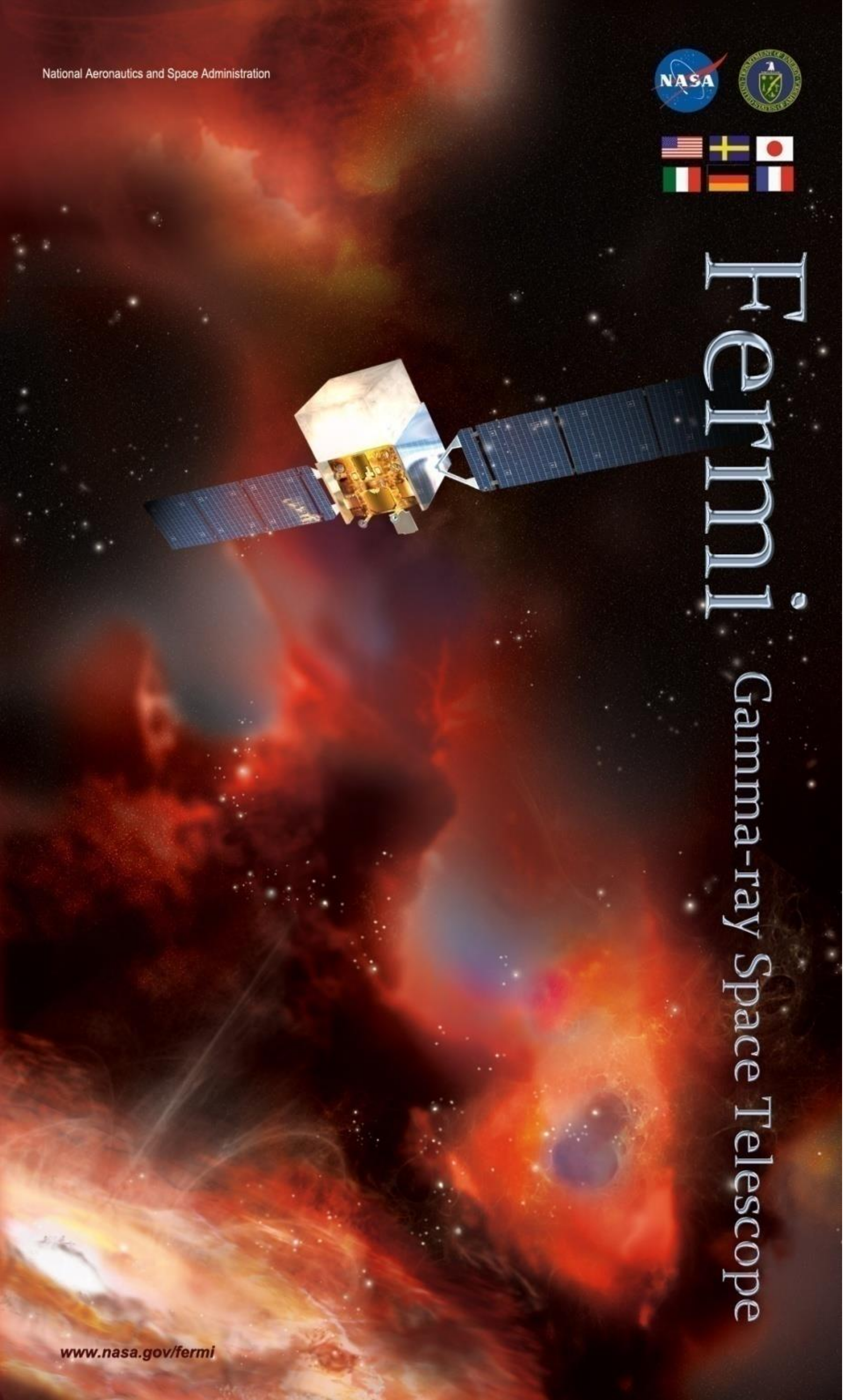


Istituto Nazionale di Fisica Nucleare

Fermi Gamma-ray Space Telescope

10 years in space: highlights of *Fermi*-LAT science

F. de Palma

(INFN Bari and Università Telematica Pegaso),

on behalf of the

Fermi LAT Collaboration

Les Rencontres de Physique de la Vallée d'Aoste

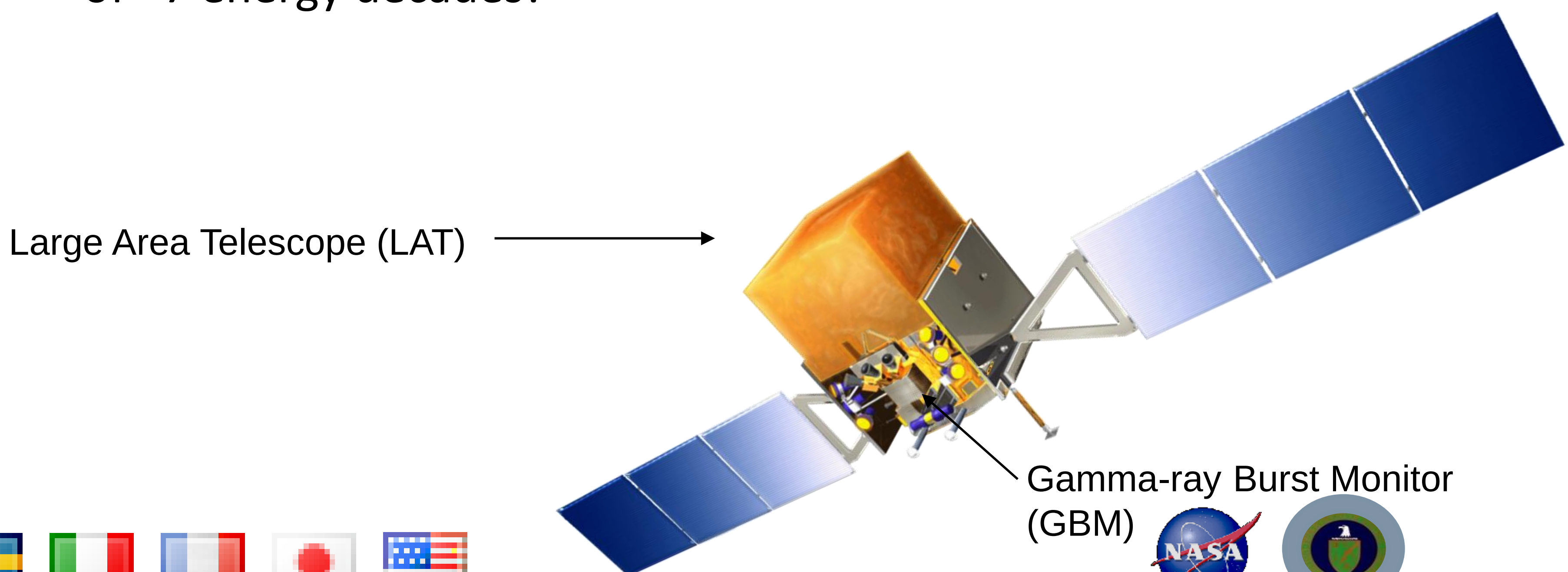
La Thuile 2018

The *Fermi* satellite: instruments

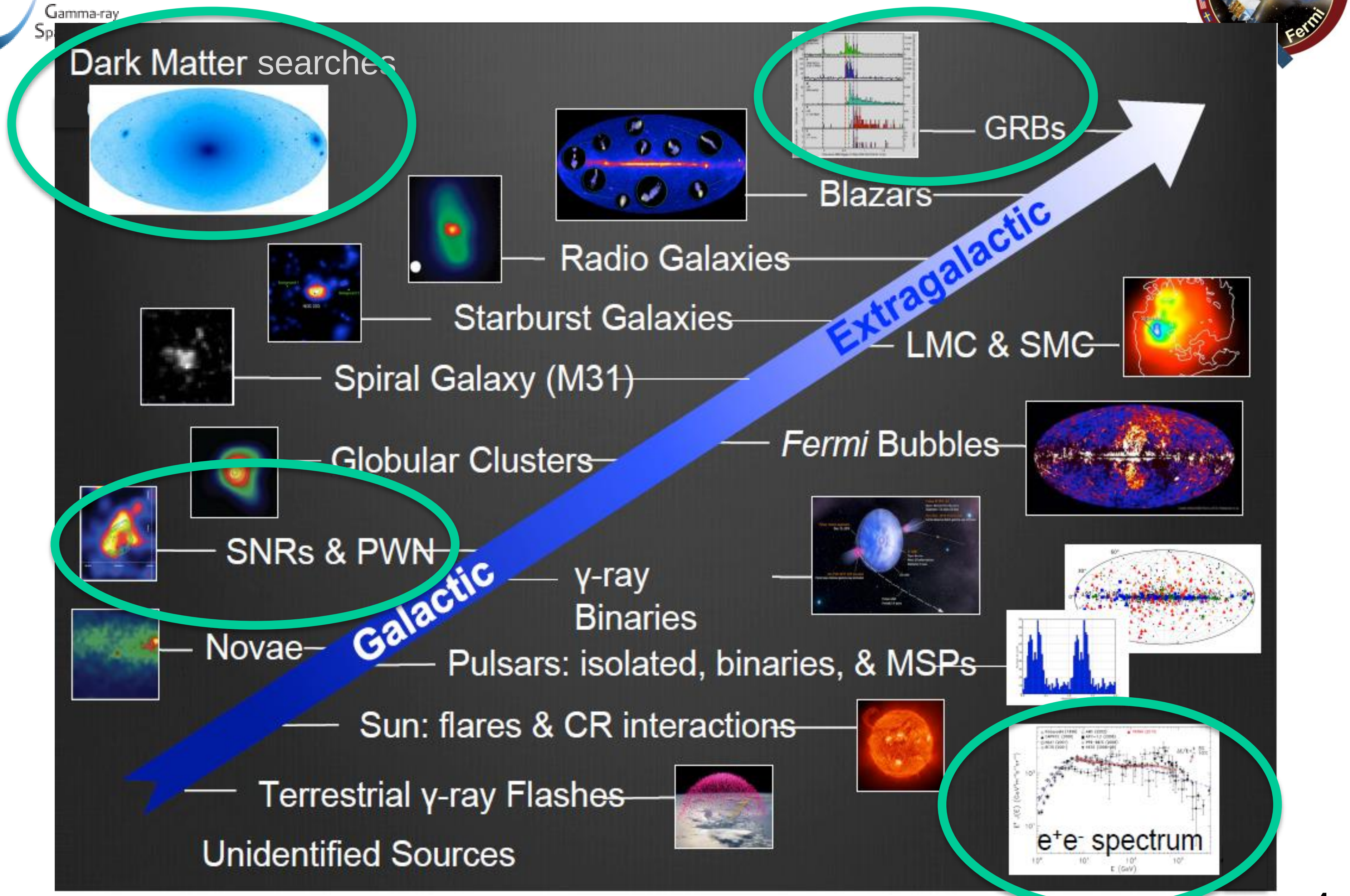
- Launched by NASA on 2008 June 11, from Cape Canaveral, Florida
  - Almost circular orbit, at 565 km altitude and 25.6° inclination
- Science mission started on August 2008
- More than 1 billion of photons available for the standard analysis
- Data and analysis SW are free on the FSSC website.
- **8th Fermi symposium Oct 14-19 2018 in Baltimore**

The *Fermi* satellite: instruments

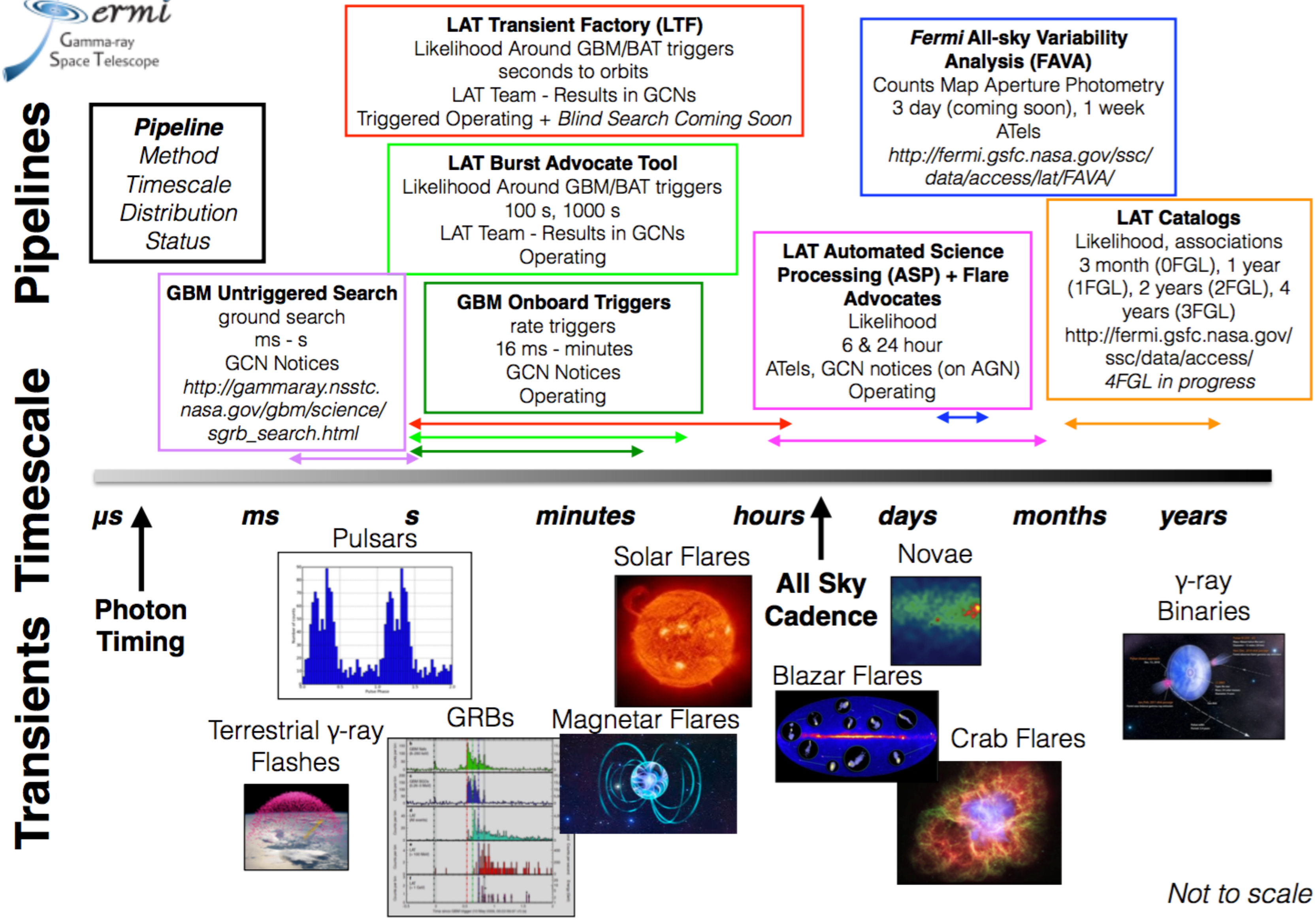
- The *Fermi* Gamma-Ray Space Telescope is an international Science Mission exploring the gamma-ray sky by means of its two main instruments:
  - Gamma-ray Burst Monitor (GBM): 8 keV → 40 MeV
  - Large Area Telescope (LAT): 20 MeV → > 300 GeV
- Huge energy range: including largely unexplored band for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



Fermi @10 Highlight & Discoveries

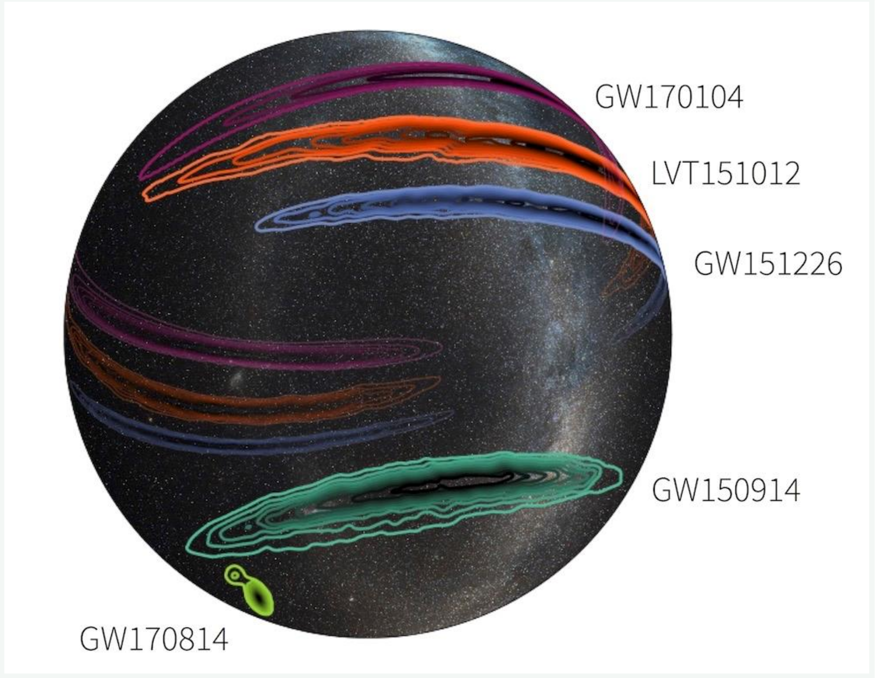


Fermi Transient Searches



Following up LIGO events

- 6 GW events announced by the LIGO/VIRGO Collaboration:
  - 5 BH- BH: GW150914, LVT151012, GW151226,GW170104, GW170814;
  - 1 NS-NS: GW170817;
- BH-BH mergers are not expected to produce EM radiation.
- NS-NS: predicted (and confirmed) to have EM radiation.

