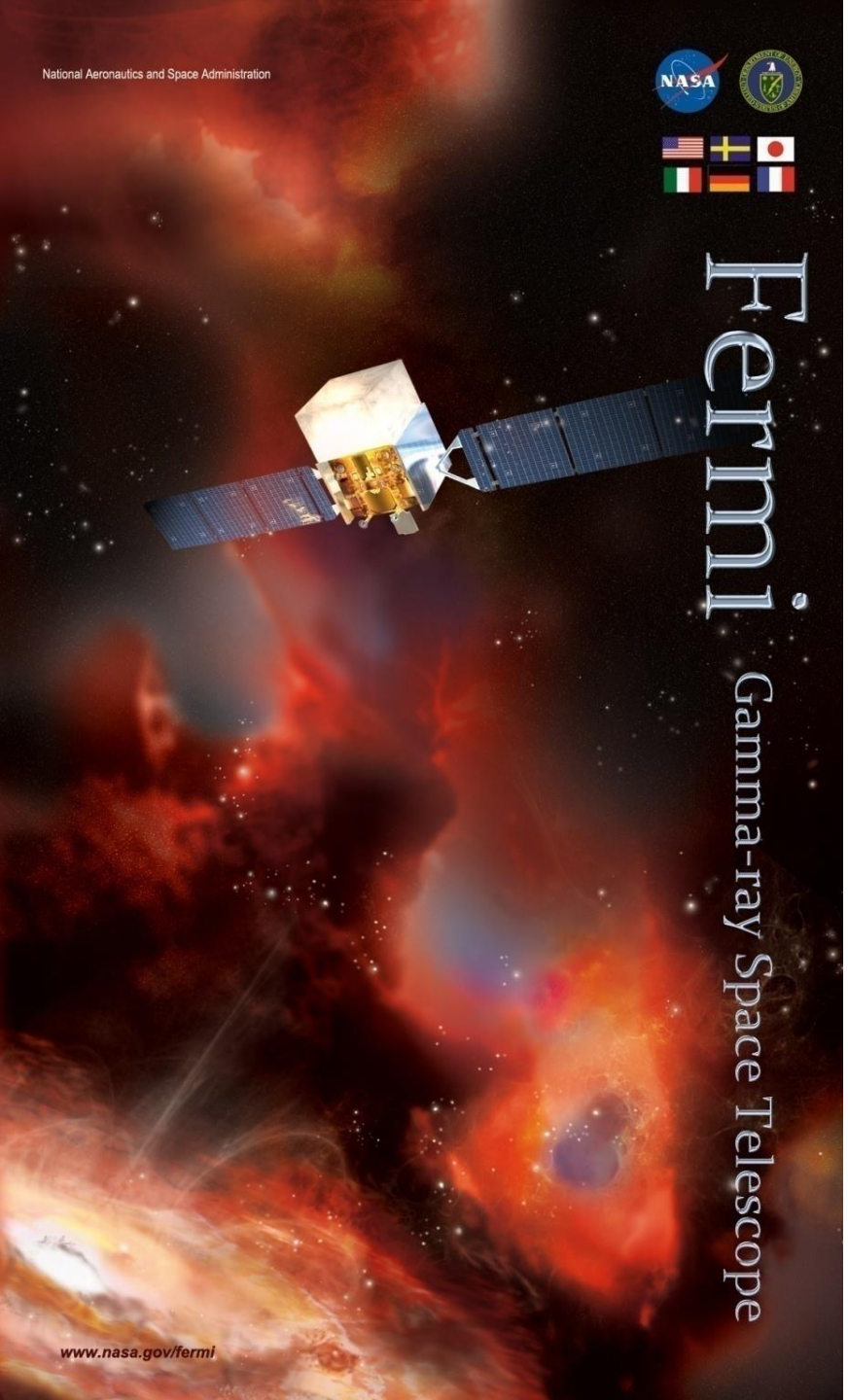

SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC

Fermi Gamma-ray Space Telescope

Update on the Two "Smoking Gun" Fermi LAT Searches for Dark Matter- Milky Way Dwarfs and Lines

Elliott Bloom

KIPAC-SLAC, Stanford University

On Behalf of the Fermi-LAT Collaboration

What We are Learning From the Gamma-Ray Sky

University of Minnesota, Minneapolis

October 10-12, 2013

Acknowledgements

- Milky Way Dwarf results are submitted for publication to PRD and the submitted paper is on the Archive, arXiv:1310.0828v1 [astro-ph.HE]. This study was the topic of the Stanford University Thesis of Alex Drlica-Wagner (now at Fermilab). Preliminary results were presented at the Fermi Symposium in Monterey, October 28 - November 2, 2012

- Line Search results paper has been accepted for publication by PRD and this version of the paper is on the Archive, arXiv:1305.5597v3 [astro-ph.HE]. This study was the topic of the Ohio State University Thesis of Andrea Albert (now at SLAC). Preliminary results were presented at the Fermi Symposium in Monterey, October 28 - November 2, 2012

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)

Gamma-rays from WIMPs

Flux from annihilating DM particles

What we observe

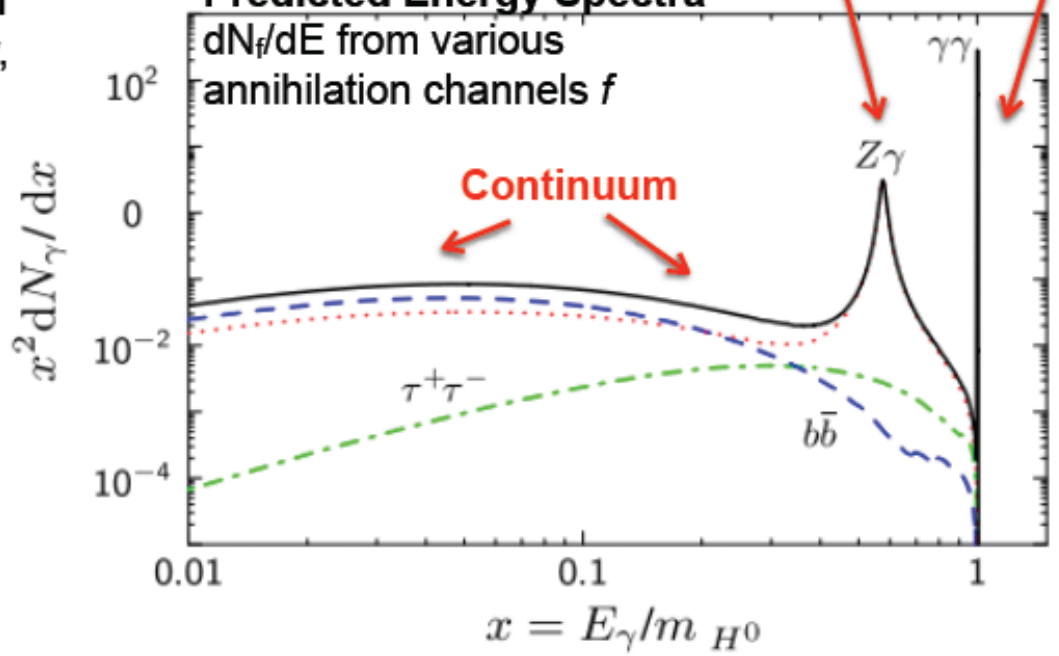
Intrinsic Particle Properties

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

DM Annihilation Cross Section
averaged cross-section × velocity,
@ freeze-out ≃ $3\cdot10^{-26}$ cm^3/s

Monochromatic lines

Predicted Energy Spectra
dN_f/dE from various annihilation channels f



Gustafsson et al. PRL 99.041301

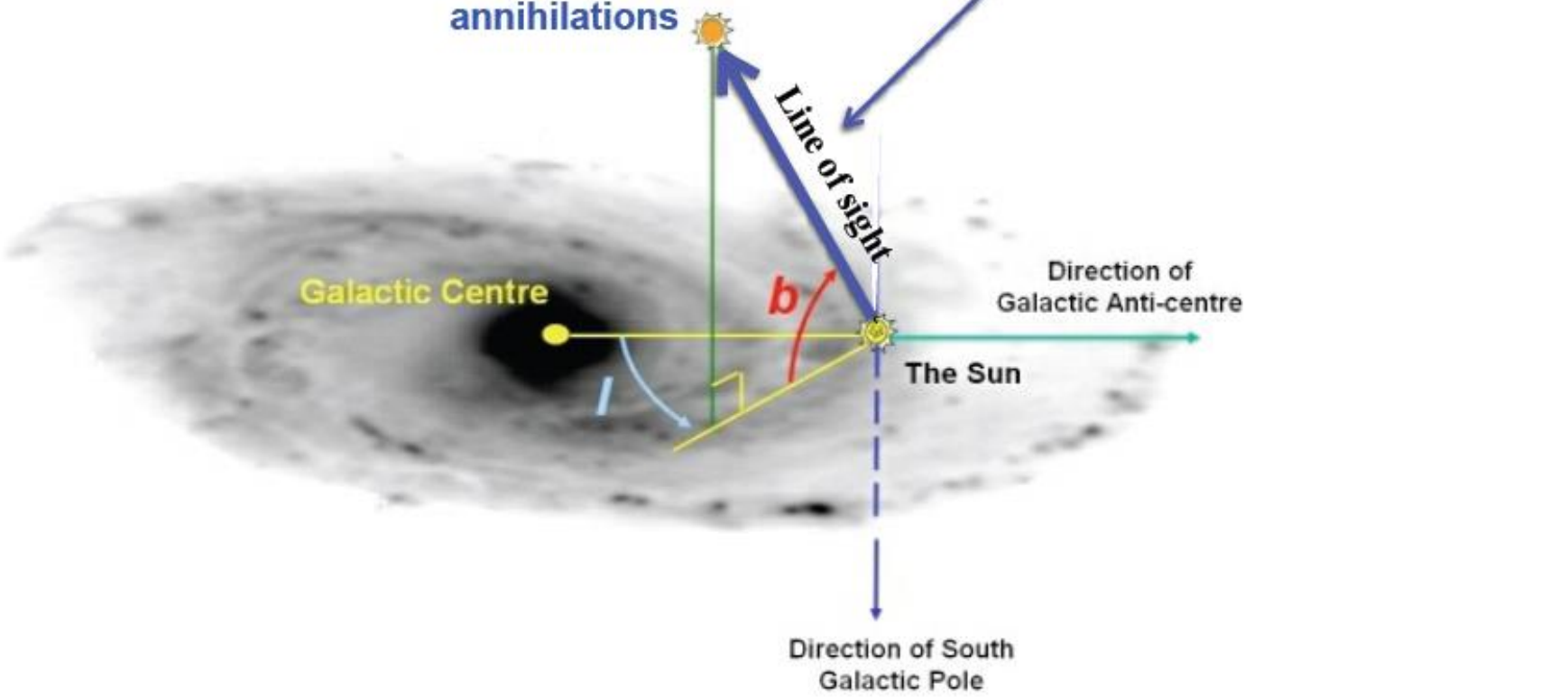
Gamma-rays from WIMPs

Flux from annihilating DM particles

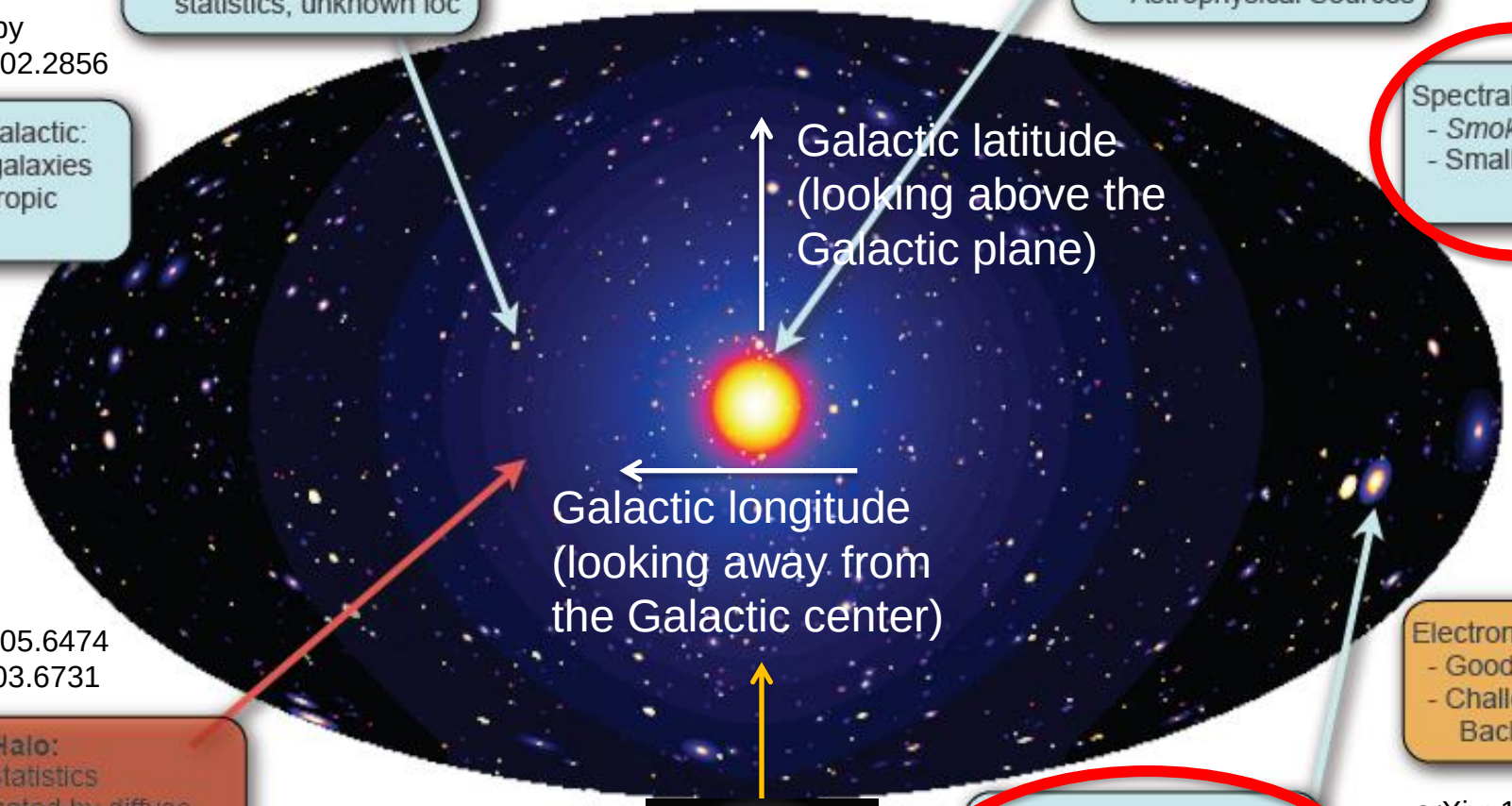
What we observe | Intrinsic Particle Properties | Astrophysics (J-factor)

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

WIMP number density squared



Galactic Distribution of DM



DM Clumps in the Halo:
- Few Astro. Bkg
- Complicated by low statistics, unknown loc

arXiv: 1201.2691

Inner galaxy
arXiv: 1308.3515

Galactic Center:
- Large Statistics
- Complicated by Astrophysical Sources

Anisotropy
arXiv: 1202.2856

Extragalactic:
- All galaxies
- Isotropic

Spectral Lines:
- *Smoking Gun*
- Small Stat.

