Results from the Fermi Large Area Telescope

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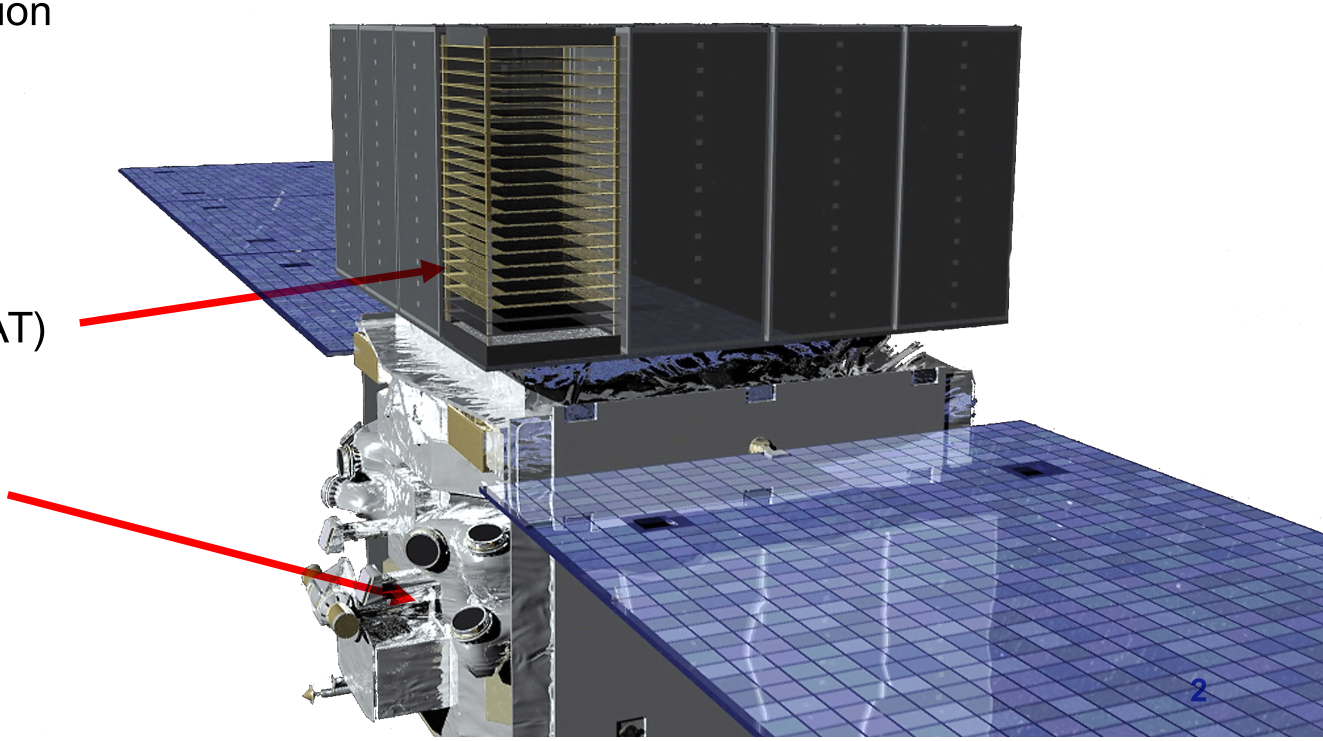
On behalf of the Fermi-LAT Collaboration

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:**
  - **Gamma-ray Burst Monitor (GBM): 8 keV - 40 MeV**
  - **Large Area Telescope (LAT): 20 MeV - ~1TeV**

Almost circular orbit, at 565 km altitude and 25.6 deg inclination

Orbit period= ~90’



The Fermi LAT

Precision Si-strip Tracker (TKR)

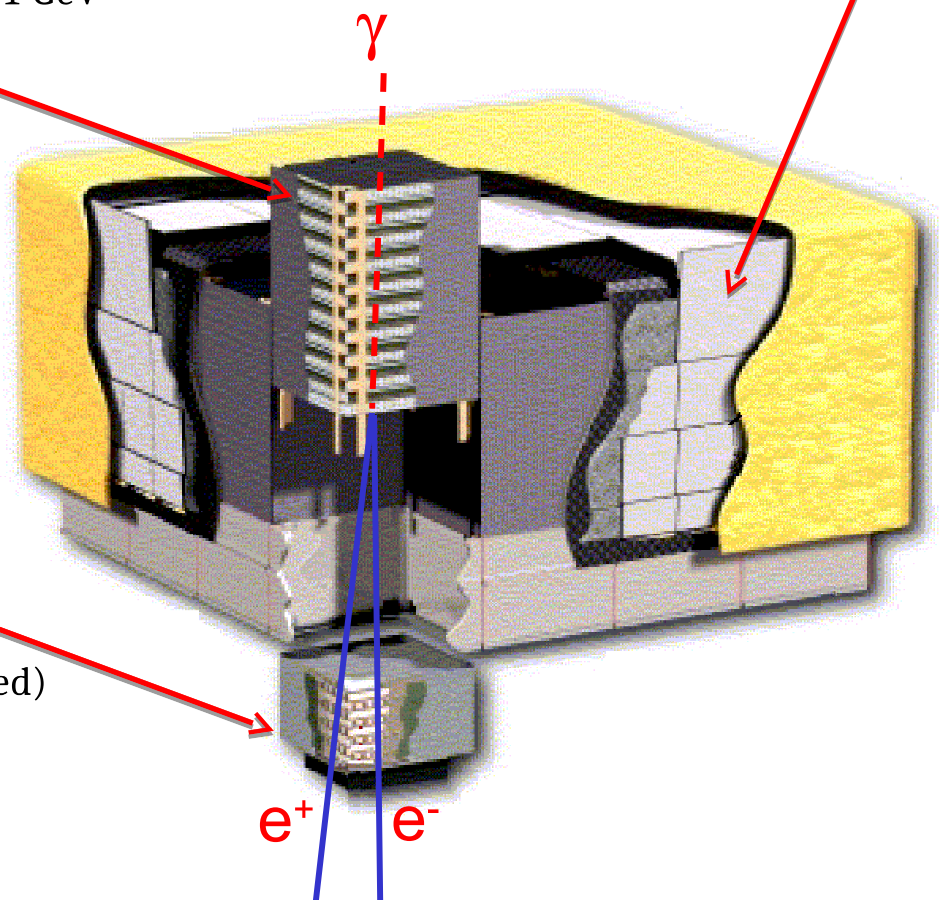
- Measures incident γ-ray direction
- 18 XY tracking planes: 228 μm strip pitch
- High efficiency. Good position resolution
- 12x 0.03 X_0 front end: reduce multiple scattering
- 4x 0.18X_0 back-end: increase sensitivity >1 GeV

Anticoincidence Detector (ACD)

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

Overall LAT Design:

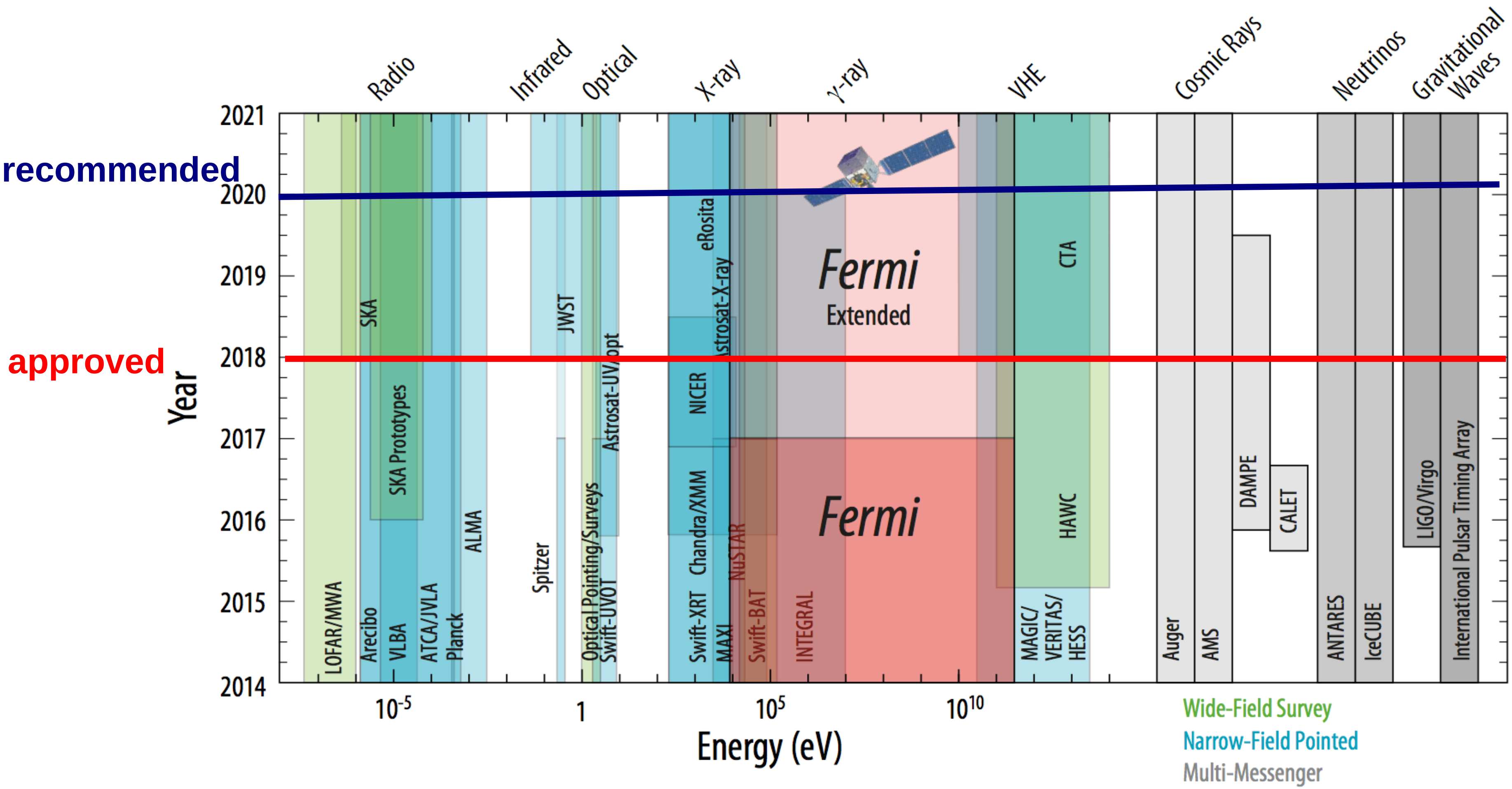
- 4x4 array of identical towers
- 3000 kg, 650 W (allocation)
- 1.8 m × 1.8 m × 1.0 m
- 20% sky in any instant
- All sky for 30' every 3 hours



