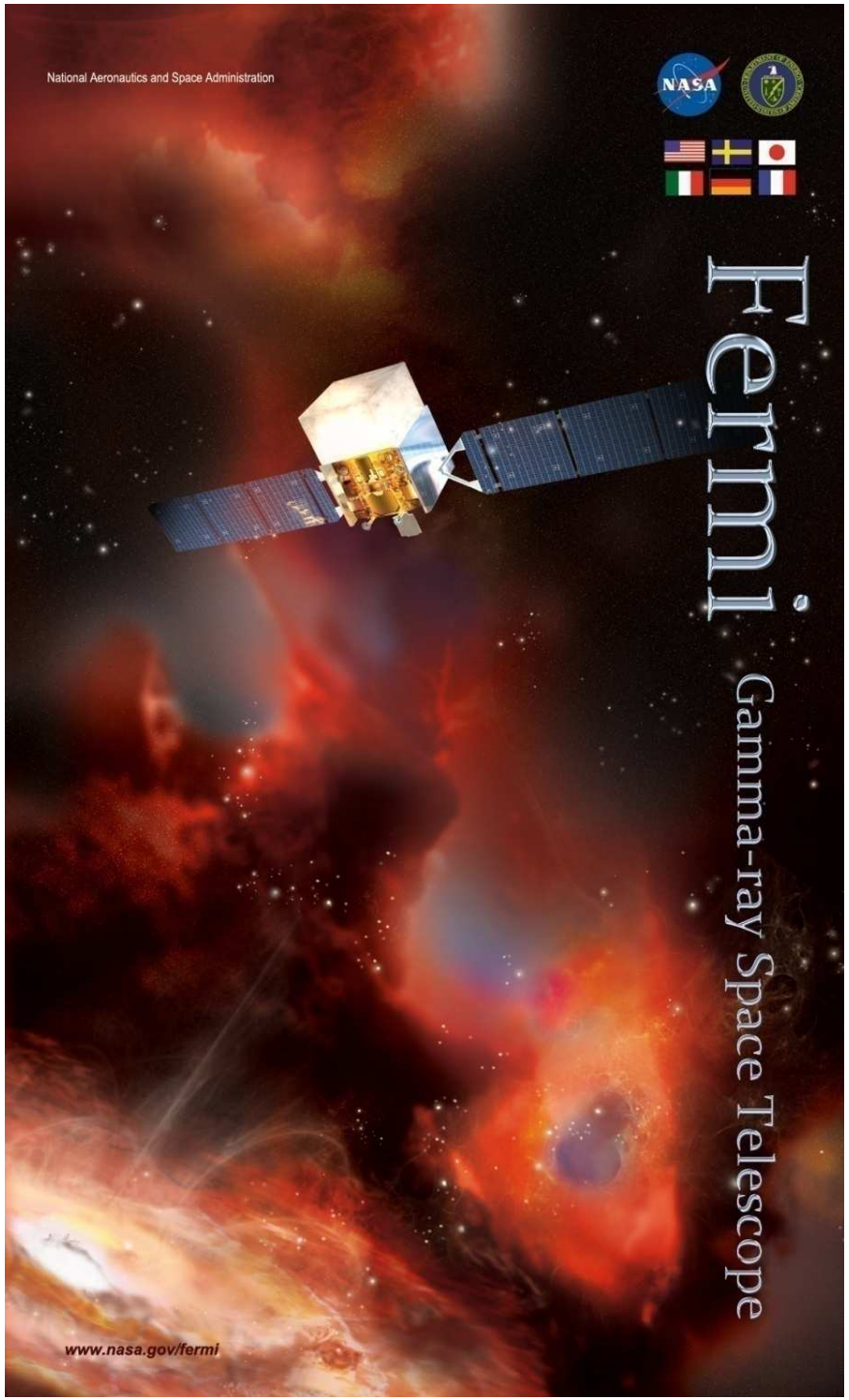


SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC

Fermi Gamma-ray Space Telescope

Search for Gamma-ray Spectral Lines with the *Fermi* Large Area Telescope and status of the 135 GeV feature

Andrea Albert (SLAC)

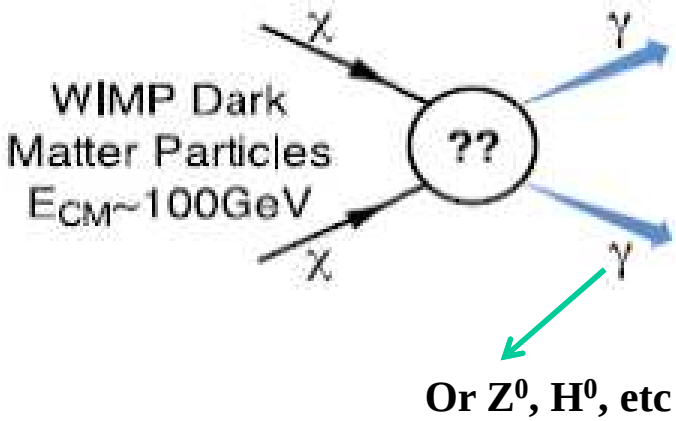
On Behalf of the Fermi-LAT Collaboration

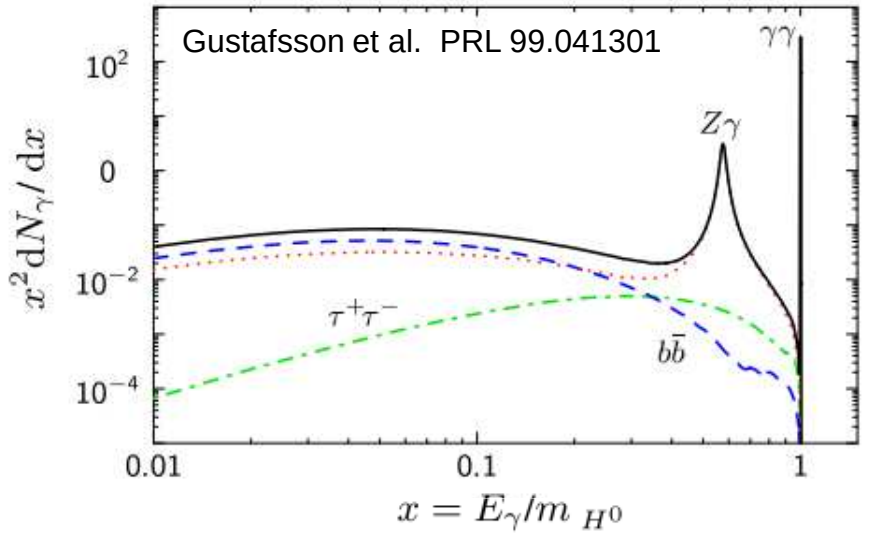
Vulcano Workshop

May 20th, 2014

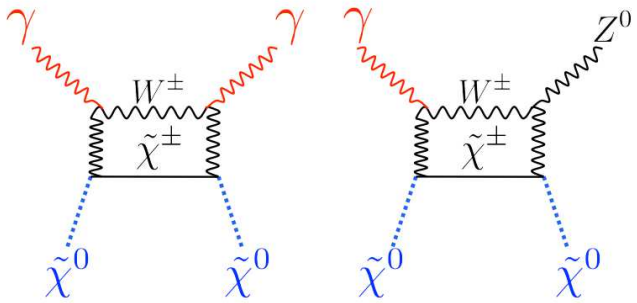
Spectral Lines from WIMPs

Spectral Line





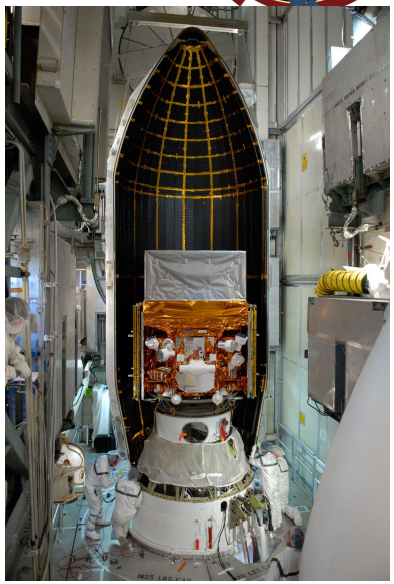
- **WIMP = Weakly Interacting Massive Particle**
  - **DM candidate (e.g. neutralino)**
  - **Believe the Milky Way sits in a large spherical "halo" or cloud of DM**
    - **Non-relativistic (cold) DM**



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

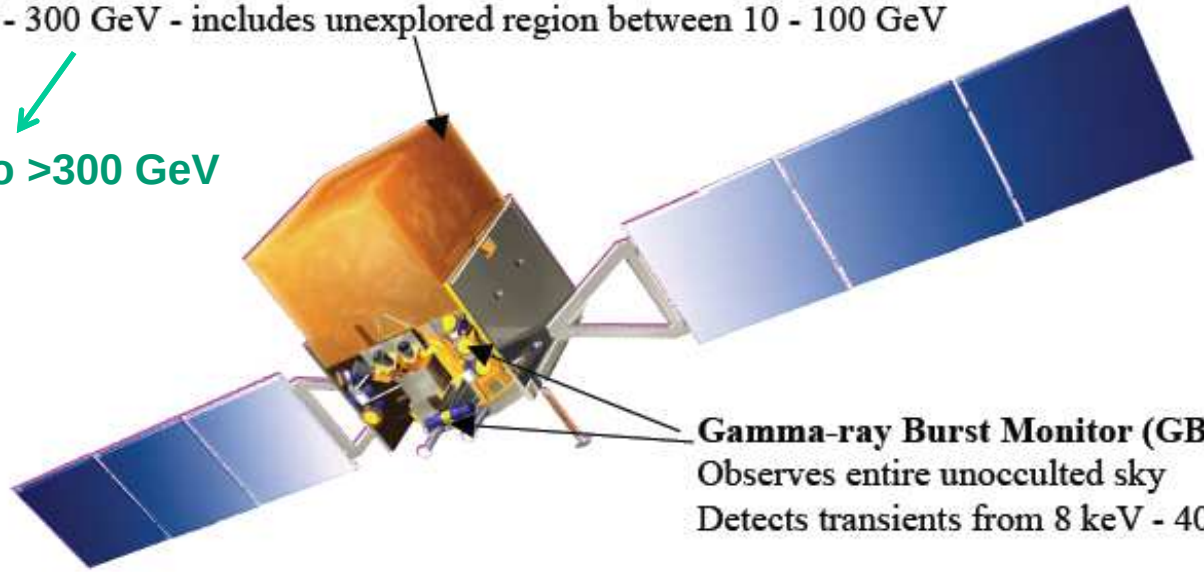
Fermi Large Area Telescope (LAT)

- **On board the Fermi Gamma-ray Space Telescope**
  - **Launched June 11, 2008**
    - **Started taking science data Aug 2008**
  - **5 year mission minimum (goal is 10 years)**
    - **Mission extended at least through 2016**



Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV

Can go >300 GeV



Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV

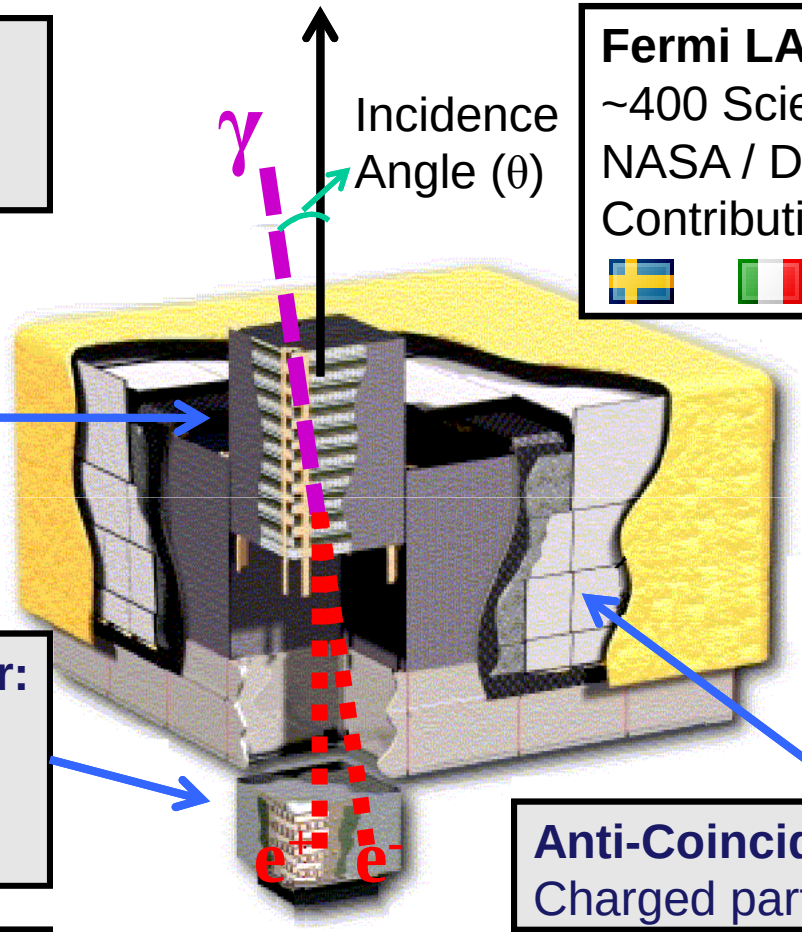
Fermi LAT

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



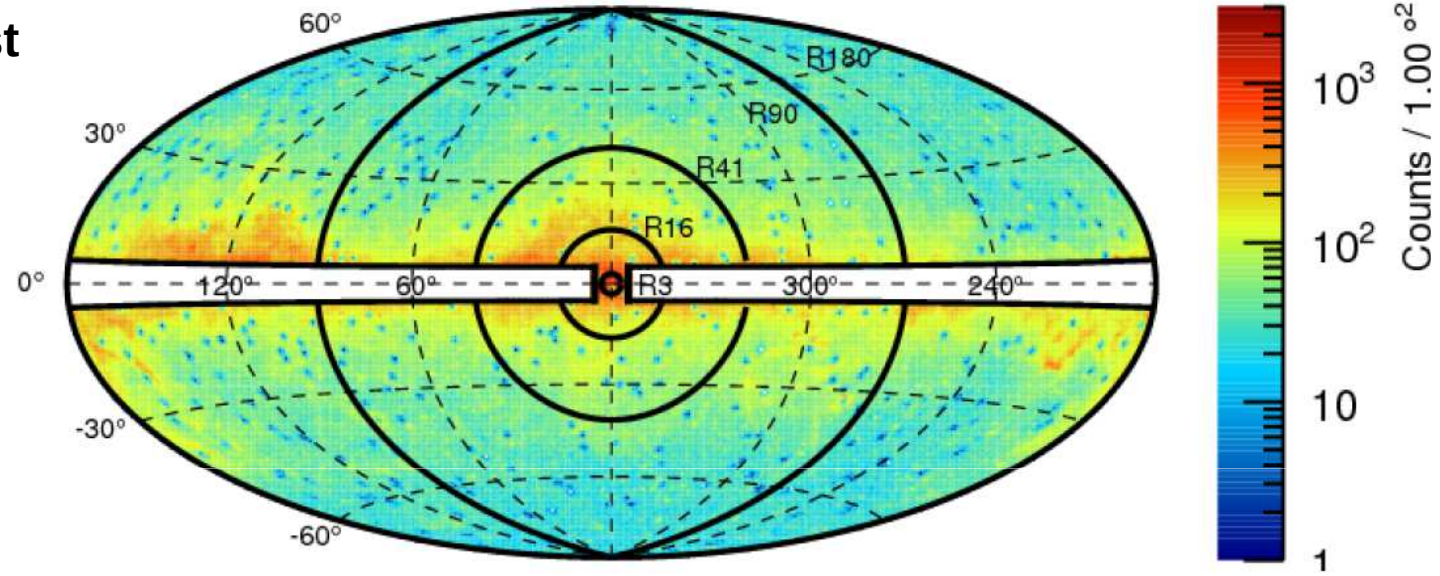
Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions

Anti-Coincidence Detector:
Charged particle separation

High Energy Line Search Dataset

5 Regions of Interest

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



- **PRD 88, 082002 (2013)**
- **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**

Fitting Method

Predicted Spectrum | Signal Model | Background Model

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

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

Effective Energy Dispersion

Incorporates energy reconstruction quality (P_E)

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

Effective 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

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

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
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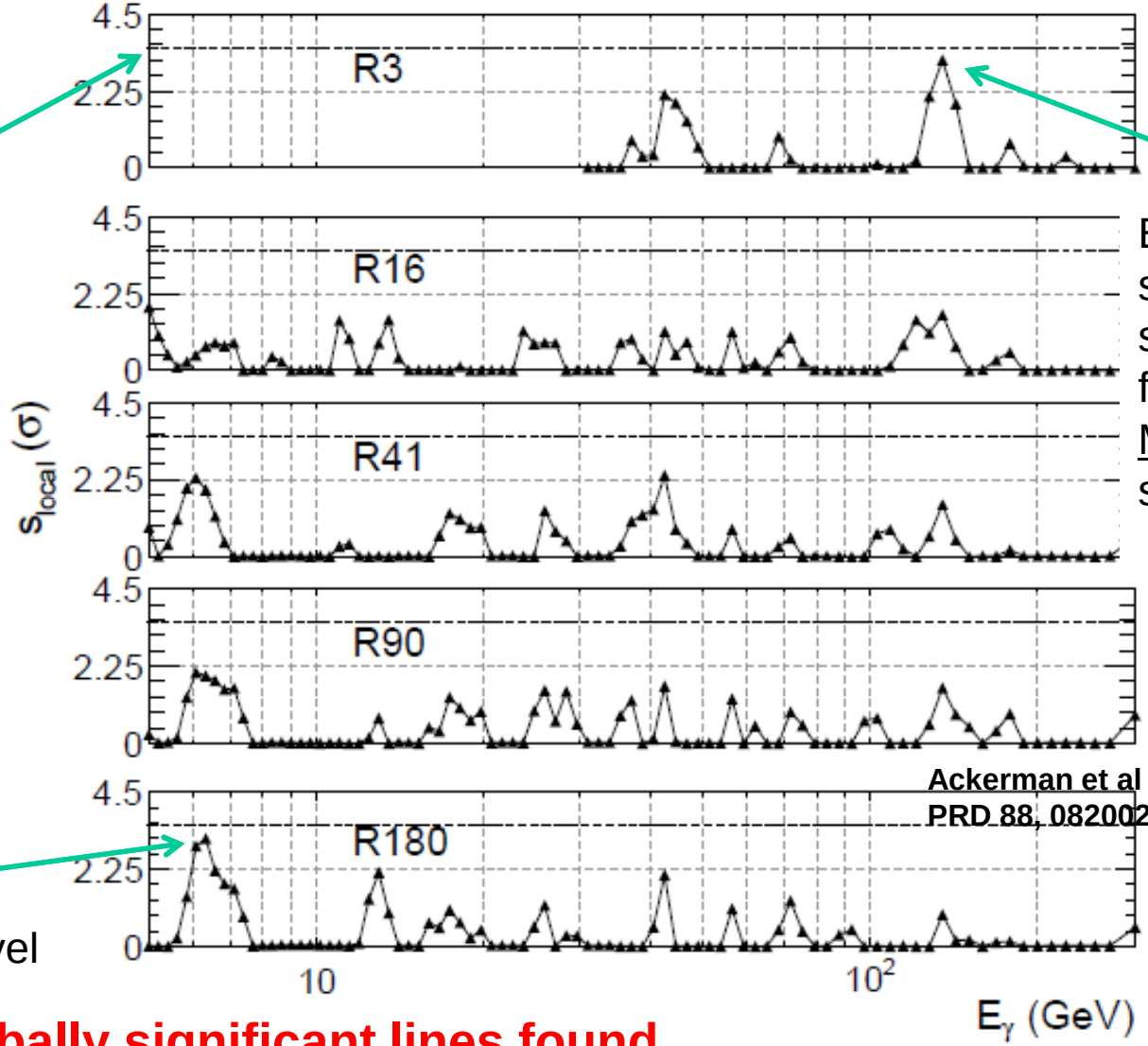
δf	50 GeV	0.024	0.024	0.015	0.015	0.015
δf	300 GeV	0.032	0.032	0.035	0.035	0.035

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

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

Fitting Results



$s_{global} = 2\sigma$

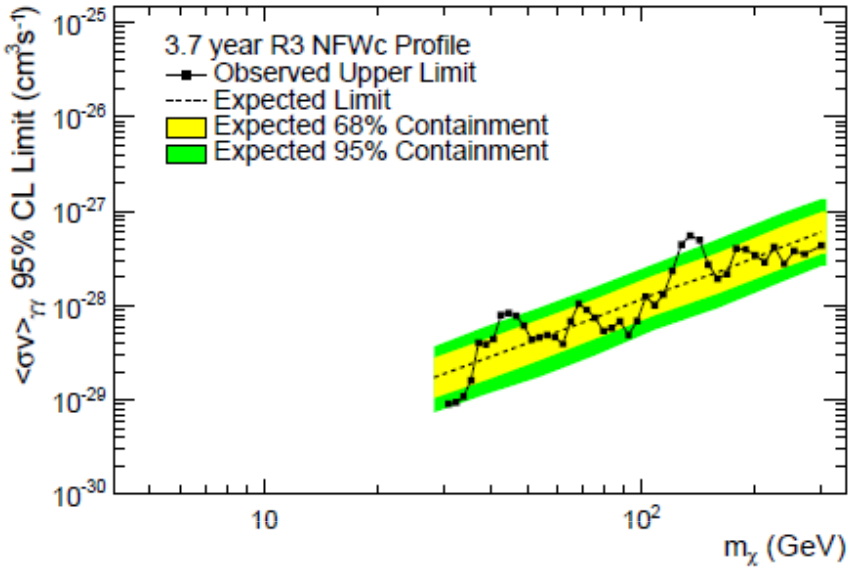
E_γ=135 GeV
$s_{local} = 3.2\sigma$
$s_{global} = 1.5\sigma$
f = 0.58
Much larger than systematic level

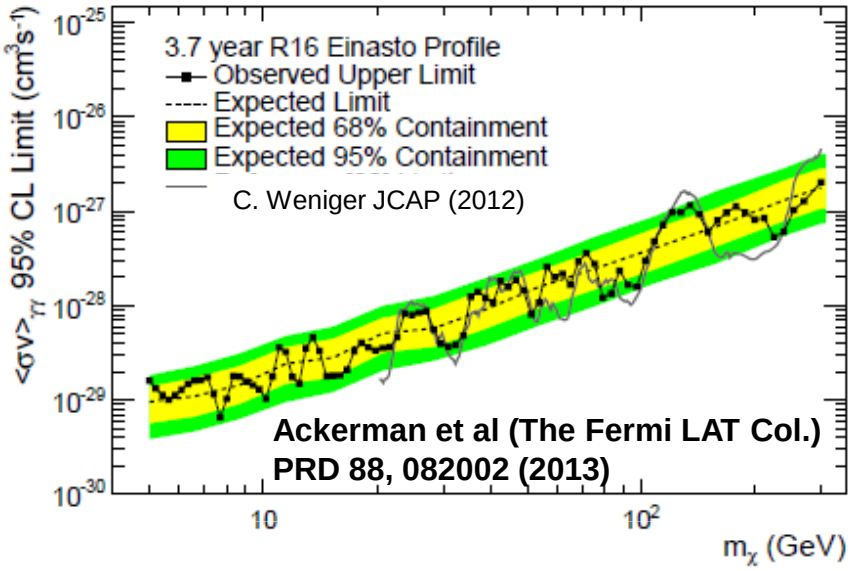
E_γ= 6 GeV
$s_{local} = 3.1\sigma$
$s_{global} = 1.4\sigma$
f = 0.01
At systematic level

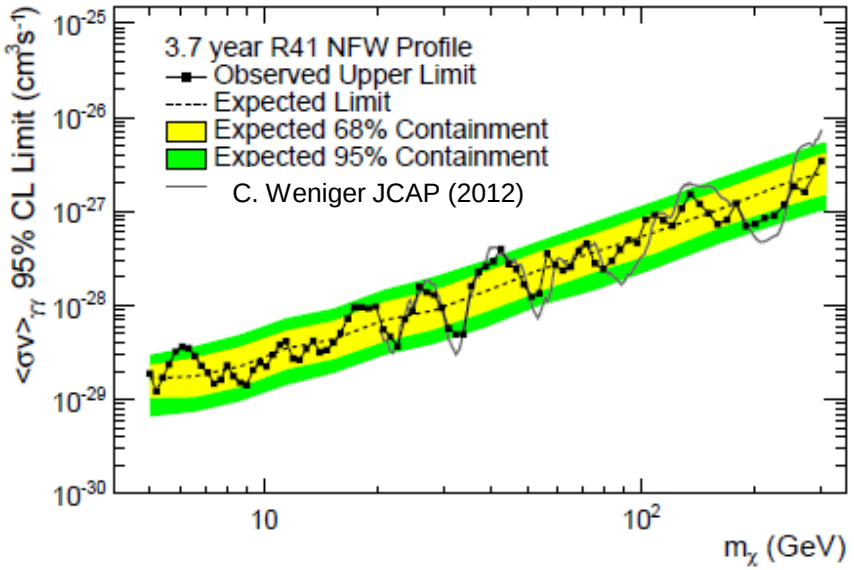
Ackerman et al (The Fermi LAT Col.) PRD 88, 082002 (2013)

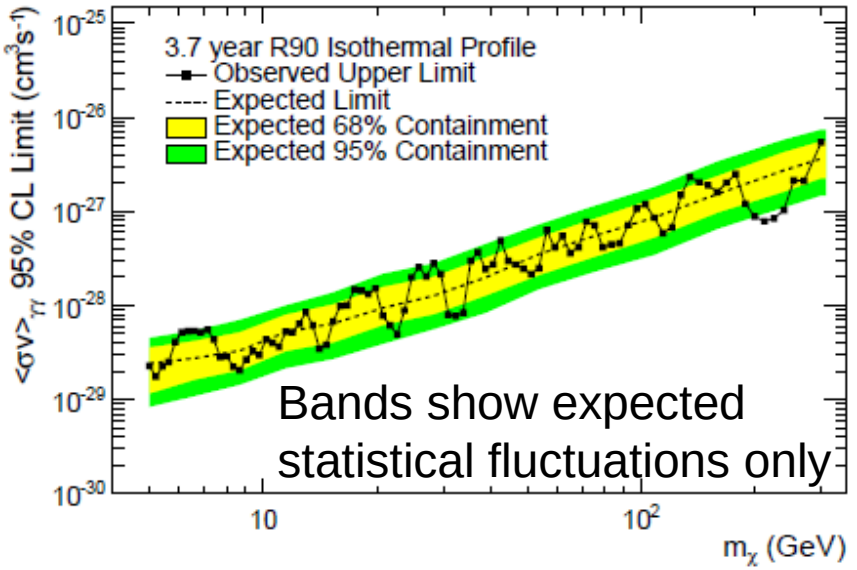
- **No globally significant lines found**

