Fermi Gamma-ray Space Telescope

An extreme point of view: the Fermi gamma-ray sky

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On behalf of the *Fermi* LAT collaboration

Les Rencontres de Physique de la Vallée d'Aoste, February 24, 2014

OUTLINE

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  - The Fermi observatory
  - The Large Area Telescope (LAT)
- Latest Highlights
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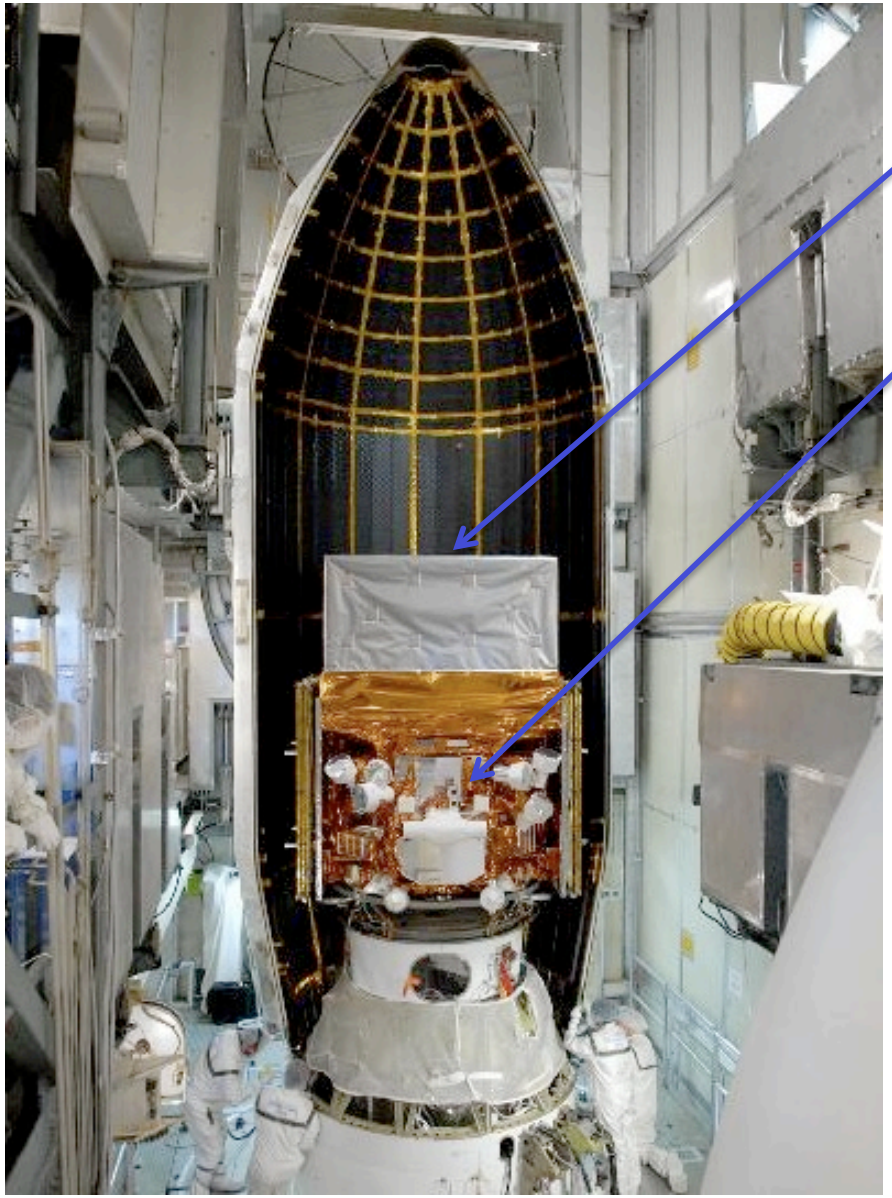
  - Galactic (Fermi bubbles, SNR, Novae)
- Dark Matter Searches
  - Overview of the basic strategies
  - Gamma-ray line searches, Dwarf Galaxies
- Summary

The Fermi observatory



- Large Area Telescope (LAT)
  - 20 MeV – > 300 GeV
- Gamma Burst Monitor (GBM)
  - 8 KeV – 40 MeV

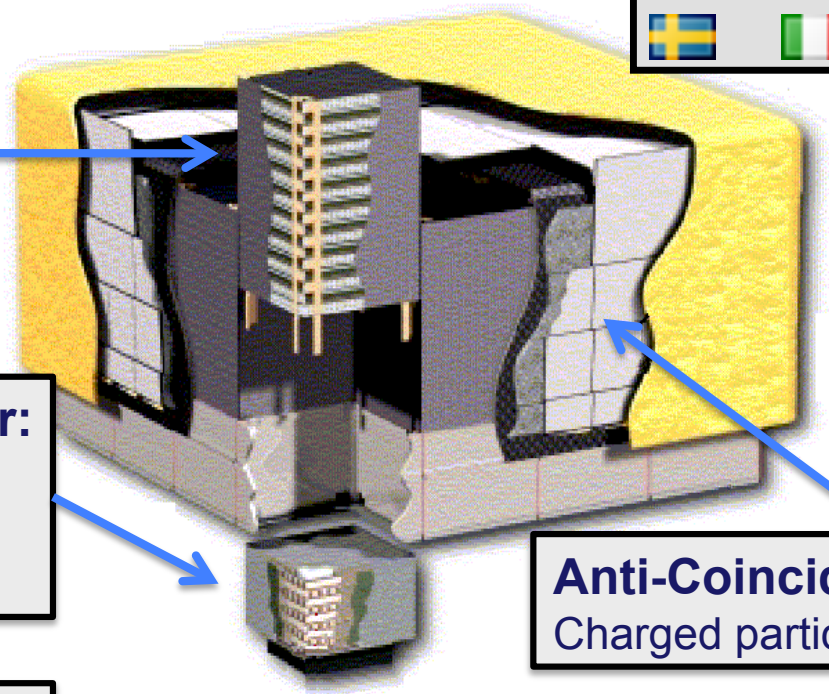
- Launched 11 June 2008, Delta II Rocket
  - Circular orbit, 565km altitude, 25.6 deg inclination
- Operations
  - Primary mode: sky survey
    - scan entire sky every 3 hours
  - Autonomous Repoint Request
  - Target of Opportunity

The Fermi Large Area Telescope

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

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

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

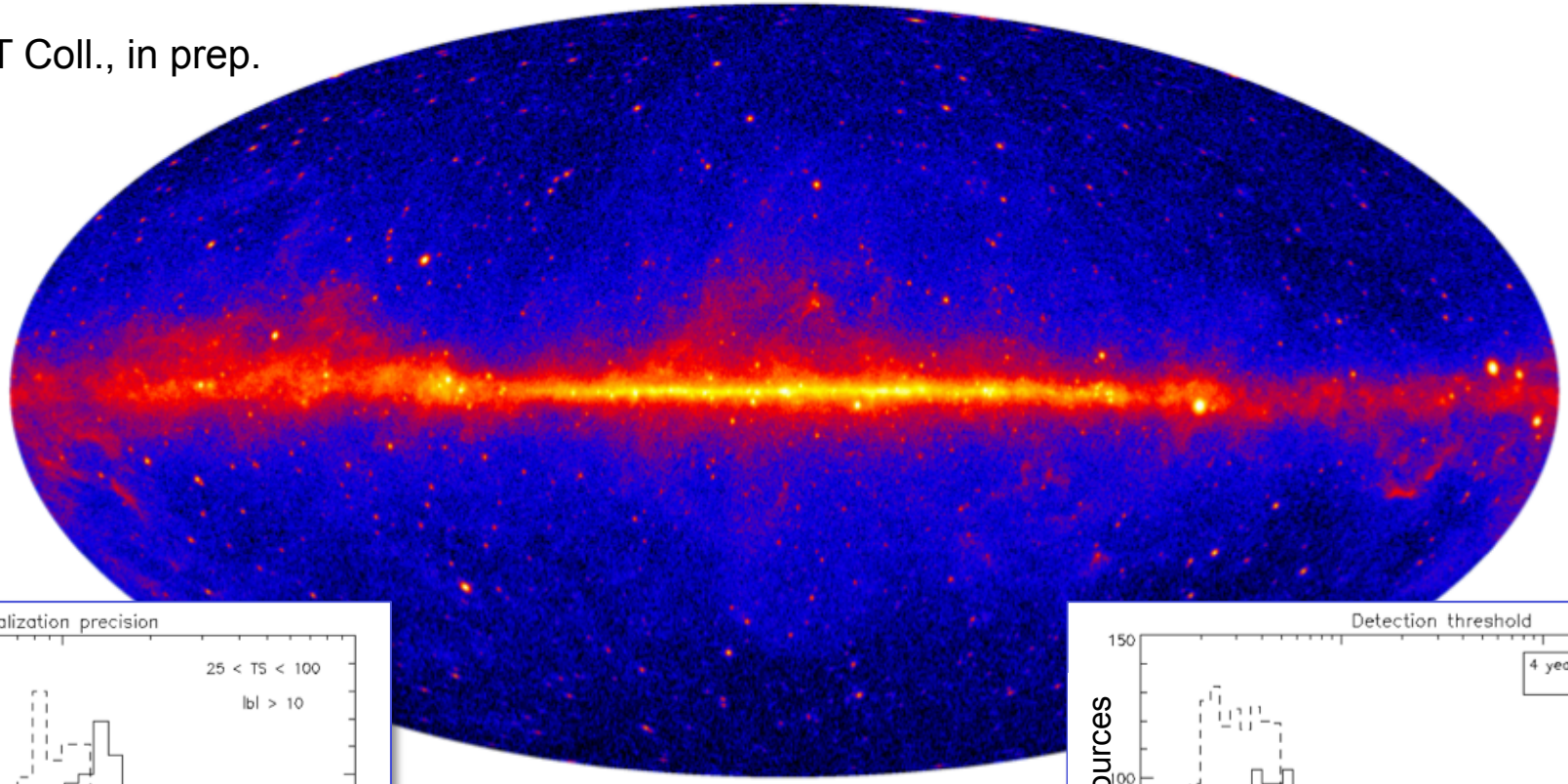
Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
With 2.5 sr Field-of-view LAT sees whole sky every 3 hours

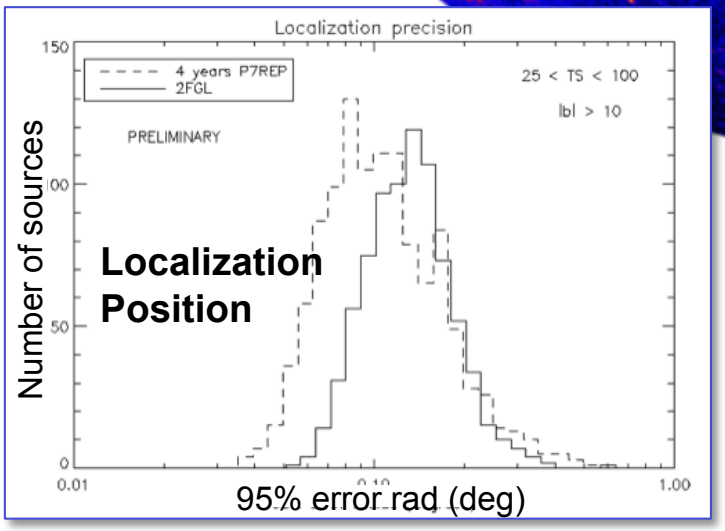
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

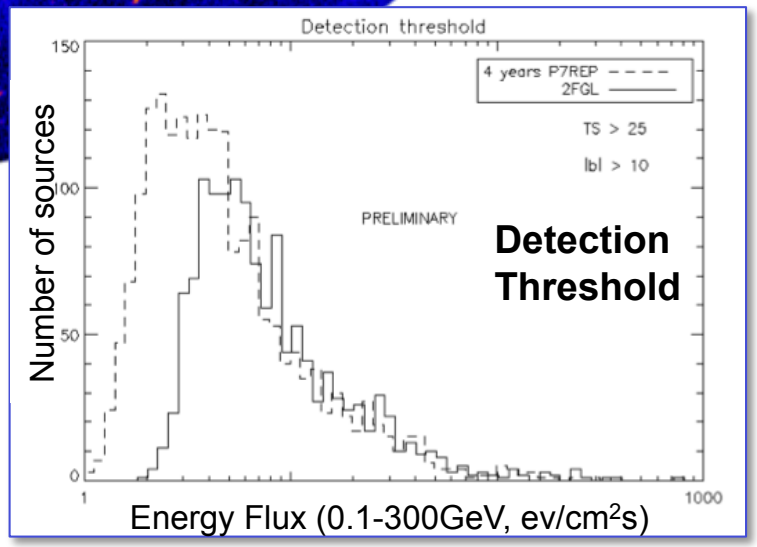
The Third *Fermi* LAT Catalog (3FGL)

Fermi LAT Coll., in prep.



