Pulsar Observations with the *Fermi* LAT

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on behalf of the *Fermi* Large Area Telescope Collaboration
and Pulsar Search and Timing Consortia

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The *Fermi Gamma-ray Space Telescope*

NASA/DOE + numerous international agencies and universities.
Launched 11 June 2008.

<u>2 Instruments</u>:

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

- Energy range 20 MeV to > 300 GeV
- ~7000 cm^2 @ 1 GeV, on-axis
- ~0.7° 68% containment radius @ 1 GeV
- 2.4 sr field of view (~20% of the sky)
- Event times accurate within < 1μs

Gamma-ray Burst Monitor (Meegan+ '09)

- ~8 keV – ~40 MeV
- Views full, unocculted sky

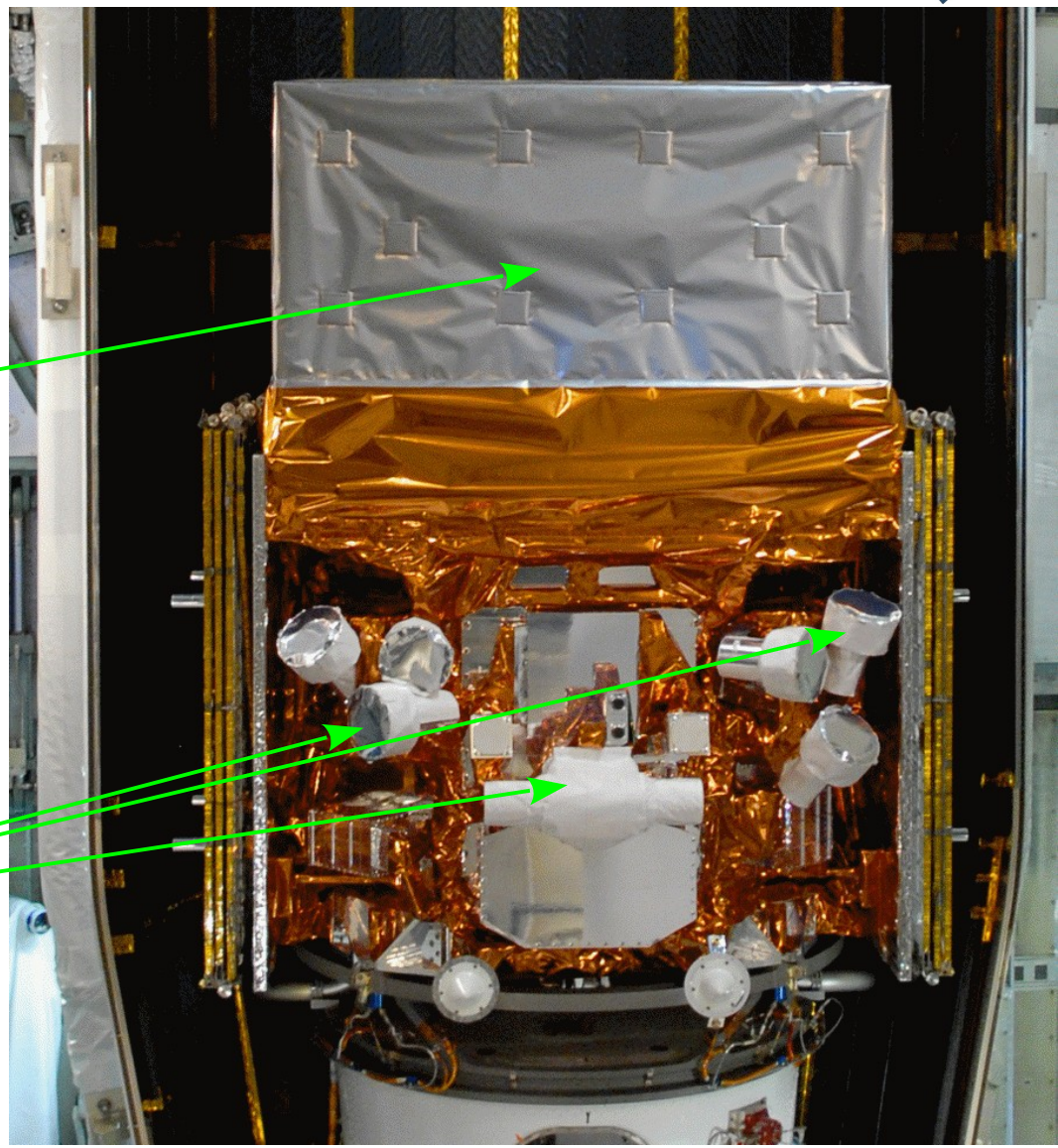


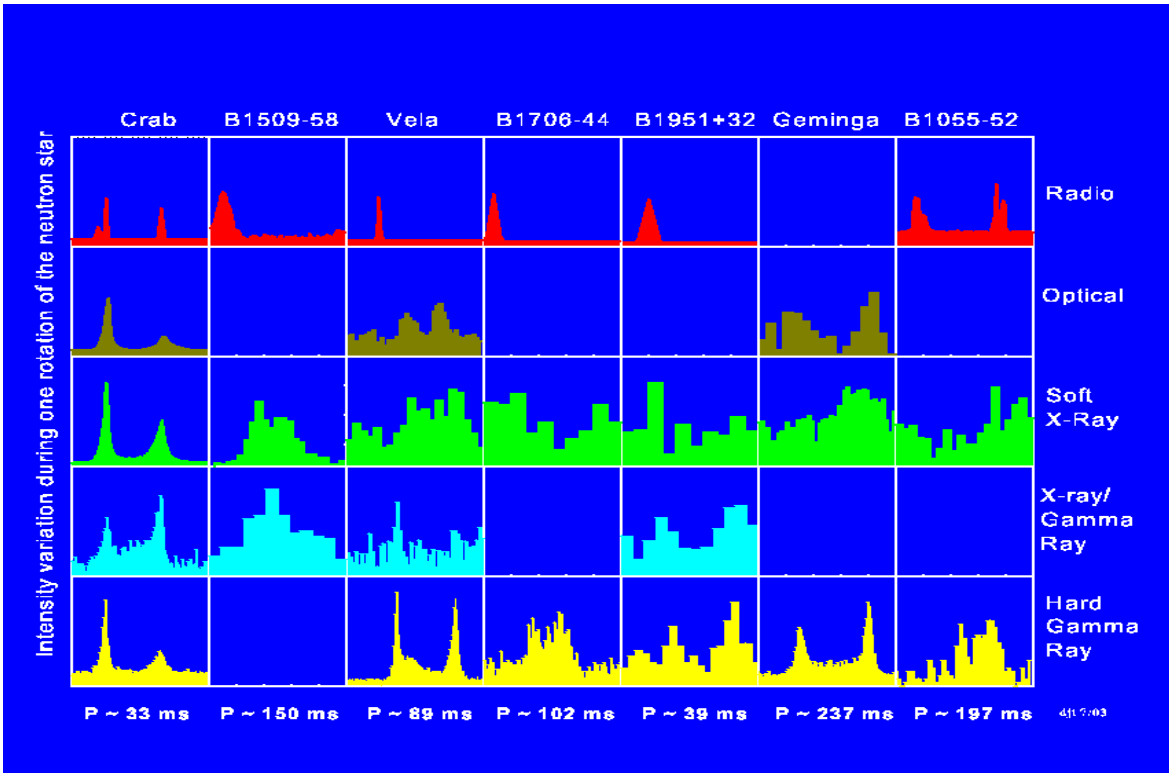
Photo Credit: NASA

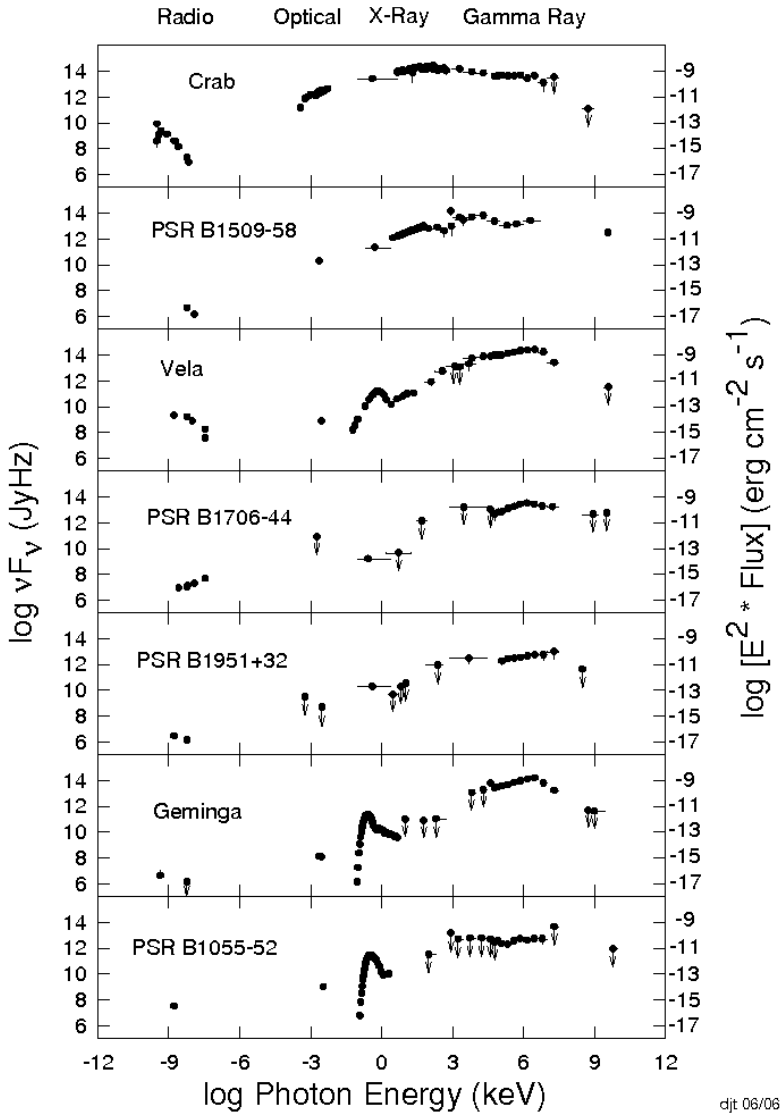
Before *Fermi*

Crab pulsar ≥ 50 MeV, Browning+ (1971)

SAS-2 detects Vela pulsar, Thompson+ 1975.

EGRET detects 6 pulsars ≥ 100 MeV +1 seen only with *OSSE* and *COMPTEL*.





Figures courtesy D. J. Thompson

Pre-launch Questions for *Fermi*

1. Are there more "radio-quiet" pulsars?
   And can we find them?

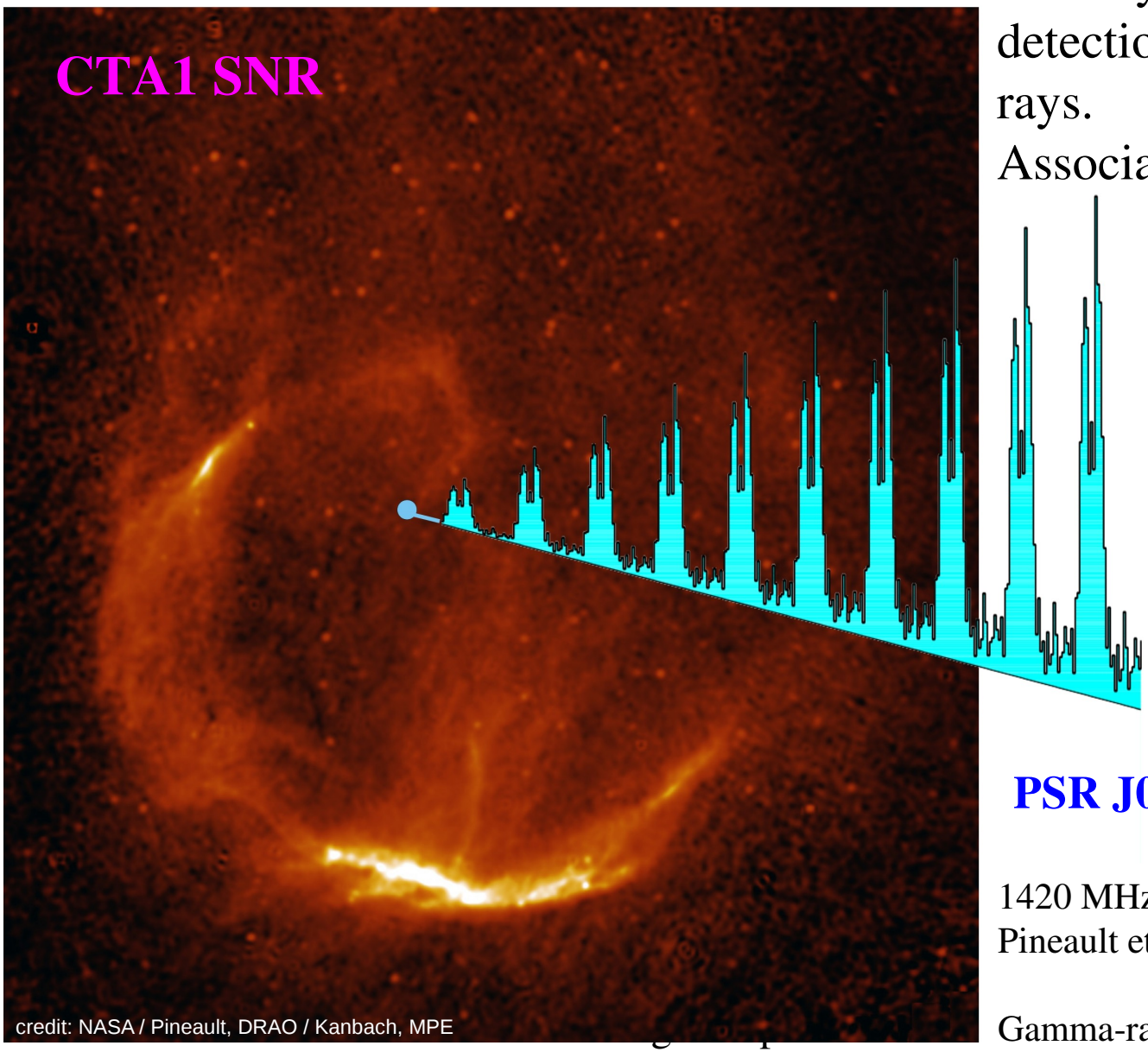
2. How many unassociated *EGRET* sources are pulsars?
   Several radio pulsars discovered in *EGRET* error circles, only positional associations.

