Dark Matter Searches with the Fermi Large Area Telescope

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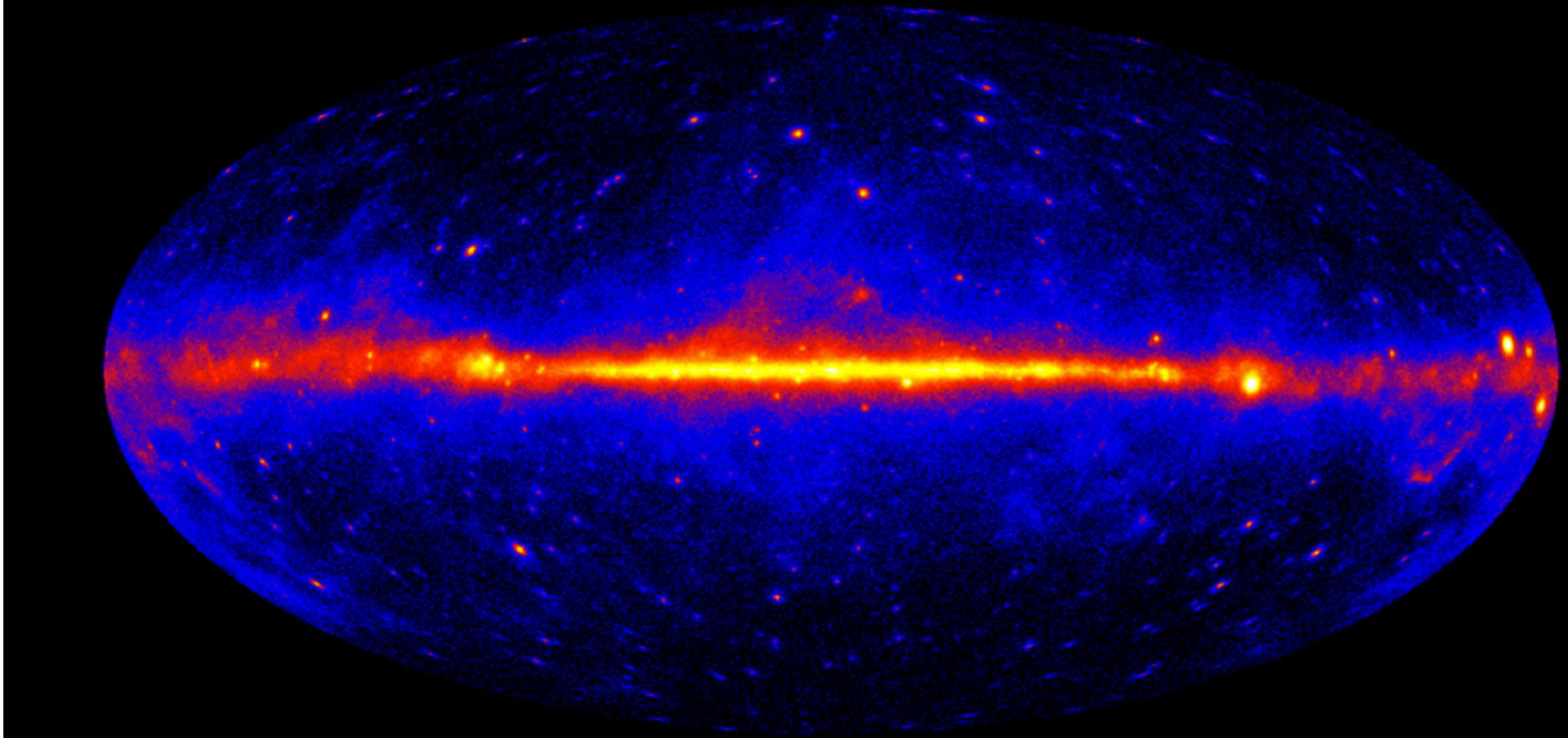
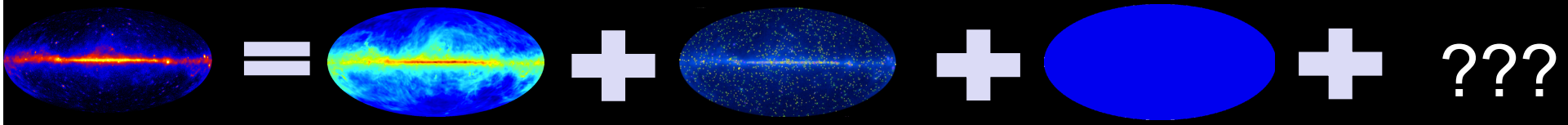
On behalf of the Fermi Mission Team

DESY Colloquium – July 2-3 / 2013

Searching Dark Matter in the gamma-ray sky

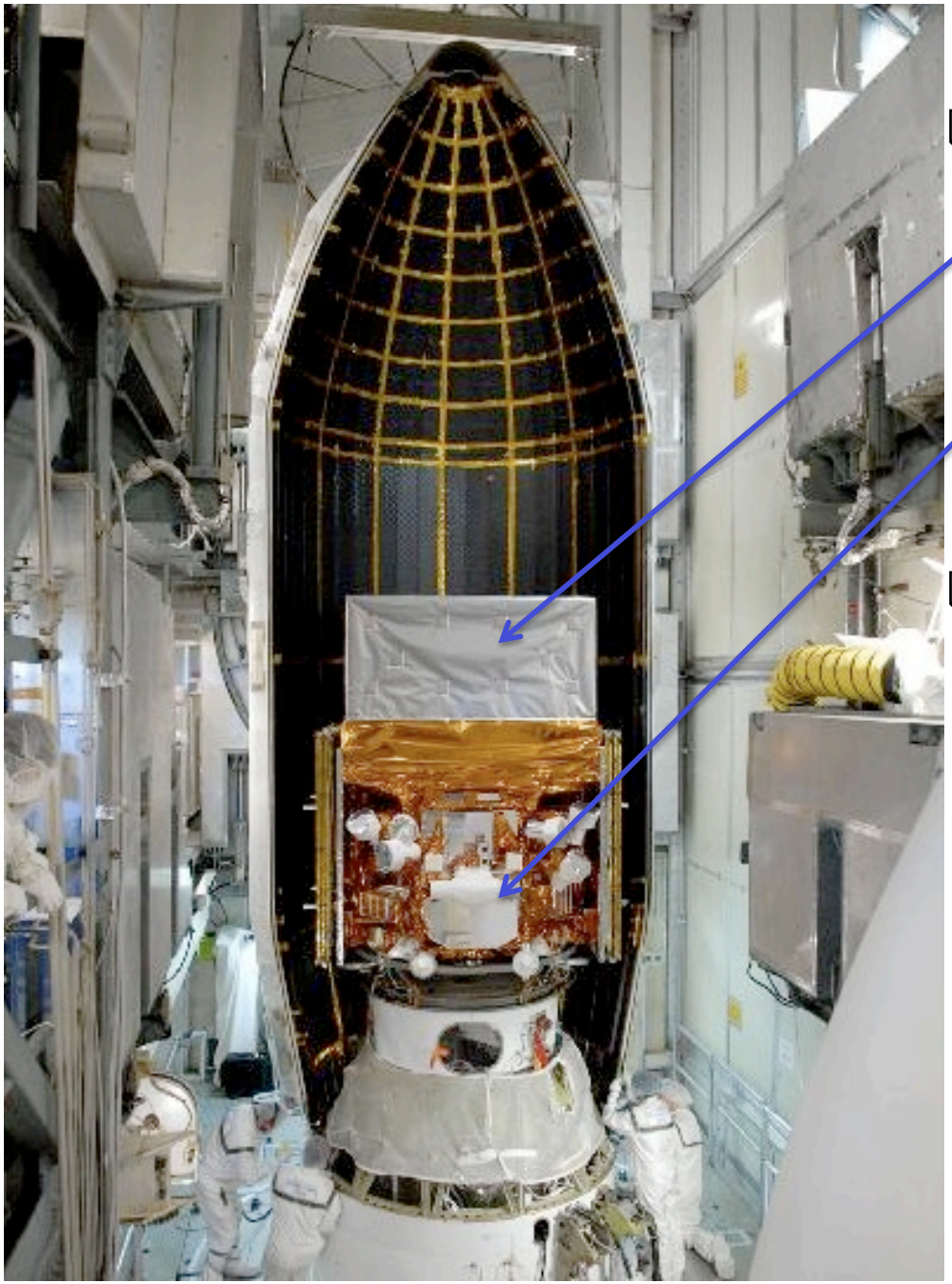




GeV Sky Galactic Point Sources Isotropic

Outline

- The Fermi observatory and the Large Area Telescope
- Fermi Science snapshot
  - Sources, catalogs and analysis challenges
- Dark Matter searches with Fermi
  - Electrons, dwarf galaxies, Galactic halo, gamma-ray lines, isotropic gamma-ray background



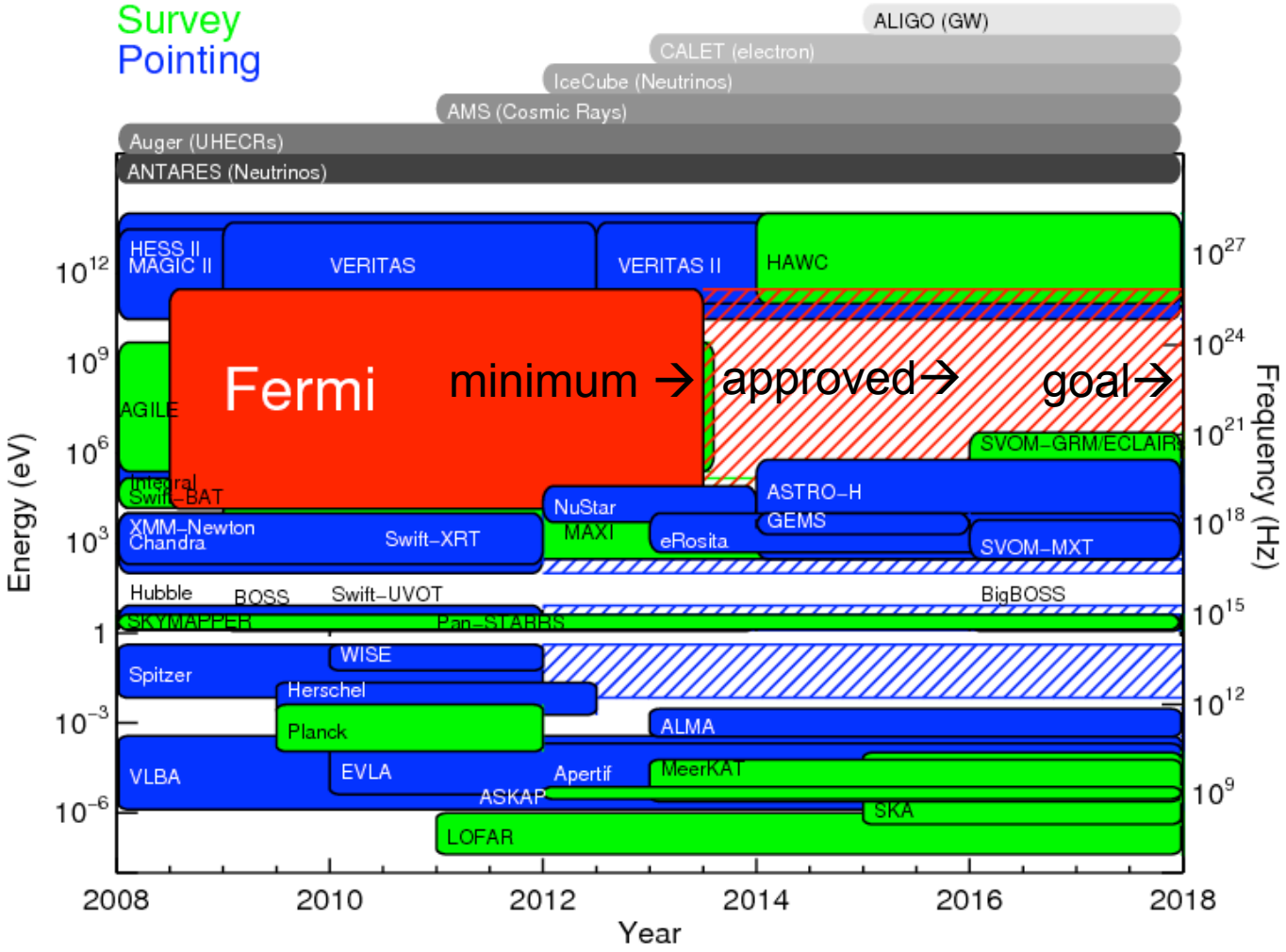
The Fermi observatory

- Satellite gamma-ray telescope
  - Large Area Telescope (LAT)
    - 20 MeV – > 300 GeV
  - Gamma Burst Monitor (GBM)
    - 8 KeV – 40 MeV
- Key features
  - Huge field of view (2.4sr)
    - 20% sky any instant
    - All sky for 30’ every 3h
  - Huge energy range
    - Including unexplored 10-100 GeV range

- Launch from Cape Canaveral, June 11, 2008
- Observing strategy
  - > 95% time in sky survey
  - ARR and ToO
- Excellent detector stability
  - > 300B triggers
  - > 50B events to ground
  - ~2000 transients
  - ~hours/year for calibrations

Fermi mission status

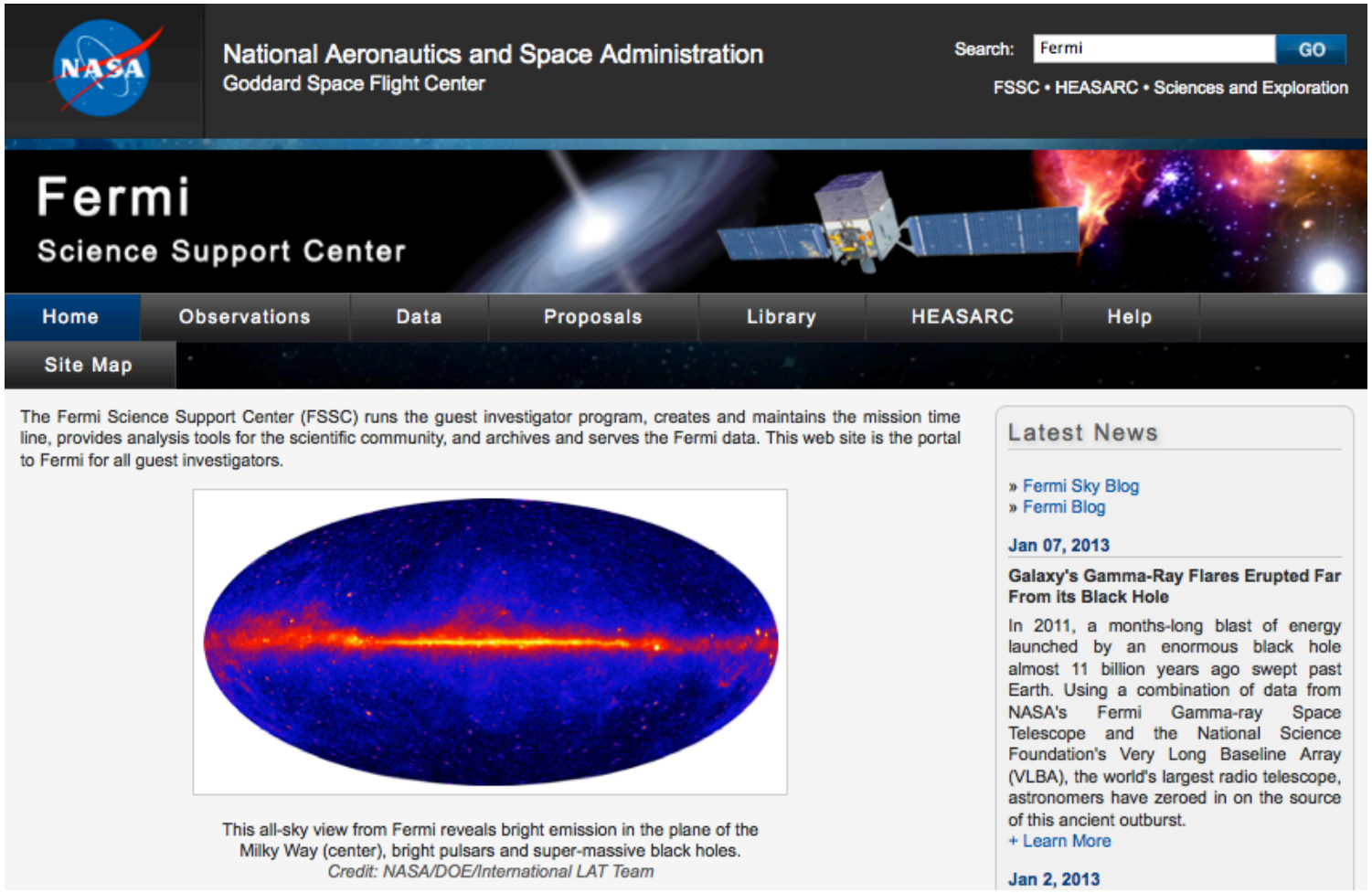
http://science.nasa.gov/astrophysics/2012-senior-review/



- ❑ **NASA 2012 Senior Review recommended extended operations**
- ❑ **NASA HQ will extend the mission to at least 2016**

Fermi as a public observatory

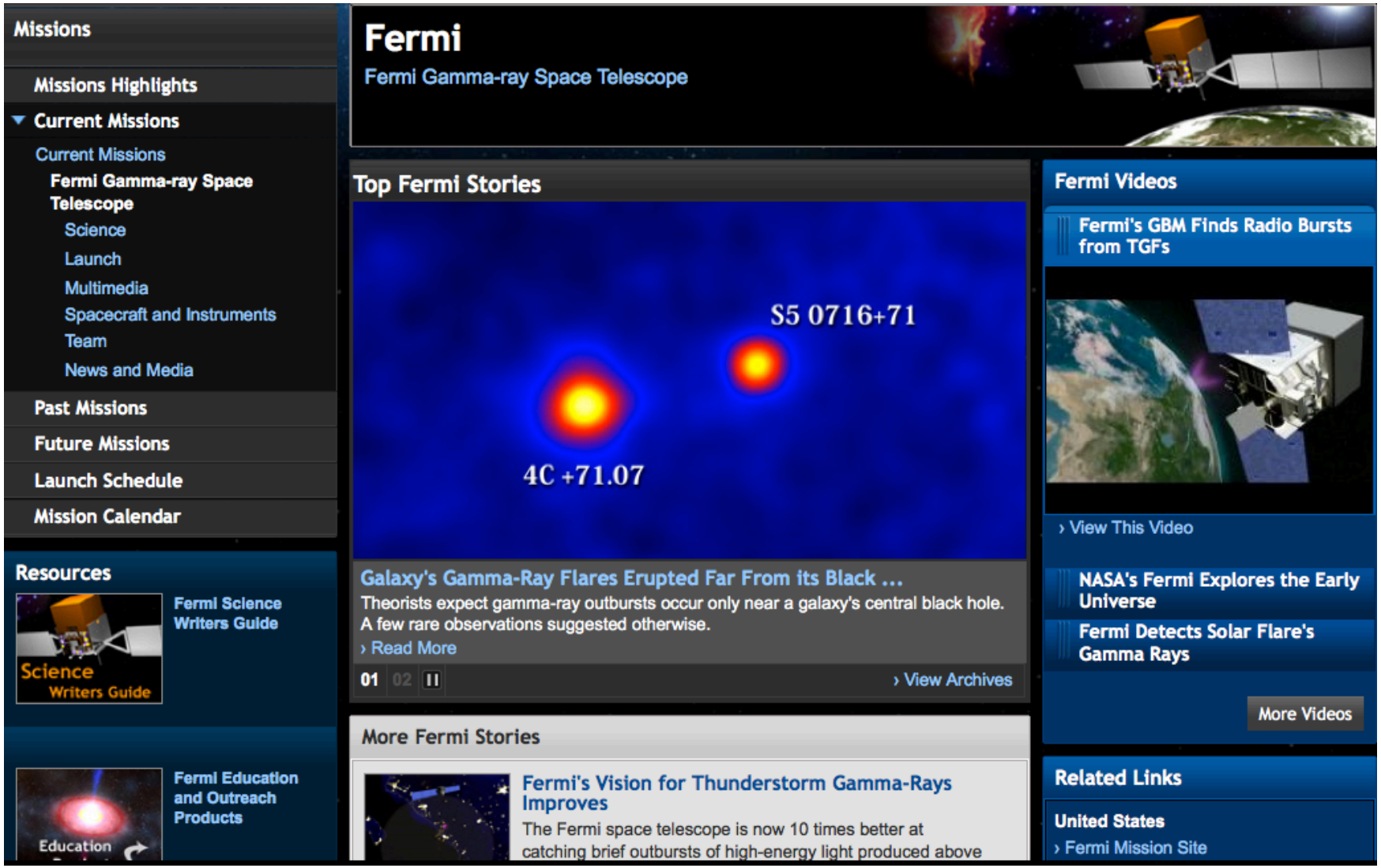
http://fermi.gsfc.nasa.gov/ssc/



- ❑ > 800M γ and public within ~hours from trigger
- ❑ Full Science Tools data analysis suite
- ❑ > 800 papers, > 10k citations collectively

