Fermi LAT Discovery of Gamma-ray Pulsars in Blind Searches

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on behalf of the Fermi LAT collaboration

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Outline

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2. Blind Frequency Searches with Fermi-LAT
    2.1 Sources we search
    2.2 The time-differencing method
    2.3 Refining the candidates
3. The new 8 gamma-selected pulsars
    3.1 Pulse profiles
    3.2 Distribution in the previously known pulsar population
4. Multiwavelength Observations
    4.1 X-ray: *Swift*, *Chandra*, *XMM*, *Suzaku*
    4.2 TeV: HESS, Milagro
5. Conclusions

Fermi Gamma-ray Space Telescope

Outline

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Figure: **14 August 2009** Science issue.

- Only 7 gamma-ray (6 EGRET) pulsars known prior to the launch of Fermi
- Currently $>$ 50 gamma-ray pulsars detected, including known young radio pulsars, old MSPs, and blind search pulsars
- No pulsars discovered in gamma rays prior to Fermi (only Geminga known to be "radio quiet")
- 16 pulsars discovered by Fermi LAT in first 5 months, mostly associated with unidentified EGRET sources (Abdo et al., Science **325**, 840, 2009)
- 8 new pulsars discovered using first year of data, mostly associated with unidentified LAT sources (Abdo et al., ApJ, *in preparation*)
- 21 of the 24 LAT-discovered pulsars remain undetected in radio despite deep searches

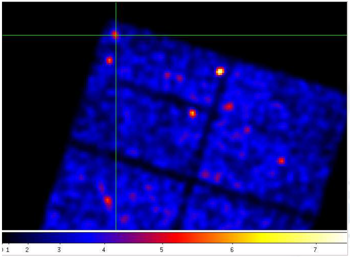
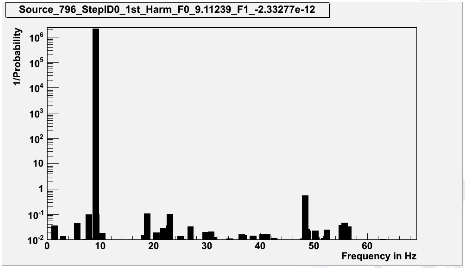
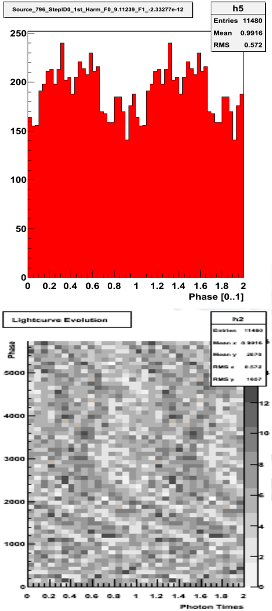


Figure: *Chandra* image centered on the EGRET source 3EG J2020+4017, including 35 X-ray sources (Weisskopf et al. ApJ **652**, 387 (2006)).

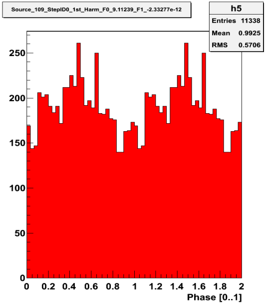
- Potential counterparts of interesting candidates
  - 3EG J1835+5918 ("Next" Geminga) [Halpern et al. ApJ **668**, 1154 (2007)]
  - 3EG J2020+4017 (Gamma-Cygni) [Weisskopf et al. ApJ **652**, 387 (2006)]
- LAT source locations
  - ~650 sources
  - Mostly unidentified/unassociated sources
  - Exclude "most" extra-galactic sources

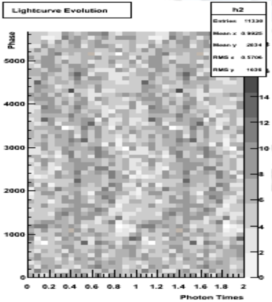


- Sparse gamma-ray data make standard FFT techniques expensive
- A periodic signal should show up in the (FFT of) differences of photon times
- Differences computed only up to a maximum T_w (days or weeks)
- Interesting candidates are investigated using standard techniques
- See Atwood et al., ApJL **652**, L49 (2006)
- For application to EGRET, see Ziegler et al., ApJ **680**, 620 (2008)



- LAT source locations are often ~ arc minutes away from the true pulsar location (e.g. PSR J1413–6205 was 2.3 arc minutes away)
- When the position of the pulsar is off by even just 1 arc minute, it is hard to detect in >1 year of data
- Promising candidates followed up by scanning in position for maximum χ^2 (PSR J1413–6205 χ^2 3.7–>9.7)
- Once a pulsar is detected, position can be determined with arc second accuracy
- Timing solution is refined in $f - \dot{f}$ space using PRESTO
- Final timing solution is obtained using Tempo2





- LAT source locations are often $\sim$ arc minutes away from the true pulsar location (e.g. PSR J1413–6205 was 2.3 arc minutes away)
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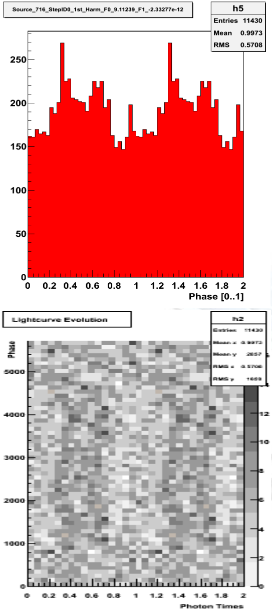

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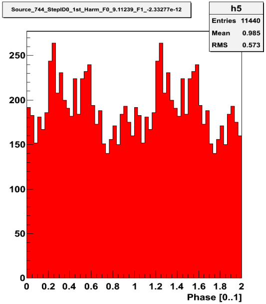

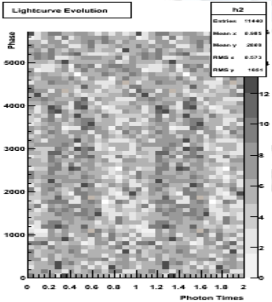

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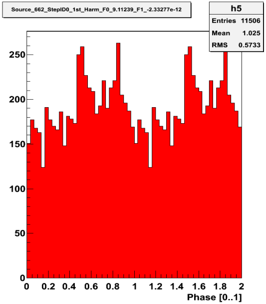