3. Are gamma rays generated near the surface or the light cylinder?
   Spectral signature, light curve morphologies, population predictions.

4. Do millisecond (recycled) pulsars also emit gamma rays?
   Possible detection of MSP J0218+4232 with *EGRET*

5. How does the gamma-ray luminosity behave at lower Ė?
   And where is the death line?

(Q1) We Have a Pulse



~12 days into early calibrations, detection of pulse period in gamma rays.
Associated with 3EG J0010+7309.

P = 316.86 ms
dP/dt = 3.614 10^{-13} s s^{-1}

PSR J0007+7303

1420 MHz Radio Map:
Pineault et al., A&A **324**, 1152 (1997)

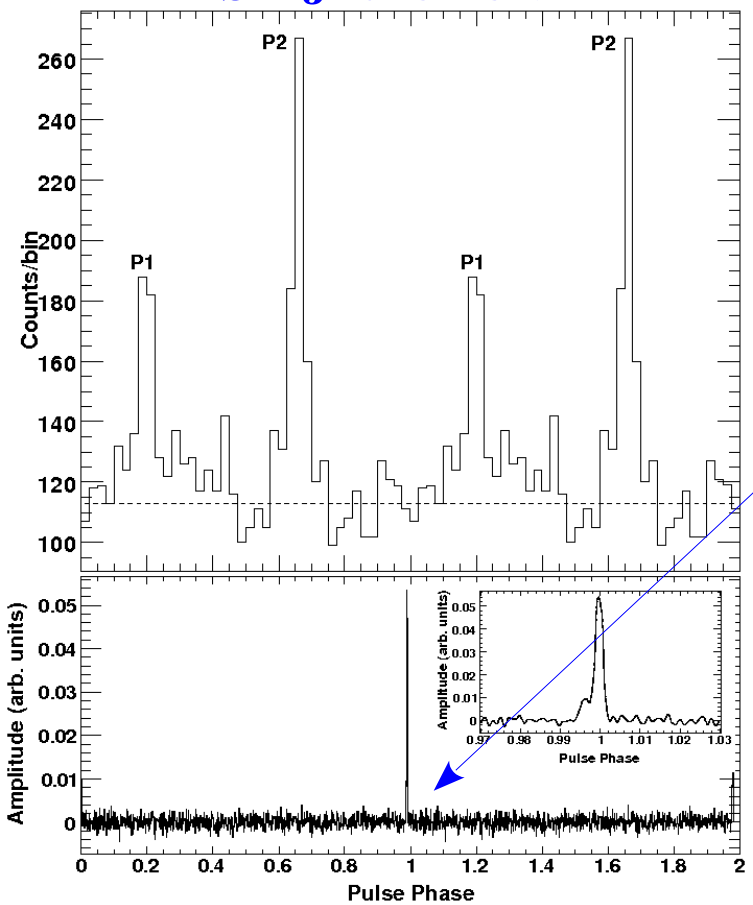
Gamma-ray pulsar:
Abdo+ (2008)

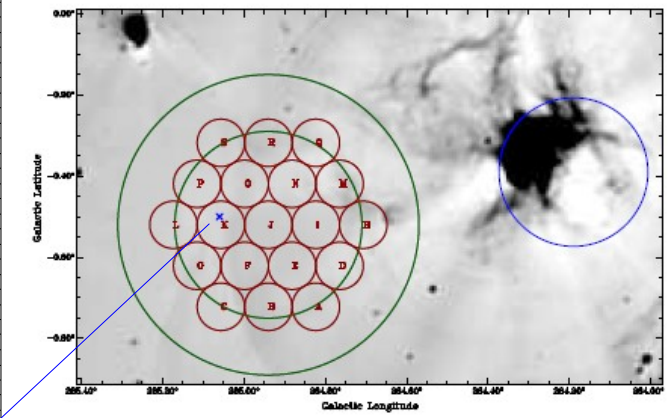
(Q2) If it looks like a pulsar...

...it might be a pulsar!

Successful discovery of non-recycled pulsars in *EGRET* error circles, find more with LAT?

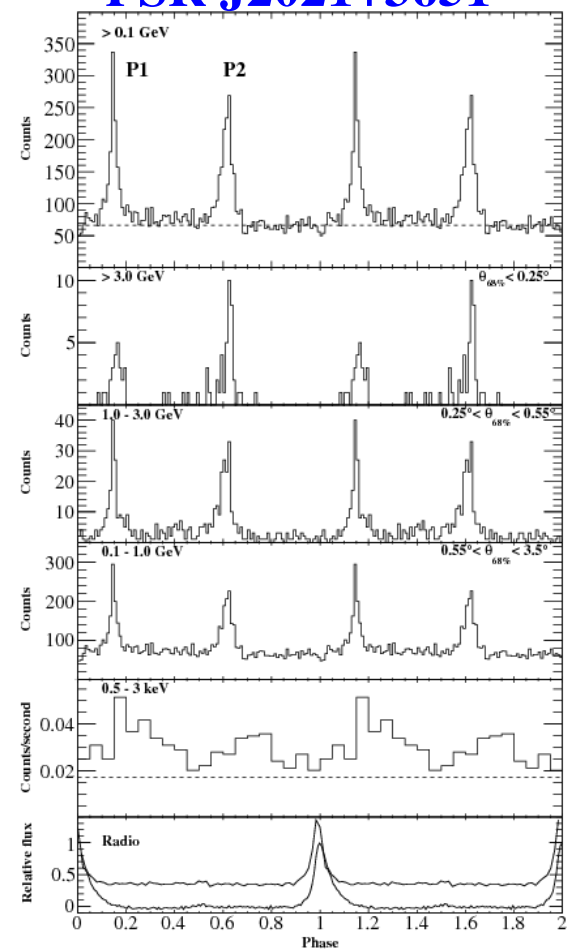
PSR J1028-5819





Keith+ (2008)

PSR J2021+3651



Pulsar discovered by Roberts+ (2002)
associated with dragonfly nebula
Also seen by *AGILE* (Halpern+ 2009)

(Q3) It's Out There Man

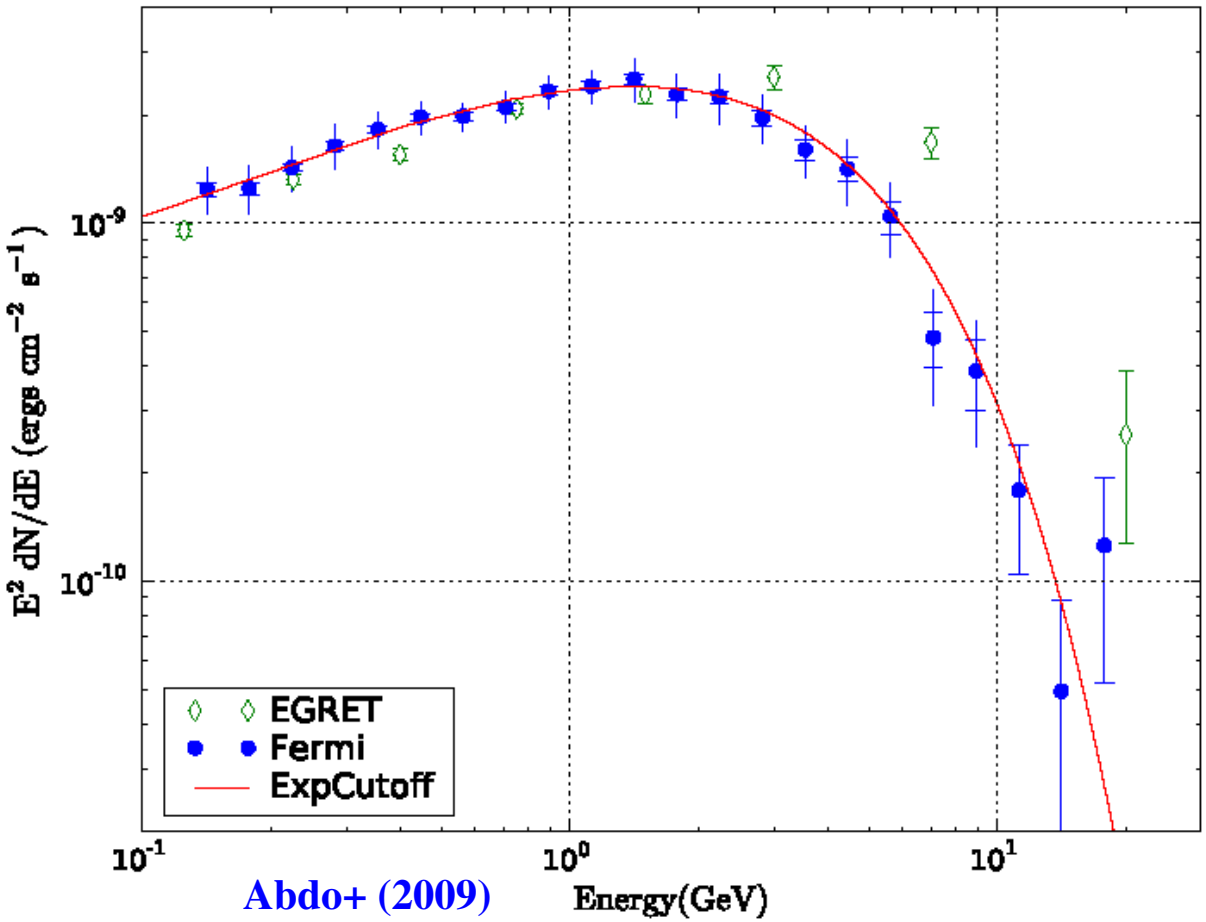
Vela Pulsar:
Calibration pointing-mode and early sky-survey data

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

$E_{Cut} = 2.86 \pm 0.09$ GeV

$\Gamma = 1.51 \pm 0.01$

$b = 1$

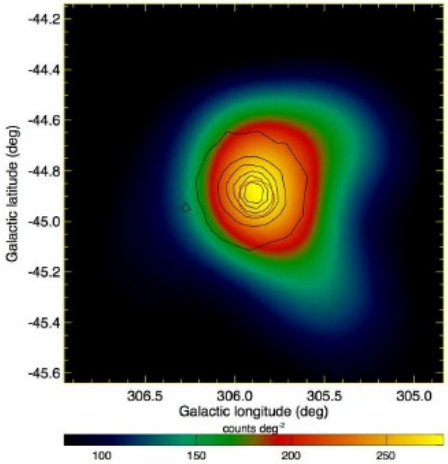


Abdo+ (2009)

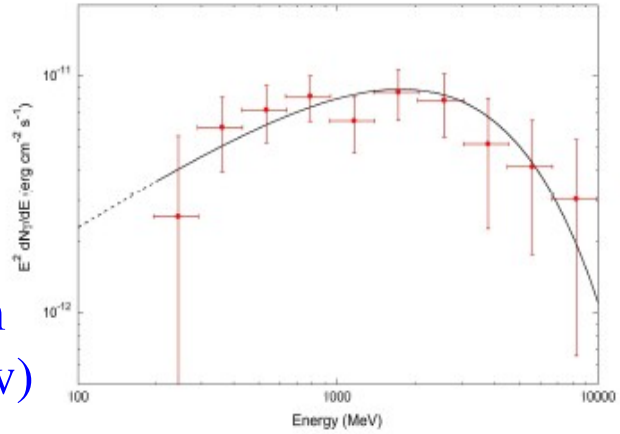
$b = 2$ excluded at 16.5σ

More pulsars detected, similar result...near-surface emission ruled out as dominant gamma-ray emission site.

