A gamma-ray view of pulsars

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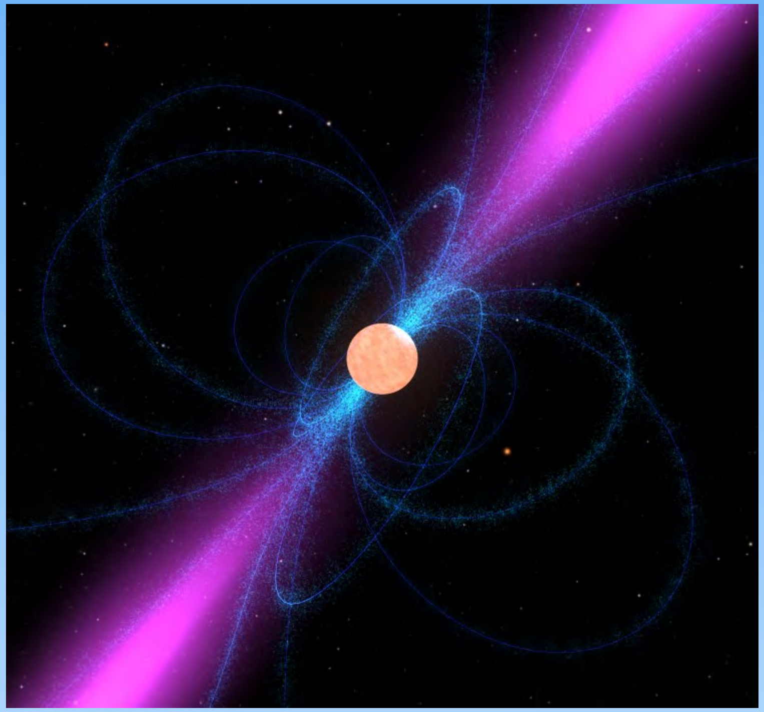
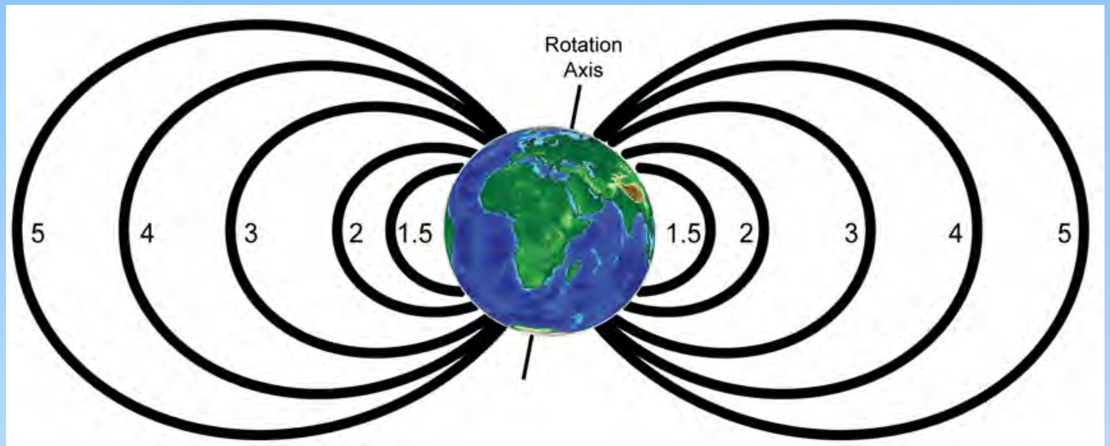
Pulsar (highly-magnetized rotating NS)



Credit: NASA

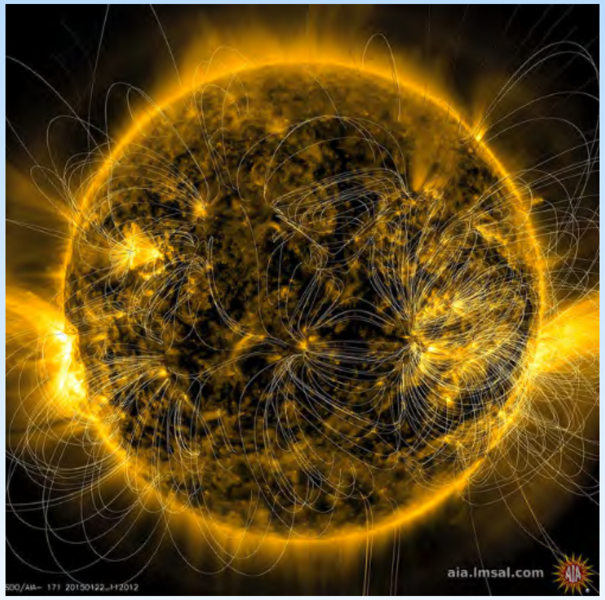
up to ~ 10^{15} Gauss

"... a supernova
represents the transition of an ordinary star in to a
<u>neutron star</u> ..."
- Walter Baade and Fritz Zwicky (1934)

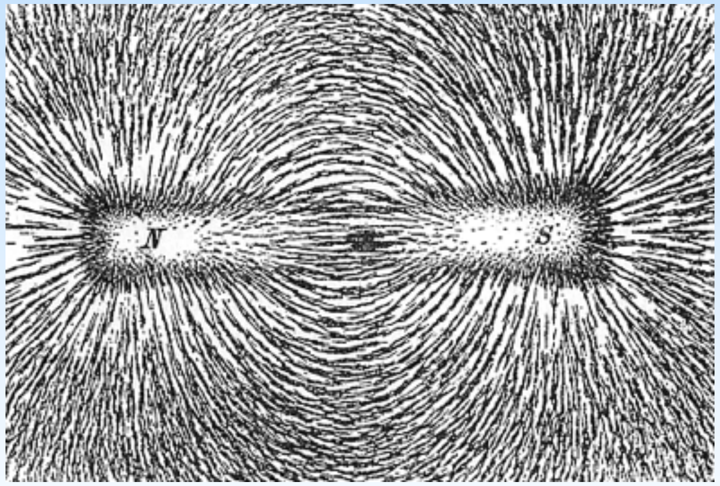


0.5 Gauss

1 Gauss



National High Magnetic Field Laboratory



100 Gauss

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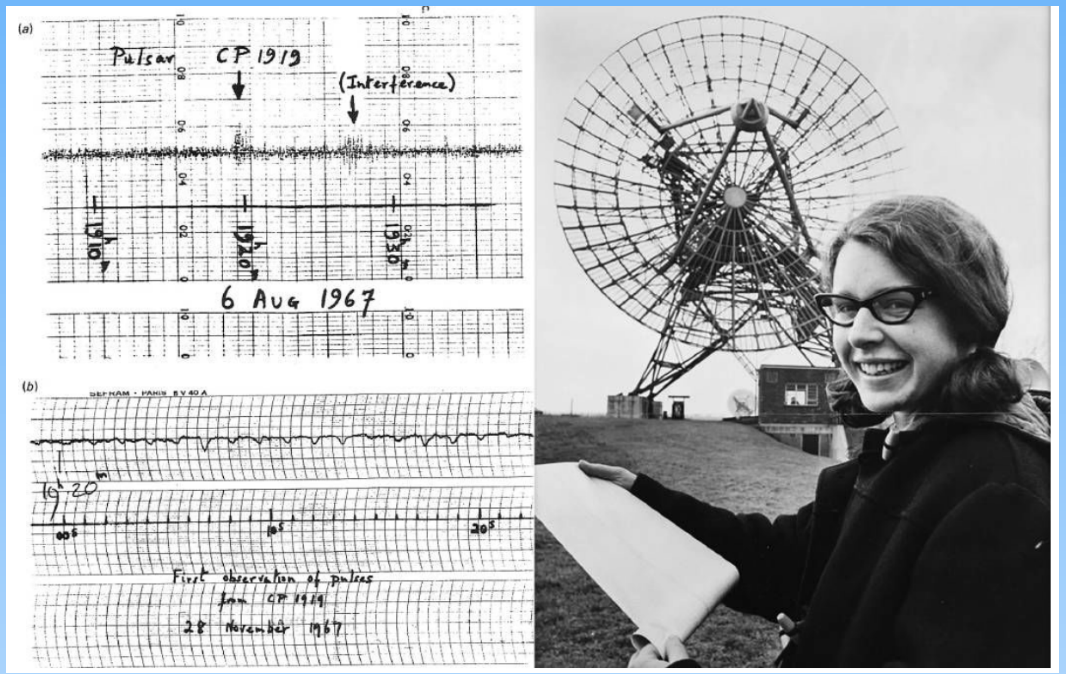
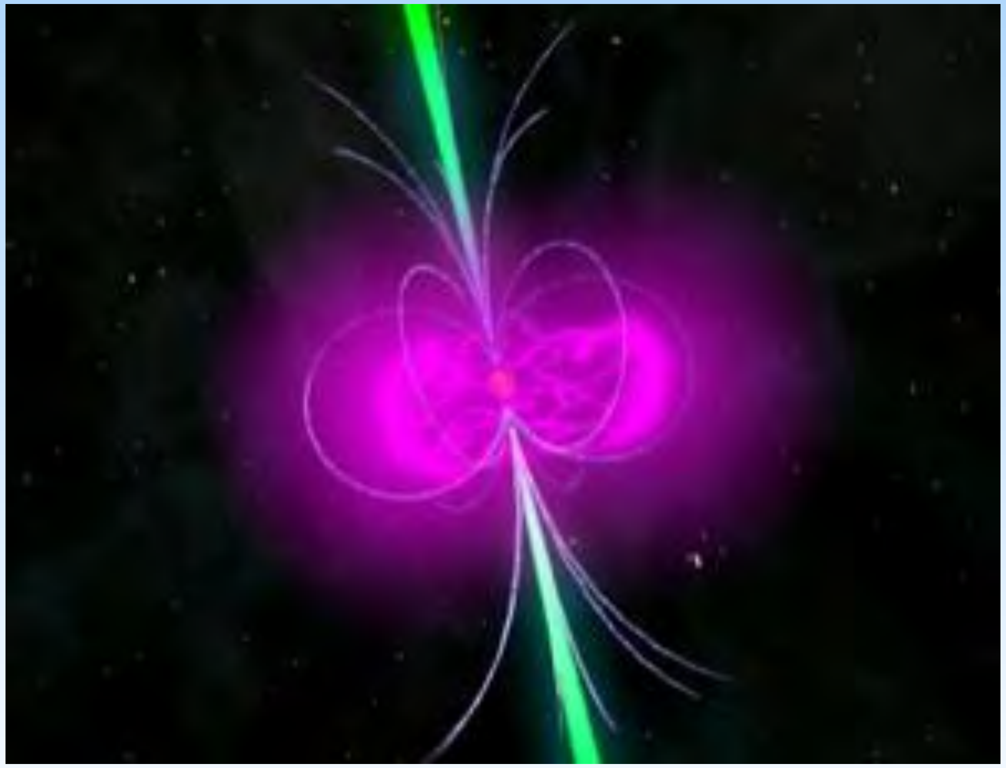
Pulsar Basics

- Discovered ~ 60 years ago but still not completely understood
- Rapidly-spinning (0.1 Hz - 700 Hz),
- highly-magnetised (1E9 to 1E15 G)
- neutron star (R ~ 10 km, M ~ Sun)
- >3000 known pulsars
- Two main "varieties": young and millisecond pulsars
- multi-wavelength emission (over 20 decades)





Credit: NASA

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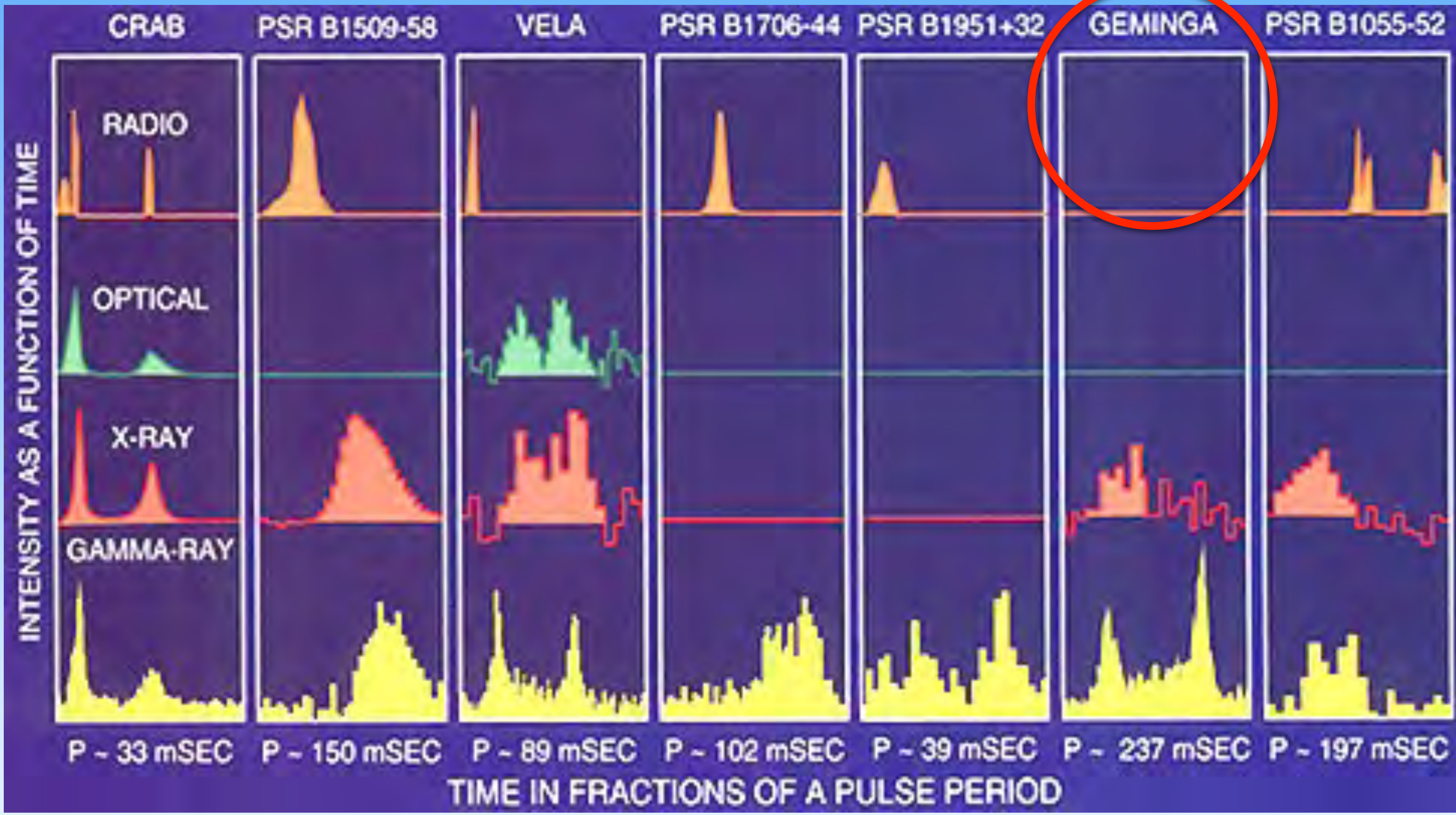
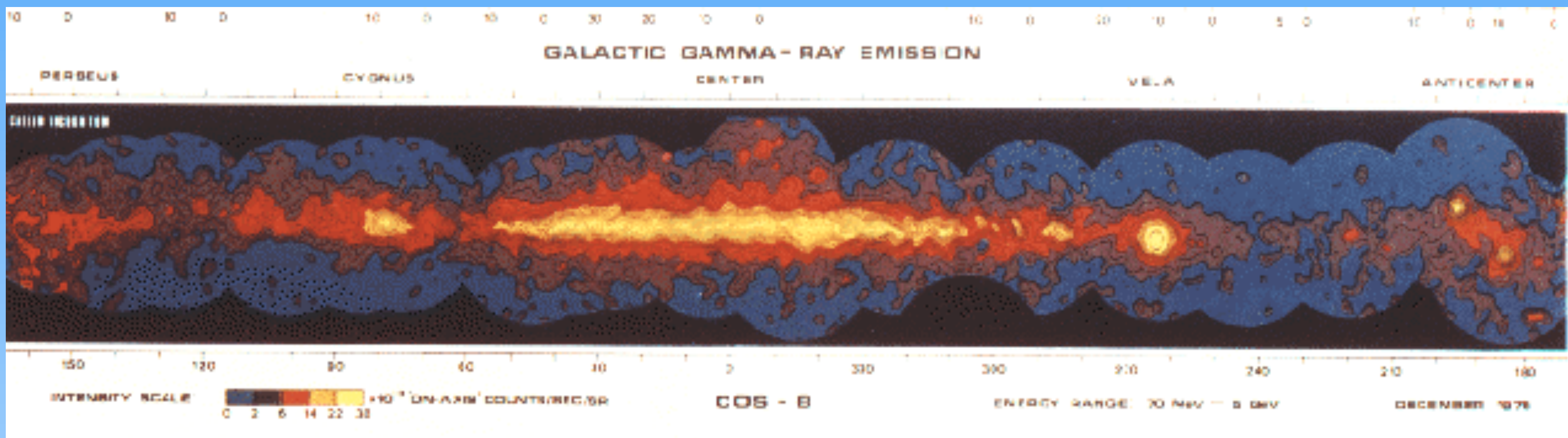
Pulsars across the spectrum