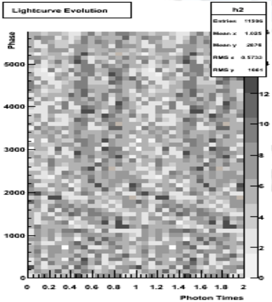

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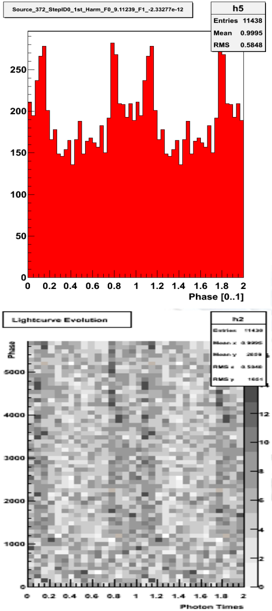

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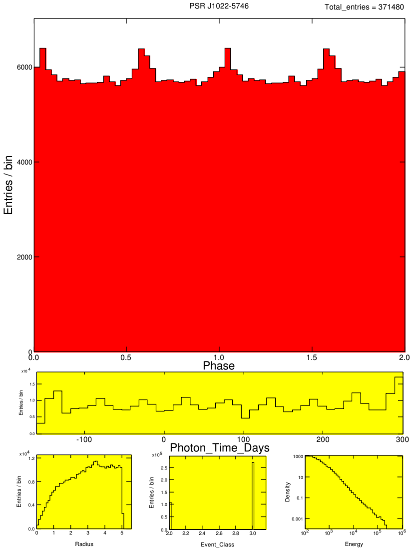
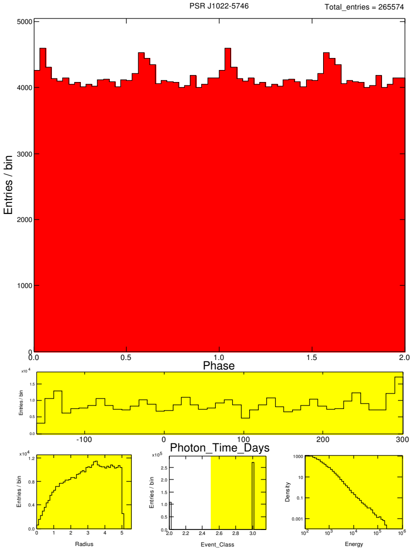


- We choose cuts in radius, event class, and energy, to maximize the significance
- Significance is measured using the χ^2 statistic or the Fourier power
- Optimum cuts depend on location of the pulsar and energy spectrum



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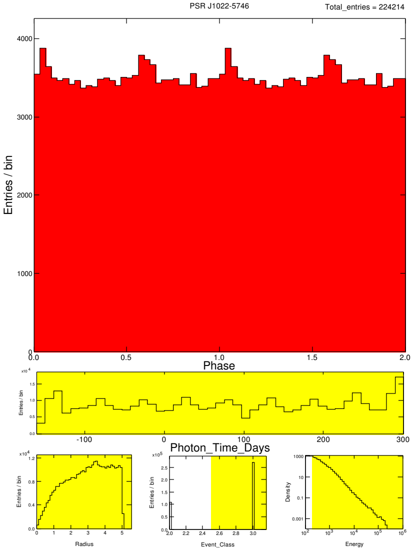

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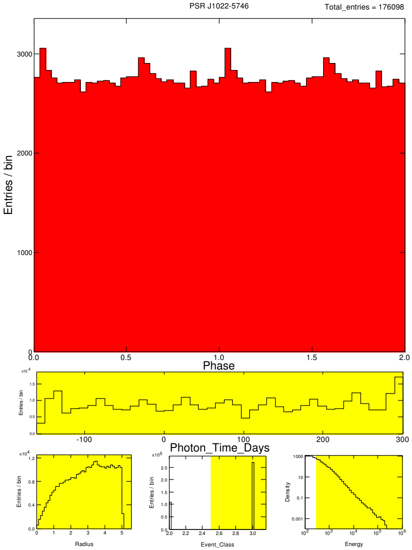

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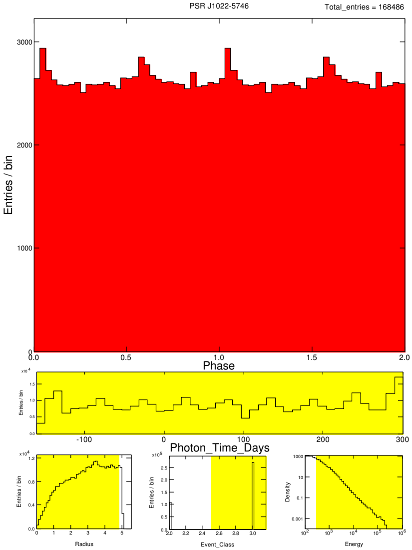

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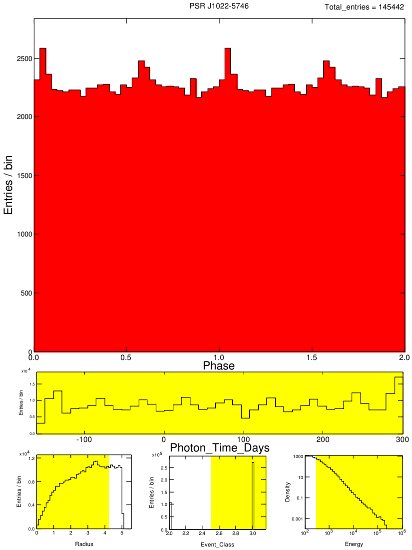

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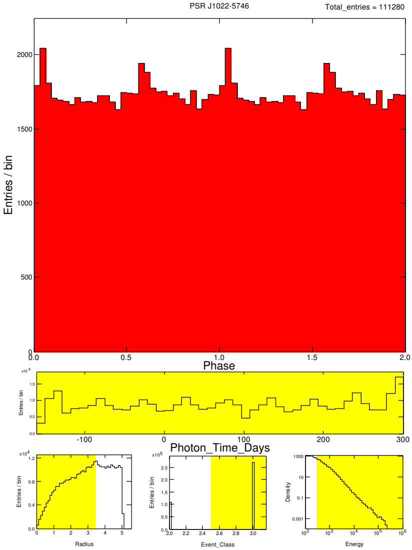

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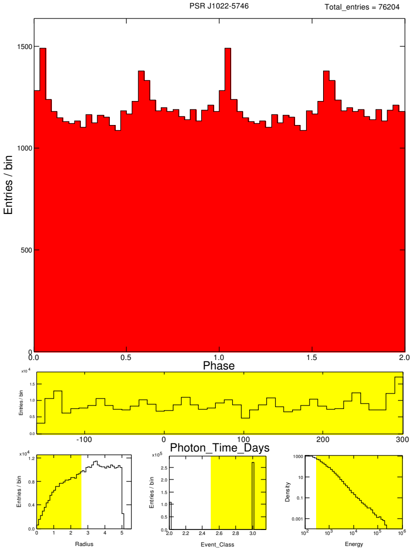

