Fermi Gamma-ray Space Telescope

Fermi Results on High-Energy Gamma-Ray Sources

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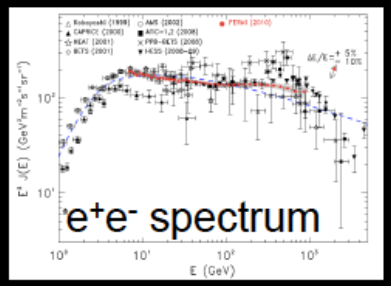
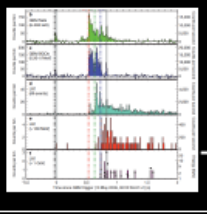
NASA Goddard Space Flight Center

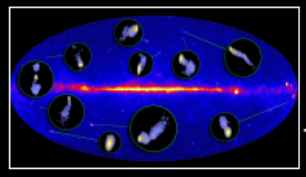
on behalf of the *Fermi* Collaboration

Fermi Highlights and Discoveries

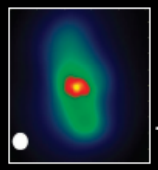




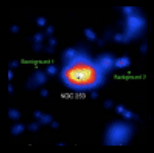
GRBs



Blazars (782)

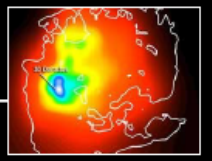


Radio Galaxies (12)

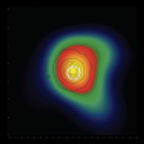


Star Burst Galaxies (4)

Extragalactic

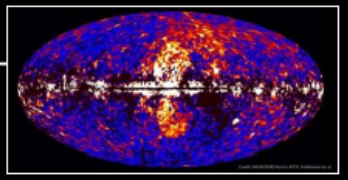


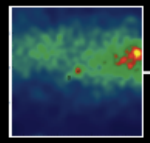
LMC & SMC



Globular Clusters (11)

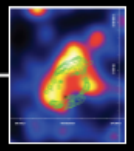
Fermi Bubbles

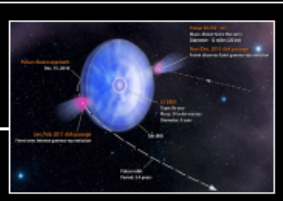




Nova (1)

SNRs & PWN (68)

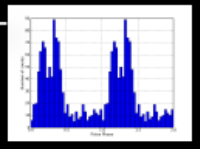




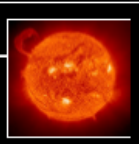
Galactic

γ-ray Binaries (6)

Pulsars: isolated, binaries, & MSPs (122)



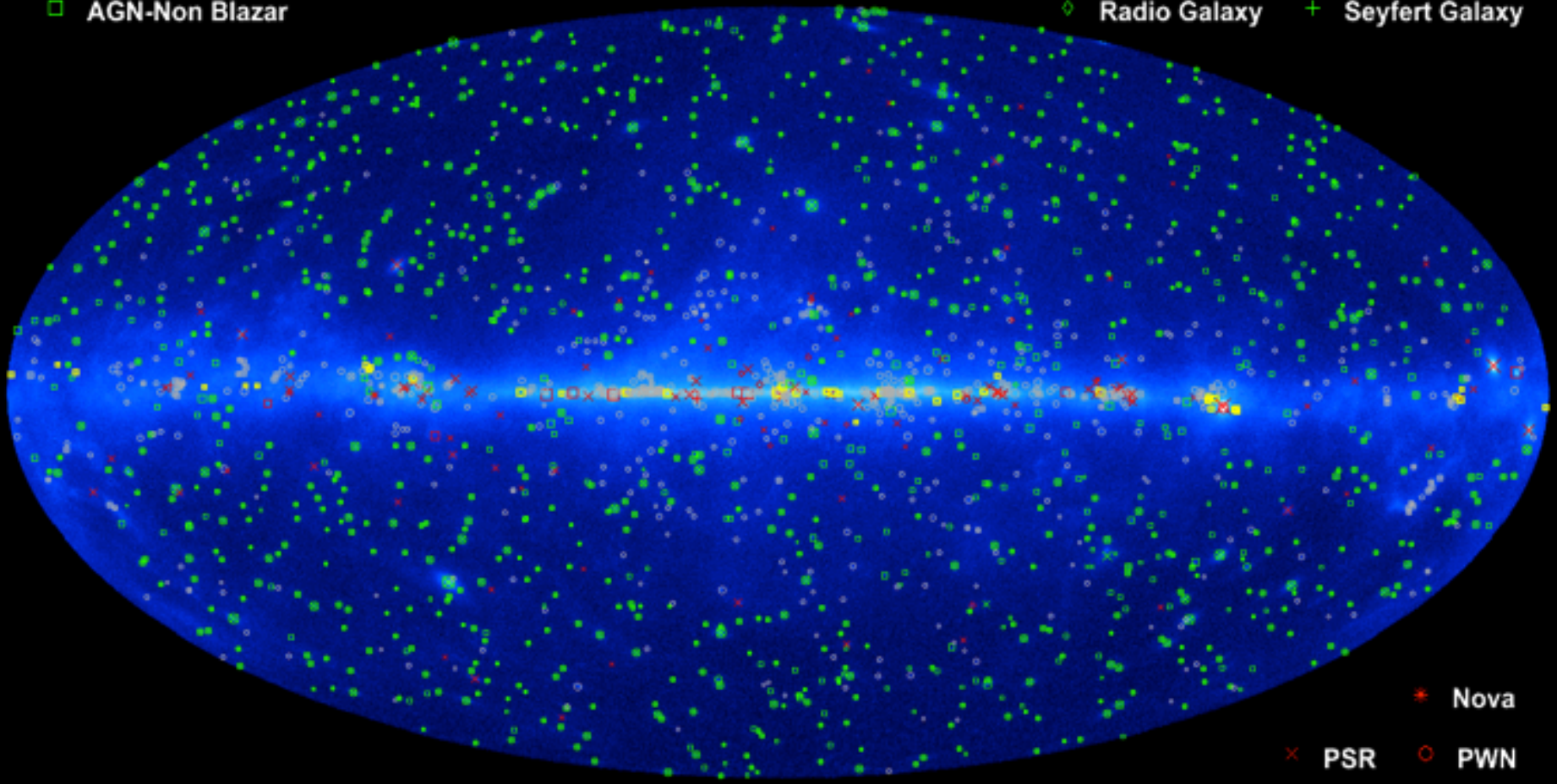
Sun: flares & CR interactions



TGFs

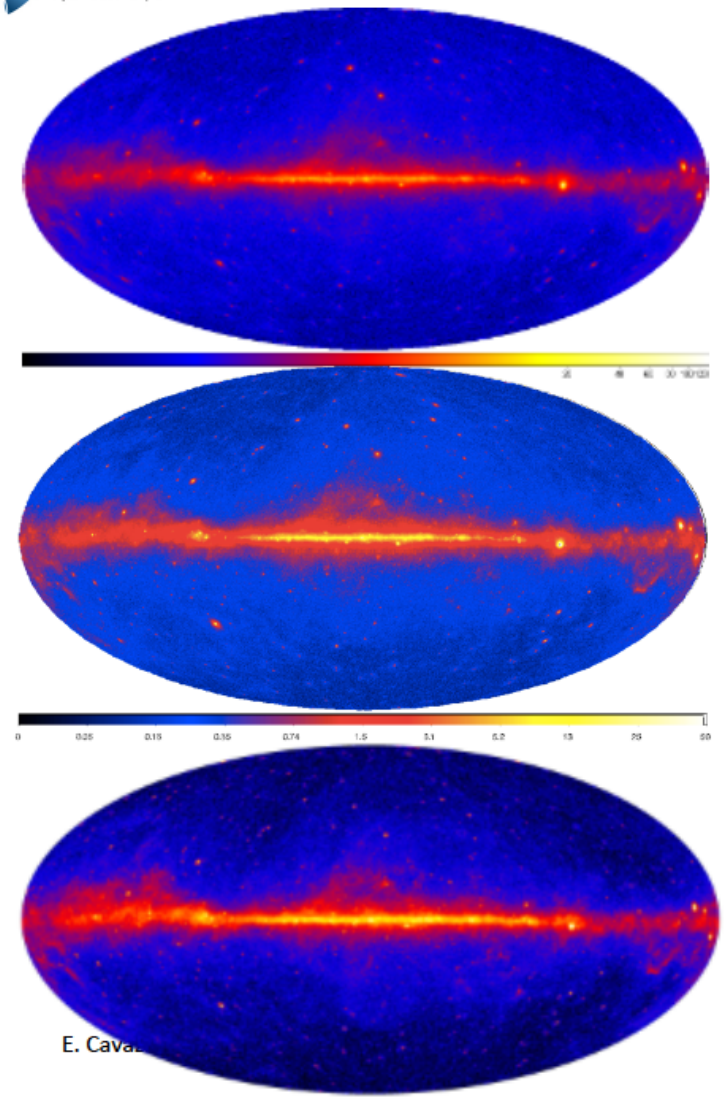
Unidentified Sources (600)

Fermi Large Area Telescope 2FGL catalog



Credit: Fermi Large Area Telescope Collaboration

Fermi LAT source catalogs



1FGL
11 m
1451 srcs
43% unassoc.

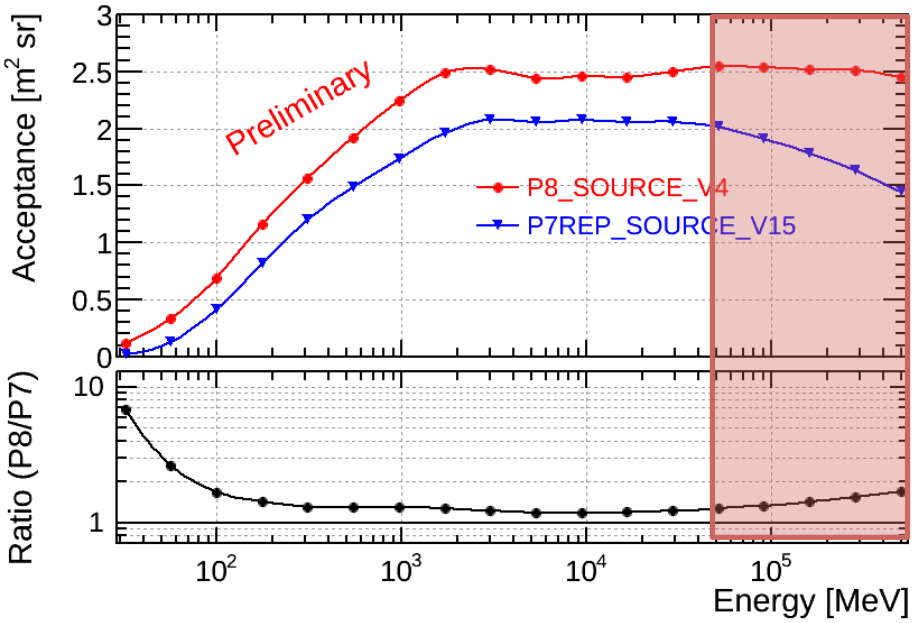
2FGL
2 y
1873
35% unassoc.

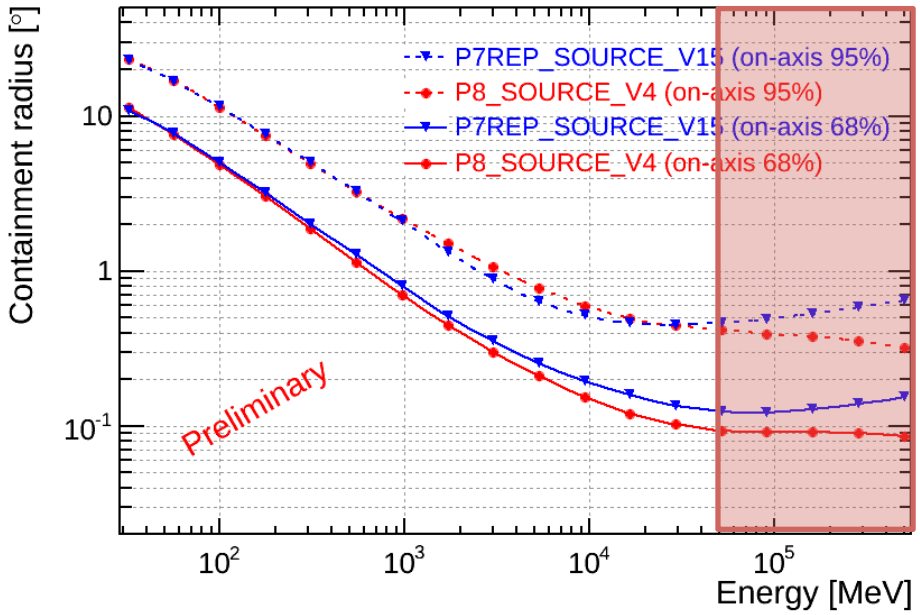
3FGL
4 y
3033
33% unassoc.

http://arxiv.org/abs/1501.02003

Pass 8

Constant PSF at >50 GeV !