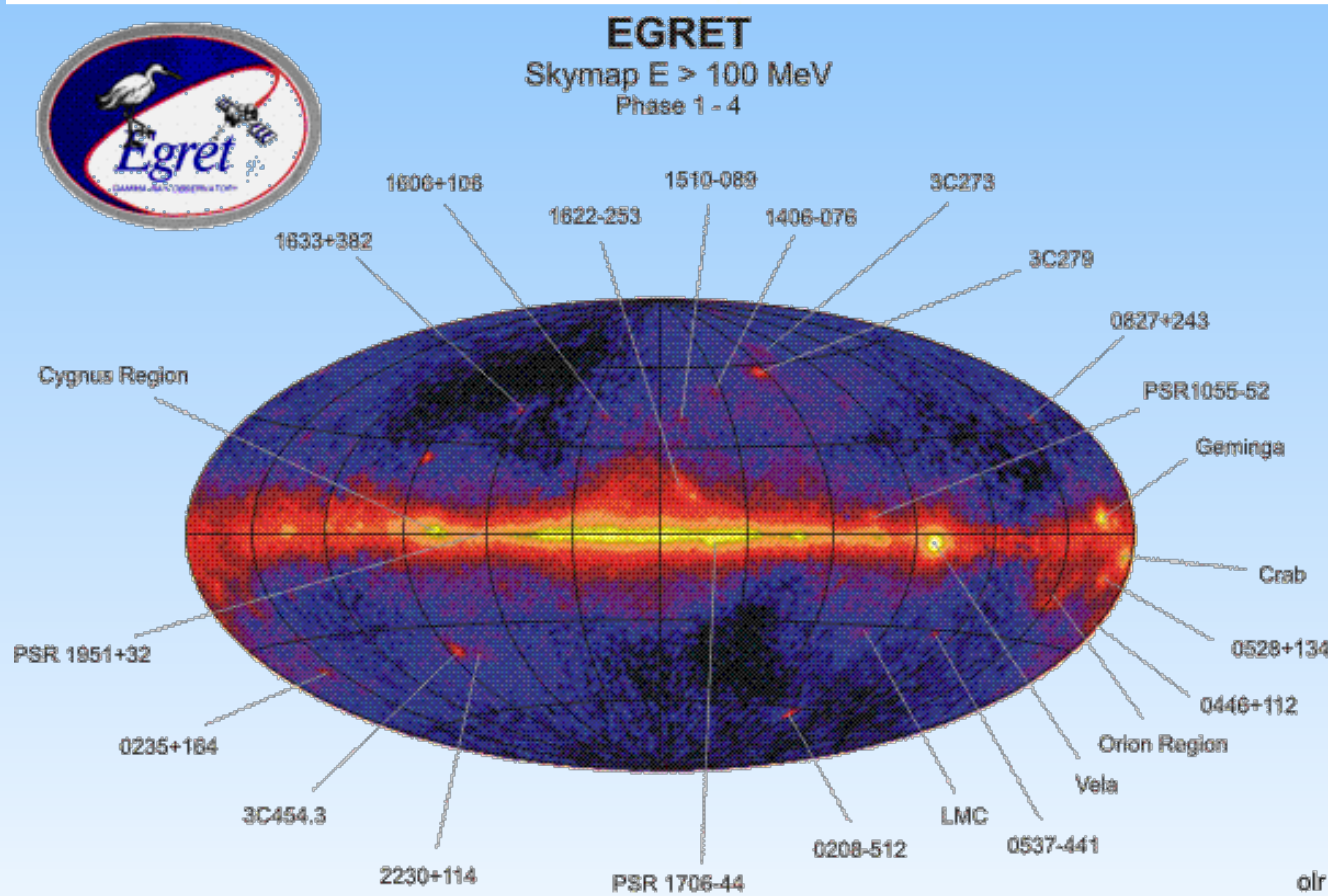


Credit: D. Thompson

Gamma-ray missions pre-Fermi



COS-B (1975-1982): ~200,000 photons



SAS-2 (1972-1973): ~8000 photons

EGRET (1991-2000): 1.4E6 photons, ~300 sources

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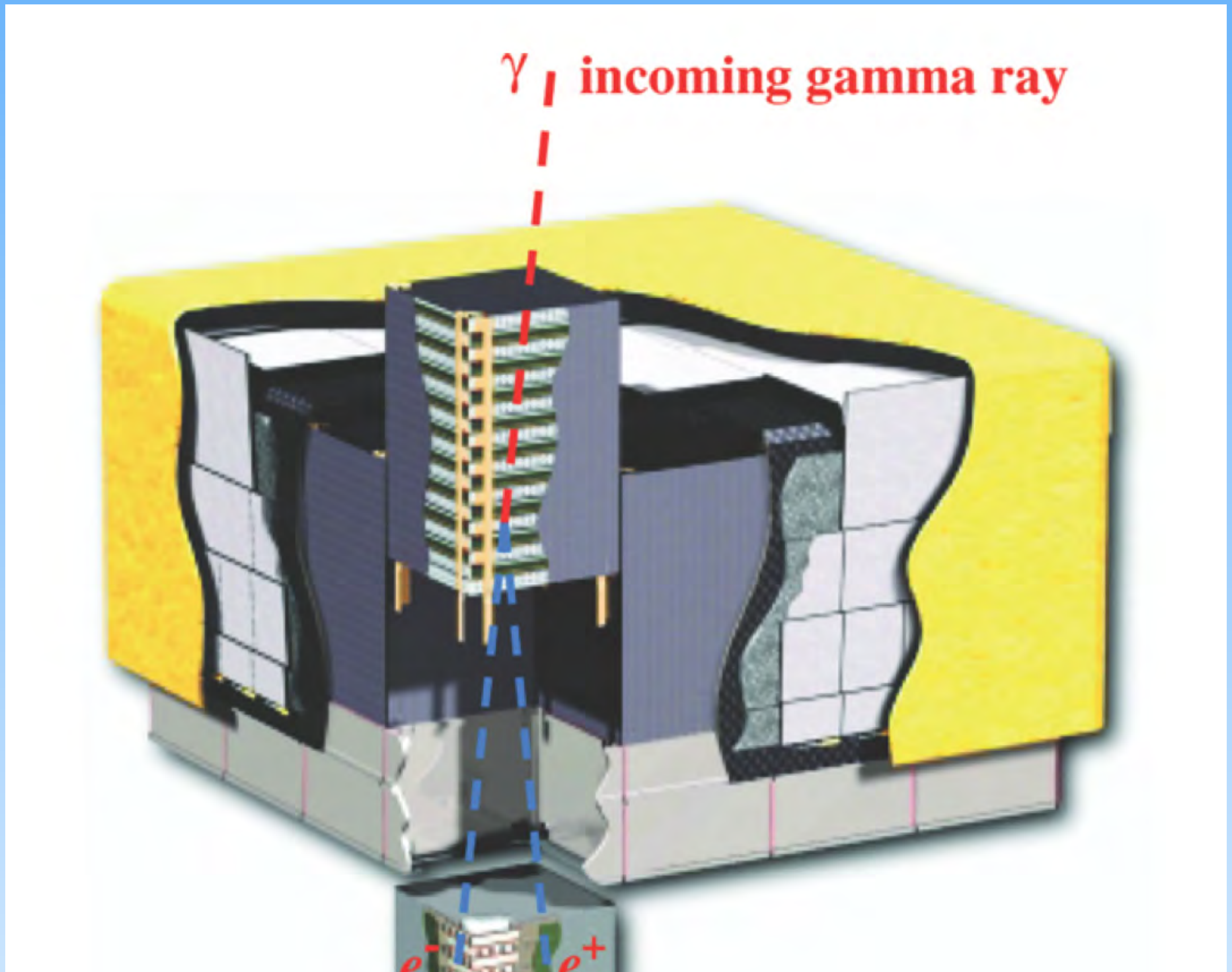
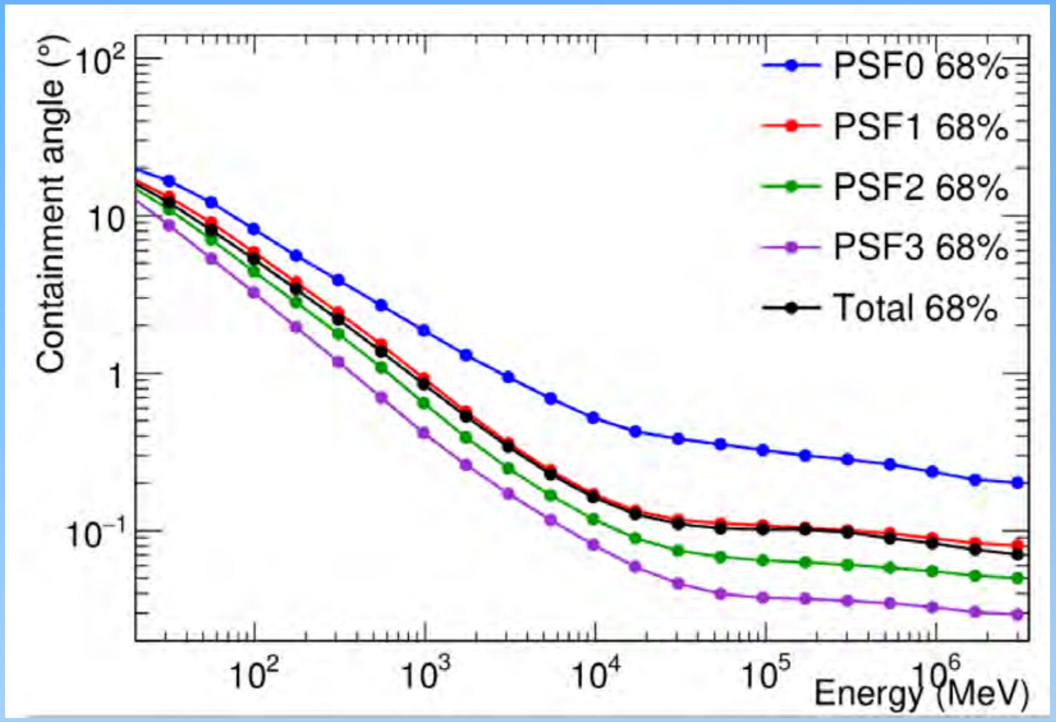
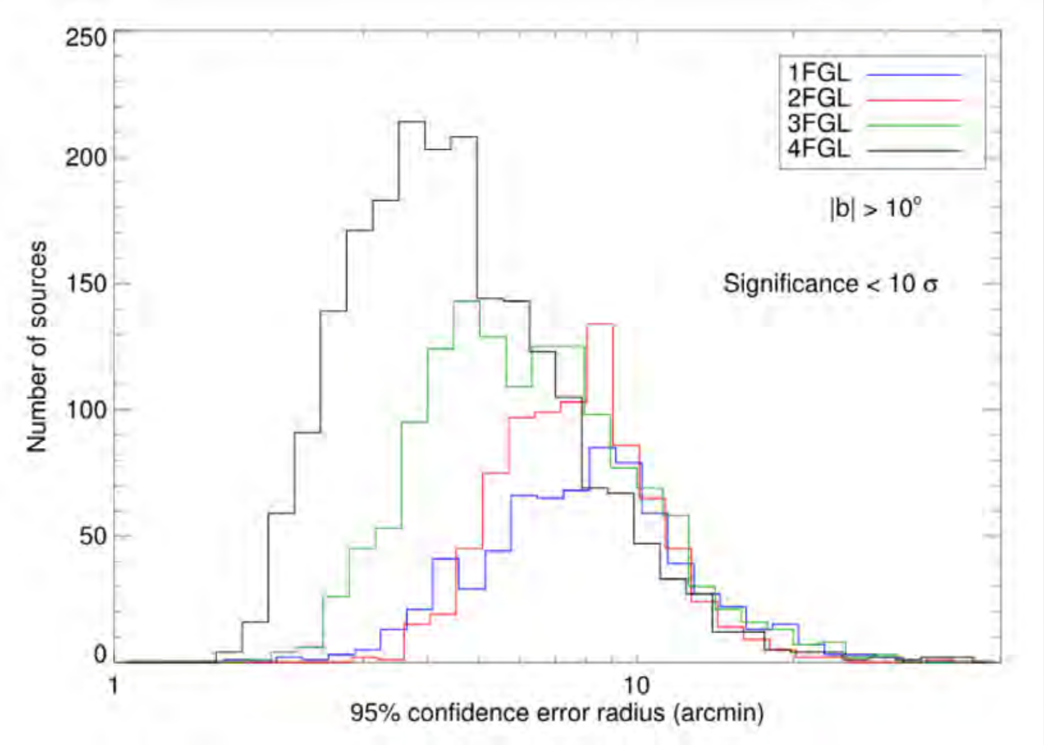
Fermi LAT (2008 - ??)



Atwood et al. 2009





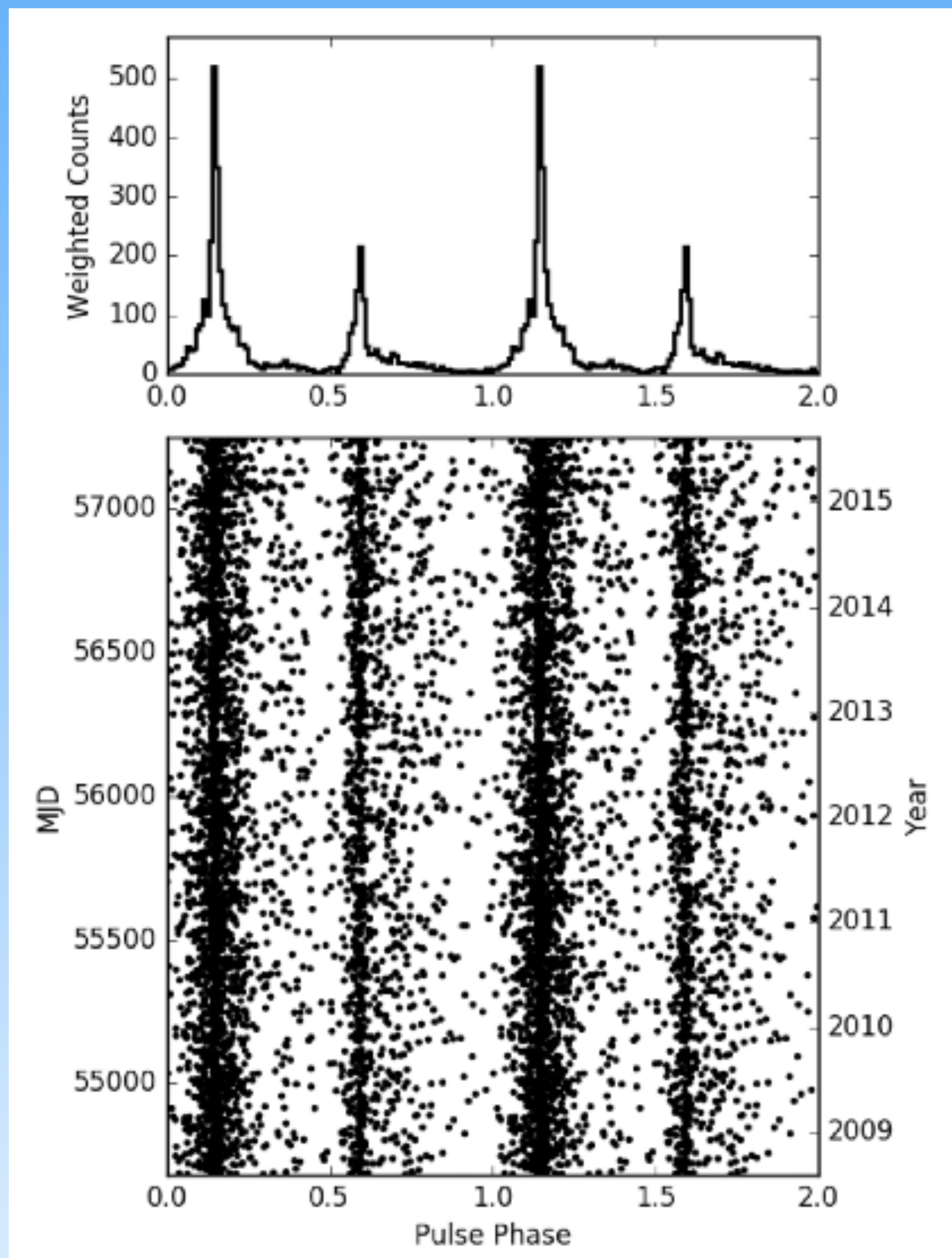
Abdollahi et al. 2020 (4FGL)

GPS timing ; accuracy ~ 300 ns

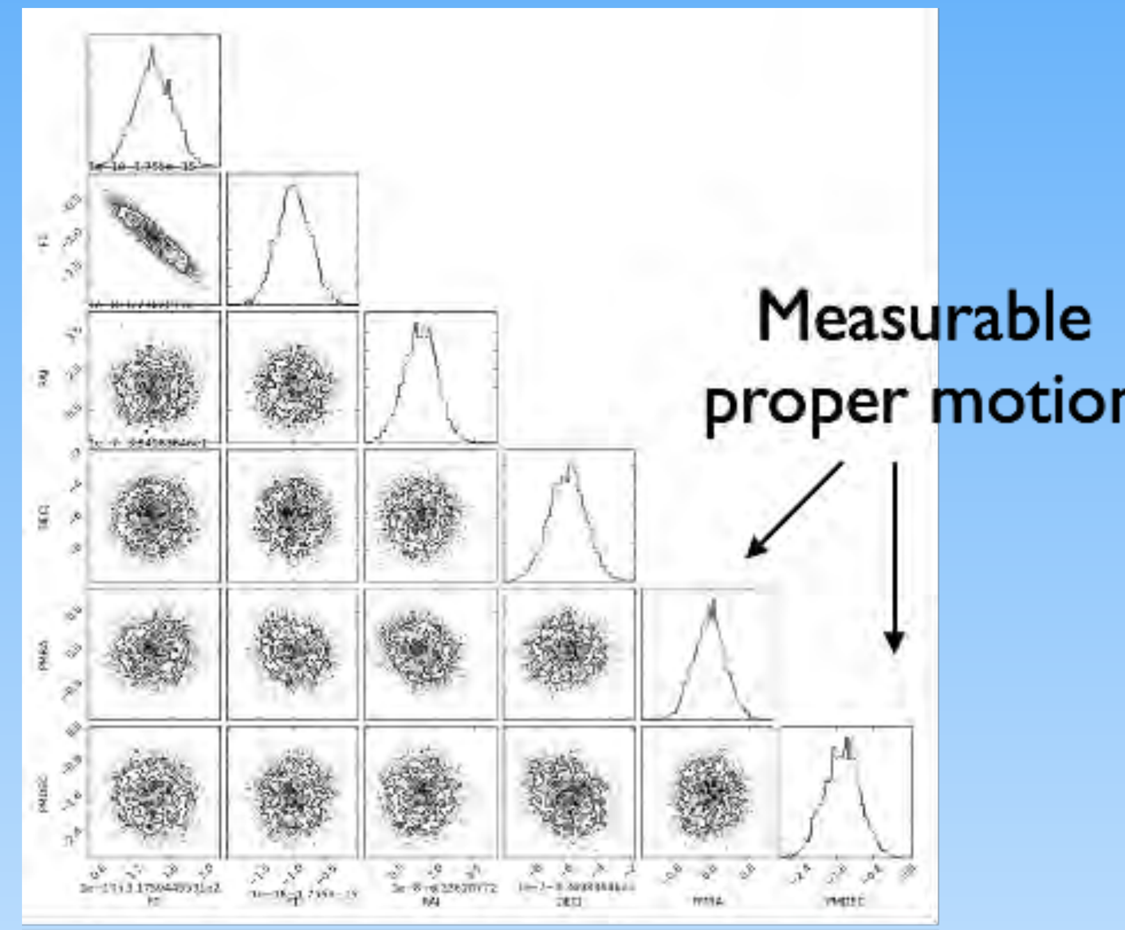
> 1.5 billion "source" photons (and counting)

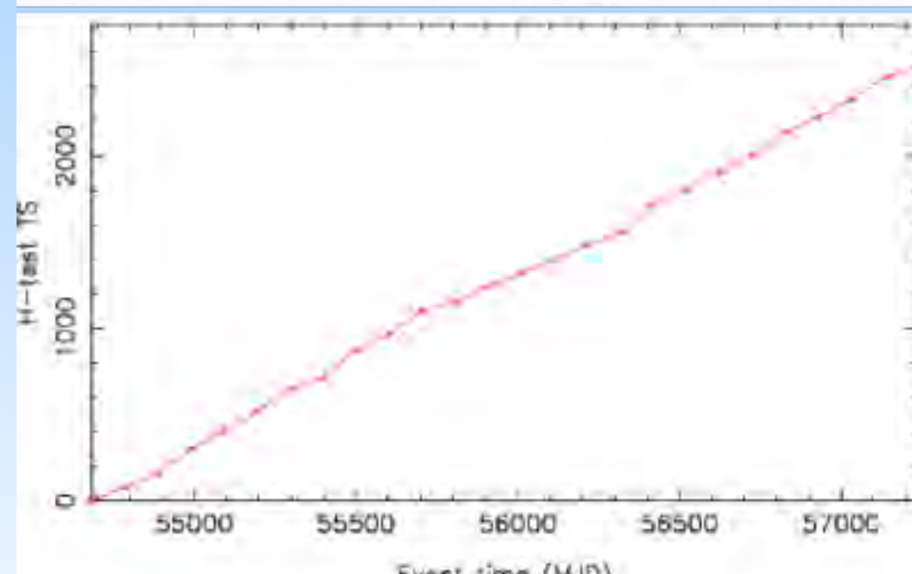
See: Ballet et al. 2024 (4FGL-DR4)

Pulsar timing (in gamma rays)

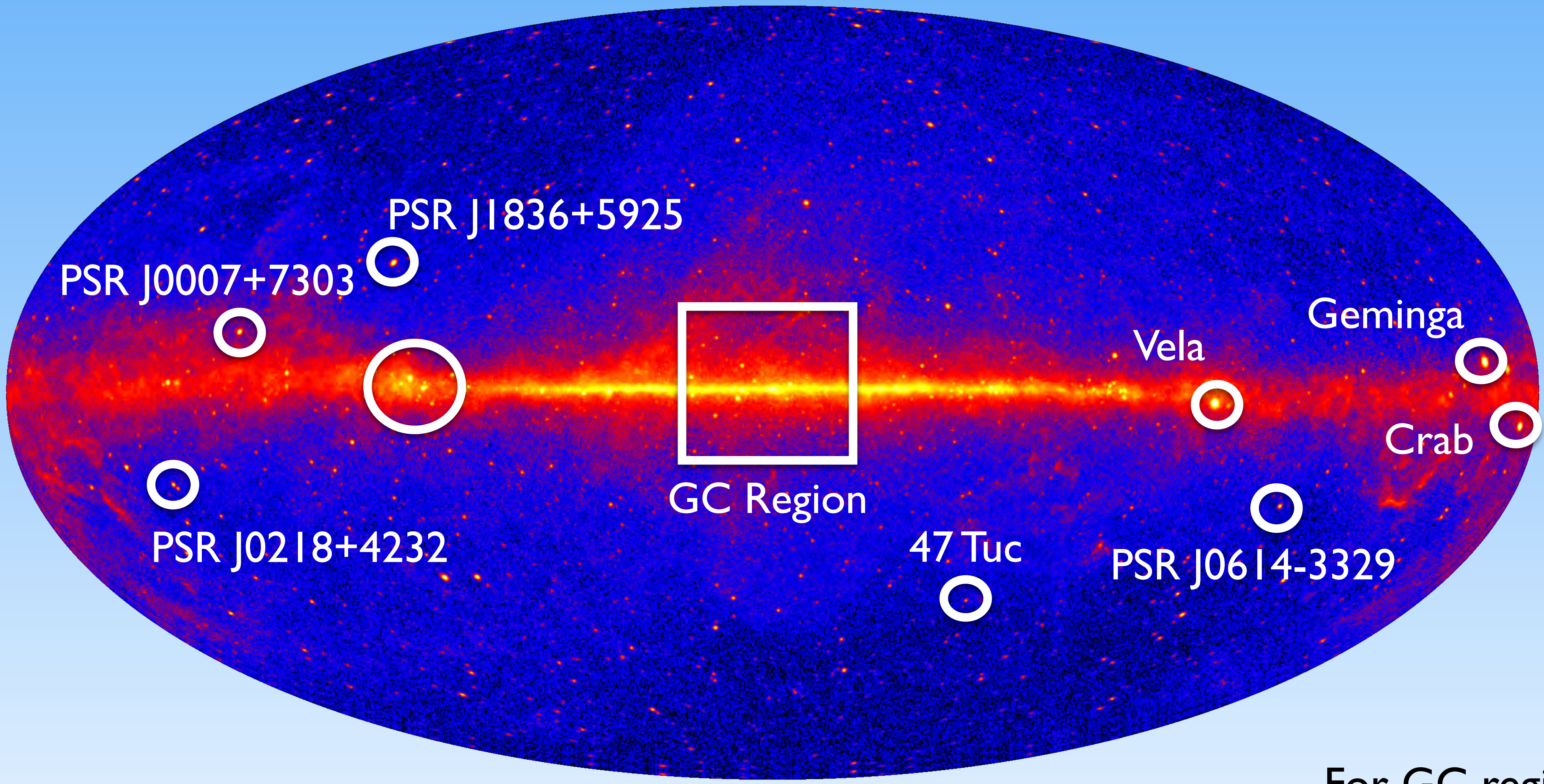


~ 3000 days
> 80 billion rotations
< 20,000 photons
~ 1 photon every 5 million rotations





