Fermi Gamma-ray Space Telescope

Dark Matter Searches with the Fermi Large Area Telescope

Michael Gustafsson

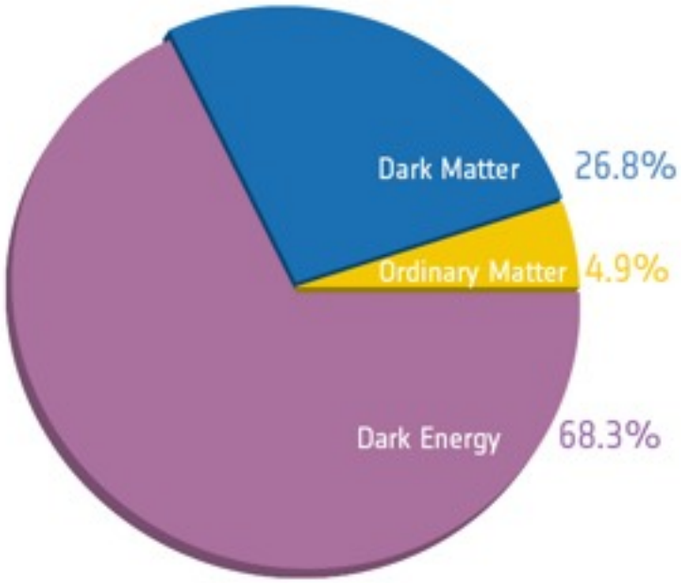
ULB Université Libre de Bruxelles

On behalf of the Fermi-LAT Collaboration

IOP Institute of Physics 2013 High Energy and Astro Particle Physics

April 9th, 2013

Dark Matter



$\Omega_{CDM} \simeq 27\%$ (in ΛCDM)

Beyond standard model physics needed!

WIMPs a 'popular' DM scenario that give gamma-ray signals:

Weakly
Interacting
Massive
Particle

DM particles with EW couplings. Typical mass ~ 1 GeV to 10 TeV and the DM relic density thermally produced when annihilation x-section:

$$\langle \sigma v \rangle_{\rm thermal} \sim 3 \times 10^{-26} {\rm cm}^3/{\rm s}$$

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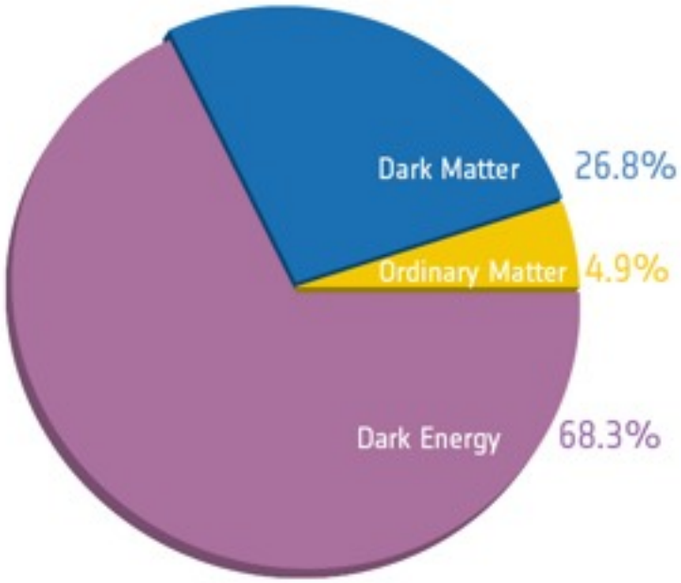

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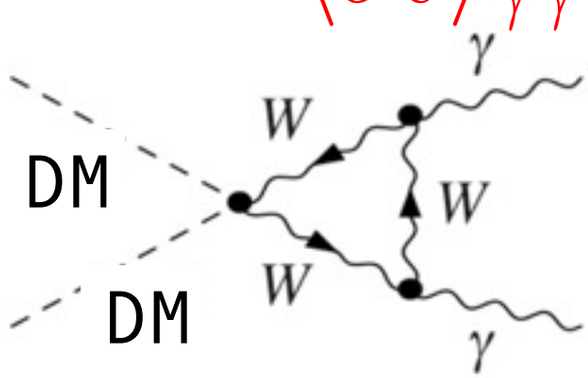
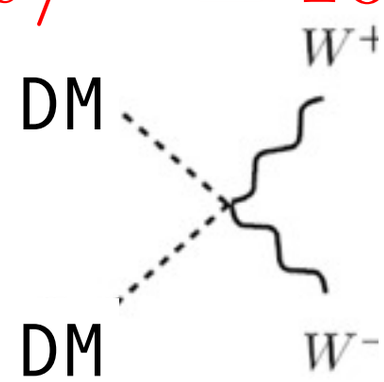
Monochromatic gamma-rays

$$\langle \sigma v \rangle_{\gamma\gamma} \simeq \alpha^2 \langle \sigma v \rangle \simeq 10^{-30} {\rm cm}^3/{\rm s}$$

"toy example"



$\simeq \alpha^2 \times$



Gamma-rays from WIMPs

Flux from annihilating DM particles

What we observe

$$\Phi_\chi(E,\psi) = \frac{\langle \sigma_\chi v \rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_\chi^2}$$

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Photon Flux
(events/area/time/energy)

Energy
spectrum

Region of Interest (ROI)
(dwarf galaxy, the whole sky, etc)

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What we observe

Intrinsic Particle Properties

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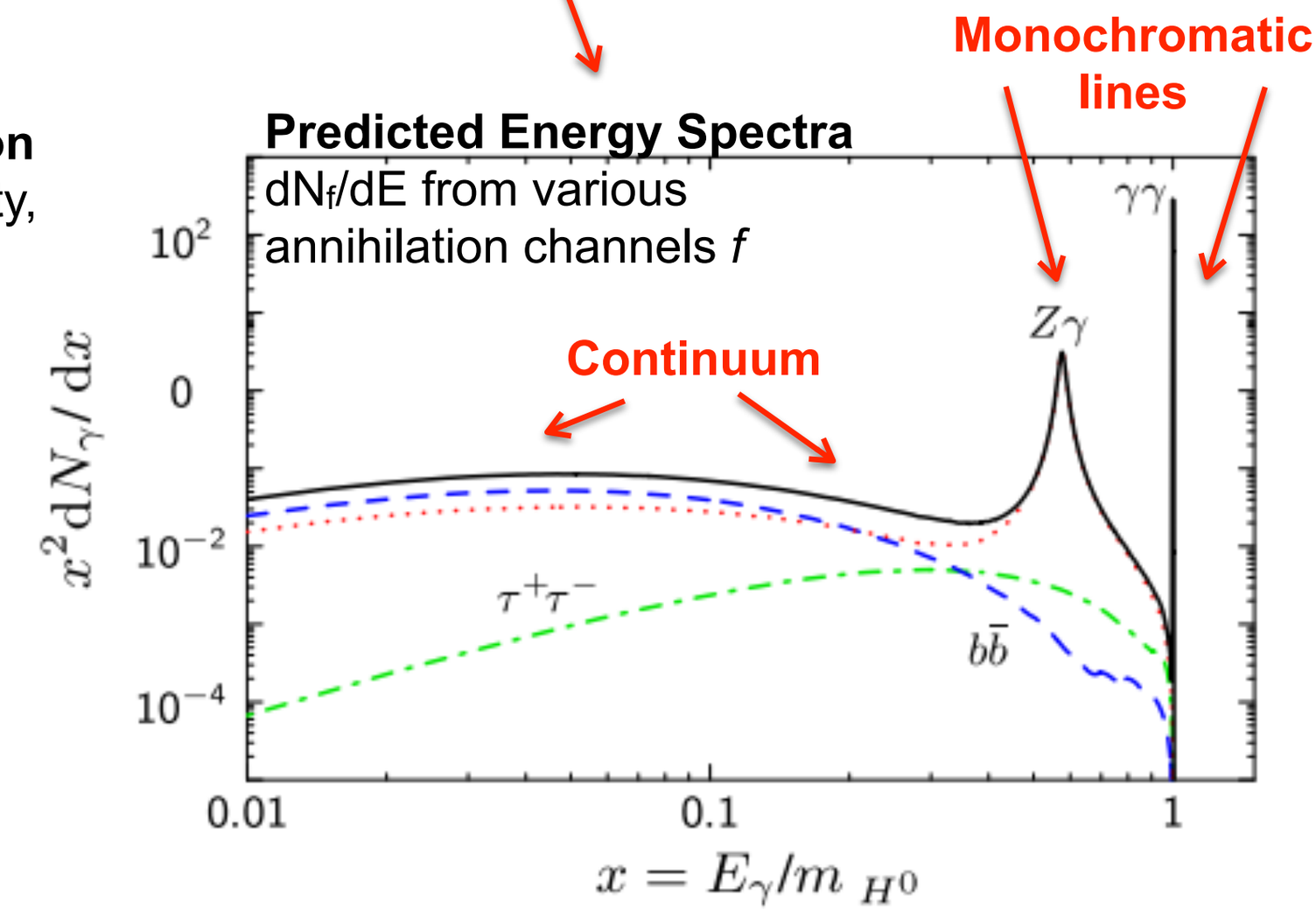
DM Annihilation Cross Section
averaged cross-section × velocity,
@ freeze-out ≃ $3 \cdot 10^{-26}$ cm^3/s

Predicted Energy Spectra



Gustafsson et al. PRL 99.041301

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Flux from annihilating DM particles

What we observe | Intrinsic Particle Properties | Astrophysics (J-factor)

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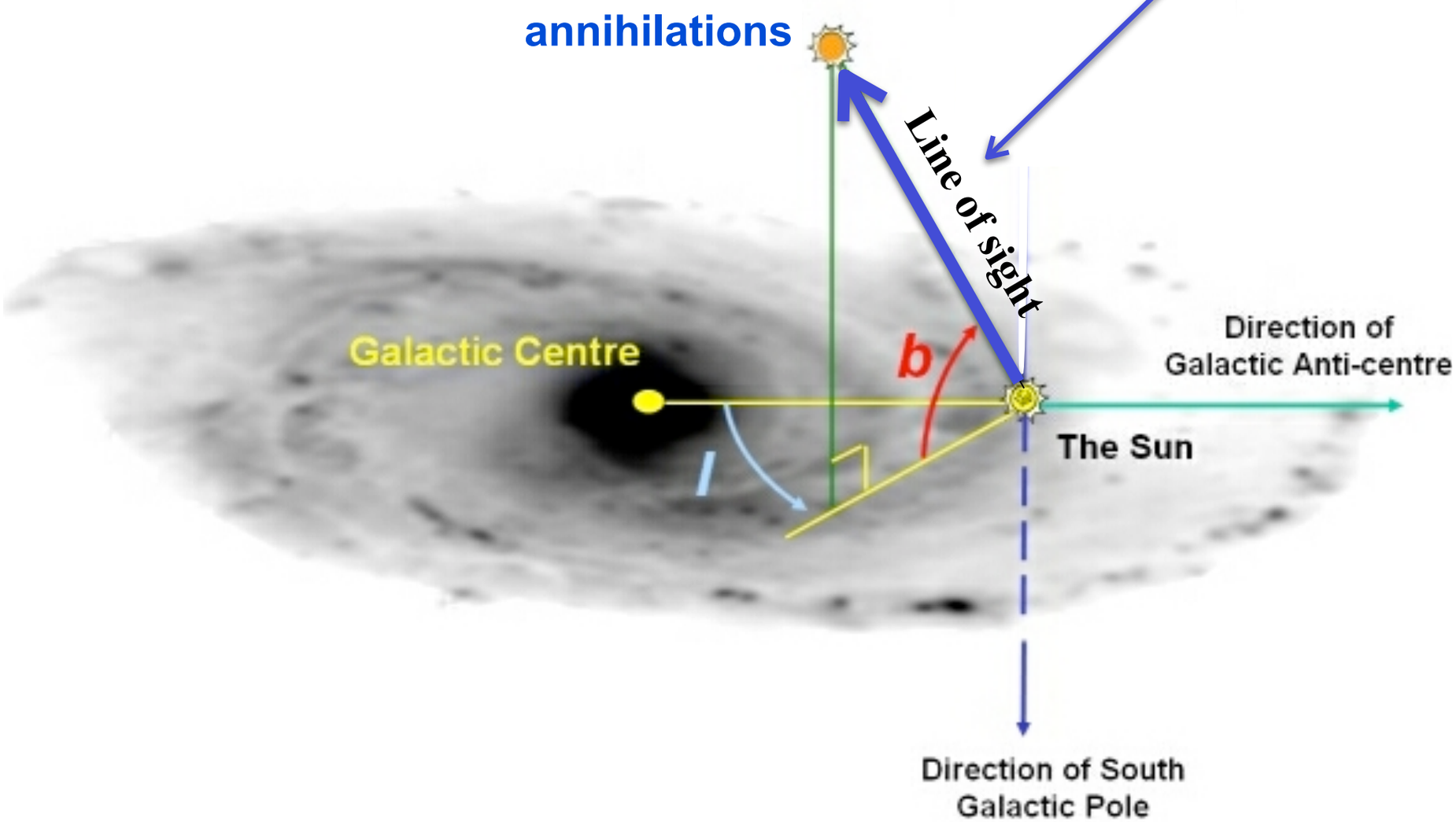
WIMP number density squared



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Extended DM halo

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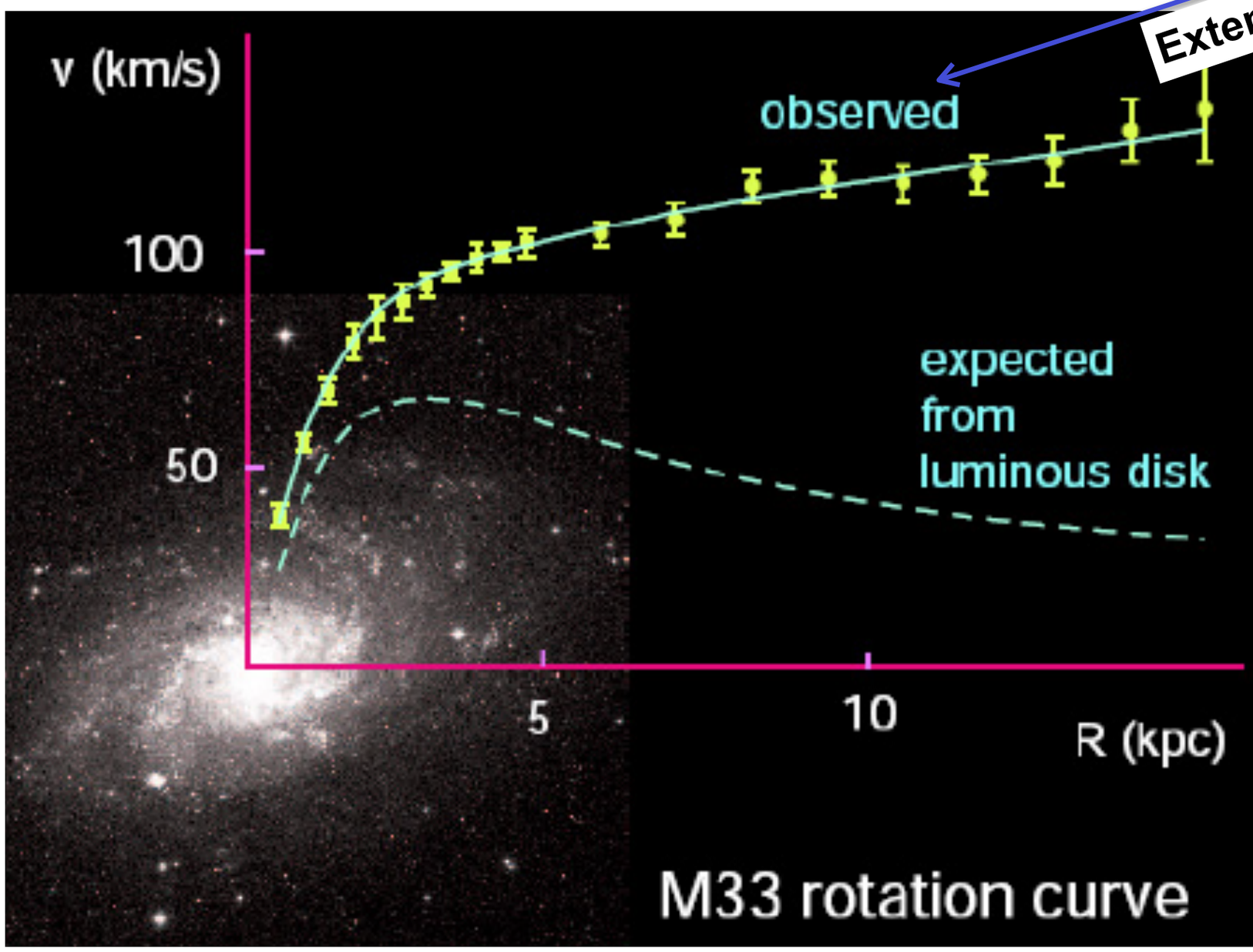

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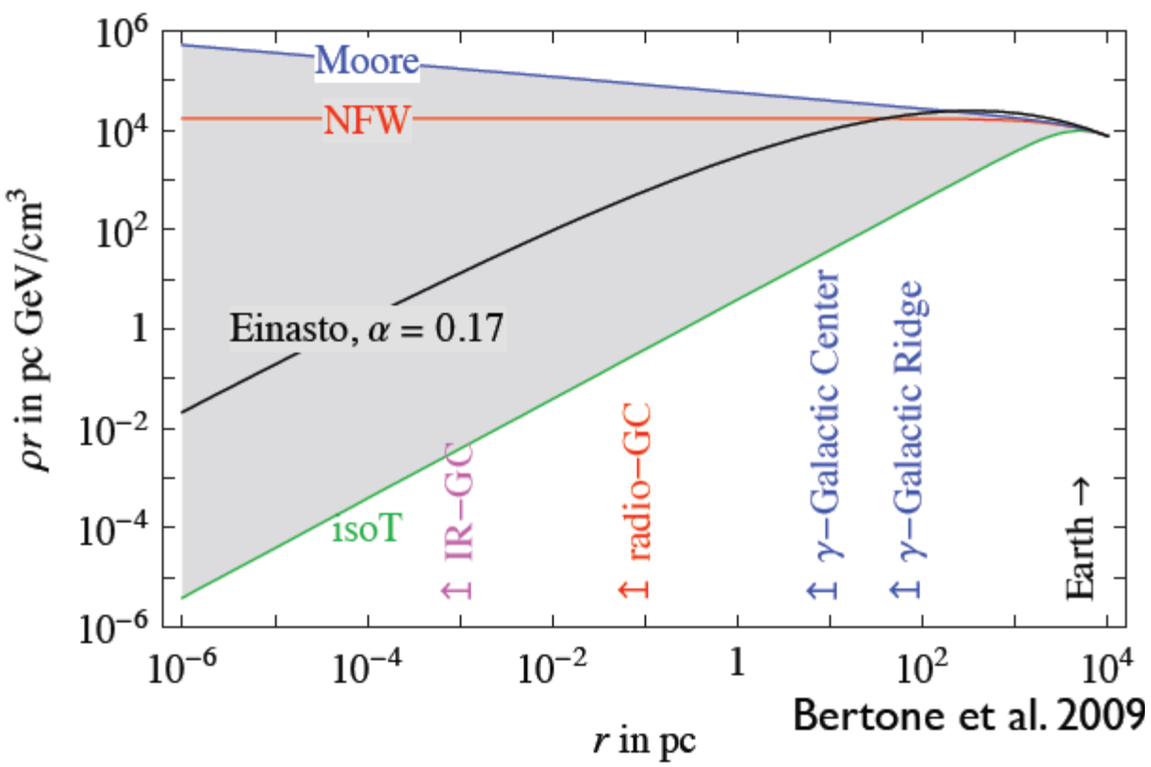
Dark matter distributions (from sim. and obs.)



Bertone et al. 2009

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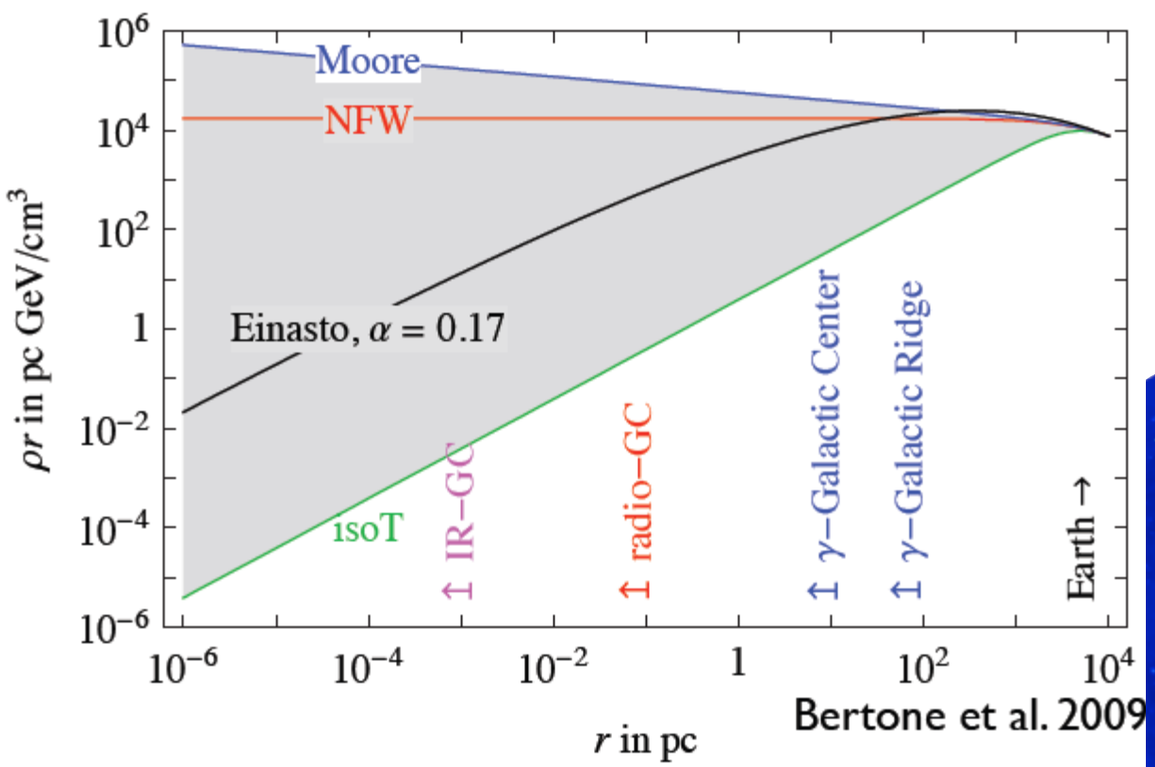
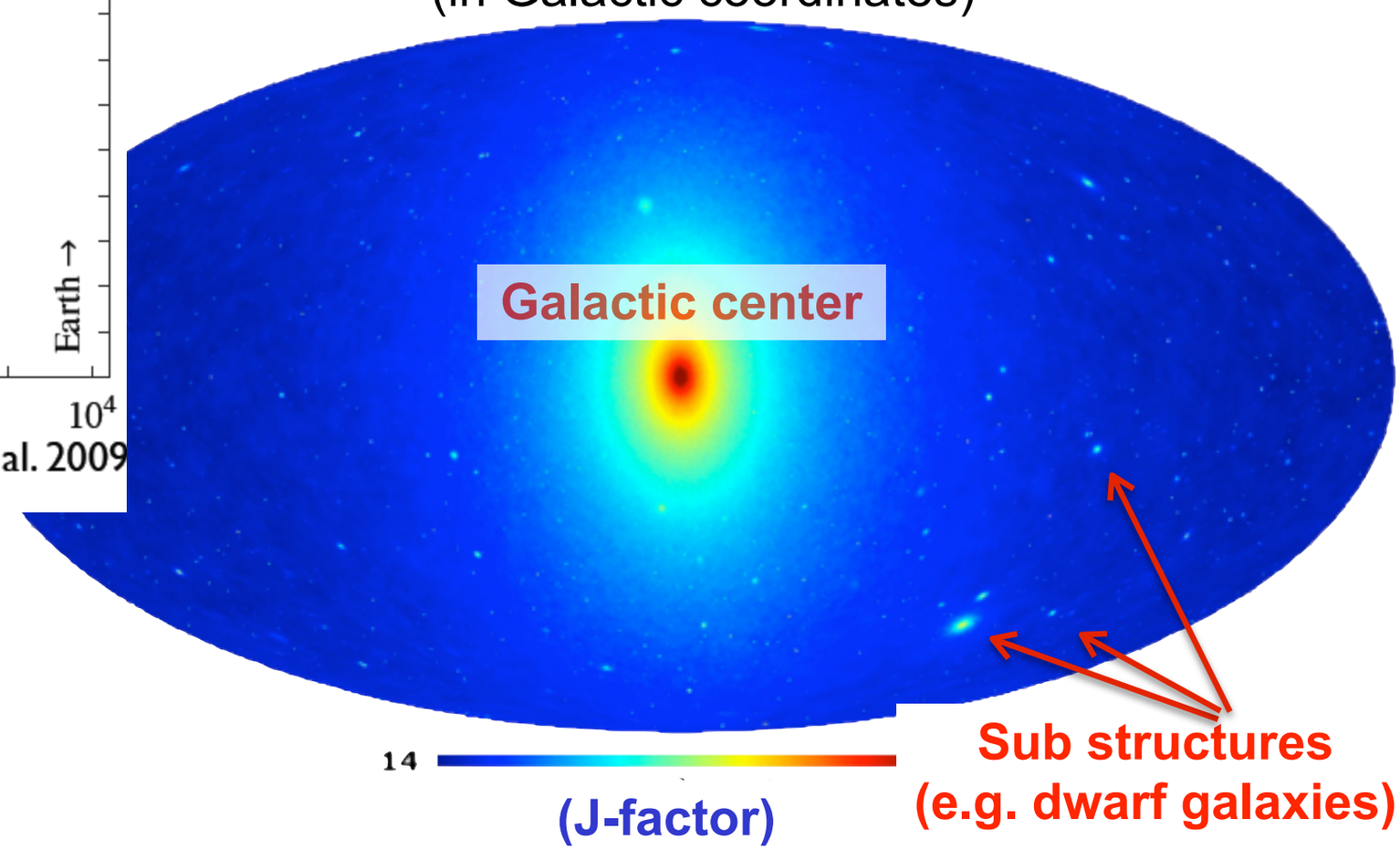
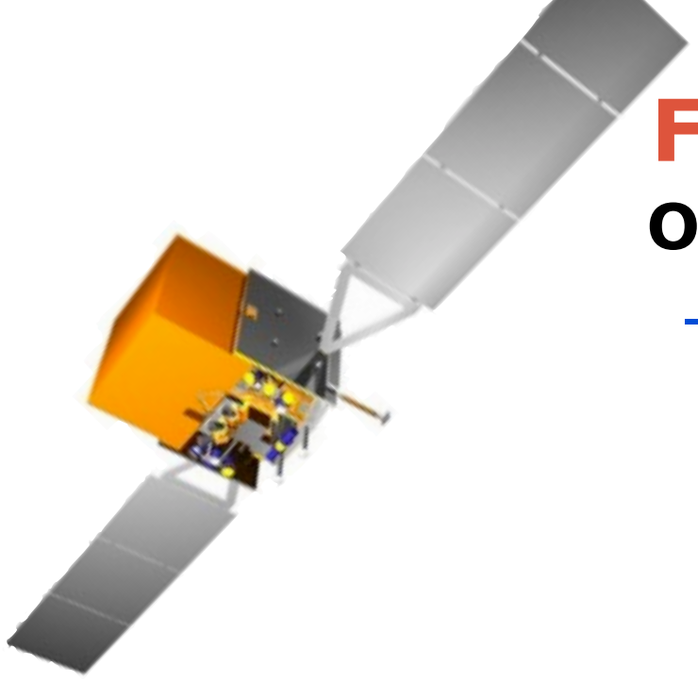


Bertone et al. 2009

Signal morphology
(in Galactic coordinates)

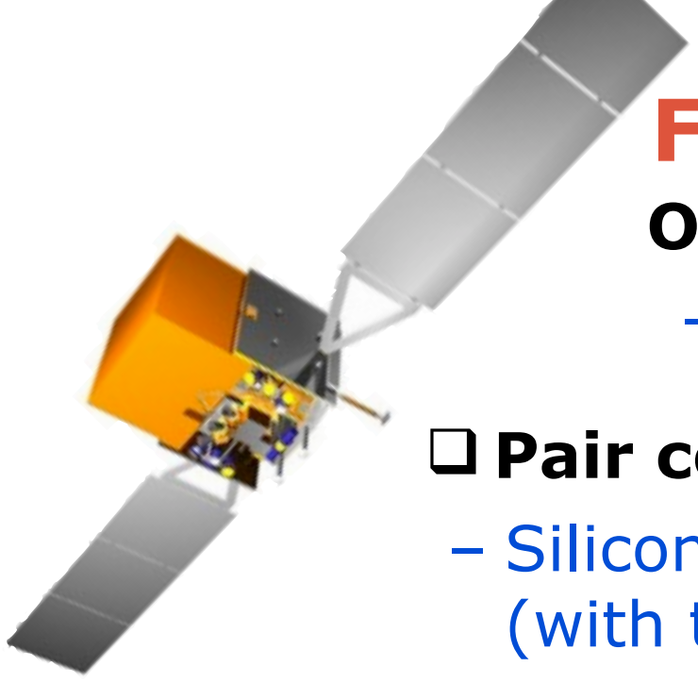




Fermi Large Area Telescope (LAT)

