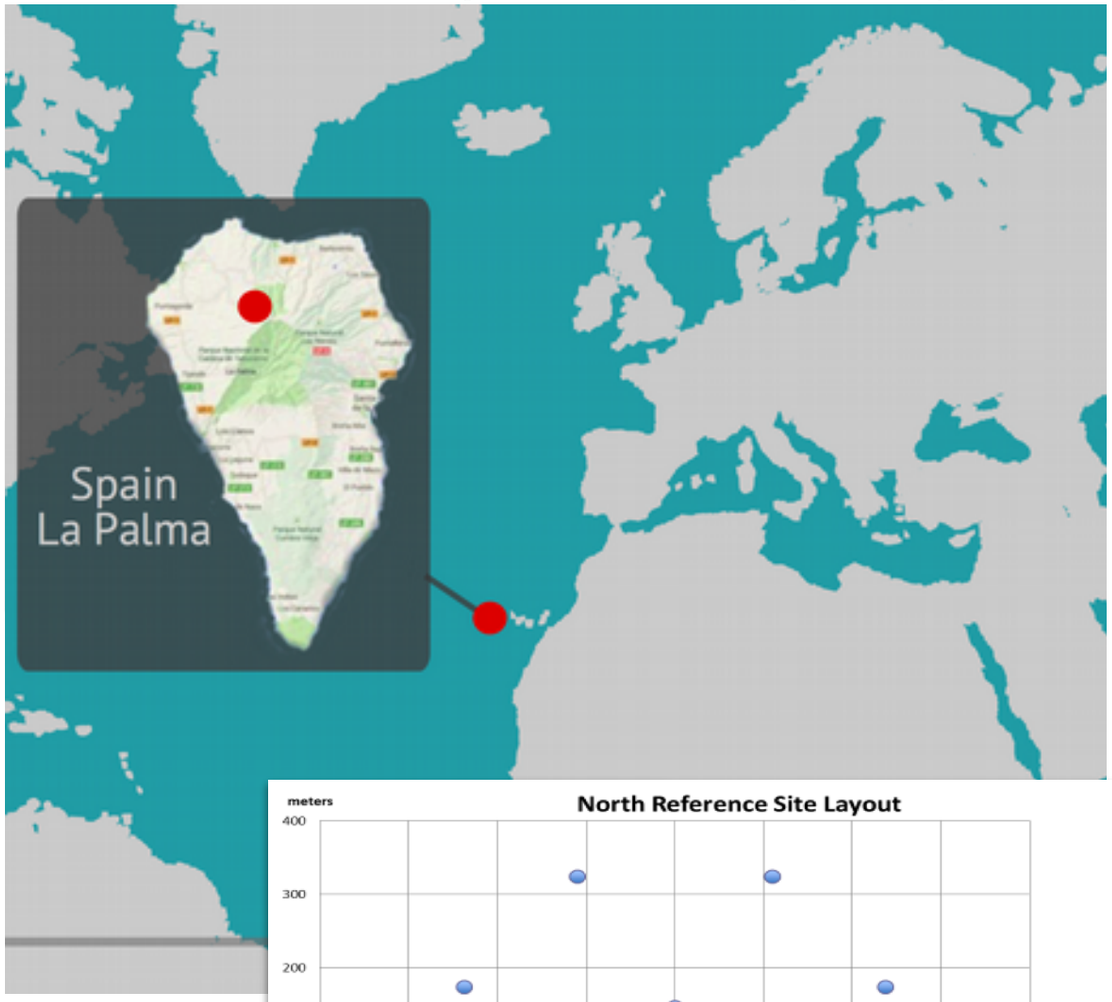
Future with the CTA

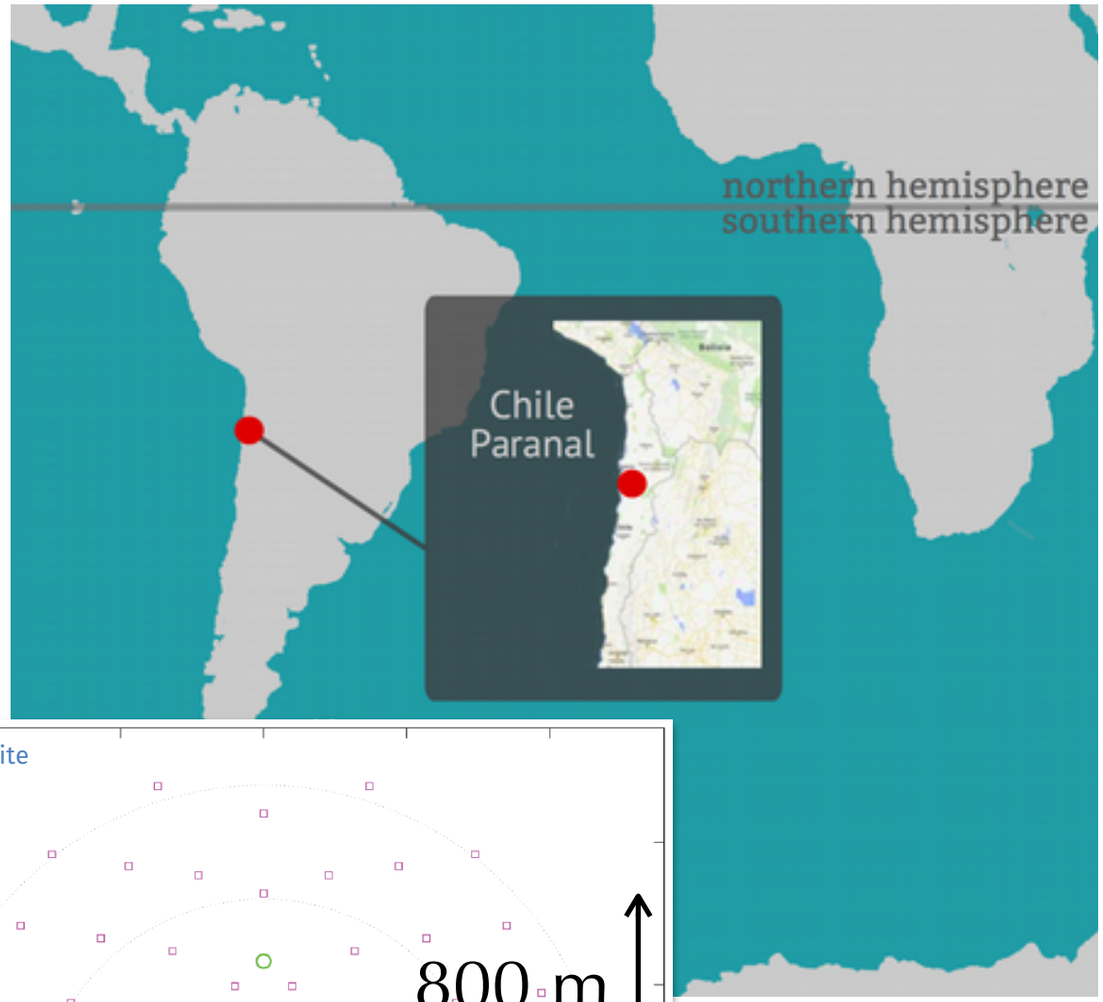
one of the biggest projects in high energy astrophysics

