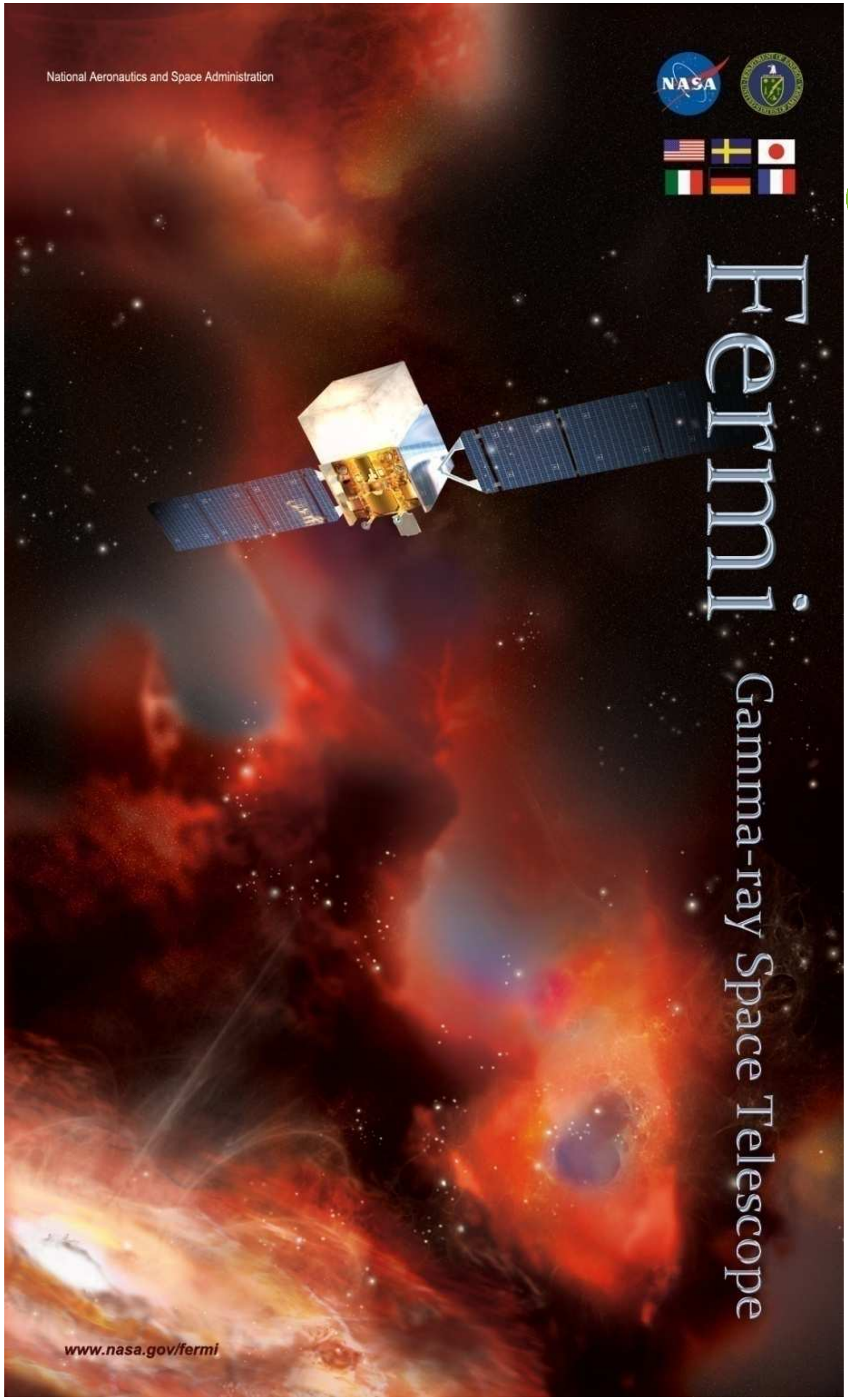

Indirect Searches for Dark Matter with the Fermi Large Area Telescope

Andrea Albert
(The Ohio State University)
on behalf of
The Fermi LAT Collaboration

HEP Seminar
University of Virginia
12/05/12

Outline

- **Dark Matter Overview**
- **The Fermi Large Area Telescope**
- **The Gamma-ray Sky**
- **Recent Dark Matter Results**
  - **Focus on spectral line search**

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- **Dark Matter Overview**
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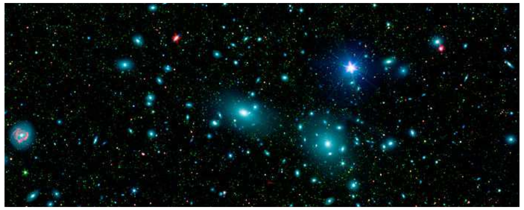
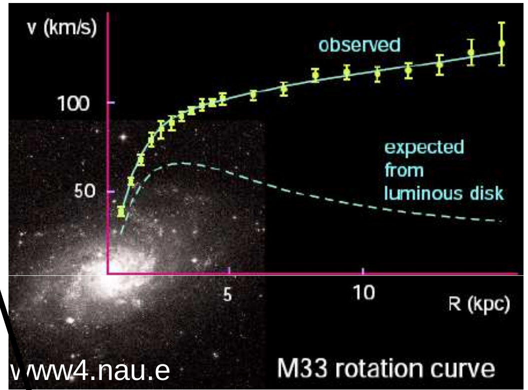
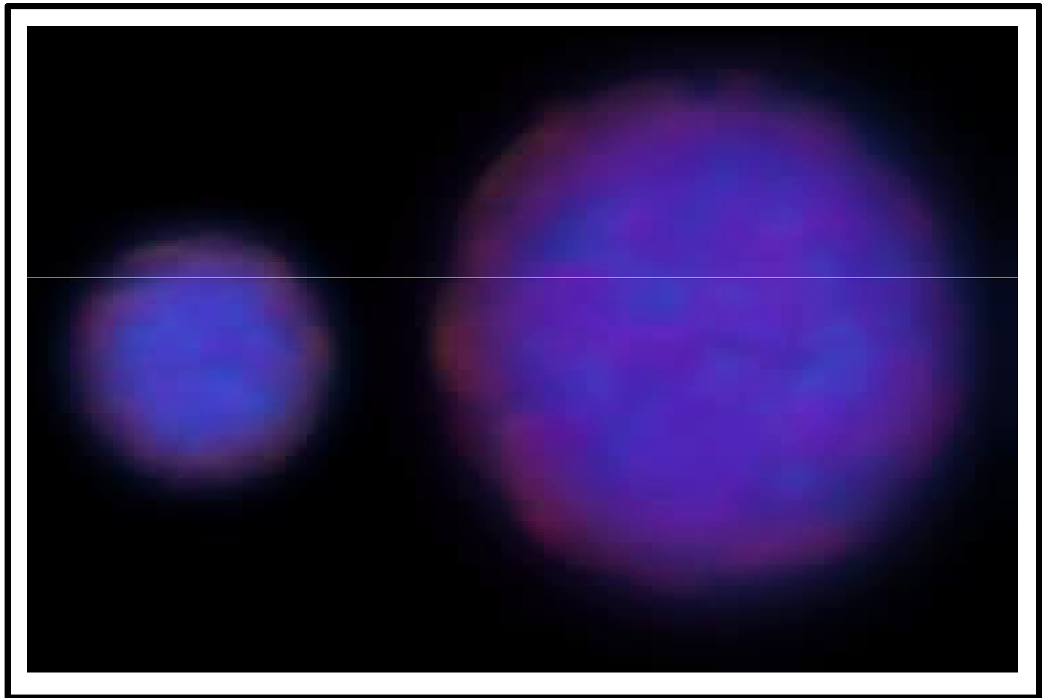
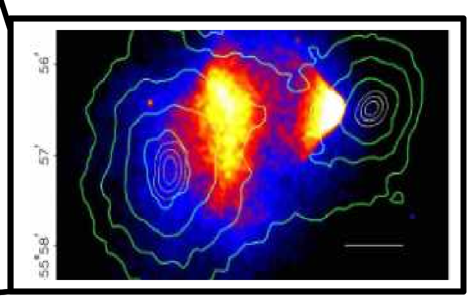
Astrophysical Evidence for Dark Matter

- **Majority of mass in galaxies is *dark***
  - **Coma Cluster + Virial Theorem**
    F. Zwicky (1937)

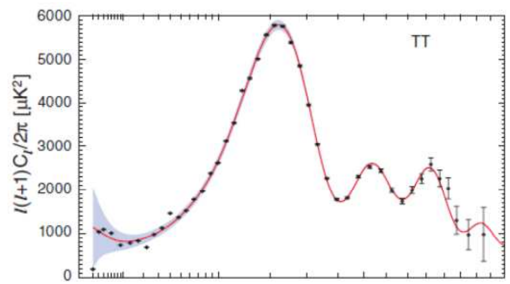








- **Dark Matter is *non-baryonic***
  - **CMB Acoustic Oscillations**
    WMAP (2010)



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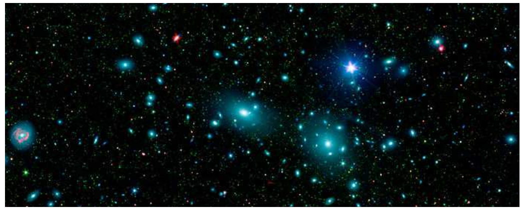
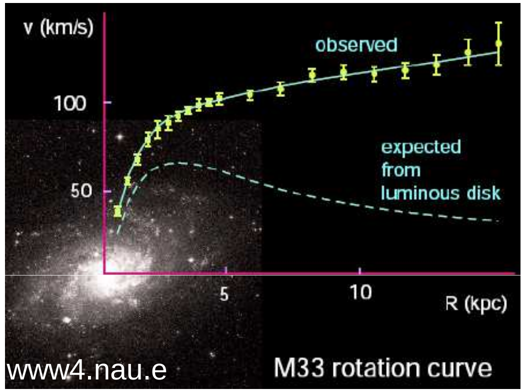
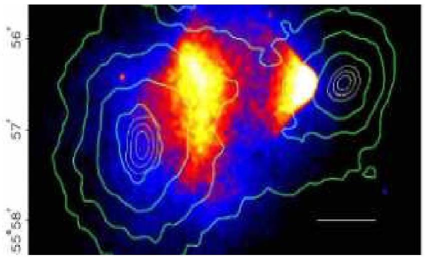


- **Dark Matter clumps in large *halos* around galaxies**
  - **Galactic Rotation Curves**
    V. Rubin et al (1980)



- **Dark Matter is virtually *collisionless***
  - **The Bullet Cluster**
    D. Clowe et al (2006)



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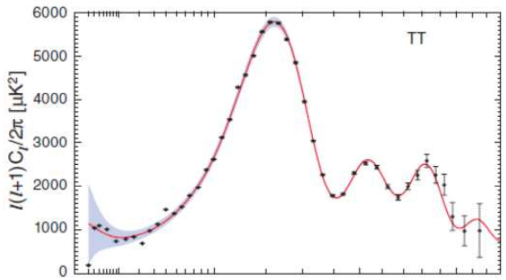
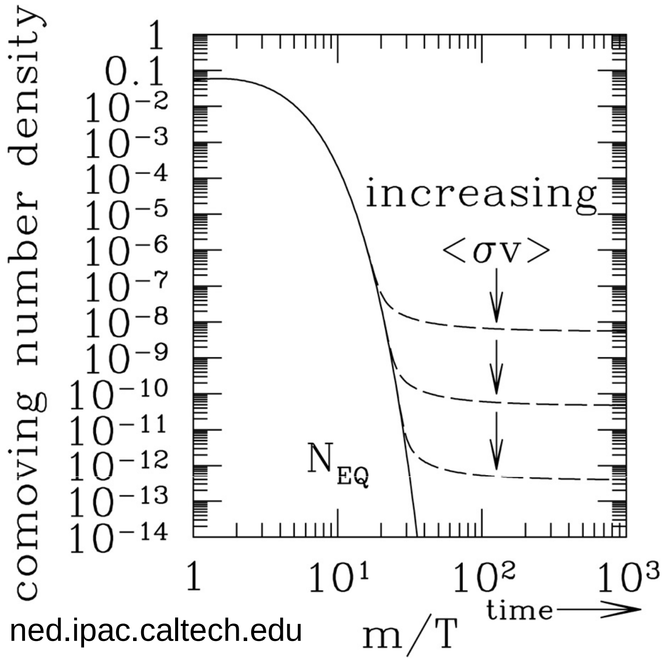


WIMPs detectable by Fermi LAT

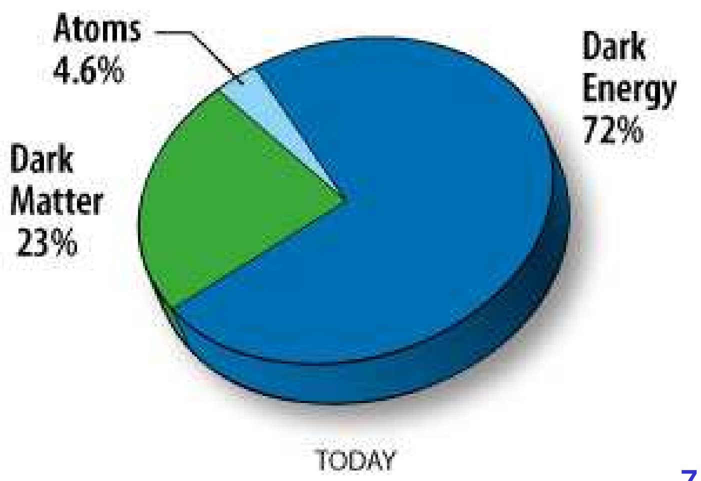
- Weakly Interacting Massive Particle (WIMP)
- GeV-TeV mass scale
- *Assume*: Can annihilate or decay into SM particles
- *Assume*: Accounts for measured DM density
- Ex) Neutralino
  - Predicted by many SUSY models
    - LHC experiments starting to put strong constraints on SUSY
  - Electrically neutral
  - LSP → stable particles
  - GeV-TeV mass

WIMPs as a Thermal Relic

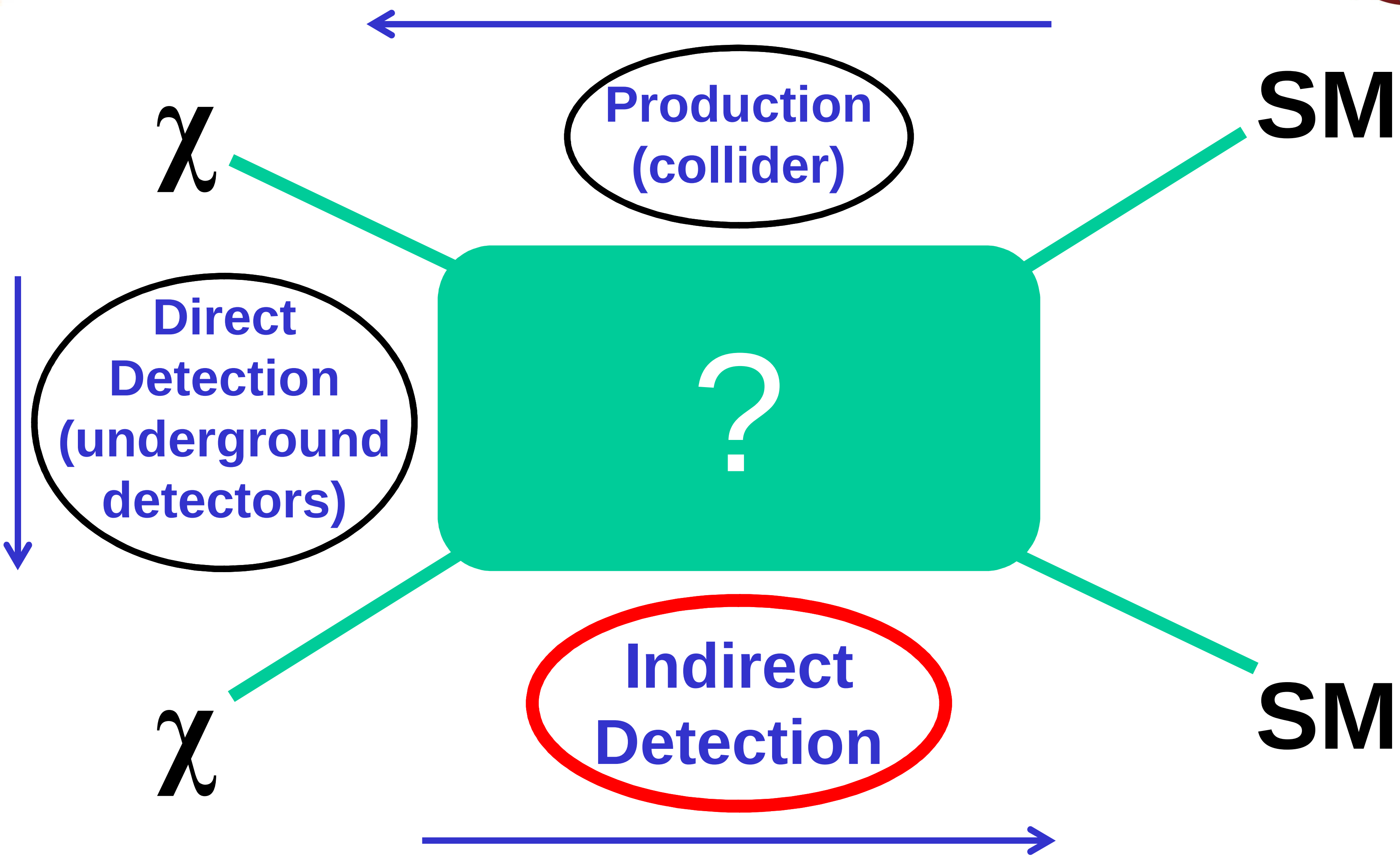
- **If WIMP was a thermal relic, then it was in creation/annihilation equilibrium in early universe**
- **Once universe cools enough, amount of dark matter freezes out**
  - **No longer created, and expansion causes annihilation rate to drop to ~0**
- **Assume *weak scale* $\sigma_{ann} \rightarrow$ observed abundance (~23%)**
  - **$<\sigma v>_{ann}$ ~ 3e-26 cm^3/s (σ_{ann} ~ 3 pb)**
  - **v_{CDM} ~ 0.3c**
    - **Virial theorem -> to form stable halos around galaxies, DM particle should be non-relativistic (cold dark matter)**



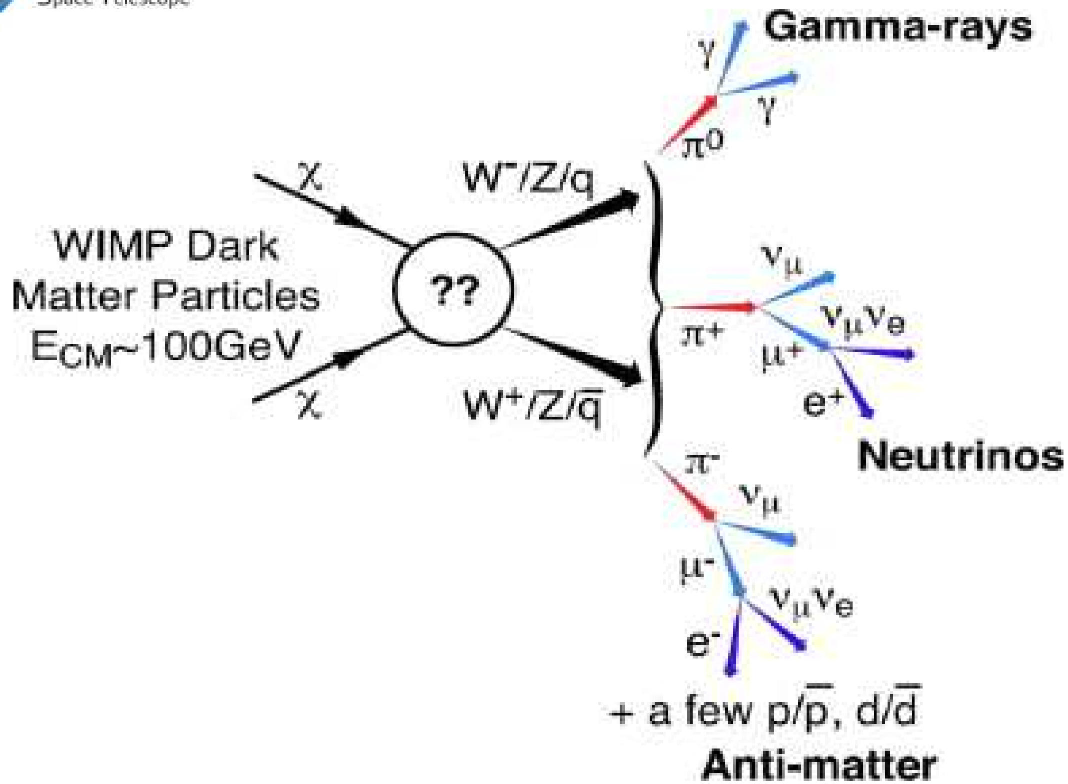
ned.ipac.caltech.edu

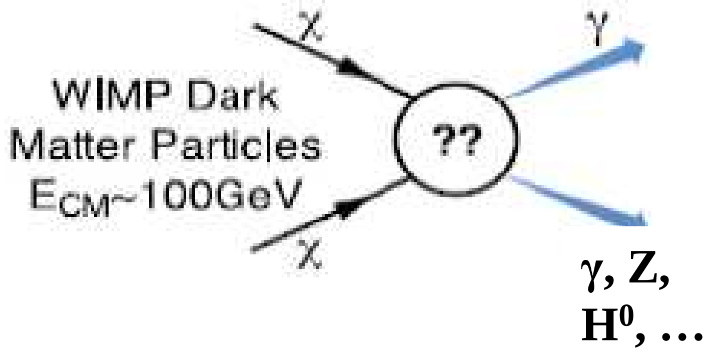


How to Detect WIMPs



WIMP Signatures (1)





- **WIMP annihilation or decay can produce a variety of detectable SM particles**

- **Goal is to detect these particles and disentangle intrinsic WIMP properties**

WIMP Signatures (2)

What we observe

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

DM Flux (events/cm^2/s)

