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EXPLORING THE UNIVERSE WITH GAMMA RAYS

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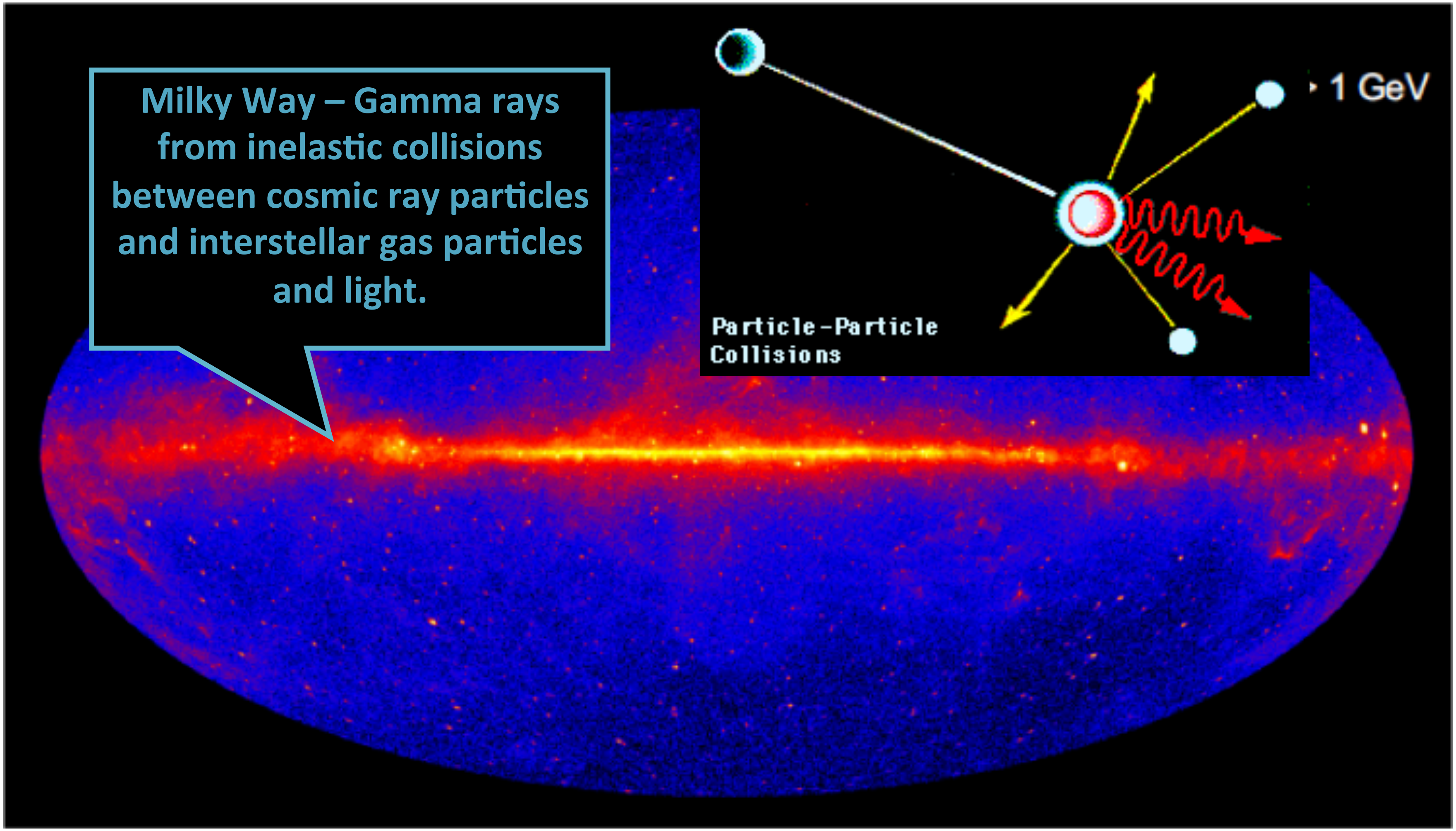
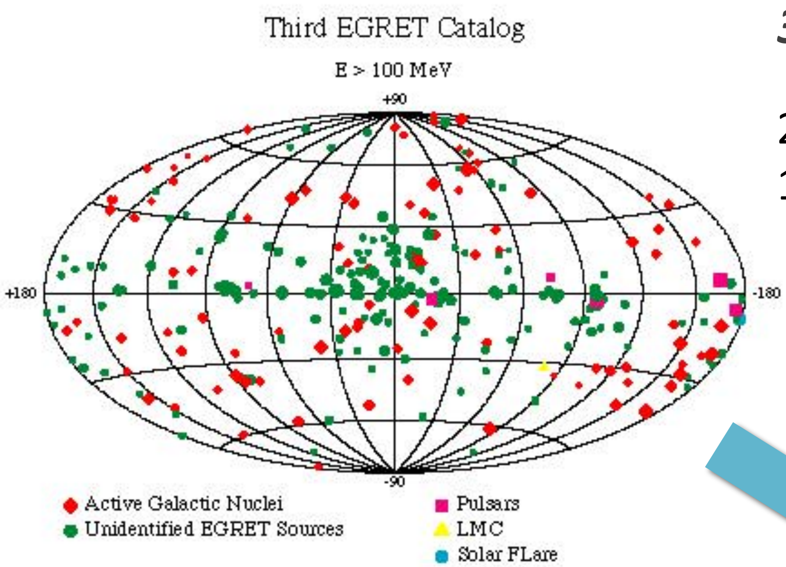
The Gamma-ray Sky

Gamma-ray emission dominantly comes from gas and point-like sources in the Milky Way and other galaxies

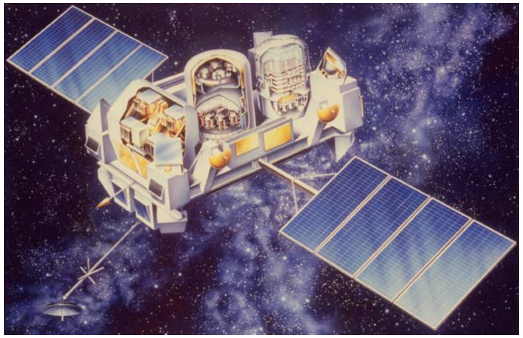


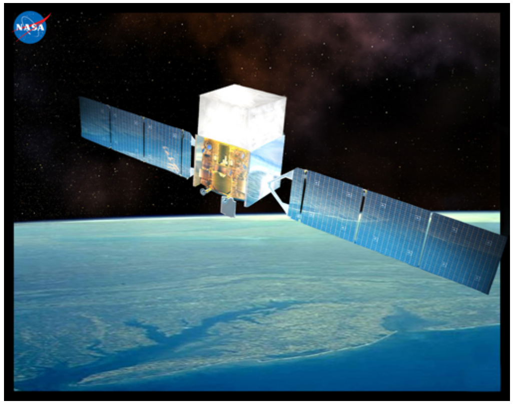
More sensitive instruments – more sources

