Gamma-ray pulsars with the Fermi LAT

Lucas Guillemot,
on behalf of the Fermi *LAT Collaboration*

14th rencontres du Vietnam
Very High Energy Phenomena in the Universe

Quy Nhon, 13 August 2018

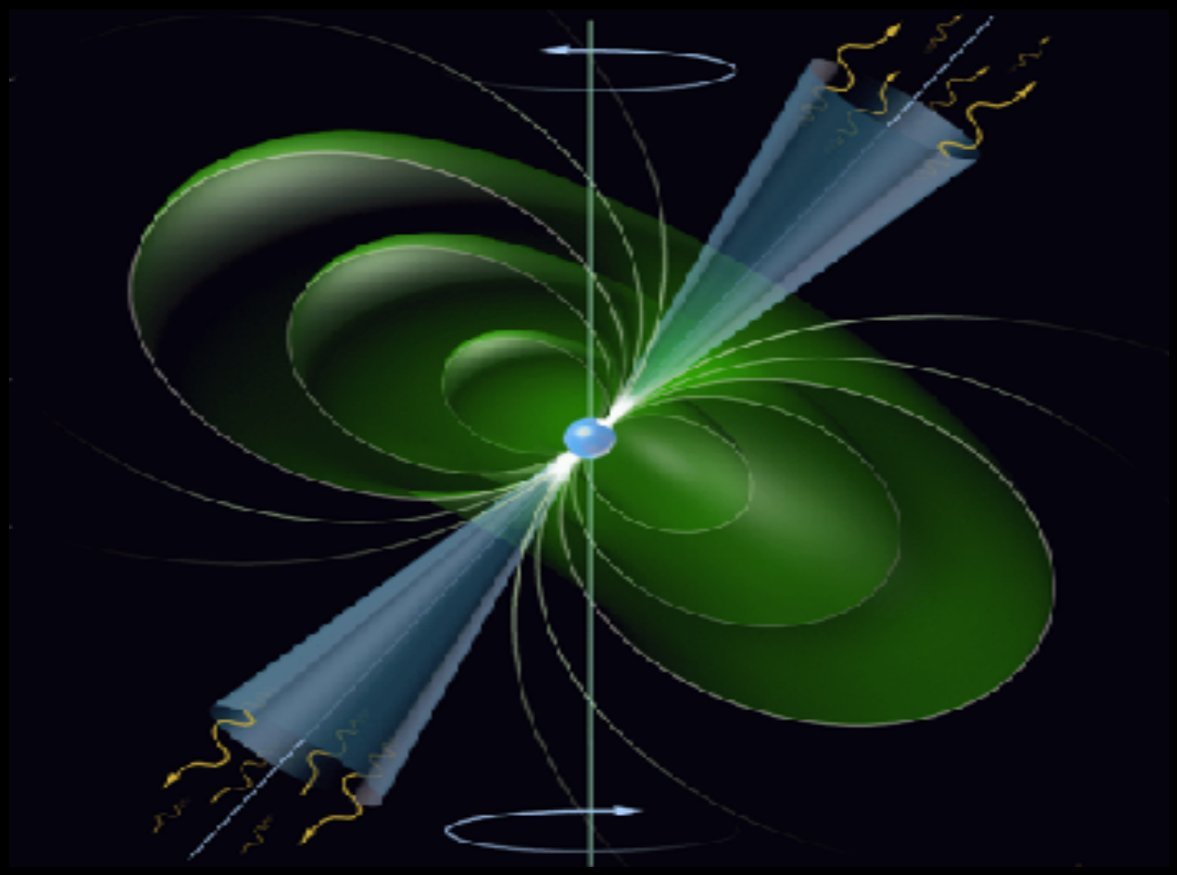
LPC2E

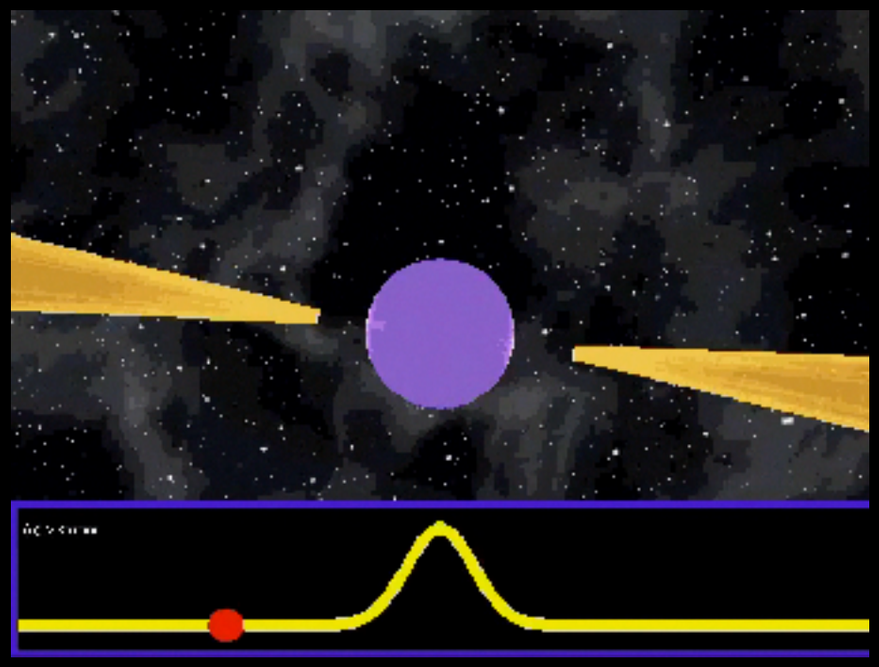
OSUC Observatoire des Sciences de l'Univers en région Centre