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

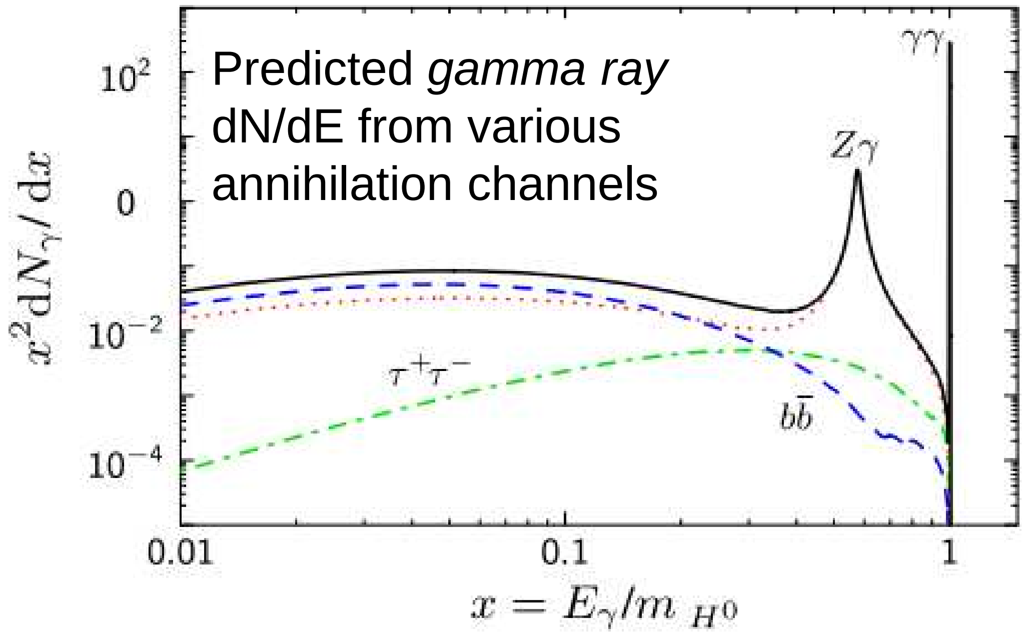
WIMP Signatures (2)

Intrinsic Particle Properties

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

Annihilation Cross Section * velocity (v ~ 0.3c)
$\langle\sigma v\rangle_{ann}$ ~ 3e-26 cm^3/s (σ_{ann} ~ 3 pb)

Note: large fraction of predicted gamma's have $E_\gamma < m_{DM}$



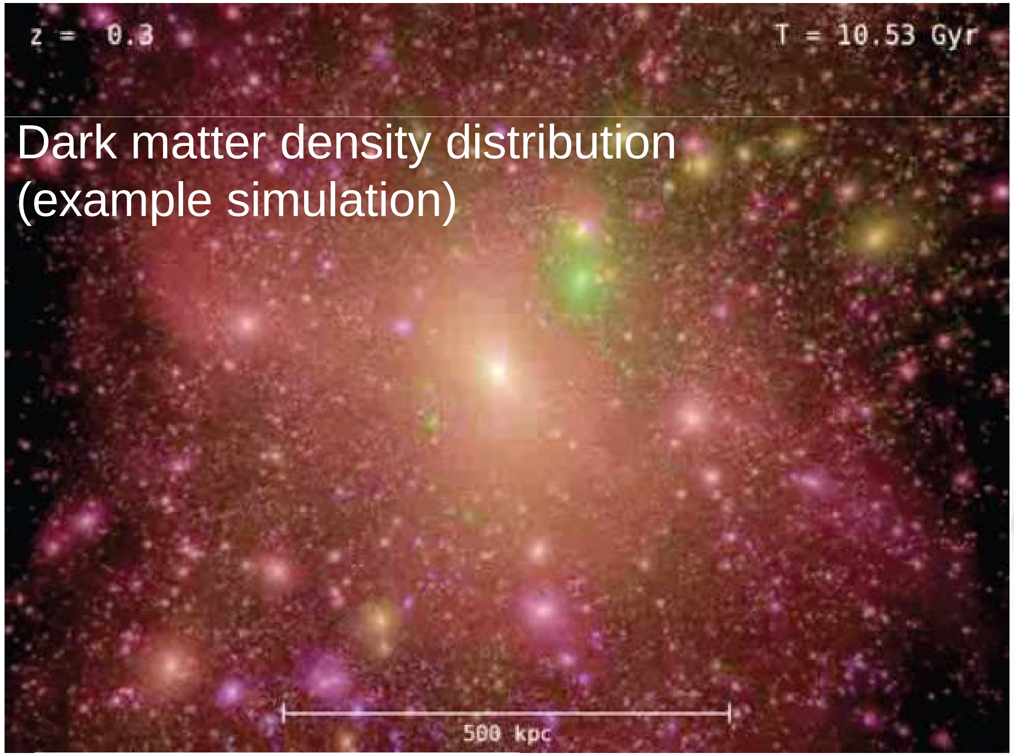
Gustafsson et al. PRL 99.041301

WIMP Signatures (2)

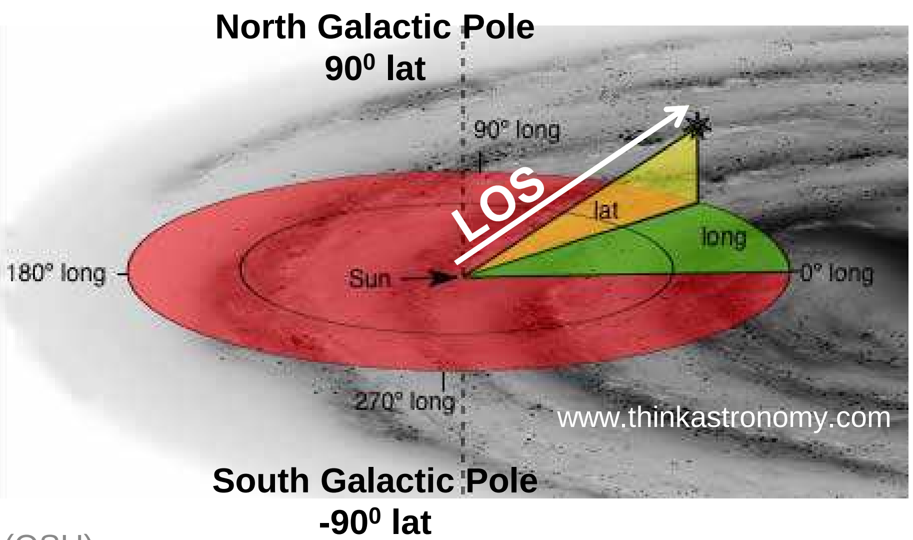
Astrophysics

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

J-factor – Line of sight integral over a ROI



Credit: Springel et al. (Virgo Consortium)



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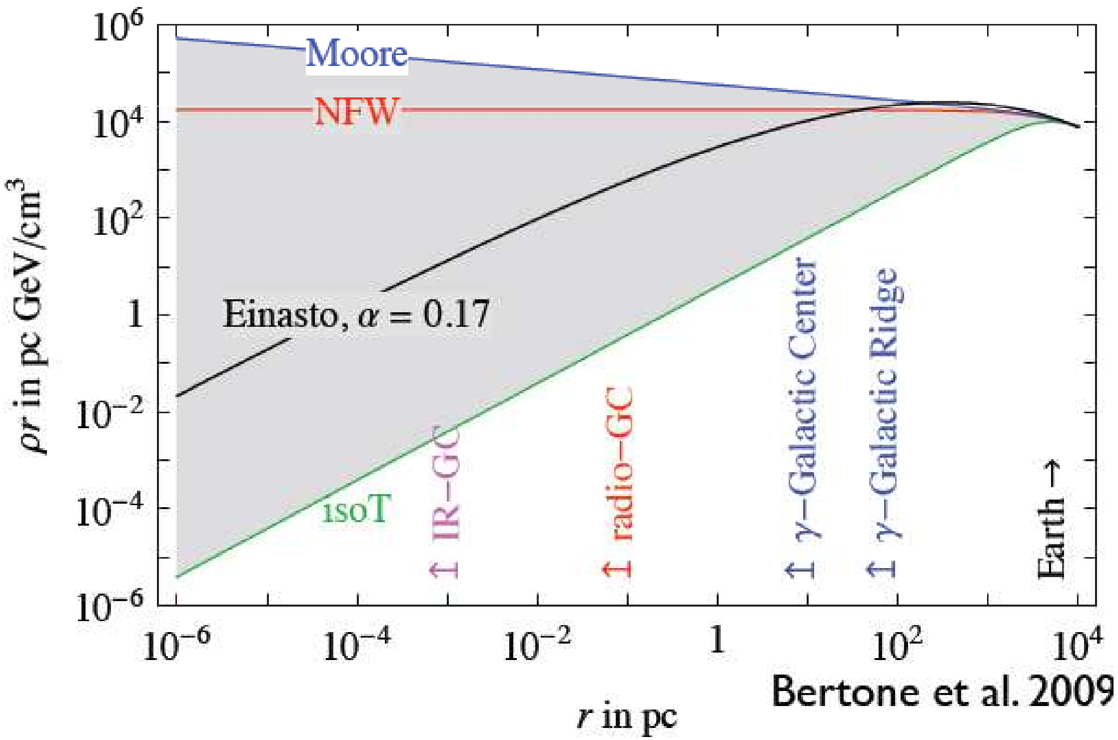
"J-factor" – Line of sight integral over a ROI



Bertone et al. 2009

Various models for the smooth DM density as a function of distance from galactic center (r) Derived from fits to N-body simulations

Outline

- Dark Matter Overview
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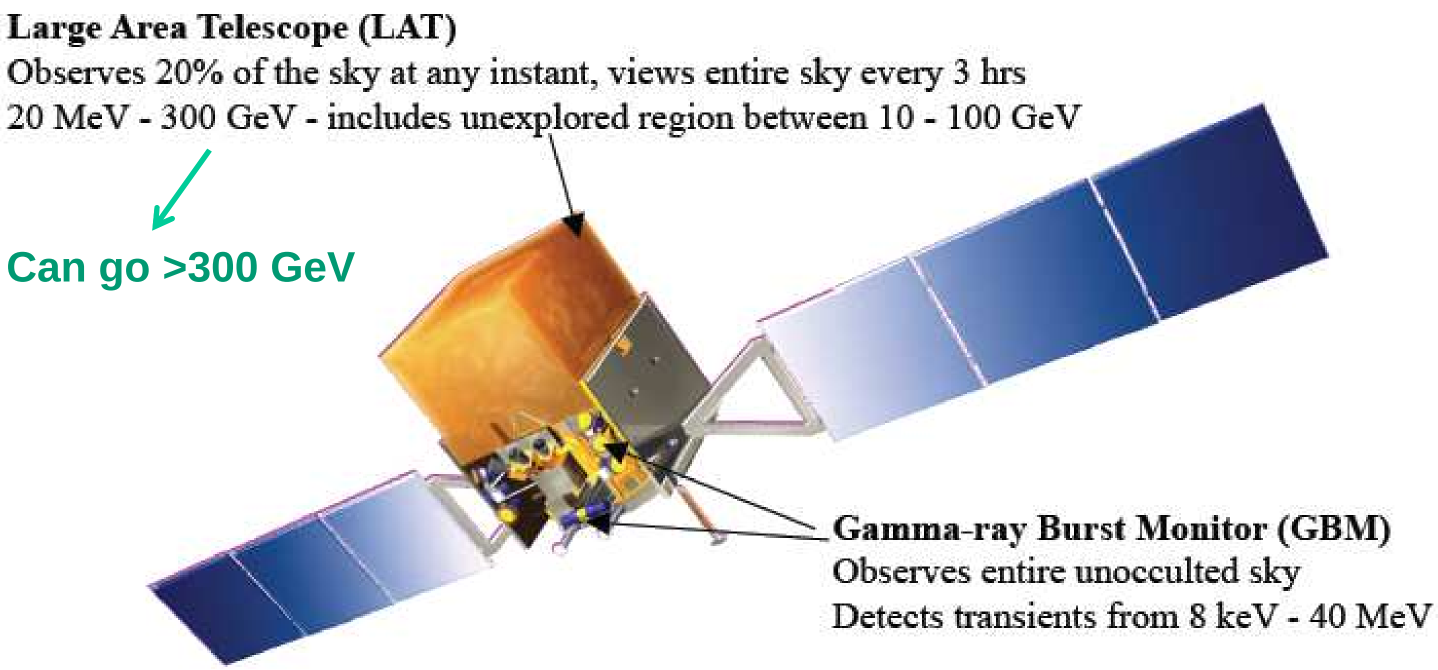
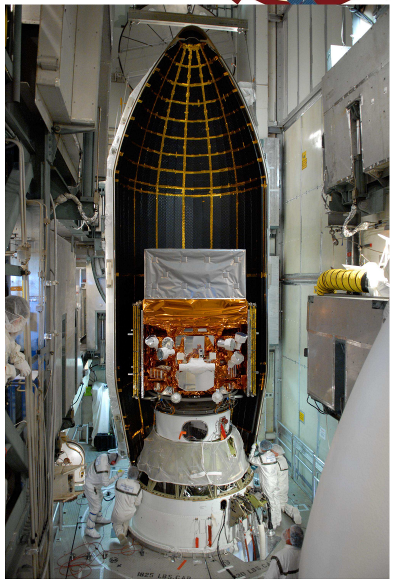
Fermi Large Area Telescope (LAT)

- **On board the Fermi Gamma-ray Space Telescope**
  - **Launched June 11, 2008**
    - **Started taking data Aug 2008**
  - **5 year mission**
    - **Mission extended at least through 2016**





Gamma Ray Pair Conversion

Energy loss mechanisms

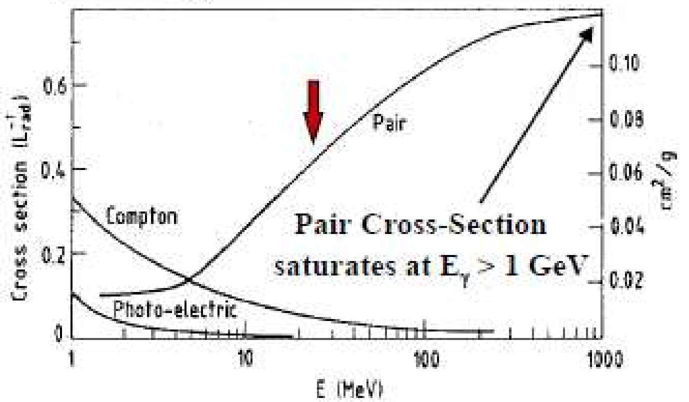
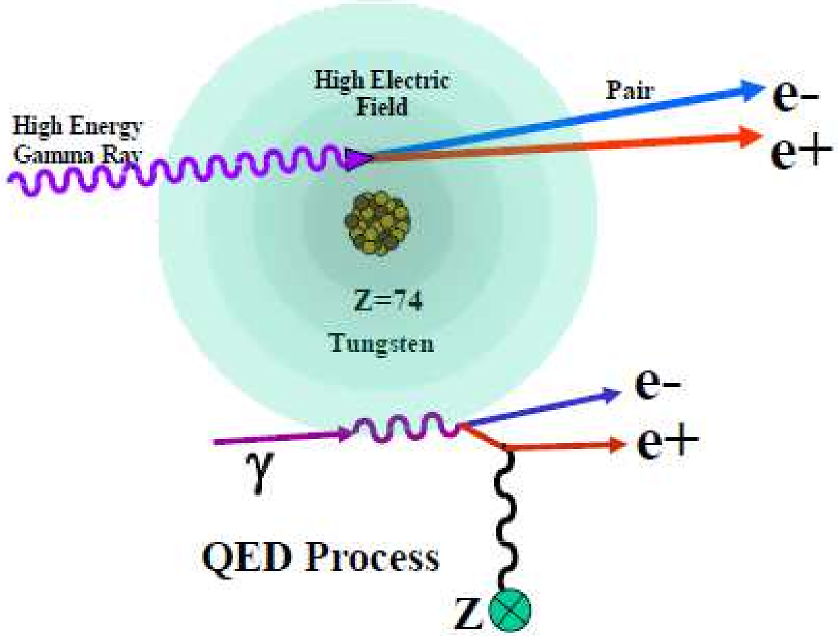


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

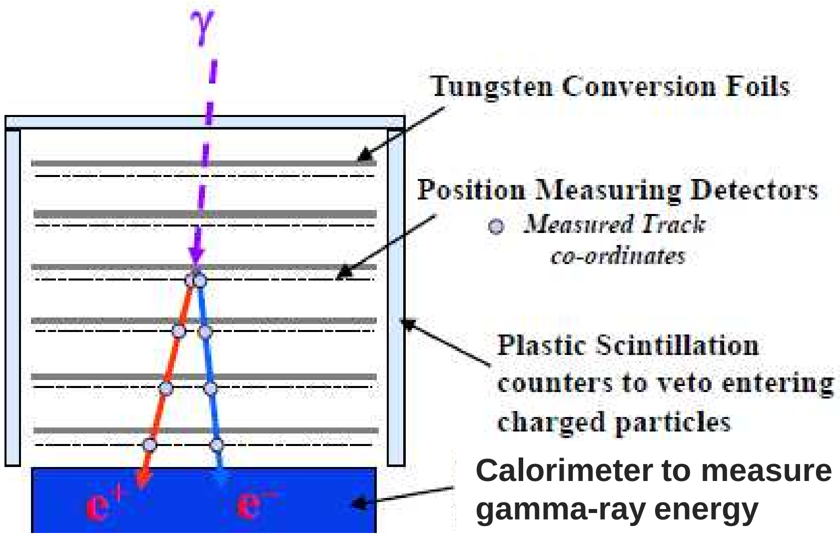


Opening Angle

$$\theta_{Open} \approx \frac{4m_e}{E_\gamma}$$

At 100 MeV

$\theta_{Open} \sim 1^o$

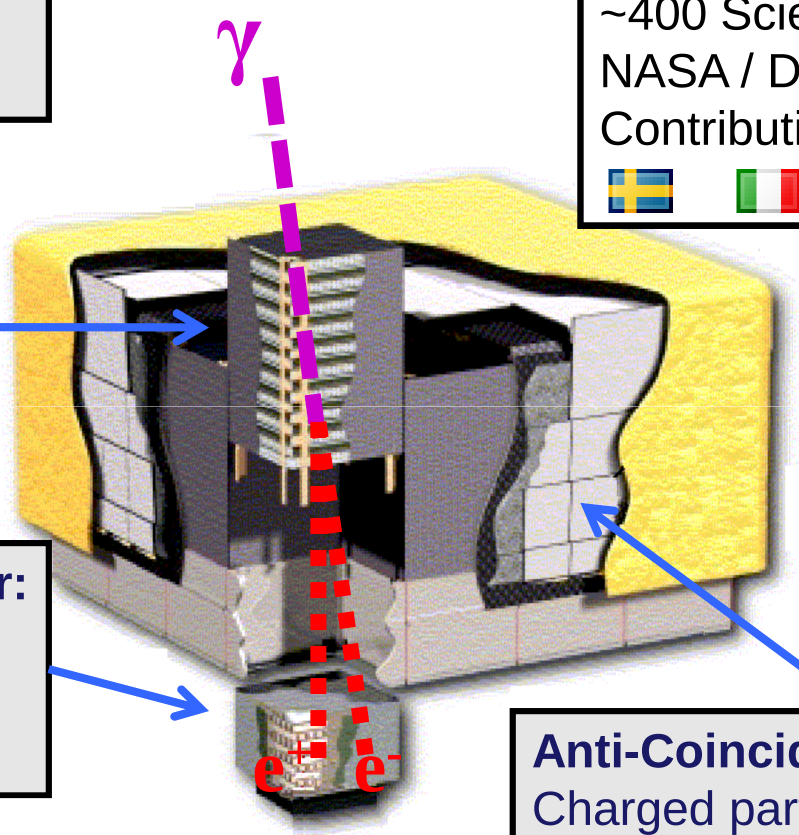


Fermi LAT

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 $\gamma \to e^+e^-$
reconstruct γ direction
EM v. hadron separation

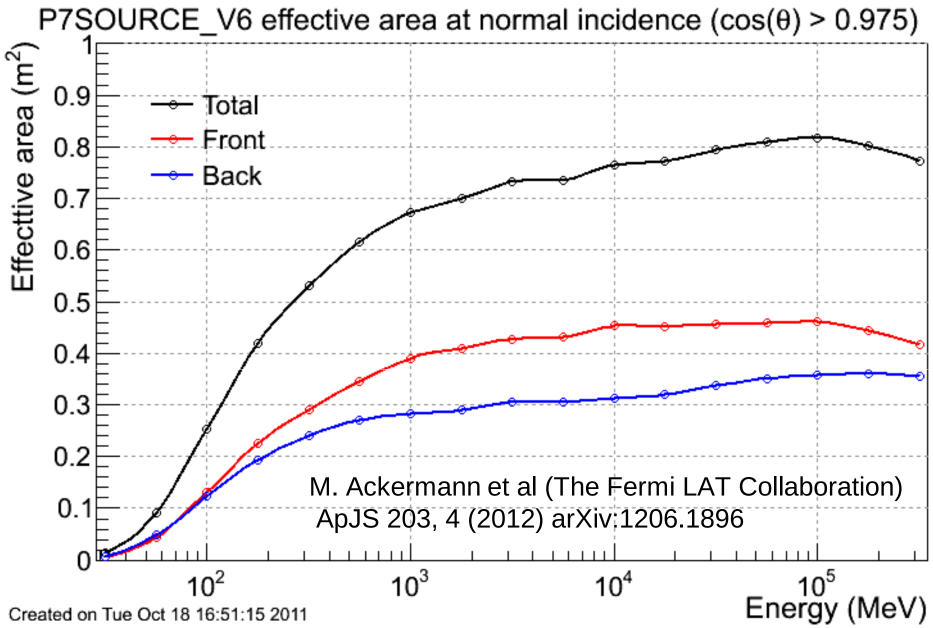


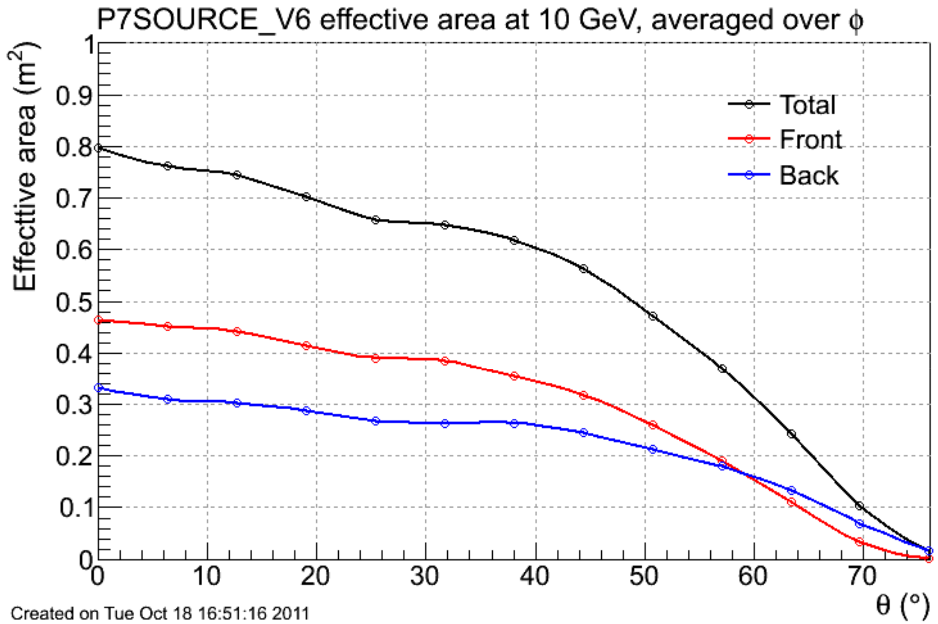
Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

