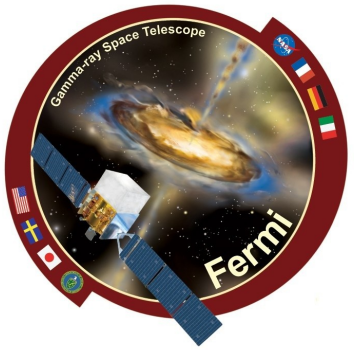

The *Fermi* Large Area Telescope View of Gamma-ray Pulsars

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with content and input from Alice Harding and Christo Venter
on behalf of the *Fermi* LAT collaboration
and Pulsar Timing and Search Consortia

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Gamma-ray Pulsars

Rotationally-induced E field, canceled by charges except in vacuum gaps.

- Charges accelerated along B field → curvature radiation.
- Expect non-variable phase-averaged flux (but then PSR J2021+4026).
- Exponentially cutoff power-law spectrum (b=1):

$$\frac{dN}{dE} \propto E^{-\Gamma} e^{-\left(\frac{E}{E_{Cut}}\right)^b}, E_{Cut} \propto \frac{\gamma_{CR}^3}{\rho_c}$$

Low-altitude models (polar cap) predict sharper cutoff due to pair-production attenuation on strong near-surface field.

- Disfavored by LAT observations as primary source of gamma rays.
- Observed gamma rays predominantly from the outer magnetosphere.

Proposed Emission Models

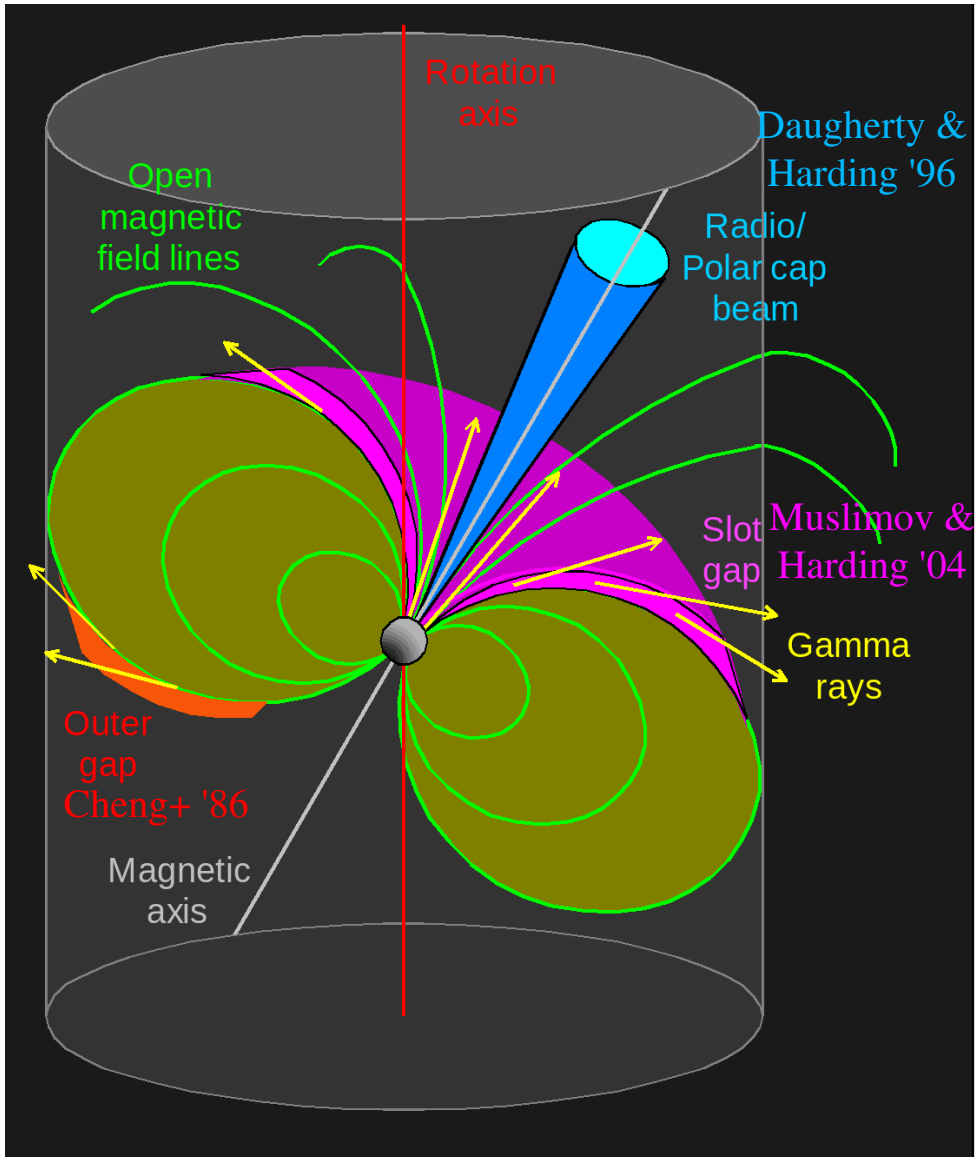
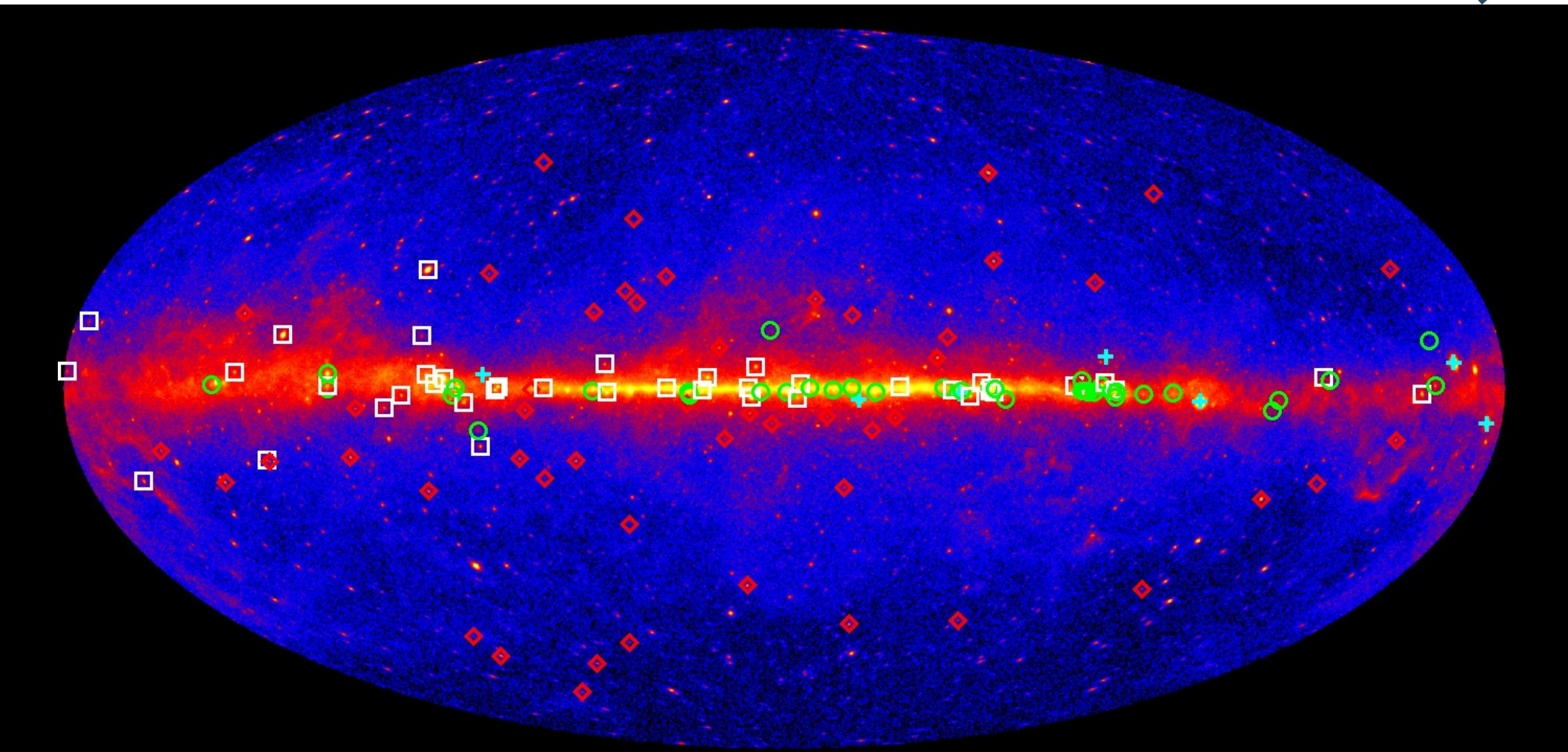