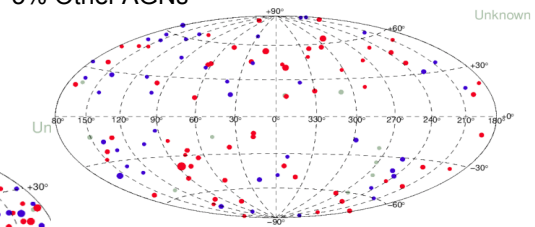
Counts map of 4 years of *Fermi* LAT data, E > 1GeV



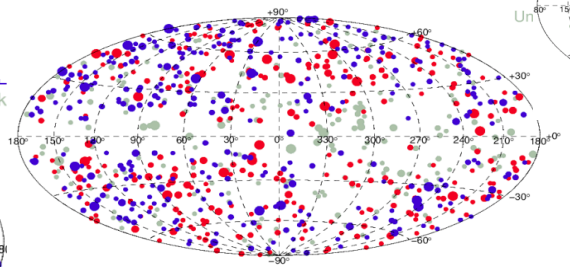


Fermi LAT AGN Catalogues

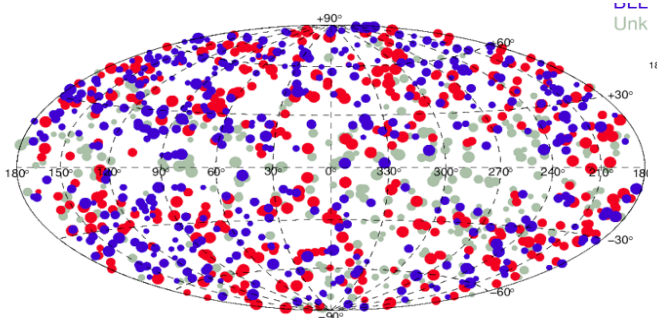
LBAS-high latitude (Abdo et al 09)
(3 months of data, TS>100, P6_V1)
50% FSRQs
36% BL Lacs
5% Other AGNs

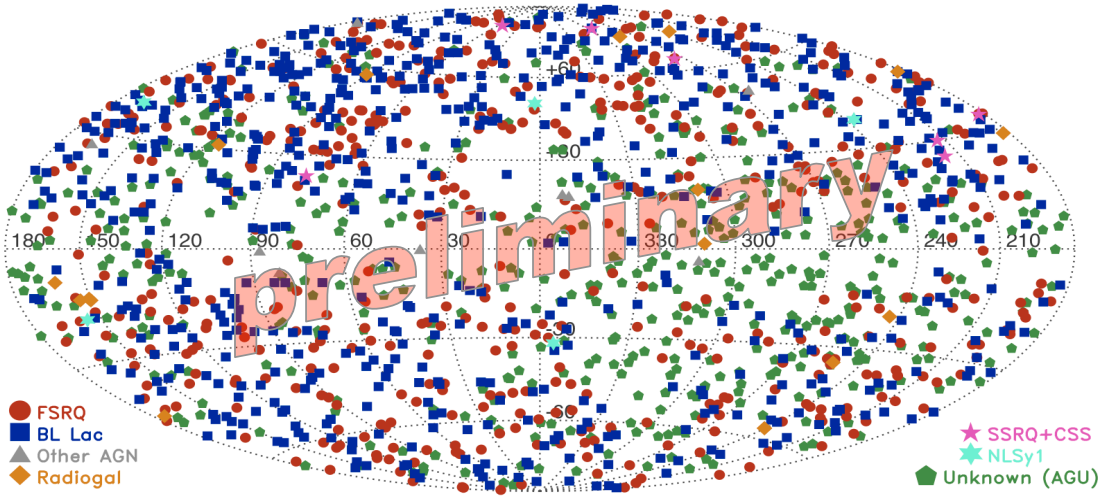


1LAC-clean sample (Abdo et al 10)
(11months of data,TS>25, P6_V3)
44% FSRQs
49% BL Lacs
9% AGU (AGN-like spectra)
4% Other AGNs



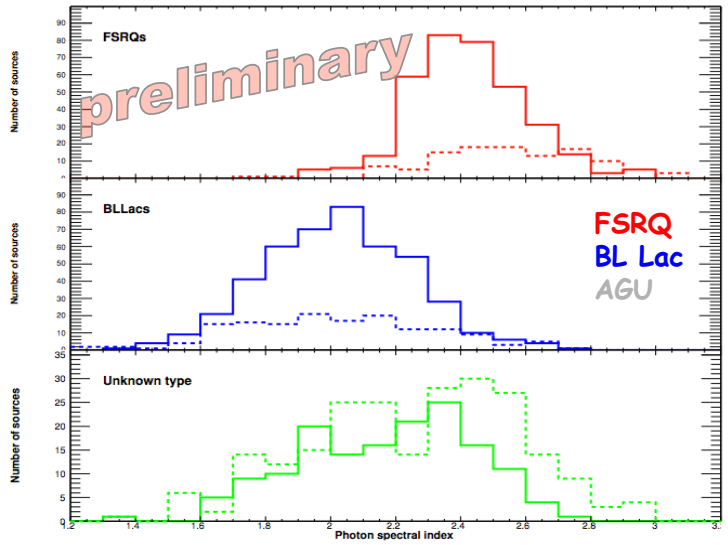
2LAC-clean sample (Ackermann et al. 11)
(24 months of data, TS>25, P7_V6)
35% FSRQs
44% BL Lacs
17% AGU (AGN-like spectra)
2% Other AGNs

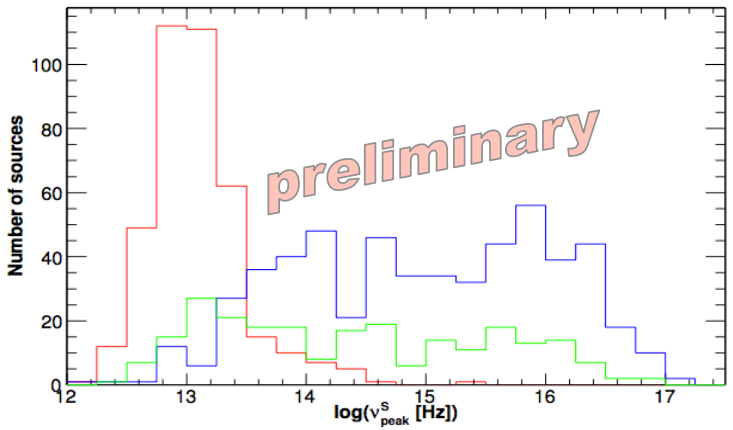


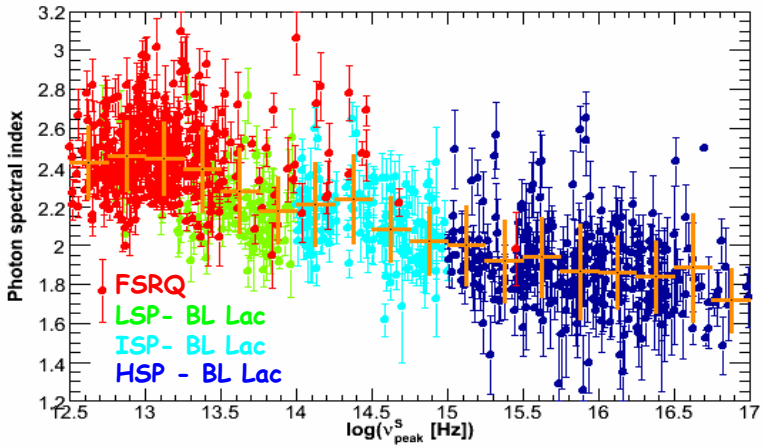


3LAC (Fermi LAT coll., in prep.)
(48 months, TS>25, P7rep)
29% FSRQ
39% BL Lacs
30% AGU (AGN-like spectra)
1% Other AGNs

Properties of 3LAC sources
SED classification

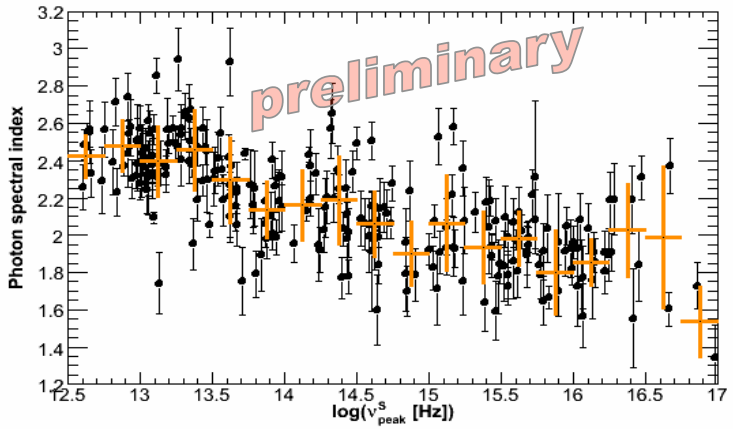






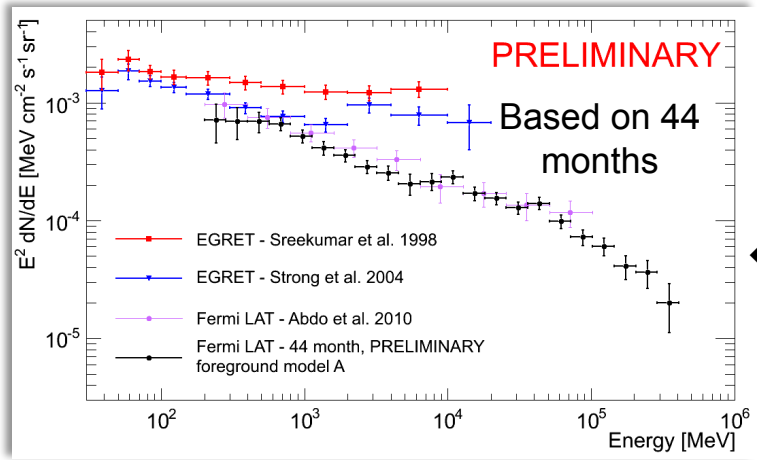
Fermi LAT Coll., in prep.

Cutini, AAS talk 2014



- FSRQ: $\langle \log \nu^{S}_{peak} \rangle \sim 13.0$
- BL Lac: $\langle \log \nu^{S}_{peak} \rangle$ spread the whole parameters space from LSP to HSP (consistent with 2LAC and Giommi et al 11)
- The newly-detected FSRQ seem slightly softer than 2LAC
- Same trend of ν^{S}_{peak} vs photon index both FSRQ, BL Lac and AGU.

Astrophysics for Fundamental Physics



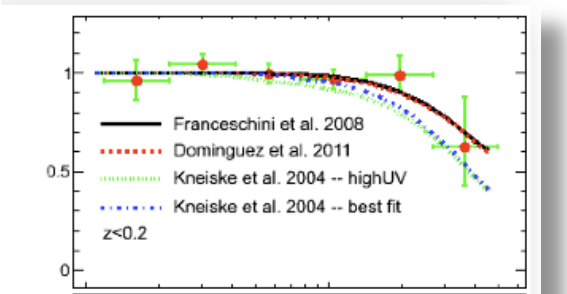
Extragalactic Gamma-ray Background

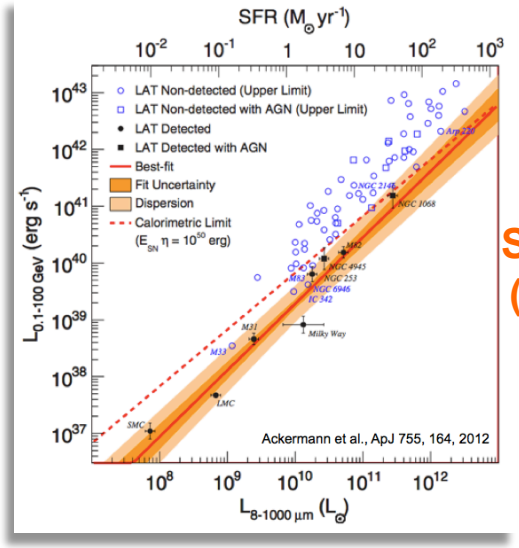
↓

Opacity of the Universe

Intensity of residual Isotropic Diffuse Gamma-ray Background (IGRB)

