Lessons learnt from Fermi-LAT pulsars

Dr. Pablo Saz Parkinson
Santa Cruz Institute for Particle Physics (SCIPP), UCSC
for the Fermi LAT Collaboration

HONEST 3 - The high end of pulsar spectra
Tuesday, 26 November 2024

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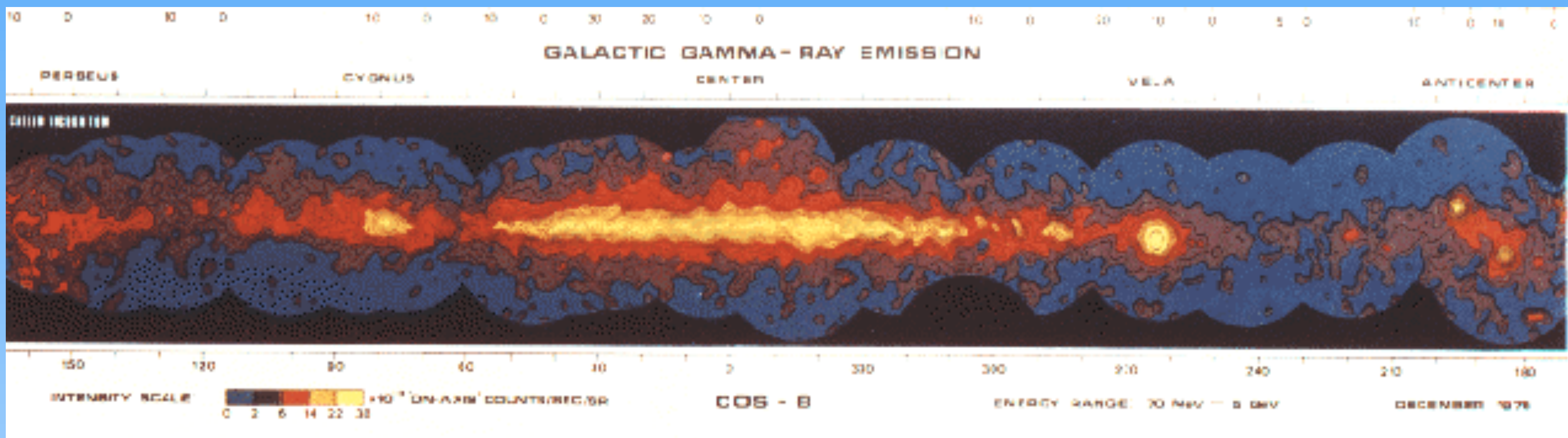
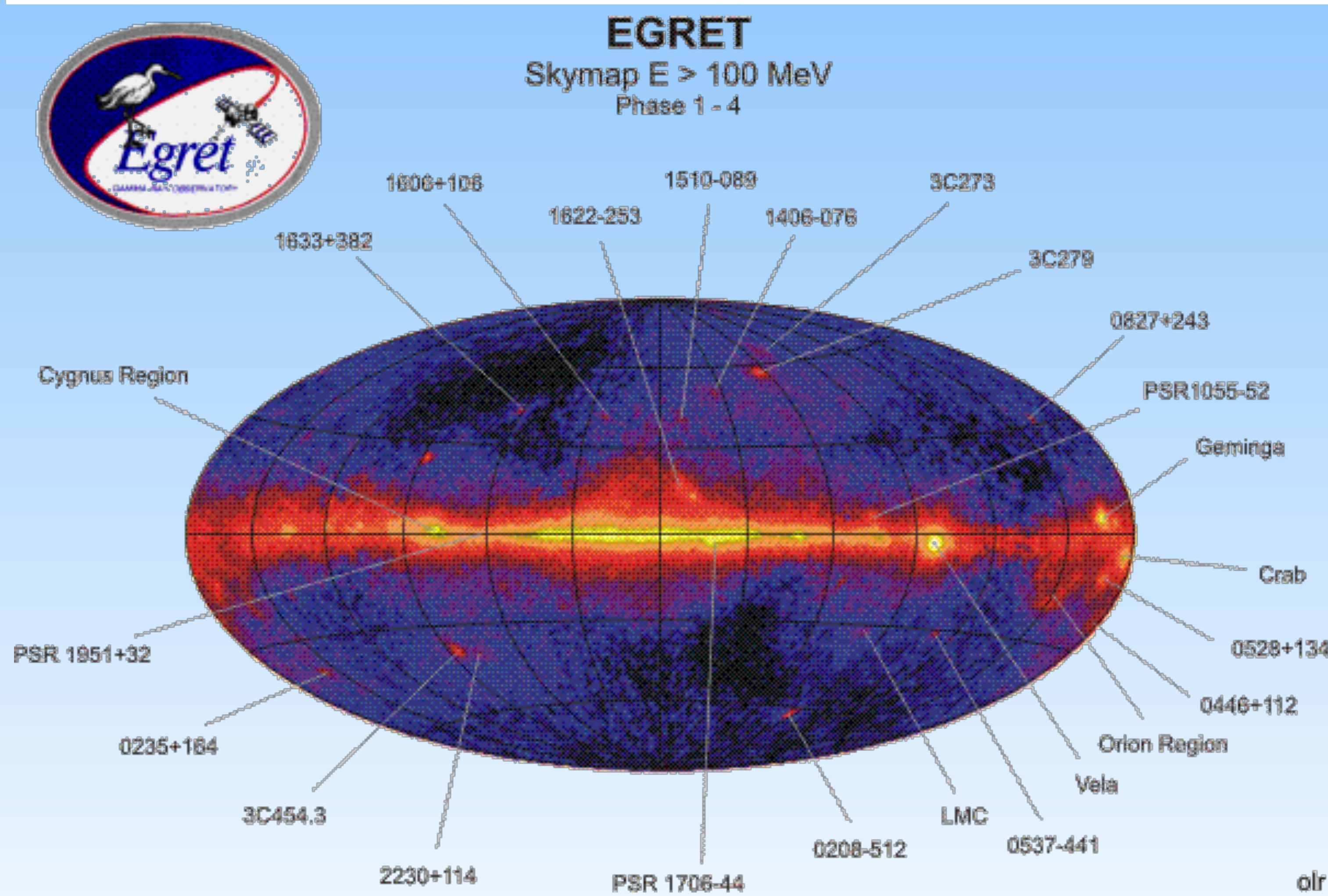
Gamma-ray missions pre-Fermi



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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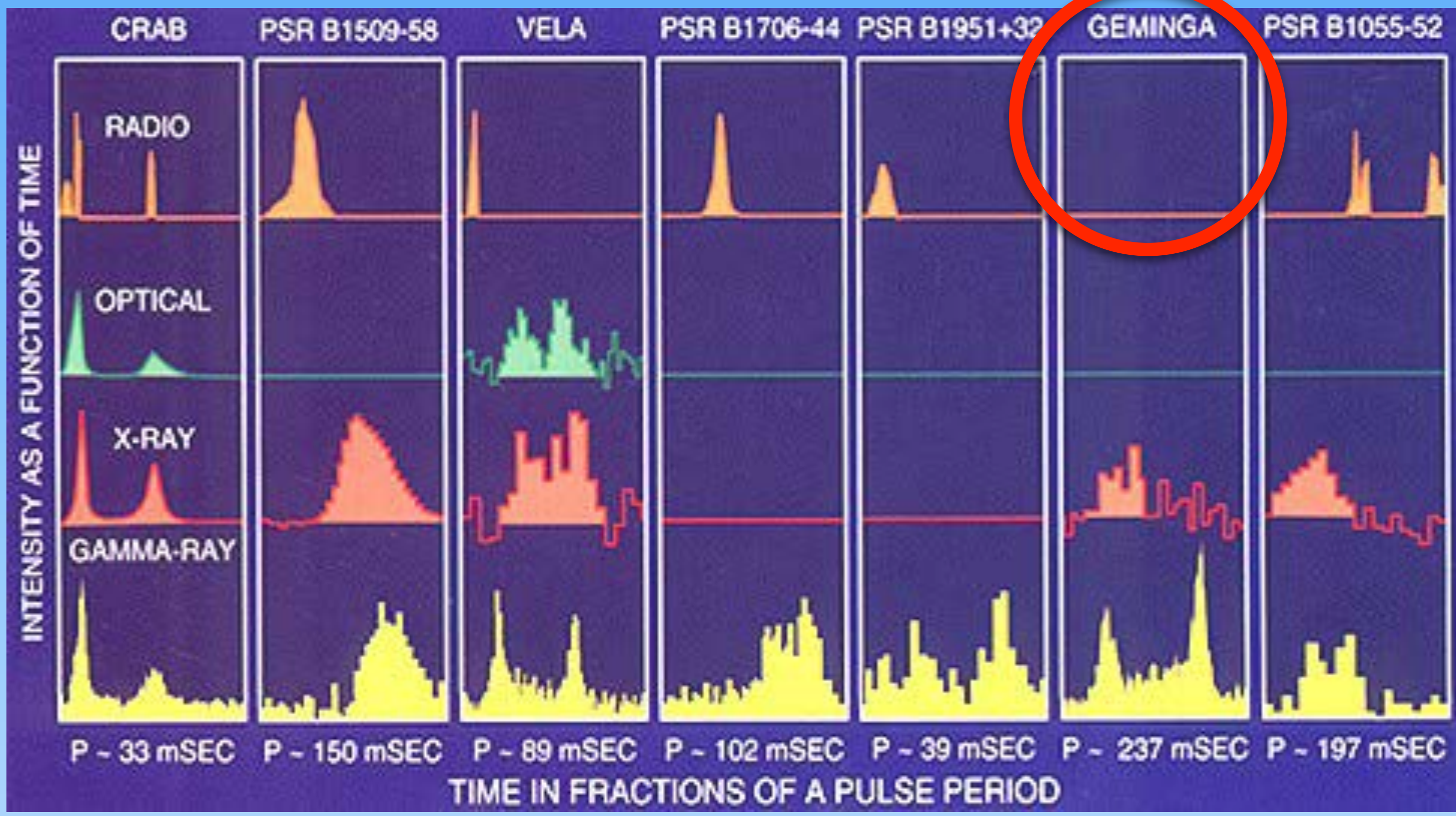
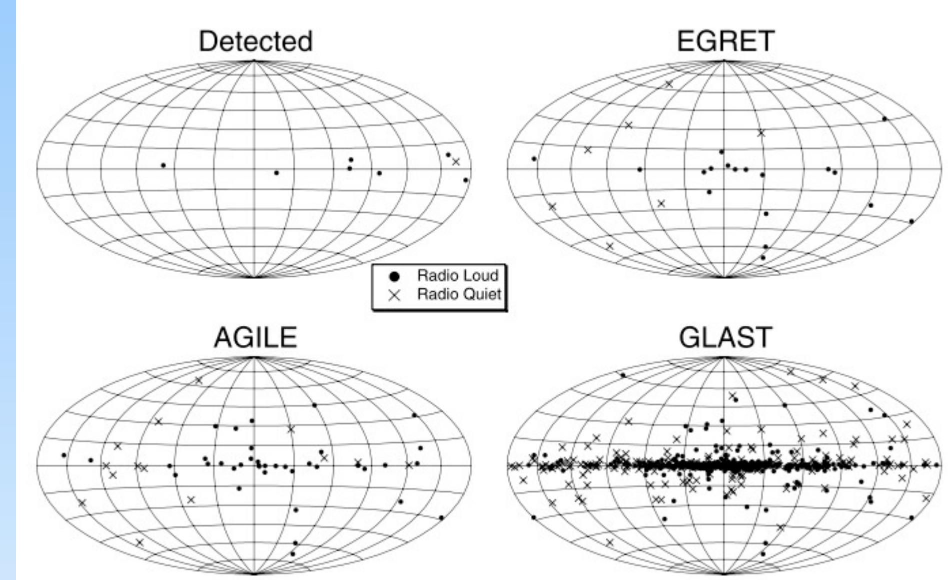
EGRET Pulsars / Fermi expectations



Credit: D. Thompson

- ***Number of CGRO pulsars = 7 (6 by EGRET)***
- ***Number of "Gemingas" = 1 (Geminga)***
- ***The "Geminga fraction" can tell us about the different mechanisms responsible for radio and gamma-ray pulsations***



Gonthier, Van Guilder, & Harding (2004)

ASTRONOMY & ASTROPHYSICS SUPPLEMENT SERIES — DECEMBER III 1996, PAGE 465

Astron. Astrophys. Suppl. Ser. **120**, 465-469 (1996)

Study of the spectral characteristics of unidentified galactic EGRET sources.

Are they pulsar-like?