Galactic latitude (looking above the Galactic plane)

Galactic longitude (looking away from the Galactic center)

arXiv: 1205.6474
arXiv:1203.6731

Galactic Halo:
- Large Statistics
- Complicated by diffuse Y-rays from Cosmic Rays

Electrons:
- Good Stats.
- Challenge: Backgrounds

arXiv: 1109.0521
arXiv:1107.4272

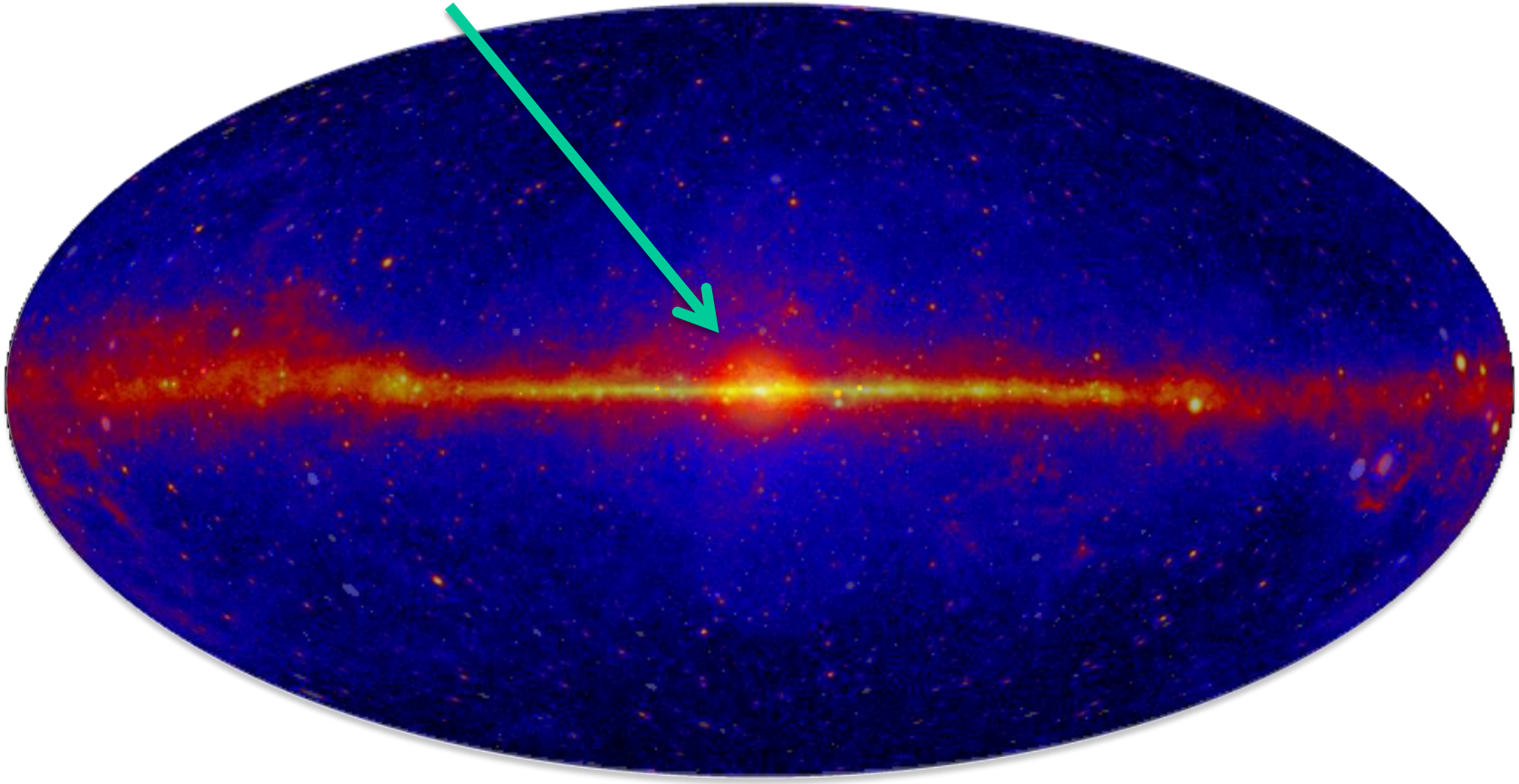
Nearby Galaxies:
- dSph DM Enriched
- Known location
- Lower Statistics
- *Smoking Gun*

Milky Way Halo simulated by Taylor & Babul (2005)

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

Large Astrophysical Background

Smooth component peaked in Galactic Center
(central cuspiness has large uncertainties)

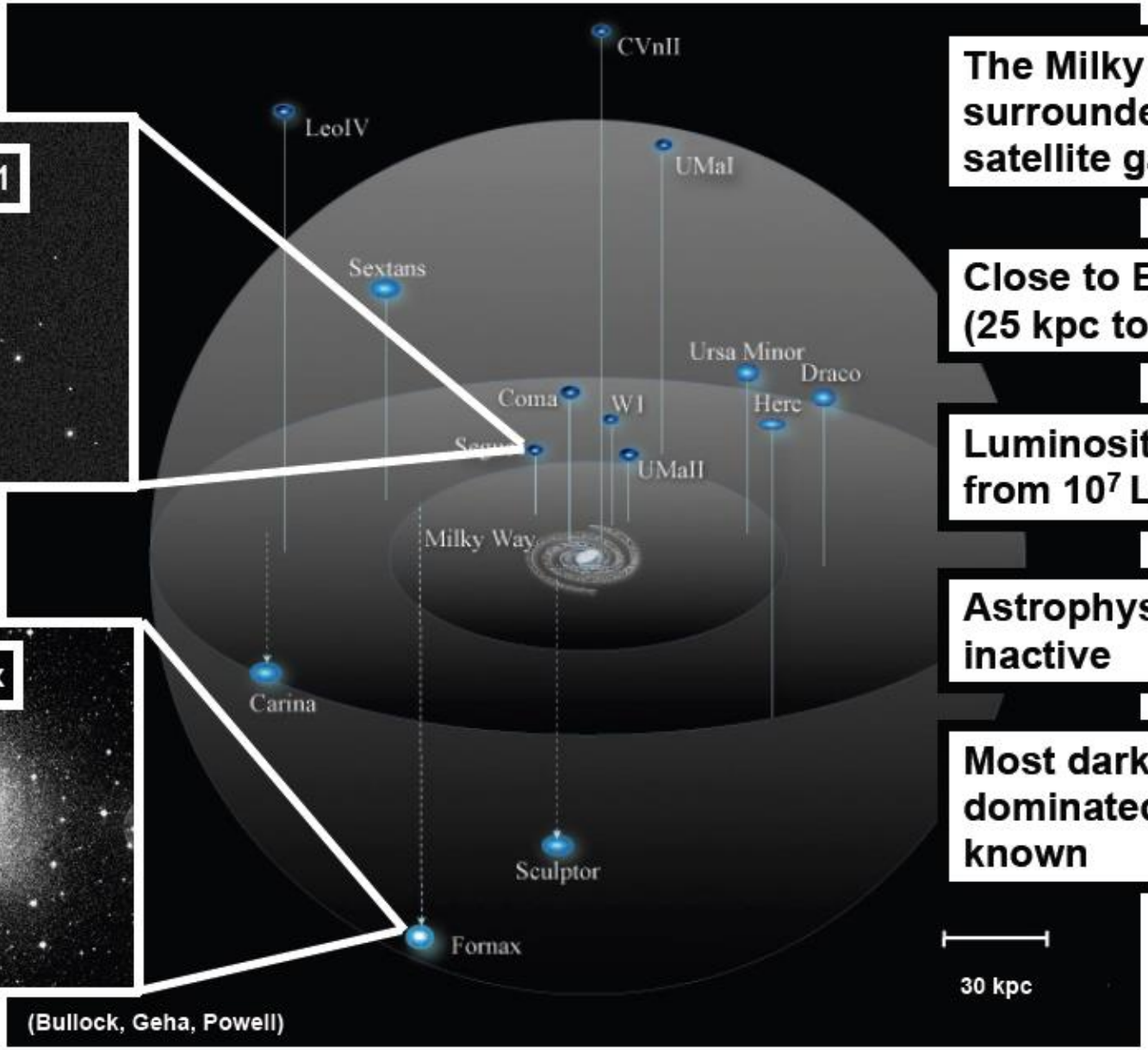


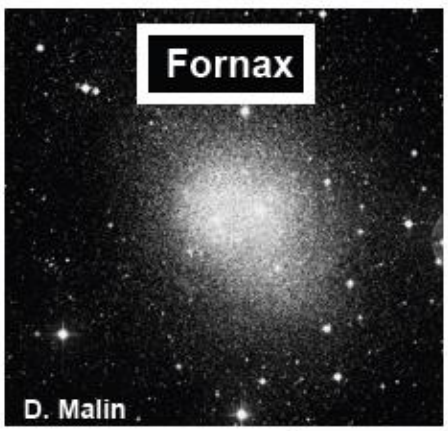
Milky Way Halo simulated by Taylor & Babul (2005)
All-sky map of DM gamma-ray emission (Baltz 2006)

2 Smoking Guns for Indirect Detection

- **Dwarf Galaxies**
  - **Very few stars**
  - **Signal in gammas is difficult to explain without DM origin.**
    - **not seen in other wavelengths – radio, x-ray**
      - **absence of pulsars, SNR**
      - **very little gas**
      - **small magnetic fields**
  - **DM signal will have common spectral characteristics in many dwarf galaxies, i.e., common WIMP annihilation/decay.**
    - **Can measure J factors from stellar motion.**
- **Narrow Gamma line**
  - **can't ascribe to other sources besides DM signal**
    - **same energy line over a large region of the sky**
    - **signal should follow a DM profile**
    - **not associated with a single "point" source**

Fermi LAT DM Search in MW Dwarf Galaxies





The Milky Way is surrounded by small satellite galaxies

Close to Earth (25 kpc to 250 kpc)

Luminosities range from $10^7 L_\odot$ to $10^3 L_\odot$

Astrophysically inactive

Most dark matter dominated objects known

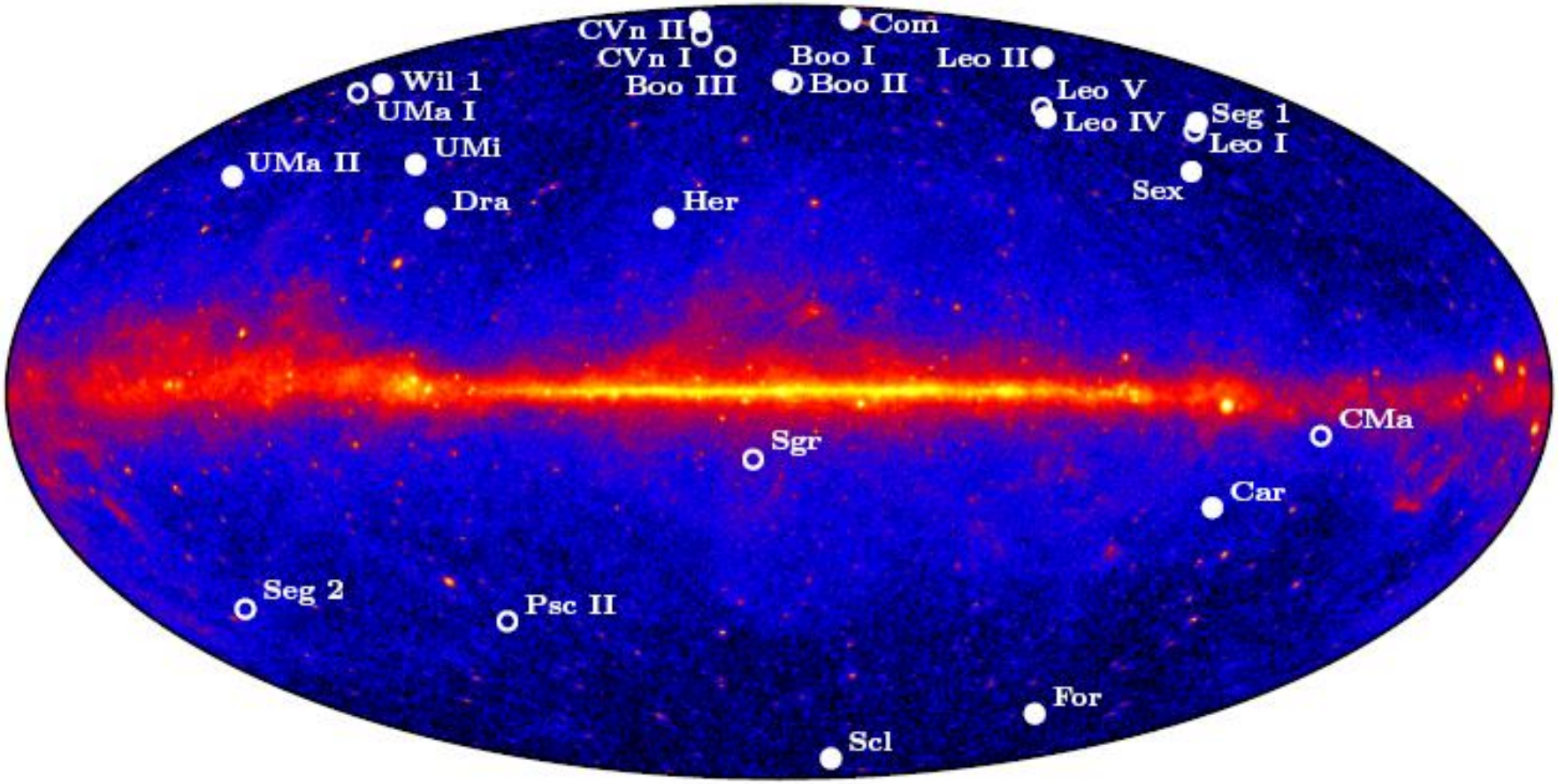
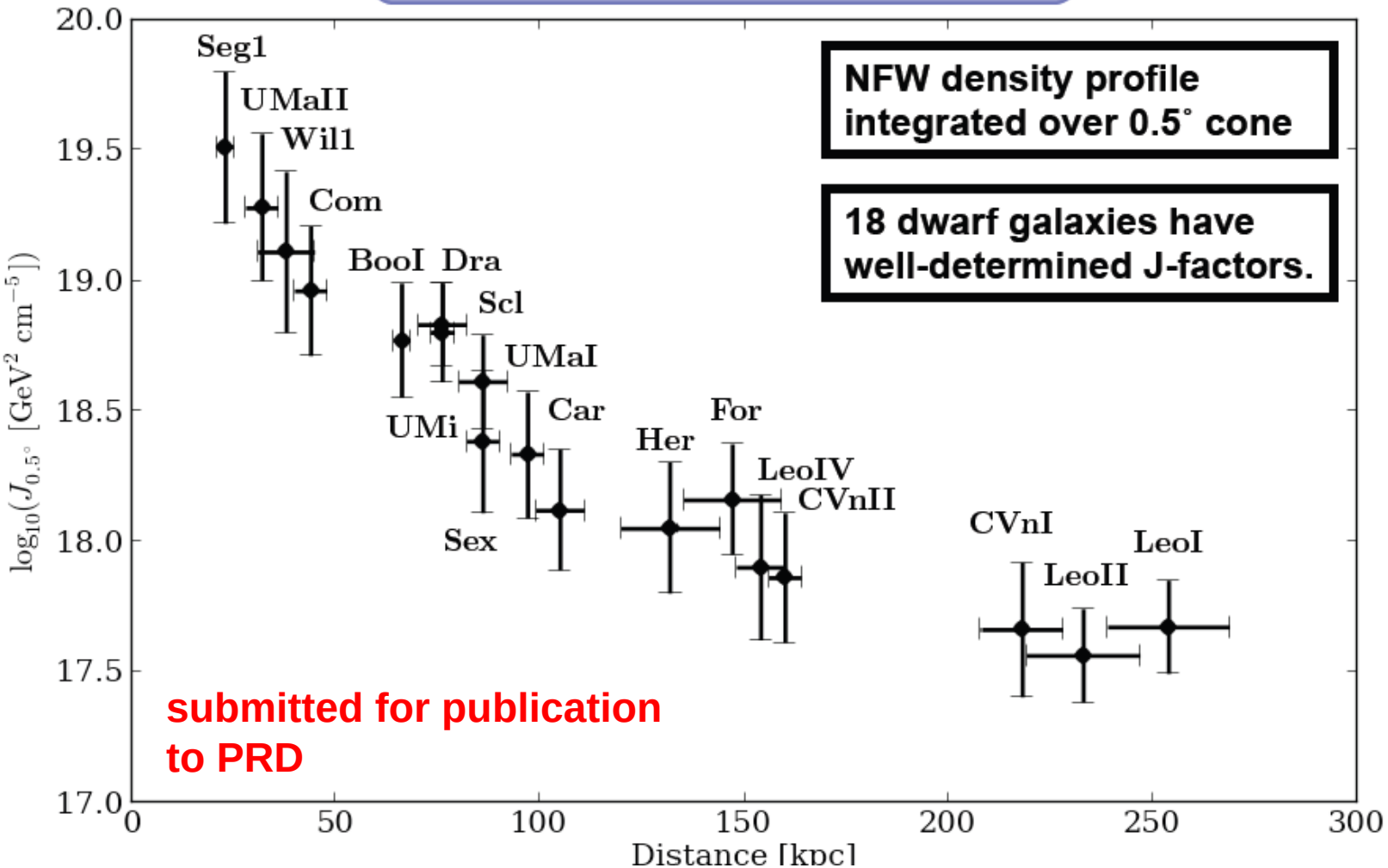


FIG. 1. Known dwarf spheroidal satellite galaxies of the Milky Way overlaid on a Hammer-Aitoff projection of a 4-year LAT counts map ($E > 1$ GeV). The 15 dwarf galaxies included in the combined analysis are shown as filled circles, while additional dwarf galaxies are shown as open circles.

