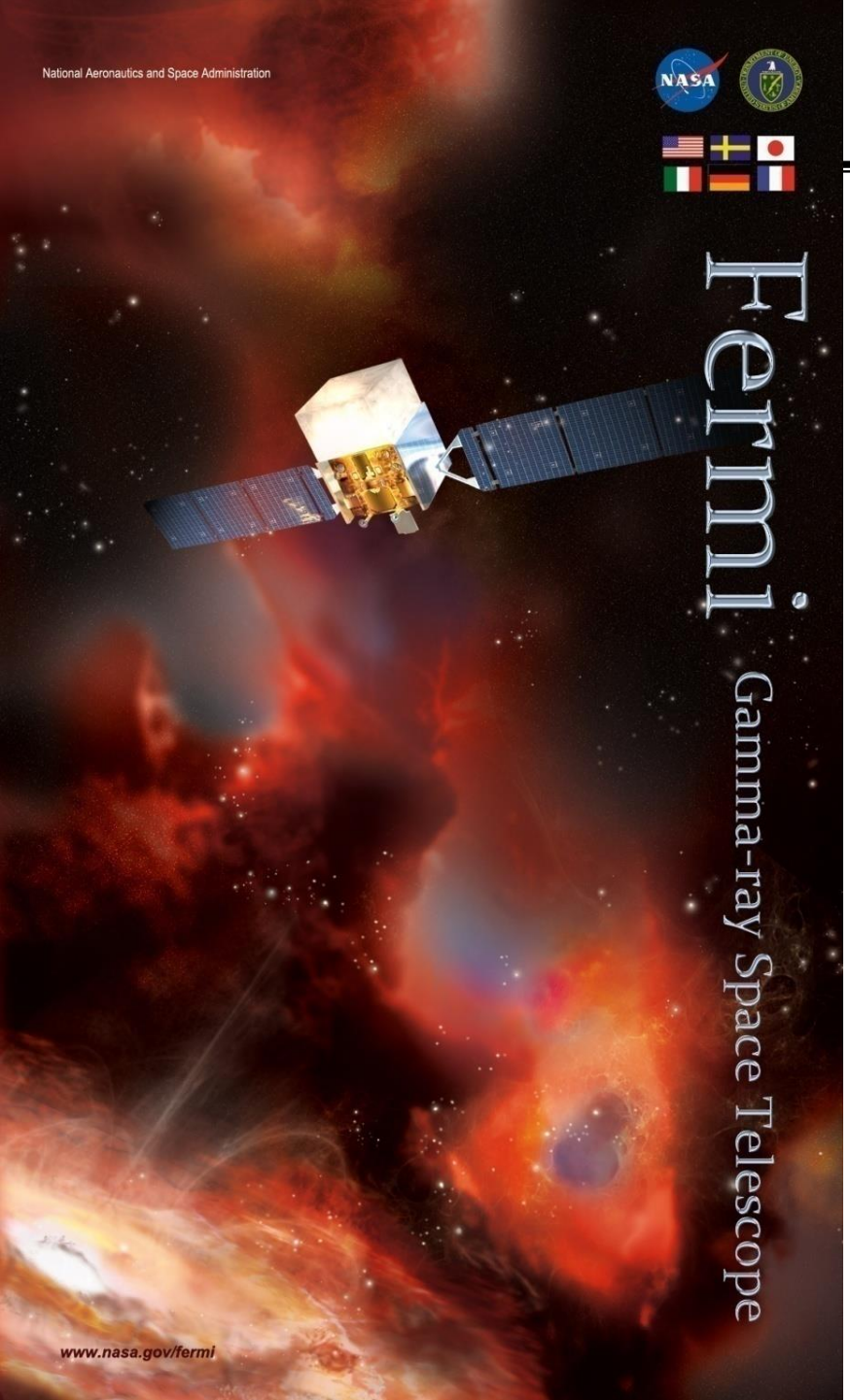


Seven years of gamma-ray astrophysics with the Fermi LAT

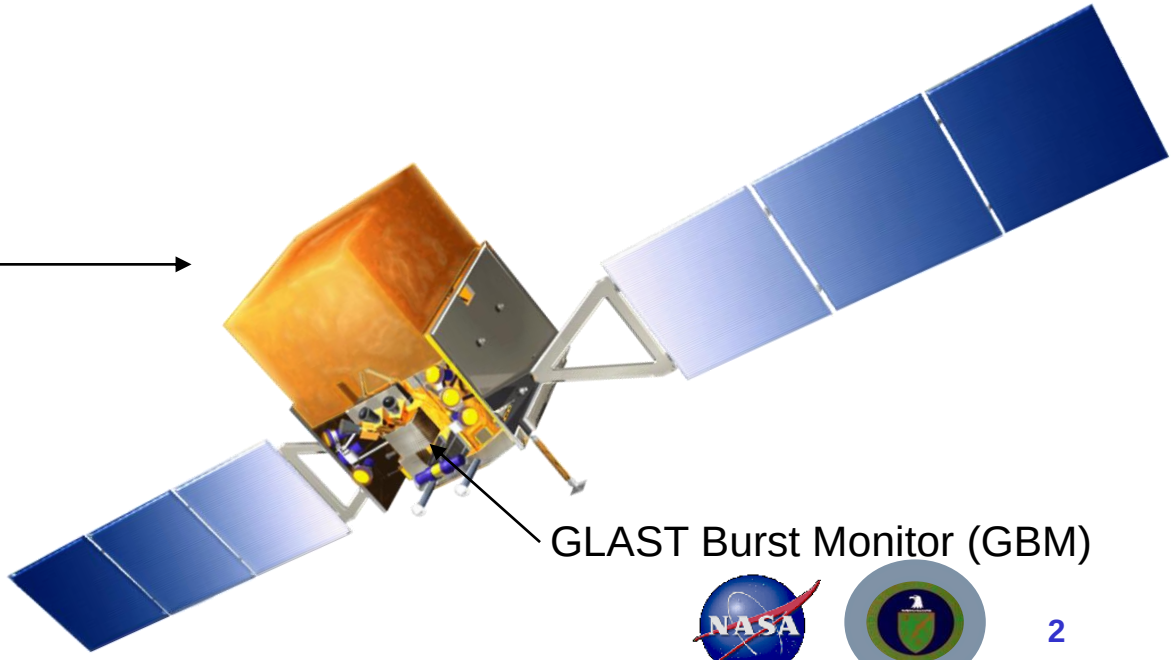
Francesco Loparco

(Bari University & INFN)

on behalf of the Fermi LAT Collaboration

The Fermi satellite

- **The Fermi Gamma-Ray Space Telescope is an International Science Mission exploring the gamma-ray sky by means of its two main instruments:**
  - **GLAST Burst Monitor (GBM): 8 keV → 40 MeV**
  - **Large Area Telescope (LAT): 20 MeV → > 300 GeV**
- **Huge energy range: including largely unexplored band for a total of >7 energy decades!**



The Fermi LAT

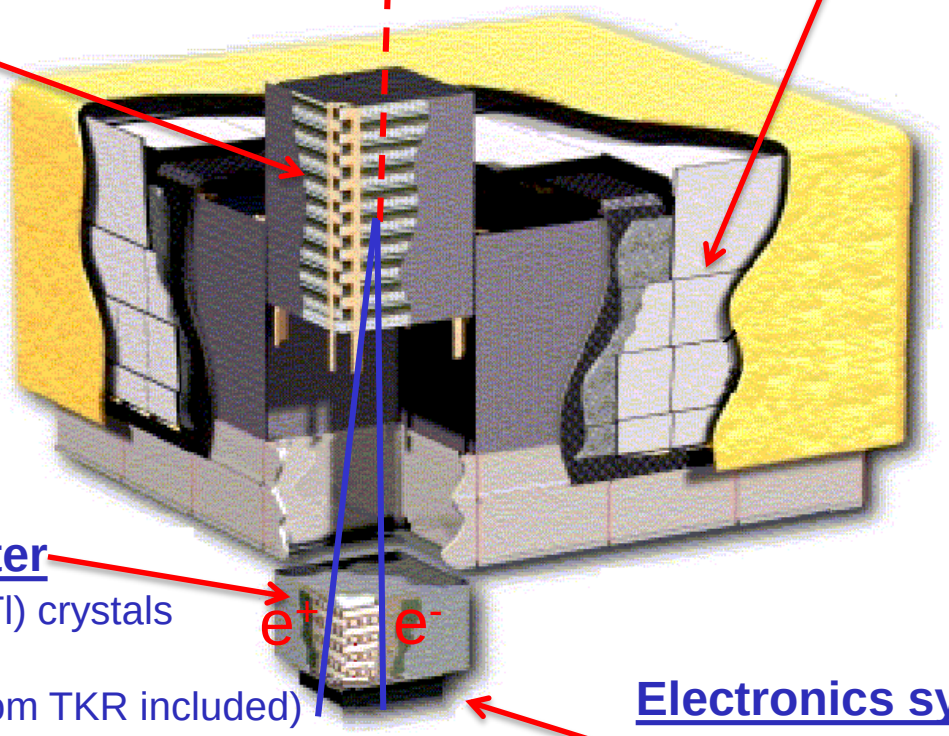
Precision Si-strip Tracker (TKR)

- Measures incident γ-ray direction
- 18 XY tracking planes: 228 μm strip pitch
- High efficiency. Good position resolution
- 12x 0.03 X_0 front end → reduce multiple scattering
- 4x0.18X_0 back-end → increase sensitivity >1 GeV

Anticoincidence Detector (ACD)

- 89 scintillator tiles
- First step in the reduction of large charged cosmic ray background
- Segmentation reduces self-veto at high energy

The LAT is also an excellent electron detector! See the presentation by Carmelo Sgrò



Hodoscopic CsI Calorimeter

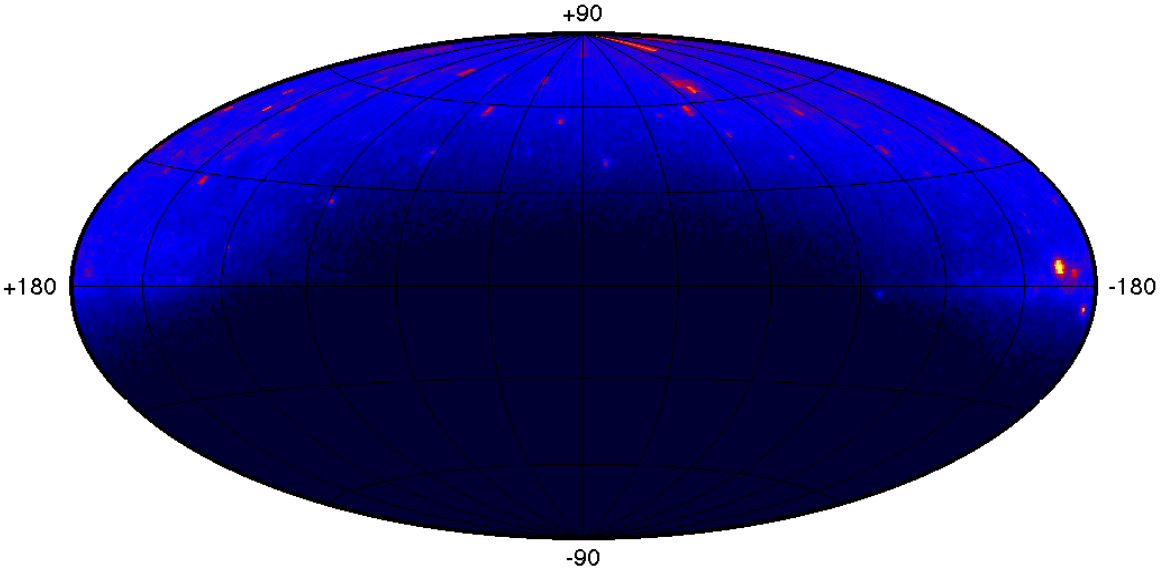
- Segmented array of 1536 CsI(Tl) crystals
- 8.6 X_0: shower max contained
  - ~ 200 GeV normal (1.5X_0 from TKR included)
  - ~ 1TeV @ 40° (CAL-only)
- Measures the incident γ-ray energy
- Rejects cosmic-ray background

Electronics system

- Includes flexible, highly efficient, multi-level trigger

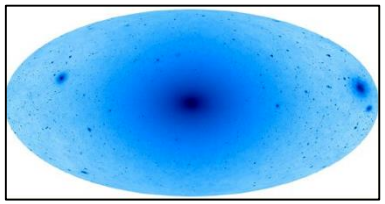
Fermi observation strategy

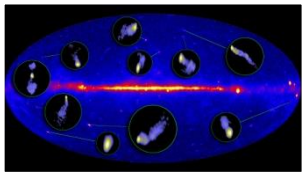
- **Mostly ~uniform sky survey**
  - **Dec 2013 – Dec 2014, transitioned to galactic center biased survey for 1 year**
- **Target of opportunity observations generally between 1 day – few weeks in duration:**
  - **flaring AGN, Novae, Sun, Crab, Binary systems, etc**
- **2.5 hour autonomously commanded pointed observations following detection of bright hard-spectrum GRB**
- **The wide field of view and survey mode operation allows Fermi to explore the high energy gamma-ray sky on timescales from milliseconds to years**