(Q4) They're Everywhere

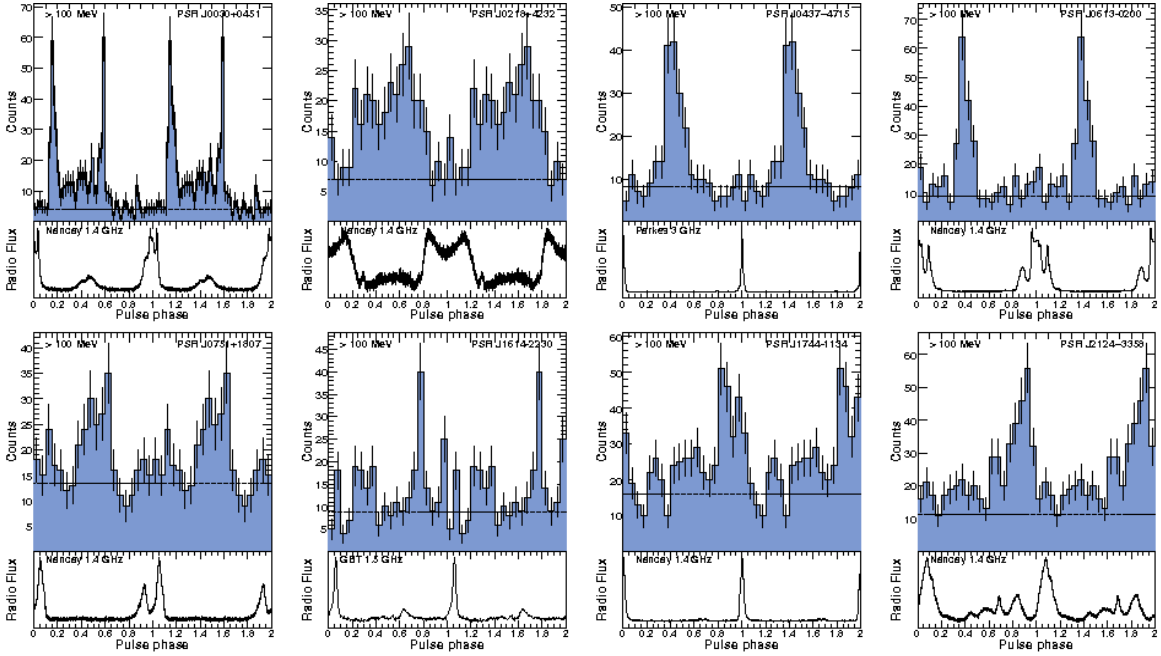


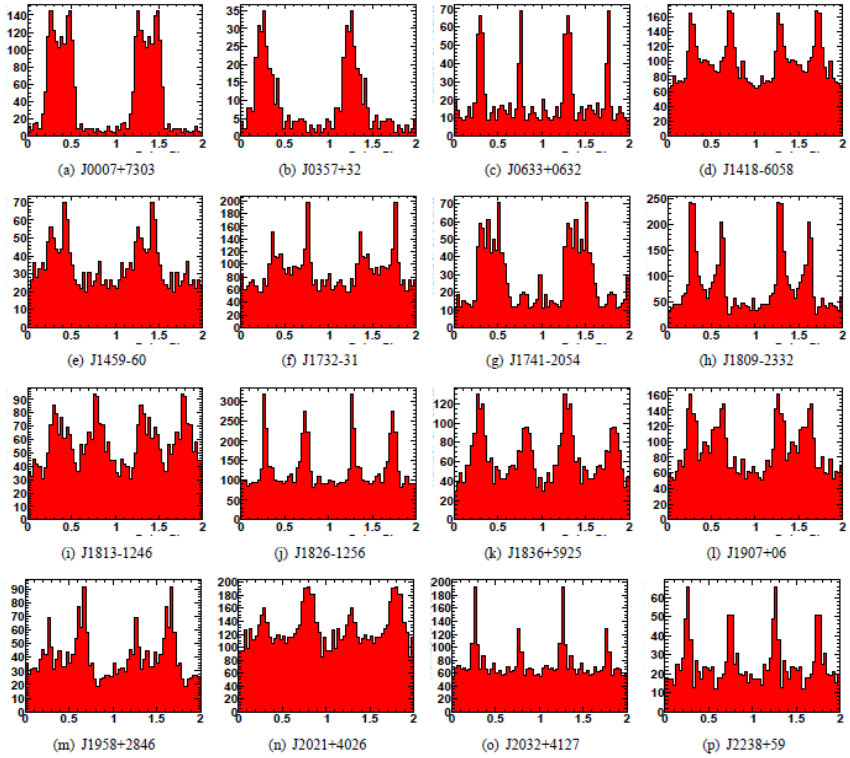
Globular cluster 47 Tucanae,
23 known MSPs
pulsar-like
gamma-ray spectrum
(>12 clusters seen now)



16 blind search pulsars, all young
13 with 3EG associations

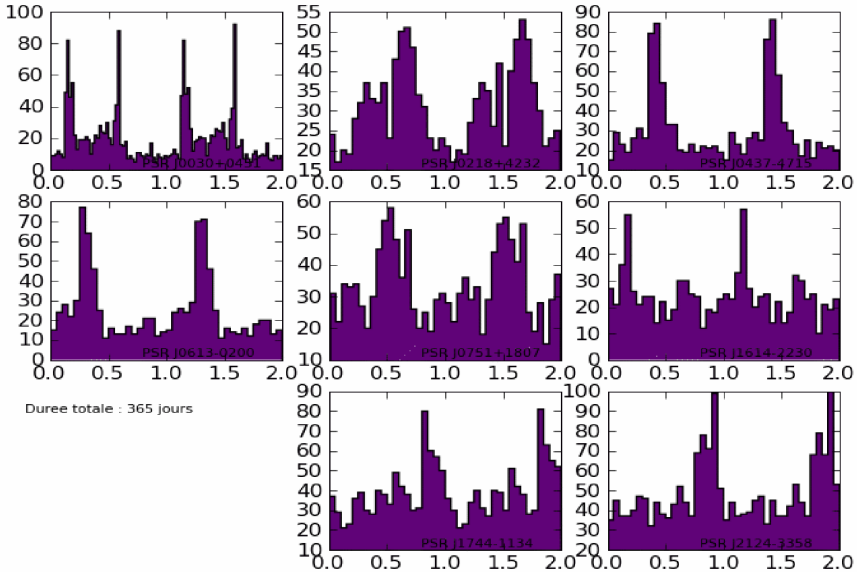
8 MSPs





Ground Testing is Important

Muon events were used to verify the LAT timing system pre-launch.
A 2.0083 μs clock drift identified and corrected.
Later ground testing identified and fixed another issue related to a drift with respect to the GPS signal. (Smith+ 2006)



Top: First 8 gamma-ray MSPs detected with the LAT

Bottom: Same MSPs but with arrival times modified as if the timing issues had not been identified and fixed.

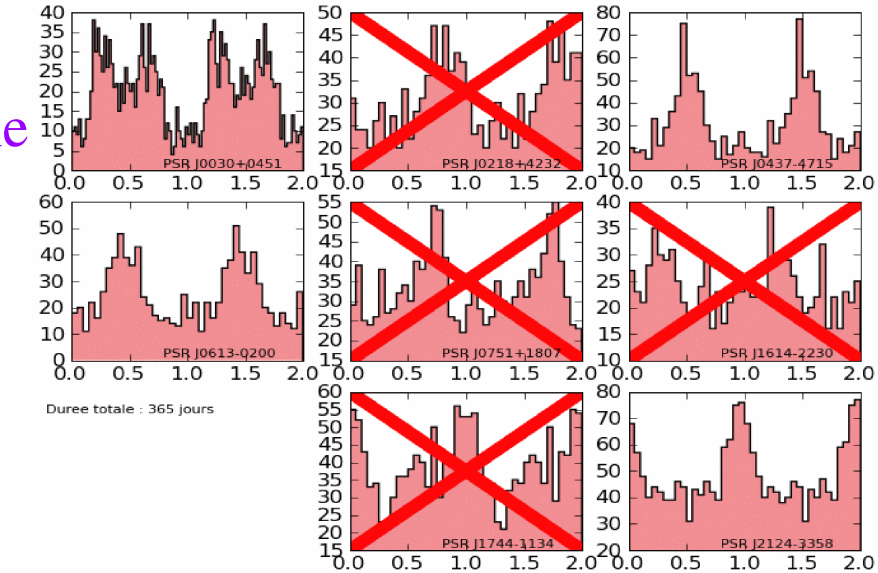


Figure courtesy D. Dumora

(Q5) The Second LAT PSR Catalog

117 pulsars: 77 young:

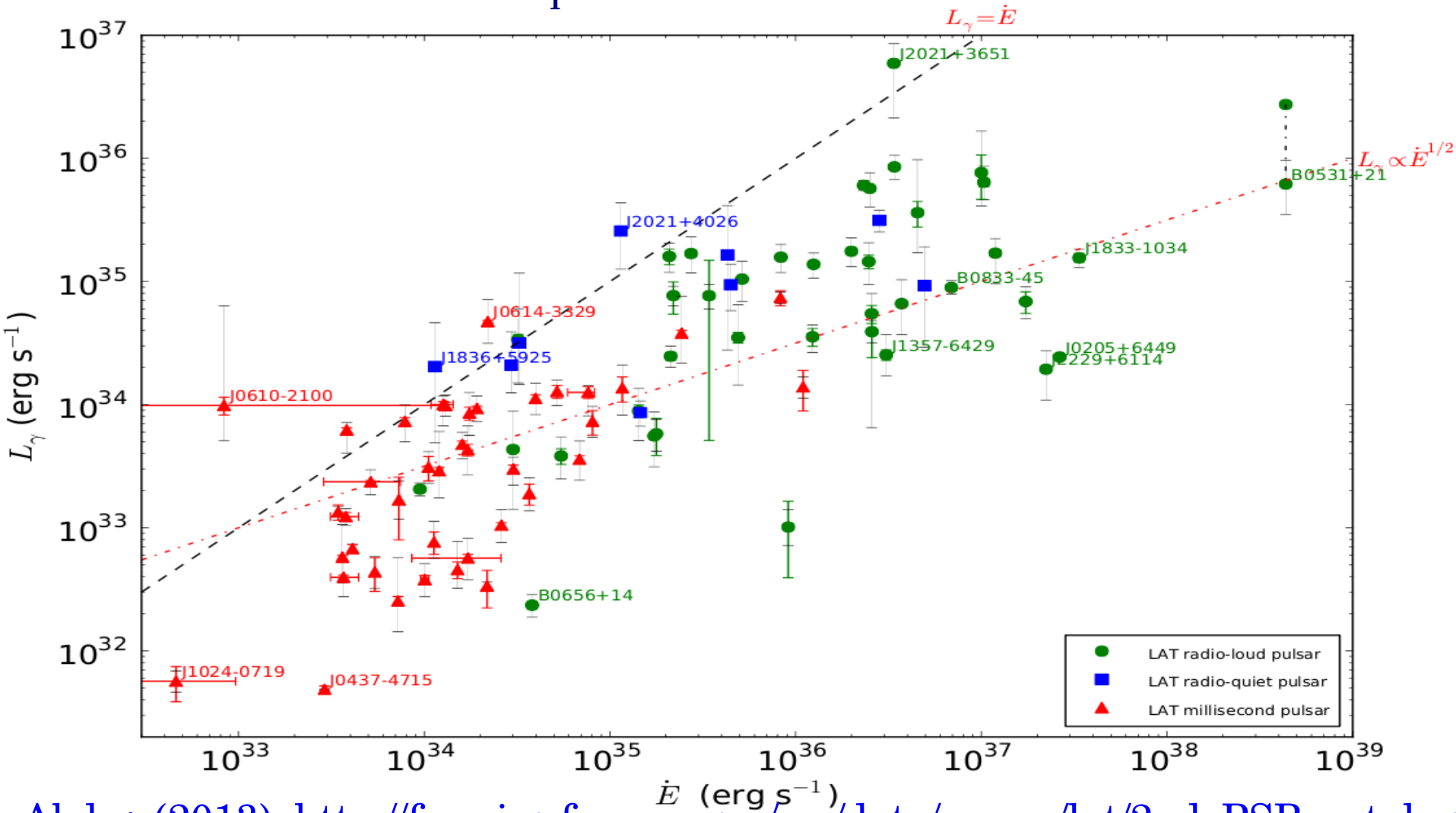
42 radio-loud

35 radio-quiet

40 millisecond:

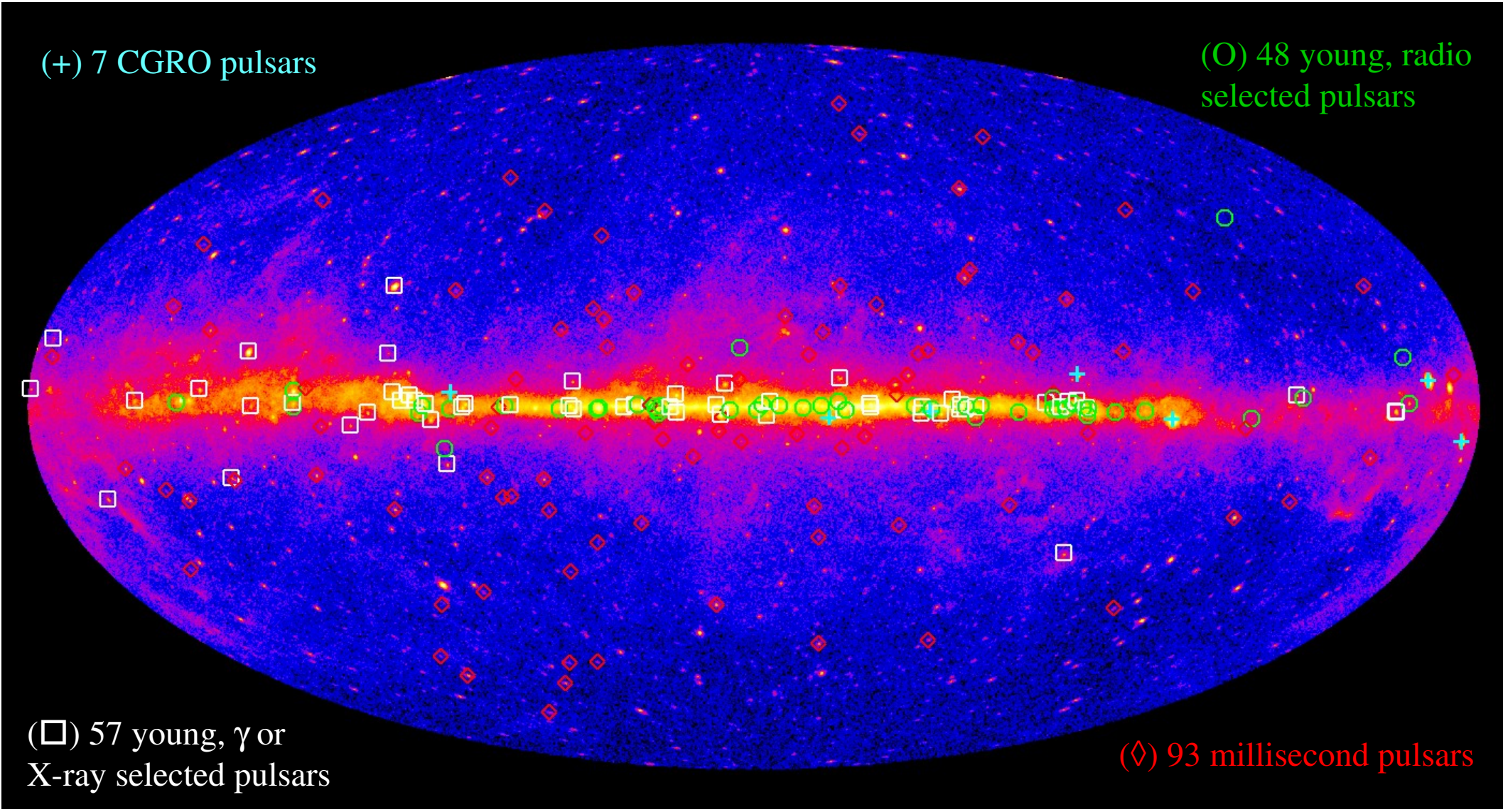
20 known before *Fermi*

20 discovered in LAT sources



Abdo+ (2013): http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2nd_PSR_catalog/

Latest Gamma-ray Pulsar Count...205



Public List: https://confluence.slac.stanford.edu/x/5Jl6Bg

Surprises & New Questions

Excellent spectra and higher energy reach

- Not just b > 1 ruled out, but b < 1 often preferred.
- Crab at TeV energies and LAT detections above 10 GeV.

