Fermi LAT Observations of Two Be-Pulsar Binary Systems at GeV Energies

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Be-PSR Binaries (1)

What are Be-PSR Binaries?

- MS Be stars (B or late O type, T_{eff} near 30,000 K), masses in range ~10-30 $M_\odot$; Balmer emission lines.
  - Rotating near critical velocity, may have disk-like outflow (decretion disk), which is often tilted from orbital plane.
- Pulsar (short spin period, energetic) in orbit around Be star, interacting with Be star disk. *(review: Rivinius et al. (2013))*

Why interesting and important?

- ***Repeatable*** **experiments**, in **interaction of outflows:**
  - **NS wind and Be disk**
- **Evolutionary sequence of massive binaries**
  - Connections to other binary populations

Will review the systems, then say what the LAT saw in 2017

Be-Pulsar Binaries (2)

- For many years prime (sole?) example was **PSR B1259-63/LS2883**
  - Observed through many periastron passages ((P_{orb} = 3.4 y)
  - Three complete orbits now observed by *Fermi*
- *Second example now:* **PSR J2032+4127/MT91 213**;
  - Recognized as binary since 2017 (P_{orb} ~ 50 yr)
  - Discovered as gamma-ray pulsar by *Fermi;* binary orbit recognized later; *Fermi* had one chance (2017) at periastron
- *Third case* to keep in mind, often compared to PSR B1259-63 in earlier literature: **A0538-66, located in LMC**
  - Another Be-pulsar binary, P_{orb} = 16.65 d, P_{spin} = 69 ms,
  - Not reported as γ source; **but X-ray-quiescent in *Fermi* era**

PSR B1259-63/LS 2883

- Radio pulsar discovered with Parkes – (Johnston *et al.* 1996 & Shannon *et al.* 2014)
  - **48 ms spin period**
  - Spin-down power 8.2e35 erg/s
  - **3.4 year orbit with a Be star**
  - **High eccentricity, e = 0.87**
  - No pulsations reported at any other wavelength except radio
  - **Radio pulses not seen around periastron**
  - Outflow tilted 10º - 40º from orbit plane (Melatos et al. 1995)
  - Recent updated distance of 2.7 kpc (Miller-Jones et al. 2018)

- High energy detections (X-rays, TeV) *preceded* the *Fermi* era
  - But GeV emission was an early *Fermi* result

