Indirect Detection of Dark Matter with Gamma Rays

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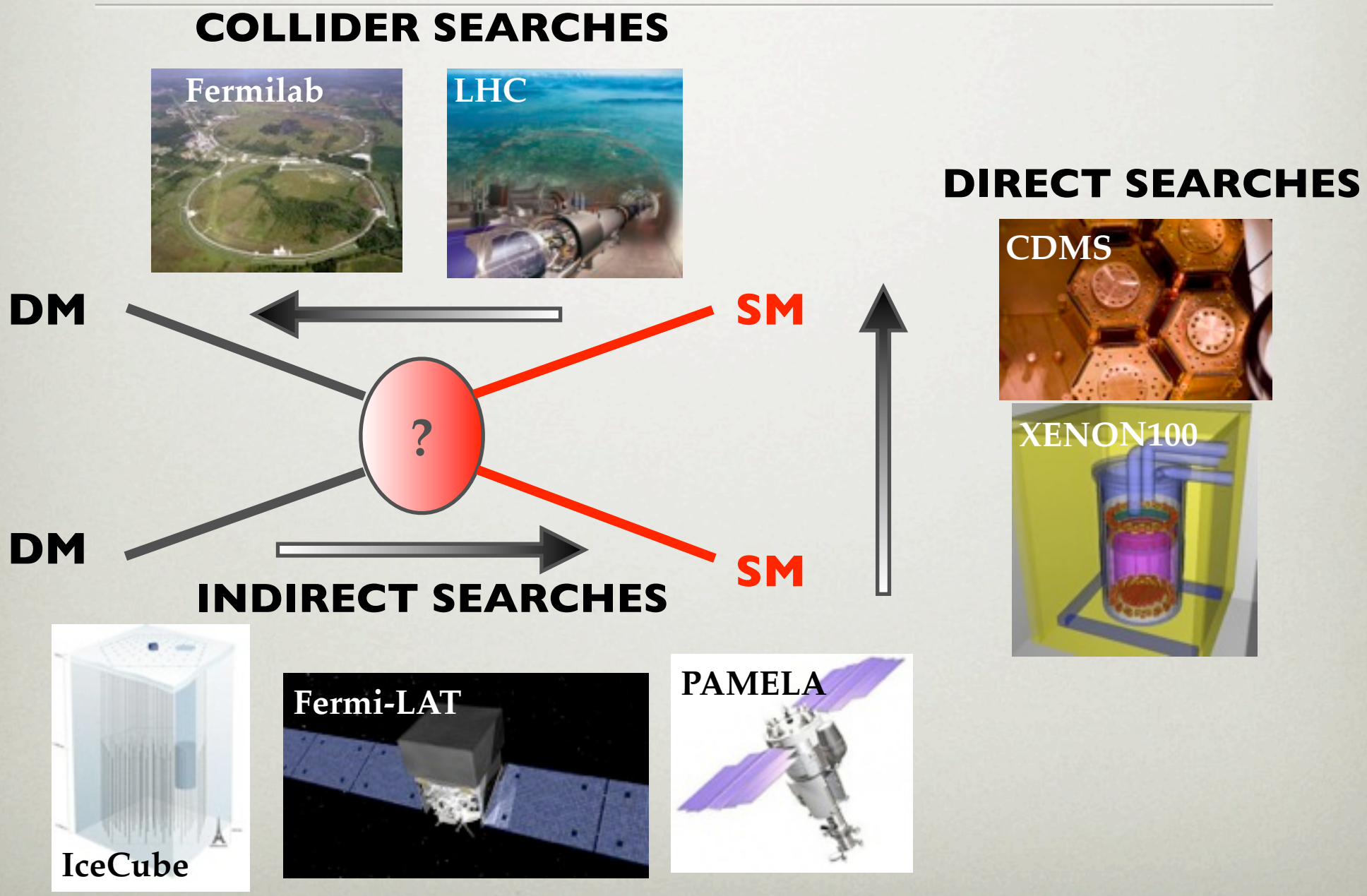
on behalf of the Fermi LAT Collaboration

Dark Attack 2012
Ascona, Switzerland
15-20 July 2012

WIMP Searches



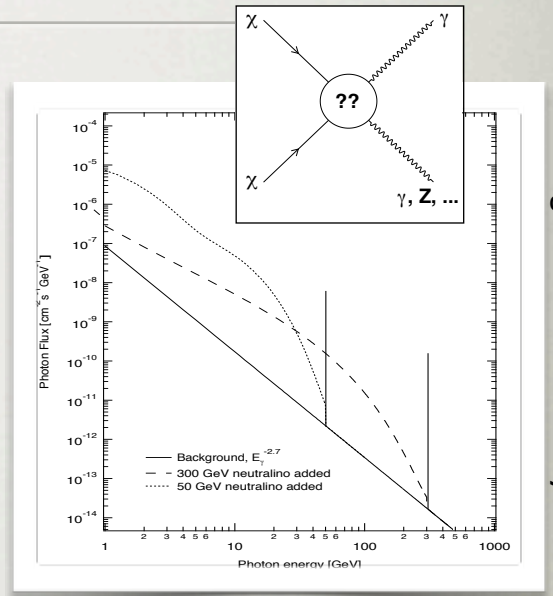
WIMP Signal

- Gamma rays from DM annihilation:

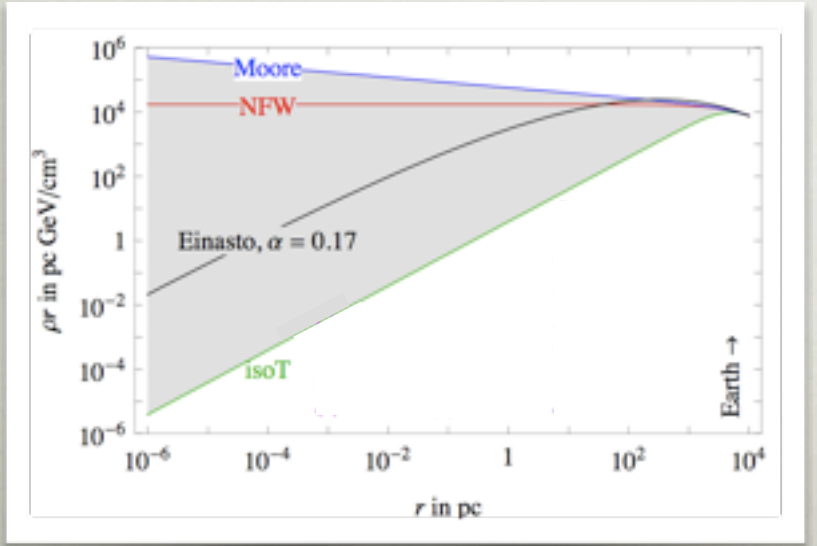
particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

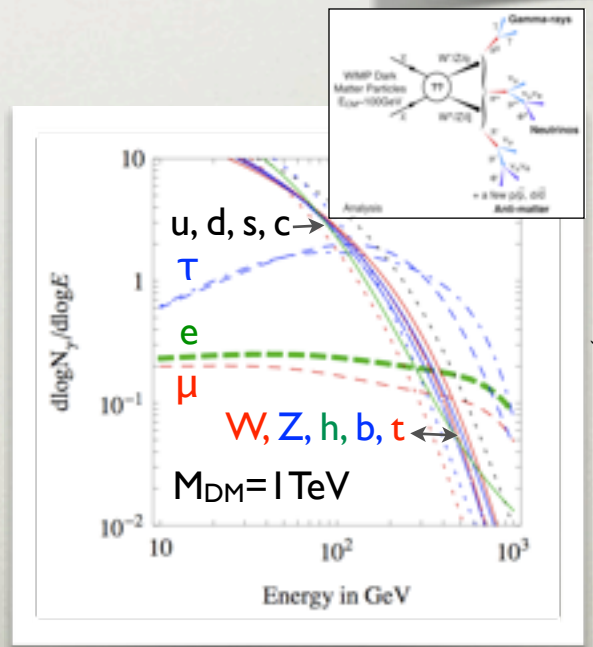
DM distribution



Bergstrom, Ullio, Buckley



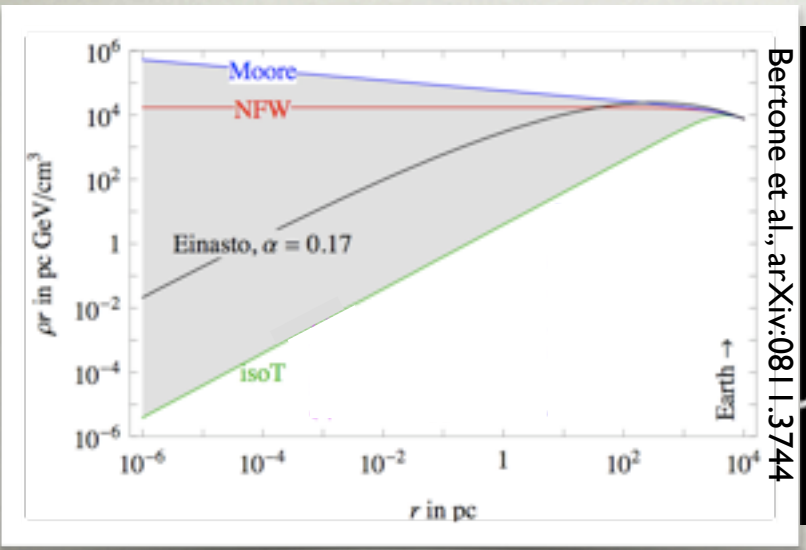
Bertone et al., arXiv:0811.3744



Cirelli et al, arXiv:0809.2409

Dark Matter Distribution

- We generally heavily rely on simulations of the dark matter distribution to make predictions for DM searches...
- ... but much is still unknown on how DM is distributed, e.g.:
  - cuspiness of the profile
  - halo shape (spherical, prolate, oblate, triaxial, dark disk, ...)
  - substructure



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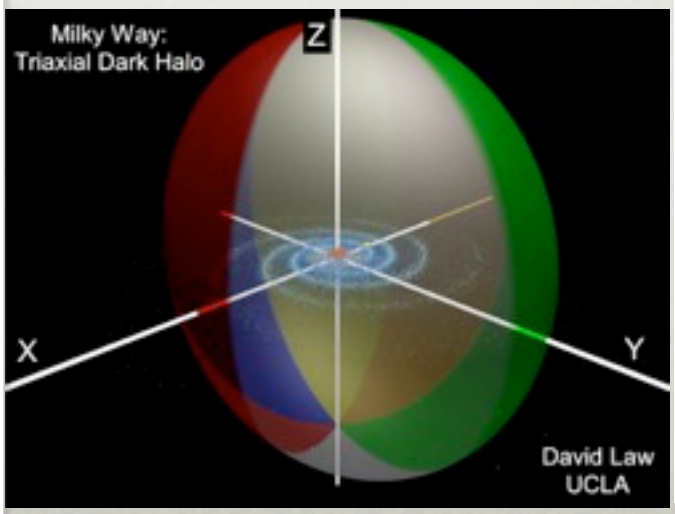
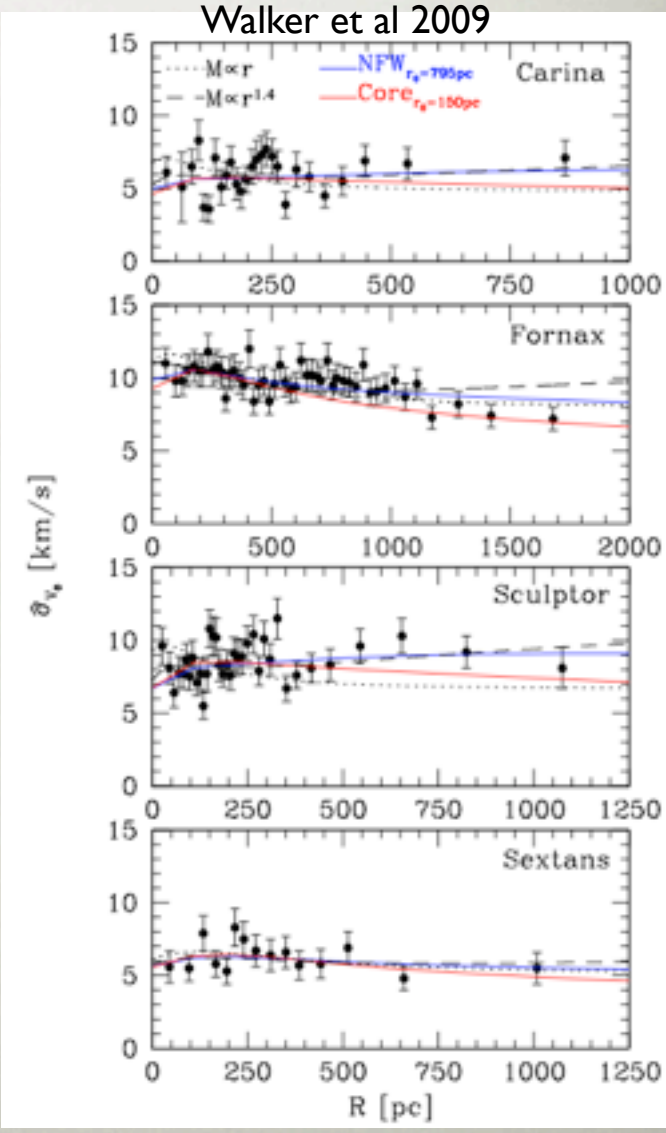
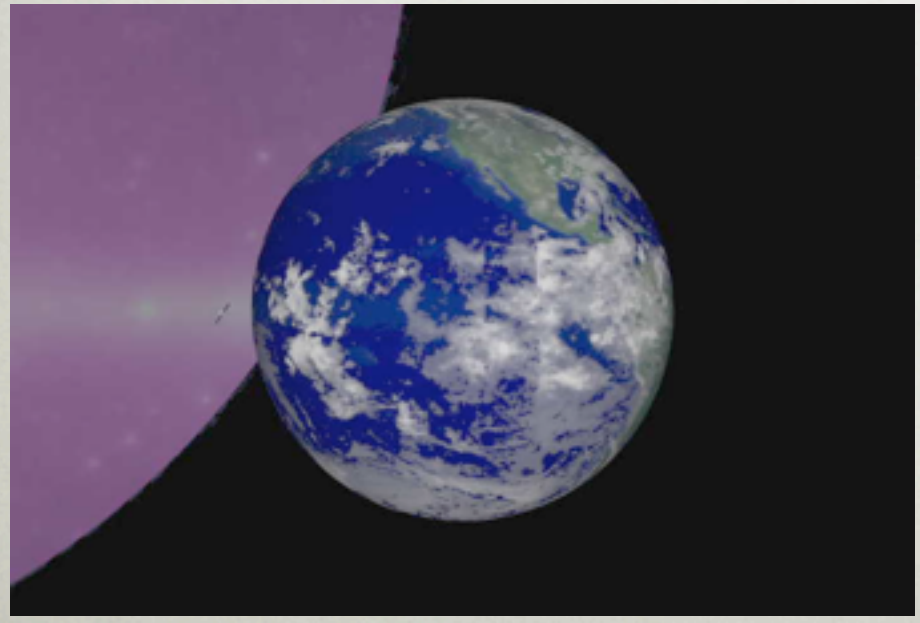


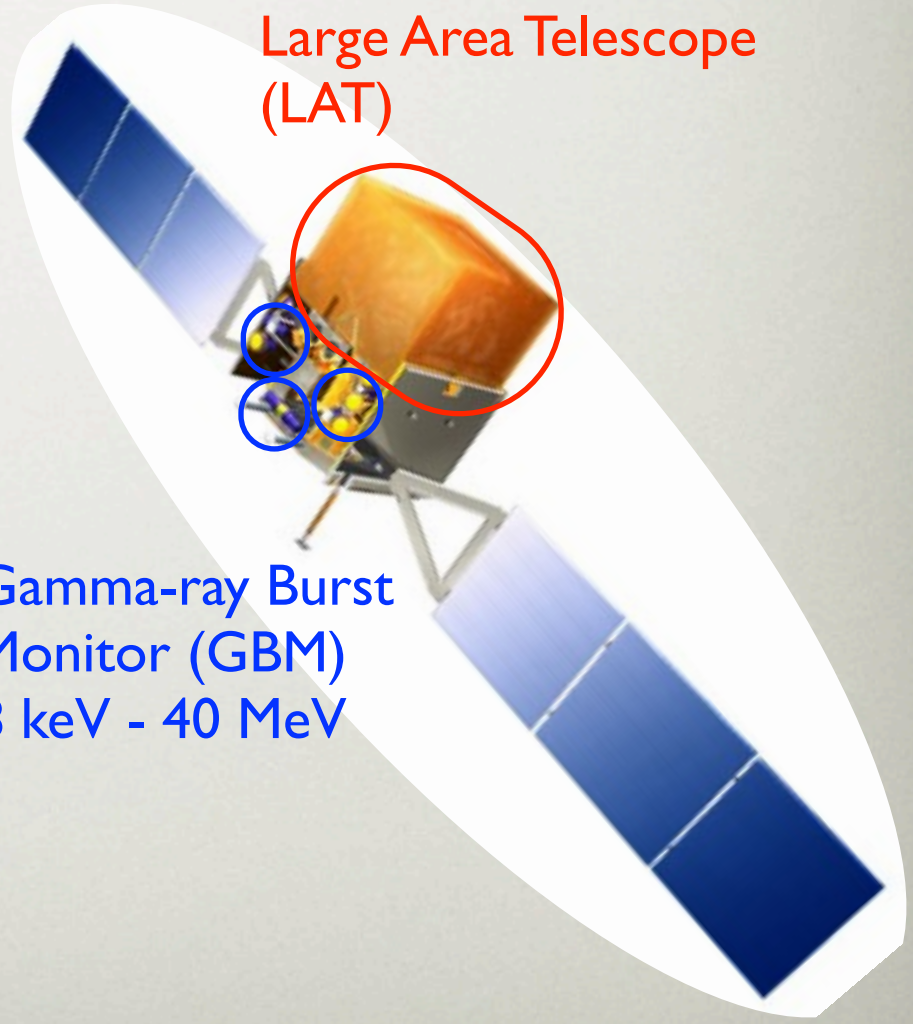
Walker et al 2009



Fermi Mission
The Large Area telescope

- The Fermi Large Area Telescope observes the gamma-ray sky in the 20 MeV to >300 GeV energy range with unprecedented sensitivity
- Orbit: 565 km, 25.6° inclination, circular. The LAT observes the entire sky every ~3 hrs (2 orbits)





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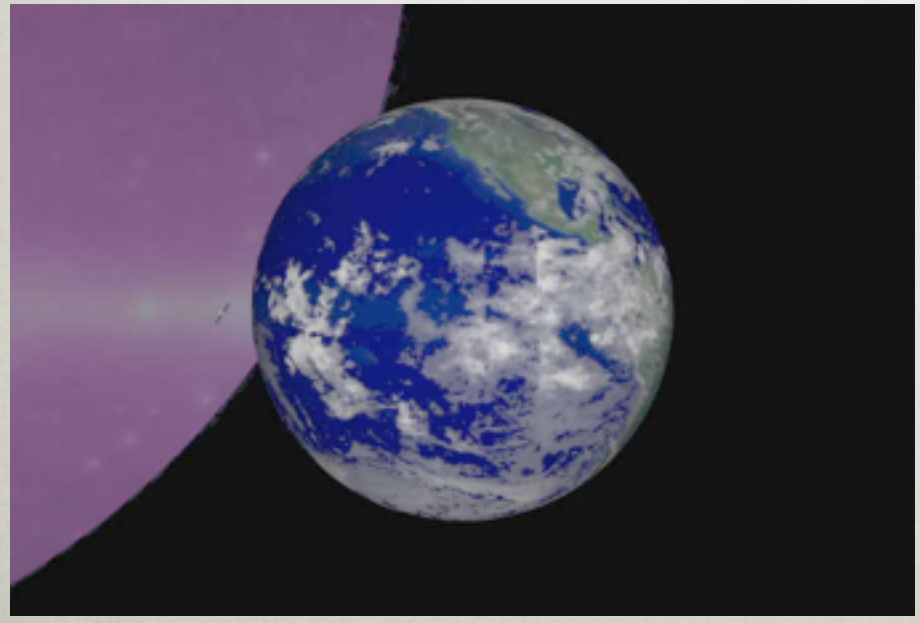
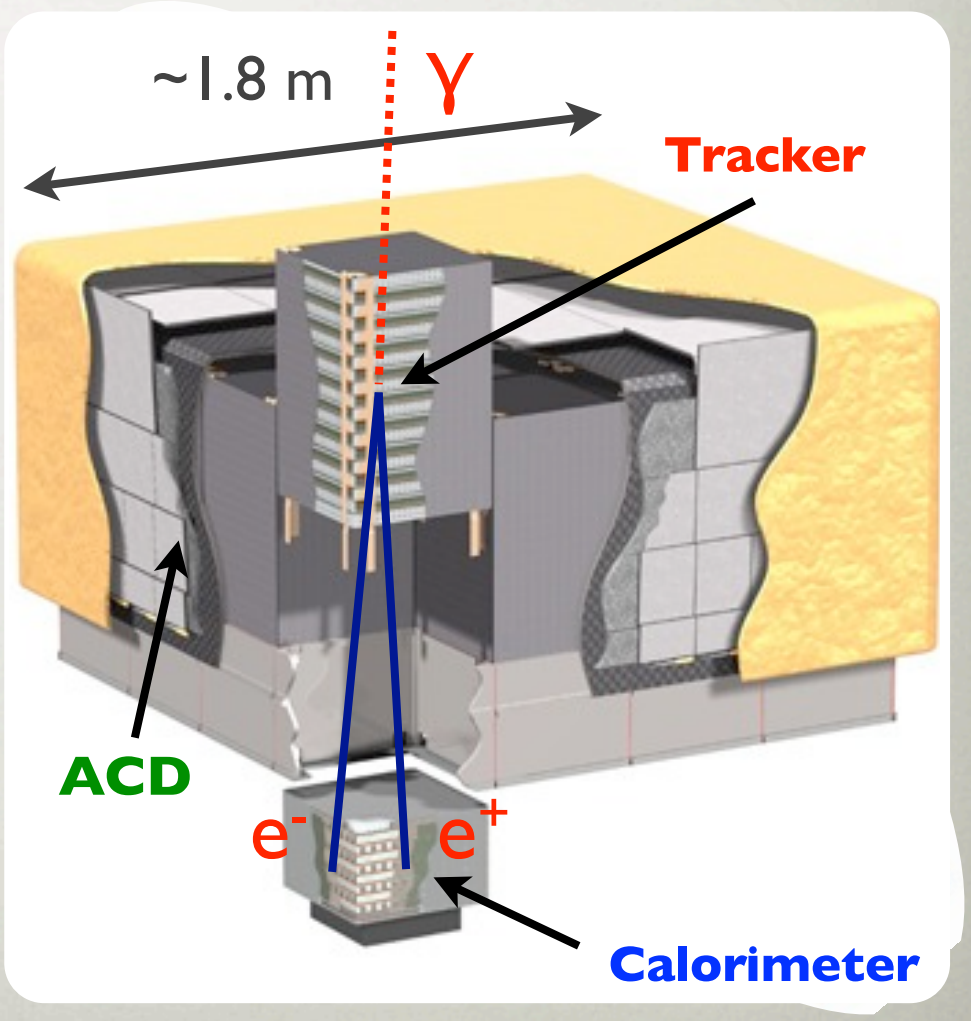
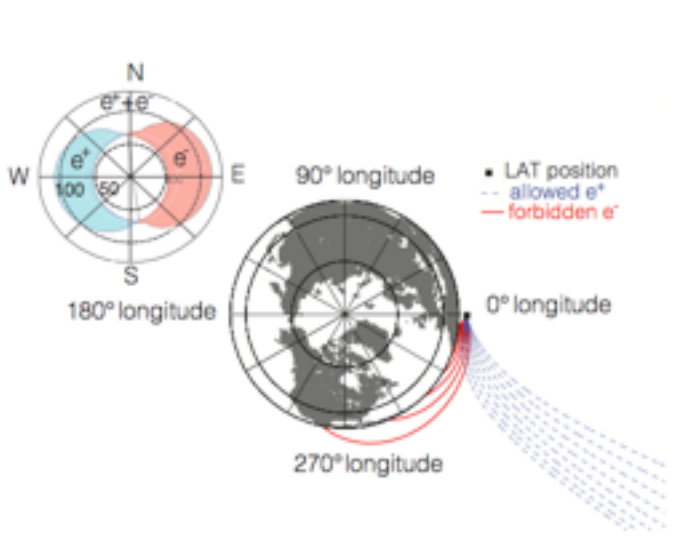