Figure Credit: Alice Harding

136 Gamma-ray Pulsars



LAT 5-year sky map (front-converting events, ≥ 1 GeV)

CGRO PSRs (✚), young radio-selected (○), young gamma-selected(□), and MSPs(◇)

For an up-to-date list see: http://tinyurl.com/fermipulsars

Current Pulsar Count

136 detected gamma-ray pulsars:

85 young, non-recycled pulsars:

42 radio-selected, 39 X/gamma-ray selected

4 new radio-quiet pulsars found using Einstein@Home (Pletsch+ '13)

51 millisecond (recycled) pulsars:

1 with pulse period discovered first in gamma-rays (Pletsch+ '12)

1 mildly-recycled pulsar (PSR J0737-3039A; Guillemot+ '13)

2 globular cluster MSPs (Freire+ '11; Johnson+ '13)

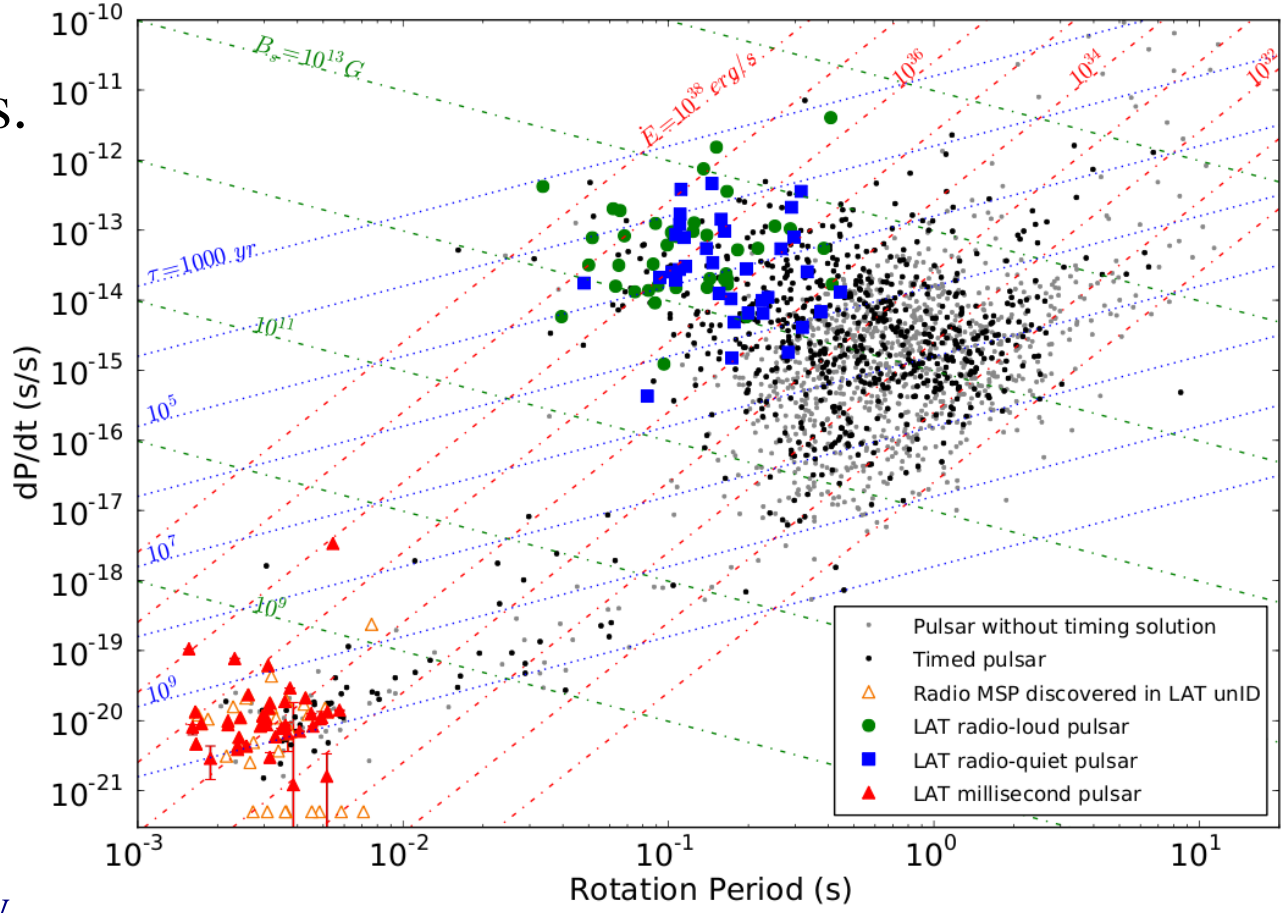
The 2nd LAT Pulsar Catalog

117 pulsars with significant (≥5σ) LAT pulsations in 3 years.