- ***Recipe for success:***
  1. **Improve PSF and Acceptance (factor of 0.5-2 in P8)**
  2. **Low background and good PSF (0.1 deg at 68%)**
  3. **All-sky exposure**

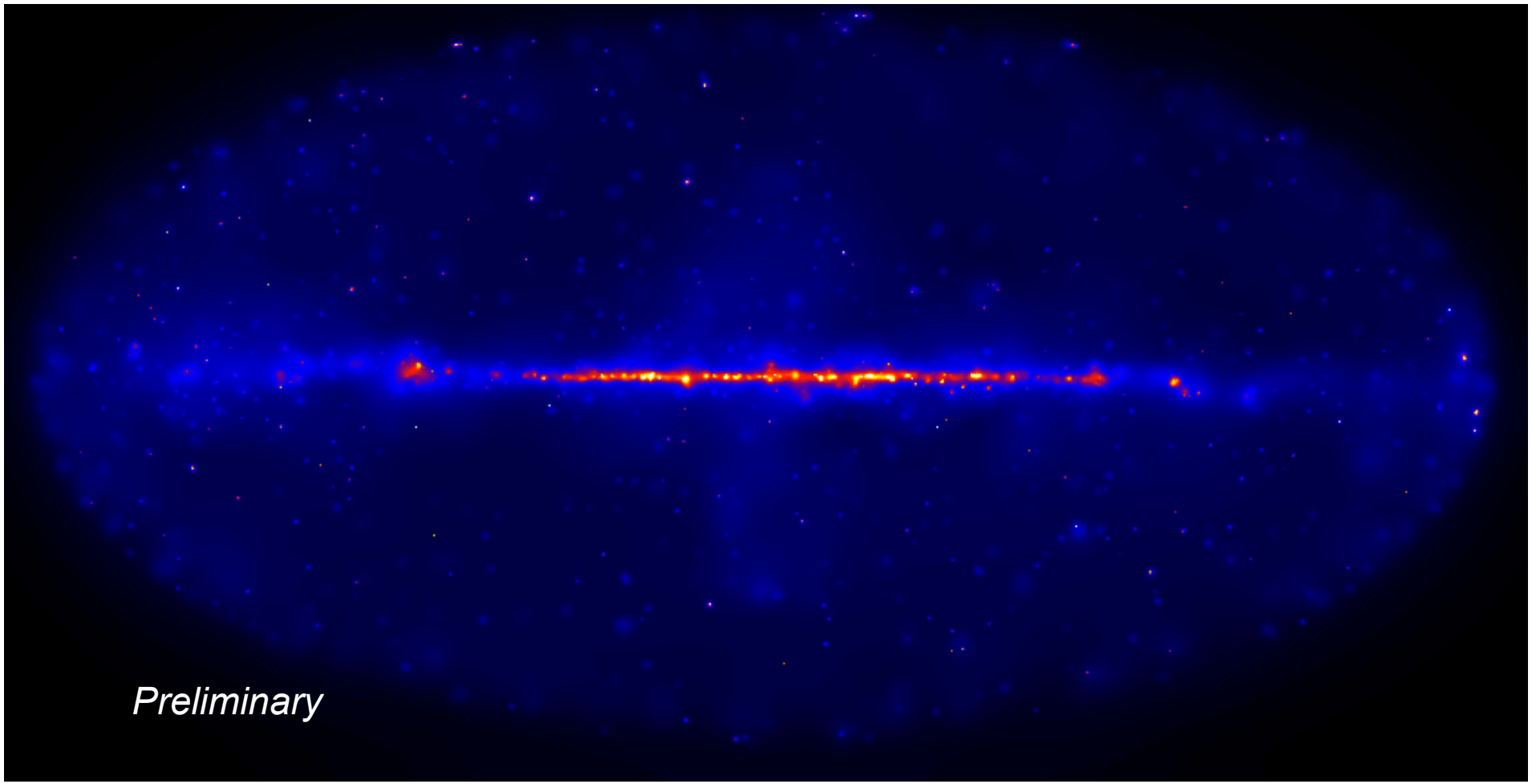
- **Catalog of sources detected at >50 GeV**
  - **Allows study of the EBL, EGB, Galactic plane etc.**
  - **Continues our effort to characterize sources at high energies**
  - **Connects well to ACTs, HAWC and the upcoming CTA**

2FHL Count Map

~6 years of P8 data (50 GeV – 2 TeV)

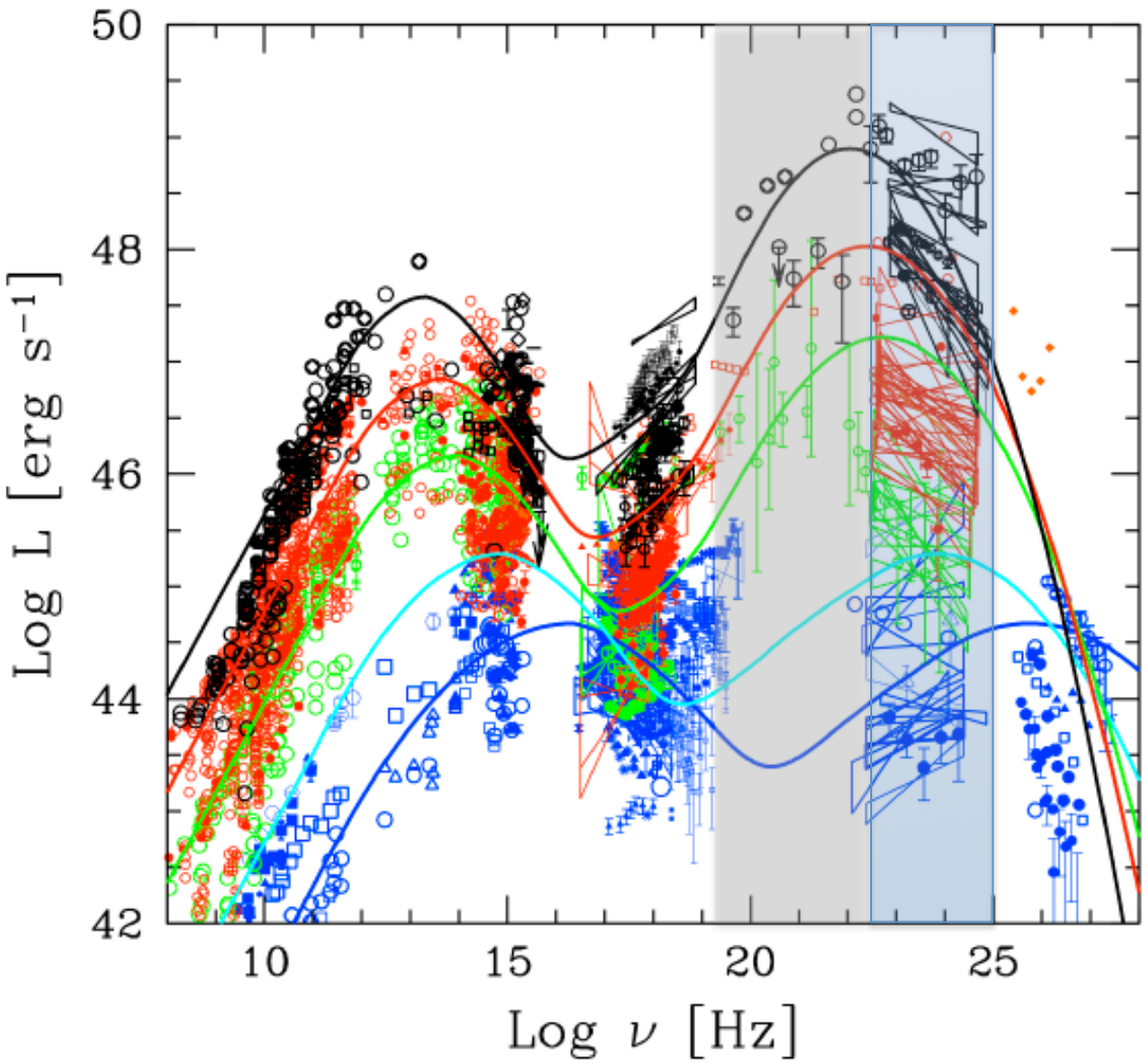
51,000 photons E > 50 GeV
18,000 photons E > 100 GeV
2,000 photons E > 500 GeV

~320 sources
71 detected by ACTs (TeVCat)
234 detected in 3FGL (<- 4 years up to 300 GeV)
~60 brand new sources



Fermi and the blazar sequence

3rd LAT AGN Catalog (Lott et a. 2015): 1591 sources (98% blazars)