UNIVERSITE D'ORLEANS

Station de Radioastronomie de Nançay

Pulsars





Pulsars are rapidly rotating highly magnetized neutron stars, born in supernova explosions of massive stars.

Masses: 1.2 - 2 $M_\odot$, Radii ~ 13 km.

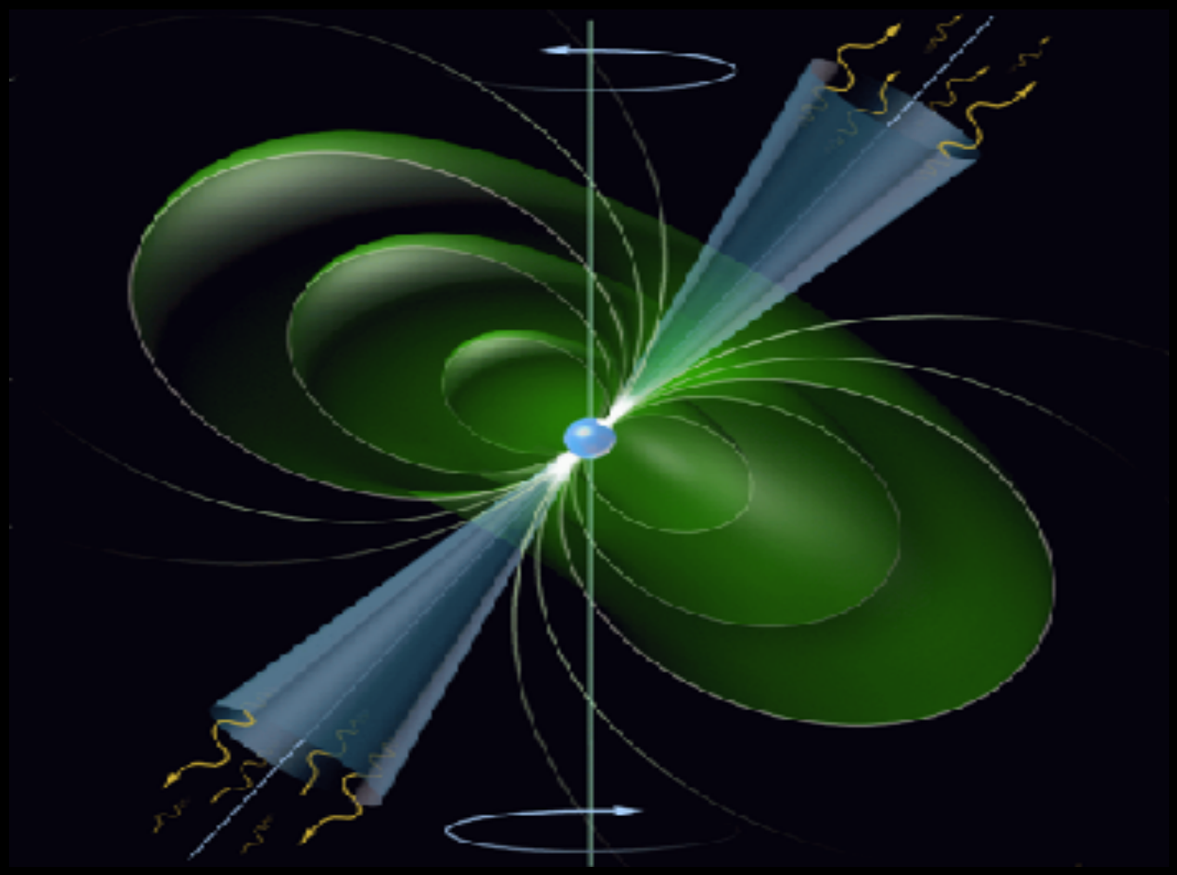
Emission (radio, optical, X-ray, gamma rays…) produced in beams around the star.

