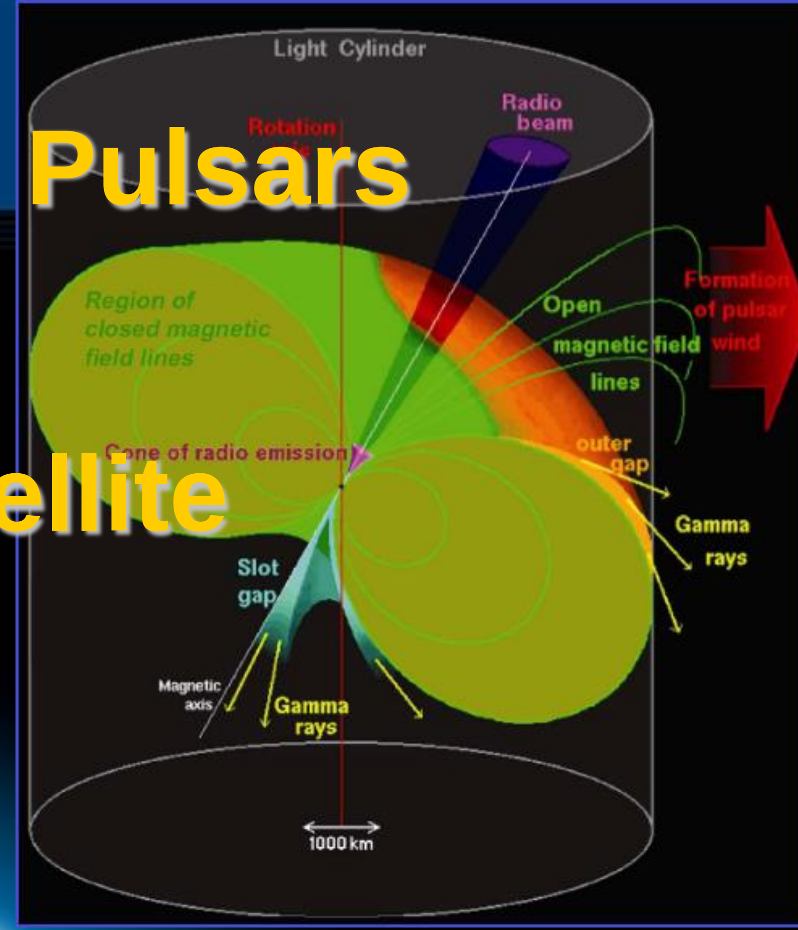
>200 Gamma-ray Pulsars

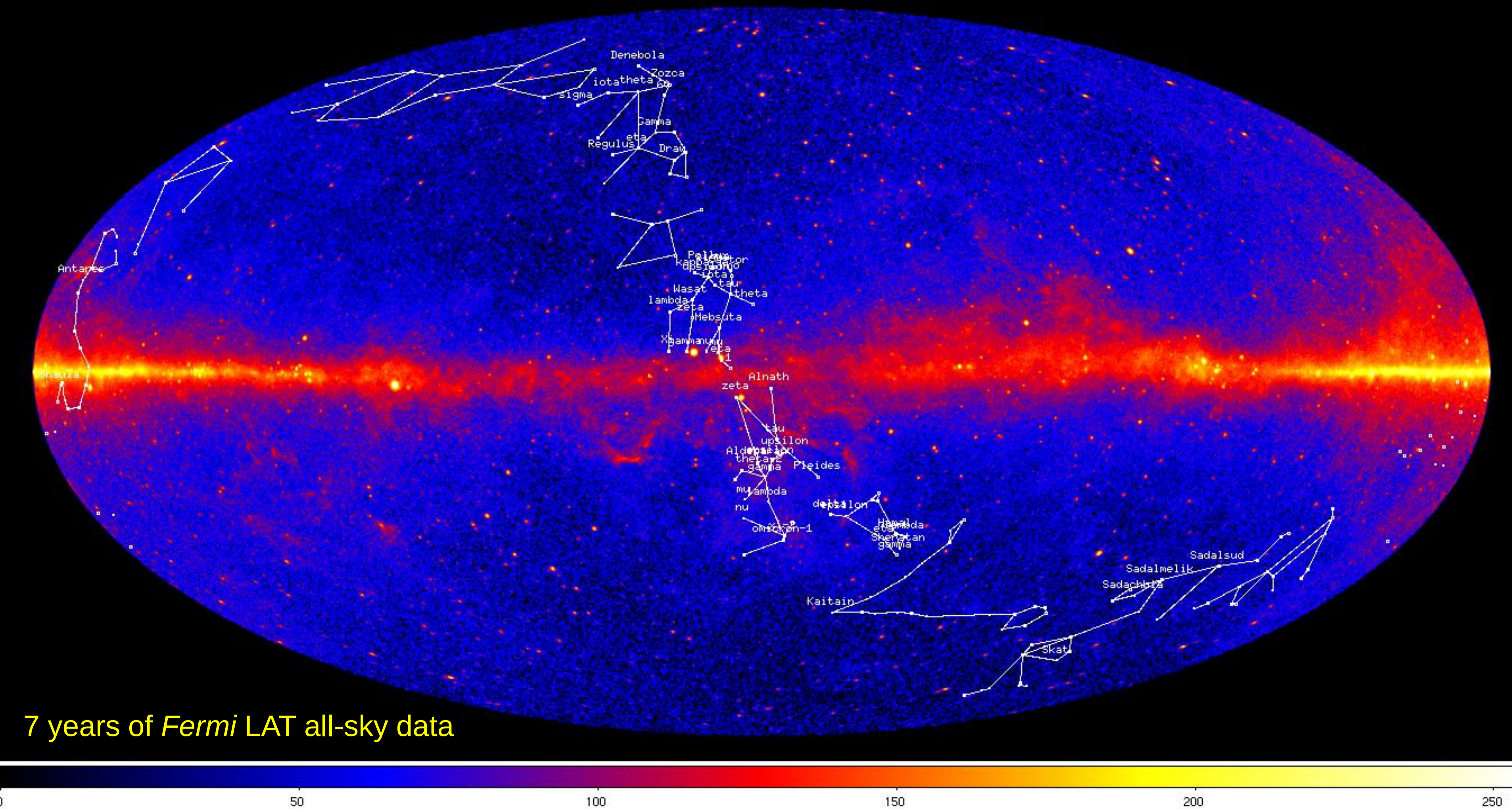
with

the *Fermi* satellite



David A. Smith, for the *Fermi* LAT collaboration and the pulsar consortia
Centre d'Études Nucléaires de Bordeaux-Gradignan
CENBG (CNRS)
smith@cenbg.in2p3.fr

MODE
Meudon, 18 May 2016

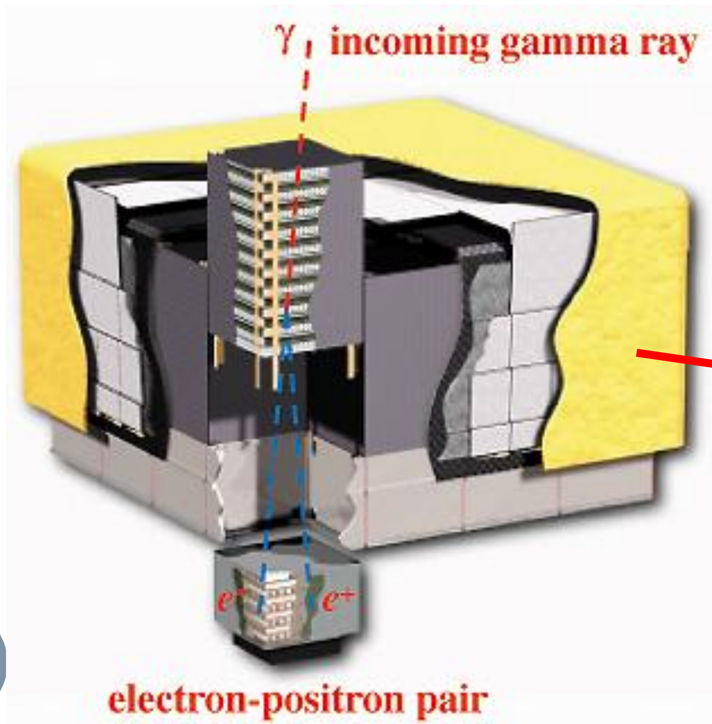


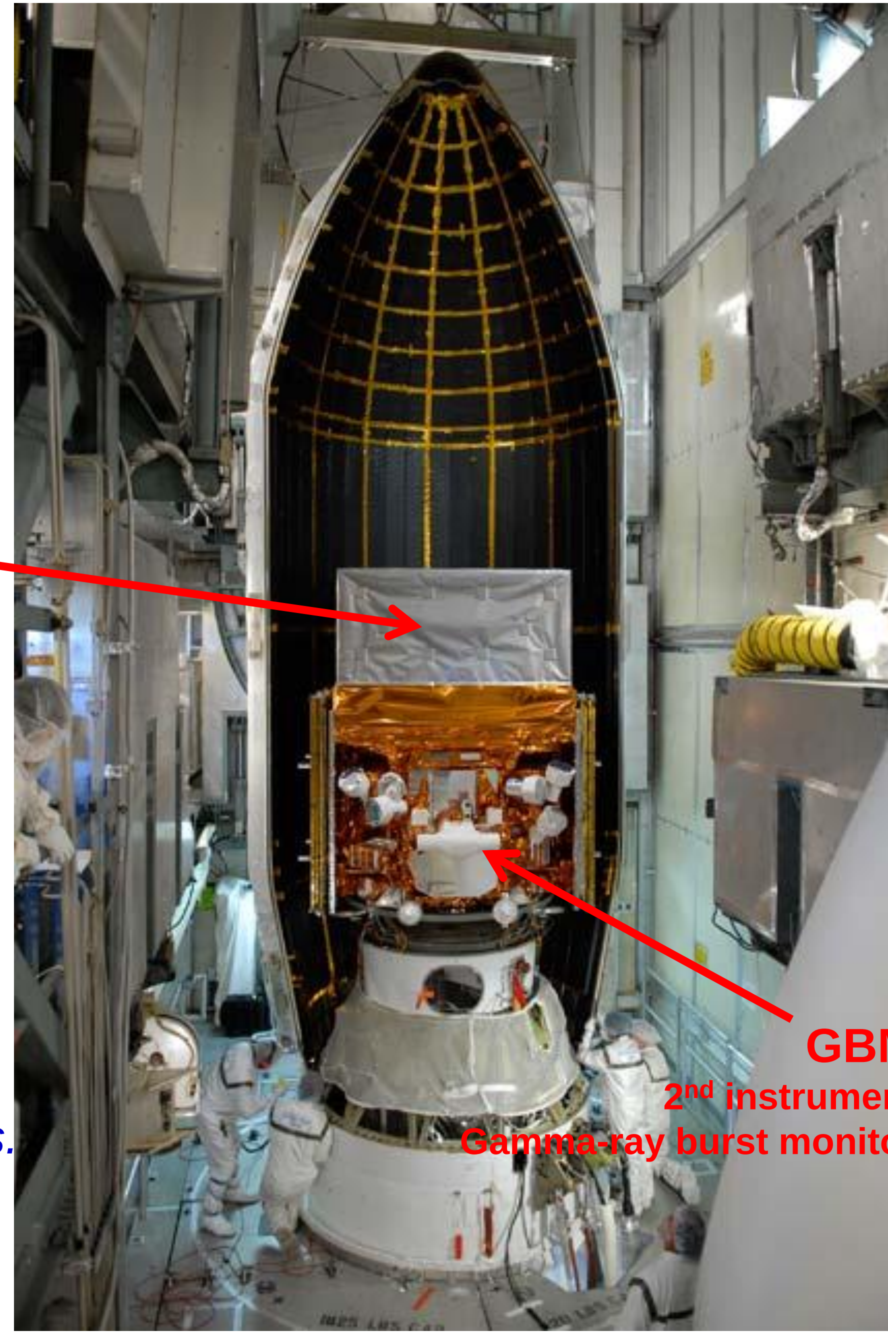
7 years of *Fermi* LAT all-sky data

Anti-center at the center. Zodiac constellations along the ecliptic.

June 11, 2008
Eight years next month
fermi
Gamma-ray
Space Telescope
Formerly "GLAST"

Large Area Telescope
30 MeV to 300 GeV





The whole sky, 8 times per day

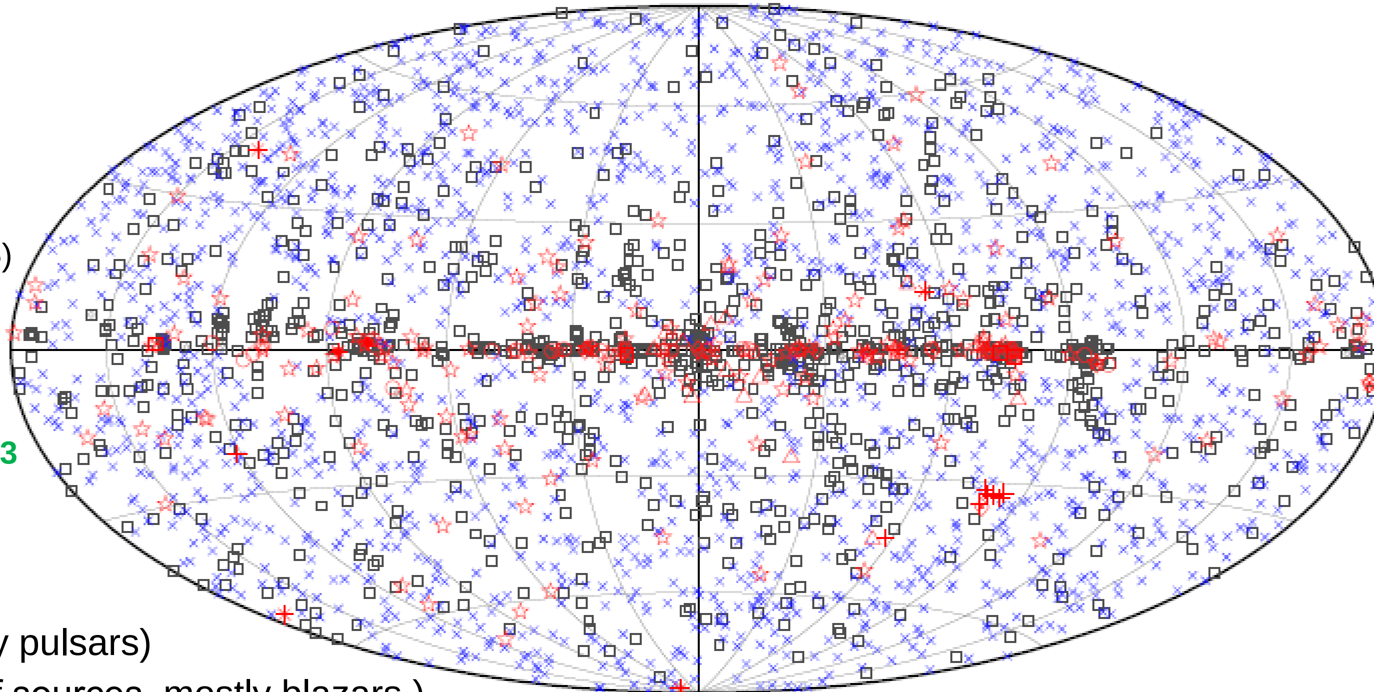
Better localization than previous instruments.