FSRQs

Low synchrotron peak

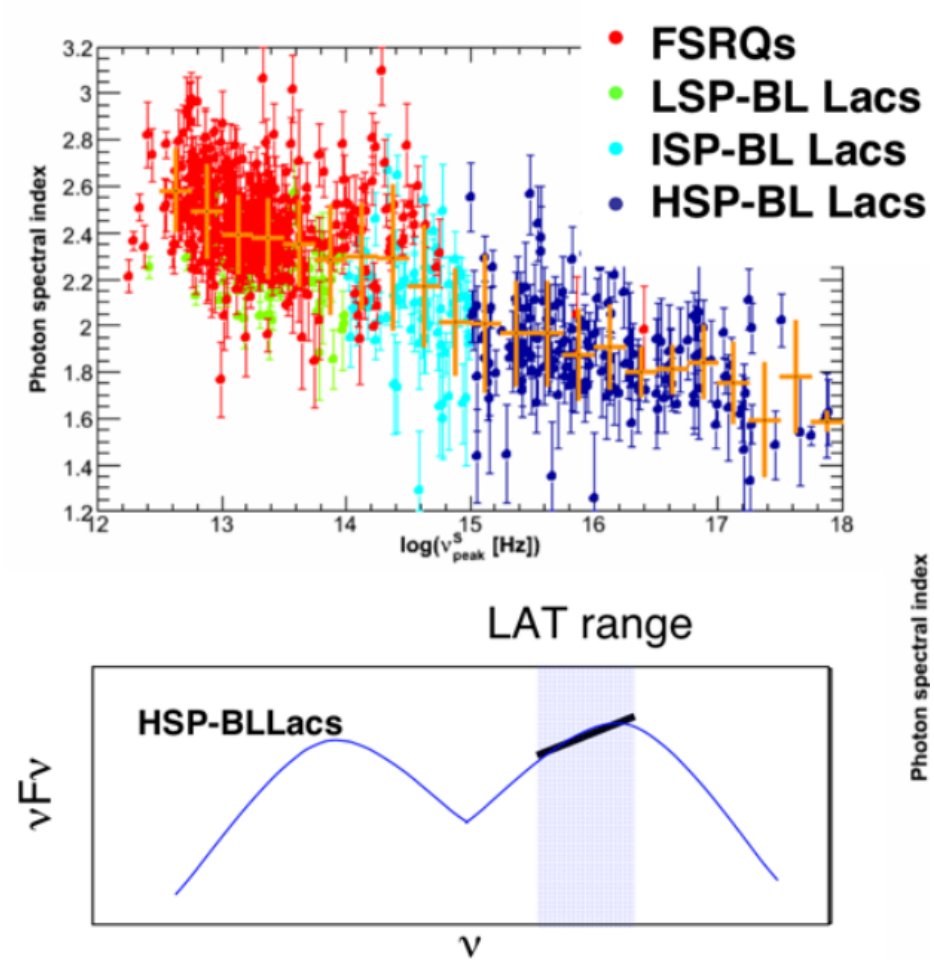
External radiation field

High synchrotron peak

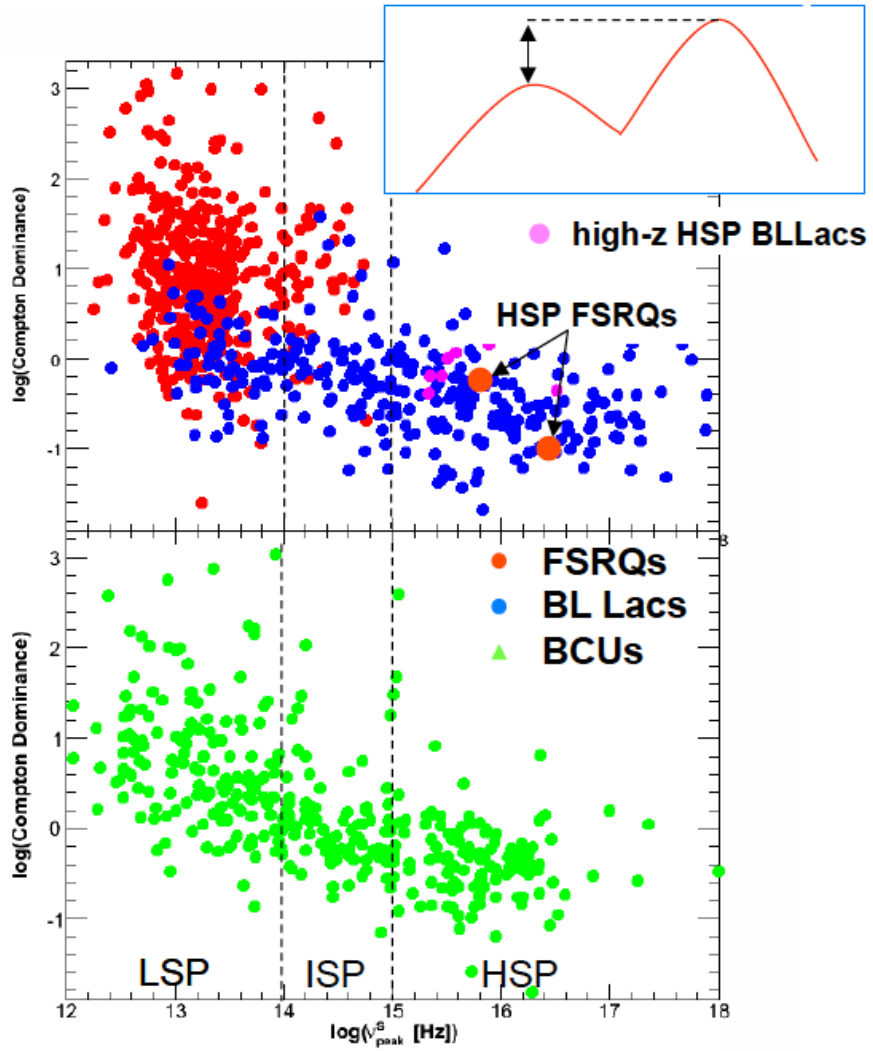
BL Lacs

Blazar spectral correlation

Correlation between spectral hardness and ν_{peak}



Credit: J. Perkins and Fermi-LAT Collaboration



Credit: B. Lott

Leptonic and hadronic emission models

- Leptonic models (Maraschi et al. 1992, Dermer et al. 1992)
  - Low energy

    $e^{\pm}B \rightarrow \gamma$
  - High energy (either SSC or external IC)

    $e^{\pm}\gamma \rightarrow e^{\pm}\gamma$

- Hadronic models (Stecker et al. 1991, Bottcher et al. 2012)
  - Low energy

    $e^{\pm}B \rightarrow \gamma$
  - High energy

$p\gamma \rightarrow n\pi^{+}$

$e^{-}\tilde{\nu}_{e}p \rightarrow \mu^{+}e^{+}\nu_{\mu}\tilde{\nu}_{\mu}\nu_{e}$

$pp \rightarrow pN^{*} \rightarrow \pi^{+}\pi^{0}$

$\pi^{0} \rightarrow \gamma\gamma$

$e^{\pm}B \rightarrow \gamma$ $\quad e^{\pm}\gamma \rightarrow e^{\pm}\gamma$

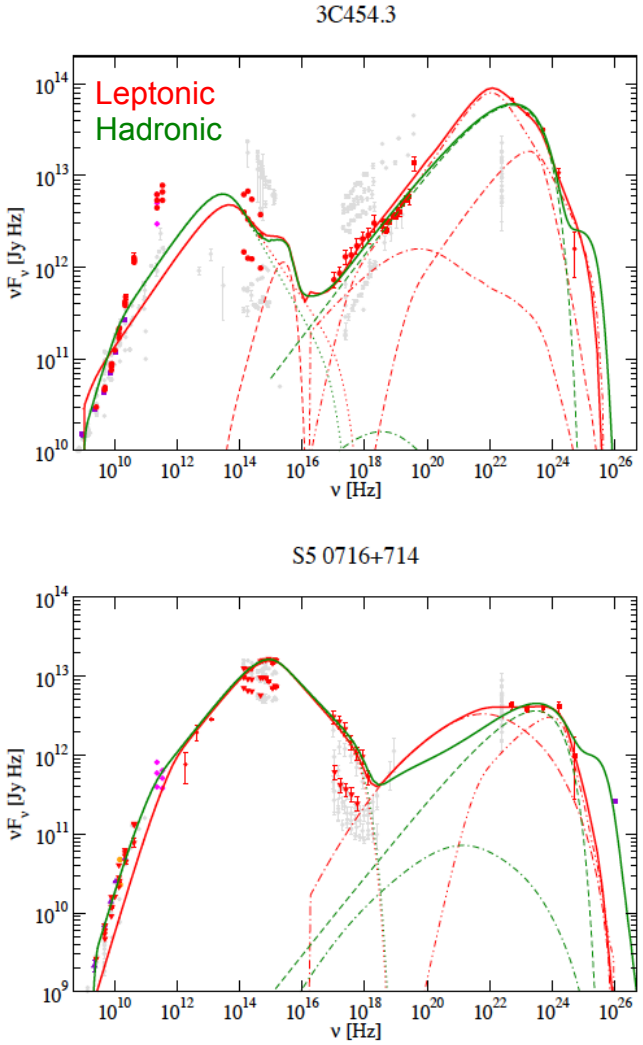
$\mu^{\pm}B \rightarrow \gamma$ $\quad \mu^{\pm}\gamma \rightarrow \mu^{\pm}\gamma$

$\pi^{\pm}B \rightarrow \gamma$

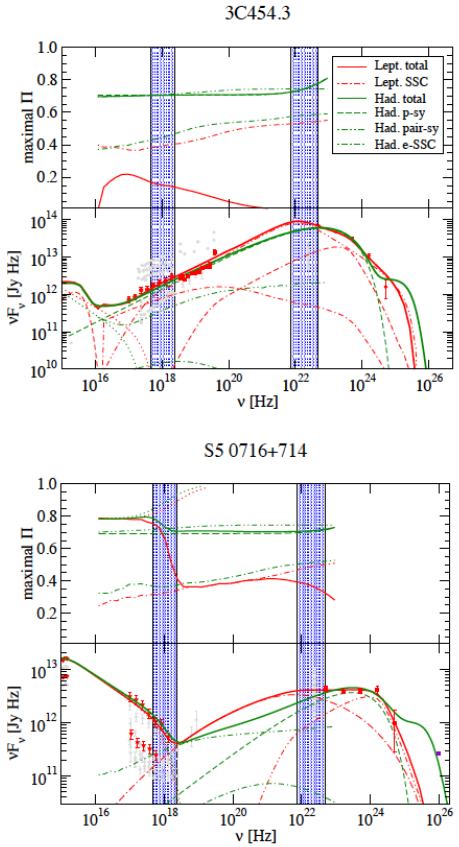
$p\,B \rightarrow \gamma$

Leptonic or hadronic emission??

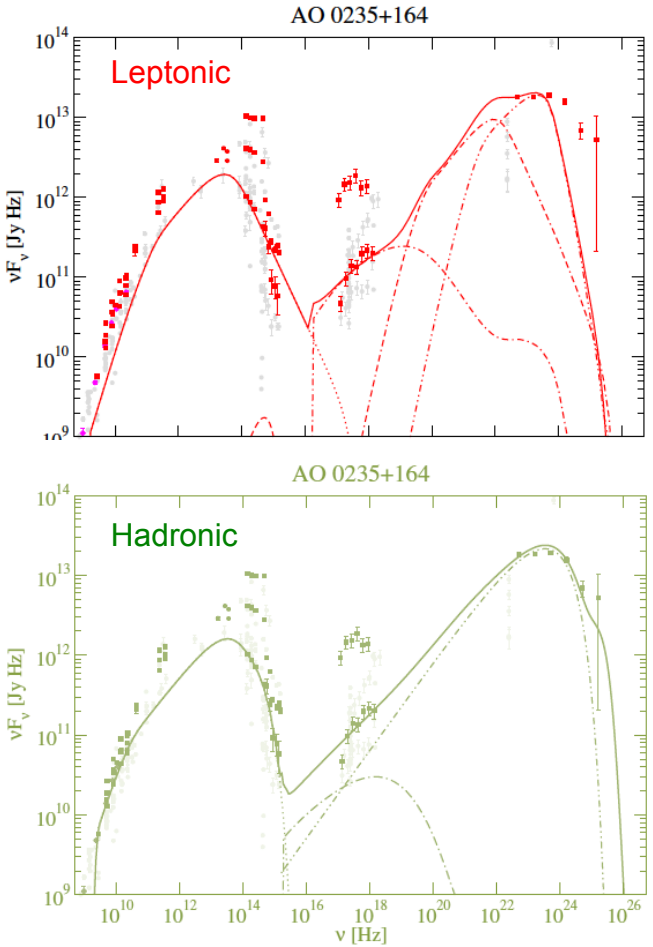
Most blazar spectra well fit by leptonic models



Optical/X-ray polarization can decide

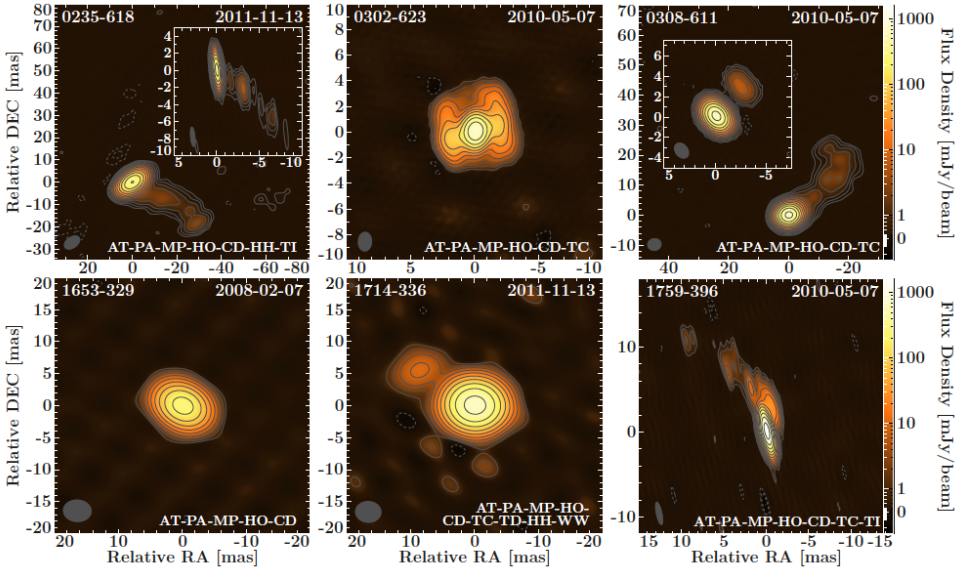


But a few are better fit by hadronic models

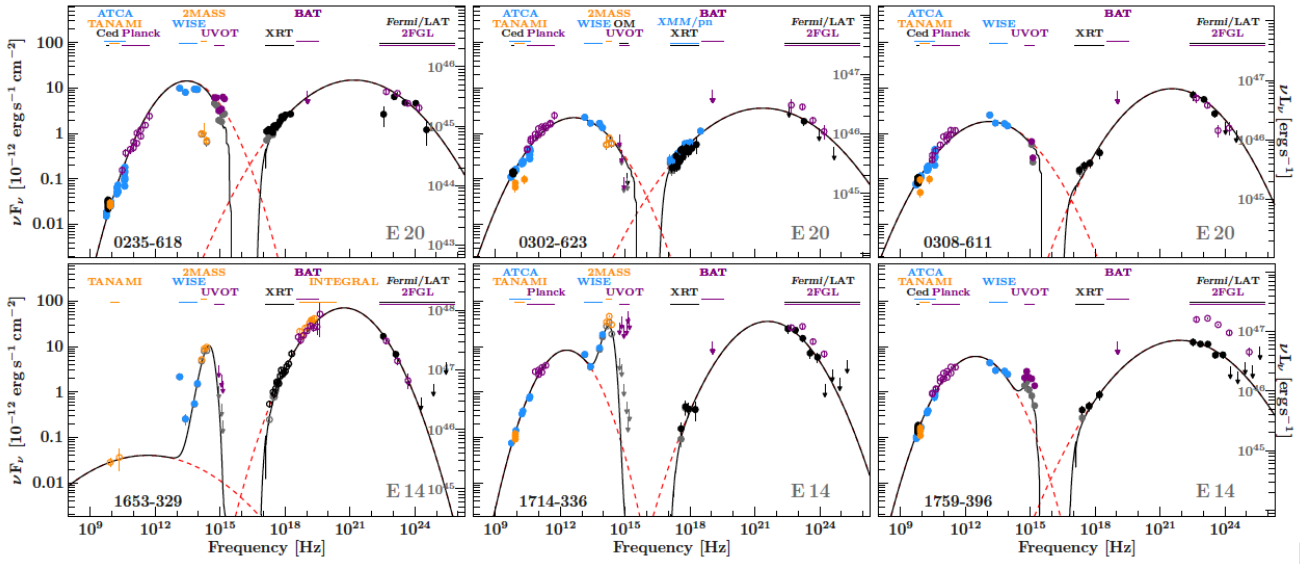


Bottcher et al. 2013

TANAMI blazars and neutrinos



Six brightest blazars in TANAMI radio sample are coincident with 2 reported IceCube PeV neutrino events