Hodoscopic CsI Calorimeter

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

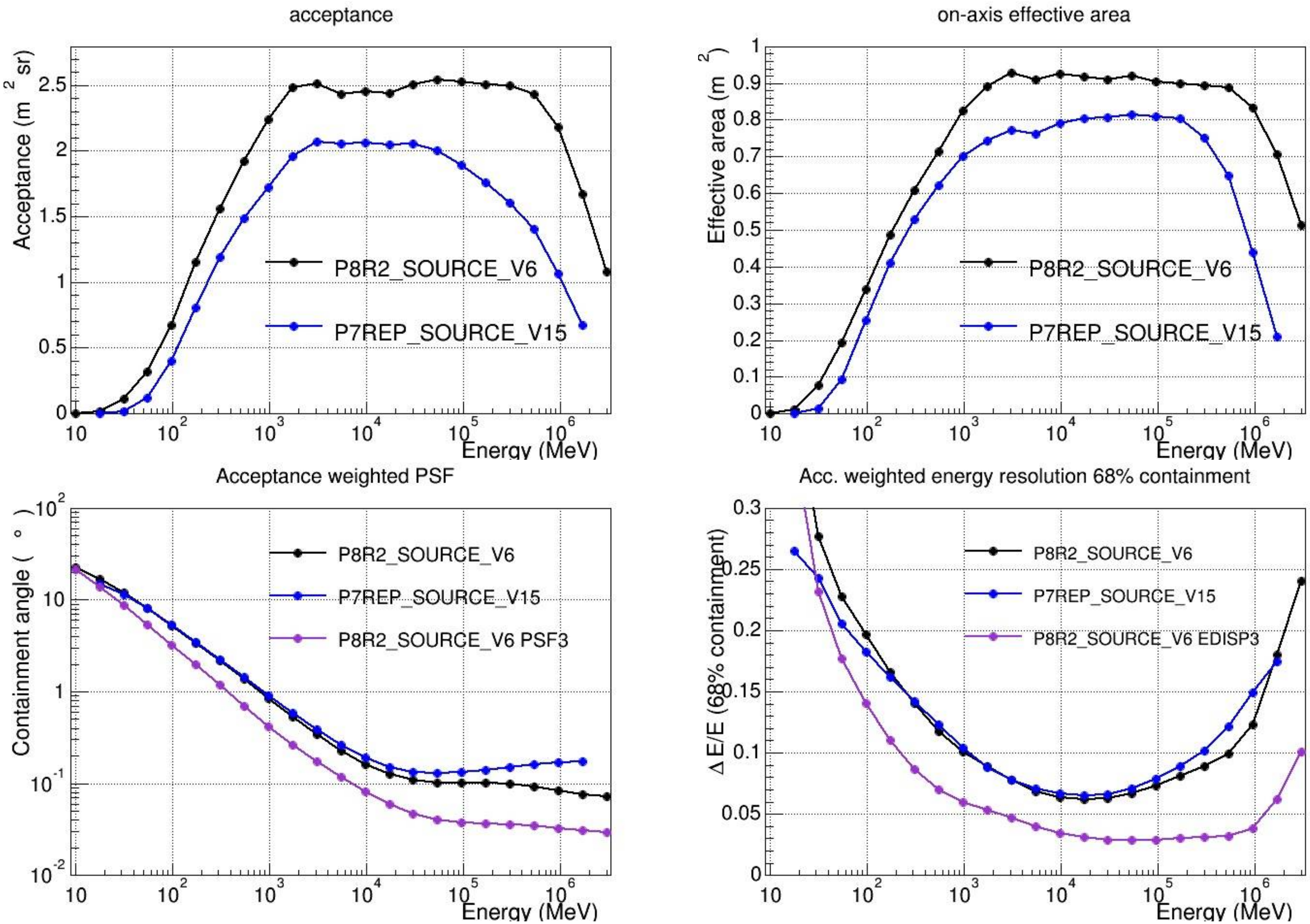
Operating context



NASA senior review 2016:
confirm operations through 2018 and recommend through 2020

https://science.nasa.gov/astrophysics/2016-senior-review-operating-missions

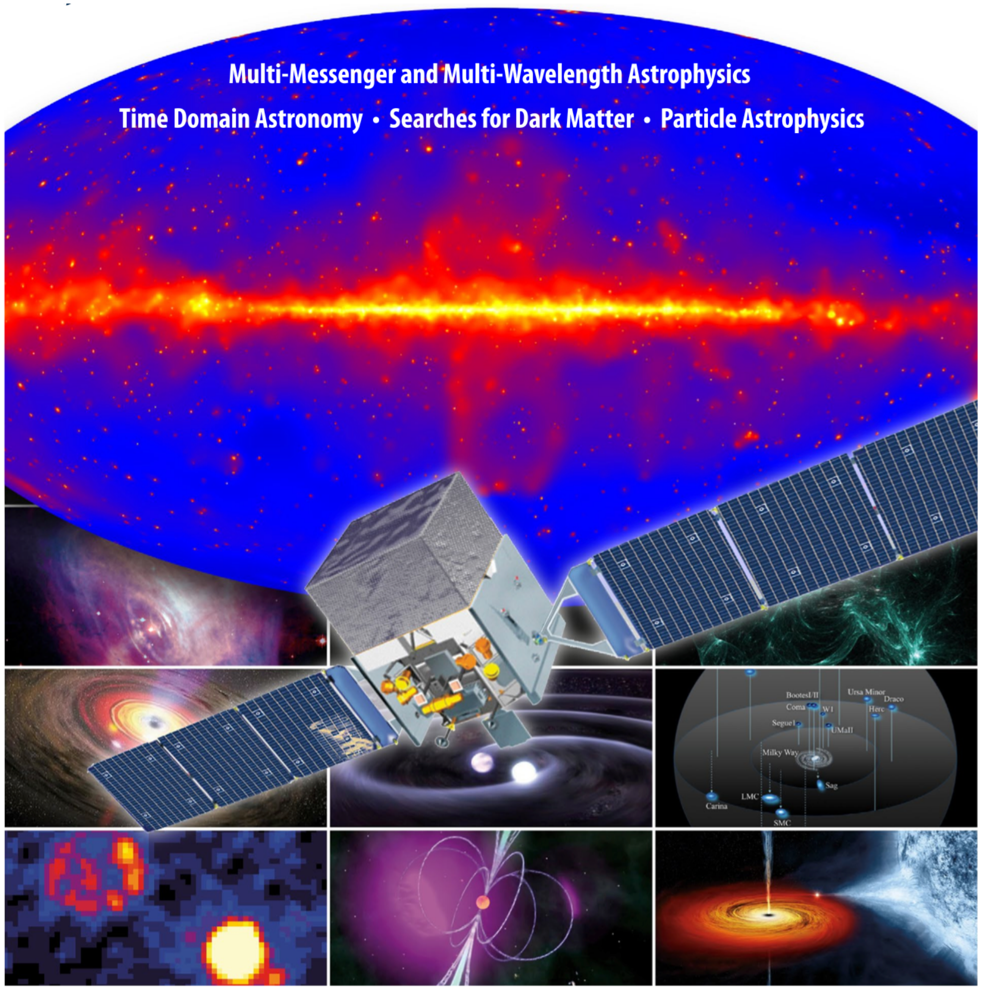
LAT performances



Larger energy range, higher acceptance, better resolution

Pass 8 **performance and data publicly released June 2015**

Science themes



Messengers

gammas, electrons

Time

ms transients to multi-year periodicities

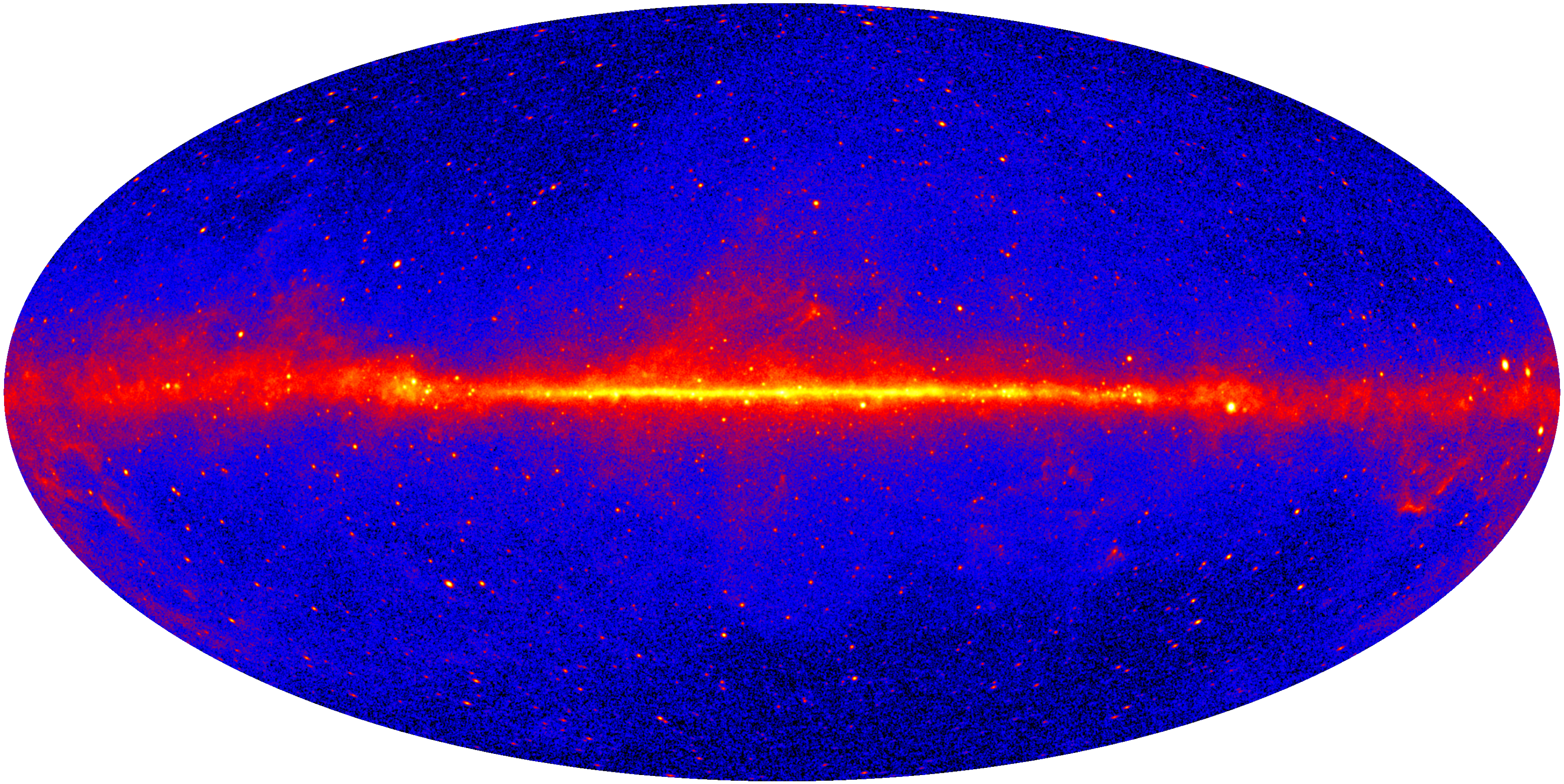
Dark Matter

WIMP and axion candidates

Particle Astrophysics

CR acceleration sites and mechanisms

The gamma-ray sky above 1 GeV



The gamma ray source catalogs

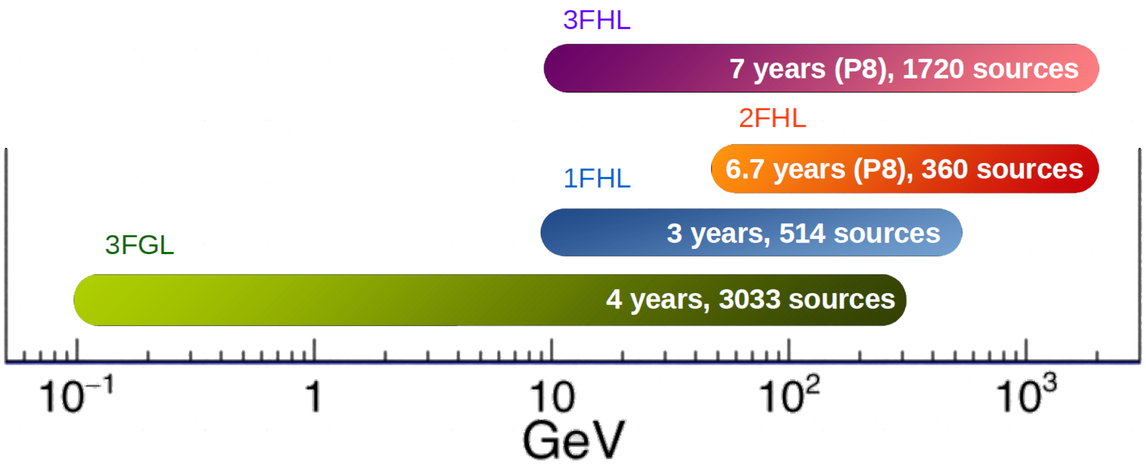
Catalogs:

Classification of sources, population studies, possibility of finding new classes of sources

FERMI -LAT general catalogs:

*n*FGL Catalogs detect and characterize sources in the ~0.1-100 GeV energy range

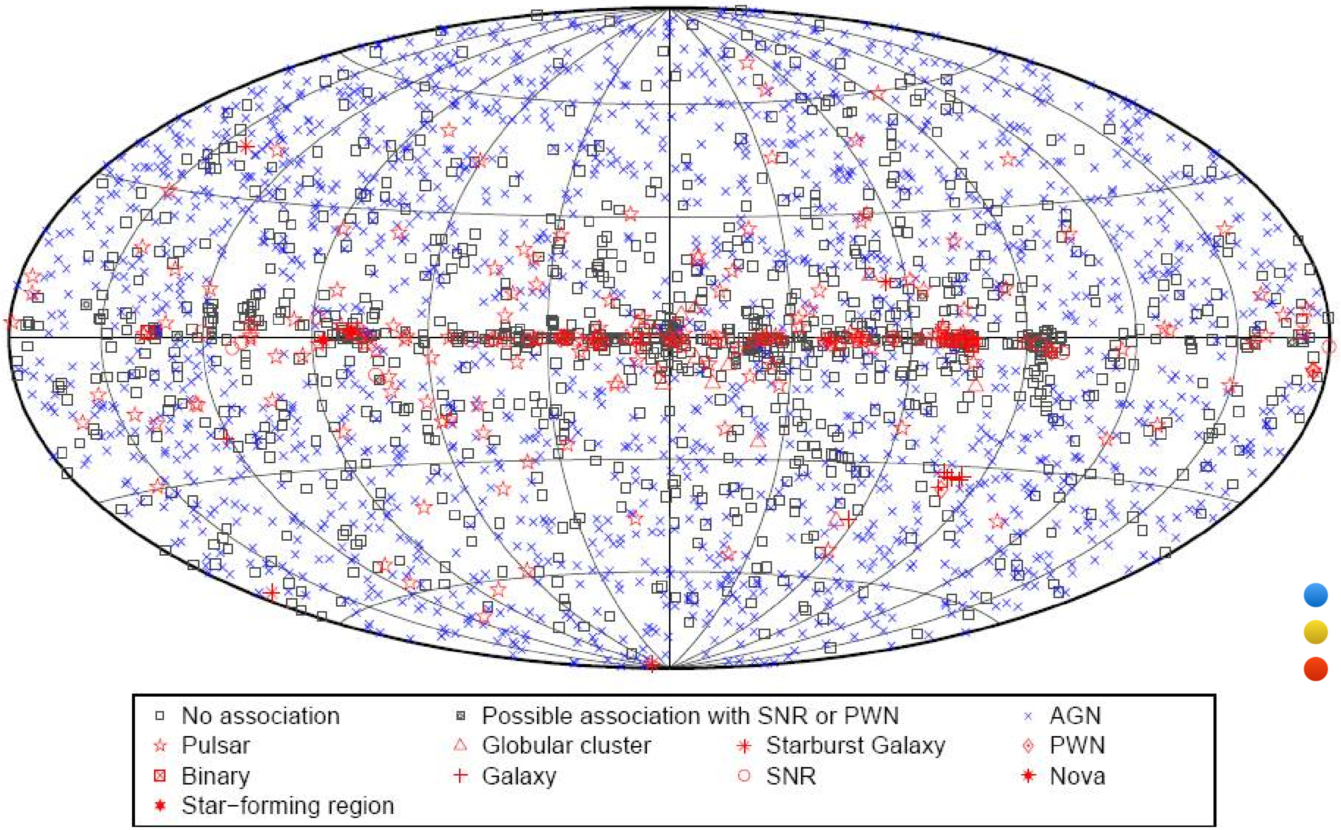
*n*FHL Catalogs explore the higher-energy sky

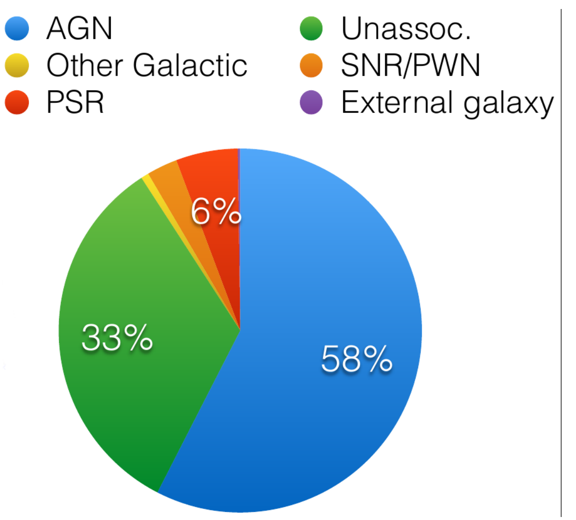


class-specific catalogs:

– **AGNs, Pulsars, GRBs, SNRs, transients…**

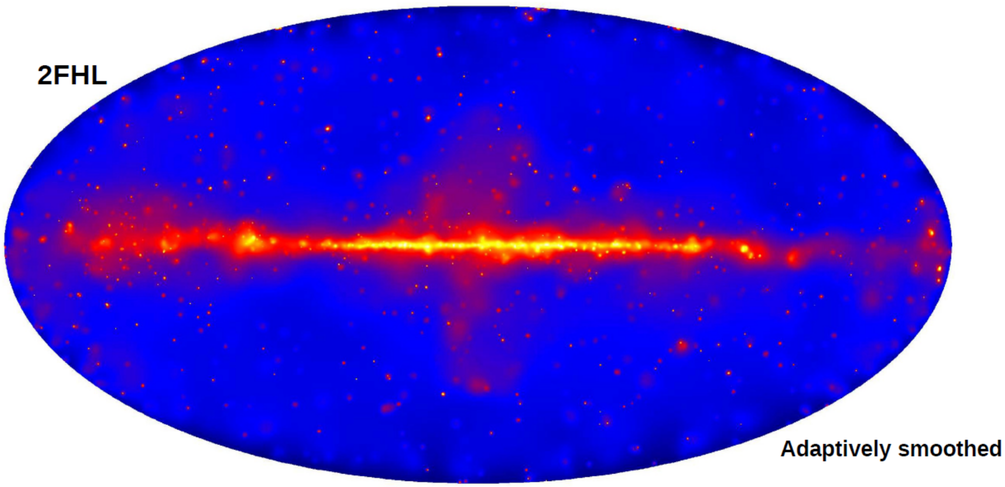
Fermi LAT 3rd Source Catalog (3FGL)





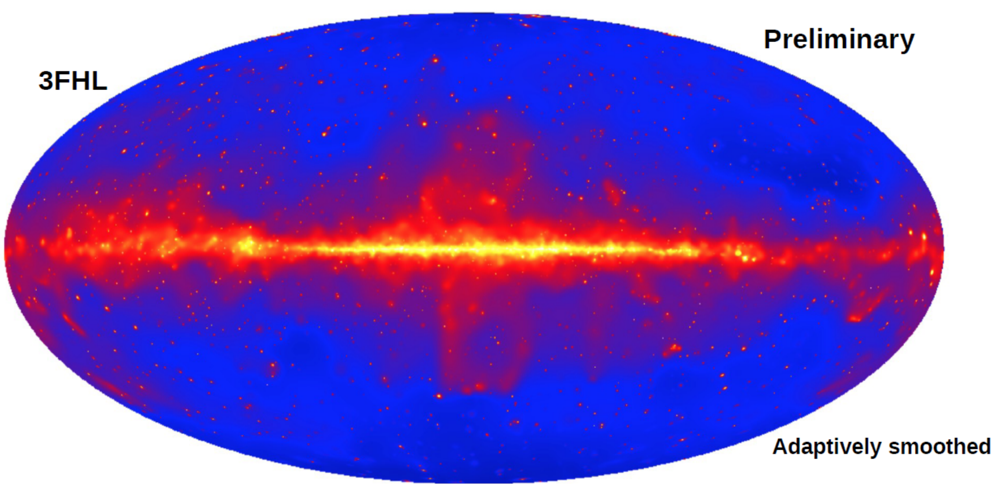
- **4-years data sample with P7 reprocessed data**
- **3033 sources detected with >4σ significance**
  - **Mostly blazars and pulsars**
  - **Roughly 1/3 of the sources are unassociated**
- **See Astrophys. J. Suppl. 218 (2015), 23 (arXiv 1501.02003)**

LAT Hard Sources Catalogs (2FHL-3FHL)



2FHL: E>50 GeV
360 sources in 80 months

- 75% blazars,
- 11% Galactic sources,
- 14% unassociated

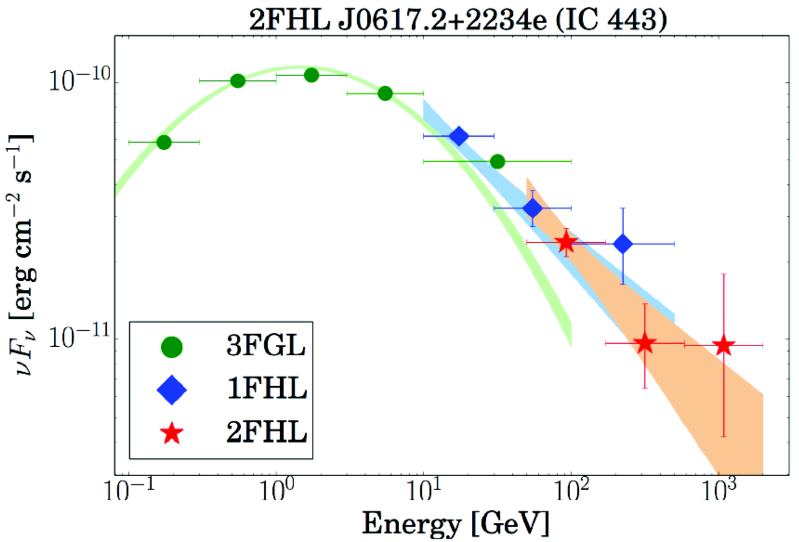


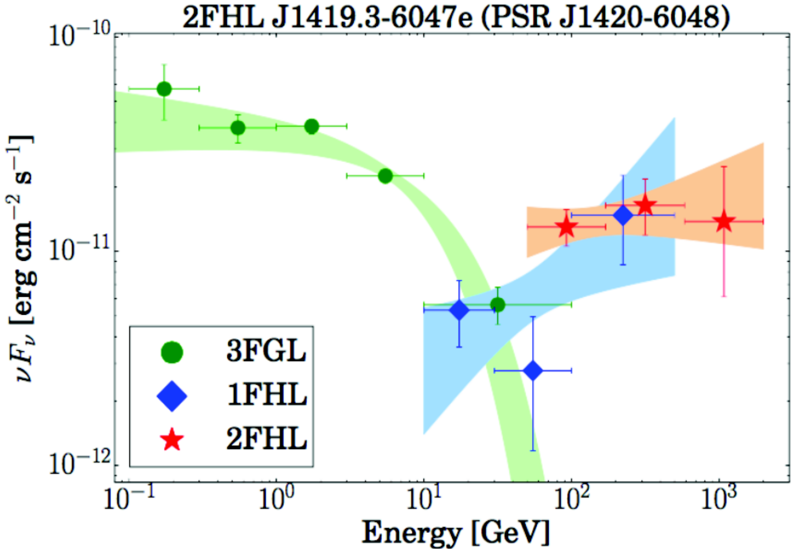
PRELIMINARY

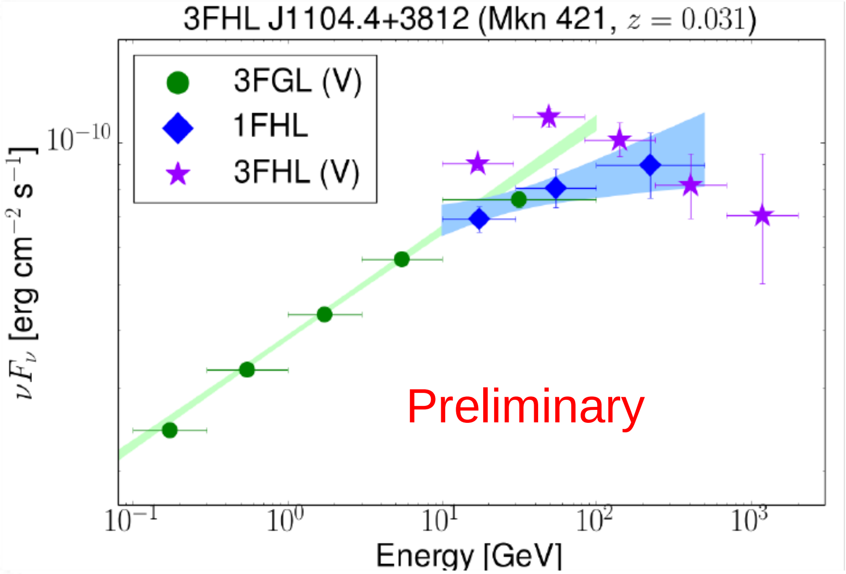
3FHL: E> 10GeV
1720 sources in 84 months