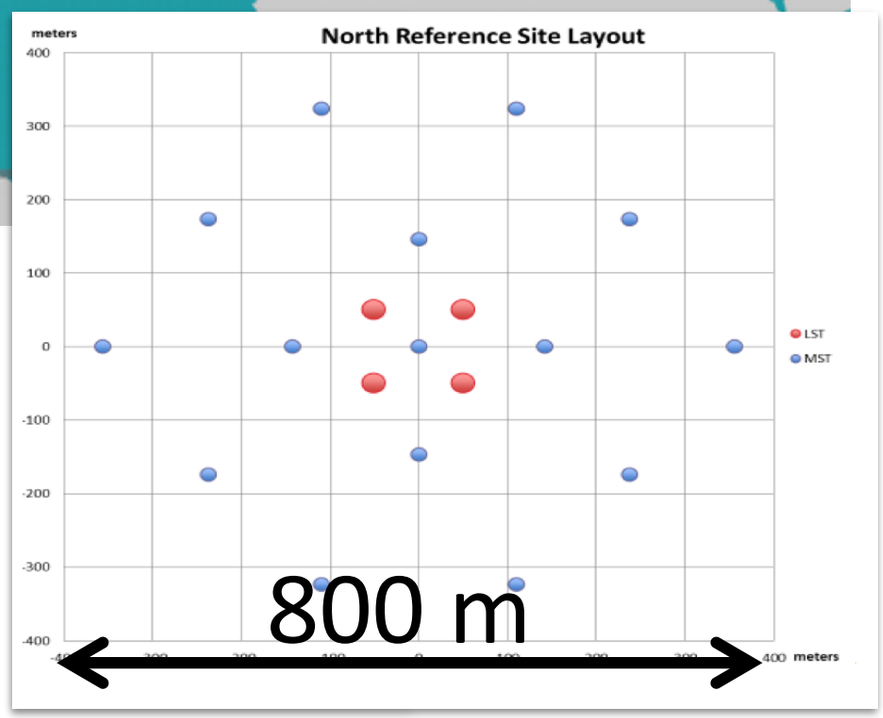


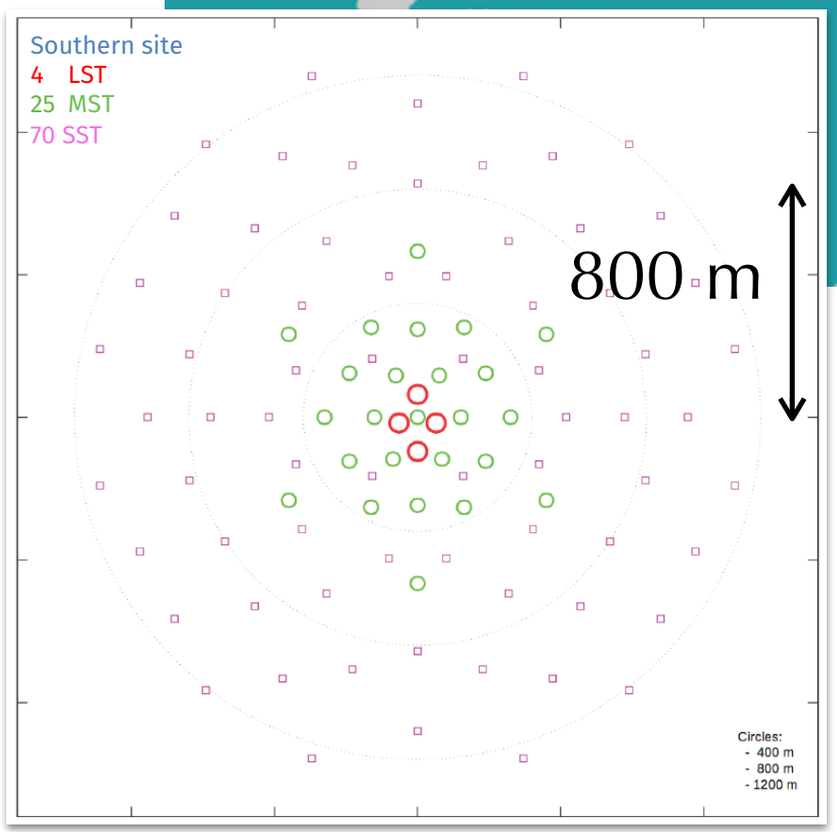
Future with the CTA

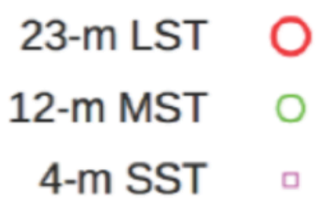
sites and example telescope layouts







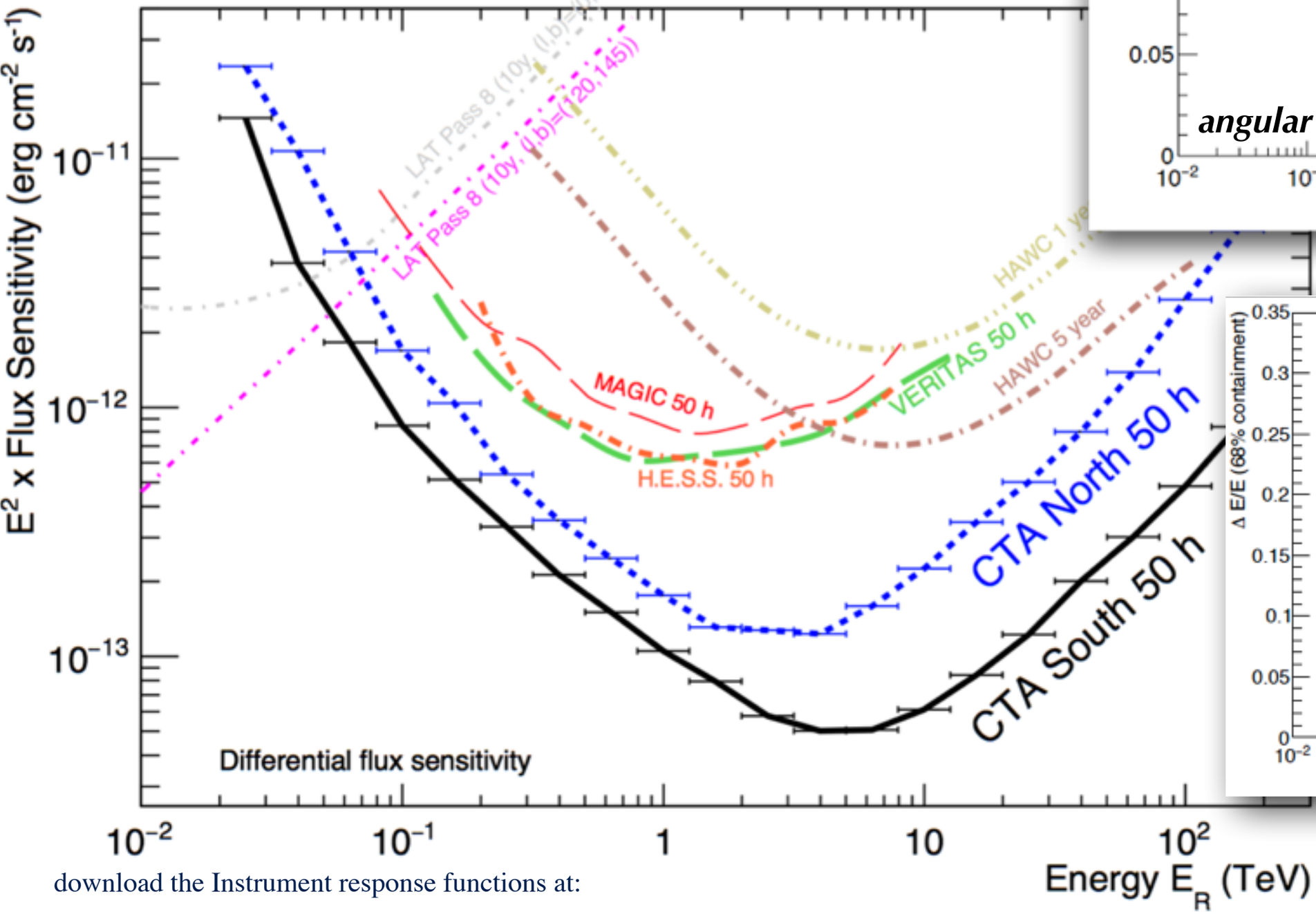


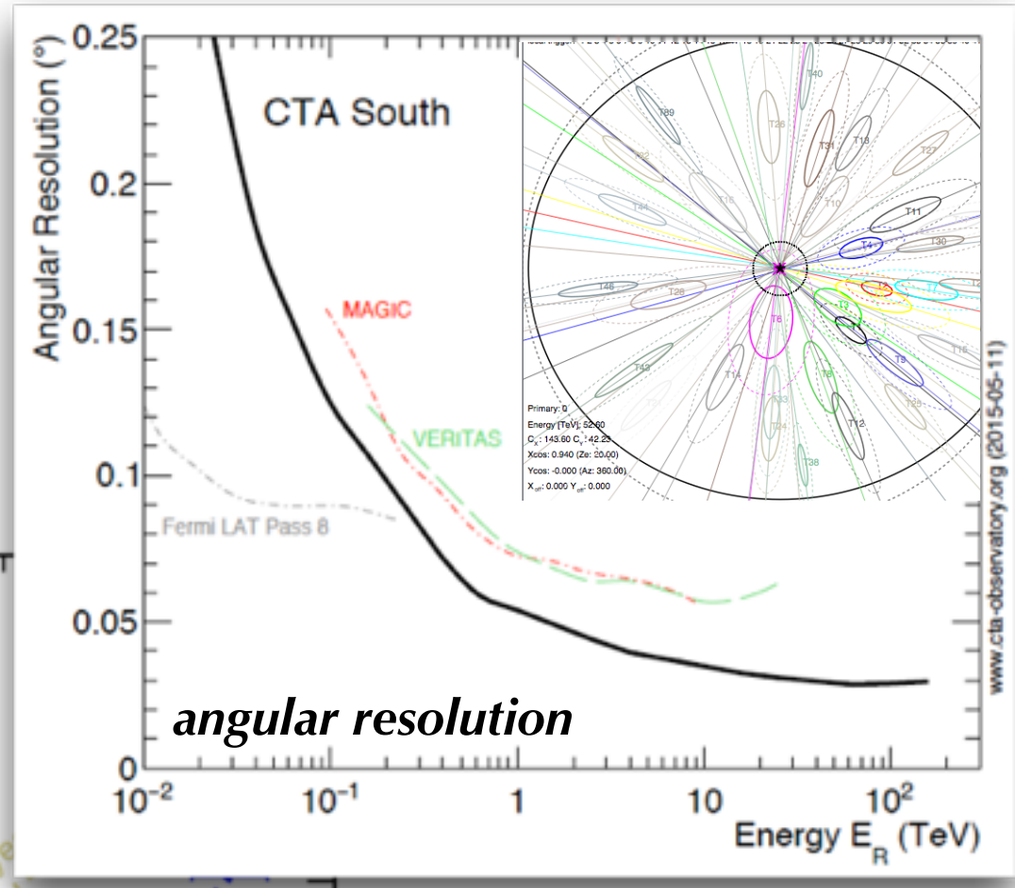


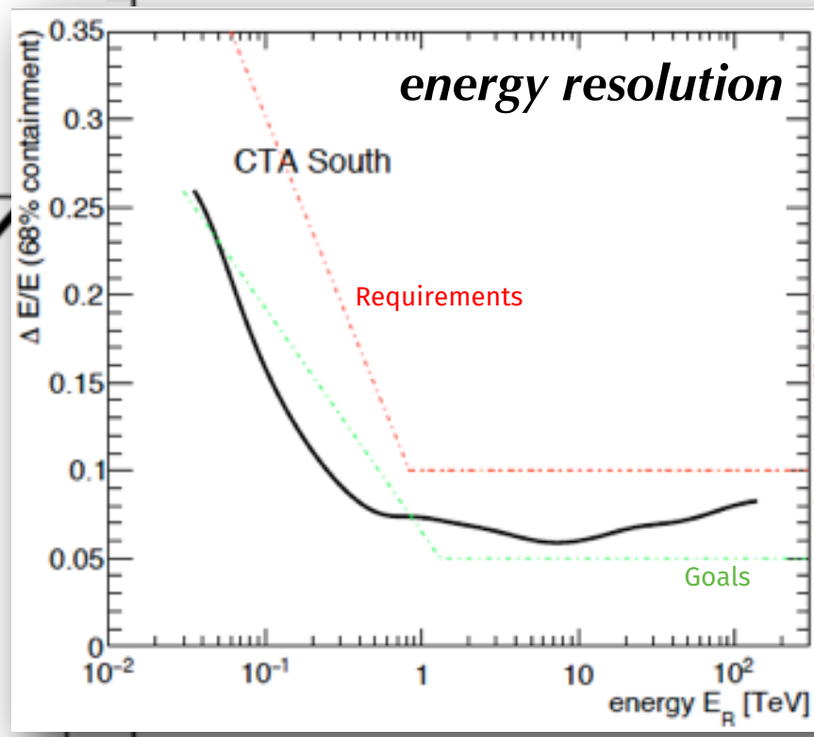
[credit: T. Hassan, CTA consortium]

CTA

Comparison with state-of-the-art







download the Instrument response functions at:

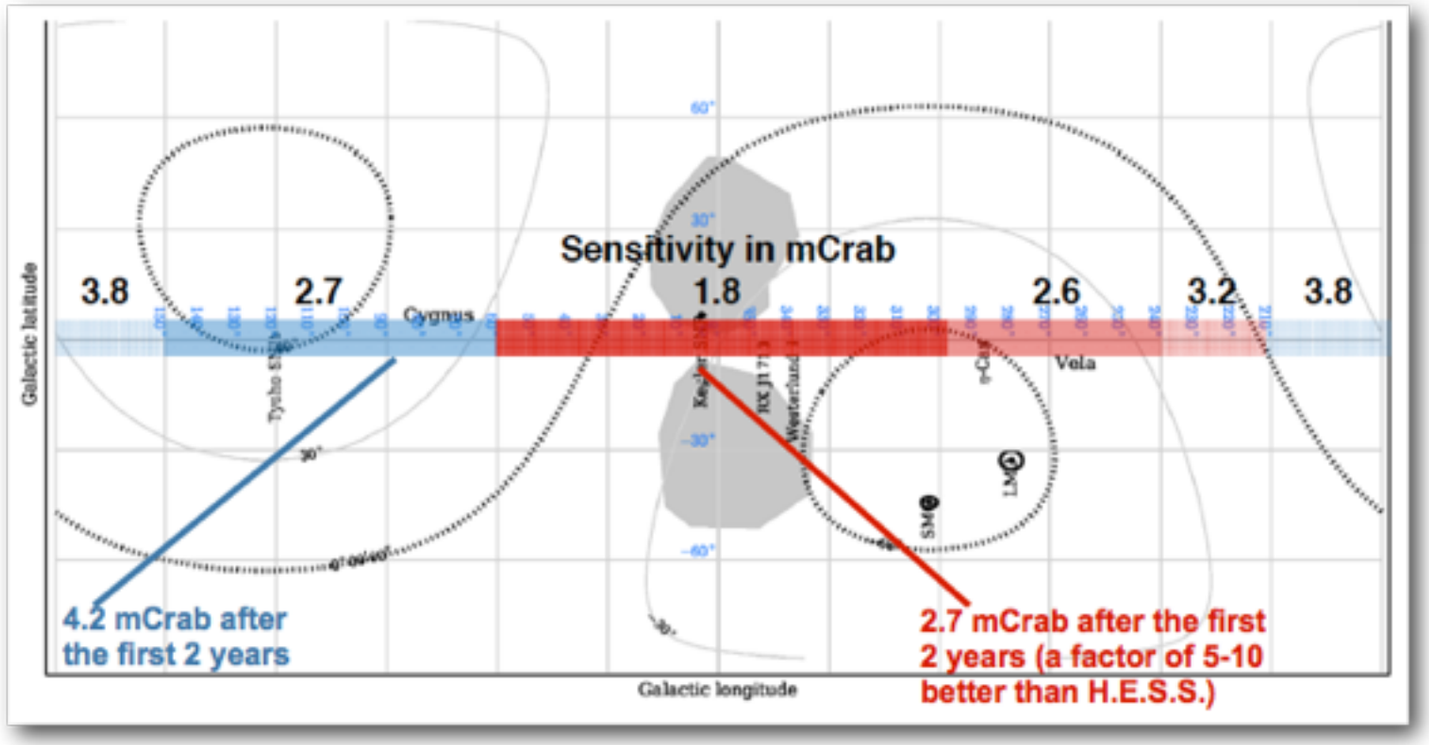
https://portal.cta-observatory.org/Pages/CTA-Performance.aspx

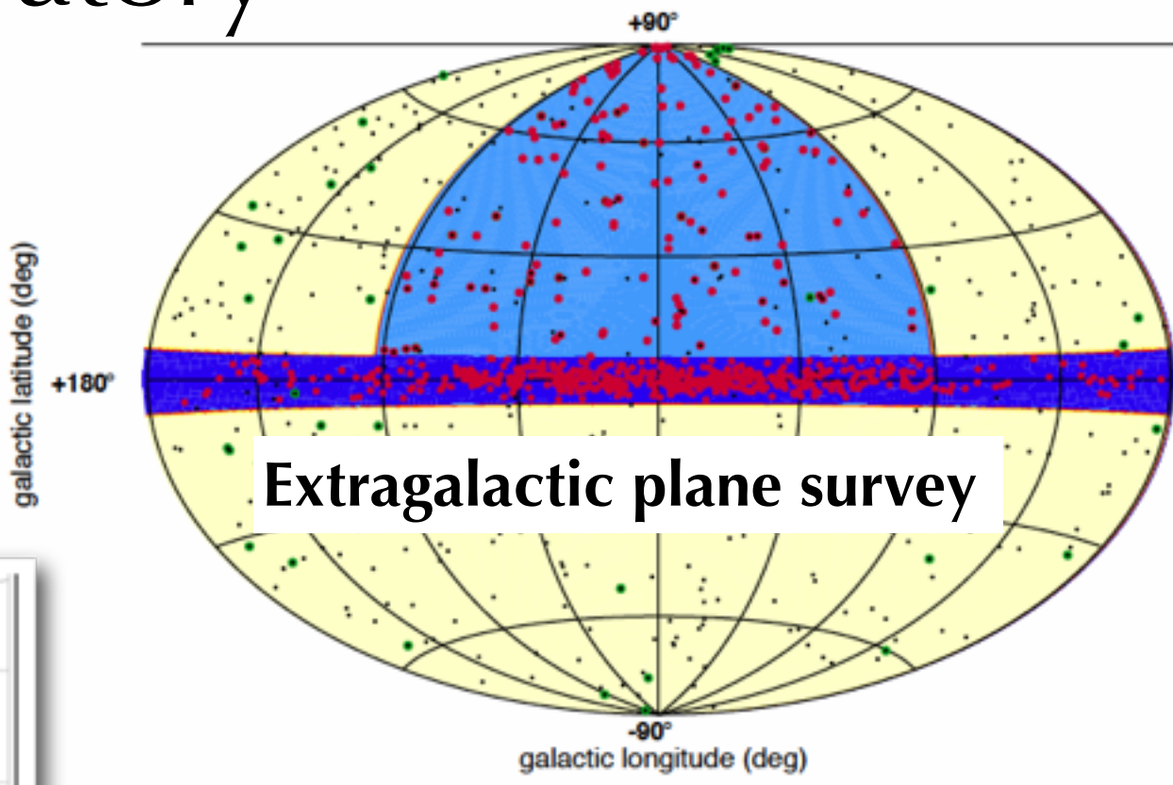
Credits: W. Hofmann and The CTA Consortium

CTA as a whole-sky observatory

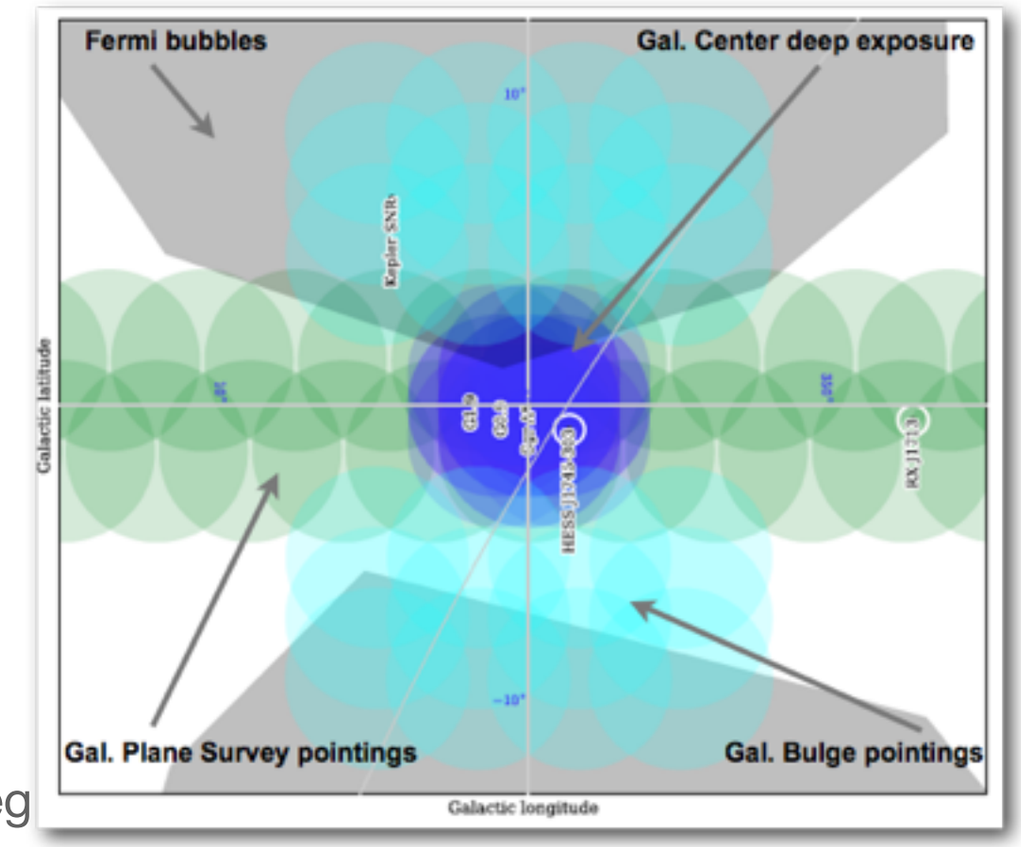
ground based telescopes are **pointing**,
but **large sky surveys** planned for CTA
(thanks to a large number of CTA telescopes)

Galactic plane survey





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



Galactic centre

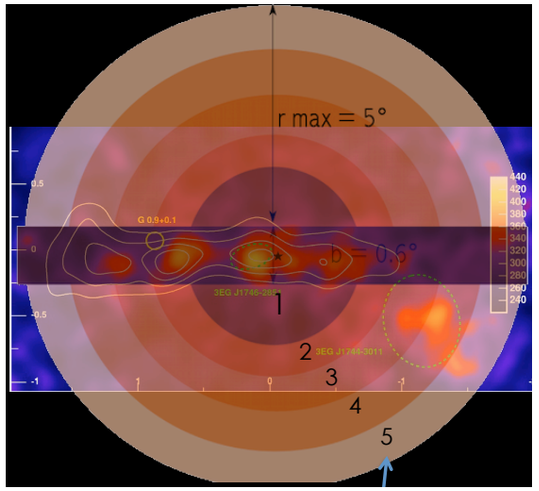
525 h deep exposure to uniformly cover the central 5 deg

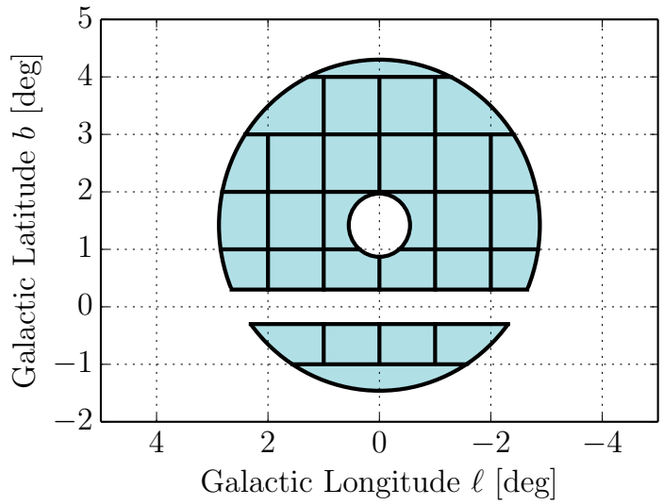
+ 300 h extended survey,10x10 deg

CTA @ the Galactic centre

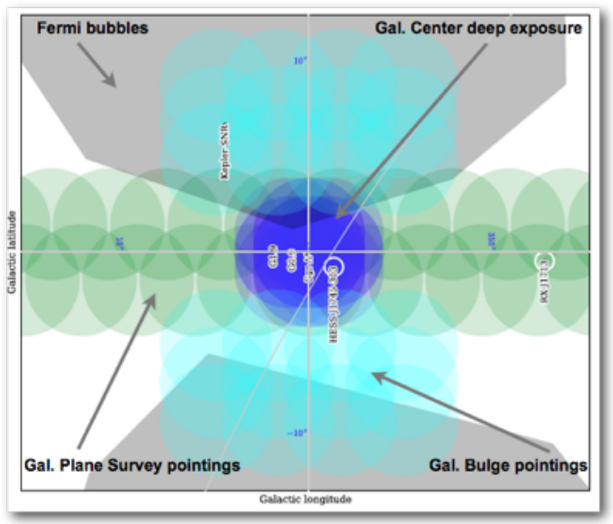
Exploration of the most promising techniques and strategies ongoing:

- data analyses approaches:
  traditional ‘ring background’ method vs 2D likelihood morphology studies to fight CR backgrounds