3FGL

3[rd] LAT source catalog

Acero et al. ApJS <u>218</u>, 23 (2015)

http://arxiv.org/abs/1501.02003



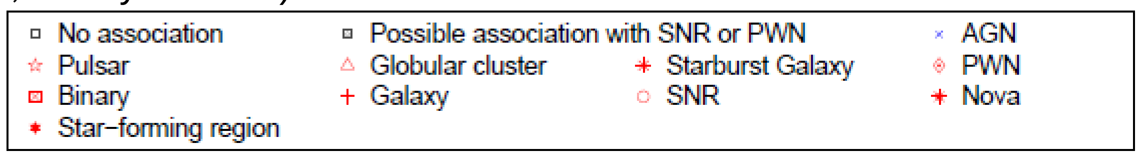
3033 total sources (>4σ)

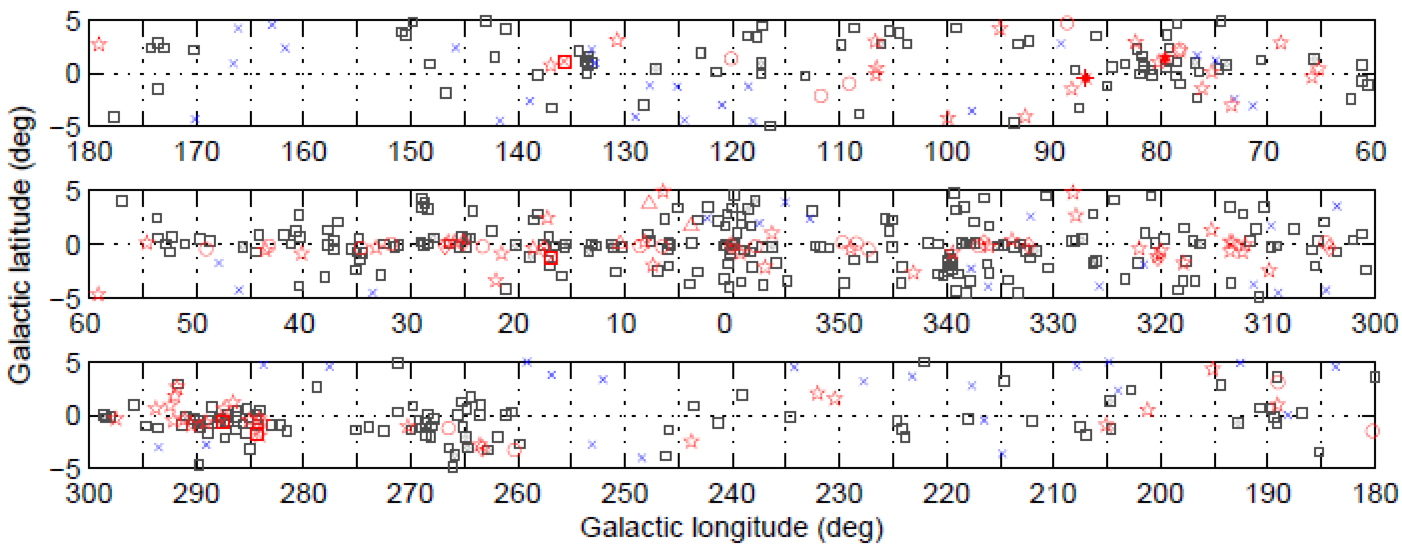
Red: Firm I.D. (232, mostly pulsars)

Blue: ‘Association’ (> ⅓ of sources, mostly blazars.)

Black: No I.D. (< ~⅓ of sources)

Un Id’s == *Gold* mine!



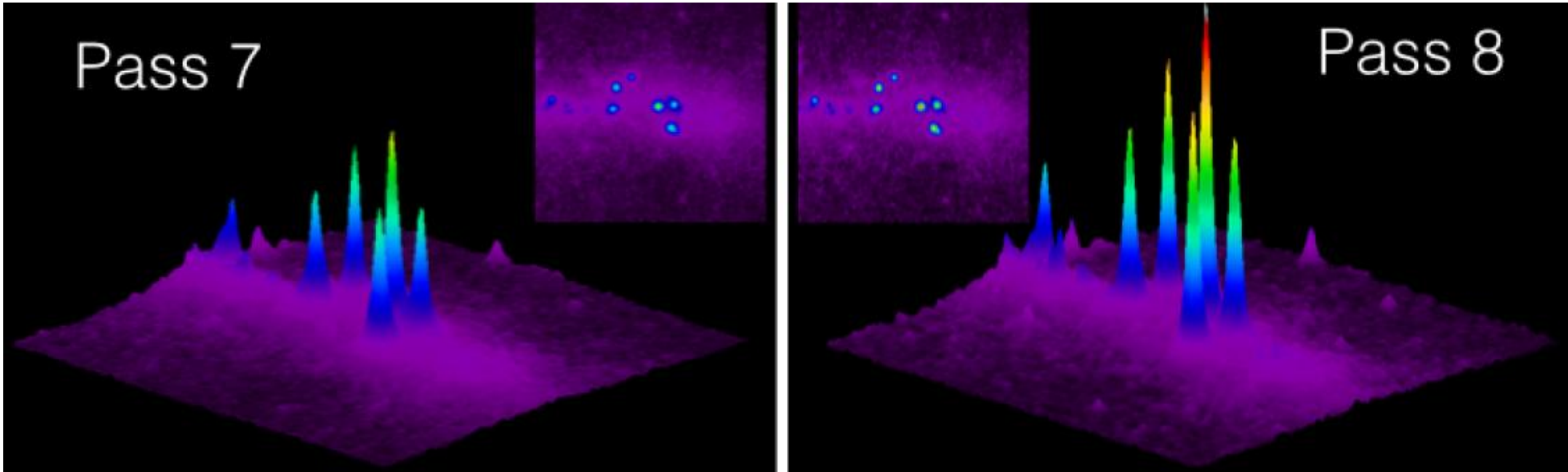


Pass 8: Toward the Full Realization of the Fermi-LAT Scientific Potential

W.Atwood, A. Albert, L. Baldini, M. Tinivella, J. Bregeon, M. Pesce-Rollins, C. Sgrò, P. Bruel, E. Charles, A. Drlica-Wagner, A. Franckowiak, T. Jogler, L. Rochester, T. Usher, M. Wood, J. Cohen-Tanugi, S. Zimmer for the Fermi-LAT Collaboration

- Event reconstruction completely re-thought.
- Significant improvement. Data public since 2015.
- Several pulsars popped into view.

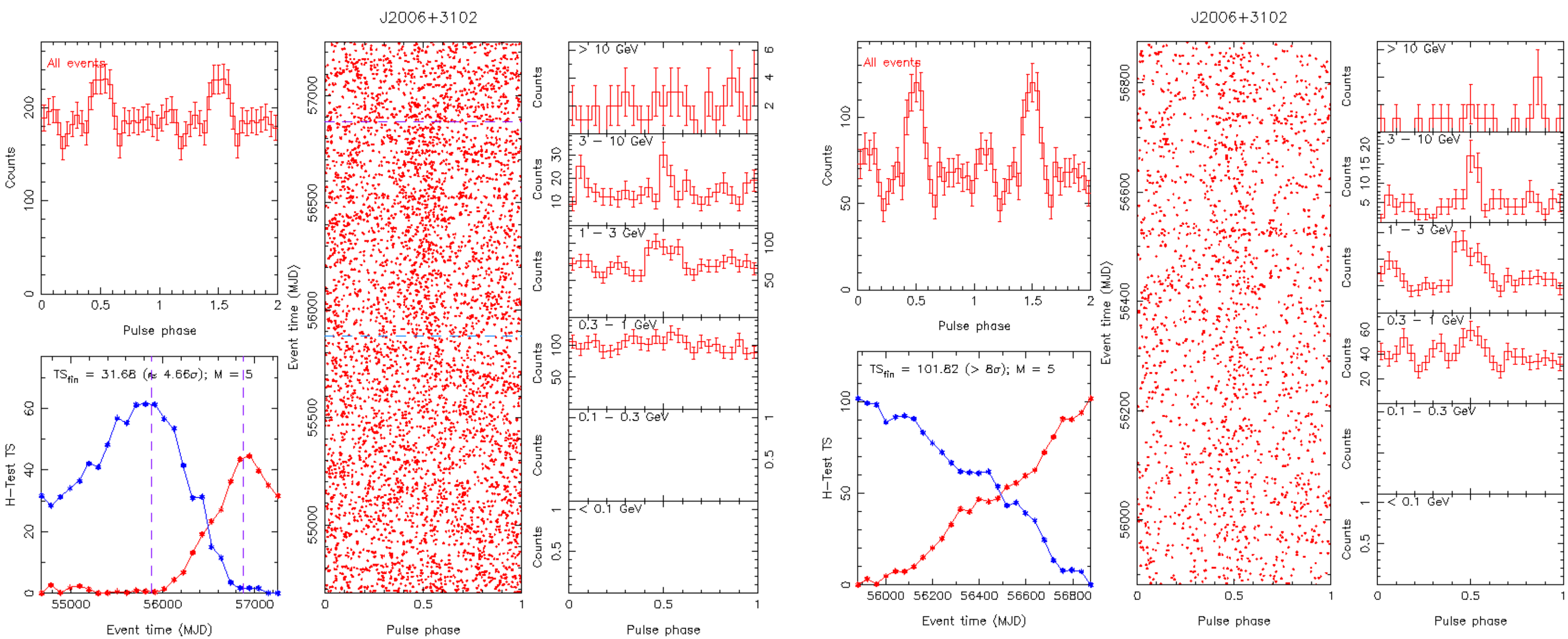
Figure from 2016 NASA Senior Review.



• 4FGL is well underway. 7 years of data and "Pass 8".

• New sources at positions of known pulsars.

• Example: got a radio rotation ephemeris for one near Cygnus.
Phase-folded (="psue"), and… *voilà*! Bright gamma pulsations.



Currently, 205 gamma-ray pulsars listed at
https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

½ are young, ½ are recycled (= millisecond pulsars = MSPs).

Of the young: ½ radio loud, ½ radio quiet.

½ already known. ½ found from *Fermi* data (¼ radio MSPs, ¼ young gamma).

¼ of known MSPs are gamma MSPs.
For spindown power $\dot{E}$>5E33 erg/s is >¾ (!)

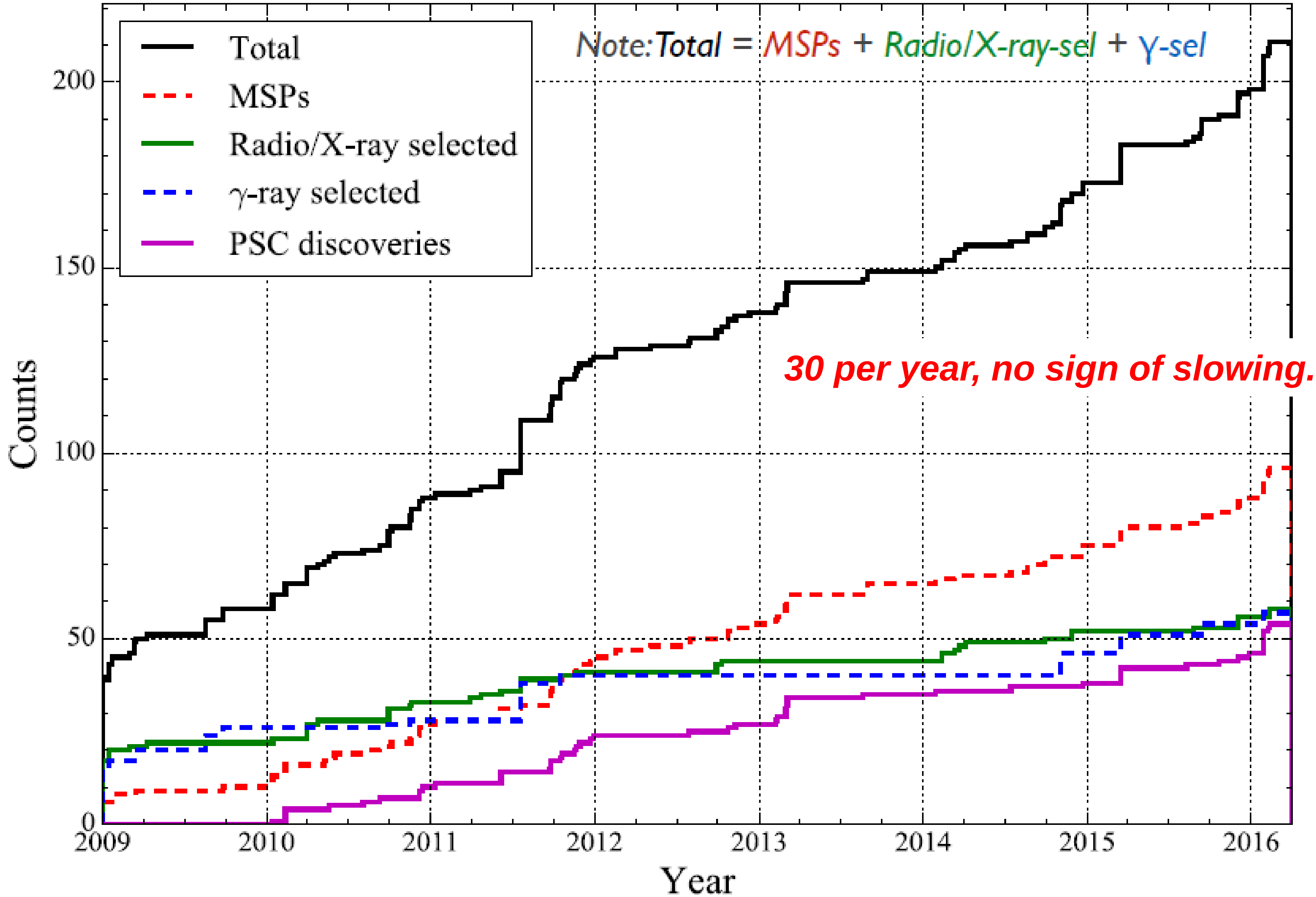
70 MSPs discovered in radio searches of LAT sources. Gamma-pulses now for 58.
(takes a year or two to establish a rotation ephemeris good enough to phase-fold the gammas)

1 MSP found in "nearly blind" gamma searches: optical companion's orbit, then pulsar period. 2 isolated MSPs found in blind searches! (*Hannover*)