- Abdo+ '13
- 77 young pulsars:
  - (42 radio-loud)
  - (35 radio-quiet)
- 40 millisecond pulsars (MSPs)

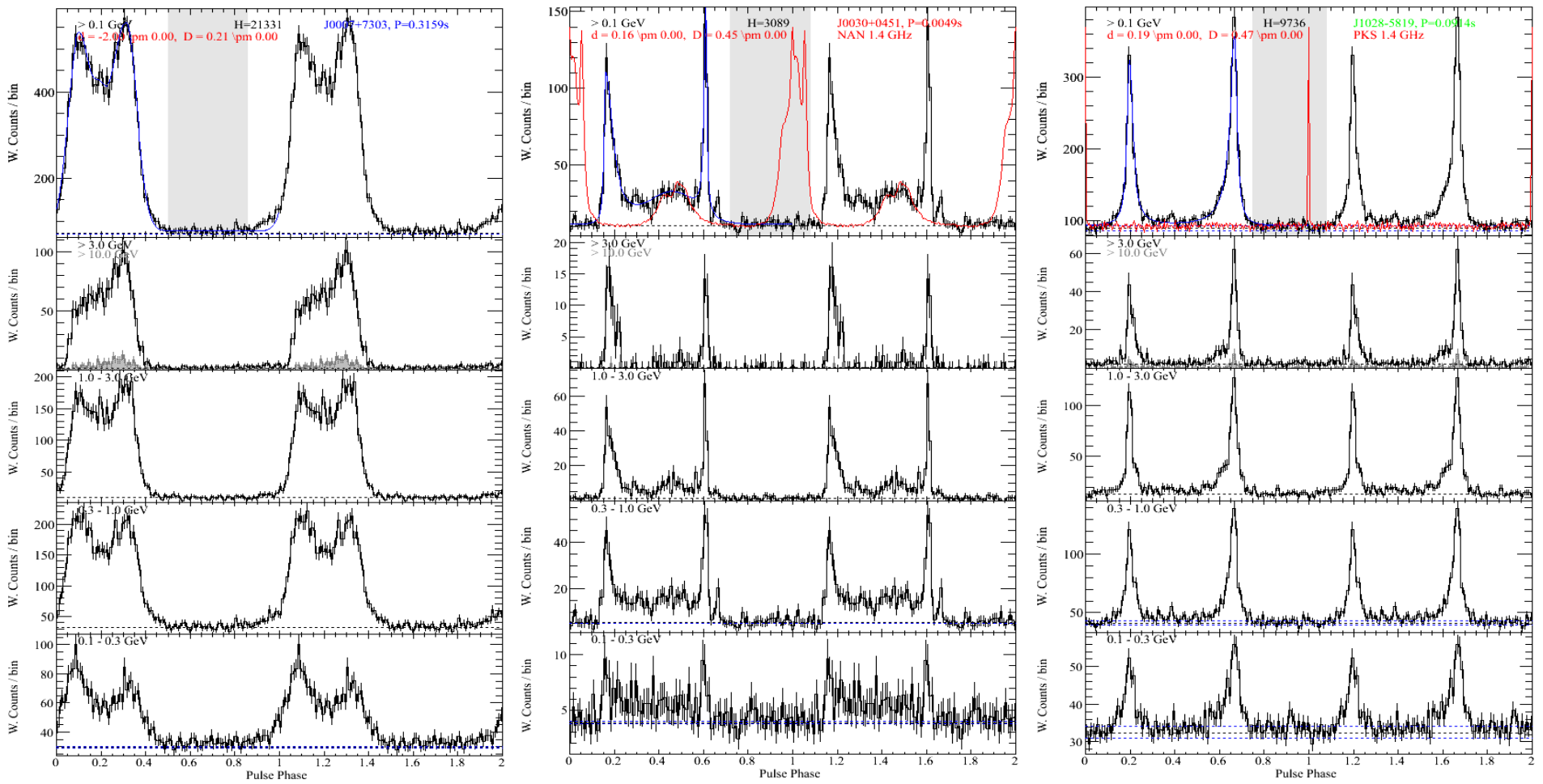
Catalog (2PC) includes:

- Gamma-ray spectral and light curve characterizations,
- Radio flux density,
- X-ray and optical characteristics,
- Estimate of pulsar flux sensitivity over the sky.



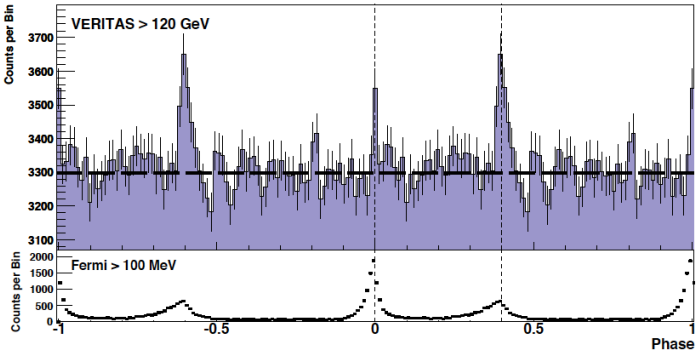
For data files, figures, and timing solutions, see:
http://tinyurl.com/fermi2pc

LAT Pulsar Light Curves



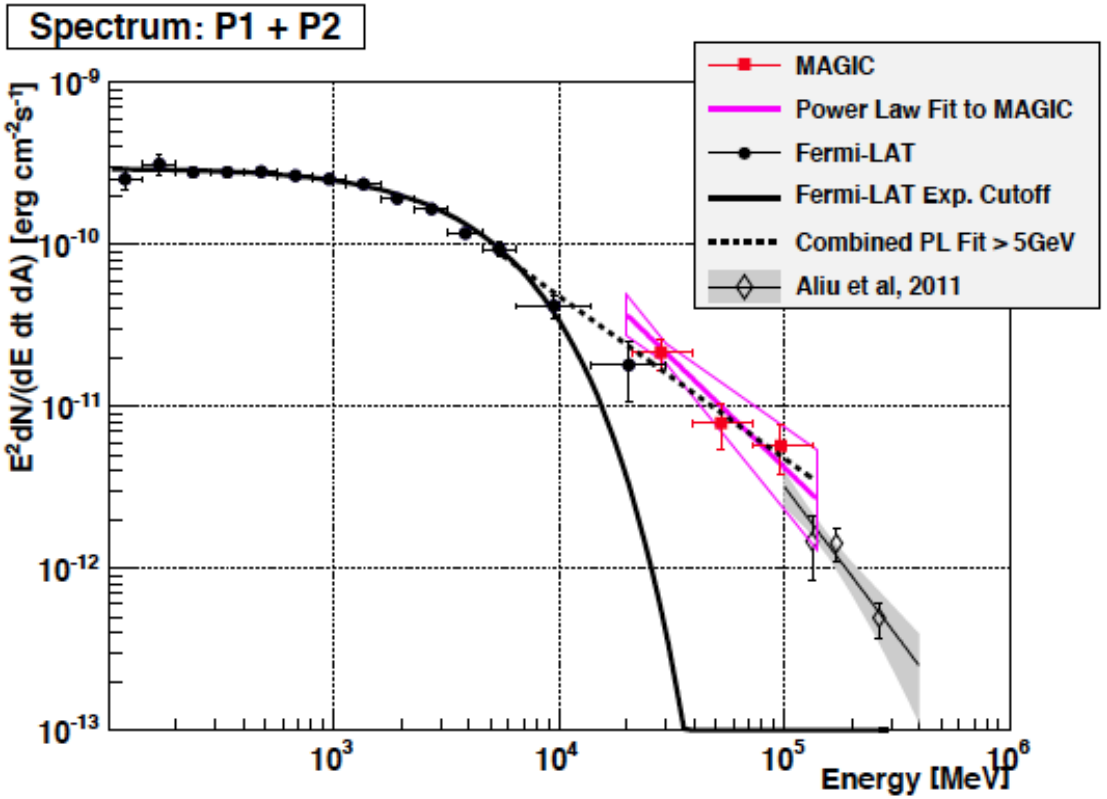
Large variety of pulsar light curves, if radio detected usually significant lag, except for Crab and growing class of MSPs (6 to date) with aligned radio and gamma-ray peaks.

