



Fermi

Gamma-ray Space Telescope



# Observations of Gamma-ray “Spiders” with the *Fermi* Large Area Telescope

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with

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NASA/DOE + numerous international agencies and universities.

Launched 11 June 2008.

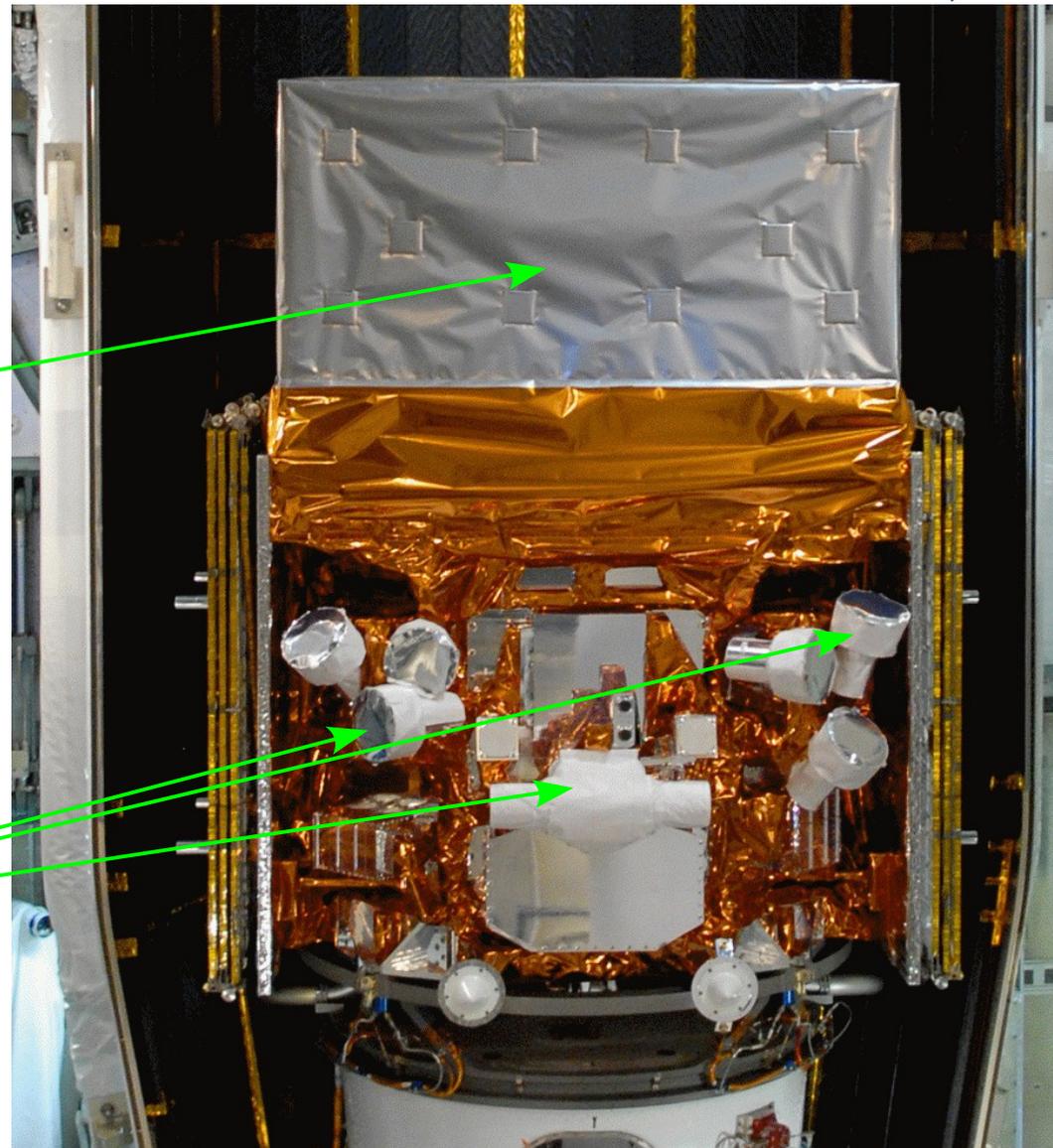
2 Instruments:

Large Area Telescope (LAT) (Atwood+ '09)

- From 20 MeV to  $> 300$  GeV
- $\sim 7000$  cm<sup>2</sup> @ 1 GeV, on-axis
- $\sim 0.7^\circ$  68% containment radius @ 1 GeV
- 2.4 sr field of view ( $\sim 20\%$  of the sky)
- Event times accurate within  $< 1\mu\text{s}$

Gamma-ray Burst Monitor (Meegan+ '09)