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

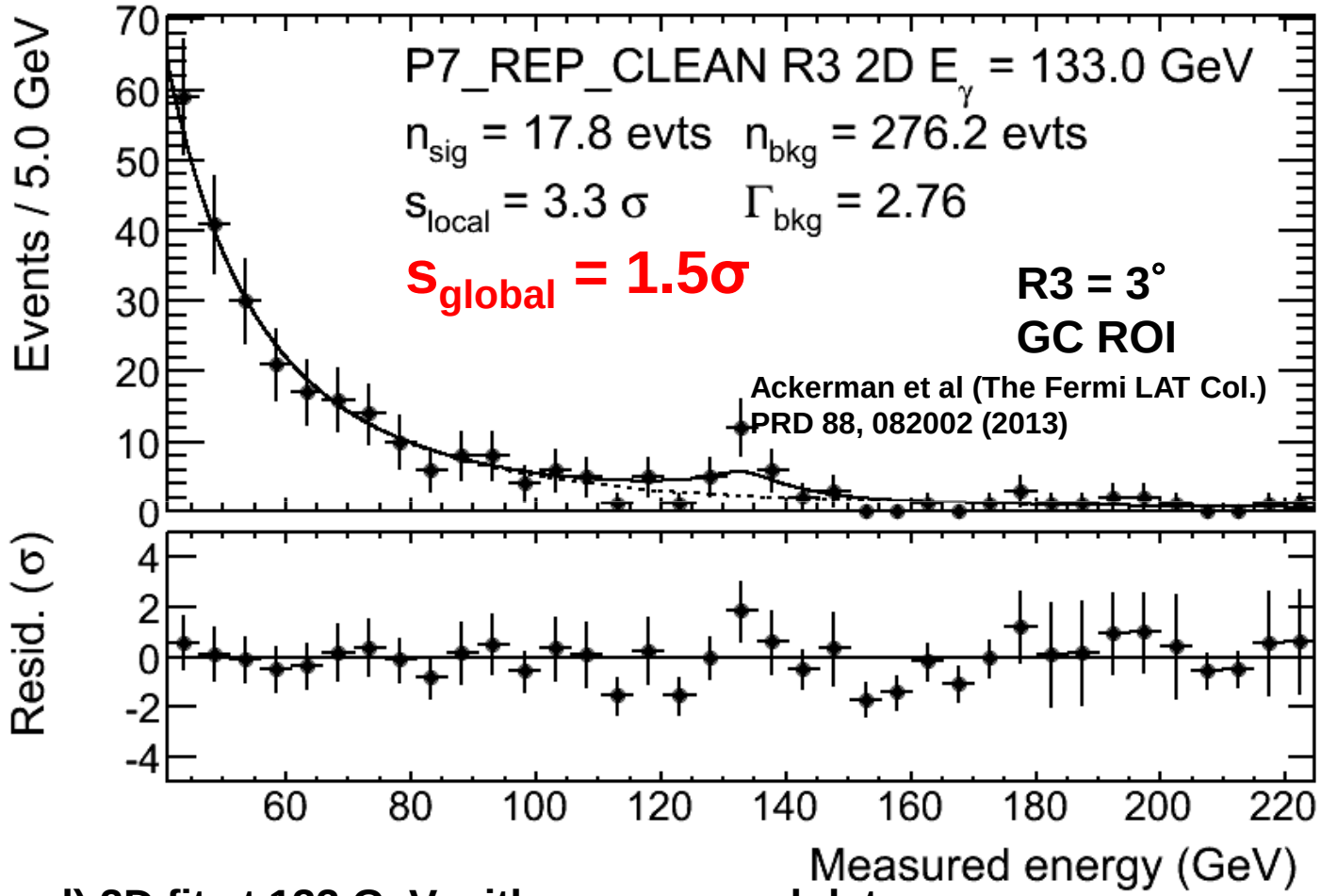






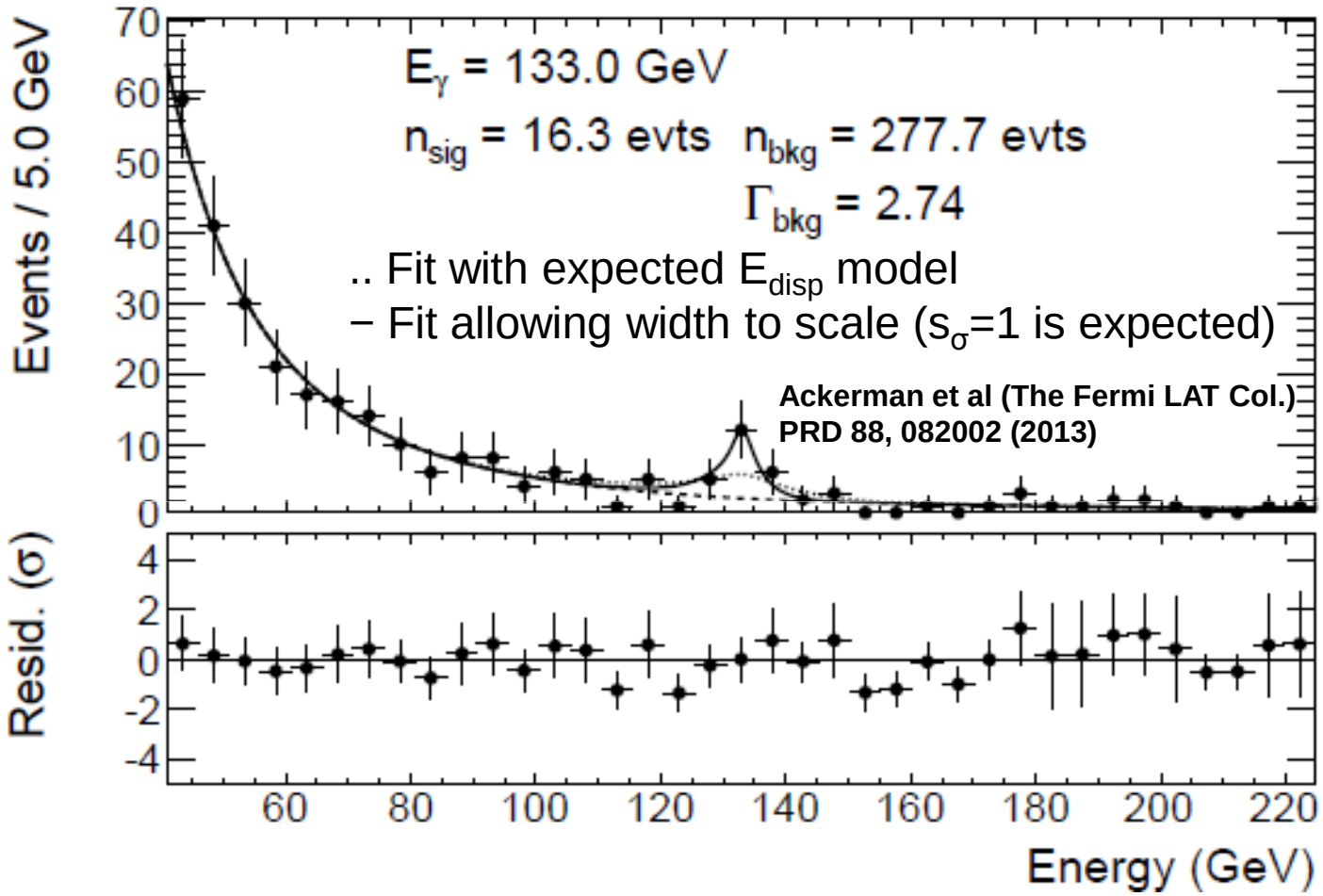


The Line-like Feature near 133 GeV



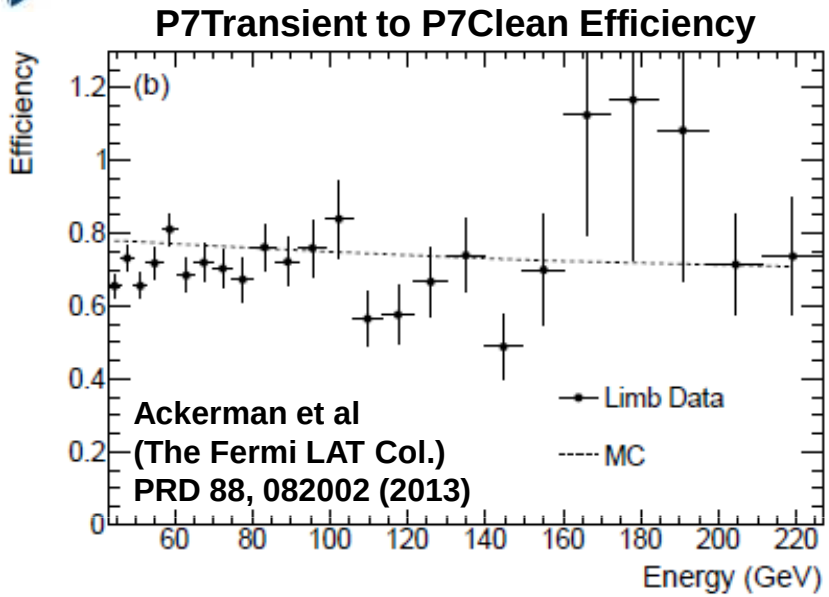
- **3.3σ (local) 2D fit at 133 GeV with reprocessed data**
  - **Fit with energy dispersion model that includes event-by-event energy recon. quality estimator P_E ("2D" model)**
    - **Expected 2D signal model to increase signif. of signals by ~15%**

