Scientific Interest of GAMMA-400: Astrophysics

GAMMA-400 Worksop

29-30 June 2015
ICCUB & IFAE

Barcelona

Josep M. Paredes

UNIVERSITAT DE BARCELONA

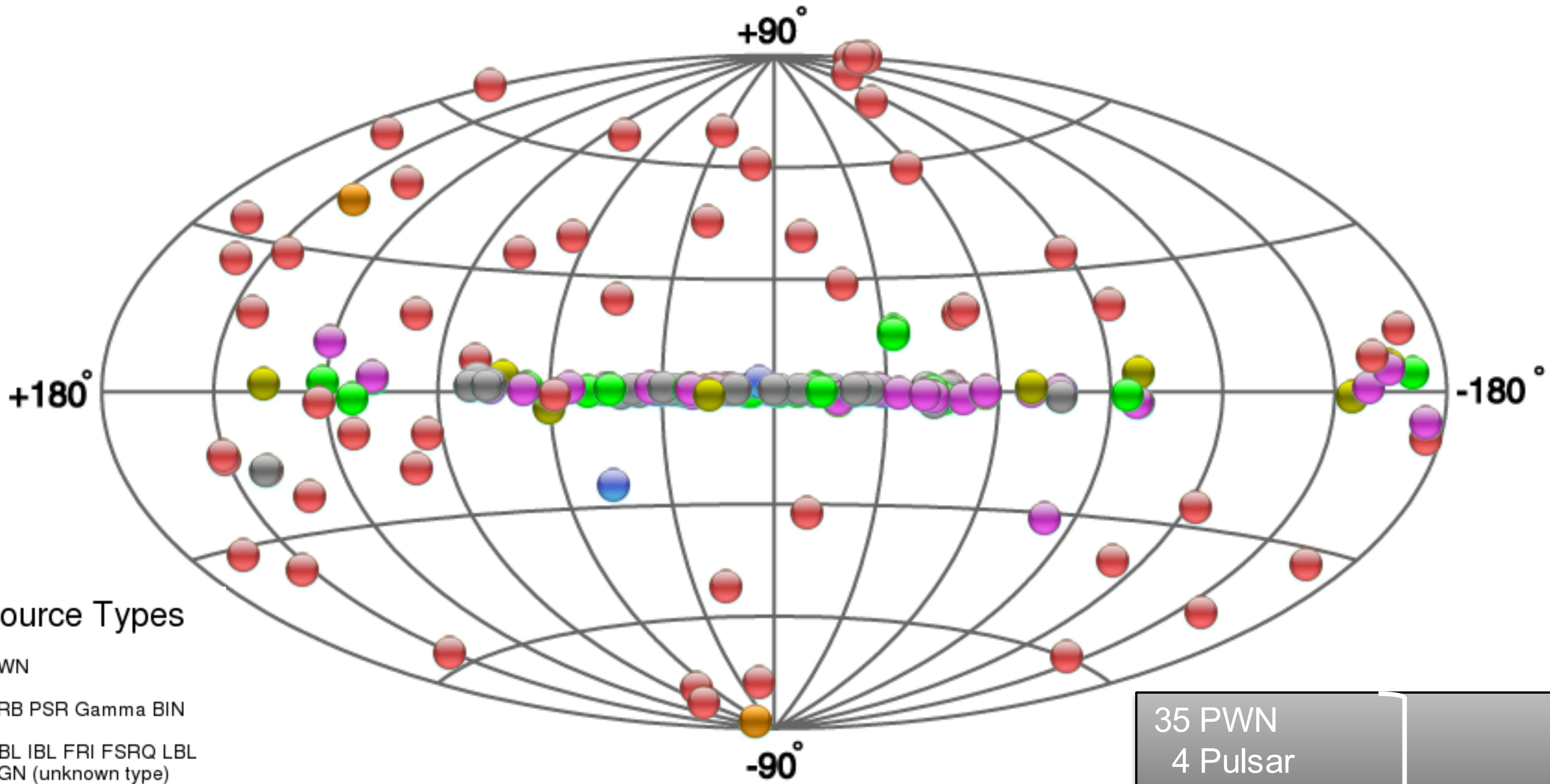
Institut de Ciències del Cosmos

EXCELENCIA MARÍA DE MAEZTU

OUTLINE

1. The Gamma-ray sky
2. Extragalactic sources
3. Galactic sources
4. Unidentified sources
5. Summary

The VHE (E_γ > 100 GeV) gamma-ray sky



Source Types

- PWN
- XRB PSR Gamma BIN
- HBL IBL FRI FSRQ LBL AGN (unknown type)
- Shell SNR/Molec. Cloud
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

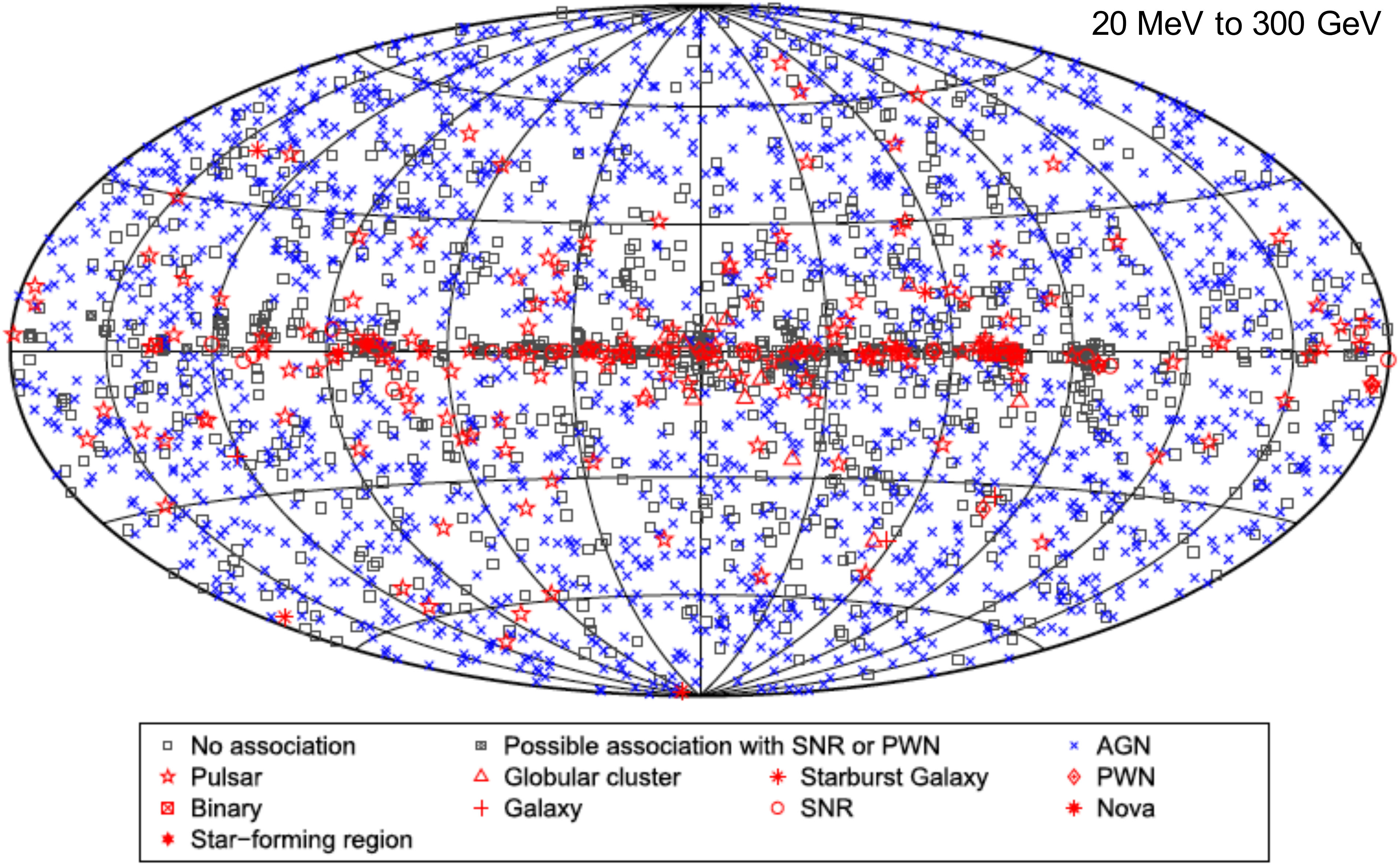
56 extragalactic
76 galactic
30 unidentified

