Investigating off-pulse gamma-ray emission from millisecond pulsars

Ming-Yu Lei (雷鸣宇)

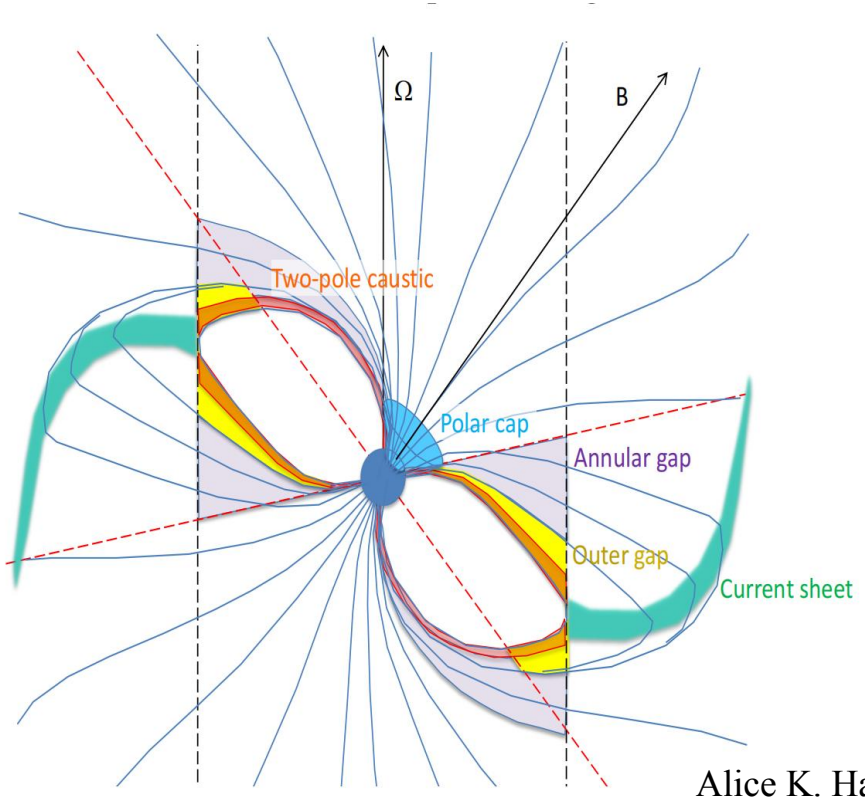
With Xiaoyuan Huang, Zi-Qing Xia, Zhao-Qiang Shen

Purple Mountain Observatory

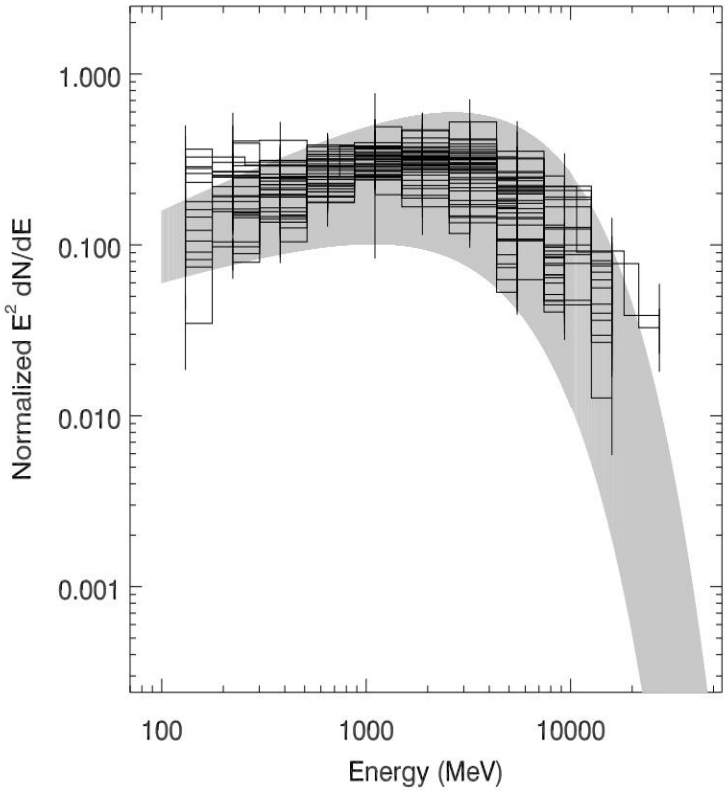
2024 年 SKA 脉冲星科学研讨会

& 第十三届全国脉冲星研讨会

High energy radiation from pulsar



Alice K. Harding (2021)



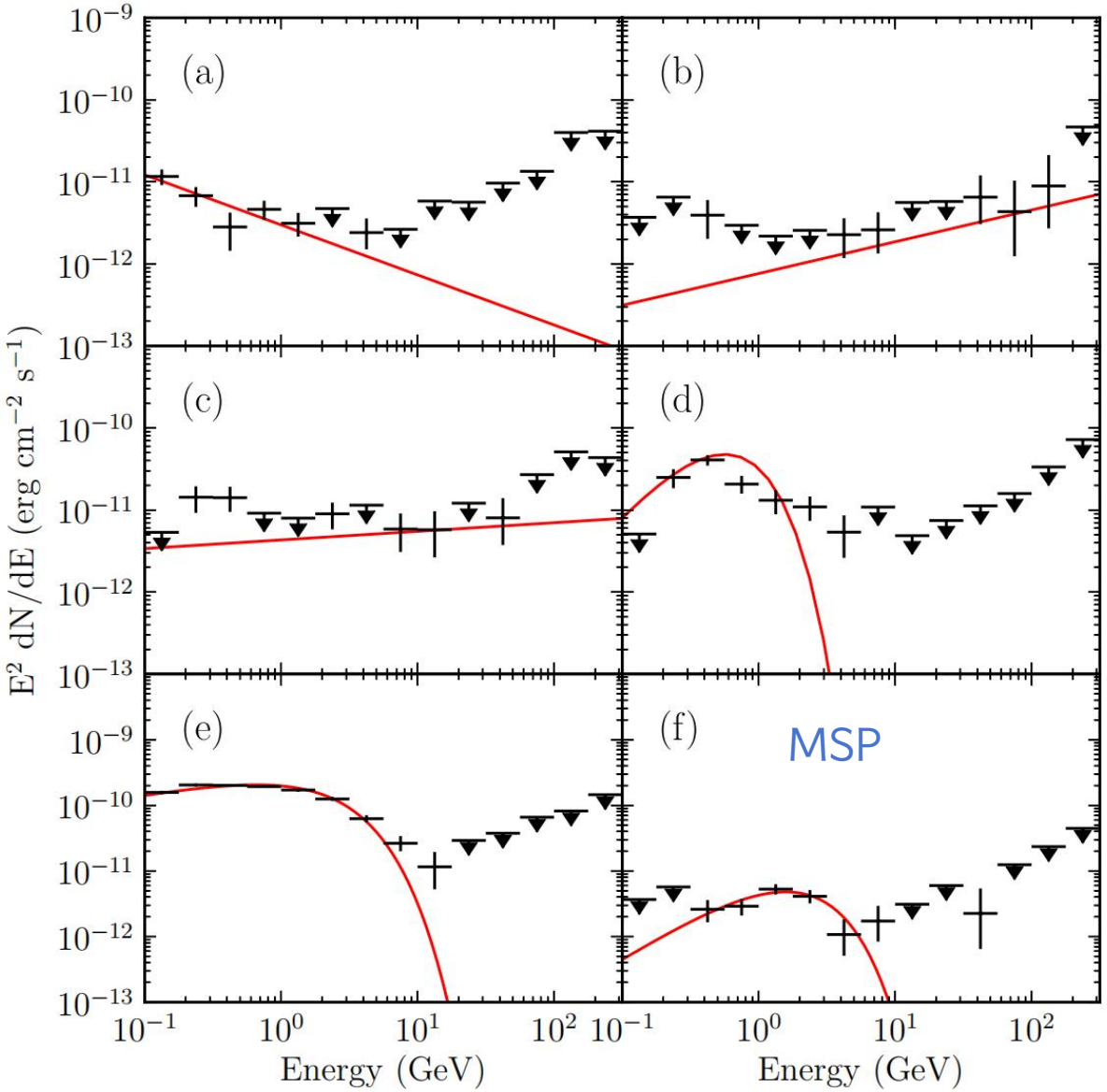
Xing et al. (2016)