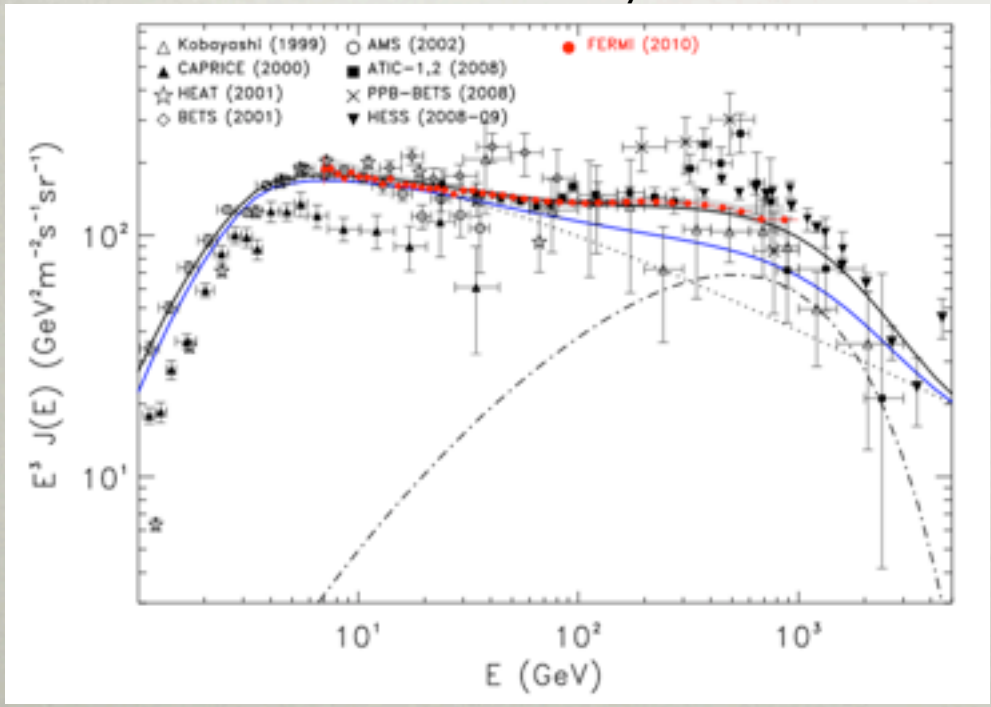


Direct Measurement of Local Cosmic Rays

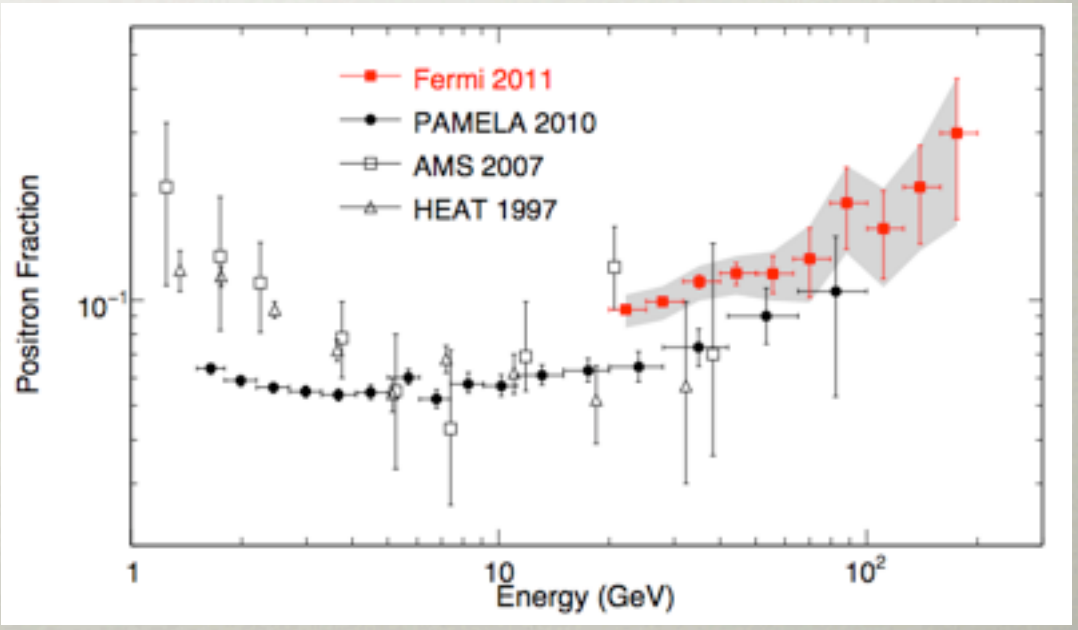
- Fermi LAT measured the cosmic ray e^++e^- spectrum from 7 GeV to 1 TeV
- Fermi LAT confirms the raise in the cosmic ray positron fraction observed by PAMELA and extends it to 200 GeV
- Measurements consistent with a nearby source contributing to the observed e^+ and e^-
- DM interpretation can be constrained by gamma-ray data (shown later)

Fermi LAT Collaboration 2010, Phys.Rev. D82 092004

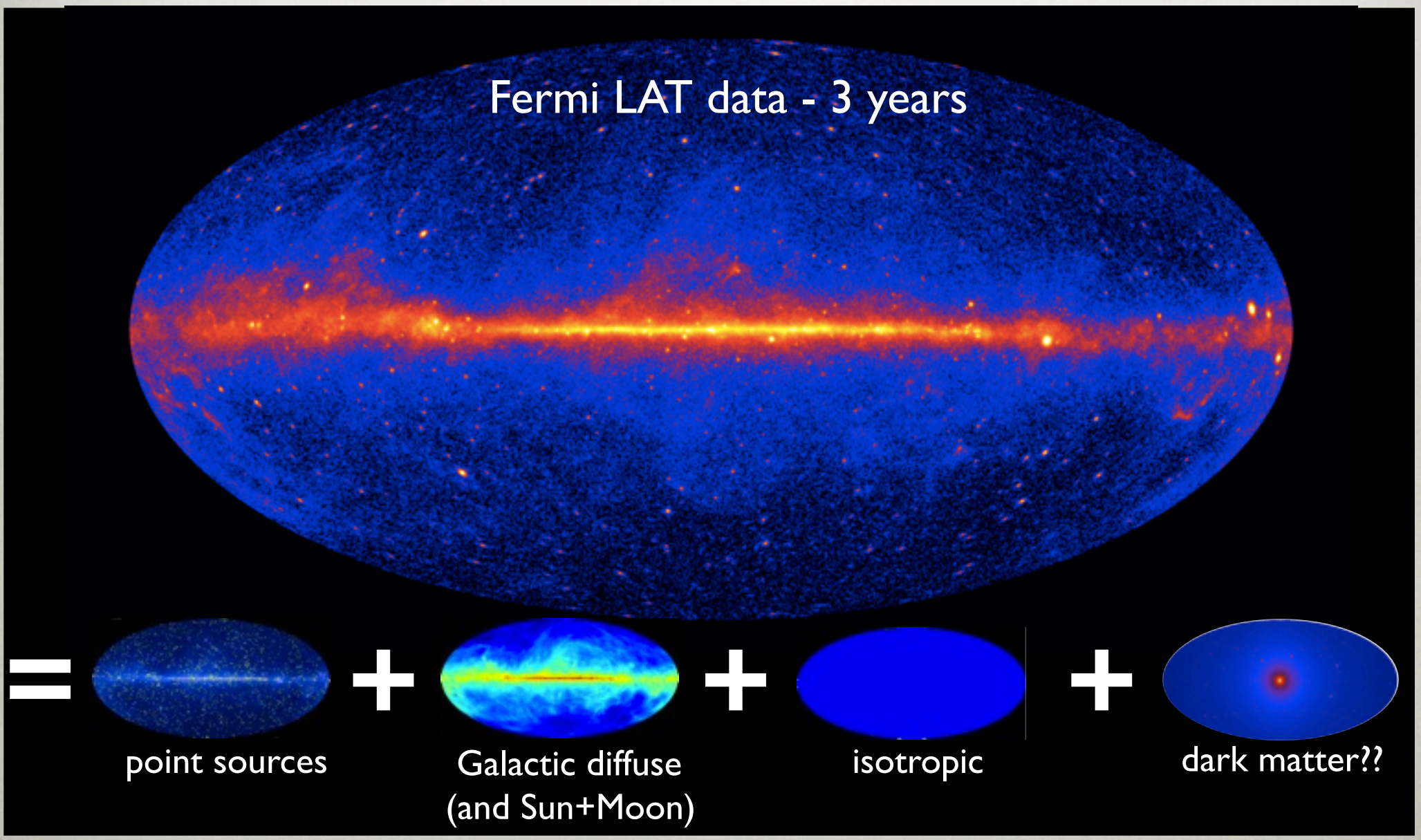




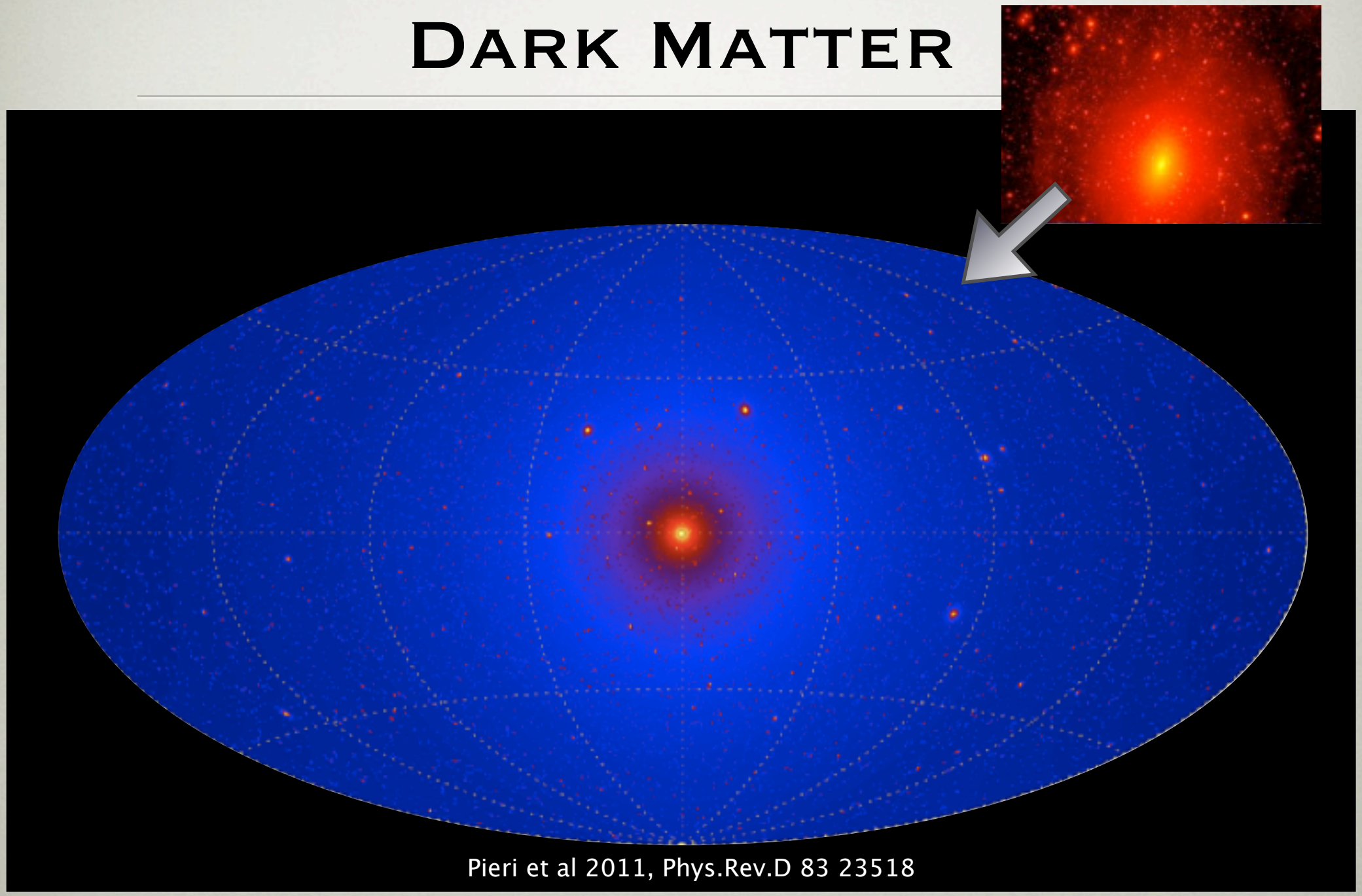
Fermi LAT Collaboration 2012, Phys.Rev.Lett. 108 011103



Understanding the Gamma-ray Sky

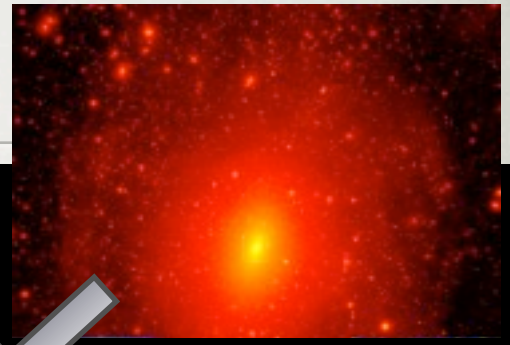


Gamma Rays from Dark Matter



Pieri et al 2011, Phys.Rev.D 83 23518

Gamma Rays from Dark Matter



Galactic center:

Good statistics but source confusion/diffuse background

Satellites:

Low background and good source ID, but low statistics

JCAP 1204 (2012) 016
ApJ 747, 121 (2012)
Phys. Rev. Lett. 107, 241302 (2012)
ApJ 712, 147 (2010)
JCAP 01 (2010) 031
ApJ 718, 899 (2010)

Milky Way halo:

Large statistics but diffuse background

arXiv:1205.6474

+Electrons and Positrons!

Phys.Rev.Lett., 108 011103 (2012)
Phys. Rev. D84, 032007 (2011)
Nucl. Instrum. Meth. A630 (2011) 48-51
Phys. Rev. D82, 092003 (2010)
Phys.Rev.Lett., 102 181101 (2009)

Spectral lines:

Good source ID, but low statistics

Phys. Rev. D, In press (2012)
Phys. Rev. Lett. 104, 091302 (2010)

Anisotropies

MNRAS 414, 2040 (2011)

Galaxy clusters:

Low background but low statistics

JCAP 05 (2010) 025

Extragalactic diffuse:

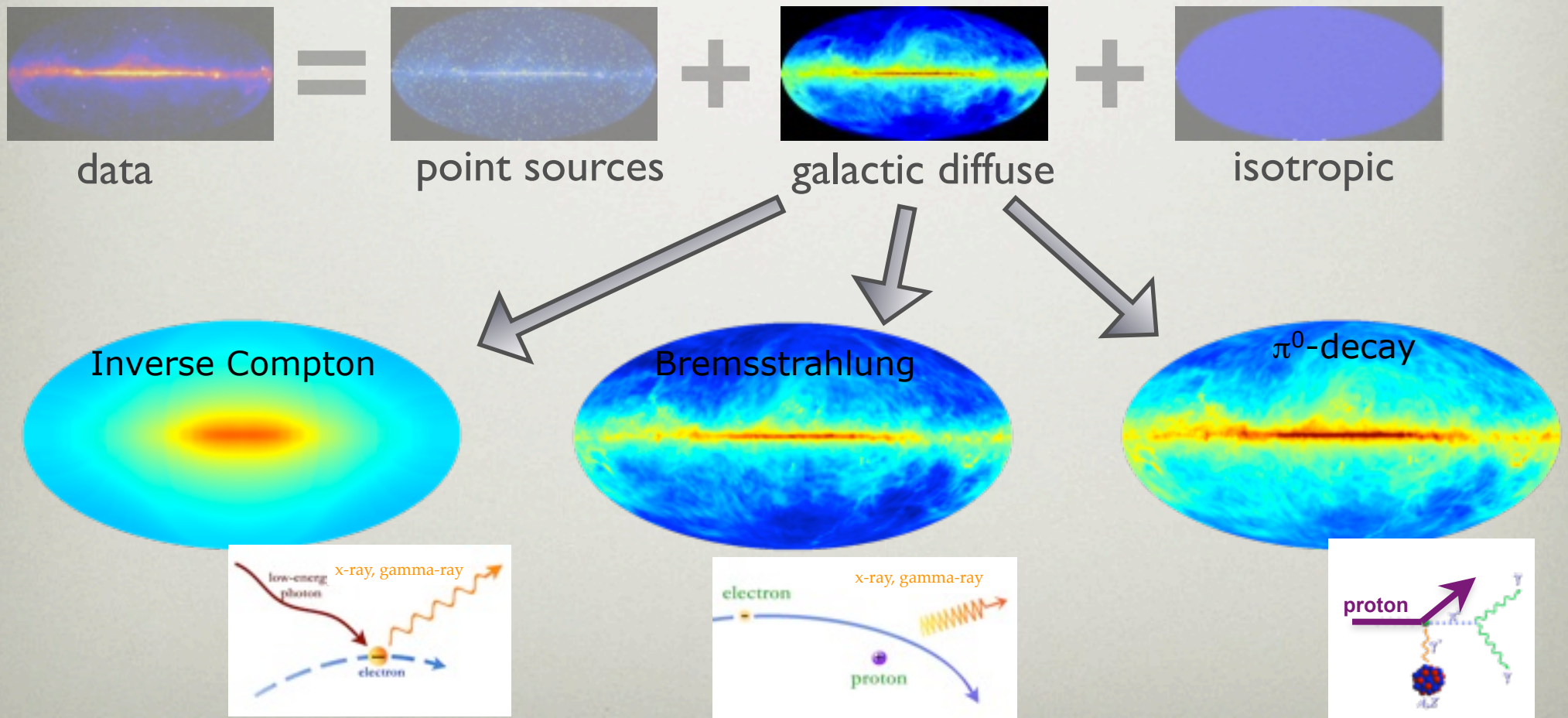
Large statistics, but astrophysics, Galactic diffuse background

JCAP 04 (2010) 014

Pieri et al 2011, Phys.Rev.D 83 23518

Galactic Diffuse Emission

- The diffuse gamma-ray emission from the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field and carries important information on the acceleration, distribution, and propagation of cosmic rays.

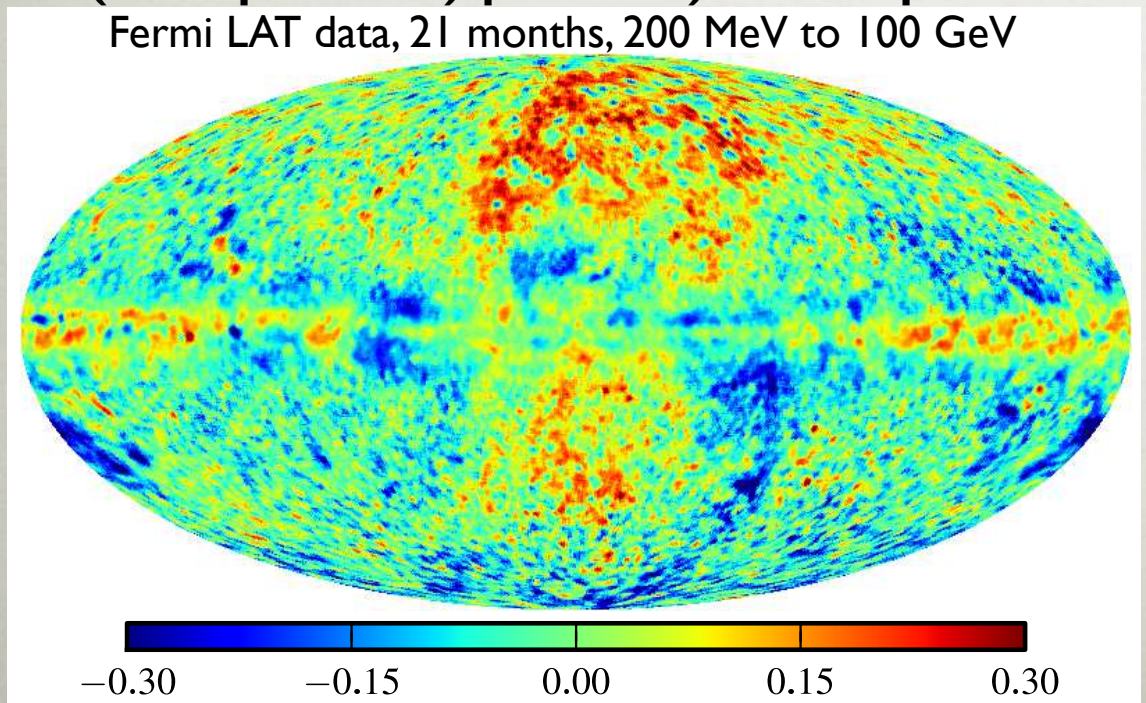


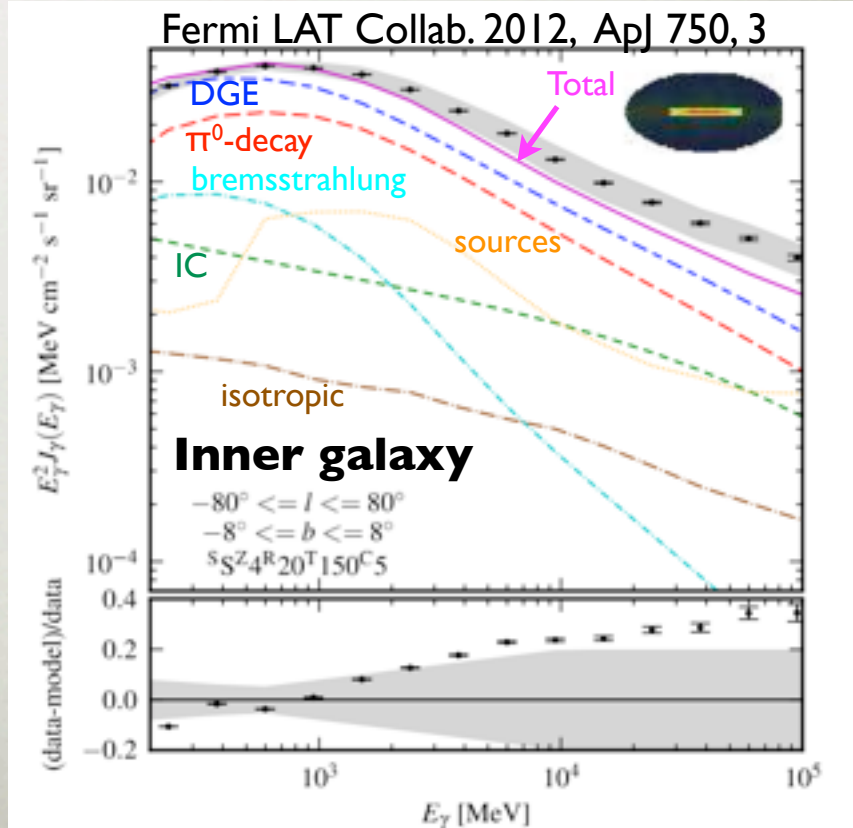
Galactic Diffuse Emission

- Cosmic ray origin, propagation, and properties of the interstellar medium can be constrained by comparing the data to predictions
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution (GALPROP) and compare with Fermi LAT data

Example model:
CR source distribution: SNRs
CR confinement region: 20 kpc radius, 4 kpc height

(data - prediction)/prediction) for example model





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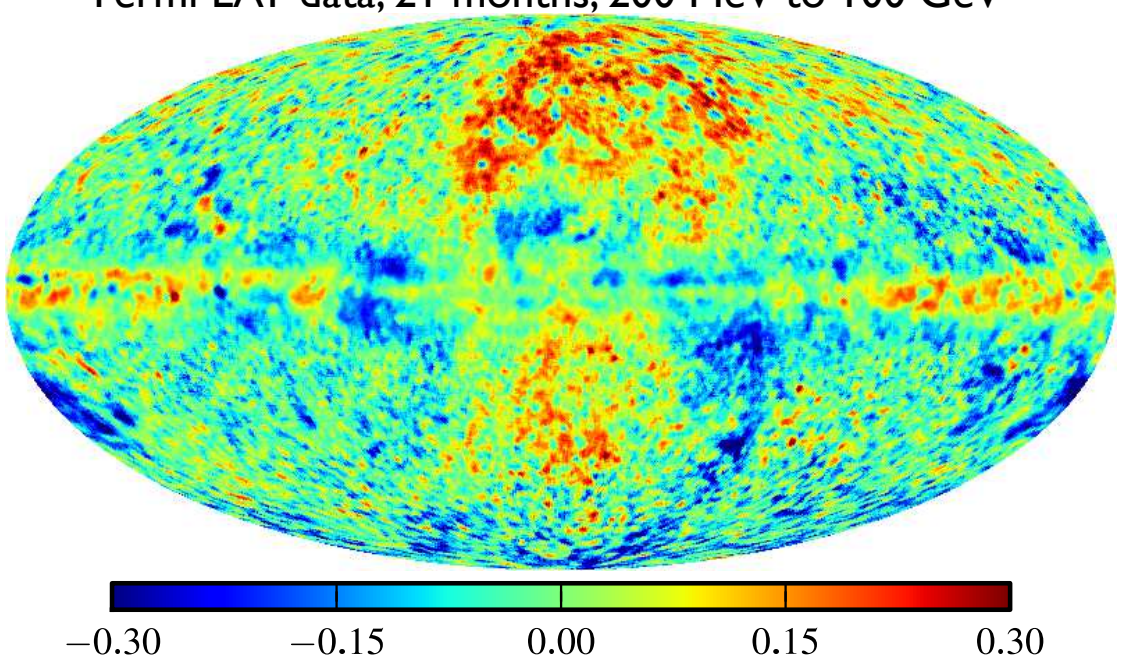
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution (GALPROP) and compare with Fermi LAT data

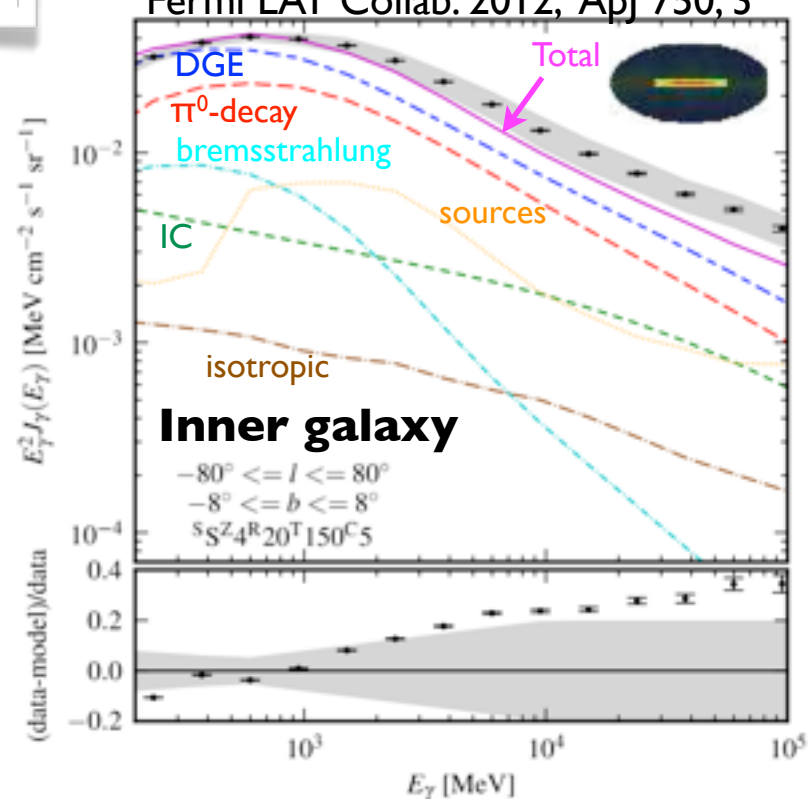
On a large scale the agreement between data and prediction is overall good, however some extended excesses stand out.