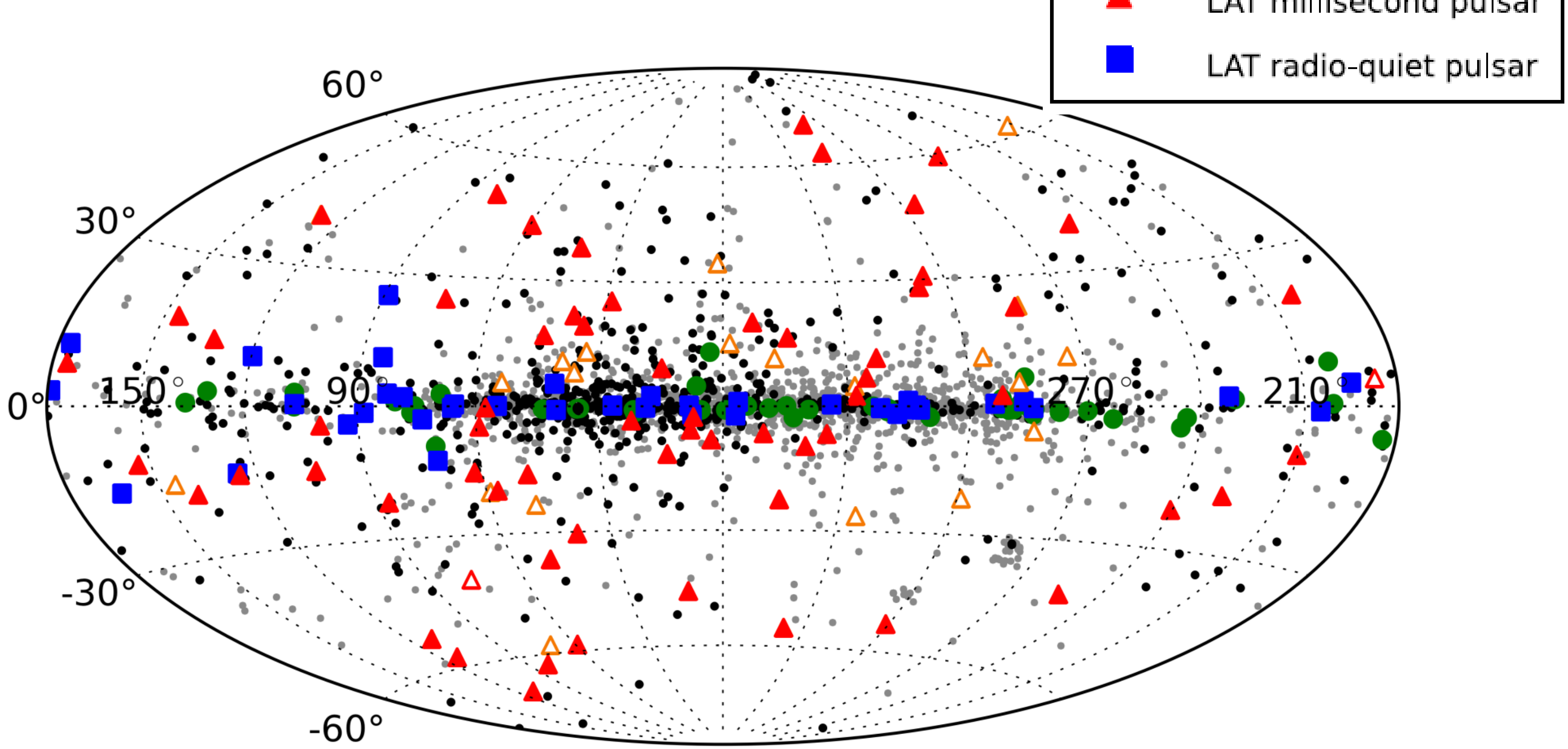
Most LAT MSPs *faster* and *noisier* ('black widows', 'redbacks') than 'traditional' MSPs.

Many interesting individual objects.

Detected pulsars versus time



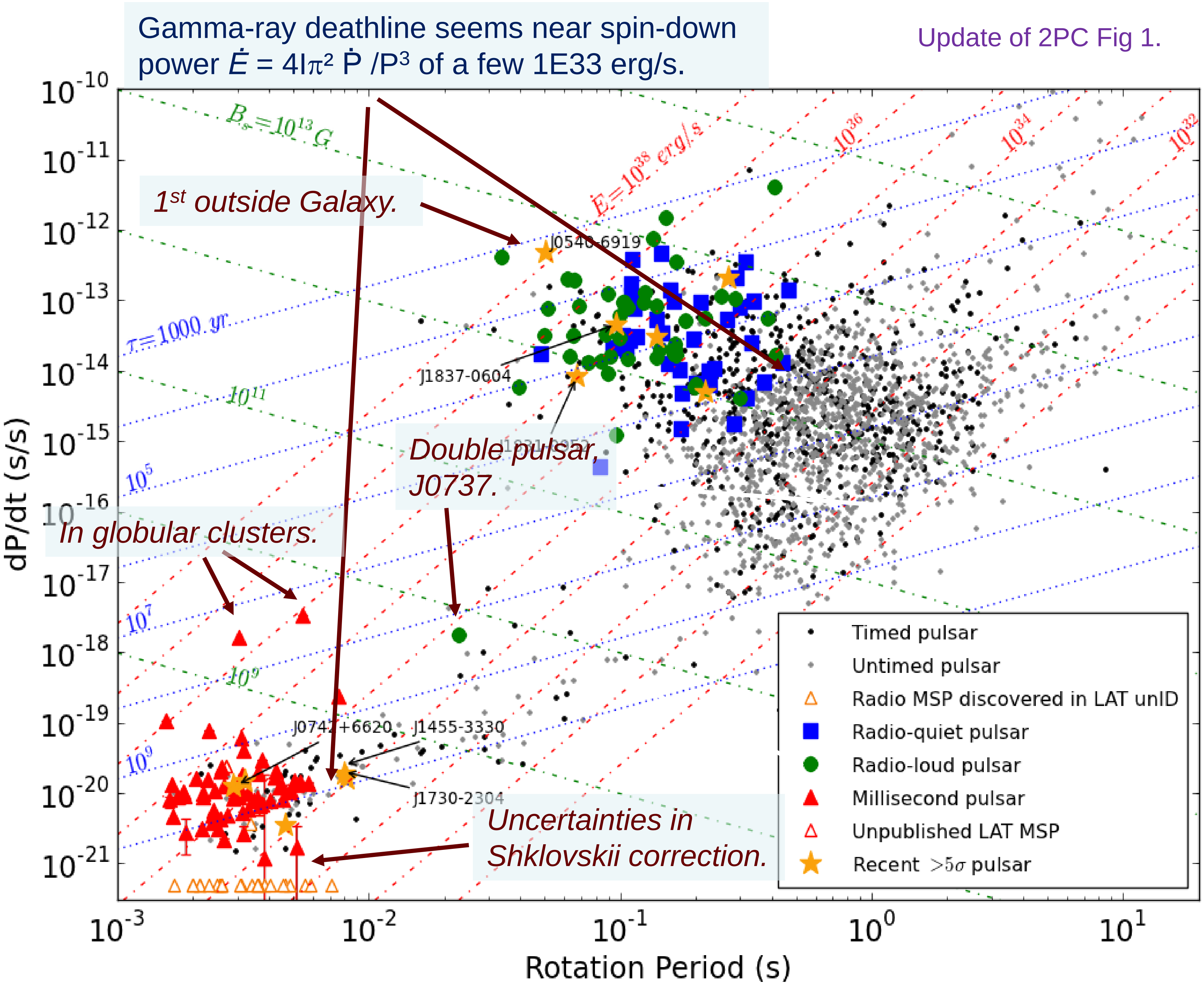
Lucas Guillemot, 2016



Two excellent recent reviews:

Gamma-Ray Pulsar Revolution, P. Caraveo, Annual Review of Astronomy and Astrophysics 52, 2014.

Gamma-ray pulsars: A gold mine, I. Grenier & A.K. Harding, Compte rendus Physique 16, 2015



Gamma-ray deathline seems near spin-down power $\dot{E} = 4I\pi^2 \dot{P} / P^3$ of a few 1E33 erg/s.
Update of 2PC Fig 1.
1st outside Galaxy.
Double pulsar, J0737.
In globular clusters.
Uncertainties in Shklovskii correction.
J0540-6919
J1837-0604
J0742+6620
J1455-3330
J1730-2304
$B_s = 10^{13}$ G
10^{11}
10^9
τ=1000 yr
10^5
10^7
10^9
$\dot{E} = 10^{38}$ erg/s
10^{36}
10^{34}
10^{32}
Timed pulsar
Untimed pulsar
Radio MSP discovered in LAT unID
Radio-quiet pulsar
Radio-loud pulsar
Millisecond pulsar
Unpublished LAT MSP
Recent $>5\sigma$ pulsar
dP/dt (s/s)
Rotation Period (s)

Three ways to discover gamma-ray pulsars

1. "PSUE" = "*Pulsar Search Using Ephemerides*":
   - Phase-fold gamma-rays using rotation parameters of a known pulsar.
   - Weights from spectrum⊗point-spread-function eliminate trials over ROI & energy cuts.

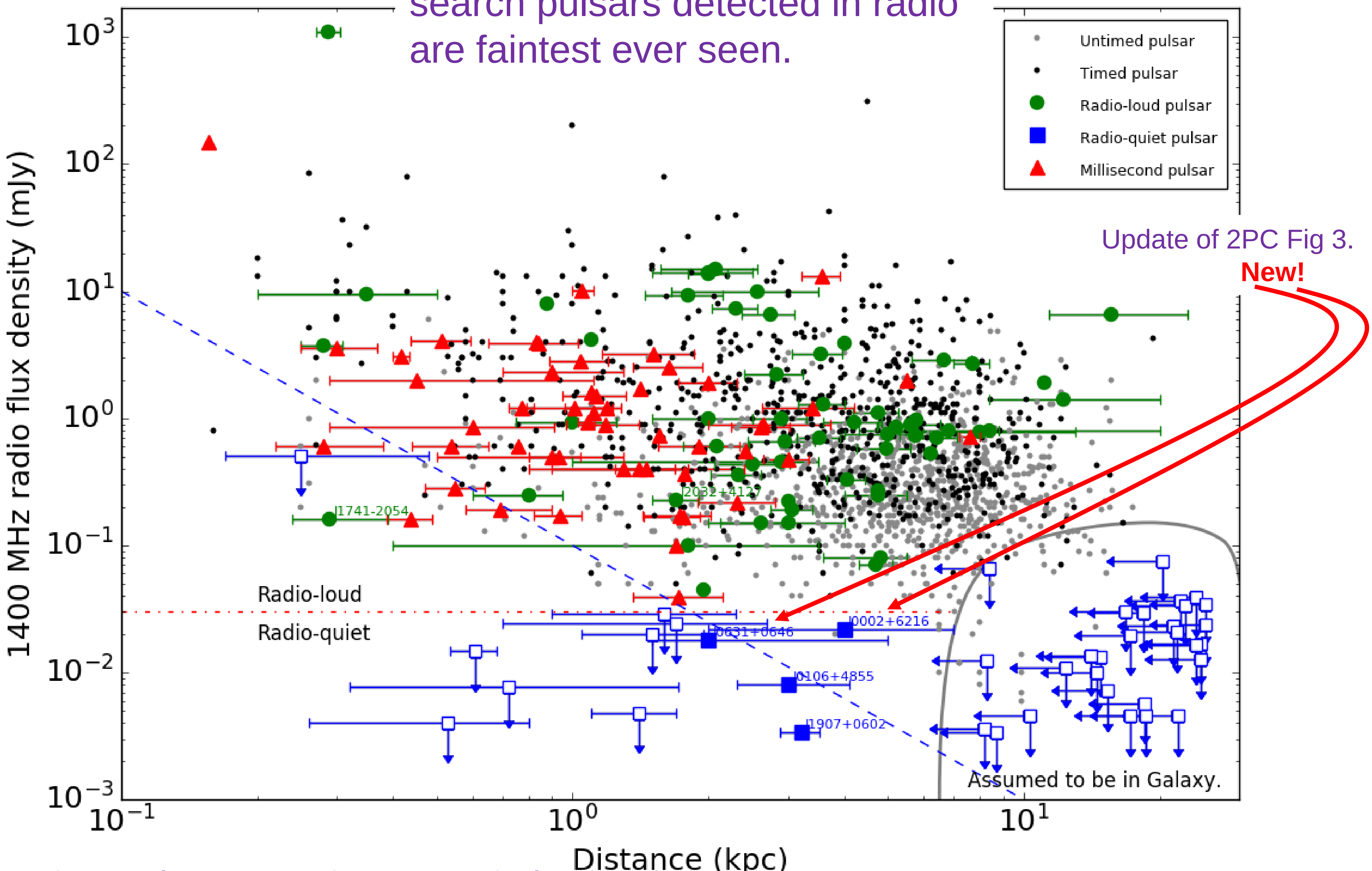
   >800 ephemerides from main radio telescopes

2. Deep radio searches at unidentified source positions :
   - 70 MSPs, off the plane.
   - Can take a year before PSUE allows pulsed gamma detection.

3. Blind period, position search in gamma-rays :
   - 54 young PSRs, 2 MSPs, 1 binary MSP (near-sighted).
   - Only 4 radio detections.

Einstein@Home : 10 kyrs of CPU!
See their 18 discoveries at
https://einstein.phys.uwm.edu/gammaraypulsar/FGRP1_discoveries.html

Four of the six gamma blind-search pulsars detected in radio are faintest ever seen.



Diagonal : 100 μJy-kpc² pseudo-luminosity.

Gamma-Ray Timing of Redback PSR J2339-0533: Hints for Gravitational Quadrupole Moment Changes

Holger J. Pletsch[1,2] and Colin J. Clark[1,2]
Show affiliations

Holger J. Pletsch and Colin J. Clark 2015 *ApJ* **807** 18. doi:10.1088/0004-637X/807/1/18
Received 11 February 2015, accepted for publication 21 April 2015. Published 25 June 2015.

Abstract

We present the results of precision gamma-ray timing measurements of the binary millisecond pulsar PSR J2339–0533, an irradiating system of the "redback" type, using data from the *Fermi* Large Area Telescope. We describe an optimized analysis method to determine a long-term phase-coherent timing solution spanning more than six years, including a measured eccentricity of the binary orbit and constraints on the proper motion of the system. A major result of this timing analysis is the discovery of an extreme variation of the nominal 4.6 hr orbital period $P_{\rm orb}$ over time, showing alternating epochs of decrease and increase. We inferred a cyclic modulation of $P_{\rm orb}$ with an approximate cycle duration of 4.2 yr and a modulation amplitude of $\Delta P_{\rm orb}/P_{\rm orb} = 2.3 \times 10^{-7}$. Considering different possible physical causes, the observed orbital-period modulation most likely results from a variable gravitational quadrupole moment of the companion star due to cyclic magnetic activity in its convective zone.

<u>Another example:</u> A braking index for PSR J1208-6238.

n < 3, of course. But why?

Clark, Wu, Pletsch, Guillemot, et al, ApJ in prep.

Radio searches of LAT unassociated sources

« Pulsar Search Consortium » (PSC).
Telescopes involved: GBT, Arecibo, Parkes, GMRT, Nançay, Effelsberg, etc.