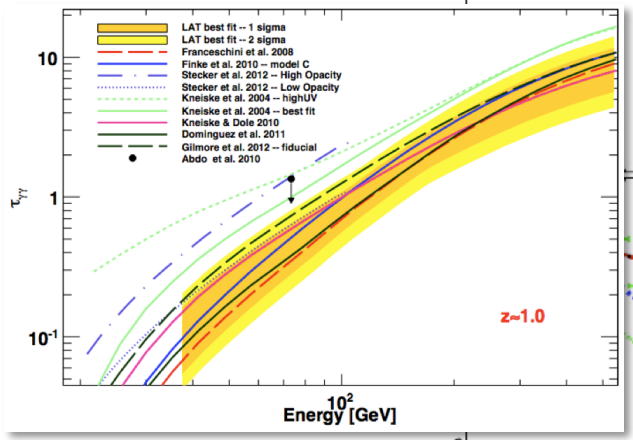
Fermi Coll., in prep





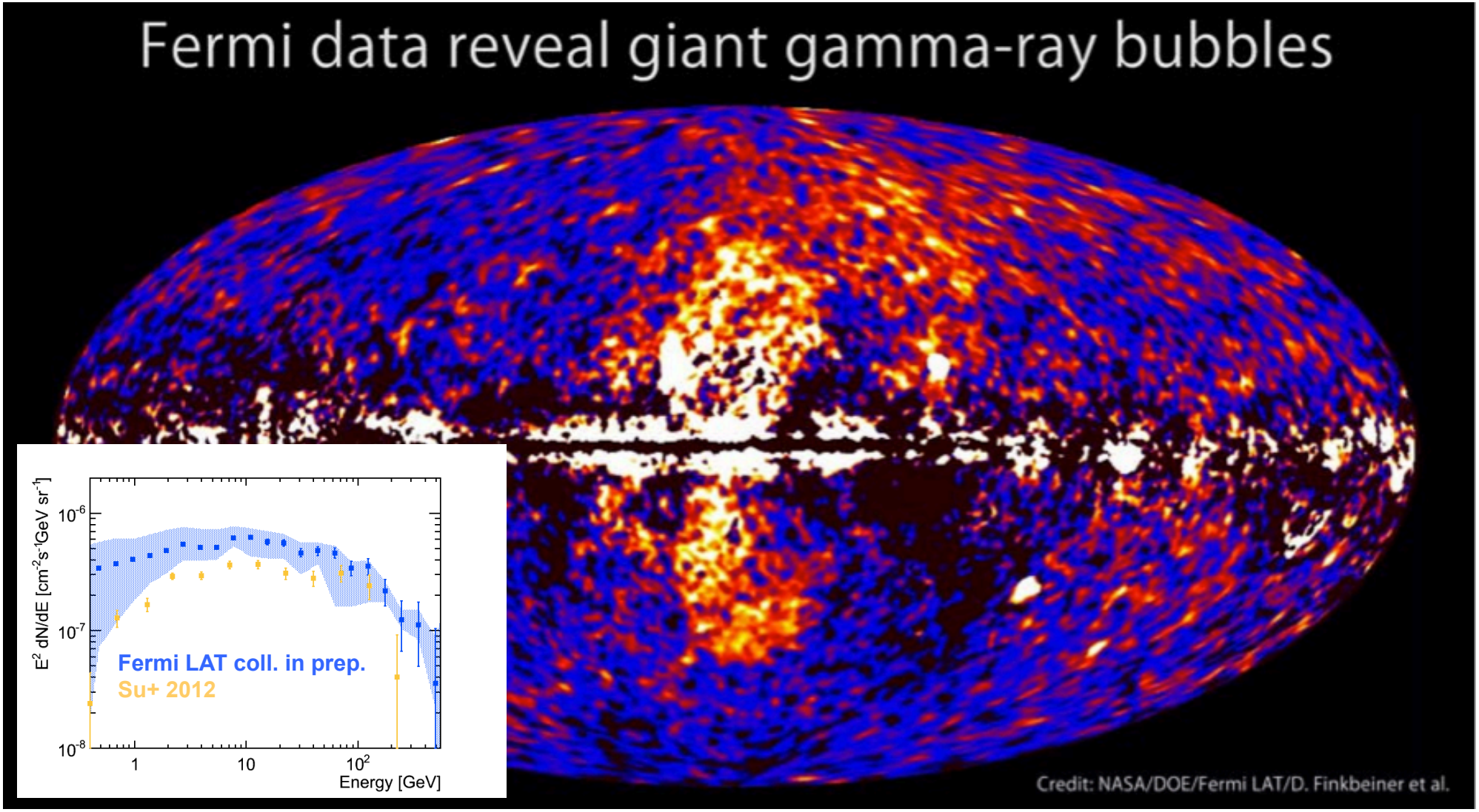
Starburst galaxies (CR accelaration)

2012 ApJ, 755, 164A

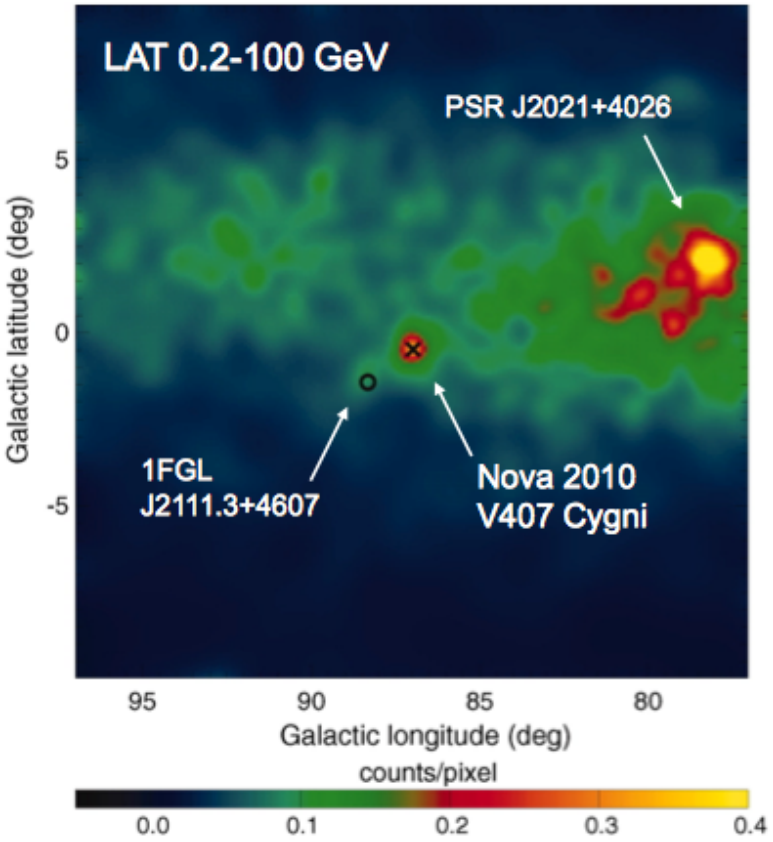


2012, Science 338, 1190

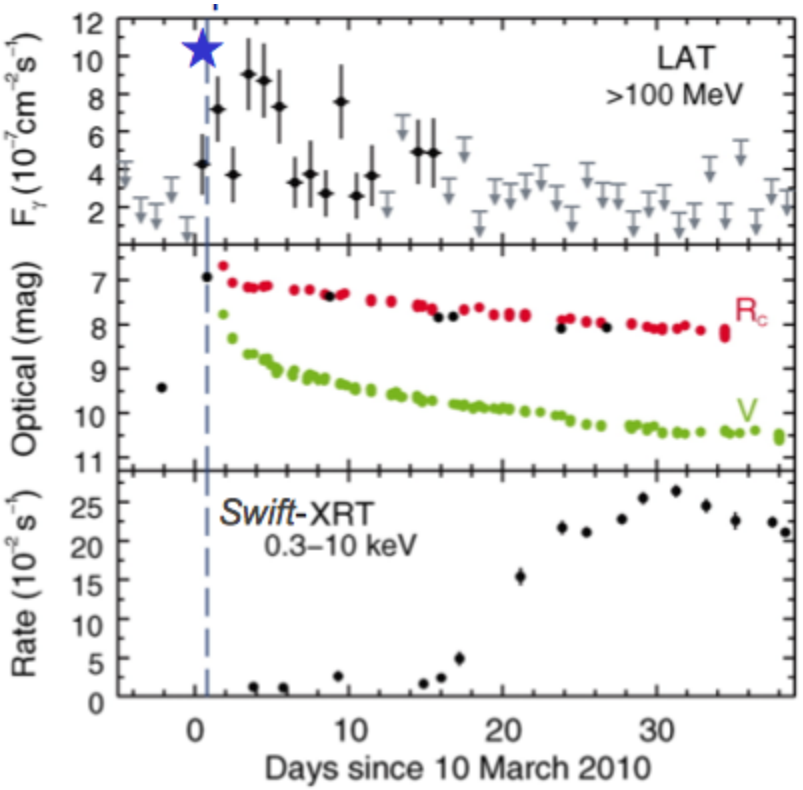
Fermi Lobes: Unexpected Diffuse Emission



Fermi LAT as Novae Finder – the First



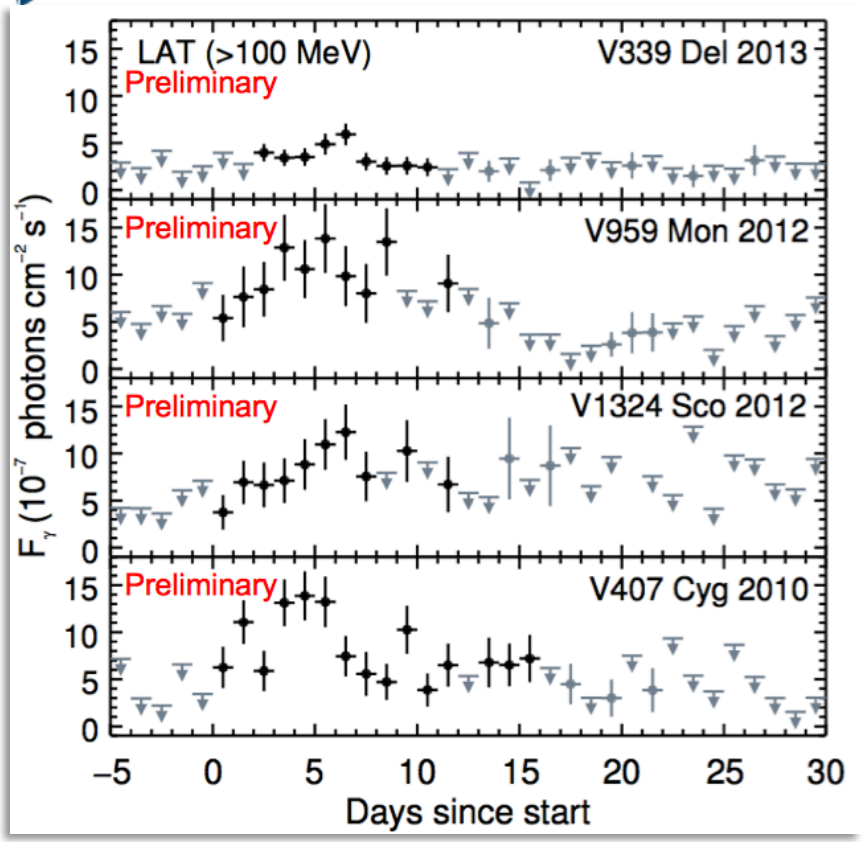
Optical Peak

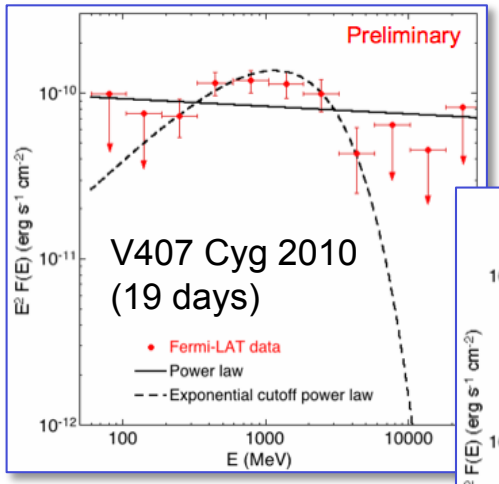


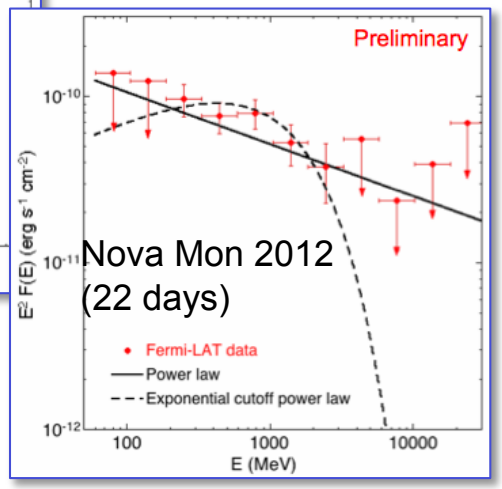
Initial LAT detection 2010 March 10, same day as nova V407 Cyg optical discovery
→ γ-ray identification via spatial (r95%=3.7') & temporal coincidence with a symbiotic recurrent nova

2010, Science, 329, 817

New Population of Gamma-ray Novae







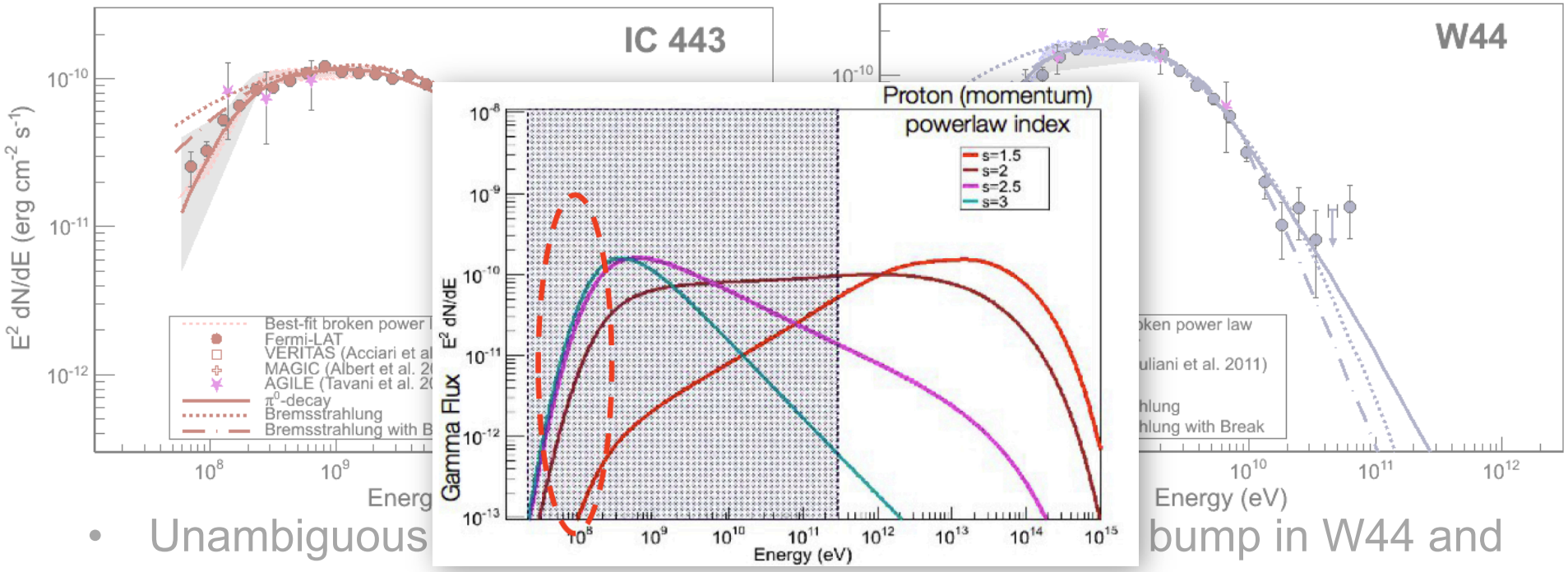
Cheung 2013, arXiv:1304.3475v1

- Similarities & differences may not necessarily point to the same γ-ray emission mechanism
- Fermi acceleration in nova shell & interaction with massive red giant wind plays important role in symbiotic recurrent novae

- Necessary conditions: massive WD & fast and massive ejecta; companion, environment come into play, and all appear nearby
- Hadronic and leptonic model fits for the LAT spectra considered for the classical novae

CR protons in SNR

Despite wide agreement that supernova remnants (SNRs) are the sources of galactic cosmic rays, unequivocal evidence for the acceleration of protons in these objects is still lacking.