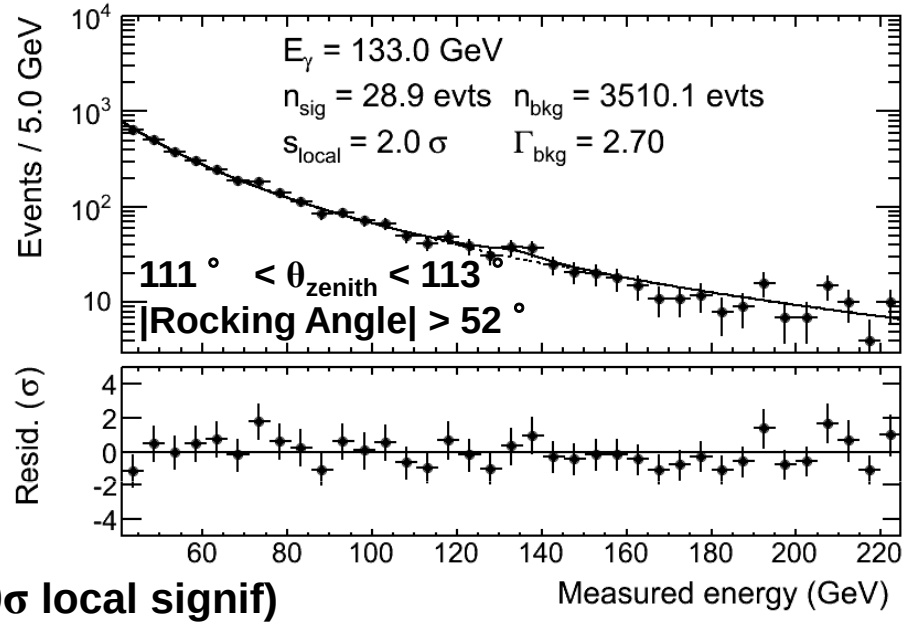
Width of 133 GeV Feature



- **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)**

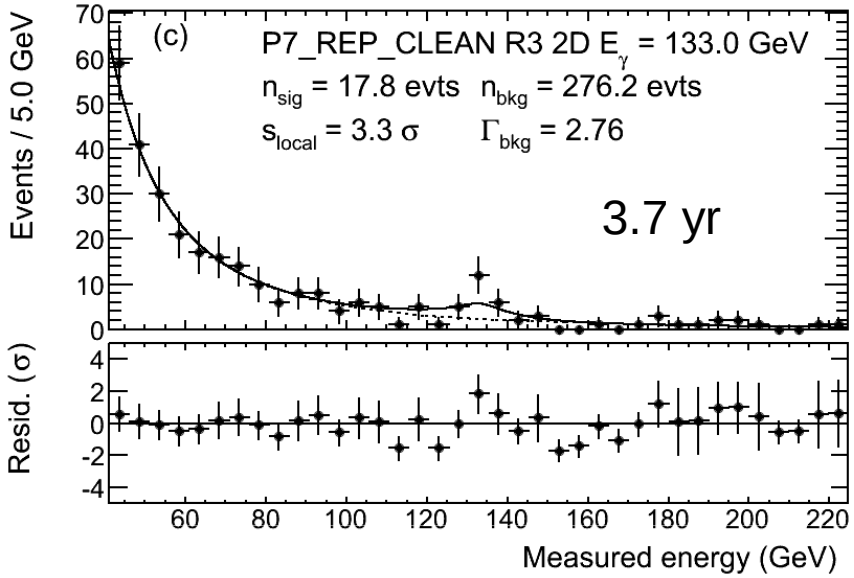
133 GeV in the Earth Limb spectrum

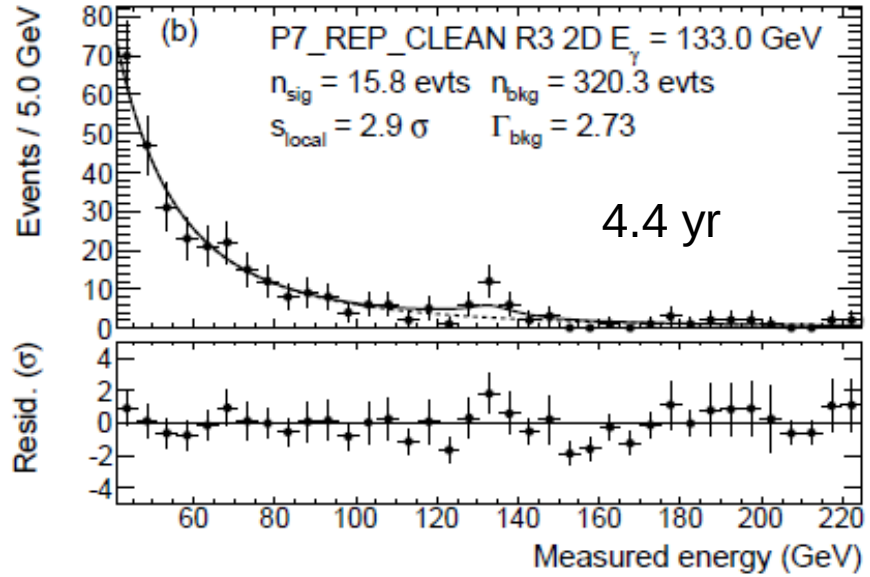




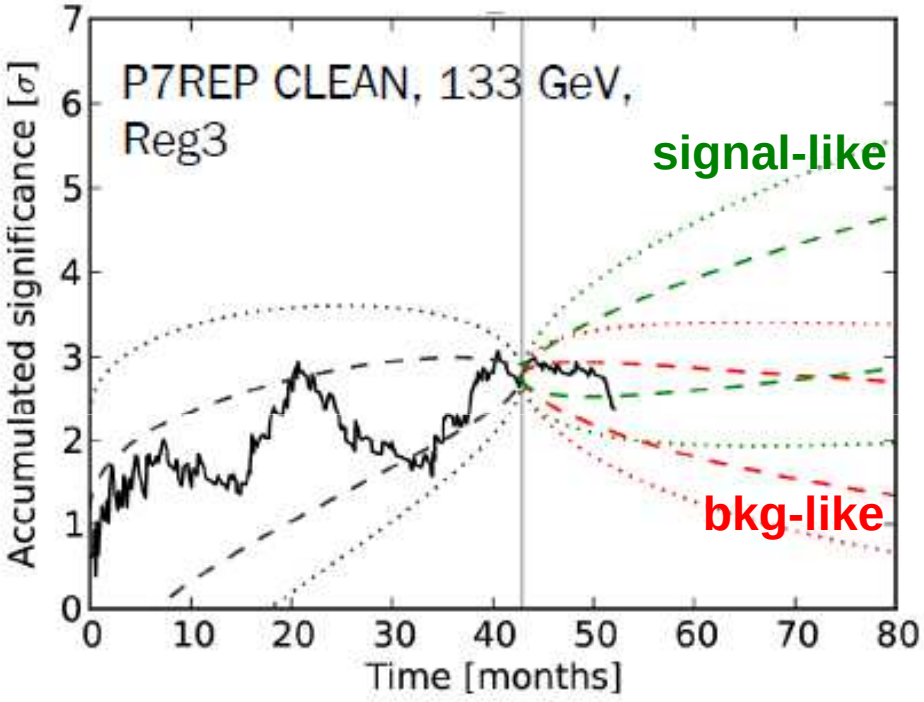
- **Line-like feature in the limb at 133 GeV (2.0σ local signif)**
  - **Appears when LAT is pointing at the Limb ($|\theta_r|<52^0$)**
  - **Surprising since limb should be smooth power-law**
  - **S/N_{limb} ~14%, while S/N_{R3} ~61%**
    - **Limb feature not large enough to directly explain all the GC signal**
    - **Just *f* = 0.14 in GC (fewer events) would be ~0.8σ**
- **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 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"**

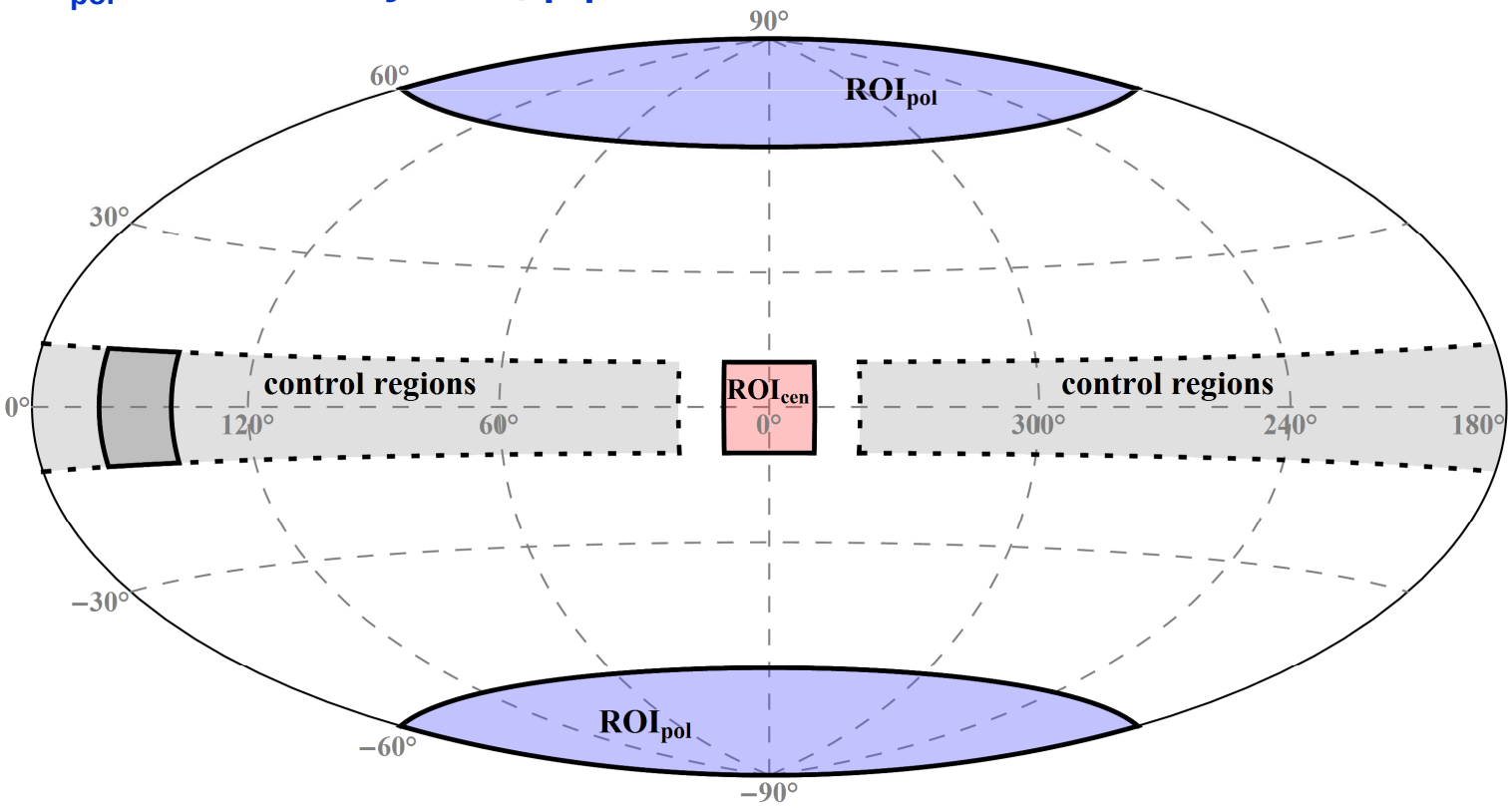
Ackerman et al (The Fermi LAT Col.)
PRD 88, 082002 (2013)

Low Energy Line Search

- **Purpose:**
  - **To search for DM lines from 100 MeV to 10 GeV**
    - **This would constrain models of Gravitino decay ($\Psi_{3/2} \rightarrow \nu\gamma$) see Takayama & Yamaguchi (PhysLettB485:388-392, 2000)**
      - **Focus on Gravitinos in the $\mu\nu$SSM**
        - » **See Lopez-Fogliani & C. Muñoz (Phys.Rev.Lett. 97 (2006) 041801) K-Y. Choi, et.al. (JCAP 1003 (2010) 028) and G. A. Gomez-Vargas et al. (JCAP02 (2012) 001)**
- **People:**
  - **LAT Collaboration: Andrea Albert, German GV et al**
  - **External: Carlos Munoz (U.A. Madrid), Michael Grefe (U.A. Madrid), & Christoph Weniger (GRAPPA, Amsterdam)**
- **Data:**
  - **P7 REP Clean, ZA < 100°**
  - **239557447 < MET < 403509423 (5.2 years)**
  - **Fit for lines from 100 MeV to 10 GeV**
    - **$\pm 2\sigma_E$ windows -> 56.5 MeV to 11.5 GeV**

Low Energy Line Search
Region of Interest (ROI) Optimization

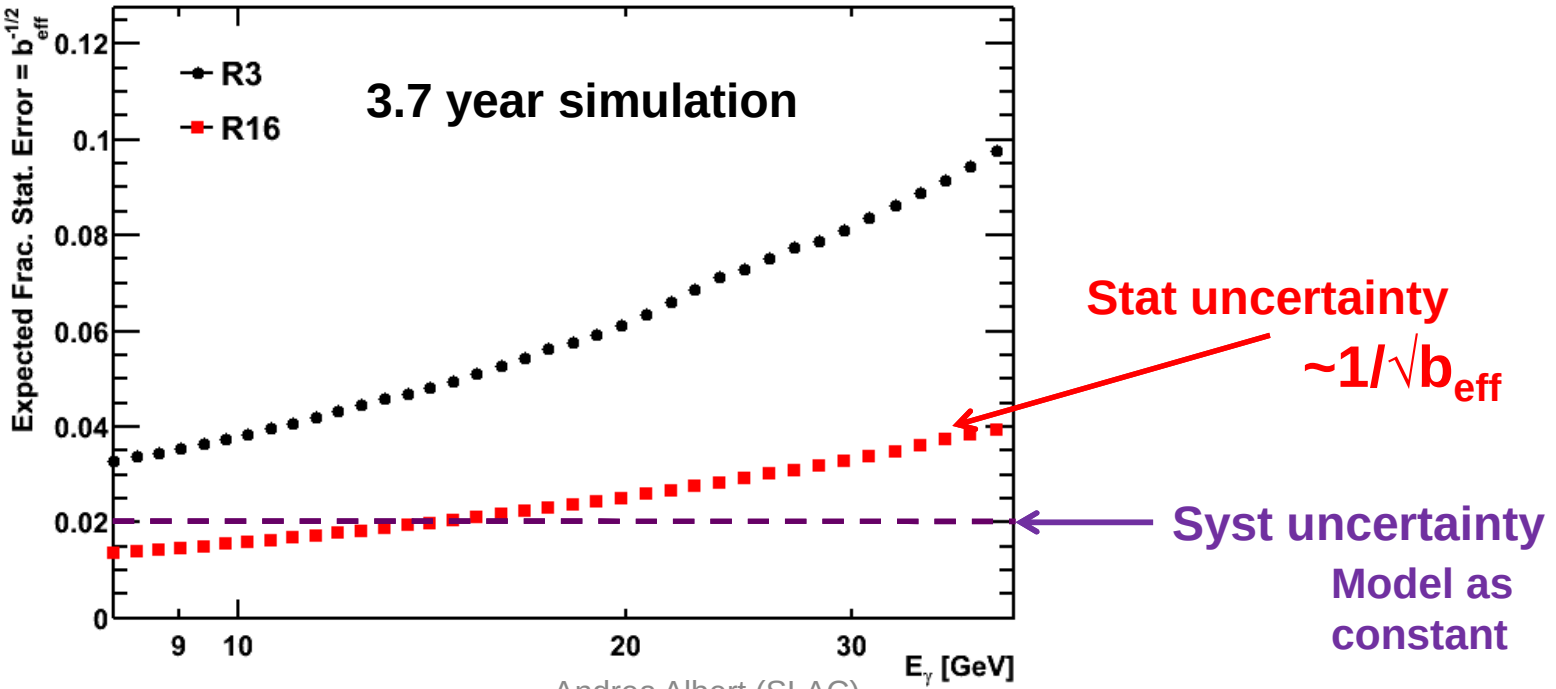
- **Use Einasto Profile (α=0.17, $\rho_\odot$=0.4 GeV/cm^3, $R_\odot$ = 8.5 kpc)**
- **Optimize for annihilation ($\chi\chi \rightarrow \gamma\gamma$) and decay ($\Psi_{3/2} \rightarrow \nu\gamma$)**
  - **Gravitino decay is the primary model we are testing, but wanted to expand scope to include annihilation too**
- **Use same ROI parameter definition as high-energy line paper**
  - **"ROI$_{cen}$" is the annihilation ROI; |b| < 10˚ , |l| < 10˚**
  - **"ROI$_{pol}$" is the decay ROI ; |b| > 60˚**