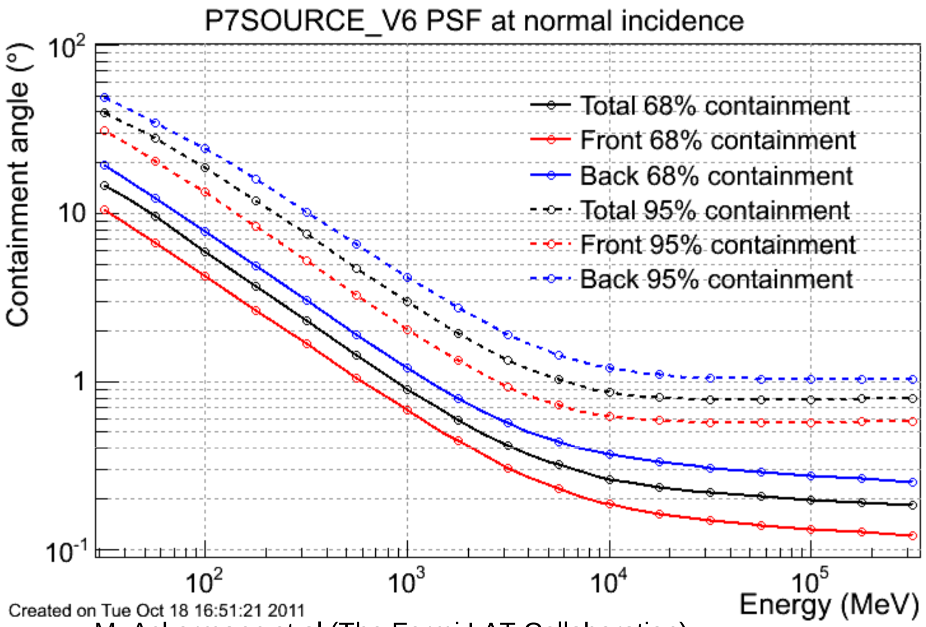
Fermi LAT Effective Area





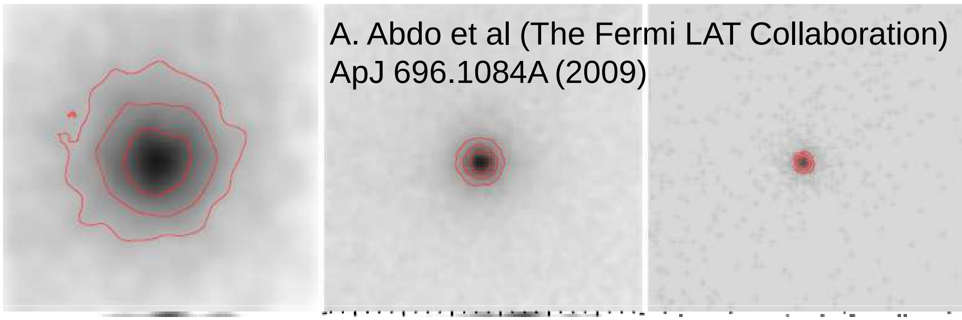
- < 100 MeV limited by 3 in-a-row trigger requirement & drop in pair production cross section (see slide 16)
- > 100 GeV limited by backsplash
- See arXiv:1206.1896 for more info on Fermi LAT performance/validation

Fermi LAT Point Spread Function (PSF)



M. Ackermann et al (The Fermi LAT Collaboration)
ApJS 203, 4 (2012) arXiv:1206.1896

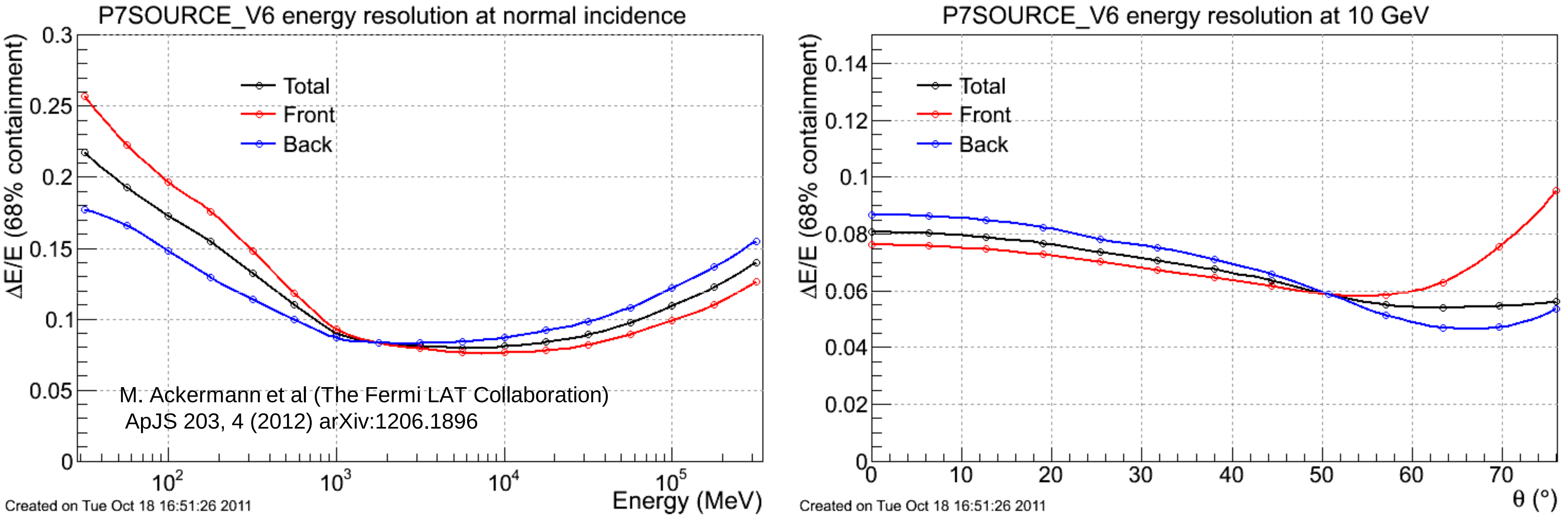
Vela Pulsar Counts Map (10^0x10^0)



30 – 300 MeV **0.3 – 3 GeV** **>3 GeV**

- **Limited by multiple scattering at low E**
- **Limited by strip pitch at high E (pitch = 228 μm)**
- **See arXiv:1206.1896 for more info on Fermi LAT performance/validation**

Fermi LAT Energy Dispersion



- **Limited by energy loss in tracker at low E**
- **Limited by leakage and CAL saturation at high E**
- **See arXiv:1206.1896 for more info on Fermi LAT performance/validation**

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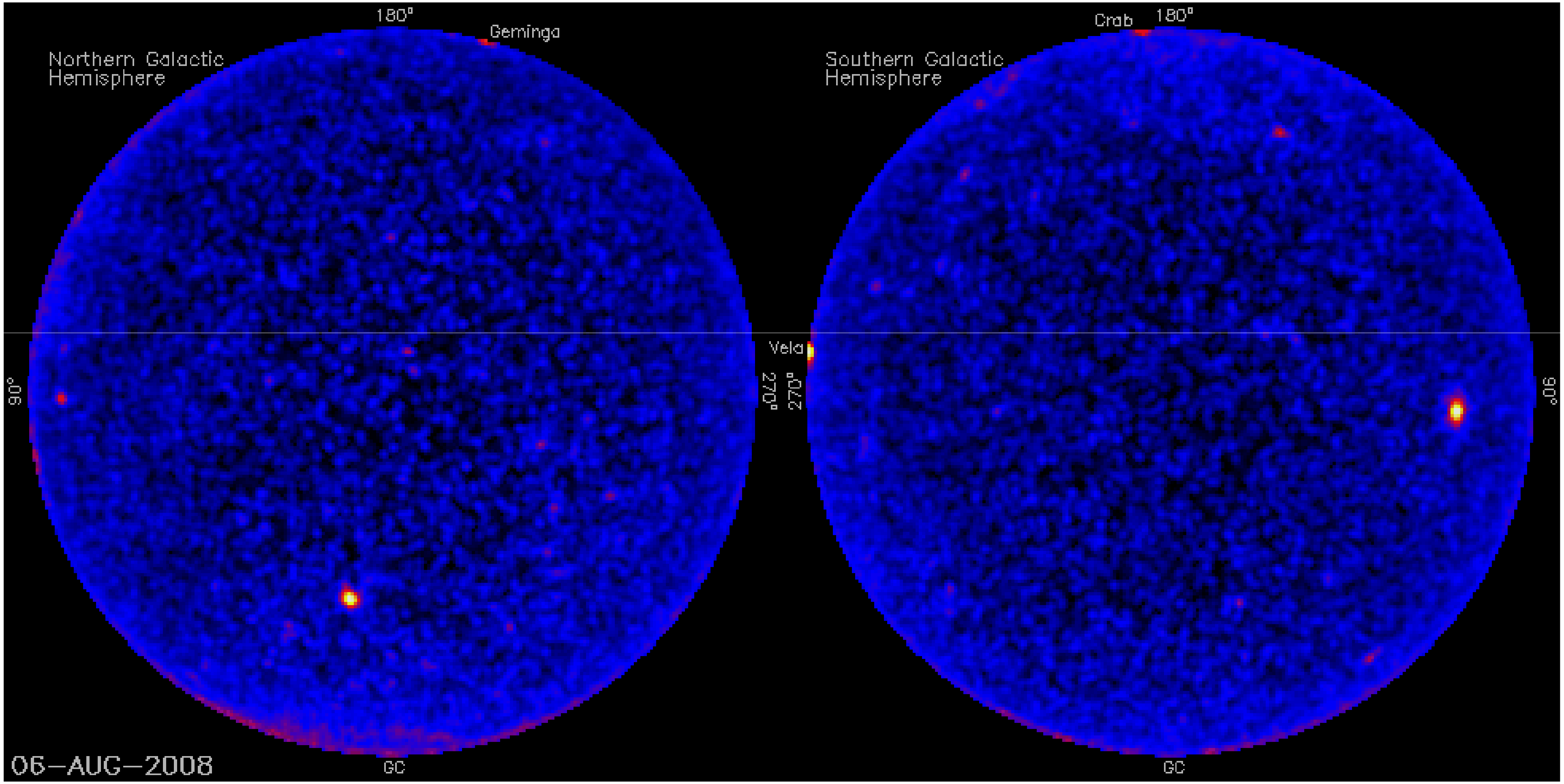
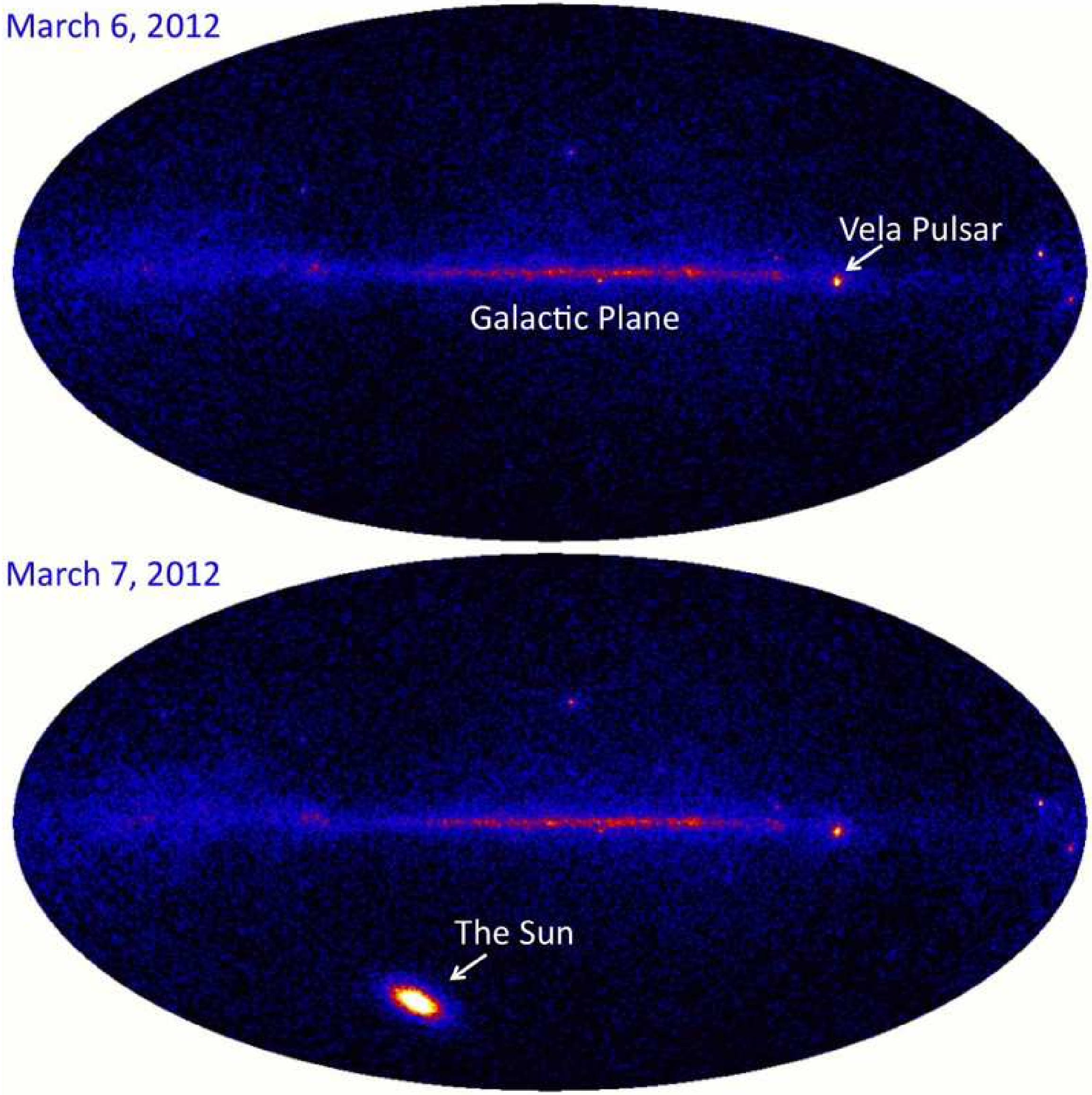
Daily Gamma-ray Sky



Gamma-ray Sun

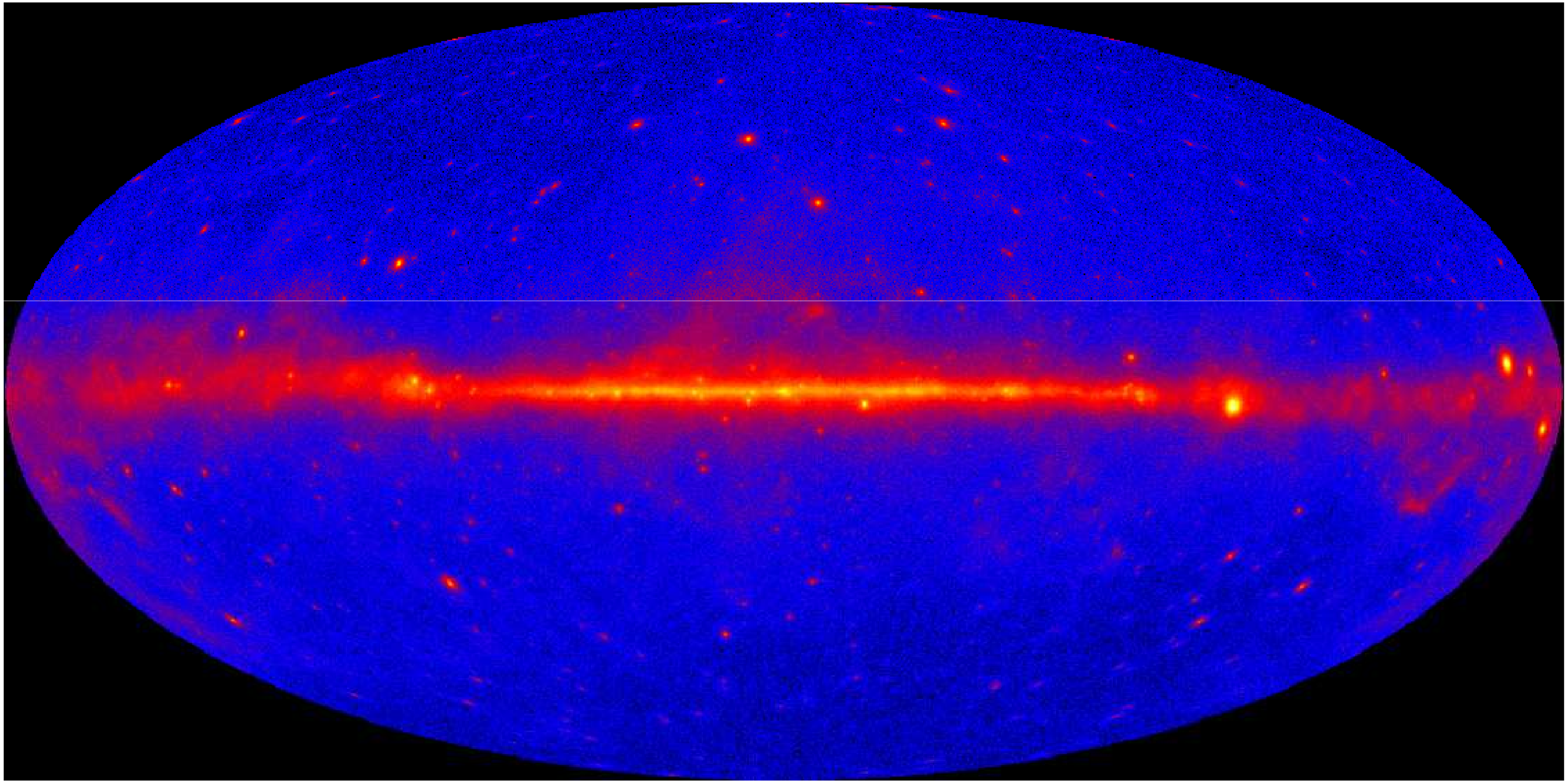
- **Sun is typically not the brightest gamma-ray source**
  - **Solar flares however…**



APOD
March 15, 2012
http://apod.nasa.gov/apod/ap120315.html

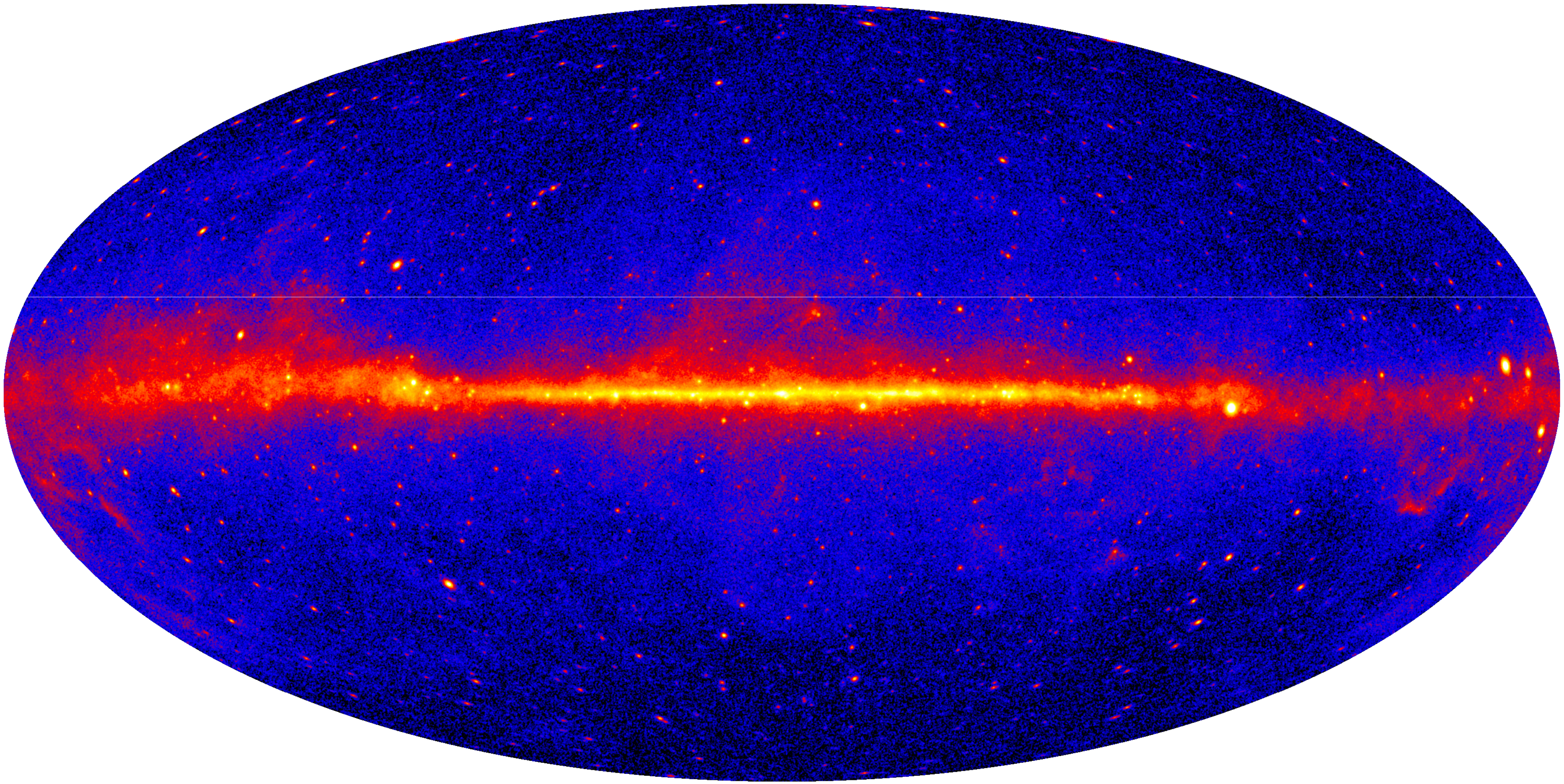
Fermi LAT Gamma-ray Sky

1 year all sky map (E > 1 GeV)