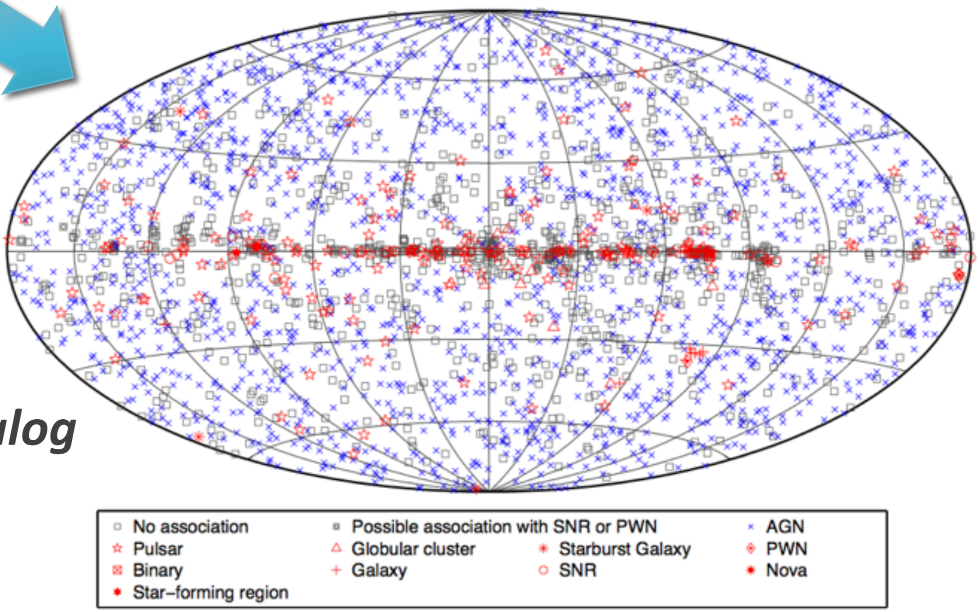


3rd EGRET Catalog

271 sources (170 unID)
1991-1995





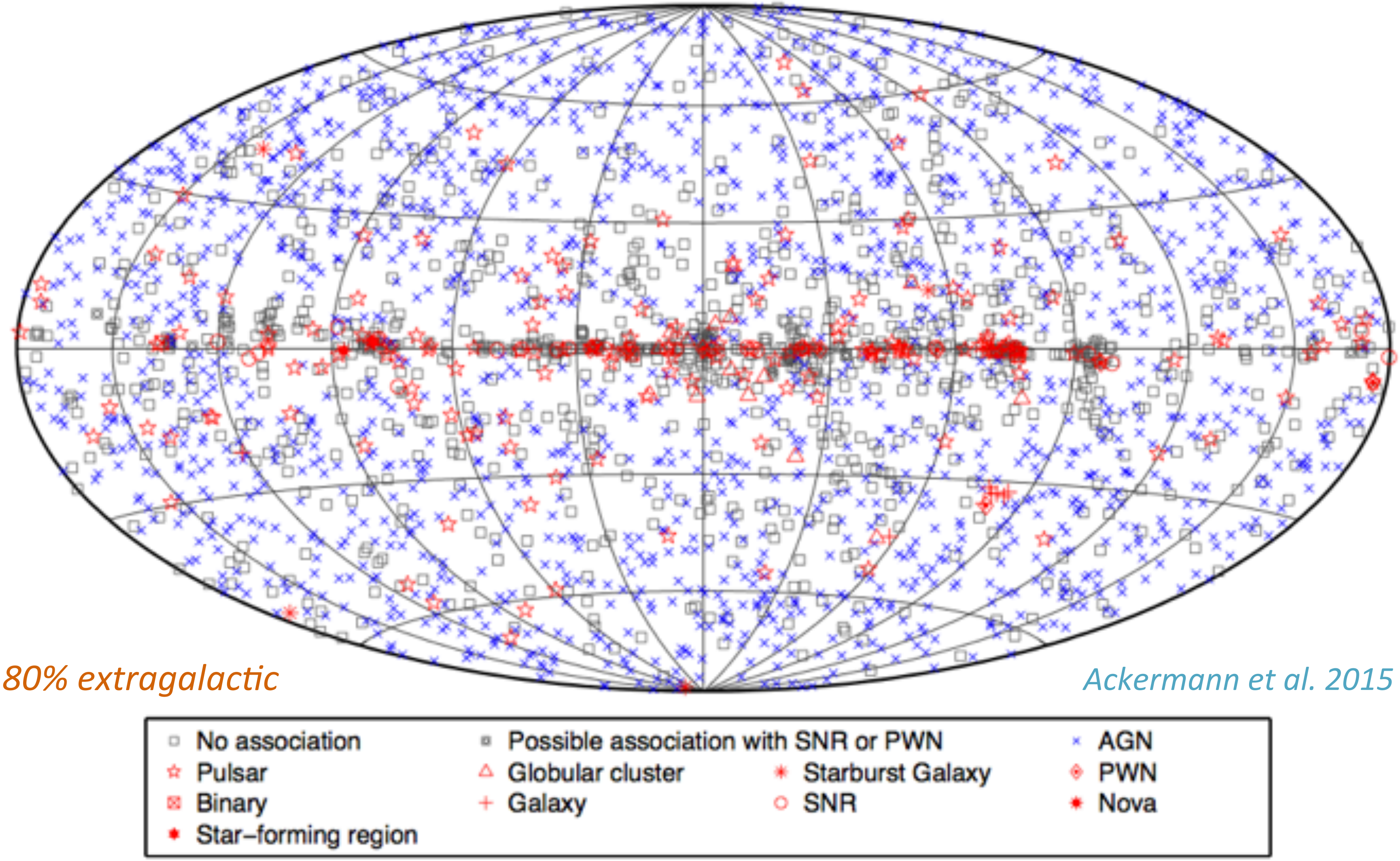


3rd Fermi Catalog

3033 sources
2008-2012

Point-like sources

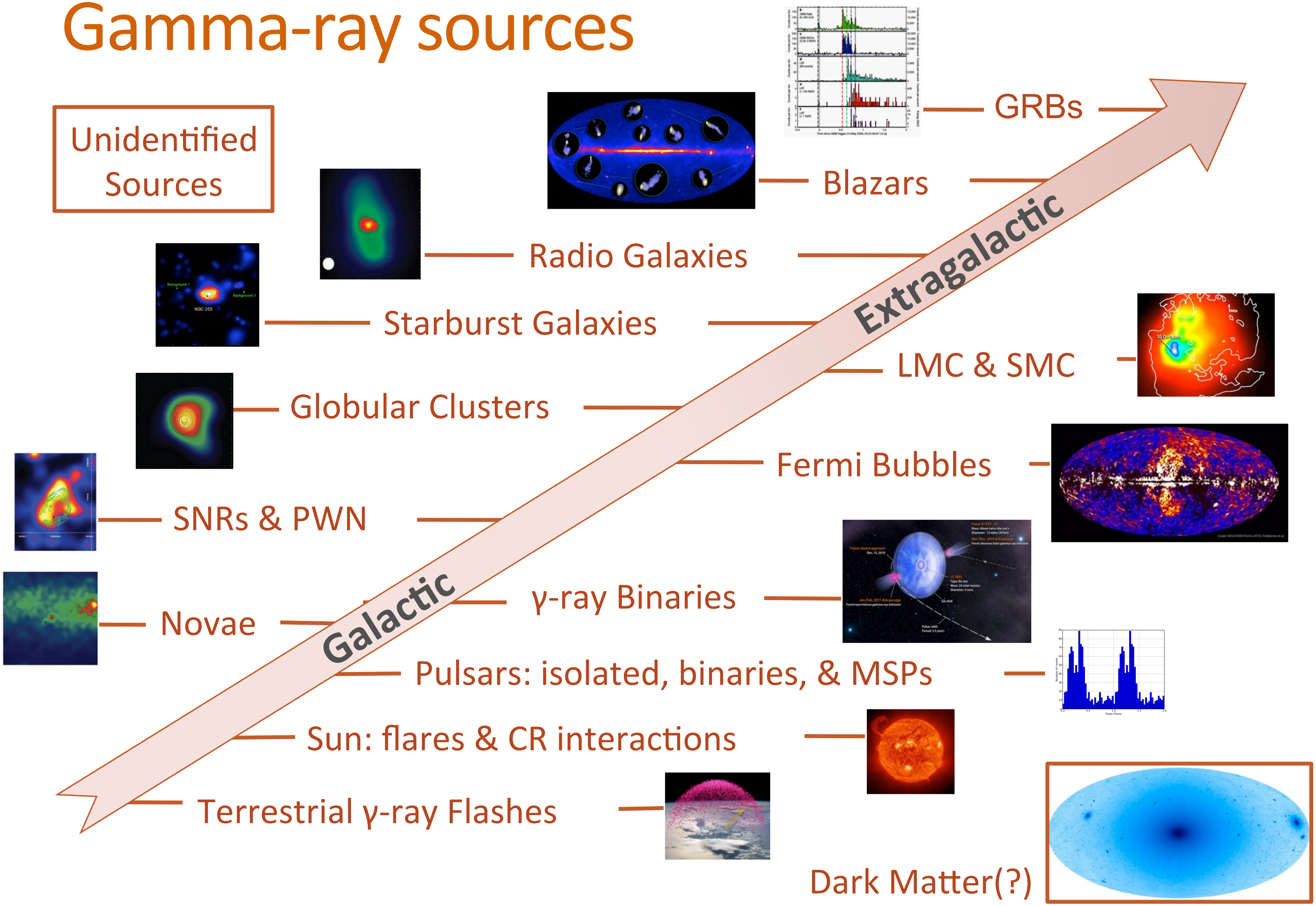
Fermi Large Area Telescope 3rd Source Catalog: 3033 sources (4 yr)



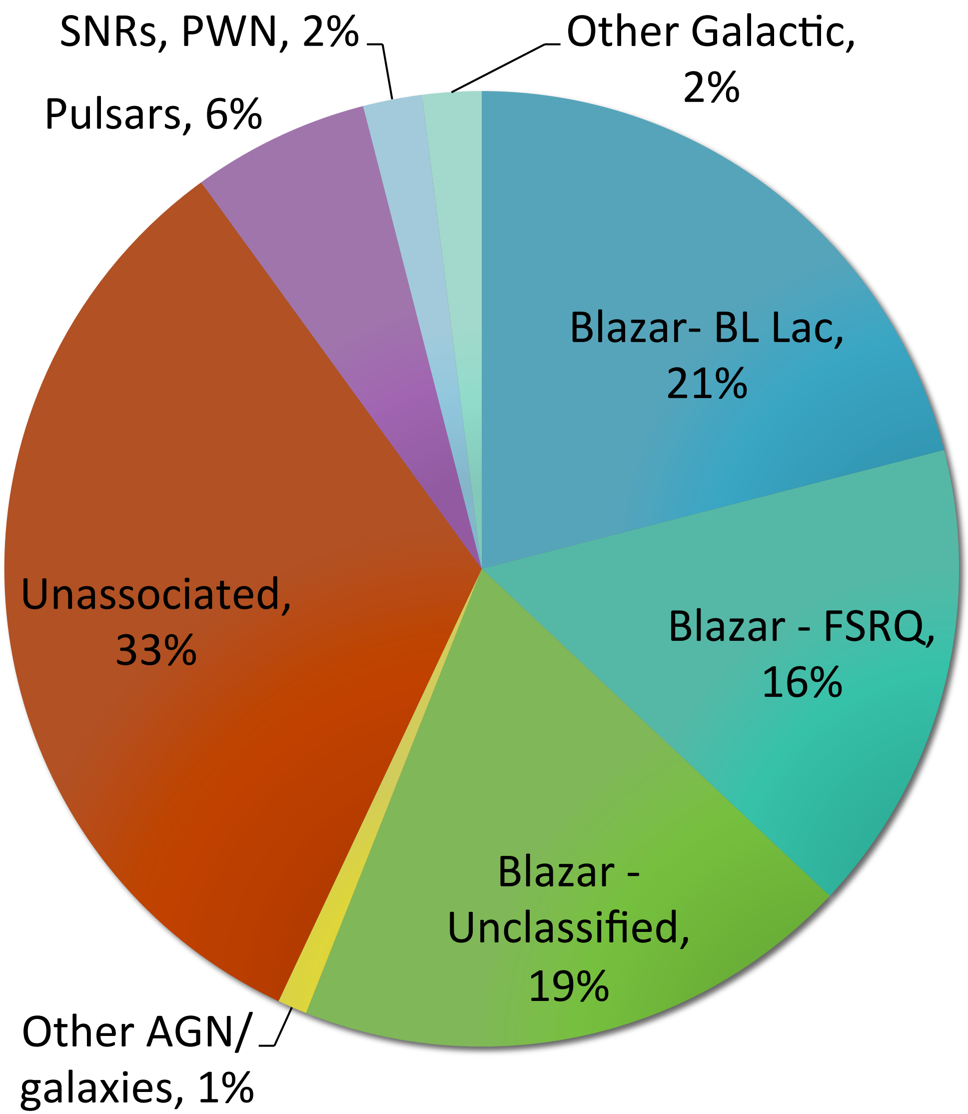
80% extragalactic

Ackermann et al. 2015

Gamma-ray sources

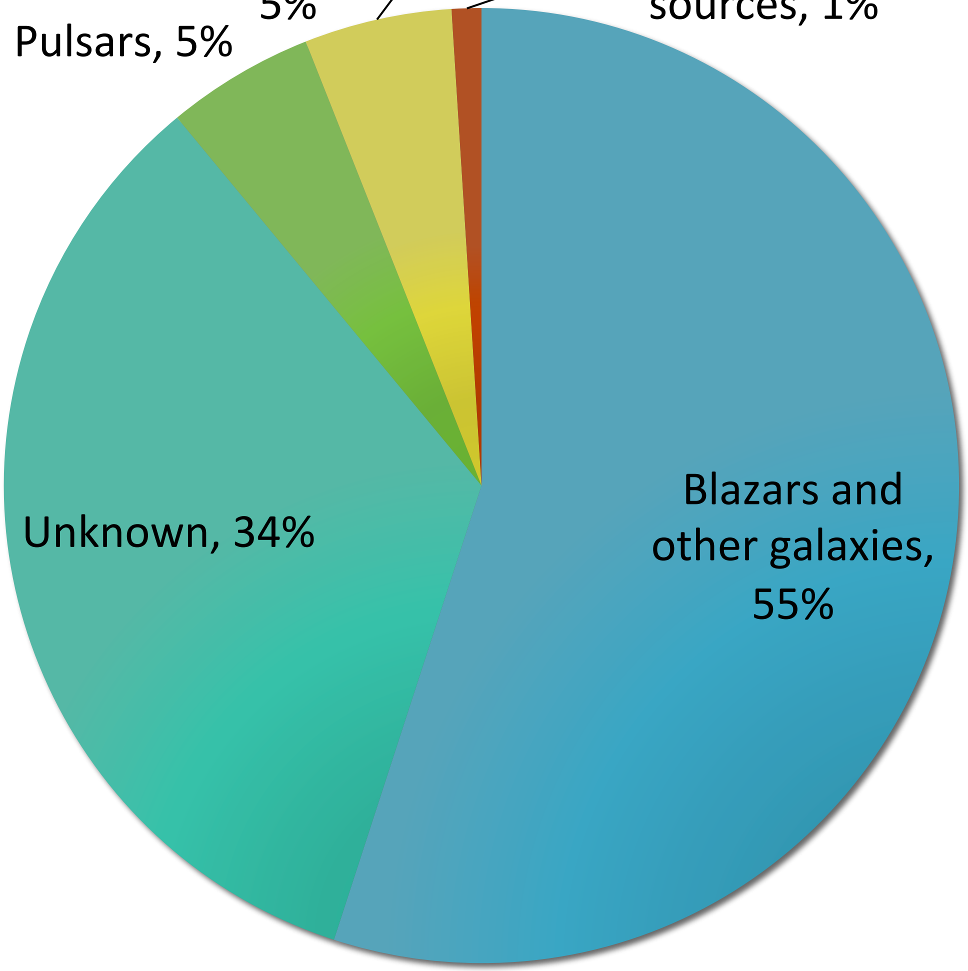


Break-down of source classes: Fermi-3FGL



4 years
3033 sources
>100 MeV

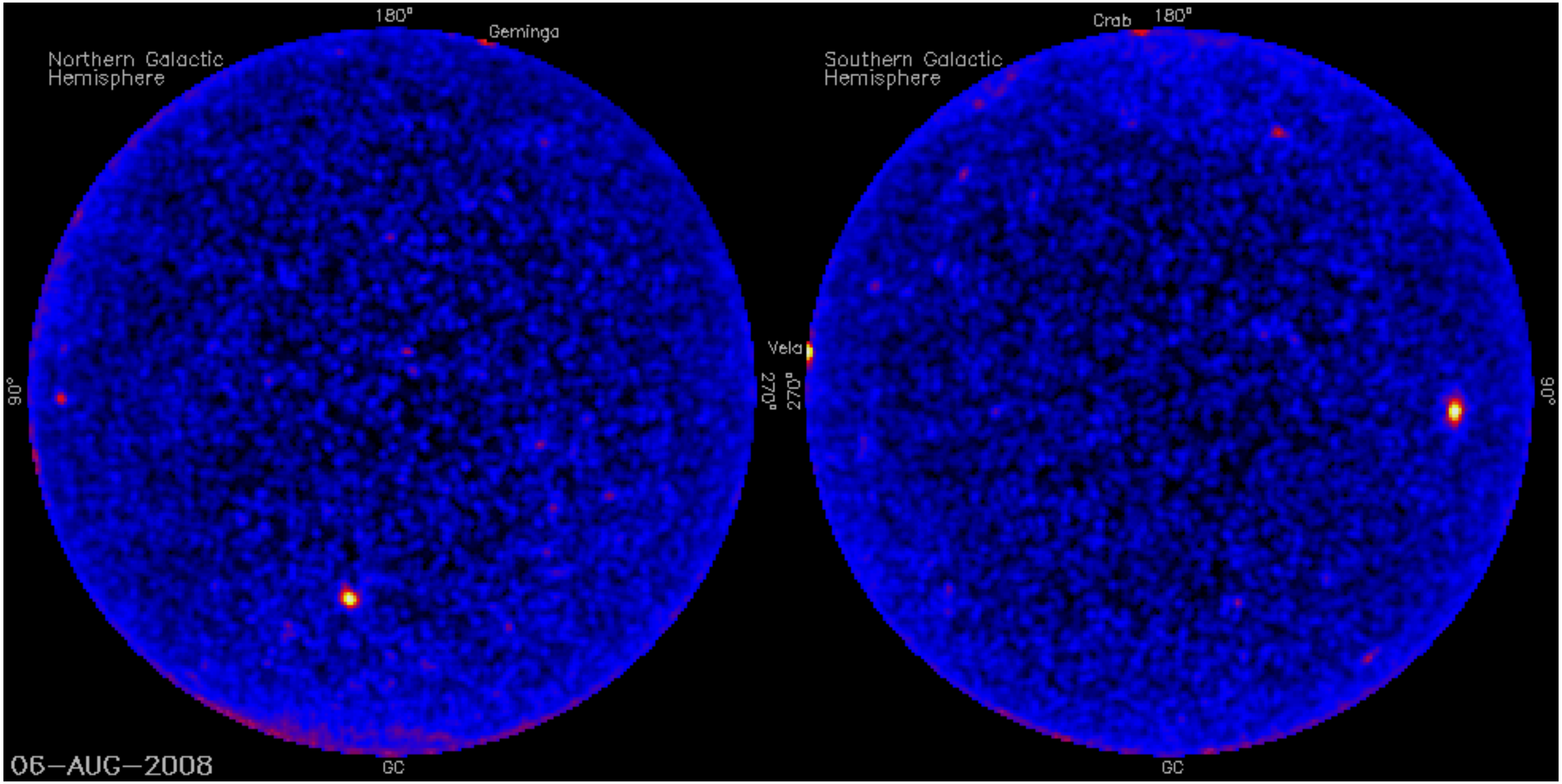
Break down of source classes: Fermi-3FHL



