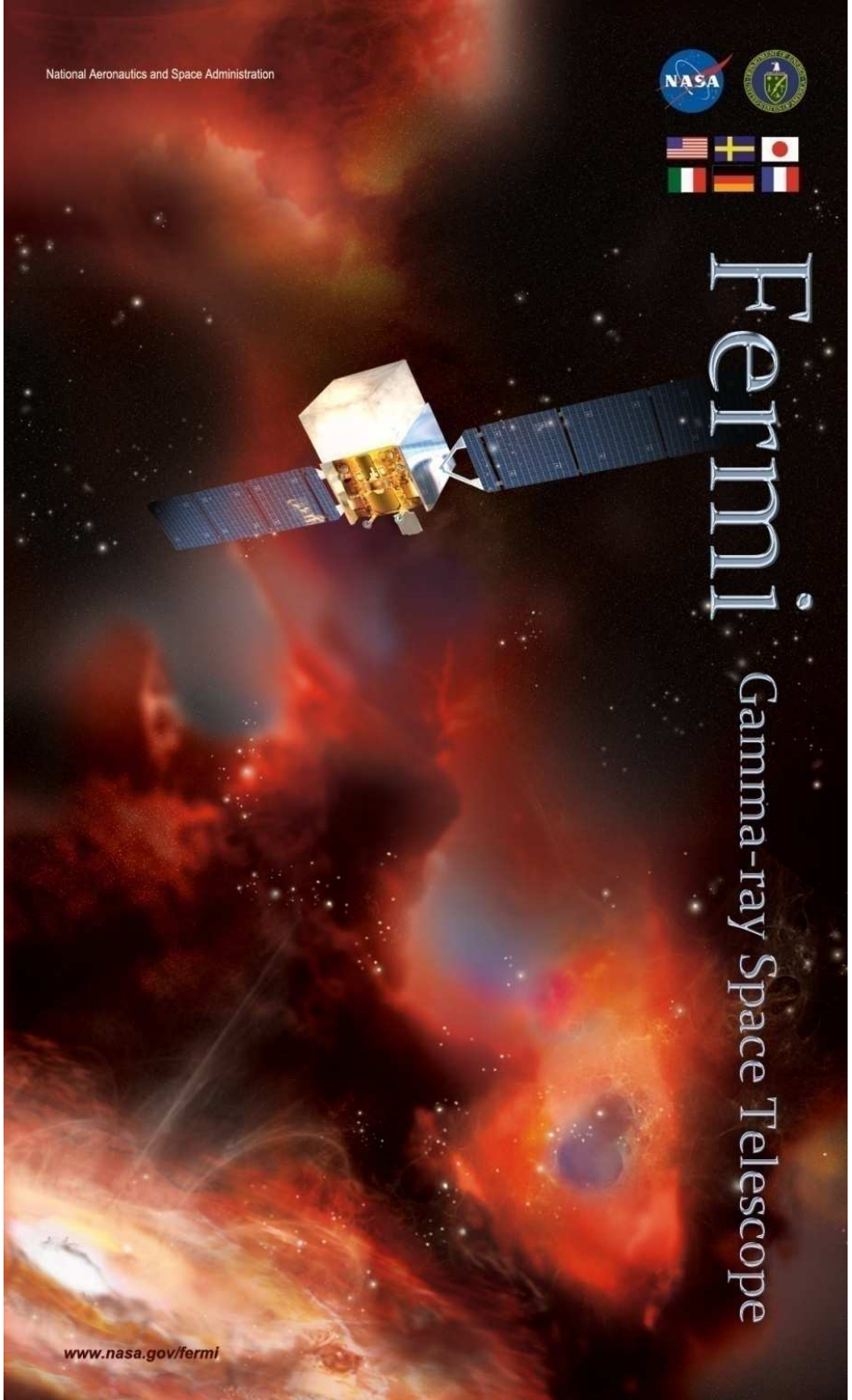


SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC

Fermi Gamma-ray Space Telescope

Search for Gamma-ray Spectral Lines with the *Fermi* Large Area Telescope and Dark Matter Implications

Andrea Albert (SLAC)

B. Winer (OSU), E. Charles (SLAC), E. Bloom (SLAC), et al

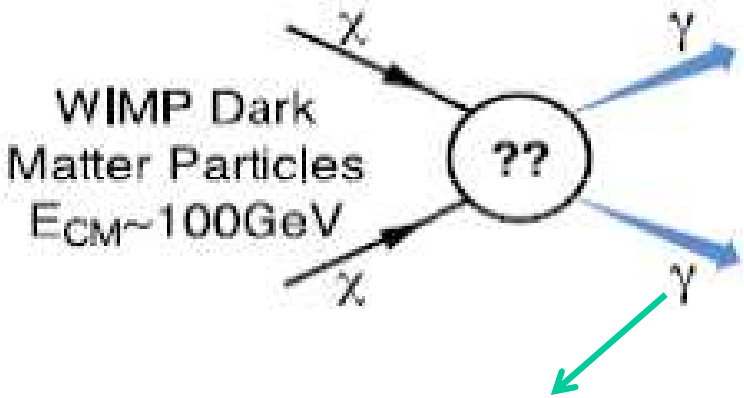
On Behalf of the Fermi-LAT Collaboration

TeVPA at UC Irvine

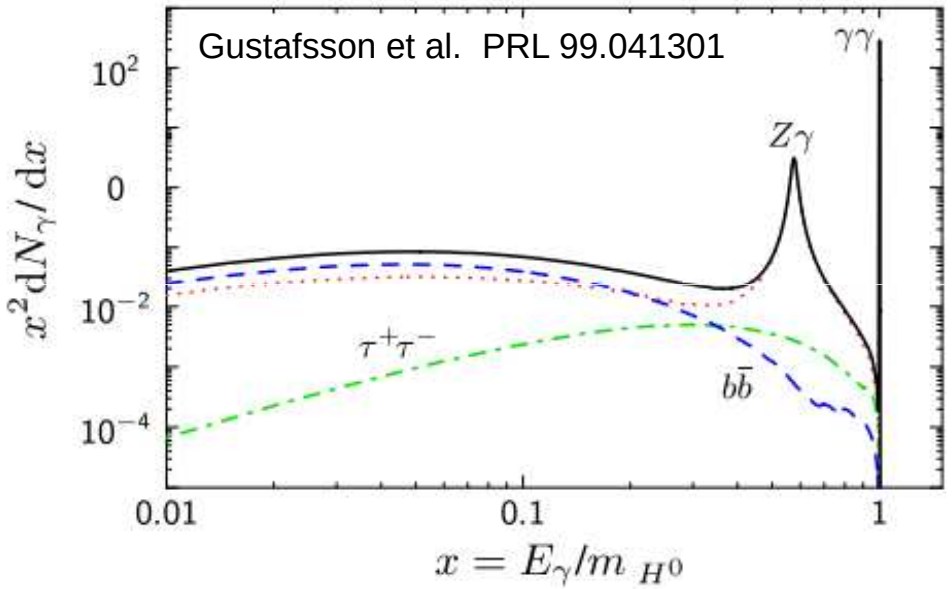
August 29th, 2013

Spectral Lines from WIMPs

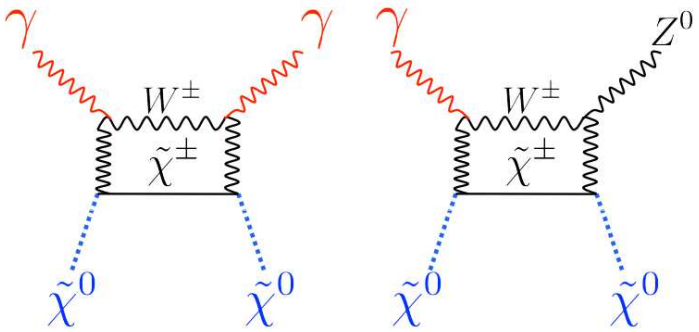
Spectral Line



Or Z^0, H^0, etc



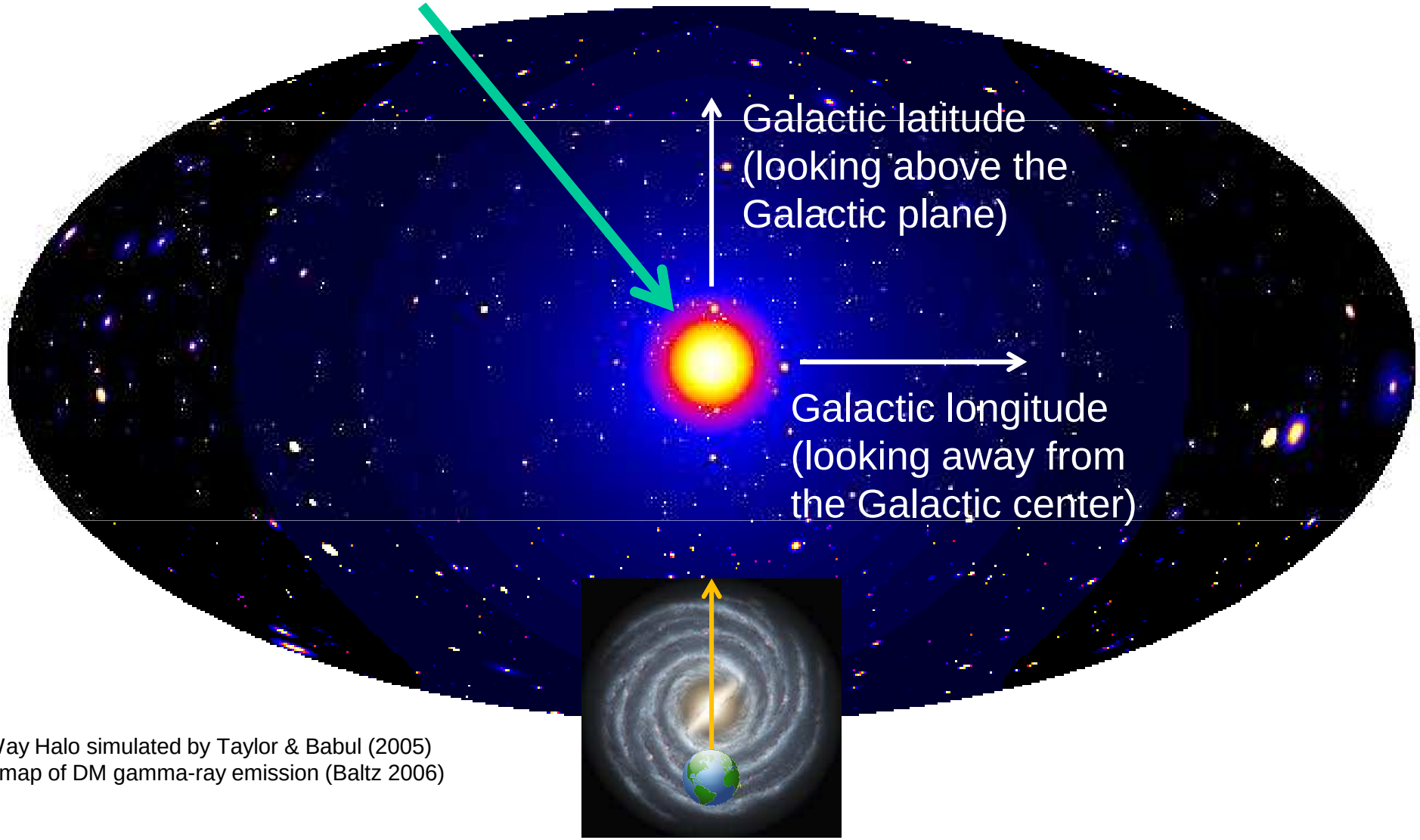
- **WIMP = Weakly Interacting Massive Particle**
  - **DM candidate (e.g. neutralino)**
  - **Believe the Milky Way sits in a large spherical "halo" or cloud of DM**
    - **Non-relativistic (cold) DM**



- **$\chi\,\chi \rightarrow \gamma X$ (X = γ, Z, H) gives monochromatic signal**
  - **Advantage: sharp, distinct feature (WIMP "smoking gun")**
  - **Disadvantage: low predicted counts (loop suppressed)**

Galactic Distribution of DM

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)