(data - prediction)/prediction) for example model

Fermi LAT data, 21 months, 200 MeV to 100 GeV



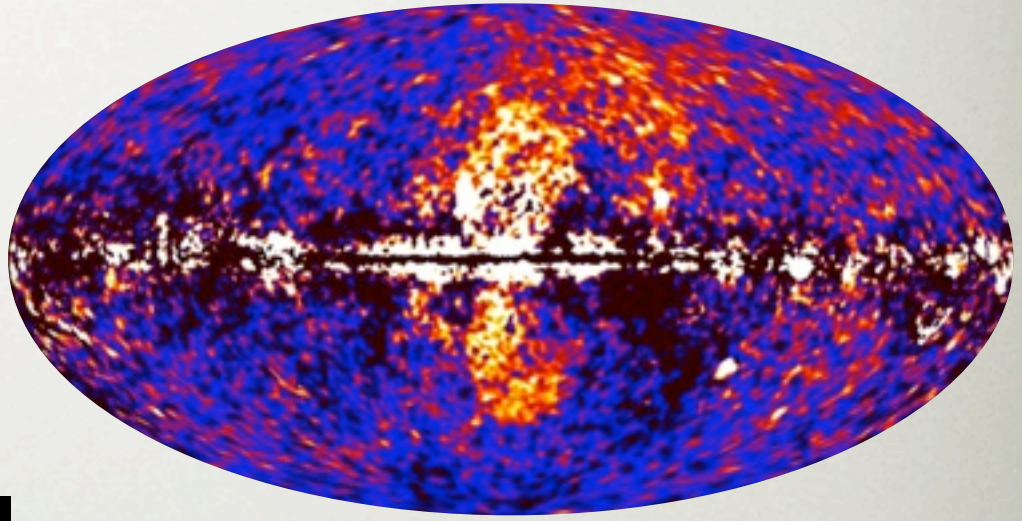
Fermi LAT Collab. 2012, ApJ 750, 3

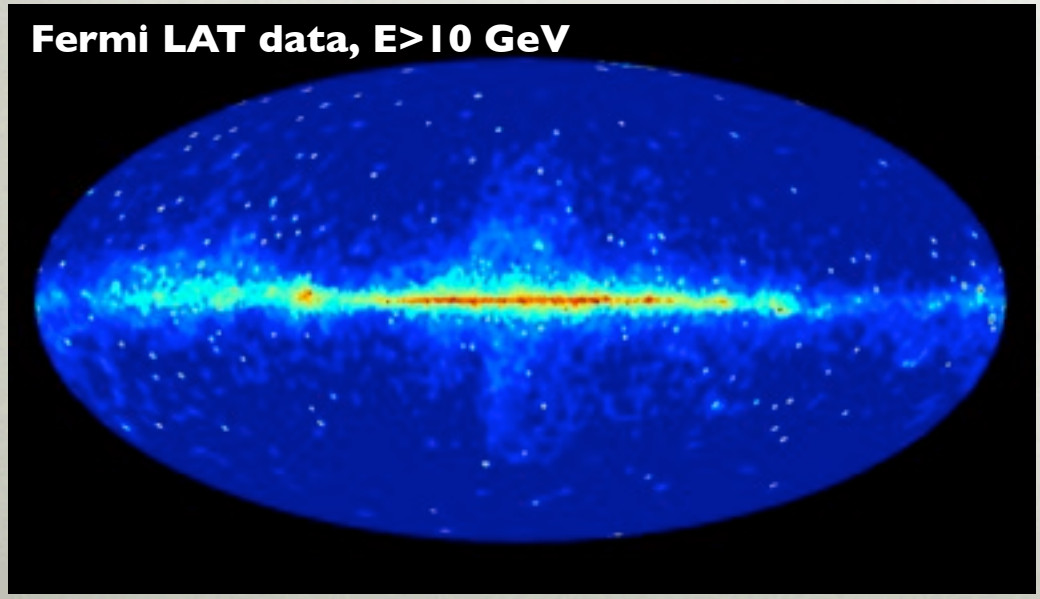


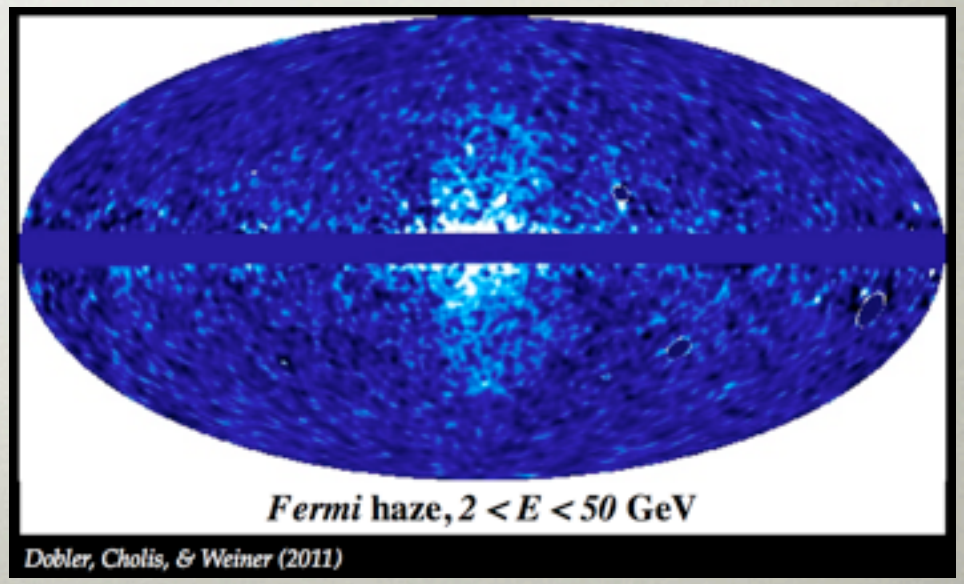
Extended Lobe-like Features in the Fermi Sky

- Gamma-ray bubbles (Su et al 2010, ApJ 724, 1044):
  - very extended (~ 50° from plane)
  - hard spectrum (~E^{-2}, 1-100 GeV)
  - sharp edges
  - possible counterparts in other wavelengths (ROSAT, WMAP, and Planck)
- Outflow from the center of the Milky Way: jets from the supermassive black hole? starburst?

Su et al 2010, ApJ 724, 1044







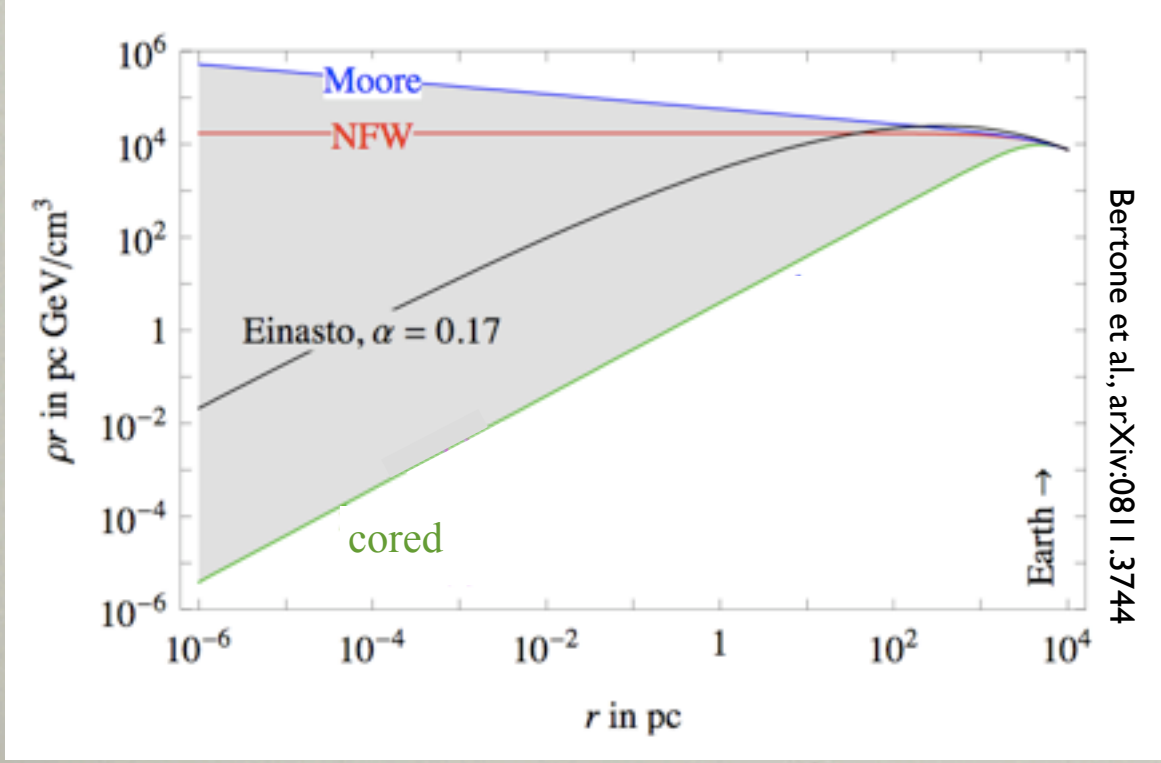
Galactic Center Region

☺ Steep DM profiles predicted by CDM ⇒ Large DM annihilation/decay signal from GC!

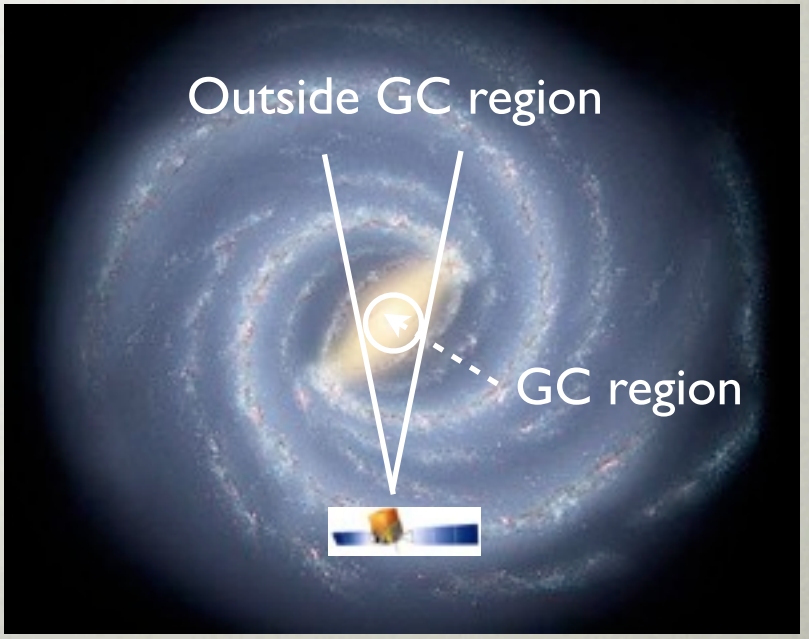
☹ Good understanding of the conventional astrophysical background is crucial to extract a potential DM signal from this complex region of the sky:

- sources: many energetic sources near to or in the line of sight of the GC
- Galactic diffuse emission modeling: large uncertainties complicated by overlap of structures along the line of sight, difficult to model. Also, unresolved source component likely.

☹ Large uncertainties in the dark matter distribution

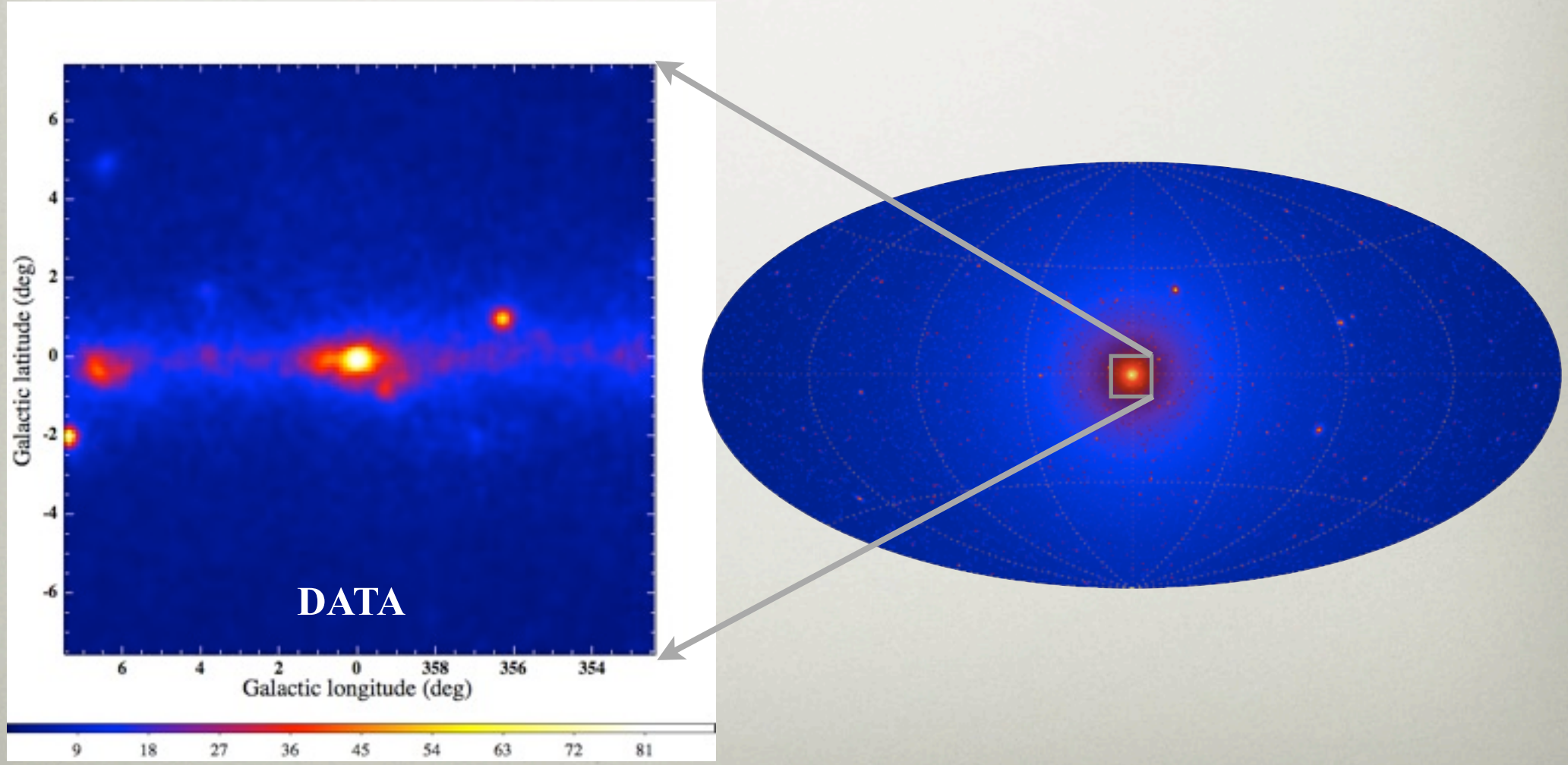


Bertone et al., arXiv:0811.3744



Fermi LAT View of the Galactic Center Region

- Fermi LAT preliminary results for a 15°x15° region around the direction of the Galactic center with 32 months of data, 1-100 GeV. P7CLEAN data, FRONT only.



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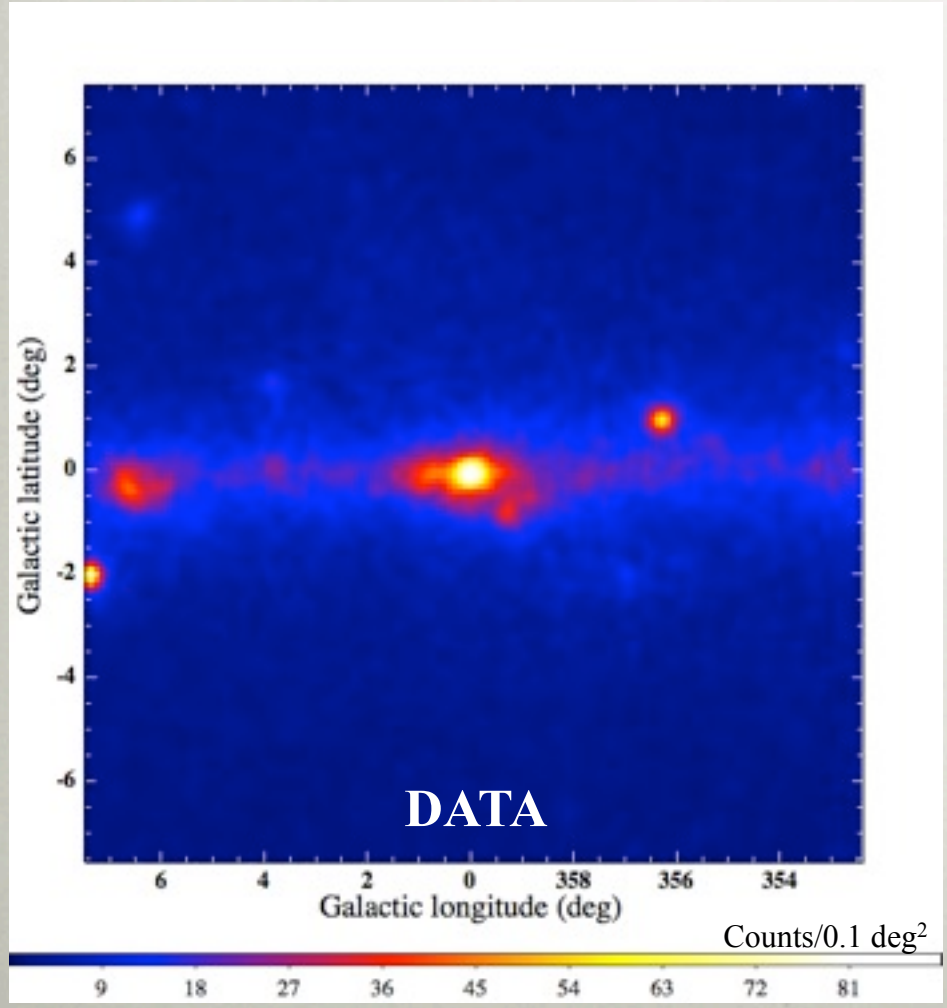
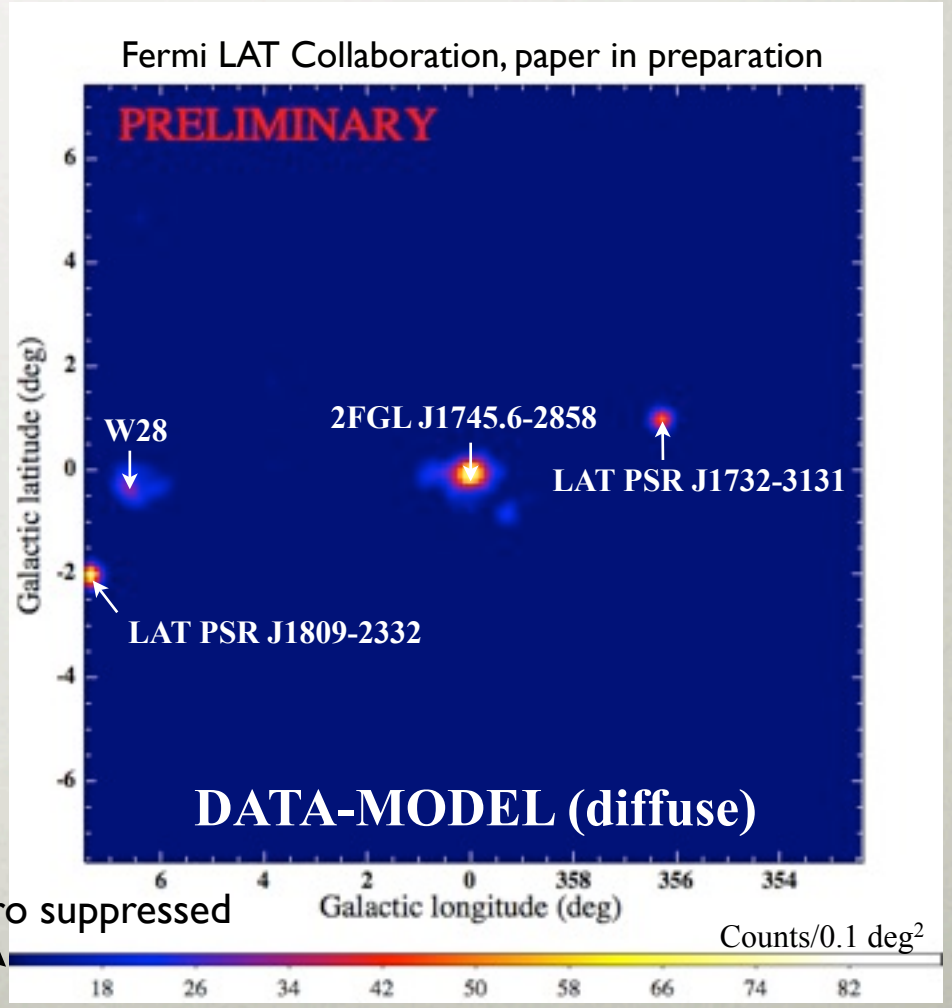
- Bright excesses after subtracting diffuse emission model are consistent with cataloged sources



Fermi LAT Collaboration, paper in preparation



zero suppressed

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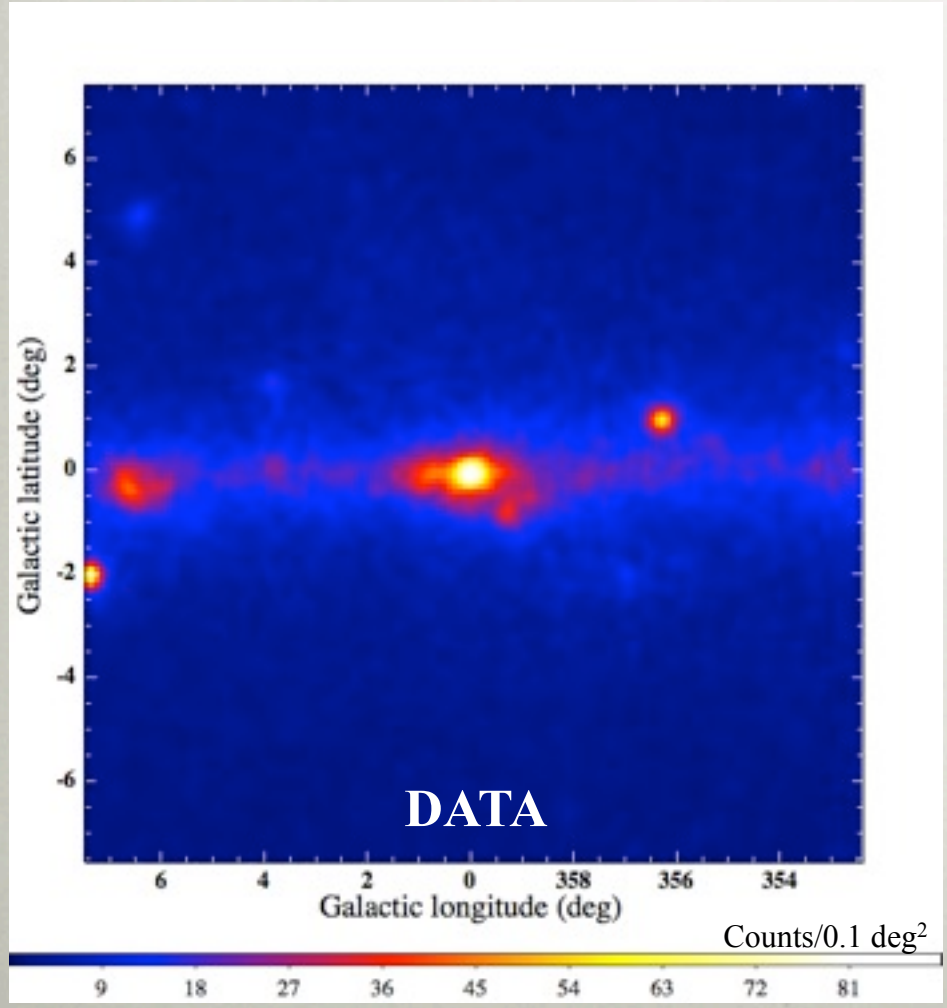

