Fermi Large Area Telescope Results on Dark Matter searches Focus on spectral lines

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On behalf of the Fermi LAT Collaboration

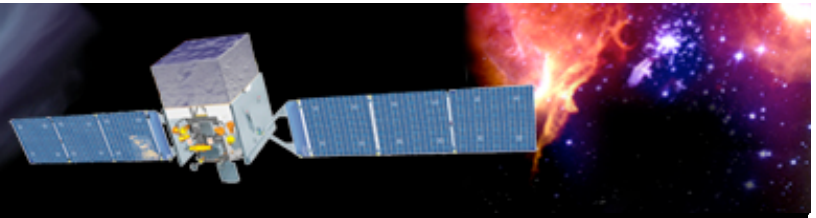
SciNeGHE 2014
04-06 June - Lisbon - Portugal

Talk outline

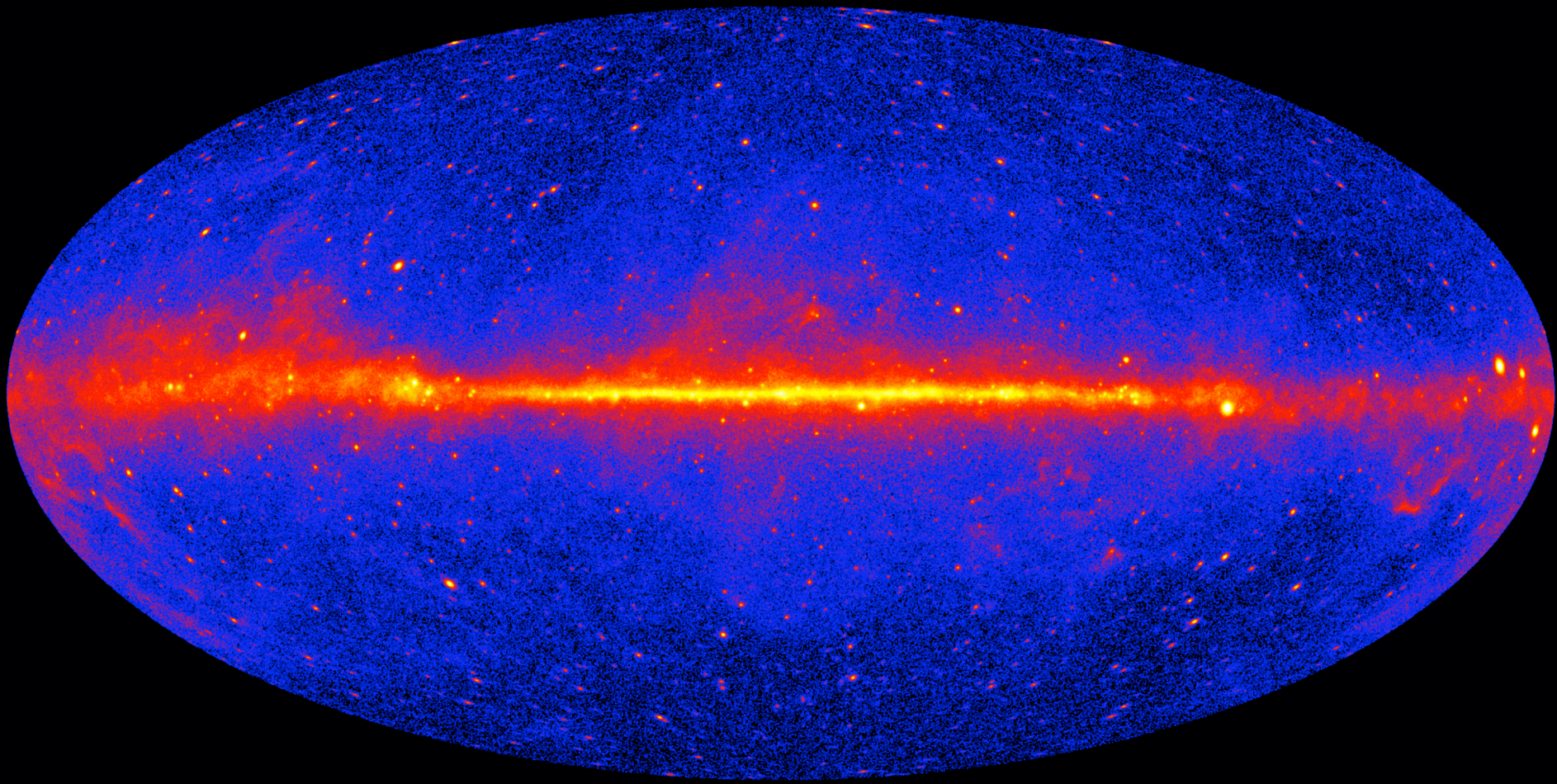
- The Fermi LAT gamma-ray sky
- Searches for Dark Matter
  - Known and new targets
  - Searches for spectral lines
- Future prospects with the LAT

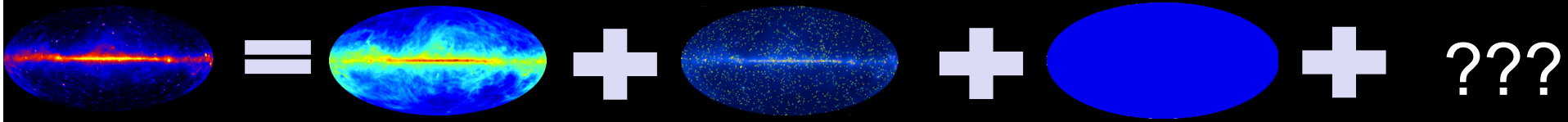
Fermi

Gamma-ray Space Telescope



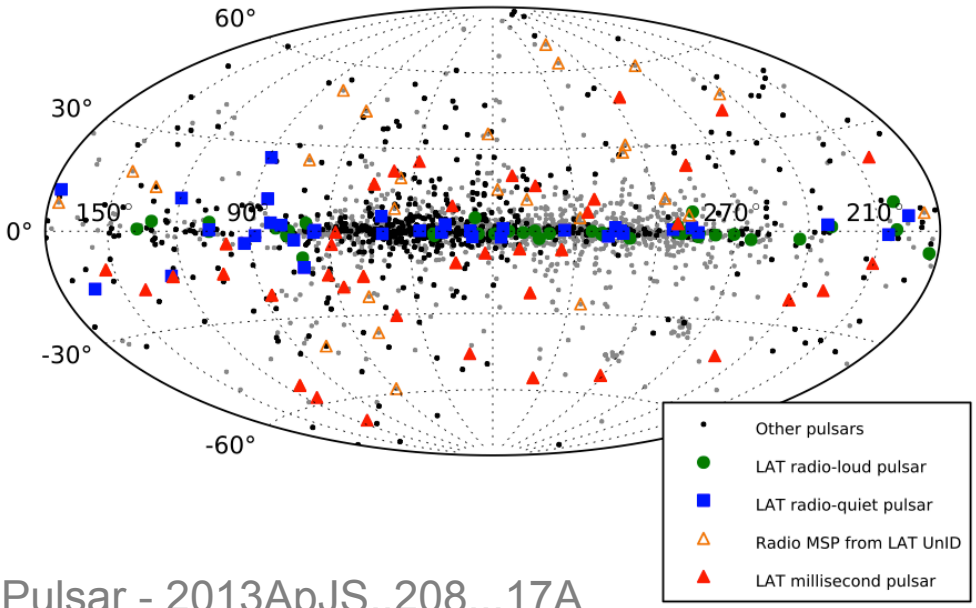
5 years γ-ray skymap showing thousands of sources and Galactic plane glowing in γ-rays



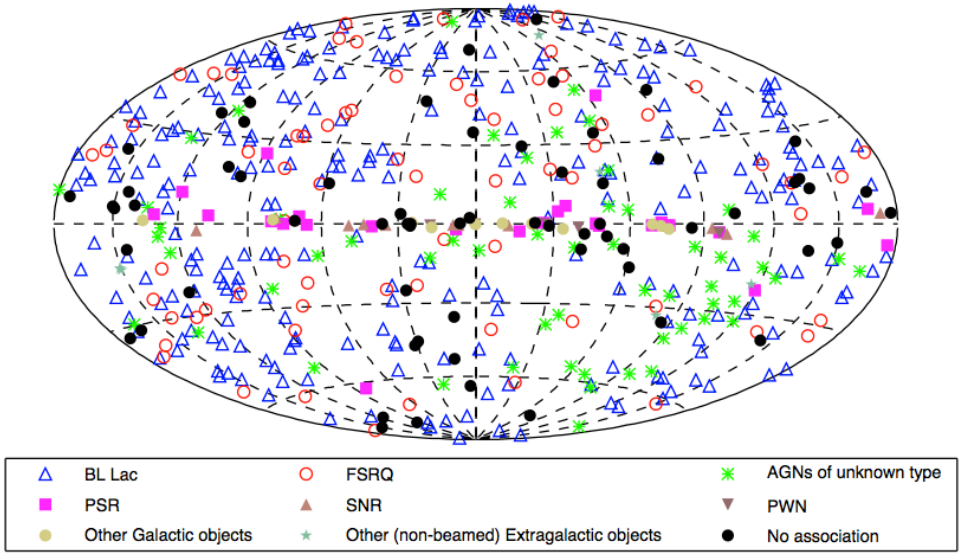


GeV Sky = Galactic + Point Sources + Isotropic + ???

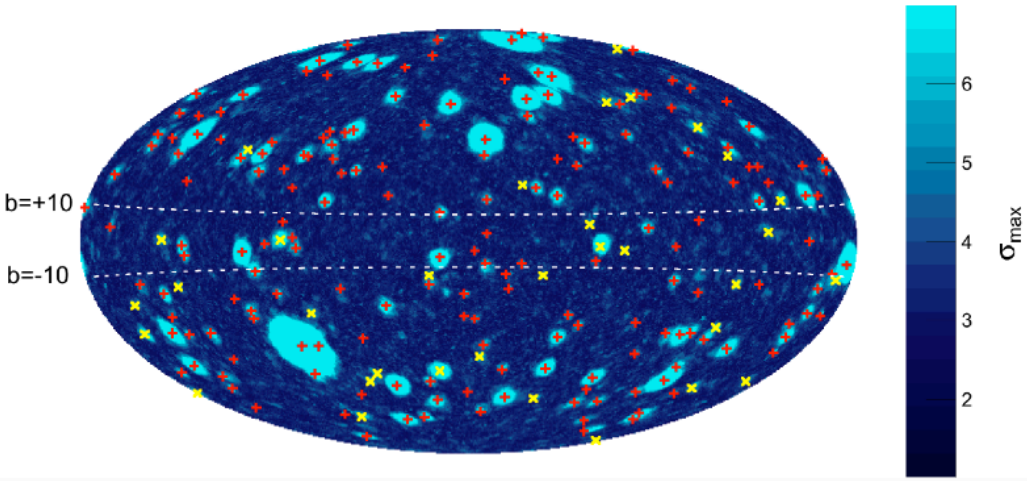
Fermi LAT γ-ray sky - catalogs



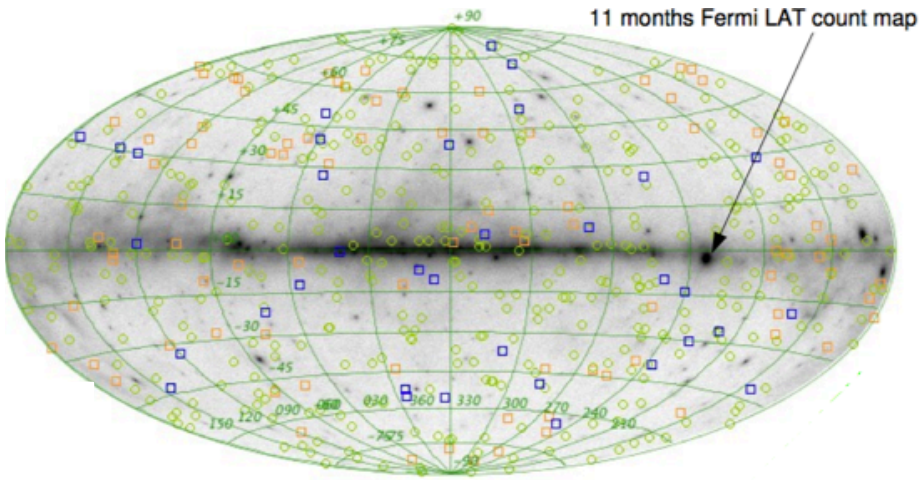
Pulsar - 2013ApJS..208...17A



Hard Sources - 2013, ApJS, 209, 34



All-sky variability - 2013, ApJ, 771, 57

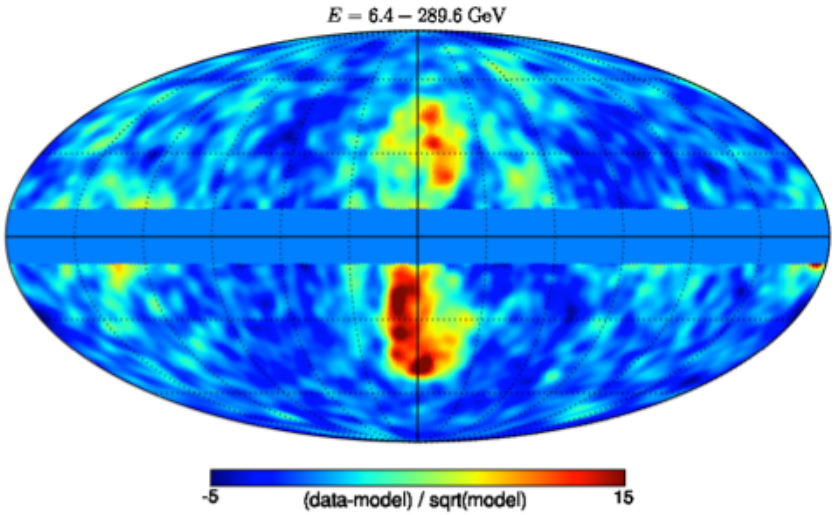


GRB - 2013ApJS..209...11A

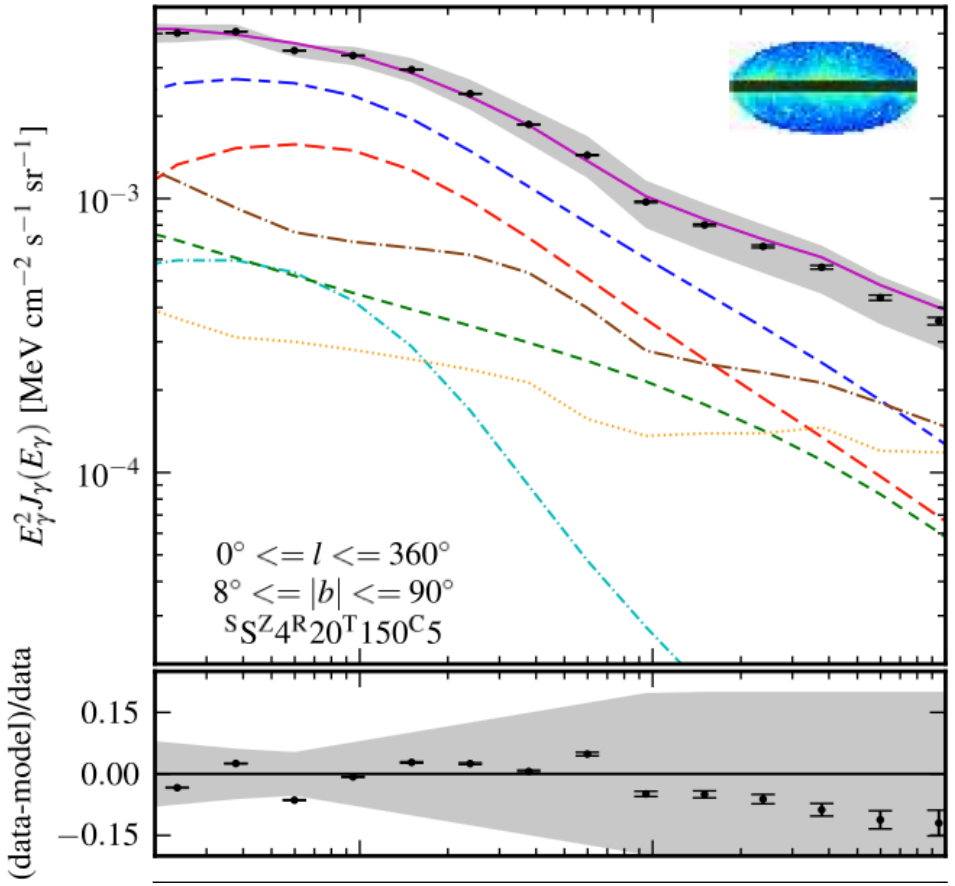
Fermi LAT γ-ray sky – Diffuse emission

Diffuse emission is ~90% of LAT photons and most prominent foreground for all analyses

Accurate quantitative modeling and assessment of systematics is a continuous challenge



LAT counts residual map after masking bubbles region



Diffuse emission spectral components

2012, ApJ, 750, 3

- The Fermi LAT gamma-ray sky
- **Searches for Dark Matter**
  - Known and new targets
  - Searches for spectral lines
- Future prospects with the LAT