7 years
1556 sources
>10 GeV

Transient sky

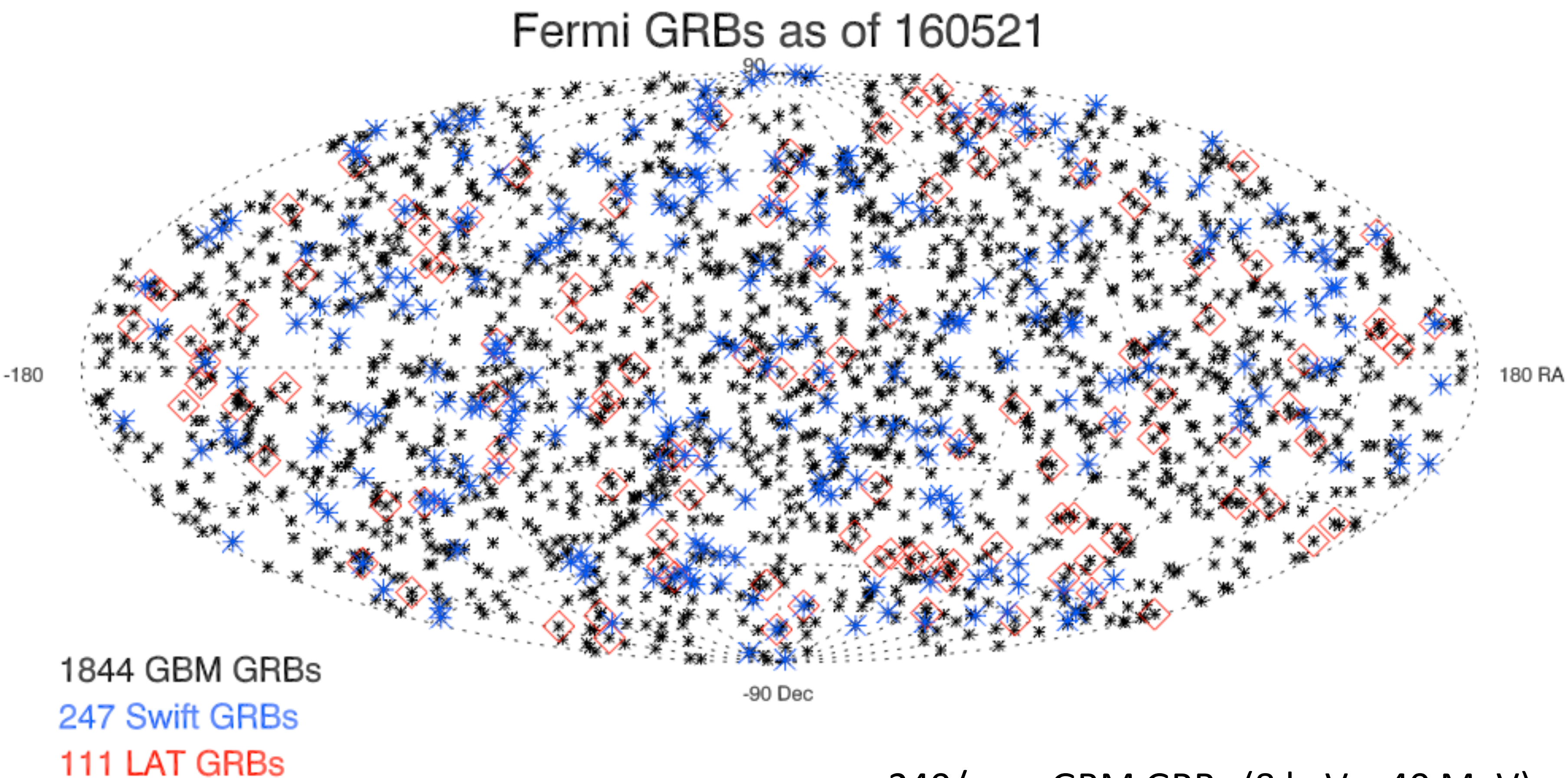
Various sources start and stop gamma ray emission at various time scales



Fermi-LAT

Gamma-Ray Bursts – most powerful transient

Detected by Fermi- Gamma-ray Burst Monitor (GBM) and LAT

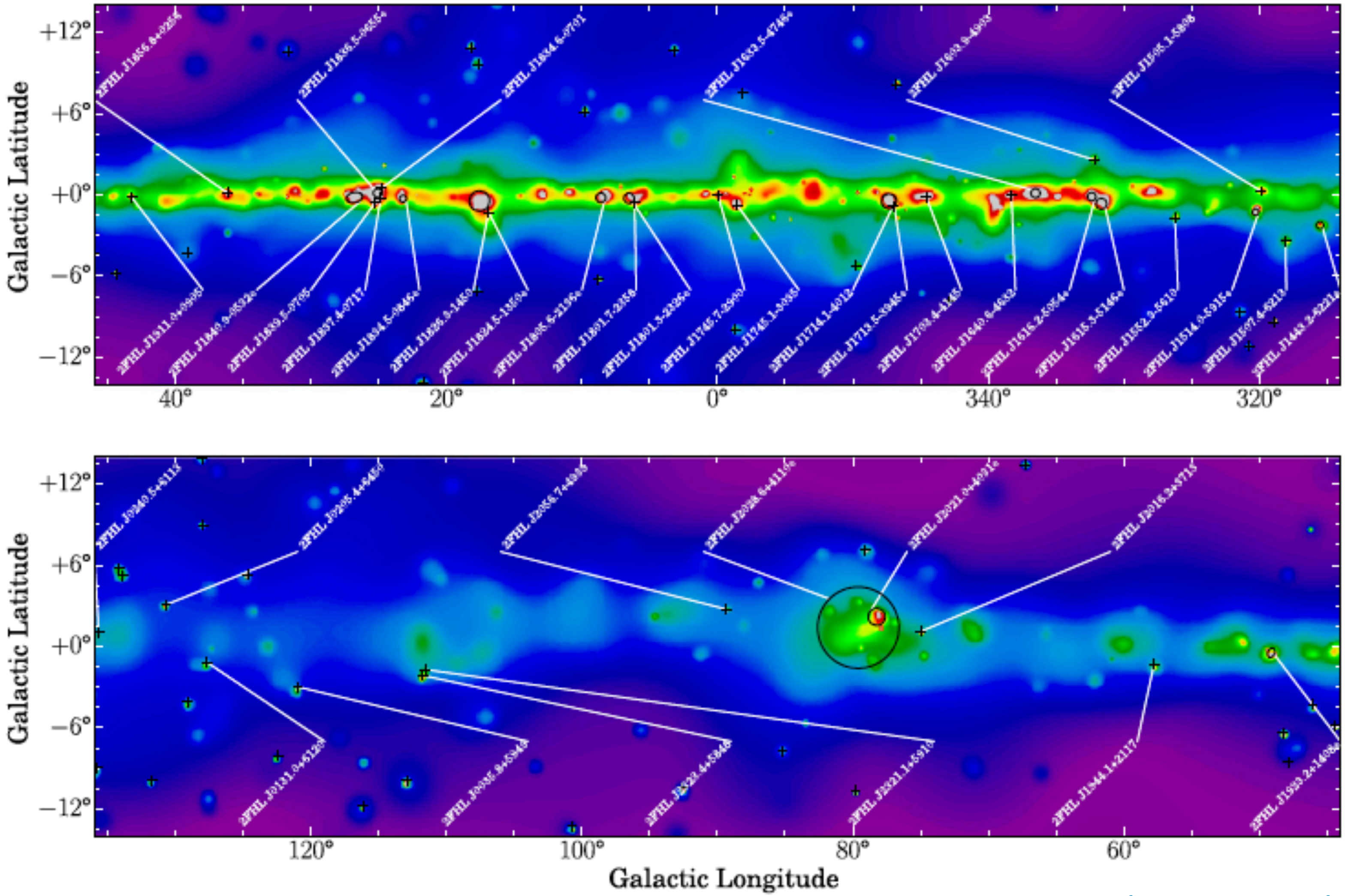


≈ 240/year GBM GRBs (8 keV – 40 MeV)

≈ 15/year LAT GRBs (>100 MeV)

Fermi Galactic plane survey– 2FHL

Sources with energy >50 GeV



Ackermann et al. 2016

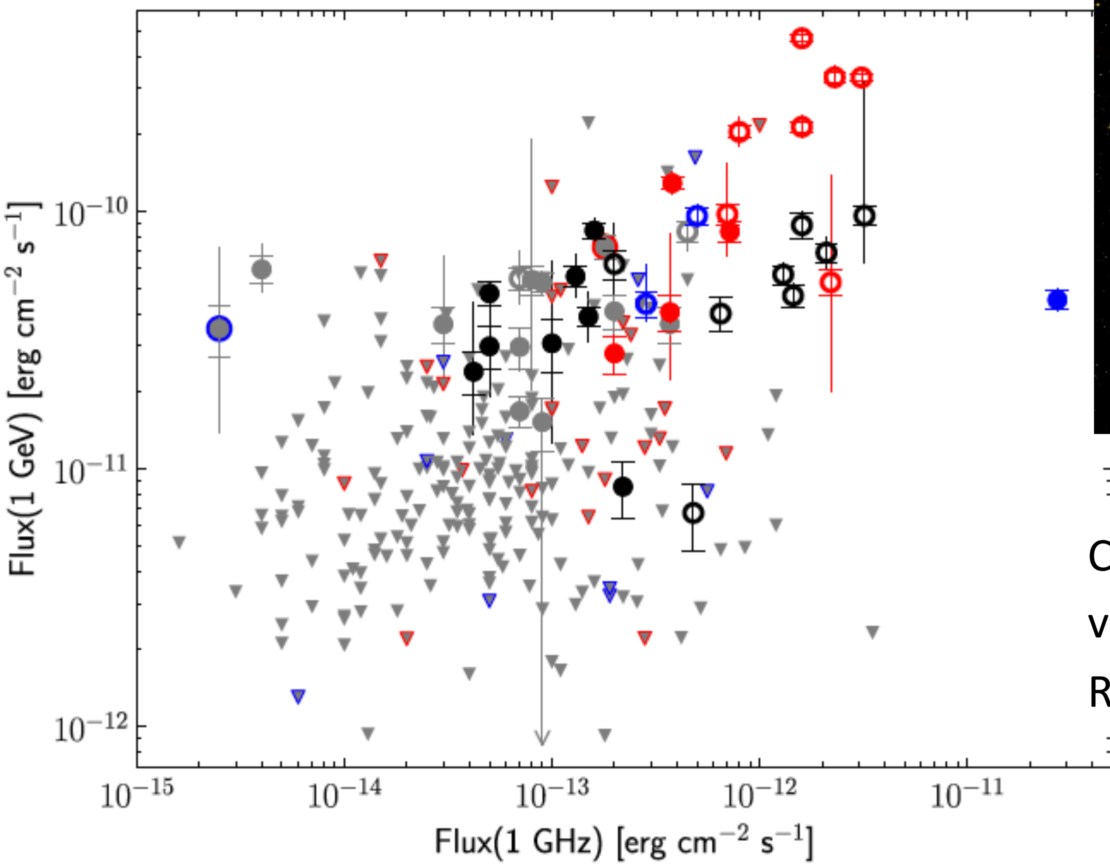
Galactic sources - Supernova Remnants

Fermi 1st SNR Catalog (1-100 GeV)

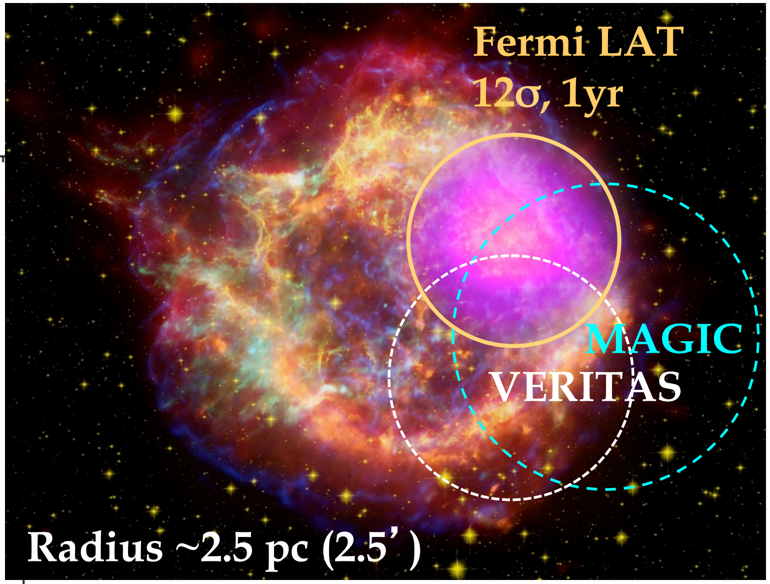
30 confirmed association

14 marginal association

245 Flux upper limits



SN 1680 (Cassiopeia A)



