PSR J2021+4026 in the Gamma Cygni region: the first variable pulsar seen by the *Fermi* LAT

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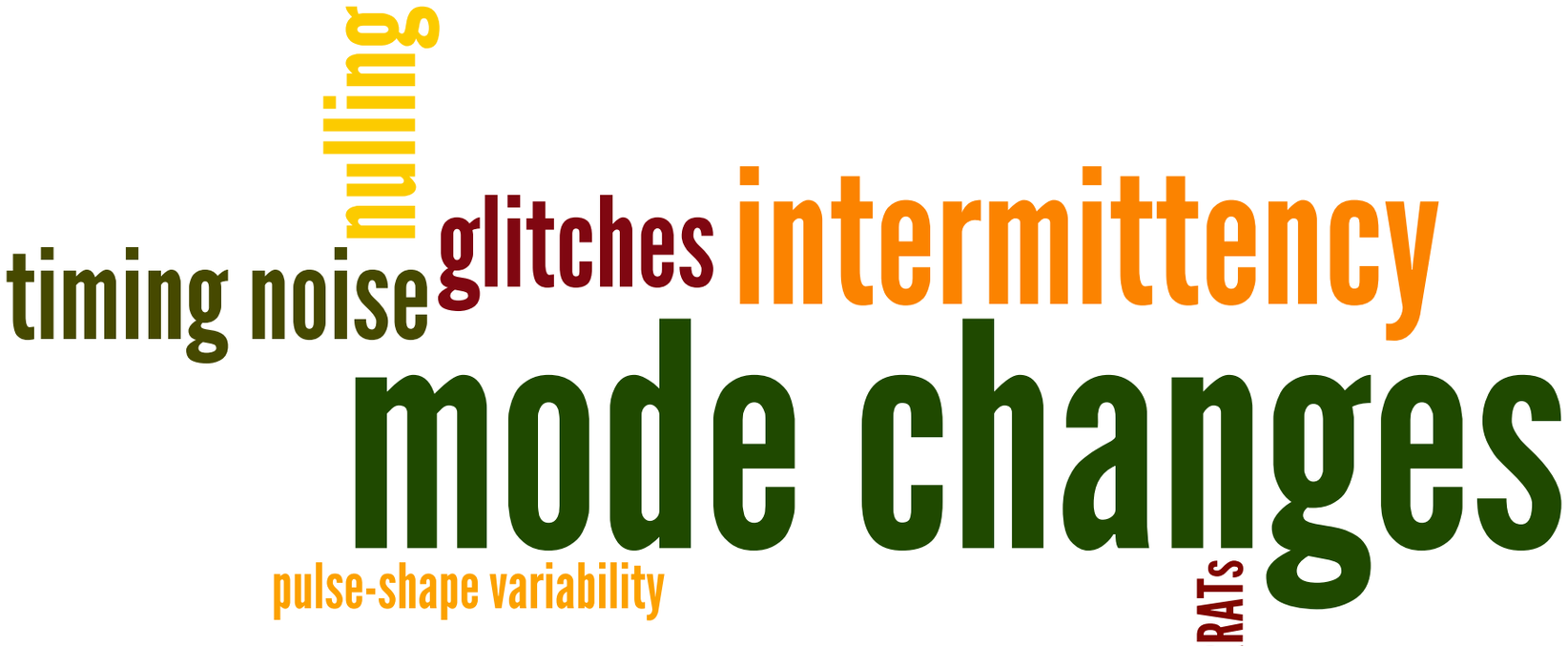
Pulsars: not always stable rotators