VERITAS and MAGIC detection of the Crab pulsar



Aliu et al. 2011
Aleksic et al. 2011

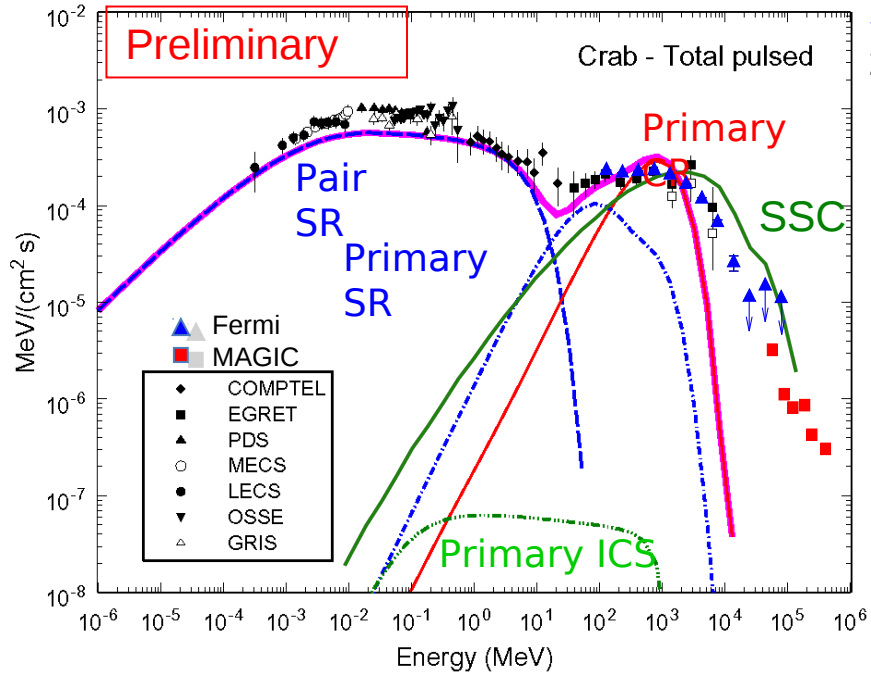
Crab pulsar above 100 GeV?
No theory predicted this!



- Above 100 GeV, peaks are narrower
- Cutoff of combined spectrum is not exponential (sub-exponential?)
- Extension of Fermi spectrum or separate component (e.g., inverse Compton, Lyutikov 2012)?
- Is the Crab unique or do other pulsars have > 100 GeV emission as well?

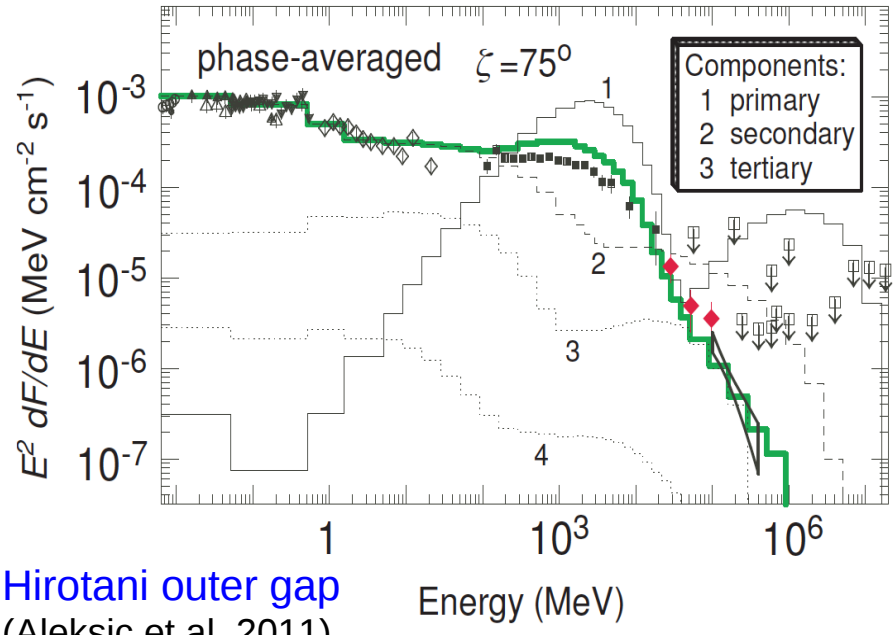
Slide text from Alice Harding and images from references

SSC models of Crab pulsar



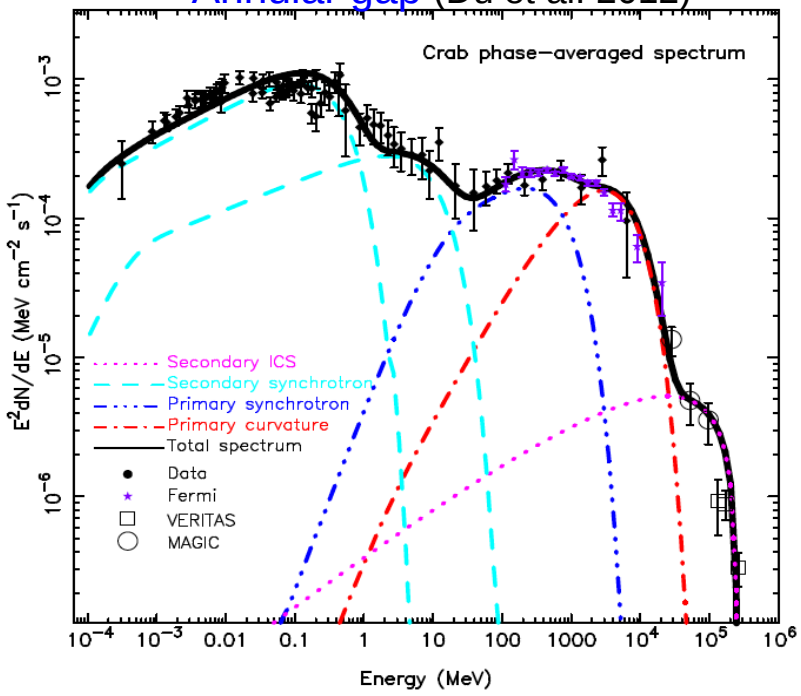
Slot gap (Harding et al. 2008, Harding 2013)