◆ The gamma-ray radiation of pulsar **pulse** comes from the curvature radiation of electrons in the magnetosphere.

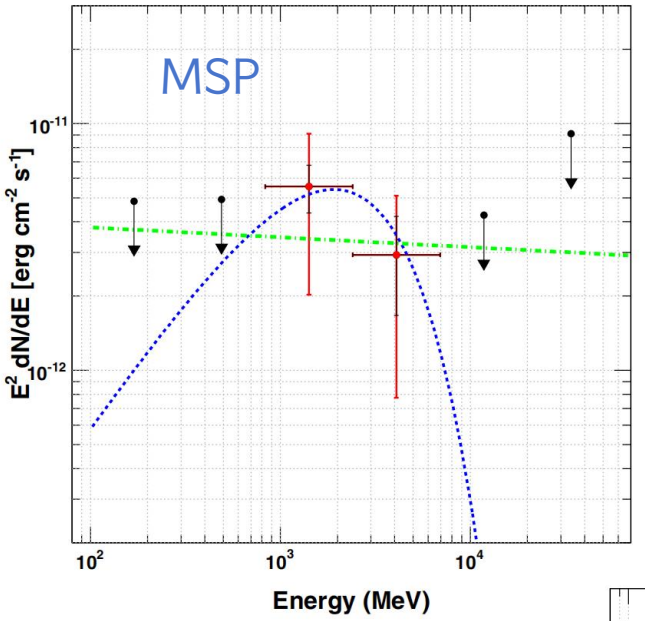
↓

off-pulse emisson

The off-pulse gamma-ray emission from millisecond pulsars (MSPs)



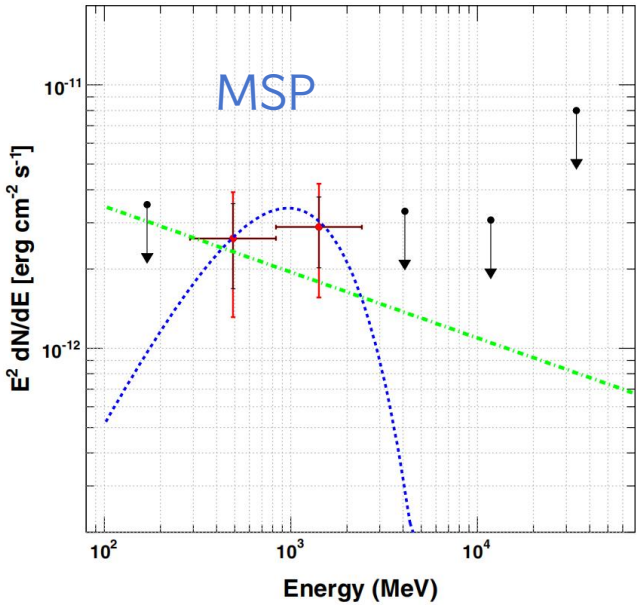
A. A. Abdo et al. (2013)



PSR J0034−0534

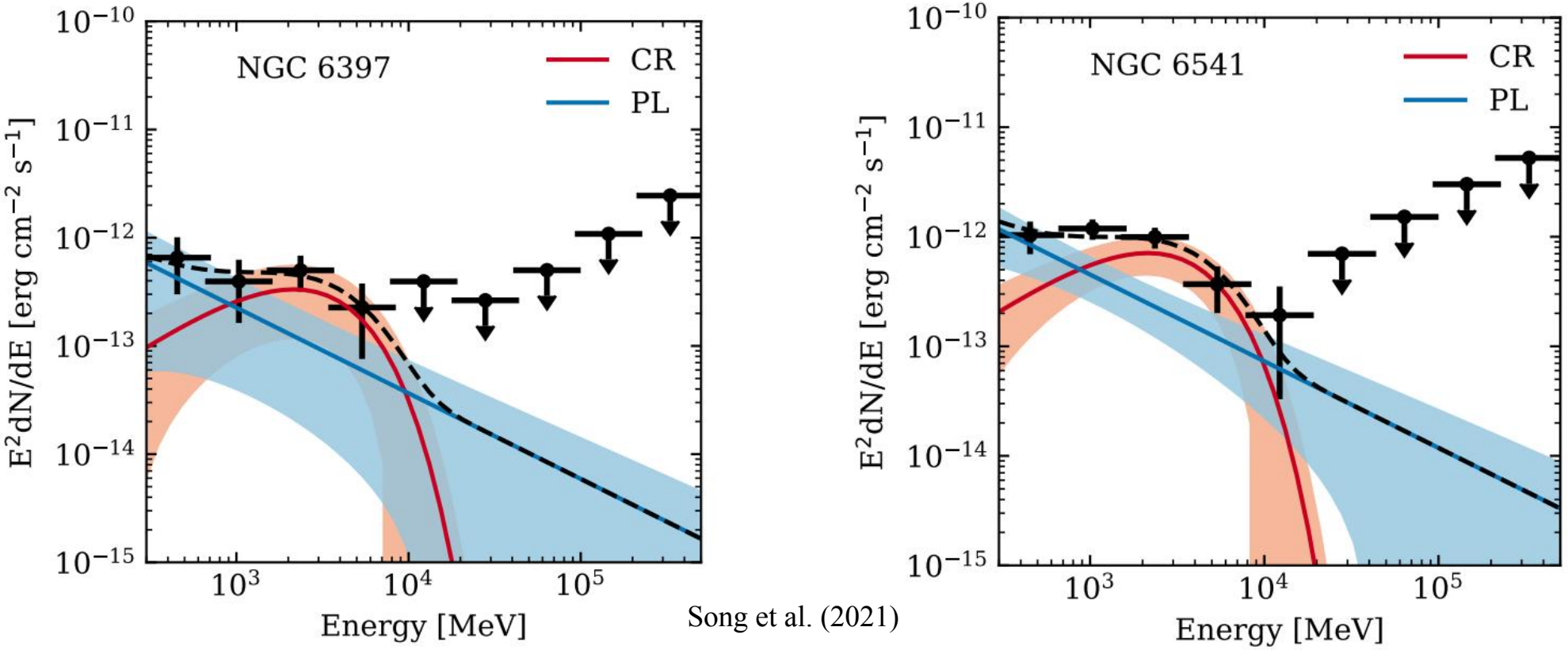
M. Ackermann et al. (2011)