Science trends IV - Dark Matter Searches

Satellites

Low background and good source id, but low statistics

Galactic Center

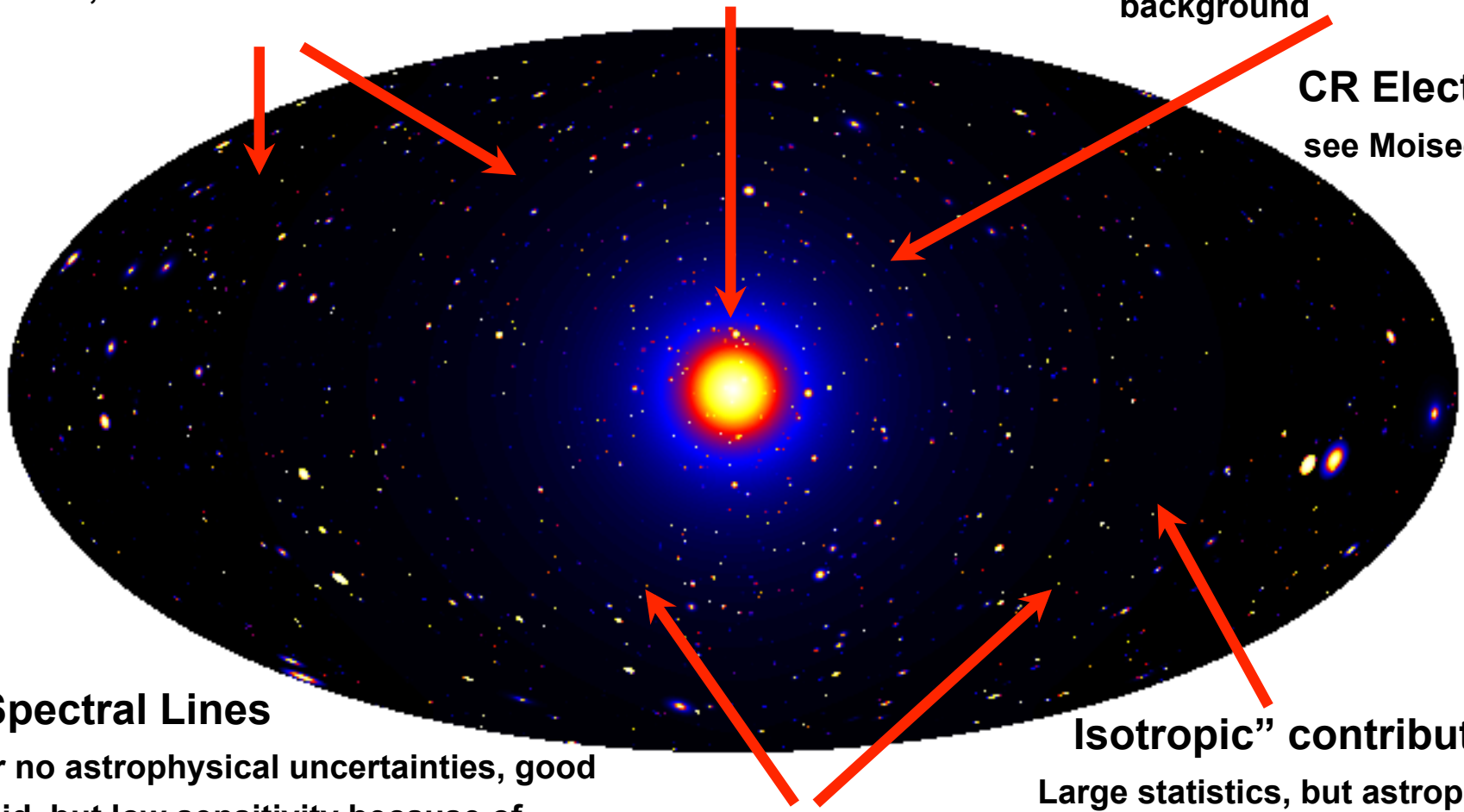
Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background

CR Electrons

see Moiseev talk



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

Low background, but low statistics

Isotropic" contributions

Large statistics, but astrophysics, galactic diffuse background

Dark Matter simulation:
Pieri+(2009) arXiv:0908.0195

Limits on $\langle\sigma v\rangle$ at 10GeV ($cm^3 s^{-1}$)

Satellites

dSph ~ 2×10^{-26}

UNID ~ 2×10^{-24}

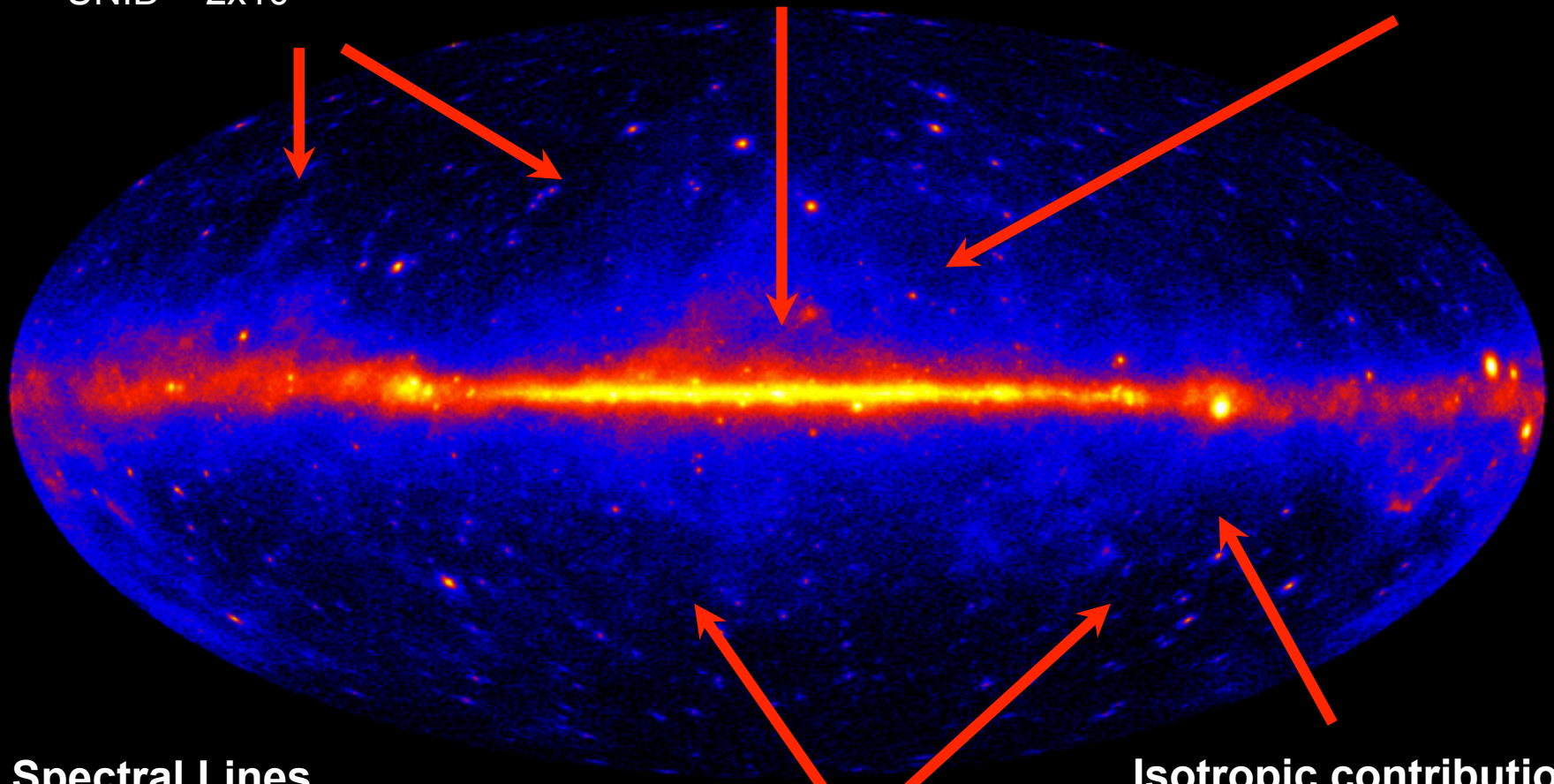
Galactic Center

Vary w/ model & method

Milky Way Halo

W/ bkg. model: 2×10^{-26}

No bkg. model: 2×10^{-25}



Spectral Lines

100 GeV ~ 8×10^{-27}

Galaxy Clusters

~5×10^{-25}

Isotropic contributions

Vary w/ model & method

Generic DM analysis – how to

- **Compute expected signal**
  - **Usually for 100% branching fraction in final channel**

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

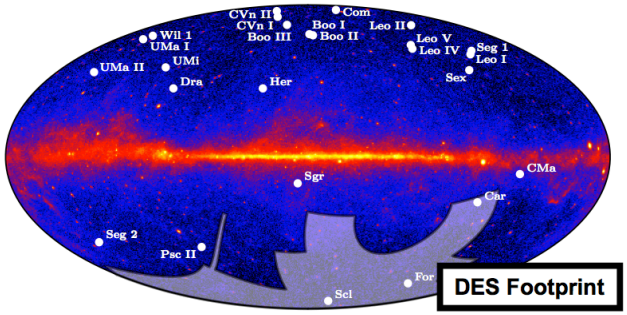
DM distribution

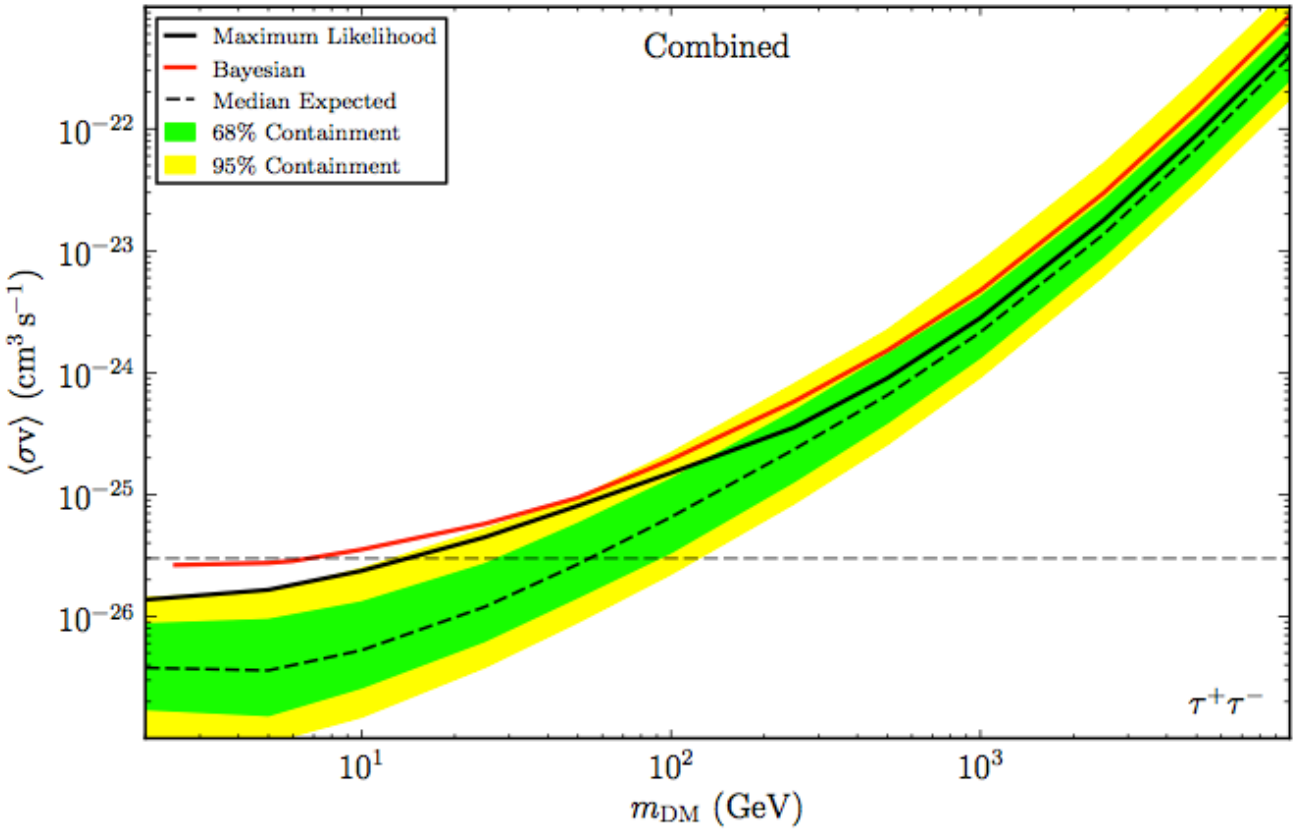
- **Perform likelihood analysis**
  - **Fold with instrument response, build model count spectrum with and w/o DM component, compare with data**
- **Estimate systematic uncertainties on DM flux Upper Limit**
  - **instrument performance, (optional) subtraction of astrophysical foreground (diffuse emission, unresolved sources), DM distribution**

Dark Matter constraints with dwarf spheroidals

2011, PRL 107, 241302 - 2012, AstroPart. Phys., 37, 2014 2014, PRD, 89

- Dwarfs are DM dominated
  - up to ~1000x visible matter
  - No star-formation, no gas, no magnetic field
- Clean Upper Limit analysis of high latitude point sources
- Current limit close to thermal relic σ_{ann} <~ 30 GeV for $\tau^+\tau^-$

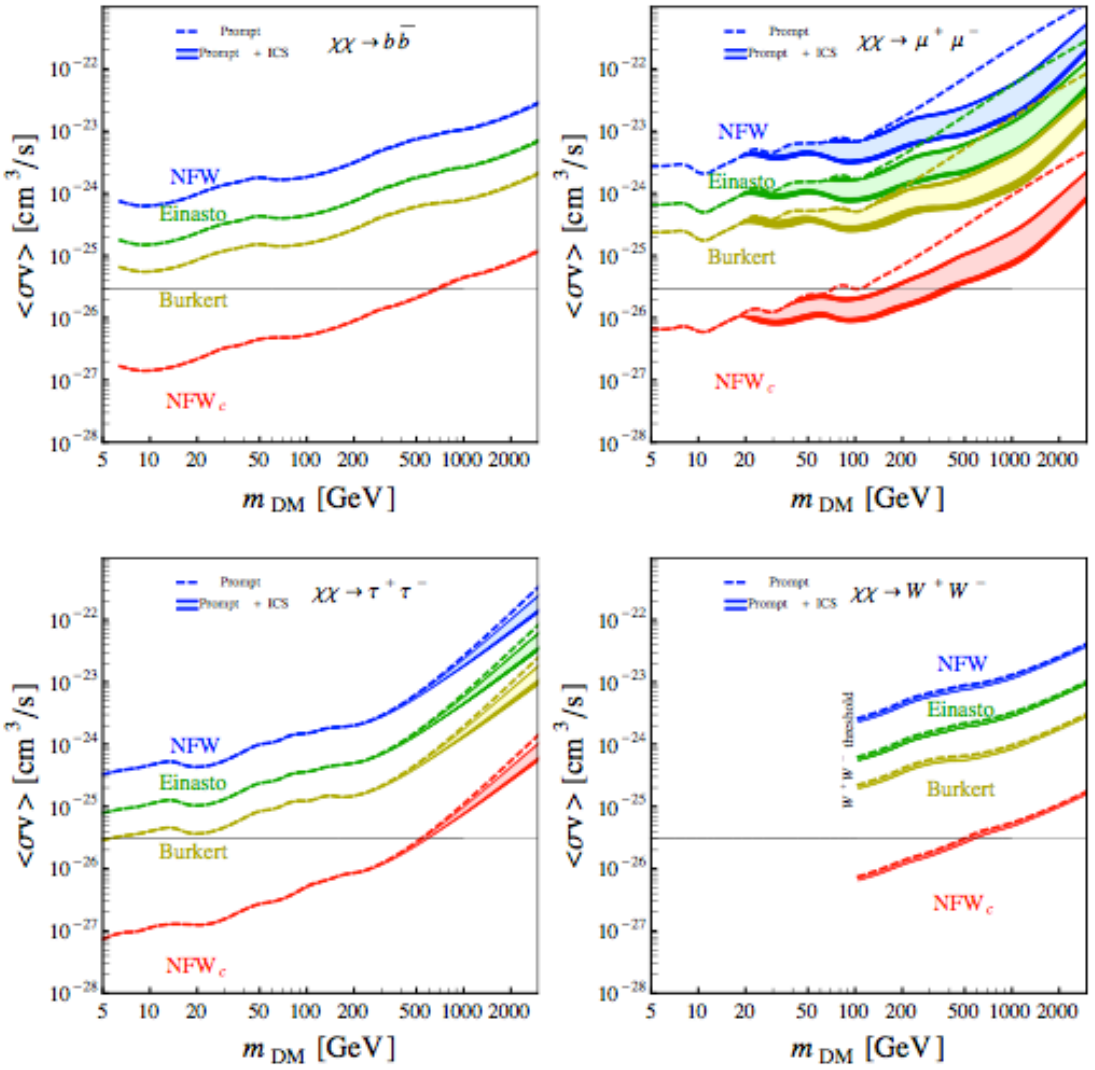




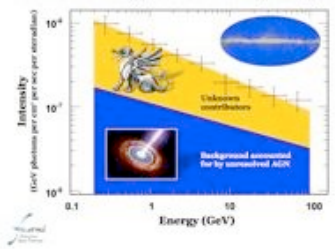
Dark Matter Constraints from Inner Galaxy

2013, JCAP, 10, 29

- Conservative limits
  - Does not subtract diffuse emission and sources
- Optimized Region of Interest
  - For standard DM profiles
- Strong constraints for very cuspy profiles
  - Close or below thermal limit