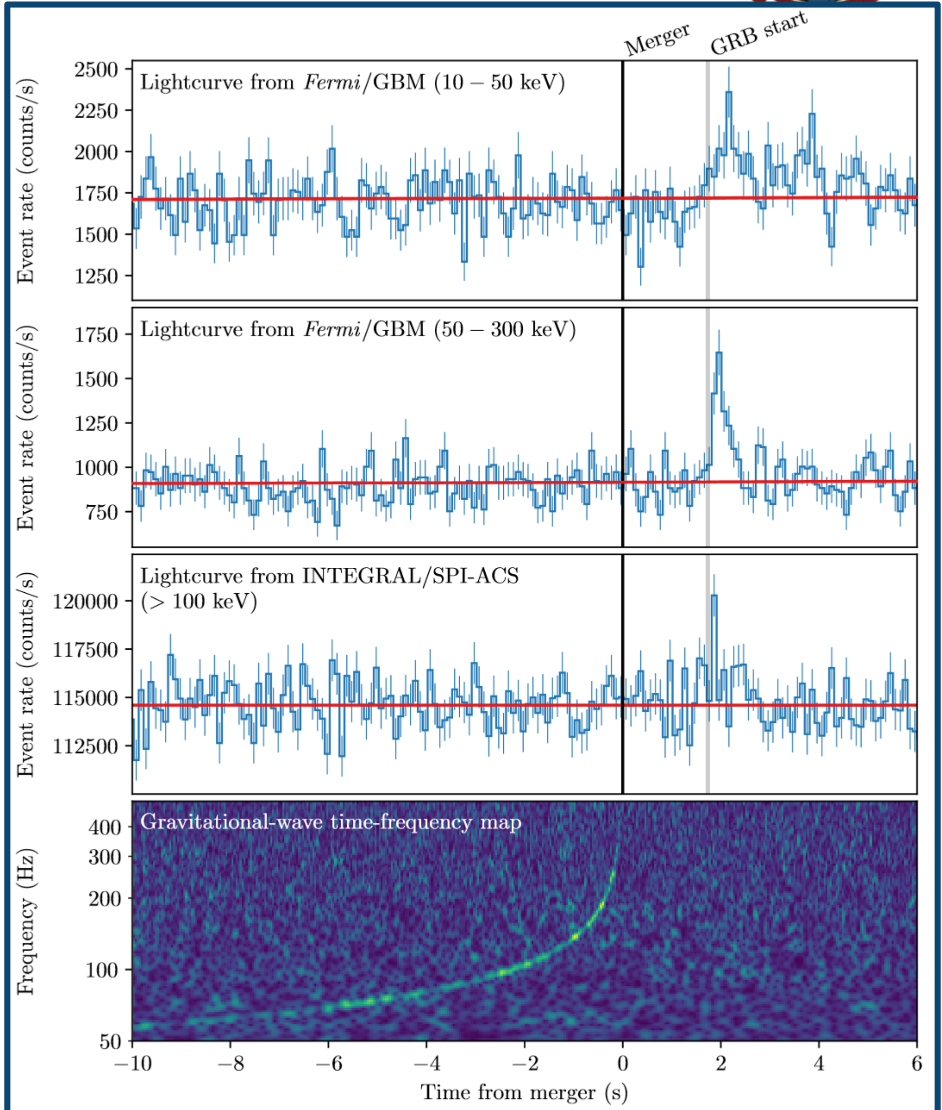


- General strategy for *Fermi*-LAT searches at high-energy:
  - Automated full sky searches of transients;
  - Specific searches in the LIGO contours;
  - Specific follow-ups of detected counterparts;
  - All done automatically in pipelines to quick alert the community;

An historical event: GW170817

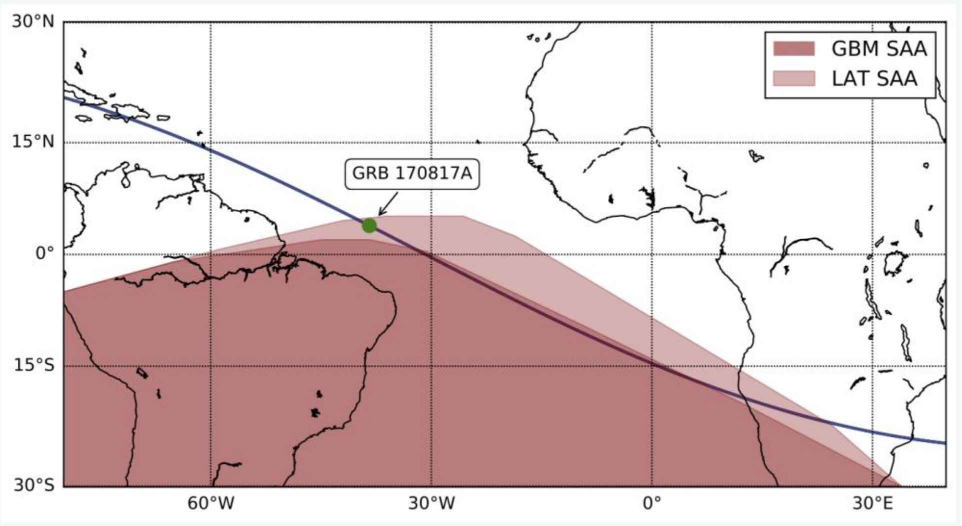
- **Δt = 1.74 +/- 0.05 s**
- Another gamma-ray instrument, the Anti-Coincidence Shield for the SPectrometer for **Integral** (**SPI-ACS**), also detected GRB170817A!
- Conclusive evidence for the **BNS-SGRB connection**
  - Chance temporal and spatial coincidence for GRB170817A and GW170817 arising from two independent astrophysical events: P = 5 x 10^{-8}

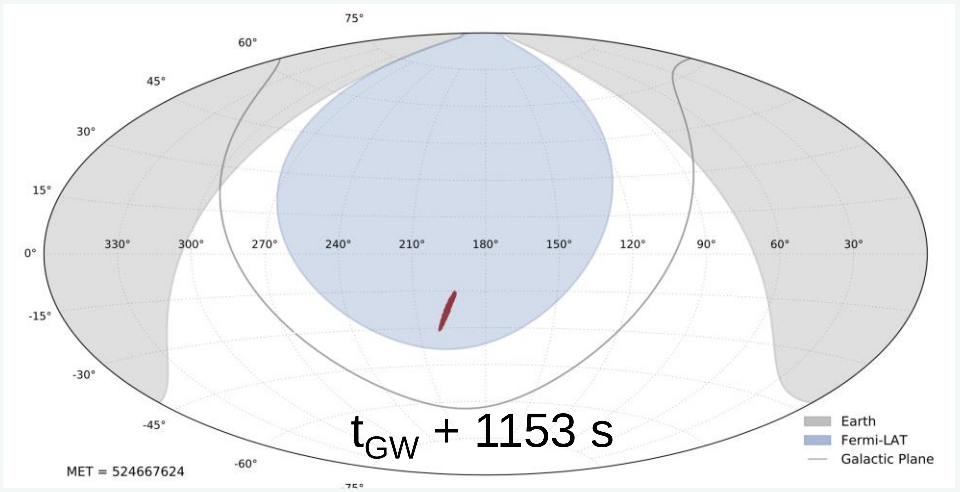
➔ GW-GRB association significance: 5.3 σ



Abbott+2017 ApJ 848, 13

GW170817/GRB170817A, an unlucky event

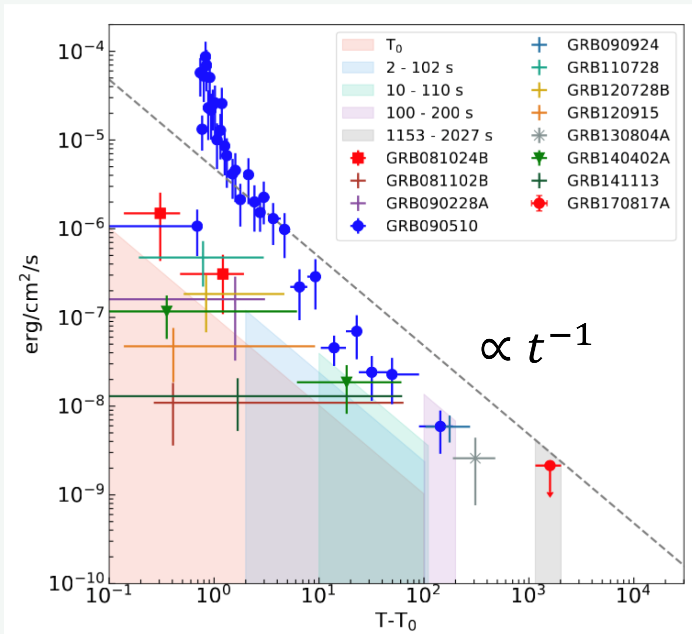


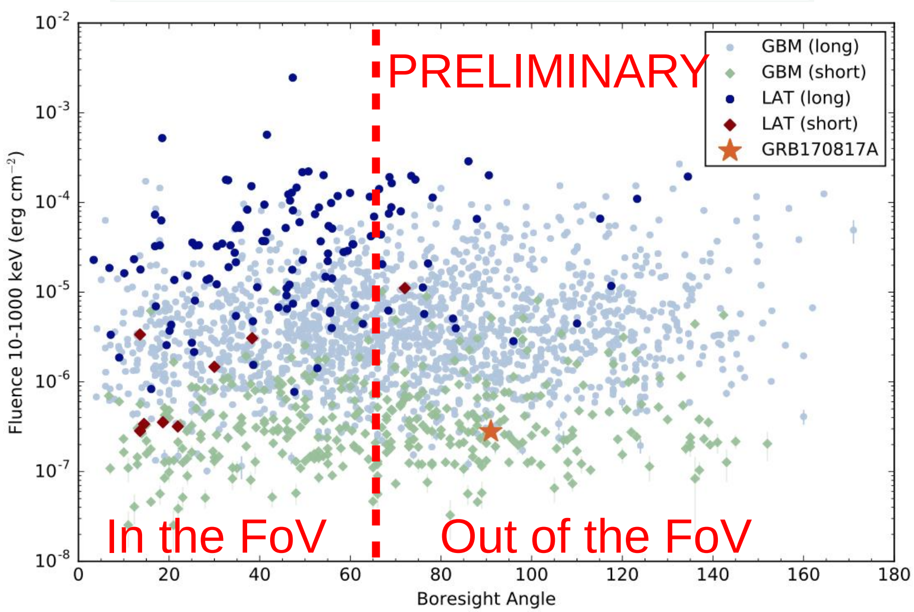


- The LAT and the GBM do not collect data when in the SAA
  - For different instrument requirements, the SAA definition for the LAT is slightly larger (14%) than the GBM one;
  - At the time of the GW event (and GBM trigger), the LAT was in the SAA;
  - We observe the entire region between t_{GW}+1153 – t_{GW}+2017;

Arxiv: 1710.05450

Fermi LAT sensitivity to SGRBs



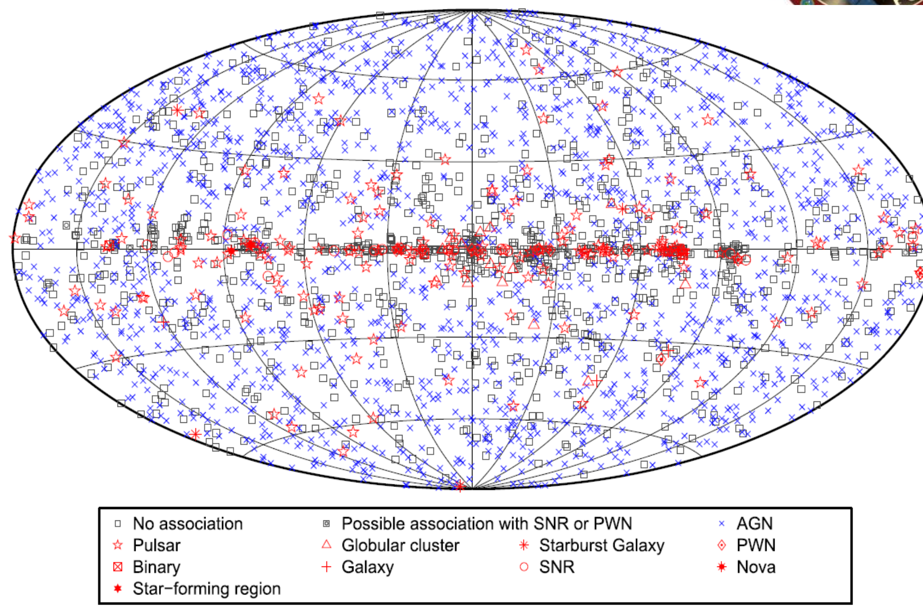


- Rate estimation:
  - LAT sees 23% of the all sky SGRBs within 100 s (either a detection or upper bound)
  - LAT detects 5% of all GBM-detected SGRB
  - Assuming 1 (2) GW+SGRB events per year : 5% (10%) probability to detect it in the LAT
  - Modifying the observing profile (re-pointing every SGRB within 100 seconds): 7% (13%)

Arxiv: 1710.05450

Fermi-LAT source catalogs

- Purely gamma-ray based (associations only post facto)
- Concentrate on **persistent** sources, detection over time-integrated data set
- 0/1/2/3FGL: full energy range (> 100 MeV)
- 1/2/3FHL: high-energy only (> 10 / 50 GeV)
- Each generation has used **improved data/calibration**:
  P6 ->P7 ->P7Rep ->P8