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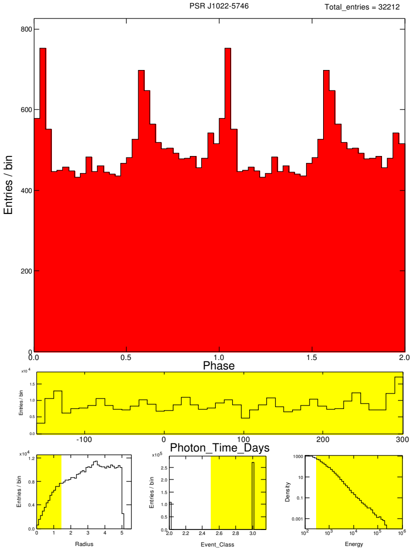

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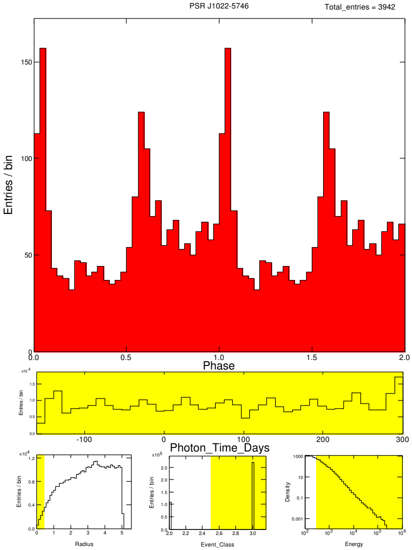

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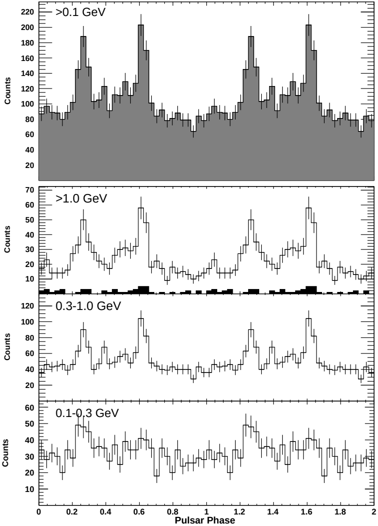
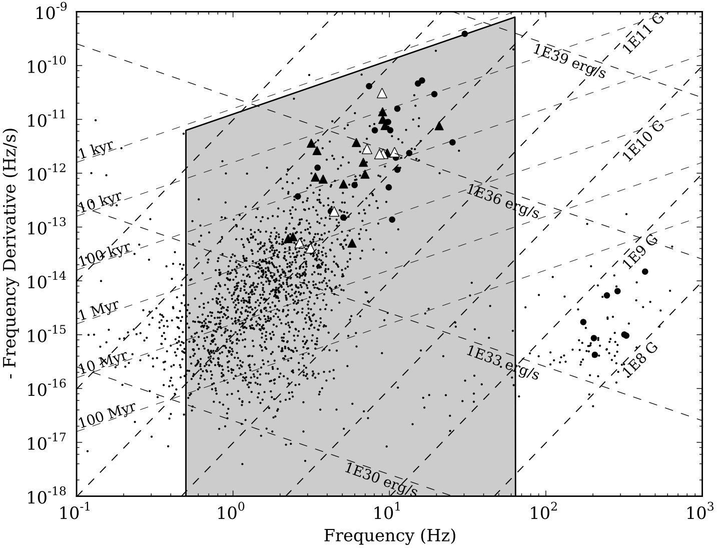


- All light curves shifted to have peak 1 at $\phi = 0.25$
- Important features
  - Peak multiplicity
  - Peak Separation (calculated by fitting a constant plus two gaussians)
  - Off-pulse region (e.g. $\phi \in [0, 0.21] \cup [0.65, 1]$)
- 5 energy bands:
  - > 0.1 GeV
  - 0.1–0.3 GeV
  - 0.3–1 GeV
  - > 1 GeV
  - > 5 GeV


10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
- Frequency Derivative (Hz/s)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Frequency (Hz)
1 kyr
10 kyr
100 kyr
1 Myr
10 Myr
100 Myr
1E39 erg/s
1E36 erg/s
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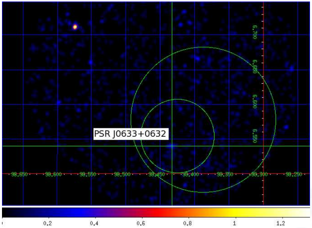
1E30 erg/s
1E11 G
1E10 G
1E9 G
1E8 G



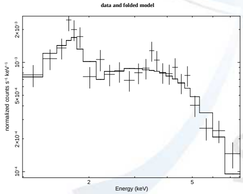
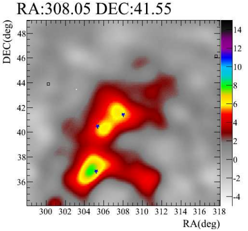


Figure: **Top** – *Swift* $\sim$ 5 ksec observation of PSR J0633+0632. **Bottom** – *Chandra* X-ray spectrum of CXOU J102302.8-574607.

- Short *Swift* observations of unidentified LAT sources help us make our searches more sensitive
- Short *Swift* observations of newly-discovered LAT pulsars often allow us to identify counterparts
- Subsequent observations by *XMM*, *Chandra*, or *Suzaku* allow for a deeper understanding of the source, including constraining the distance, studying the morphology, and even searching for pulsations.