B1259 System Geometry

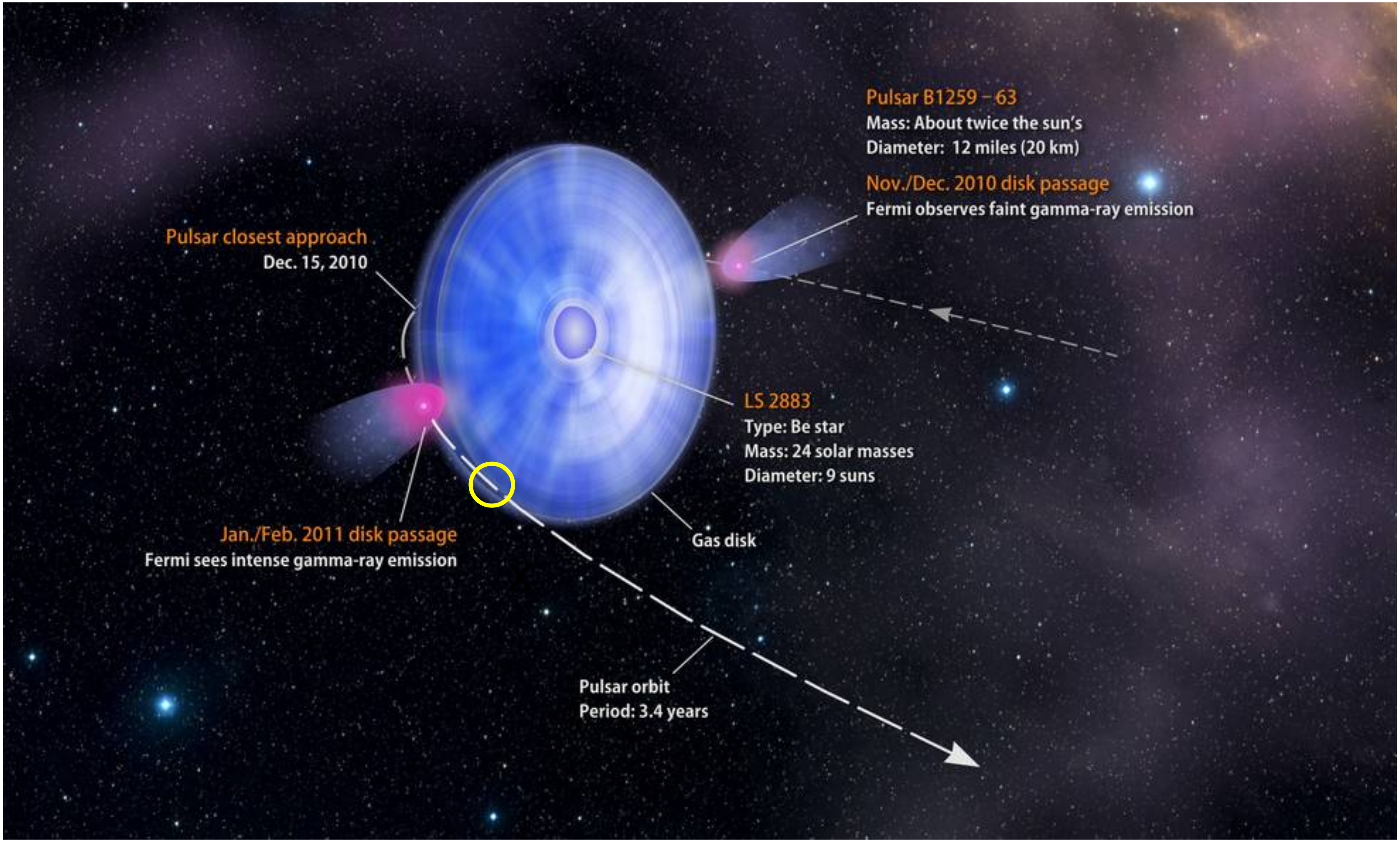


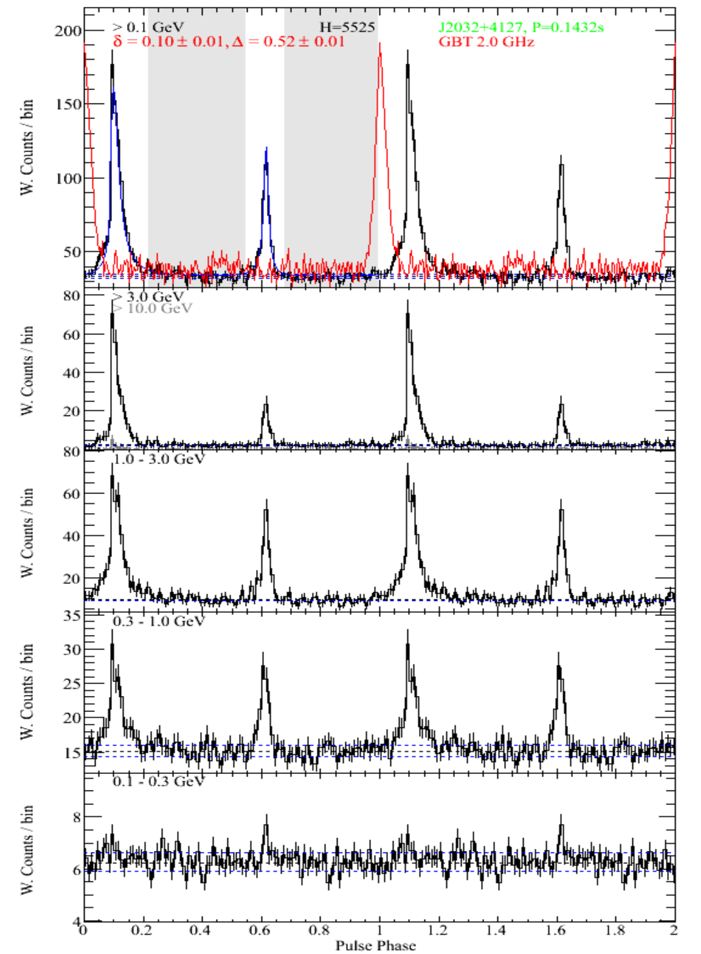
Fig. Credit: NASA

PSR J2032+4127

- **Discovered in gamma rays** (early in Fermi's 10 years) **as a rotation powered pulsar**, quickly followed up in radio (Abdo et al. 2009 & Camilo et al. 2009).
    - P = 143 ms
    - dP/dt = 1.2e-14 s/s
    - Spin-down power, dE/dt =1.6e35 erg/s

- Positional coincidence with Be star MT91 213 noted, but initially no evidence for binary orbit in timing, unless P_{orb} very long

- Then …



Abdo et al. (2013)

A Binary After All

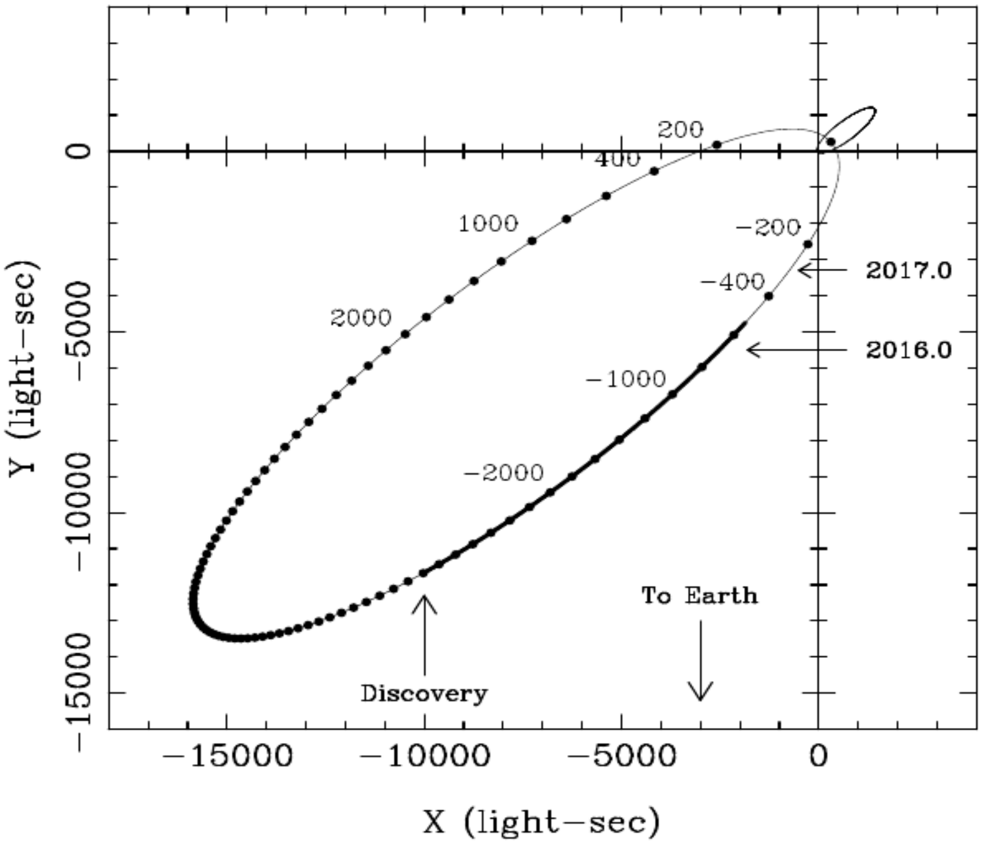


Figure 1. Schematic diagram illustrating the approximate orbital motion of PSR J2032+4127 and its Be-star companion MT91 213 about their common

