Prospects of Pulsar Investigations with CTA

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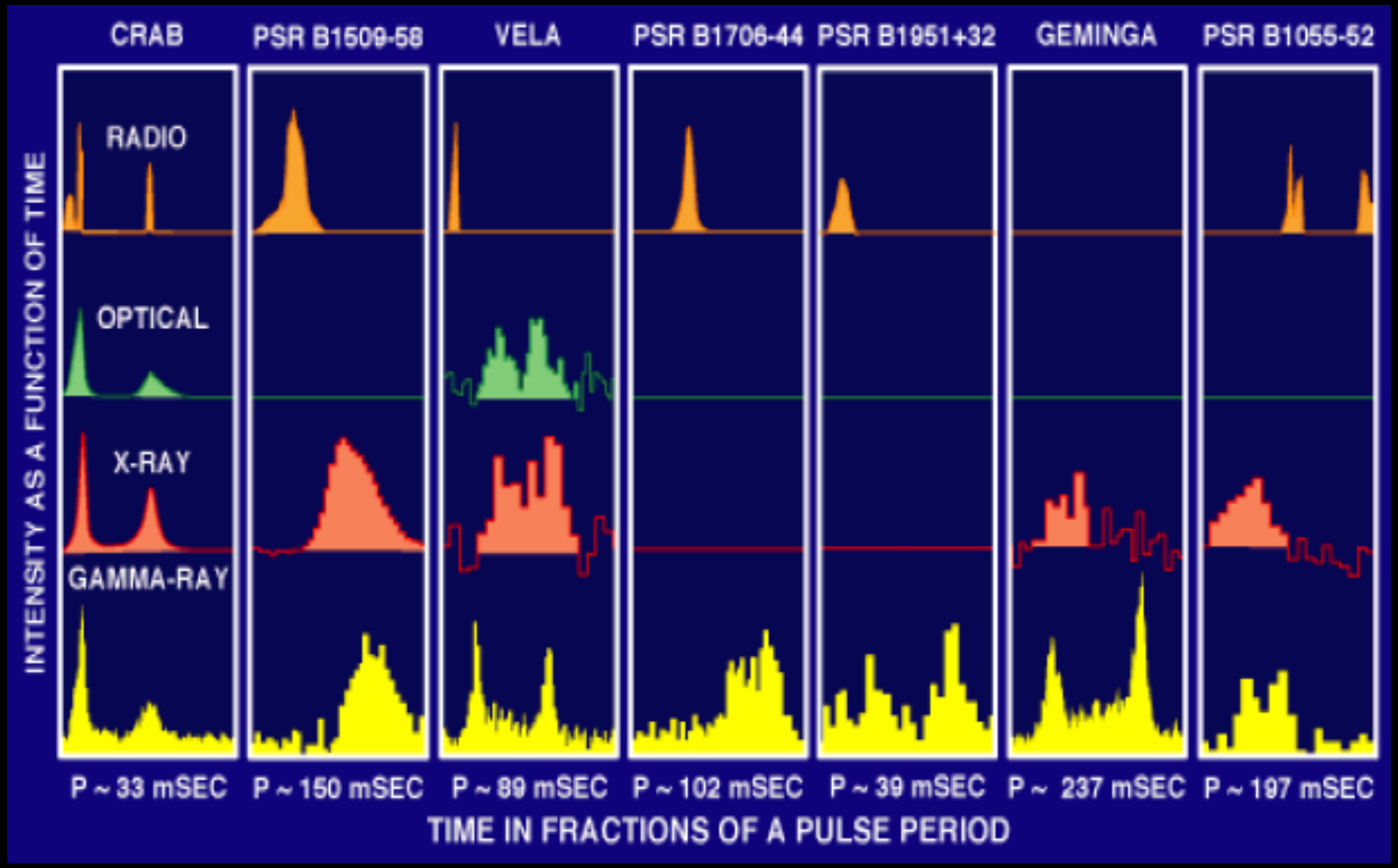
1. Revolution of Pulsar Astronomy by *Fermi*

2. Challenges and Expectations for CTA

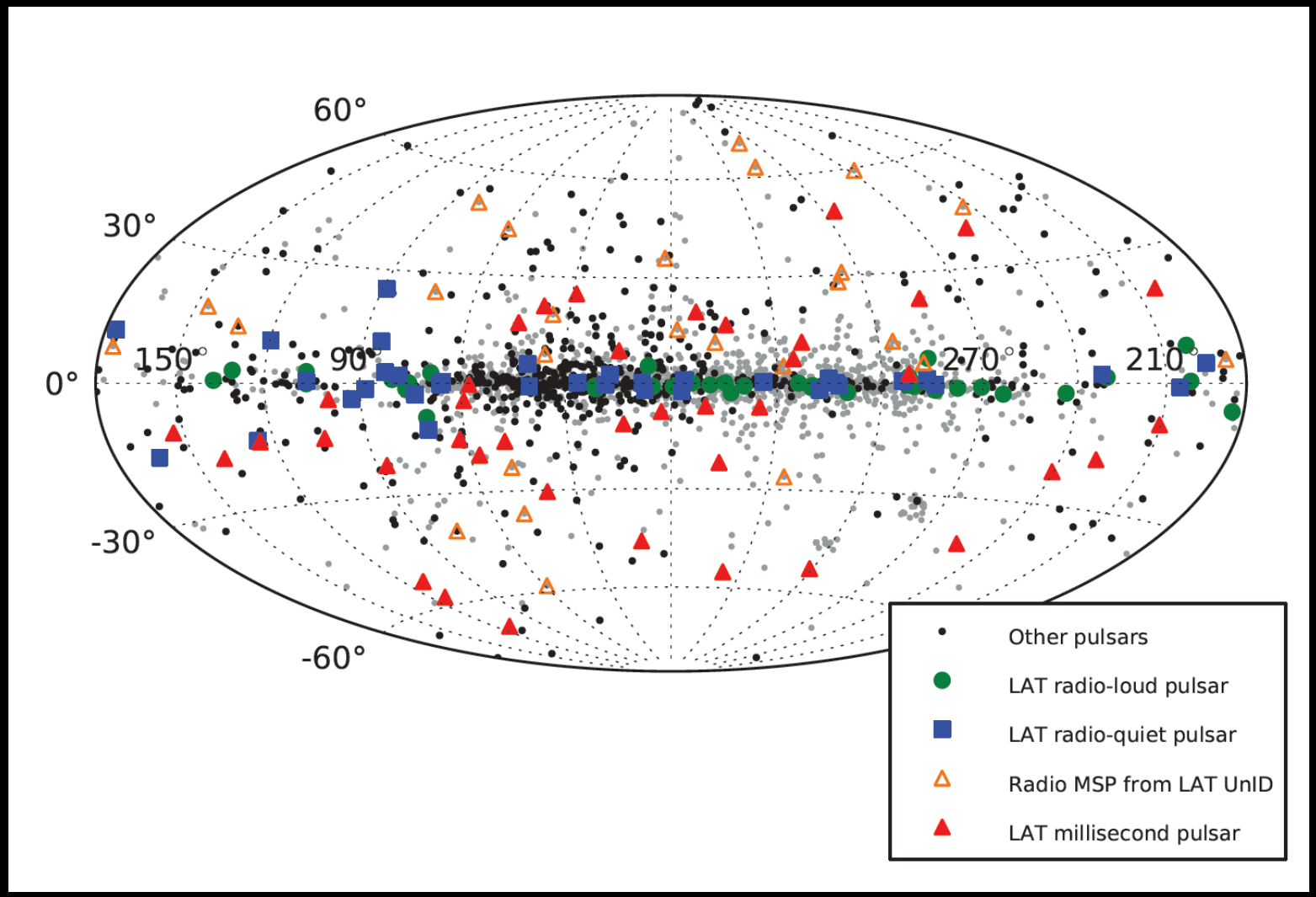
Revolution of Pulsar Astronomy by *Fermi*

- Radio-quiet gamma-ray Pulsars
- Millisecond Pulsars
- Globular Clusters

Gamma-ray Pulsar Population before Fermi



Revolution of Pulsar Astronomy



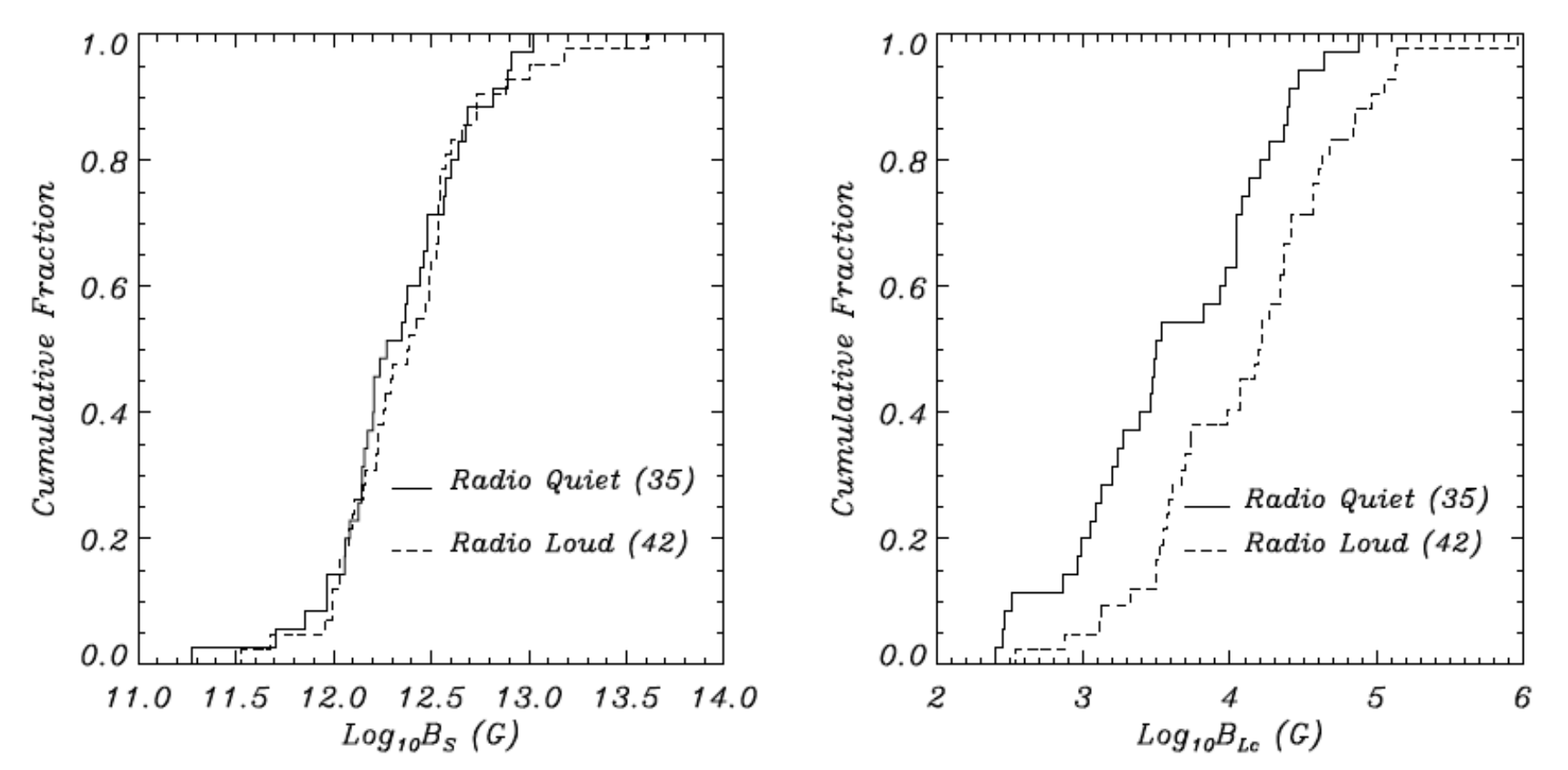
Abdo et al. (2013)

Differences between Radio-loud vs Radio-quiet Populations

- ***Magnetic field strength***
- ***Spectral Properties***
- Gamma-ray to X-ray flux ratios

