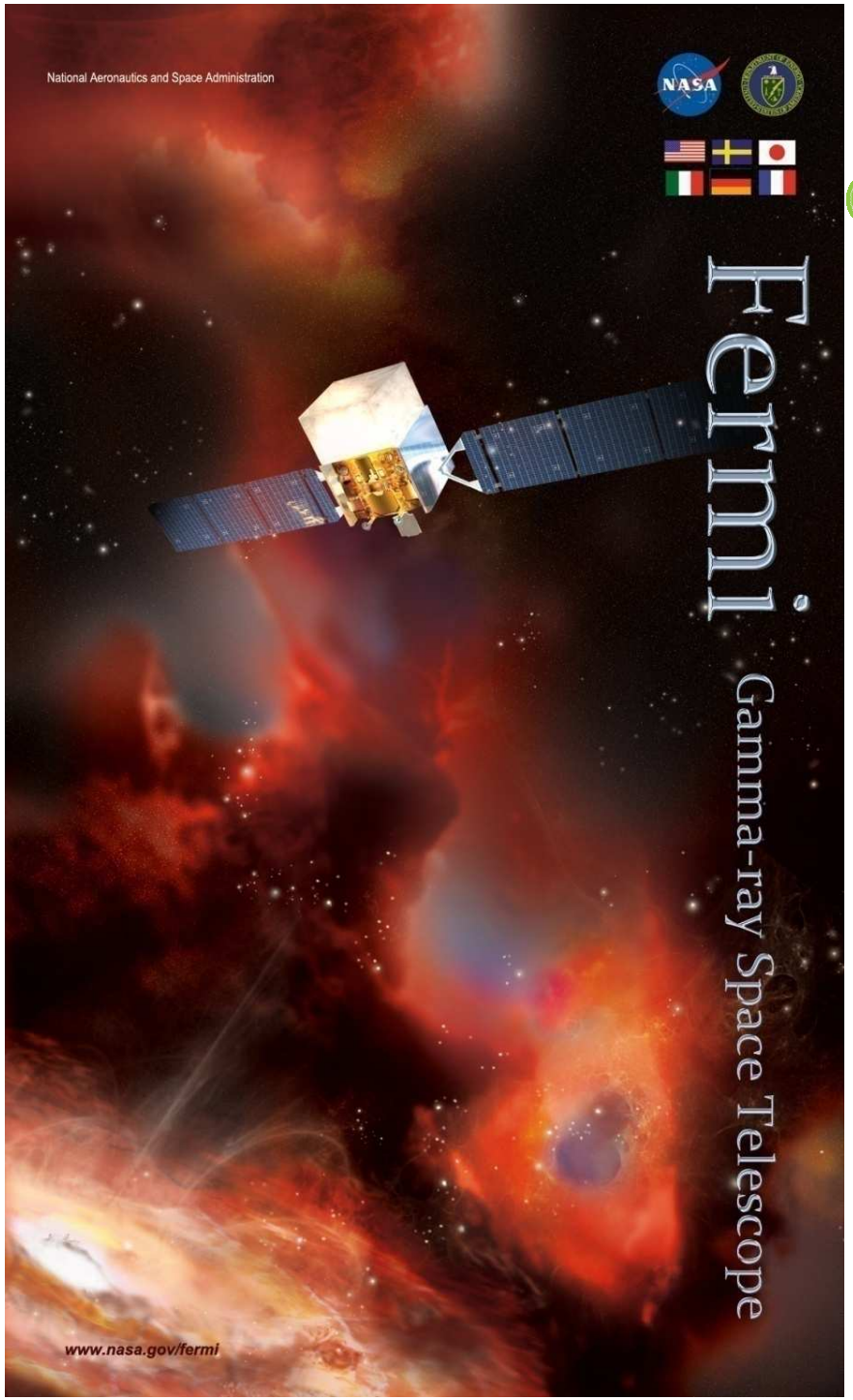


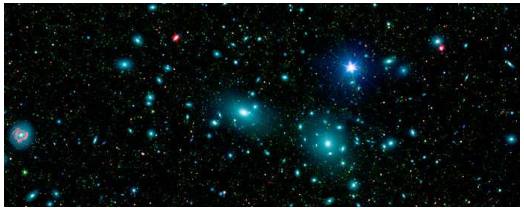

# Indirect Searches for Dark Matter with the Fermi Large Area Telescope

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

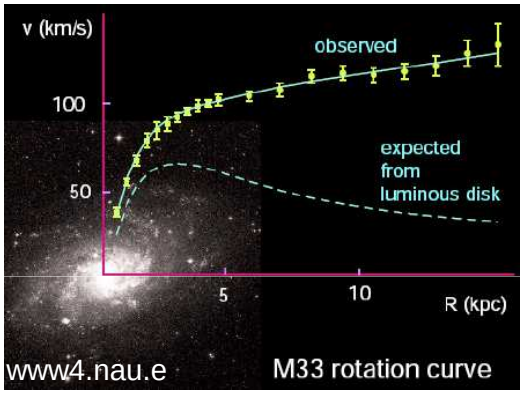
**Dark Matter Parallel**
**IPA 2013**
**May 13th, 2013**

# Astrophysical Evidence for Dark Matter

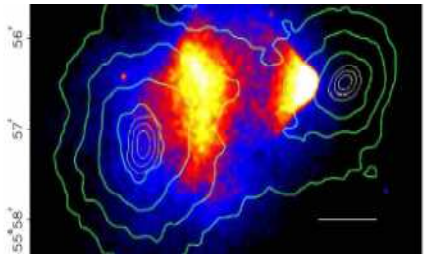
- **Majority of mass in galaxies is *dark***
  - **Coma Cluster + Virial Theorem**
    **F. Zwicky (1937)**



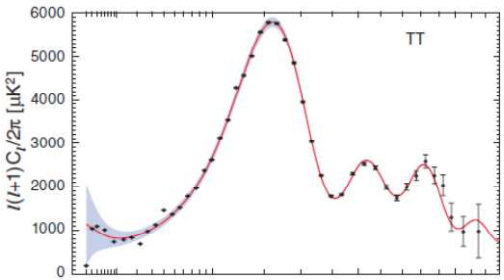
- **Dark Matter clumps in large *halos* around galaxies**
  - **Galactic Rotation Curves**
    **V. Rubin et al (1980)**




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

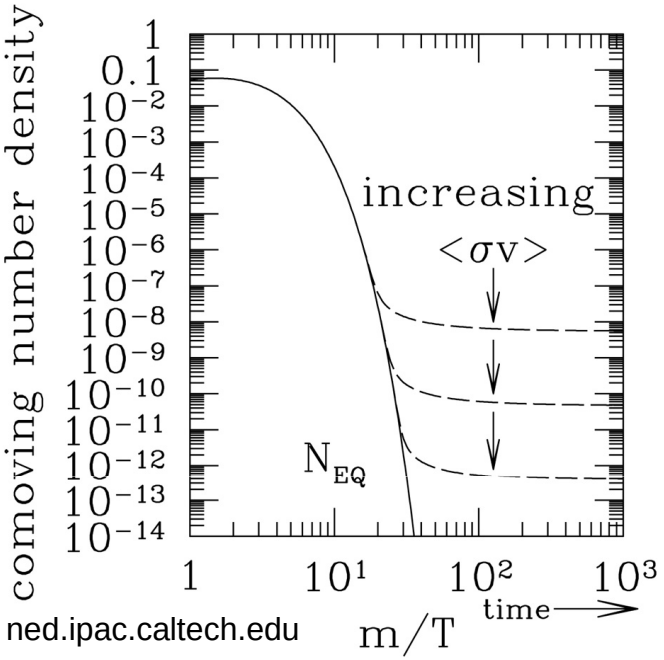


- **Dark Matter is *non-baryonic***
  - **CMB Acoustic Oscillations**
    **WMAP (2010)**



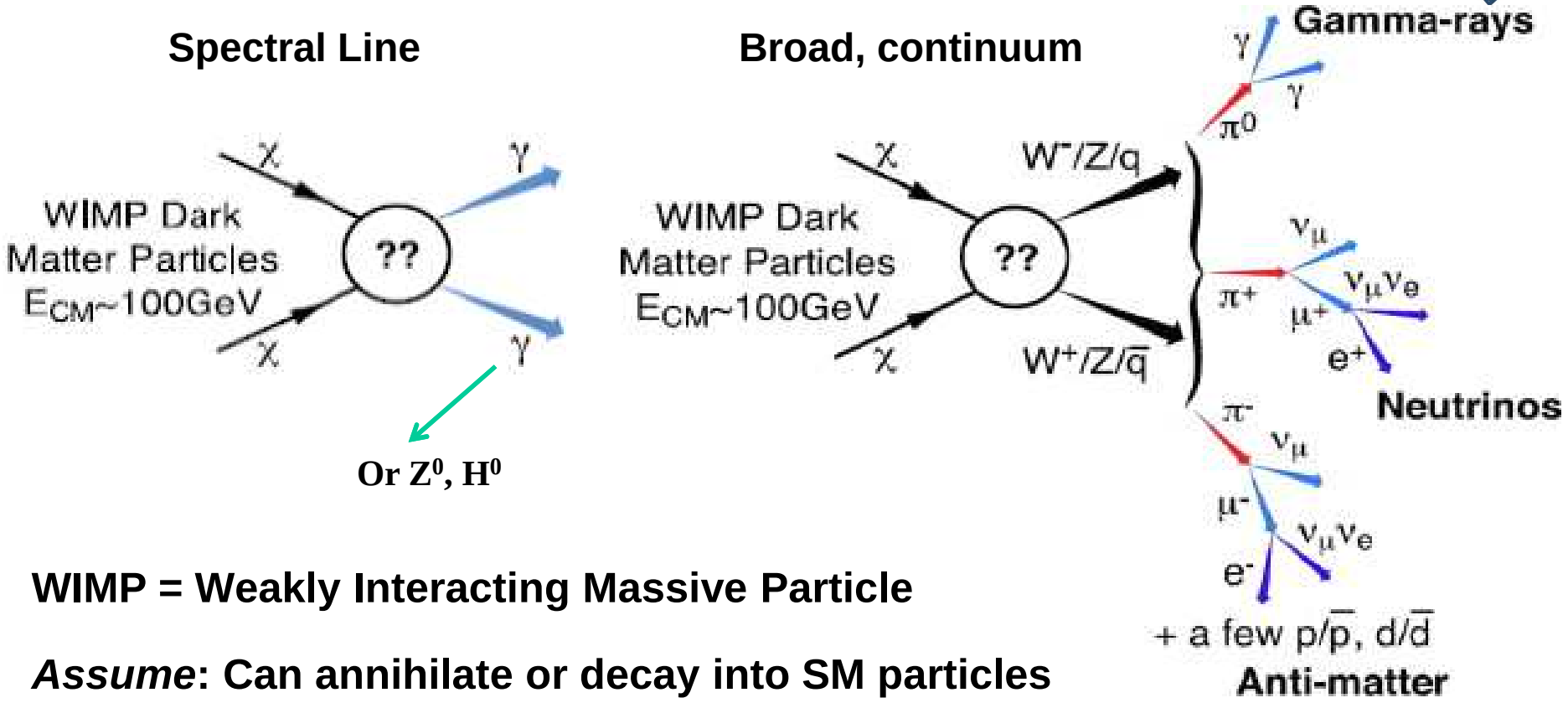
# WIMPs as a Thermal Relic

- **Weakly Interacting Massive Particle (WIMP)**
- **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* $\sigma_{ann}$ → observed abundance (~27% of energy density)**
  - **$\langle\sigma v\rangle_{ann}$ ~ 3e-26 cm$^3$/s ($\sigma_{ann}$ ~ 3 pb)**
  - **$v_{CDM} << c$**
    - **Virial theorem -> to form stable halos around galaxies, DM particle should be non-relativistic (cold dark matter)**



ned.ipac.caltech.edu

# Indirect WIMP Signatures (1)




- **WIMP = Weakly Interacting Massive Particle**
- ***Assume*: Can annihilate or decay into SM particles**
- ***Assume*: Accounts for measured DM density**
- **WIMP annihilation or decay can produce a variety of detectable SM particles**
- **Goal is to detect these particles and characterize intrinsic WIMP properties**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# Indirect WIMP Signatures (2)

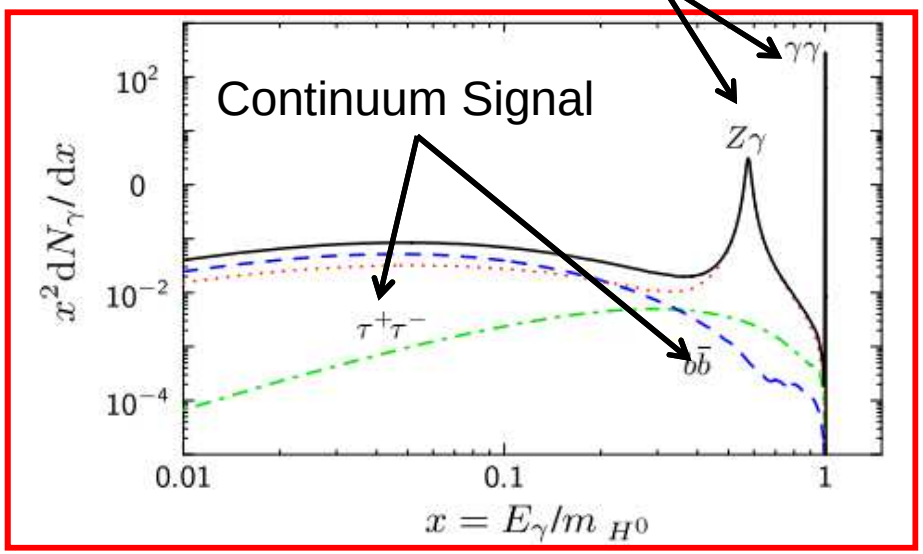
**What we observe** | **Intrinsic Particle Properties** | **Astrophysics**