35 PWN
4 Pulsar
23 SNR
7 BS
4 MSC
3 GC, SFR
} 76

30 UNID

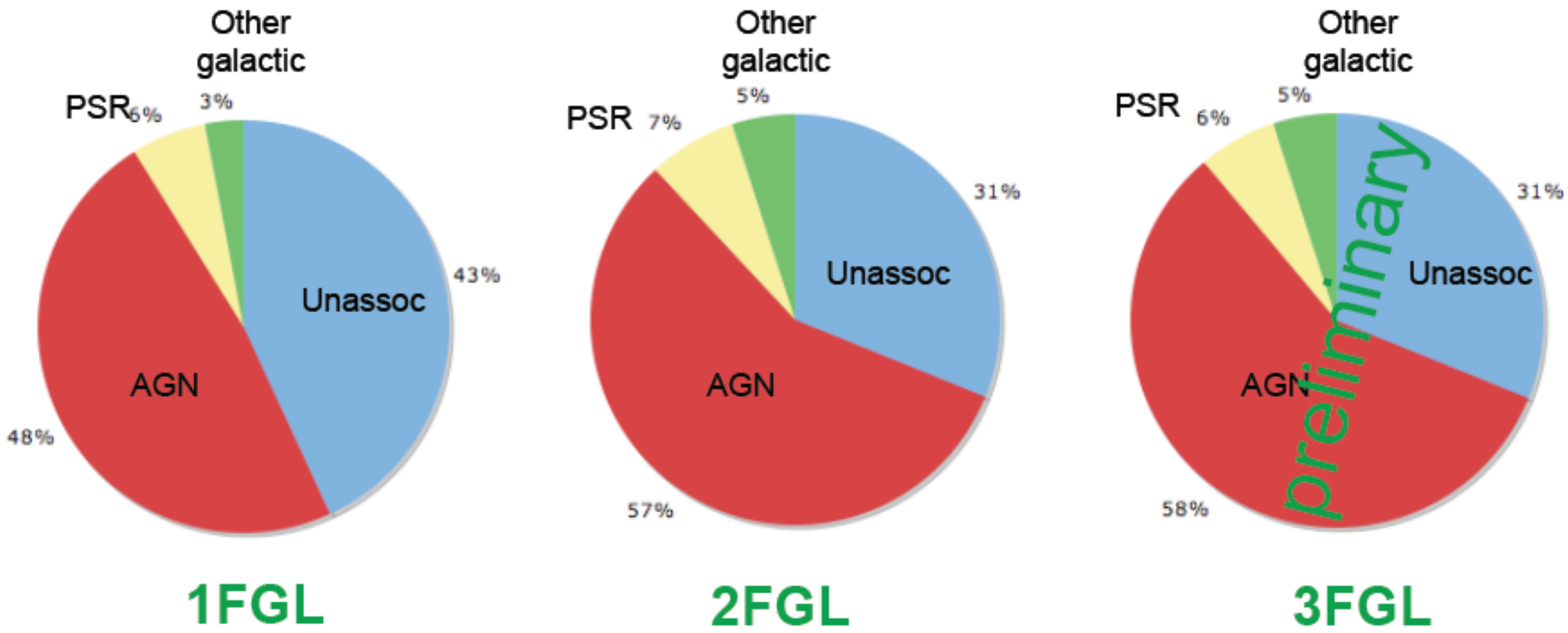
http://tevcat.uchicago.edu/

The HE (Fermi) gamma-ray sky

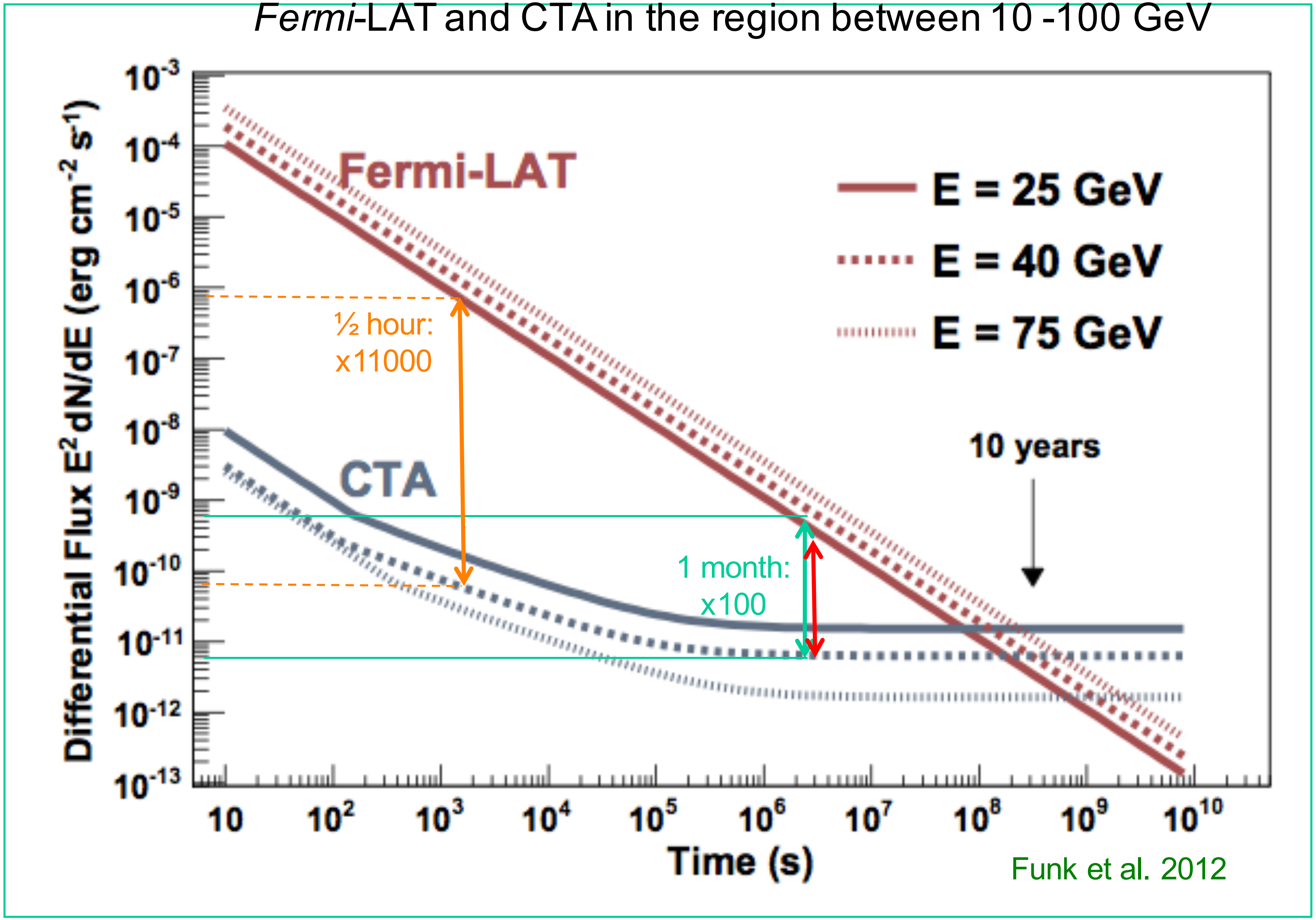


Acero et al. 2015, ApJSS 218:23 (41pp)

1FGL - 2FGL - 3FGL



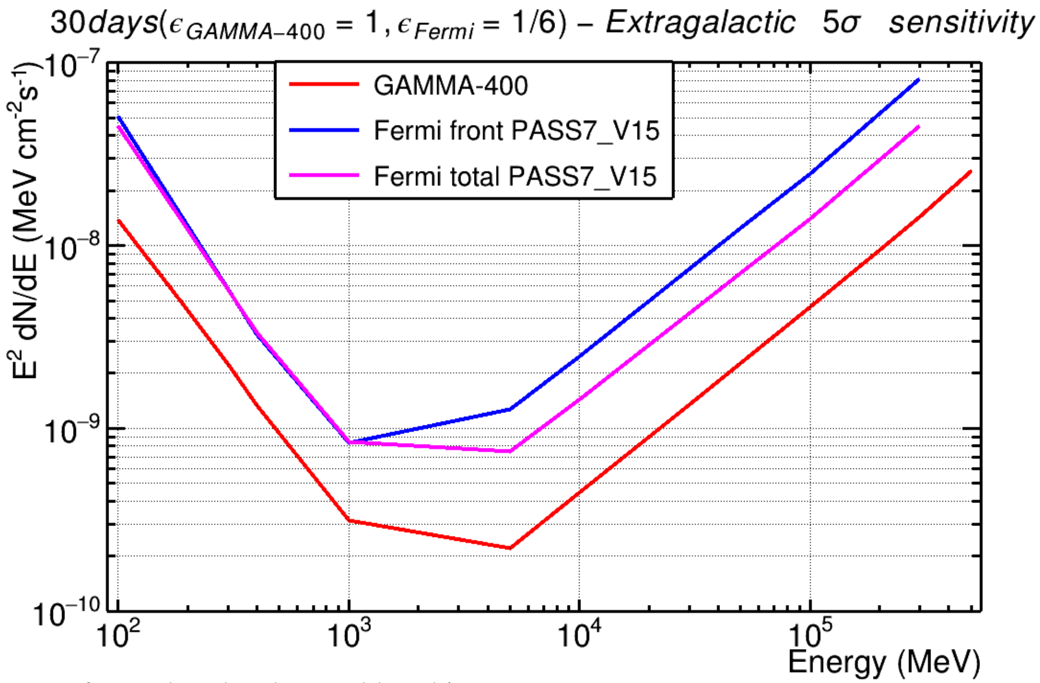
N. sources	1FGL	2FGL	3FGL
Total	1451	1873	~ 3000
High/Low |b|	72%/28%	71%/29%	~ 72%/28%



- CTA has a huge discovery potential over *Gamma*-400 for **short-transient** phenomena
- For **GRBs**, CTA has an advantage over the *Gamma*-400 by many orders of magnitude
- However, the larger **field of view** of *Gamma*-400 makes catching transients much more likely

Fermi vs GAMMA-400

Paolo Cumani, PhD Thesis



A comparison of basic parameters of space-based and ground-based instruments.

