Recent Experimental Results in Indirect Searches for Dark Matter

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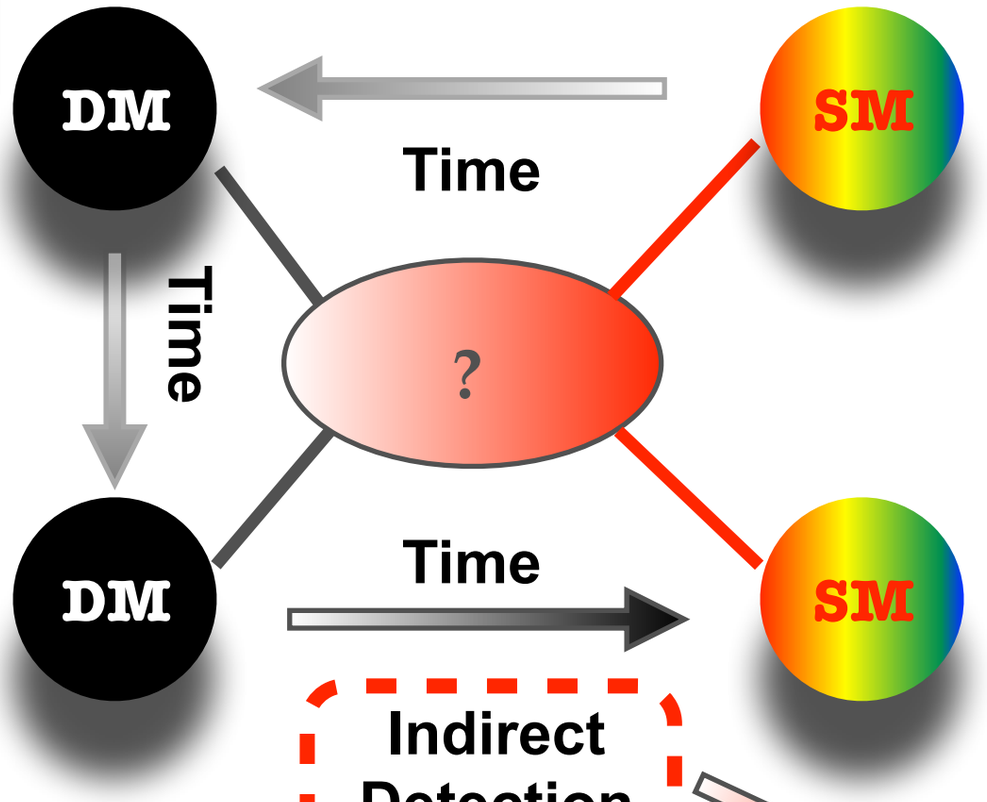
100TeV Collider Workshop
December 5, 2015

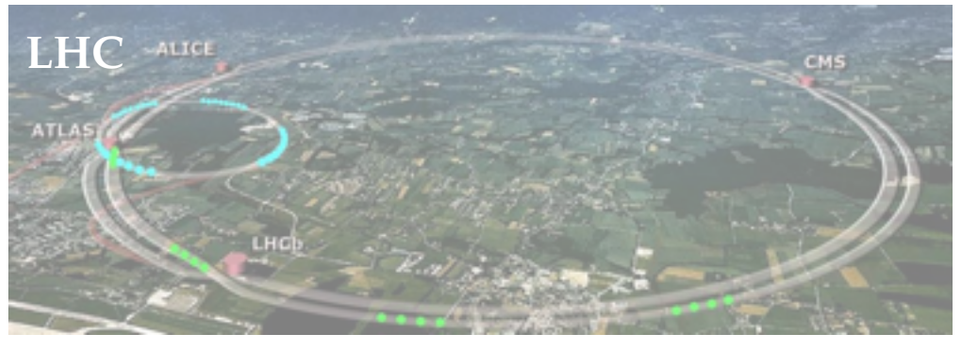
Fermilab | Center for Particle Astrophysics

Indirect Detection
(mostly WIMP searches)

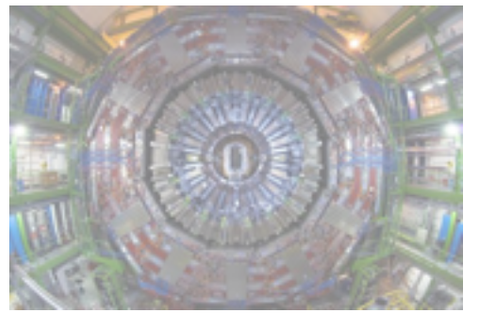
Hunting for WIMPs

Mass set by the weak scale: GeV to TeV

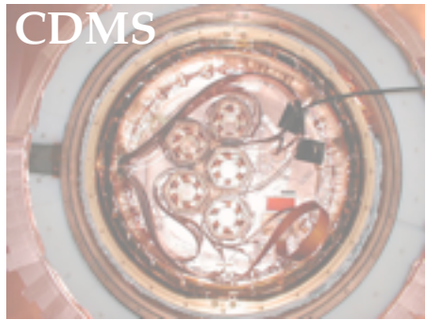




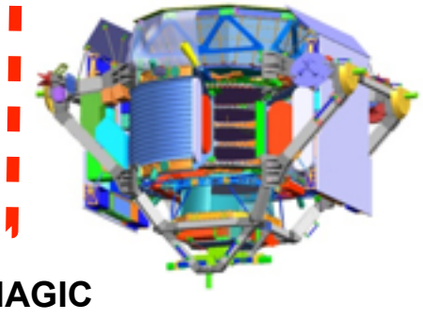
ATLAS



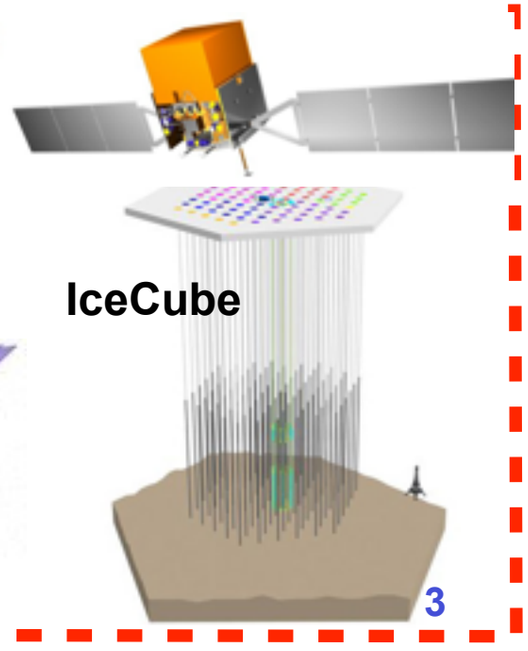
CMS



AMS-02



Fermi-LAT



VERITAS/HESS/MAGIC

PAMELA

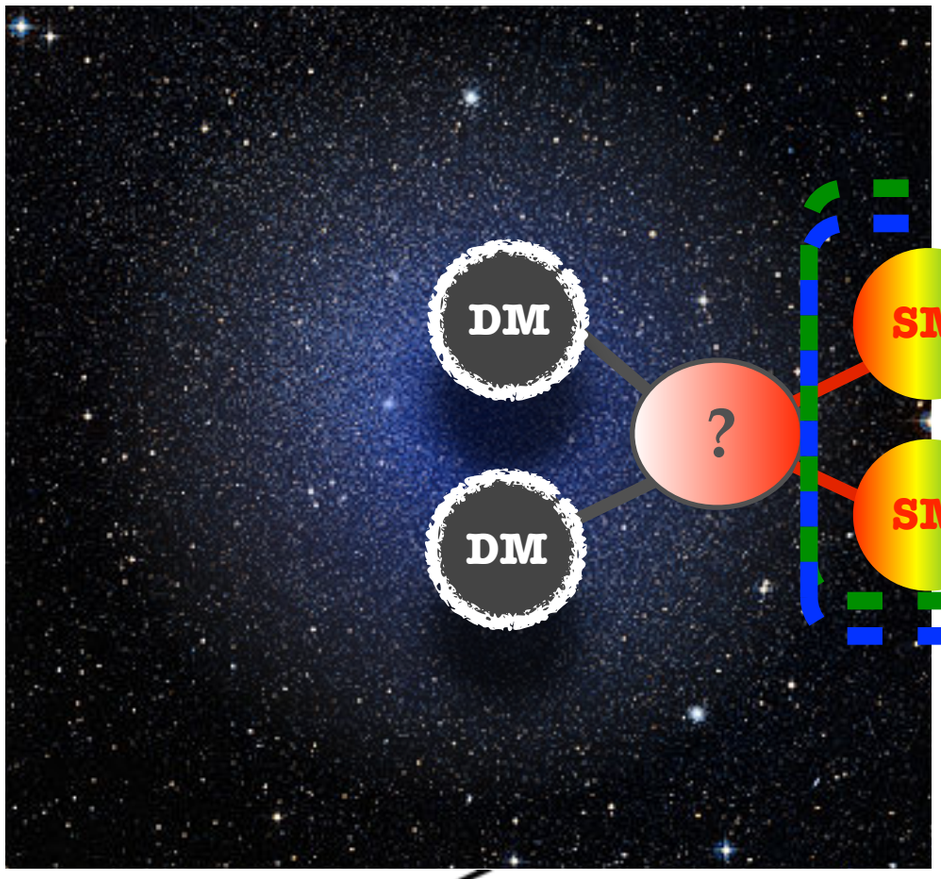
IceCube

Dark Matter Annihilation or Decay

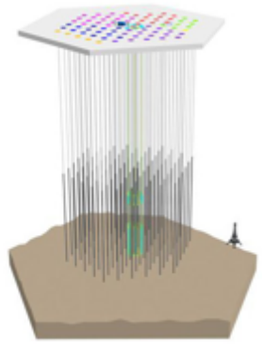
Particle Detection

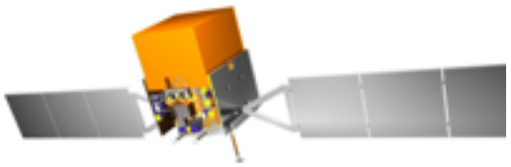
Dark Matter Distribution

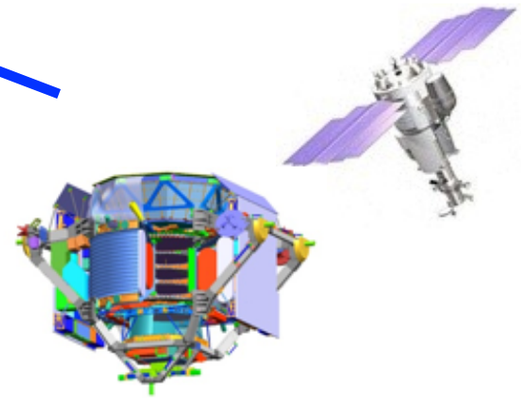
Particle Propagation



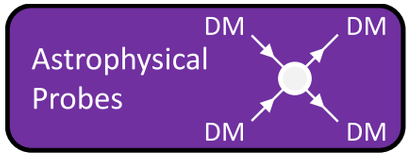
Neutral Particles
(γ, ν)



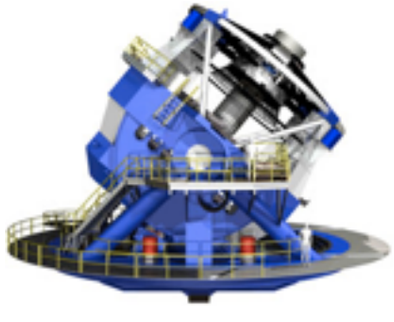


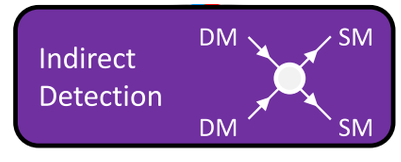


Charged Particles
($e^{\pm}$, $p^{\pm}$, *etc.*)



Photons
(optical, infrared, etc.)



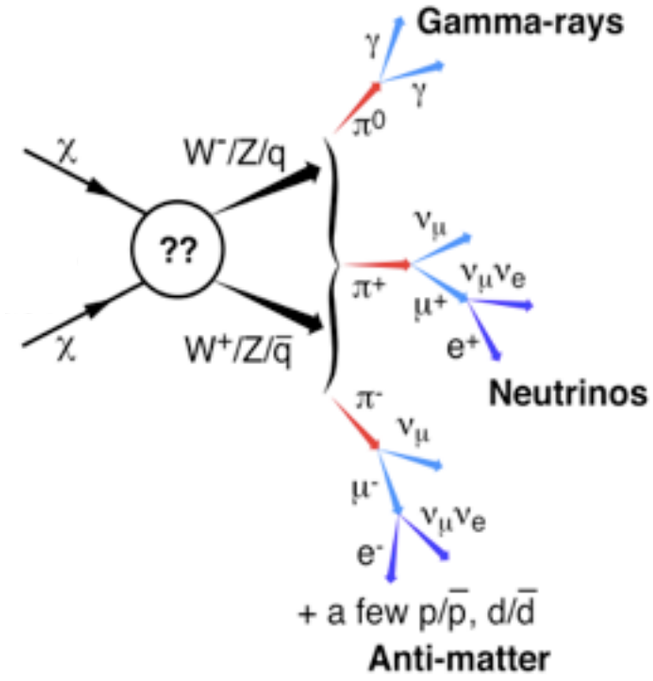


Indirect Detection

Particle Flux
(signal in data)

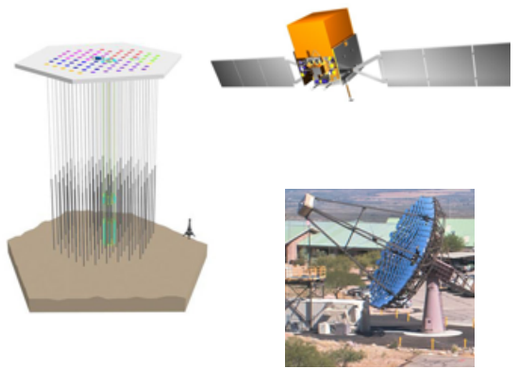
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f}{dE}B_f$$

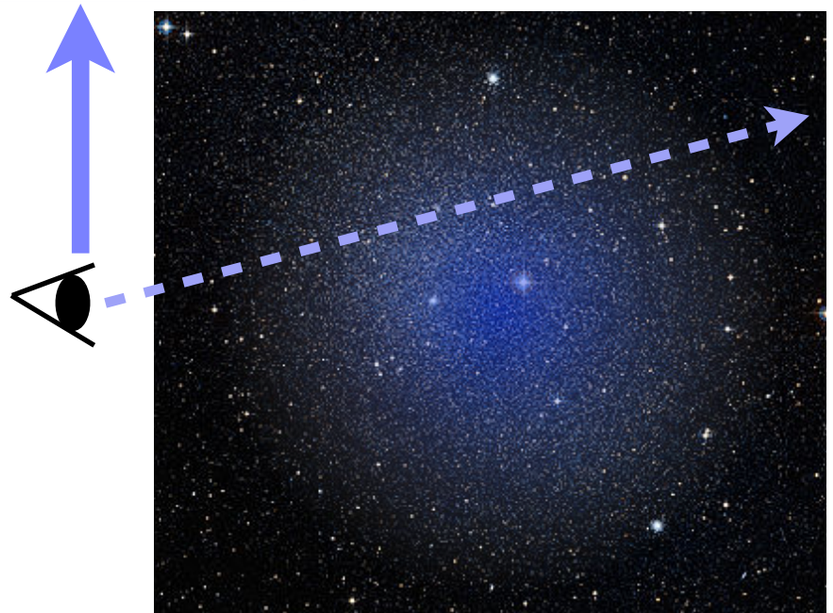
Particle Physics
(particles per annihilation)



$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

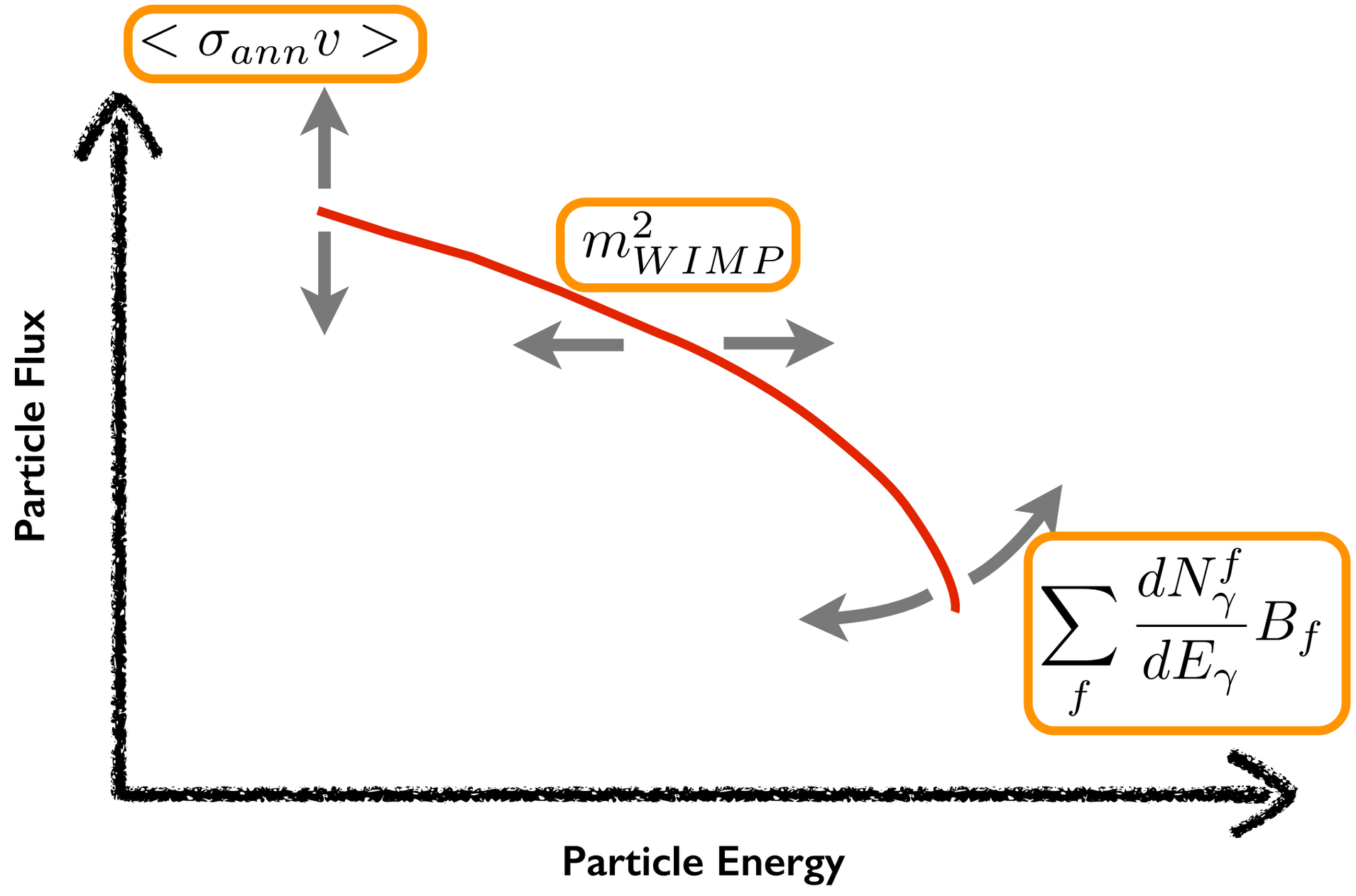
Dark Matter Distribution
(line-of-sight integral)





Particle Spectrum

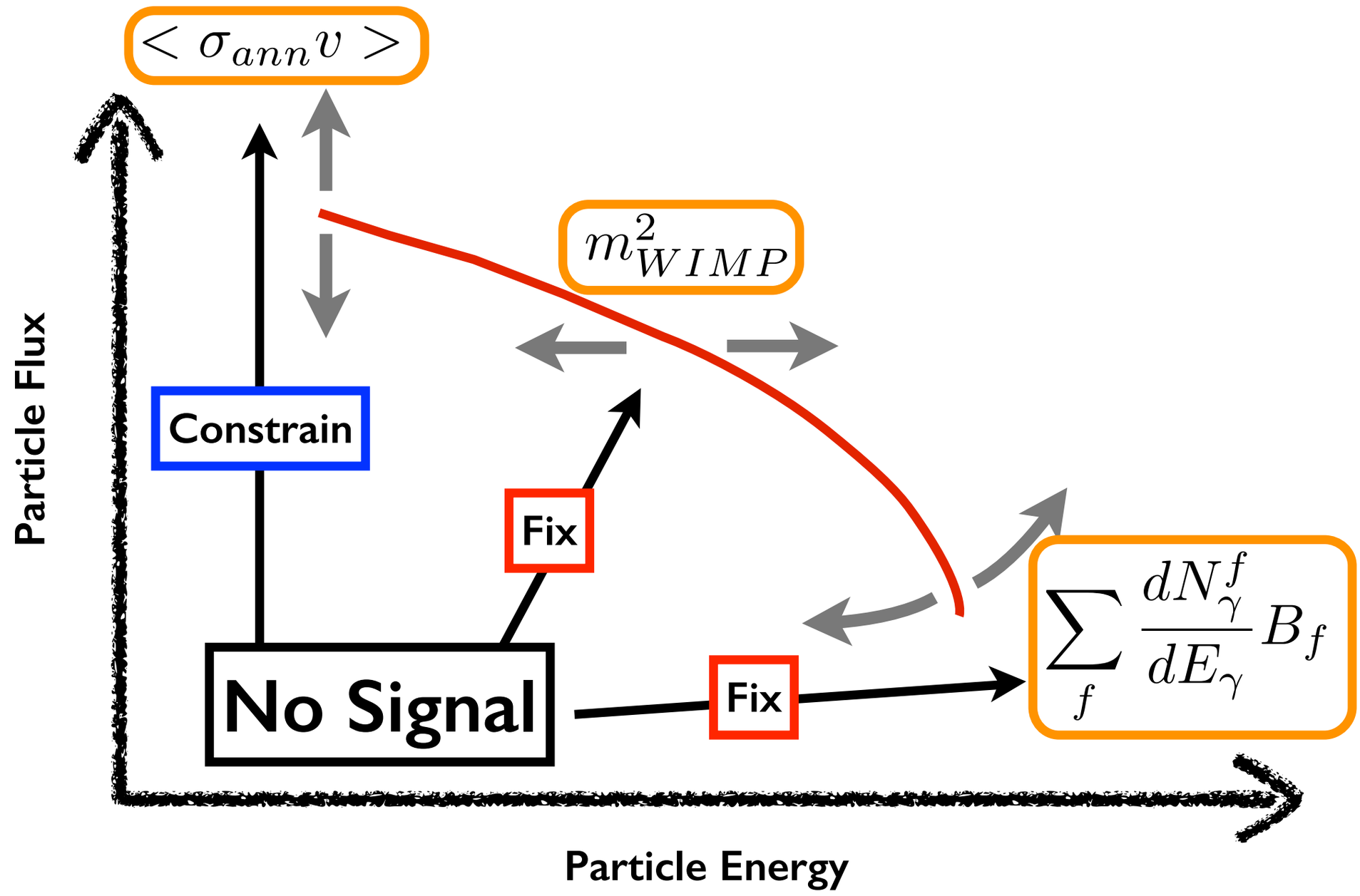
$$\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f}{dE}B_f$$



Particle Spectrum

$$\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f}{dE}B_f$$

$$\langle\sigma v\rangle \sim 3\times10^{-26}\mathrm{cm}^3\,\mathrm{s}^{-1}$$



Particle Spectrum

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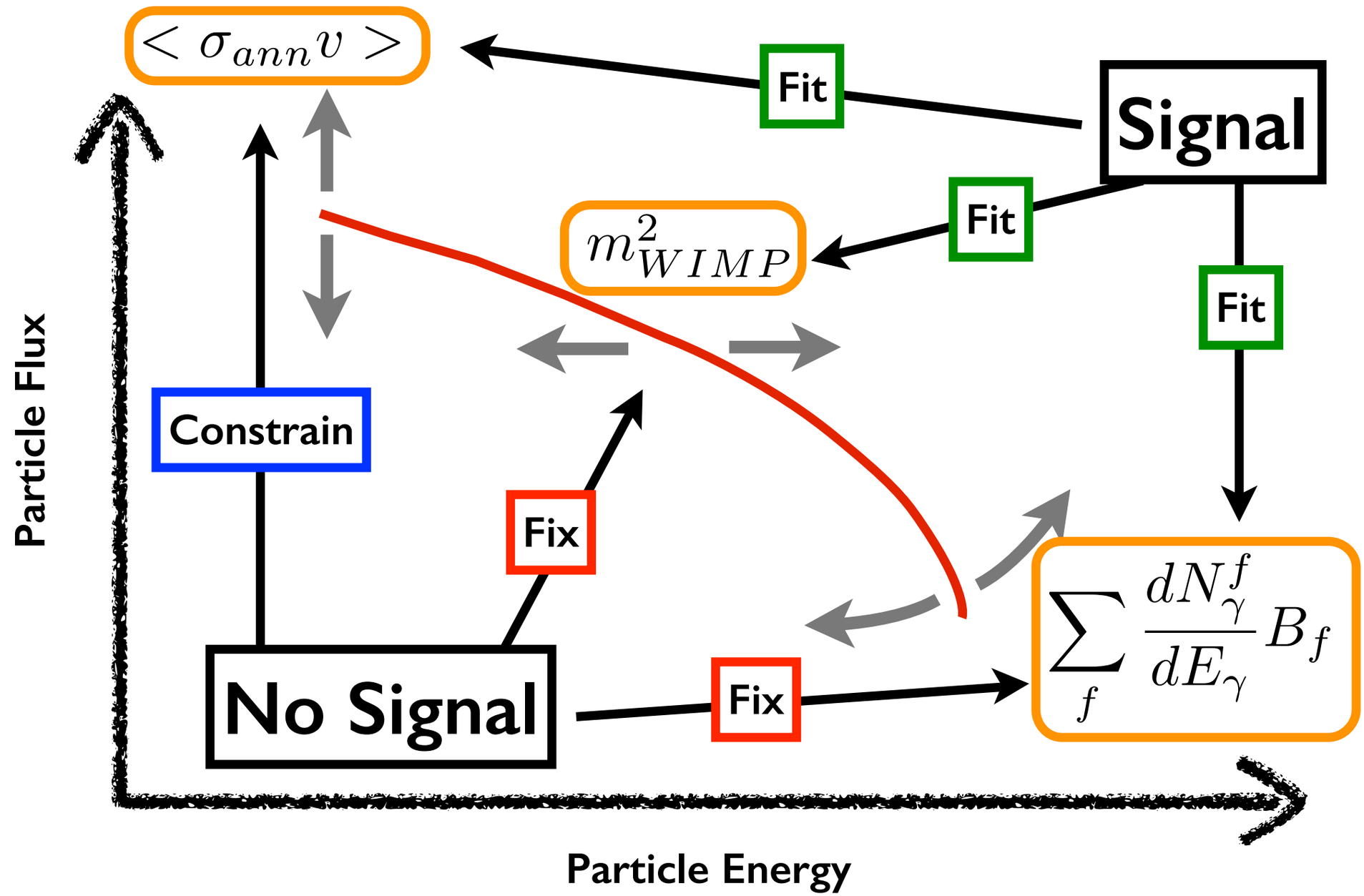
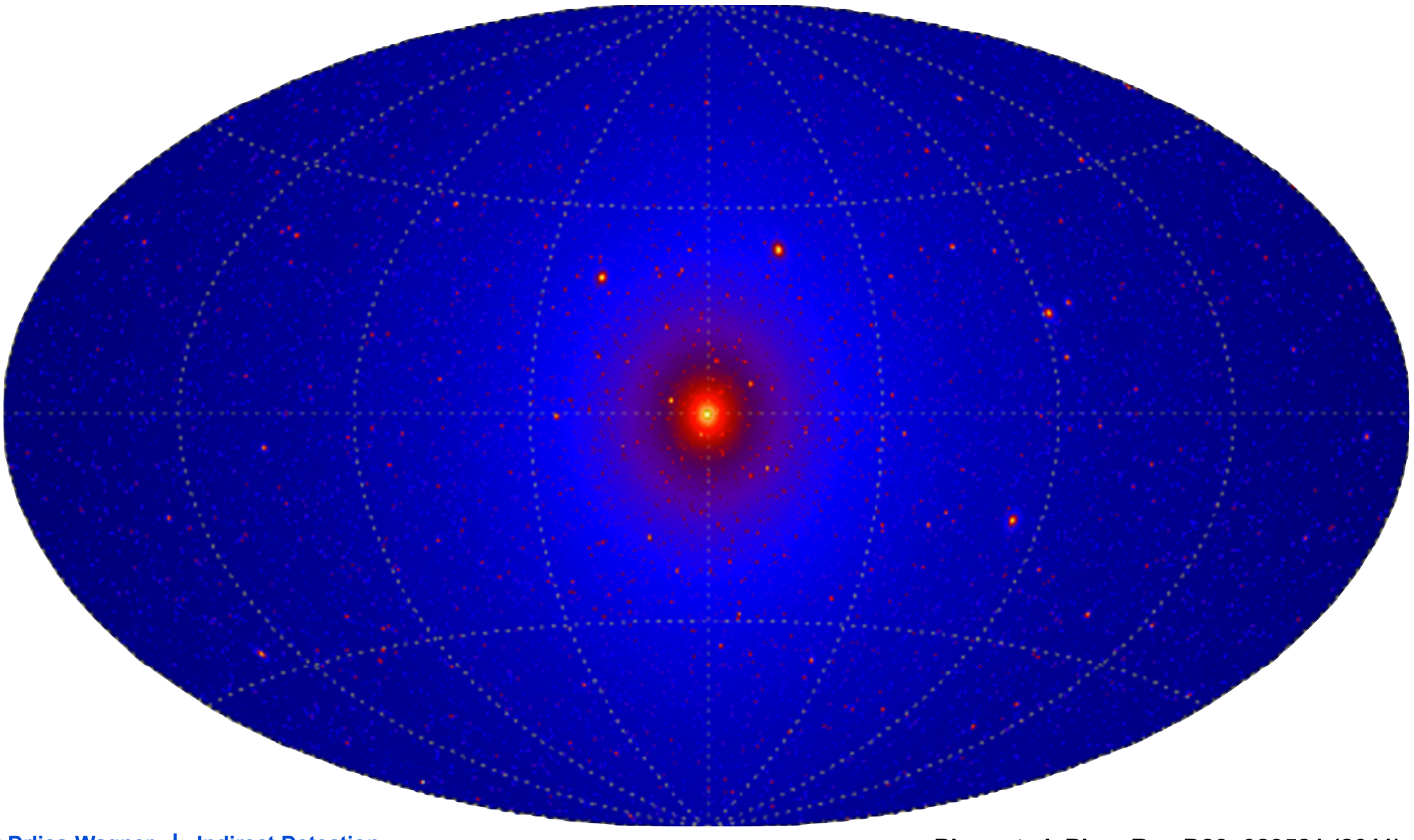


Dark Matter Distribution

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



Piere et al. Phys Rev D83, 023581 (2011)

Dark Matter Distribution

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Extragalactic background:
- Large statistics
- Large astrophysical contribution

Electrons and Positrons

Dwarf Galaxies:
- Known location and dark matter content
- Low statistics

Low-Mass Satellites:
- Gamma-ray source
- Unknown origin

Galaxy clusters:
- Possibly large statistics
- Astrophysical signal expected

Milky Way halo:
- Large statistics
- Diffuse background

Spectral lines:
- "Clean" from astrophysics
- Low statistics

Galactic Center:
- Large statistics
- Large background

The Sun

Piere et al. Phys Rev D83, 023581 (2011)

Dark Matter Distribution

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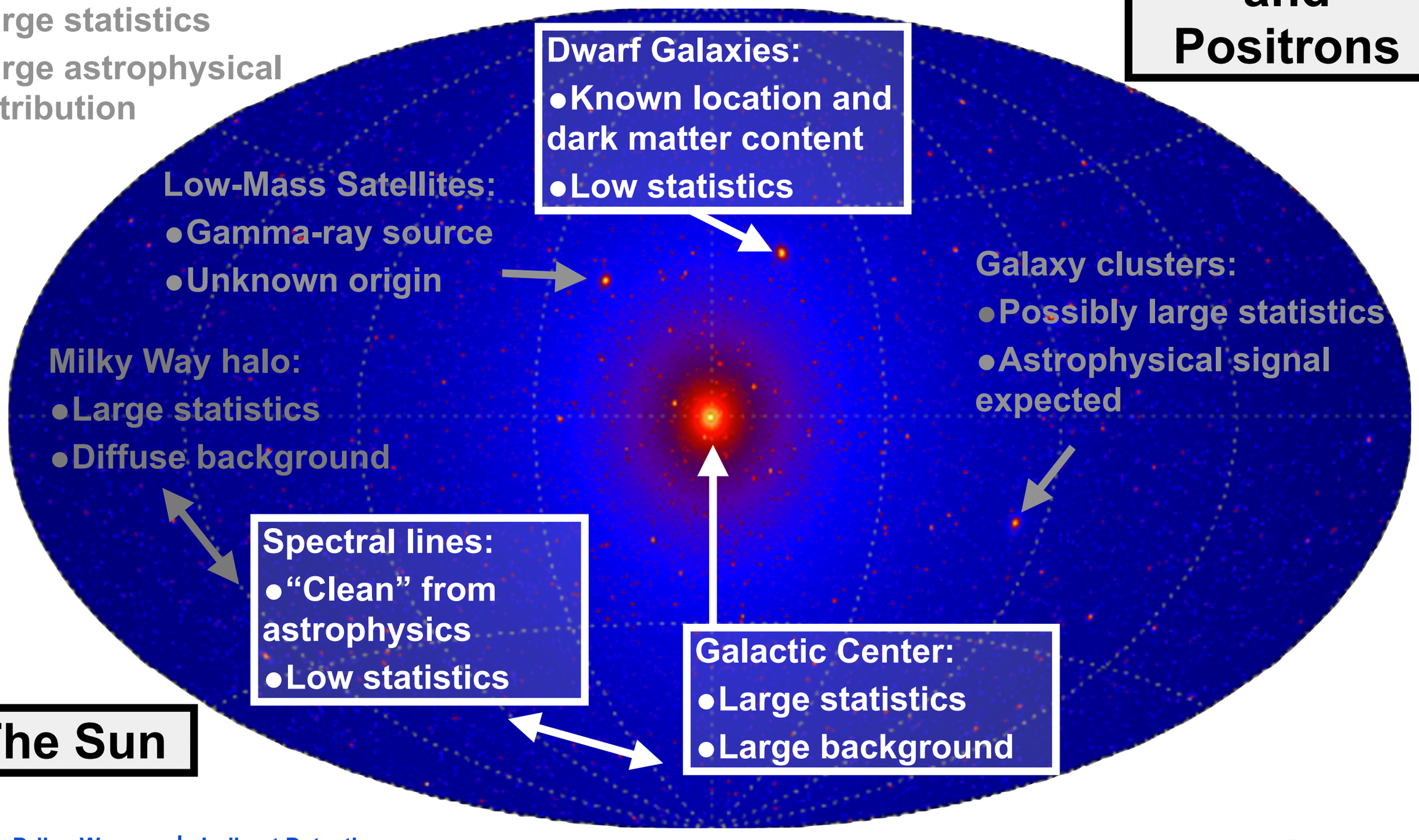
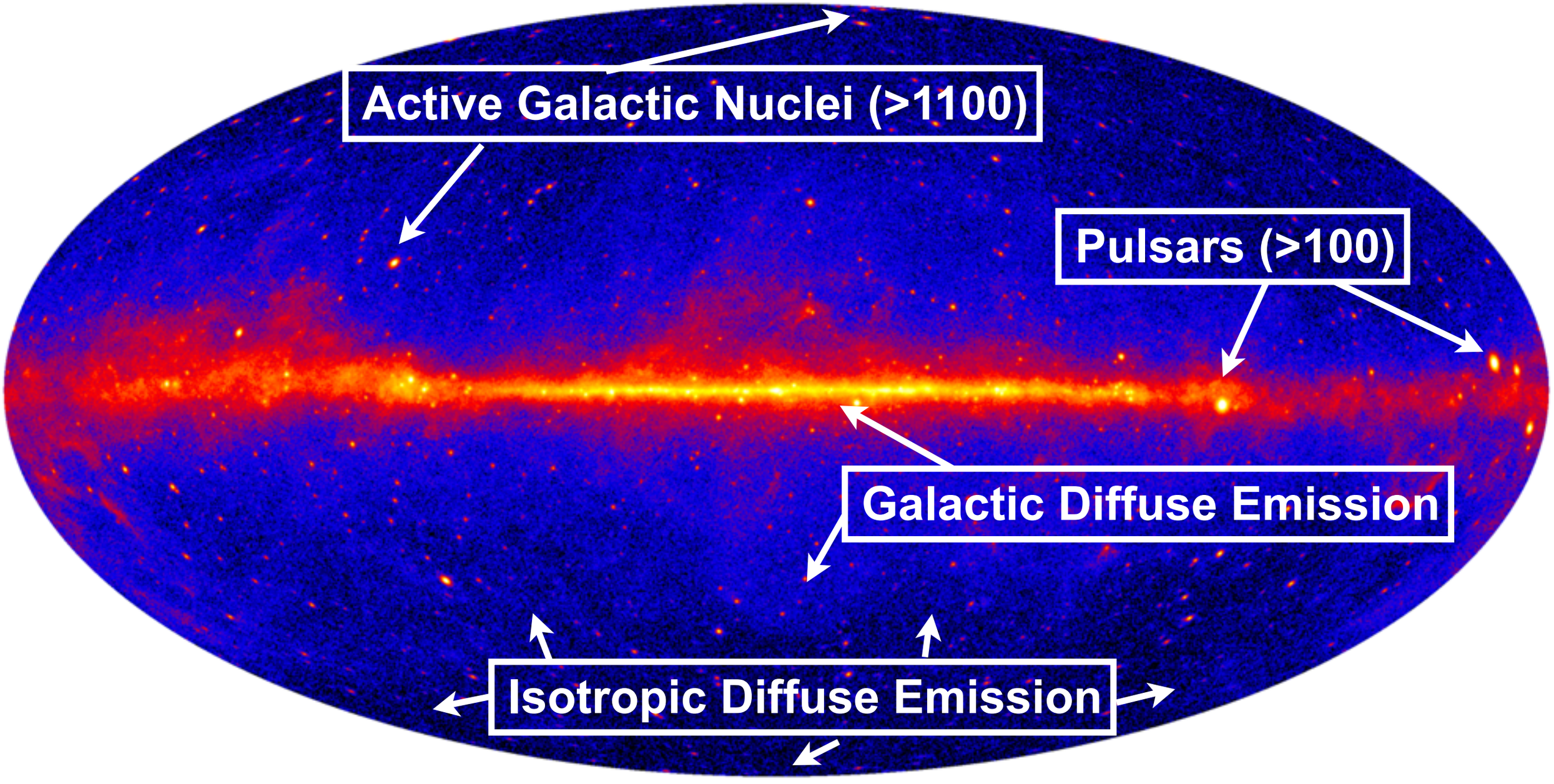


Piere et al. Phys Rev D83, 023581 (2011)

Fermi-LAT 4-Year Gamma-Ray Sky Map (E>1GeV)



+ Pulsar Wind Nebulae + Supernova Remnants + Globular Clusters + Starburst Galaxies + Unassociated Sources + ...