On board the Fermi Gamma-ray Space Telescope

– Launched June 2008, mission to at least 2016



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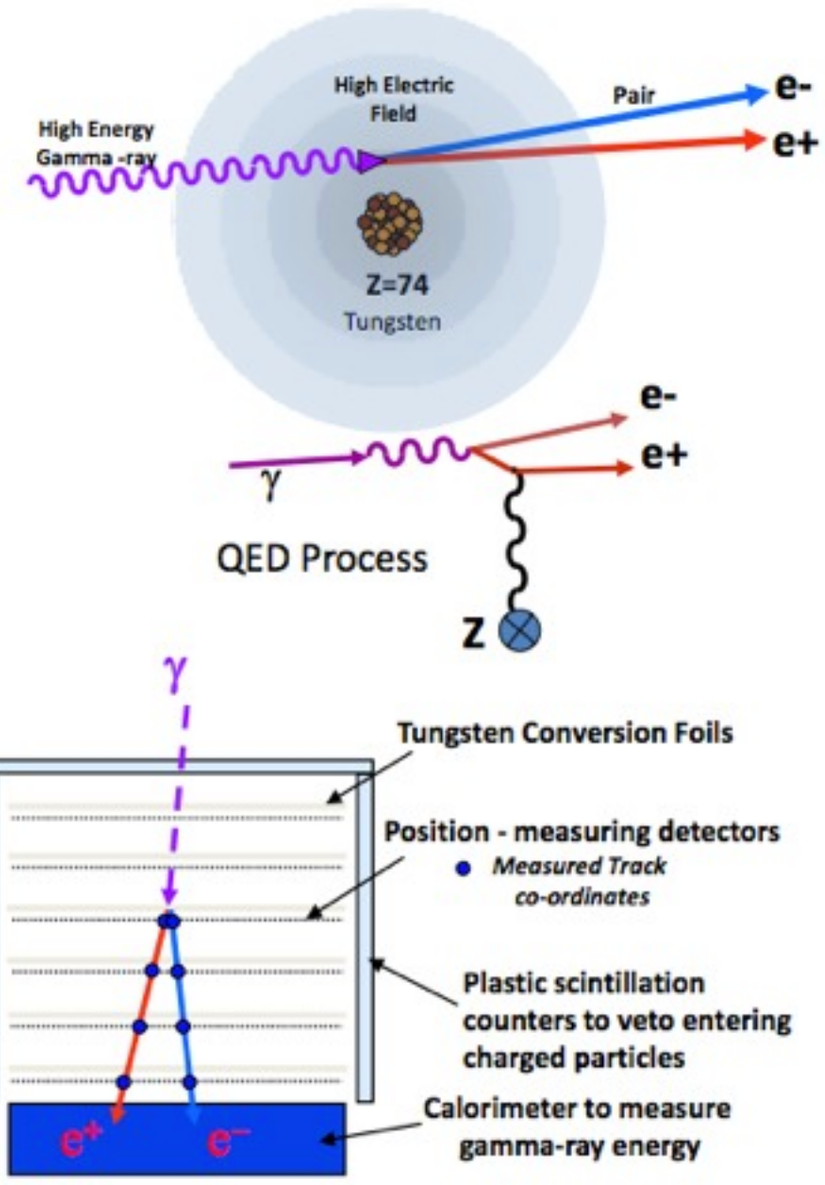
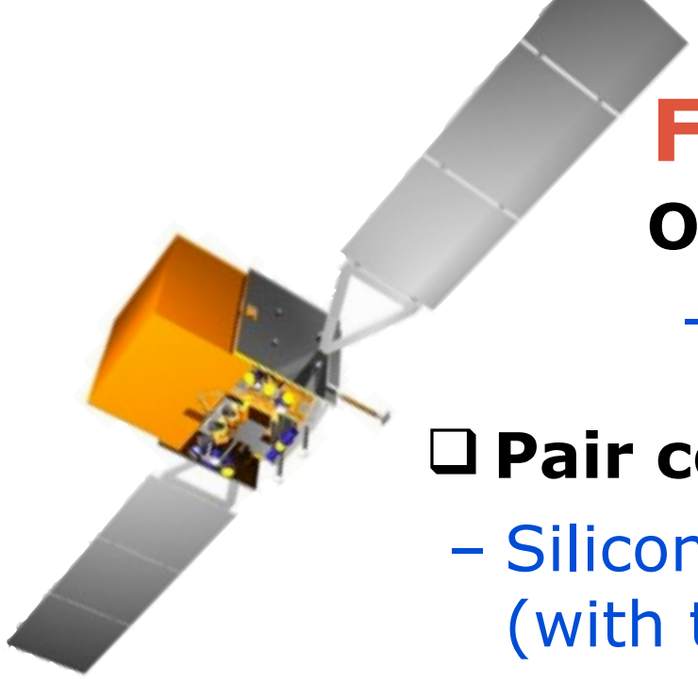
- **Pair conversion detector**
  - Silicon strip tracker (with tungsten converter foils)
  - Electromagnetic CsI calorimeter
  - Anti-coincidence shield (plastic scintillators to veto charge particles, eff. >99.97%)



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

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



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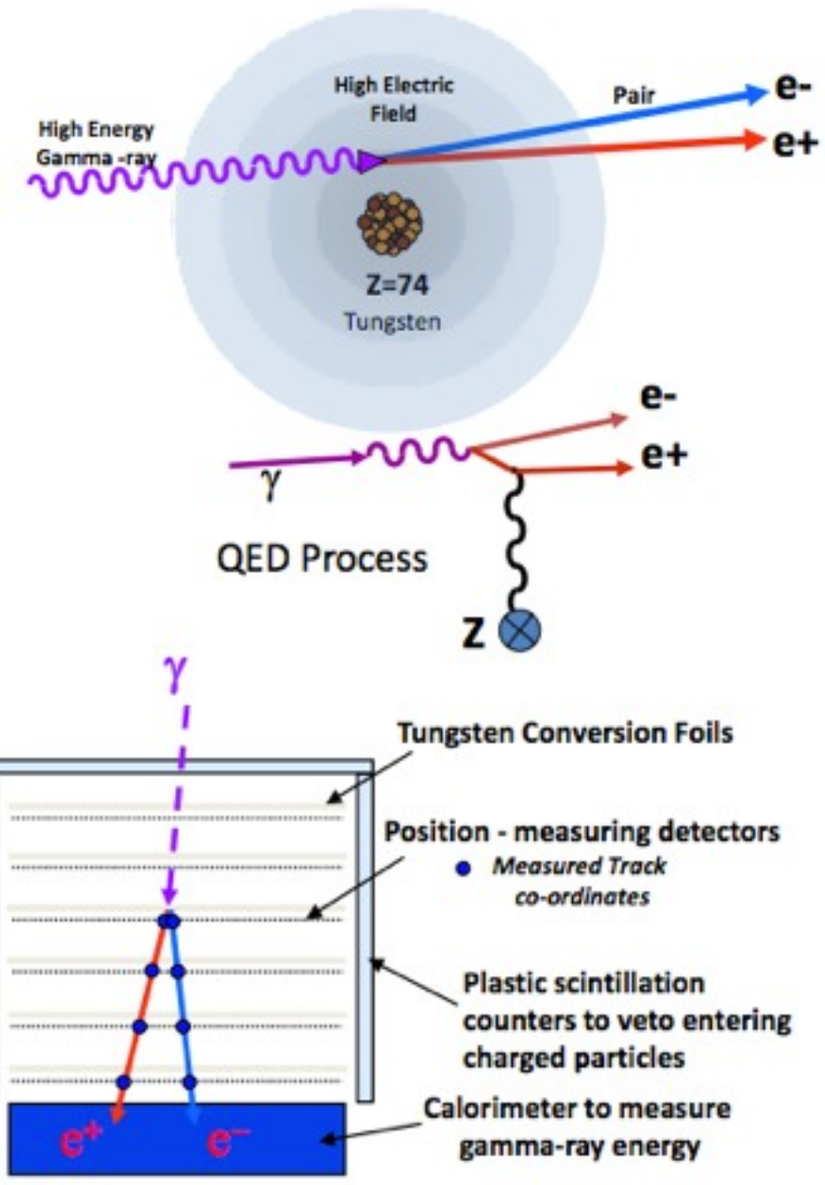

❑ Key features for DM searches

- Effective area ~0.8 m^2
- Energy range: 20 MeV to >300 GeV
  resolution: σ_E<10% (for E>10 GeV)
- Angular resolution: <0.2° (for E>10 GeV)
- Full-sky coverage (~2.4sr)
  - All sky in 2 orbits (3 hrs)

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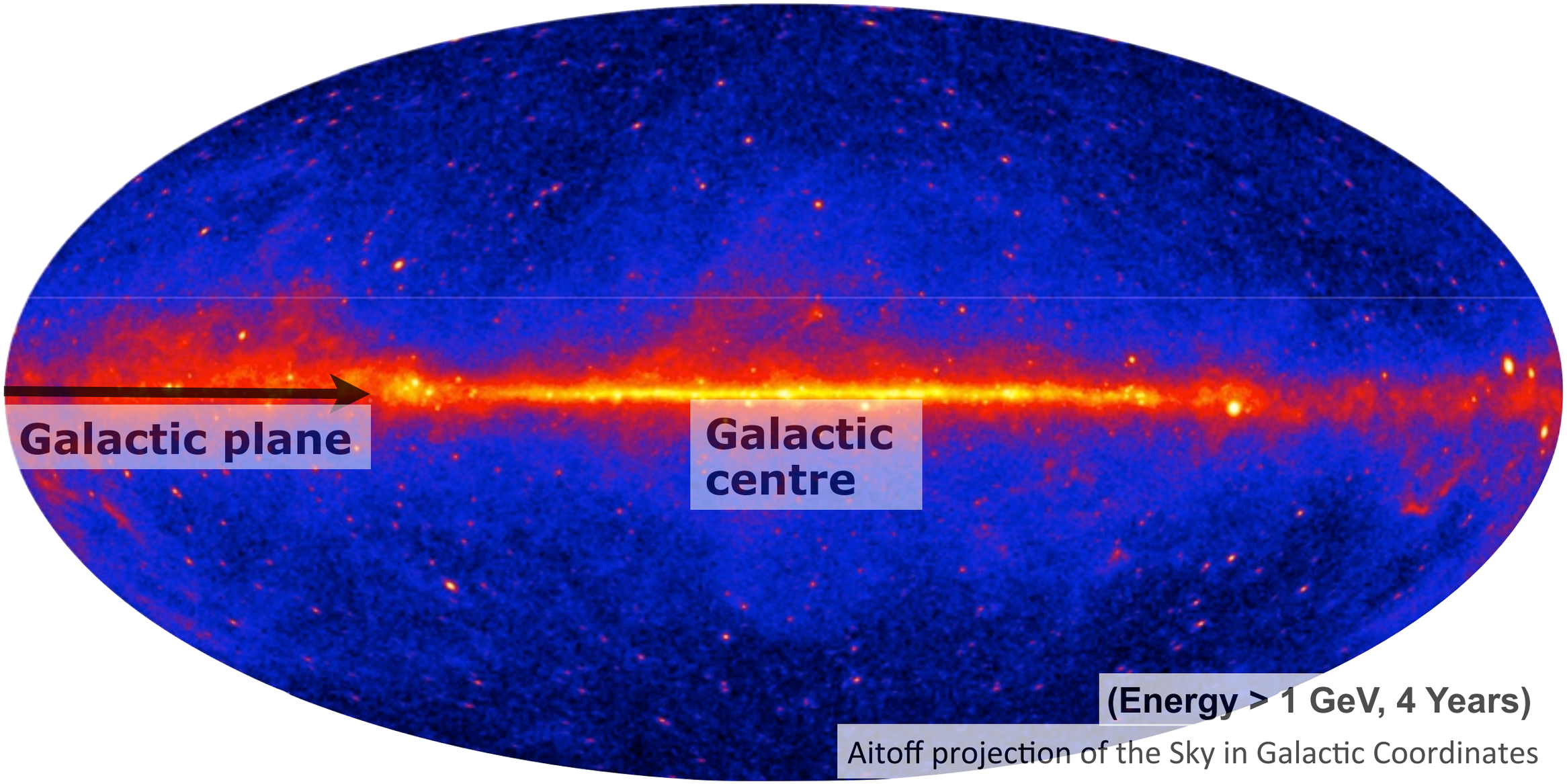
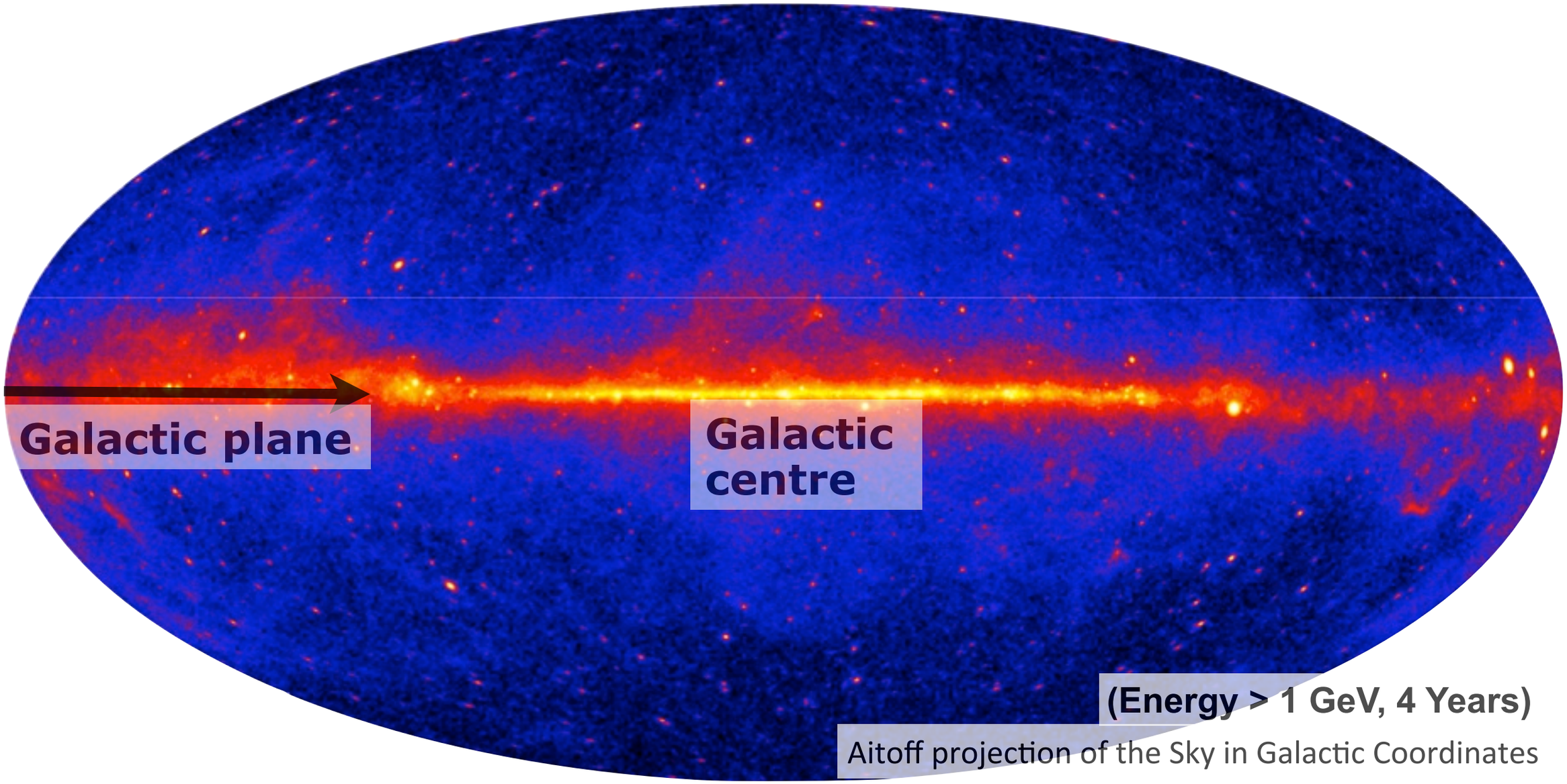
The Gamma-ray Universe as seen by Fermi-LAT



Are there any hiding DM signals?



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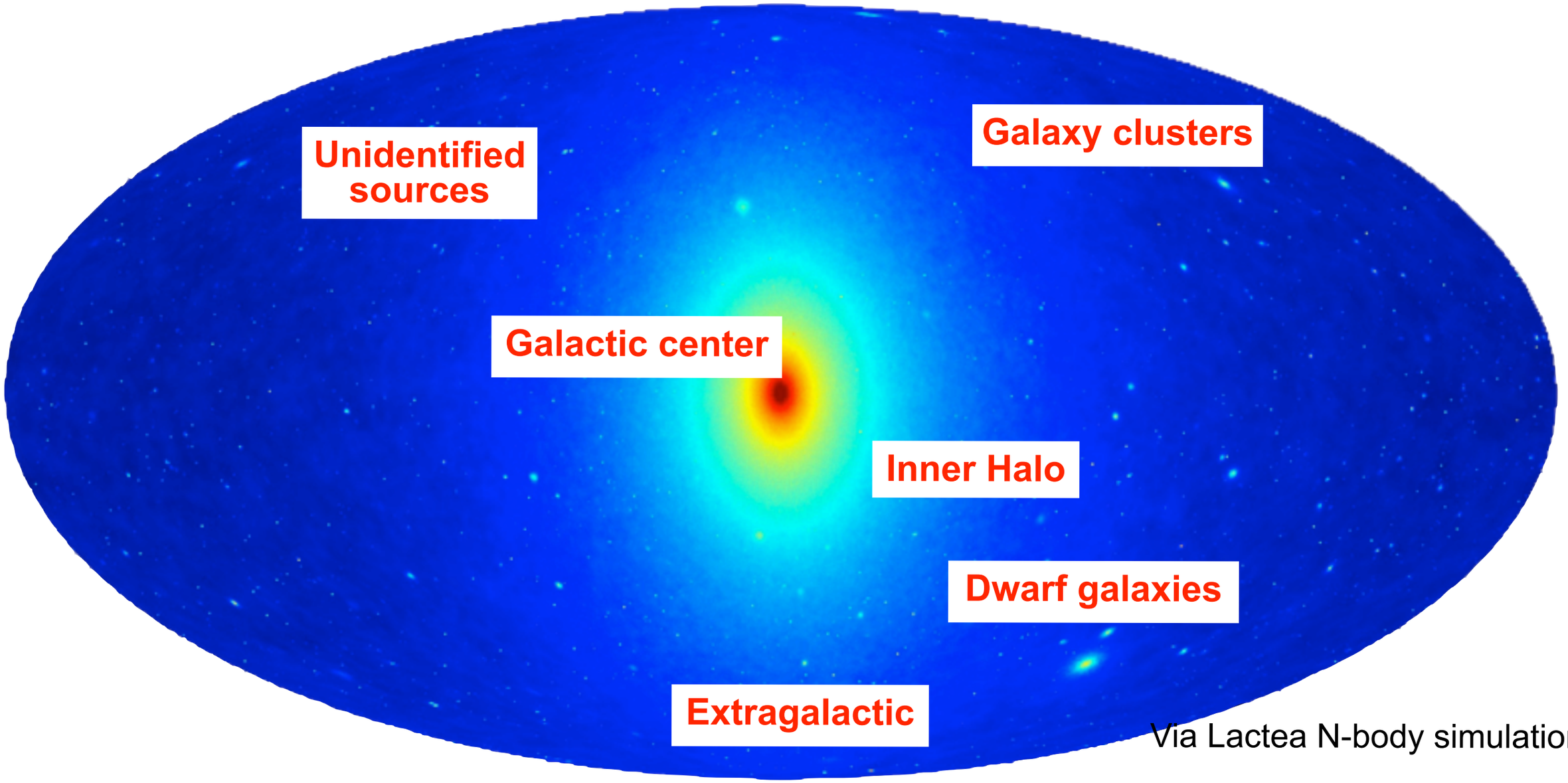

Via Lactea N-body simulation

Dark matter N-body simulation: log(J-factor)

Colors span 4 orders of magnitude for the l.o.s. intensity $\mathrm{J-factor} \propto \int_{LOS} dl(\psi) \frac{\rho(l)^2}{m_\chi^2}$

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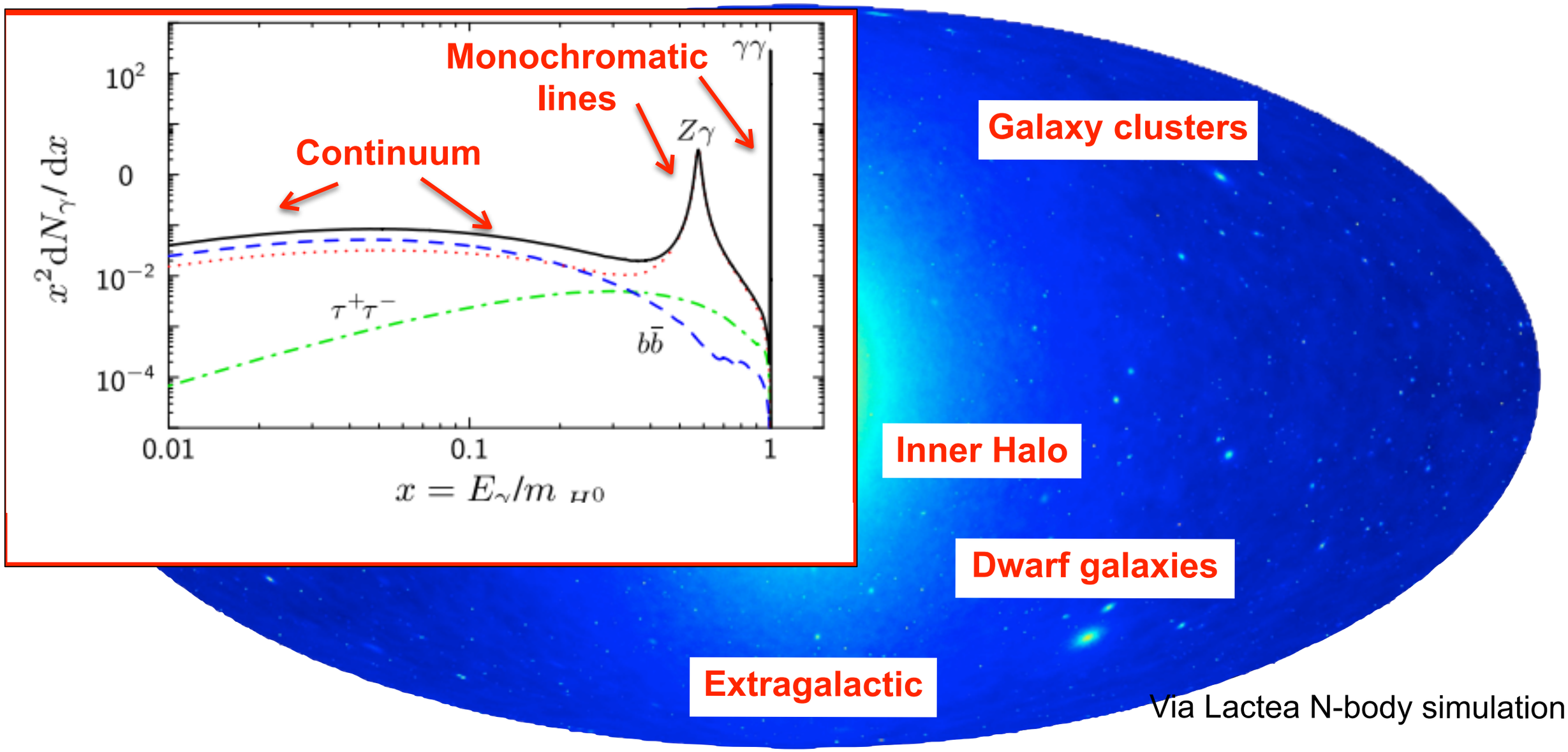

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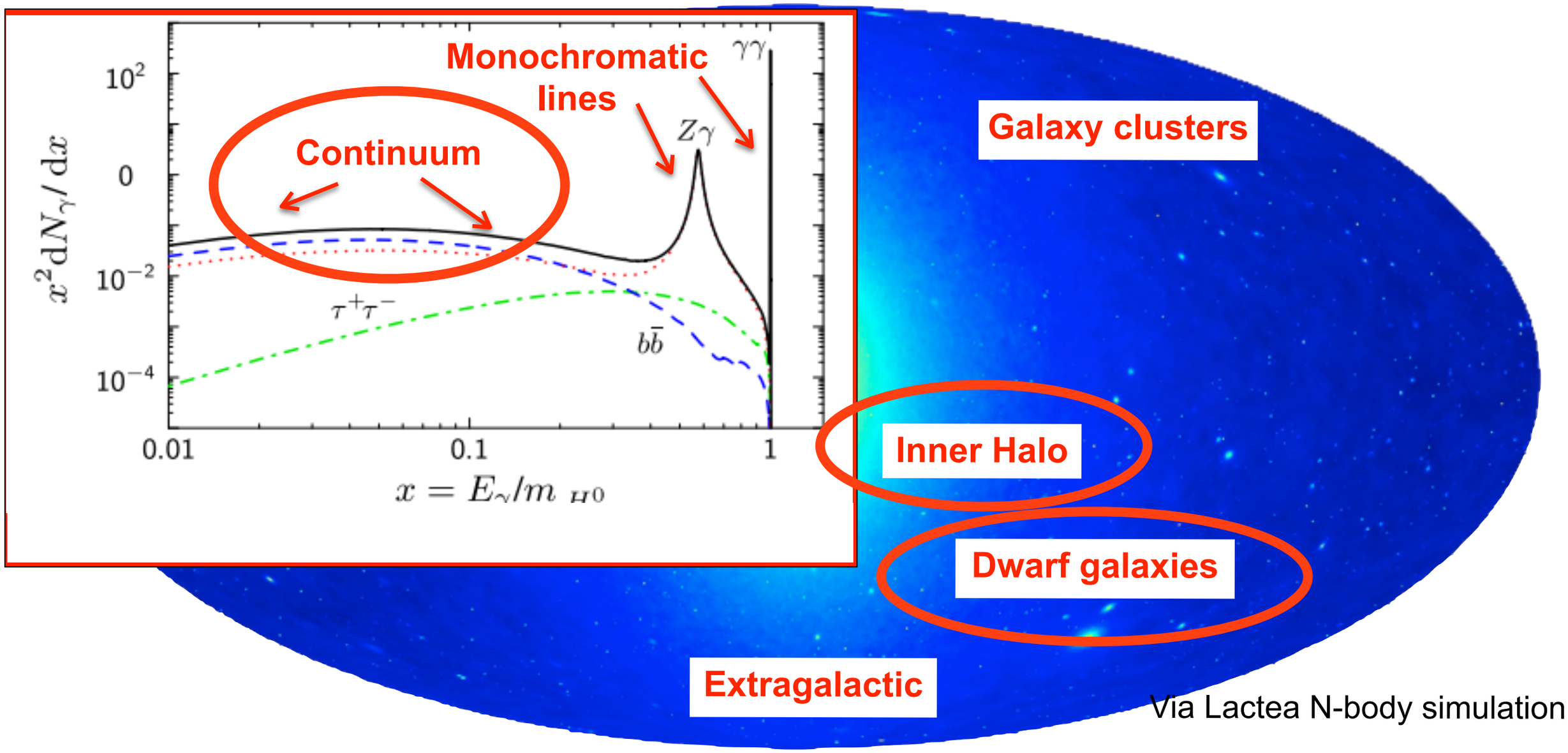

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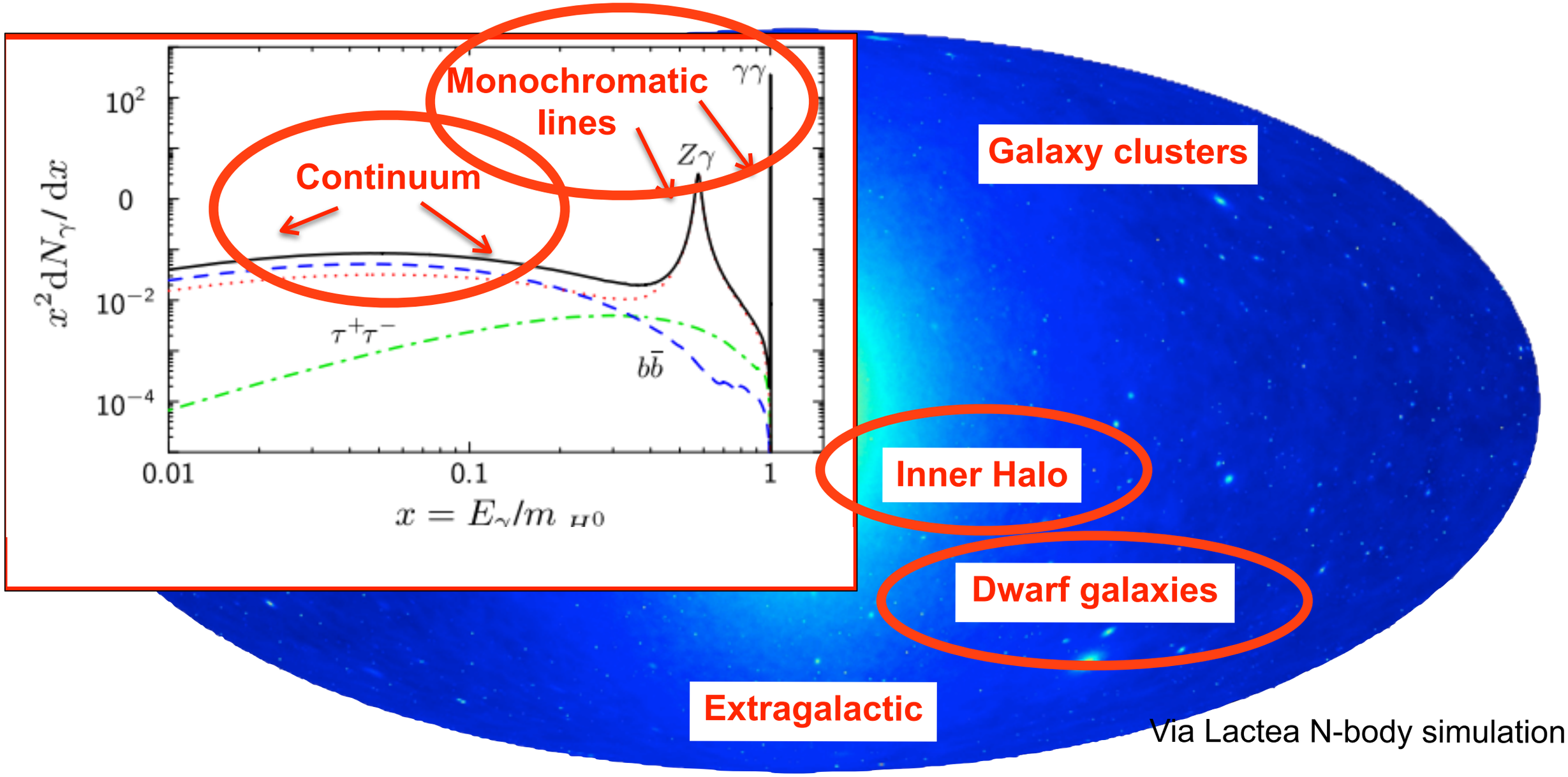

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[1]

Search for a DM signal from dwarf galaxies

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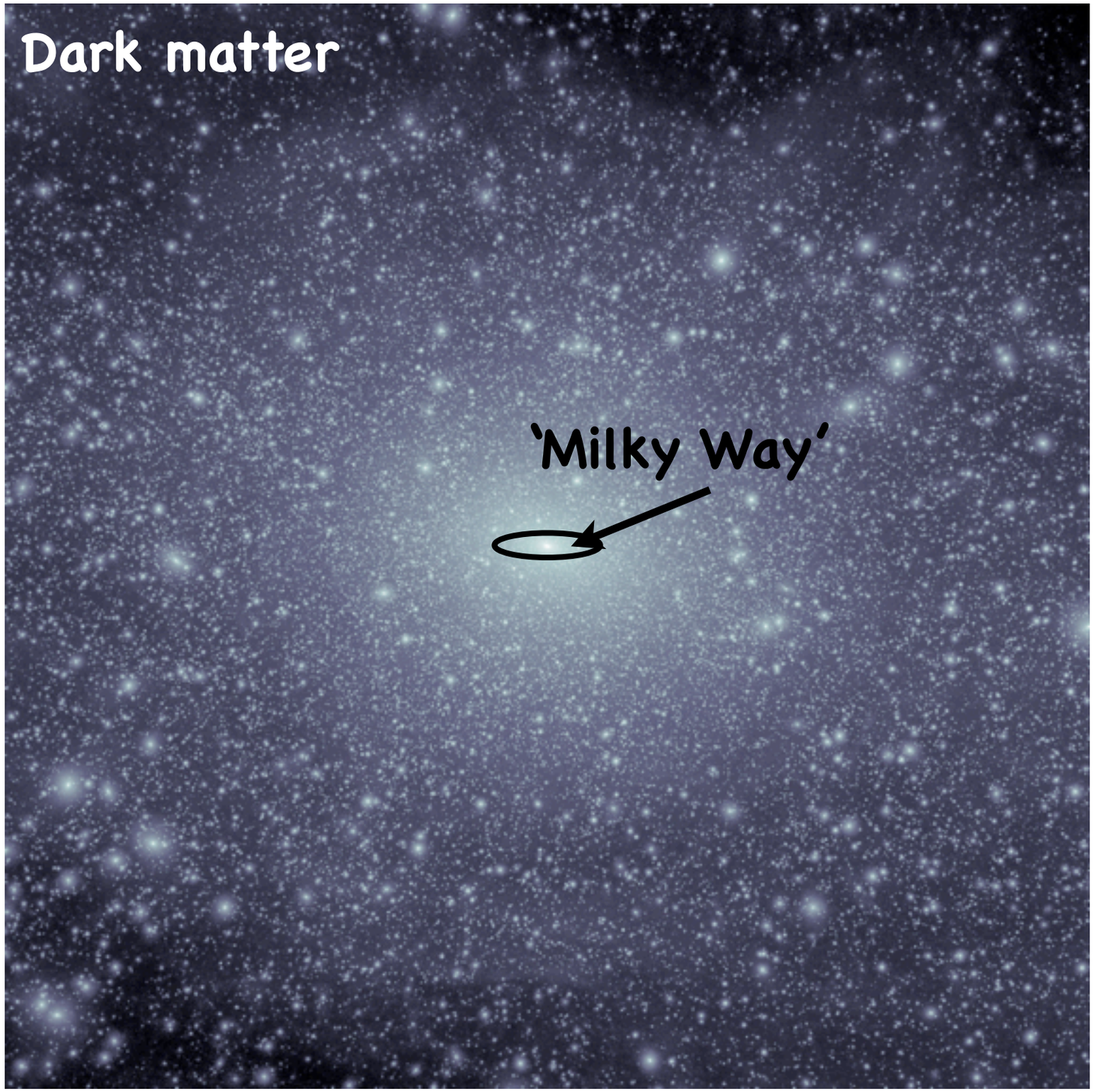
✓ Numerical simulations predict that the DM halos hosting galaxies should be surrounded by many smaller DM halo structures.