M. Merck[1], D.L. Bertsch[2], B.L. Dingus[2,3], J.A. Esposito[2,3], C.E. Fichtel[2], J.M. Fierro[4], R.C. Hartman[2], S.D. Hunter[2], G. Kanbach[1], D.A. Kniffen[5], Y.C. Lin[4], H.A. Mayer-Hasselwander[1], P.F. Michelson[4], C. von Montigny[2,6], A. Mücke[1], R. Mukherjee[2], P.L. Nolan[4], M. Pohl[1], E. Schneid[7], P. Sreekumar[2,3], D.J. Thompson[2], and T.D. Willis[4]

- See also:
- Yadigaroglu, I. -A. & Romani, Roger W. (1995)

"Estimates for the number of pulsars GLAST will detect in blind searches have ranged from tens to many hundreds. I argue that the number will be near the low end of this range" - Scott Ransom, First GLAST Symposium (5-8 Feb, 2007)

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Fermi Gamma-Ray Space Telescope

- Launched June 11, 2008
  - Data taking in August 2008
- 15+ Years of Operation
- Two Instruments
  - LAT
  - GBM

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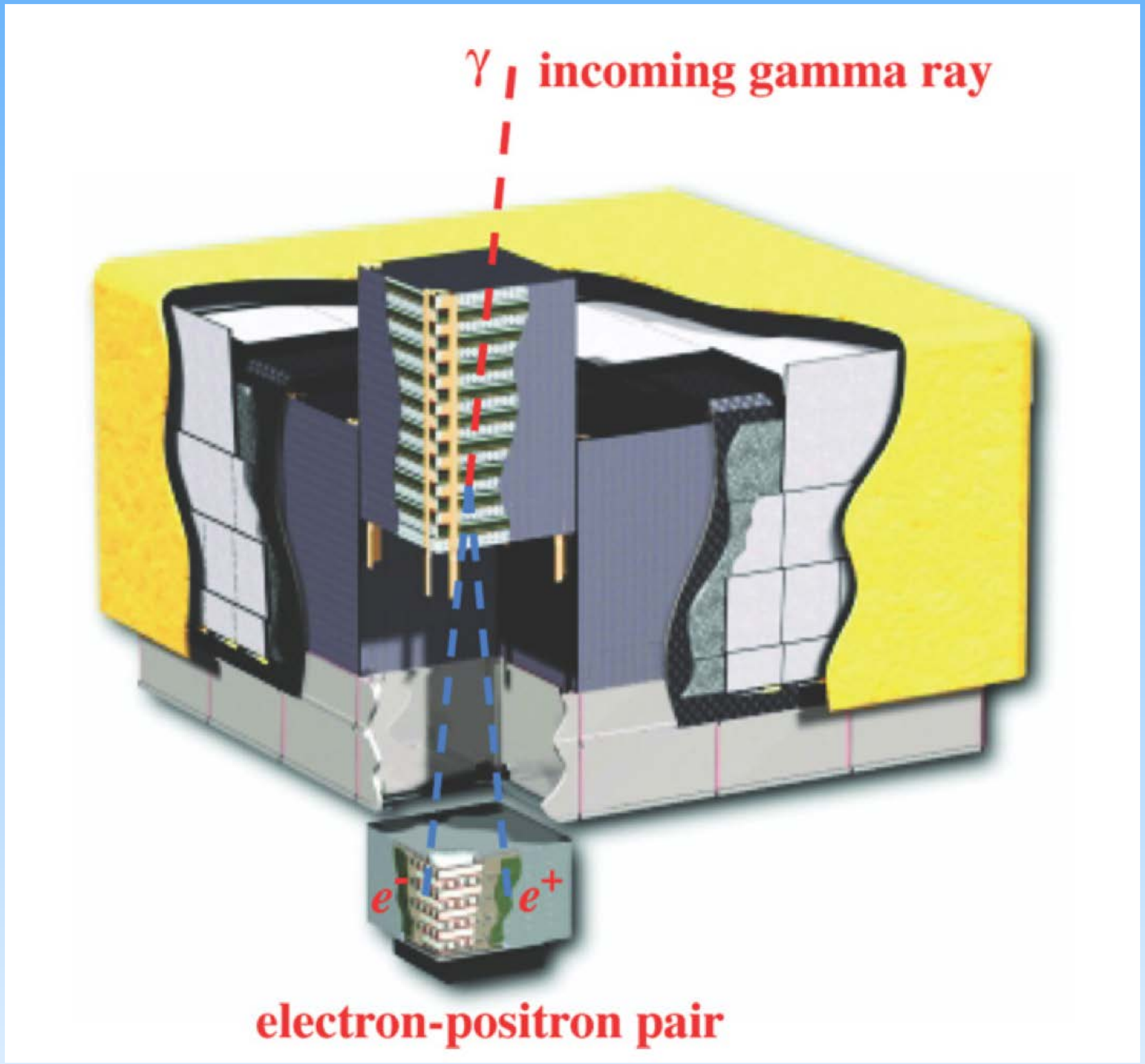
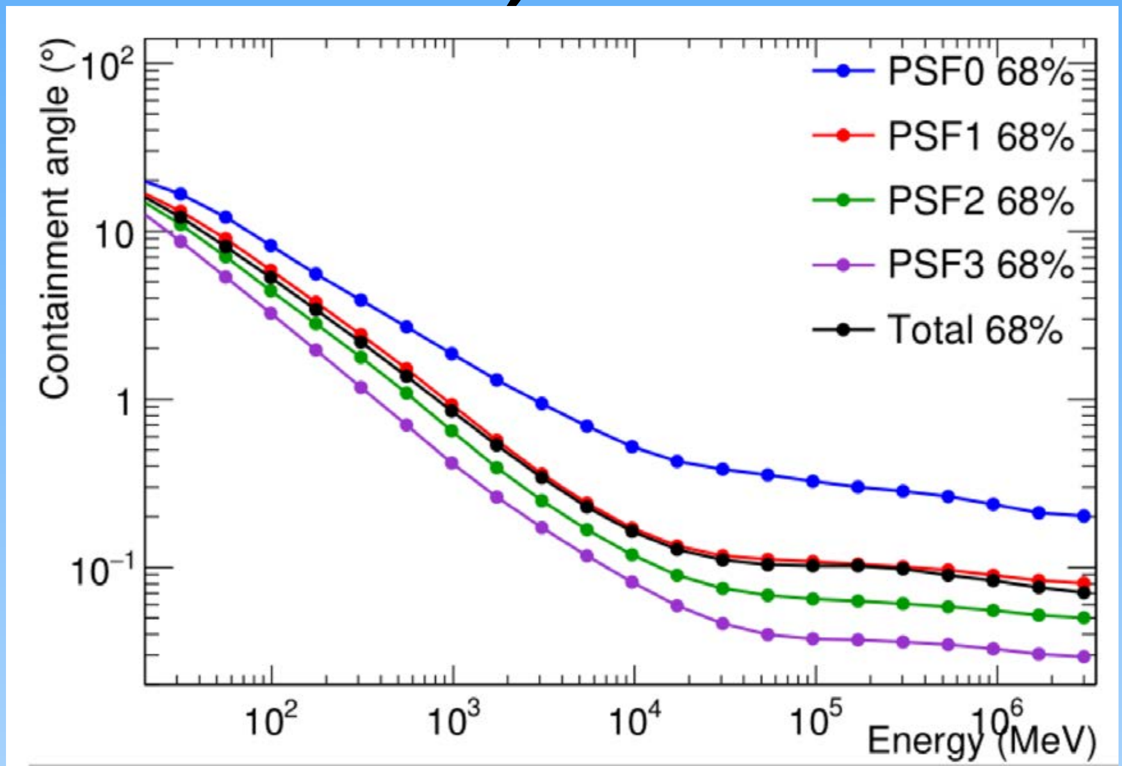
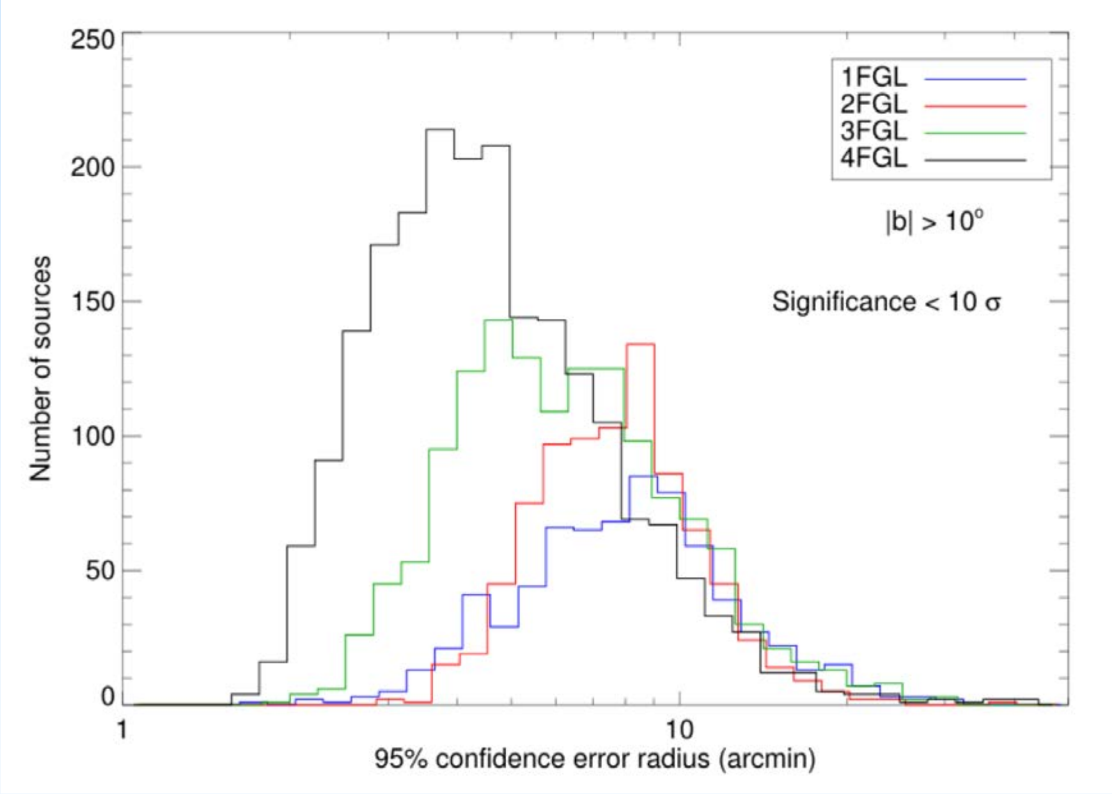
Fermi LAT (2008 - ??)



Atwood et al. 2009





Abdollahi et al. 2020 (4FGL-DR1)

GPS timing accuracy ~ 300 ns

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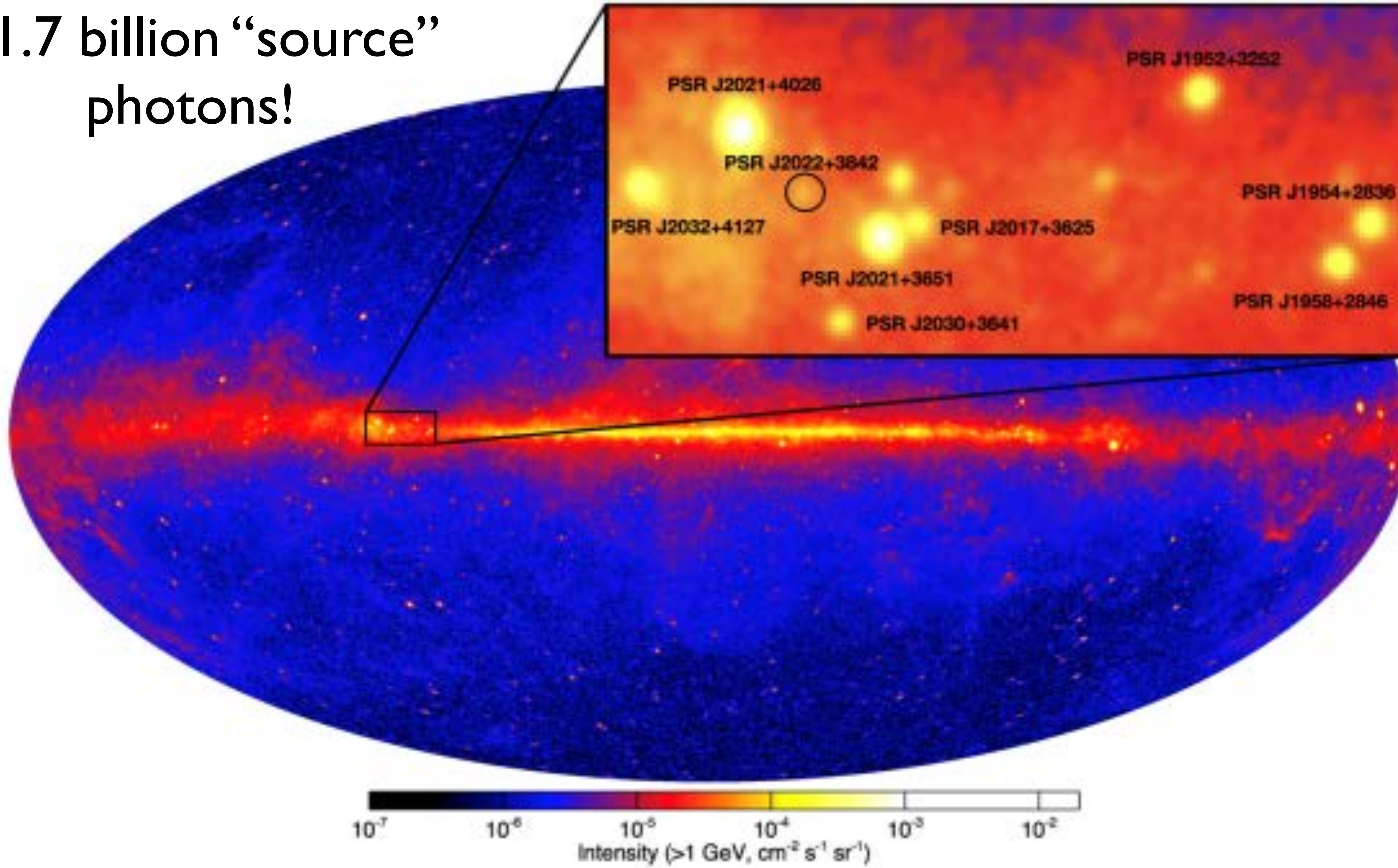
Fermi Large Area Telescope (LAT) sky

> 1.7 billion "source" photons!