Experimental Results

Experimental Results

- Gamma Rays
  - Spectral Lines
  - Galactic Center
  - Dwarf Galaxies
- Neutrinos
  - Solar Neutrinos
- Charged Particles
  - Positron Fraction
- CMB

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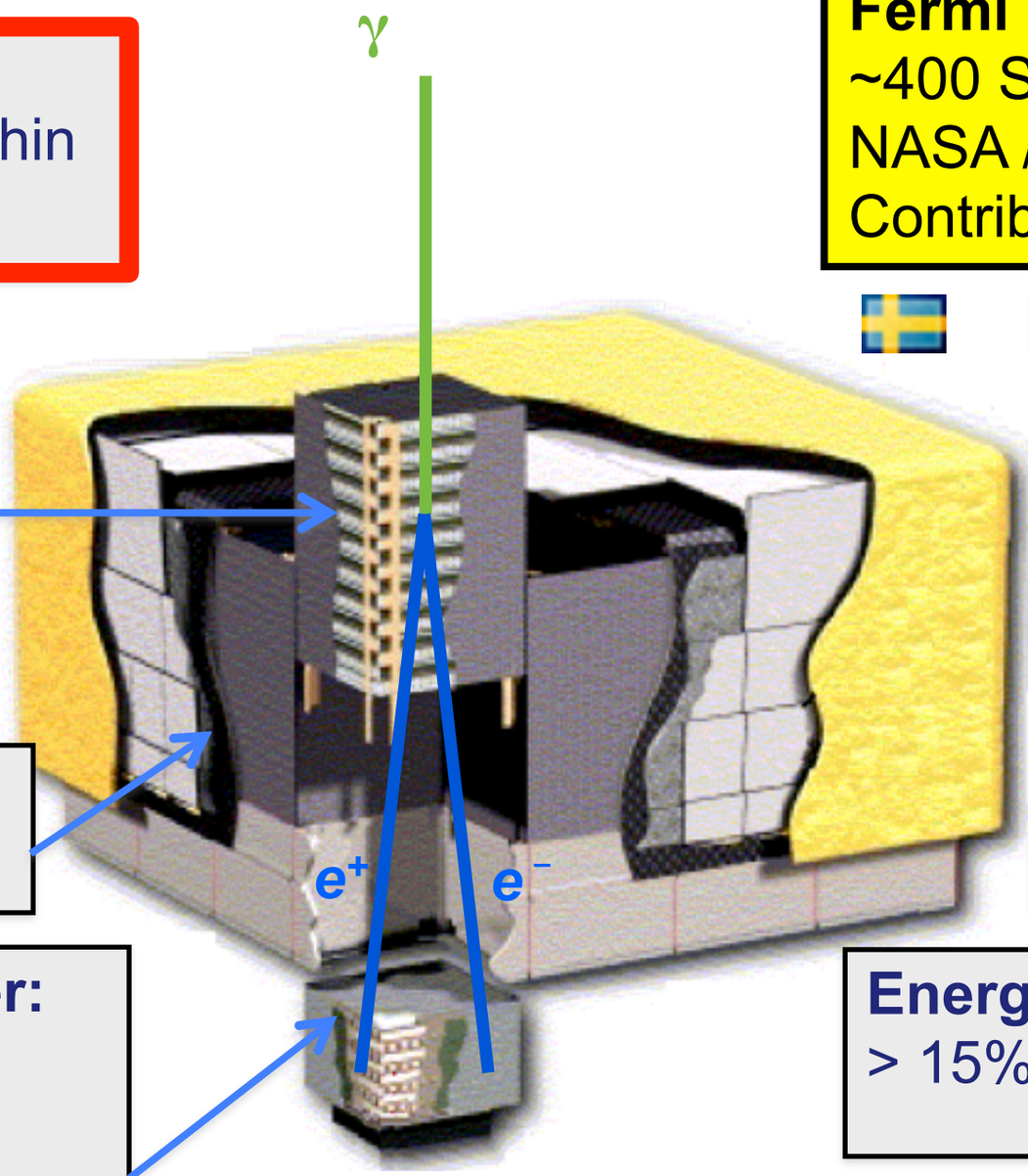
The Fermi Large Area Telescope

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions



Si-Strip Tracker:
convert γ->e^+e^-
reconstruct γ direction
EM vs. hadron separation

Anti-Coincidence Detector:
Charged particle separation

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Field of Veiw:
2.4 sr (whole sky in 3h)

Energy Range:
20 MeV to > 300 GeV

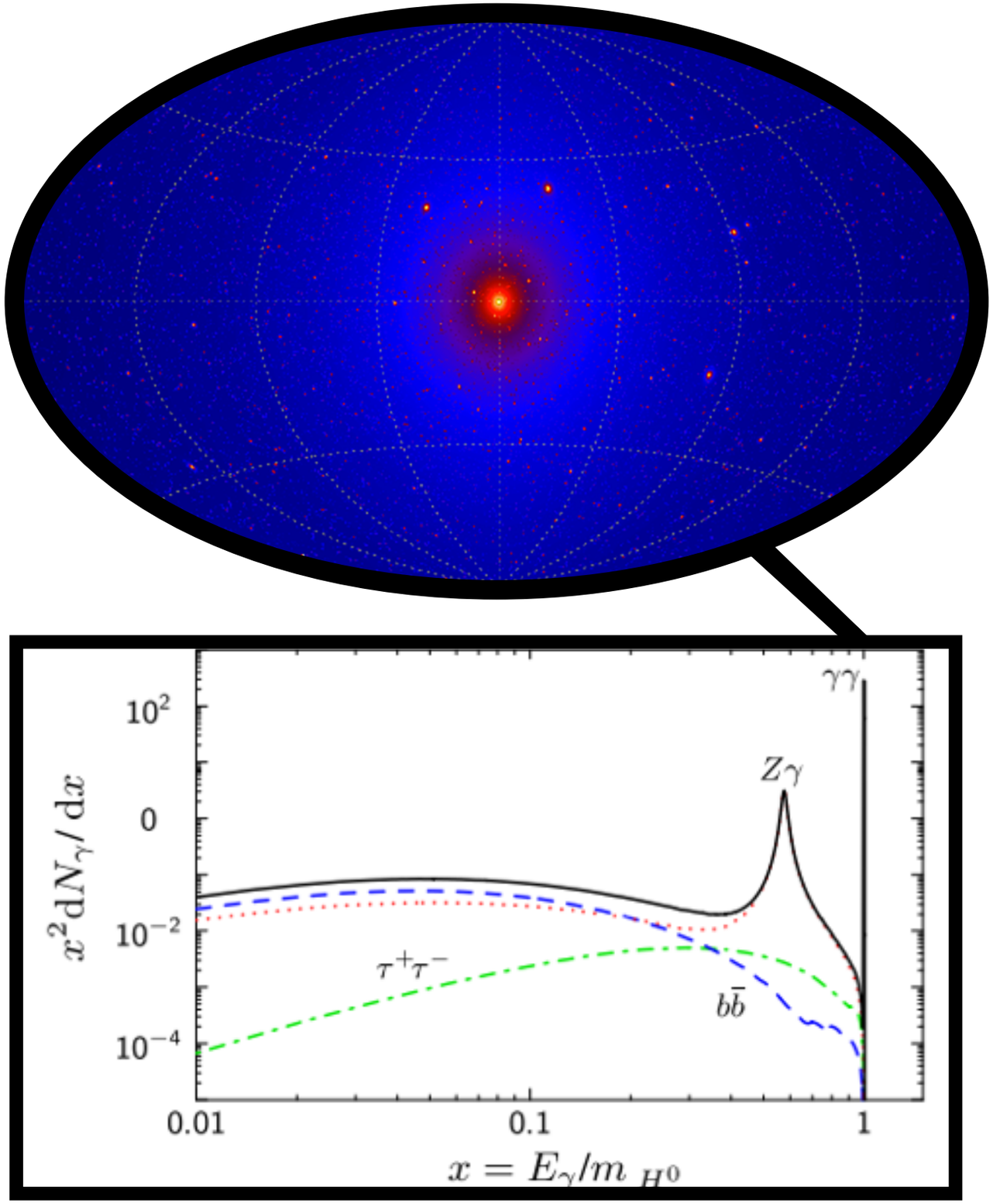
Energy Resolution:
> 15% (100 MeV to 300 GeV)

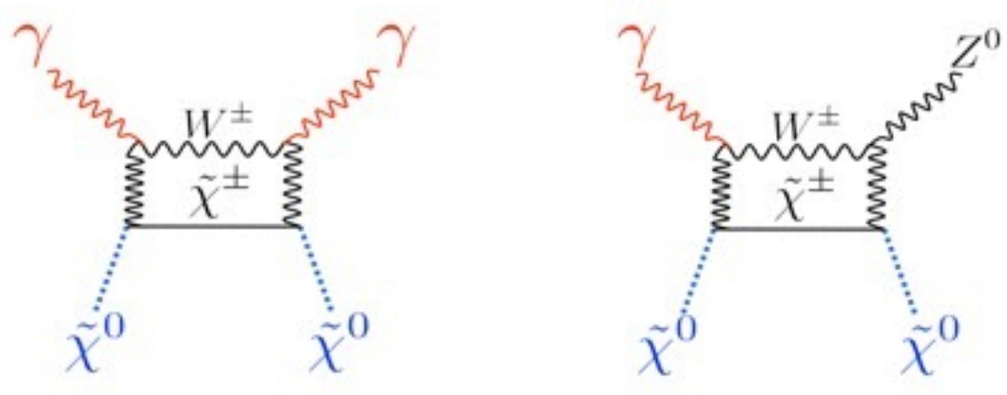
Point Spread Function:
$r_{68} \sim 0.8\ (E/1Gev)^{-0.8}$

Atwood et al., ApJ 697, 1071 (2009)
Ackermann et al. ApJS 203, 4 (2012)

Gamma-Ray Lines

- **Annihilation into $\gamma\gamma$ or γX ($X = Z^0, H^0, \ldots$) will produce a distinct spectral feature**
  - **Clean signal (hard to mimic with astrophysics)**
  - **Low statistics (suppressed by a factor of 10^2 to 10^3 in many models)**





Bergstrom et al. Nucl. Phys. B504, 27 (1997)

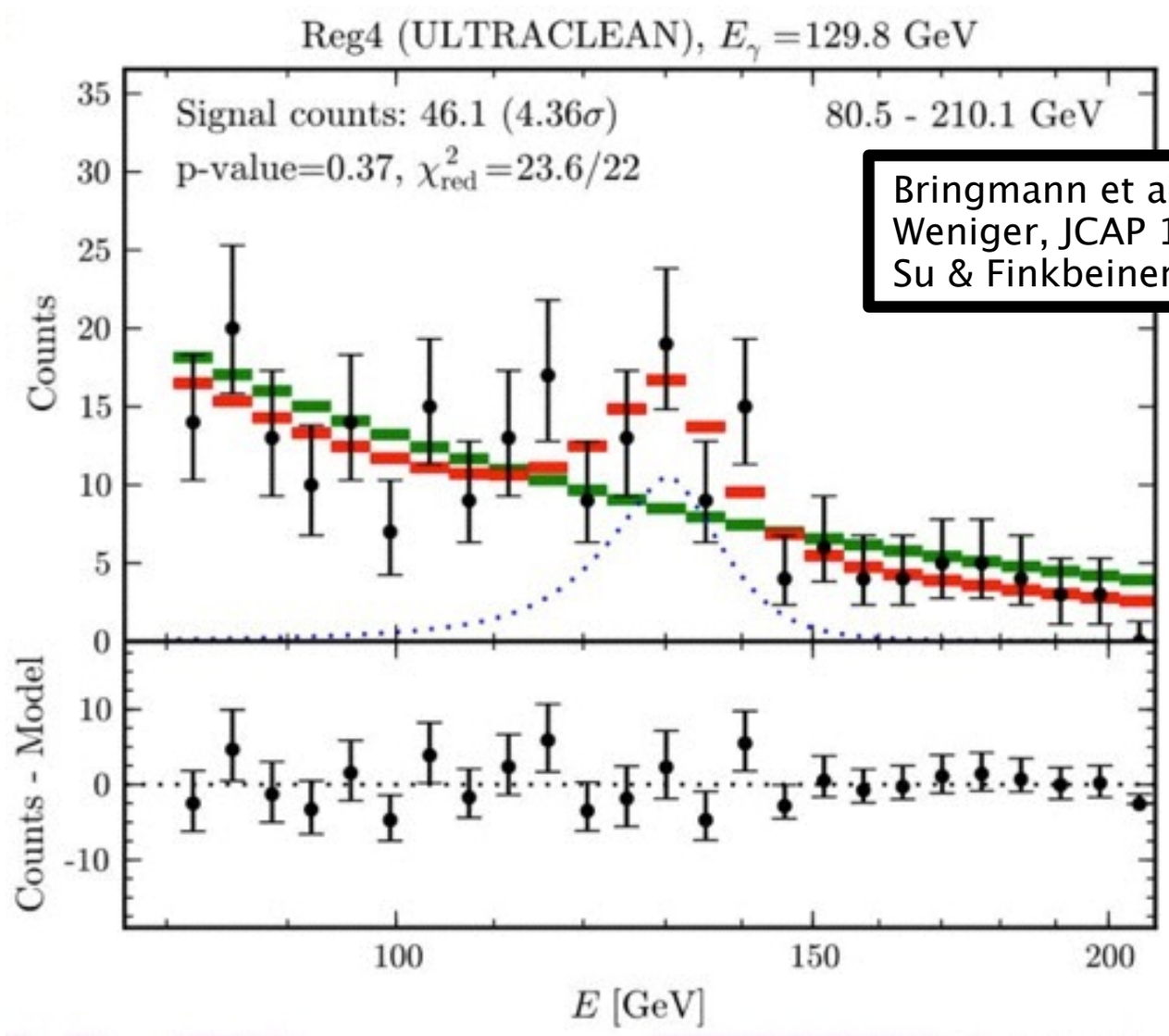
Ferrer et al., Phys. Rev D74, 115007 (2006)

Gustafsson et al. PRL 99, 041301 (2007)

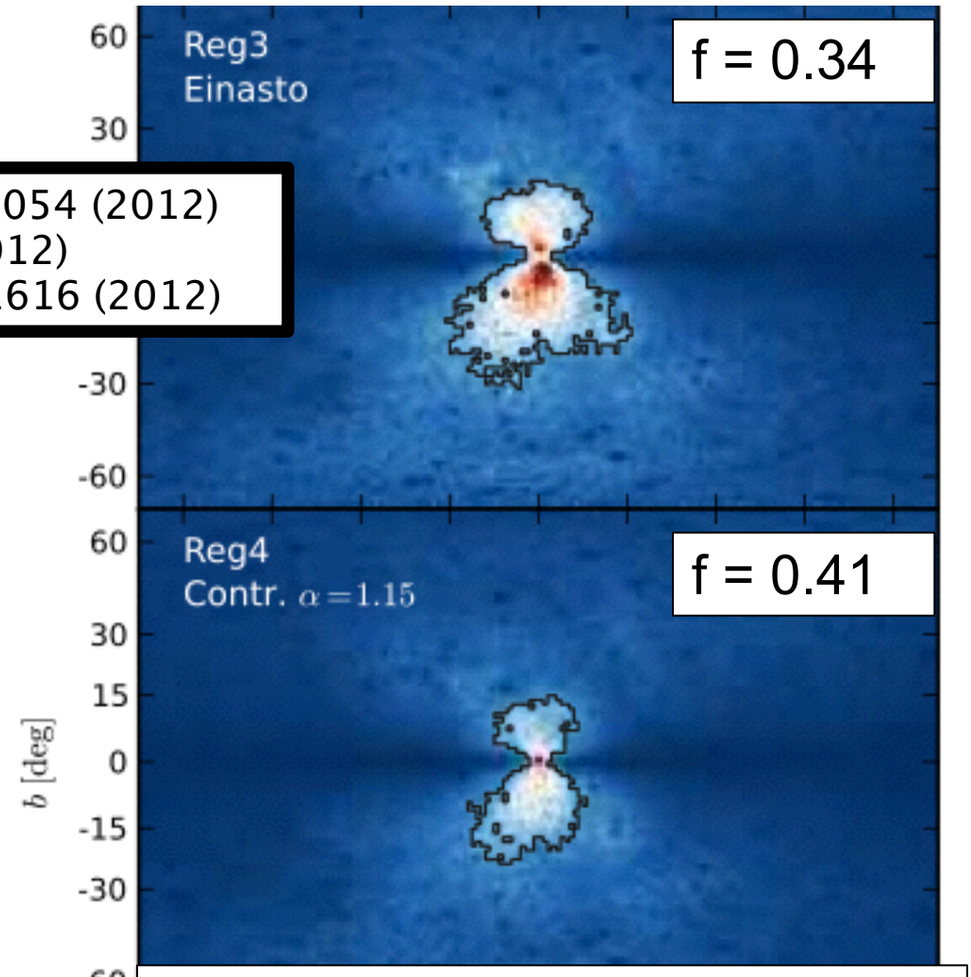
Profumo, Phys. Rev. D78, 023507 (2008)

... etc.

Claim of Gamma-ray Line in Public LAT Data



Bringmann et al. JCAP 1207, 054 (2012)
Weniger, JCAP 1208, 007 (2012)
Su & Finkbeiner arXiv:1206.1616 (2012)



Fractional Residual (i.e., S/N):
$f = s_{local}^2 / n_s$

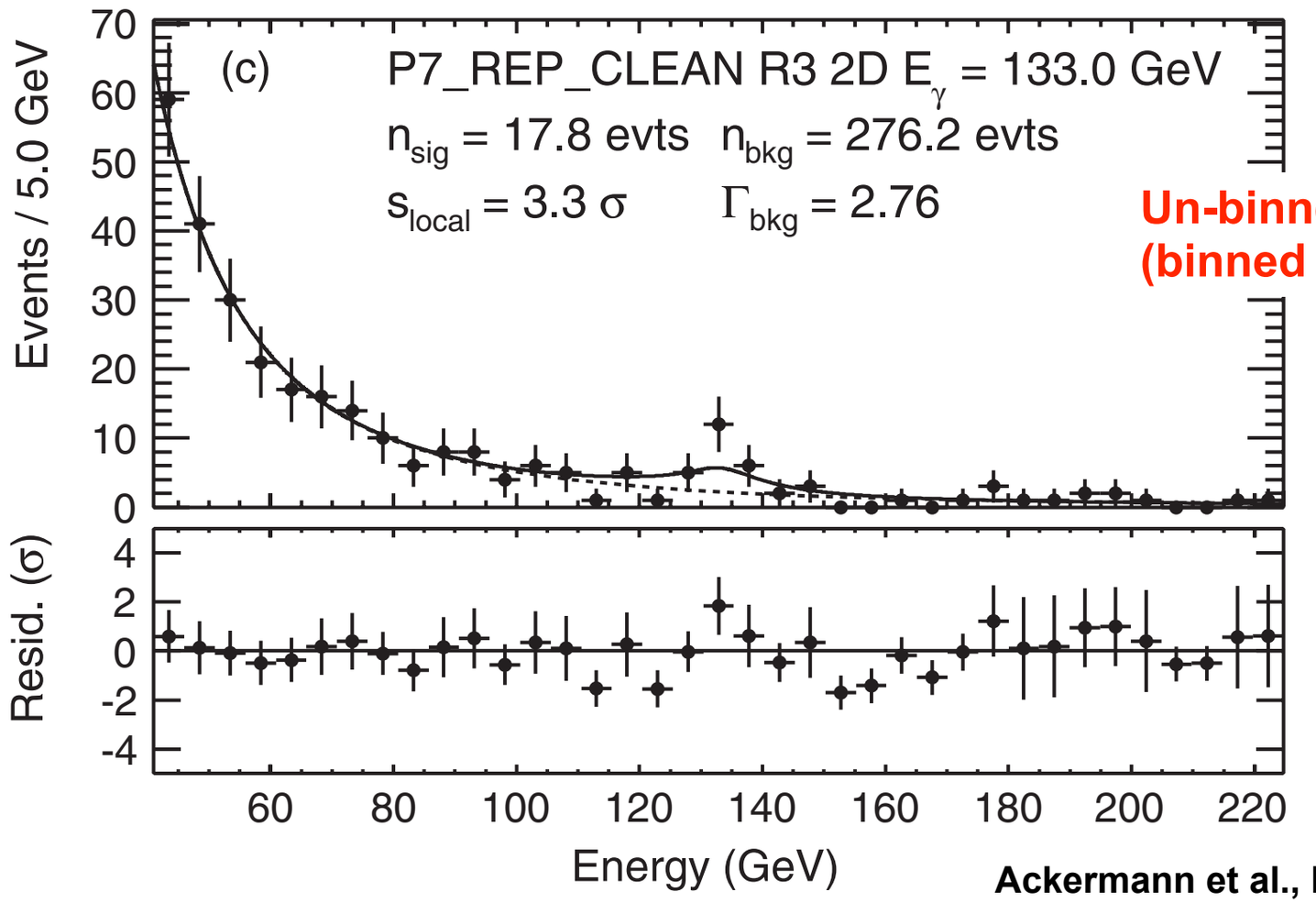
2012: Evidence for a narrow spectral feature at ~130 GeV near the Galactic center (GC):

- Signal is particularly strong in 2 out of 5 test regions, shown above.
- 4–5σ (local), with S/N ≈ 30% – 60% in optimized regions of interest.

A Deeper Look with Pass 7

Fermi-LAT Collaboration line analysis incorporates:

- **Systematic effects: peaks and dips in the effective area, particle backgrounds, energy redistribution, signal in the Earth Limb data set**
- **Improved calibrations, analysis techniques (energy reconstruction probability), integration time, ...**

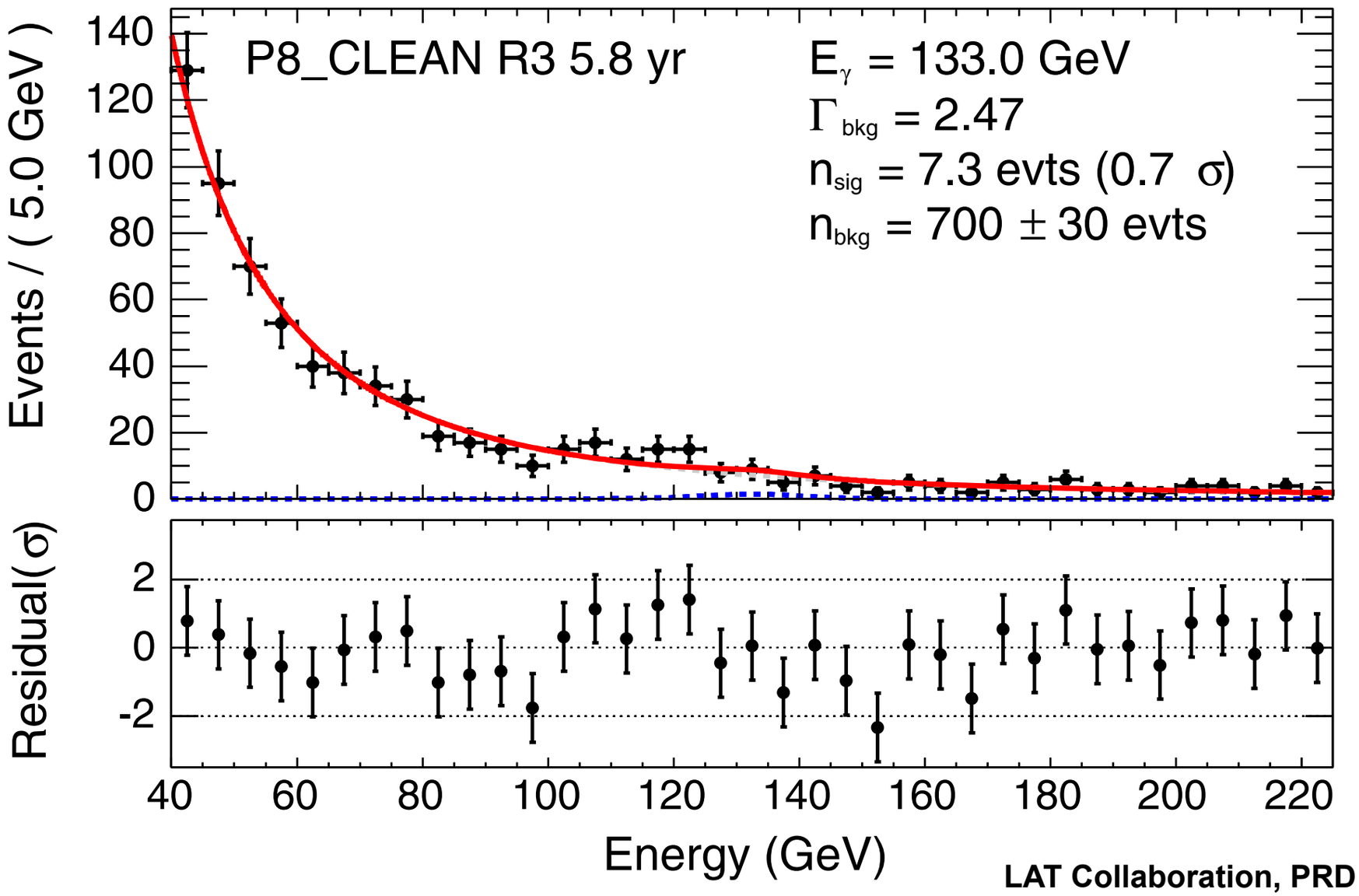


Un-binned fit in 4°x4° GC ROI (binned for plotting)

Ackermann et al., PRD 88, 082002 (2013)

- **4.5**
- **4.1**
- **3.3σ (local) 2D fit at 135 GeV with 4-year reprocessed data; < 2σ (global)**

Line-like Feature with Pass 8

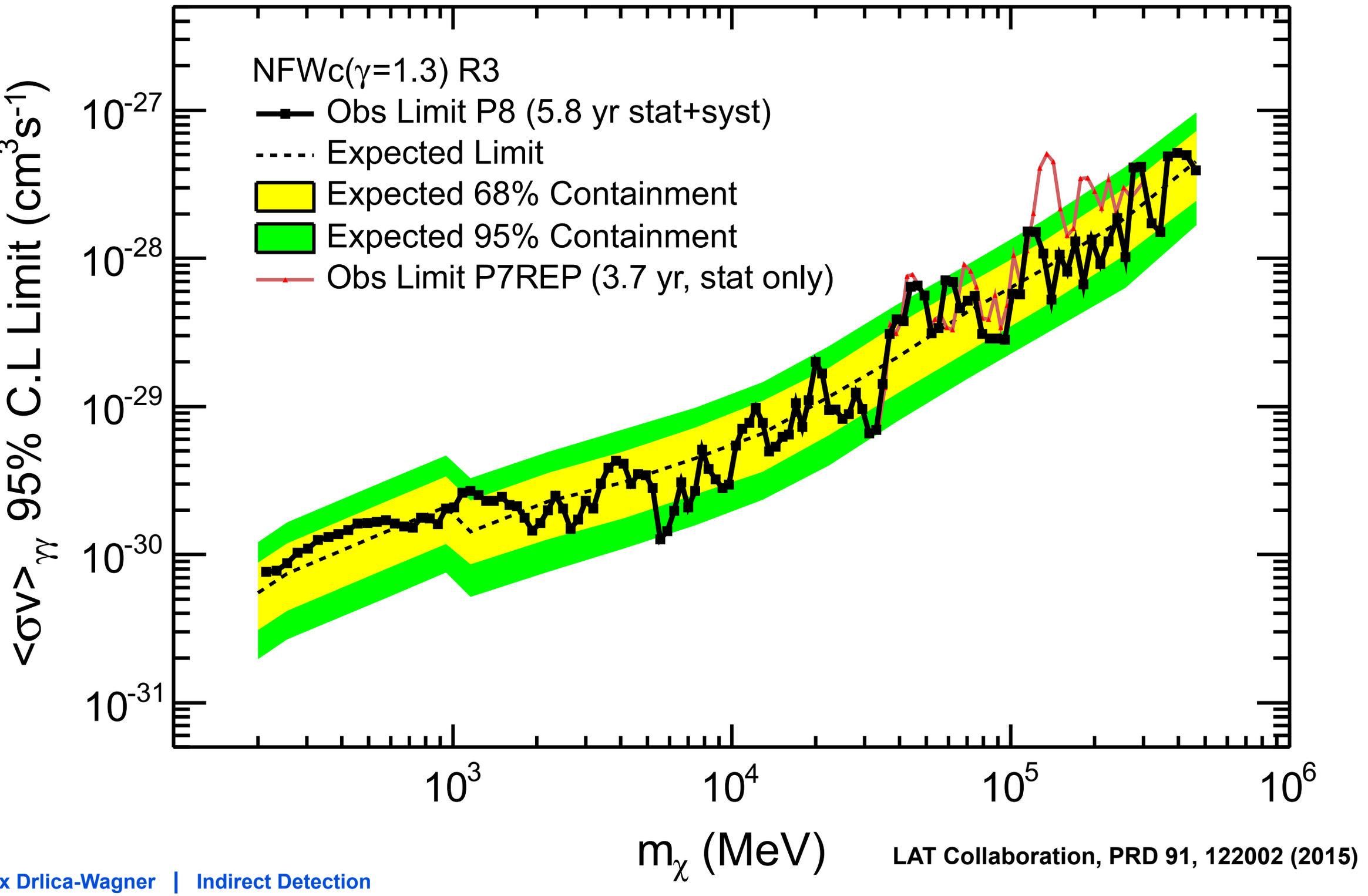


LAT Collaboration, PRD 91, 122002 (2015)

Feature is not significant (<1σ) in 5.8 years of Pass 8 data.