Hui et al. (2017) arXiv:1611.07428

Magnetic Field Strength



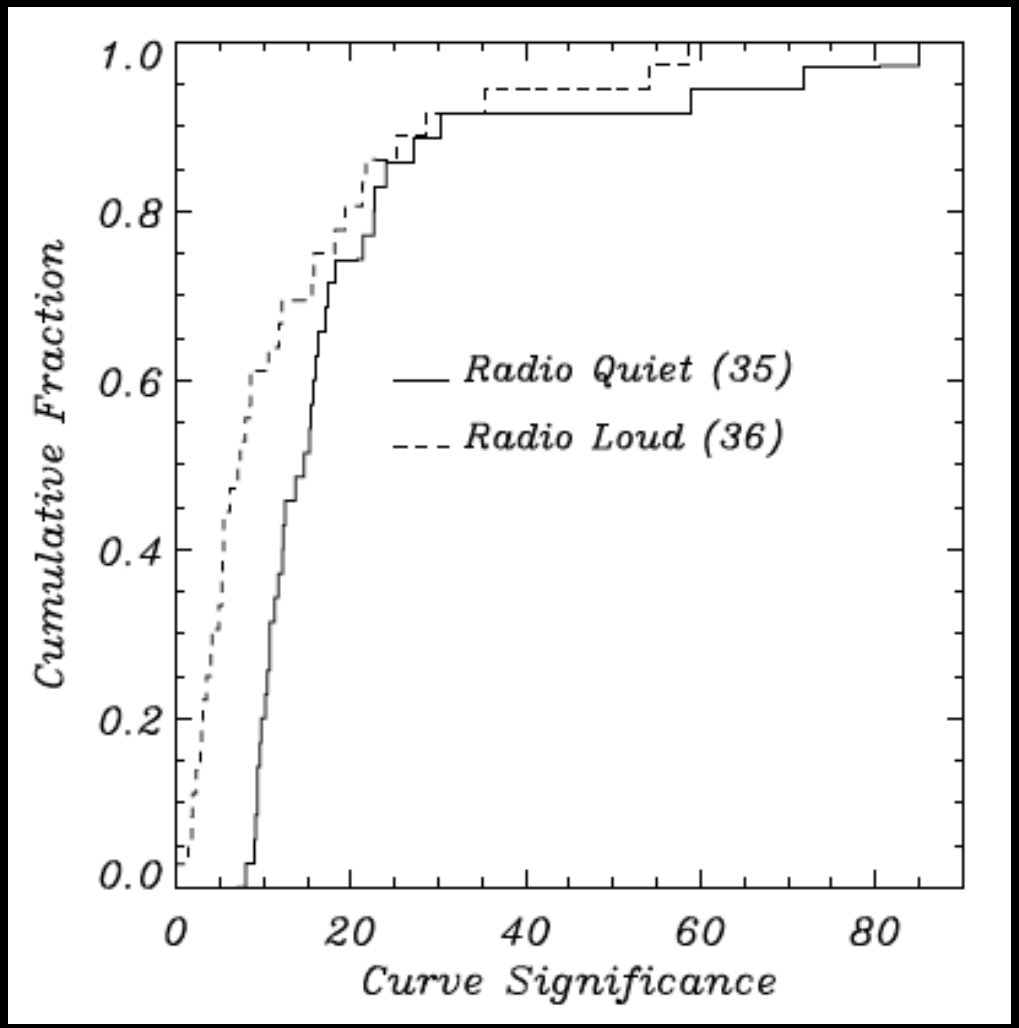
Hui et al. (2017) arXiv:1611.07428

Spectral Properties

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

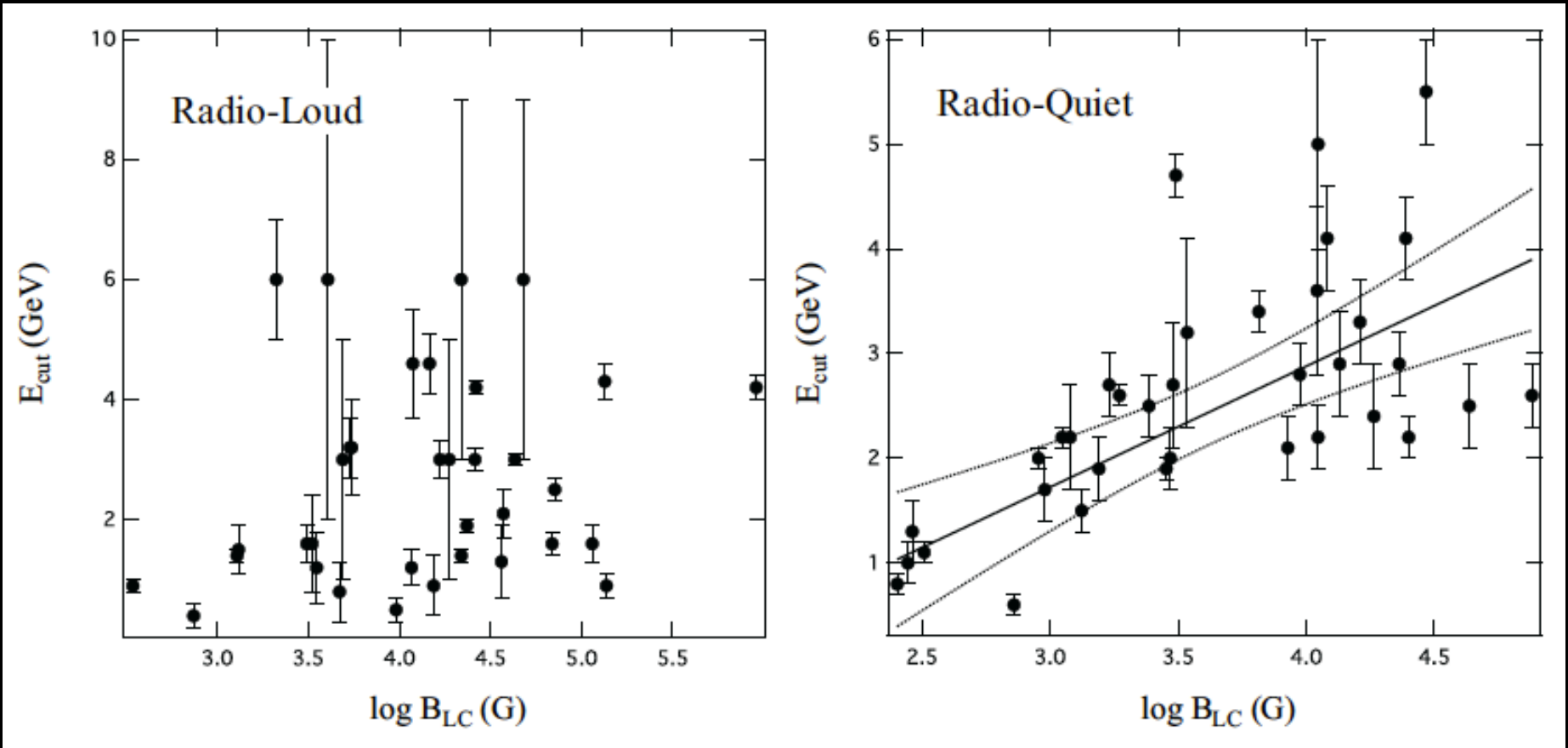
vs

$$\frac{dN}{dE} = N_0 E^{-\Gamma}$$



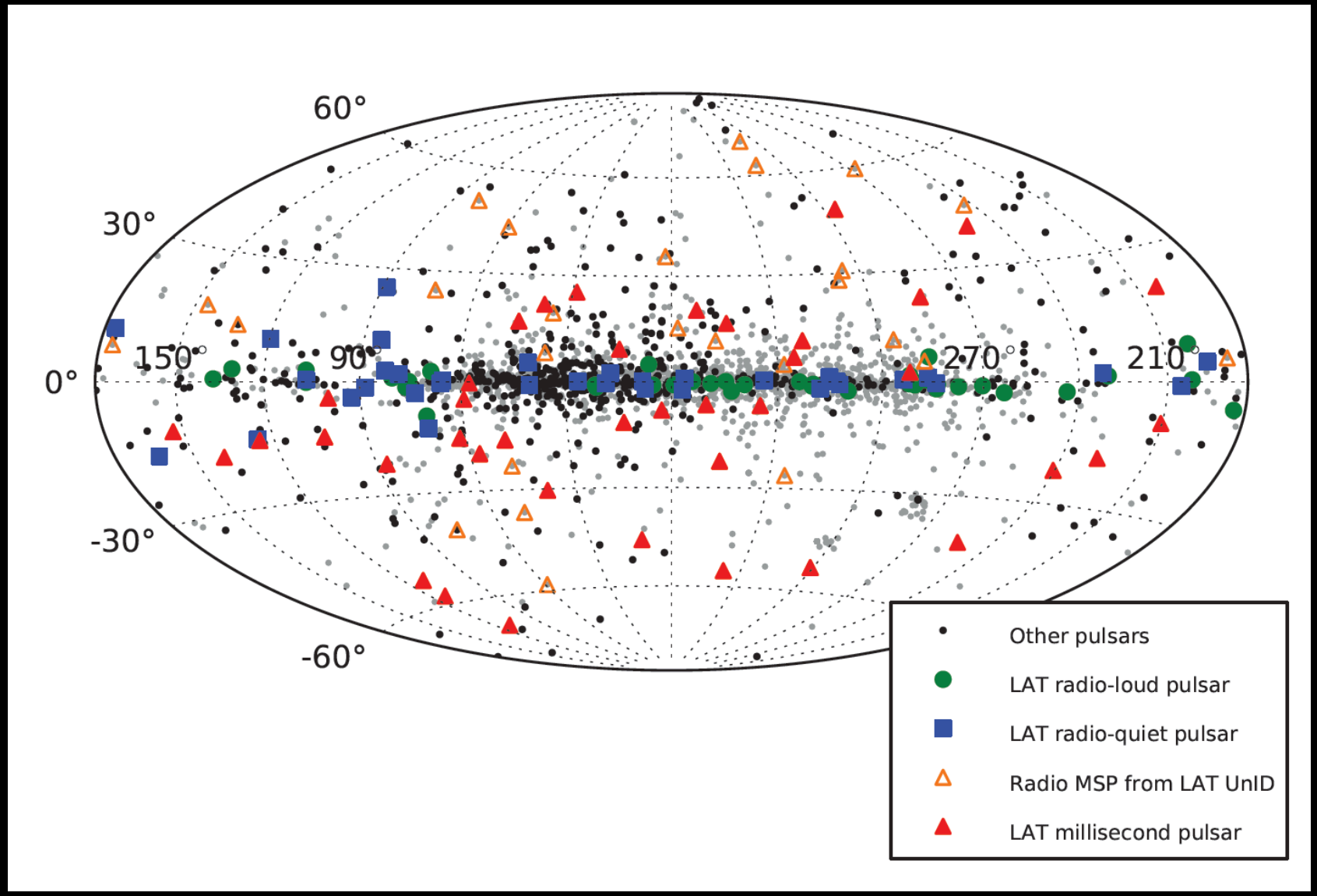
Hui et al. (2017) arXiv:1611.07428

Spectral Properties

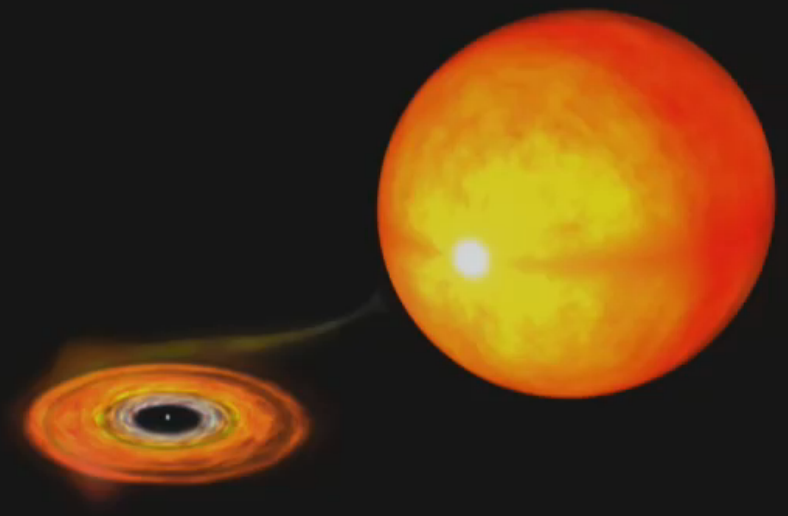


Hui et al. (2017) arXiv:1611.07428

Millisecond Pulsars



LMXBs are progenitors of MSPs



A new class of MSPs - *Redbacks*

Similar to black widow: Tight orbit (< 1 day), presence of radio eclipses

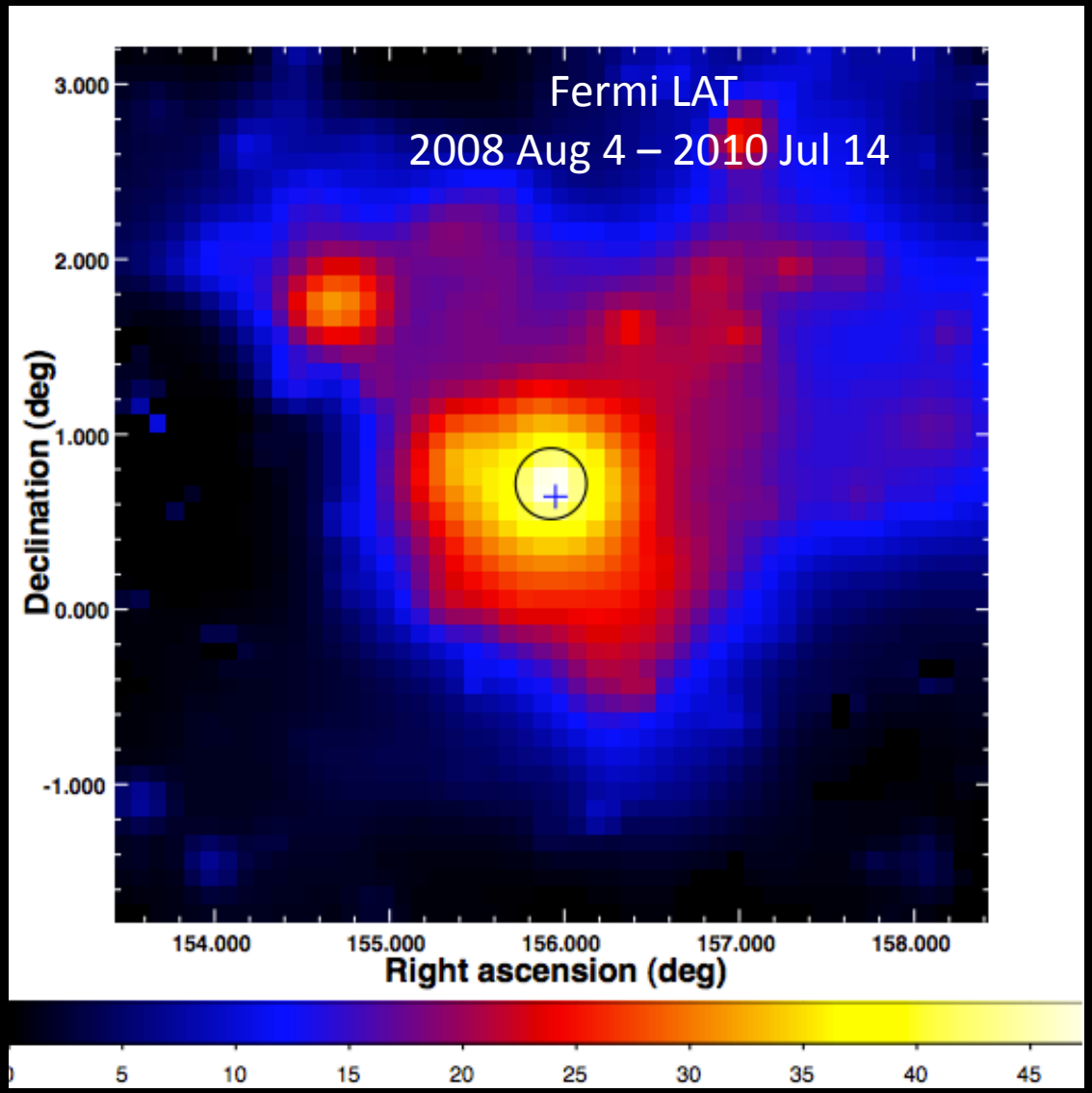
Different from black widow: Companion masses are > 0.2 M_{sun}.