Early pulsar *Science* with Fermi



For GC region,
see Clark et al. 2025

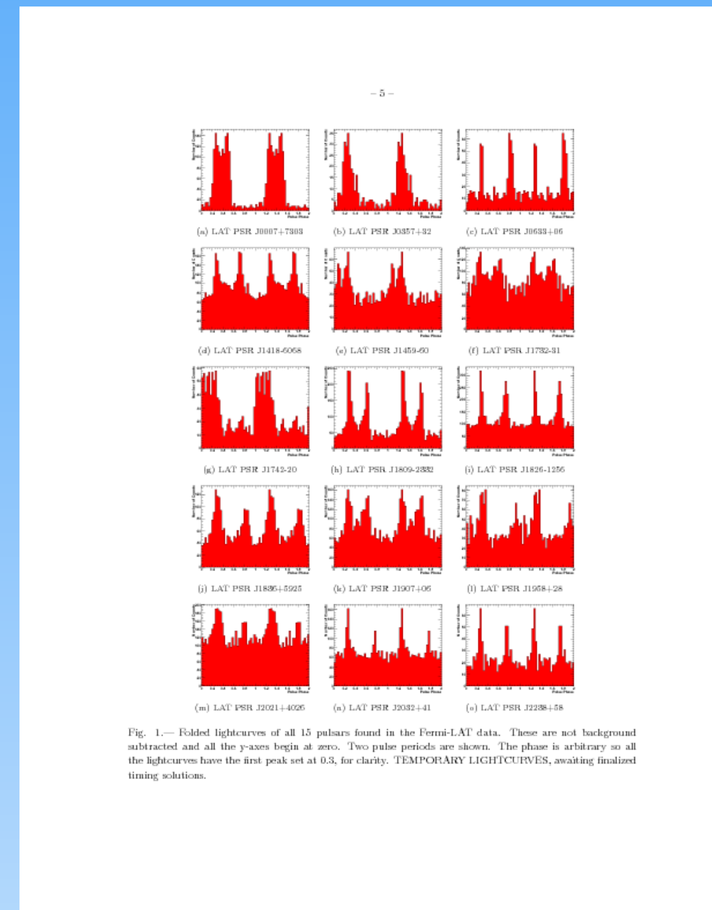
Abdo et al., *Science*, **325**, 840 (2009): *Gemingas*

Abdo et al., *Science*, **325**, 845 (2009): Globular Clusters

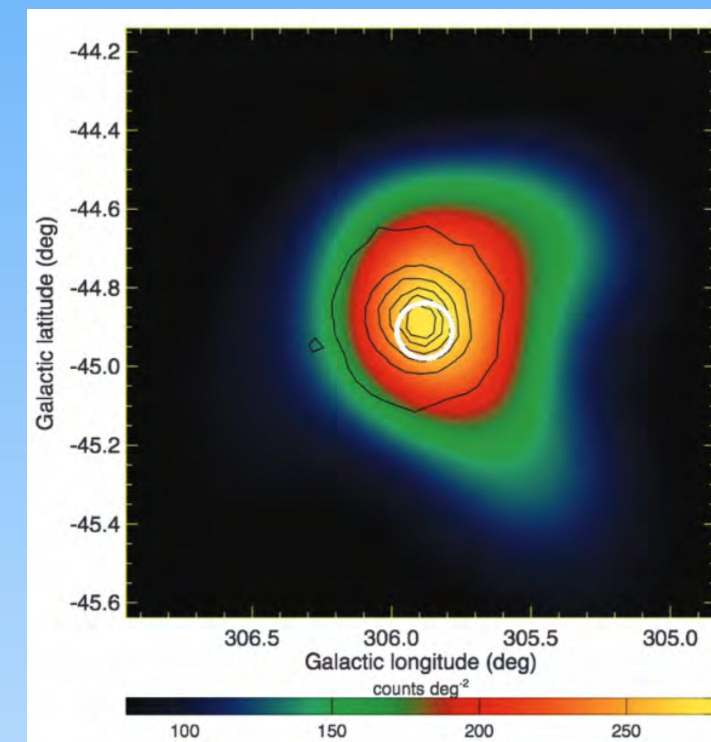
Abdo et al., *Science*, **325**, 848 (2009): MSPs

Early *Science* pulsar results

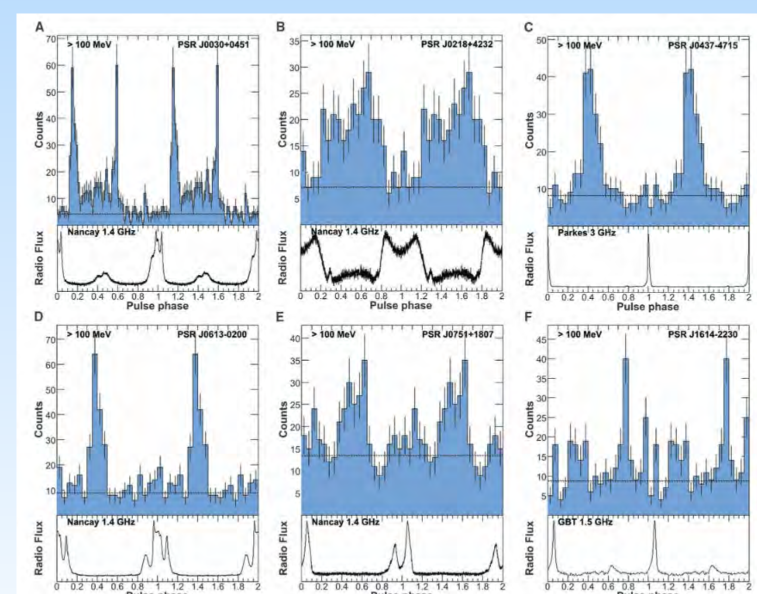
Abdo et al. 2009



Blind Search Pulsars



GC 47Tuc



MSPs

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The Pulsar Consortia

Formed between LAT pulsar searchers and radio astronomers (Smith et al. 2008, Ray et al. 2012)

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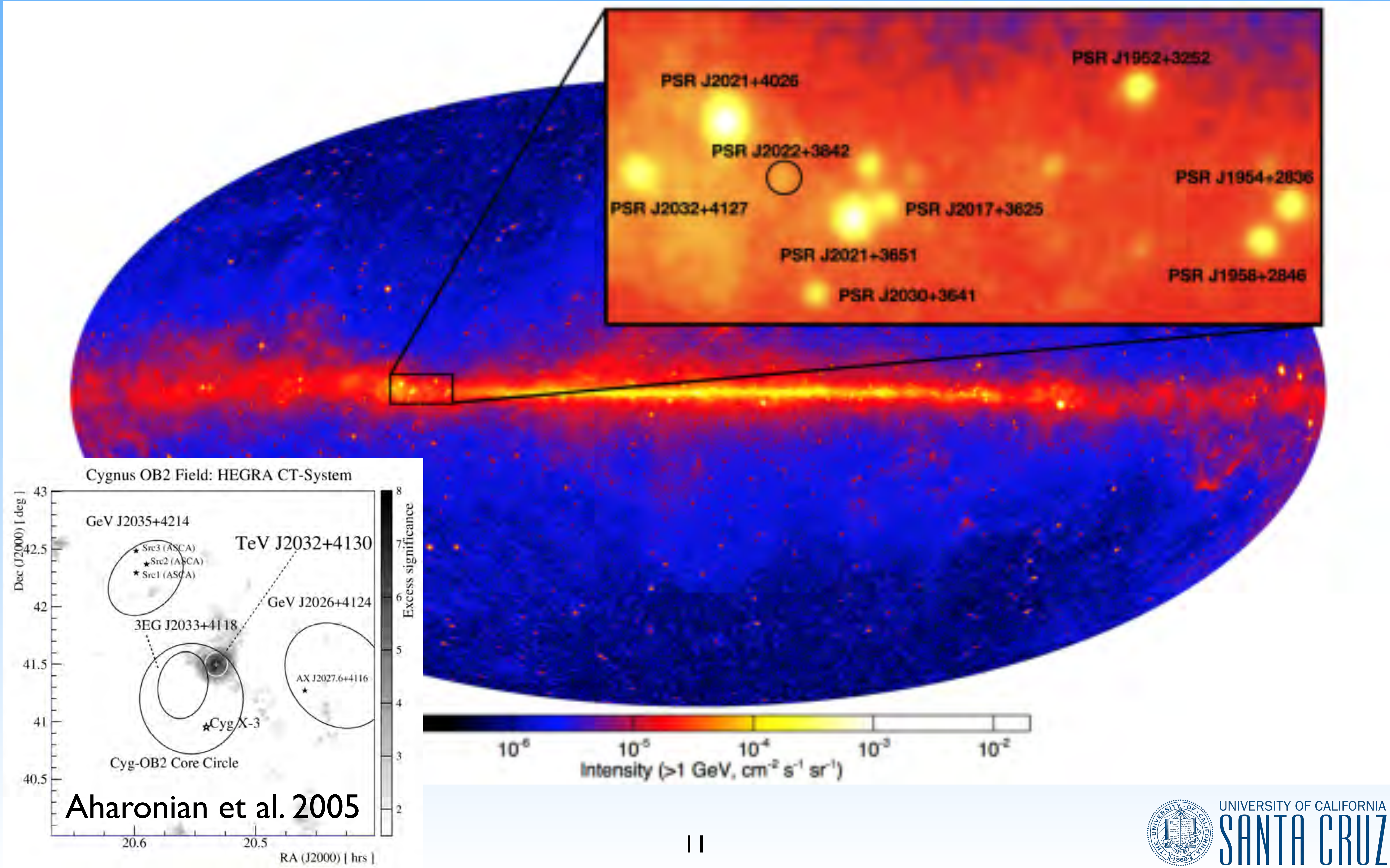
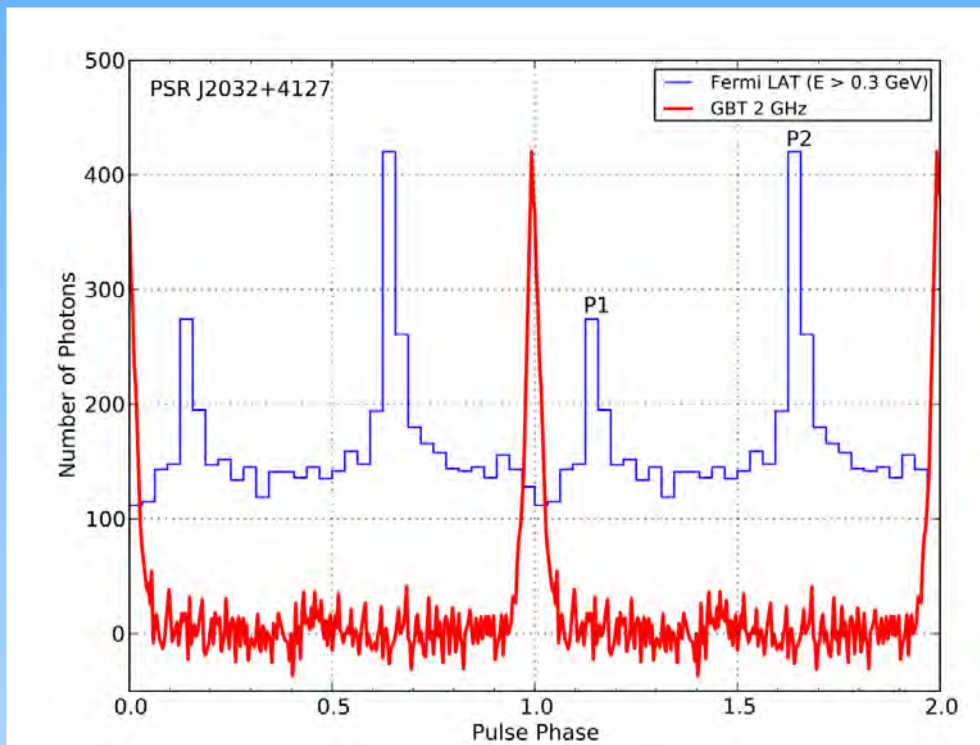
Fermi Large Area Telescope (LAT) sky

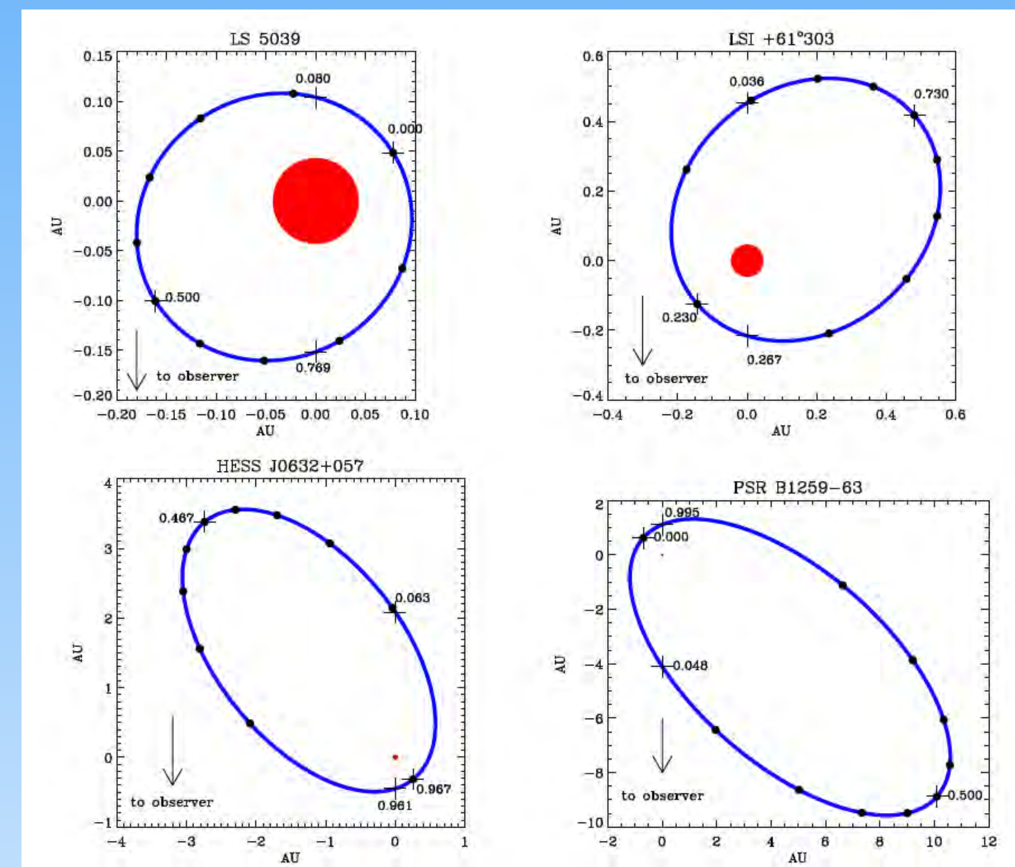


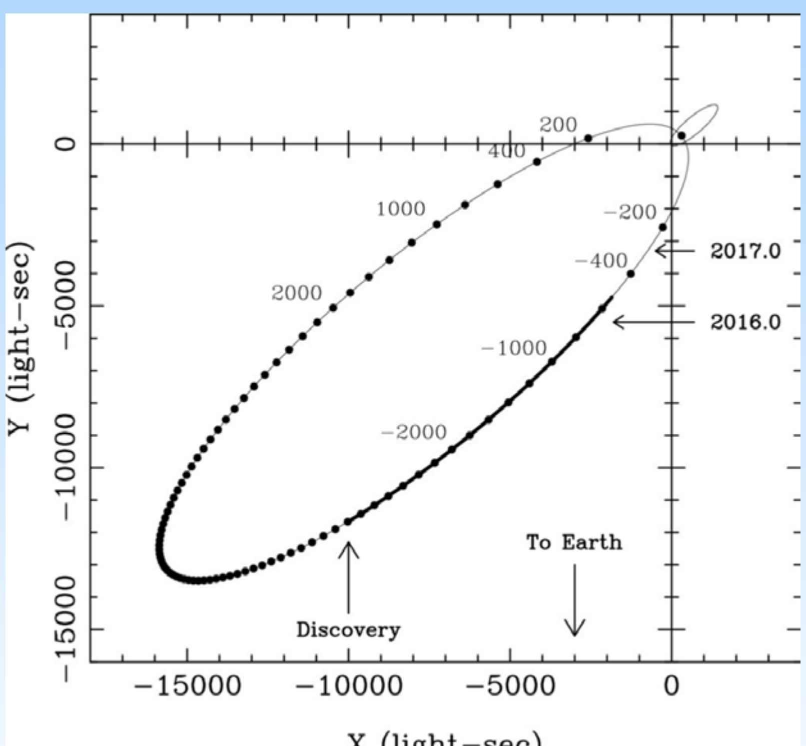
Aharonian et al. 2005

Young gamma-ray binary pulsars



Camilo et al. 2009





Lyne et al. 2015

Gamma-ray binaries: typically consist of a massive star in orbit with a compact object, often a pulsar.