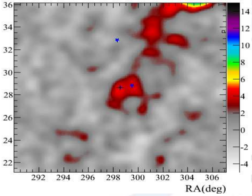
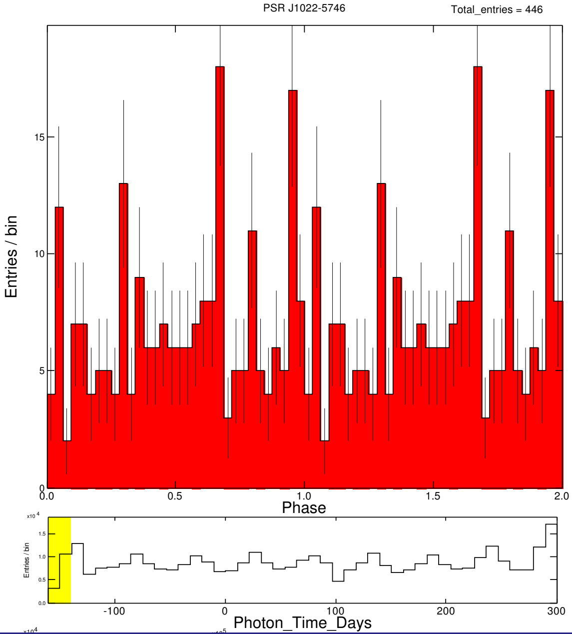


Figure: **Top** – Milagro map of the Cygnus region. **Bottom** – Milagro map of significances around PSRs J1954+2836 and J1958+2846.

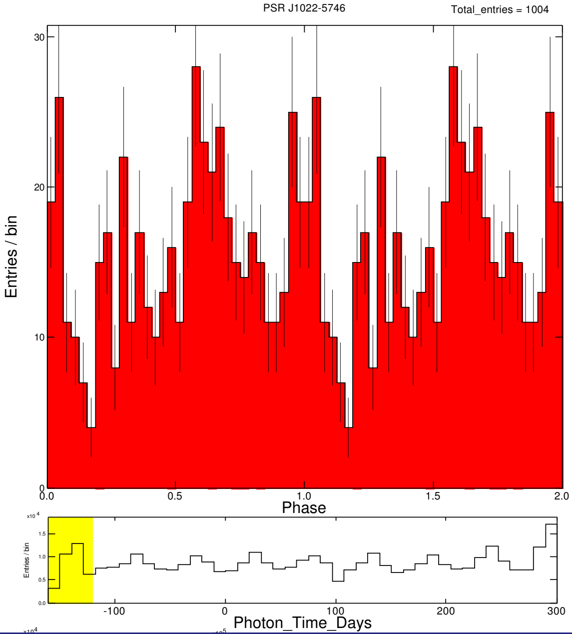
- Many young pulsars have TeV PWN
- HESS J1023−575 (Westerlund 2) coincident with PSR J1022−5746 [Aharonian et al., A&A **467**, 1075 (2007)]
- MGRO J1908+06 and MGRO J2031+41 coincident with PSR J1907+0602 and PSR J2032+4127 [Abdo et al., ApJL **664**, L91 (2007)]
- Milagro marginal detection ($> 4\sigma$) of PSR J2021+4026, PSR J1954+2836, and PSR J1958+2846 [Abdo et al., ApJL **700**, L127 (2009)]
- Talk by M. Dormody (HESS source)
- Talk by A. Abdo (PSR J1907)
- Talk by A. Smith (Milagro sources)

- The first year of pulsar hunting with the LAT has resulted in the discovery of 24 previously unknown pulsars
- A majority (21, for now) of these *g*amma-selected pulsars remain undetected in radio
- Discovering new pulsars is increasingly challenging and will require improvements in our techniques
- Multiwavelength observations (e.g. *Swift*) can be extremely helpful in making our searches "less blind"
- The fun has just begun ...

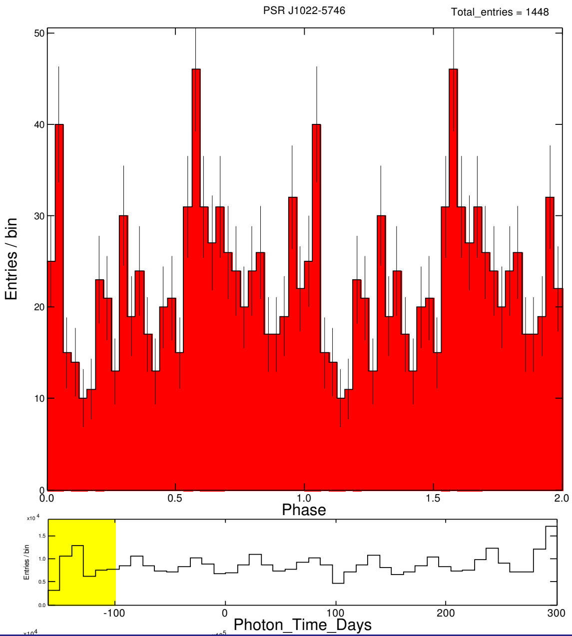
Thank You


PSR J1022-5746
Total_entries = 446
Entries / bin
Phase
0.0
0.5
1.0
1.5
2.0
0
5
10
15
Photon_Time_Days
-100
0
100
200
300

Thank You



PSR J1022-5746
Total_entries = 1004
Entries / bin
Phase
Entries / bin
Photon_Time_Days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Total_entries = 1448
Entries / bin
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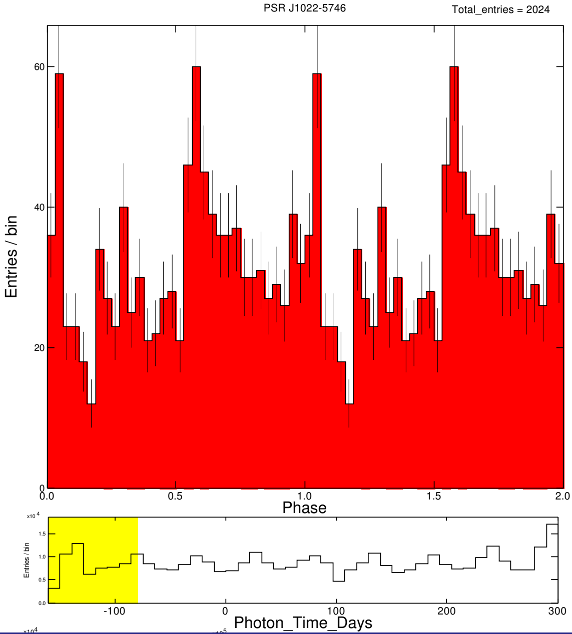
1.0
1.5
2.0
0
10
20
30
40
50
Entries / bin
Photon_Time_Days
-100
0
100
200
300