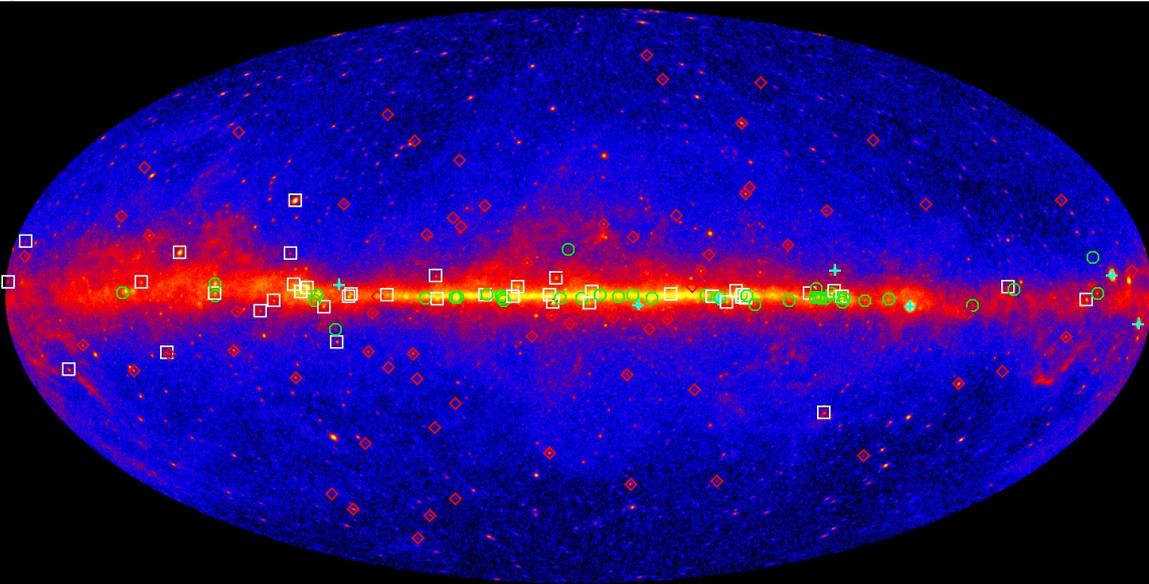
- $\sim 8$  keV –  $\sim 40$  MeV
- Sees full, unocculted sky



*Photo Credit: NASA*

TJJ – “Neutron Stars at the Crossroads” – 25 June 2015

# Shock Emission



LAT 5-year sky map (front events,  $\geq 1$  GeV)

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

161 pulsars, for an up-to-date list see:

<http://tinyurl.com/fermipulsars>

Second LAT pulsar catalog (2PC) Abdo+ 2013

<http://tinyurl.com/fermi2pc>

Bulk of GeV emission is  
pulsed/magnetospheric

Typically cutoff above ~few GeV

Shock between winds of “spider”  
MSPs and companions

Produce GeV emission?

(Harding & Gaisser 1990, Arons  
& Tavani 1993)

How to detect?

Different spectrum?

(not cutoff, higher energies)

Orbital modulation?

(phase-averaged, off-peak)



Systematically search LAT data for evidence of emission from wind-wind interactions in black widow (BW) and redback (RB) systems

~5.3 years P7REP data, 0.1 to 100 GeV

Search for spectral signatures:

Off-peak emission – define using Bayesian blocks

$E \geq E_{th}$ , extra component – with  $F(E_{th}-100 \text{ GeV}) \approx 1\%F(0.1-100 \text{ GeV})$

Search for orbital modulation:

Test phase-averaged, off-peak, &  $E \geq E_{th}$  selections

Correct for exposure variation with orbital phase

Use spectral weights to reduce dependence on energy and radius cuts

Preliminary Results:

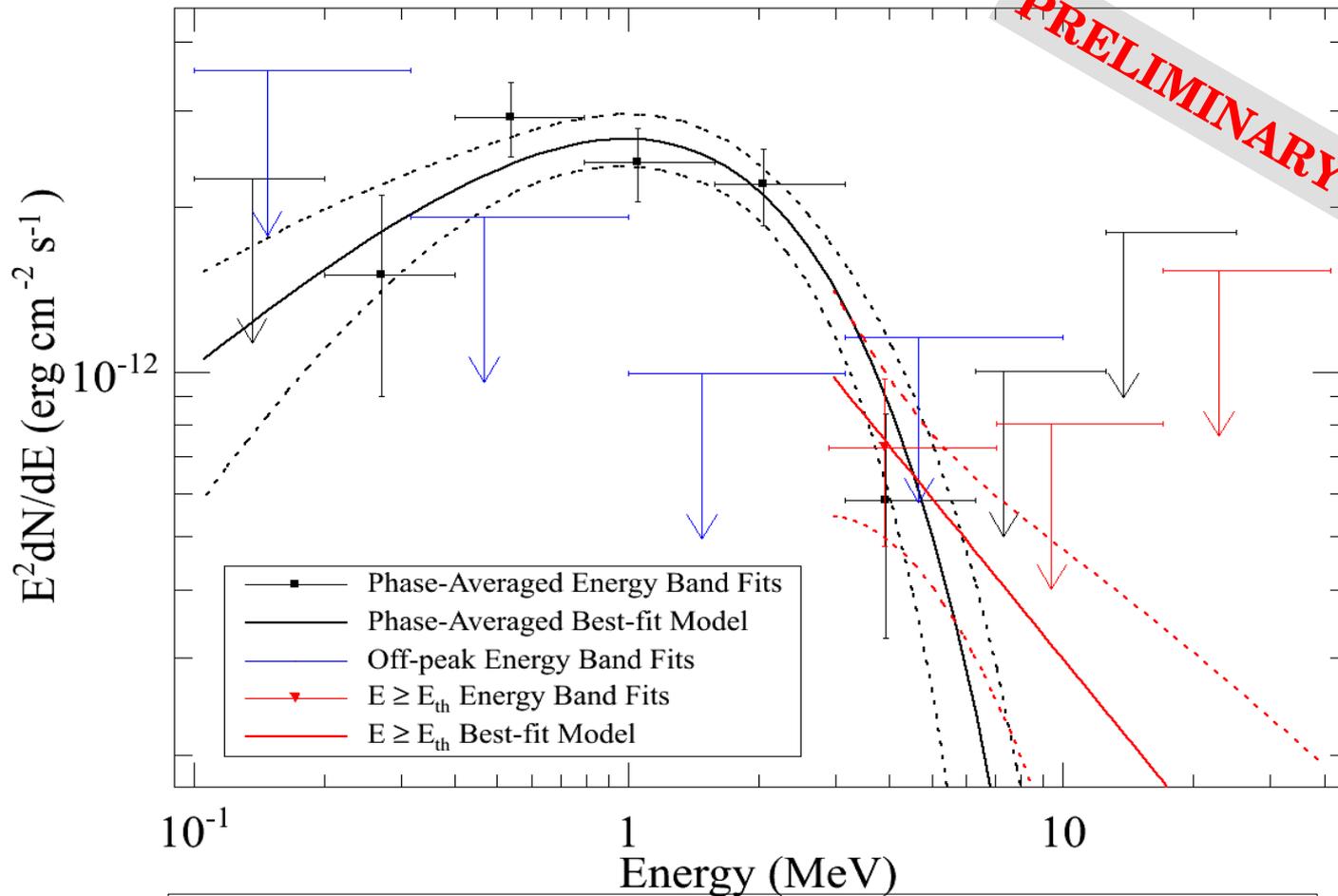
Adequate timing solutions for 14 BWs and 2 RBs