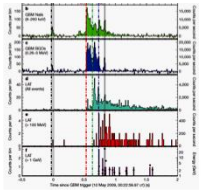


An overview of the Fermi LAT Science

Dark Matter searches

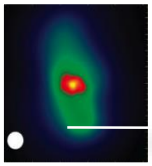




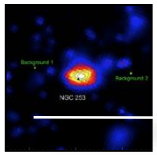


GRBs

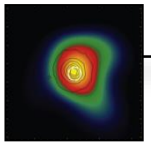
Blazars



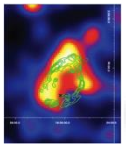
Radio Galaxies



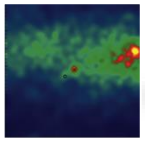
Starburst Galaxies



Globular Clusters



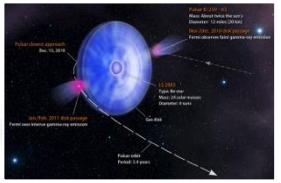
SNRs & PWN



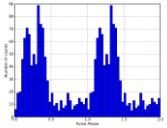
Novae

Extragalactic

Galactic



γ-ray Binaries



Pulsars: isolated, binaries, & MSPs

Moon

Earth

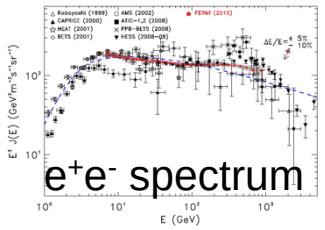
Limb

Sun: flares & CR interactions

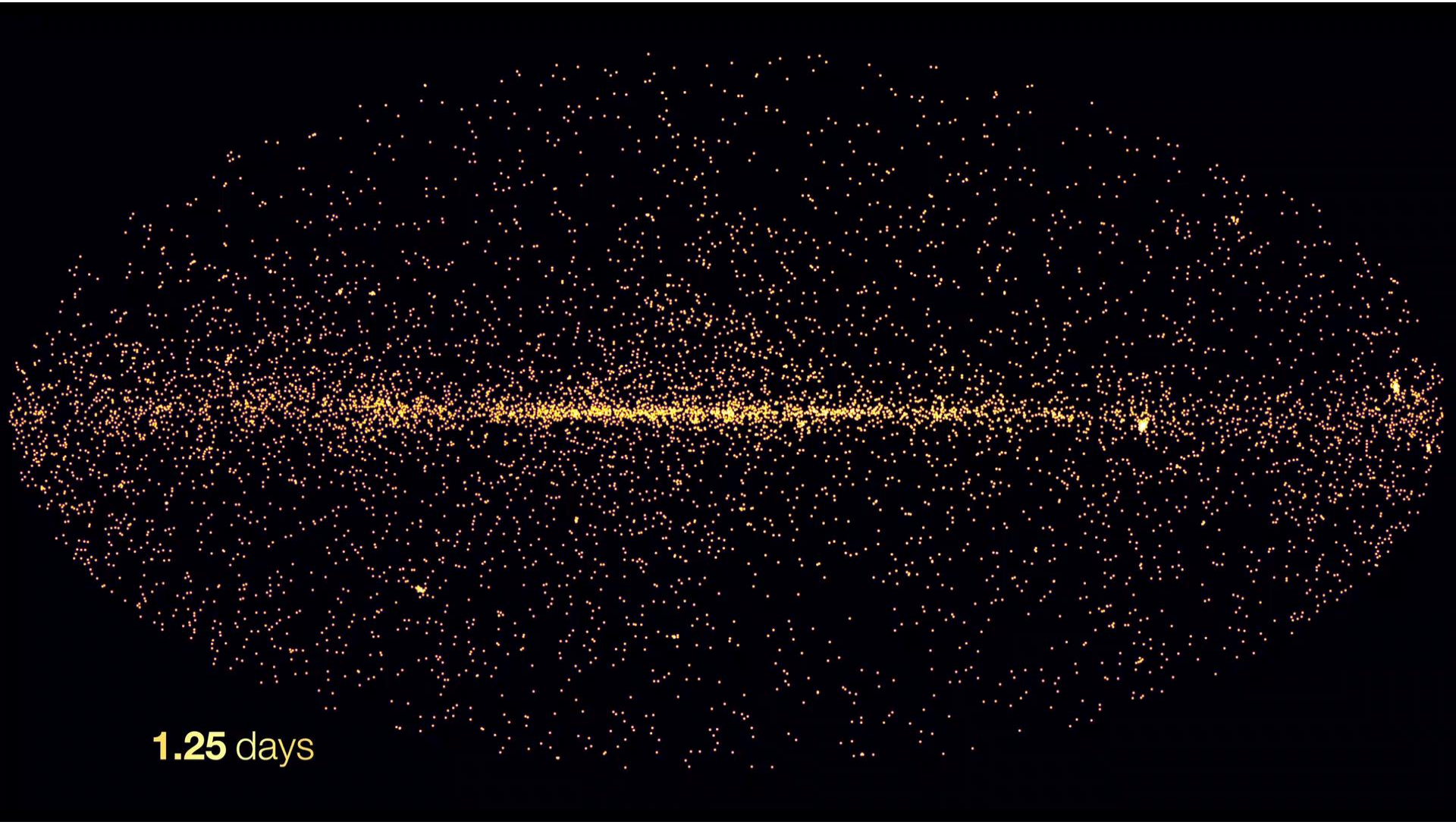
Local

Terrestrial γ-ray Flashes

Unidentified Sources



The gamma-ray sky above 1 GeV



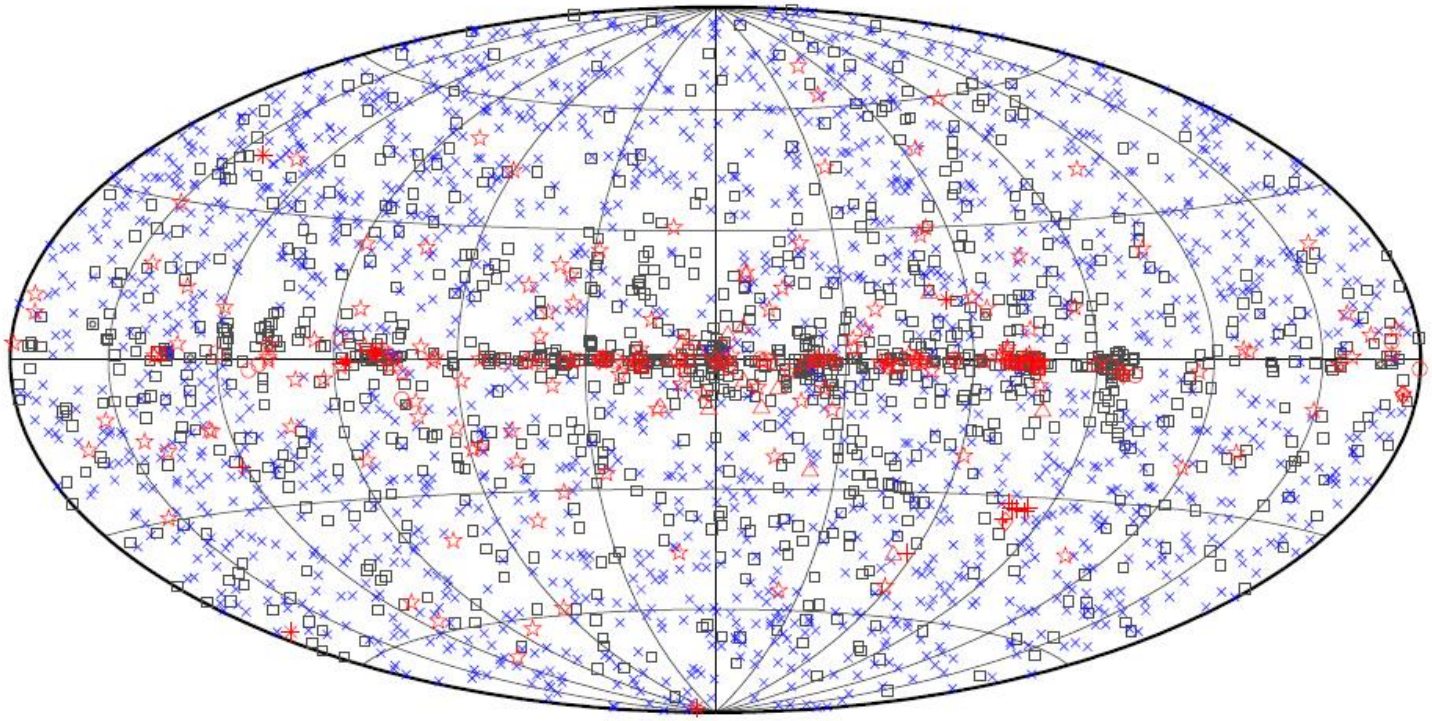
The LAT Catalogs

Catalog	Energy Range (GeV)	Data Interval (months)	Sources	Event Selection	Release Date
0FGL	0.2-100	3	205	P6V1 DIFFUSE	Feb. 2009
1FGL	0.1-100	11	1451	P6V3 DIFFUSE	Feb. 2010
2FGL	0.1-100	24	1873	P7V6 SOURCE	Aug. 2011
1FHL	10-500	36	511	P7V6 CLEAN	Jun. 2013
3FGL	0.1-300	48	3033	P7V15 SOURCE	Jan. 2015
2FHL	50-2000	80	360	P8_SOURCE	In press

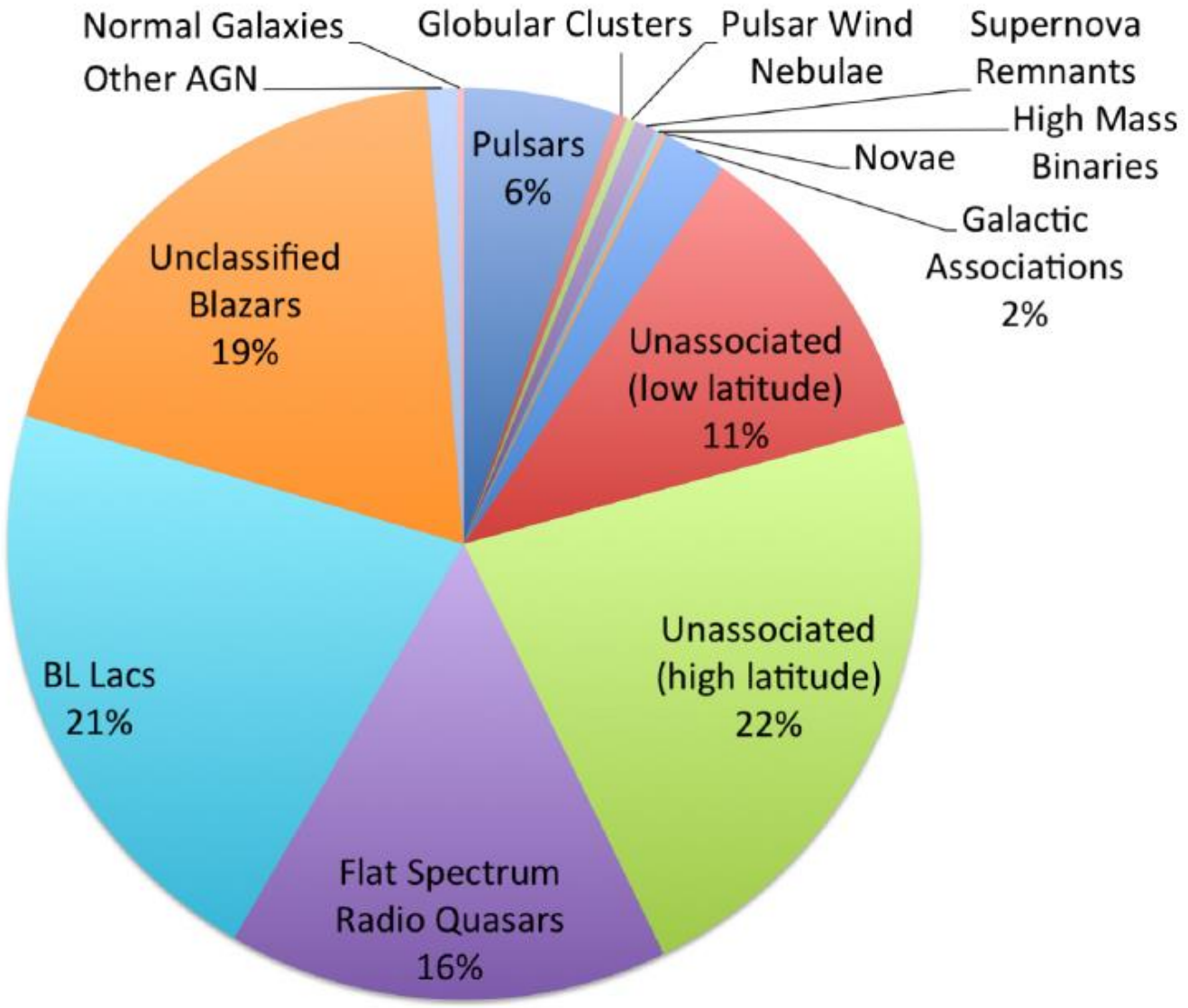
- **There are also class-specific LAT source catalogs**
  - **AGN, Pulsars, GRBs, SNRs, transients…**