The Crab is no longer alone with multi-λ peaks (nearly) aligned in phase

- Link to high B_{LC}, giant pulses, $\dot{E}$?

Not just lots of MSPs, but interesting sources/systems.

- Spiders, the double pulsar, etc.

Not necessarily constant gamma-ray flux sources.

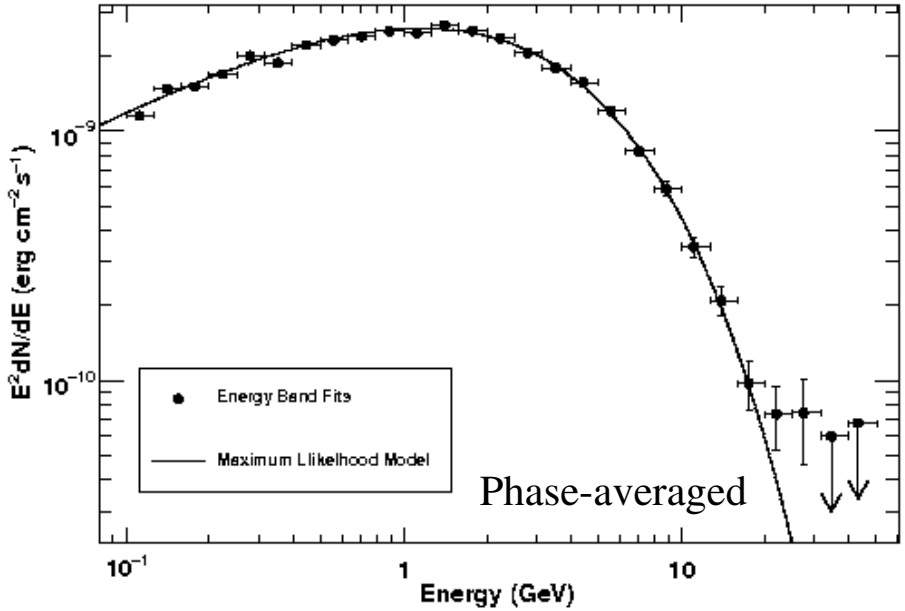
- Mode-change like variability? Long-period binary systems

What about that deathline?

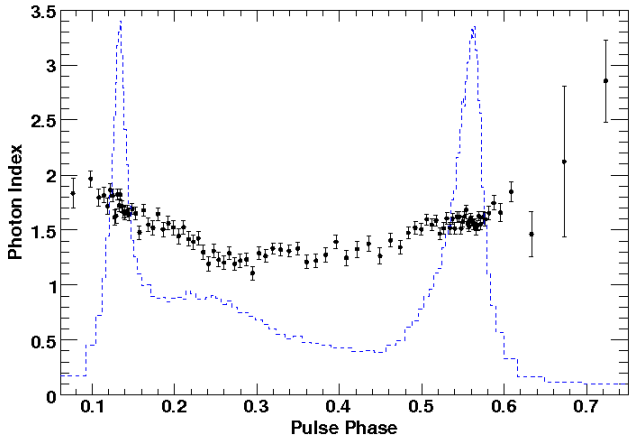
- Does it even exist?

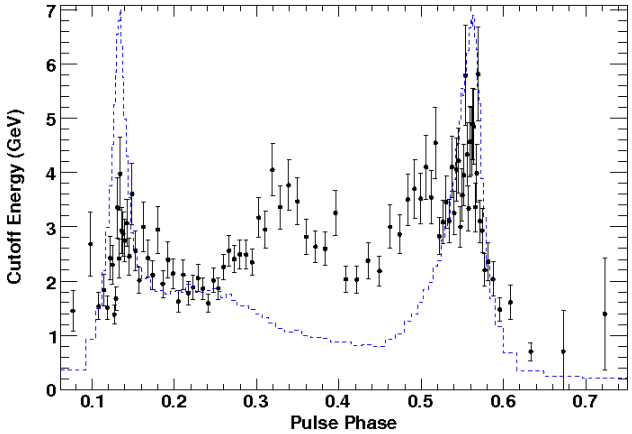
Changing Viewpoints

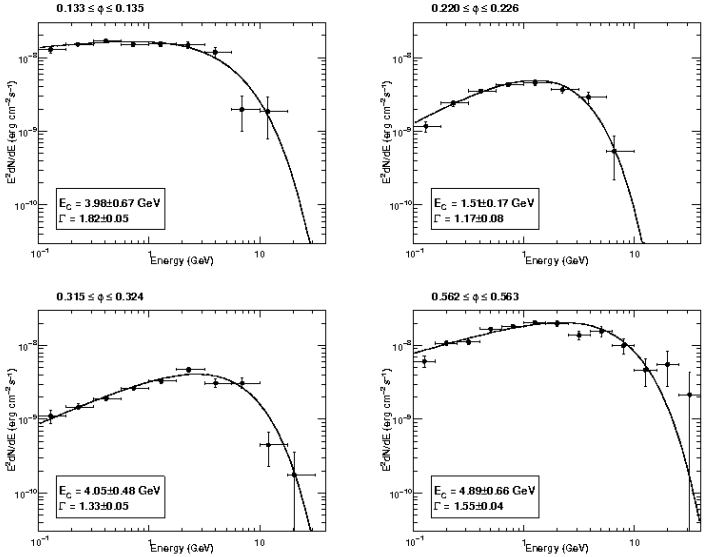
The Vela pulsar after 11 months, Abdo+ (2010)



Best-fit spectrum has b < 1, superposition of spectra with varying E_{Cut} and Γ.



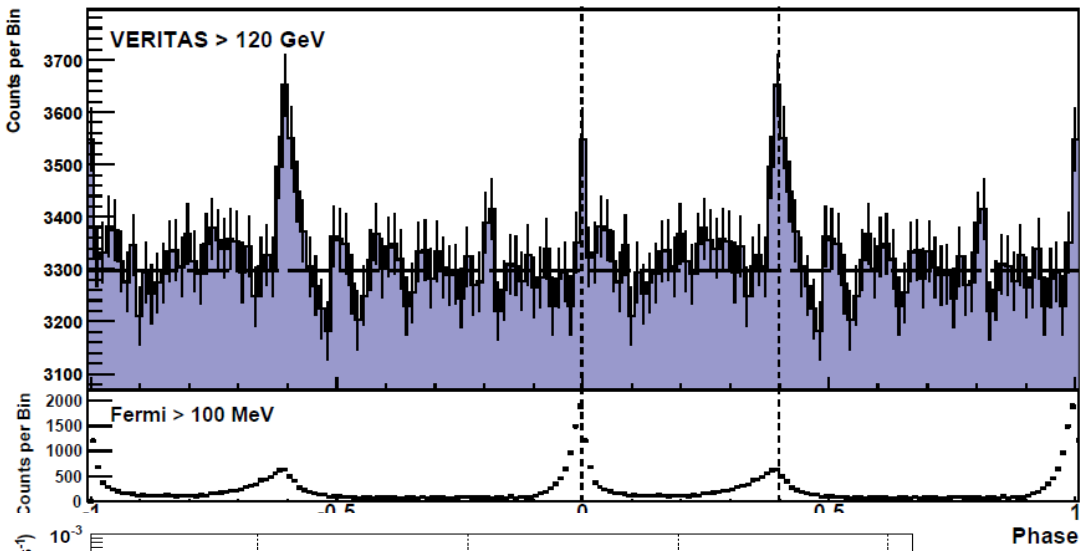




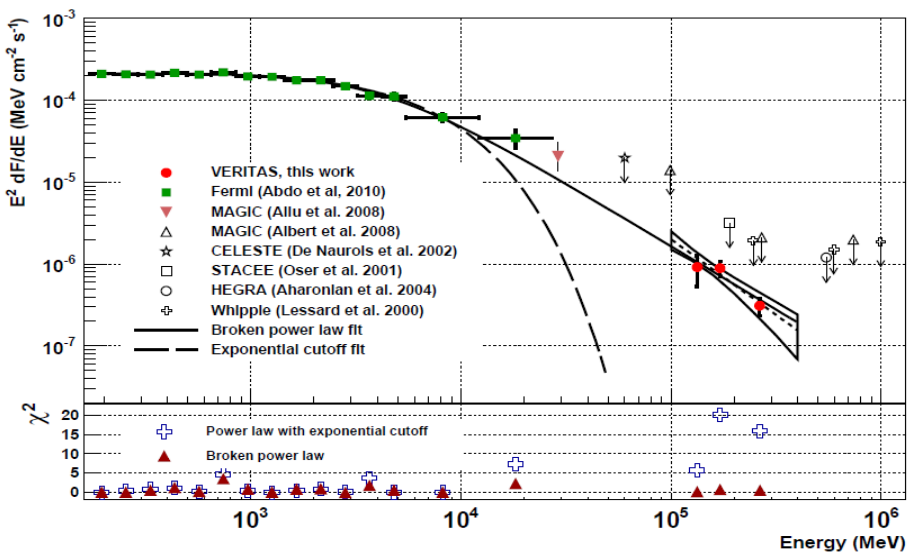
Phase-resolved, consistent with b=1

Could also mean emission isn't curvature radiation...

VHE Pulsations from the Crab

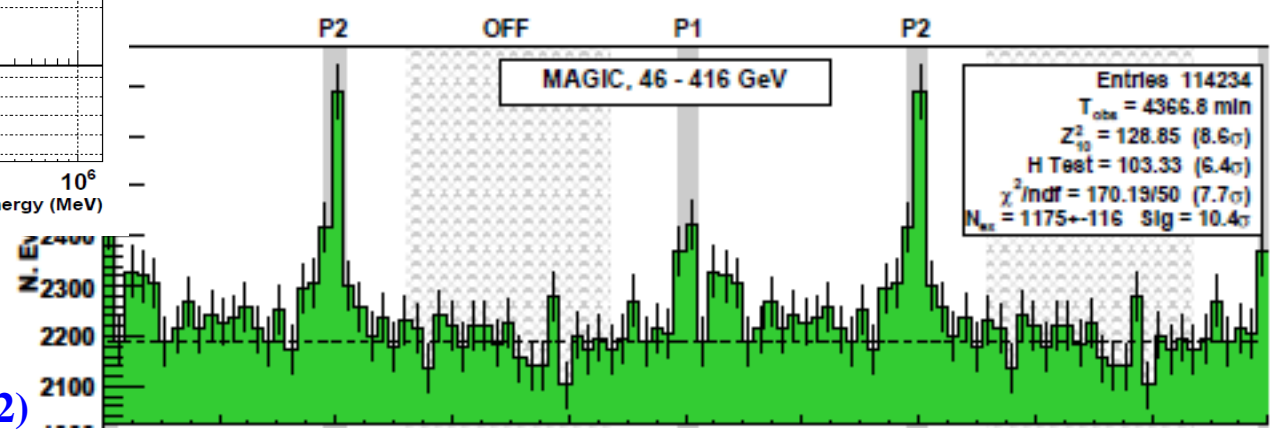


Aliu+ (2011)



Pulsations detected out to ~400 GeV
Curvature radiation ruled out at these energies, second component or different mechanism?

Phase-resolved spectroscopy and light curve morphology with energy will be important.



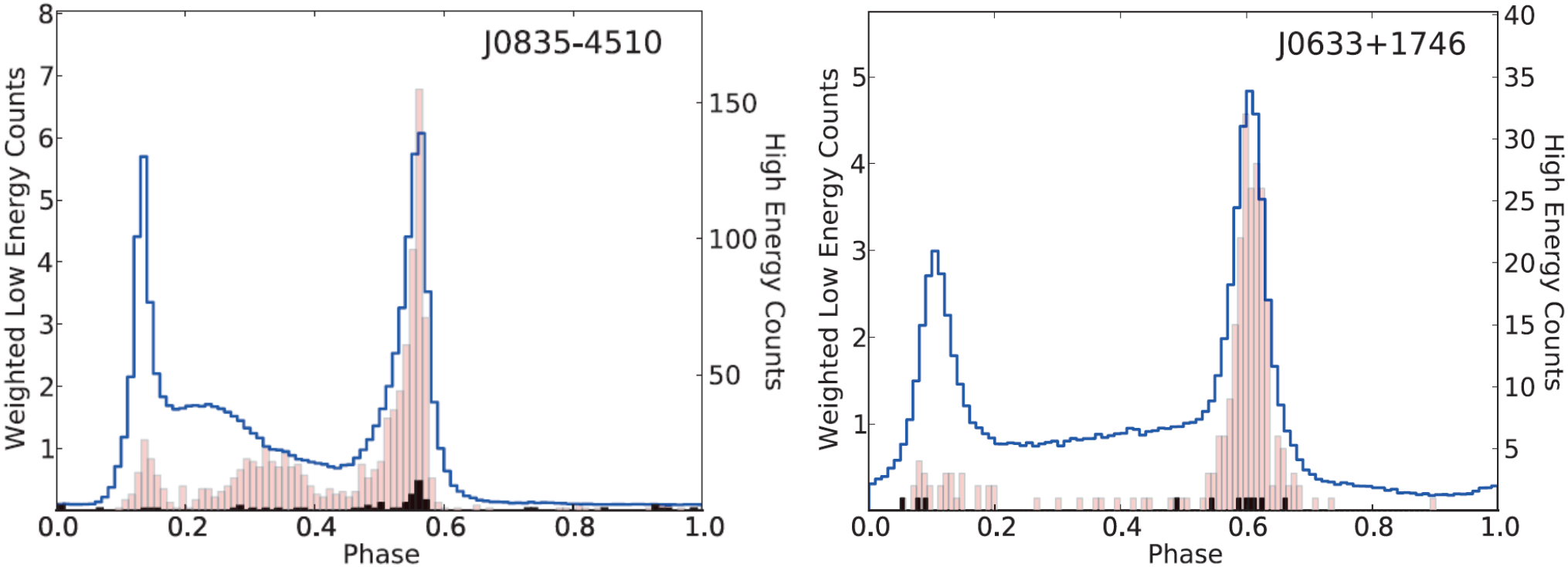
Aleksic+ (2012)

Looking for VHE Candidates

1FHL catalog, 3 years, ≥10 GeV. Difficult to predict what TeV telescopes will see using LAT data (improvements with Pass 8, CAL only events, ?)