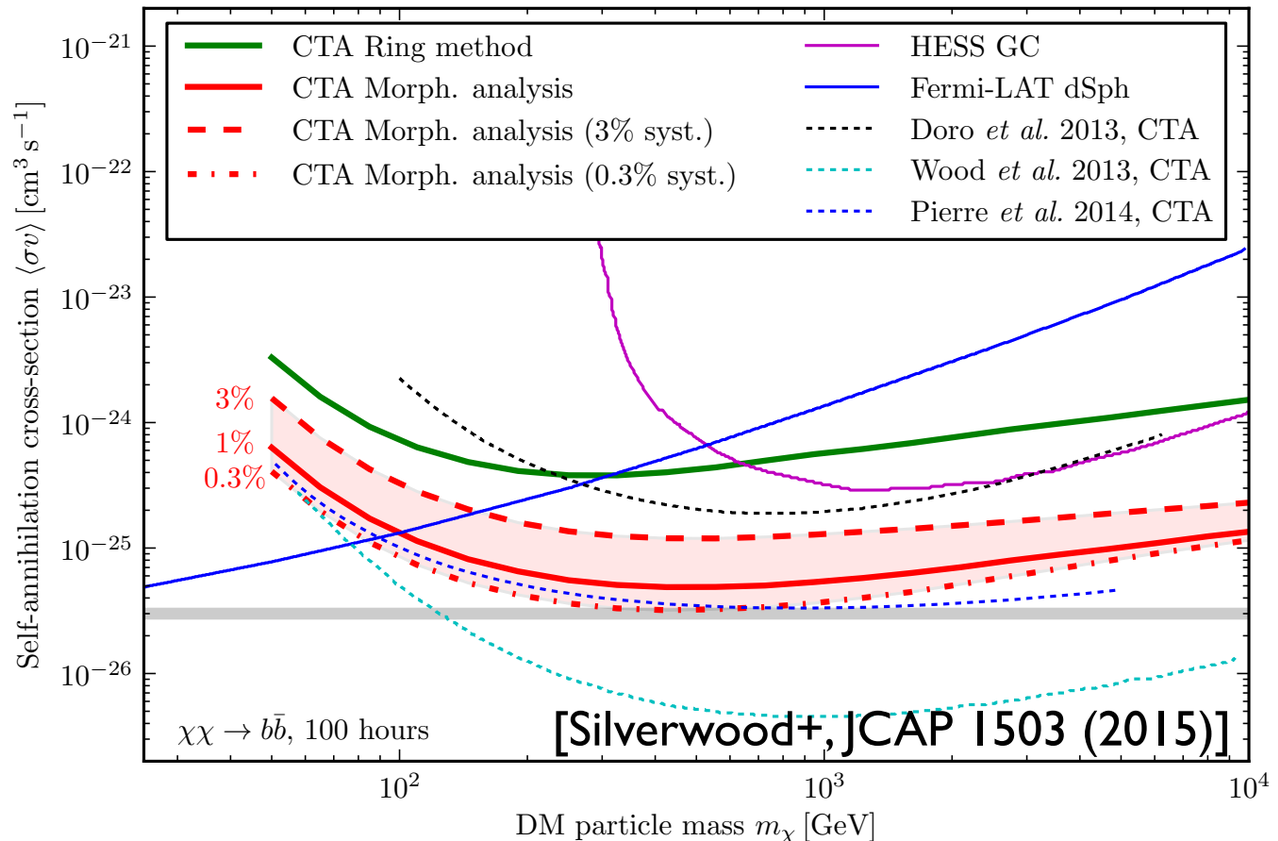




- impact of Galactic diffuse emission
- instrumental systematics

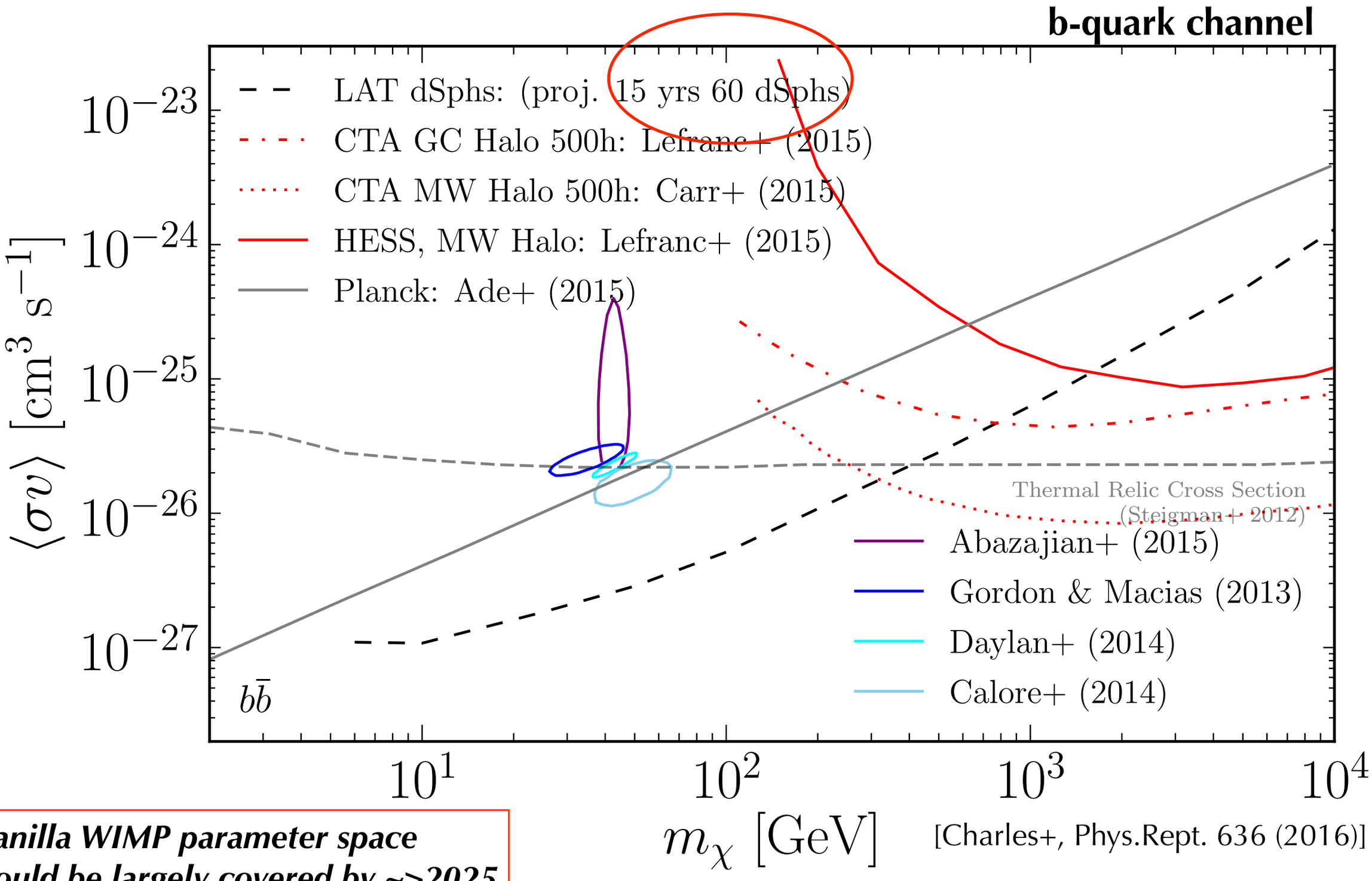


[Lefranc+, Phys.Rev. D91 (2015)]



[Silverwood+, JCAP 1503 (2015)]

Outlook - LAT & CTA

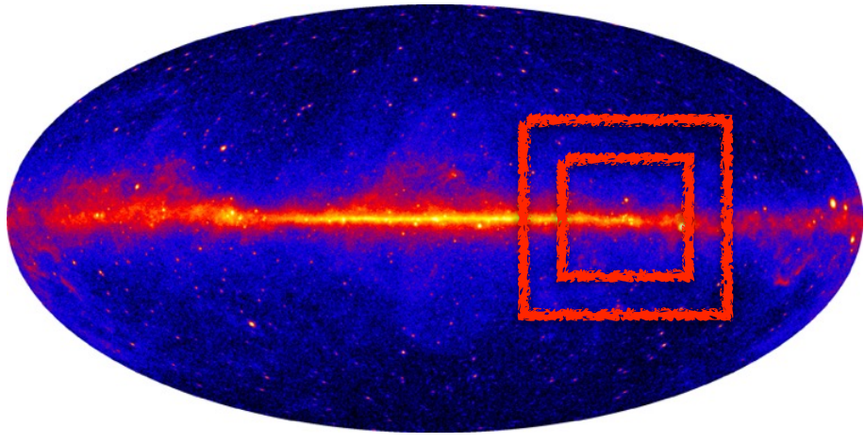


vanilla WIMP parameter space could be largely covered by ~>2025

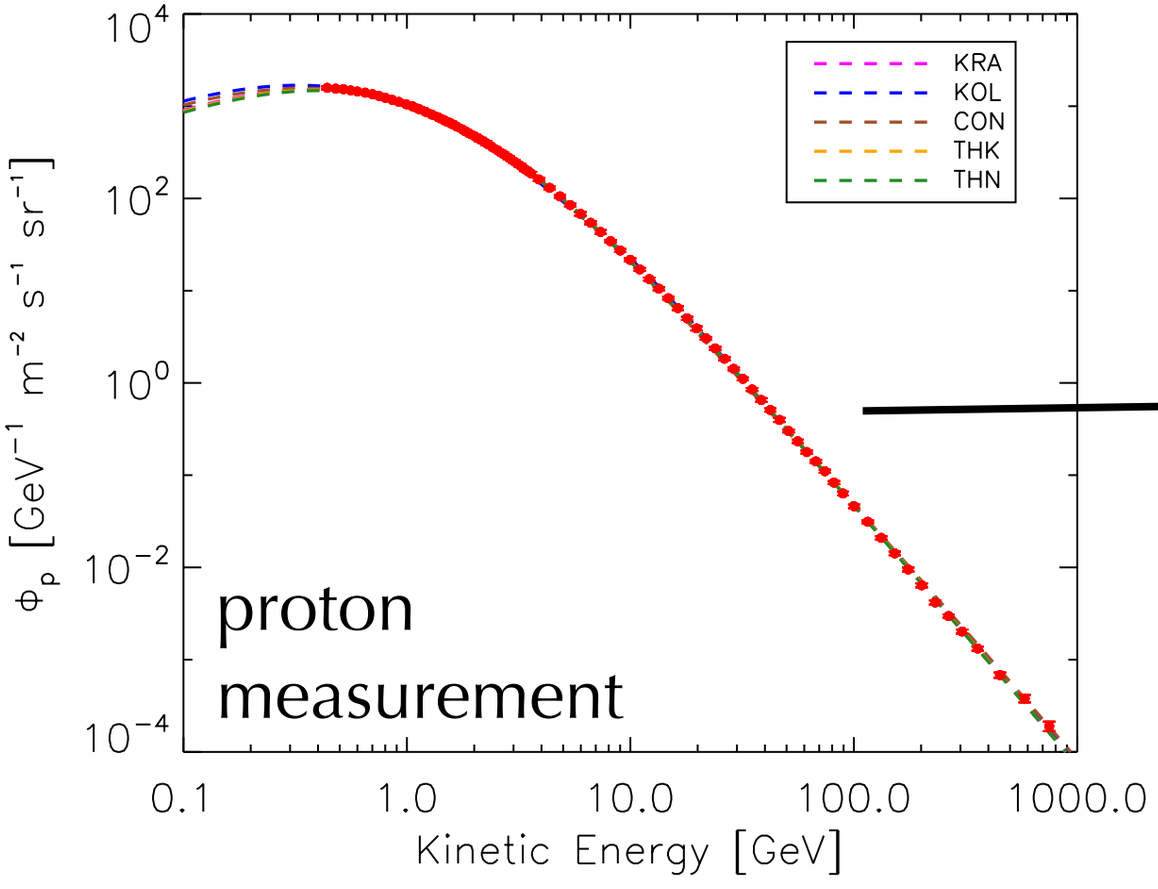
[Charles+, Phys.Rept. 636 (2016)]

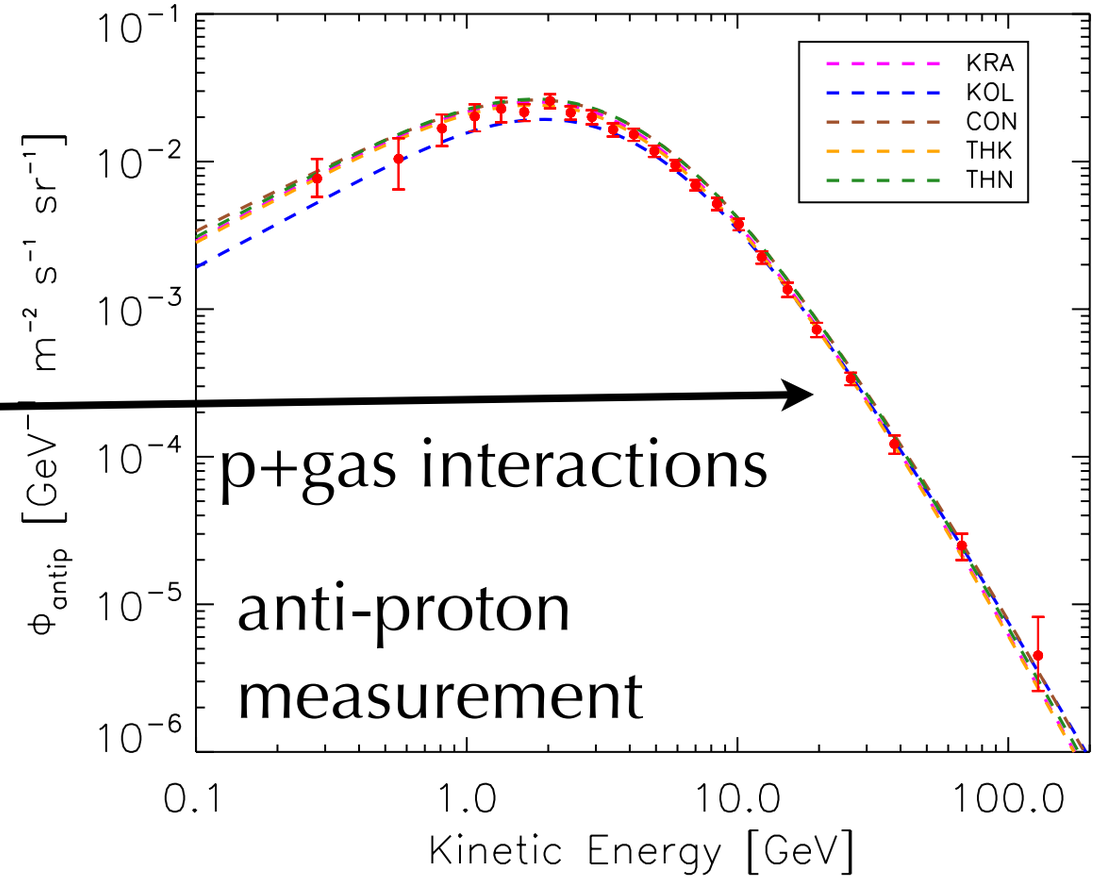
[new HESS limits, 1607.08142]

Anti-protons



- reasonable handle on astrophysical backgrounds: anti-protons are mainly produced in pp or pHe interactions and constrained by measured p fluxes
- good containing power on exotic contributions