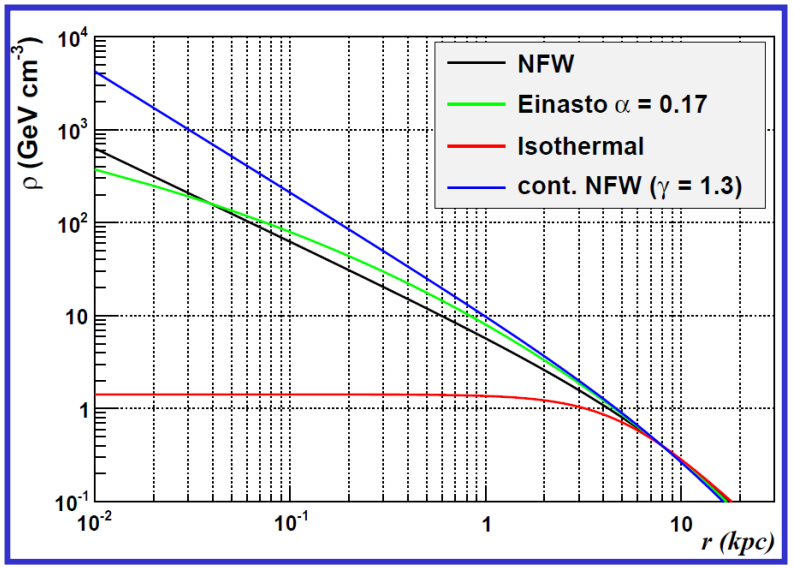
$$\Phi_\chi(E,\psi) = \frac{\langle\sigma_\chi v\rangle}{2}\sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi)\,\frac{1}{4\pi}\,\frac{\rho(l)^2}{m_\chi^2}$$

$\langle\sigma v\rangle_{ann}$ ~ 3e-26 $cm^3/s$ for thermal relic

J-factor – Line of sight integral over a ROI

Monochromatic Signal




Gustafsson et al. PRL 99.041301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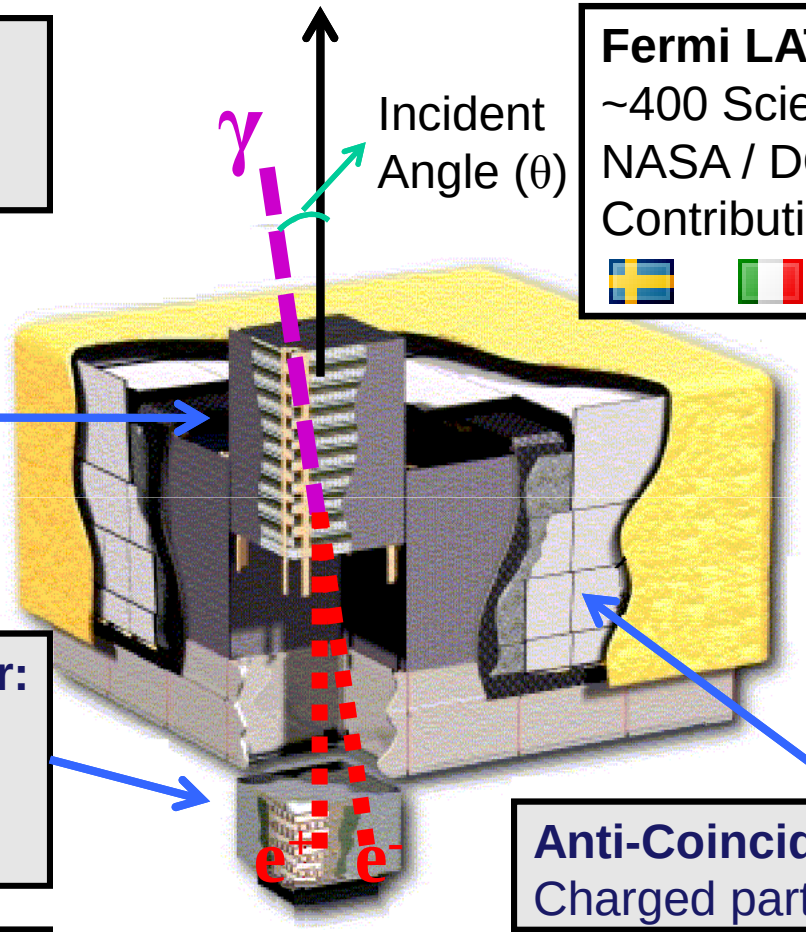
# Fermi LAT

**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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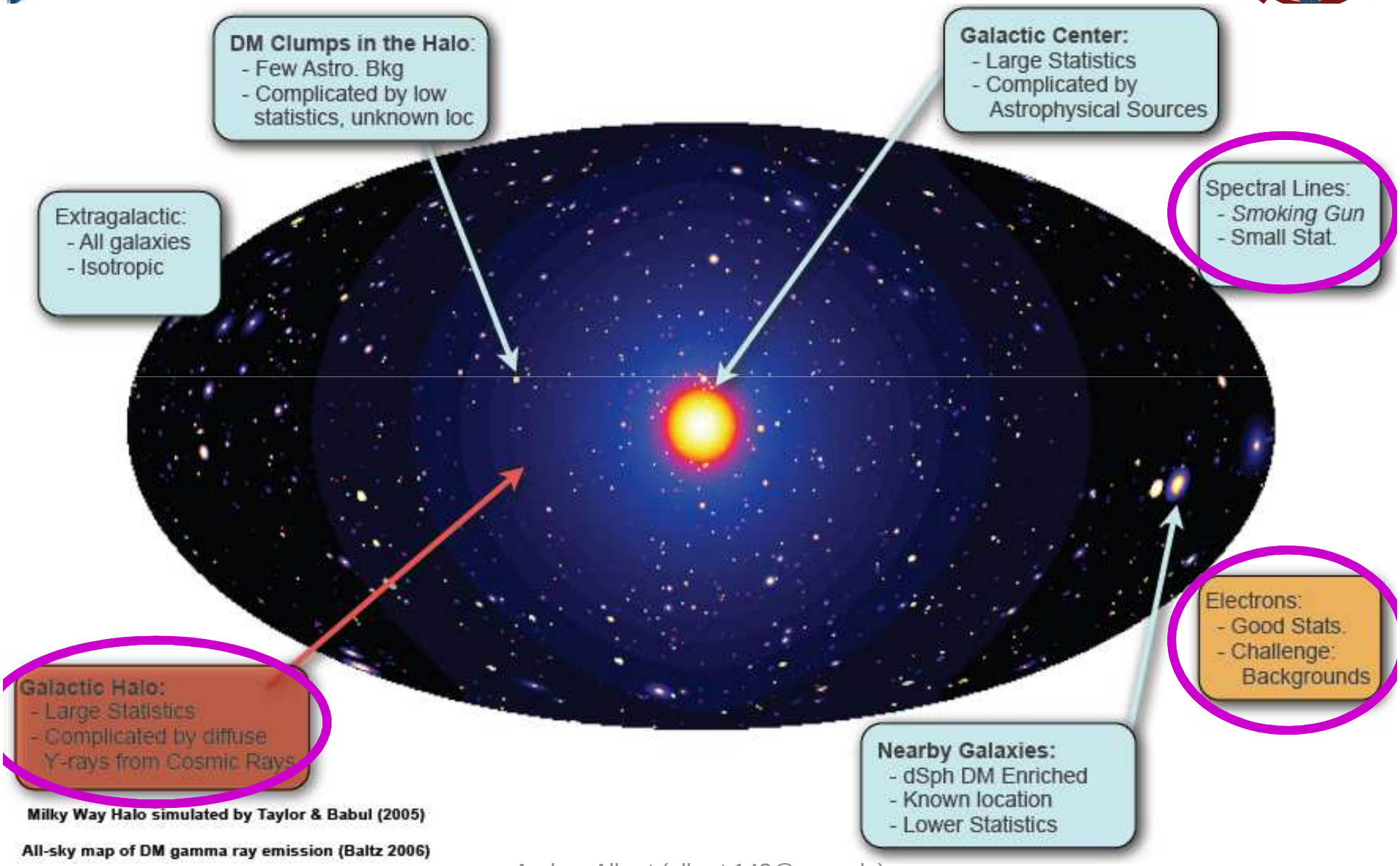
# Dark Matter Searches with the Fermi LAT




Milky Way Halo simulated by Taylor & Babul (2005)

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



Andrea Albert (albert.143@osu.edu)

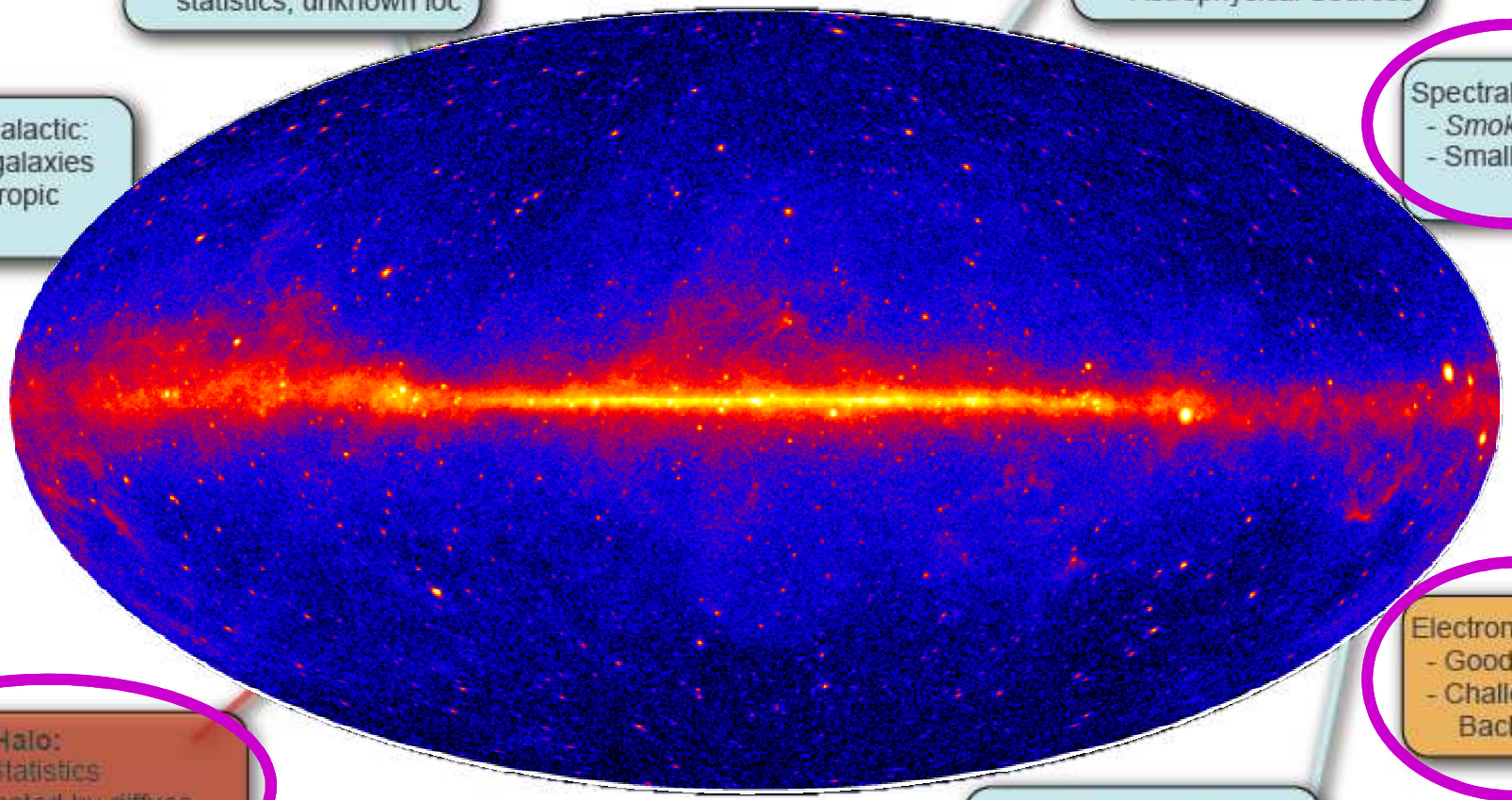
# Dark Matter Searches with the Fermi LAT

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

**Galactic Center:**
- Large Statistics
- Complicated by Astrophysical Sources

Extragalactic:
- All galaxies
- Isotropic

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



Electrons:
- Good Stats.
- Challenge: Backgrounds

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

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

**Milky Way Halo simulated by Taylor & Babul (2005)**

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



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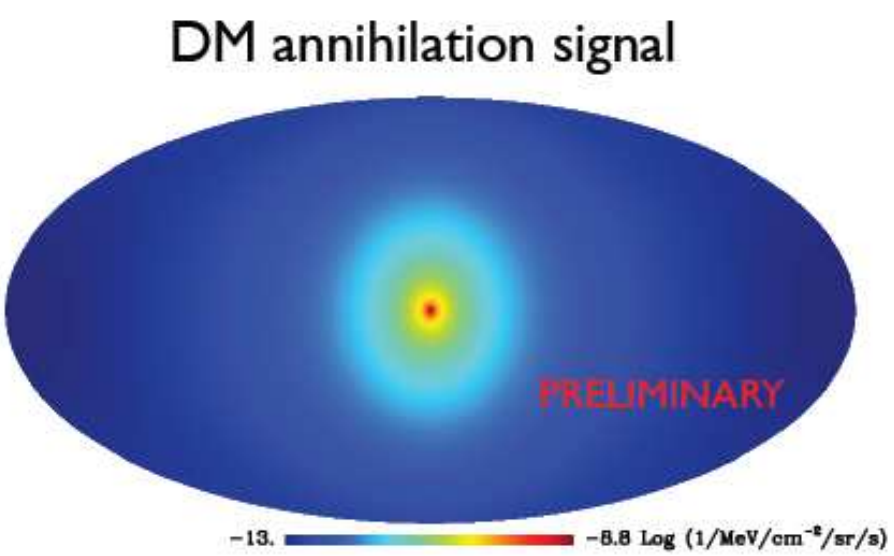
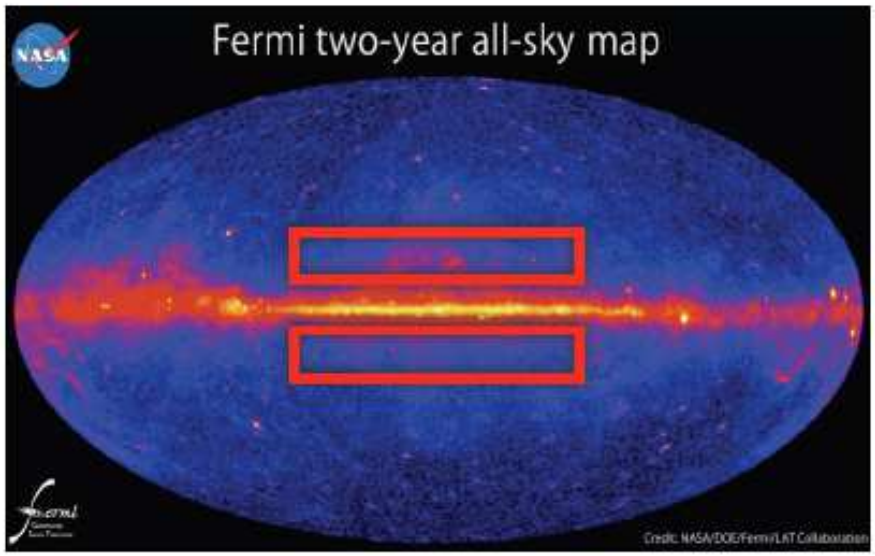
# DM Constraints from the Milky Way Halo