Galactic Distribution of DM

Smooth component peaked in Galactic Center
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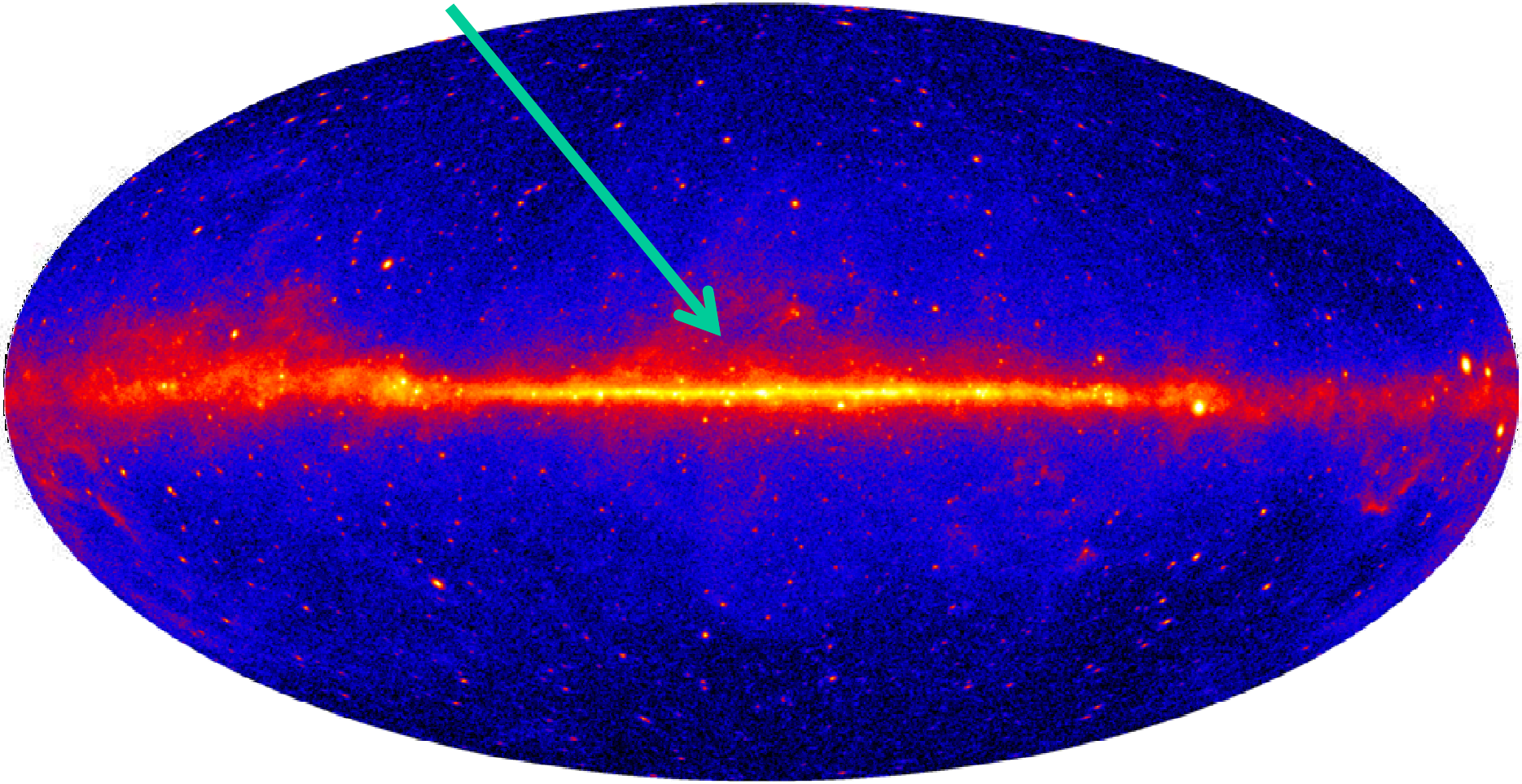


Milky Way Halo simulated by Taylor & Babul (2005)
All-sky map of DM gamma-ray emission (Baltz 2006)

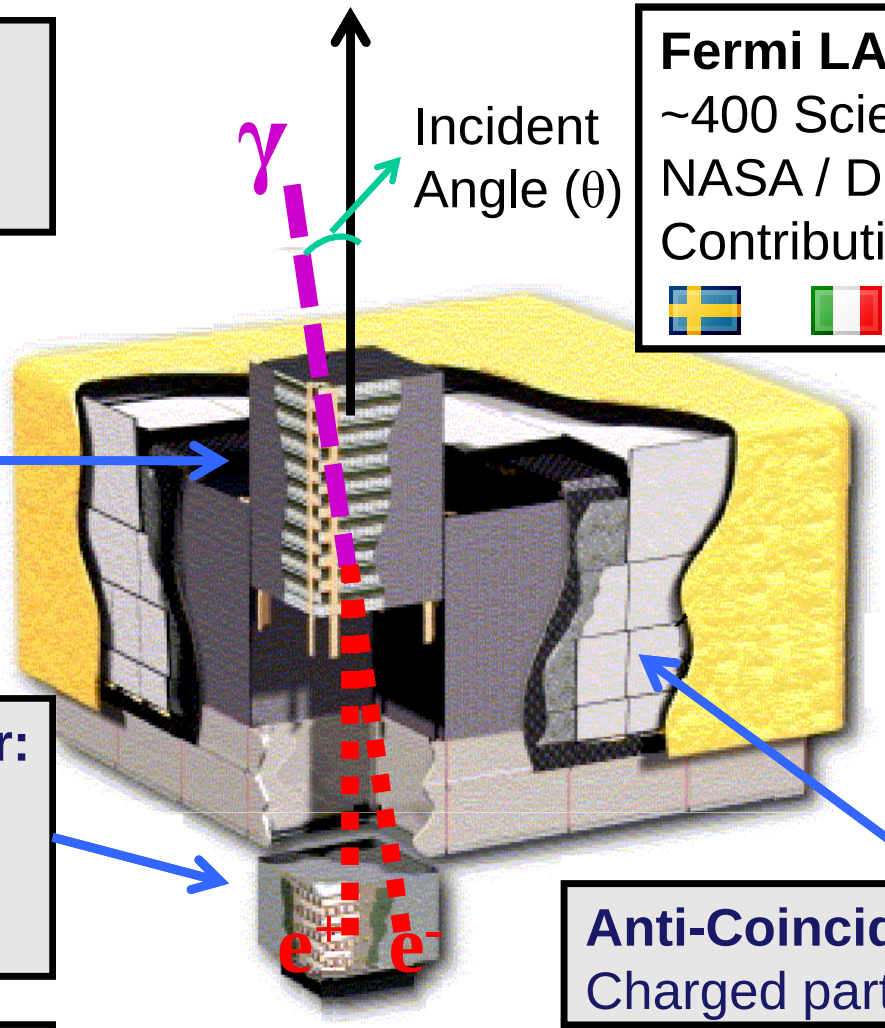
Fermi LAT

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

Anti-Coincidence Detector:
Charged particle separation

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

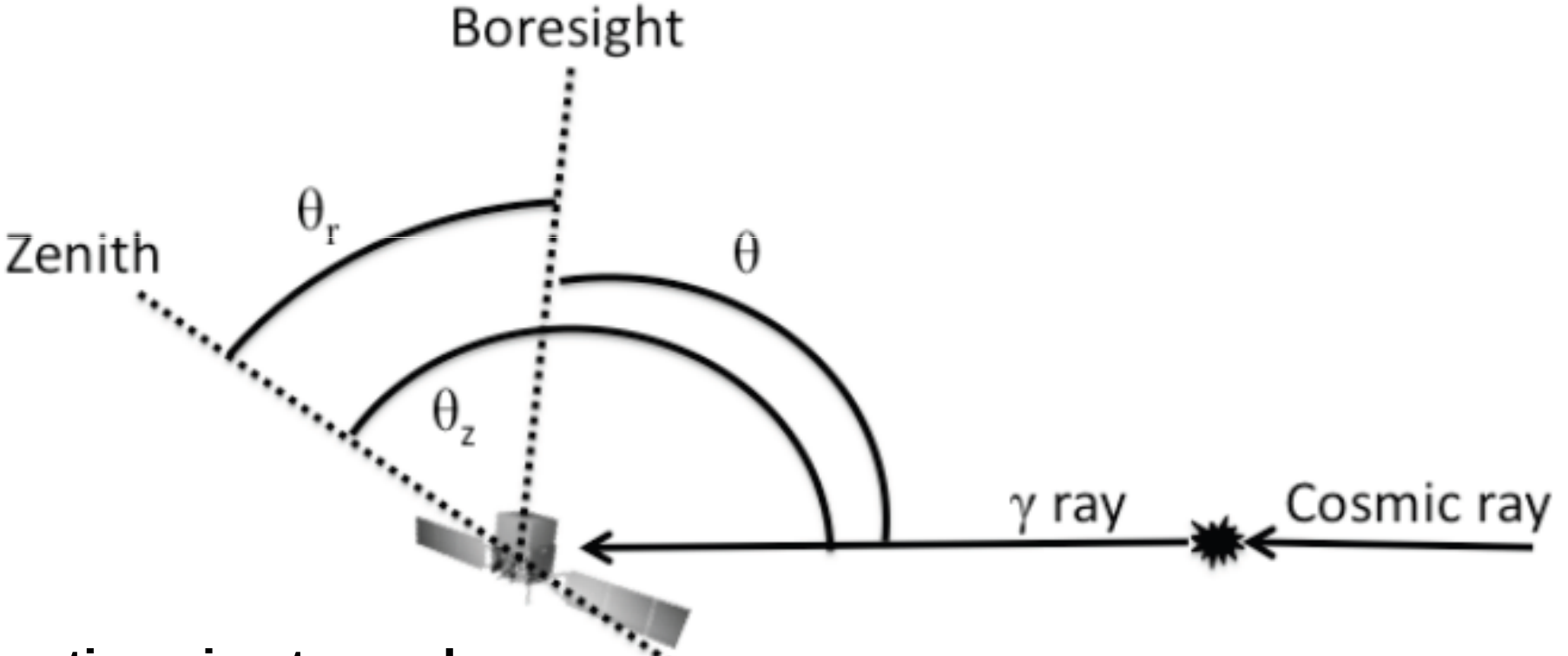
Dataset

TABLE I. Summary table of data selections.

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

- **Search for lines from 5 – 300 GeV using 3.7 years of data**
- **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**

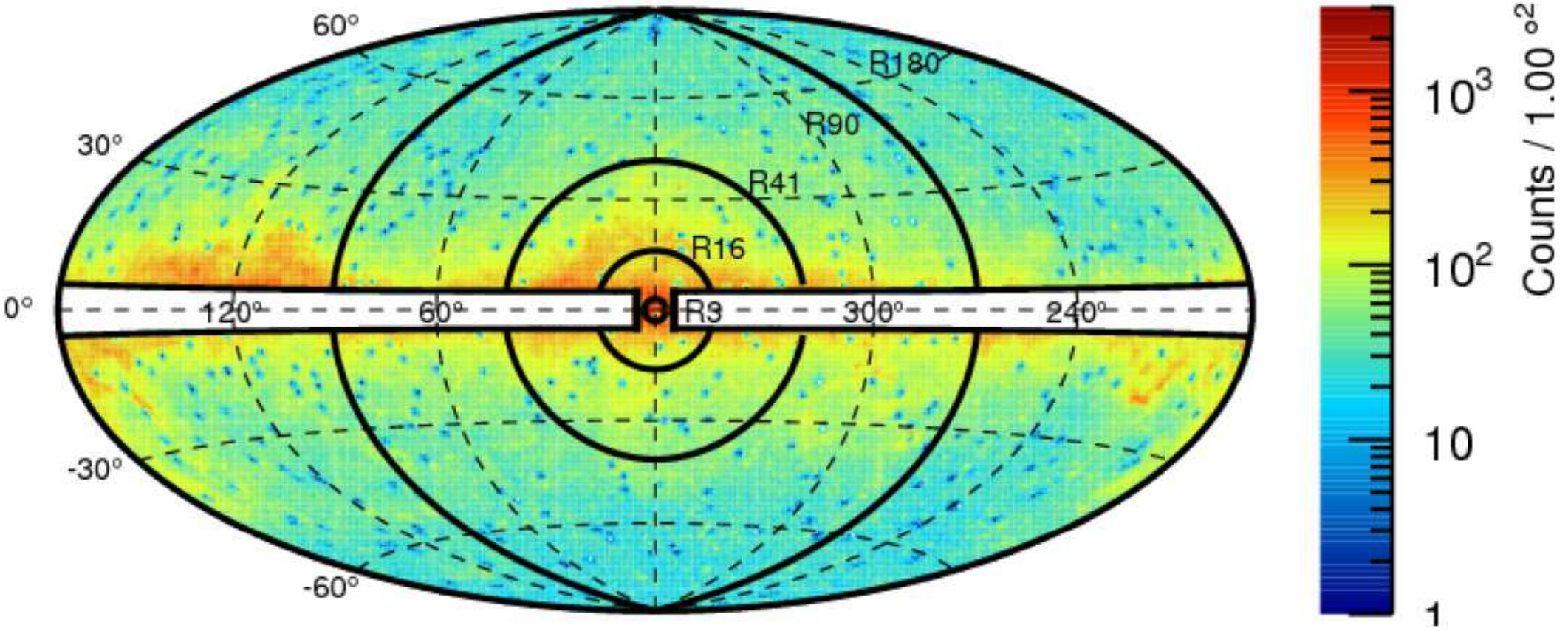
Earth Limb Control Dataset



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

Optimized Regions of Interest (ROIs)

3.7 year Counts Map



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

Fitting Method

Predicted Spectrum — Signal Model — Background Model

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

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

Effective Energy Dispersion

Incorporates energy reconstruction quality (P_E)