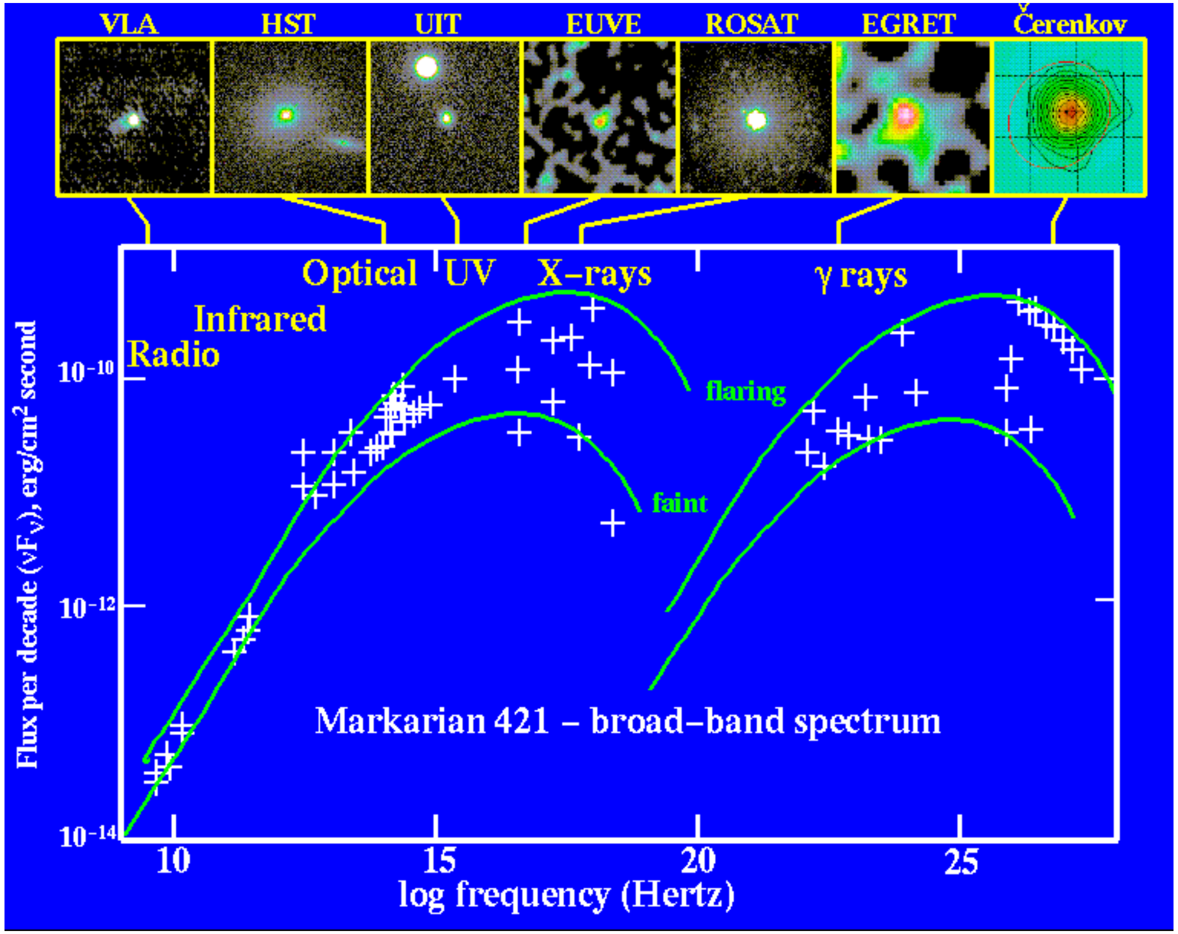
	Spaced-based					Ground-based			
	EGRET	AGILE	Fermi	CALET	**GAMMA-400**	H.E.S.S.	MAGIC	VERITAS	CTA
Energy range, GeV	0.03–30	0.03–50	0.1–300	10–10000	**0.1–3000**	>100	>50	>100	>10
Angular resolution, deg ($E_\gamma > 100$ GeV)	0.2 $E_\gamma \sim 0.5$ GeV	0.1 $E_\gamma \sim 1$ GeV	0.1	0.1	**~0.01**	0.1	0.1	0.1	0.1
Energy resolution, % ($E_\gamma > 100$ GeV)	15 $E_\gamma \sim 0.5$ GeV	50 $E_\gamma \sim 1$ GeV	10	2	**~1**	15	20	15	15

Galper et al 2013, Advances in Space Research 51, 297

Gamma-400 will be able to do a better measurement of a source if it is able to detect it

Blazars

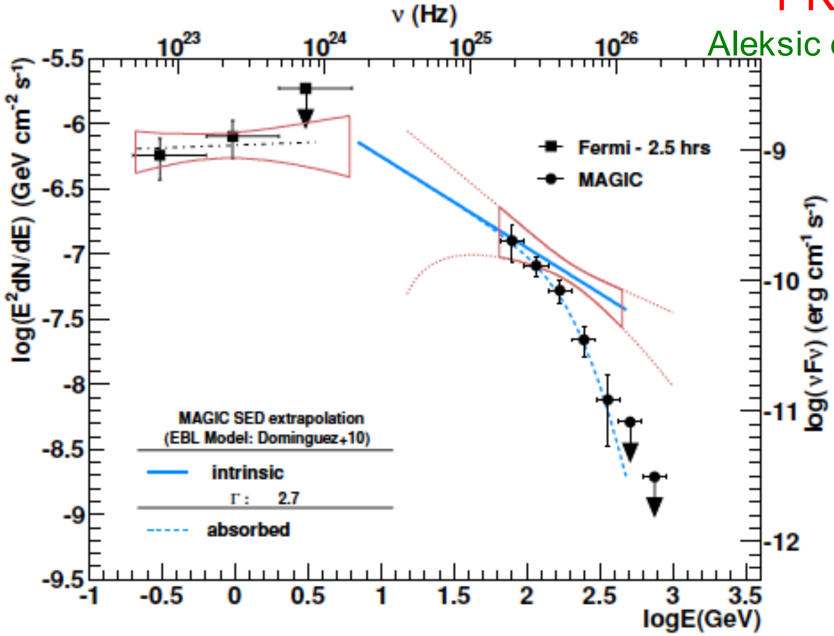
AGN with a jet oriented close to the line of sight and display a synchrotron bump and an Inverse Compton bump

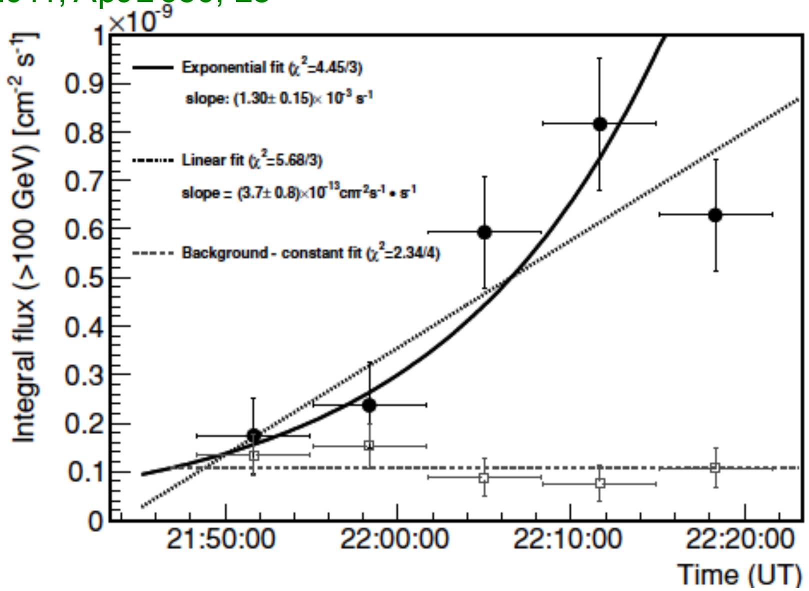


- Rapid variability
- Strong correlation between X-ray and gamma-ray fluxes
  → common e^- population
- Relative spacing and height of the two peaks of the SED
  → B