- **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)**





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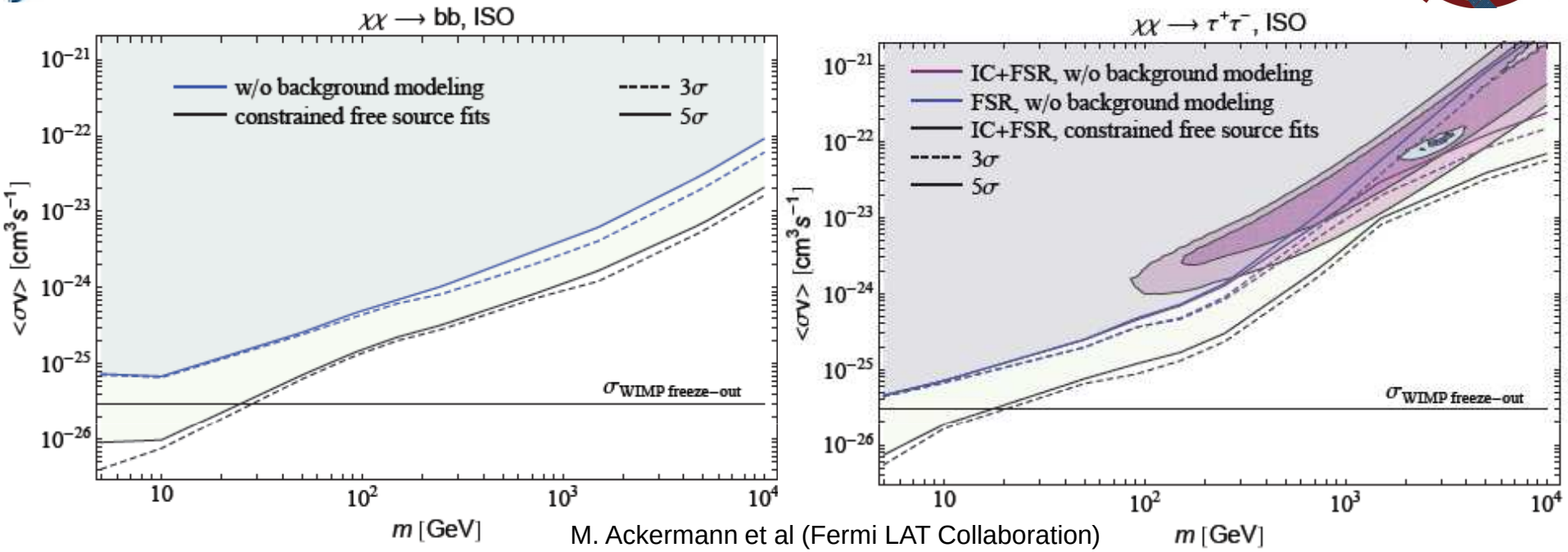
# MW Halo Results




M. Ackermann et al (Fermi LAT Collaboration)
ApJ 761, 91 (2012)

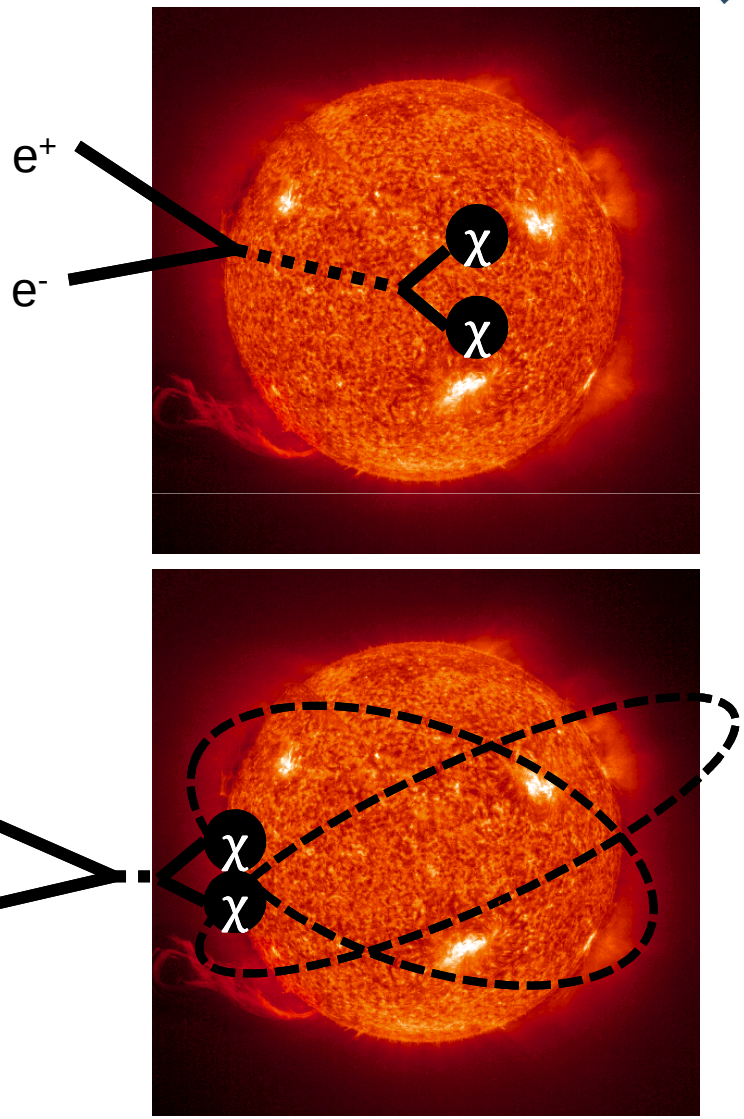
- **$b\bar{b}$ annihilation spectrum is similar in shape to DM annihilations/decays producing heavy quarks and gauge bosons in this energy range**
- **Set $\tau^+\tau^-$ limits assuming only Final State Radiation and FSR + Inverse Compton**
  - **Only FSR = only photons produced by taus (no electrons)**
  - **"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)**
- **Exclude canonical thermal relic WIMPs for masses below ~20 GeV in $b\bar{b}$ and $\tau^+\tau^-$**

# Electrons from the Sun

- **Combination of direct and indirect detection mechanisms**
  - **WIMP-nucleon scattering leads to WIMP capture by the Sun**
  - **WIMP-WIMP annihilation leads to the production of cosmic rays**

- **DM capture and annihilation through an intermediate state**
  - **WIMP accretion rate determined by scattering cross section**
  - **Annihilation through an intermediate particle that can travel out of the Sun and decay into cosmic rays**

- **Inelastic DM**
  - **WIMP accretion via inelastic scattering (maintain large orbits)**
  - **Annihilation directly into cosmic-ray electrons in the solar neighborhood**





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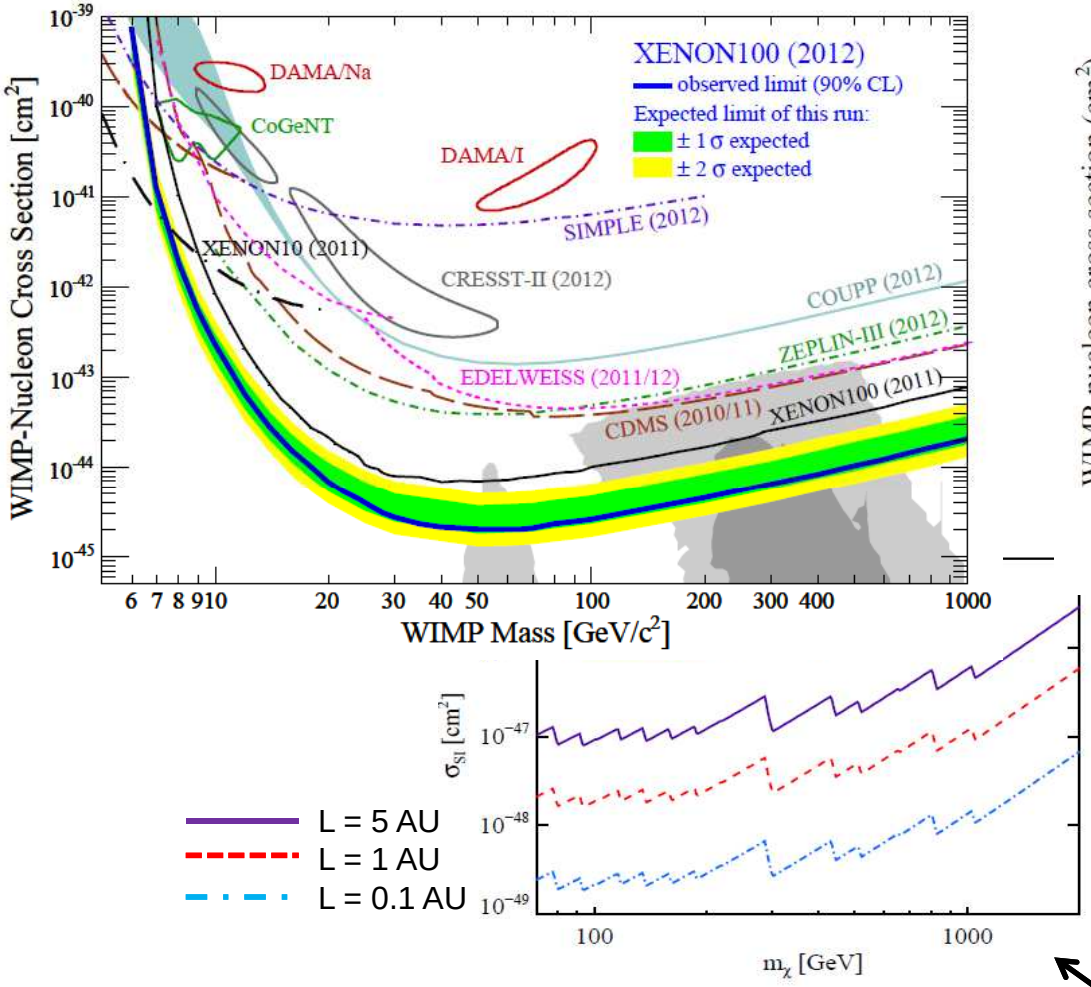
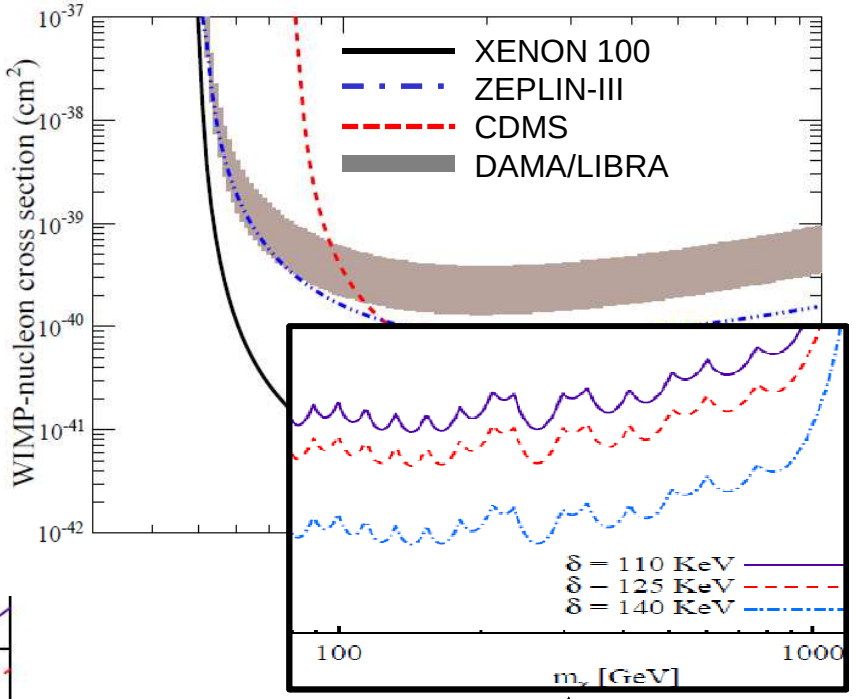
# Electrons from the Sun Results



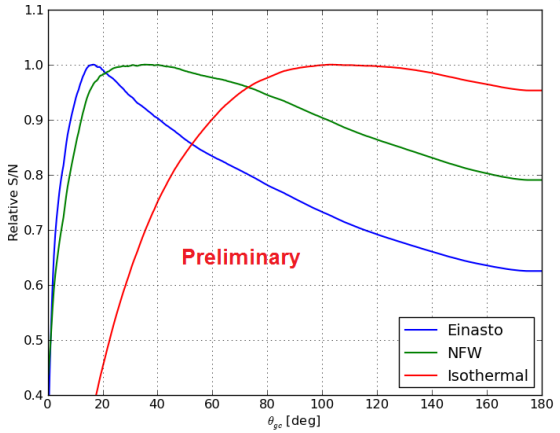

Assumes WIMP capture through inelastic scattering and annihilation to e+e-

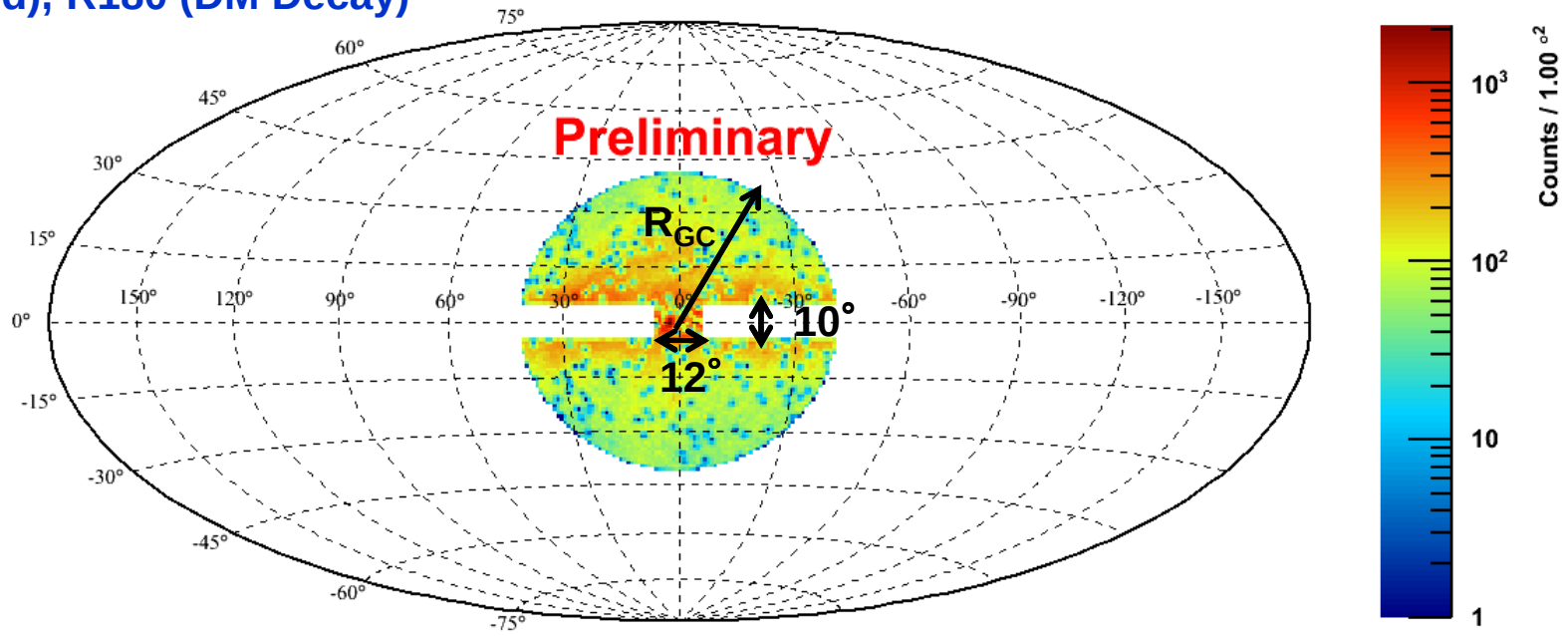
Assumes WIMP annihilation through an intermediate particle to e+e- (spin-indep.)