Can be extended or point-like sources

various ages

Radio – gamma correlation

Acero et al. 2016

Galactic sources - Pulsars

117 High-confidence pulsars at >100 MeV

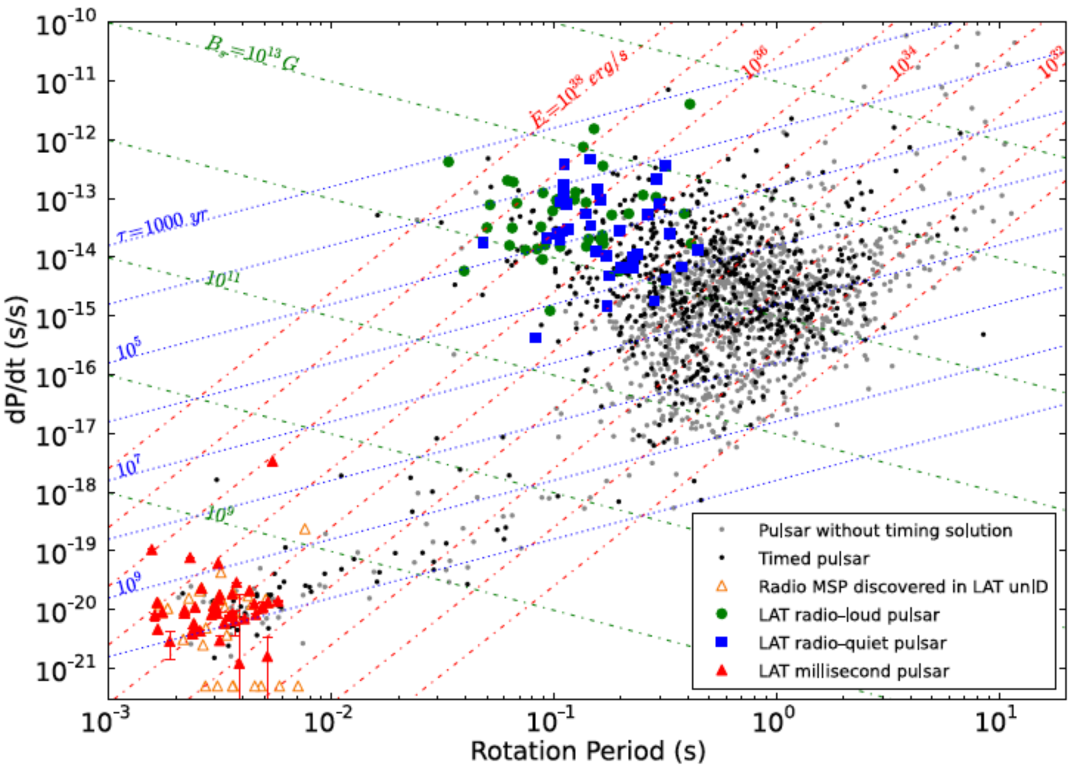
Millisecond pulsars

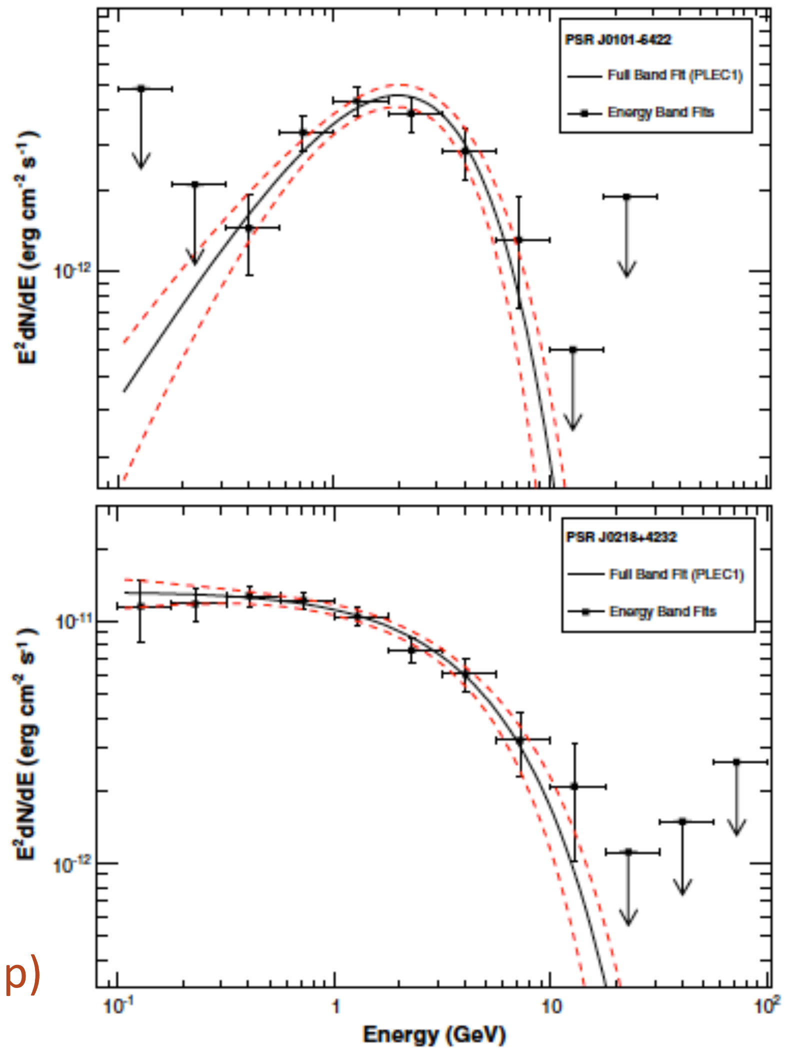
Young radio-loud pulsars

Young radio-quiet pulsars

Fermi 2nd pulsar catalog
3 year data

Abdo et al. 2013





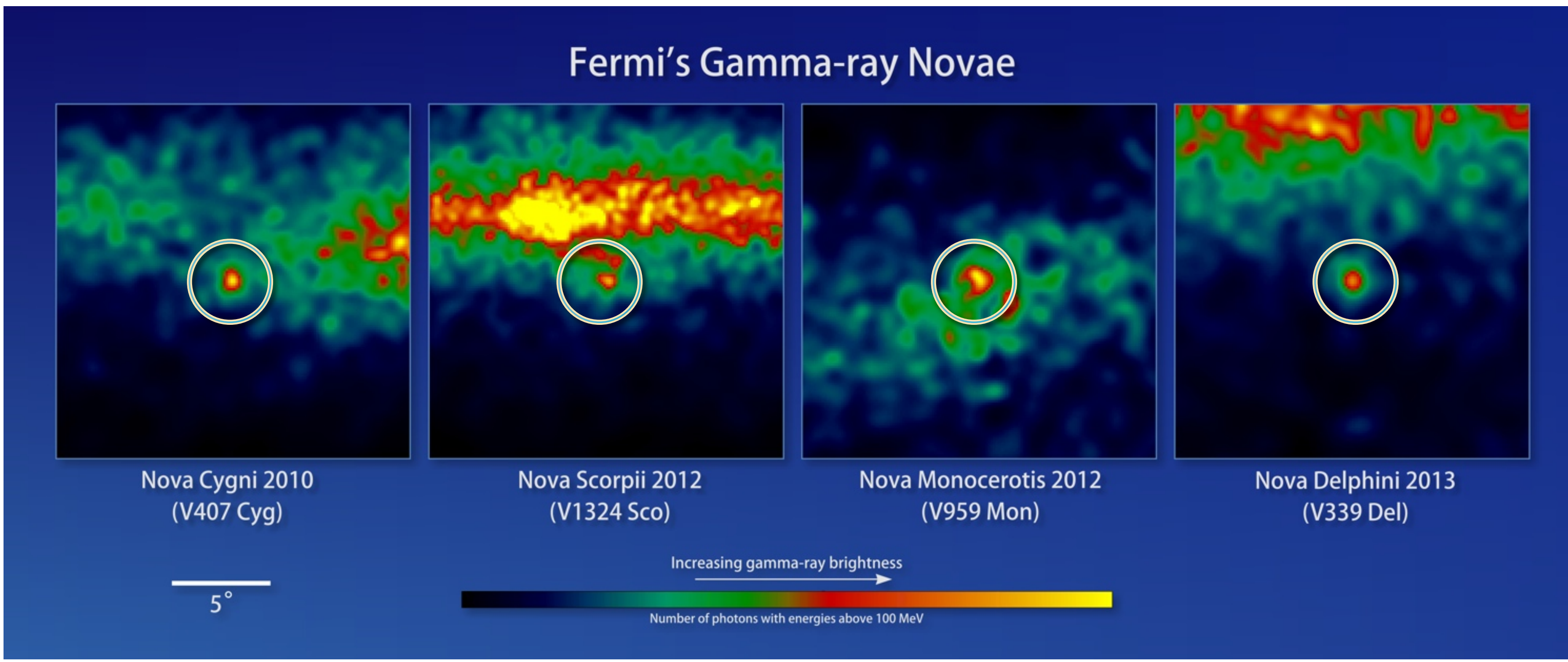
Modeling effort – emission region (inner/outer/slot gap)

Galactic sources - Novae

Not expected but detected anyway

Thermonuclear explosions on White Dwarf stars accreting material from a companion star

Gamma-ray emission coincides with optical light curve and lasts for ~1-2 weeks time scale