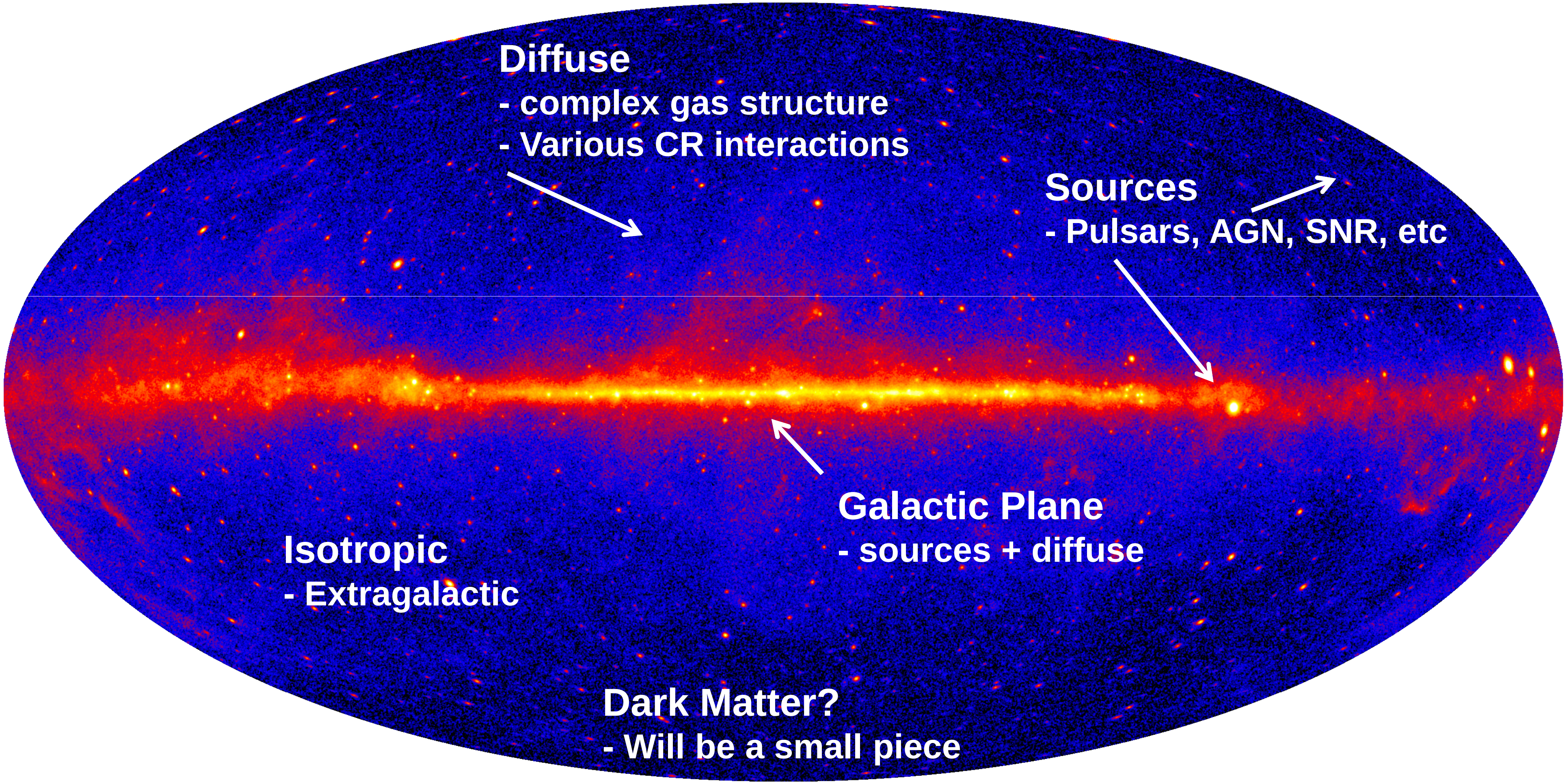
Fermi LAT Gamma-ray Sky

4 year all sky map (E > 1 GeV)



Fermi LAT Gamma-ray Sky

Nature has given us a rich and complicated gamma-ray sky!



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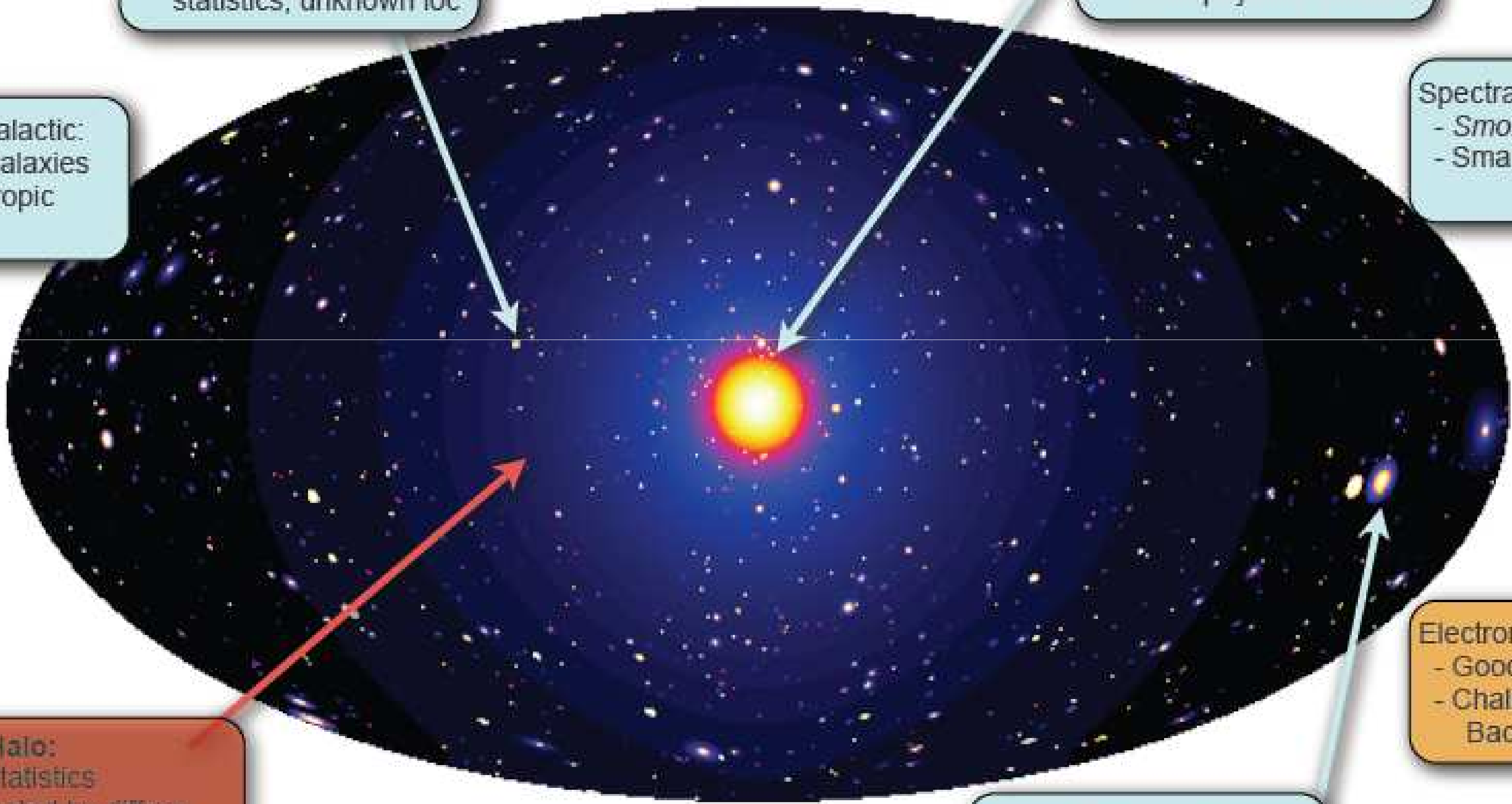
Dark Matter Searches with the Fermi LAT

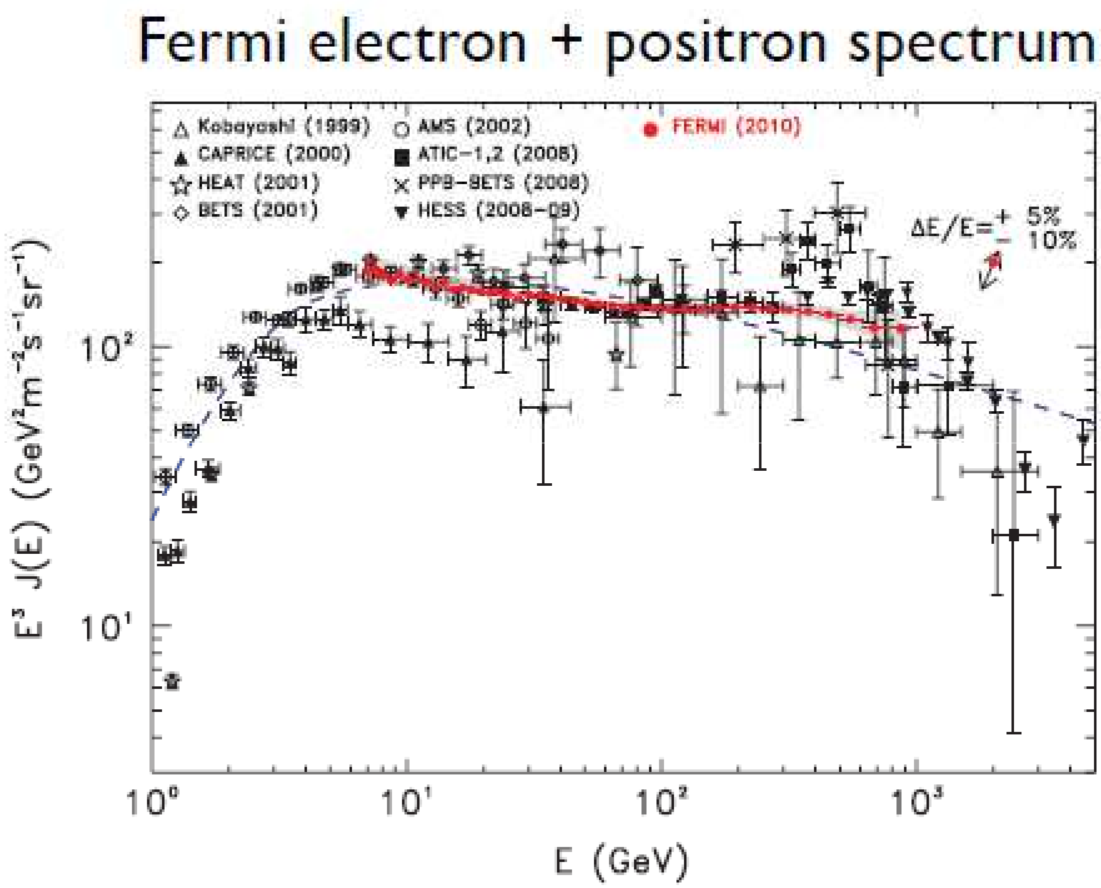


Milky Way Halo simulated by Taylor & Babul (2005)

All-sky map of DM gamma ray emission (Baltz 2006)

Unexpected Excess in the Cosmic Ray e± Spectrum

- **ATIC observed an unexpected bump in the CR e± spectrum**
- **Fermi observes a broader excess around the same energy**
- **This feature can be accounted for by adjusting the CR injection spectrum or nearby pulsars**
- **Can also be explained with leptophillic DM annihilation models**
  - **Requires large <σv>$_{ann}$ to explain excess**

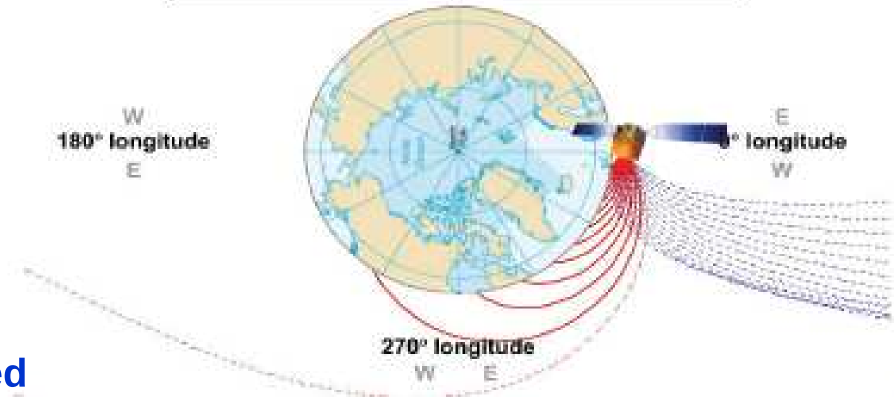


Ackermann et al. [Fermi LAT Collaboration] 2010

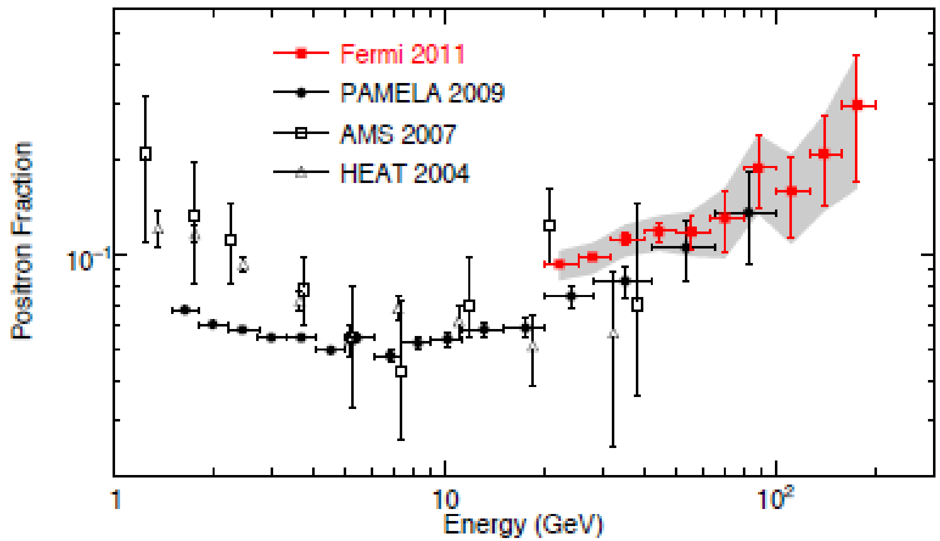
Unexpected Rise in local CR Positron Fraction

- **Fermi measures a rise in the local high-energy CR positron fraction, consistent with the PAMELA results**
- **No magnet on-board, so use Earth's magnetic field**
- **Rise in local positron fraction disagrees with conventional model for cosmic rays**
  - **Local positrons are secondaries created by CR nuclei interactions (this should cause fraction to *decrease*)**
- **This can be explained with leptophilic annihilating/decaying DM**
  - **Requires large $<\sigma v>_{ann}$ to explain excess**
  - **Antiproton fraction does *not* rise; need to suppress hadronic modes**
  - **see T. A. Porter et al. (2011) arXiv:1104.2836v1; D. Grasso et al. (2009) arXiv:0905.0636v3 for more**

events arriving from West:
e^+ allowed, e^- blocked



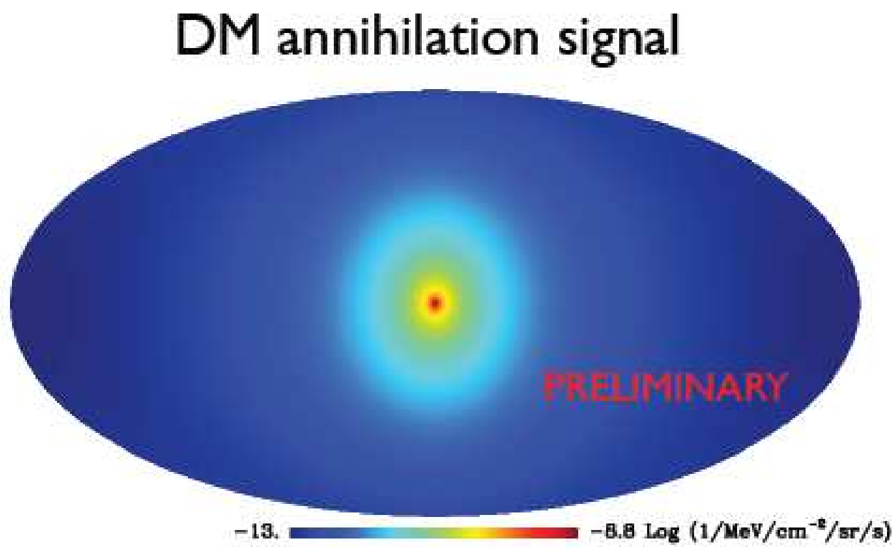
Fermi positron fraction

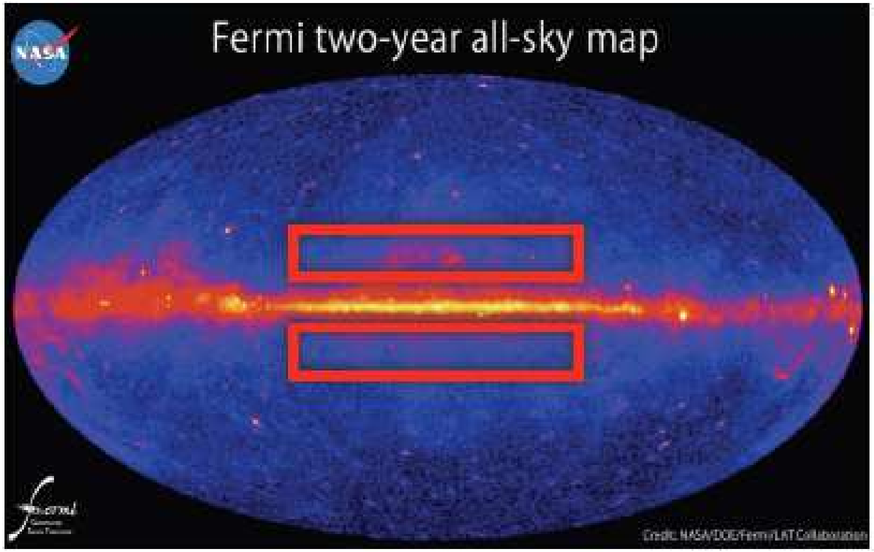


Ackermann et al. [Fermi LAT Collaboration] 2011

DM Constraints from the Milky Way Halo

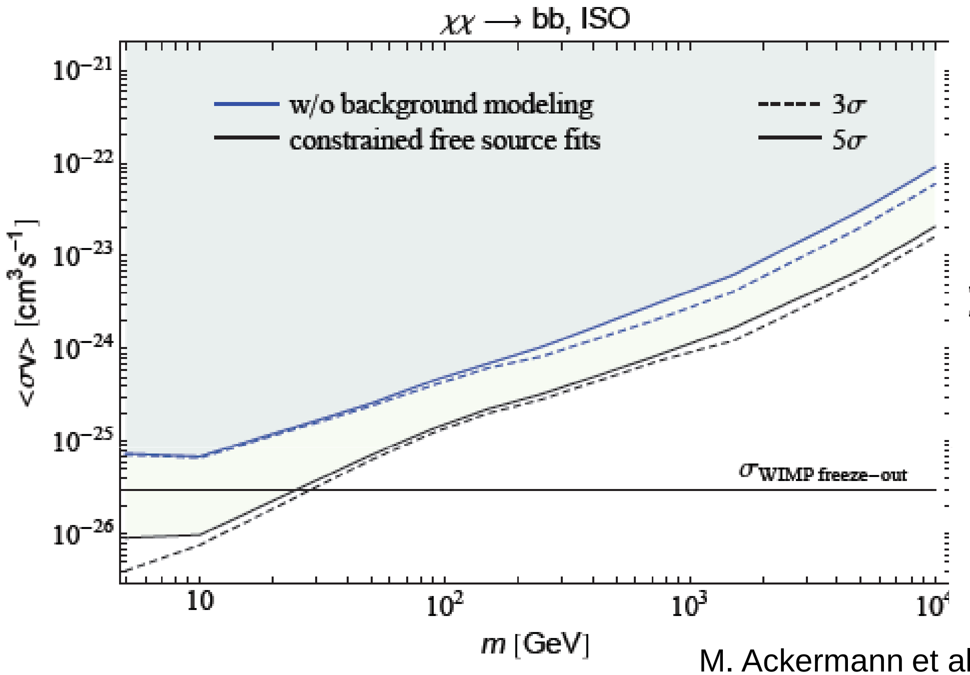
- **Look in 2 year diffuse from 1 – 100 GeV**
  - **Mask out known gamma-ray sources**
- **Region of Interest: two off-plane rectangles ($5^0<|b|<15^0$ & $|l|<80^0$)**
  - **Minimizes DM profile uncertainties (central cuspiness varies)**
  - **Limits astrophysical uncertainties (mask bright plane, avoid high latitude Fermi lobes and Loop I)**
- **This analysis focuses on setting limits on possible DM signals**
  - **See non-DM like residuals (e.g. not centrally peaked)**