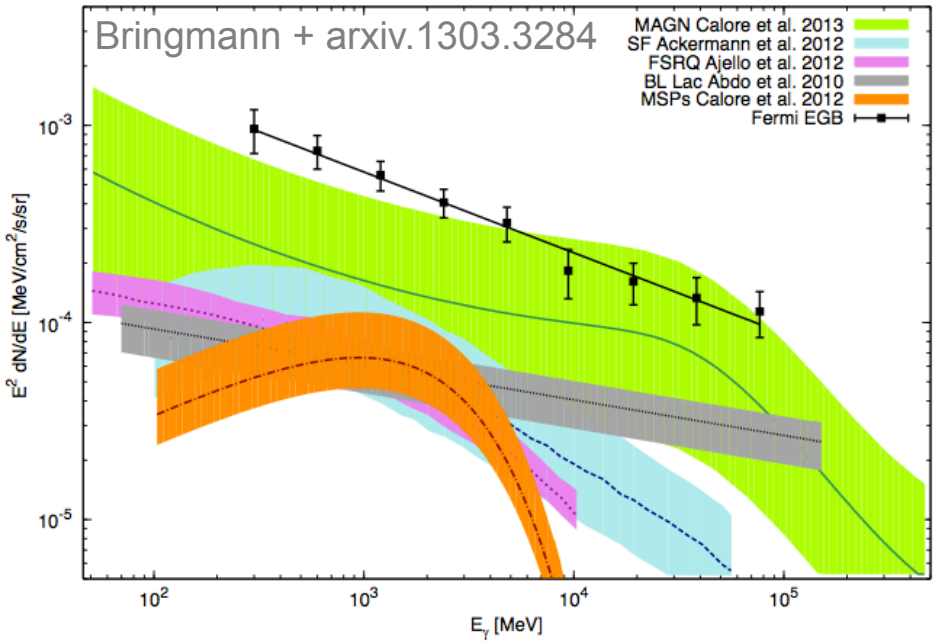


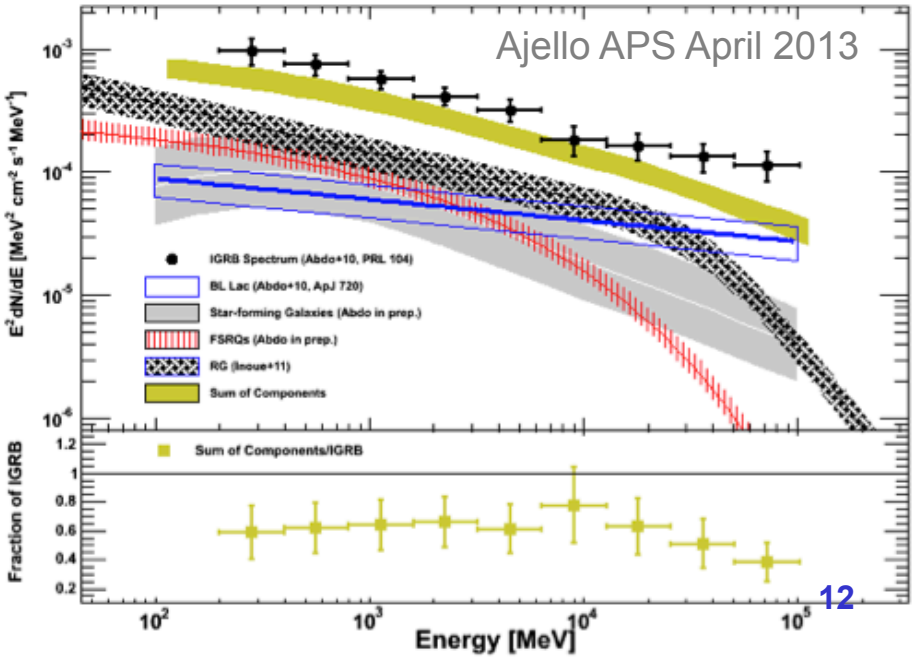
see talk from A. Morselli – this session



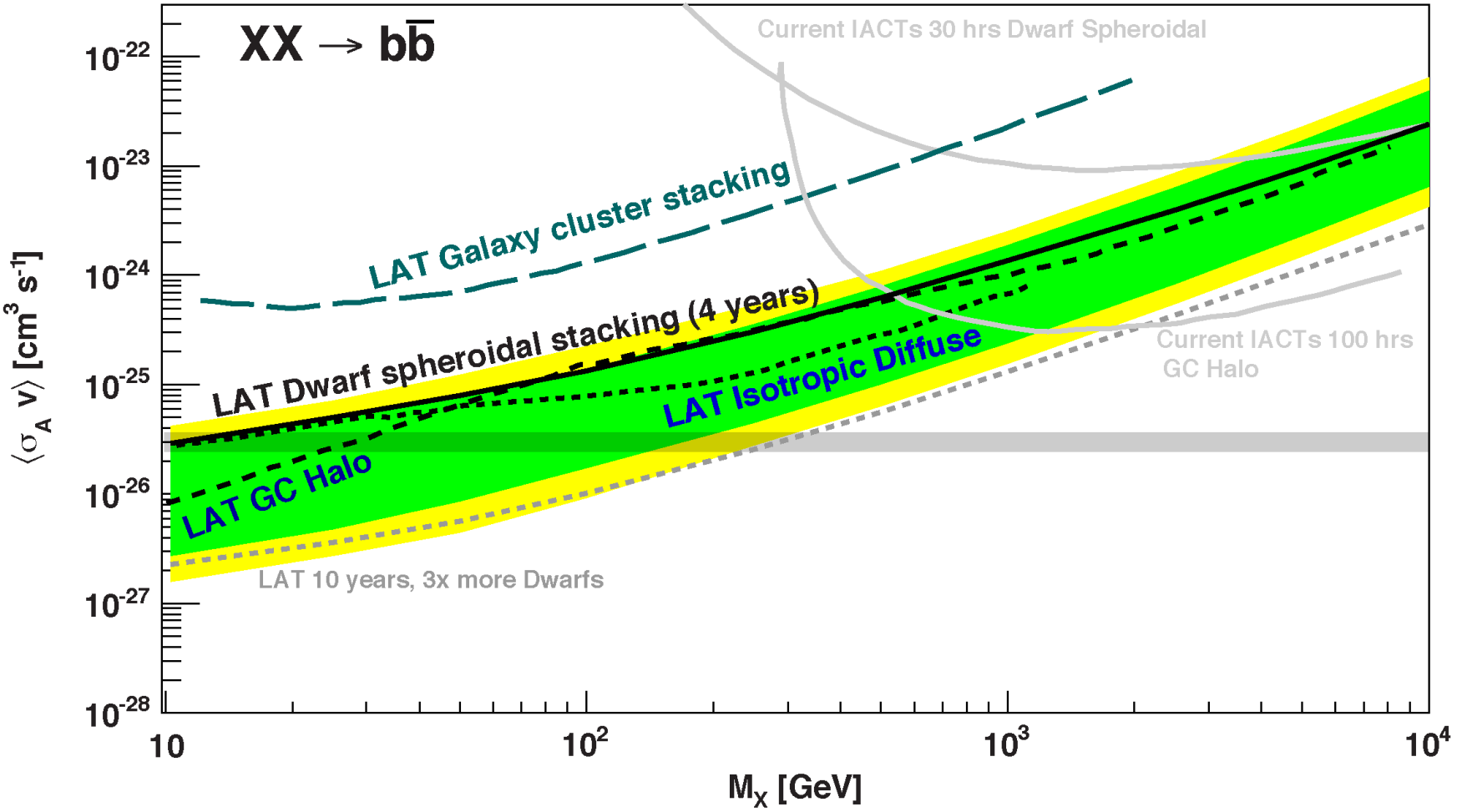
Isotropic γ-ray spectrum – room for DM?

- **Modeling astrophysical contributions to IGRB**
  - **Undetected sources**
    - **AGN, Star-Forming Galaxies, ms PSR, Gamma-Ray Bursts**
  - **Diffuse processes**
    - **Shocks, UHECR scattering EBL, large CR halo**
  - **Large uncertainties from theory and population studies**
- **Constrain residual DM contribution**





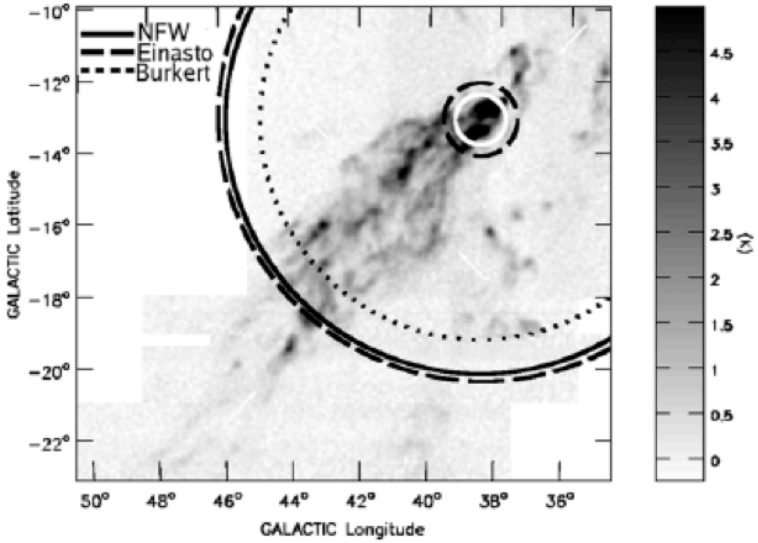
WIMP annihilation constraints – summary



The Smith Cloud - a novel target for DM search

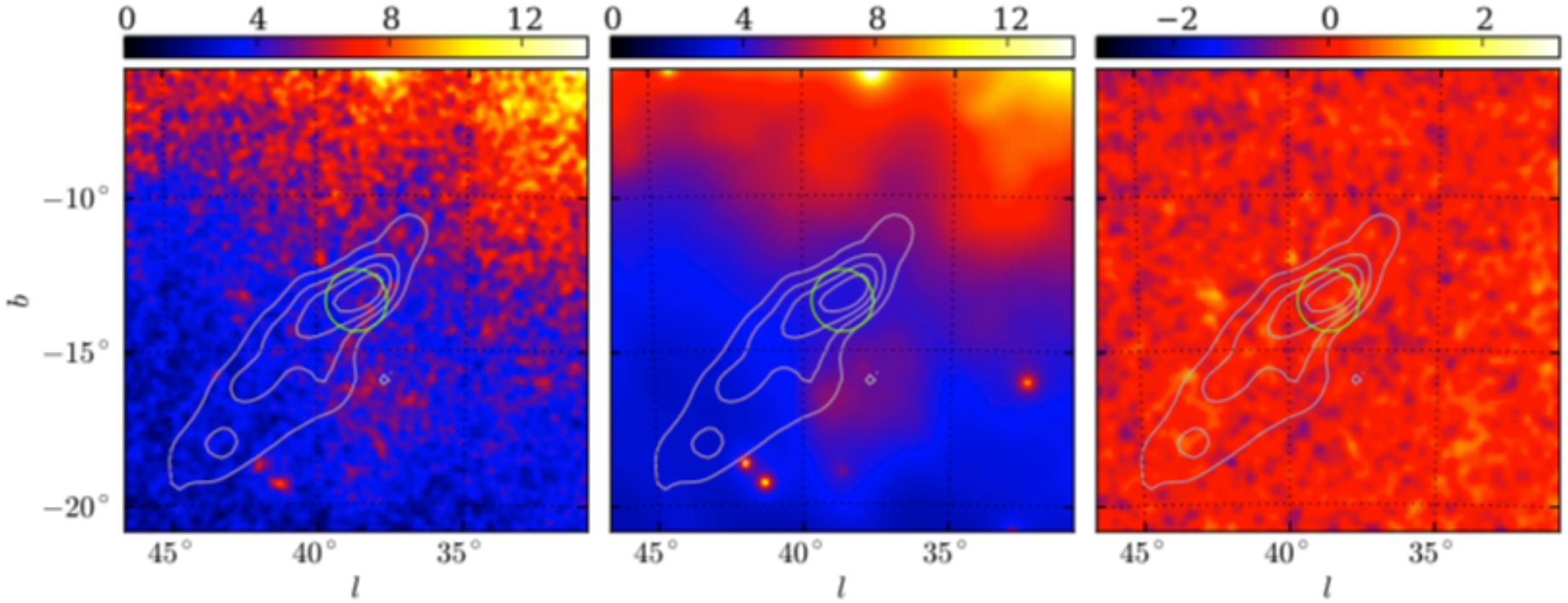
arxiv 1405.1030 – accepted by ApJ

- **Motivation:**
  - High Velocity Clouds of HI and HII gas (~$10^6 M_{sun}$)
    - Low galactic latitude, ~12.4Kpc
  - Trajectory suggest is passed through Galactic disk ~70Myear ago
  - Current bound state of gas suggest ~100/1000x DM halo to confine gas through Milky way passage
    - Large uncertainty in DM content



- **People:**
  - LAT Collaboration: Alex Drlica-Wagner, German Gomez Vargas, John Hewitt, Luigi Tibaldo
  - External authors: Tim Linden
- **Data:**
  - 5.2 years, Pass7 reprocessed data, need specific model of diffuse γ-rays

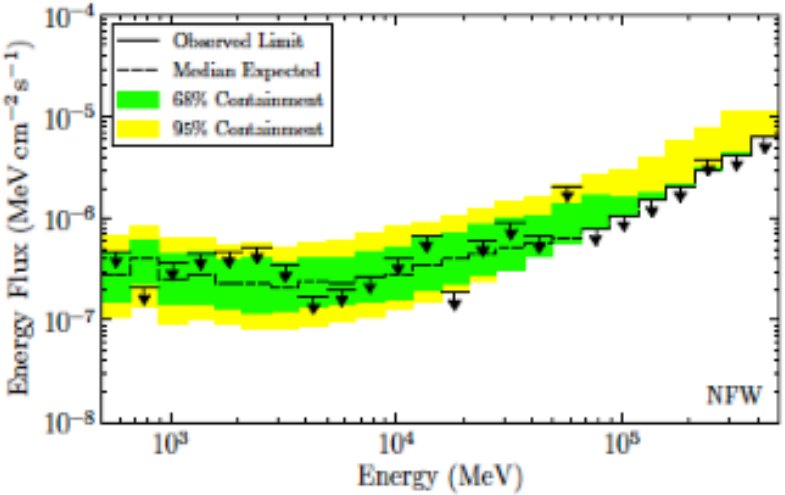
Smith Cloud – Diffuse emission modeling

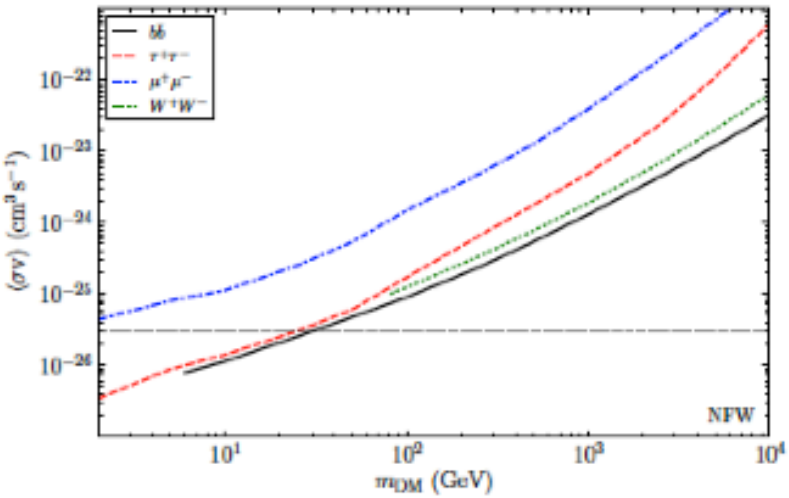


- Do not use standard diffuse model distributed for source analysis
- Build GALPROP templates of standard components of diffuse γ-rays using InfraRed observations of Smith Cloud

Smith Cloud- DM annihilation constraint

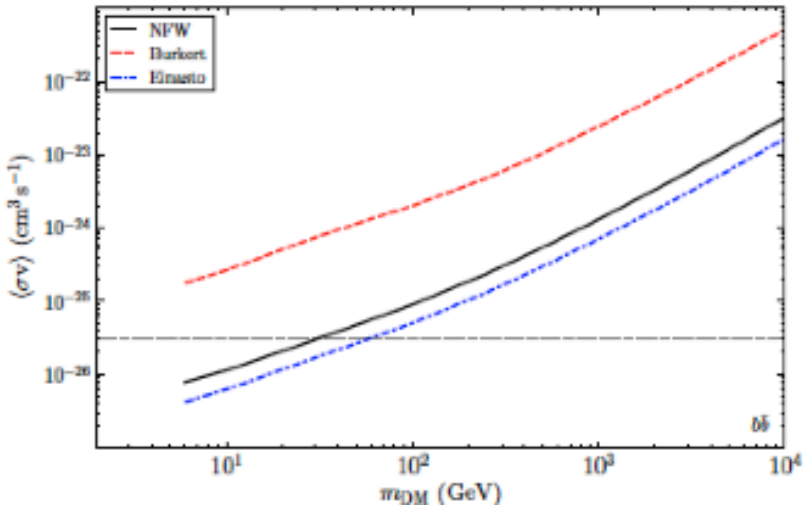
Drlica-Wagner, GAGV, J. Hewitt, T. Linden & L. Tibaldo
arXiv:1405.1030