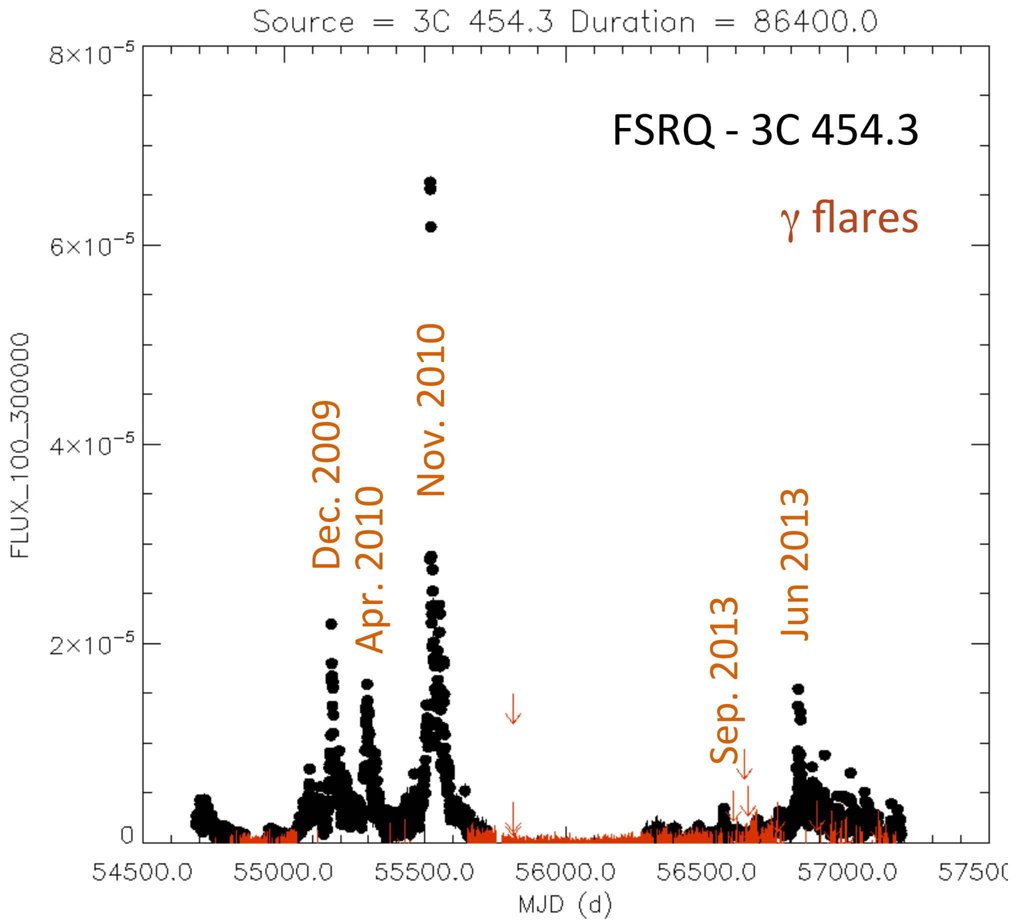


Ackermann et al. 2015

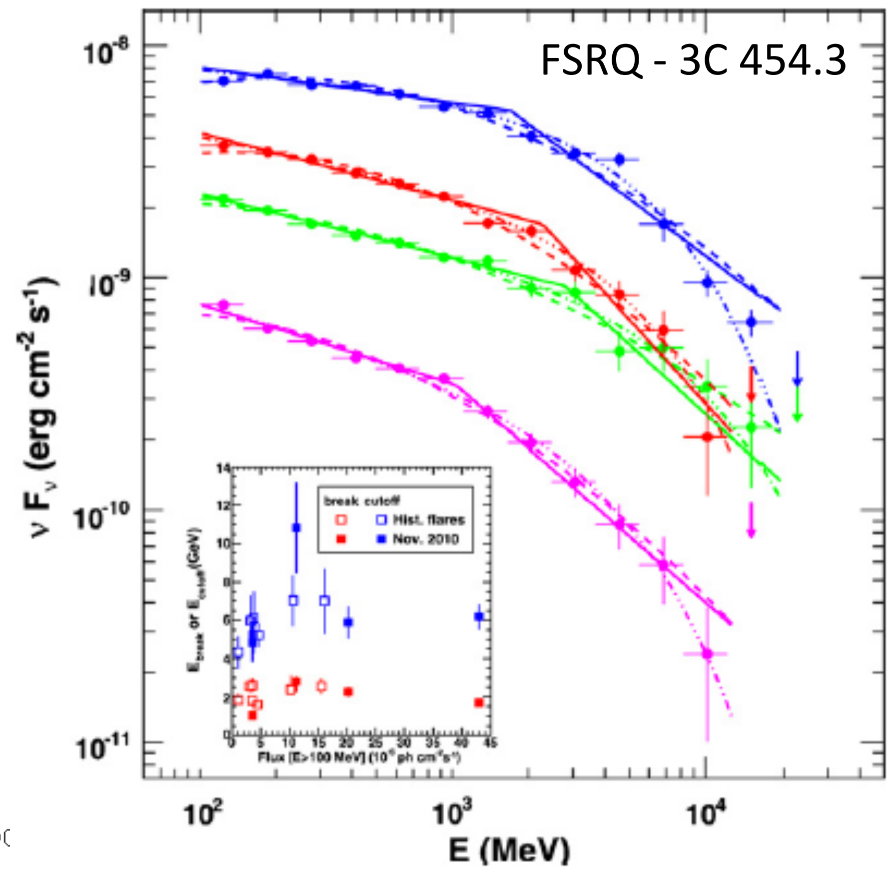
Extra-Galactic sources: Active Galactic Nuclei

Sporadic multiwavelength outbursts from known galaxies

Sub-class: Blazars – BL lac objects and Flat Spectrum Radio Quasars (FSRQ)



Spectral variation with time



Abdo et al. 2011

Extra-Galactic sources: Gamma-Ray Bursts

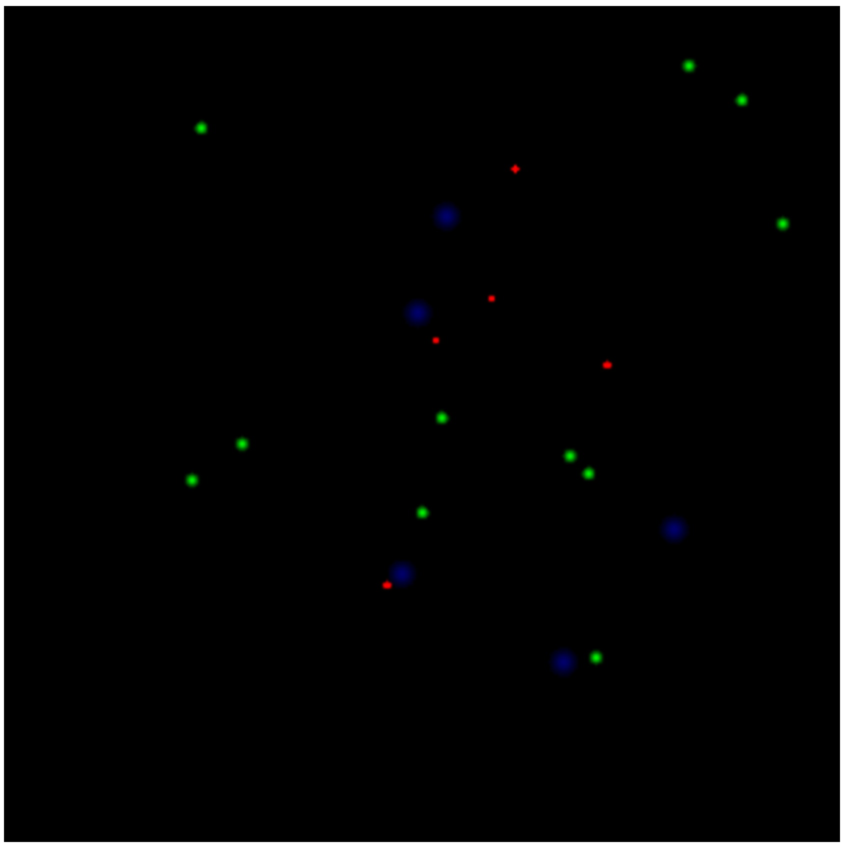
Most powerful electro-magnetic explosions in the universe

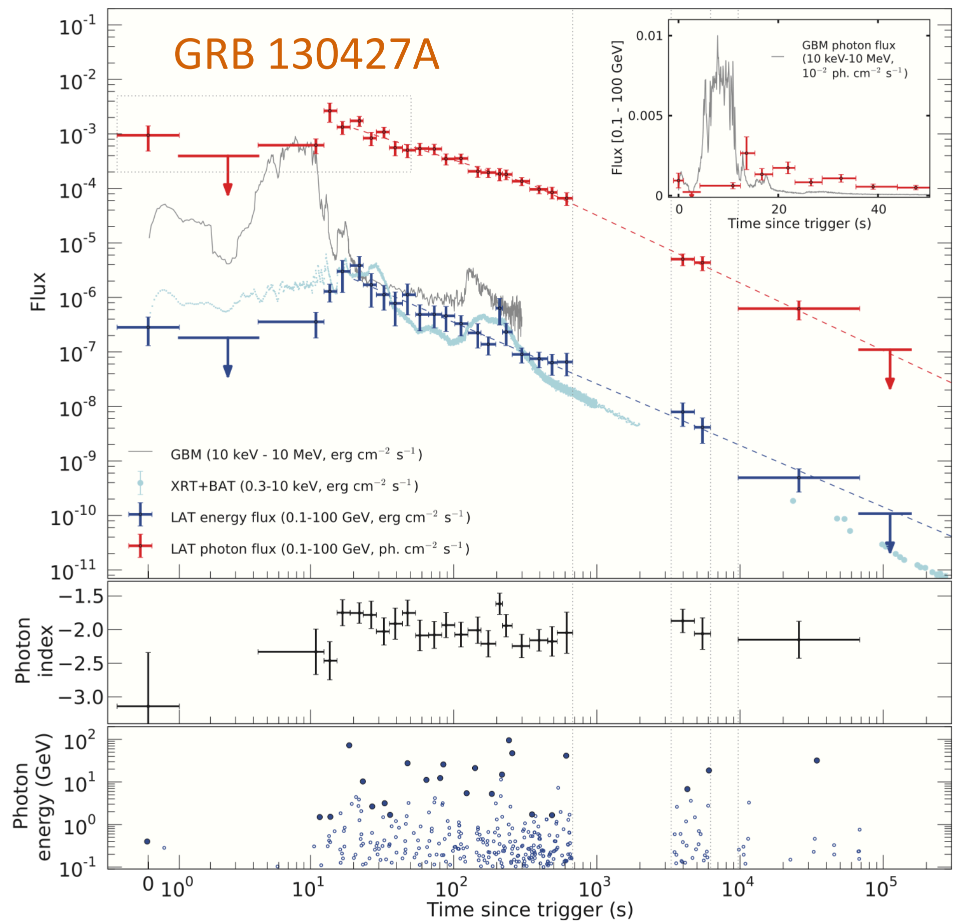
Detected at redshift up to 9!

<2 s, short GRB, >2 s, long GRB

Multi-wavelength non-thermal emission over 7 decades in energy

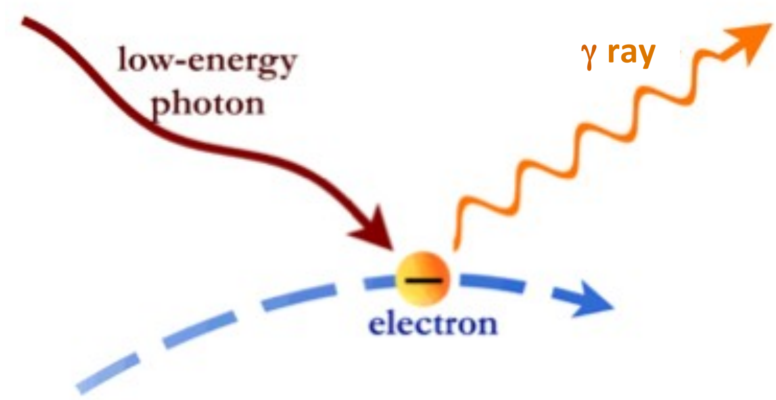
Prompt and afterglow phases





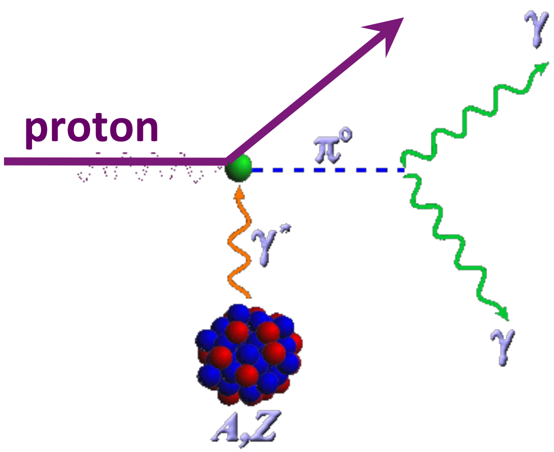
Few Big Questions in Gamma-ray Astronomy

Gamma-ray emission processes: Which one?



Leptonic Model

Inverse Compton scattering



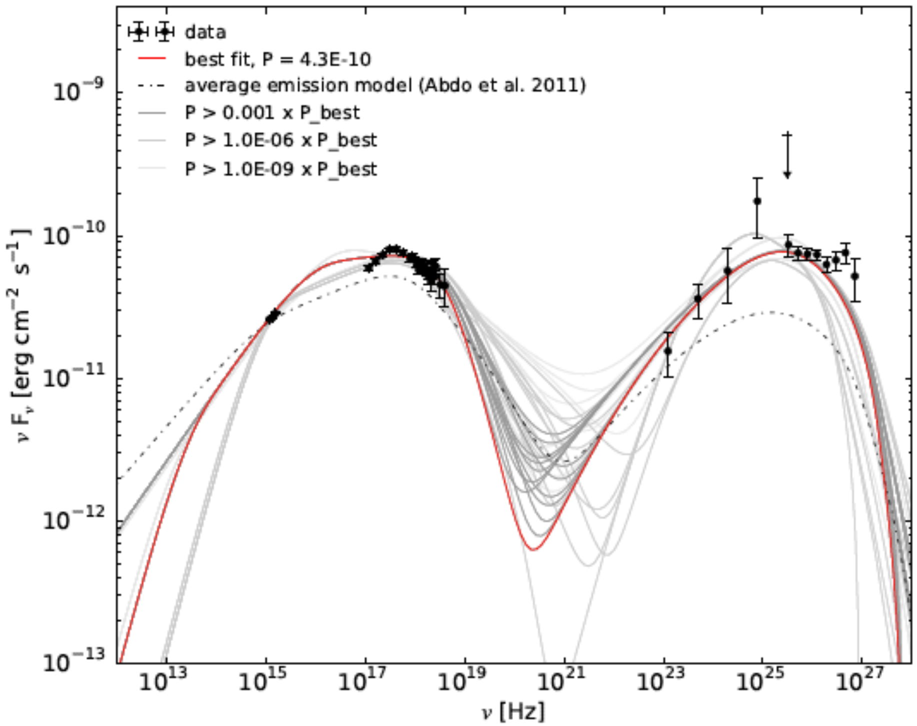
Hadronic Model

Nuclear interactions

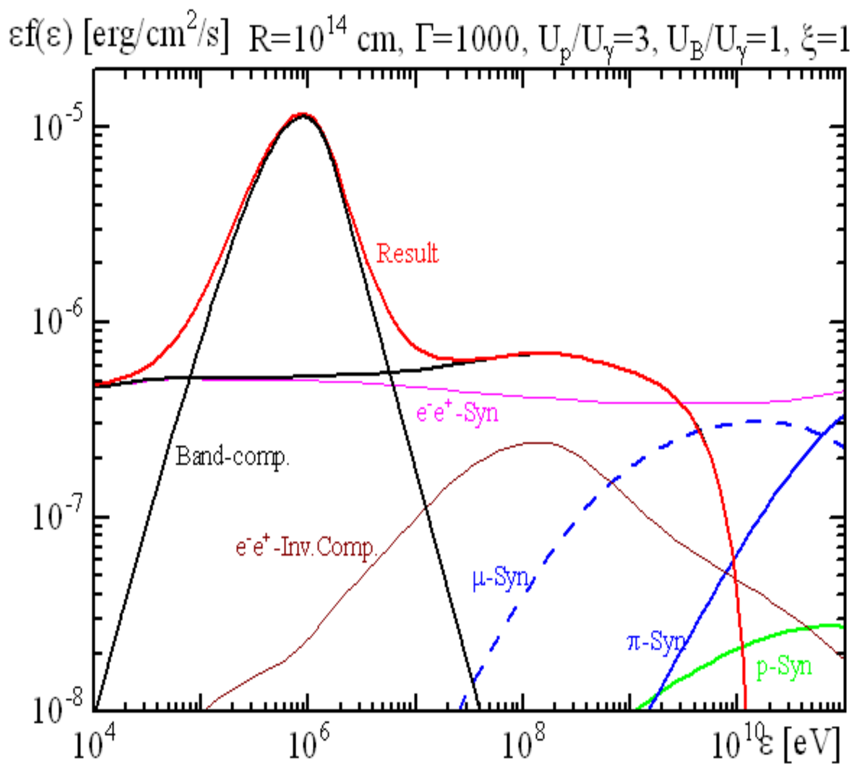
Which mechanism works in which source? How to distinguish?