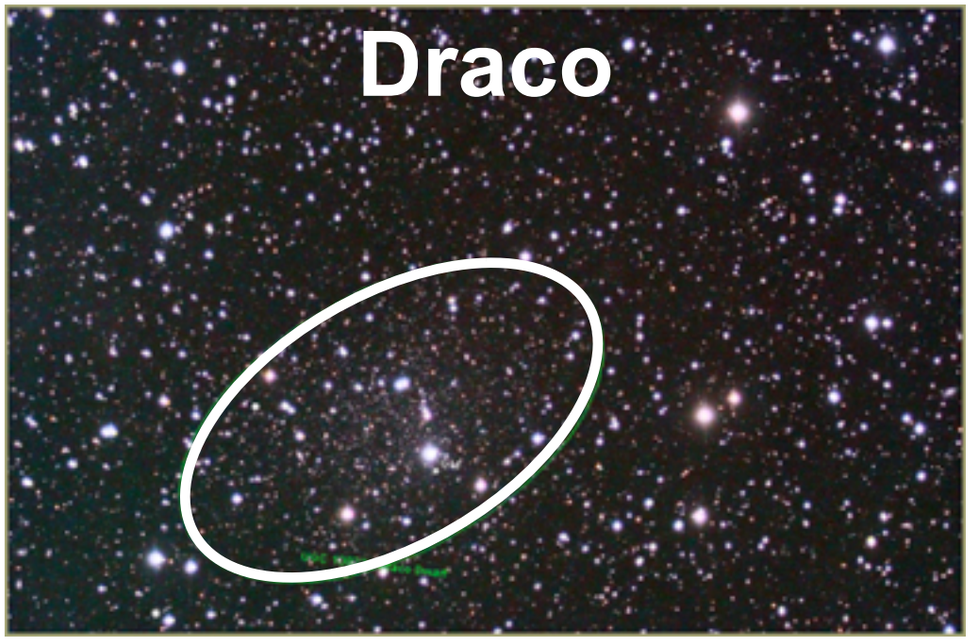


N-body simulation of galactic size Dark Matter halo.

Via Lactea II (Diemand et al. 2008)

Search for a DM signal from dwarf galaxies

- ✓ Optically observed **Dwarf Spheroidal (dSphs) galaxies** the most attractive DM subhalo candidates
  - ✓ Relatively nearby, known positions
  - ✓ Low gamma-ray backgrounds



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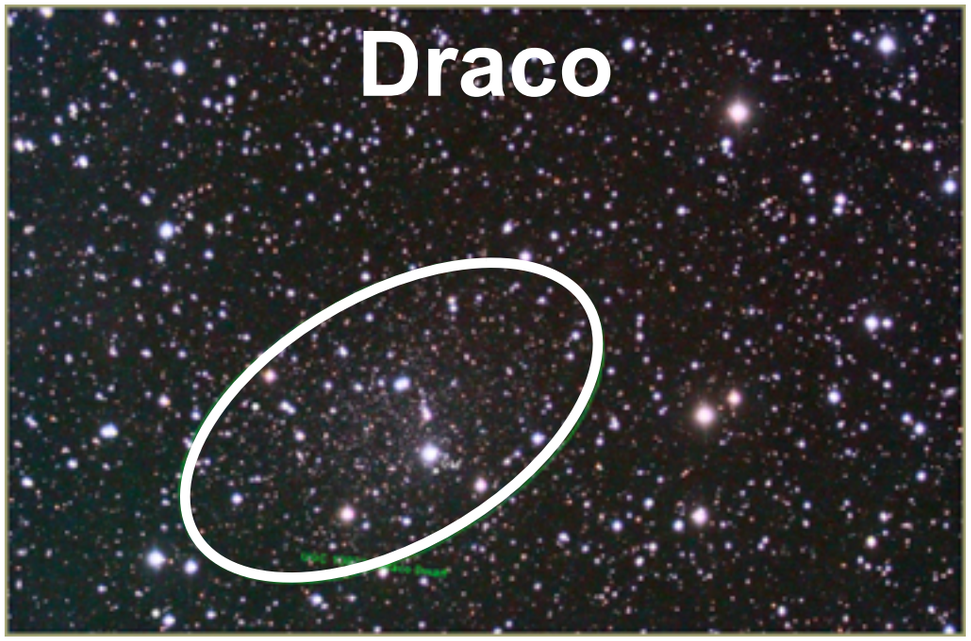

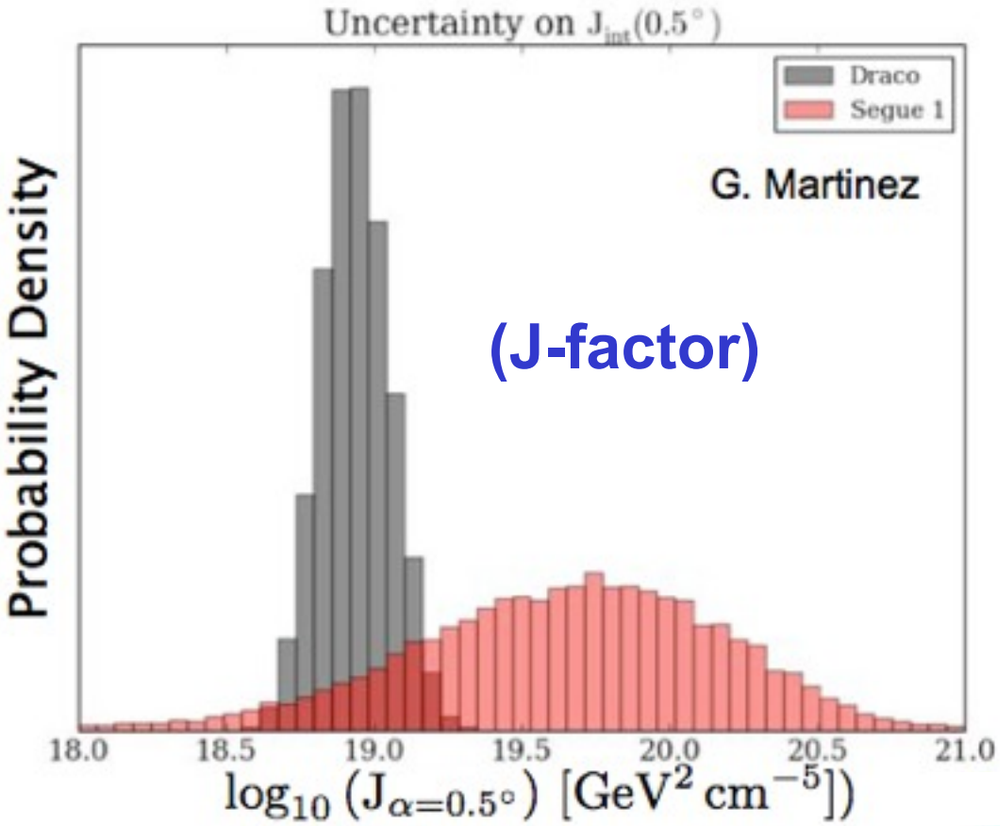

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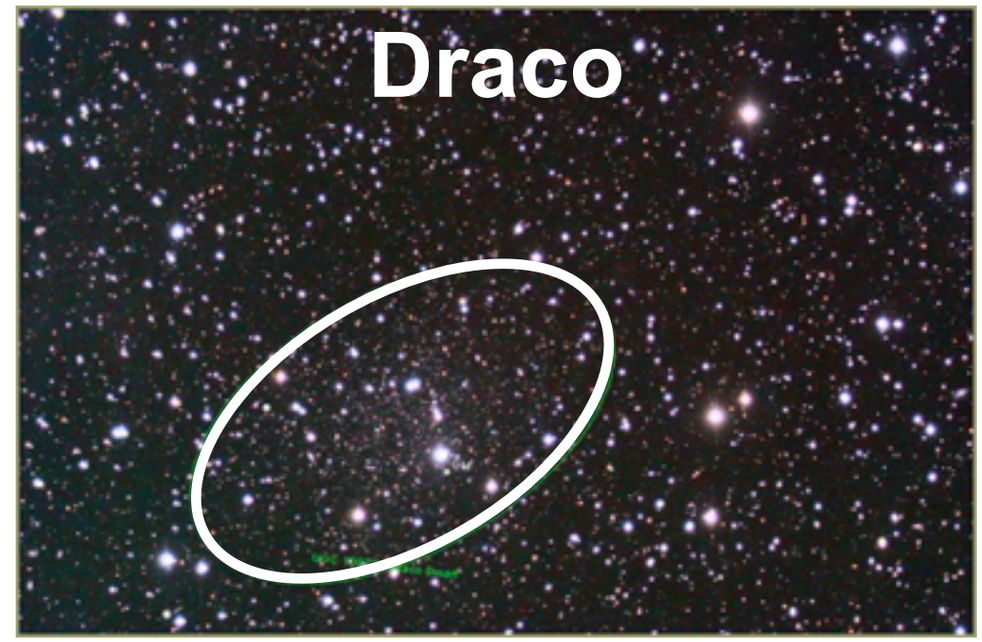
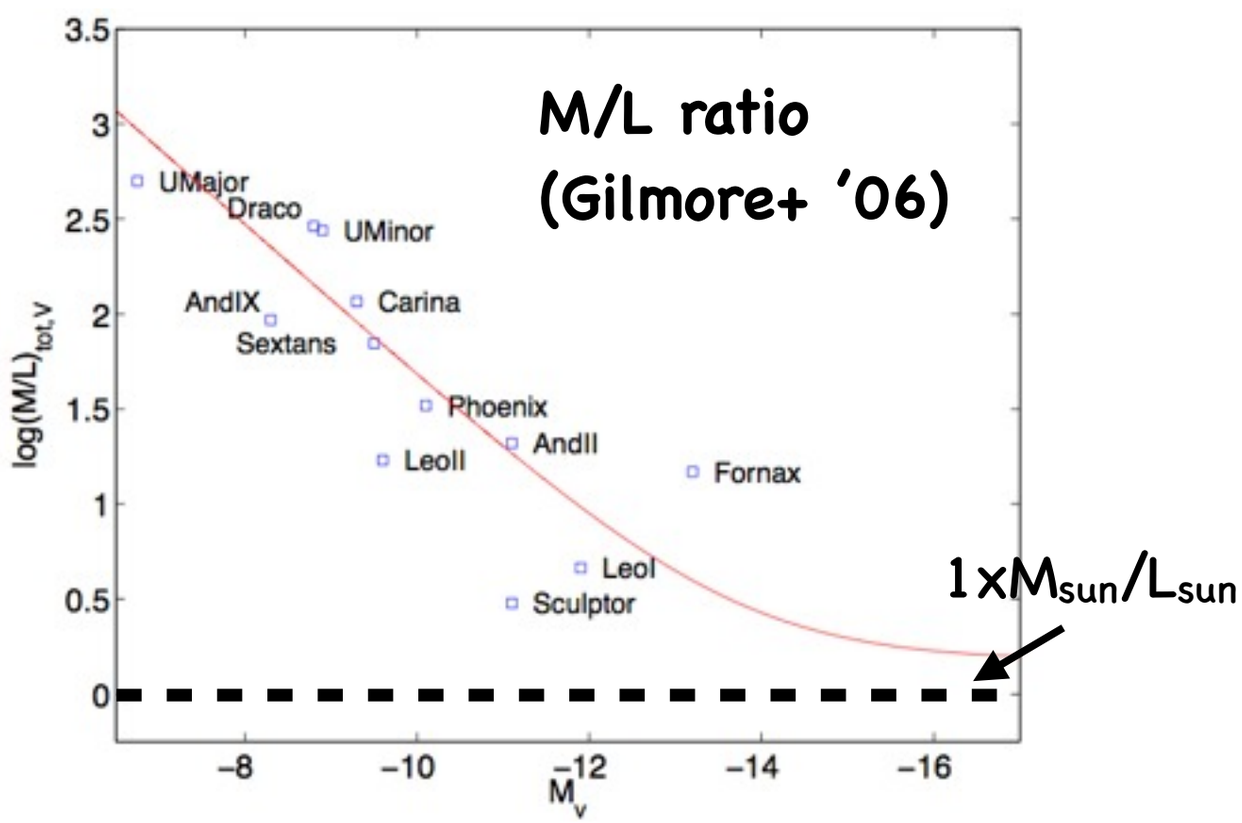
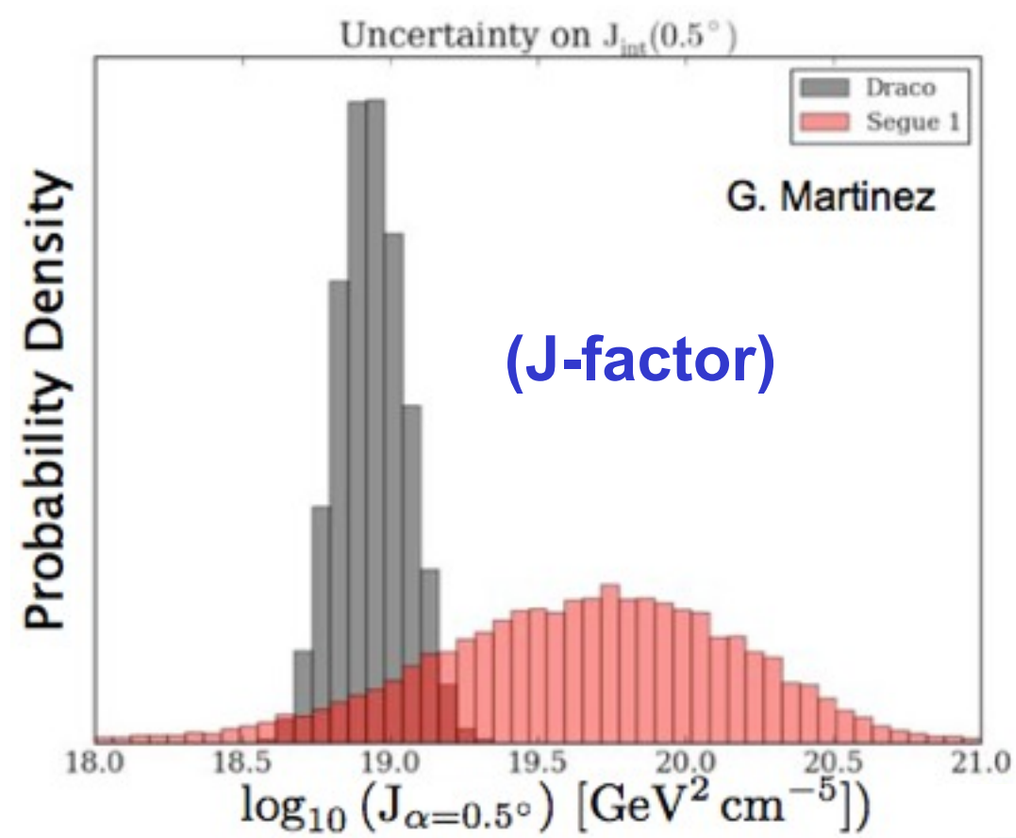
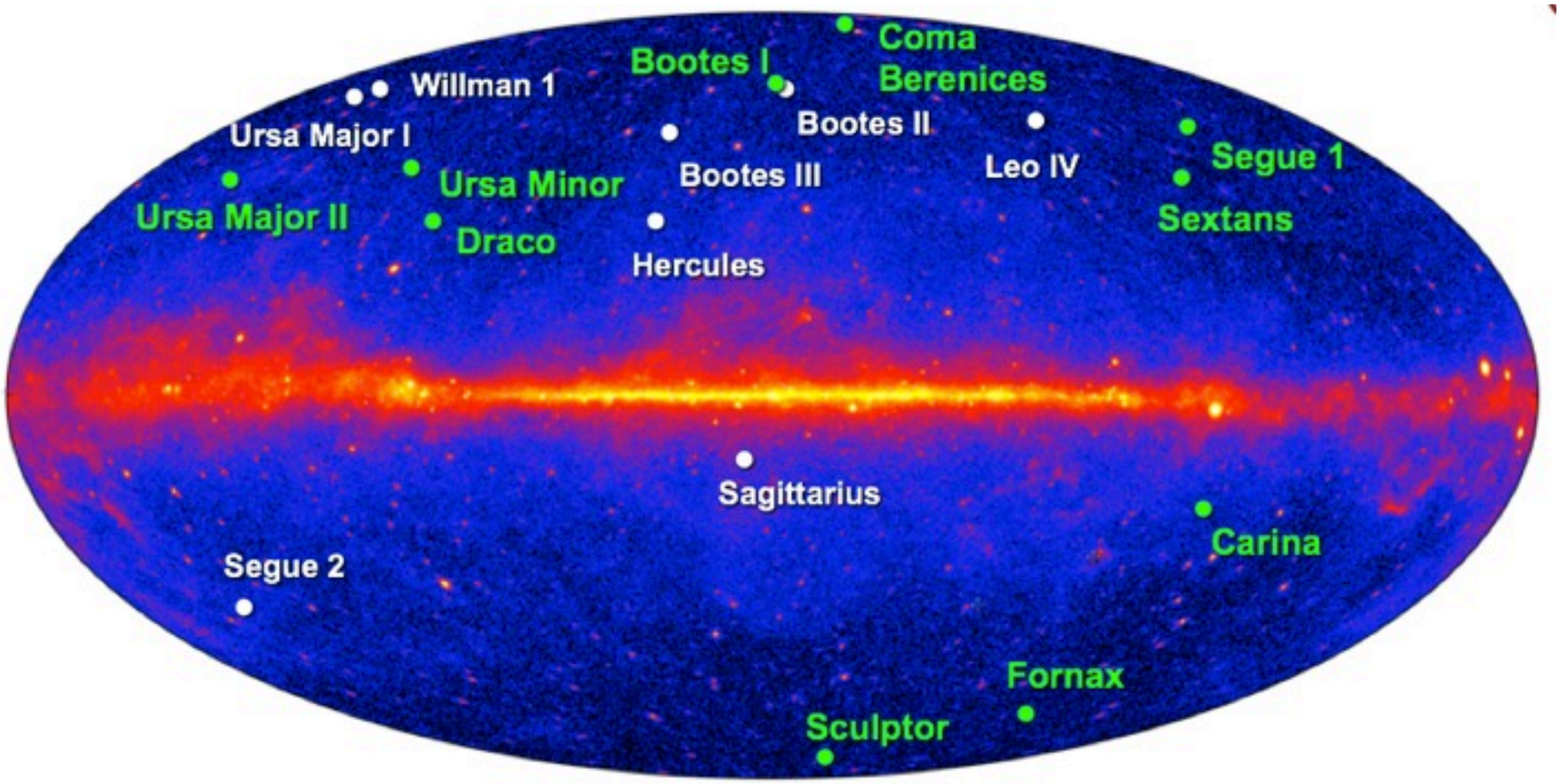
  - ✓ DM density measured (from stellar velocity dispersion)
  - ✓ Mass–to-Light ratio indicate DM dominated ($M/L>100\ M_{sun}/L_{sun}$)







Dwarf Spheroidal Galaxies (dSphs)



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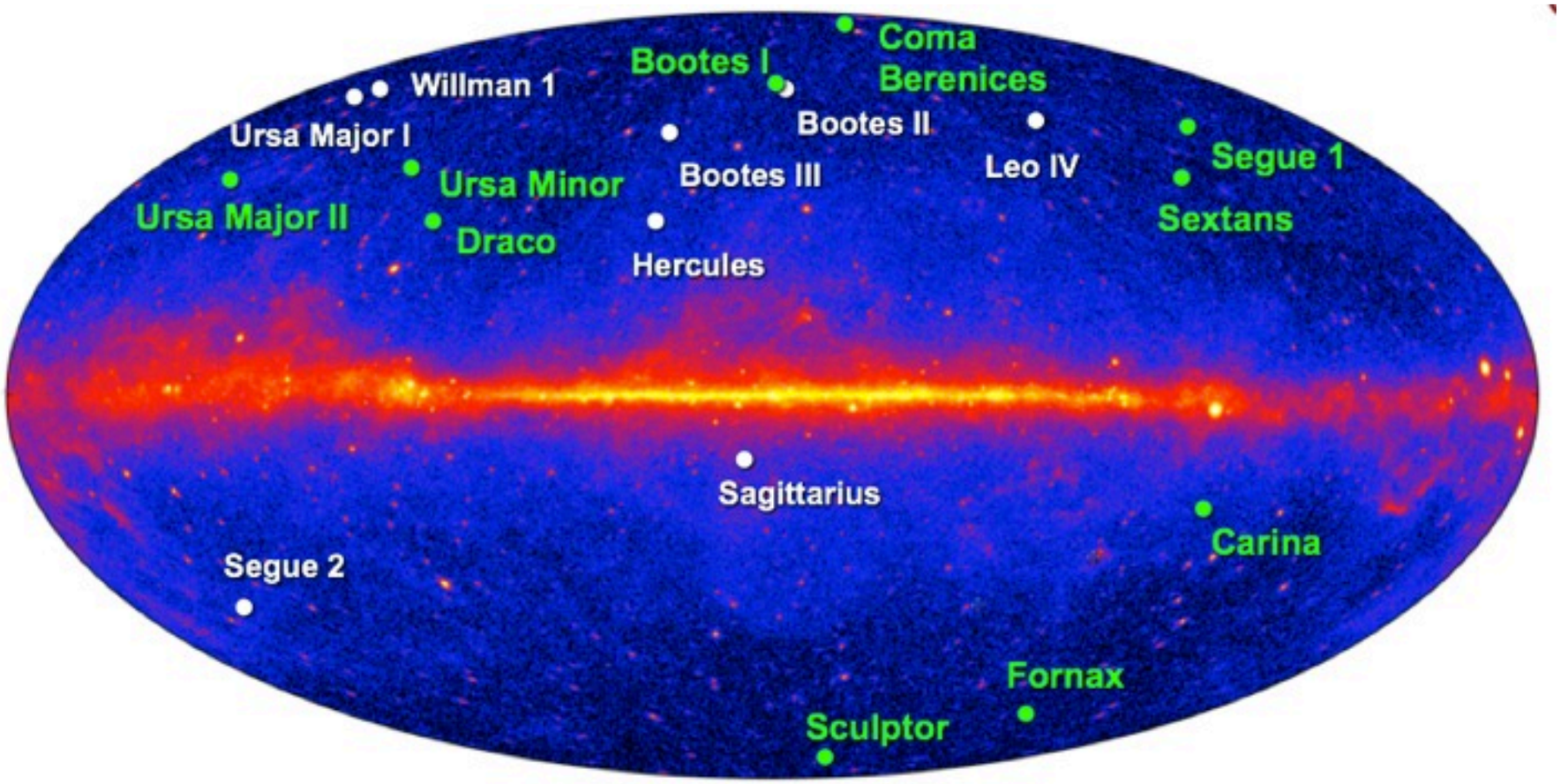

No gamma-ray signals from any individual dSPh.