The Fermi LAT 3rd Source Catalog (3FGL)

- **4-years data sample with P7 reprocessed data**
- **3033 sources detected with >4σ significance**
- **See Astrophys. J. Suppl. 218 (2015), 23 [arXiv 1501.02003]**

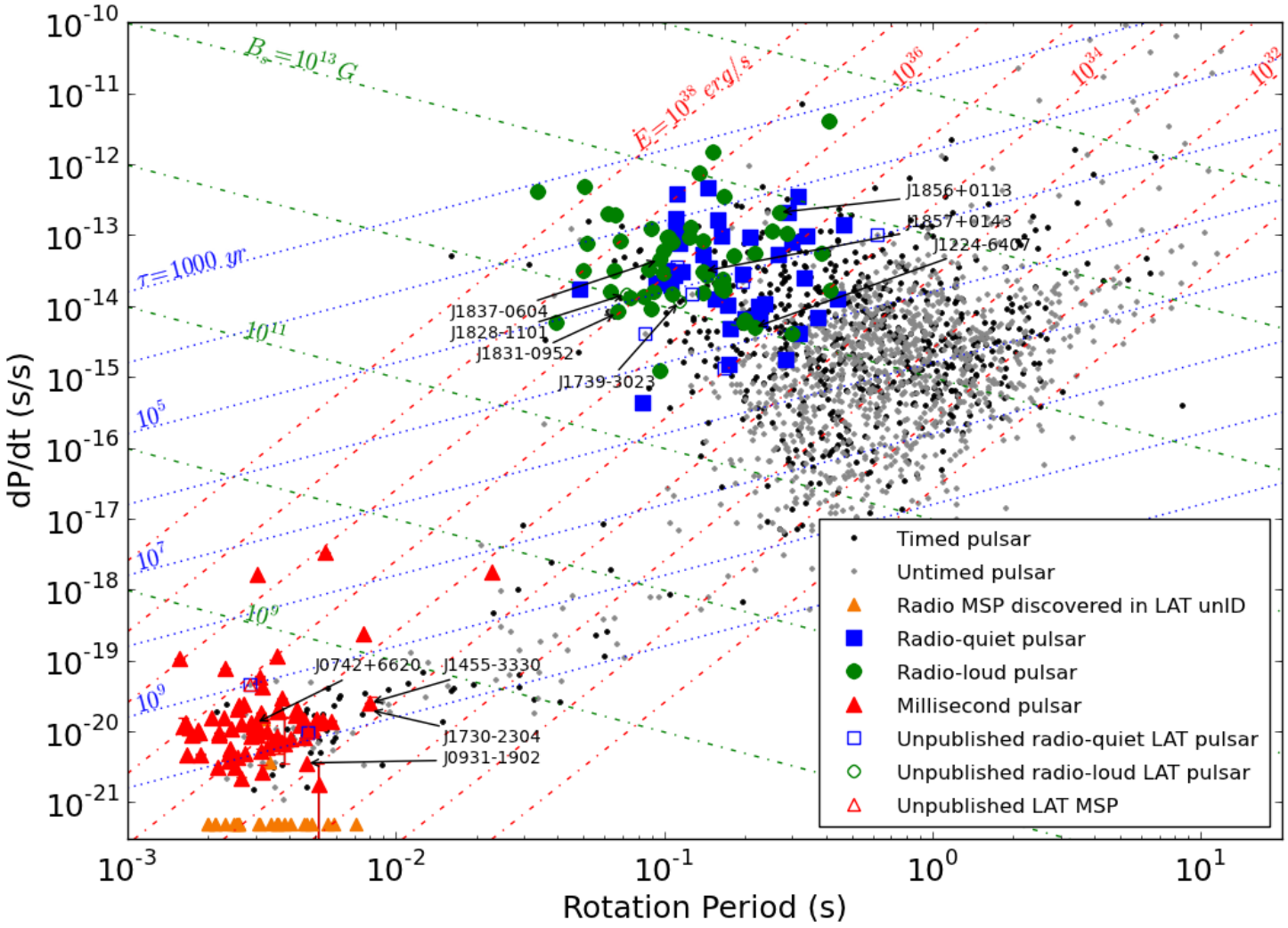


The 3FGL gamma-ray sources



The Fermi LAT pulsars

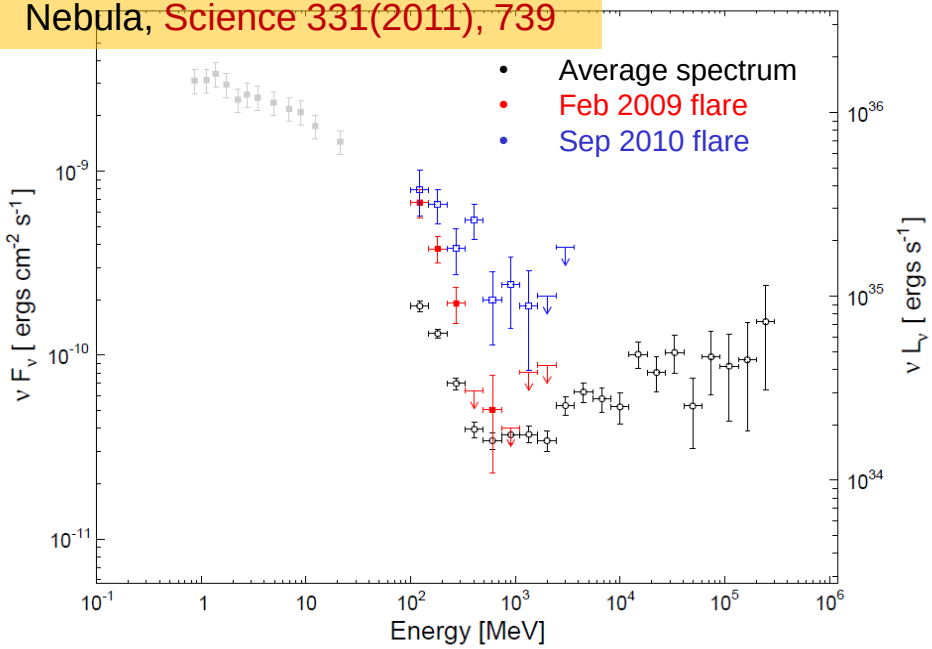
- **At present the LAT has detected 161 gamma-ray pulsars**
  - **Half of the gamma-ray pulsars were not known before Fermi**



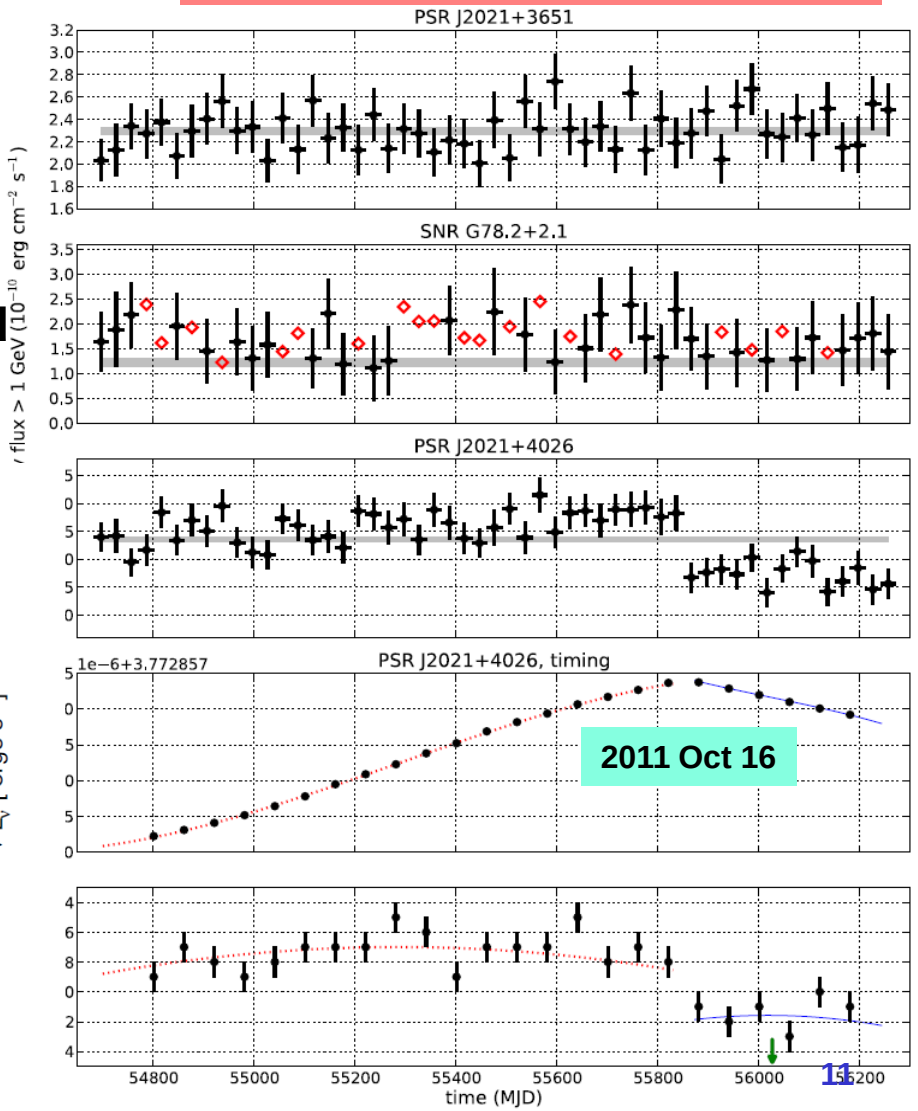
The Fermi LAT pulsars: main discoveries

- **Before Fermi only 7 gamma-ray pulsars were detected → now 161!**
  - **Discover of gamma-ray MSPs**
- **Emission region: outer gap model preferred wrt polar cap model**
- **Pulsars considered to be stable gamma-ray sources were discovered to be variable!**