1st Redback – PSR J1023+0038

- FIRST J102347.6+003841 is a qLMXB that clearly showed an accretion disk before 2002 (Wang et al. 2009).
- *Since then the disk was disappeared!*
- And a radio MSP has been found in 2007 (Archibald et al. 2009)

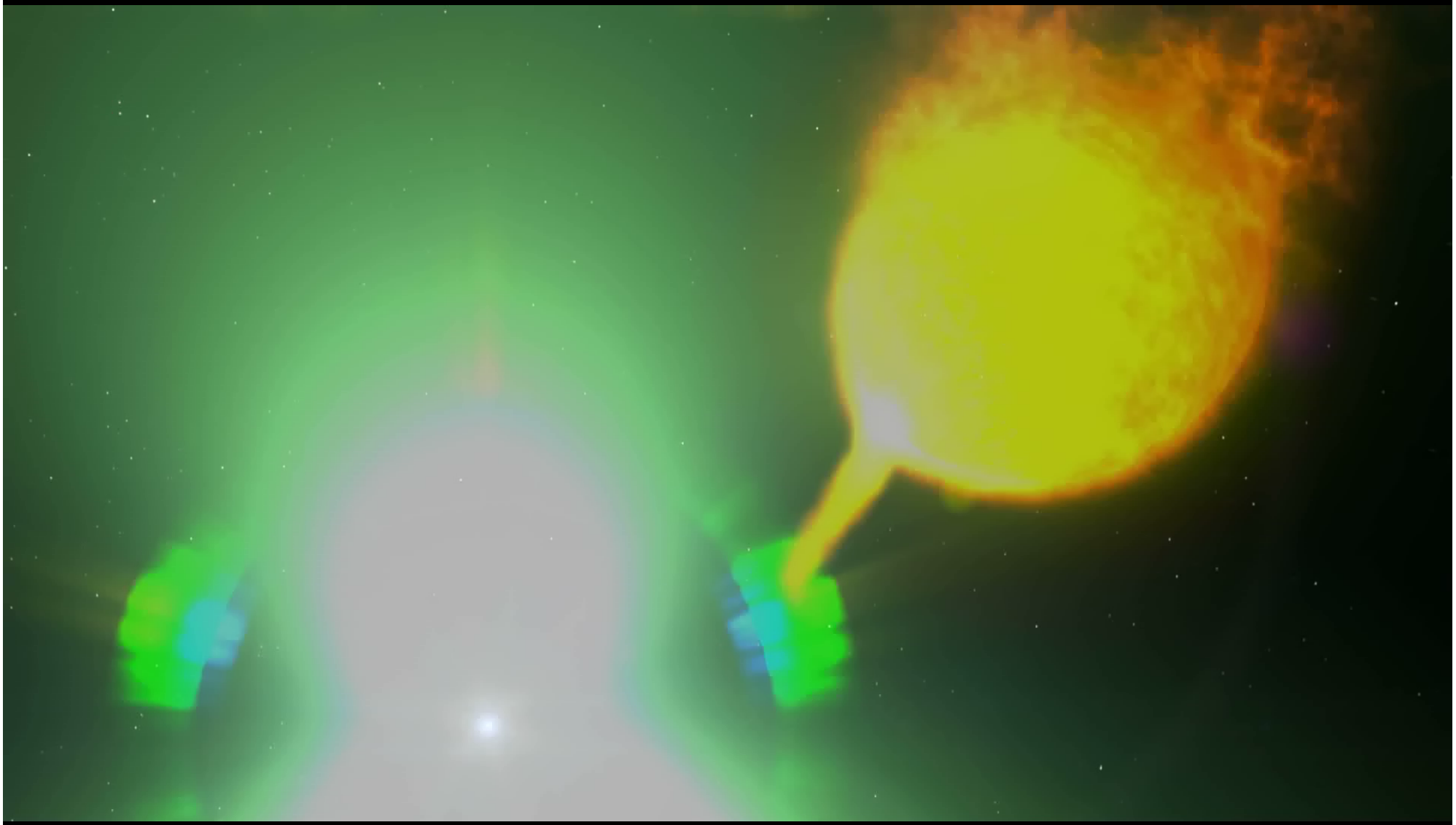
PSR J1023+0038
is a
newly-born radio MSP!

Gamma-ray emission from PSR J1023+0038



Tam et al. (2010)

Catch the transition on the act!



Catch the transition on the act!

State-change in the "transition" binary millisecond pulsar J1023+0038

ATel #5513; ***B. W. Stappers (University of Manchester), A. Archibald (ASTRON), C. Bassa (ASTRON), J. Hessels (ASTRON), G. Janssen (ASTRON), V. Kaspi (McGill University), A. Lyne (University of Manchester), A. Patruno (University of Leiden), A. B. Hill (Stanford Linear Accelerator Lab).***

*on **25 Oct 2013; 18:32 UT***

Distributed as an Instant Email Notice Transients

Credential Certification: Ben Stappers (ben.stappers@manchester.ac.uk)

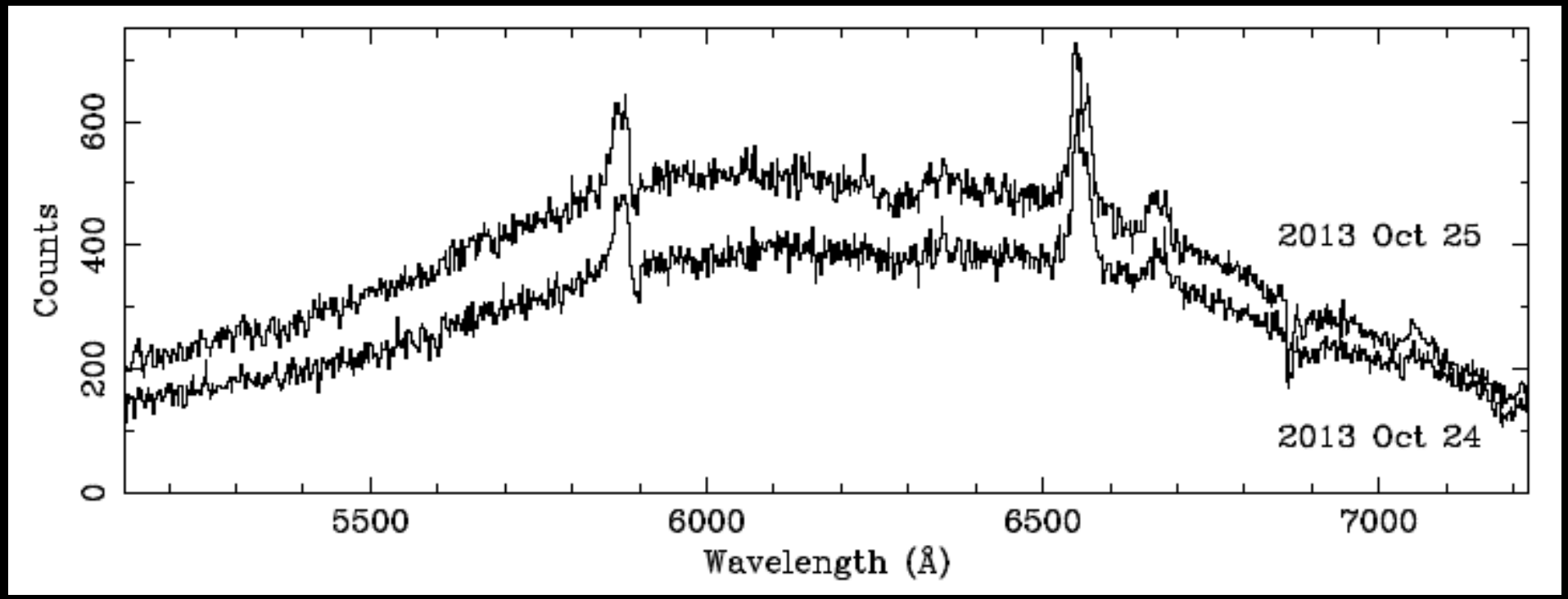
However this changed on June 23rd 2013, when the LT failed to detect PSR J1023+0038 at 1.4 GHz. Observations with the WSRT at 350 MHz and 1380 MHz showed that it was present on June 15th 2013. Since then, we have not detected PSR J1023+0038 in any of our, at least weekly, radio pulsar observations, including a full-orbit scan with the Green Bank Telescope (GBT) at 2.3 GHz (August 11th 2013) and a high-frequency scan with the Arecibo telescope (AO) (August 28th 2013) at 5 GHz. The corresponding pulsed flux density upper limits for typical observations at the aforementioned frequencies, assuming a 10-sigma detection threshold, are 0.8, 0.06, 0.016 and 0.003 mJy for the WSRT, LT, GBT and AO observations respectively. This contrasts with representative fluxes, away from eclipse, of 16 mJy and 0.9 mJy at 350 and 1380 MHz respectively. Thus, PSR J1023+0038 disappeared as an observable radio pulsar sometime between 19-23 June 2013.

ATel# 5513

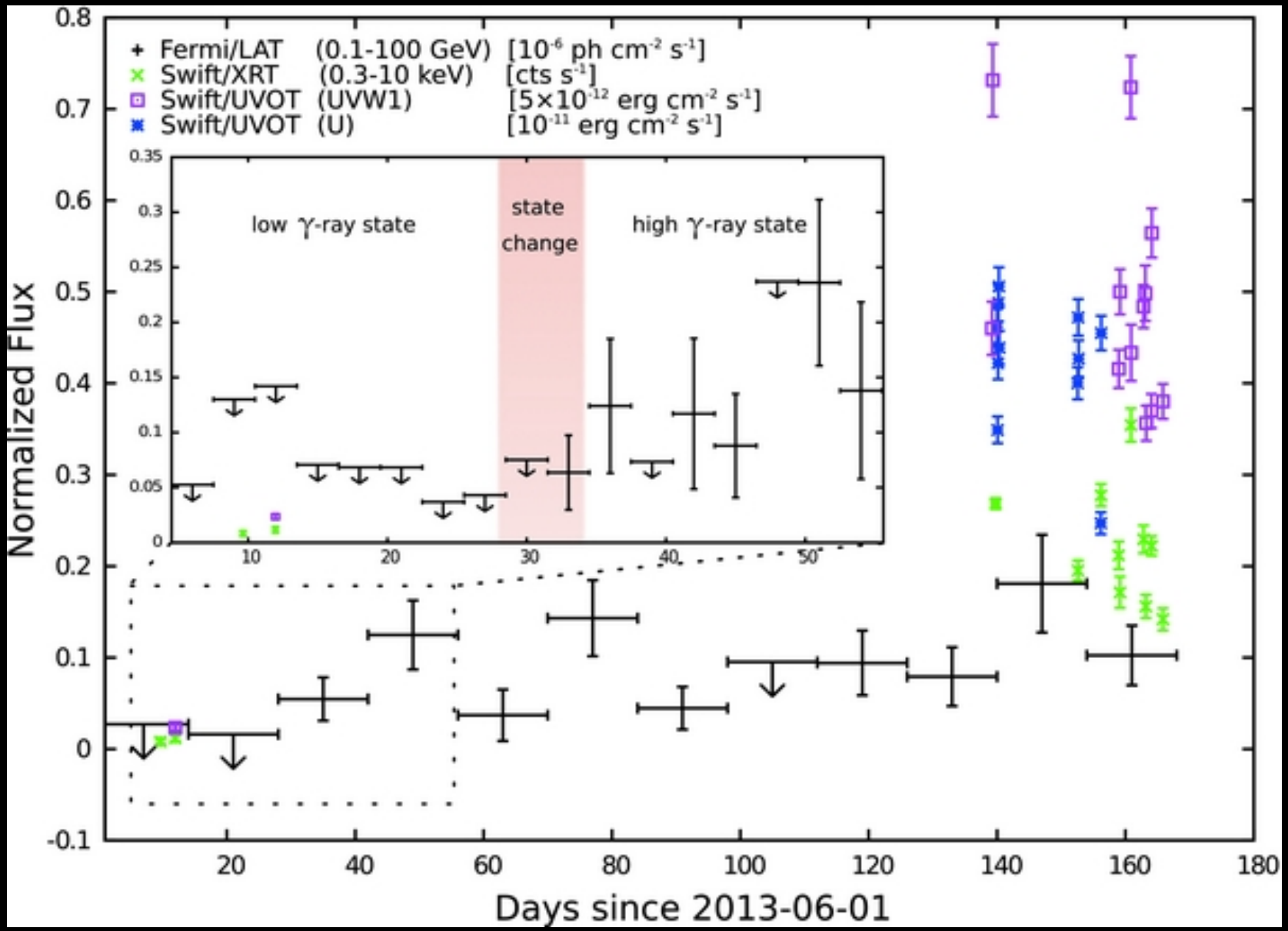
Catch the transition on the act!

Optical Observations of the Binary MSP J1023+0038 in a New Accreting State

ATel #5514; *J. P. Halpern (Columbia U.), E. Gaidos (U. Hawaii Manoa), A. Sheffield, A. M. Price-Whelan, S. Bogdanov (Columbia U.)*
on 25 Oct 2013; 19:10 UT
Credential Certification: Jules Halpern (jules@astro.columbia.edu)

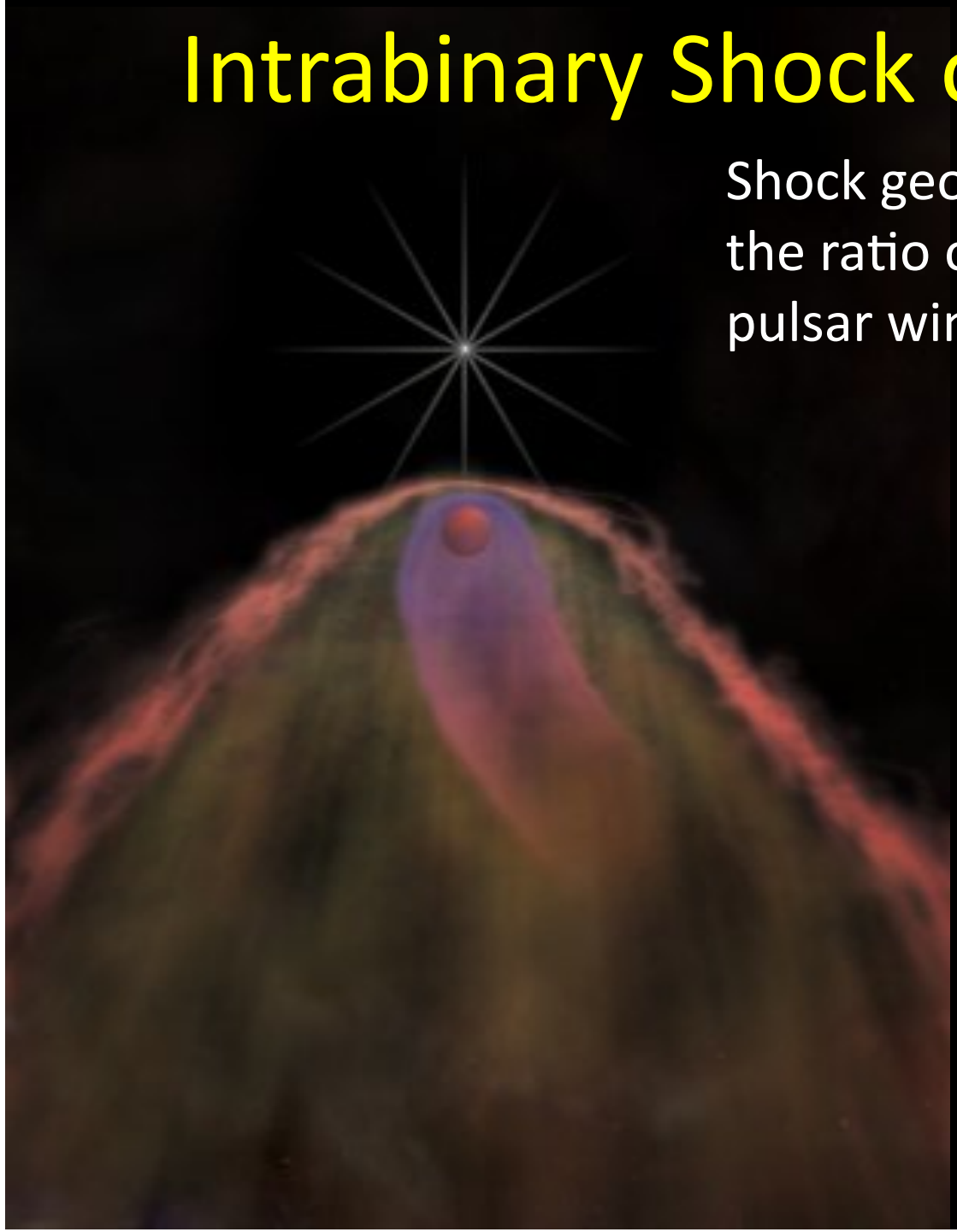


Catch the transition on the act!