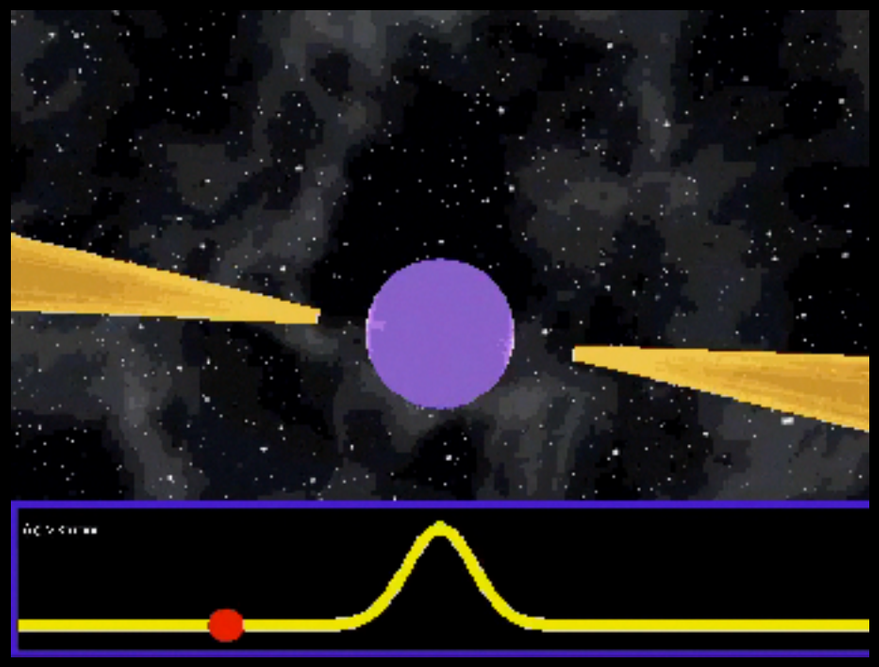
Pulsars are cosmic lighthouses!

Extreme objects:

- Luminosities up to 10^4 $L_\odot$
- Surface temperature ~ 10^6 K
- Surface gravity ~ 10^{11} Earth's
- Surface magnetic fields: 10^8 - 10^{15} G

Pulsars





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Why study pulsars in gamma rays?

Radio: negligible fraction of the energy output.

In contrast, gamma-ray efficiencies $\eta = L_\gamma/\dot{E}$ are often larger than 10%.