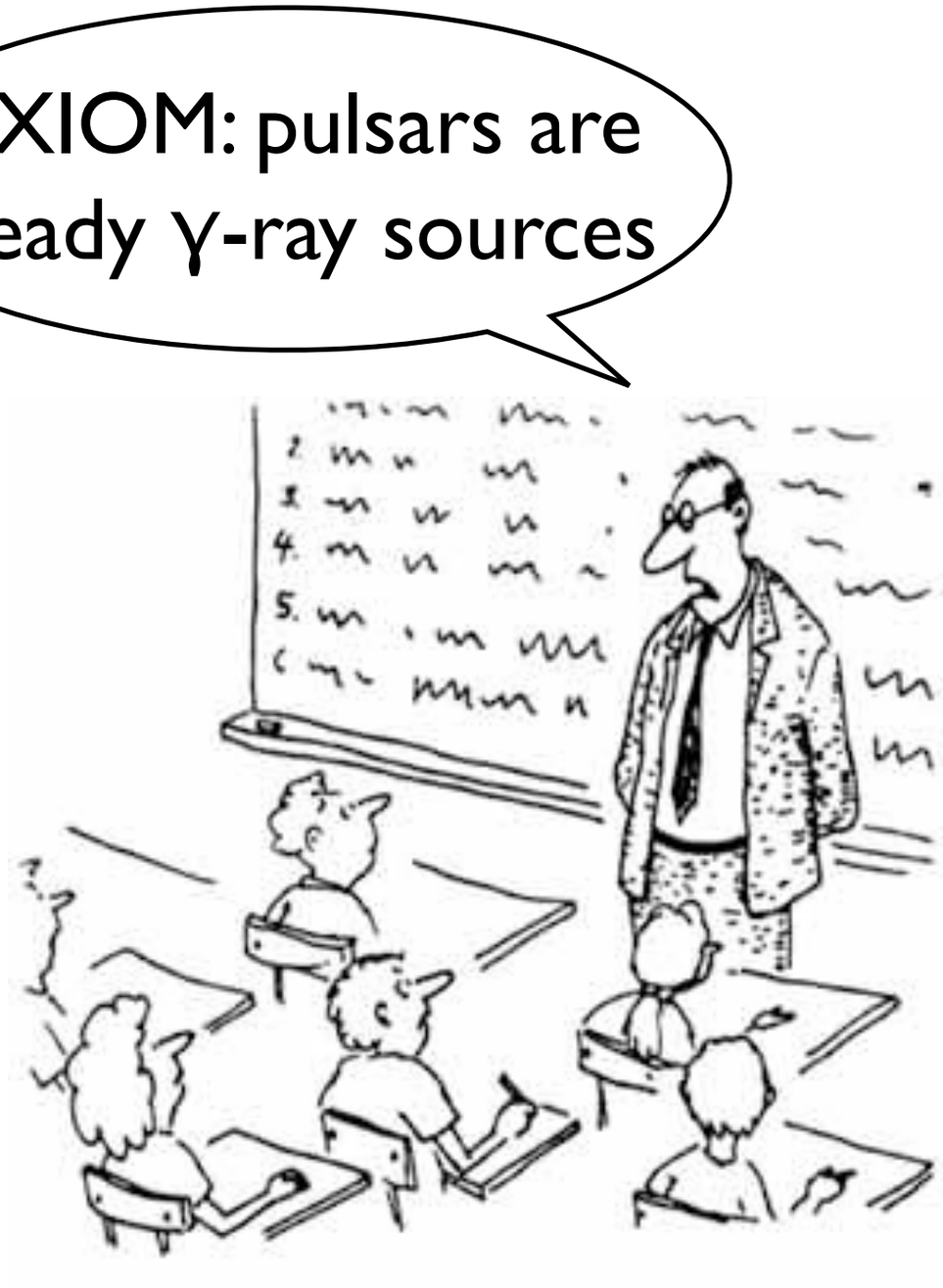


Radio/X-ray variability → insights into magnetospheric physics

- measure charge density $\rho = 0.034$ C m^{-3} (Kramer+ 2006)
- discrete metastable states (Lyne+ 2010)
- few-second reconfiguration (Hermsen+ 2013)

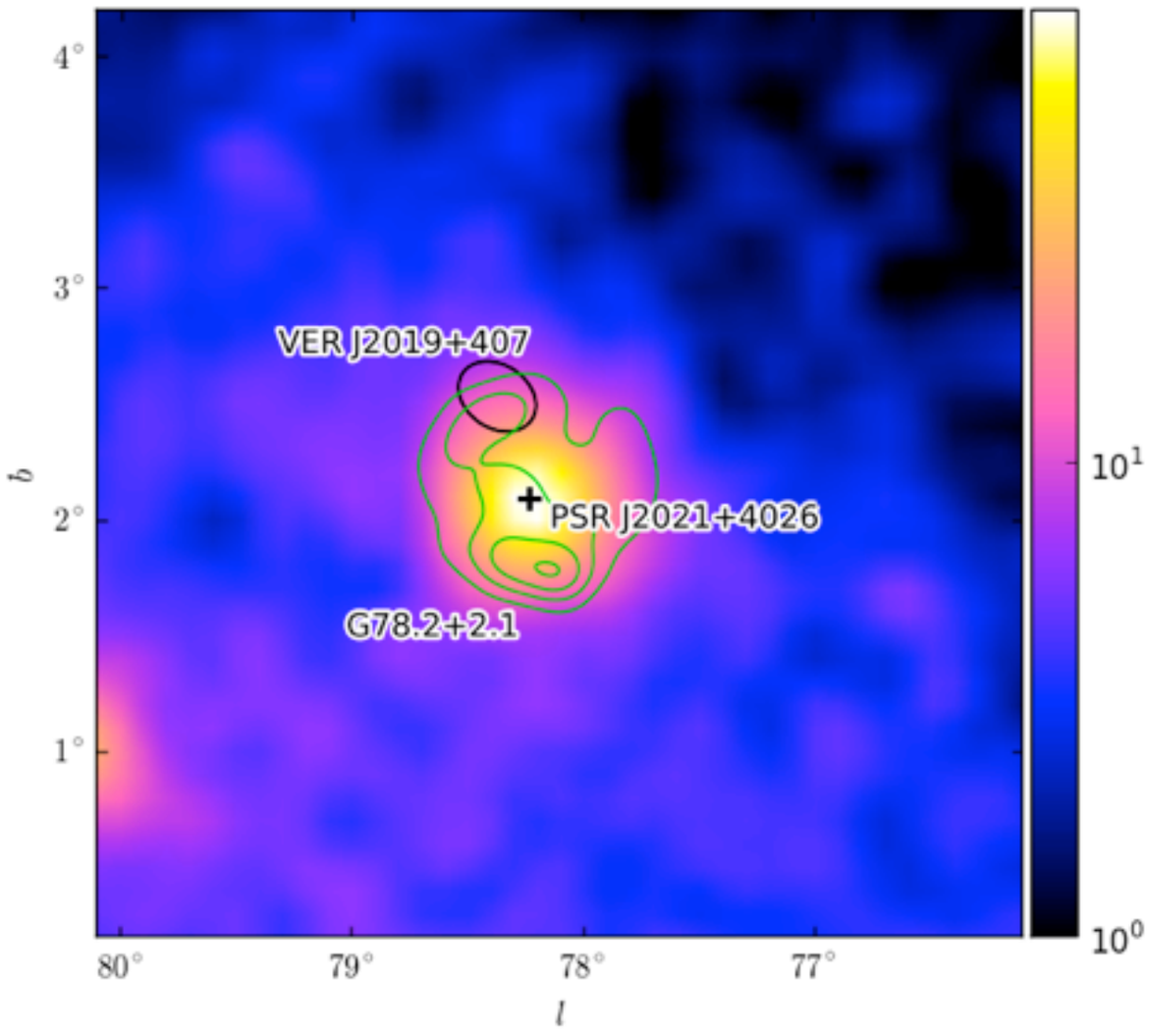
But not in gamma rays! Oh, well ...