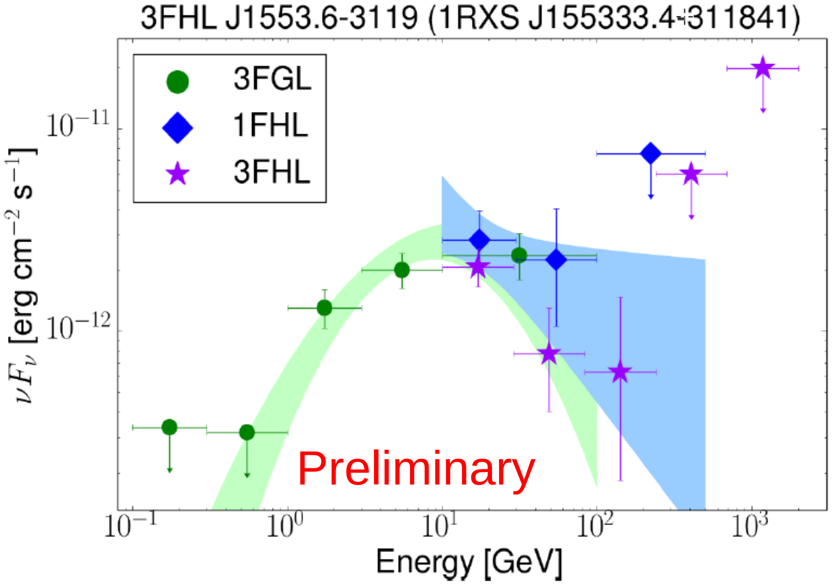
74% extragalactic, 7% Galactic sources, 19% unassociated

LAT Hard Sources Catalogs (2FHL-3FHL)





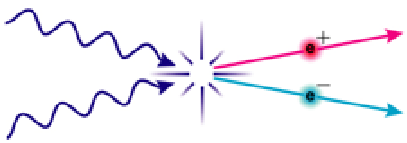




Fermi Gamma-ray Space Telescope

EBL and gamma ray horizon

Intrinsic spectrum is attenuated due to interaction with EBL (photo pair production)



$$\frac{dN_{\rm obs}}{dE} = \frac{dN_{\rm int}}{dE} \times e^{-\tau_\gamma(E,z)}$$

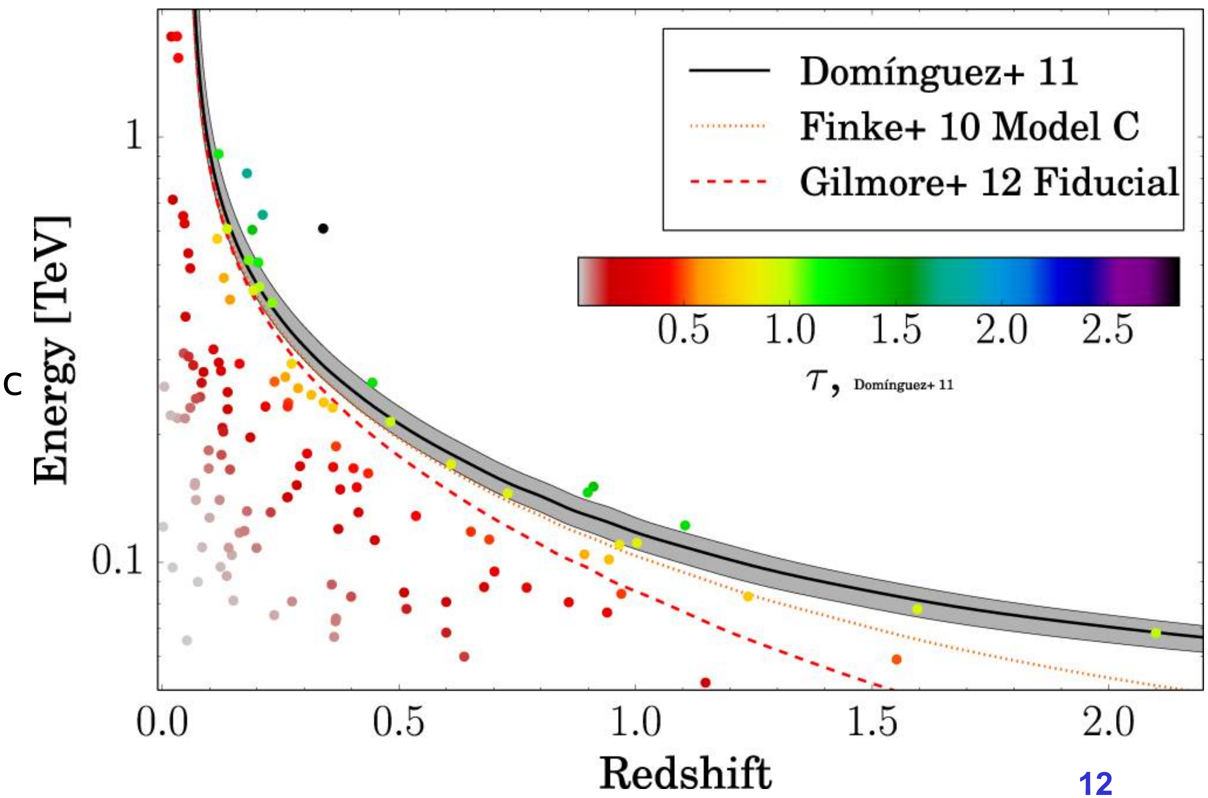
Cosmic gamma ray horizon

2016, ApJS, 222, 5
ArXiv: 1508.04449

Highest energy photon vs source redshift (for associated sources in 2FHL with known redshift)

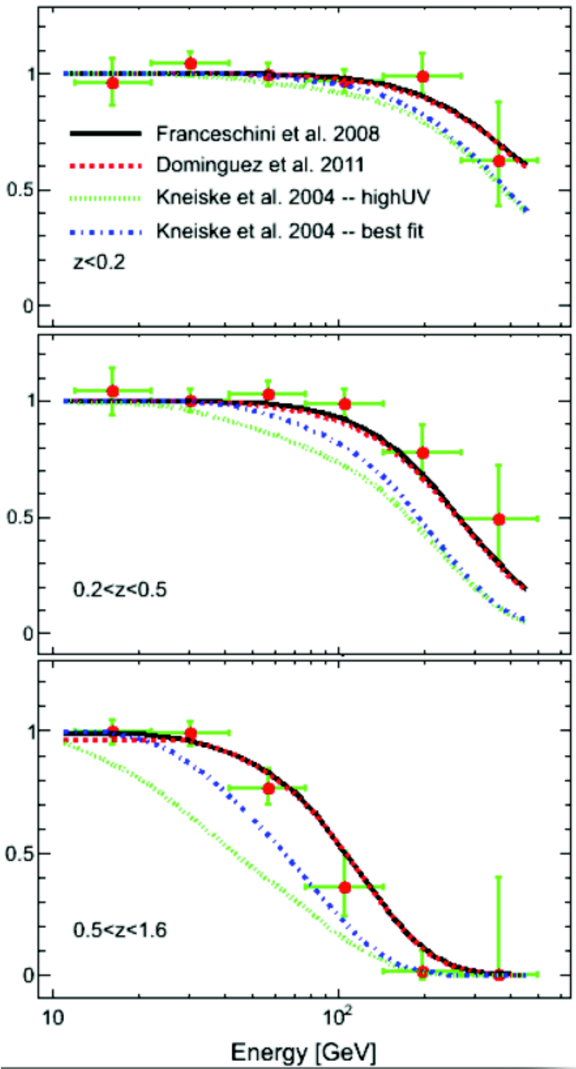
Different estimates of the cosmic γ-ray horizon are also shown (derived from the EBL models)

Cosmic Gamma Ray Horizon: energy at which $\tau = 1$ as a function of redshift.



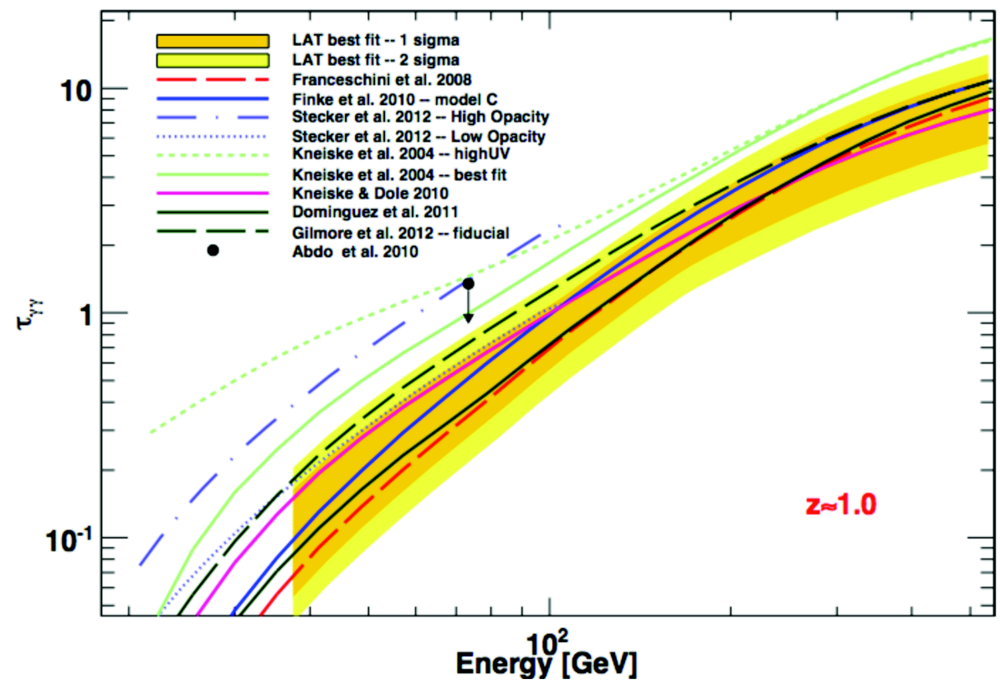
EBL and gamma rays horizon

Effect of the EBL on blazar gamma rays spectra



look for the collective deviation of the spectra of blazars from their intrinsic ones in three different redshift bins