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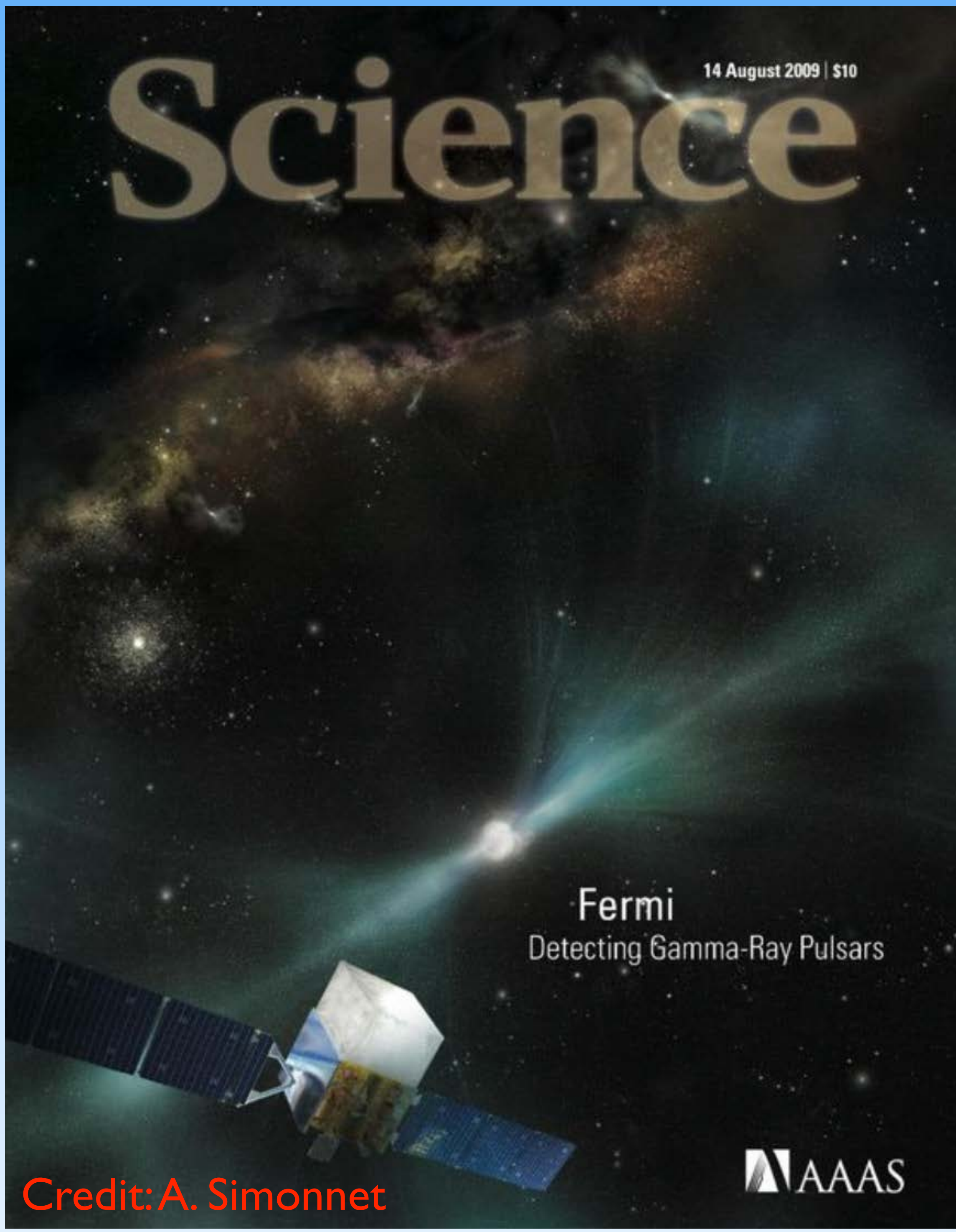
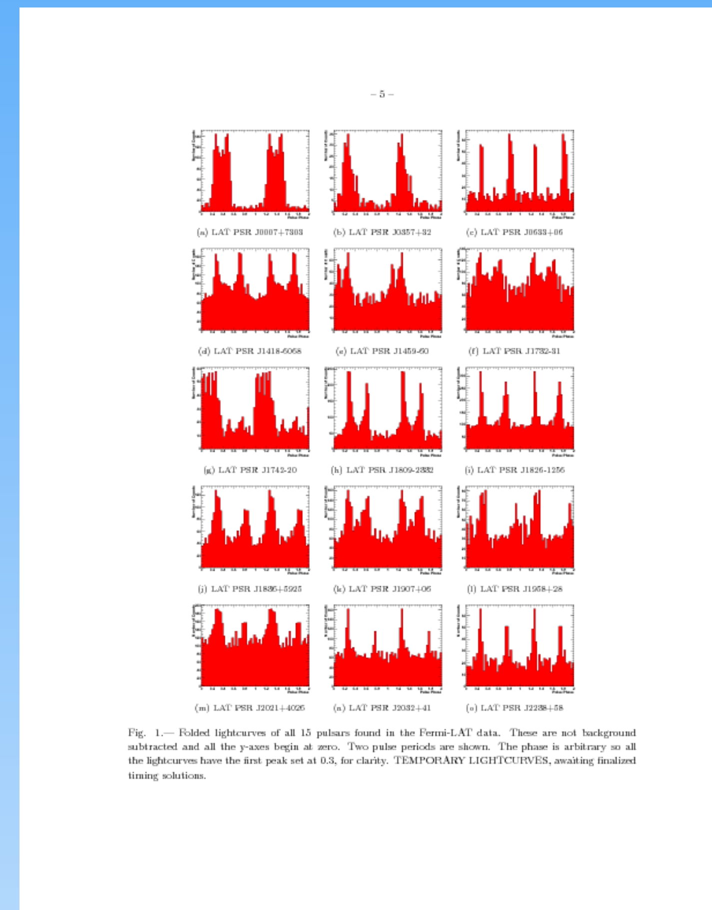
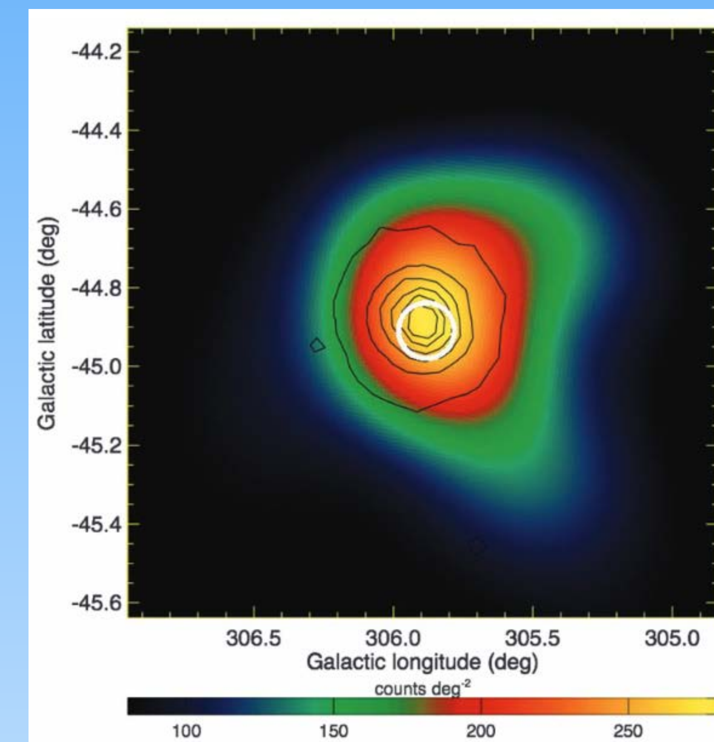
Early *Science* pulsar results



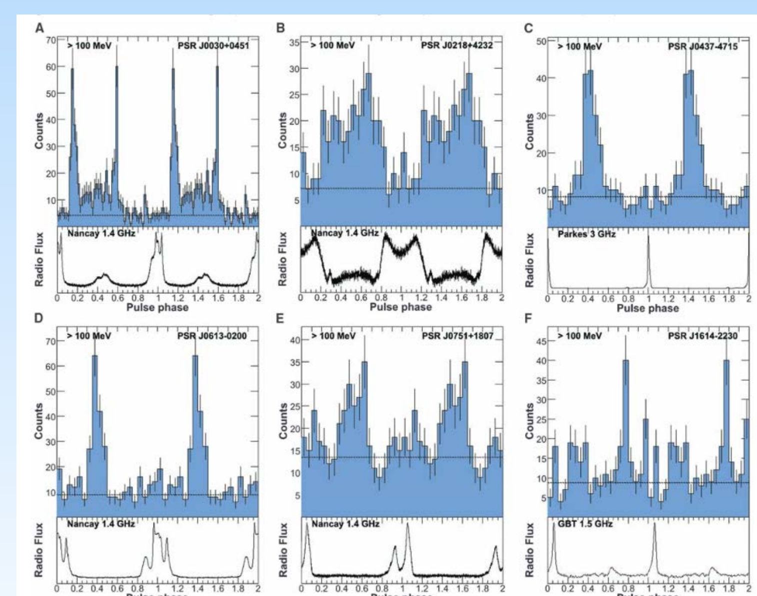
Abdo et al. 2009



Blind Search Pulsars



GC 47Tuc



MSPs

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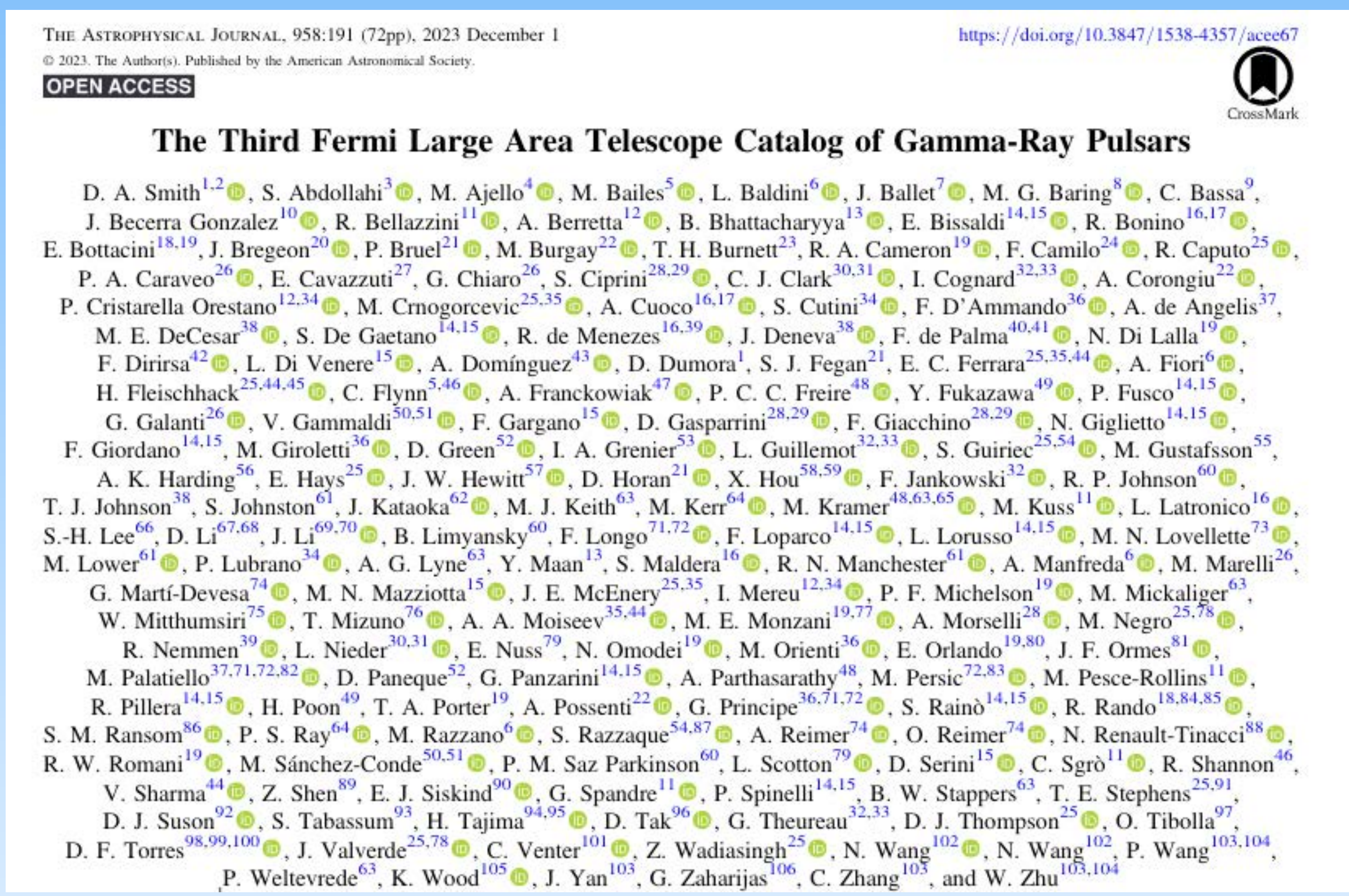
The LAT Third Catalog of Pulsars (3PC)



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

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

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

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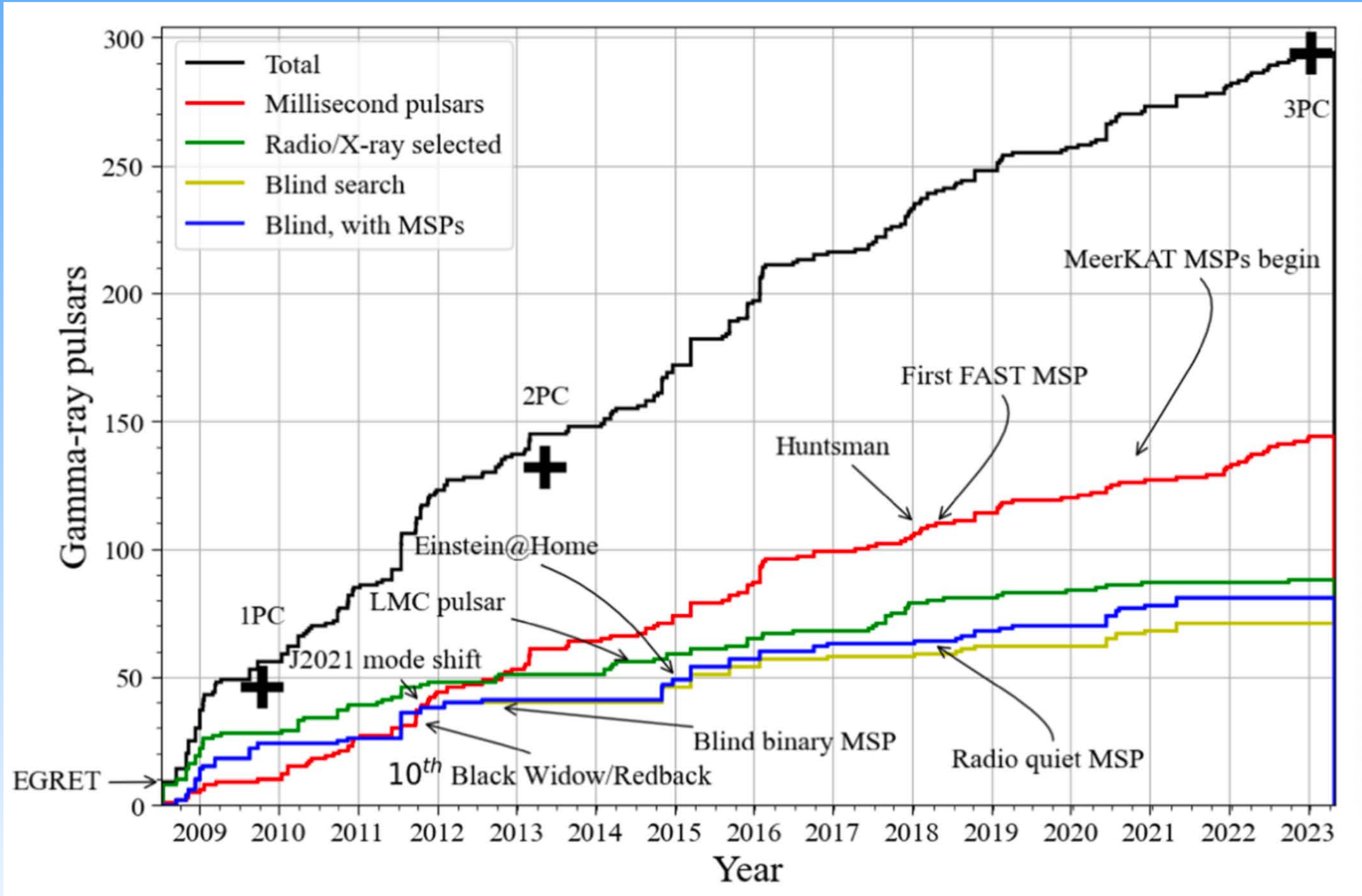
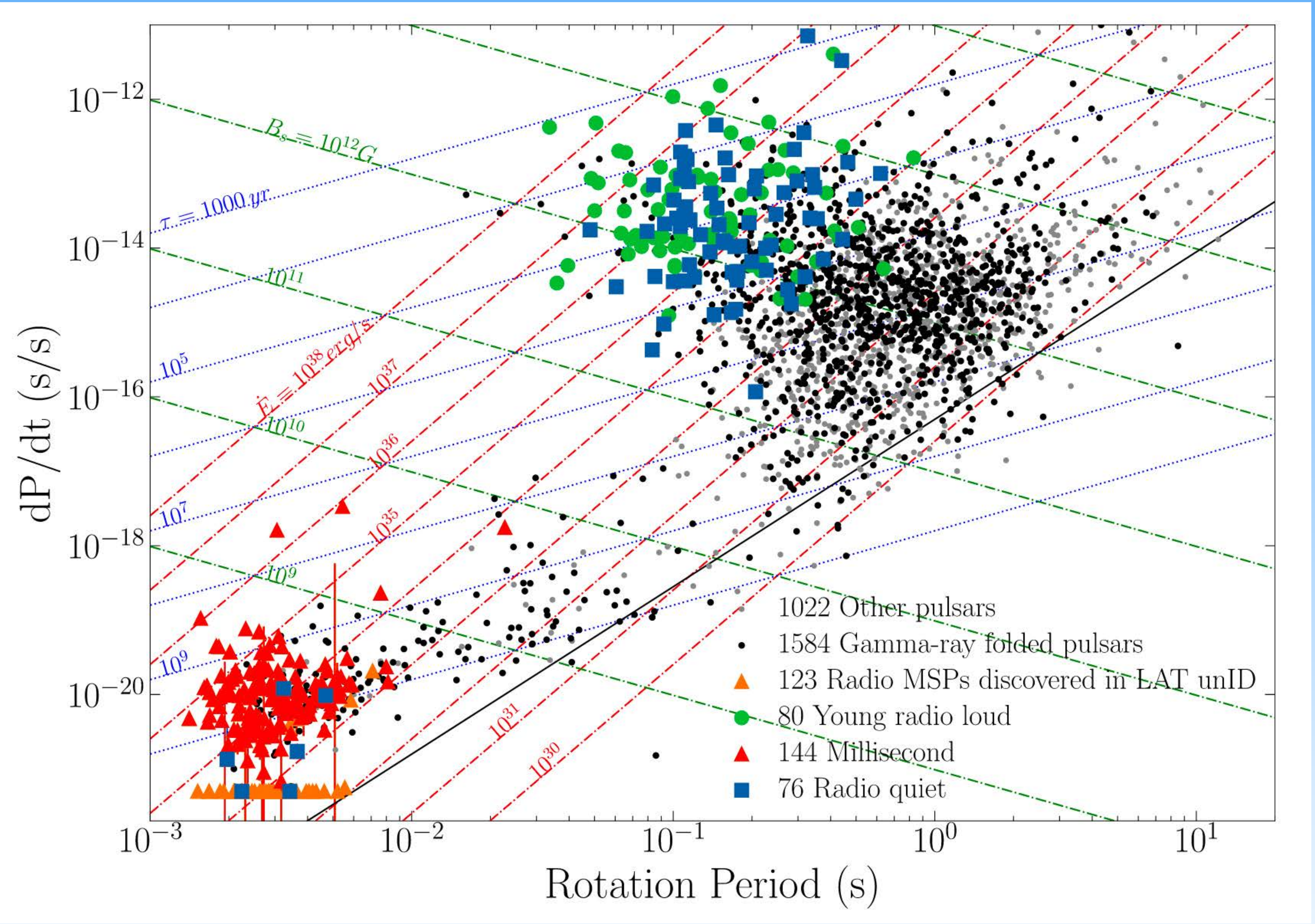
Fermi LAT Pulsars