- sizable fraction of $\dot{E}$ in γ rays
- *CGRO*-EGRET: stability of pulsar γ-ray emission (Nolan+ 2003)
- no significant variability in 2-year *Fermi*-LAT source Catalog (Nolan+ 2012)



The Gamma Cygni pulsar

- PSR J2021+4026
  - discovered by LAT in blind search (Abdo+ 2009)
  - $f \sim 4\,\mathrm{Hz},\ \dot{f} \sim -8 \times 10^{-13}\,\mathrm{Hz\ s^{-1}}$
  - no radio counterpart, X-ray detection (Lin+2013)
- same region
  - supernova remnant G78.2+2.1 at > 10 GeV (Lande+ 2012)
  - TeV source VER J2019+407 (Aliu+ 2013)



Fermi LAT E > 2 GeV, front-converting events
408 MHz (CGPS)

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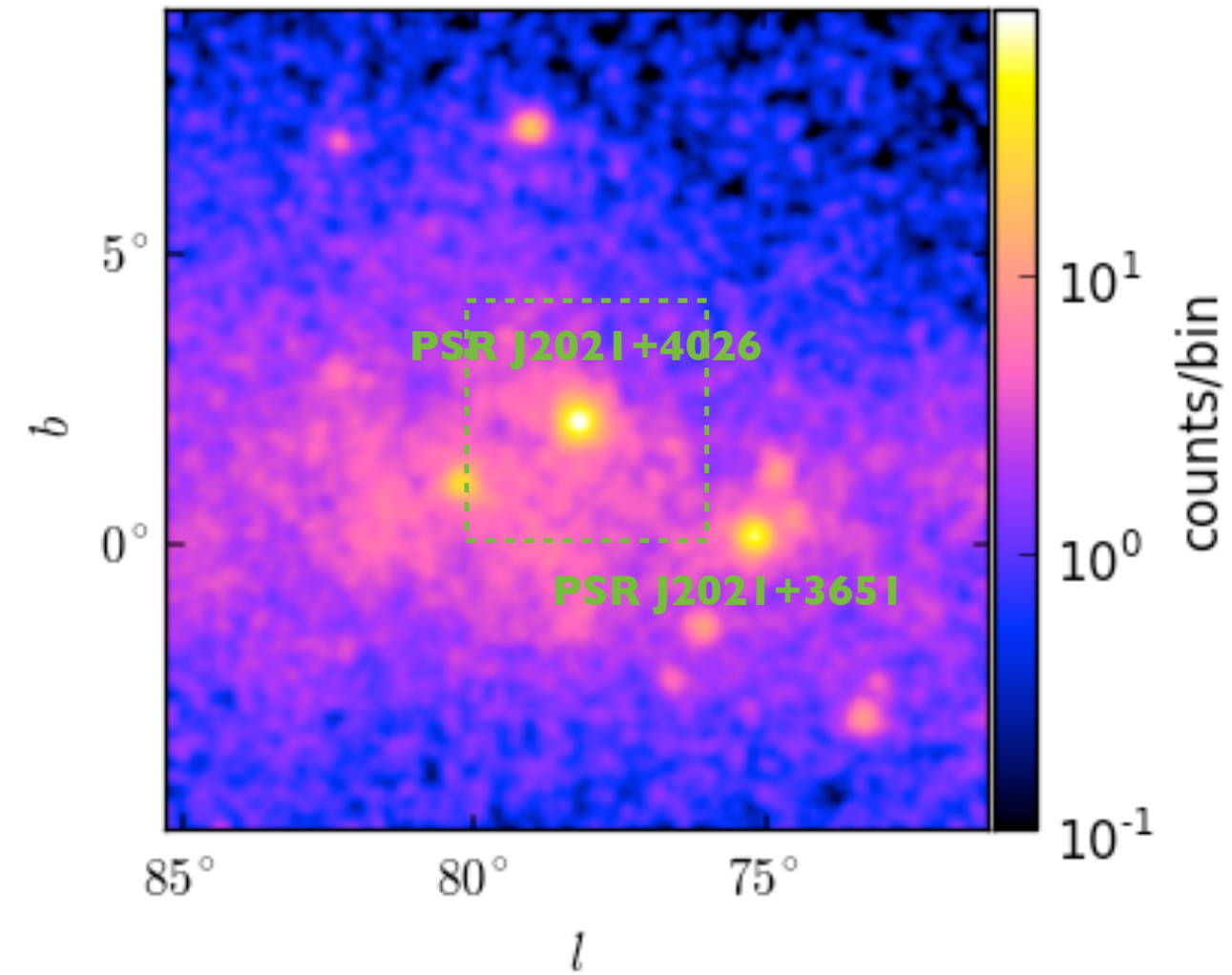
Variability search

- 1AGL J2022+4032
  - variable in 2007-2009 (Chen+ 2011)
  - coincident with PSR J2021+4026
  - variable source not firmly identified
- 52-month *Fermi* LAT observations (2008-2012)100 MeV to 300 GeV