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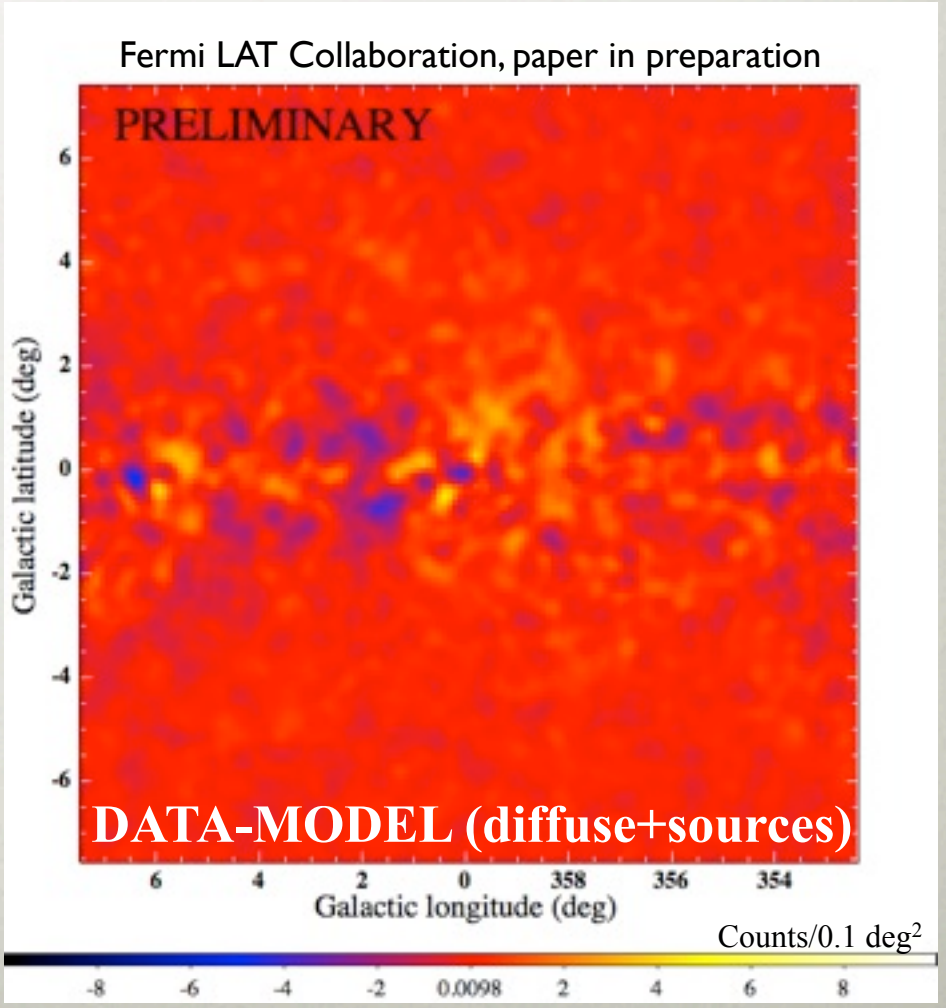

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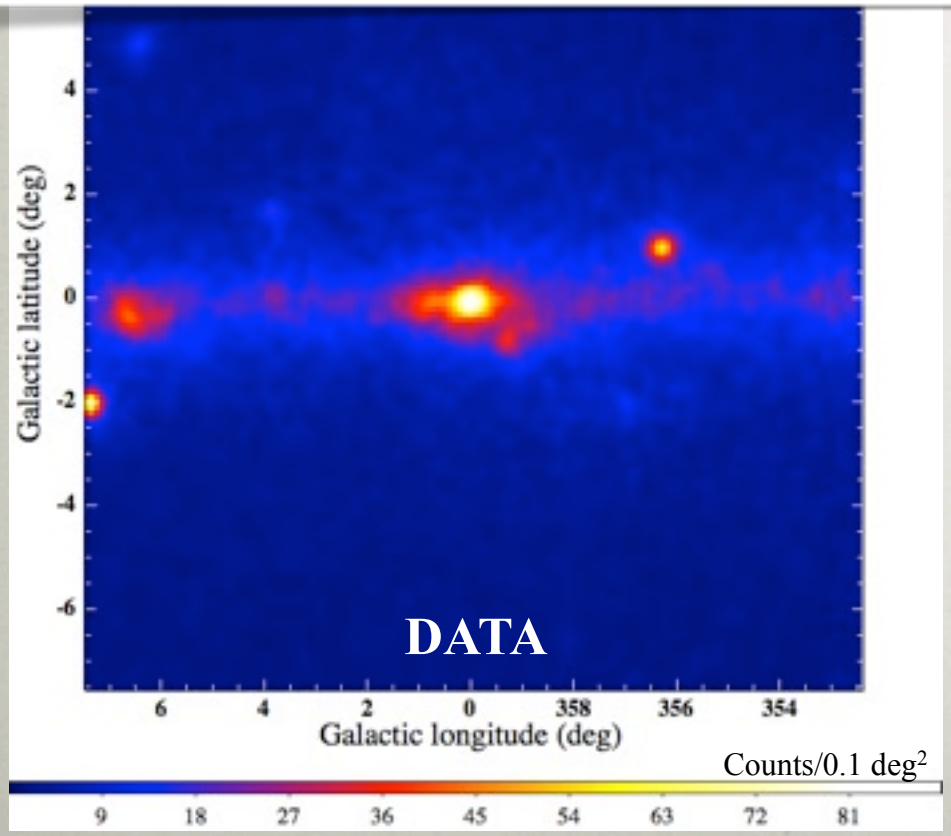
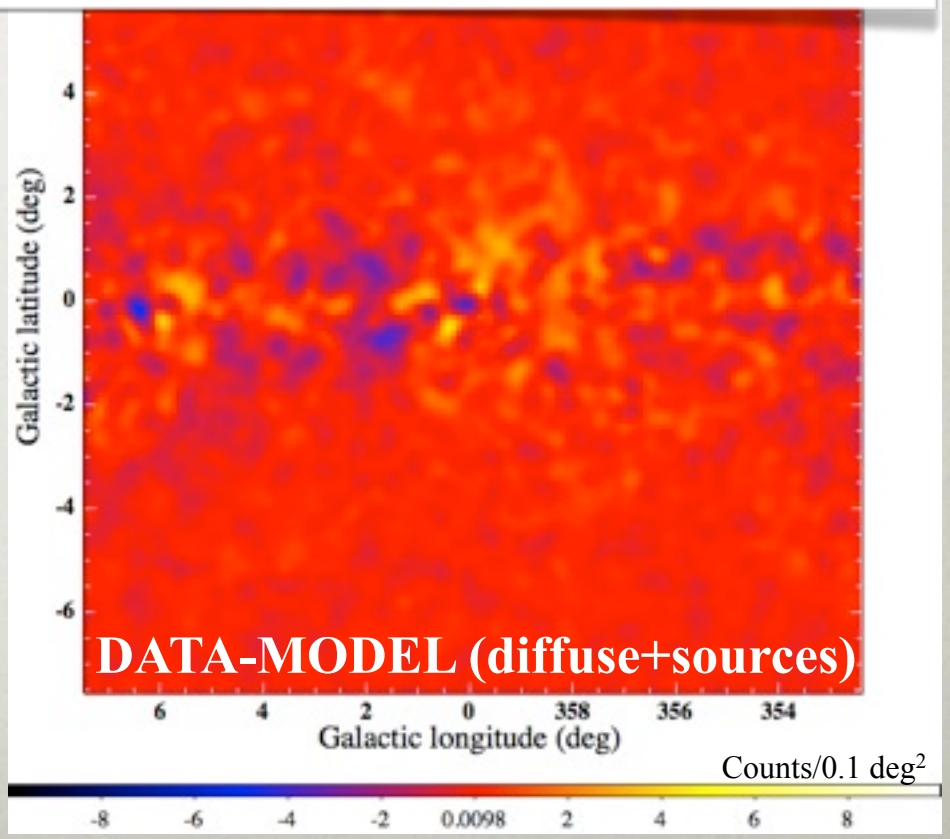
Good agreement between data and model within 5-10%. Investigating low level residuals

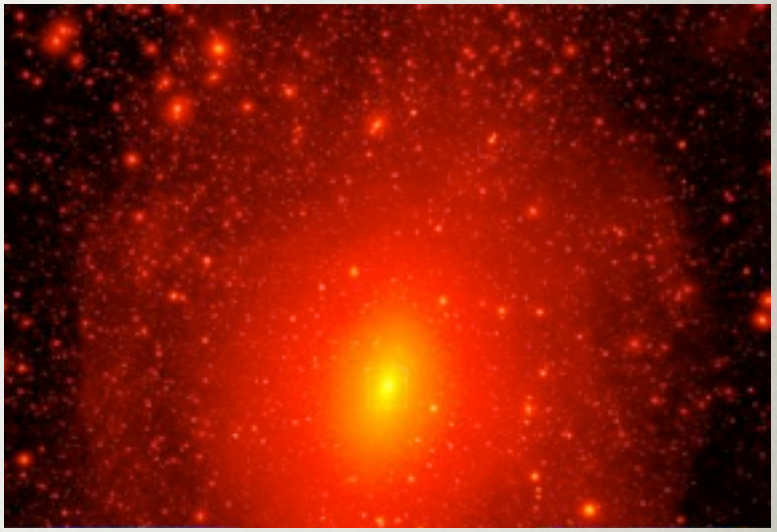
Dark matter analysis ongoing

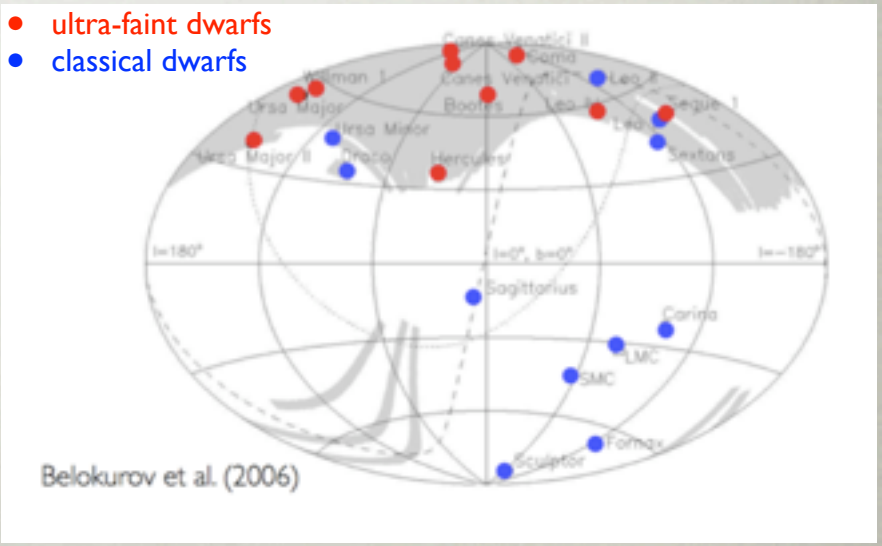




Dwarf Spheroidal Galaxies

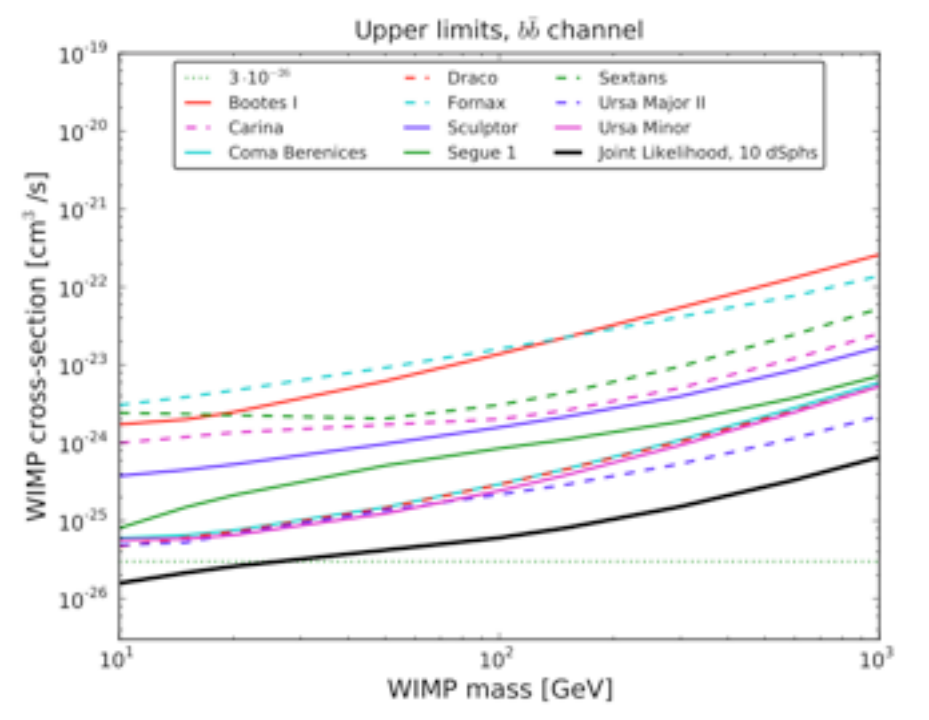
- Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.
- Excellent targets for gamma-ray DM searches
  - Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
  - DM density inferred from the stellar data! Data so far cannot discriminate, in most cases, between cusped or cored dark matter profiles. However, Fermi's DM constraints with dSph do not have a strong dependence on the inner profile
  - Expected to be free from other gamma ray sources and have low dust/gas content, very few stars
- Only a handful of dwarfs are known (SDSS) but more should be discovered (DES, LSST)

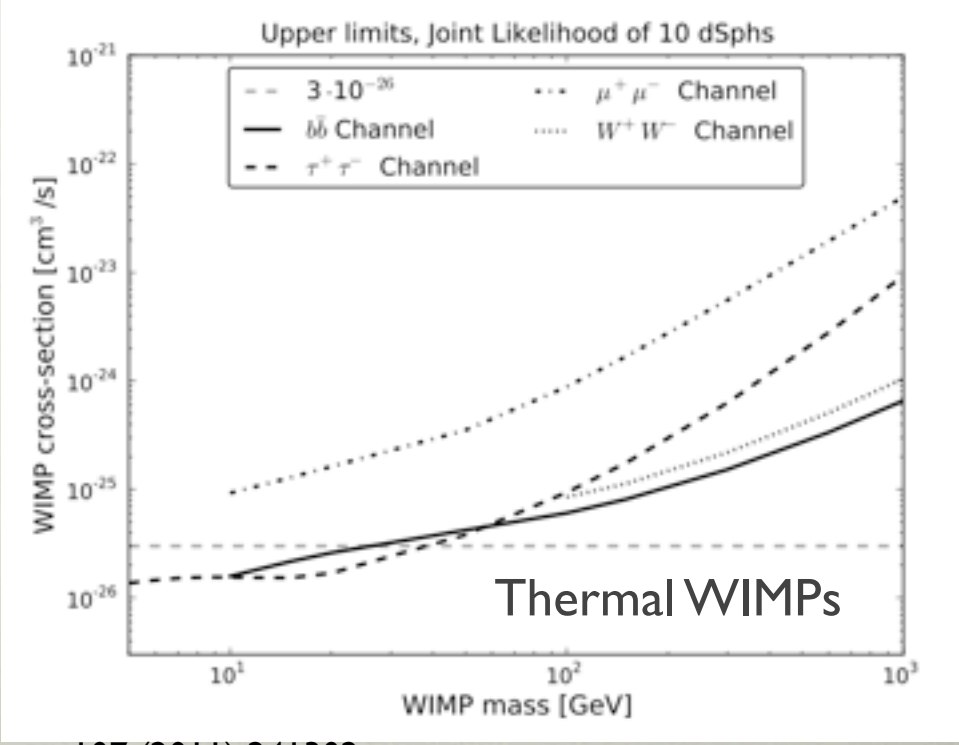




Dwarf Spheroidal Galaxies

- Bootes I, Carina, Coma Berenices, Draco, Fornax, Sculptor, Segue I, Sextans, Ursa Major II, Ursa Minor
  - ➡ No detection of dSph by Fermi with 2 years of data
- Determine 95% flux upper limits for several possible annihilation final states
- Combine with the DM density inferred from the stellar data (assume NFW profile) to set constraints on the annihilation cross section
- Constraints include systematic uncertainties on the DM content!





Fermi LAT Collaboration, Phys. Rev. Lett., 107 (2011) 241302

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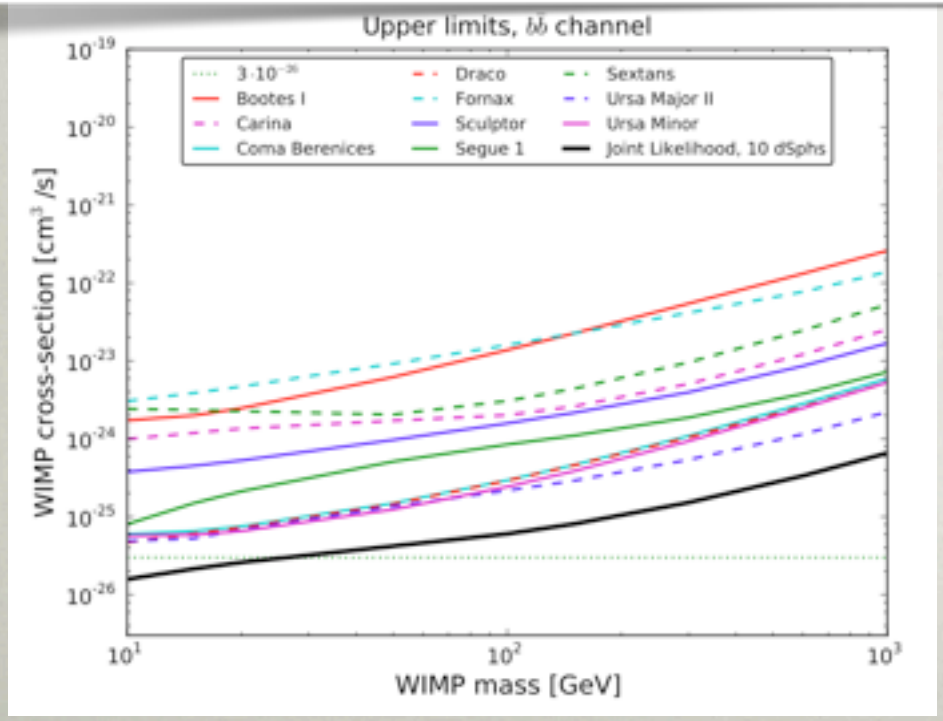
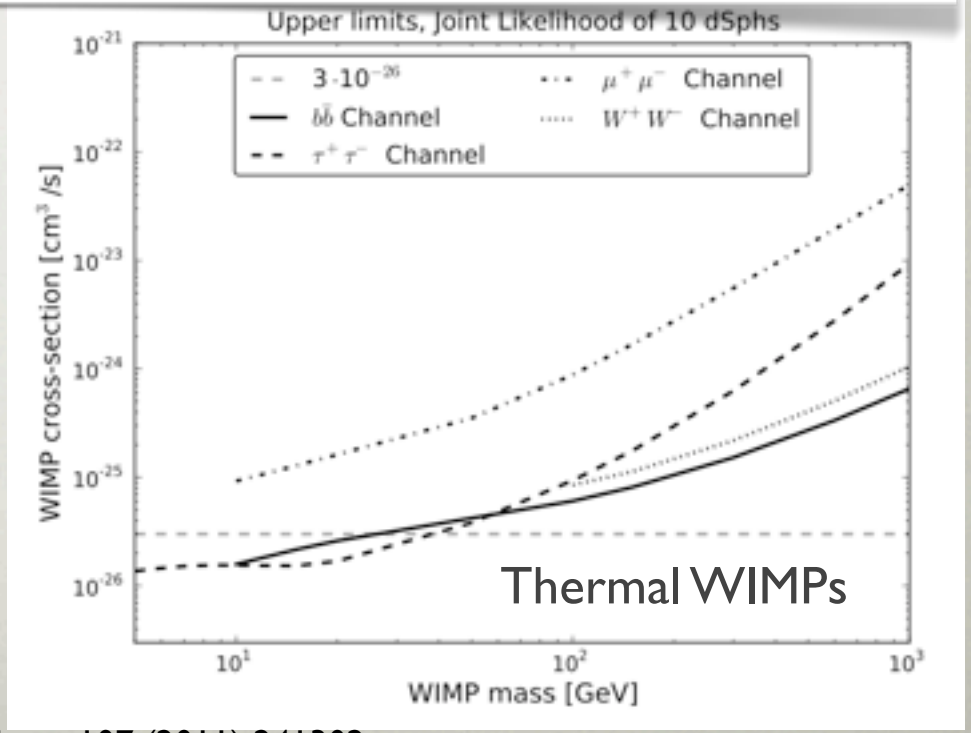
Fermi LAT rules out some WIMP models with generic cross section (3×10^{-26} $cm^3 s^{-1}$, s-wave) for a thermal relic

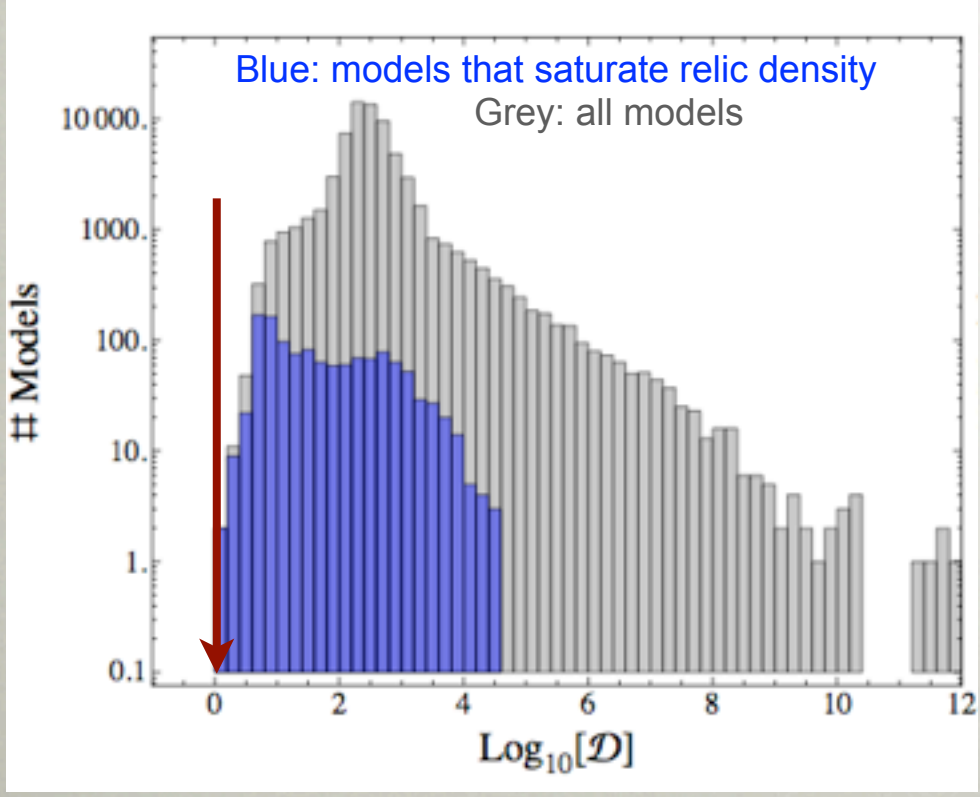


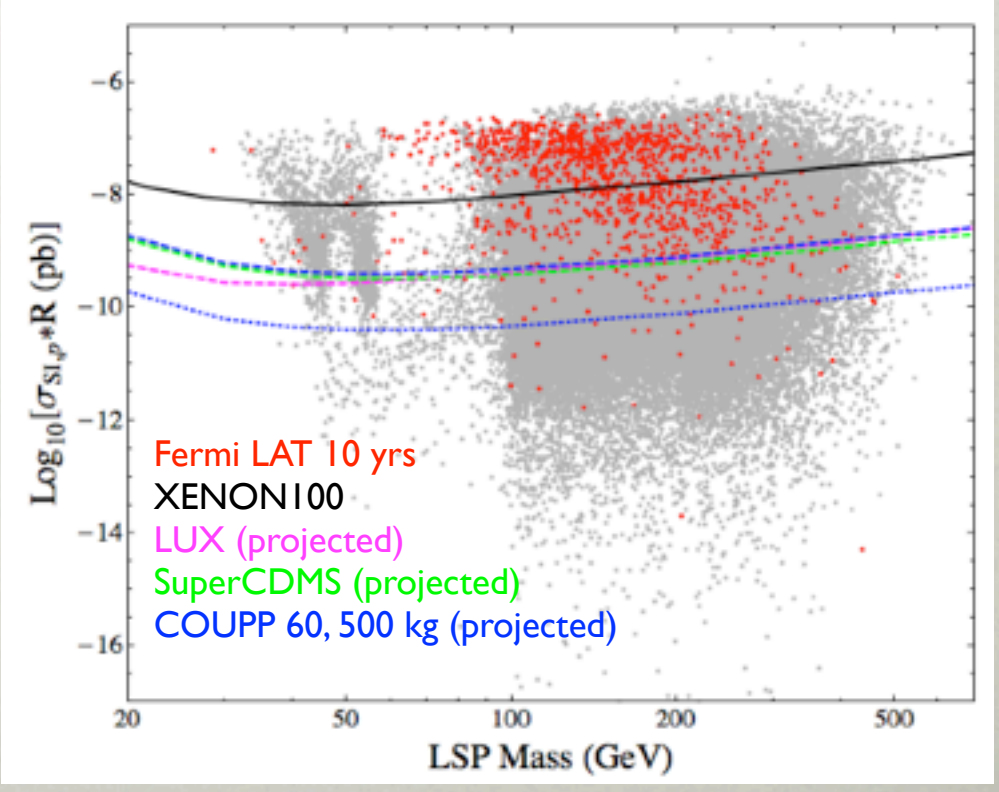


Fermi LAT Collaboration, Phys. Rev. Lett., 107 (2011) 241302

Constraining the pMSSM with Fermi LAT

- Use combined likelihood formalism with dSphs to constrain the phenomenological MSSM (19 parameter scan, ~70k models survive existing experimental bounds
- Closest model to discovery/exclusion ~1.5x away
- Assuming an improvement in sensitivity of ~10x with a10 year mission, many models within reach
- Complementarity with direct detection experiments