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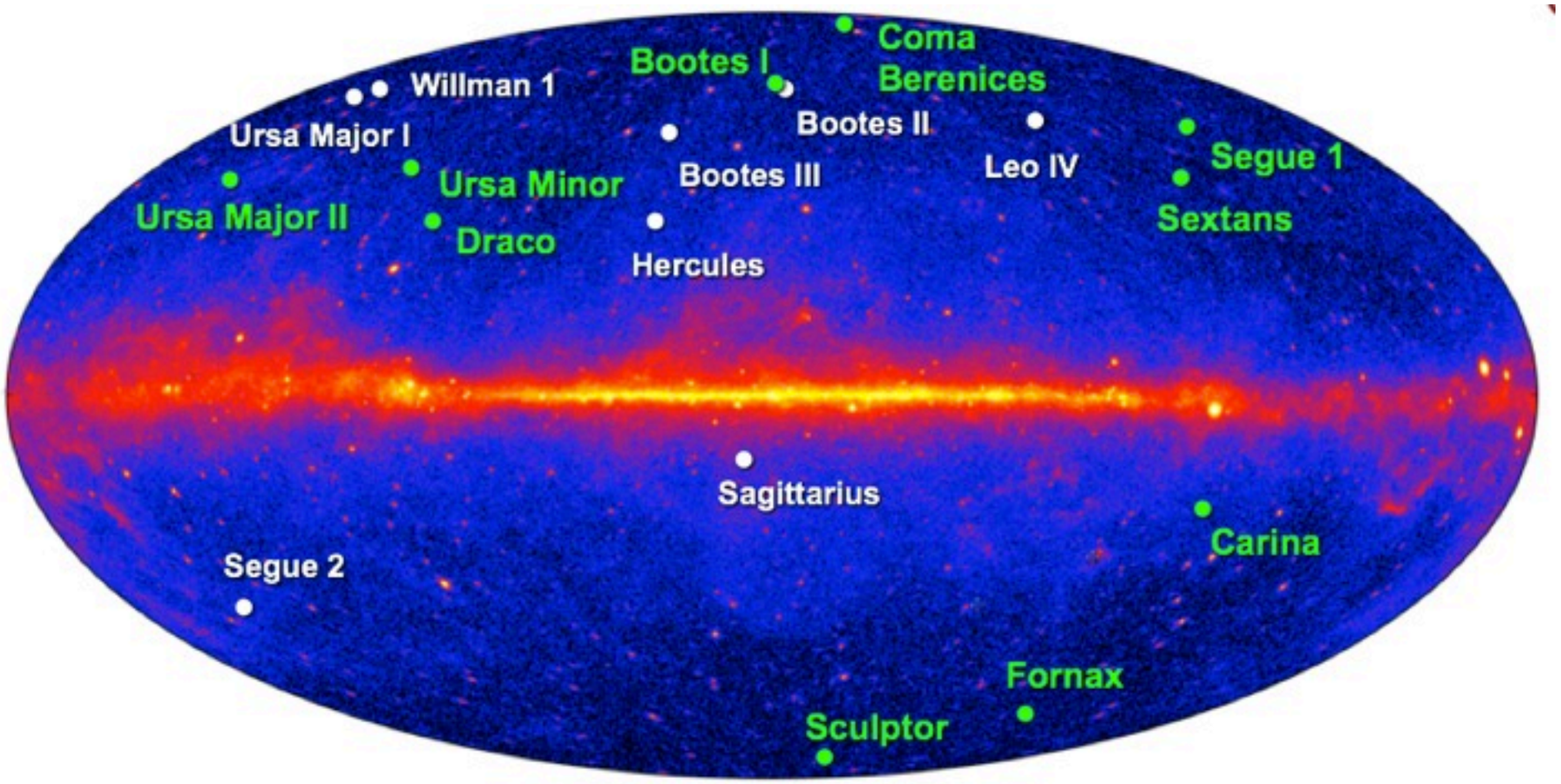

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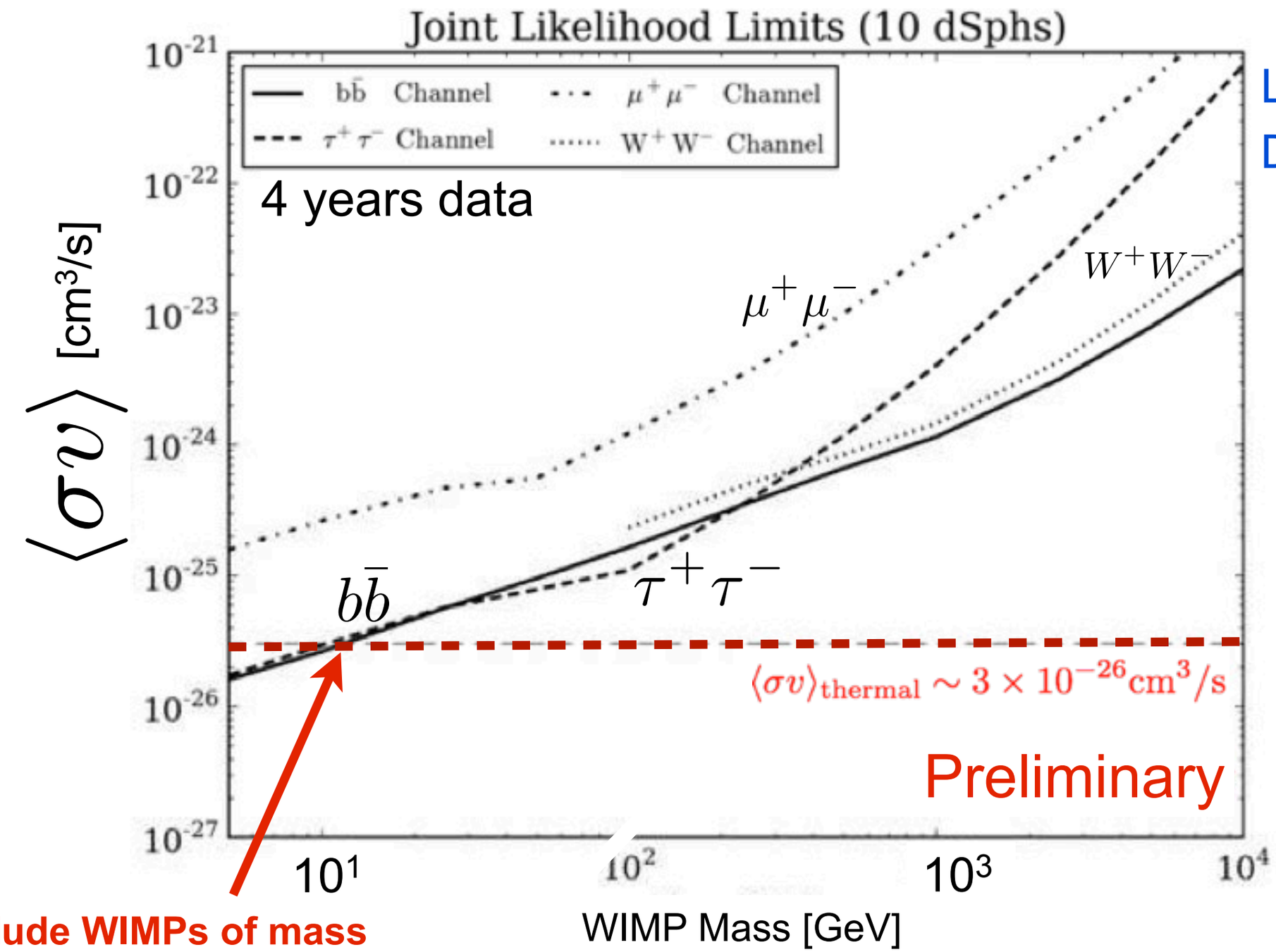
Select the 10 "best" high latitude dShps and do a joined Likelihood analysis

⇒ To set upper bounds on DM annihilations

Upper bounds on DM annihilations $\langle \sigma v \rangle$



Limits on DM+DM

-> b-quarks

-> taus

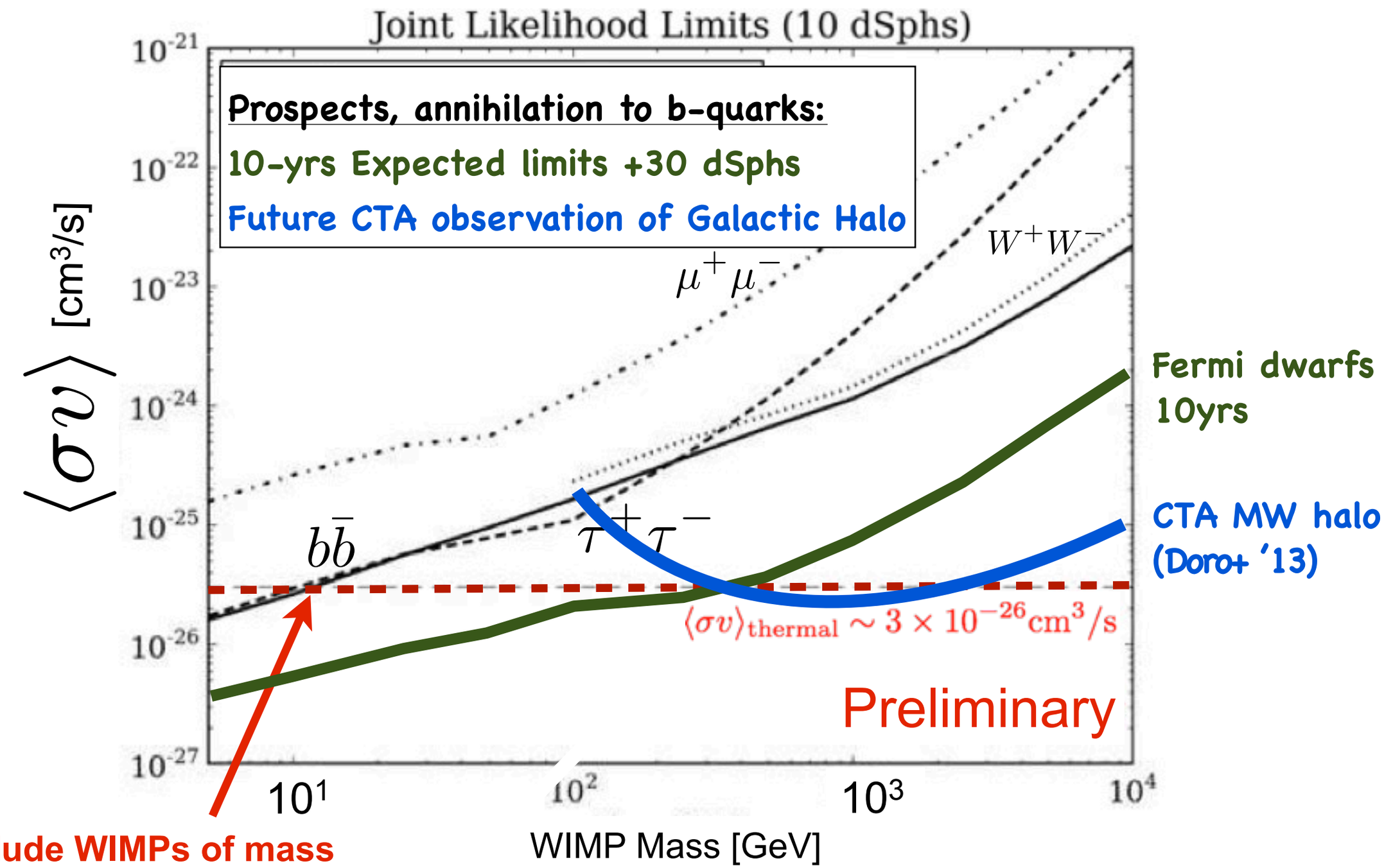
-> muons

-> W bosons

Exclude WIMPs of mass $\lesssim$ 10 GeV, with annihilations into $b\bar{b}, \tau^+\tau^-$.

Similar results already by Fermi 2yrs, Ackermann et al. PRL 107, 241302 (2011)

Upper bounds on DM annihilations $\langle \sigma v \rangle$



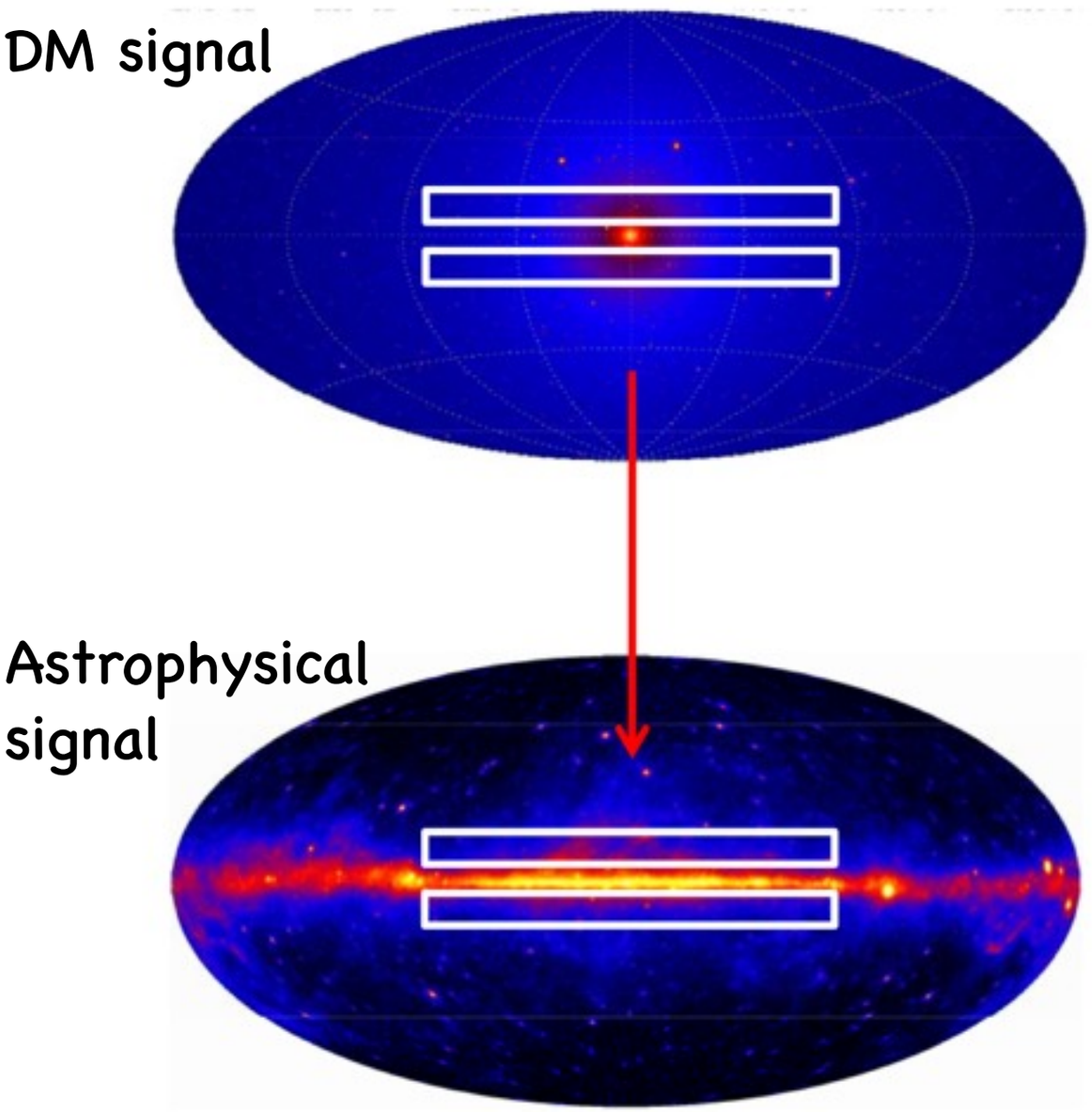
Exclude WIMPs of mass $\lesssim$ 10 GeV, with annihilations into $b\bar{b}, \tau^+\tau^-$.

[2]

Milky Way Dark Matter Halo

Milky Way Dark Matter Halo

Search for emission from annihilating or decaying DM in an extended region of the Milky Way DM halo



- **Analyze two 10x80 degree bands 5 degrees off the plane**
  - ✓ to decrease astrophysical background
  - ✓ to mitigate uncertainties from inner DM density profile

- **Two approaches to set limits:**
  I. more conservative —
     Assume emission only from DM
  II. more accurate —
     Fit the the DM and astrophysical emission simultaneously

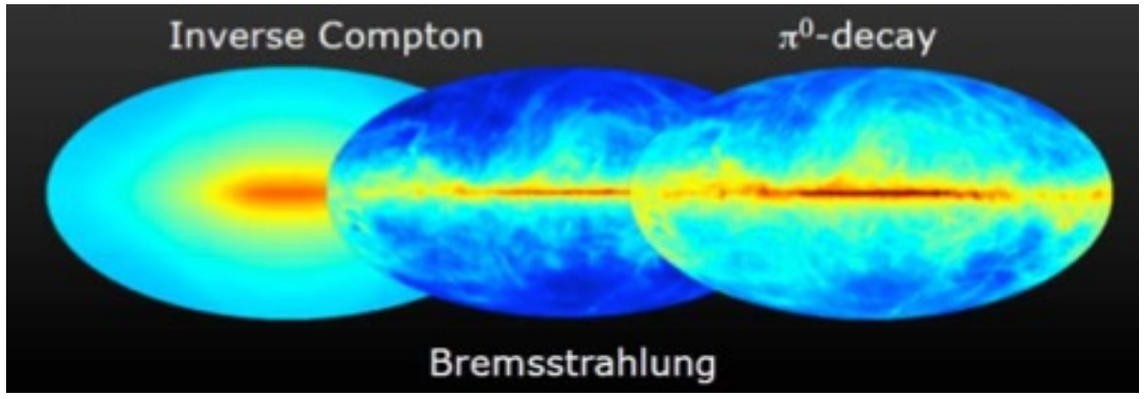
Ackermann+ `12, ApJ 761, 91

Method I **Compare expected counts from DM (n_{DM}) to observed counts (n_{obs}) to set 3σ upper limit by**

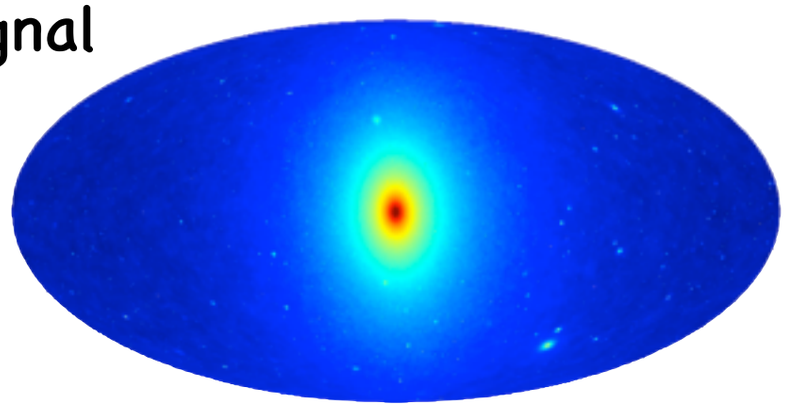
$$n_{\rm DM} - 3\sqrt{n_{\rm DM}} \leq n_{\rm data}$$

Method II **Find the maximal possible contribution from DM, while astrophysical background models are allowed to vary within certain ranges.**

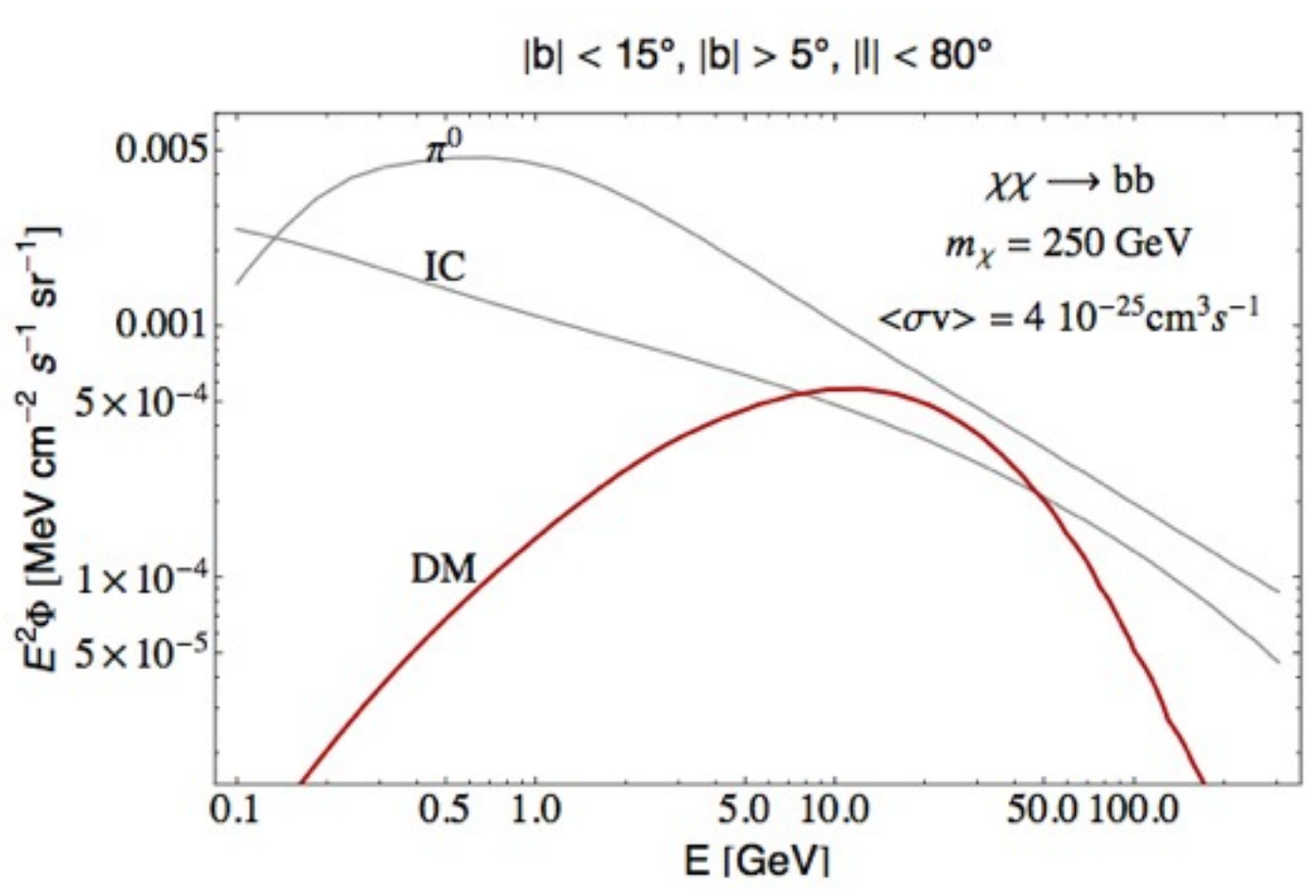
Allows to **disentangle** DM signal by utilizing both **spatial** and **spectral shape** (good astrophysical model important)



DM signal



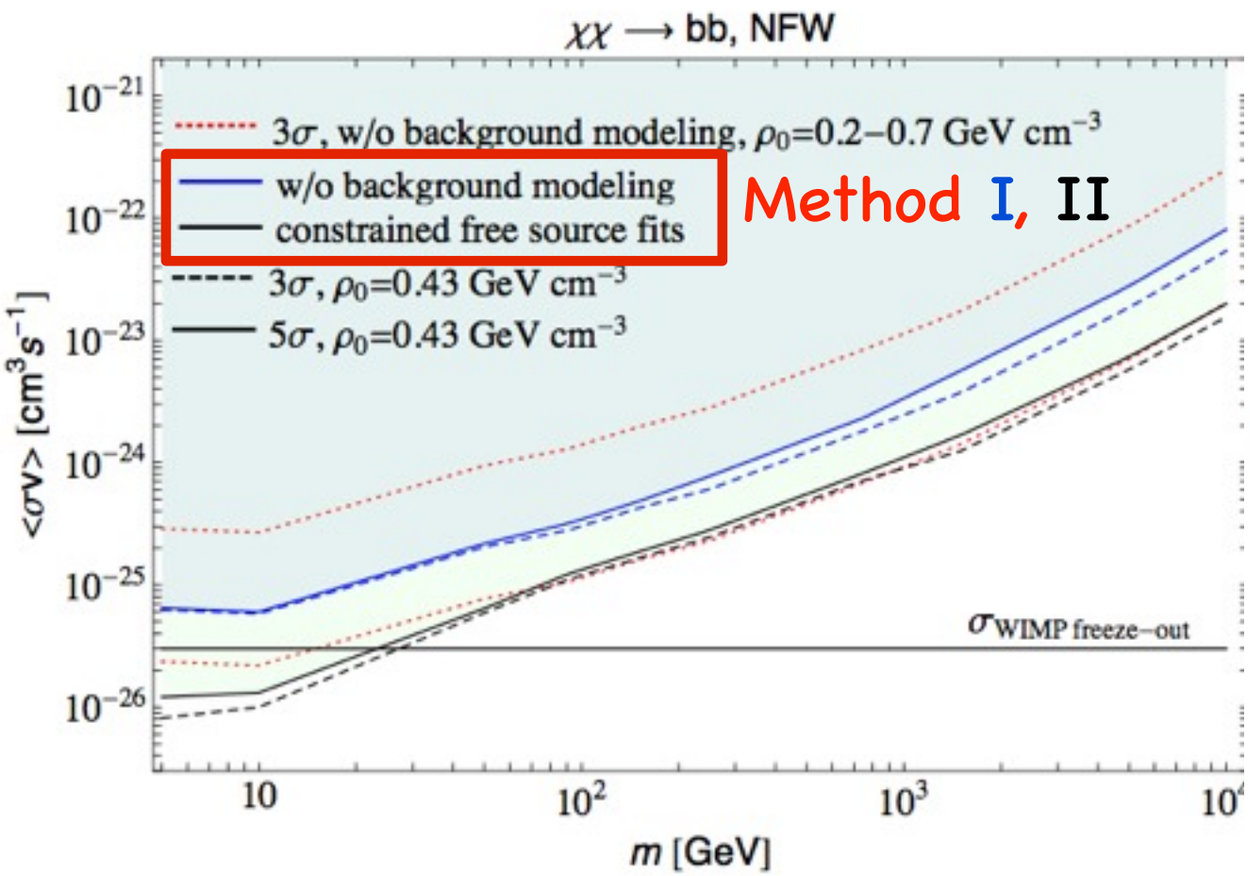
Spatial distributions

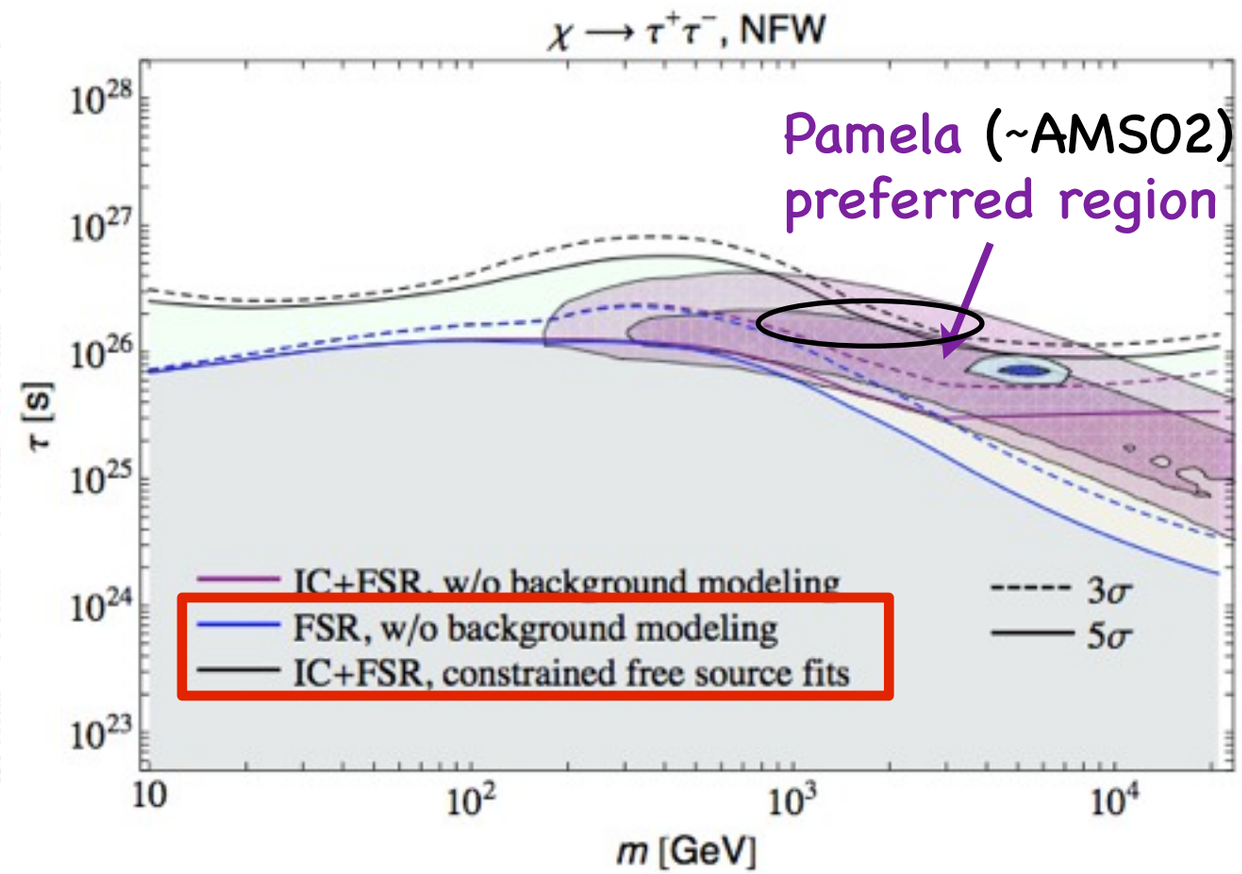


Energy spectra

Constraints from Milky Way Halo

- **Including modeling of the astrophysical emission improves the DM constraints by a factor of ~5**





DM annihilation x-section to b-quarks limits

DM lifetime limits for decay into tau-leptons

- **with inclusion of astrophysical backgrounds, a canonical thermal cross section into b-quarks limits the WIMP mass to $\gtrsim$ 20 GeV (comparable to the dSphs limits)**

[3]

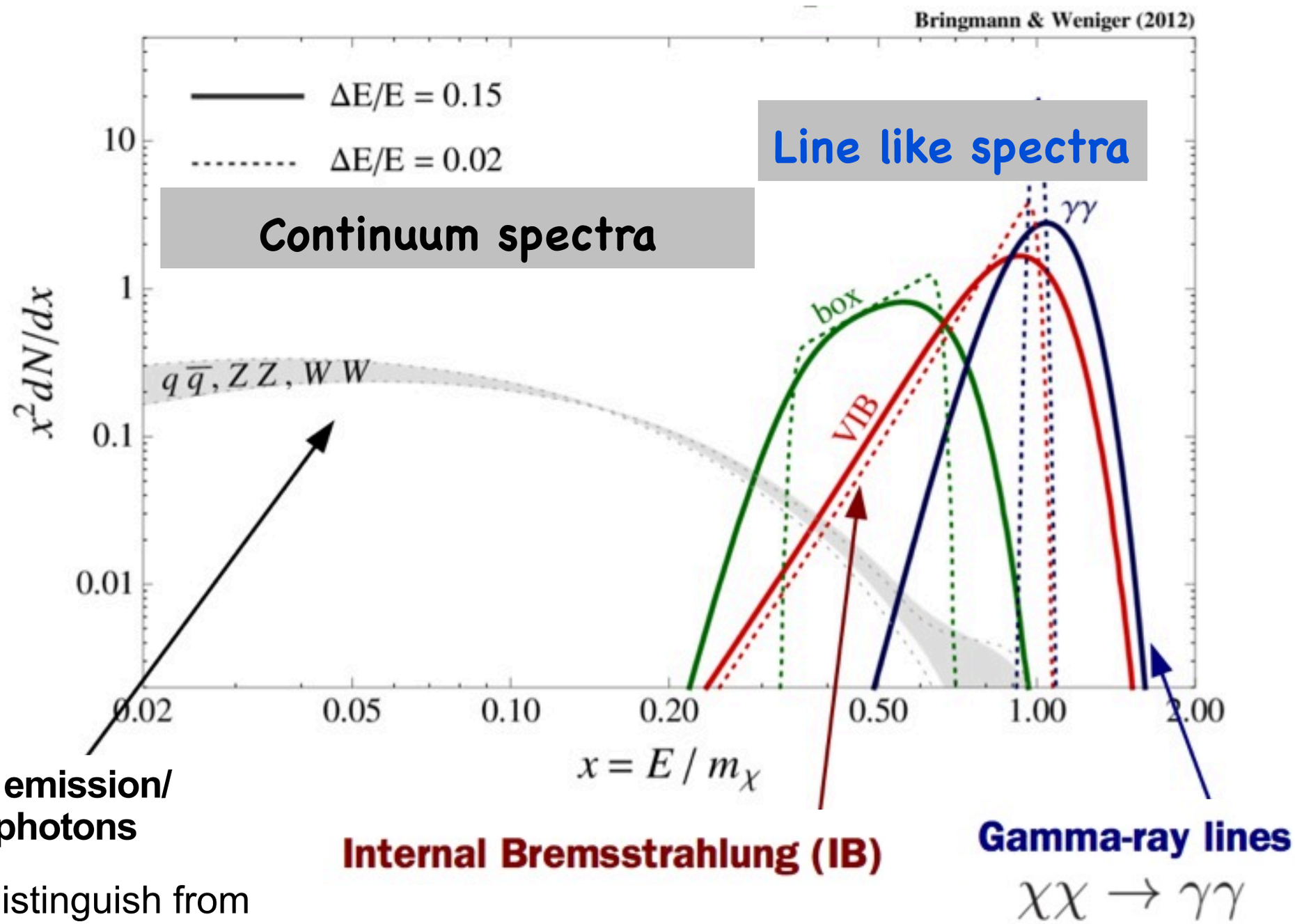
Gamma-ray Line Searches

[3]

Gamma-ray Line Searches

Evidence for 130 GeV gamma-ray line?