PSR J2124−3358



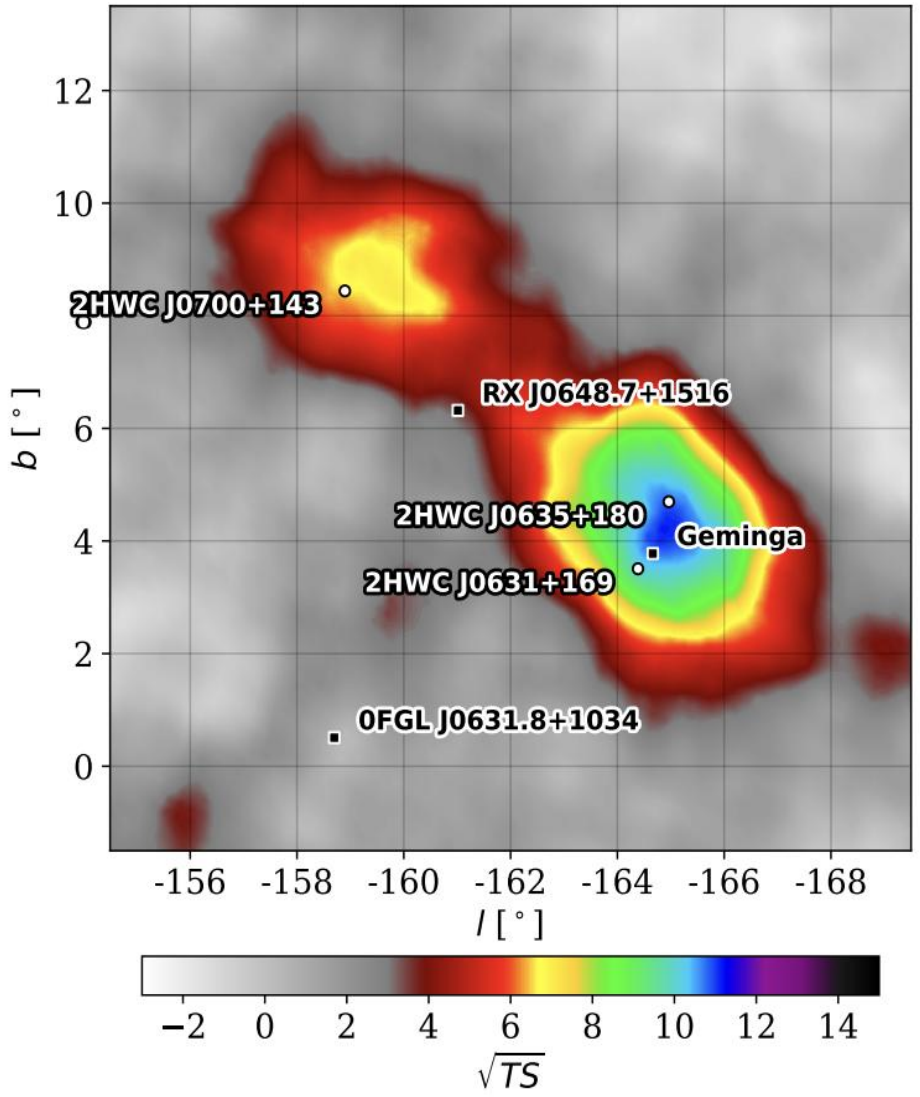
Inverse Compton (IC) radiation processes around MSPs

- A high-energy tail in the gamma-ray spectra of globular clusters



Song et al. (2021)

Inverse Compton (IC) radiation processes around MSPs



A. U. Abeysekara et al. (2017)

- HAWC data suggest (~3σ) that MSPs produce TeV halos with a similar efficiency as young pulsars.

  Dan Hooper et al. (2022)

- The IC processes around MSPs may contribute to the off-pulse emission.

Data Information

Pulsar Information

https://doi.org/10.1126/science.abm3231

A gamma-ray pulsar timing array constrains the nanohertz gravitational wave background

The Fermi-LAT Collaboration*†

*Fermi-LAT Collaboration authors and affiliations are listed in the supplementary materials.

†Corresponding authors: Matthew Kerr (matthew.kerr@gmail.com); Aditya Parthasarathy (adityapartha3112@gmail.com)