No significant signals detected

# “Spider” Gamma-ray Spectra



PSR J0023+0923



No significant  
off-peak emission

$E \geq E_{th}$  emission  
consistent with  
magnetospheric  
component

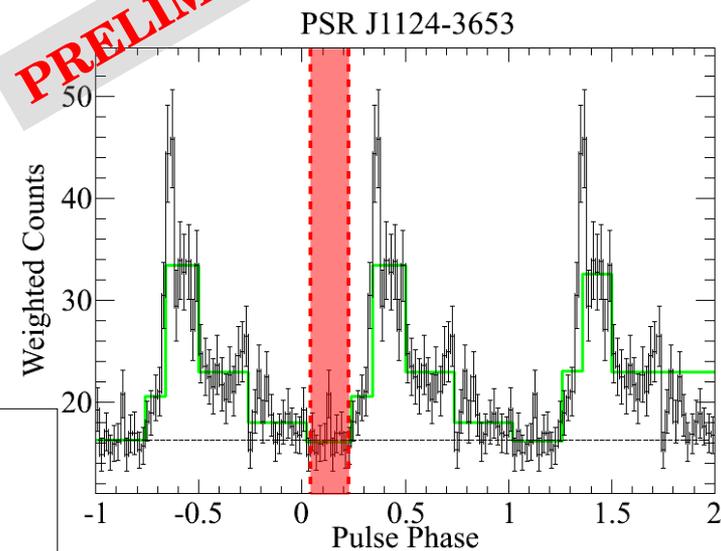
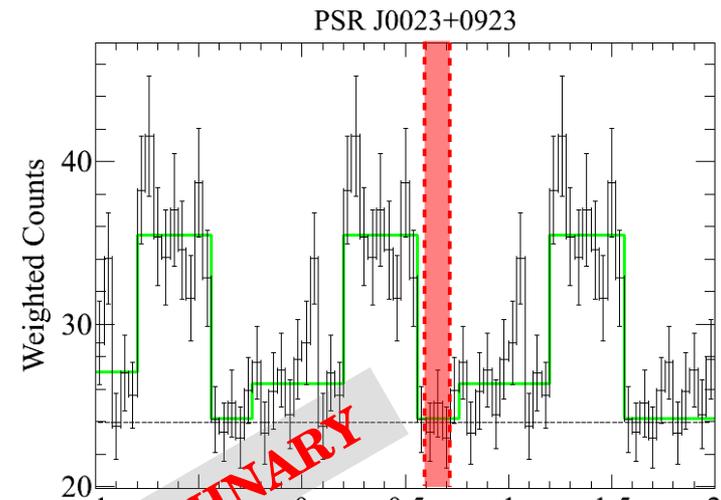
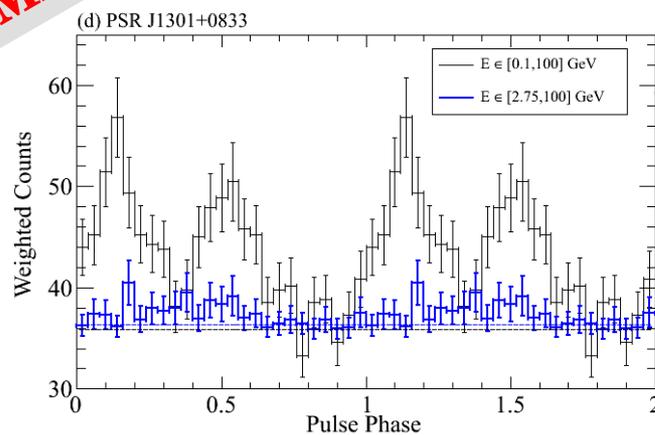
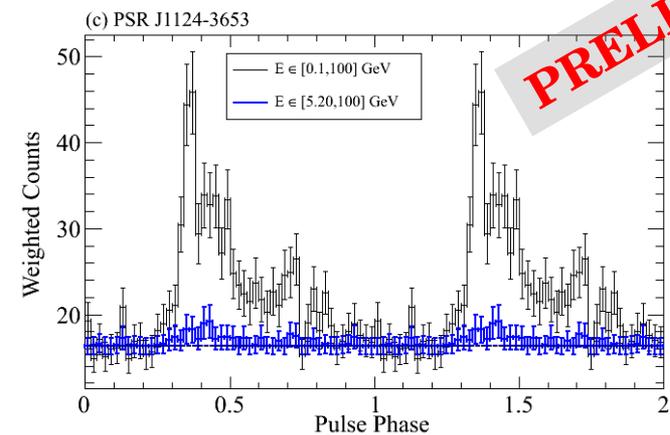
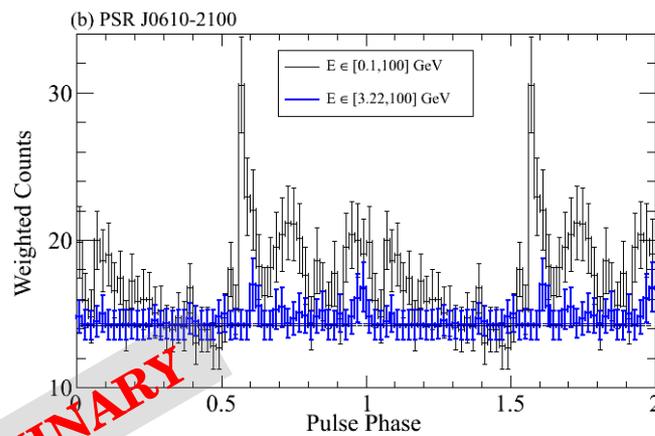
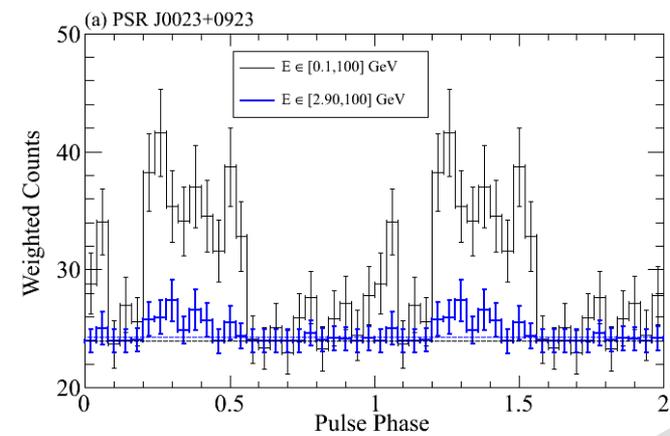
Black spectrum: Phase-averaged, 0.1 to 100 GeV