J-Factors for Dwarf Galaxies

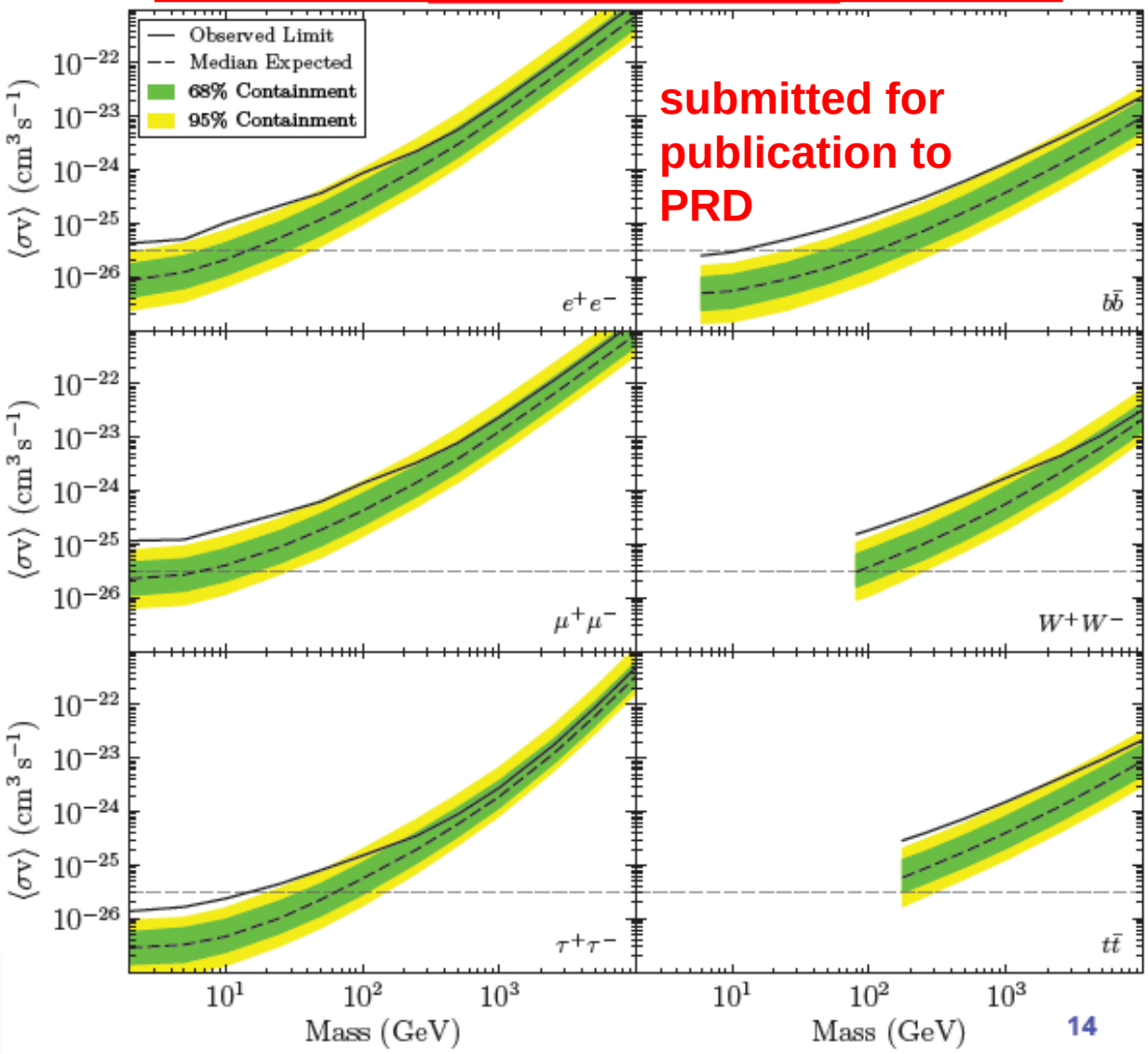
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



Combined Limits at 95%CL

Gtobssim Simulation for bands and median

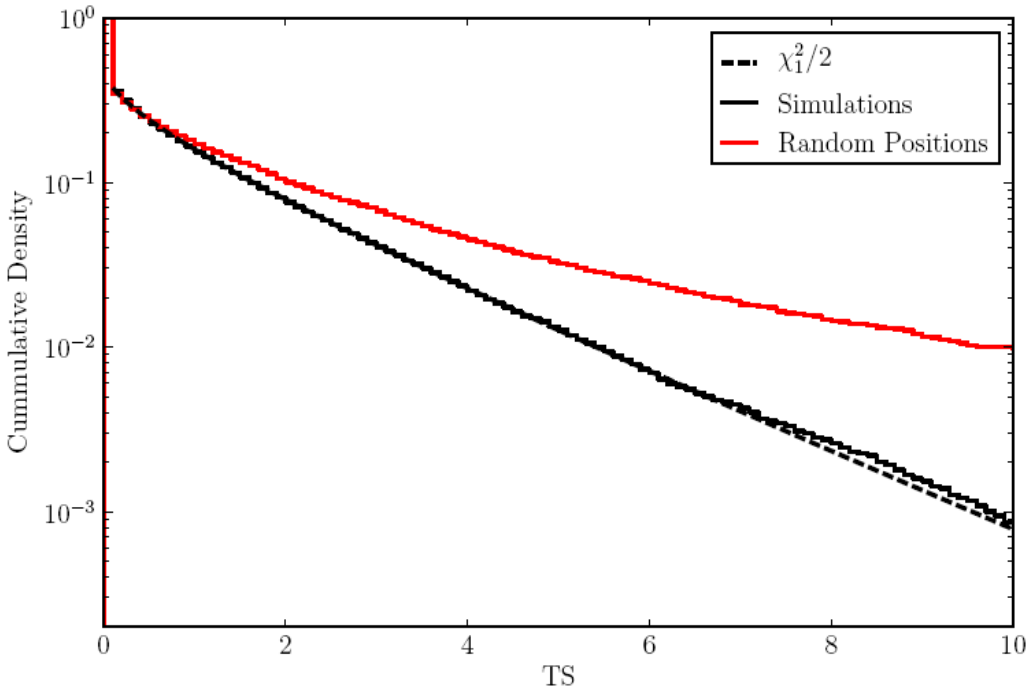
- 4 years of LAT data
- 15 dwarf galaxies
- Expected sensitivity calculated from 2000 sets of 15 realistic simulations
- 6 prototypical dark matter annihilation channels
- Dark matter particle masses ranging from 2 GeV to 10 TeV (when kinematically allowed)
- Observed limits (solid line) from data



Statistical and Systematic Effects

- Distribution of TS values in the data does not follow asymptotic theorems
- Local significance:
  - Simulations: p-value = 1.6×10^{-3} (~2.9σ)
- Global significance:
  - Simulations: p-value = 2.4×10^{-2} (~2.0σ)
  - Data : p-value = 8.3×10^{-2} (~1.4σ)
- Confounding features of the data:
  - Unresolved background sources
  - Instrumental features
  - Imperfect modeling of the diffuse background
- Additional systematic uncertainties:
  - Instrument response (< 15%)
  - Diffuse backgrounds (< 10%)
  - Dark matter profile (< 20%)

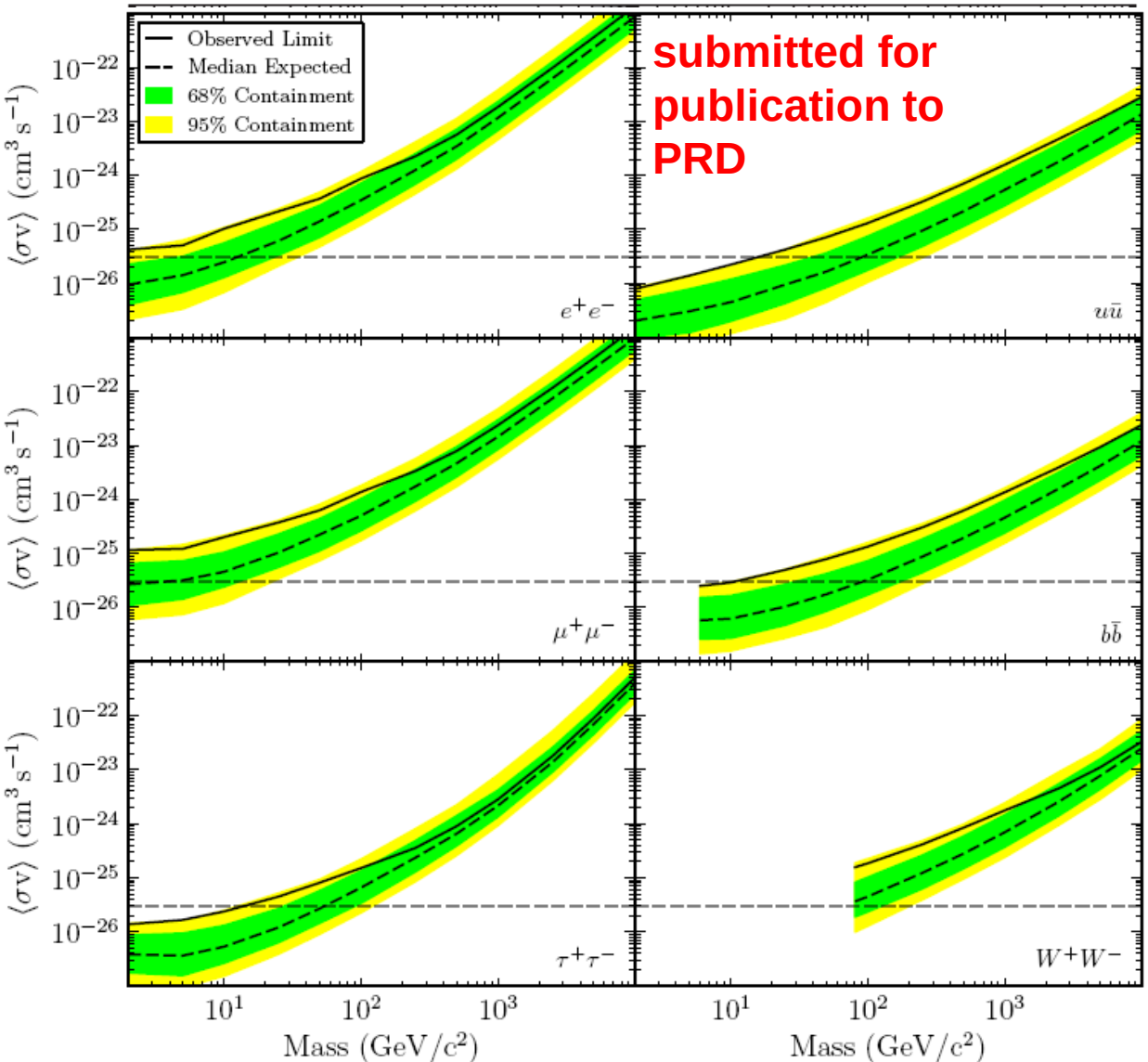
BBbar = 25 GeV
TS vs. N>TS



Combined Limits at 95%CL

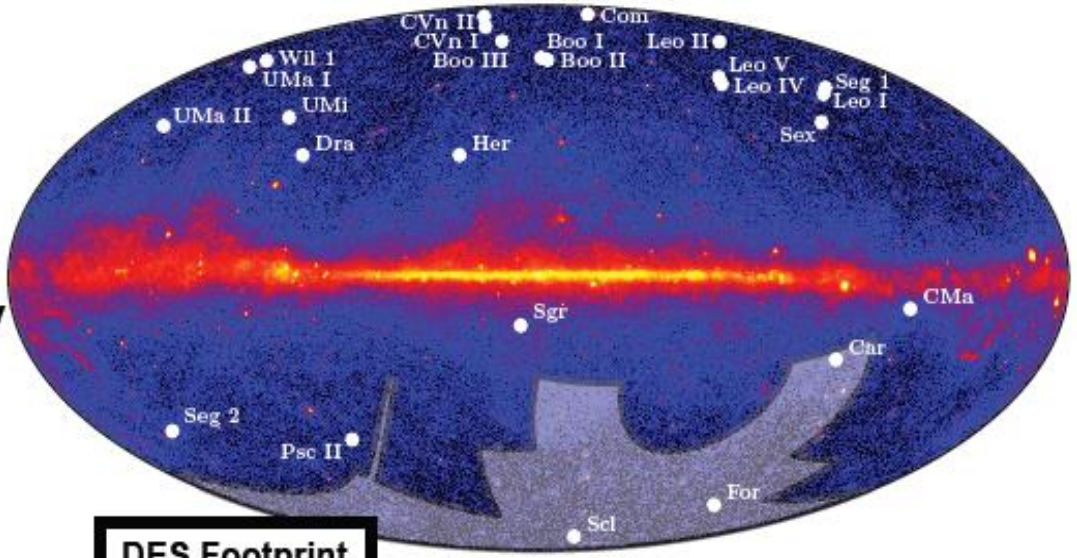
All Data

- Same observed limits
- Expected sensitivity calculated from the data
- 300 sets of 15 random sky locations
- High-Galactic-latitude (|b|>20)
- >1˚ from LAT catalog sources
- Reduces discrepancy between observations and expectations
- **No DM seen**

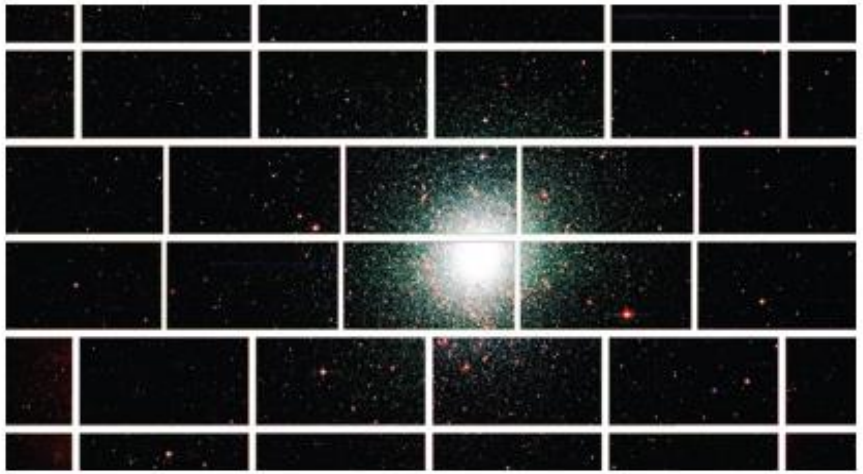


Finding More Dwarf Galaxies

- The number of known dSphs has doubled due to SDSS.
  - SDSS only covers ~25% of the sky
  - SDSS has a magnitude limit of ~22
- New wide-field surveys plan to greatly expand our coverage:
  - Pan-STARRS:
    ~75% of the sky from the north
  - Southern Sky Survey:
    ~75% of the sky from the south
  - DES:
    ~5000 deg^2 in the south (deeper)
  - LSST:
    ~50% of the sky (much deeper)
- Eventually hope to be complete for all bound dwarf galaxies ($L > 10^2\ L_\odot$)
- Simulations predict hundreds of Milky Way satellite galaxies