- No very significant signal
  - TS ~4.7 for 5 GeV WIMP going to τ+τ-
- Constraints are highly dependent on the assumed DM profile
  - J-factors vary by a factor of ~40
- Uncertainty in the DM profile dominates over other systematic and statistical uncertainties

Drlica-Wagner, GAGV, J. Hewet, T. Linden & L. Tibaldo
arXiv:1405.1030



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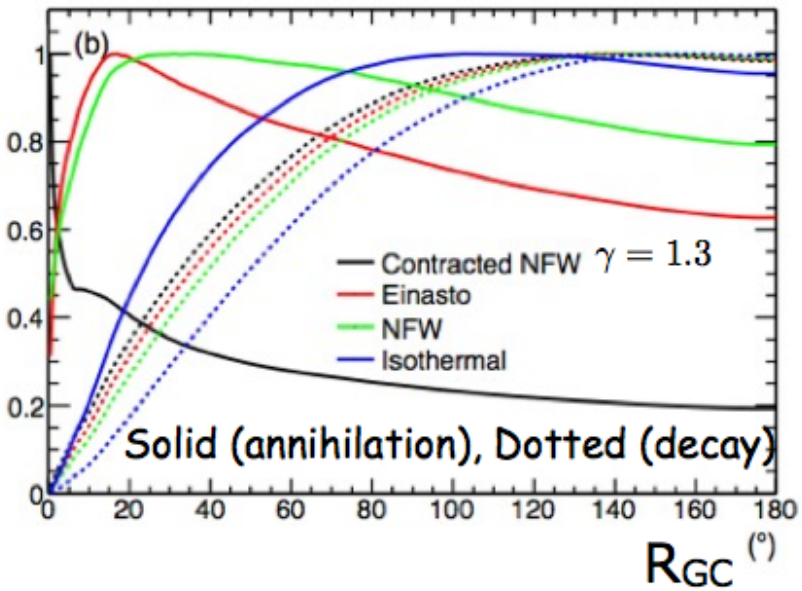
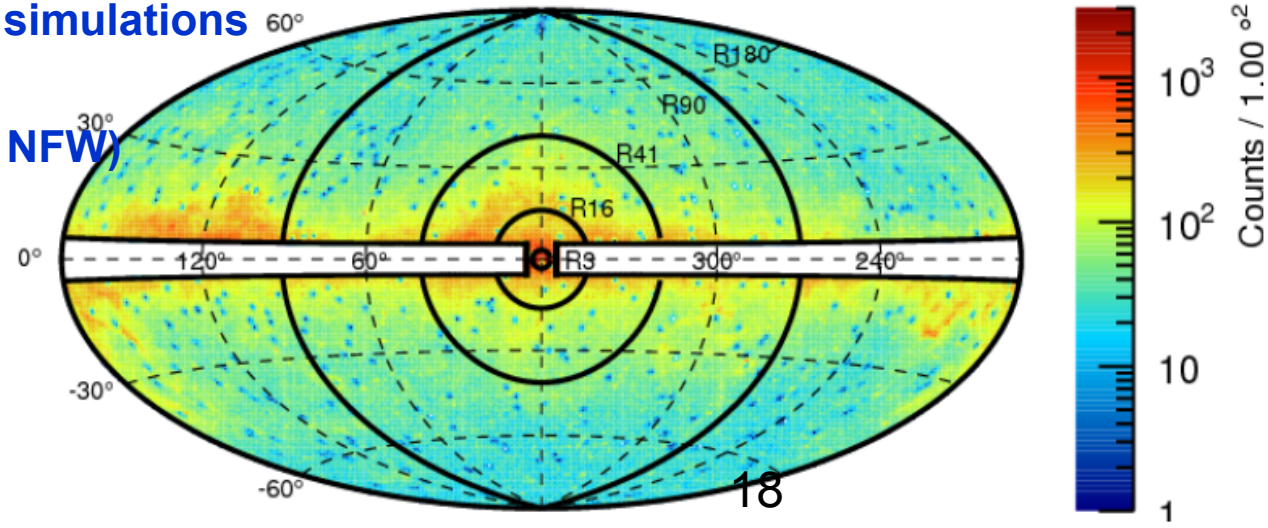
Fermi-LAT High Energy Line Search

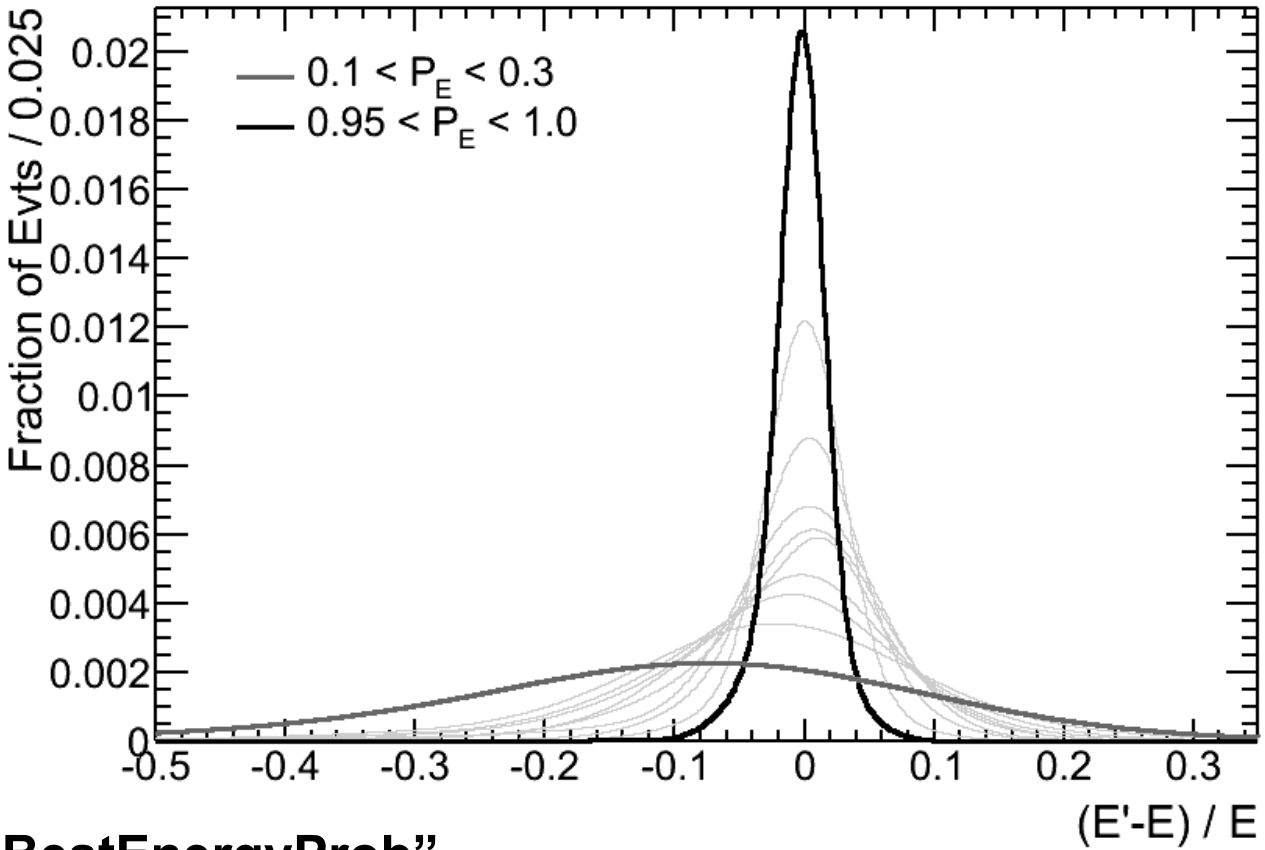
PRD 88, 082002 (2013)

- Search for lines from 5 – 300 GeV using 3.7 years of data
- Use P7REP_CLEAN (REP = "reprocessed")
  - Updates to CAL calibration and reconstruction
    - Improved PSF
    - Energy shifts upwards ~3-4%
  - 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)
  - Background from LAT simulations
- Search in 5 ROIs
  - R3 (3° GC Circle, cont. NFW)
  - R16 (Einasto)
  - R41 (NFW)
  - R90 (Isothermal)
  - R180 (DM Decay)





HE Line search - 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

HE Line Search - Fitting Method

Predicted Spectrum | Signal Model | Background Model

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

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

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

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)**

HE Line Search - Systematic Effects

- **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

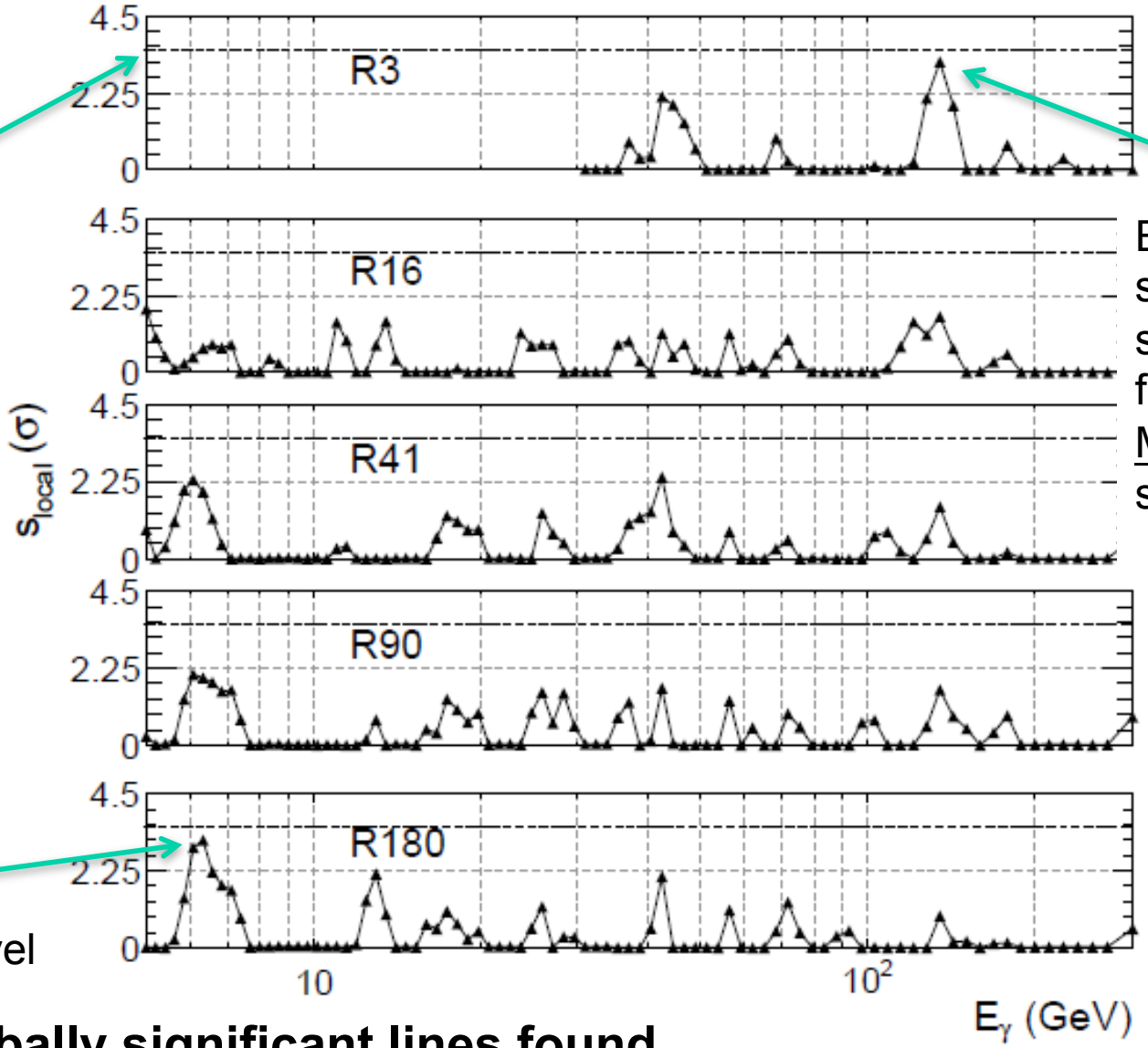
- **Uncertainties that induce or mask a signal**
  - Modeling bkg as PL dominates in R3, R16
  - CR contamination dominates in larger ROIs
  - Express as uncertainty in fractional signal, δf

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

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

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

HE Line Search - Fitting Results



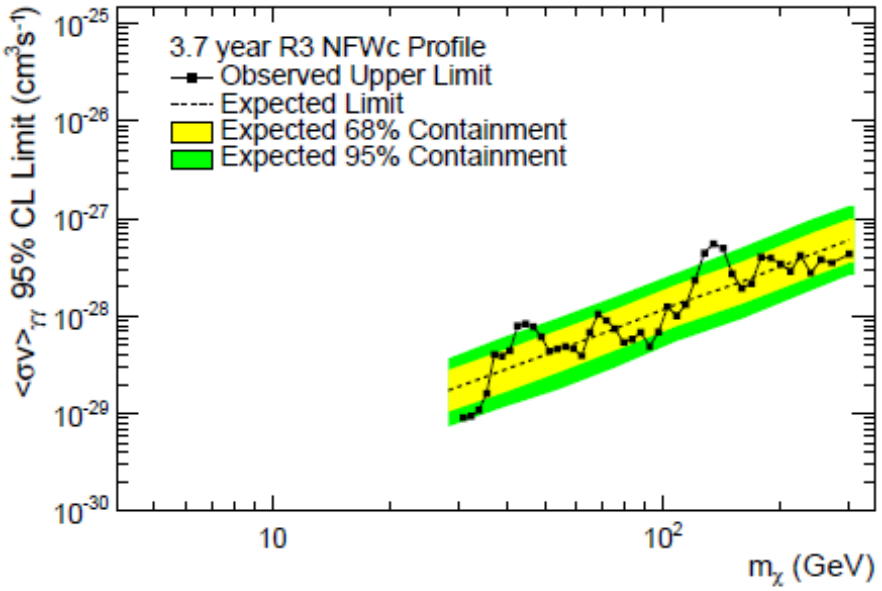
s_{global} = 2σ

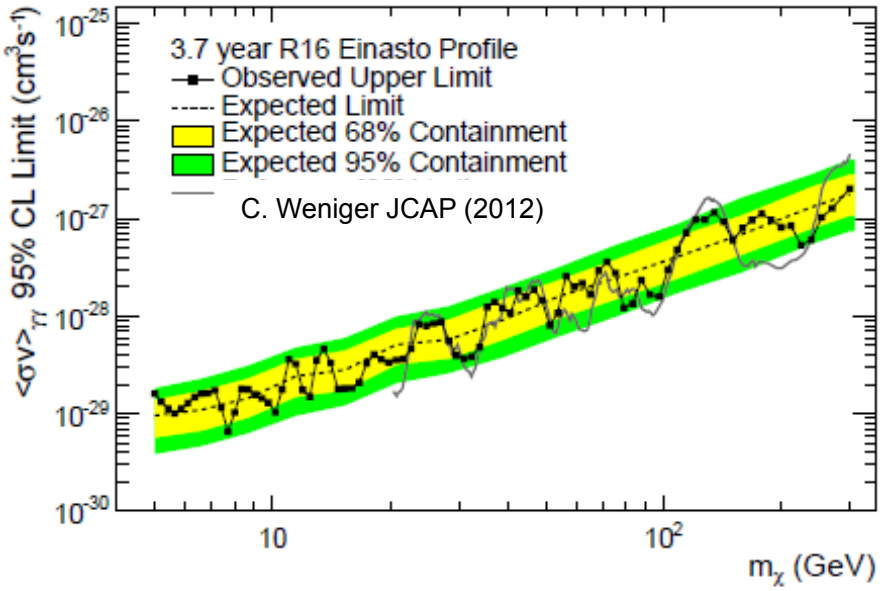
E_γ=135 GeV
s_{local} = 3.2σ
s_{global} = 1.5σ
f = 0.58
Much larger than systematic level

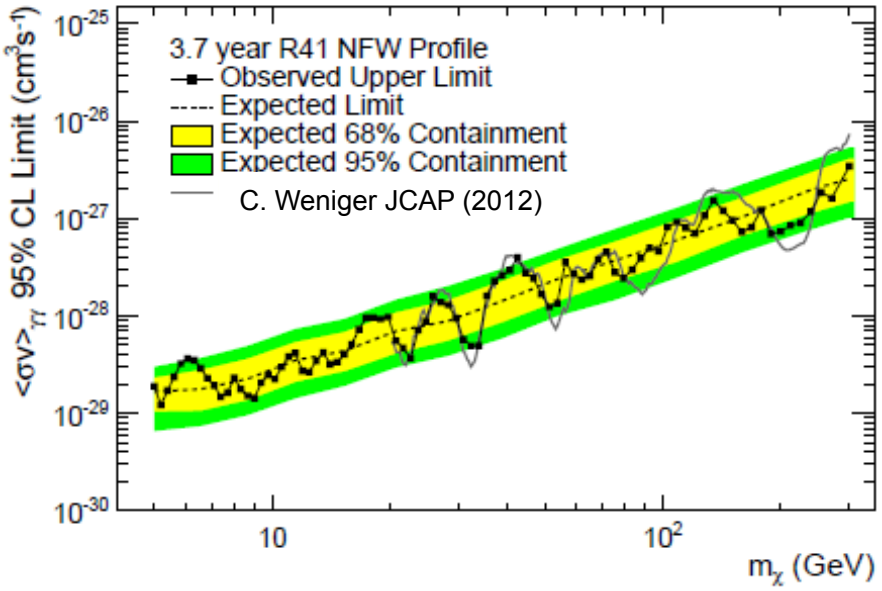
E_γ= 6 GeV
s_{local} = 3.1σ
s_{global} = 1.4σ
f = 0.01
At systematic level