Gamma-ray flares from the Crab Nebula, Science 331(2011), 739

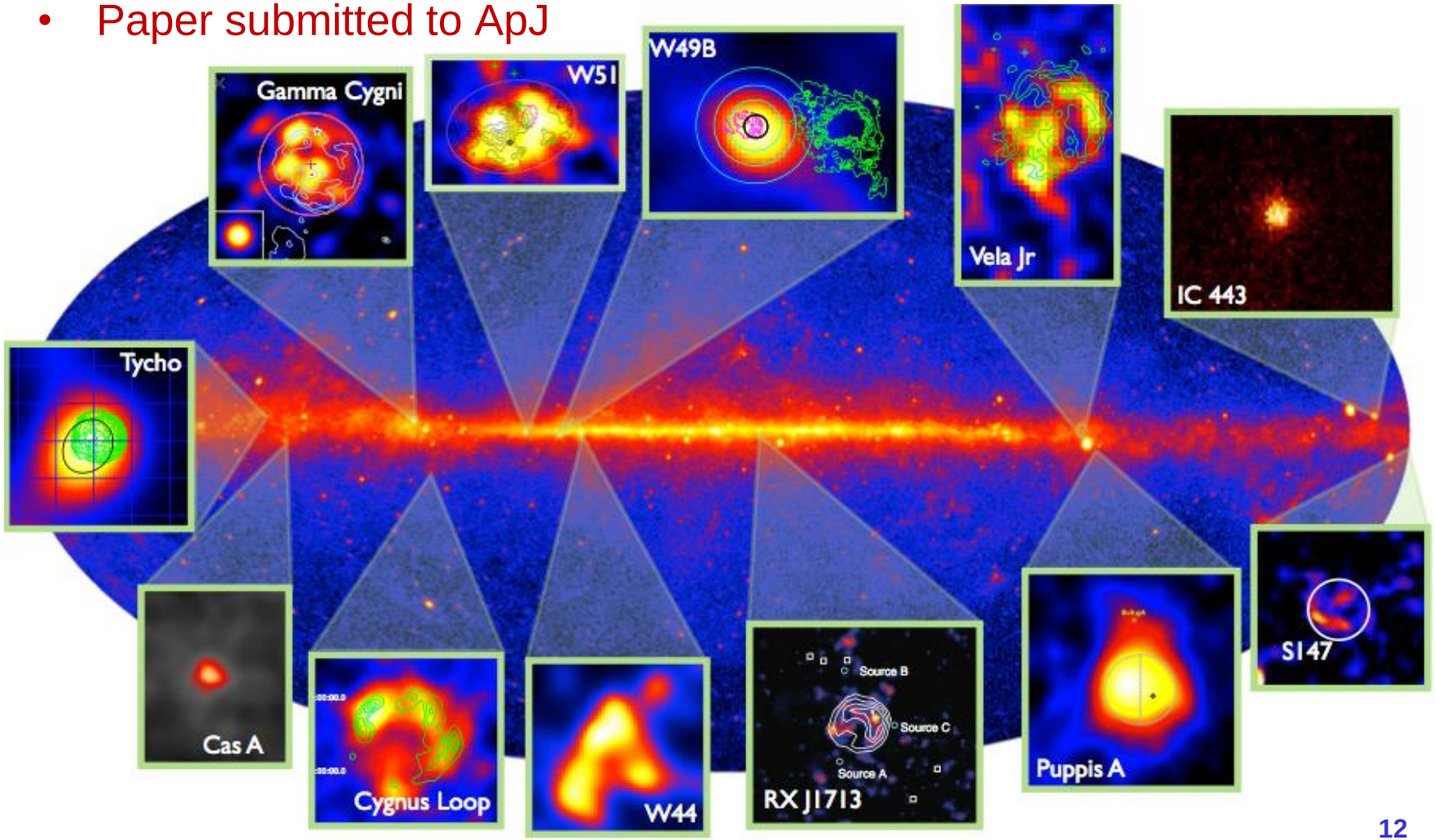


PSR J2021+4026 in the Cygnus region, ApJ Letters 777 (2013), L2



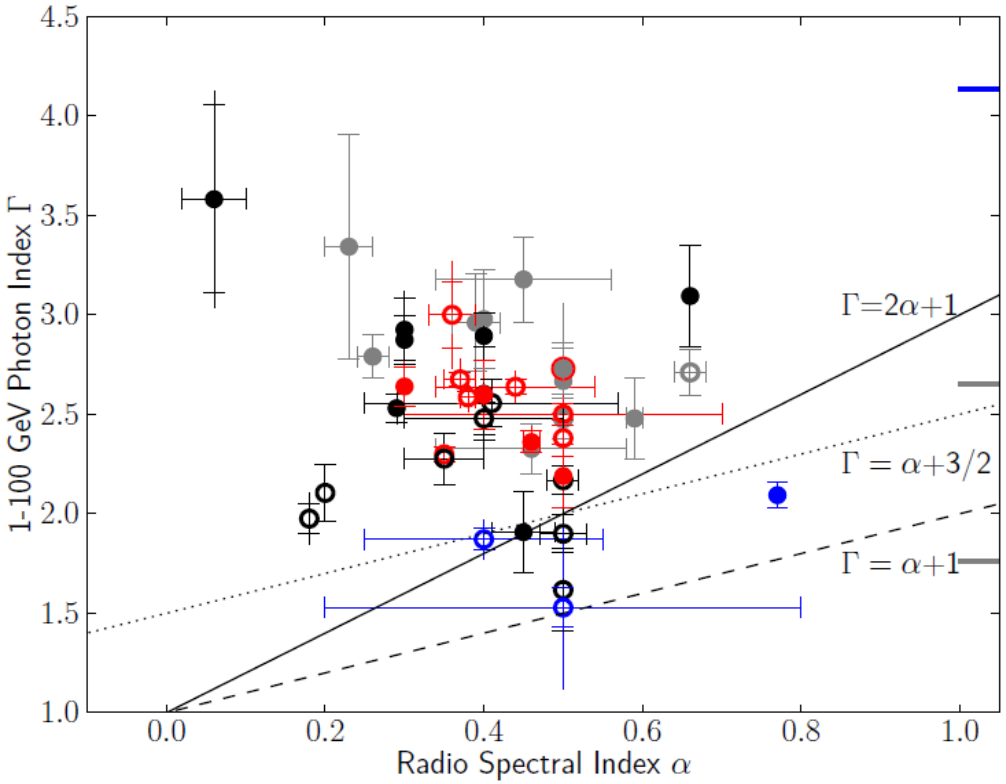
1st Fermi LAT SNR Catalog

- 3 years Pass7 data, 279 ROIs studied, 102 detections
  - population studies, spectral and morphology studies
- Paper submitted to ApJ



Correlations between radio and GeV spectra

- **If radio and GeV emissions originate from the same particle population the spectral indices should be correlated**
- **Data challenge model assumptions**
  - **Underlying particle populations may have different indices**
  - **Emitting particle populations may not follow power law: breaks?**
  - **Multiple emission zones?**



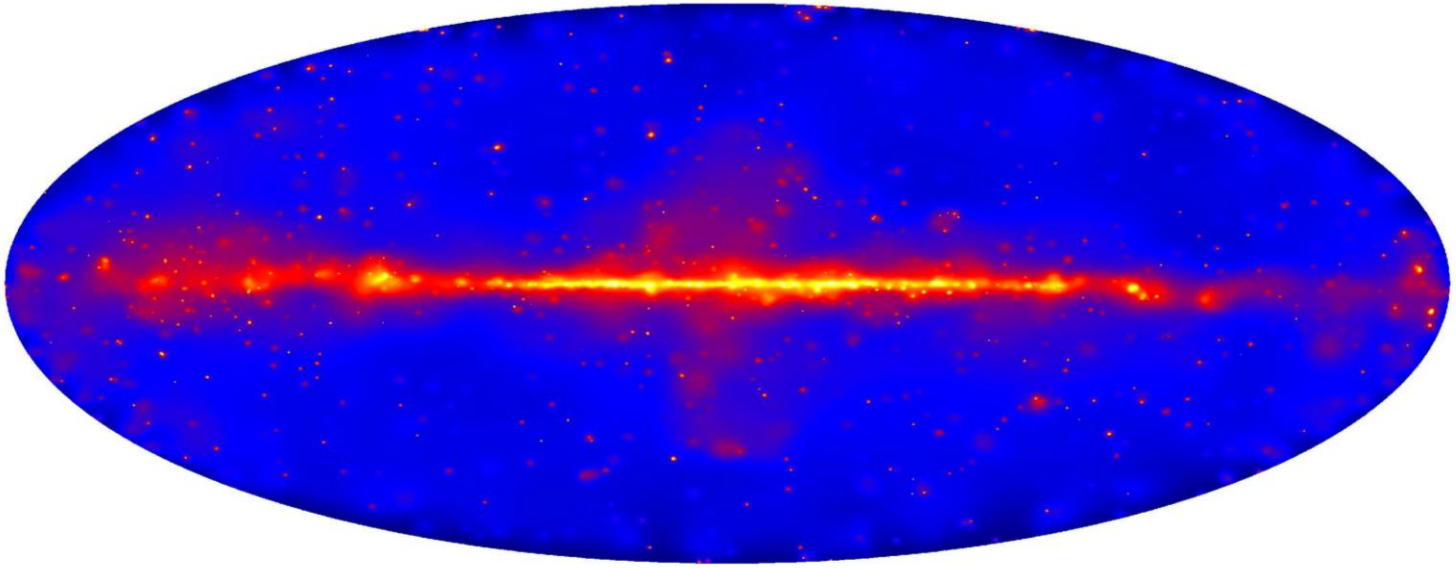
π^0 decay or $e^{+/-}$ bremsstrahlung

Inverse Compton with cooling

Inverse Compton without cooling

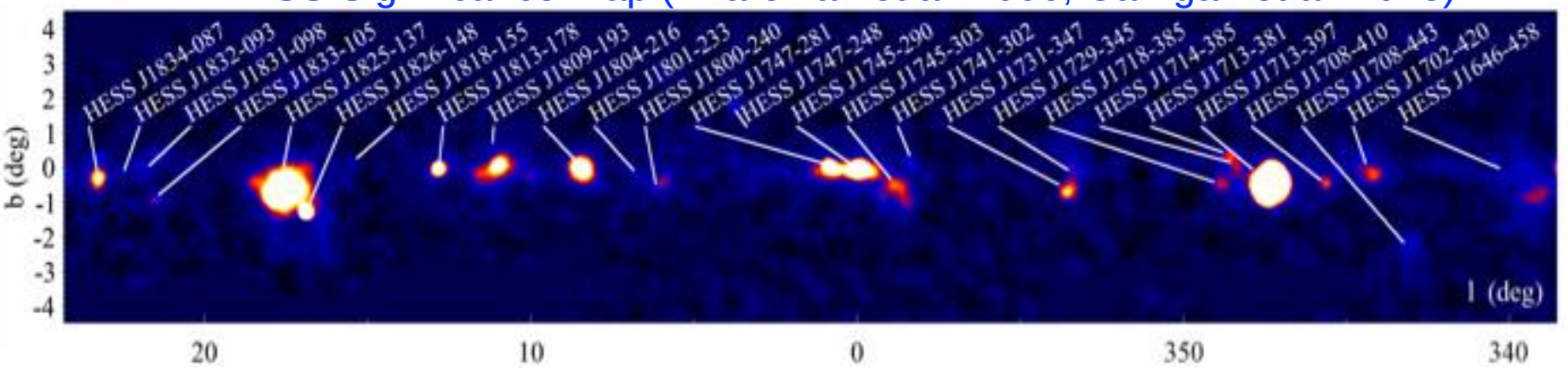
The gamma-ray sky above 50 GeV: 2FHL catalog

- Paper submitted to ApJ, see arXiv 1508.04449
- Energy range from 50 GeV to 2 TeV
- 80 months of data
- 360 sources detected:
  - 78 detected by IACTs (TeVCat)
  - 230 detected in 1FHL
  - 303 detected in 3FGL
  - 57 brand new sources (not 1FHL/3FGL)

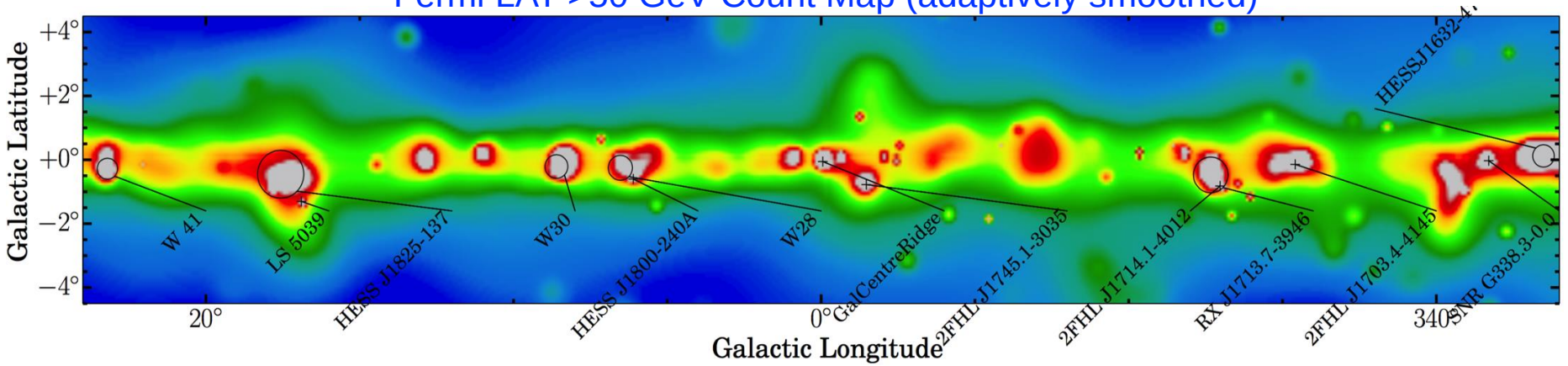


Comparison with HESS GP survey

HESS Significance Map (Aharonian et al. 2006, Carrigan et al. 2013)



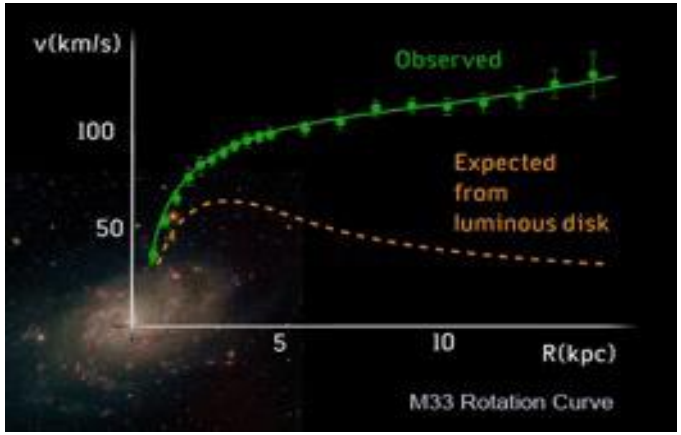
Fermi LAT >50 GeV Count Map (adaptively smoothed)