Fermi LAT E > 2 GeV, front-converting events



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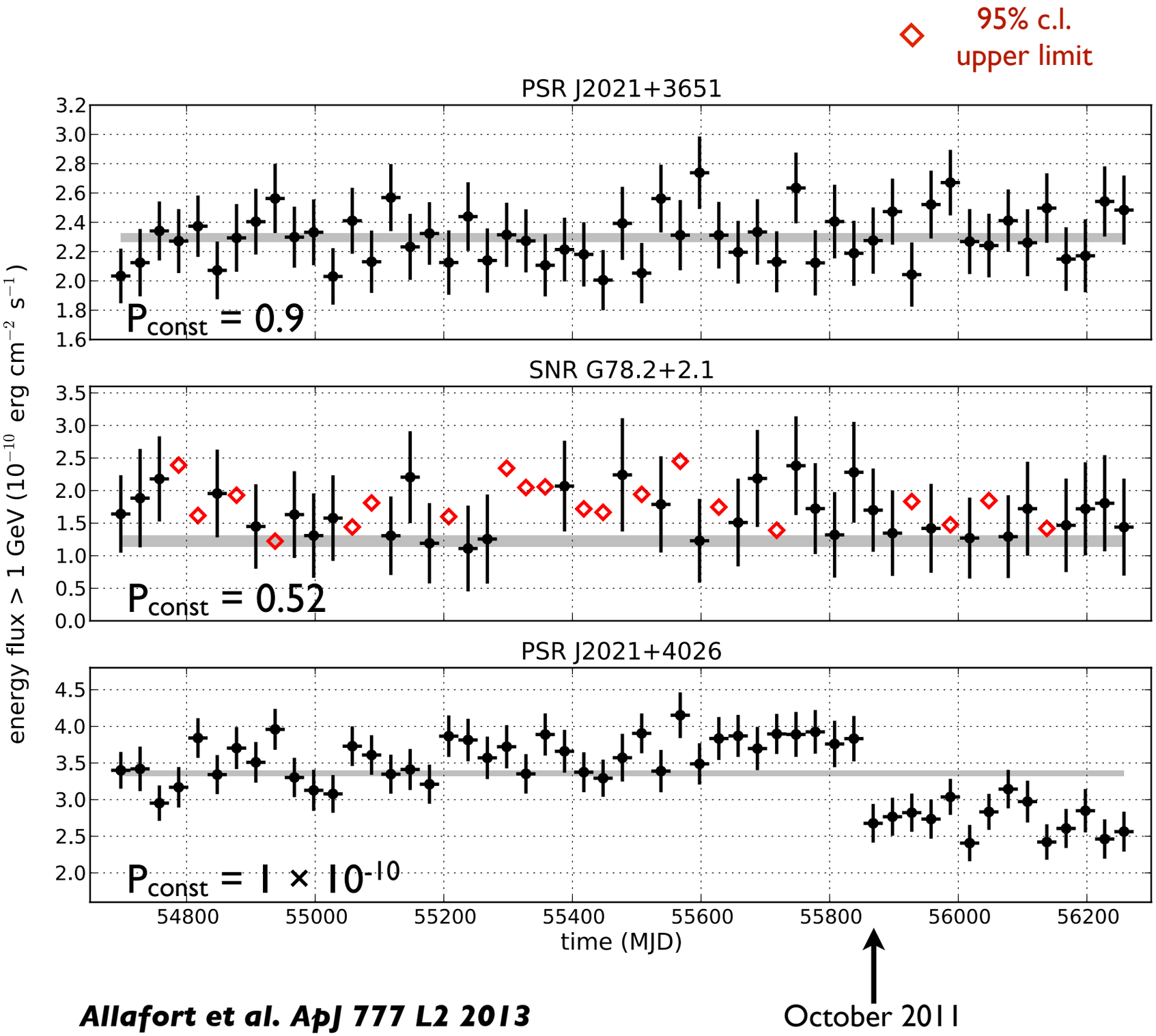
A flux jump

- variability from PSR J2021+4026
  - > 1 GeV, > 100 MeV
  - 30 days, 7 days
  - point-like
- flux - 20% < 1 week around MJD 55850
- steady increase before MJD 55850 (3σ), ~ 4% yr^{-1}
- PSR J2021+3651 stable → no instrumental effects



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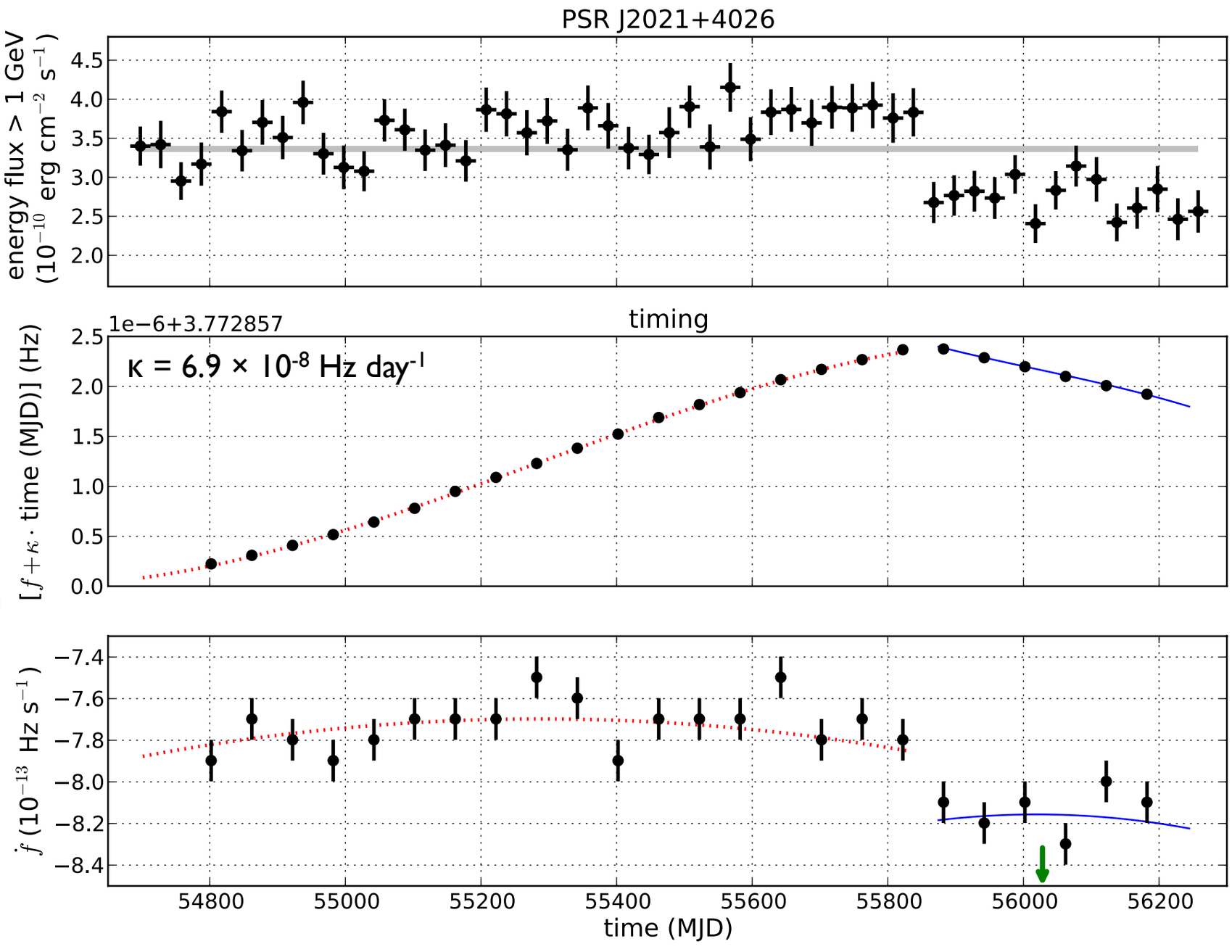
It was the pulsar!