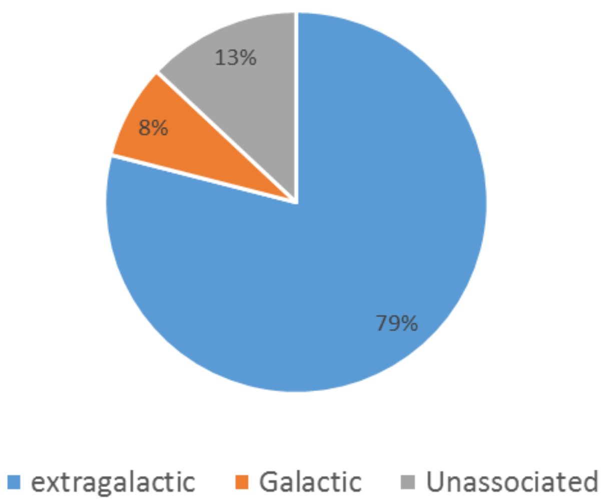


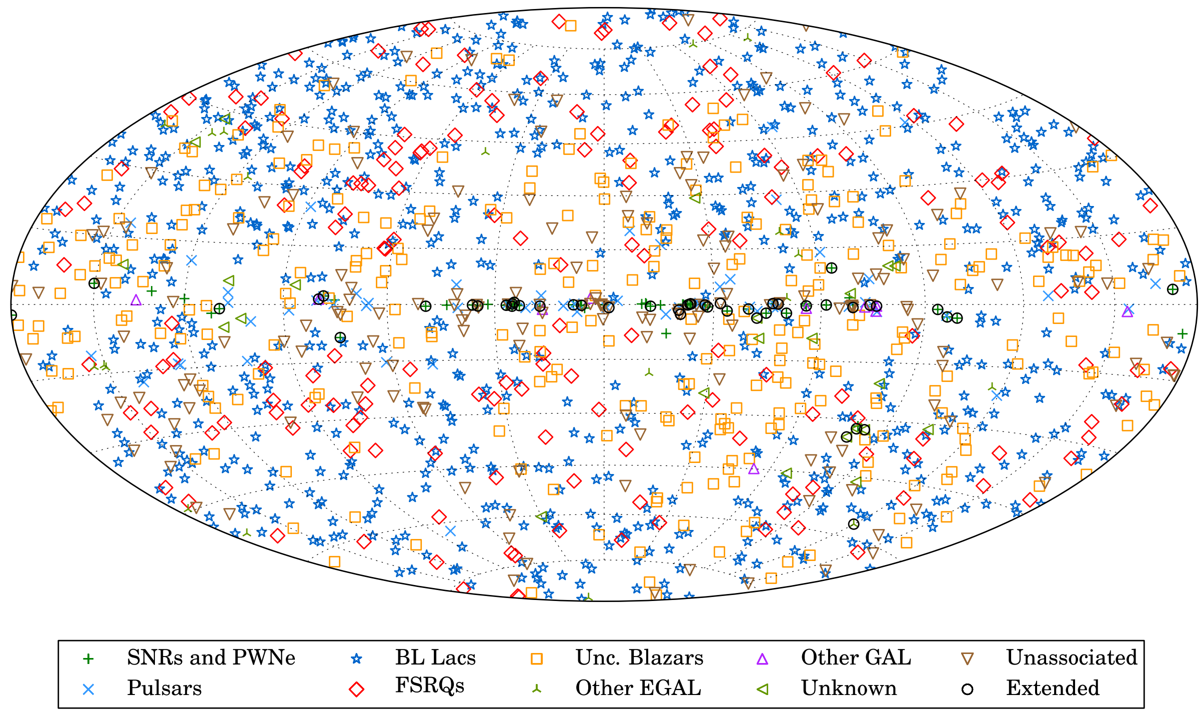
	0FGL[a]	1FGL	2FGL	1FHL[b]	3FGL
Total	205	1451	1873	514	3033
High-latitude sources	132	1043	1319	399	2193
Low-latitude sources	73	408	554	115	841
"Lost" sources[c] in 3FGL	12	310	300	17	…

Acero F. + 2015 ApJS 218, 23

The 3FHL Catalog

- 1556 sources:
  - 79% extragalactic,
  - 8% Galactic
  - 13% unassociated





- 1286 in 3FGL
- 133 in TeVCat
- 211 new sources (not in 1FHL/2FHL/3FGL/TeVCat)
- 16 with redshift > 2

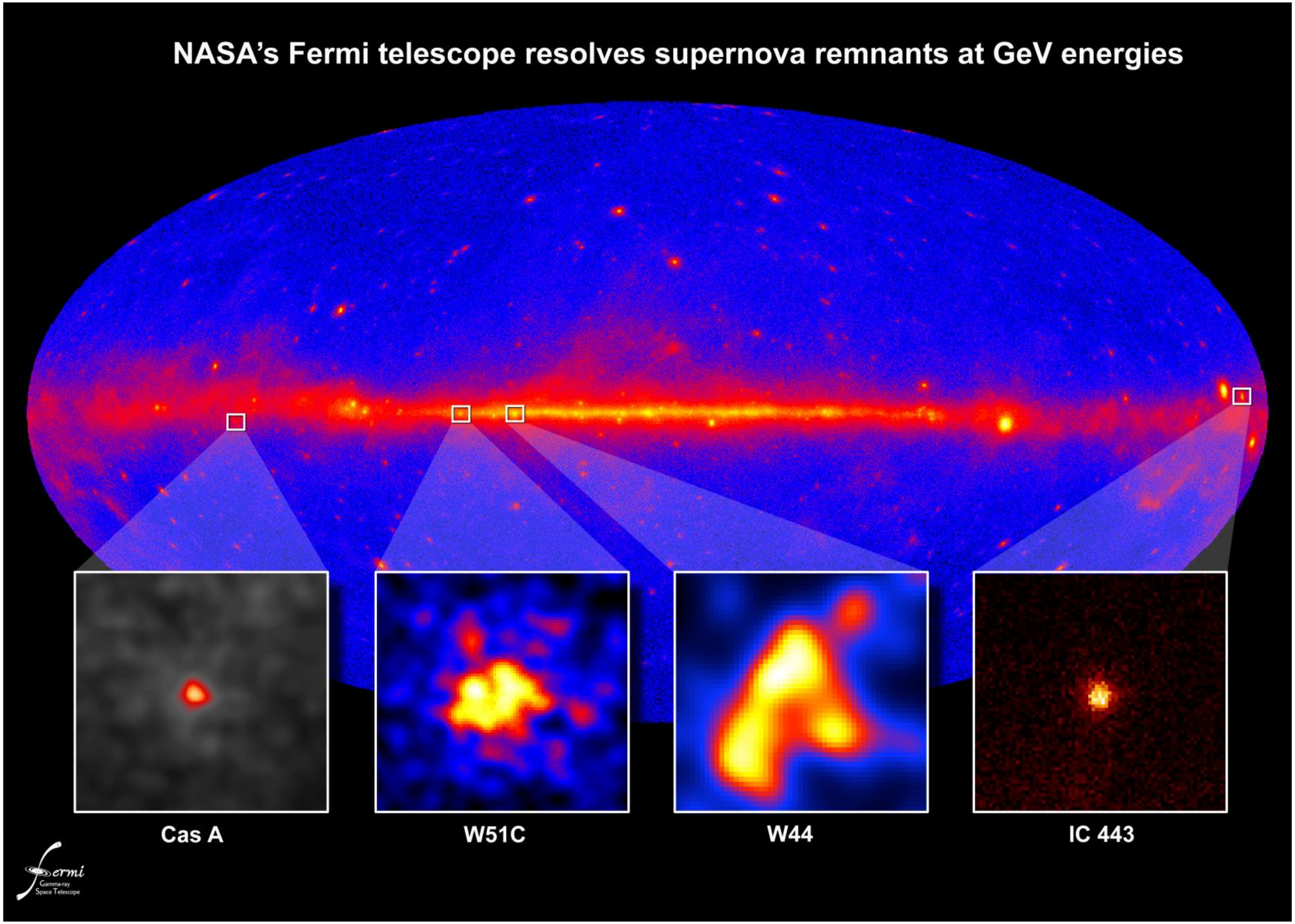
Ajello M+ 2017 ApJS 232, a8A

Toward the 4FGL

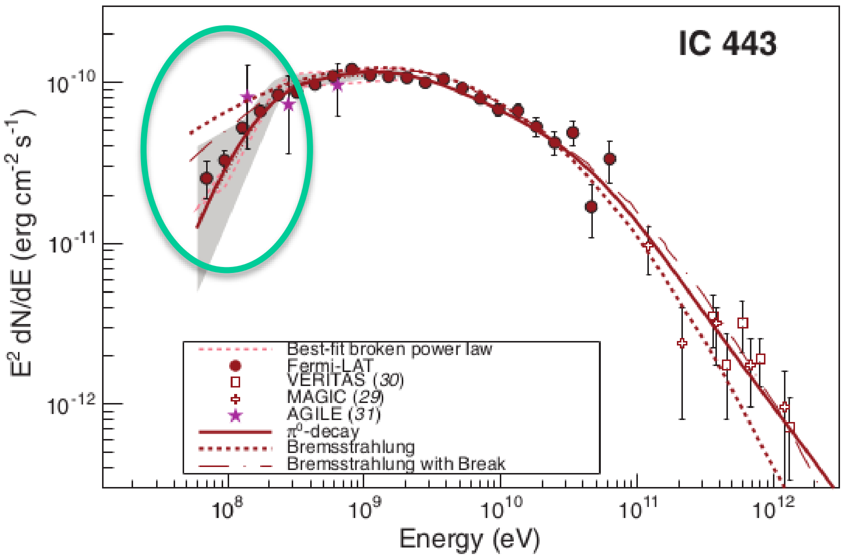
- The last main source list in the full energy range (E> 100 MeV) is the 3FGL based on 4 years of data.
- Improvements in the 4FGL:
  - Longer dataset
  - Improved interstellar emission model
  - Energy dispersion
  - Earth limb suppression
  - Weighted likelihood
- Preliminary 8 year source list with 5524 sources above 4 sigma (2500 were not in the 3FGL) available here:
  - https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/