http://tinyurl.com/fermipulsars

The pulsar population



Smith et al. 2023 (3PC)

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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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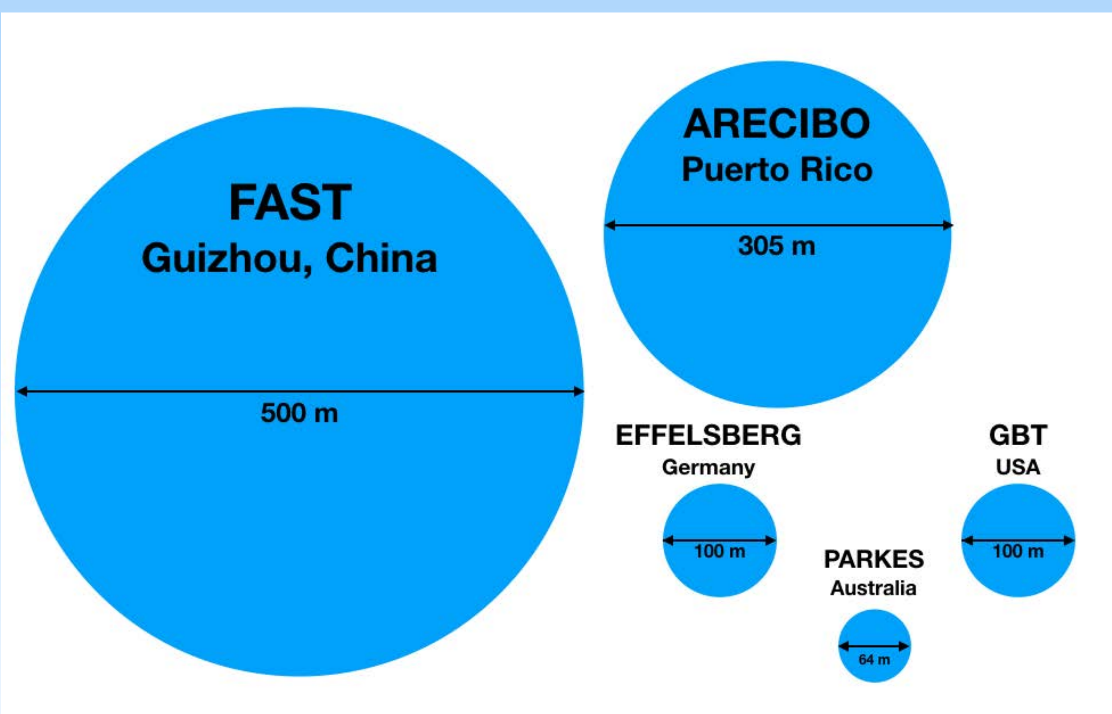
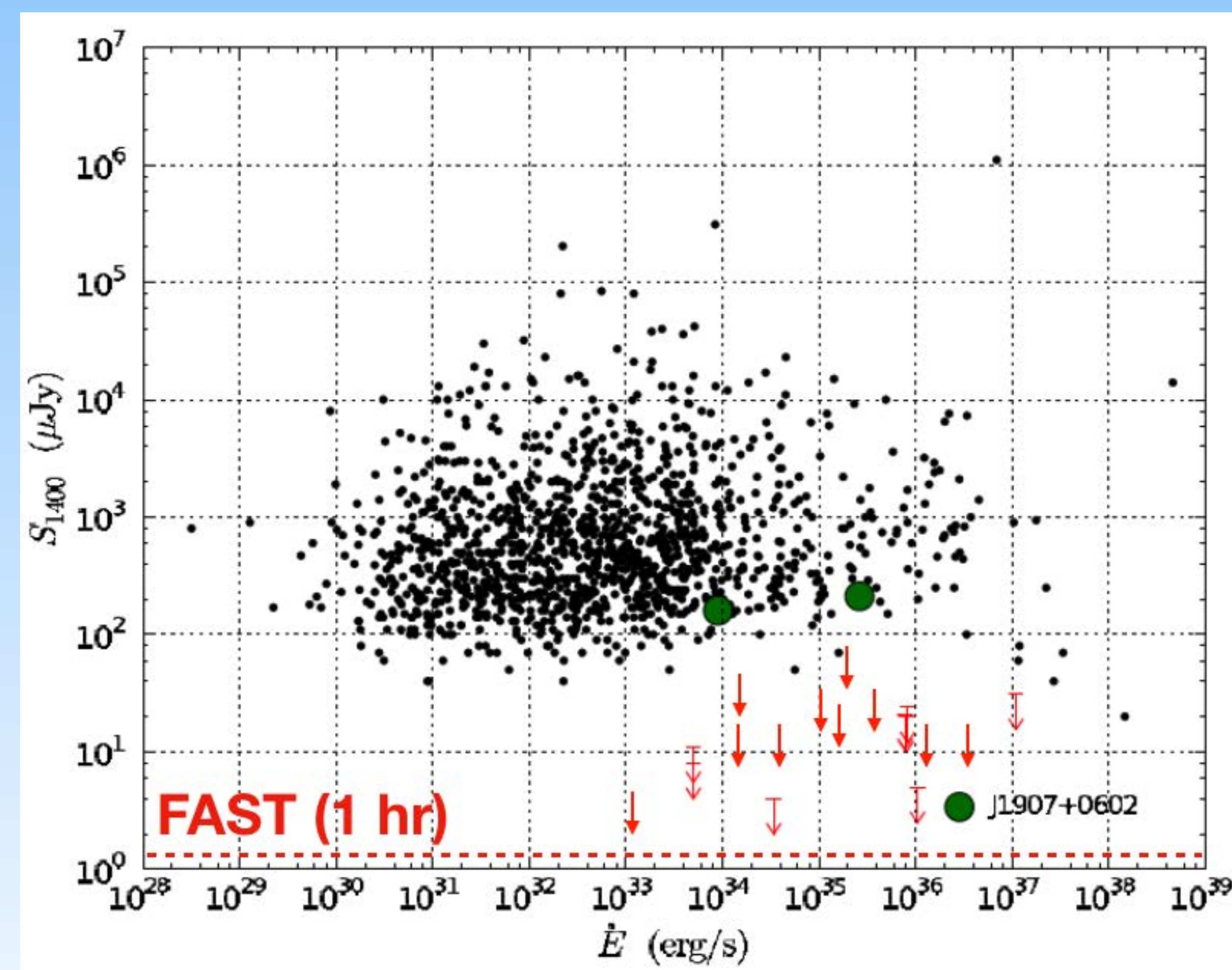
Radio follow-up observations

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



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



Adapted from Saz Parkinson et al. 2010

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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

Accepted 2022 December 13. Received 2022 December 13; in original form 2022 October 14

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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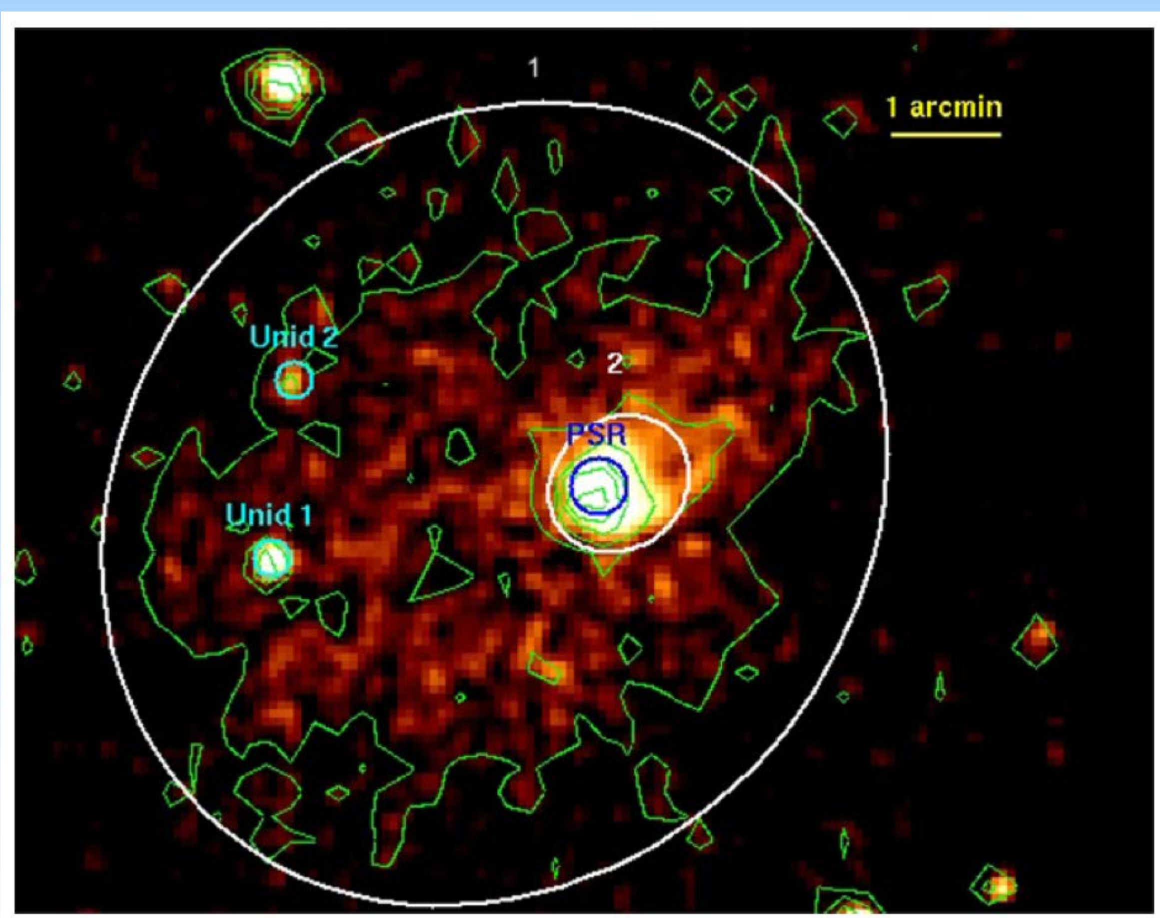
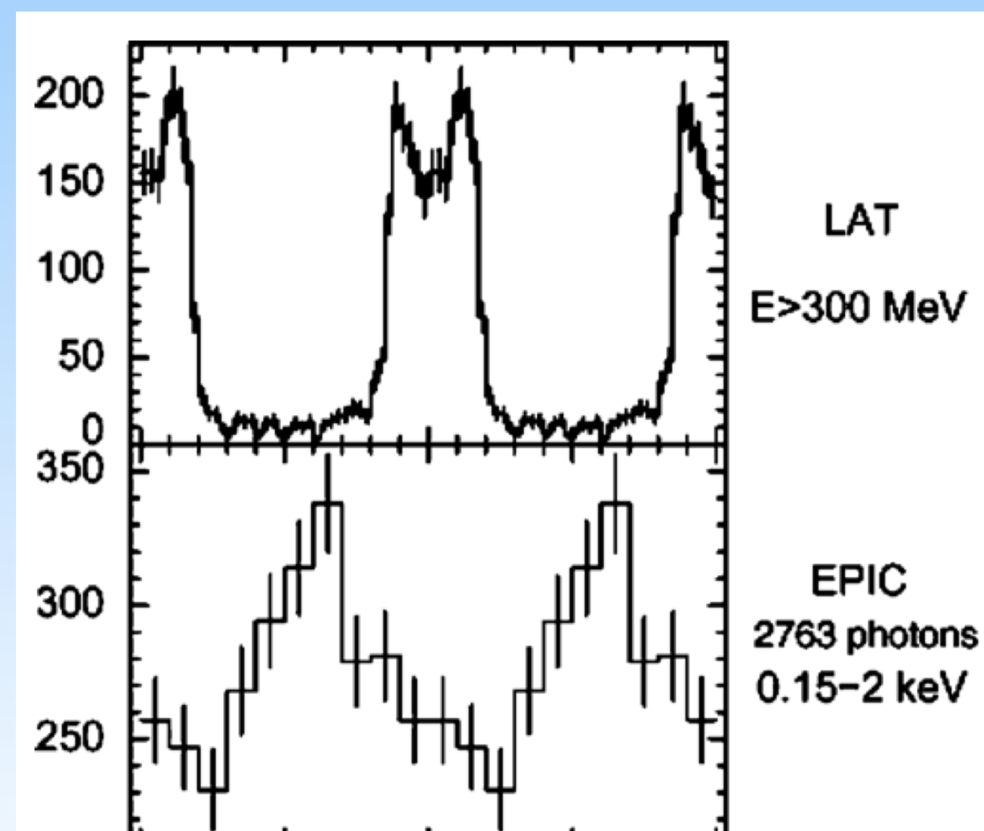
X-ray observations still important