1. periodicity test on 60-day bins (f, $\dot{f}$)
2. timing solution before/ after MJD 55850



- 4% change in $\dot{f}$ near MJD 55850
- simultaneous with flux change
- no change in f

1167 d | 423 d

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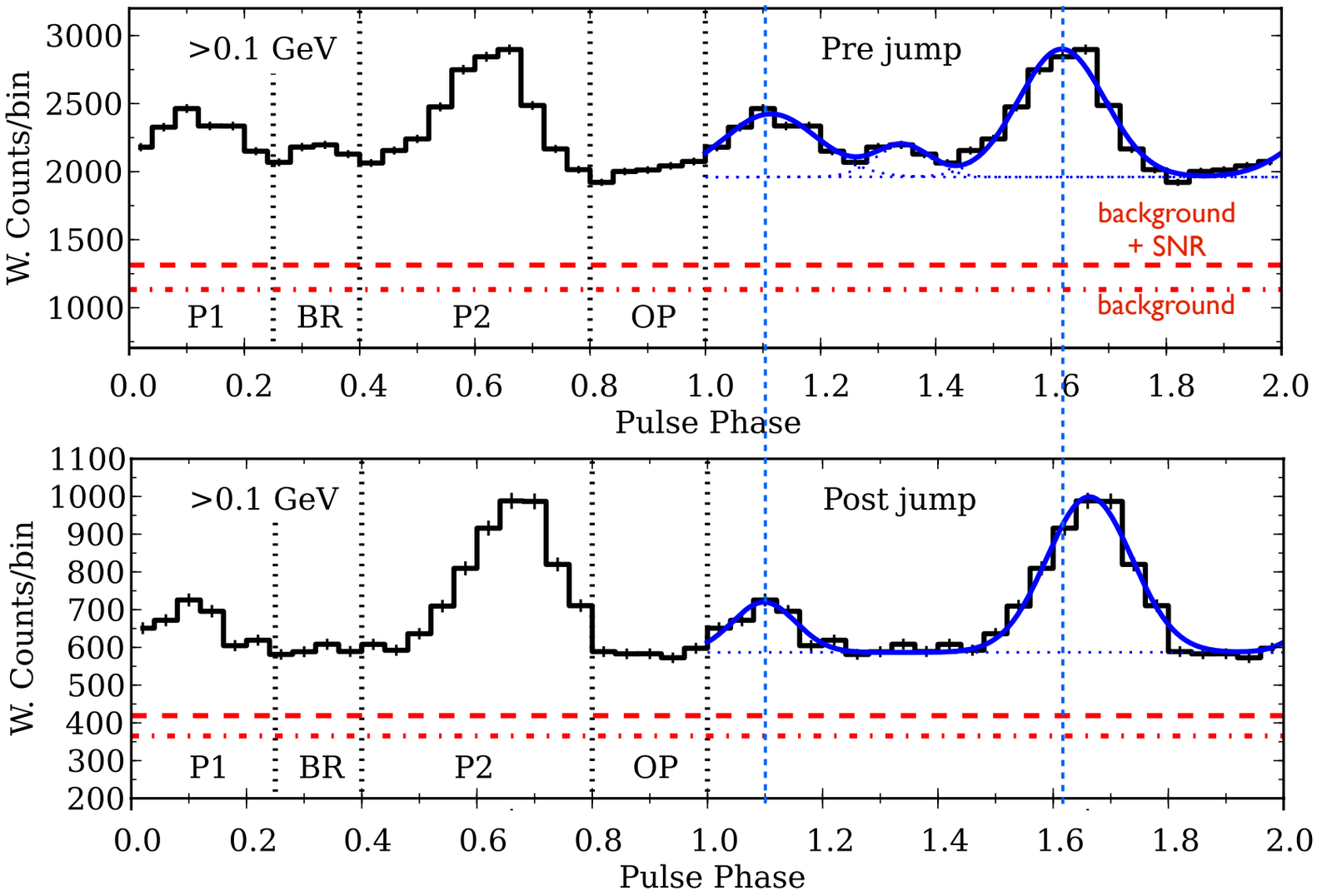
Pulse profile changes



- P1-P2 lag: 0.505 ± 0.005 → 0.565 ± 0.006
- total constant/P2 amplitude: 1.83 ± 014 → 1.09 ± 0.06
- P1/P2 amplitude: 0.54 ± 0.06 → 0.24 ± 0.03