Emission process is ambiguous in most cases

Synchrotron self-Compton model for blazar Mrk 501



Hadronic (pγ and secondary cascade) model for GRB 090902B



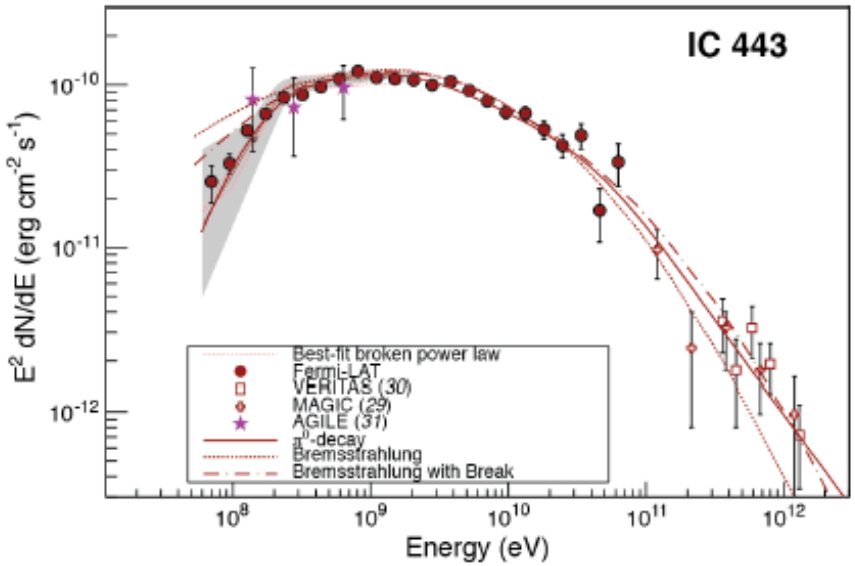
Fits are poor to constrain model
Large uncertainties on parameters

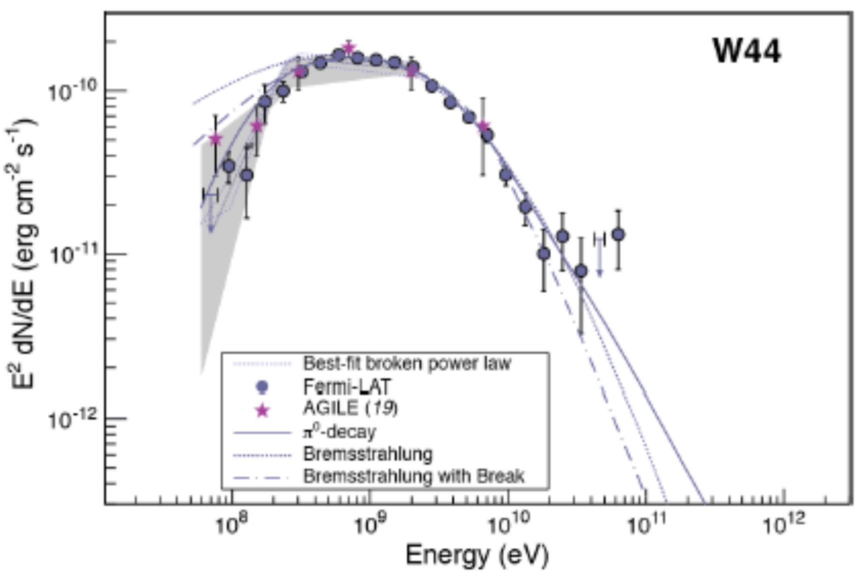
Total energy needs to be ~100-1000 times larger than observed in γ

Ahnen et al. 2017

Asano et al. 2009

Where are cosmic-ray accelerators?





Supernova remnants are well-motivated sources of cosmic rays (up to ~ PeV)

Old SNRs (~10,000 yr) are often found interacting with nearby molecular clouds

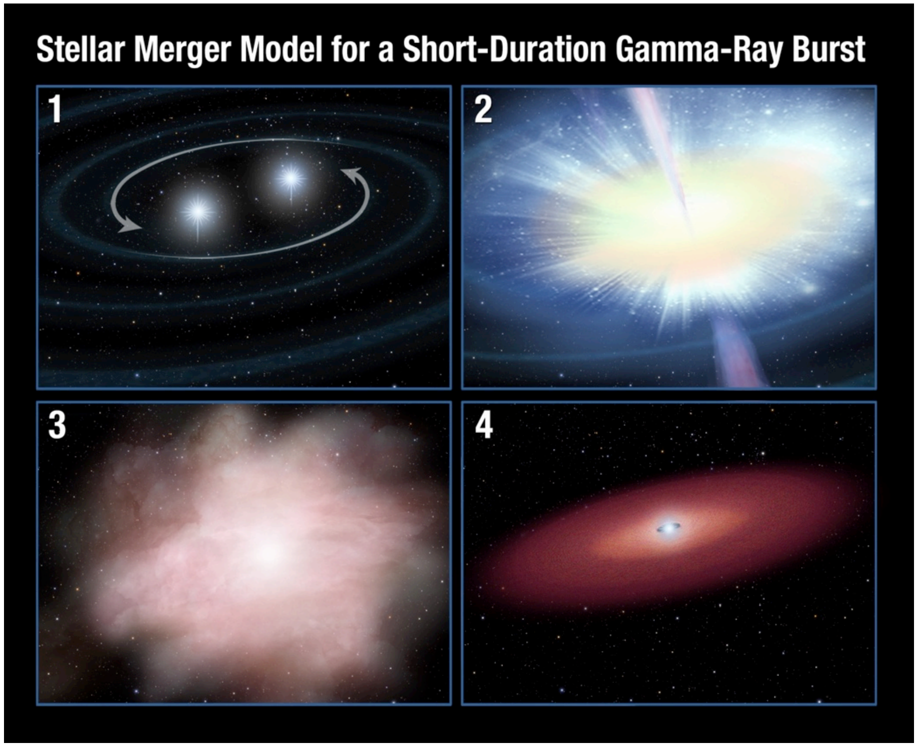
Cosmic-ray protons, escaping from the SNRs interact (pp) with gas in molecular cloud

π^0 decay gamma rays have a characteristic turnover at ≤ 100-200 MeV

Signature of hadronic emission, Cosmic Ray acceleration

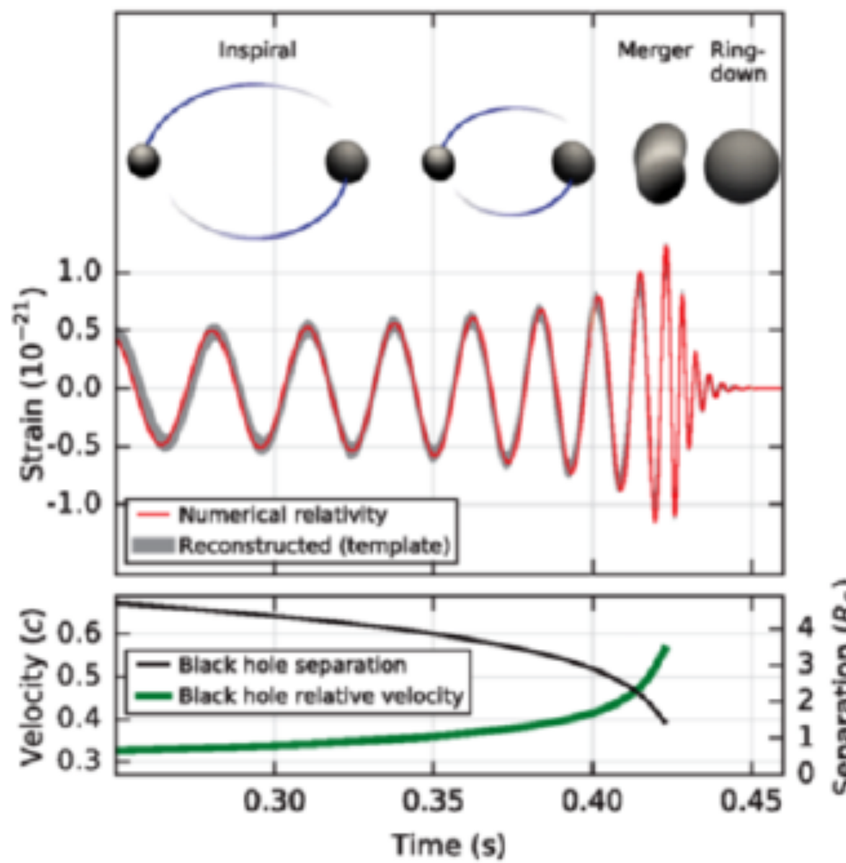
Ackermann et al. 2013

Gamma-ray follow-up of Gravitational Wave



Fermi-GBM is the most prolific detector for short GRBs ~ 45 /year

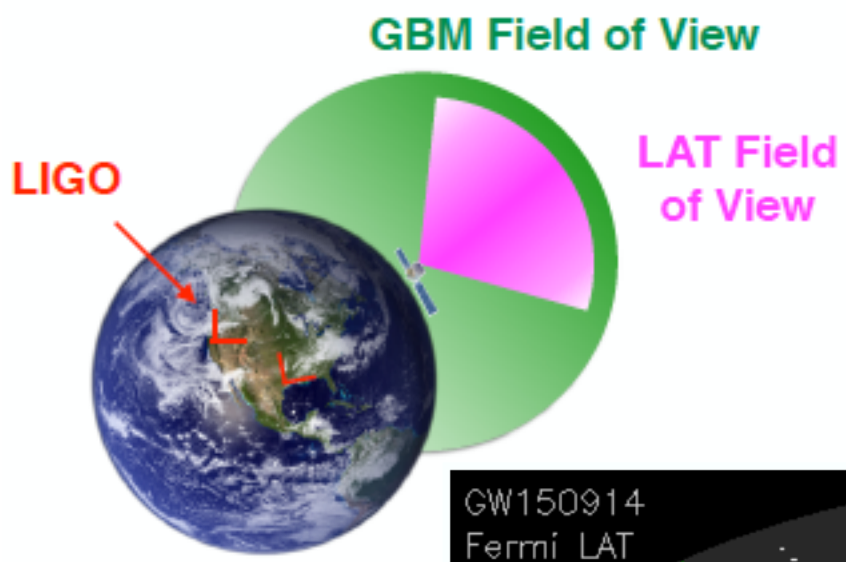
➔ Sees the full un-occulted sky at <40 MeV