Gamma-ray line — a 'smoking gun' for DM



Continuum emission/ secondary photons

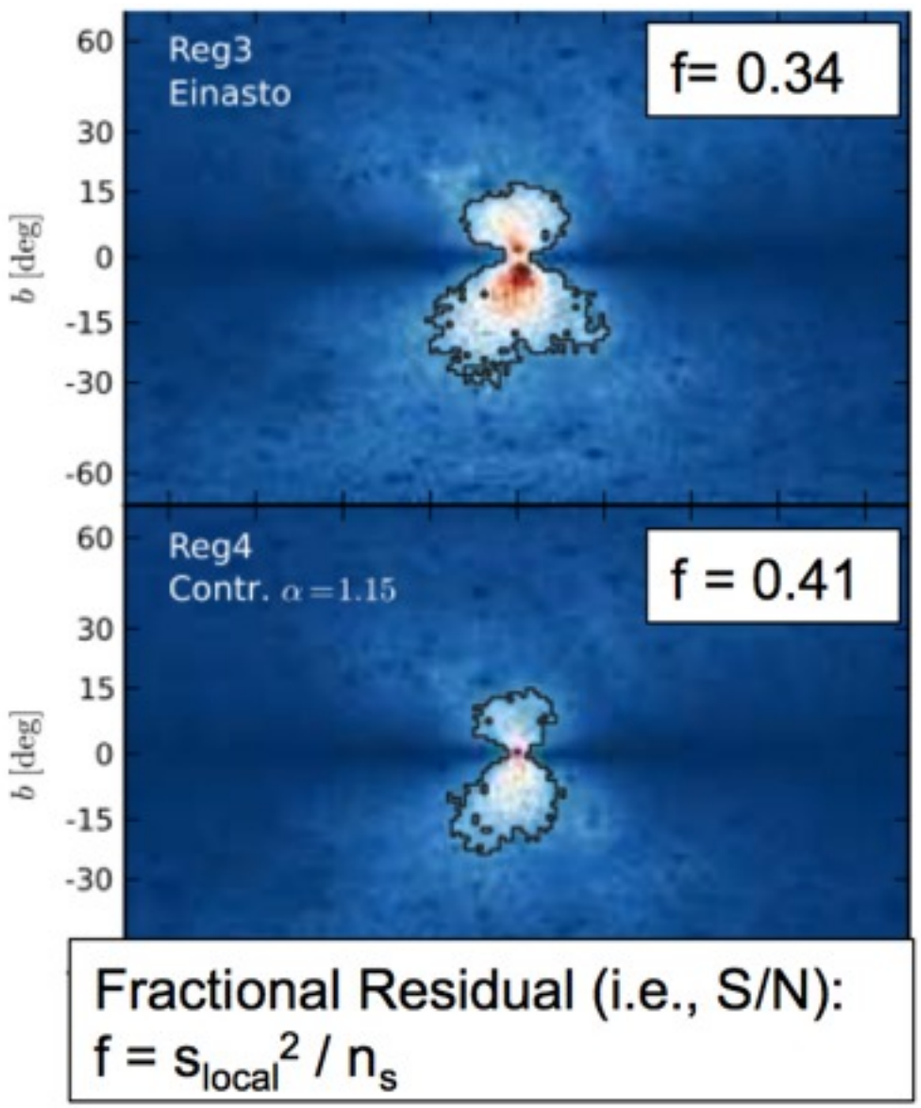
Difficult to distinguish from astrophysical backgrounds

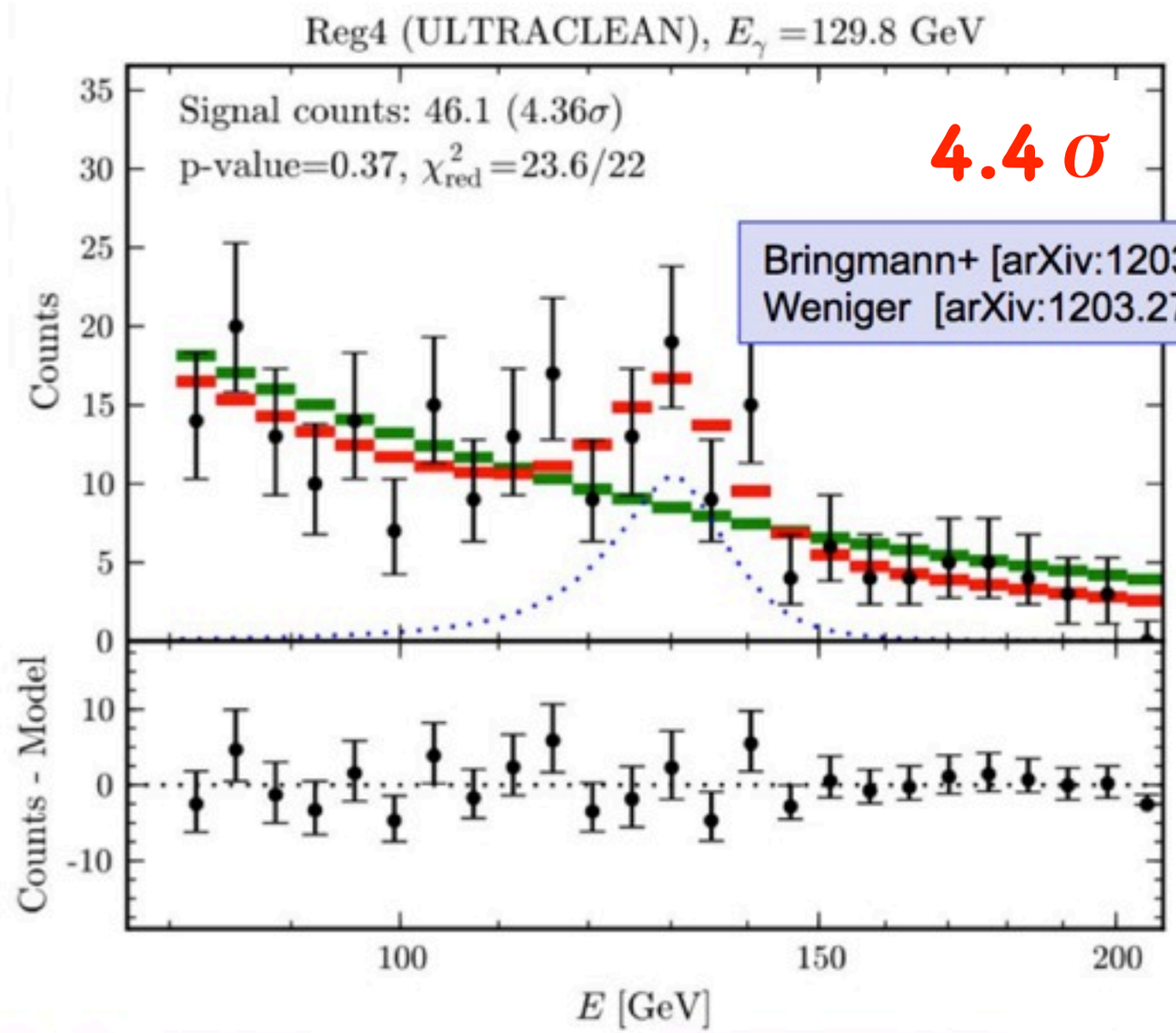
$$\chi\chi \to \bar{q}q \to \pi^0 \ldots$$

$$\pi^0 \to \gamma\gamma$$

Direct annihilation into photons. Forbidden at tree-level.

Evidence for 130 GeV gamma-ray line?

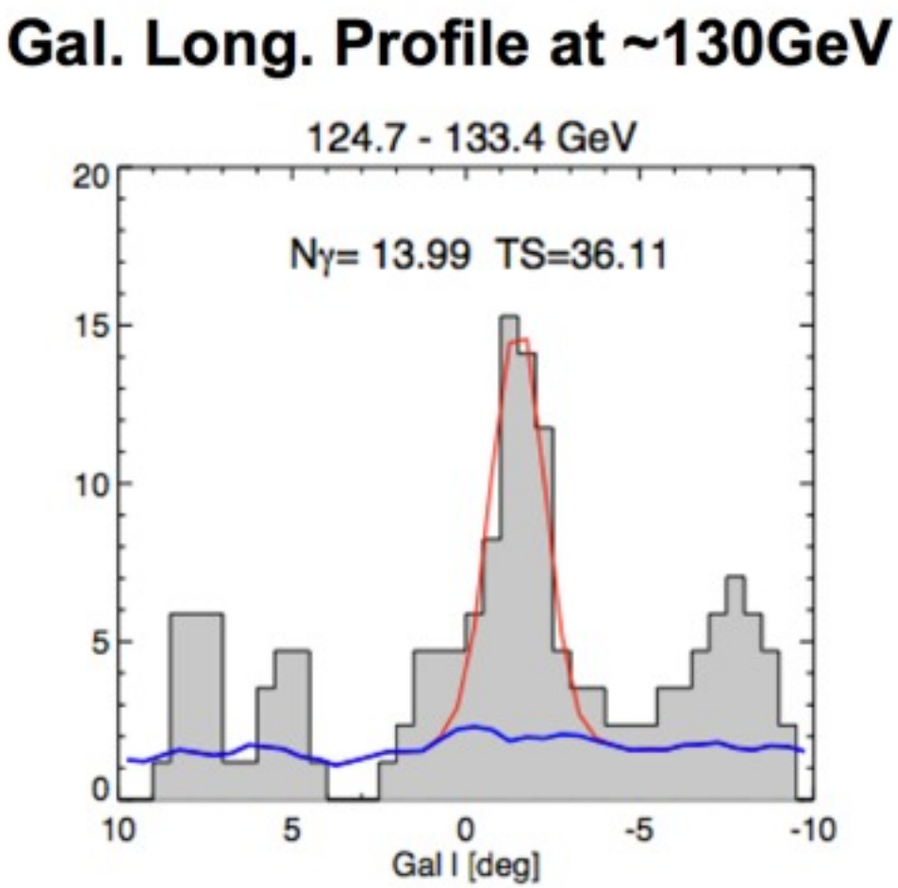


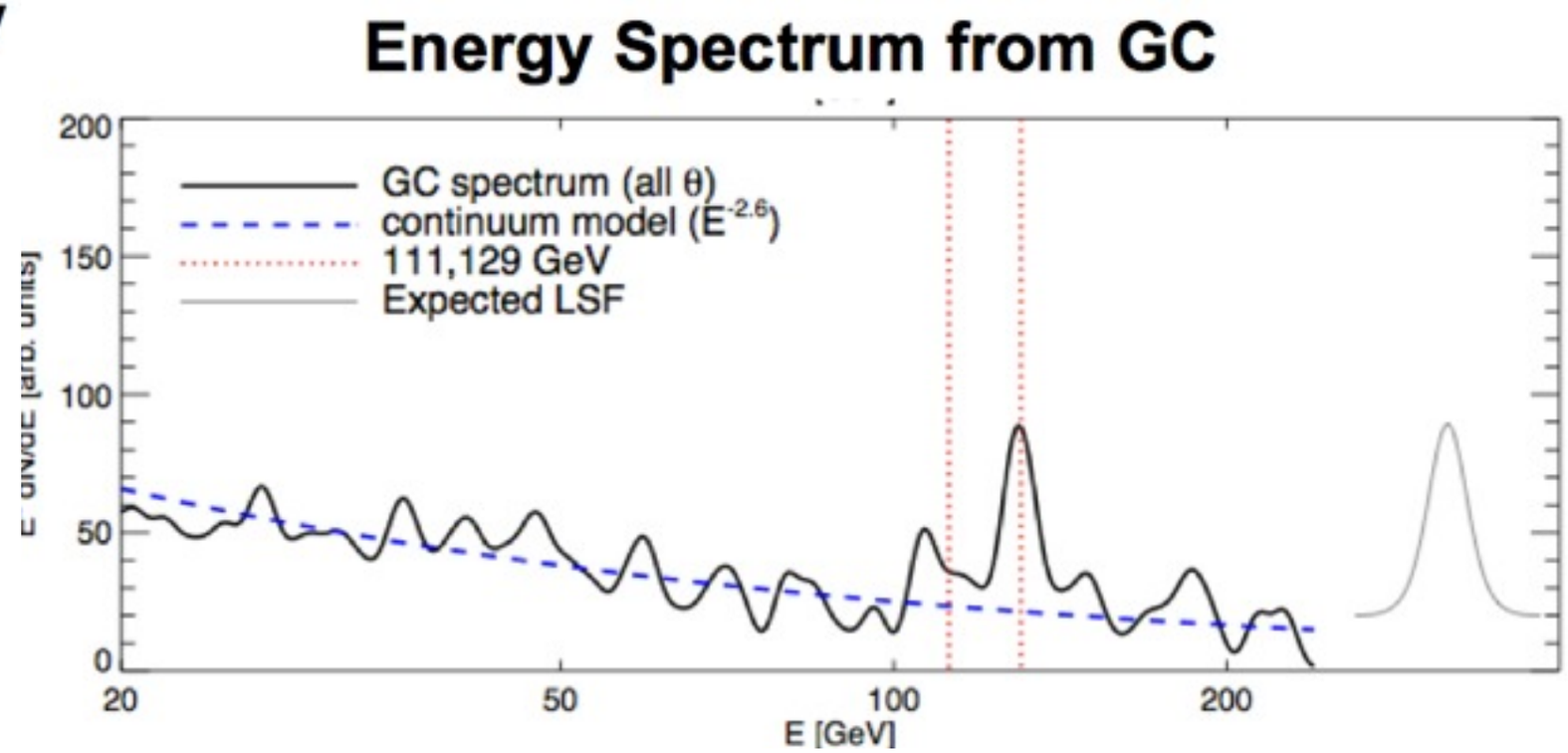


Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV and near the Galactic centre:

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

Evidence for 130 GeV gamma-ray line?





Su & Finkbeiner showed that the spectral feature was close to, but slightly (~1.5 deg) offset from, the Galactic centre [arXiv:1206.1616].

- Their likelihood analysis included a spatial morphology of signal, and data-driven model of Galactic astrophysical backgrounds.
- Claimed **6 σ statistical significance**, after a **trials factor of ~6000**, but acknowledge uncertainties of modeling the Galactic astrophysical backgrounds.

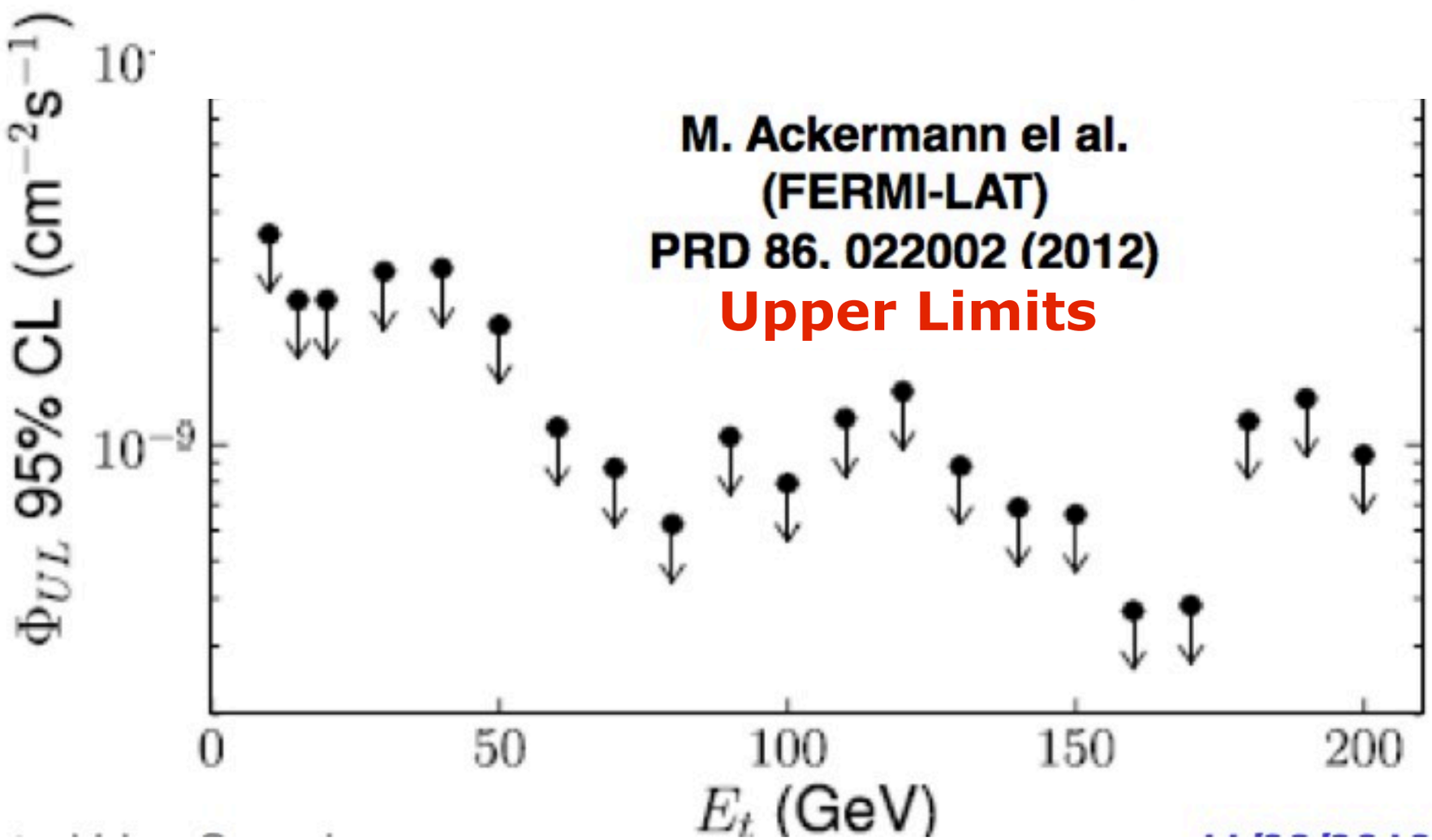
+ many many more papers

Fermi-LAT line search

Fermi-LAT line search

Latest Fermi publication put upper limits on gamma-lines

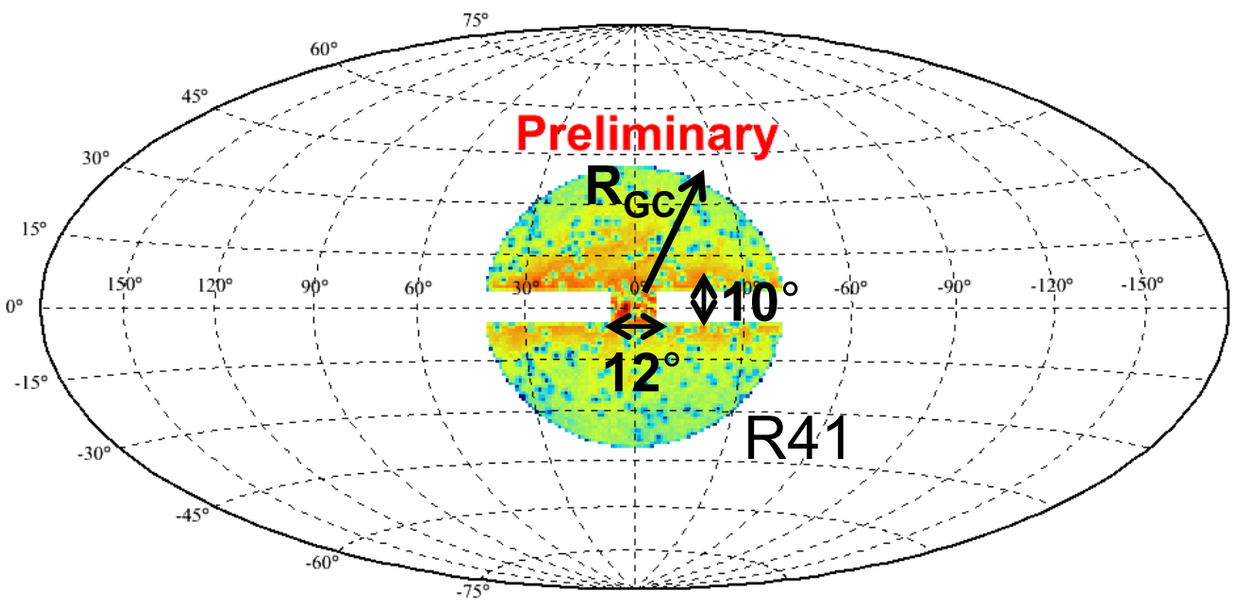
(before claims of a 130 GeV γ-line)



Methodology improvements:

1. Region Of Interest (ROI)

– Optimize: signal/sqrt(Bkg)
for a given DM profile against template model of the diffuse gamma-ray bkg.

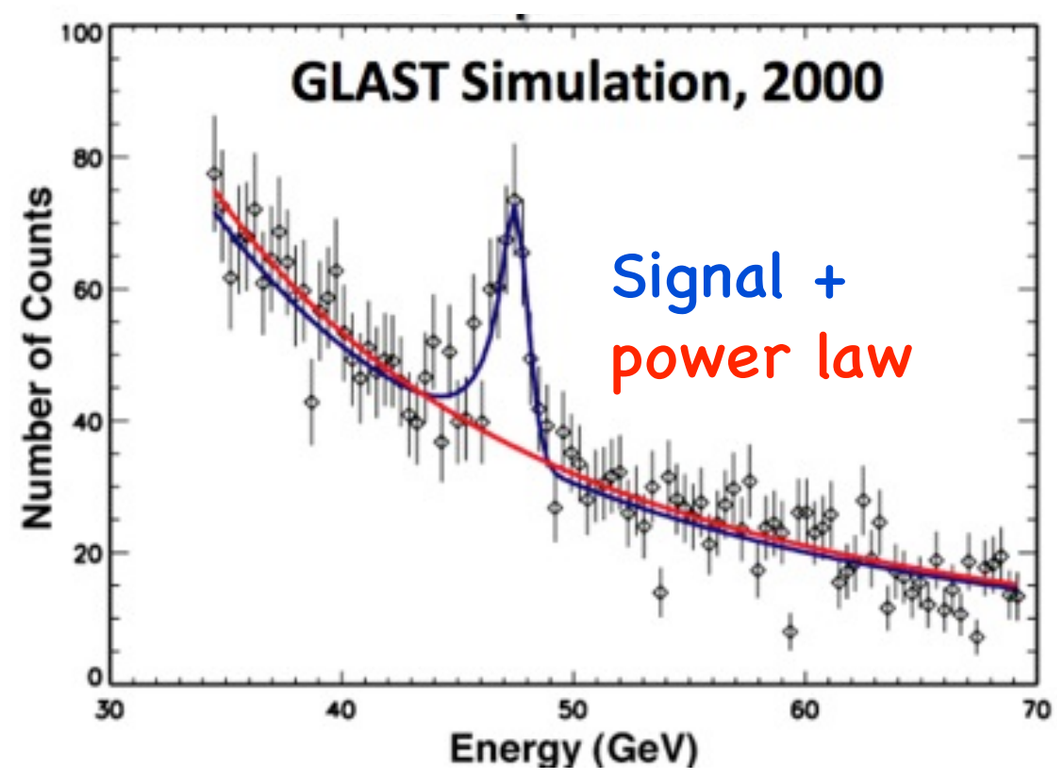


Search in 5 ROIs:

- 3° circle (R3)
- Einasto Optimized (R16)
- NFW Optimized (R41)
- Isothermal Optimized (R90)
- 2 year Analysis ROI (R180)

2. Spectral analysis (5-300 GeV)

– Unbinned maximum likelihood
– Model bkg as single powerlaw
– bkg n_{bkg} and signal n_{sig} free
– Use sliding $\pm 6\sigma_E$ windows
– Fit for energies in 0.5 σ_E steps

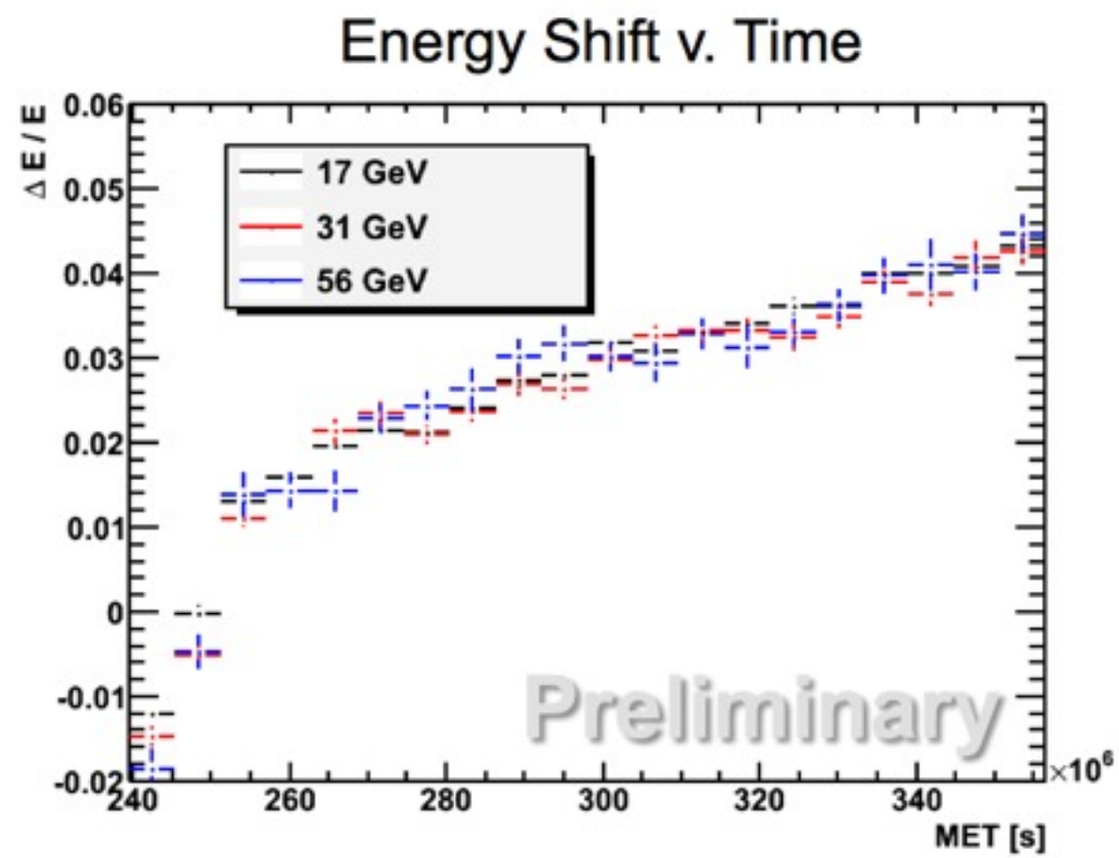


Fitting window ($\pm 6\sigma_E$)

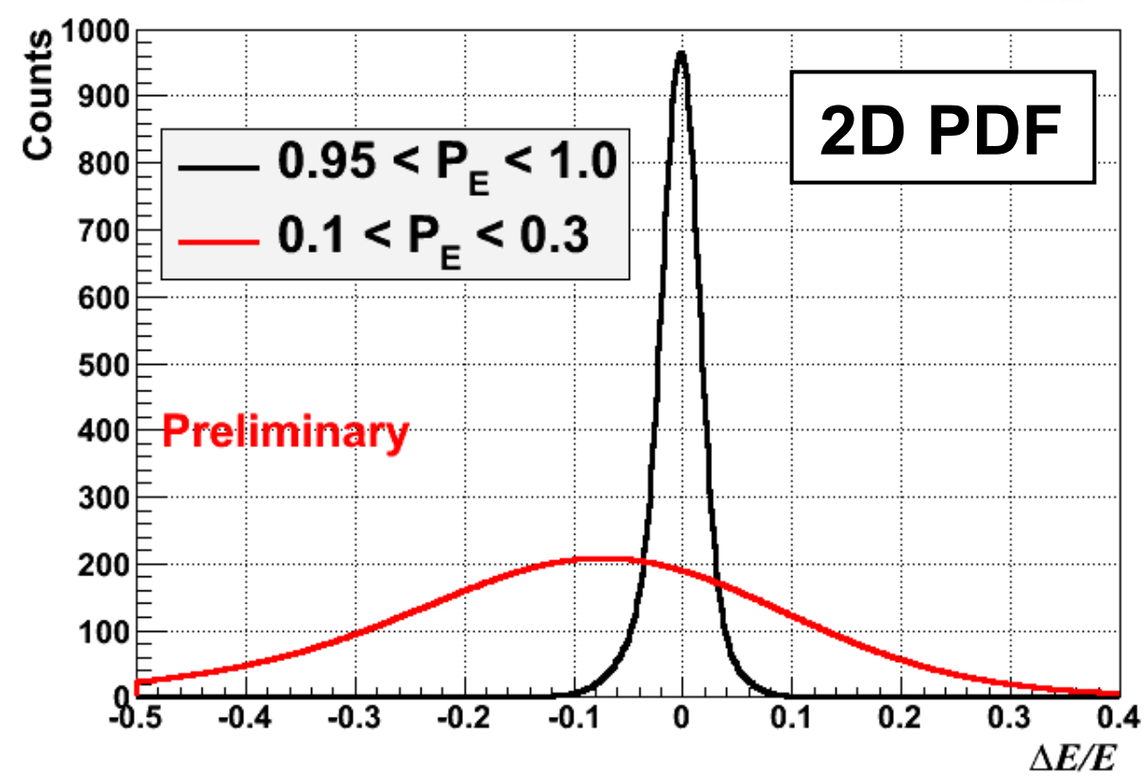
Further improvements

- **Data reprocessed** (Pass7 clean rep.)
  - ✓ Updated calorimeter response
  - ➡ Affects energy reconstruction: up to 5% shift in energy scale
  - ➡ Improves PSF at high energies

(80%+ overlap in events after reprocessing)