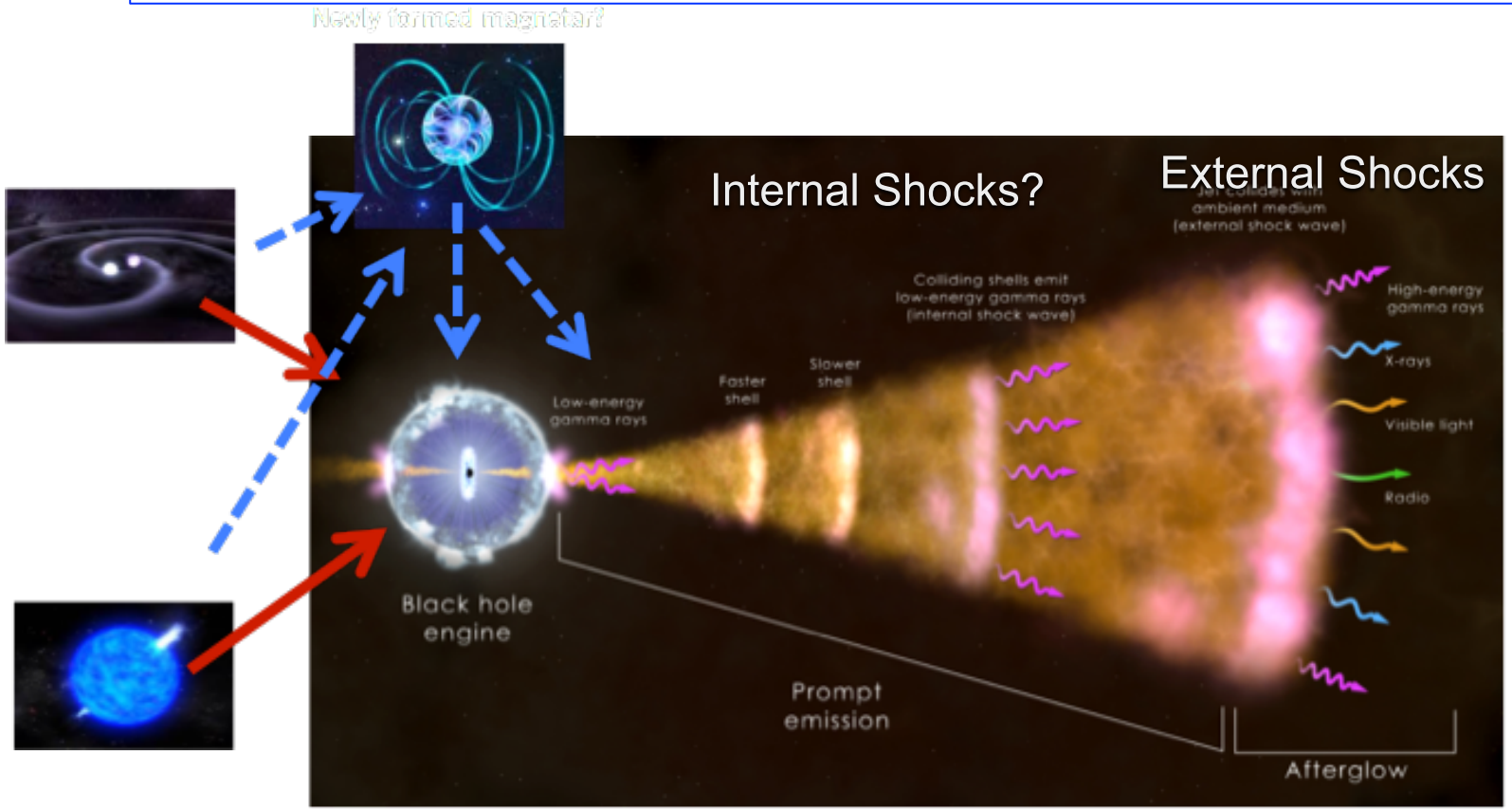
Assume photopion production in jet

Integrated ν flux can explain 2 PeV events

Krauss et al. 2014

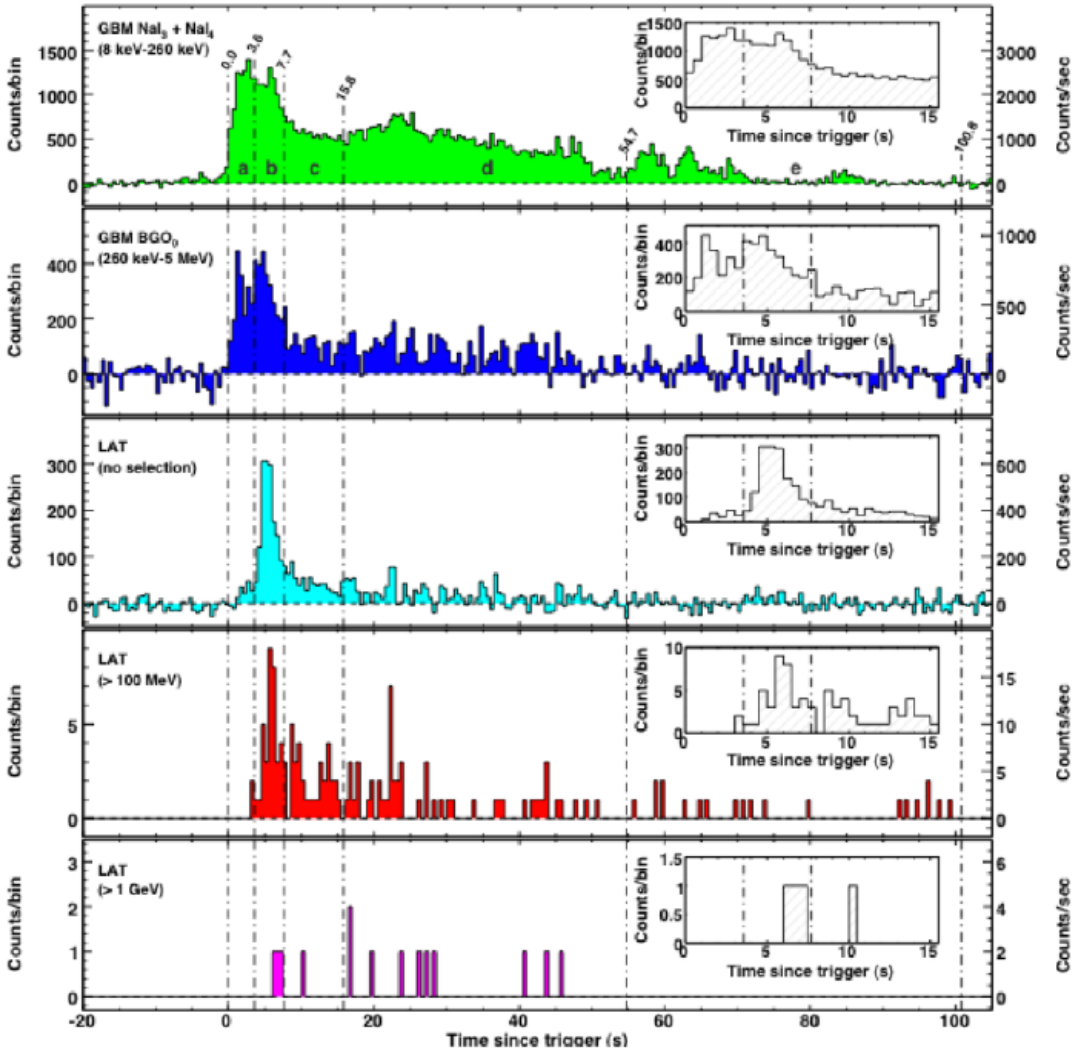
Gamma-ray bursts

Major questions:
What is the jet composition (leptons, baryons, Poynting flux)?
What is the energy dissipation and particle acceleration mechanism in the jet (shocks, magnetic reconnection)?
Where is the location of particle acceleration?
What is the radiation mechanism(s) (synchrotron, inverse Compton)?



High energy delayed emission

GRB 080916C (Abdo et al. 2009)



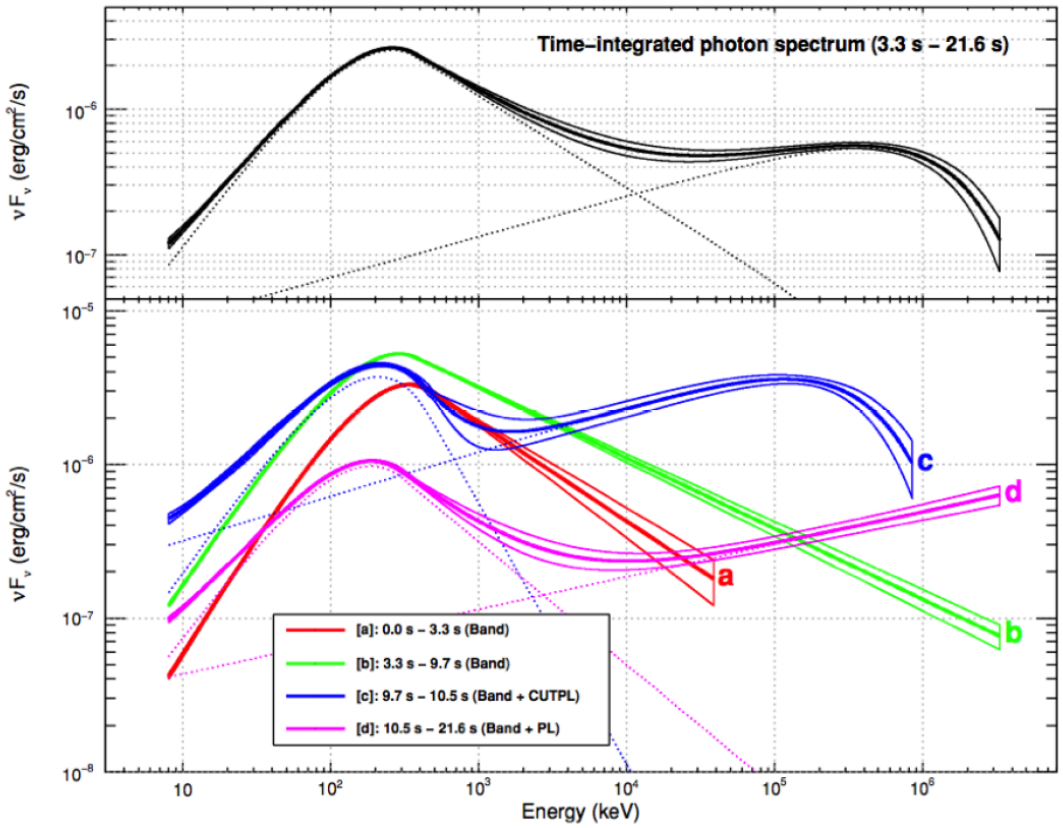
Emission at higher energy is delayed and lasts longer

Smoother HE temporal decay

High energy emission also seen in short bursts!