Blue spectrum: Off-peak, 0.1 to 100 GeV

Red spectrum: Phase-averaged,  $E_{th}$  to 100 GeV

Dashed lines show 1 $\sigma$  uncertainty on the models

# “Spider” Gamma-ray Pulse Profiles



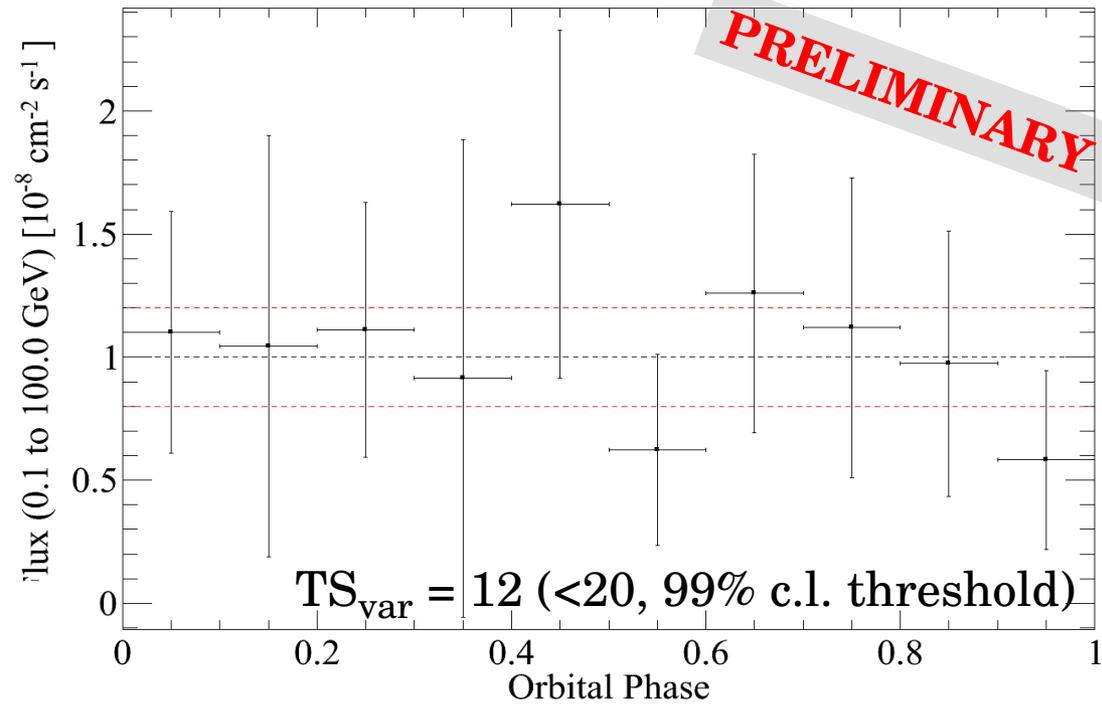
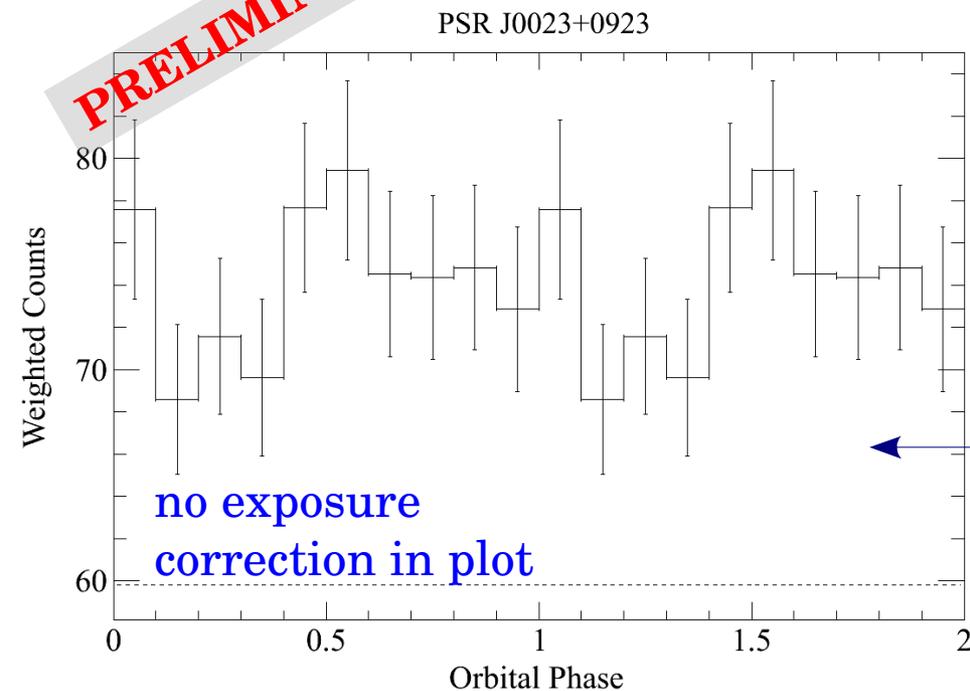
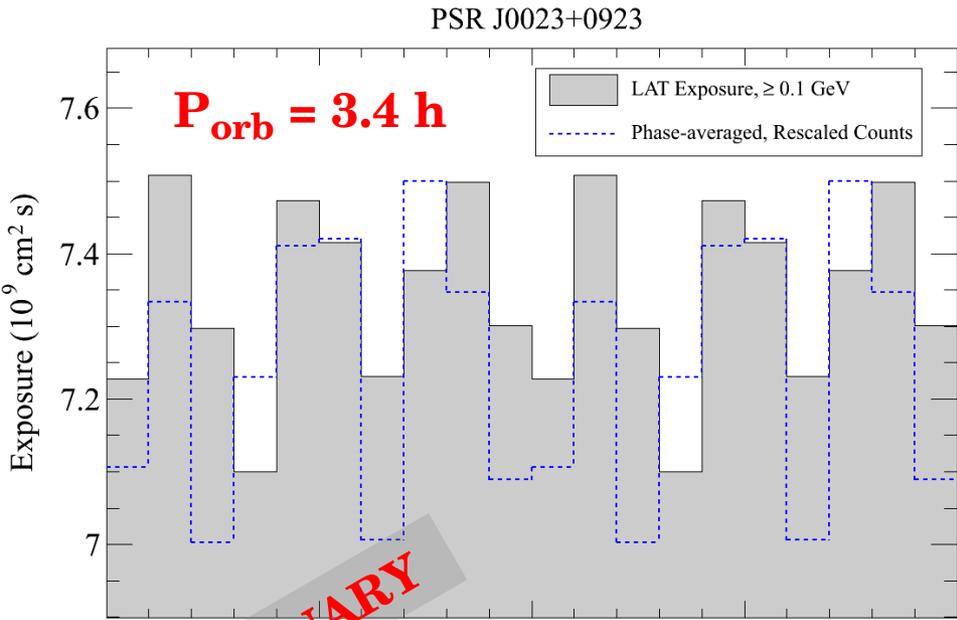
**PRELIMINARY**

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Black histograms: 0.1 to 100 GeV wtd. cts. light curves  
 Blue histograms:  $E_{th}$  to 100 GeV wtd. cts. light curves  
 (pedestals have been increased for viewing purposes)  
 Green histograms: Bayesian block decomposition  
 Red regions: Off-peak intervals

2PC off-peaks slightly larger.  
 Lower-level pulsed features more prominent?  
 Peaks have long tails

# Correcting for Exposure Variations



Exposure may not be uniform across orbit  
particularly if  $P_{\text{orb}} \sim n * \text{Fermi orbit}$

May induce fake  $P_{\text{orb}}$  modulation

Follow Kerr (2010) to modify periodicity tests.

← PSR J0023+0923:  $\sim 1\sigma$

Likelihood fits in orbital phase bins

correct good time intervals for phase cuts.