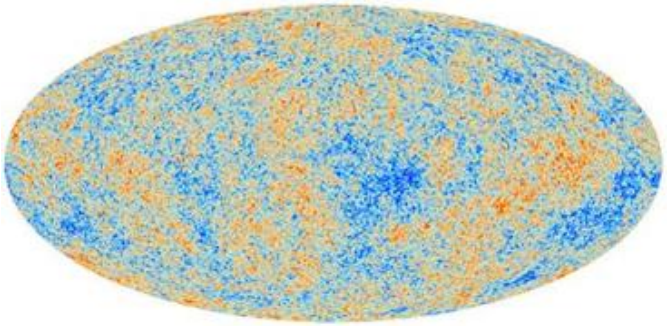


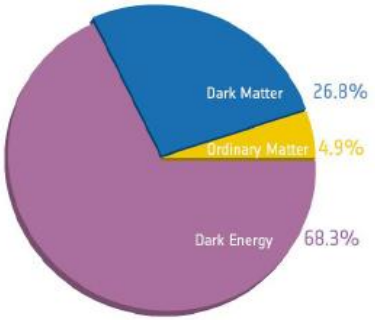
- H.E.S.S. detected 69 sources reaching a sensitivity of ~2% of the >1 TeV Crab Nebula flux
- The LAT detects 36 sources with an average sensitivity of 3-4% of the Crab Nebula flux
- The LAT detects an equal number of PWNe/SNRs while for H.E.S.S they are in a 1.5:1 ratio

Dark Matter

- **Astrophysical evidence for missing mass**
  - **Galaxy rotation curves**
  - **Colliding clusters**
  - **Cosmological probes ($\Omega_{dm}\ h^2 \approx 0.1$)**
- **Observational evidence indicates:**
  - **Non-baryonic**
  - **(Almost totally) neutral**
  - **(Almost totally) collisionless**
- **Theoretical candidates:**
  - **Axions, sterile neutrinos, etc.**
  - **Modifications to gravity**
  - **Weakly Interacting Massive Particles (WIMPS)**

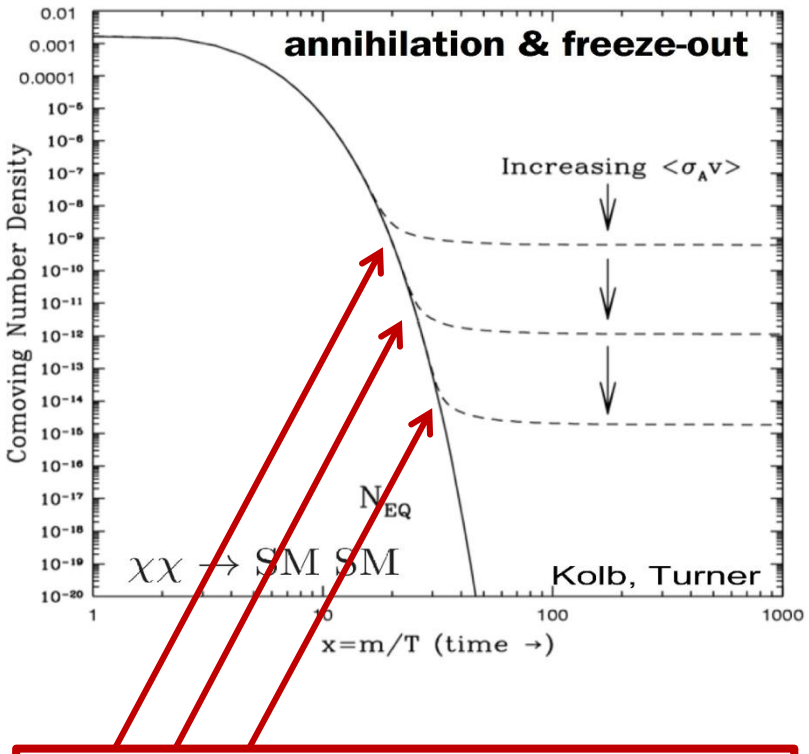






WIMPs as DM candidates

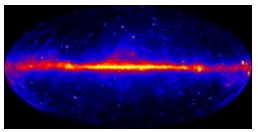
- **A WIMP in chemical equilibrium in the early universe naturally has the right density to be Cold Dark Matter**
  - **At early times, WIMPs are produced in l^+l^-, ... collisions in the hot primordial soup (thermal production)**
  - **WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate (freeze-out)**
  - **After freeze-out, the number of WIMPs per photon is constant**
- **Standard relic density calculation yields for nonrelativistic relics:**
  - $\Omega_{dm}h^2 \approx \frac{3\times10^{-27}cm^3s^{-1}}{\langle\sigma v\rangle} \approx 0.1$
- **Electroweak cross-sections are in correct range:**
  - $\sigma v \sim 10^{-26}cm^3s^{-1}$



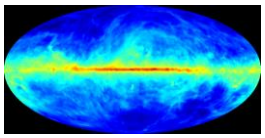
Freeze-out:
$\Gamma_{ann} = n \langle\sigma v\rangle \sim H$
annihilation rate ~ expansion rate

$\langle\sigma v\rangle_{ann} \sim 3 \times 10^{-26}$ cm^3/s for thermal relic

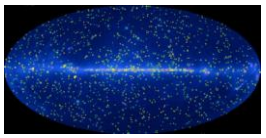
Indirect searches for dark matter in the GeV gamma-ray sky


GeV Sky

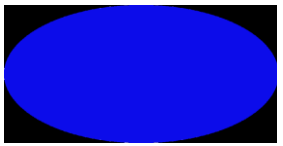
=


Galactic

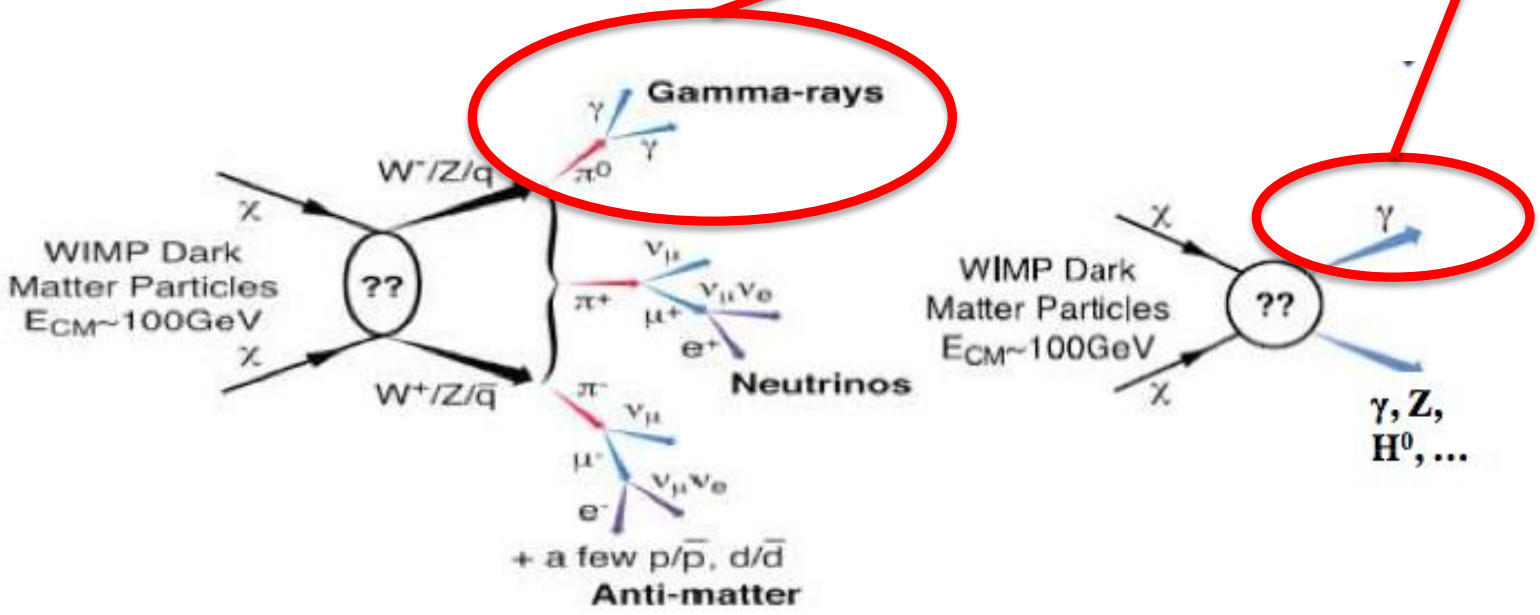
+


Point Sources

+


Isotropic

+ ???



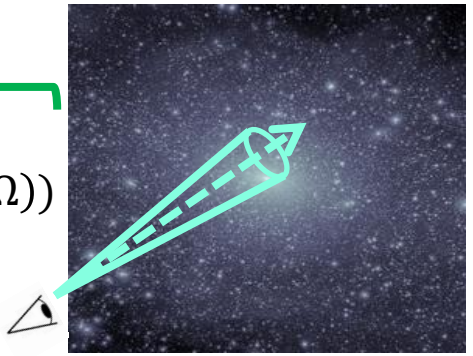
Dark matter signatures in gamma-rays

Observed flux | **Intrinsic Particle Properties** | **Astrophysics**

Annihilation $$\phi(E,\Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2\,m_\chi^2}\sum_f \frac{dN_f}{dE} B_f \int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\ \rho^2(l(\Omega))$$

Decay Γ_D/m_χ

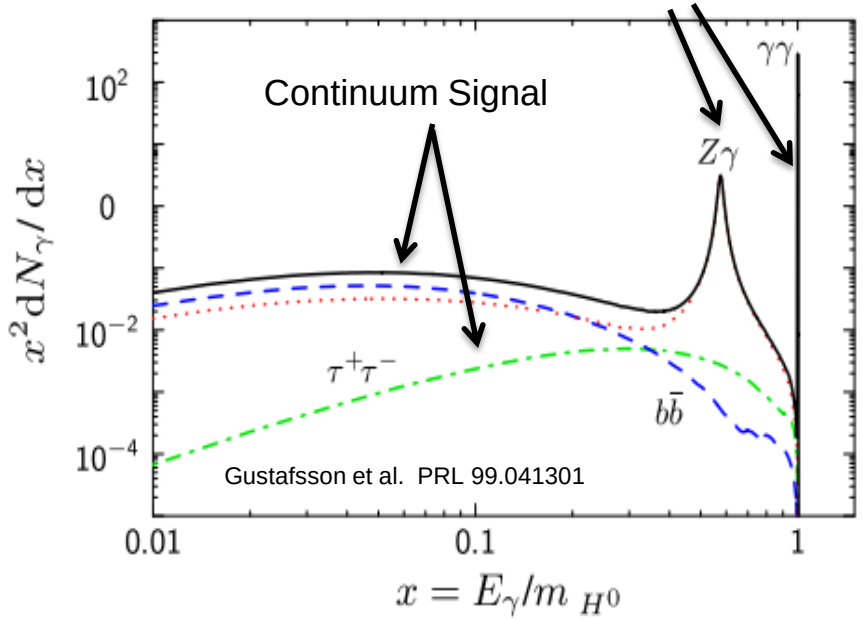
$\rho(l)$

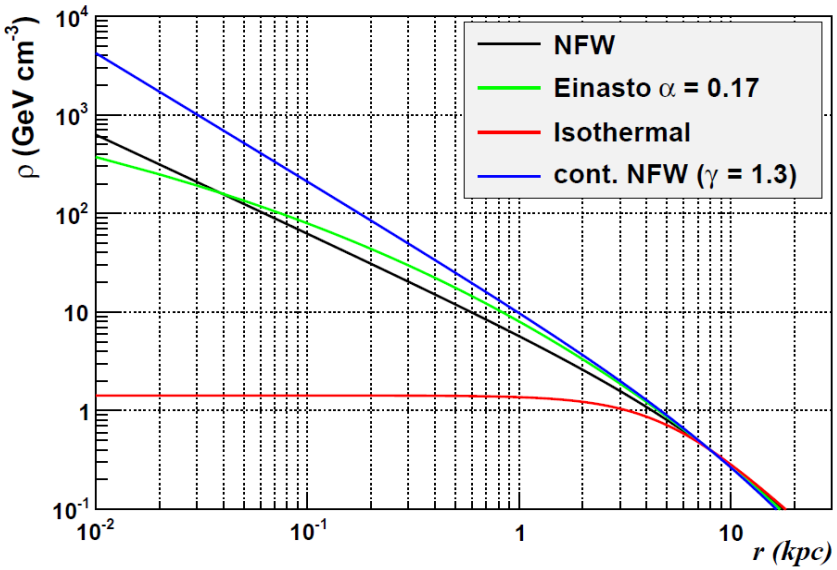


$\langle\sigma v\rangle_{ann}$ ~ 3 ×10^{-26}cm^3/s for thermal relic

J-factor – DM distribution (line-of-sight integral)