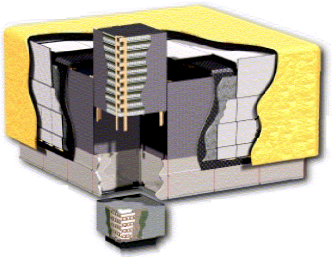
Fermi for the General Public

http://www.nasa.gov/fermi



Overview of the Large Area Telescope

Atwood, W. B. et al. 2009, ApJ, 697, 1071

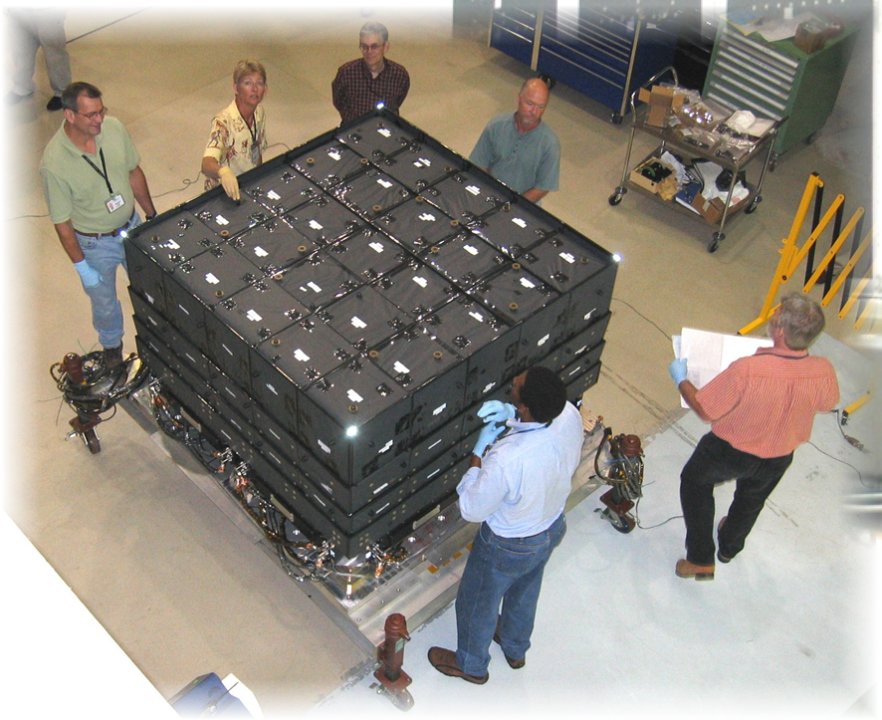


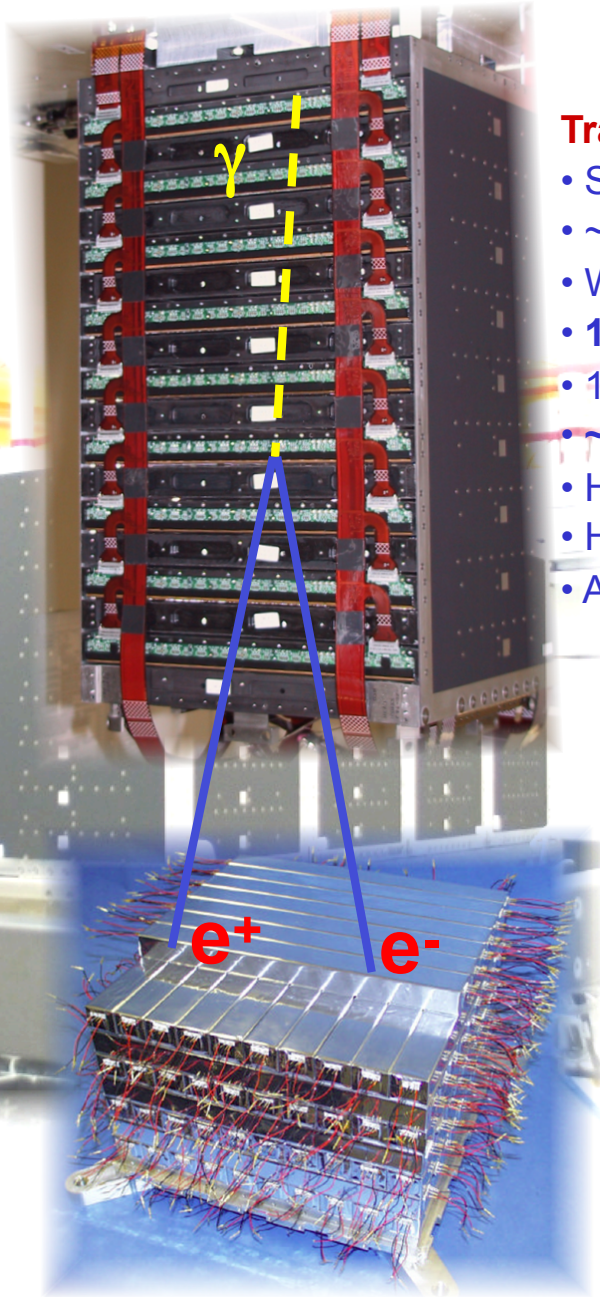
LAT:

- modular - 4x4 array
- 3ton – 650watts

Anti-Coincidence (ACD):

- Segmented (89 tiles + 8 ribbons)
- Self-veto @ high energy limited
- **0.9997 detection efficiency**





Tracker/Converter (TKR):

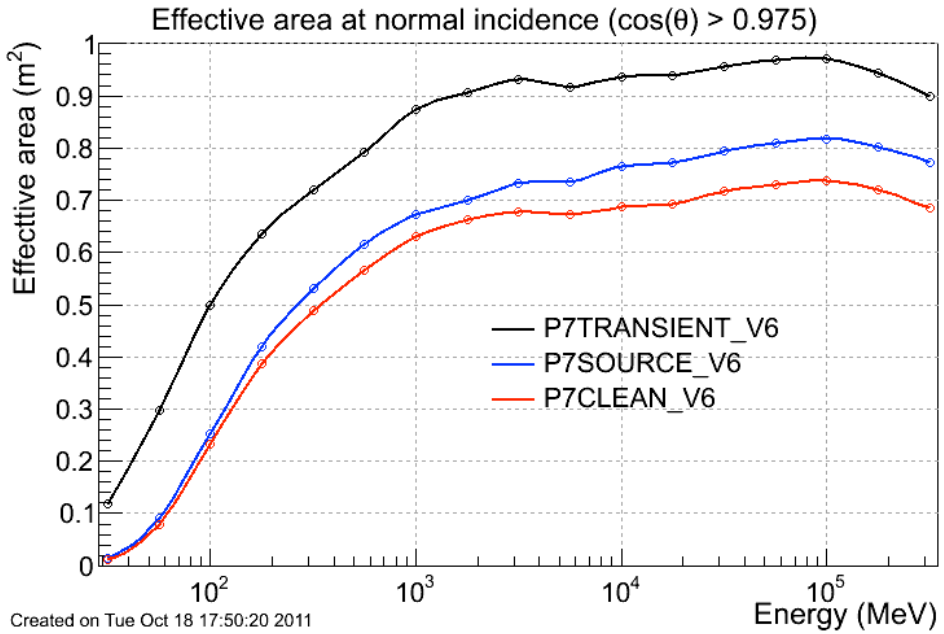
- Si-strip detectors
- ~80 m^2 of silicon (total)
- W conversion foils
- **1.5 X0 on-axis**
- 18XY planes
- **~10^6 digital elx chans**
- Highly granular
- High precision tracking
- Average plane PHA

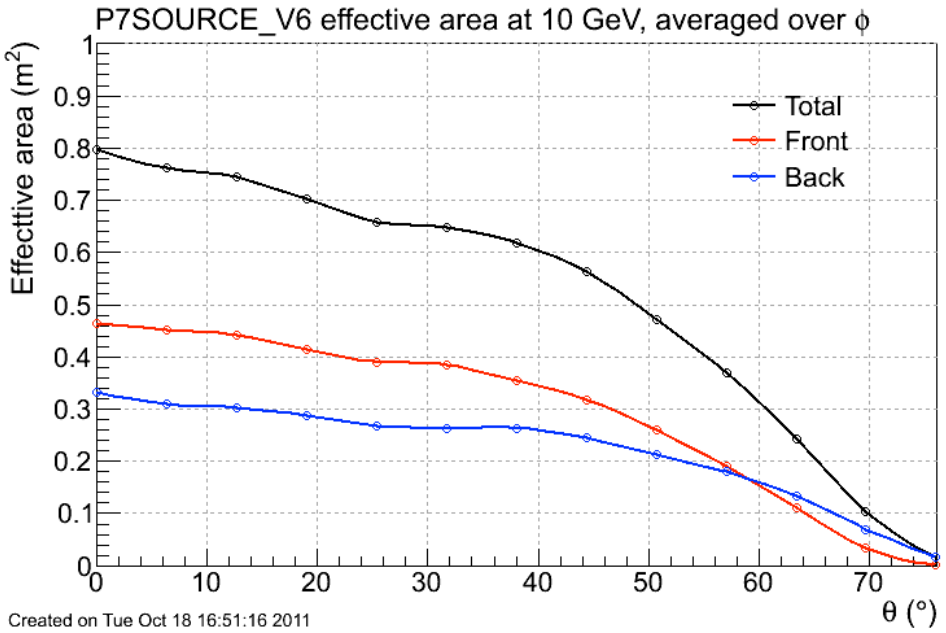
Calorimeter (CAL):

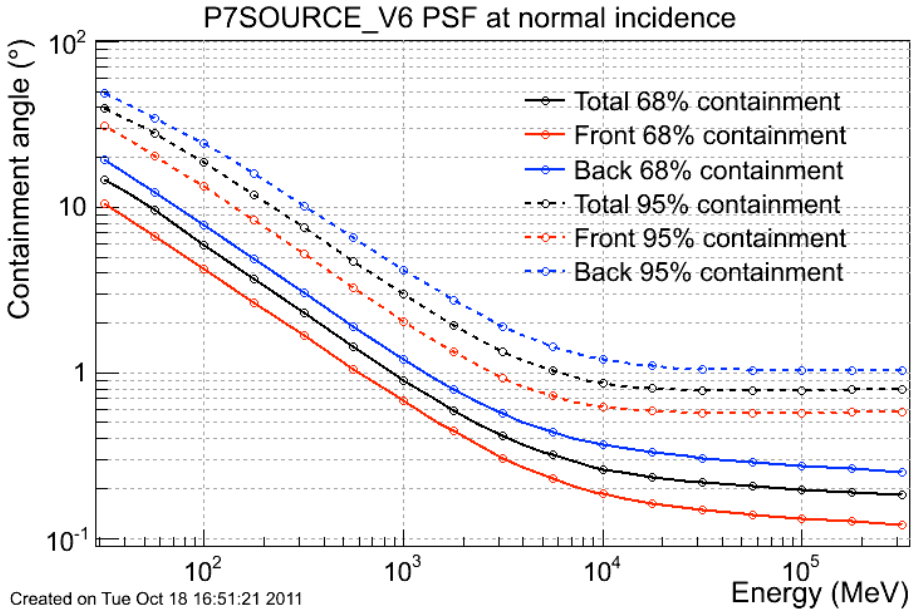
- 1536 CsI(Tl) crystals
- **8.6 X0 on-axis**
- large elx dynamic range (2MeV-60GeV per xtal)
- **Hodoscopic (8x12)**
- Shower profile recon
- leakage correction
- EM vs HAD separation

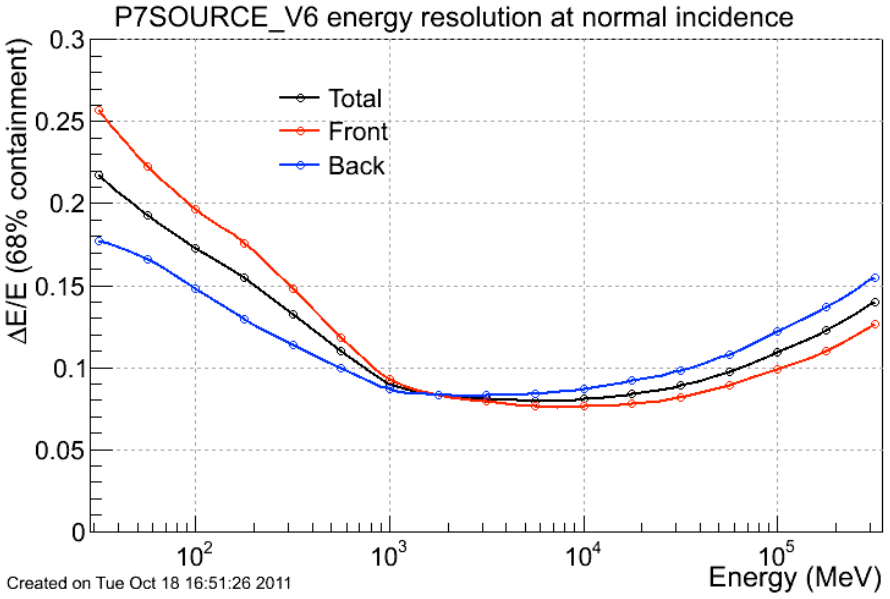
LAT performance

http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm



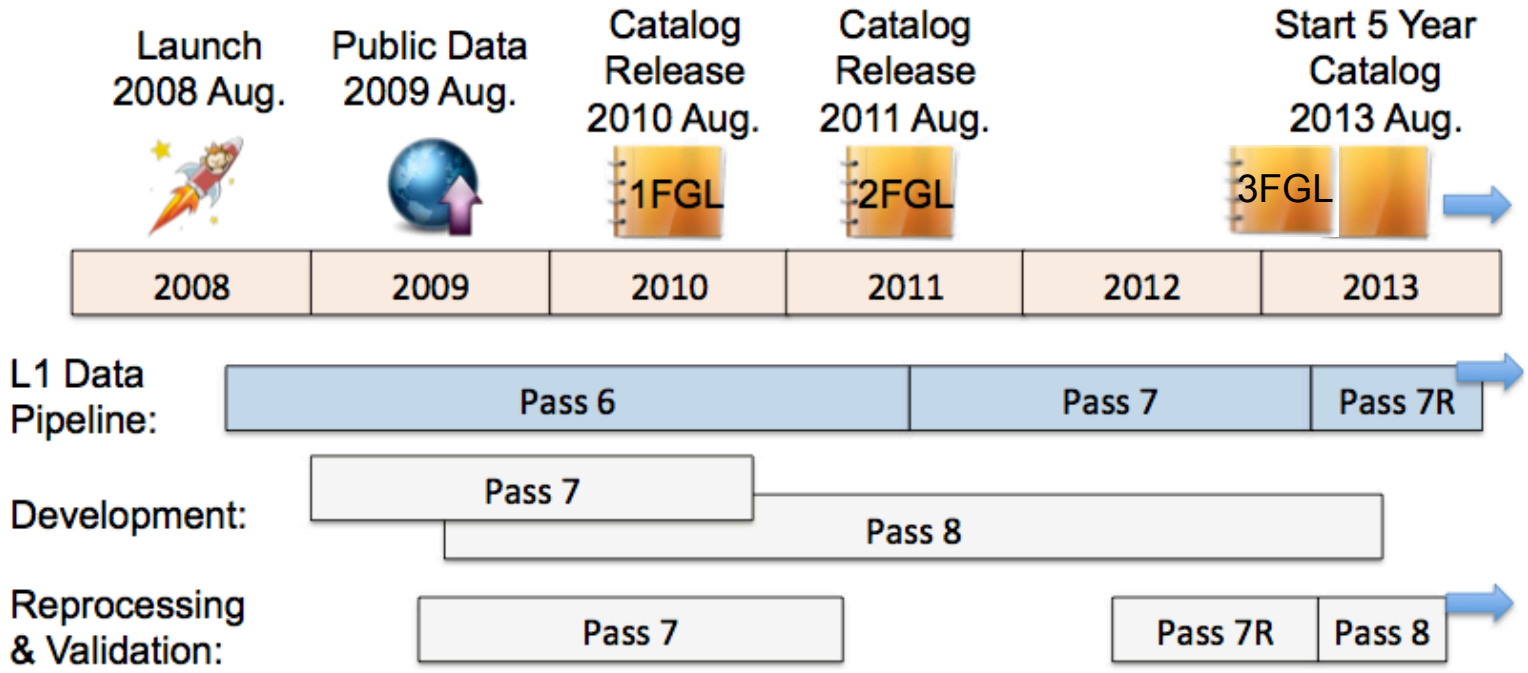




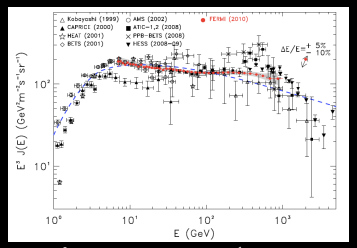


Still improving the LAT Performance

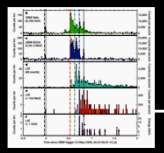
- **Continuous effort to improve performance and release improved datasets**
  - **Pass6: pre-launch recon and event selection, optimized post-launch IRFs (to describe effect of ghosts)**
  - **Pass7: pre-launch recon, optimized post-launch event selection and associated IRFs**
  - **Pass8: post-launch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



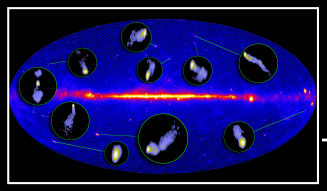
Increasing Classes of Fermi-LAT Sources



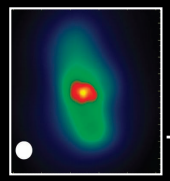
e^+e^- spectrum



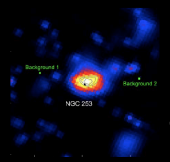
GRBs



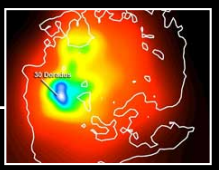
Blazars (782)



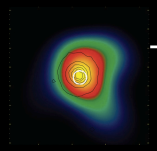
Radio Galaxies (12)



Starburst Galaxies (4)

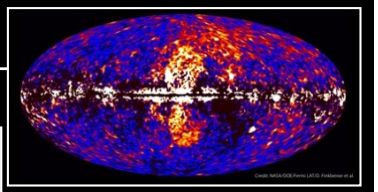


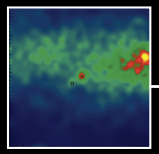
LMC & SMC



Globular Clusters (11)

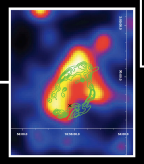
Fermi Bubbles

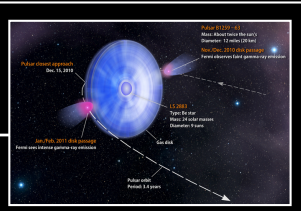




Nova (1)

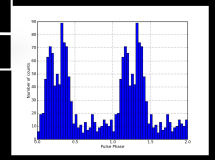
SNR & PWN (68)



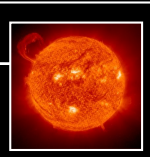


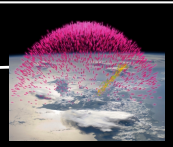
γ-ray binaries (6)

Pulsars: young & millisecond (MSP) (117+)



Sun: flares & CR interactions





Terrestrial Gamma-ray Flashes

Ackermann+ (LAT) [arXiv:1108.1202]

Unidentified Sources (~600)