- **VHE Emission is SSC from pairs**
- **SSC spectrum reflects pair spectrum**
- **Possibility of structure in HE spectrum**



Hirotani outer gap (Aleksic et al. 2011)

Annular gap (Du et al. 2012)



Slide text from Alice Harding and images from references

More Pulsars above 10 GeV

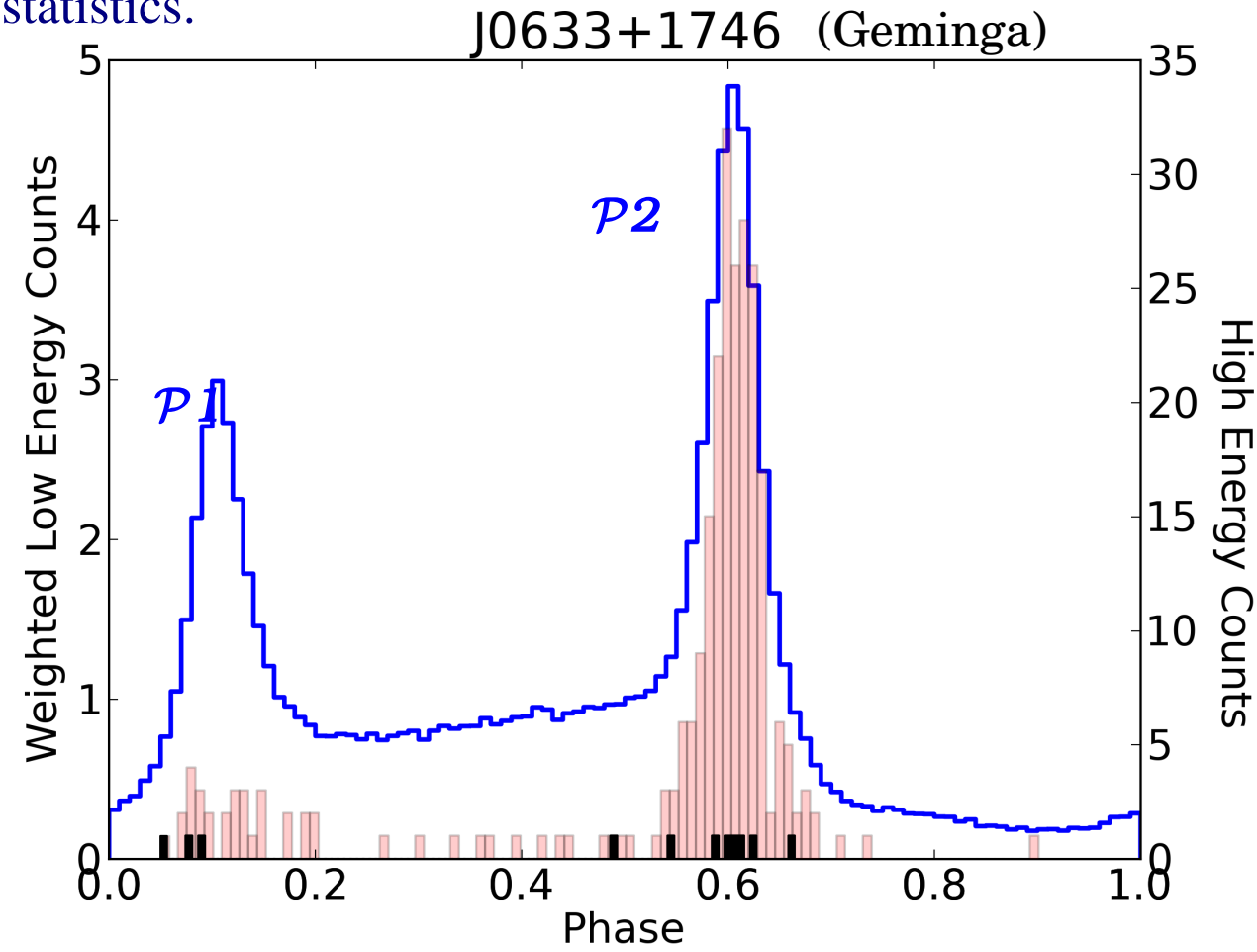
First *Fermi* LAT catalog of ≥10 GeV sources (1 FHL, 3 years, Ackermann+ '13).

- 28 pulsars pulsing above 10 GeV and 13 above 25 GeV.
- Spectral characterization limited by statistics.
- Ongoing investigation.

Pulsar spectra often consistent with b<1.