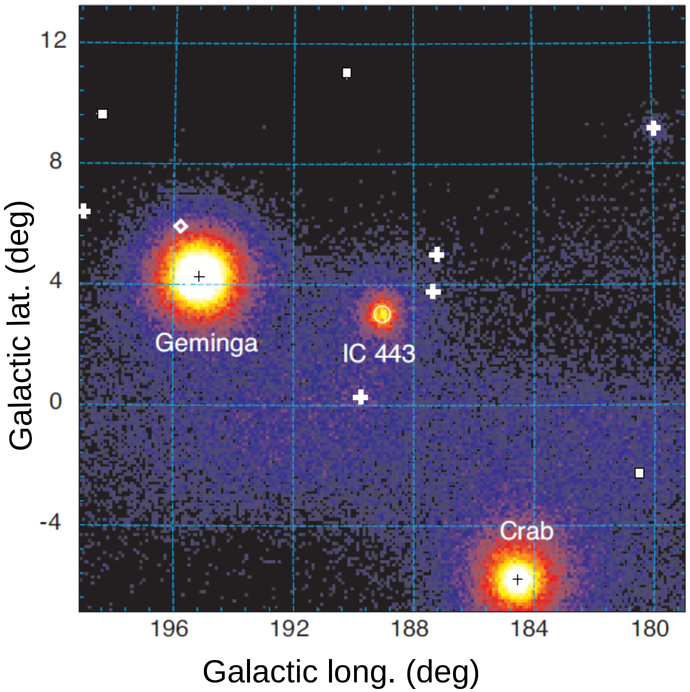
Inferred optical depth

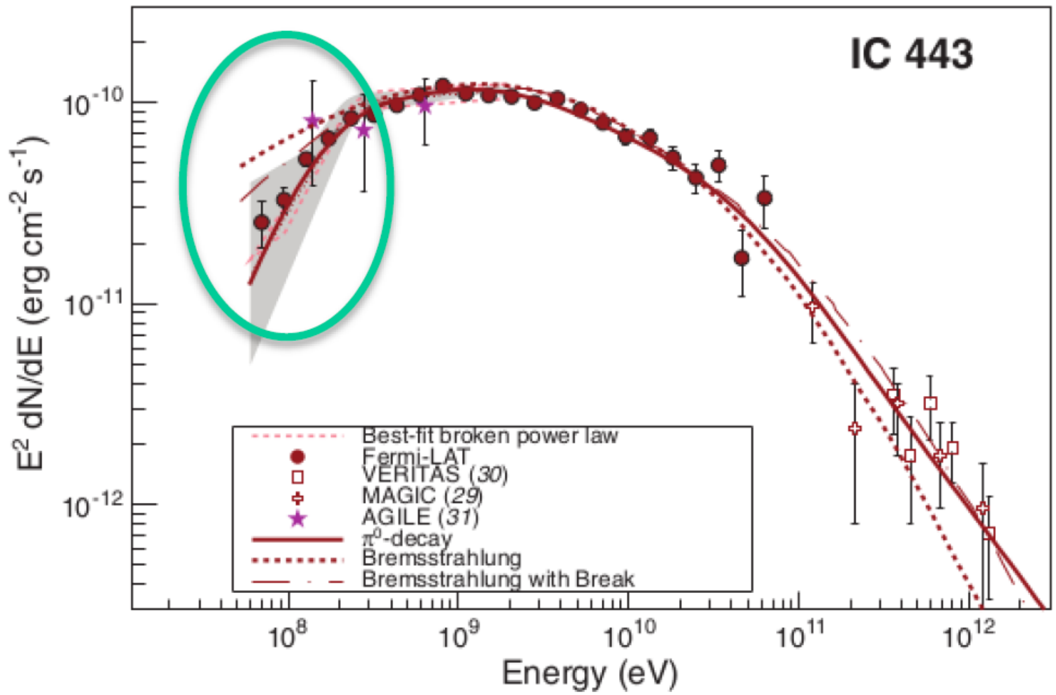


LAT-collaboration, 2012, Science, 338, 1190

Hadronic emission from SNRs

Evidence for hadronic acceleration in some bright nearby SNR





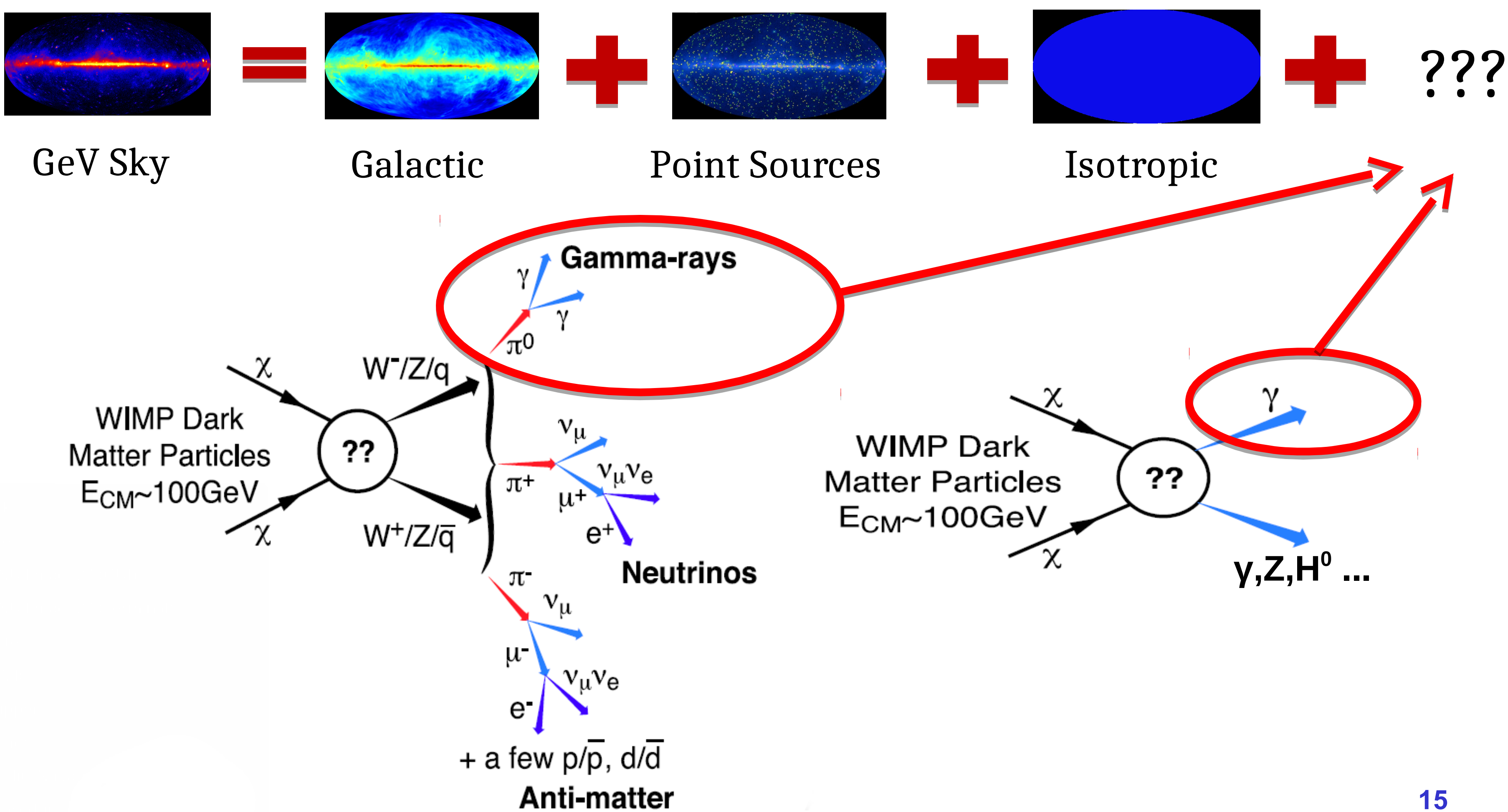
2013, Science, 339, 807
ArXiv: 1302.3307

IC444 and W44 SNR:

Gamma emission from pion decay ⇒ accelerated protons

DM searches in the GeV gamma-ray sky

- **Indirect detection (i.e. astrophysical) searches for DM in the astrophysical targets where it is known to exist**



DM search targets

Satellites

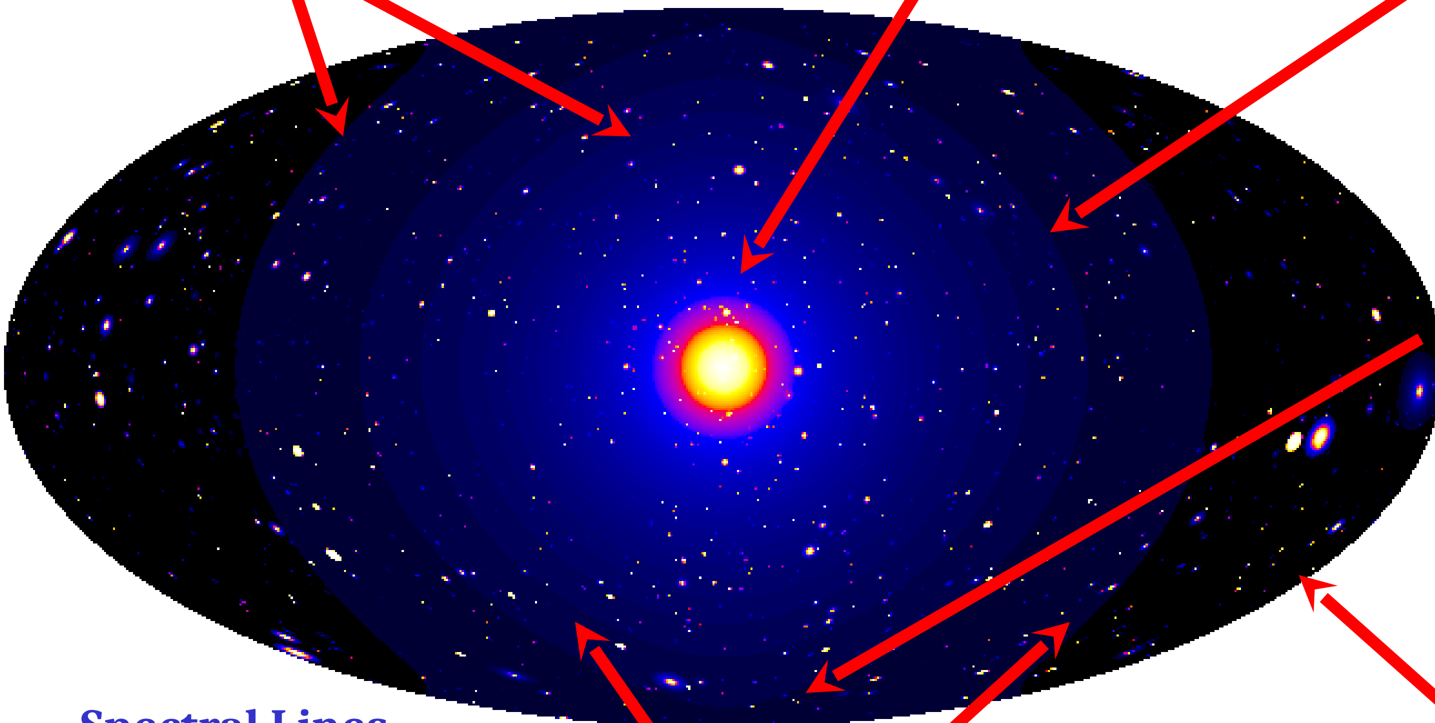
Low background and good source id, but low statistics