High energy spectral components

GRB 090926A (Ackermann et al. 2011)

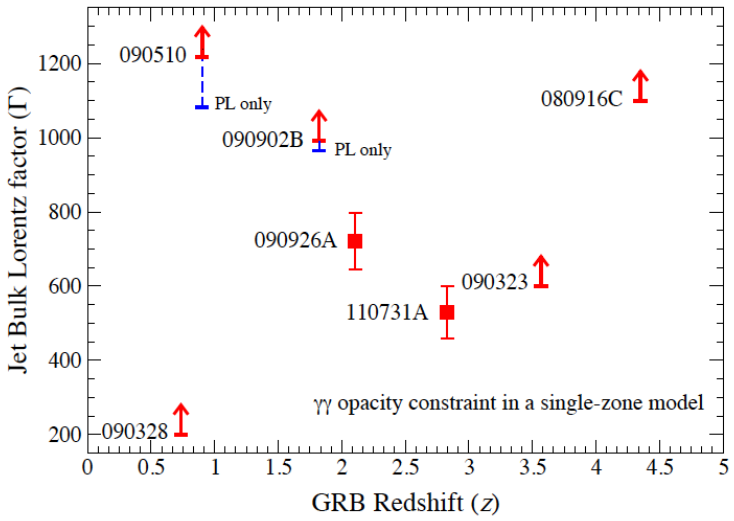


Some bursts show additional spectral component at late times

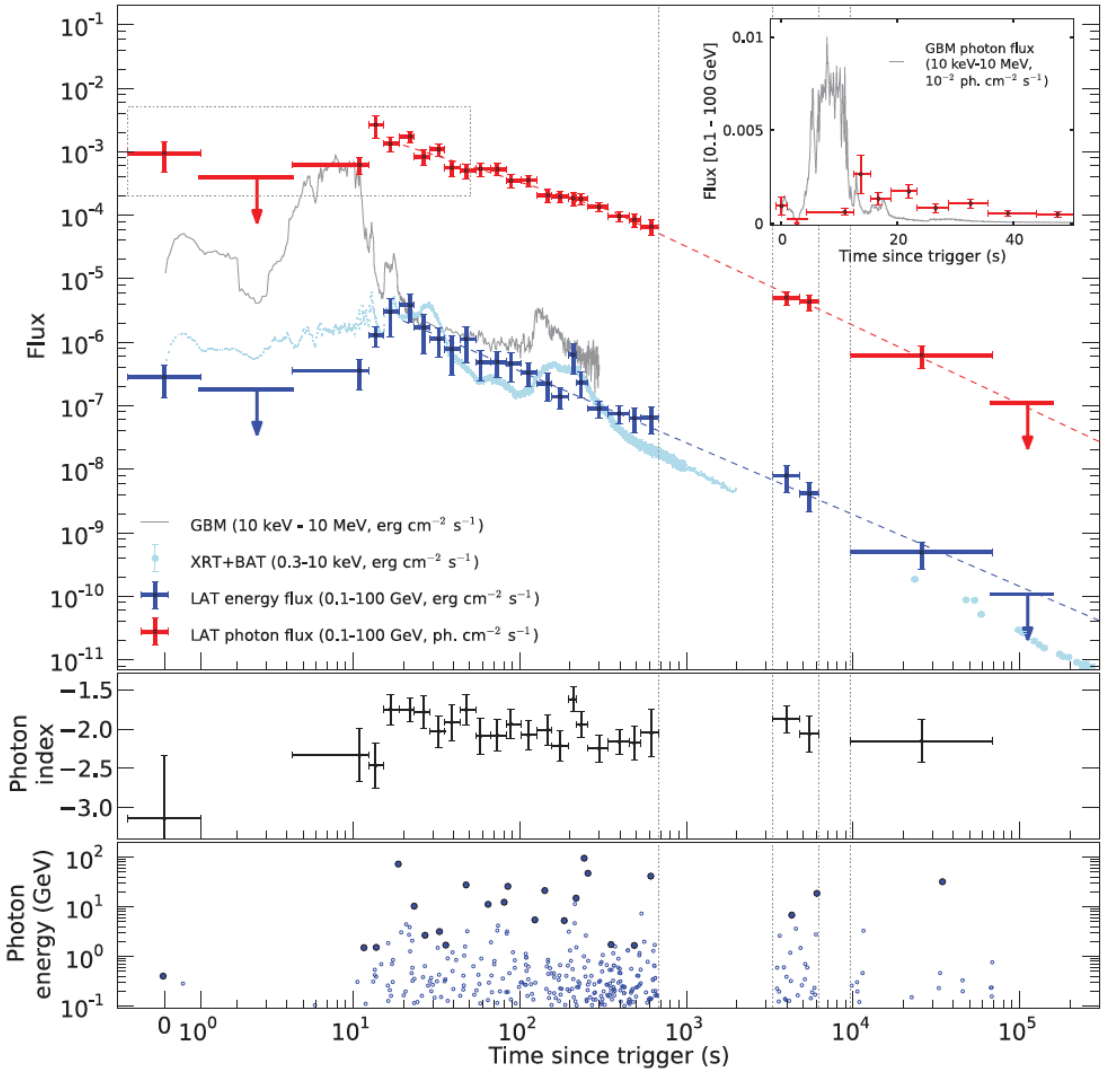
Synchrotron Self-Compton (leptonic)?
(Wang et al. 2009, Toma et al. 2011)

Hadronic processes?
(Razzaque et al. 2010, Asano et al. 2009)

Lack of $\gamma\gamma$ absorption gives high Lorentz factors

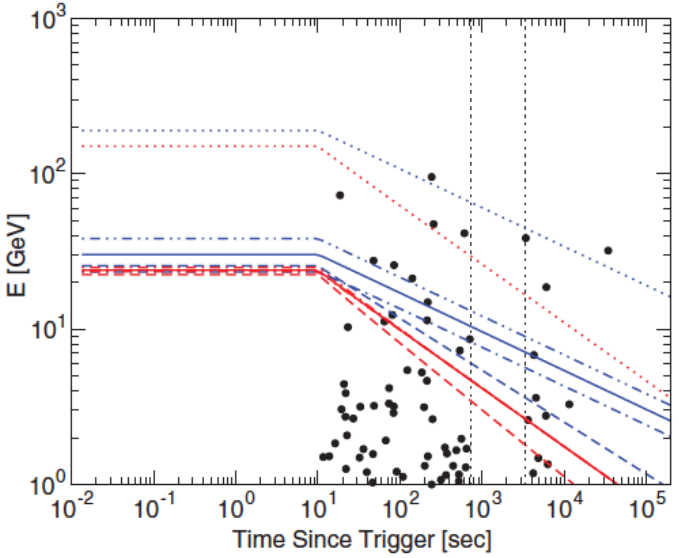


GRB 130427A



Longest of any GRB γ-ray duration – 20 hrs

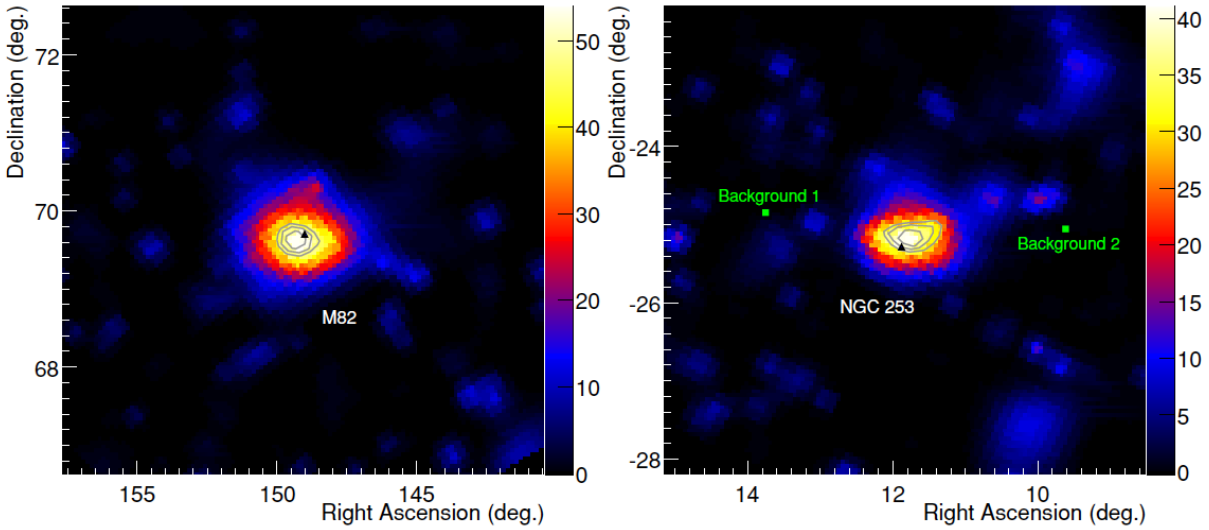
Exceeds maximum synchrotron photon energy

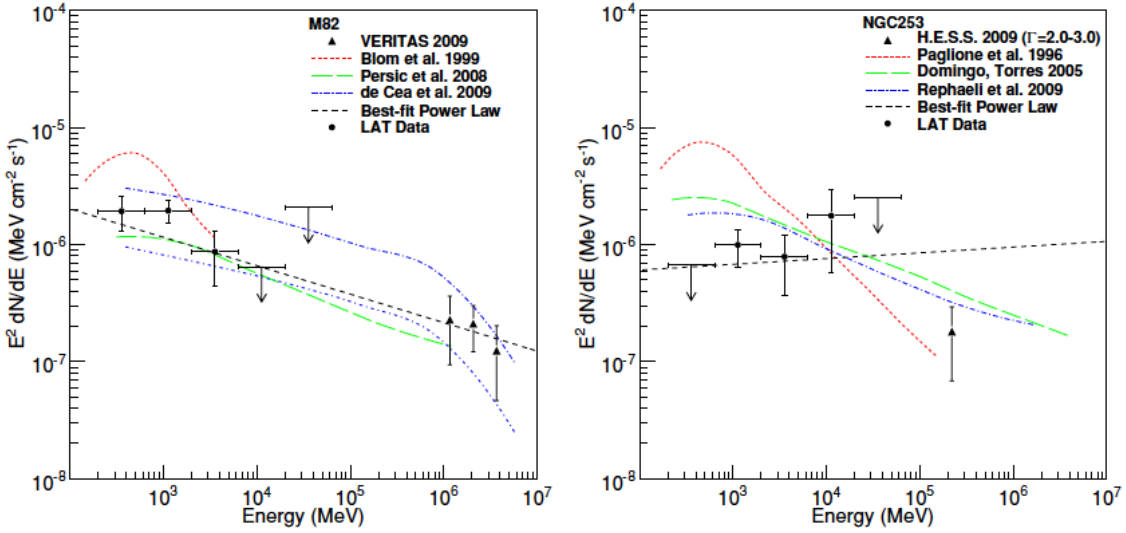


Ackermann et al. 2014

Starburst Galaxies

Abdo et al. 2010





- Total γ−ray flux consistent with CR interactions with gas and radiation fields
- CR density increases with star formation rate – Starburst galaxies are proton calorimeters?
- Expect some neutrino flux (Lacki et al. 2011, Chang & Wang 2014)

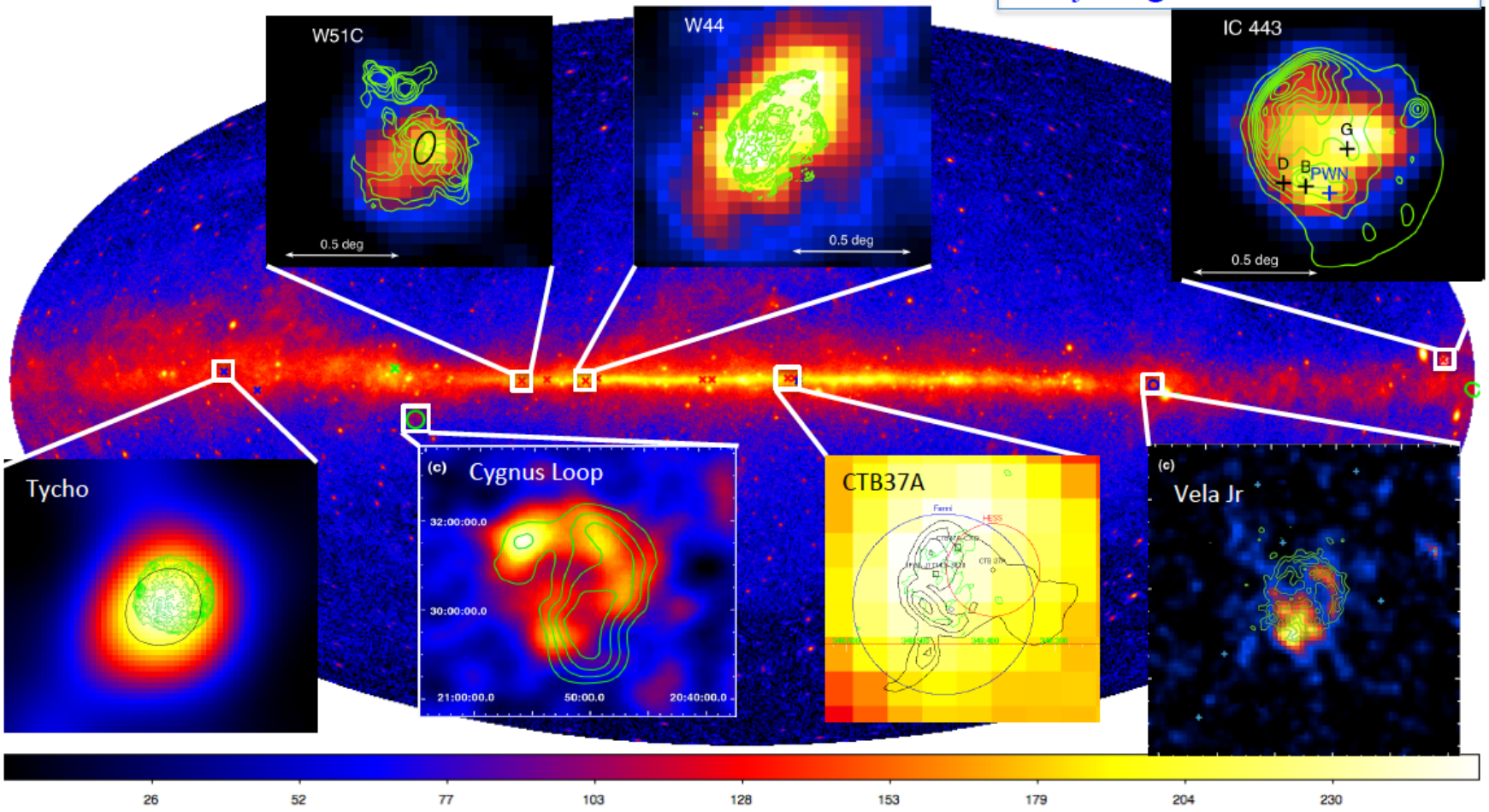
γ-ray flux detected from NGC 4945 may also be due to starburst activity (Lenain et al. 2010)