Aprile et al., arXiv:1207.5988
Aprile et al., arXiv:1104.3121
**Ajello et al., arXiv:1107.4272**

# Fermi-LAT Line Search -- Dataset

- Search for lines from 5 – 300 GeV using 3.7 years of data
- Use P7REP_CLEAN (REP = “reprocessed”)
  - Mask bright (>10σ for E > 1 GeV) 2FGL sources
- Optimize ROI for a variety of DM profiles
  - Find $R_{GC}$ that optimizes S/sqrt(B)
- Search in 5 ROIs
  - R3 (3˚GC Circle, cont. NFW Optimized), R16 (Einasto Optimized), R41 (NFW Optimized), R90 (Isothermal Optimized), R180 (DM Decay)





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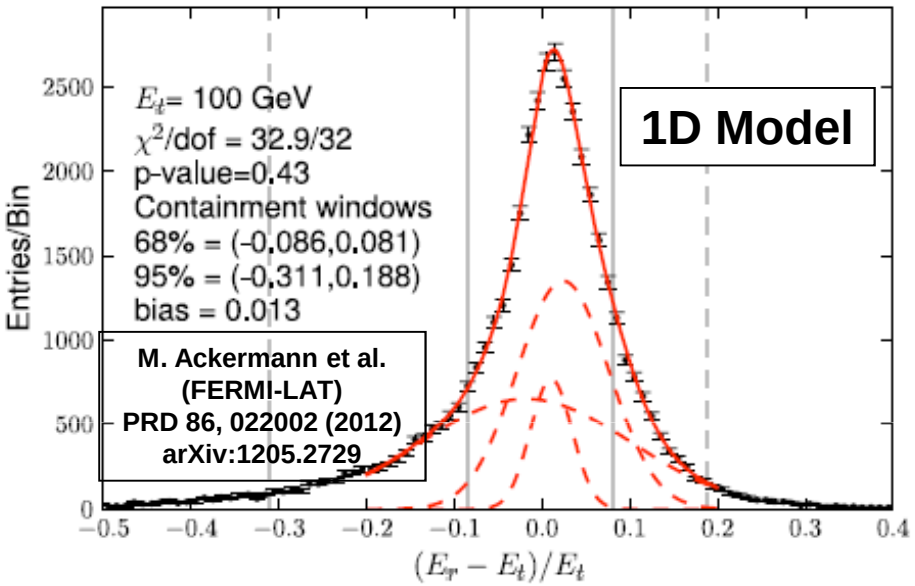
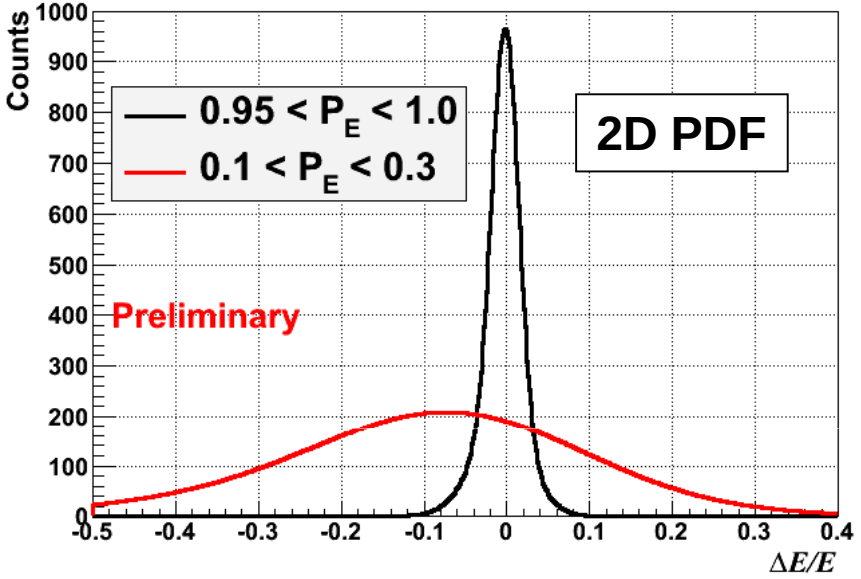
# 2D Energy Dispersion Model

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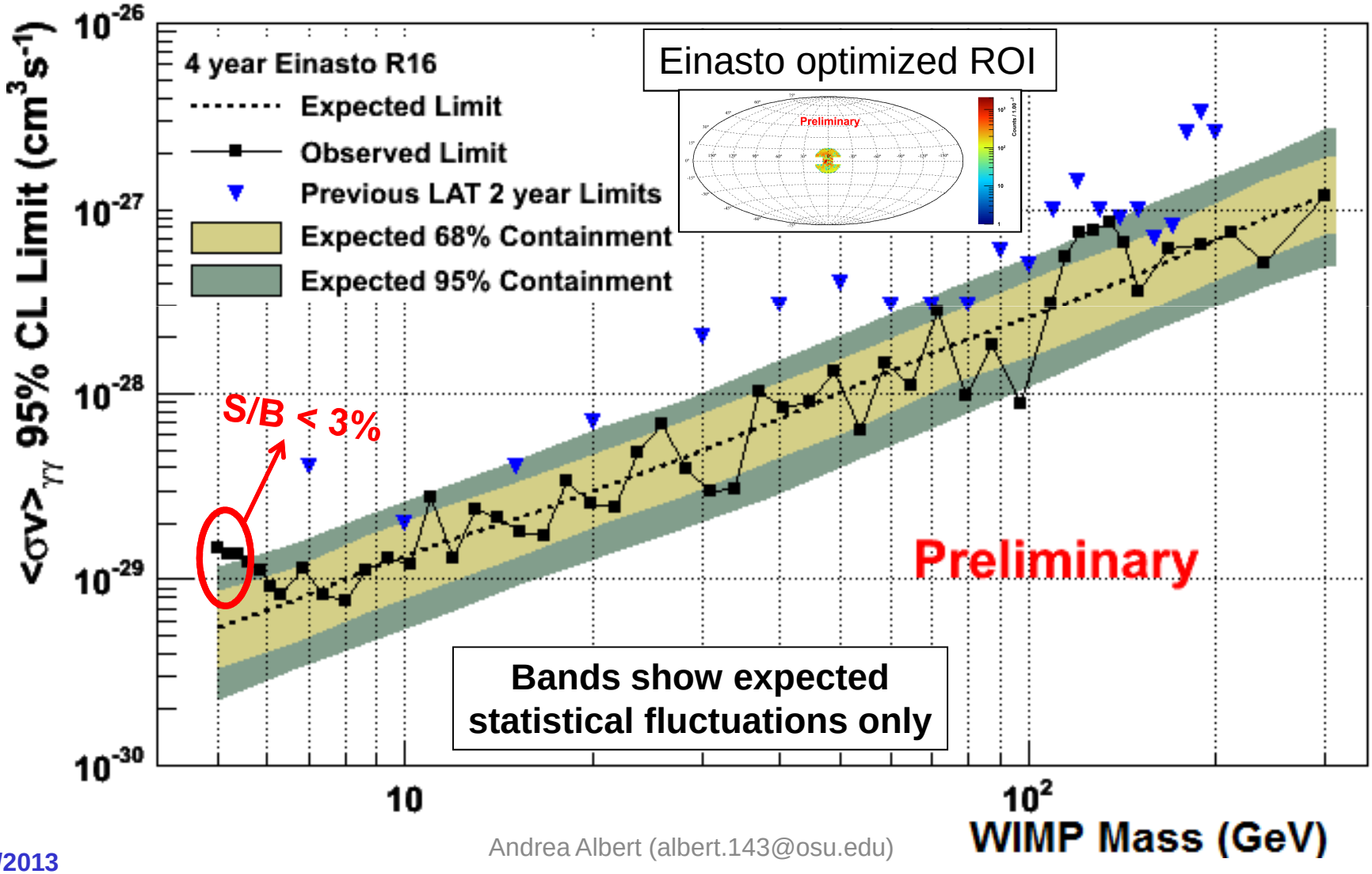
# 95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ Einasto Upper Limit R16

- **No globally significant lines detected**
  - **All fits have global significance < 2σ**





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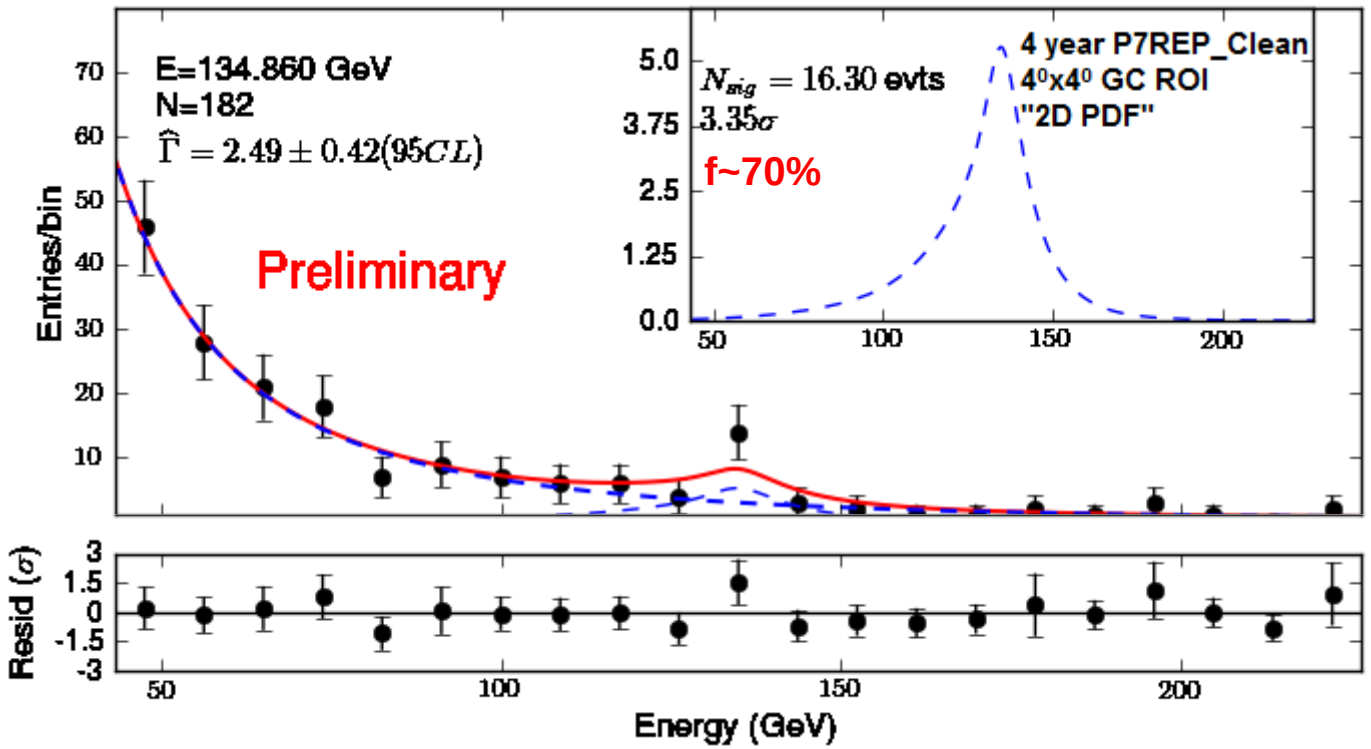
# Fermi-LAT Team Line Search at 135 GeV