Photon Information

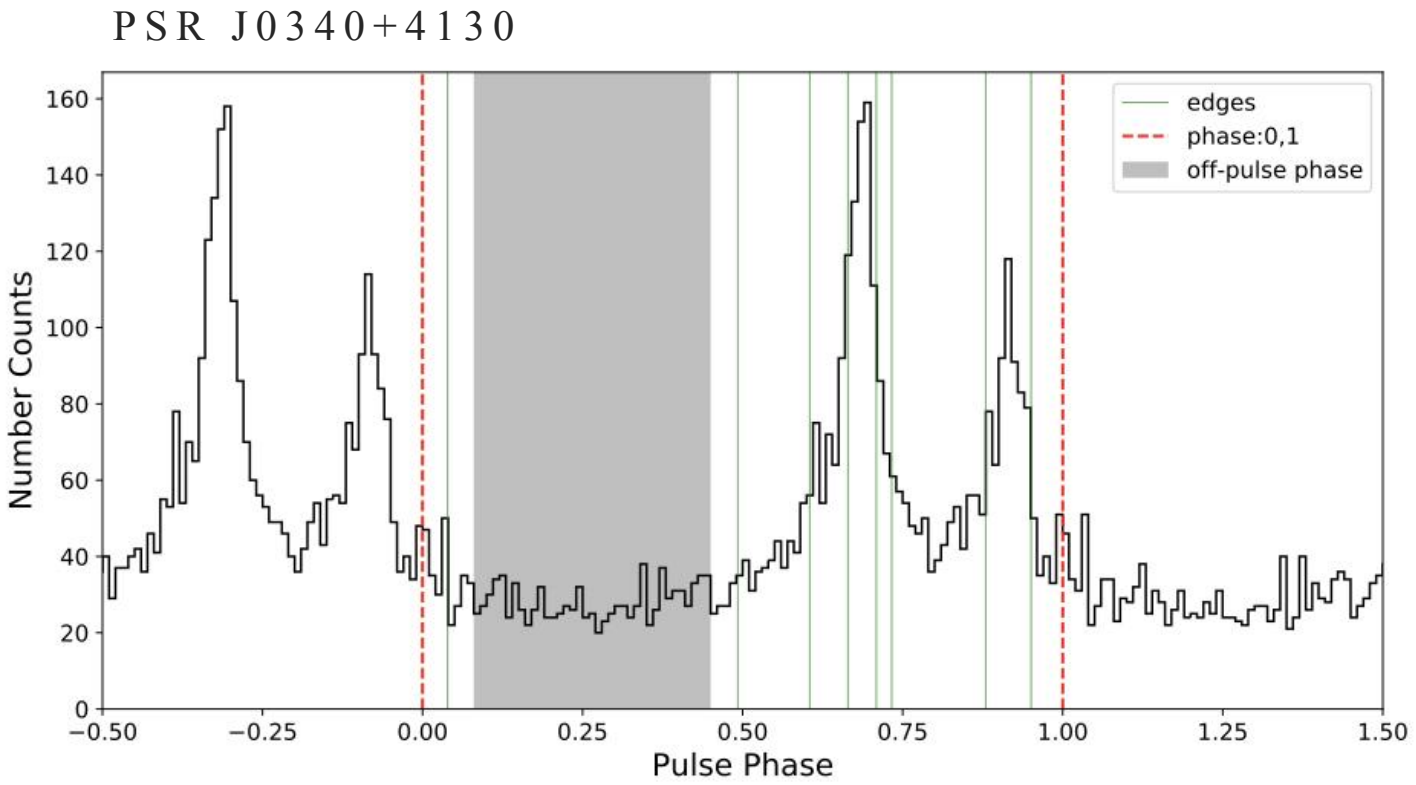
Time(UTC)	2008-08-04 , 2023-07-01
Time(MJD)	54682 , 60126
Time(MET)	239557417 , 709862405
Energy(MeV)	300 , 500000
Radius(°)	10
Zenith Angle(°)	<100

◆ A total of 35 millisecond pulsars

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{\gamma_1} \exp\left(-\left(\frac{E}{E_c}\right)^b\right)$$

with $E_0 = 1\text{GeV}$ and $b = 1$

Off-pulse Phase Selection



- **Unweighted-counts** light curve(r=0.5˚) with bayesian blocks.

Significant off-pulse emission (TS ≥ 25)

TABLE III: Spectral fit results for MSPs with significant off-pulse emission

PSR	TS	TS_{cutoff}	E_{cut} (GeV)	Γ	Γ (PL)
J1536−4948	35	1	2.39±2.62	2.50±0.59	3.02±0.23
J2256−1024	66	2	2.38±2.60	2.45±0.55	3.01±0.19
J0613−0200	51	4	2.44±1.73	2.16±0.45	2.87±0.17
J0034−0534	253	8	3.82±1.90	2.09±0.23	2.59±0.09
J0102+4839	122	11	1.39±0.72	1.38±0.51	···
J0340+4130	86	12	4.03±1.87	1.24±0.40	···
J1630+3730	56	16	0.95±0.42	0.40±0.90	···
J2043+1711	231	28	1.03±0.36	0.92±0.48	···
J0614−3329	773	37	1.88±0.51	1.62±0.21	···
J0533+6759	409	48	2.15±0.53	1.08±0.27	···
J2302+4442	776	64	2.02±0.40	1.41±0.18	···

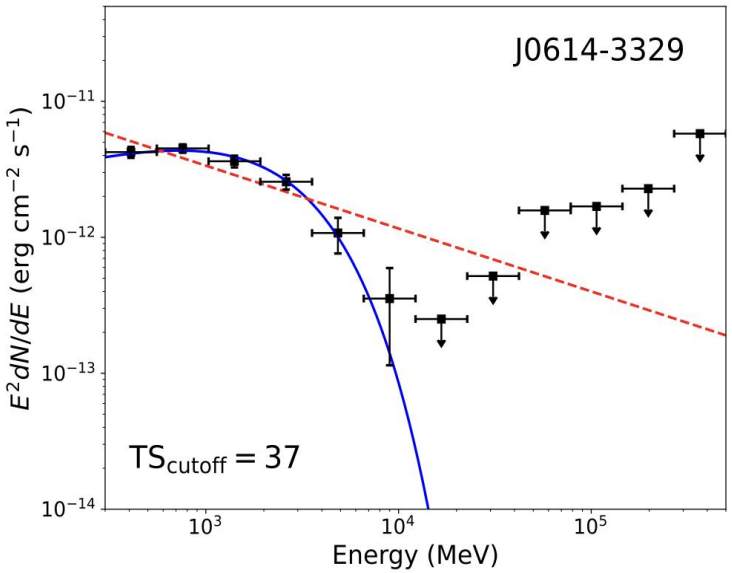
② ①

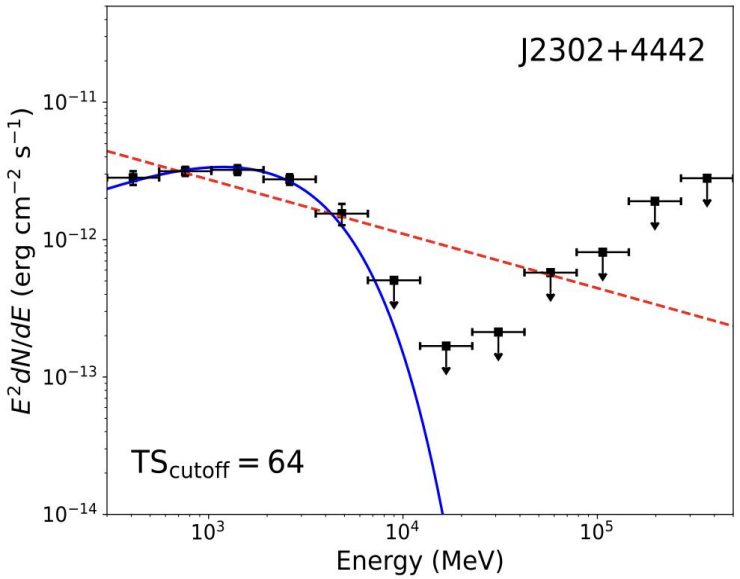
- ①: The energy spectrum has **significant cutoff** ($TS_{cutoff} \geq 9$) → from the magnetosphere
- ②: The energy spectrum has no significant cutoff and the spectral index is soft.