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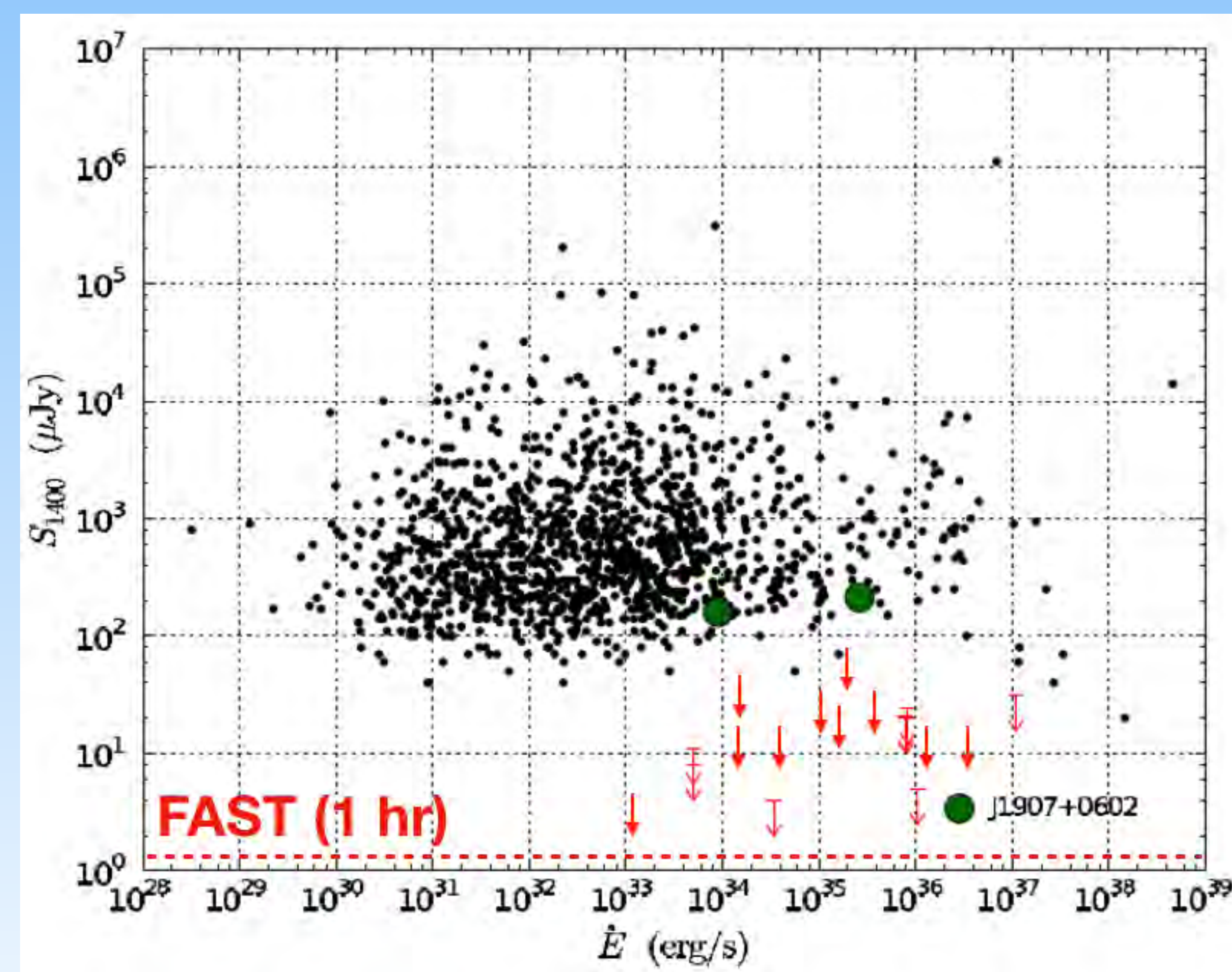
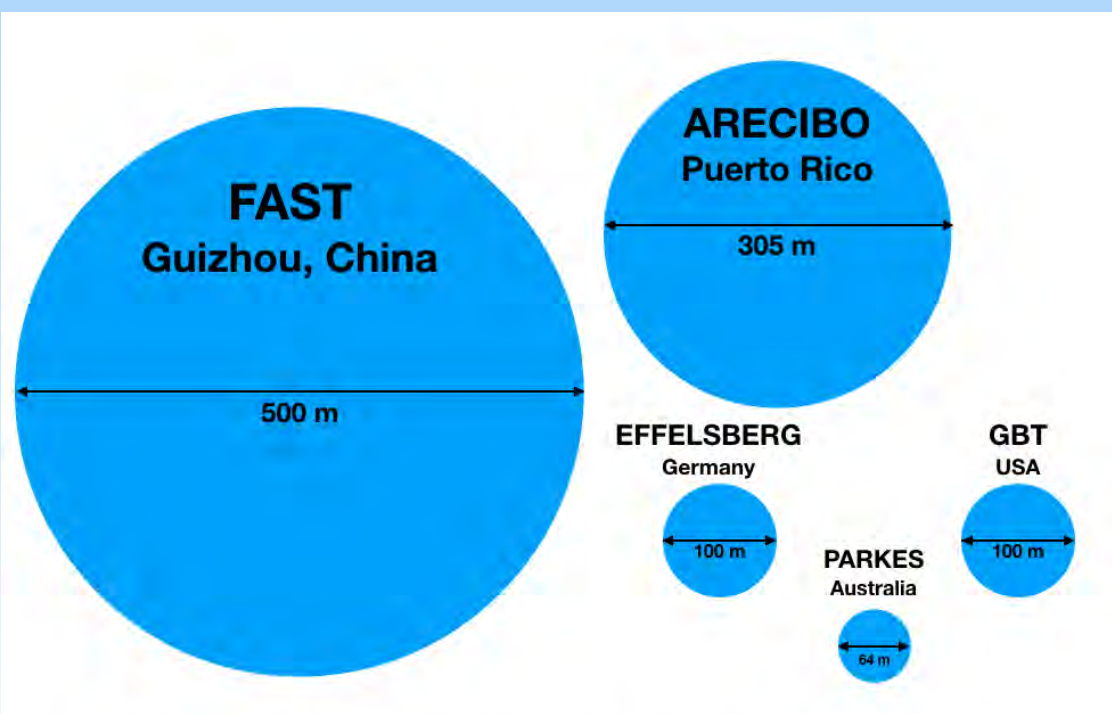
Radio follow-up observations

The Pulsar Search Consortium (PSC) was set up to search for radio pulsars in LAT sources/pulsars (Ray et al. 2012)

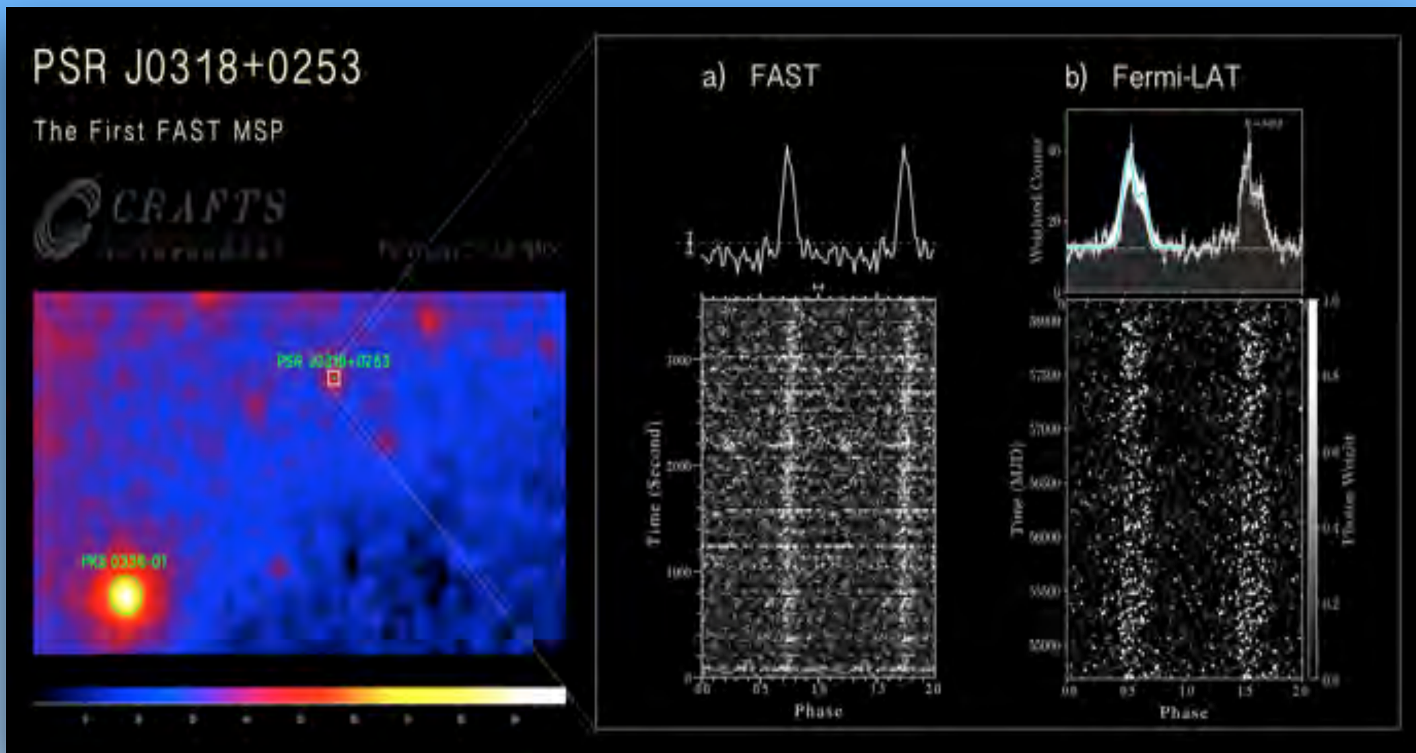


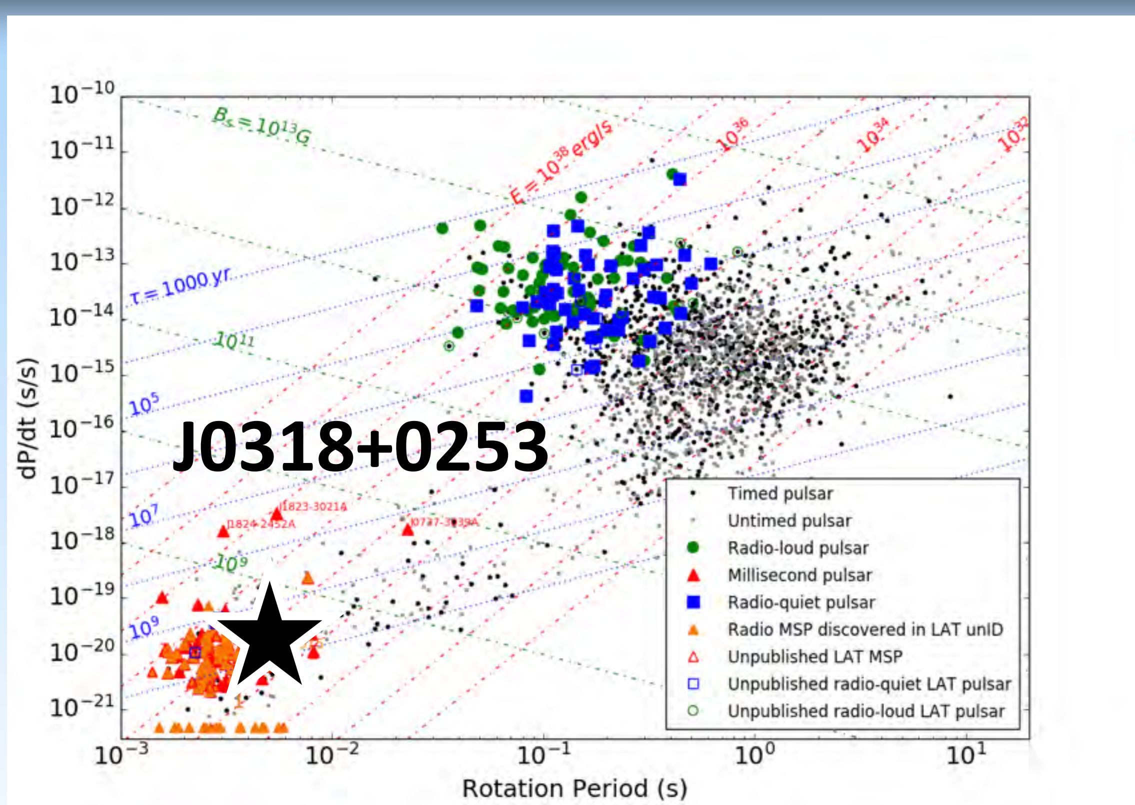
Adapted from Saz Parkinson et al. 2010

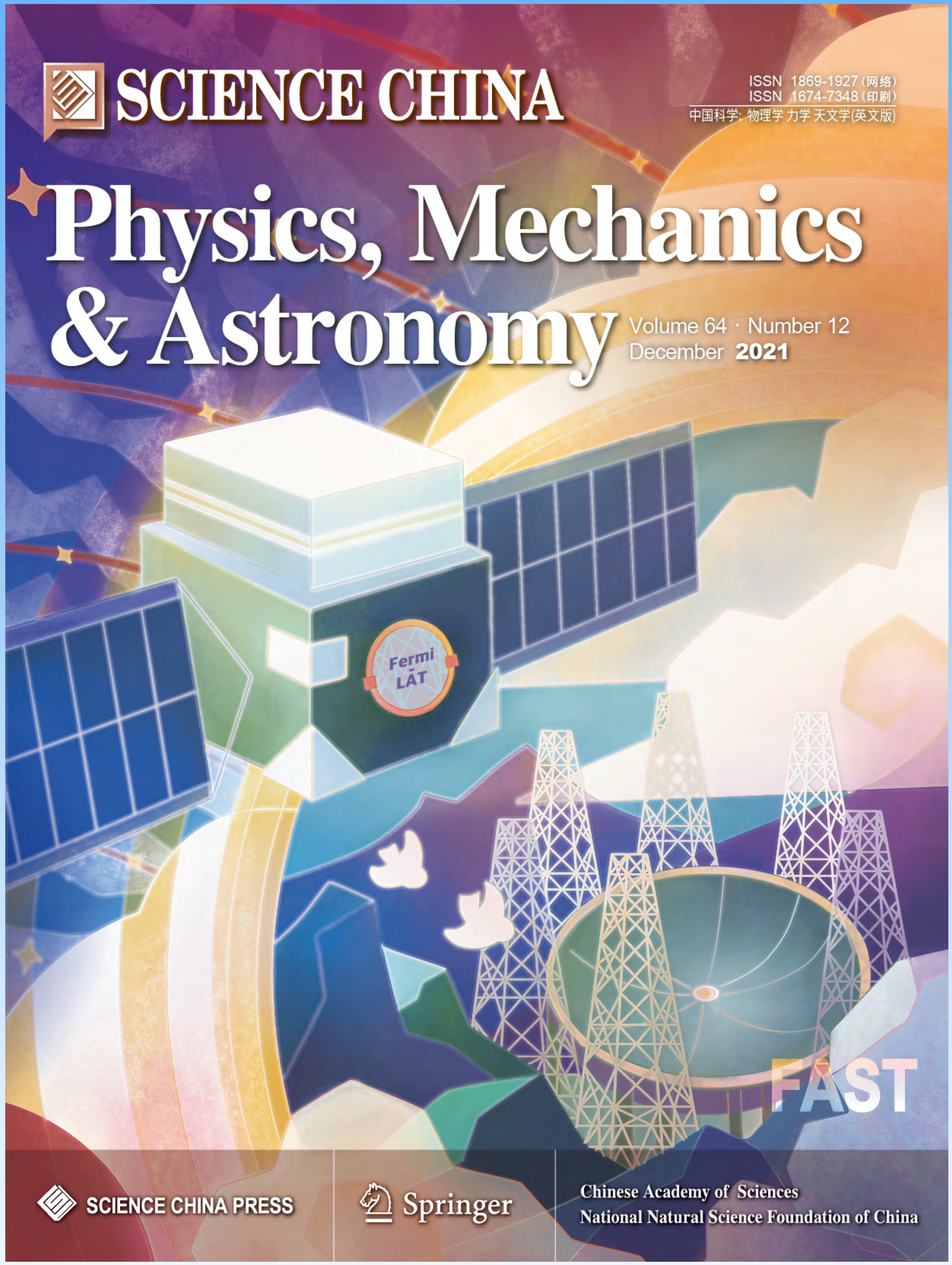


Comparison of the world's largest single-dish radio telescopes
(All members of the Fermi LAT Pulsar Search Consortium)

A Fermi/FAST radio-faint MSP







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TRAPUM (MeerKat)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **519**, 5590–5606 (2023) https://doi.org/10.1093/mnras/stac3742
Advance Access publication 2023 January 6

The TRAPUM *L*-band survey for pulsars in *Fermi*-LAT gamma-ray sources

C. J. Clark,[1,2,3★] R. P. Breton,[3] E. D. Barr,[4] M. Burgay,[5] T. Thongmeearkom,[3] L. Nieder,[1,2] S. Buchner,[6] B. Stappers,[3] M. Kramer,[4,3] W. Becker,[7,4] M. Mayer,[7] A. Phosrisom,[3] A. Ashok,[1,2] M. C. Bezuidenhout,[3] F. Calore,[8] I. Cognard,[9,10] P. C. C. Freire,[4] M. Geyer,[6] J.-M. Grießmeier,[9,10] R. Karuppusamy,[4] L. Levin,[3] P. V. Padmanabh,[4,1,2] A. Possenti,[5] S. Ransom,[11] M. Serylak,[12,13] V. Venkatraman Krishnan,[4] L. Vleeschower,[3] J. Behrend,[4] D. J. Champion,[4] W. Chen,[4] D. Horn,[6] E. F. Keane,[14] L. Künkel,[15] Y. Men,[4] A. Ridolfi,[5,4] V. S. Dhillon,[16,17] T. R. Marsh[18] and M. A. Papa[1,2]

Affiliations are listed at the end of the paper

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ABSTRACT

More than 100 millisecond pulsars (MSPs) have been discovered in radio observations of gamma-ray sources detected by the *Fermi* Large Area Telescope (LAT), but hundreds of pulsar-like sources remain unidentified. Here, we present the first results from the targeted survey of *Fermi*-LAT sources being performed by the Transients and Pulsars with MeerKAT (TRAPUM) Large Survey Project. We observed 79 sources identified as possible gamma-ray pulsar candidates by a Random Forest classification of unassociated sources from the 4FGL catalogue. Each source was observed for 10 min on two separate epochs using MeerKAT's *L*-band receiver (856–1712 MHz), with typical pulsed flux density sensitivities of $\sim 100\,\mu$Jy. Nine new MSPs were discovered, eight of which are in binary systems, including two eclipsing redbacks and one system, PSR J1526−2744, that appears to have a white dwarf companion in an unusually compact 5 h orbit. We obtained phase-connected timing solutions for two of these MSPs, enabling the detection of gamma-ray pulsations in the *Fermi*-LAT data. A follow-up search for continuous gravitational waves from PSR J1526−2744 in Advanced LIGO data using the resulting *Fermi*-LAT timing ephemeris yielded no detection, but sets an upper limit on the neutron star ellipticity of 2.45×10^{-8}. We also detected X-ray emission from the redback PSR J1803−6707 in data from the first eROSITA all-sky survey, likely due to emission from an intrabinary shock.

Clark et al. 2023

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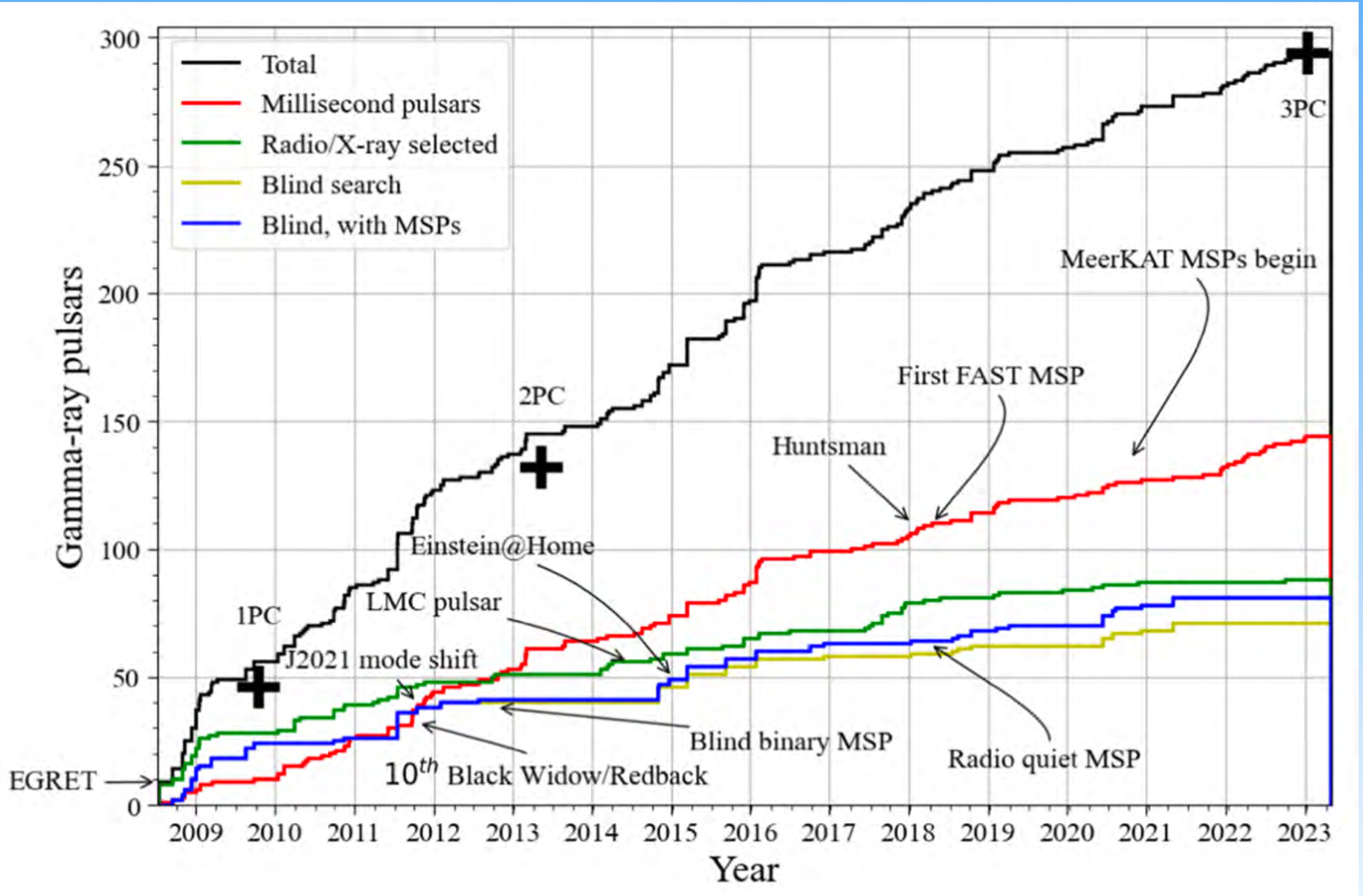
Fermi LAT Pulsars



http://tinyurl.com/fermipulsars

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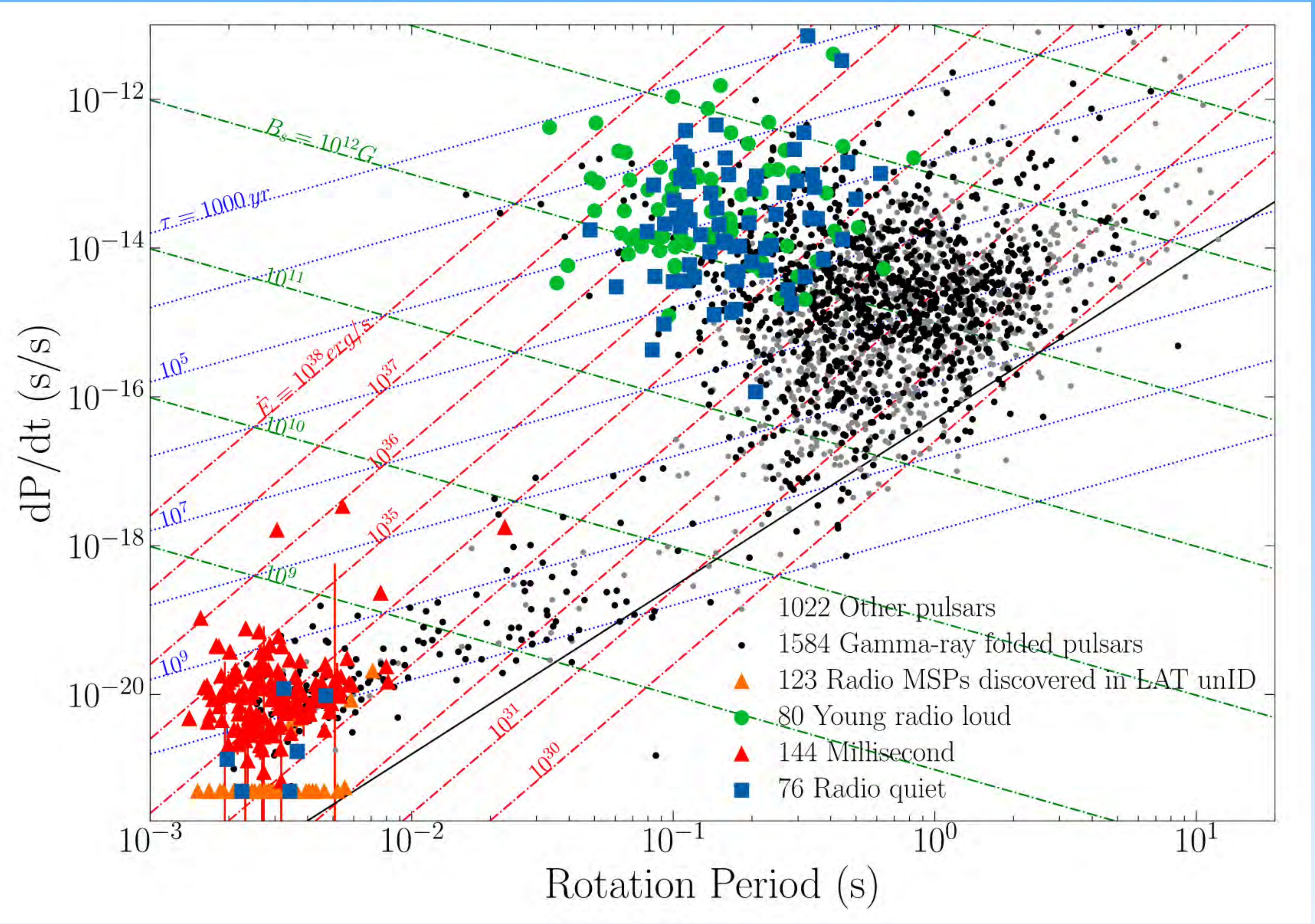
The pulsar population