LIGO/VIRGO discovery: GW 150914

Merger of binary black holes of mass ~ 30 solar mass each

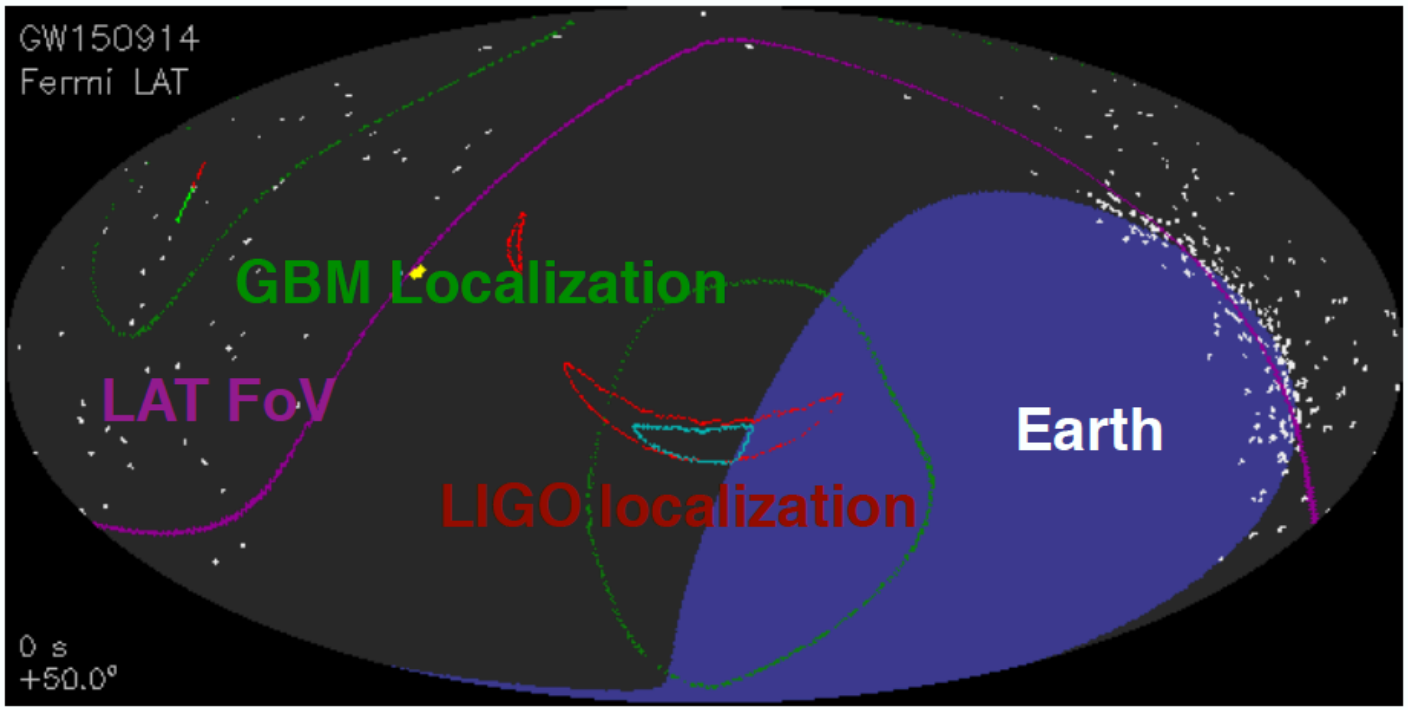
Gamma-ray follow-up of Gravitational Wave



GW 150914

~ 600 square degrees localization by LIGO
Fermi-GBM saw a weak (~ 3σ) signal
Fermi-LAT saw nothing → upper limit on flux

EM signal is not expected for BH-BH mergers

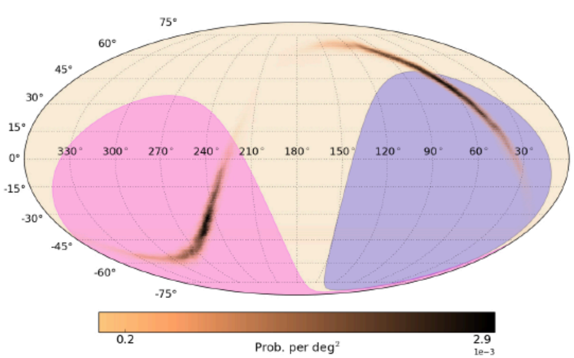


Ackermann et al. 2016

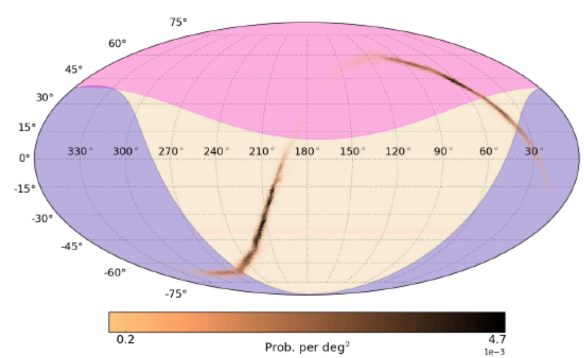
Gamma-ray follow-up of Gravitational Wave

	GW 150914	LVT 151012	GW 151226	GW 170104
GBM coverage of LIGO map at trigger time	75%	68%	83%	82%
GBM observed entire LIGO map within	25 min	8 min	34 min	
LAT coverage of LIGO map at trigger time	0%	47%	32%	55%
LAT observed entire LIGO map within	70 min	113 min	140 min	83 min

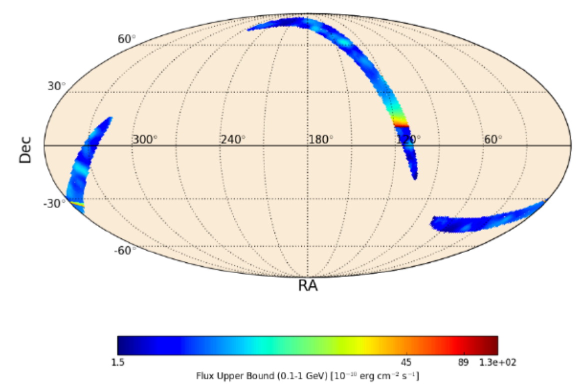
LVT 151012



GW 151226

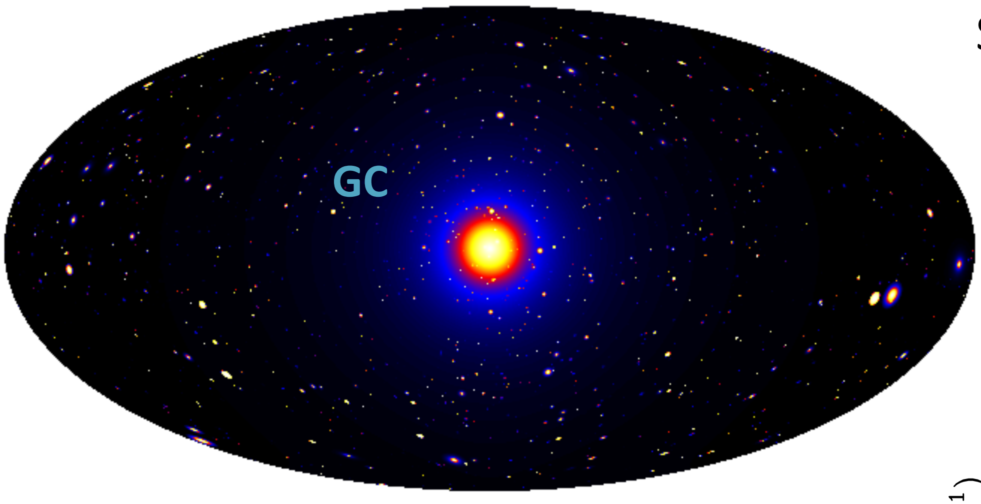


GW 170104



Racusin et al. 2017, Goldstein et al. 2017

Search for γ-ray signature of Dark Matter

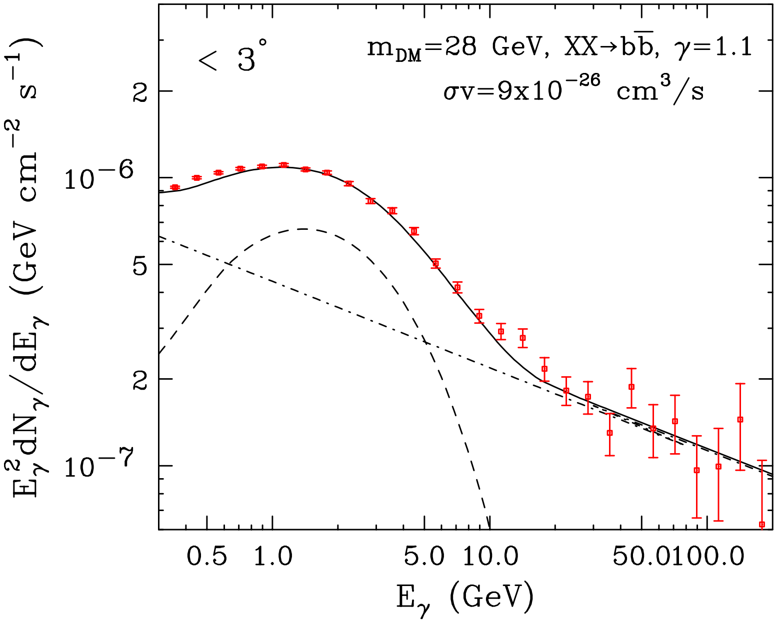


Simulated DM concentration map

Pieri et al. 2011

DM annihilation to SM particle → γ

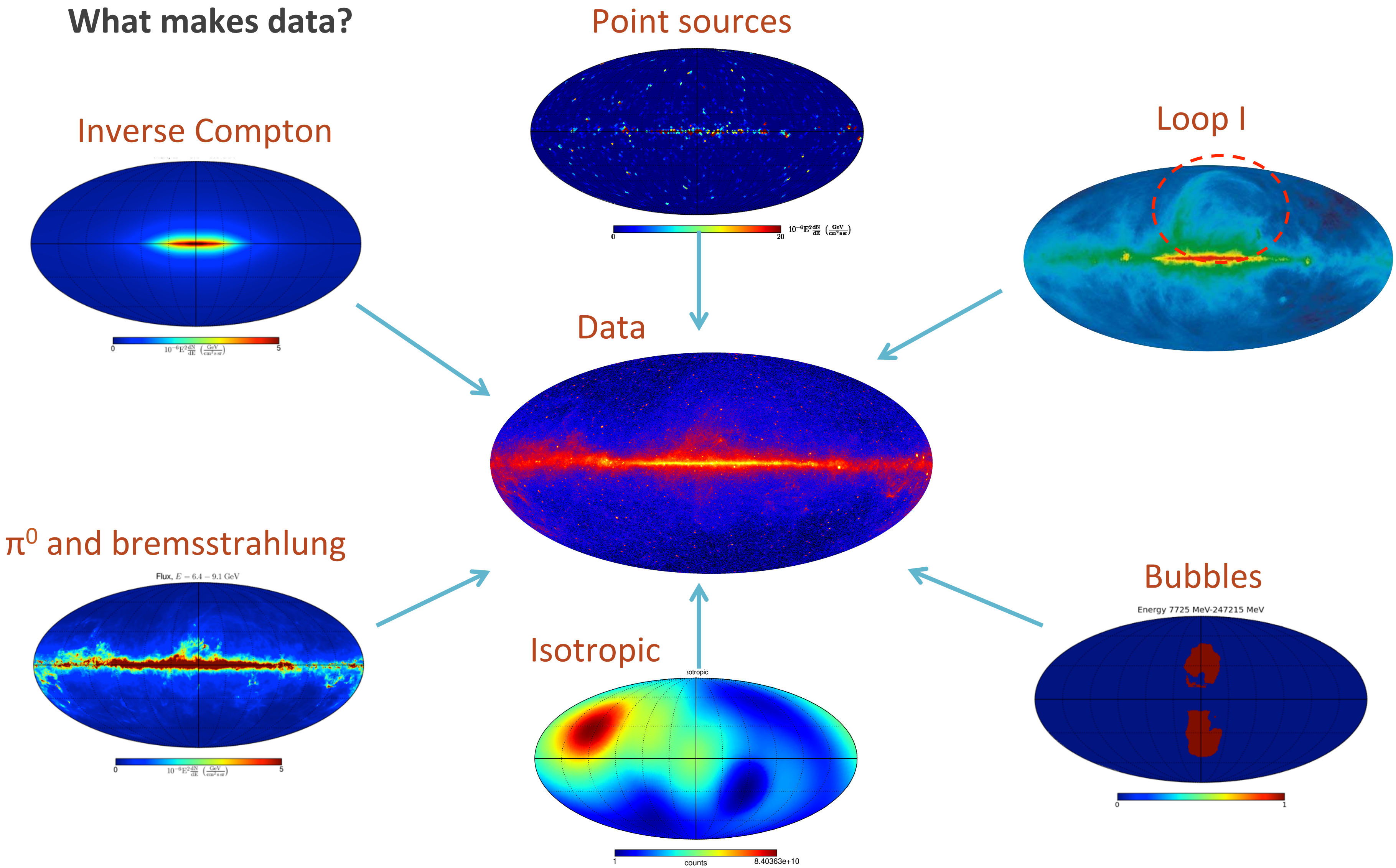
gamma-ray excess towards the GC



Goodenough and Hooper 2009

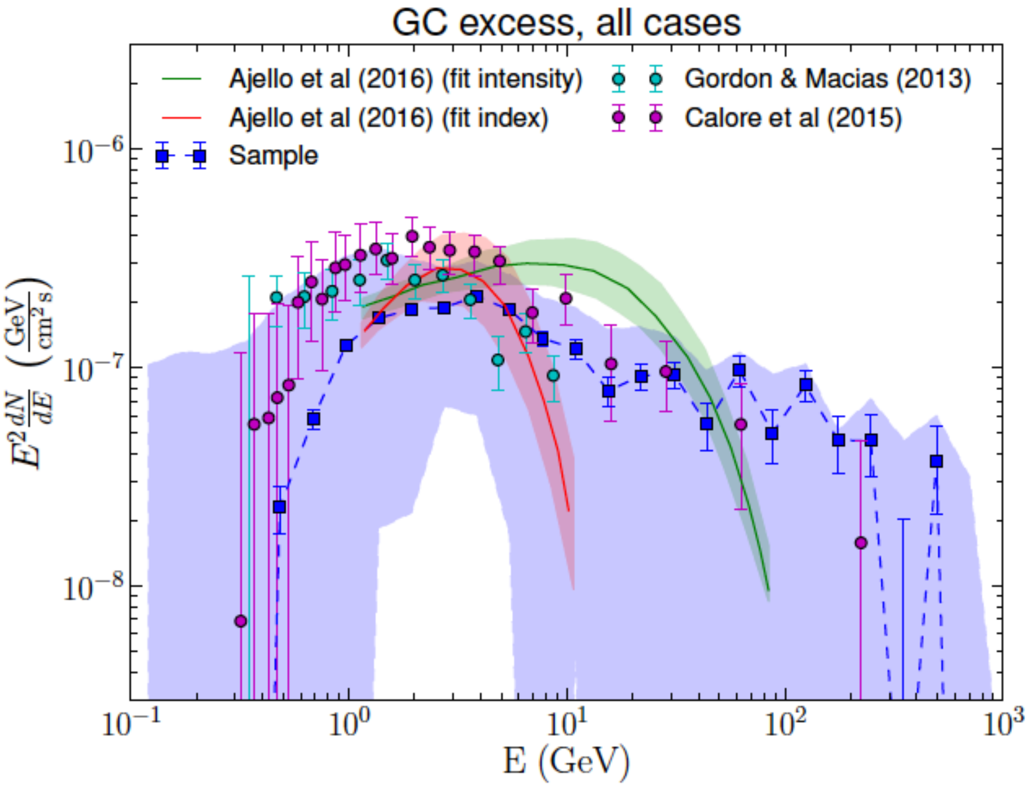
Search for γ-ray signature of Dark Matter

What makes data?