- Unambiguous … bump in W44 and IC443 (thanks to increased low energy Pass7 acceptance)
- Proof that SNR accelerate protons

Detection of the pion-decay cutoff in Supernova remnants
2013, Science, 339, 807

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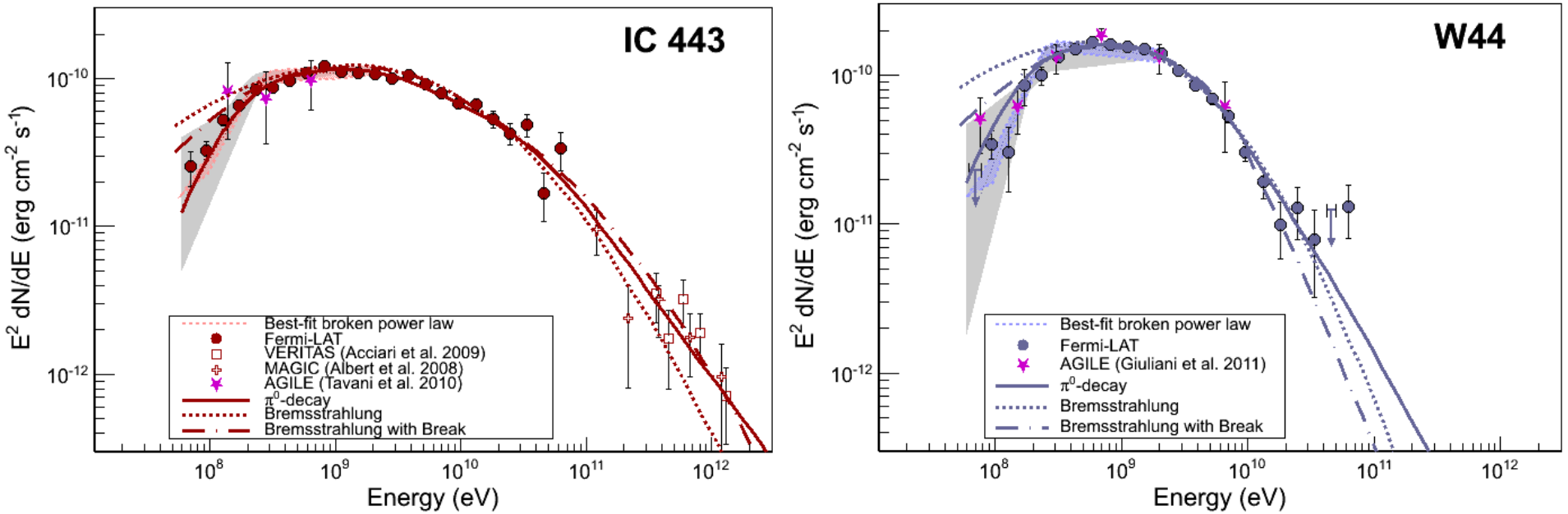

- Unambiguous and robust detection of pion decay bump in W44 and IC443 (thanks to increased low energy Pass7 acceptance)
- Proof that SNR accelerate protons

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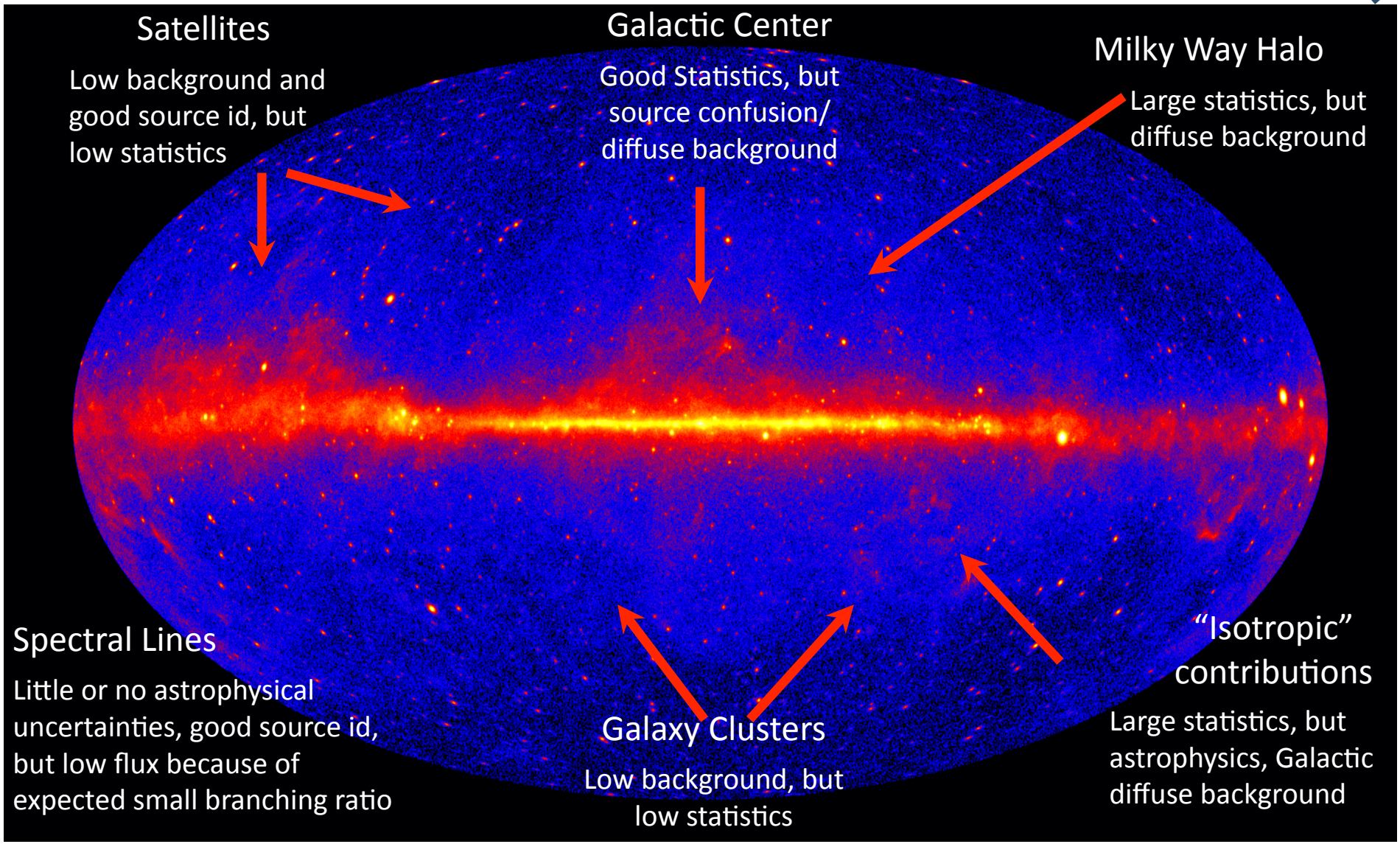
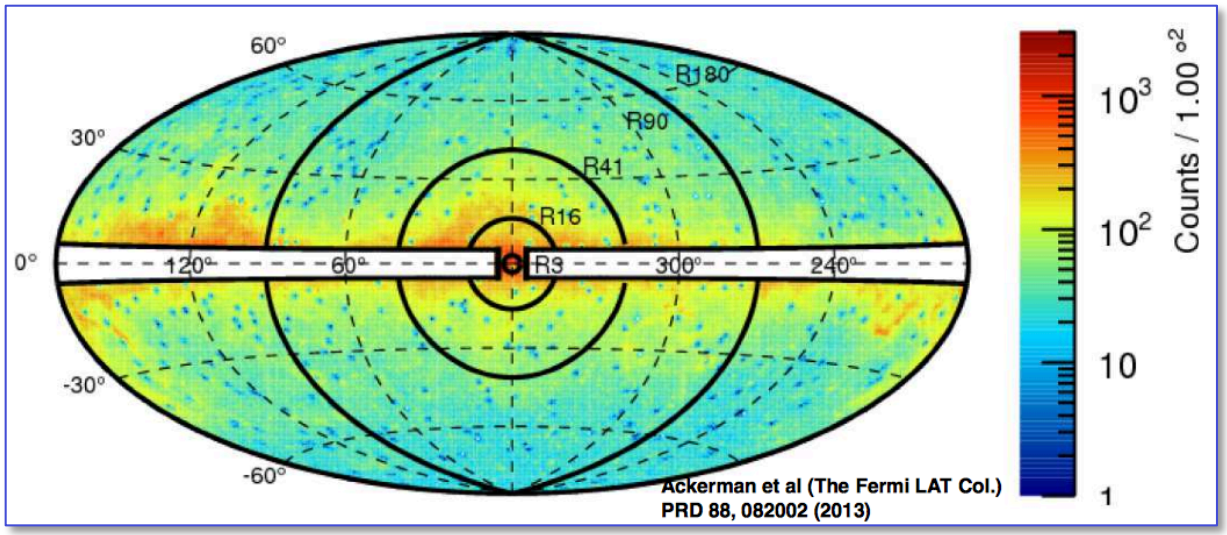
2013, Science, 339, 807

Dark Matter Search Strategies



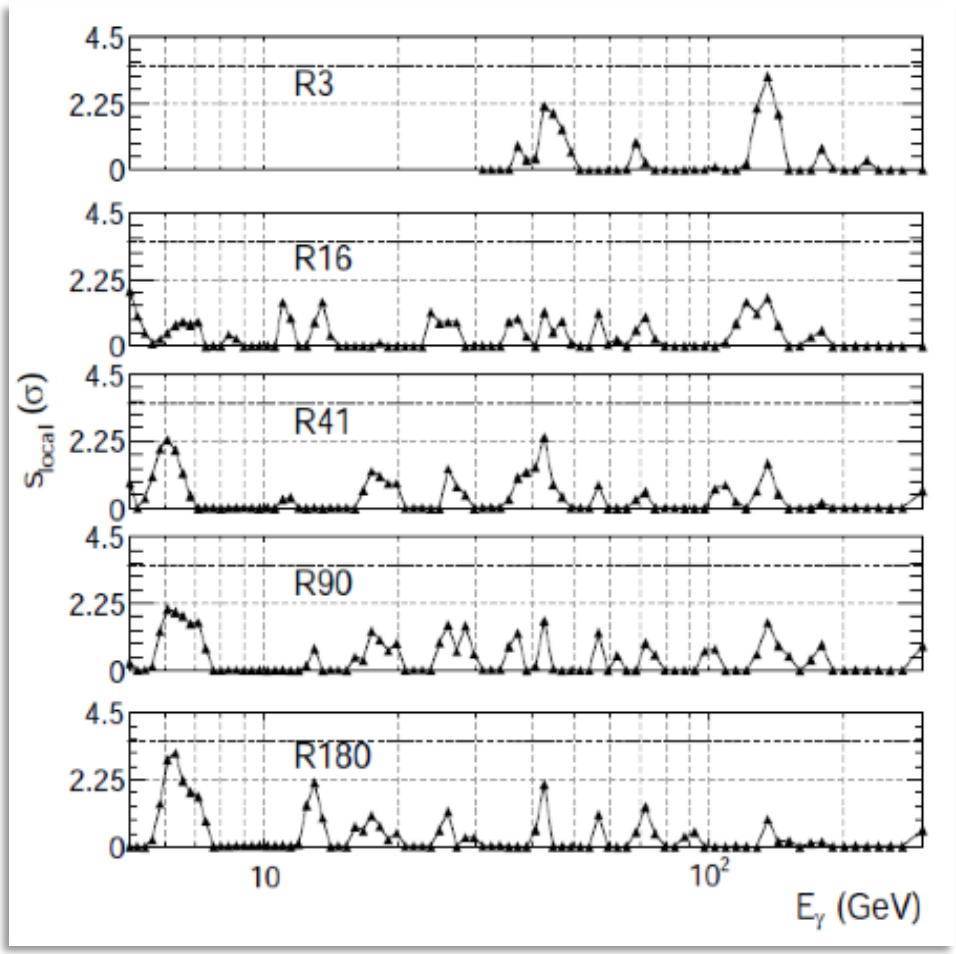
Spectral Lines from WIMPs

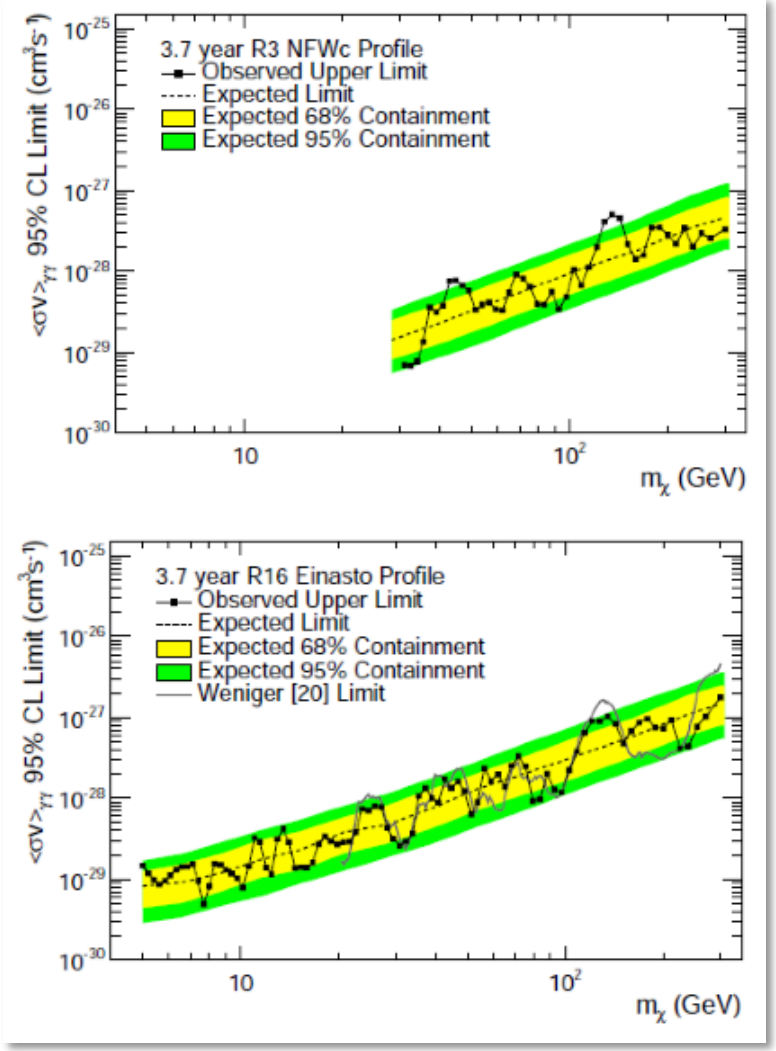
- **Search for lines from 5 – 300 GeV, using 3.7 years of data, P7REP_CLEAN event selection**
  - **Reprocessed data with updated calorimeter calibration constants**
  - **Clean cuts are recommended for faint diffuse emission analysis**
- **Mask bright (>10σ for E > 1 GeV) 2FGL sources**