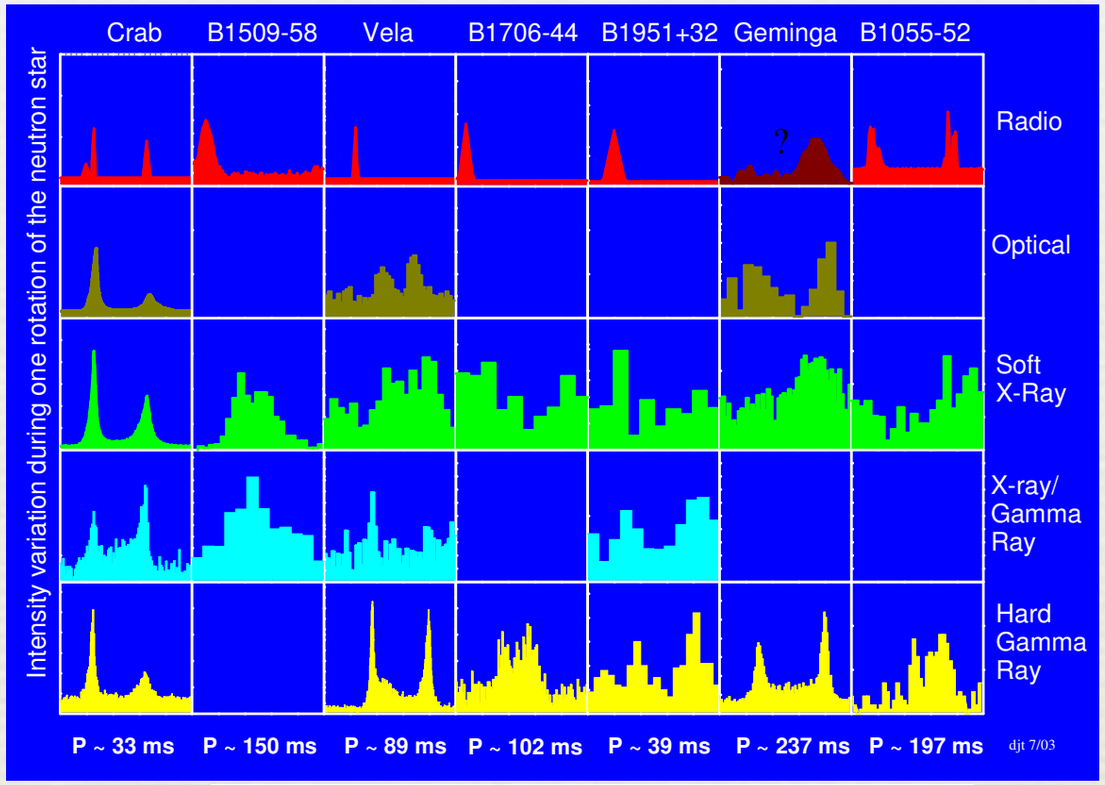
Gamma rays are a probe of primary acceleration processes in the magnetosphere.

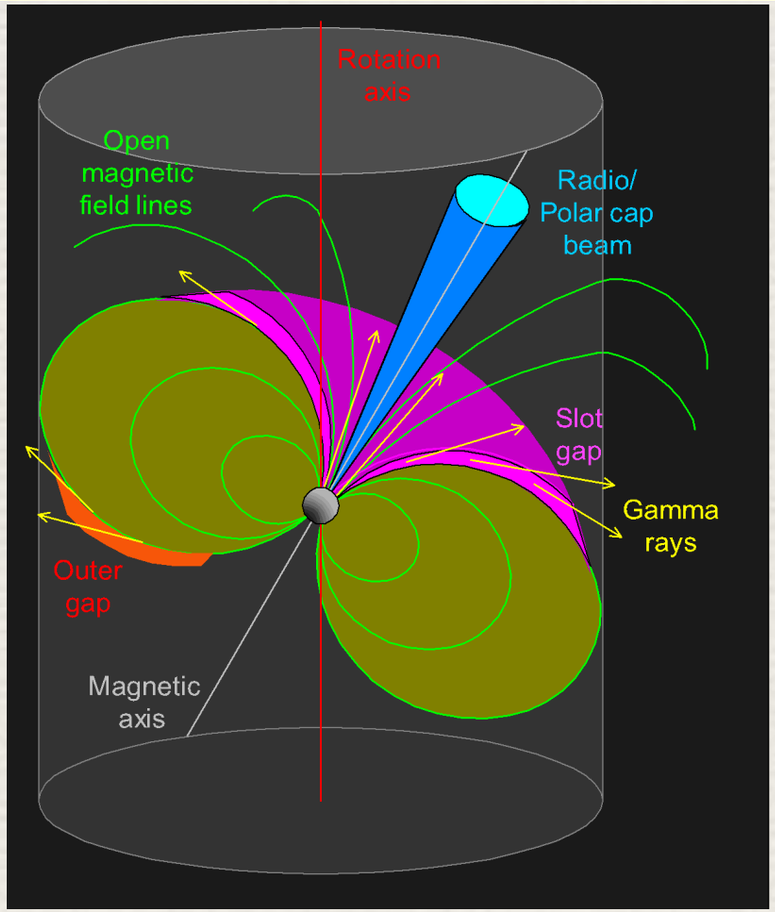
Also, gamma rays are beamed along magnetic field lines with small pitch angles.