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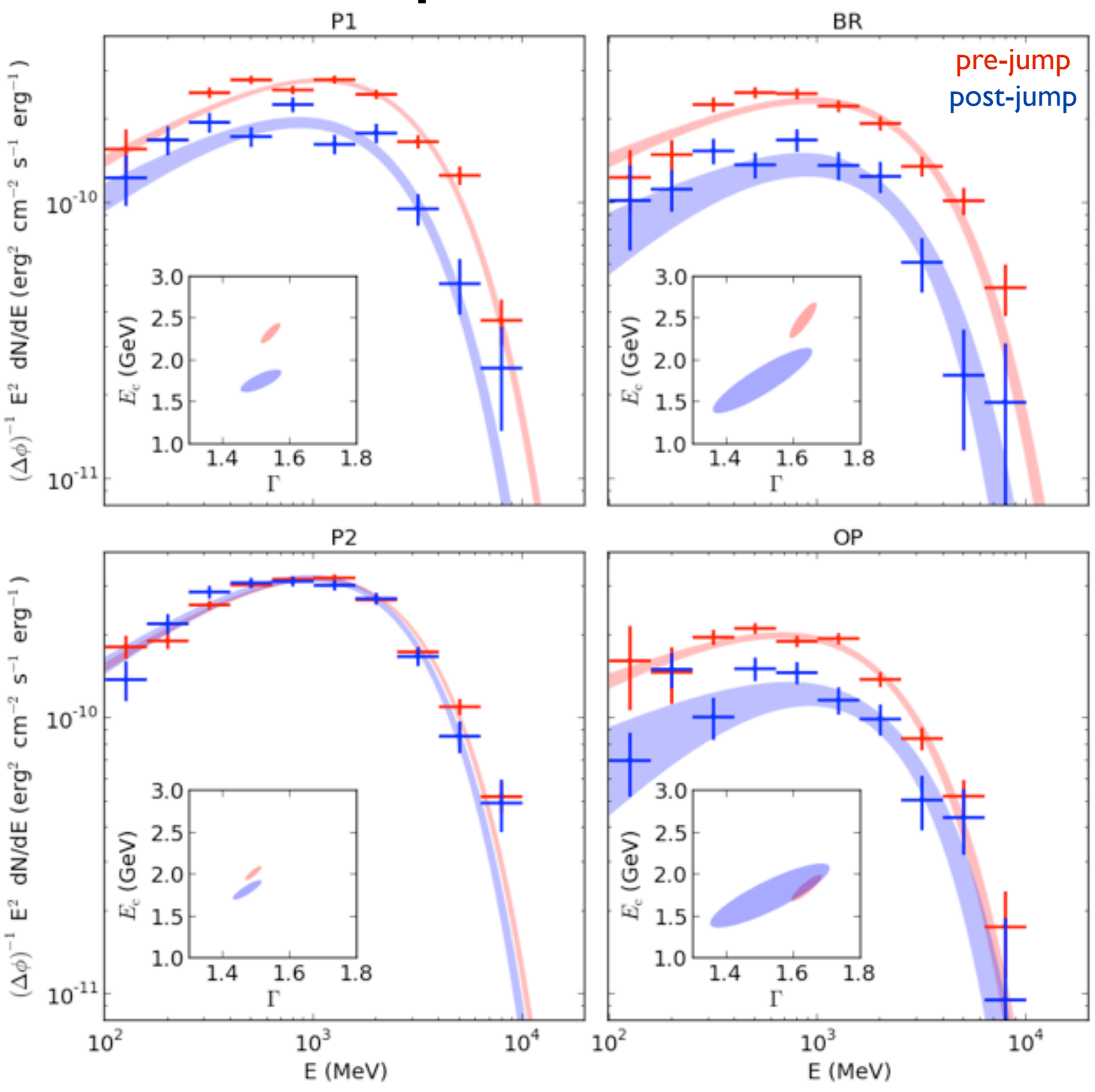
Phase-resolved spectra

$$\frac{\mathrm{d}N}{\mathrm{d}E} = k\, E^{-\Gamma}\, \mathrm{e}^{-\left(\frac{E}{E_c}\right)}$$

- flux decrease phase-dependent → magnetospheric origin
- hints of spectral changes in P1?



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What is going on?

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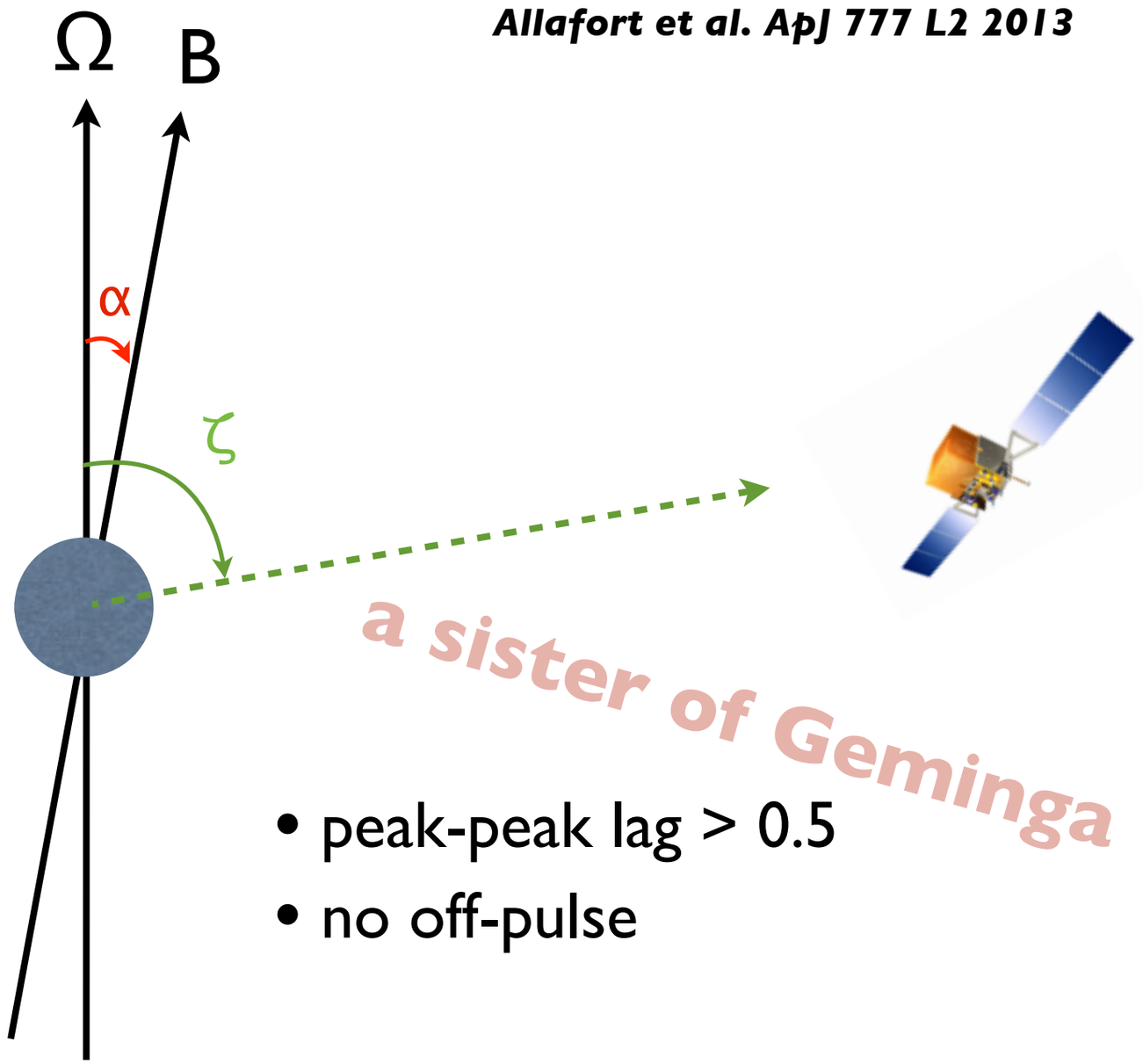
- mode change: magnetic field reconfiguration
  - torque → $\dot{f}$
  - move beam along line of sight → flux