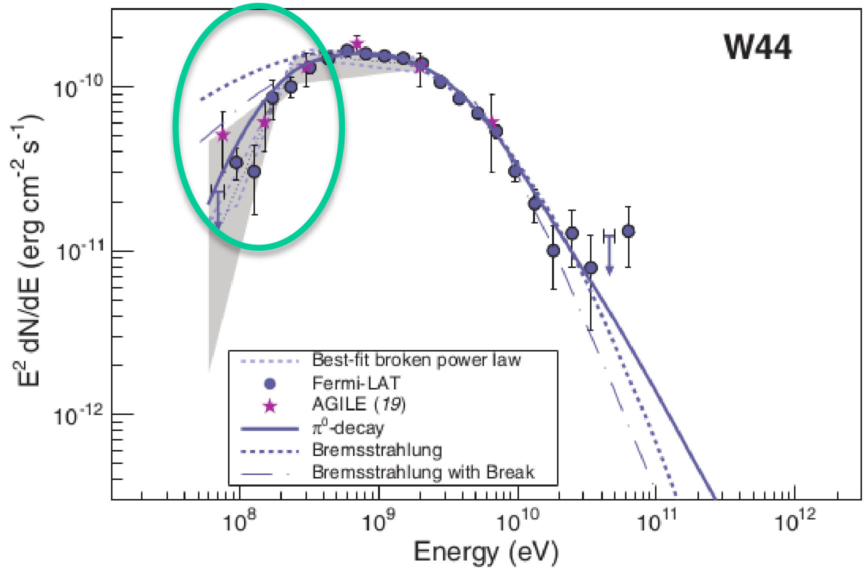
J. Ballet @ Fermi Symposium 17

Supernova Remnants

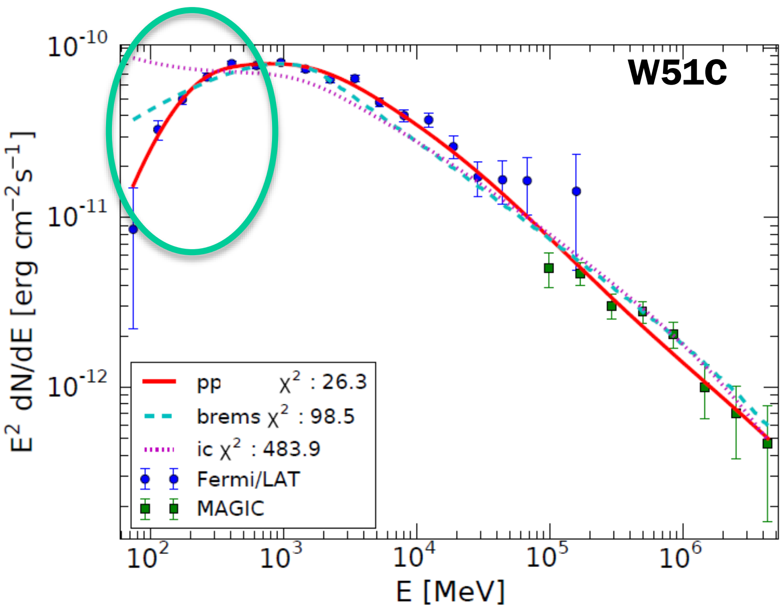


SNRs with hadronic emission

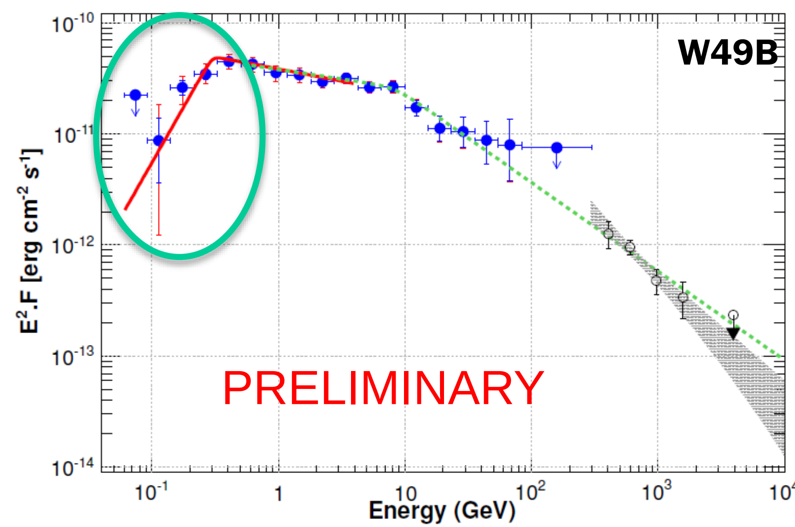




M. Ackermann+ 2013 (detected also by AGILE: Giuliani+ 2011)



T. Jogler and S. Funk, ApJ 2016



HESS + Fermi-LAT
Accepted for publication in A&A

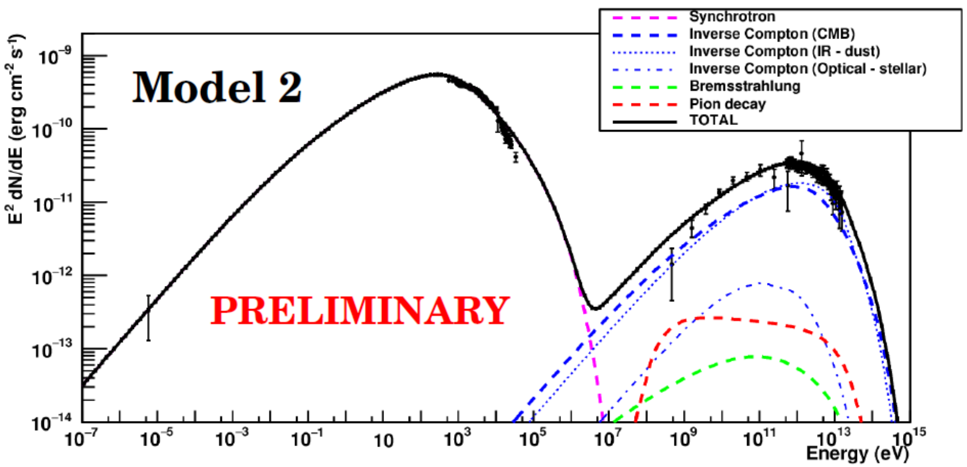
Young SNRs

- Approx. few thousands years old
- Simple environments
- Small energy losses

→ <u>Ideal targets to test the acceleration theory and look for 'Pevatrons'</u>

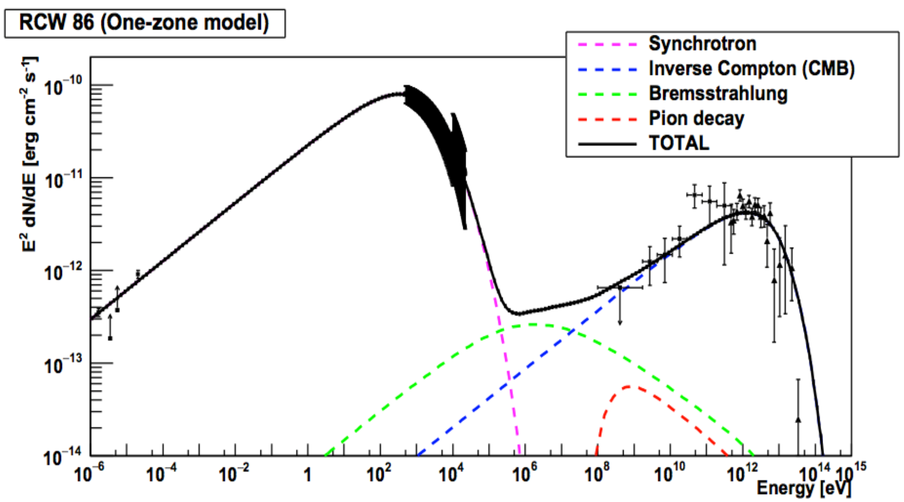
<u>Leptonic scenario</u>

RX J1713.7-3946



B. Condon+ @ Gamma 2016

RCW 86

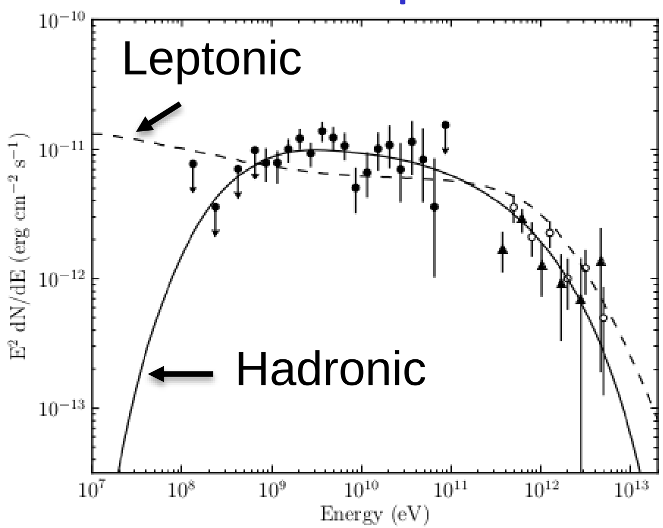


M. Ajello+ ApJ 2016

γ-ray emission dominated by Inverse Compton

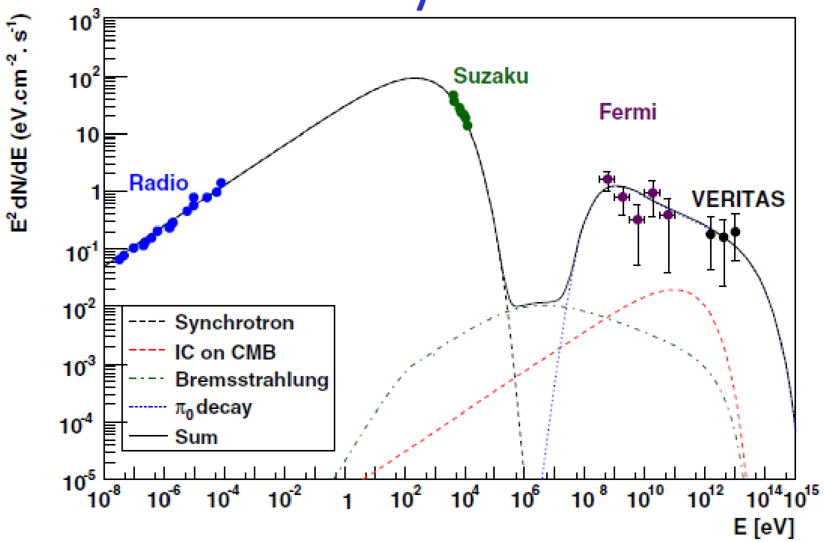
Hadronic scenario

Cassiopeia A



Y. Yuan+ ApJ 2013

Tycho

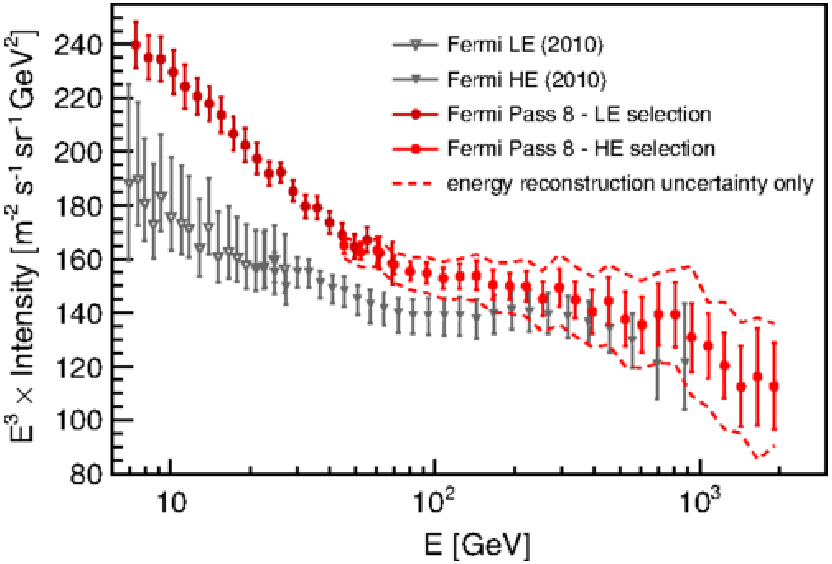


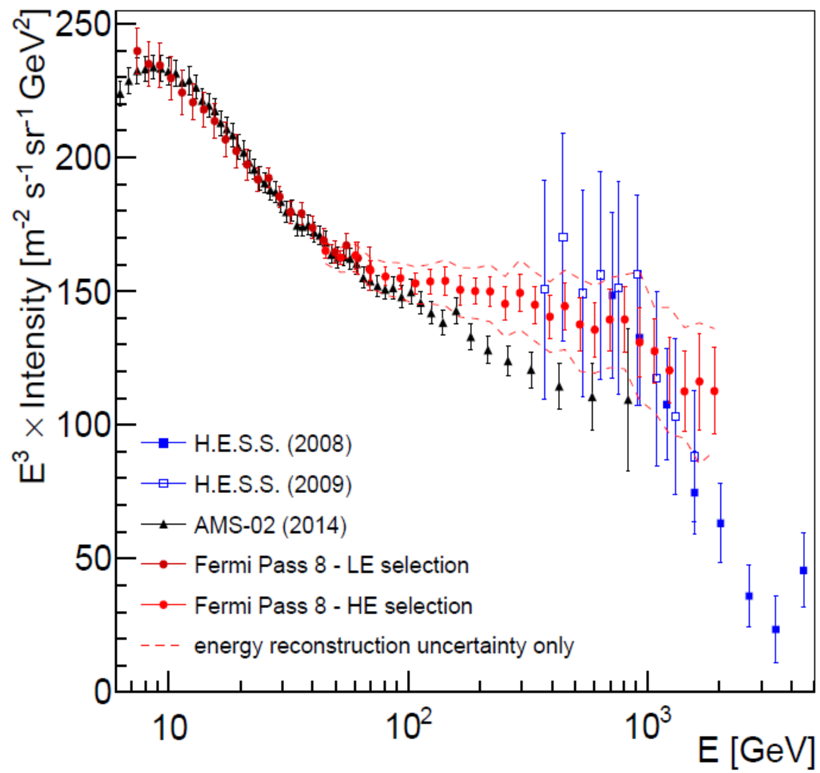
F. Giordano+ ApJL 2012

γ-ray emission dominated by pion decay

Presence of accelerated protons

The CRE energy spectrum





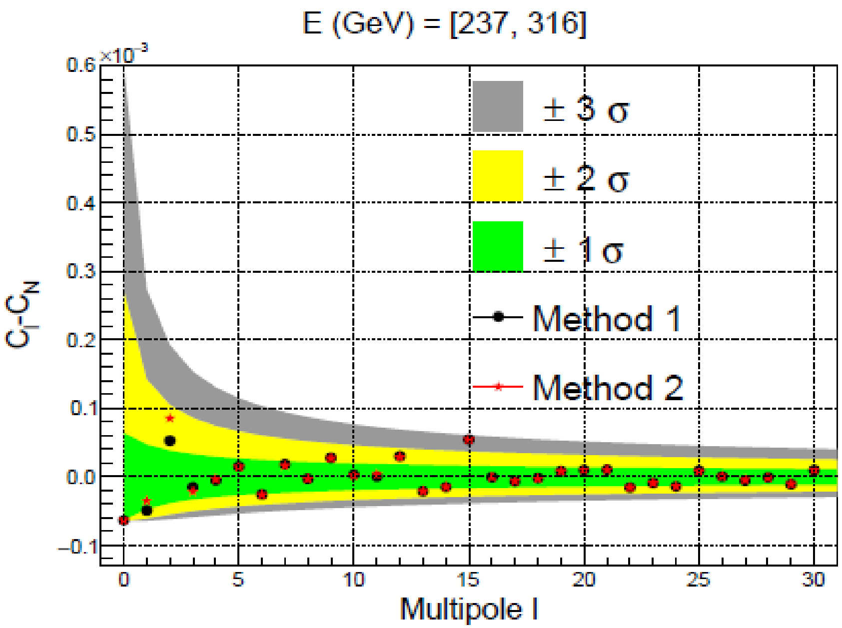
Differences up to 30% wrt previous results:

- loss of CREs due to the geomagnetic field
- “ghost events” in the MC simulation

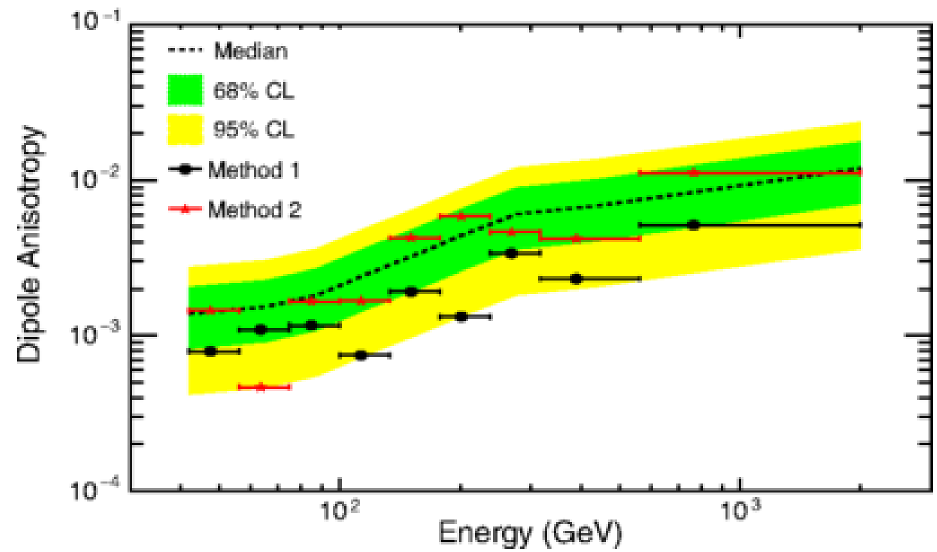
- The spectrum is well fitted by a broken power law:
  - Break energy: 53±8 GeV
  - Spectral index below the break: 3.21±0.02
  - Spectral index above the break: 3.07±0.02
- An exponential cutoff lower than 1.8 TeV is excluded at 95% CL

Abdollahi S. + 2017 PrD 95h2007A

Angular power spectra (APS)



- The measured APS are consistent with the white noise APS in all the energy bins



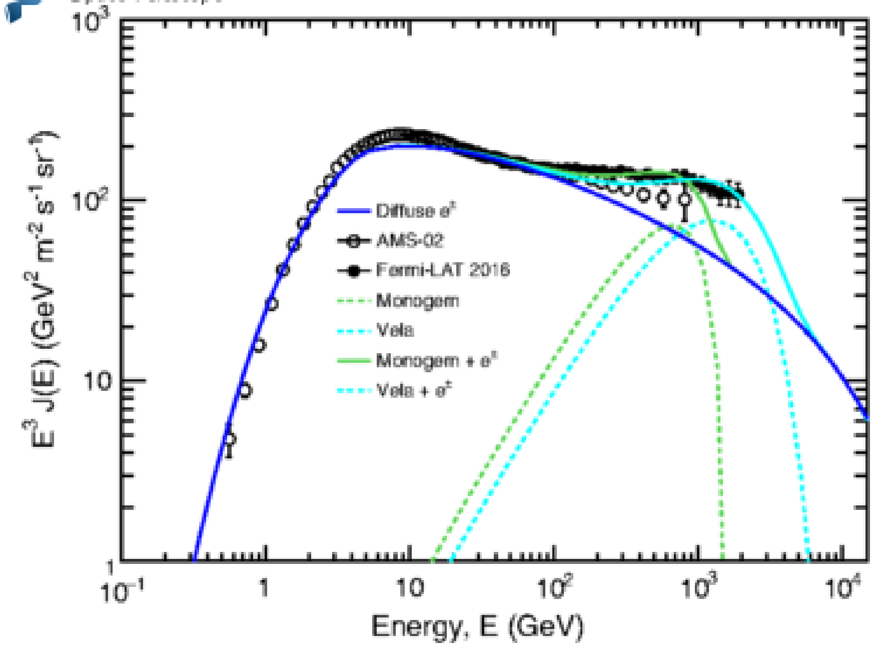
- The dipole anisotropy is evaluated from the multipole coefficient C_1 of the APS:

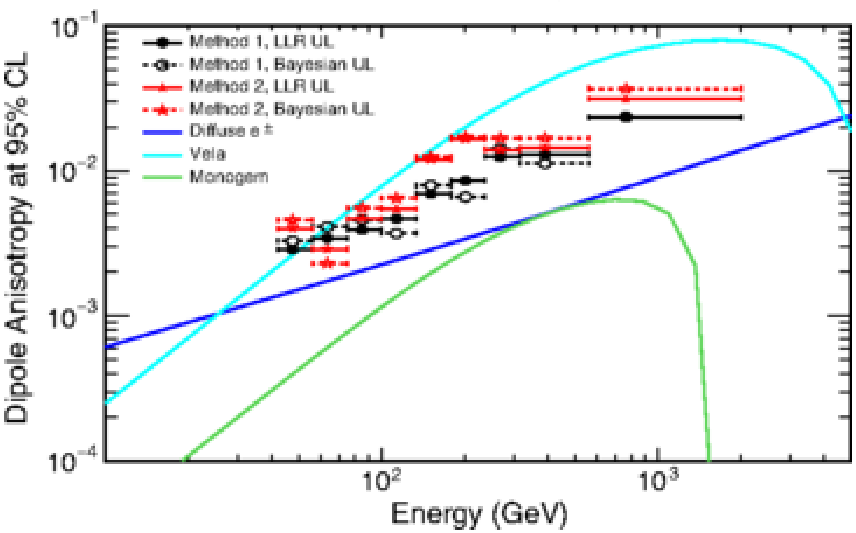
$$\delta = 3\sqrt{C_1/4\pi}$$

- The measured values are consistent with those expected in the isotropic case

Abdollahi S. + 2017 PrL 118i1103A

Interpretation of the results





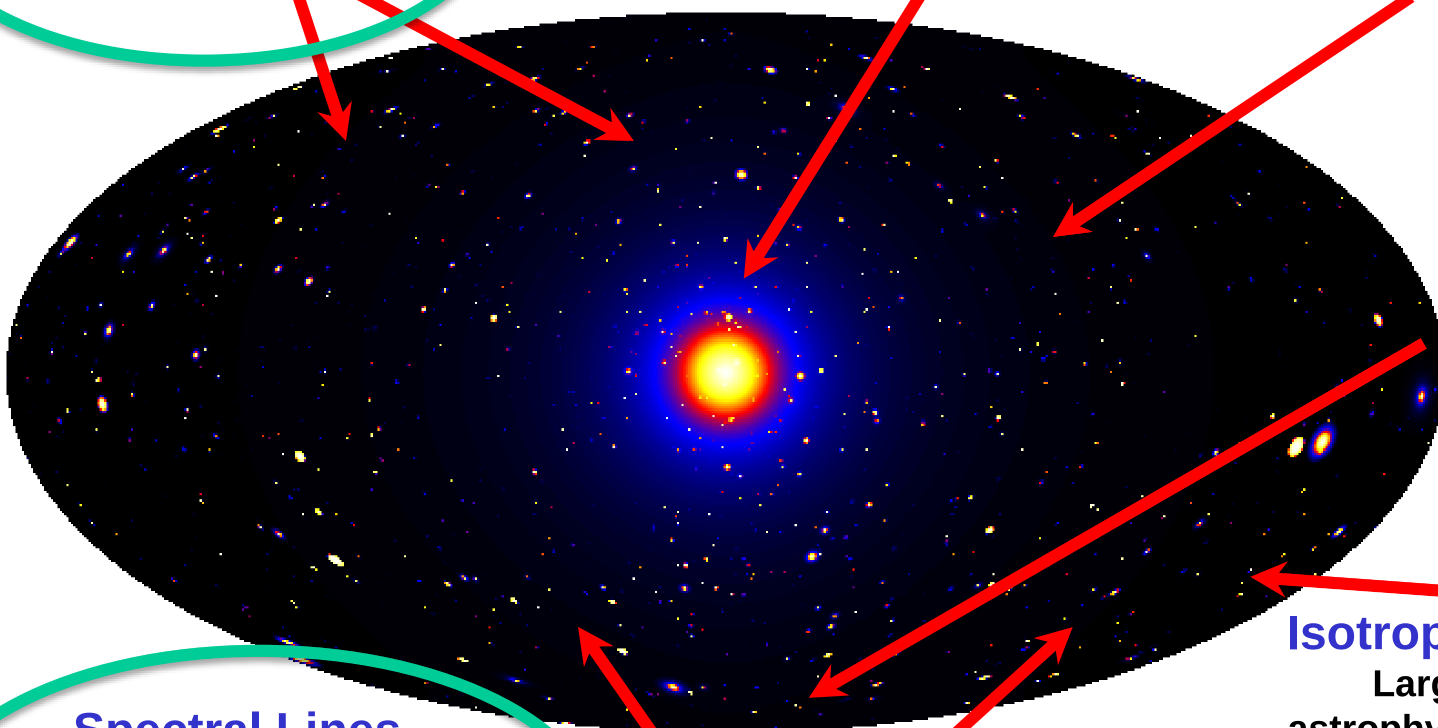
- The CRE spectrum can be reproduced assuming the presence of an additional high-energy source
- The Galactic CRE component is evaluated using a simulation based on the DRAGON propagation code
- We have evaluated the contributions from Vela and Monogem:
  - The injected luminosity of each source is such that the total flux is not higher than the one measured by the Fermi-LAT and AMS-02
  - The injection spectrum of both sources is a power law with spectral index 1.7 and cut-off energy at 1.1 TeV
- The anisotropy limits disfavor a scenario with a nearby young source

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

Isotropic contributions
Large statistics, but astrophysics, galactic diffuse background

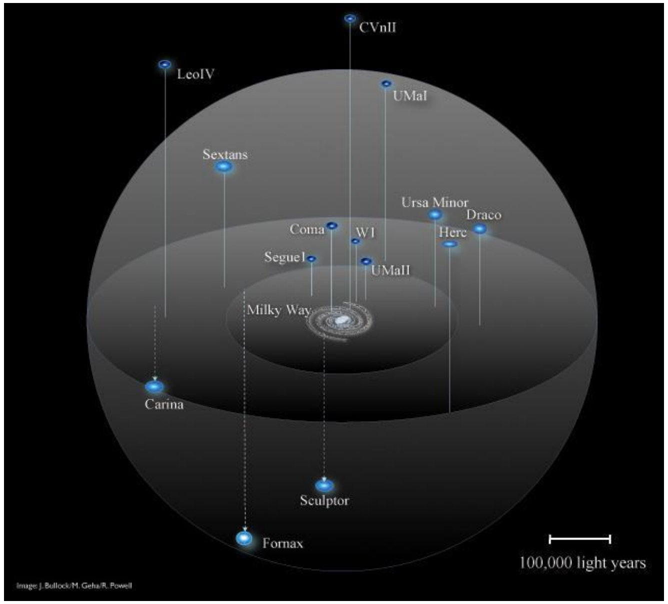
Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

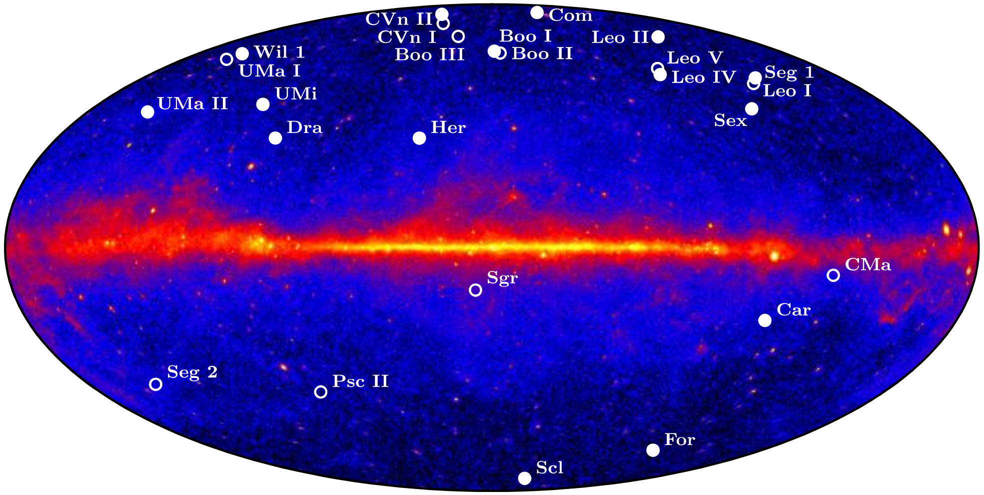
Galaxy Clusters
Low background, but low statistics

For a recent overview:
Charles, E +2016 PhR 636, 1

DM searches in dSph Galaxies

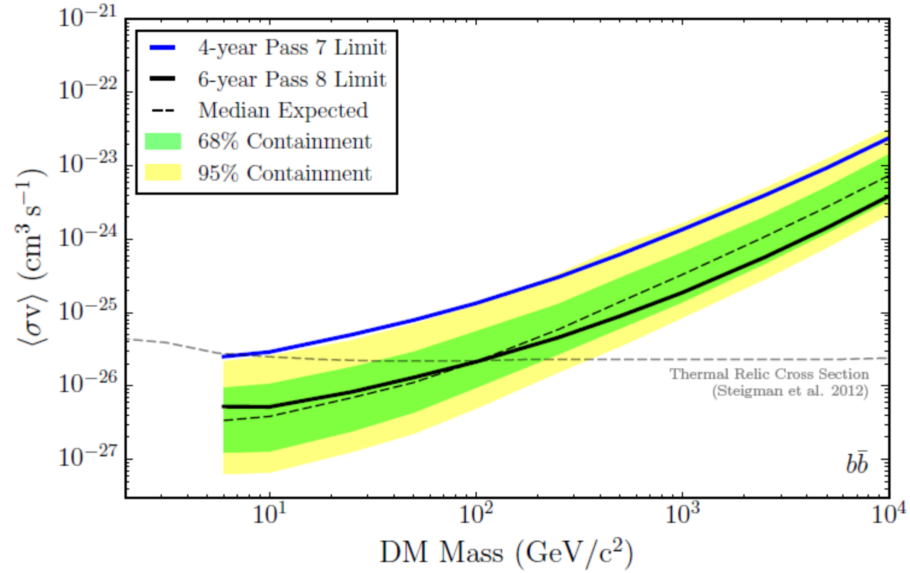
- dSph Galaxies are the cleanest target for DM searches:
  - DM-dominated (1000:1)
  - 10s to 1000s of stars
    - Mostly old stars
    - Few gamma-ray emitters (pulsars, SNRs)
    - Little gas content
  - often high latitude ➔ low diffuse background
  - nearby (<250 kpc)
  - many! (50+) ➔ allows for joint analyses

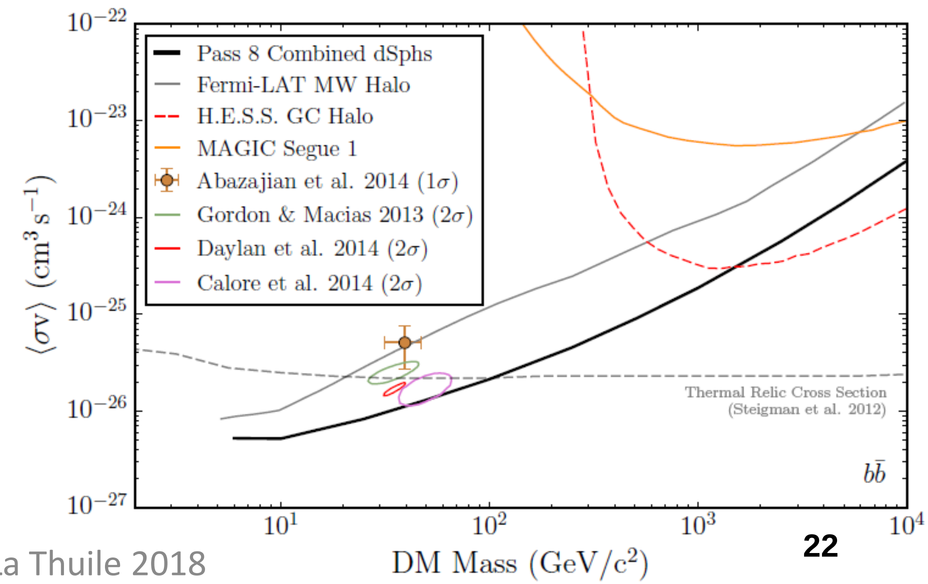




Upper limits on DM annihilation cross section from dSph analysis

- 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)





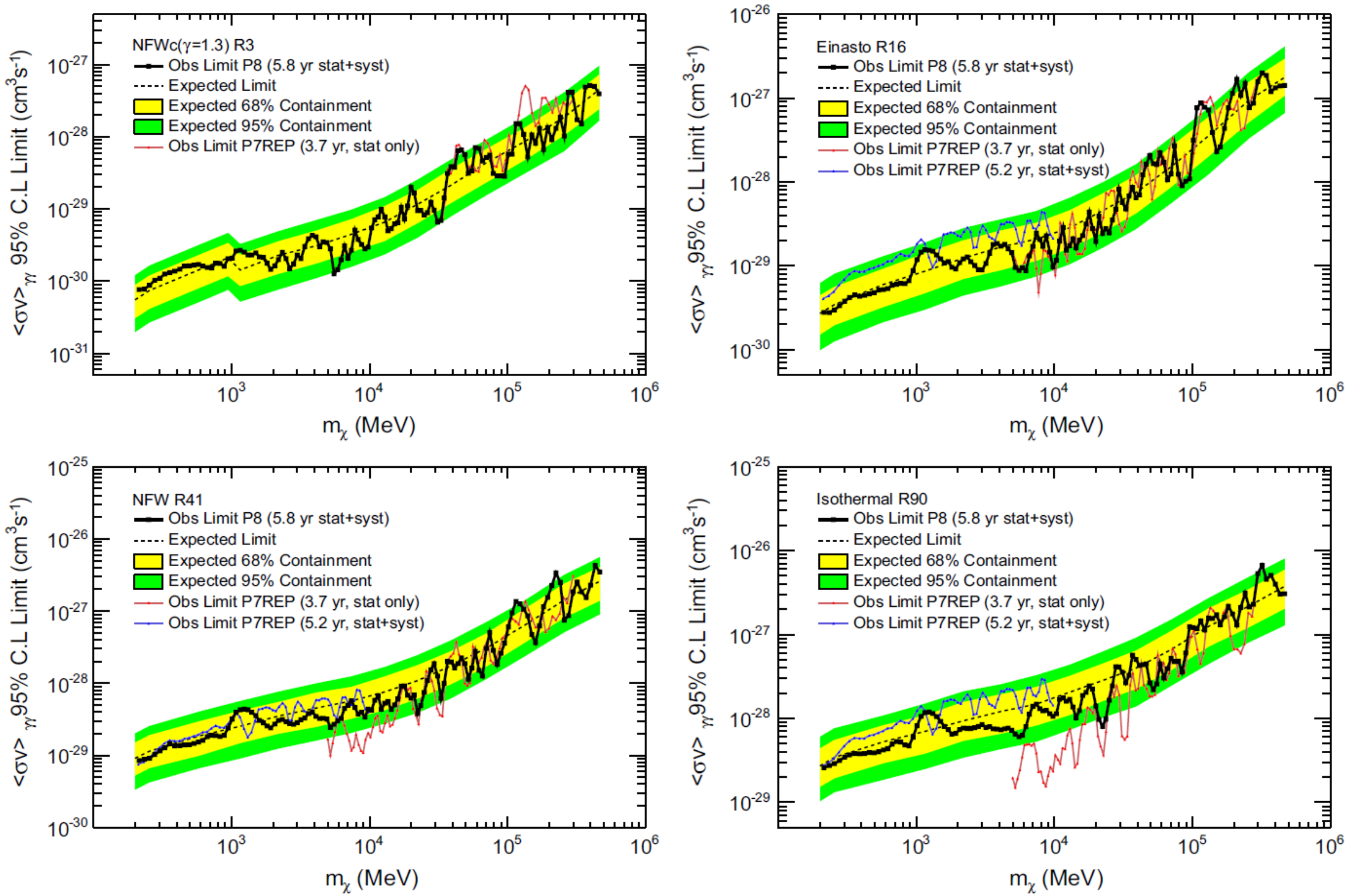
Ackerman, M + 2015 PRL 115, 231301

Search for γ-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 (~10^{-2} to 10^{-4})
    - Signal predicted to be small
- 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

Ackerman, M + 2015, PRD 91, 122002 (2015)

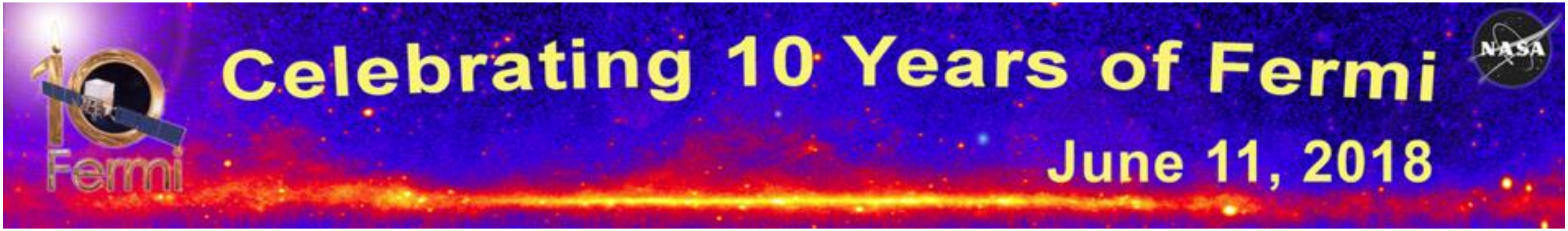
Upper limits on the WIMP mass from line searches



No evidence of spectral lines found!