- **Optimize ROI for a variety of DM profiles**
- **Search in 5 ROIs**
  - **R3 (3 ° GC Circle, cont. NFW Optimized)**
  - **R16 (Einasto Optimized)**
  - **R41 (NFW Optimized)**
  - **R90 (Isothermal Optimized)**
  - **R180 (DM Decay)**

Fitting Results
95% CL <σv> upper limits



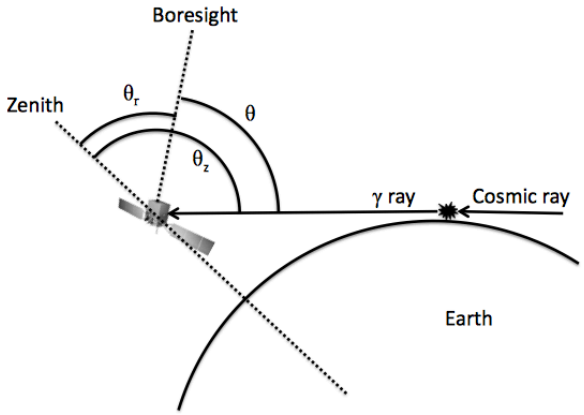


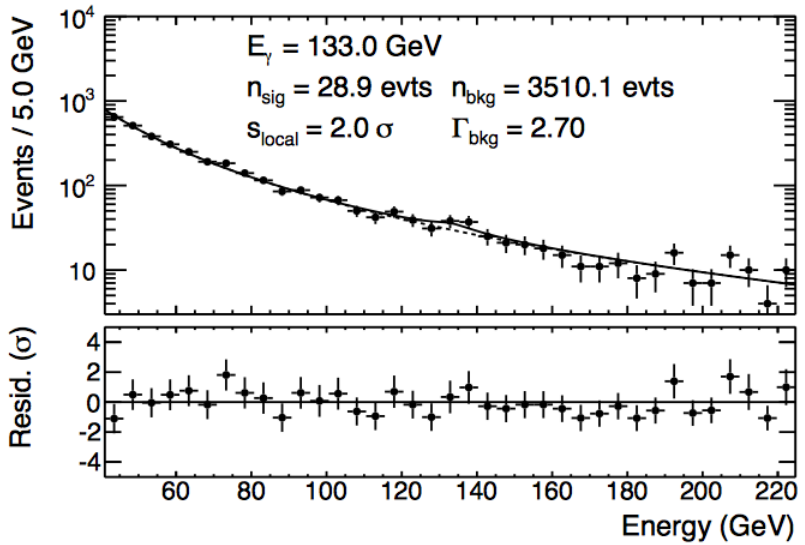
No globally significant lines detected
→ All fits have global significance < 2σ

Fermi LAT Coll., PRD 88, 082002 (2013)

Bands show expected statistical fluctuations only

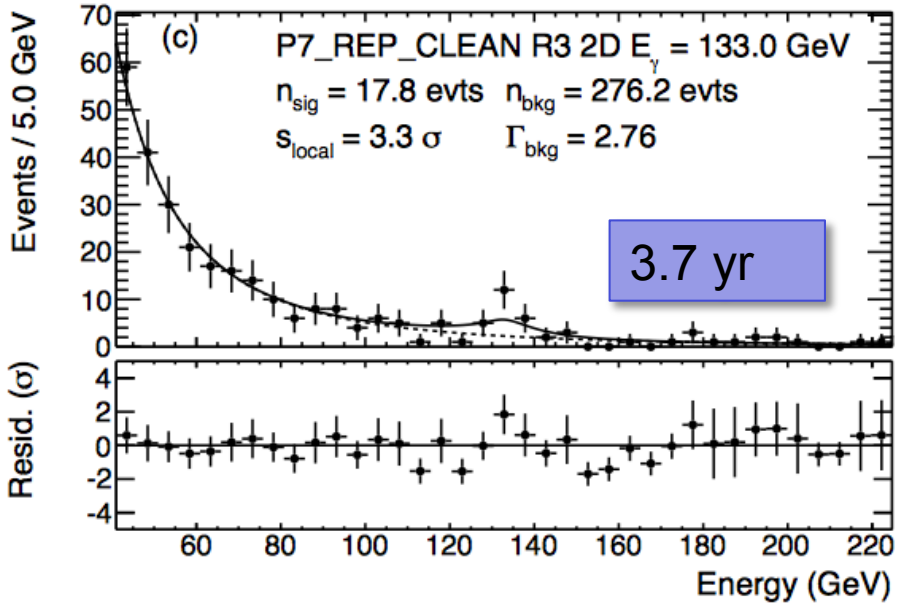
133 GeV in the Earth Limb spectrum

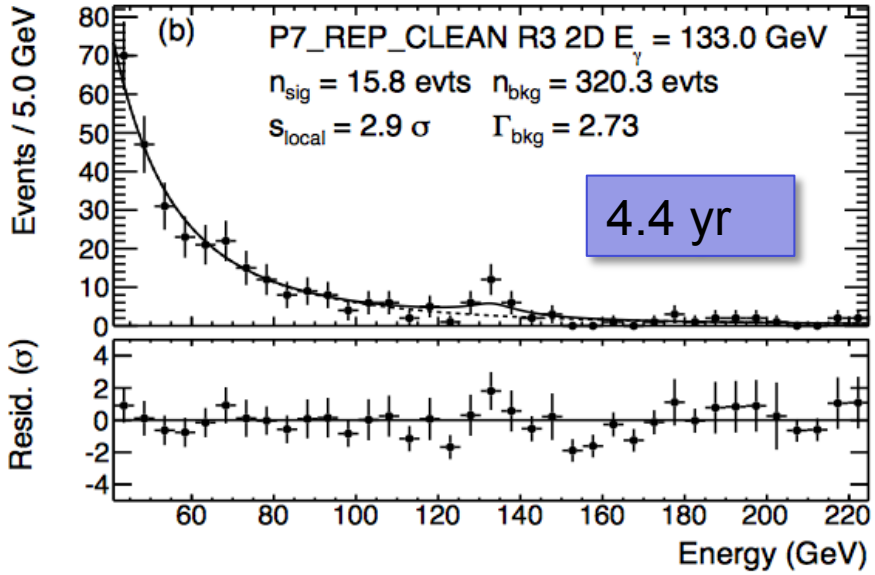


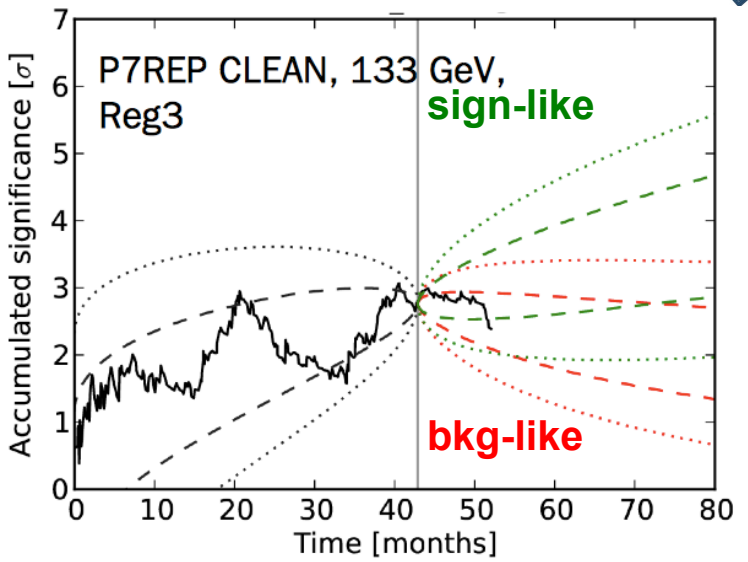


- **Line-like feature in the limb at 133 GeV (2.0σ local significance)**
  - **Appears when LAT is pointing at the limb**
  - **Surprising since limb should be smooth power-law**
  - **S/Nlimb ~ 14%, while S/NR3 ~ 61%**
    - **Limb feature not large enough to directly explain all the GC signal**
- **Dips in efficiency (less stringent Transient cuts → Clean cuts) below and above 133 GeV**
  - **Appear to be related with Calorimeter-Tracker event direction agreement**
  - **Could be artificially sculpting the energy spectrum**
- **Feature in data is much narrower than expected energy resolution**

Line-like Feature near 133 GeV







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

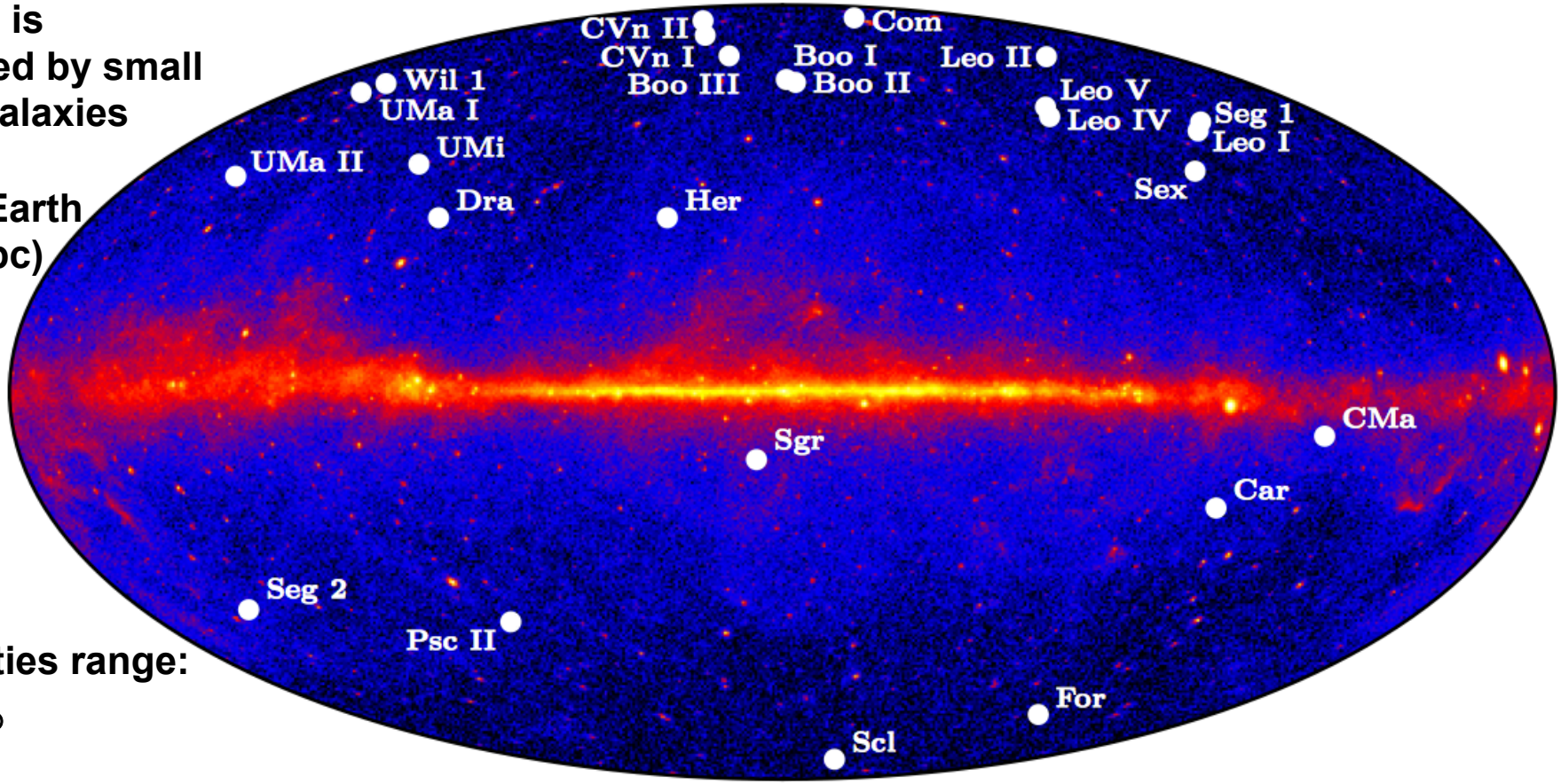
s_{local} decreased in 4.4 yr data by ~10% compared to 3.7 yr data