Associations with 27 pulsars

≥ 10 GeV pulsations from 20 pulsars, and 12 ≥ 25 GeV

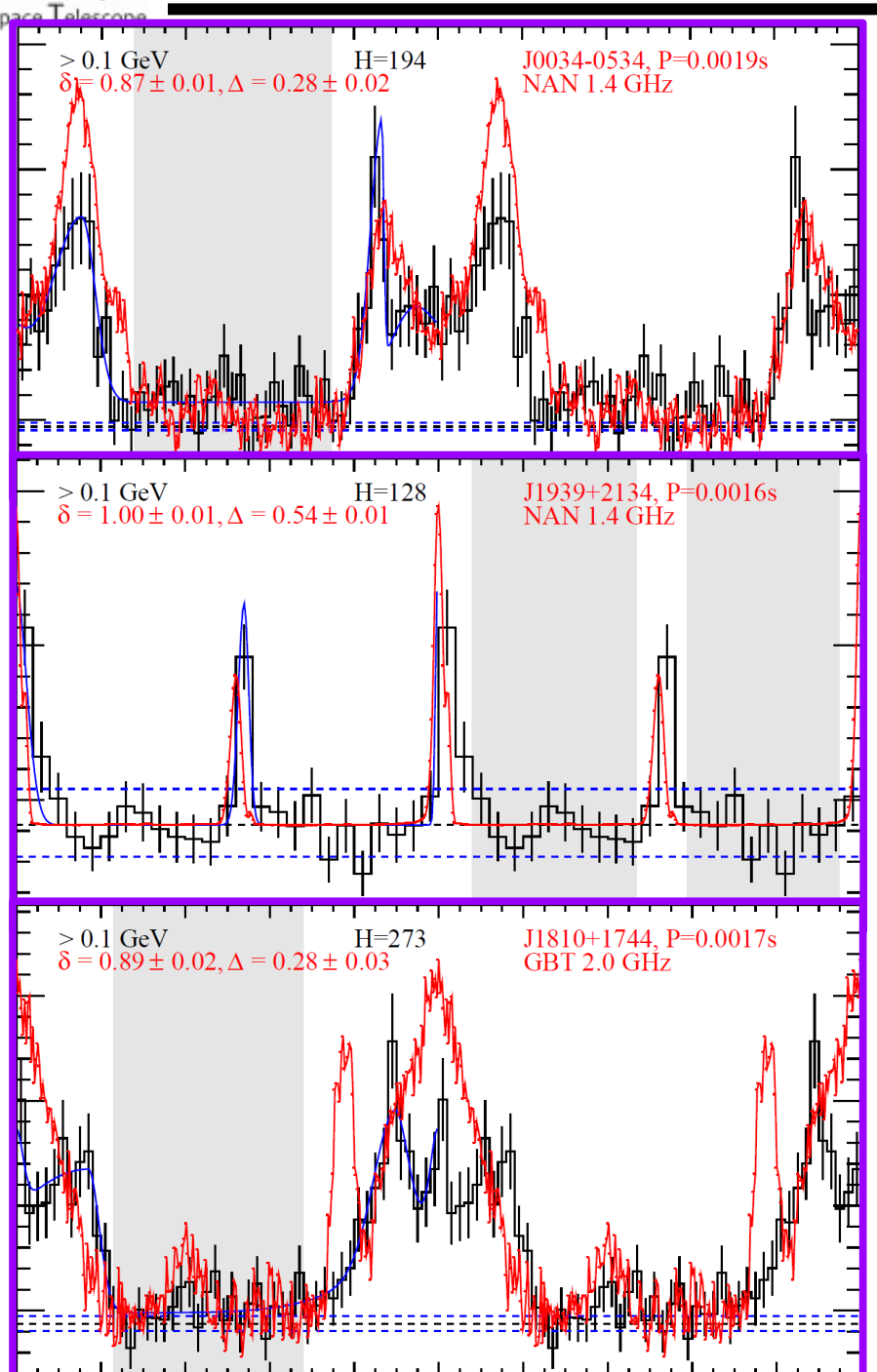


Normalized weighted light curve 0.1-10 GeV

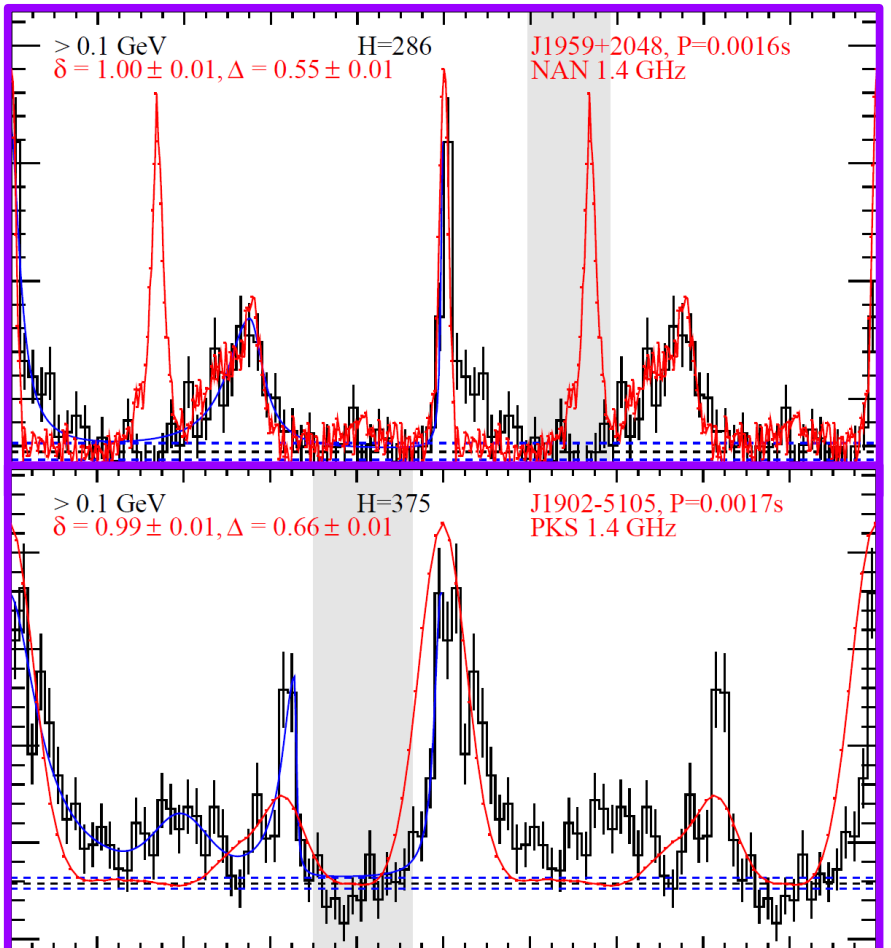
Counts light curve above 10 GeV

Counts light curve above 25 GeV

MSPs with "Aligned" Profiles



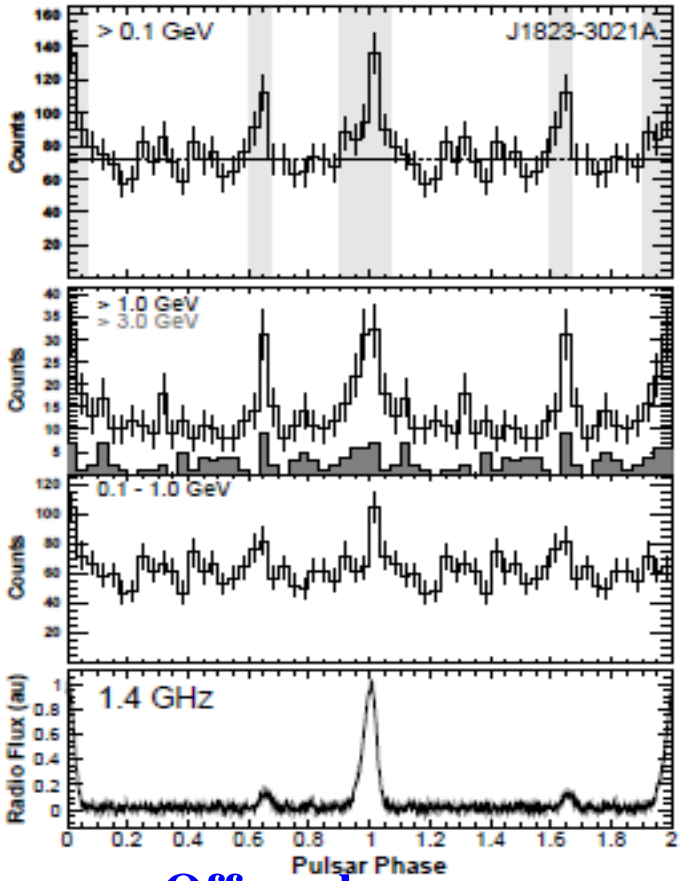
Radio and gamma-ray profiles strikingly similar in some cases.
Radio profile evolution with frequency, not all features matched.
Some, but not all, known to emit giant pulses.

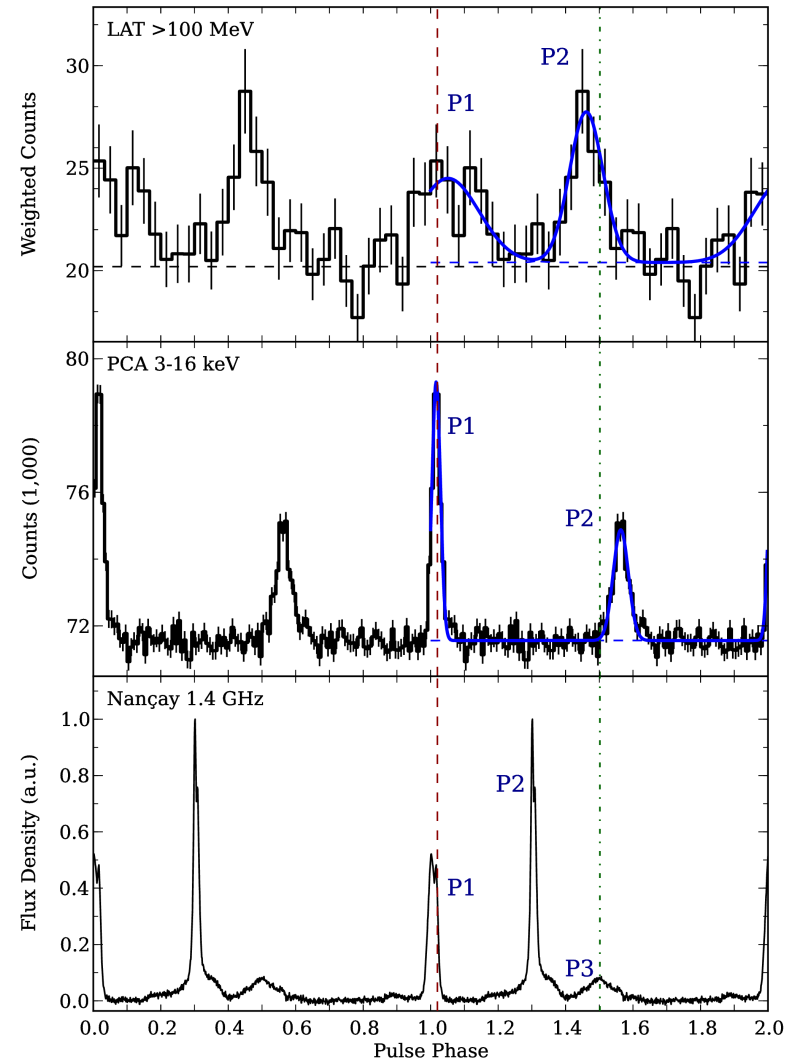


Cluster MSPs Shining from Afar

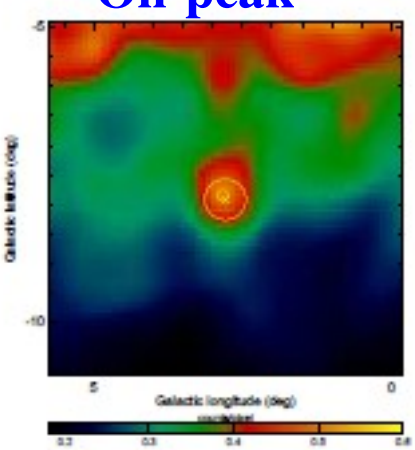
Freire+ (2011), luminous MSP in globular cluster NGC 6624, d = 8.4 kpc, P = 5.4 ms

Accounts for all LAT emission.

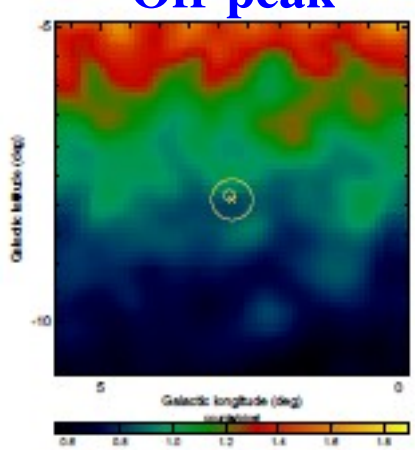




On-peak



Off-peak



Johnson+ (2013) PSR B1821-24 in M28.
D = 5.1 kpc, P = 3.05 ms.
Doesn't account for all LAT emission.