Espinoza+ (2013), PSR J0610-2100

3 years, Pass 7,  $2\sigma > 3$  GeV

Similar to exposure variation and background

Our results:  $E_{th} = 3.22$  GeV,  $1\sigma$

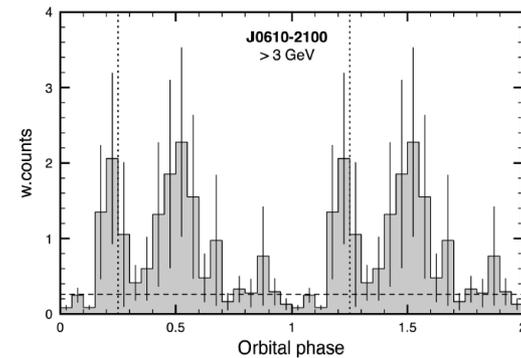


Figure 7. Gamma-ray emission above 3 GeV folded on the orbital period

Wu+ (2012), PSR J1959+2048

~3.3 years, Pass 7, no exposure correction

$2.3\sigma$  (post-trials)  $> 2.7$  GeV

Claimed spectral “bump” in half of orbital phase

Our results:  $E_{th} = 2.68$  GeV,  $0.5\sigma$ ,

investigating “bump”

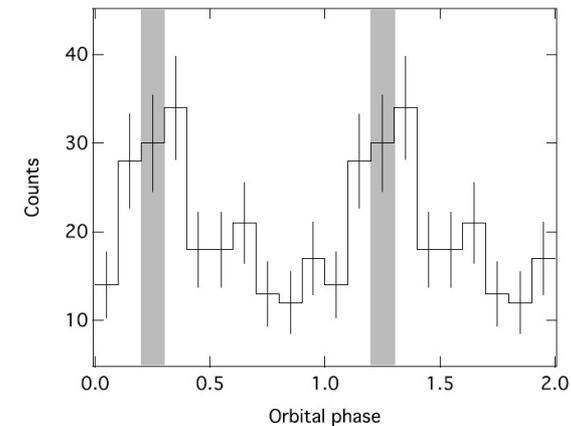


Figure 4.  $\gamma$ -ray light curve of PSR B1957+20 folded at the orbital period using

Xing & Wang (2015), PSR J1311-3430

~6.4 years, P7REP, no exposure correction

off-peak (0.5 in phase),  $> 0.2$  GeV,  $0.4^\circ$  radius,

$\sim 3\sigma$  (post-trials),

Our results: off-peak (0.35 in phase),  $0.7\sigma$

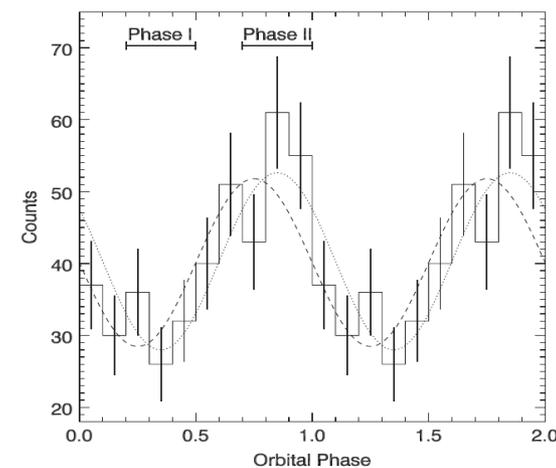


Figure 2. 0.2–300 GeV light curve folded at the orbital period using the off-



## Advances in gamma-ray pulsar science

*Fermi* LAT – nearly 30x's more gamma-ray pulsars  
pointing to new radio MSPs, BWs & RBs aplenty  
variability, “mode changes” and transitional systems  
more to come...

TeV Telescopes – Crab pulses at  $> 100$  GeV

## Systematic search for emission from intrabinary shocks from “spiders”

Search for spectral and temporal signatures

Correct for exposure variations with orbital phase

No significant modulation seen to date

## Future

Take advantage of Pass 8 data (e.g., Atwood+ 2013)

increased acceptance, new event types, try  $< 100$  MeV

More “spiders”

Stacking analysis



- Abdo, A. A., et al. 2009, ApJ, 696, 1084  
Abdo, A. A., et al. 2013, ApJS, 208, 17  
Allafort, A., et al. 2013, ApJL, 777, L2  
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Cheng, K. S., et al. 1986, ApJ, 300, 500  
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Dyks, J. & Rudak, B. 2003, ApJ, 598, 1201  
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Romani (1996), ApJ, 470, 469  
Wu, E. M. H., et al. 2012, ApJ, 761, 181  
Xing, Y. & Wang, Z. 2015, ApJL, 804, L33