- Since spring 2012, feature has decrease

Good targets: Nearby Dwarfs Galaxies

Milky way is surrounded by small satellite galaxies

Close to Earth (25-250 kpc)



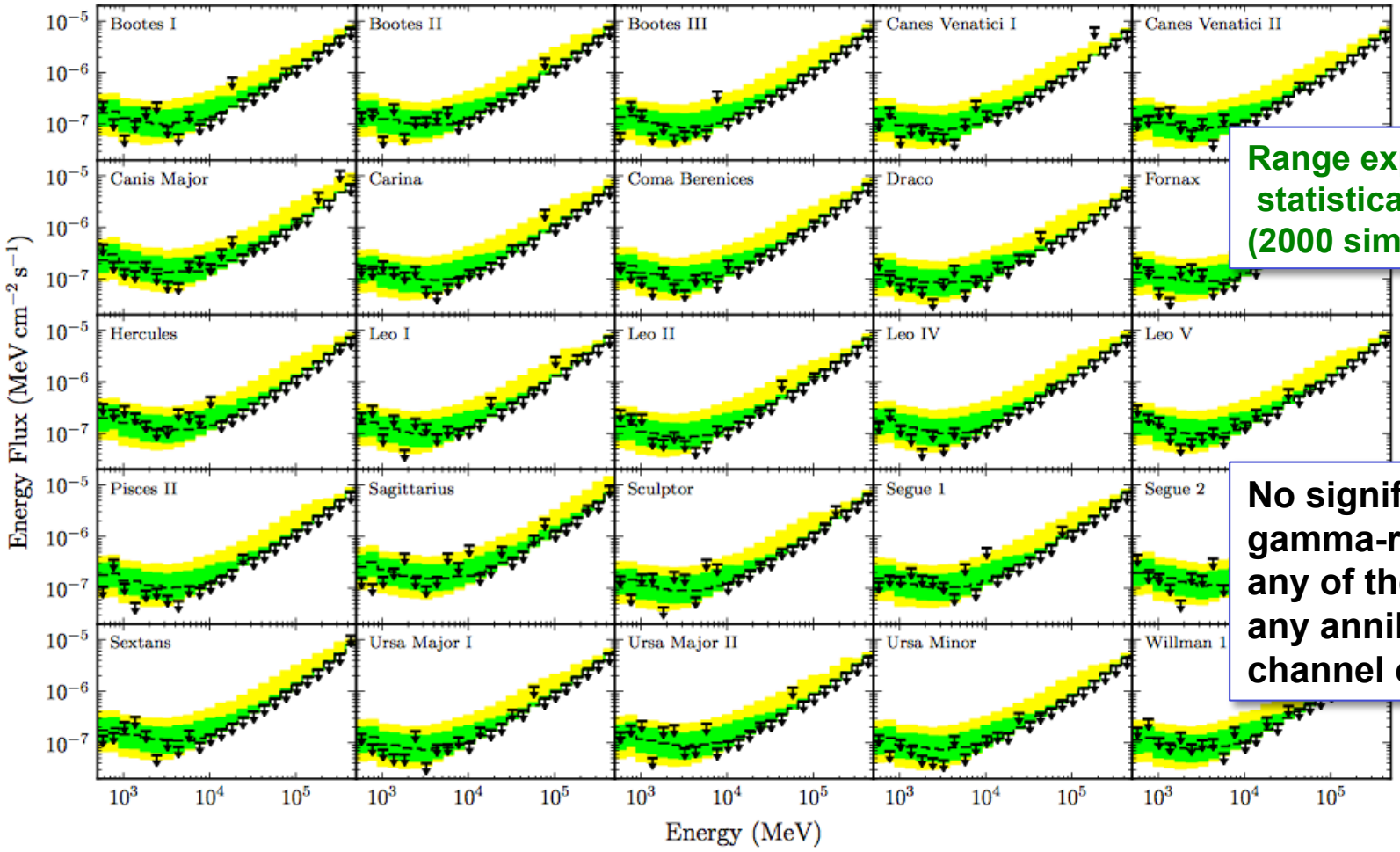
Luminosities range: 10^7-10^3 $L_\odot$

Astrophysical inactive

Most dark matter dominated objects known

Systems with very large mass/luminosity ratio
25 discovered so far, more will be by current/upcoming experiments

Individual Dwarf Galaxies



Range expected from statistical fluctuations (2000 simulations)

No significance gamma-ray excess for any of the 25 dSphs for any annihilation channel or mass

Bin-by-bin integrated energy-flux upper limits and expected sensitivities for each dSph galaxy

2014, PRD, 89, 042001

Joint dSphs Likelihood : increasing the sensitivity to weak signal

- Assume same dark matter particle in all dwarf spheroidal galaxies
- Use all dwarf galaxies with well-determined J-factors in non-overlapping regions (N=15)
- Perform a combined likelihood analysis:
  - Predicted flux for each dwarf will depend on individual dark matter content (J-factor)
  - Include statistical uncertainties from stellar kinematic data.
  - Fit backgrounds independently
- Joint likelihood function:

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN^f}{dE}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

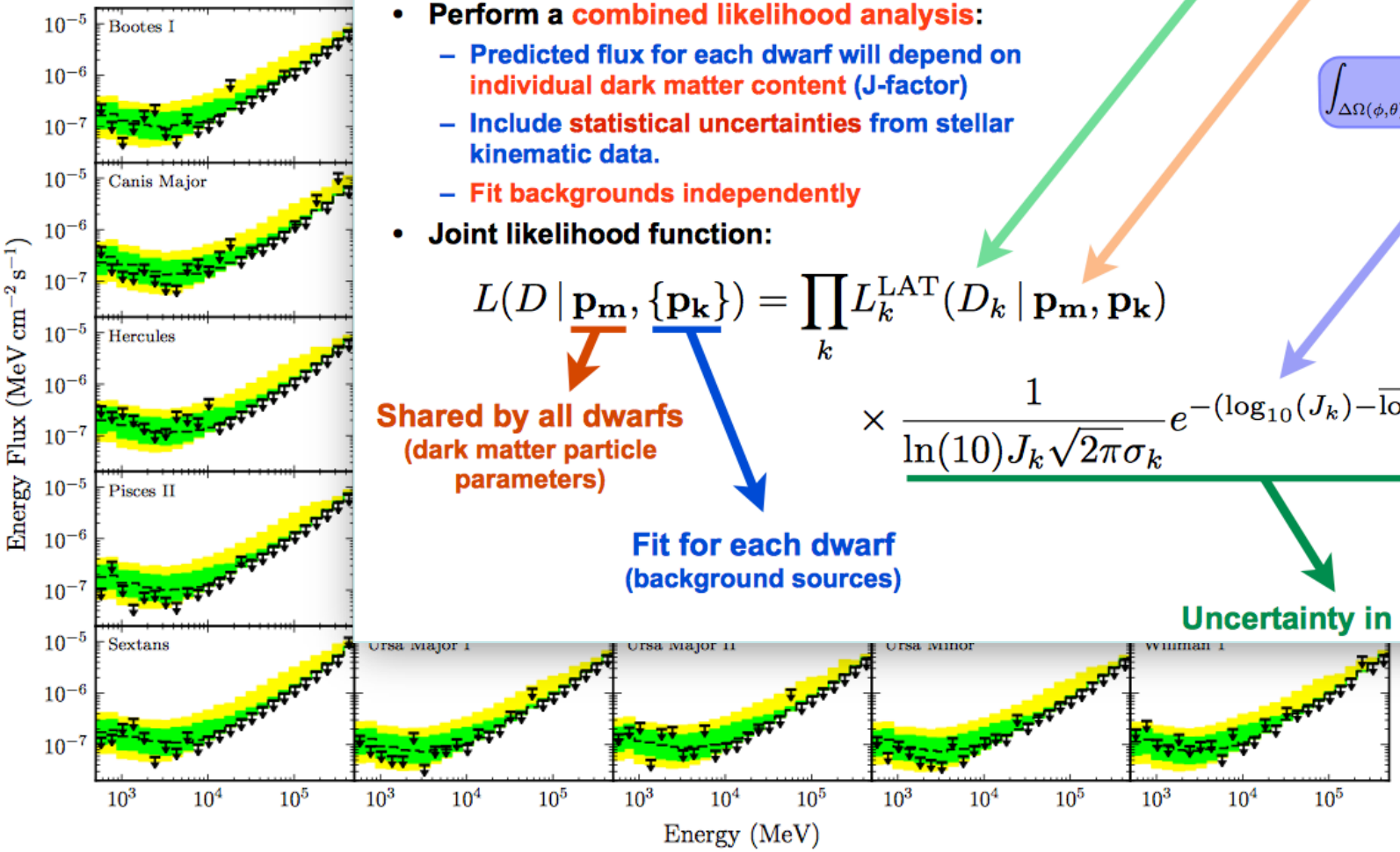
$$L(D\,|\,\mathbf{p_m},\{\mathbf{p_k}\}) = \prod_k L_k^{\rm LAT}(D_k\,|\,\mathbf{p_m},\mathbf{p_k}) \times \frac{1}{\ln(10)J_k\sqrt{2\pi}\sigma_k} e^{-(\log_{10}(J_k)-\overline{\log_{10}(J_k)})^2/2\sigma_k^2}$$

Shared by all dwarfs (dark matter particle parameters)

Fit for each dwarf (background sources)

Uncertainty in J-factor

Drlica-Wagner talk, UCLA DM 2014



Combined Limits at 95%CL

Combine 15 dSphs

Expected sensitivity calculated from the data and stellar kinematics of dSphs

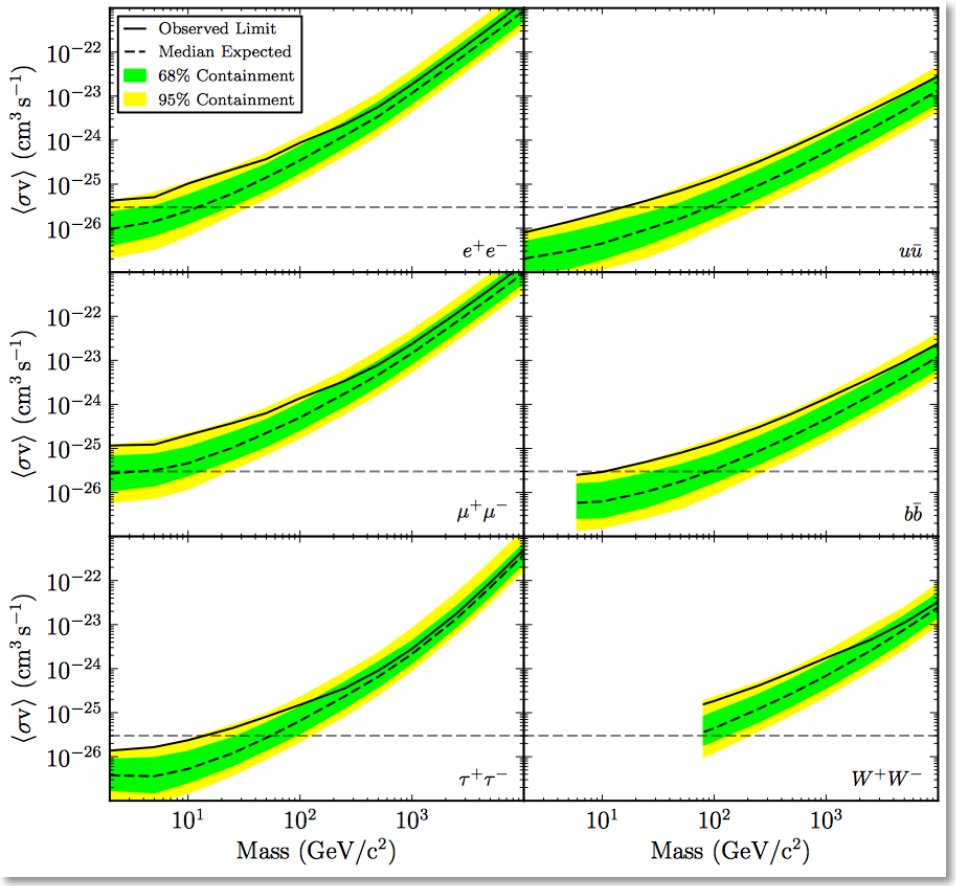
300 sets of 15 random sky locations

High-Galactic-latitude (|b|>20)

>1° from LAT catalog sources

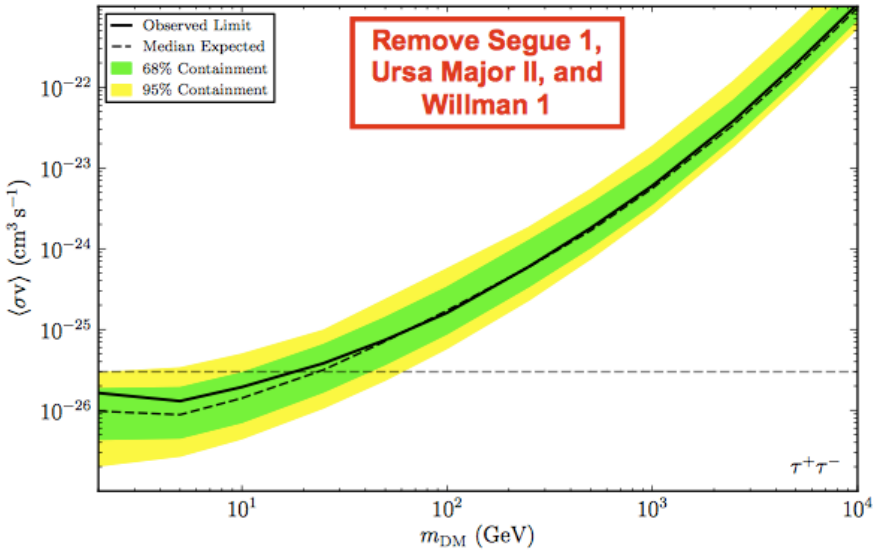
<u>Largest excess for 25 GeV WIMP to $b\bar{b}$, (TS= 8.7)</u>