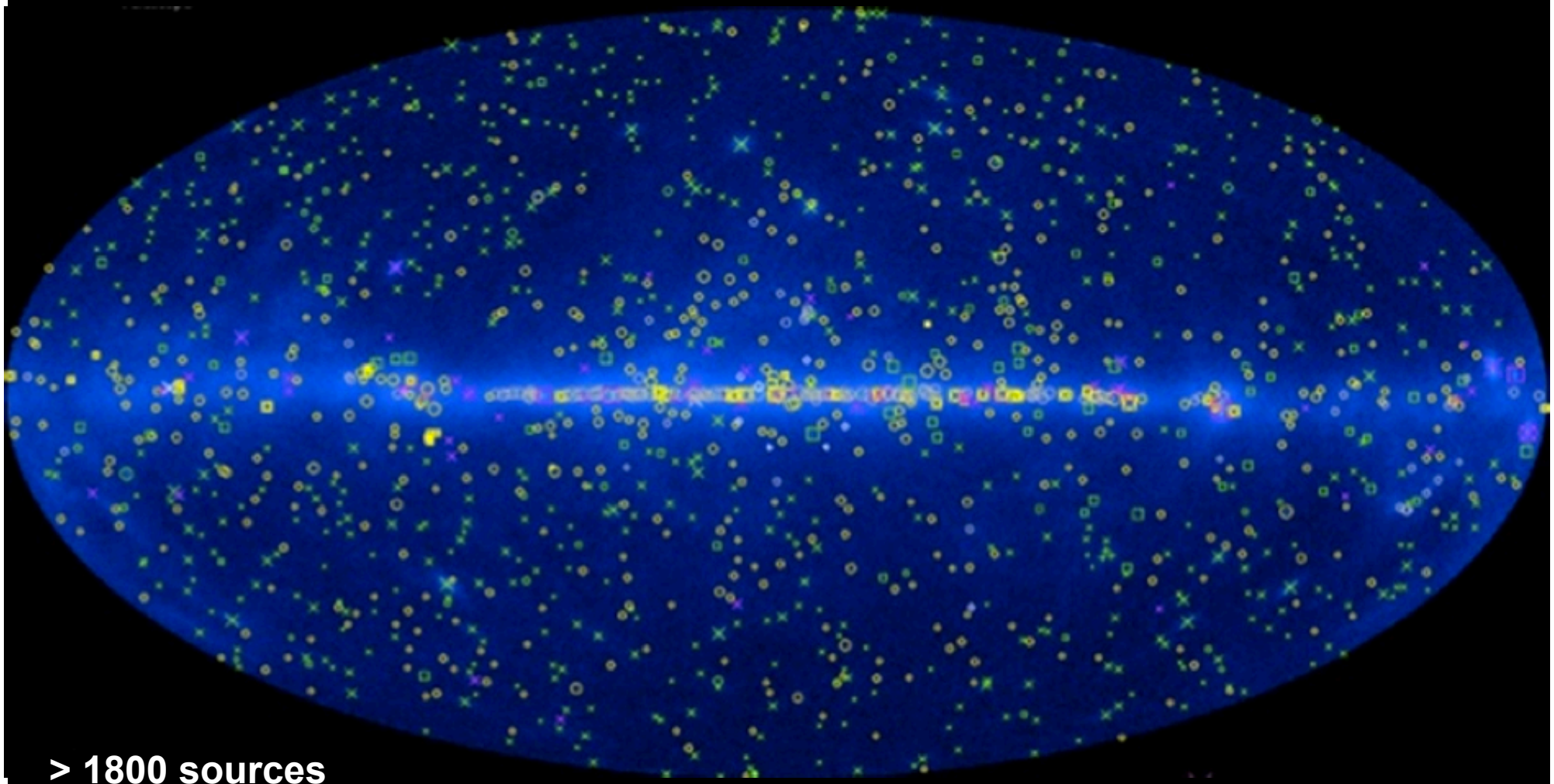
Extragalactic

Galactic

Local

Fermi 2FGL catalog

Nolan et al.: 2012ApJS..199...31N

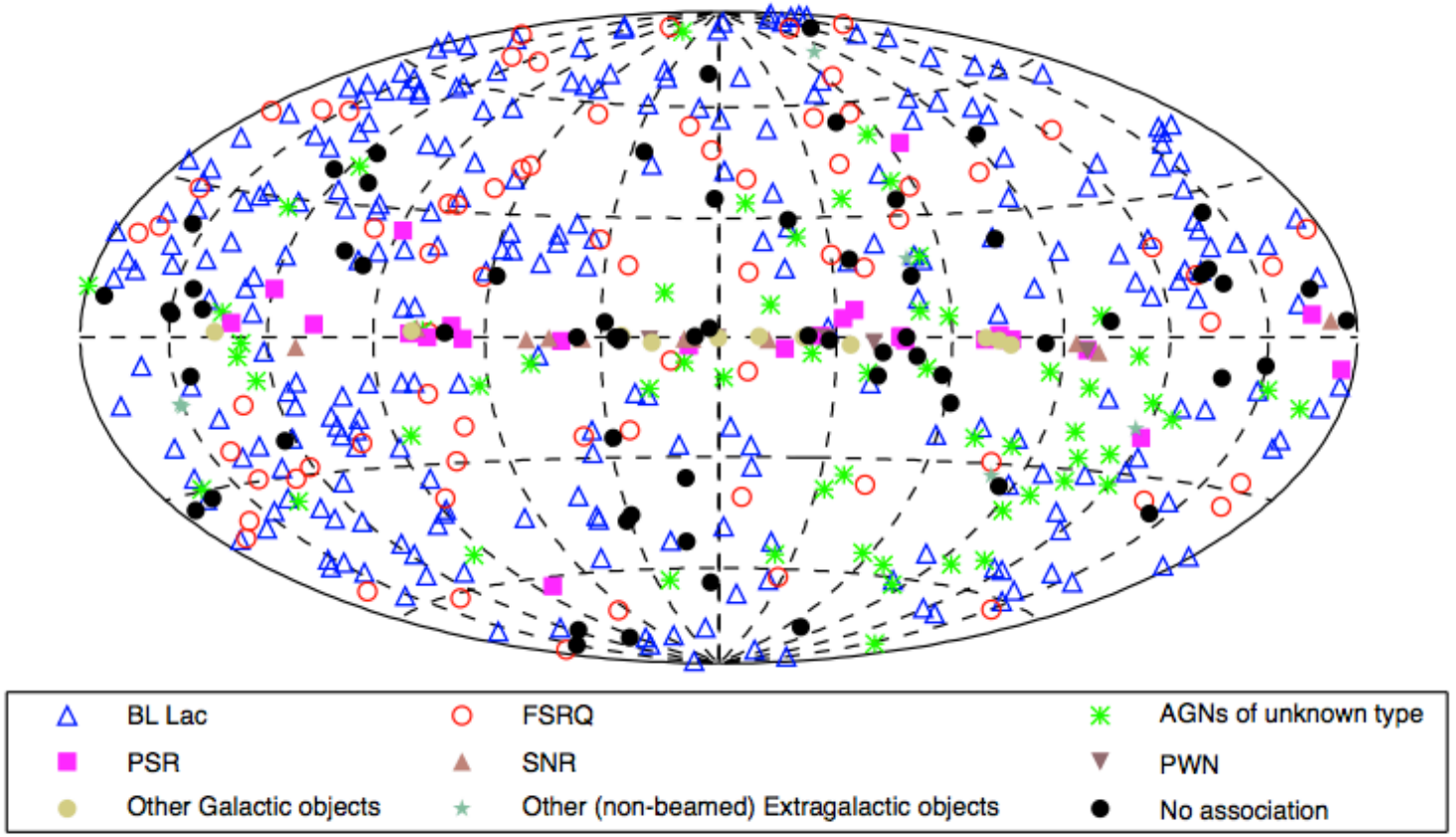


> 1800 sources
> 10 source classes
known classes (AGN, Pulsars, PWN, SNR...)
New emitters (Novae, ms PSR, starbursts,
~30% unidentified

3FGL in preparation

Hard Source List

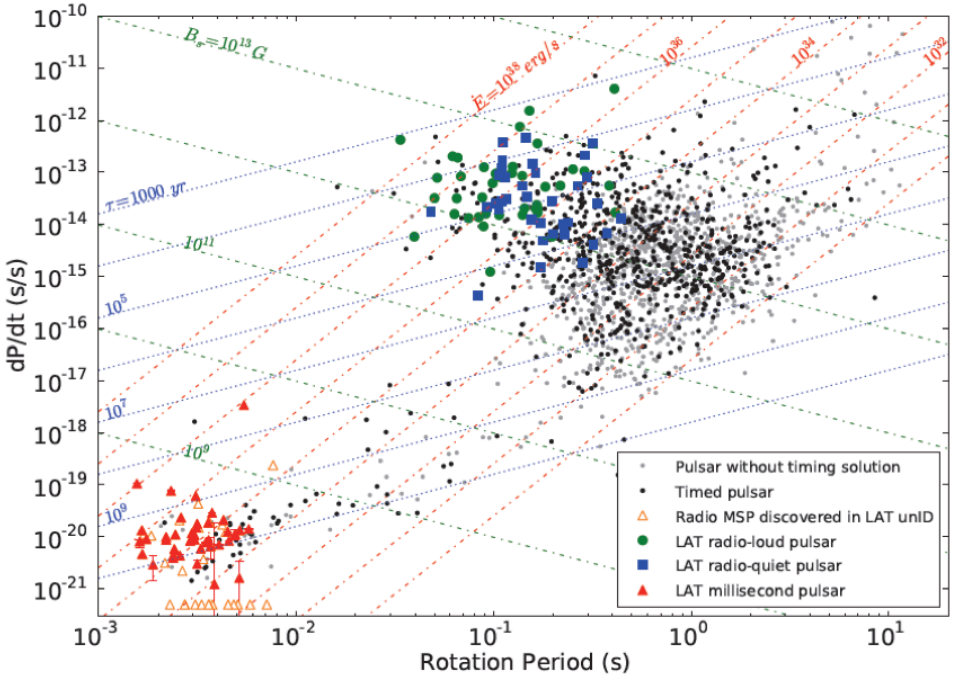
arxiv 1306.6772

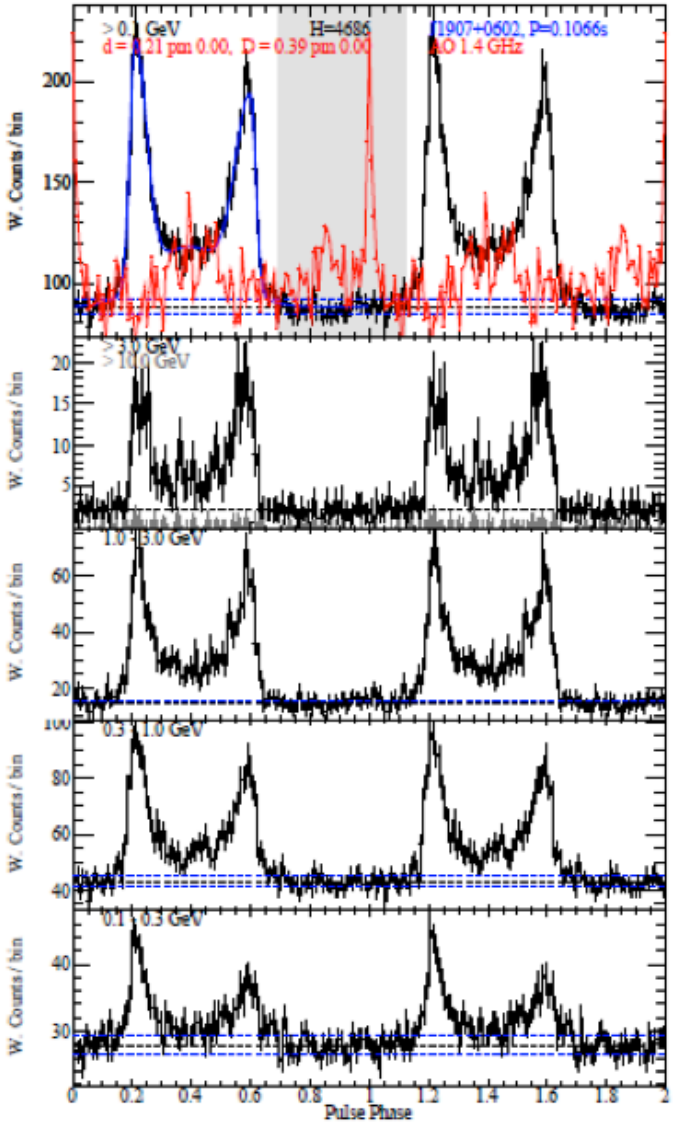


First catalog of source above 10 GeV
514 sources

The 2nd Fermi-LAT Catalog of γ-ray pulsars

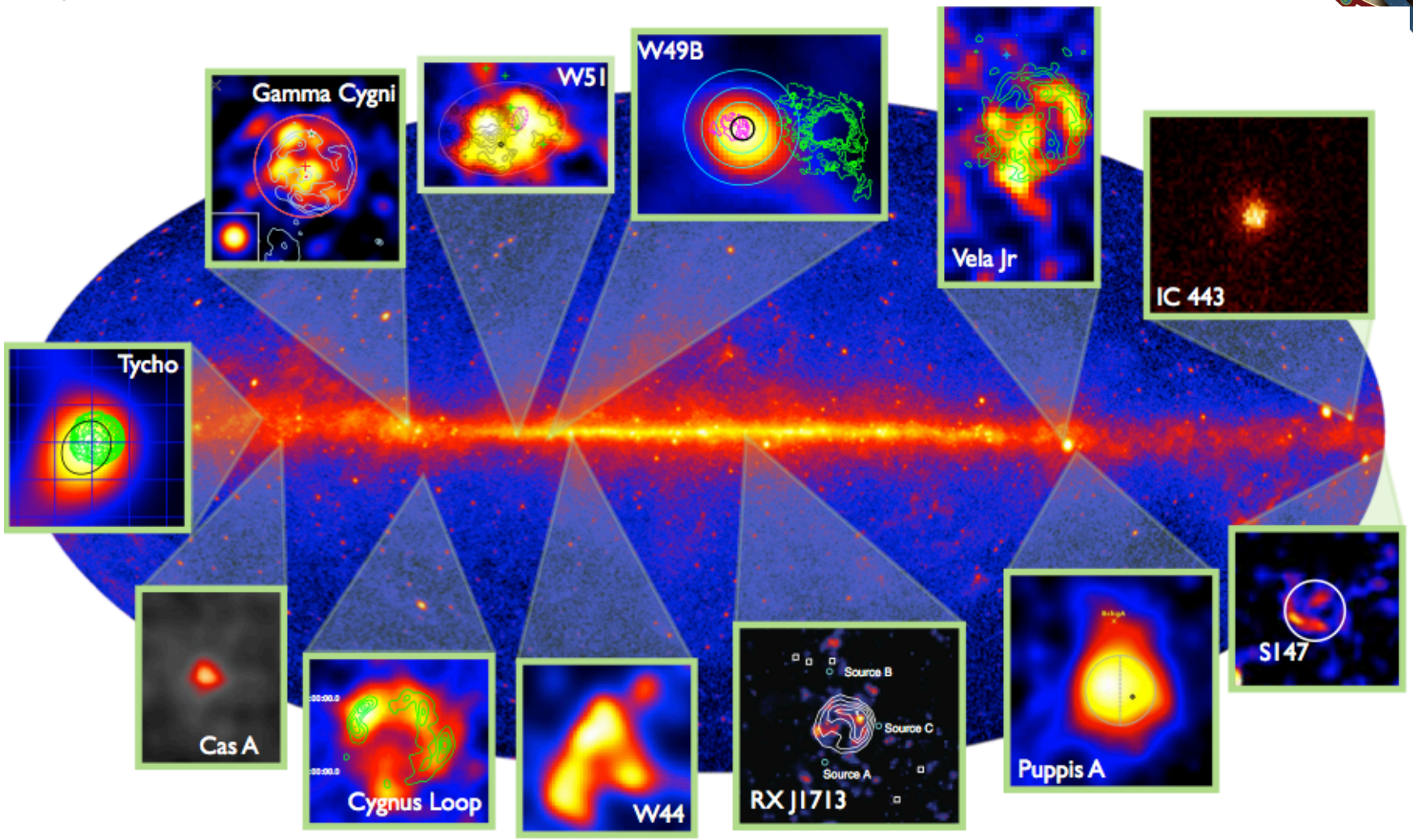
arxiv 1305.4385, accepted by ApJS





- 117 pulsars (and counting)
- Complementary searches
  - Blind searches, also on gravitational waves clusters
  - Constant synergy with radio (ephemeris, ms PSR in LAT UNIDs)

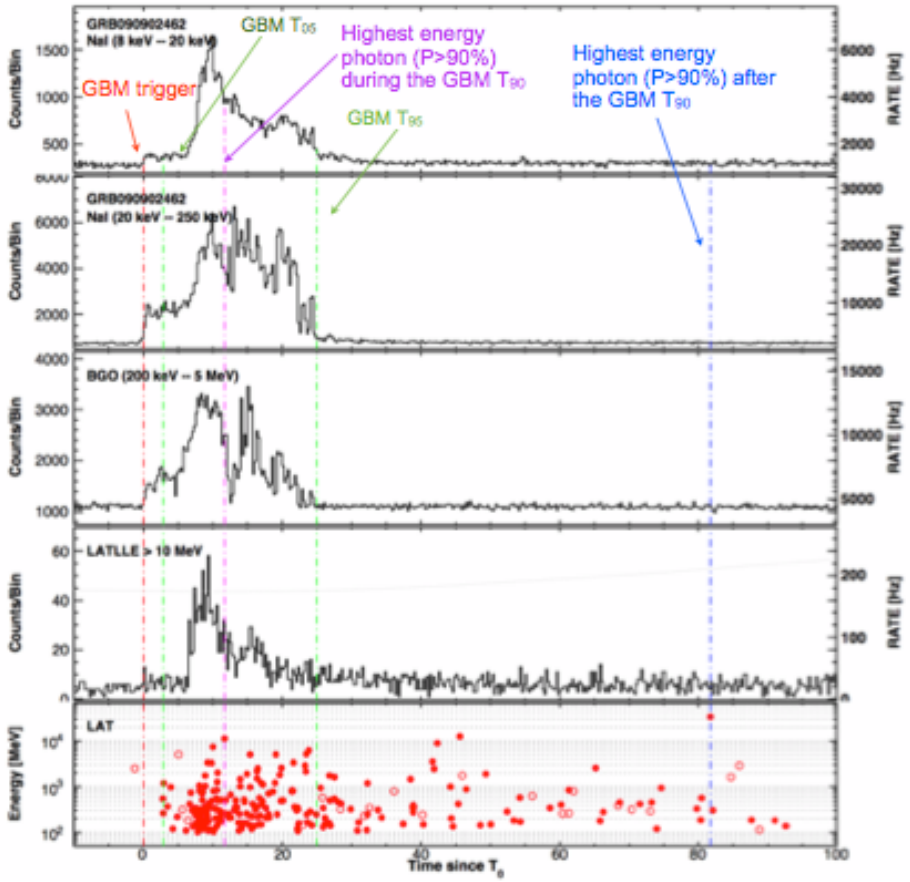
SuperNova Remnants – towards a catalog



- 25 published SNRs + 30 candidates in 2FGL
- Requires combination of spatial and energy information
- Diffuse emission modeling is a key systematic uncertainty

Gamma-Ray Bursts with the Fermi-LAT

- Individual bursts plus LAT GRB catalog
- Common properties in the sample
  - Delayed HE emission
  - Longer HE duration
  - Evidence for multi-component spectra
- Emission mechanism
  - And connection to Cosmic Rays
- Fundamental physics
  - Lorentz Invariance Violation
  - Limits on Extra Galactic Background Light from single high energy photons



Abdo, A. A. et al. 2009, Nature, 462, 331
Abdo, A. A. et al. 2009, Science, 323, 1688
The First LAT GRB Catalog, arxiv 1303.2908, Submitted to ApJS

Dark Matter Search Strategies

Satellites

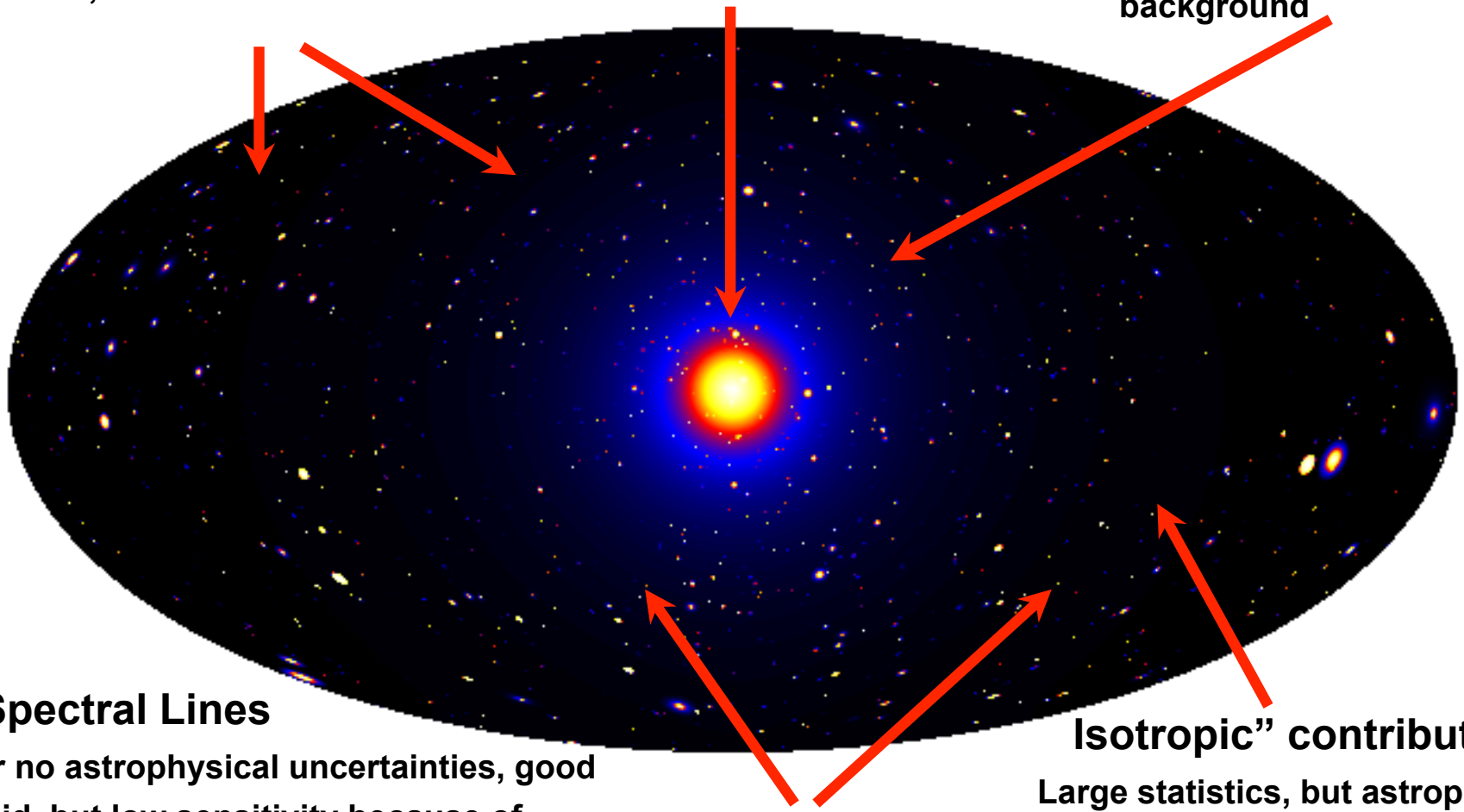
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