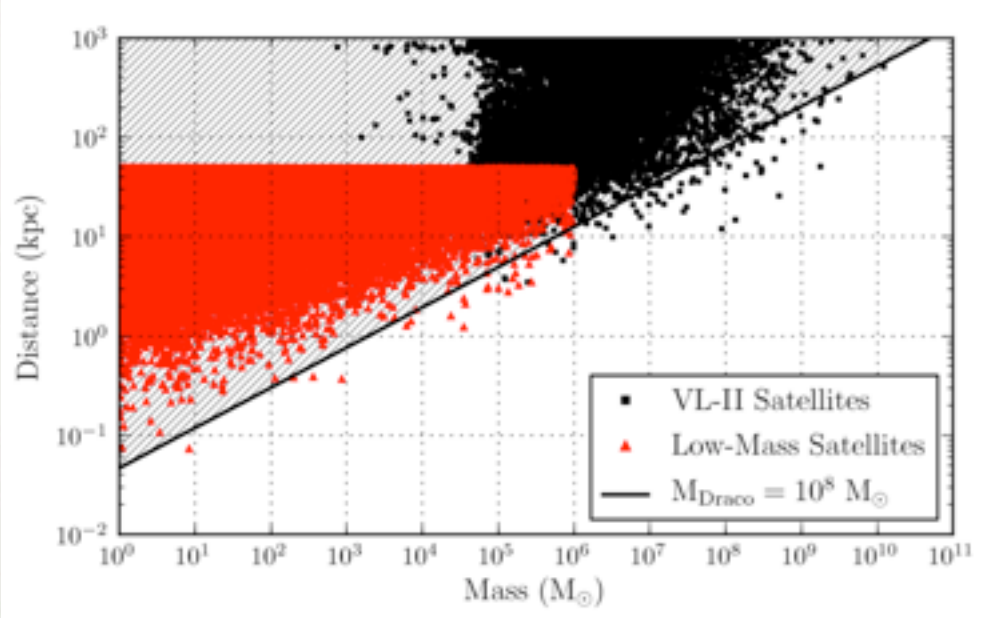
Cotta, R. C. et al., JCAP 1204 (2012) 016

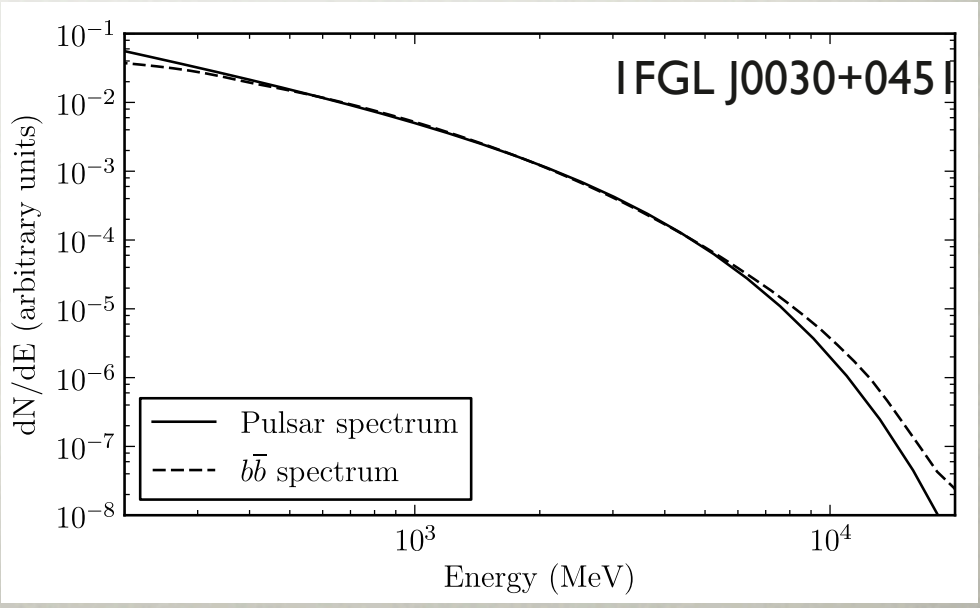
Search for Unknown Dark Matter Satellites

- Search the Fermi sky for DM satellites (1 year of data, 200 MeV-300 GeV)
- DM satellite candidates (|b|>20°):
  - unassociated sources in 1FGL (231)
  - non-1FGL source candidates (154)
- Test for:
  - DM spectrum (power law vs b-bbar)
  - Test for spatial extension (point vs NFW)
- Two sources pass tests, but rejected after further inspection

➡ No DM satellites found

- Set 95% CL upper limit for 100 GeV WIMP annihilating into b-bbar, 1.95×10^{-24} cm^3 s^{-1}



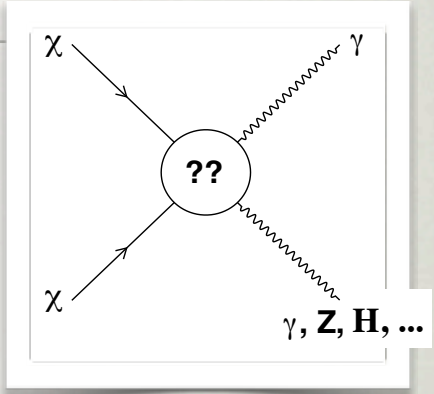


Fermi LAT Collaboration, Astrophys. J. 747 (2012) 121

Search for Spectral Lines

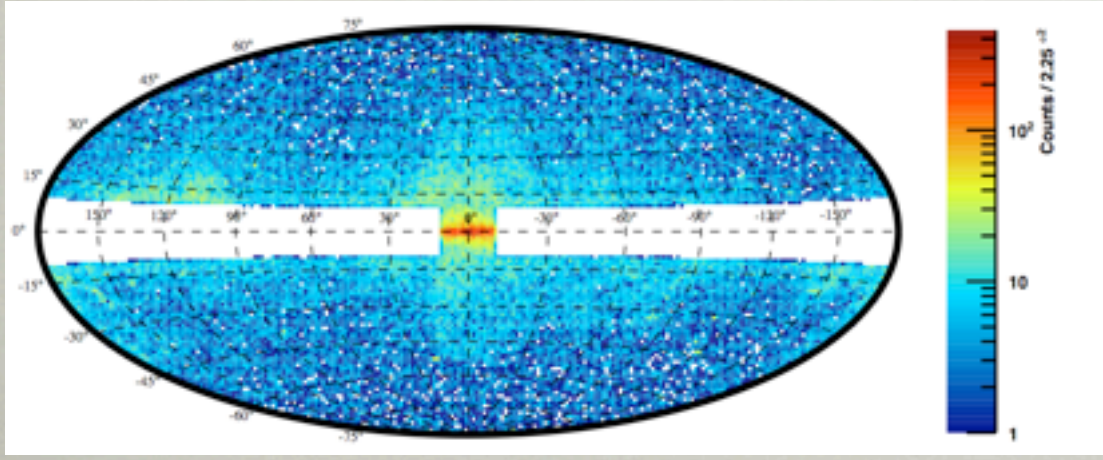
☺ "Smoking gun" signal of dark matter.

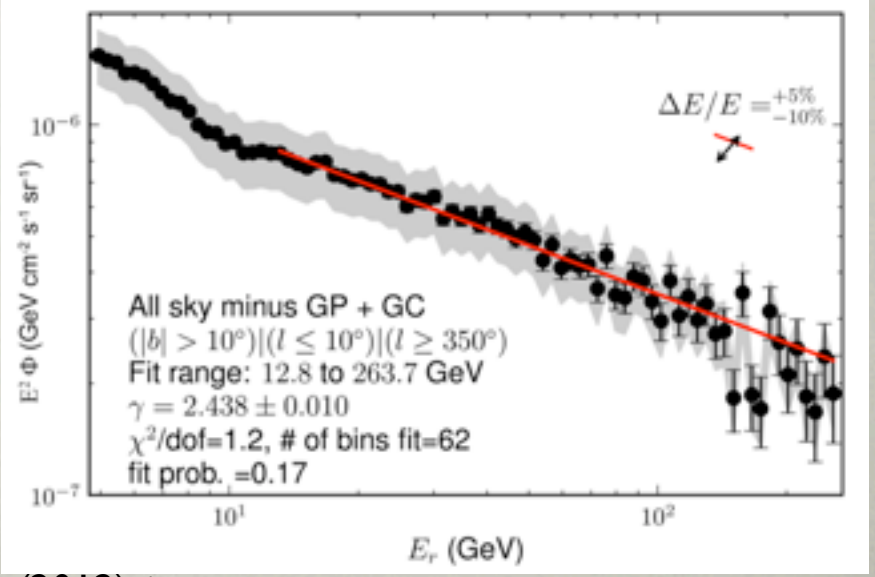
☹ The line signal is generally suppressed (but enhanced in some models!)



- The signal is the LAT line response function. The background is modeled by a power-law function and determined by the fit
- Search for lines in the first 2 years of Fermi data and include the data from most of the sky (remove point sources and most of the Galactic disk)

Fermi LAT data (5-264 GeV)



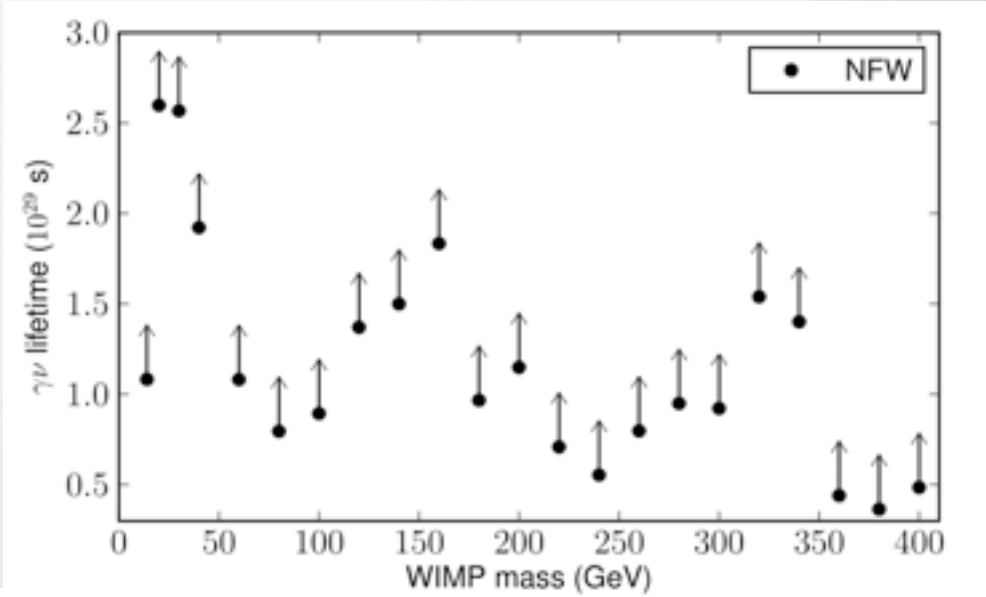


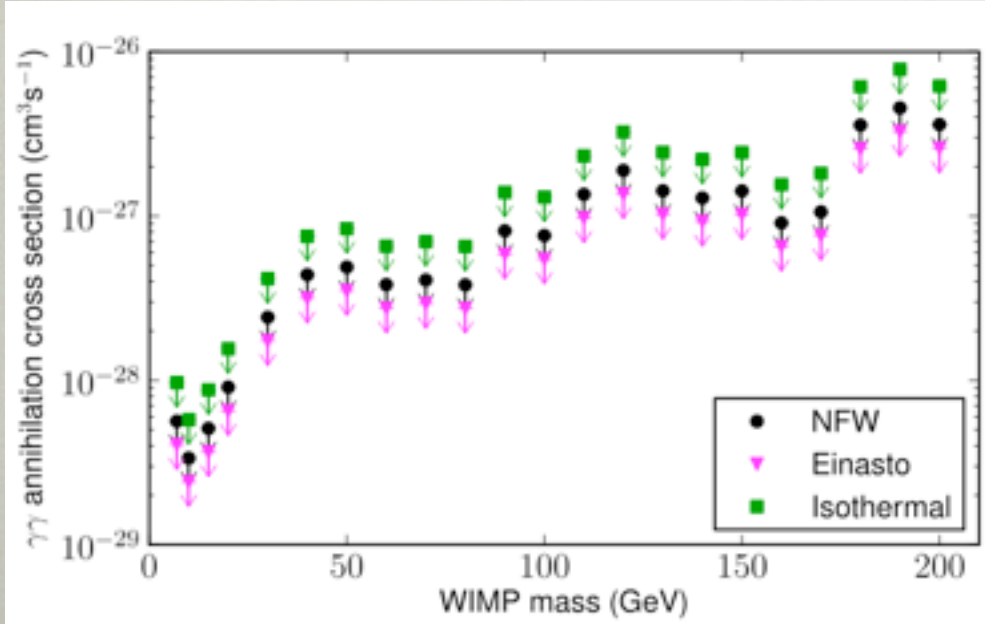
Fermi LAT Collaboration, Phys. Rev. D (2012), in press

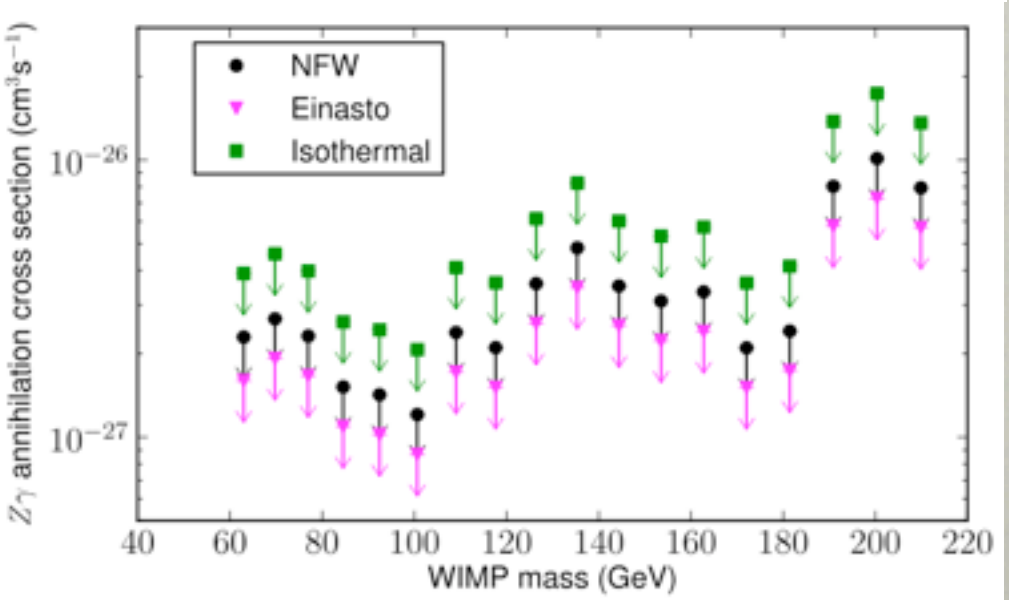
Search for Spectral Lines

- No line detection. 95% CL flux upper limits, 7-200 GeV energy range

- With assumptions on the dark matter density distribution, we extract constraints on the dark matter annihilation cross-section and decay lifetime







Fermi LAT Collaboration, Phys. Rev. D (2012), in press

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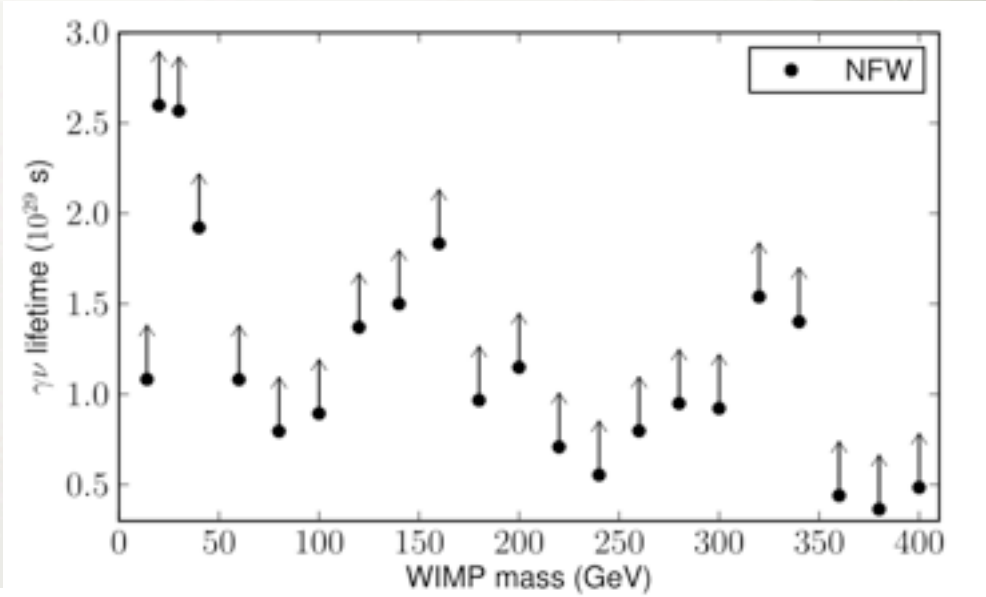

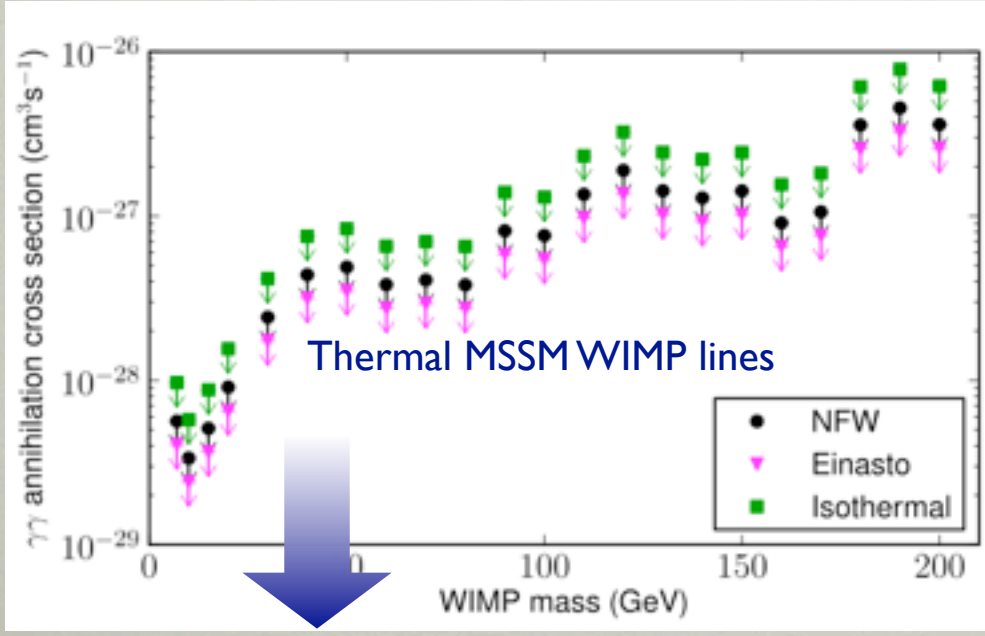

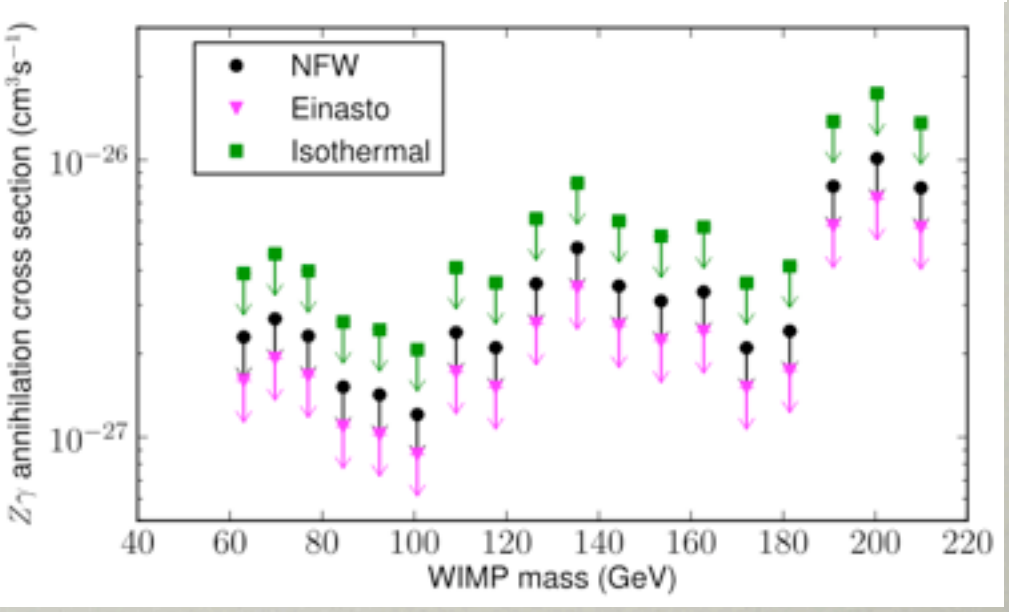

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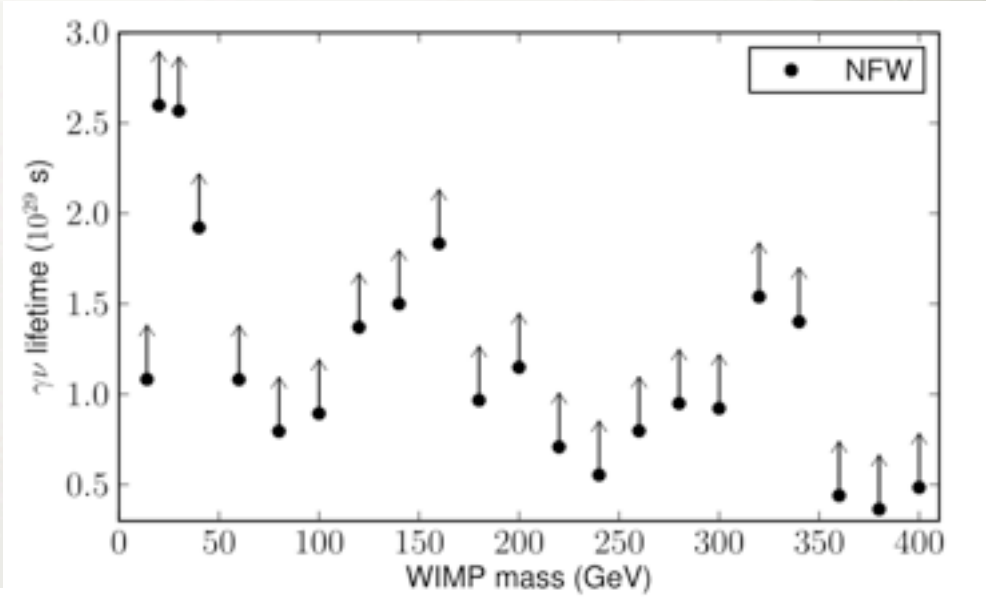