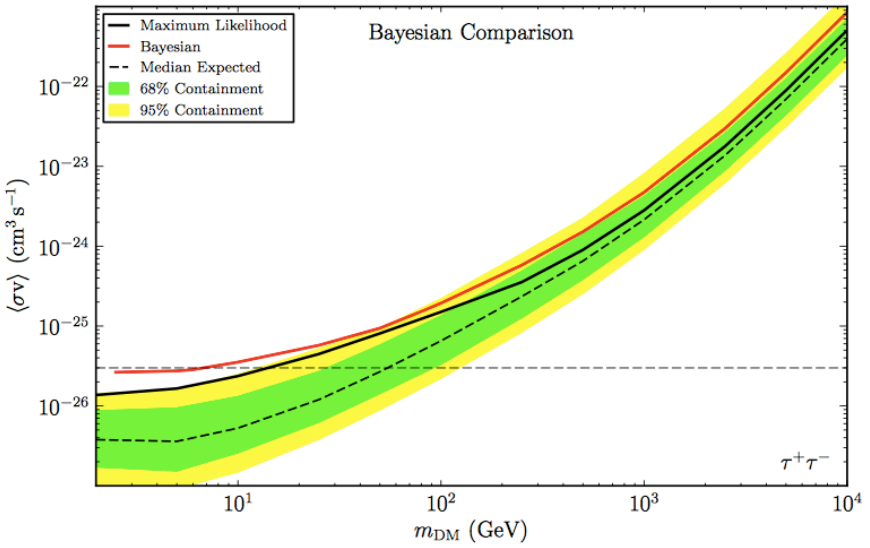
<u>(TS > 25 threshold)</u>



2014, PRD, 89, 042001

Ultra-Faint Galaxies Excluded



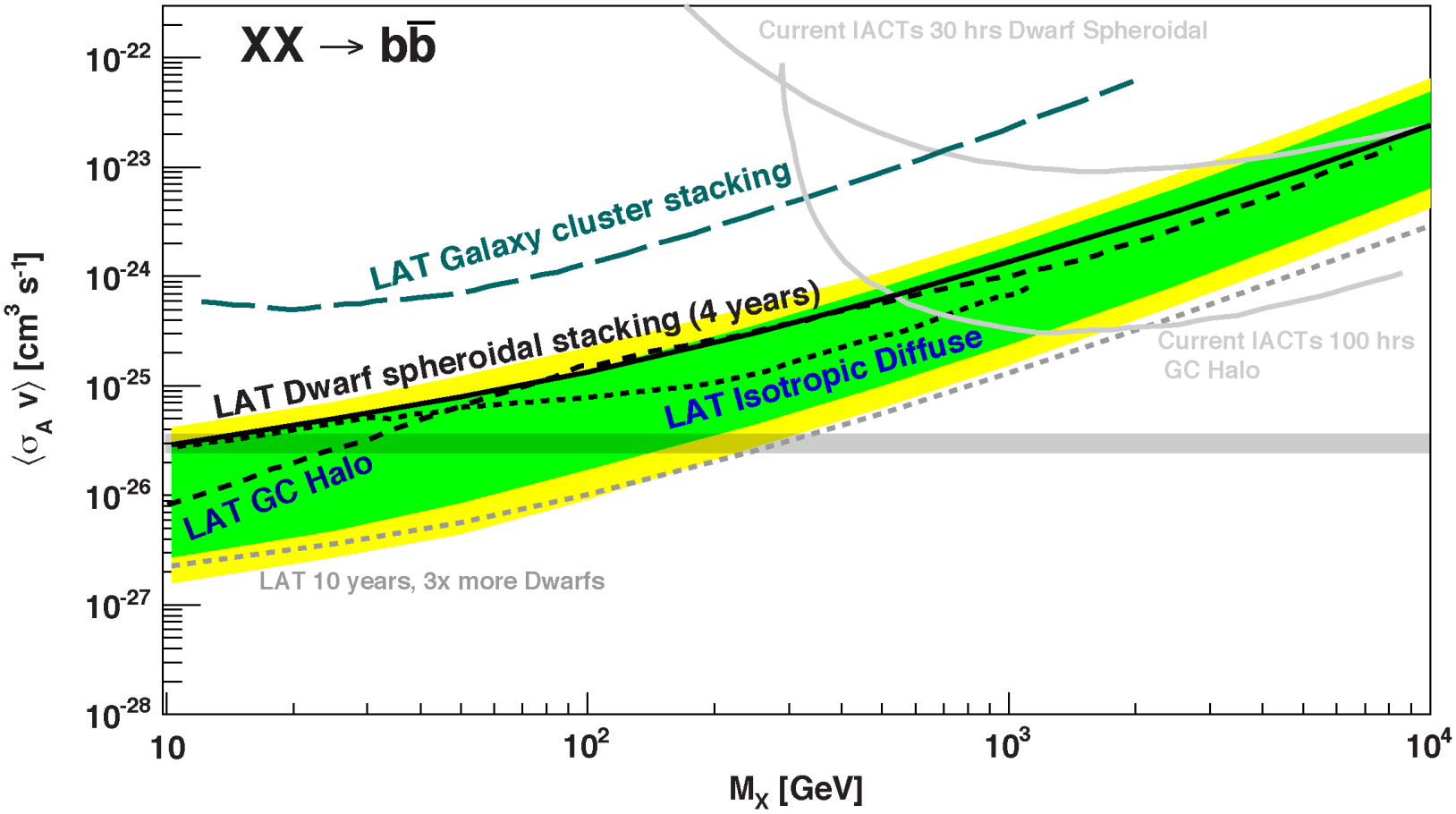


→ When removing the primary contributors to the deviation
(these 3 Ultra-Faint dSphs, which have also large uncertainty on their J-factor)
→ The deviation from expectation is less prominent

→ the **deviation** is **not correlated** to those dwarfs with **highest J-factor**
→ **not supporting a detection**

2014, PRD, 89, 042001

Current and Projected Dark Matter Limits



Colored bands → expected limits from Dwarf Spheroidal search

Horizontal gray band → "canonical" thermal wimp cross section of 3×10^{-26} cm^3 s^{-1}

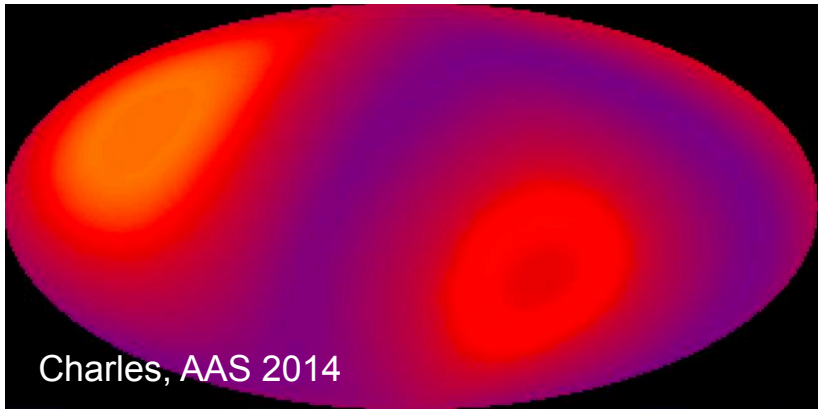
Upcoming *Fermi* LAT Developments

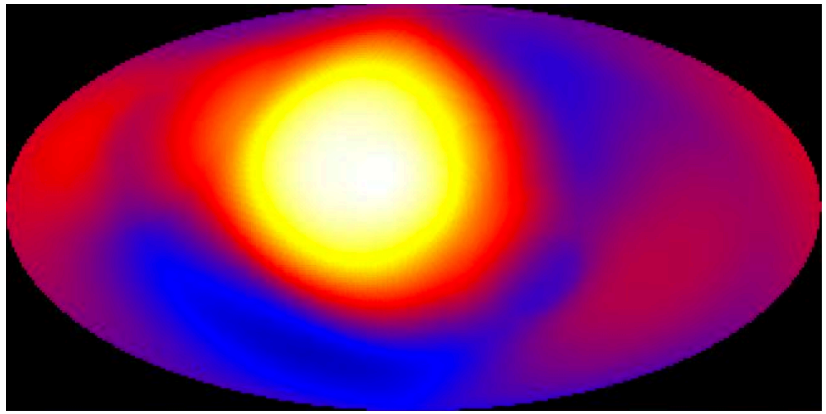
Two **major changes** affecting the *Fermi* LAT data are underway:

→ **Development of "Pass 8"** version of the reconstruction and event classification algorithms. Preliminary versions of "Pass 8" show a **25% or more increase in the acceptance at all energies**, with over a factor of 2 below 100 MeV.

→ As of 2013 December, **the *Fermi* LAT observing strategy changed to favor the Galactic center**. The increased exposure toward the Galactic center coupled with the *Planck* maps of Galactic dust will help us to

– resolve claims about a line-like spectral feature near 130 GeV
– disentangle Galactic diffuse emission from Dark Matter signatures.





Relative exposure at 10GeV for standard and Galactic-center biased survey modes.

Summary

- The *Fermi* LAT is offering a large contribute to the understanding of HE particles in the Universe
  - Enables gamma-ray population studies for the first time
  - Probes the most powerful acceleration sites
  - Reveals to be a necessary complement/link with accelerator experiments, neutrino experiments, charged cosmic-ray detectors, gravitational waves searches
- Dark matter searches
  - No smoking gun yet..
  - Important constraints set
  - Upcoming developments will lead to improvements, allowing to reach interesting areas of the parameter space
- Fermi is a 5 to 10 years mission … great potential to exploit!

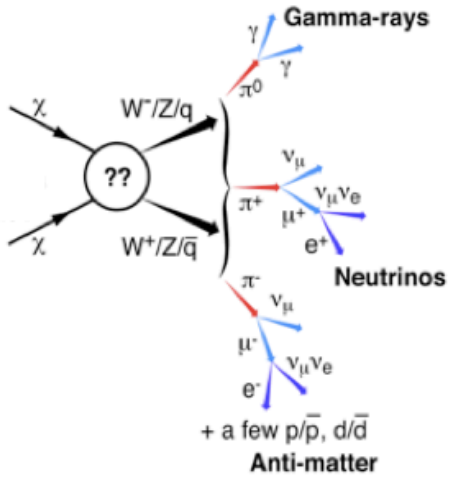
BACK UP

Indirect Detection of Dark Matter with dSphs

Gamma-Ray Flux
(signal in data)

Particle Physics
(particles per annihilation)

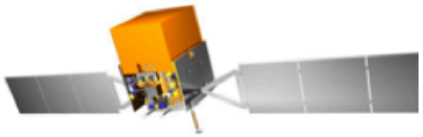
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN^f}{dE}B_f$$

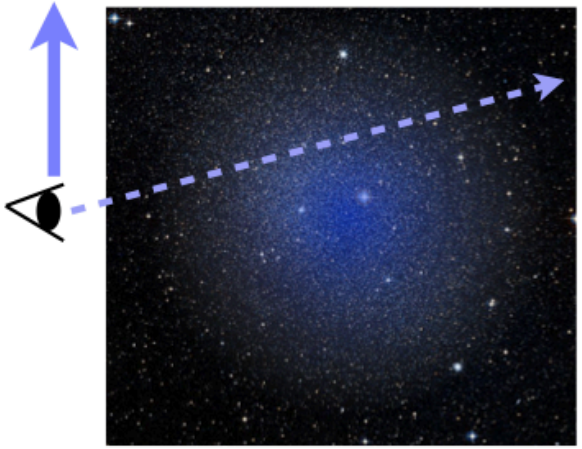


$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Dark Matter Distribution
(line-of-sight integral)





Good targets: Nearby Dwarfs Galaxies

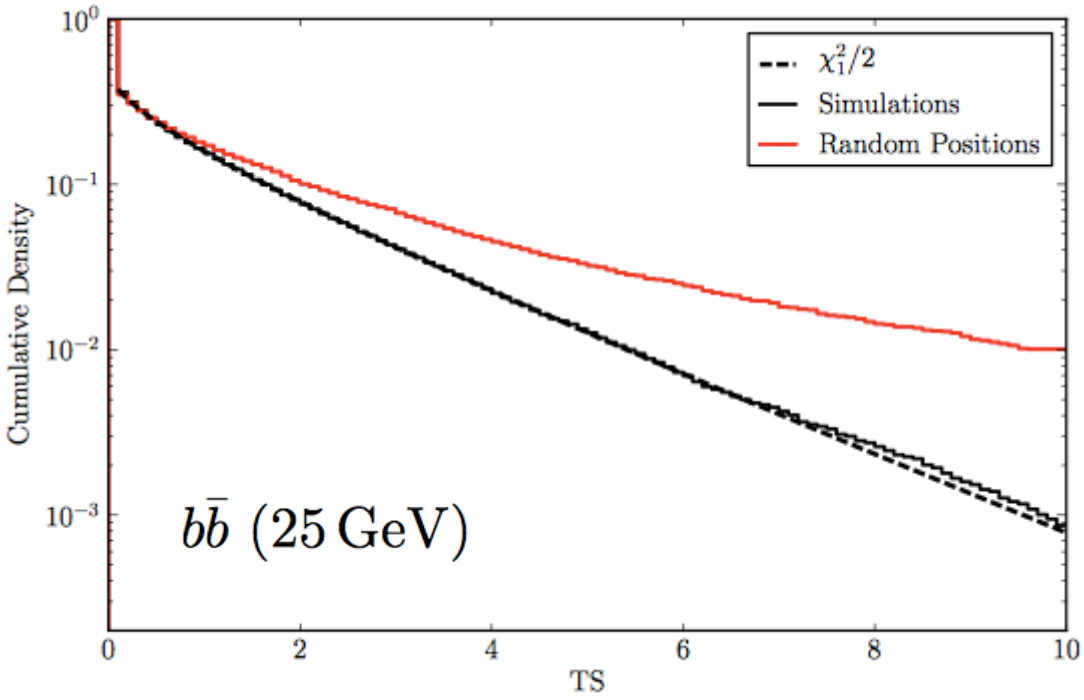
- **Dark matter content determined from stellar velocity dispersion**
  - **Classical dwarfs: spectra for several thousand stars**
  - **Ultra-faint dwarfs: spectra for fewer than 100 stars**
- **Fit stellar velocity distribution of each dwarf (assume an NFW profile)**
- **Calculate the J-factor by integrating out to a radius of 0.5 deg (Martinez, 2013)**
  - **Encloses the half-light radii of the dwarfs**
  - **Minimizes uncertainty in the J-factor**
  - **Large enough to be insensitive to the inner profile behavior (core vs. cusp)**
- **Include the J-factor uncertainty in the gamma-ray analysis**