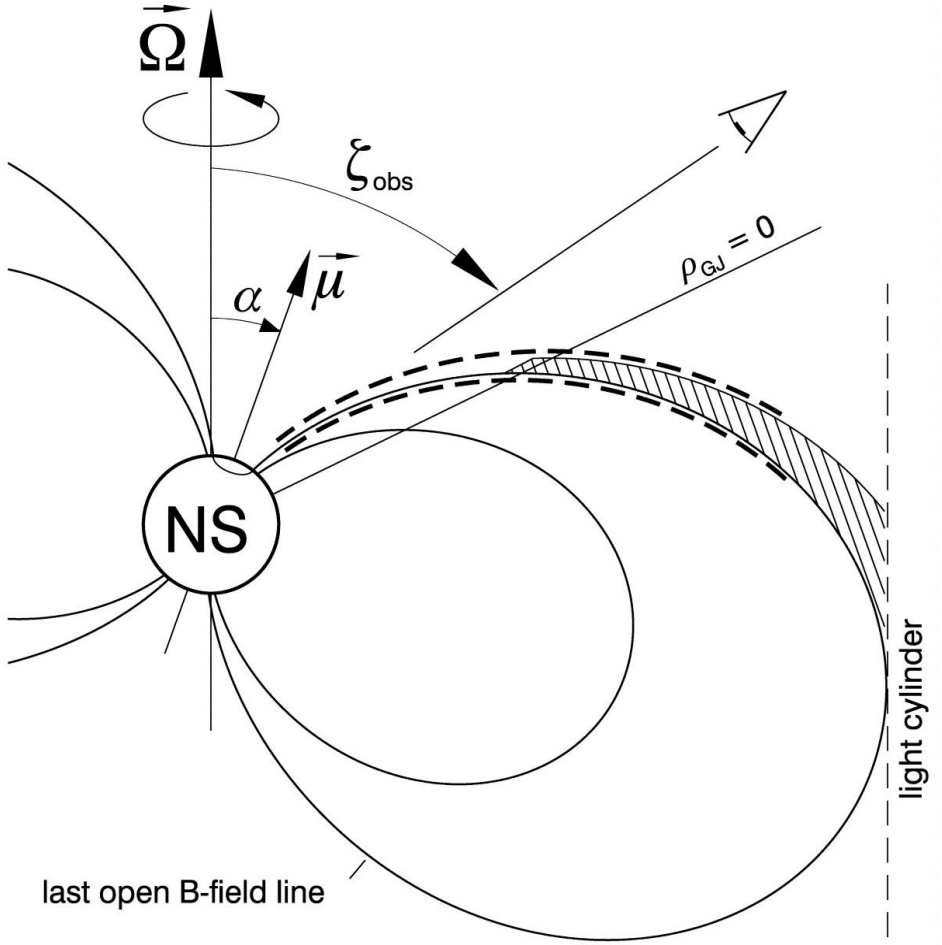
↓

from other physical process ?

Radiation from pulsar magnetosphere



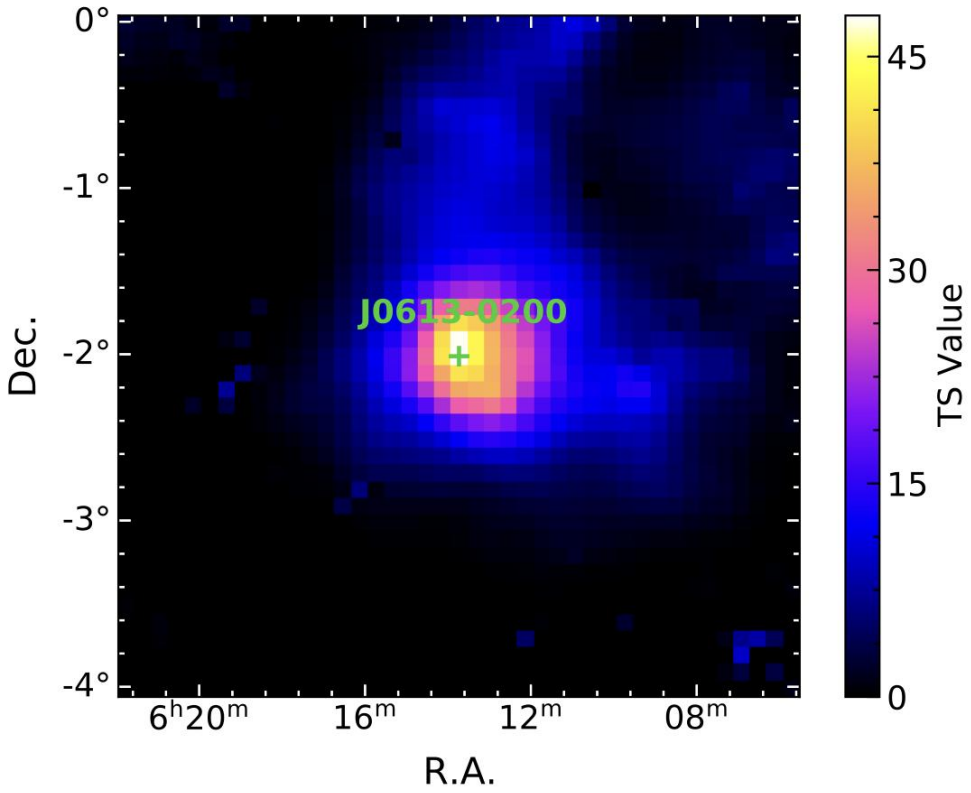


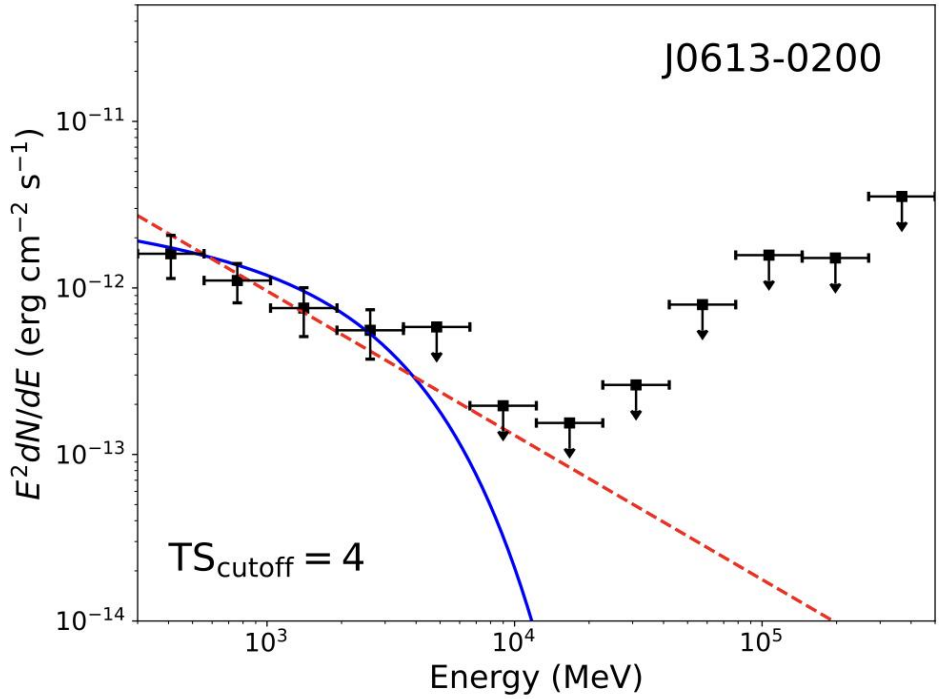


J. Dyks & B. Rudak 2003 ApJ 598 1201

◆ The detection of off-pulse emission from the magnetosphere can be used to constrain the radiation model.