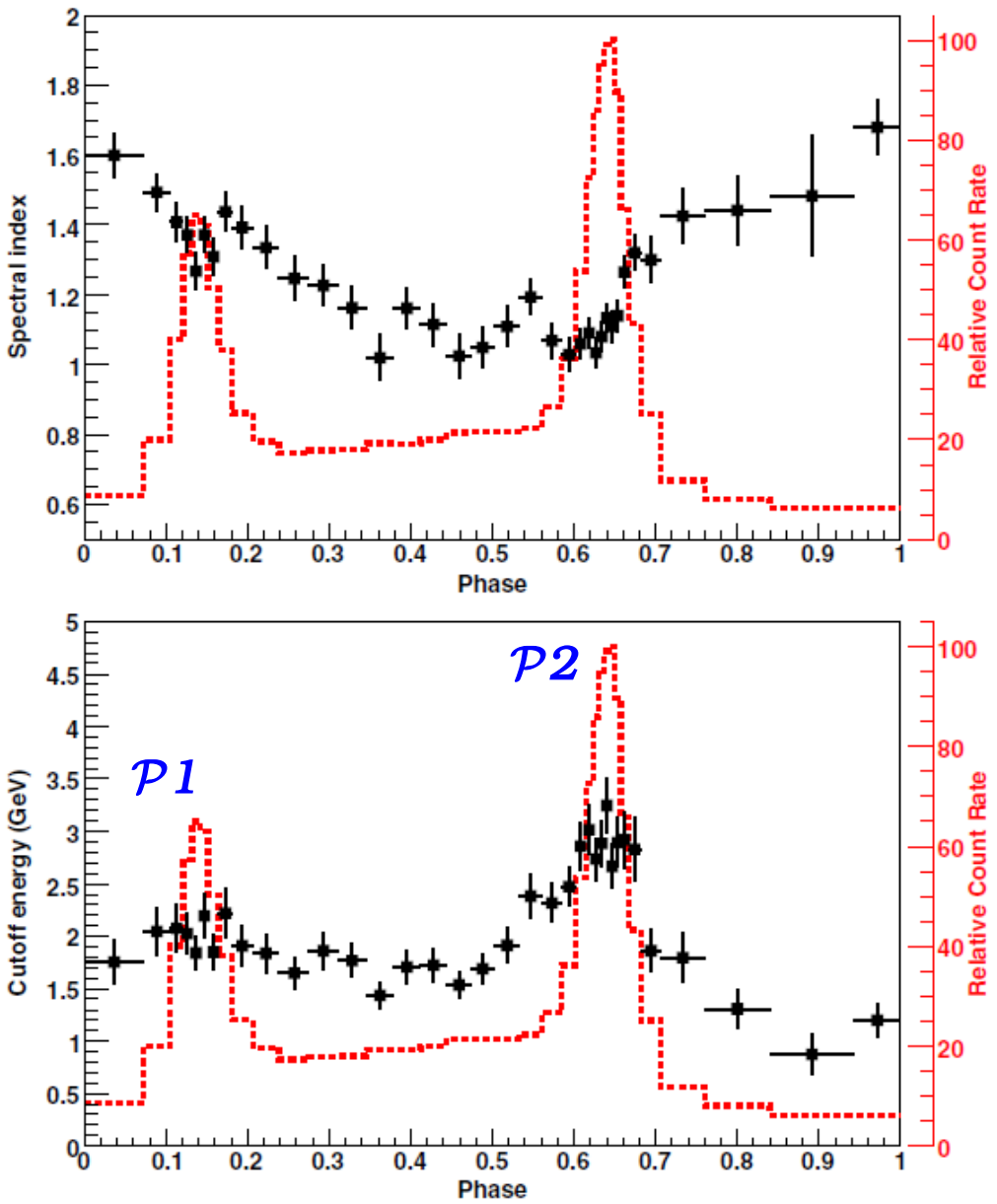
- Superposition of different cutoffs and indices, or indication of an extra component/different mechanism (Lyutikov 2012)?

$$\frac{dN}{dE} \propto E^{-\Gamma} e^{-\left(\frac{E}{E_{Cut}}\right)^{b}}$$



Blue: ≥ 100 MeV
Pink: ≥ 10 GeV
Black: ≥ 25 GeV

Geminga in More Detail



Abdo et al. 2010, ApJ 720, 272

P2 has highest cutoff energy and hardest index,
also has more >10 GeV events

Phase-resolved studies indication of when in phase to see TeV emission (if at all)?

PSR J1057-5226 consistent with b=1.

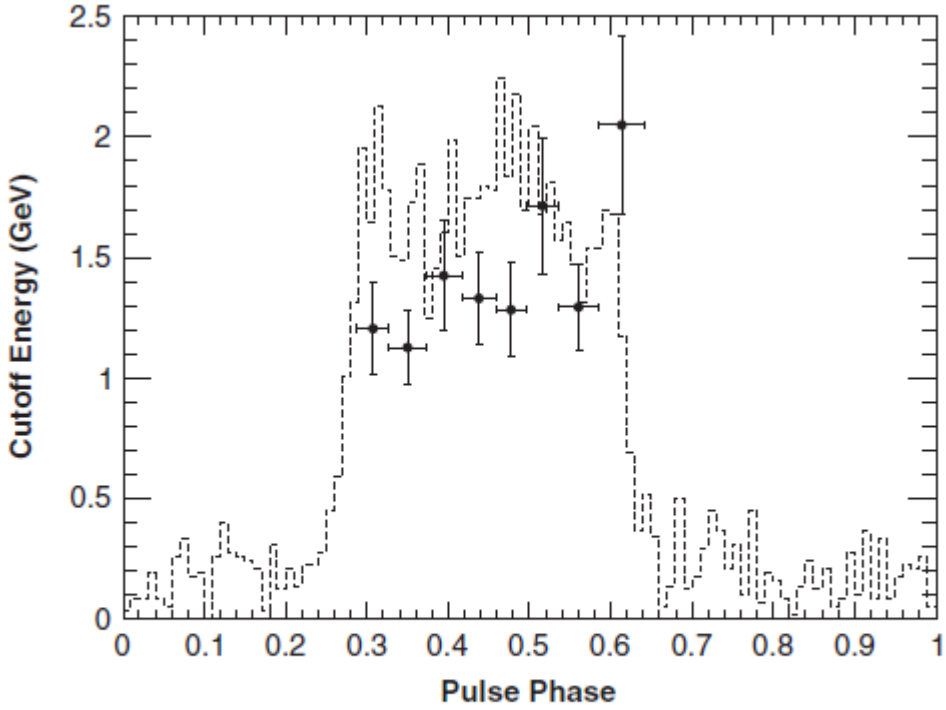
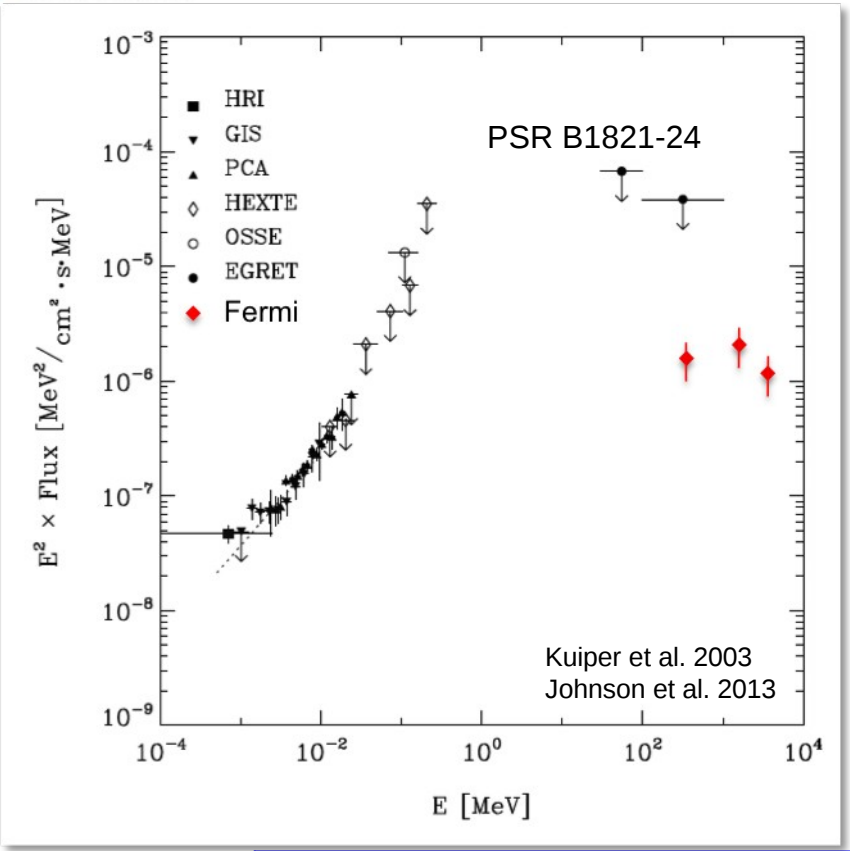