Low Energy Line Search
This Analysis is Systematics Limited

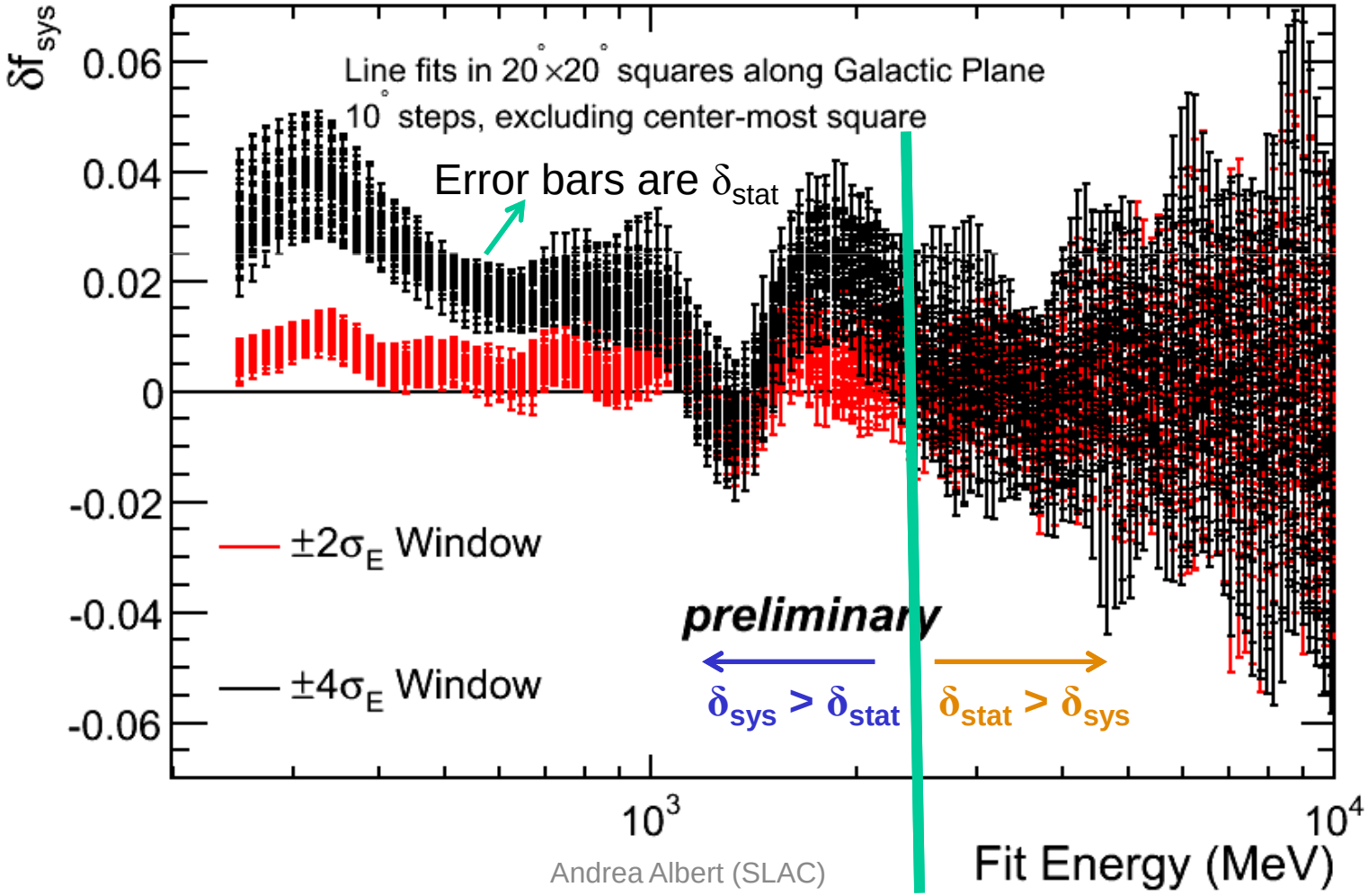
- **Focus on systematics that appear at fixed fractional size (δf_{sys})**
  - **These will mask or induce false signals**
- **Below ~15 GeV our line search is systematics-limited**
  - **Fractional statistical uncertainty is δf_{stat}~ 1/sqrt(b_{eff})**
  - **Compare to estimated systematic uncertainties ($\delta f_{sys} \leq 2\%$)**
- **Can estimate δf_{sys} by fitting for lines in control regions**
  - **Galactic Ridge (|L|>10˚) δf_{sys} from Bkg modelling, A_{eff}, and Sources**

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



Low Energy Line Search
f_{sys} from Galactic Plane scans

- **There are some common features likely from the effective area (Aeff)**
- **Displacement from 0 is mostly from Aeff, while spread is from bkg. modeling**
- **Larger systematic effect with wider windows (since power law approx. gets worse)**



Low Energy Line Search
Accounting for f_{sys} in Likelihood

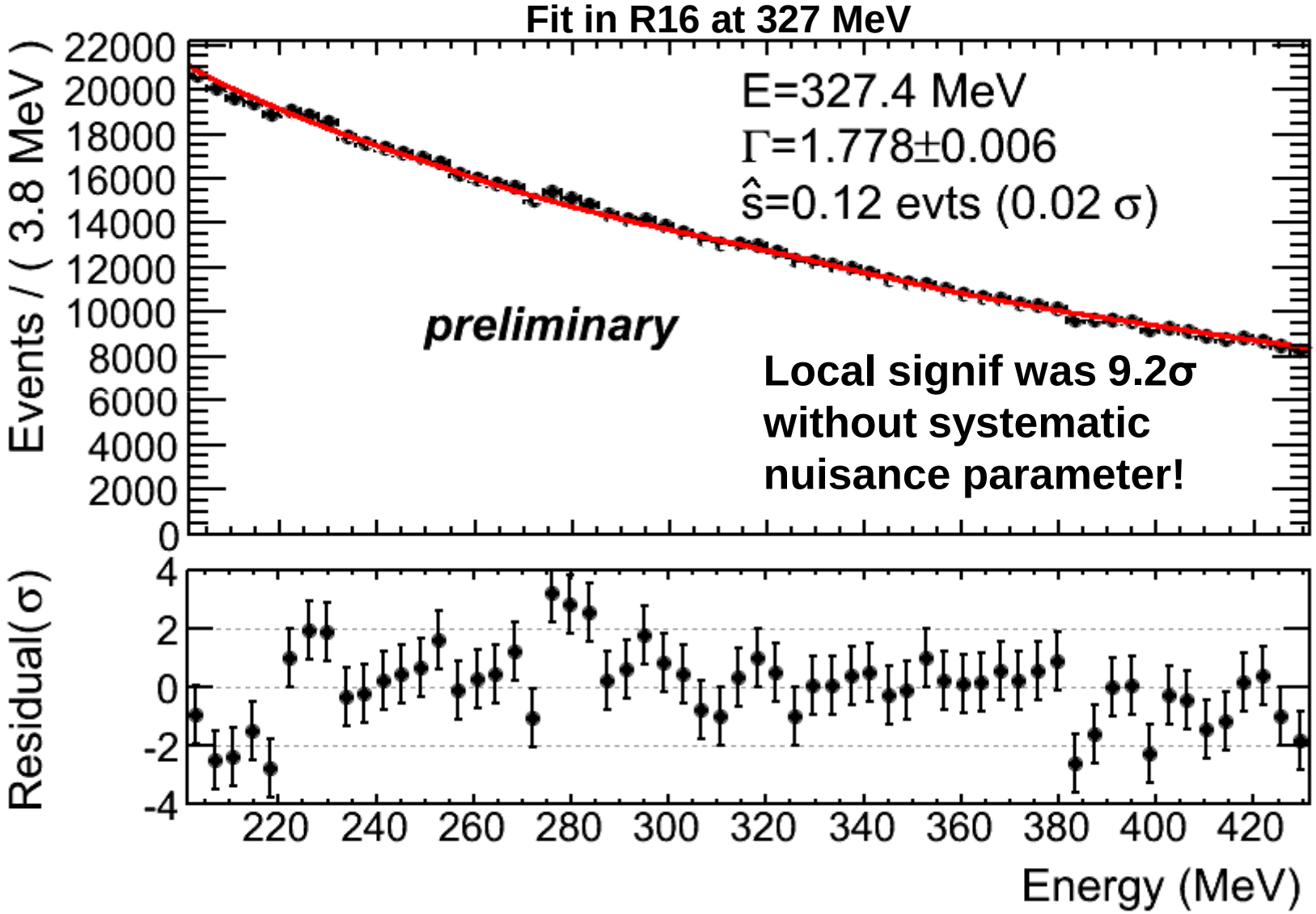
- **Include nuisance parameter (n_{sys}) for systematically-induced line-like features**
  - **For each fit energy in each ROI we determine b_{eff}**
  - **We add a Gaussian constraint on n_{sys} to the likelihood fit with ($\sigma_{sys} = \delta f_{sys} * b_{eff}$, $\mu = 0$) to break the degeneracy between n_{sys} and n_{sig}**
    - ***f_{sys}* determined by control regions fits (i.e. off-center Galactic Ridge)**
    - **Will only be sensitive to detecting lines *above* *f_{sys}***
      - **Will only detect a significant line if it is larger than the line-like features we see in the control regions**
  - **Similar technique used to incorporate J-factor systematic uncertainties in LAT Collaboration dSph analysis**
    - **Can be applied whenever accounting for systematic uncertainties is important**

$$C(E,\vec{\alpha}) = \left((n_{sig} + n_{sys})S(E,E_{\gamma}) + n_{bkg}B(E,\Gamma_{bkg})\right) * G_{sys}$$

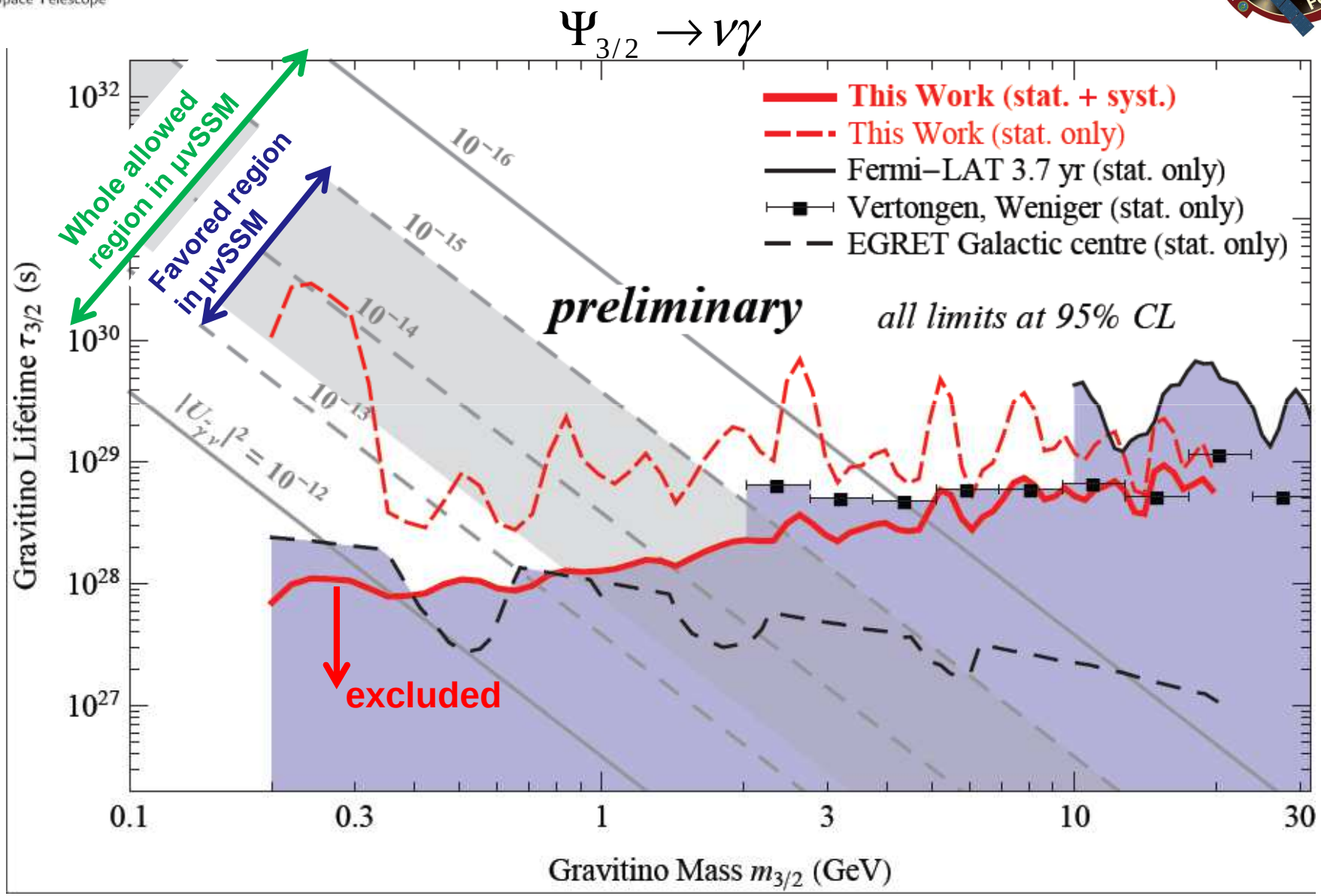
Gaussian constraint on n_{sys}

$$\sigma_{sys} = \delta f_{sys} * b_{eff} \qquad G_{sys} = \frac{1}{\sigma_{sys}\sqrt{2\pi}} e^{-n_{sys}^2/2\sigma_{sys}^2}$$

Low Energy Line Search
Example Fit – Including n_{sys} is essential!