Smith et al. 2023 (3PC)

The LAT Third Catalog of Pulsars (3PC)

The Astrophysical Journal, 958:191 (72pp), 2023 December 1 https://doi.org/10.3847/1538-4357/acee67

CrossMark

The Third Fermi Large Area Telescope Catalog of Gamma-Ray Pulsars

D. A. Smith[1,2], S. Abdollahi[3], M. Ajello[4], M. Bailes[5], L. Baldini[6], J. Ballet[7], M. G. Baring[8], C. Bassa[9], J. Becerra Gonzalez[10], R. Bellazzini[11], A. Berretta[12], B. Bhattacharyya[13], E. Bissaldi[14,15], R. Bonino[16,17], E. Bottacini[18,19], J. Bregeon[20], P. Bruel[21], M. Burgay[22], T. H. Burnett[23], R. A. Cameron[19], F. Camilo[24], R. Caputo[25], P. A. Caraveo[26], E. Cavazzuti[27], G. Chiaro[26], S. Ciprini[28,29], C. J. Clark[30,31], I. Cognard[32,33], A. Corongiu[22], P. Cristarella Orestano[12,34], M. Crnogorcevic[25,35], A. Cuoco[16,17], S. Cutini[34], F. D'Ammando[36], A. de Angelis[37], M. E. DeCesar[38], S. De Gaetano[14,15], R. de Menezes[16,39], J. Deneva[38], F. de Palma[40,41], N. Di Lalla[19], F. Dirirsa[42], L. Di Venere[15], A. Domínguez[43], D. Dumora[1], S. J. Fegan[21], E. C. Ferrara[25,35,44], A. Fiori[6], H. Fleischhack[25,44,45], C. Flynn[5,46], A. Franckowiak[47], P. C. C. Freire[48], Y. Fukazawa[49], P. Fusco[14,15], G. Galanti[26], V. Gammaldi[50,51], F. Gargano[15], D. Gasparrini[28,29], F. Giacchino[28,29], N. Giglietto[14,15], F. Giordano[14,15], M. Giroletti[36], D. Green[52], I. A. Grenier[53], L. Guillemot[32,33], S. Guiriec[25,54], M. Gustafsson[55], A. K. Harding[56], E. Hays[25], J. W. Hewitt[57], D. Horan[21], X. Hou[58,59], F. Jankowski[32], R. P. Johnson[60], T. J. Johnson[38], S. Johnston[61], J. Kataoka[62], M. J. Keith[63], M. Kerr[64], M. Kramer[48,63,65], M. Kuss[11], L. Latronico[16], S.-H. Lee[66], D. Li[67,68], J. Li[69,70], B. Limyansky[60], F. Longo[71,72], F. Loparco[14,15], L. Lorusso[14,15], M. N. Lovellette[73], M. Lower[61], P. Lubrano[34], A. G. Lyne[63], Y. Maan[13], S. Maldera[16], R. N. Manchester[61], A. Manfreda[6], M. Marelli[26], G. Martí-Devesa[74], M. N. Mazziotta[15], J. E. McEnery[25,35], I. Mereu[12,34], P. F. Michelson[19], M. Mickaliger[63], W. Mitthumsiri[75], T. Mizuno[76], A. A. Moiseev[35,44], M. E. Monzani[19,77], A. Morselli[28], M. Negro[25,78], R. Nemmen[39], L. Nieder[30,31], E. Nuss[79], N. Omodei[19], M. Orienti[36], E. Orlando[19,80], J. F. Ormes[81], M. Palatiello[37,71,72,82], D. Paneque[52], G. Panzarini[14,15], A. Parthasarathy[48], M. Persic[72,83], M. Pesce-Rollins[11], R. Pillera[14,15], H. Poon[49], T. A. Porter[19], A. Possenti[22], G. Principe[36,71,72], S. Rainò[14,15], R. Rando[18,84,85], S. M. Ransom[86], P. S. Ray[64], M. Razzano[6], S. Razzaque[54,87], A. Reimer[74], O. Reimer[74], N. Renault-Tinacci[88], R. W. Romani[19], M. Sánchez-Conde[50,51], P. M. Saz Parkinson[60], L. Scotton[79], D. Serini[15], C. Sgrò[11], R. Shannon[46], V. Sharma[44], Z. Shen[89], E. J. Siskind[90], G. Spandre[11], P. Spinelli[14,15], B. W. Stappers[63], T. E. Stephens[25,91], D. J. Suson[92], S. Tabassum[93], H. Tajima[94,95], D. Tak[96], G. Theureau[32,33], D. J. Thompson[25], O. Tibolla[97], D. F. Torres[98,99,100], J. Valverde[25,78], C. Venter[101], Z. Wadiasingh[25], N. Wang[102], N. Wang[102], P. Wang[103,104], P. Weltevrede[63], K. Wood[105], J. Yan[103], G. Zaharijas[106], C. Zhang[103], and W. Zhu[103,104]

Smith et al. 2023

National Aeronautics and Space Administration
Goddard Space Flight Center

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Fermi
Gamma-ray Space Telescope

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- **Data Access**
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  - LAT Light Curve Repository
  - GBM Data
- Data Analysis
- Caveats
- Newsletters
- FAQ

LAT Third Catalog of Gamma-ray Pulsars

Having discovered pulsations from nearly 300 rotation-powered pulsars, and steady point sources colocated with another 40 millisecond pulsars (MSPs), the Fermi LAT established pulsars as the dominant GeV gamma-ray source class in the Milky Way. Among them are dozens of young radio-quiet pulsars discovered via pulsations in LAT data, dozens of radio-loud young and recycled pulsars previously known from their radio pulsations, and dozens of MSPs detected in the radio following their discovery as unassociated LAT sources.

This catalog characterizes the known gamma-ray pulsars as uniformly as feasible using as much as 14 years of on-orbit data. The Third Fermi LAT Catalog of Gamma-ray Pulsars Catalog (3PC) paper details the catalog and its construction.

Catalog Data Products

- LAT Third Pulsar Catalog Paper
- Main catalog data file:
  - README_Pulsars_3PC_Catalog+SEDs.txt
  - Main catalog file (FITS format)
  - Main catalog file (Excel format)
  - Example Python script to read the catalog FITS file: Example_3PC_CatalogReader.py
  - Catalog BROWSE table (under construction)
- Individual pulsar summary HTML pages
- Timing model files (par files):
  - README_3PC_TimingModels.txt
  - 3PC_TimingModels_20230725.tgz
- LAT SED plots for all pulsars:
  - README_3PC_SEDs.txt
  - Python script to generate SEDs from 3PC catalog: 3PC_SEDPlotter.py
  - SED plots in single PDF file
  - SED plots tar file (individual PDF, PNG, and ASCII files)
- Pulse profile (LC) data and plots for all pulsars:
  - README_3PC_ProfileData.txt
  - Pulse profile plots in tar files (PNG format)
  - Pulse profile plots in tar files (PDF format)
  - Pulse profile data in FITS and ASCII format
  - Example python script that reads ProfileData FITS files: Example_3PC_PlotProfileData.py
  - Energy resolved pulse profile fits in tar file (PNG format)
  - Energy resolved pulse profile fits in tar file (PDF format)
- All-Sky Sensitivity map:
  - README_3PC_SensitivityMap.txt
  - 3PC_SensitivityMap_20230629.fits
  - Python script to read map: Example_3PC_SensitivityMap.py
- Combined tar file of all of the above products
- Photon data files for each pulsar
- 3PC is now at the Fermi LAT Light Curve Repository (LCR). Scroll down to "Data Overlays" at the left and slide the 3PC button to "on". The 3PC will now appear as a tab under "Catalog Sources". Clicking on one of the Source IDs in the table will take you to the individual pulsar summary page.
- Updates for post-3PC pulsar discoveries
  - Gamma-ray PSR J1356+0230
  - Gamma-ray PSR J2116+3701
  - Gamma-ray PSR J2333-5526

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/3rd_PSR_catalog/

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X-ray observations still important

The Astrophysical Journal Letters, 725:L6–L10, 2010 December 10 doi:10.1088/2041-8205/725/1/L6

X-RAY PULSATIONS FROM THE RADIO-QUIET GAMMA-RAY PULSAR IN CTA 1*

P. A. Caraveo[1], A. De Luca[1,2,3], M. Marelli[1,4], G. F. Bignami[1,2], P. S. Ray[5], P. M. Saz Parkinson[6], and G. Kanbach[7]
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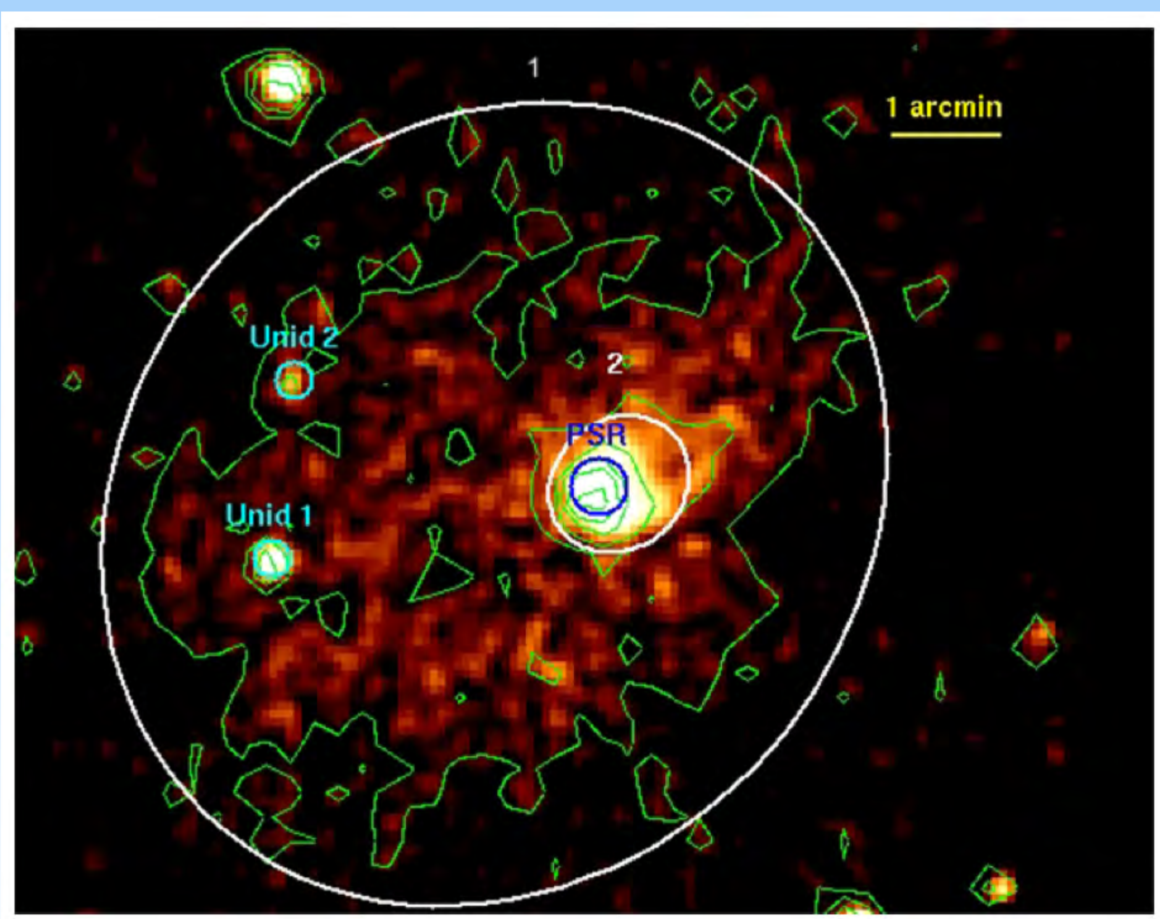
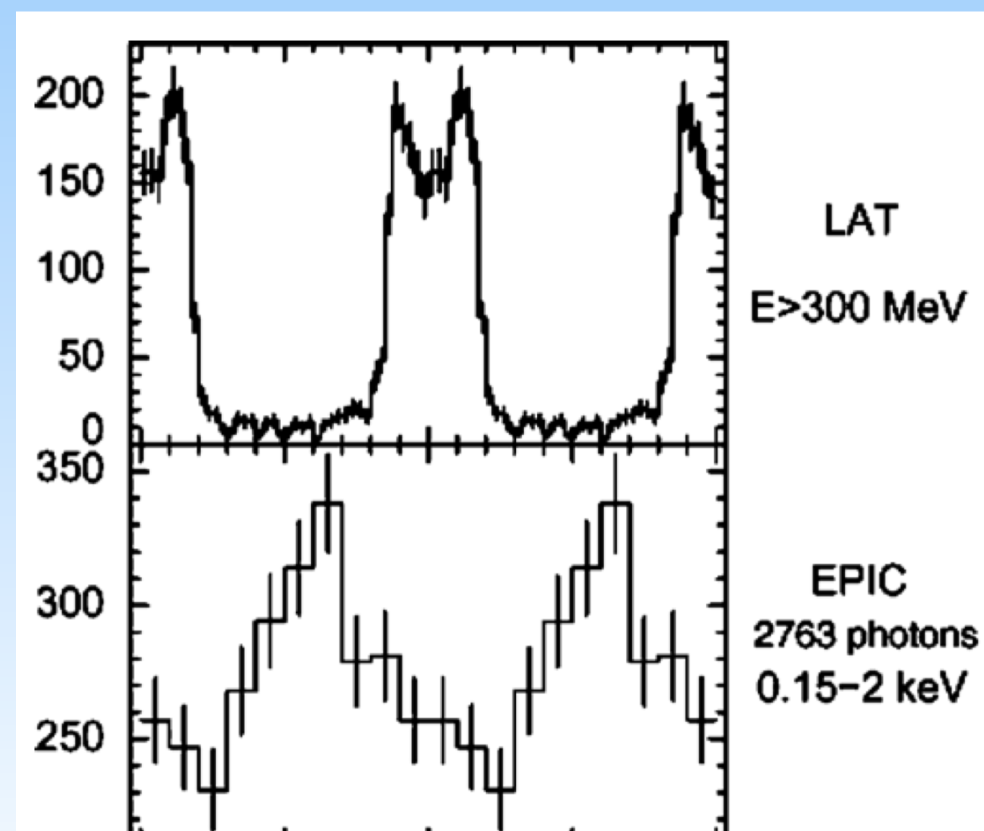
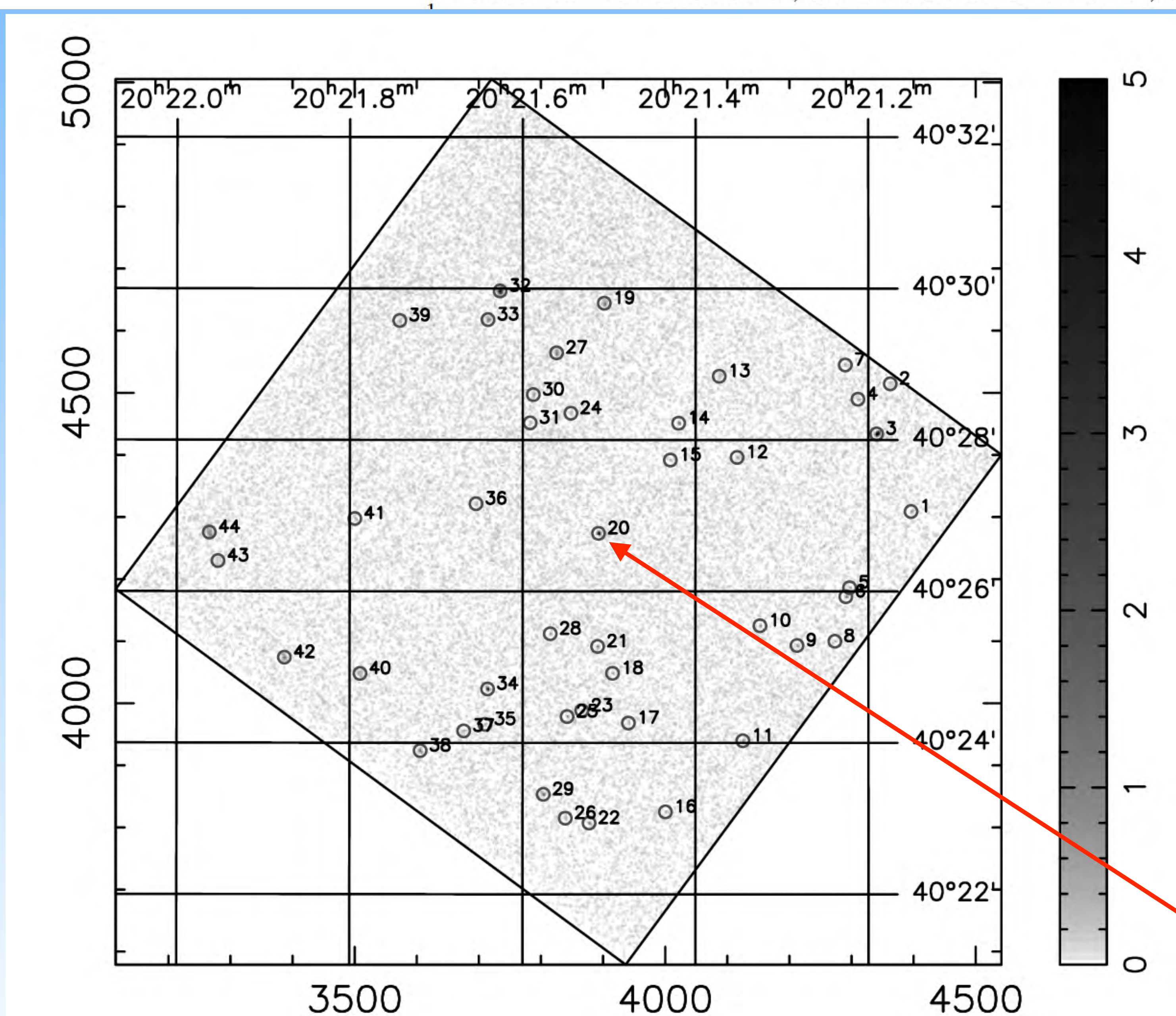




The Astrophysical Journal, 743:74 (12pp), 2011 December 10 doi:10.1088/0004-637X/743/1/74

THE IDENTIFICATION OF THE X-RAY COUNTERPART TO PSR J2021+4026

Martin C. Weisskopf[1], Roger W. Romani[2], Massimiliano Razzano[3,4,5], Andrea Belfiore[4,6,7], Pablo Saz Parkinson[4], Paul S. Ray[8], Matthew Kerr[9], Alice Harding[10], Douglas A. Swartz[11], Alberto Carramiñana[12], Marcus Ziegler[4], Werner Becker[13], Andrea De Luca[6,14,15], Michael Dormody[4], David J. Thompson[16], Gottfried Kanbach[13], Ronald F. Elsner[1], Stephen L. O'Dell[1], and Allyn F. Tennant[1]



56 ks Chandra observation (ObsID 11235, 2010 August 27)

X-ray source dominated by thermal (not power law) emission.
One of 44 sources detected in a 2010, 56 ks *Chandra* observation.