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

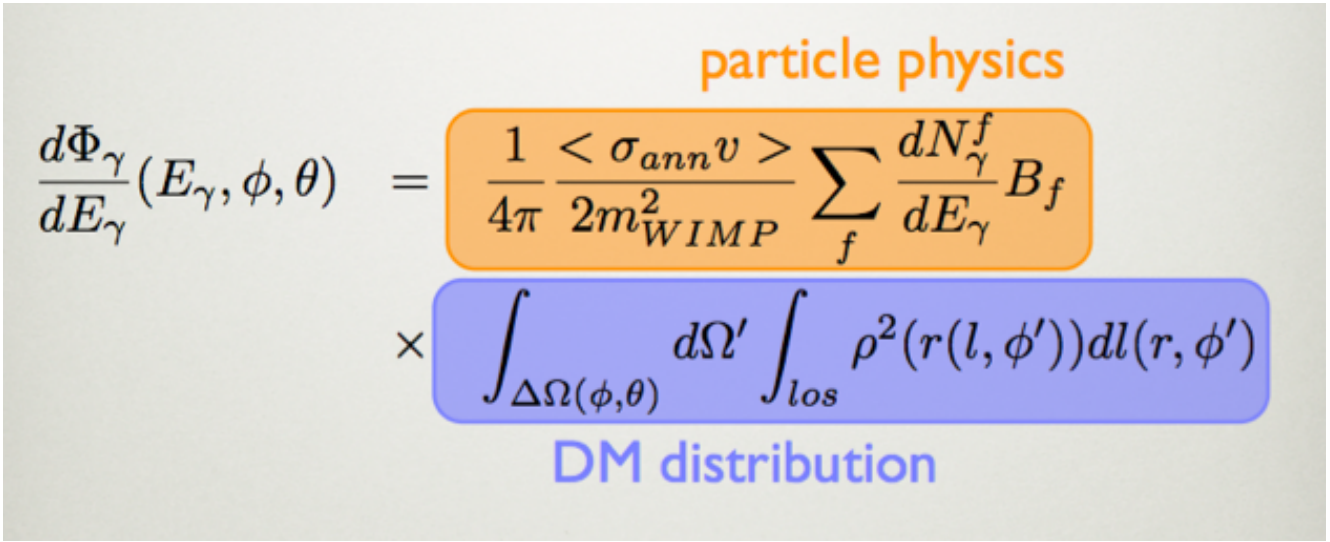
Isotropic" contributions

Large statistics, but astrophysics, galactic diffuse background

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

Building your DM analysis

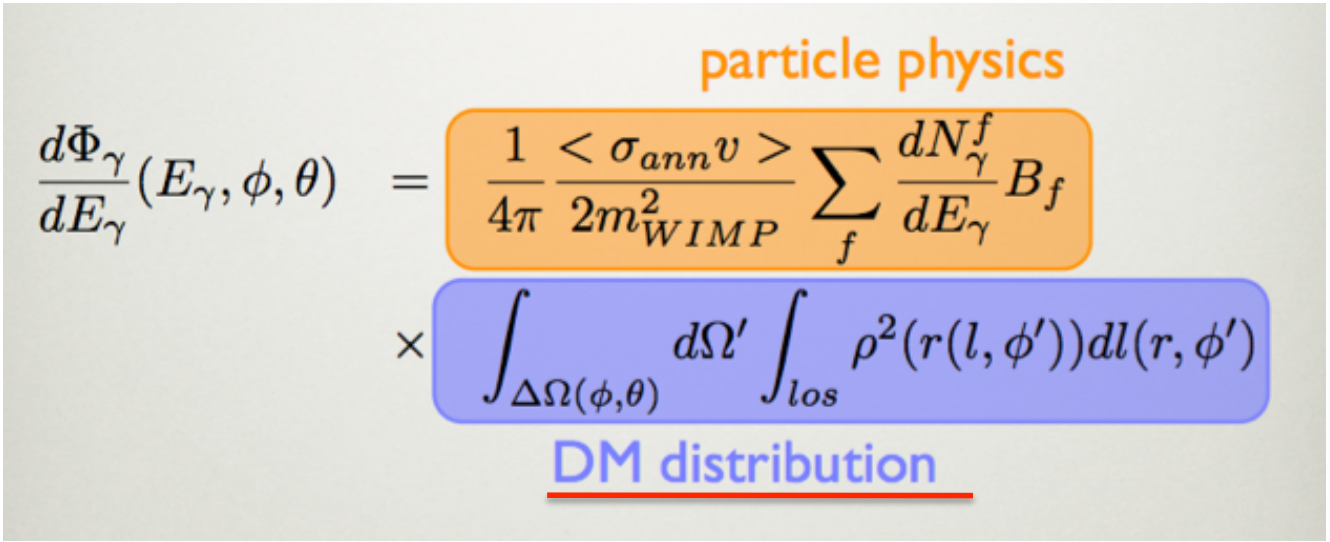
1. **Compute expected signal**



2. **Fold with instrument performance**
   - **Effective area**
   - **Point Spread Function**
   - **Energy resolution**
3. **Build you model counts**
   - **Includes known sources and diffuse emission**
4. **Compare likelihood of model vs data**

Building your DM analysis

1. **Compute expected signal**



2. **Fold with instrument performance**
   - **Effective area**
   - **Point Spread Function**
   - **Energy resolution**

Known with some uncertainty

3. **Build you model counts**
   - **Includes known sources and diffuse emission**
4. **Compare likelihood of model vs data**

Search Strategies (against the g-ray Sky)

Satellites

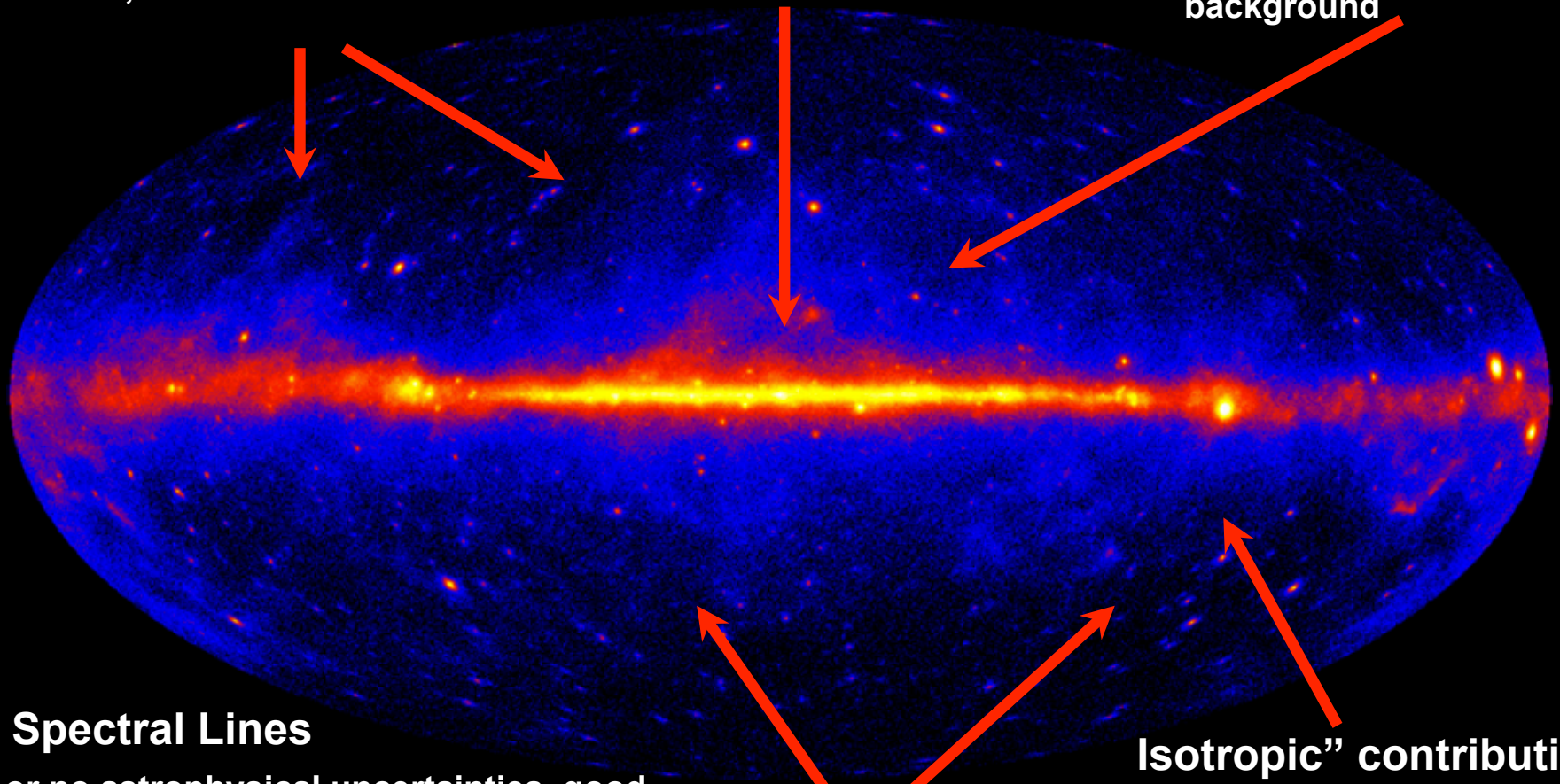
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

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

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Low background, but low statistics

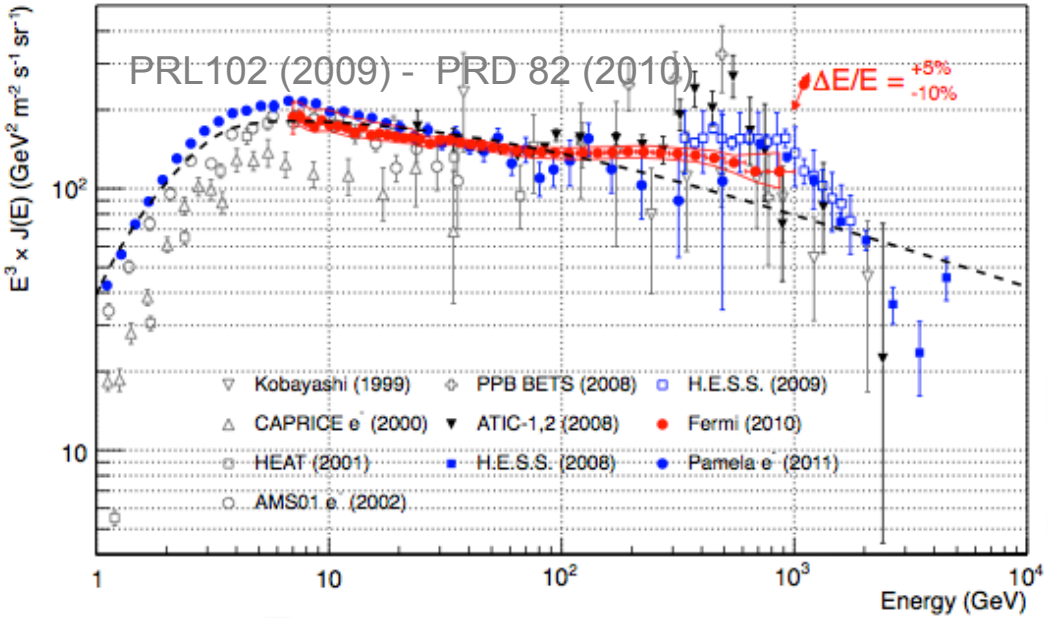
Isotropic" contributions

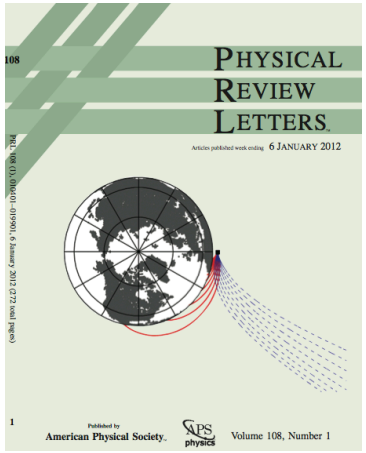
Large statistics, but astrophysics, galactic diffuse background

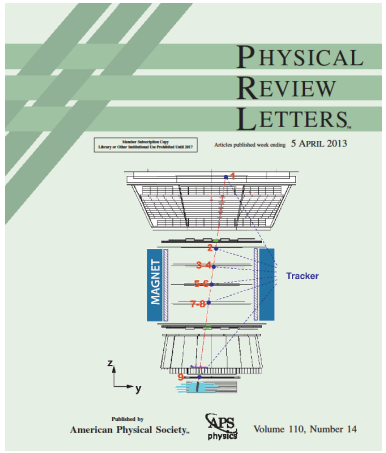
3 Years Sky > 1 GeV

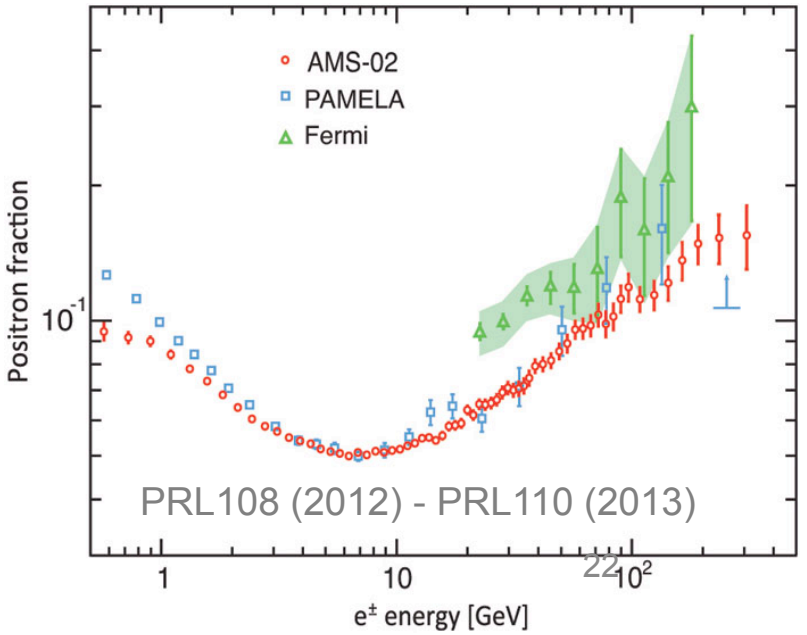
Direct Cosmic Ray Electron measurements

- Creative use of a γ-ray telescope
  - Dedicated event selection
  - Same event reconstruction
  - Earth magnetic field
- Surprising results with independent confirmations
  - Hard inclusive spectrum
  - Rising positron fraction



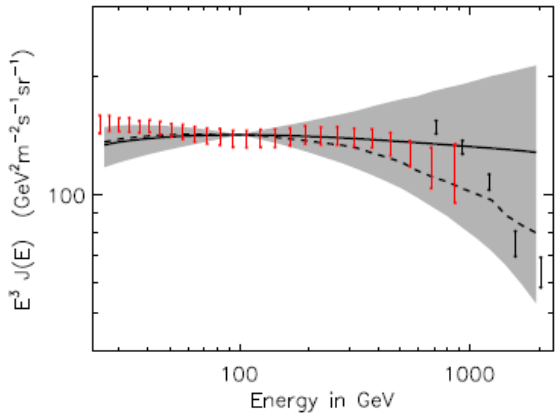






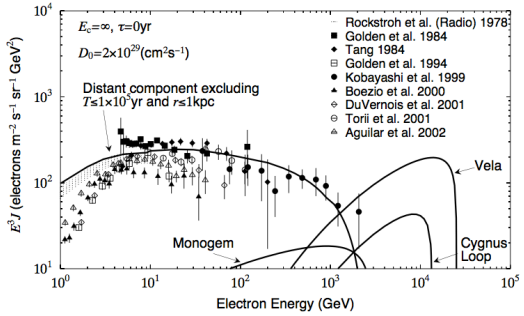
Other possible interpretations? Many !

1) Source stochasticity



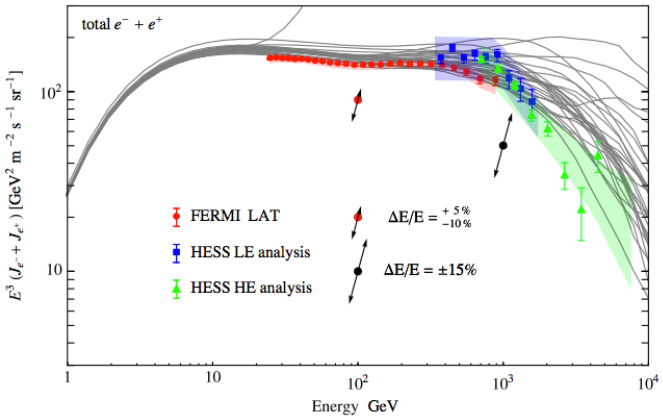
Grasso et al. arXiv 0905.0636

2) Nearby PSR



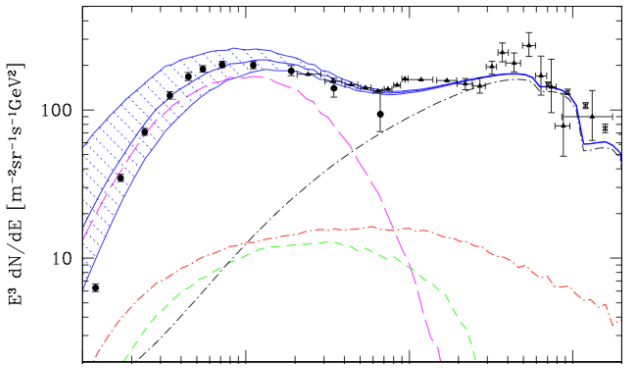
Kobayashi et al. arXiv 038470
(before Fermi and PAMELA)

3) Secondary CR acc.



Blasi arXiv 0903.2794
Ahlers et al. arXiv 0909.4060

4) SNR inhomogeneity



Piran et al. arXiv 0902.0376

But with specific signatures

1. Spectral features
2. CRE anisotropy
3. Rising fractions of secondaries (i.e. antiprotons/p, B/C)
4. Falling positron ratio above 100 GeV

… plus if it is DM it should be detected elsewhere

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

Satellites

dSph ~ 2×10^{-26}

UNID ~ 2×10^{-24}

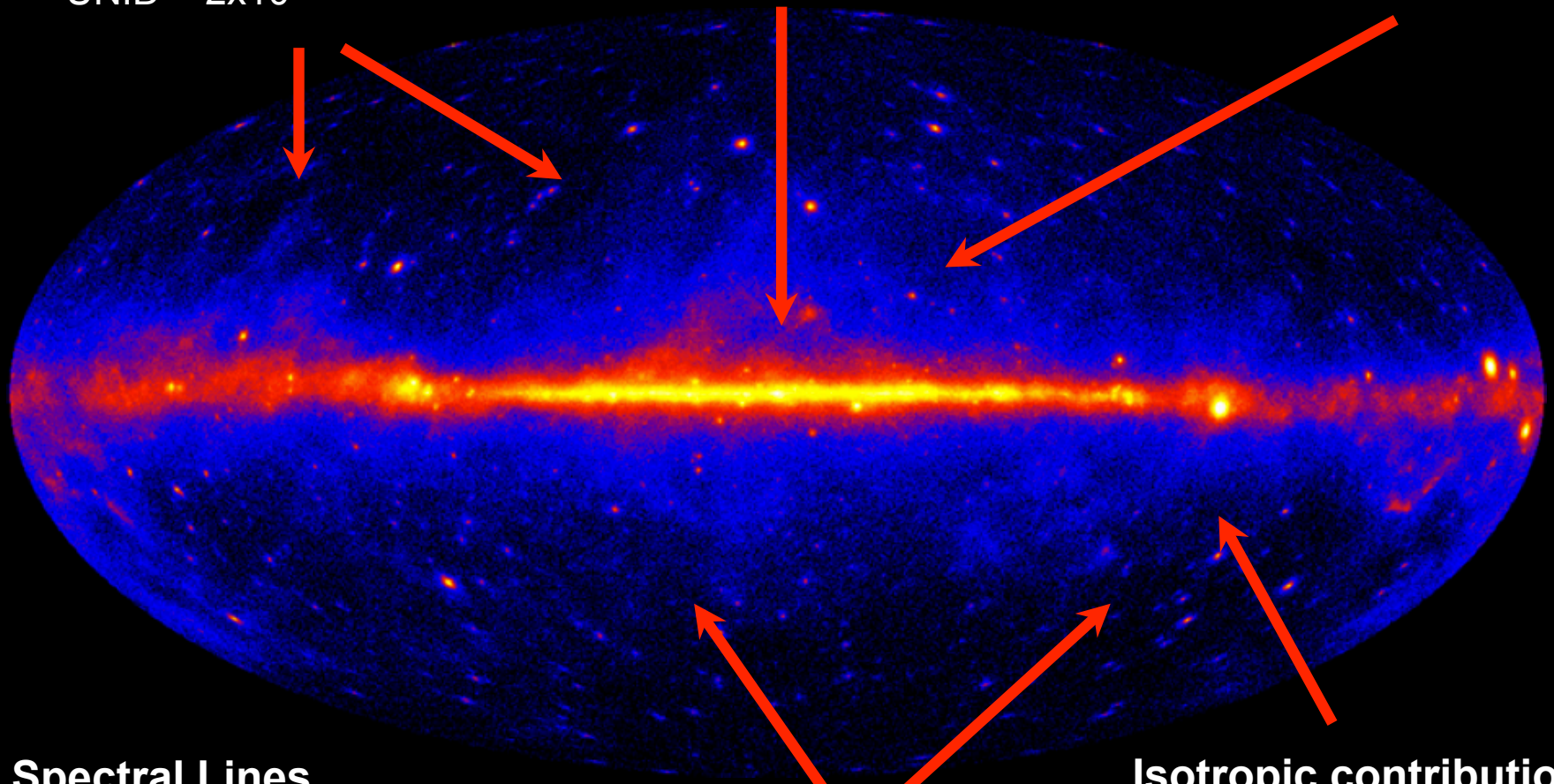
Galactic Center

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

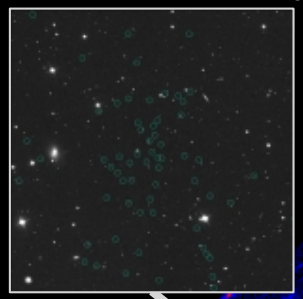
~5×10^{-25}

Isotropic contributions

Vary w/ model & method

Searches for DM in Dwarf Spheroidal Galaxies

Segue 1
Keck Observatory

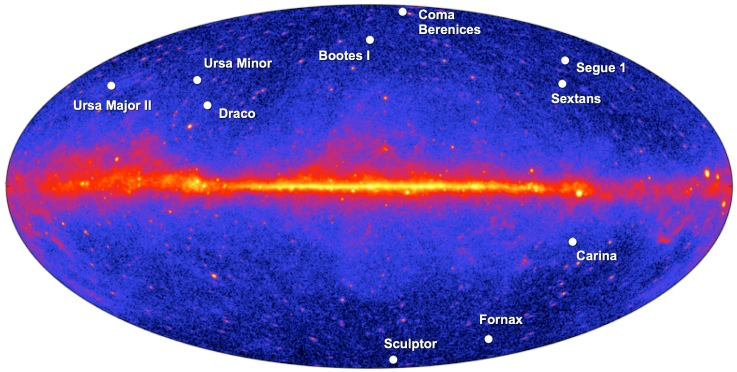


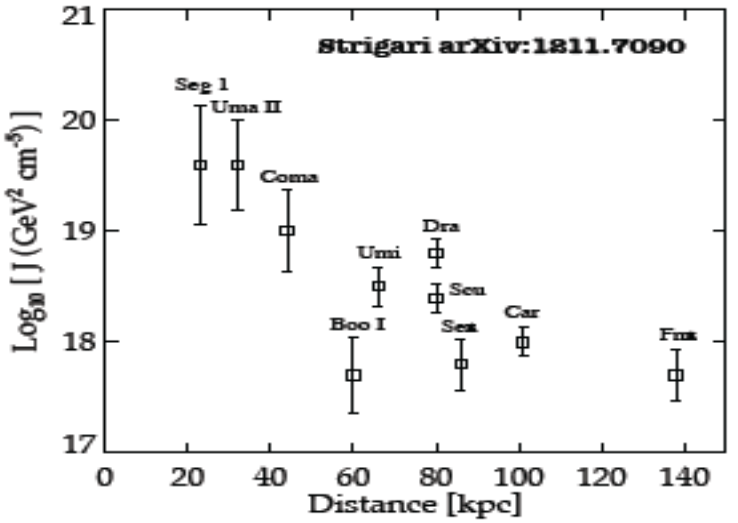
2010ApJ...712..147A [arXiv:1001.4531]
2011PhRvL.107x1302A [arXiv:1108.3546]
2012JCAP...04..016C [arXiv:1111.2604]
arXiv:1205.3620 arXiv:1203.6731