Preliminary Limits for (|B|>60° ROI)



Summary

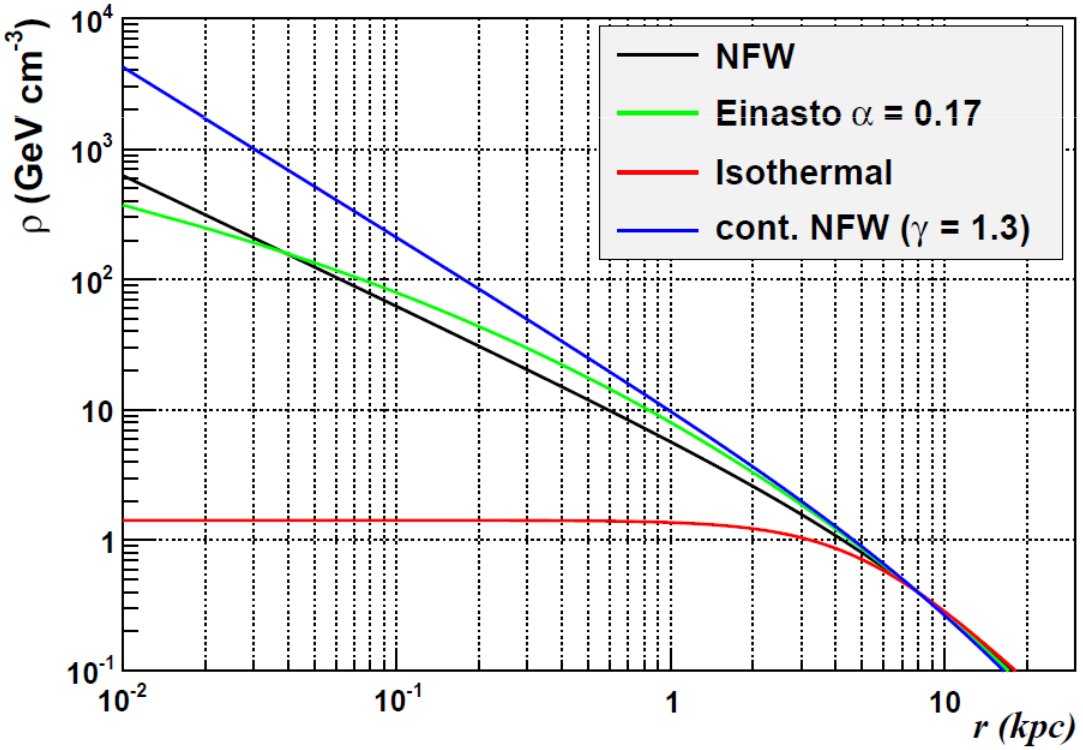
- **Search for spectral lines from 5--300 GeV in 5 ROIs**
  - **Use 3.7 year P7_REP_CLEAN dataset**
    - **Have set 95% CL $\Phi_{\gamma\gamma}$, $\langle\sigma v\rangle_{\gamma\gamma}$, and $\tau_{\gamma\gamma}$ limits**
- **Search for spectral lines from 100 MeV – 10 GeV**
  - **Dominated by systematic uncertainties**
  - **Publication being prepared**
- **See a narrow residual near 133 GeV in the GC**
  - **Not (completely) an obvious systematically induced feature**
    - **Larger than expected systematic uncertainty**
    - **Limb feature cannot account for entire GC feature**
  - **Bkg fluctuation?**
    - **Much narrower than expected energy resolution**
    - **Decreasing with more data**
- **No globally significant lines detected by LAT Collaboration**
- **More data and study will improve future line analyses**
  - **More Limb data from pole stares and future ToOs**
  - **Pass 8 → ~25% increase in A_{eff} and better (different) systematics**

BACKUP SLIDES

Indirect WIMP Signatures

Astrophysics

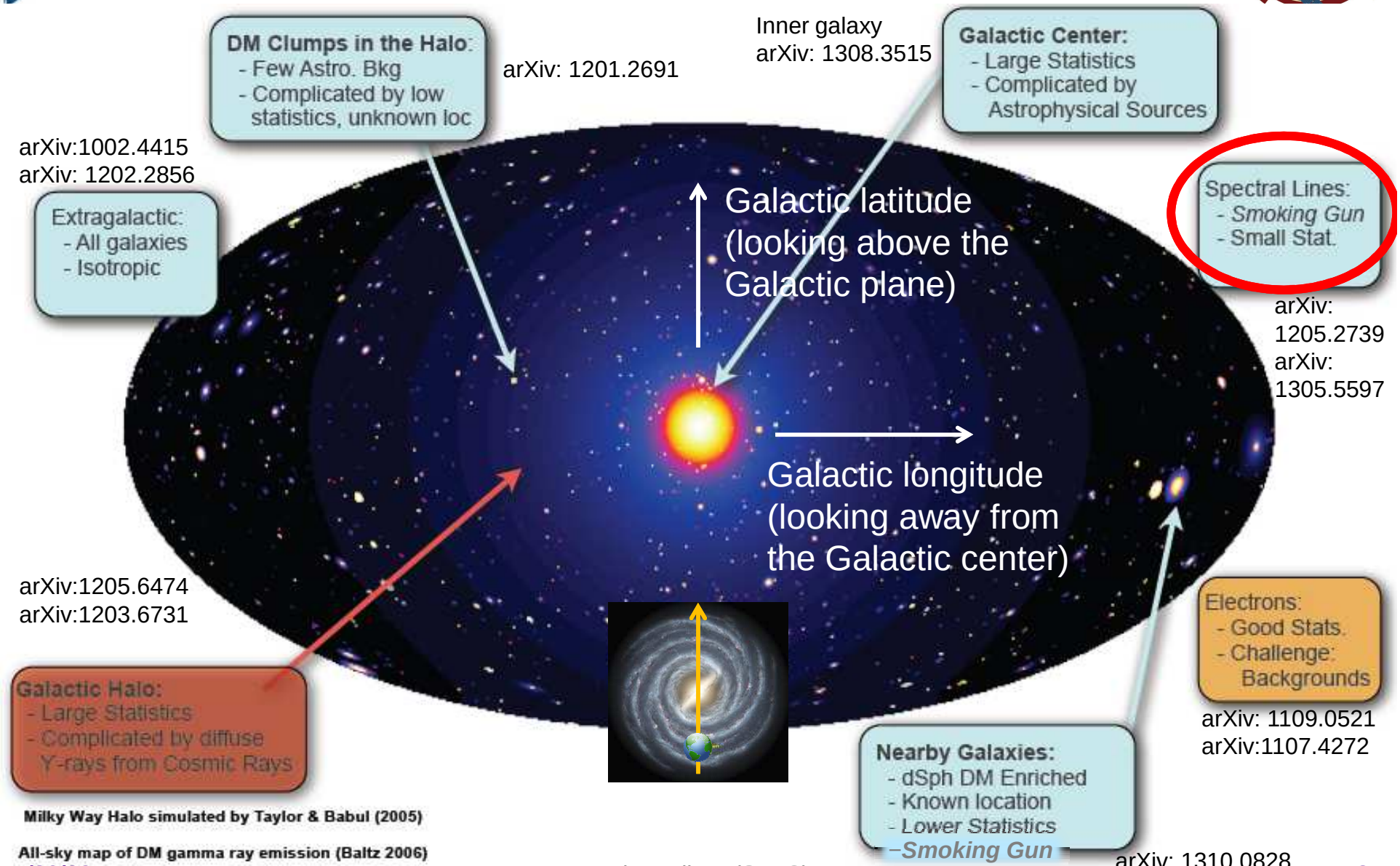
$$\Phi_\chi(E,\psi) = \frac{\langle\sigma_\chi v\rangle}{2}\sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi)\,\frac{1}{4\pi}\frac{\rho(l)^2}{m_\chi^2}$$



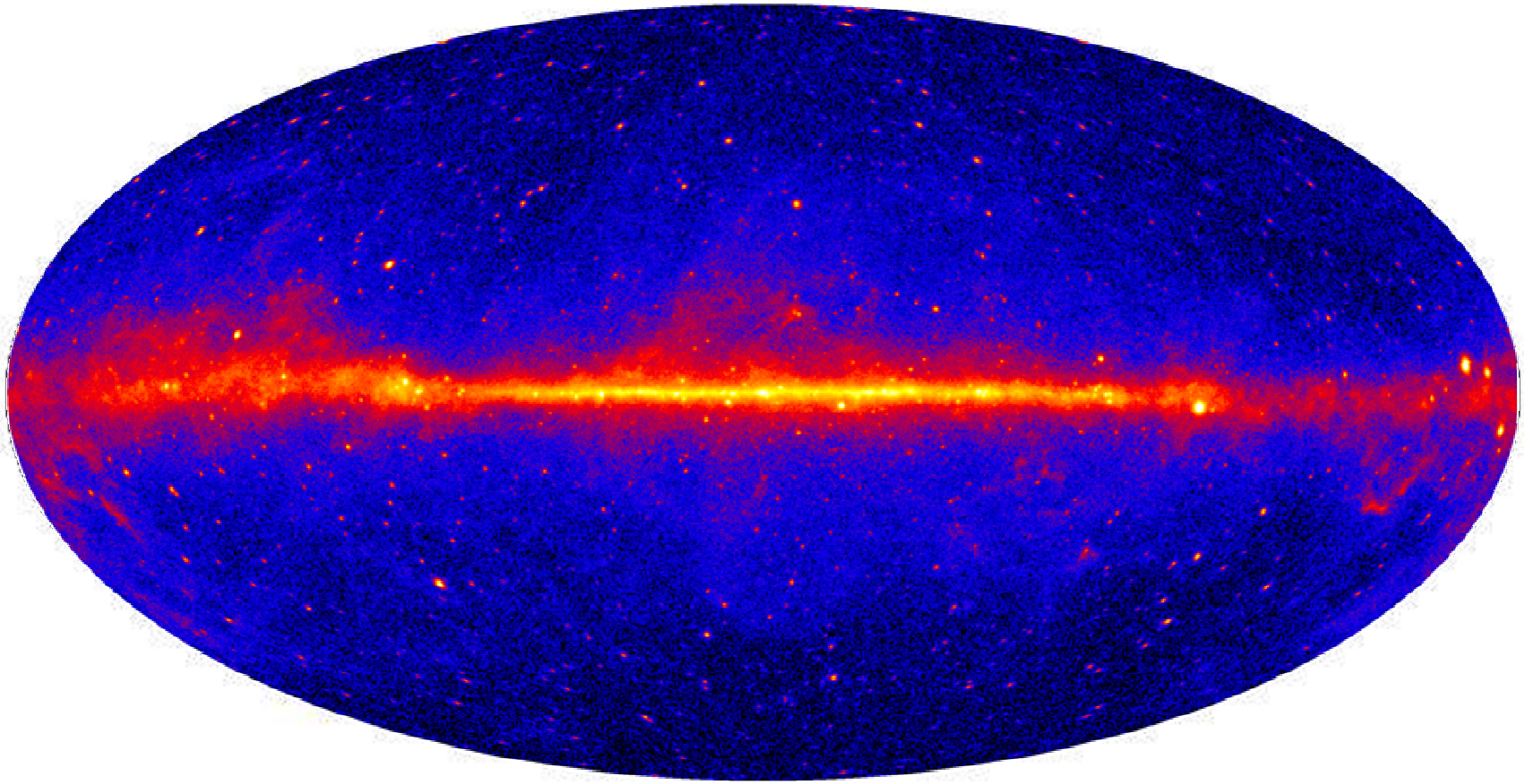
J-factor – Line of sight integral over a ROI

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

DM Searches with the Fermi LAT

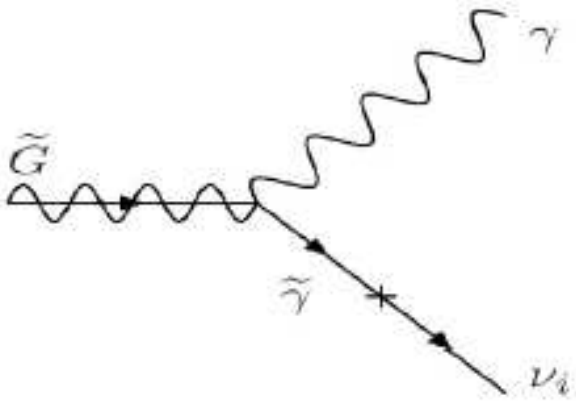


Large Astrophysical Background!