R.A. $20^h21^m30^s.733$, decl. $+40°26'46''.04$ (J2000)

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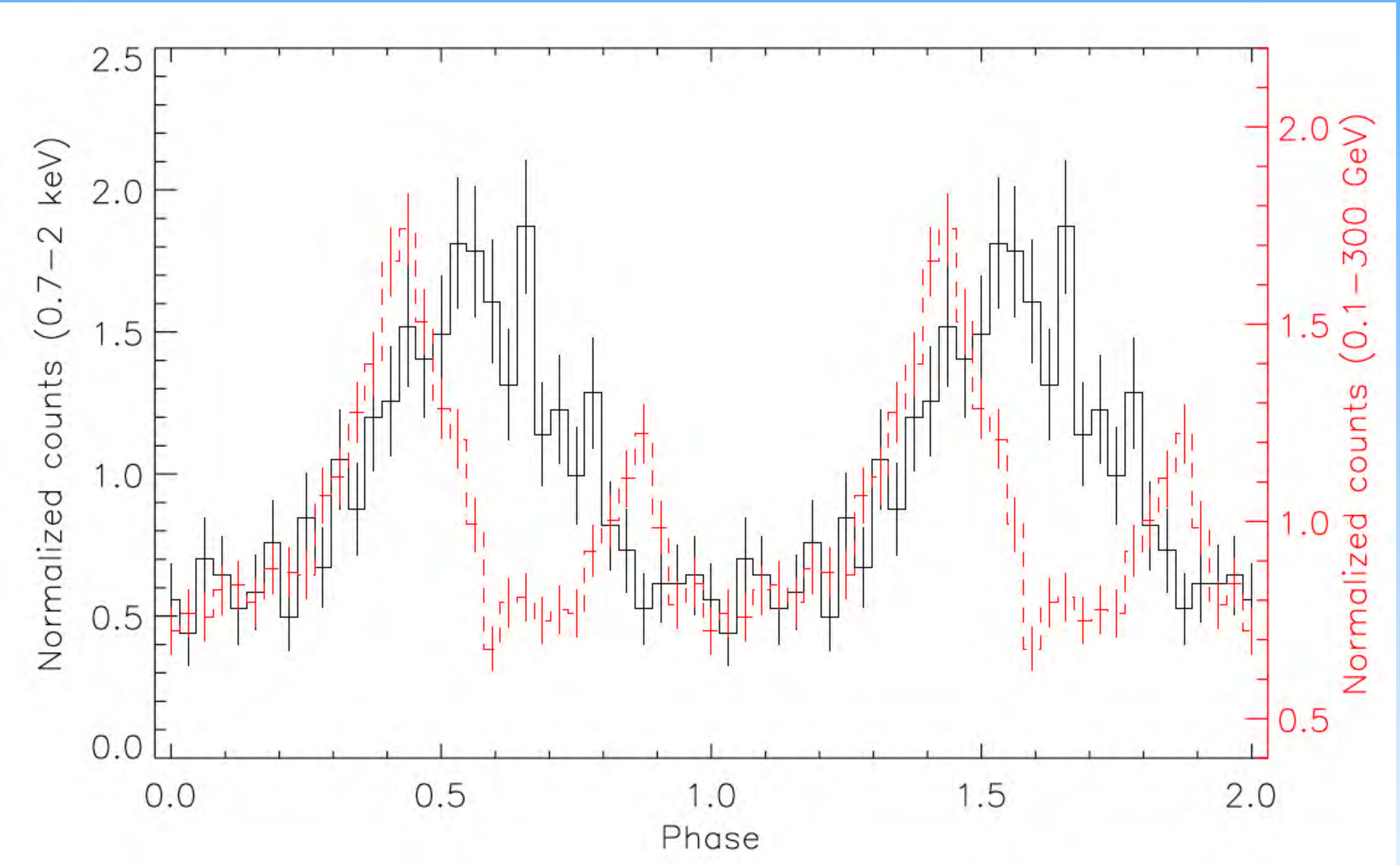
X-ray pulsations

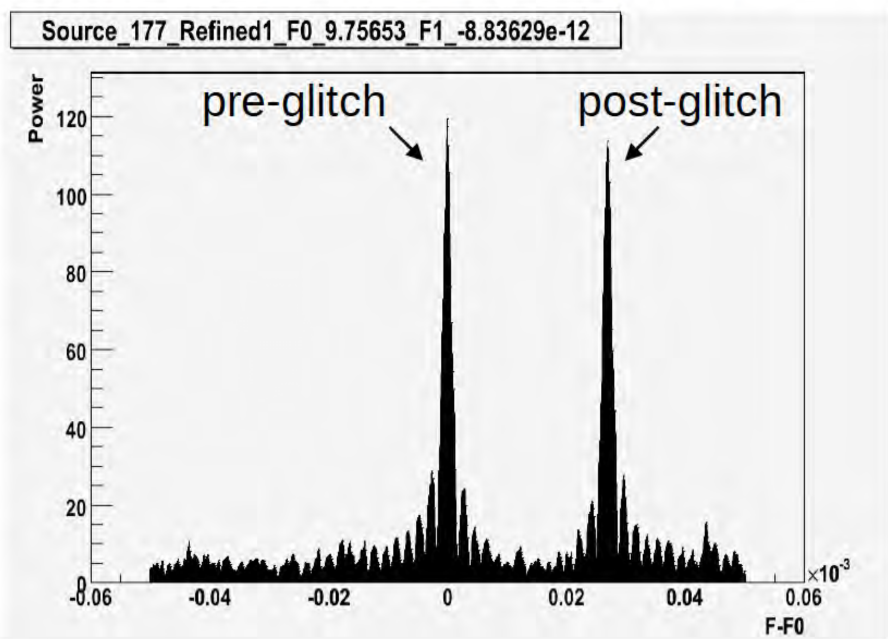


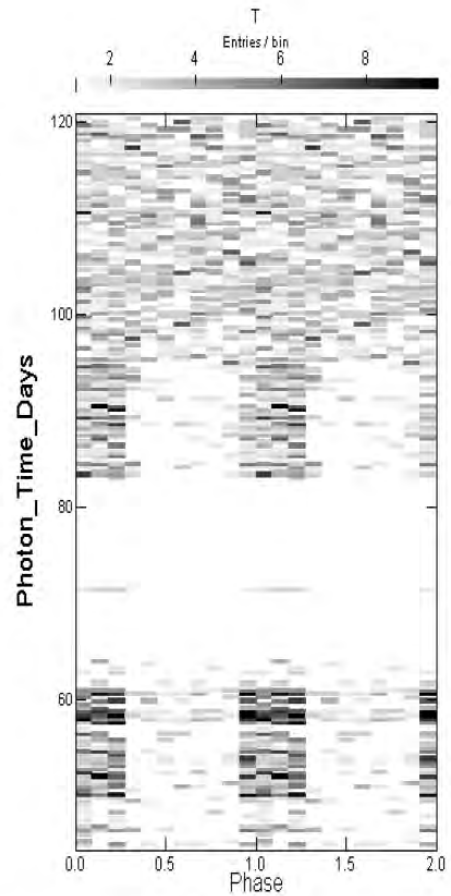
~133 ks XMM-Newton Observation, 2012, April 11 (Obs. ID: 0670590101)

Lin et al. 2013

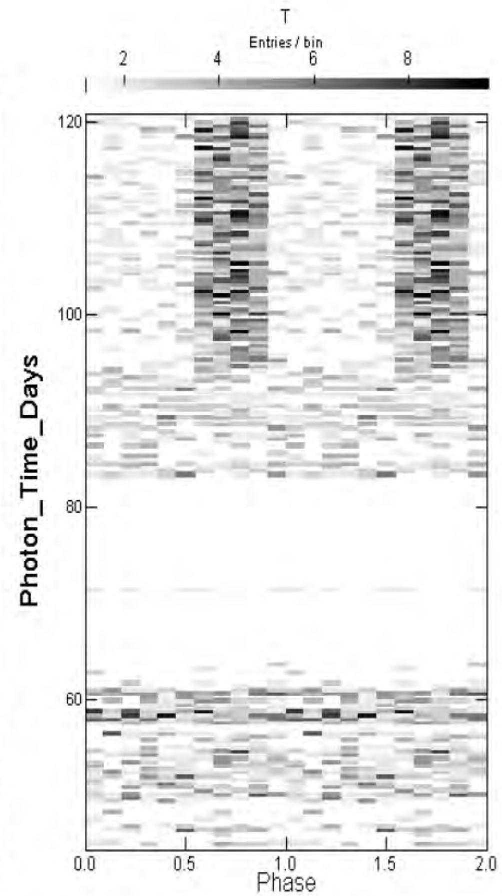
Gamma-ray pulsar *glitches*

- A search around a narrow range of frequencies centered on known ephemeris results in two peaks in power spectrum
- Glitch occurred between 14-15 August
- Known to glitch (e.g. 1992, 1995)
- Radio observations are planned

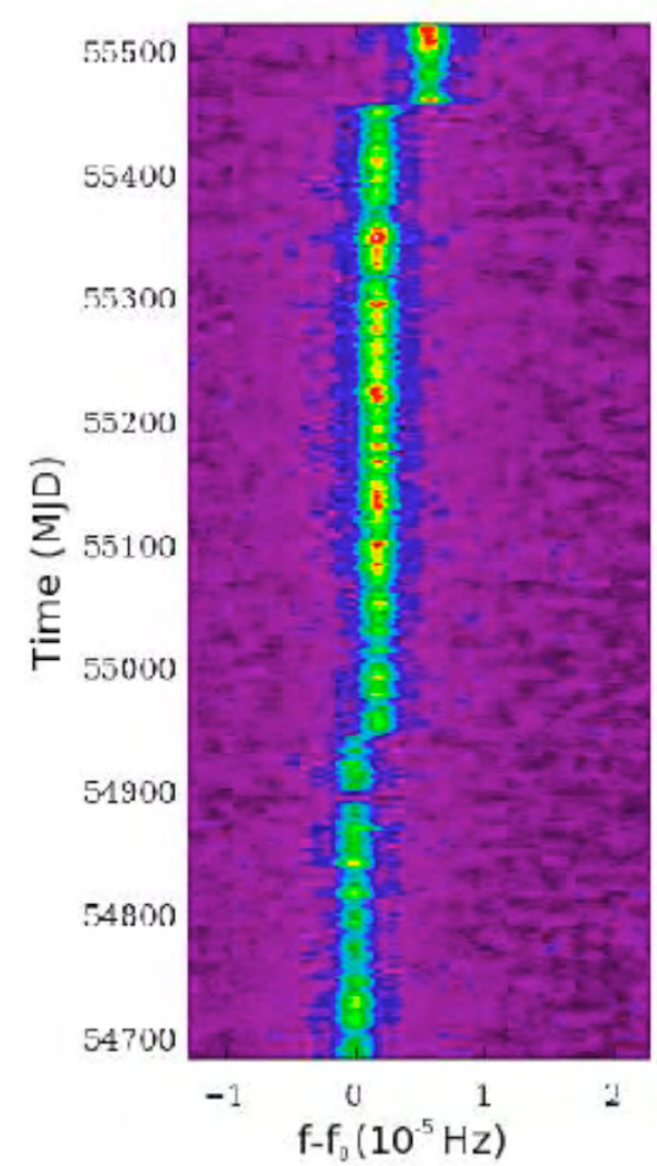




Pre-glitch ephemeris



Post-glitch ephemeris



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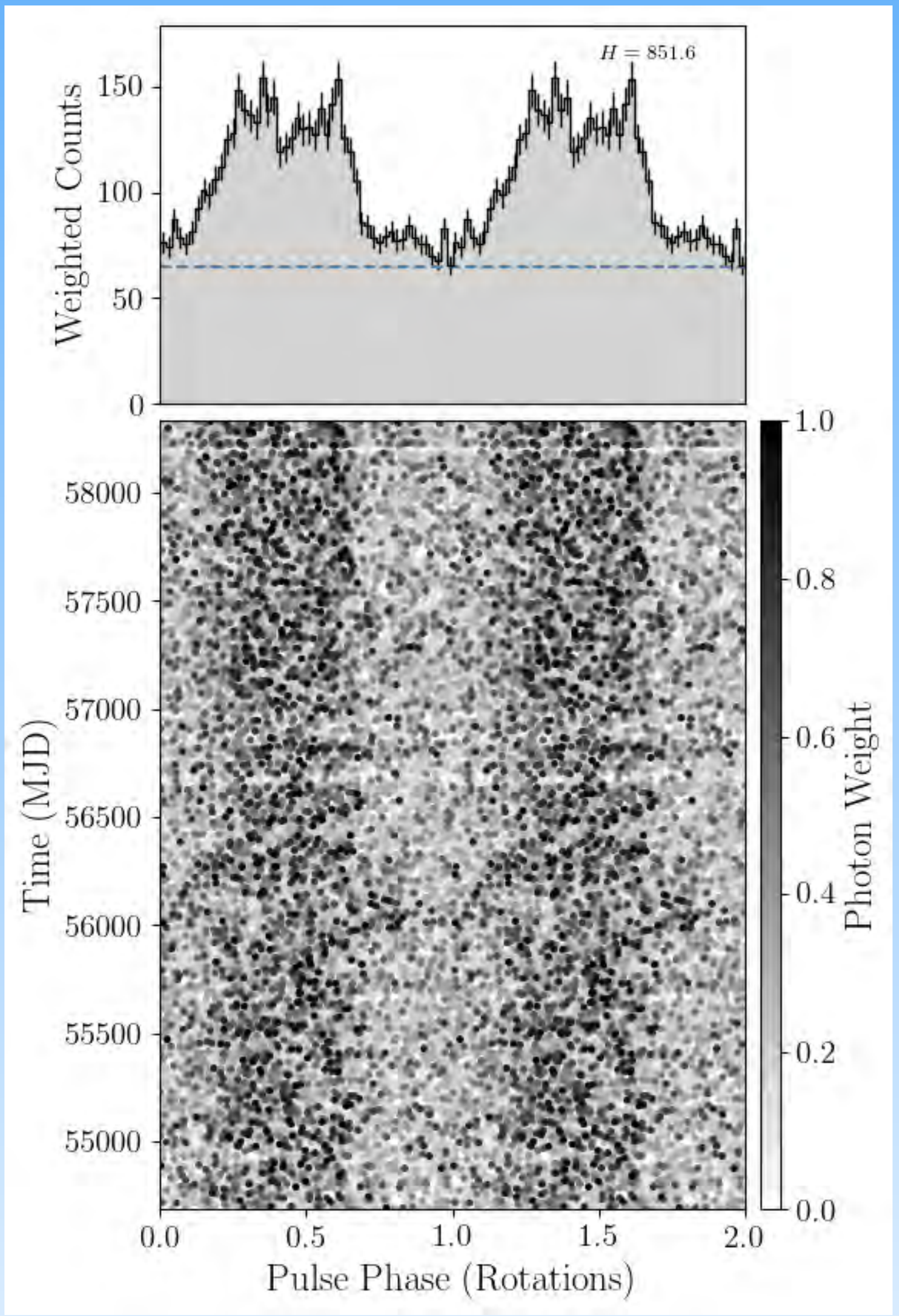
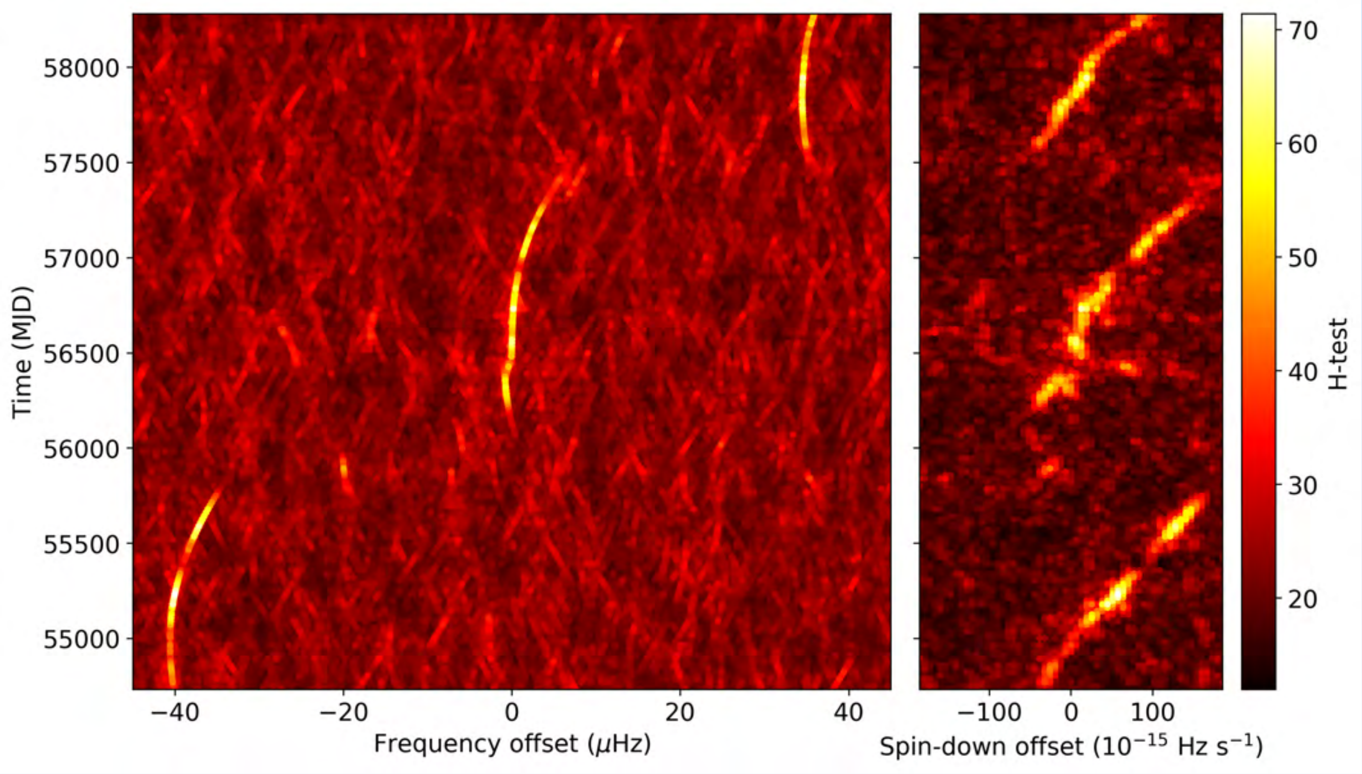
PSR J1111-4039

SNR MSH 11-62
(G291.0-0.1)





$$\dot{E} \sim 7 \times 10^{36} \mathrm{erg\,s^{-1}}$$

$$B_s \sim 4.9 \times 10^{12}\ \mathrm{G}$$

$$\tau \sim 7.8\,\mathrm{kyr}$$

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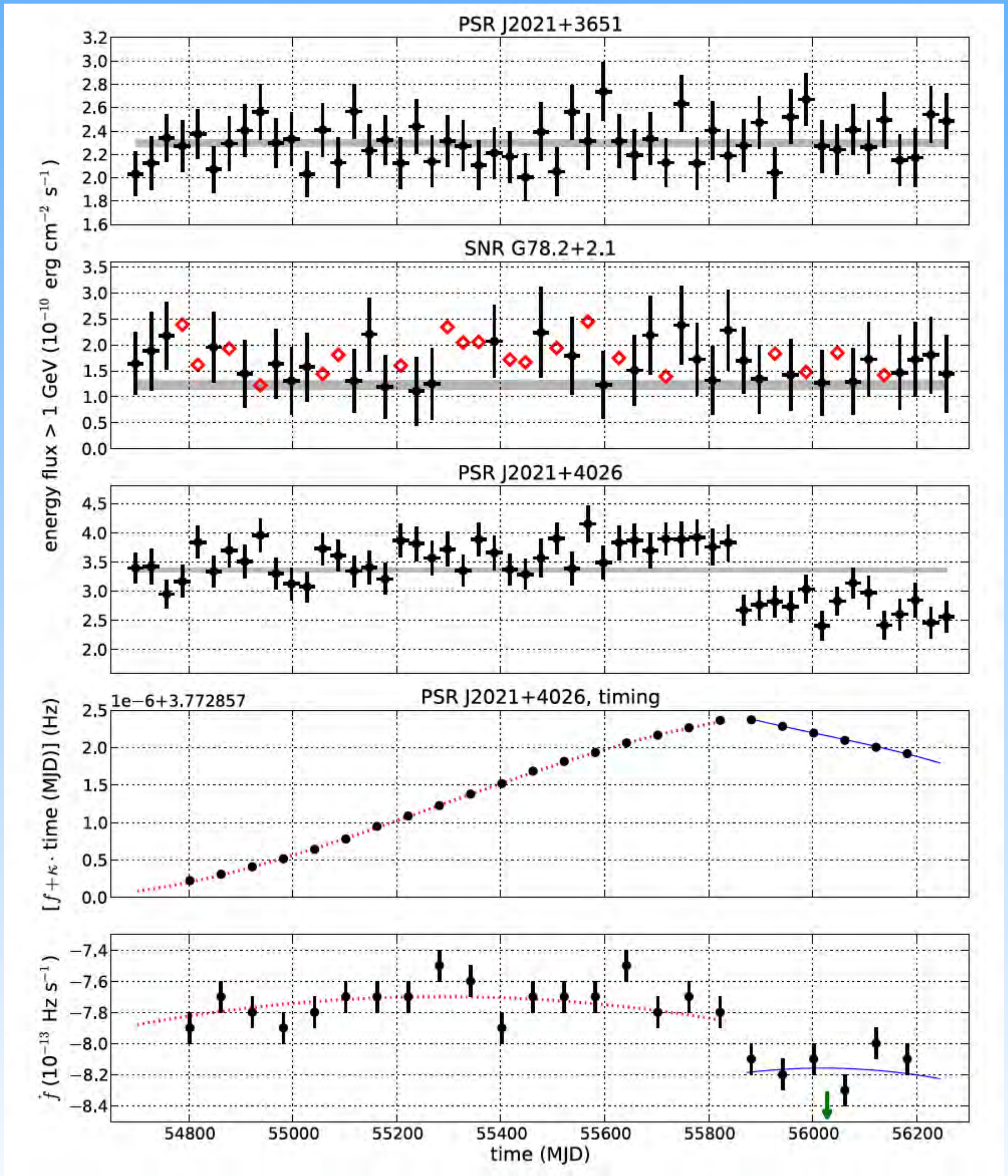
Variability in PSR J2021+4026!