Gamma rays track the structure of the magnetic field.

In addition, radio and gamma-ray beams have very different structures.

⇒ different pulsar populations.





The pulsar detection problem

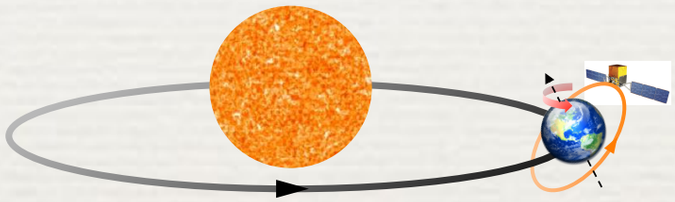
High-energy data: typically sparse, many pulsar rotations ⇒ blind search difficult.

Goal: phase-fold the data with a timing model accounting for every single pulsar rotation over a given interval.

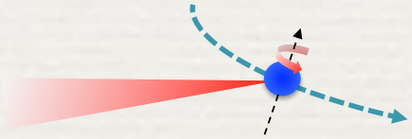
Typical parameters:

- right ascension α and declination δ, for converting the photon times to the Solar System Barycenter (SSB).
- rotational frequency and time derivatives: f_0, f_1, ...
- orbital parameters for pulsars in binary systems.

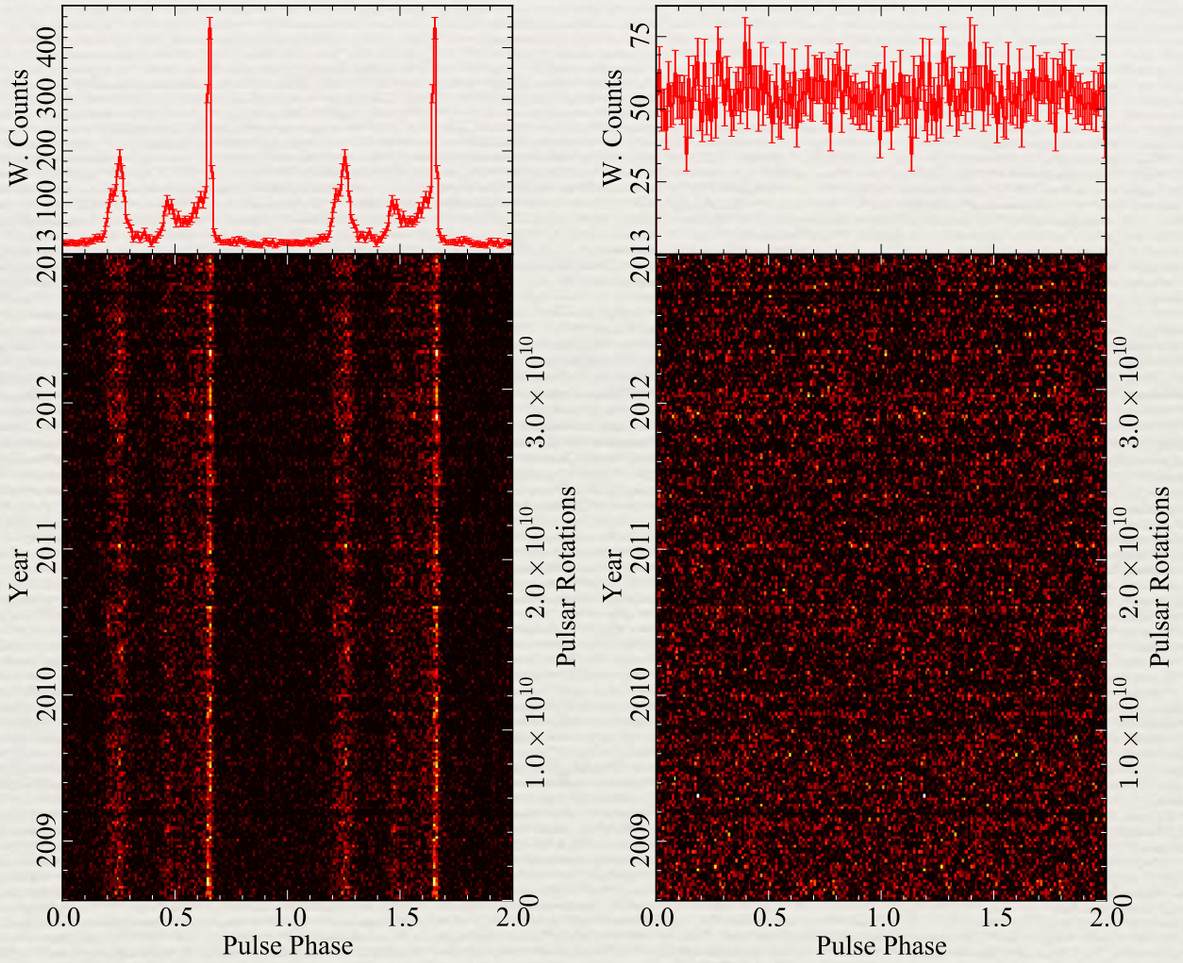
Earth and satellite motion around the SSB:
α, δ