- Look for γ-ray emission from Dwarf Spheroidal galaxies with large, well measured, J-factors at high Galactic latitudes
- This is as a low-signal, low-background search strategy

Dwarf spheroidal galaxies

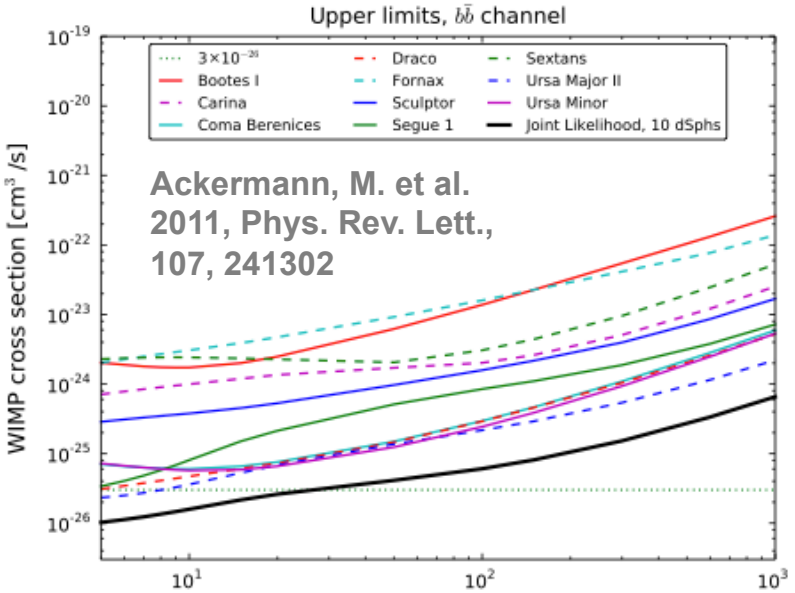
- Dark Matter Dominated
  - 100-1000x visible matter
  - DM estimated from stellar velocity → uncertainties!
- Close (25-150 kpc)
- Free from astrophysical background
  - No active star formation (no energy injection)
  - No appreciable magnetic fields (no acceleration)
  - No gas or dust (no target material)
- Good prospects for significantly more dwarfs
- Standard clean search for isolated source away from Galactic plane

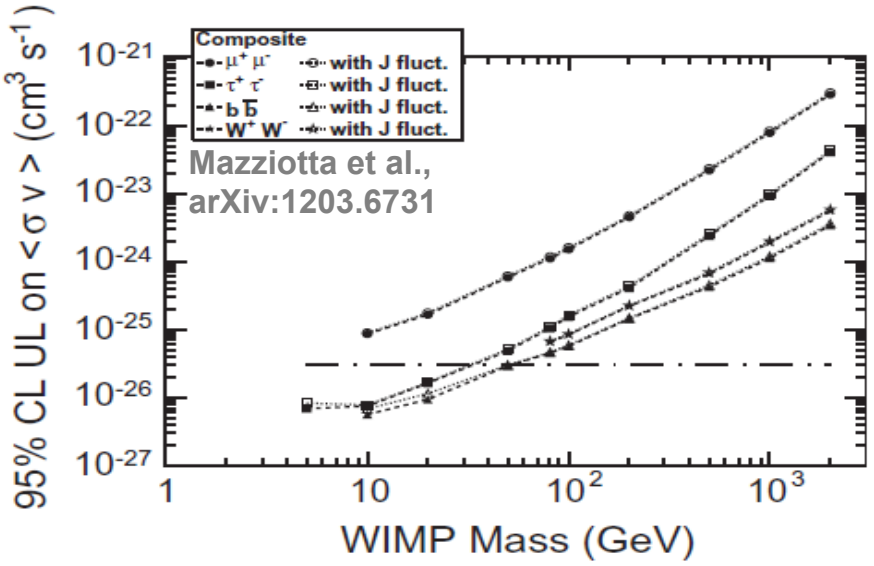


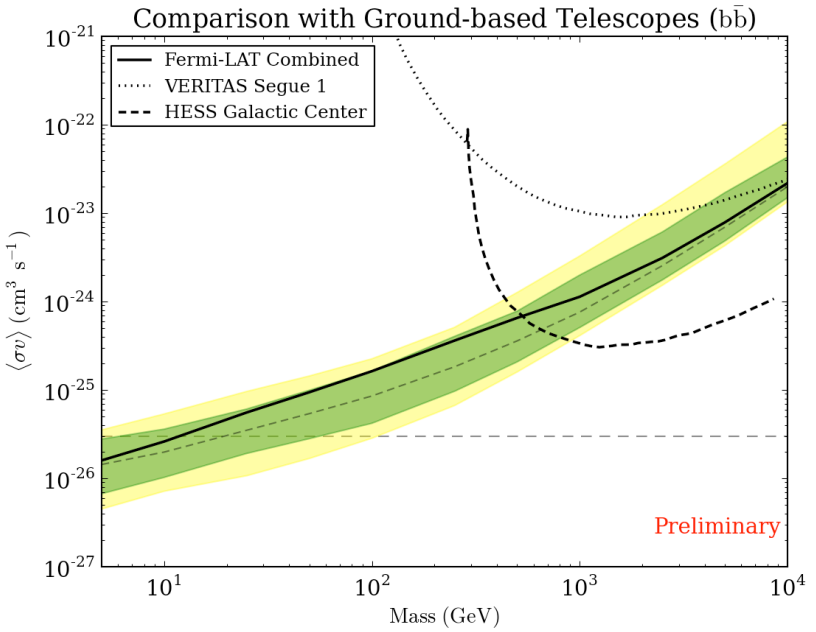


Dark Matter constraints with dwarfs

- Current limit close to thermal relic σ below ~30 GeV
- Different statistical techniques for combined limits from many sources
- Upcoming publication with studies of systematics of the method

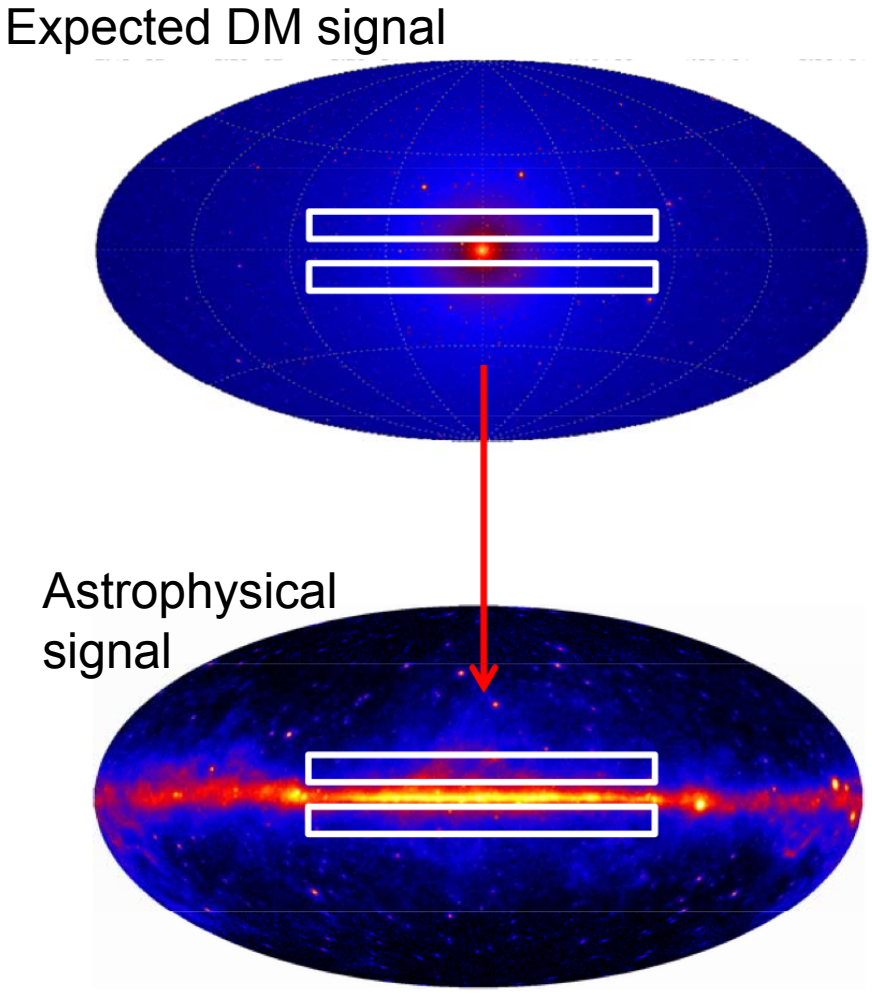






Constraints from Milky Way Halo

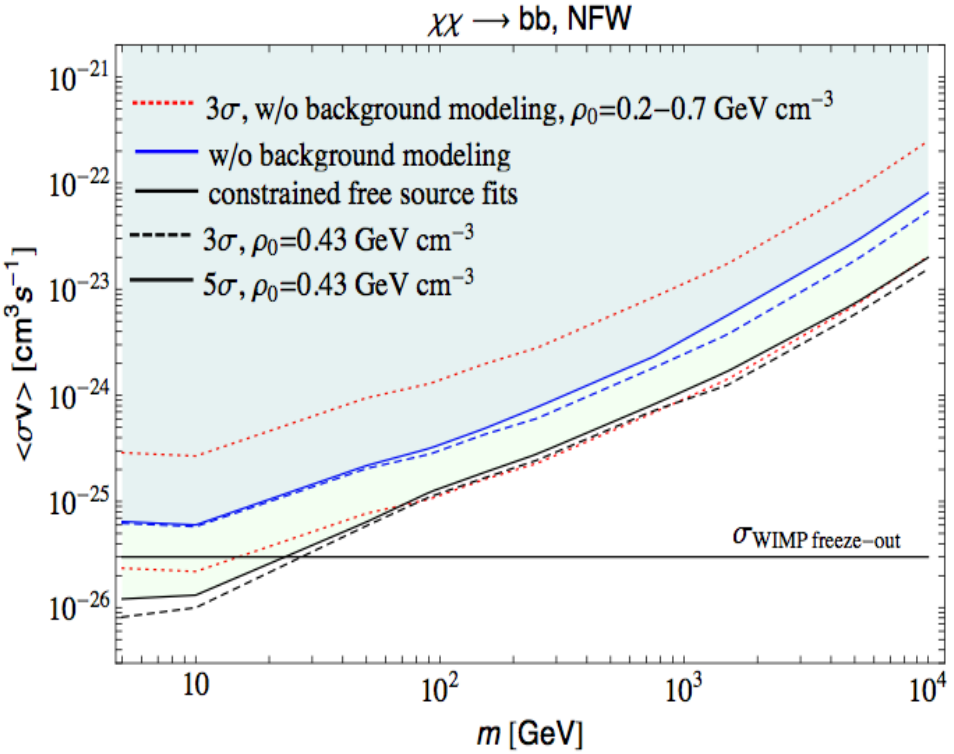
Ackermann+ ApJ 761 (2012) 91

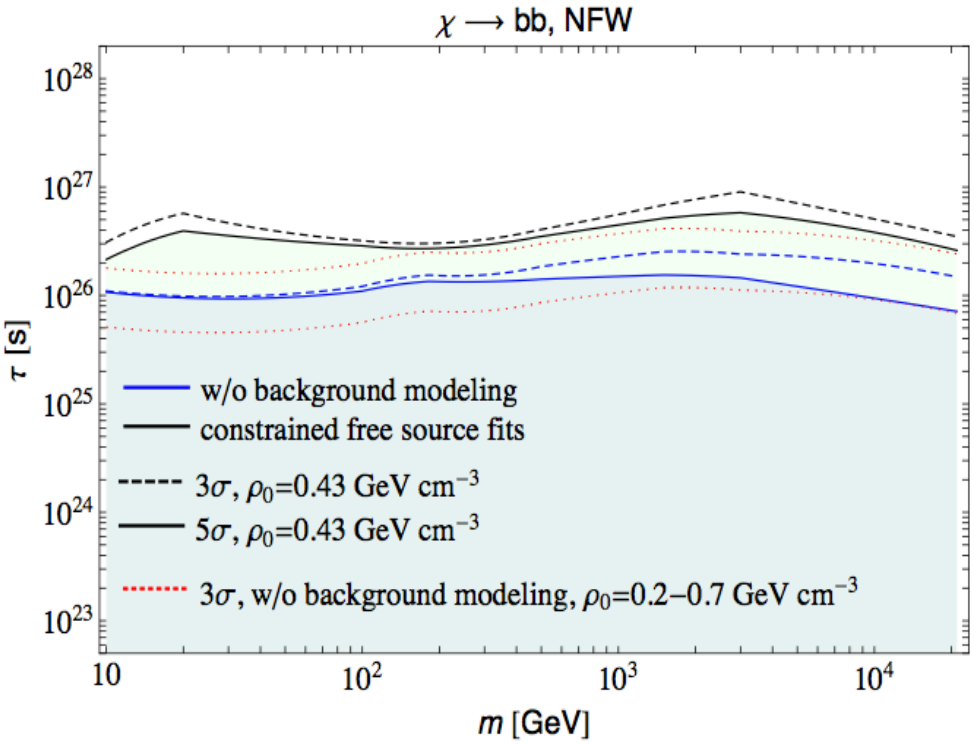


- **two 10^o bands 5^o off the plane**
  - **minimize astrophysical background**
  - **mitigate uncertainties from inner DM density profile**
- **Two approaches to set limits:**
  1. **more conservative: assume emission only from DM**
  2. **more accurate: fit the DM and astrophysical emission simultaneously**
- **Explores systematics of diffuse emission modeling**

Constraints from Milky Way Halo

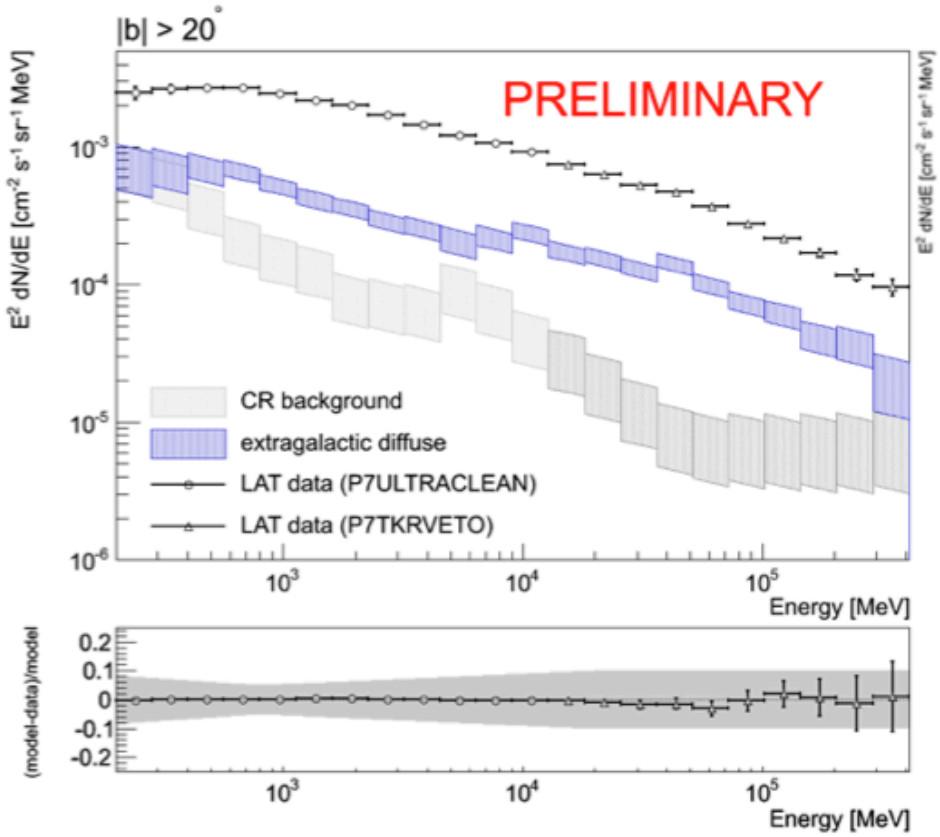
Ackermann+ ApJ 761 (2012) 91

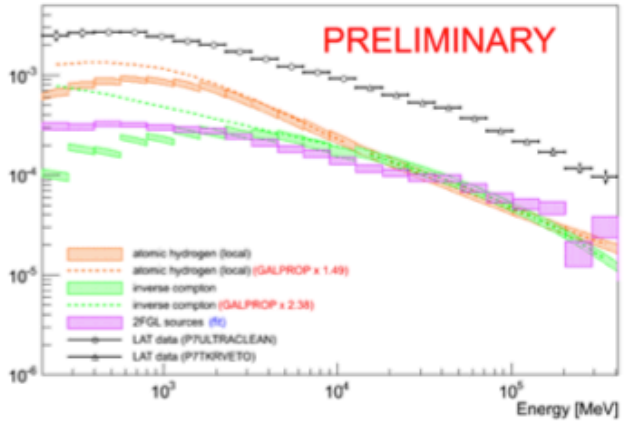




- **Including modeling of the astrophysical emission improves the DM constraints by a factor of ~5**
- **With inclusion of astrophysical backgrounds, the limit constrains a canonical thermal annihilation cross section into b-quarks to a WIMP mass $\gtrsim$ 30 GeV**
- **Marginalizes over many different diffuse emission models to take into account uncertainties in astrophysical foreground subtraction**

Preliminary new LAT EGB spectrum





- Preliminary EGB spectrum between 200 MeV to 410 GeV for default foreground model.
- Error bands include systematics from effective area uncertainty and CR background subtraction.
- ... but **NOT** systematics from foreground model uncertainties. (still under evaluation).

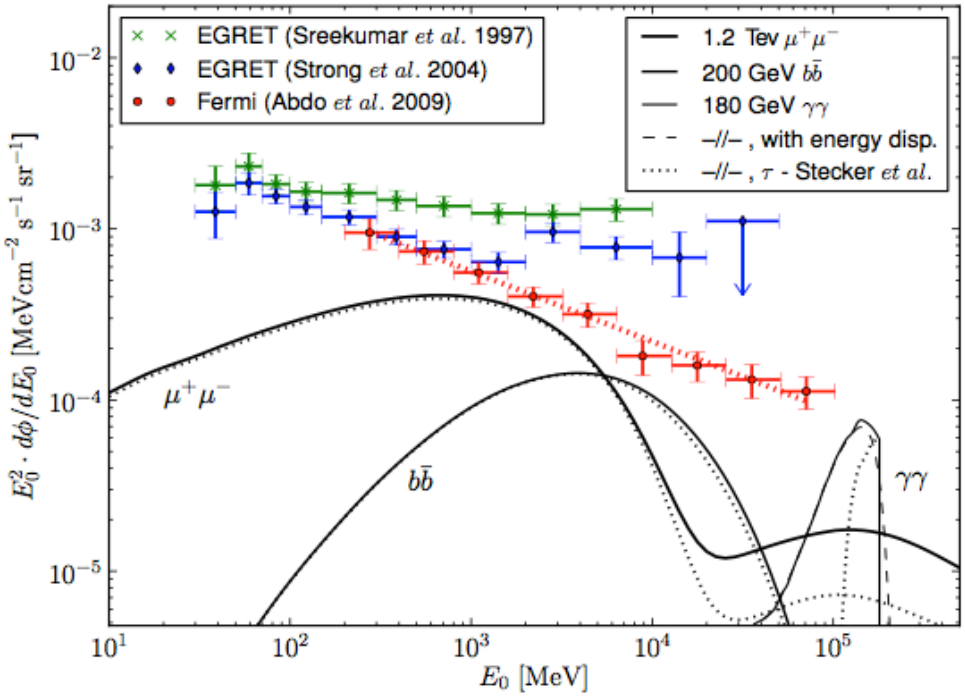
- Publication in preparation for EGB spectrum up to 820 GeV.