DES Footprint



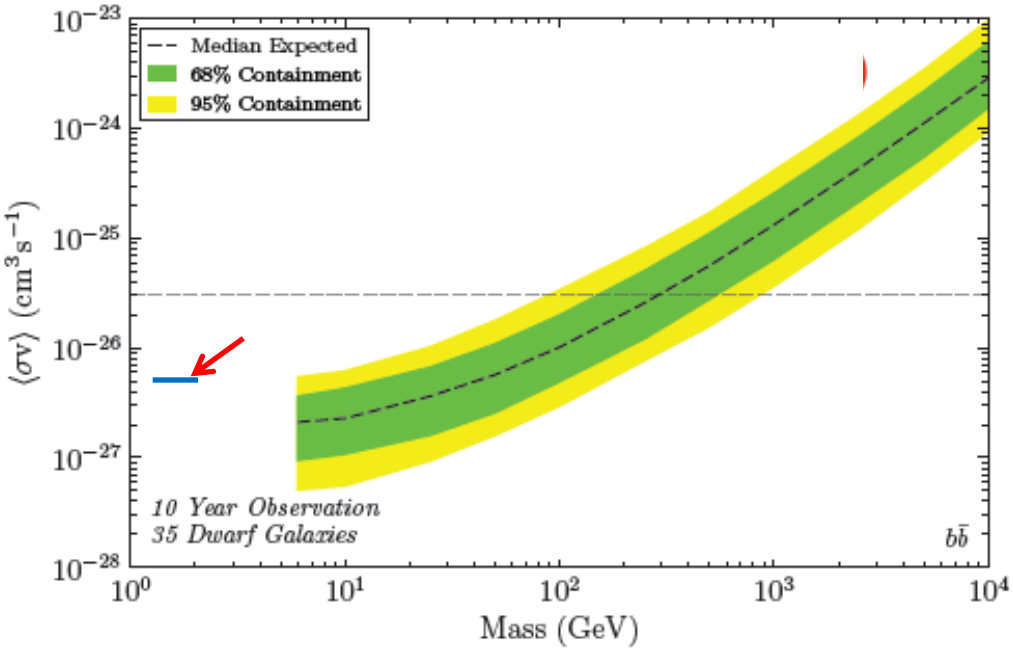
Globular Cluster 47 Tuc (DES Collaboration)

Tollerud et al. "Hundreds of Milky Way satellites? Luminosity bias in the satellite luminosity function." Ap.J. 668:227 (2008)

Finding More Dwarf Galaxies

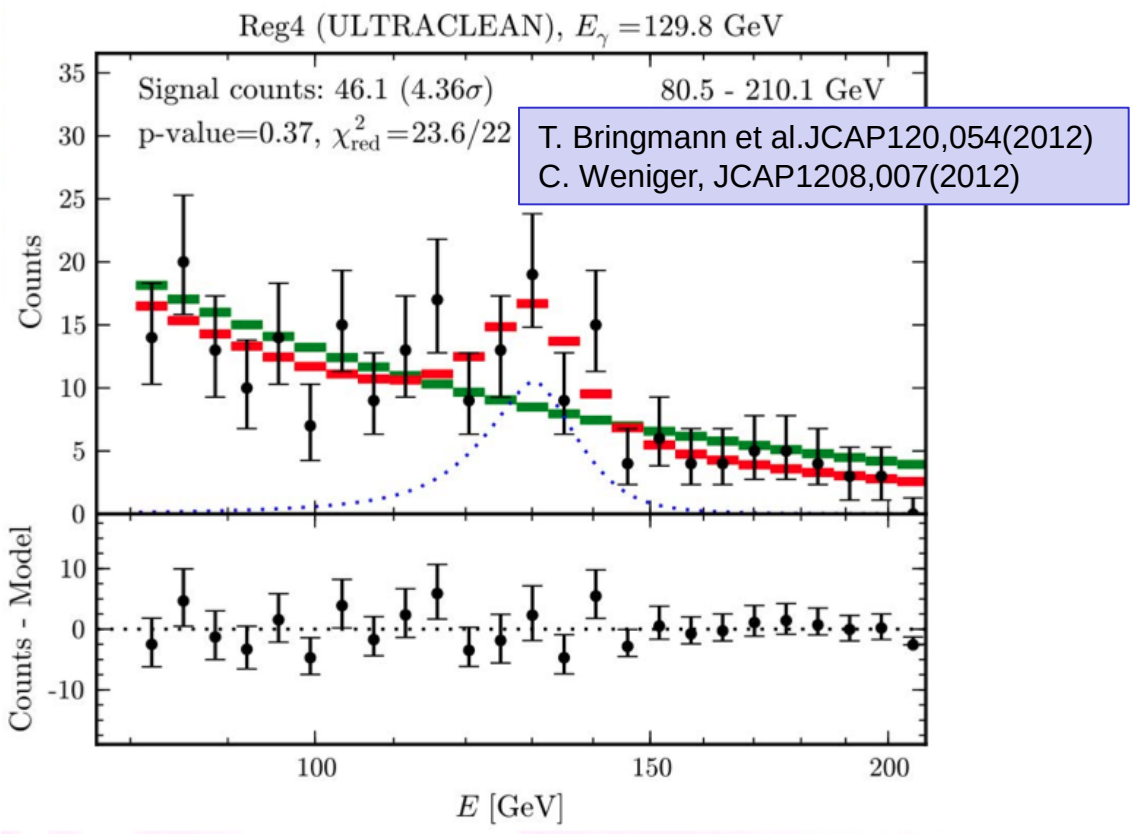
- **Conservatively assume that upcoming surveys find 20 more dwarf galaxies.**
- **Assume that the characteristics of these new galaxies are similar to those recently discovered by SDSS.**
  - **High Galactic Latitude**
  - **Comparable J-factors and uncertainties**
- **Combine additional dwarfs with continued LAT operations.**
  - **10 years of LAT data taking**
  - **Current instrument performance**
- **Expect sensitivity to the thermal relic cross section for dark matter particles with masses ~350 GeV**
- **Does not include improvements to the LAT instrument...**

BBbar

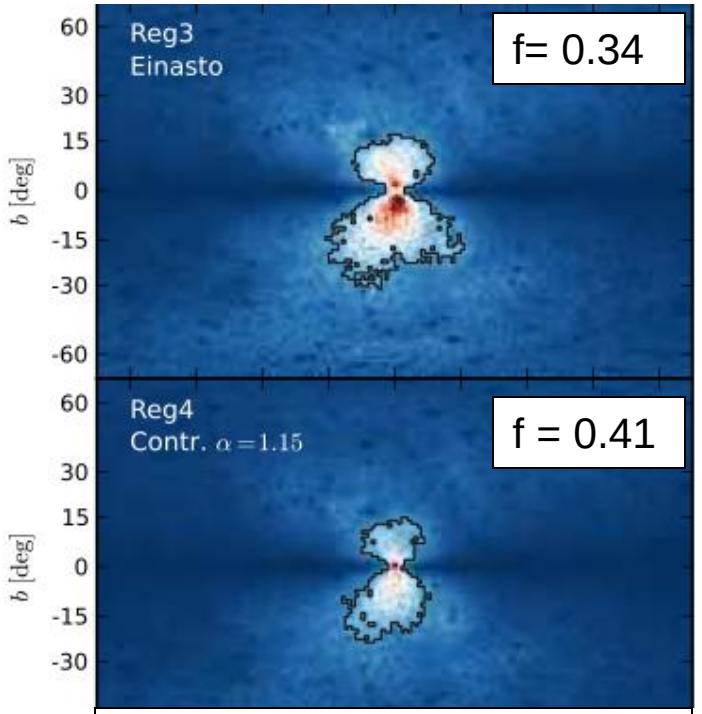


Only valid if systematics can be controlled

Reported Narrow Feature at 130 GeV



T. Bringmann et al.JCAP120,054(2012)
C. Weniger, JCAP1208,007(2012)

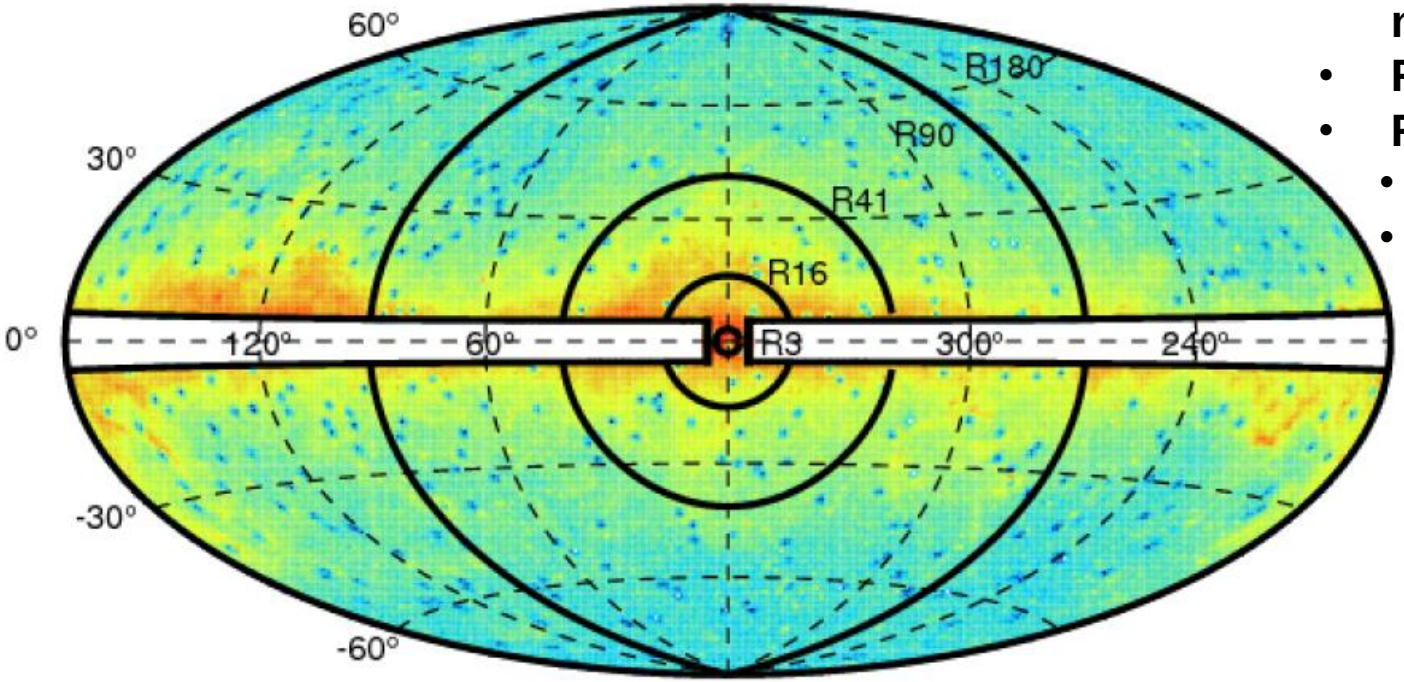


Frac Residual (i.e., S/N):
$f = s_{local}^2 / n_s$

- **Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC)**
- **Signal is particularly strong in 2 out of 5 test regions, shown above**
- **Over 4σ, with S/N > 30%, up to ~60% in optimized regions of interest (ROI)**

Fermi LAT Search for Spectral Lines

3.7 year Fermi LAT all-sky Counts Map

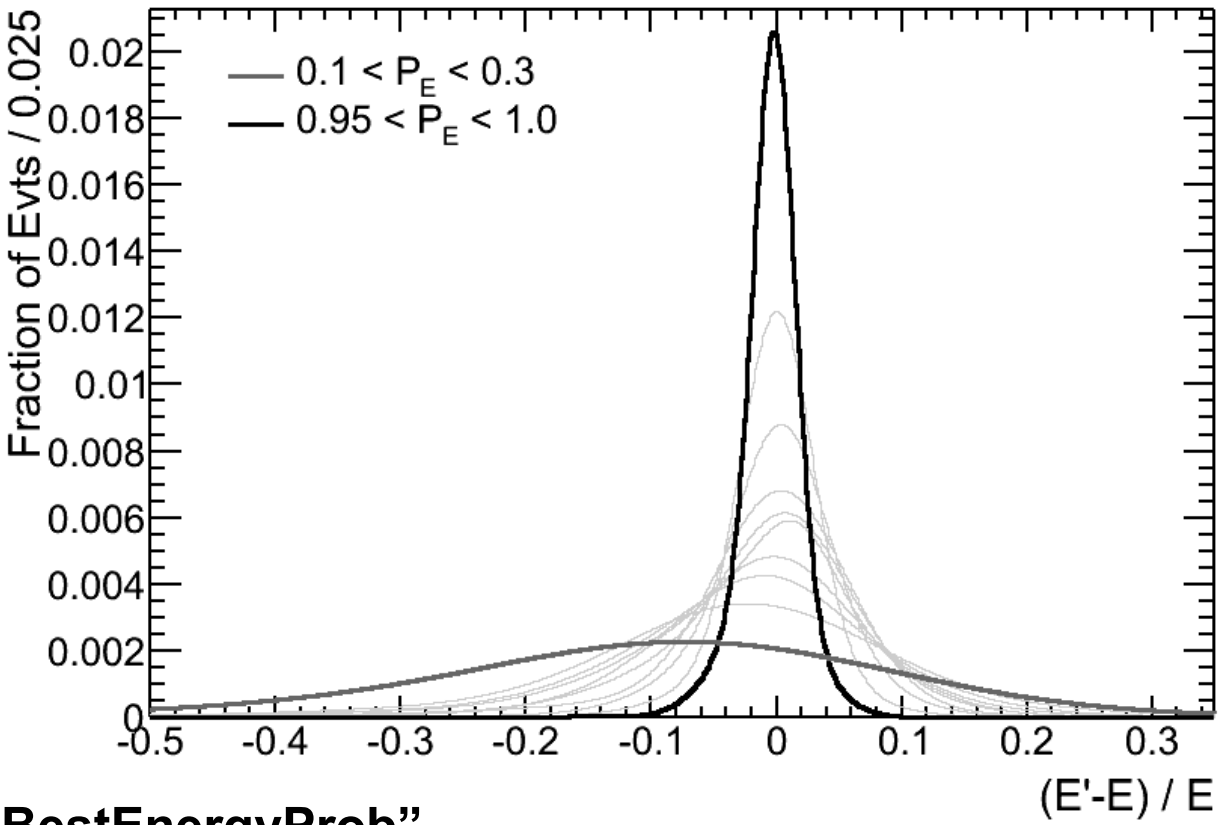


- R3 (contracted NFW, no src masking)
- R16 (Einasto)
- R41 (NFW)
  - R90 (Isothermal)
  - R180 (DM Decay)

ROI optimization motivated by: Bringmann et al 2012, and Weniger 2012

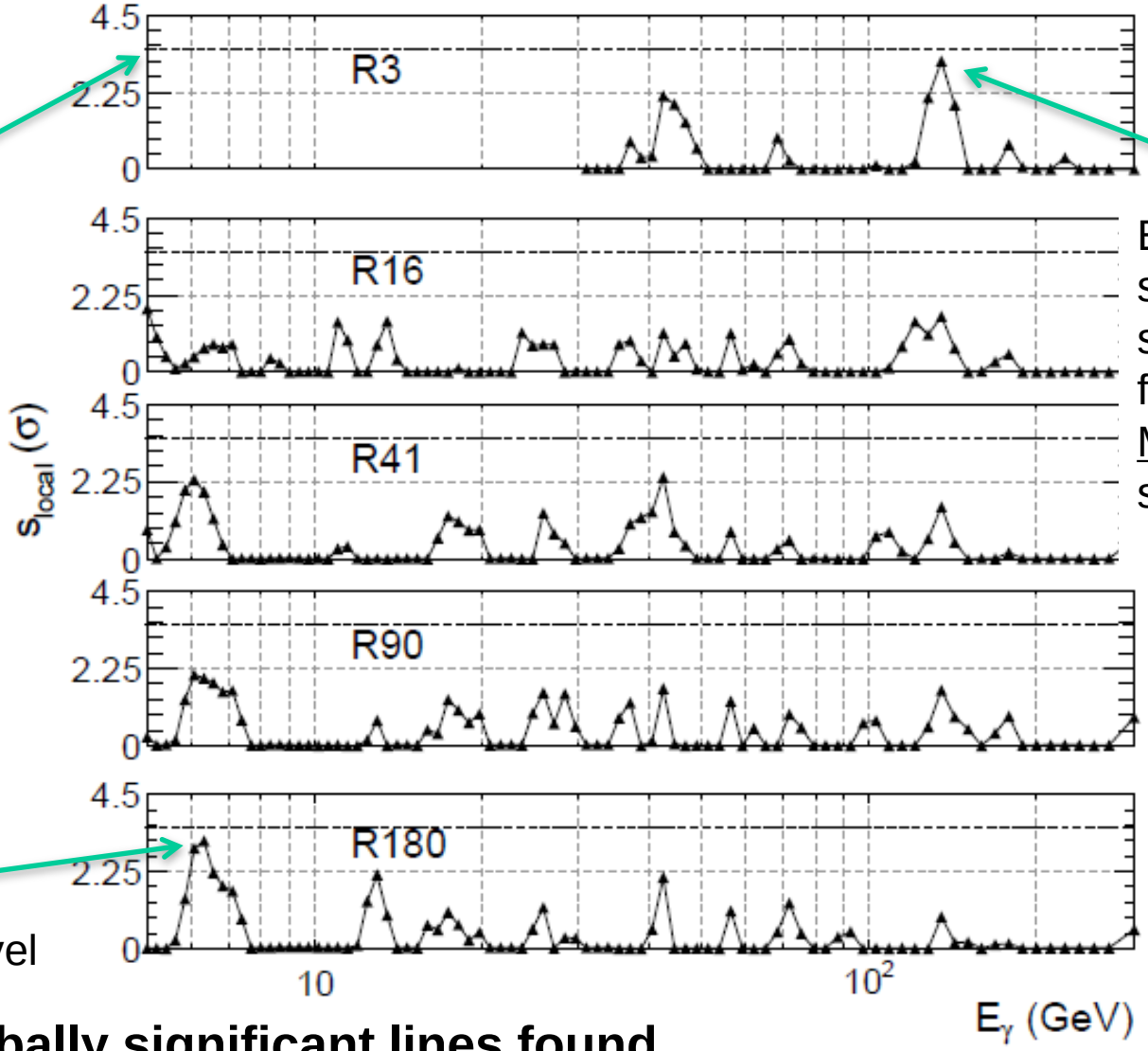
- Search for lines from 5 – 300 GeV using 3.7 years of data
  - Maximum likelihood fit with improved energy dispersion model
- Use P7REP_CLEAN event selection
  - Reprocessed data with updated calorimeter calibration constants
  - Clean cuts are recommended for faint diffuse emission analysis
- Mask bright (>10σ for E > 1 GeV) 2FGL sources