Ho et al. (2017)

- **Continued timing revealed binary** orbit (Lyne et al. 2015 & Ho et al. 2017).
  - **Orbital period ~50 years**
  - Eccentricity ~ 0.96
  - Periastron 13 November 2017
- Another B1259?
  - Spin-down power of J2032 is 20% that of B1259
  - J2032 is closer at 1.4 kpc

J2032 in 2017: Toward Periastron

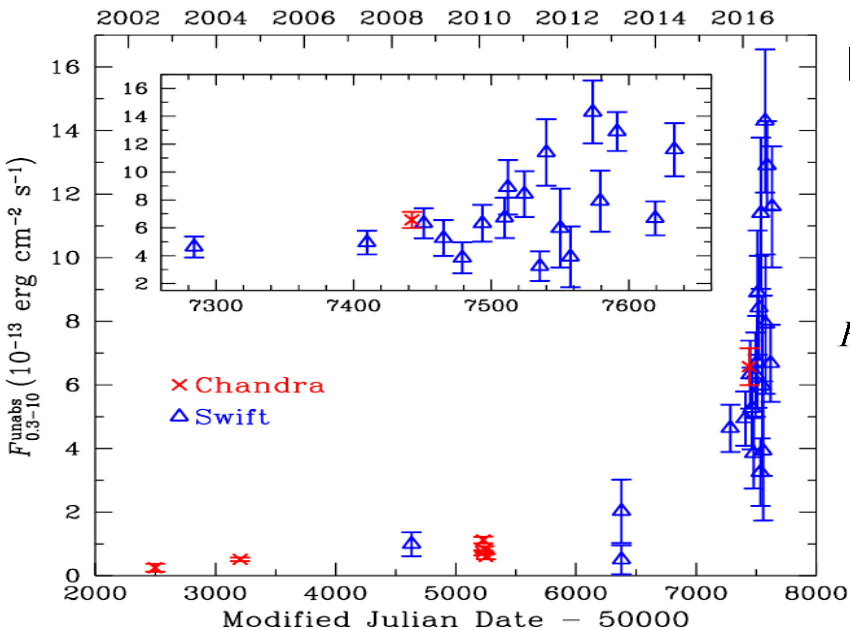


Figure 6. X-ray light curve of PSR J2032+4127/MT91 213 from 2002 to 2016. Points (and 1σ error bars) are *Chandra* (crosses) and *Swift* (triangles) unabsorbed 0.3–10 keV flux (see Table 2). Inset: closer view of the data covering the period from 2015 September to 2016 September.

- ❑ **X-ray flux increasing** by a factor of 70 since 2002, 10 since 2010.

Ho et al. (2017)

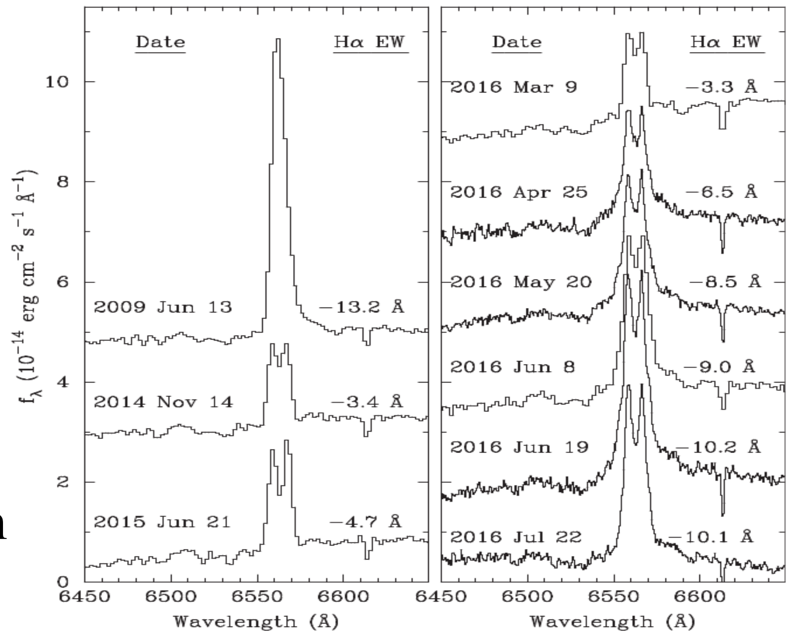
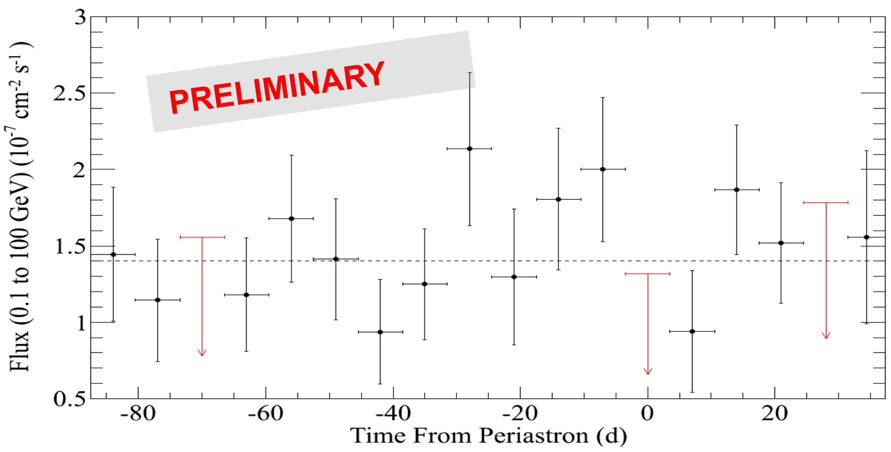


Figure 7. Hα region of spectra of MT91 213 (see Table 5). Spectra have been shifted vertically for clarity. The 2009 spectrum is the same as appears in Camilo et al. (2009). Absolute flux densities for MDM spectra are not reliable due to the narrow (1 arcsec) slit width used.