- 4.01σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  - Look in 4° x4° GC ROI, Use 1D PDF (no use of $P_E$)
- 3.73σ (local) 1D fit at 135 GeV with 3.7 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 3.7 year reprocessed data**
  - **Look in 4° x4° GC ROI, Use 2D PDF ($P_E$ in data)**
  - **<2σ global significance after trials factor**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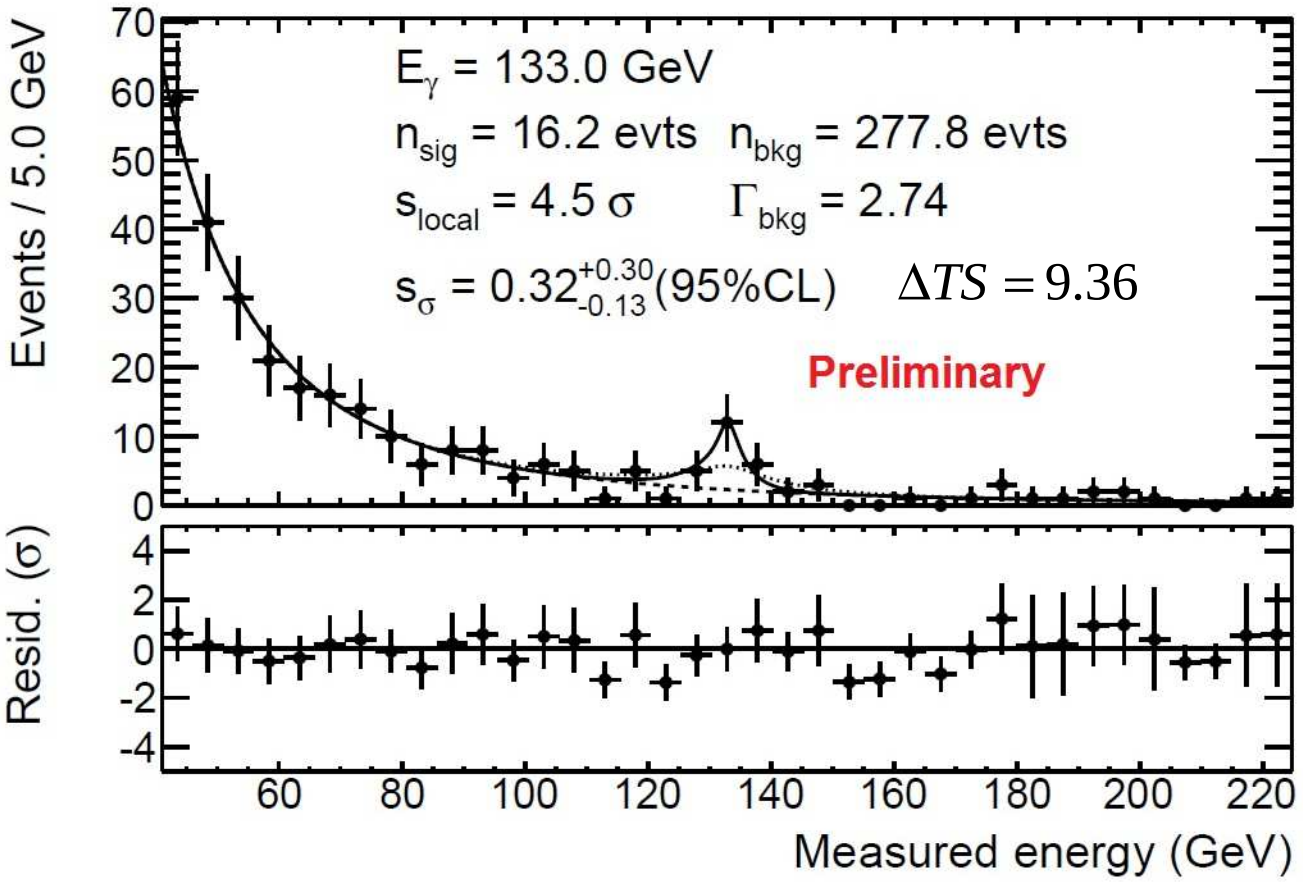
# Width of Feature near 135 GeV




- **Let width scale factor float in fit (while preserving shape)**
- $s_\sigma = 0.32^{+0.30}_{-0.13}(95\%CL)$
  - **Feature in data is narrower than expected energy resolution**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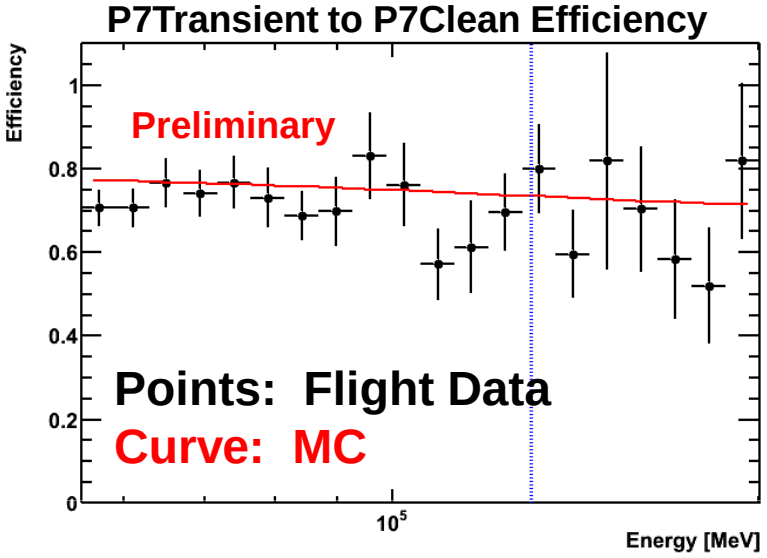
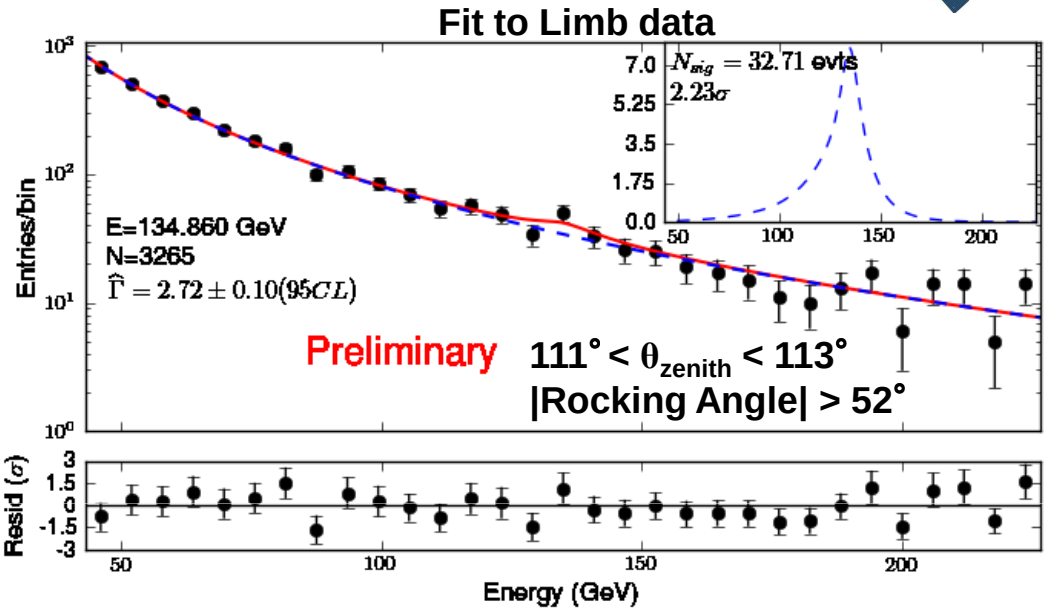
# Variations in Effective Area




- Study Limb spectrum, which should be a smooth power law
  - No line-like features expected in Limb → from stat. flucs and/or systematics
  - $\delta f_{aeff}$ ranges from 0.5% to 2.5% (larger at high energies)
- See a slightly larger than average feature at ~135 GeV ($S/N_{limb}$ ~14%)
  - Dips in efficiency below and above 135 GeV
  - Appear to be related to CAL-TKR agreement
  - Could be artificially sculpting the energy spectrum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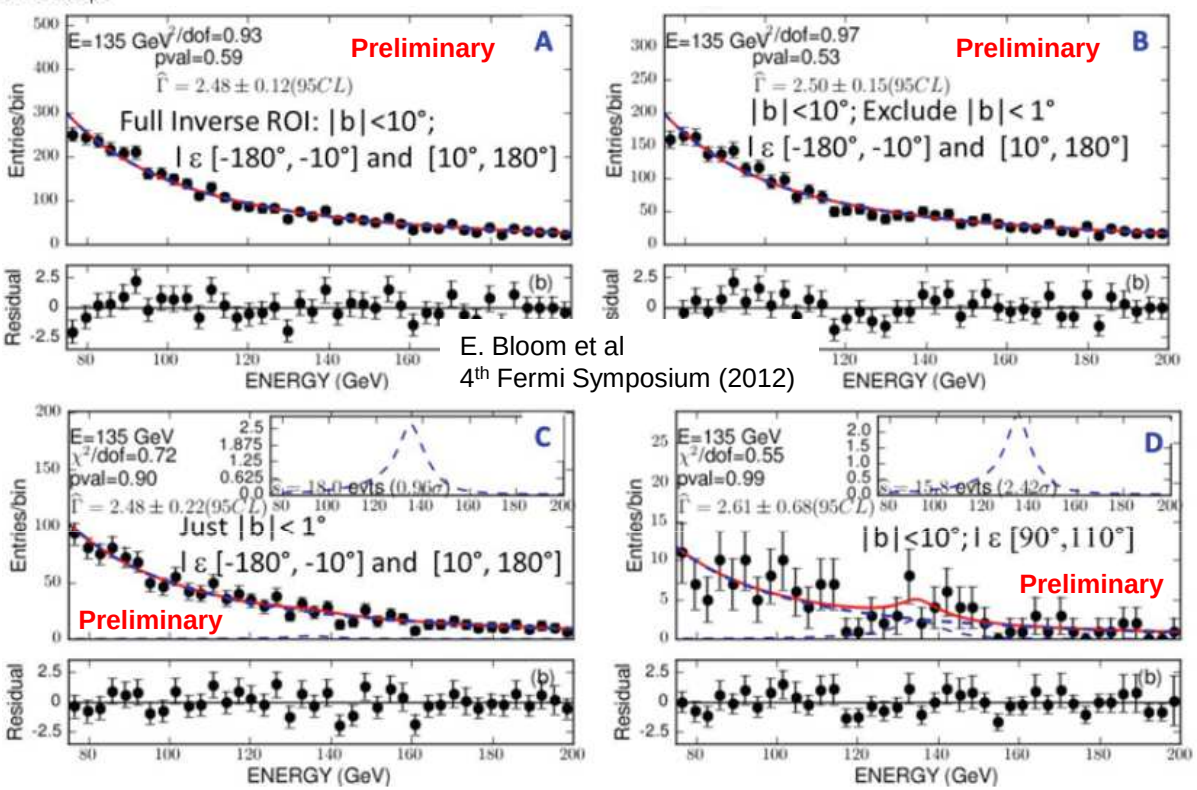
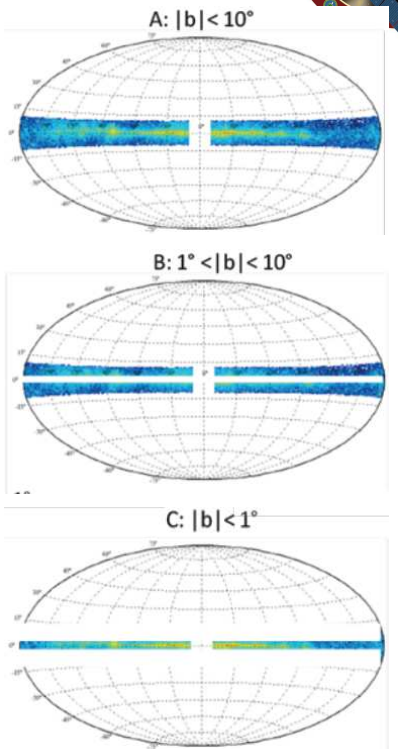
# 135 GeV in the inverse ROI spectrum




E. Bloom et al
4th Fermi Symposium (2012)




- **No significant feature at 135 GeV seen in inverse ROI searches (2D fits)**
- **If instrumental cause, then why isn't it in the inverse ROI?**
  - **Distributions of cut variables in specific ROIs affect cut efficiencies**
  - **Possible multivariate explanation (might not just be one culprit)**
    - **The story in Pass 7 may be more complicated than it was in Pass 6**
- **Investigations still on going**

# 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**
- **Search for spectral lines from 5 – 300 GeV in 5 ROIs**
  - **We do not see any globally significant spectral lines**
- **Uncovered some aspects of the 135 GeV line that require more study**
  - **Much narrower than expected energy resolution**
  - **Similar feature seen in Limb**
    - **Limb feature is smaller than GC feature**
  - **Larger than expected systematic uncertainty**
  - **Does not appear in the inverse ROI**
- **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!**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# 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**


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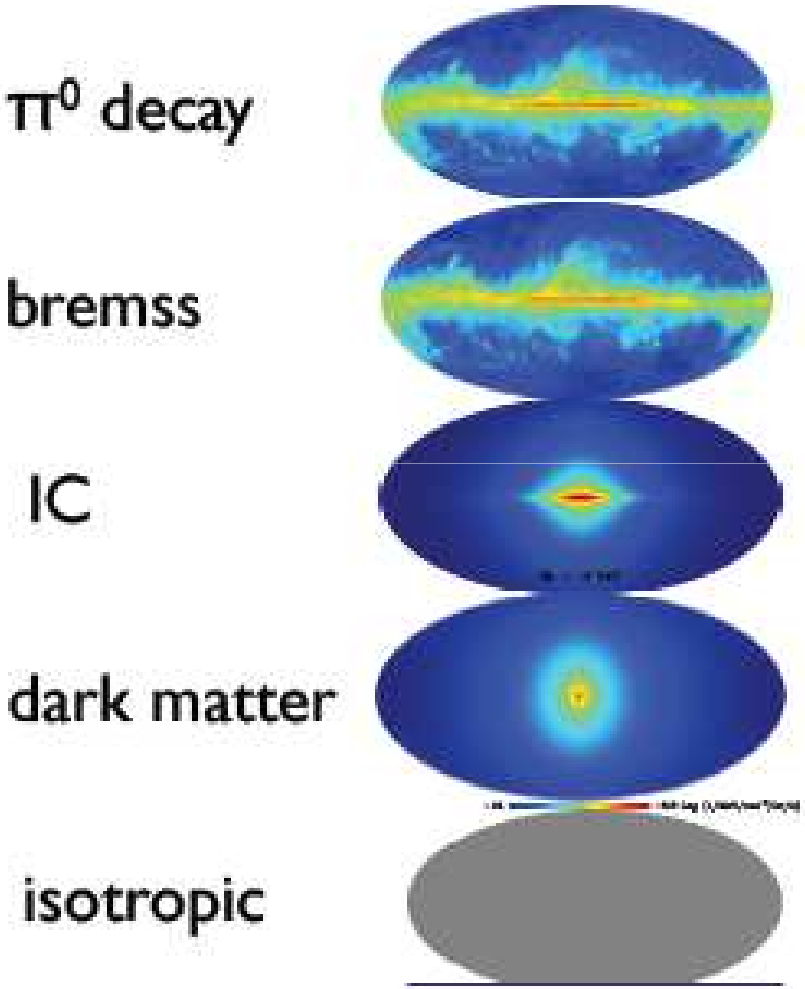
# Halo Method II – Limits + Bkg Modeling