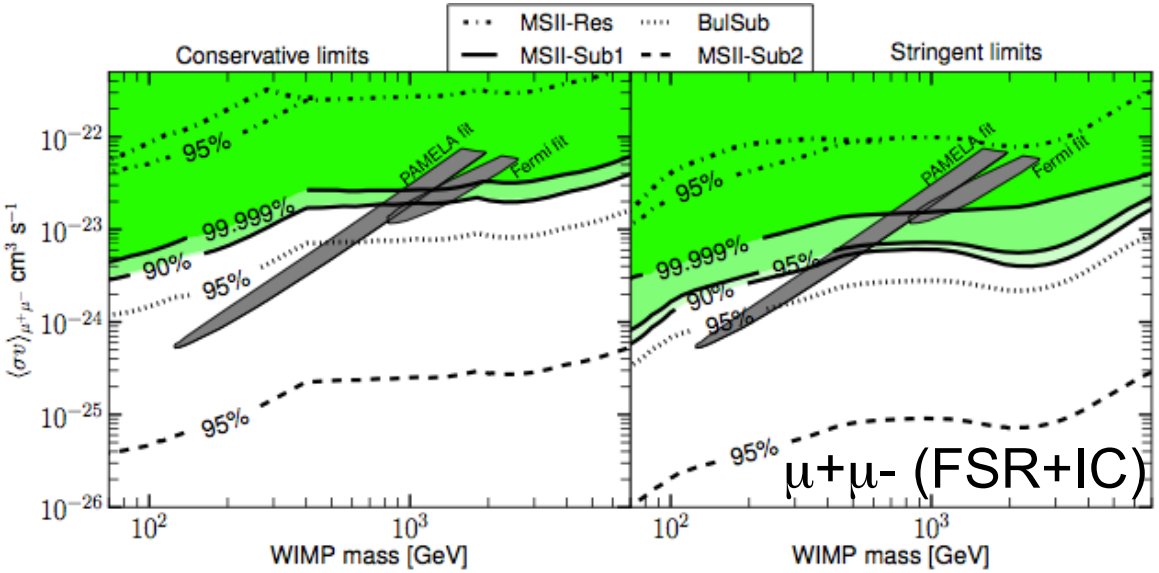
Will follow earlier publication Abdo, A. A. et al. 2010, Phys. Rev. Lett., 104, 101101

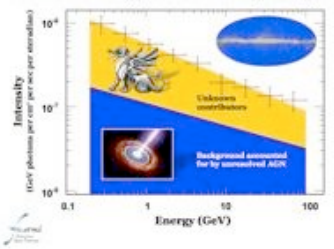
Constraints on Cosmological DM

Ackermann, M. et al. 2011, ApJ, 726, 81

- Search for a DM signal from all halos at all redshifts
- Limits from Fermi EGB
- Predictions affected by
  - DM distribution
  - γ-ray opacity
- Under reasonable assumptions can exclude most DM models explaining CR lepton excess from Fermi and Pamela

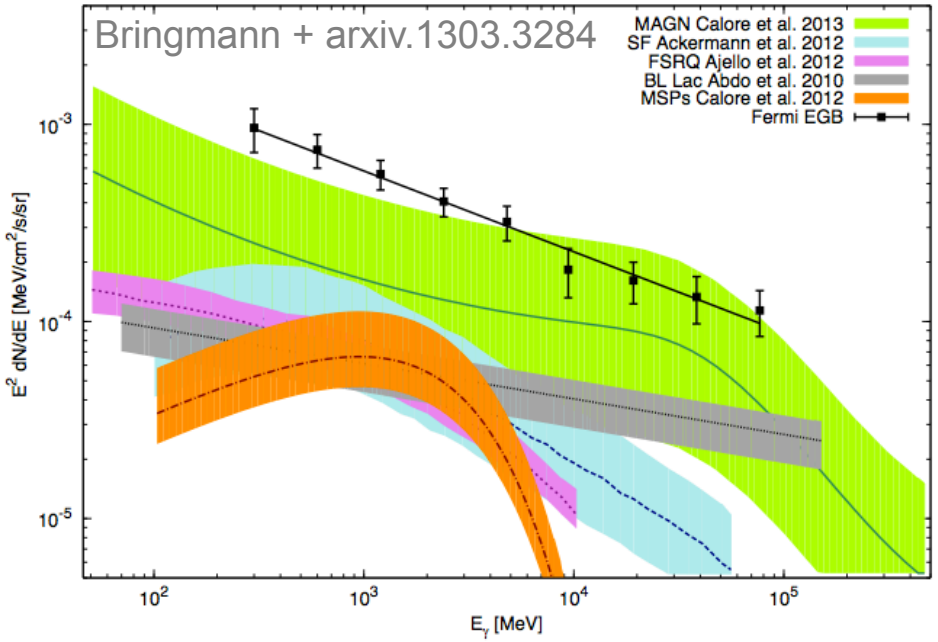


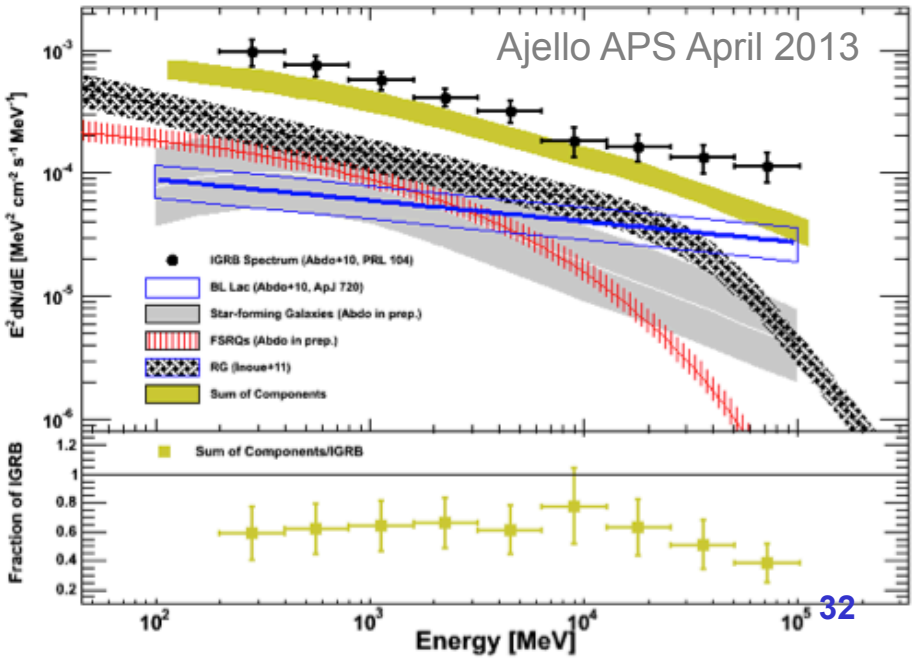




EGB – modeling source contributions

- Undetected sources
  - AGN, Star-Forming Galaxies, ms PSR, Gamma-Ray Bursts
- Diffuse processes
  - Shocks, Dark Matter, UHECR scattering EBL, large CR halo
- Large theoretical uncertainties
- For some classes no gamma-ray luminosity functions
  - Using radio / IR correlation functions

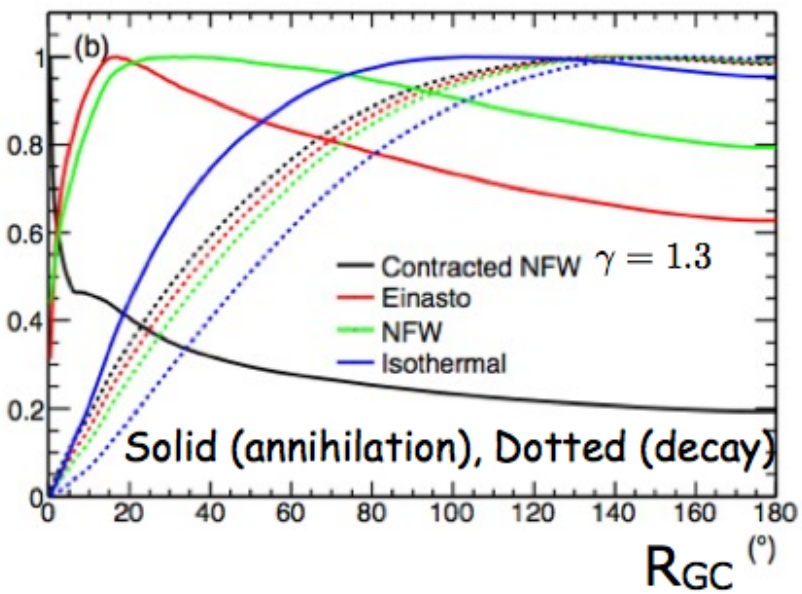


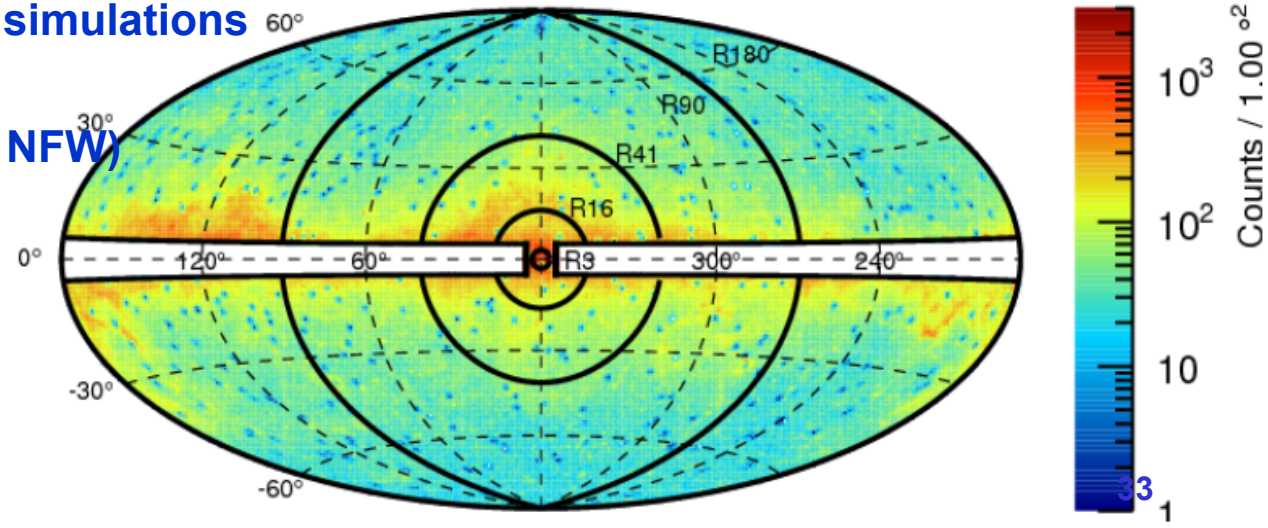


Fermi-LAT Line Search - 4 years data

arXiv:1305.5597

- 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)

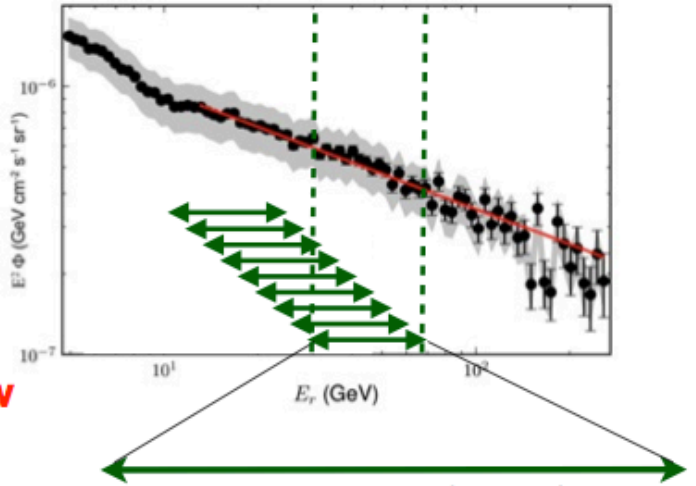




Monochromatic line search

Line search from 5-300 GeV

- Use a sliding $\pm 6\sigma_E$ energy window technique
- Energy steps of $0.5\ \sigma_E$



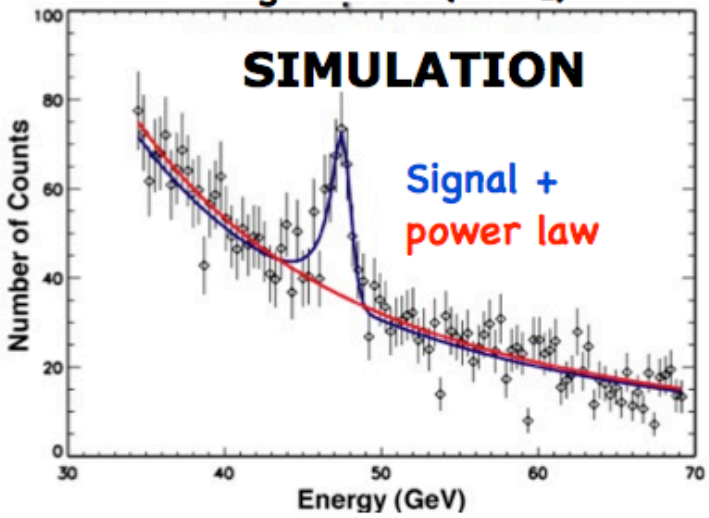
- **Background modeled as single power-law** (in each energy window)
- **Standard: "1D" PDF for the line shape**

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

normalization

Effective Area Corrections

- D_{eff}, effective energy dispersion
- n_{sig}, n_{bkg} and Γ_{bkg} free in fits



2D PDF for Energy Dispersion modeling

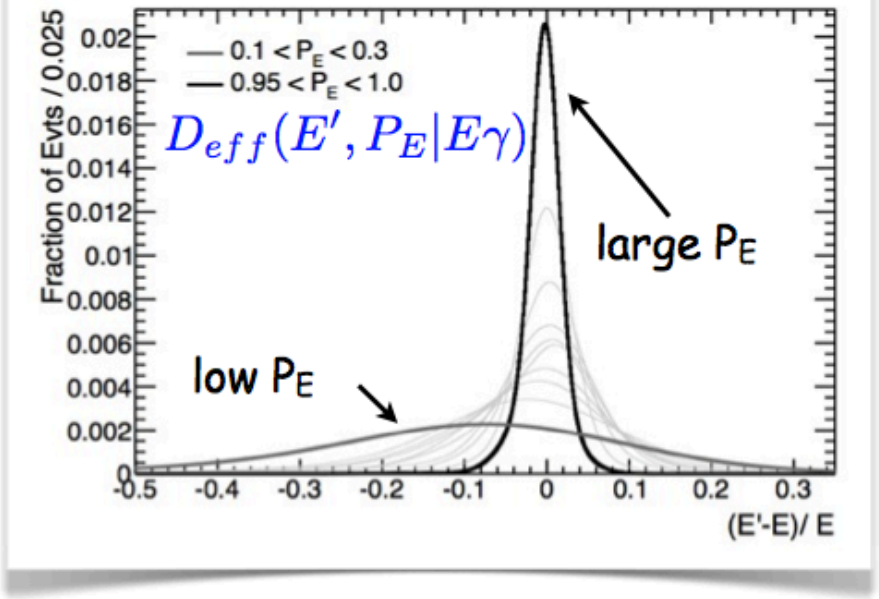
Updated analysis, adds a 2nd dimension to line model: P_E

- P_E is the probability that measured energy is close to the true energy
- Line shape **determined event by event** from a 2D pdf – function of both E and P_E

Predicted Spectrum = Signal Model + Power-law Background

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

Dispersion — "2D" PDF in (E,P_E)

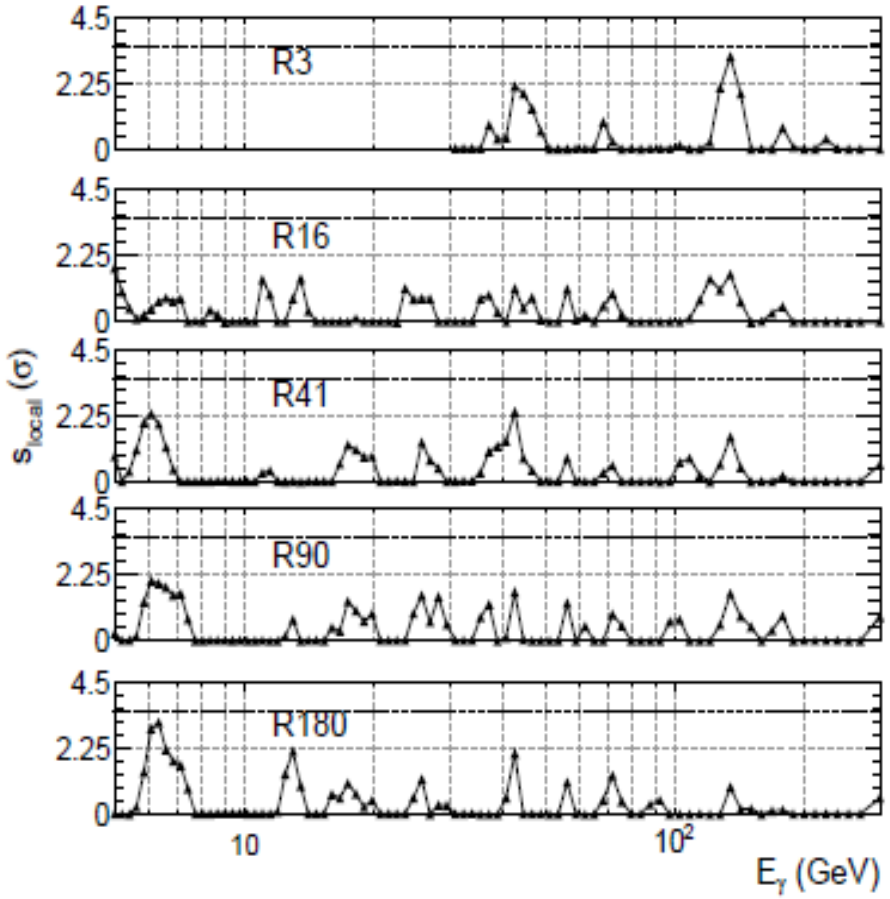


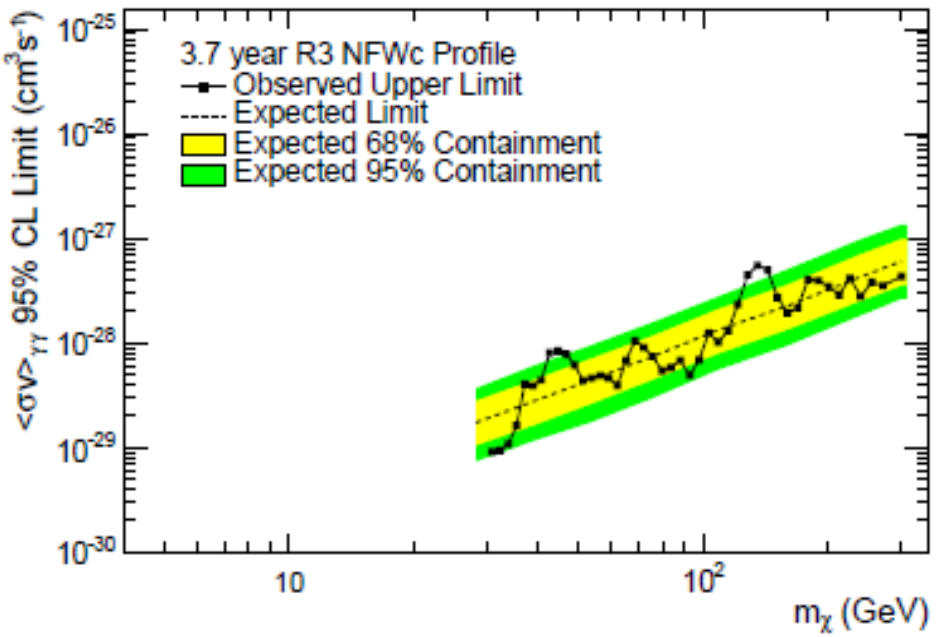
Including P_E in energy dispersion model

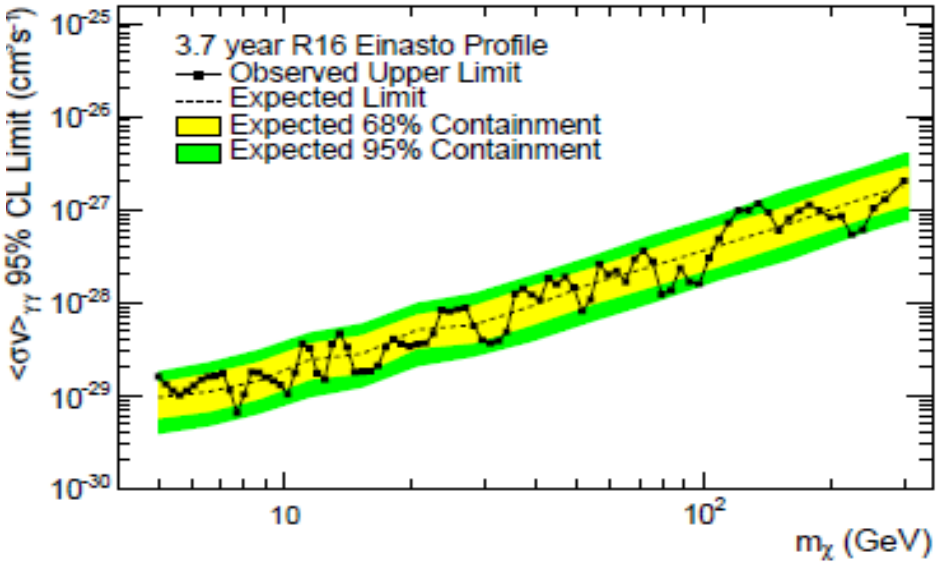
⇒ ~15% improvement to signal sensitivity (when there is signal) and counts upper limit (when there is no signal).