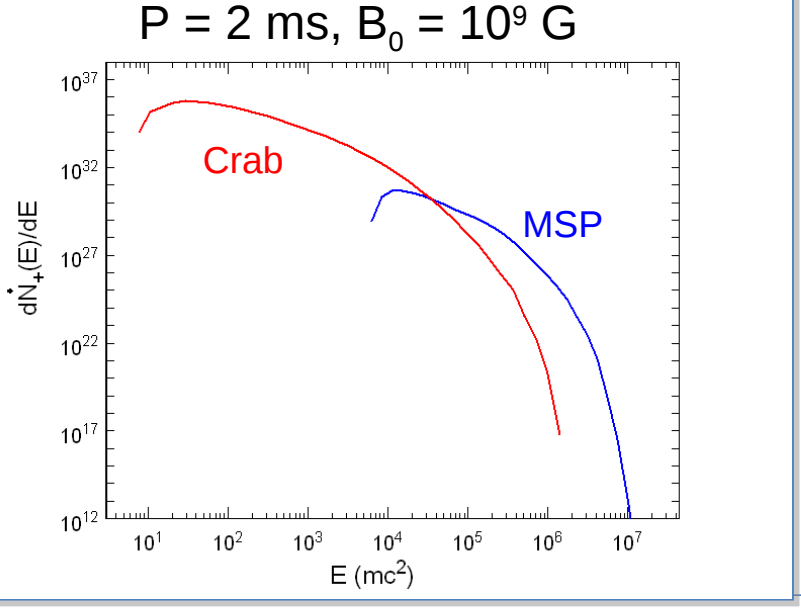
Figure 8. Evolution of the photon index (top panel) and the cutoff energy (bottom panel) of the pulsed emission spectrum through the pulse profile of the PSR J1057−5226.

Abdo et al. 2010, ApJ 720, 26

Synchrotron self-Compton emission from MSPs?

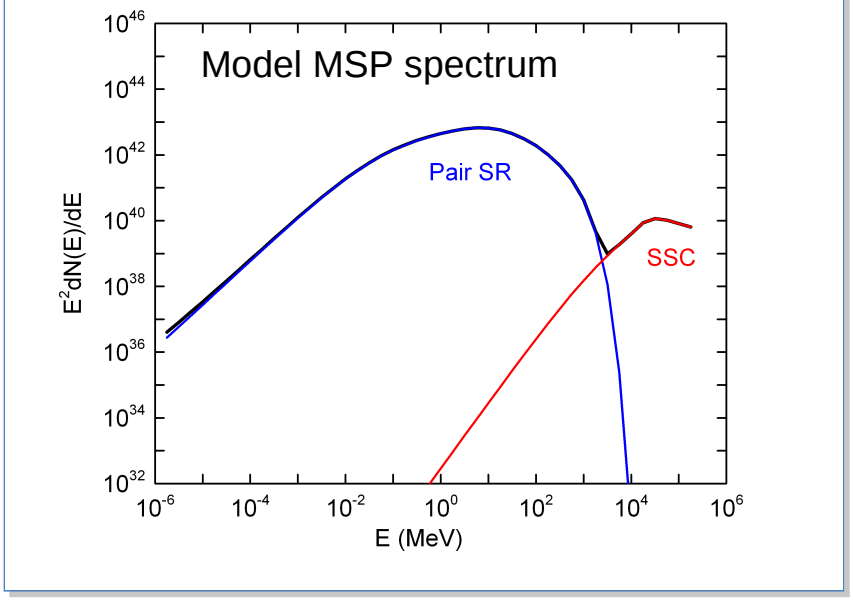


Pair cascade spectrum (polar cap)



Energetic pair spectrum and high non-thermal X-rays produce high level of SSC

SSC from MSPs?