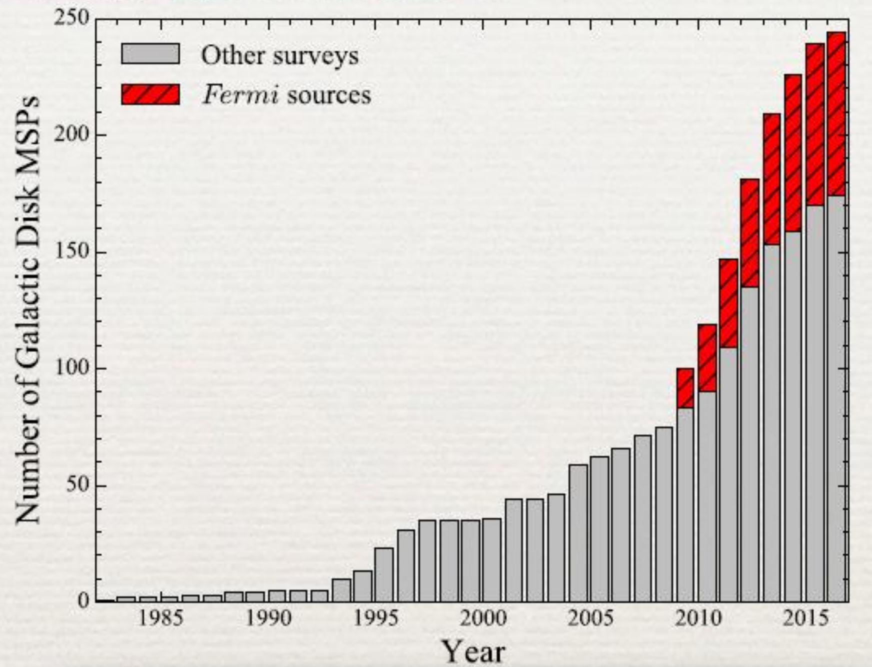
Significant contribution to the hunt for Galactic-disk MSPs!

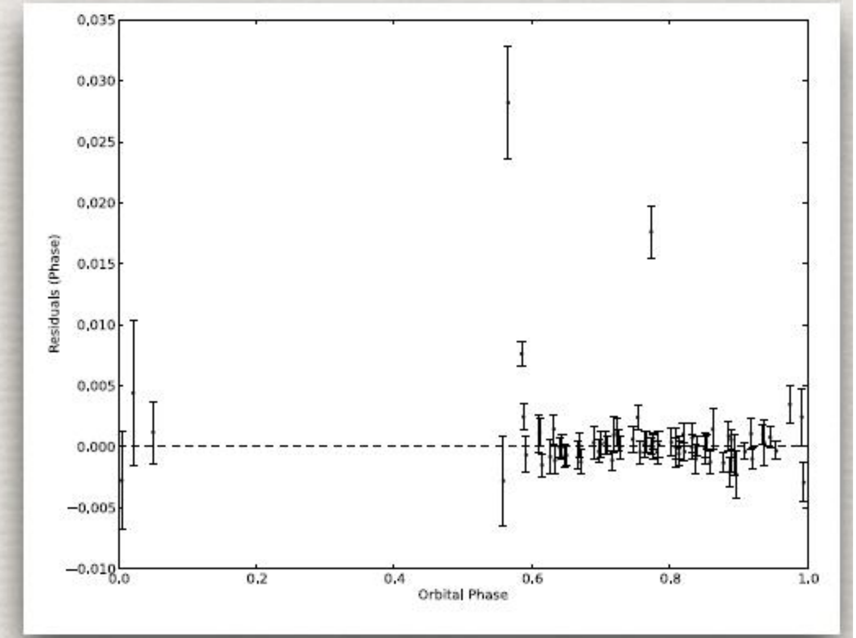
MANY new redback and black widow systems.

Some of the new MSPs are being added to pulsar timing arrays (PTAs) to search for GWs.

Re-observations crucial: interferences, scintillation, eclipses, etc.

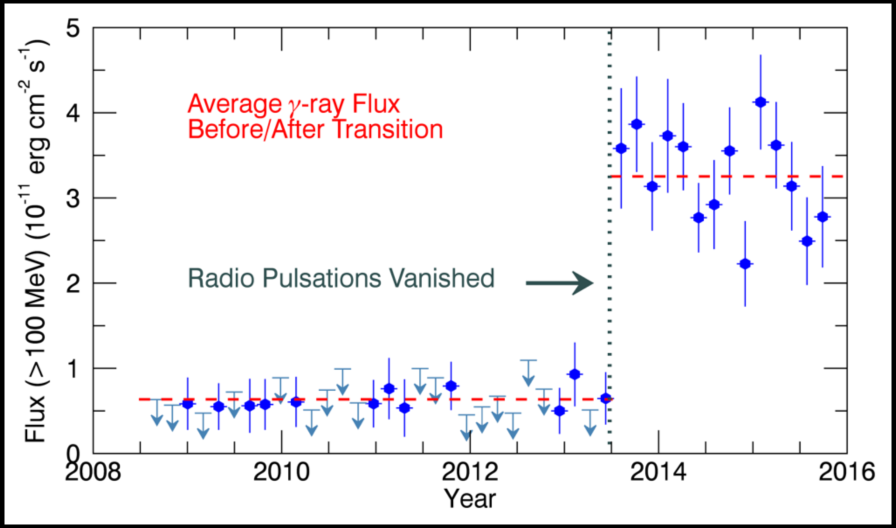
Deneva et al. (in press): J1048+2339 is eclipsed over half of the orbit at 327 MHz!



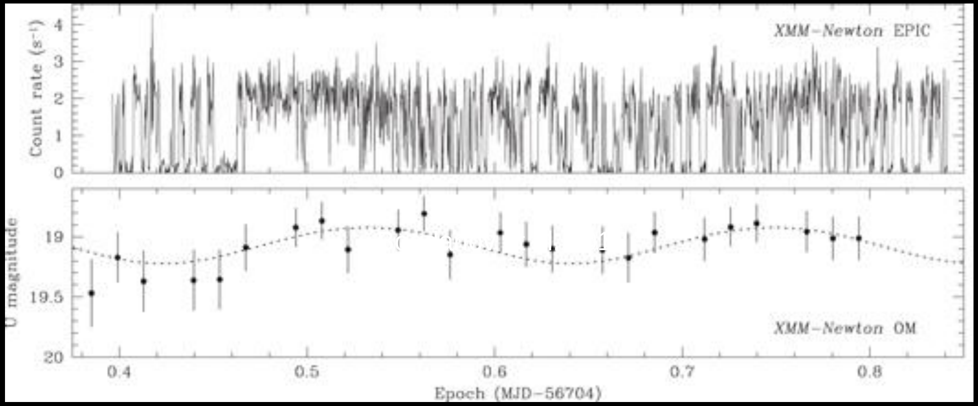


Transitional Millisecond Pulsars

Gamma-ray Transition of PSR J1023+0038



X-ray and U Band Light Curves of 3FGL J1544.6-1125



- 40% of MSPs discovered in searches of LAT sources are interacting binaries (\`black widows' and \`redbacks')
- Prior to *Fermi* only 1 redback and ~6 black widows were known outside of globular clusters (now ~12 and 24)
- More expected - LAT already detected two transitions between accreting and radio MSP states
- γ-ray emission brighter in the accreting state – a mystery since accreting sources are *not* typical γ-ray emitters. What is the mechanism?
- Optical searches of LAT sources have revealed new candidates

A new area of study for *Fermi*

25-Year Period Pulsar Binary

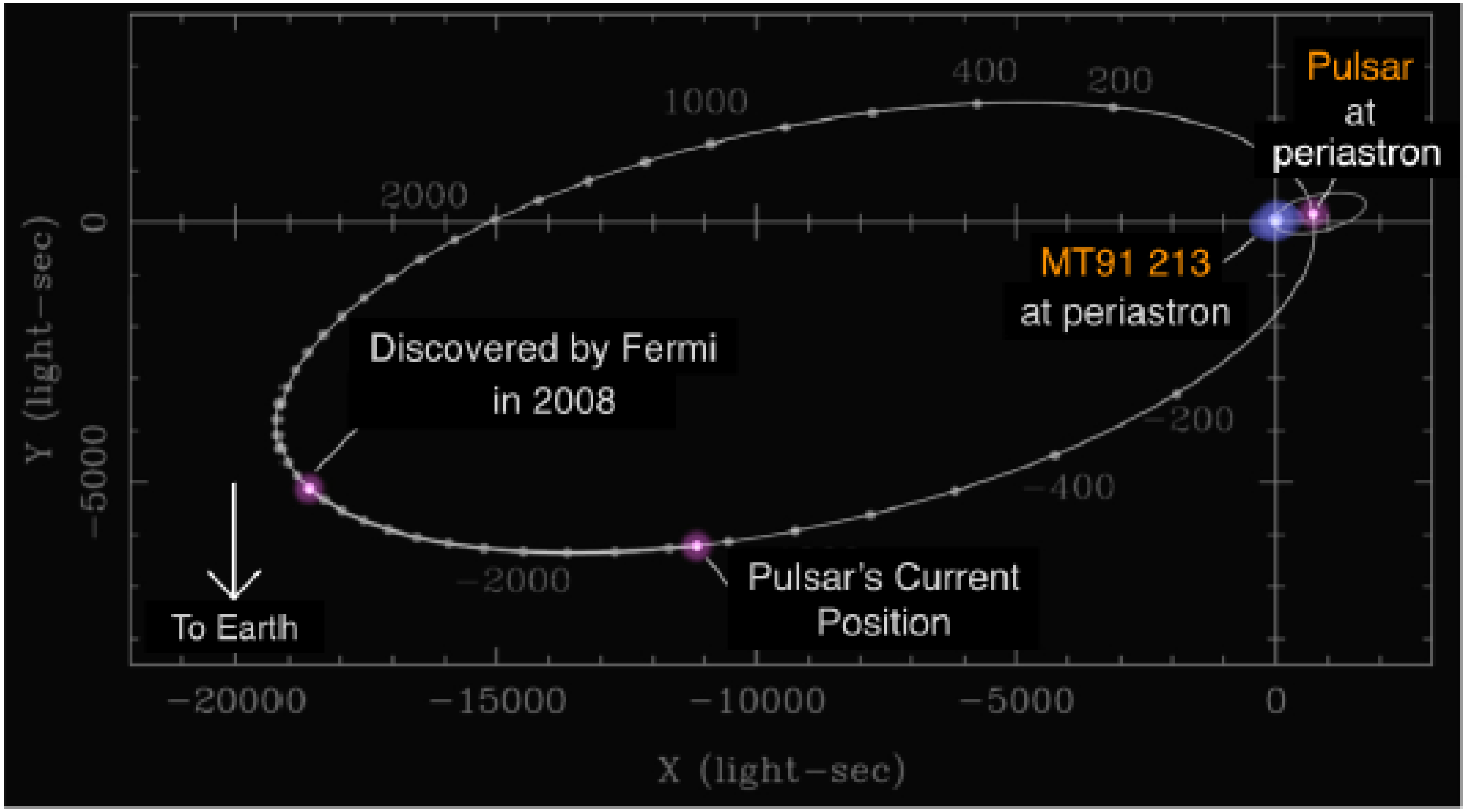
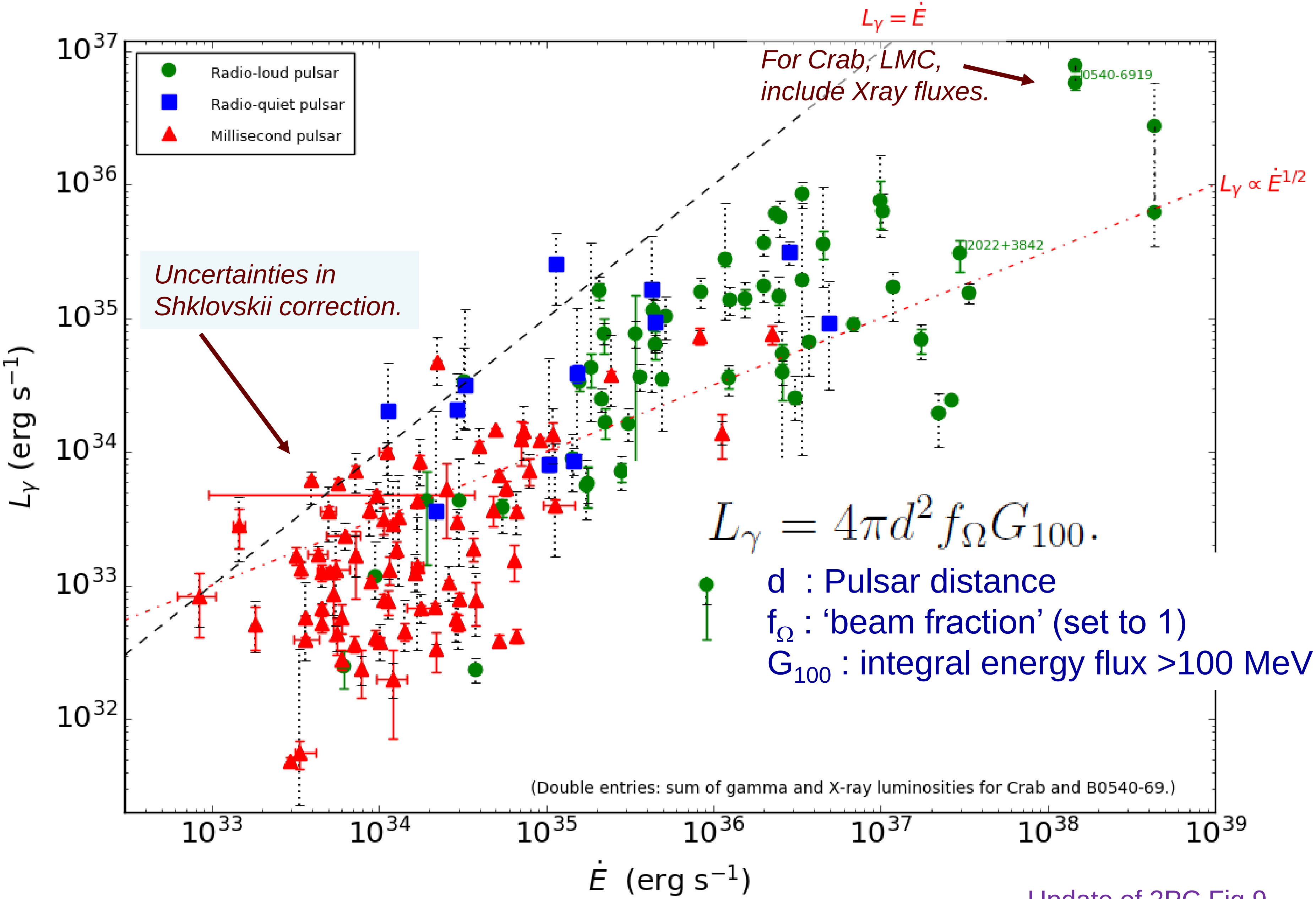


Figure 6: In 2018 *Fermi* will provide critical observations of the periastron passage of the 25-year binary system MT91 213/PSR J2032+4127 [31].

[31] Lyne, A. G. et al. *MNRAS* 451, 581, 2015

Gamma-ray luminosity versus spindown power



$$L_\gamma = 4\pi d^2 f_\Omega G_{100}.$$

d : Pulsar distance

f_Ω : 'beam fraction' (set to 1)

G_{100} : integral energy flux >100 MeV

Update of 2PC Fig 9.