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# Backup Slides

# Gamma-ray Pulsars



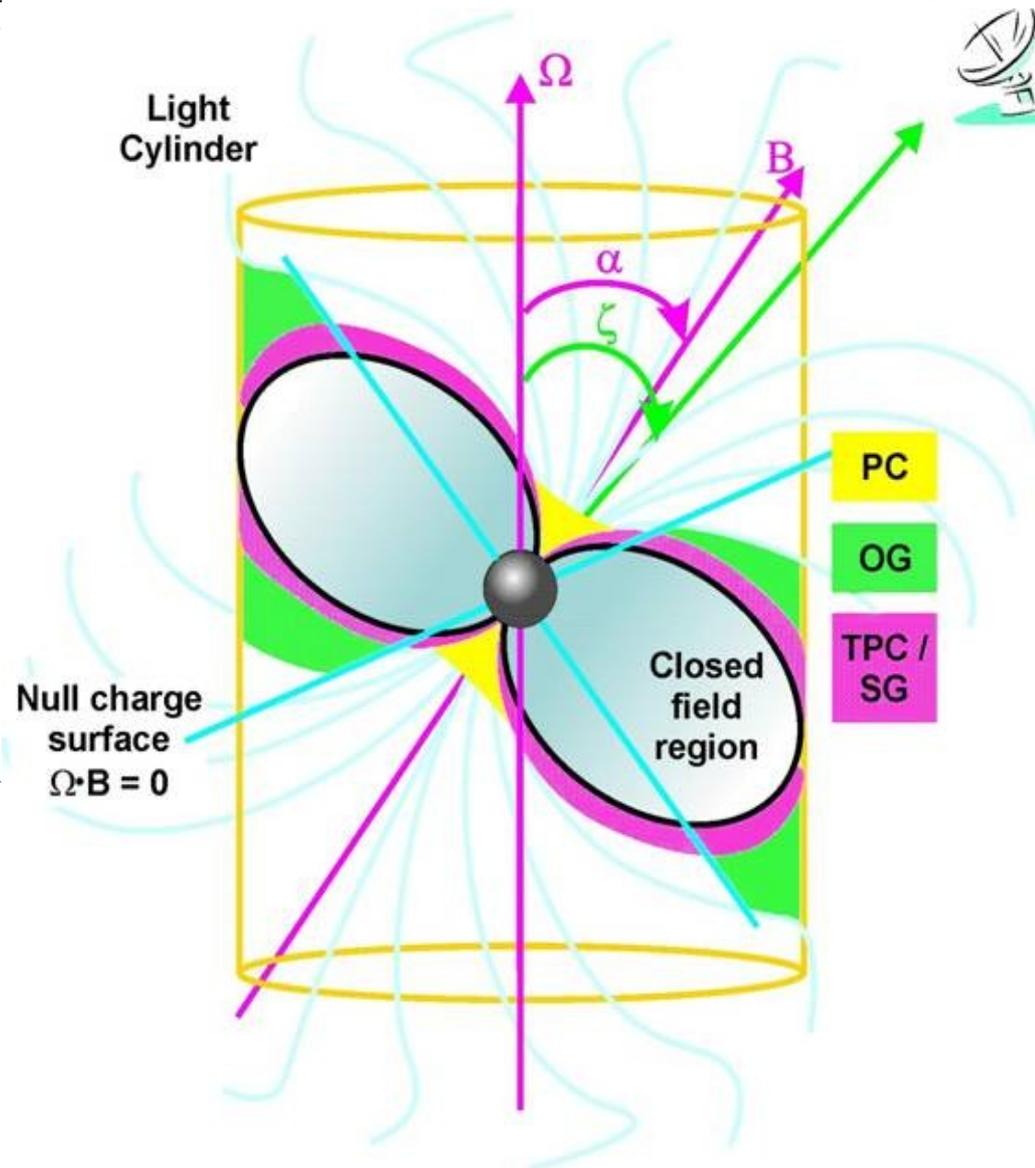
Curvature radiation, exponentially-cutoff  
power-law spectrum, non-variable

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma} \exp \left\{ - \left( \frac{E}{E_C} \right)^b \right\}$$

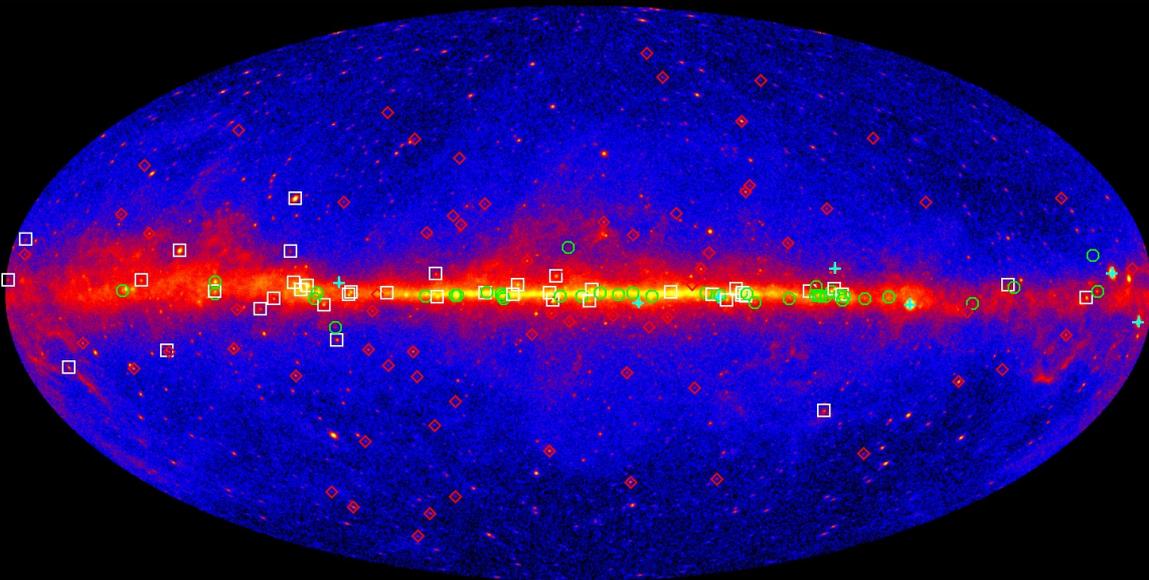
Polar cap – emission from just above the surface, strong B-field, one-photon pair production,  $b > 1$  (e.g., Daugherty & Harding 1996)