- **A slight feature is seen at a similar energy in a control sample of gamma rays from the Earth's limb (indicative of a systematic effect)**
- **The previous feature probably resulted from a statistical fluctuation on top of a small systematic in the characterization of the effective area.**

Fermi-LAT Limits using Pass 8

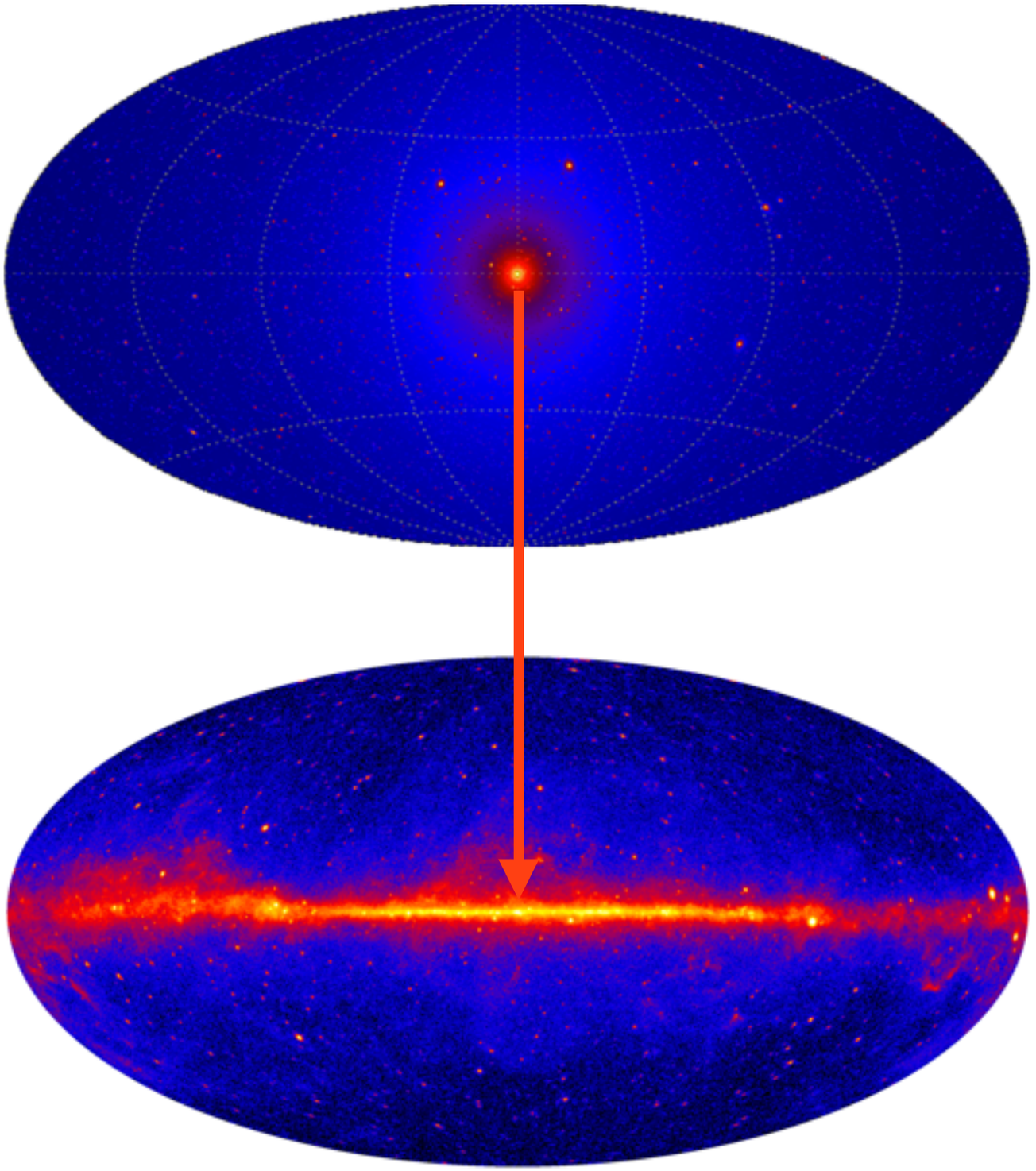


LAT Collaboration, PRD 91, 122002 (2015)

Experimental Results

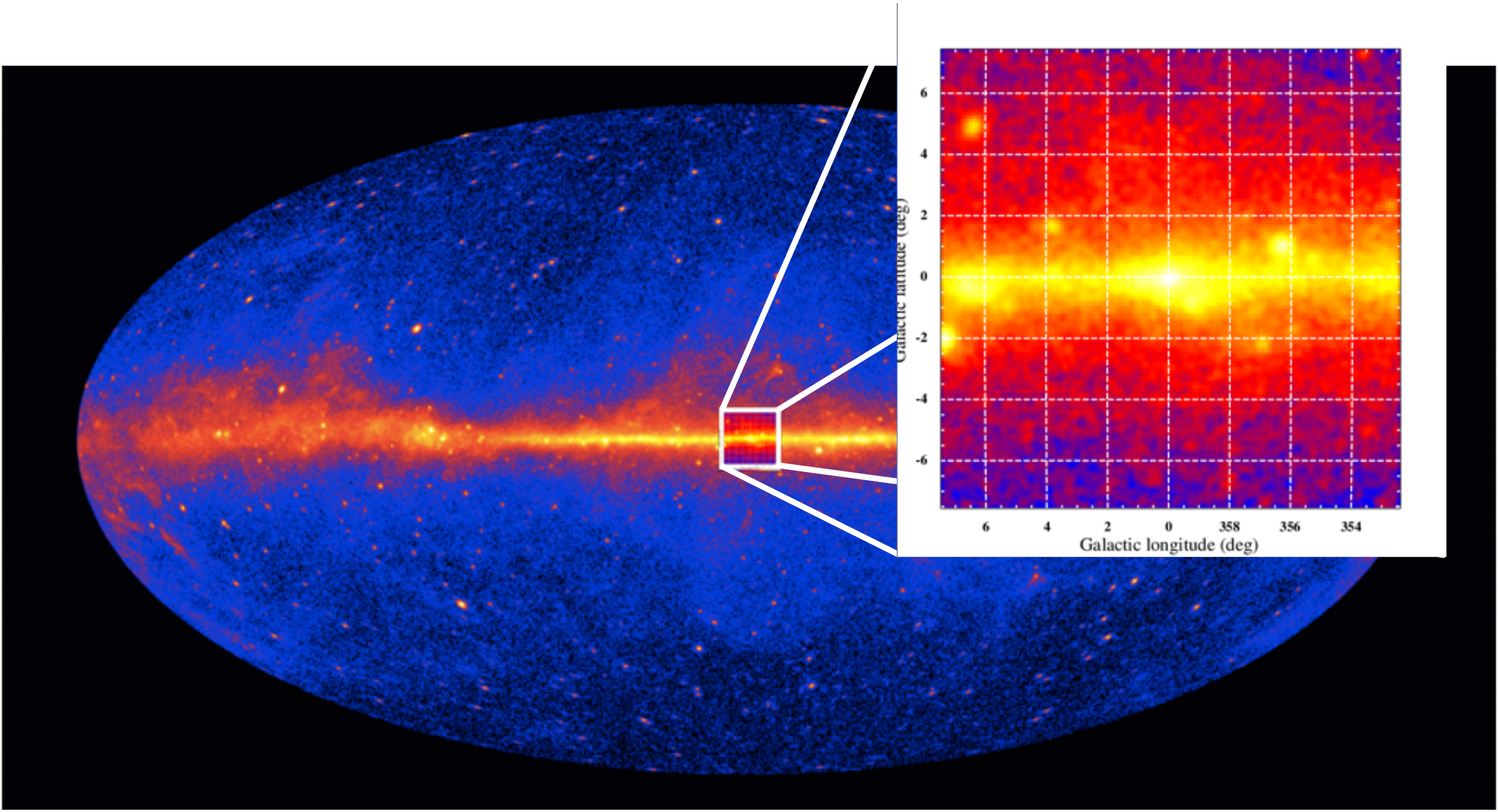
- **Gamma Rays**
  - Spectral Lines
  - **Galactic Center**
  - Dwarf Galaxies
- Neutrinos
  - Solar Neutrinos
- Charged Particles
  - Positron Fraction
- CMB

The Galactic Center



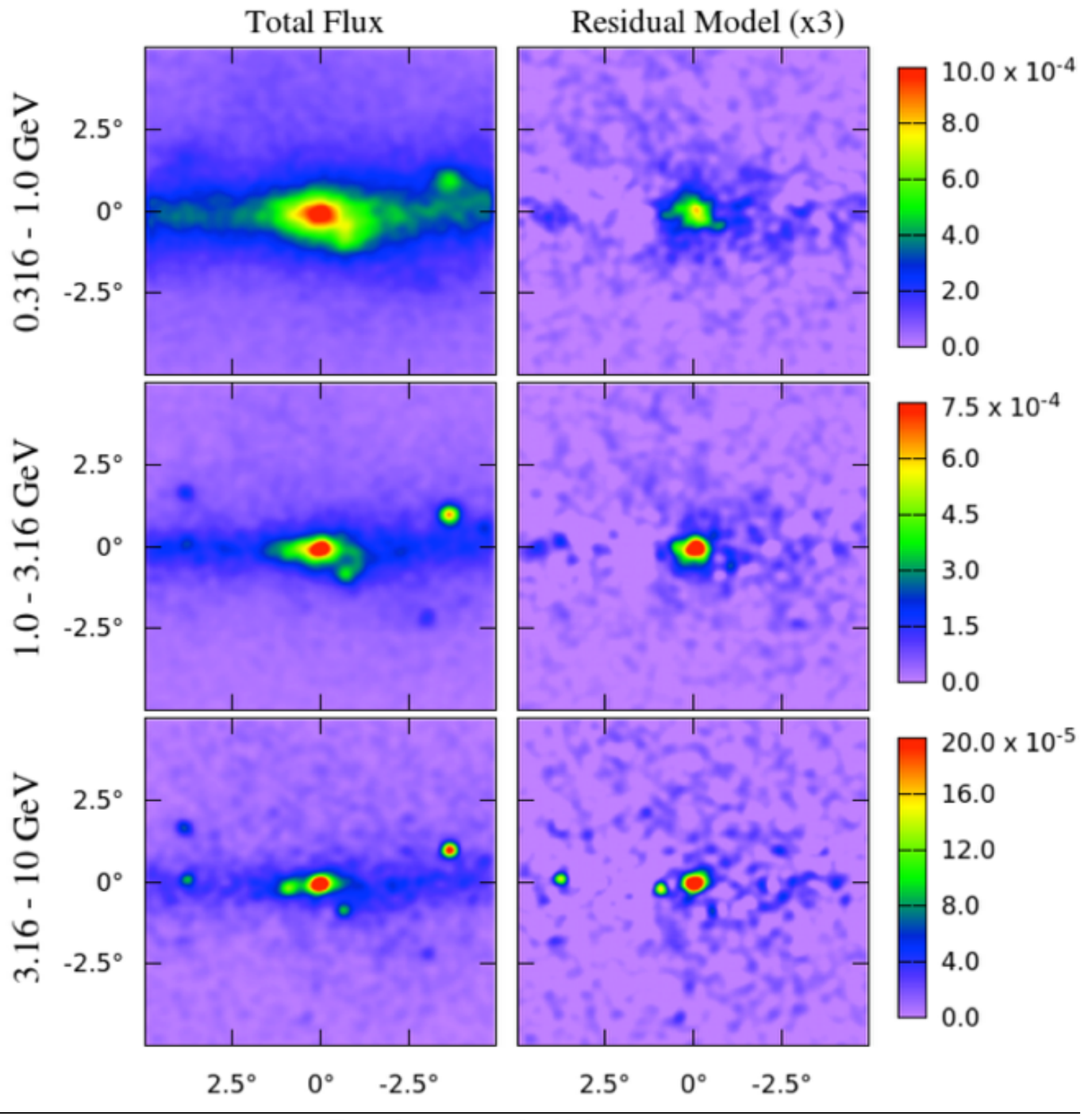
- **The Galactic Center is an appealing target for dark matter searches**
  - **Deep gravitational potential**
  - **Relatively nearby**
- **However, it is extremely complicated**
  - **Diffuse emission from cosmic-ray interactions with Galactic gas and dust**
  - **Densely populated by astrophysical sources (e.g., pulsars, SNR)**
  - **Detected in other wavelengths (e.g., radio, X-ray, TeV)**
- **Topic of much study...**
  - **Hooper & Linden PRD 84, 123005 (2011)**
  - **Gordan & Macias PRD 88, 083521 (2013)**
  - **Abazajian et al. PRD 90, 023526 (2014)**
  - **Daylan et al. arXiv: 1402.6703 (2014)**
  - **Calore et al. PRD 91, 063003 (2014)**
  - **Ajello et al. arXiv: 1511.02938 (2015)**
  - **etc.**

The Galactic Center



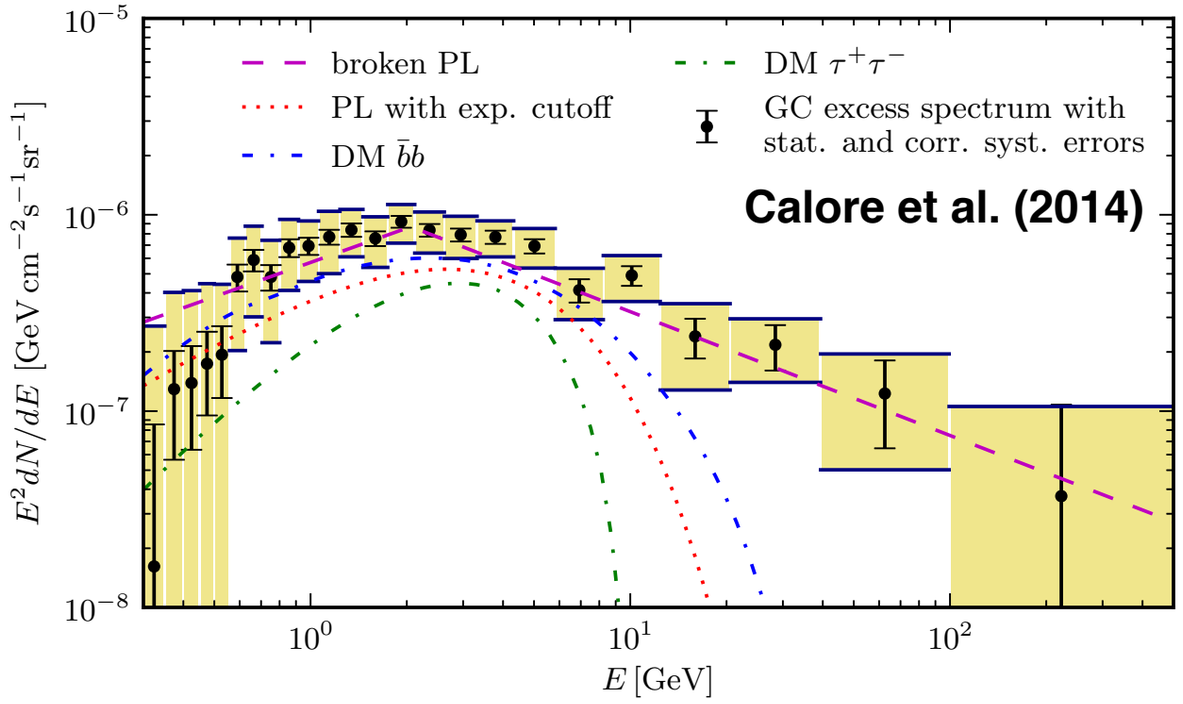
Galactic Center

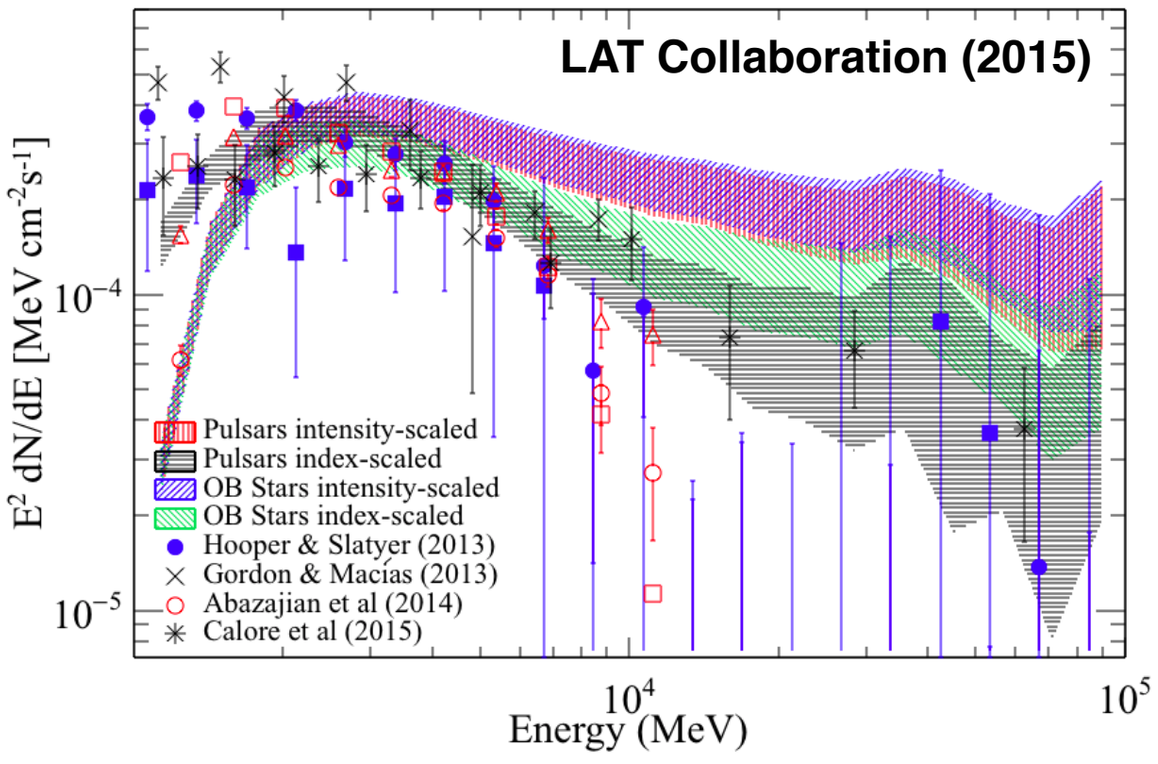
Spatial Map



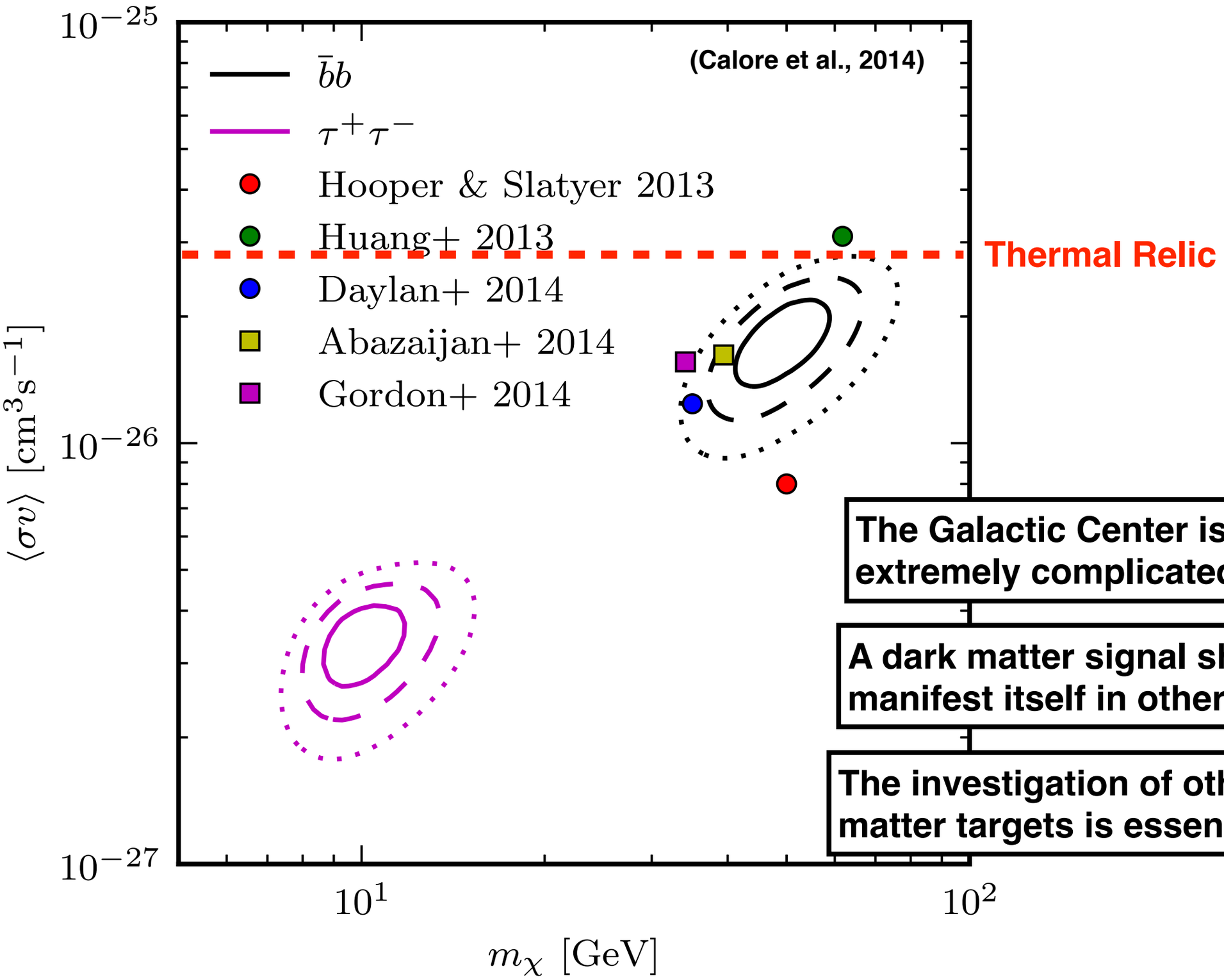
Daylan et al. (2014)

Gamma-ray Spectrum





The Galactic Center

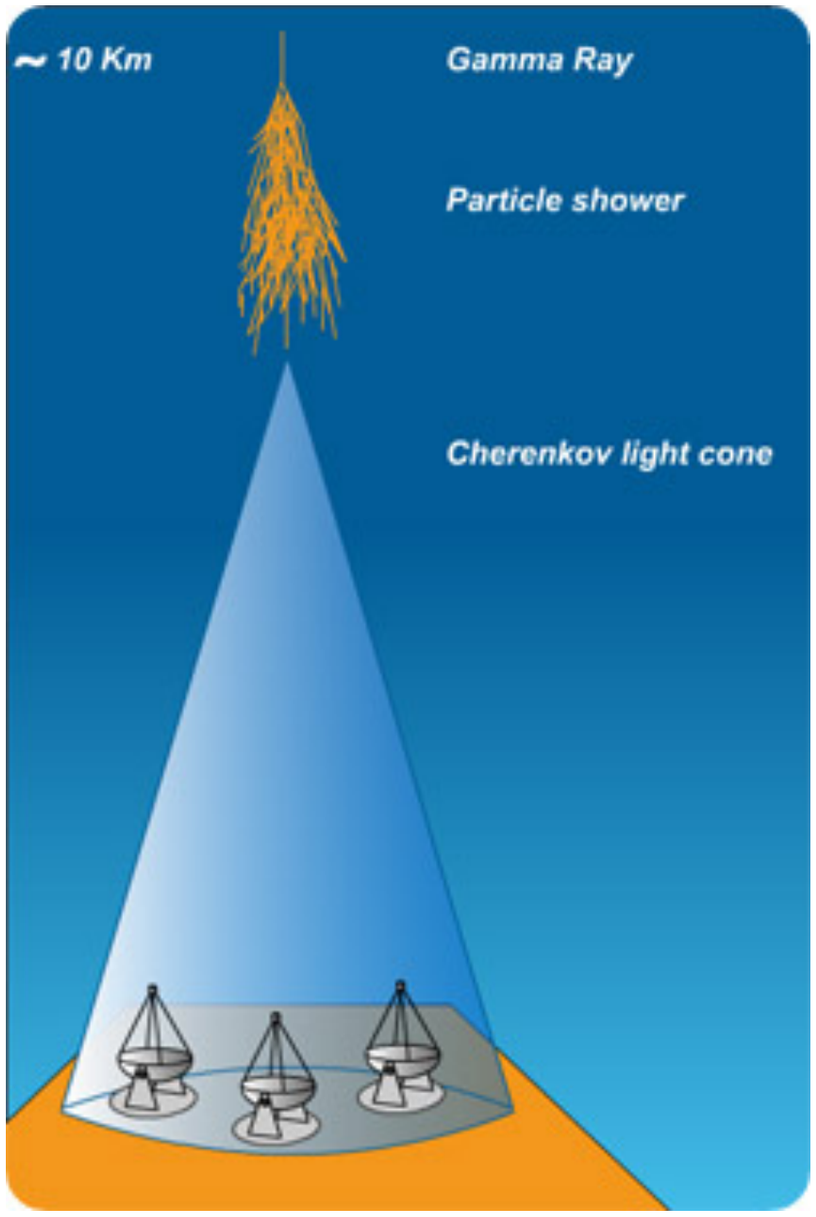


The Galactic Center is an extremely complicated region

A dark matter signal should manifest itself in other regions

The investigation of other dark matter targets is essential

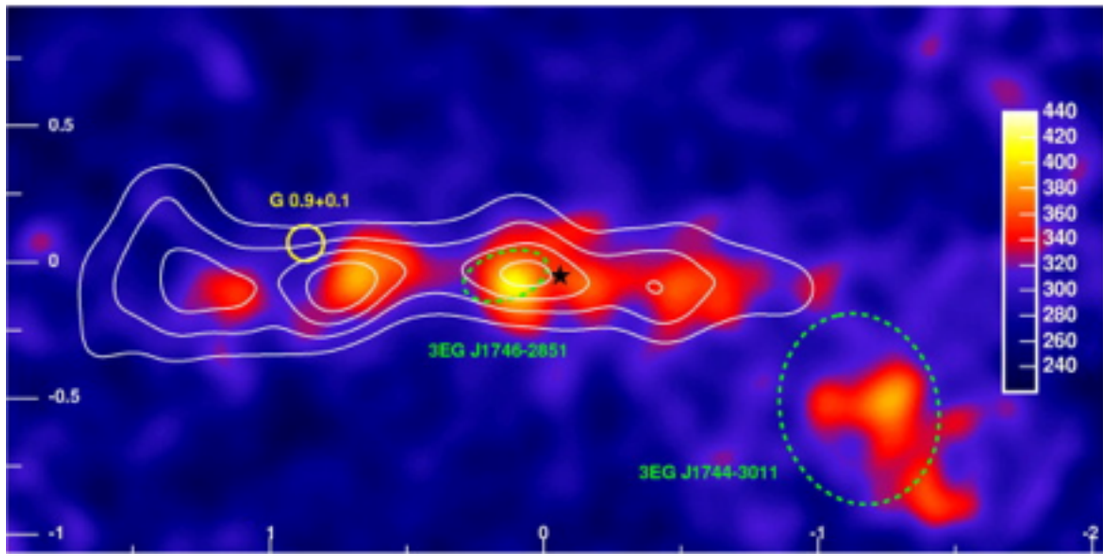
Air Cherenkov Telescopes



- **Use Cherenkov light from air showers produced from gamma rays interacting with the Earth's atmosphere.**
- **Use an array of telescopes for improved shower imaging (angular resolution and background rejection)**
- **Large collecting area (~10^5 m^2 at 100 GeV)**
- **"Excellent" angular resolution (<0.1 deg.)**
- **Threshold at low energy (pushing 100 GeV)**
- **Limited livetime (moon, zenith angle, etc.)**

Galactic Center

H.E.S.S. (E > 100 GeV)



Abramowski et al. PRL 106, 16 (2012)

Galactic Center

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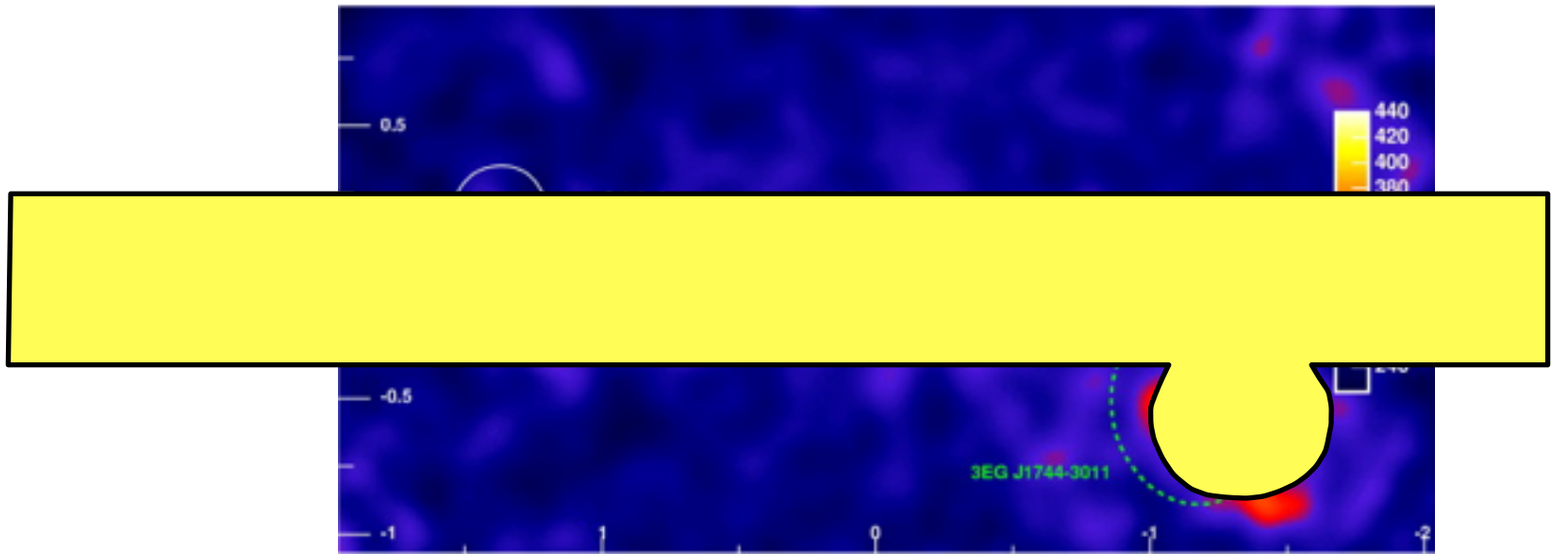

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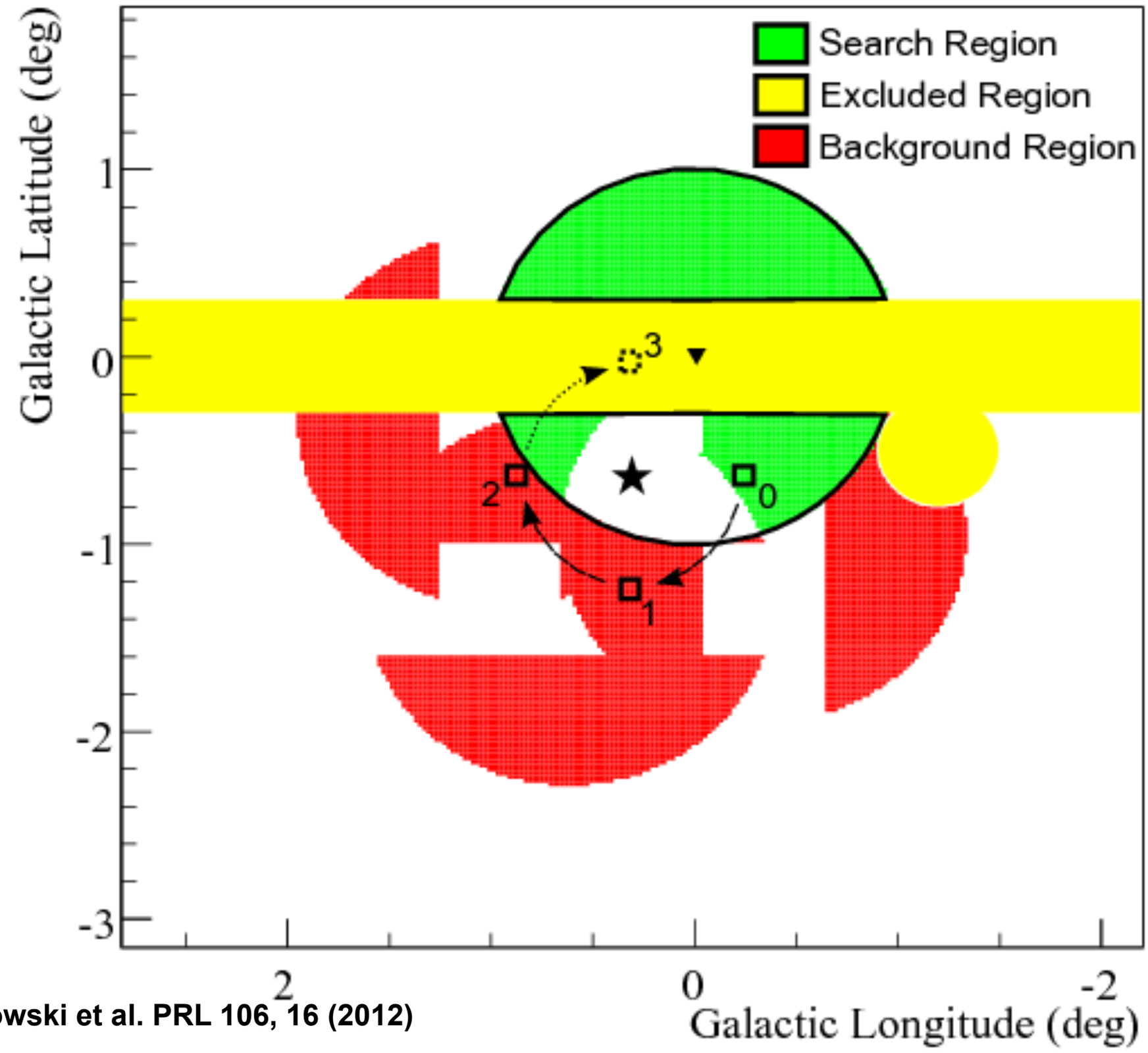

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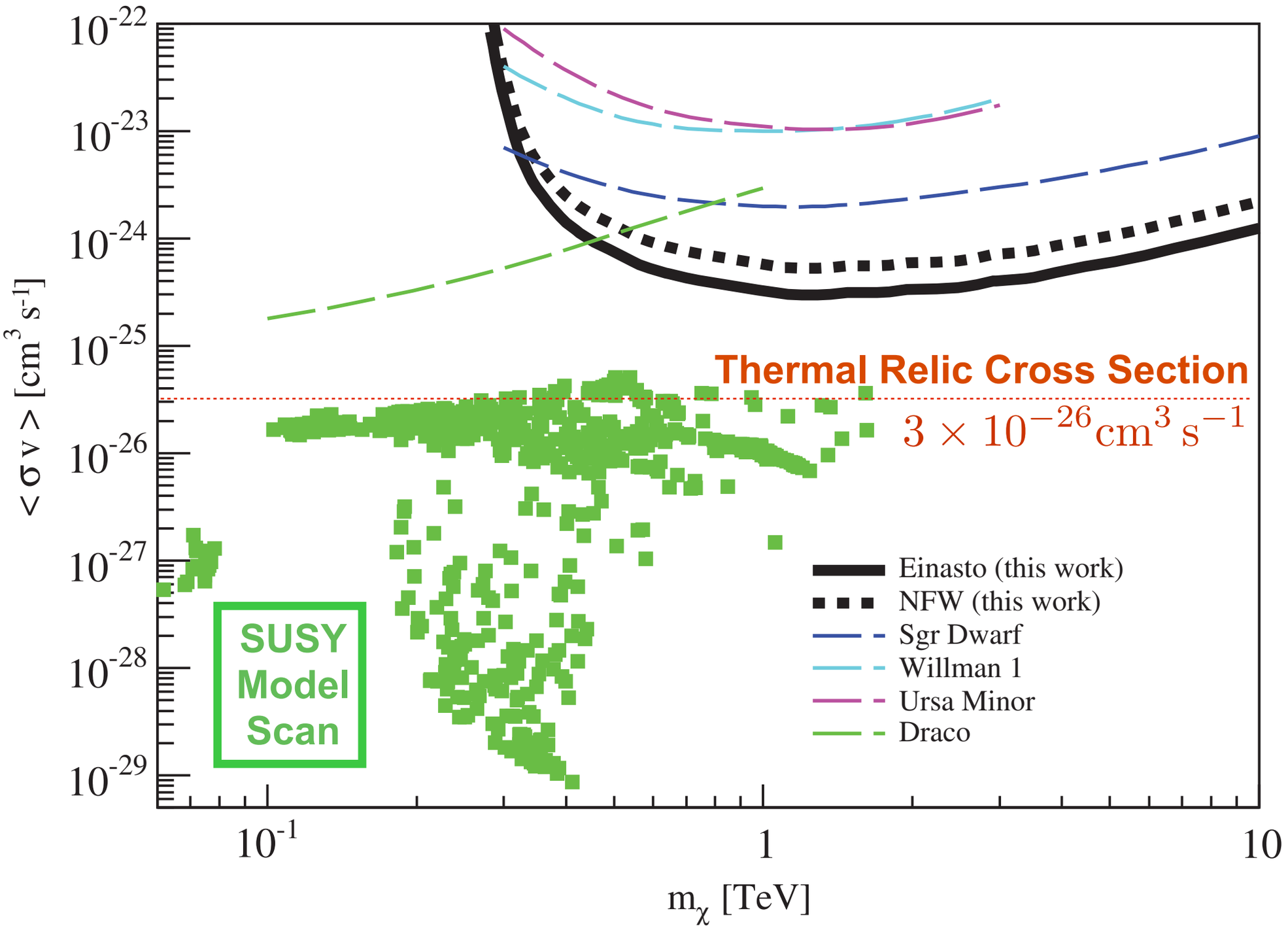

Abramowski et al. PRL 106, 16 (2012)