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

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)**

Systematic Effects in each 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

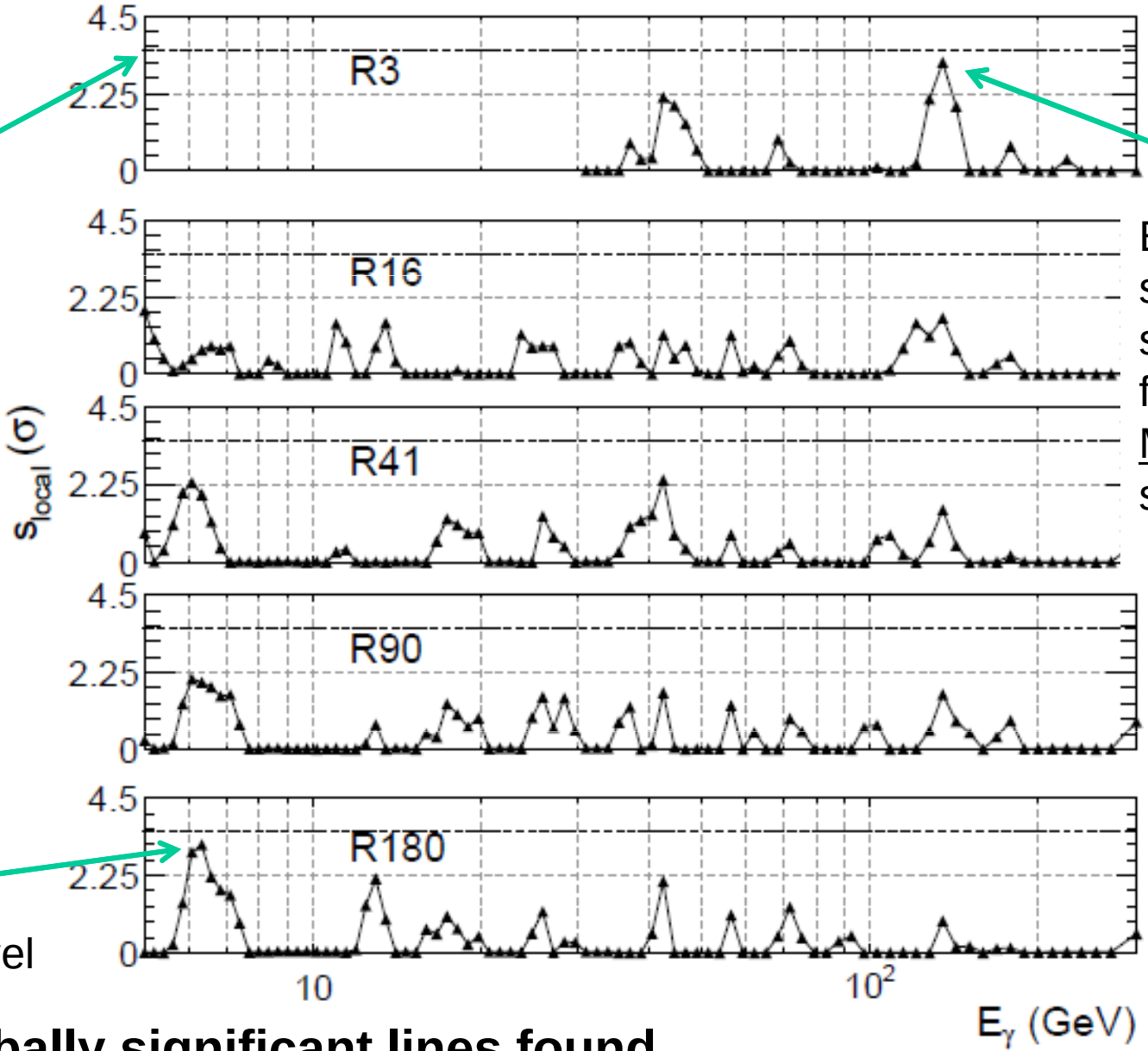
Quantity	Energy	R3	R16	R41	R90	R180
$\delta\epsilon/\epsilon$	5 GeV	0.10	0.10	0.11	0.12	0.14
$\delta\epsilon/\epsilon$	300 GeV	0.10	0.10	0.12	0.13	0.16
$\delta n_{sig}/n_{sig}$	All	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$
δf	5 GeV	0.020	0.020	0.008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

$s_{global} = 2\sigma$

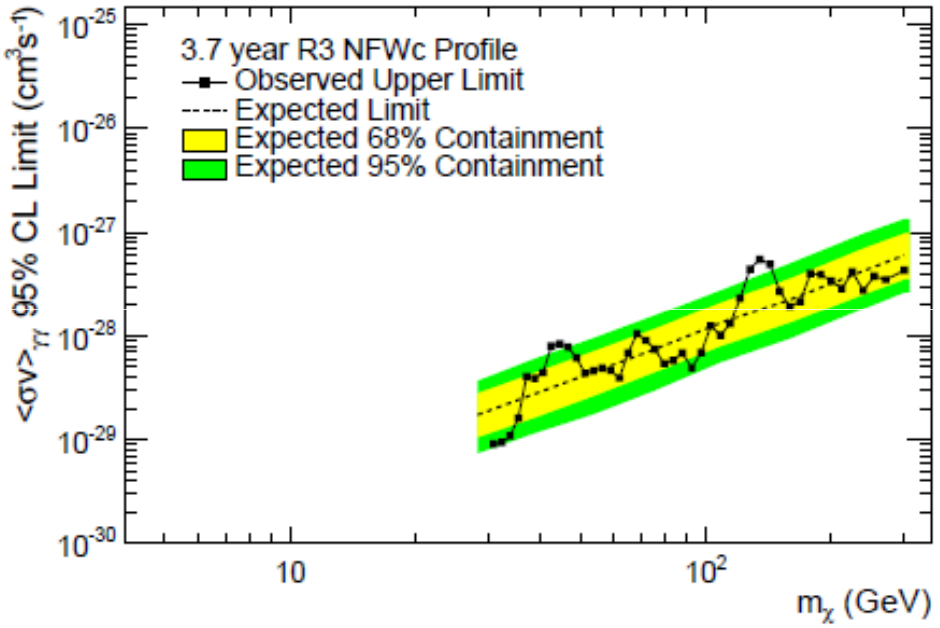


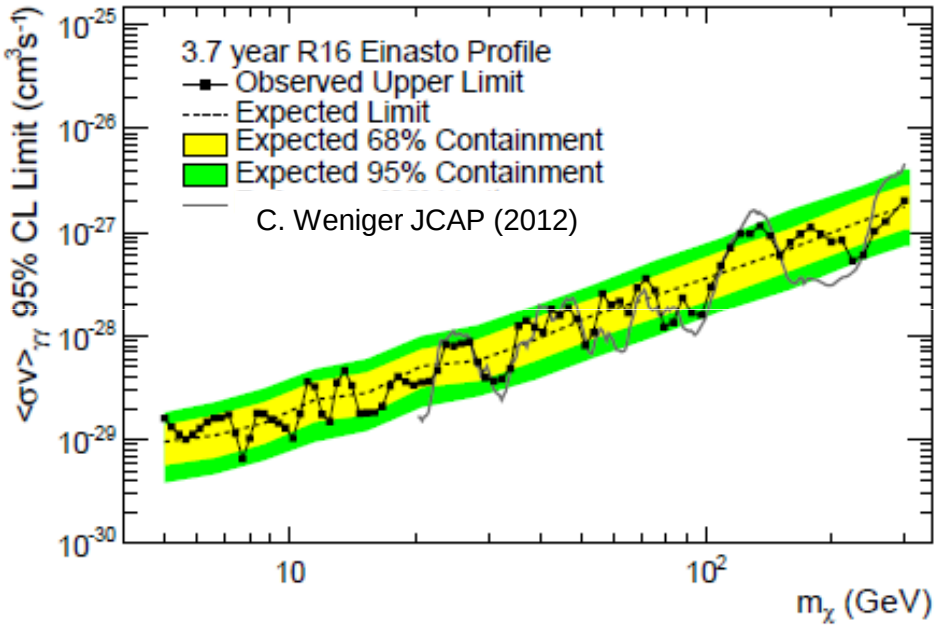
E_γ=135 GeV
s_{local} = 3.2σ
s_{global} = 1.5σ
f = 0.58
Much larger than systematic level

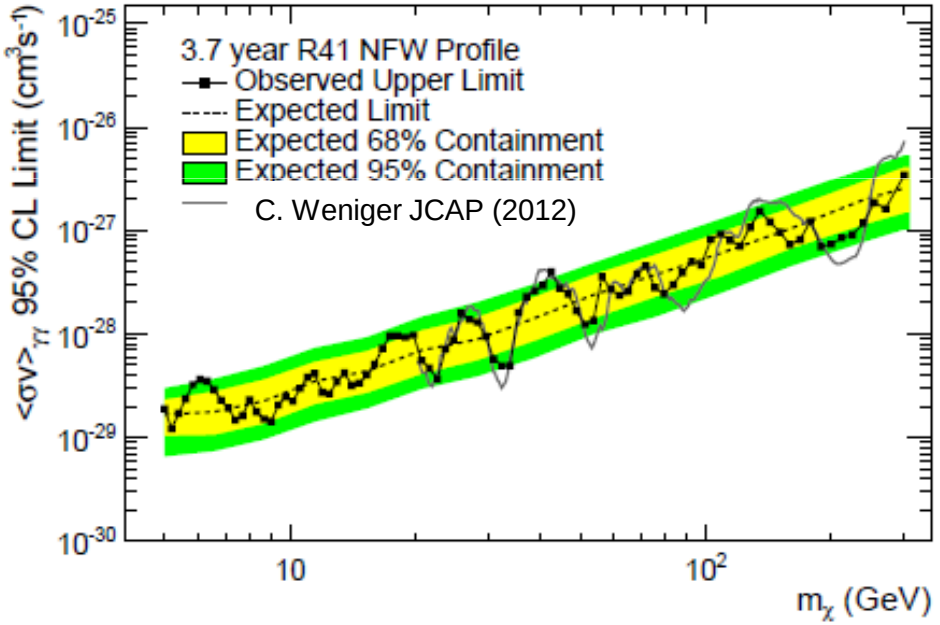
E_γ= 6 GeV
s_{local} = 3.1σ
s_{global} = 1.4σ
f = 0.01
At systematic level

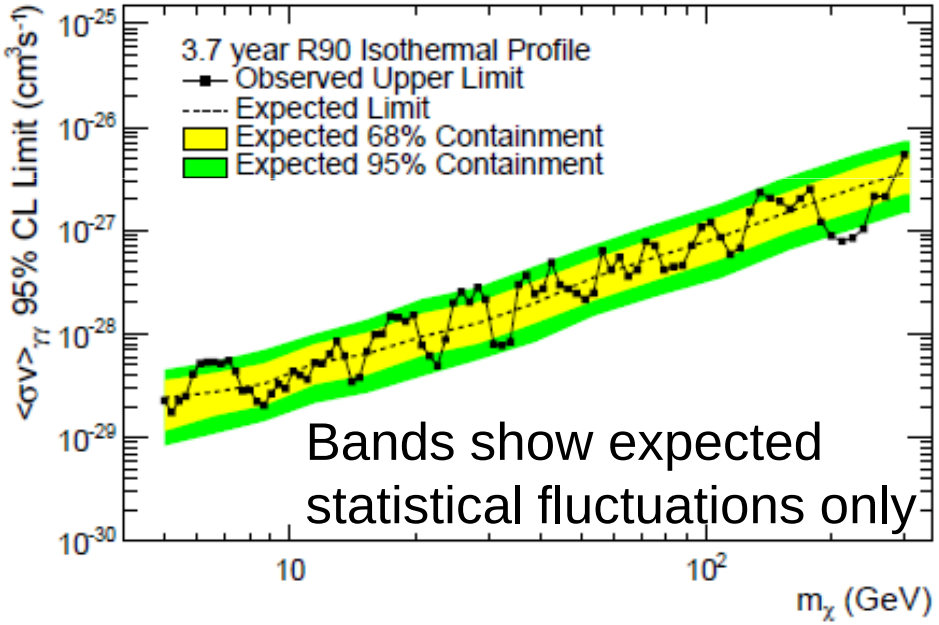
- **No globally significant lines found**