PKS1222+21

Aleksic et al. 2011, ApJL 630, L8

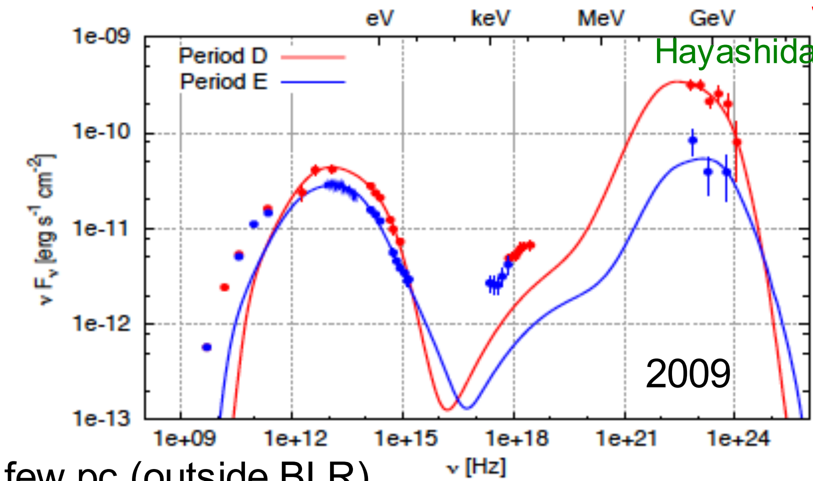




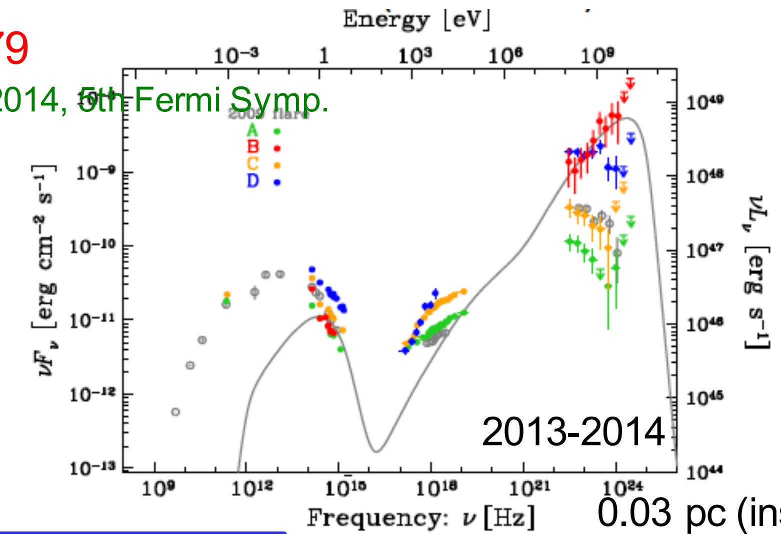
Absence of a spectral cutoff → emission region lies outside the broad-line region, which would otherwise absorb the VHE γ-rays. Together with the detected fast variability, this challenges present emission models from jets in FSRQs

3C 279

Hayashida et al, 2014, 5th Fermi Symp.



A few pc (outside BLR)



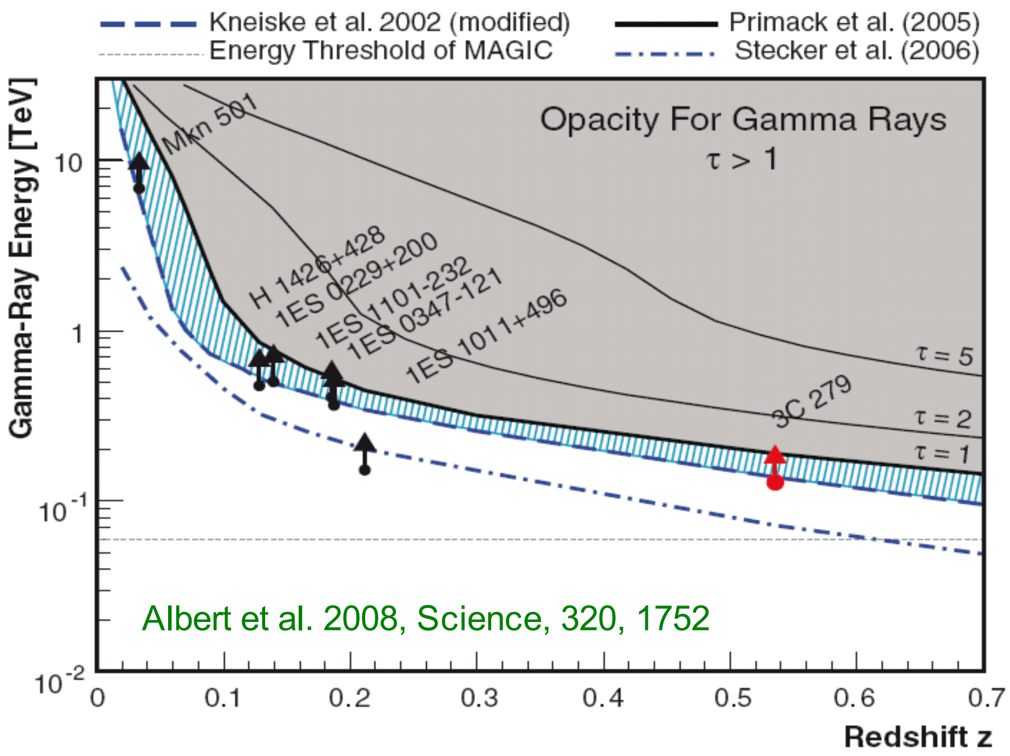
0.03 pc (inside BLR)

Emission site is not unique !

Extragalactic Background Light (EBL)

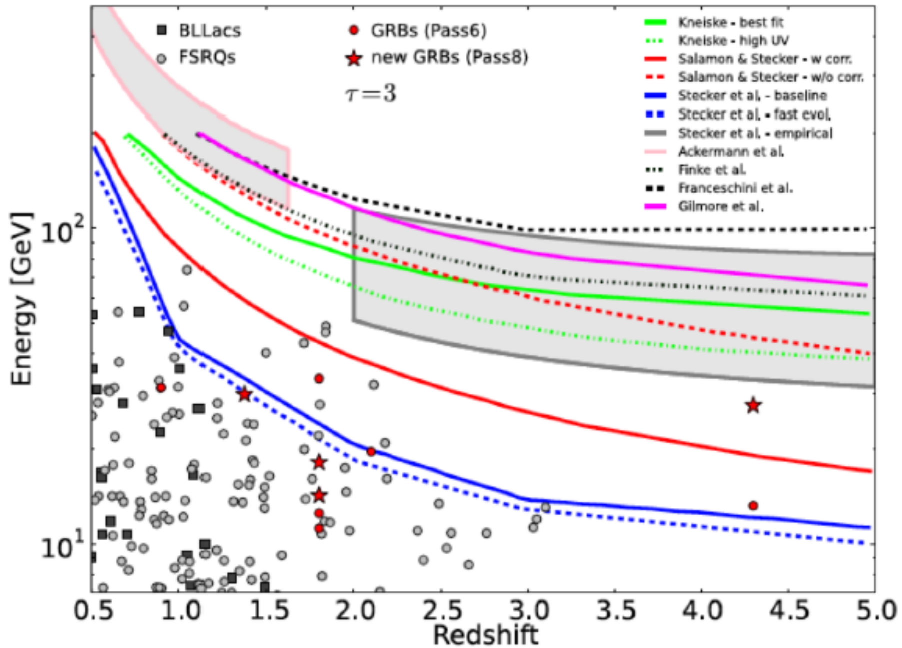
Constraining the opacity of the Universe

- γ-rays from distant sources can pair produce (γγ →e+e−) on the way to us with the extragalactic background light (EBL)
- This can test the transparency of the Universe and constrain EBL models (or the massive star formation rate at z ≳ 1)
- GRBs are already competitive with AGN, & probe higher z



Albert et al. 2008, Science, 320, 1752

Abdo et al. 2010;
Atwood et al. 2013



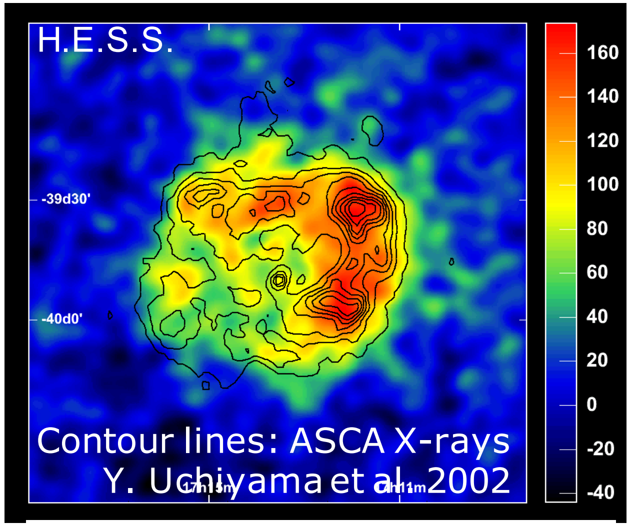
Supernova Remnants

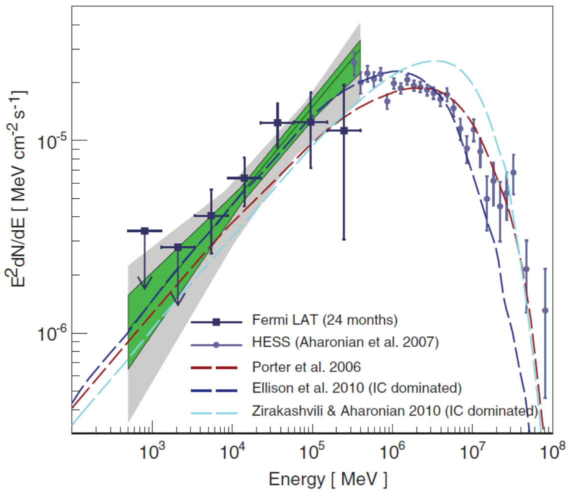
Galactic sources

Young shell-type TeV

RX J1713.7–3946 (Aharonian et al. 2008)

- Non-thermal spectrum in X-rays
- Significant VHE emission beyond 30 TeV
  → efficient acceleration up to 100 TeV