Energy Dispersion Model ("2D model")



- **P_E = "CTBBestEnergyProb"**
  - **Probability that the reconstructed energy is within expected 68% containment**
- **Use triple Gaussian model in 10 P_E bins**
- **Gives ~15% increase in statistical power**
  - **Similar to adding ~30% more data**

Fitting Results



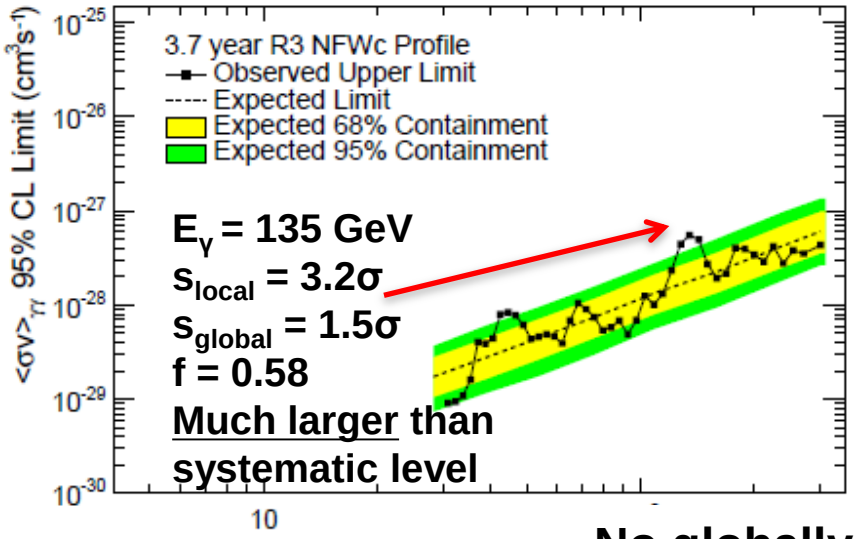
$s_{global} = 2\sigma$

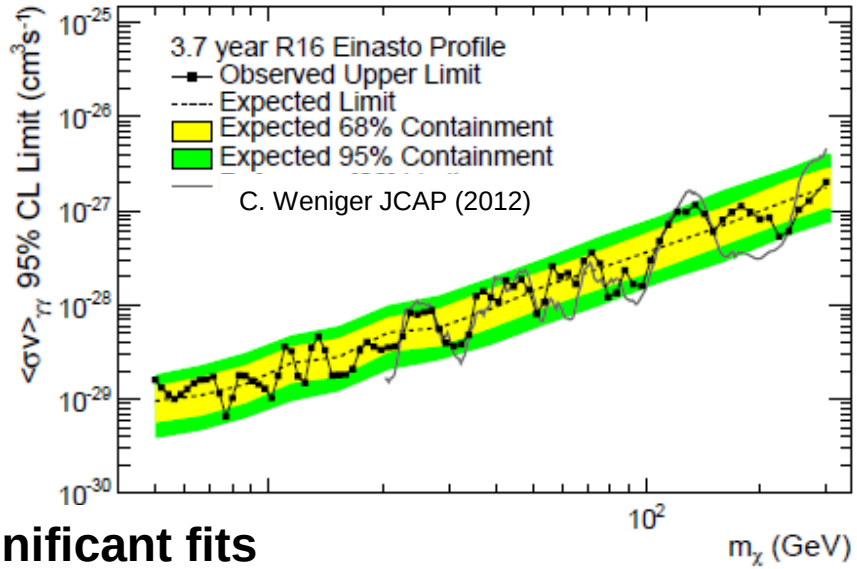
E_γ=135 GeV
s_{local} = 3.2σ
s_{global} = 1.5σ
f = 0.58
Much larger than systematic level

E_γ= 6 GeV
s_{local} = 3.1σ
s_{global} = 1.4σ
f = 0.01
At systematic level

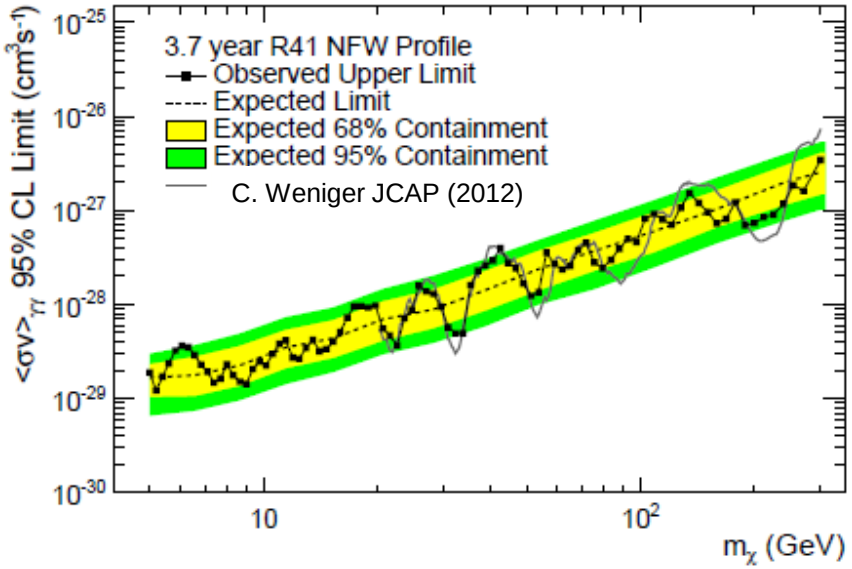
- **No globally significant lines found**

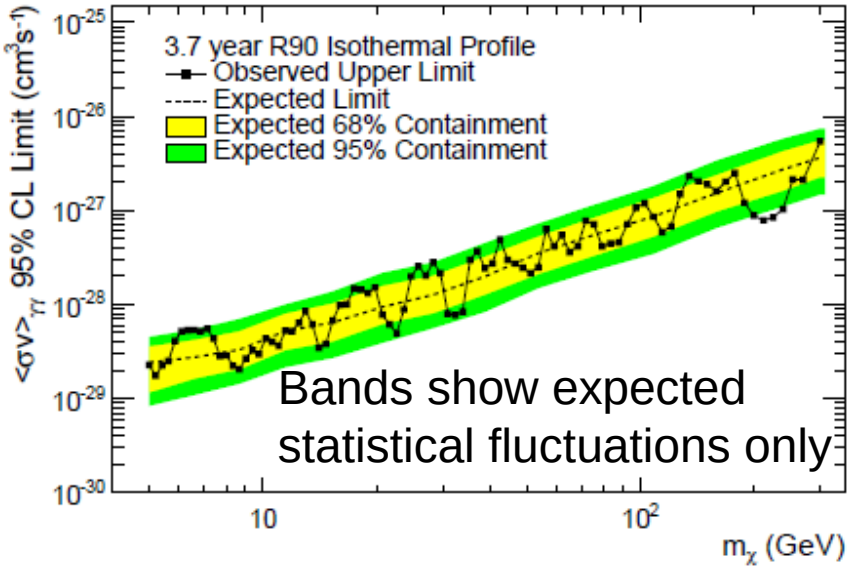
95% CL <σv> upper limits



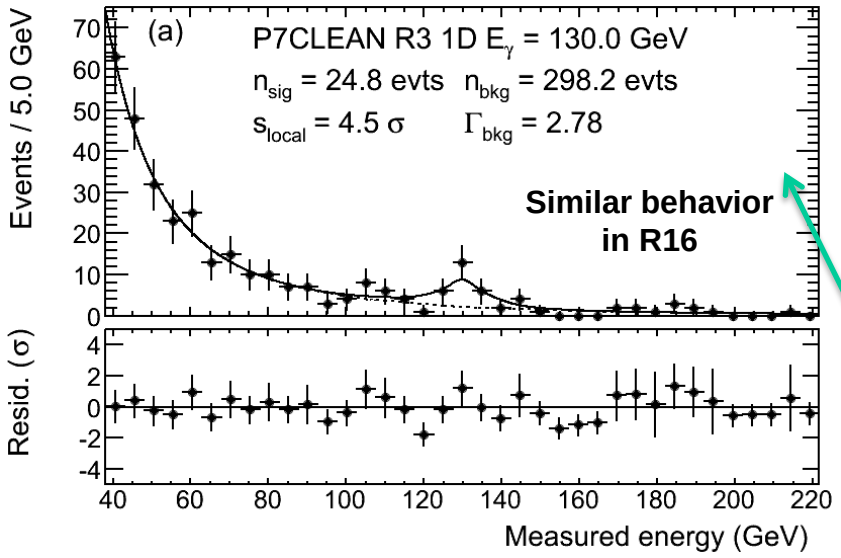


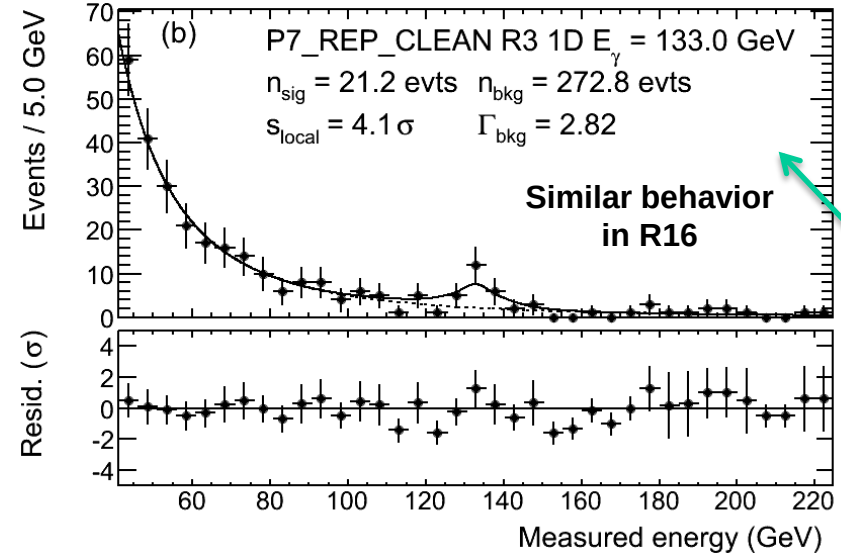
No globally significant fits





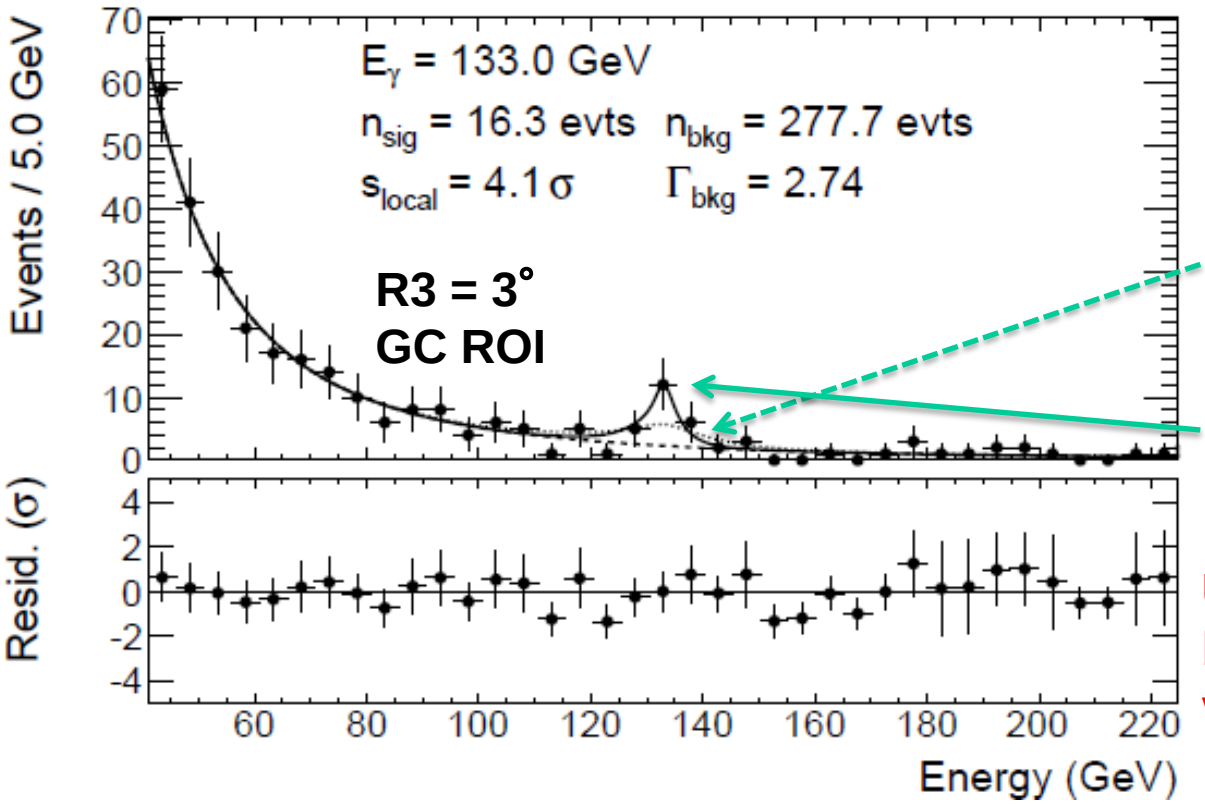
Studies of Line-like Feature near 133 GeV





- **Fits using simpler energy dispersion model**
  - **no use of energy reconstruction quality: P_E**
- **4.5σ (local) 1D fit at 130 GeV with unreprocessed data**
  - **Comparable to significance reported in C. Weniger JCAP 1208 (2012) 007 arXiv:1204.2797**
- **4.1σ (local) 1D fit at 133 GeV with reprocessed data**
  - **Shifts higher in energy by a few percent, as expected**