Supernova remnants

13 identified SNRs, including
- 9 interacting
- 4 young SNRs

Fermi SNR Catalog

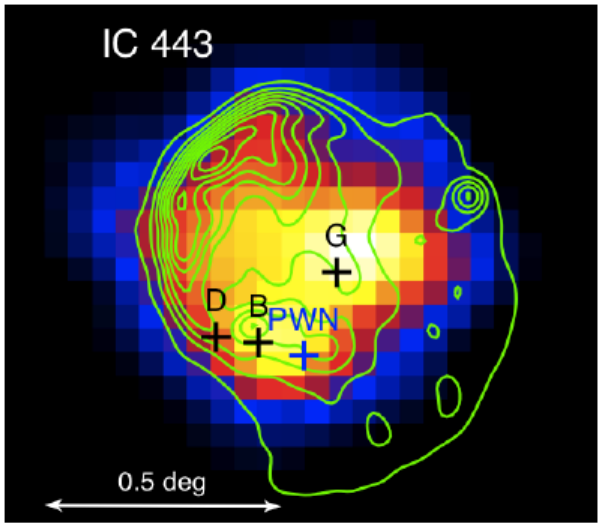
30 classified SNRs, including
- 11 interacting
- 4 young SNRs

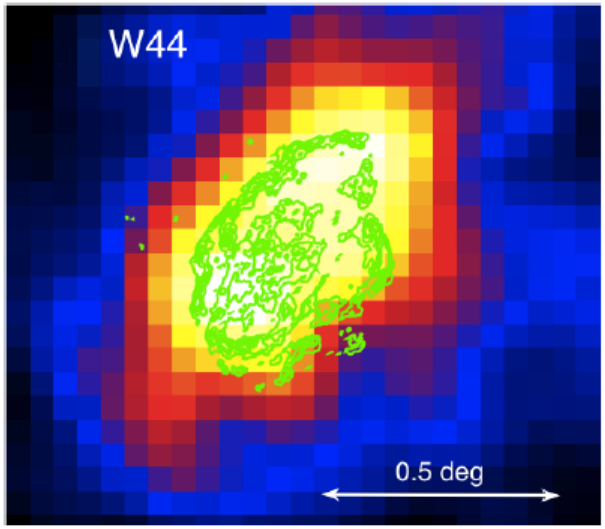


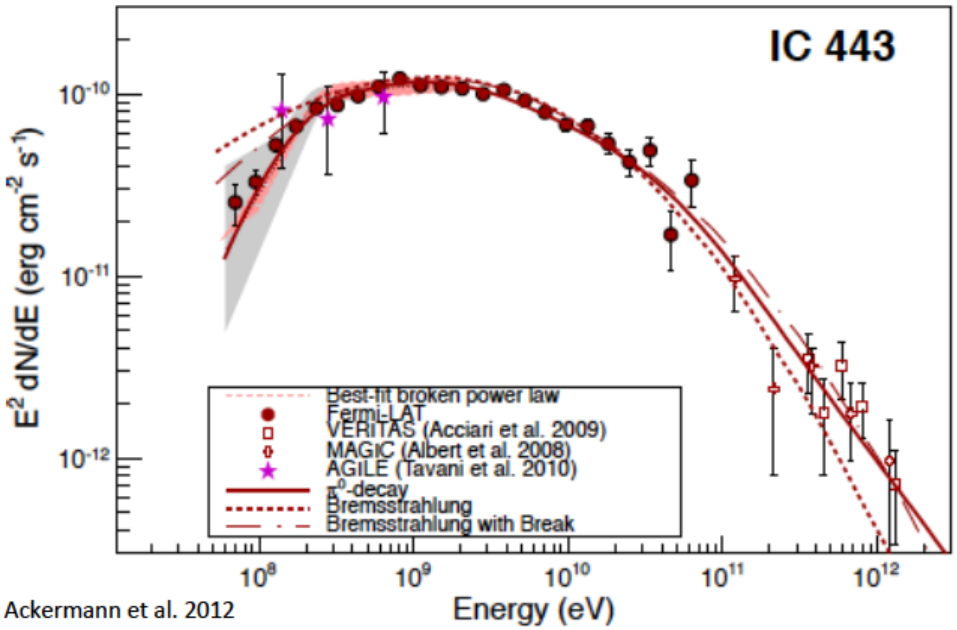
Credit: T. Brandt

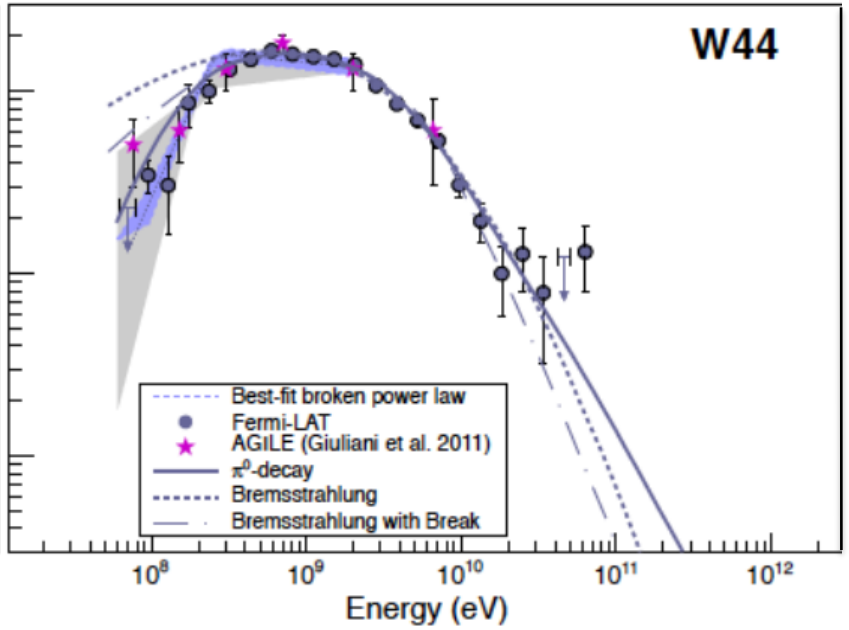
Pion decay bumps

Detection of low energy pion-decay cutoff in 2 SNRs' spectra suggests proton acceleration:





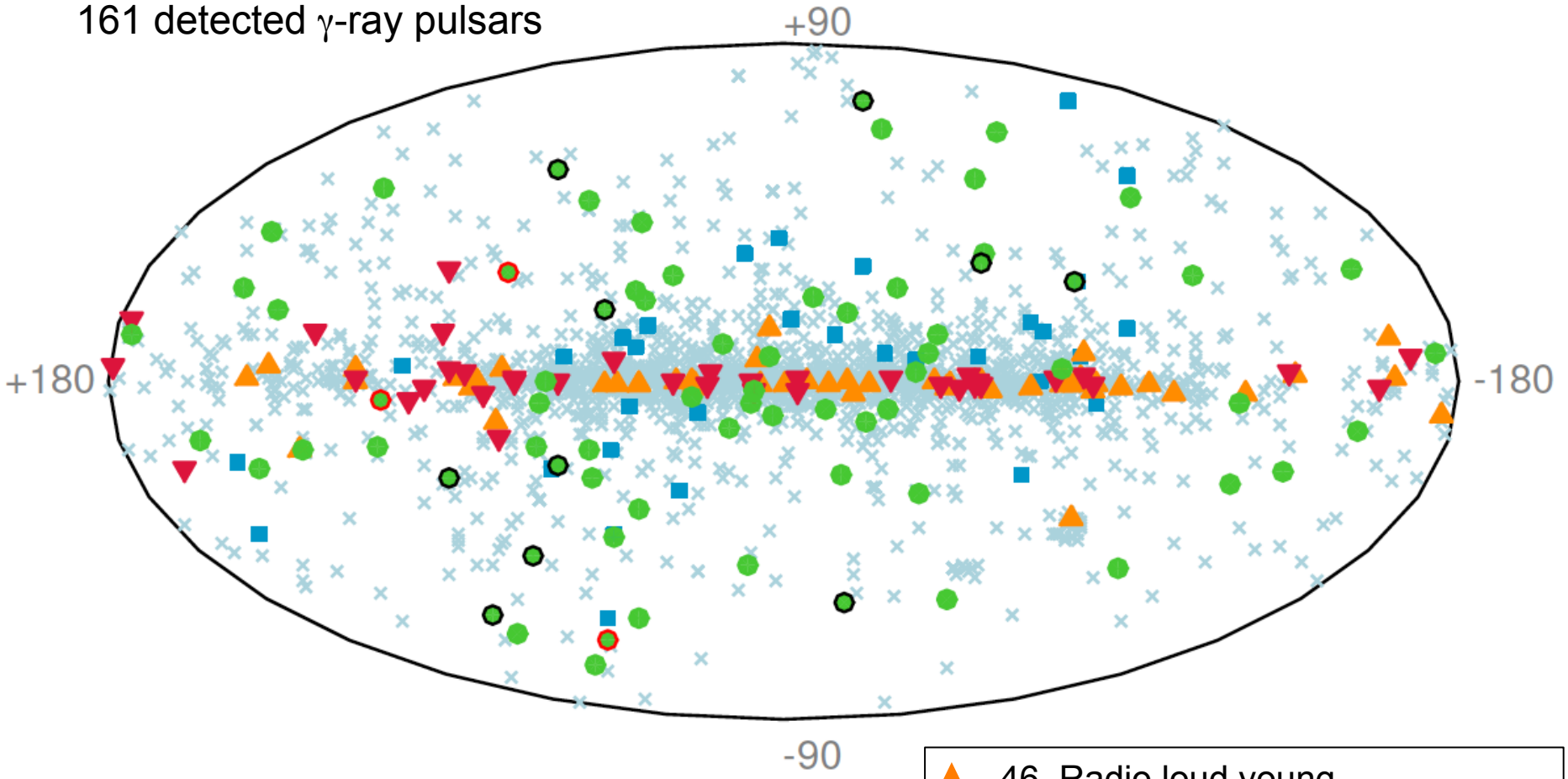




Ackermann et al. 2012

Pulsars

161 detected γ-ray pulsars

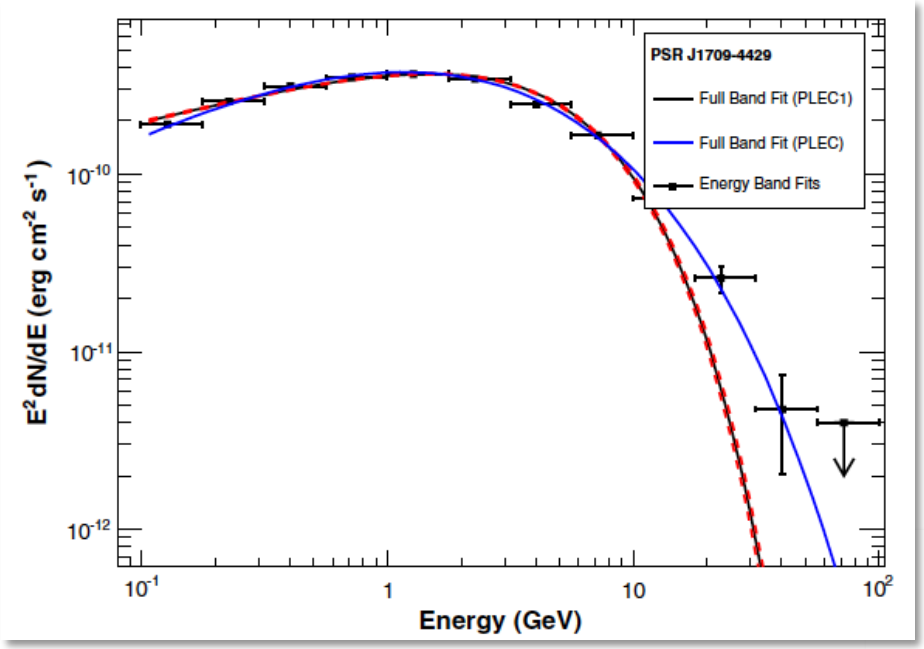


Current public gamma-ray pulsar list
http://tinyurl.com/fermipulsars

Grenier & Harding 2015

46	Radio loud young
44	Radio quiet young
70	Radio loud millisecond
24	Black widow or redback MSPs
67	Radio MSP from LAT UnID