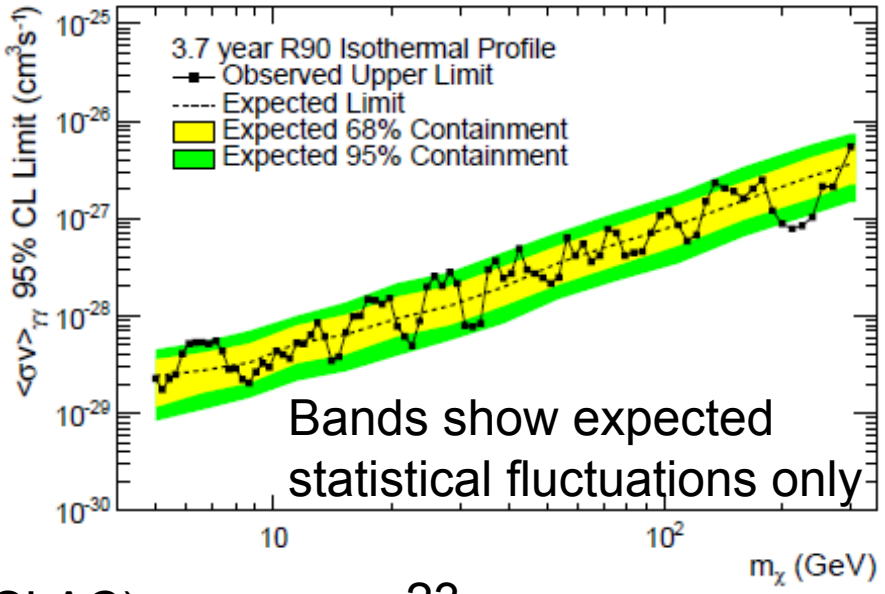
- **No globally significant lines found**

HE Line Search - 95% CL <σv> upper limits

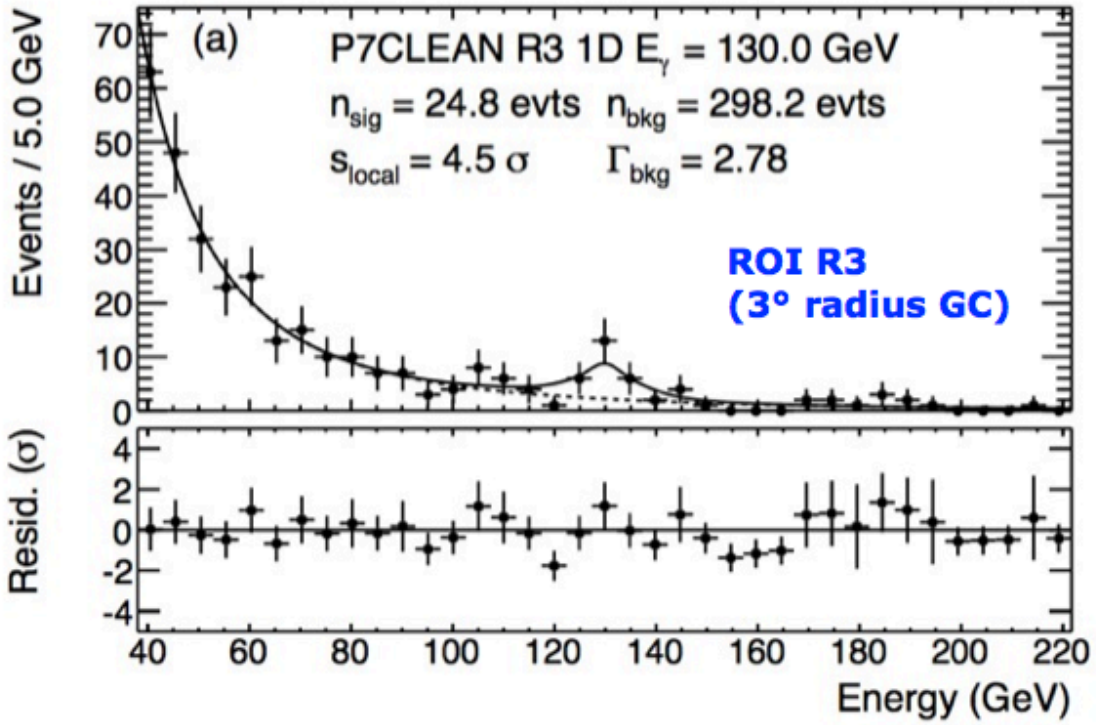








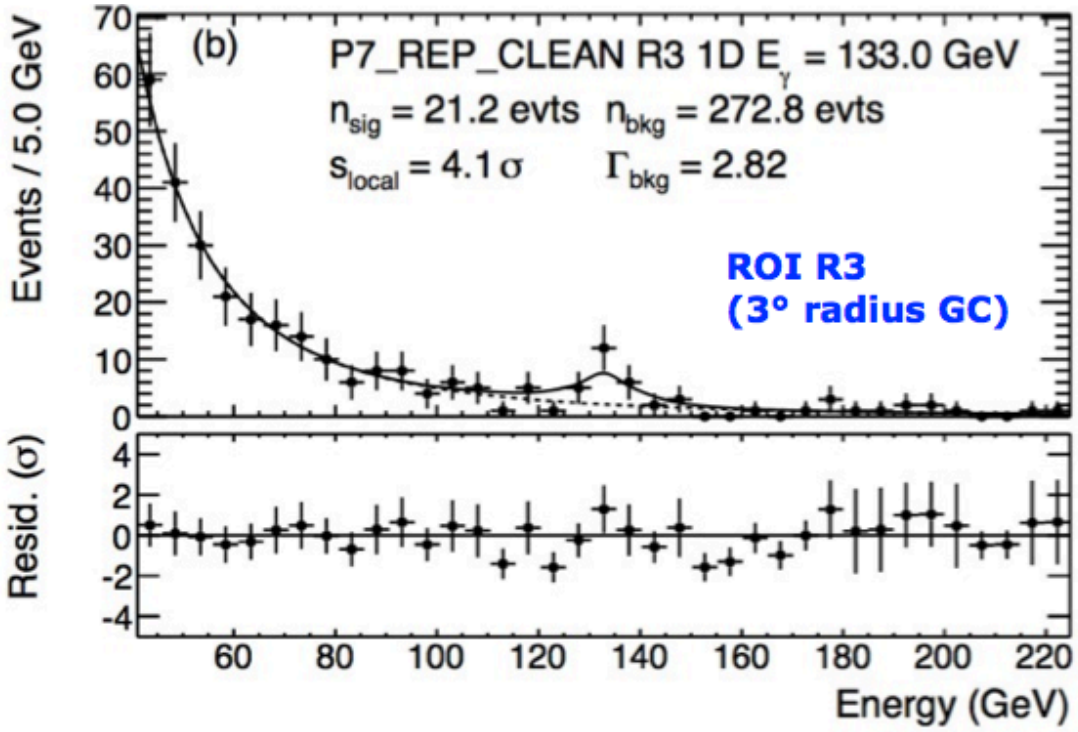
Fermi LAT HE line search near 133 GeV



- **4.5σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data**
  1D PDF (no use of P_E), P7CLEAN data

As Weniger's significance 4.6σ

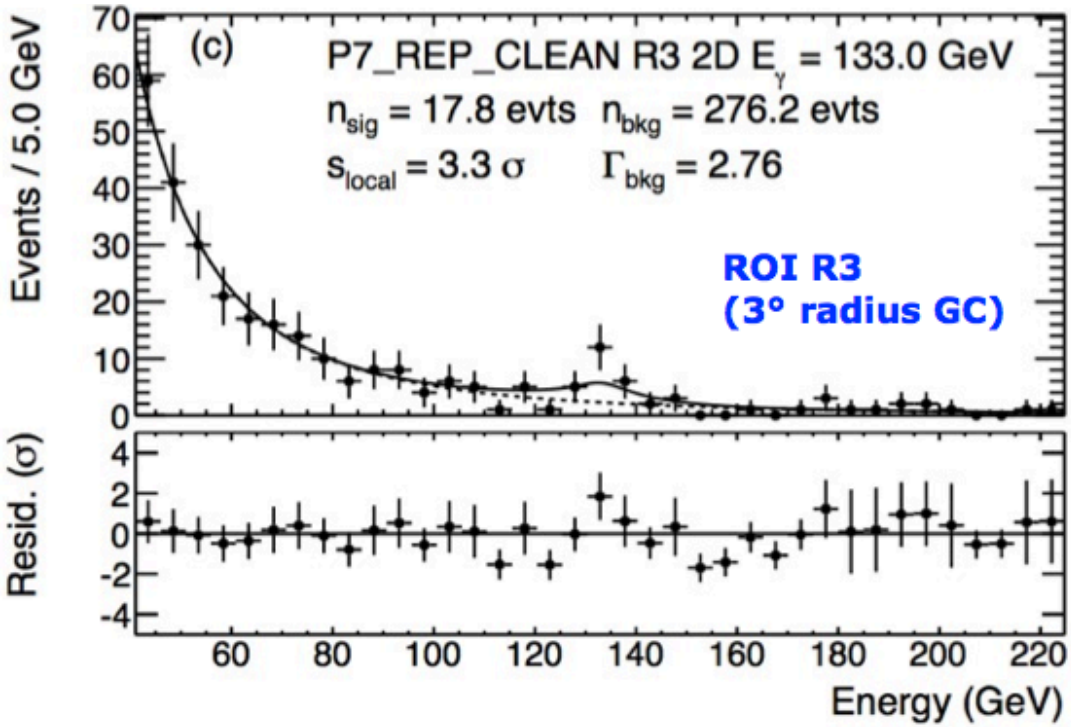
Fermi LAT HE line search near 133 GeV



- 4.5σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data 1D PDF (no use of P_E), P7CLEAN data
- **4.1σ (local) 1D fit at 133 GeV with 3.7 year reprocessed data 1D PDF (no use of P_E), P7REP_CLEAN**

Peak shifts from 130 to ~133 GeV

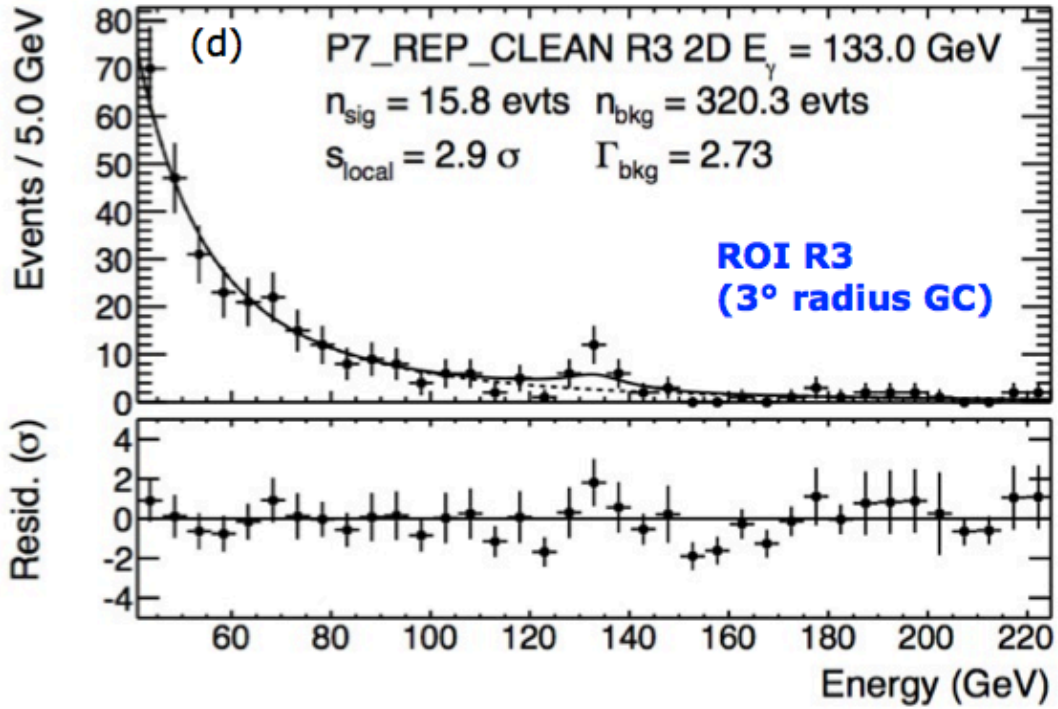
Fermi LAT HE line search near 133 GeV



- 4.5σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  1D PDF (no use of P_E), P7CLEAN data
- 4.1σ (local) 1D fit at 133 GeV with 3.7 year reprocessed data
  1D PDF (no use of P_E), P7REP_CLEAN
- **3.3σ (local) 2D fit at 133 GeV with 3.7 year reprocessed data**
  2D PDF (P_E in data), P7REP_CLEAN

Peak 'too' narrow

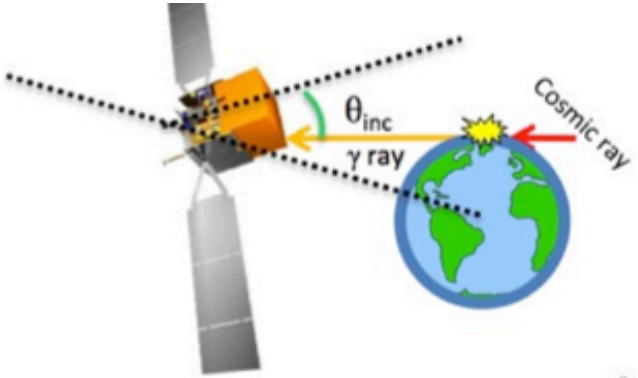
Fermi LAT HE line search near 133 GeV



- 4.5σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  1D PDF (no use of P_E), P7CLEAN data
- 4.1σ (local) 1D fit at 133 GeV with 3.7 year reprocessed data
  1D PDF (no use of P_E), P7REP_CLEAN
- 3.3σ (local) 2D fit at 133 GeV with 3.7 year reprocessed data
  2D PDF (P_E in data), P7REP_CLEAN
- **2.9σ (local) 2D fit at 133 GeV with 4.4 year reprocessed data**
  2D PDF (P_E in data), P7REP_CLEAN

Few new events

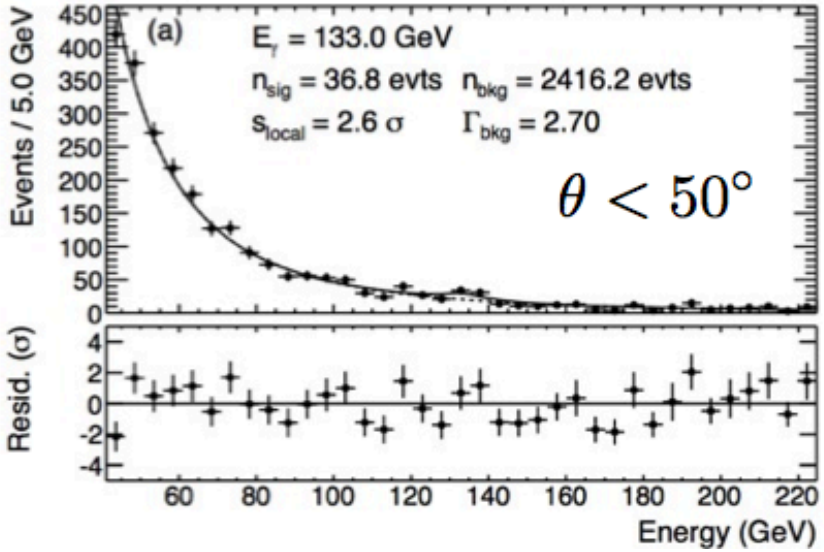
HE Line Search - Control regions

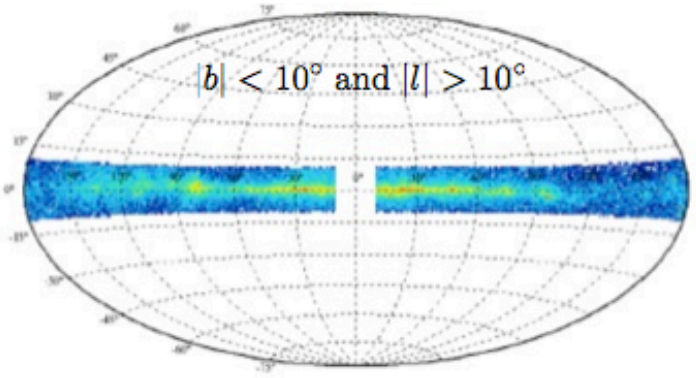


Earth Limb: expect a bright smooth power-law spectrum

Weaker feature around 130 GeV

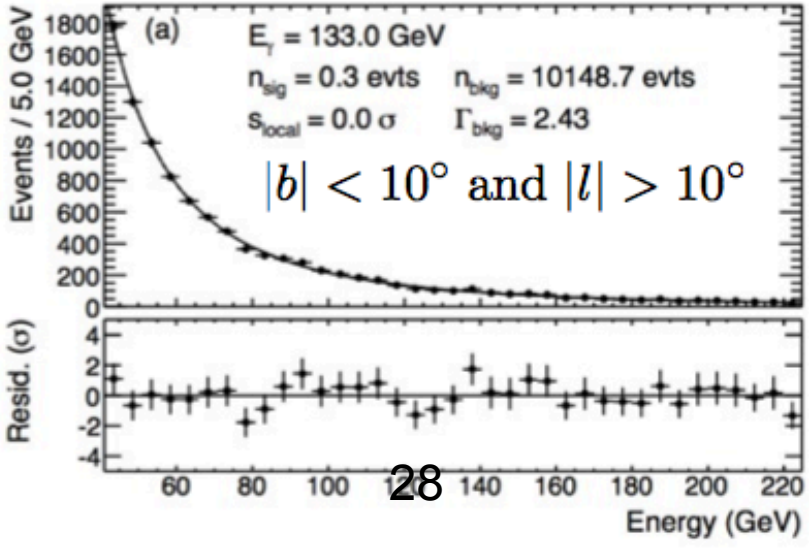
2.0σ, s/b≈14±7% (GC:3.3σ, s/b≈58±18%)