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

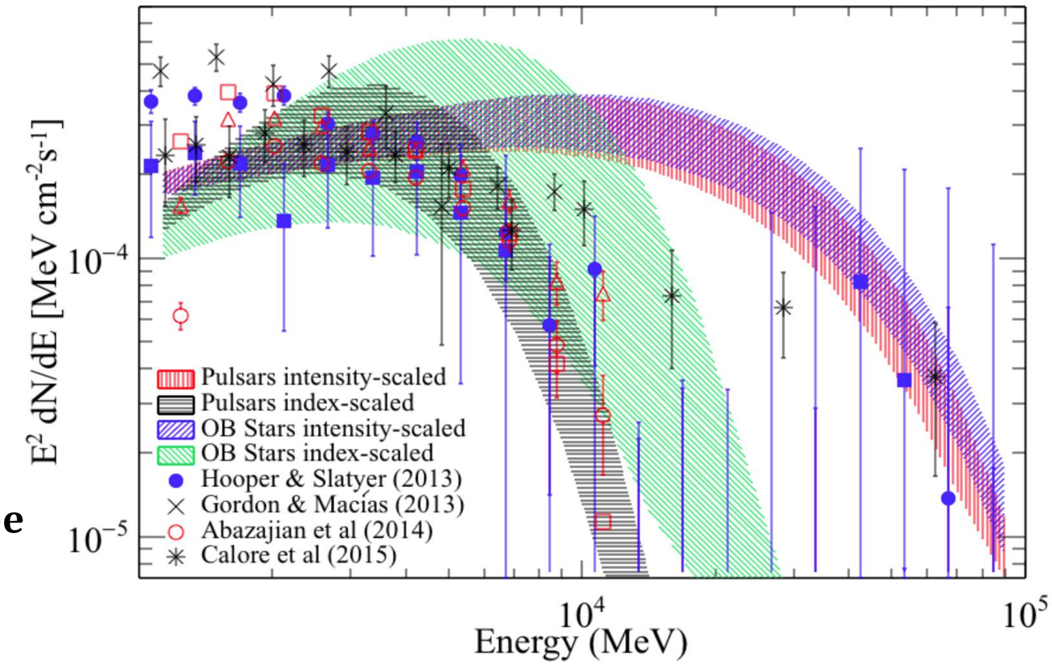
Low background, but low statistics

Isotropic contributions

Large statistics, but astrophysics, galactic diffuse background

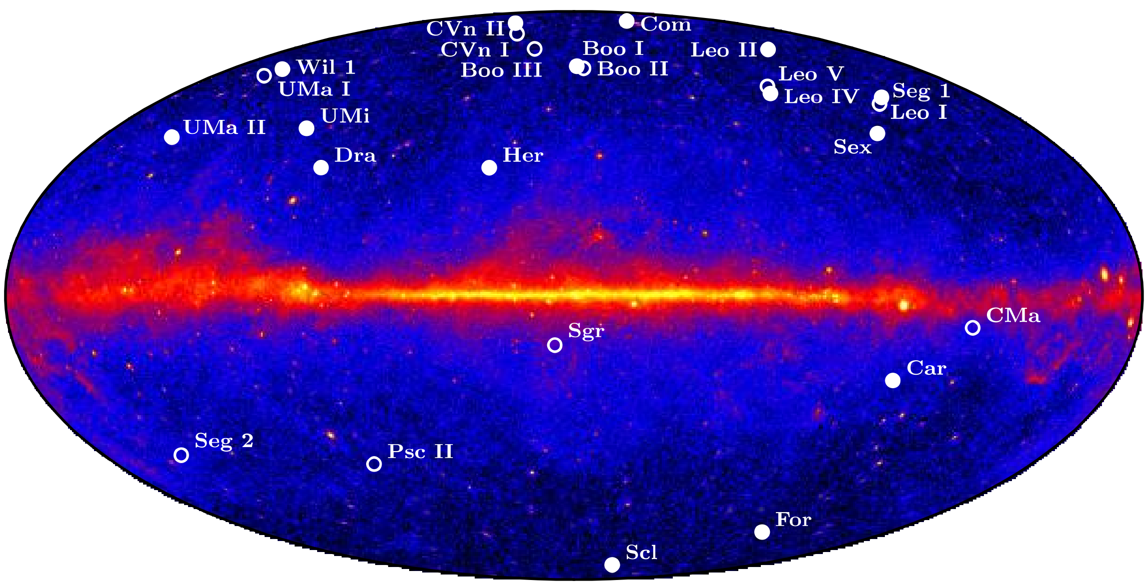
Dark matter in the Inner Galaxy?

- **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 and its spatial extension are robust**
  - **The spectrum of the excess depends strongly on the emission model**
- **The excess at the Galactic Center could be due to:**
  - **dark matter**
  - **unresolved sources (e.g. MSPs)**
- **DM best fit cross section is in mild tension with other limits**
- **See Astrophys. J. 819 (2016), 1**



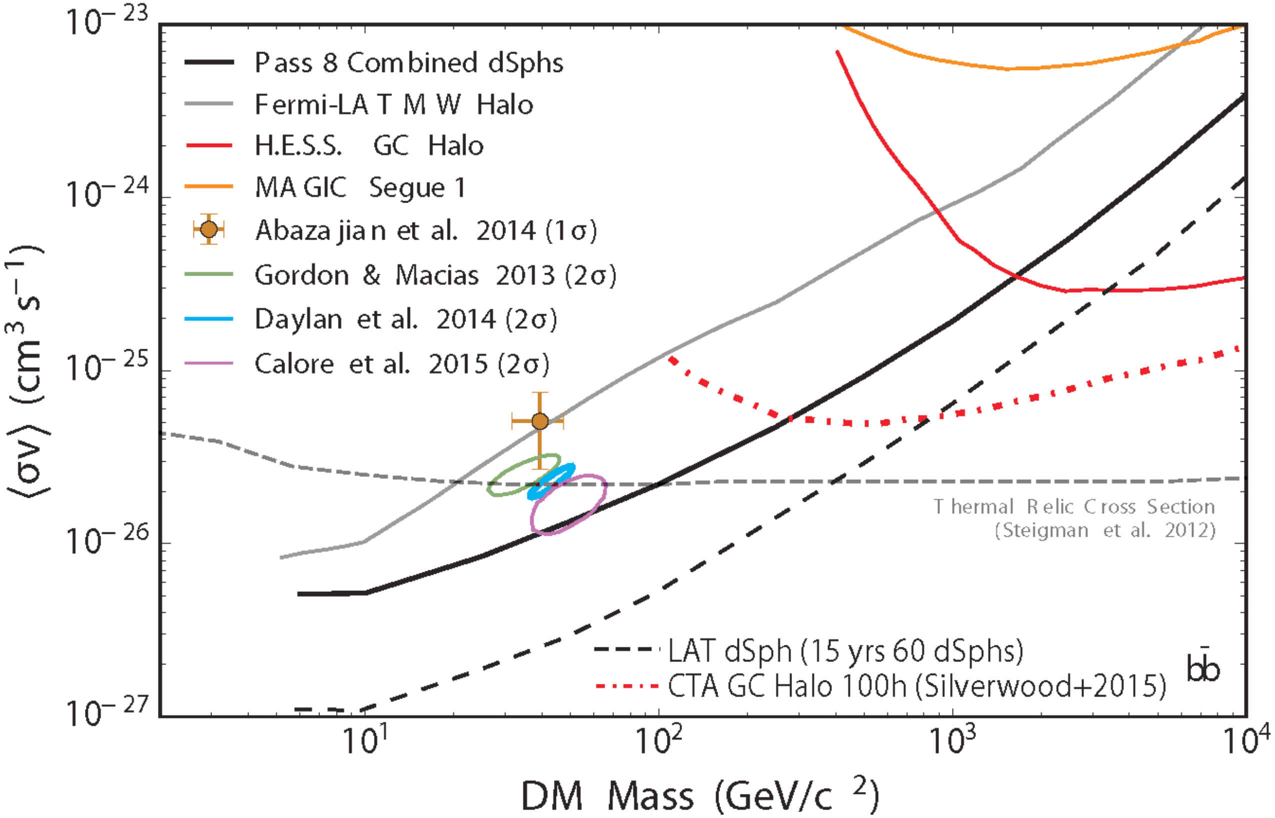
DM searches in dSph Galaxies

- **dSph Galaxies are the cleanest target for DM searches:**
  - **DM-dominated (1000:1)**
  - **10s to 1000s of stars**
    - **Mostly old stars**
    - **Few gamma-ray emitters (pulsars, SNRs)**
    - **Little gas content**
  - **often high latitude: low diffuse background**
  - **nearby (<250 kpc)**
  - **Many!   allows for joint analyses**



DM searches in dSph Galaxies

95% CL upper limit on DM annihilation cross section from combined analysis of 15 dSphs



optical surveys are significantly increasing number of dwarfs

non observation of gamma-rays from dSphs in the next 4 years can exclude WIMPs below ~400GeV (thermal relic cross-section into bbar) and DM GC excess

Phys. Rev. Lett. 115, 231301 (**arXiv 1503.02641**)

Constrains on ALPs

The Galaxy NGC 1275:

At 72 Mpc from Earth

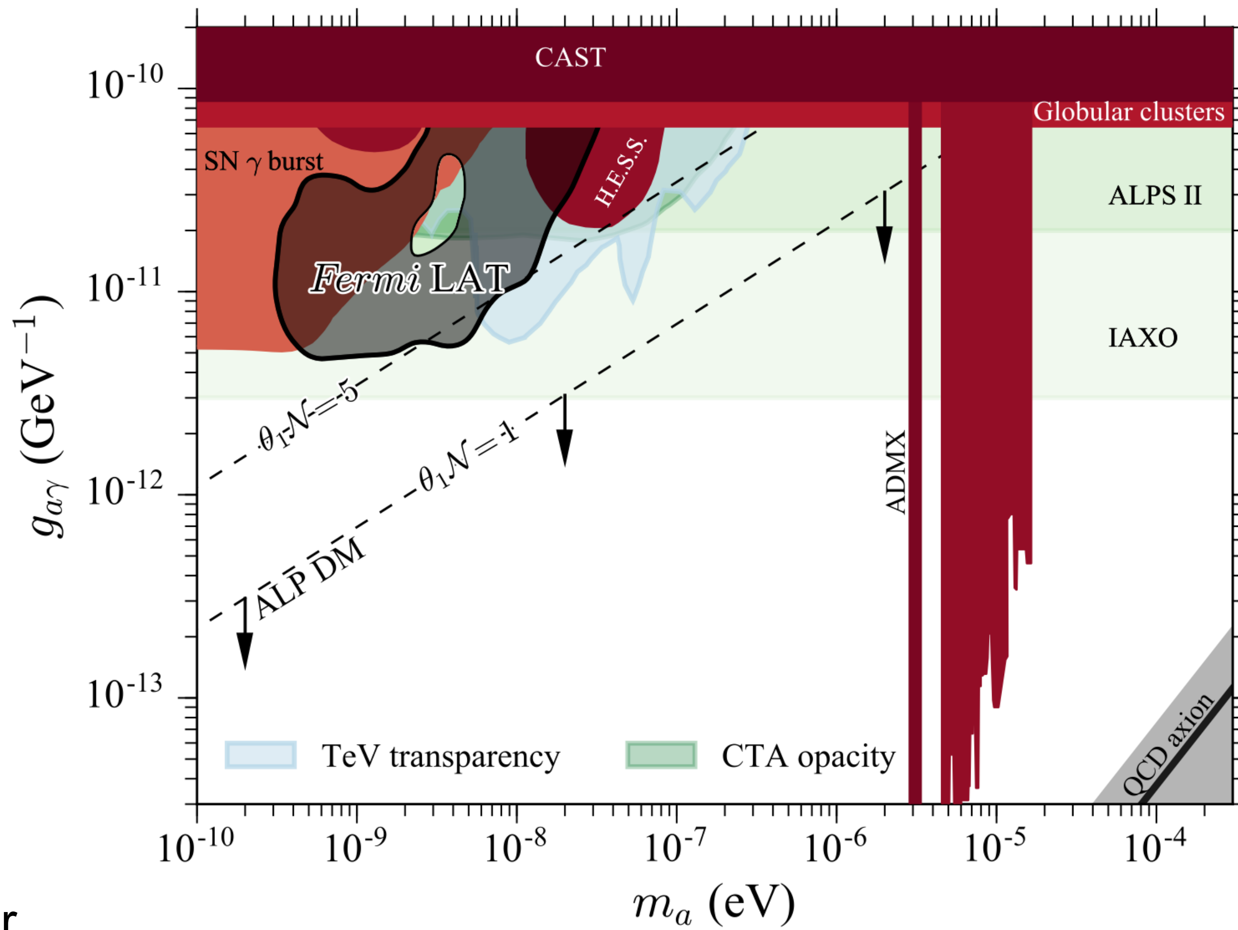
Bright gamma-ray emitter

Located in the center of the Perseus Cluster

strong magnetic field (tens of μG)