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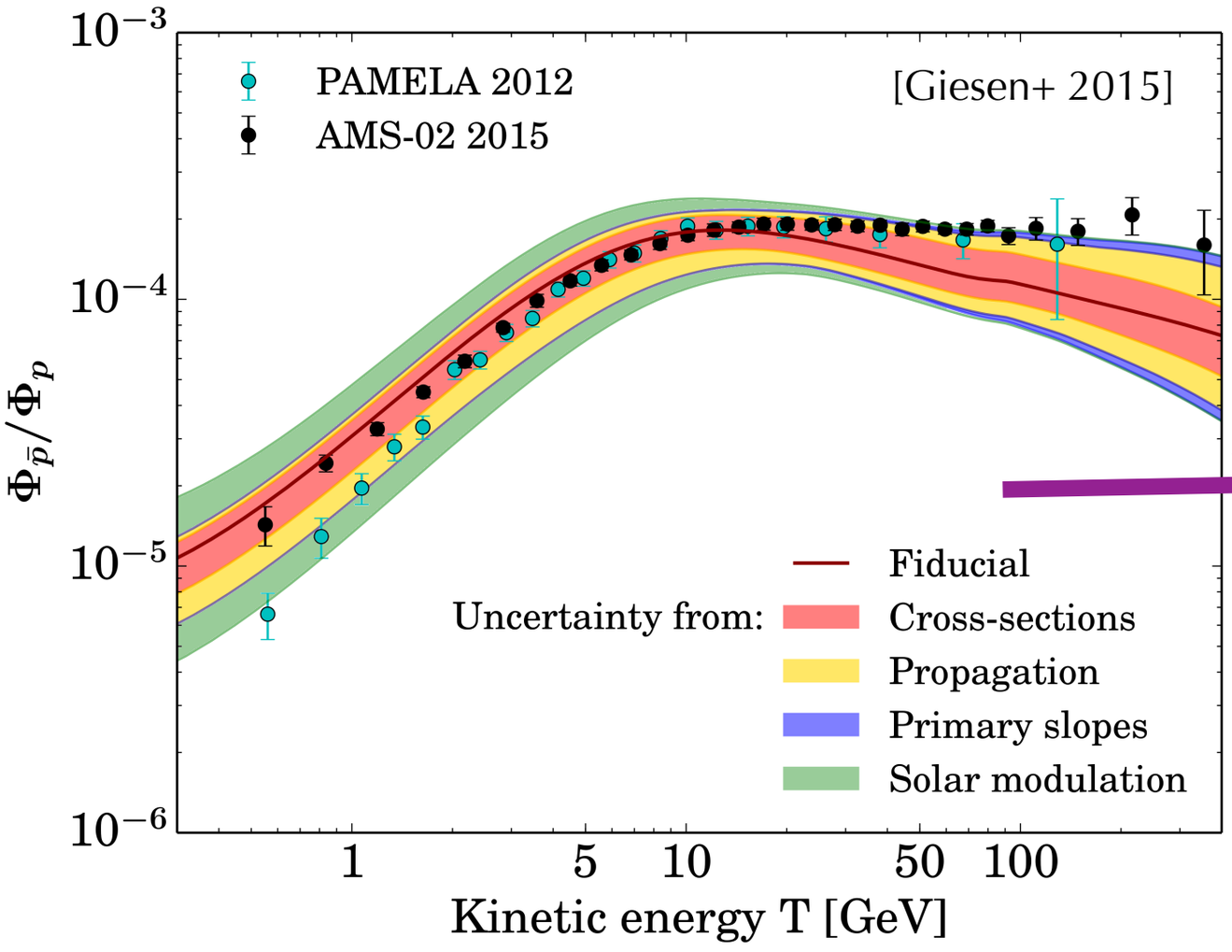
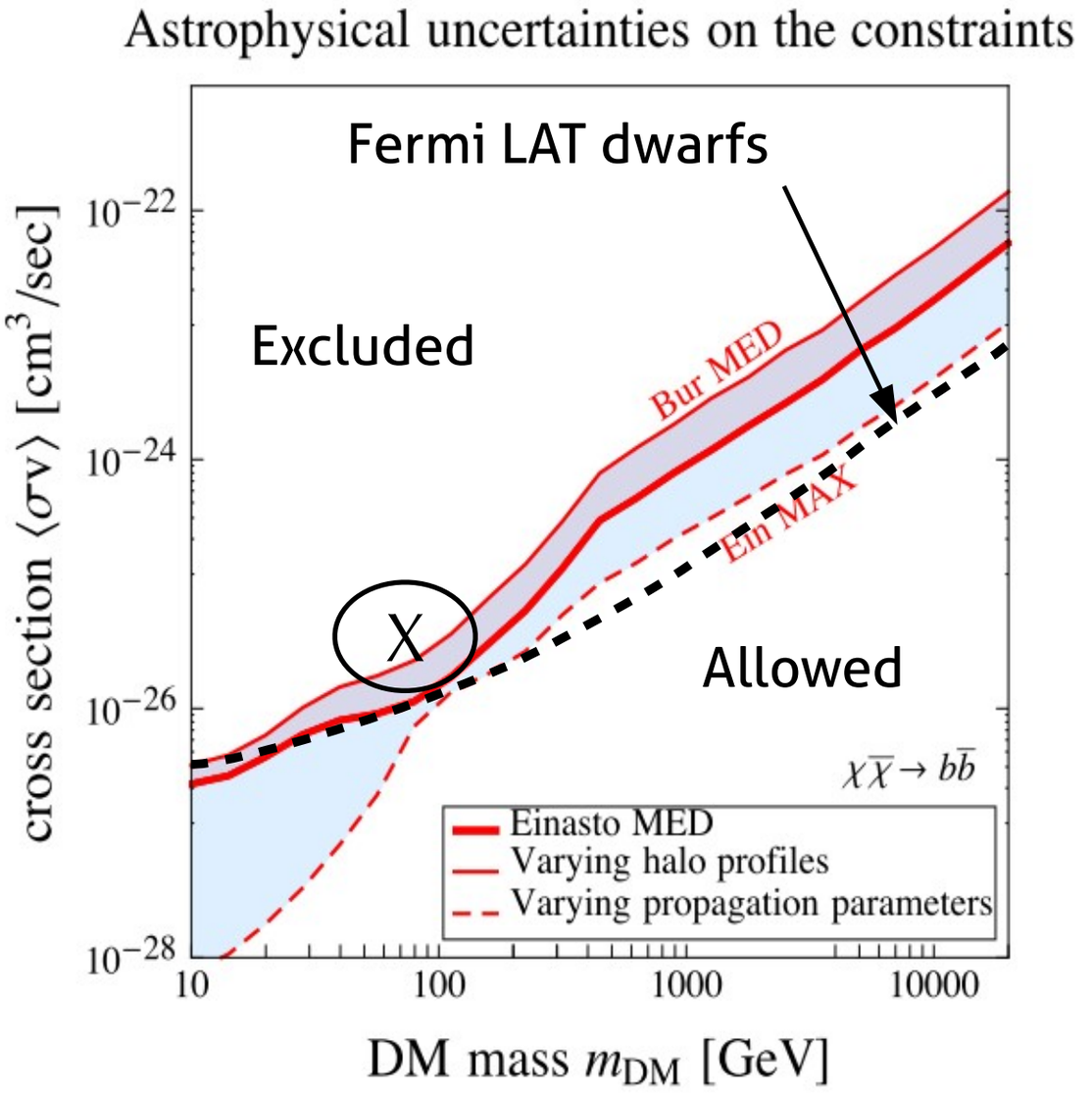




Relevant uncertainties for CR BG:

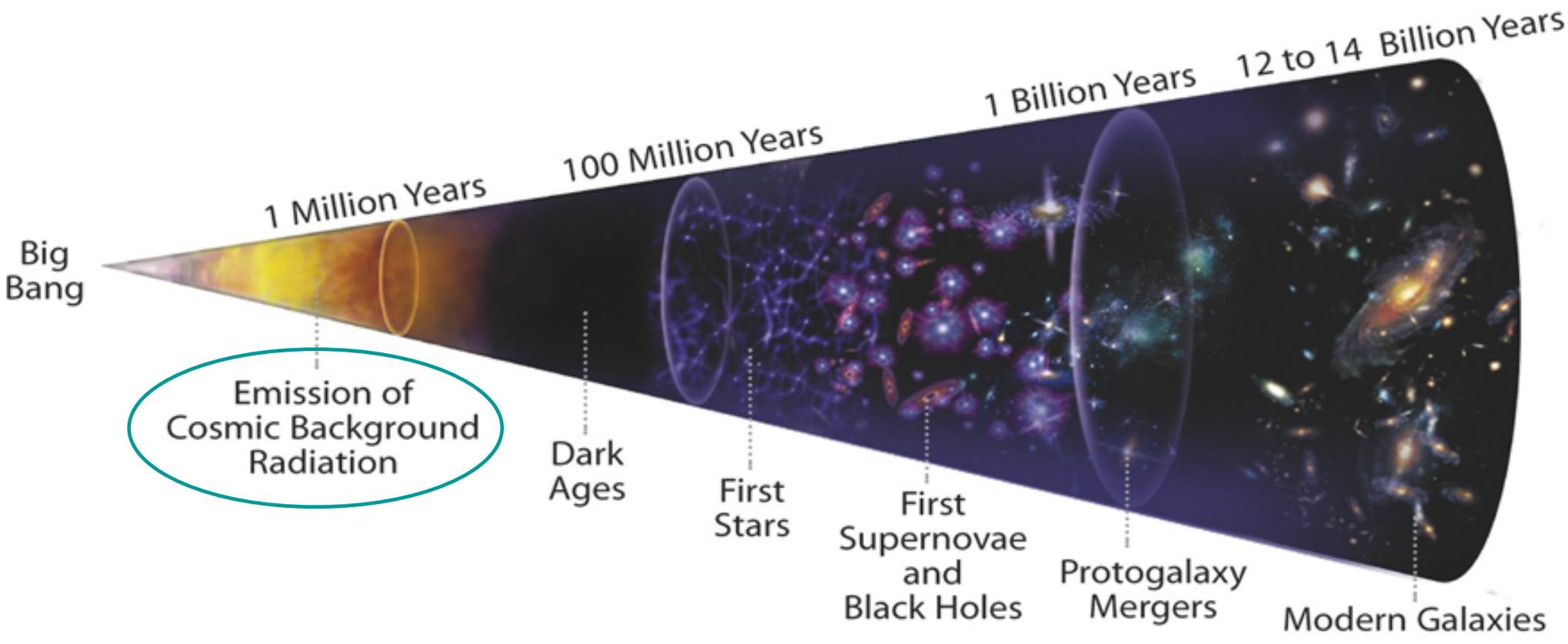
- pbar production cross-section
- spectrum of CR primaries
- CR propagation
- solar modulation (below ~10 GeV)

No excess above secondary backgrounds! (Giesen+ 2015, Kappl+ 1506.04145, Evoli+ 1504.05175)

Early Universe

Y. Ali-Haimoud's talks

- DM ann/decays could affect the early universe evolution:
  - ***BBN*** (T~1 MeV): energy injections destroy formed nuclei
  - ***CMB*** (z ~ 1000): The increased ionization fraction leads to a broadening of the last scattering surface.
  - ***re-ionization*** ($6 < z < 20$): ionization and heating after recombination and during the epoch of structure formation affect optical depth of the Universe.



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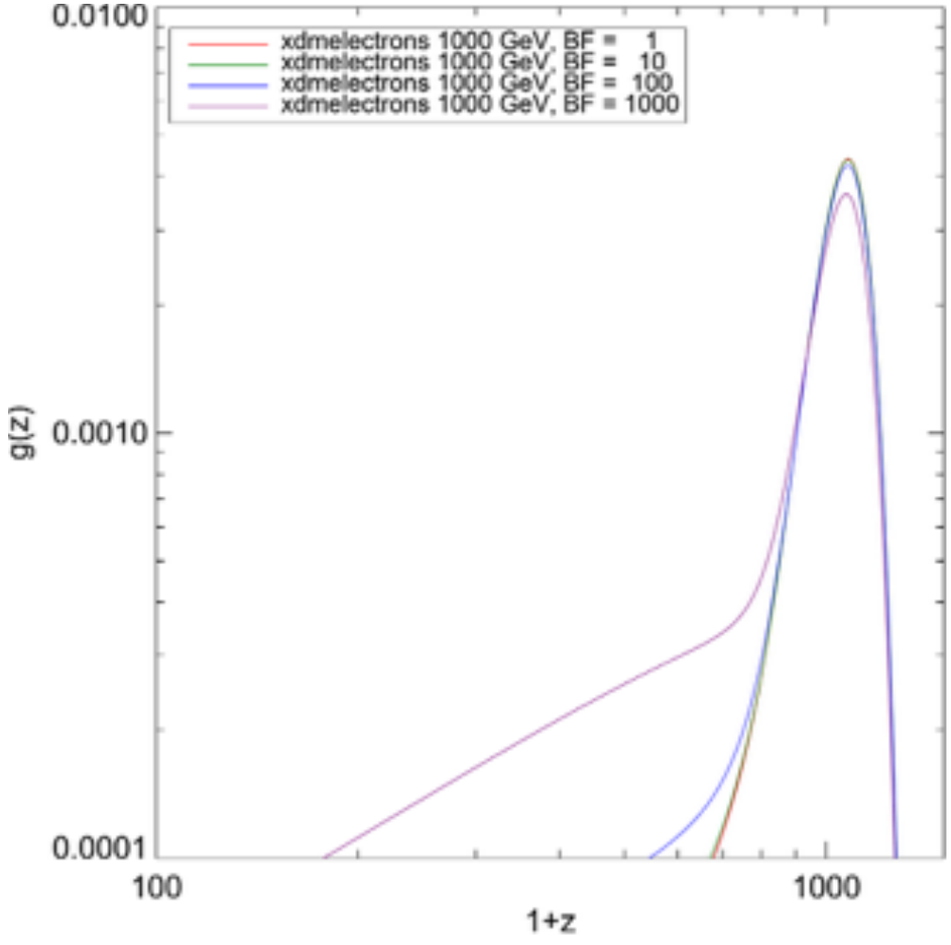
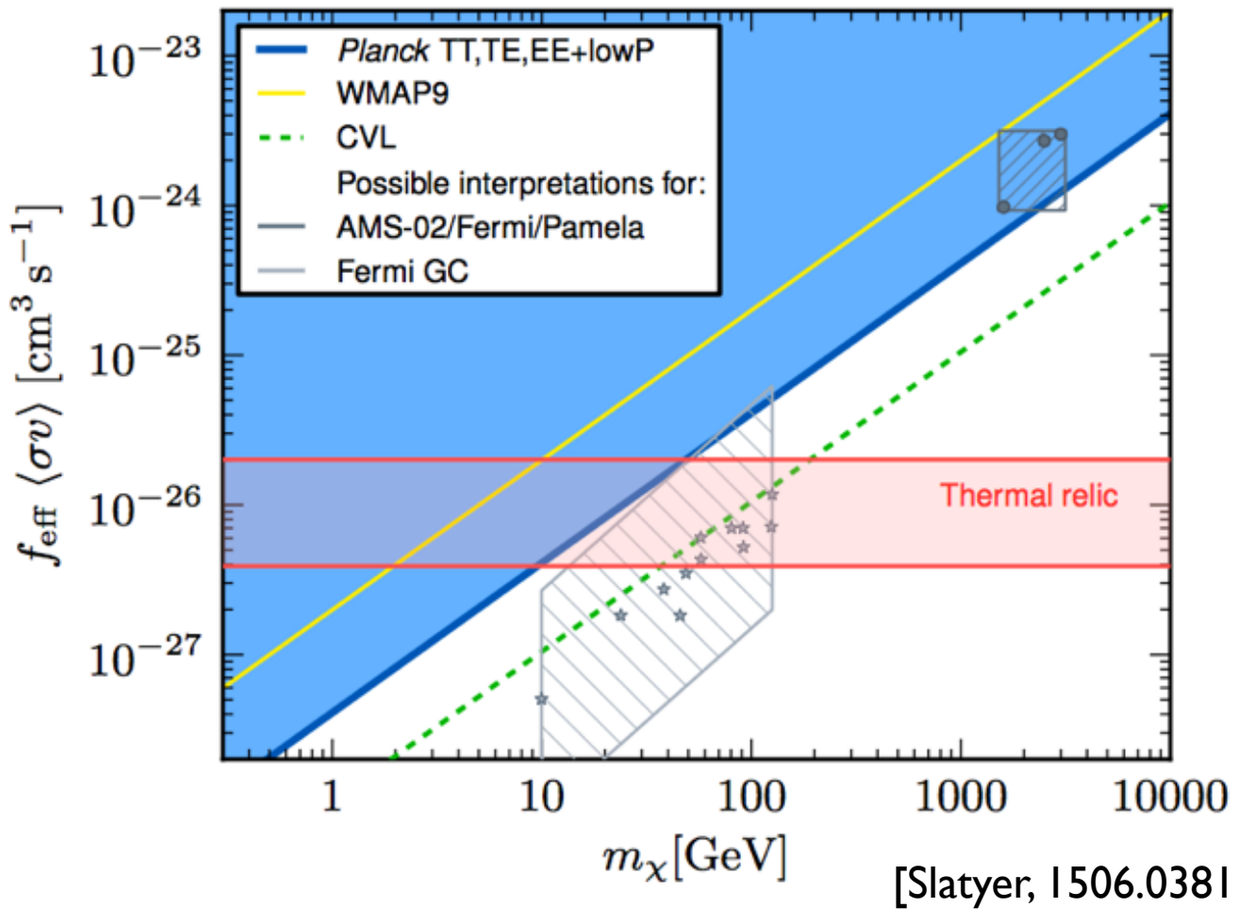
  - ***re-ionization*** (6 < z < 20): ionization and heating after recombination and during the epoch of structure formation affect optical depth of the Universe.