Some folks think the LAT excess is particle Dark Matter (e.g. neutralinos).

PHYSICAL REVIEW D **88**, 083009 (2013)

Millisecond pulsars cannot account for the inner Galaxy's GeV excess

Dan Hooper,[1,2] Ilias Cholis,[1] Tim Linden,[3] Jennifer M. Siegal-Gaskins,[4] and Tracy R. Slatyer[5]
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[2]*Department of Astronomy and Astrophysics, University of Chicago, 5640 S Ellis Avenue, Chicago, Illinois 60637, USA*
[3]*Department of Physics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, California 95064, USA*
[4]*California Institute of Technology, 1200 East California Boulevard, Pasadena, California 91125, USA*
[5]*School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*
(Received 7 June 2013; published 18 October 2013)

Using data from the Fermi Gamma-Ray Space Telescope, a spatially extended component of gamma rays has been identified from the direction of the Galactic center, peaking at energies of ~2–3 GeV. More recently, it has been shown that this signal is not confined to the innermost hundreds of parsecs of the Galaxy, but instead extends to at least ~3 kpc from the Galactic center. While the spectrum, intensity, and angular distribution of this signal is in good agreement with predictions from annihilating dark matter, it has also been suggested that a population of unresolved millisecond pulsars could be responsible for this excess GeV emission from the inner Galaxy. In this paper, we consider this later possibility in detail.

But

a) large uncertainties on diffuse gamma spectrum of central galaxy,

Fermi-LAT Observations of High-Energy Gamma-Ray Emission Toward the Galactic Center

Ajello, M. et al. 2016, ApJ, 819, 44

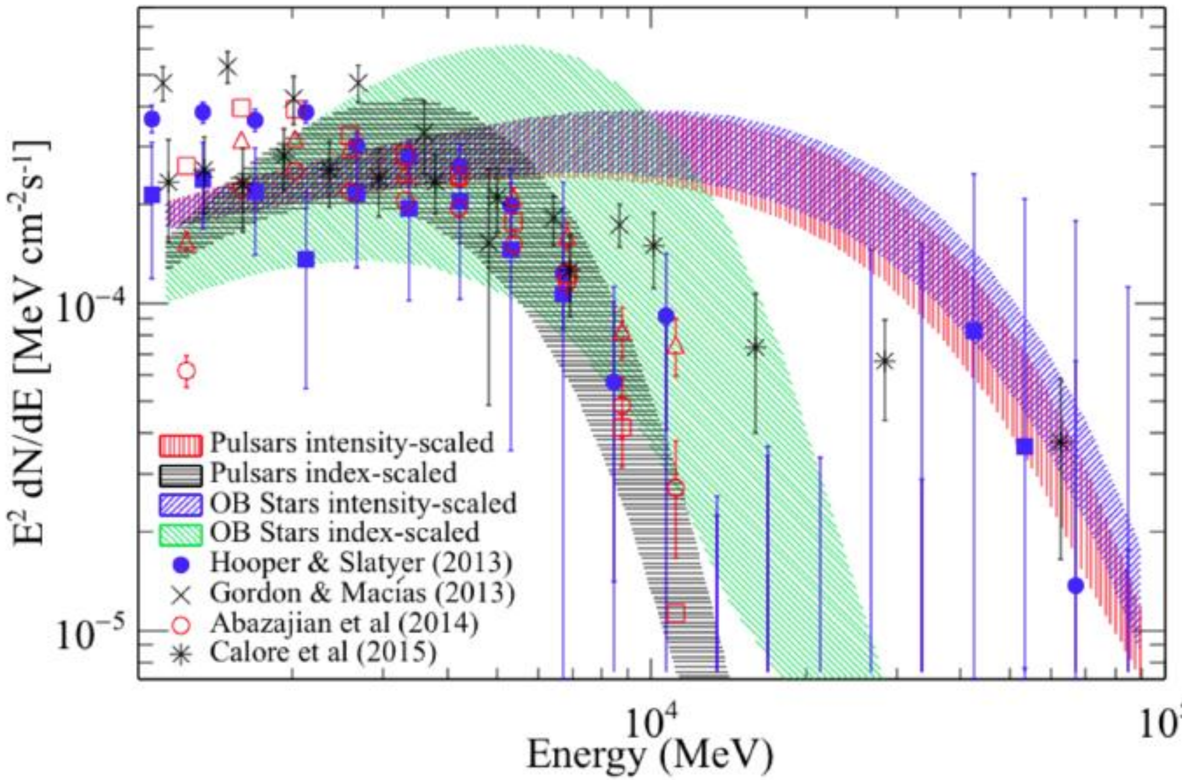
and

b) Surely more unresolved gamma PSRs and MSPs than once thought.

Young pulsars bright but short-lived. MSPs dim but last ~forever.

Determining pulsar luminosities and the pulsar population requires finding as broad a variety of gamma-ray pulsars as possible.

Probing the dark corners of parameter space…



Fermi-LAT Observations of High-Energy Gamma-Ray Emission Toward the Galactic Center

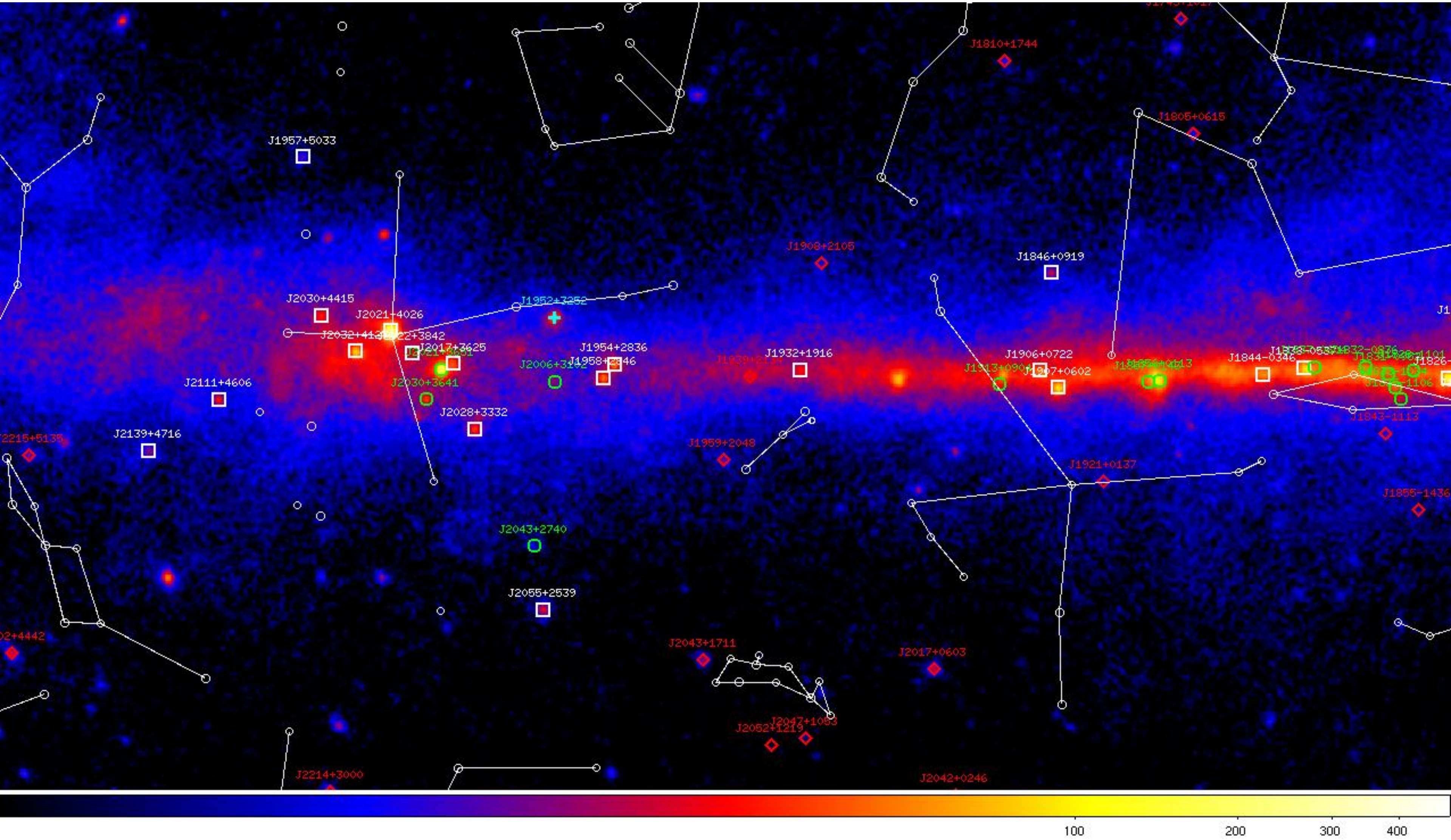
Ajello, M. et al. 2016, ApJ, 819, 44

See also *Fermi*-LAT Dark Matter "white paper", Phys. Reports, in press (Charles *et al*.)

arXiv:1605.02016

What I personally am working on:
"*near-blind*" search of
PSR J2022+3842 (and J1101-6101, and J1640-4631)

= SNR G338.3-0.0 = HESS J1640-465

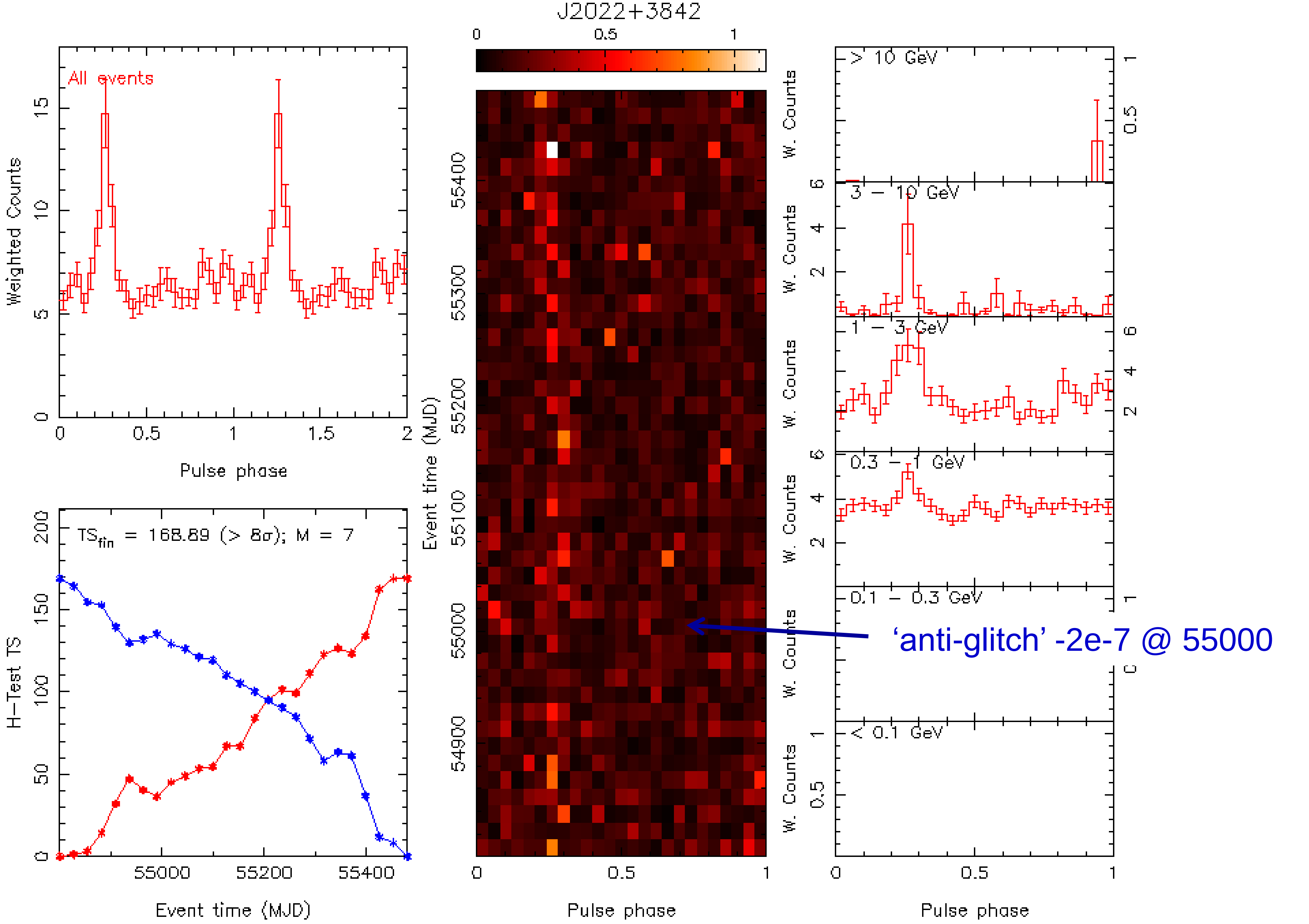


PSR J2022+3842

- Chandra found a pulsar-like source in SNR G76.9+1.0
- Deep GBT radio search: P0=24 ms pulsar discovered
- ~10 kpc, behind Cygnus.
- One week of RXTE observations: one of highest known Ė's. *Arzoumanian et al (2011)*
- XMM observations: P0=48 ms and '*only*' Ė = 3E37 erg/s (#8) *Arumugasamy et (2014)*
- No phase connected ephemeris. 3FGL no, 4FGL yes.

- March 2015: Haruka Ohuchi discovers gamma pulsations using *gtpsearch* in the F0,F1 range around the RXTE, XMM values.
- Haruka also showed , all near MJD ~ 55000:
  i. Evidence for flare
  ii. Evidence for glitch
  iii. Possible profile change.

- Since September 2015: Smith & Guillemot working to improve the ephemeris.
  Ray, Ransom, Gotthelf, Clark helping at times.



J2022+3842
All events
Weighted Counts
Pulse phase
TS_{fin} = 168.89 (> 8σ); M = 7
H−Test TS
Event time (MJD)
Pulse phase
> 10 GeV
3 − 10 GeV
1 − 3 GeV
0.3 − 1 GeV
0.1 − 0.3 GeV
< 0.1 GeV
W. Counts
Pulse phase
'anti-glitch' -2e-7 @ 55000

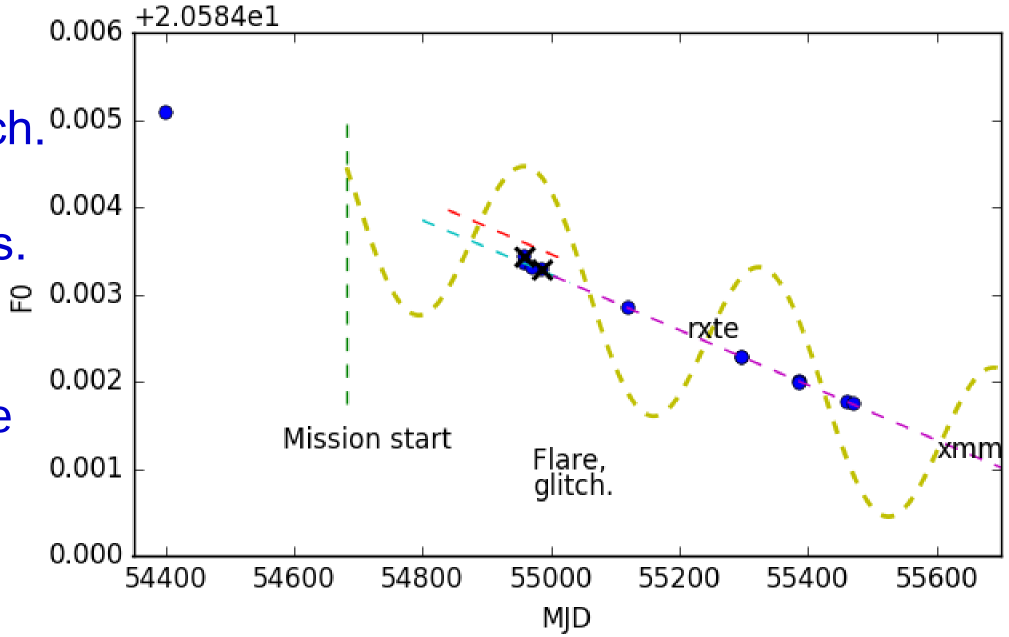
Dots: GBT rotation frequencies.