γ-ray pulsar spectra

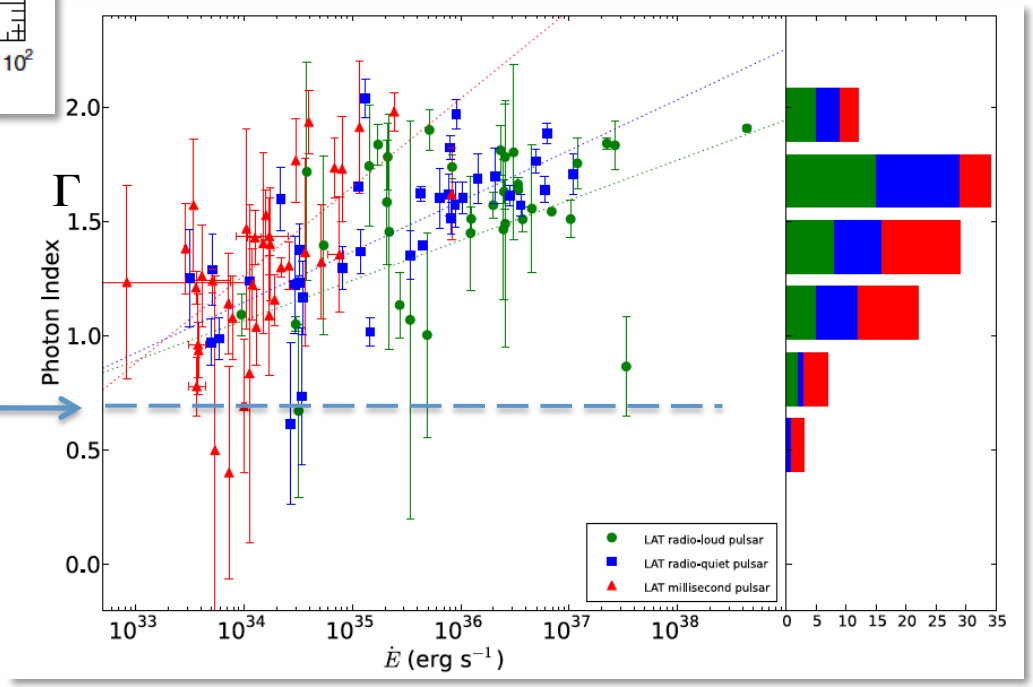


$$N(E) = N_0 E^{-\Gamma} e^{-(E/E_c)^b}$$

Spectrum falls off *slower* than exponential, b < 1

→ emission not close to neutron star

Single particle synchrotron or curvature radiation



γ-ray luminosity and efficiency

Pair cascades limit acceleration voltage to $V_0 \sim 10^{13}$ V

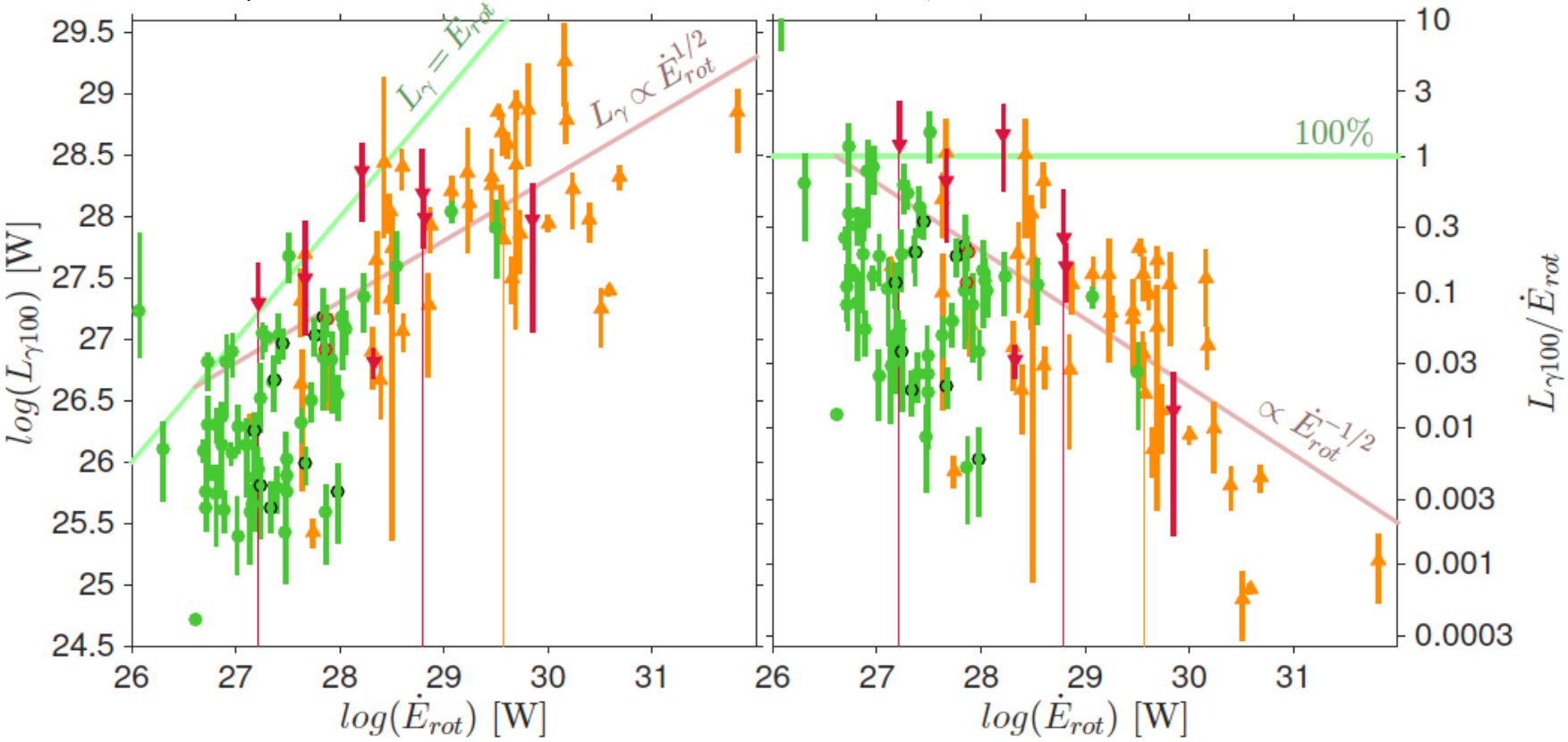
Upper limit inside magnetosphere

Young pulsars $V > V_0$:

$$L_\gamma \approx \dot{n}_{GJ} V_o \propto \dot{E}_{rot}^{1/2}$$

Old pulsars $V < V_0$:

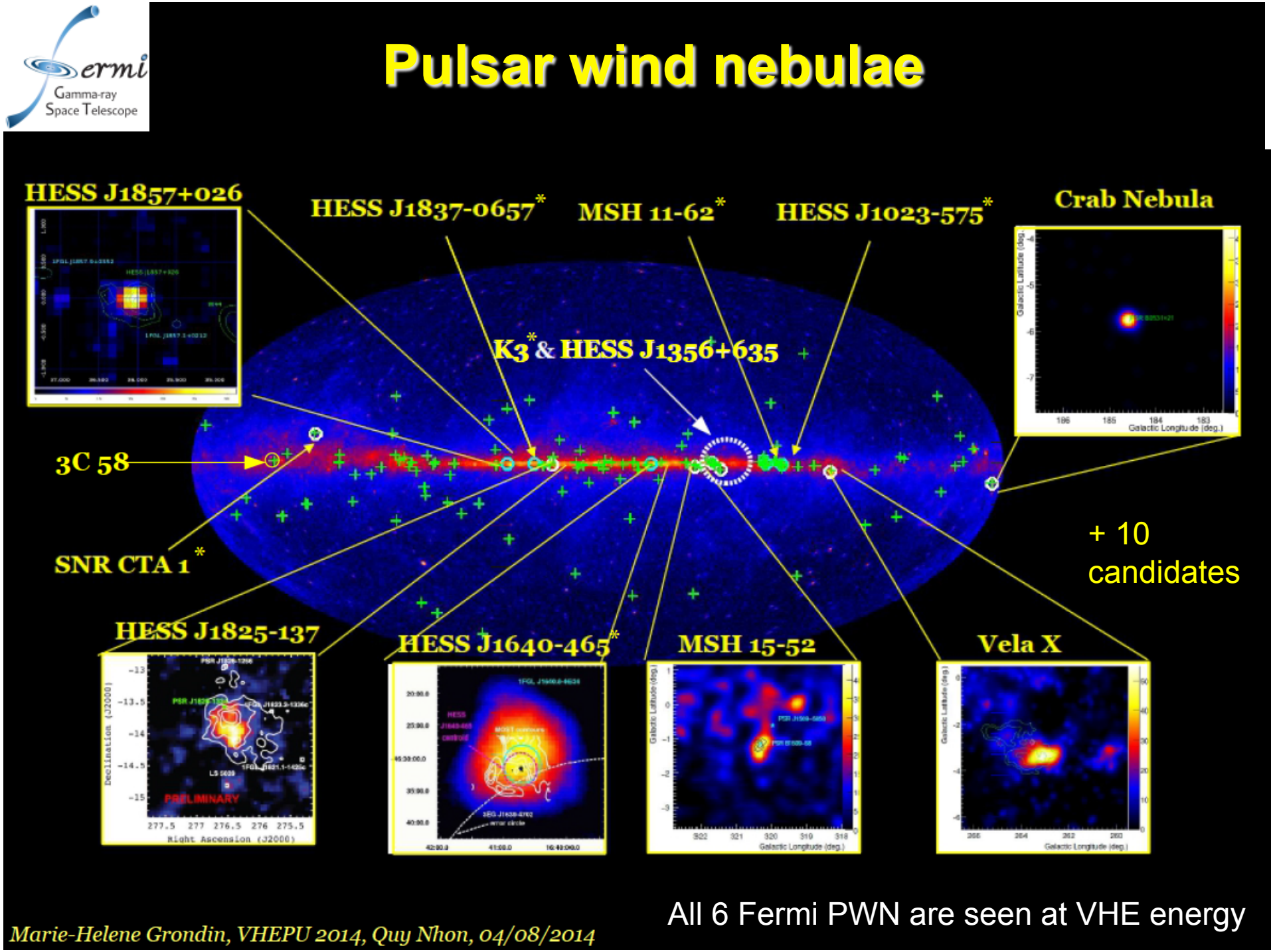
$$L_\gamma \approx \dot{n}_{GJ} V \propto \dot{E}_{rot}$$