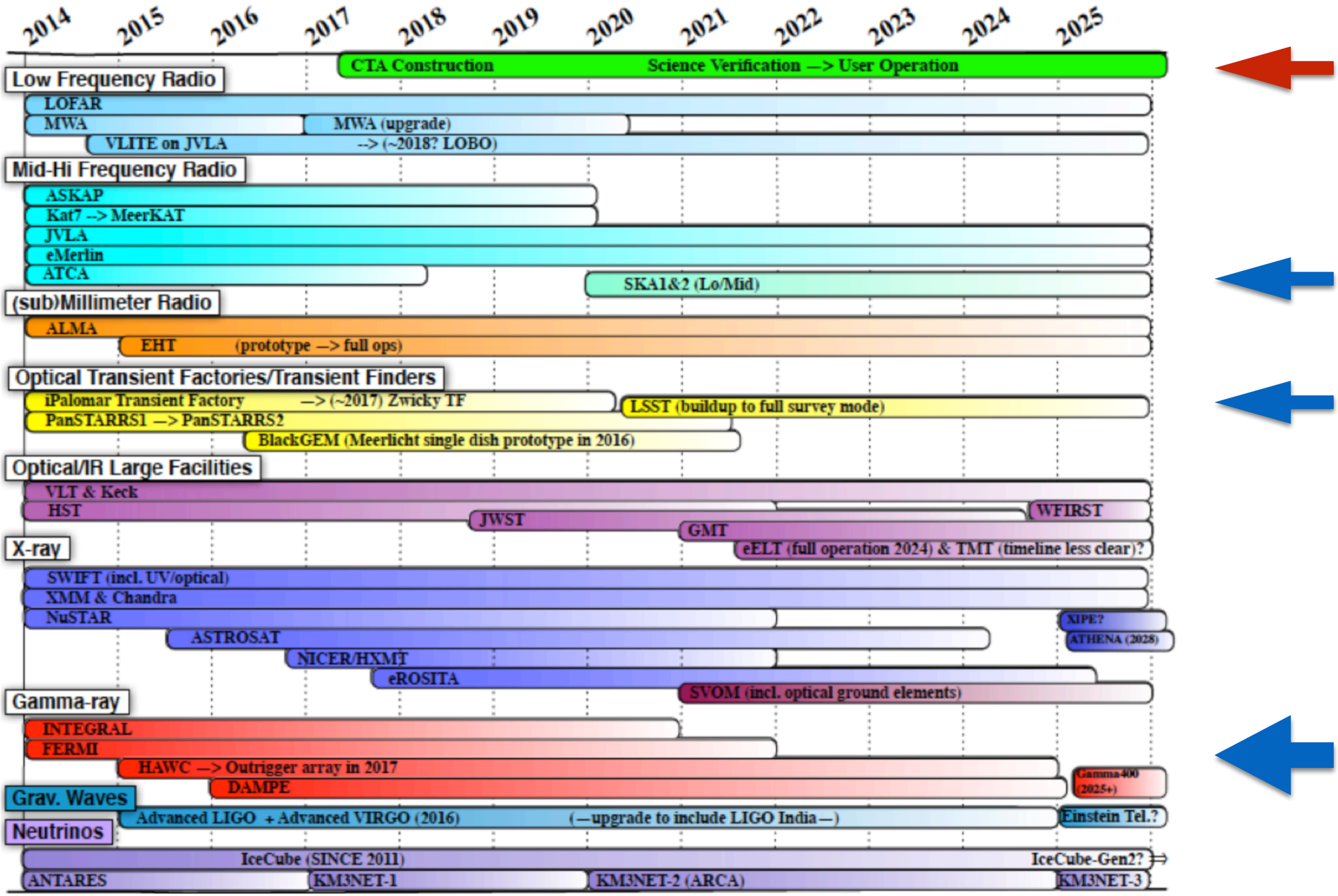




[Slatyer, 1506.03811]

Future?

more observations!



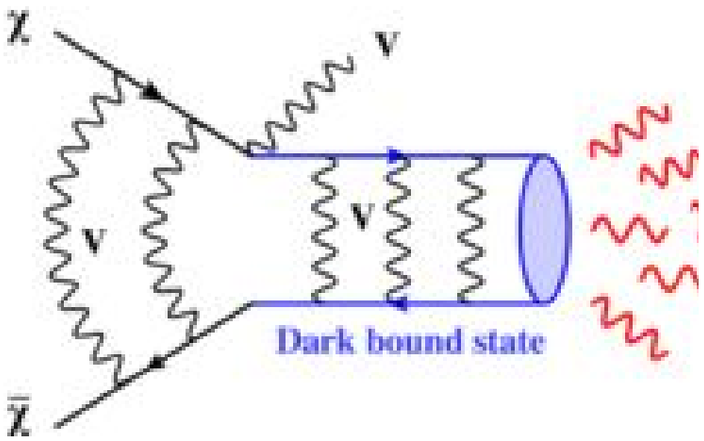
Credits: S. Markoff & The CTA Consortium

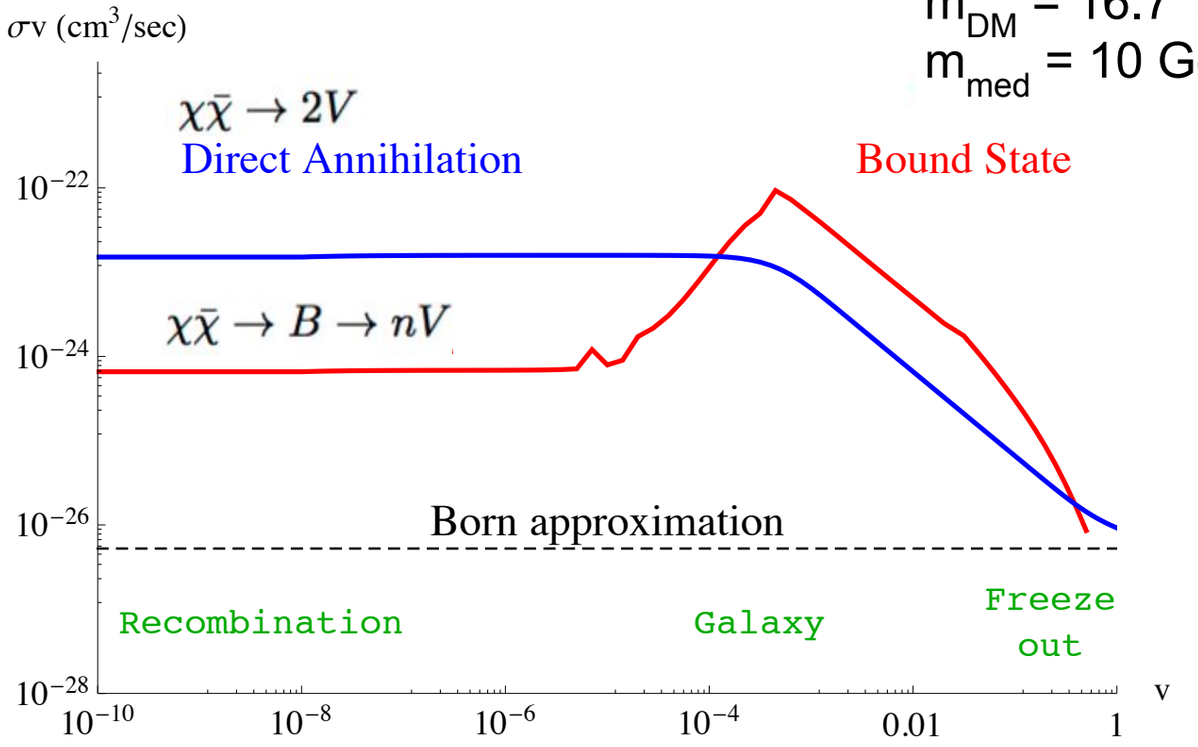
Future?

theoretical advances

R. Essig's talk

e.g. relax an assumption on trivial dark sector -> **bound states of DM** (WIMPonium, Darkonium…) and their signatures





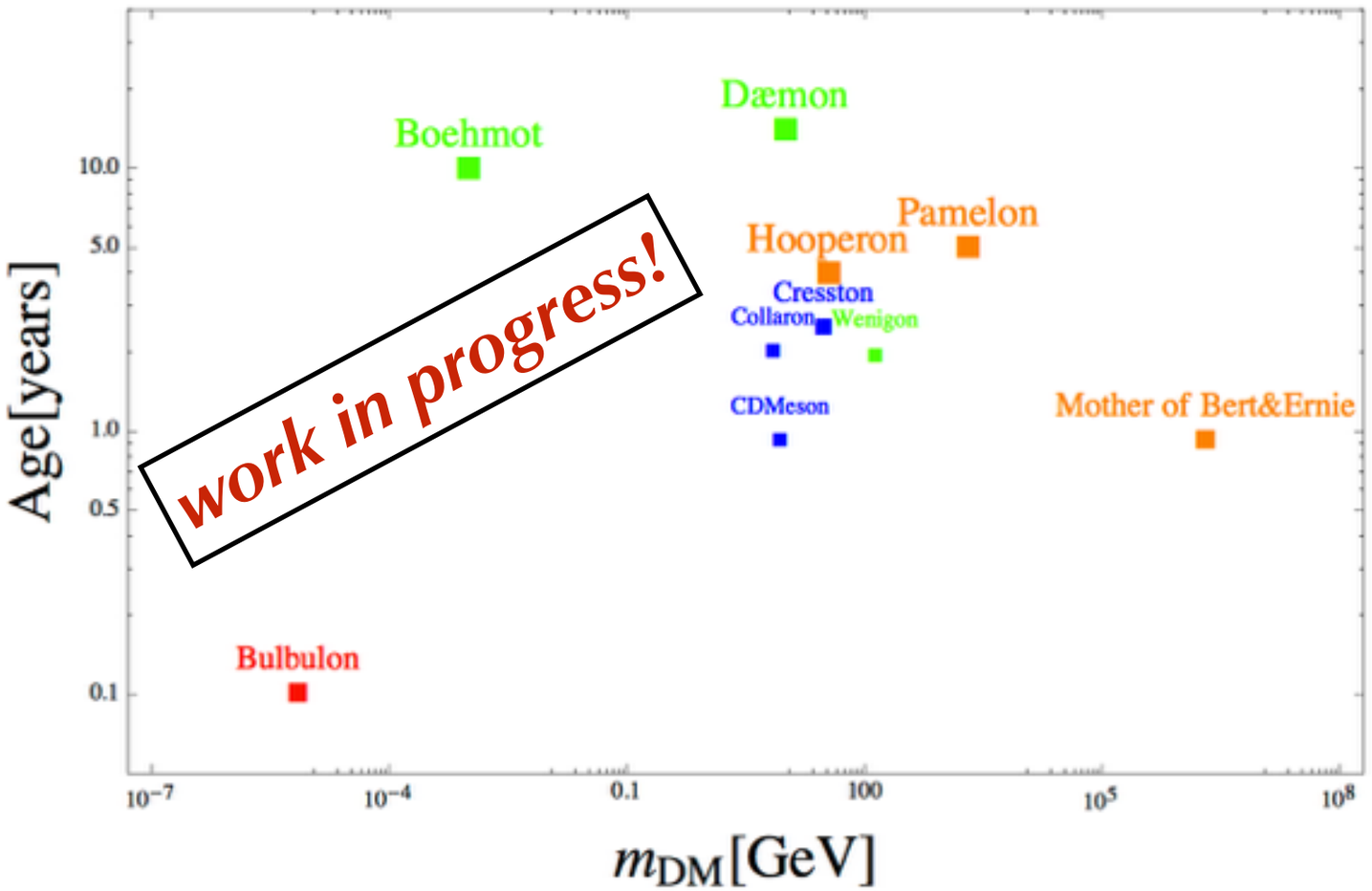
m_{DM} = 16.7 TeV
m_{med} = 10 GeV

[Zhang+, PRD2016]

Future?

- The field of astrophysics is being re-defined by high-quality data, extending over a larger dynamical range.
- DM search is an outstanding effort for over 50 years: the tools are now finally in the right ballpark!

- ***More data coming up - stay tuned!***



[RESONAANCES: http://resonaances.blogspot.it/]

Extra Slides

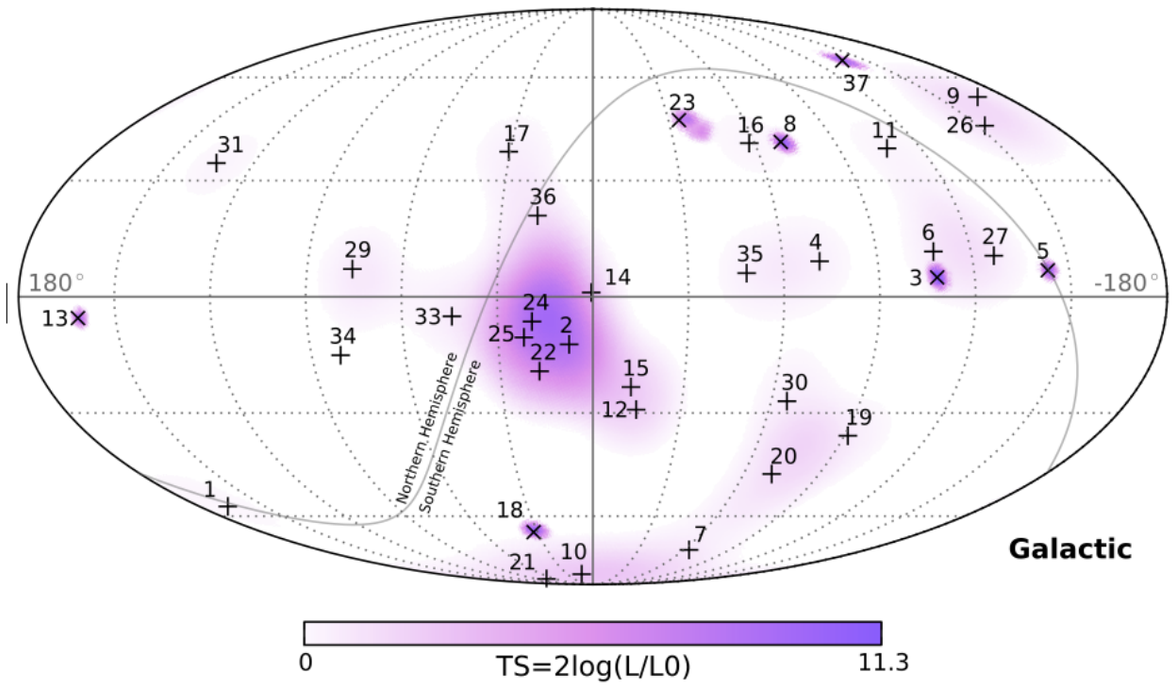
Neutrinos?