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]
[1] INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica, Via Bassini 15, I-20133 Milano, Italy; pat@iasf-milano.inaf.it
[2] Istituto Universitario di Studi Superiori (IUSS) di Pavia, Viale Lungo Ticino 56, I-27100 Pavia, Italy
[3] Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, Via Bassi 6, I-27100 Pavia, Italy
[4] Università degli Studi dell'Insubria, Via Ravasi 2, 21100 Varese, Italy
[5] Space Science Division, Naval Research Laboratory, Washington, DC 20375-5352, USA
[6] Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA
[7] Max-Planck Institut für Extraterrestrische Physik, 85748 Garching, Germany
Received 2010 June 18; accepted 2010 October 19; published 2010 November 12





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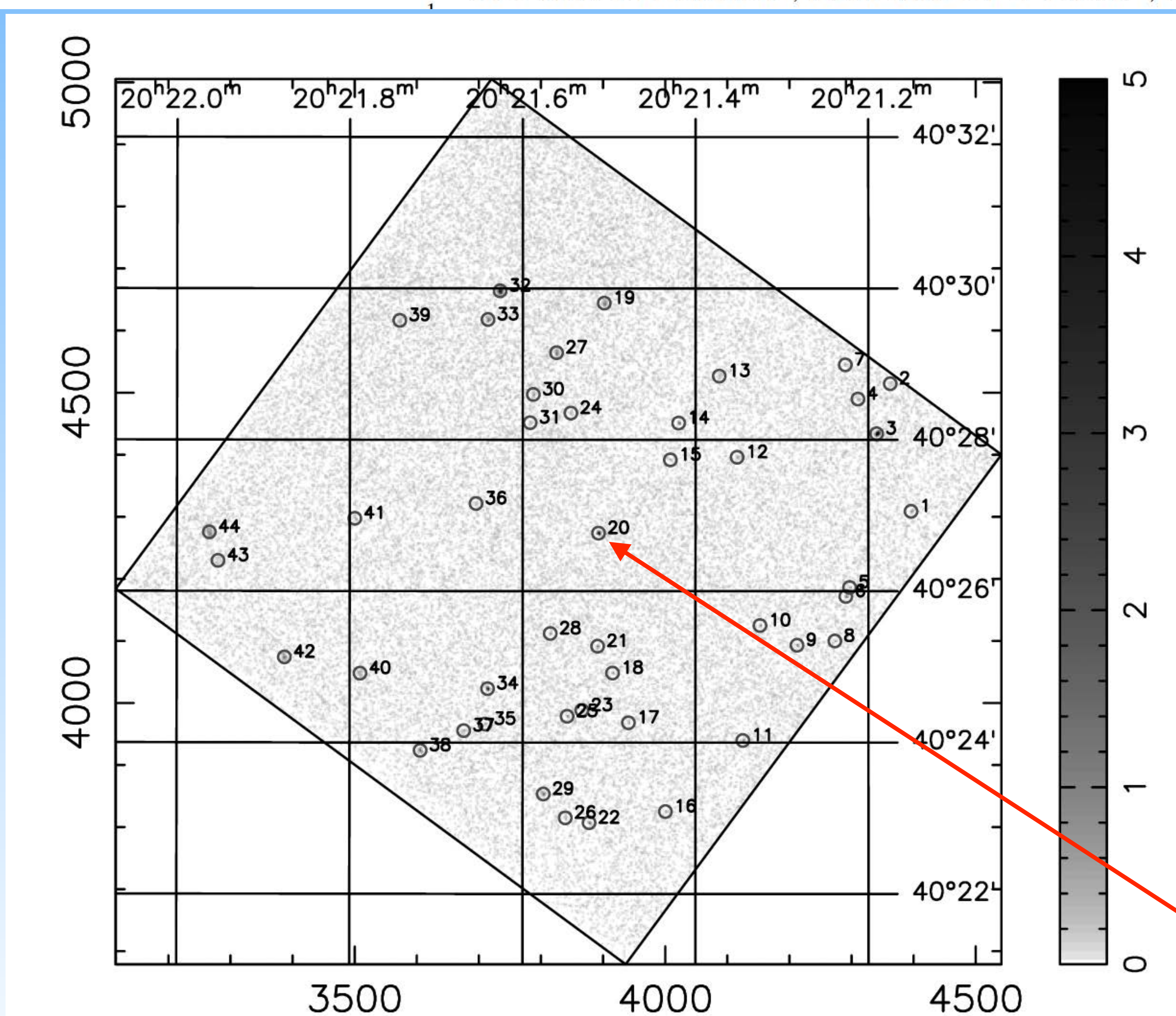
THE ASTROPHYSICAL JOURNAL, 743:74 (12pp), 2011 December 10 doi:10.1088/0004-637X/743/1/74

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]



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)

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

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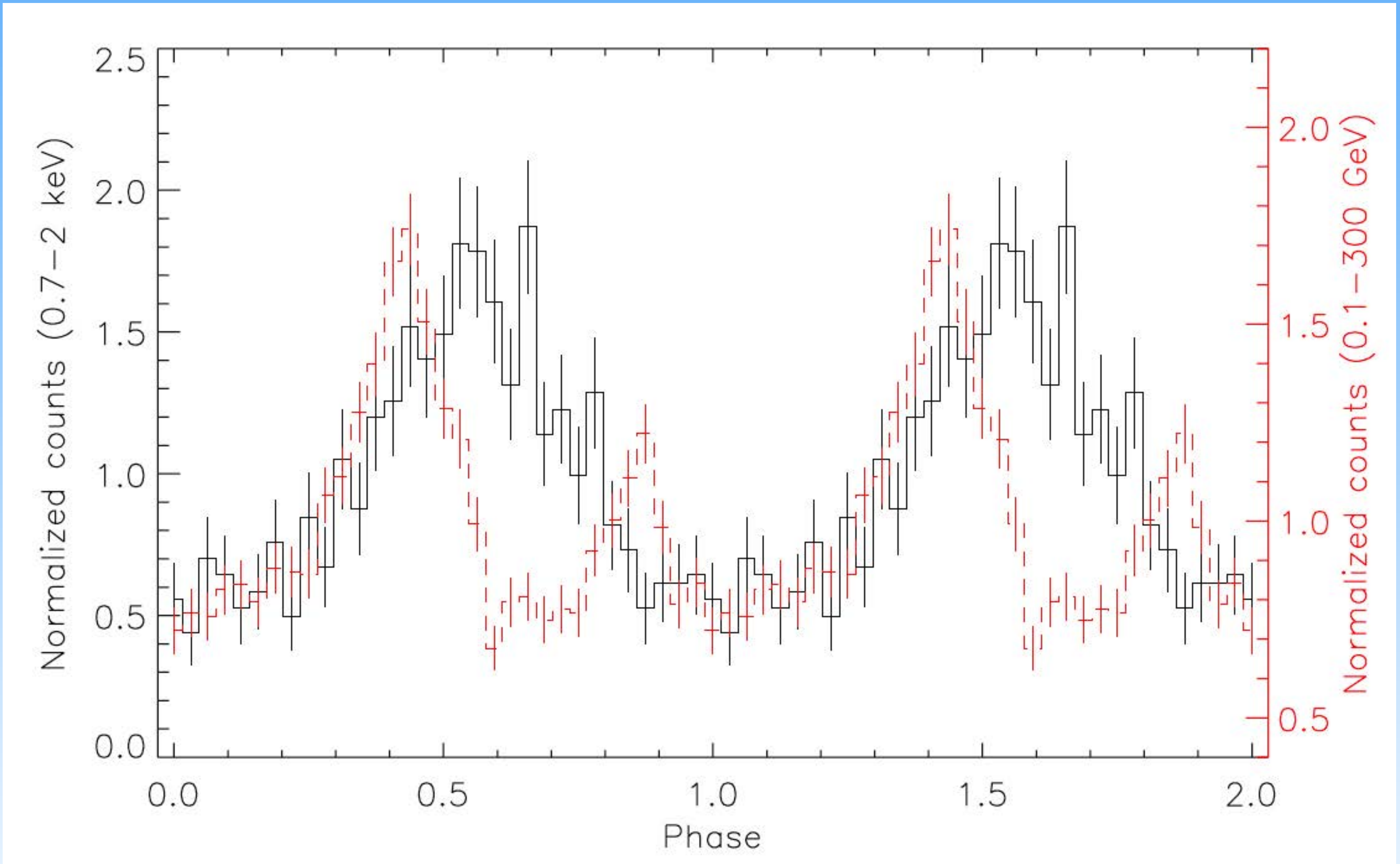
X-ray pulsations



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

Lin et al. 2013

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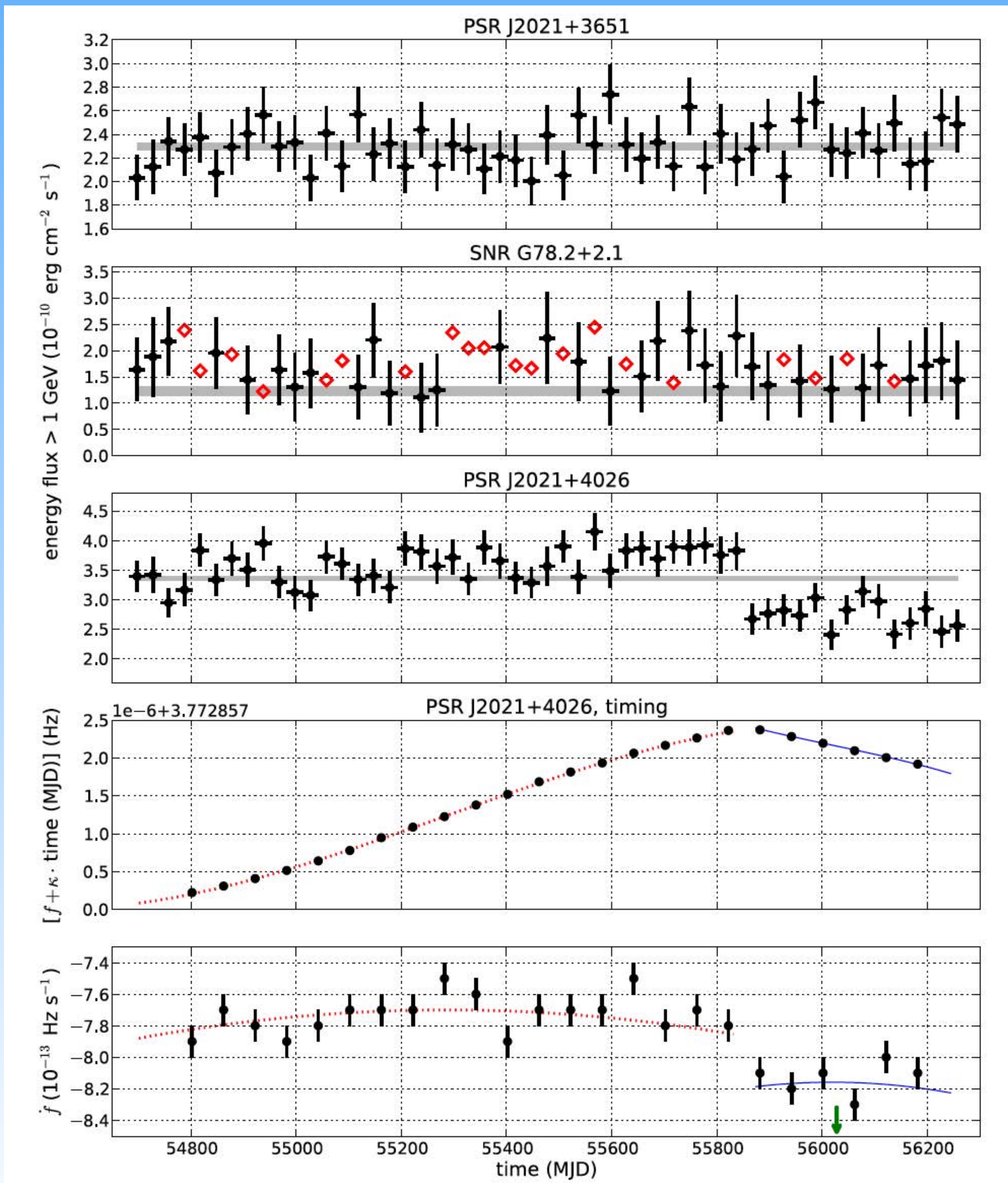
Variability in PSR J2021+4026!