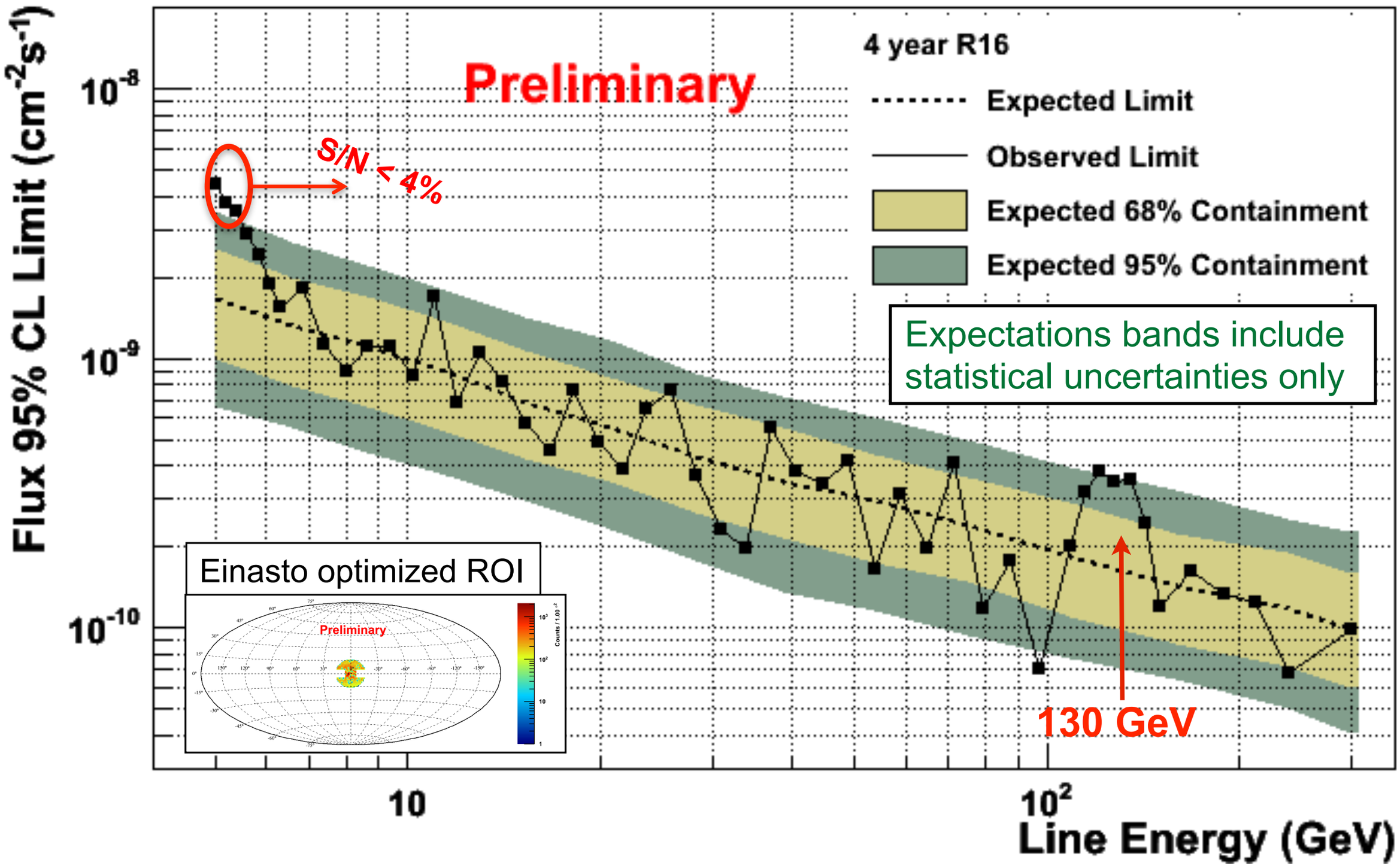


- **Improved line shape**
  - ✓ Line shape determined event by event w/ "2D pdf" – function of both E and P_E (P_E is an assigned probability that measured energy is close to true energy).
  - ➡ Incl. P_E gives ~15% improvement to signal sensitivity (when there is signal) and upper limits (when there is no signal)

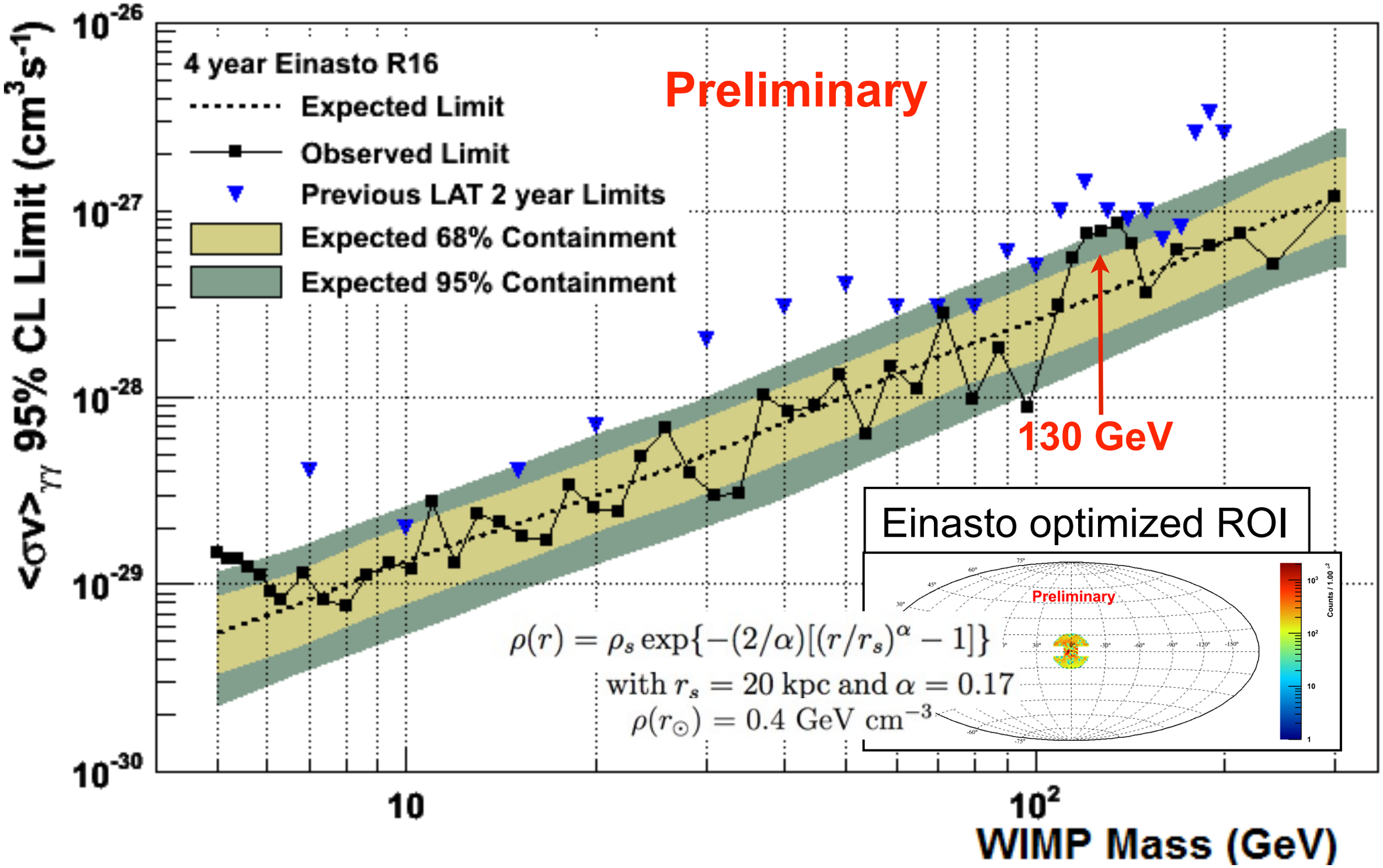


Results

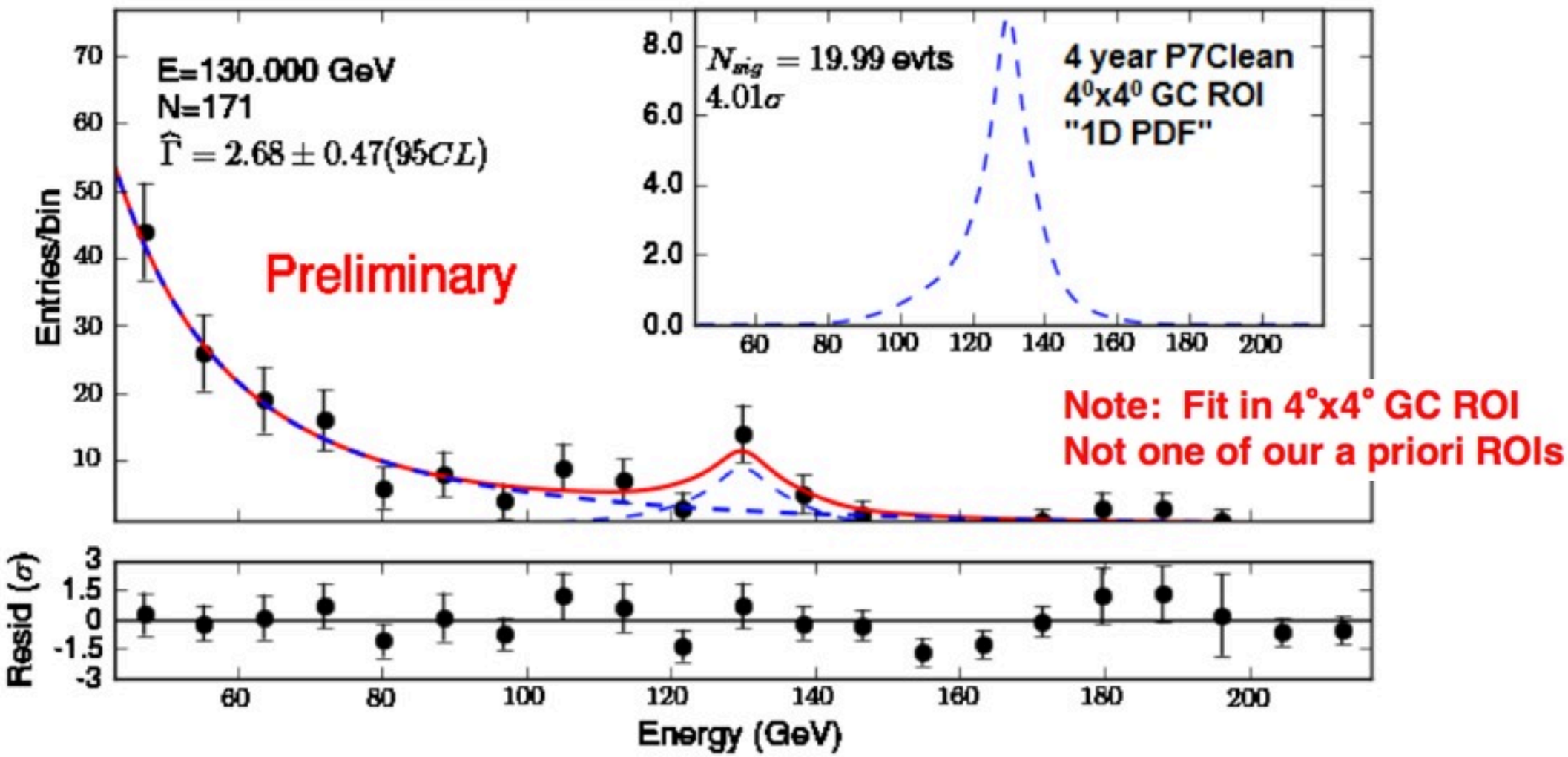
Spectral line 95% CL Flux upper limit



95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ upper limits (Einasto)



Fermi-LAT feature near 130 GeV



- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
- Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)

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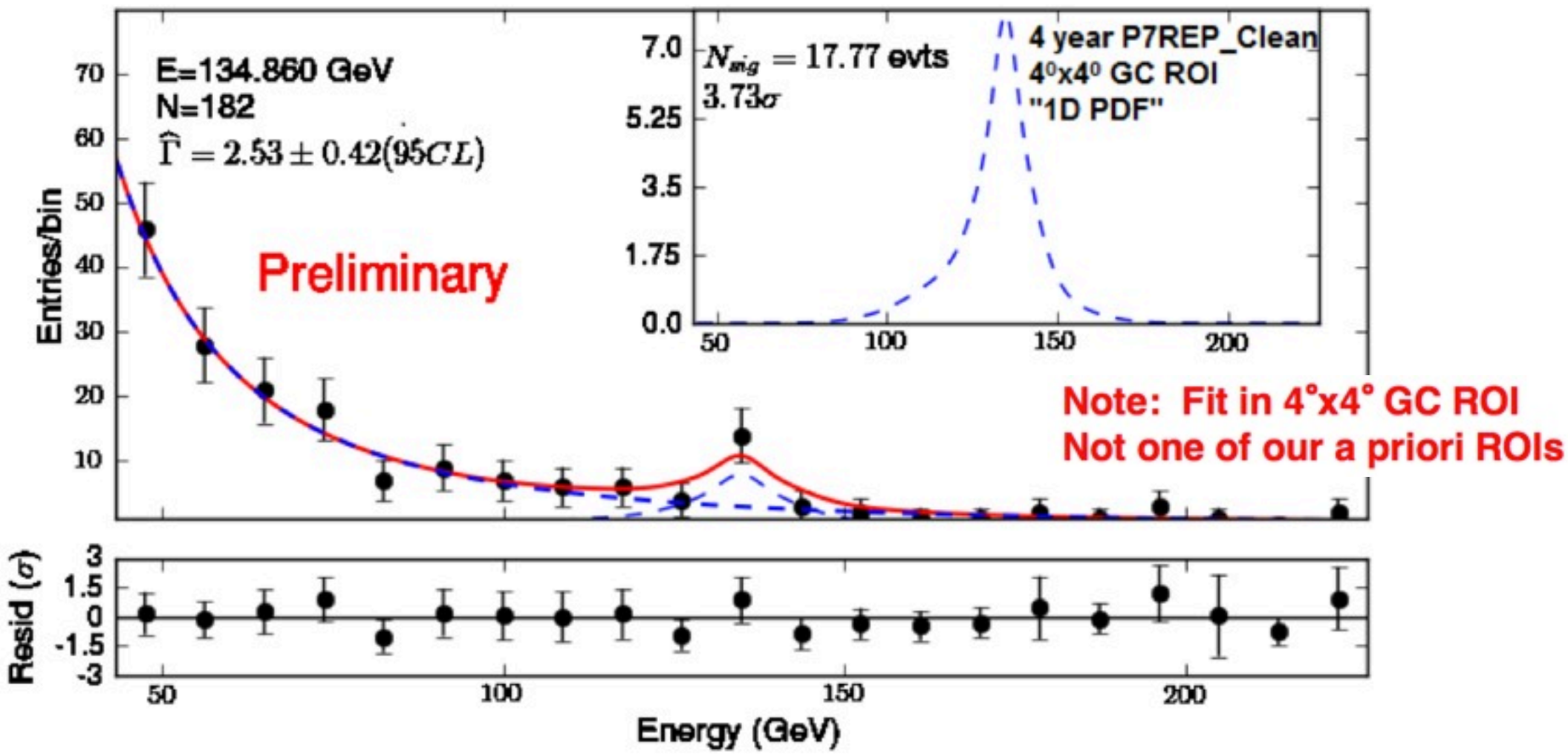
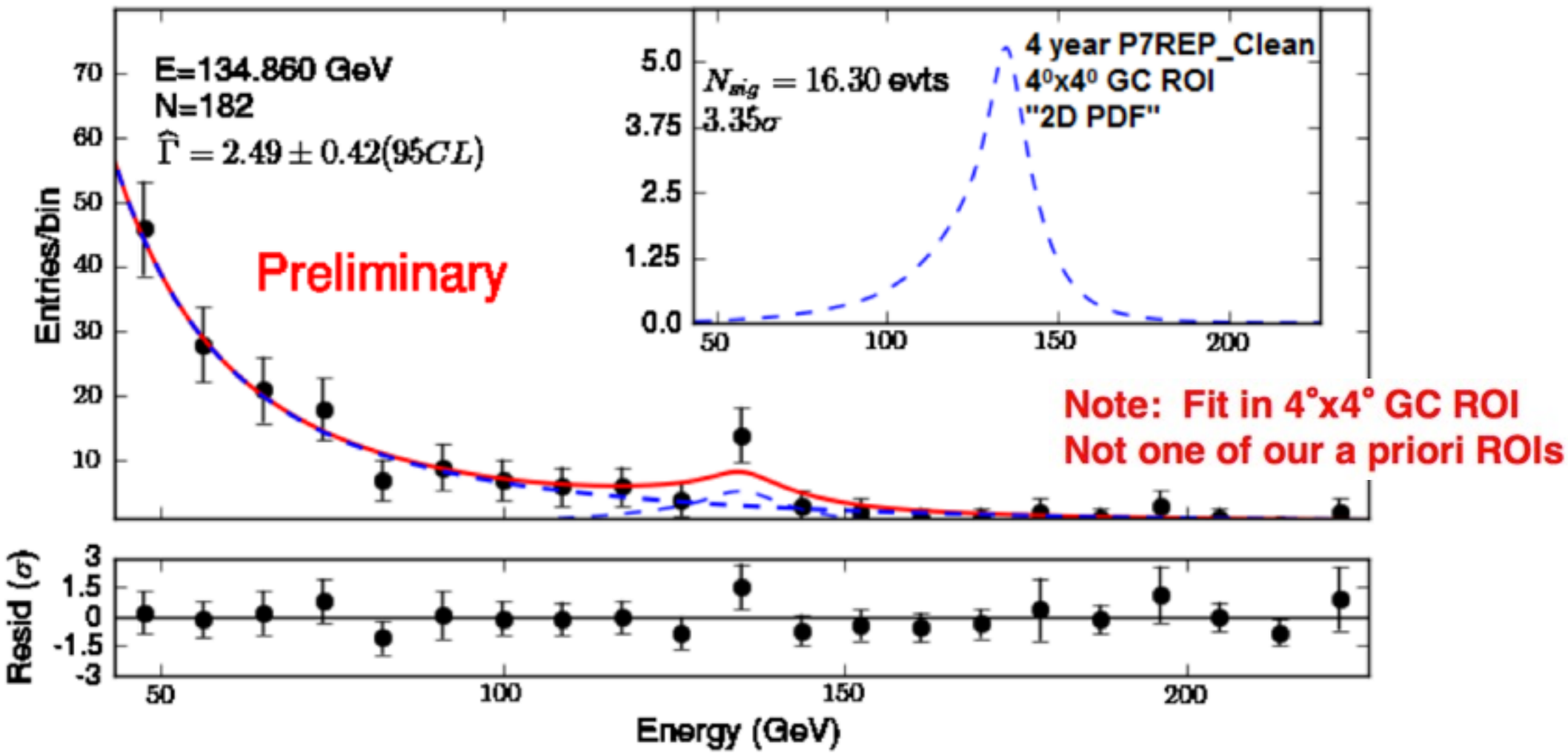


- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- **3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data**
  - **Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)**

Peak shifts from 130 to ~135 GeV

Fermi-LAT feature near 130 GeV

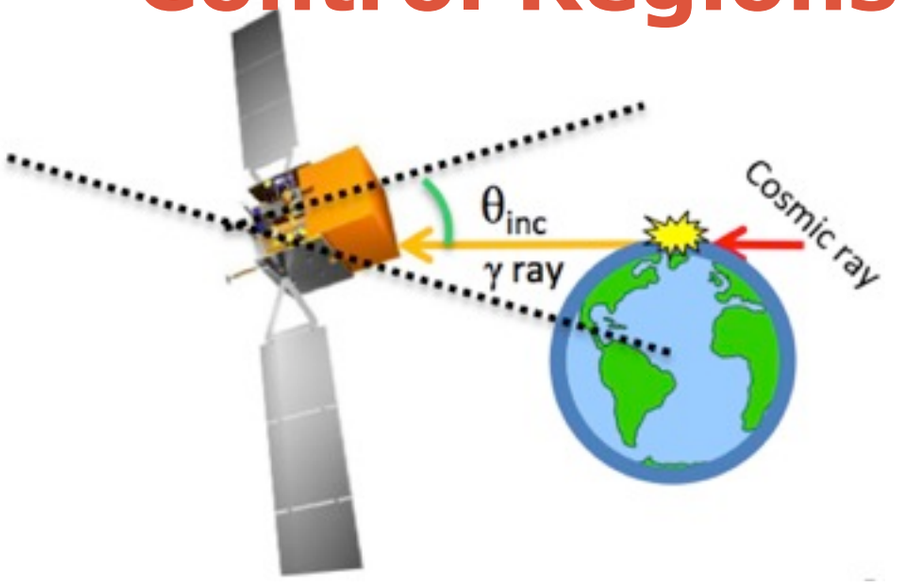


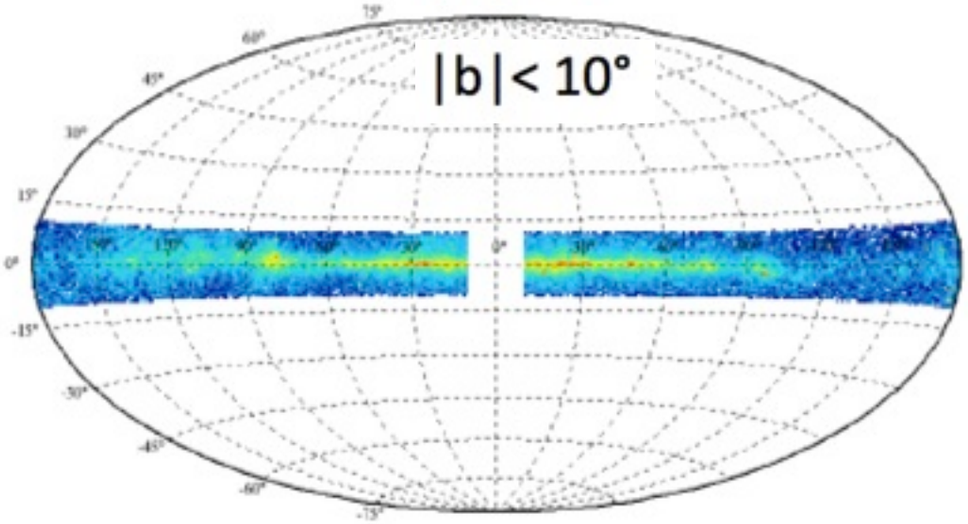
- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- **3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data**
  - **Look in 4°x4°GC ROI, Use 2D PDF (P_E in data)**
  - **<2σ global significance after trials factor**

Peak shifts from 130 to ~135 GeV

Peak 'too' narrow

Control Regions (No DM signal regions)

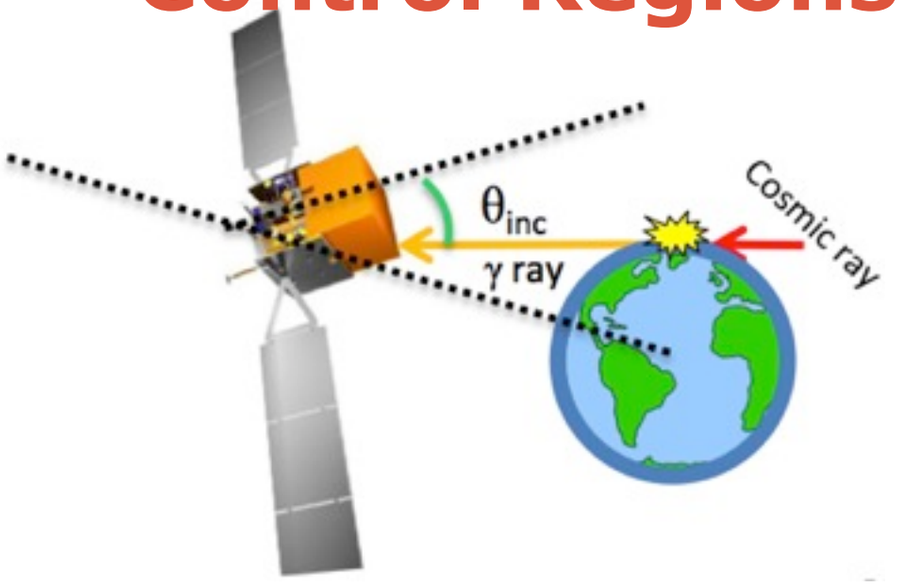


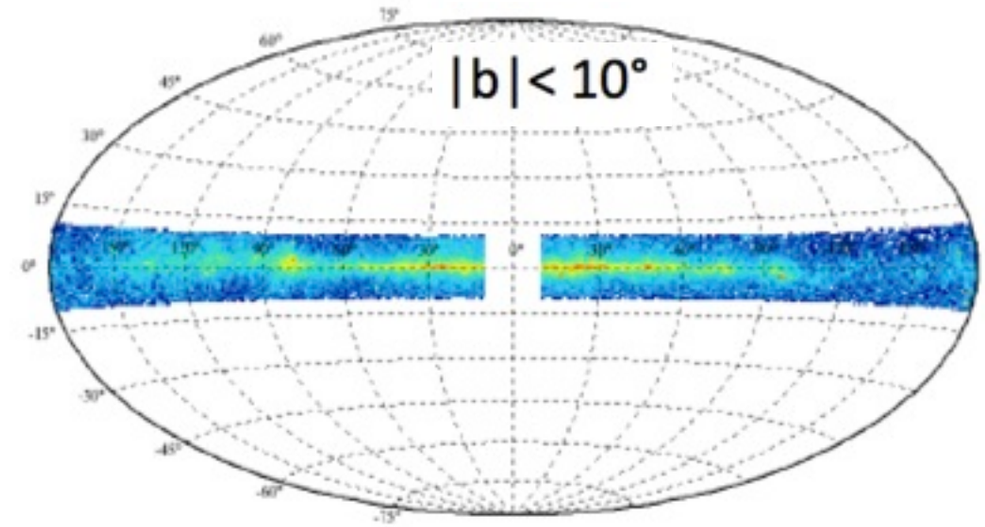


The **Earth Limb**: bright, and expected to be a smooth power-law

The **Galactic Disk**: bright, and astrophysical source dominated

Control Regions (No DM signal regions)

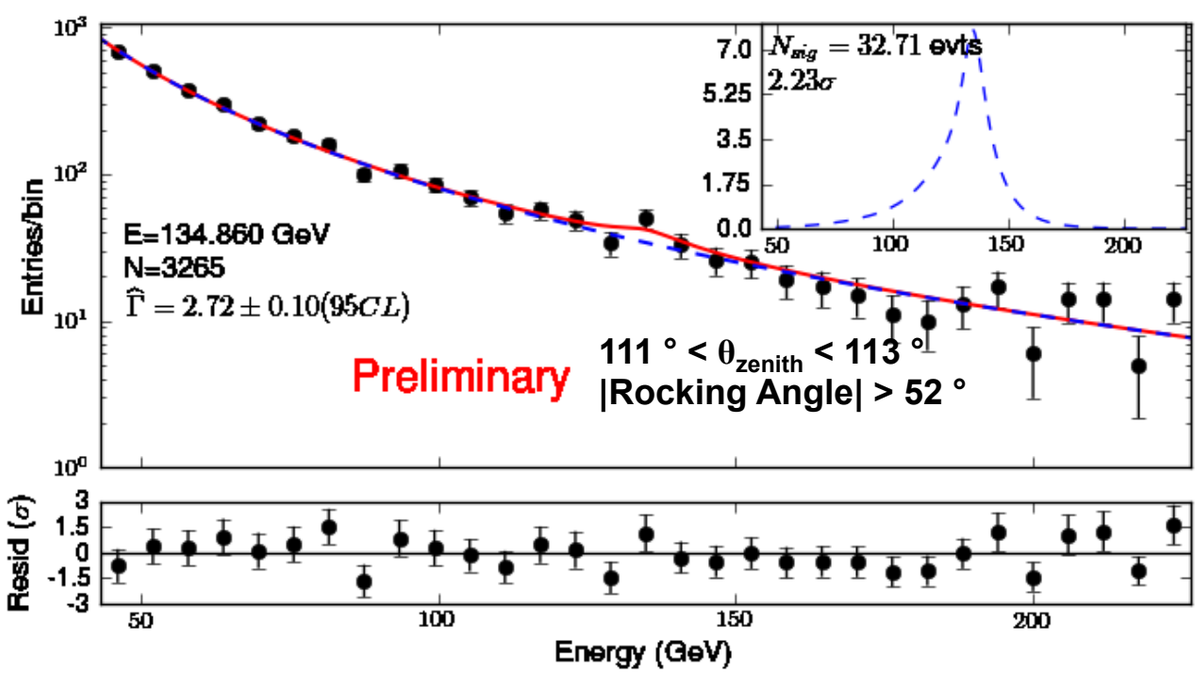




The **Earth Limb**: bright, and expected to be a smooth power-law

Line-like feature in limb near 130 GeV

2.2σ, S/N ≈ 15% (GC: 3.4σ, S/N≈70%)



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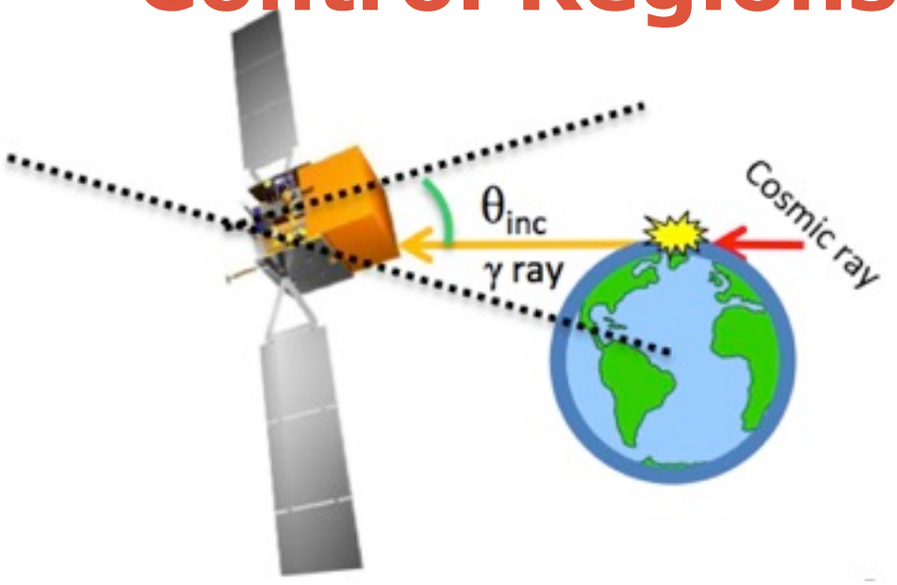