Slide text and images from from Alice Harding and references

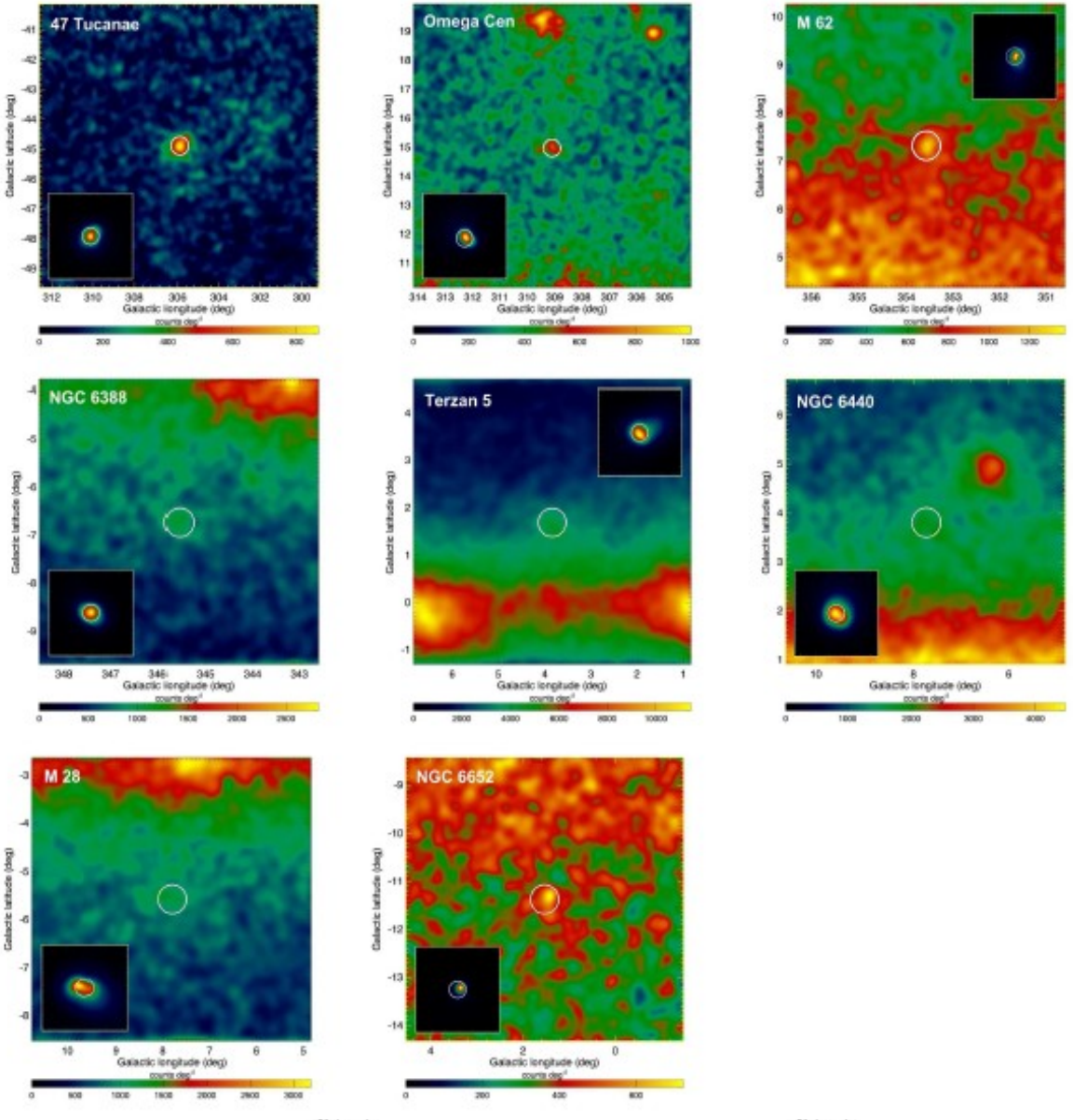
Globular Clusters

Detection of steady emission from >~ 12 globular clusters.

Pulses from MSPs in 2 clusters

Display characteristic pulsar spectrum.

Constraints on MSP populations.



12

Abdo et al. 2010, A&A, 524, A75

Globular Clusters at Higher Energies

Detection of steady emission from Terzan 5 with H.E.S.S. (extended and offset from core).

Extrapolates back to LAT spectrum well, but what happens inbetween?

- Combined signal from MSPs
- Remnant of a powerful, short GRB (Domainko+ '11)
- Population of fast-rotating, magnetized white dwarfs (Bednarek '12)
- Dark matter annihilation (Feng+ '12)

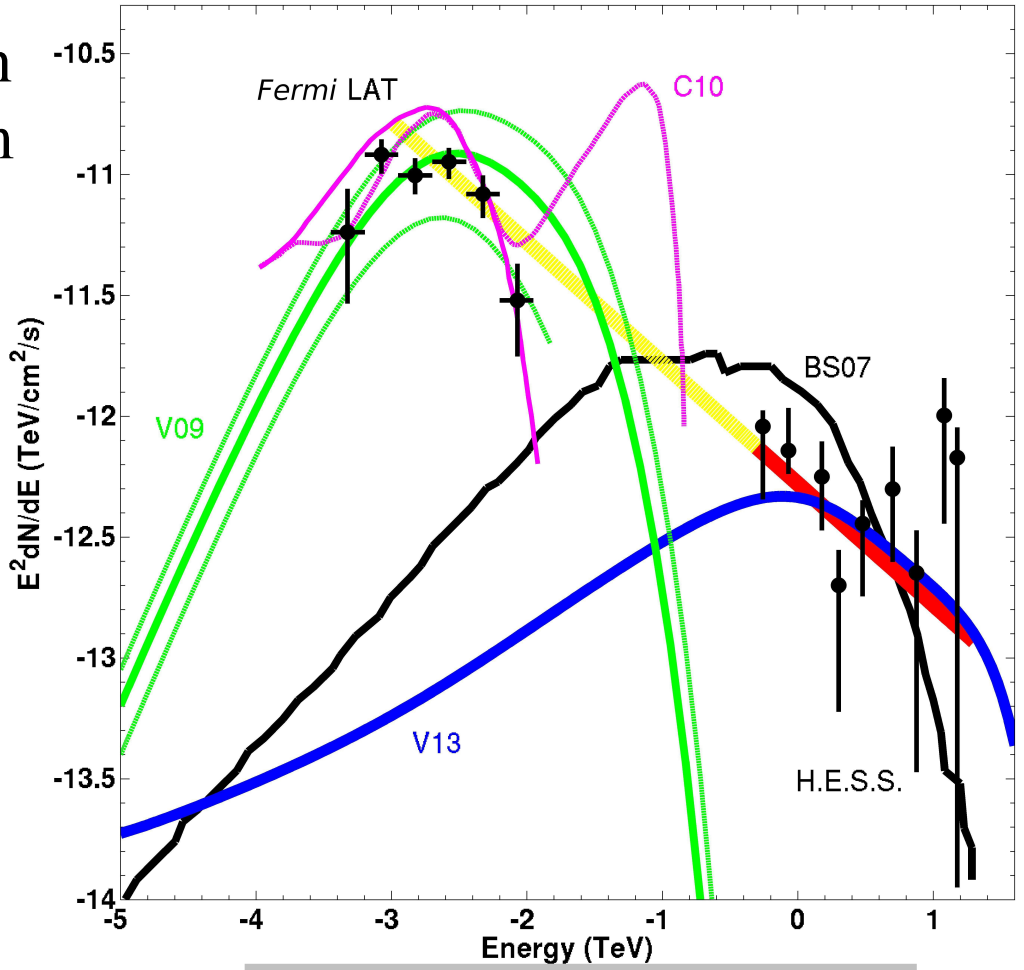


Figure courtesy C. Venter:
VHE Extrapolation
Curvature radiation model
Cheng+ '10 IC model
Bednarek & Sitarek '07 IC
IC calculation

Conclusions

Observations with the *Fermi* LAT have revolutionized gamma-ray pulsar science.

- Number of known gamma-ray pulsars increased by a factor of almost 20.
- Clearly established outer magnetosphere as dominant source of gamma rays.

Pulsars at several 10's of GeV (and beyond).

- Is the Crab unique?
- Open/ongoing aspect of LAT pulsar science.
- Still interesting things to learn about pulsar gamma-ray emission.

Want an up-to-date LAT timing solution?:

- Published: http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ephems/
- Need one made:

https://confluence.slac.stanford.edu/display/GLAMCOG/LAT+Gamma-ray+Pulsar+Timing+Models

- Contact Paul Ray: paul.ray@nrl.navy.mil

----------Backup Slides----------

Gamma-ray Luminosity

$$L_\gamma = 4\pi d^2 f_\Omega G_{100} \propto V \propto \sqrt{\dot{E}}$$

Expect gamma-ray luminosity to scale as square root of spin-down power (Ė):

- f_Ω a beaming factor (set to 1 for 2PC),
- d pulsar distance typically large uncertainty,
- G_{100} LAT energy flux,

Break needed at low Ė:

- ~few × 10^{34} erg/s.
- Different model predictions, still unclear.