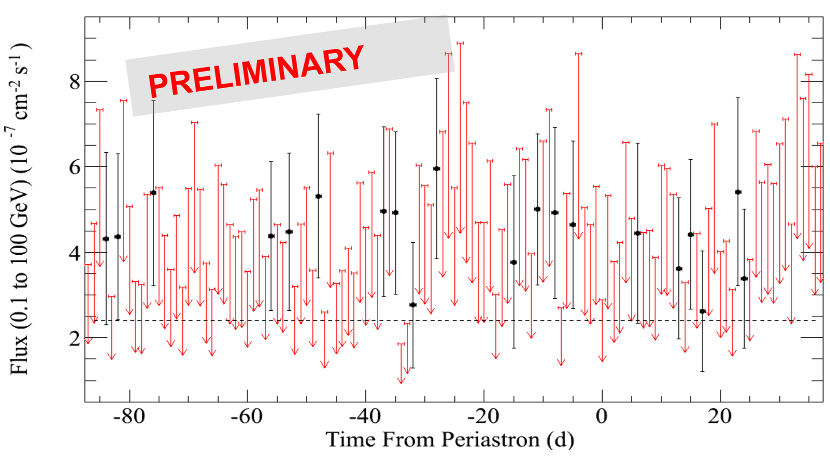
- ❑ H-α variations suggest changes in size of outflow by a factor of ~2.

J2032 at 2017 Periastron

PSR J2032+4127, one-week bins



PSR J2032+4127, one-day bins



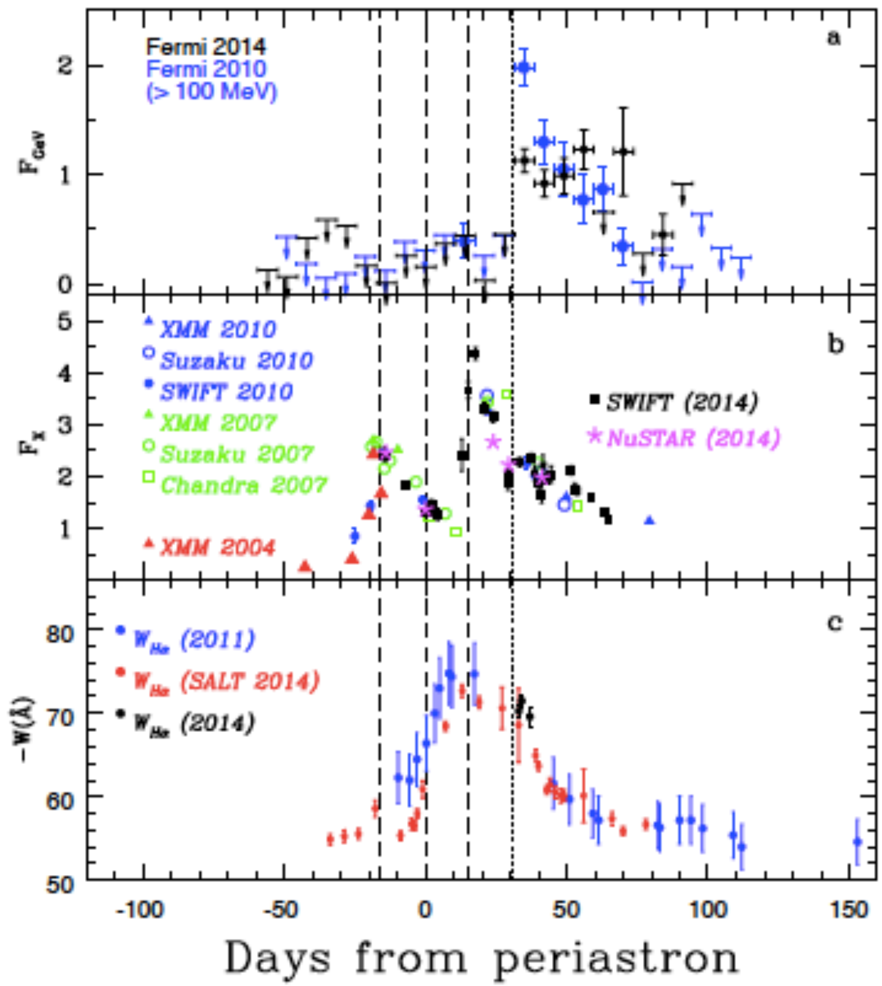
- ❑ **GeV γ-rays...pulse remained detectable in long integrations,… but no detectable (DC) enhancement**
  (see also Li et al. 2018)
- ❑ Other wavelengths … much variability; also **TeV seen**.