⇒ Includes a more complete understanding of the expected shape of a gamma-line

95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ Upper Limit R3-R16

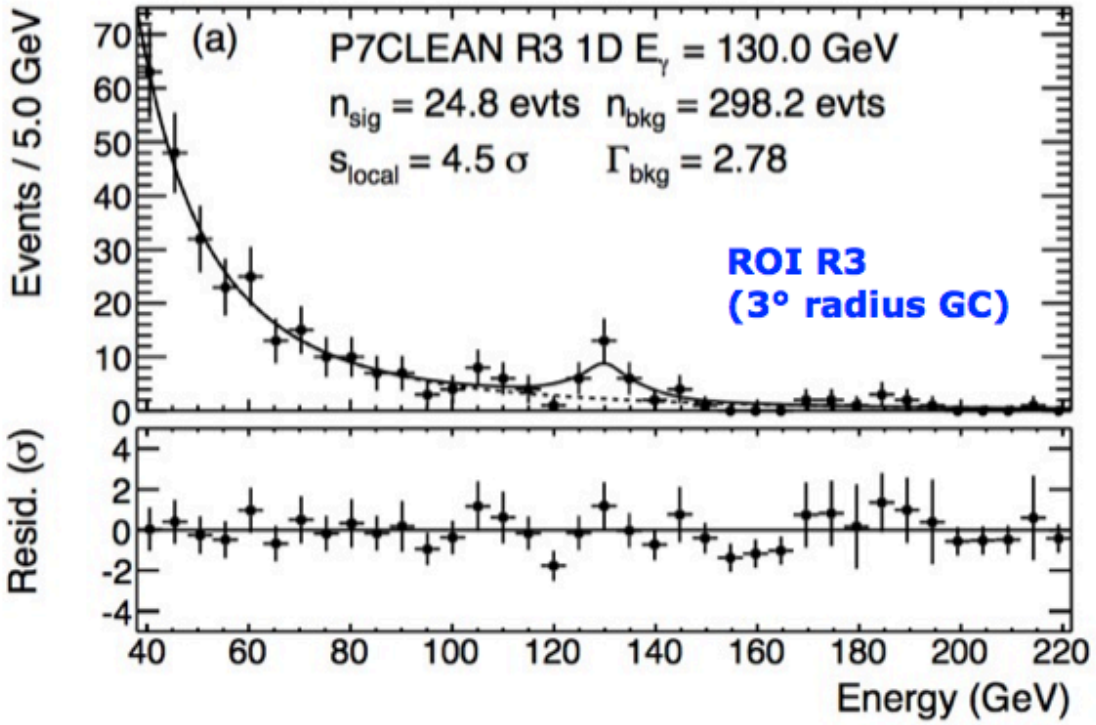






- **No globally significant lines detecte**
  - **All fits have global significance < 2σ**

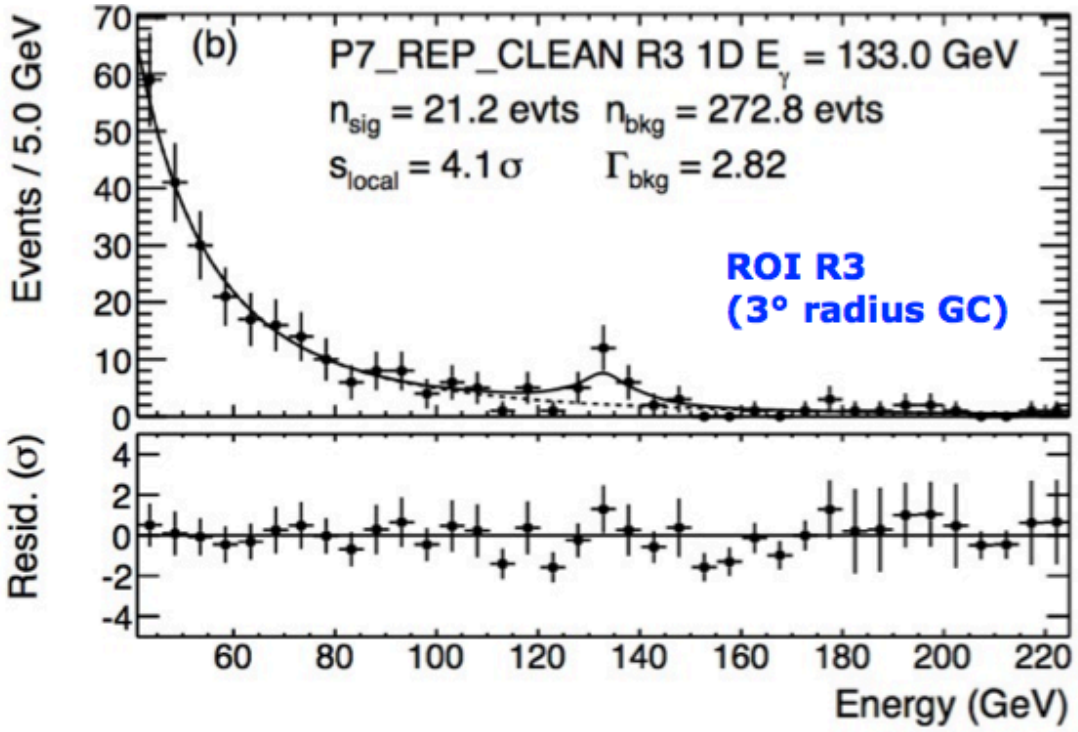
Fermi LAT line search near 133 GeV



- **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

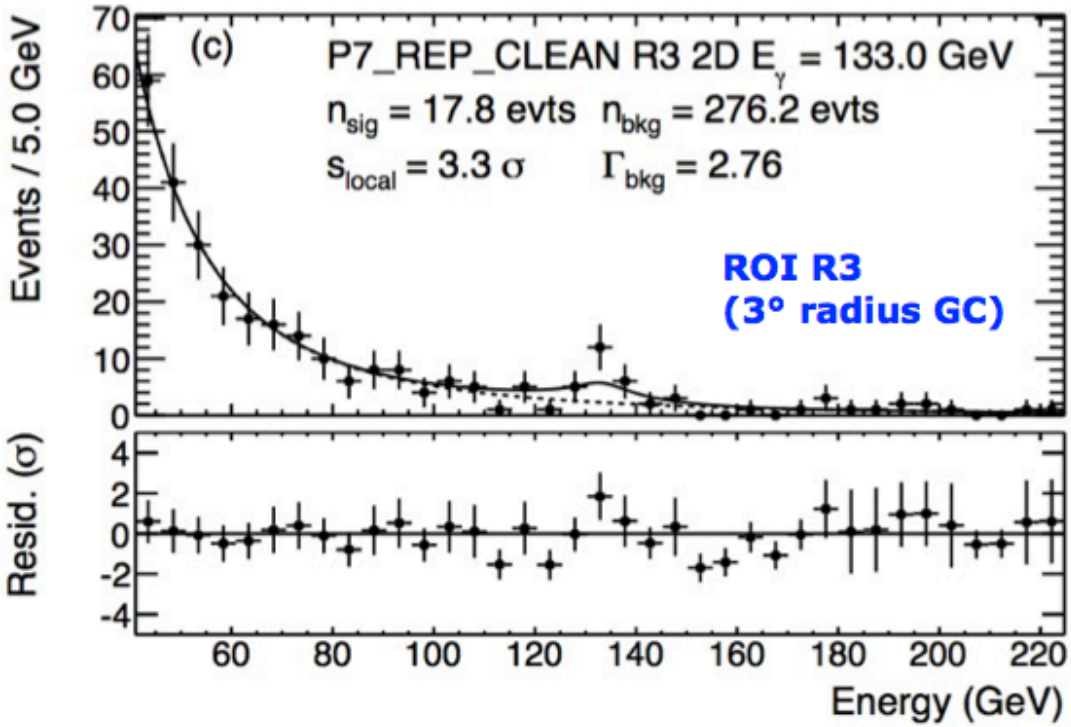
Fermi LAT line search near 133 GeV



- 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

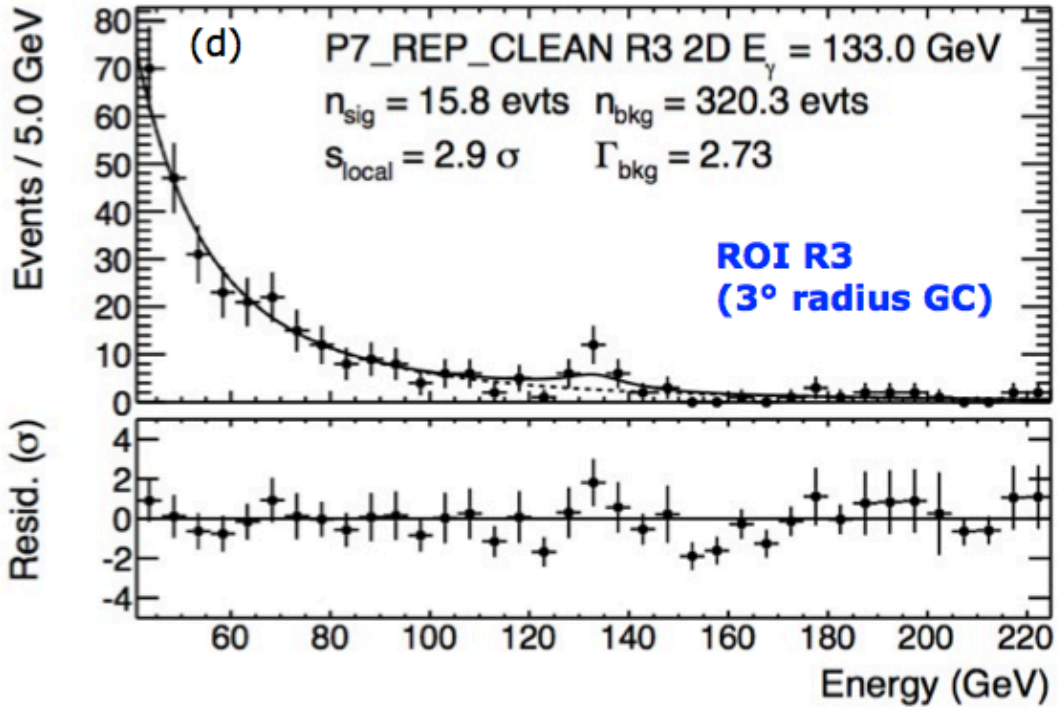
Fermi LAT line search near 133 GeV



- 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

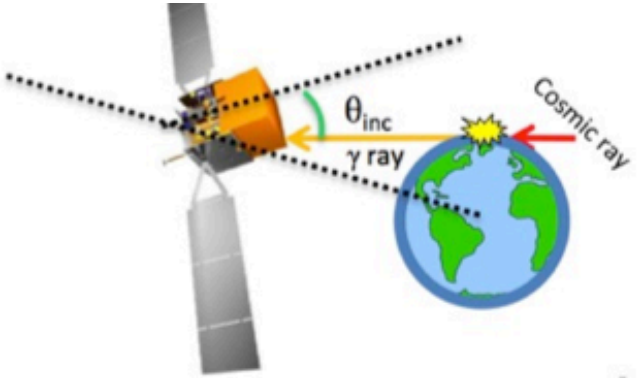
Fermi LAT line search near 133 GeV

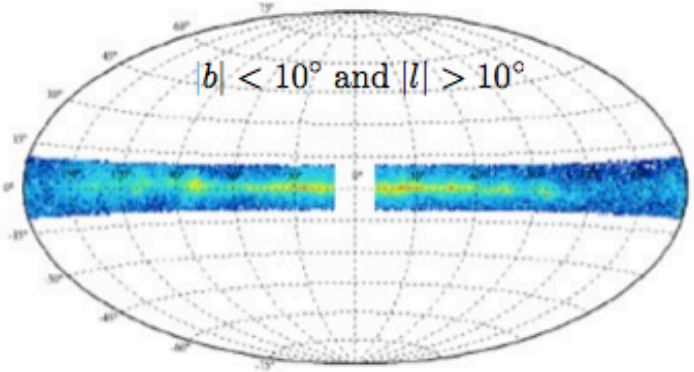


- 4.5σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  1D PDF (no use of P_E), P7CLEAN data
- 4.1σ (local) 1D fit at 133 GeV with 3.7 year reprocessed data
  1D PDF (no use of P_E), P7REP_CLEAN
- 3.3σ (local) 2D fit at 133 GeV with 3.7 year reprocessed data
  2D PDF (P_E in data), P7REP_CLEAN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

Control regions

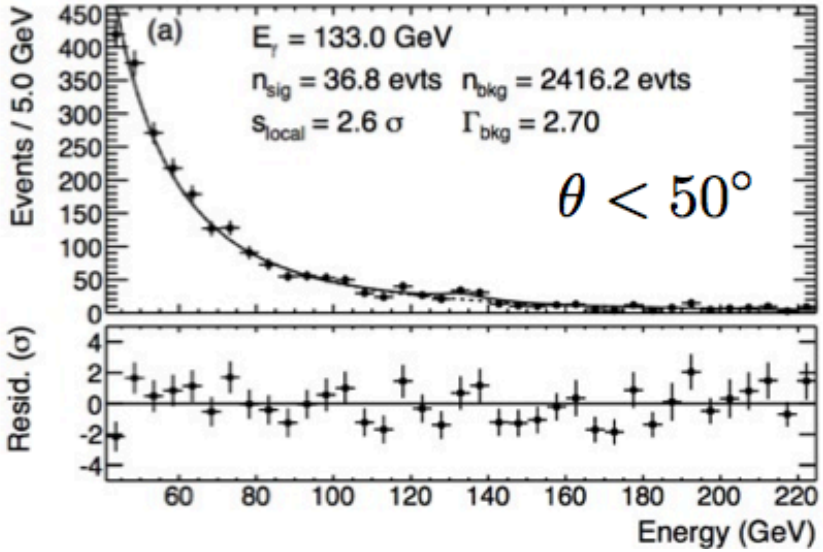




Earth Limb: expect a bright smooth power-law spectrum

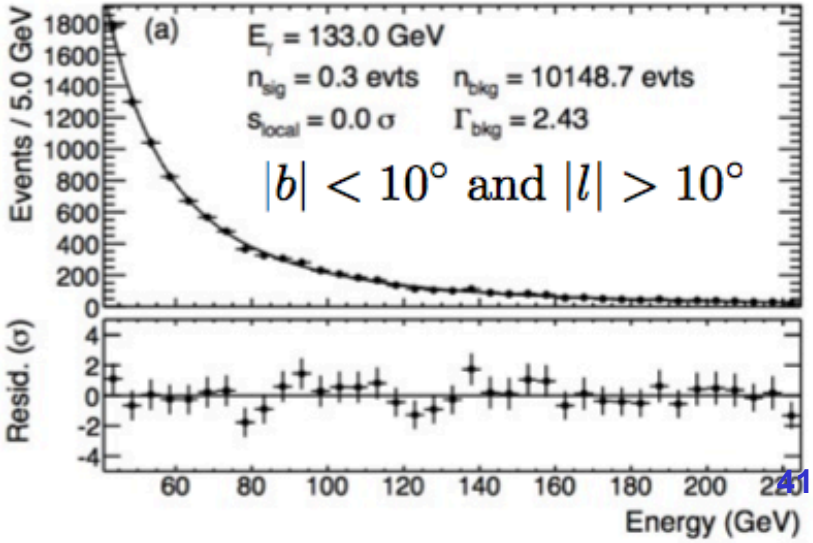
Weaker feature around 130 GeV

2.0σ, s/b≈14±7% (GC:3.3σ, s/b≈58±18%)

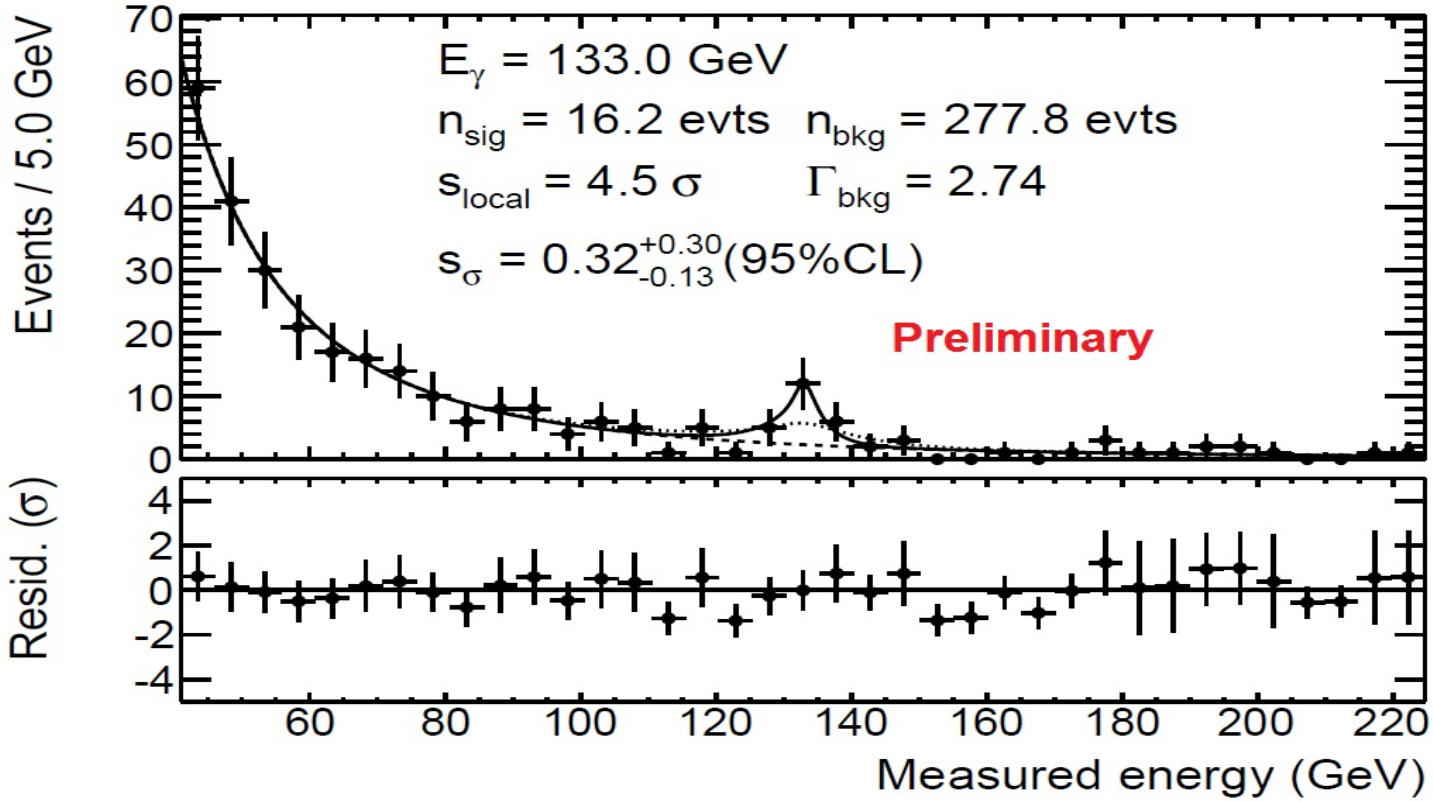


Galactic Disk: expect bright and astrophysical source dominated

No features seen around 130 GeV



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 measured in beam tests and detector simulations**

Systematic uncertainties

Three classes of possible effects:

1. signal to flux conversion $\delta\mathcal{E}$; e.g. exposure, effective area
2. signal strength rescaled $\delta n_{\rm sig}$; e.g. line shape, search step-size
3. induce or mask a signal δf; e.g. bkg curvature, CR contamination

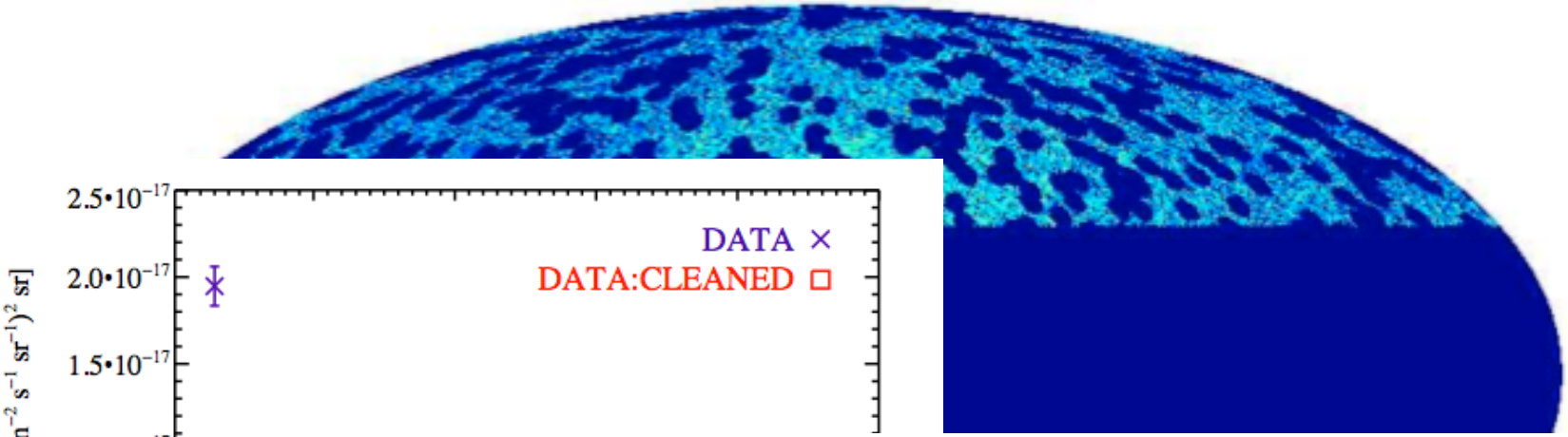
	Quantity	Energy	R3	R16	R41	R90	R180
1	$\delta\mathcal{E}/\mathcal{E}$	5 GeV	±0.10	±0.10	±0.11	±0.12	±0.14
	$\delta\mathcal{E}/\mathcal{E}$	300 GeV	±0.10	±0.10	±0.12	±0.13	±0.16
2	$\delta n_{\rm sig}/n_{\rm sig}$	All	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$
3	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