95% CL <σv> upper limits

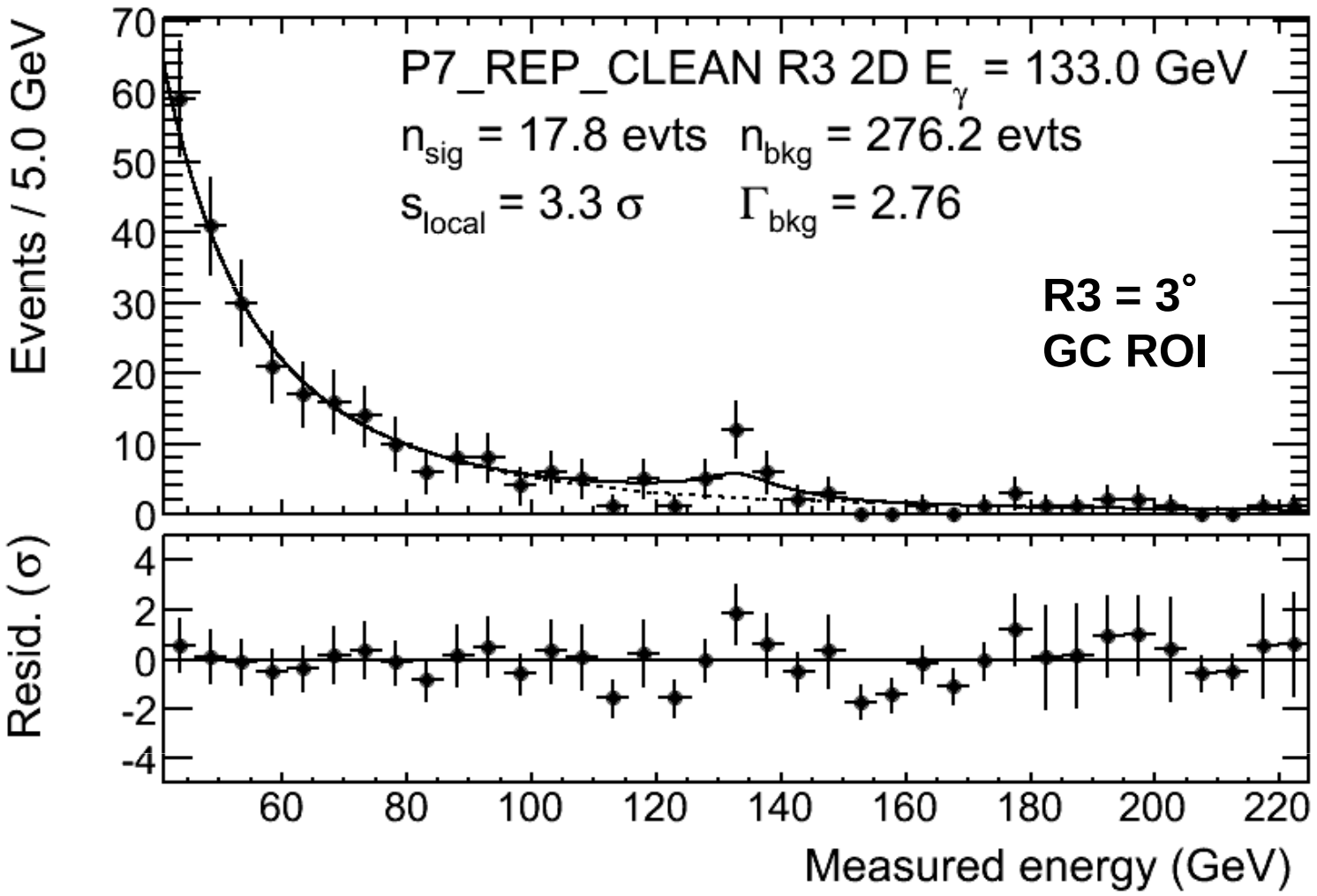






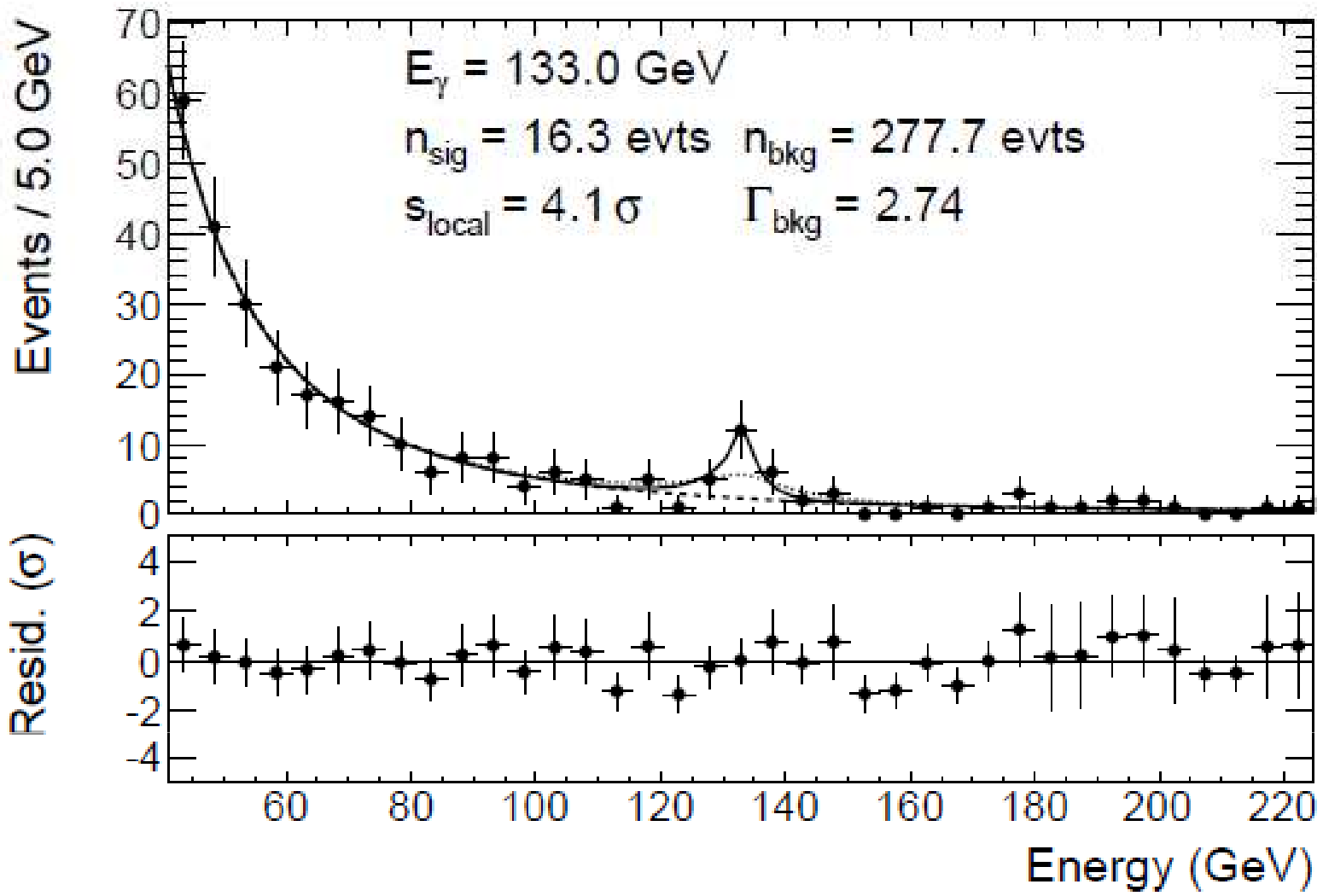


The Line-like Feature near 133 GeV



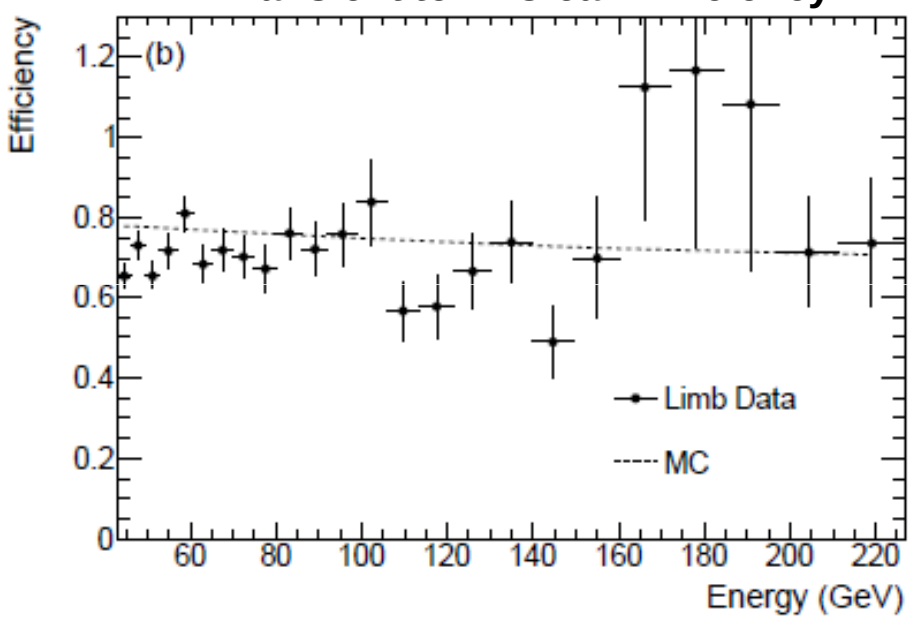
- **3.2σ (local) 2D fit at 133 GeV with reprocessed data**
  - **Fit with energy dispersion model that includes event-by-event energy recon. quality estimator P_E ("2D" model)**
    - **Expected 2D signal model to increase signif. of signals by ~15%**

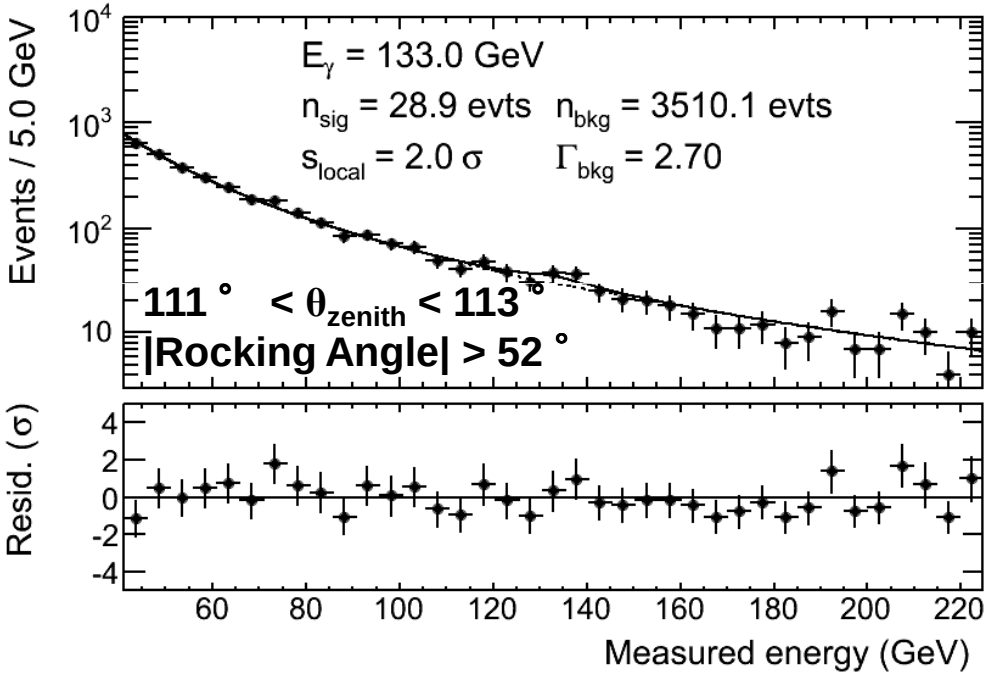
Width of 133 GeV Feature



- **Let width scale factor float in fit (while preserving shape)**
- $s_\sigma = 0.32^{+0.22}_{-0.07}(95\%CL) \quad \Delta TS = 9.4$
  - **Feature in data is <u>much narrower</u> than expected energy resolution (s_σ=1)**