Thank You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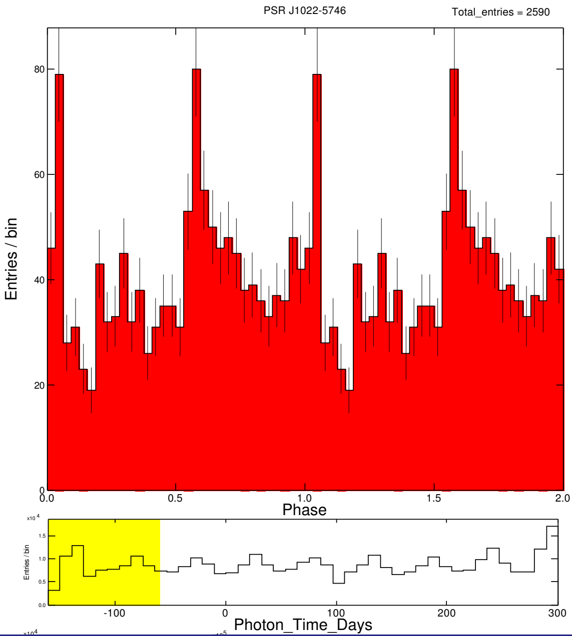
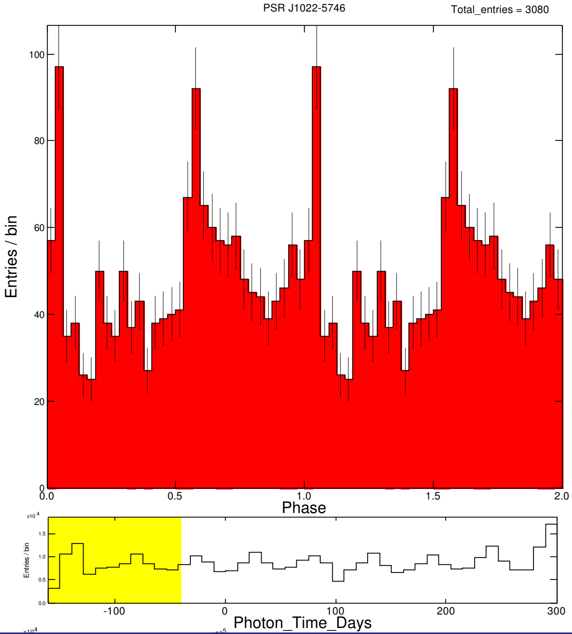
Total_entries = 2024
Entries / bin
60
40
20
0
0.0
0.5
1.0
1.5
2.0
Phase
x10 4
1.5
1.0
0.5
0.0
Entries / bin
-100
0
100
200
300
Photon_Time_Days

Thank You



PSR J1022-5746
Total_entries = 2590
Entries / bin
Phase
Photon_Time_Days

Thank You



PSR J1022-5746
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Entries / bin
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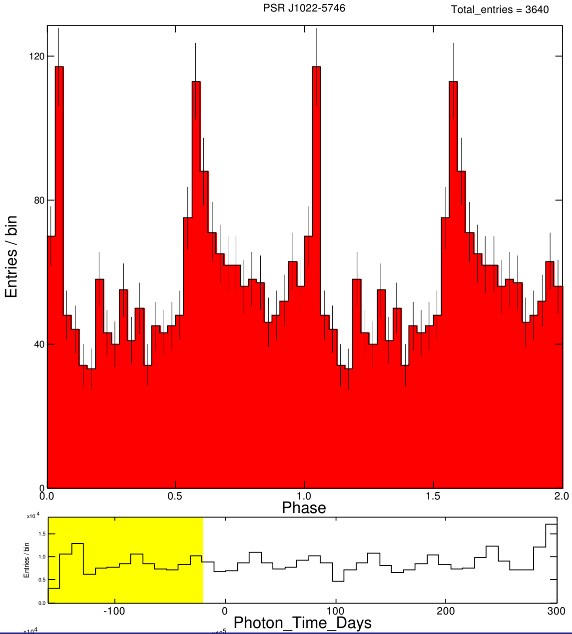
1.0
1.5
2.0
0
20
40
60
80
100
Entries / bin
Photon_Time_Days
-100
0
100
200
300

Thank You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Total_entries = 3640
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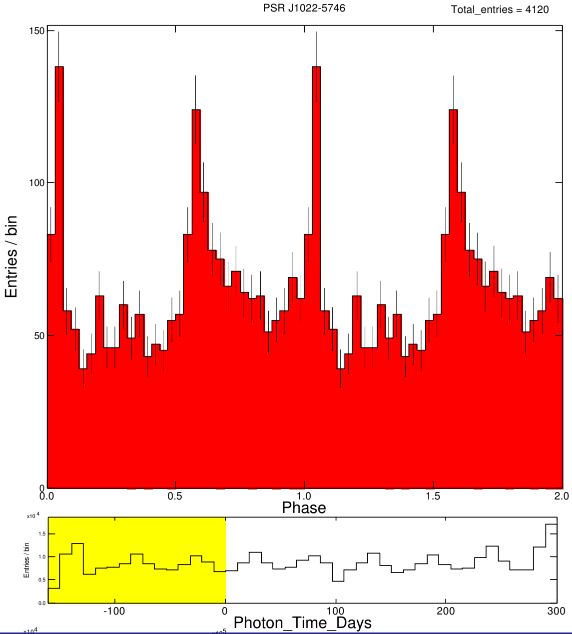
Phase
Entries / bin
Photon_Time_Days

Thank You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Entries / bin
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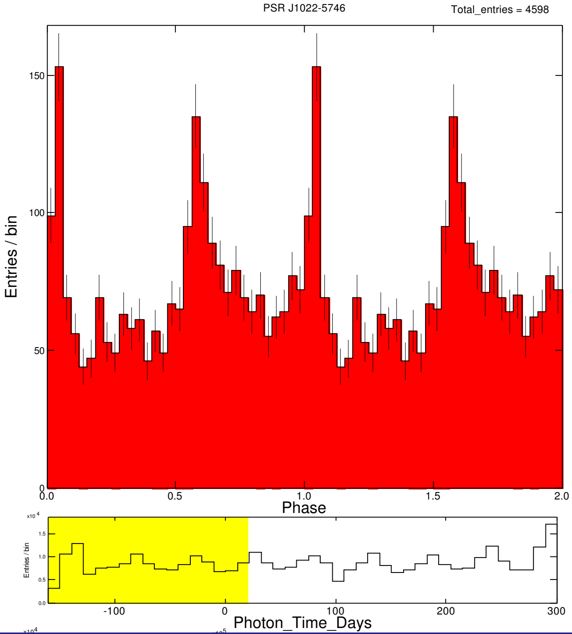
0
0.0
0.5
1.0
1.5
2.0
Phase
Entries / bin
-100
0
100
200
300
Photon_Time_Days