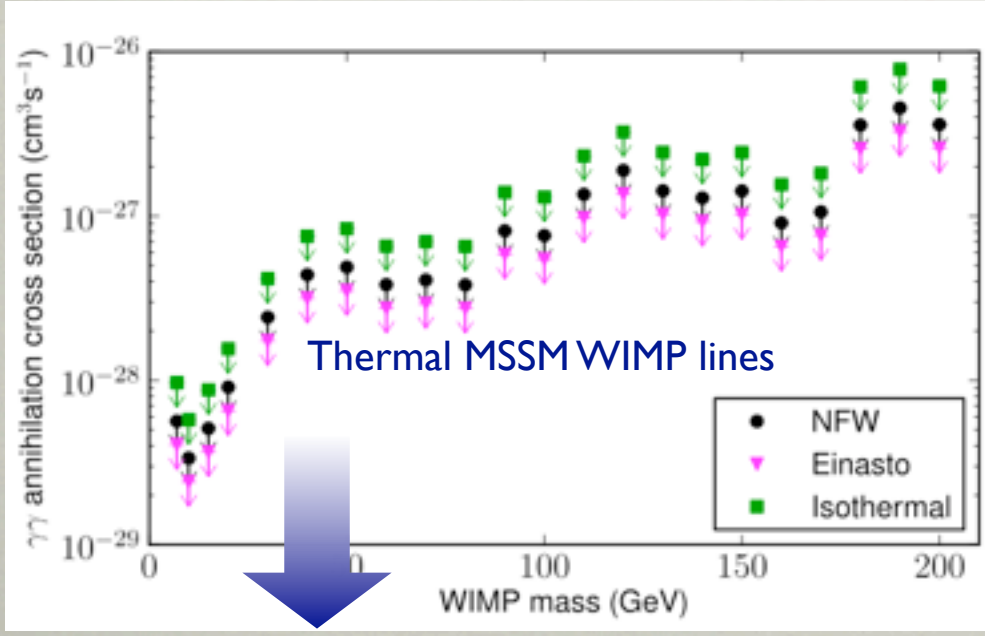

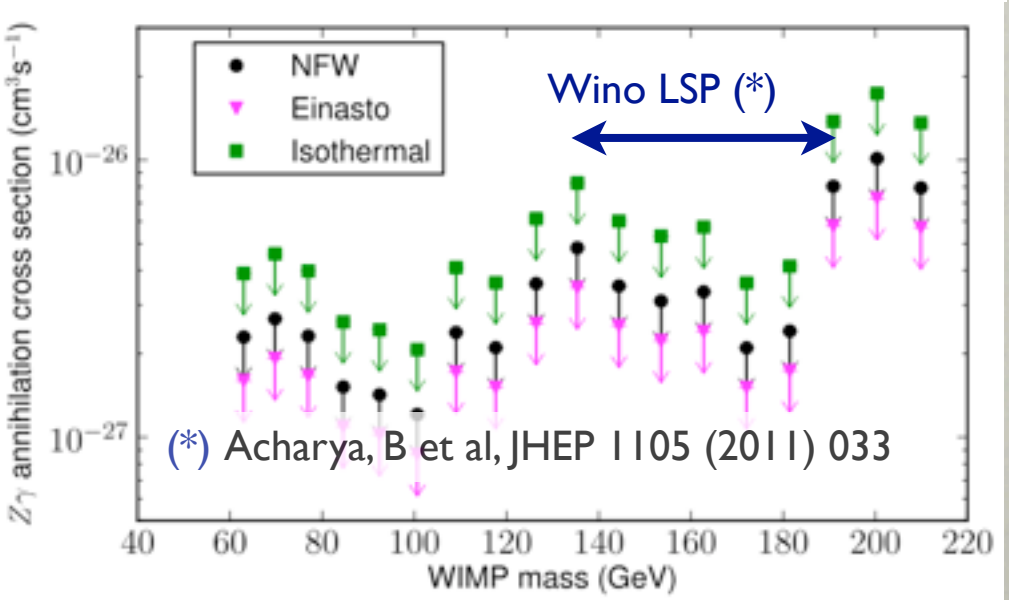

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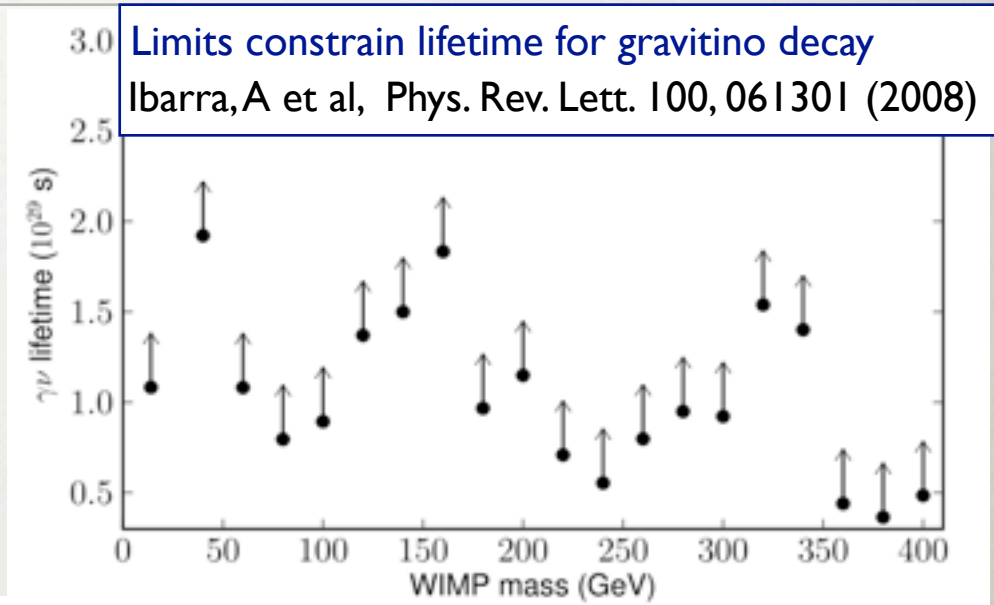
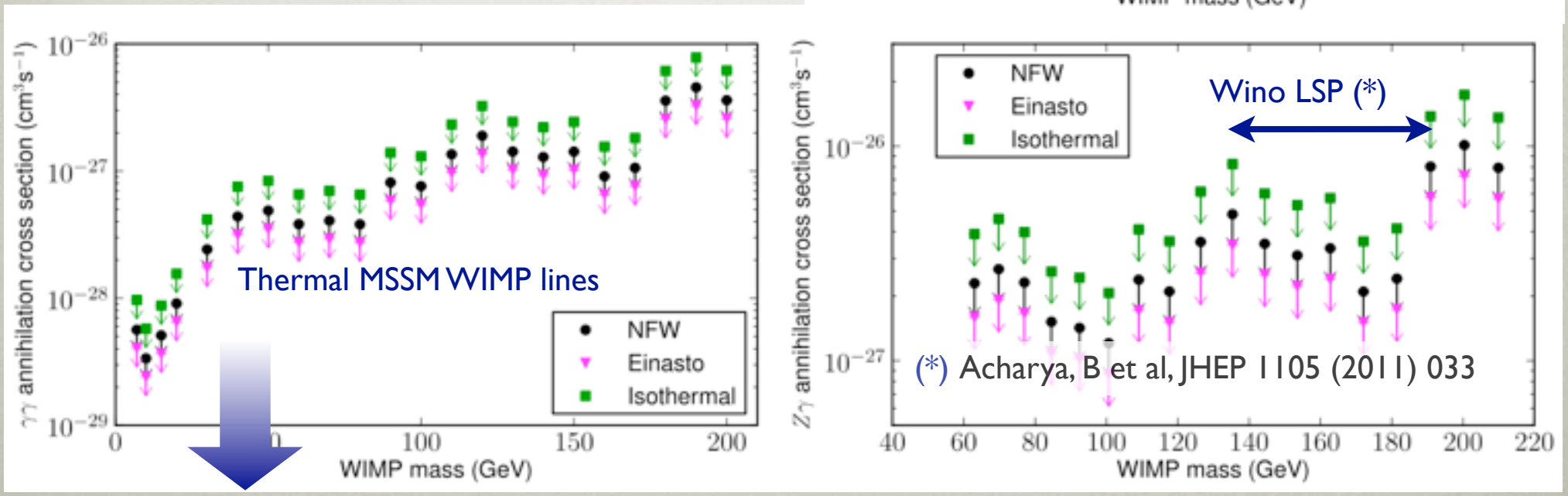
Limits constrain lifetime for gravitino decay
Ibarra, A et al, Phys. Rev. Lett. 100, 061301 (2008)





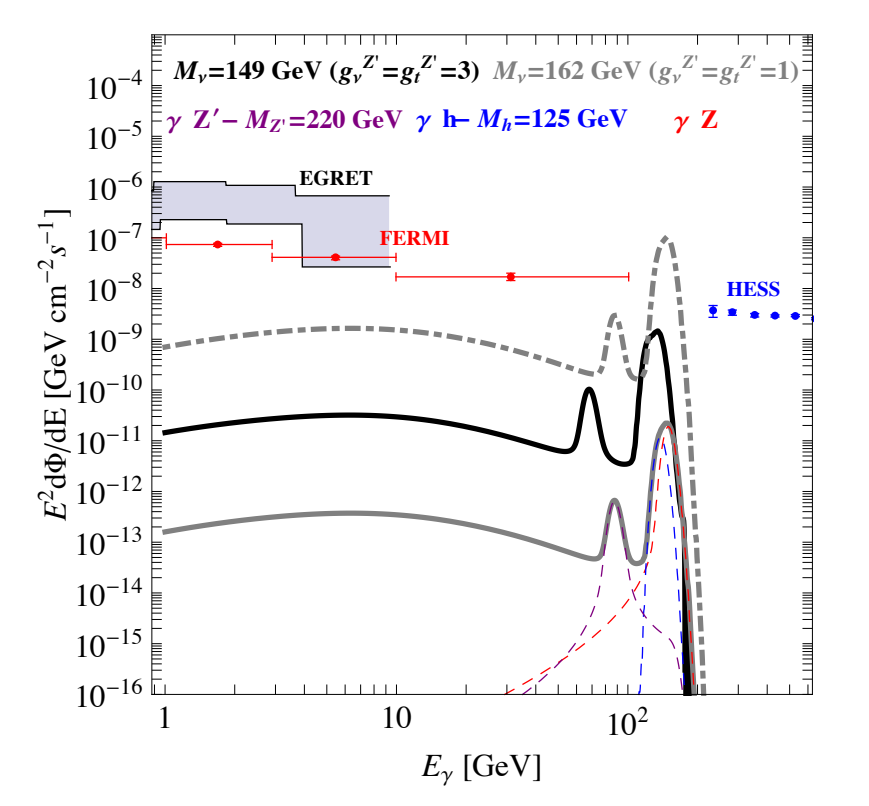
Fermi LAT Collaboration, Phys. Rev. D (2012), in press

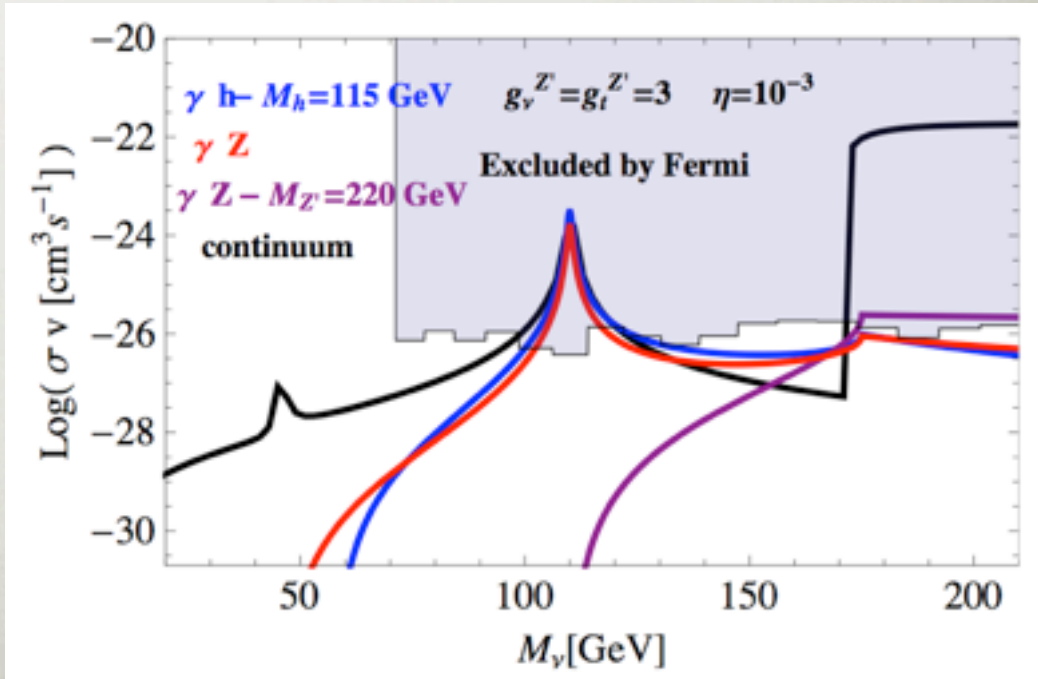
More DM constraints from Lines

- Constraints have also been placed on recently-proposed models that predict WIMPs annihilating into γ+Higgs.

Higgs in space!

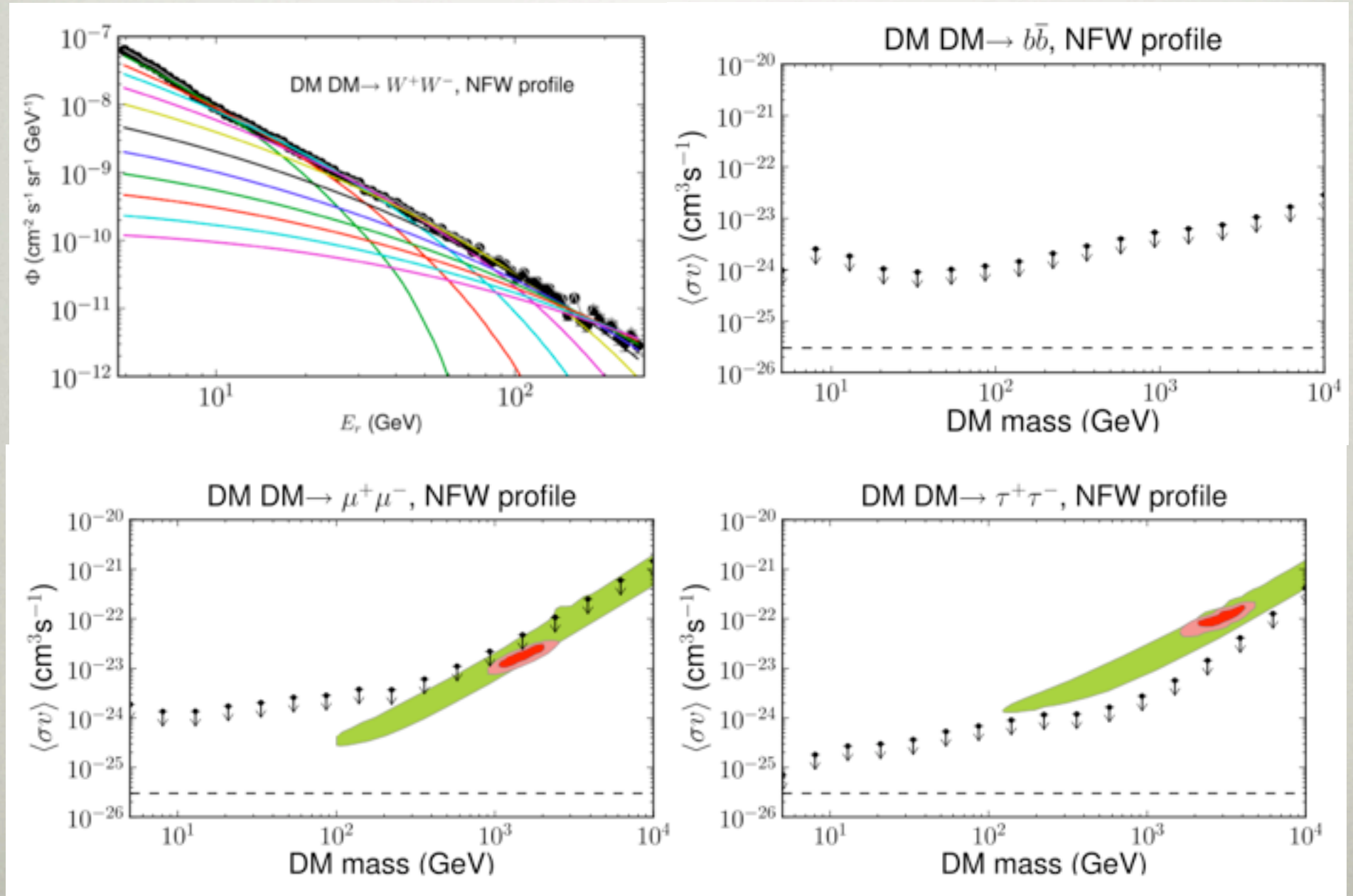
Jackson, C et al JCAP 1004 (2010) 004





Inclusive spectrum limits

Fermi LAT Collaboration, Phys. Rev. D (2012), in press



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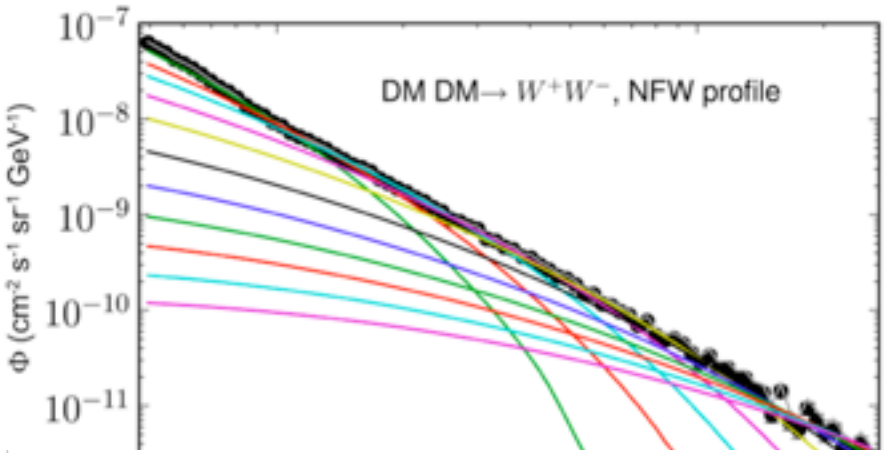
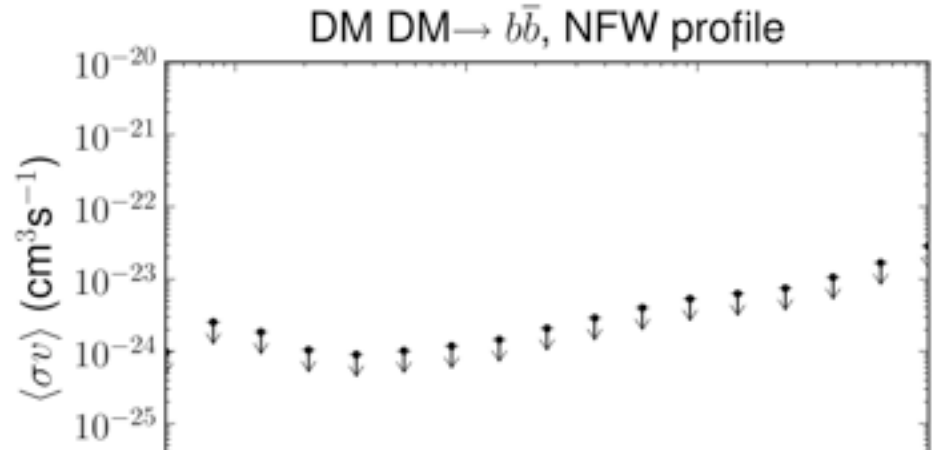
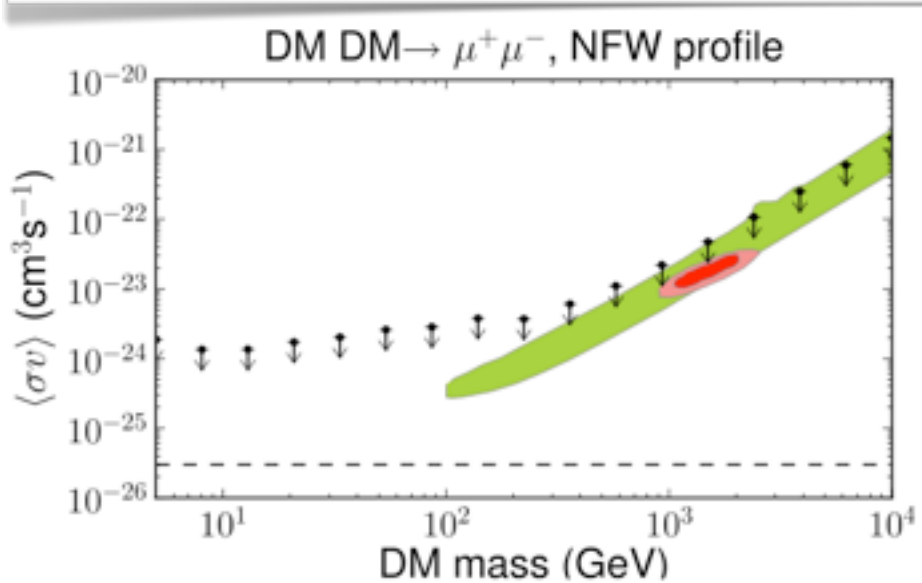
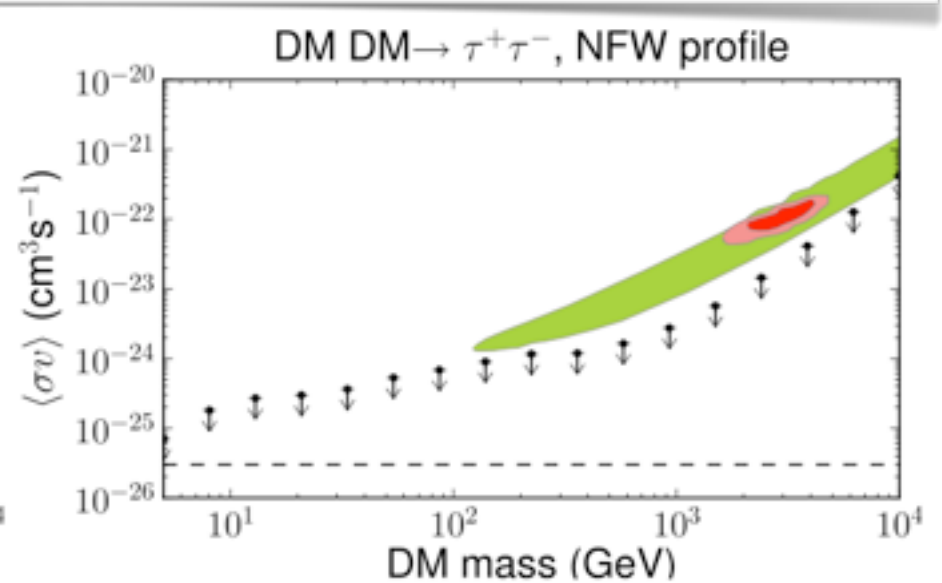




Strongly disfavors DM interpretation of Fermi/PAMELA electron and positron measurements for annihilation into taus and constrains annihilation into muons

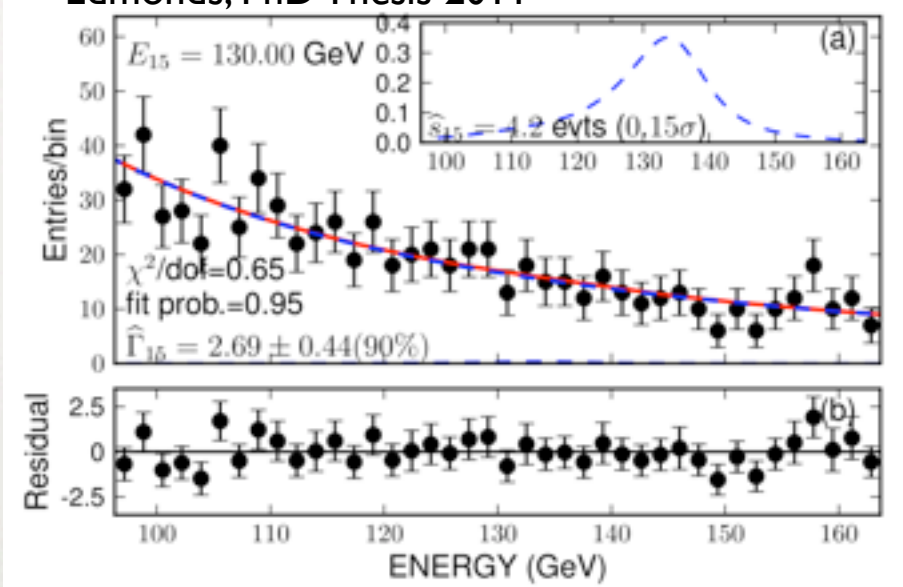


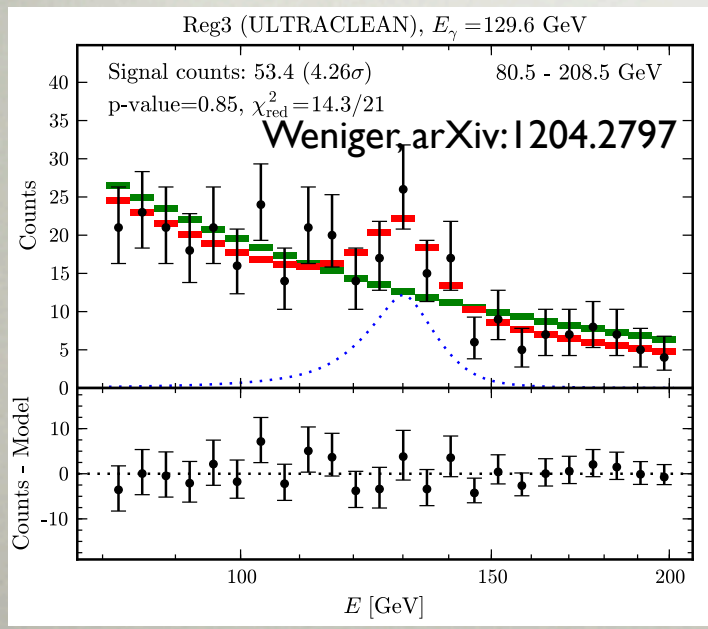


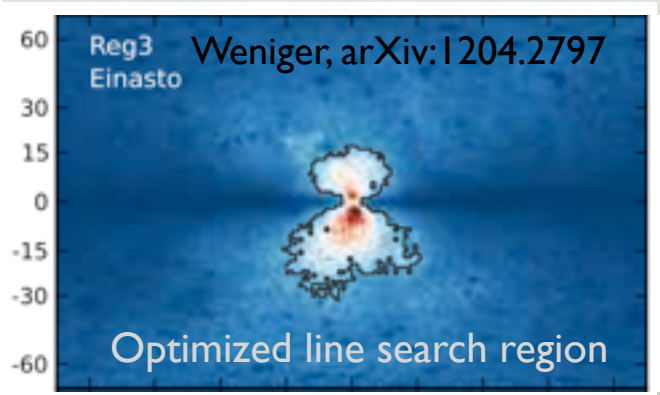
A Spectral Line from the Galactic Center Region?