Galactic Disk: expect bright and astrophysical source dominated

No features seen around 130 GeV

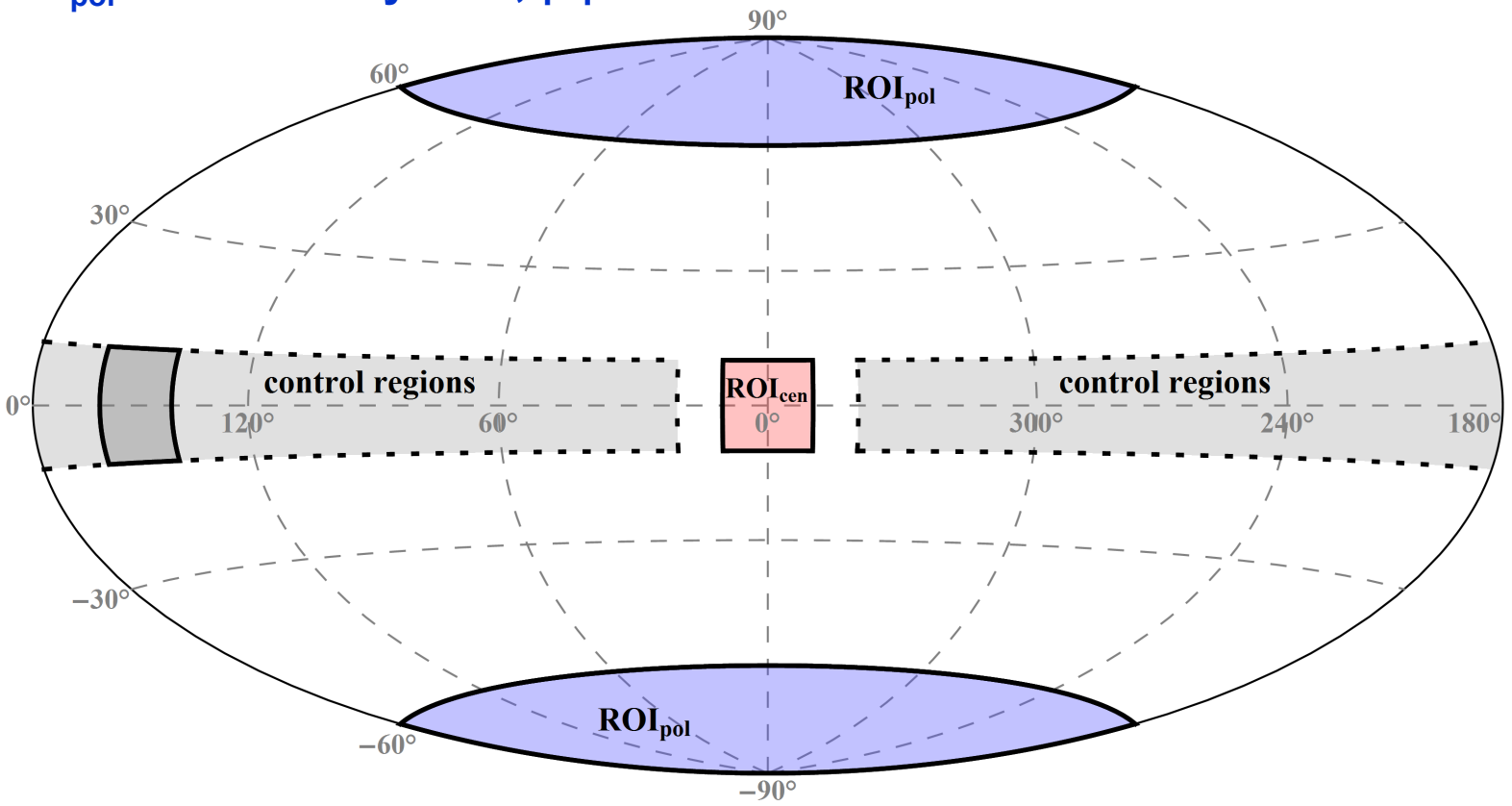


Low Energy Line Search

- **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, G.A. Gomez-Vargas, Elliott Bloom, Eric Charles, MarioNicola Mazziotta, Aldo Morselli
  - External: Carlos Munoz (UAM 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

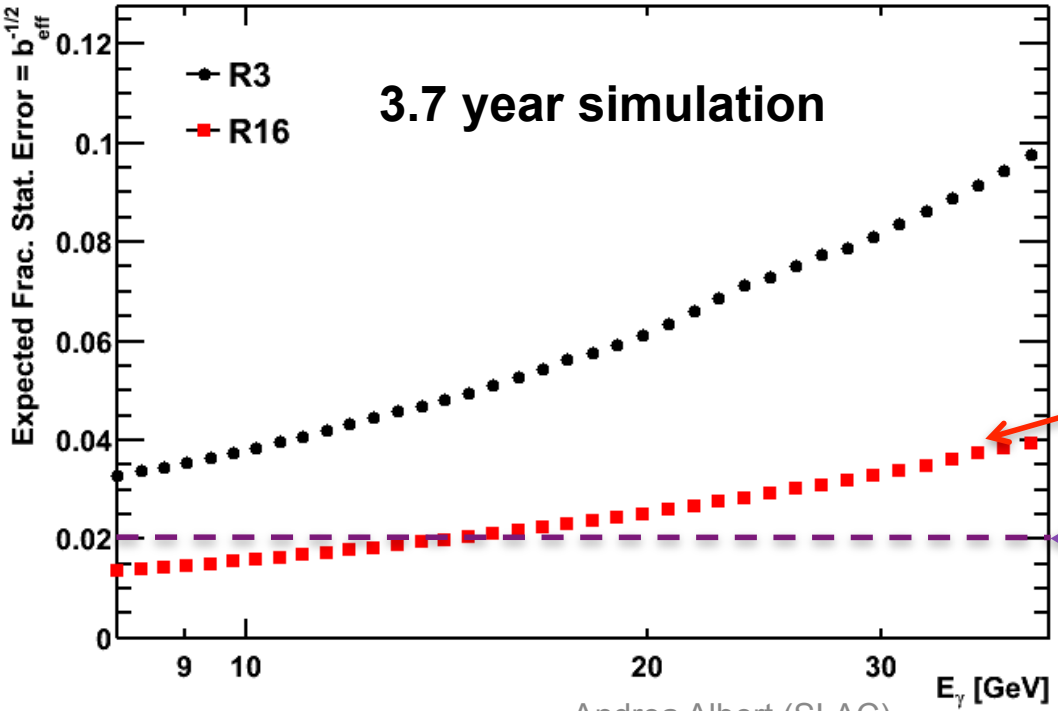
- Use Einasto Profile (α=0.17, $\rho_\odot$=0.4 GeV/cm^3, $R_\odot$ = 8.5 kpc)
- Optimize for annihilation ($\chi\chi \rightarrow \gamma\gamma$) and decay ($\Psi_{3/2} \rightarrow \nu\gamma$)
  - Gravitino decay is the primary model we are testing, but wanted to expand scope to include annihilation too
- 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**

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



Stat uncertainty

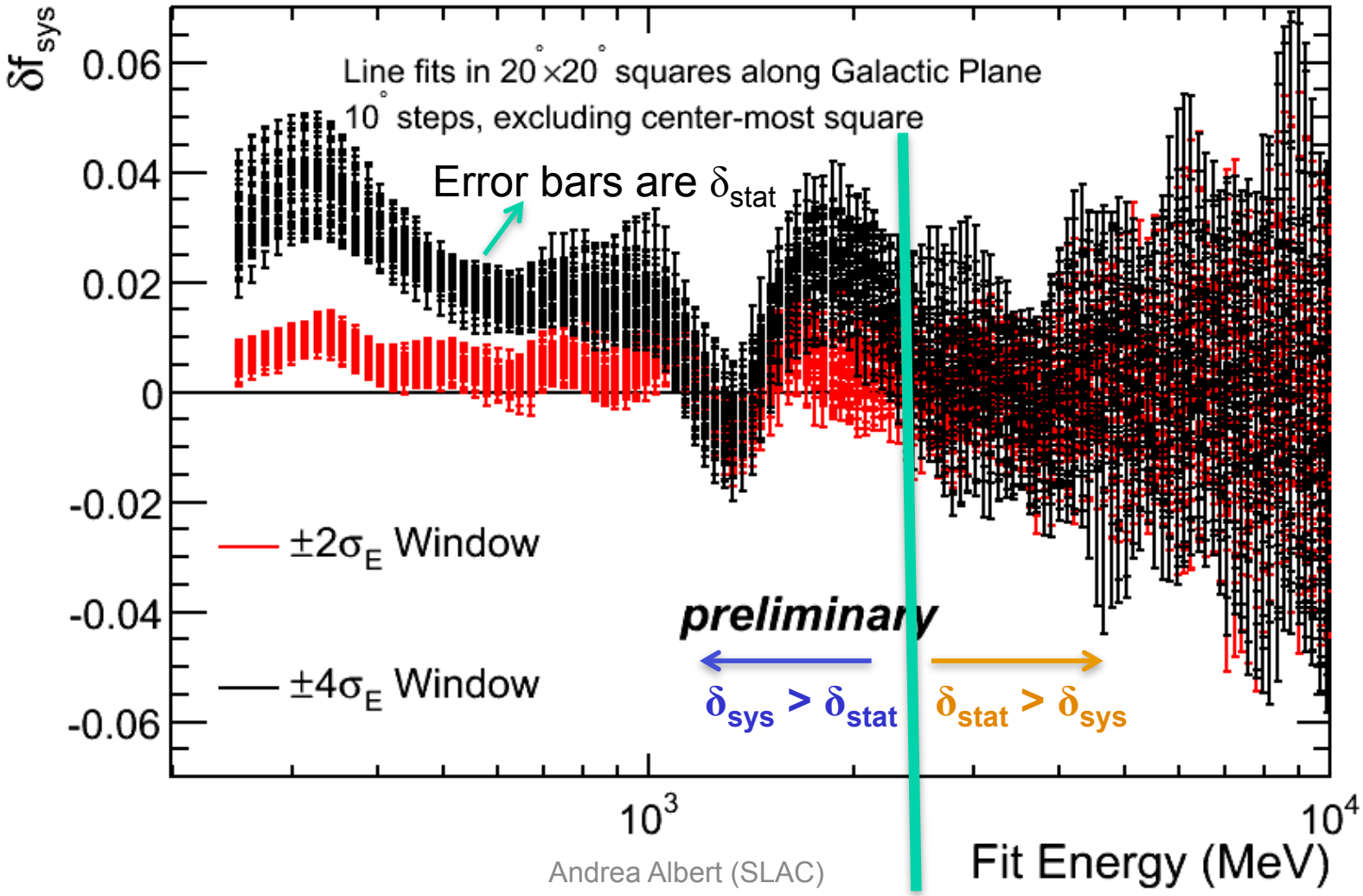
~1/√b_{eff}

Syst uncertainty

Model as constant

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

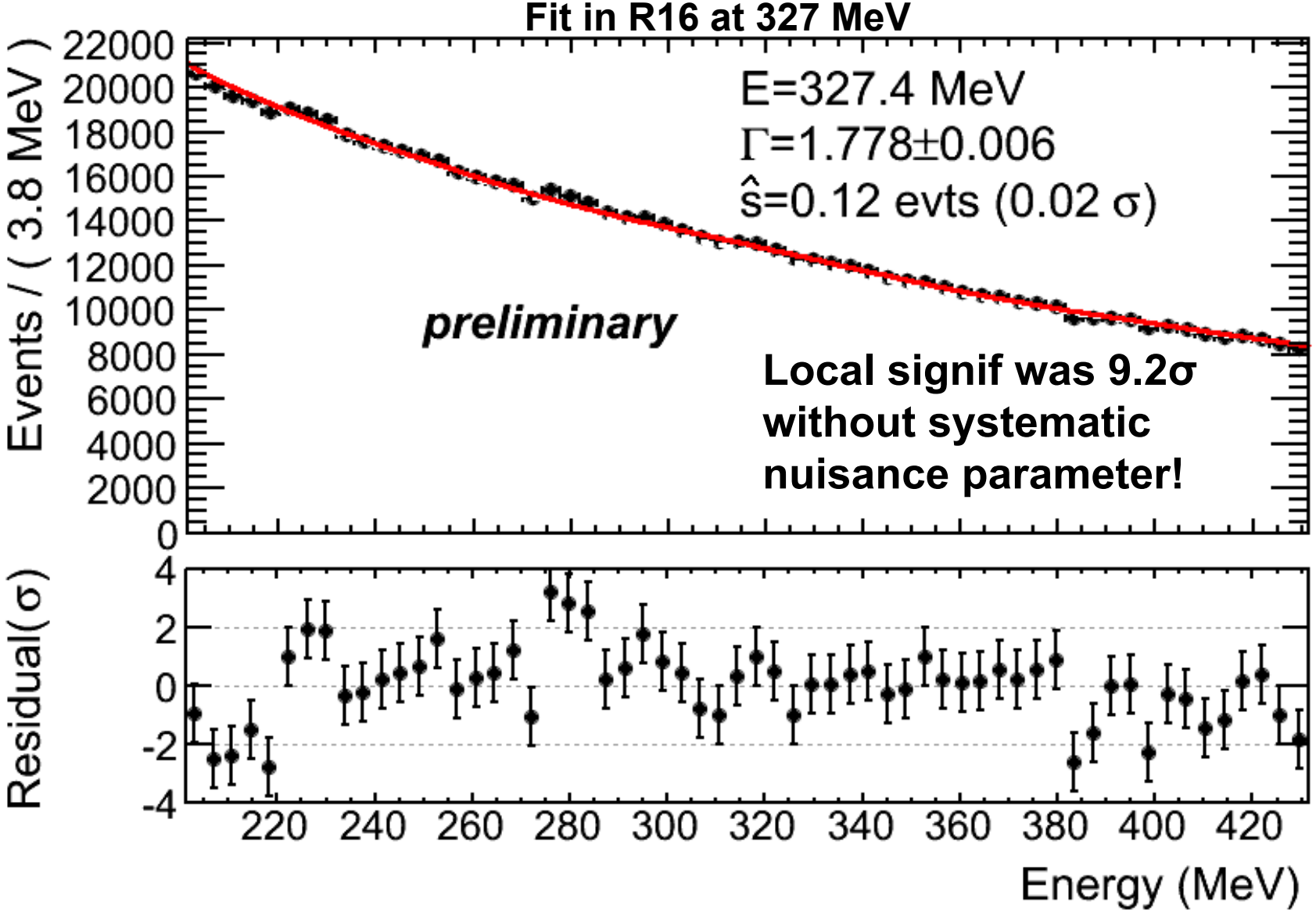
- **Include nuisance parameter (n_{sys}) for systematically-induced line-like features**
  - **For each fit energy in each ROI we determine b_{eff}**
  - **We add a Gaussian constraint on n_{sys} to the likelihood fit with ($\sigma_{sys} = \delta f_{sys} * b_{eff}$, $\mu = 0$) to break the degeneracy 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**