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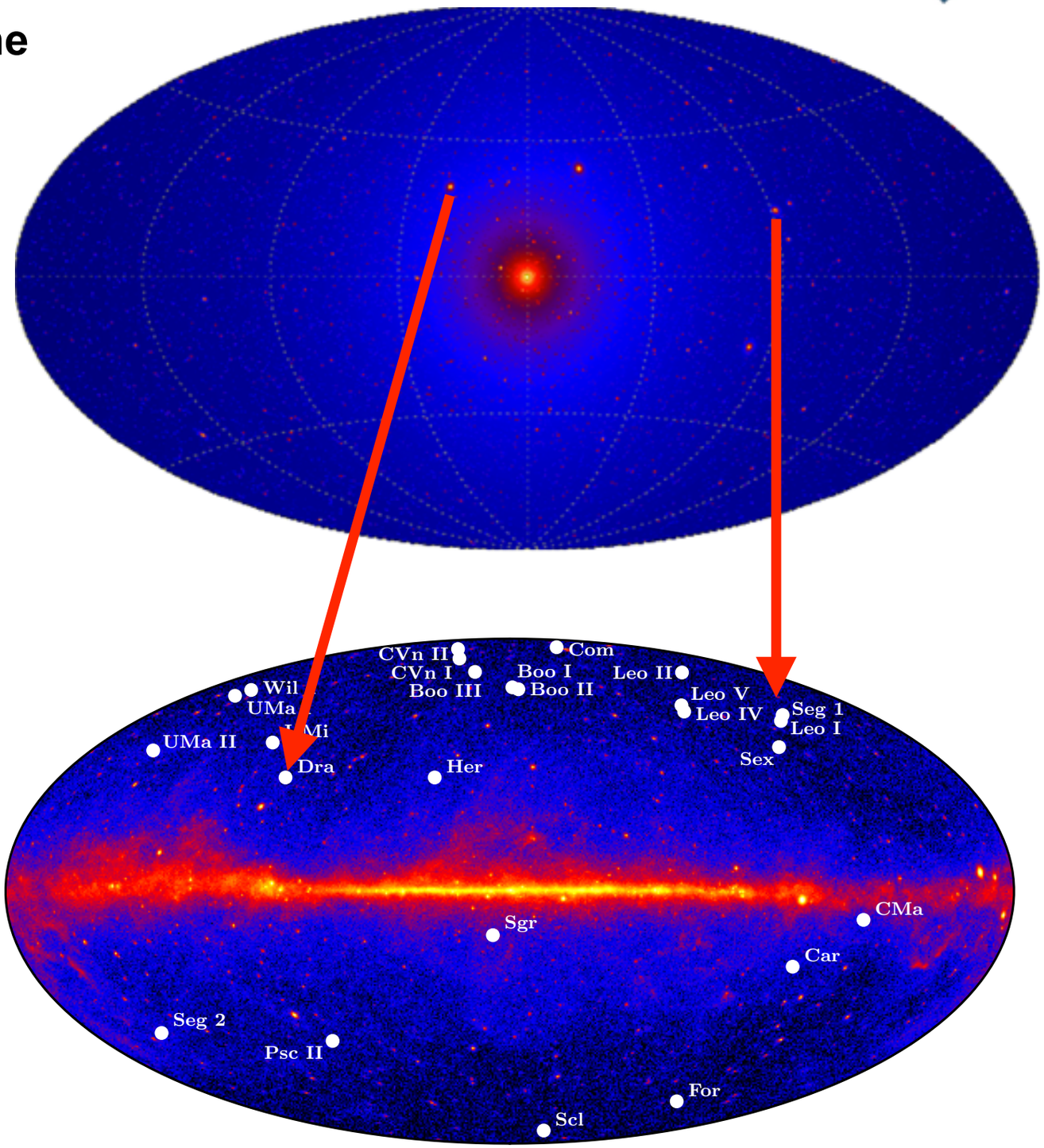
Dwarf Spheroidal Galaxies

- **Most dark-matter dominated objects in the universe (100 - 1000 times more dark matter than visible matter)**
- **Relatively nearby (25 - 150 kpc)**
- **High galactic latitudes (minimize astrophysical foregrounds)**
- **Multi-wavelength observations show no evidence for astrophysical gamma-ray production**
  - **No active star formation (no energy injection)**
  - **No appreciable magnetic fields (no acceleration)**
  - **No no gas or dust (no target material)**



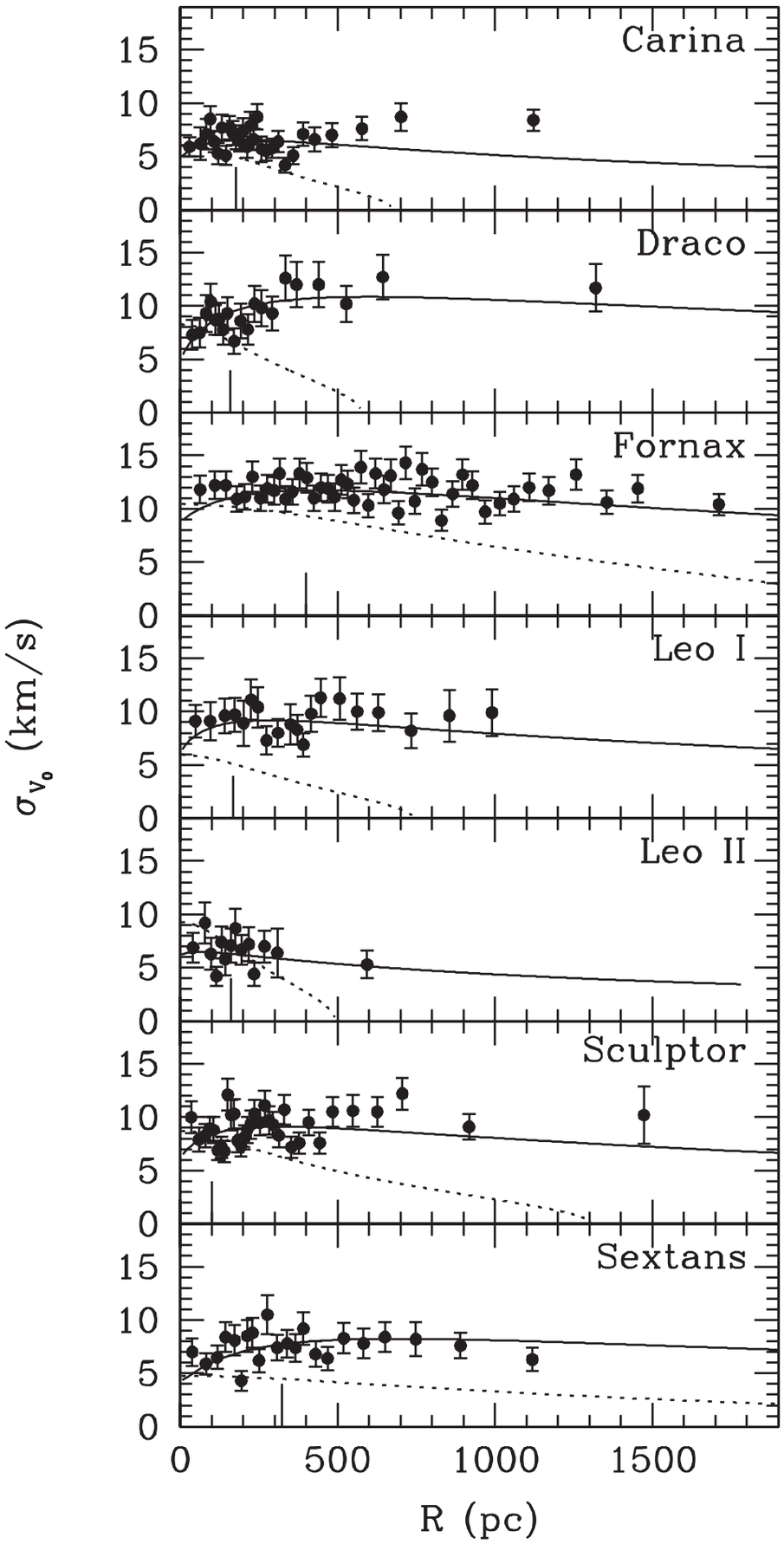
Ackermann et al., PRL 115, 231301 (2015)
Geringer-Sameth et al., PRD 91, 083535 (2015)

Dark Matter Content

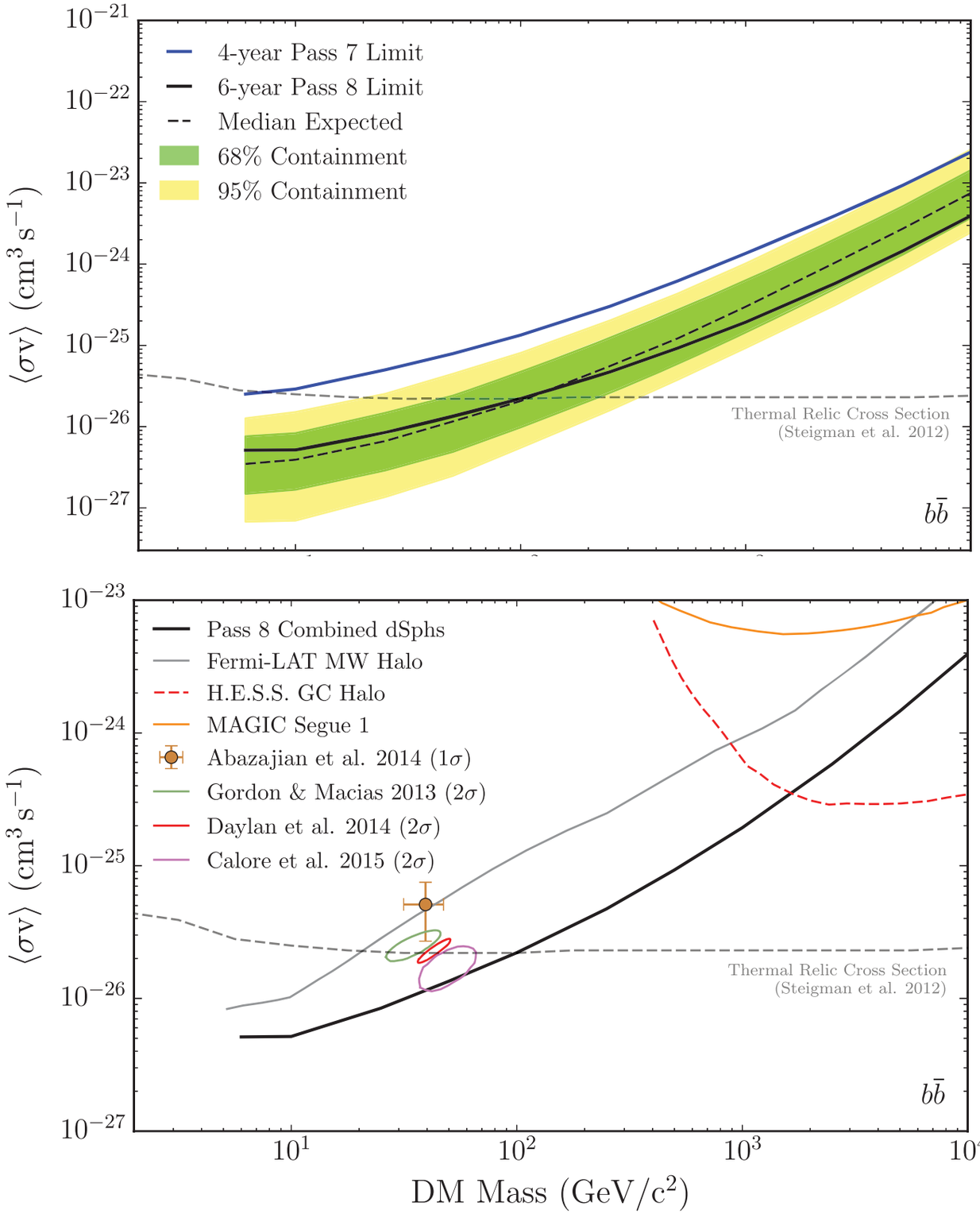
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

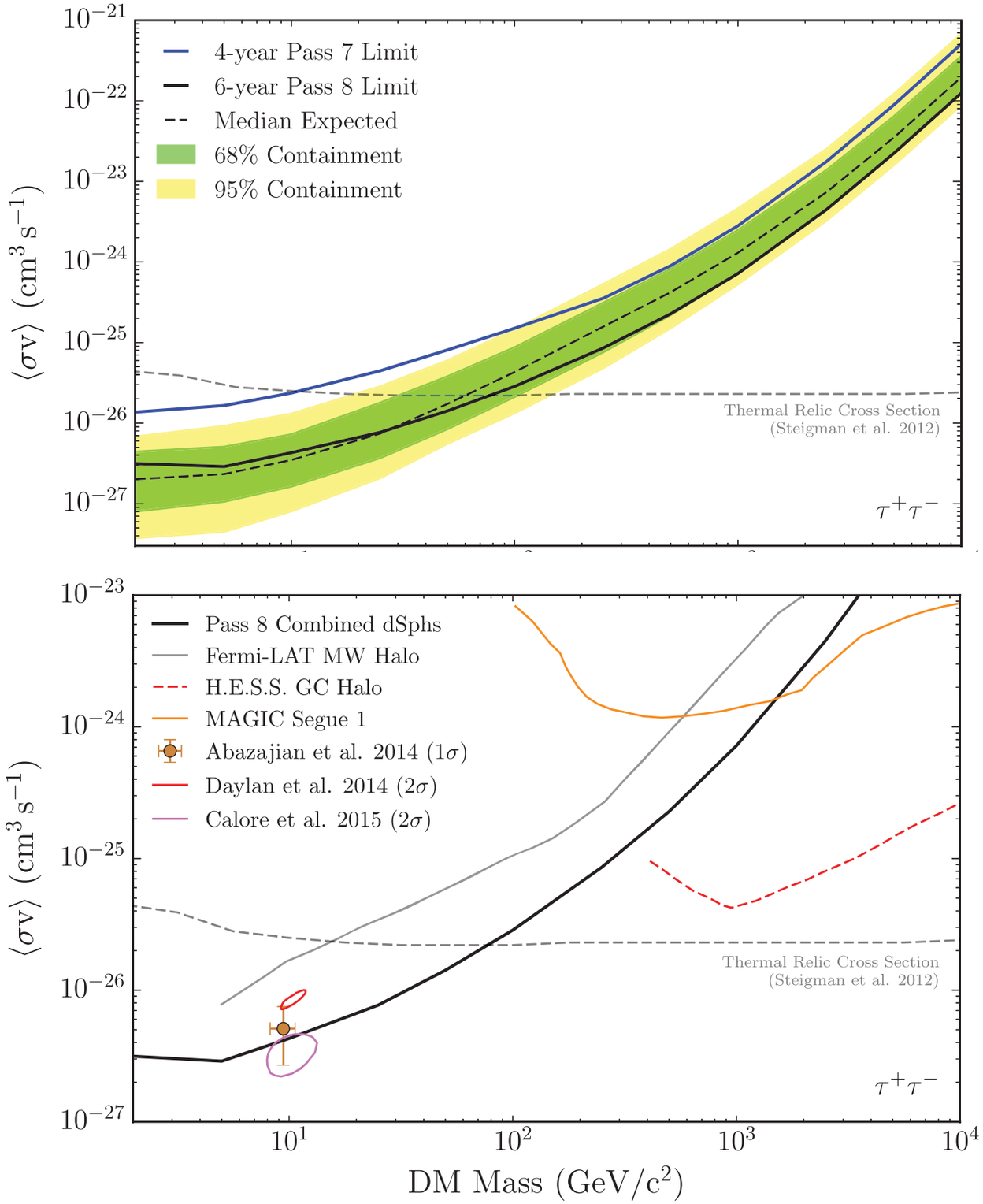
- **Dark matter content determined spectroscopically from stellar velocity dispersion**
  - **Classical dwarfs: spectra for several thousand stars**
  - **Ultra-faint dwarfs: spectra for fewer than 100 stars**
- **Assume a DM density profile to calculate a J-factor (Martinez, 2013)**
  - **Minimize J-factor uncertainty by enclosing the half-light radius**
  - **Become insensitive to the inner profile behavior (core vs. cusp) at large enough radii**
- **Include the statistical uncertainty in the J-factor in gamma-ray analysis**

Walker et al. 2007



Pass 8 Dwarf Galaxy Constraints



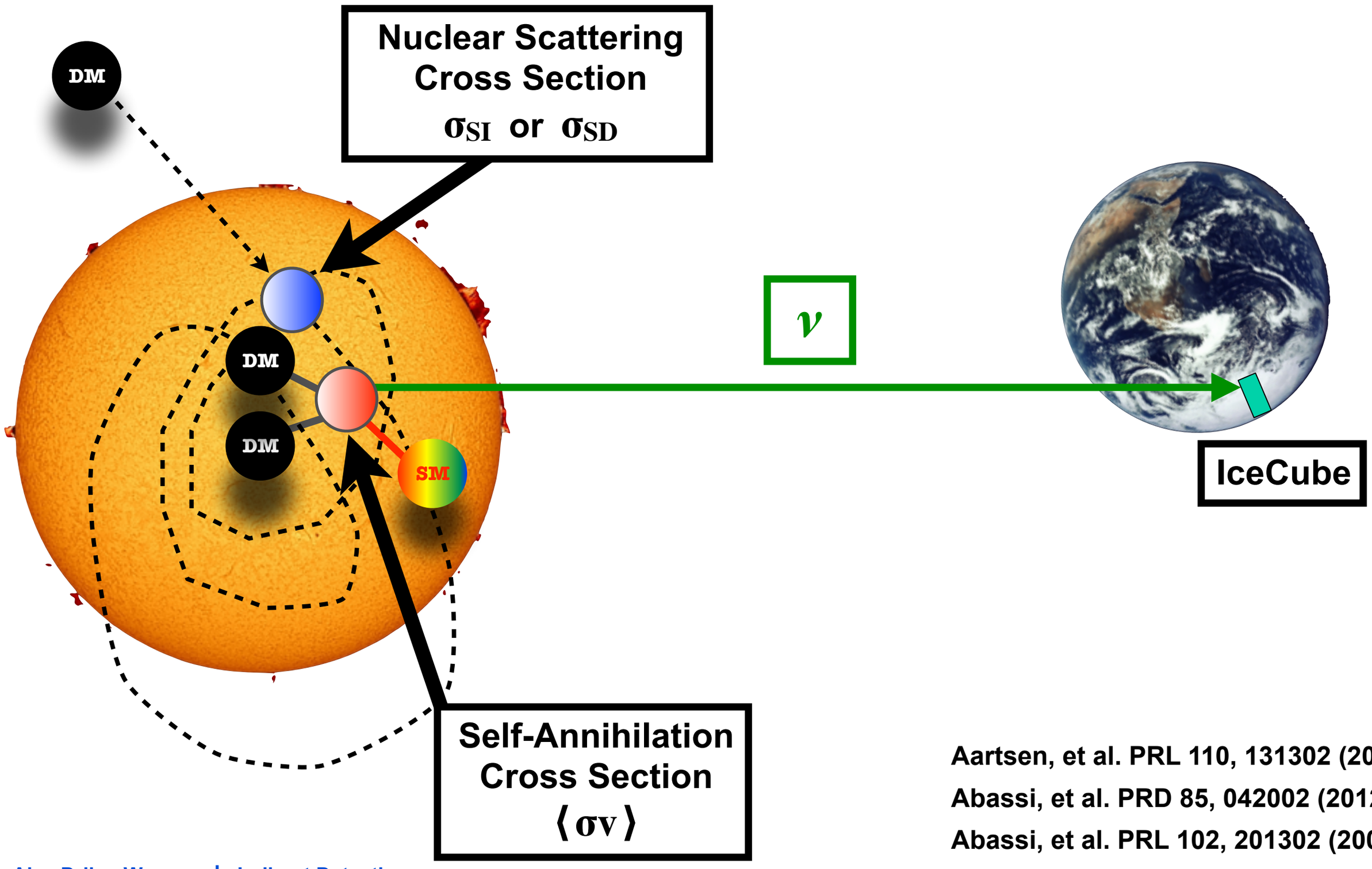


Ackermann et al., PRL 115, 231301 (2015)

Experimental Results

- Gamma Rays
  - Spectral Lines
  - Galactic Center
  - Dwarf Galaxies
- Neutrinos
  - Solar Neutrinos
- Charged Particles
  - Positron Fraction
- CMB

Neutrinos from the Sun

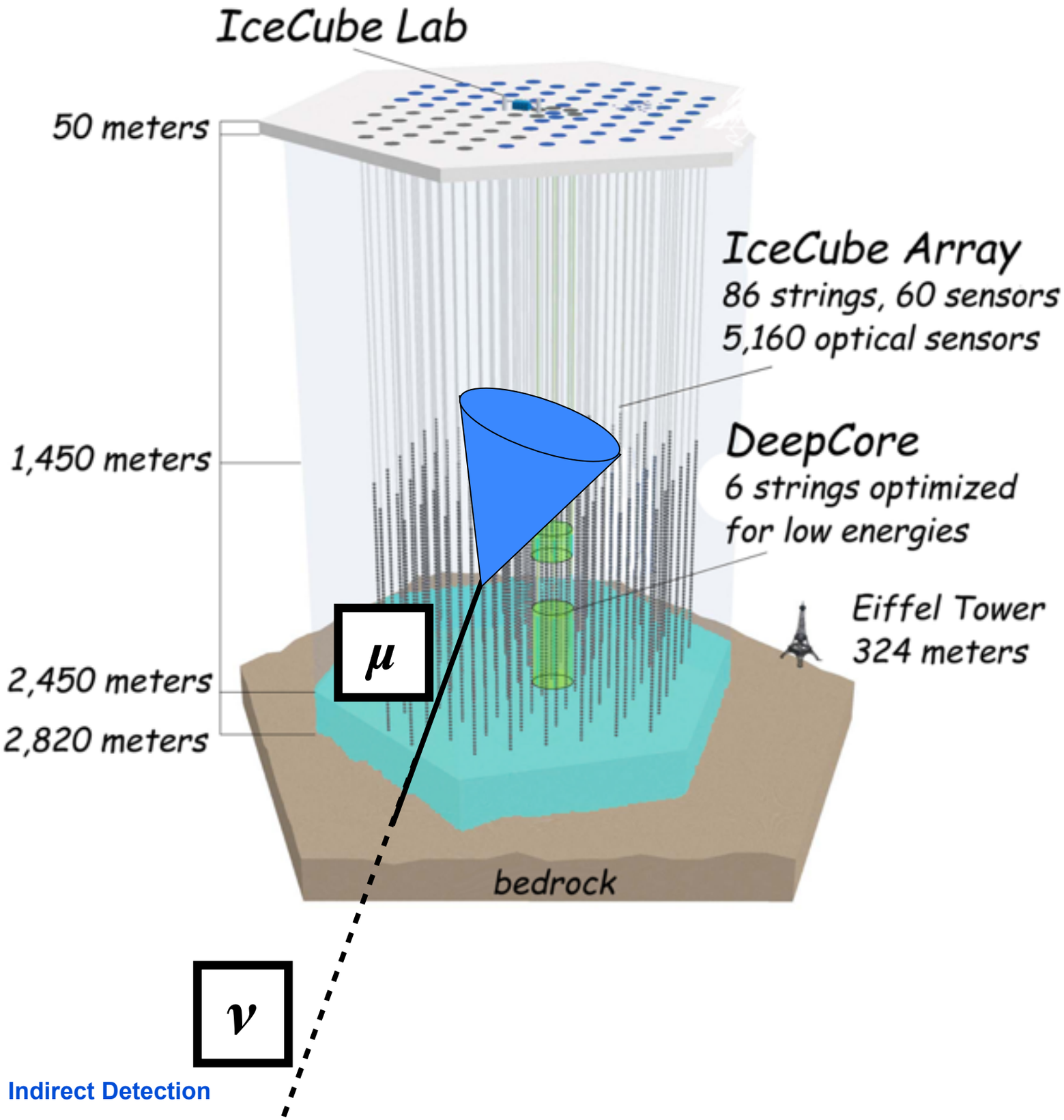


Aartsen, et al. PRL 110, 131302 (2013)

Abassi, et al. PRD 85, 042002 (2012)

Abassi, et al. PRL 102, 201302 (2009)

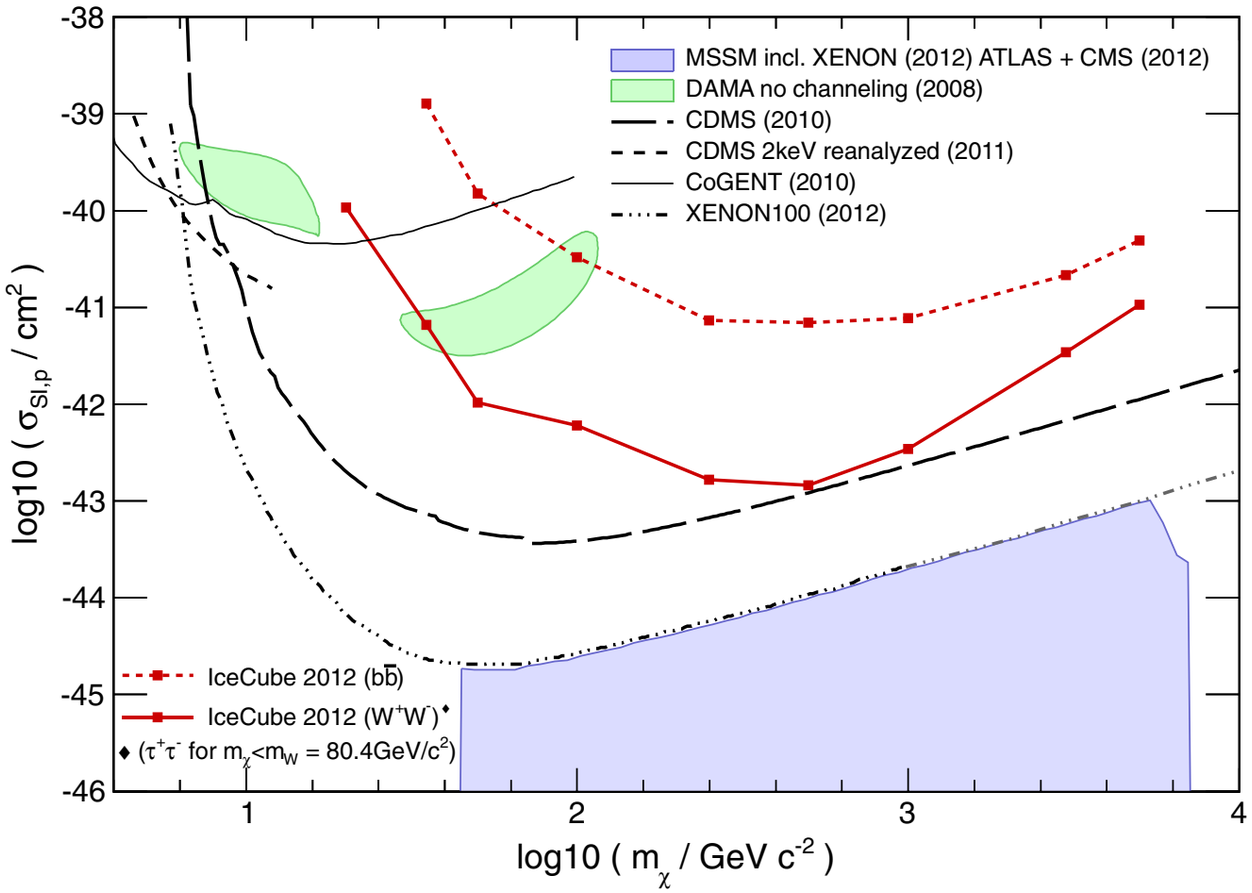
IceCube


IceCube Lab
50 meters
1,450 meters
2,450 meters
2,820 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
DeepCore
6 strings optimized
for low energies
Eiffel Tower
324 meters
μ
bedrock
ν

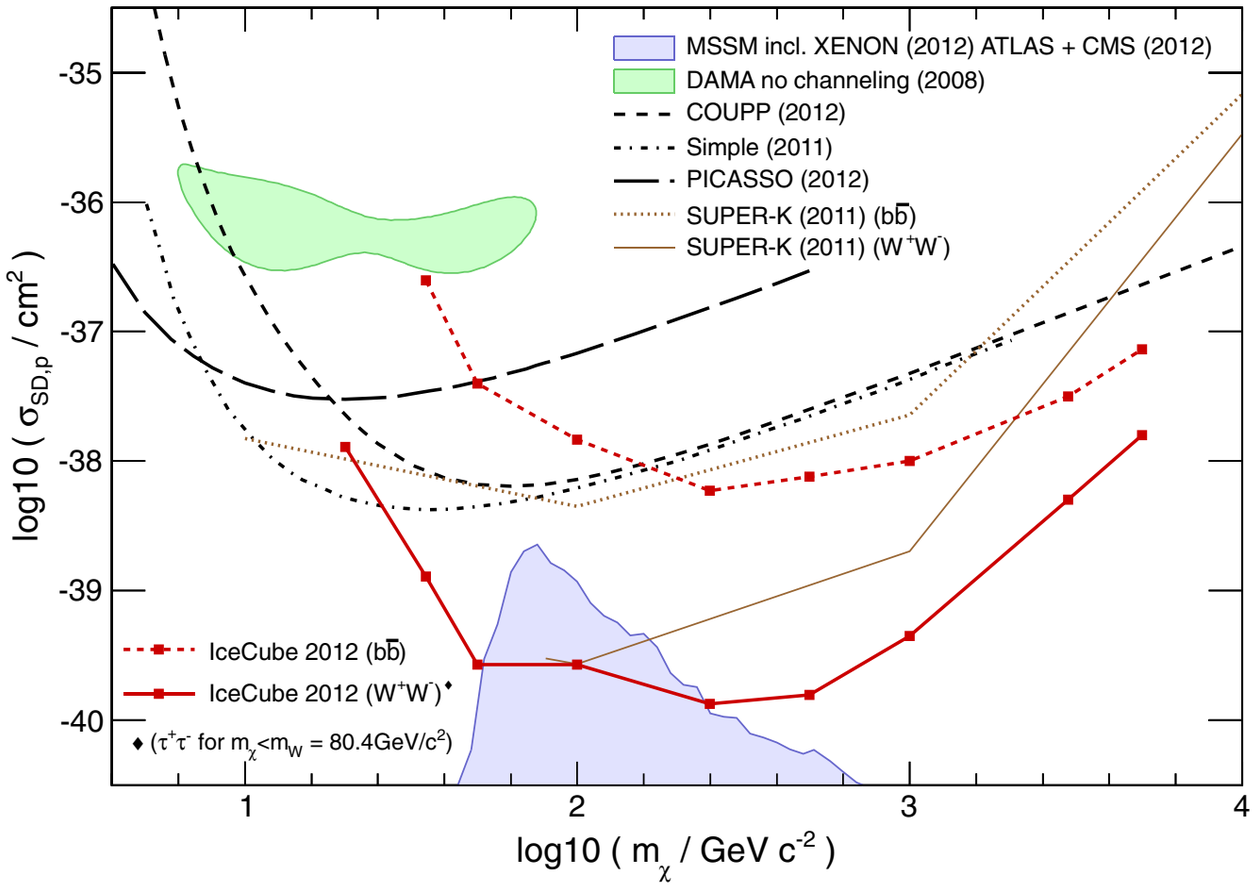
Neutrinos from the Sun

IceCube

Spin Independent



Spin Dependent



Aartsen, et al. PRL 110, 131302 (2013)

Experimental Results

- Gamma Rays
  - Spectral Lines
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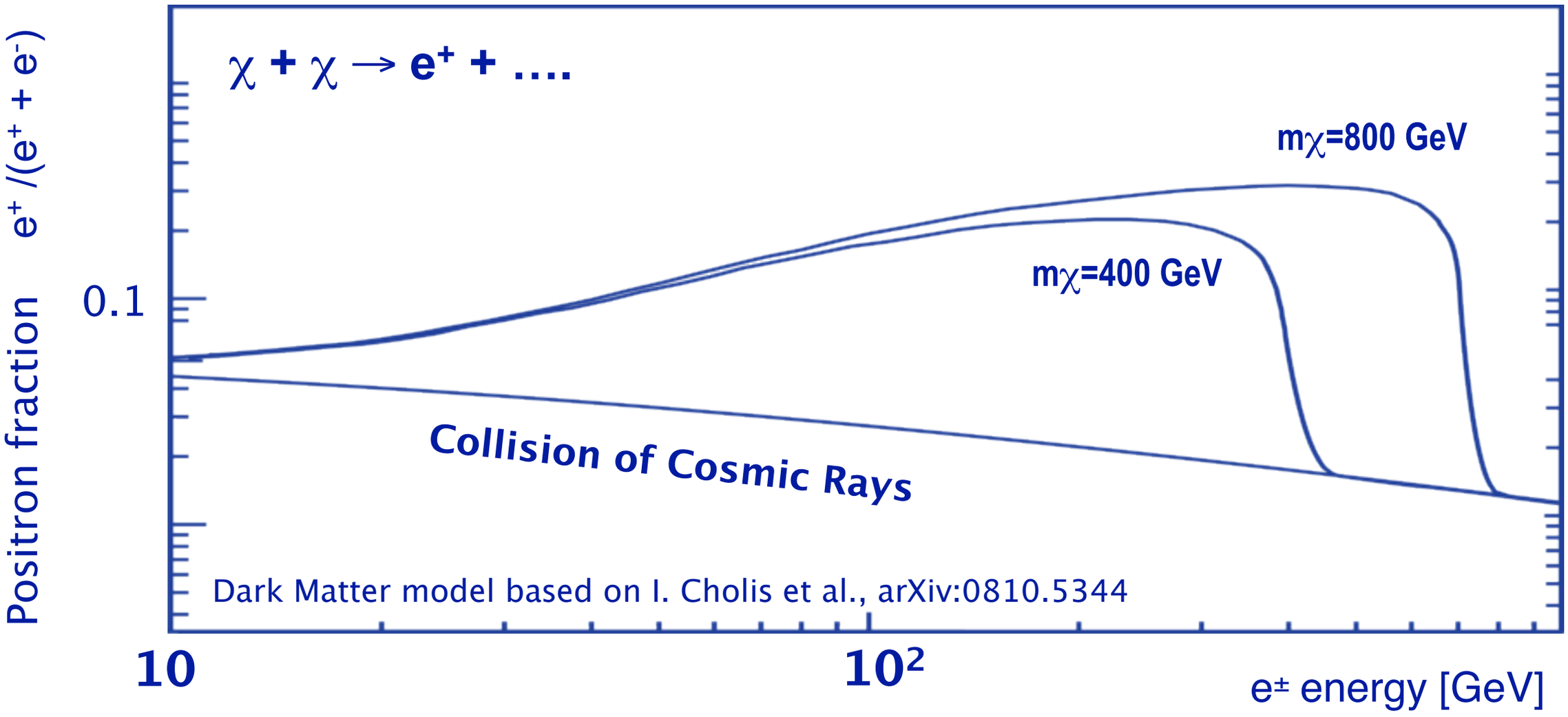
  - Dwarf Galaxies
- Neutrinos
  - Solar Neutrinos
- Charged Particles
  - Positron Fraction
- CMB

Positron Fraction



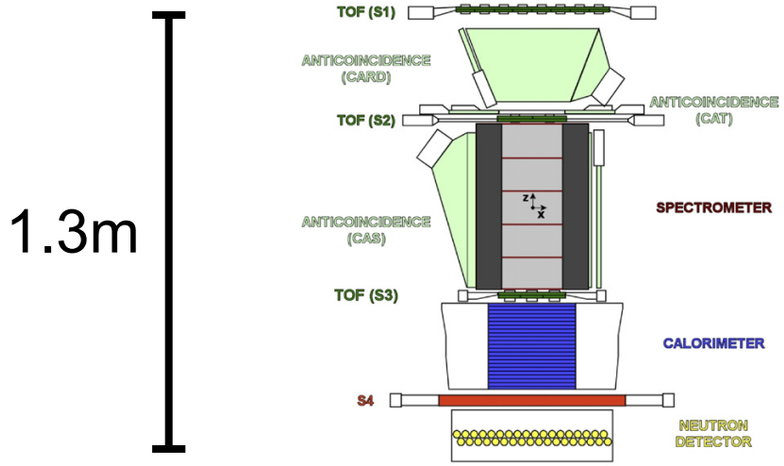
M. Turner et al., Phys. Rev. D42 (1990) 1001;
J. Ellis, 26th ICRC Salt Lake City (1999) astro-ph/9911440;
H. Cheng, et al., Phys. Rev. Lett. 89 (2002) 211301;
S. Profumo et al, JCAP 07 (2004) 006;
D. Hooper et al. Phys. Rev. D 71 (2005) 083503;

E. Ponton et al., JHEP 0904 (2009) 080;
G. Kane, et al., Phys. Lett. B681 (2009) 151;
D. Hooper, et al., JCAP 0901 025 (2009) 0810.1527; B2
Y–Z. Fan et al., Int. J. Mod. Phys. D19 (2010) 2011;
M. Pato, et al., JCAP 1012 (2010) 020.