Monochromatic Signal





Dark matter search targets

Satellites

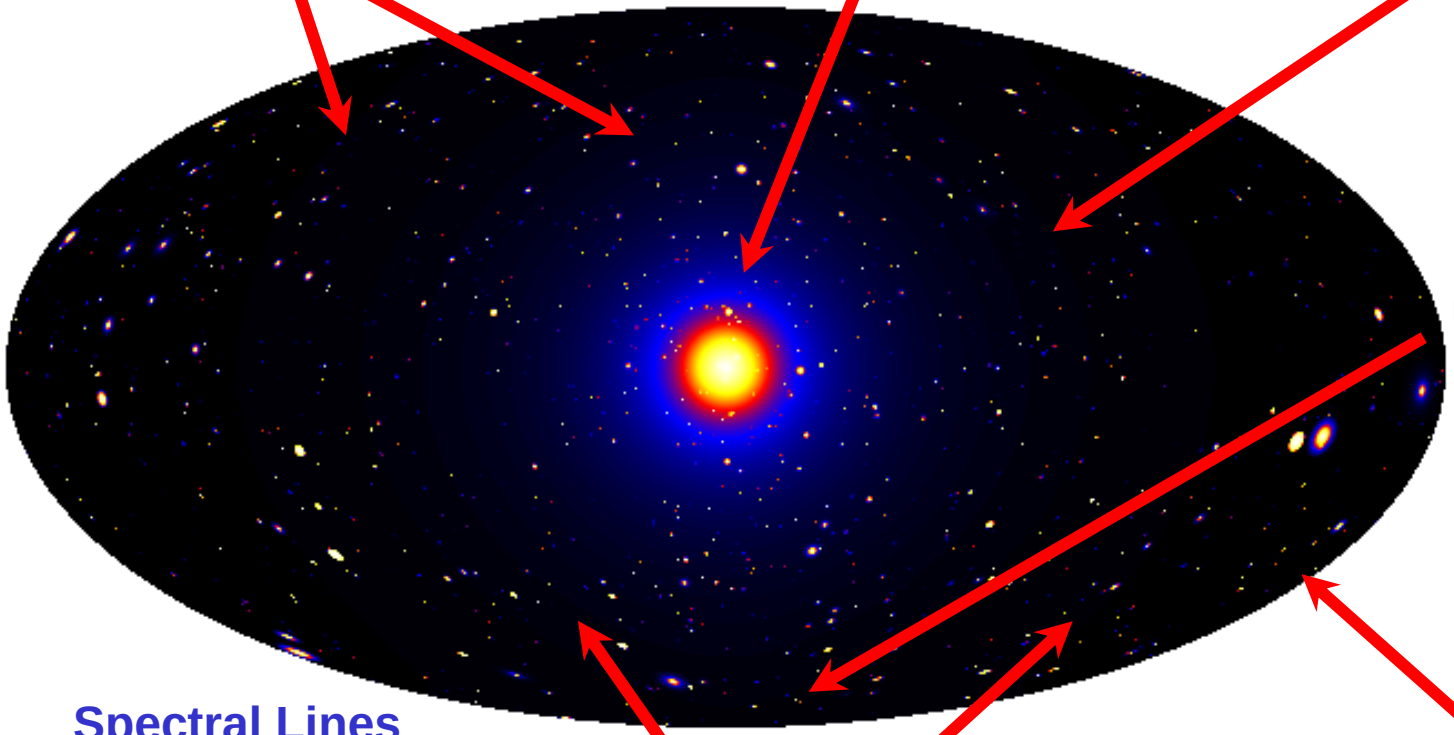
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Dwarf Galaxies

Known location and DM content
Low statistics

Spectral Lines

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

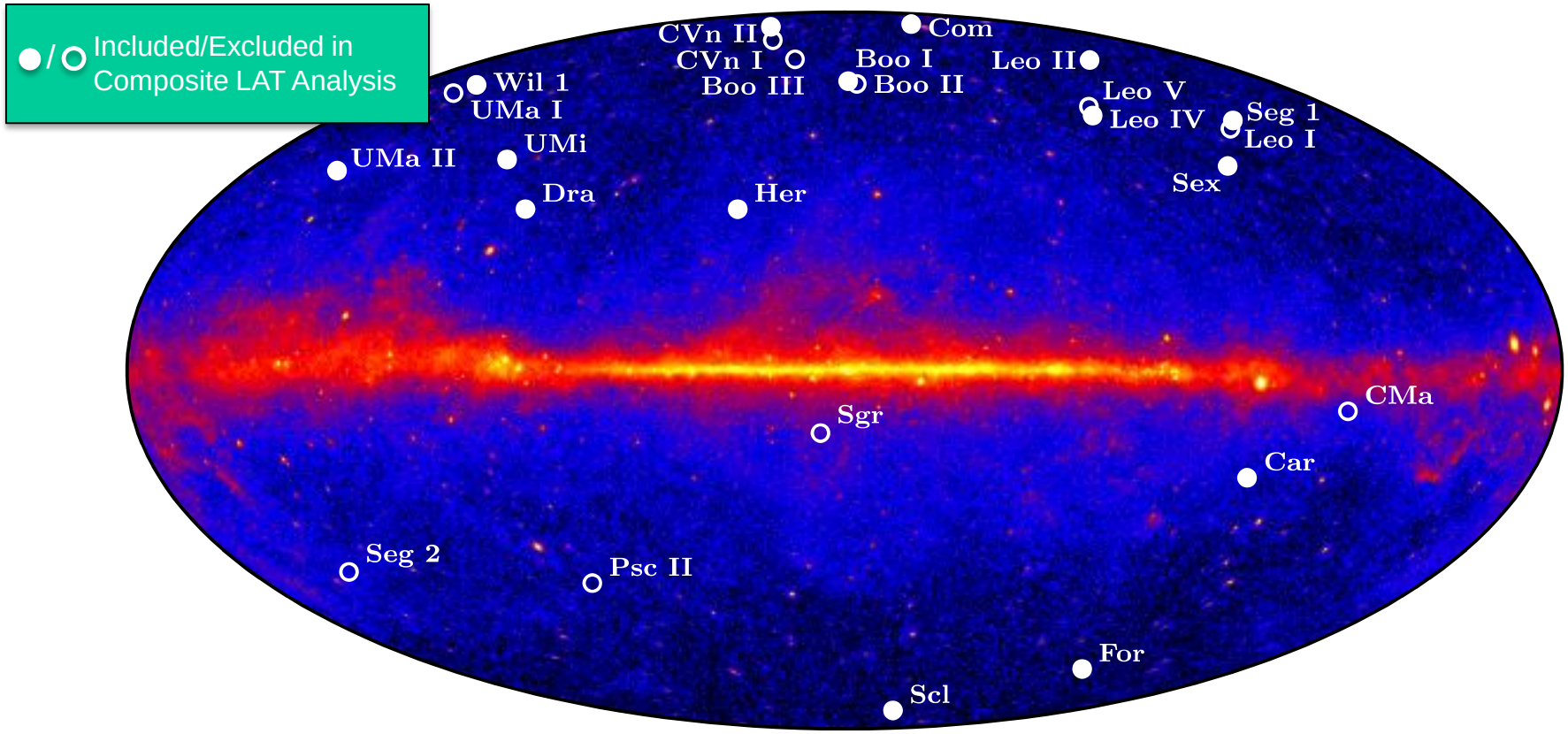
Galaxy Clusters

Low background, but low statistics

Isotropic contributions

Large statistics, but astrophysics, galactic diffuse background

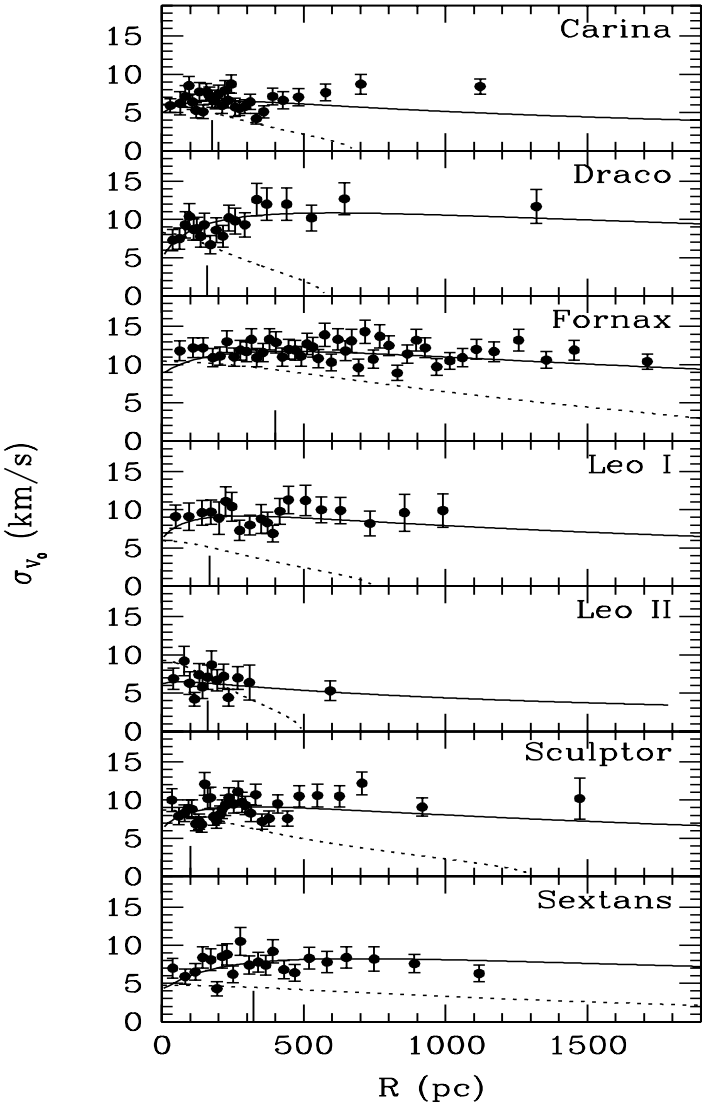
Dark Matter searches in dSph Galaxies



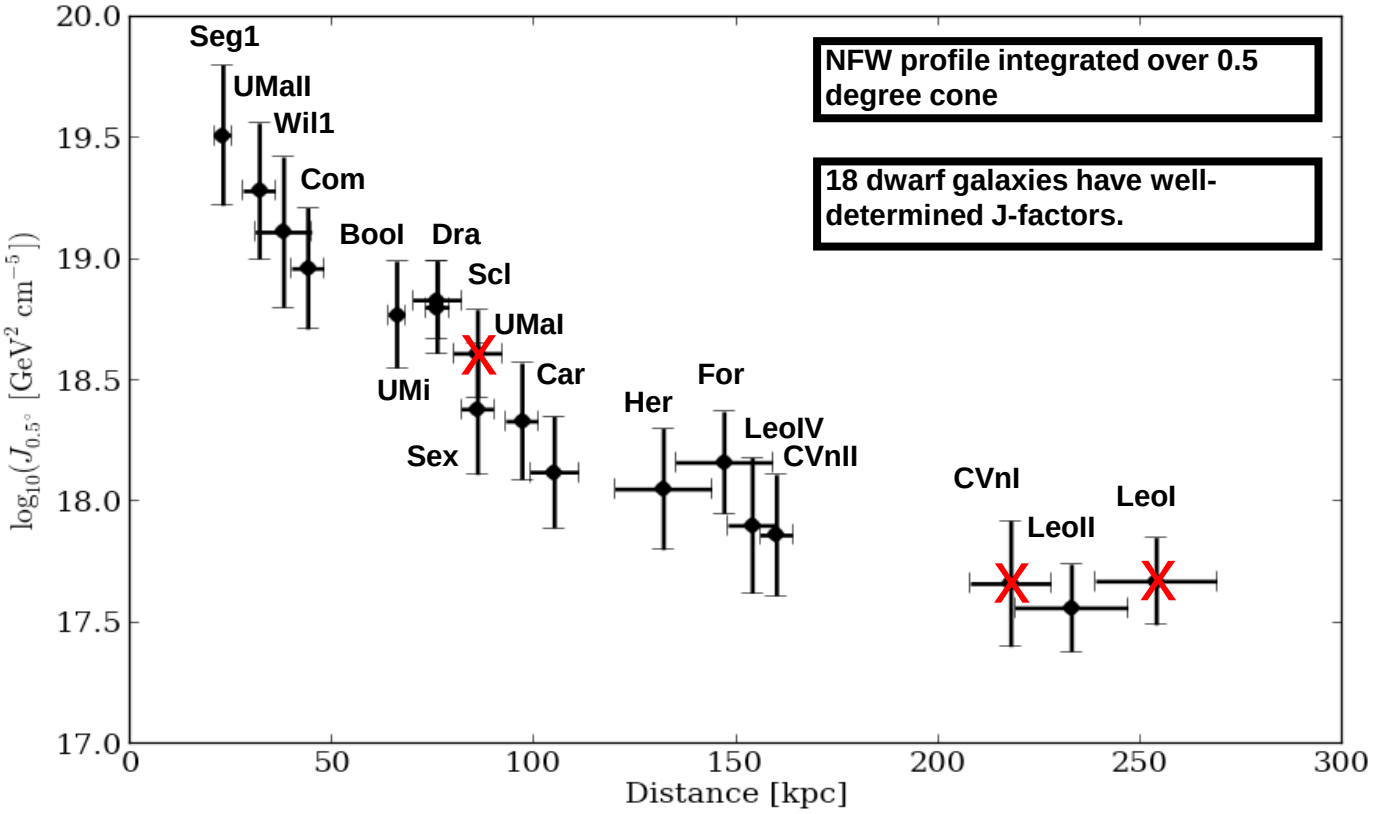
- Dwarf spheroidal galaxies (dSphs) are **dark** and highly **DM-dominated** systems
- Most are found at high latitude where astrophysical foregrounds are low
- Low backgrounds make these a very clean target for indirect DM searches