$$\Phi_\gamma = \eta \frac{1}{f_\Omega} \frac{\dot{E}}{4\pi D^2}$$

- peak-peak lag > 0.5
- no off-pulse

→ small α, large ζ

→ radio quiet

→ $f_\Omega < 1$

Final remarks

- gamma-ray pulsars can have mode changes
- new avenue to understand magnetospheric physics
- continued survey by *Fermi* LAT

Backup slides

Variability statistical tests

Likelihood

likelihood

$$\sum_{\text{time bins}} \left[\mathcal{L}(P, M) - \mathcal{L}(P, \bar{M})\right]$$

photons

model
source of interest
fixed to long-term average

Kendall rank correlation test

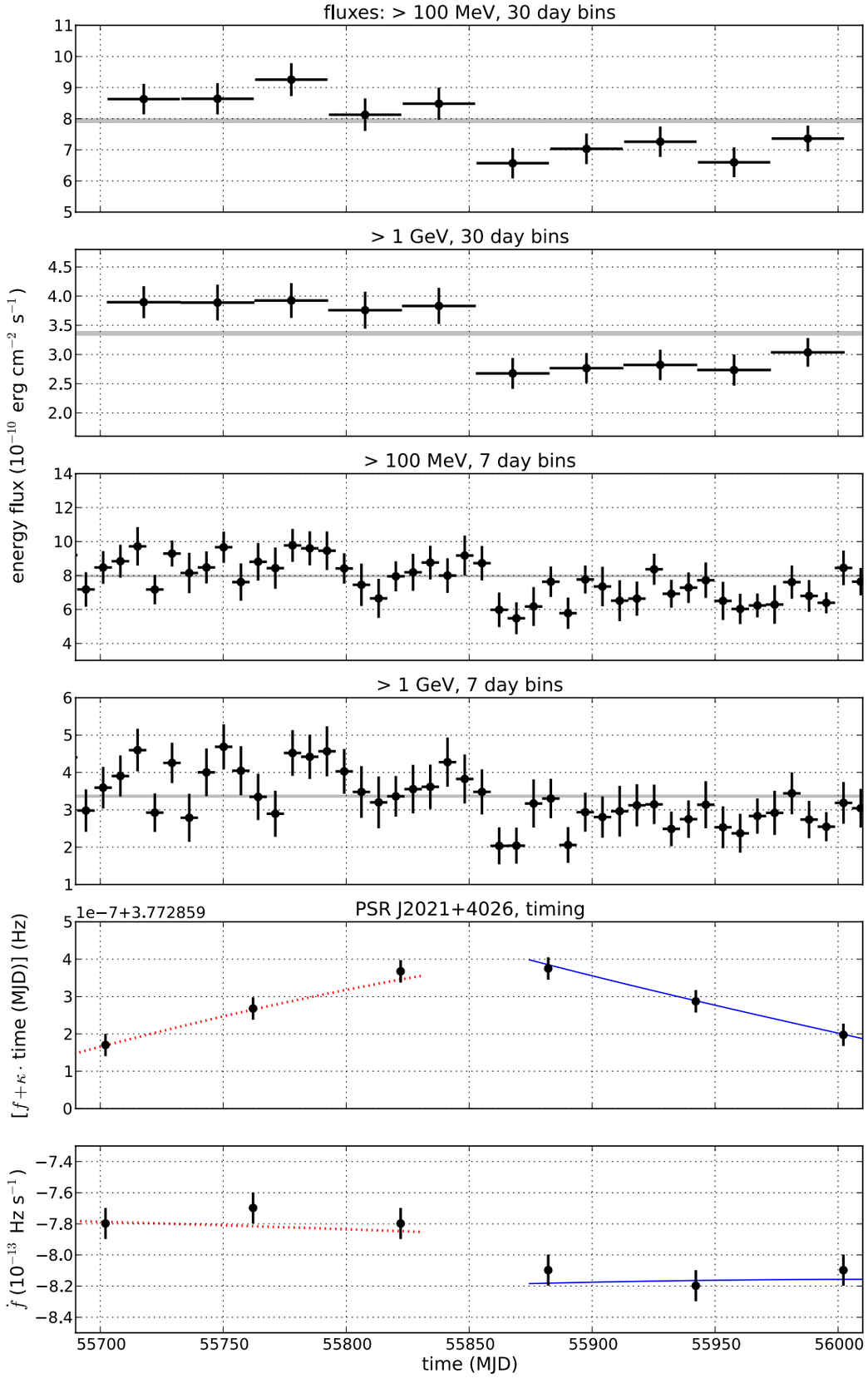
concordant pairs

discordant pairs

$$\tau = \frac{n_\mathrm{c} - n_\mathrm{d}}{n_\mathrm{tot}(n_\mathrm{tot} - 1)/2}$$