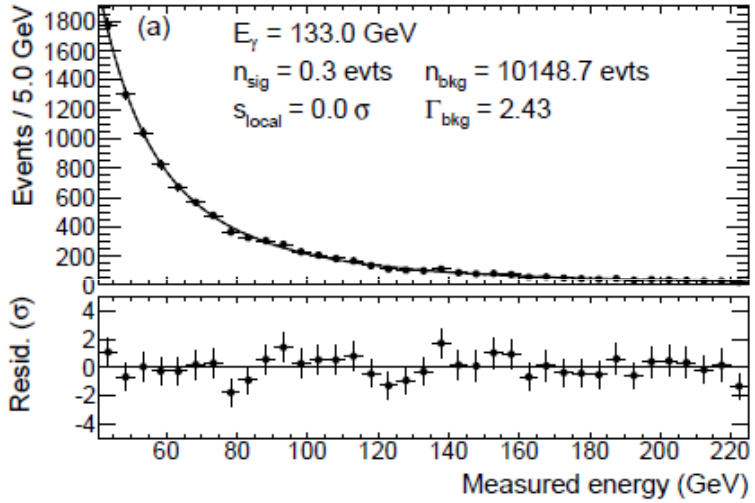
133 GeV in the Earth Limb spectrum

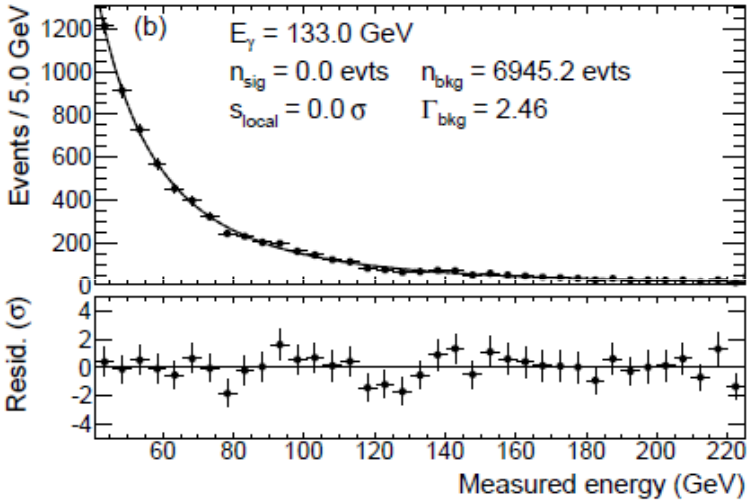


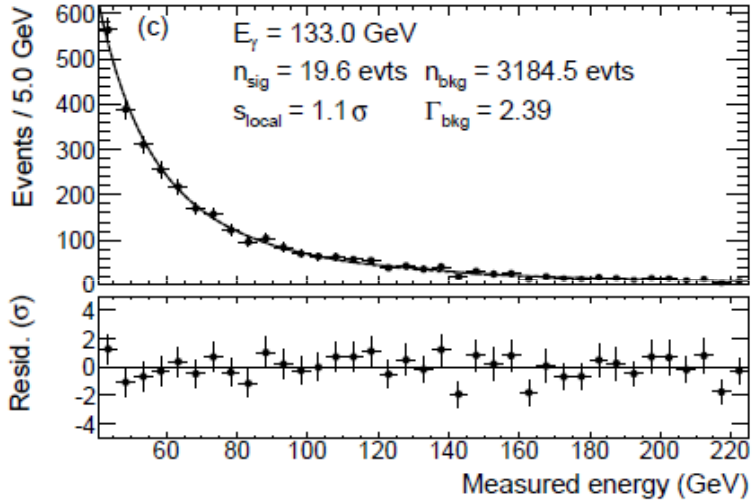


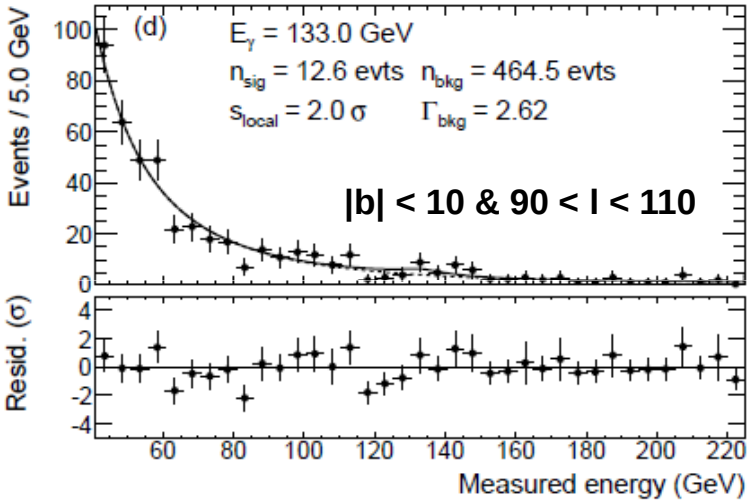
- **Line-like feature in the limb at 133 GeV (2.0σ local signif)**
  - **Appears when LAT is pointing at the Limb ($|\theta_r|<52^0$)**
  - **Surprising since limb should be smooth power-law**
  - **S/N_{limb} ~14%, while S/N_{R3} 61%**
    - **Limb feature not large enough to directly explain all the 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**

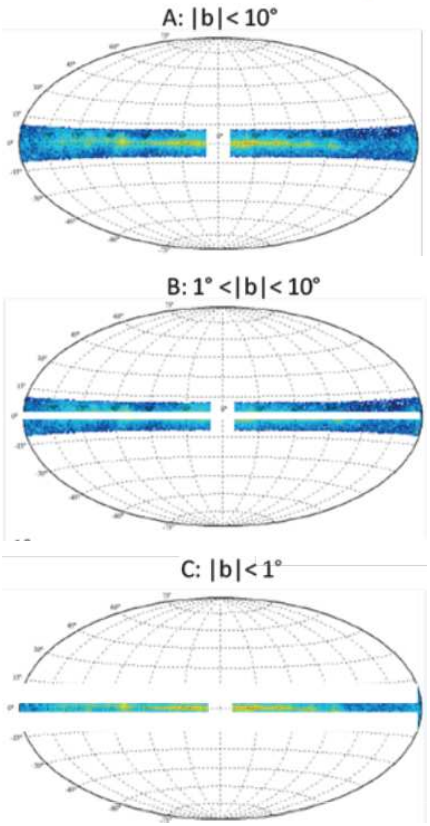
133 Feature in the inverse ROIs







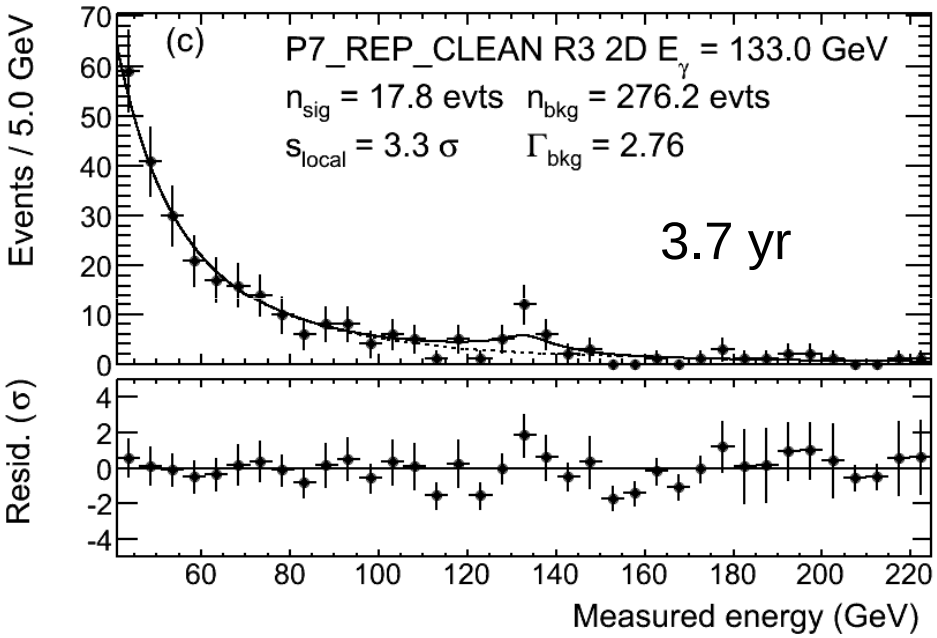


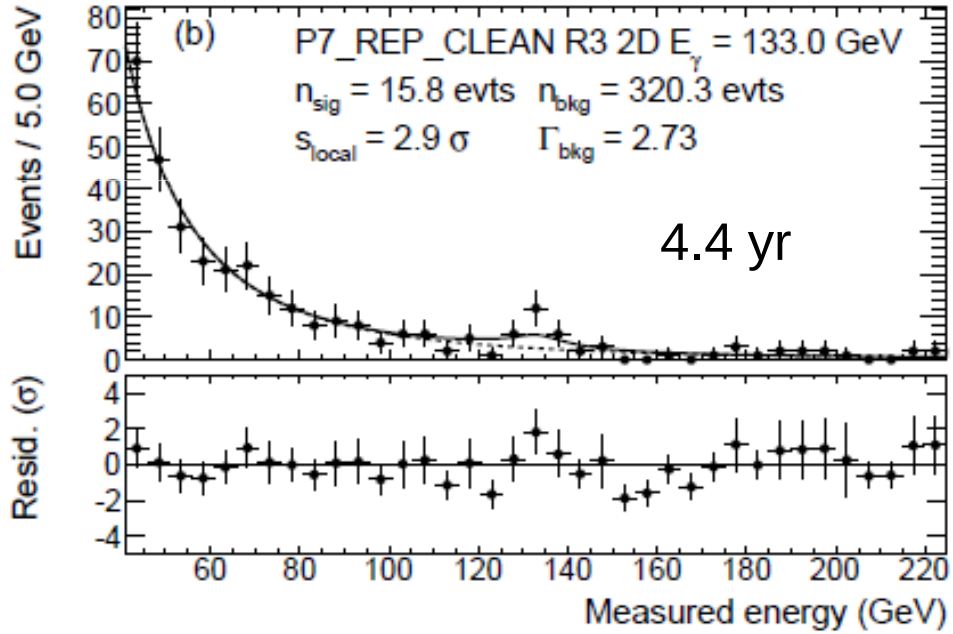


E. Bloom Fermi Symposium 2012

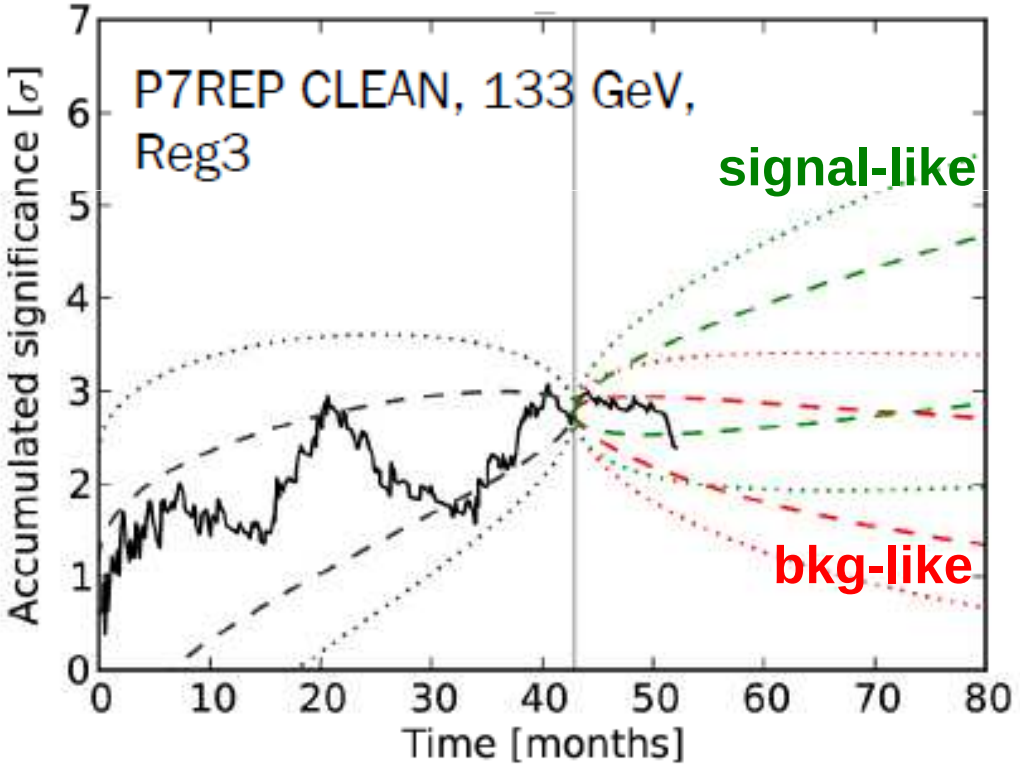
- **No obvious feature at 133 GeV in the inverse ROIs**
  - **Would naively expect an instrumental effect to show up everywhere**

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 decrease**
  - **More "background-like"**

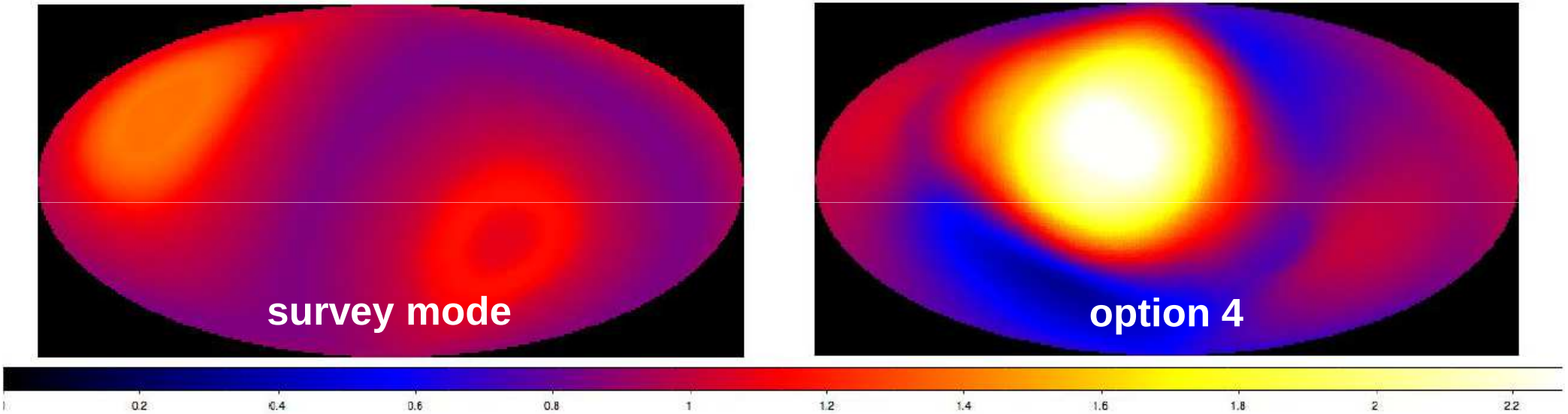
Summary

- **Search for spectral lines from 5--300 GeV in 5 ROIs**
  - **Use 3.7 year P7_REP_CLEAN dataset**
  - **Submitted for publication in PRD (http://arxiv.org/abs/1305.5597)**
- **No globally significant lines detected**
  - **All below 2σ global significance**
  - **Have set 95% CL $\Phi_{\gamma\gamma}$, $\langle\sigma v\rangle_{\gamma\gamma}$, and $\tau_{\gamma\gamma}$ limits**
- **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 line analyses**
  - **Pass 8 → ~25% increase in A_{eff} and better (different) systematics**
  - **More Limb data from pole stares and future ToOs**

BACKUP SLIDES

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" around December 2013.**
  - **Option 4 points to keep the GC in the field of view, while still providing relatively uniform all-sky coverage**