Searched for irregularities in gamma rays spectrum from NGC1275

couplings > 5 × 10^{-12} GeV^{-1} for ALP masses 0.5 <~ m_a <~ 5 neV

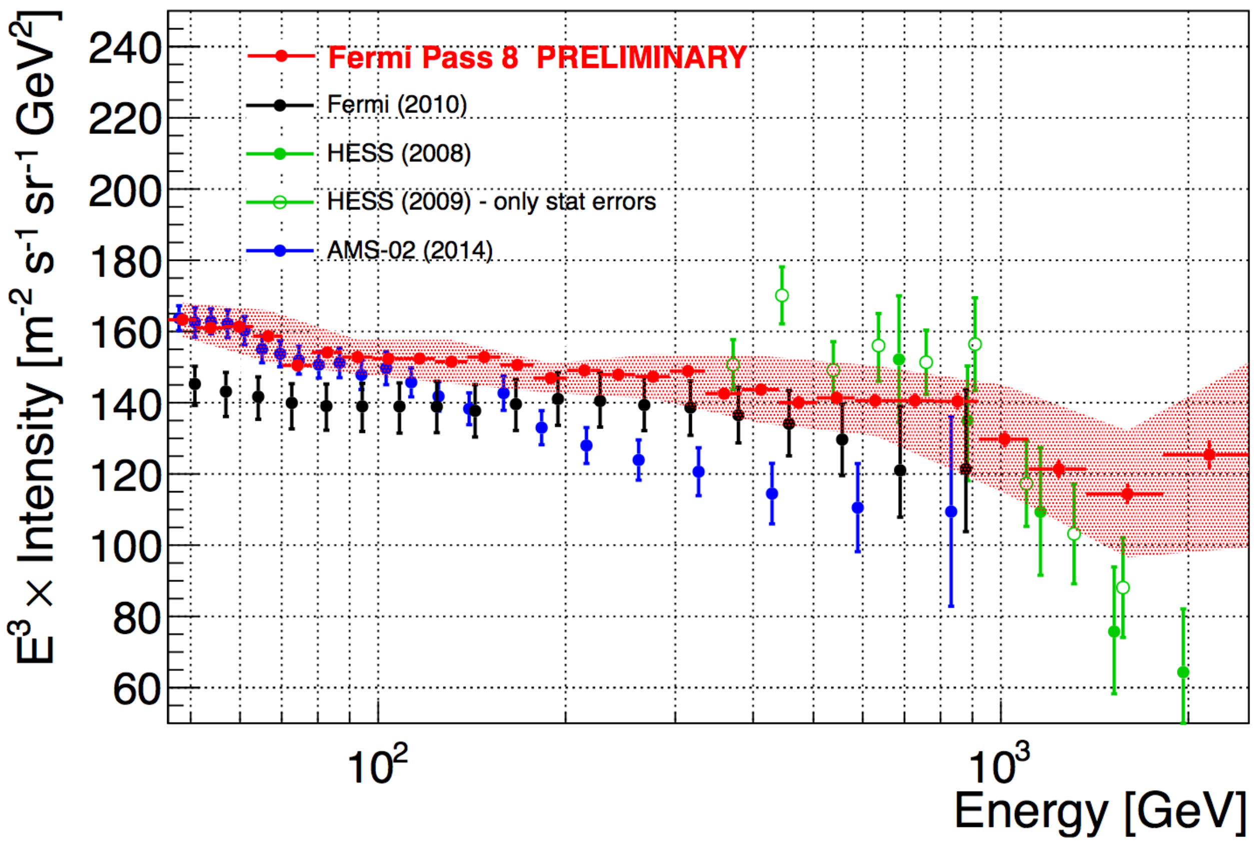


2016, PRL arxiv:1603.06978

No evidence of ALPs

The LAT as a CRE observatory

Dedicated event selection to identify electrons (and positrons)



new measurement of the CRE spectrum with Pass8, achieving the first direct measurement above 1 TeV

Search for anisotropies in CRE arrival directions:
no anisotropy observed in the first year of operation: -> upper limits
new analysis with current CRE selected data set (7 years) at an advanced stage

Followup of Gravitational Waves

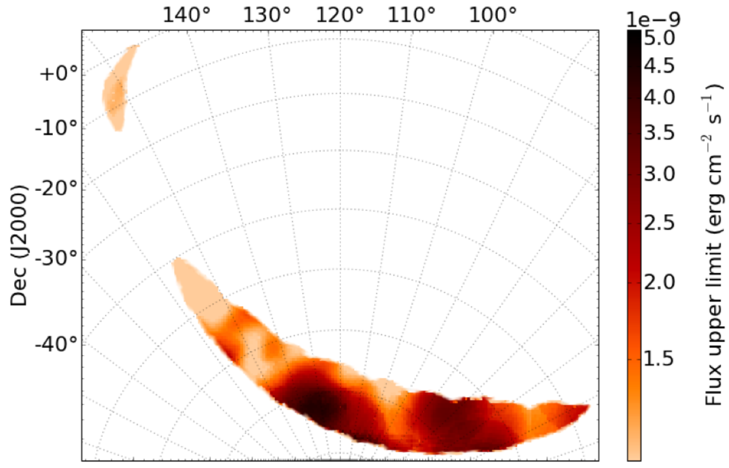
Fermi is an excellent instrument for searches of EM counterparts of GW events:

- Large FOV → entire sky coverage in 3 hours
- localization ~ 0.1-1 °
- sensitive to transients from ms to years timescales
- GBM sensitive to impulsive flares

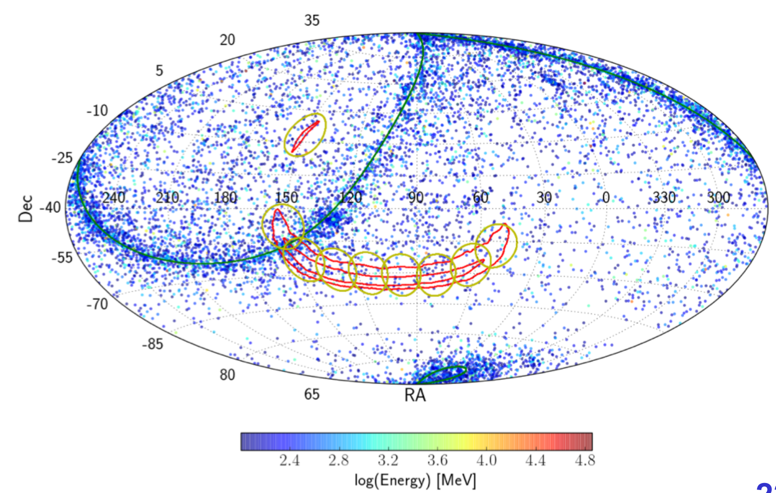
Routine searches under MoU with Ligo Virgo Consortium

No excess found for the 3 GW events analyzed so far

Upper limits for GW150914



Short baseline search



long baseline search

Conclusions

The LAT is an astroparticle observatory with unprecedented capabilities that has been exploring the gamma-ray sky since 2008

- **The LAT has been monitoring the gamma-ray sky for 8 years and is still in good health**
- **Significant improvements of the LAT performance thanks to the newest Pass 8 event reconstruction and classification**
- **~1G photons, thousands sources, public database**

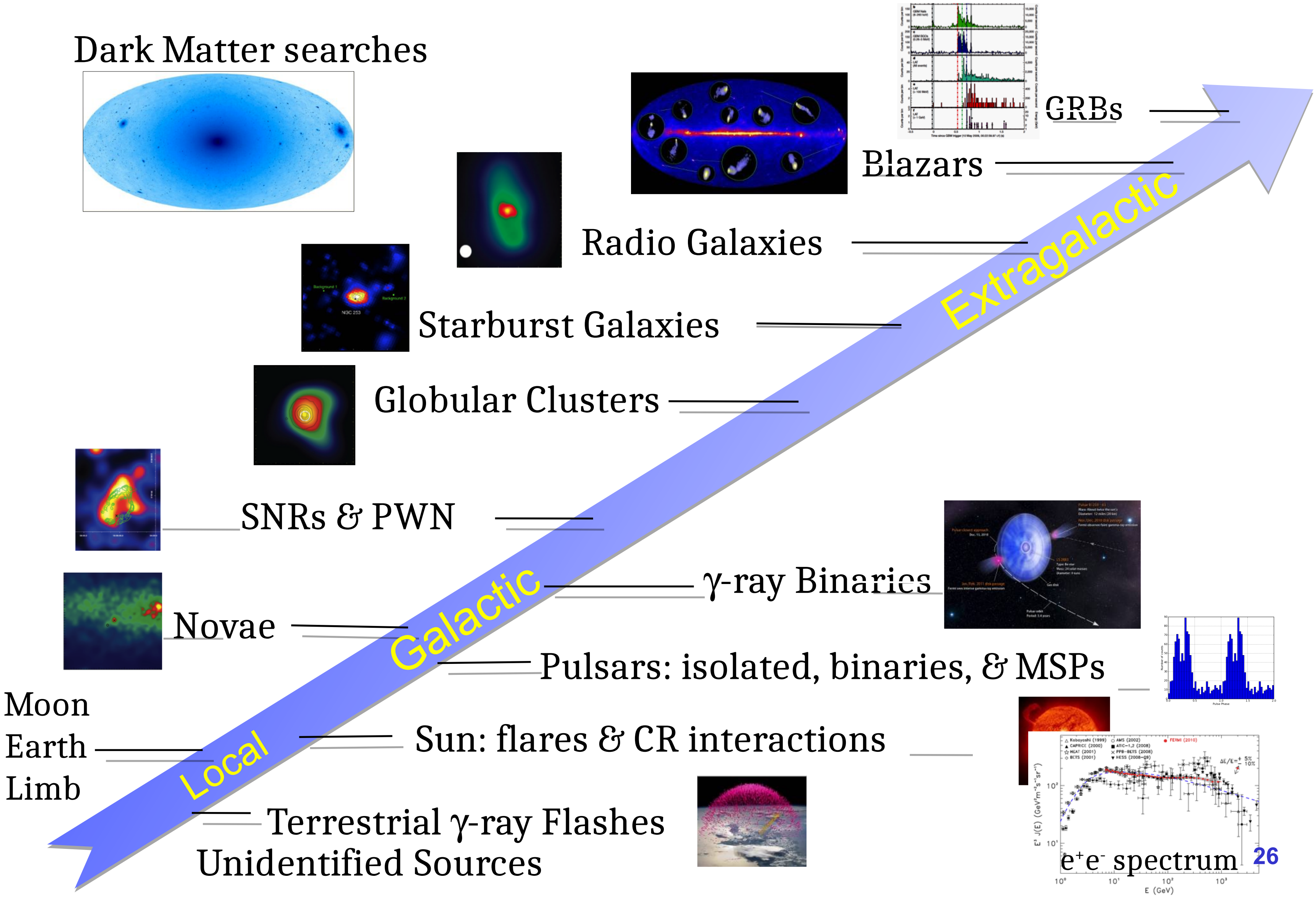
Fermi data probe fundamental questions

- **CR origin, particle acceleration and propagation**
- **Dark Matter Identification**

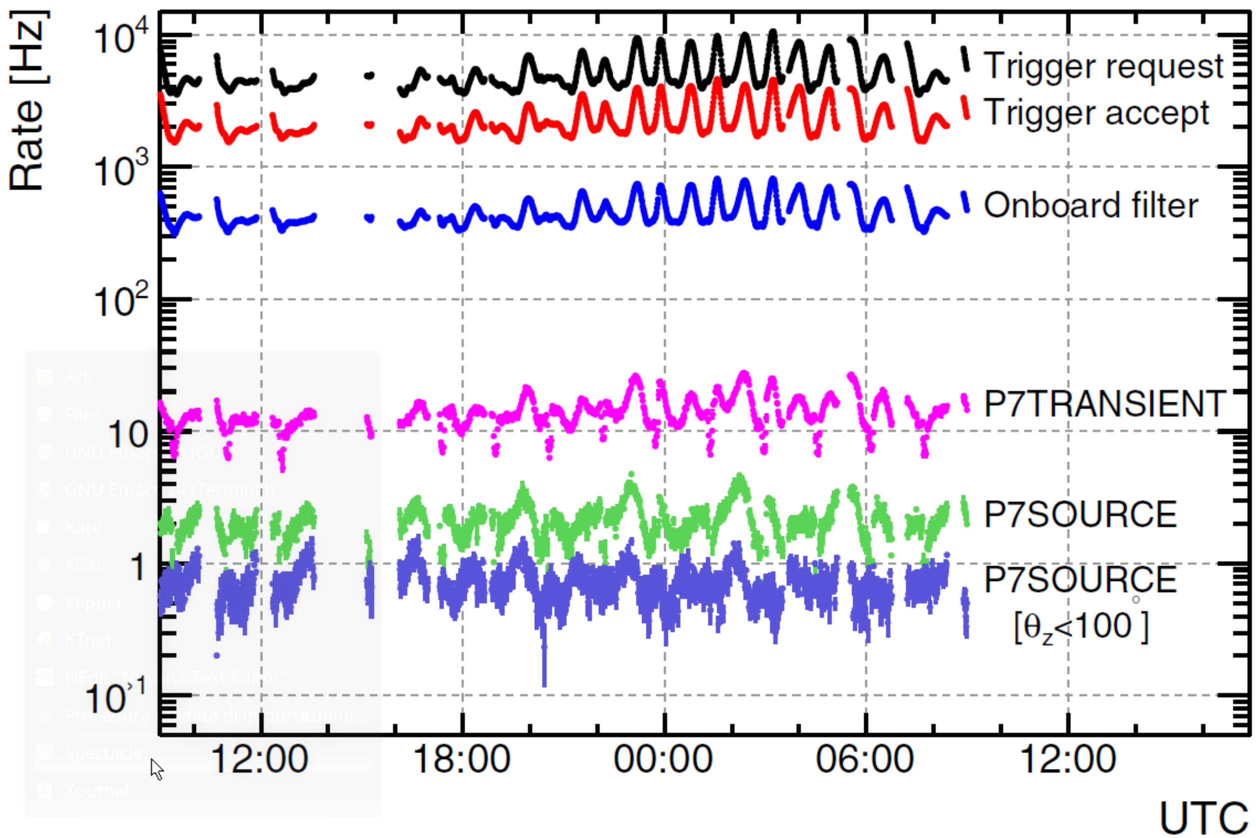
  dSphs are a promising target
- **EM counterparts to Gravitational Waves**