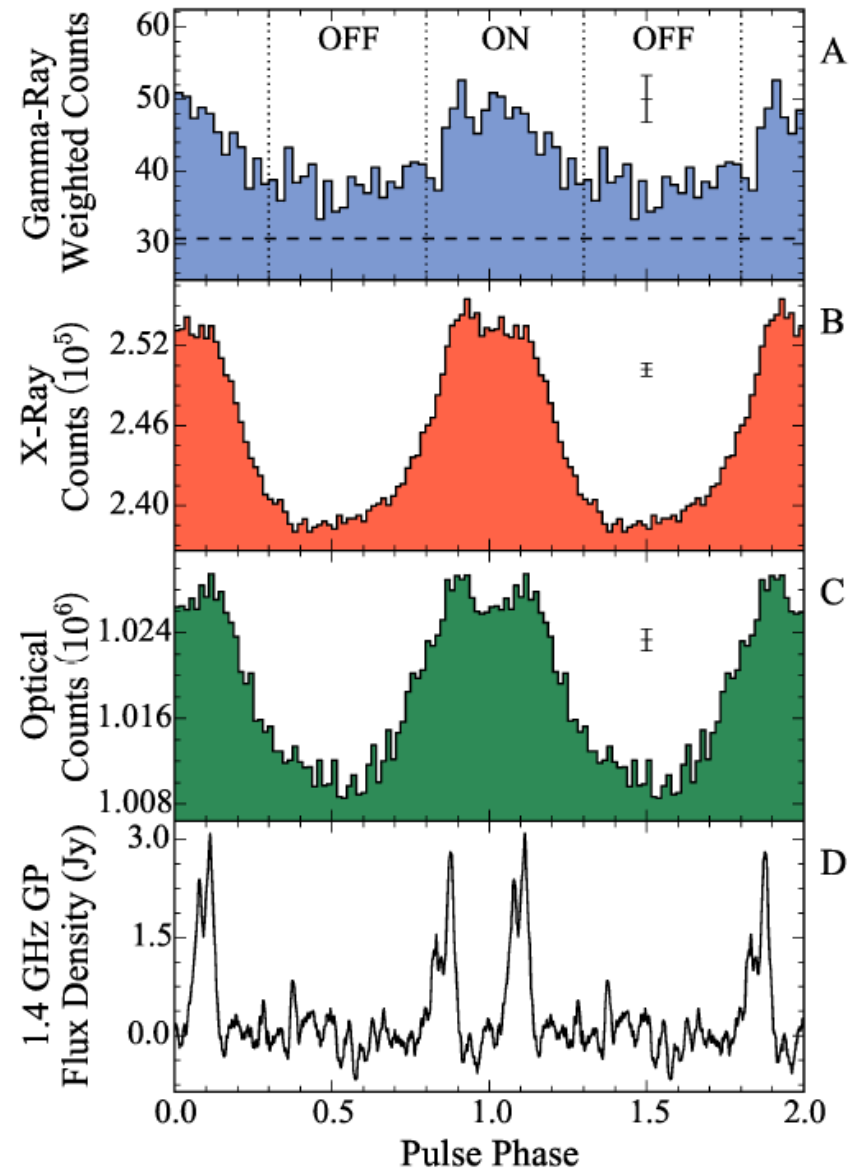
Meanwhile, even farther away

Ackermann+ (2015), first extragalactic gamma-ray pulsar, located 50 kpc away in the LMC.

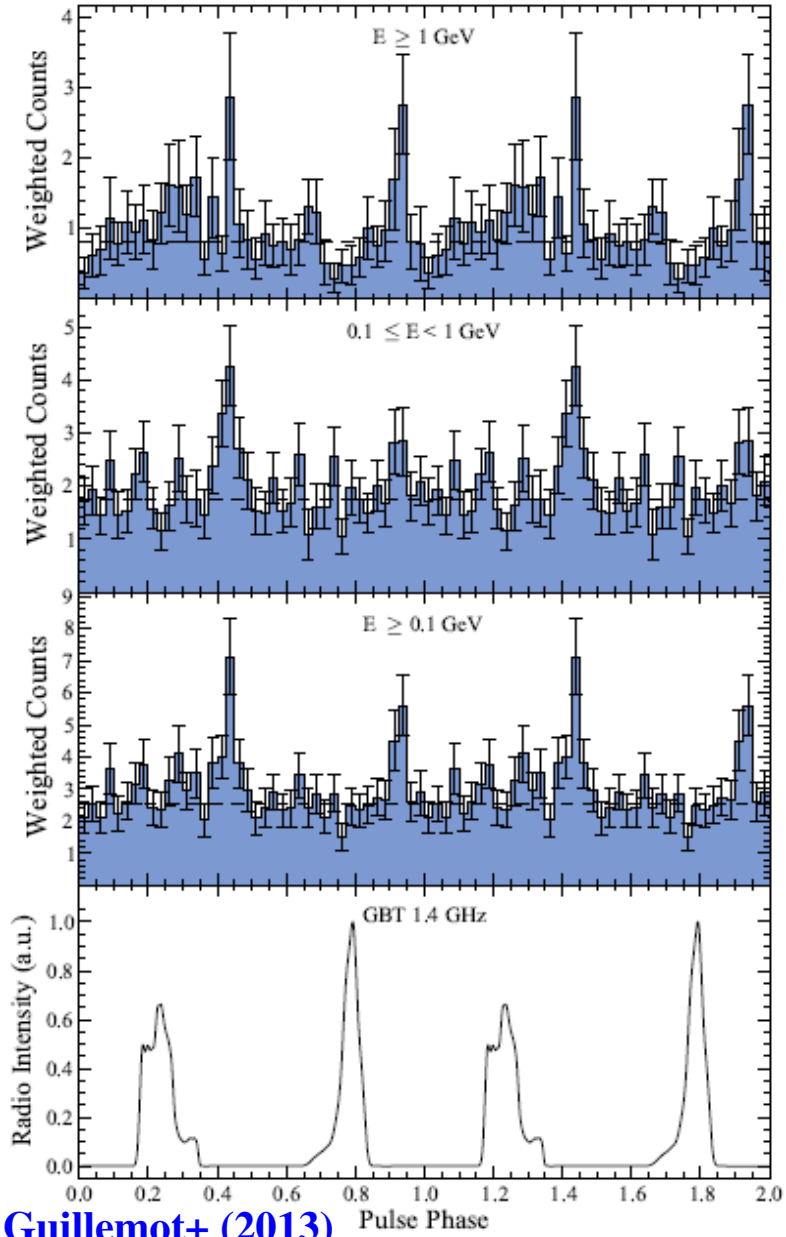
Uses RXTE timing solution, radio profile combination of 18 giant pulses at 1.4 GHz. Multi-λ peaks at same phase but different morphology.

Like the Crab, PSR J0540-6919 has higher pair densities than other gamma-ray pulsars.
⇒ Synchrotron self-Compton emission?
⇒ VHE emission?
Current LAT data is insufficient to confirm or rule out a high-energy tail.

PSR J0540-6919



Double Pulsar System



Guillemot+ (2013)

PSR J0737-3039A/B:

- double neutron star binary (2.4 hr orbital period)
- radio pulsations from both A & B
- used to show general relativity correct to within 0.05% (McLaughlin, Aspen 2013)

PSR A, P = 22 ms:

- partially recycled
- $\dot{E}$ makes it a gamma-ray pulsar candidate

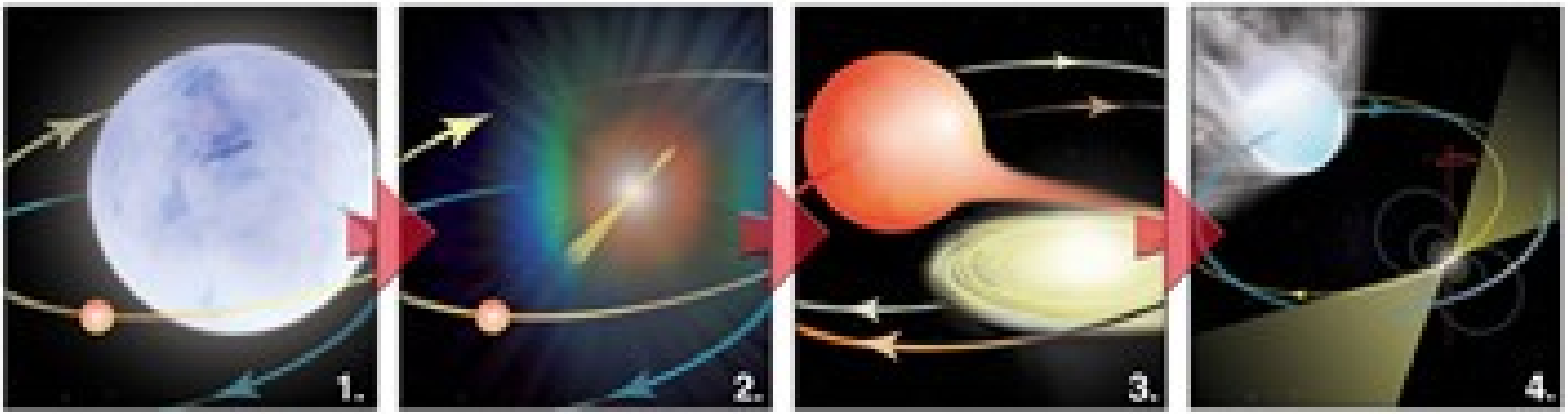
Gamma-ray detection:

- light curve modeling and radio polarization suggest orthogonal rotator viewed edge on
- Support electron-capture supernova formation for PSR B

Gamma-ray Spiders

"Black Widows" (BWs) and "Redbacks" (RBs)

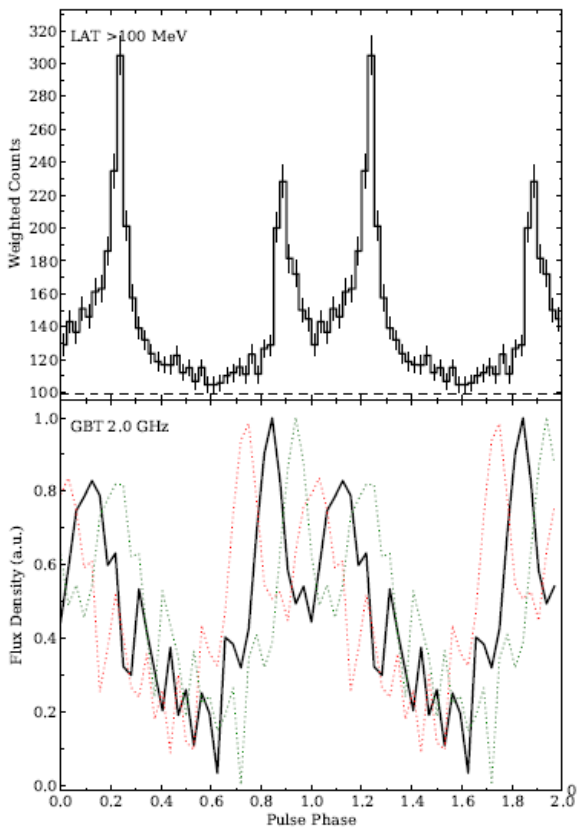
- MSPs in binaries with low-mass companions (~0.02$M_\odot$, BW; ~0.2$M_\odot$, RB)
  - Low-mass X-ray Binary ⇔ MSP link?
- Short orbital periods (<1day)
- Companions ablated by pulsar winds
- 3 BWs and 1 RB pre-*Fermi* (not in globular clusters)
  - At least 17 BWs and 9 RBs post-*Fermi*
  - Majority detected in radio observations of LAT unassociated sources
  - Hot topic/question: Gamma rays from intra-binary shock?



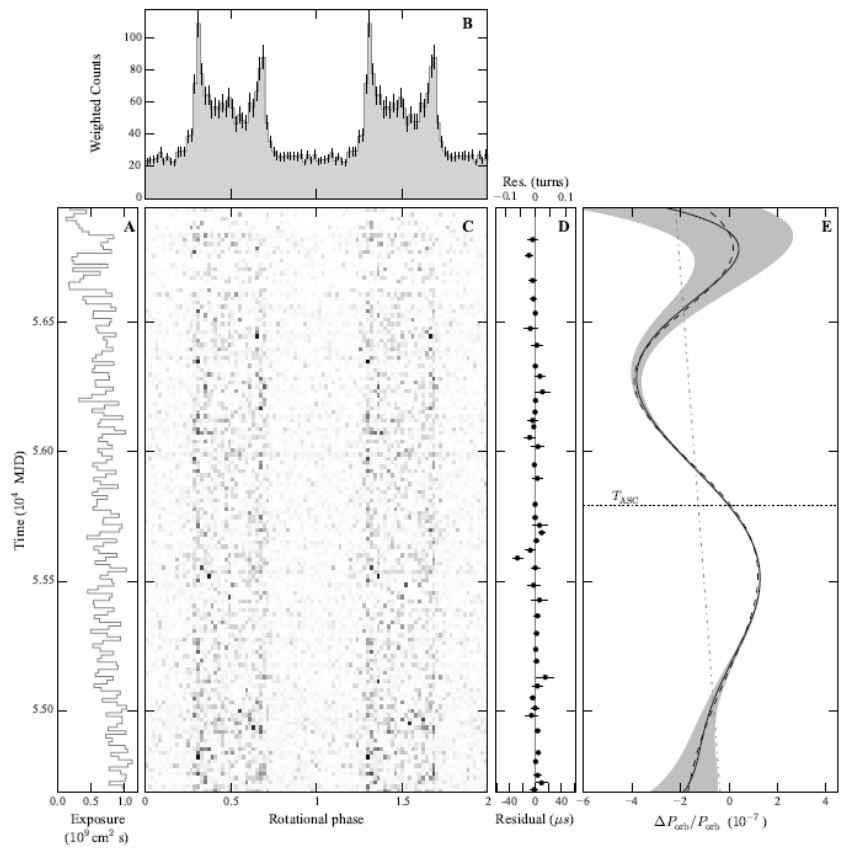
Blind Search Spiders

Identify orbital periods (via opt. and X-rays, e.g., Romani, Kong) in pulsar-like unassociated LAT sources in which no radio pulsar has been found, use that for constrained blind search

PSR J1311-3430
Blind search Pletsch+ (2012)
Radio detection Ray+ (2013)