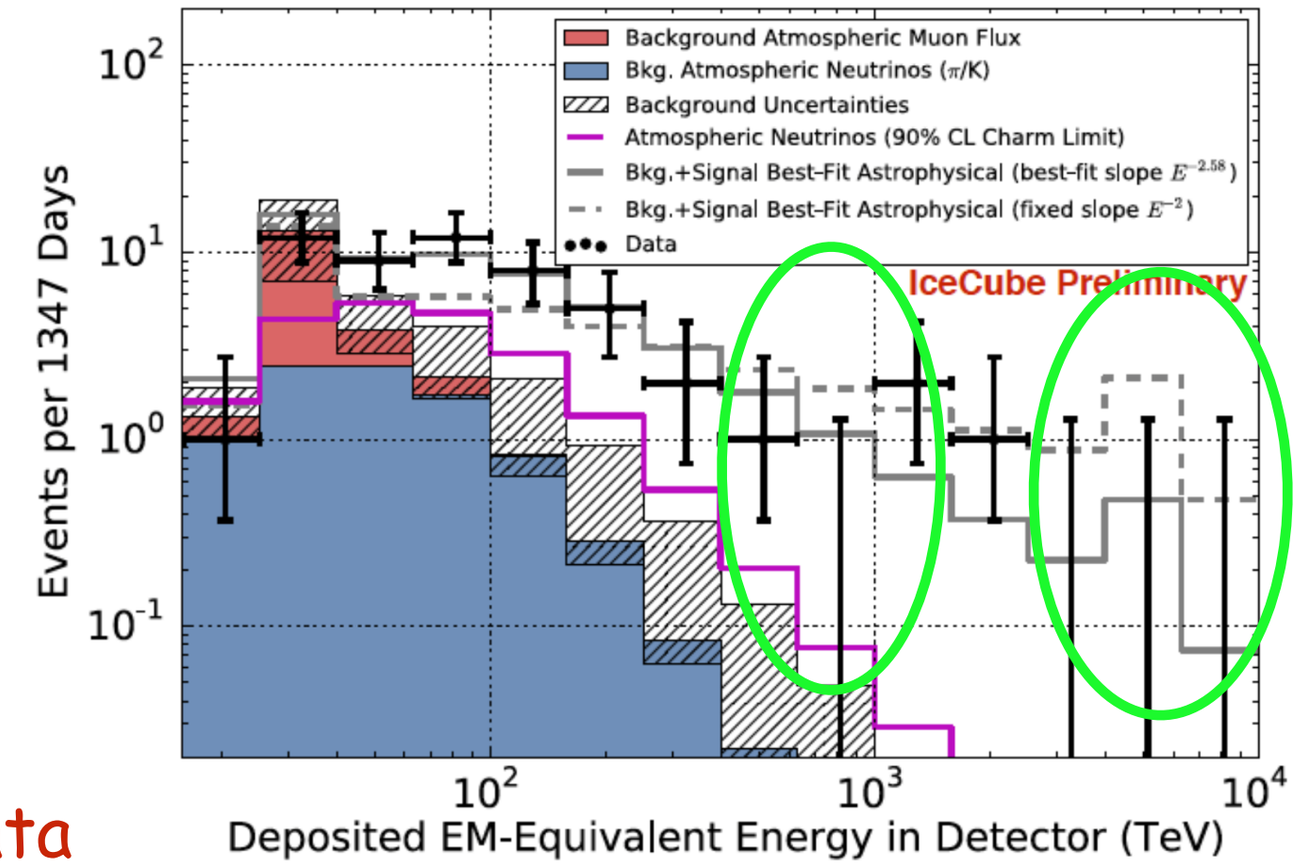
✓ deficit of events in the energy range ~ (400 - 1000) TeV

✓ cut-off in events: no events observed with energy > 2 PeV

✓ angular distribution of events show mild anisotropies (enhanced toward GC)

⚠ none of the above-mentioned issues are significant



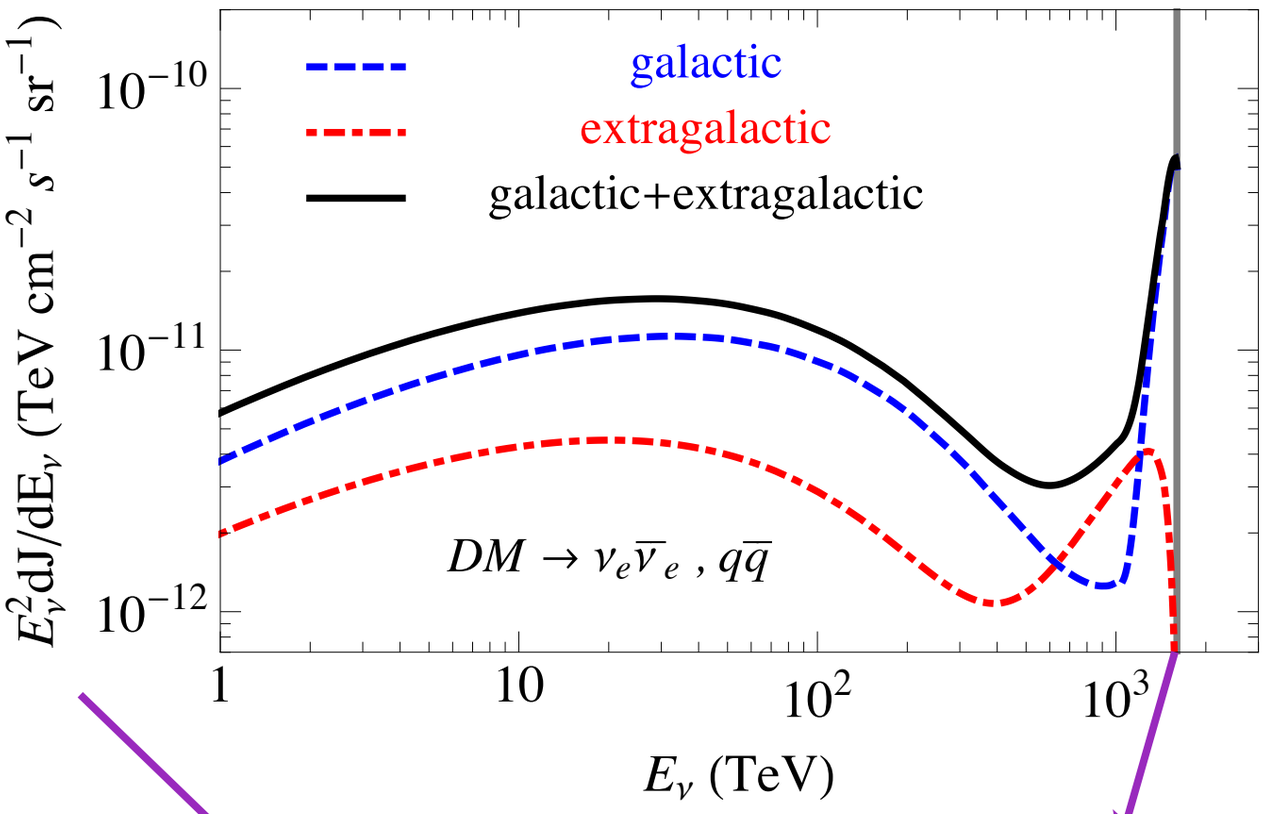


4 years of data

[slide credit: A. Ismaili]

Neutrinos?

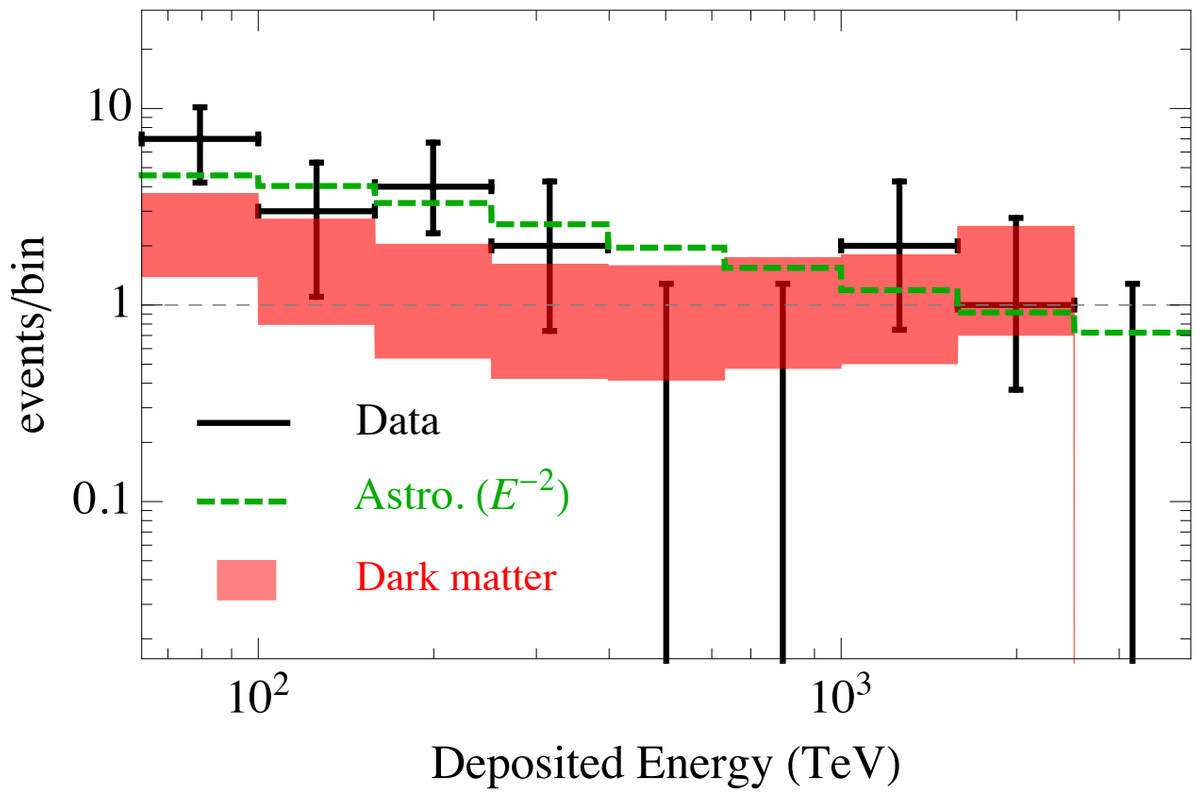
A. E., P. Serpico,
JCAP (2013) [1308.1105]



NH

$\tau_{DM} = 7.3 \times 10^{27}$ s

shaded: ±1σ



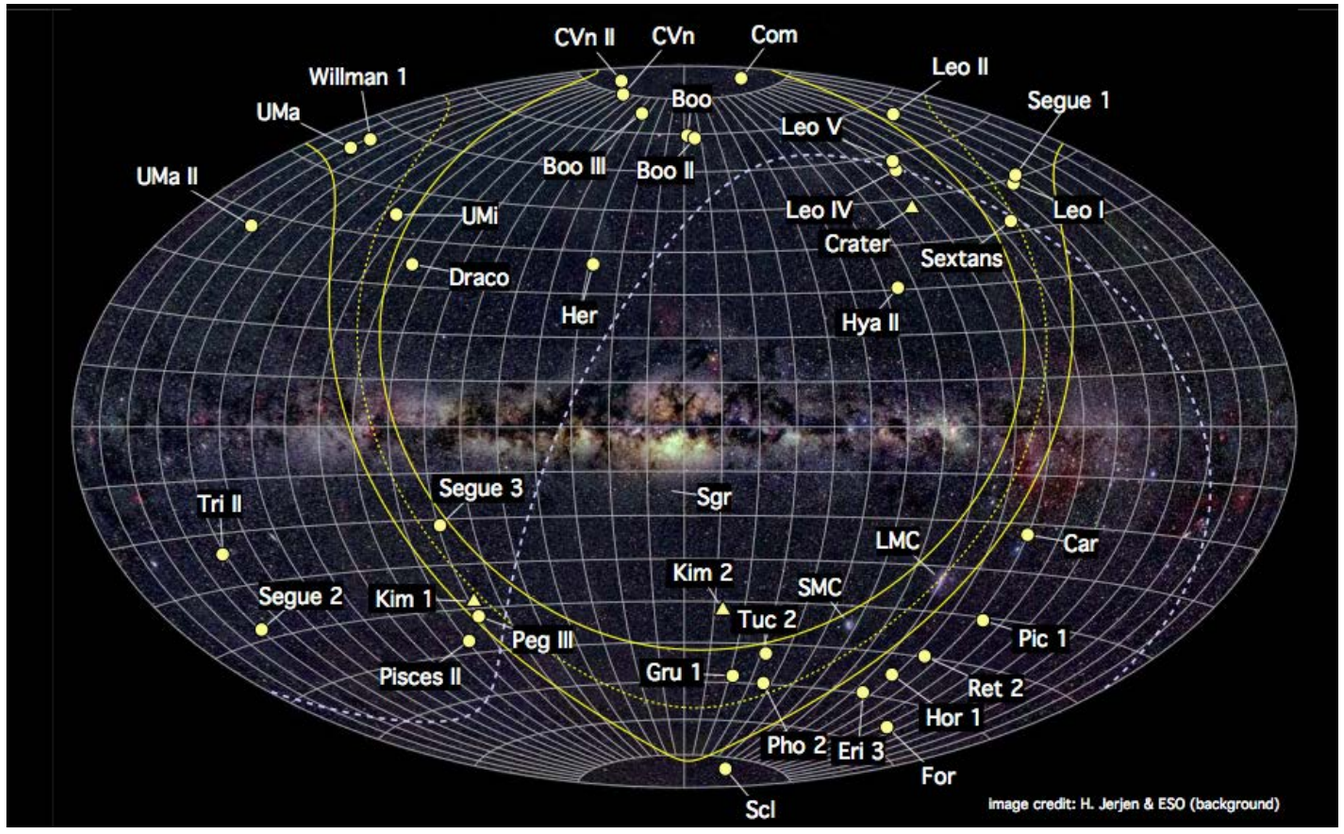
($\upsilon_e + \upsilon_\mu + \upsilon_\tau$)/3

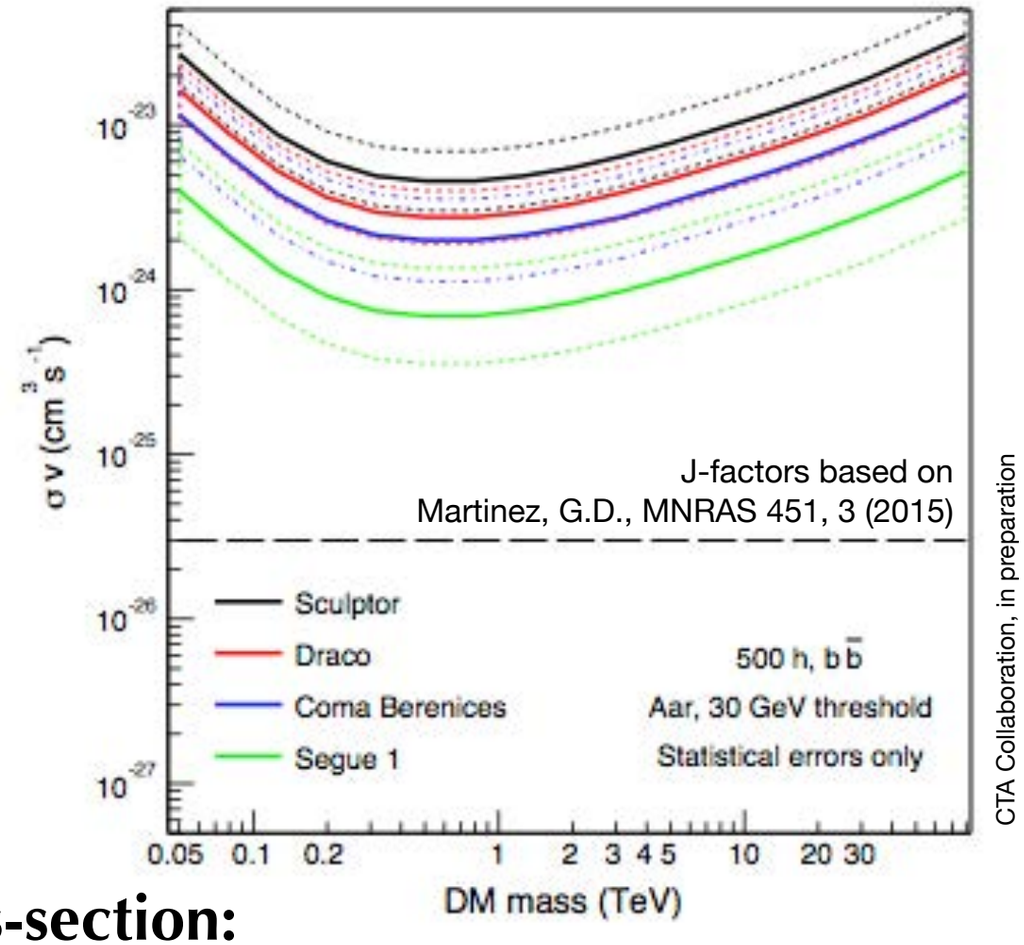
$m_{DM}/2$ = 1.6 PeV

PeV-scale decaying DM with generic decay channels, can naturally explain these features. The required lifetime is allowed by the current limits. Both the energy and angular distributions mildly prefer DM interpretation.