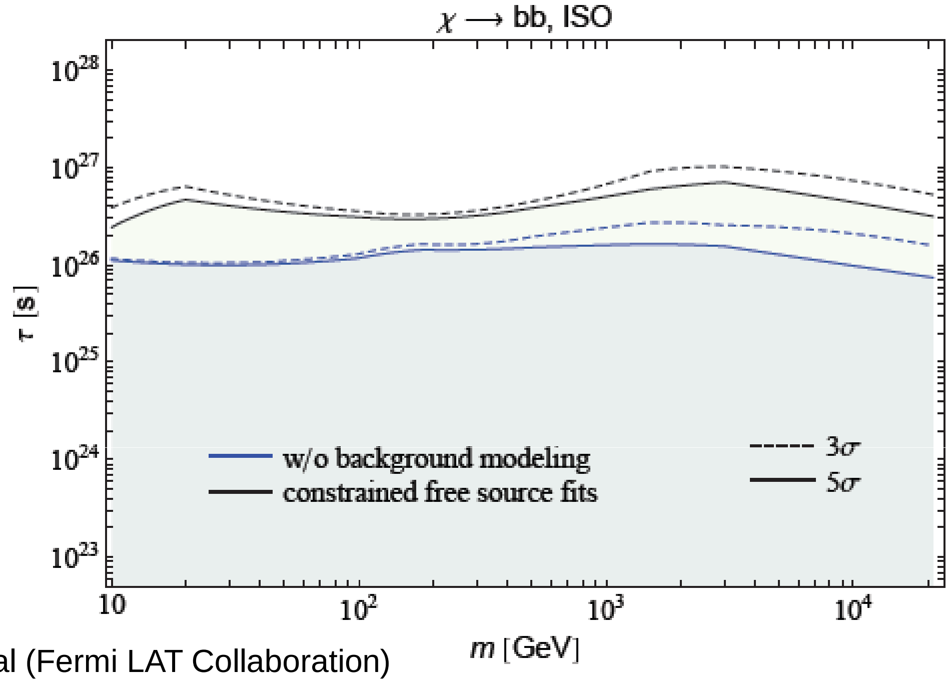


MW Halo Results- b$\bar{b}$

Annihilation



Decay



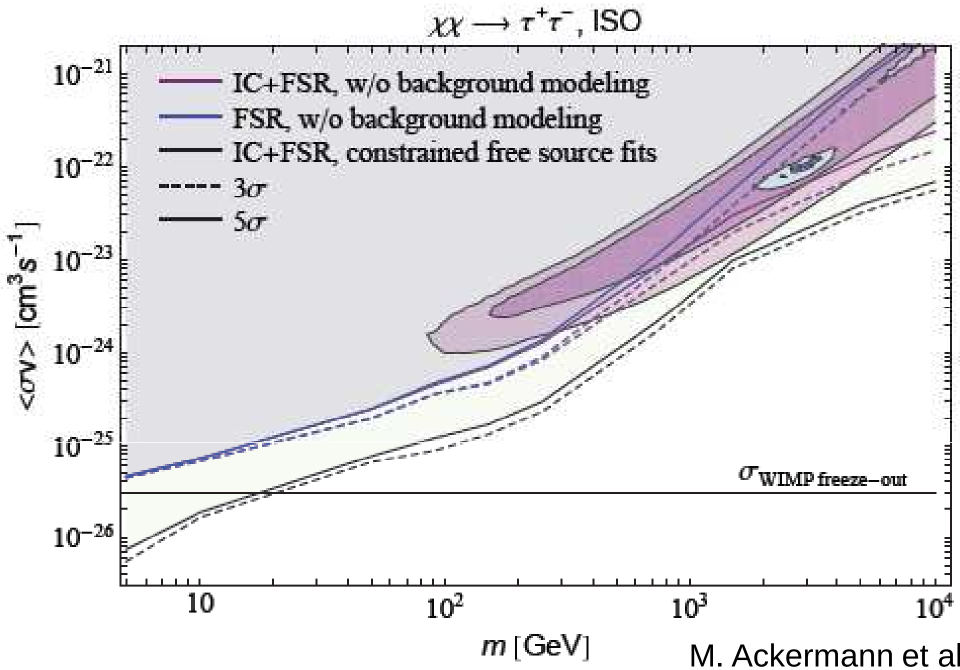
M. Ackermann et al (Fermi LAT Collaboration)
Accepted for publication in ApJ (arXiv:1205.6474)

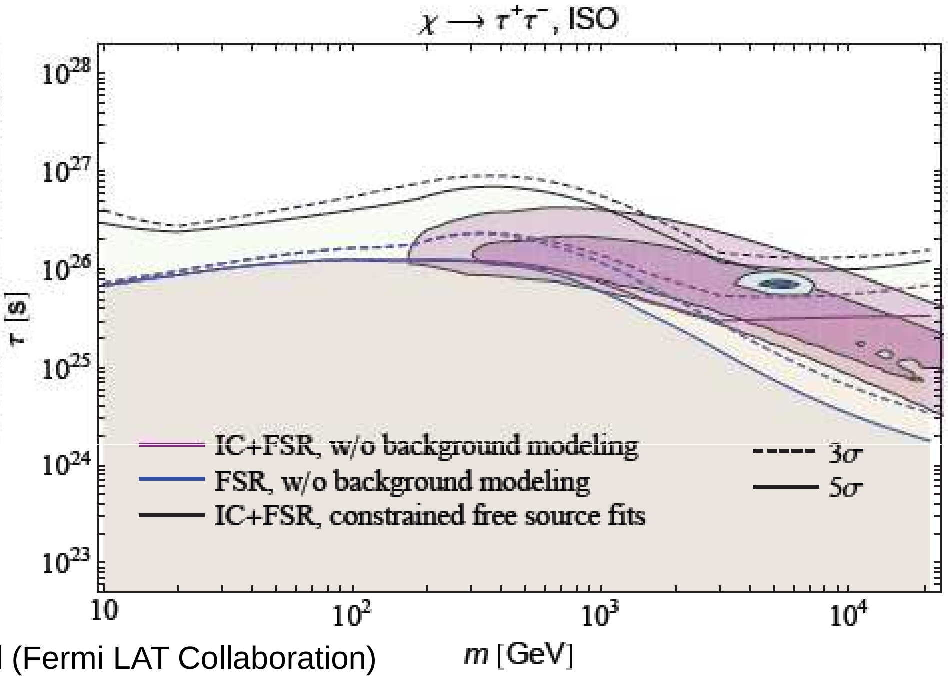
- **b$\bar{b}$ annihilation spectrum is similar in shape to DM annihilations/decays producing heavy quarks and gauge bosons in this energy range**

- **Exclude canonical thermal relic WIMPs for masses below ~30 GeV in b$\bar{b}$**

MW Halo Results- $\tau^+ \tau^-$

Annihilation **Decay**

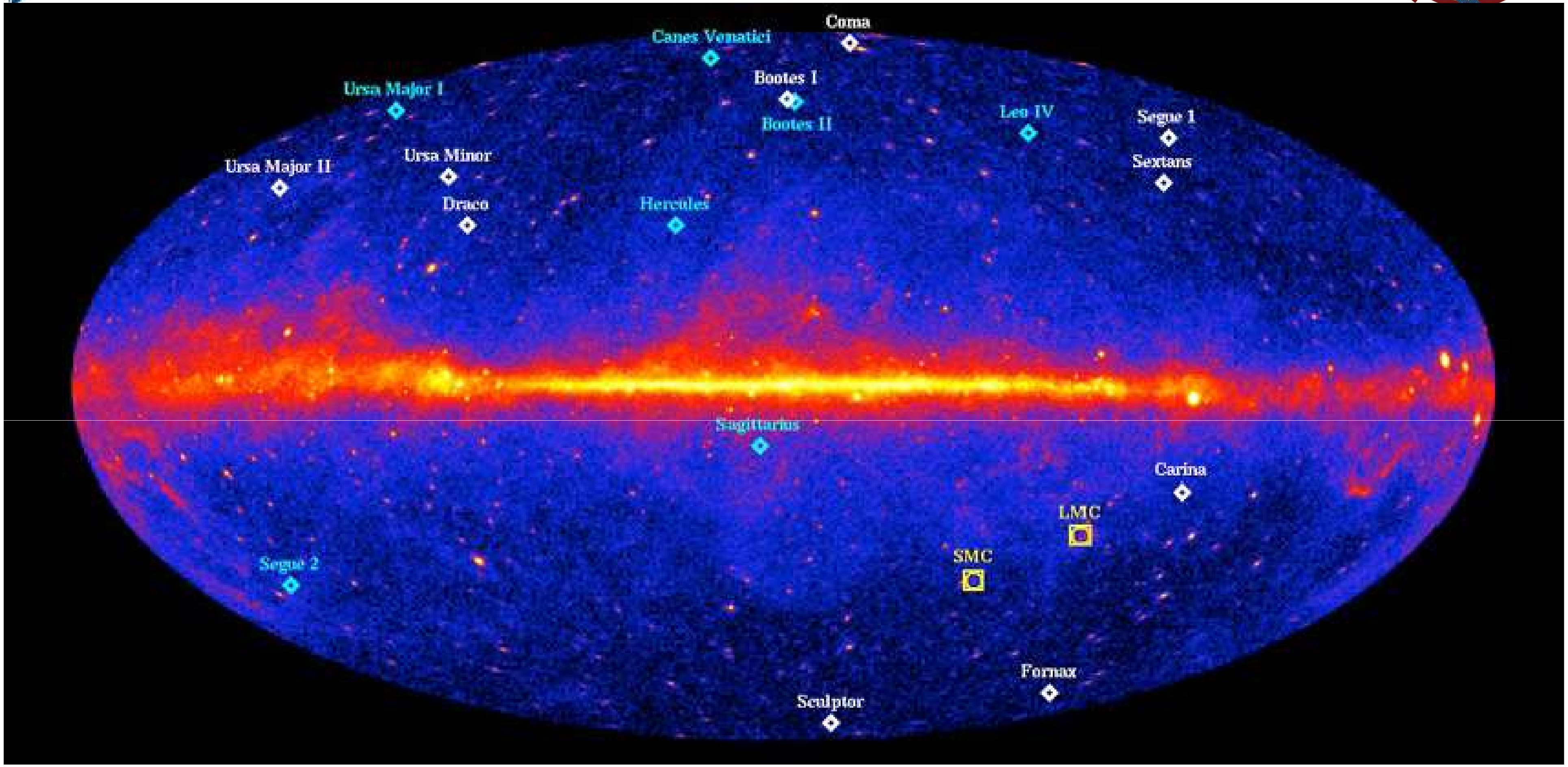




M. Ackermann et al (Fermi LAT Collaboration)
Accepted for publication in ApJ (arXiv:1205.6474)

- **Set limits assuming only Final State Radiation and FSR + Inverse Compton**
  - **Only FSR = only photons produced by taus (no electrons)**
  - **"FSR + IC" includes IC gamma rays from electrons produced via DM annihilation/decay**
- **Contours show 2σ and 3σ CL fits to PAMELA (purple) and Fermi (blue) positron fraction**
  - **DM interpretation of positron fraction strongly disfavored (for annihilating DM)**

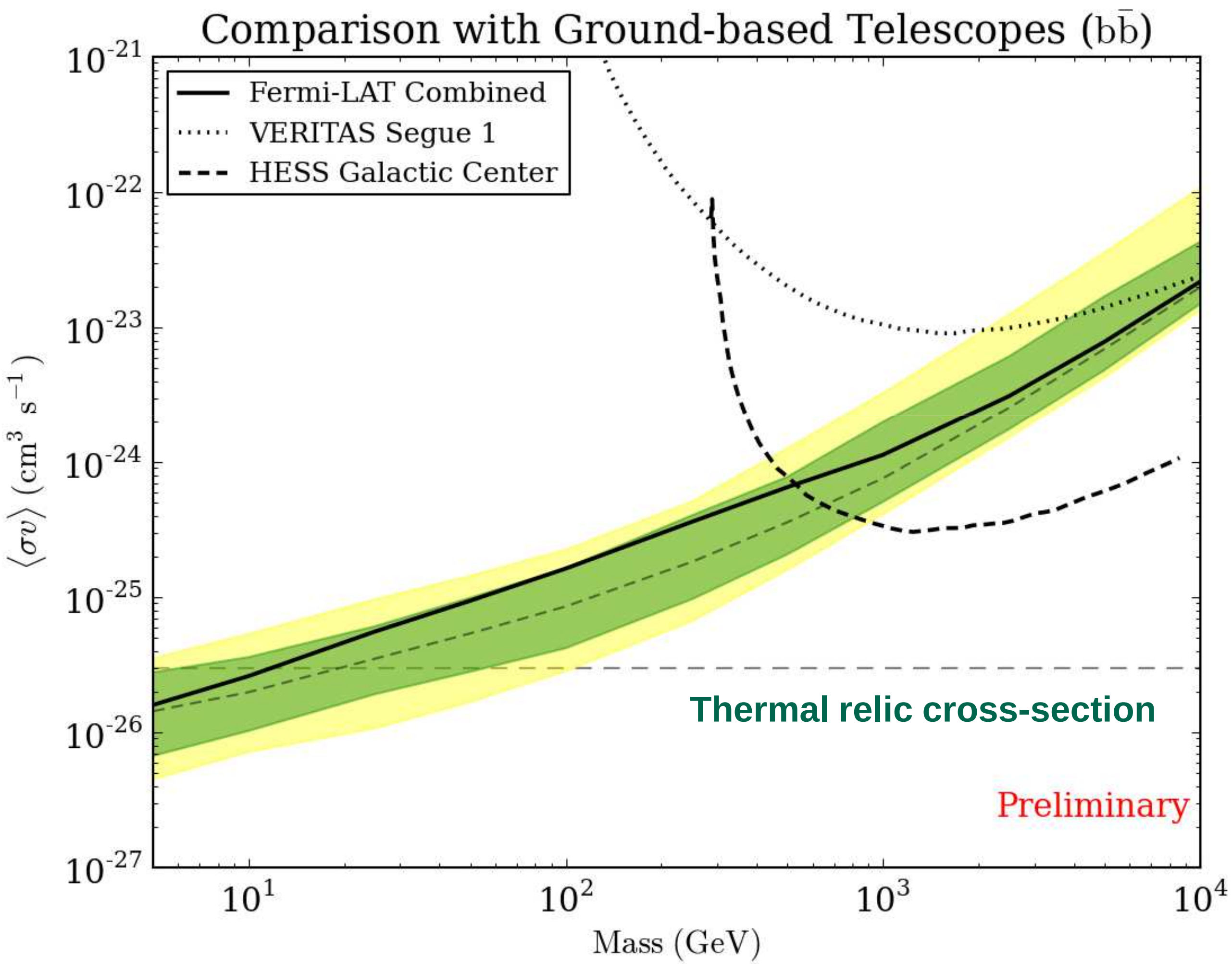
Constraints from dwarf galaxies



- Dwarf galaxies have a large mass-to-light ratio
- Good signal-to-noise for a DM search

Combined dSphs Results

- **Joint likelihood analysis of 10 dwarf galaxies**
- **4 years of data in energy range 100 MeV – 500 GeV**
- **Account for uncertainties in J-factor**
  - **DM distribution determined using observed stellar velocities**
- **4 annihilation channels considered**
- **No DM seen**
  - **Exclude canonical thermal relic cross-section for masses less than ~10 GeV (in $b\bar{b}$ and tau's)**



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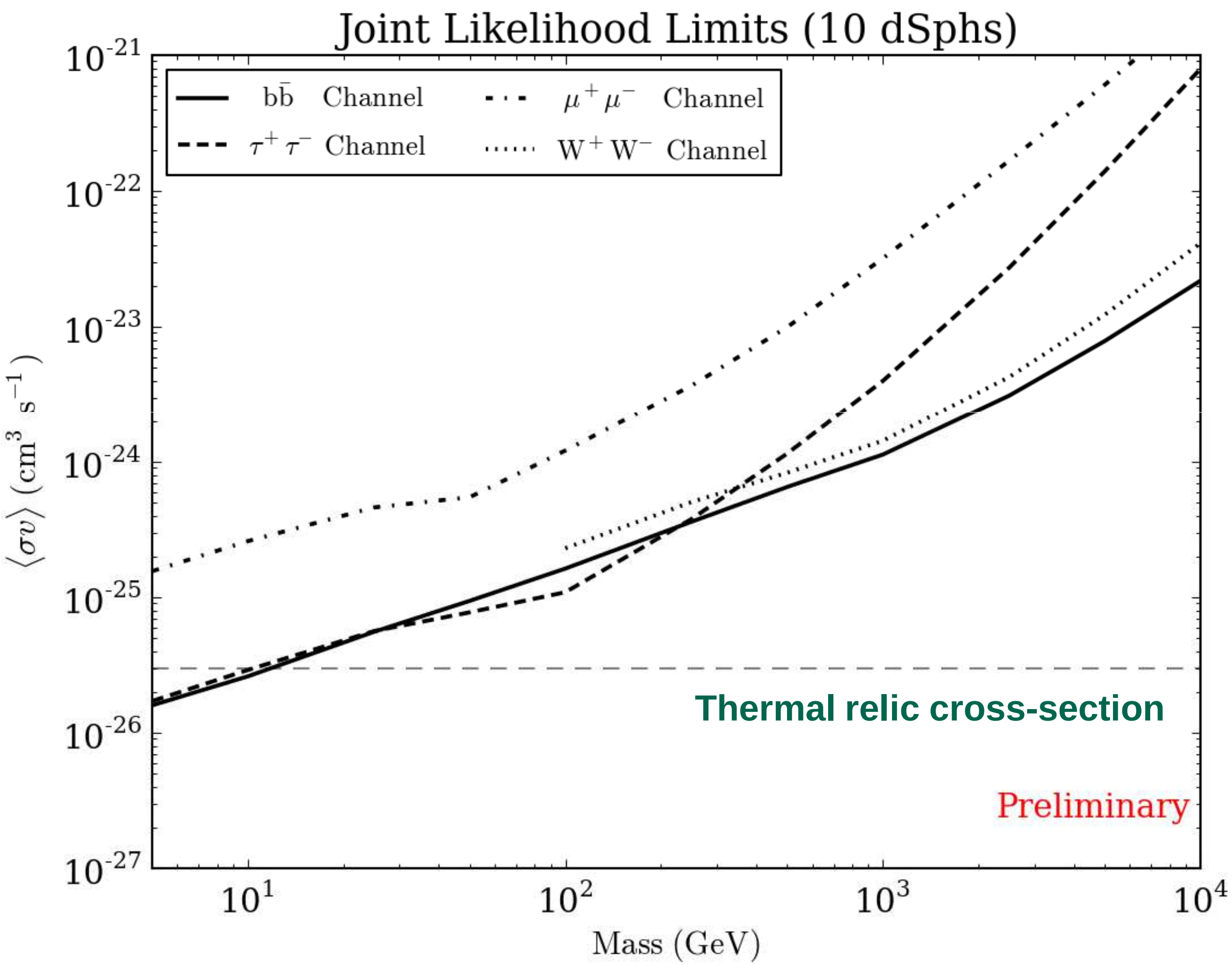
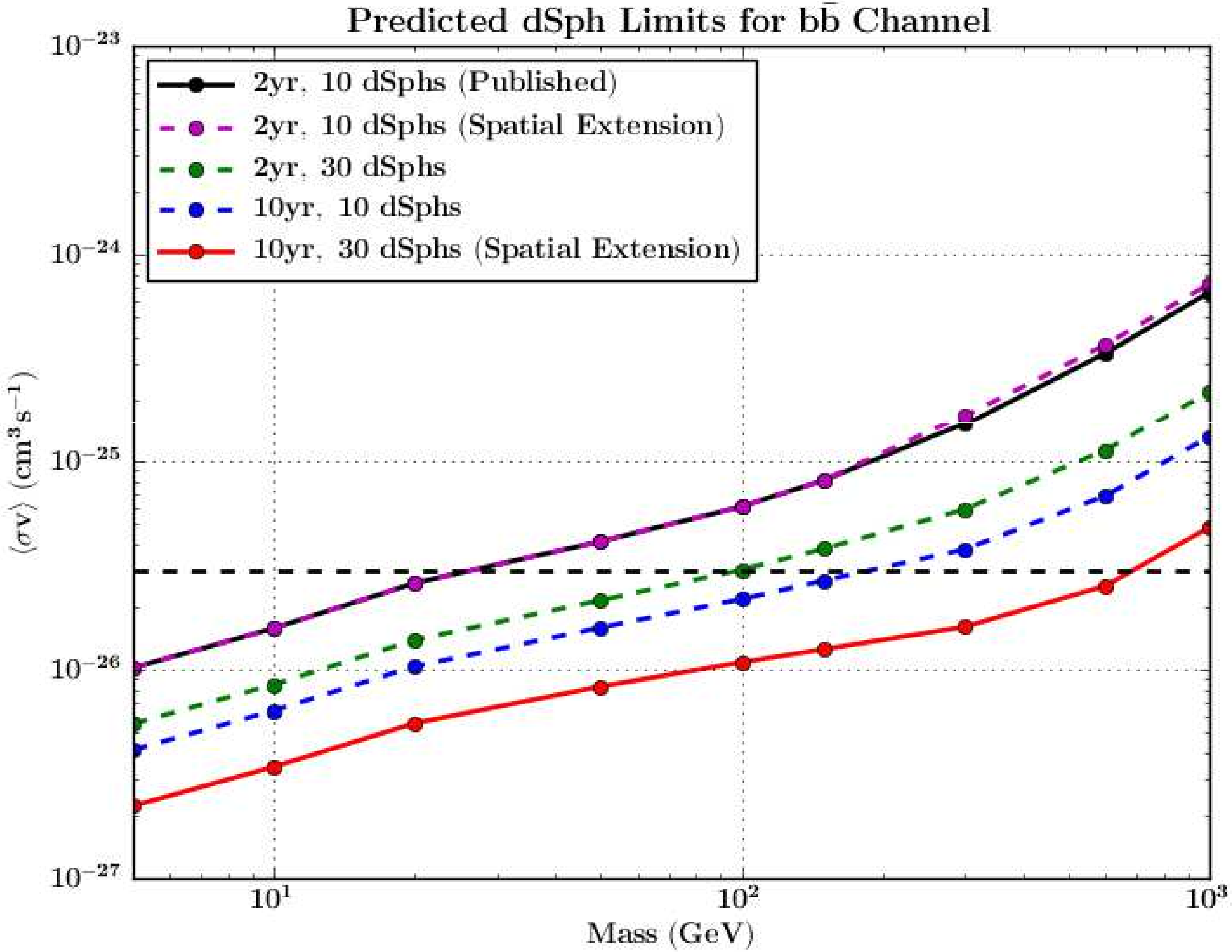
- No DM seen
  - Exclude canonical thermal relic cross-section for masses less than ~10 GeV (in $b\bar{b}$ and tau's)