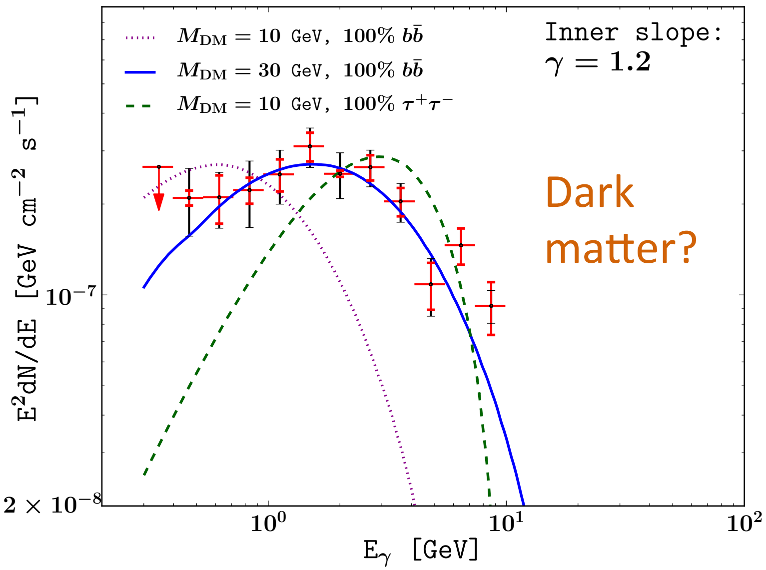


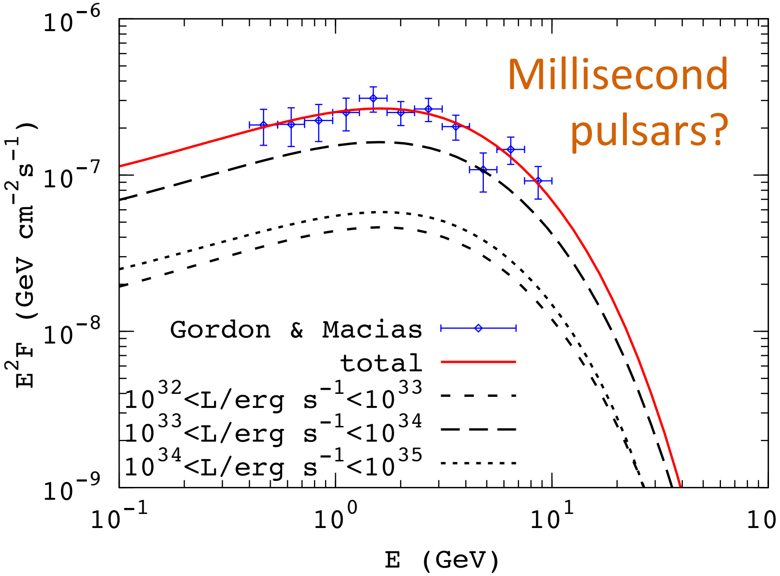
Search for γ-ray signature of Dark Matter

After accounting for known contribution, GC excess is there!



Ackermann et al. 2017

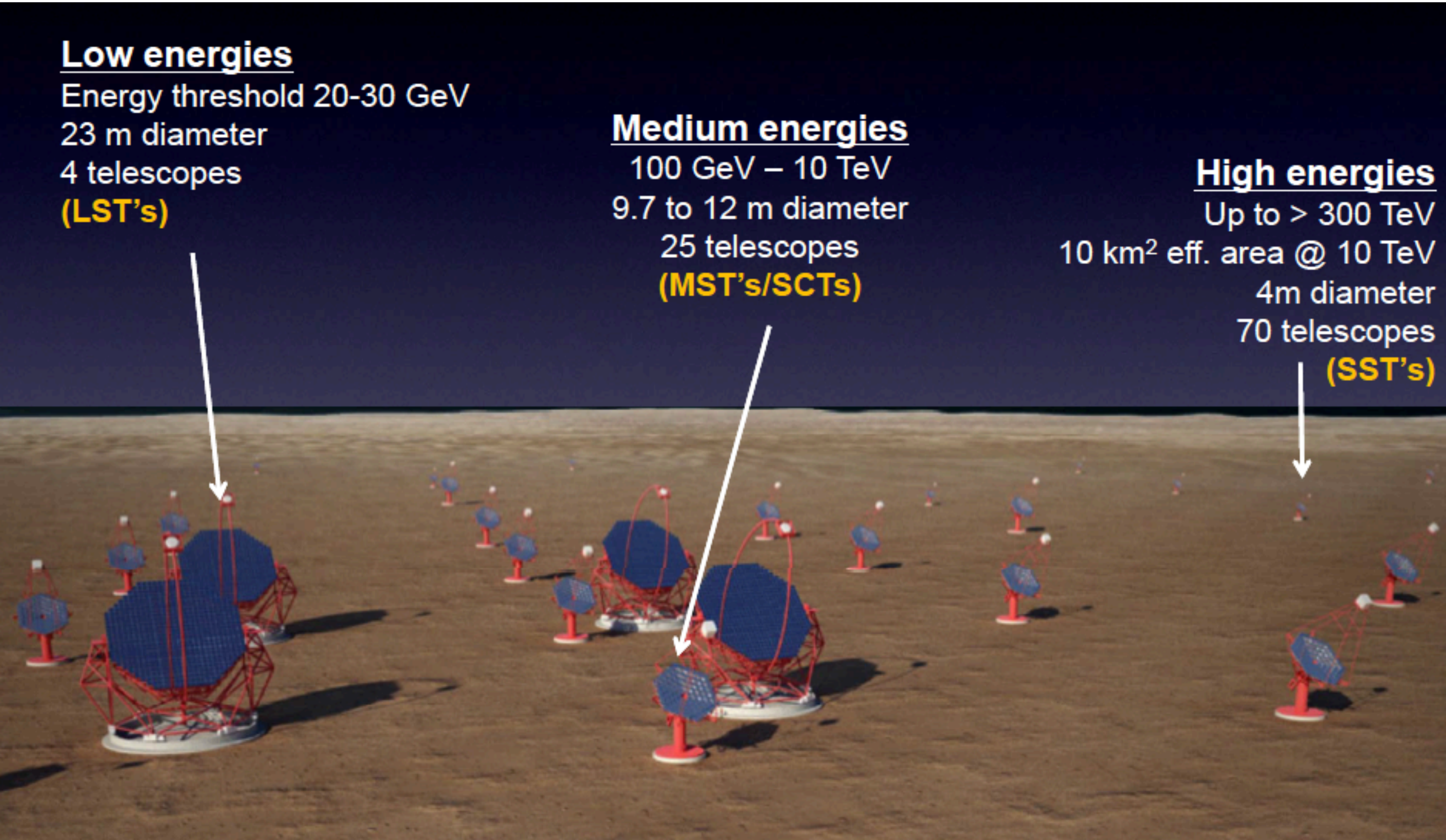




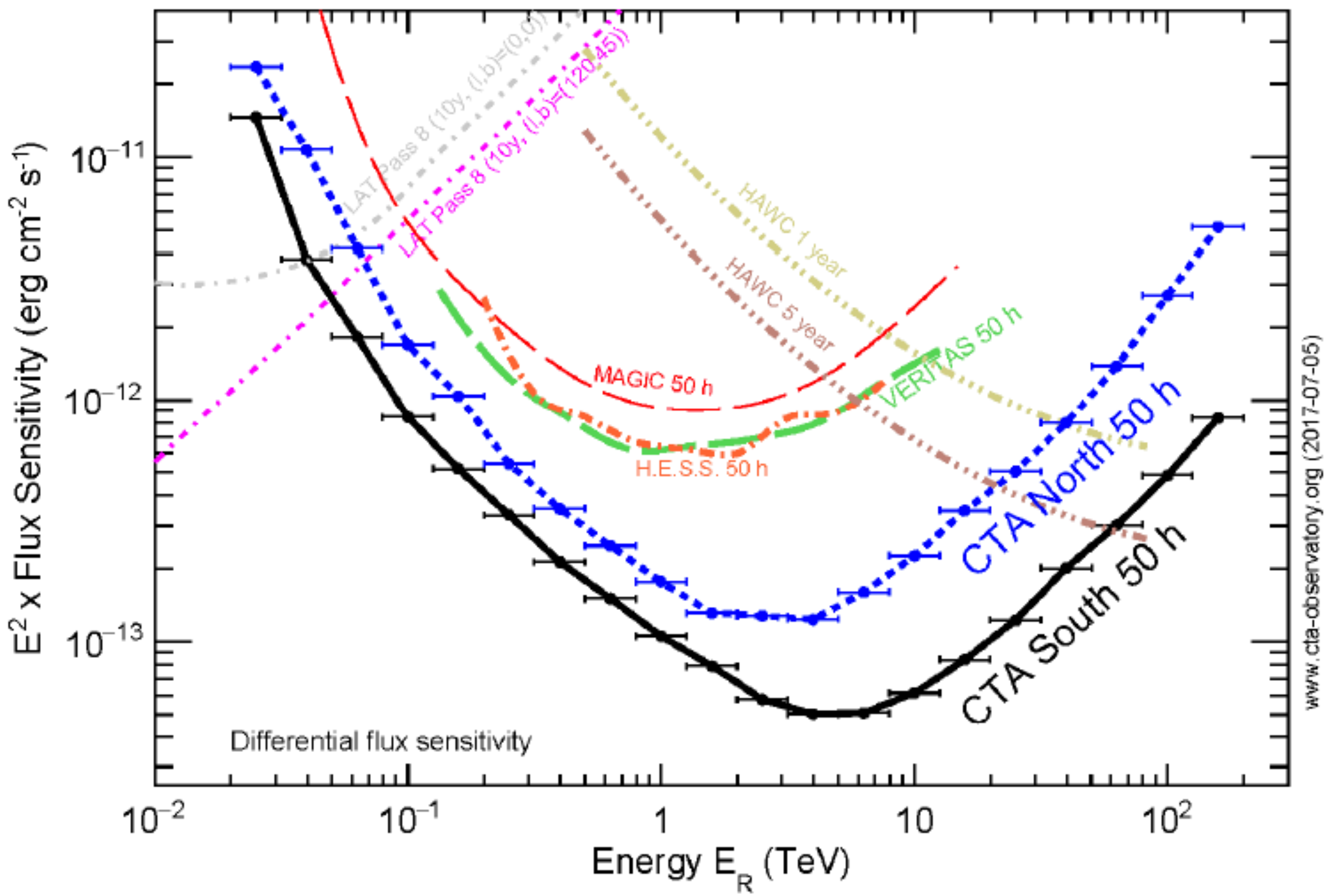
Gordon and Macias 2013
Yuan and Zhang 2014

Future of HE gamma-ray Astronomy

Cherenkov Telescope Array: North and South locations



Improved sensitivity at high energy



Summary and Outlook

- Gamma-ray sky is full of sources, variable and also contain diffuse emission
  - Known sources are Galactic and extragalactic
  - A large fraction (⅓) of sources are unknown (unidentified)
- Science program of gamma-ray astronomy
  - Gamma-ray emission mechanism (leptonic, hadronic)
    - Search for cosmic-ray accelerators
  - Probing source environment
    - jet structure, explosion mechanism, accretion, etc.
  - Multi-wavelength and multi-messenger follow-up of transients
    - Radio, optical, X-ray
    - Gravitational wave, neutrinos
  - Physics frontiers – beyond the Standard Model
    - Dark matter, axion-like particles, Lorentz invariance violation

Future is extremely bright!!!