[slide credit: A. Ismaili]

CTA @ the dSphs



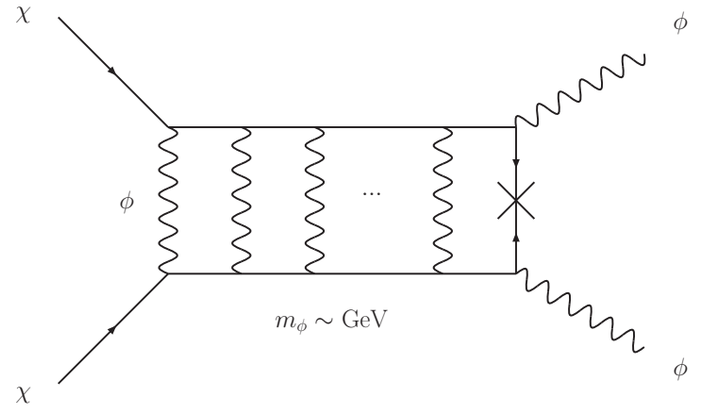


CTA Collaboration, in preparation

Expected sensitivity does not reach the thermal cross-section:

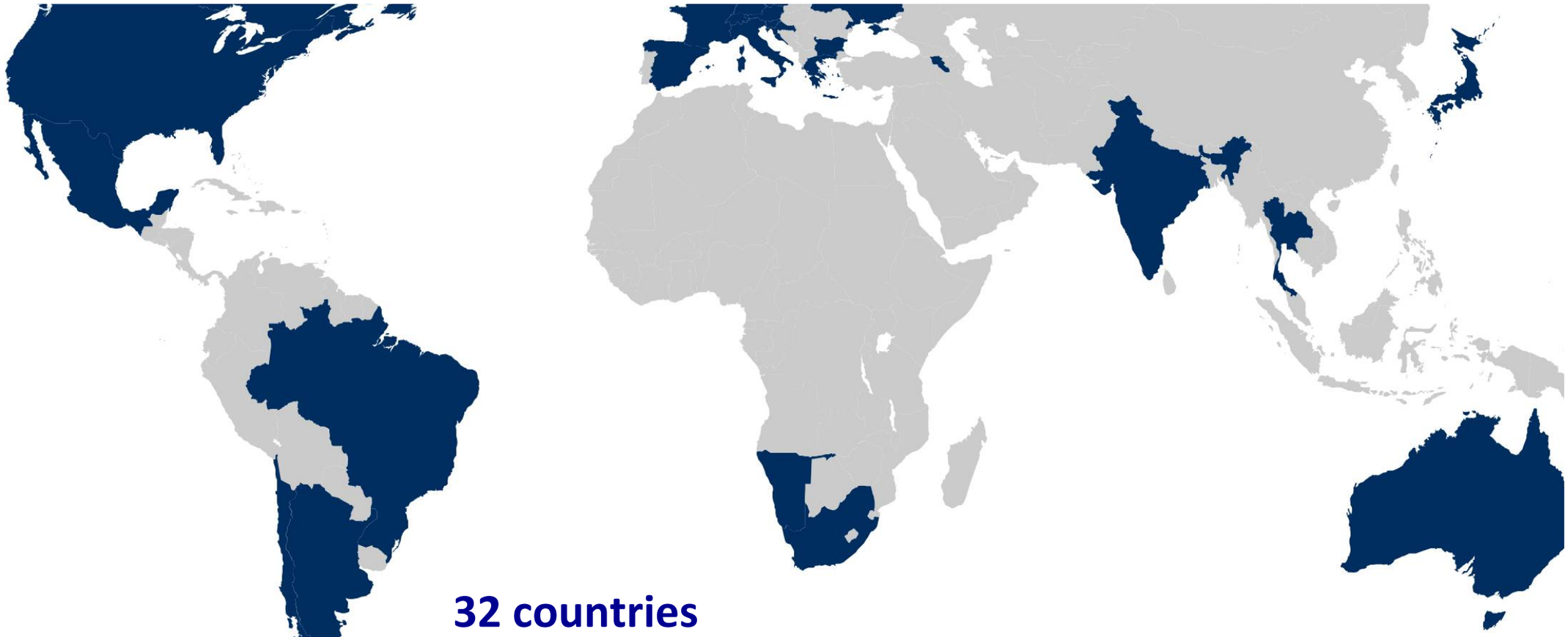
- sensitive to models with significant ***Sommerfeld enhancement*** *(TeV dark matter)* α/v [e.g. Hisano+, 2008; Abazajian+ 2012; Bringmann+, 2014; Garcia-Cely+, 2016; …]

Current plan: focus on the most promising dSph target



CTA

one of the biggest projects in high energy astrophysics



32 countries
88 parties
202 institutes
1308 members (438 FTE)

June 14, 2016:

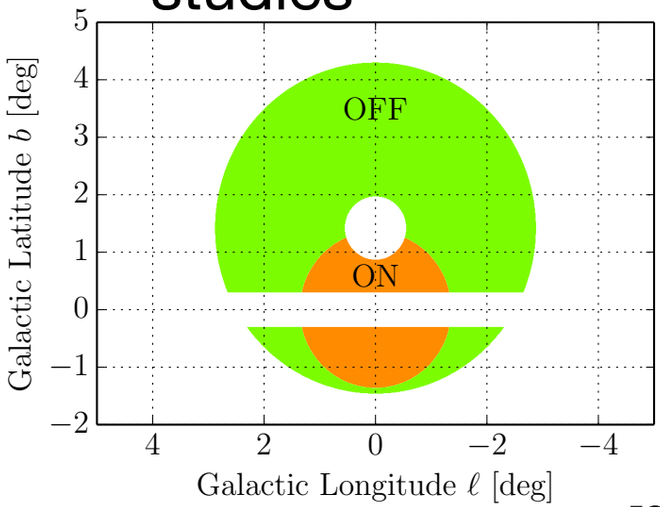
CTA Headquarters: Bologna
Science Data Management Centre: Zeuthen

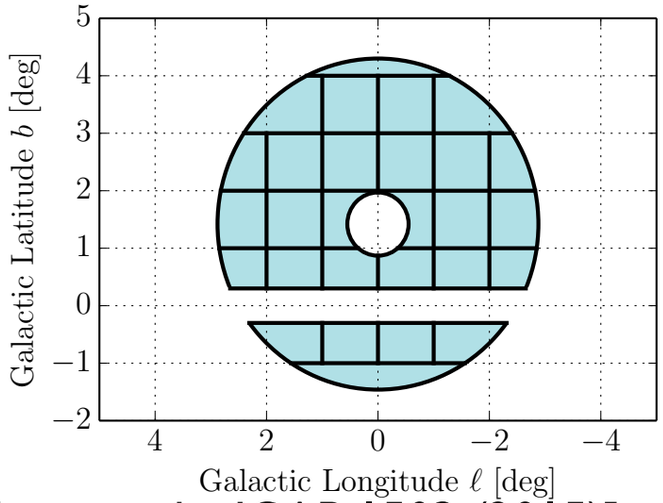
Credits: W. Hofmann and The CTA Consortium

CTA @ the Galactic centre

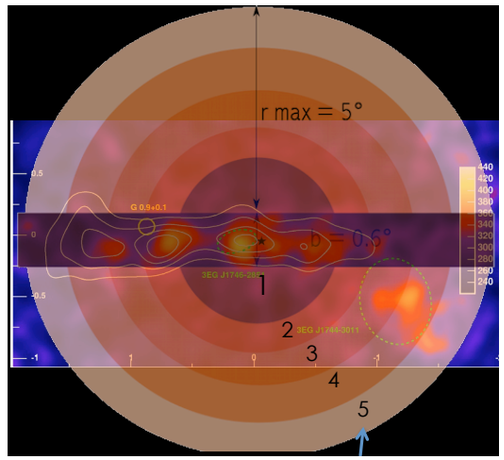
Exploration of the most promising techniques and strategies ongoing:

- CR backgrounds: traditional ‘ring background’ method vs 2D likelihood morphology studies





[Silverwood+, JCAP 1503 (2015)]

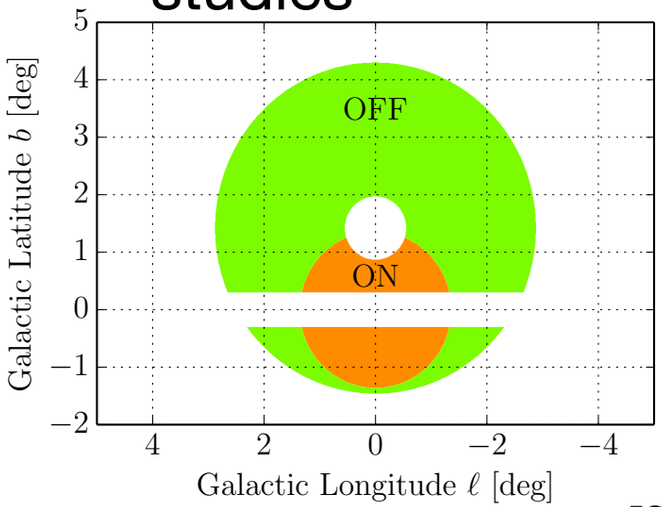


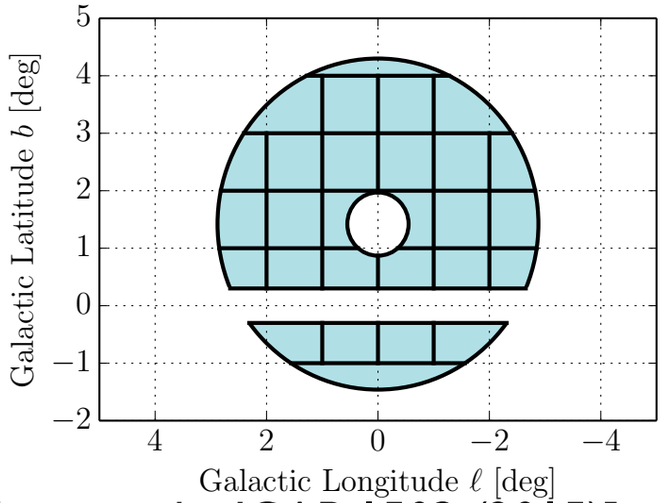
[Lefranc+, Phys.Rev. D91 (2015)]

CTA @ the Galactic centre

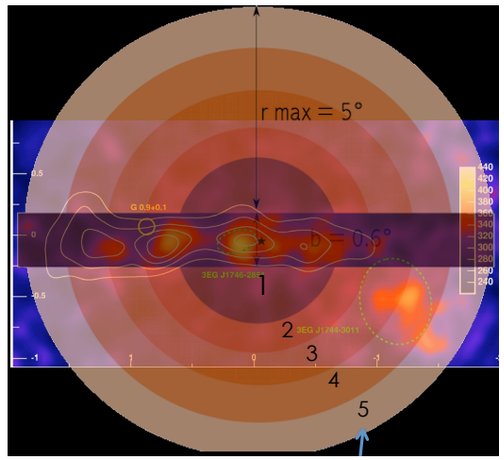
Exploration of the most promising techniques and strategies ongoing:

- CR backgrounds: traditional ‘ring background’ method vs 2D likelihood morphology studies



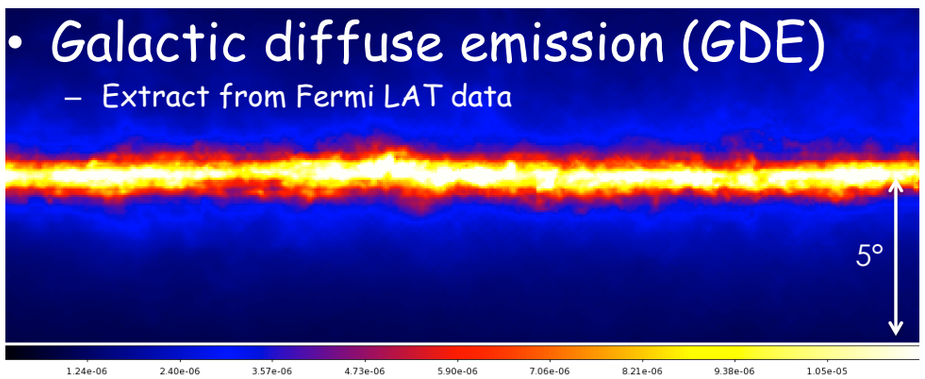


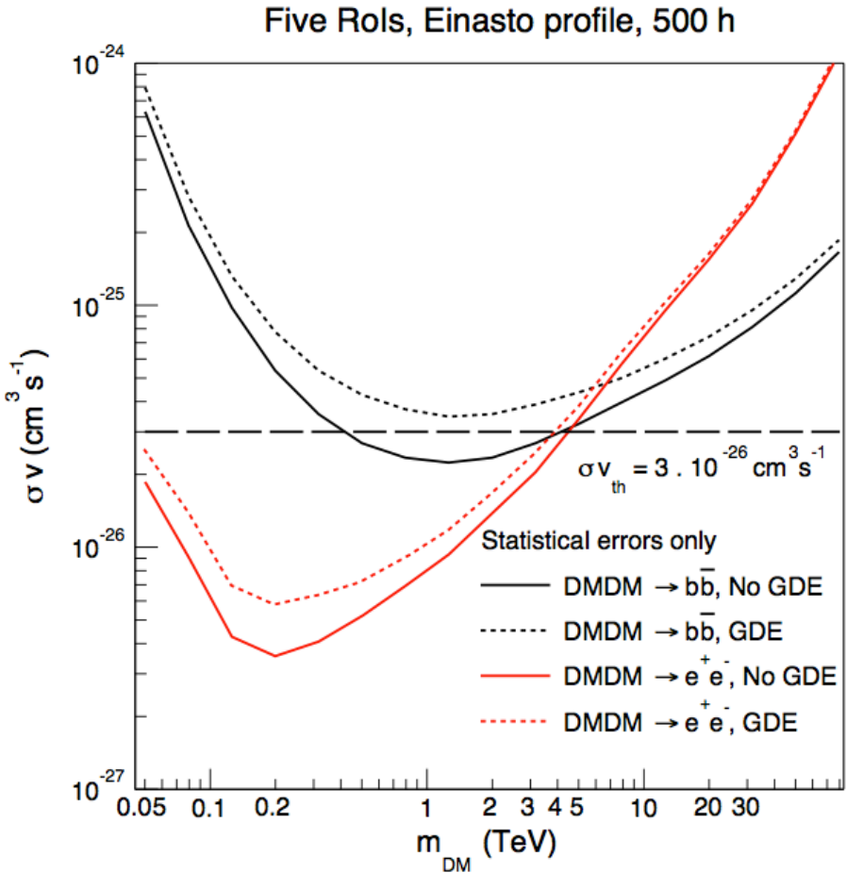
[Silverwood+, JCAP 1503 (2015)]



[Lefranc+, Phys.Rev. D91 (2015)]

- impact of Galactic diffuse emission





[Lefranc+, Phys.Rev. D91 (2015)]

CTA @ spectral lines

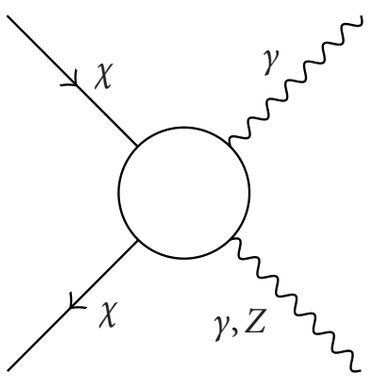
CTA excellent energy resolution — high sensitivity to spectral line search!