Allafort et al. 2013

- Flux decrease (~20%) around October 2011
- Frequency spin down rate increase (~5%)
- Changes in pulse profile observed

The first *variable* gamma-ray pulsar seen by Fermi LAT

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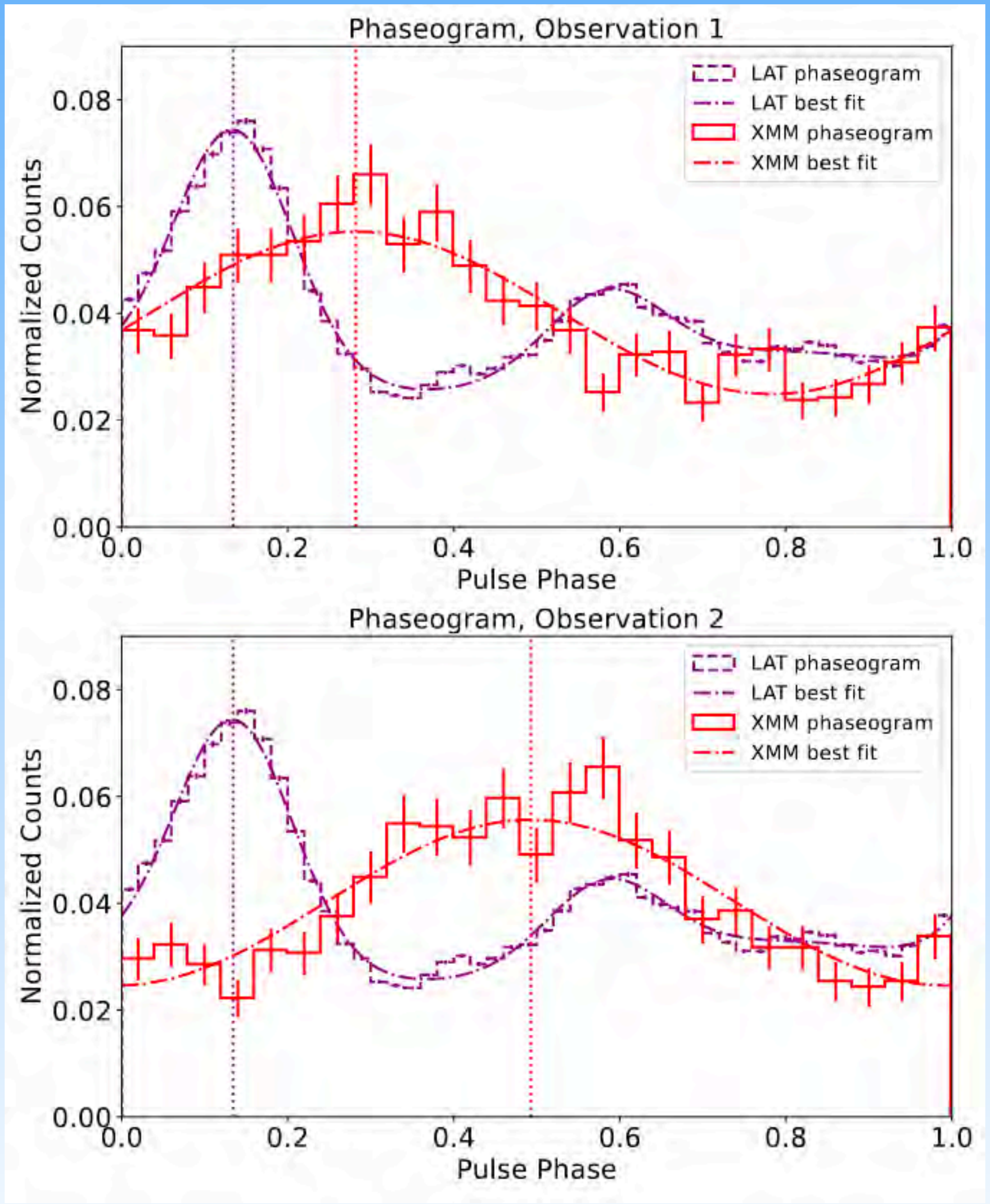
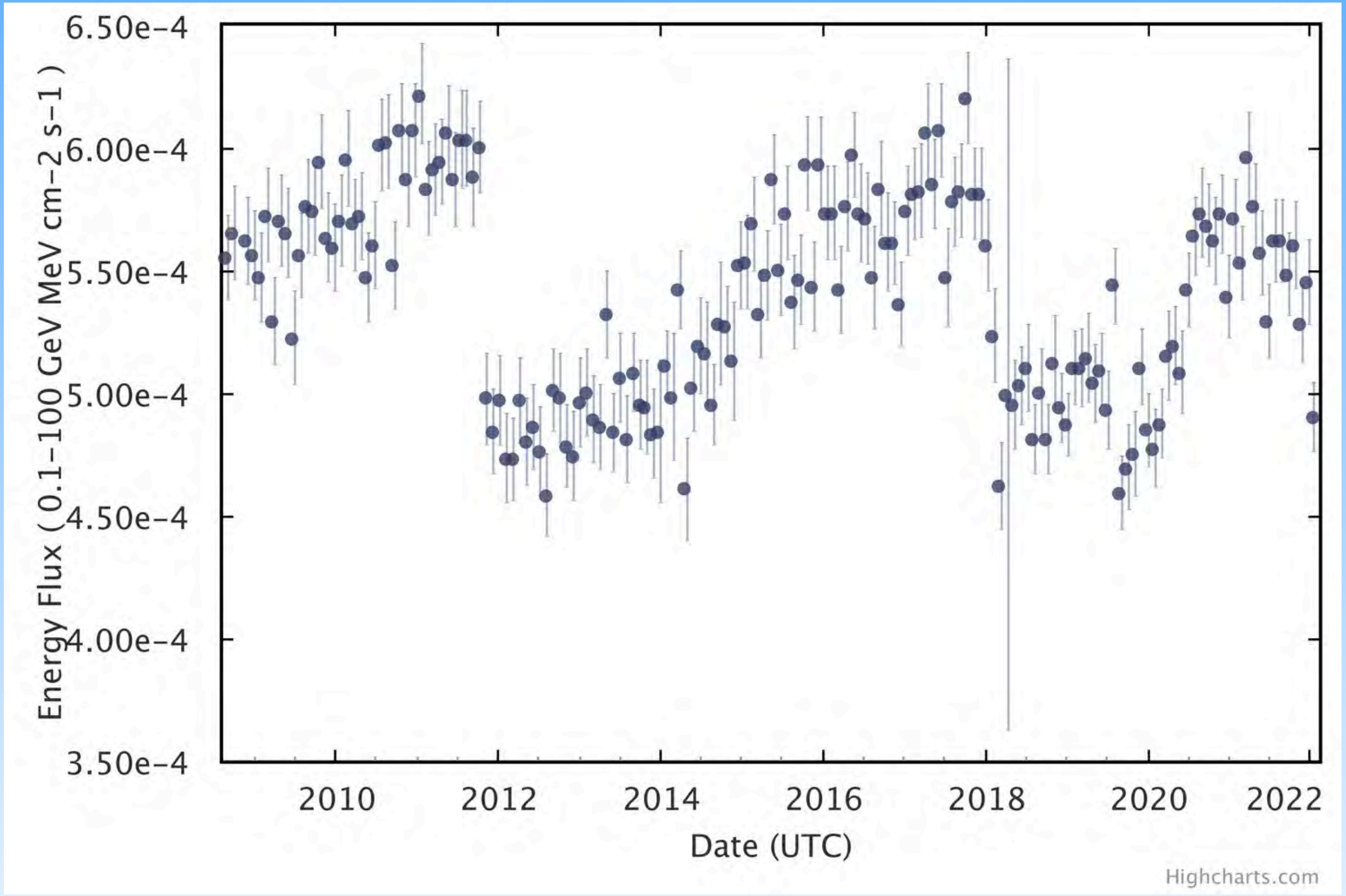
Gamma-ray/X-ray pulse shifts



Razzano et al. 2023

- 12 Years of data
- 100 MeV to 300 GeV
- Full mission timing analysis
- XMM Observation 1 and 2 roughly equal length (~130 ks) separated by 3.7 yr

Variability in PSR J2021+4026



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/

Abdollahi et al. 2023

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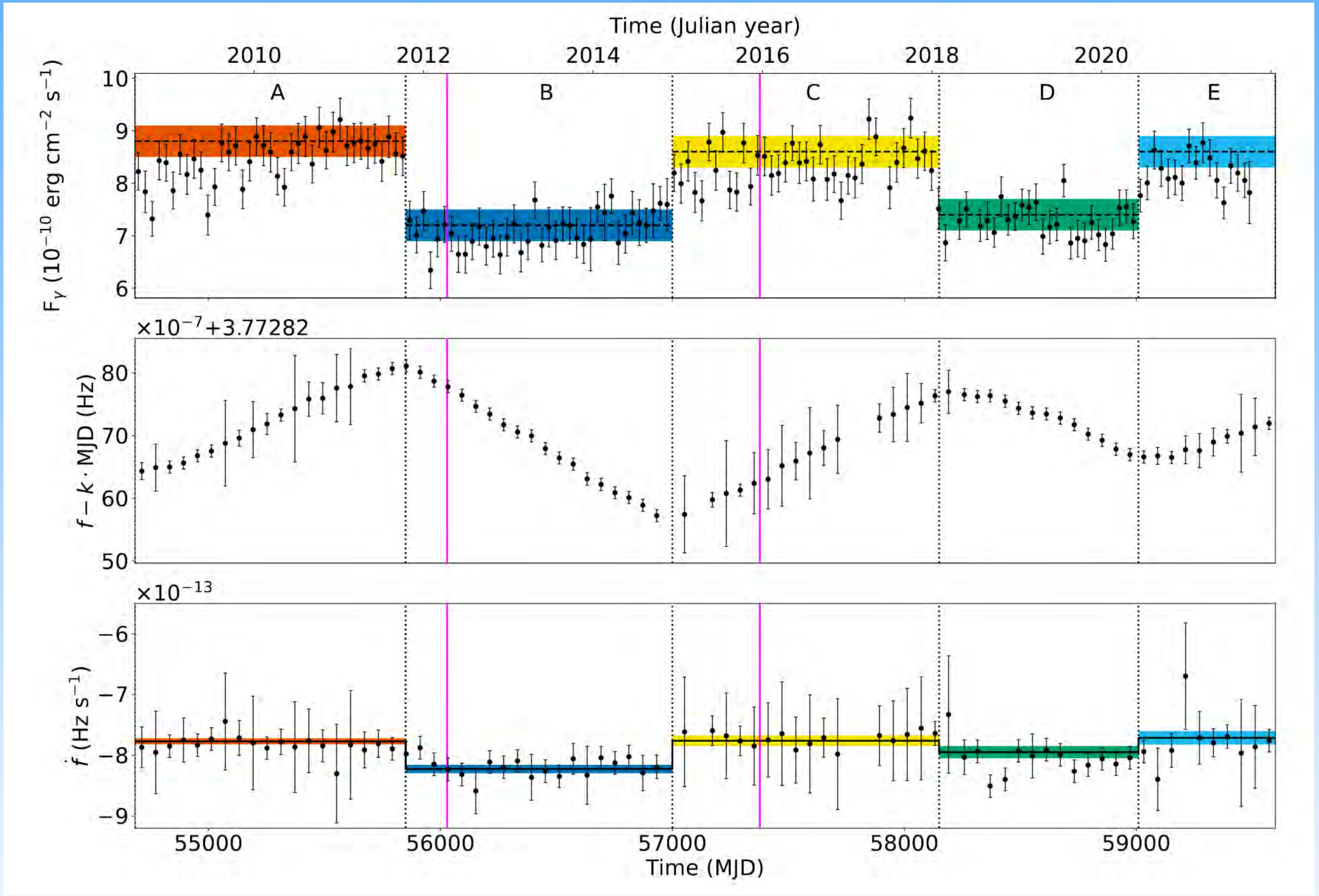
PSR J2021+4026



Fiori et al. 2024

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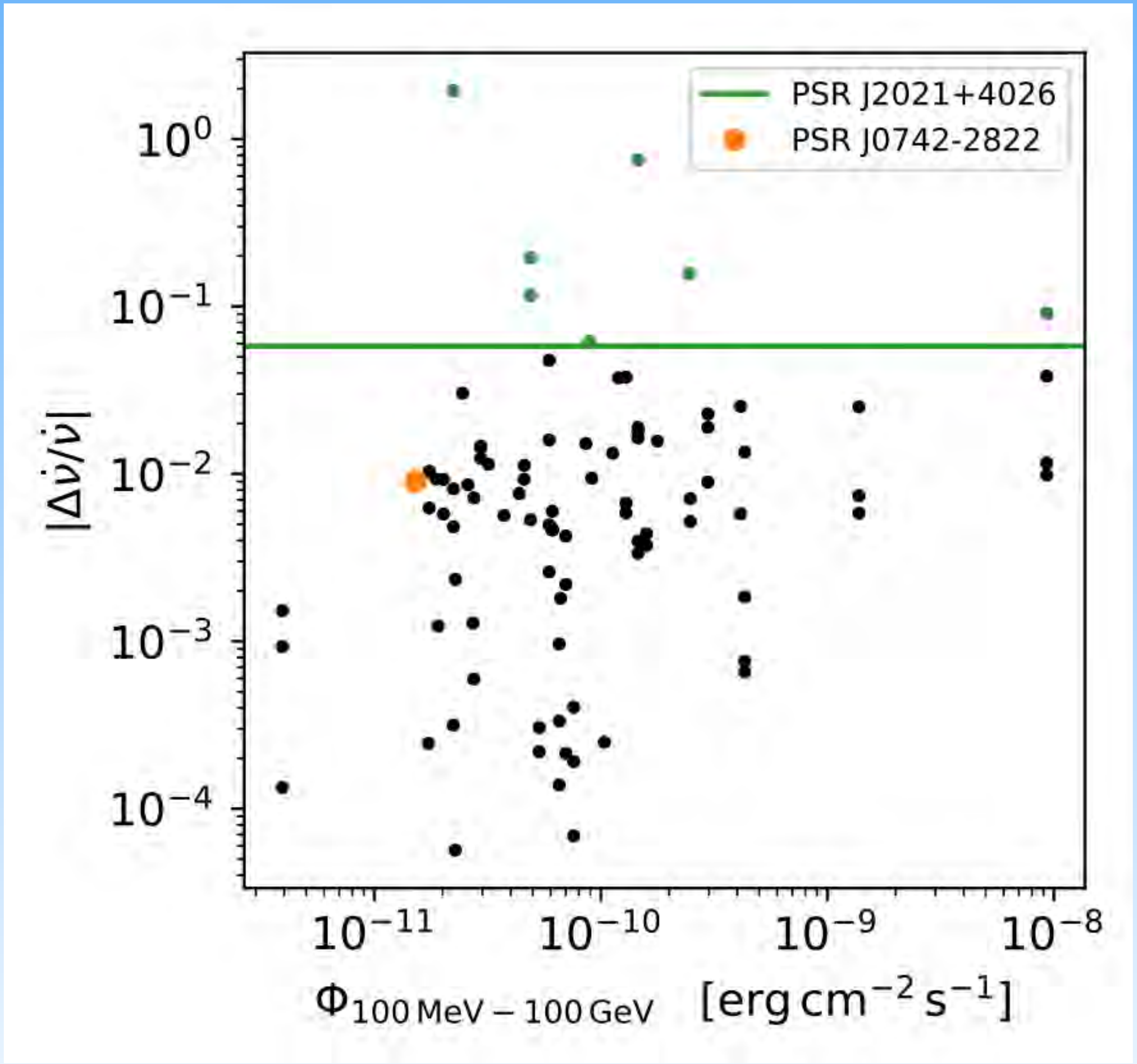
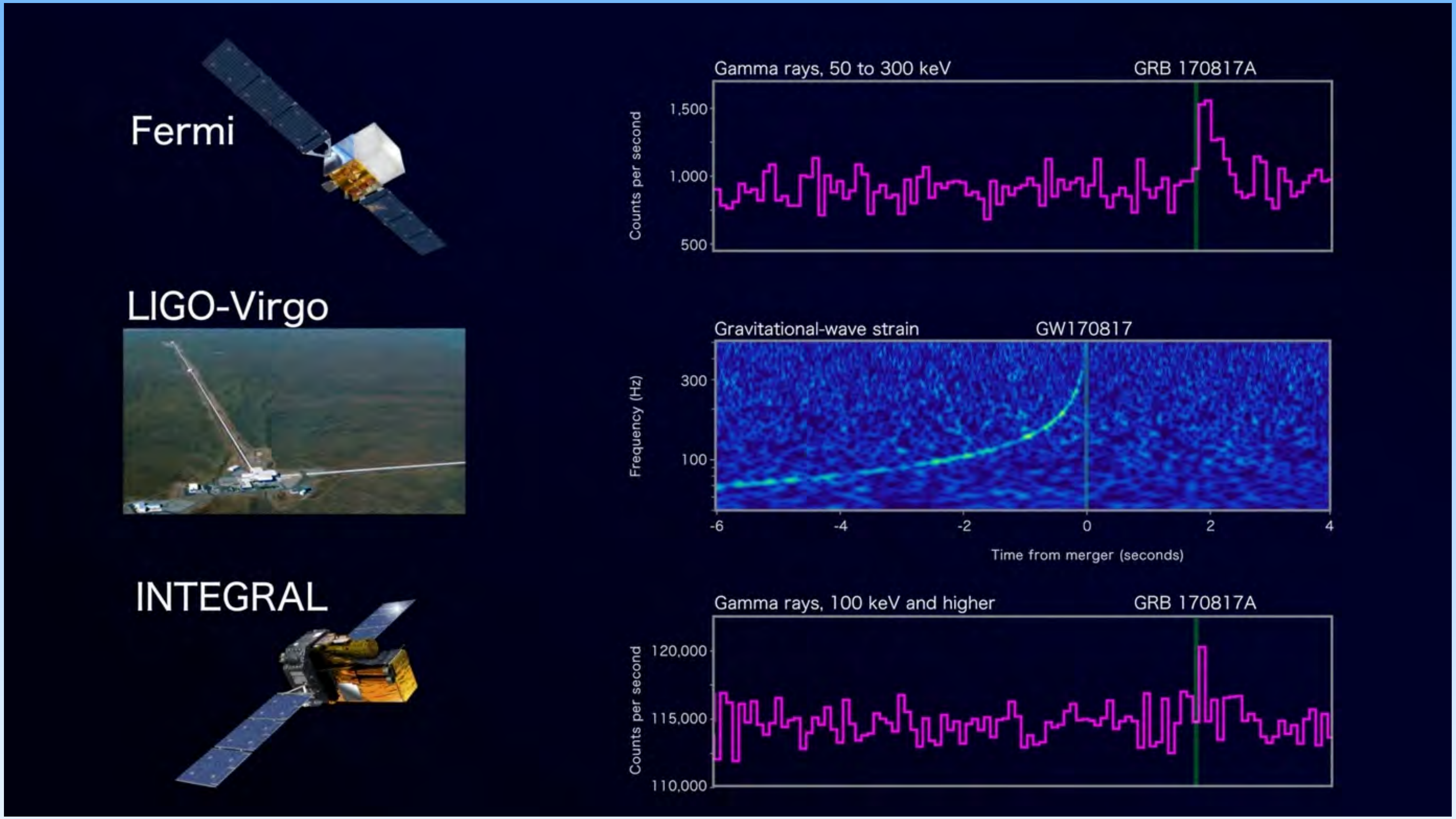
Search for variability around glitches