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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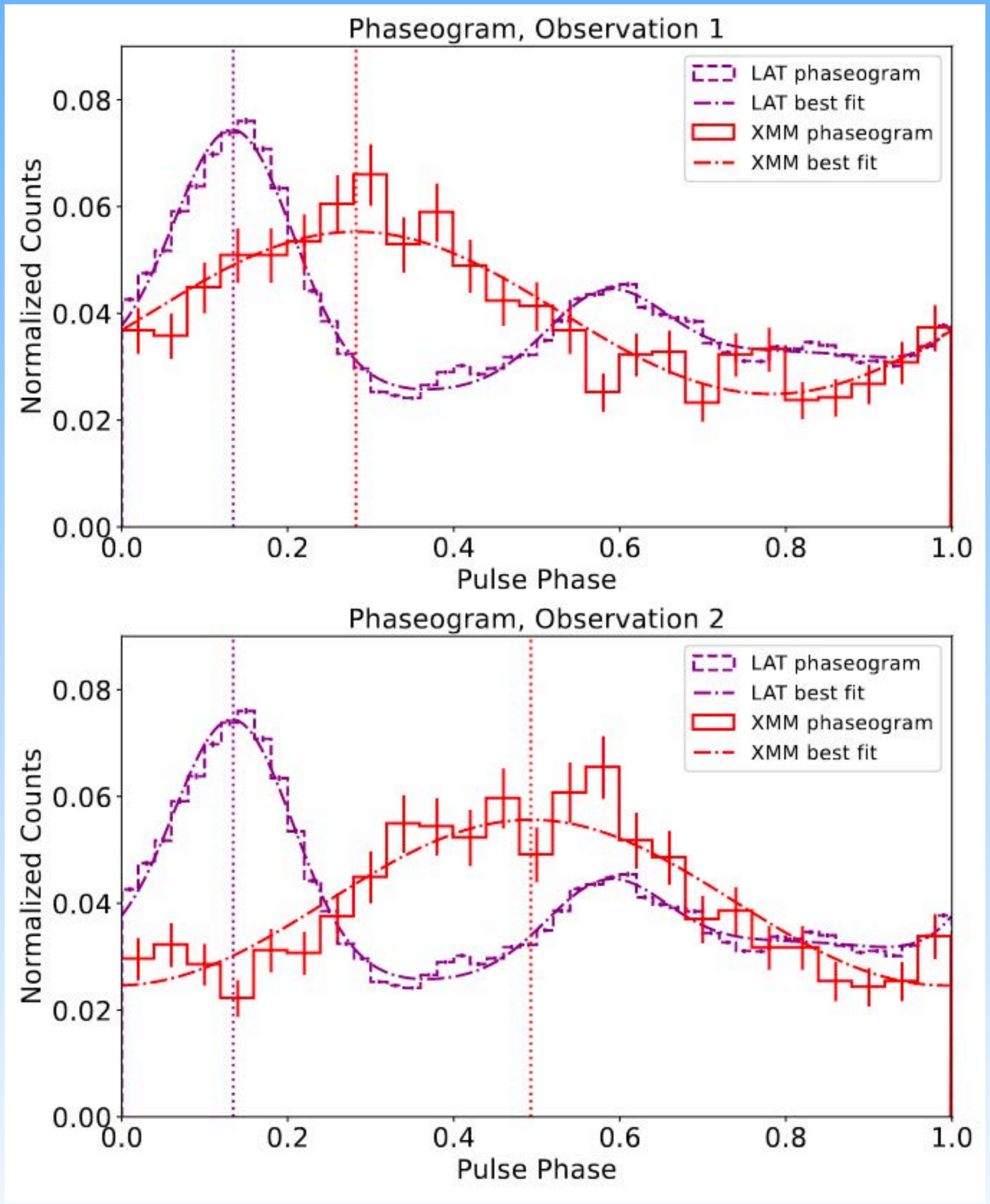
Gamma-ray/X-ray pulse shifts



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

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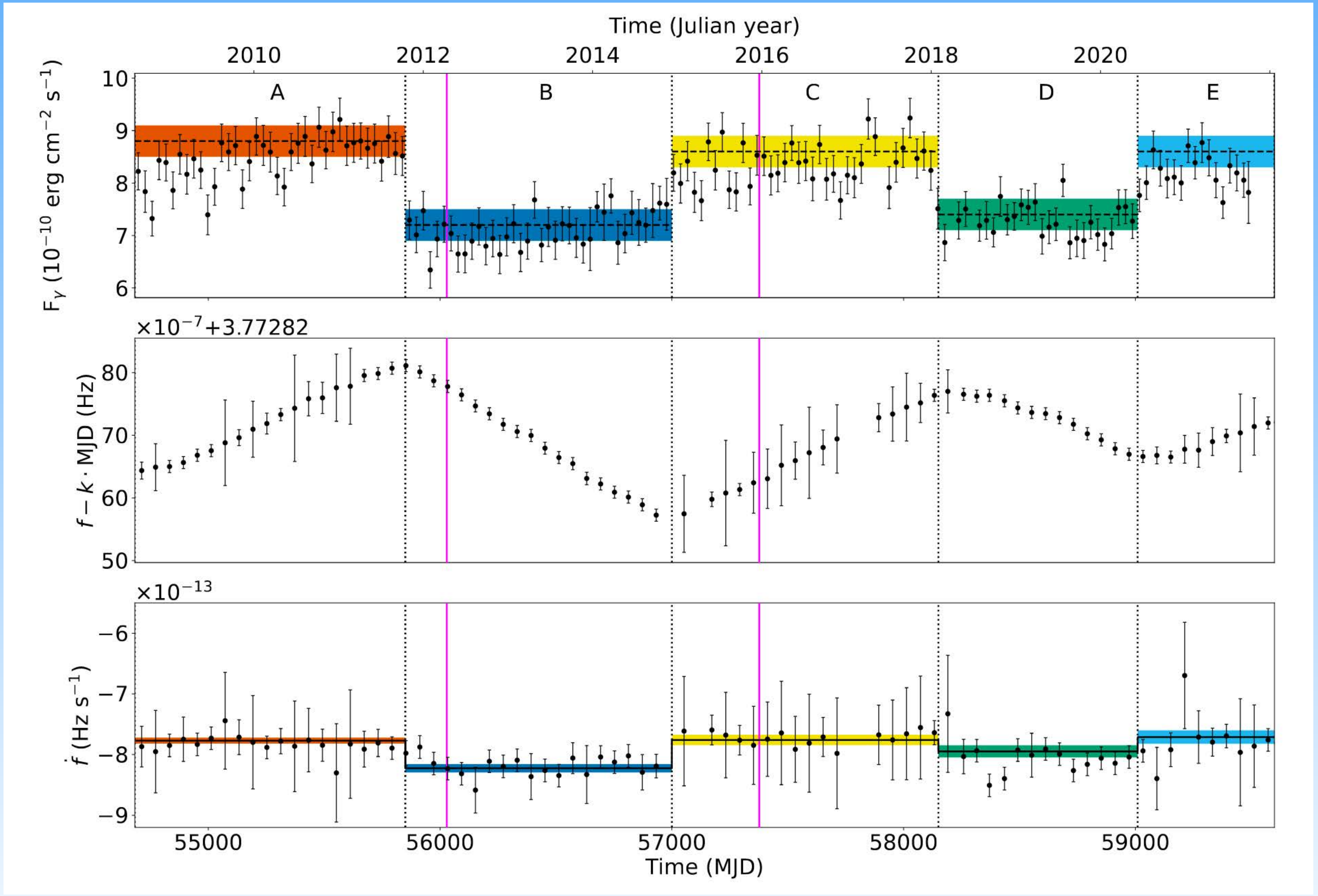
PSR J2021+4026



Fiori et al. 2024

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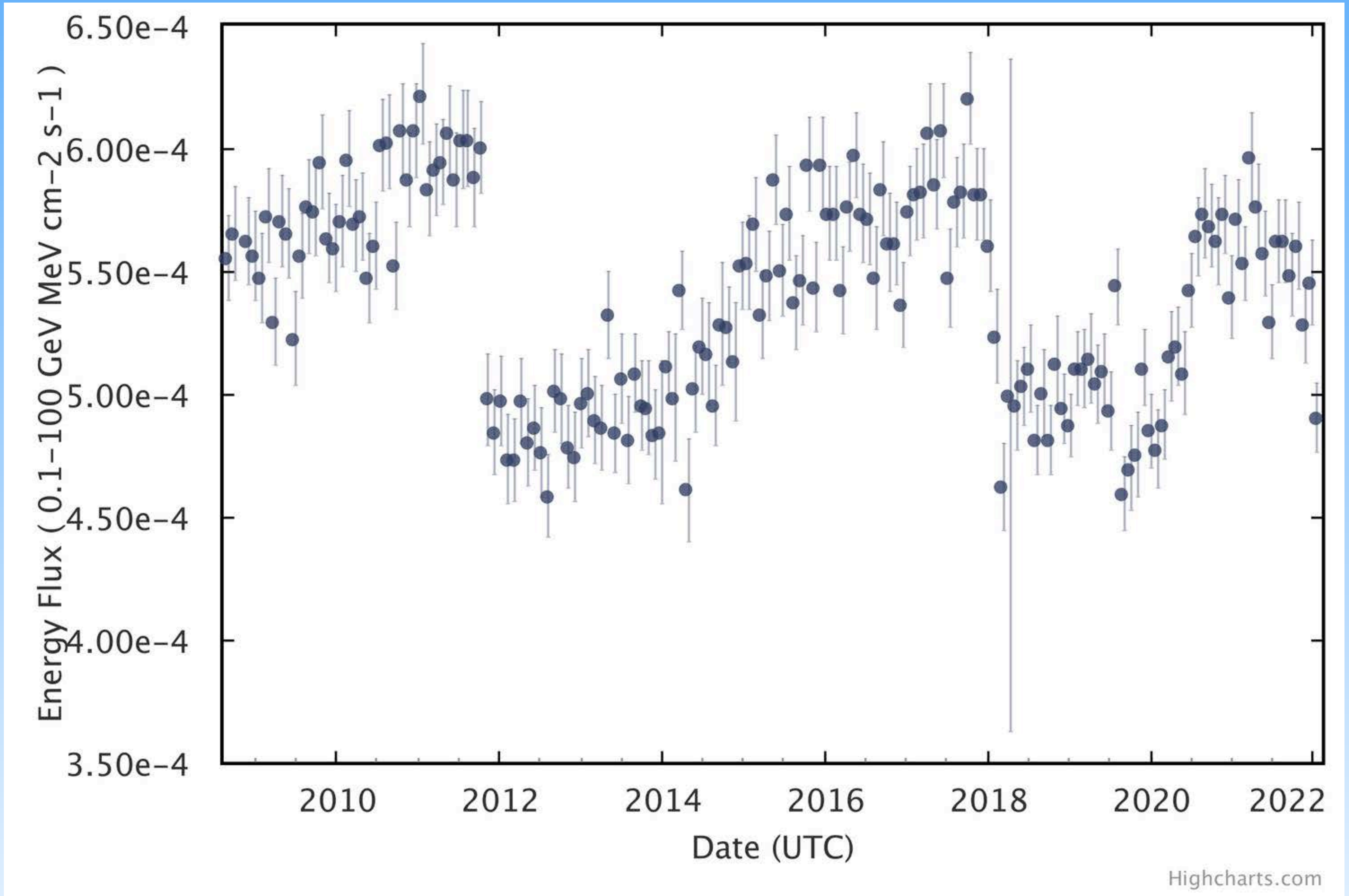
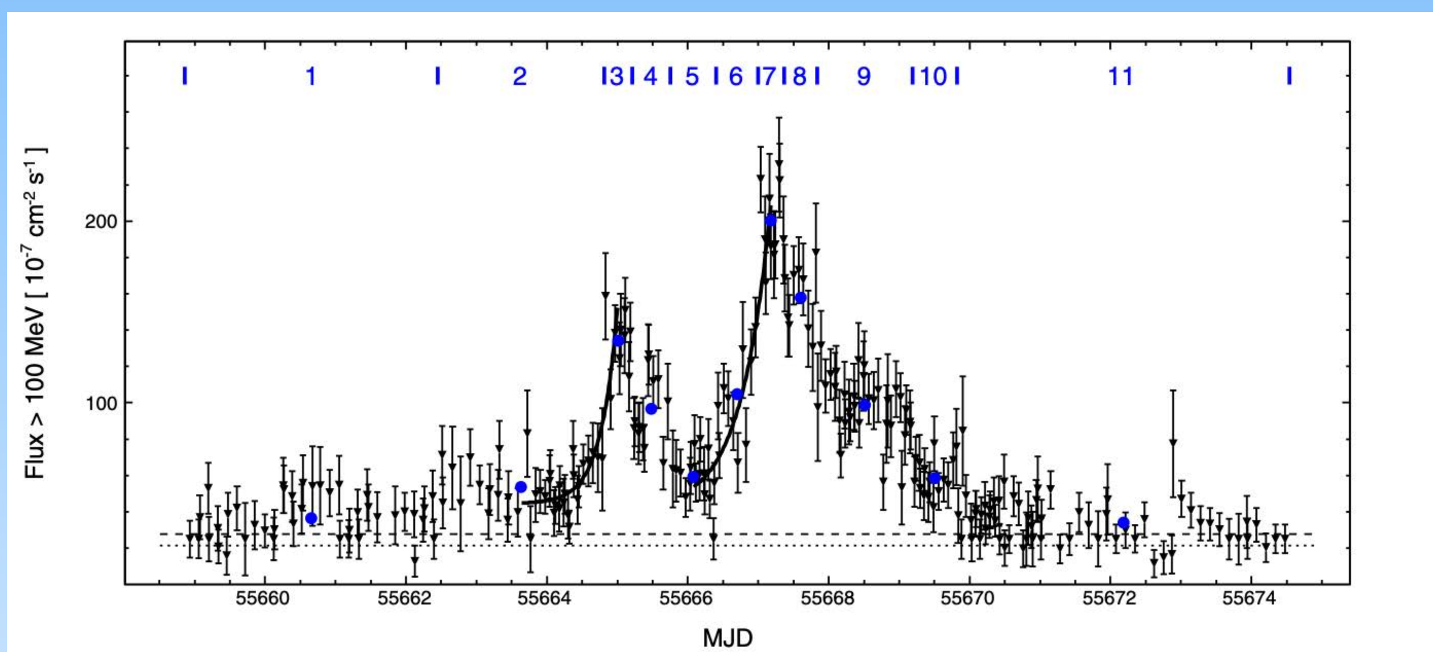
Variability in PSR J2021+4026