Slot gap/two-pole caustic – emission from surface to light cylinder,  $b = 1$  (e.g., Dyks & Rudak 2003; Muslimov & Harding 2004)

Outer gap – emission above NCS only,  $b = 1$  (e.g., Cheng+ 1986; Romani 1996)



# LAT Pulsar Science – A Taste



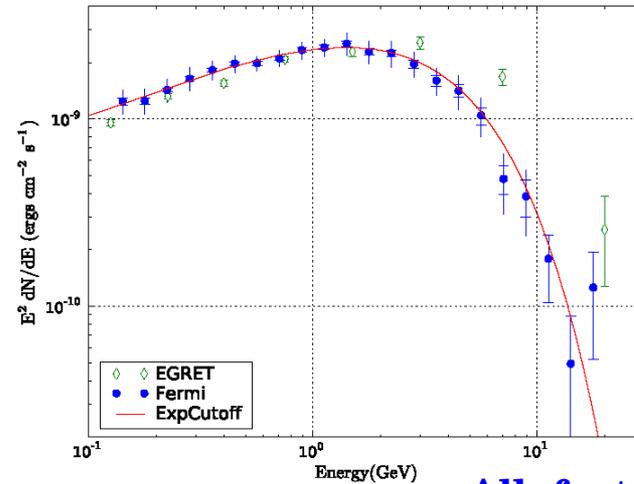
LAT 5-year sky map (front events,  $\geq 1$  GeV)  
 CGRO PSRs (+), young radio-selected ( $\odot$ ),  
 young gamma-selected ( $\square$ ), and MSPs ( $\diamond$ )

161 pulsars, for an up-to-date list see:

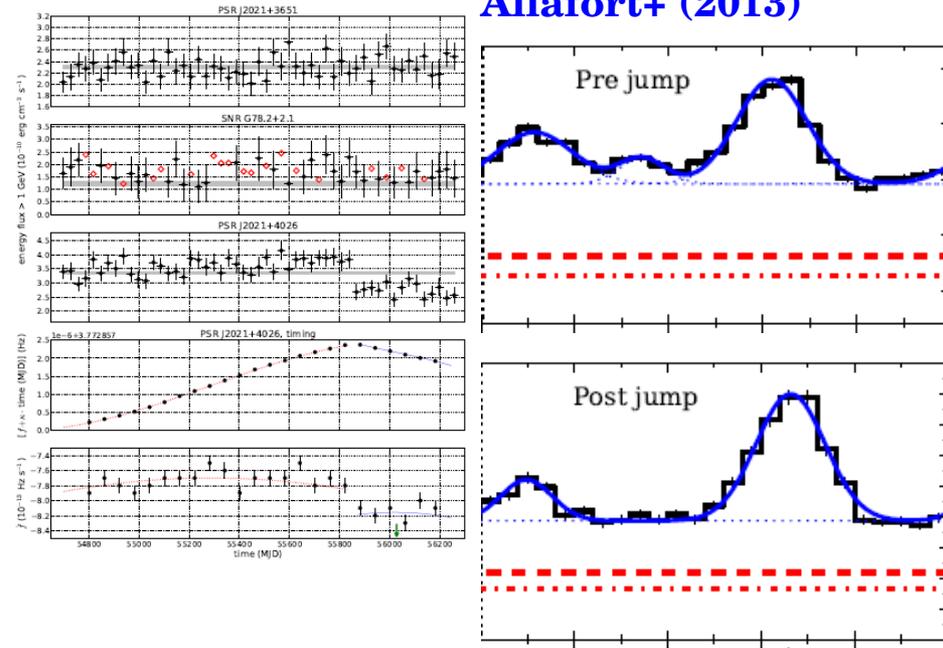
<http://tinyurl.com/fermipulsars>

Second LAT pulsar catalog (2PC) Abdo+ 2013  
<http://tinyurl.com/fermi2pc>

Abdo+ (2009):  $b=1$ , PC ruled out



Allafort+ (2013)



Also, some pulsars pulsing  $> 10$  GeV, Crab at  $> 100$  GeV!

TJJ – “Neutron Stars at the Crossroads” – 25 June 2015



“Black Widows” (BW) and “Redbacks” (RB)

MSPs in binaries with low-mass companions & short orbital periods

$\sim 0.02M_{\odot}$ , BW;  $\sim 0.2M_{\odot}$ , RB;  $P_{\text{orb}} < 1\text{day}$

Companions ablated by pulsar winds

Shock between two winds leading to high-energy emission

(e.g., Harding & Gaissner 1990; Arons & Tavani 1993)

3 BWs and 1 RB pre-*Fermi* (not in globular clusters)

At least 16 BWs and 9 RBs post-*Fermi*

RBs show radio eclipses & orbitally-modulated X-ray emission

Not necessarily companion blocking beam

X-rays – shock emission, between pulsar and companion winds

“MSP near the end of, but maybe not totally done with, the recycling phase”

See Roberts+ (2013) for a review