Origin of off-pulse emission with $\mathrm{TS}_{\mathrm{cutoff}} < 9$

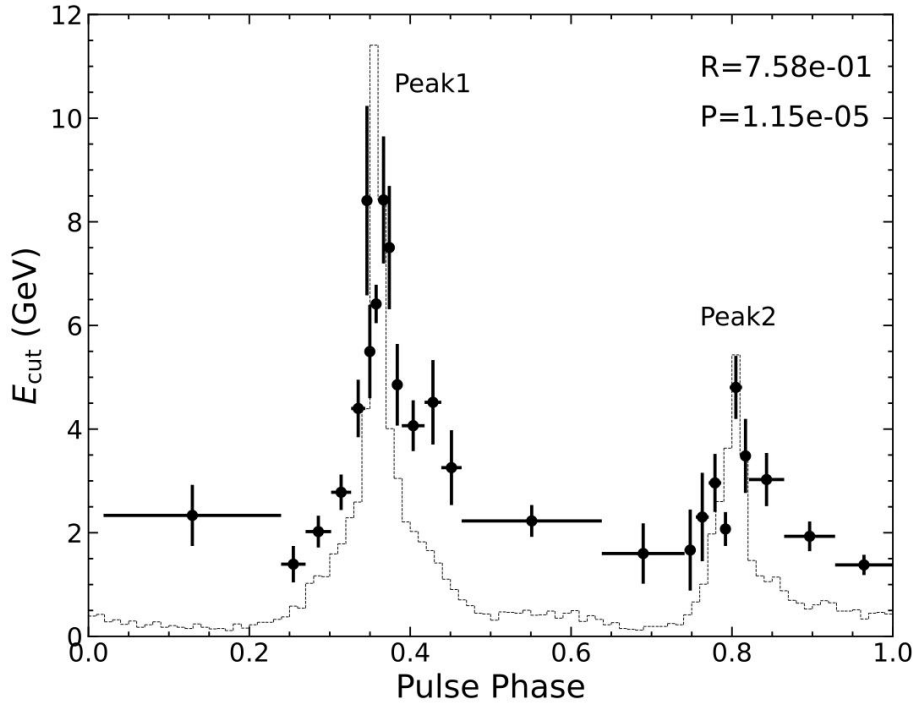


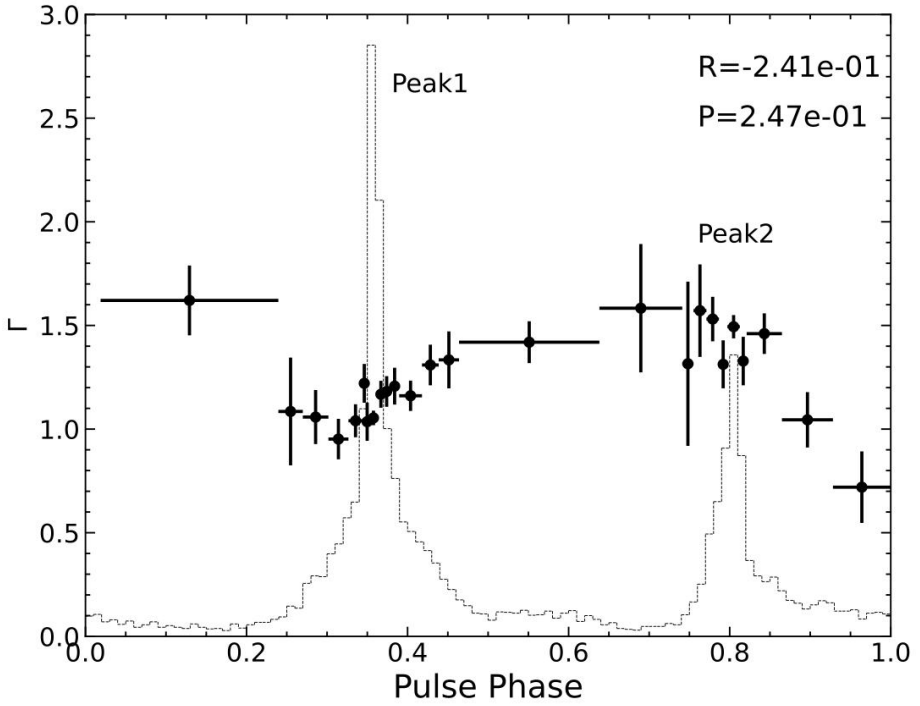


- Adding this component would make the overall fit worse, so it is **not** a new stable component.
  It is curvature radiation from pulsar.