Slide adapted from A. Kounine

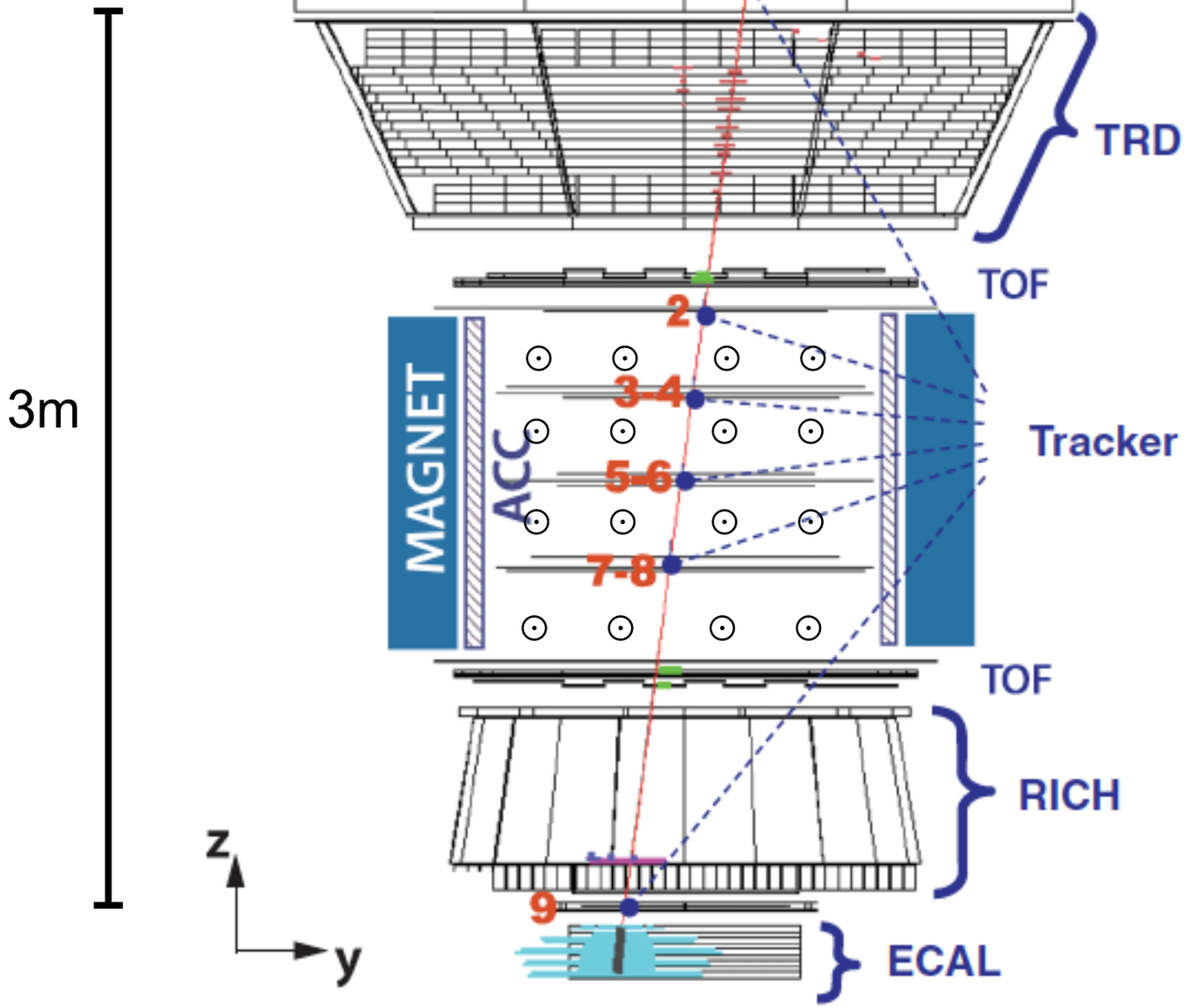
Charged Particles

PAMELA



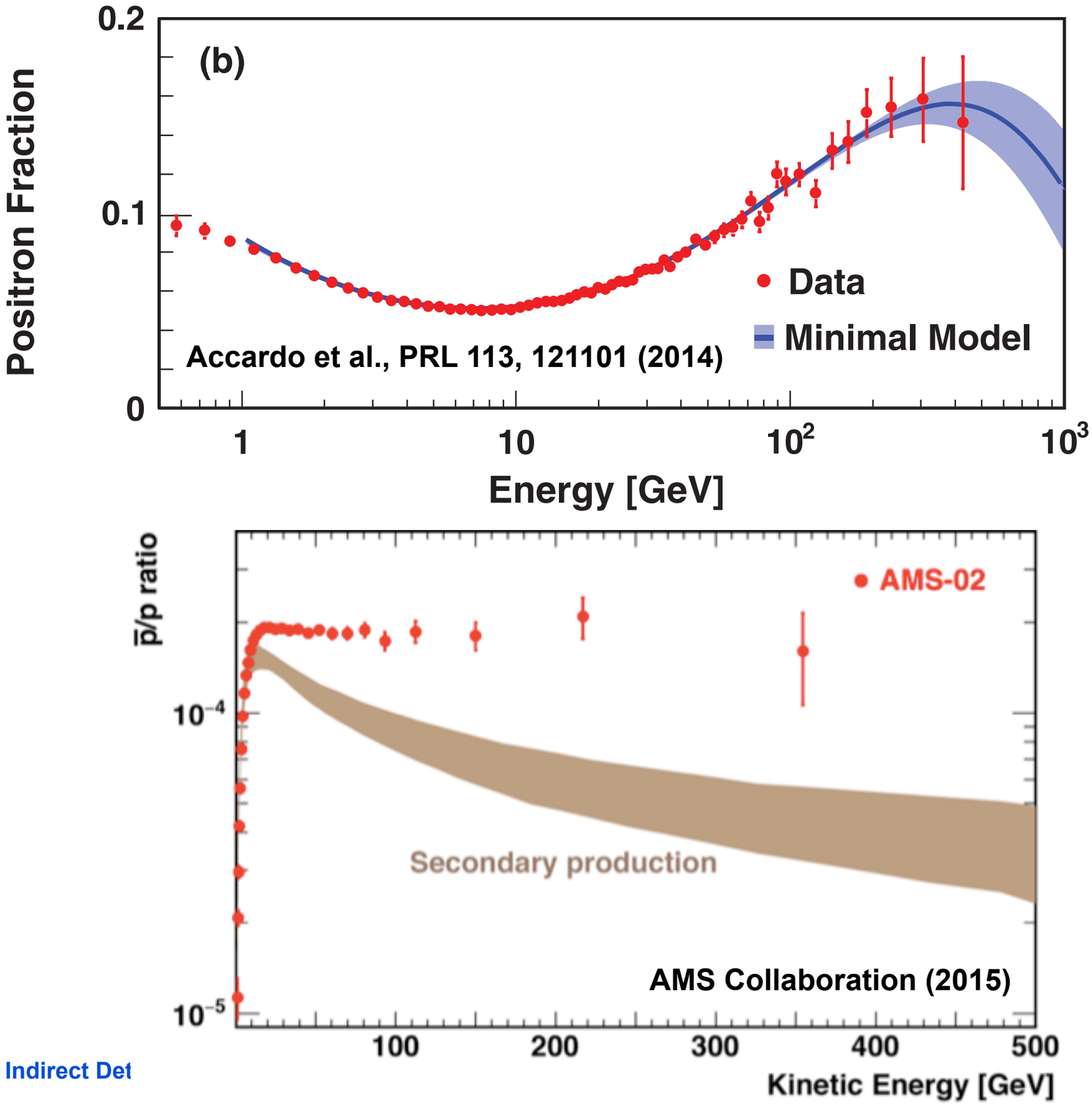
Picozza et al., Astropart. Phys. 27, 296 (2007)
Adriani et al., Nature 458 (2009)

AMS-02

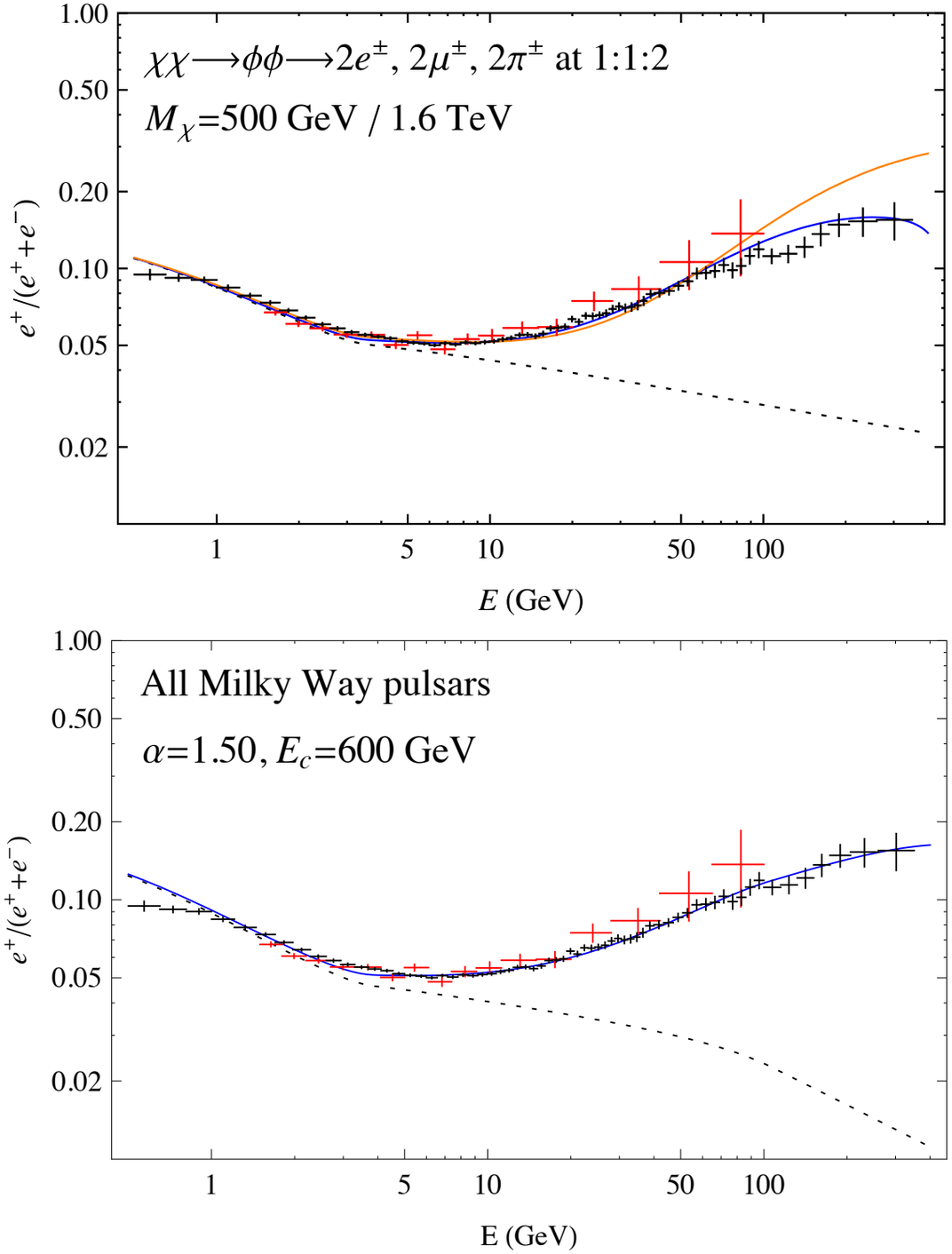


Aguilar et al., PRL 110, 141102 (2013)
Kounine, et al. Int. J. Mod. Phys. E. 21, 08 (2012)

Antimatter Fraction



Positron Fraction



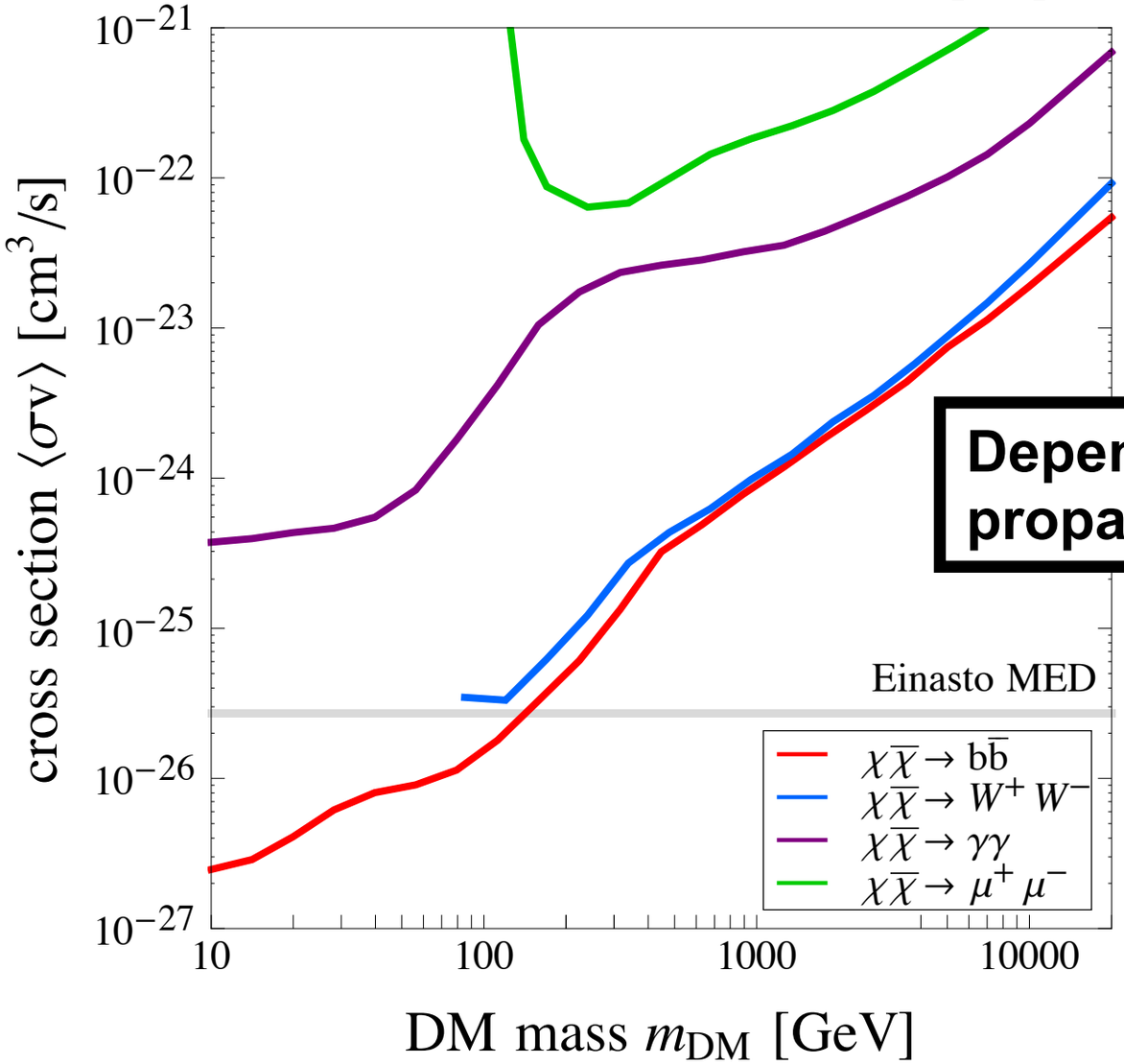
Cholis & Hooper, PRD 88, 023013 (2013)

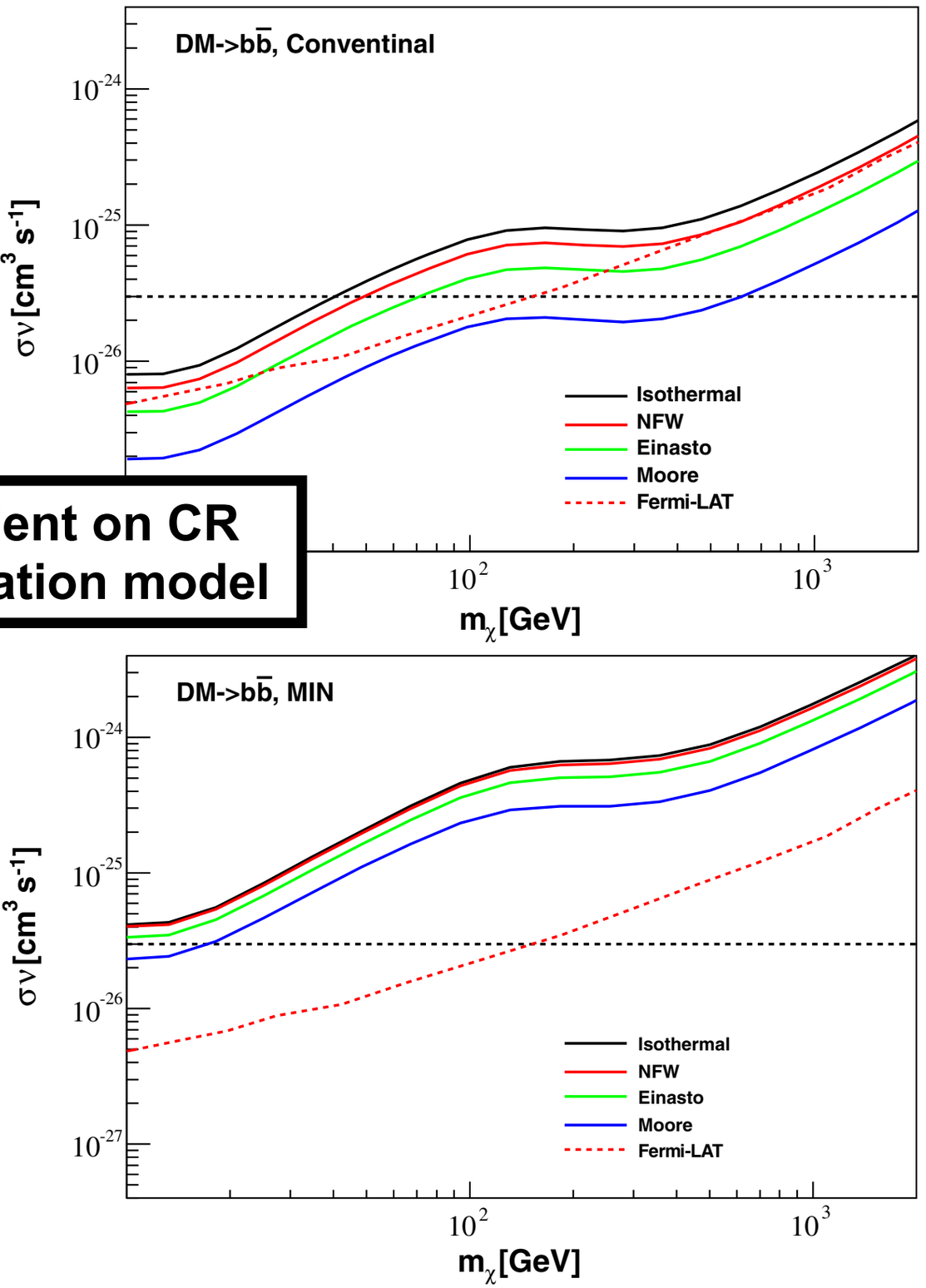
- **Observed positron fraction does not well-matched the simplest dark matter scenarios (DM → e^+e^- or $\mu^+\mu^-$)**
- **However, more complex scenarios involving intermediate states may not yet be ruled out.**
- **Pulsars are another promising candidate to explain the rising positron fraction**
- **However, AMS-02 see no signs of anisotropy (0.03 at 95% C.L.)**
- **Gamma-ray observations are important for both hypotheses:**
  - **Search for nearby pulsars**
  - **Constraints on prompt gamma-ray emission from annihilation**

Ackermann et al., Phys. Rev. D86, 022002 (2012)

Meade et al., Nucl. Phys. B831, 178 (2010)

Antiproton Fraction





Dependent on CR propagation model

Giesen et al., JCAP 09, 023 (2015)

Jin et al., PRD 92, 055027 (2015)

Experimental Results

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  - Spectral Lines
  - Galactic Center
  - Dwarf Galaxies
- Neutrinos
  - Solar Neutrinos
- Charged Particles
  - Positron Fraction
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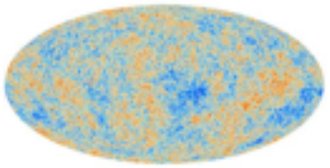
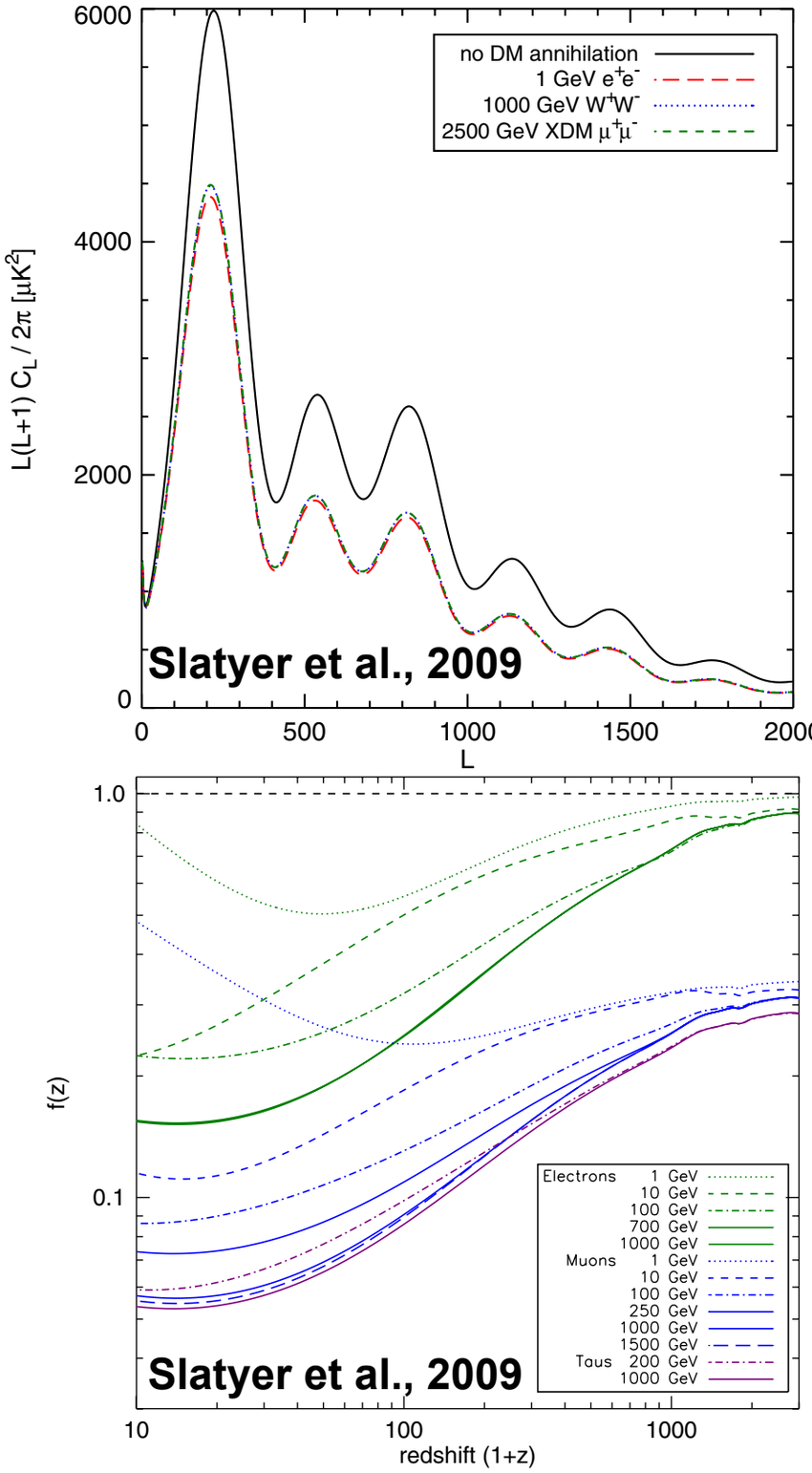


Constraints from the CMB



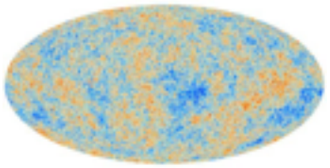
- **Dark matter annihilation not limited to current epoch**
- **CMB power spectrum sensitive to the injection of energy near the time of recombination**
- **Limit the dark matter annihilation cross section from matter power spectrum**
- **Redshift-dependent injection fraction, f(z), depends on dark matter model**
- **Degeneracy with other parameters of the matter power spectrum**

$$\langle \sigma v \rangle = \frac{p_{ann}}{f(z)} m_\chi$$

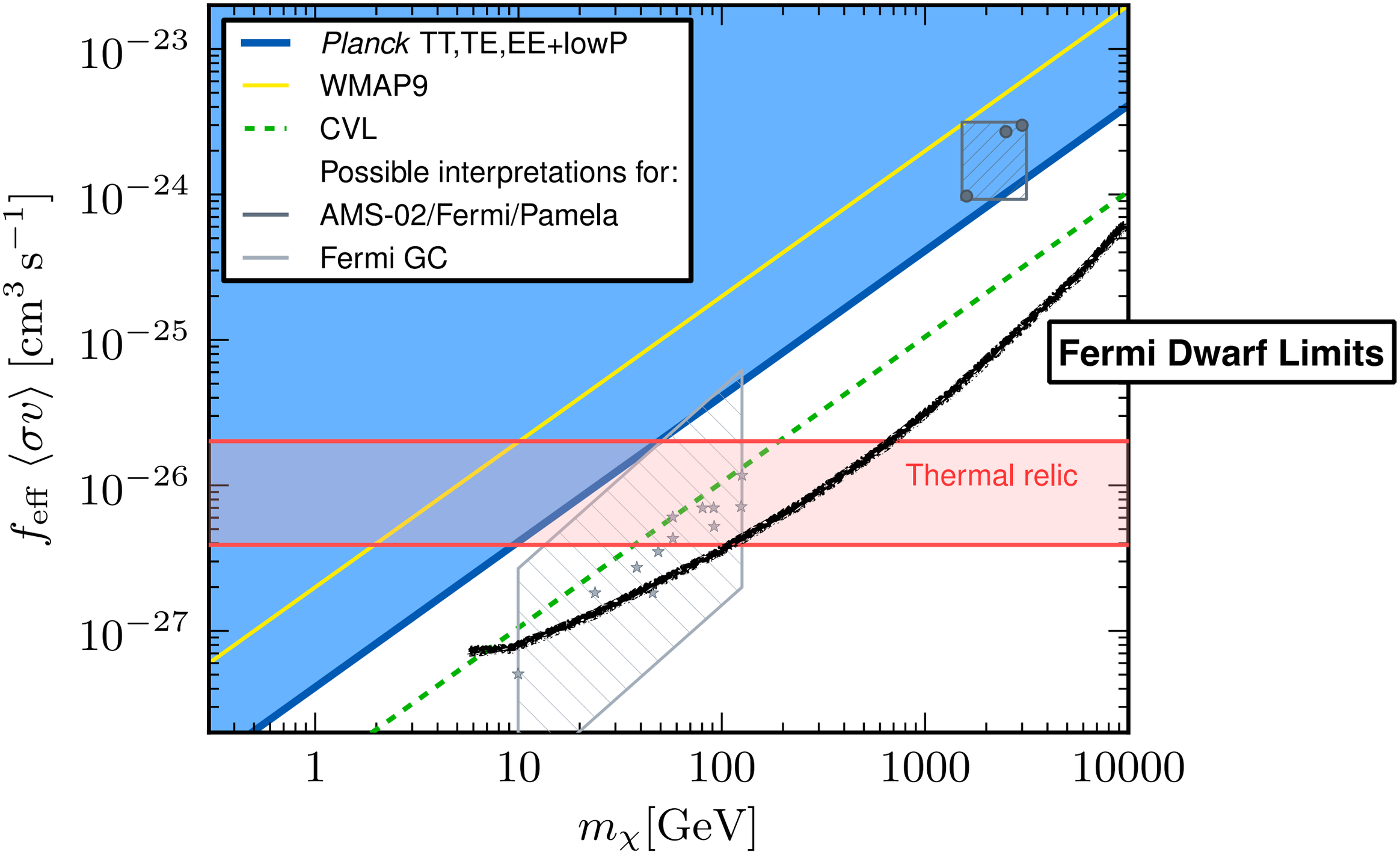
$$= 9.6 \times 10^{-25} \mathrm{cm}^3\,\mathrm{s}^{-1} \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)\left(\frac{1}{f(z)}\right)$$

$$f(z) \sim 0.05 - 1$$

Padmanabhan et al. PRD 72, 023508 (2005)
Slatyer et al. PRD 80, 043526 (2009)
Ade et al., (Planck), arXiv: 1502.01589 (2015)



Constraints from the CMB



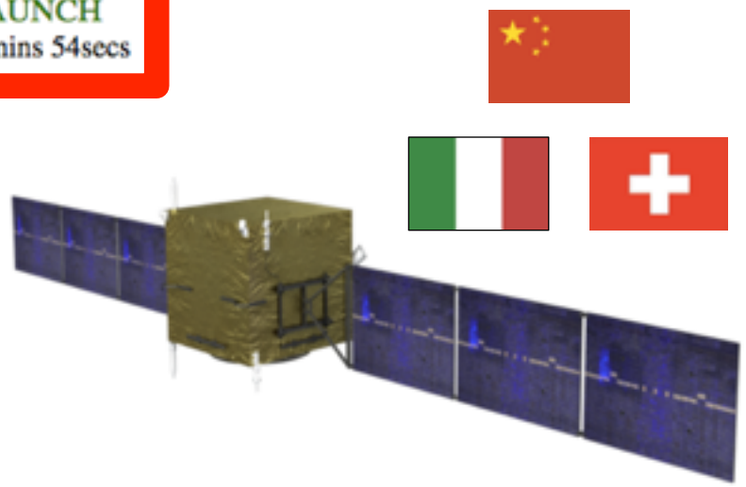
Ade et al., (Planck), arXiv: 1502.01589 (2015)

Future Prospects

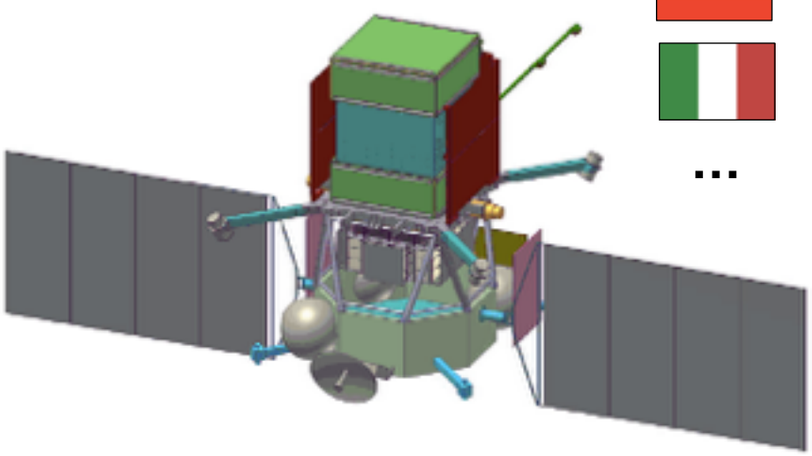
Future Prospects

DArk Matter Particle Explorer

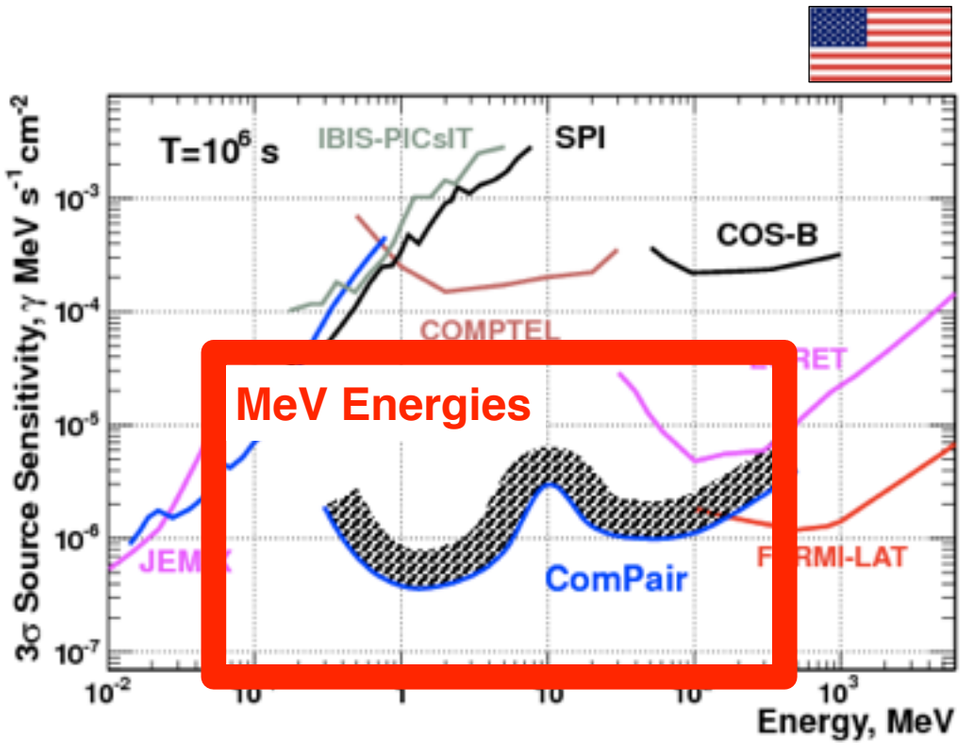
TIME TO LAUNCH
11days 12hrs 32mins 54secs



Gamma-400



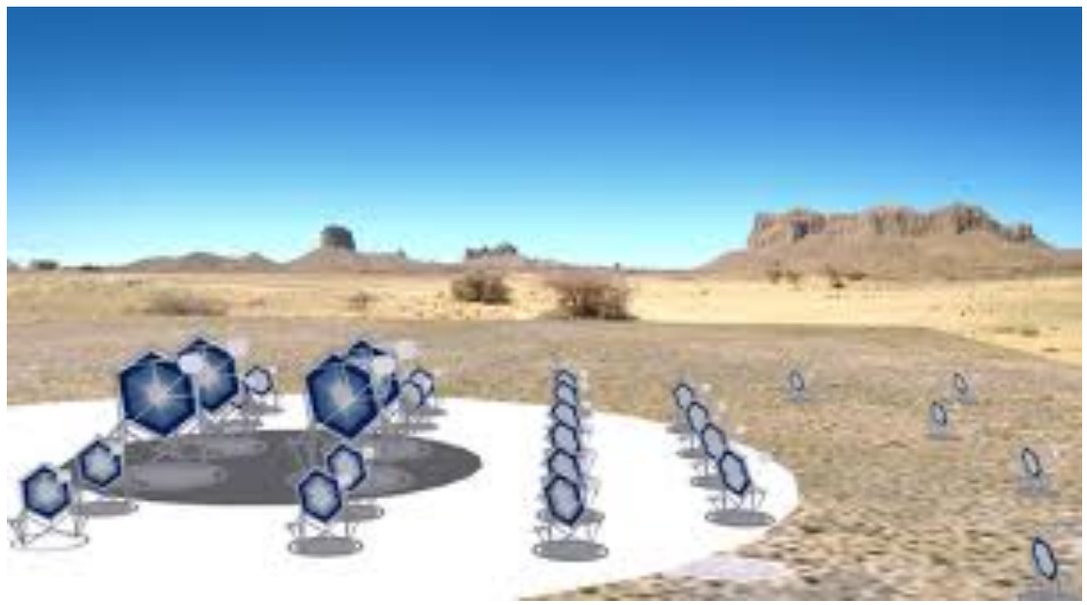
...