Takata et al. (2014)

Intrabinary Shock of MSP Binary



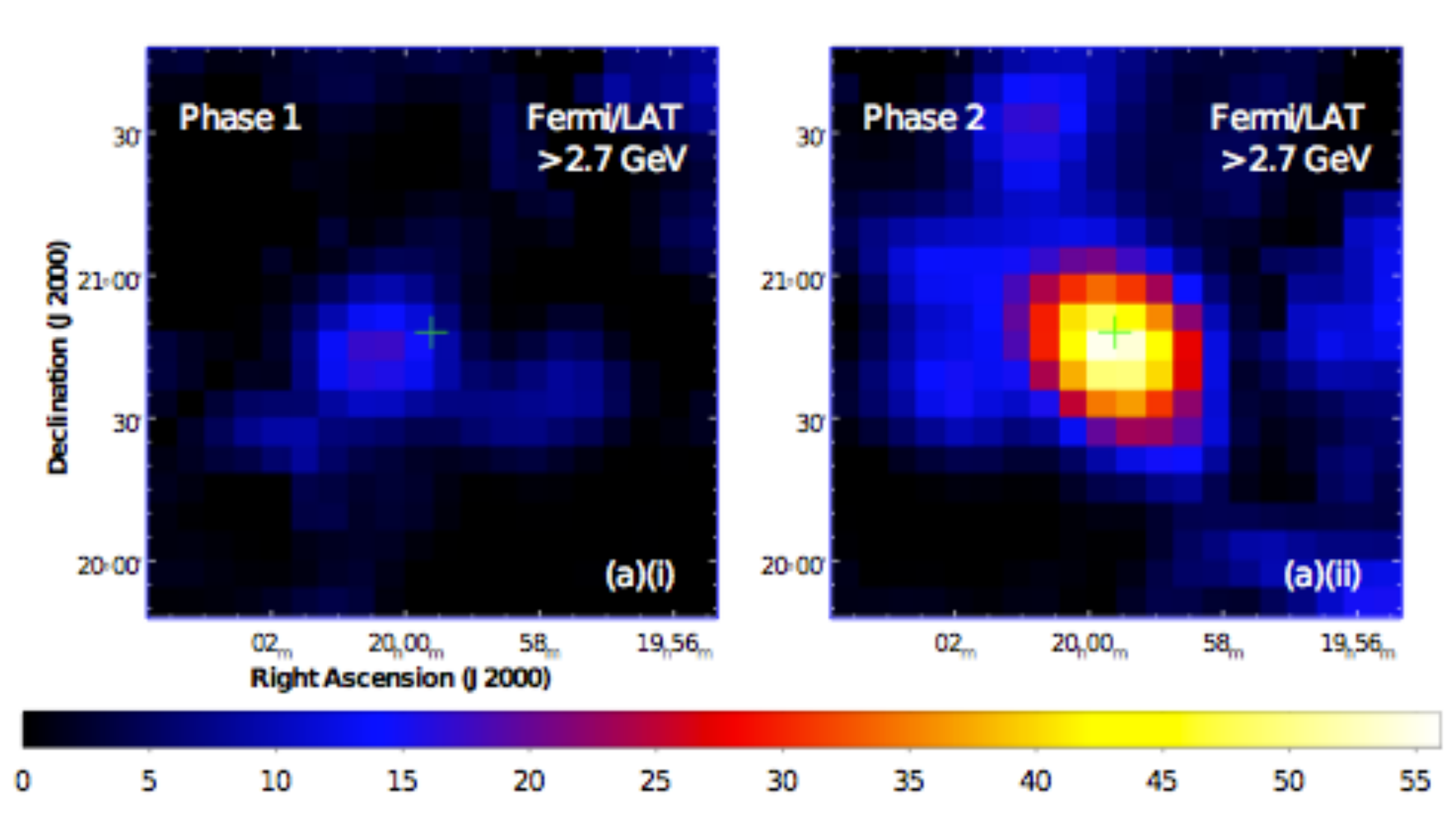
Shock geometry is determined by the ratio of momentum fluxes of the pulsar wind to the stellar wind:

$$\eta = \frac{L_{sd}/c}{dM_*/dt\ V_{escape}}$$

For B1957+20: $\eta \sim 10$

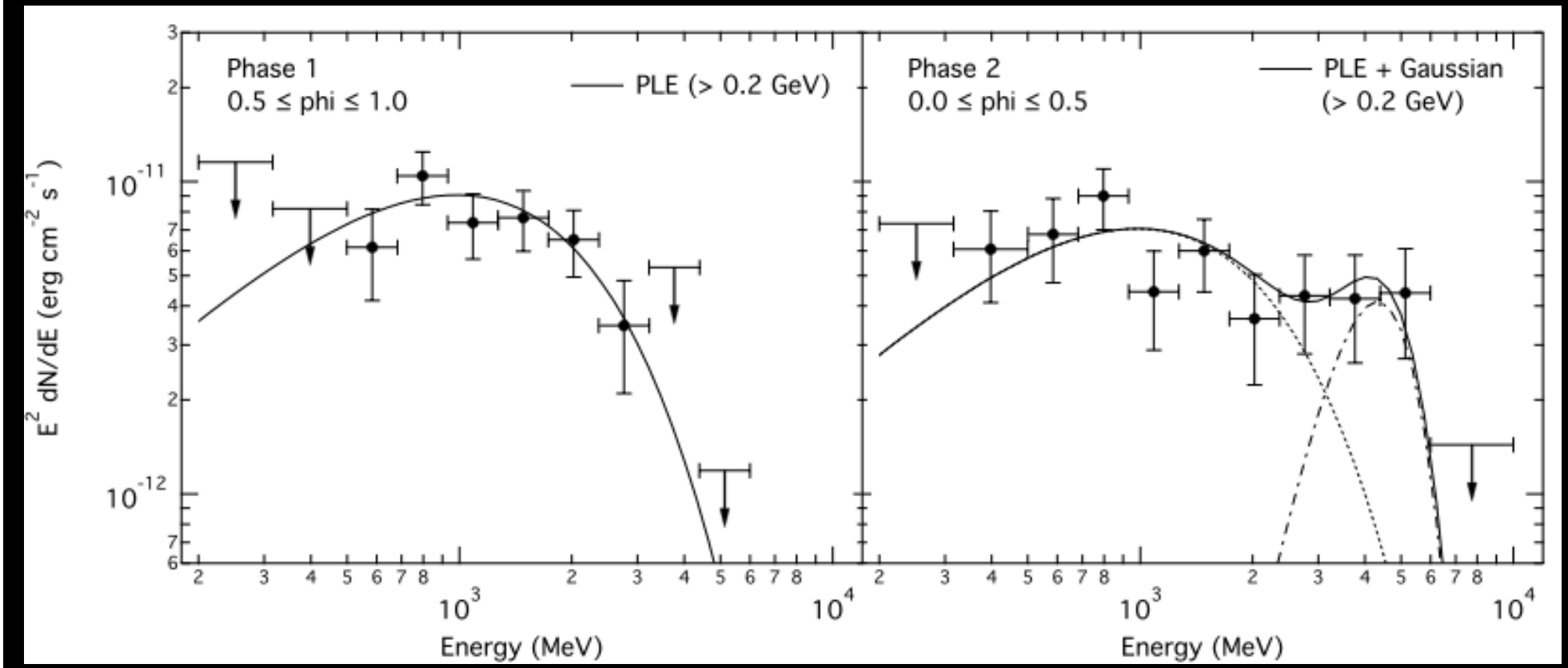
For the cone-like shock, X-ray peaks are results of Doppler boosting before/after the radio eclipse.

Orbital dependence of γ-ray emission from Black Widow



Wu et al. (2012)

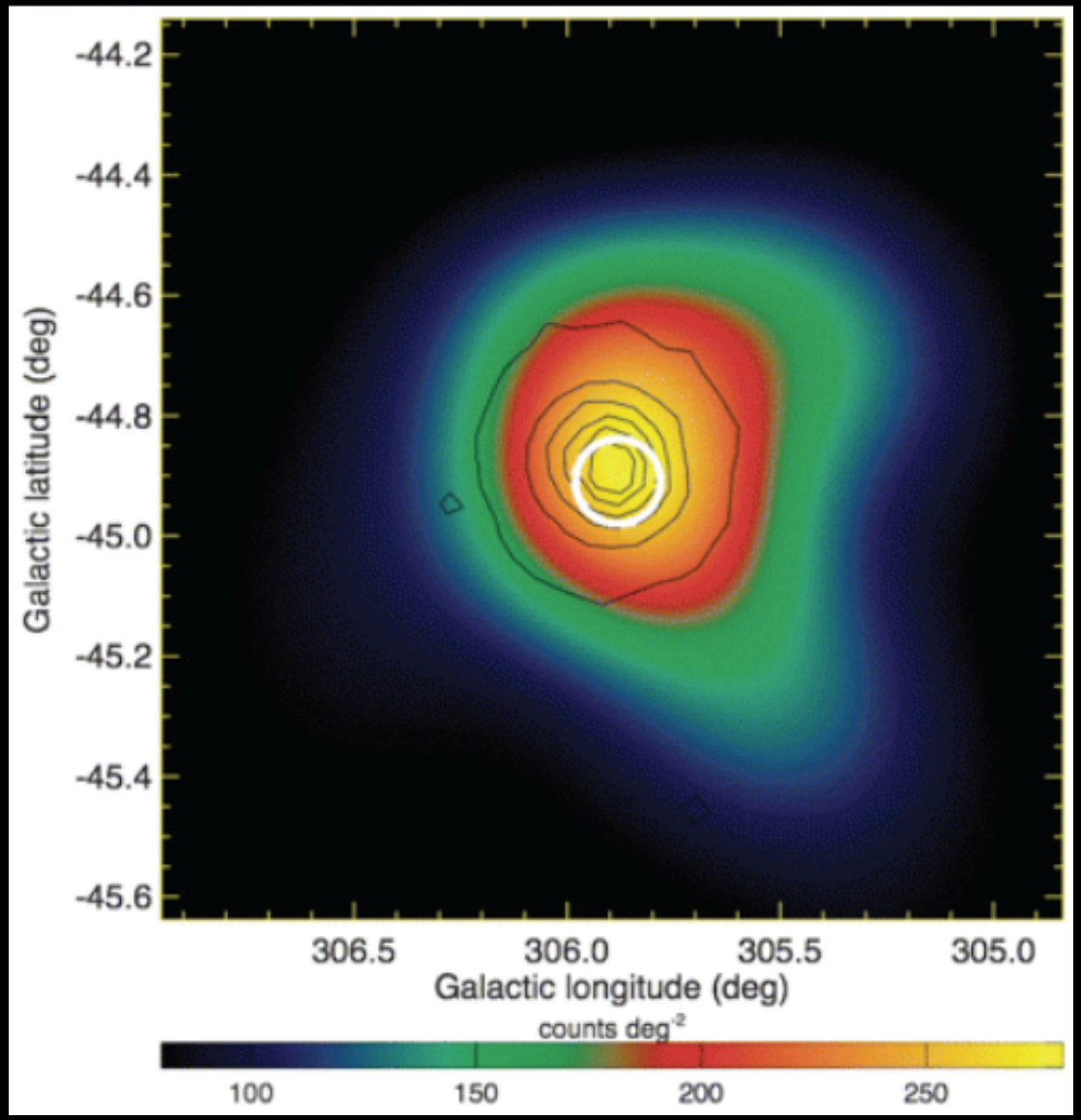
Orbital dependence of γ-ray emission from Black Widow



Wu et al. (2012)