Dark Matter content of dSph Galaxies

- **Gamma-ray signal from each dwarf is proportional to its J-factor:**
  - $J = \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{l.o.s.} \rho^2\big(r(l,\phi')\big) dl(r,\phi')$
- **Dwarf J-factors are determined spectroscopically from stellar velocity dispersions**
  - **Classical dwarfs: spectra for several thousand stars**
  - **Ultra-faint dwarfs: spectra for fewer than 100 stars**
- **Using the LOS velocity dispersion and an assumed DM density profile (NFW) we can calculate a J-factor for each dwarf (Martinez, 2013)**
- **Statistical uncertainty in the J-factor is folded into the gamma-ray analysis**



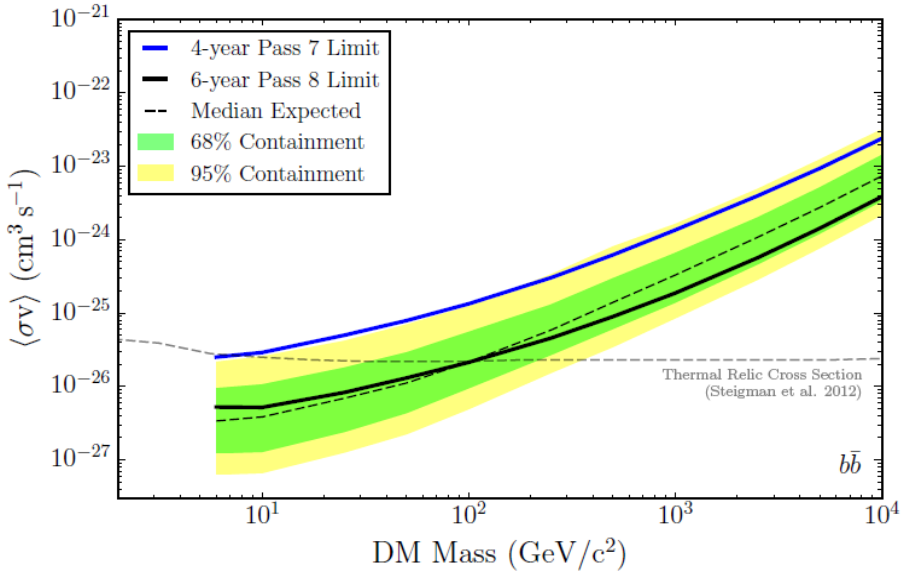
J-factors for 18 dSph Galaxies

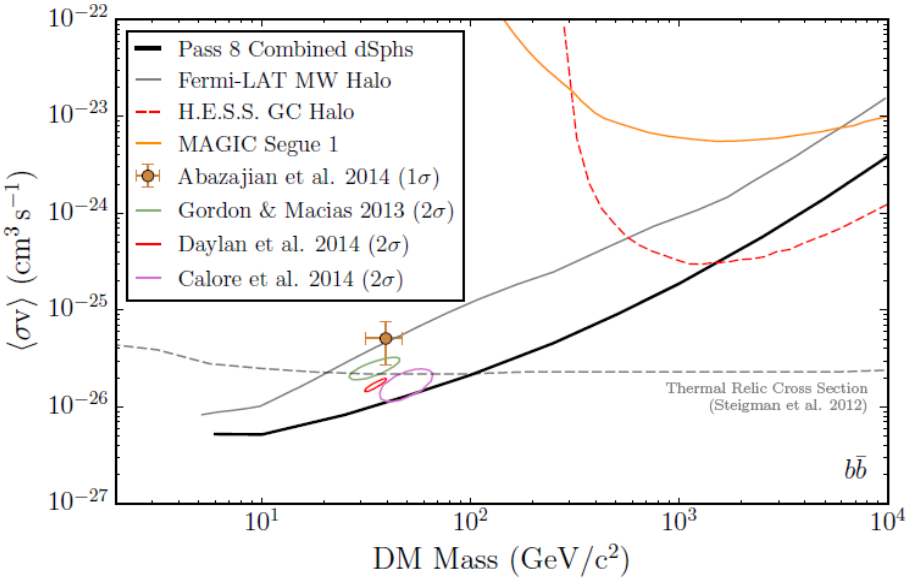


- **15 dwarfs used for composite analysis (UMaI,CVn1, and Leo1 excluded due to ROI overlap).**

Upper limits on DM annihilation cross section from dSph analysis

- **6 years of Fermi-LAT Pass8 data from 15 dwarf spheroidal galaxies constrain the thermal relic cross section for low mass dark matter**
- **DM Limits from the LAT Dwarf stacking analysis are highly competitive with those provided by ground-based gamma-ray observatories (HESS, MAGIC)**
- **LAT Dwarf limits are more constraining for WIMP models with mass below 1 TeV**
- **Currently, statistically limited (especially at high masses)**
- **Paper accepted by PRL (arXiv 1503.02641)**

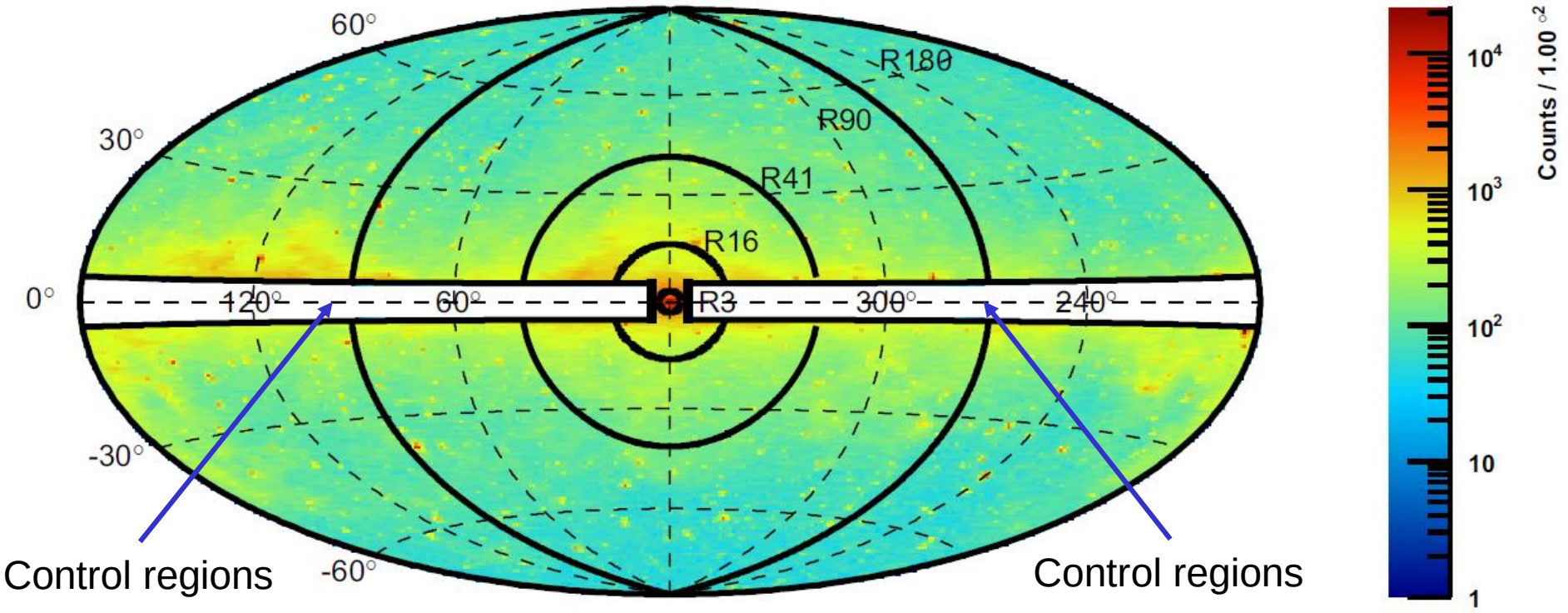




Search for gamma-ray lines

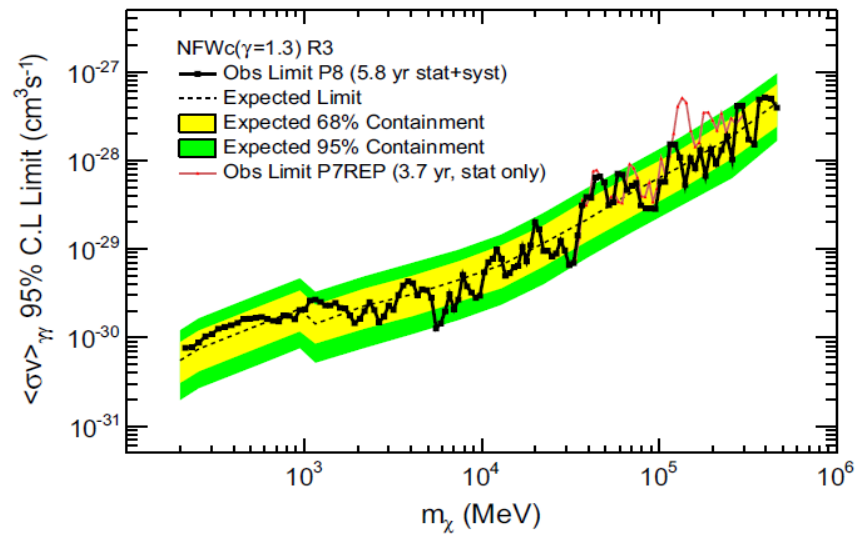
- **WIMP annihilations in the Universe may produce gamma rays detectable by the LAT**
  - **$\chi\chi \rightarrow \gamma\gamma$, γZ^0, γH^0 would produce a narrow feature**
  - **Sharp, distinct spectral feature ("smoking gun")**
    - **Likely a small branching fraction**
    - **Signal predicted to be small (b.f. typically ~10^{-2} to 10^{-4})**
- **Most recent line search from the LAT Collaboration:**
  - **5.8 years Pass 8 data sample**
    - **Improved energy reconstruction**
    - **Increased effective area**
  - **Energy interval from 200 MeV to 500 GeV**
  - **Improved understanding of systematics**
  - **See Phys. Rev. D91, 122002 (2015)**