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

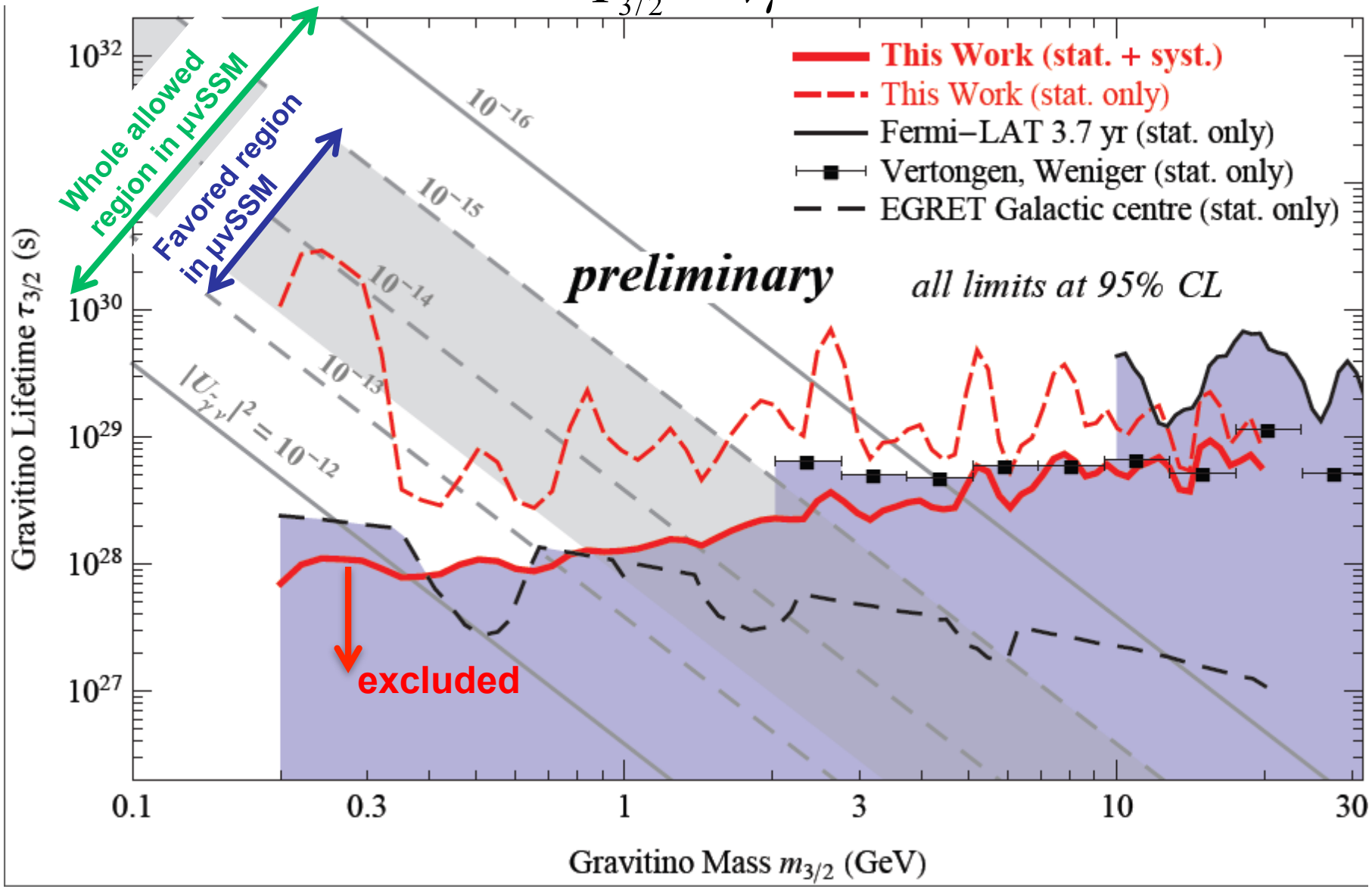
Gaussian constraint on n_{sys}

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

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



Preliminary Limits for (|B|>60°ROI)



Search for spectral lines - summary

- **No globally significant lines detected**
  - **133 GeV feature observed from GC and Earth limb**
    - **not fully explained by known systematics**
    - **Narrower than resolution and decreasing with time**
- **Working on updates with new Pass8 event analysis**
  - **Will benefit from increased exposure at GC and Earth limb from recent modified survey**
  - **Expect different systematics**

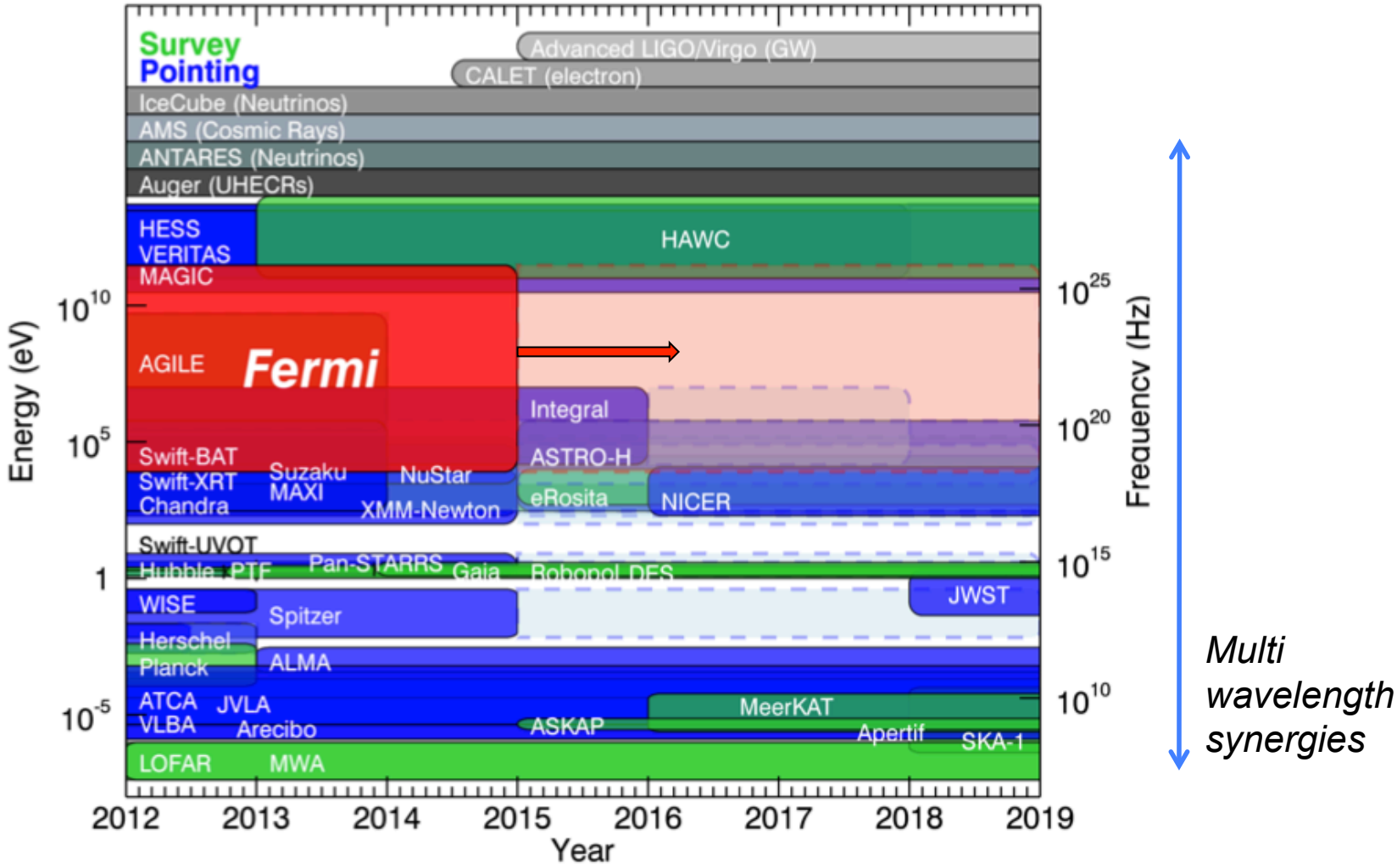
Search	Range (GeV)	ROIs	Energy quality estimator	Main uncertainty	Point source masking	Systematics Included in fit	Window size
High Energy	5 – 300	5 (best S/N)	yes	statistical	Yes (ex. R3)	No	$6\sigma_E$
Low Energy	0.1 - 10	2 (best S/B)	no	systematic	No (large PSF)	Yes	$2\sigma_E$

- The Fermi LAT gamma-ray sky
- Searches for Dark Matter
  - Known and new targets
  - Searches for spectral lines
- **Future prospects with the LAT**

Fermi mission status

http://science.nasa.gov/astrophysics/2014-senior-review-operating-missions/

Multi Messenger synergies

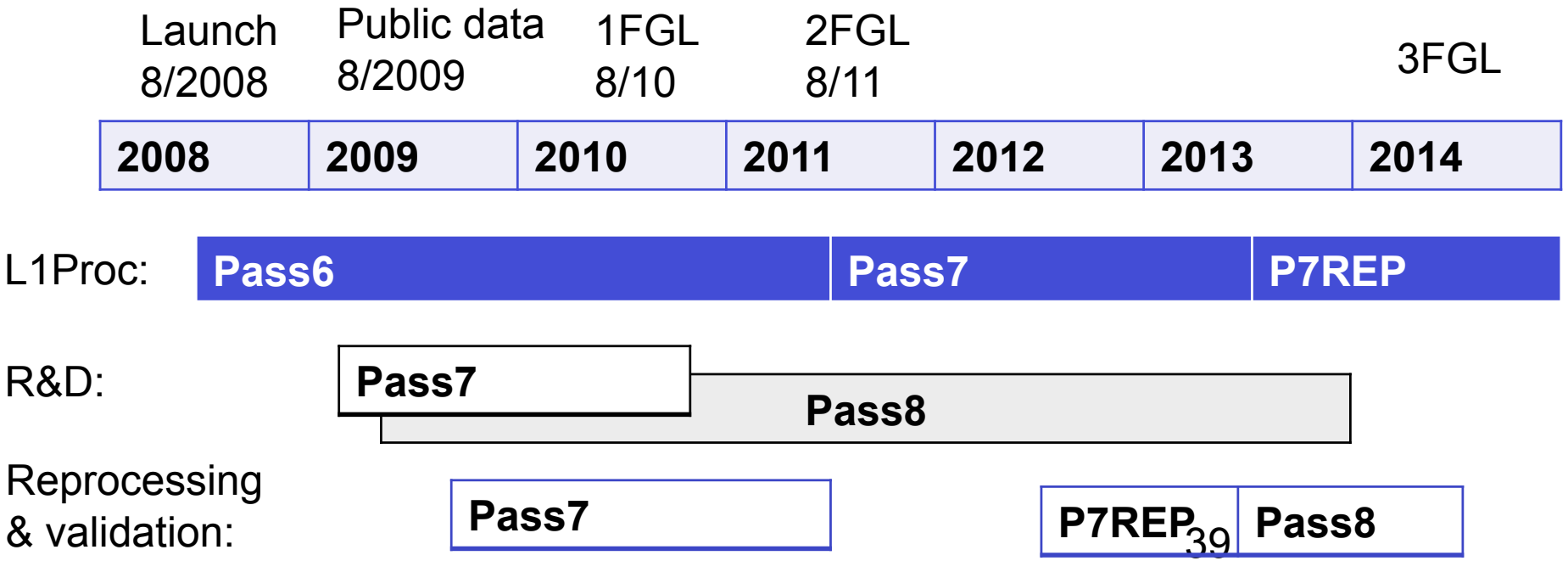


Multi wavelength synergies

- **Now into extended operations, since 2013**
- **NASA 2014 Senior Review just approved operations through 2016**

LAT collaboration datasets timeline

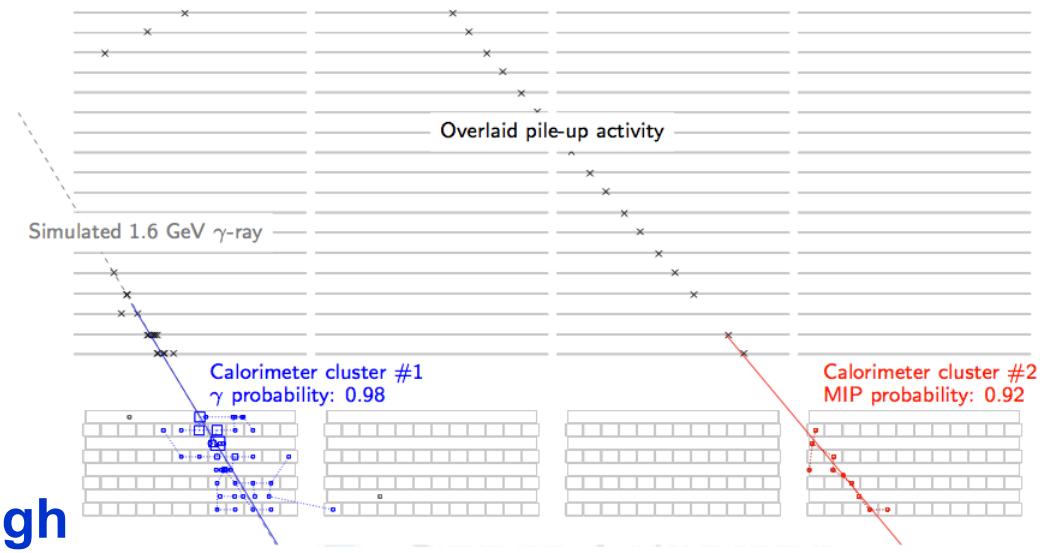
- **Continuous effort to improve performance and release better datasets**
  - **Pass6: pre-launch recon and event selection, optimized post-launch IRFs (to describe effect of ghosts)**
  - **Pass7: pre-launch recon, optimized post-launch event selection and associated IRFs**
  - **Pass8: post-launch recon, event selection and IRFs**



Pass8 New Event Reconstruction

arxiv 1303.3514

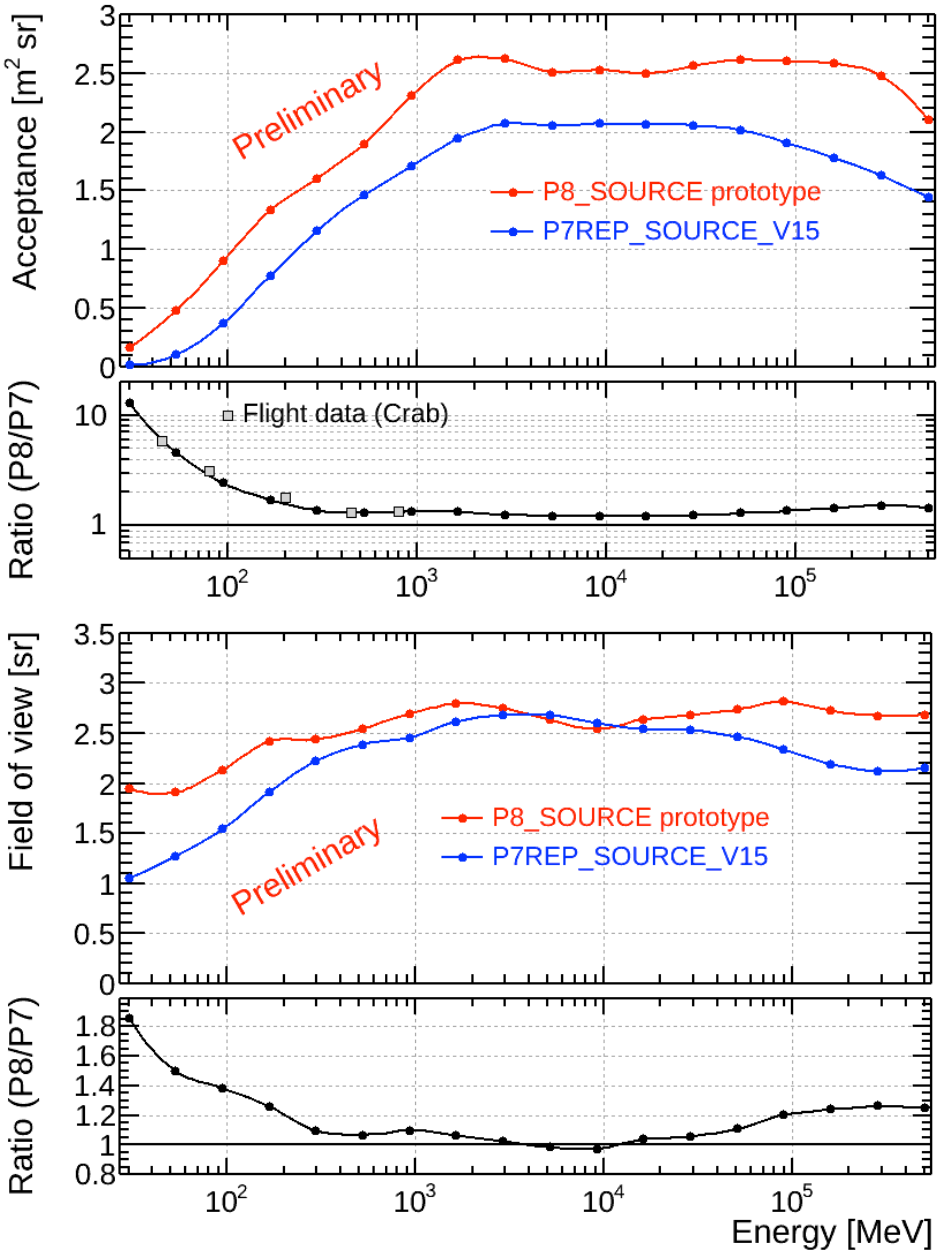
- Complete subsytems recon rewrite (ACD, CAL, TKR)
  - Well beyond original motivation of suppressing cosmic-ray pileup
- TKR: new tree-based pattern recognition
  - Mitigates mistracking at high energy and angle



- CAL: new clustering stage
  - Separates ghost from primary photon
- CAL: revamped calorimeter shower profile fitting
  - Mitigates crystal saturation, opens multi-TeV domain
- ACD: improved track/cluster to tile fitting
  - Uses full covariant errors, avoids harsh background rejection cuts

Pass8 preliminary performance

- Larger acceptance
  - Dramatic increase < 100 MeV
- Larger field of view
  - more off-axis effective area
- Similar E dispersion and PSF
  - Narrower PSF at highest energies, reduced tails
  - Can improve PSF by tightening event selection