BACKUP

Science with the Fermi LAT



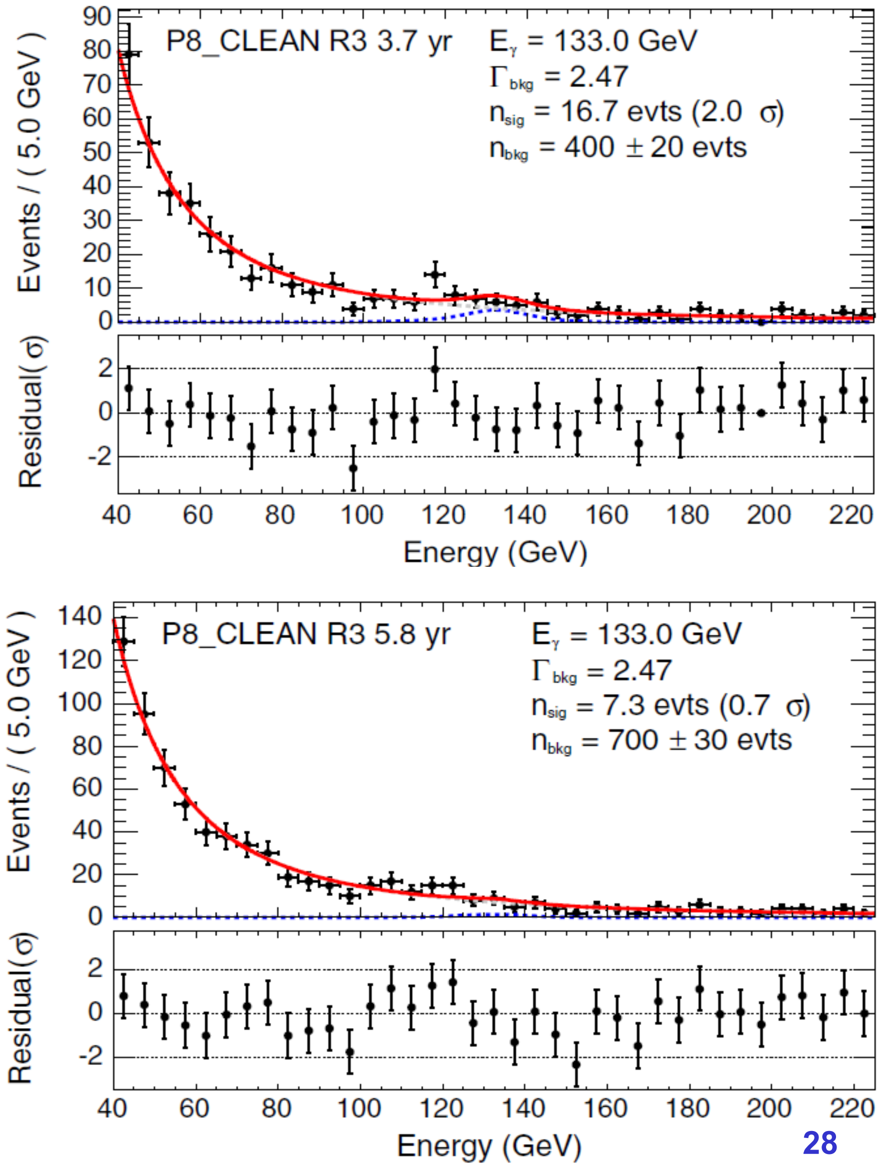
Onboard trigger and filtering



- **Five hardware trigger primitives**
- **Upon L1 trigger the entire detector is read out**
- **Need onboard filtering to fit the data volume within the allocated bandwidth**

The line feature at 133 GeV

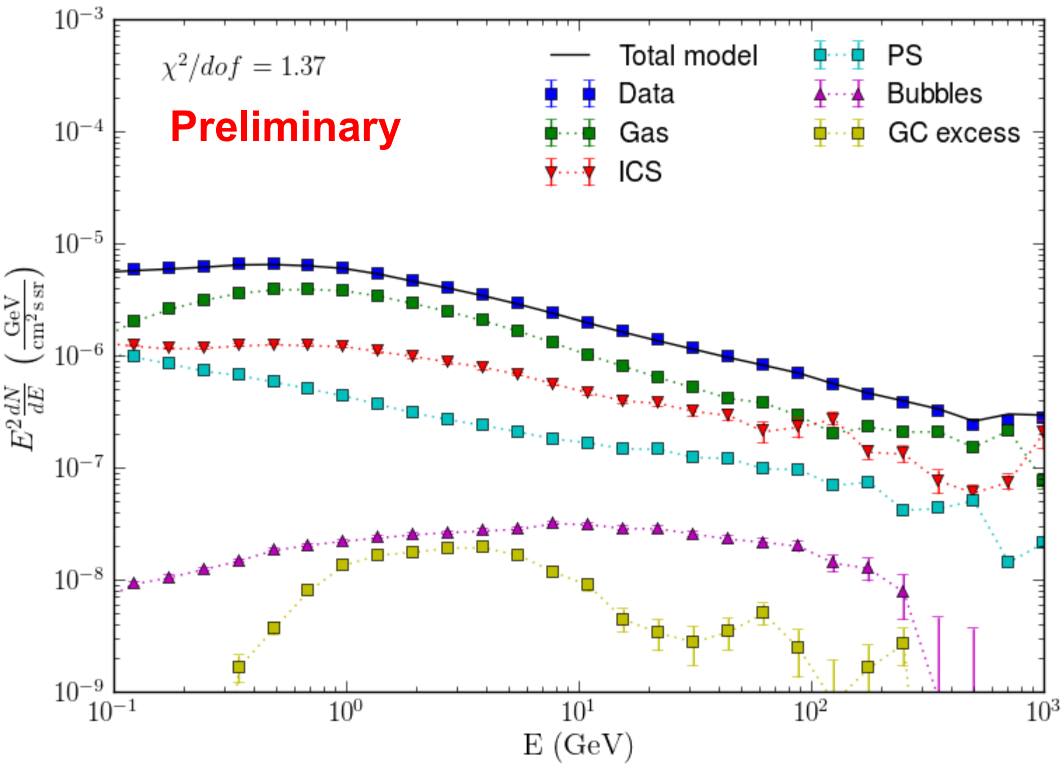
- **A potential signal was reported in the 3.7yrs data sample for a small ROI containing the GC**
  - **Bringmann+, JCAP 07 (2012), 054**
  - **Weniger+, JCAP 08 (2012), 007**
- **The LAT detected the feature, although with low global significance**
- **Newest LAT data analysis:**
  - **Increased data 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**



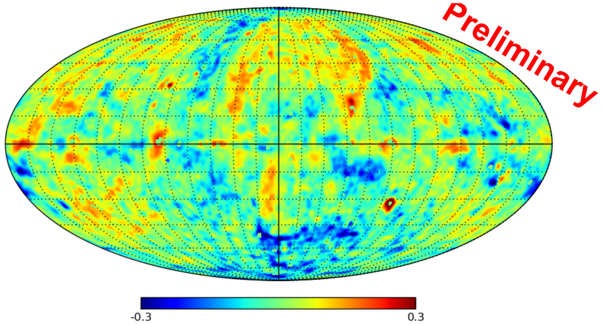
Modeling the GC emission

- **Generalized NFW (gNFW), gamma = 1.25**
  - **All sky-fit**
  - **Fit normalization in each energy bin for each template**

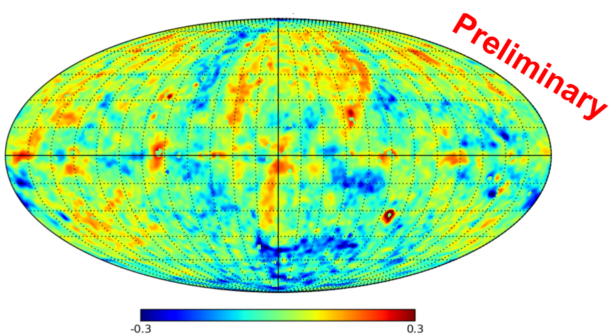
$$\rho(r) \propto \frac{1}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$



Fractional residual, 1.1 – 6.5 GeV

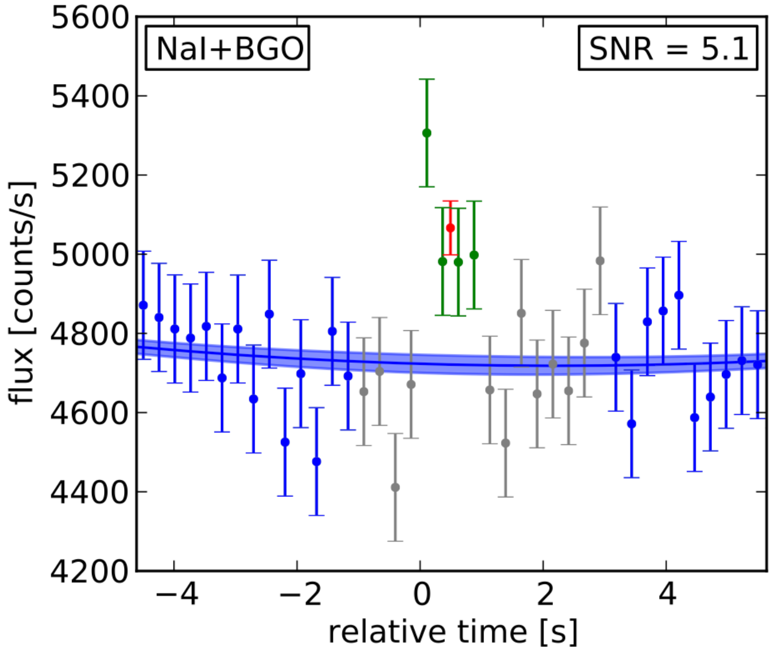


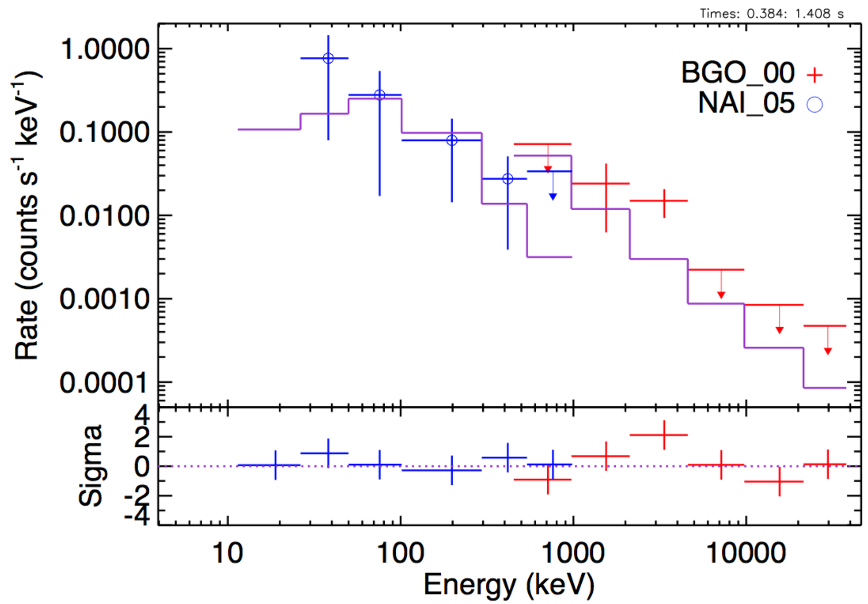
GC excess added back



GBM Observations of GW150914

GBM detectors at 150914 09:50:45.797 +1.024s





weak transient in offline seeded searches around t_{GW}

excess is 0.4s long, ~1s after t_{GW}

false probability is 0.0022

cannot be attributed to known astrophysical, solar, terrestrial or magnetospheric activity (arxiv 1602.03920)