Thank You



PSR J1022-5746
Total_entries = 4598
Entries / bin
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1.0
1.5
2.0
Phase
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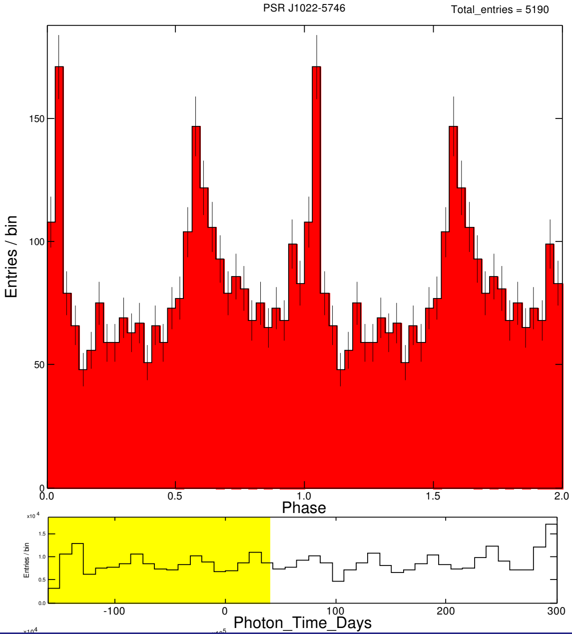
100
200
300
Photon_Time_Days

Thank You



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1.5
2.0
Phase
Entries / bin
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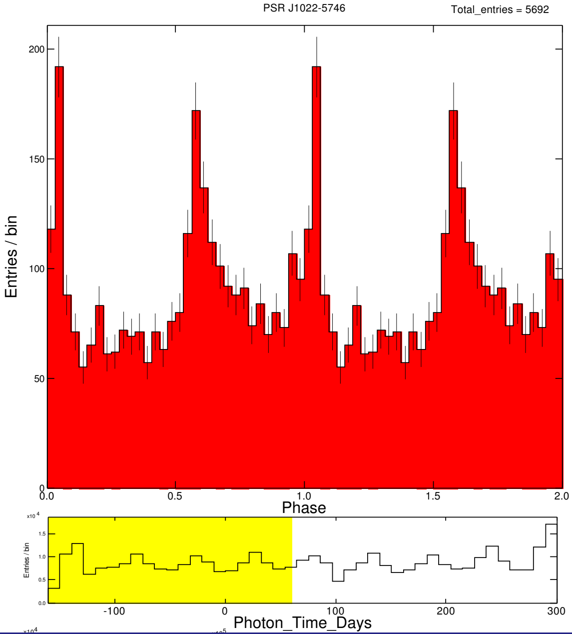
0
100
200
300
Photon_Time_Days

Thank You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0
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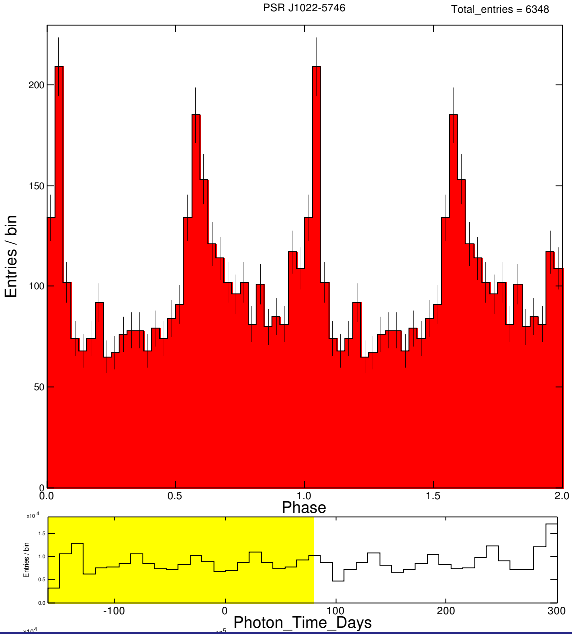
0.5
1.0
1.5
2.0
Phase
Entries / bin
-100
0
100
200
300
Photon_Time_Days

Thank You


PSR J1022-5746
Total_entries = 6348
Entries / bin
Phase
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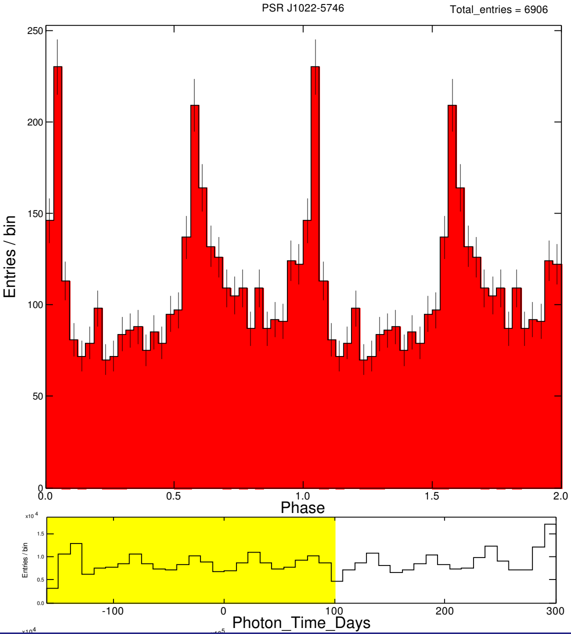
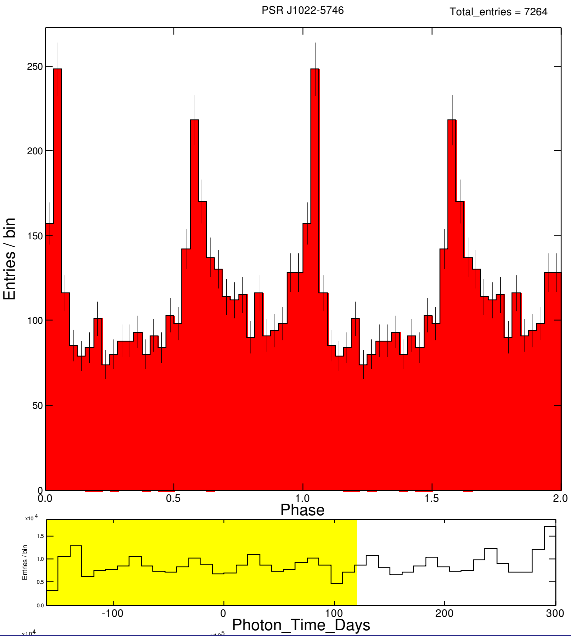
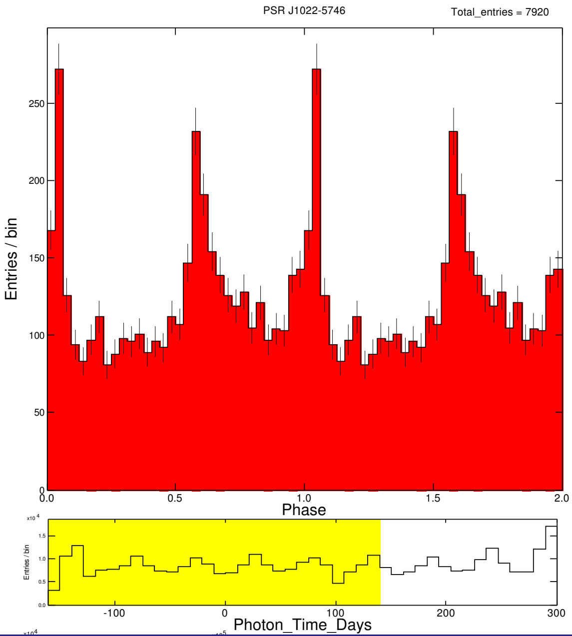
0.5
1.0
1.5
2.0
0
50
100
150
200
Photon_Time_Days
-100
0
100
200
300