Gamma-ray Globular Clusters

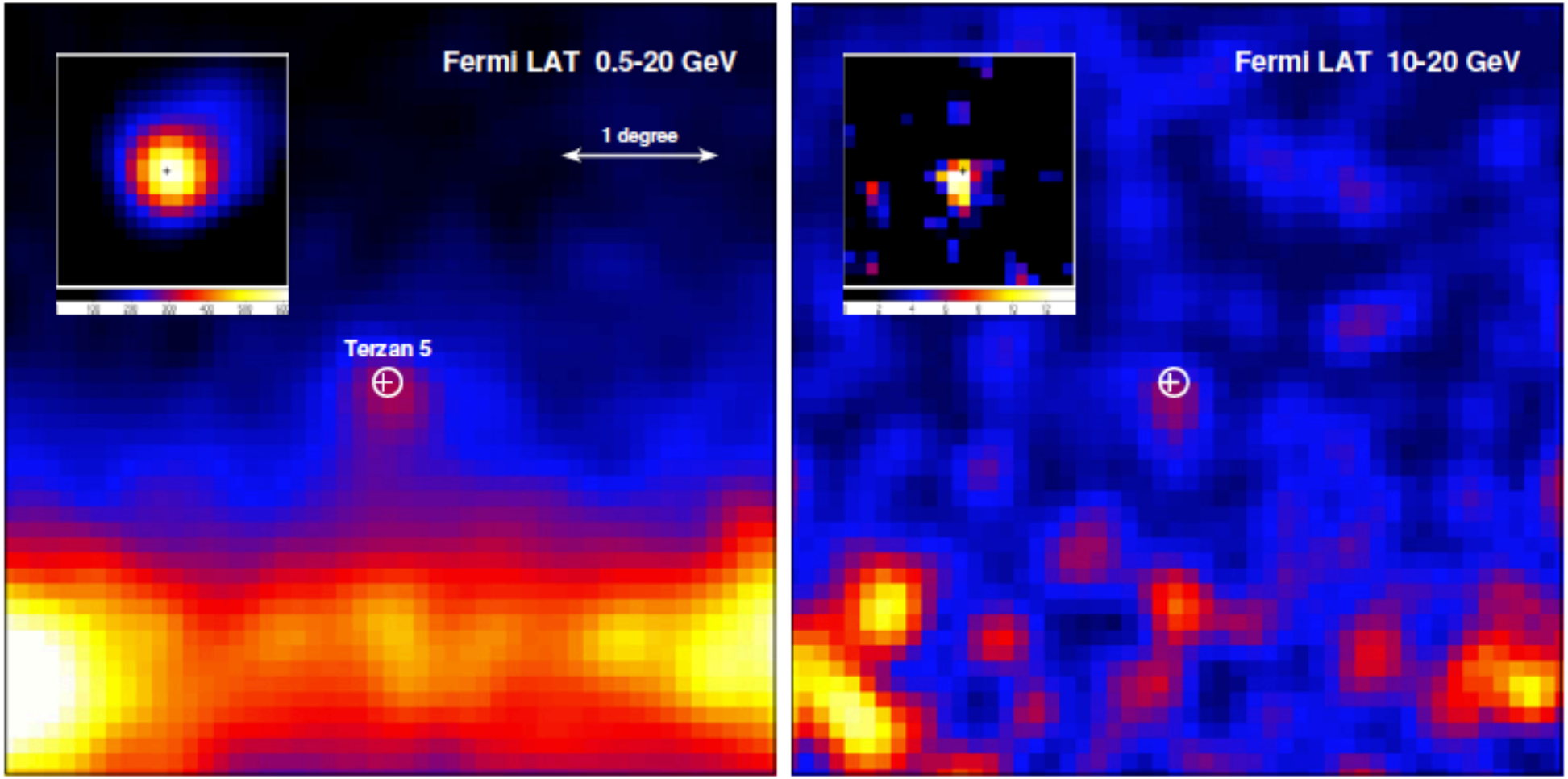
47 Tuc - *First Gamma-ray detection of a GC*



Abdo et al. (2009)

Gamma-ray Globular Clusters

Terzan 5 – *GC that host the largest known MSP population*



Kong, Hui & Cheng(2010)

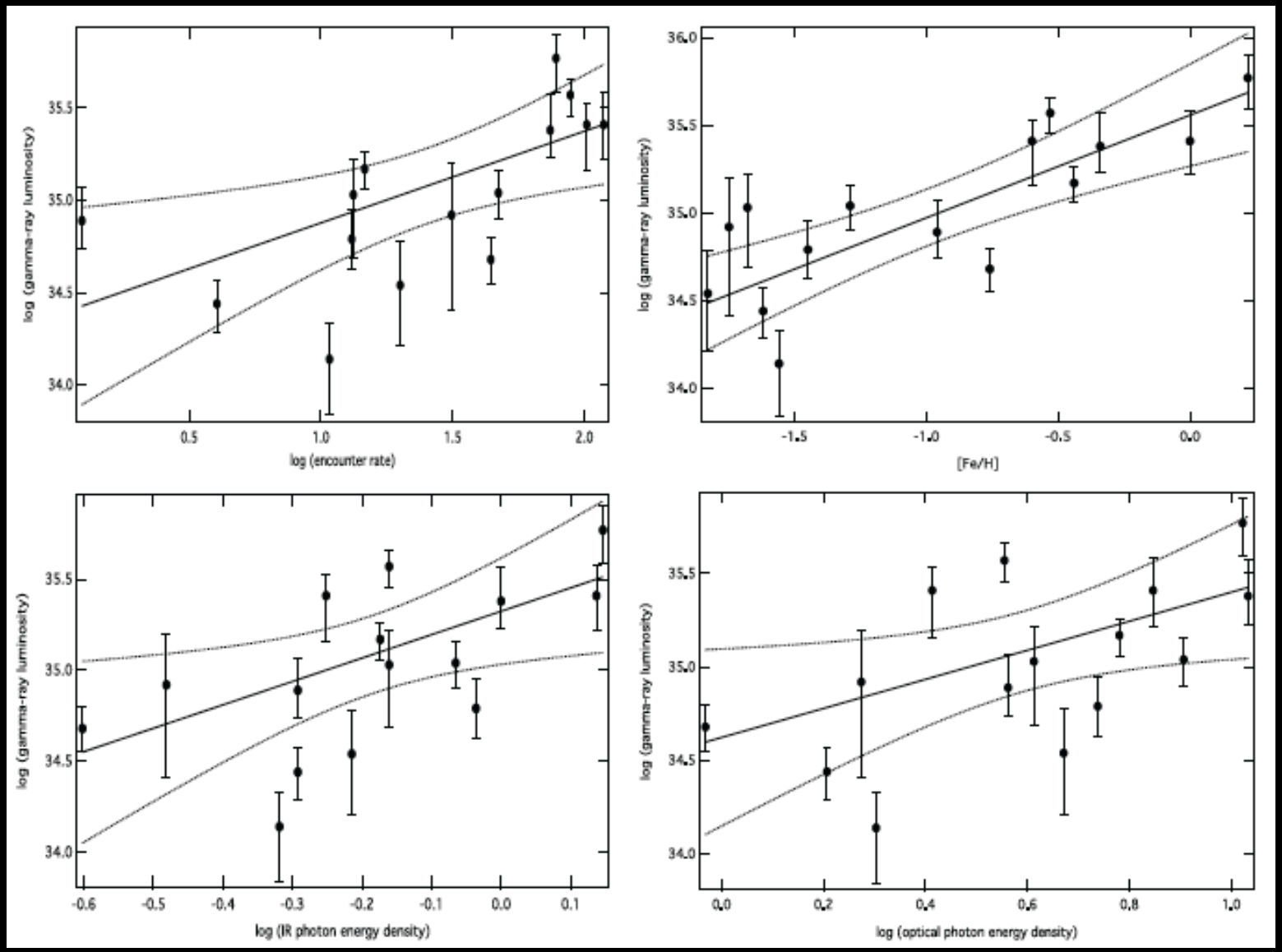
Origin of the Gamma-rays from GCs

Inverse Compton Scattering vs Magnetospheric origin

- **Magnetospheric origin** – L_γ depends solely on the MSP population.

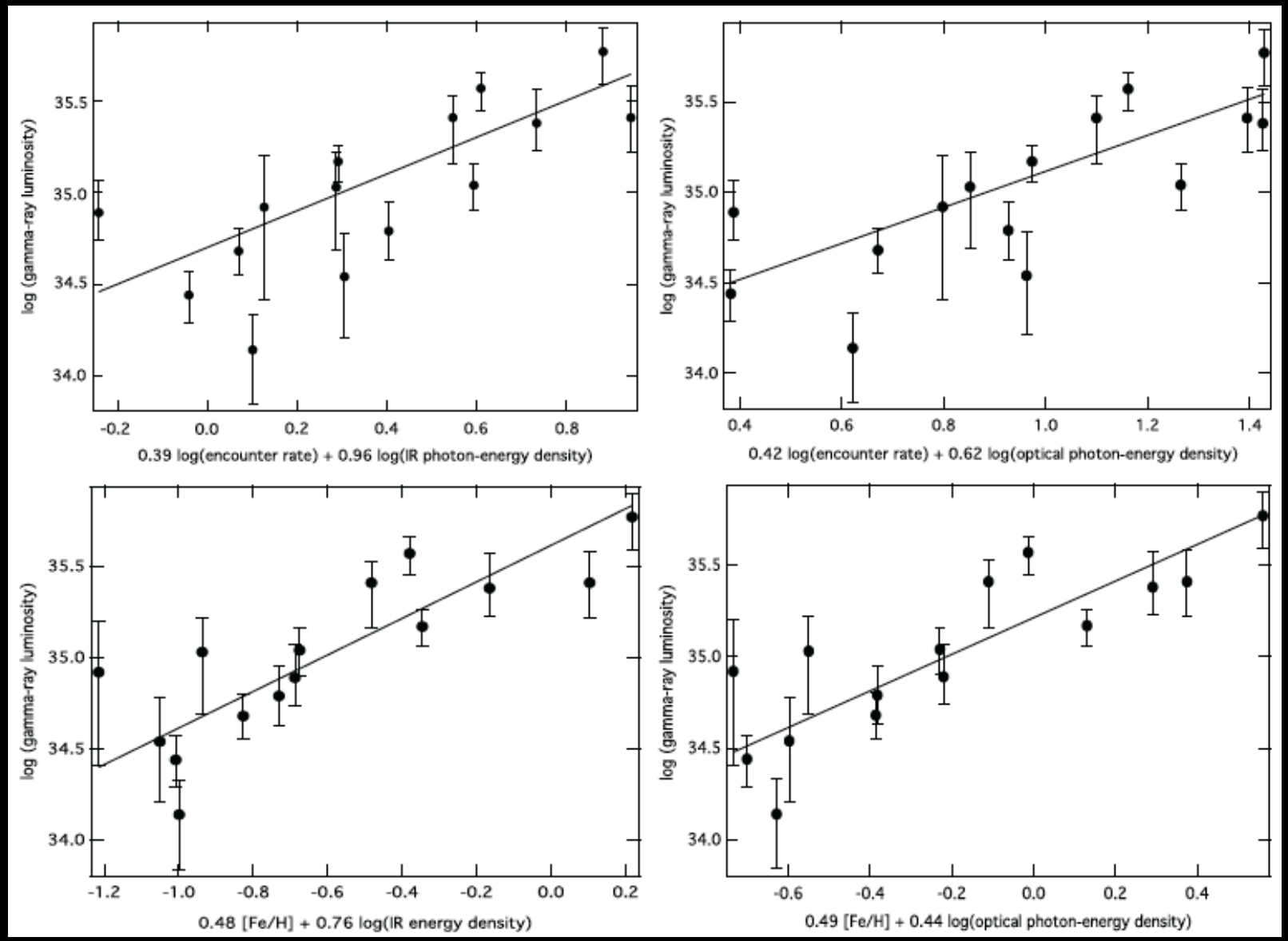
- **ICS scenario** - L_γ depends on the MSP population **AND** the energy densities of soft photon fields.

Properties of Gamma-ray GCs



Hui et al. (2011)

Fundamental Plane of Gamma-ray GCs

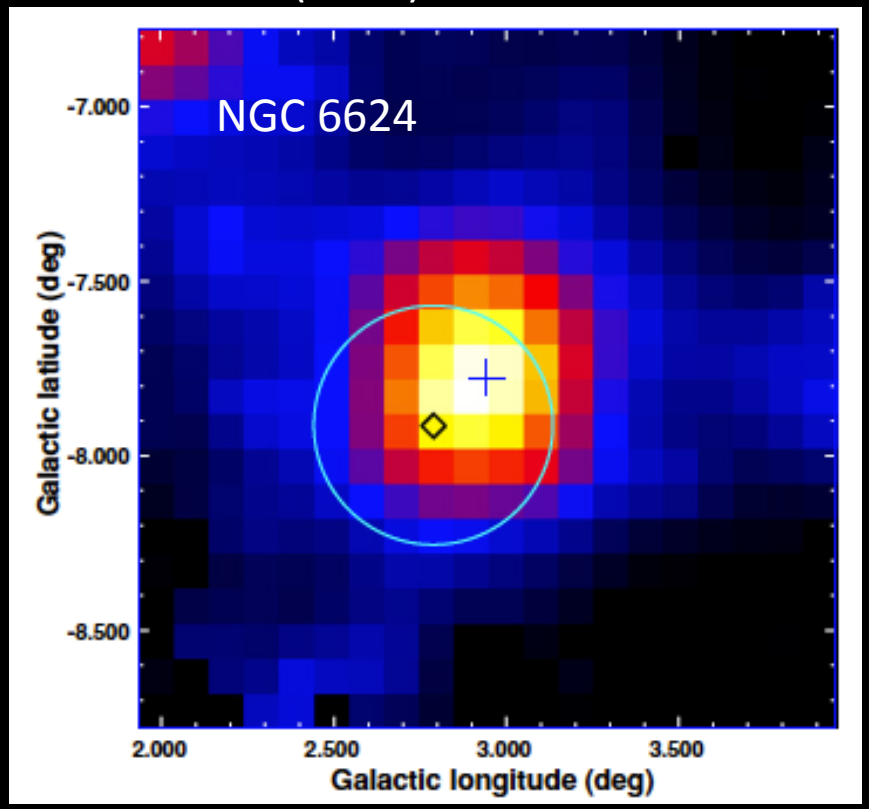


Hui et al. (2011)

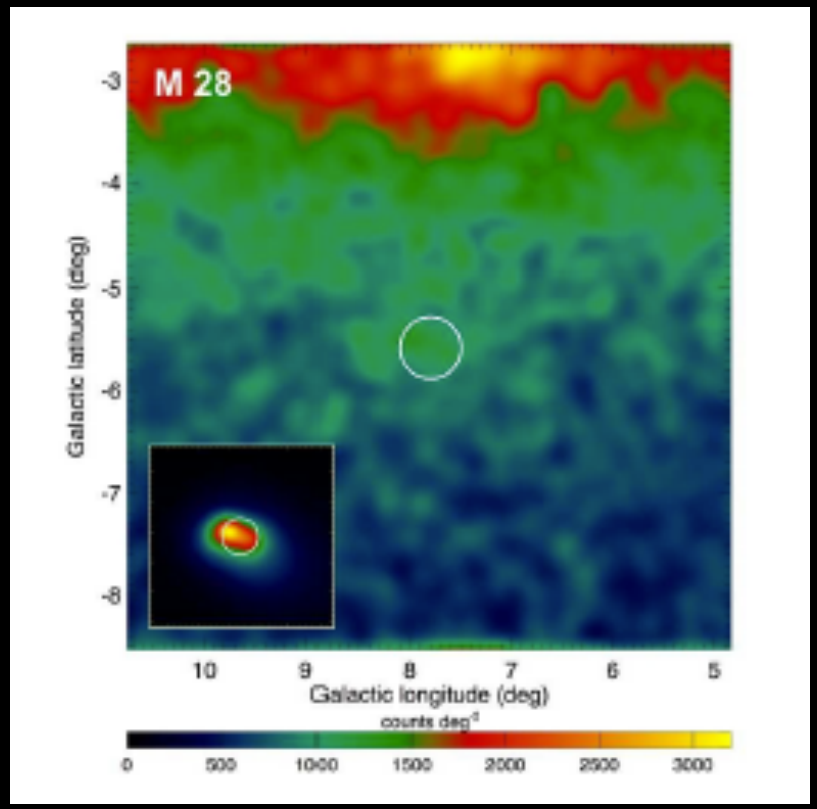
MSPs in Globular Clusters

- But 2 gamma-ray GCs are exceptional:

Tam et al. (2011)



Abdo et al. (2010)

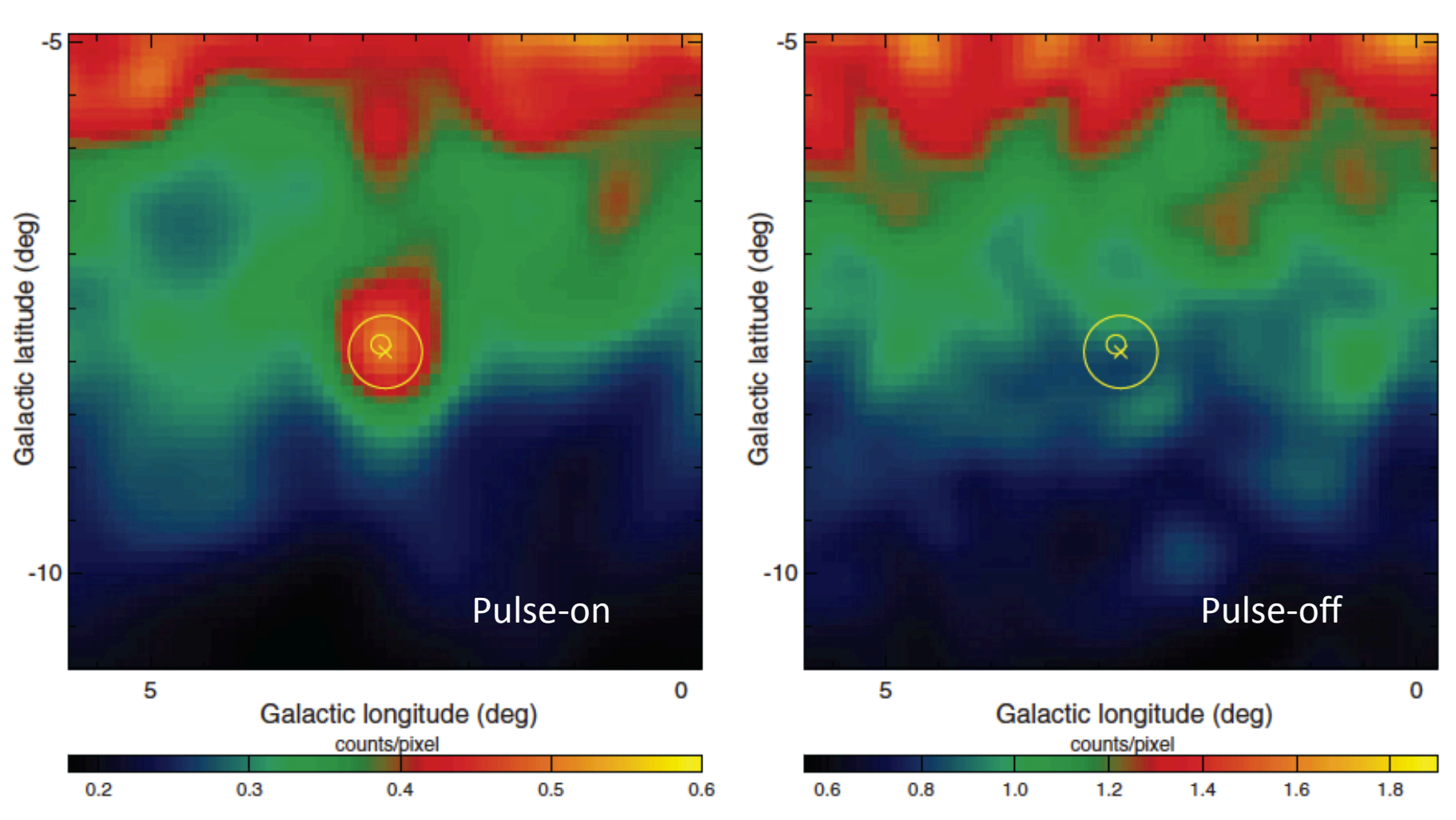


These 2 GCs contain energetic young MSPs.

Period	3.05 ms	Period	5.44 ms
dP/dt	1.61×10^{-18} s/s	dP/dt	3.38×10^{-18} s/s
Distance	5.5 kpc	Distance	7.9 kpc
Age	30 Myrs	Age	25 Myrs
B_{surf}	2.24×10^{9} G	B_{surf}	4.34×10^{9} G
dE/dt	2.2×10^{36} erg/s	dE/dt	8.3×10^{35} erg/s
B1821-24@M28		**J1823-3021A@NGC 6624**	

PSR J1823-3021A @ NGC 6624

A single PSR dominates the total gamma-ray emission of the GC.

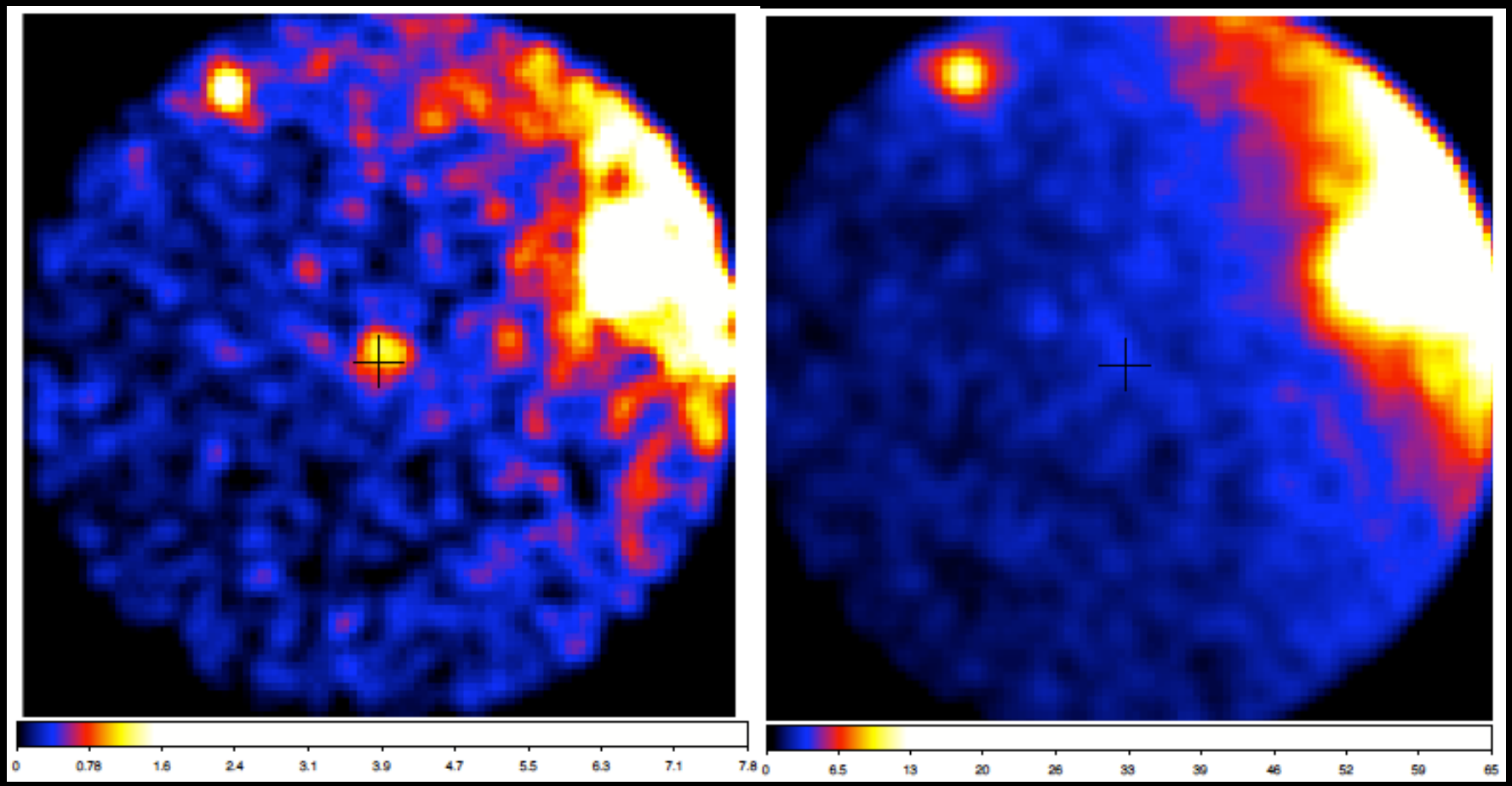


Freire et al. (2011)

γ-ray Pulsation from M28A

Pulse on

Pulse off

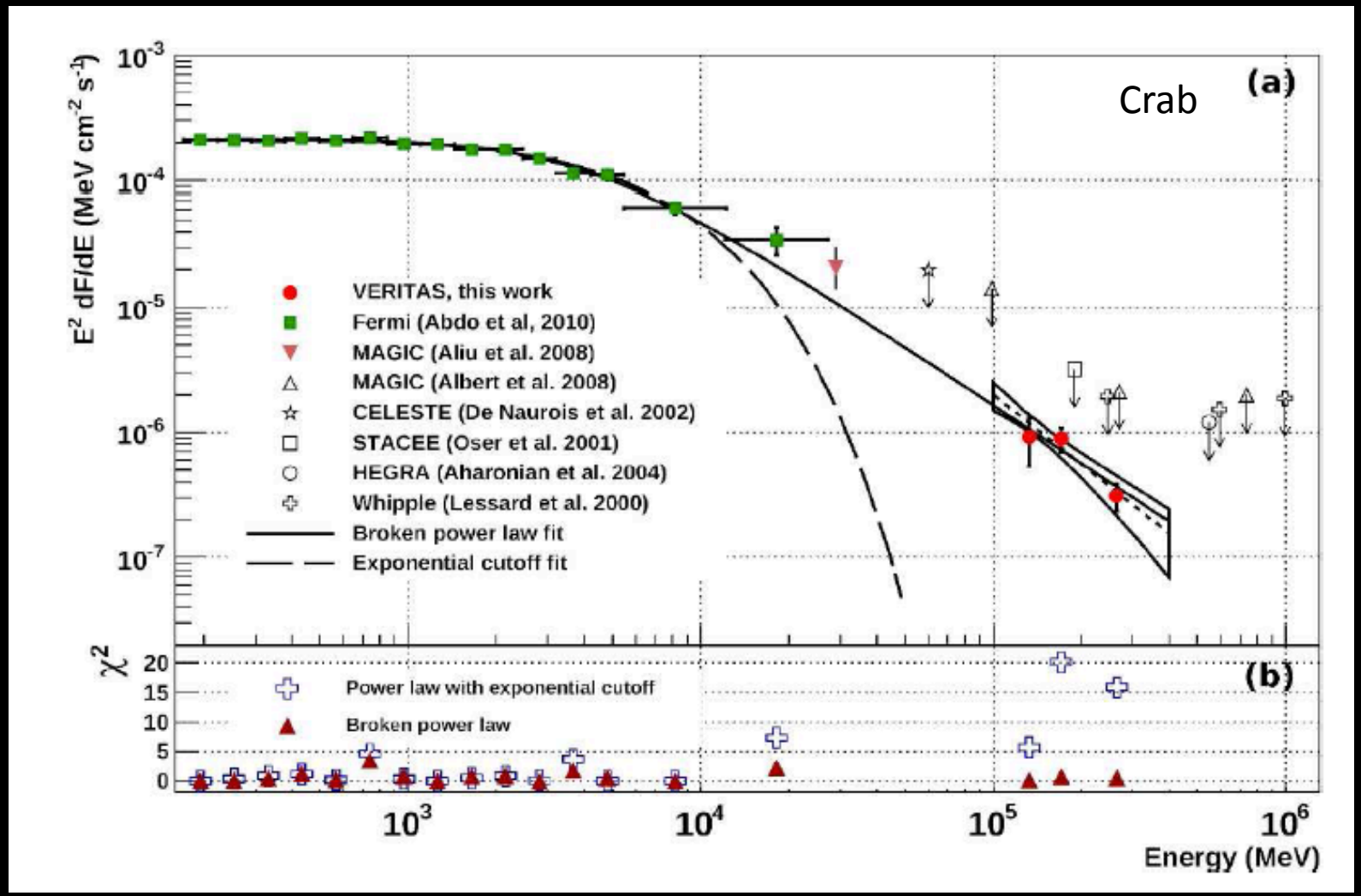


Wu et al. (2013)