▲ Radio loud young
▼ Radio quiet young
● Radio loud MSP

Grenier & Harding 2015

Pulsar wind nebulae



All 6 Fermi PWN are seen at VHE energy

The flaring Crab nebula

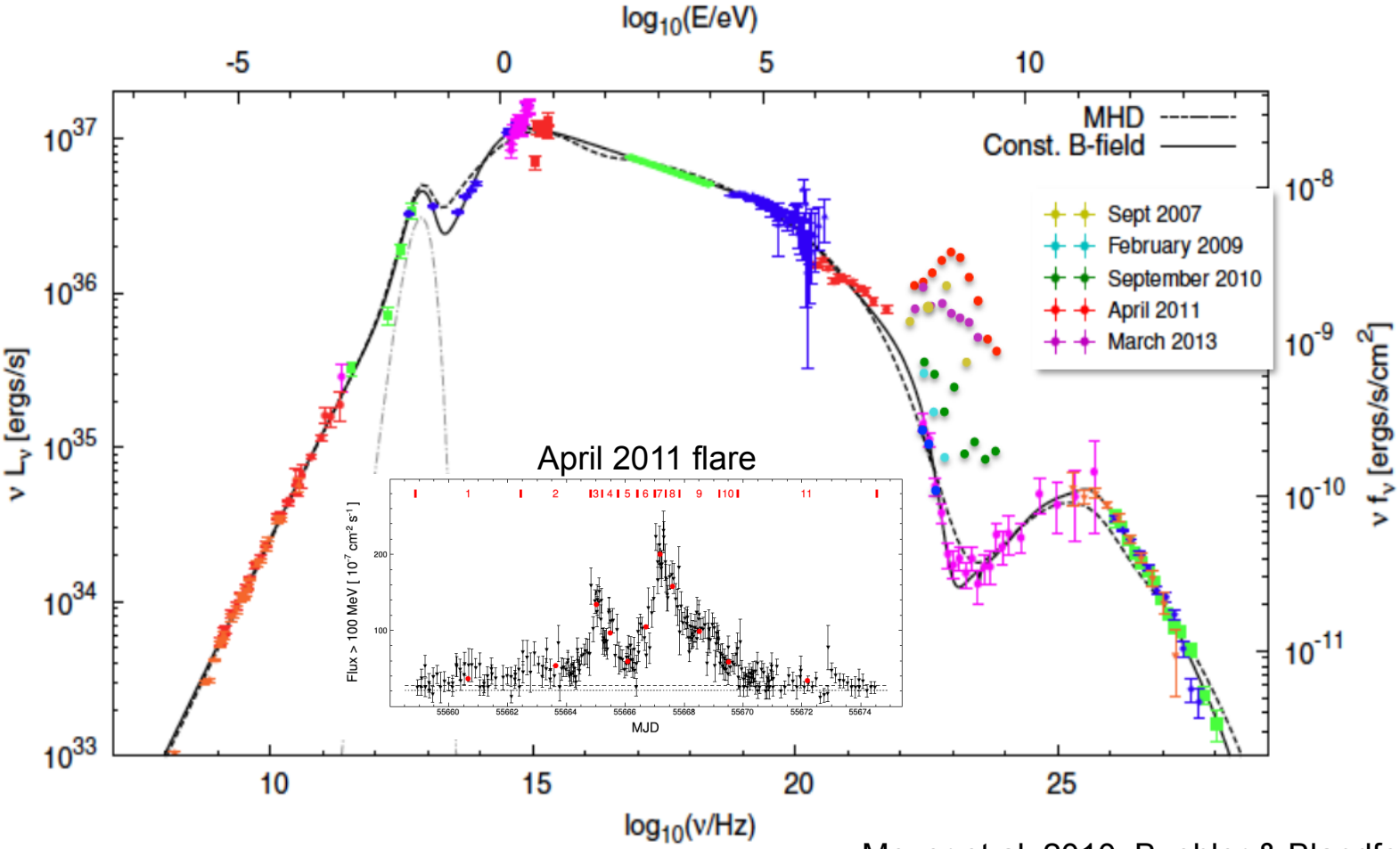
Crab nebula flares

Non-flaring: E_{max} ~ 1 PeV

Flaring: E_{max} ~ 2-3 PeV

$$\varepsilon_{syn}^{\max} = \frac{3}{2}\gamma_{\max}^2 B \approx \frac{9}{4}\frac{mc^2}{\alpha} = 160\,MeV$$

$$\varepsilon_{syn} = 500\,MeV$$



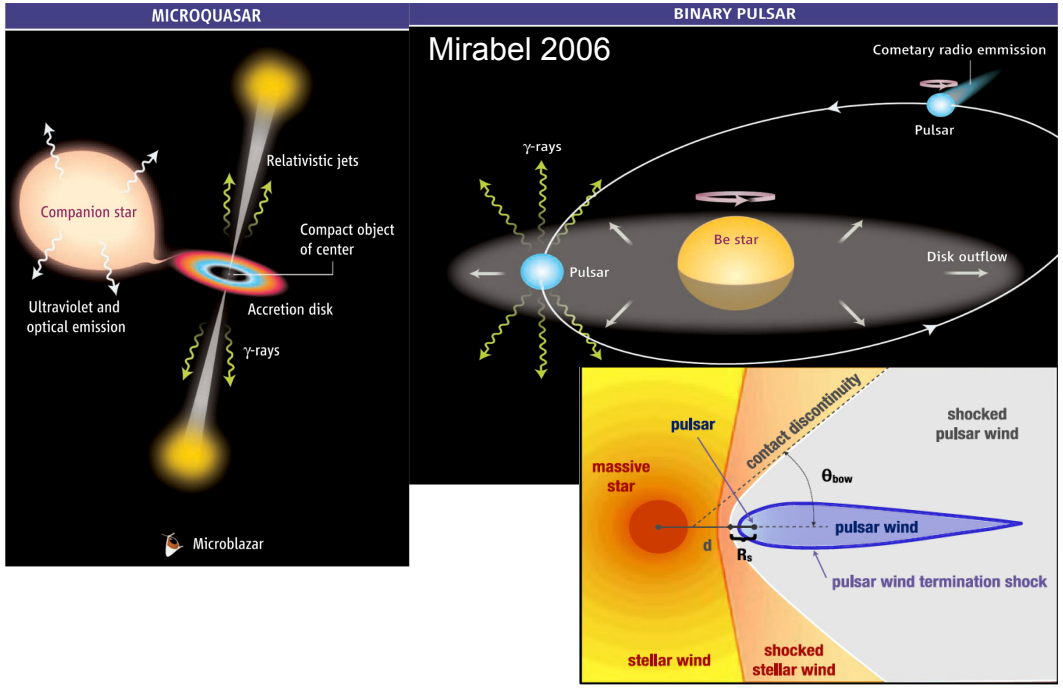
Meyer et al. 2010, Buehler & Blandford 2014

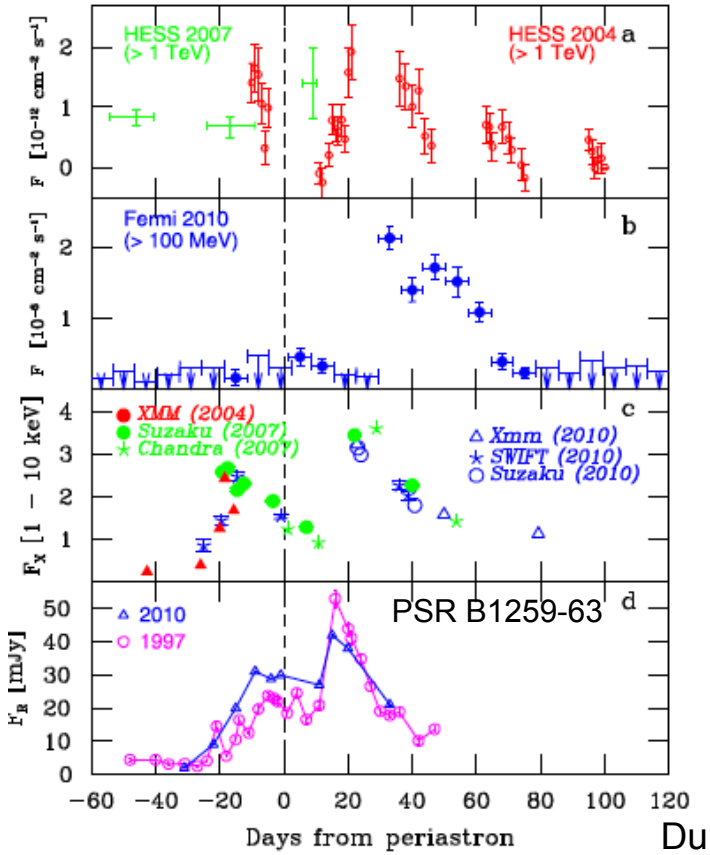
Gamma-ray binaries

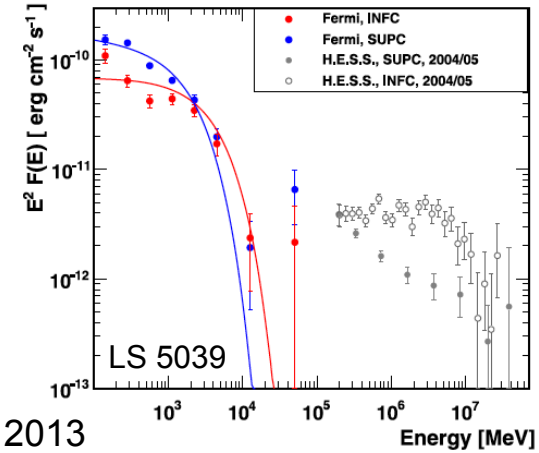
5 γ-ray binaries detected by LAT:

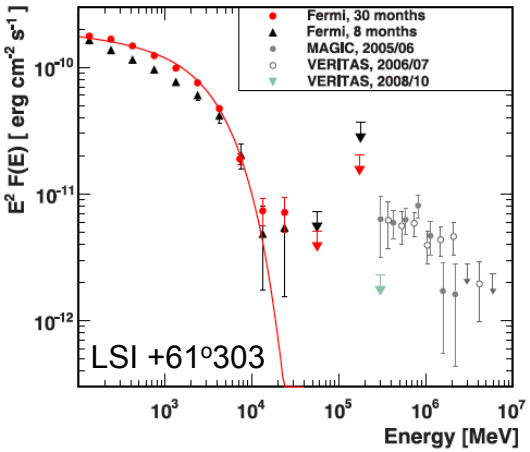
PSR B1259-63
LSI +61°303
LS 5039
HESS J0632+057
1FGL J1018.6-5856

Microquasars or binary pulsars?









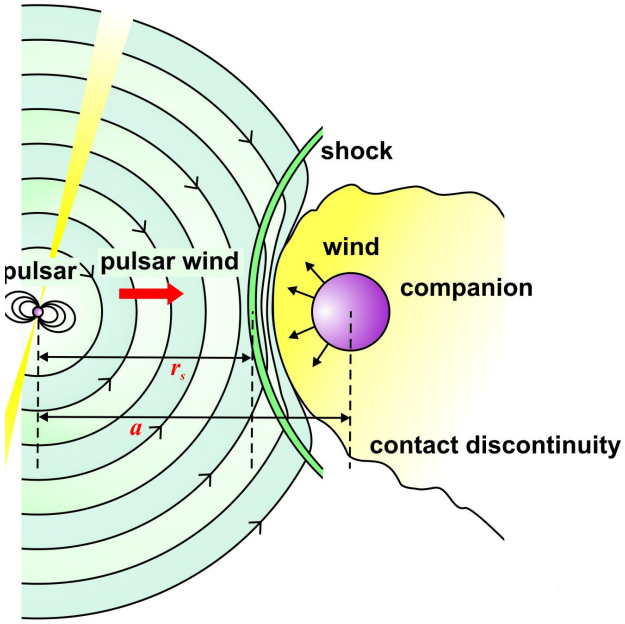
Dubus 2013

Black widow and redback systems

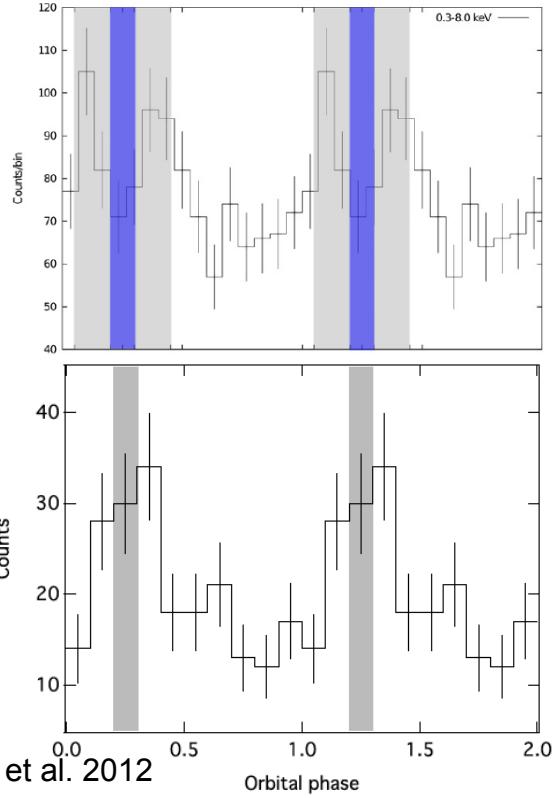
Before Fermi launch: 3 black widows, 1 redback
In LAT sources: 15 black widows, 9 redbacks
Total of 28!

PSR B1957-20:
X-rays (Chandra) and possibly γ-rays (Fermi) modulated at orbital period

- **MSPs with very low-mass binary companions**
  - **10 – 80 Jupiter masses (~.01 $M_\odot$)**
- **Pulsar wind ablates companion by exciting stellar winds**
- **Redbacks (cousins)**
  - **~0.1 $M_\odot$ companions**



Huang et al. 2012)



Wu et al. 2012

Particle acceleration at intra-binary shock:
(Harding & Gaisser 1990, Venter et al. 2015)

Leptons: few TeV
Protons (?): 2 – 100 TeV

Summary

Particle accelerators seen by Fermi

	Leptons	Hadrons
Blazars	100 TeV	10 EeV
Gamma-ray bursts	10 TeV	few PeV
Starbursts	?	0.1 - 1 PeV
Supernova remnants	10 TeV	100 TeV
Pulsars	10 TeV	?
Pulsar wind nebulae	1-3 PeV	?
Binaries	few TeV	2 – 100 TeV