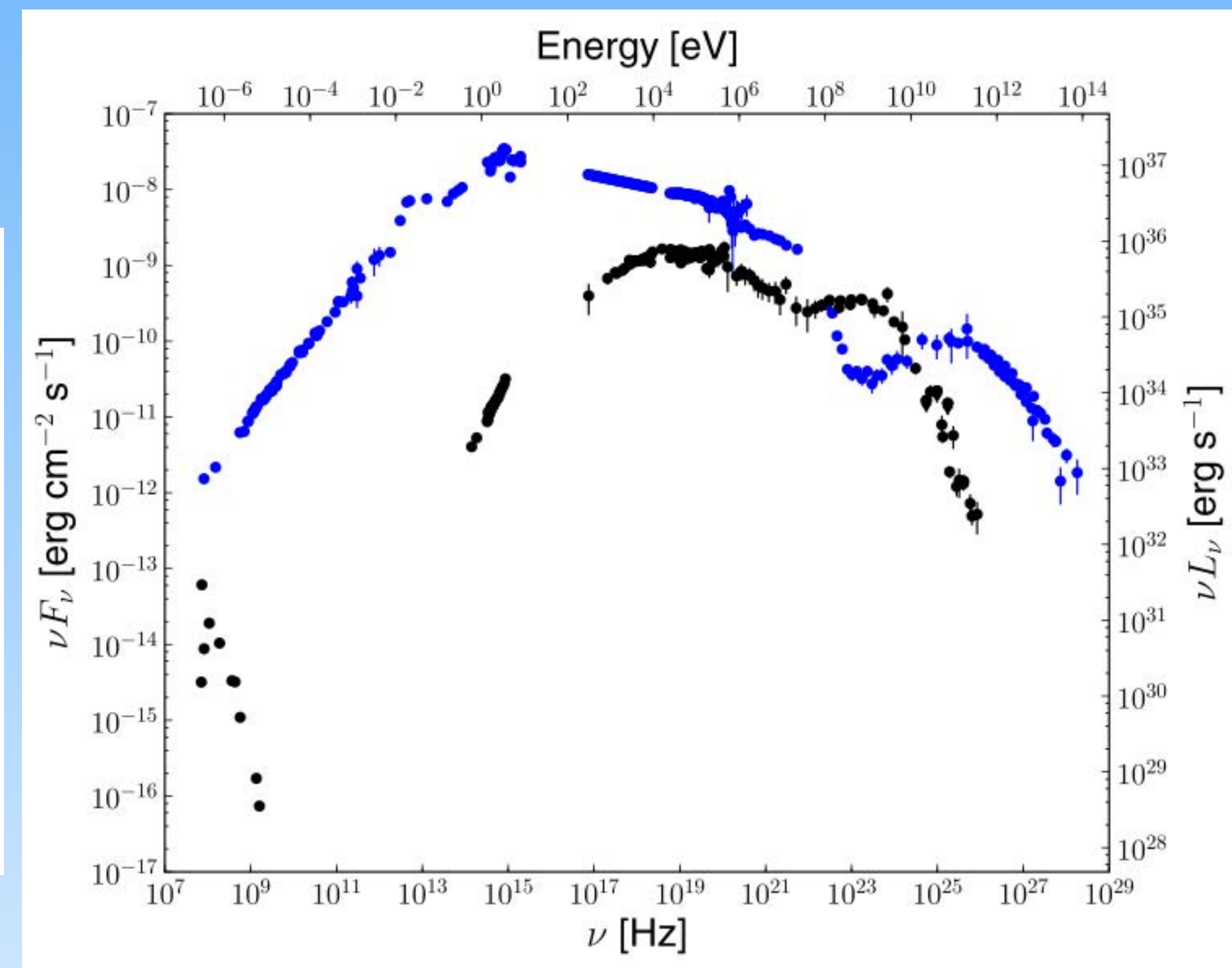
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/

Abdollahi et al. 2023

The surprising Crab



Buehler et al. 2012



Buehler and Blandford 2014

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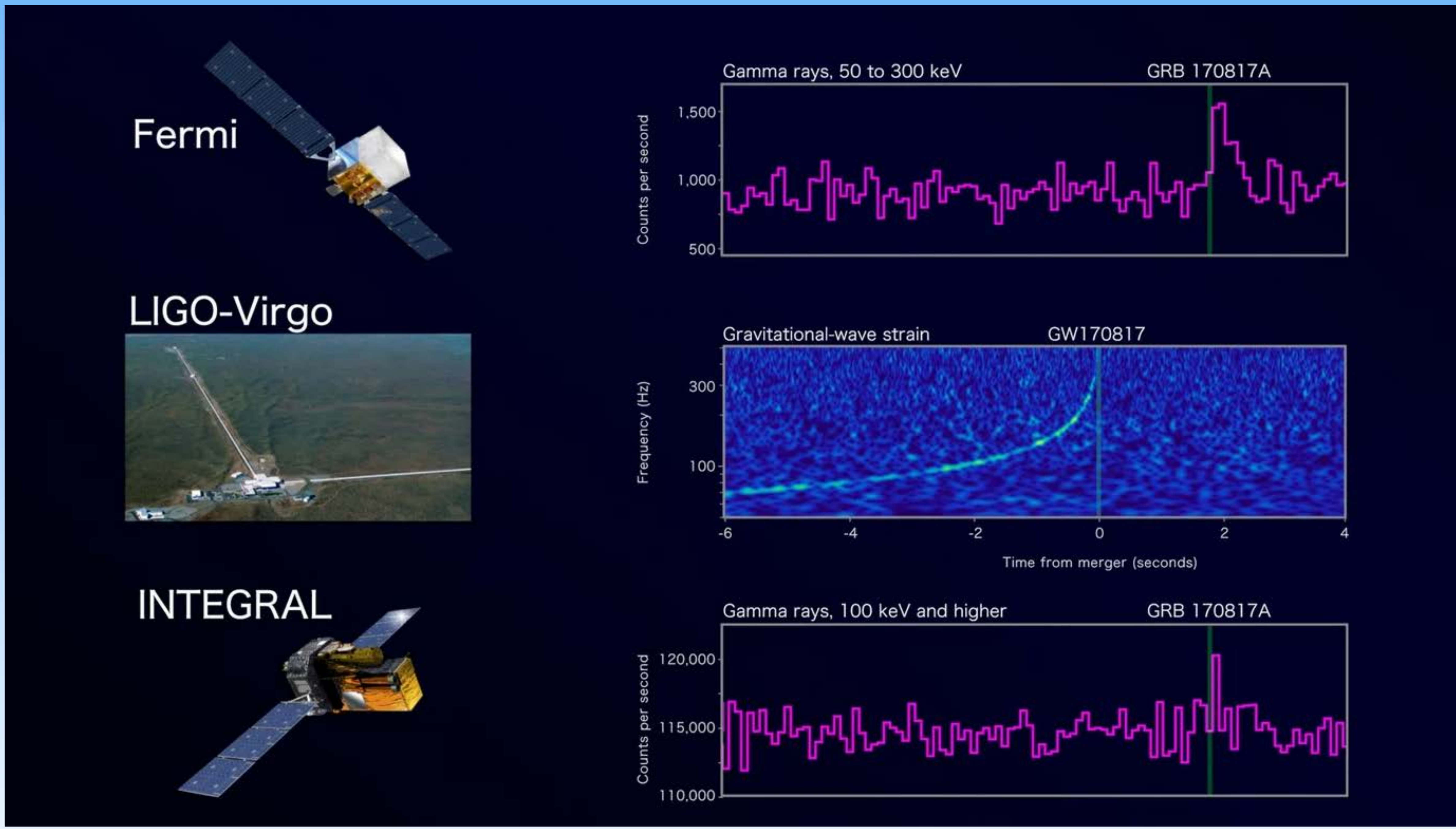
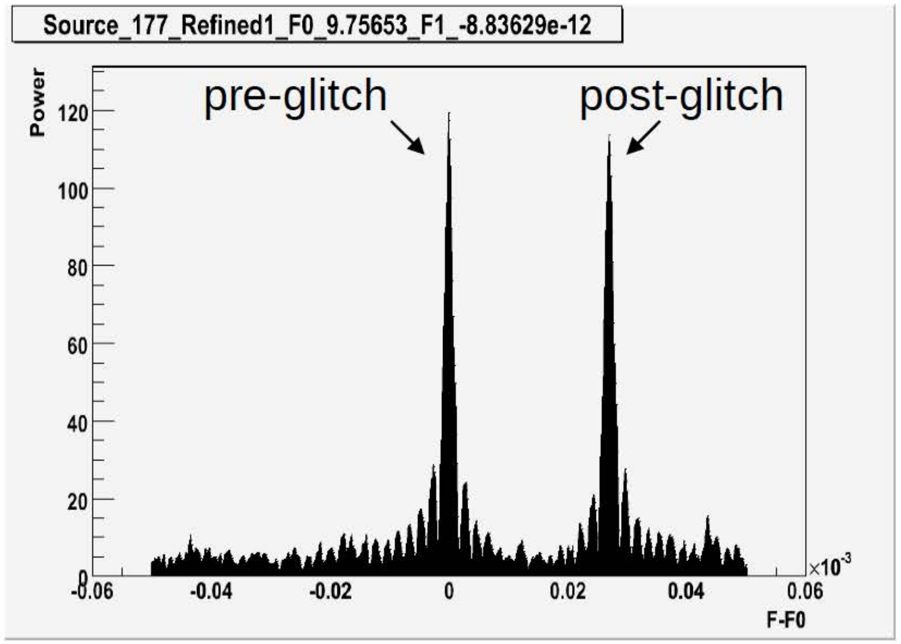
Multi-messenger observations of merging NS