Cozzolongo et al. 2025

Multi-messenger observations of merging NS



Credit: NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

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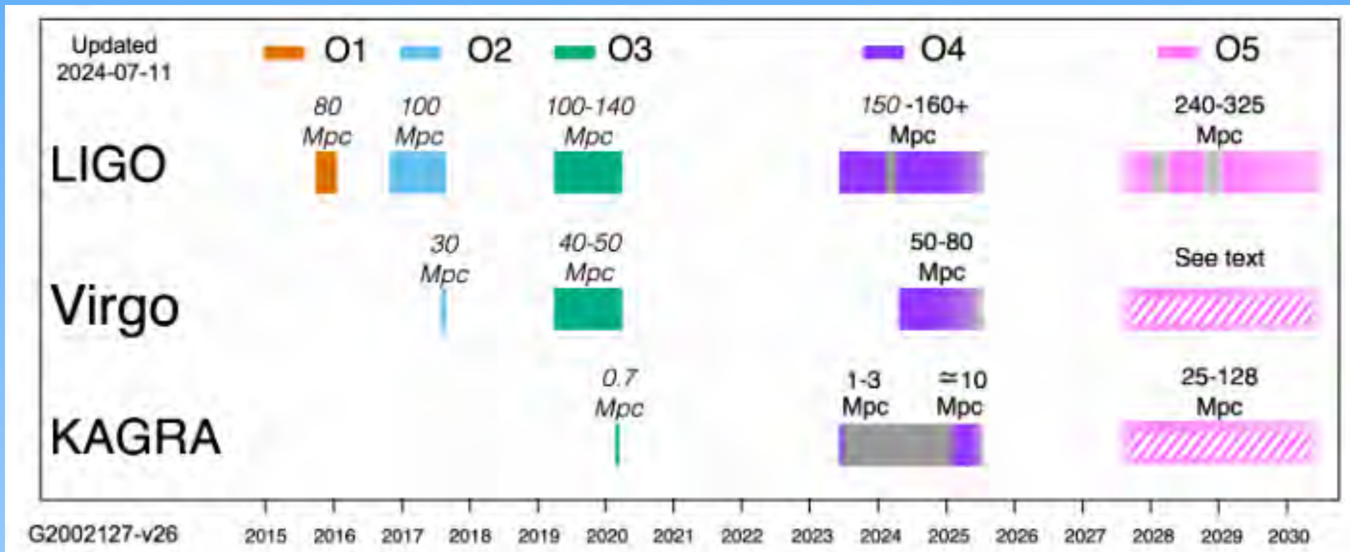
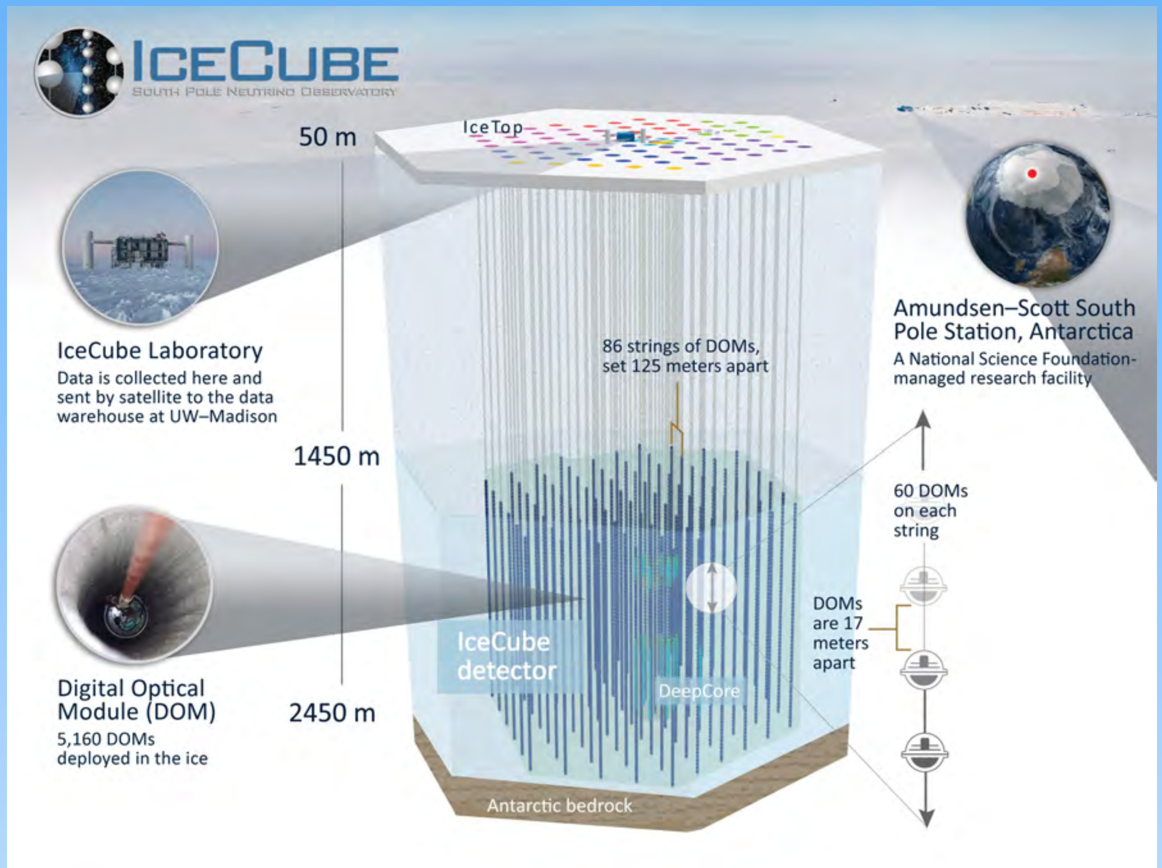
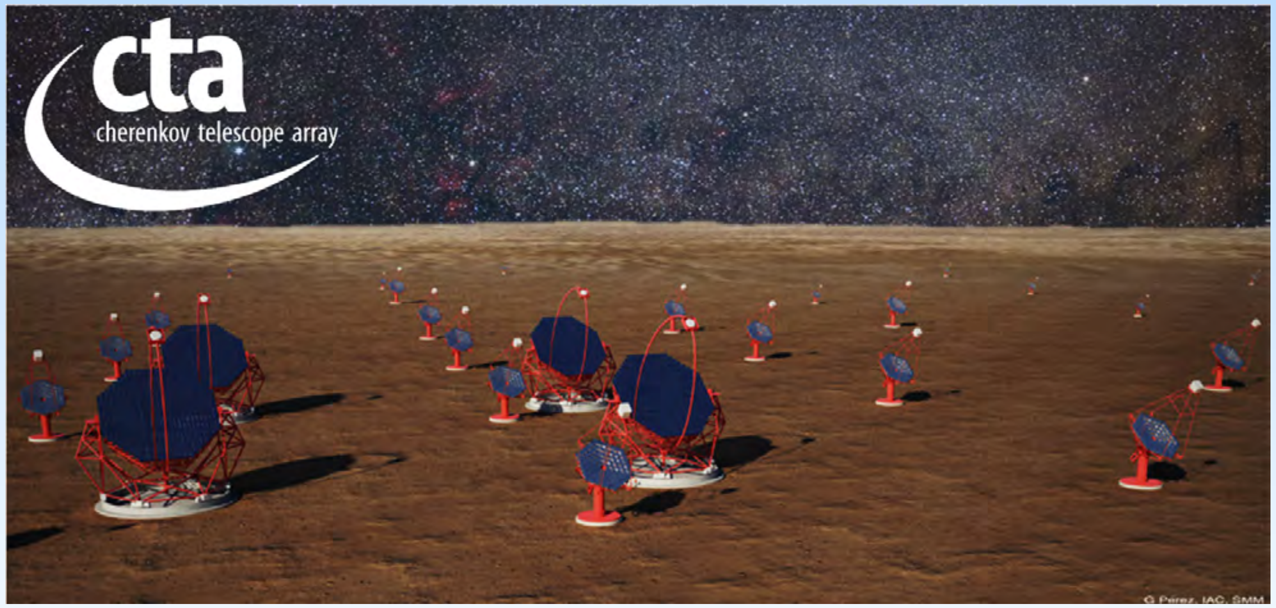
Fermi in the era of TDAMM





Credit: Rubin Obs./NSF/AURA



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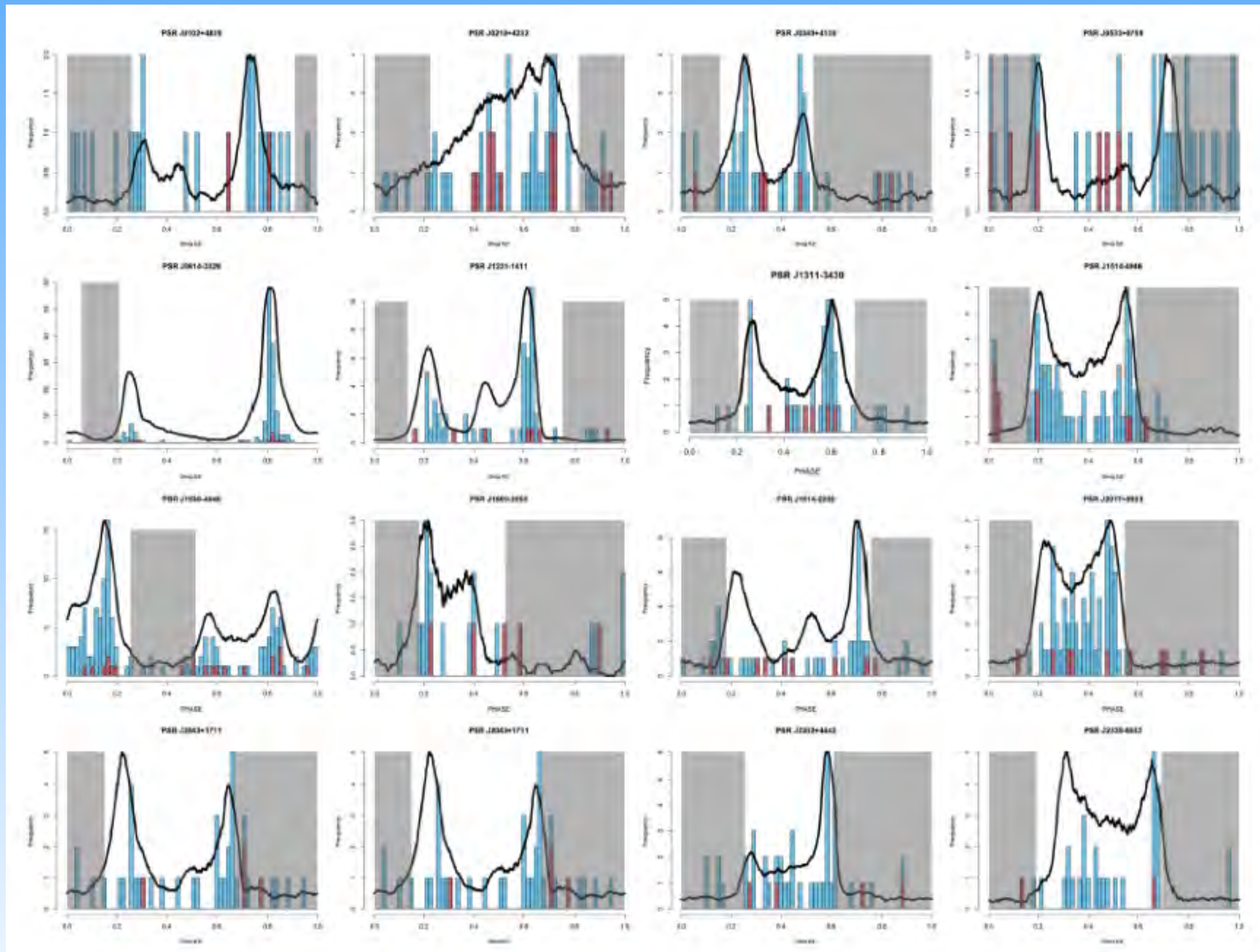
Searching for VHE emission



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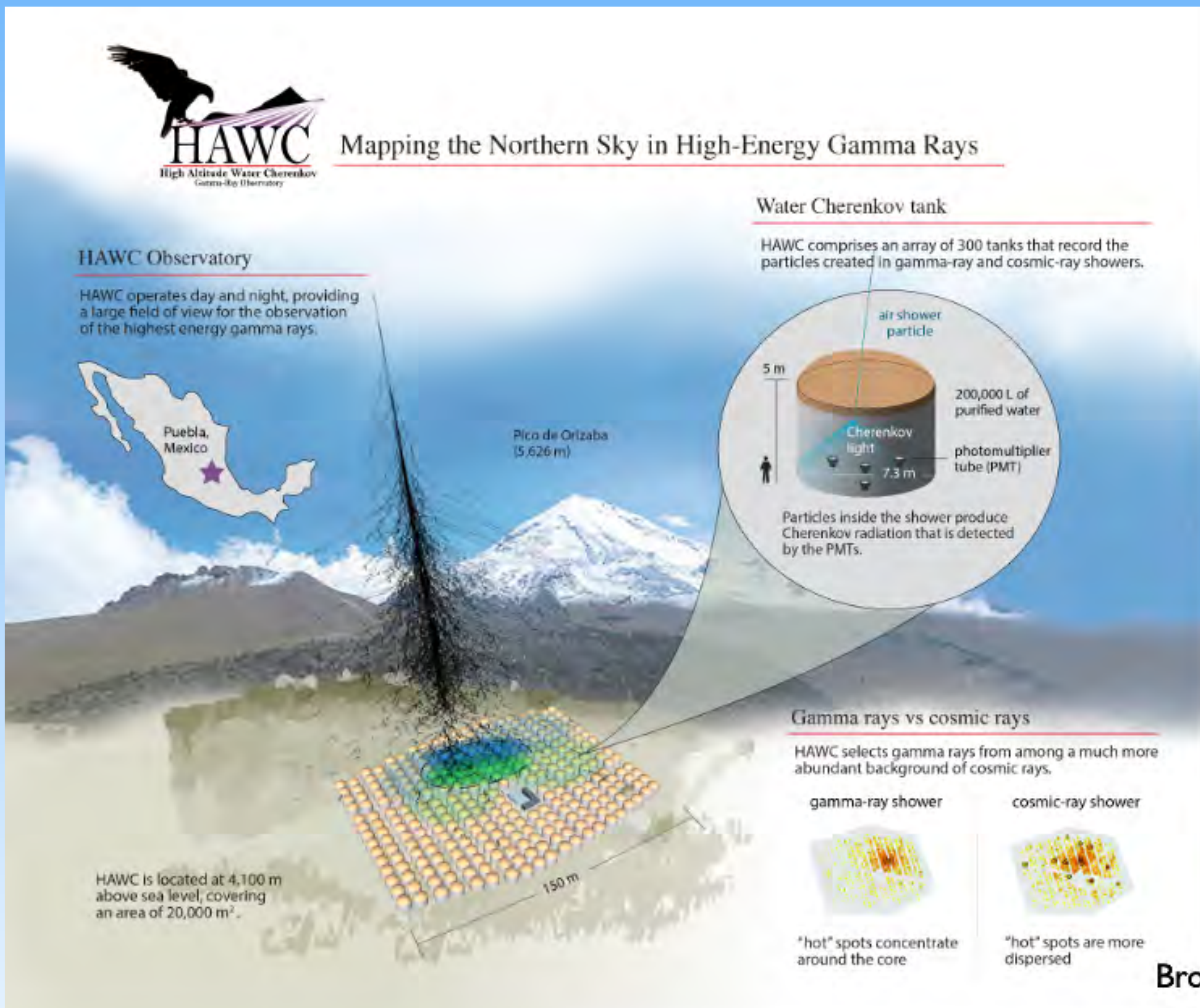
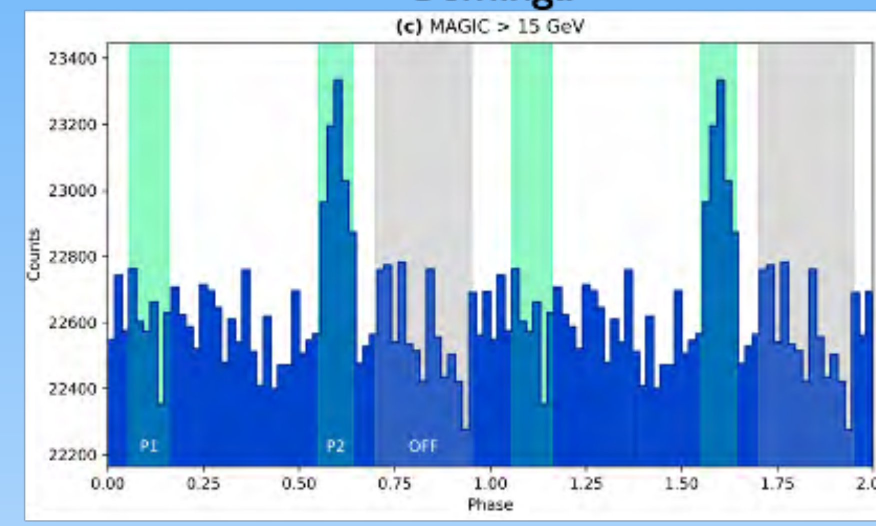
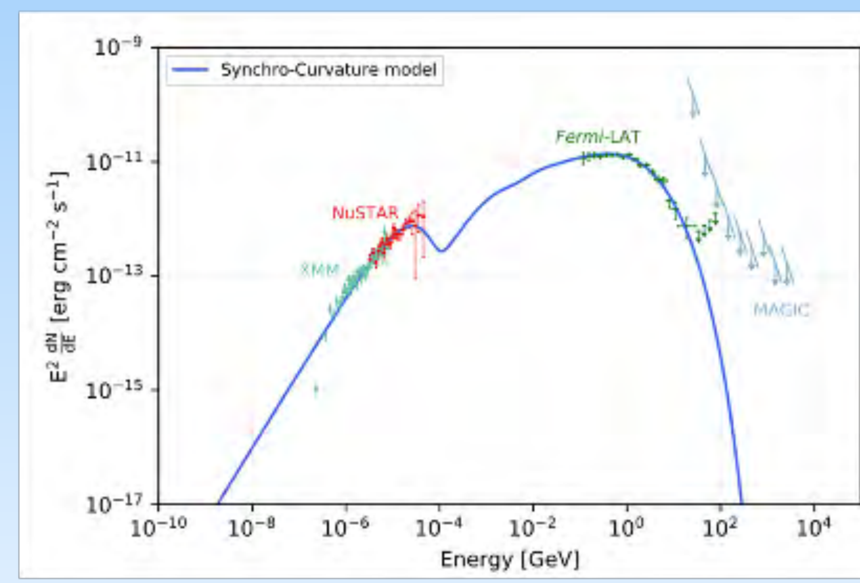
Searching for VHE emission



Geminga



Acciari et al. 2020



Broadband spectrum of PSR J0218+4232, from the X-ray (XMM and NuSTAR) to the γ-ray (Fermi-LAT and MAGIC)

Acciari et al., The Astrophysical Journal, 922:251 (14pp), 2021 December 1

Summary

- Fermi LAT has revolutionized pulsar astrophysics (despite detecting only ~10% of known pulsars)
    - In addition to uncovering new populations of pulsars undetectable in radio, it has enabled the discovery of a large number of (mostly millisecond) pulsars
    - The complementary characteristics (strengths and limitations) of Fermi LAT, compared to radio telescopes, allows for a more complete understanding of the pulsar population and associated physics questions
    - The extension of the Fermi LAT data set will open up (enable) new possibilities for the study of gamma-ray pulsars (e.g. VHE)
- Fermi will continue to help uncover new pulsar surprises in the TDAMM era, especially with the arrival of new survey instruments, including CTA.

NSF

Thank you

NASA

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