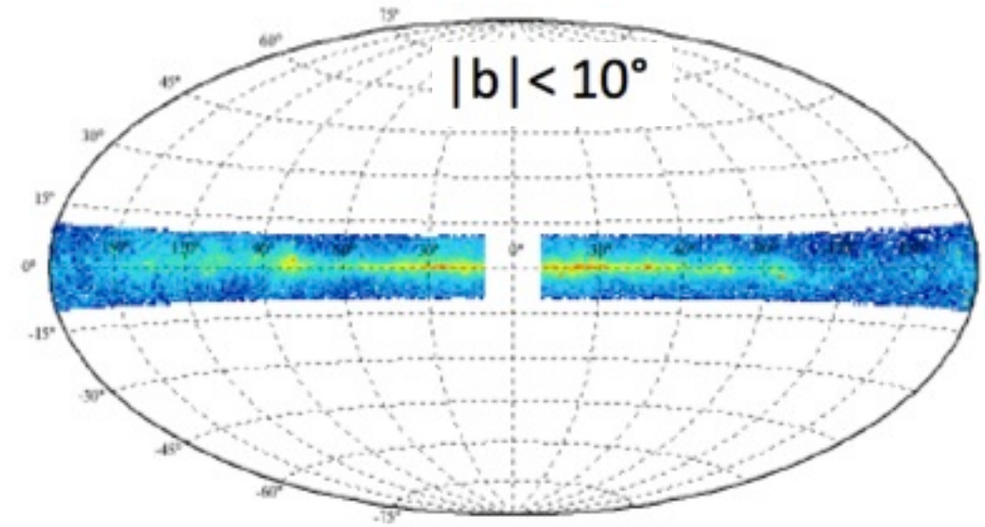

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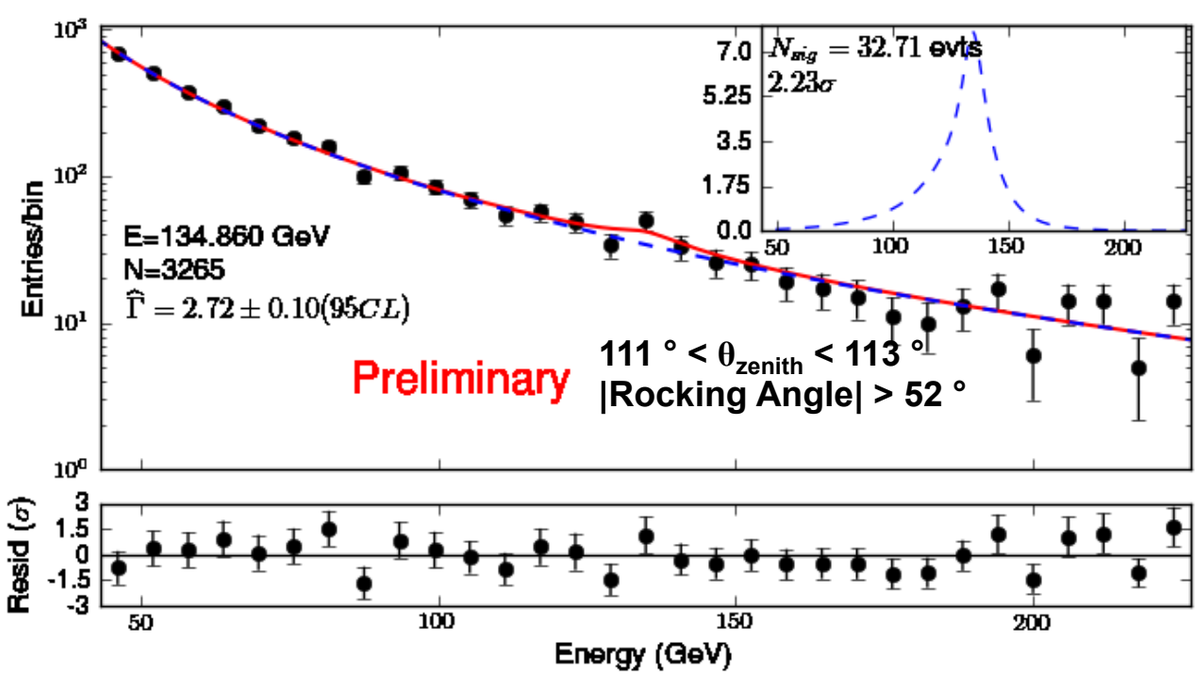
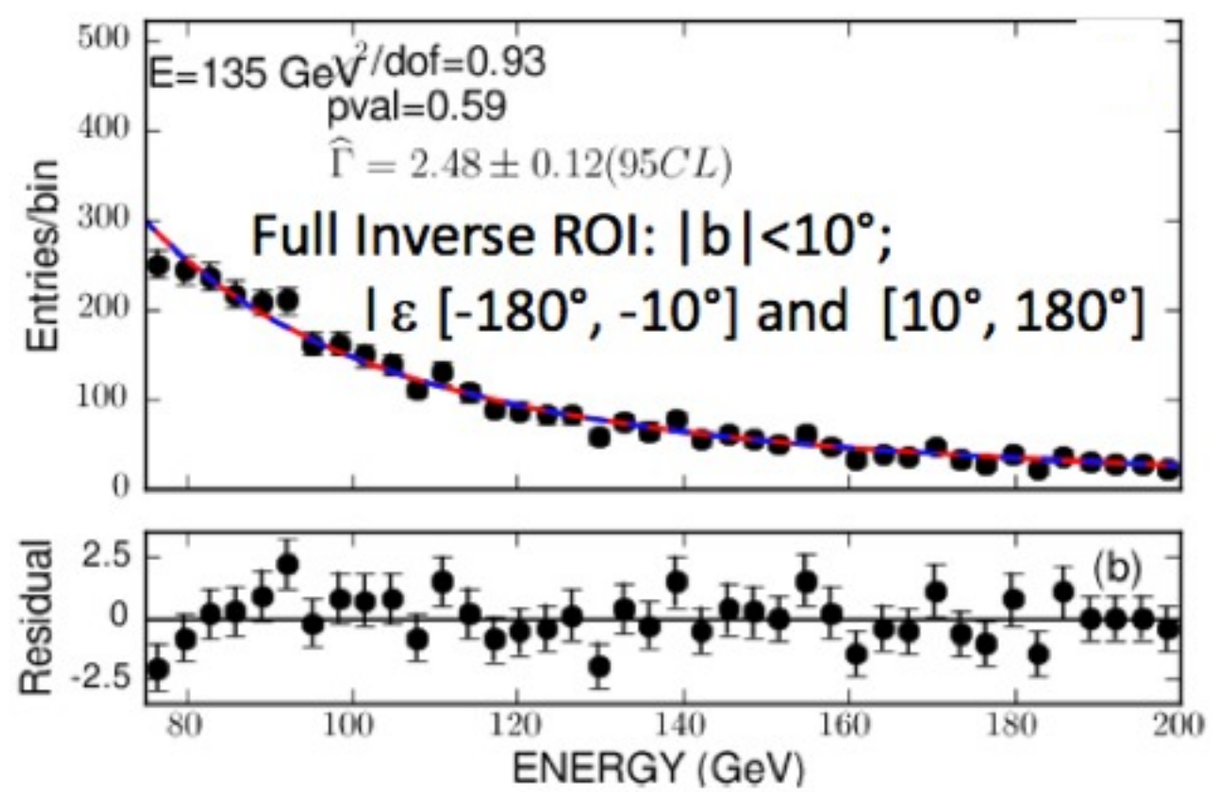


The **Galactic Disk**: bright, and astrophysical source dominated

No feature near 130 GeV



Summary

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The Fermi LAT team looks for indirect DM signals in a wide variety of methods

- ✓ So far no unambiguous DM like signal detected.
- ✓ Strong constraints have been set.

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The Fermi LAT team looks for indirect DM signals in a wide variety of methods

- ✓ So far no unambiguous DM like signal detected.
- ✓ Strong constraints have been set.

Still too soon for definite statements about claimed evidence of a line:

Pros & Cons for ~130 GeV line

❑ PROS

- Tantalizing signal (>3σ)
- Signal from the GC region
- No signal in Galactic plane
- Signal (roughly) consistent with expected DM profiles

❑ CONS

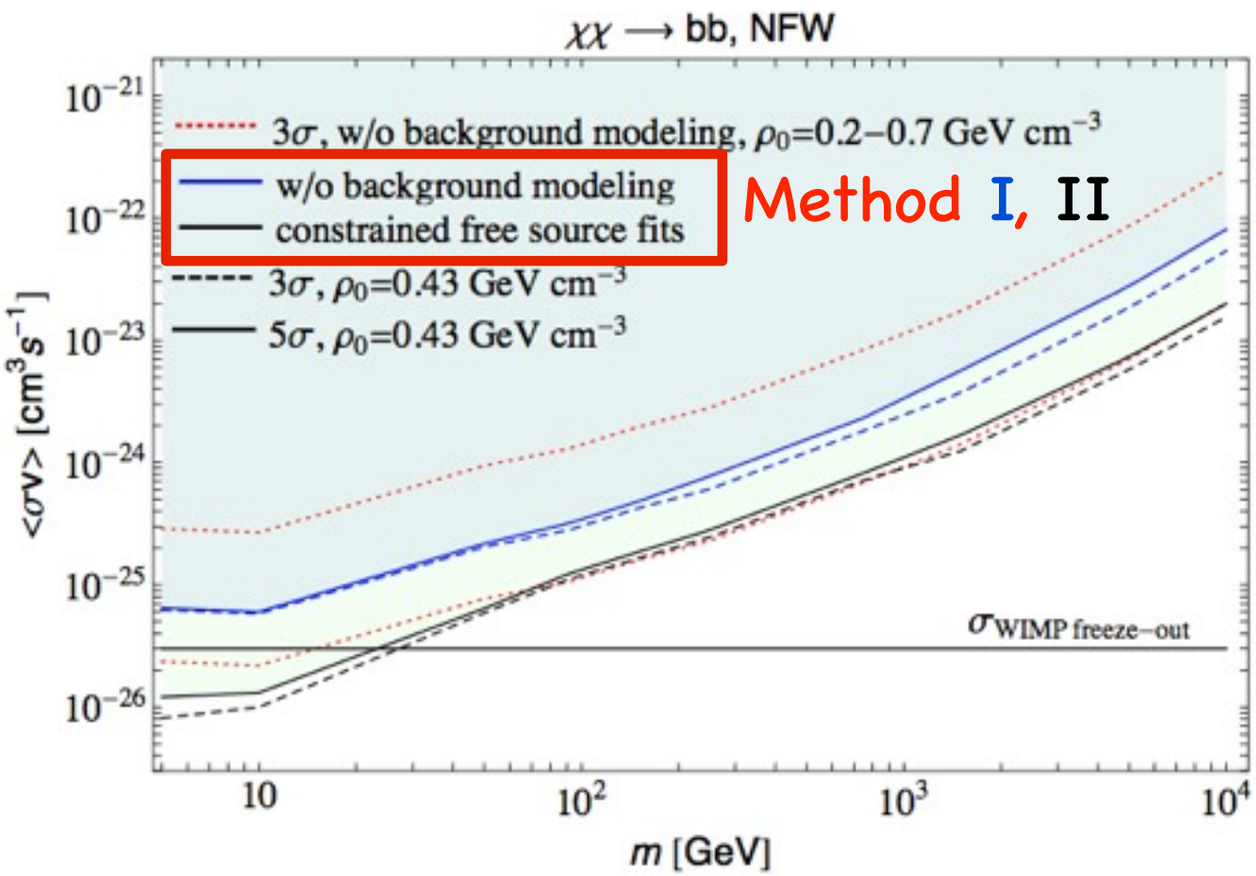
- Similar signal in limb data (not as strong)
- Similar features at other energies
- Decreased in significance w/ more data and analysis improvements ('too' narrow line)
- Global significance (incl. trial factors) $\lesssim 2\sigma$ with Fermi energy scan and ROI:s
- Requires large $\gamma\gamma$ BR. Displaced from GC

More Fermi-LAT data + Pass 8 processed data will give more information. Cherenkov telescopes (HESS II), future CTA, Gamma400...

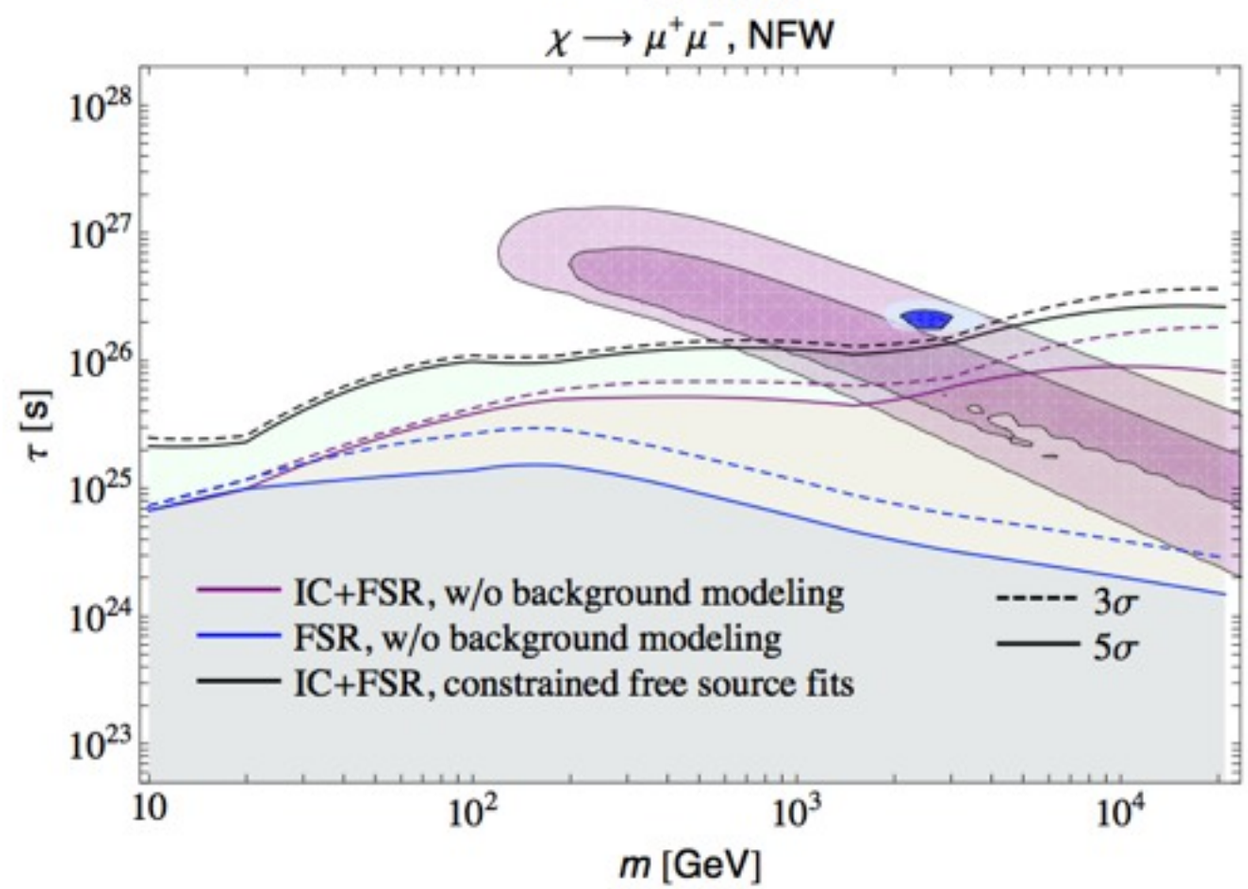
BACKUP SLIDES

Constraints from Milky Way Halo

- **Including modeling of the astrophysical emission improves the DM constraints by a factor of ~5**



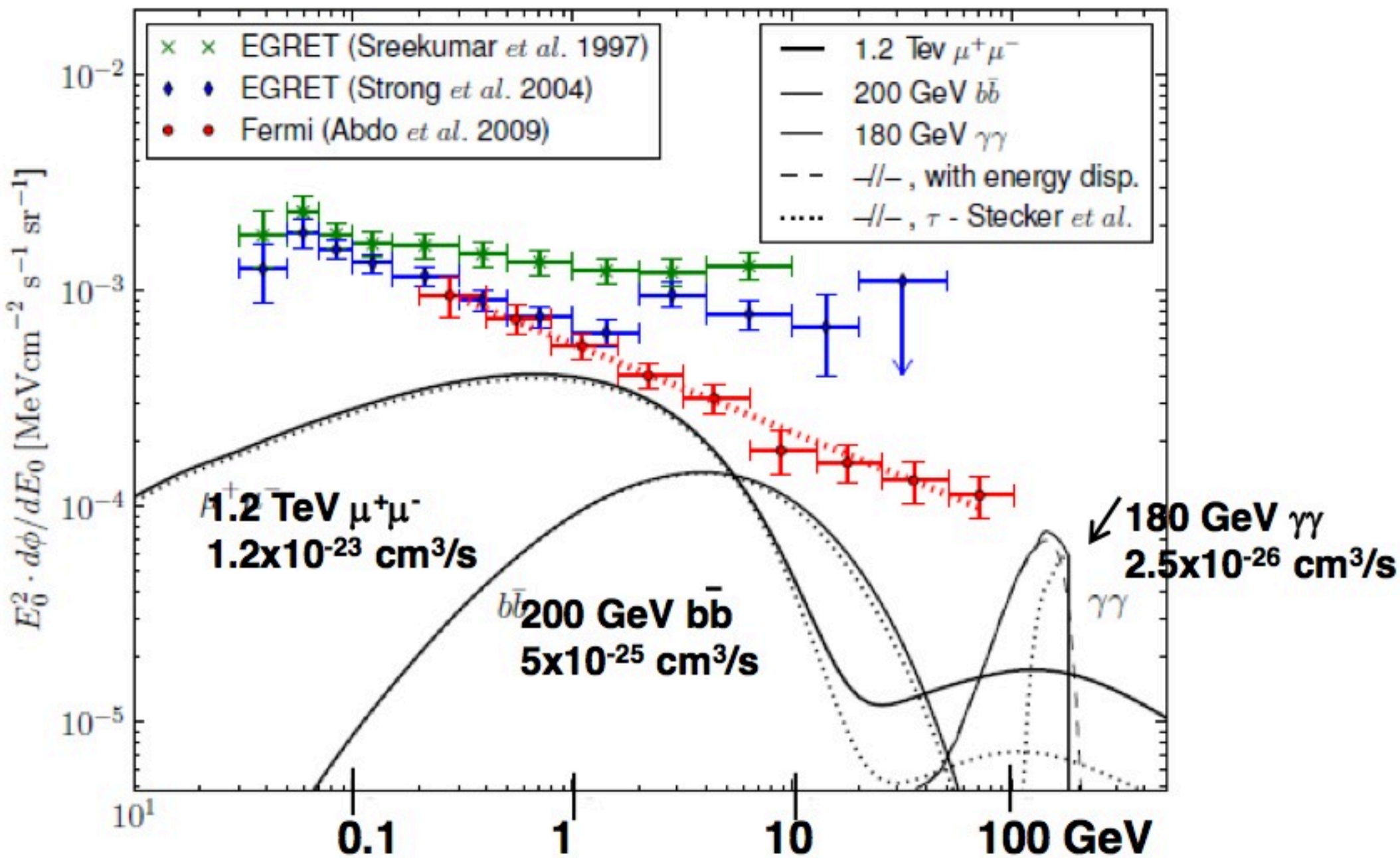
DM annihilation x-section to b-quarks limits



DM decay lifetime limits

- **with inclusion of astrophysical backgrounds, a canonical thermal cross section into b-quarks limits the WIMP mass to $\gtrsim$ 20 GeV (comparable to the dSphs limits)**

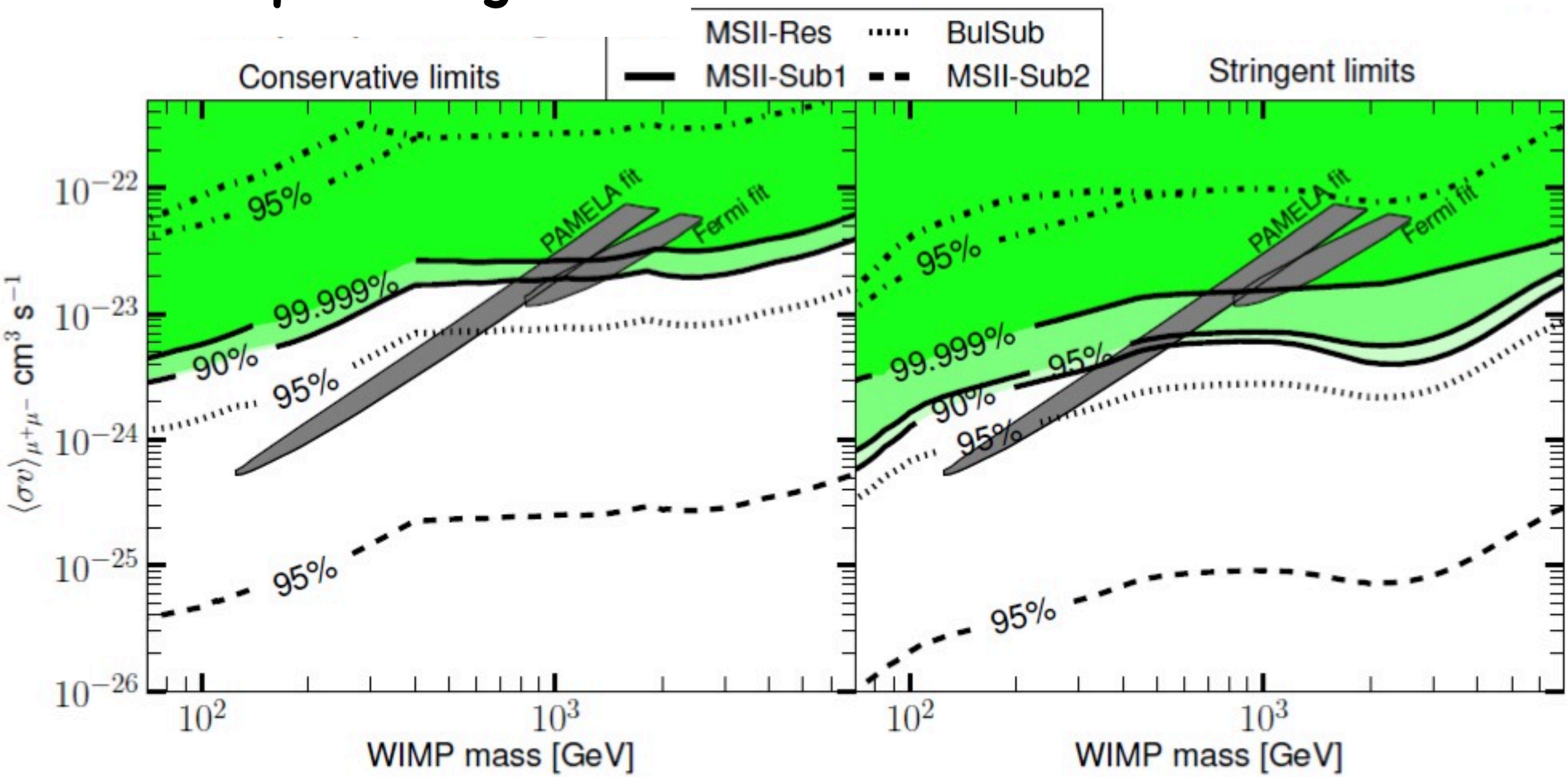
Isotropic Extra Galactic DM Signal

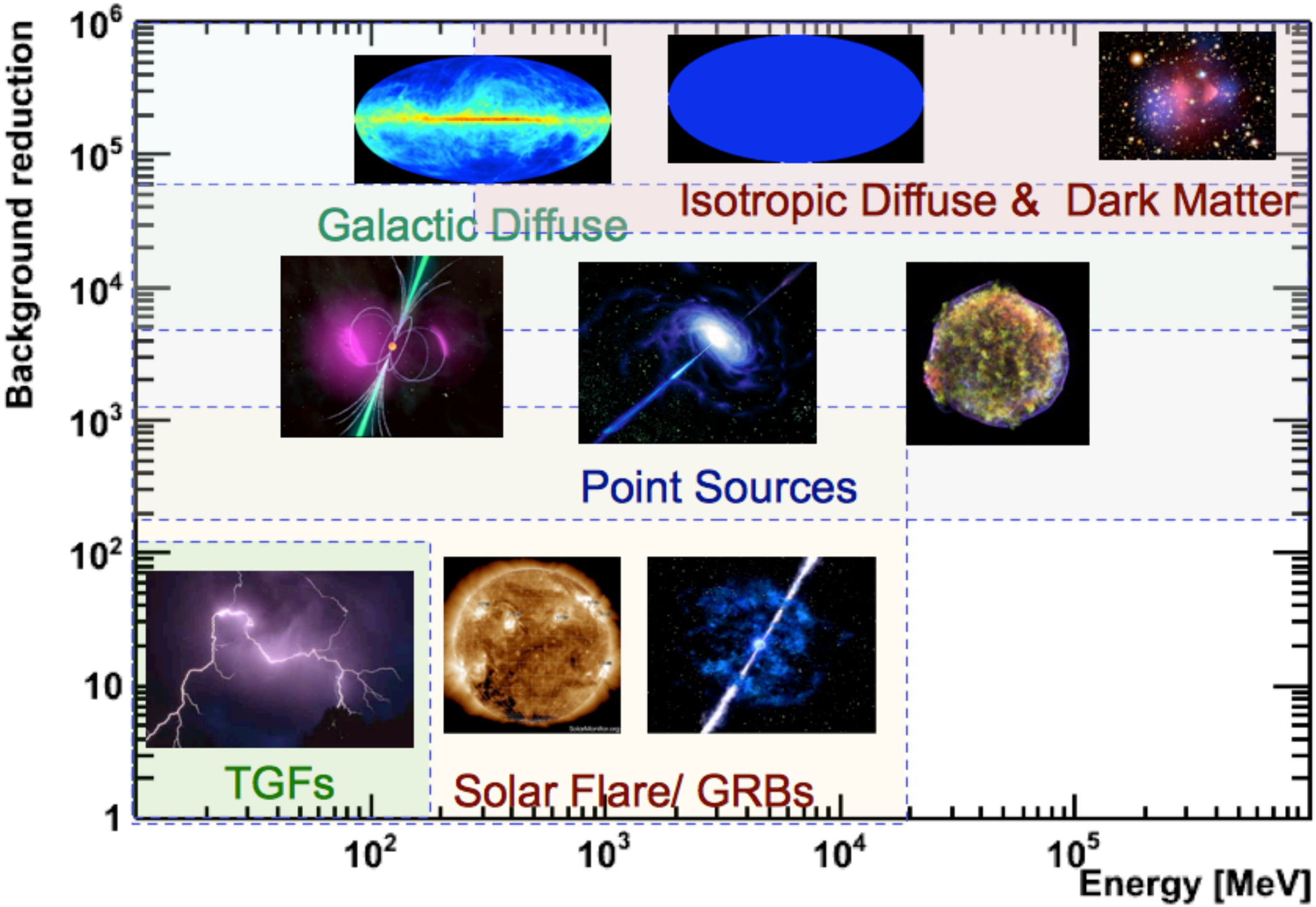


$\mu^+\mu^-$ final state

Not exceed the isotropic background

Not above power-law background





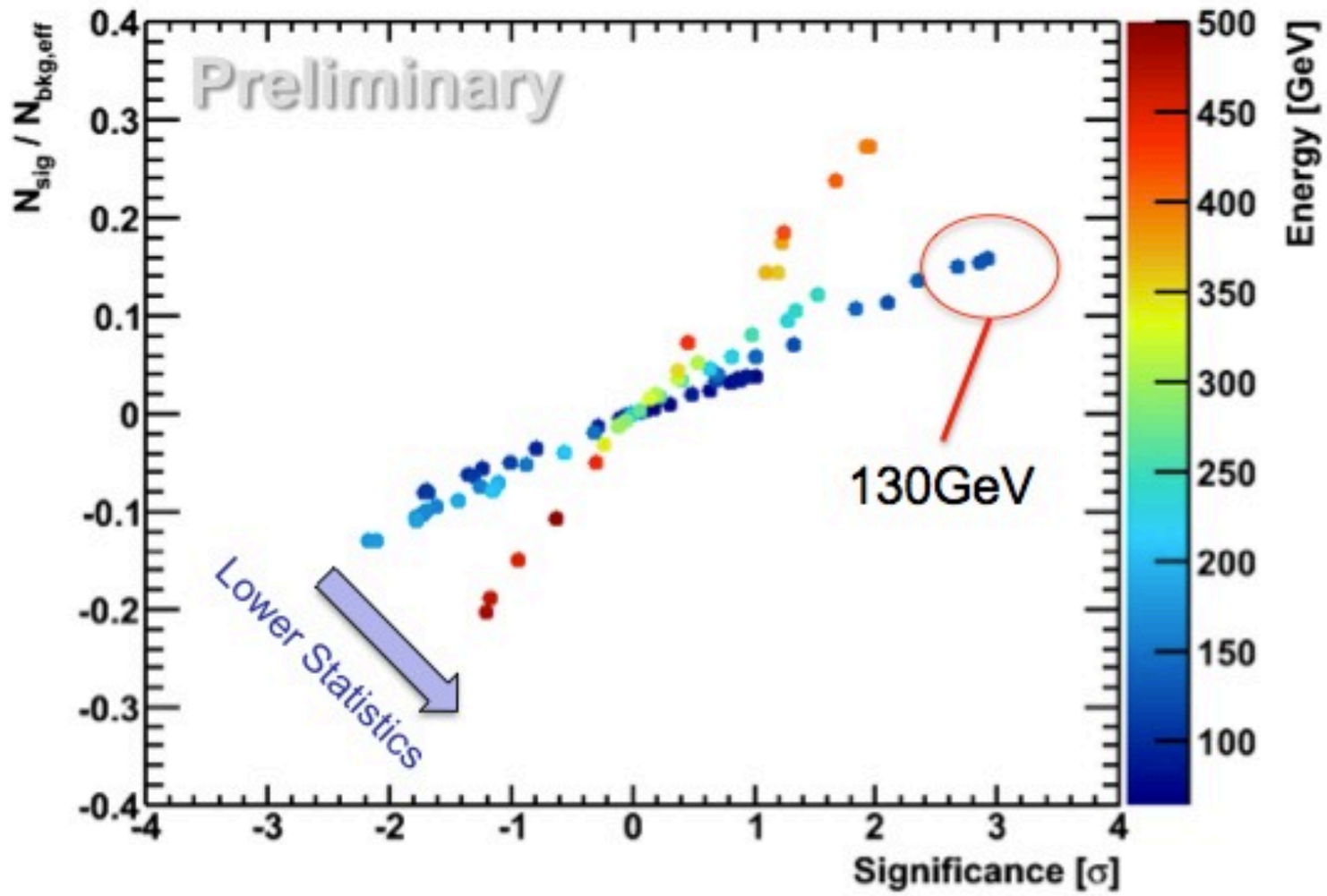
Different data selections for different science cases

Data selection for line search

TABLE I. Summary table of data selections.