$\mu\nu$SSM gravitino dark matter

Due to the breaking of R-parity in the $\mu\nu$SSM, the photino and the left-handed neutrinos are mixed, and thus the gravitino will be able to decay, through the interaction term, into a photon and a neutrino.



Gravitino lifetime as function of mass and $|U|^2$

Neutrino content of the photino.

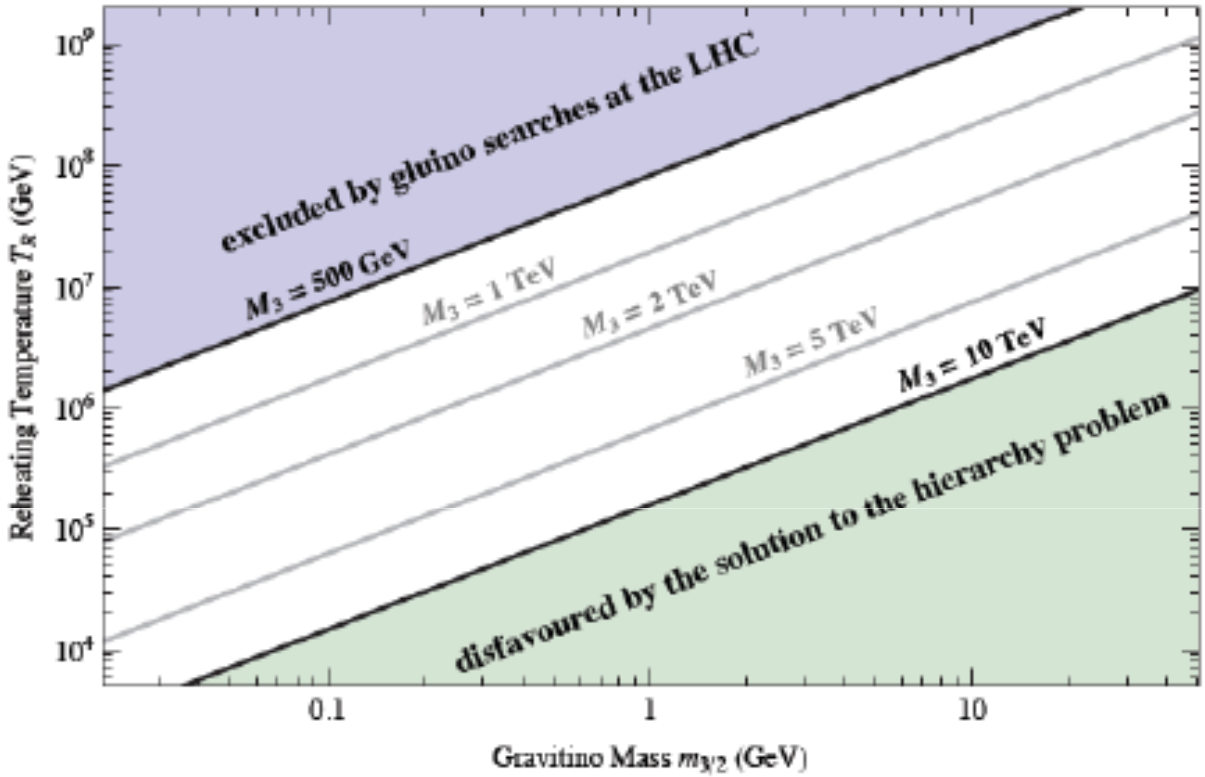
$$\tau_{3/2} \simeq 3.8 \times 10^{27}\,\mathrm{s} \left(\frac{|U_{\tilde{\gamma}\nu}|^2}{10^{-16}}\right)^{-1} \left(\frac{m_{3/2}}{10\,\mathrm{GeV}}\right)^{-3}.$$

In the $\mu\nu$SSM in order to reproduce neutrino data:

$$10^{-15} \lesssim |U_{\tilde{\gamma}\nu}|^2 \lesssim 5 \times 10^{-14}.$$

For this $|U|^2$ range and $m_{3/2}$ ~ GeV the gravitino is very long lived w.r.t. the universe ~4×10^{17}s.

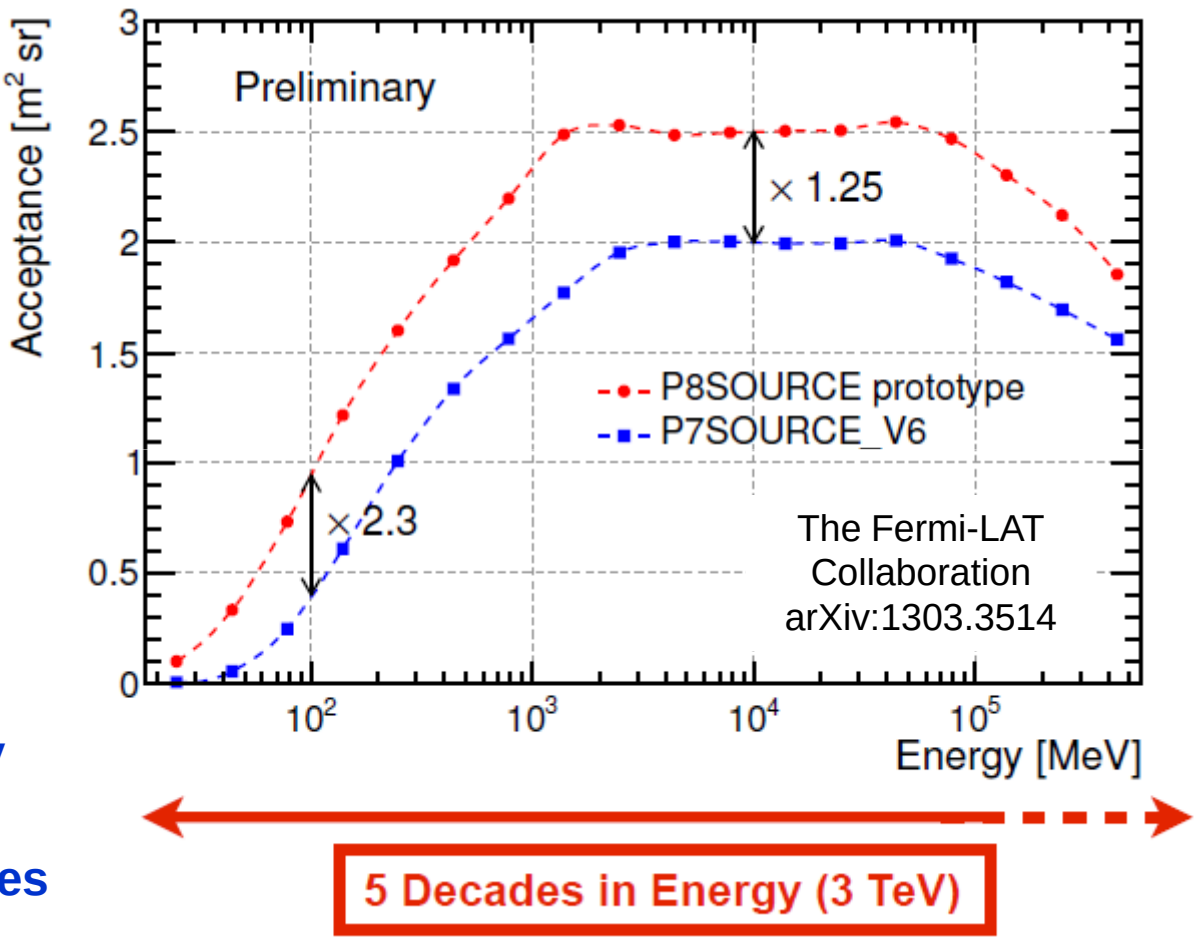
gravitino relic density



If the gravitino is thermally produced its relic density can match the observed dark matter density tuning the reheating temperature after inflation.

Upcoming Developments -- Pass 8

- **Improvements to LAT performance**
  - **Increased energy range**
  - **Increased effective area**
  - **Improved angular resolution**
  - **Better bkg rejection**
  - **New event classes**
- **Impacts for DM searches**
  - **Explore new high-mass parameter space**
  - **Increased flux sensitivity**
  - **Greater sensitivity to spatially extended sources**
  - **Better handle of systematics**



Effective Background

F_{sig} and F_{bkg} are the signal and bkg PDFs

$$I_{00} = \sum_i \frac{F_{sig}^2(\vec{x}_i)}{F_{bkg}(\vec{\alpha} \mid \vec{x}_i)}$$

$$b_{eff} \sim \frac{1}{I_{00} - 1}$$

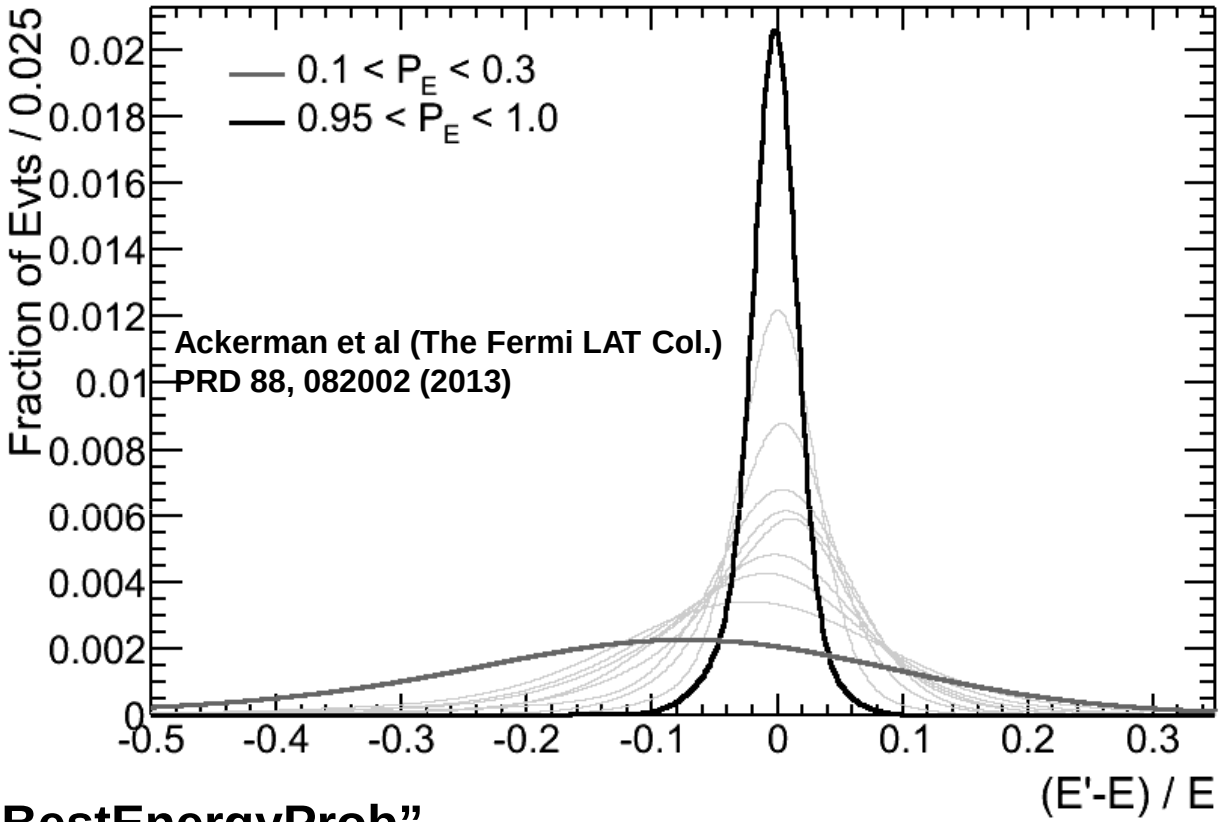
I_{00} can be interpreted as how much you can distinguish signal from bkg PDFs.