Conclusions

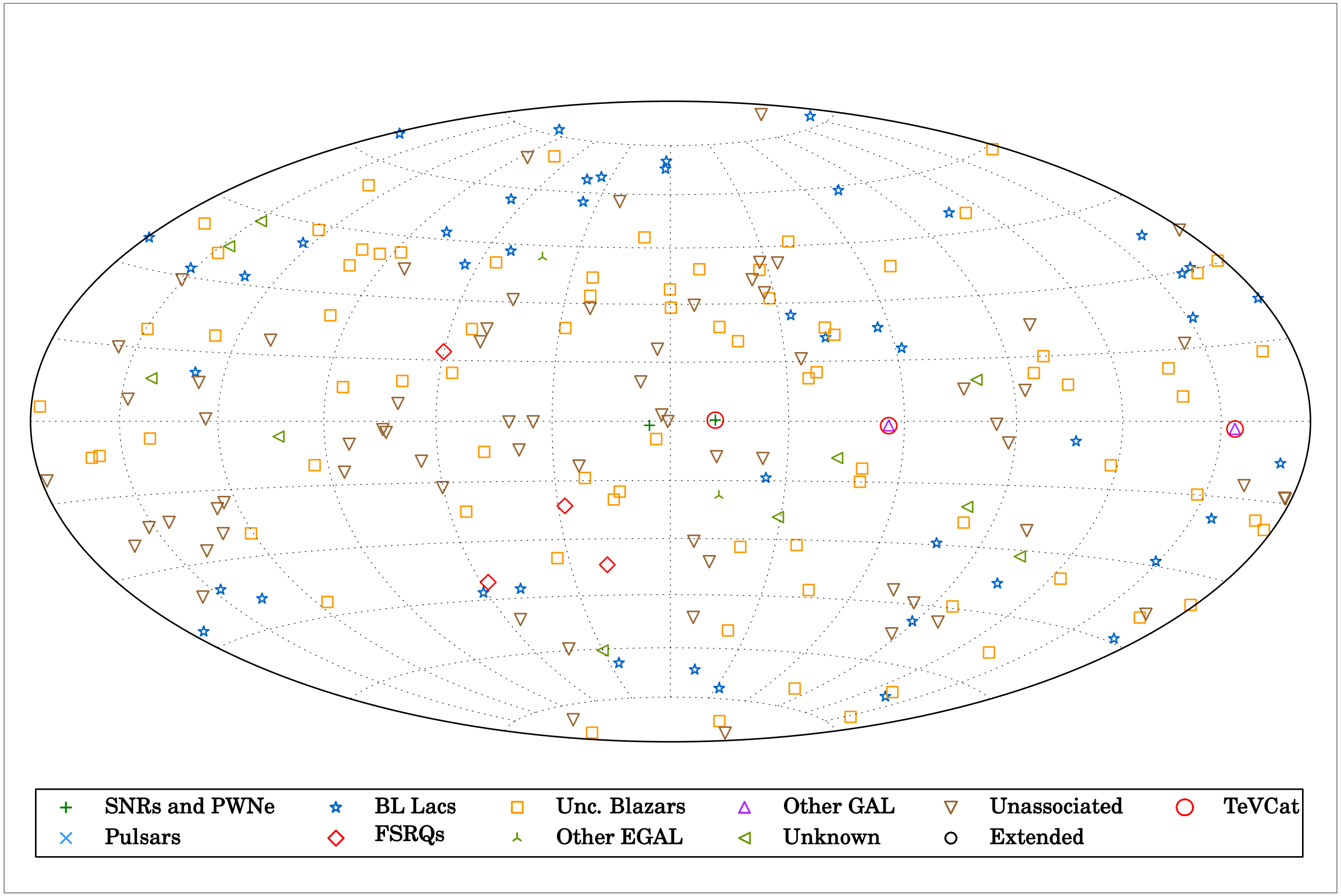
- Fermi has been extremely successful in the last ten years;
- Still in perfect active data taking with an increasing focus on transient sources;
- Fermi covers a fundamental energy range in various multi-wavelength and multi-messenger analysis;
- Part of his strength is the large community that uses LAT and GBM data outside the collaboration.



- https://fermi.gsfc.nasa.gov/fermi10/

Backup

New Sources in the 3FHL Catalog

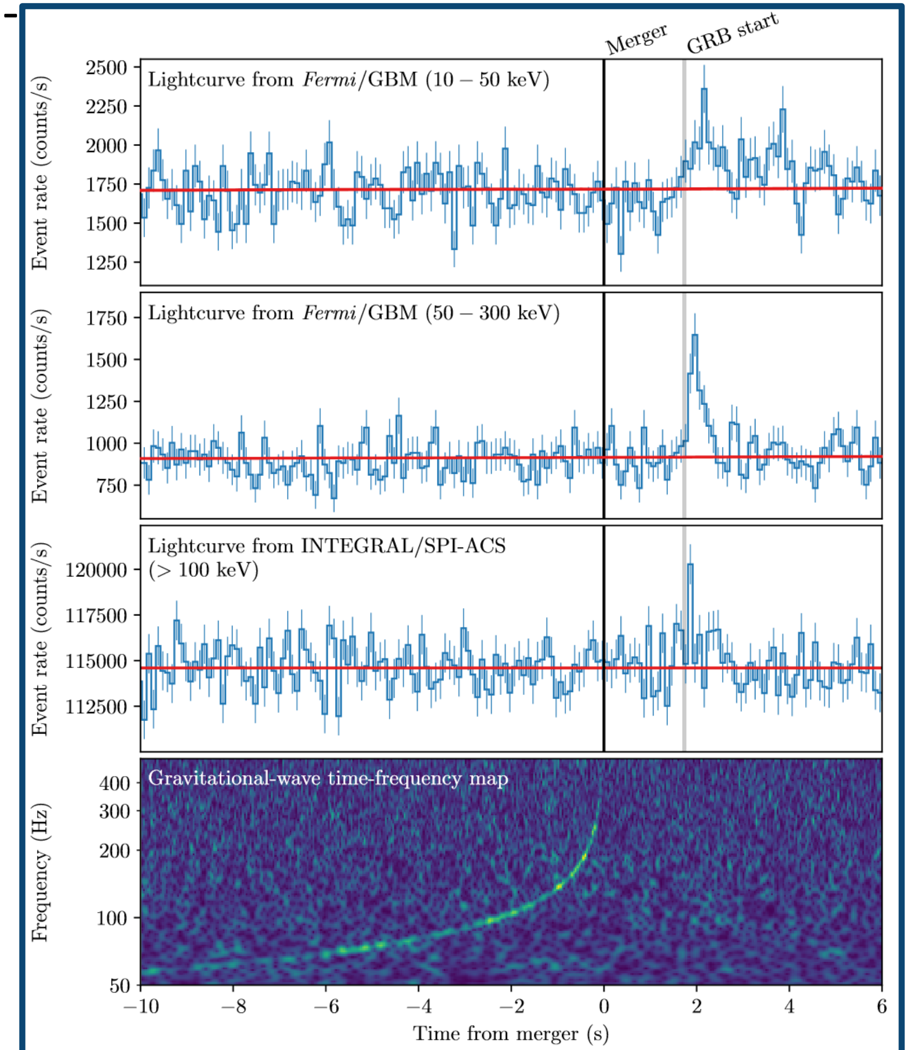


214 sources not included in previous LAT catalogs. 3 of these have been seen by IACTs.

GRB 170817A and GW170817

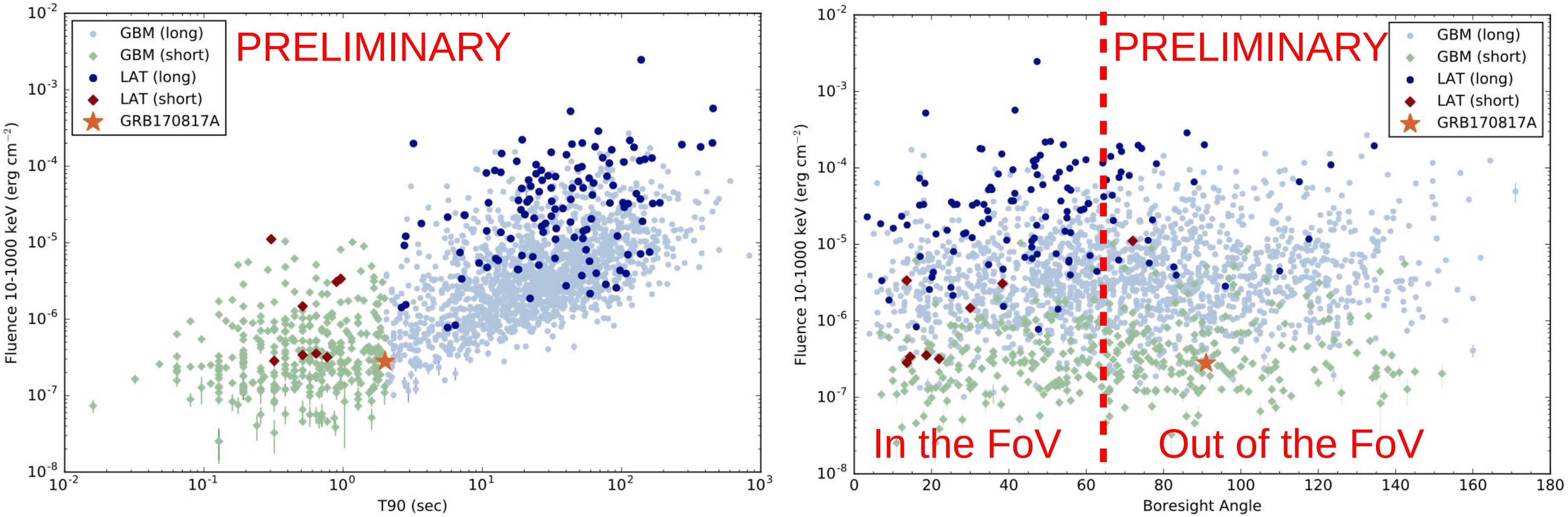
- Another gamma-ray instrument, the Anti-Coincidence Shield for the SPectrometer for **Integral** (**SPI-ACS**), also detected GRB170817A!
- Conclusive evidence for the **BNS-SGRB connection**
  - Chance temporal and spatial coincidence for GRB170817A and GW170817 arising from two independent astrophysical events: P = 5 x 10^{-8}

➔ **GW-GRB association significance: 5.3 σ**



Abbott+2017 ApJ 848, 13

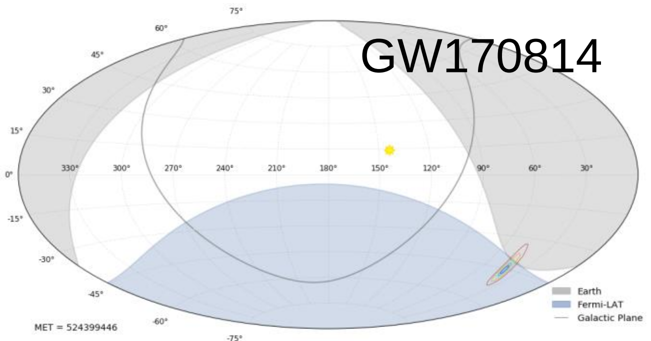
GW170817/GRB170817A, and other GBM GRBs



- GBM flux (10 keV – 1 MeV): in the middle of the GBM SGRB population:
  - other 4 SGRBs of similar fluence have been detected by the LAT at high-energy (>100 MeV);
- Detectability of SGRBs depends on the off-axis angle:
  - LAT can repoint within few hundreds of seconds;

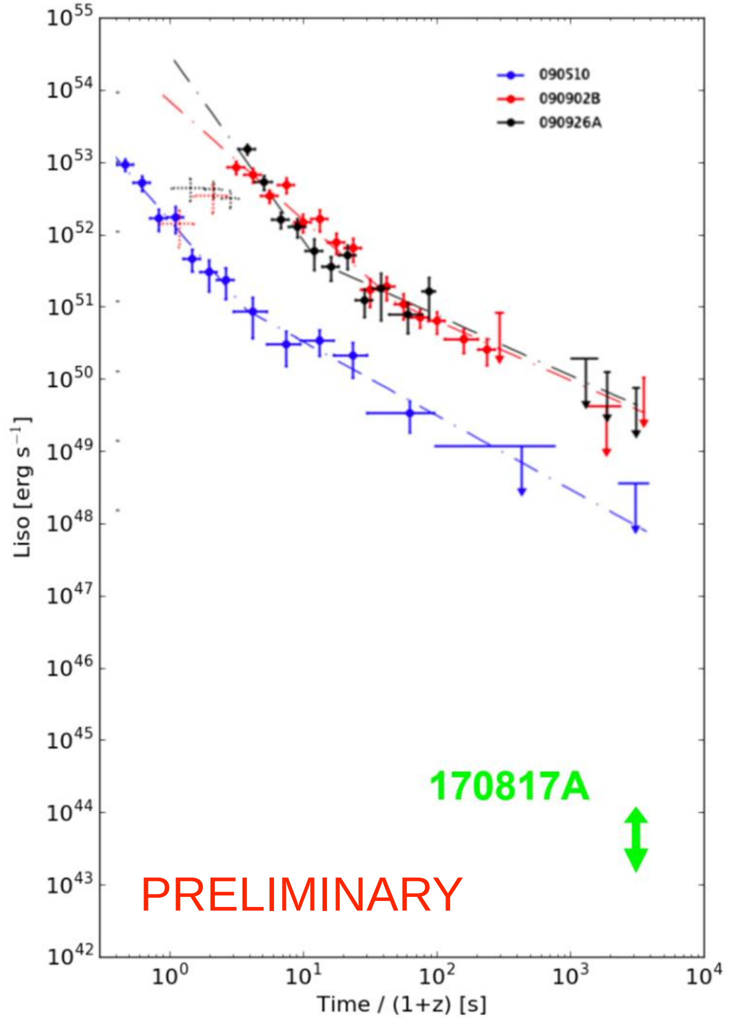
From LVC probability maps to LAT analysis