For optical, X-ray and TeV results at this periastron passage, see the talks by Wynn Ho and Jamie Holder

B1259 in the Era of *Fermi*

Chernyakova et al. (2015)

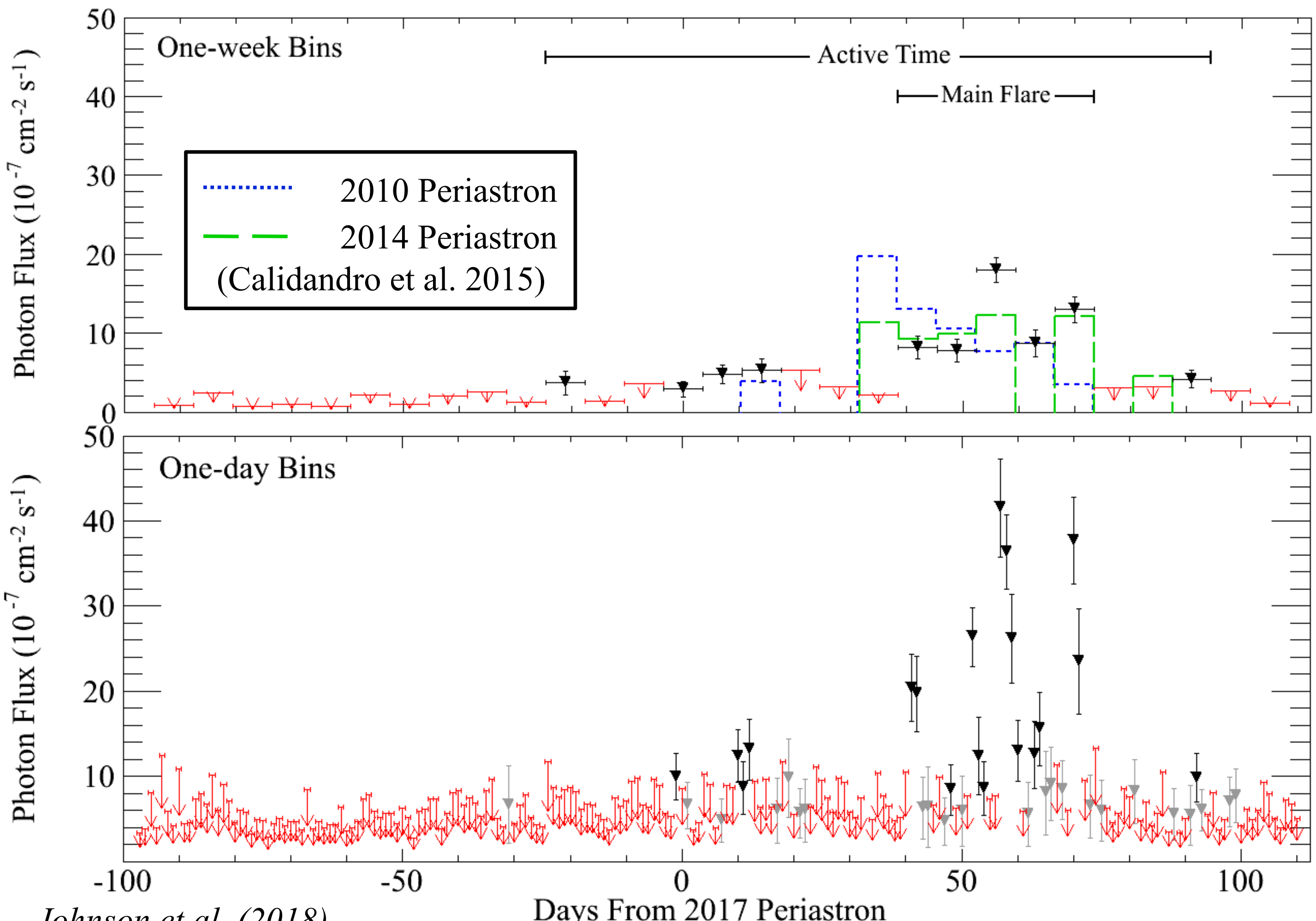
- First periastron passage *Fermi* observed was Dec 2010.
- Detections near periastron:
  - Low-significance.
- Unexpected flare ~30 days after periastron.
  - No corresponding flares at other wavelengths, but note change of X-ray decay rate and sudden drop of $W_{H\alpha}$
- **2nd periastron; 2014** *(see Caliandro et al., 2015)*
- **3rd periastron; 2017**
- **4th will be 2021**



B1259 at 2017 Periastron

- **Most recent periastron on 22 September 2017**
  - Several ATels – #10775, 10818, 10924, 10925, 10972, 10973
- **Strikingly different behavior**
  - Weak signal leading up to periastron
  - Small flare ~9-11 days after periastron
- **More-intense flaring** ~40-70 days after periastron
  - **Variability on timescales < 6 hours**
  - Significant spectral curvature