The Line-like Feature near 133 GeV For R3



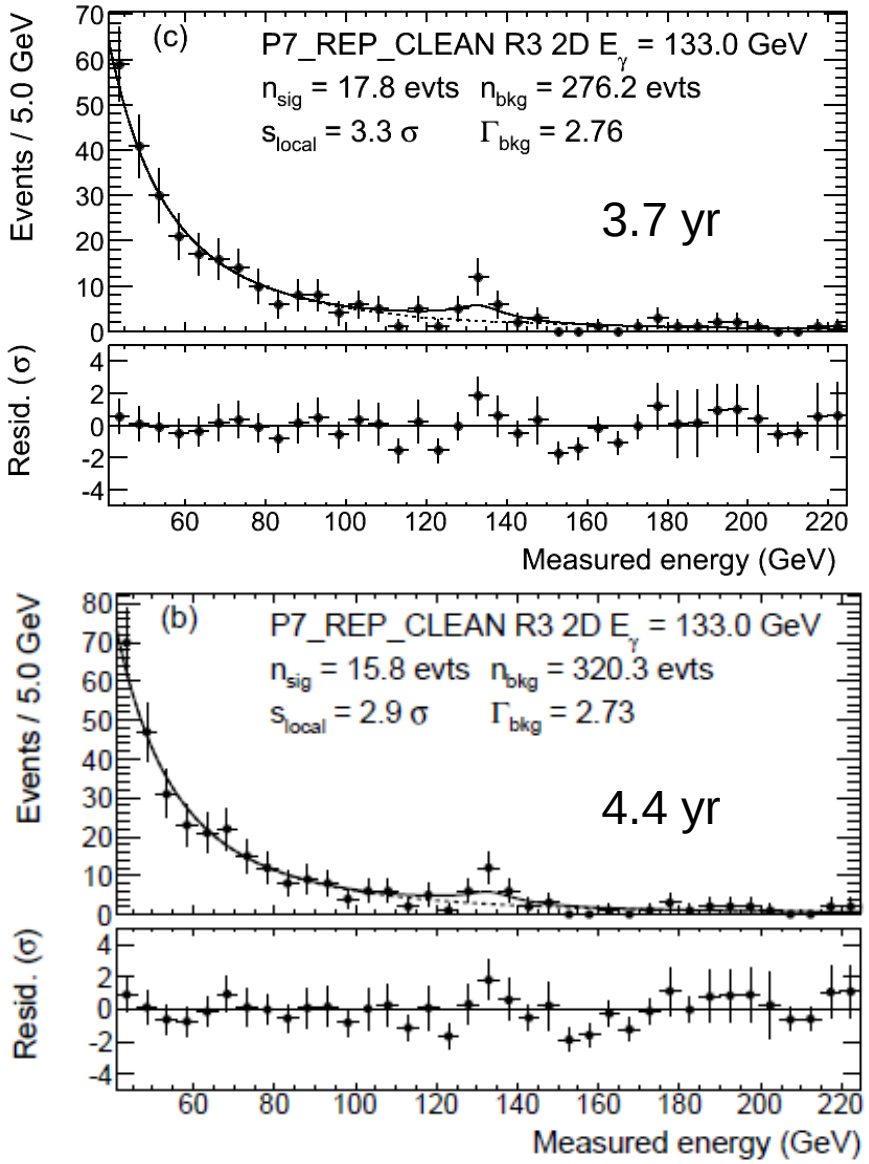
Dashed is fit with s_σ=1 s_{local} = 4.1σ

Solid is fit with best fit s_σ and s_{local} = 3.2σ

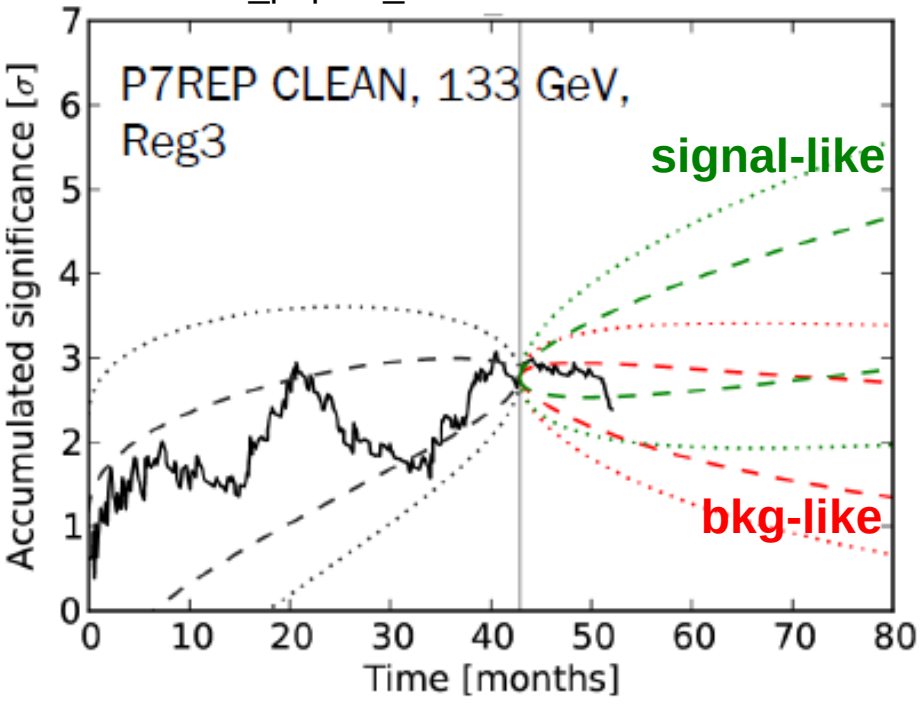
Unbinned fit, the binning is for visualization only

- **3.2σ (local) 2D fit at 133 GeV with reprocessed data**
  - **Fit with energy dispersion model that includes event-by-event energy reconstruction quality estimator P_E ("2D" model)**
- **Let width scale factor float in fit (while preserving shape). Best fit:**
  - $s_\sigma = 0.32^{+0.22}_{-0.07}(95\%CL) \quad \Delta TS = 9.4$
- **Feature in data is narrower than expected energy resolution**

133 GeV Feature in 4.4 year dataset

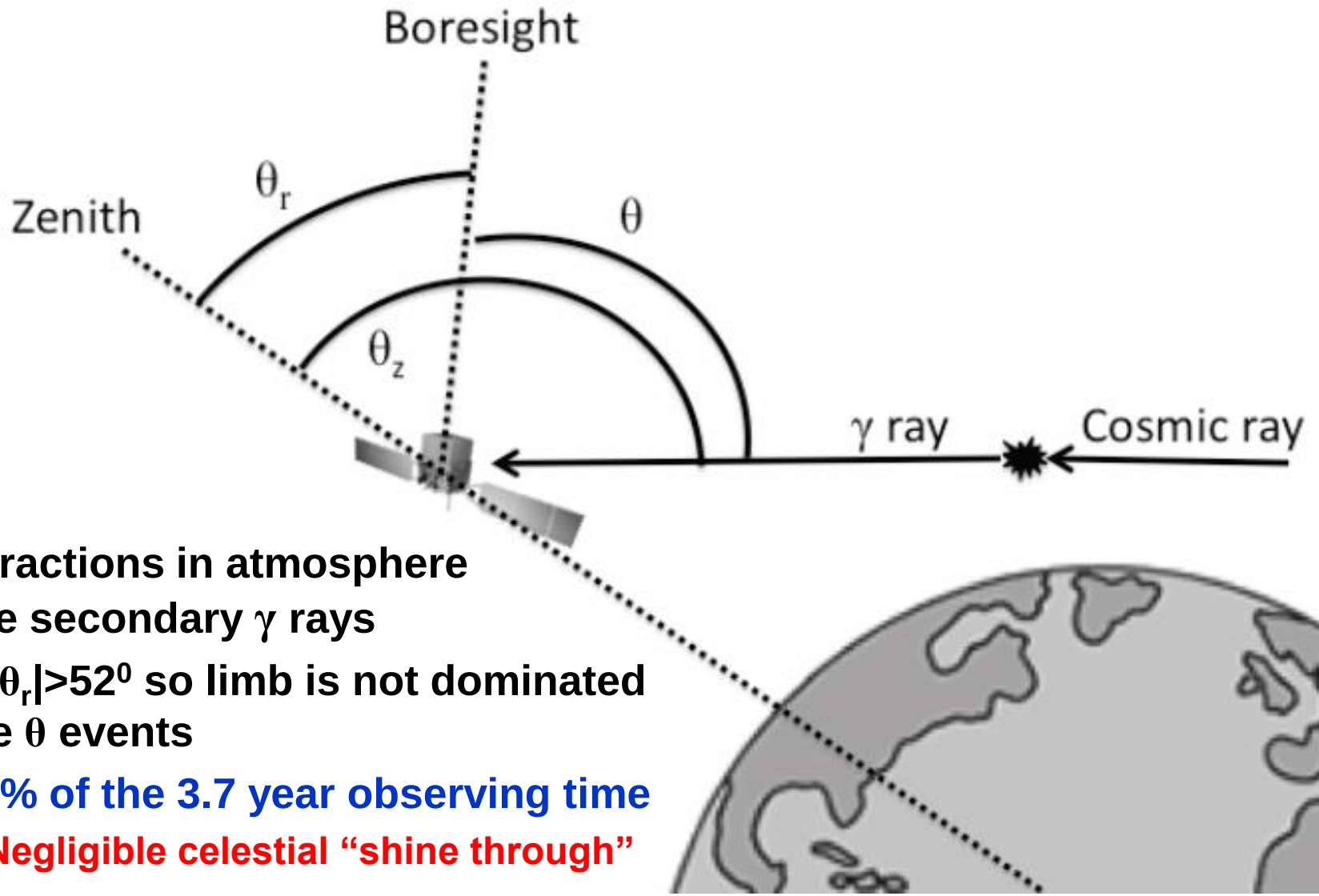


Weniger et al (2013)
http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/white_papers_eval.html



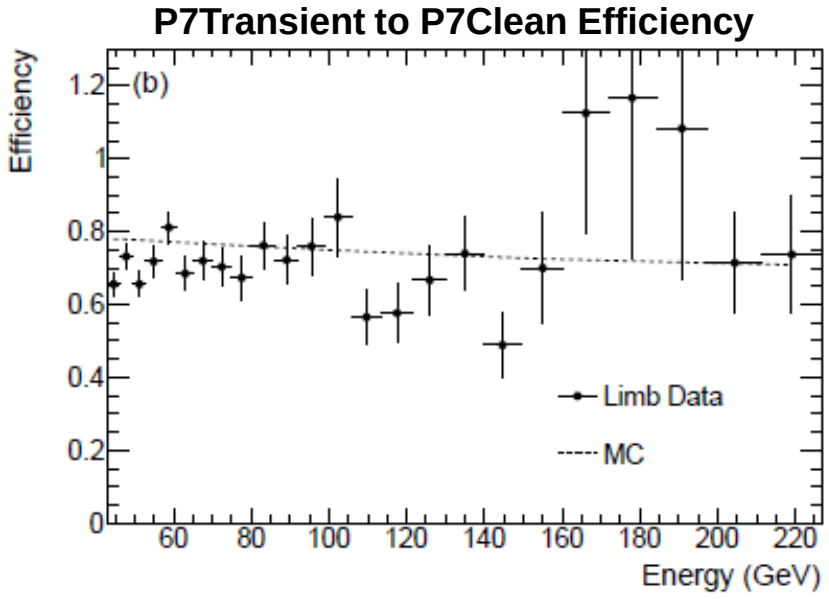
- **s_{local} decreased in 4.4 yr data by ~10% compared to 3.7 yr data**
- **Since spring 2012, feature has decreased in significance**
  - **More "background-like"**

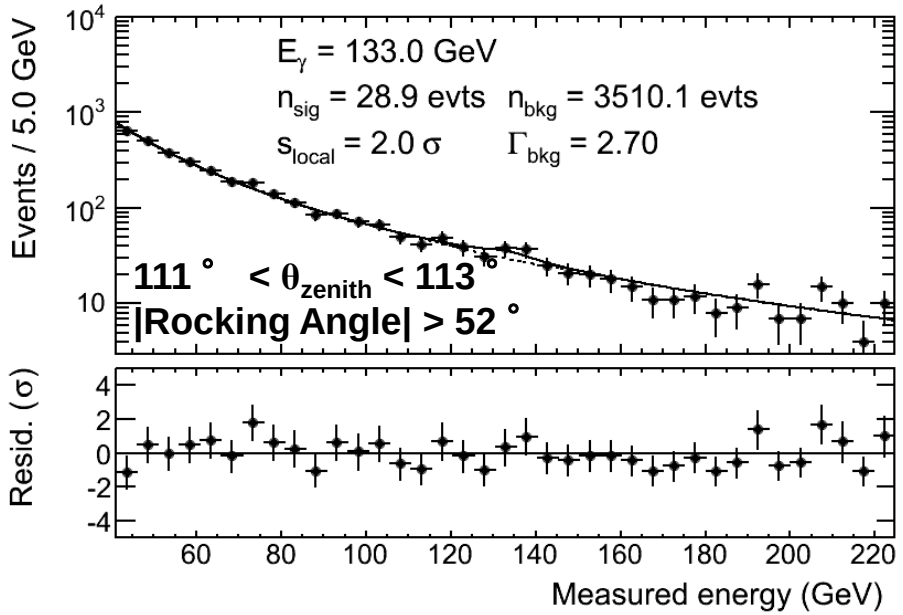
Earth Limb Control Dataset



- **CR interactions in atmosphere produce secondary γ rays**
- **Select $|\theta_r|>52^0$ so limb is not dominated by large θ events**
  - **0.03% of the 3.7 year observing time**
    - **Negligible celestial "shine through"**

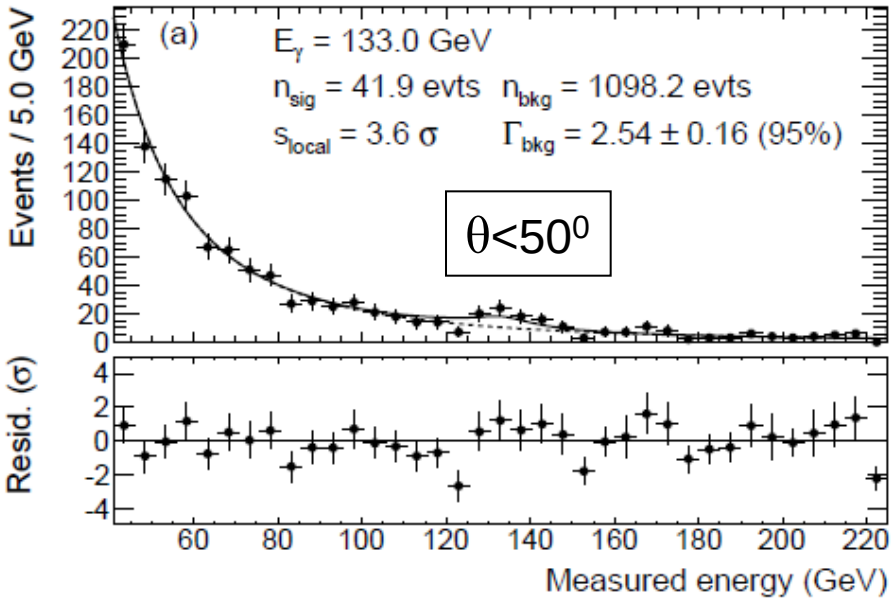
133 GeV in the Earth Limb spectrum

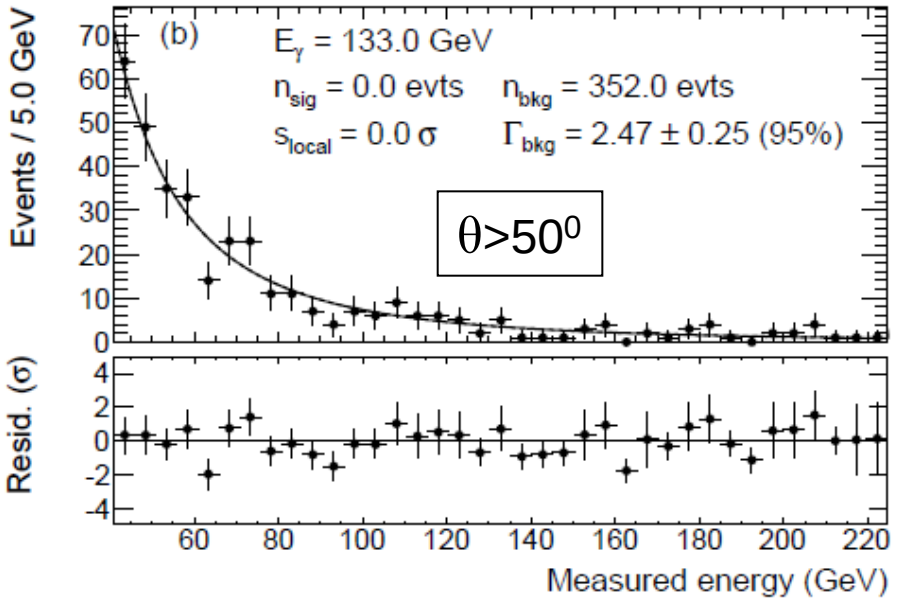




- **Line-like feature in the limb at 133 GeV (2.0σ local significance)**
  - **Also reported by others: D. Whiteson (arXiv:1208.3677), A. Hektor et al (arXiv:1209.4548), and D. Finkbeiner et al (arXiv:1209.4562)**
  - **Appears when LAT is pointing at the Limb ($|\theta_{rock}|>52^0$)**
  - **Surprising since limb should be smooth power-law**
  - **f_{limb} ~14%, while f_{R3}~ 61%**
    - **Limb feature not large enough to directly explain all the GC signal**
- **Dips in efficiency (less stringent Transient cuts -> Clean cuts) below and above 133 GeV**
  - **Appear to be related to CAL-TKR event direction agreement**
  - **Could be artificially sculpting the energy spectrum**