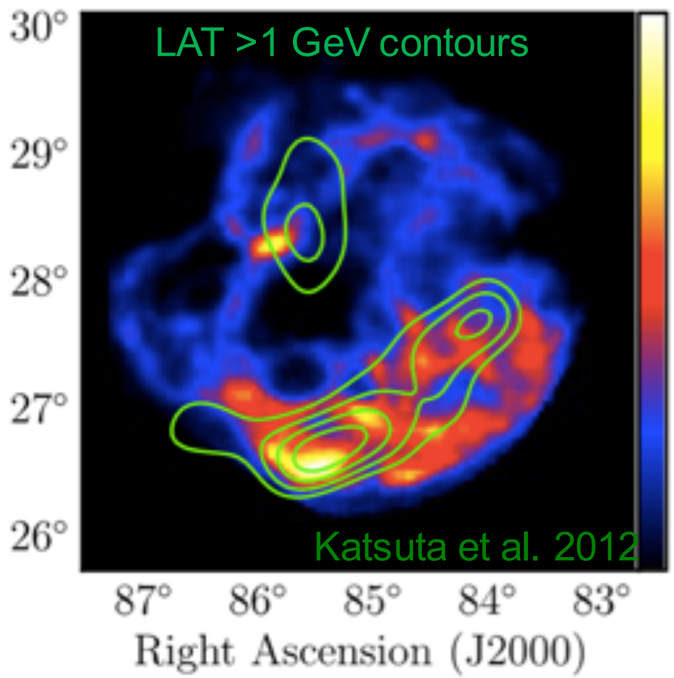




GeV shell-type SNR S147

Age ~$3x10^4$ yr, with radiative Hα filaments

γ-rays dominated by π^0-decay in filaments



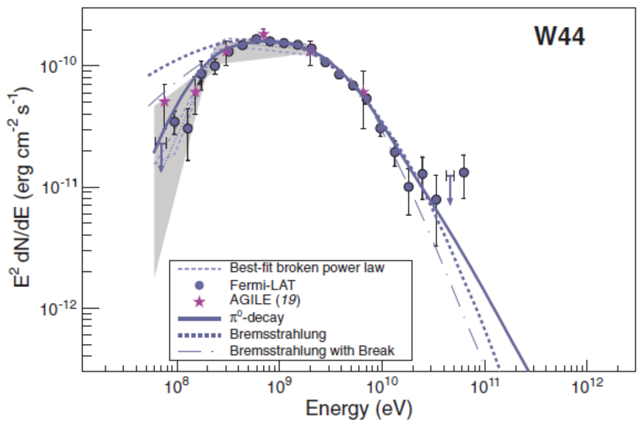
Supernova Remnants

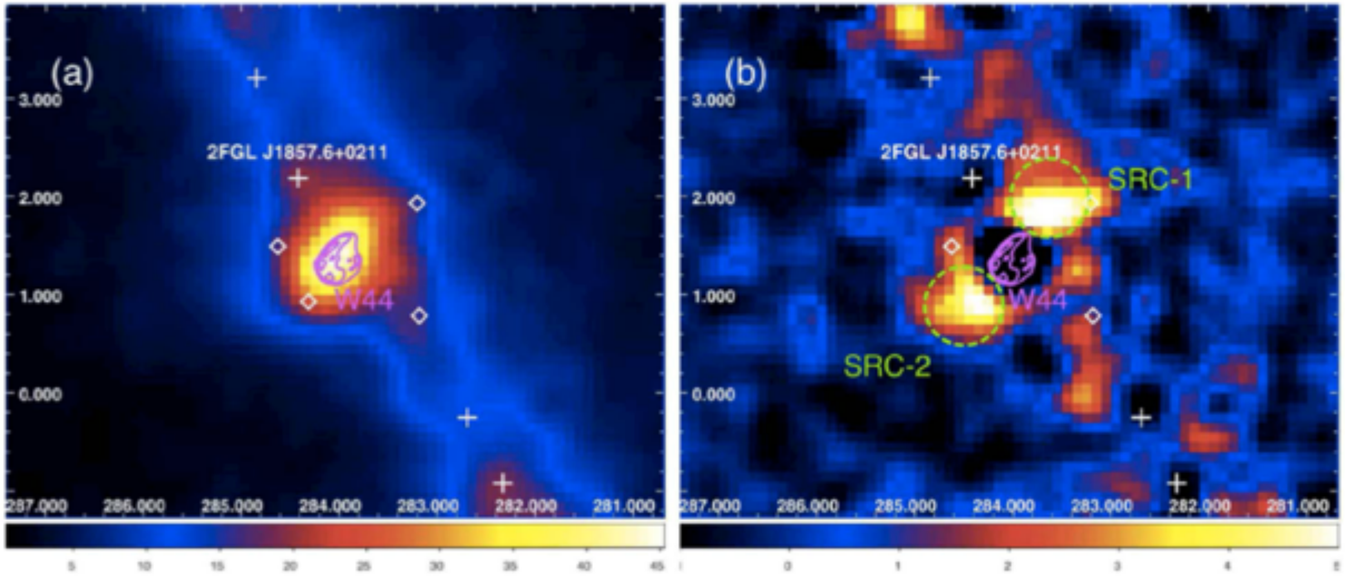
Detection of the Characteristic Pion-Decay Signature in SNR

(Ackermann et al. 2013, Sci 339, 807)

- When accelerated *p* encounter interstellar material, they produce π^0, which in turn decay into γ-rays → a way to detect the acceleration sites of *p*

- ***Fermi*** (**MAGIC**) detected the characteristic pion-decay feature in the γ-ray spectra of two SNRs, IC 443 and W44. This detection provides direct evidence that cosmic-ray protons are accelerated in SNRs.



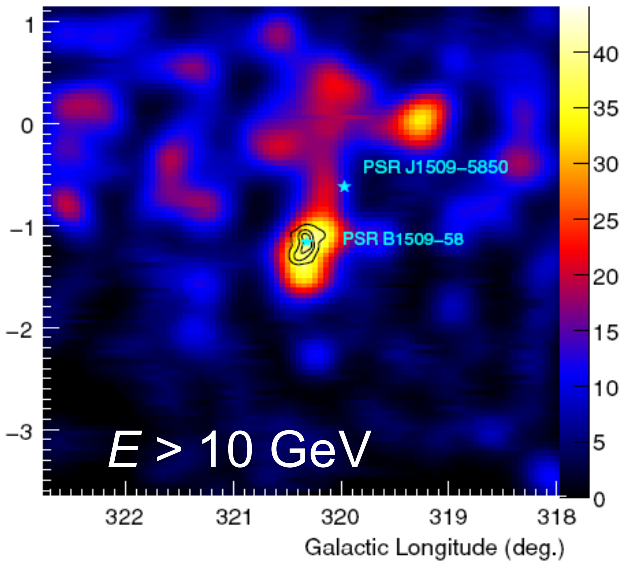


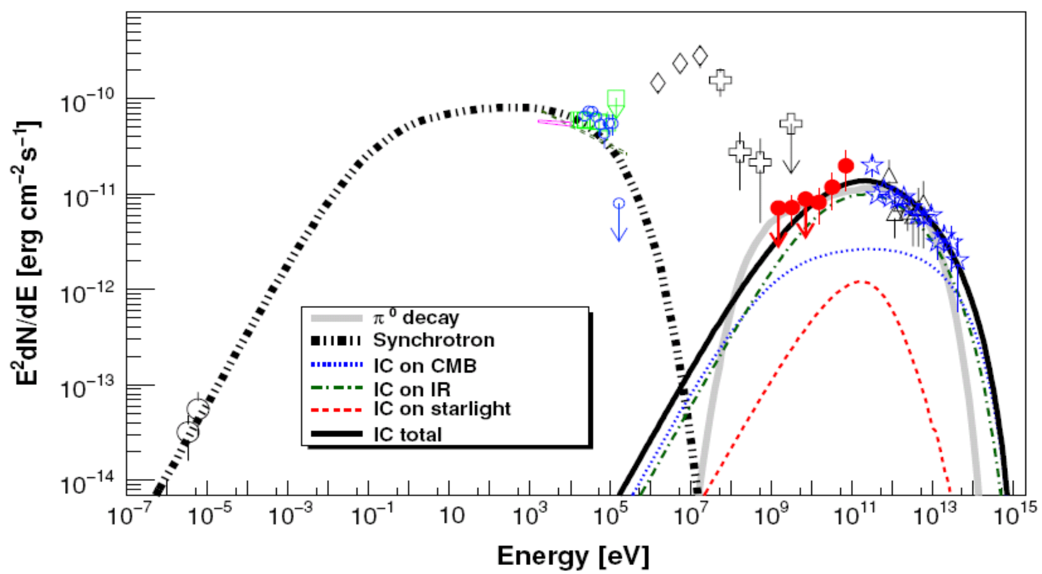
Subtracting the SNR (radio model) reveals emission at 2-100 GeV (SRC-1,2) coincident with nearby CO complex

Pulsar Wind Nebulae (PWNe)

- Young (<10^5 year old) pulsars produce relativistic winds of electron/positron pairs
- In the presence of magnetic fields, these pairs produce synchrotron radiation from radio to keV-MeV energies. Photon fields from CMB or nearby stars give rise to IC radiation from MeV to TeV energies
- The extended morphologies of these radio, X-ray and TeV emissions are often trailing the motion of the pulsar in the ISM

PWN MSH 15-52 (PSR B1509-58) (Abdo et al. 2010)





- Hadronic models are disfavored. Leptonic models fit the data with B=17 μG and a break in the energy spectrum of the electrons

The Crab Nebula Flares

The standard candle that does not behave as such!