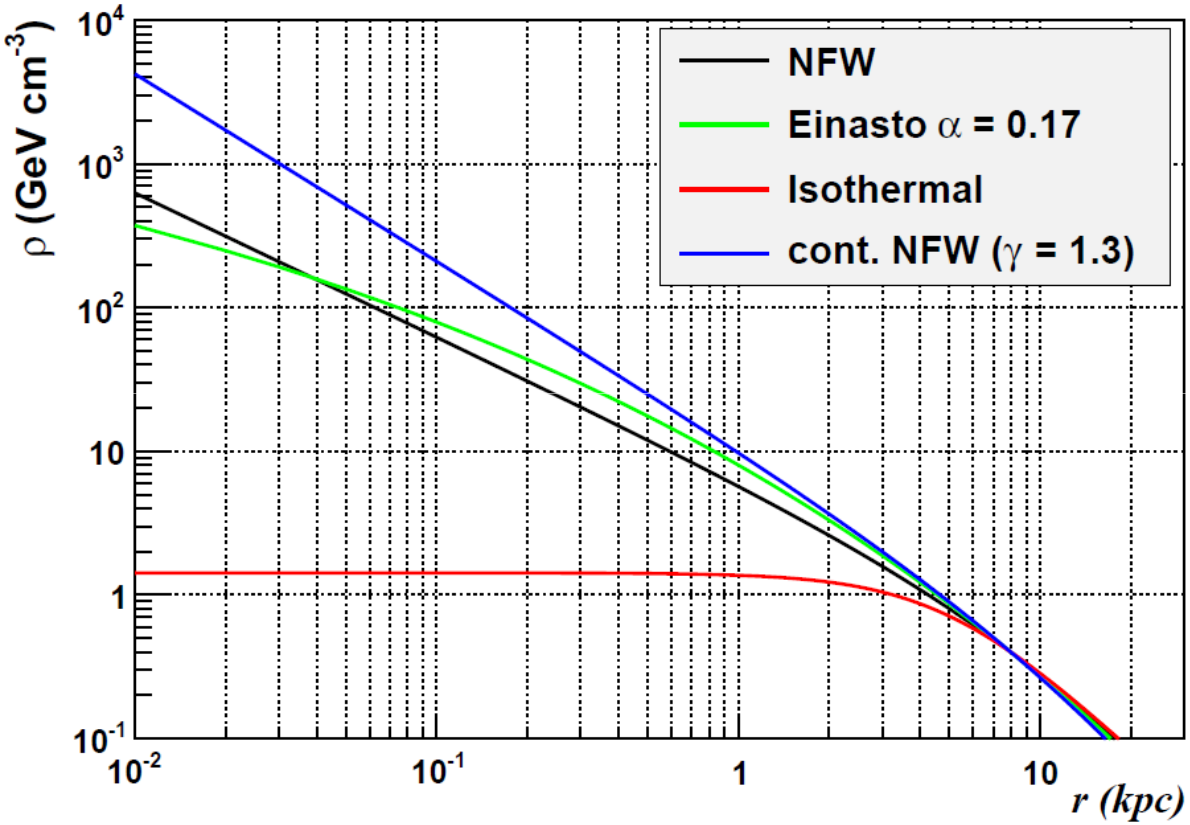


exposure maps

Indirect WIMP Signatures (2)

Astrophysics

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



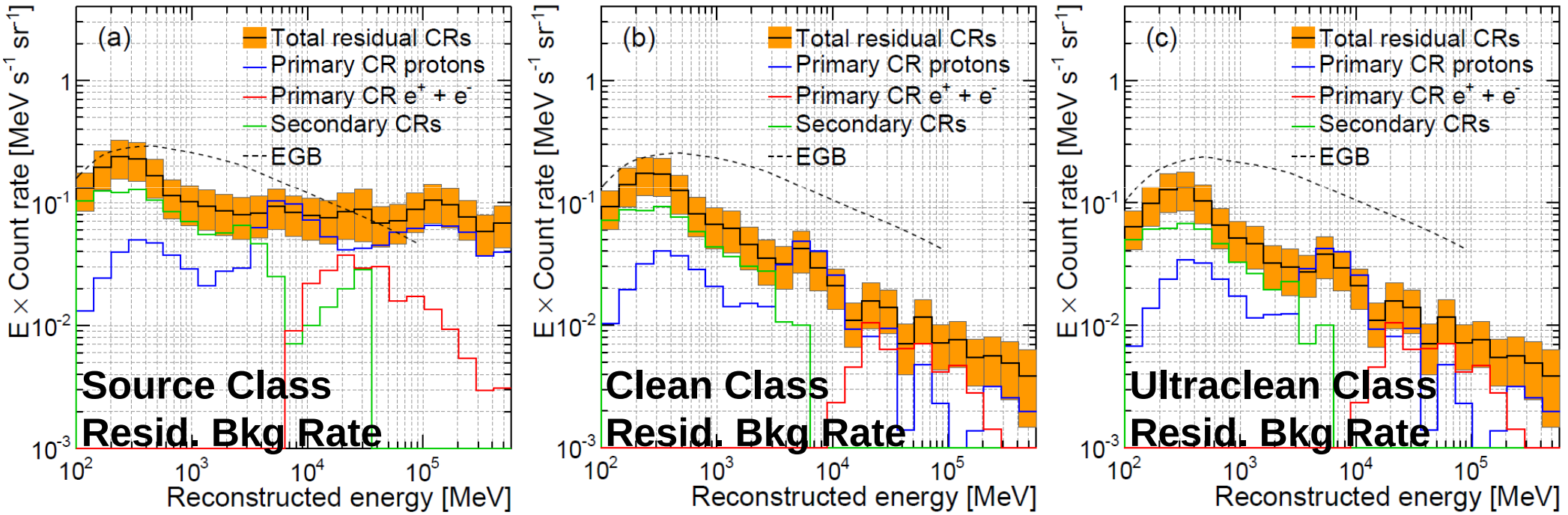
J-factor – Line of sight integral over a ROI

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

Gamma-ray Event Classes

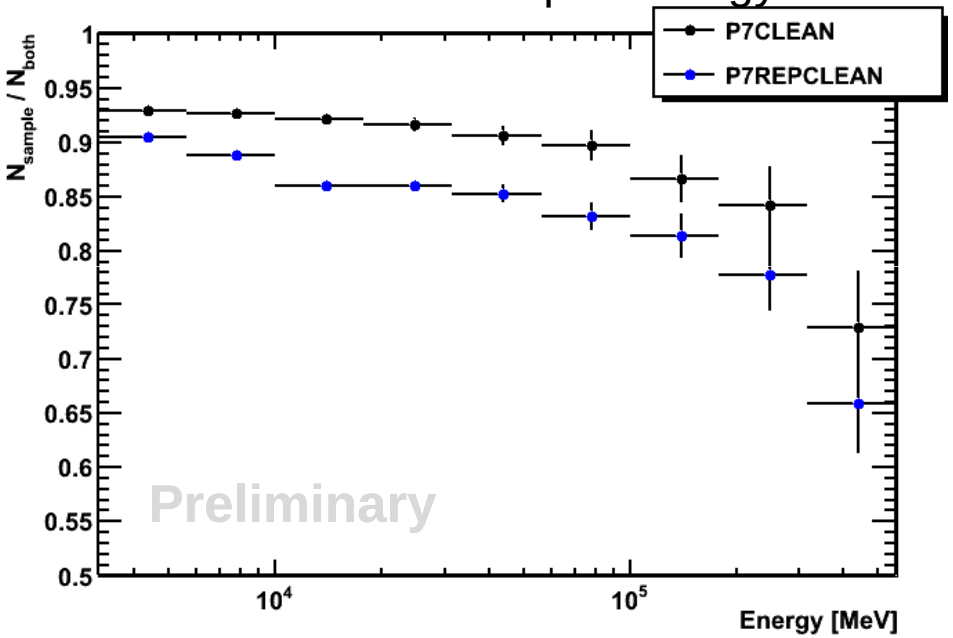
- **Triggered events are dominated by CR background events**
  - **Need to define additional cuts to get γ-ray rich dataset**
- **Nested "event classes" for various types of γ ray sources**
  - **Transient: loosest, for flaring sources (cut in time)**
  - **Source: moderate, for bright sources (cut in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