- **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**




PRELIMINARY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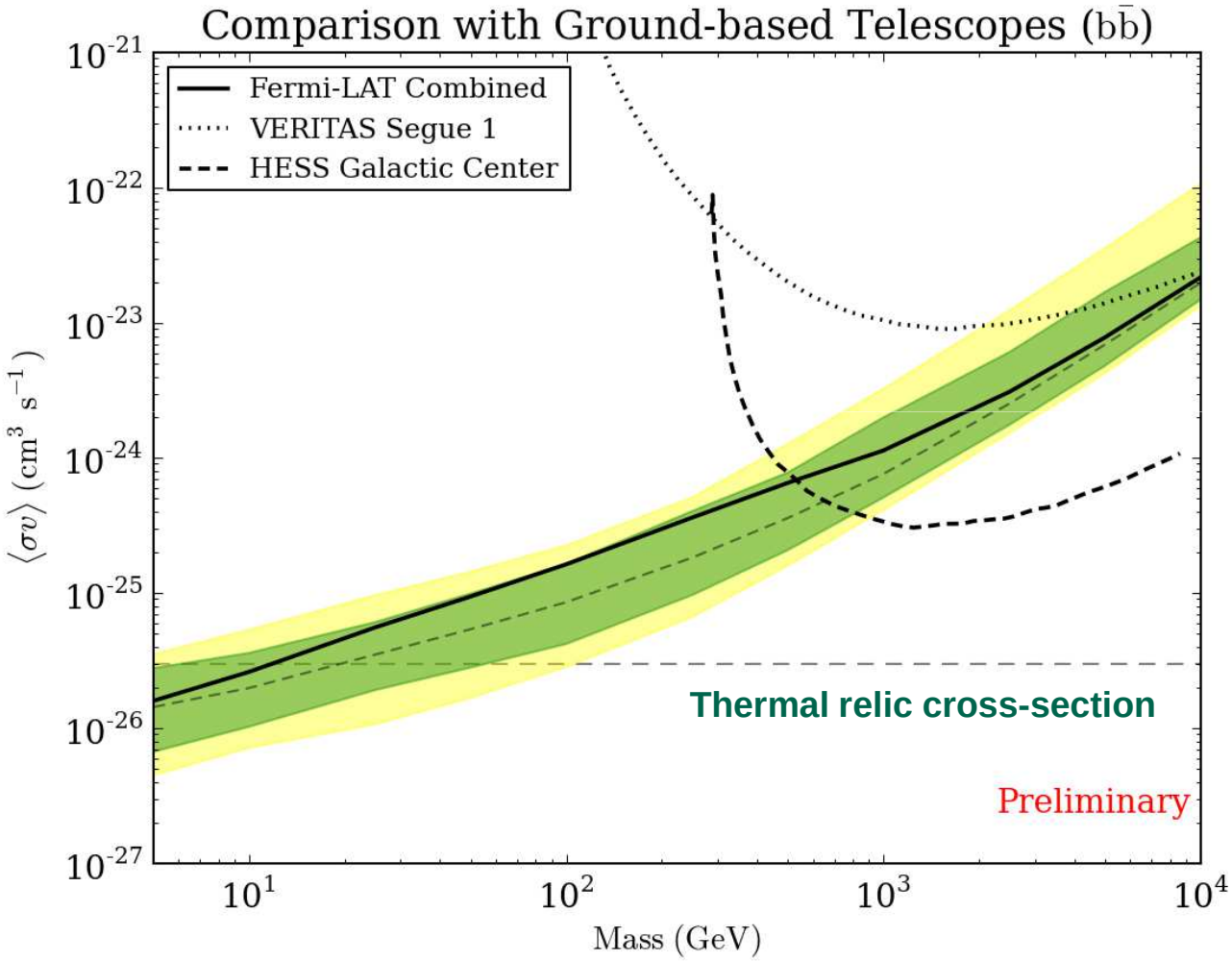
# Combined dSphs Results

- **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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# Combined dSphs Results

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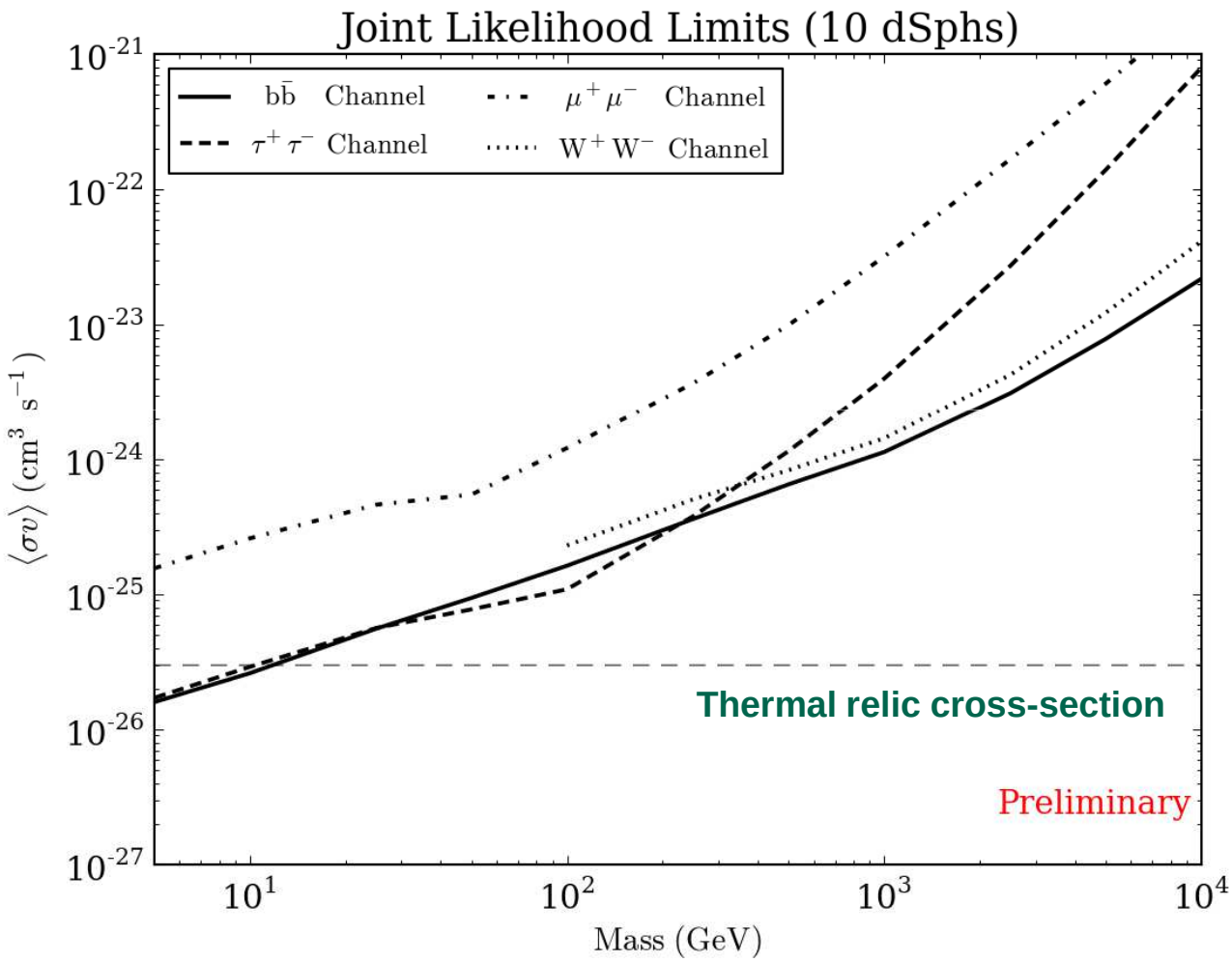



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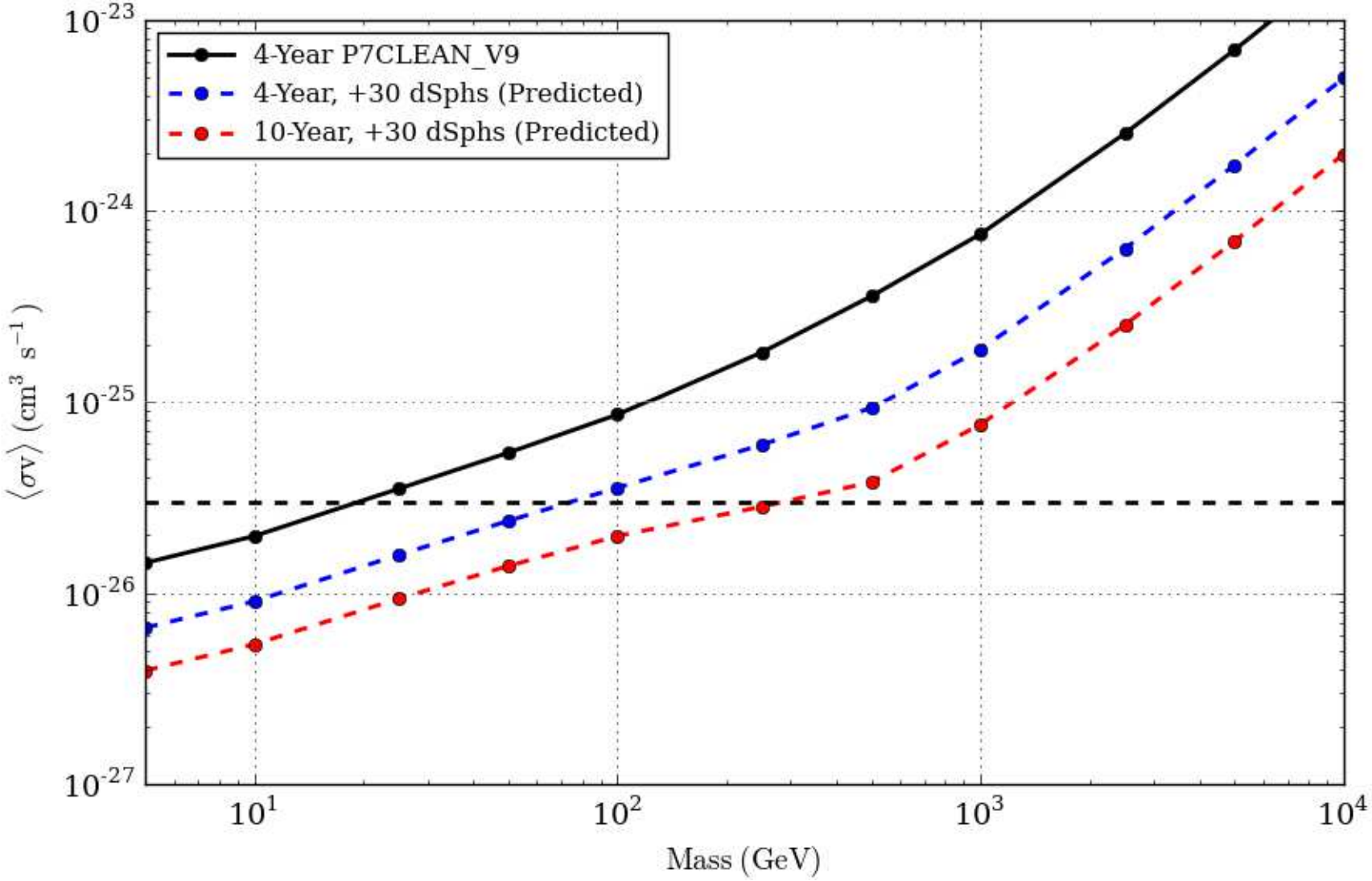
# Projected Limit Improvement with dSphs



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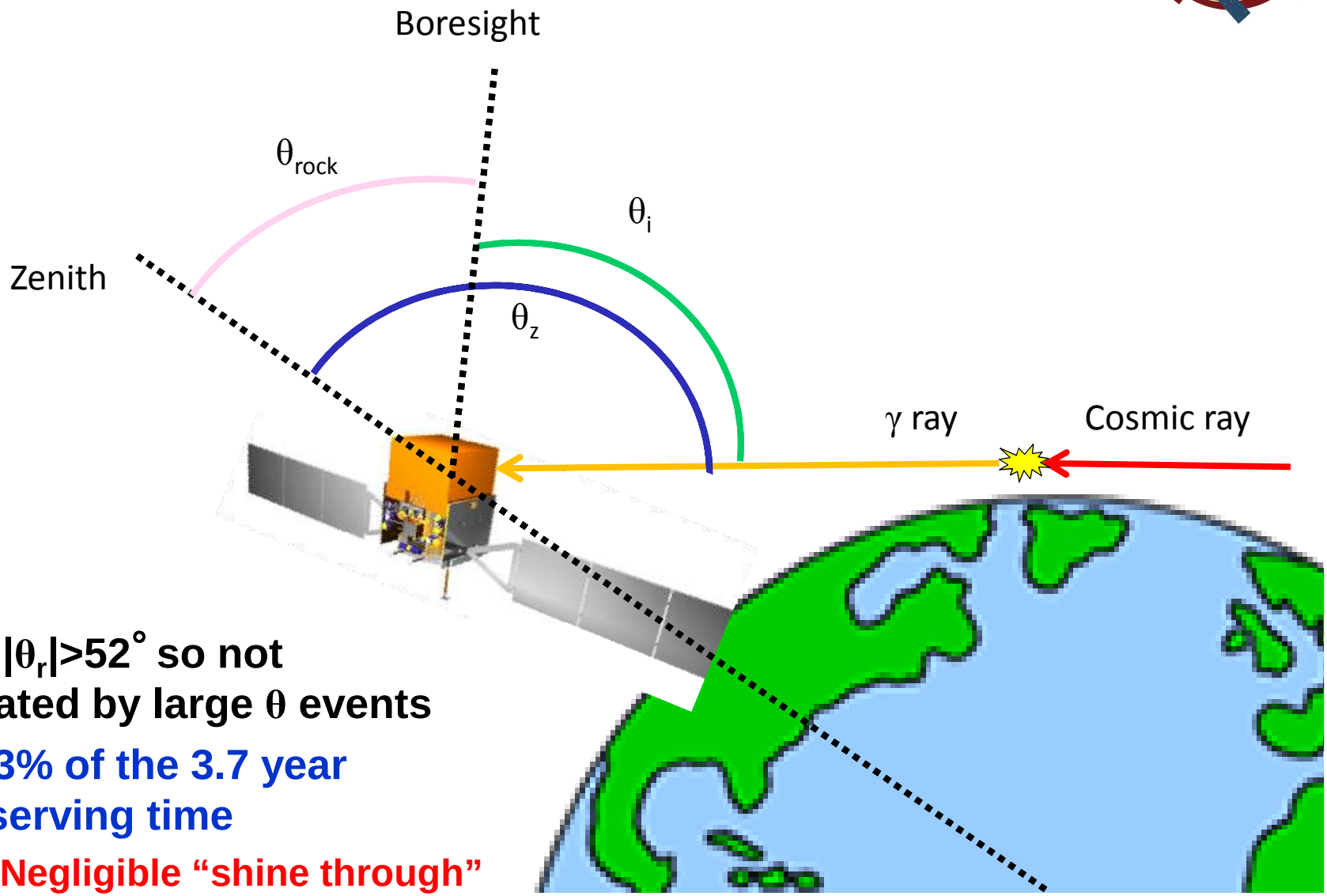
# Earth Limb Control Dataset