Pulsar rotation and spin-down:
f_0, f_1, …



Binary motion?
P_b, a, e, T_0, …



PSR J1231-1411 (P = 3.684 ms) as seen with *Fermi* LAT.
Left: valid timing model, right: wrong timing model.

Ways to find new γ-ray pulsars

- Folding the LAT data using known pulsar timing models, obtained from radio or X-ray timing measurements

  Large pulsar timing campaign, allowing pulsation searches for >700 pulsars! (See Smith et al., A&A 2008).

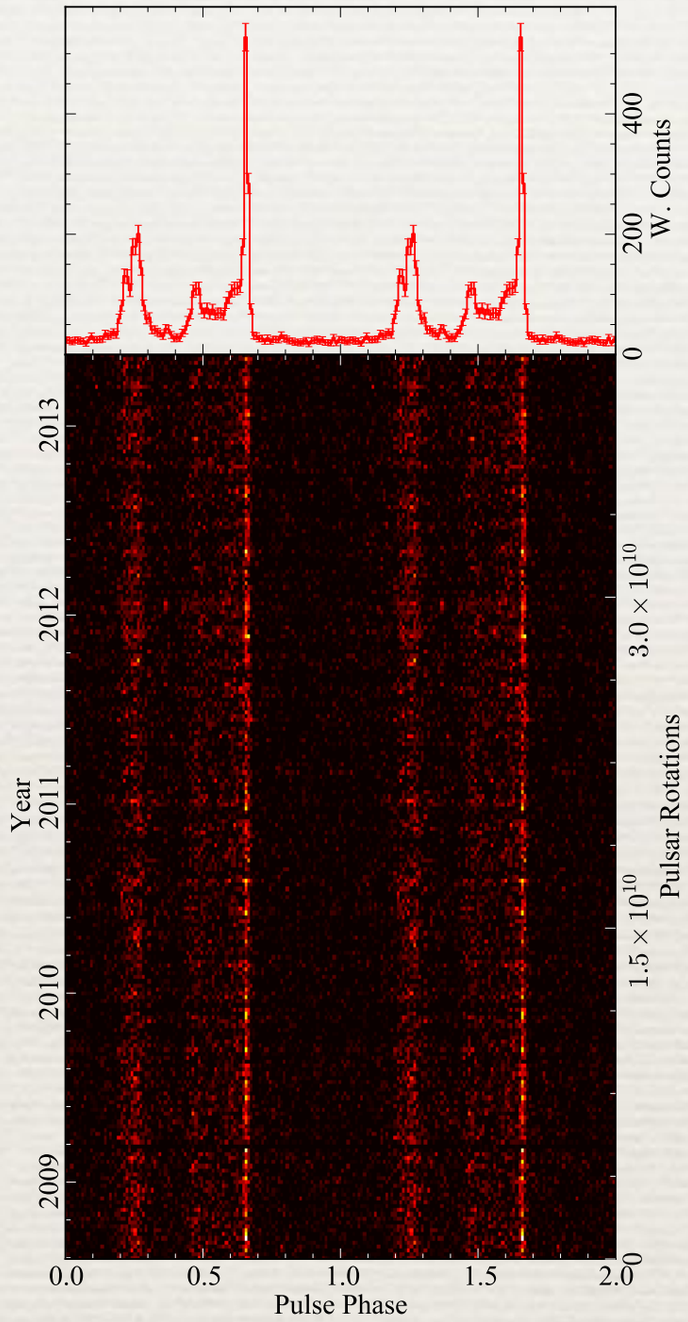
- Blind pulsation searches, directly in the LAT data

  Only way of finding radio-quiet objects. Extremely computer intensive!