Statistical and Systematic Effects in dSphg study

• Distribution of TS values in the data does not follow asymptotic theorems
Global significance:
– Simulations: p-value = 0.024
– Data: p-value = 0.083

• Confounding features of the data:
– Unresolved background sources
– Instrumental features
– Imperfect modeling of the diffuse background

• Additional systematic uncertainties:
– Instrument response (< 15%)
– Diffuse backgrounds (< 10%)
– Dark matter profile (< 20%)



2014, PRD, 89, 042001

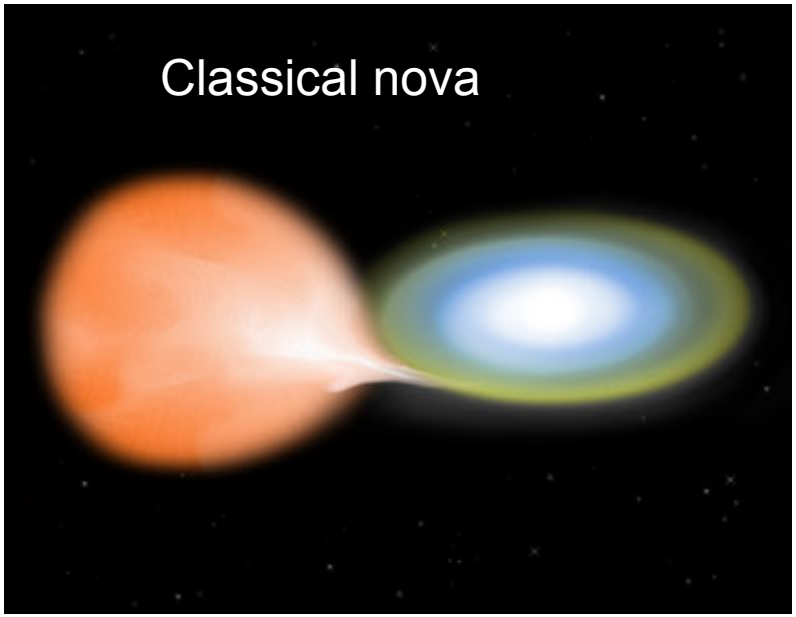
White Dwarf in Close Binary Systems
(Nova: thermonuclear explosion in WD)

Compact cataclysmic variable:

WD + Main Sequence

↓

Roche lobe overflow

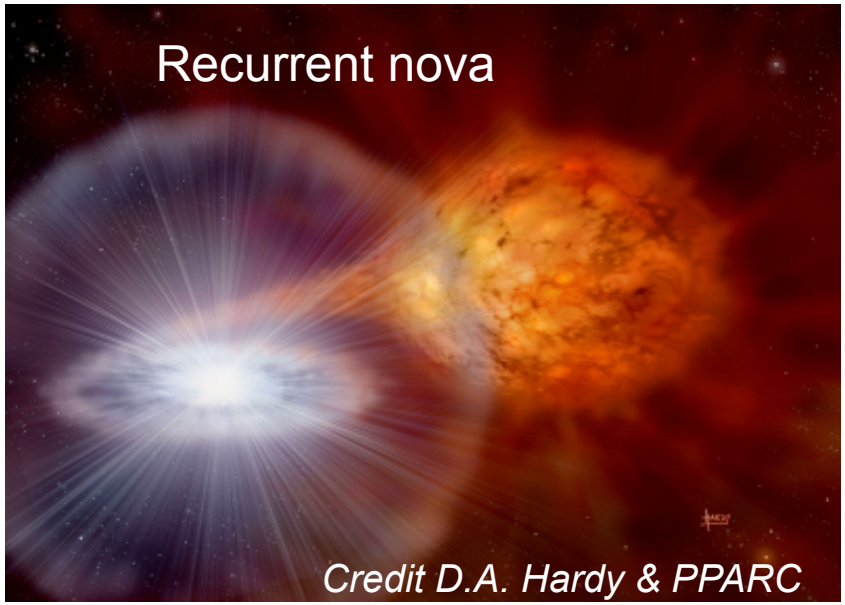


Symbiotic system:

Massive WD + Red Giant

↓

accretion from a red giant wind



Hydrogen burning in degenerate conditions on top of the white dwarf

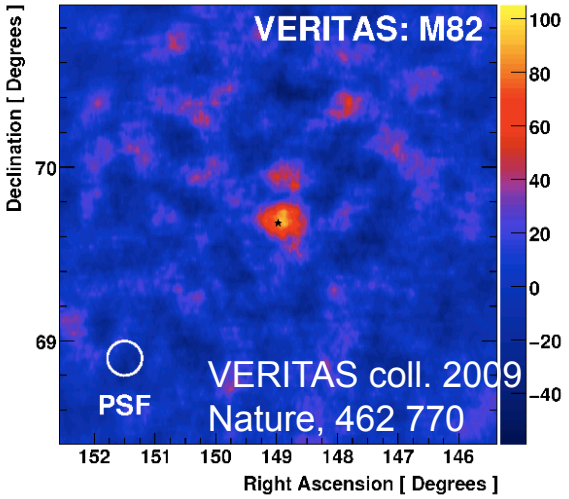
P_{rec}~10^4-10^5 yr; P_{orb}~hr-day
a ~ 10^{10}cm; rate ~35/yr

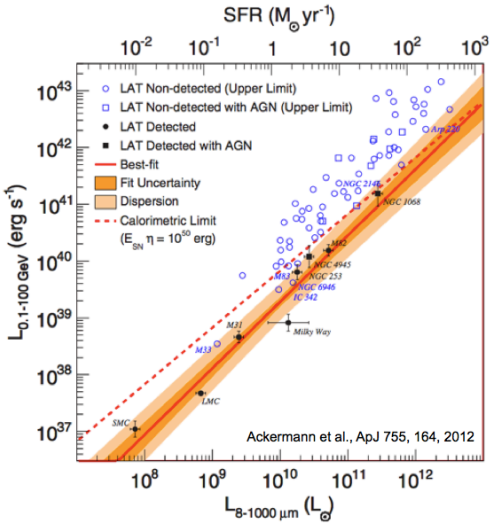
P_{rec}<100 yrs; P_{orb}~100's days
a ~ 10^{13}-10^{14} cm; rate ~10 known

Adapted from M. Hernanz X-ray Universe 2011 talk

Starburst galaxies at γ rays

- Veritas 2007-2009 observations: first detection of gamma-ray signal (at 5σ) from M 82
- Strong **correlation** between the **star-formation activity** and the **cosmic-ray production** in M82.
- Star forming → cosmic rays → interact with interstellar gas and radiation → production of diffuse gamma rays
- Results strongly support that cosmic-ray acceleration is tied to star formation activity

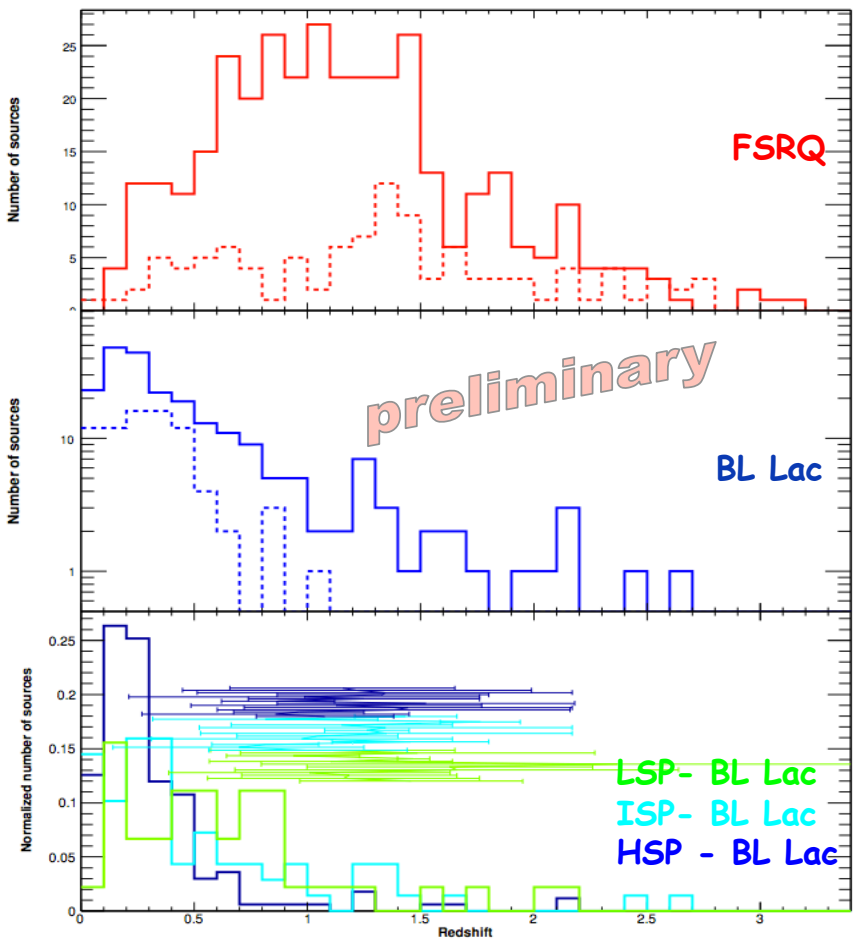




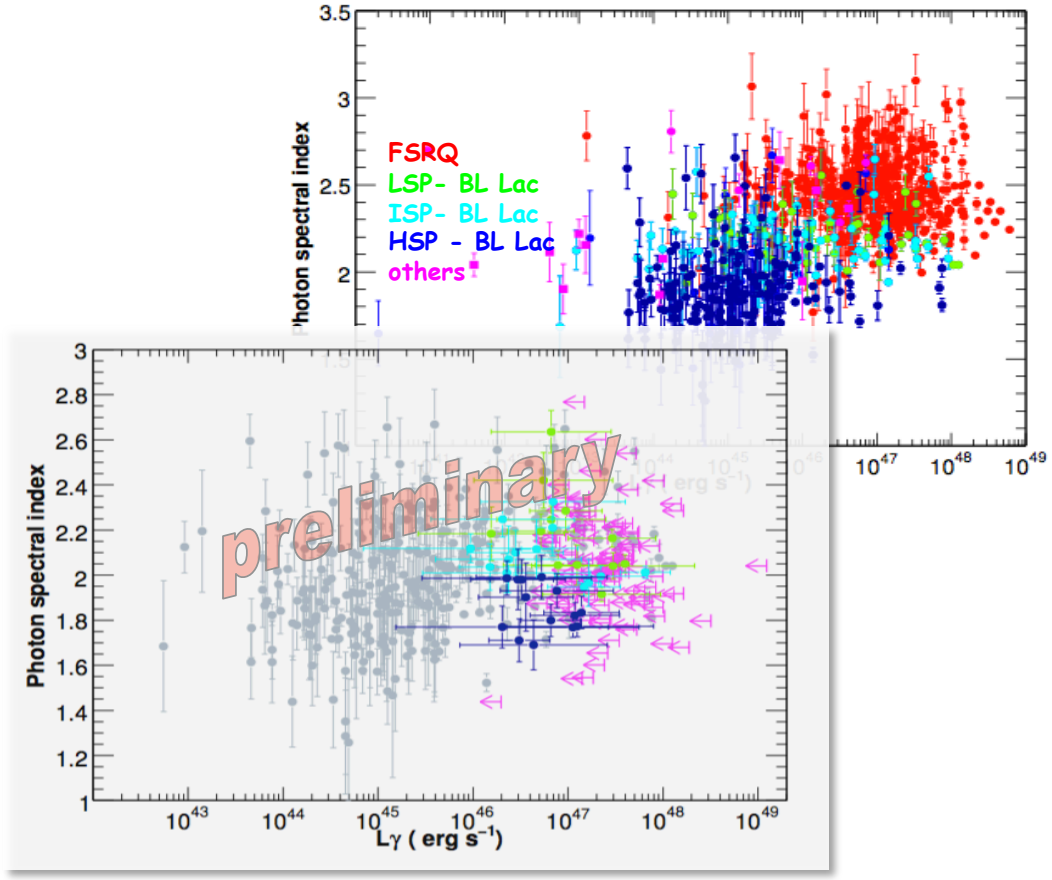
- Several detected by the LAT
- almost linear correlation between γ-ray luminosity and tracers of star formation
  - bolometric infrared luminosity
  - 1.4GHz radio continuum emission

2012 ApJ, 755, 164A

Properties of 3LAC sources: Redshift Distribution



(3LAC, Fermi LAT coll., in prep.)



- 50% of BL Lac have no measured redshift
- Distribution of BL Lac redshift gradually extend to lower z as the location of the synchrotron peak shifts to higher frequency
- Lower limits on redshift for BL Lacs are higher then the mean of measured ones.

The First LAT Supernova Catalog