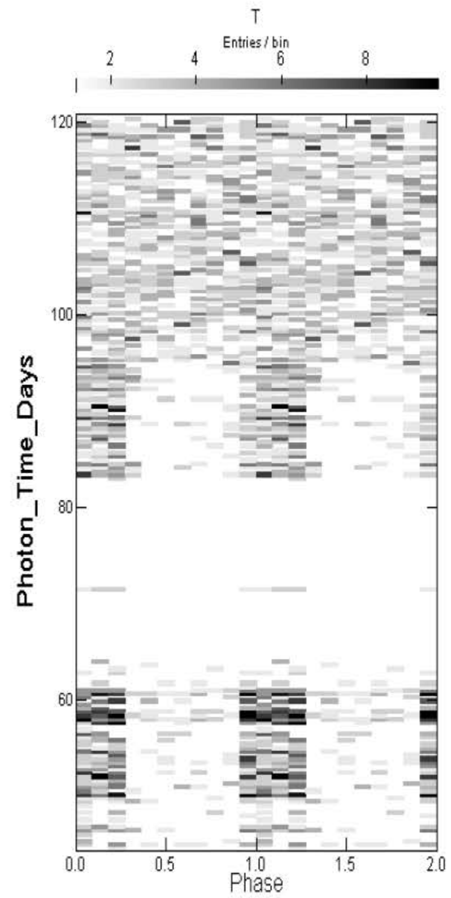


Credit: NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

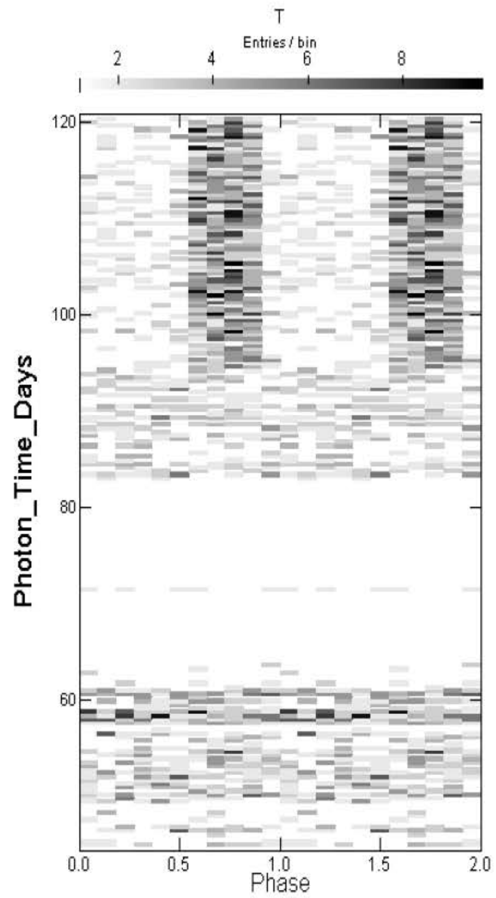
Gamma-ray pulsar *glitches*

- 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

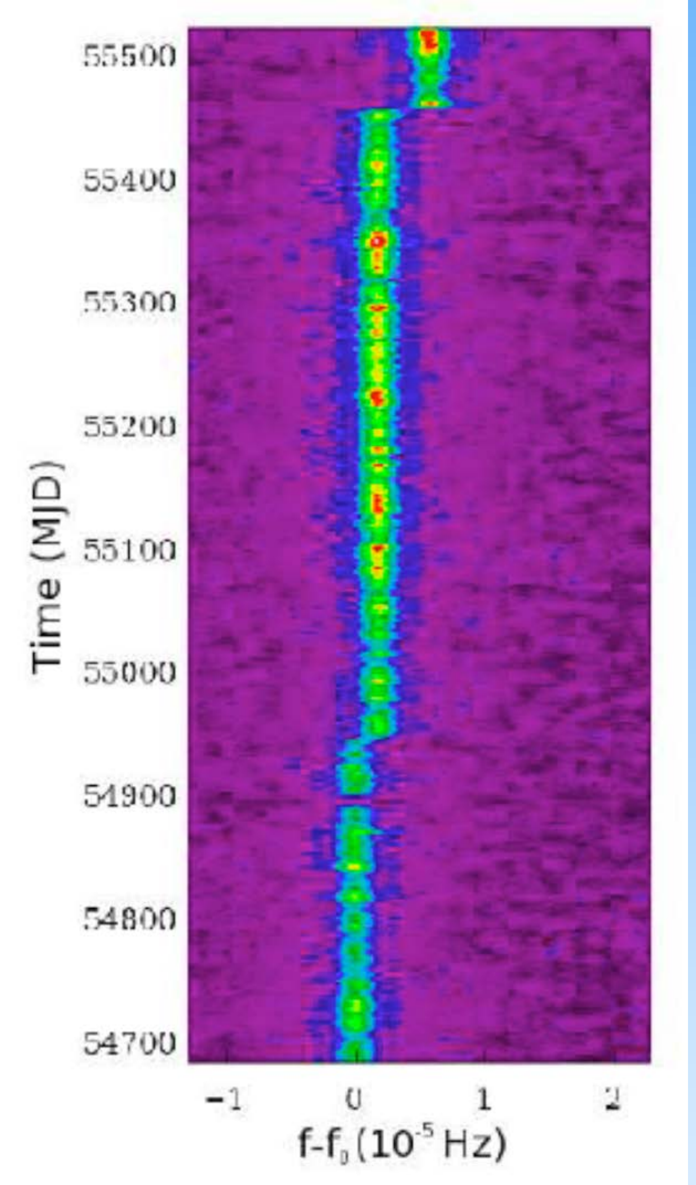




Pre-glitch ephemeris

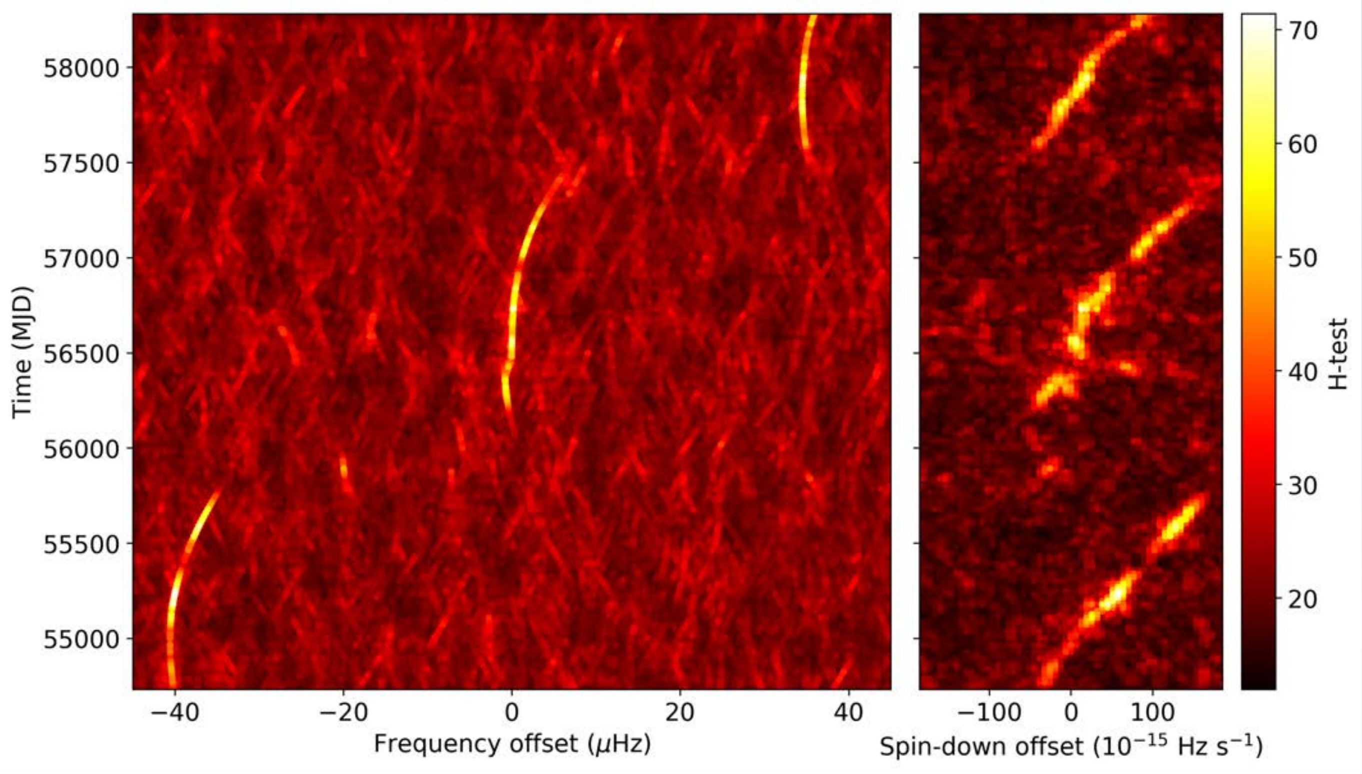


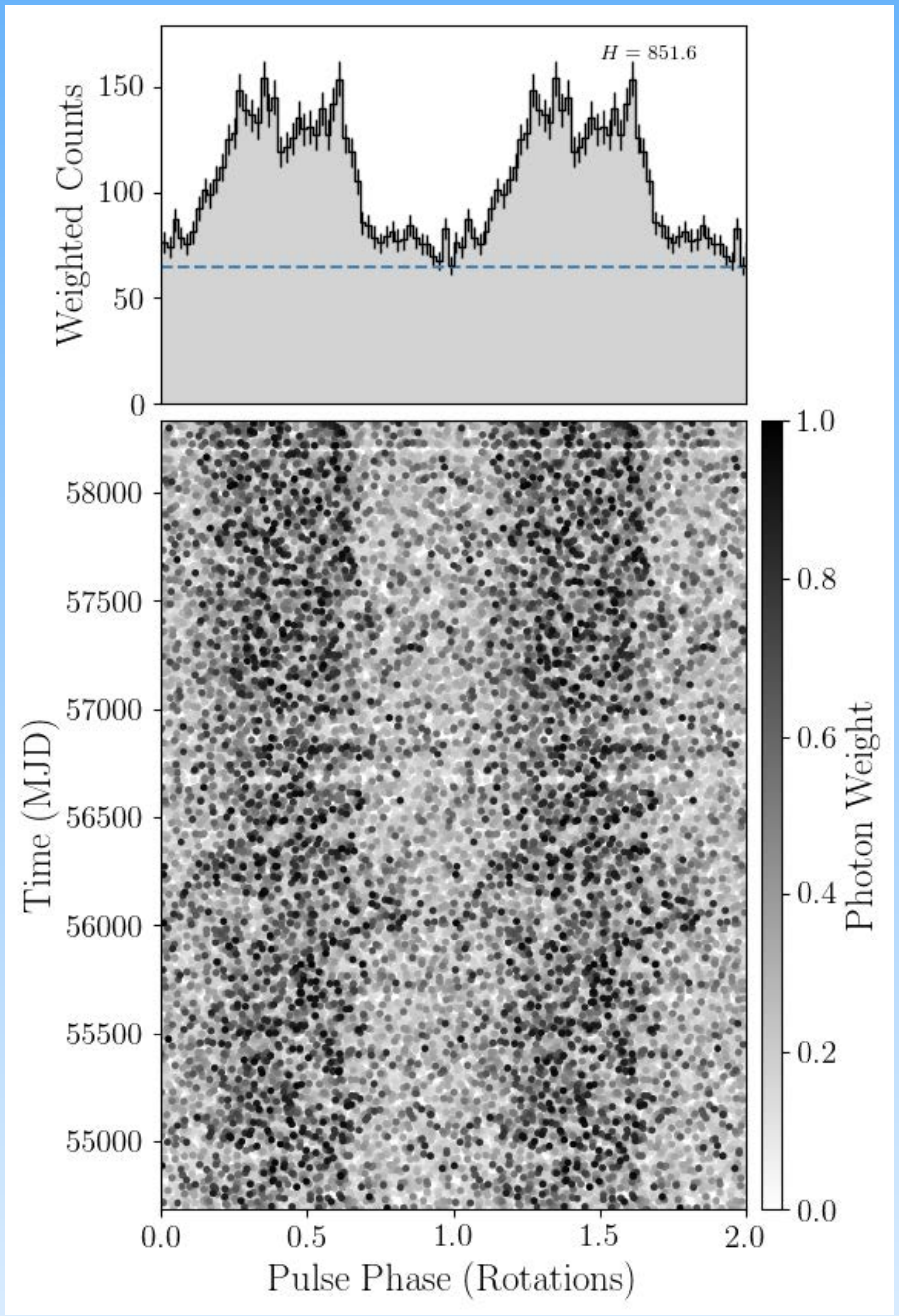
Post-glitch ephemeris



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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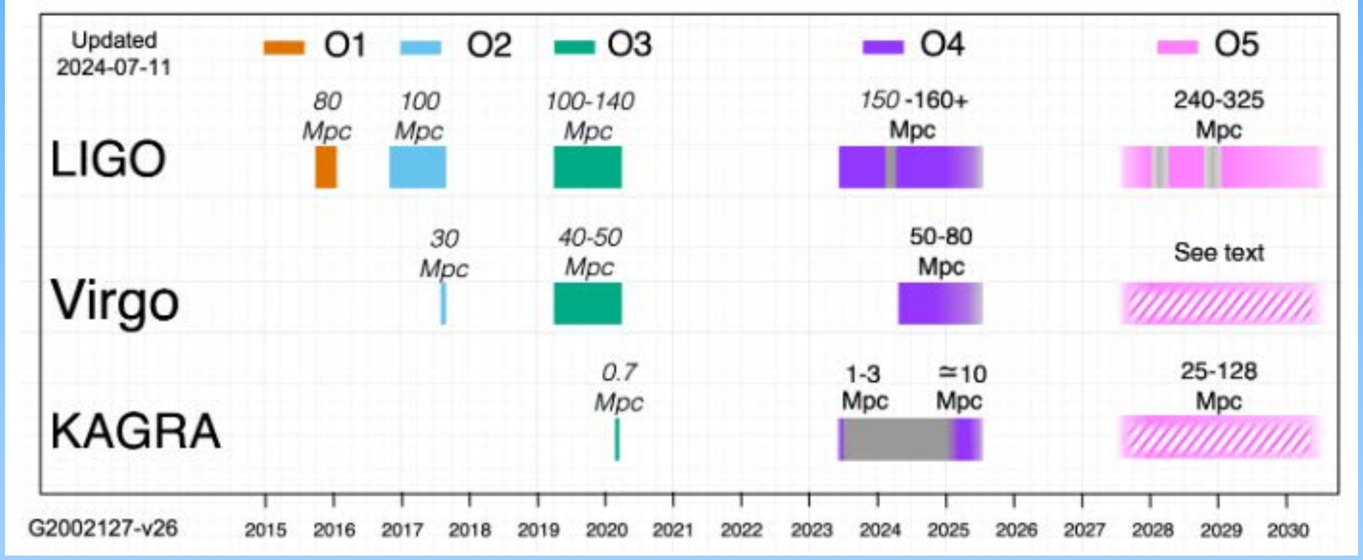
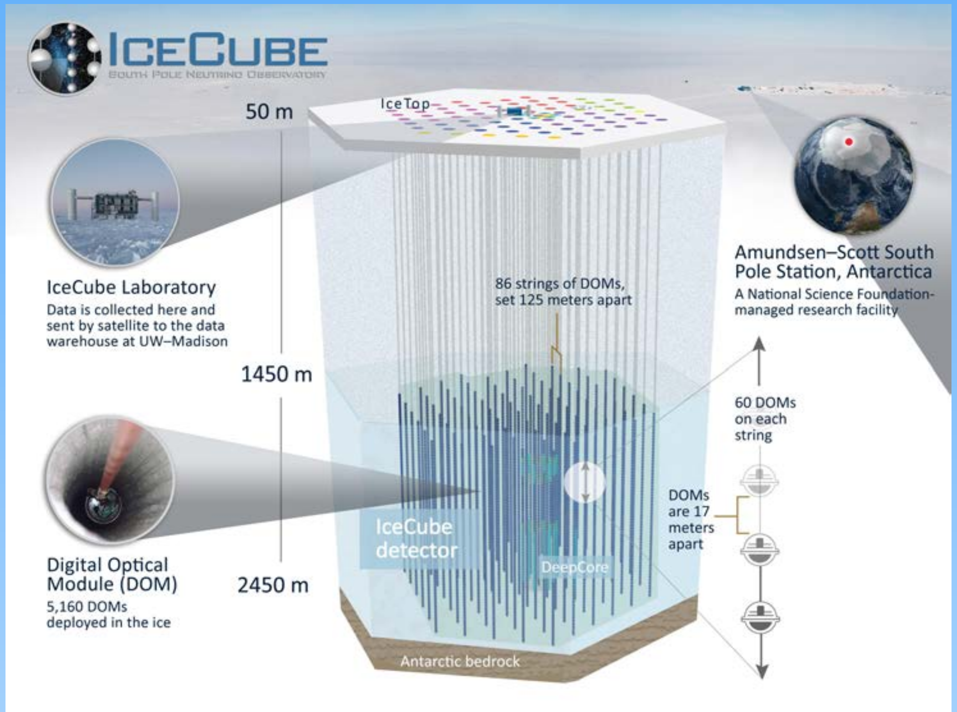
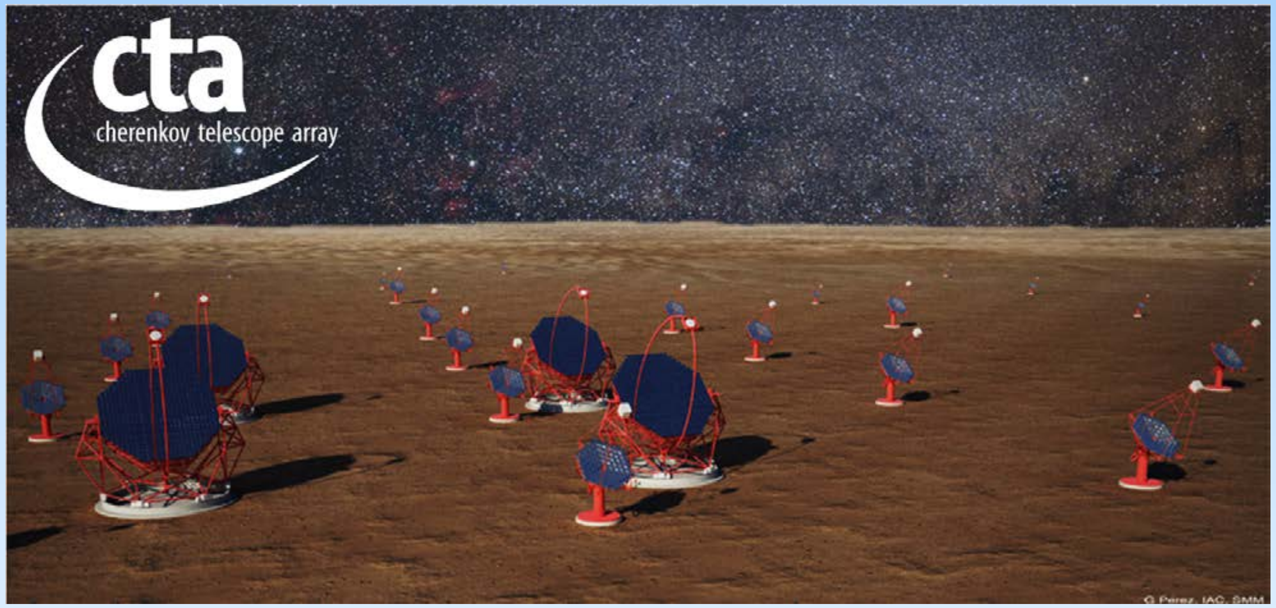
Fermi in the era of TDAMM





Credit: Rubin Obs./NSF/AURA



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Summary

- The success of Fermi LAT in the area pulsars cannot be attributed to one single reason:
  - The LAT was a giant leap in capabilities, brought about by technology that was ripe for application to space
  - New analysis techniques (e.g. time differencing) as well as increase in resources (e.g. Einstein@Home) were crucial
  - Good leadership and a strong collaboration (within the LAT and with outside groups, e.g. radio, X-ray) is key
  - Publicly available data and tools have been essential
- Fermi will continue to help uncover new pulsar surprises in the TDAMM era, especially with the arrival of new survey instruments, including CTA!

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Thank you

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