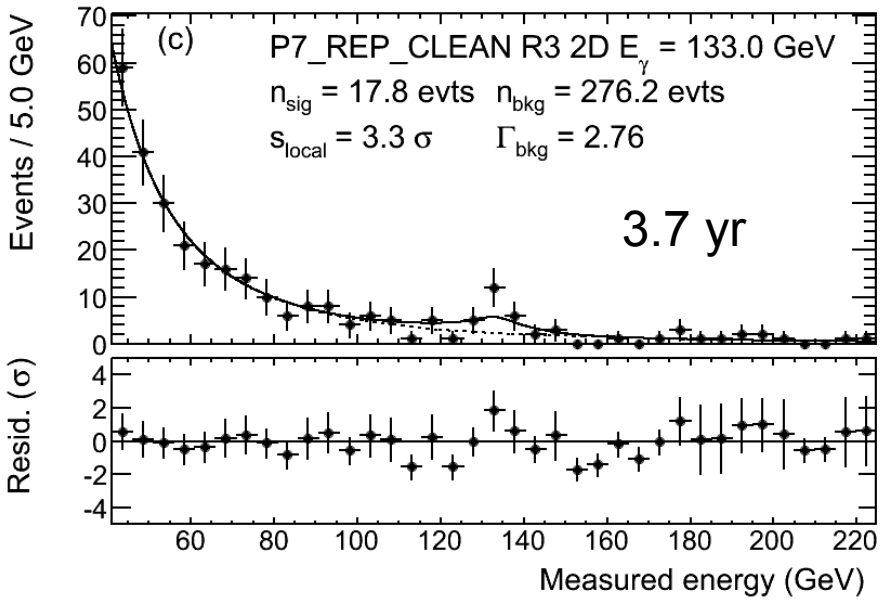


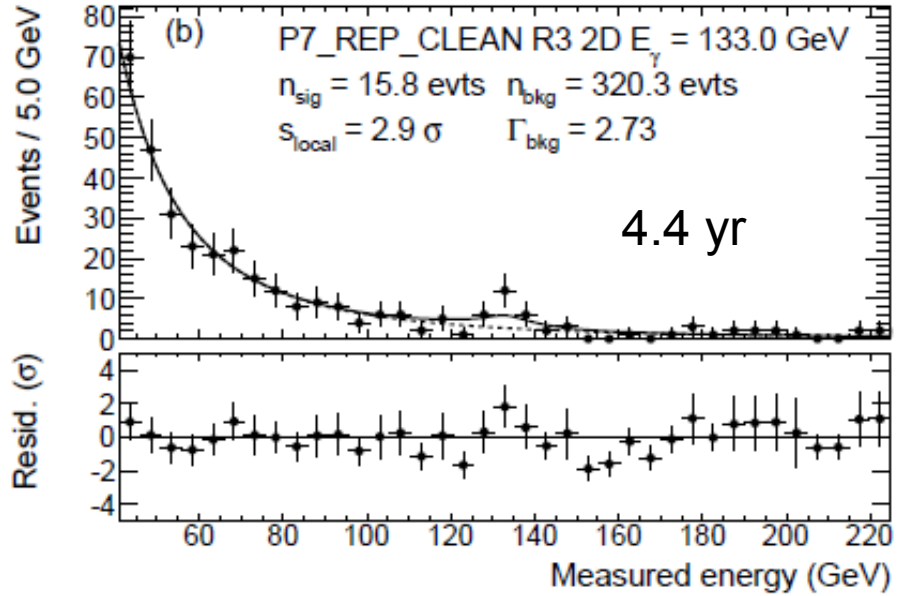
Summary

- Fermi stable operations give lots of γ-rays to many users
- Dark Matter annihilation constraints approaching thermal relic limit using many targets and techniques
  - Diffuse emission modeling often critical
- No globally significant lines across in 100 MeV – 300 GeV
  - control regions key to control systematics
- Pass8 will boost Fermi science and Dark Matter searches
  - Planning updates for most analyses for Fermi Symposium (Nagoya, October 20-24 2014)
  - http://fermi.gsfc.nasa.gov/science/mtgs/symposia/2014/

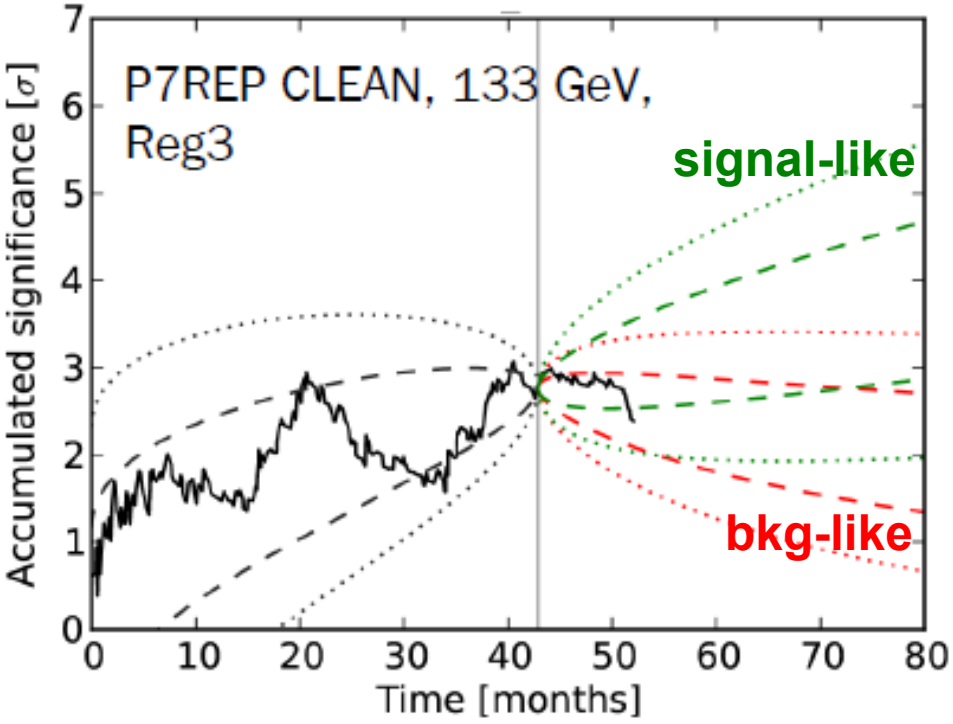
BACKUP

133 GeV Feature in 4.4 year dataset





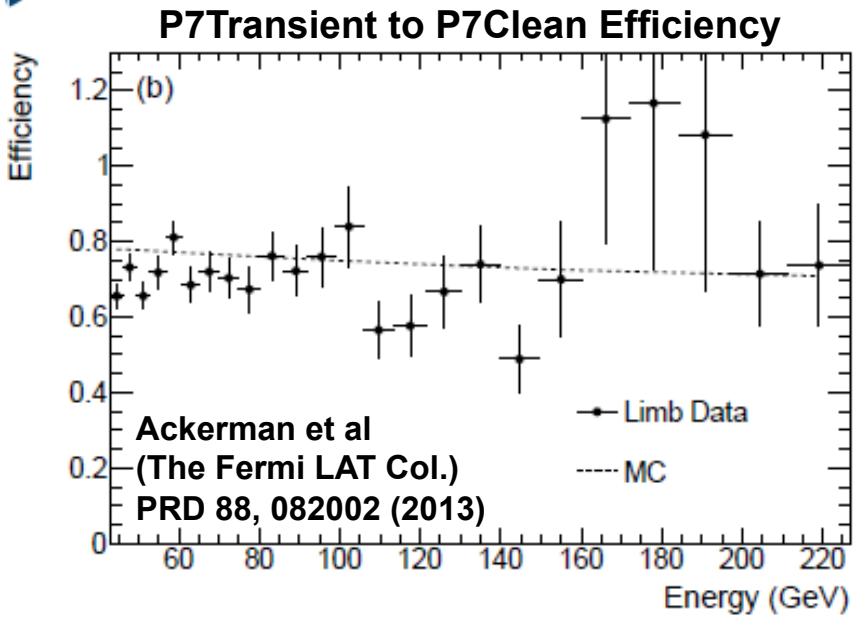
Weniger et al (2013)
http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/white_papers_eval.html

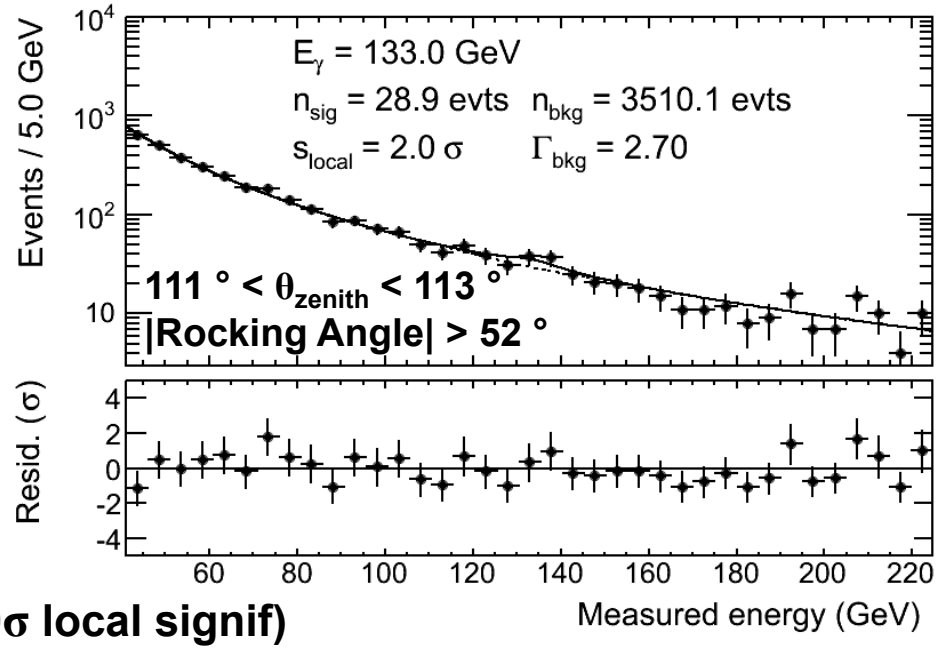


- **s_{local} decreased in 4.4 yr data by ~10% compared to 3.7 yr data**
- **Since spring 2012, feature has decrease**
  - **More "background-like"**

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

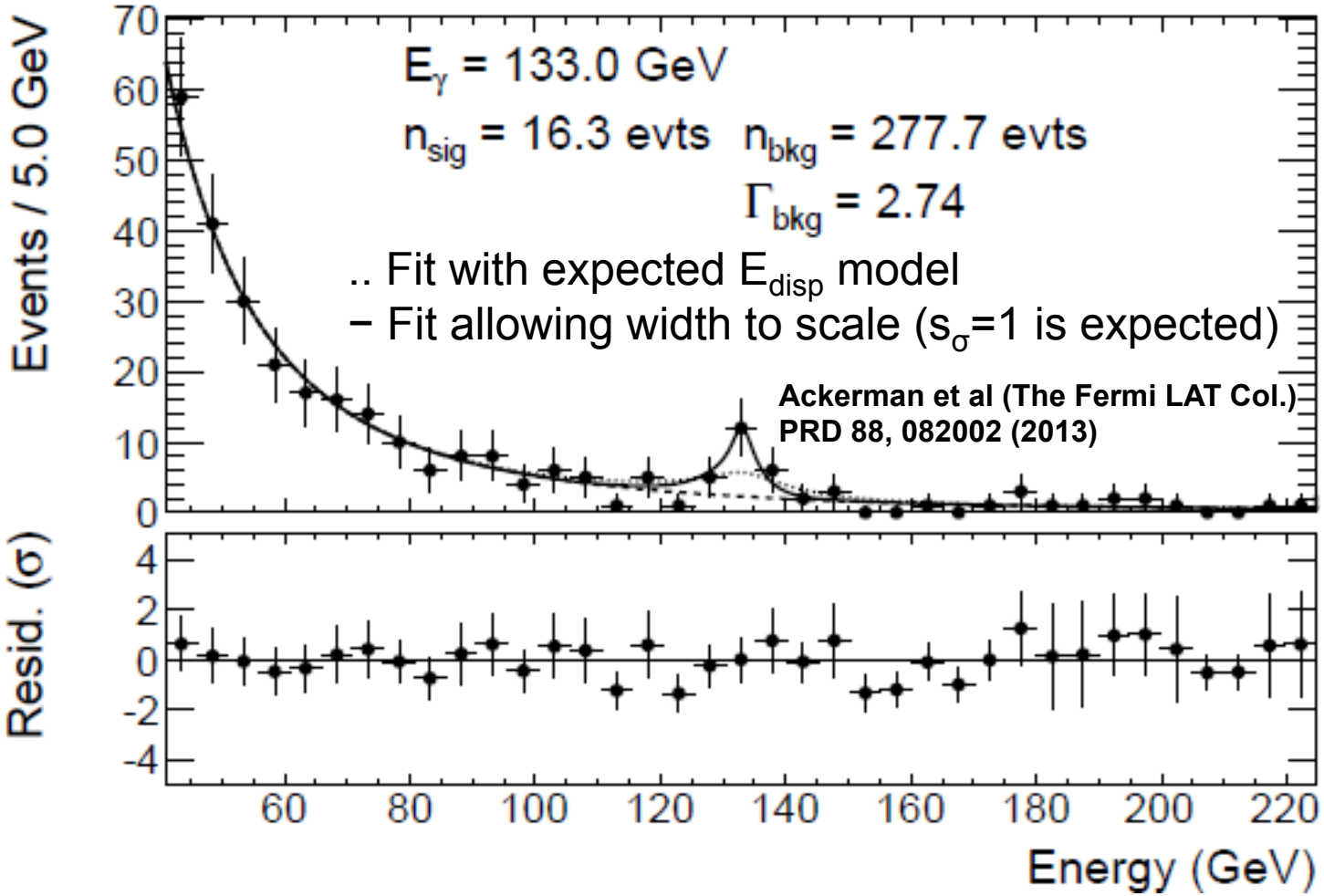
HE Line Search - 133 GeV in the Earth Limb





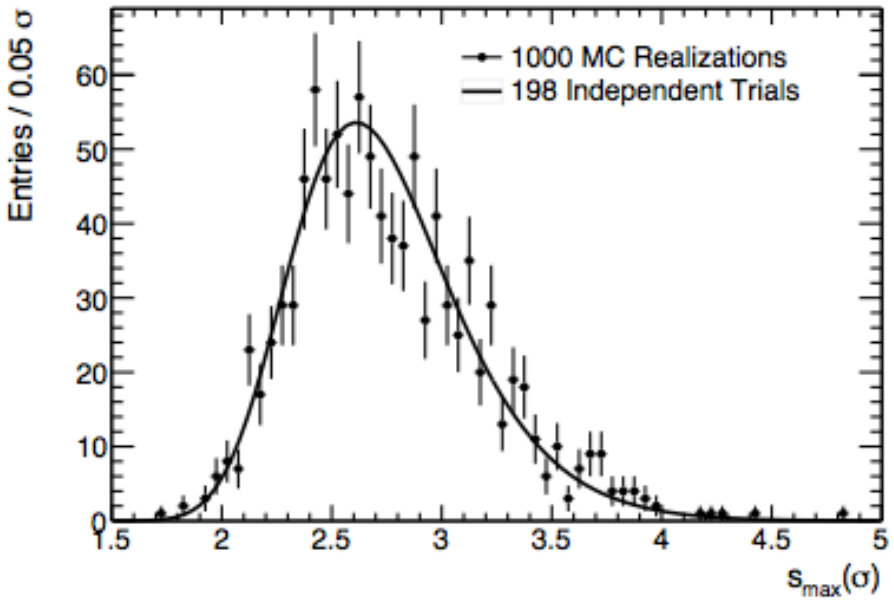
- **Line-like feature in the limb at 133 GeV (2.0σ local signif)**
  - **Appears when LAT is pointing at the Limb ($|\theta_r|<52^0$)**
  - **Surprising since limb should be smooth power-law**
  - **S/N_{limb} ~14%, while S/N_{R3} ~61%**
    - **Limb feature not large enough to directly explain all the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

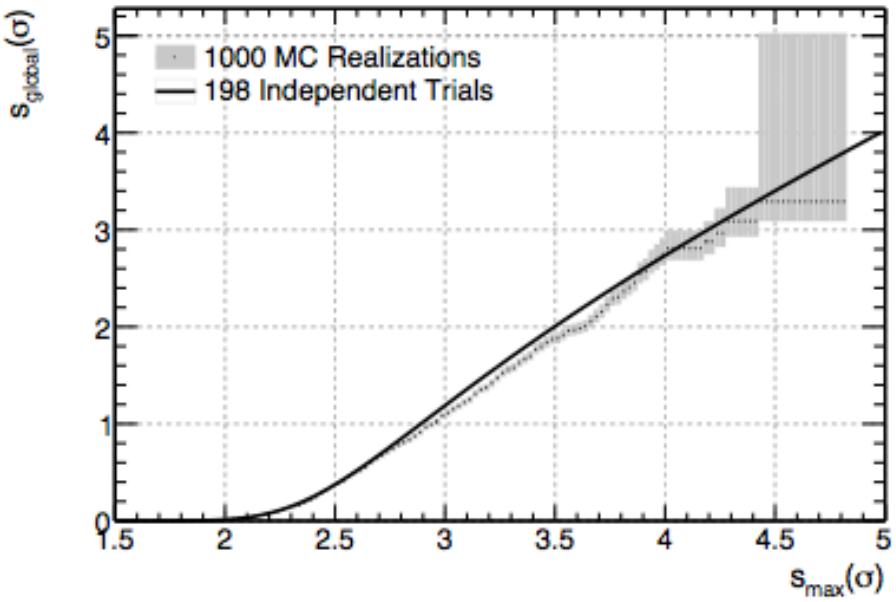
Width of 133 GeV Feature



- **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 much narrower than expected energy resolution (s_σ=1)**

Relating global to local significance





- Perform 1000 MC background realizations
- Extract maximum σ_{local}
- Fit distribution with expected X^2 distribution with nt independent trials and use relationship to relate σ_{local} to σ_{global}