The Crab Nebula is powered by the Crab pulsar, which has a rotational energy loss of 5×10^{38} erg s^{-1}, and a period of 33 ms

September 2010, October 2007 flares seen by ***AGILE*** (Tavani et al. 2011)

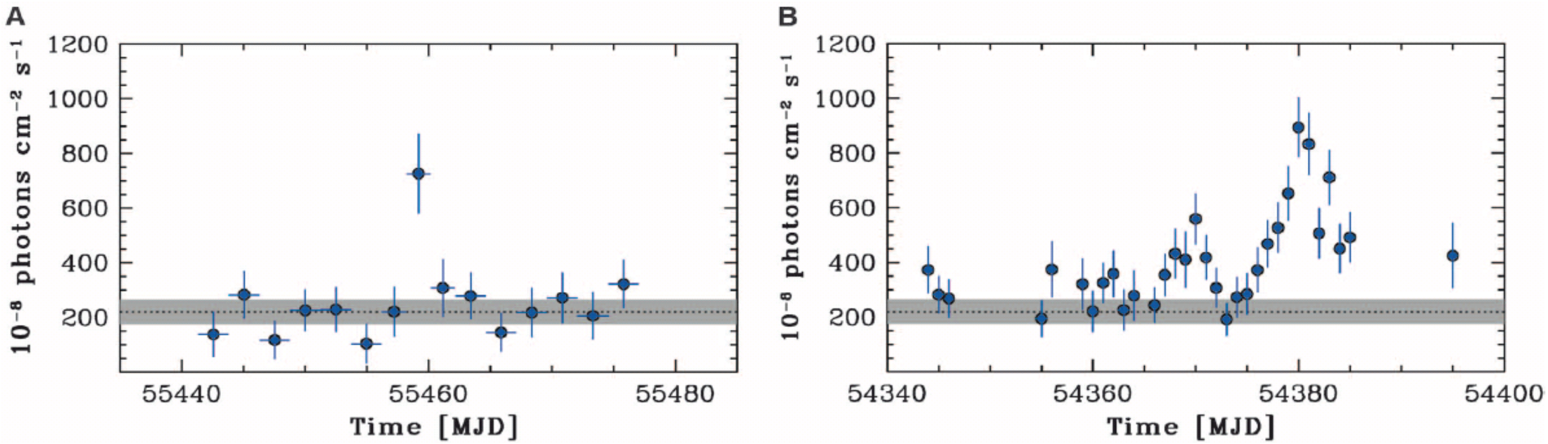


Table 1: Major gamma-ray flares of the Crab Nebula

Flare date	Duration	Peak flux (*) (pulsar + nebula)	Instrument	Ref.
October 2007	$\sim$ 15 days	9×10^{-6} ph cm^{-2} s^{-1}	AGILE	[51]
February 2009	$\sim$ 15 days	7×10^{-6} ph cm^{-2} s^{-1}	*Fermi*-LAT	[2]
September 2010	$\sim$ 4 days	7×10^{-6} ph cm^{-2} s^{-1}	AGILE, *Fermi*-LAT	[51, 2]
April 2011	$\sim$ 10 days	30×10^{-6} ph cm^{-2} s^{-1}	AGILE, *Fermi*-LAT	[16, 52, 27, 47]

* Average peak fluxes obtained for different integration times: 1 day (October 2007), 4 days (February 2009), 2 days (September 2010), 12 hours (April 2011).

The brevity of the flares implies that the γ-rays were emitted via synchrotron radiation from PeV e^- in a region smaller than 1.4×10^{-2} pc.

These are the highest-energy particles that can be associated with a discrete astronomical source, and they pose challenges to particle acceleration theory (Abdo et al. 2011, Sci 331, 739)

Pulsars

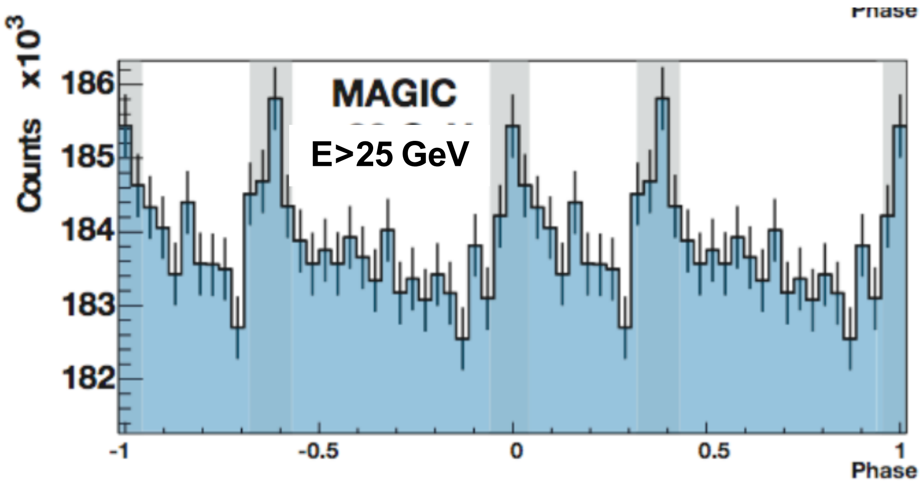
- **MAGIC** has detected a pulsed signal from the Crab at *E* > 25 GeV with 6.4σ (Teshima et al. 2008 ATel, # 1491, Aliu et al. 2008, Science)

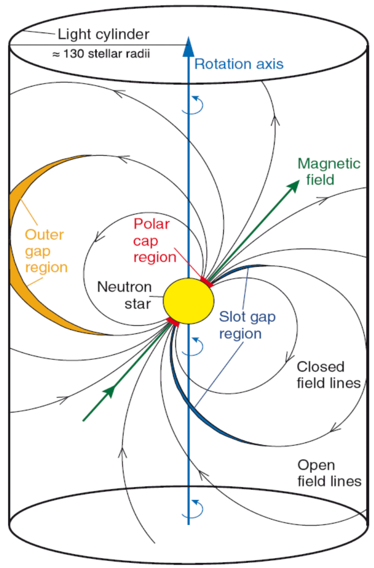
  → First pulsar seen by a Cherenkov Telescope

  The energy cut-off in the phase-averaged spectrum is relatively high

  → the emission happens far out in the magnetosphere

  These results exclude the polar cap model and challenge the slot gap model for the Crab pulsar





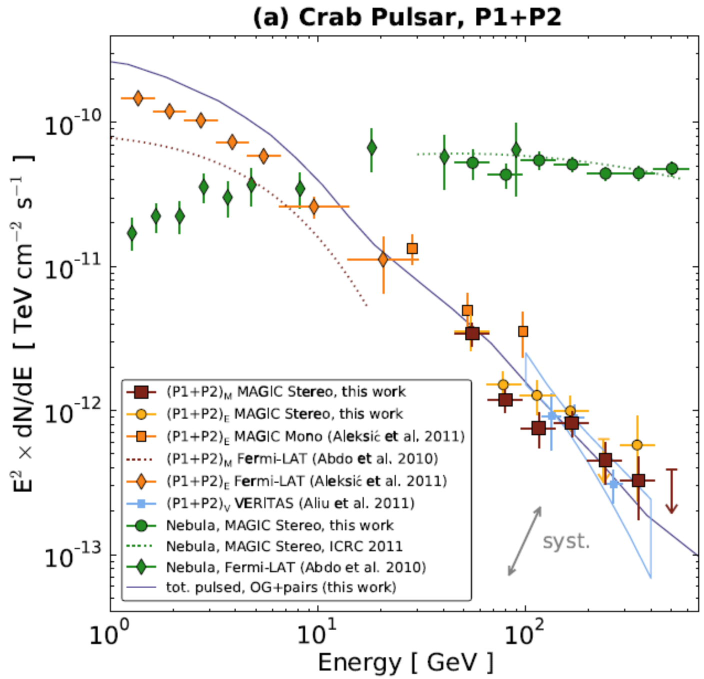
- But pulsations have been found

  up to energies of 250 GeV by **VERITAS** (Aliu et al. 2011),

  up to 400 GeV by **MAGIC** (Aleksic et al. 2012)

  > 100 MeV by ***Fermi*-LAT** (Abdo et al. 2010)

  The data challenged all available models



- A Population of Gamma-Ray Millisecond Pulsars Seen with *Fermi*-LAT (Abdo et al. 2009, Science 325, 848)

Binary systems with HE and/or VHE γ-ray emission

- **Gamma-ray binaries:** Young non-accreting pulsars + massive star
  - SED peak at MeV-GeV
  - PSR B1259-63, detected at HE by *Fermi*-LAT and at VHE by H.E.S.S. (Abdo et al. 2011, Aharonian et al. 2005)

- **Microquasars:** Accreting XRBs with relativistic jets
  - SED peak at keV
  - Cygnus X-3, detected at HE by *AGILE* and *Fermi*-LAT (Tavani et al. 2009, Abdo et al. 2009)