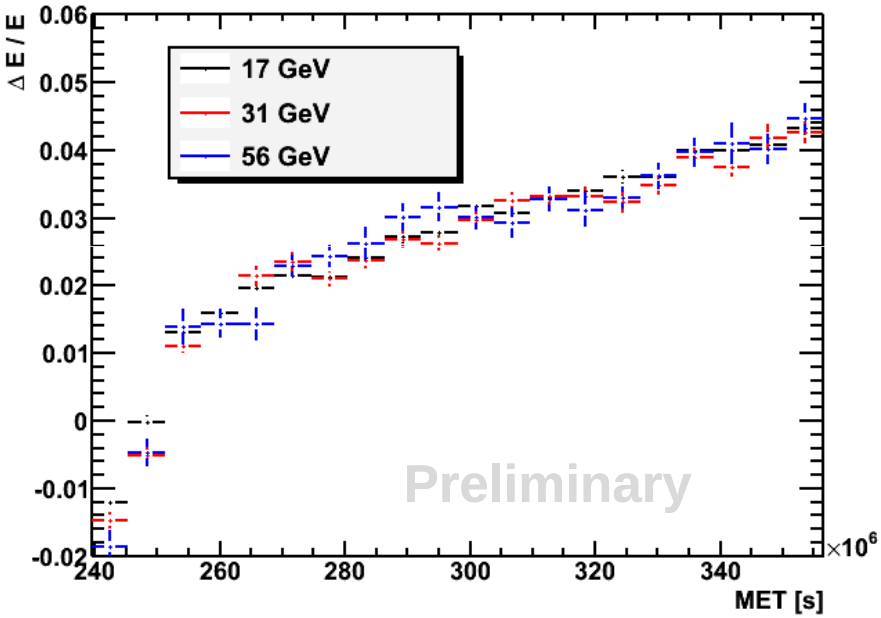


Data Reprocessing with Updated Calibrations

Event Overlap v. Energy

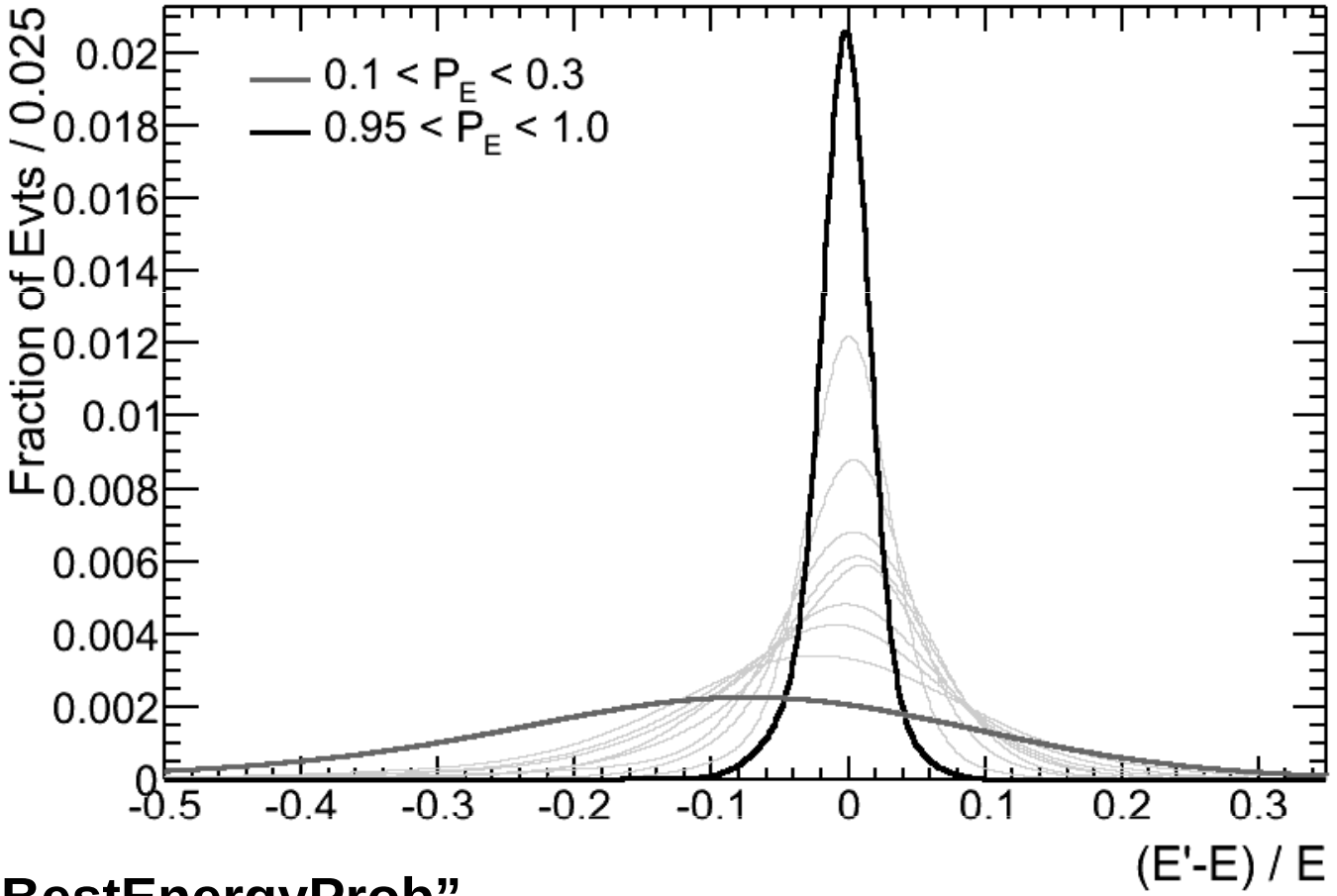


Energy Shift v. Time



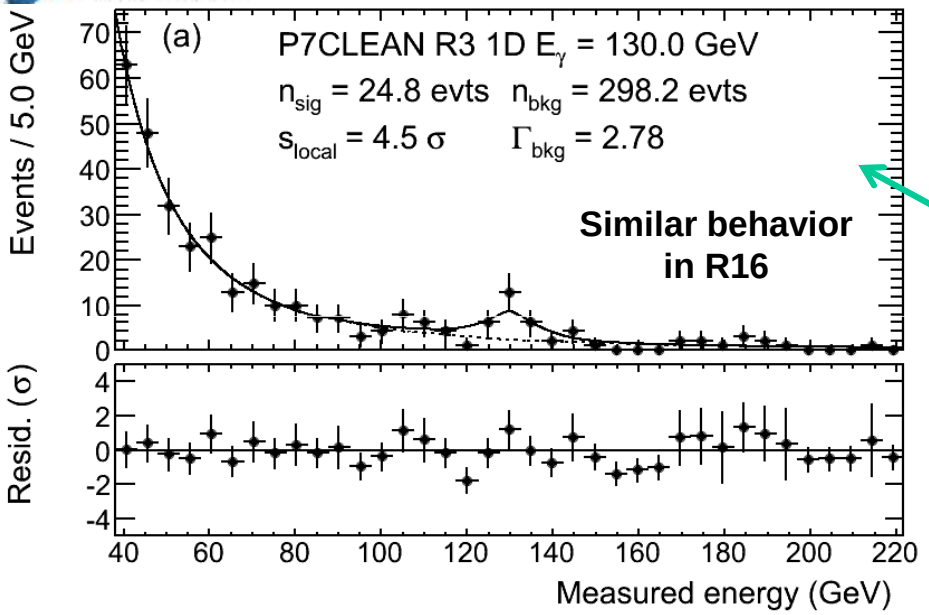
- Reprocessing Data with updated calibrations (primarily Calorimeter)
- Improves the agreement between the TKR direction and the CAL shower axis and centroid at high E, improving the direction resolution
- Corrects for loss in CAL light yield b/c of radiation damage (~4% in mission to date)
- 80%+ overlap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

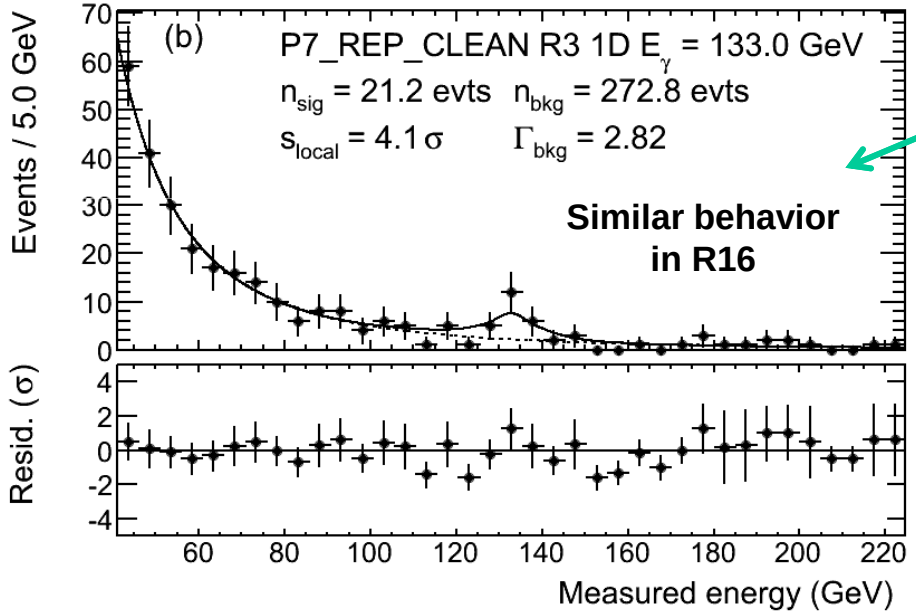
Energy Dispersion Model ("2D model")



- **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**

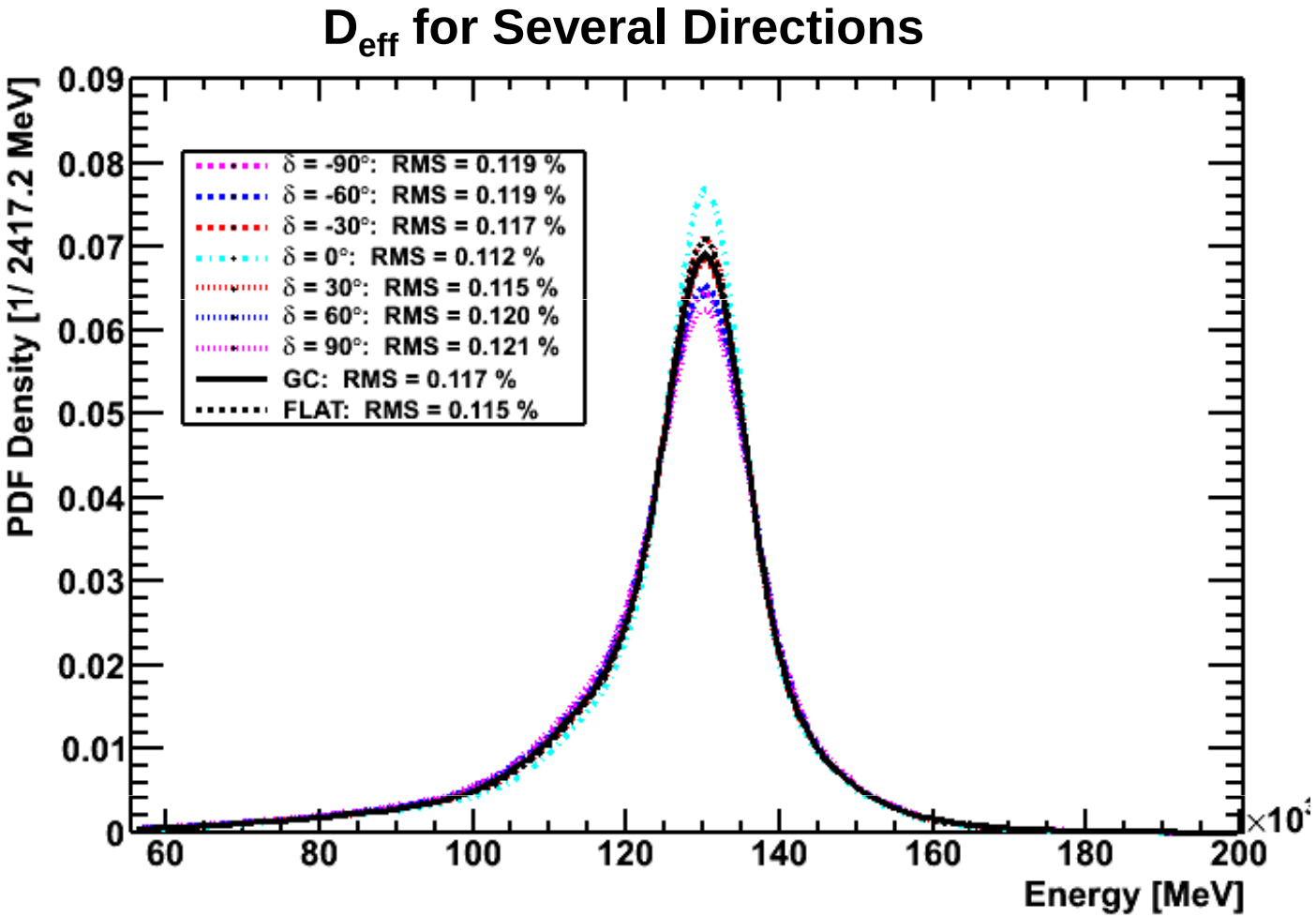
Studies of Line-like Feature near 133 GeV (1)





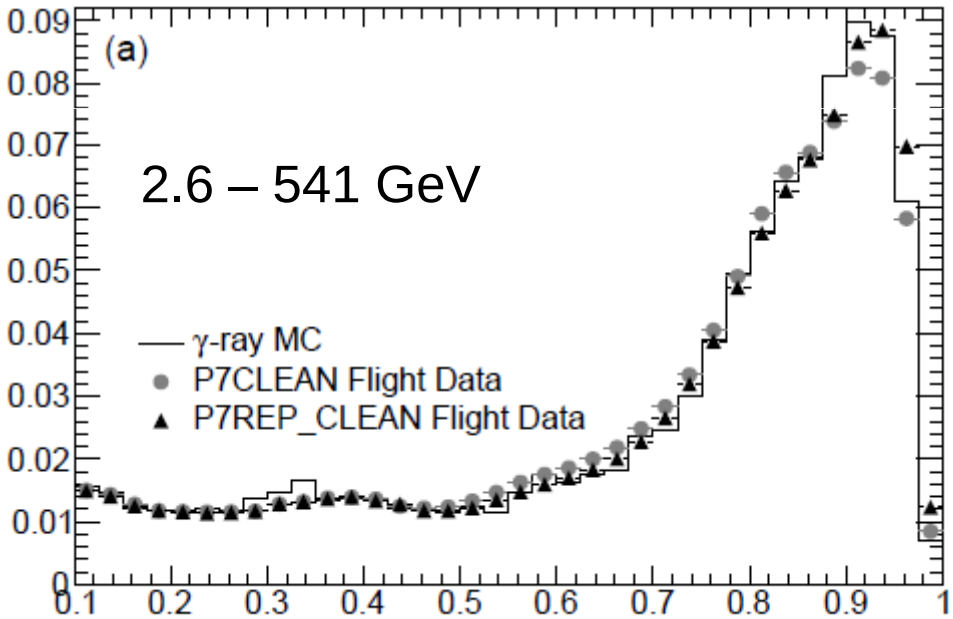
- **Fits using simpler energy dispersion model**
  - **no use of energy recon. quality: P_E**
- **4.5σ (local) 1D fit at 130 GeV with unreprocessed data**
  - **Comparable to signif. reported in C. Weniger JCAP 1208 (2012) 007 arXiv:1204.2797**
- **4.1σ (local) 1D fit at 133 GeV with reprocessed data**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

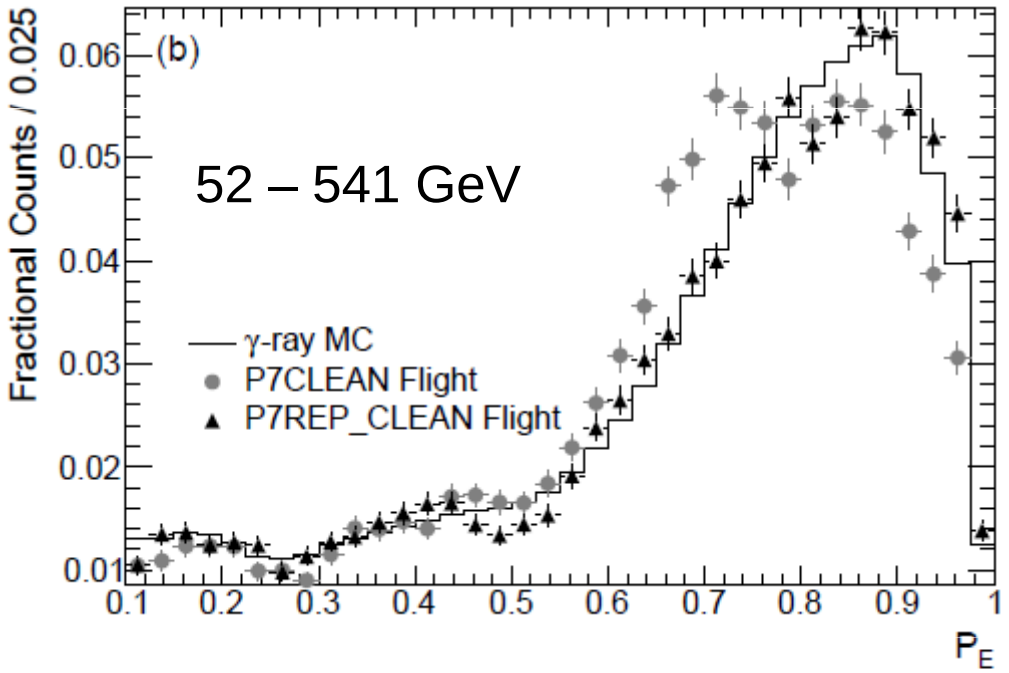
θ-averaged Energy Resolution by Declination



- The θ-averaged D_{eff} weighted for observing profile varies moderately with declination (δ).
- Using the wrong profile will not induce a signal, but can scale the n_{sig} and the significance of a signal by up 25%.