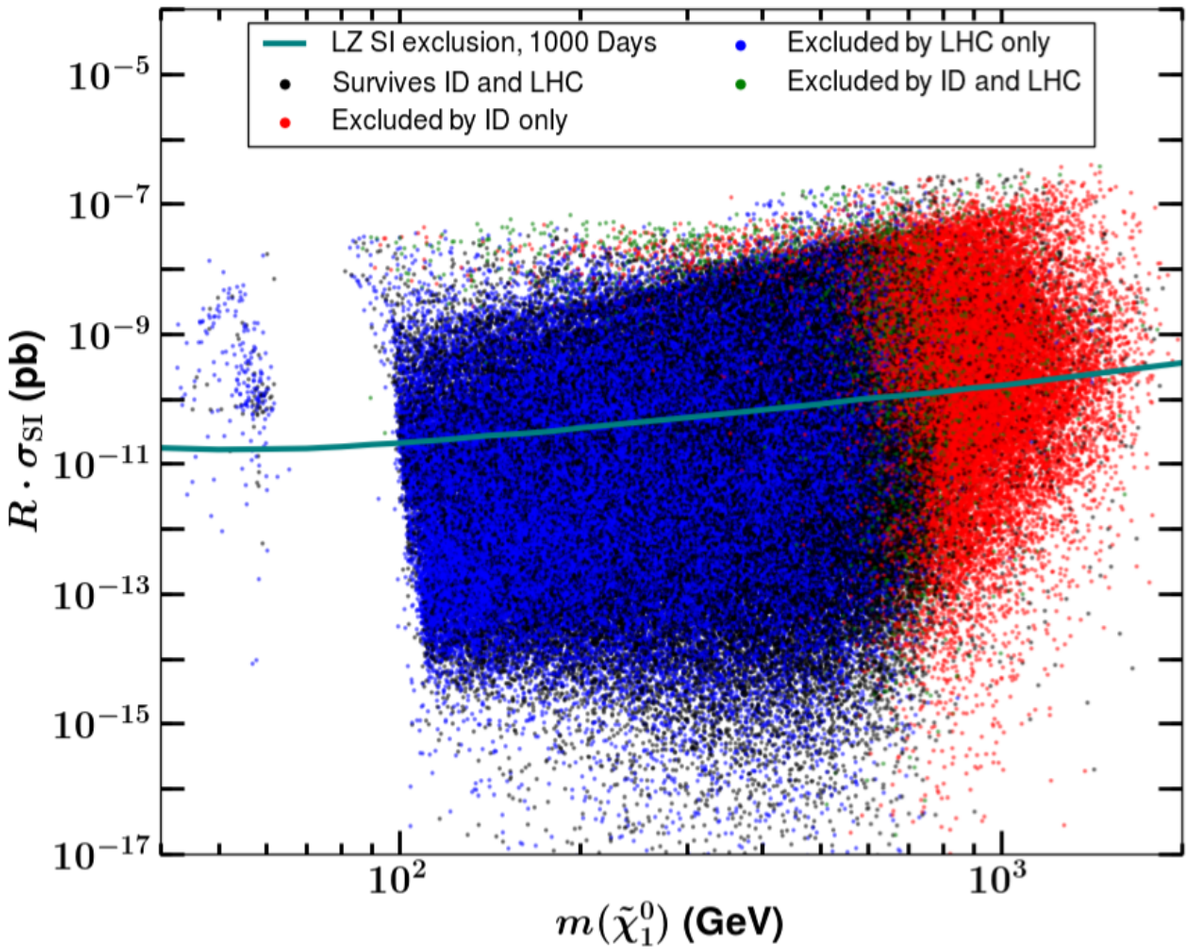
Future Prospects

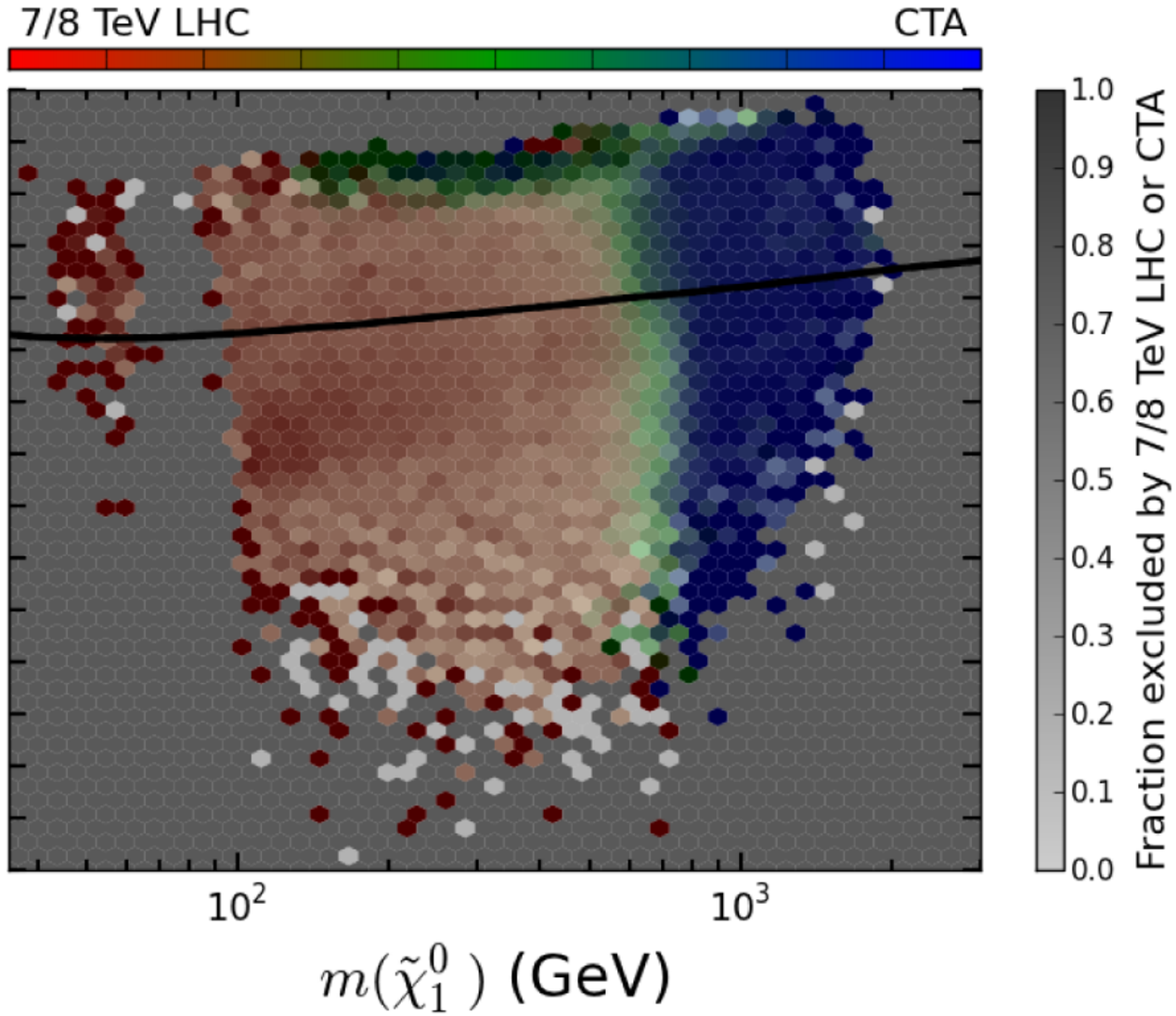
- **H.E.S.S. II**
  - The HESS telescope array has been augmented with a large fifth telescope
  - Lower gamma-ray energy threshold (~20-50 GeV)
  - Projected to extend sensitivity to dark matter in the GC < 10^{-25} cm^3s^{-1} at 1 TeV (see arXiv:1509.04123)

- **Cherenkov Telescope Array (CTA)**
  - Array of small-, medium-, and large-size ground-based air Cherenkov telescopes
  - Two locations (Chile and Canary Islands)
  - European-led (US contribution yet to be determined)
  - Constrain the thermal relic cross section for dark matter masses >100 GeV using observations of the Galactic Center



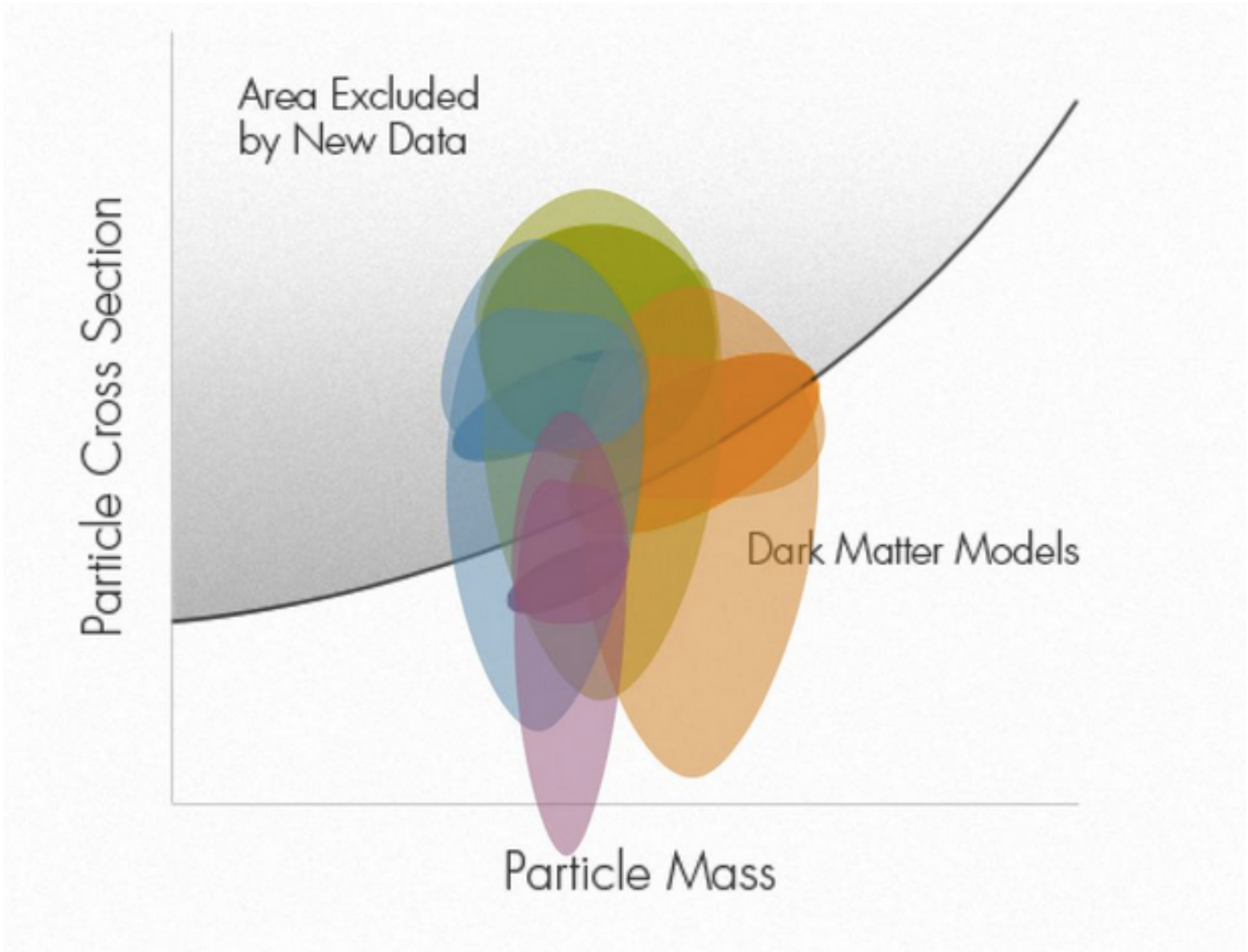
Dark Matter Searches with CTA





Cahill-Rowley et al., PRD 91, 055011 (2015)

Galactic Center Comparison

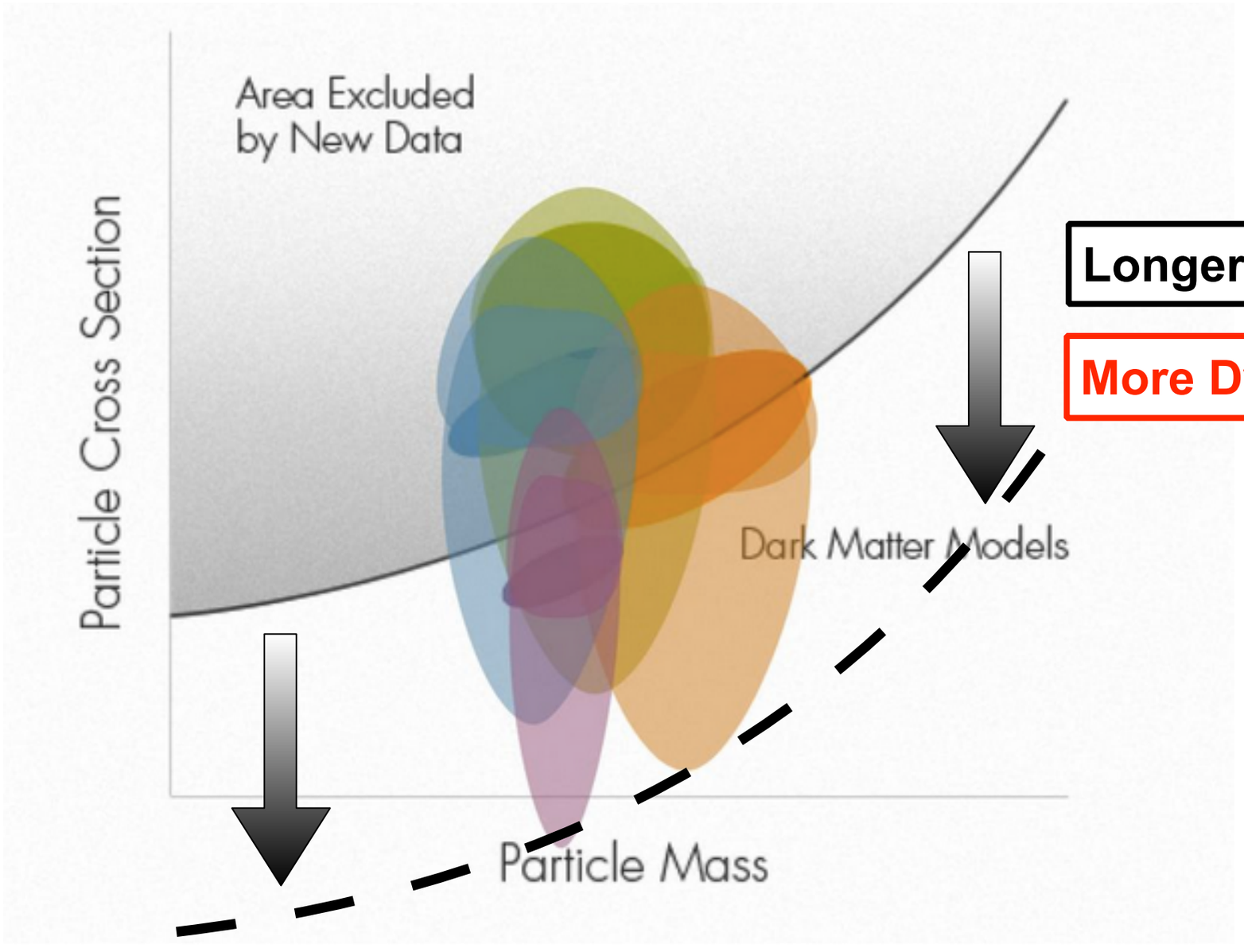


Kevork Abazajian @kevaba · Oct 25

@QuantaMagazine @nattyover I corrected the figure for the article to reflect the approx. halo density uncert to 2σ

1

Galactic Center Comparison

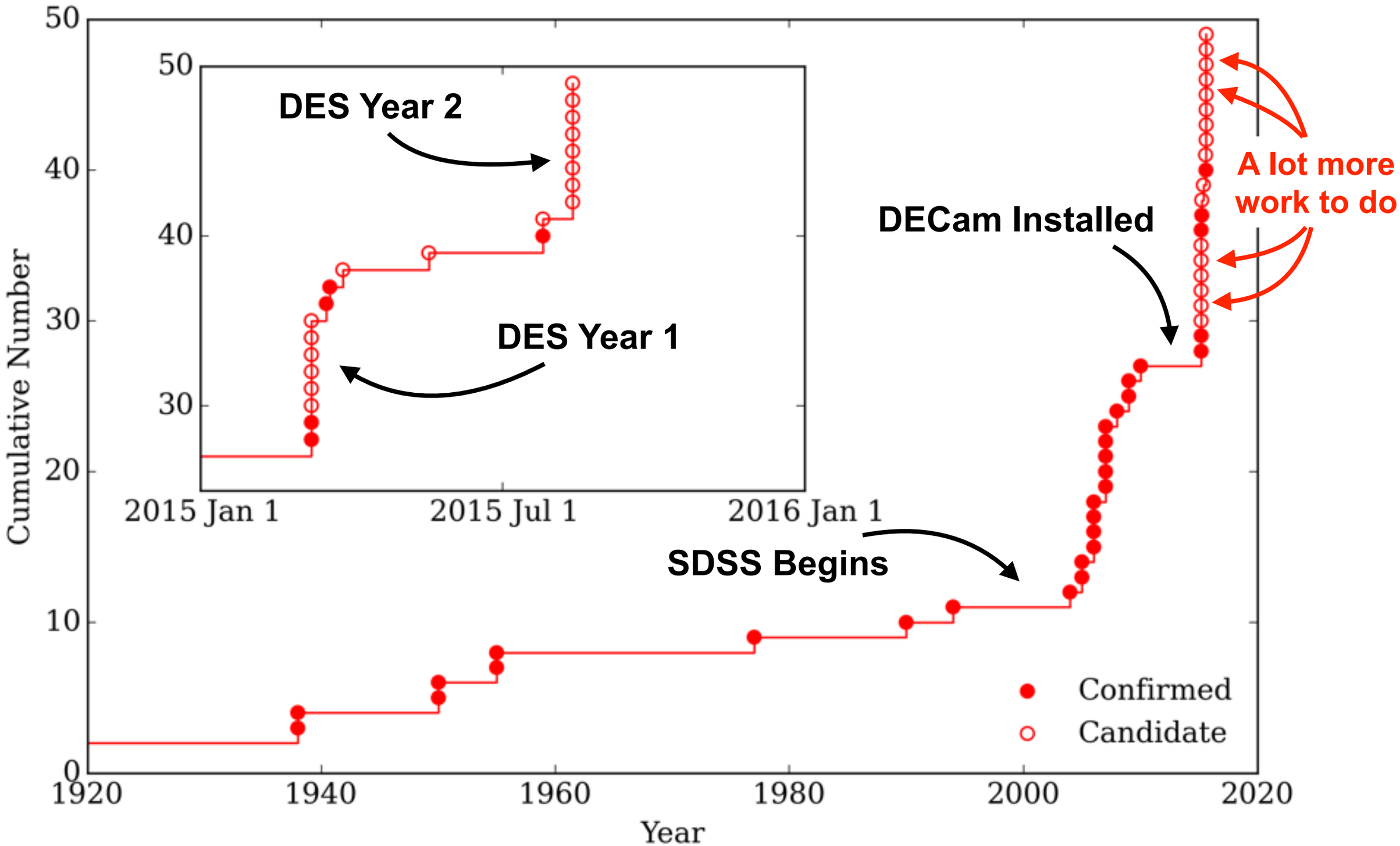


Kevork Abazajian @kevaba · Oct 25

@QuantaMagazine @nattyover I corrected the figure for the article to reflect the approx. halo density uncert to 2σ

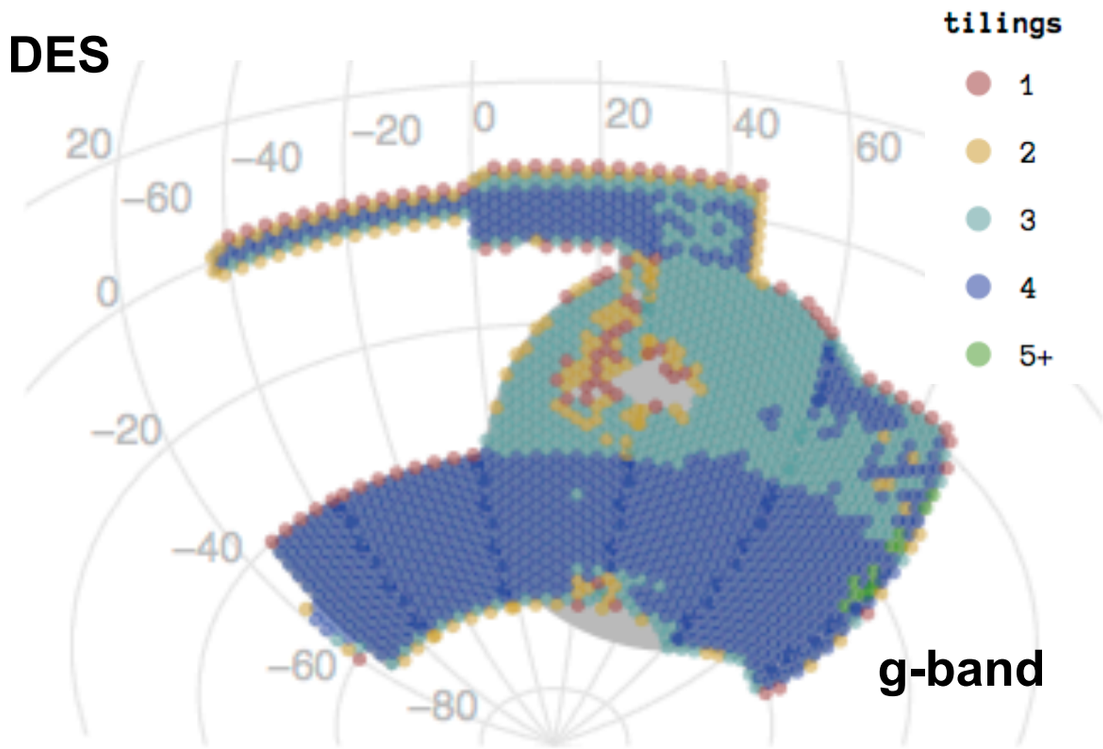
1

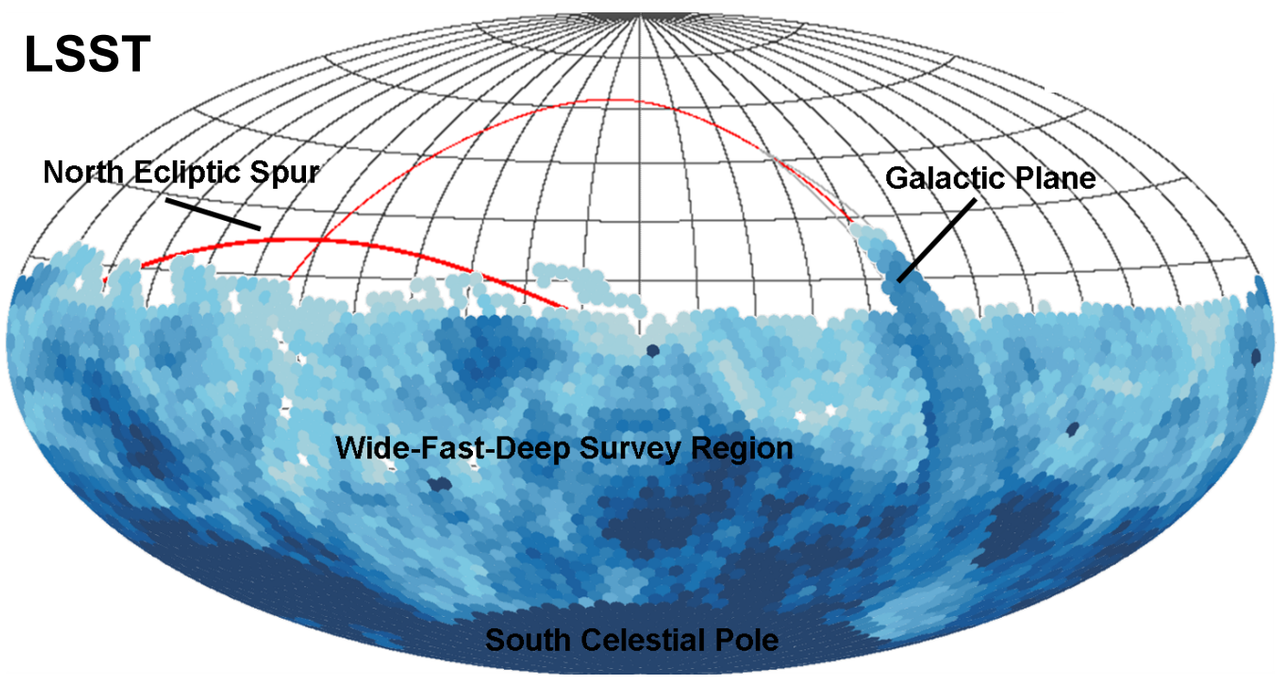
Dwarf Galaxy Discovery Timeline



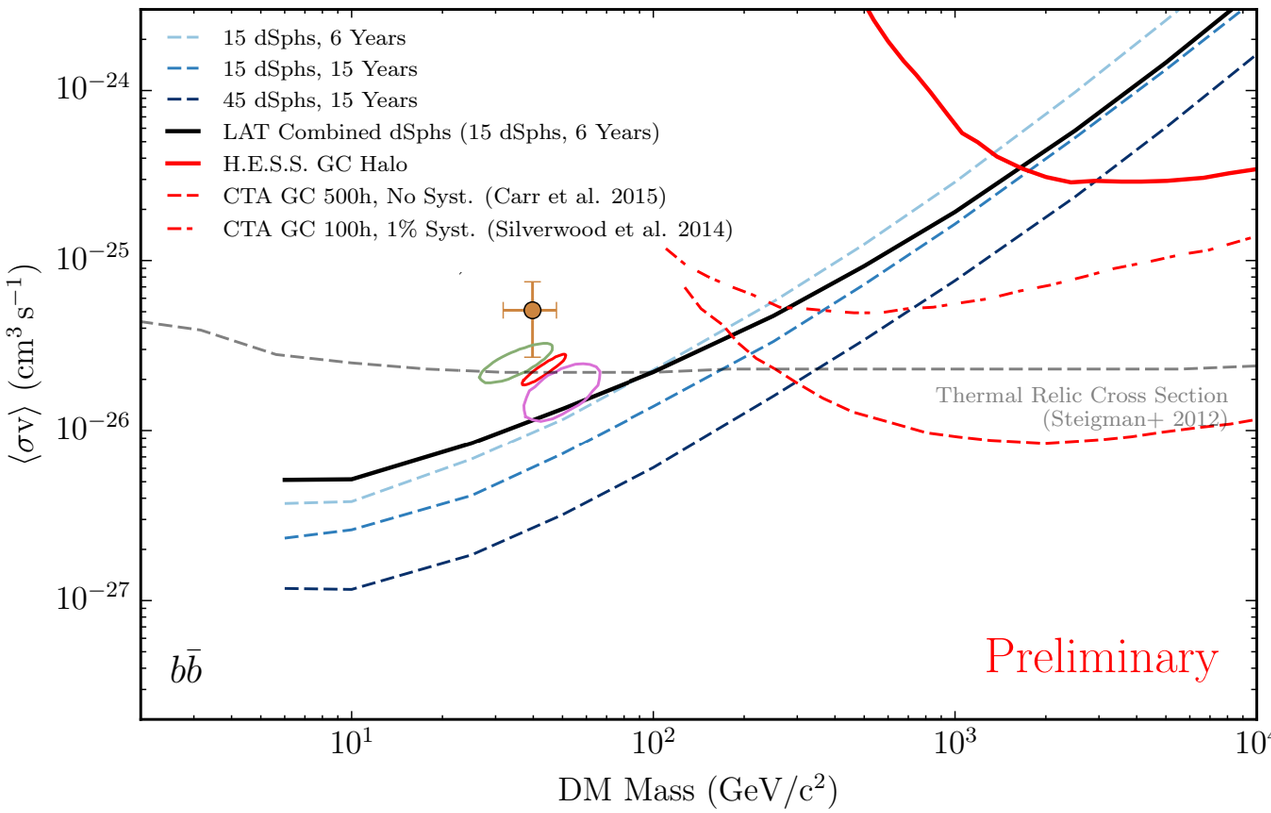
Looking Forward

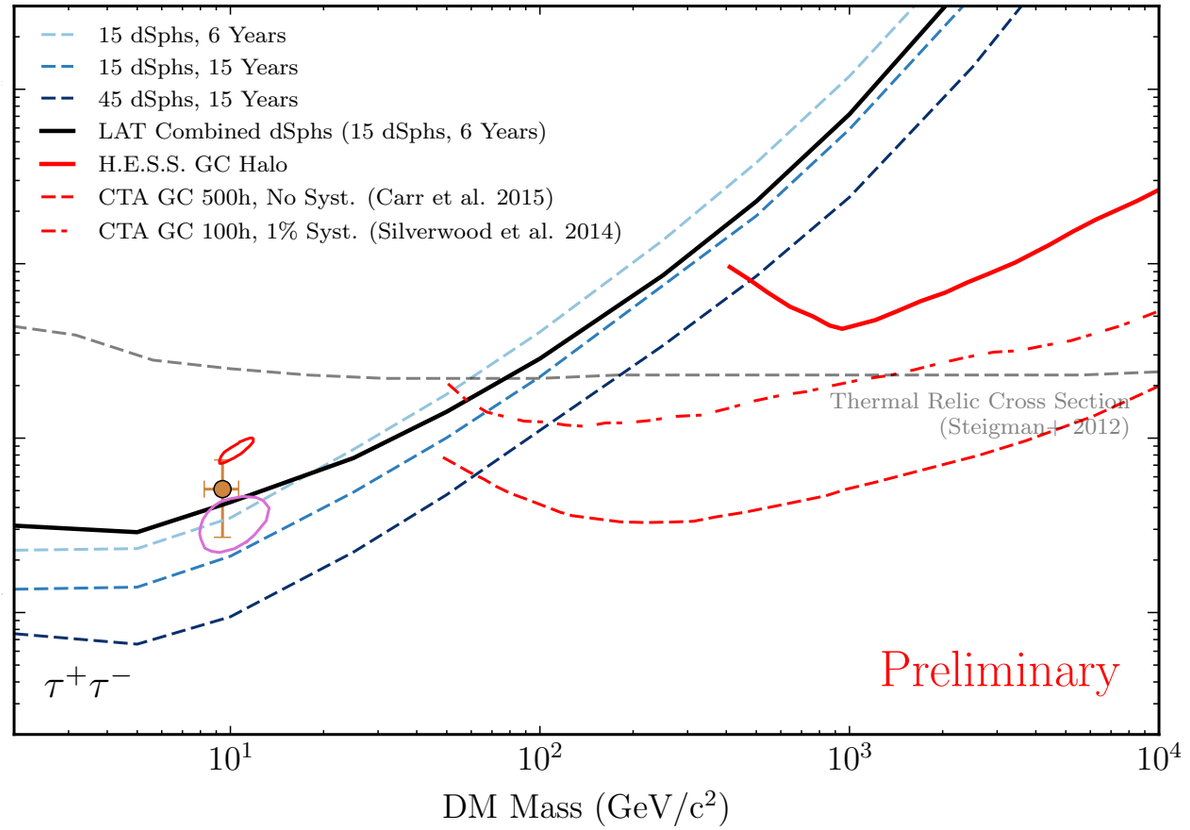
- A large spectroscopic campaign is underway to classify and characterize newly discovered systems
- Future sky coverage:
  - DES Y3+: a few hundred deg^2 (and greater sensitivity)
  - Additional DECam observations beyond DES
  - LSST: 20,000 deg^2 (and much greater sensitivity)
- The LAT continues to survey the entire gamma-ray sky.
  - With 45 dwarfs and 15 years of LAT data, expect sensitivity to thermal relic dark matter with a mass of ≳400 GeV
  - Dwarfs will provide a sensitive test of DM interpretations of the Galactic center excess.