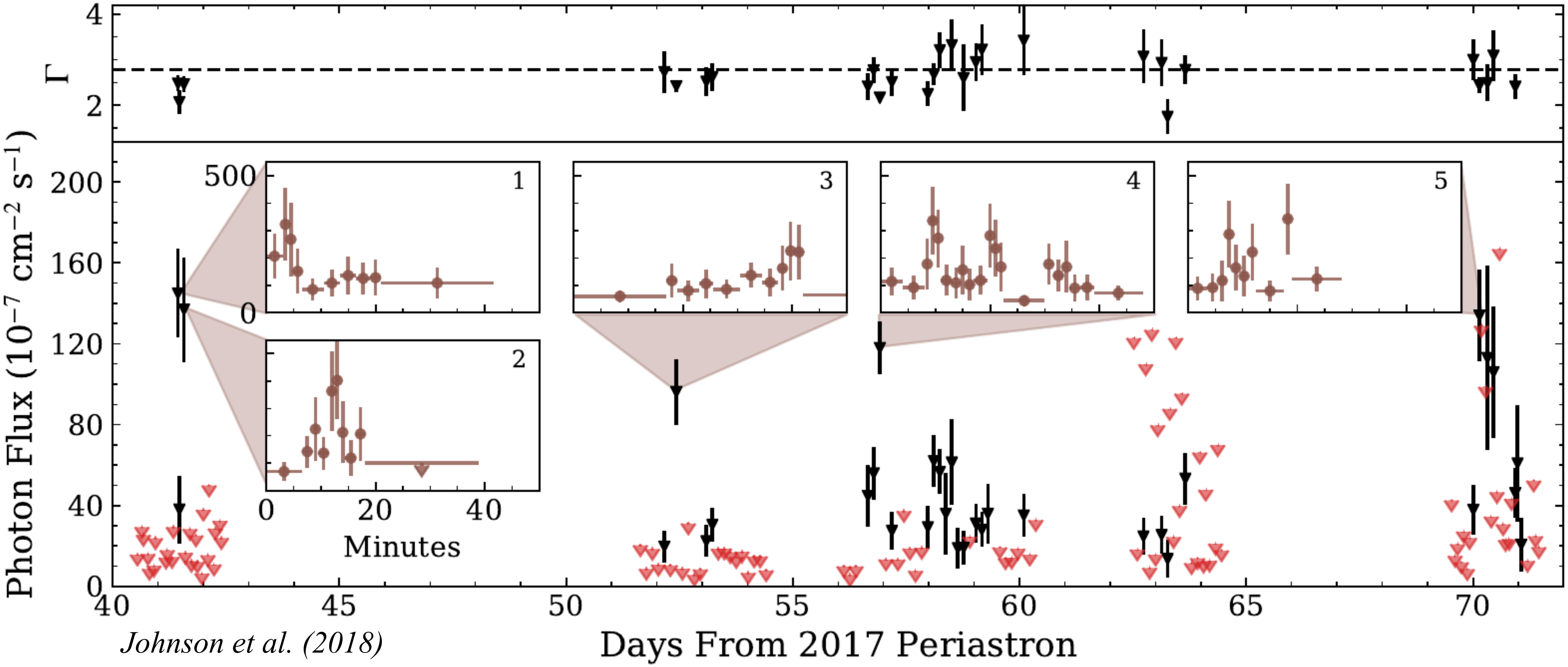
B1259 2017 Periastron



Johnson et al. (2018)

See also Chang et al (2018) and Tam et al. (2018)

B1259 at 2017 Periastron



Johnson et al. (2018)

- ❑ Flux variability on spacecraft orbit, and sub-orbit, timescales
  - ❑ Photon index not clearly variable
- ❑ Rise and fall times suggest factor of 2 changes in 1-1.5 minutes
  - ❑ Insets show 5 highest TS orbits

Energetics

Table 2. Maximum Gamma-ray Energetics on Different Time Scales

Time Scale	G (10^{-10} erg cm^{-2} s^{-1})	L_γ (10^{35} erg s^{-1})	$L_\gamma/\dot{E}$
One-week	7.3±0.6	$6.4^{+2.0}_{-1.6}$	0.8±0.2
One-day	14±2	12^{+4}_{-3}	$1.5^{+0.5}_{-0.4}$
One-orbit	70±16	61^{+18}_{-14}	$7.4^{+2.2}_{-1.7}$
Intra-orbit	280±100	244^{+74}_{-56}	$29.8^{+9.0}_{-6.8}$

NOTE—For the time scales listed during the 2017 periastron passage, this table provides the maximum energy flux (G), gamma-ray luminosity (L_γ), and luminosity as a fraction of the spin-down power $\dot{E} = 8.2 \times 10^{35}$ erg s^{-1} ($L_\gamma/\dot{E}$). For the uncertainty on L_γ, we incorporate both the energy flux and distance uncertainties.

- ❑ Previous periastrons already pushed the spin-down power limit
- ❑ 2017 exceeds even on 1-day timescales:
- ❑ **need boosted/ beamed emission**

Johnson et al. 2018, ApJ, 863, 27

Conclusions (1): the Repeatable Experiment

- **PSR B1259-63 continues to provide surprises**
  - Three periastron passages, three different light curves
  - 2017 event showed the fastest variability seen in LAT data(excluding GRBs and solar flares)
  - **Next showing will be in early 2021 … keep *Fermi* going**
- Gamma-ray luminosity suggests Doppler boosted emission
  - Estimate a maximum Doppler factor ~ 3
  - ~1.5 minute variability; emission region radius ≲ 8e7 km (~30 - 40% of distance to Be star)

- **No GeV flare from PSR J2032+4127 near periastron**
  - Is this geometry? Energetics?

    Let's be ready with more sensitive GeV instrument in 2067

- ***Full multi-wavelength picture takes more time…***

  (results for B1259 in 2010 were finally published 2014…)

Conclusions (2): Transitional Population?

- **PSR B1259-63/LS2883** has associates
  - Has the most energetic GeV γ-ray flares; never seen accreting, never seen pulsing in X-rays, γ-rays, whether by EM or accretion
- **PSR J2032+4127/MT91 213**;
  - Repeats some aspects of high-energy flaring, up to TeV
  - Pulsed in GeV γ-rays; no evidence of accretion
- *Third case ?* **A0538-66, located in LMC**
  - Seen in 1970s, 80s at energies up to X-rays; quiescent in *Fermi* era; transient outbursts at periastron
  - Pulse *only when accreting* at high dM/dt, with P_{spin} (69 ms) intermediate between above cases *(Skinner et al. 1982)*
  - This population may transition to accreting pulsars, including ULX sources, which have longer spin periods.
- **All three could eventually evolve to NS-NS or NS-BH**

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Acknowledgments:

The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

Portions of this research performed at NRL are sponsored by NASA DPR S-15633-Y and *Fermi* Guest Investigator grant 16-FERMI-0006.