1. Revolution of Pulsar Astronomy by *Fermi*

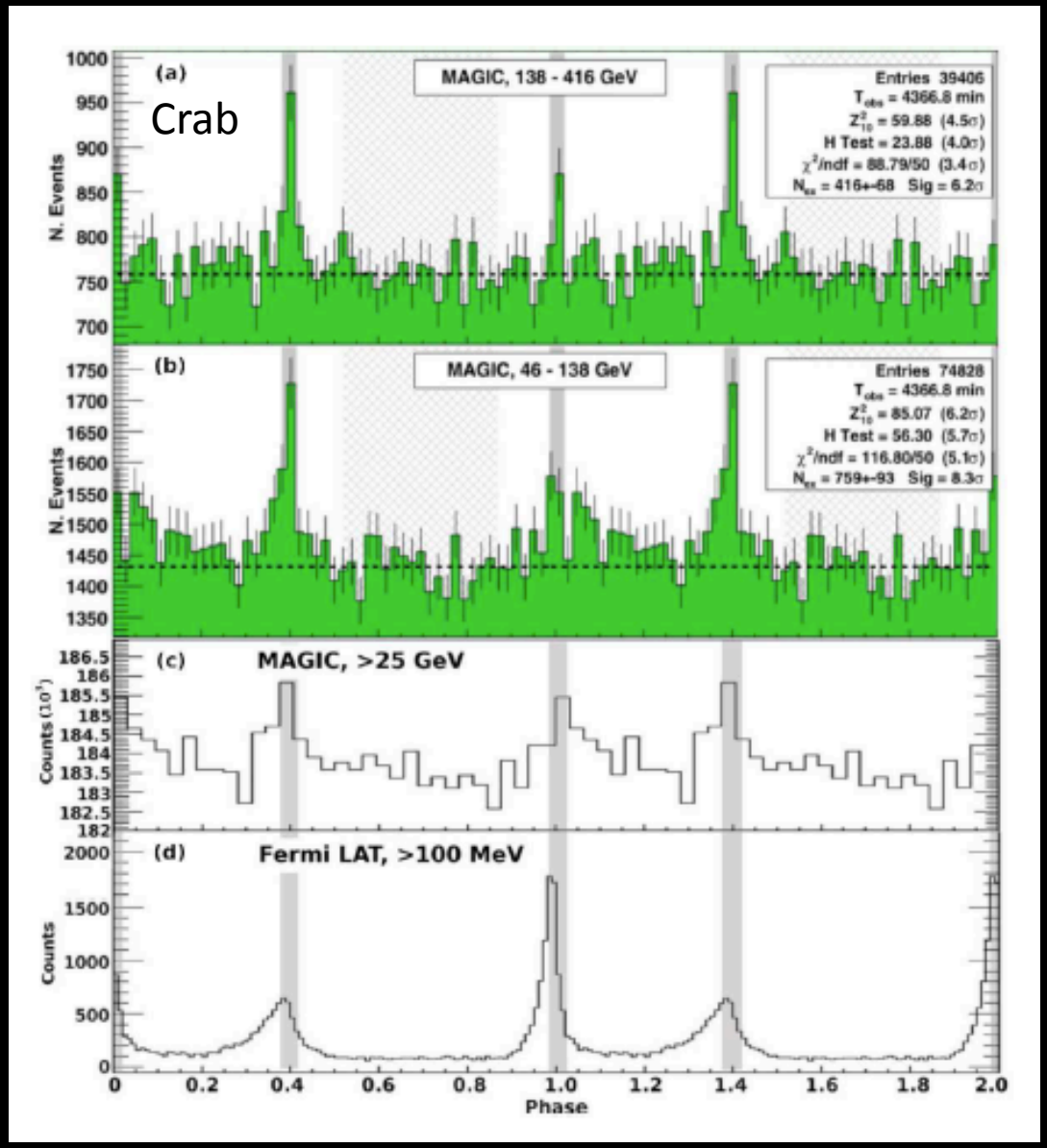
2. **Challenges and Expectations for CTA**

Pulsars at VHE Regime



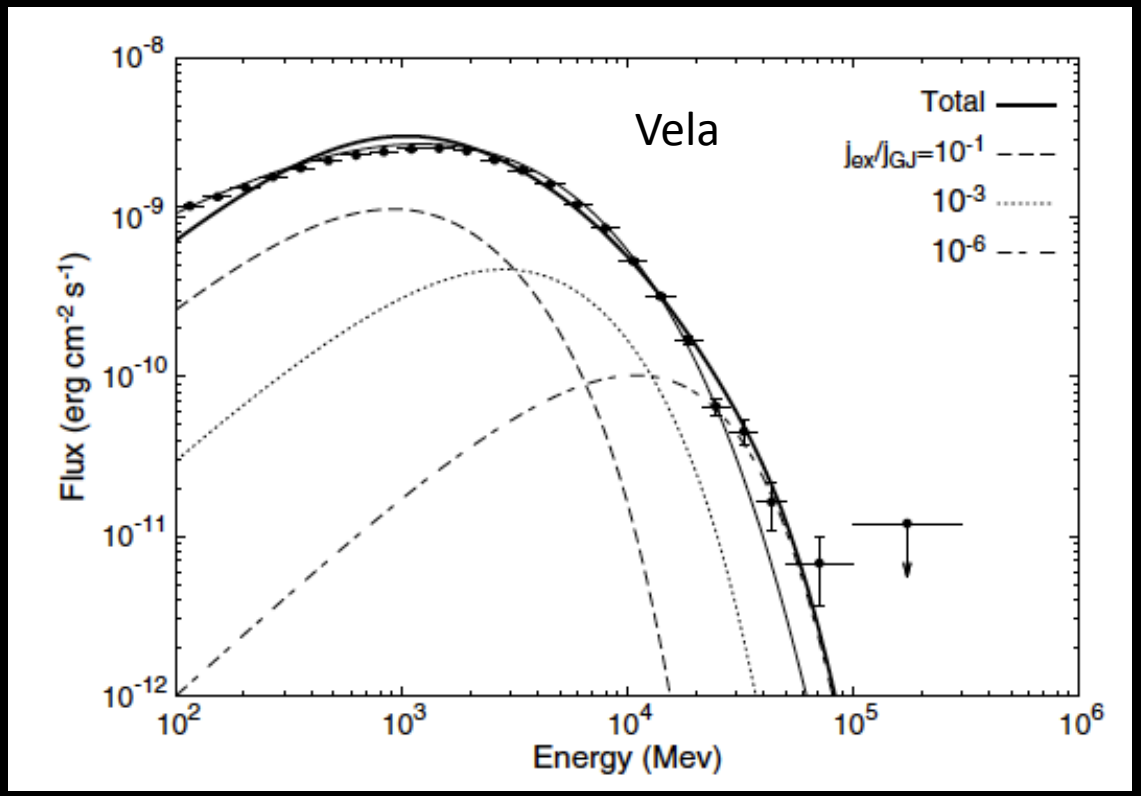
Aliu et al. (2011)

Pulsars at VHE Regime



Aleksic et al. (2012)

Pulsars at VHE Regime



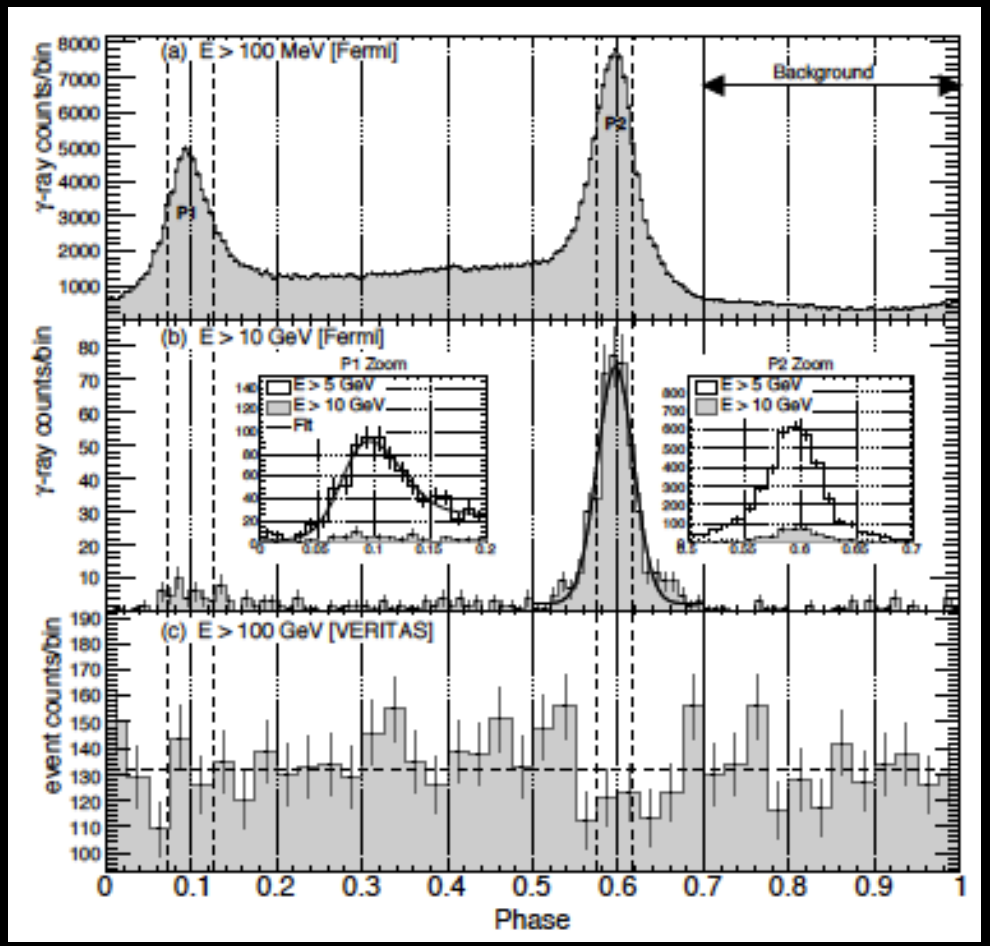
$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left[-\left(\frac{E}{E_{\rm cut}}\right)^{b}\right]$$

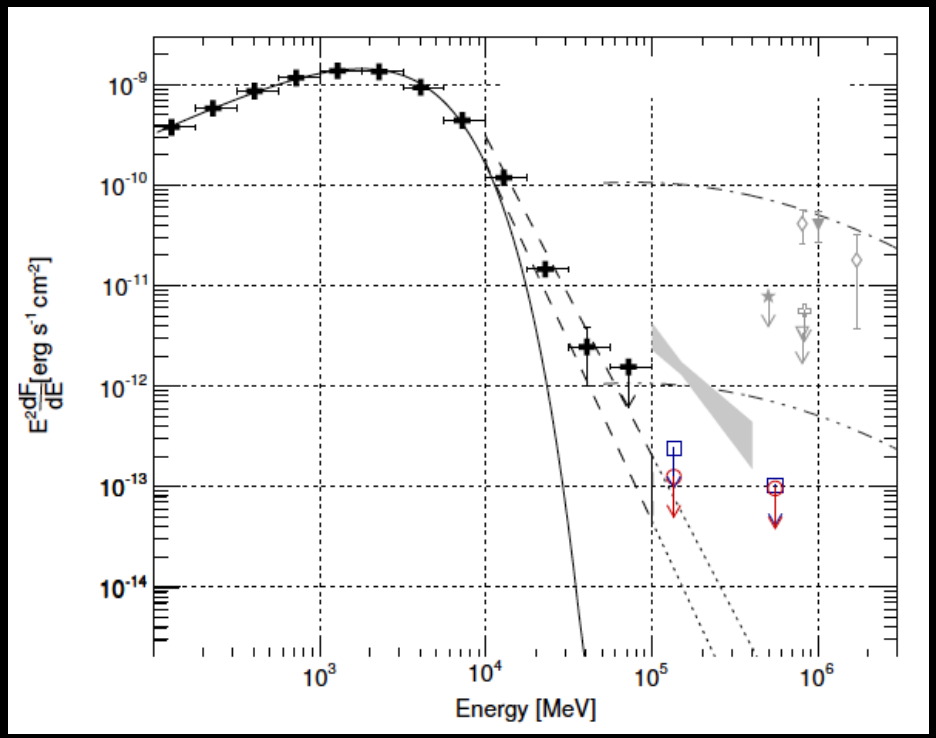
$$b = 0.510 \pm 0.002$$

Leung et al. (2014)

Pulsars at VHE Regime

- Geminga – the 1st CTA pulsar??





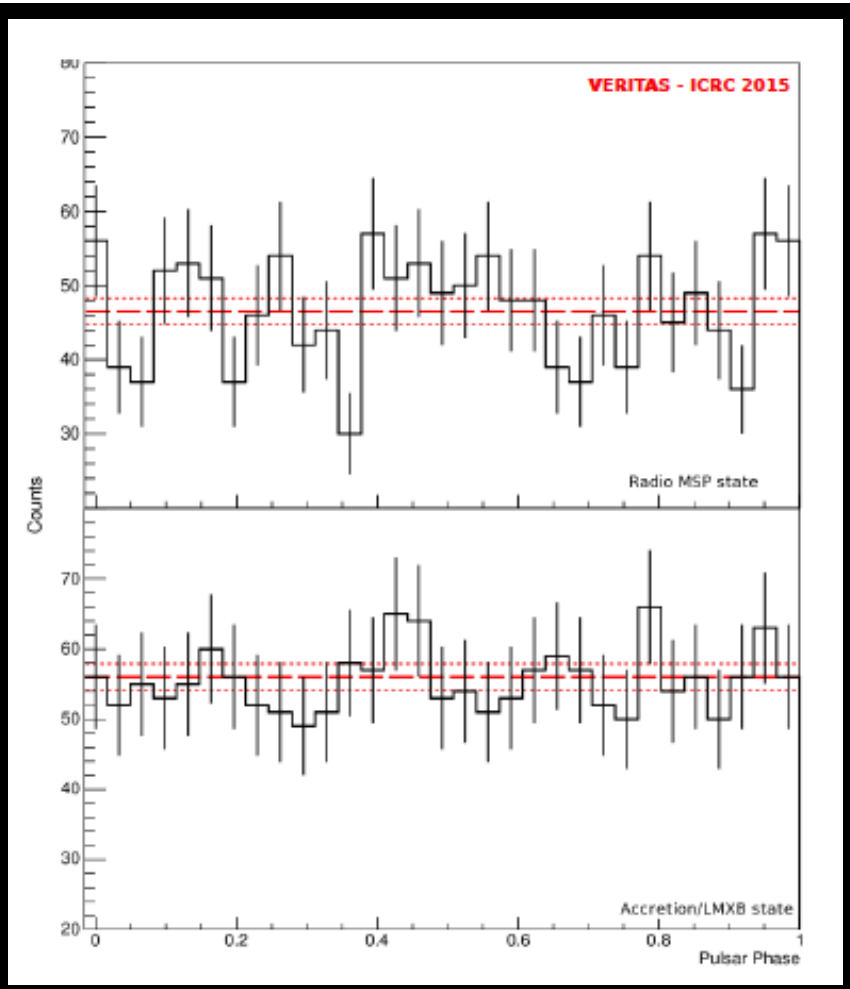
Aliu et al. (2015)

Pulsars at VHE Regime

- How does the gamma-ray spectra look like from MeV to TeV?
- Is there any difference between radio-loud and radio-quiet populations?
- *Compiling an updated catalog for Fermi pulsars with energies > 50 GeV can provide a good cadidate list for CTA*