Looking Forward





Fermi-LAT Collaboration (2015)

Backup Slides

Dark Matter

Astrophysical evidence for missing mass

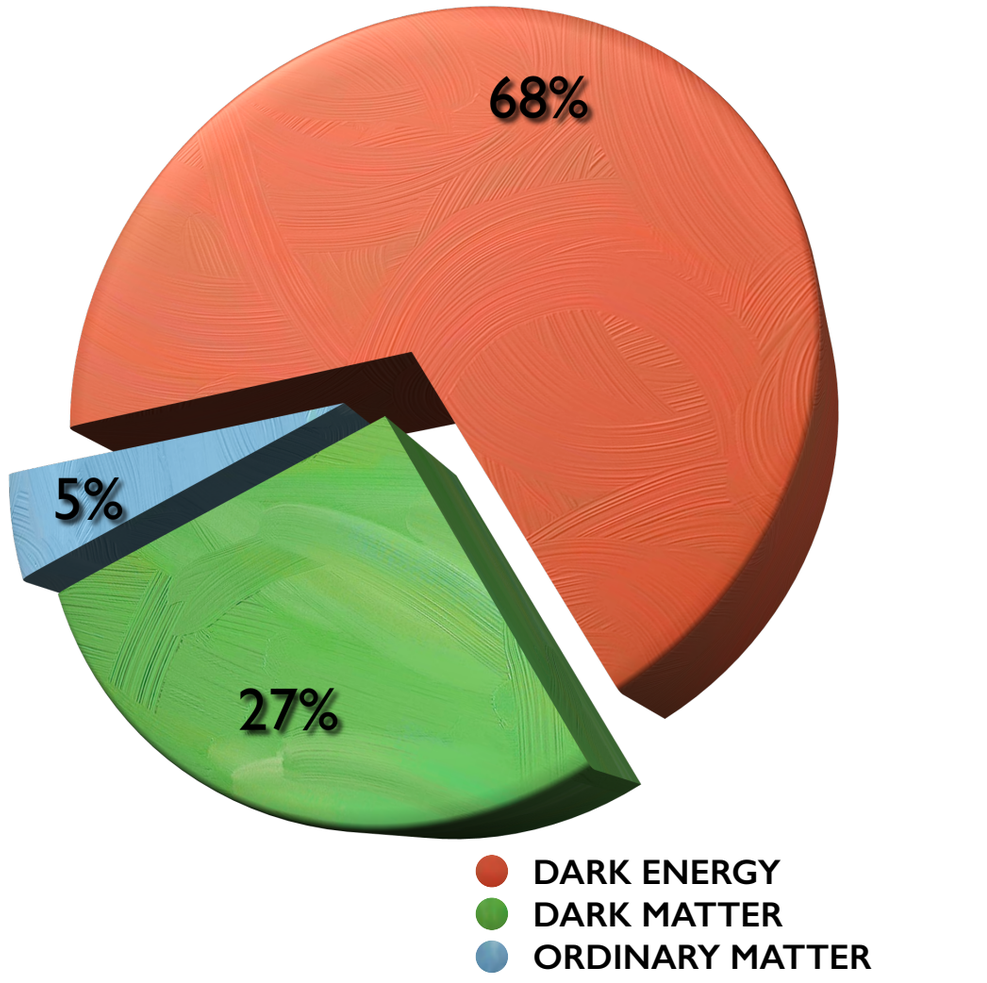
- **Galaxy rotation curves**
- **Colliding clusters**
- **Cosmological probes**

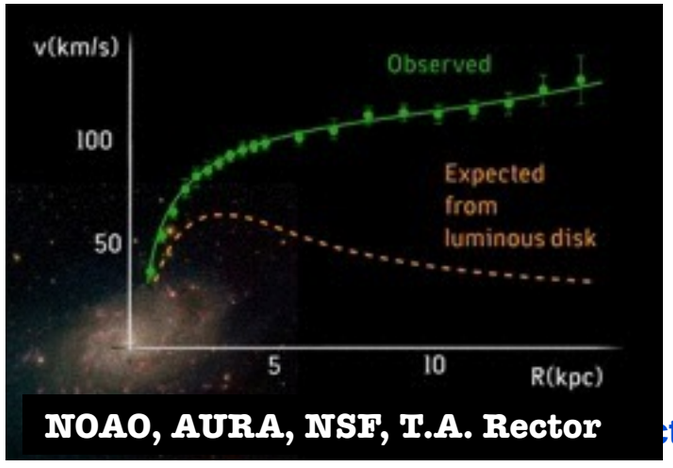
Observations constrain a solution to be

- **Non-baryonic**
- **(Almost totally) neutral**
- **(Almost totally) collisionless**

Plethora of theoretical candidates:

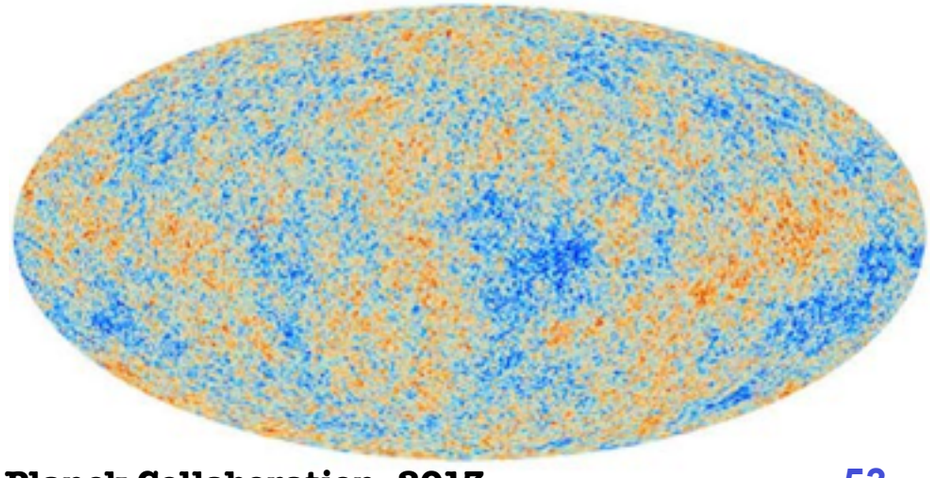
- **Axions, sterile neutrinos, etc.**
- **Modifications to gravity**
- **Weakly Interacting Massive Particles (WIMPS)**



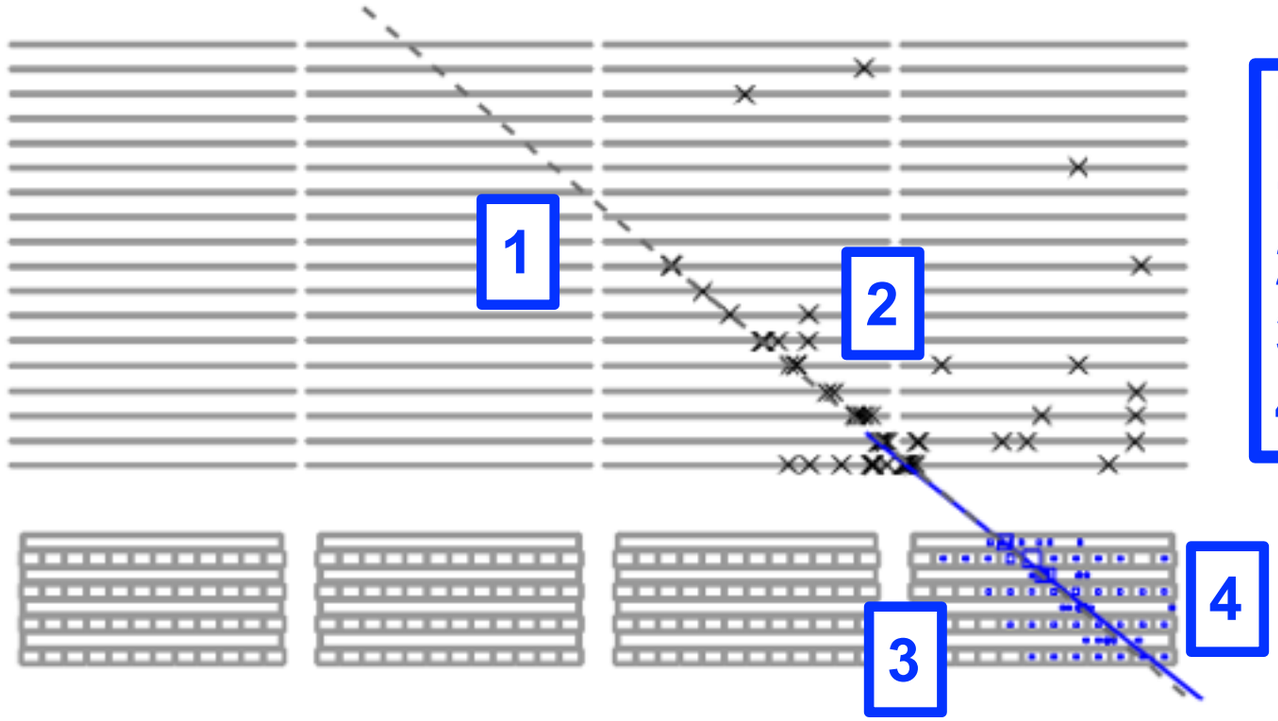


NOAO, AURA, NSF, T.A. Rector


Markevitch & Clowe, 2006

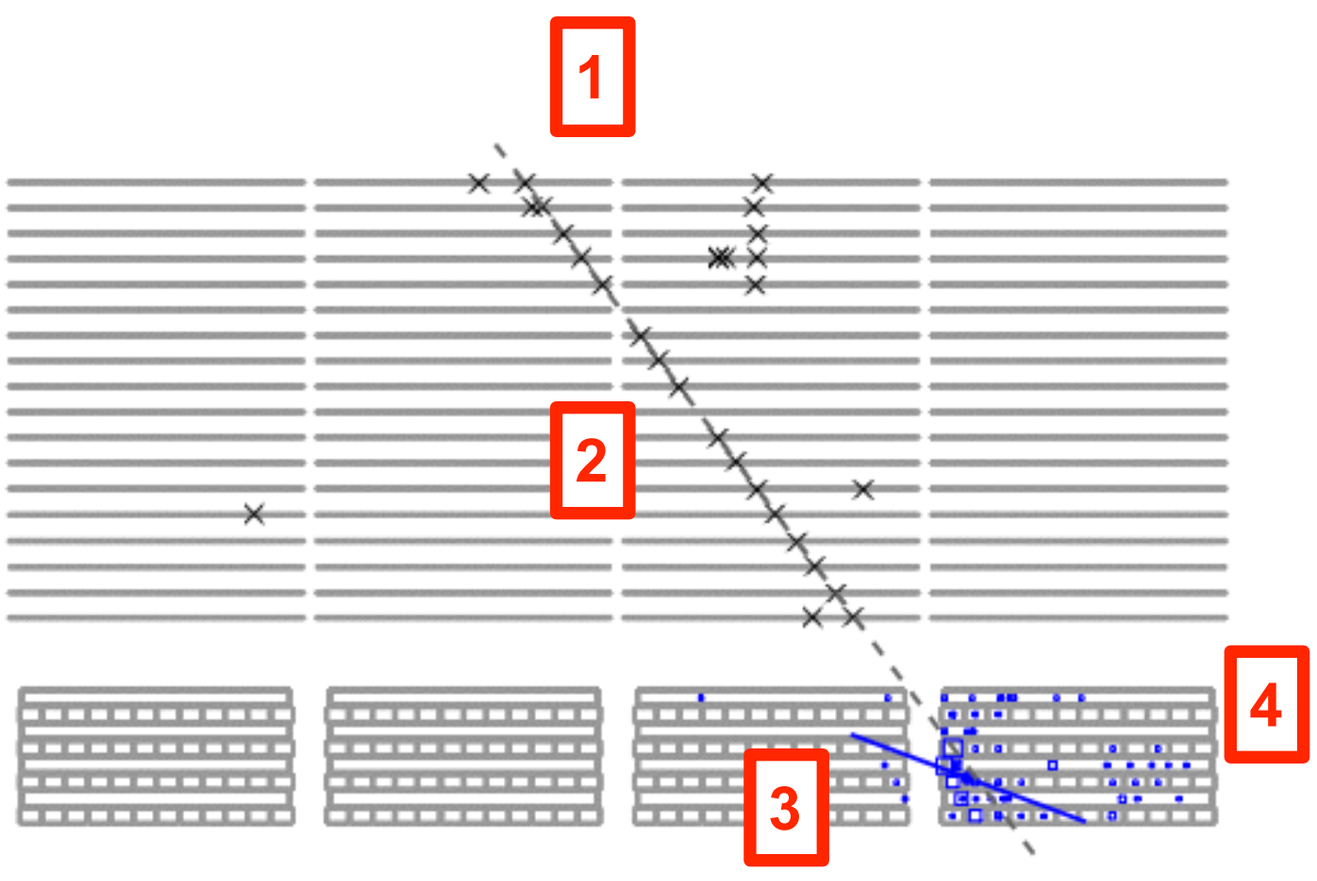

Planck Collaboration, 2013

Event-by-Event Detection

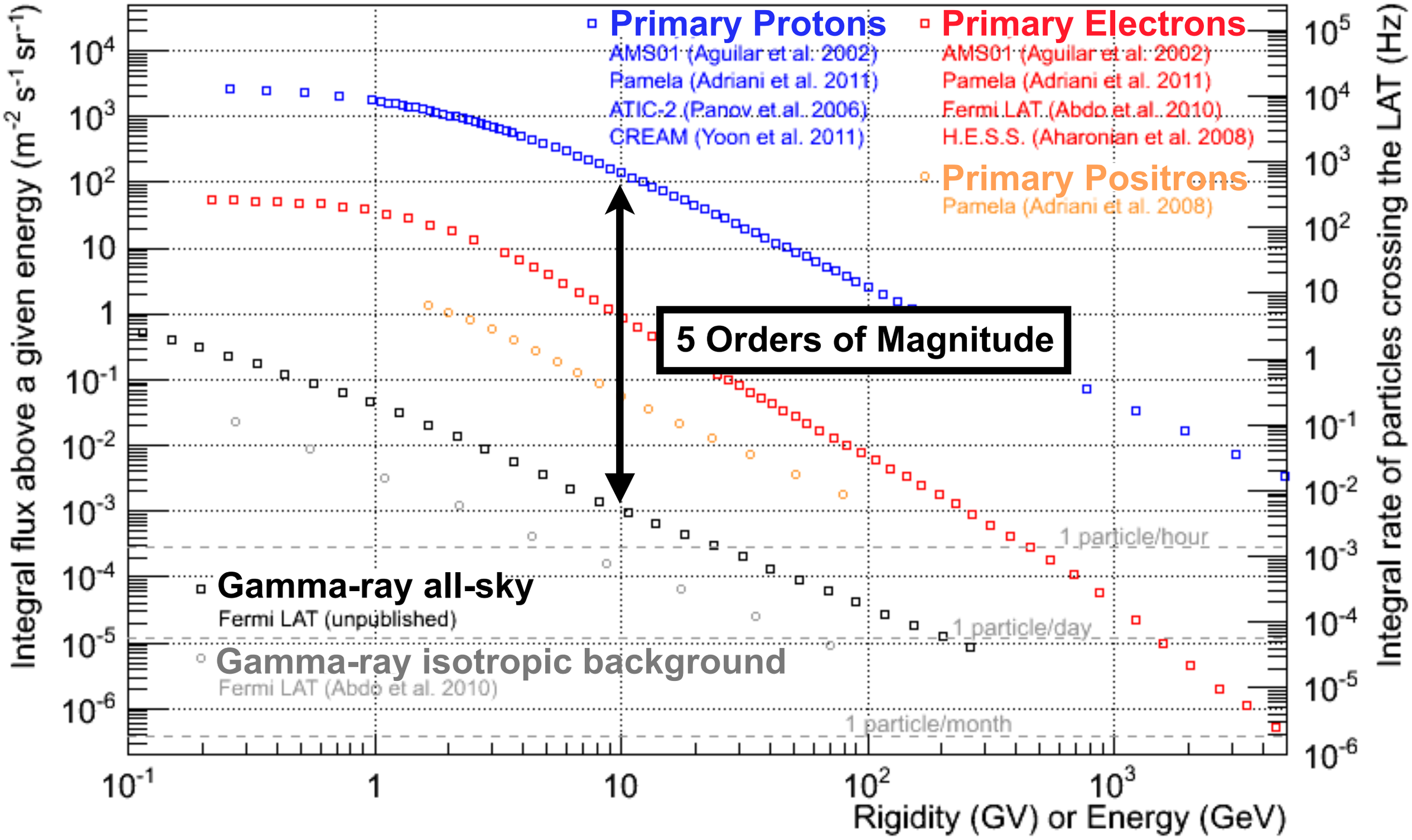


Nearly ideal γ-ray candidate:
1. Track starts in middle of TKR
2. Extra hits near track
3. CAL axis aligned with track
4. CAL energy confined near axis

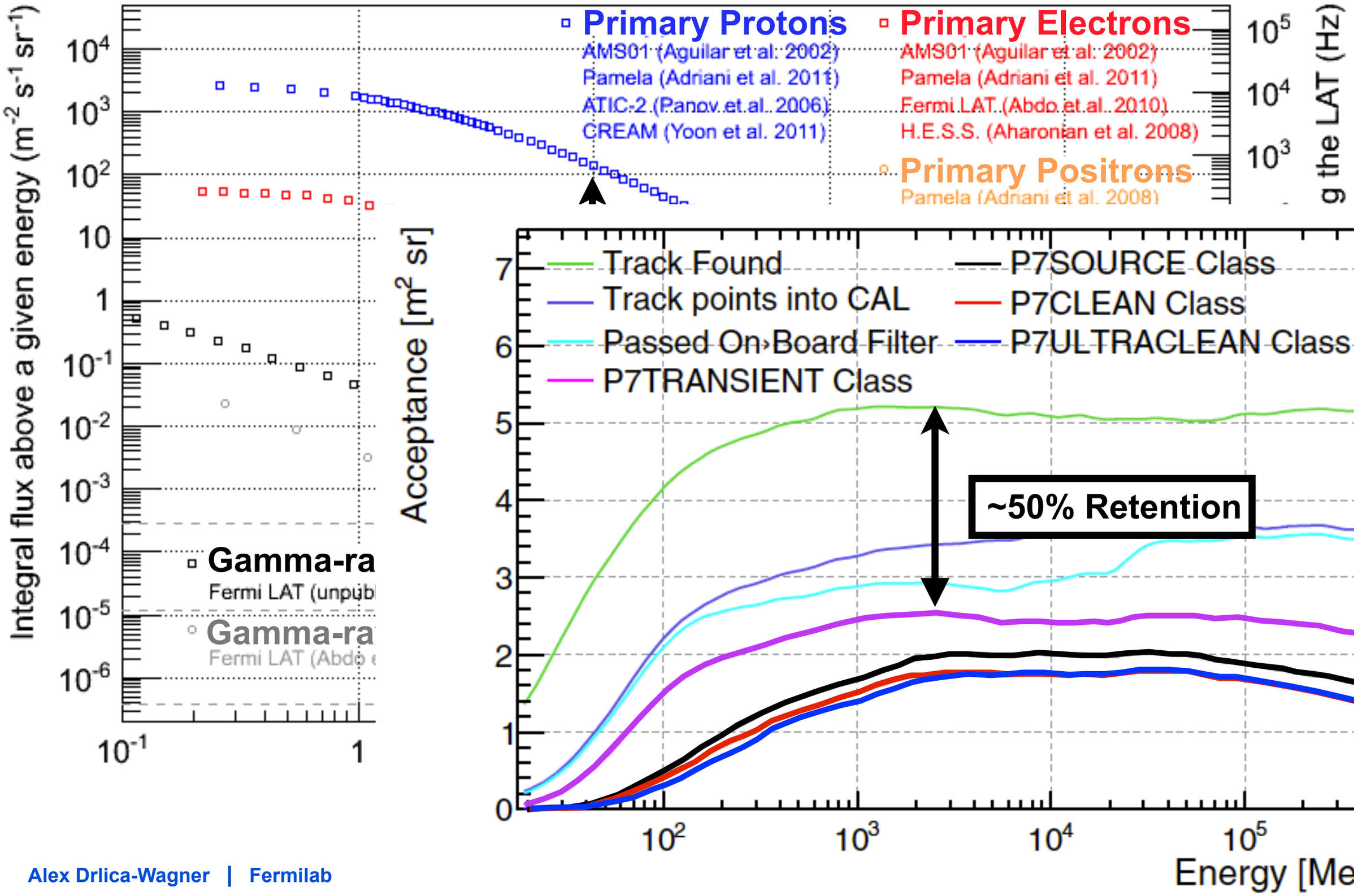
Nearly ideal proton candidate:
1. Starts at top of TKR
2. Few extra hits near track
3. CAL axis not-aligned with track
4. CAL energy “lumpier”
5. Signal in the ACD (not shown)



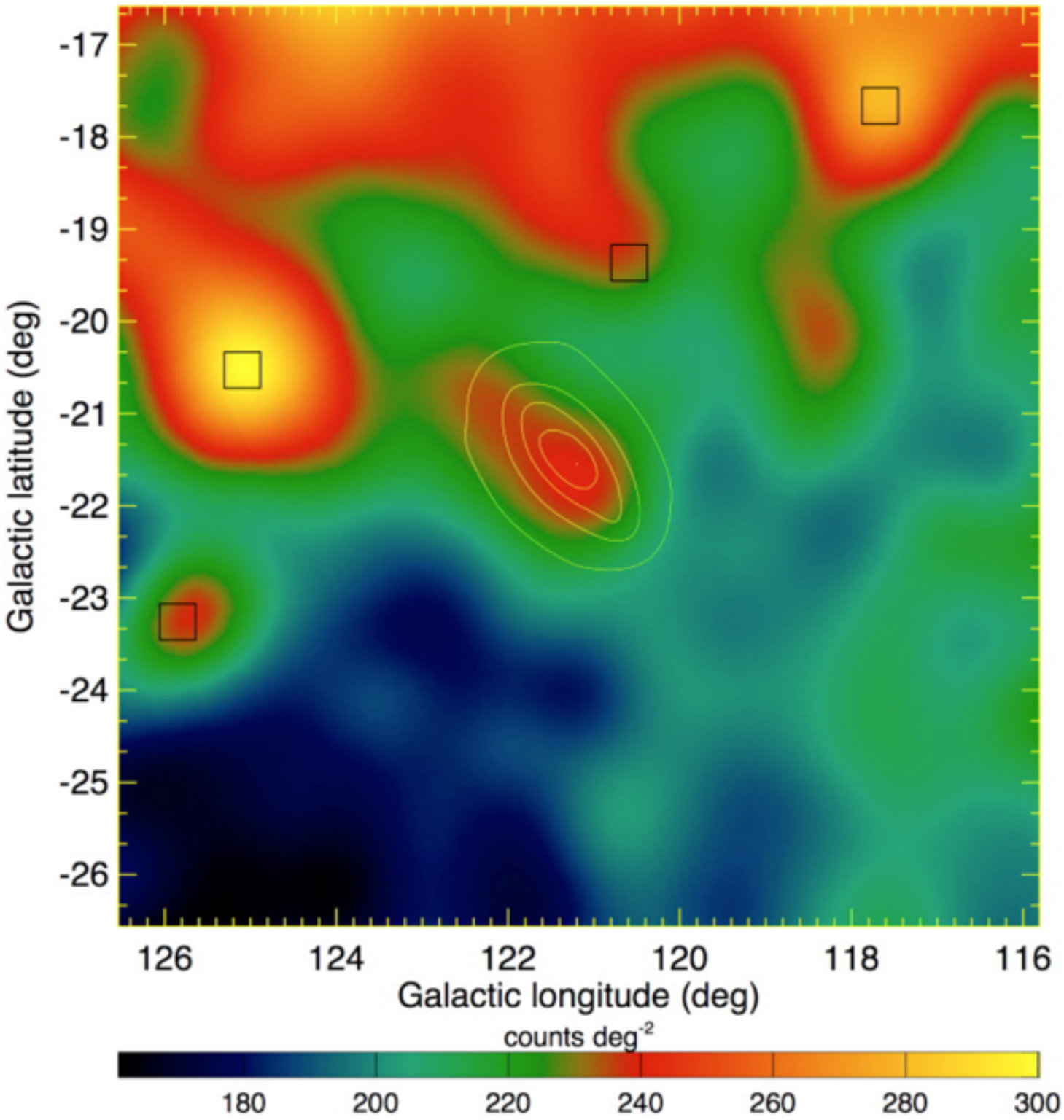
Background Rejection



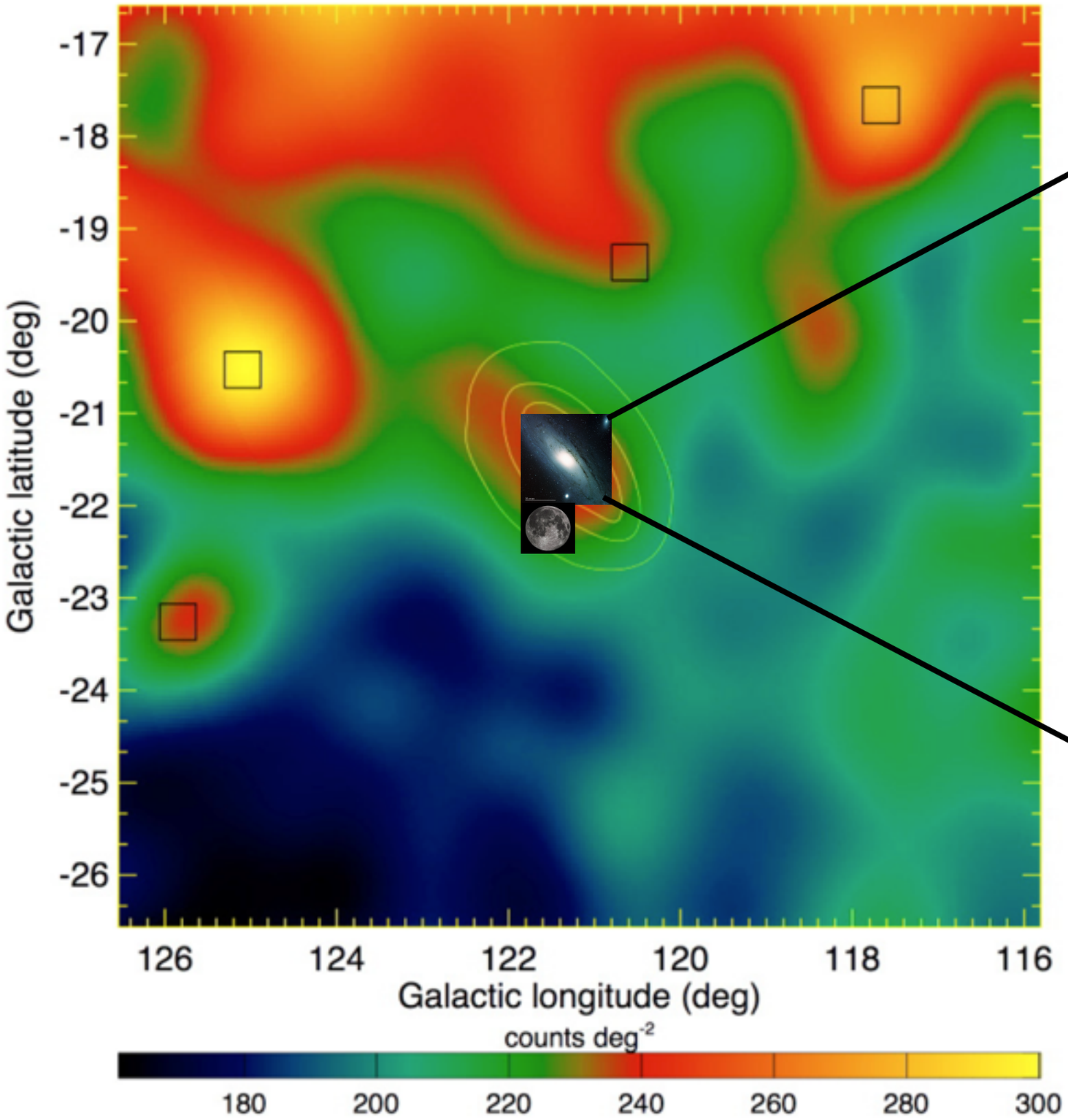
Background Rejection



Fermi-LAT Performance

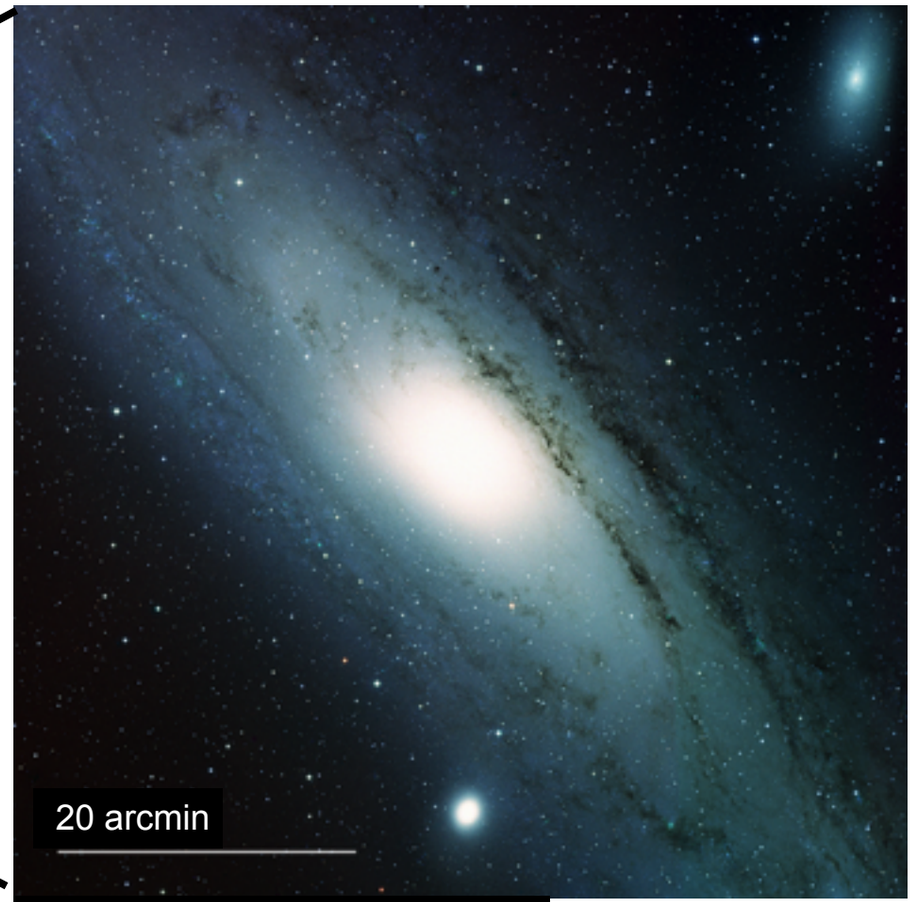


Fermi-LAT Performance



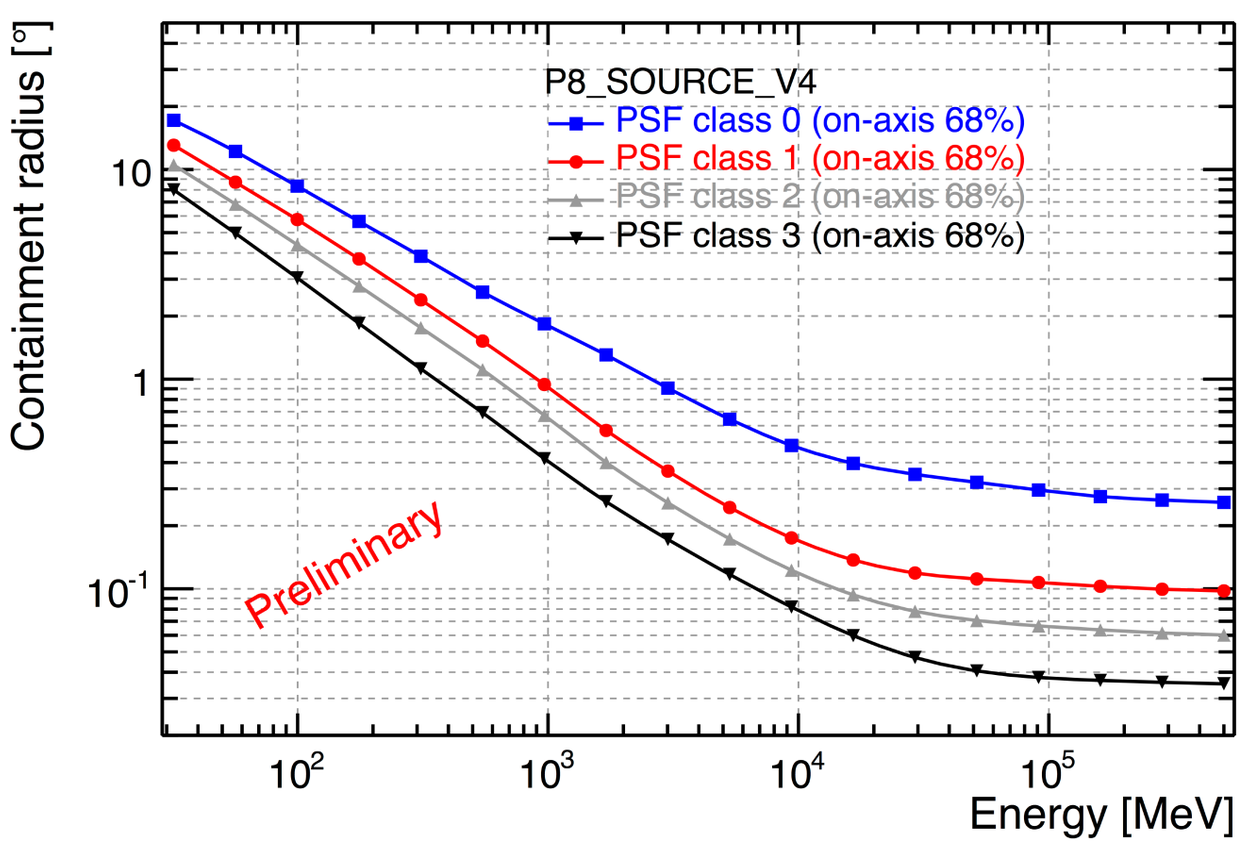
Andromeda (M31)

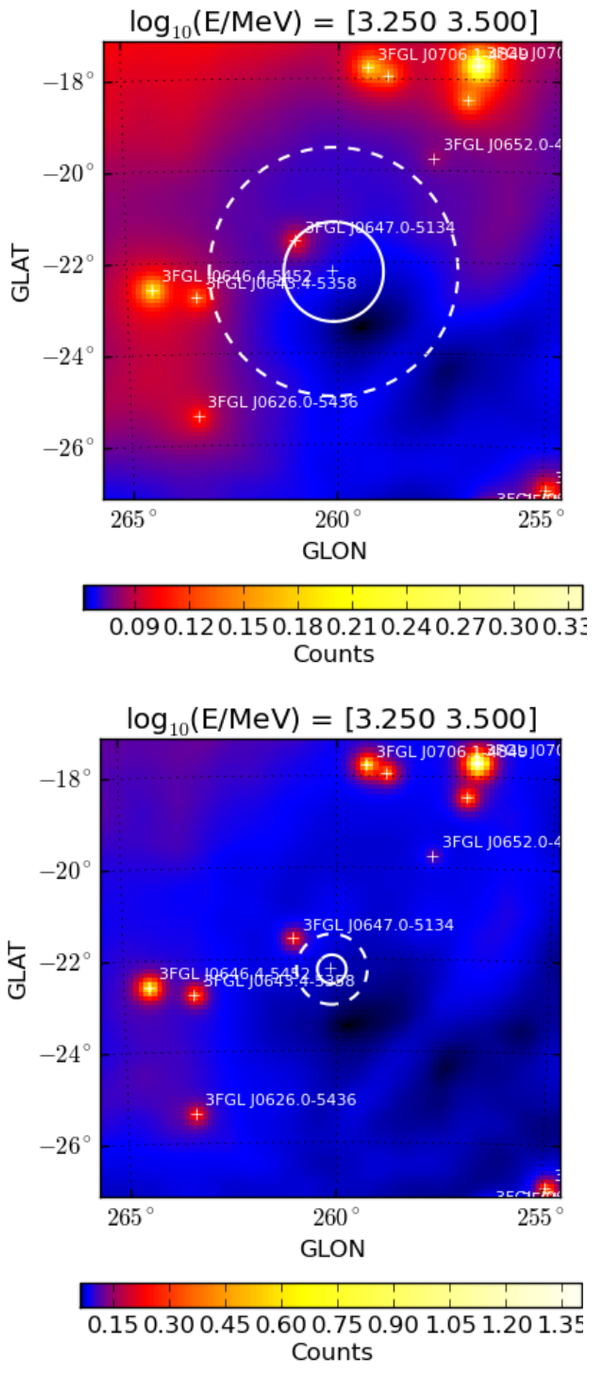
Optical DSS Image

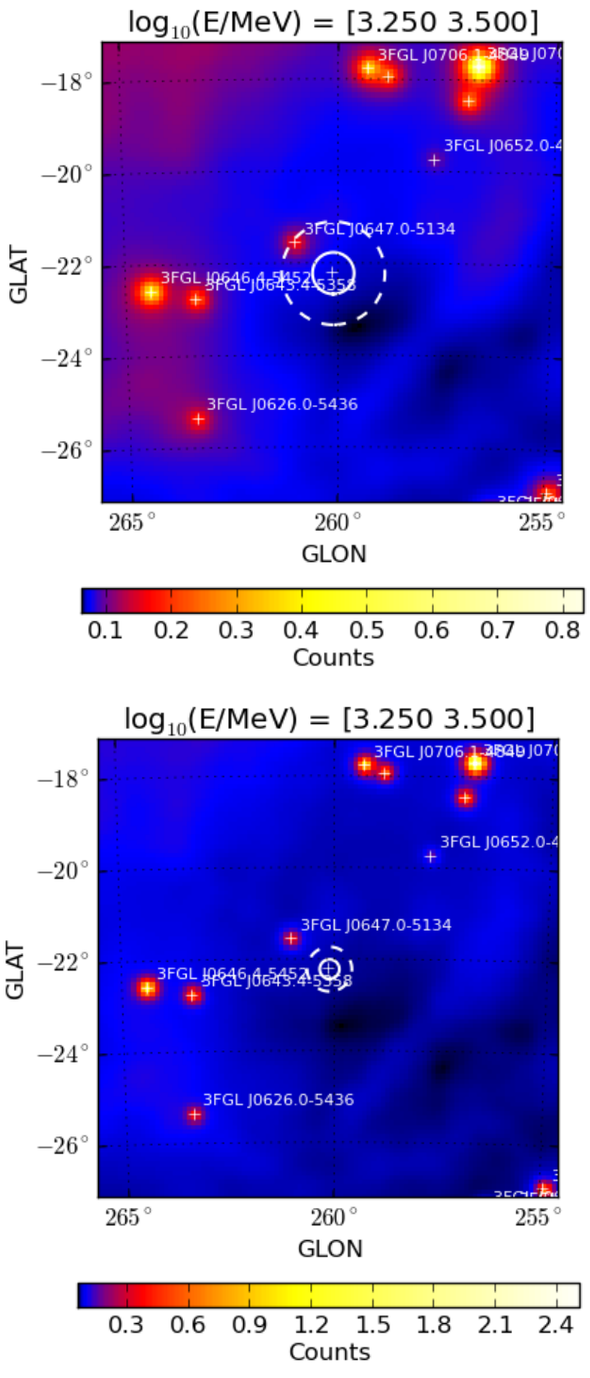


Pass 8: Better "Seeing"

- **Events can be divided into classes based on the quality of the event reconstruction.**
- **Combine events from all PSF event classes into a joint likelihood fit to avoid loss in effective area.**
- **Results in another ~10-20% gain in point-source sensitivity.**