Thank You


PSR J1022-5746
Total_entries = 6906
Entries / bin
Phase
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
Entries / bin
Photon_Time_Days
-100
0
100
200
300

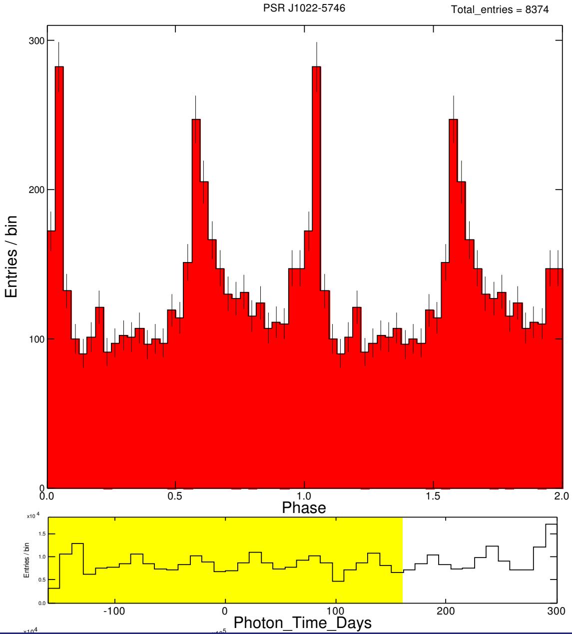

PSR J1022-5746
Total_entries = 7264
Entries / bin
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
Phase
Entries / bin
-100
0
100
200
300
Photon_Time_Days

Thank You



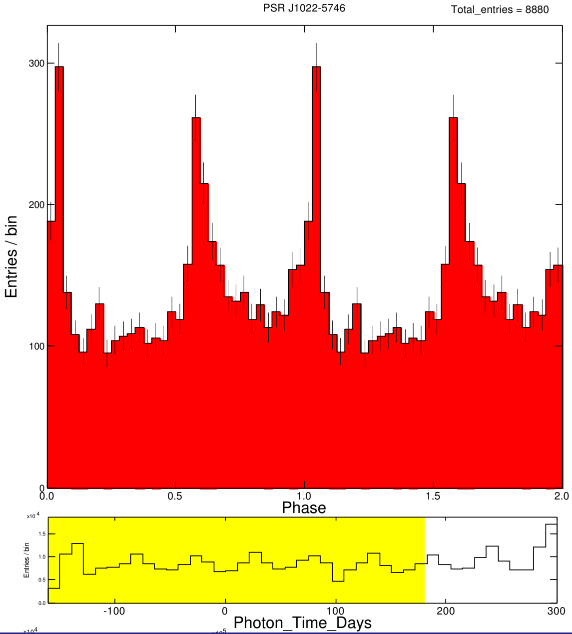
PSR J1022-5746
Total_entries = 7920
Entries / bin
Phase
Photon_Time_Days

Thank You

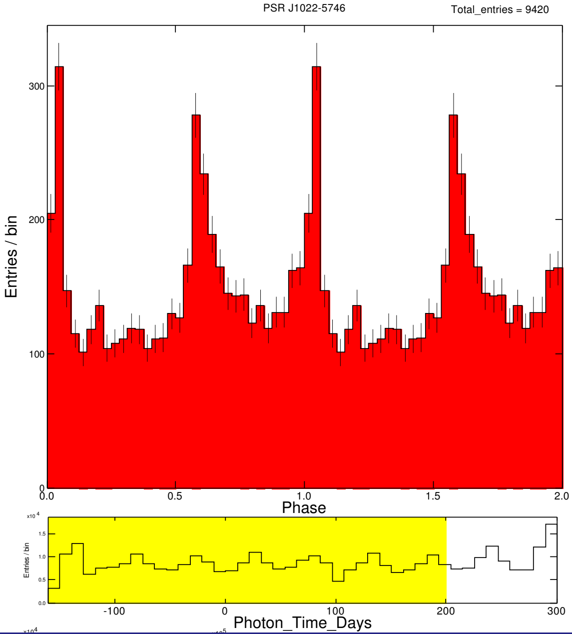


PSR J1022-5746
Total_entries = 8374
Entries / bin
300
200
100
0
0.0
0.5
1.0
1.5
2.0
Phase
Entries / bin
-100
0
100
200
300
Photon_Time_Days

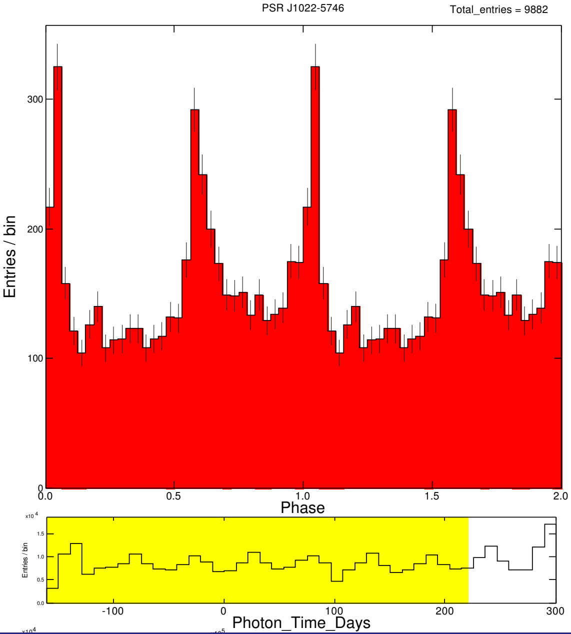
Thank You


PSR J1022-5746
Total_entries = 8880
Entries / bin
300
200
100
0
0.0
0.5
1.0
1.5
2.0
Phase
-100
0
100
200
300
Photon_Time_Days