Phase-resolved spectrum

PSR J0614-3329

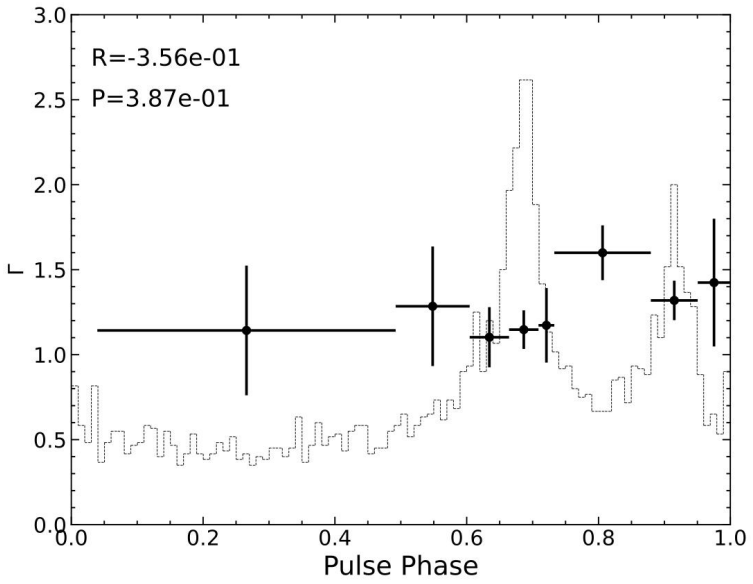


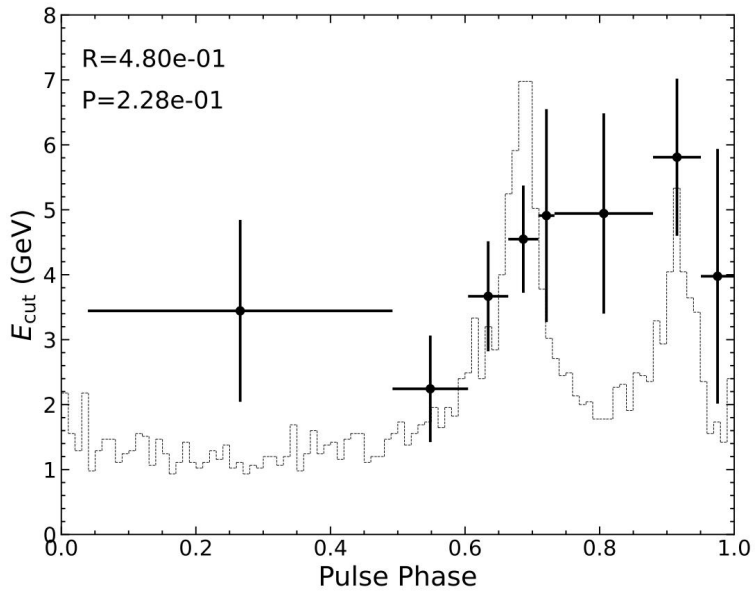


- Cutoff energy is highly correlated with the phase, but index is not.

Other sources ?

Phase-resolved spectrum



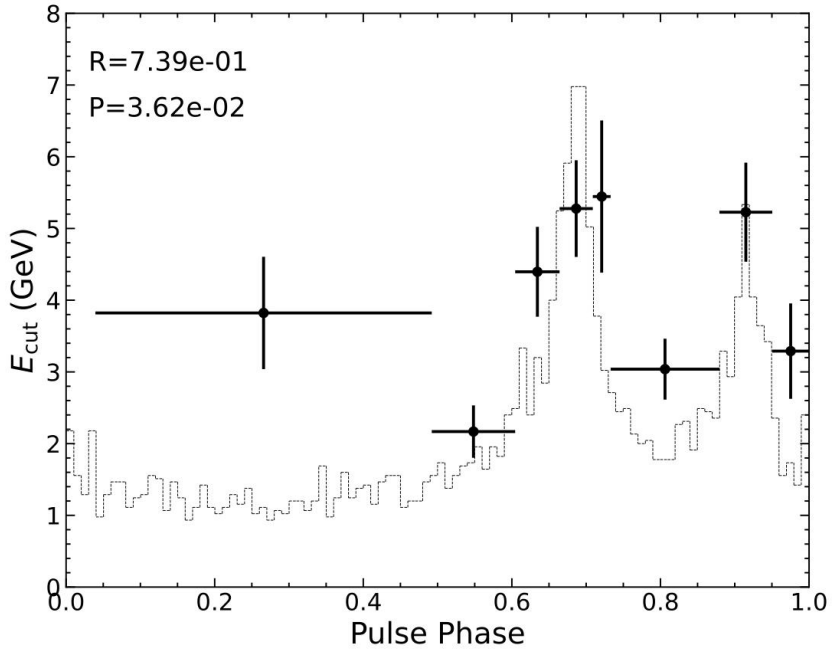


PSR J0340+4130

CompositeLikelihood

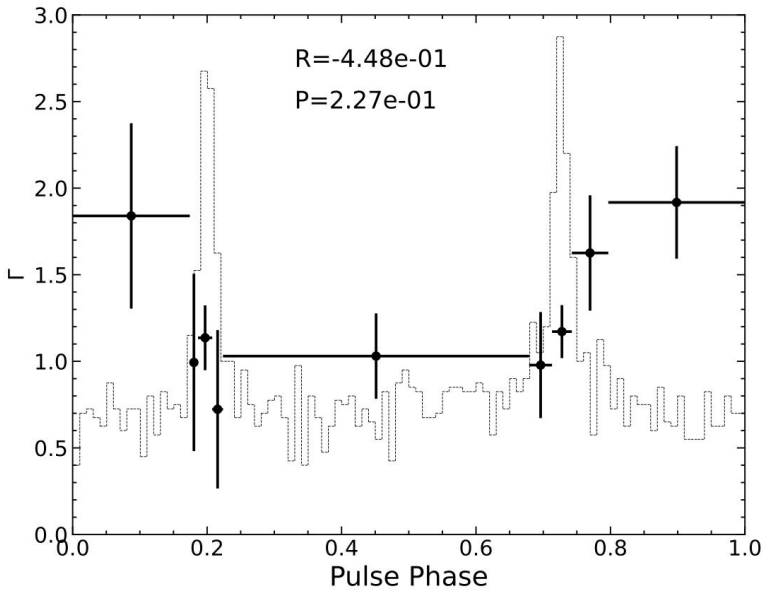
tieParameters(Index)

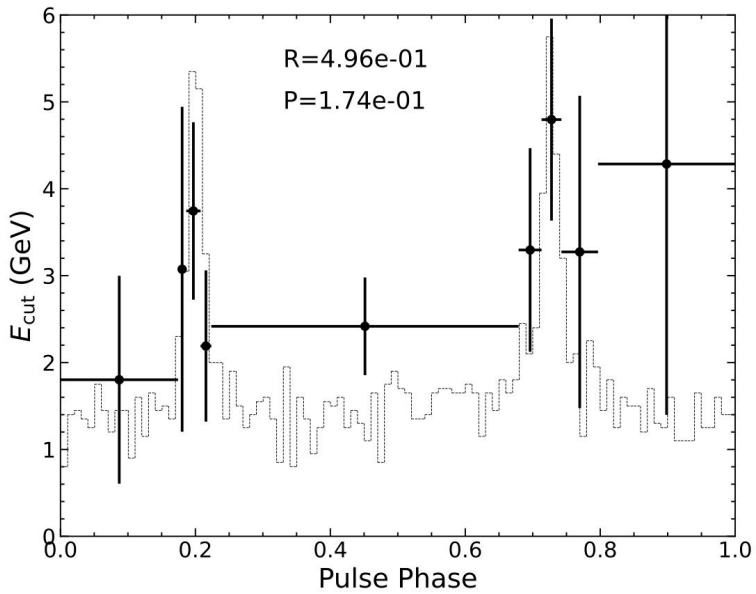
0.66 sigma



◆ The cutoff energy and phase exhibit a clear correlation.