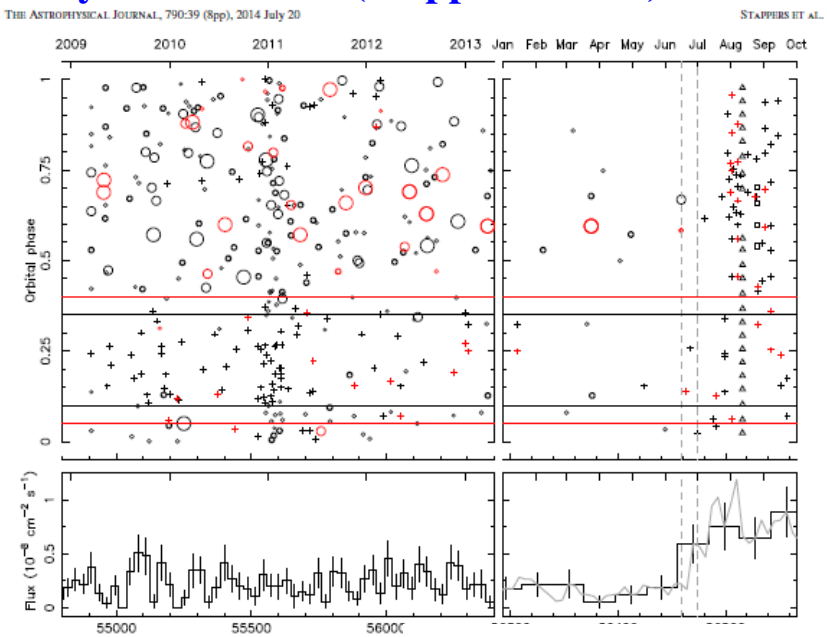
PSR J2339-0533
Radio detection Ray+ *(in prep)*
Gamma-ray timing Pletsch+ (2015)

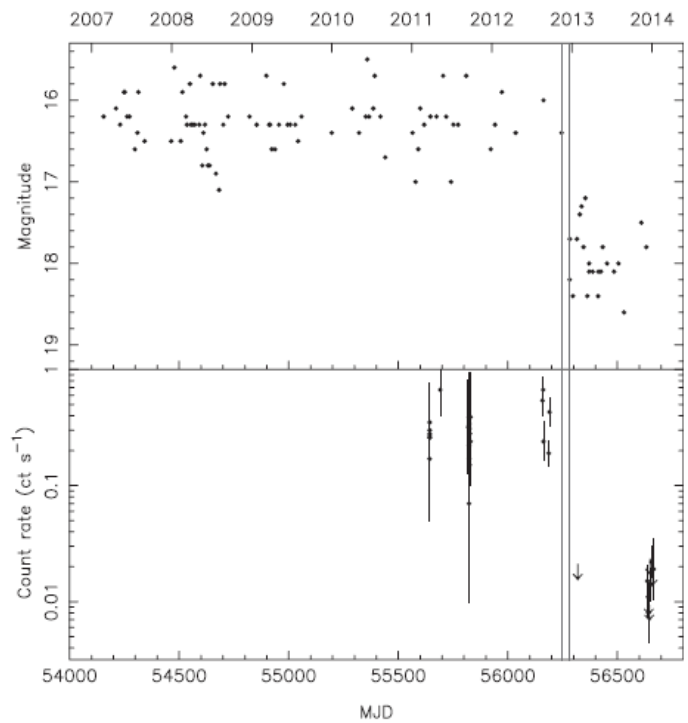


Quasi periodicity in orbital period changes suggest changes in companion gravitational quadrupole moment, also seen in the RB J1048+2339 (Deneva+ 2016)

Transitional MSPs

PSR J1023+0038 transitions to LMXB-like state, radio pulsations gone, gamma-ray flux increase (Stappers+ 2014)

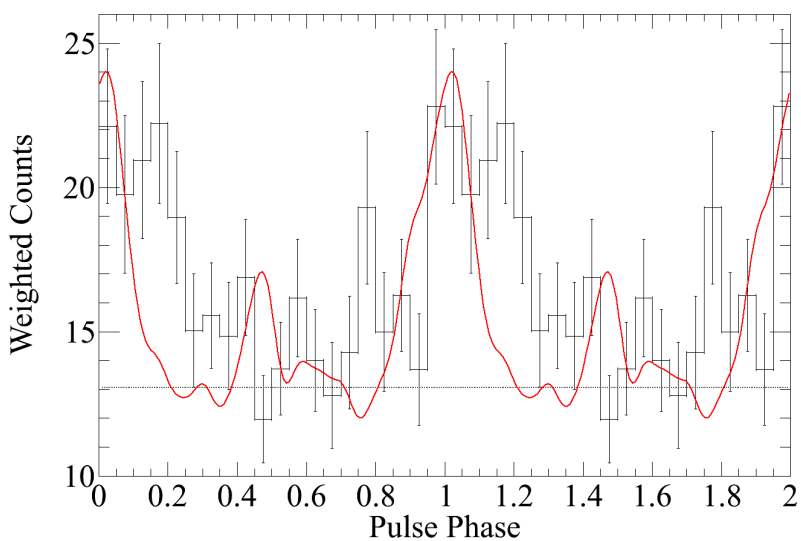


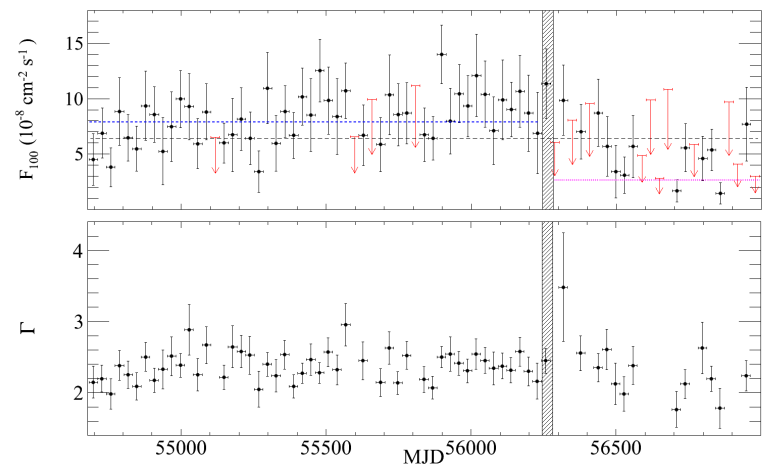


Bassa+ 2014 note opt. and X-ray decline in XSS J12270-4859. Gamma-ray flux change noted.

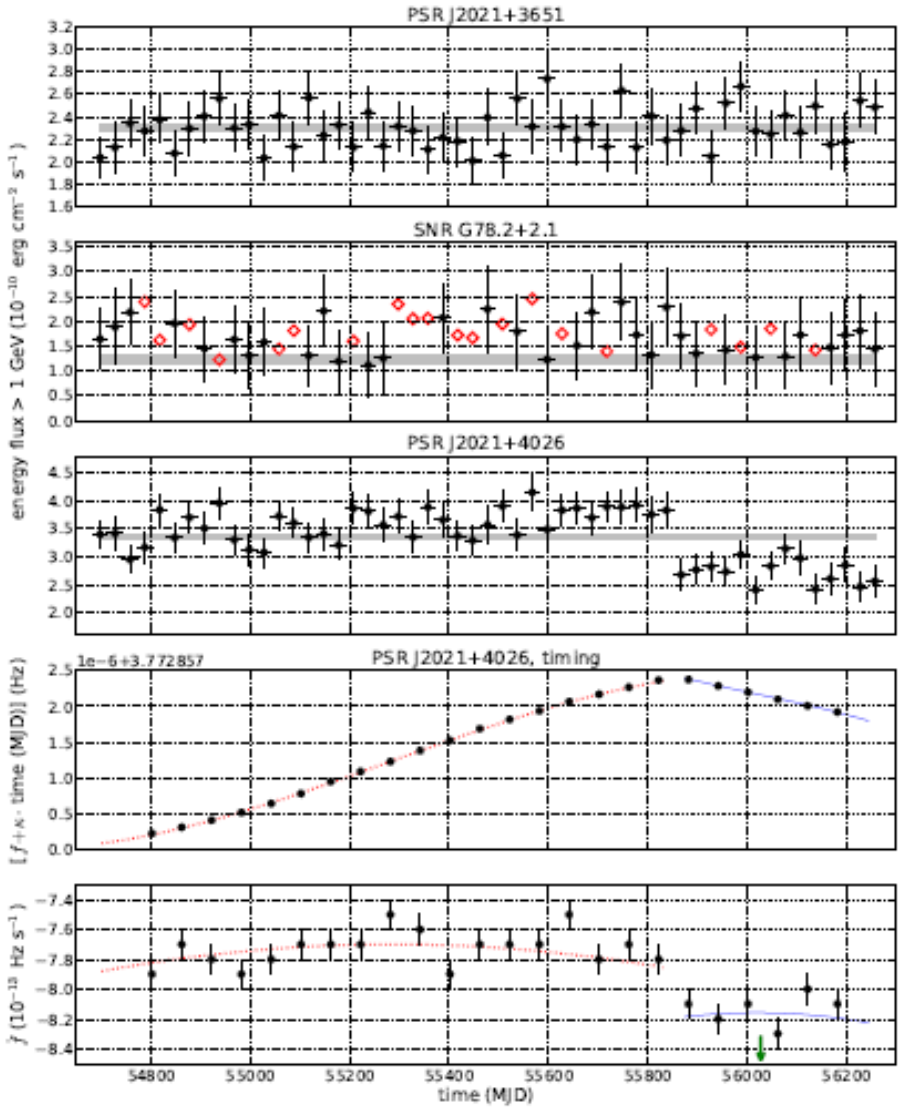
Roy+ 2014 detect new radio MSP, a RB, J1227-4853.

Johnson+ 2015 report gamma-ray pulsations

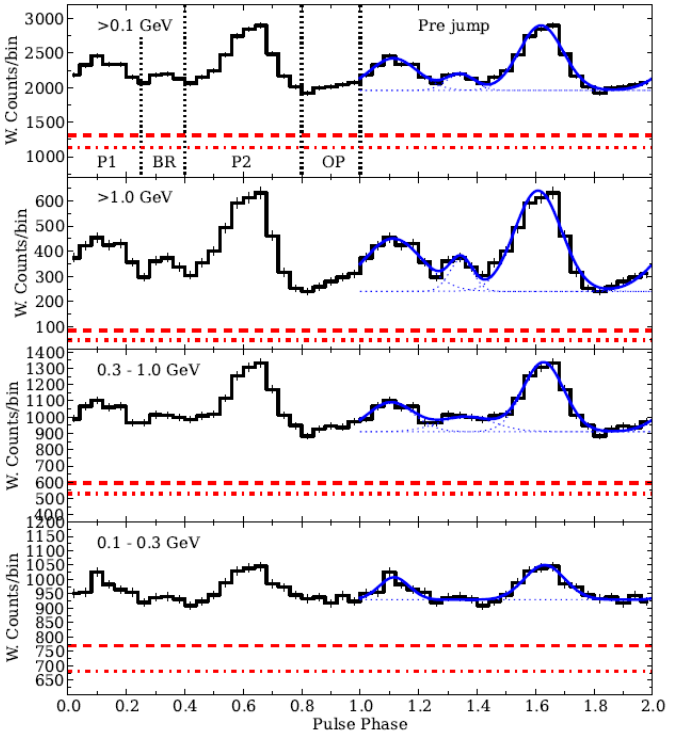




Flux Variability!

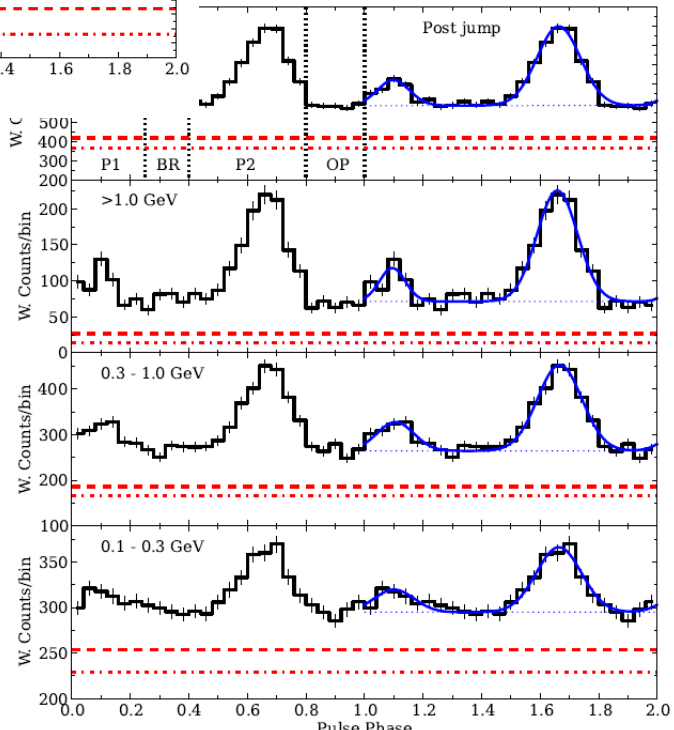


PSR J2021+4026
Allafort+ (2013)



Flux drop coincident with timing change.