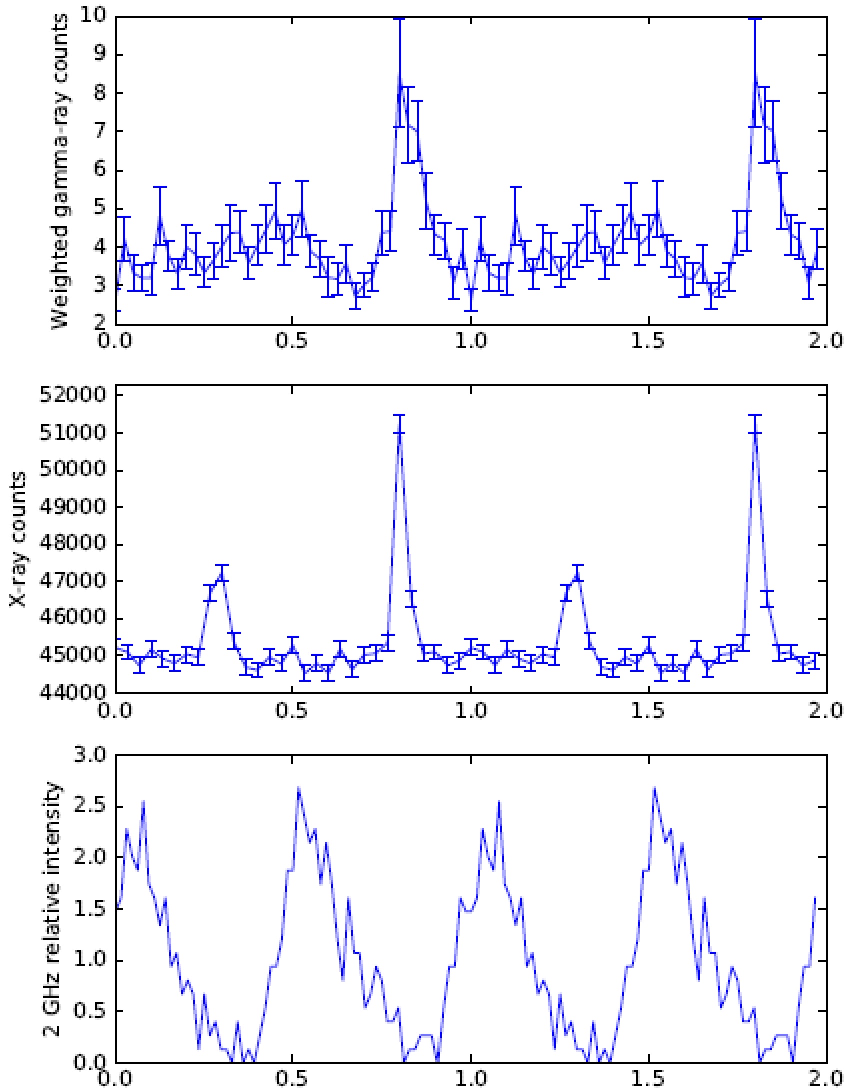
X's: Only 2 of 4 are good at this epoch.

Red-dash: F0,F1 that gives >5σ in γ's.
Huge anti-glitch.

Light blue dash: F0,F1,F2 compatible with radio & X-ray measurements.
Anti-glitch -2e-7.

(sinusoïd: topocentric-barycentric)





>300 MeV gammas

RXTE

GBT 2 GHz

PRELIMINARY

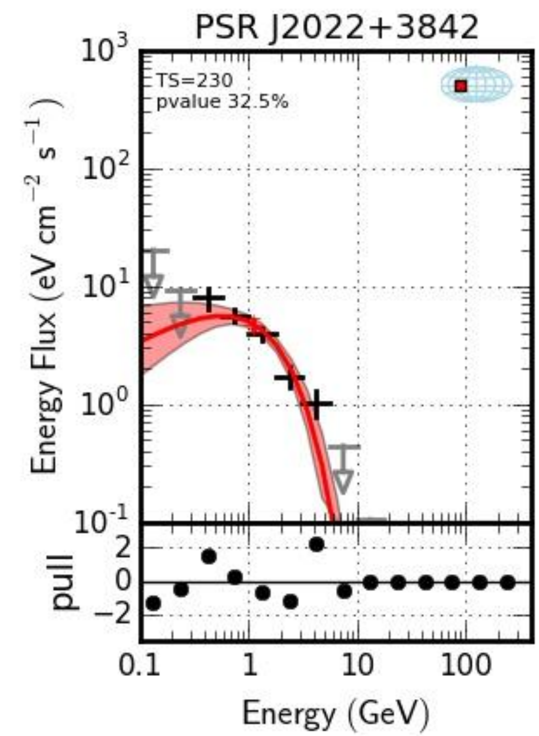
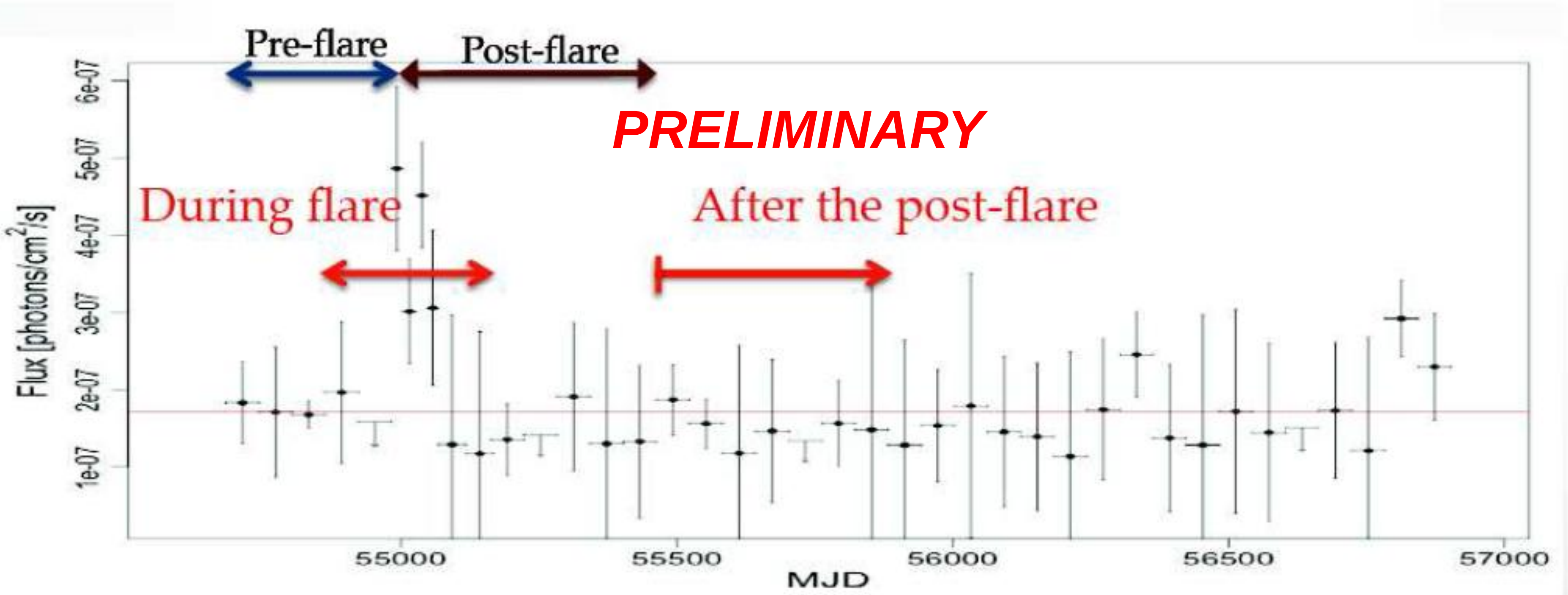


Fig. 3.— Placeholder plot. Top frame: Weighted > 300 MeV gamma-ray profile. Middle frame: RXTE data from Arzou et al (2011), corrected to the 48 ms period using the Fermi rotation ephemeris. Bottom frame: Robert C. Byrd Green Bank Telescope (GBT) 2 GHz profile, corrected to the 48 ms period using the Fermi rotation ephemeris. The X-rays are phase-aligned but the GBT profile needs to be worked on a bit.

Haruka's March 2015 Collaboration meeting presentation



- Haruka showed evidence for a glitch near MJD 55000.
- Pulsar flare at same time as a glitch? Would be the first ever seen.

- Haruka is working on demonstrating that the flare is real.
- Lucas and I working to understand which glitches are real.

Why is J2022+3842 so difficult?

For reasonable cuts, 220 on-peak photons over 450 b'grd counts (8.5σ), in 730 days .

10 signal photons per month.

Poisson: 6 of the 53 months will have <6 photons.

($\sqrt{450} = 21$ ➔ b'grd fluctuations larger than the average signal.)

F0, F1 over a sparse sample can be skewed by a few on-source, on-phase background photons in that interval (plus pulsar timing jitter).

When you extend the maybe not-quite-right F0,F1 to an epoch with a downward S/N fluctuation

the signal violently disappears!

Why keep banging your head against this?

We've said for years: build as thorough a gamma-ray pulsar sample as possible.
"Probing the dark corners of parameter space"

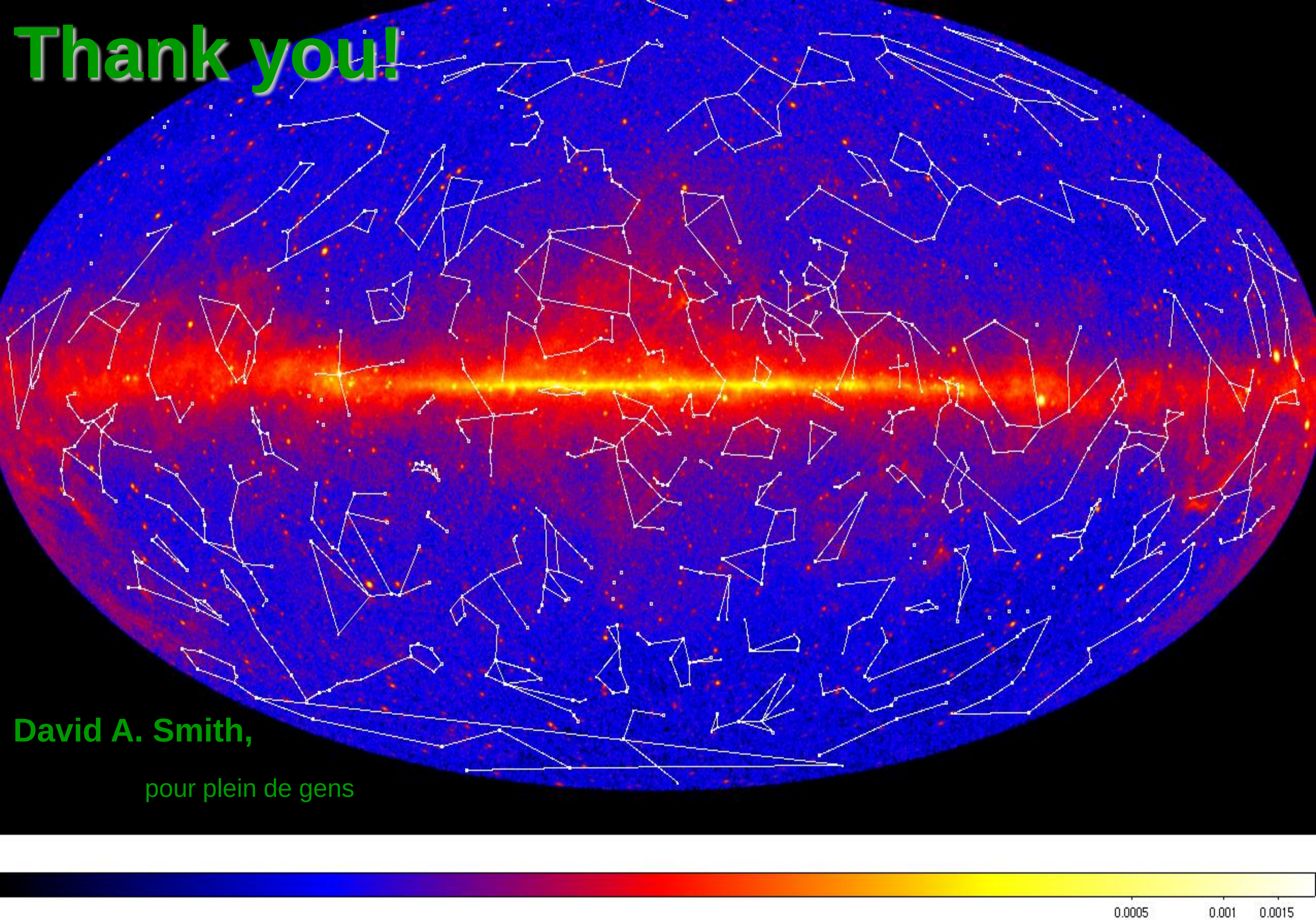
PSRs J2022+3842, J1101-6101, J1640-4631 and others are *special* –

- $\dot{E}$ > 1.E35 erg/s
- Gotthelf, Halpern, and others identify neutron star candidates in SNRs ; then obtain XMM and/or Chandra and/or Swift data at 1 year intervals to characterize the neutron star = pulsar.
- X-ray loud, gamma and radio faint ➔ rare.

Halpern, Gotthelf, et al's gamma non-detections lead to wrong conclusions about these particular supernova remnants.

My hope: once we can handle J2022+3842, others will follow.

Thank you!



David A. Smith,

pour plein de gens

Conclusions

- Pulsars are the end-point of stellar evolution. Gamma-rays key to understand how they convert rotational energy into radiation.

- *Fermi* LAT sees a broad variety of high-power pulsars in a variety of environments.

- The pulsars play a central role in a range of topics.

- We continue to detect about 30 per year.