- Recent papers on evidence for a line at 130 GeV (Bringmann et al, arXiv:1203.1312 (internal brem), Weniger, arXiv:1204.2797, Su et al, arXiv:1206.1616)
- LAT collaboration has published line search with upper limits using 2 years of data (N.B. Different studies have used different search regions)
  - developed control samples to evaluate instrumental effects (e.g. Earth limb)
- Comprehensive Fermi LAT team analysis on line searches based on 4 years of data (Pass 7) ongoing

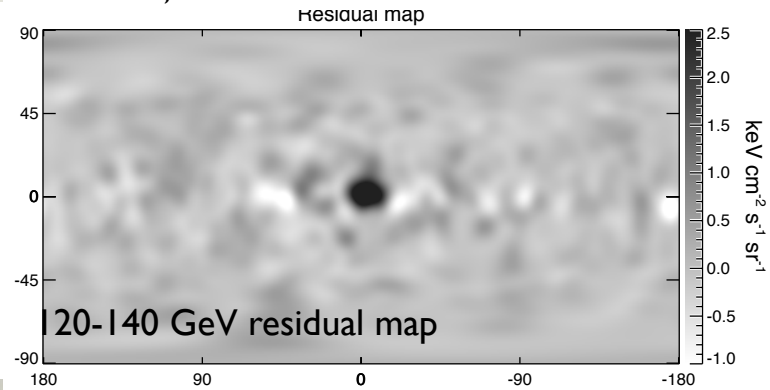
Edmonds, PhD Thesis 2011







Su et al, arXiv:1206.1616



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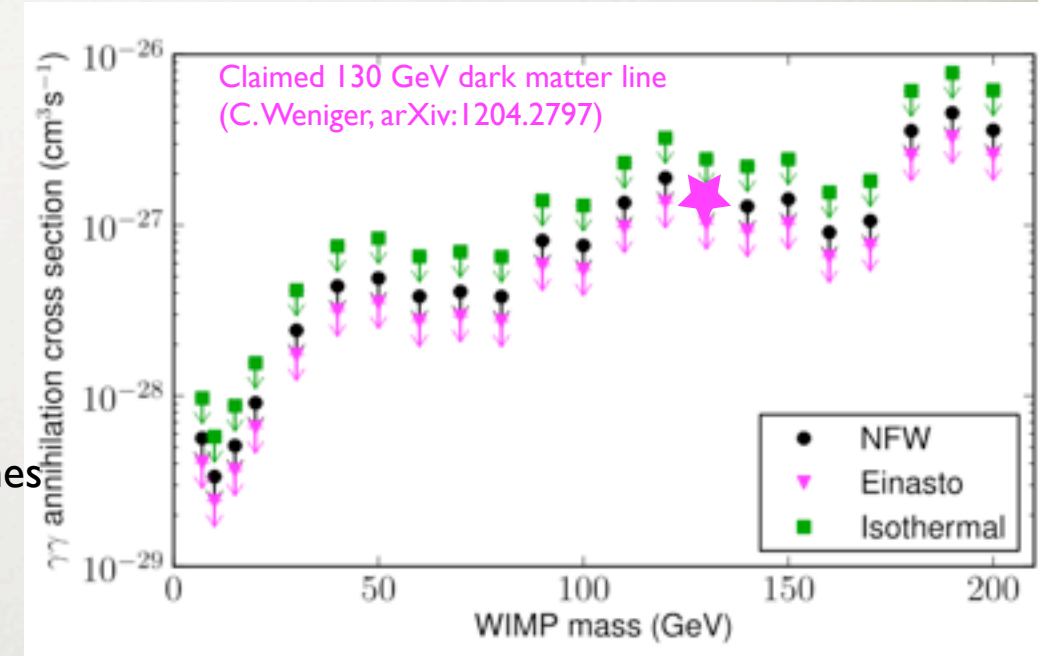
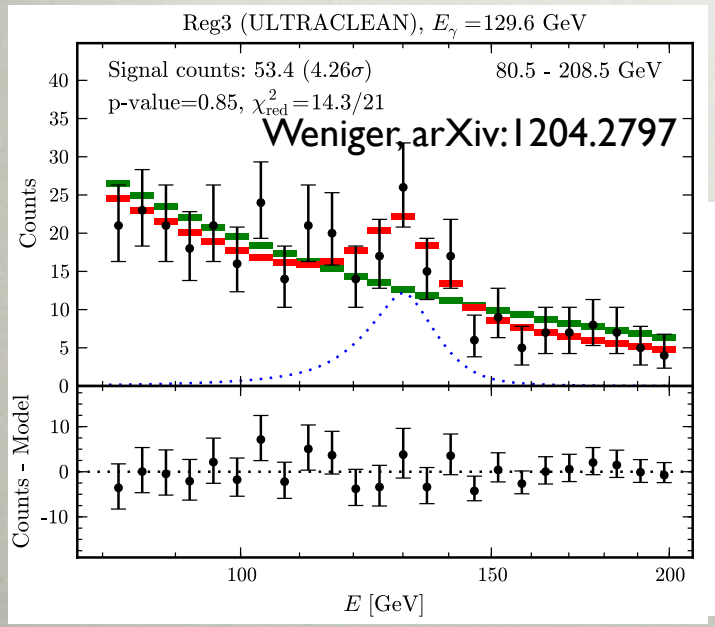
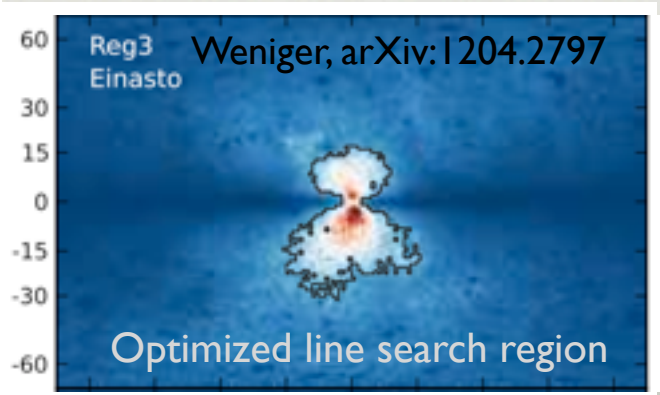
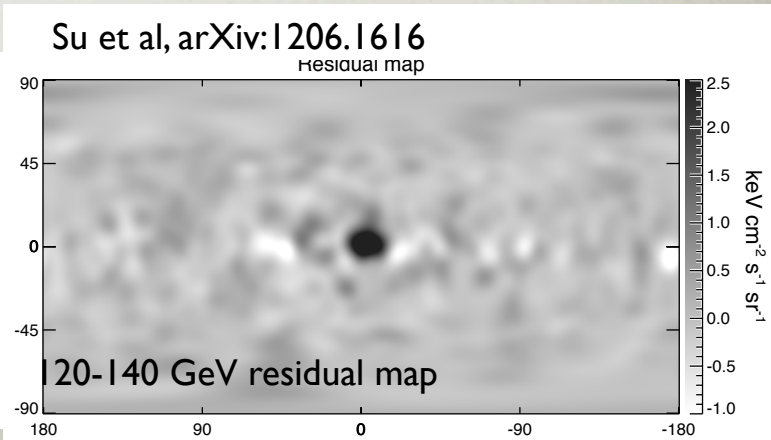




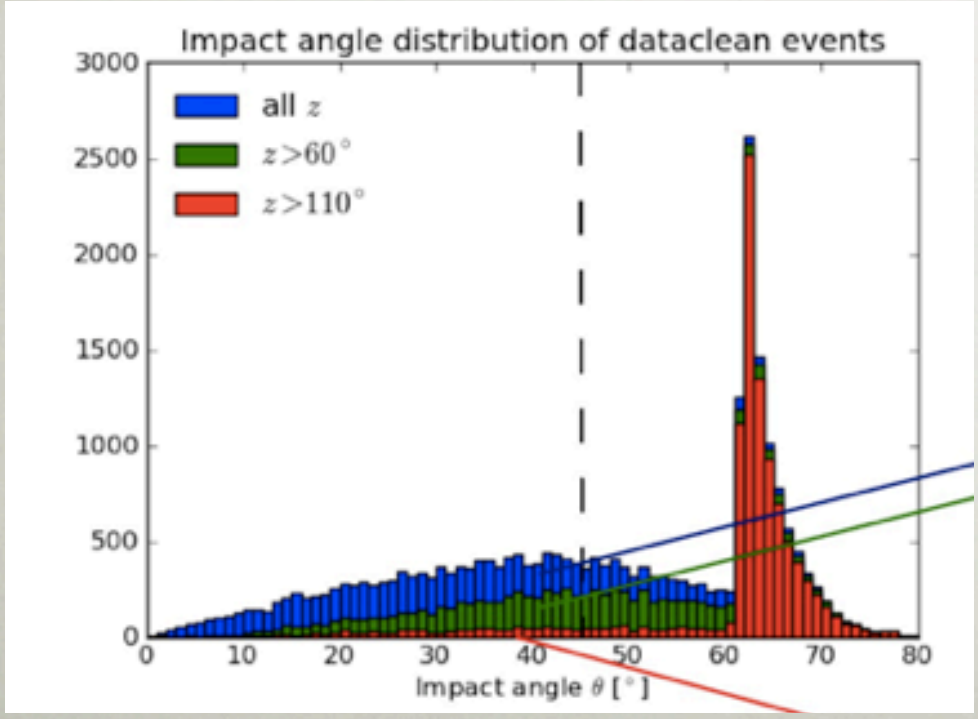


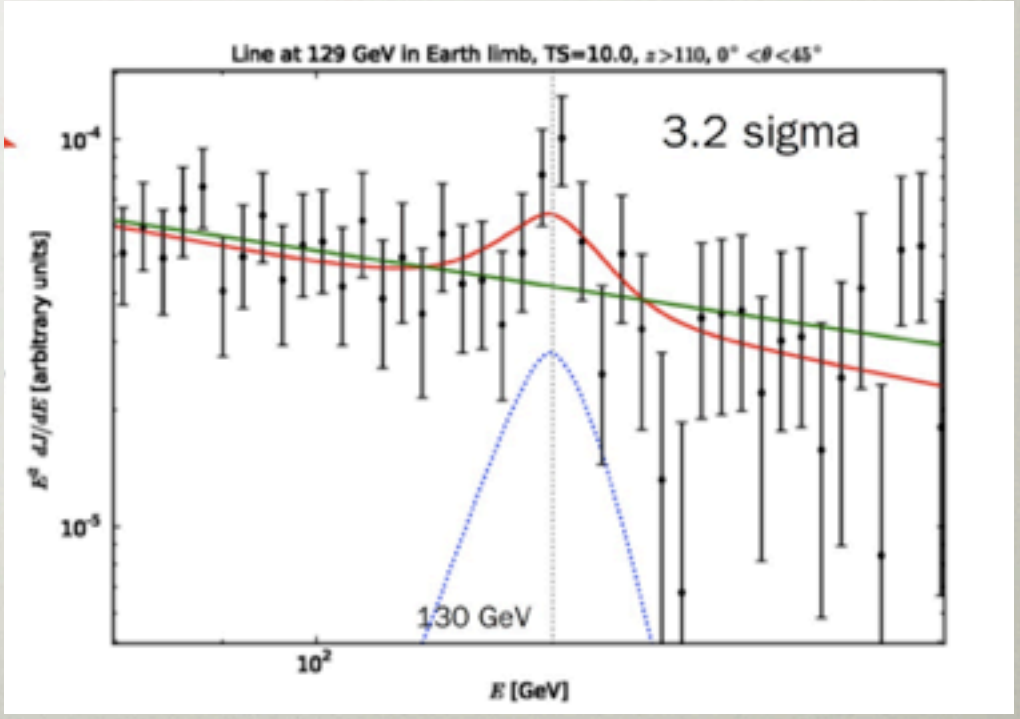


A spectral Line from the Galactic Center Region?

- Astrophysical interpretations have been proposed, e.g.:
  - "Spectral and spatial variations of the diffuse gamma-ray background in the vicinity of the Galactic plane and possible nature of the feature at 130 GeV" Boyarsky et al, arXiv:1205.4700
  - "Cold ultrarelativistic pulsar winds as potential sources of galactic gamma-ray lines above 100 GeV" Aharonian et al, arXiv1207.0458
- Possible line feature in Earth limb data (C. Weniger, talk at Gamma2012, similar analysis also in Su et al)

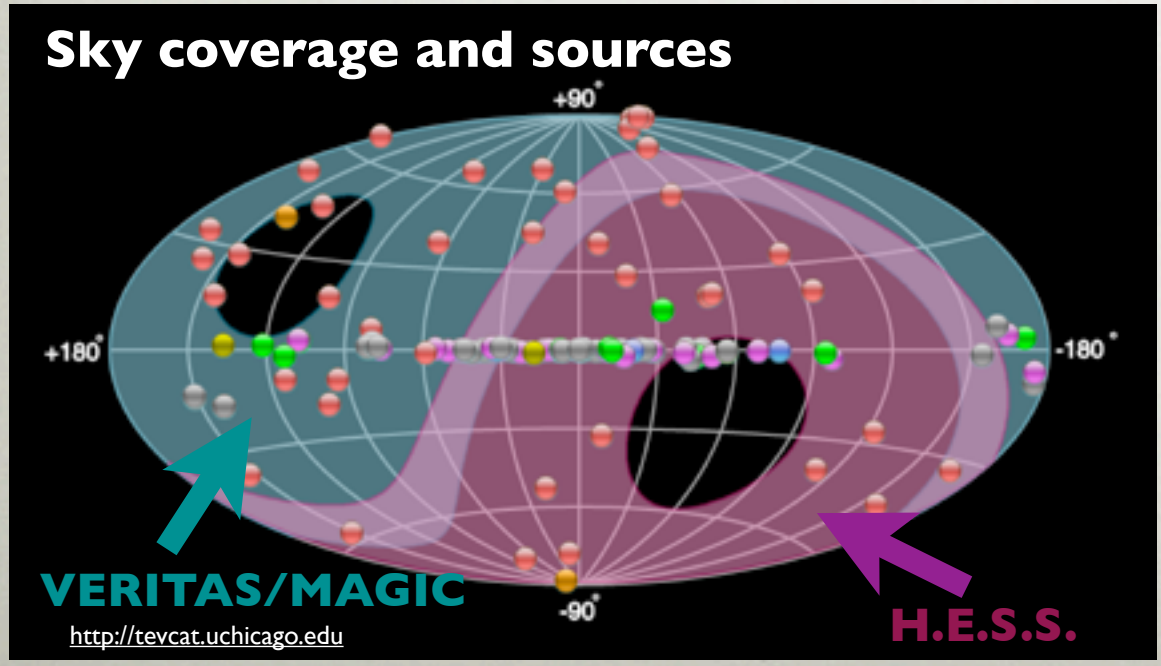
Plots from C. Weniger talk at Gamma2012

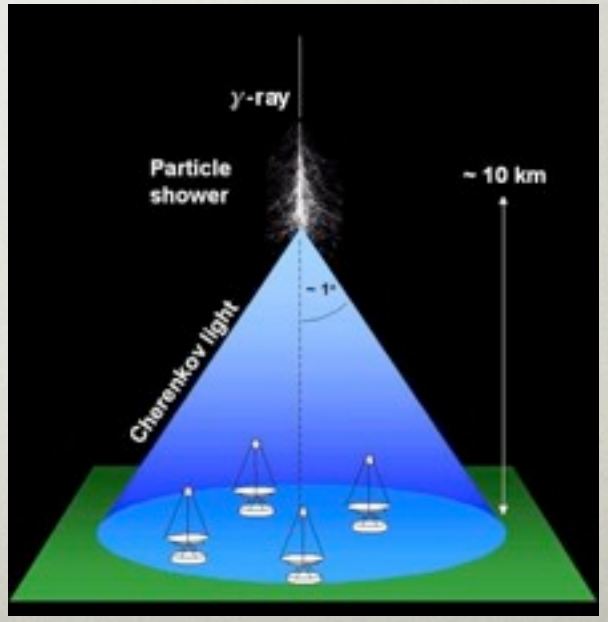




Very High Energy Gamma rays

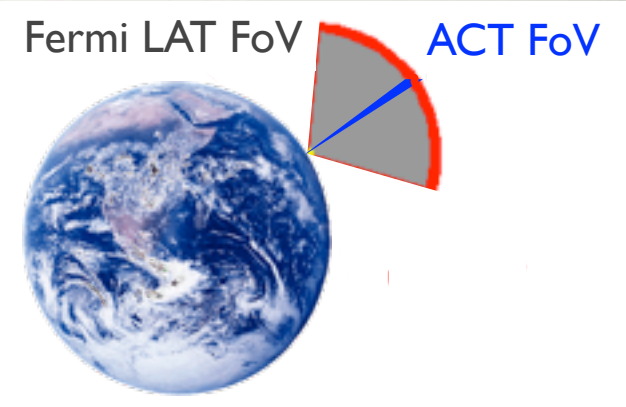
Imaging Atmospheric Cherenkov Telescopes (IACTs)

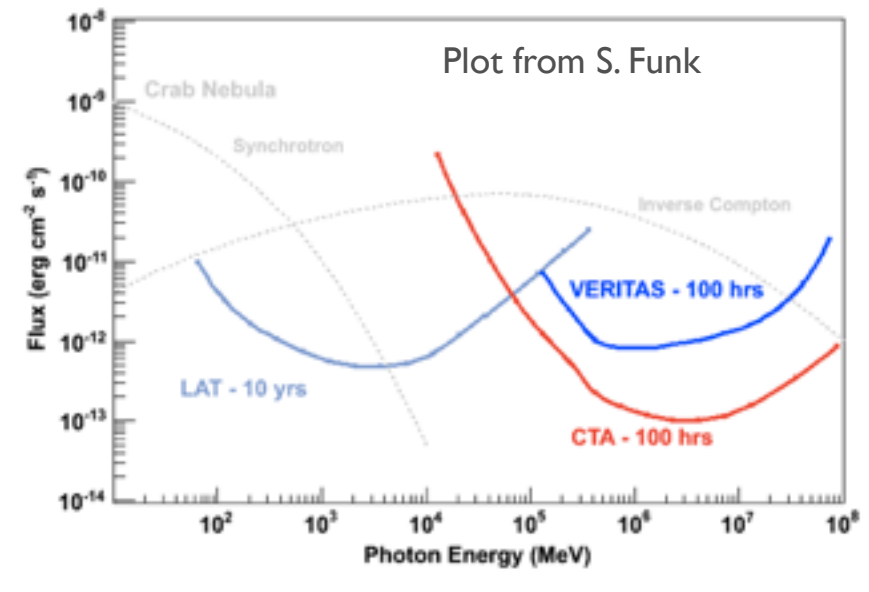


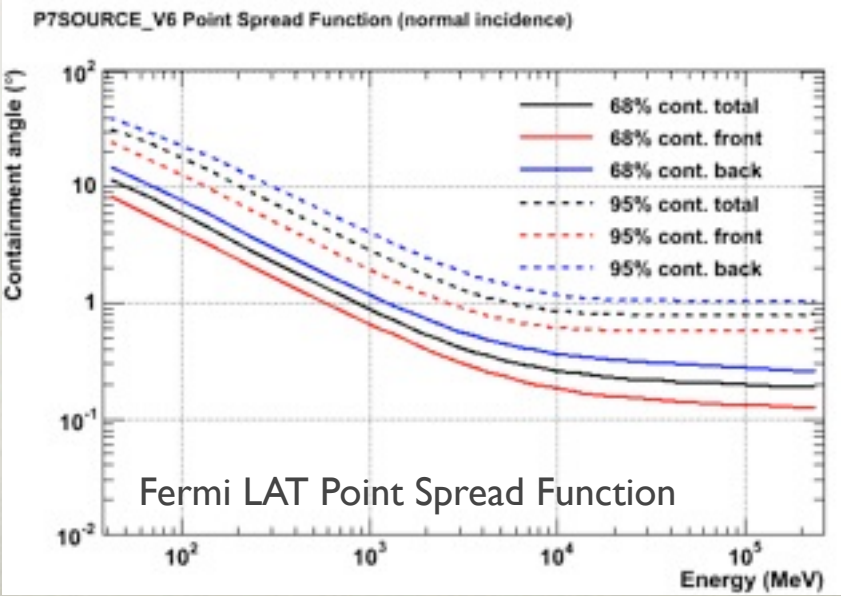


Ground vs Space Gamma-ray experiments

- Lower energy thresholds accessible in space, and up to ~100 TeV energies with experiments on the ground. Overlap in the ~100 GeV region
- Larger field of view, great duty cycle, and all sky coverage in space
- Single photon angular resolution: ~1° at 1 GeV (Fermi LAT), ~0.1° at 100 GeV (ACTs, Fermi LAT), ~0.05° at 1 TeV (ACTs)
- Energy resolution: ~ 8% at 10 GeV (Fermi LAT), ~15% at 1 TeV (ACTs)
- Large collecting area on the ground (high sensitivity)

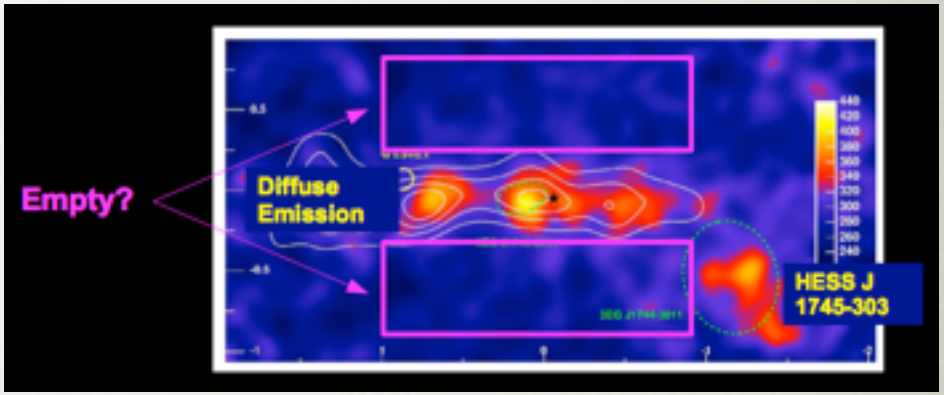


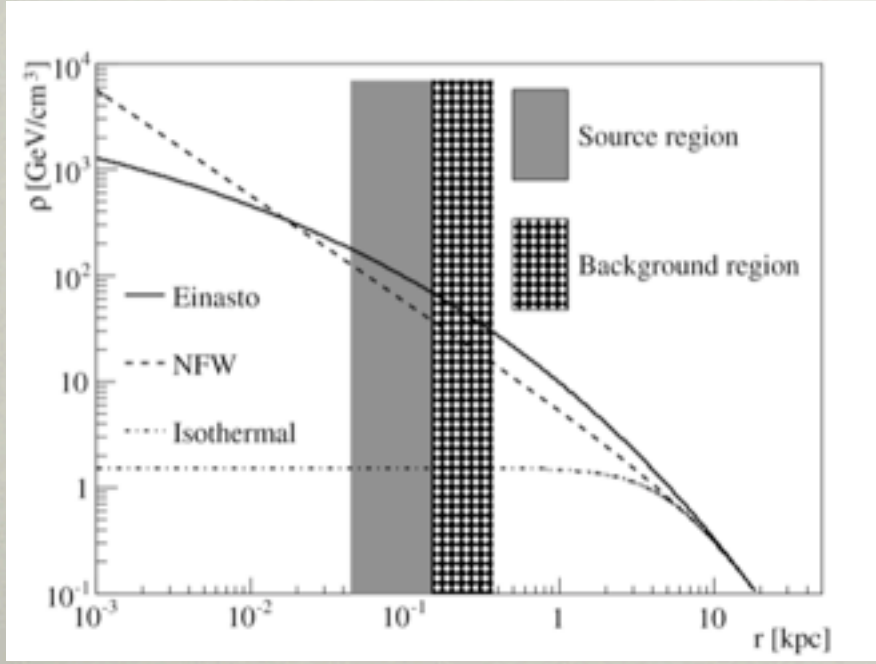




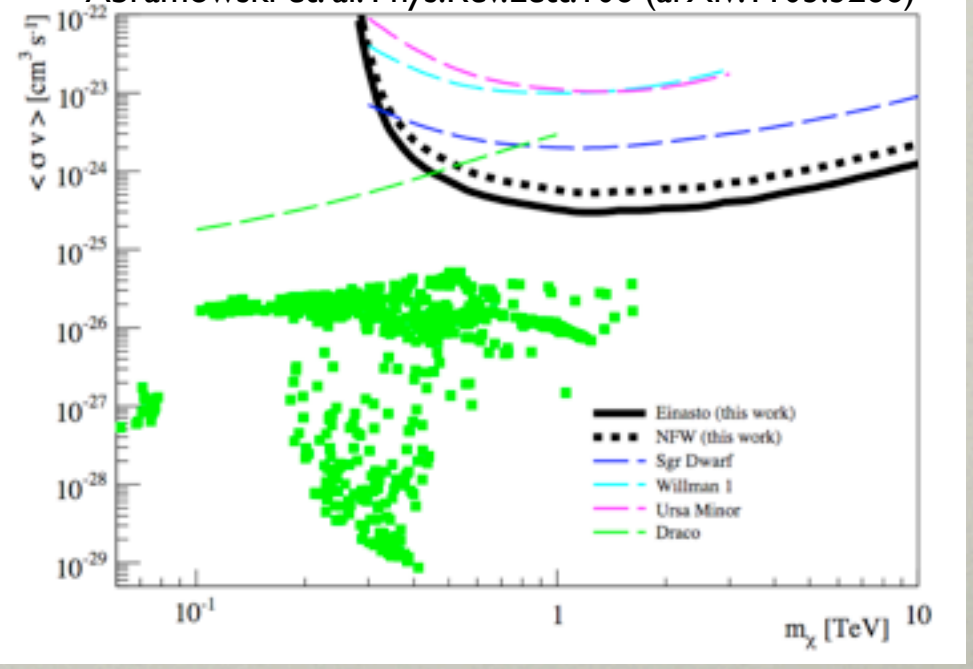
H.E.S.S.: Galactic Halo

- GC is complicated by astrophysics, look away from it!
- Signal region: relatively close to GC but "free" from astrophysical background
- Select a region where the contribution from DM is smaller for background subtraction (background region)
- Small dependence on DM profile