- **Select $|\theta_r|>52^\circ$ so not dominated by large θ events**
  - **0.03% of the 3.7 year observing time**
    - **Negligible "shine through"**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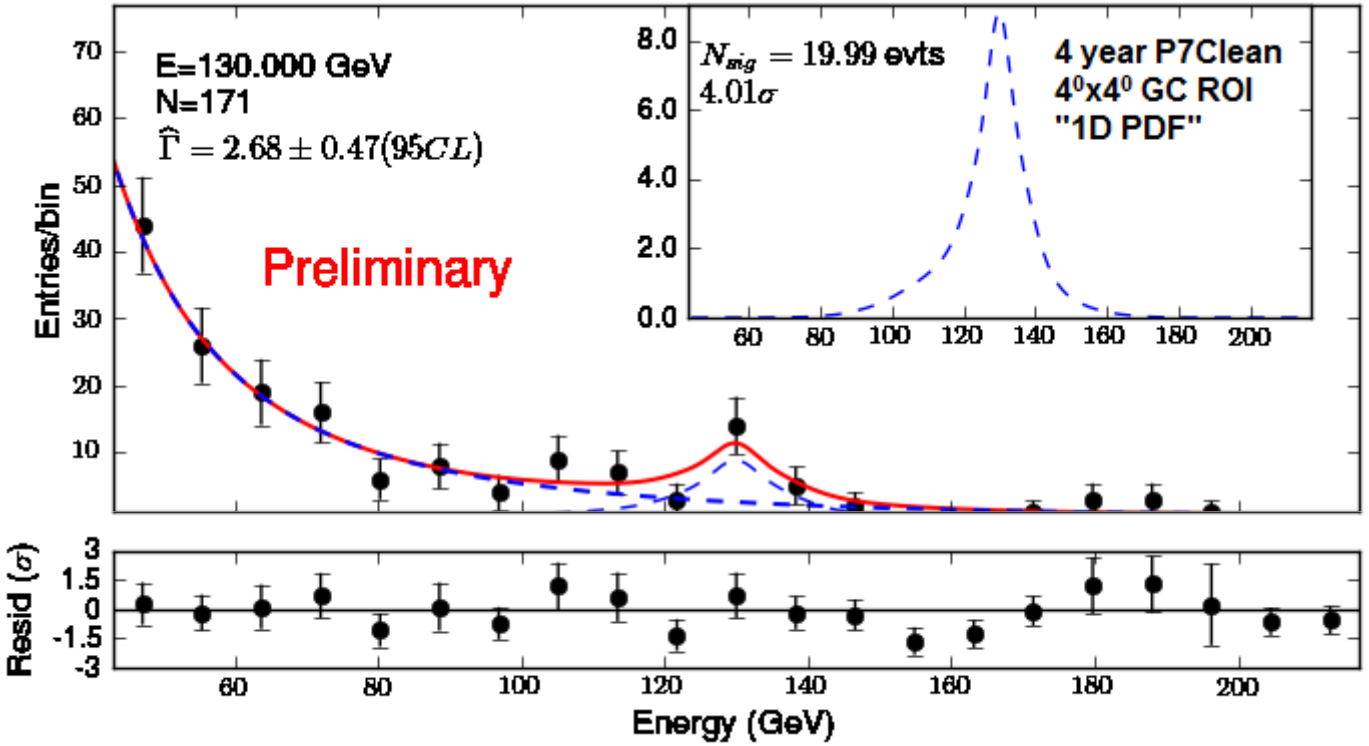
# Fermi-LAT Team Line Search at 135 GeV




- **4.01σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data**
- **Look in 4° x4° GC ROI, Use 1D PDF (no use of $P_E$)**



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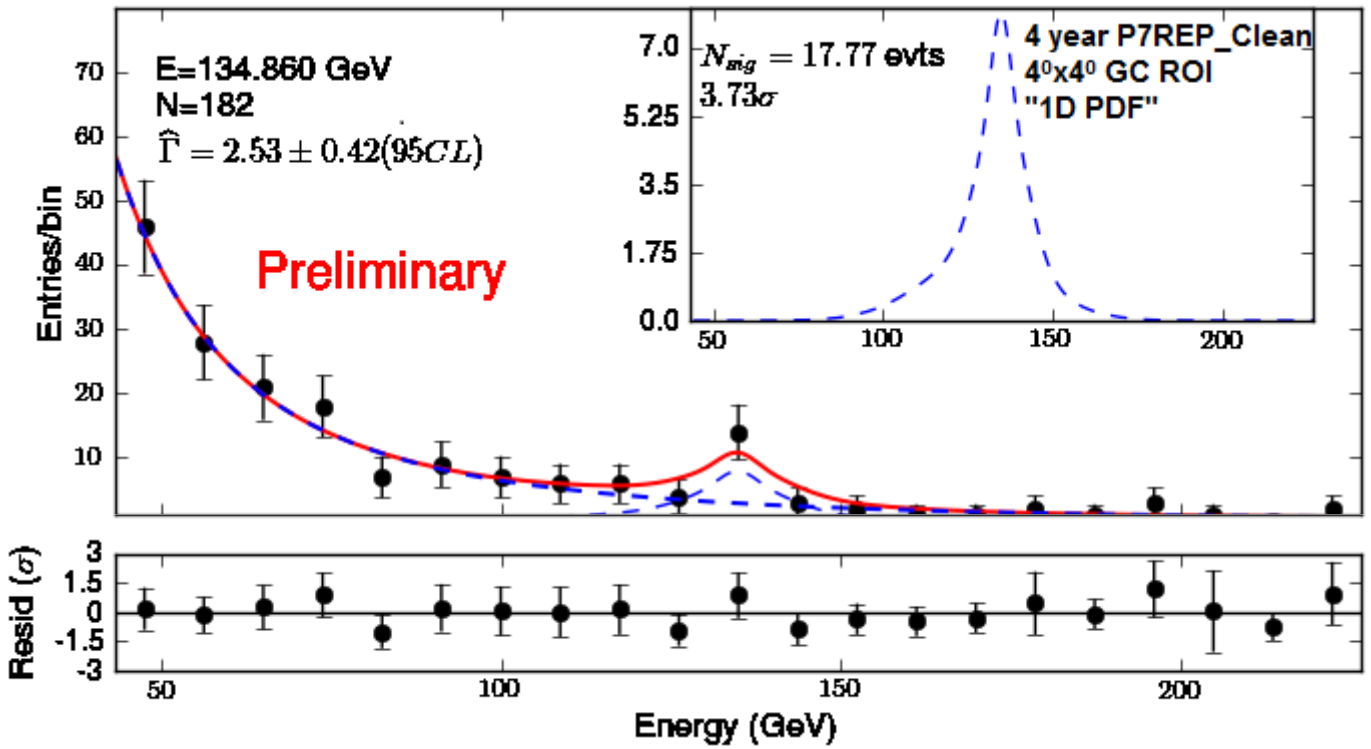
# Fermi-LAT Team Line Search at 135 GeV




- 4.01σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  - Look in 4° x4° GC ROI, Use 1D PDF (no use of $P_E$)
- **3.73σ (local) 1D fit at 135 GeV with 3.7 year reprocessed data**
  - **Look in 4° x4° GC ROI, Use 1D PDF (no use of $P_E$)**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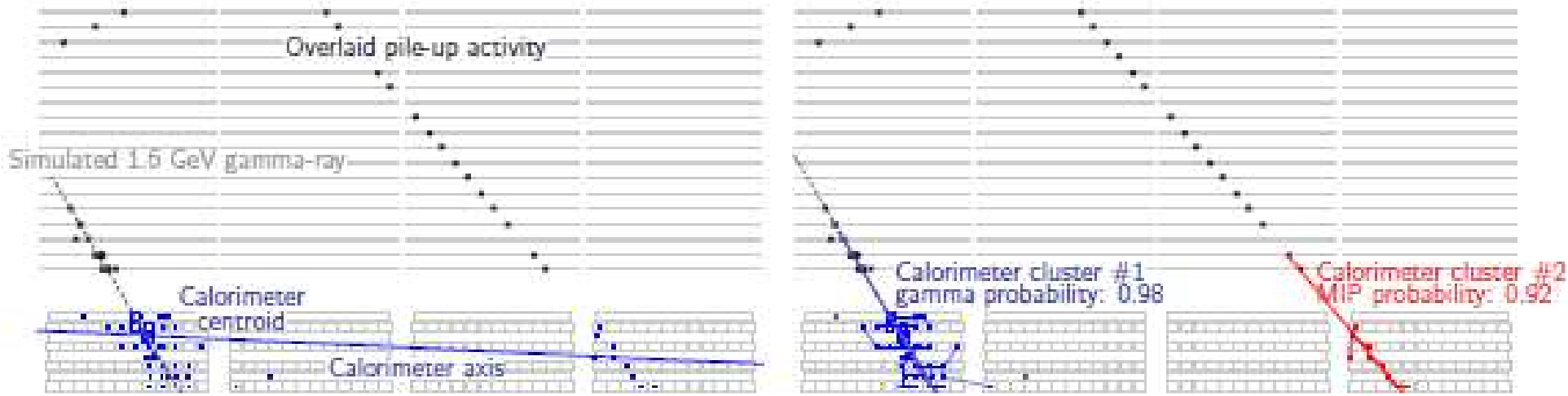
# Upcoming Developments -- Pass 8




- **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**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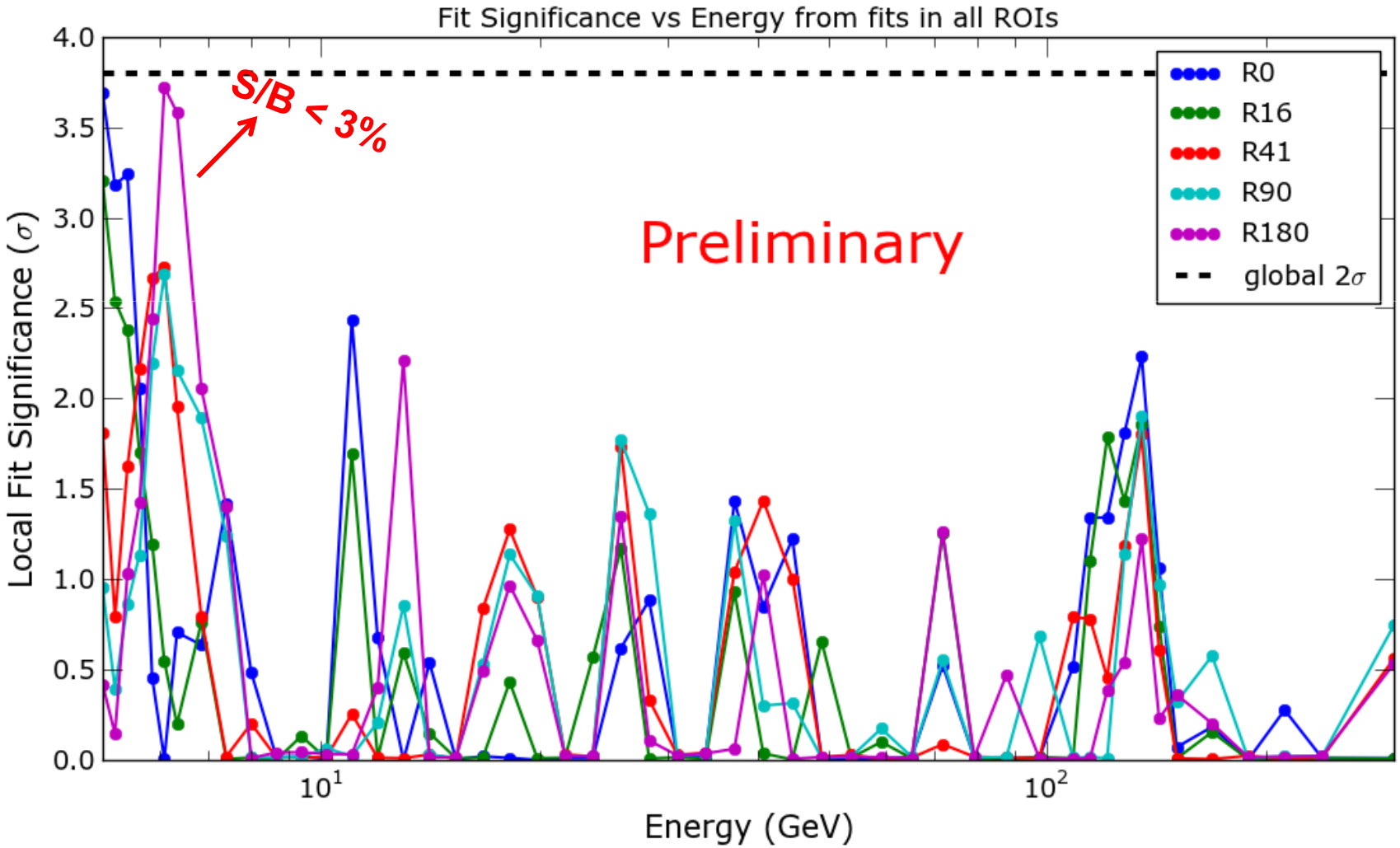
# 3.7 year Fermi-LAT Line Search Results