Two excellent recent reviews:

Gamma-Ray Pulsar Revolution, P. Caraveo, Annual Review of Astronomy and Astrophysics 52, 2014.
Gamma-ray pulsars: A gold mine, I. Grenier & A.K. Harding, Compte rendus Physique 16, 2015

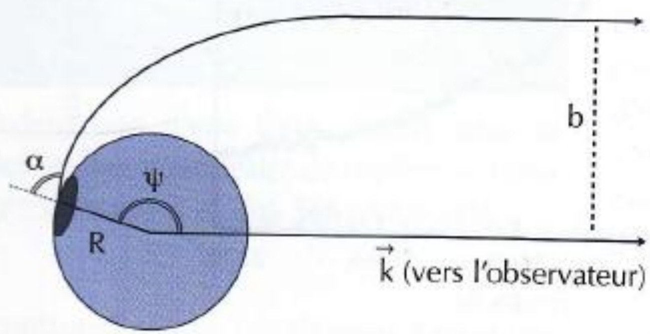
X-ray pulsars and the Equation of State

J. Margueron & R. Artigues say:

determine neutron star radius using X-rays from a hot polar cap.

"*Reflets de la Physique*",
Soc. Fr. Phys. Oct-Nov 2015.

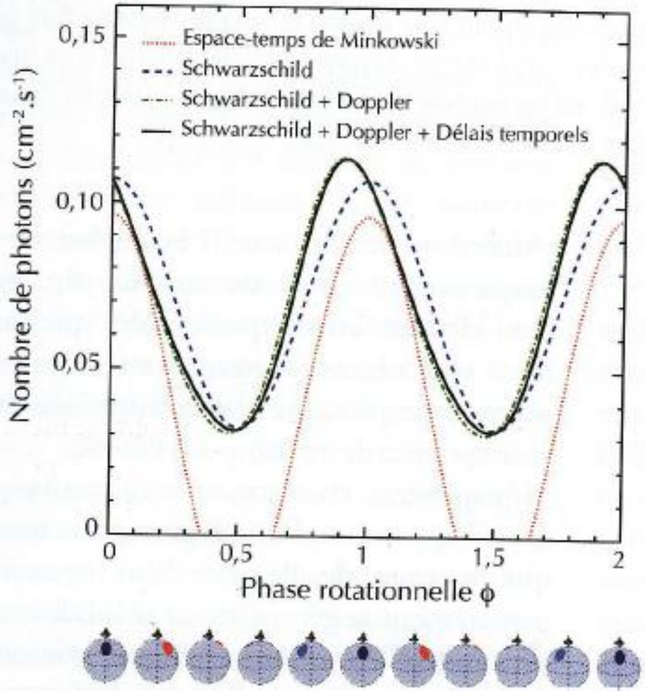
See also Anna Watts et al,
Rev. Mod. Phys. (2015).



E1. Trajectoire courbée d'un photon émis par la face cachée d'une étoile à neutrons. Cette courbure augmente avec la compacité de l'étoile.

QUESTION:
Why not use radio,
non-thermal X-rays, and gammas
to characterize (α,ζ), etc,

and *then* study
the non-thermal X-ray profile?



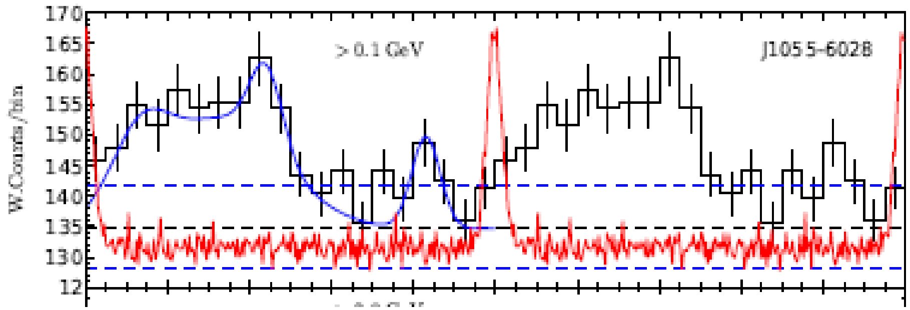
E2. Déformation des profils des oscillations de l'émission d'une tache chaude située sur une étoile en rotation rapide, sous les effets de la relativité.

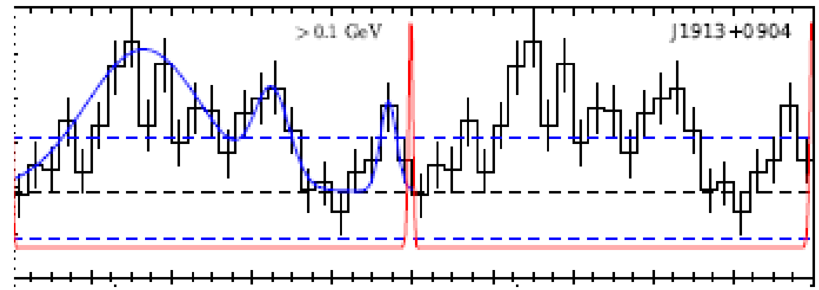
Six faint gamma-ray pulsars seen with the *Fermi* Large Area Telescope

A&A 570, A44 (2014)

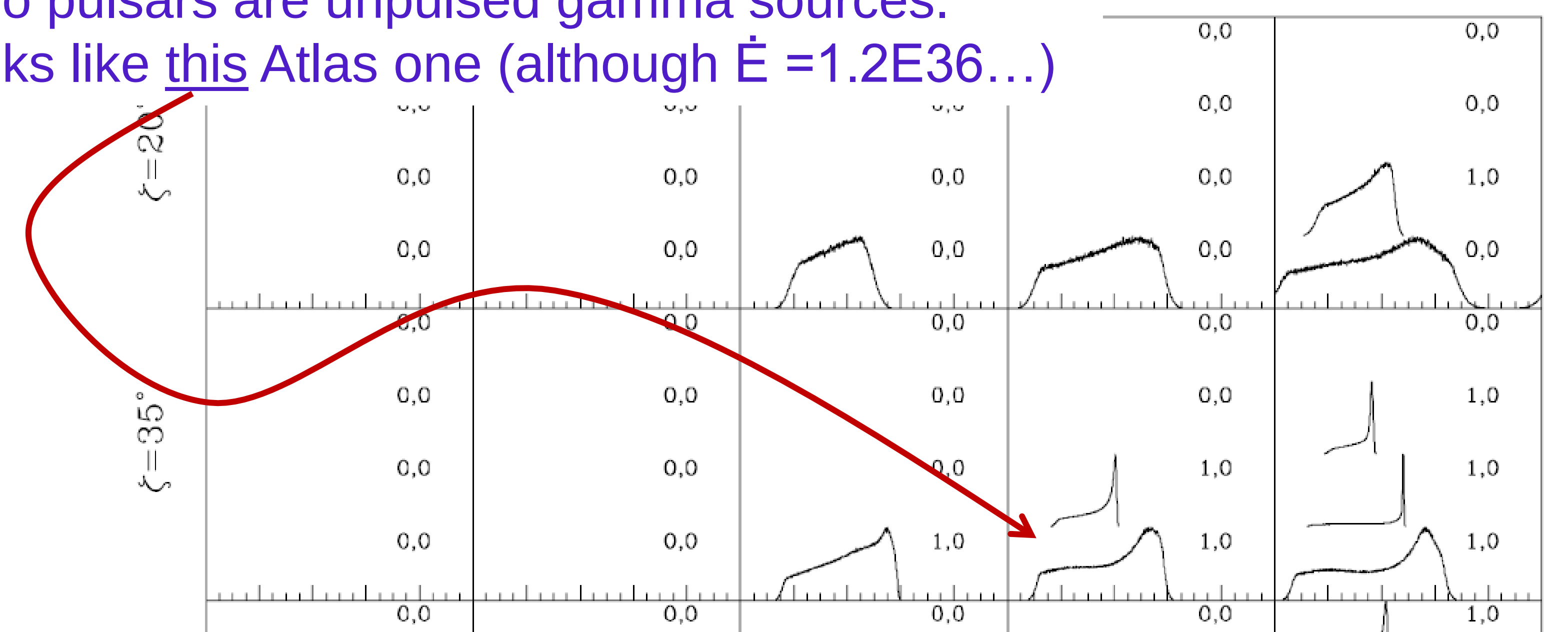
Towards a sample blending into the background

X. Hou (侯賢)[1], D. A. Smith[1], L. Guillemot[2,10], C. C. Cheung[3], I. Cognard[2,10], H. A. Craig[4], C. M. Espinoza[5], S. Johnston[6], M. Kramer[7,8], O. Reimer[9,4], T. Reposeur[1], R. Shannon[6], B. W. Stappers[7], and P. Weltevrede[7]





- 60% duty cycle larger than any 2PC young pulsars.
- A few radio pulsars are unpulsed gamma sources.
- J1055 looks like this Atlas one (although Ė =1.2E36…)



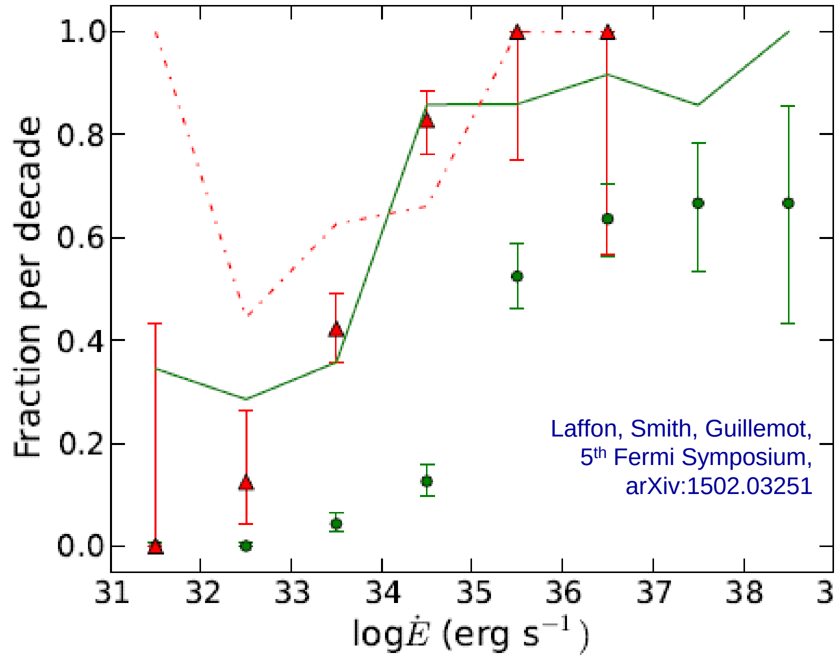
Lines:
Fraction of pulsars gamma-folded.

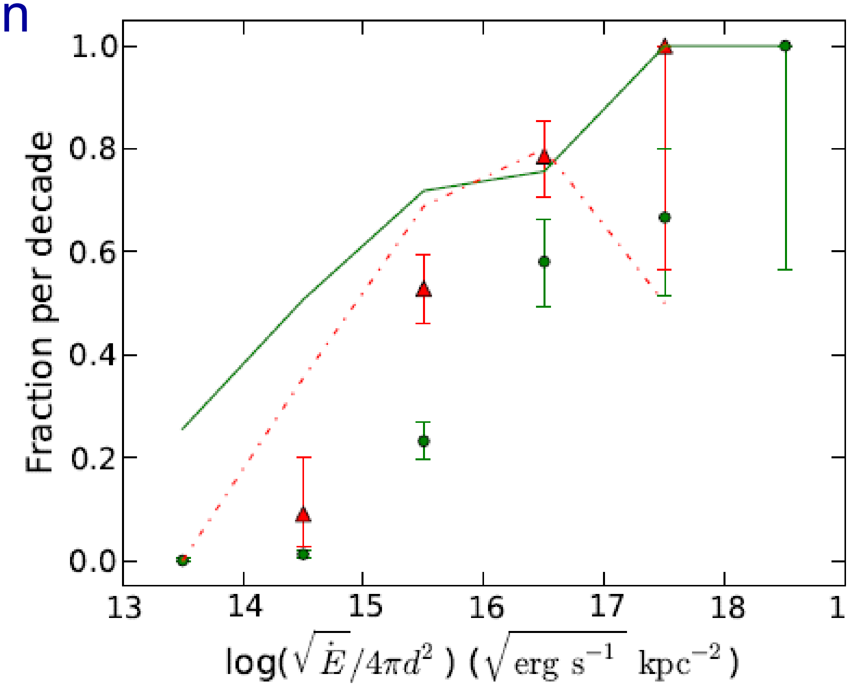
Points:
Fraction gamma-detected.

Green: Young radio loud
Red: radio MSPs

Ė for MSPs uncertain without proper motion constraint (‘Shlovskii’ doppler effect).
Revisit…. Guillemot , Smith, Laffon et al A&A (2016)

Guillemot & Tauris (2014) argue that the unseen high Ė MSPs have unfavorable inclination ζ, as traced by the orbital inclination.



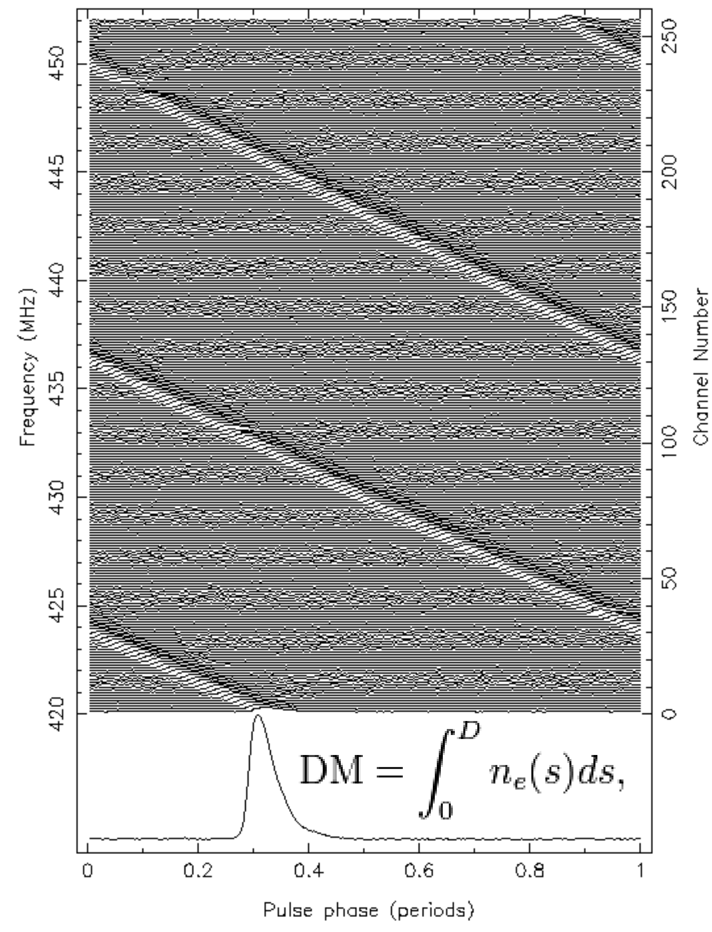


Dispersion Measure (DM) + NE2001 model : Our Main Tool for *distances*!