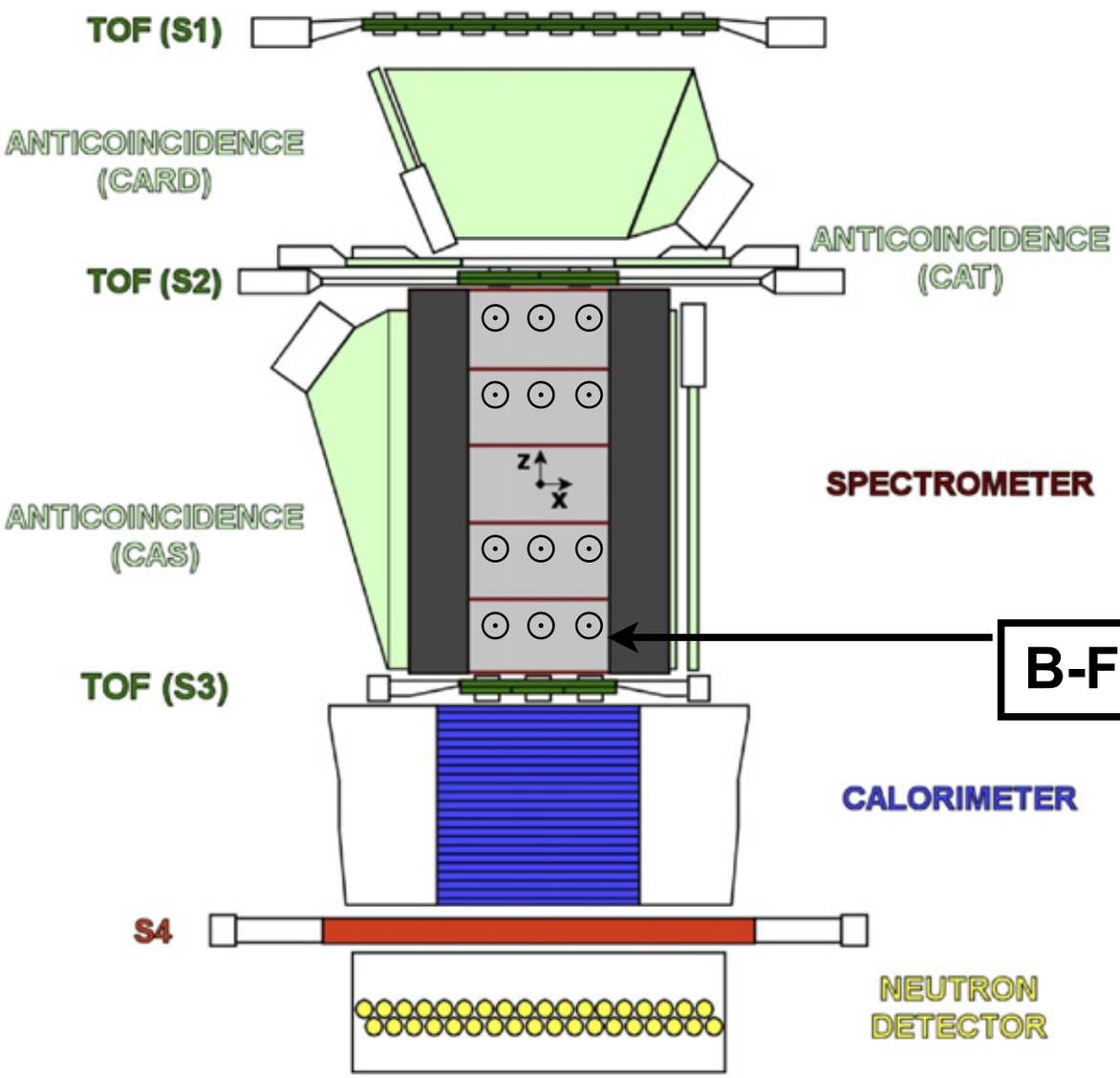






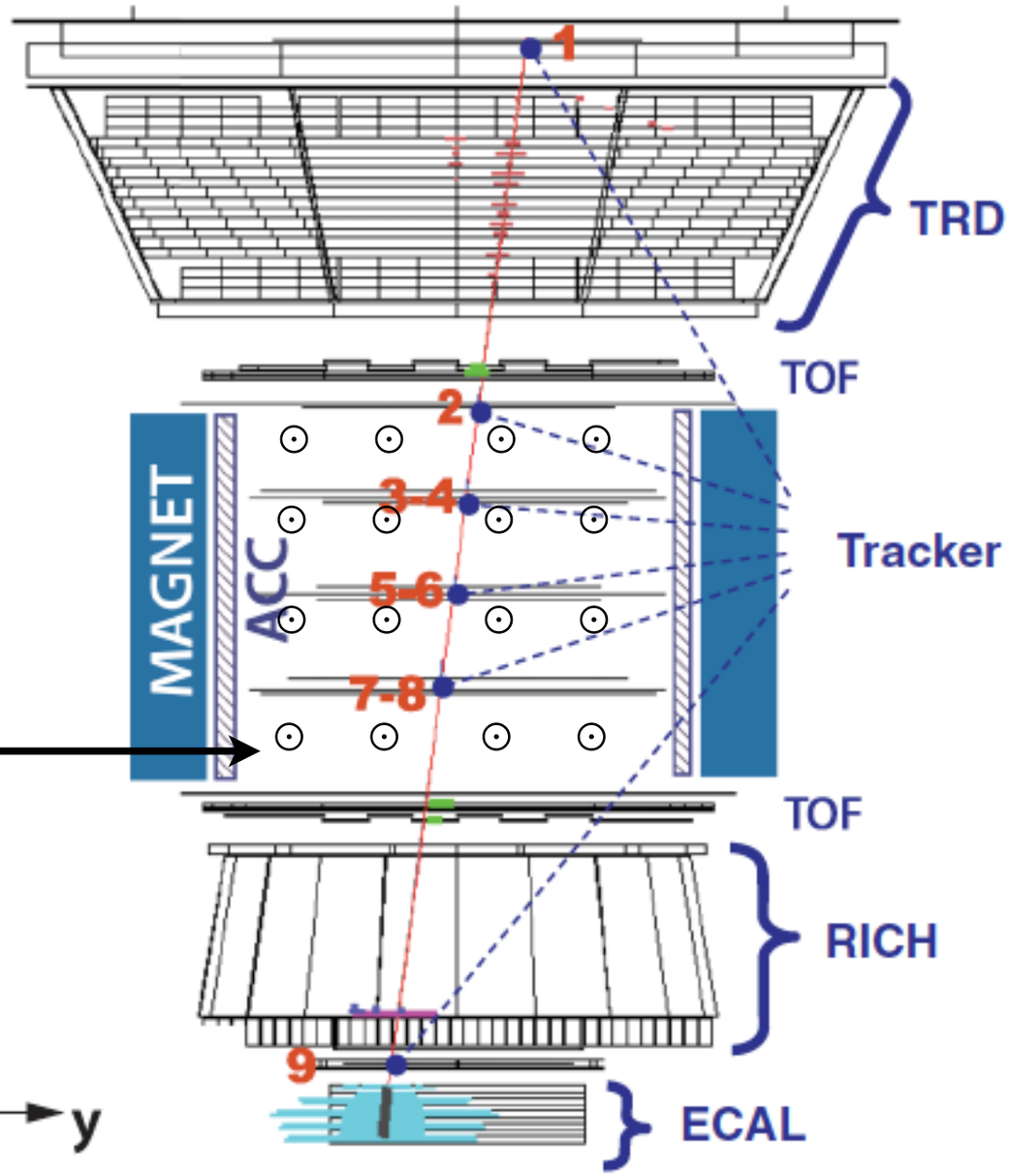
Charged Particles

PAMELA



Picozza et al., Astropart. Phys. 27, 296 (2007)
Adriani et al., Nature 458 (2009)

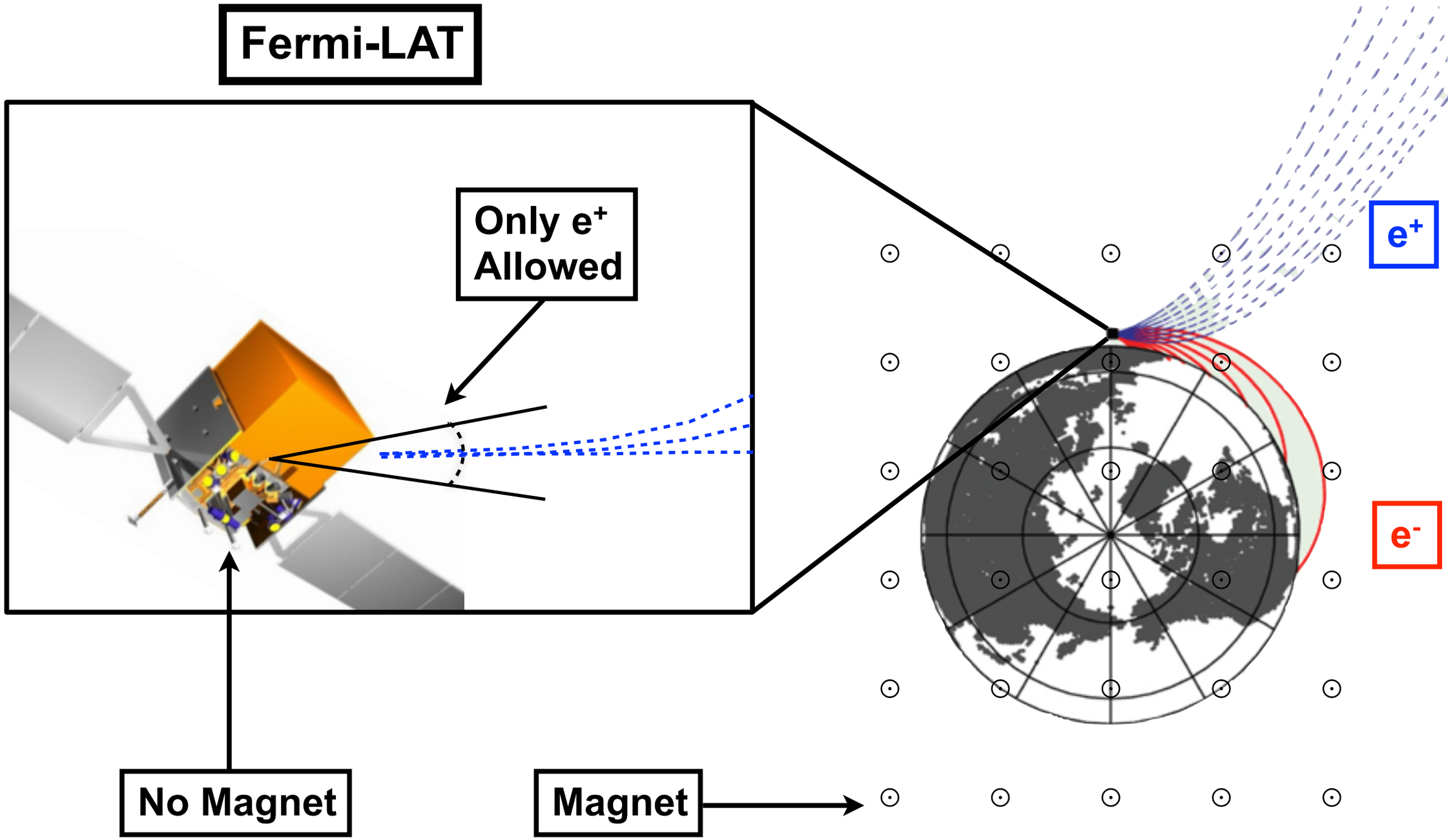
AMS-02



B-Field

Aguilar et al., PRL 110, 141102 (2013)
Kounine, et al. Int. J. Mod. Phys. E. 21, 08 (2012)

Charged Particles

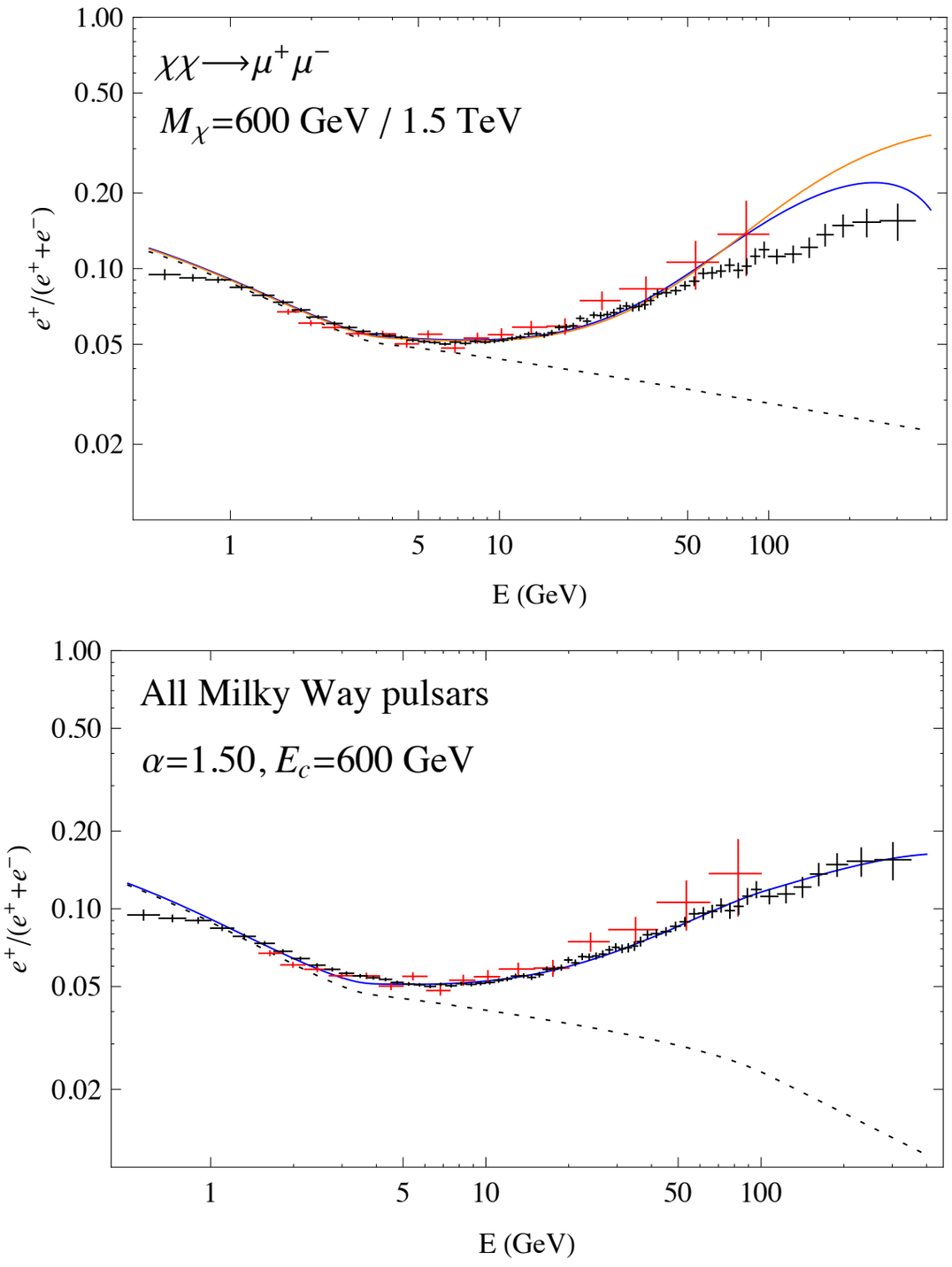


Ackermann et al., PRL 108, 1 (2012)

Daniel & Stephens, PRL 15, 769 (1965)

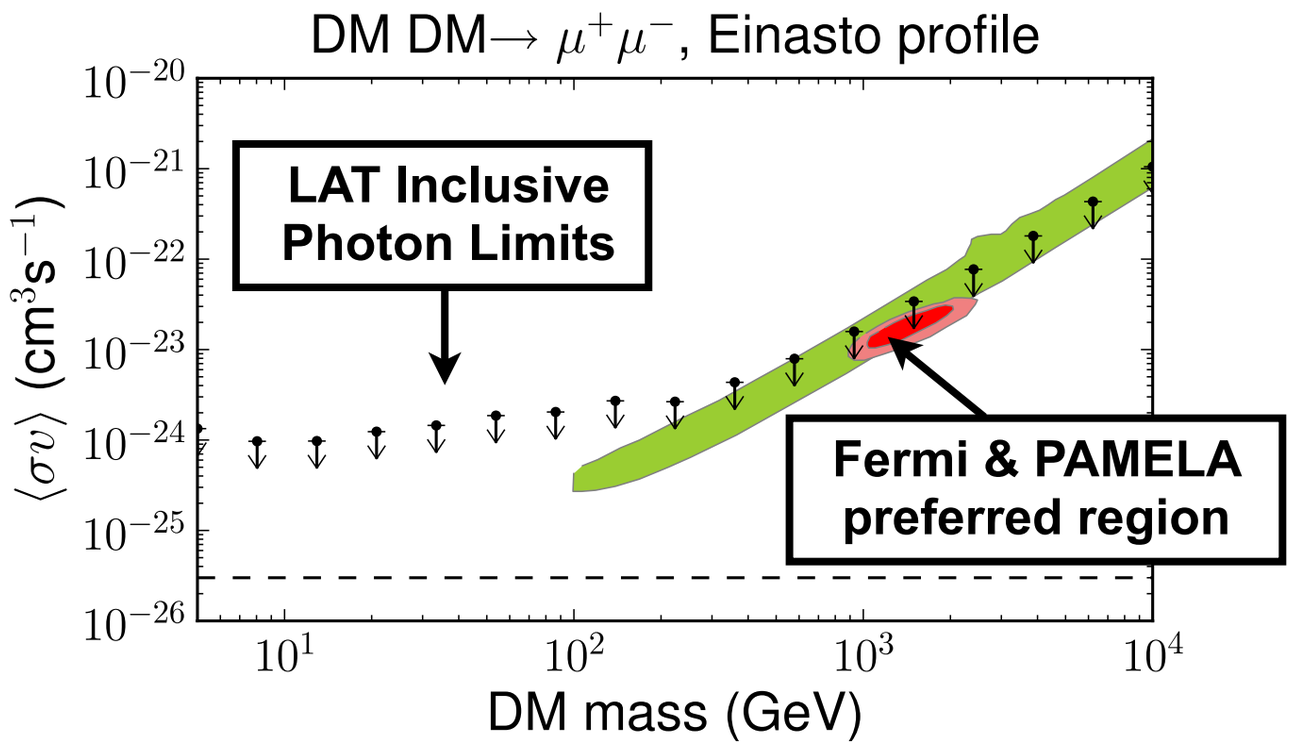
Müller & Tang, ApJ. 312, 183 (1987)

Positron Fraction



Cholis & Hooper, PRD 88, 023013 (2013)

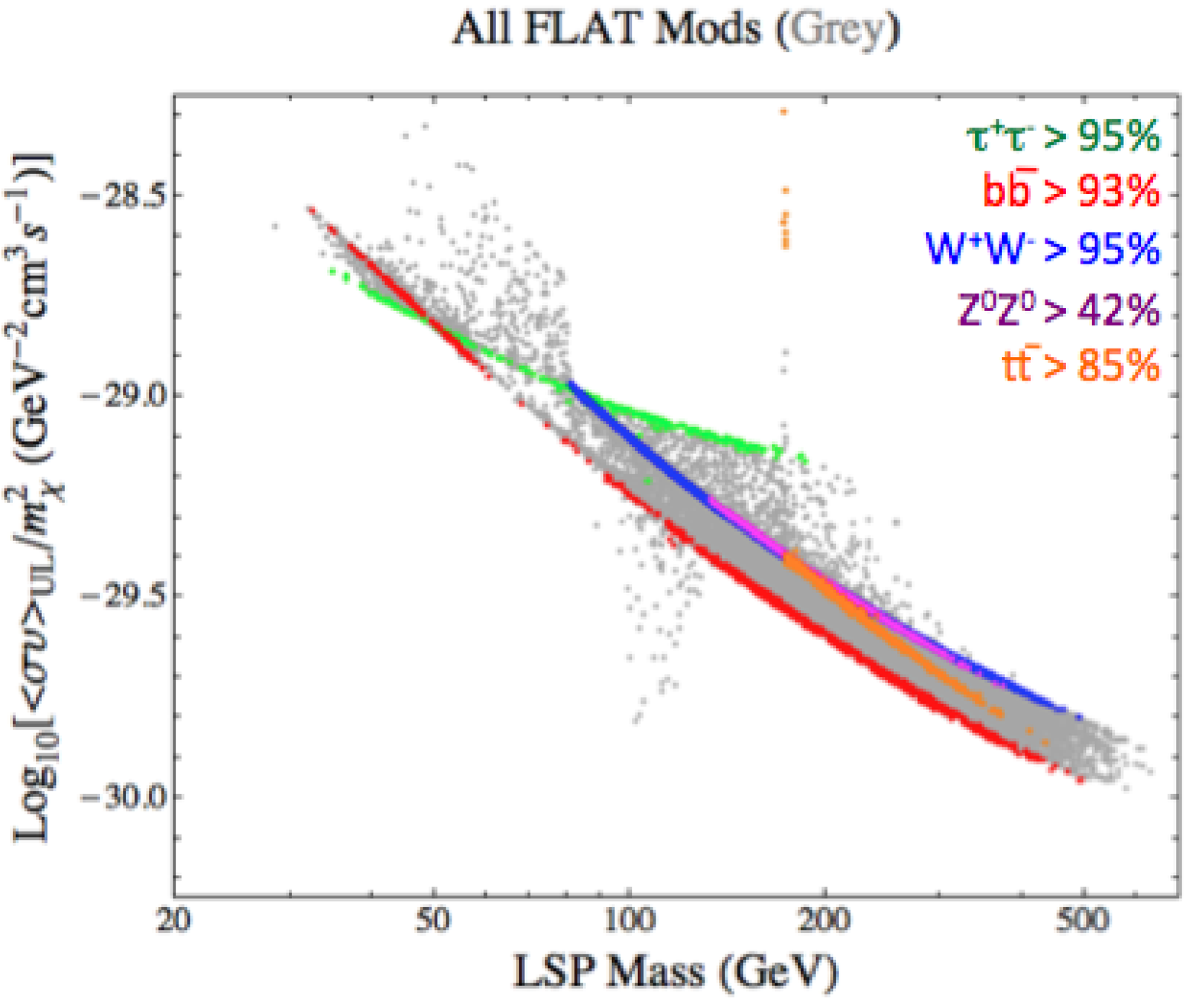
- **Pulsars are another promising candidate for the rising positron fraction**
- **AMS-02 see no signs of anisotropy (0.03 at 95% C.L.)**
- **Gamma-ray observations are important for both hypotheses:**
  - **Search for nearby pulsars**
  - **Constraints on prompt gamma-ray emission from annihilation**



Ackermann et al., Phys. Rev. D86, 022002 (2012)

Meade et al., Nucl. Phys. B831, 178 (2010)

Mixed Channels



- **The tau+tau- and b-bbar channels do a good job bracketing the allowed range of annihilation signals.**
- **(Apologies that you need to multiply this plot by m_x^2 in your head)**

Sterile Neutrinos

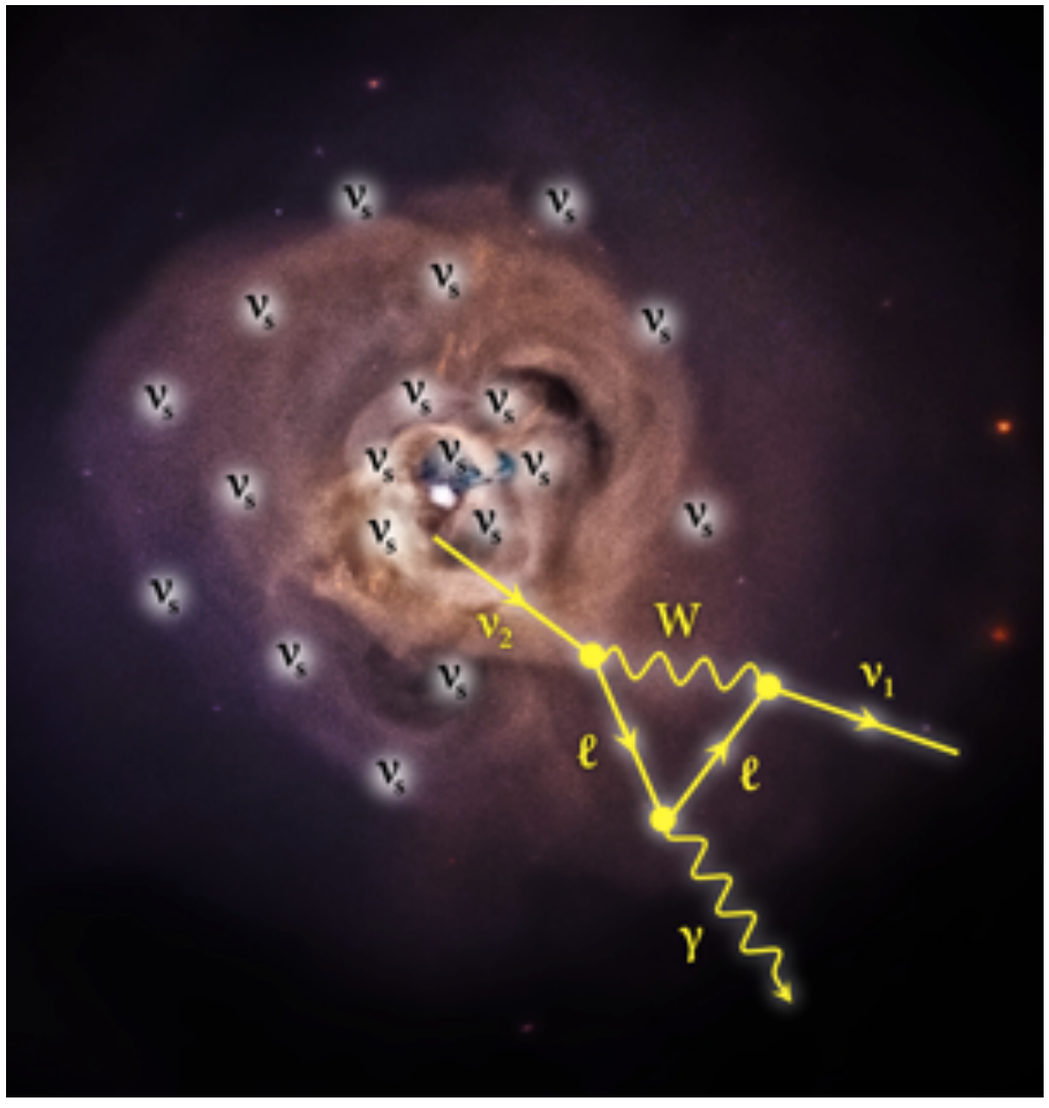
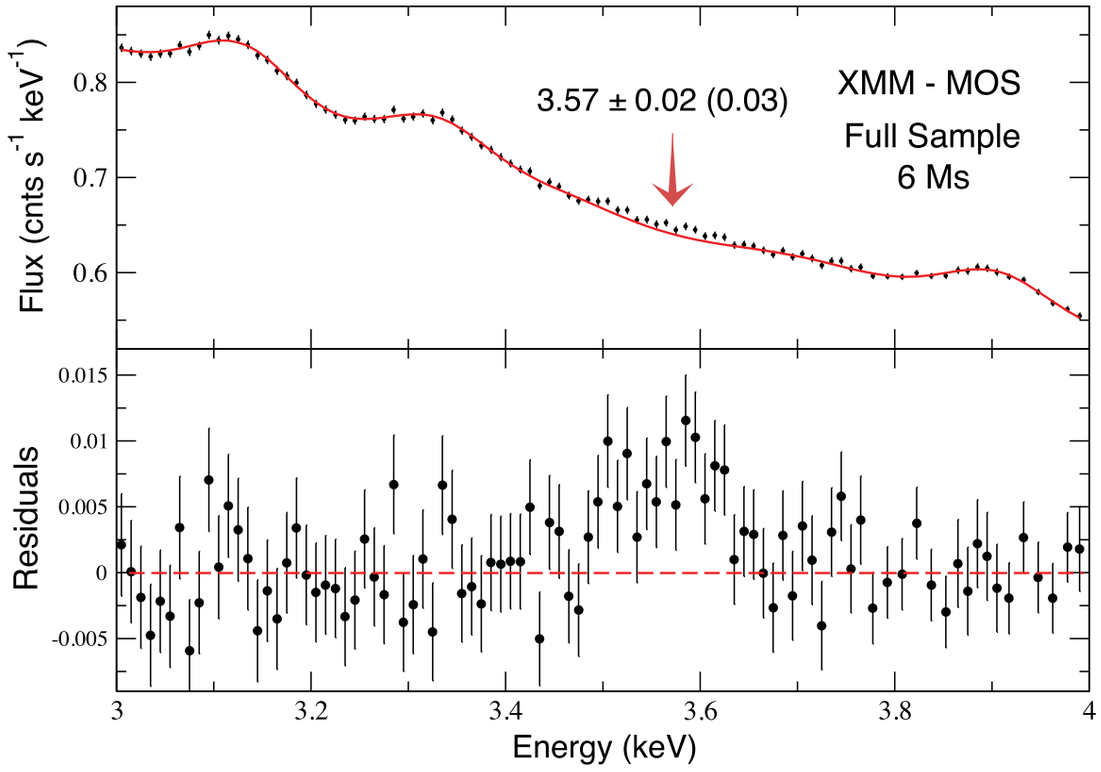


Image: NASA/CXC/SAO/E.Bulbul et al., Overlay: APS/Alan Stonebraker



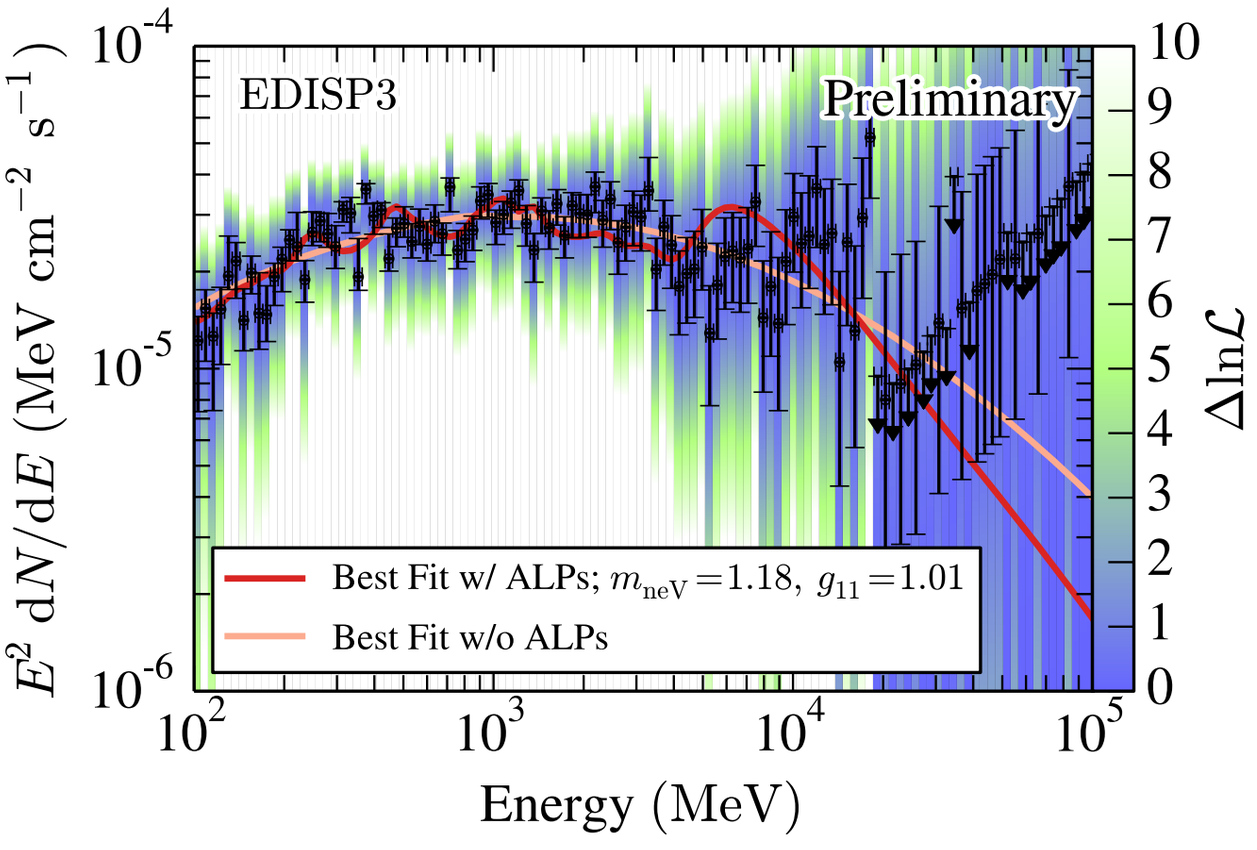
- **Unidentified x-ray line (>3) in Andromeda galaxy, Perseus galaxy cluster, and astacked sample of galaxy clusters.**
- **Lot's of active debate about possible astrophysical origins.**
- **Very deep observations of the Draco dwarf galaxy should be able to conclusively test this scenario.**

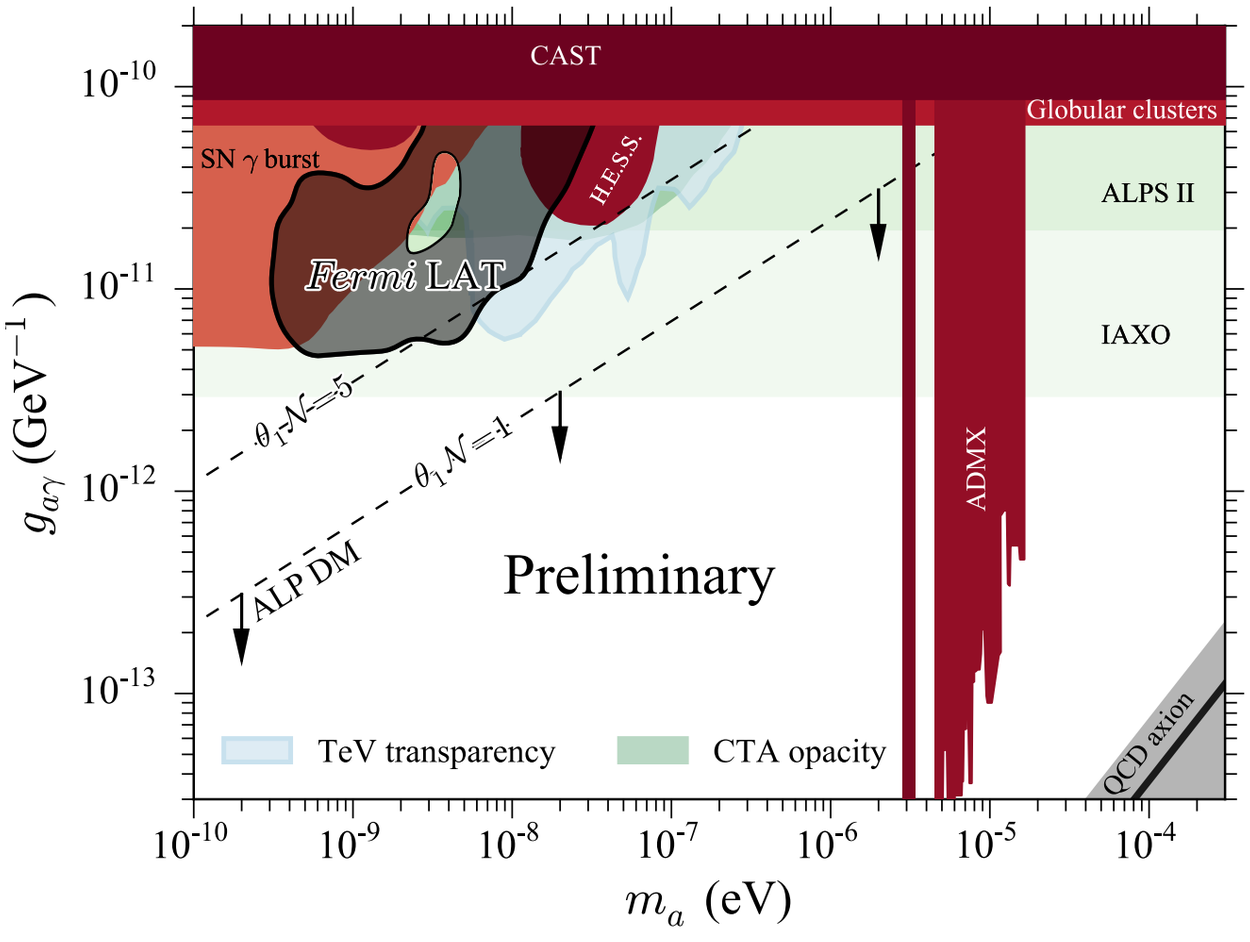
Bulbul et al. ApJ 789, 13 (2014)

Boyarsky et al. PRL 113, 251301 (2015)

Axion-Like Particles

[e.g. Essig et al. 2013;
Meyer & Conrad 2014 and references therein]





LAT Collaboration (2015)