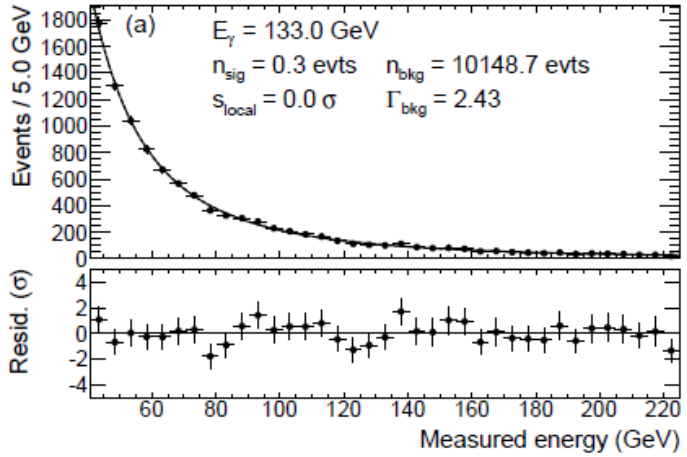
θ-dependence of 135 GeV feature

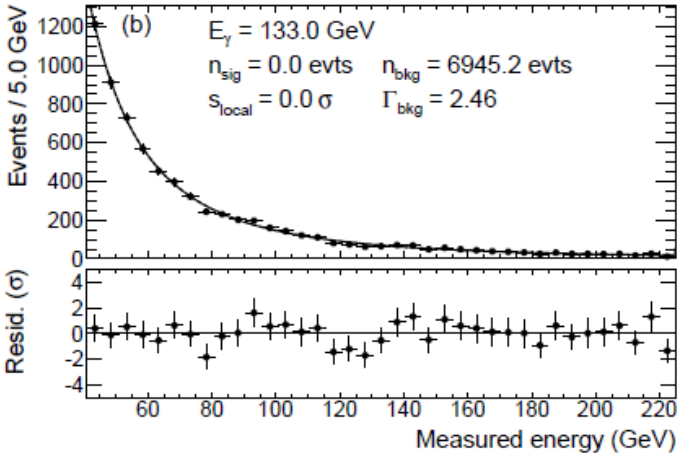


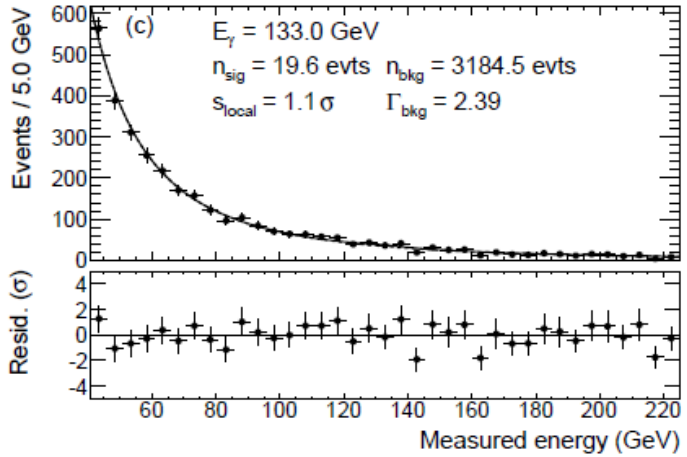


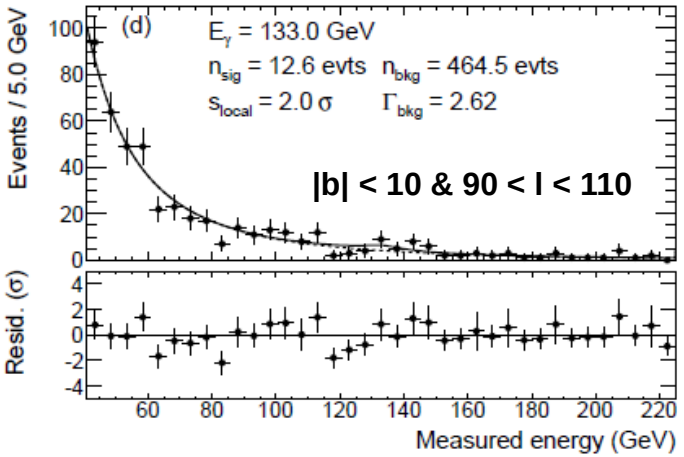
- **Search in a 20x20 GC box (no source removal, 2D model)**
- **135 GeV feature appears in low-θ events, but not in high-θ events**
  - **3.5σ in θ<50⁰ events should scale to 2σ for θ>50⁰ events**
- **Same behavior observed in the Limb feature**

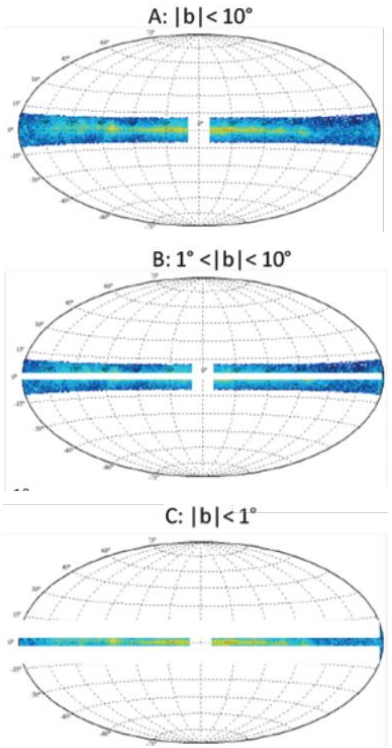
133 Feature in the inverse ROIs











- **No obvious feature at 133 GeV in the inverse ROIs**
  - **Would naively expect an instrumental effect to show up everywhere**

Summary Line Search

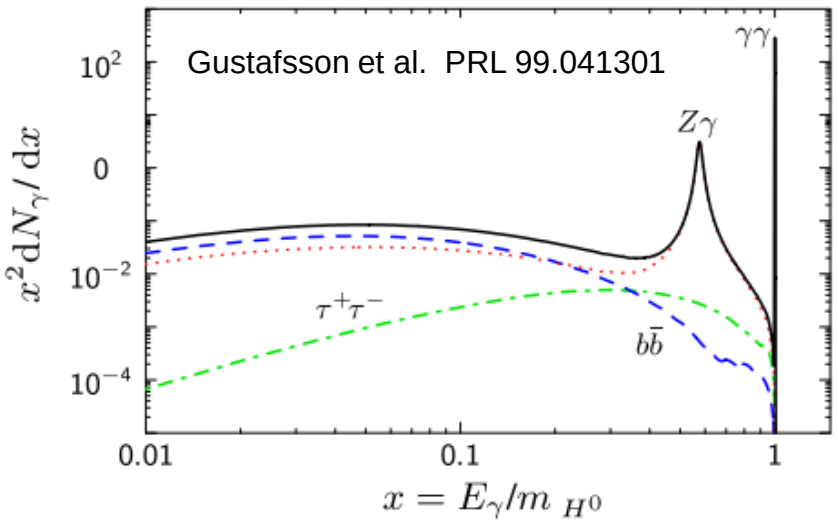
- Search for spectral lines from 5--300 GeV in 5 ROIs
  - Accepted for publication in PRD (arXiv:1305.5597v3)
  - No globally significant lines detected
- See a narrow residual near 133 GeV in the GC
  - Not (completely) an obvious systematic error
    - Larger than expected systematic uncertainty
    - Feature in Limb is smaller than GC feature
    - Feature does not appear in inverse ROI
  - Bkg fluctuation?
    - Much narrower than expected energy resolution
    - Decreasing with more data
- More data and study will improve future LAT analyses (See Matthew Wood's Talk at this conference)
  - Pass 8 → ~25% increase in A_{eff} and better (different) systematics
  - Potential Change in Fermi viewing strategy that will emphasize the Galactic center.

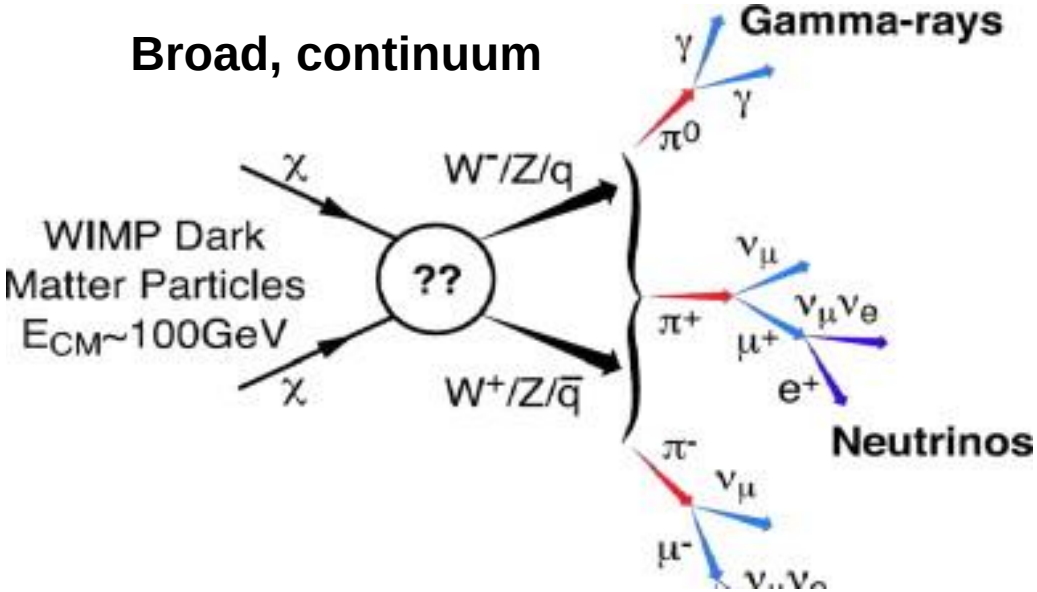
Summary Dwarfs

- **Search for DM signal from Milky Way Dwarf Galaxies**
  - **Updated 4yr limits are slightly higher than 2yr limits**
  - **No significant detection**
  - **Submitted for publication to PRD (arXiv:1310.0828v1)**
- **Have set 95% CL $\Phi_{\gamma\gamma}$, $\langle\sigma v\rangle_{\gamma\gamma}$, and $\tau_{\gamma\gamma}$ limits.**
  - **We derive a global p-value directly from random blank high-Galactic-latitude sky positions yielding p~0.08. This global p-value includes the correlated trials factor resulting from testing 70 dark matter spectral models.**
- **Longer term**
  - **More dwarfs from upcoming optical surveys – Pan-STARRS, Southern Sky survey, DES, and LSST**
  - **More Fermi LAT exposure (10 years total)**
  - **Pass 8 improvements in acceptance and systematic errors**

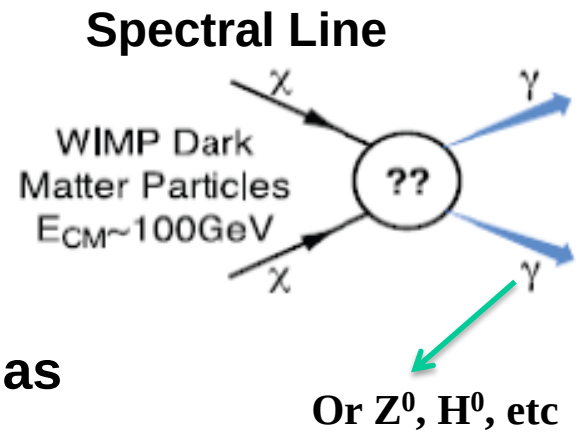
BACKUP SLIDES

Gamma-rays from WIMPs





- **WIMP = Weakly Interacting Massive Particle**
  - **DM candidate (e.g. neutralino)**
  - **Believe the Milky Way sits in a large spherical "halo" or cloud of DM**
    - **Non-relativistic (cold) DM**



- **WIMPs annihilations (decays) may produce gammas**
  - **Dominant channels -> broad continuum**
  - **Monochromatic channels expected to be rare (loop-suppressed)**

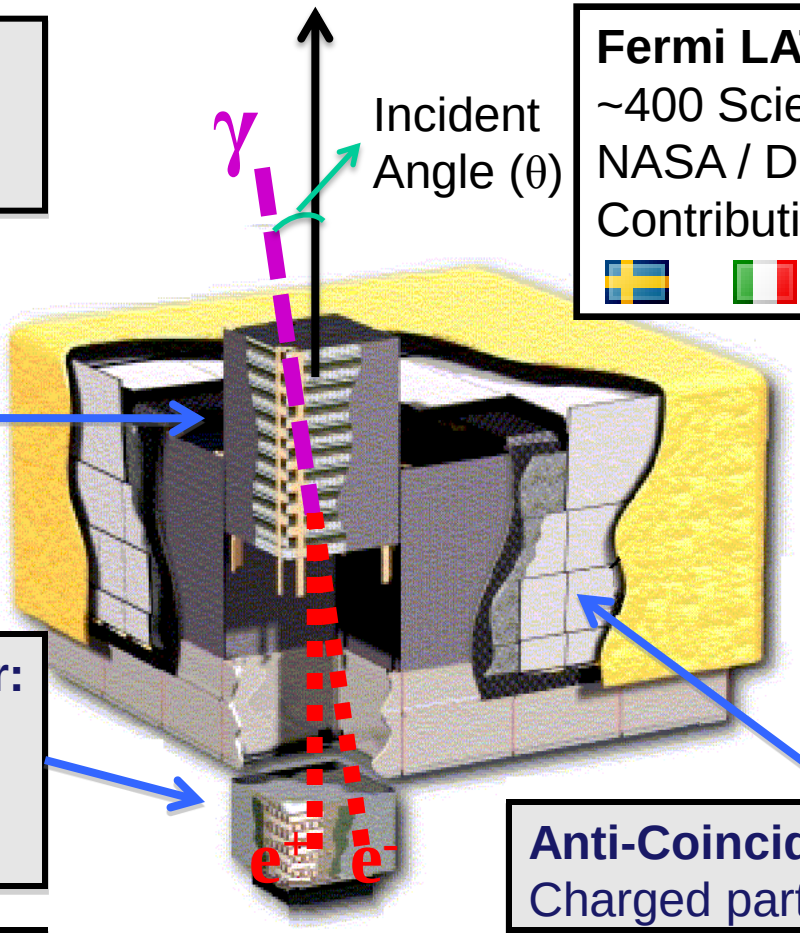
Fermi LAT

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

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

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

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



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

For detailed description of LAT performance see arXiv: 1206.1896

Anti-Coincidence Detector:
Charged particle separation

En Range and Coverage:
20 MeV to >300 GeV
See whole sky every 3 hrs

Systematic Effects in each Line Search ROI

- **Uncertainties that affect the conversion from n_{sig} to $\Phi_{\gamma\gamma}$**
  - E.g., exposure uncertainties
  - Do not affect fit significance
- **Uncertainties that scale n_{sig}**
  - E.g., modeling energy dispersion
  - Affect significance, but will not induce false signals
- **Uncertainties that induce or mask a signal**
  - Express as uncertainty in fractional signal, δf