Thank You

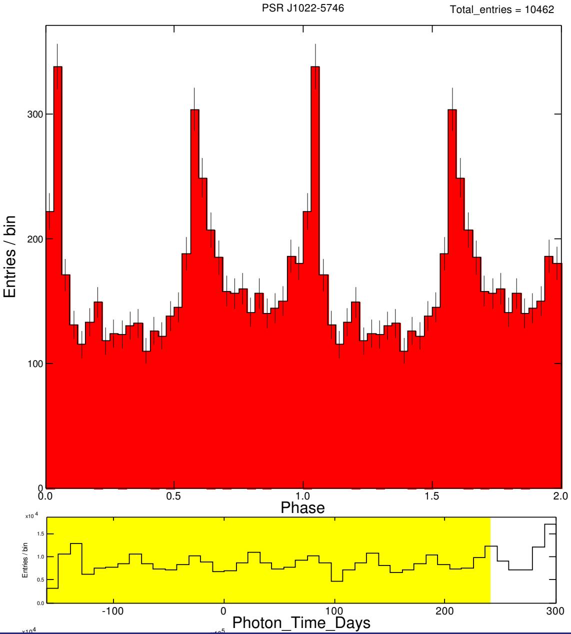

PSR J1022-5746
Total_entries = 9420
Entries / bin
300
200
100
0
0.0
0.5
1.0
1.5
2.0
Phase
Entries / bin
-100
0
100
200
300
Photon_Time_Days

Thank You

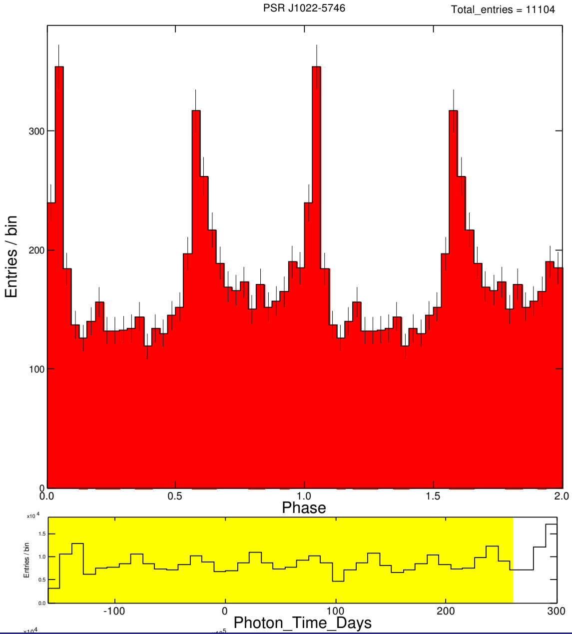


PSR J1022-5746
Total_entries = 9882
Entries / bin
300
200
100
0
0.0
0.5
1.0
1.5
2.0
Phase
x10 4
1.5
1.0
0.5
0.0
Entries / bin
-100
0
100
200
300
Photon_Time_Days

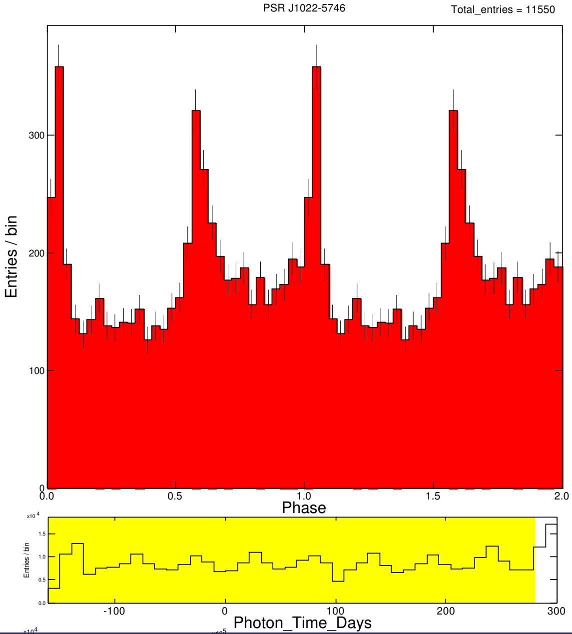
Thank You

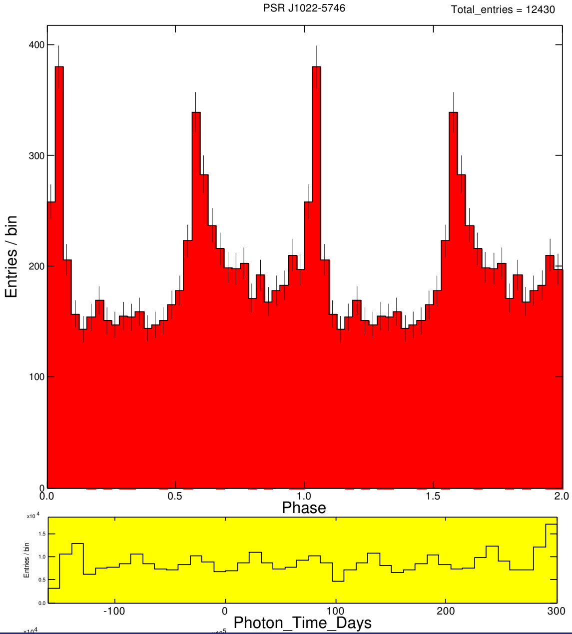

PSR J1022-5746
Total_entries = 10462
Entries / bin
300
200
100
0
0.0
0.5
1.0
1.5
2.0
Phase
Entries / bin
-100
0
100
200
300
Photon_Time_Days

Thank You


PSR J1022-5746
Total_entries = 11104
Entries / bin
300
200
100
0
0.0
0.5
1.0
1.5
2.0
Phase
Entries / bin
-100
0
100
200
300
Photon_Time_Days

Thank You


PSR J1022-5746
Total_entries = 11550
Entries / bin
300
200
100
0
0.0
0.5
1.0
1.5
2.0
Phase
Entries / bin
-100
0
100
200
300
Photon_Time_Days


PSR J1022-5746
Total_entries = 12430
Entries / bin
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
Phase
Entries / bin
-100
0
100
200
300
Photon_Time_Days