- **Search from 5 to 300 GeV**
- **No globally significant lines found**

*R0 = 12⁰x10⁰ GC box*

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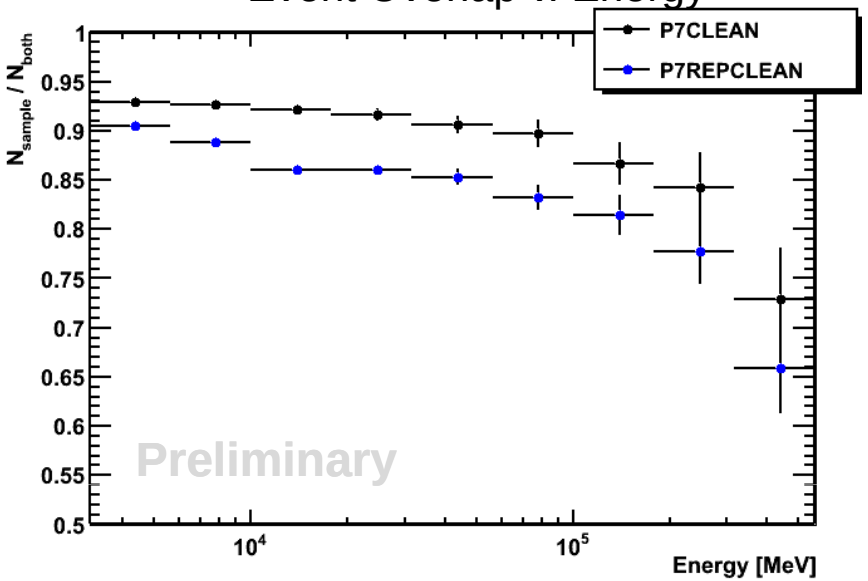
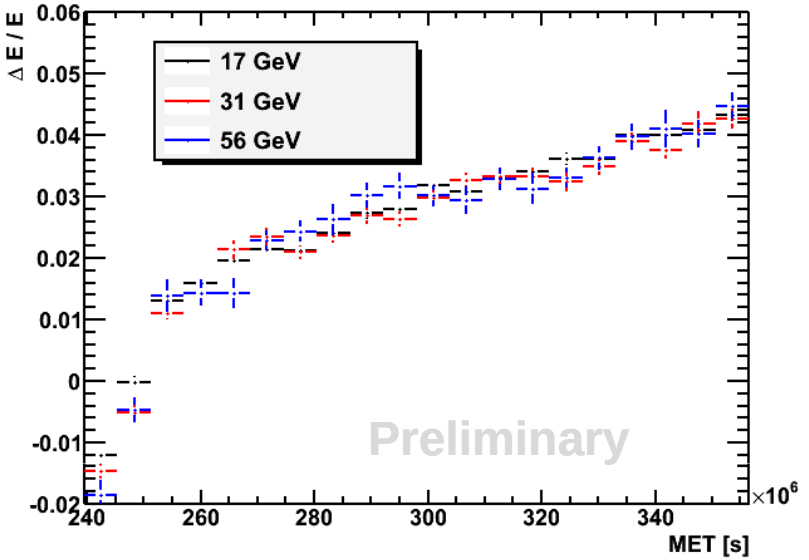
# Data Reprocessing with Updated Calibrations

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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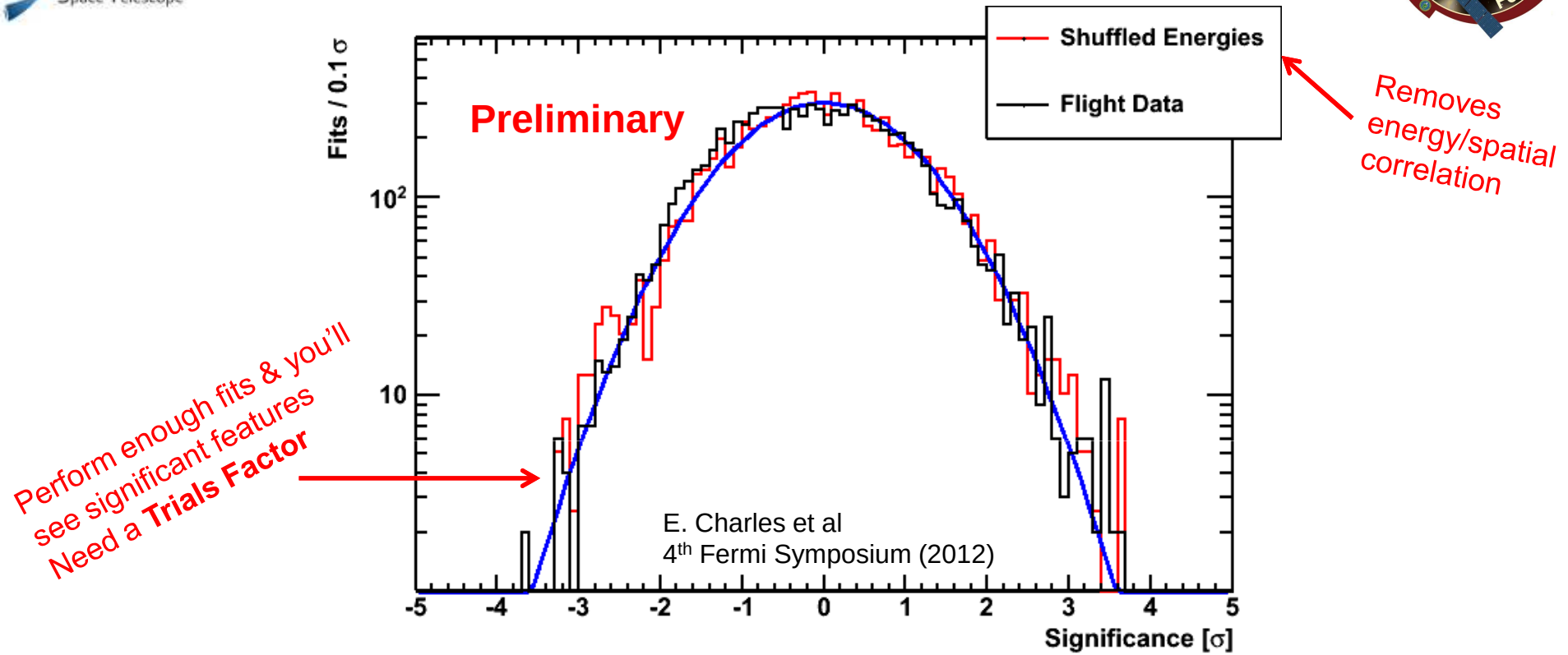
# Background Approximation




- **Scan 20˚x40˚ around the GC in 4˚x4˚ ROIs from 65 to 500 GeV (1D fits)**
  - **1˚ ROI steps, 0.25$\sigma_E$ energy steps (~50,000 fits)**
- **Look at significance distribution of data and data with shuffled energies**
  - **Both consistent with a Gaussian of width 1 center at 0**
    - **As expected for the null DM hypothesis**
    - **Approximating bkg as single powerlaw is ok**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# 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

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

Effective Area Corrections

- **Maximum likelihood fit at $E_\gamma$ in sliding energy window ($\pm 6\sigma_E$)**
  - **Fit from 5 to 300 GeV**
  - **$0.5\sigma_E$ steps (88 fit energies)**
- **$n_{sig}$, $n_{bkg}$, $\Gamma_{bkg}$ 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)**


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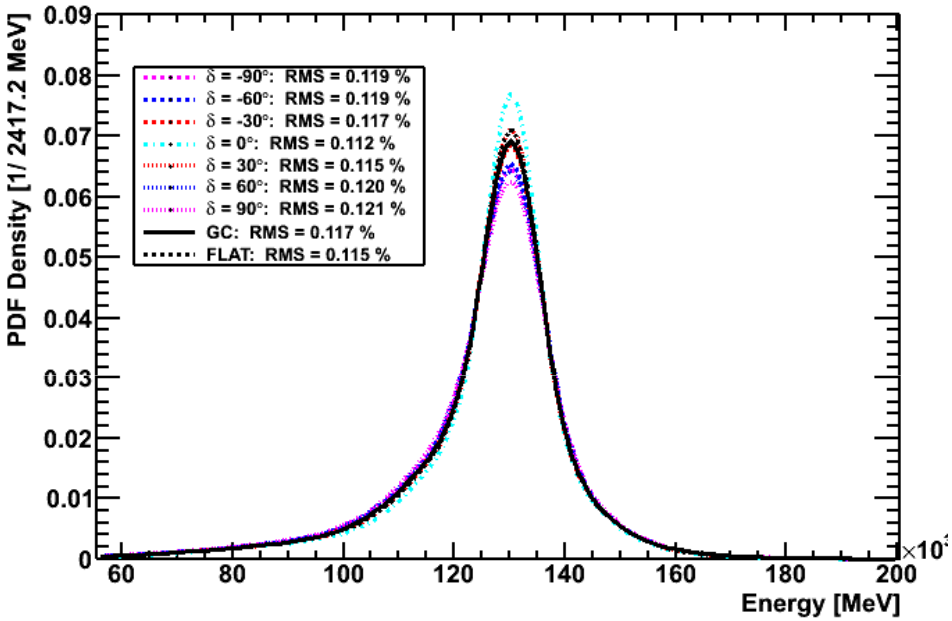
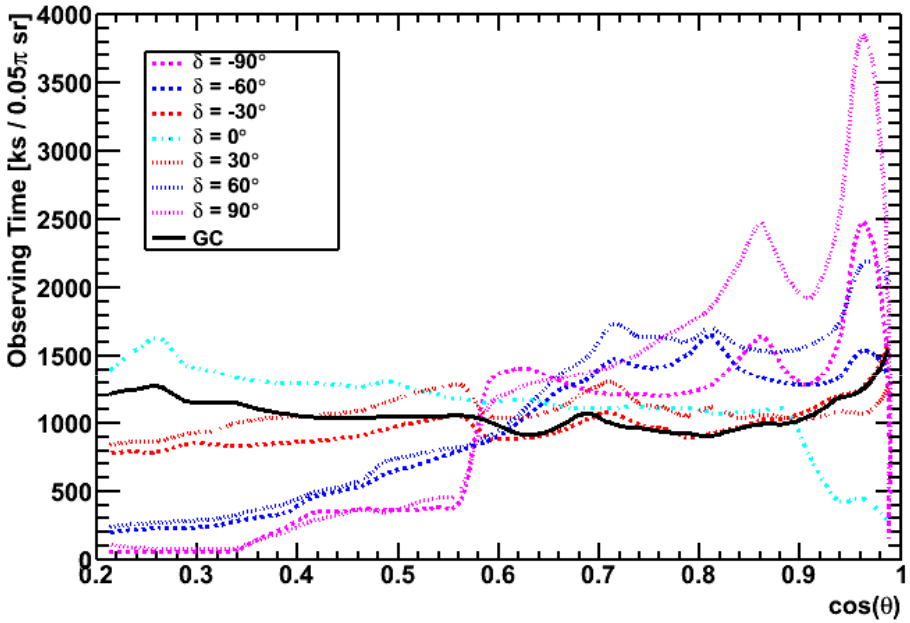
# θ-averaged Energy Resolution by Declination

## $D_{eff}$ for Several Directions




## Observing Profile for Several Directions




- 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%.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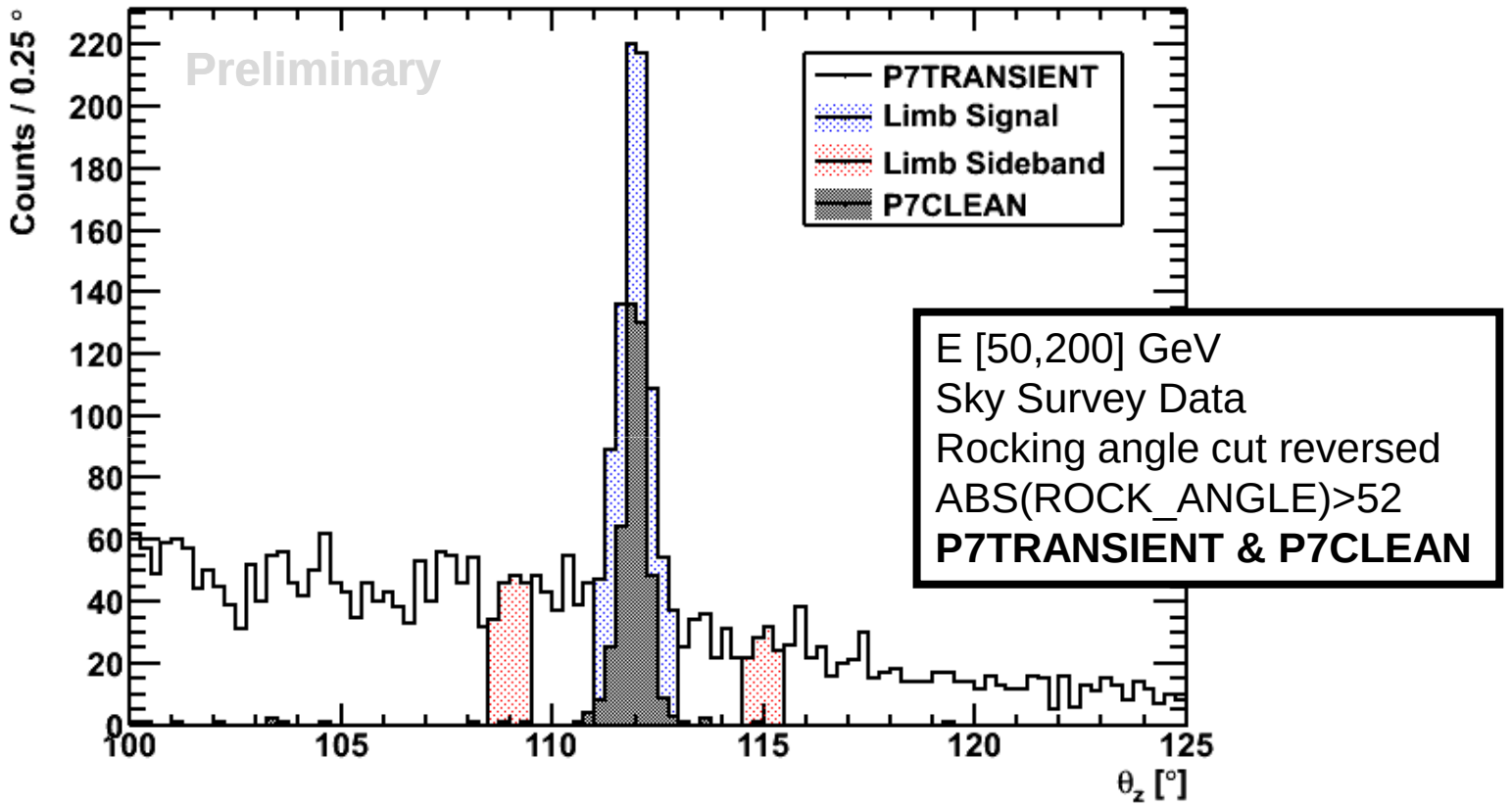
# Measuring Efficiency with the Earth Limb

**Zenith Angle Distribution for P7TRANSIENT & P7CLEAN**




- The Earth Limb is unique in that it can be seen in the loose P7TRANSIENT event class at high energies.
- This allows us to use it to measure efficiencies for tighter event classes as a function of energy.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