Quantity	Energy	R3	R16	R41	R90	R180
$\delta\epsilon/\epsilon$	5 GeV	0.10	0.10	0.11	0.12	0.14
$\delta\epsilon/\epsilon$	300 GeV	0.10	0.10	0.12	0.13	0.16
$\delta n_{sig}/n_{sig}$	All	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$
δf	5 GeV	0.020	0.020	0.008	0.008	0.008
δf	50 GeV	0.024	0.024	0.015	0.015	0.015
δf	300 GeV	0.032	0.032	0.035	0.035	0.035

$$TS = 2\ln\frac{\mathcal{L}(n_{\rm sig} = n_{\rm sig,best})}{\mathcal{L}(n_{\rm sig} = 0)} \qquad s_{\rm local} = \sqrt{TS}$$

$$f = \frac{n_{\rm sig}}{b_{\rm eff}} \simeq \frac{s^2_{\rm local}}{n_{\rm sig}}$$

Fitting Method for Line Search

Predicted Spectrum | Signal Model | Background Model

$$C(E', P_{\rm E}|\vec{\alpha}) = n_{\rm sig} D_{\rm eff}(E', P_{\rm E}|E_\gamma) w_{\rm sig}(P_{\rm E}) + \frac{n_{\rm bkg}}{c_{\rm bkg}} \left(\frac{E'}{E_0}\right)^{-\Gamma_{\rm bkg}} \eta(E') w_{\rm bkg}(P_{\rm E})$$

$$D_{\rm eff}(E'; E_\gamma) = \int^{FoV} \int^{ROI} D(E'; \theta|E_\gamma) \frac{I_{\rm sig}(\hat{p}) \mathcal{E}(\hat{p}, \theta, E_\gamma)}{n_{\rm sig}} d\Omega d\Omega_{\hat{v}}$$

$$\eta(E') = \int^{FoV} \int^{ROI} \frac{I_{\rm bkg}(\hat{p}) \mathcal{E}(\hat{p}, \theta, E_\gamma)}{n_{\rm bkg}} d\Omega d\Omega_{\hat{v}}$$

Effective Energy Dispersion

Incorporates energy reconstruction quality (P_E)

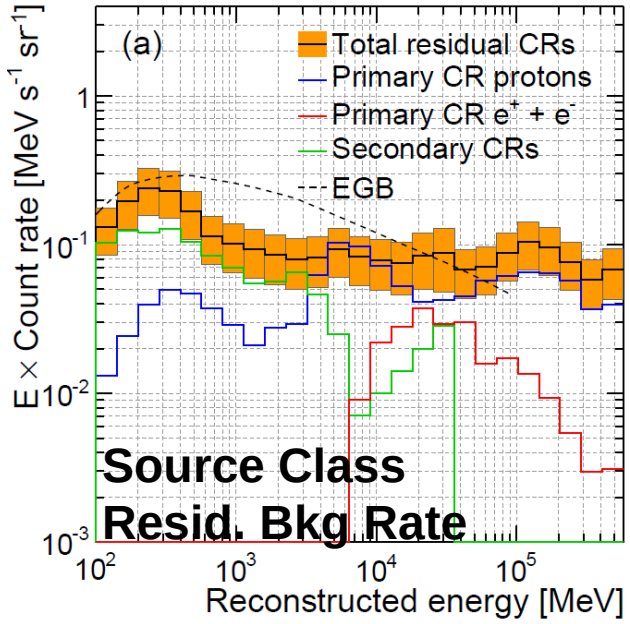
Effective Area Corrections

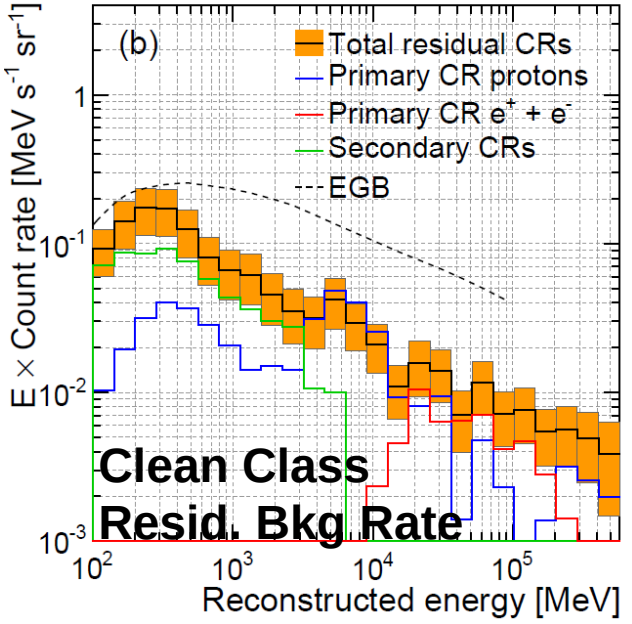
- **Maximum likelihood fit at E_γ in sliding energy window ($\pm 6\sigma_E$)**
  - **Fit from 5 to 300 GeV**
  - **$0.5\sigma_E$ steps (88 fit energies)**
- **n_{sig}, n_{bkg}, Γ_{bkg} free in fit**
- **c_{bkg} is given by normalization of background model**
- **Include P_E distributions for signal and background: $w(P_E)$**
  - **Take from data for each fit (entire ROI and energy fit window)**

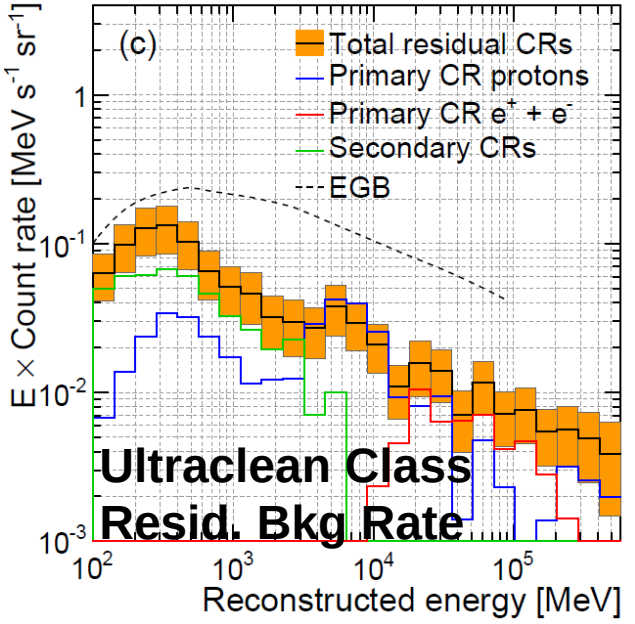
Fermi LAT Pass 7 Gamma-ray Event Classes

- **Triggered events are dominated by CR background events**
  - **Need to define additional cuts to get γ-ray rich dataset**
- **Nested "event classes" for various types of γ ray sources**
  - **Transient: loosest, for flaring sources (cut in time)**
  - **Source: moderate, for bright sources (cut in space)**
  - **Clean: tight, for γ-ray diffuse**
  - **Ultraclean: tightest, for extragalactic γ rays**

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

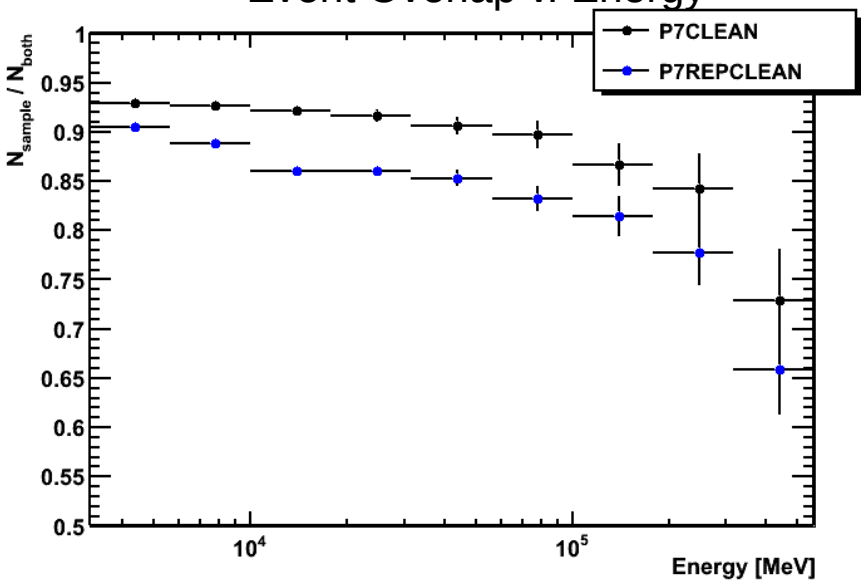




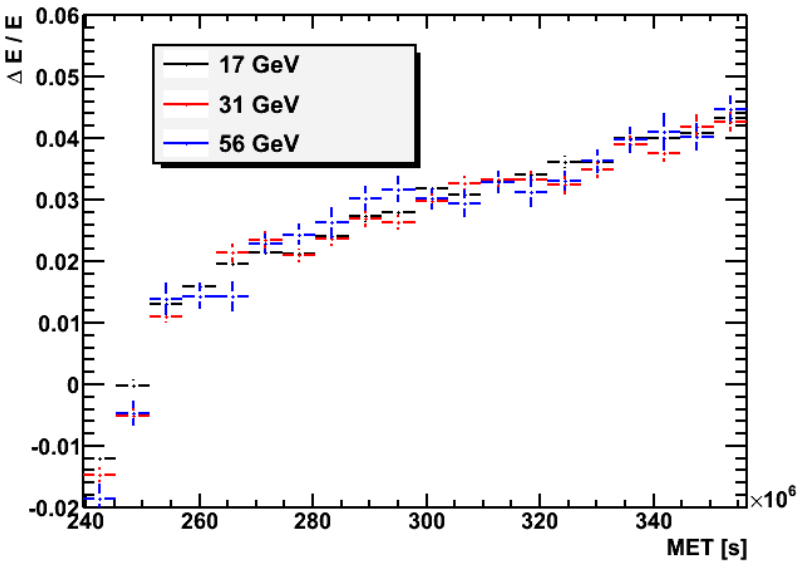


Data Reprocessing with Updated Calibrations

Event Overlap v. Energy



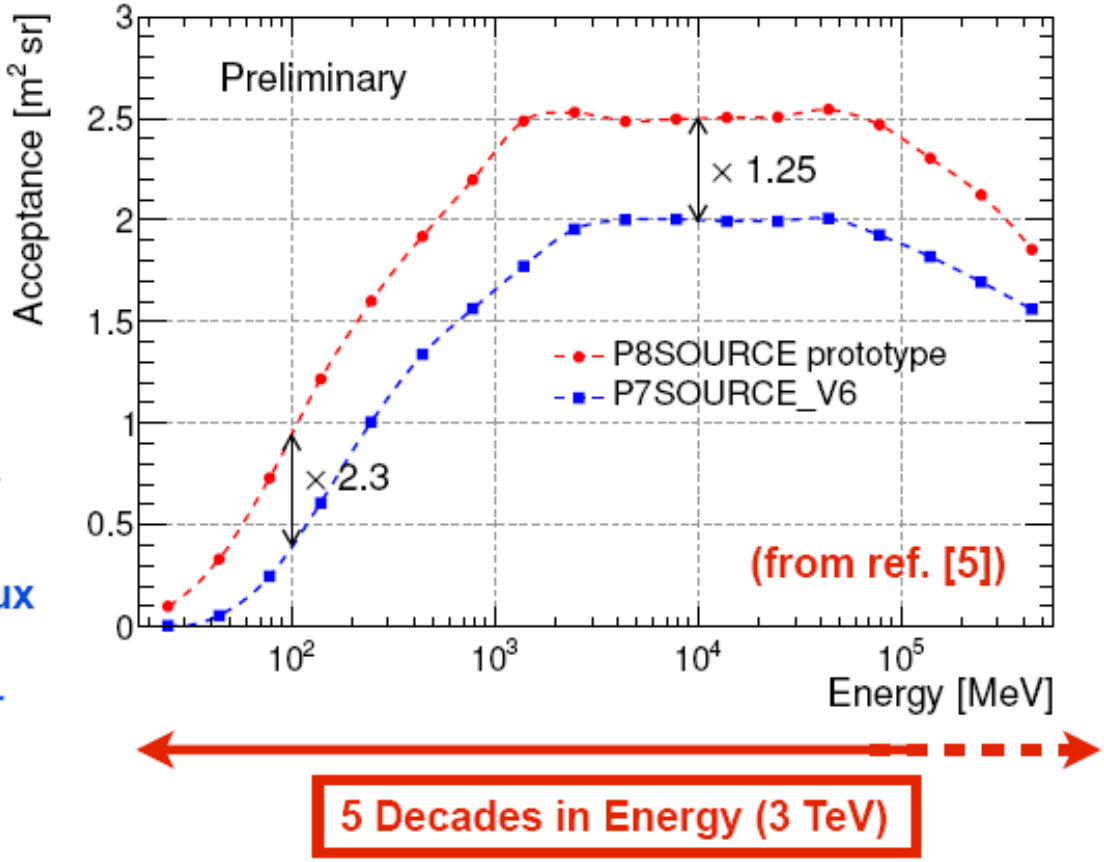
Energy Shift v. Time



- Reprocessing Data with updated calibrations (primarily Calorimeter)
- Improves the agreement between the TKR direction and the CAL shower axis and centroid at high E, improving the direction resolution
- Corrects for loss in CAL light yield b/c of radiation damage (~4% in mission to date)
- 80%+ overlap in events between original and reprocessed samples

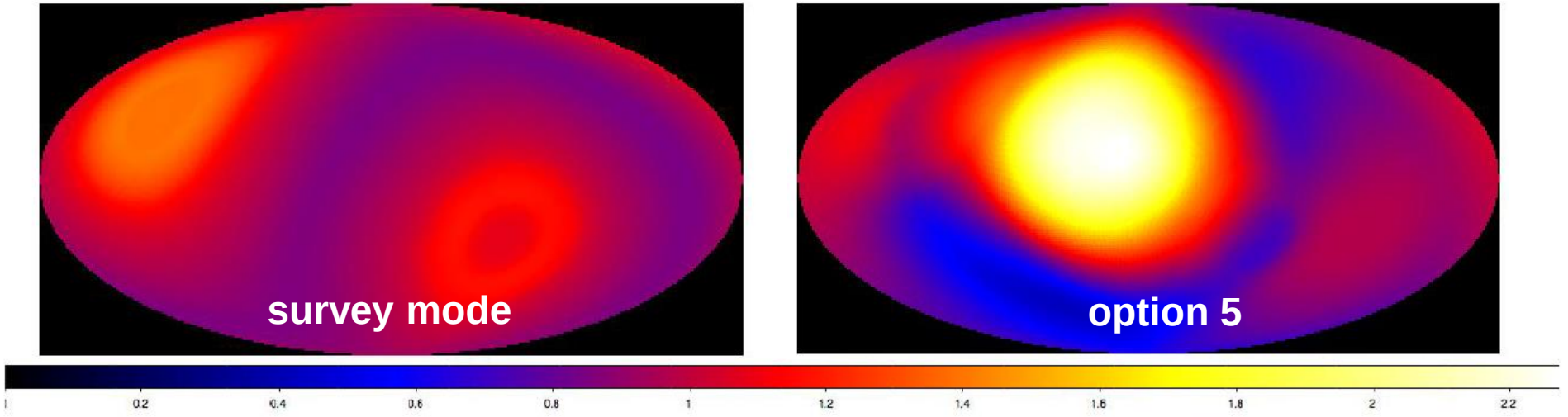
Pass8: Improved LAT Performance

- **Improvements to the LAT instrument performance:**
  - Increased energy range
  - Increased effective area
  - Improved angular resolution
  - Better background rejection
  - New event classes
- **Impacts for dark matter:**
  - Energy Range <==> explore new high-mass parameter space
  - Effective Area <==> increased flux sensitivity
  - Angular Resolution <==> greater sensitivity to spatially extended sources
  - New Event Classes <==> check systematic effects in event selection



Modified Observing Strategy

- **more info can be found on FSSC**
  http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/obs_modes.html
- **Panel discussed white paper proposals July 25th and recommended a switch to "option 4 or similar" around December 2013.**
  - **Option 4 points to keep the GC in the field of view, while still providing relatively uniform all-sky coverage**
- **Public discussion page for community input**
  - **https://groups.google.com/forum/#!forum/fermi-observation-strategy-discussion**



exposure maps