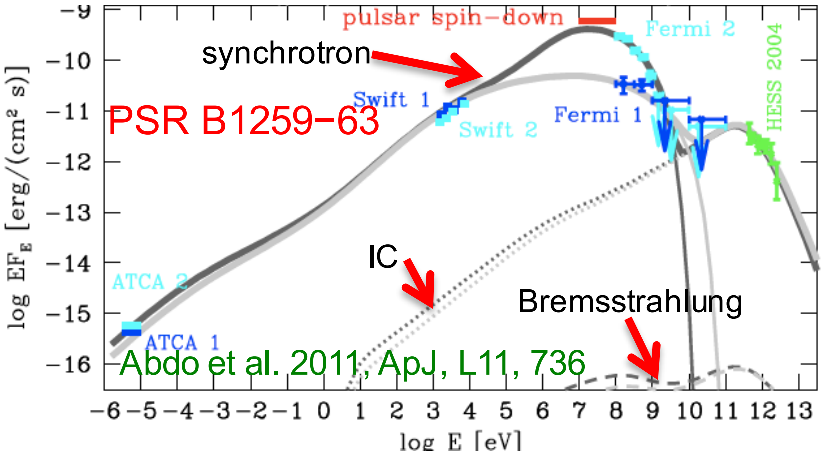
- **Colliding wind binaries:** two stars belonging to the category of OB- or WR-type stars (No compact companion). Wind-wind interaction region
  - Eta Carinae, detected at HE (*AGILE* and *Fermi*-LAT) (Tavani et al. 2009, Abdo et al 2010)

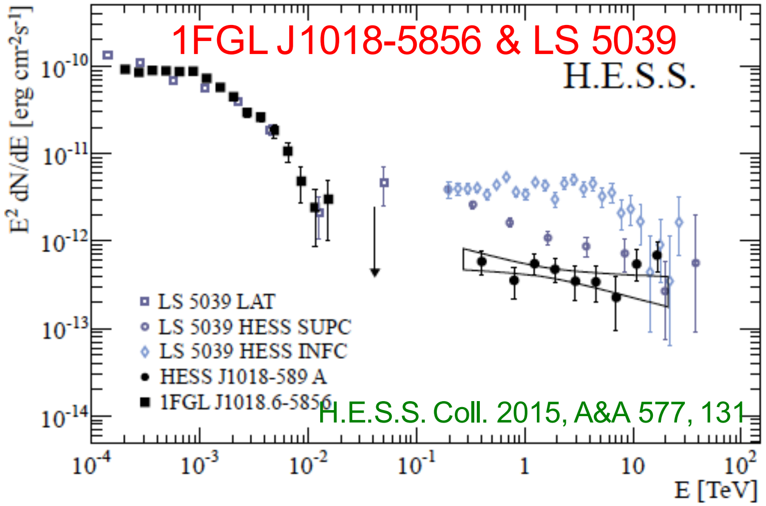
- **Recycled non-accreting ms PSRs in binary systems:** Millisecond pulsar + very low mass companion
  - Black Widow Pulsar PSR B1957+20, detected at HE by *Fermi*-LAT (Wu et al. 2012)

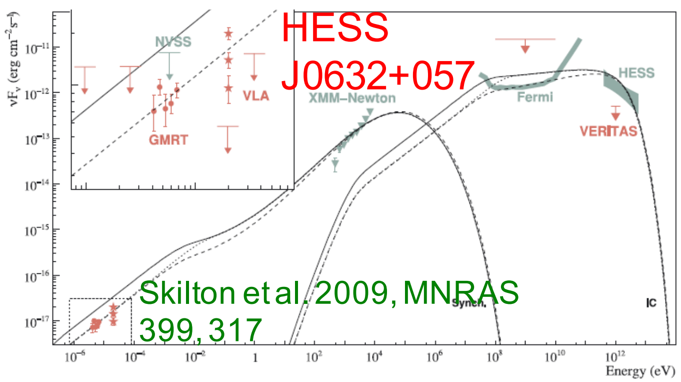
- **Transitional ms PSRs in binary systems**
  - Accreting PSR J1023+0038, detected at HE by *Fermi*-LAT (Stappers et al. 2014)

- **Novae:** WD is deep immersed in the wind of a late-type companion star. Thermonuclear explosion on the surface of the WD
  - V407 Cygni, detected at HE by *Fermi*-LAT (Abdo et al. 2010)

Gamma-ray binaries

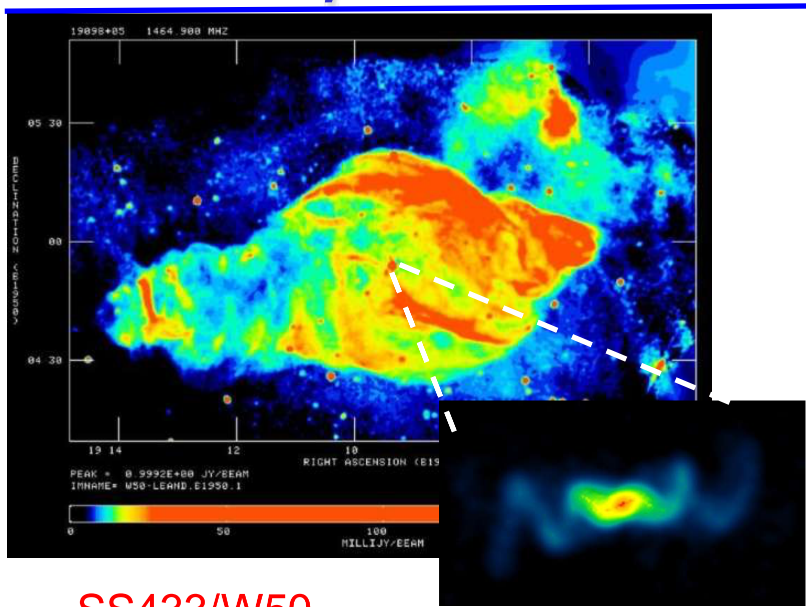




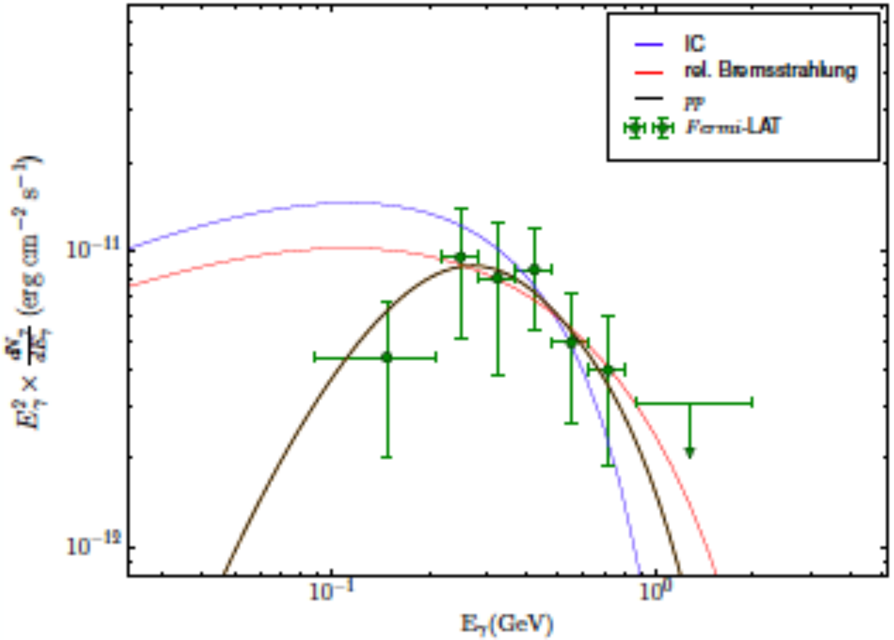


Microquasars

Dubner et al. 1998, ApJ 116, 1842

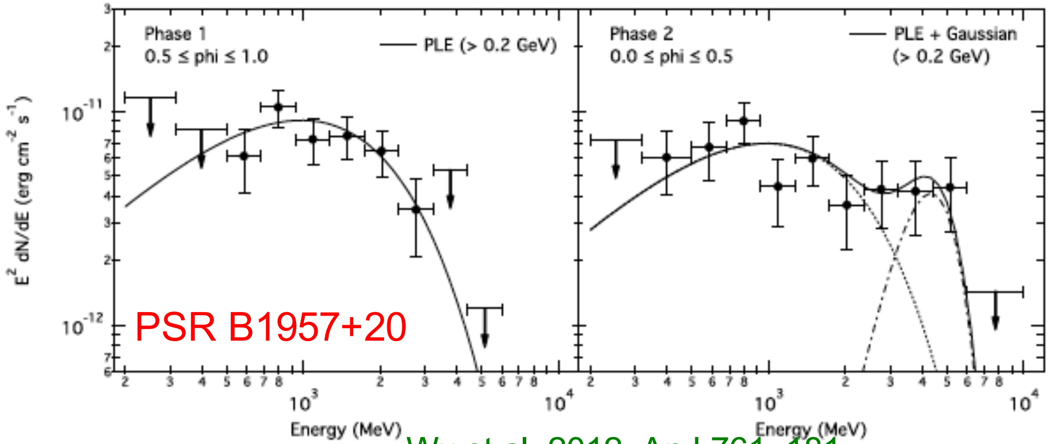


SS433/W50



Bordas et al. 2015; arXiv 1411.7413B

Recycled non-accreting MS PSRs in binary systems



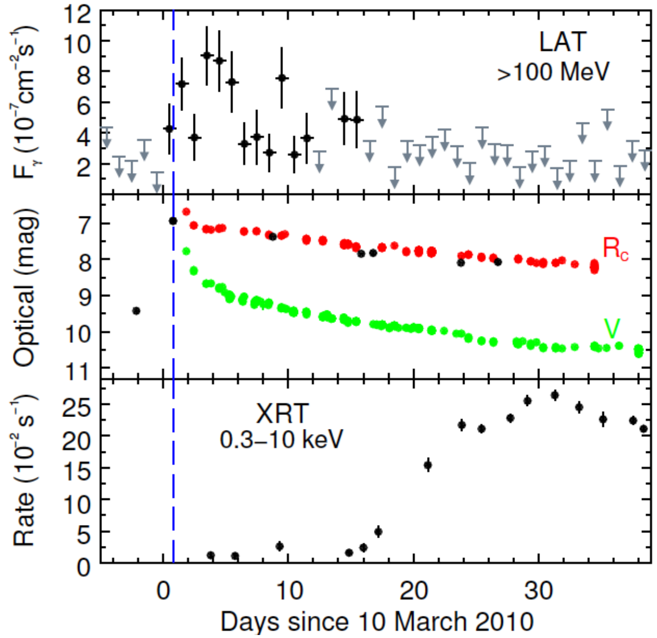
Wu et al. 2012, ApJ 761, 181

- Orbital modulation of the HE emission in the **black widow** pulsar PSR B1957+20
- Modulation restricted to the component above 2.7 GeV, attributed to pulsar wind emission (IC of the thermal radiation of the companion star off a “cold” ultrarelativistic pulsar wind)