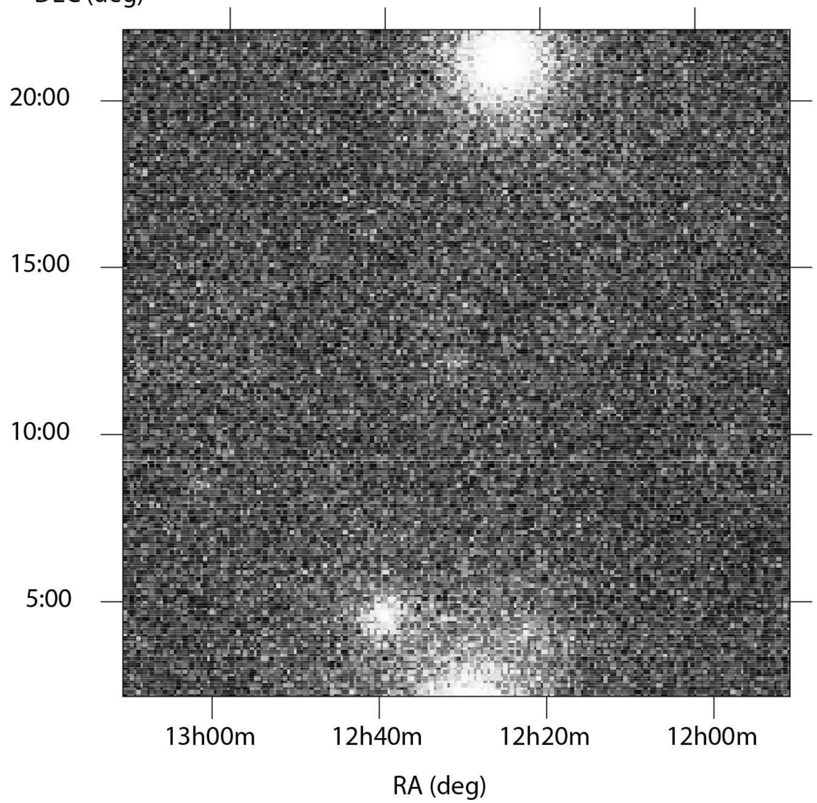


Projected Limit Improvement with dSphs

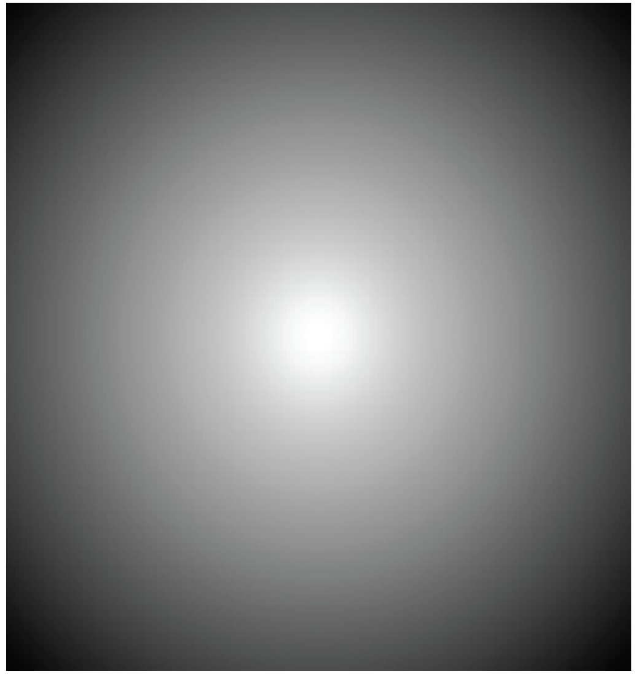


Virgo Galaxy Cluster (1)

Virgo ROI counts map



DM annihilation profile

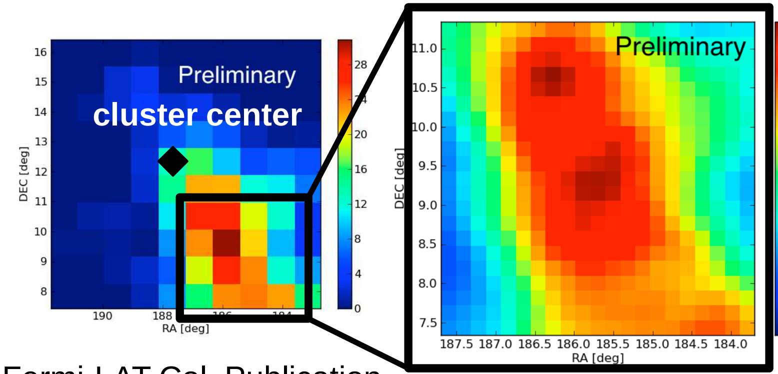


Han et al. 2012

- **Han et al 2012 (arXiv 1201.1003) claimed ~4 sigma evidence from dark matter annihilation in the Virgo galaxy cluster**
- **Very extended DM annihilation profile (from substructure), majority of excess comes from inner 3 deg of the profile**

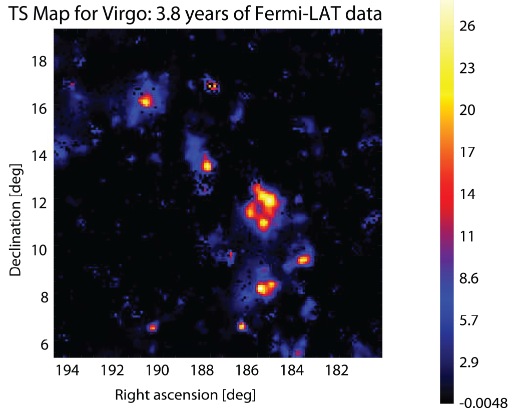
Virgo Galaxy Cluster (2)

TS map with 0.5 deg bins | **TS map with 0.2 deg bins**



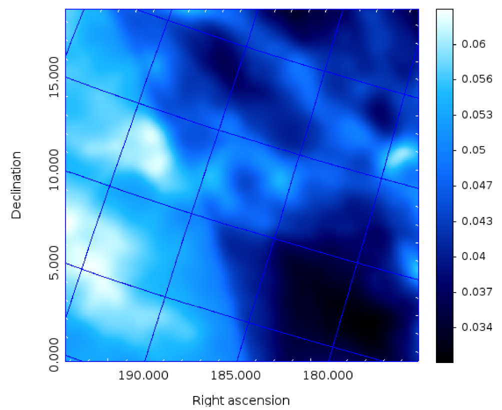
Fermi-LAT Col. Publication in preparation

New Point Sources



Macias-Ramirez et al. (2012)

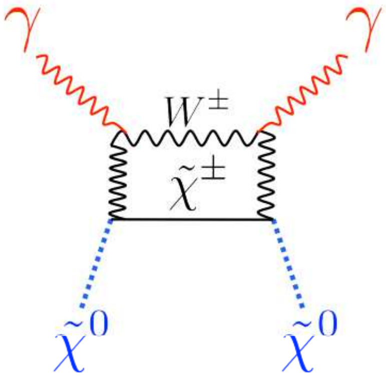
Interstellar Emission Model

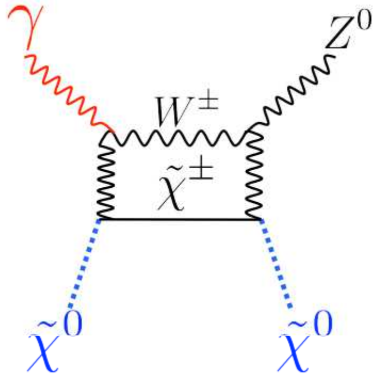


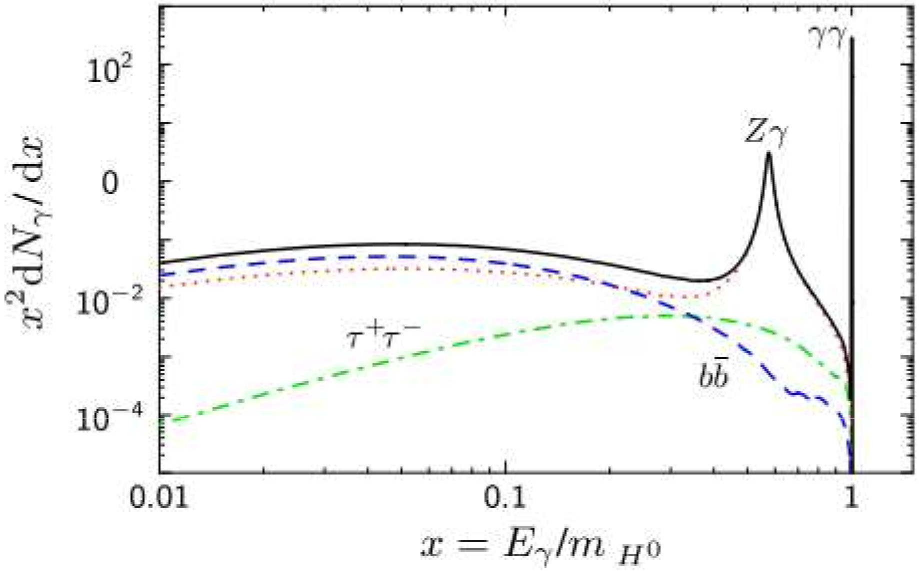
Fermi-LAT Col. Publication in preparation

- **Excess is not in the cluster center (as expected from DM)**
- **Macias-Ramirez find 7 new candidate point sources that could explain excess**
  - **Han et al 2012 (arXiv 1207.6749) find 4 new candidate point sources**
- **Significance depends strongly on the interstellar emission model**
  - **Requires a detailed study of systematic uncertainties especially of the interstellar emission model even for extragalactic regions**
  - **Virgo is at fairly low galactic latitude and in a challenging region for diffuse emission modeling.**

Search for Gamma-ray Spectral Lines





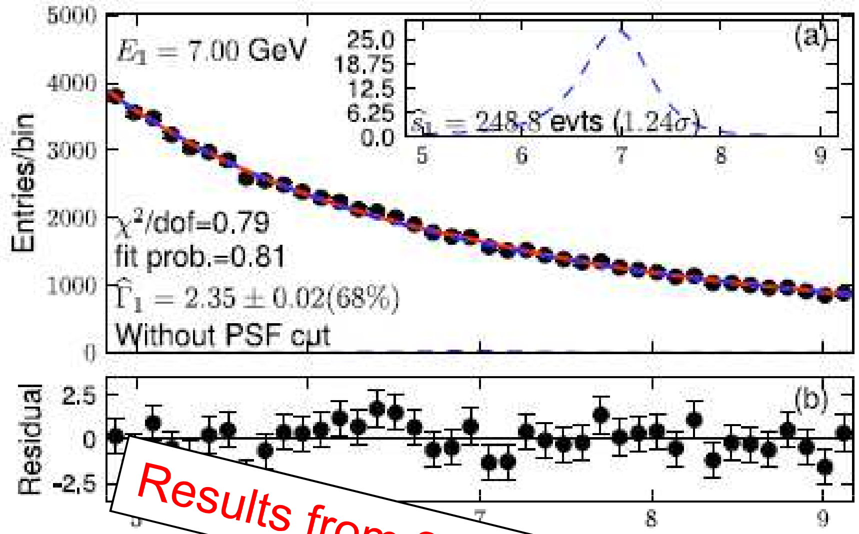


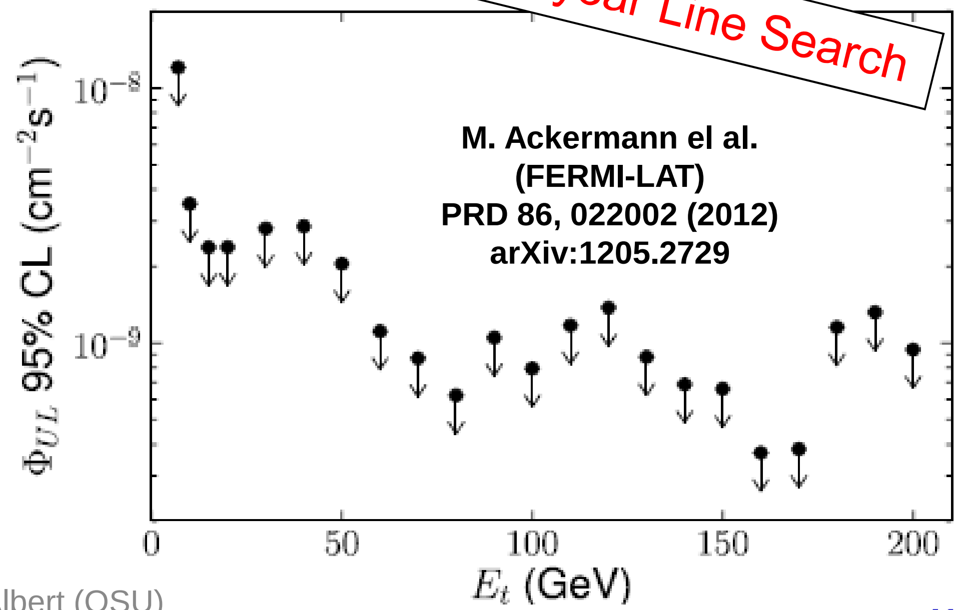
Gustafsson et al. PRL 99.041301

- **Annihilation/decay directly into γγ or Xγ (X = Z^0, H^0, …)**
- **“Smoking Gun” channel**
- **Advantage: sharp, distinct feature**
- **Disadvantage: low predicted counts**

The Fermi LAT Line Search

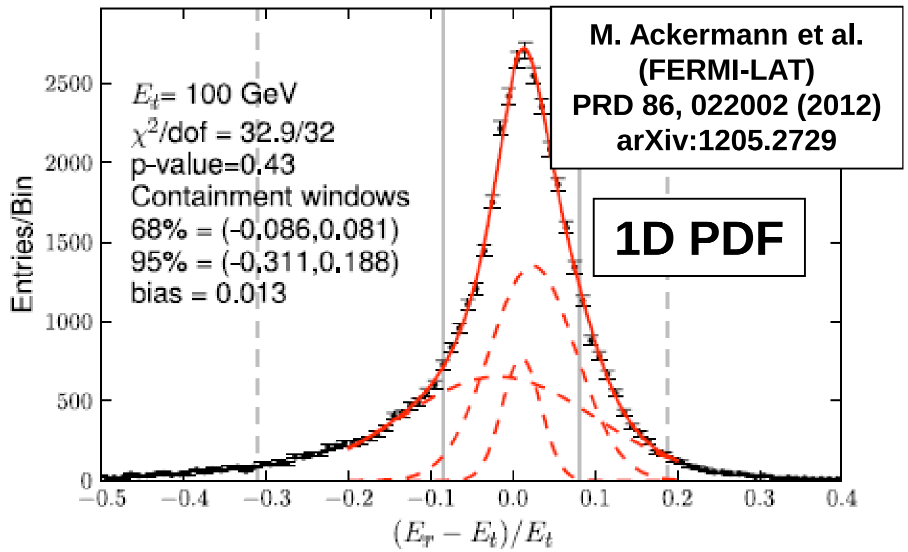
- **2 year analysis accepted for publication in PRD**
  - **Current analysis uses similar method**
- **4 year analysis nearing completion**
  - **Use Reprocessed "Pass 7 Clean" data**
    - **Low cosmic-ray contamination**
    - **Reprocessing shifts energy scale by 1-4% to account for expected accumulation of radiation damage to calorimeter**
  - **Plan to submit paper to PRD end of December 2012**
- **Search for lines from 5 to 300 GeV**
  - **Maximum Likelihood Fit**
  - **Use sliding $\pm 6\sigma_E$ windows**
  - **Fit for energies in σ_E steps**
    - **Perform finer $0.5\sigma_E$ scan near significant energies**
  - **Model bkg as single powerlaw**
  - **Γ_{bkg} and f_{sig} free in fit**

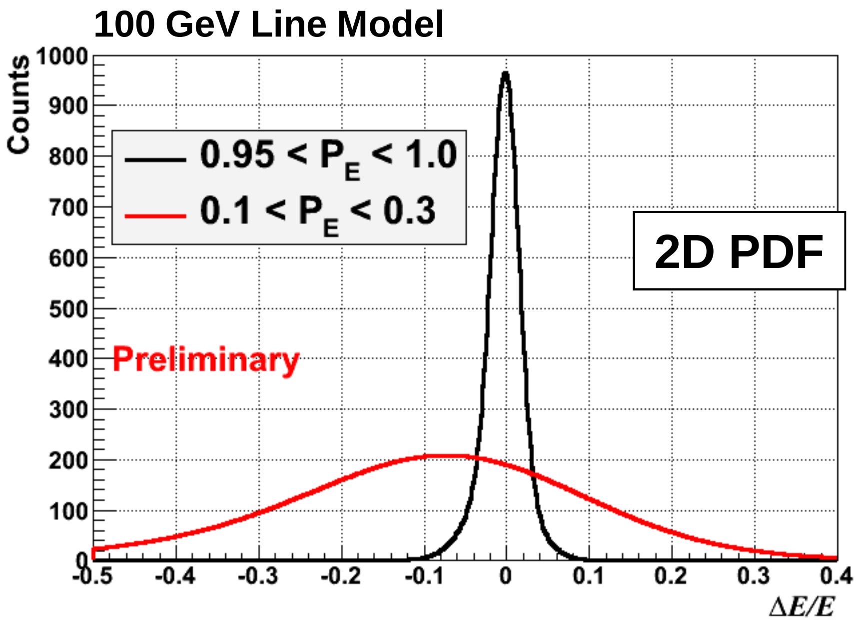




Improved Model for LAT Response to a Line

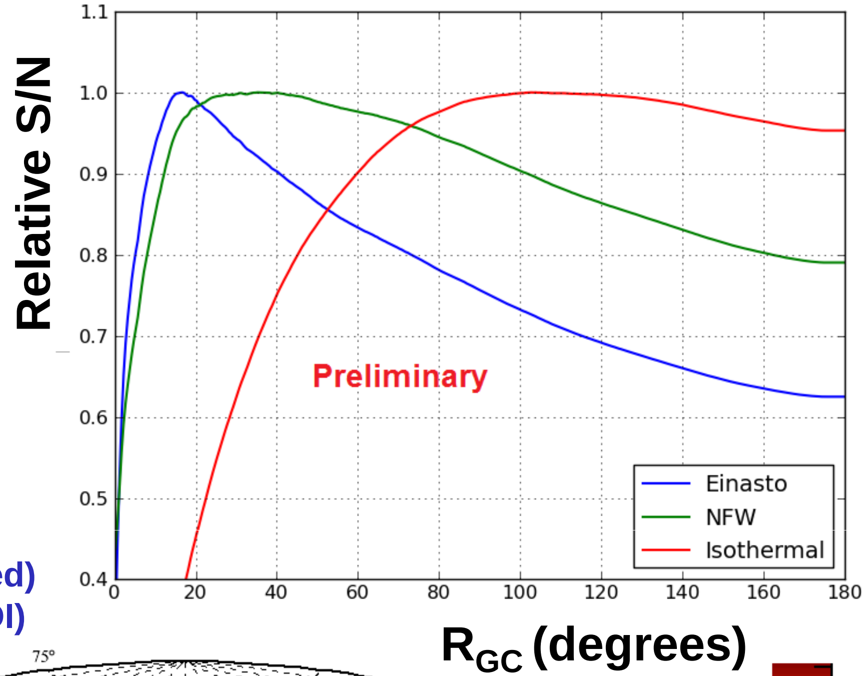
- Use full detector simulation to get Fermi LAT energy dispersion
- Previously modeled line with a triple gaussian fit ("1D PDF")
- This analysis adds a 2nd dimension to line model: P_E
  - P_E is the probability that measured energy is true energy
    - Labeled "CTBBestEnergyProb" in our extended data
  - "2D PDF" (a function of both energy and P_E)
- Break Line into 10 P_E slices and do triple gaussian fit in each slice separately
  - Fit explicitly at 9 energies and interpolate parameters in each slice to produce lines at other energies
- Including $P_E \rightarrow$ ~15% improvement to signal sensitivity (when there is signal) and counts upper limit (when there is no signal)