- We developed a novel technique to search for EM counterpart in LAT data starting from LIGO probability maps:
  - LVC probability maps (in HEALPix) downscaled to match the Fermi LAT PSF (~4 degrees at 100 MeV);
  - We center a ROI in each pixel (p>0.9), and we run standard likelihood analysis (Unbinned);
- Cumulative coverage of the map as a function of time:
  - In some cases we started with ~40-50% of the credibility region in the field of view at the time of the trigger;
  - In all cases we reached 100% of the coverage within 8 ks;
  - Different pixels of the map enter and exit at different time:
    - We set up two different analysis: fixed time window and adaptive time window
    - see: Ackermann et al. 2016 (GW150915), Racusin et al. 2017 (GW151226, LVT151012), Goldstein at al. 2017 (GW170114), Vianello et al. 2017 (Methods)



GW170817/GRB170817A, an unlucky event

- Upper bound (0.1–1 GeV):
  - $F < 4.5 \times 10^{-10}$ erg cm^{-2} s^{-1}
- At the distant of GW170817:
  - $L_{iso} < 9.3 \times 10^{43}$ erg s^{-1}
- Very strong constrain on the luminosity of GRB170817A at high energy



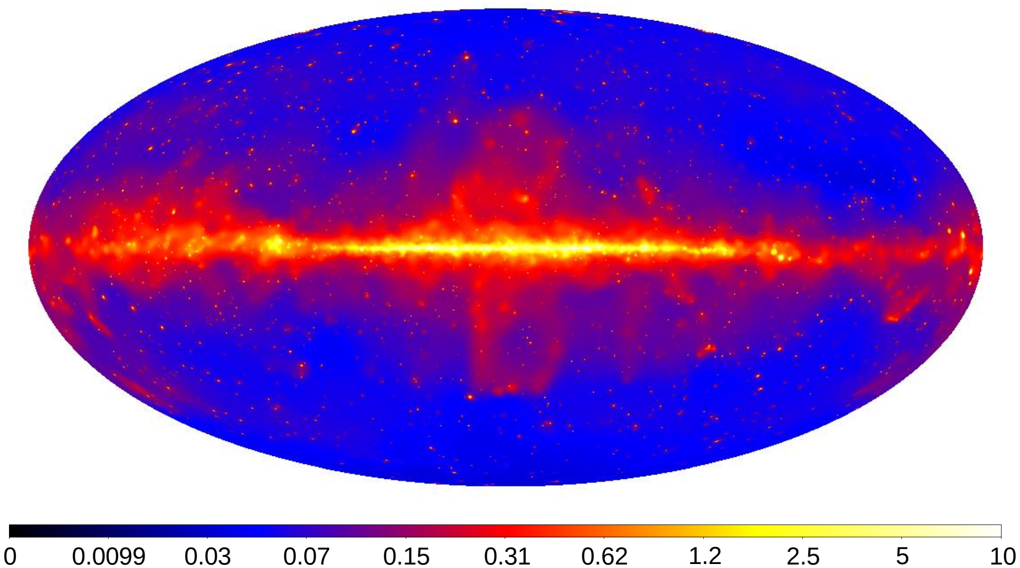
Omodei @ Fermi Symposium 17

Theory confirmed!

- The **onset** of gamma-ray emission from a binary neutron star merger progenitor is predicted to be within **a few seconds after** the merger
  - the central engine is expected to form within a few seconds
  - the jet propagation delays are at most of the order of the SGRB duration
    - Finn et al. 1999; Abadie et al. 2012 and references therein

Measured time delay between GW and light:
$\Delta t = 1.74 \pm 0.05$ s

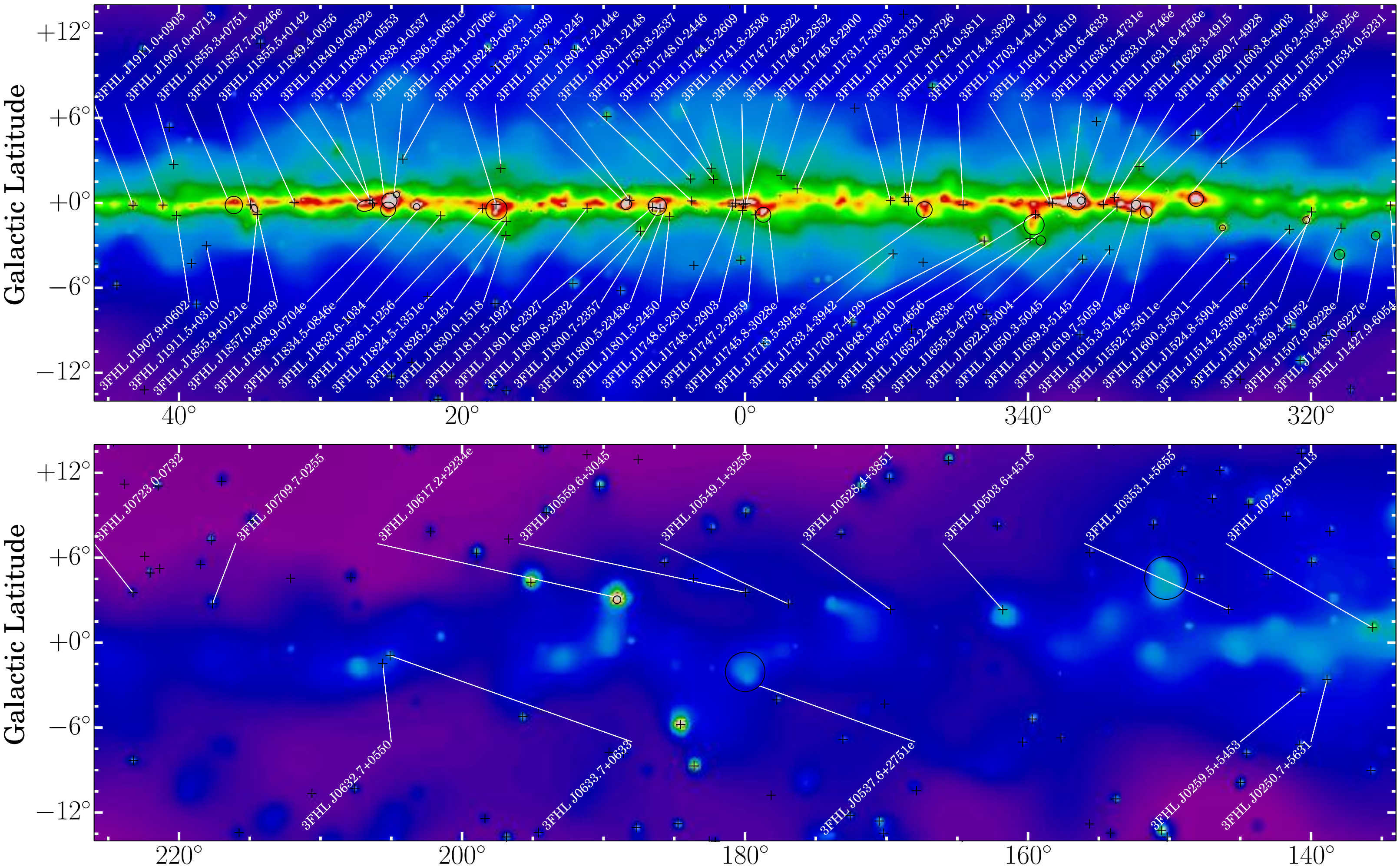
Construction of 3FHL



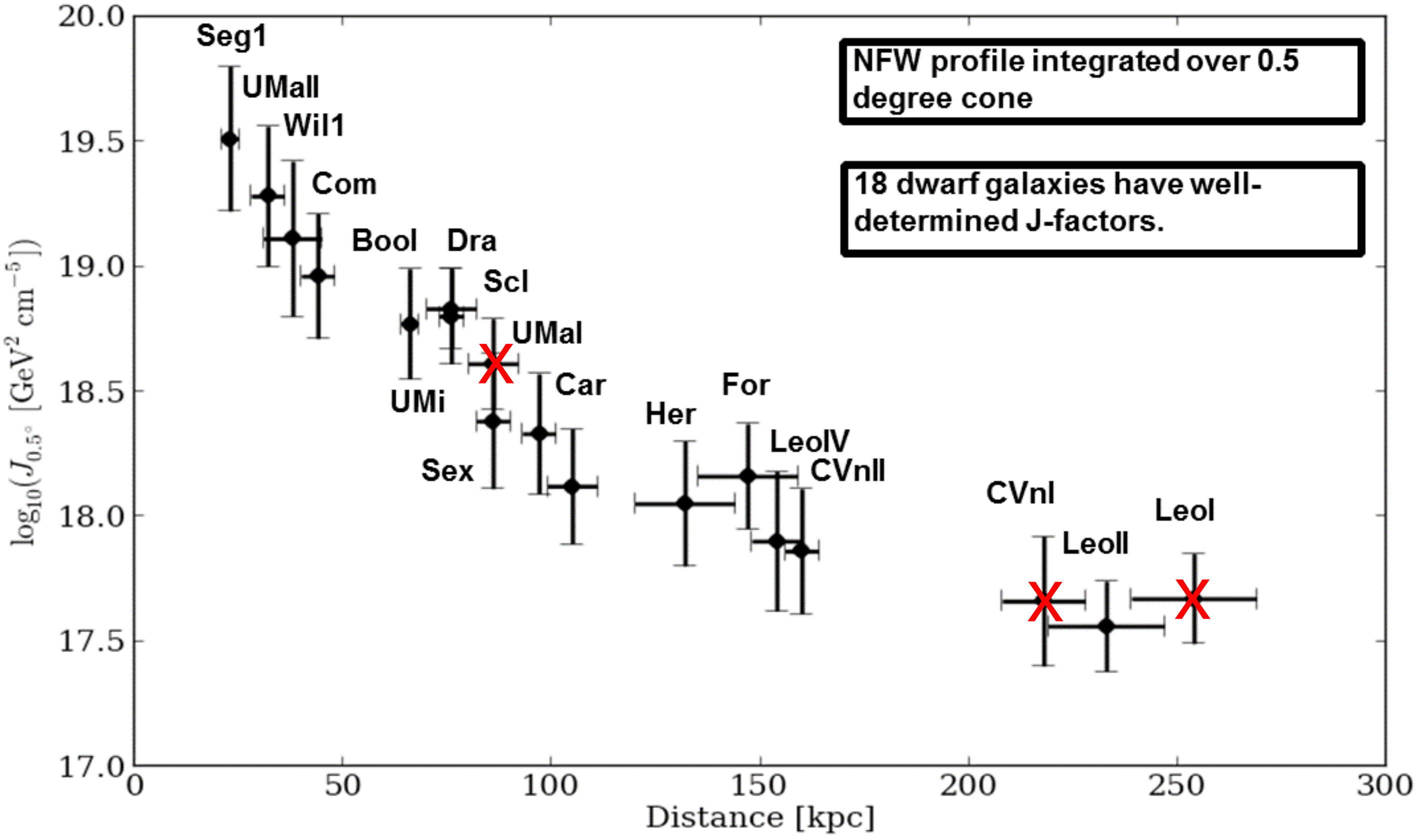
Energy Range: 10 GeV -2 TeV
Duration: 7 years
Pass 8 data, Source-class
Unbinned likelihood using PSF types
Zenith angle < 105˚
Minimum 4 photons/source

Median point source localization accuracy: 2.3 arcmin radius (95%)
48 spatially extended sources

Galactic Plane Sources in 3FHL



J-factors for 18 dSph Galaxies



- **15 dwarfs selected for composite analysis (UMaI, CVnI and LeoI excluded due to ROI overlap)**