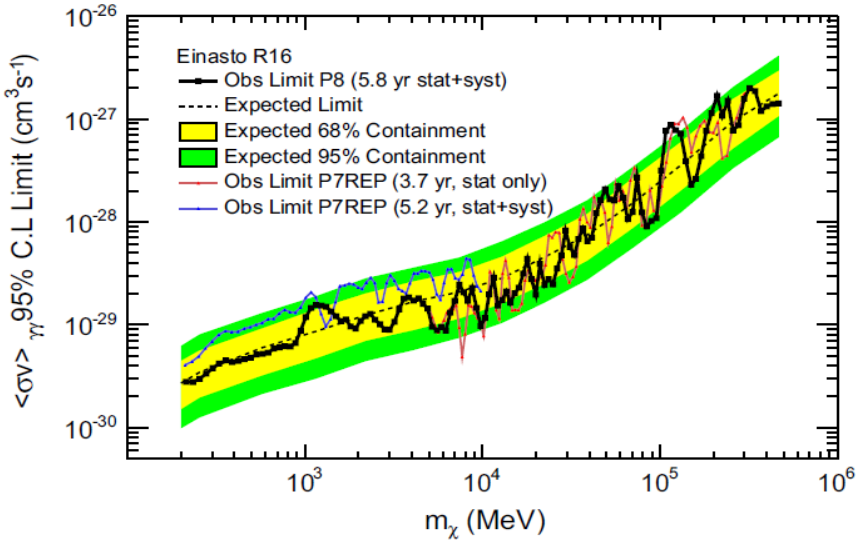
ROI optimization

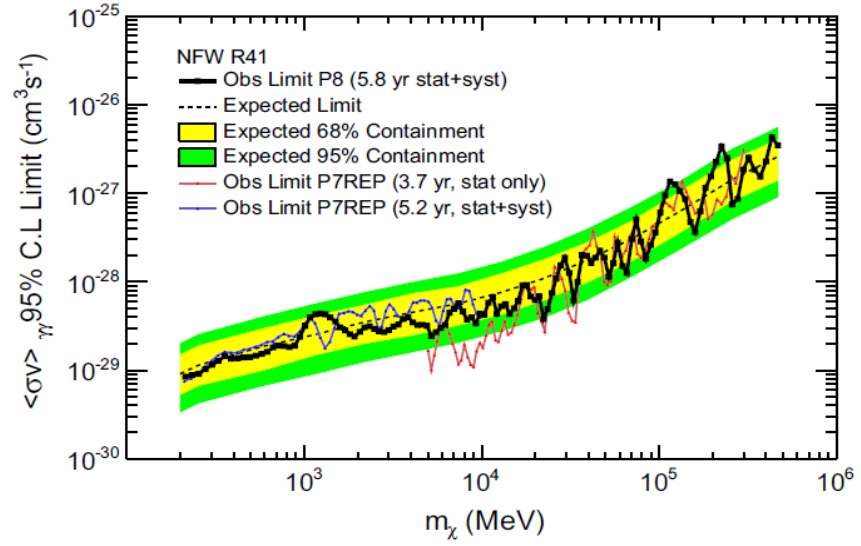


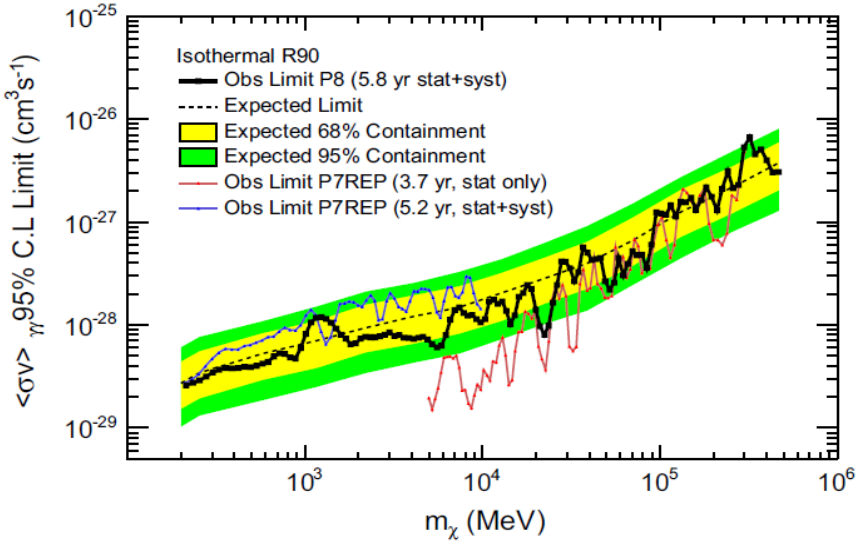
- **ROIs for line search:**
  - **R3 (circle with 3° radius centered on the GC), R16 (Einasto Optimized), R41 (NFW Optimized), R90 (Isothermal Optimized), R180 (Decay Optimized)**
- **Control regions:**
  - **31 boxes 10° × 10° along the GP**
  - **Same line search algorithms as in signal ROIs**
  - **Allow to evaluate systematics**

Upper limits on the WIMP mass from line searches





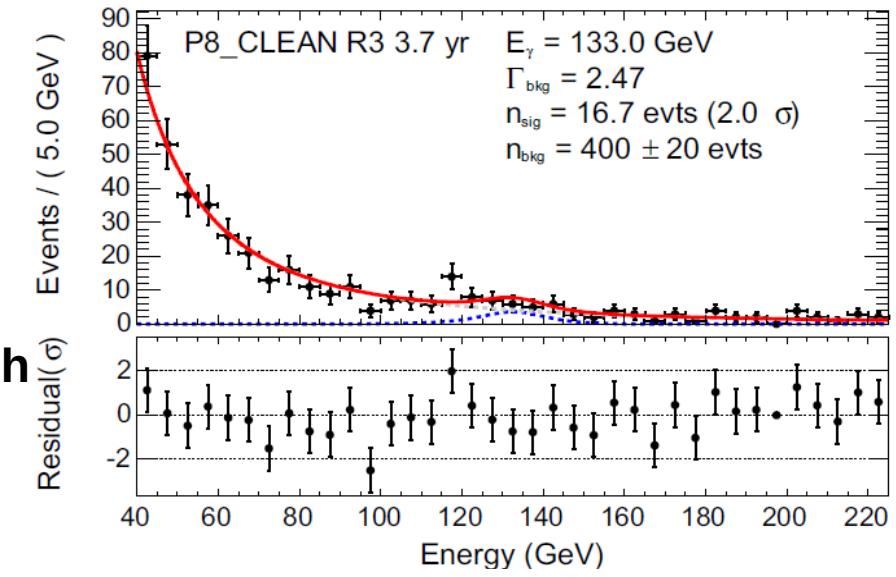


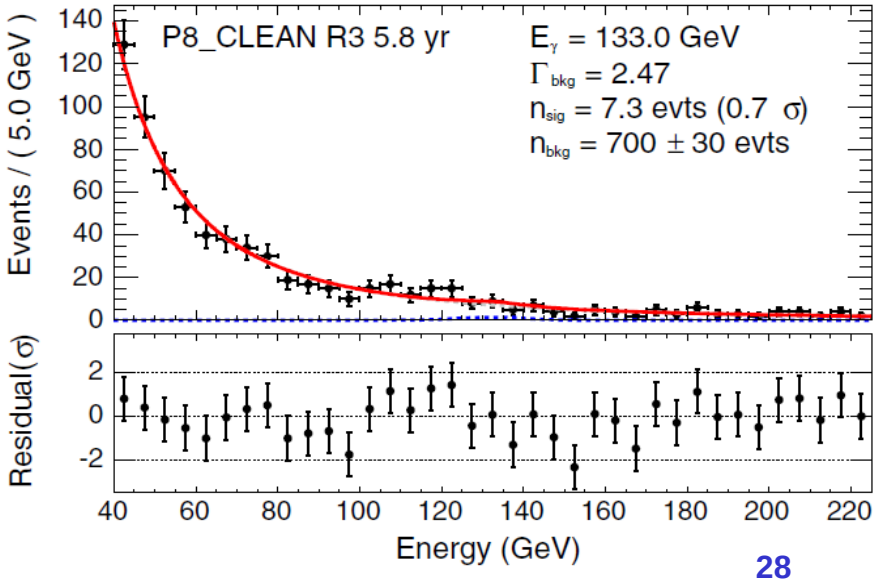


No evidence of spectral lines found!

The line feature at 133 GeV

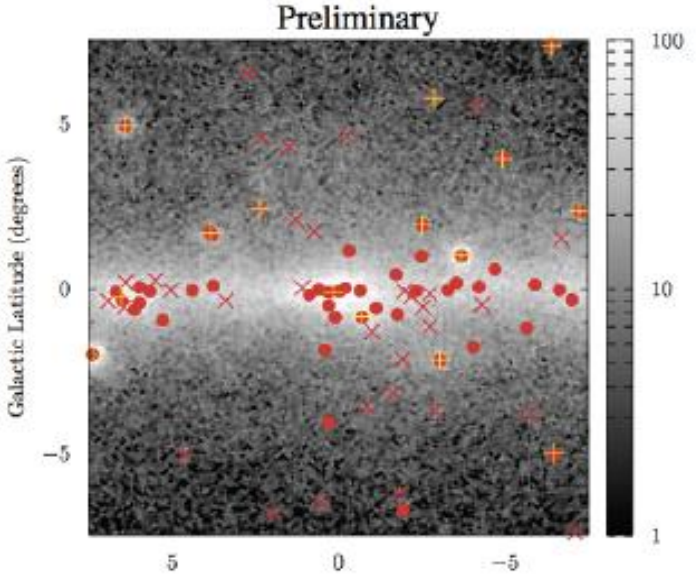
- A potential signal was reported in the 3.7yrs data sample for a small ROI containing the GC
  - Bringmann+, JCAP 07 (2012), 054
  - Weniger+, JCAP 08 (2012), 007
- The LAT detected the feature, although with low global significance
- Newest LAT data analysis:
  - Increased data set (5.8 yrs)
  - Use of Pass 8 event classification
    - Improved energy reconstruction
  - Greater exposure towards the GC
    - Modified observing strategy from Dec 2013 to Dec 2014
- The excess in the 3.7 yrs data is of 2σ (3.3σ with Pass 7 data) and decreases using the full 5.8 yrs data set





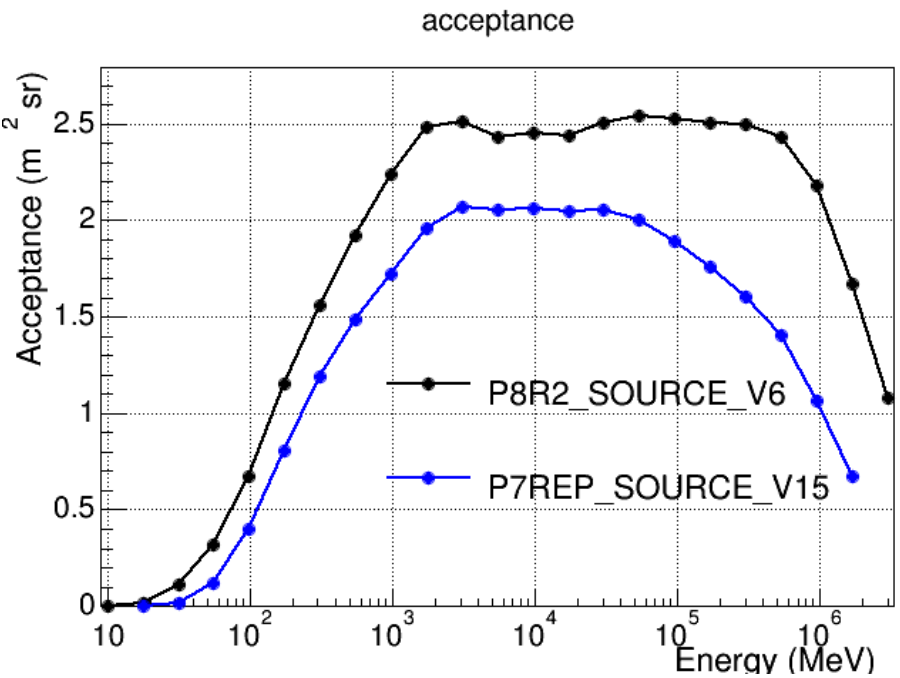
Dark Matter in the inner Galaxy?

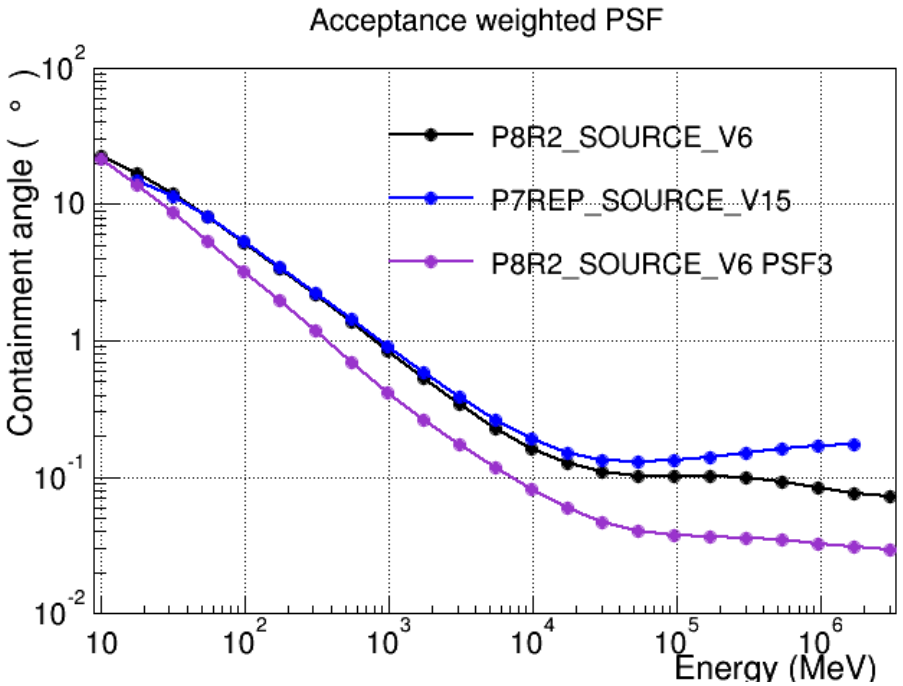
- **Likely the brightest dark matter source in the gamma-ray sky, but it is embedded in large and complicated backgrounds:**
  - **resolved sources**
  - **unresolved sources**
  - **diffuse emission**
- **Several independent studies find GeV excesses above the expected diffuse background**
- **The excess at the Galactic center could be due to:**
  - **dark matter**
  - **unresolved sources (e.g. MSPs)**
  - **…**
- **Paper submitted to ApJ**



LAT analysis upgrade: Pass 8

- **A major upgrade of the LAT (aka Pass 8) was released in 2015**
  - **Complete revamp of LAT event reconstruction algorithms**
  - **More than double acceptance below 100 MeV**
  - **Retroactively updated entire Fermi-LAT data archive**





Conclusions and perspectives

- Fermi has opened a window on the extreme high-energy Universe
- Exciting results in all fields of gamma-ray astrophysics
  - Many discoveries, many new source classes, many surprises
    - Many results not shown here!
  - The LAT gamma-ray data improved our understanding of CR accelerations processes and allowed to set more constrained limits on new physics than previously done
- The LAT has been monitoring the gamma-ray sky for 7 years and is still in good health
- Significant improvements of the LAT performance
  - Updated event reconstruction with Pass 8
  - Updated diffuse model coming soon
- Extended long term operations will provide a unique opportunity for time domain astrophysics and multi-wavelength observations