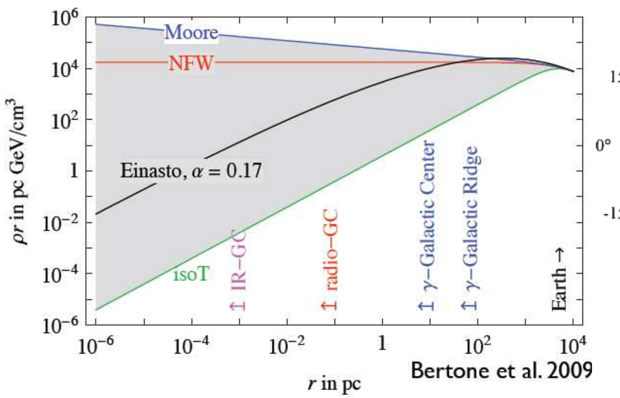


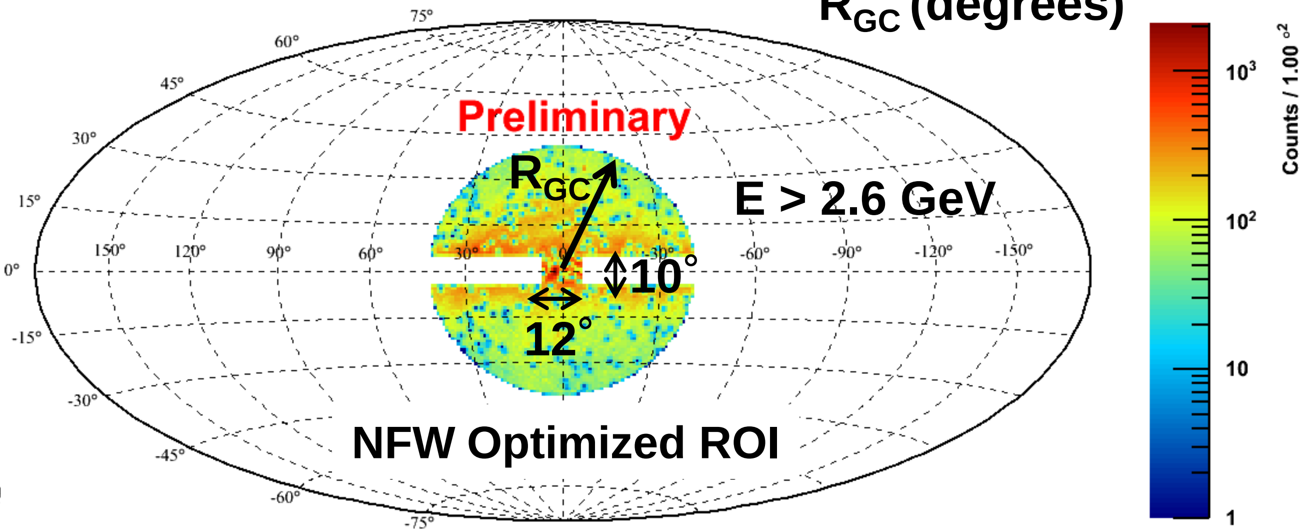


Region of Interest (ROI) Optimization

- Many have shown ROI optimization importance in line searches
  - e.g. C. Weniger JCAP 1208 (2012) 007
- Find R_{GC} that optimizes sig/sqrt(bkg)
  - ROI choices made a priori using MC
  - sig from J factor in that ROI
  - bkg from MC simulation of galactic diffuse model
    - http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model_details/Pass7_galactic.html
- Search in 5 ROIs
  - R0 (12°x10° GC box)
  - R16 (Einasto Optimized)
  - R41 (NFW Optimized)
  - R90 (Isothermal Optimized)
  - R180 (2 year Analysis ROI)

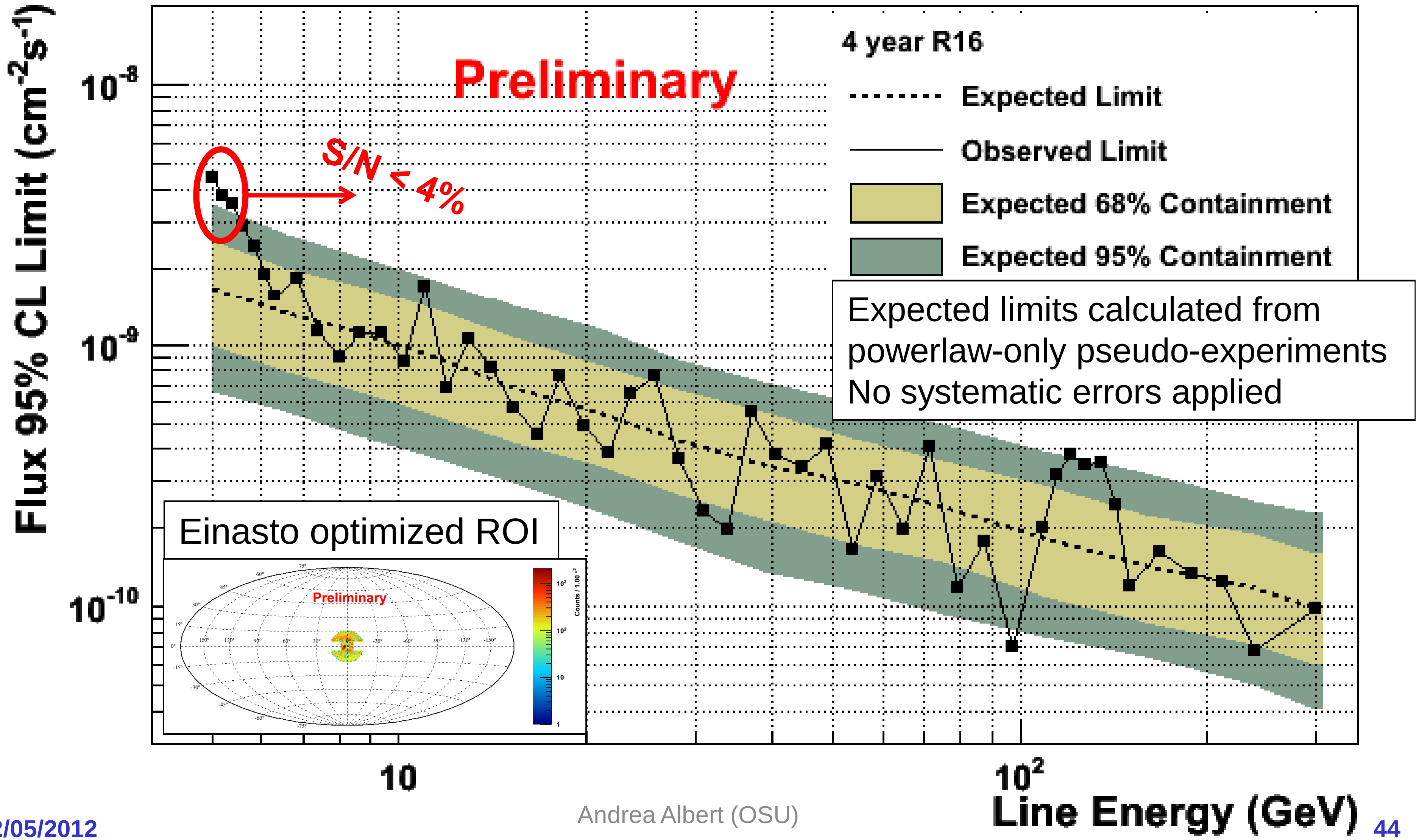




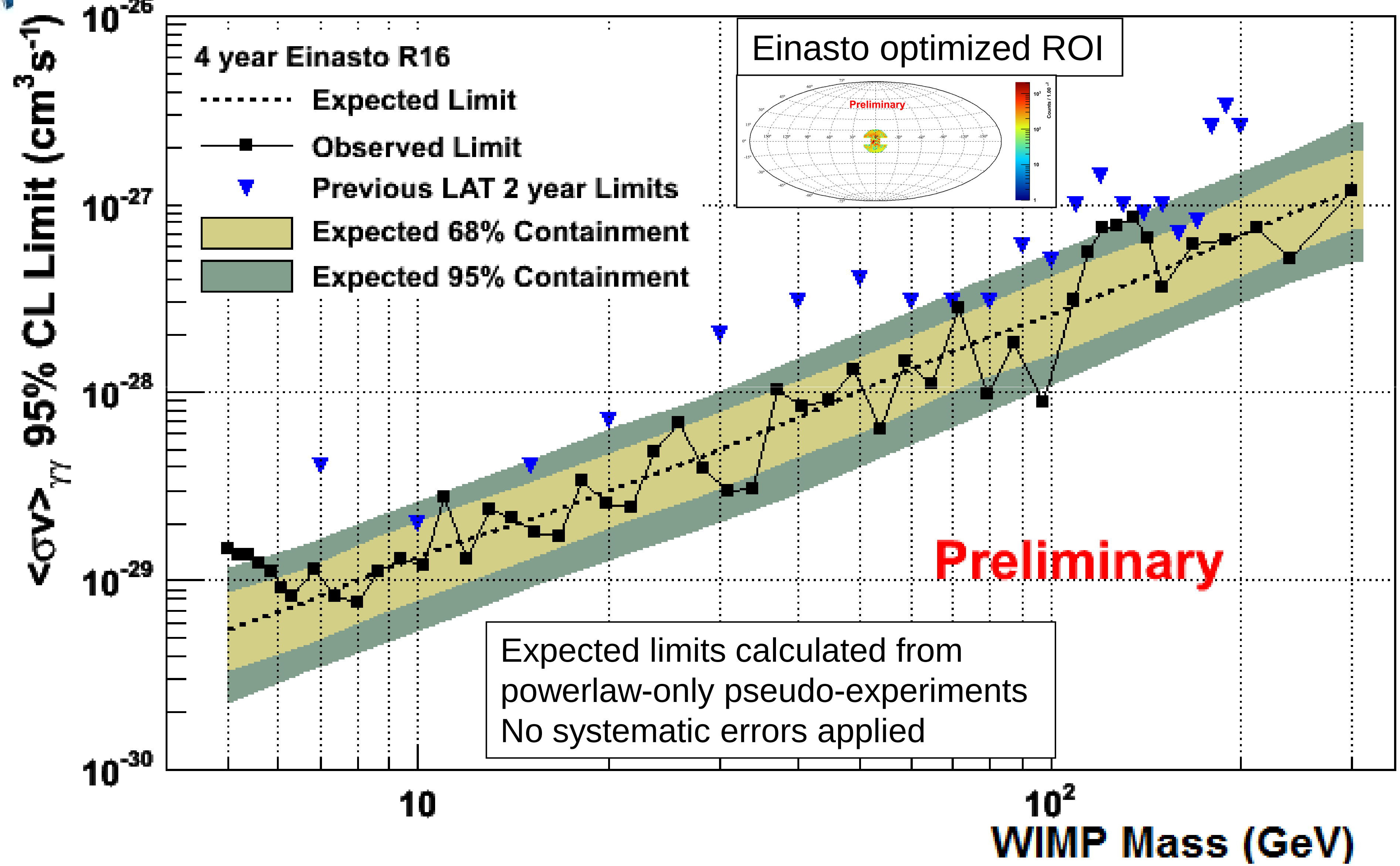


Spectral Line 95% CL Flux Upper Limit R16

- No globally significant lines found
  - Most significant fit was in R0 at 5 GeV, ~2σ (3.7σ local)

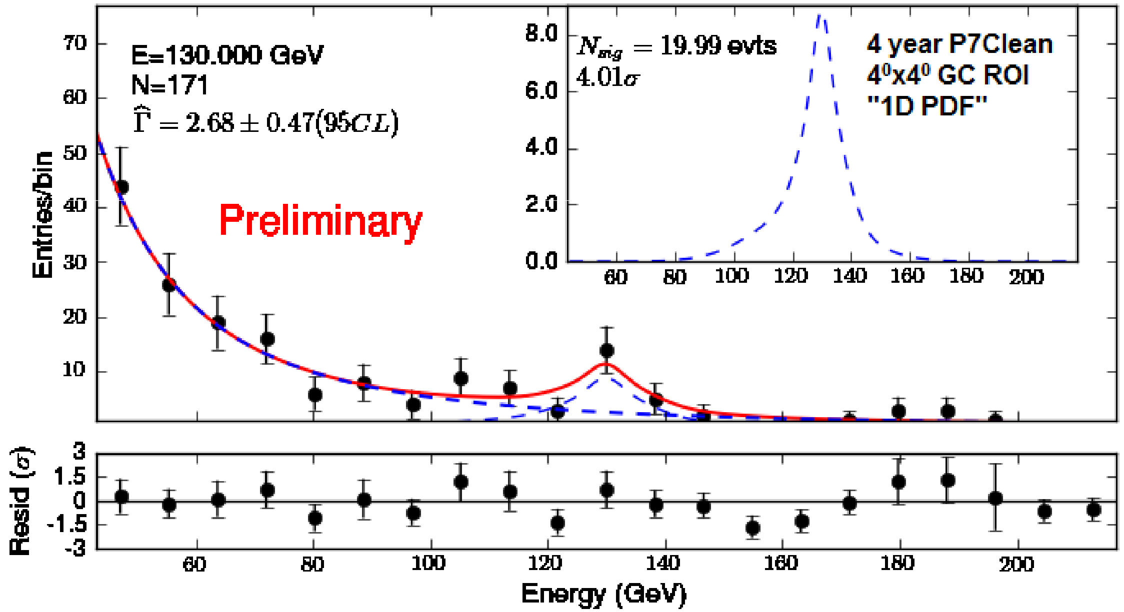


95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ Einasto Upper Limit R16



Line-like Feature near 135 GeV

- **Our blind search does not find globally significant feature near 135 GeV**
  - Reprocessing shifts feature from 130 GeV to 135 GeV
  - Most significant fit was in R0, 2.23σ local (<0.5σ global)
- **Much interest after detection of line-like feature localized in the Galactic center at 130 GeV**
  - See C. Weniger JCAP 1208 (2012) 007 arXiv:1204.2797
- **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)



Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs

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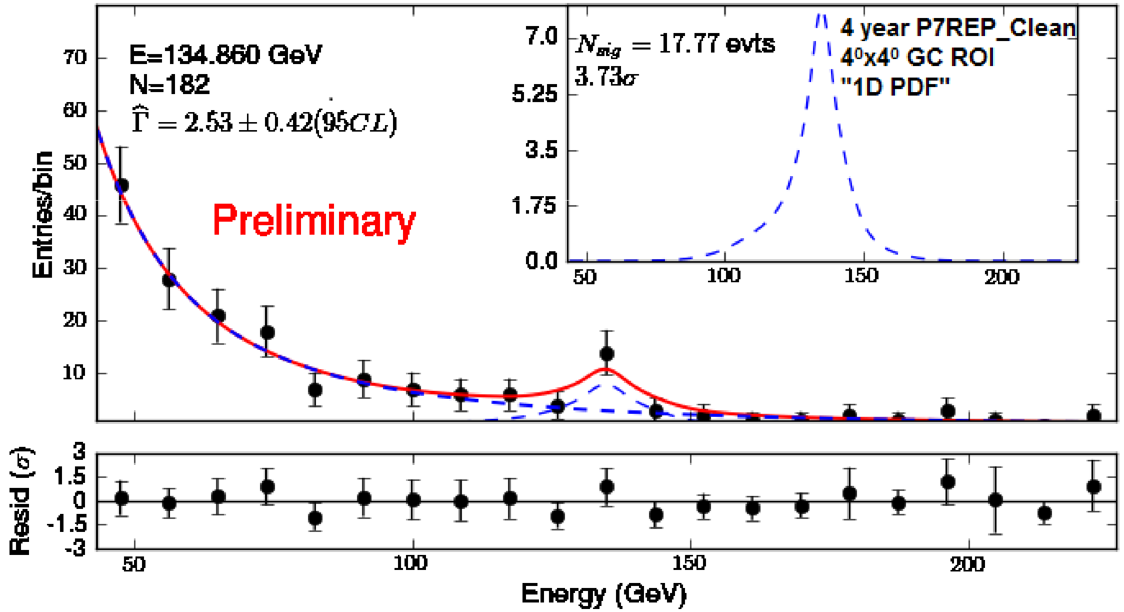
  - **Use 1D PDF (no use of P_E)**
- **3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data**
  - **Look in 4°x4° GC ROI**
  - **Use 1D PDF (no use of P_E)**



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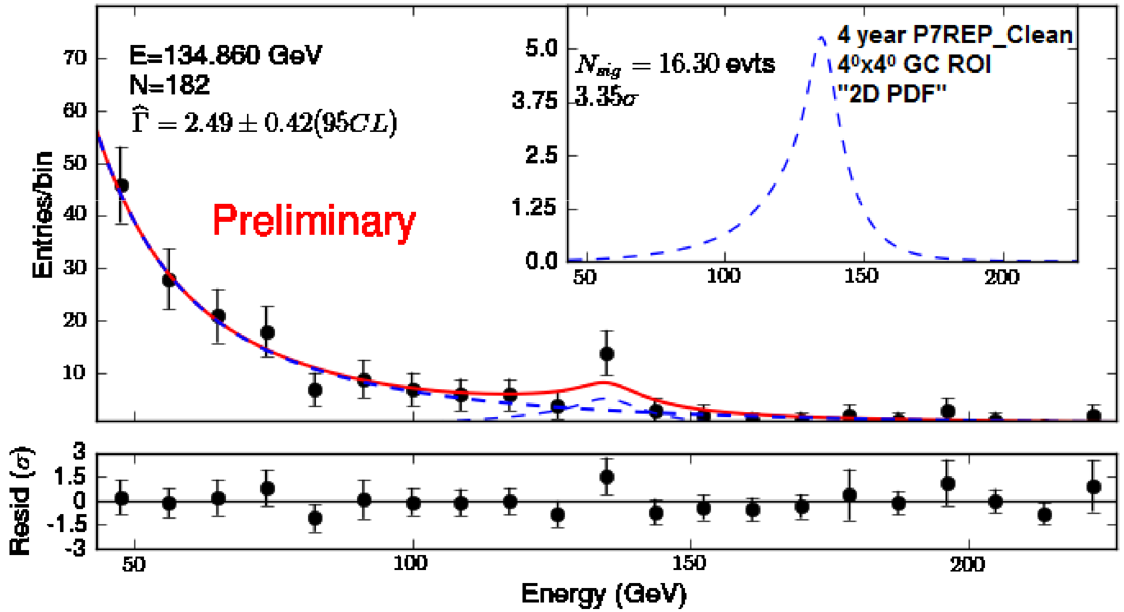
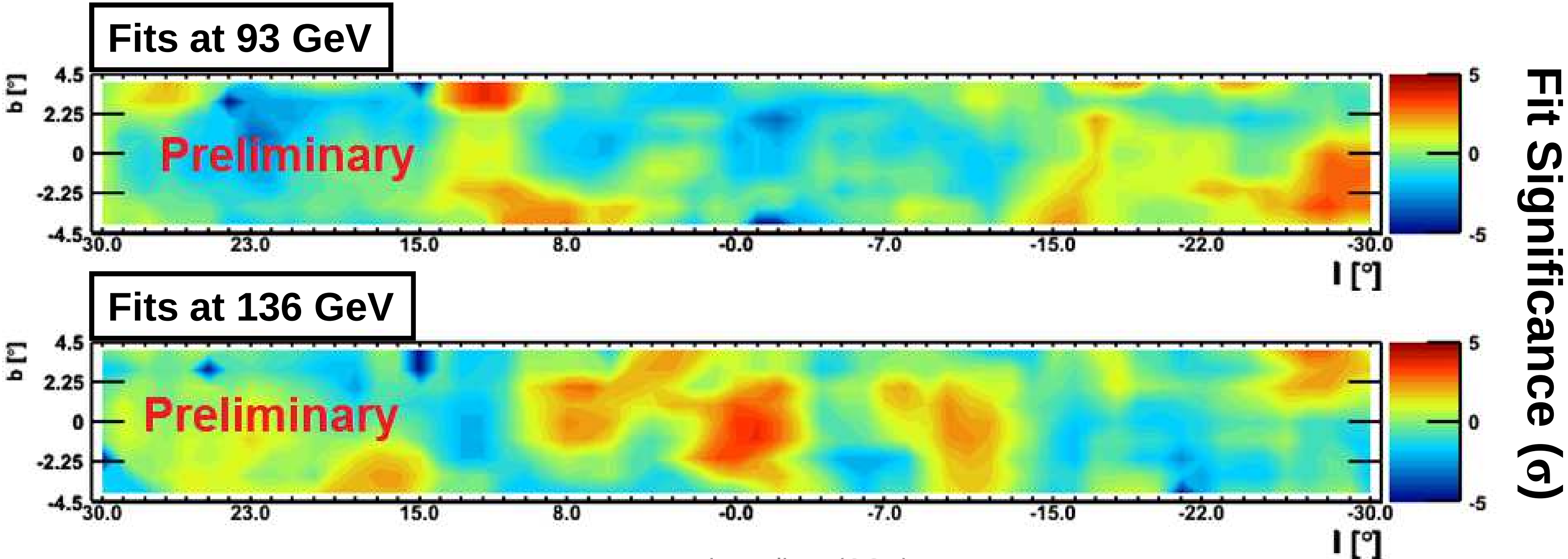
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- 3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 2D PDF
    - P_E in data → feature is slightly narrower than expected
  - <2σ global



Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs

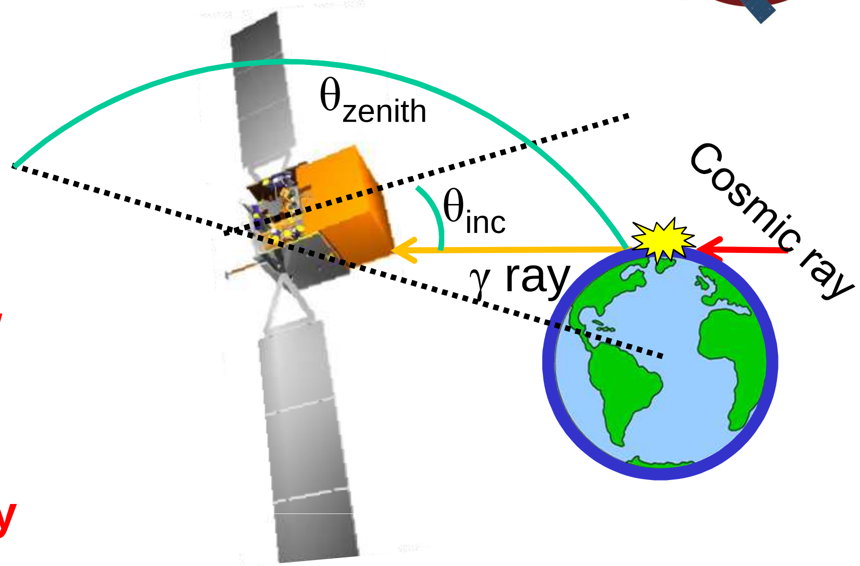
Spatial Morphology of Features in Galactic Plane