Parameter	Galactic data	Limb data
Observation Period	2008 August 4 – 2012 April 4	2008 August 4 – 2012 October 6
Mission Elapsed Time (s)	$[239557447, 356434906]$	$[239557447, 371176784]$
Energy range (GeV)	$[2.6, 541]$	$[2.6, 541]$
Zenith cut (°)	$\theta_z < 100$	$111 < \theta_z < 113$
Rocking angle cut (°) [a]	$\lvert\theta_r\rvert < 52$	$\lvert\theta_r\rvert > 52$
Data quality cut[b]	Yes	Yes
Source masking (see text)	Yes	No

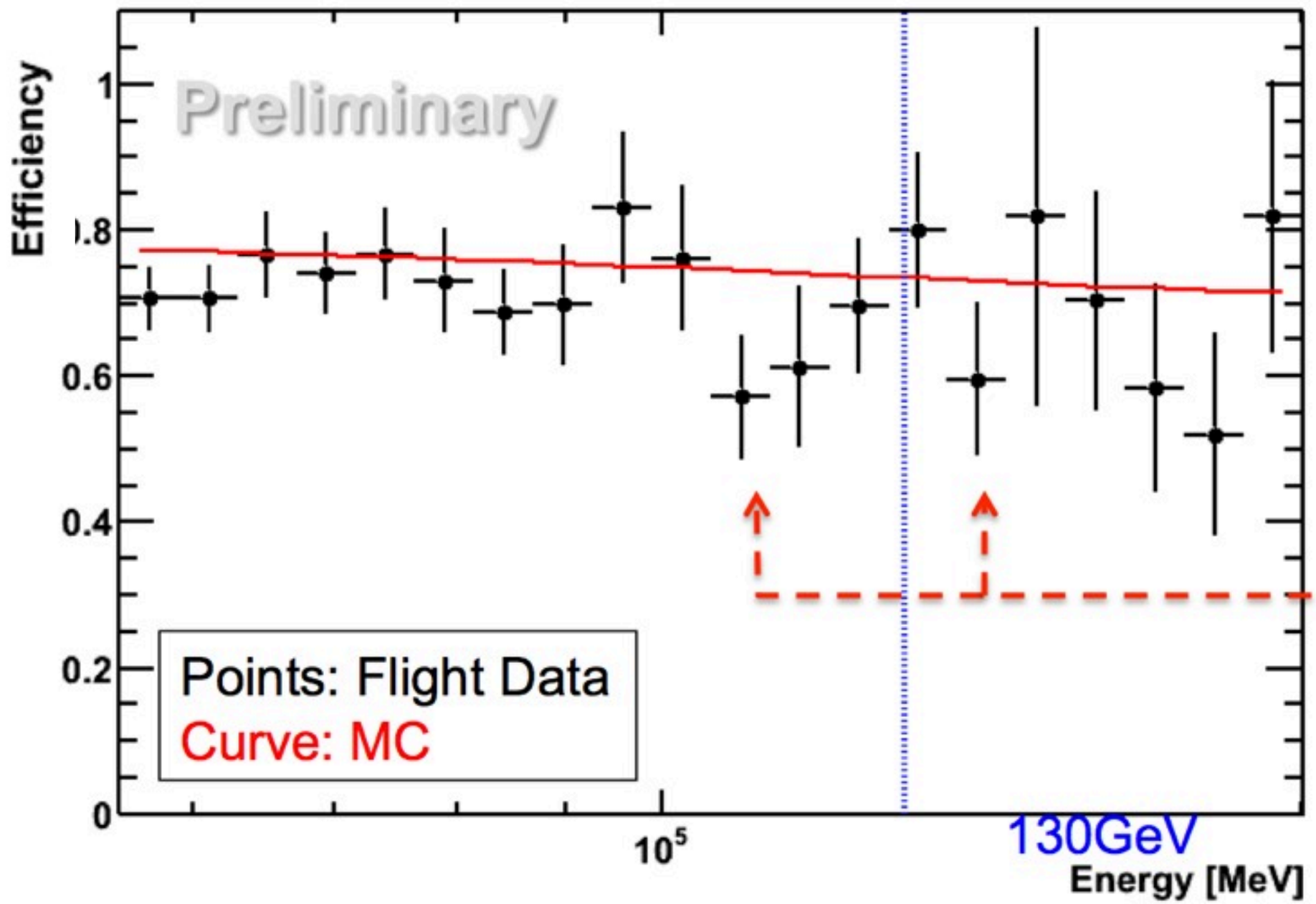
Earth Limb residuals as a function of energy



Fits to Earth Limb data at ~1.5% energy steps

- Below 100 GeV the residuals in the limb are small ($\delta f < 0.02$).
- At higher energies make it difficult to exclude large fractional residuals. At 130GeV we see S/N~18% and 3.0σ significance residuals.

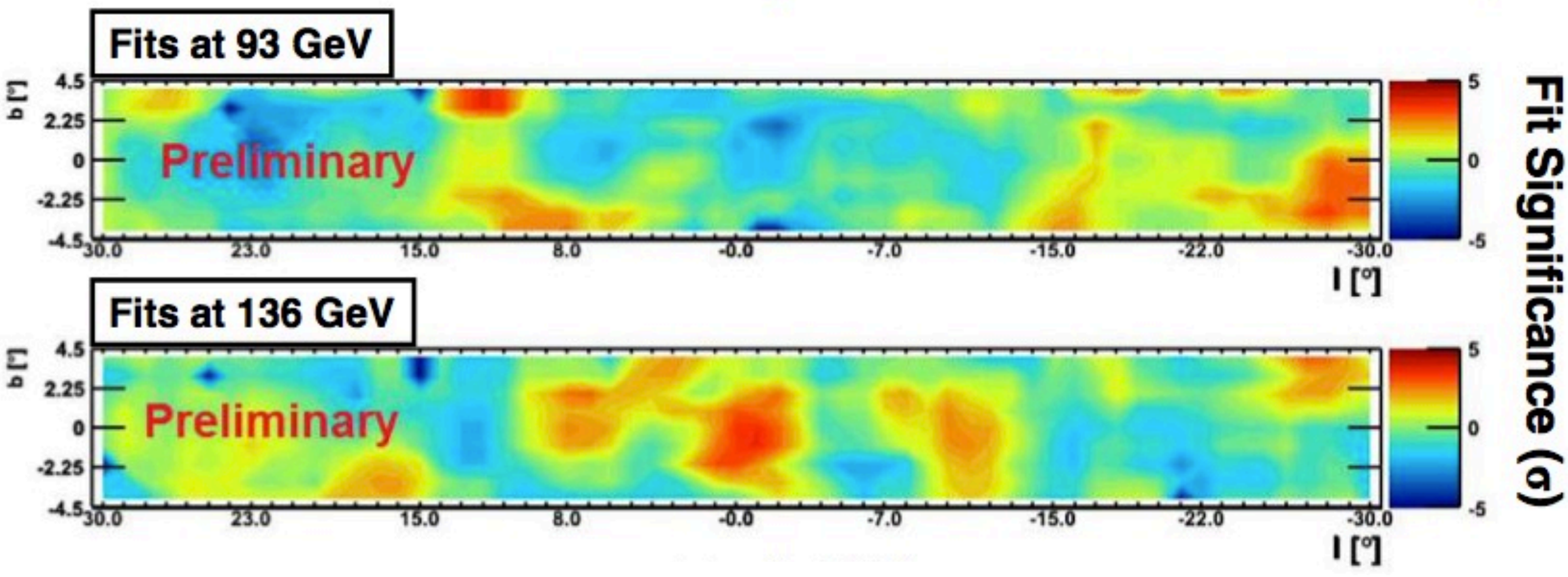
P7TRANSIENT to P7CLEAN Efficiency



The efficiency at ~115Gev is 0.57/0.75 = 75% of the MC prediction.
This would cause something < 30% boost in signal at 130 GeV relative to the prediction from nearby energy bins.

Spatial Morphology of Features in Galactic Plane

- Fit in 4°x4° ROIs along the Galactic plane in 1° steps
  - Fit with "1D PDF"
    - To find where the counts are coming from
    - Allowed for negative fluctuations
- Find excess near ~135 GeV near GC
  - But find similar features at other energies along the GP
  - Excess near 135 GeV is one of the largest and near GC, but is not otherwise unique

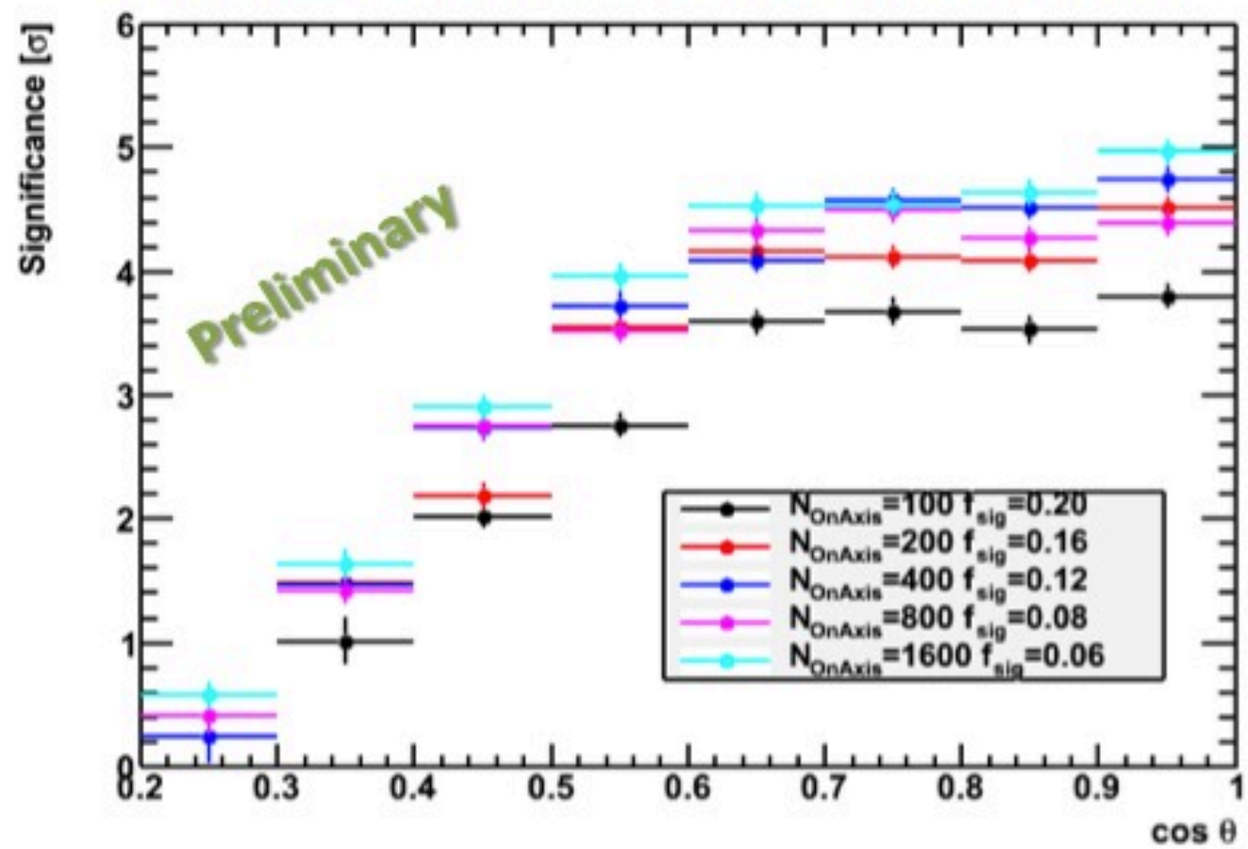


Dedicated Galactic-Center Observation

(For Line Searches)

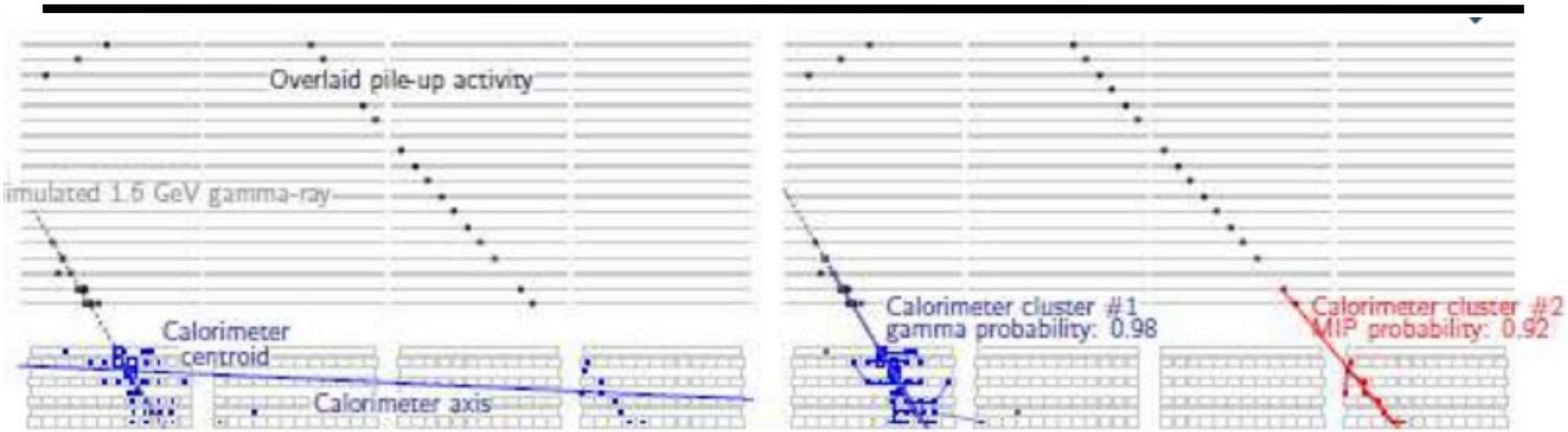
- Galactic-Center data so far has come from Survey Mode Observations
- Pointing directly at or close to GC increases rate by up to ~ 3X
- Energy resolution on-axis at 130 GeV ~ < 10%
- Energy resolution 45° off axis ~ 5%
- Lots of other science from GC region!
- How to optimize GC Pointed Mode with other science under study.

Toy MC simulations for a range of signal-to-noise ratios favor energy resolution over A_{eff} slightly less than naïve scaling predictions.



Out to about θ=50°, the improving energy resolution balances out the decreasing A_{eff}. Less sensitivity past θ=60°.

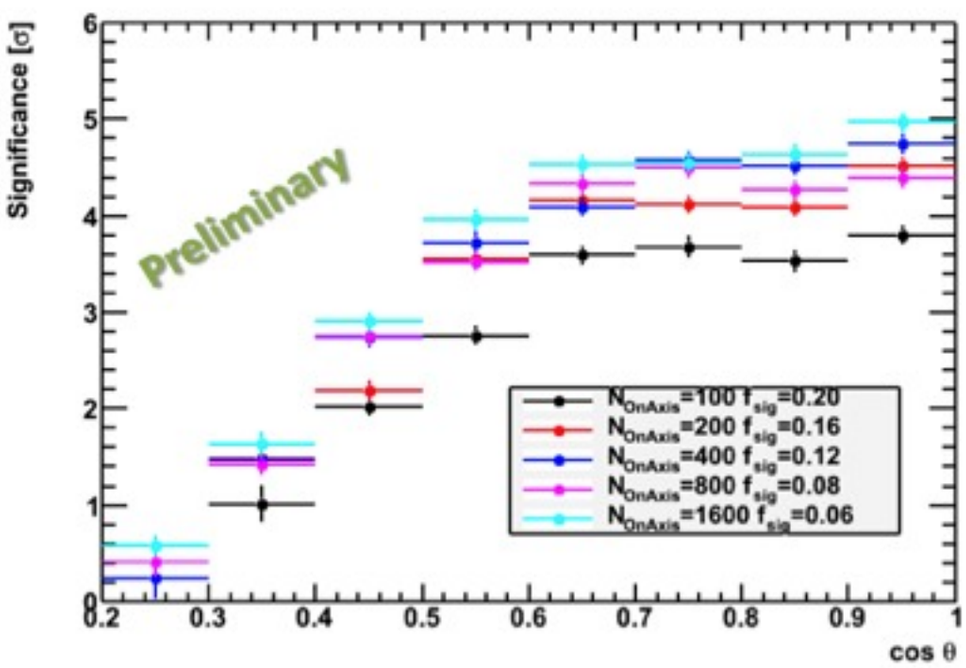
Pass8



Better event selection (higher signal efficiency at the same bkg level)

- **Expect a ~25% increase in high-energy effective area in the "standard" photon classes**

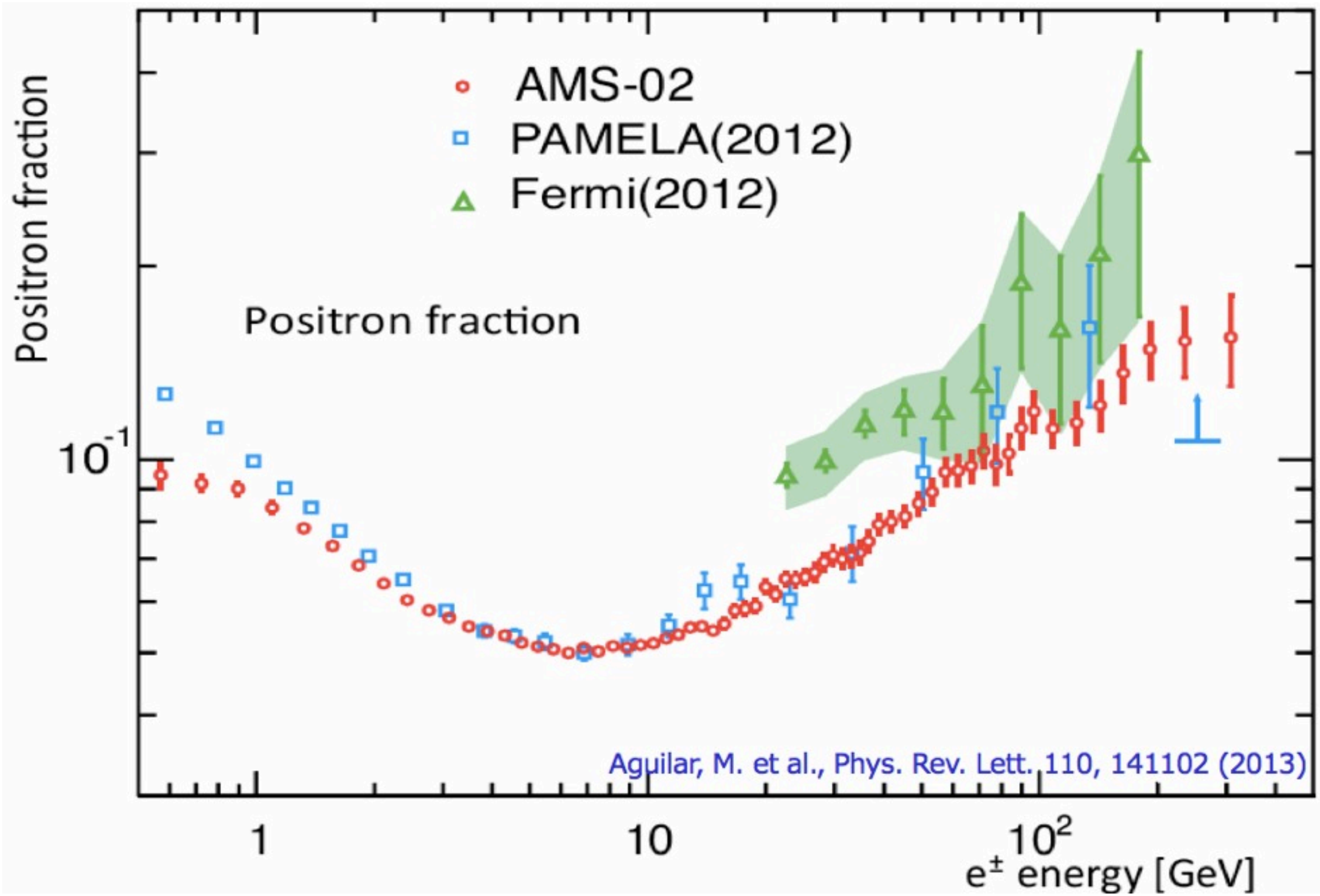
Include calorimeter-only events (substantial effective area increase above 40 GeV)



Dedicated GC observations:

- **Pointing to GC increase rate by ~3X**
- **Energy resolution at 45° off-axis is ~5%, while on-axis ~10%**
- **At about 50° the improving energy resolution balances out the decreasing effective areas.**

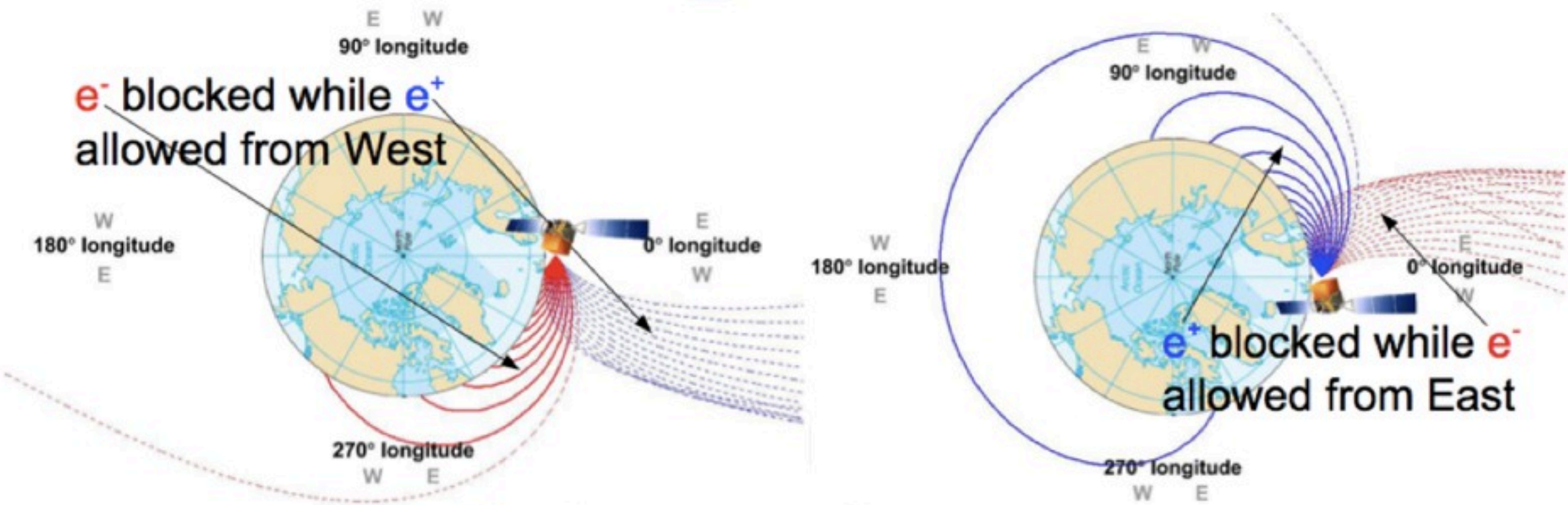
Cosmic-ray Positron fraction



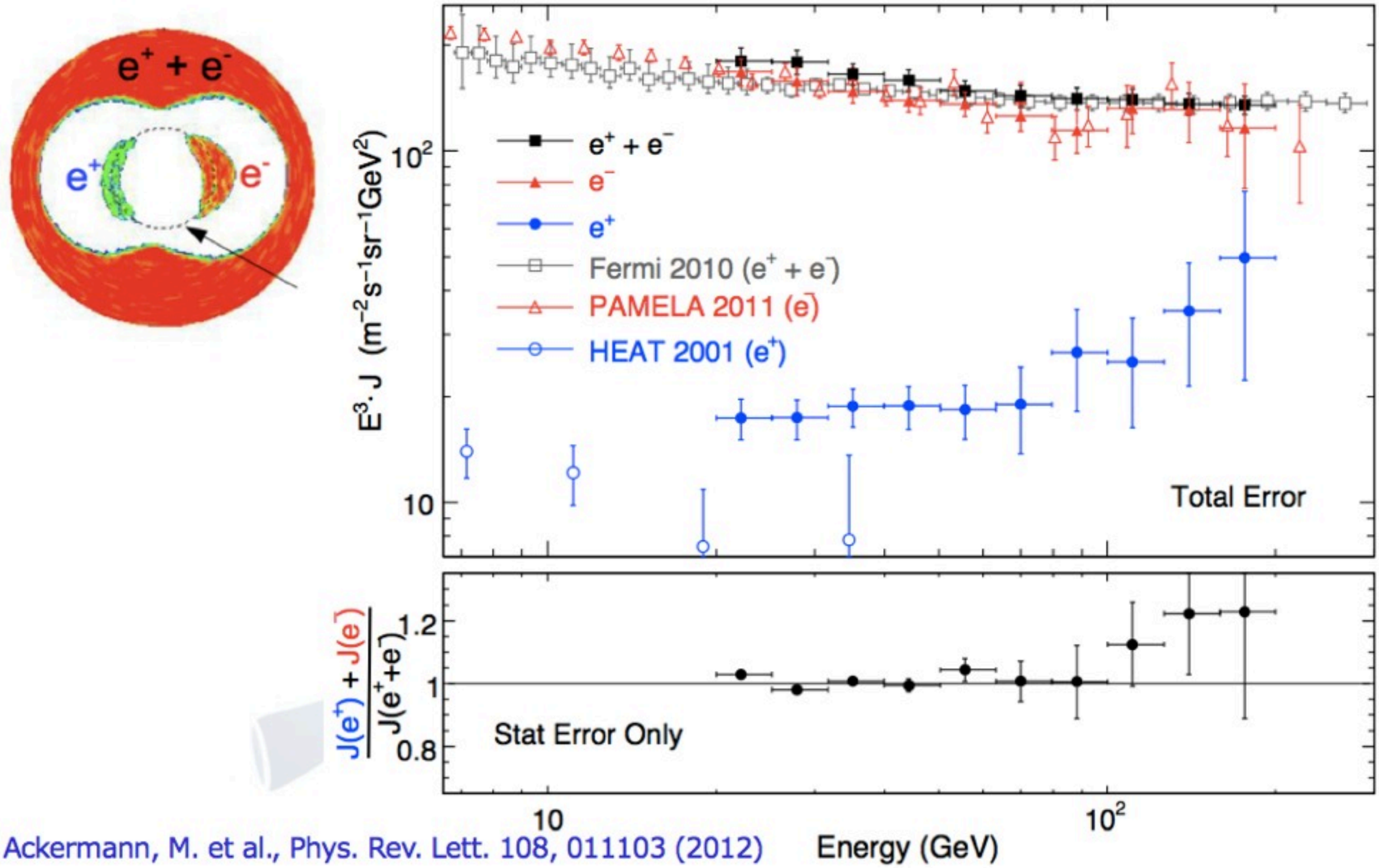
Fermi measurement of e^+ fraction

"Unfortunately" Fermi-LAT doesn't cary a magnet

IDEA: USE THE EARTH MAGNETIC FIELD TO DISTINGUISH e^+ FROM e^-

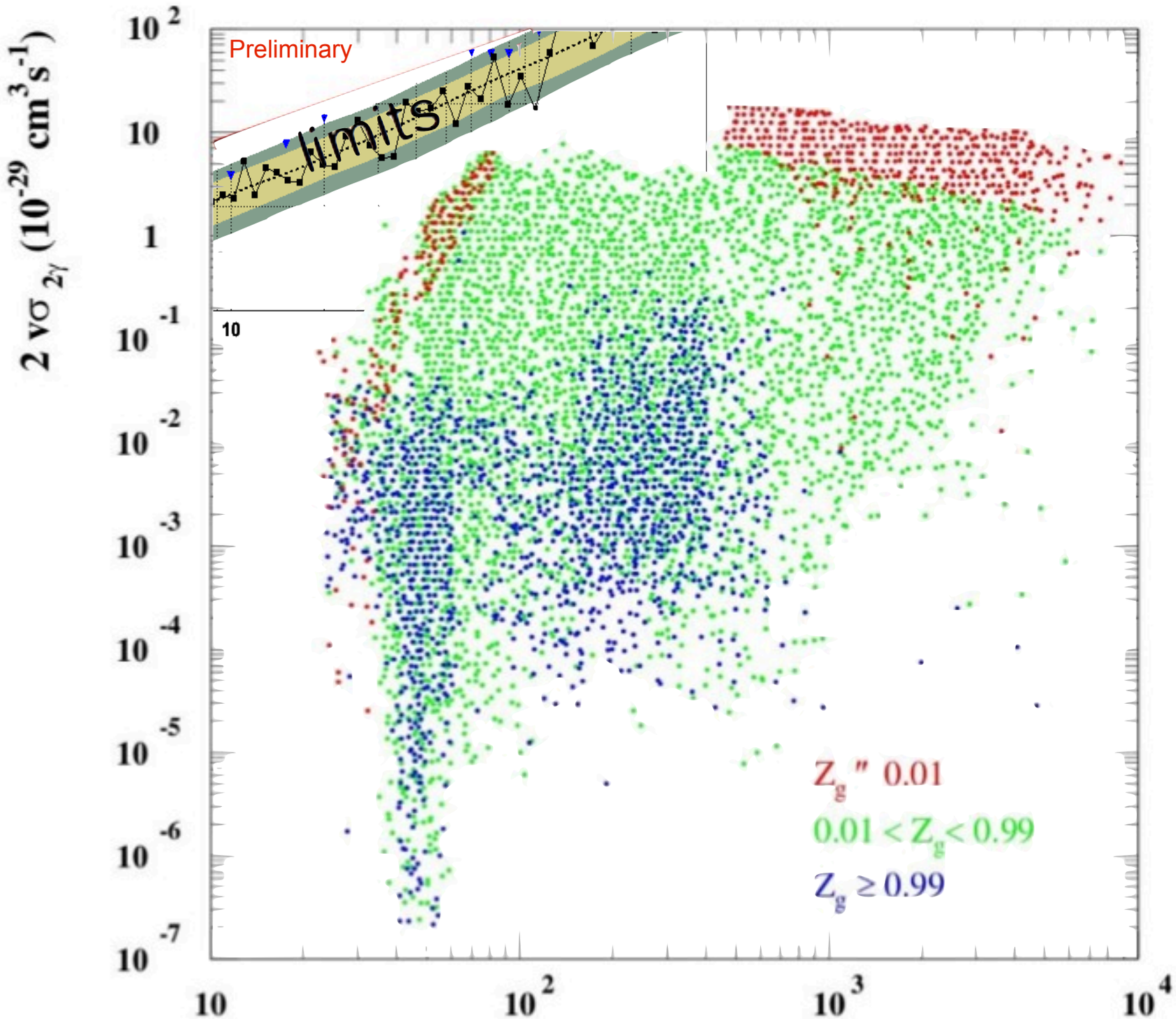


- pure e^+ region in the West and pure e^- region in the East
- the regions vary with particle energy and the LAT geomagnetic coordinates
- to locate these regions, we use a code written by Smart and Shea, which numerically calculates a particle's trajectory in the Earth geomagnetic field



Ackermann, M. et al., Phys. Rev. Lett. 108, 011103 (2012)

MSSM neutralinos remain unconstrained



[Bergström et al., 1998)]

Other models (soon) probed