Backup

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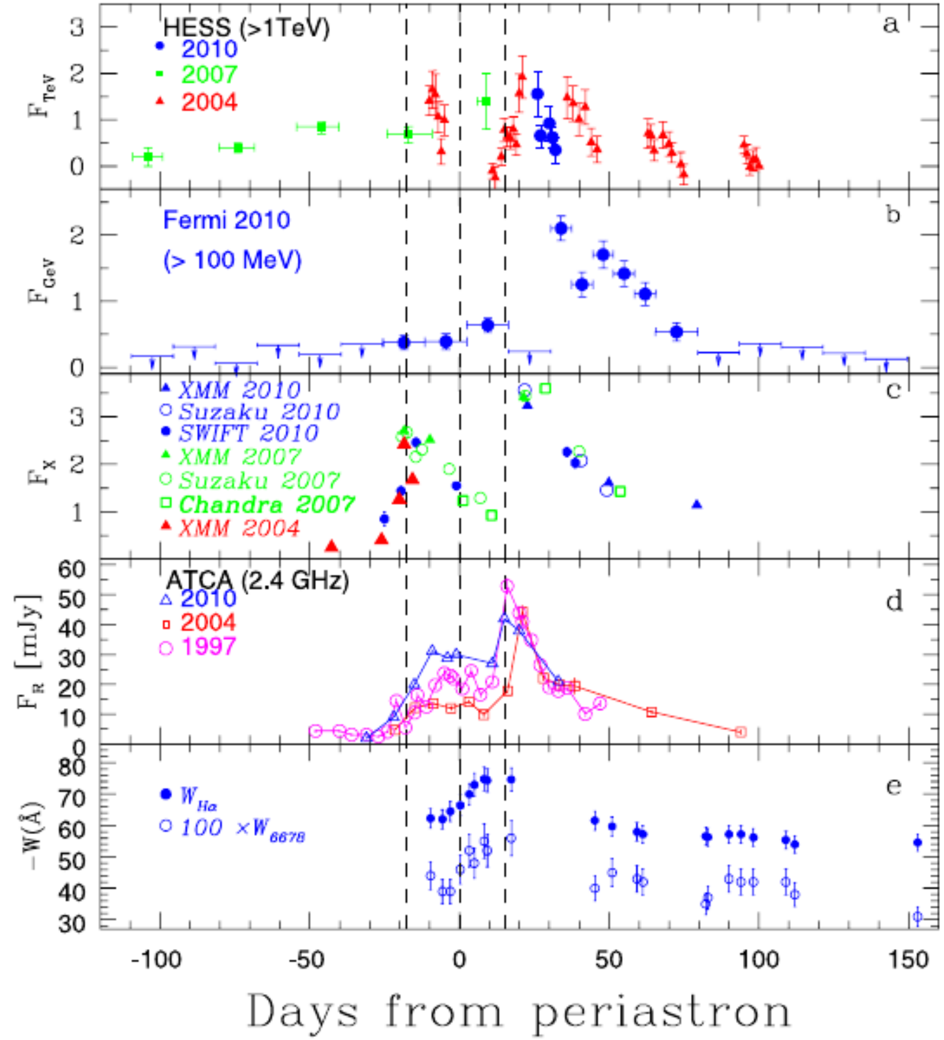
  - Unmatched at other wavelengths

Chernyakova et al. (2014)