MSPs in VHE Regime

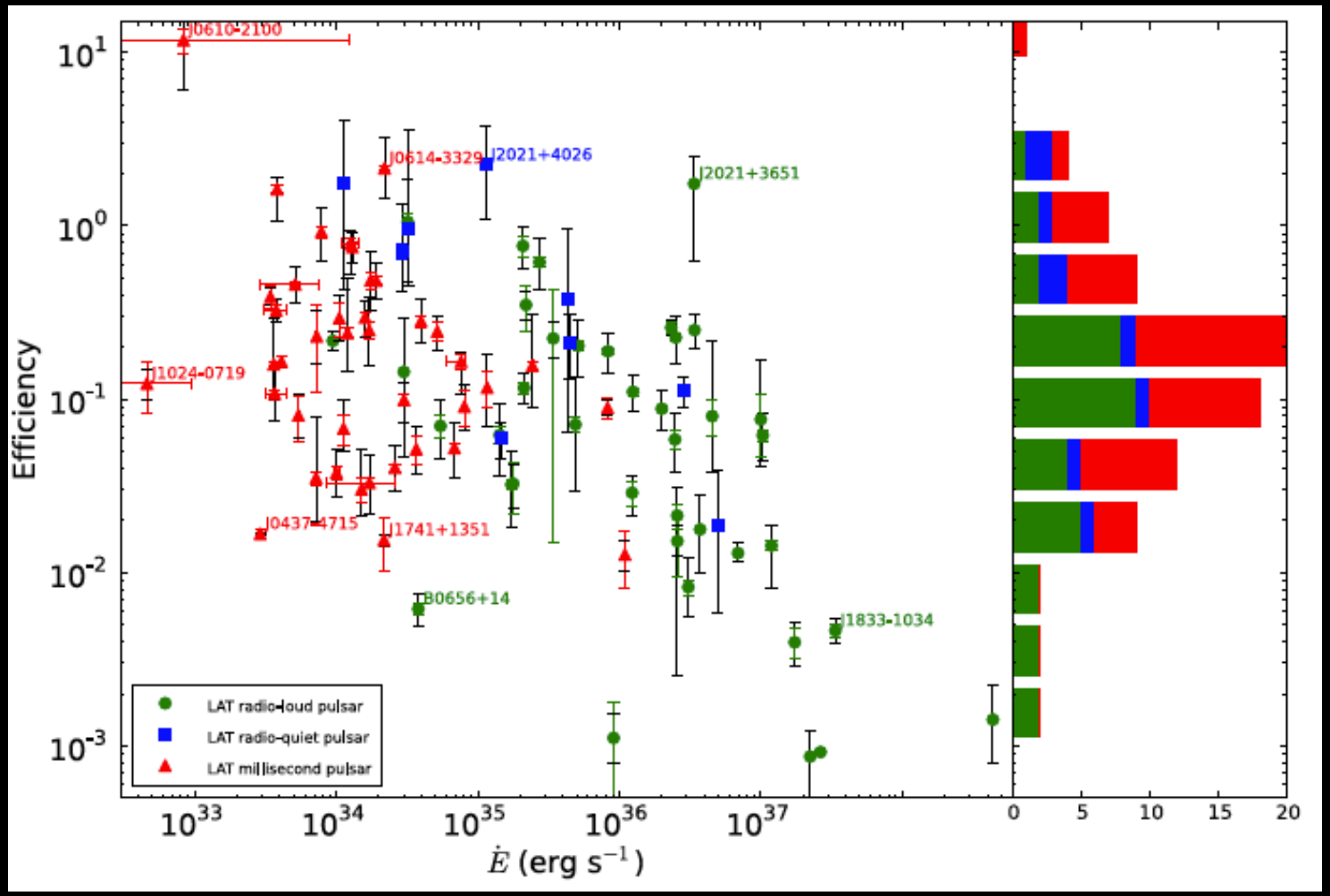
J1023 State	H statistic	2σ pulsed VHE flux UL (m^{-2} s^{-1})	3σ pulsed VHE flux UL (m^{-2} s^{-1})
Radio MSP	0.28	6.16×10^{-9}	9.73×10^{-9}
Accretion/LMXB	0.18	1.12×10^{-8}	1.97×10^{-8}



Richards et al. (2015)

MSPs in VHE Regime

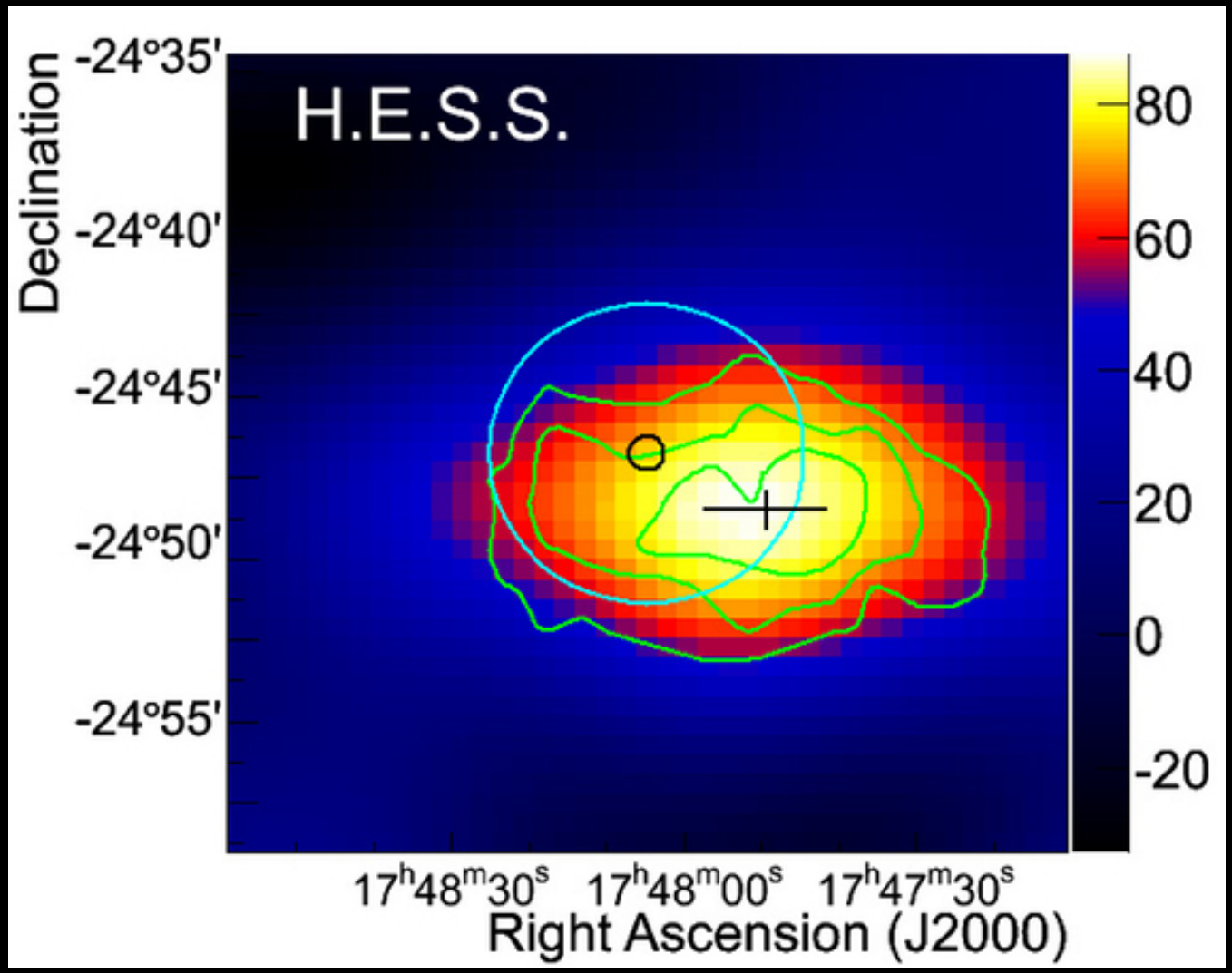
The proportion of MSP at high gamma-ray conversion efficiency is larger.



Abdo et al. (2013)

GC in VHE Regime

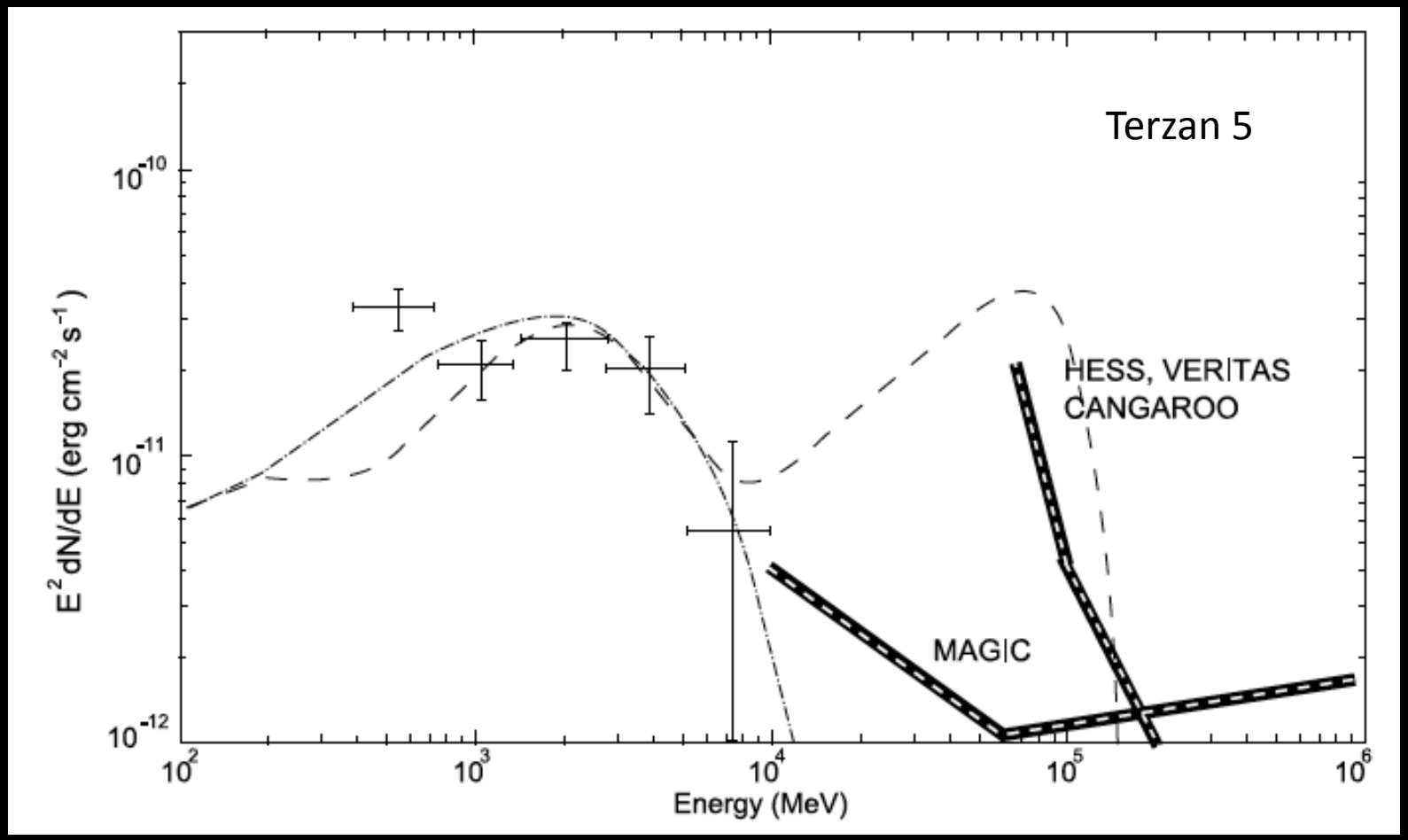
Extended VHE emission coincides with Terzan 5



Abramowski et al. (2011)

GC in VHE Regime

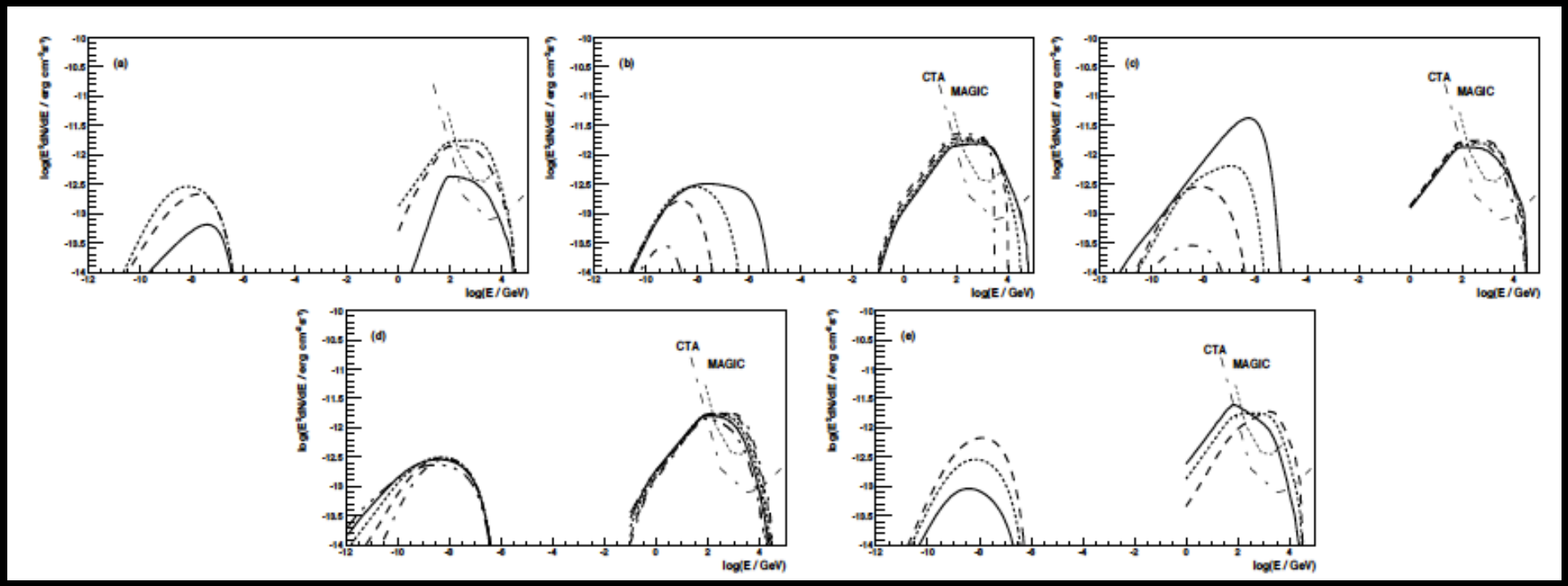
Dependence of VHE spectrum on soft photon fields



(Cheng et al. 2010; Hui et al. 2011)

GC in VHE Regime

Dependence of VHE spectrum on cluster properties (B-field, max injected energy…etc)



Bednarek et al. (2016)

Things we can do in Pre-CTA era

- Compiling a list of known pulsars > 50 GeV
- Compiling a candidate list of VHE MSPs (> 50 GeV; modulated in GeV regime)
- Feasibility studies of GCs based on the known emission models