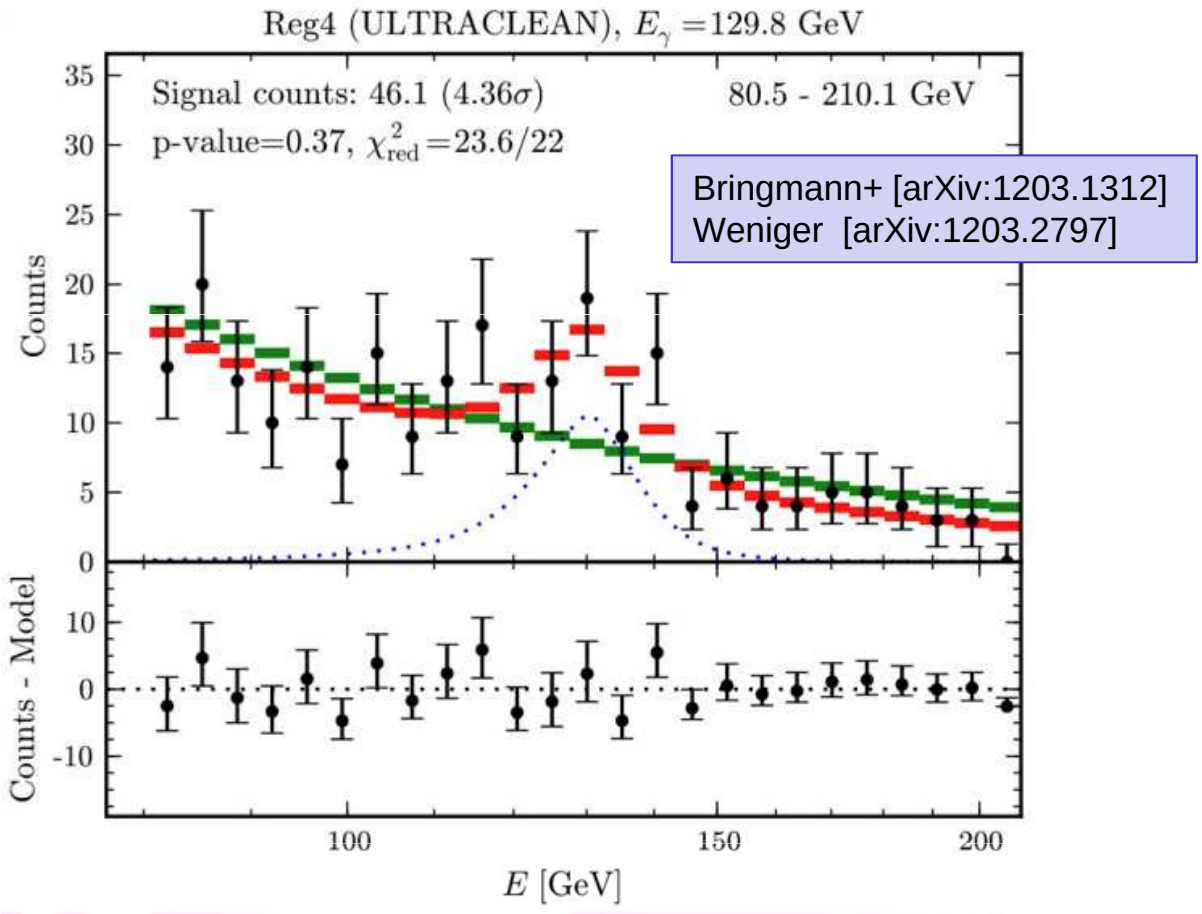
P_E distribution in data vs MC



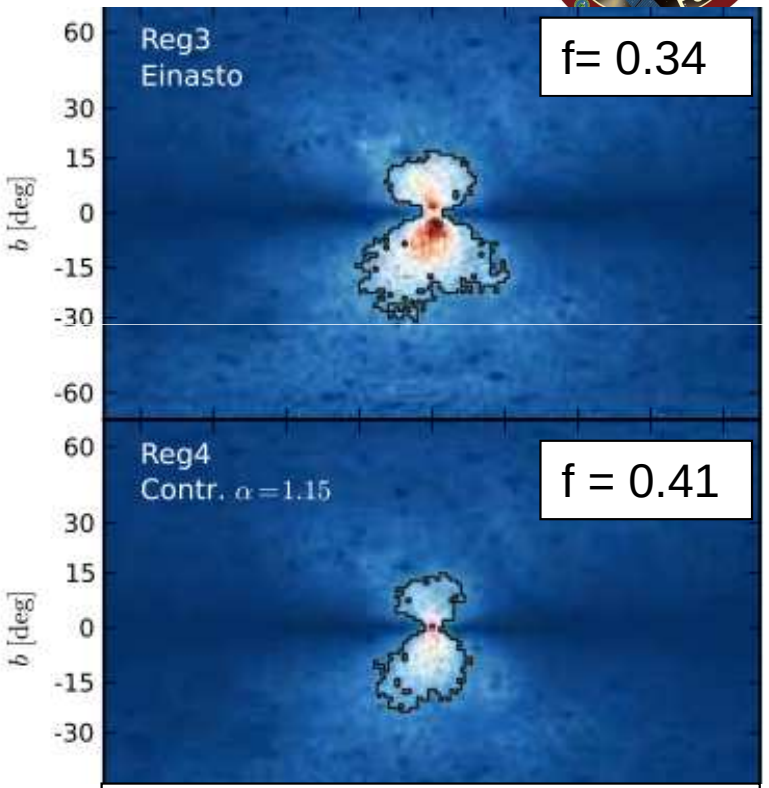


- **Use "all-sky" MC with diffuse + 2FGL and full orbit history**

Reported Narrow Feature at 130 GeV (1)



Bringmann+ [arXiv:1203.1312]
Weniger [arXiv:1203.2797]



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)**

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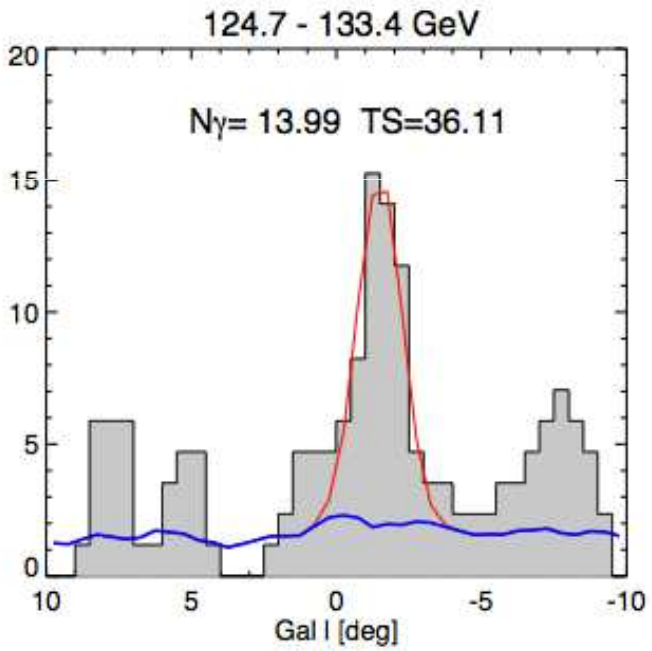
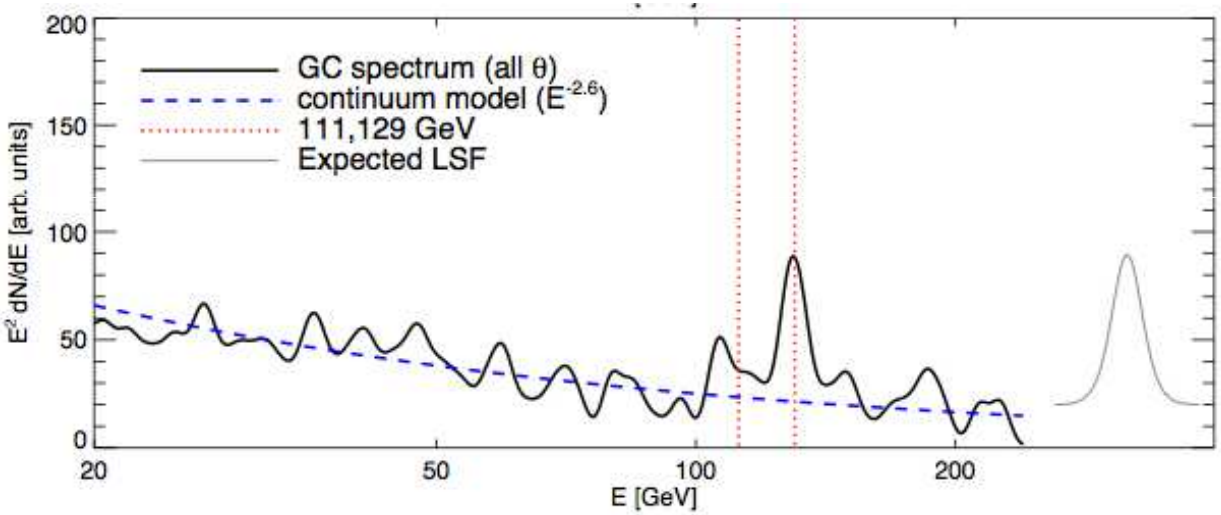
Reported Narrow Feature at 130 GeV (2)

Gal. Long. Profile at ~130GeV



Energy Spectrum from GC



Su & Finbkbeiner [arXiv:1206.1616]

- **Su & Finkbeiner [arXiv:1206.1616v2] showed that the spectral feature was close to, but slightly offset from, the GC**
- **Likelihood analysis included the spatial morphology of signal, and a data-driven model of Galactic astrophysical backgrounds**
- **~5.0σ statistical significance (one line), after a trials factor of ~6000, but acknowledged uncertainties of modeling the Galactic astrophysical backgrounds**

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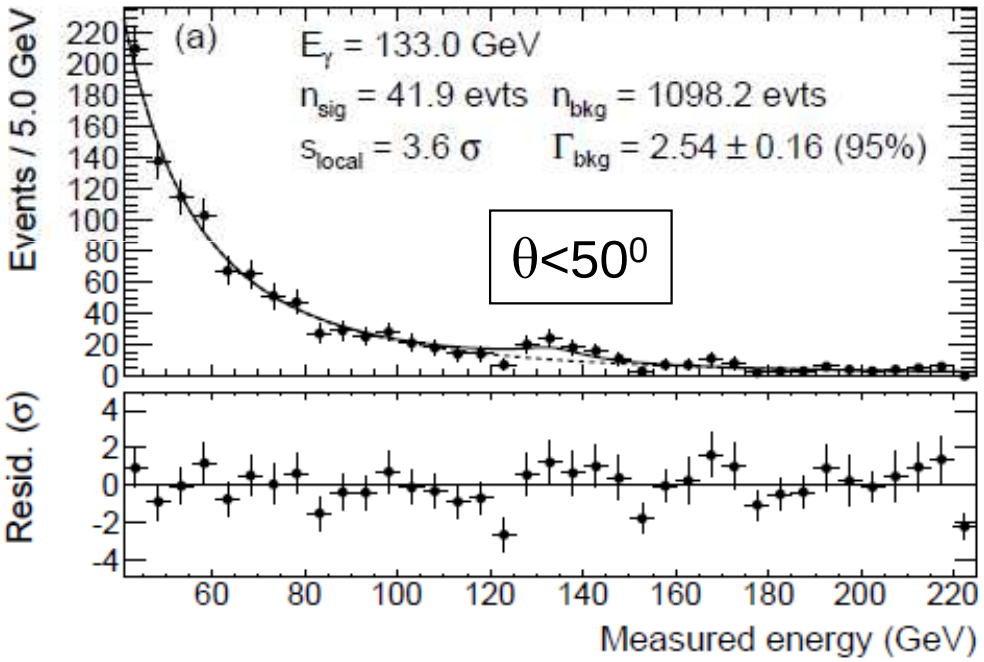
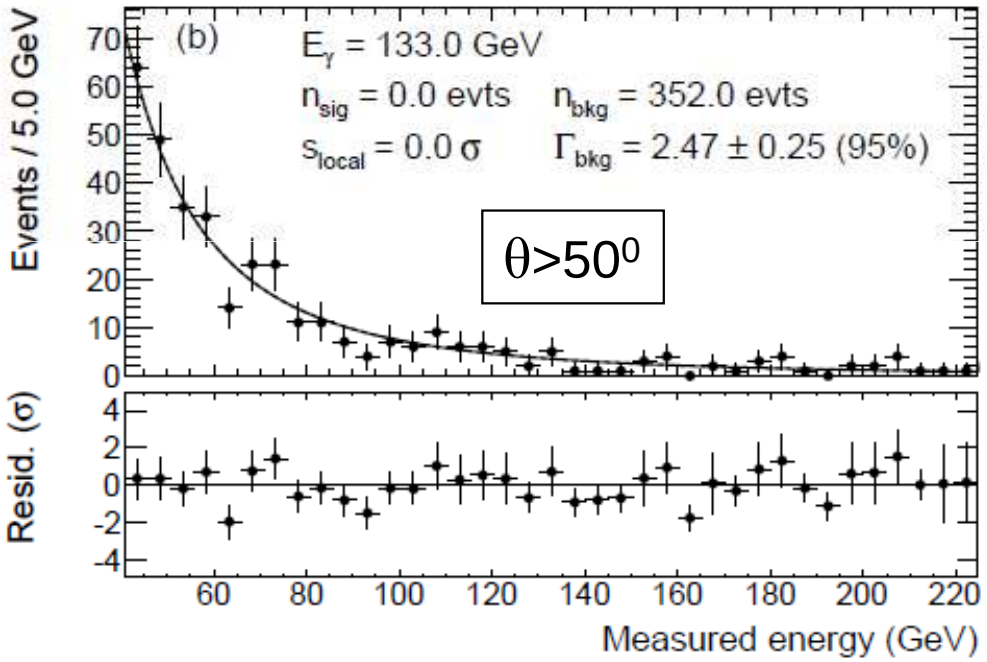
θ-dependence of 135 GeV feature





- **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**