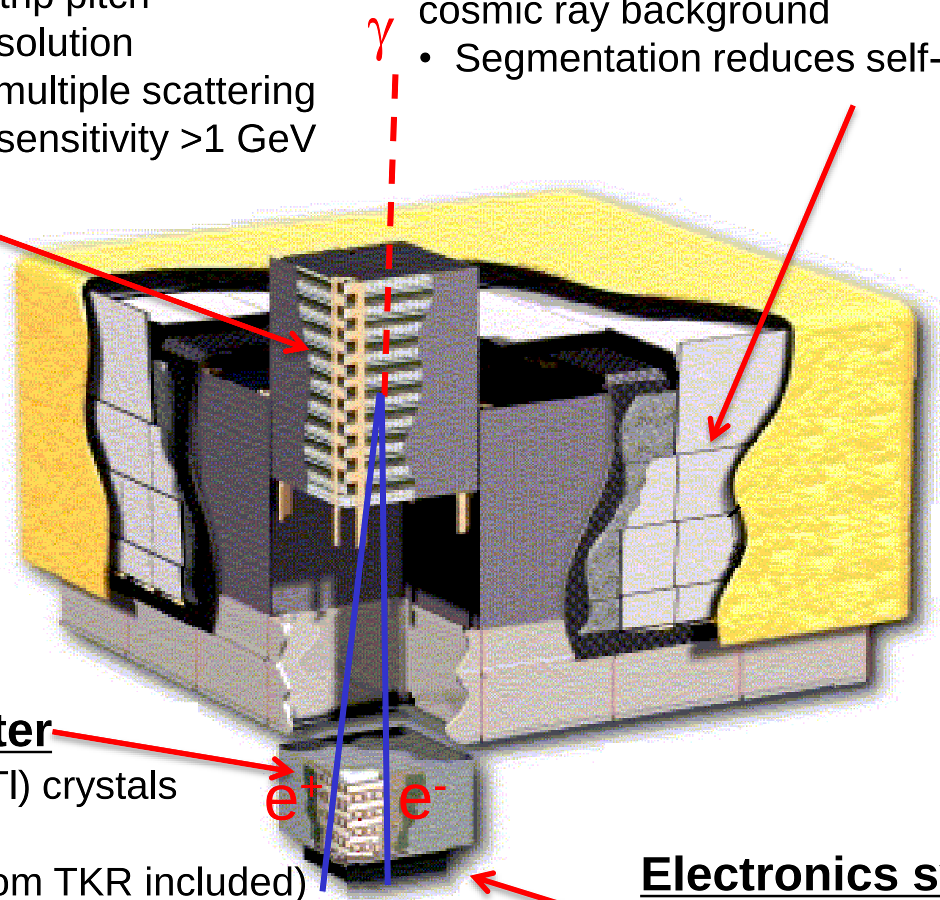
The Fermi LAT

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



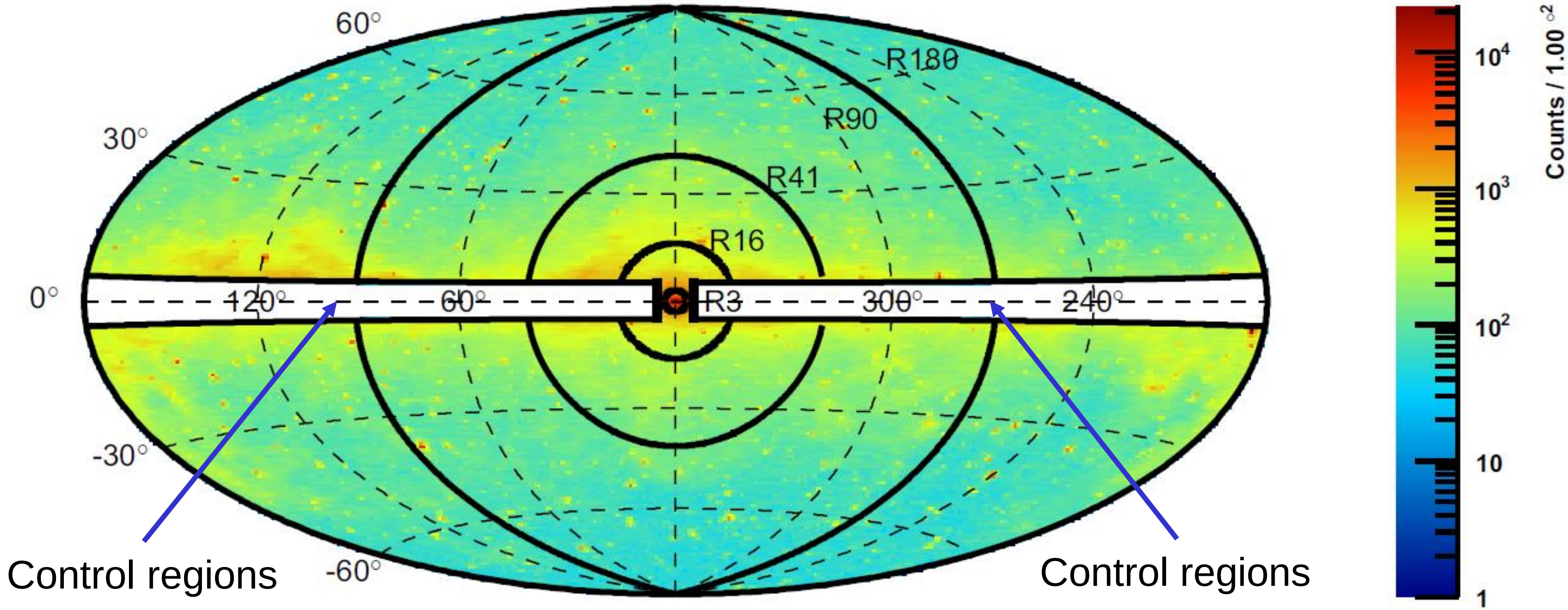
Hodoscopic CsI Calorimeter

- 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

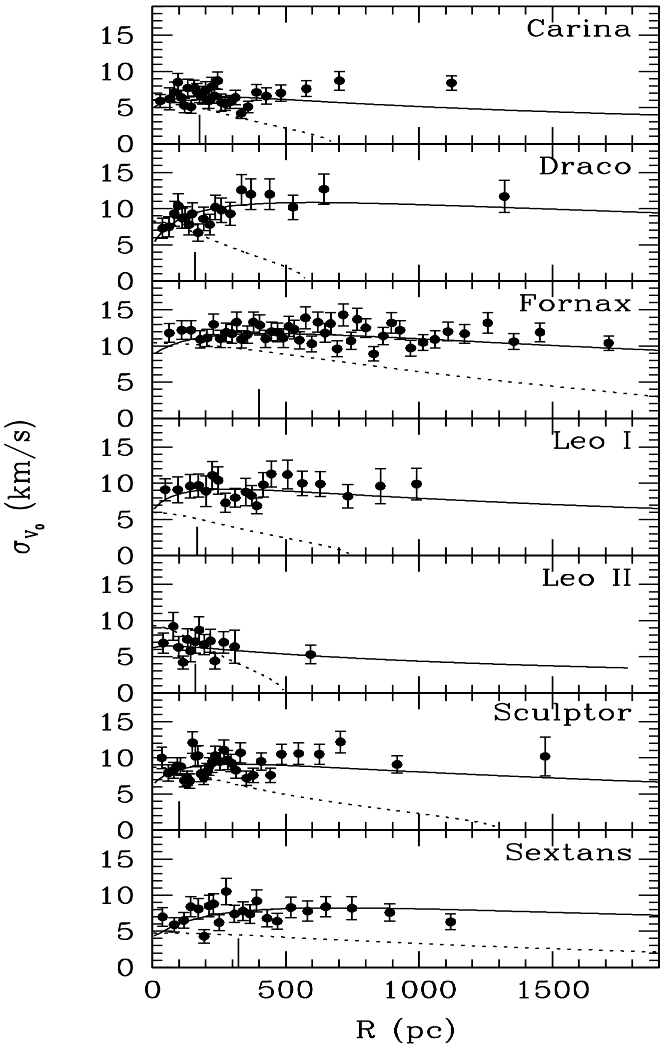
Choice of the ROI



- 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

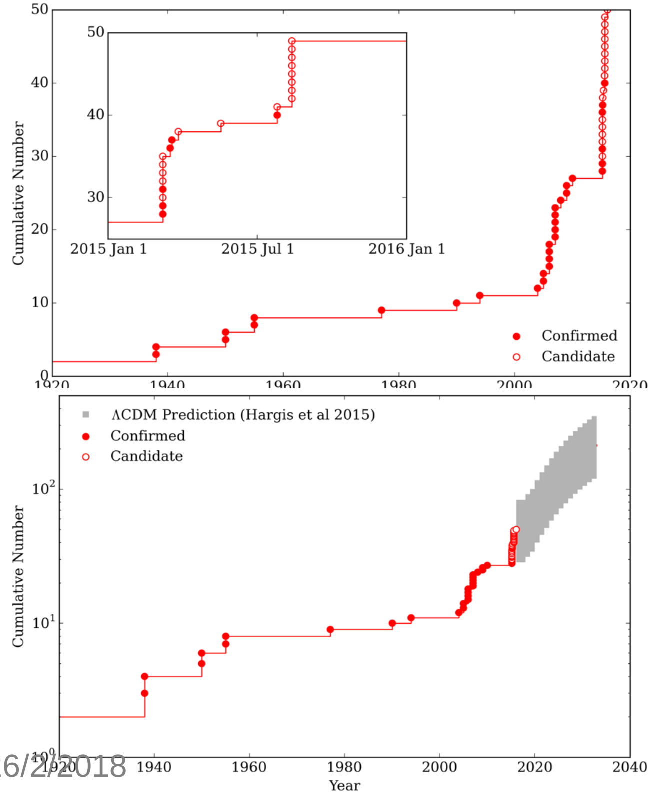
DM content of dSph Galaxies

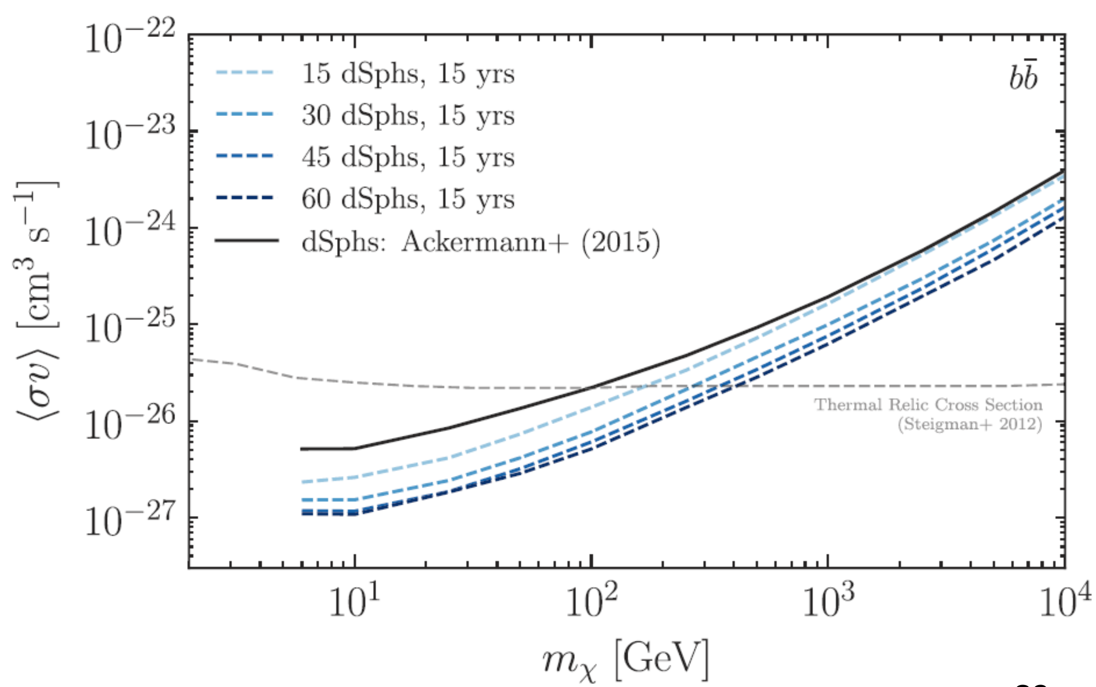
- **Gamma-ray signal from each dwarf is proportional to its J-factor:**
  - $J = \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{l.o.s.} \rho^2(r(l,\phi'))dl(r,\phi')$
- **J-factors are determined spectroscopically from stellar velocity dispersions:**
  - **Classical dwarfs: spectra for several thousand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



DM searches in dSph Galaxies: future perspectives

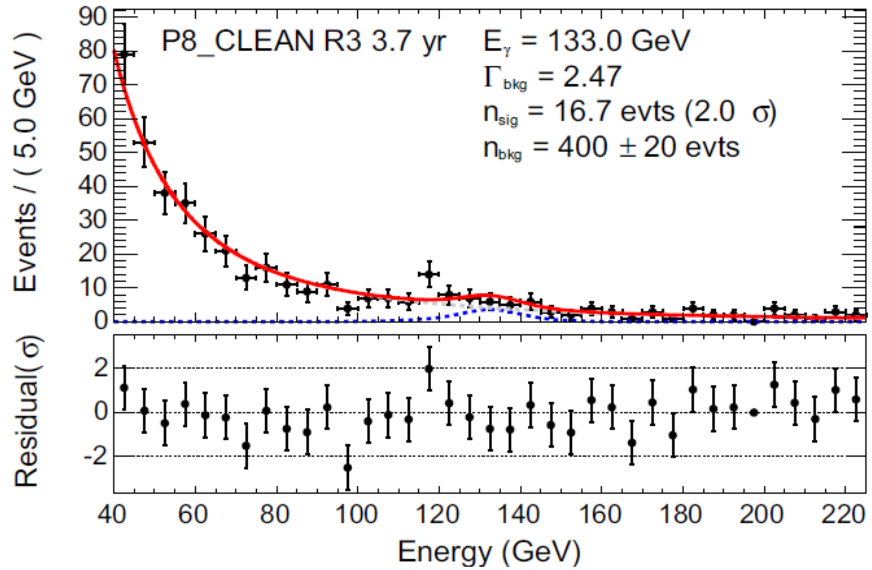
- dSph Galaxies are among the most promising target for future DM searches
  - Discovery of new dSph Galaxies
    - ~20 new targets from the dark energy survey (DES)
      - Waiting on spectroscopic follow-up for J-factors
    - Even more with the upcoming LSST survey
  - Increased statistics
- Can reach thermal relic cross section up to DM masses >100 GeV
  - For further details see Phys. Rep. 636 (2016), 1-46

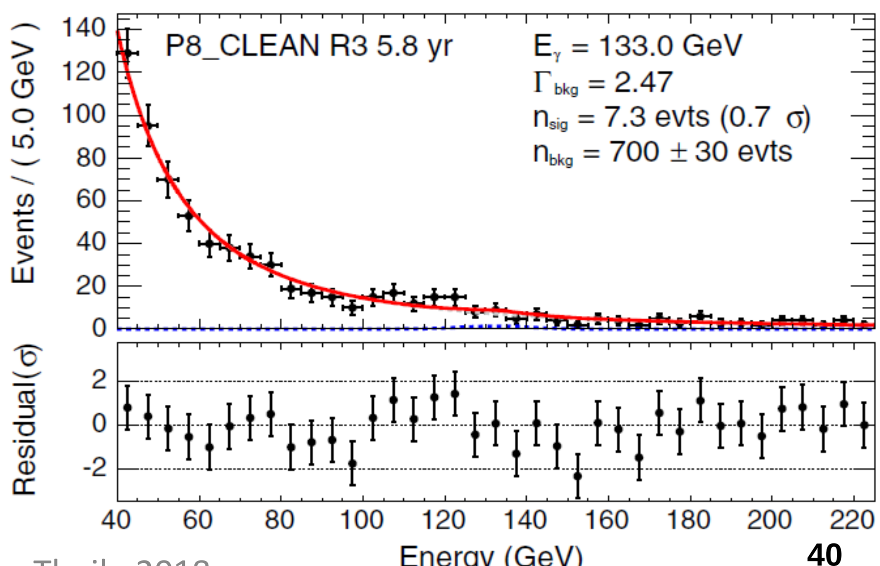




The line feature at 133 GeV

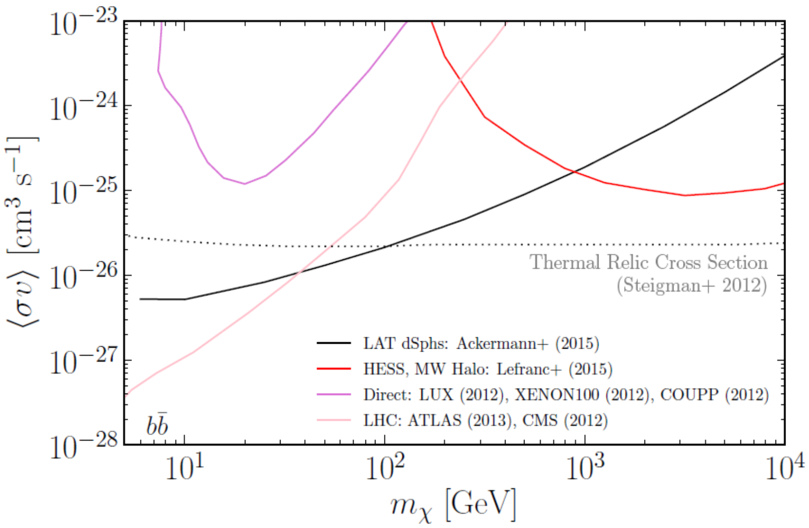
- A potential signal was reported in the 3.7yrs data sample for a small ROI containing the GC
  - Bringmann+, JCAP 07 (2012), 054
  - Weniger+, JCAP 08 (2012), 007
- The LAT detected the feature, although with low global significance
- Newest LAT data analysis:
  - Increased data set (5.8 yrs)
  - Use 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



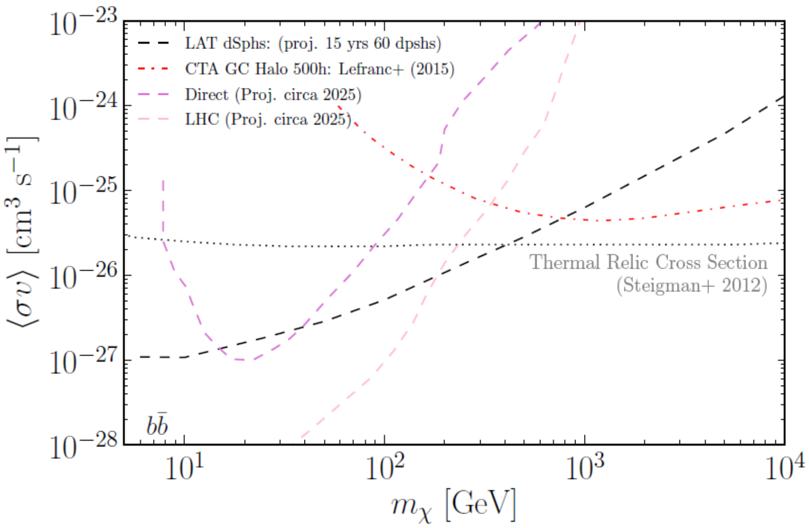


Comparison of indirect-detection, direct-detection and collider-production limits

current



projected



require assumptions about the particle interaction

Charles, E +2016 PhR 636, 1