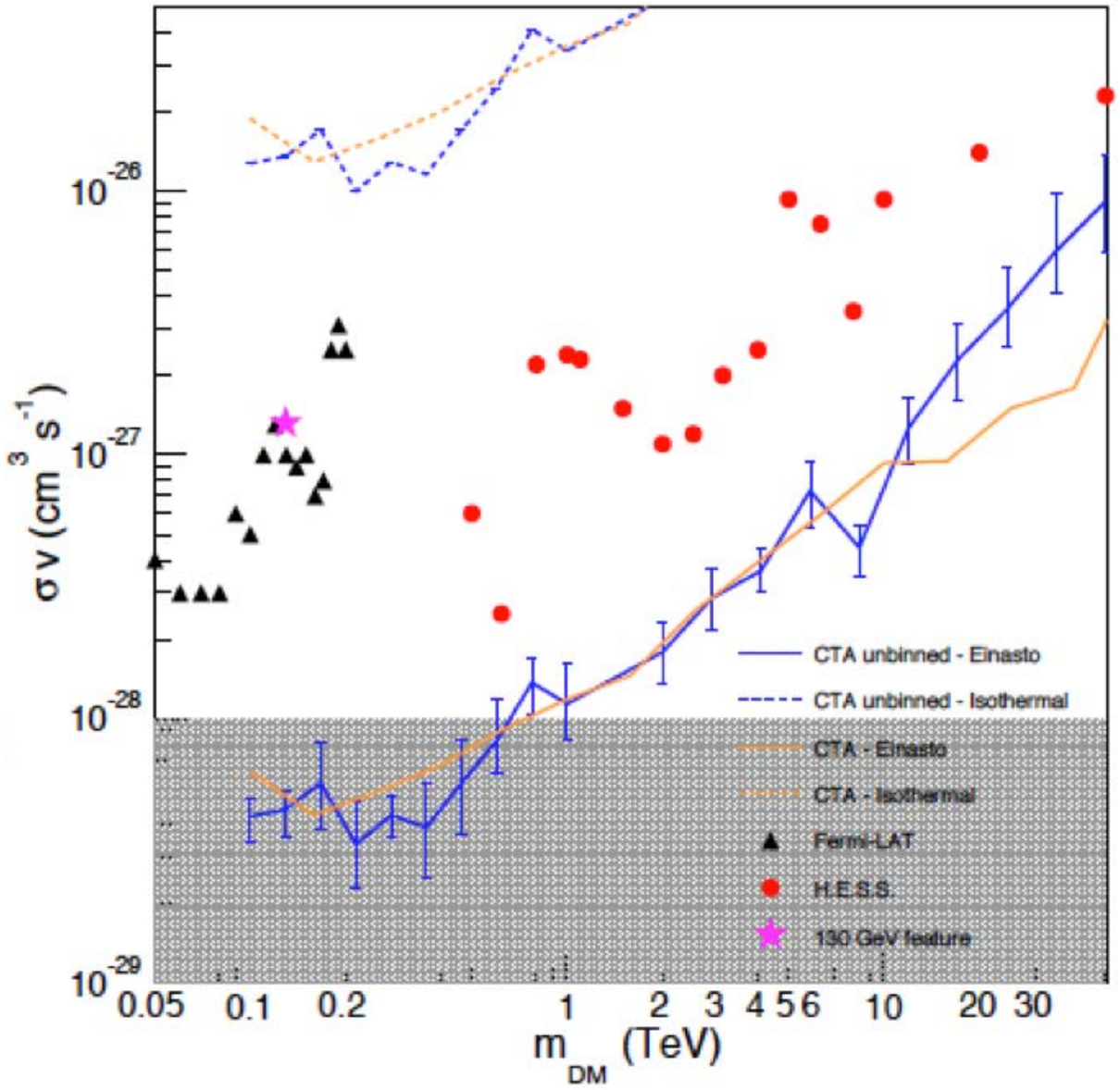
- data within a circle of 1 deg radius around the center

- standard astrophysical emission taken into account as background

- sensitivity improvement by a factor of ~10 expected

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



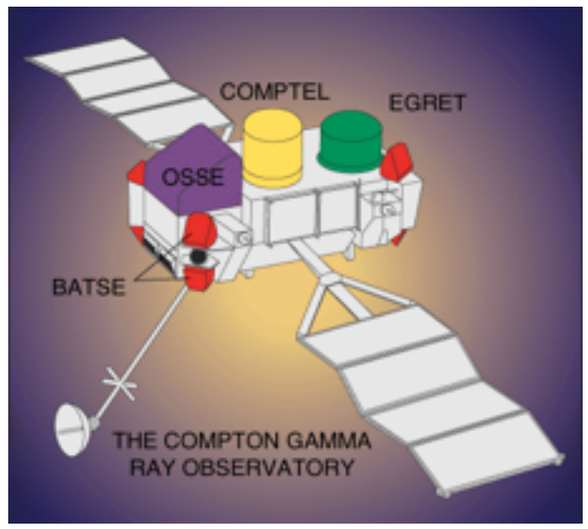


CTA Collaboration, in preparation

Gamma rays

atmosphere is not transparent to gamma rays → ***satellites***

EGRET ***1991-2001***



Fermi LAT ***2008-***

(AGILE ***2007-)***

→ ***or ground based:***

i) Imaging Atmospheric Cherenkov Telescopes

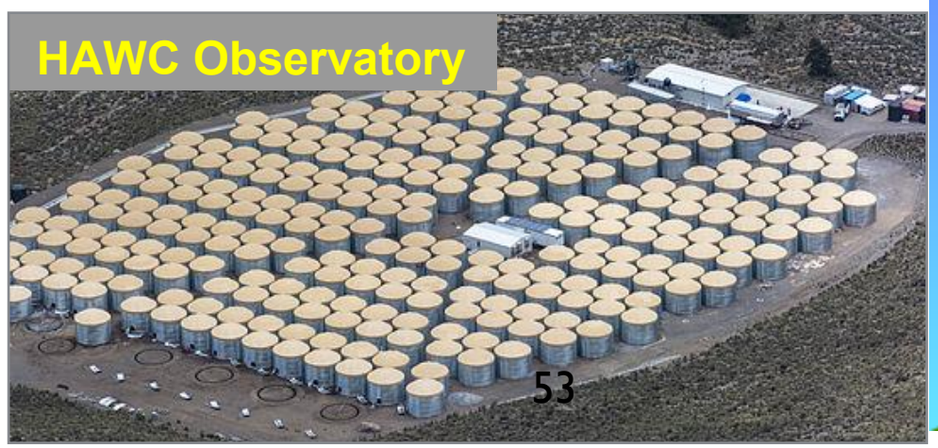
WHIPPLE 10m (1968-2013) - the beginning of gamma ray astronomy

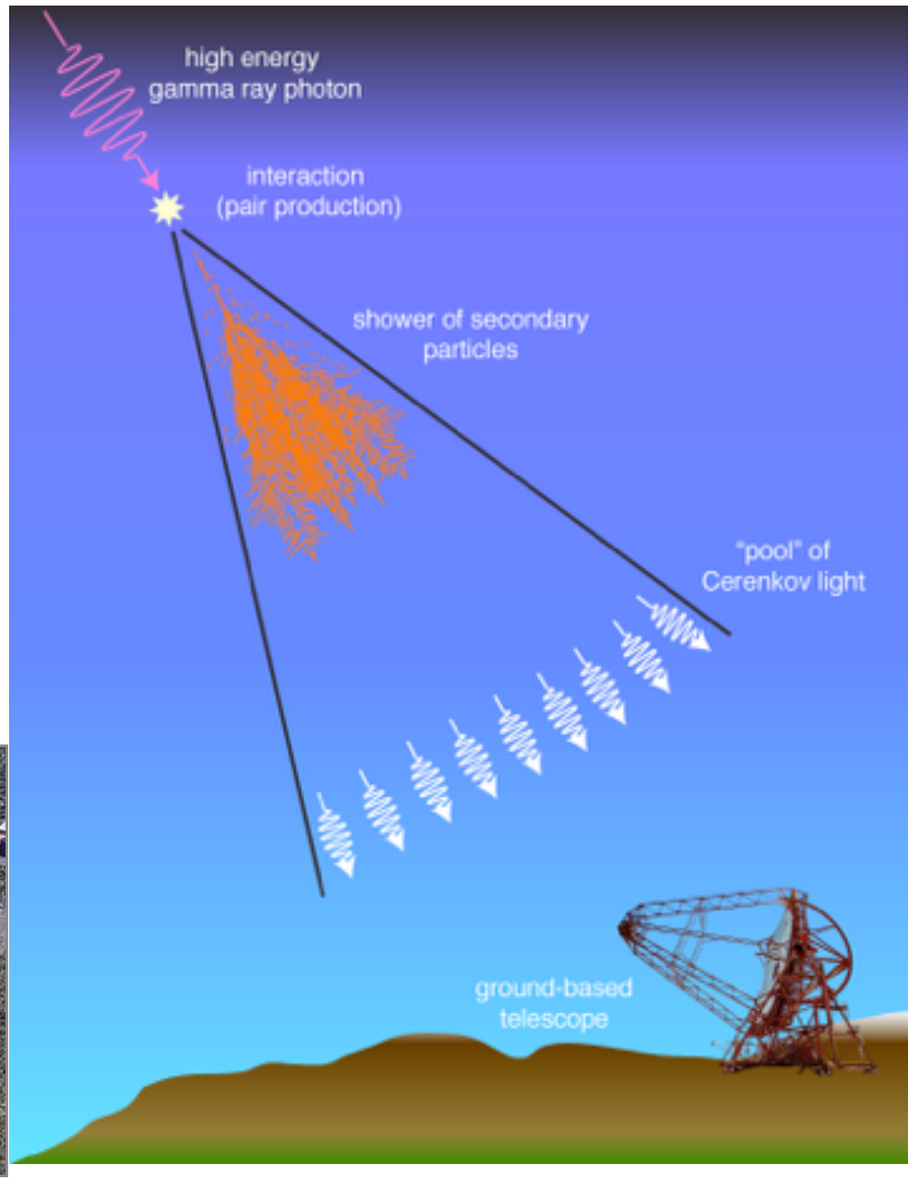
H.E.S.S. (2002 -), ***MAGIC*** (2004 -), ***VERITAS*** (2007 -)

ii) Air shower arrays ('with buckets of water')

MILAGRO (2001-2008)

HAWC (2010 -)

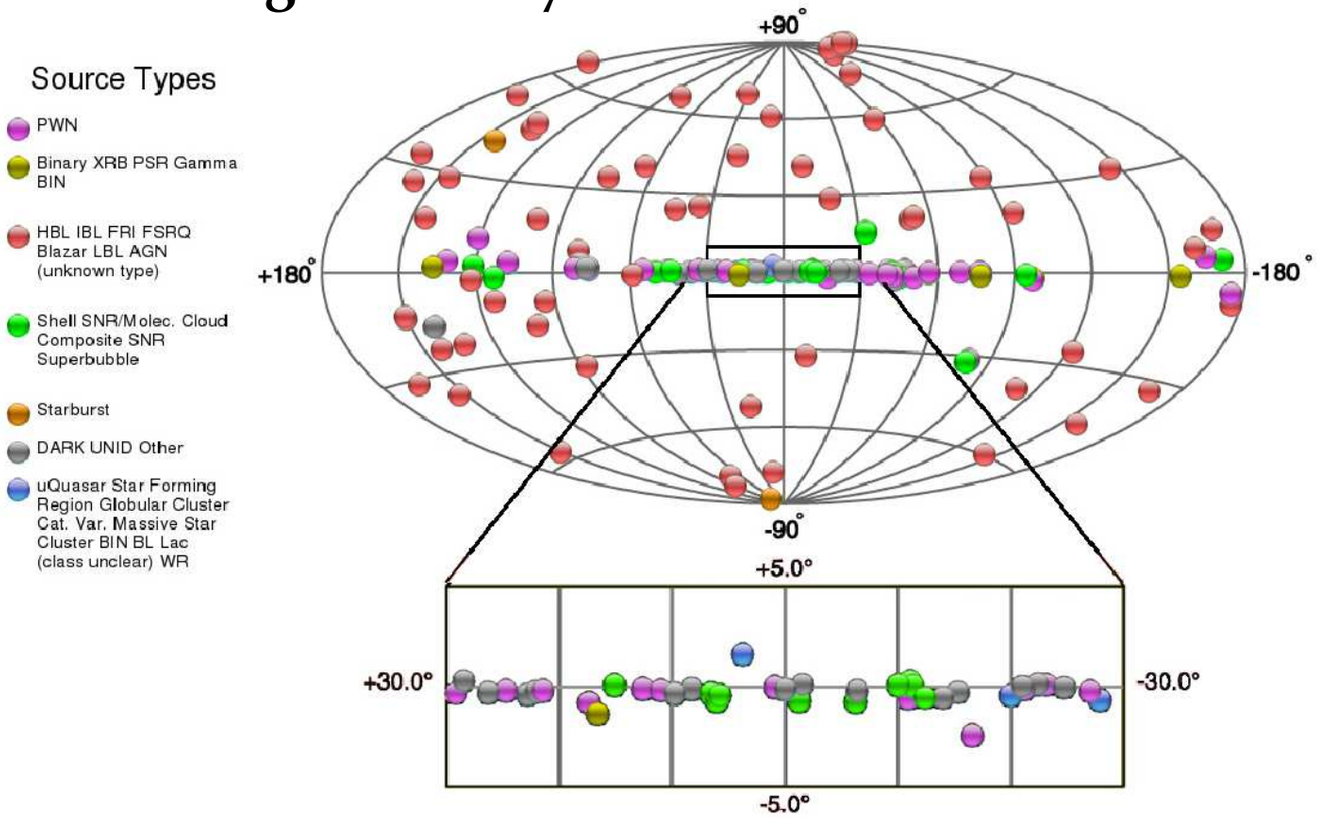




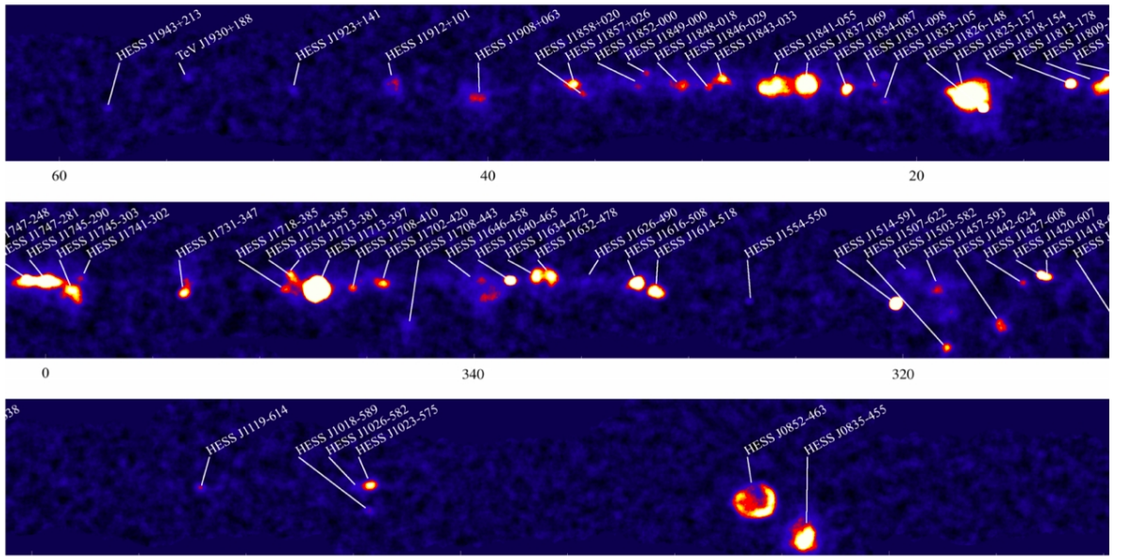
The TeV sky

IACTs are pointing telescopes!

170 VHE gamma-ray sources

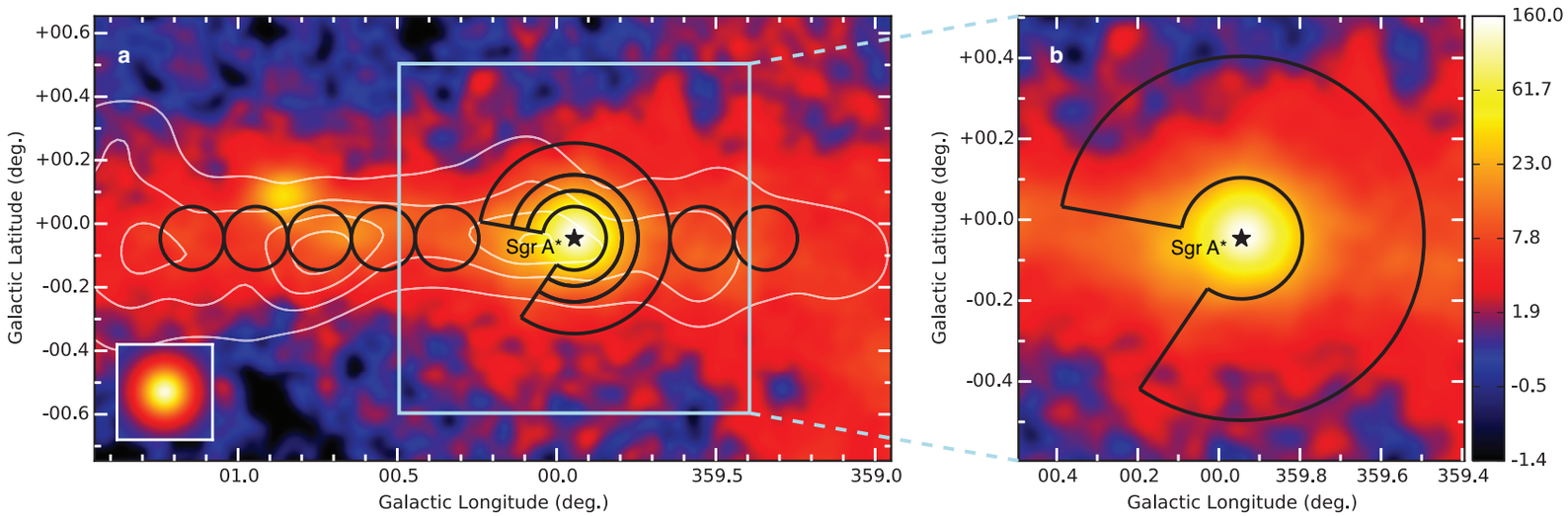


2nd Galactic plane survey, H.E.S.S.



H.E.S.S. Collaboration, 2016

Extended emission from the Galactic centre ridge



H.E.S.S. Collaboration, Nature, 2016