- Multi-wavelength observations of LAT unassociated sources

  Pulsation searches in radio (sensitivity to MSPs, binary systems).

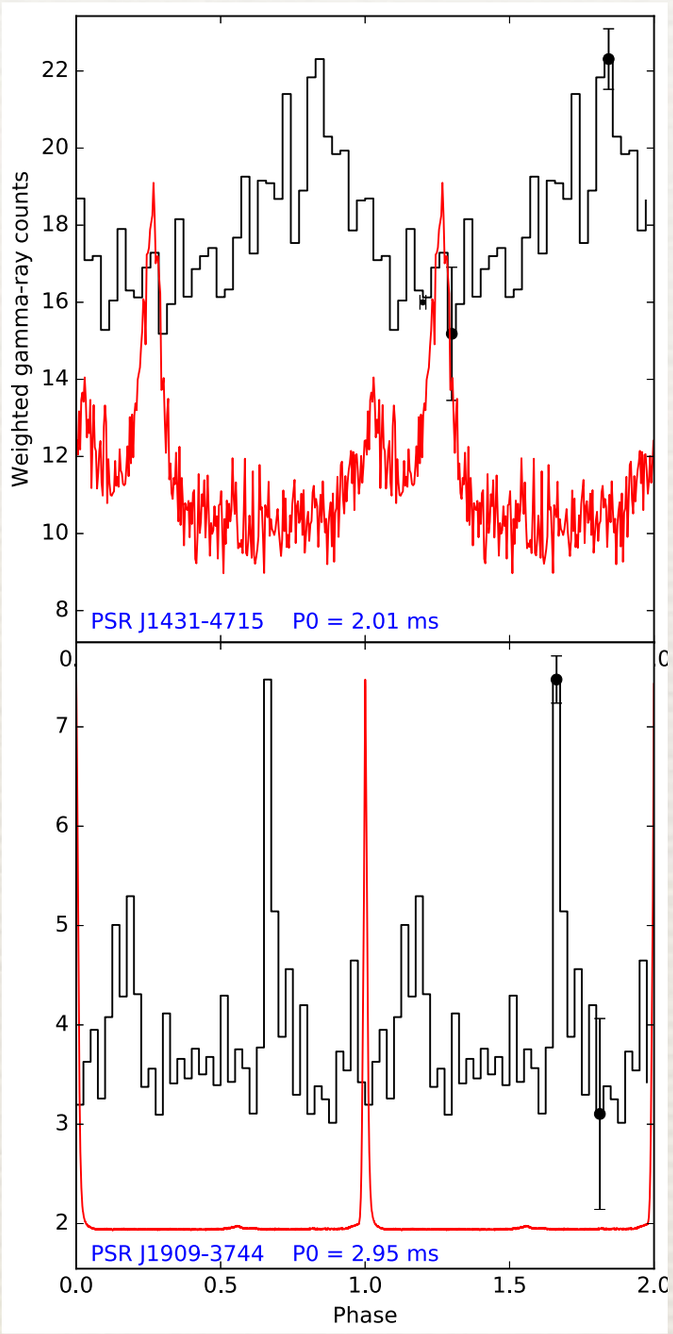
  Optical and/or X-ray studies can locate binary companions and constrain orbital parameters.



Analysis of ~4.5 yrs of LAT data for J1231-1411 (P ~ 3.684 ms, P_b~ 1.860 d).

Exposures can represent 10^{11} pulsar rotations!

Pulsation searches using ephemerides



J1431-4715 & J1909-3744, Smith et al. arXiv:1706.03592

A « Pulsar Timing Consortium » has monitored >700 pulsars, providing ephemerides.