Larger I_{00} -> smaller beff

$$f = \frac{n_{sig}}{b_{eff}}$$

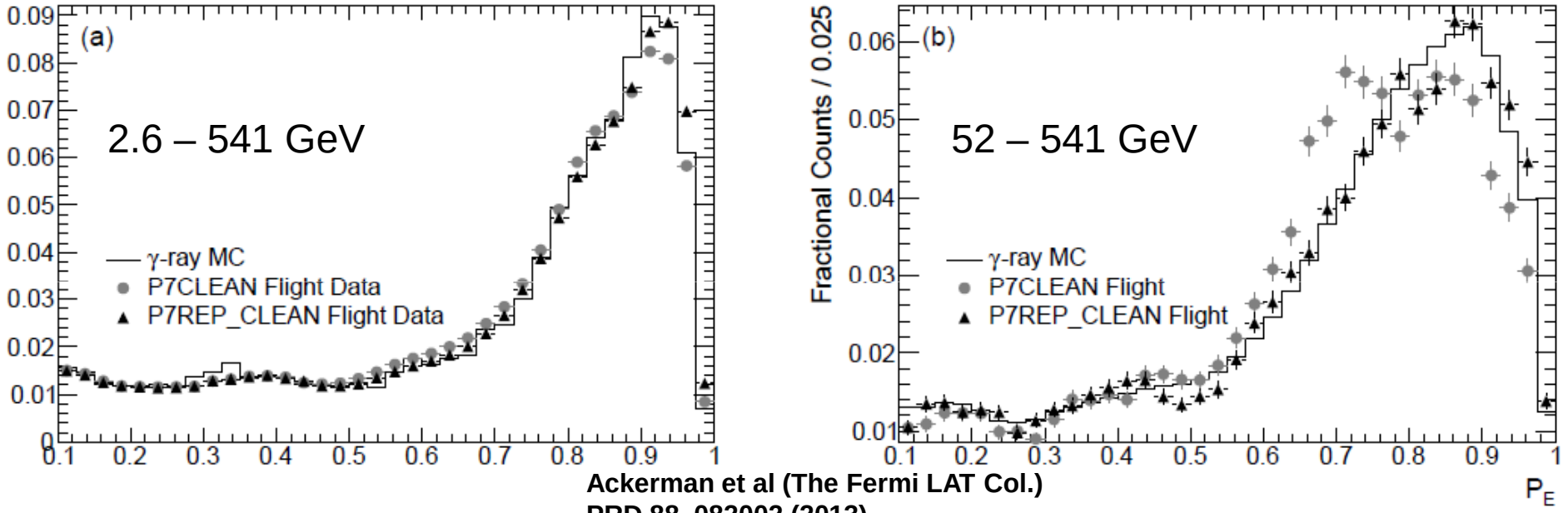
$$signif \approx \frac{n_{sig}}{\sqrt{b_{eff}}}$$

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

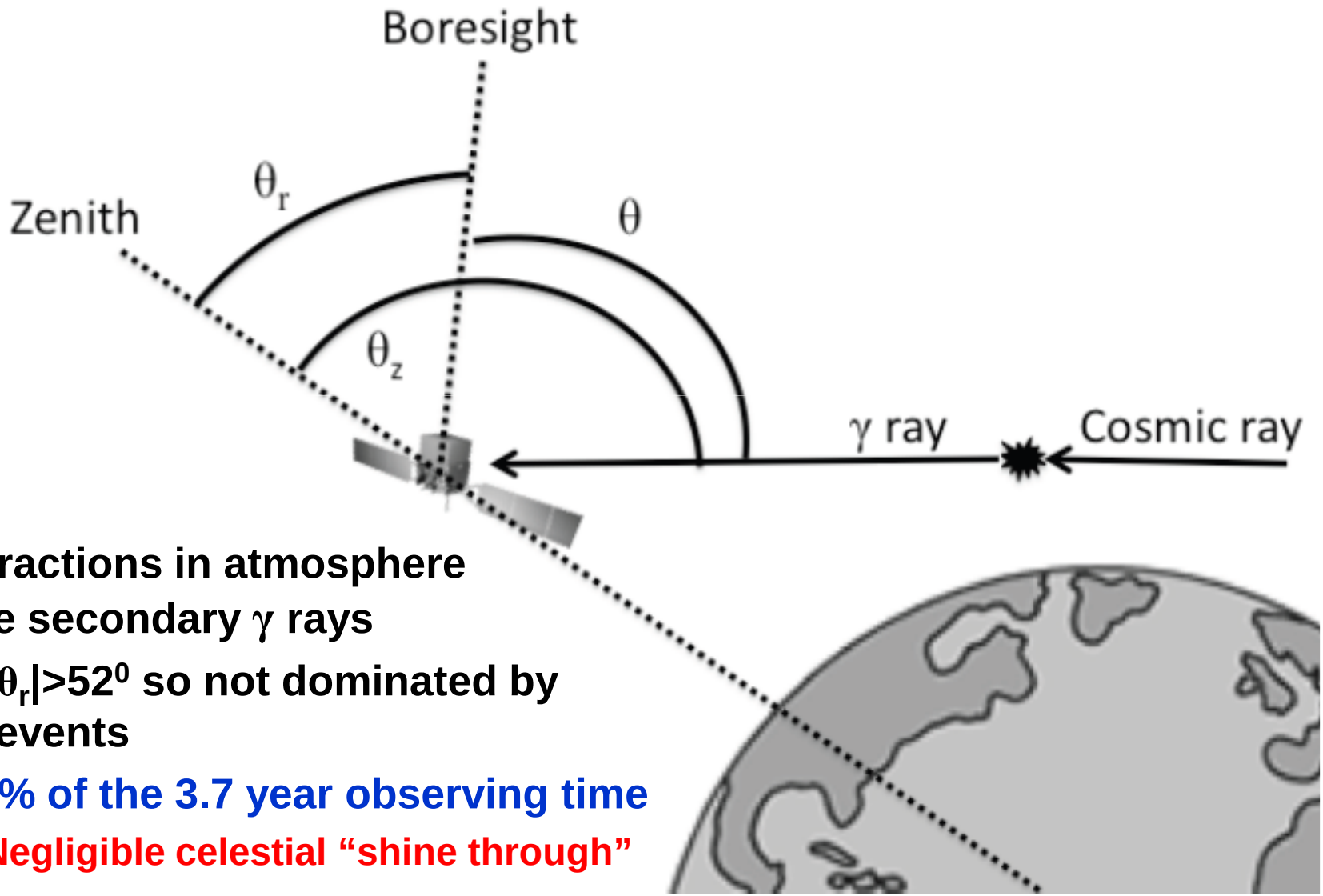
P_E distribution in data vs MC



Ackerman et al (The Fermi LAT Col.)
PRD 88, 082002 (2013)

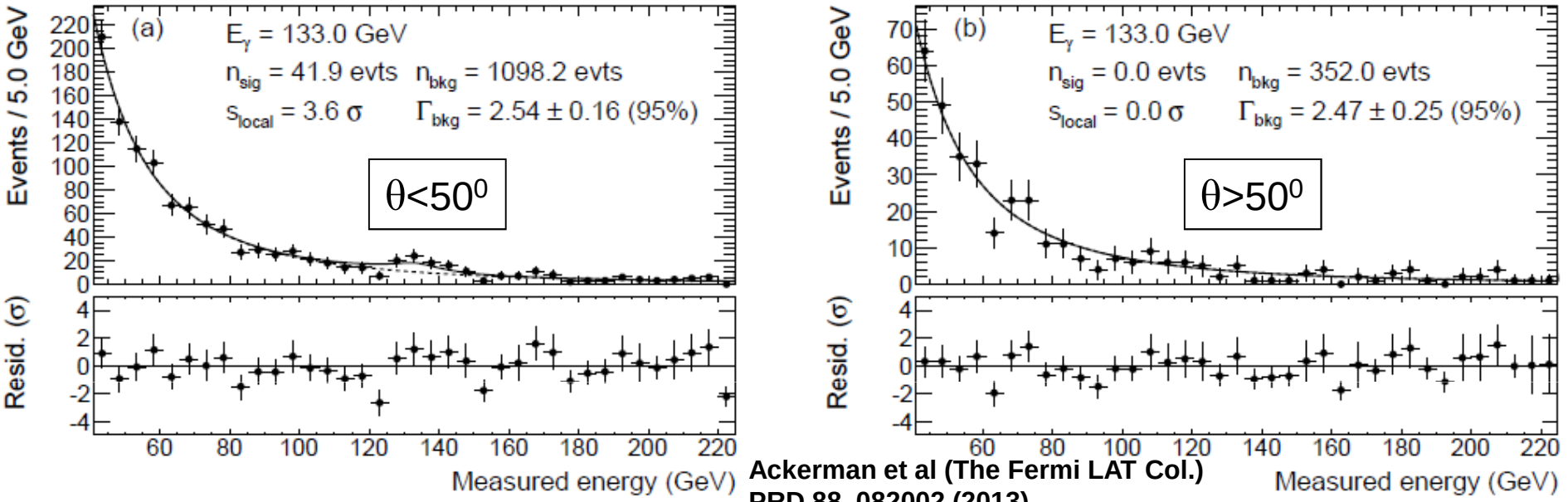
- **Use "all-sky" MC with diffuse + 2FGL and full orbit history**

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"**

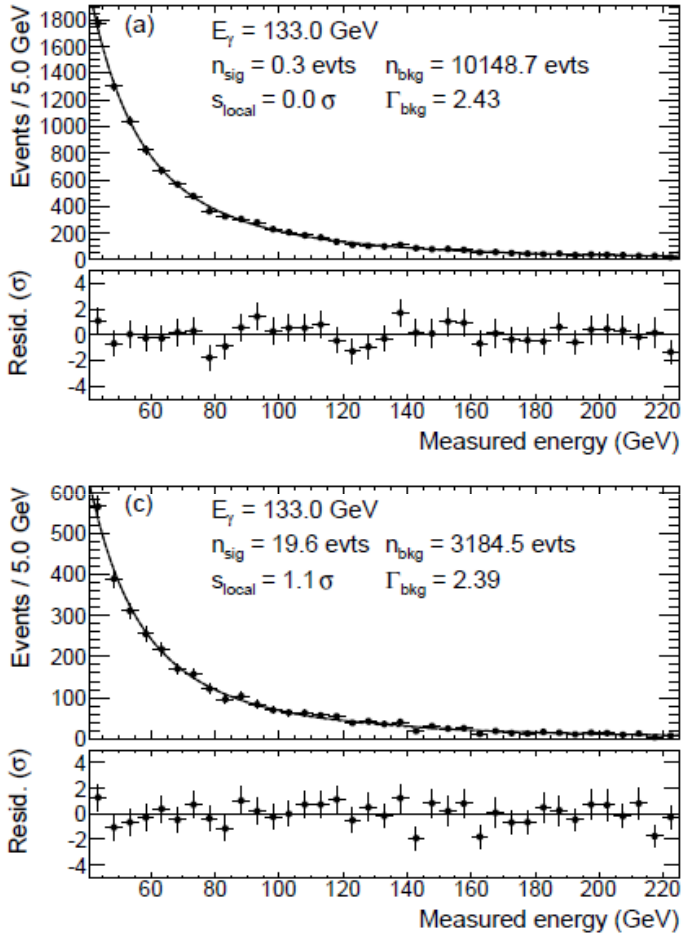
θ-dependence of 135 GeV feature

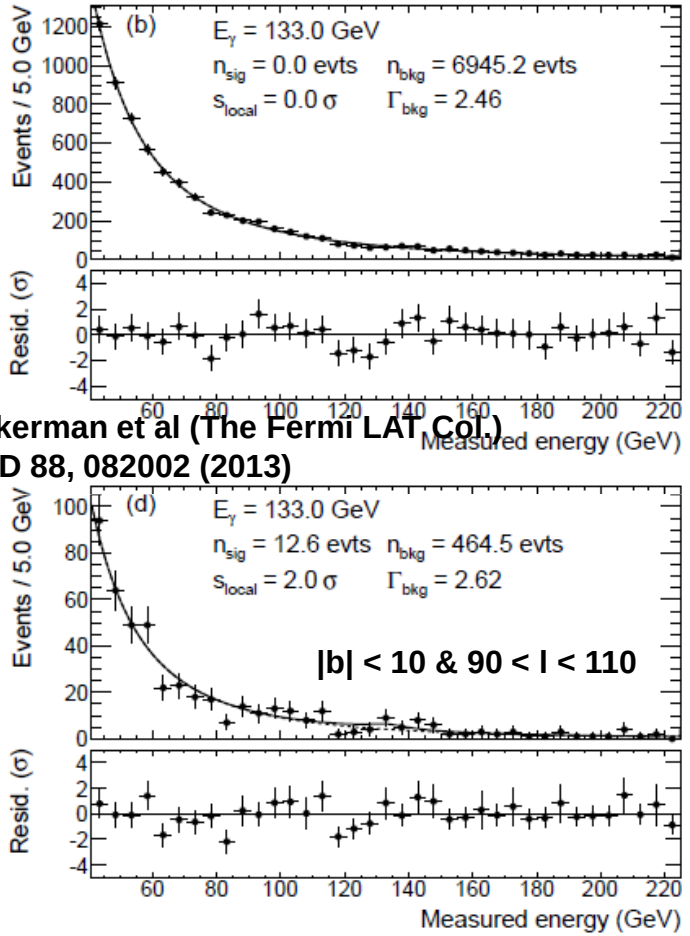


Ackerman et al (The Fermi LAT Col.)
PRD 88, 082002 (2013)

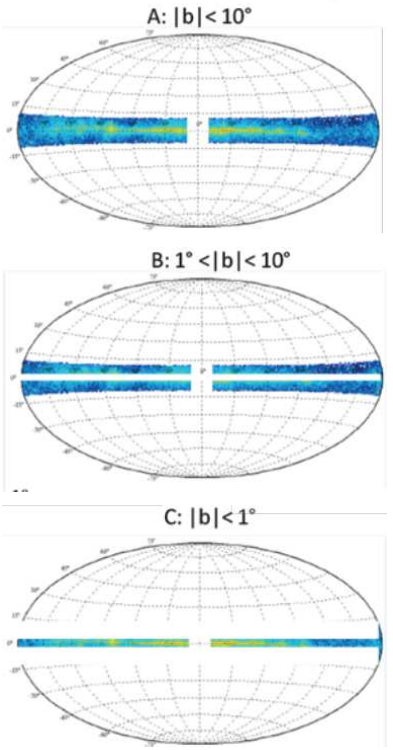
- **Search in a 20x20 GC box (no source removal, 2D model)**
- **135 GeV feature appears in low-θ events, but not in high-θ events**
  - **3.5σ in θ<50⁰ events should scale to 2σ for θ>50⁰ events**
- **Same behavior observed in the Limb feature**

133 Feature in the inverse ROIs





Ackerman et al (The Fermi LAT Col.) PRD 88, 082002 (2013)



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**