Phase-resolved spectrum



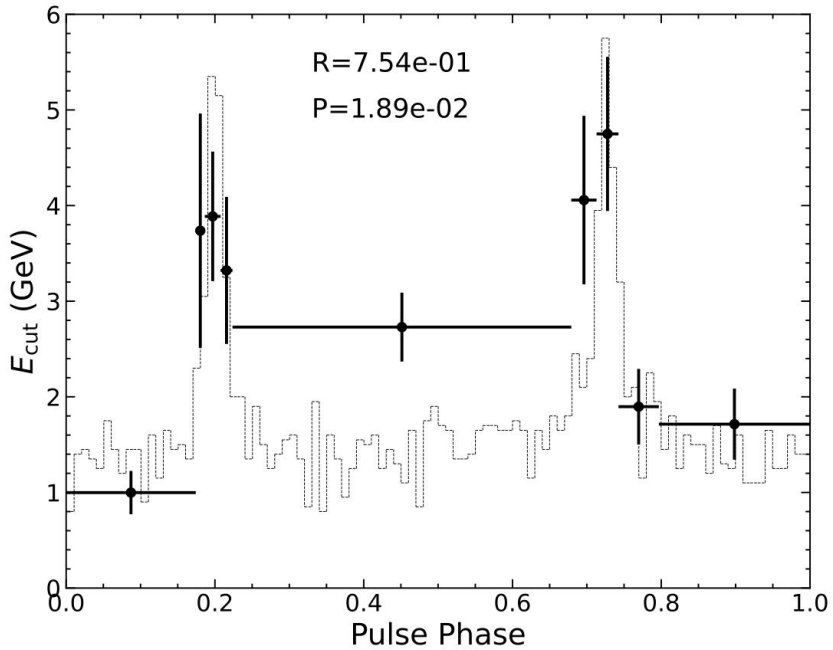


PSR J0533+6759

CompositeLikelihood

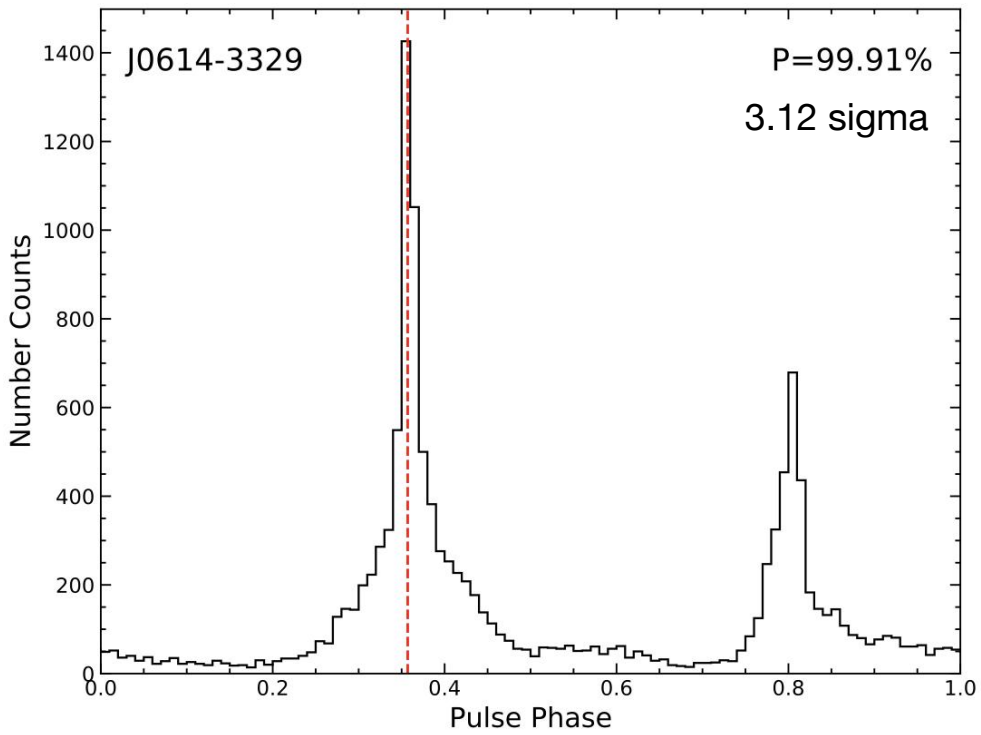
tieParameters(Index)

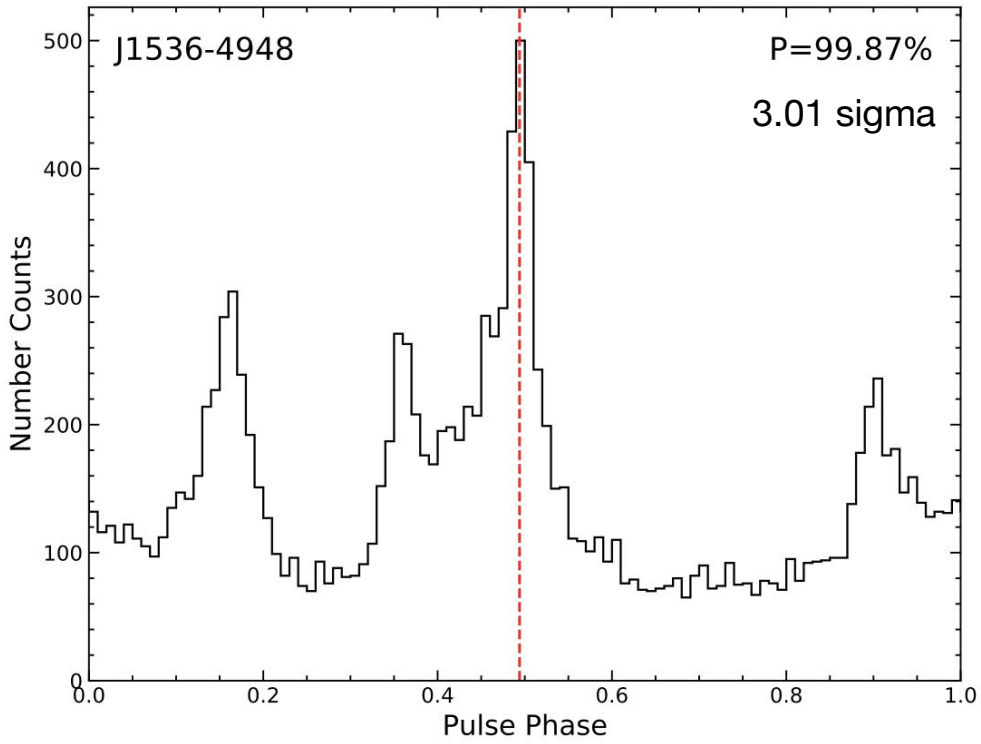
0.88 sigma



- The apparent correlation between cutoff energy and phase might be useful in distinguishing different magnetospheric models.

Analysis of > **25** GeV data





- Maximum energy photons from J0614-3329 and J1536-4948: 61 GeV and 57 GeV.

Summary

- A total of 12 millisecond pulsars have significant off-pulse emission (TS_off>25) , and all of them (whether TS_cutoff>9 or <9) emit radiation from the pulsar magnetosphere.
- There is a very clear correlation between the cutoff energy and the phase in PSR J0614-3329, and this phenomenon is also seen in some other sources.
- Maximum energy photons from J0614-3329 and J1536-4948: 61 GeV and 57 GeV.

- The detection of off-pulse emission from the magnetosphere and phase-resolved spectrum can be used to distern the magnetospheric and radiation models.