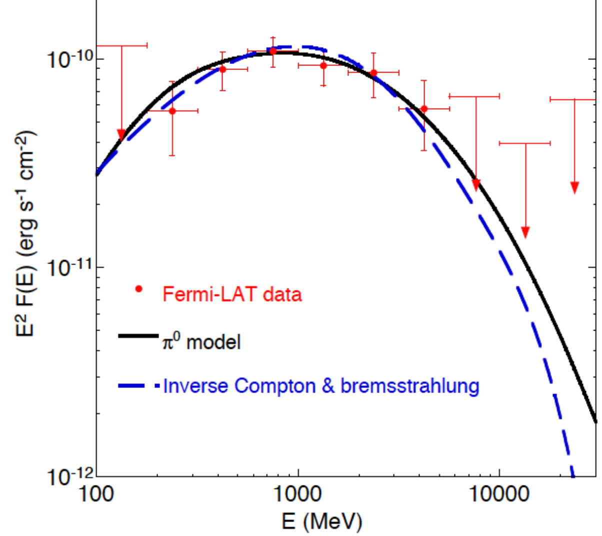
✧ In the last few years the Fermi-LAT has discovered GeV gamma-ray emission from a few more novae: V1324 Sco, V959 Mon, V339 Del, and V1369 Cen (Ackermann et al. 2014)

Novae

V407 Cygni



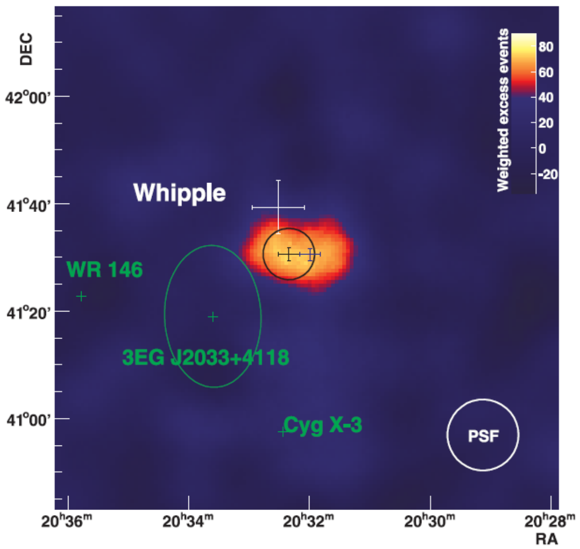
Abdo et al. 2010 Sci 329, 817A

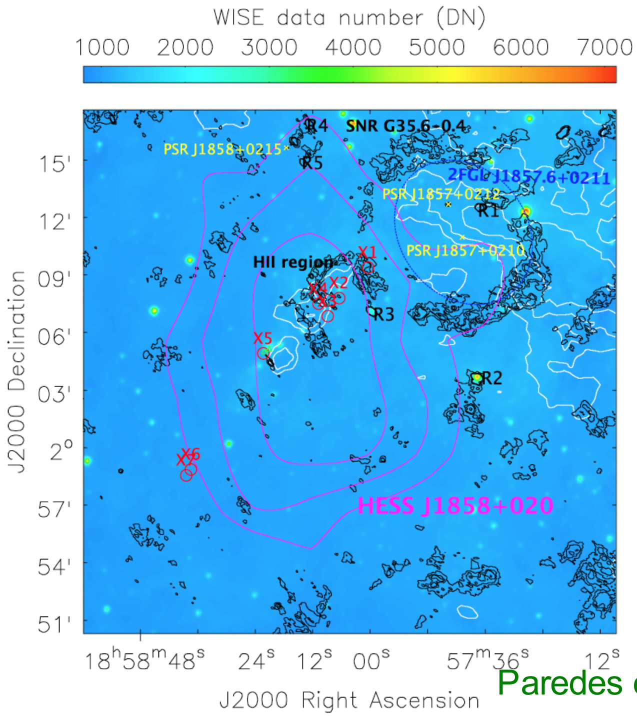


Unidentified sources

EGRET 62%	Cherenkov 18%	*Fermi* 31%

HEGRA detection (Aharonian et al. 2002, A&A 293, L37)
MAGIC (Albert et al. 2008, ApJ, 675, L25)
VERITAS (Aliu et al. 2014, ApJ 783, 16)





Paredes et al. 2014, A&A 561,A56

- ❑ Extended gamma-ray sources (HEGRA, MILAGRO)
- ❑~ Point-like non-variable gamma-ray sources (HESSJ1858+020)
- ❑ Flaring (Transient) gamma-ray sources (AGL J2241+4454)

AGL J2241+4454 Lucarelli et al. 2010, Atel 2761

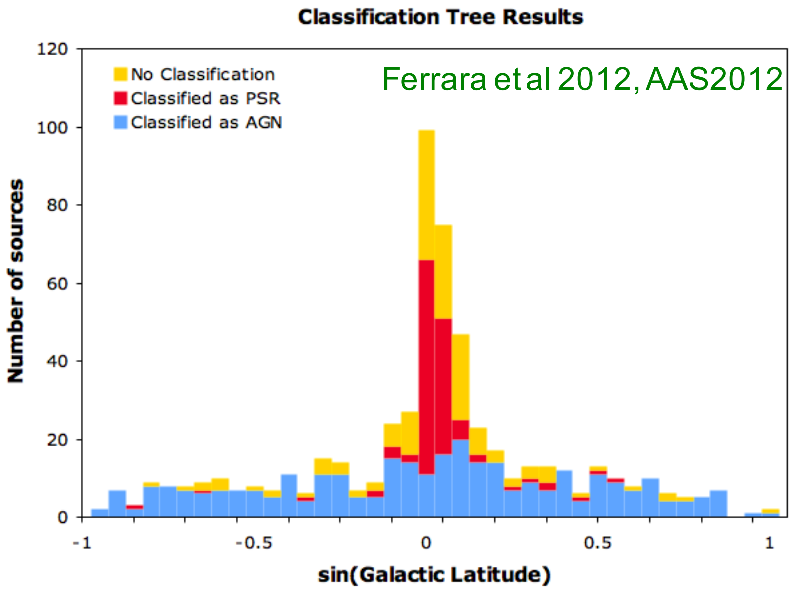
Short γ-ray flare: 2010-07-25 01:00 UT to 2010-07-26 23:30 UT,
→ detection (>5σ), flux > 1.5 × 10^{-6} ph/cm^2/s (E > 100 MeV)

Be star HD 215227 (= MWC 656)

- P= 60.37 ± 0.04 d, optical photometry
  Williams et al. 2010, ApJ 723, L93

MWC 656, the first Be/BH binary
Casares et al. 2014, Nature 505, 378

Not yet confirmed the association between AGL J2241+4454 and MWC 656
Work in progress



Fermi-LAT Unassociated Sources in the 2FGL Catalog

Using classification techniques:

315 AGN candidates,
114 pulsar candidates and
144 sources unable to be classified by this method

- Several of the unassociated GeV sources show curved spectra suggesting that their TeV emission may be on a much lower level.
  Cut-off or a second high energy spectral component?

Need of good quality spectra at energies clearly below ~100 GeV

- Observations of the unidentified GeV-TeV γ-ray objects, with an order of magnitude **more sensitive** instrument and with the **better angular resolution** will provide important constraints on the sites of particle acceleration in the Galaxy.

- Such instrument → Investigate fine structures of the much extended sources (The number of such extended sources will certainly increase with the next generation of the water tank Cherenkov detectors)
  → Locate bright transient sources with high accuracy

Conclusion

- Contribute to study all type of astrophysical sources and discover new ones

Good low-energy sensitivity and spatial resolution:

- π^0-decay bump in more (and fainter) **SNR**s
- More **nova** detections
- Fill the spectrum gap (~1 GeV) in the **gamma-ray binaries**
- Interaction between jets and ISM (**microquasars**)
- **Identify** more γ-ray SNRs
- Resolve **acceleration regions** & track escape
- For bright **transient** sources, Galactic and Extragalactic, obtain a deeper continuous short-term exposure
- Obtain **simultaneous** 1-100 GeV data in selected AGNs
- Constrain the opacity of the Universe, constrain **EBL** models
- Unveil the **nature of the unidentified** sources (high angular resolution and sensitivity)