PSR B1259 in 2010 and 2014

Inclusive Pre /Post Periastron

Post-periastron, expanded

2010, Flux

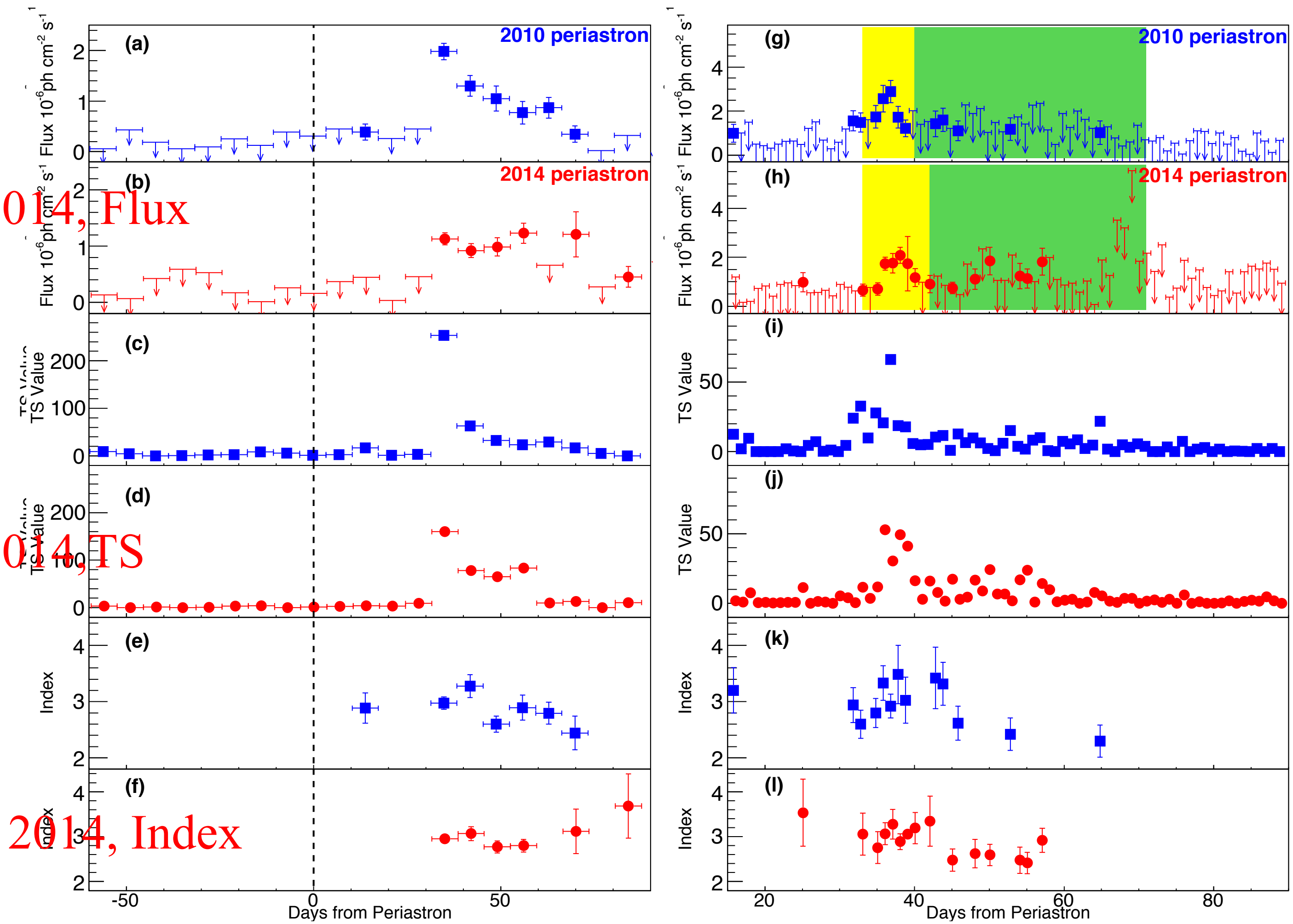
2014, Flux

2010, TS

2014, TS

2010, Index

2014, Index



Caliandro et al. (2015)

First High Energy Detections

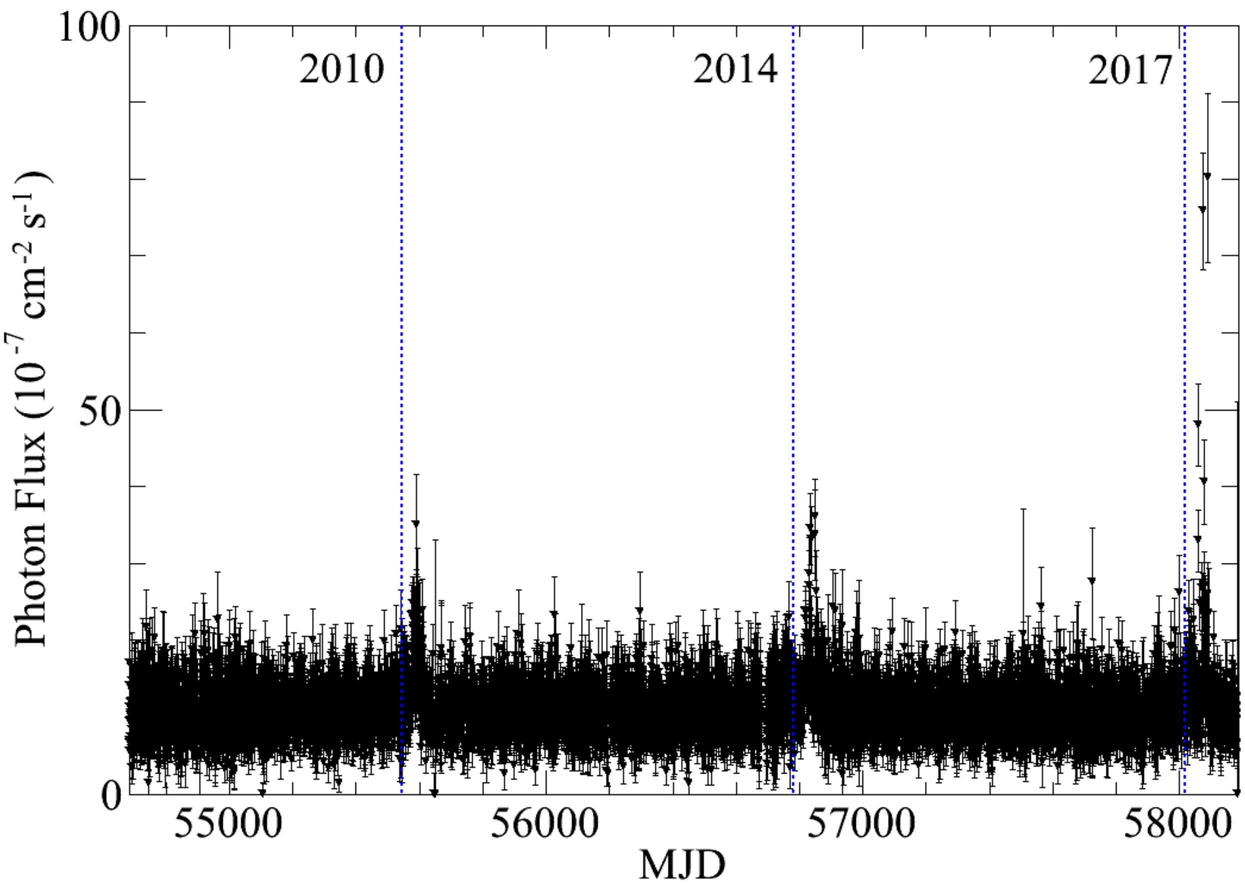
- Wind-wind interactions might produce X- and gamma-rays near periastron (King 1993 & Tavani et al. 1994)

- ASCA and OSSE X-ray detections (Kaspi et al. 1995 & Grove et al. 1995).
    - No pulsations, strongest just before/after periastron.

- No >100 MeV gamma-rays detected with EGRET (Tavani et al. 1996).
    - Observations from -6 d to +14 d from periastron.

- IC might lead to >100 GeV emission (Kirk et al. 1999).
    - VHE detection by HESS (Aharonian, et al. 2005).

Previous Periastrons



- Aperture photometry, 12 h bins
- No evidence for similar rapid variability in previous periastrons