total number of pairs

Zoom around the jump



Before and after the jump

J2021+4026's Properties Before and After the Jump

Time Range (MJD)	54682–55850	55850–56273
Number of days	1167	423
F_γ [a] >0.1 GeV	8.33 ± 0.08	6.86 ± 0.13
F_γ [a] >1 GeV	3.57 ± 0.05	2.74 ± 0.06
$\dot{f}$ [b]	-7.6978 ± 0.0007	-8.166 ± 0.002
$\delta_{\rm P1}$ [c]	0.19 ± 0.02	0.13 ± 0.02
Δ_{12} [d]	0.505 ± 0.005	0.565 ± 0.006
$\delta_{\rm P2}$ [c]	0.176 ± 0.007	0.174 ± 0.006
$\Delta_{\rm 1BR}$ [d]	0.229 ± 0.008	...
$\delta_{\rm BR}$ [c]	0.11 ± 0.02	...
P1/P2 [e]	0.54 ± 0.06	0.24 ± 0.03
BR/P2 [e]	0.16 ± 0.03	...
Constant/P2 [e]	1.83 ± 0.14	1.09 ± 0.06

Notes. Statistical uncertainties only. For details on parameters, see Sections 4 and 5.

[a] 10^{-10} erg cm^{-2} s^{-1}.

[b] At the reference epoch for the two timing solutions, 10^{-13} Hz s^{-1}.

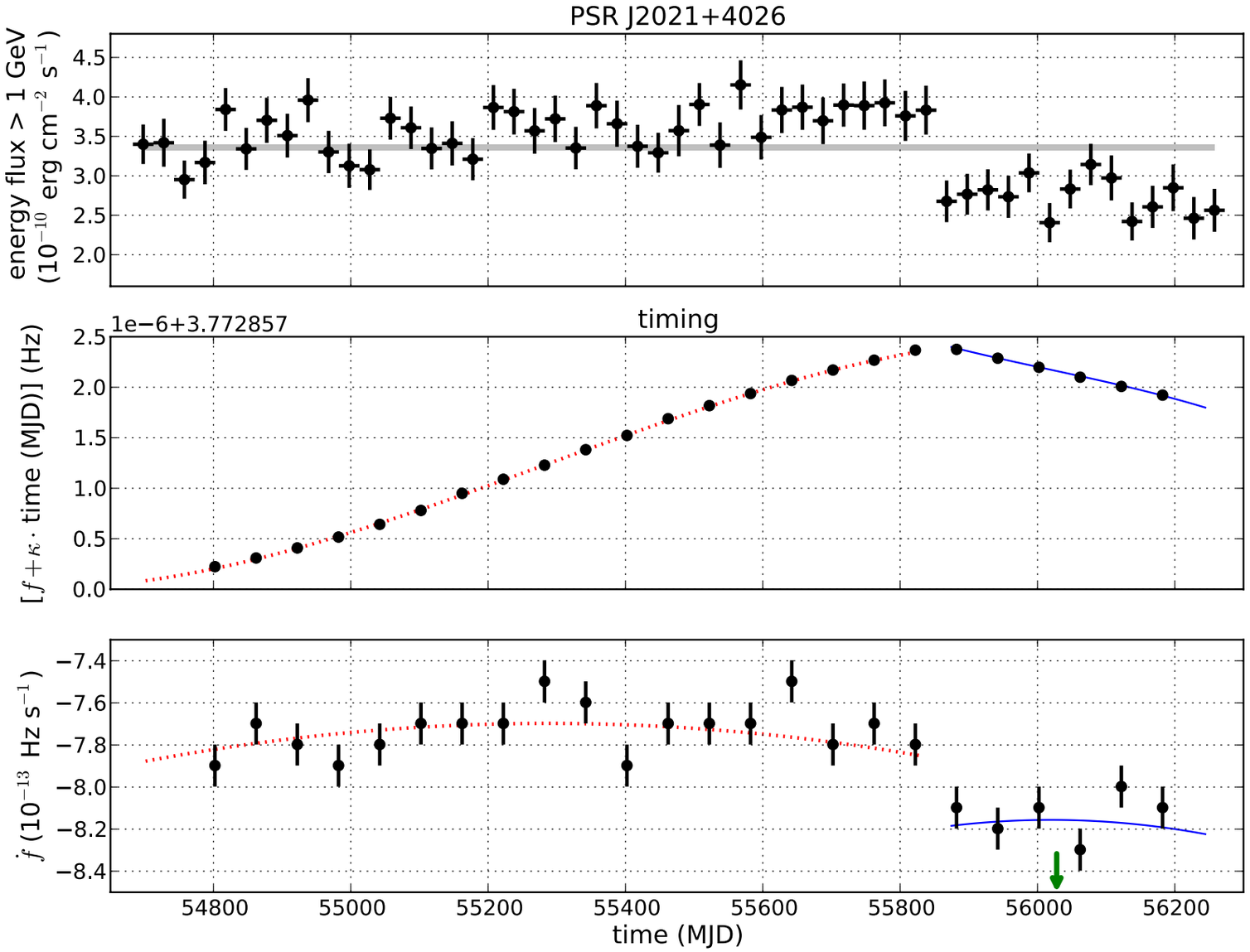
[c] Peak FWHM ($E > 0.1$ GeV).

[d] Phase lag between peaks ($E > 0.1$ GeV).

[e] Ratios of the peak amplitudes or constant-level-to-P2 amplitude ($E > 0.1$ GeV).

Doppler shift in binary system?

- circular orbit of radius 6 (1) a.u. → Doppler shift 10^{-5} (10^{-4})
- 0.04 Doppler shift → eccentric orbit with minor axis ~ 0.01 a.u. < massive star radius



~ 3 yr
half orbit?