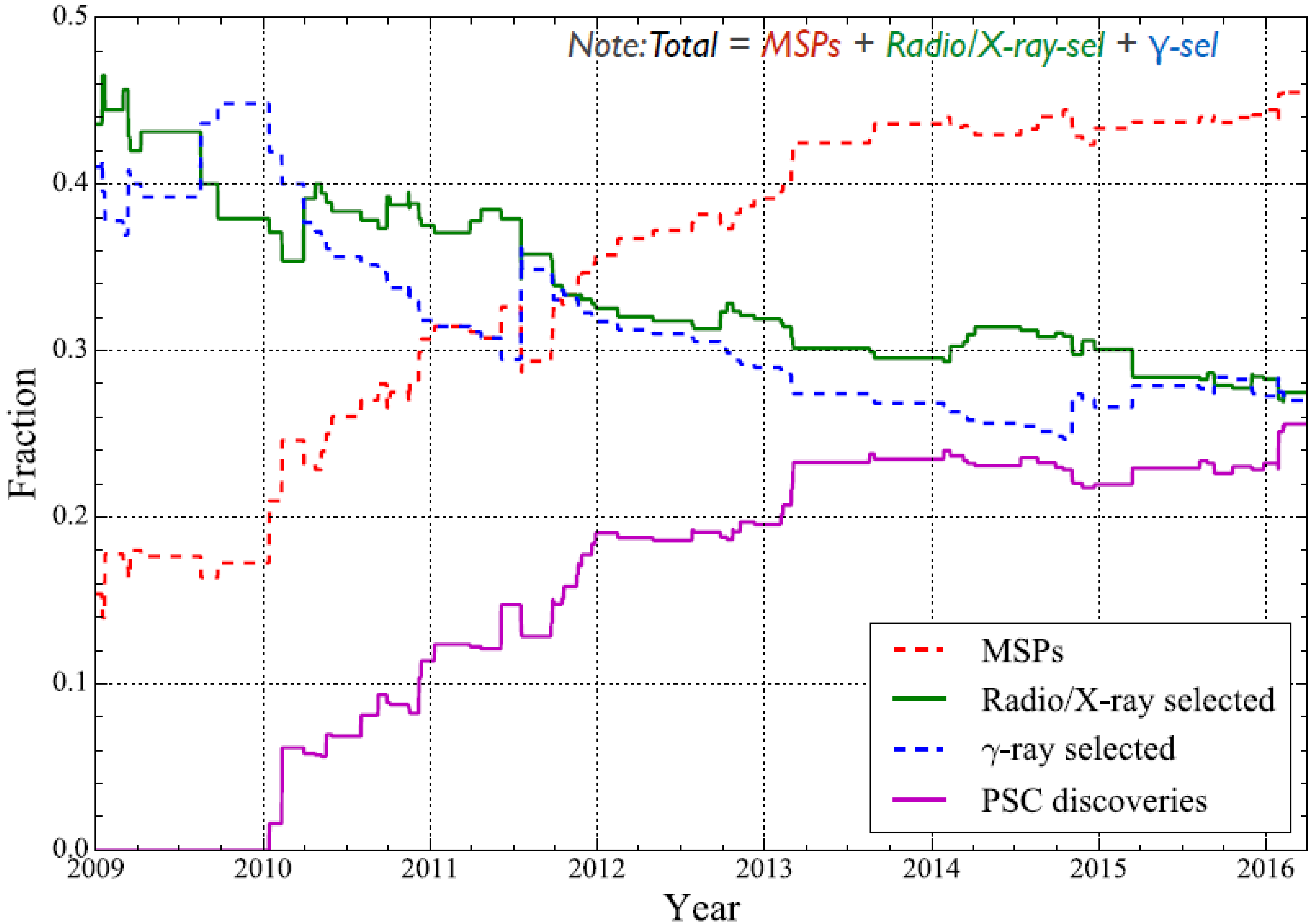
- "DM" = Precise measurement of the electron column density (pc/cm^3), for all radio pulsars.
- Combine with a map of density n_e in the Milky Way and… voilà!! Distance.
- "Standard model" is NE2001,

http://arxiv.org/abs/astroph/0207156 a.k.a. "Cordes & Lazio".

- The good news: exists, and all use.
- The bad news: terribly uniform, with ad hoc patches, "clumps" and "voids" for specific lines-of-sight.



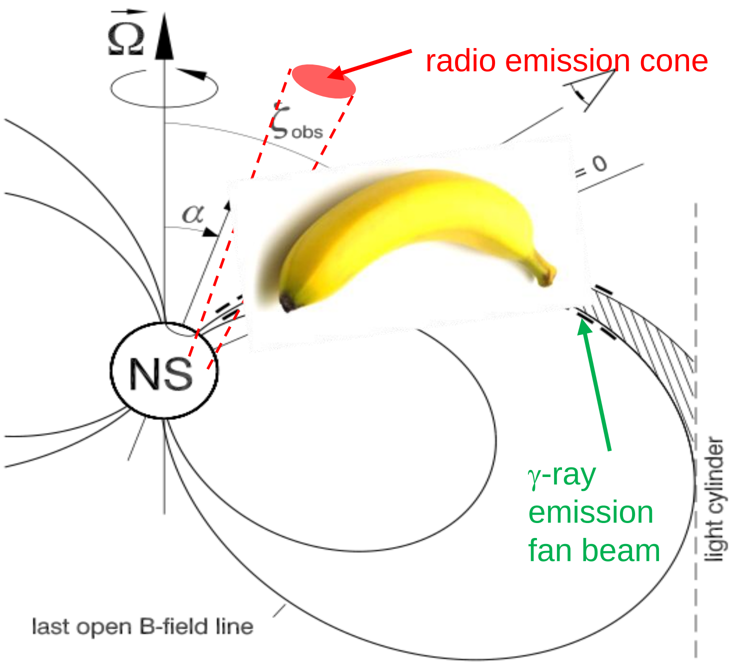
Detected pulsars versus time

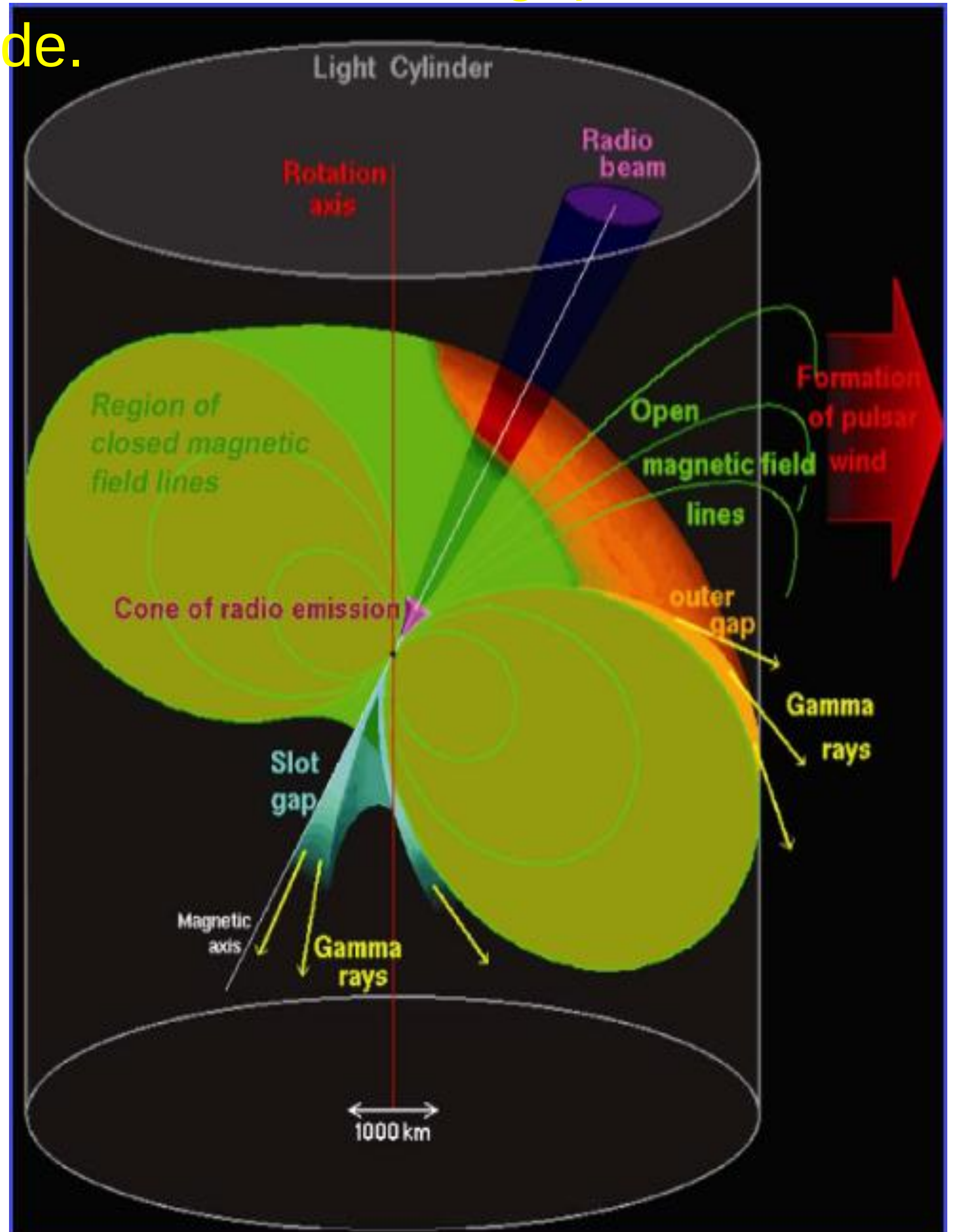


Lucas Guillemot, 2016

Gamma-ray beam: Curvature radiation in 'gaps'.

Long in latitude, thin in longitude.

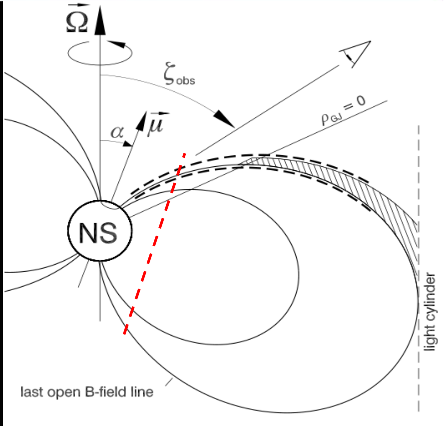




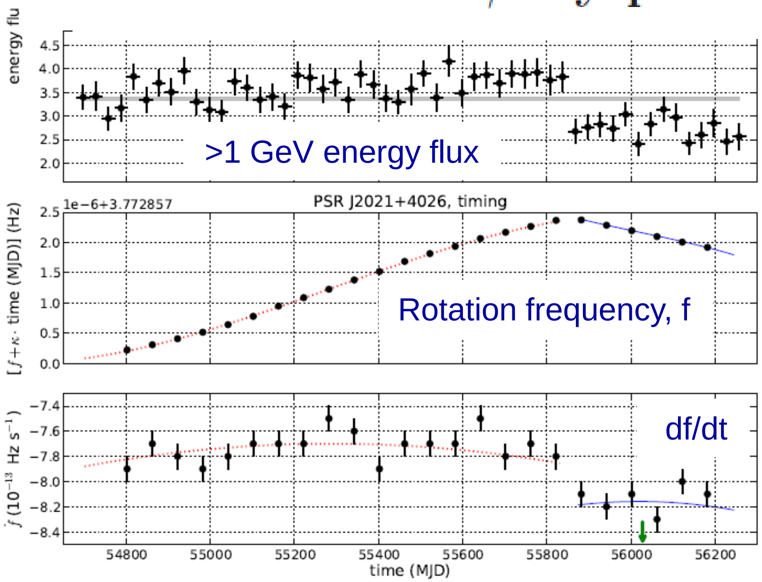
"Ballerina skirt" rather than "swordfish fin".

Aurora borealis… Variable PSR J2021+4026

http://adsabs.harvard.edu/abs/2013ApJ...777L...2A



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



http://adsabs.harvard.edu/abs/2013ApJ...777L...2A

PSR B0540-69 in the LMC is a gamma pulsar

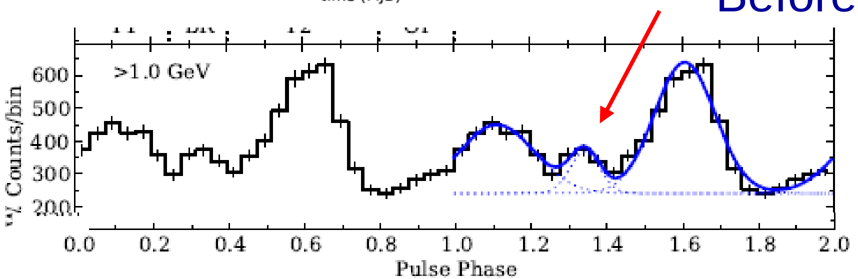
Ackermann et al. 2015, Science, 350, 801

and appears to be an "intermittent" pulsar,

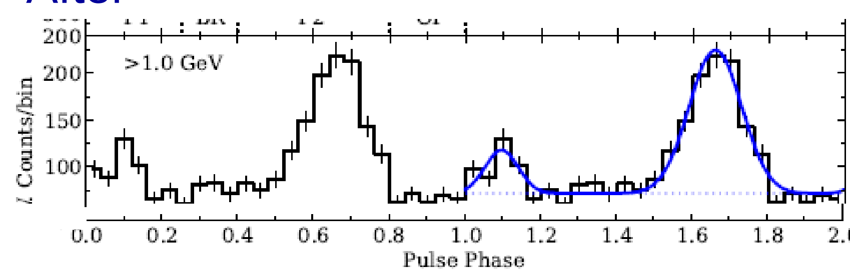
Marshall et al. 2015, Ap J Lett, 807, 27

like PSRs B1931+24, J1832+0029, J1841-0500, and a bit like gamma pulsar J2021+4026.

Before



After



A minor shift in how the magnetic field lines enter the neutron star crust can shift the complex 'aurora borealis' beam pattern.

For a fixed line of sight, intensity and profile change.

Magnetic field shift ➔ slight change in spindown rate.

(The Crab flare was the nebula, not the pulsar.)

Keck Spectroscopy of Millisecond Pulsar J2215+5135: A Moderate-MNS, High-inclination Binary

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Show affiliations

Roger W. Romani *et al*. 2015 *ApJ* **809** L10. doi:10.1088/2041-8205/809/1/L10
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Abstract

We present Keck spectroscopic measurements of the millisecond pulsar binary J2215+5135. These data indicate a neutron-star (NS) mass $M_{\rm NS} = 1.6\,M_\odot$, much less than previously estimated. The pulsar heats the companion face to $T_D \approx 9000$ K; the large heating efficiency may be mediated by the intrabinary shock dominating the X-ray light curve. At the best-fit inclination $i = 88\overset{\circ}{.}8$, the pulsar should be eclipsed. We find weak evidence for such eclipses in the pulsed gamma-rays; an improved radio ephemeris allows use of up to five times more *Fermi*-Large Area Telescope gamma-ray photons for a definitive test of this picture. If confirmed, the gamma-ray eclipse provides a novel probe of the dense companion wind and the pulsar magnetosphere.