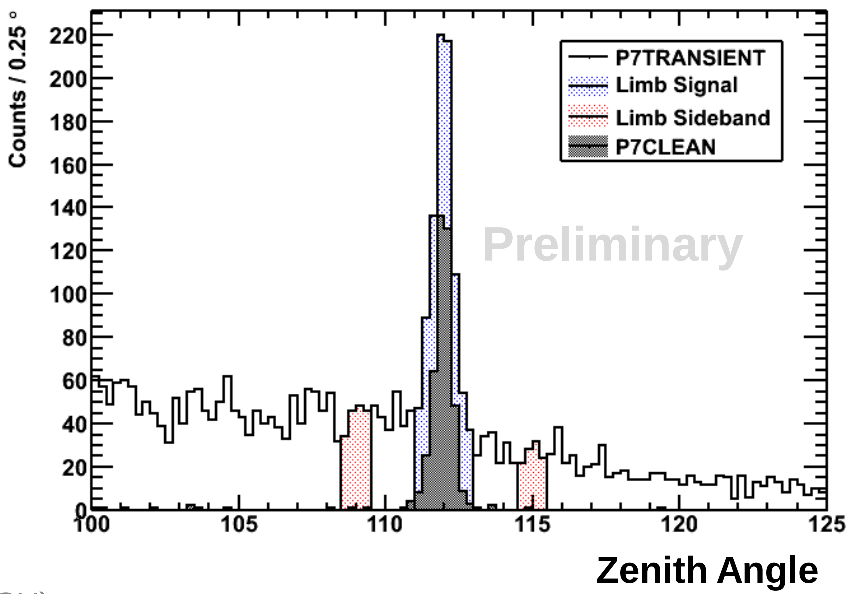
- Fit in 4°x4° ROIs along the Galactic plane in 1° steps
  - Fit with “1D PDF”
    - To find where the counts are coming from
    - Allowed for negative fluctuations
- Find excess near ~135 GeV near GC
  - But find similar features at other energies along the GP
  - Some indication the 135 feature not smooth, but 2-3 smaller “hot spots”
  - Excess near 135 GeV is one of the largest and near GC, but is not otherwise unique



135 GeV in the Earth Limb spectrum (1)

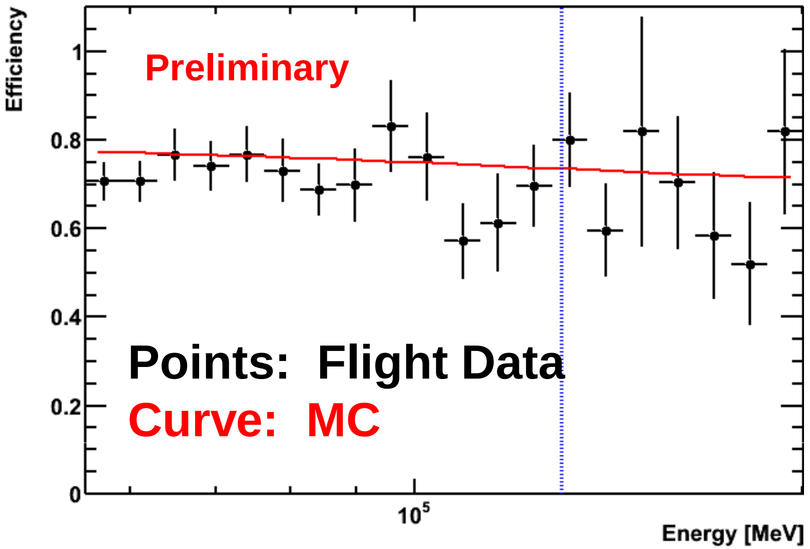
- **Earth Limb is a bright, well understood source**
  - **γ rays from CR interactions in the atmosphere**
    - **Expected to be a smooth power-law**
  - **Can be used to study instrumental effects**
    - **Can see in loosest cuts → can study cut efficiencies**
- **Need to cut on times when the LAT was pointing at the limb**
- **Have made changes to increase our Limb dataset**
  - **Pole-pointed observations each week**
  - **Extended "targets of opportunity"**
    - **Trace limb while target is occulted**



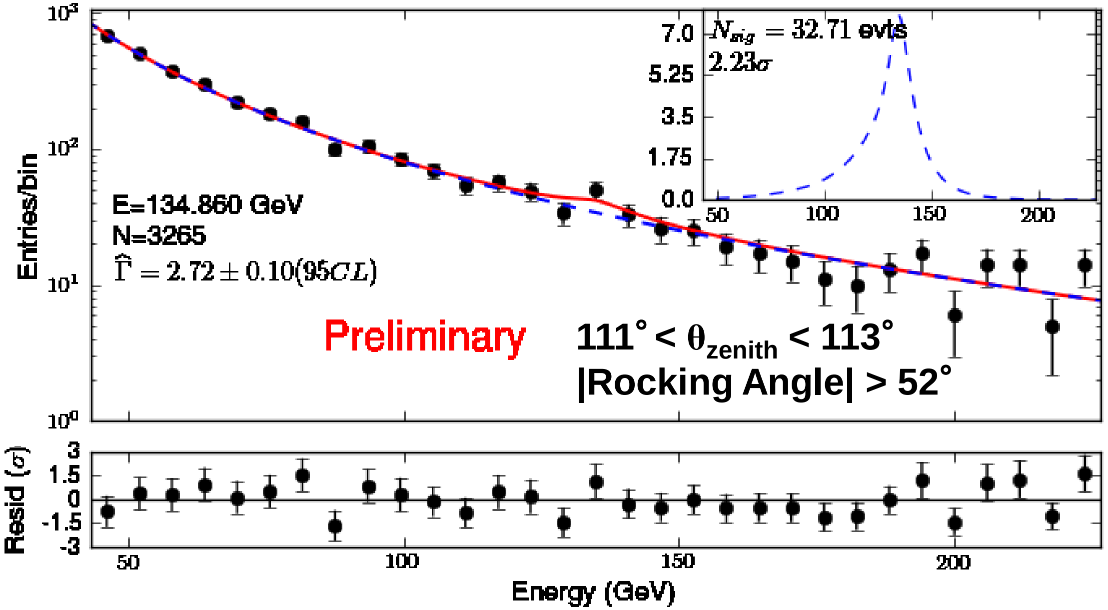


135 GeV in the Earth Limb spectrum (2)

P7Transient to P7Clean Efficiency

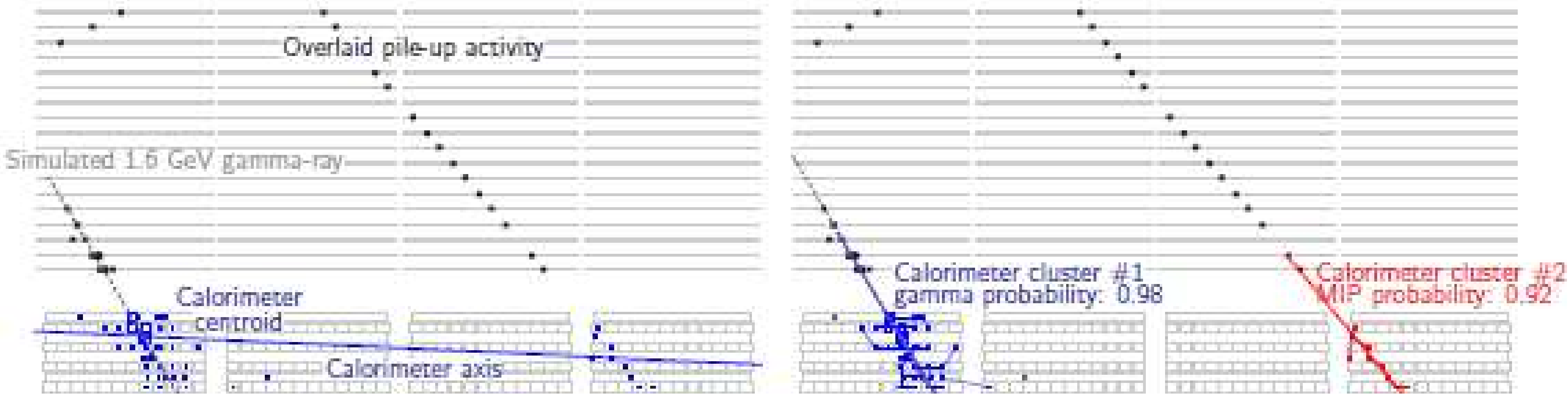


Fit to Limb data



- Dips in efficiency below and above 135 GeV
  - Appear to be related to CAL-TKR agreement
  - Could be artificially sculpting the energy spectrum
- Line-like feature in the limb at 135 GeV
  - Appears when LAT is pointing at the Limb
  - Surprising since limb should be smooth
  - S/N_{limb} ~18%, while S/N_{GC} ~30% - 66% (depending on ROI choice)
    - Limb feature not large enough to explain all the GC signal

Pass 8



- **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**
- **Better control over systematic uncertainties**
- **Extend both low and high energy reach**
- **Include calorimeter-only events (substantial effective area increase above 40 GeV)**
- **Better high-energy point spread function**

Summary

- The Fermi LAT team has looked for indirect DM signals using a wide variety of different methods
  - So far no signals have been detected and strong constraints have been set
- Observed deviations from conventional models in e^+e^- spectrum
  - Confirm PAMELA e^+ fraction increase
- We do not see any globally significant spectral lines
- Uncovered some aspects of the 135 GeV line that require more study
  - Significance decreases with analysis improvements
  - Also present in the Earth limb
  - Too soon to draw firm conclusions, more data needed
    - More data + Pass 8 will give a more definitive answer in 1 year
- Current searches are already exploring interesting parts of WIMP phase space and will just keep getting more sensitive; stay tuned for more exciting Dark Matter results from the Fermi LAT!

Fermi LAT Collaboration References

- **For a list of Fermi LAT collaboration publications**
  - **see http://www-glast.stanford.edu/cgi-bin/pubpub**
- **"The Fermi Large Area Telescope On Orbit: Event Classification, Instrument Response Functions, and Calibration**
  - **arXiv: 1206.1896**
- **"Fermi LAT observations of cosmic-ray electrons from 7 GeV to 1 TeV"**
  - **arXiv: 1008.3999**
- **"Measurement of separate cosmic-ray electron and positron spectra with the Fermi Large Area Telescope"**
  - **arXiv: 1109.0521**
- **"Constraints on the Galactic Halo Dark Matter from Fermi-LAT Diffuse Measurements"**
  - **arXiv: 1205.6474**
- **"Constraining Dark Matter Models from a Combined Analysis of Milky Way Satellites with the Fermi Large Area Telescope"**
  - **arXiv: 1108.3546**
- **"Fermi LAT Search for Dark Matter in Gamma-ray Lines and the Inclusive Photon Spectrum"**
  - **arXiv: 1205.2739**
- **"Anisotropies in the diffuse gamma-ray background measured by the Fermi LAT"*****
  - **arXiv: 1202.2856**
- **Profumo and Linden, "Gamma-ray Lines in the Fermi Data: is it a Bubble?"*****
  - **arXiv: 1204.6047**
- **M.N. Mazziotta et al "A model-independent analysis of the Fermi Large Area Telescope gamma-ray data from the Milky Way dwarf galaxies and halo to constrain dark matter scenarios"*****
  - **arXiv:1203.6731**
- **M. Ajello et al (The Fermi LAT Collaboration) "Constraints on dark matter models from a *Fermi* LAT search for high-energy cosmic-ray electrons from the Sun"*****
  - **arXiv:1107.4272**

***not discussed in this talk

BACKUP SLIDES

Halo Method I – "No-background" Limits

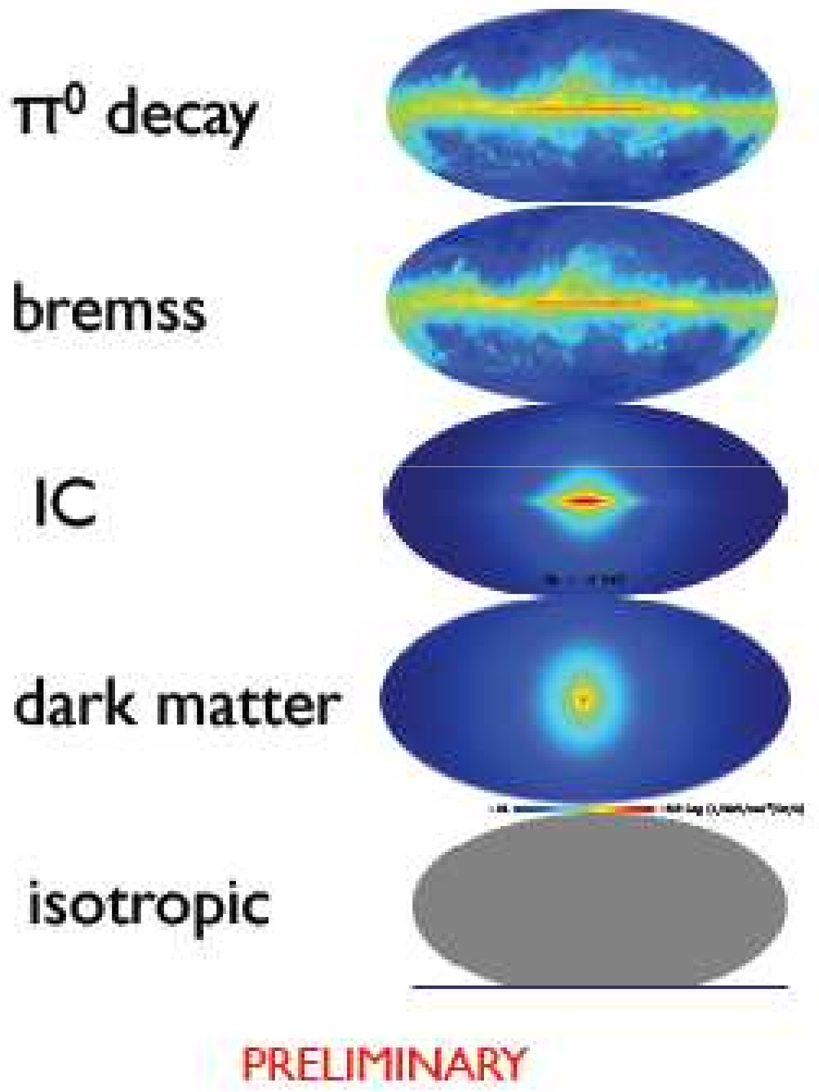
- **Conservative**
  - **Method II w/detailed bkg modeling on next slide**
- **No non-DM background modeling**
  - **Robust to many uncertainties**
- **Expected DM counts (n_{DM}) compared to observed counts (n_{data}) and 3σ and 5σ upper limits are set using**

$$n_{DM} - 3(5)\sqrt{n_{DM}} > n_{data}$$

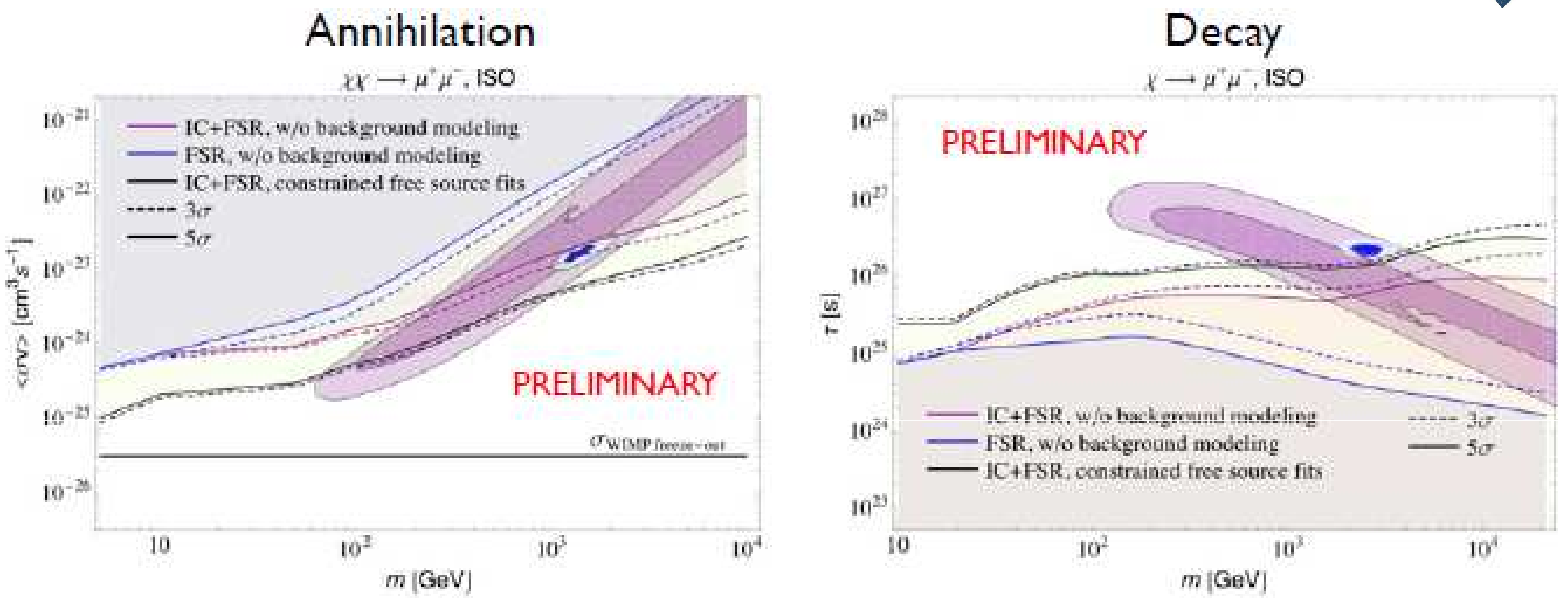
in at least one energy bin

Halo Method II – Limits + Bkg Modeling

- **Profile likelihood fit combining several GALPROP diffusion models with DM**
  - **Derives DM limits marginalized over astrophysical uncertainties**
- **Allow several bkg parameters to vary**
  - **CRE injection index, diffuse halo height, gas (HI) to dust ratio, CR source distribution, local H_2 to CO factor, and isotropic normalization**
- **Distribution of CR sources is uncertain, so left free in radial Galactic bins.**
  - **To be conservative to DM constraints, CR source distribution set to zero in the inner 3 kpc**
- **Maps of each GALPROP + DM model are made and fit to the Fermi LAT data, incorporating both morphology and spectra**



MW Halo Results- $\mu^+\mu^-$

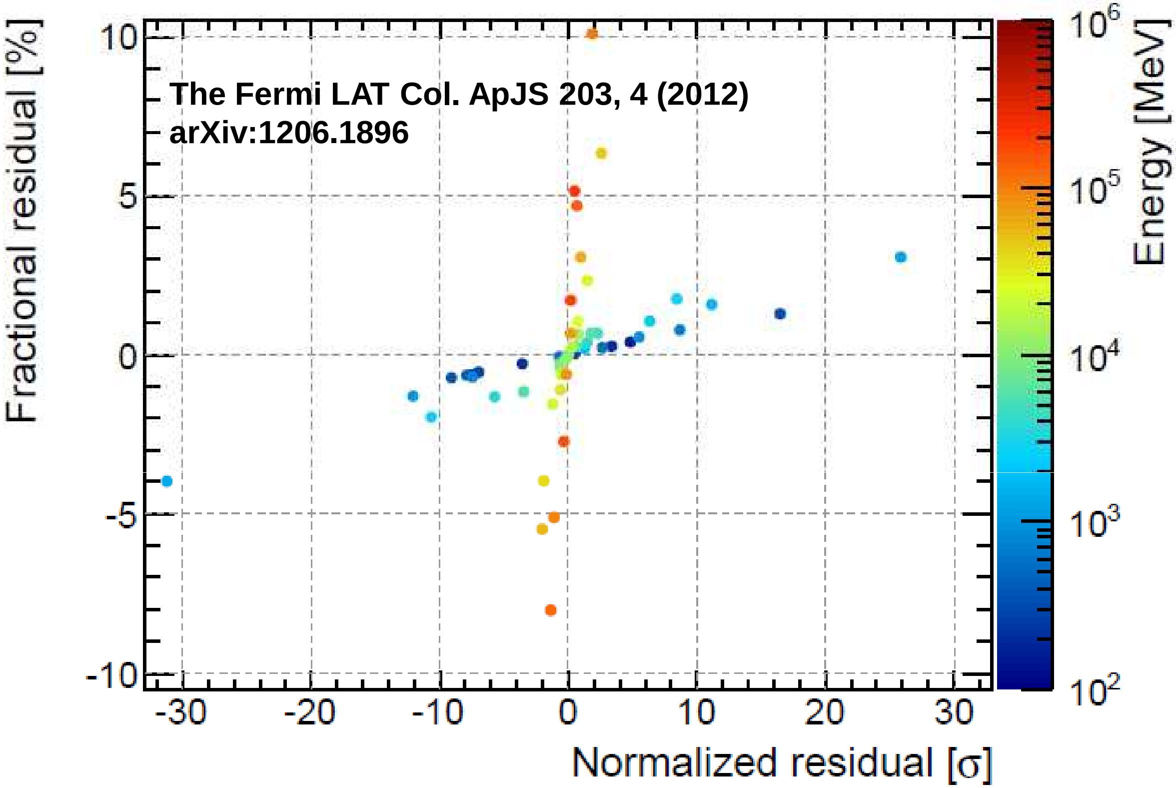


M. Ackermann et al. [Fermi LAT Collaboration], submitted

- Set limits assuming only Final State Radiation and FSR + Inverse Compton
  - Only FSR = only photons produced by muons (no electrons)
  - "FSR + IC" includes IC gamma rays from electrons produced via DM annihilation/decay
- Contours show 2σ and 3σ CL fits to PAMELA (purple) and Fermi (blue) positron fraction
  - DM interpretation of positron fraction strongly disfavored (for annihilating DM)

Fractionally small, but significant deviations

- **We see fractionally small, but significant fluctuations in the galactic data and limb spectrum at low energies**
  - **Fractional deviation ≈ or smaller than uncertainties in A_{eff}**
  - **See similar features in earth limb at low energies**
    - **See section 7.5 of Pass 7 performance paper**
      - **The Fermi-LAT Col. ApJS 203, 4 (2012)**
  - **Need to consider both fit significance *and* fractional deviation**



$$resid_{frac} = \frac{(n_i - f_i)}{f_i}$$

$$resid_{norm} = \frac{(n_i - f_i)}{\sqrt{f_i}}$$