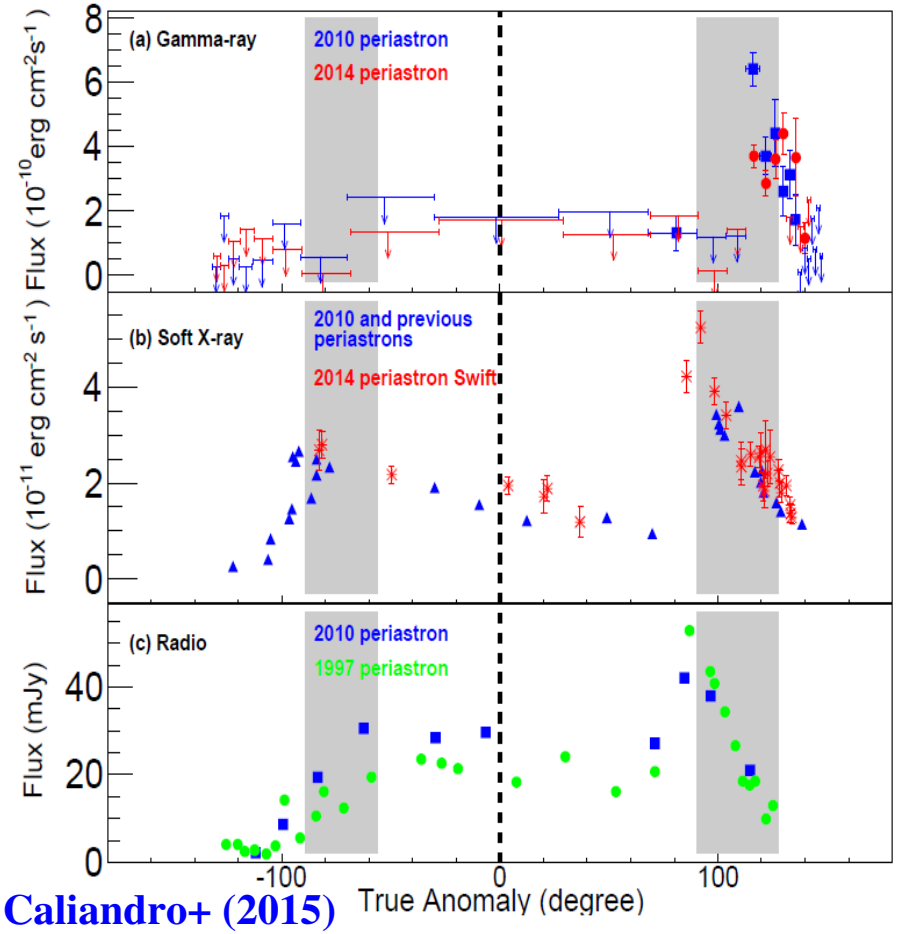
Observe spectral and pulse profile change as well.



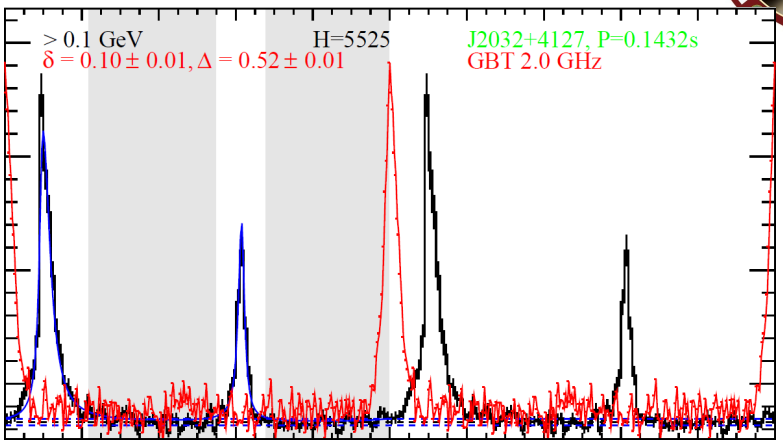
Similar to radio mode changing?

Long-period Binary Pulsars

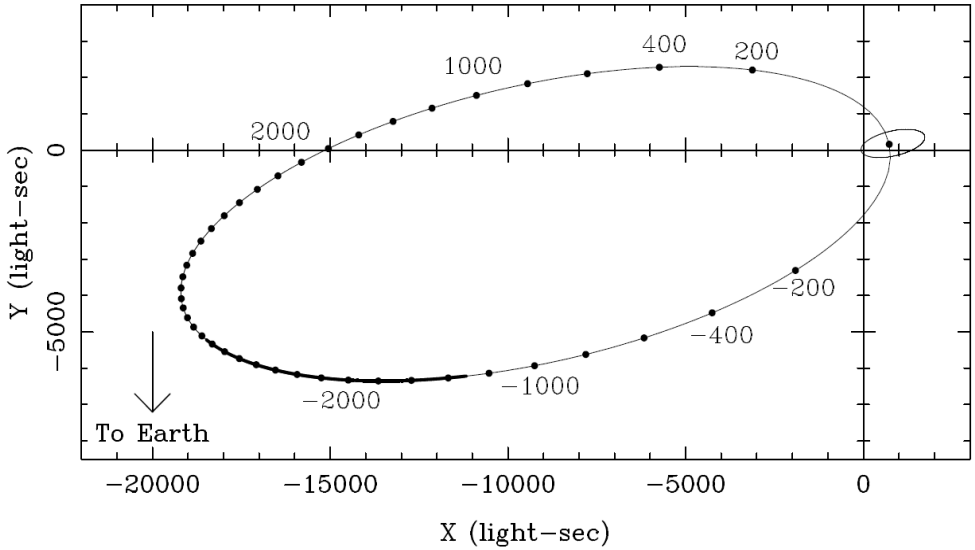
PSR B1259-63, 3.4 yr orbit with Be star
No gamma-ray pulsations, but see flare near periastron.
Interaction of Be disk and pulsar magnetosphere/wind.



Caliandro+ (2015)



PSR J2032+4127, detected first in gamma-rays, later in radio. Long term timing determined it is in a ~25 yr binary orbit with a Be star, periastron late 2017 to early 2018. Gamma-ray timing not dependent on changing DM. Will pulsations be detectable over entire orbit?



Deathline Considerations (I)

New pulsars detected with help of Pass 8 data.

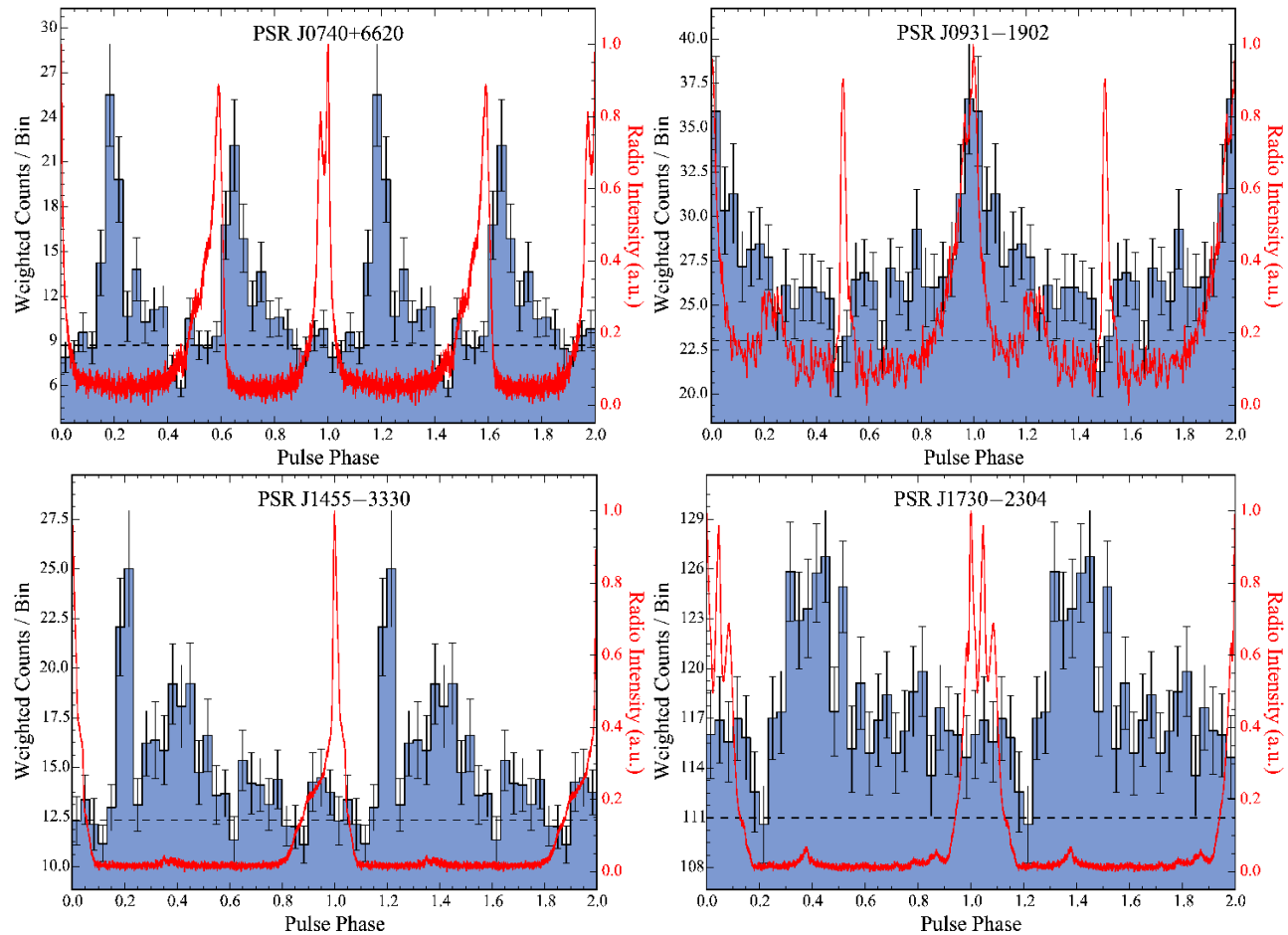
Filling in low-$\dot{E}$ population.

Correct $\dot{E}$ for Shklovskii effect and Galactic acceleration.

Also a look at distances and detection fraction vs. $\dot{E}$.

$\dot{E} = 12.0(26)\times10^{33}$ erg s^{-1}

$\dot{E} = 1.5(1)\times10^{33}$ erg s^{-1}



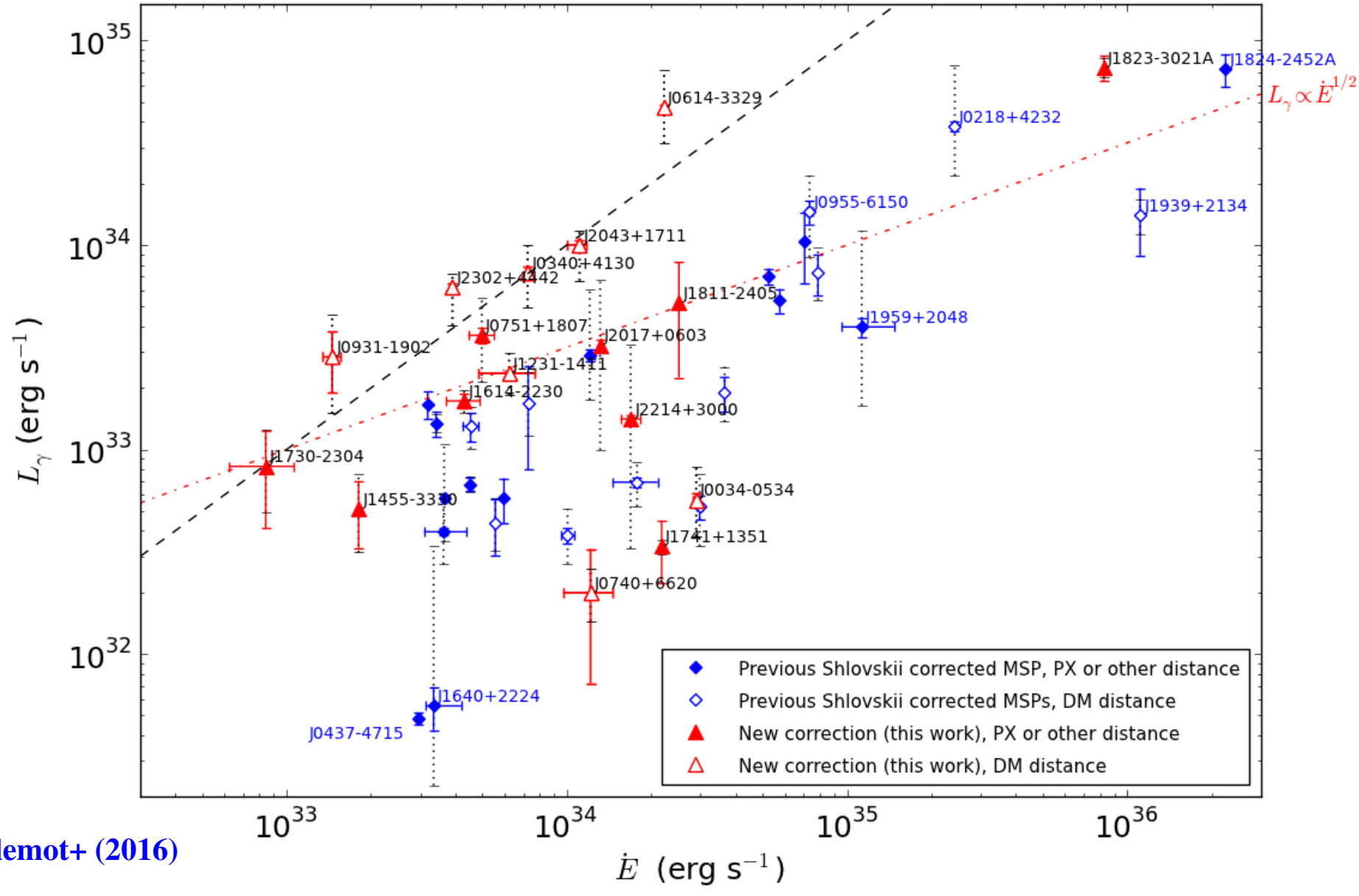
Guillemot+ (2016)

$\dot{E} = 1.806(22)\times10^{33}$ erg s^{-1}

$\dot{E} = 0.844(22)\times10^{33}$ erg s^{-1}

Deathline Considerations (II)

Dashed error bars reflect distance uncertainty.



Guillemot+ (2016)

Conclusions

The LAT is a pulsar machine

- Increased the known gamma-ray pulsars by a factor of ~30
- Increased the Galactic field MSP population by ~50%
  (even larger impact on Galactic field BWs and RBs)

Pre-launch questions have been answered (at least in part)

- Near-surface emission not dominant
- More gamma-ray selected pulsars, many MSPs

High-quality data/observations drive new developments

- More pairs in MSPs? Transitional pulsars.
- Beyond curvature radiation. More VHE pulsars?

Great pulsar science is still being done!

Acknowledgements

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BACKUP SLIDES

Timing Models

Where to find pulsar timing models:

from published papers

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ephems/

LAT timed pulsars

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

or just ask...

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