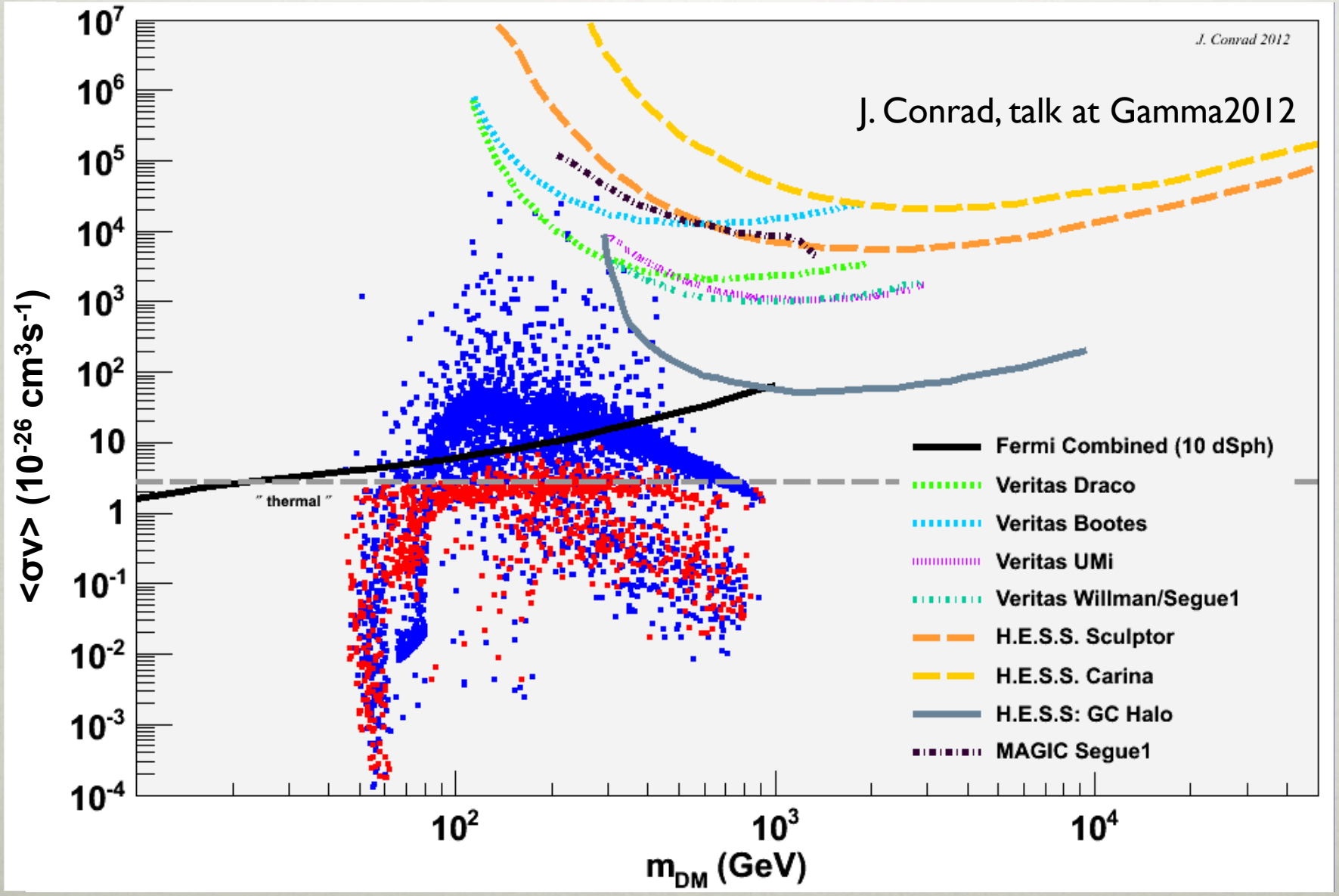




Abramowski et. al. Phys.Rev.Lett.106 (arXiv:1103.3266)



Indirect detection with γ rays: Current Best constraints

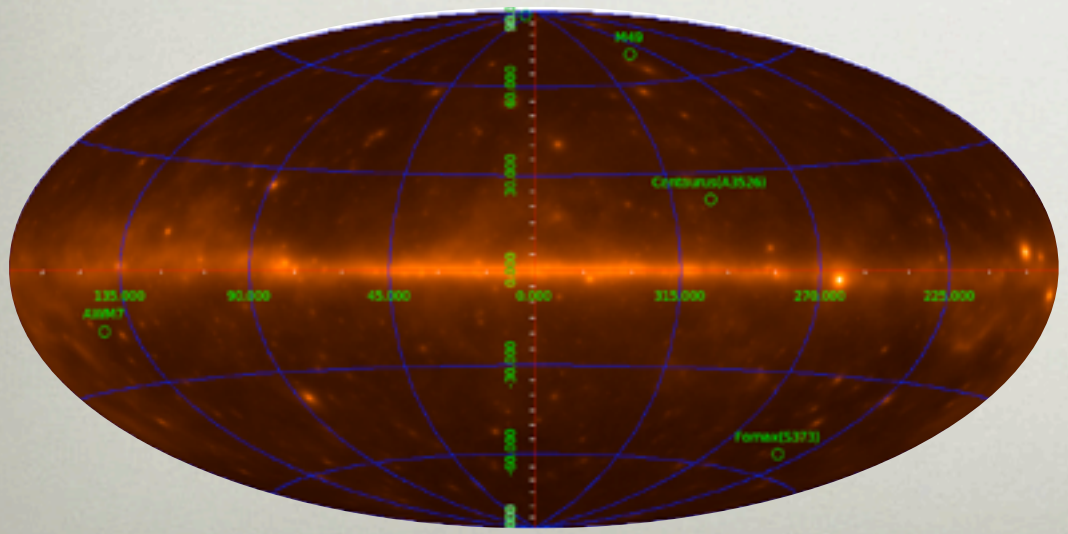


Search for DM in Galaxy Clusters

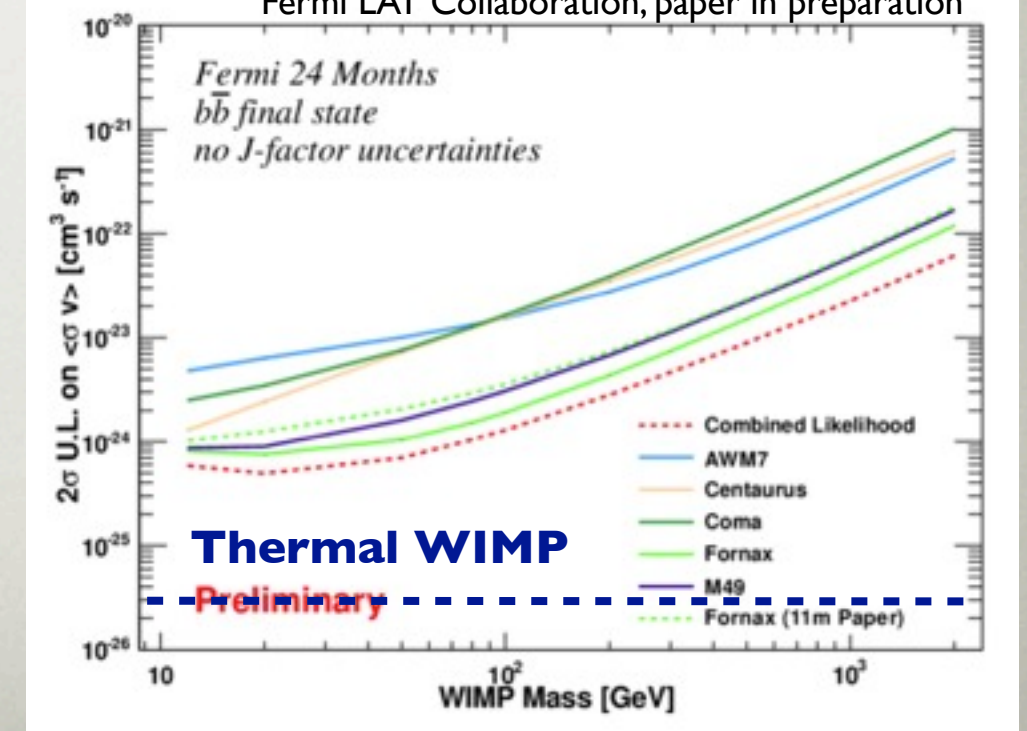
- Most massive structures observed in the Universe, very large dark matter content.
- Predicted to emit gamma rays from conventional astrophysical processes
- Search the Fermi sky for galaxy clusters (2 years of data, 200 MeV-100 GeV), modeled as point sources

➡ No detection of galaxy clusters

- Set constraints on annihilation cross section
- Claim of extended emission from the Virgo galaxy cluster from Han et al (arXiv:1201.1003). However foreground due to local extended structure (Loop I) complicates interpretation.

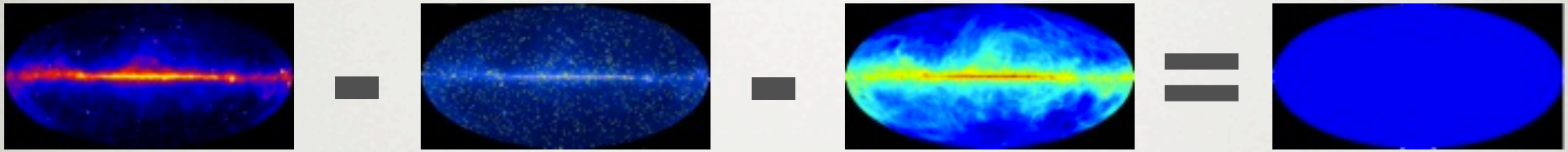


Fermi LAT Collaboration, paper in preparation



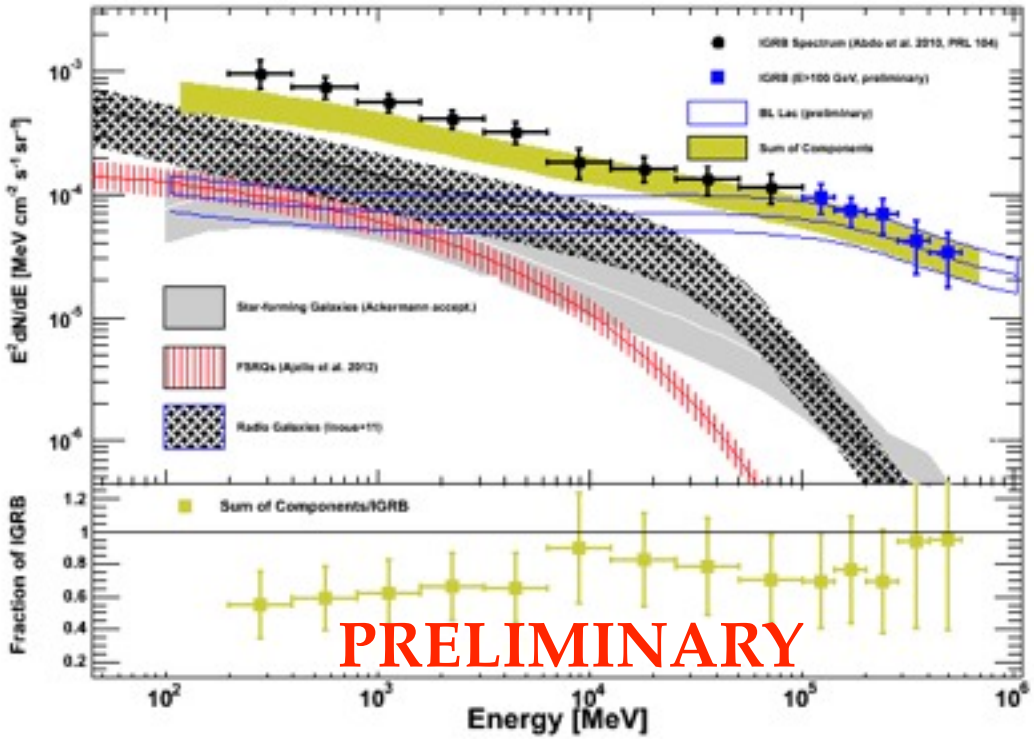
Extragalactic Gamma-ray Background

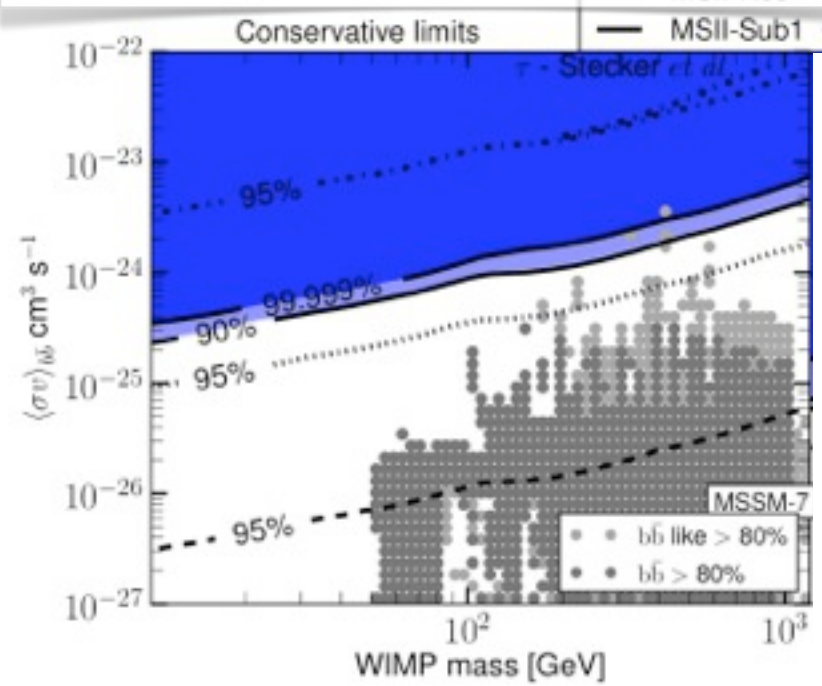
- Fermi LAT preliminary results for 24 months of data, 200 MeV-580 GeV, P7ULTRACLEAN data



data - point sources - Galactic diffuse =

DM constrains for annihilation into b quarks
Large uncertainties on DM distribution





Fermi LAT Collaboration, JCAP 04 (2010) 014

Summary/Outlook

- Very promising constraints on the nature of DM have been placed (e.g. dSph, lines)
- The astrophysical background is currently a limitation in particular for the Galactic center, which has huge potential in terms of discovery or setting constrains
- Looking forward:
  - Updated searches ongoing. Fermi LAT team paper on line searches, based on 4 years of data upcoming
  - Fermi continues to survey the sky (NASA Senior Review recommended extending operations through 2016, at least). Fermi gamma-ray data are public immediately!
  - Improvements in Fermi LAT event analysis will crucially improve the reach of some of the searches, e.g. improved PSF will somewhat mitigate source confusion in the GC region
  - Some analyses will also greatly benefit from multi-wavelength observations, e.g. dSph, GC
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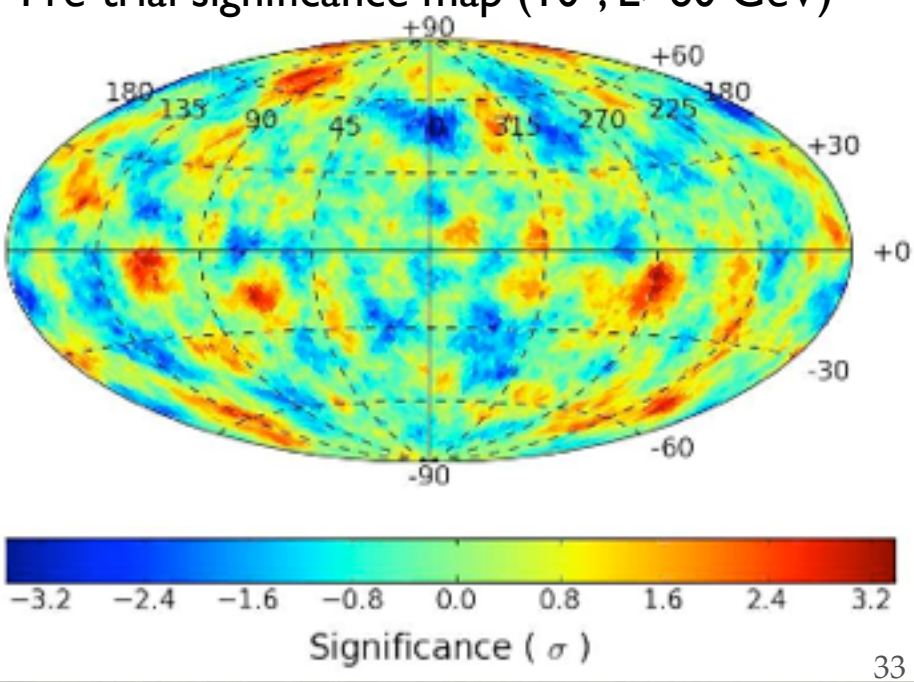
Thank you!

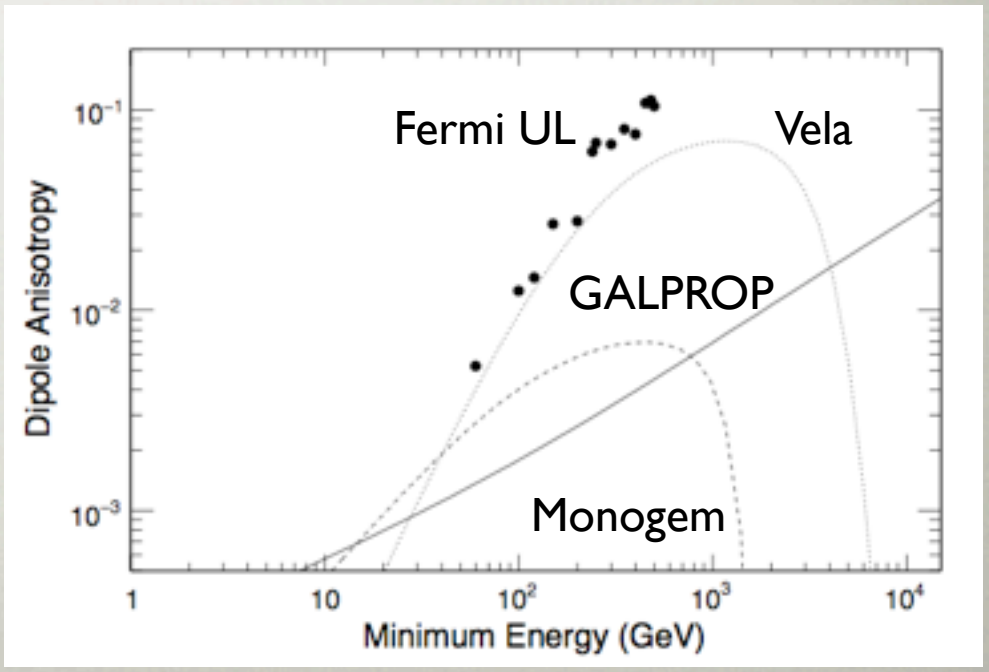
Anisotropies

- Fermi can test the nearby source hypothesis looking for anisotropies in the $e^+ + e^-$ sky
  - No significant anisotropies were found in Fermi electron data (angular scales from 10° to 90°)
  - However upper limits on dipole anisotropy cannot yet rule out individual pulsar/DM interpretation of PAMELA and Fermi e^+e^- data

Pre-trial significance map (10°, E>60 GeV)

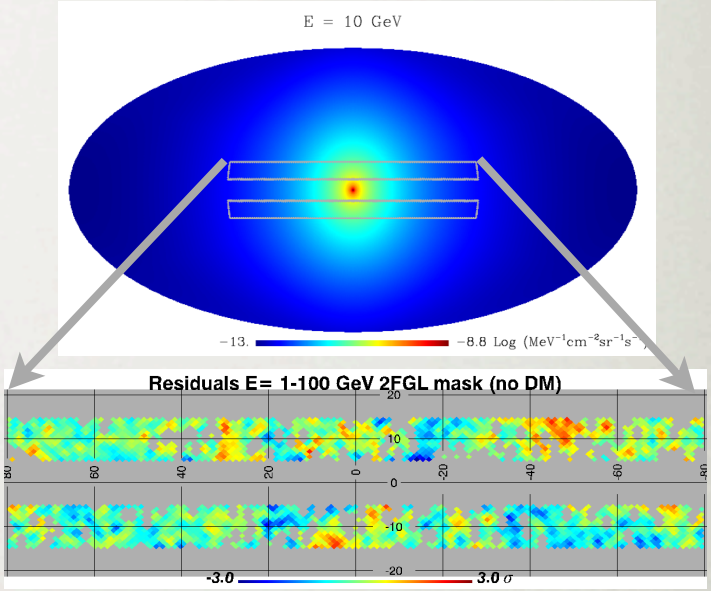


Fermi LAT Collaboration, Phys.Rev. D82 (2010) 092003

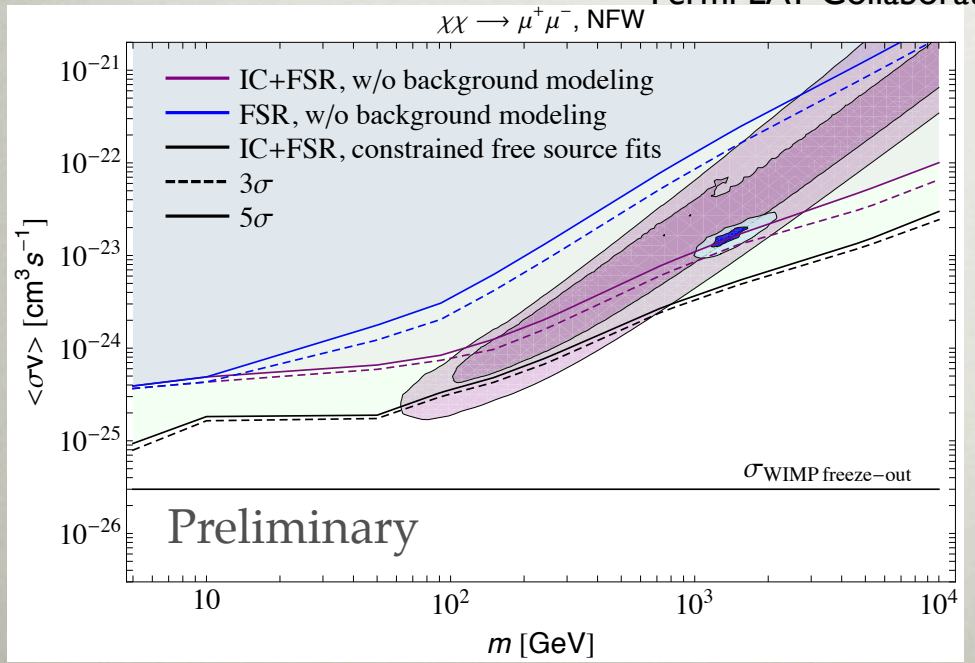


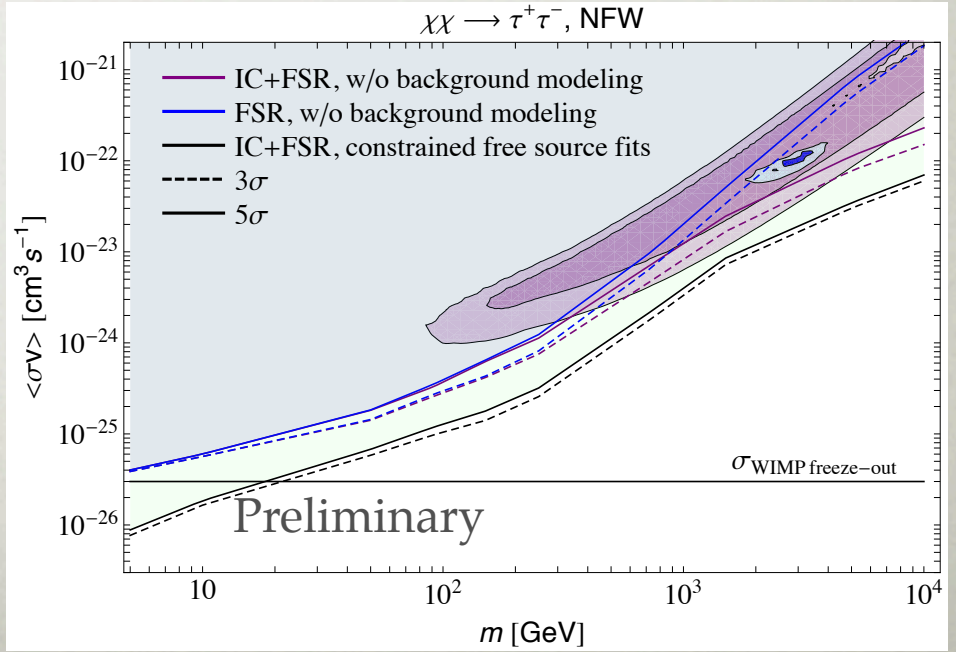
Galactic Halo

- Limit the analysis to regions of the galactic halo better described by the model.
- Robust limits can be determined by requiring that a DM contribution does not over-predict the data in these regions
- Data: 2 years, 1-100 GeV (w/ background modeling), 1-400 GeV (w/o background modeling)
- Constrains DM interpretation of Fermi/PAMELA electron and positron measurements. Significant improvements forseen as modeling of the diffuse background improves



Fermi LAT Collaboration, arXiv:1205.6474





Dwarf Spheroidal Galaxies

- Bootes I, Carina, Coma Berenices, Draco, Fornax, Sculptor, Segue I, Sextans, Ursa Major II, Ursa Minor
  - ➡ No detection of dSph by Fermi with 2 years of data
- Determine 95% flux upper limits for several possible annihilation final states
- Combine with the DM density inferred from the stellar data (assume NFW profile) to set constraints on the annihilation cross section
- Constraints include systematic uncertainties on the DM content!

$$L(D|\mathbf{pw},\{\mathbf{p}\}_i) = \prod_i L_i^{\mathrm{LAT}}(D|\mathbf{pw},\mathbf{p}_i)$$

$$\times \frac{1}{\ln(10)\, J_i \sqrt{2\pi}\sigma_i} e^{-\left(\log_{10}(J_i) - \overline{\log_{10}(J_i)}\right)^2 / 2\sigma_i^2}$$