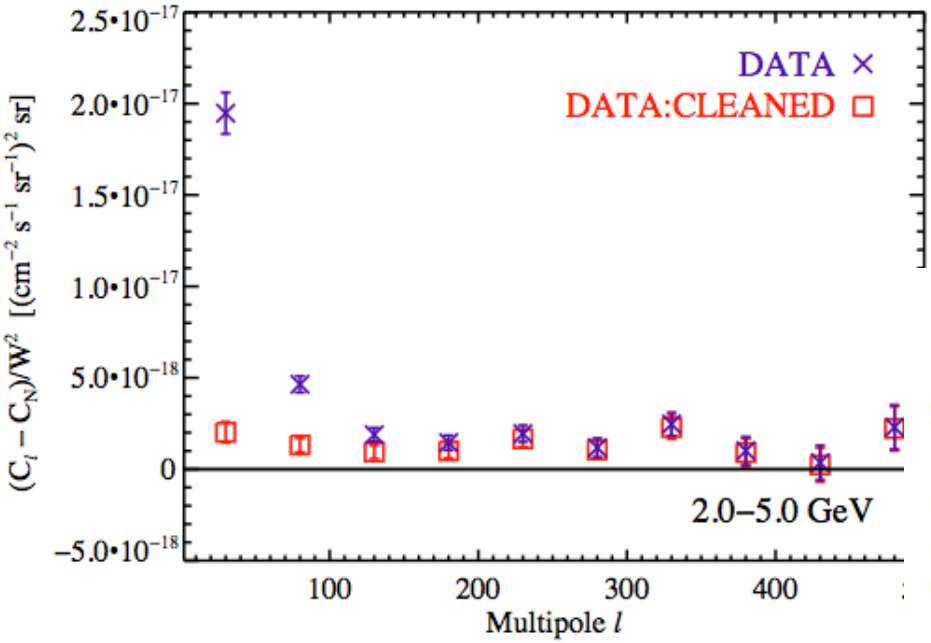
3.3σ feature @ 133GeV in R3 have much larger! signal fraction f >40%

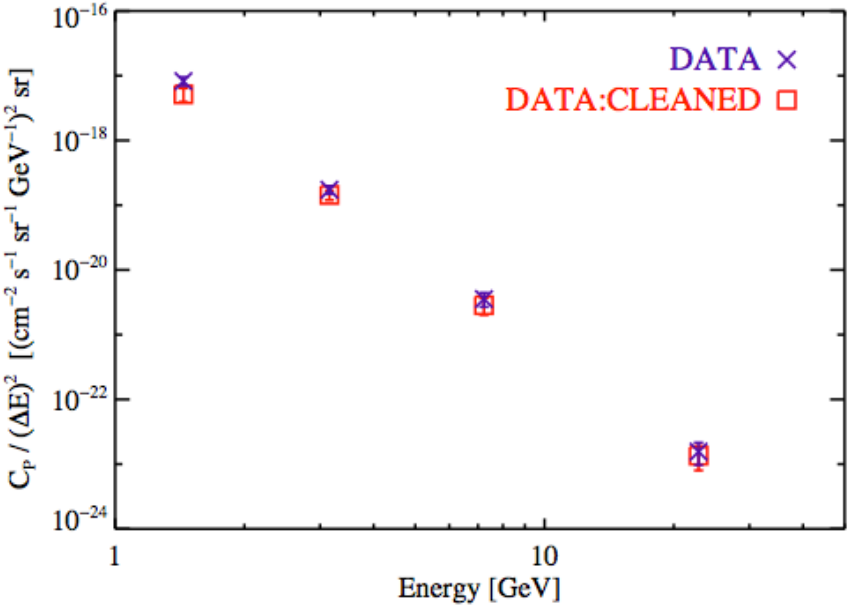
A systematic effect could explain the 3.1σ feature @ 6.3 GeV w/ f ~1%

Other targets and techniques for DM searches

2012, Phys. Rev. D, 85, 083007







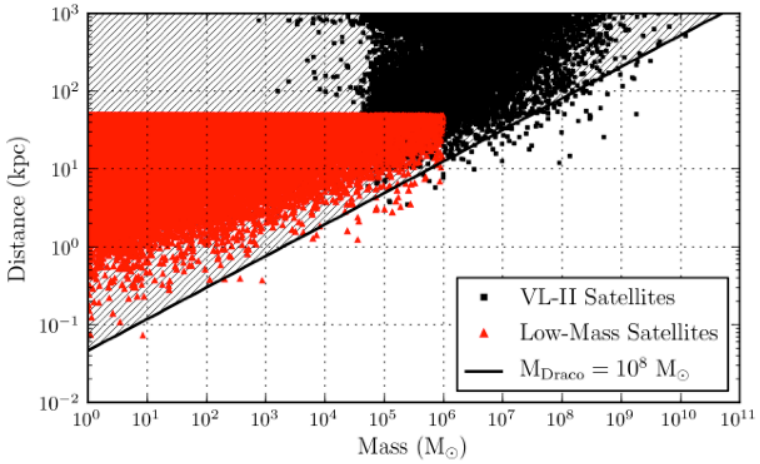
Anisotropy in diffuse emission
High multiple power spectrum

Other targets and techniques for DM searches

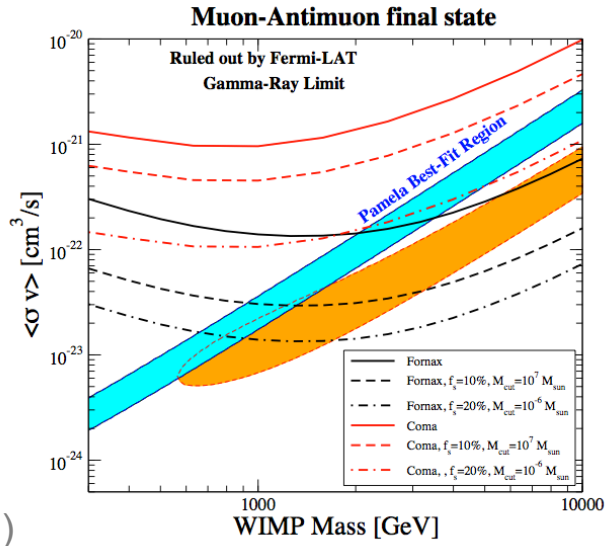
Gamma rays from Galaxy Clusters

Search for Dark Matter satellites

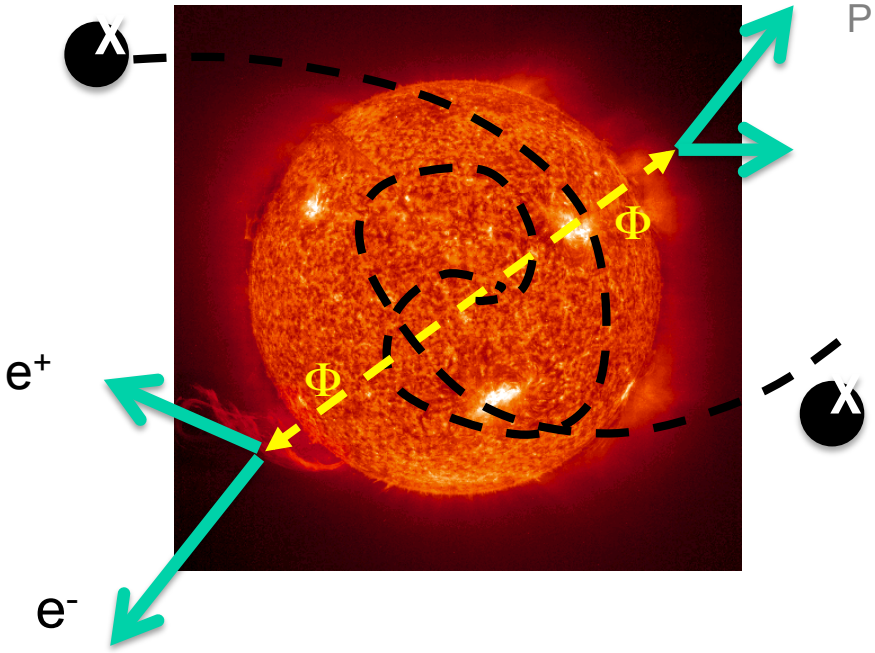
ApJ, 747, 121 (2012)



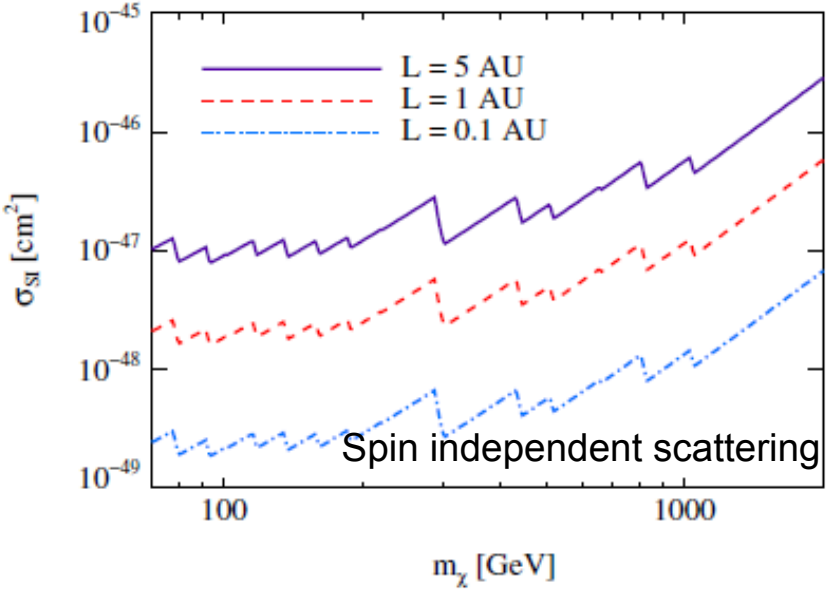
JCAP 1005:025 (2010)



Search for WIMPs through CRE excess from the Sun



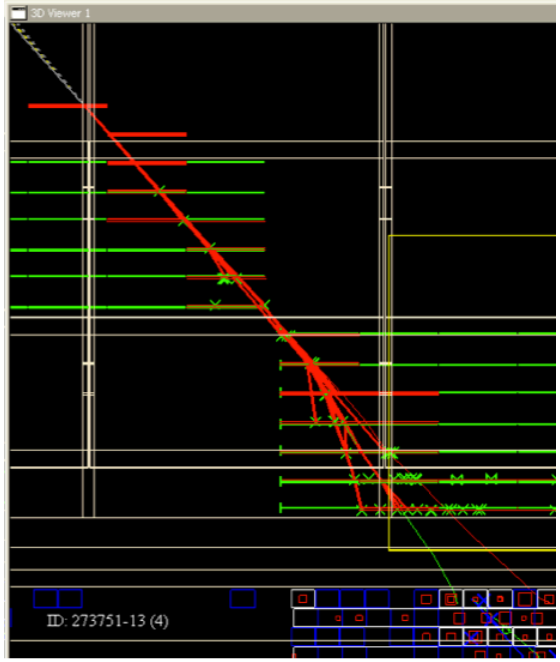
PRD 84, 032007 (2011)

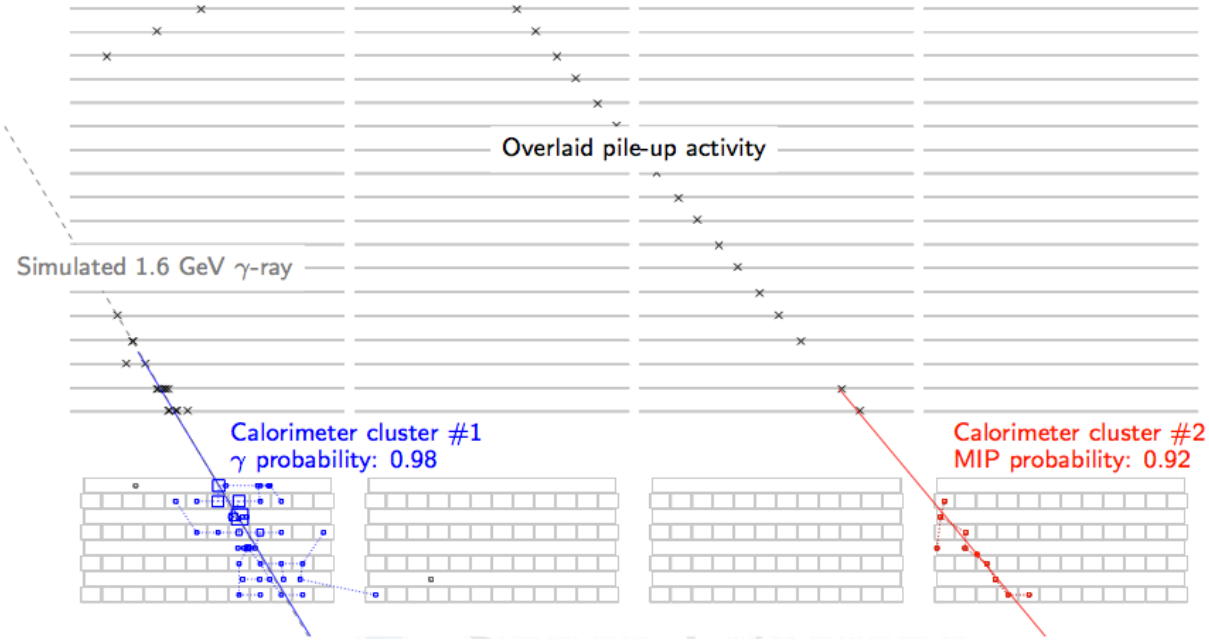


Upcoming LAT developments – Pass8

arXiv:1303.3514

- Current Pass8 development has major advances in
  - CAL recon: multiple clusters + new full 3D shower profile recon to extend up to ~3TeV
  - TKR recon: improved pat-rec to reduce PSF tails
  - `P8_PROTO_SOURCE` +25% photons wrt `P7_SOURCE` > 1 GeV
- Development heavily relies on LAT MC and data/MC agreement with flight datasets

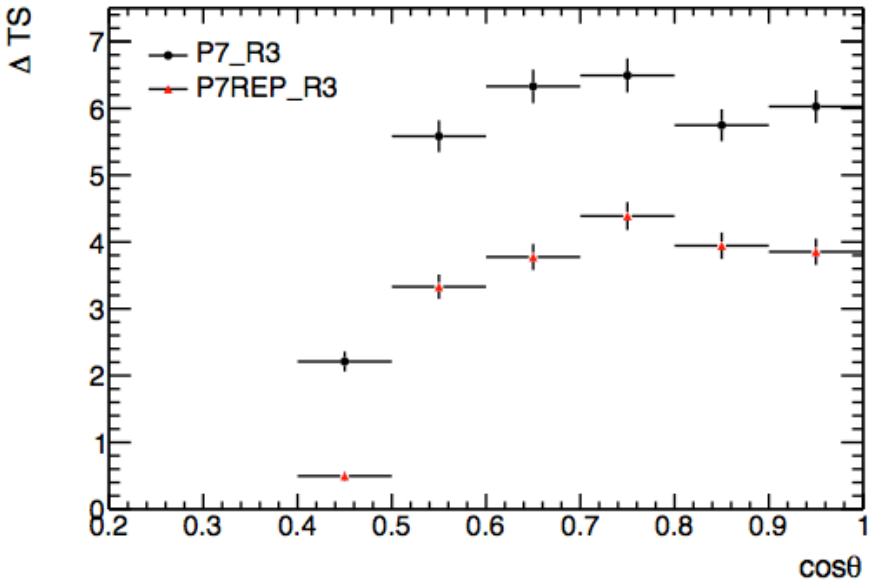


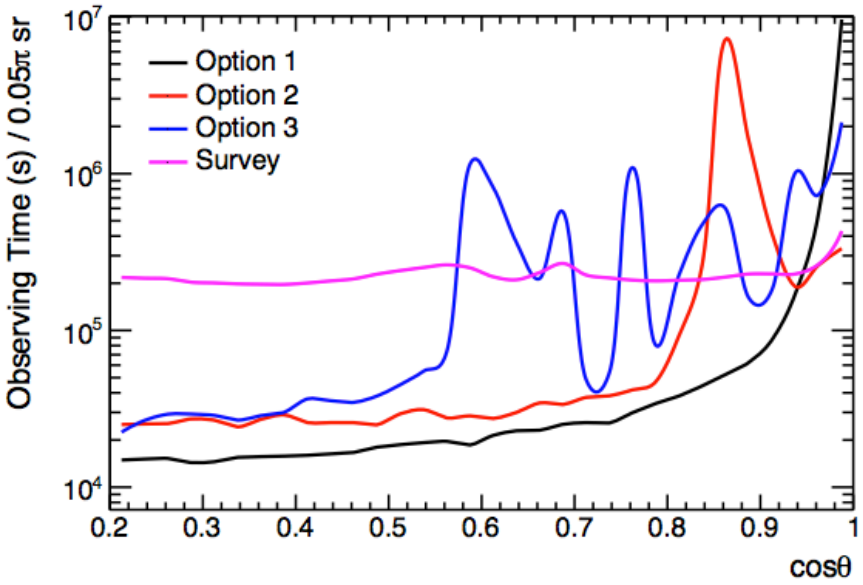


Fermi observatory - alternative observation?

http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/obs_modes.html

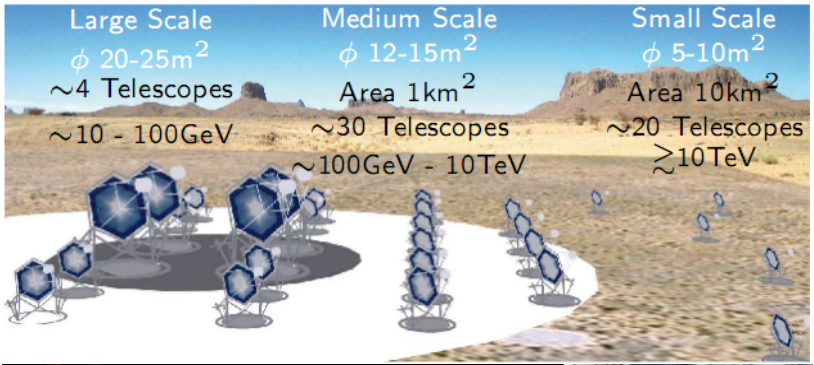
- **Mission call for white papers - 2 papers suggest increased exposure to GC via modified observations**
  - **Option3 provides reduced impact to other science**
    - ☺ line, e^+, GC emission, short transients, subset of AGN and PSR
    - ☹ dwarfs, EGB, pulsar monitoring, catalog
  - **LAT team trigger conditional to persistence of line significance with Pass8, no independent exclusion (HESS2)**

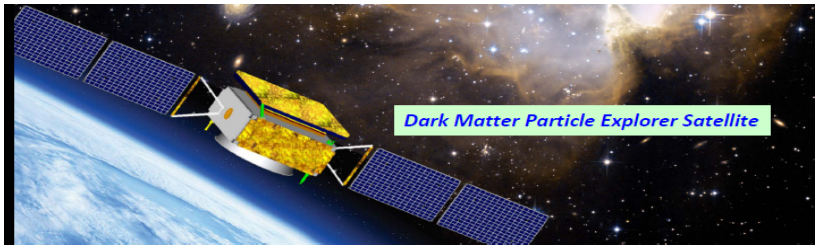


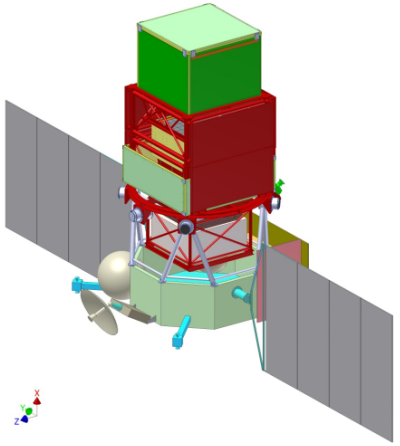


Next generation gamma ray experiments

- CTA: a km^2 Cherenkov telescopes array
  - ~10x sensitivity current IACTs
  - ~10 GeV -~10 TeV,
  - FOV up to 10°, best angular resolution 0.02°
- CALET on ISS :
  - ~% of energy resolution (30 X_0)
  - good angular resolution and high e/p separation
  - Launch planned 2014
- DAMPE satellite:
  - ~% of energy resolution (31 X_0)
  - good angular resolution and high e/p separation
  - Launch planned 2015-2016
- Gamma-400 satellite
  - good angular and energy resolution in gamma rays
  - high precision charged particles detector up to several TeV for e- ad PeV for protons!
  - launch planned 2018.







Summary

- The LAT Science Analysis continues to be rich and broad
  - Focusing on catalogs that benefit from large statistics populations
  - Exploring the richness of alternative diffuse emission models in all science areas
- Comprehensive searches for Dark Matter candidates
  - many different targets in the sky, diverse analysis techniques and systematic uncertainties
  - Complementary with direct and collider searches
  - Upcoming significant developments in LAT event data for enhanced sensitivity and resolution (Pass8)