PTC: Parkes, Nançay, Jodrell Bank, RXTE, Westerbork, others…

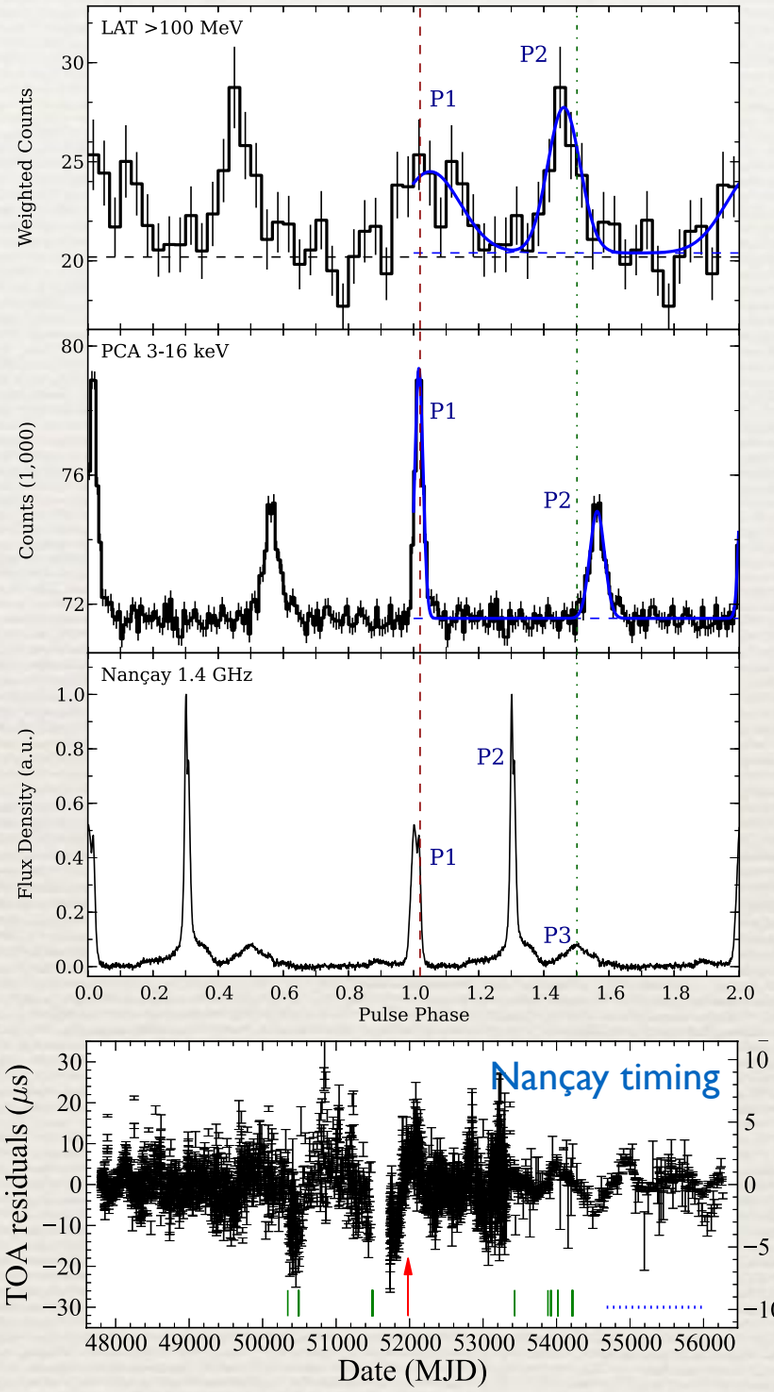
About 80 gamma-ray pulsars detected this way.

Best way to search for pulsations from gamma-ray-faint pulsars!

Some examples:

- Many young radio & gamma-ray pulsars (incl. EGRET pulsars)
- Many millisecond pulsars in the Galactic disk, such as the MSP in the « double pulsar » J0737-3039A.
- Pulsars in globular clusters: B1821-24, J1823-3021A.
- A gamma-ray pulsar in the LMC: B0540-69.

Searches still ongoing!



PSR B1821-24, Johnson et al. ApJ (2013)

New pulsars from blind γ-ray searches

LAT data sets are long and sparse, making « blind » pulsation searches extremely demanding.

Atwood et al. 2006: time differencing search technique reducing computational costs.

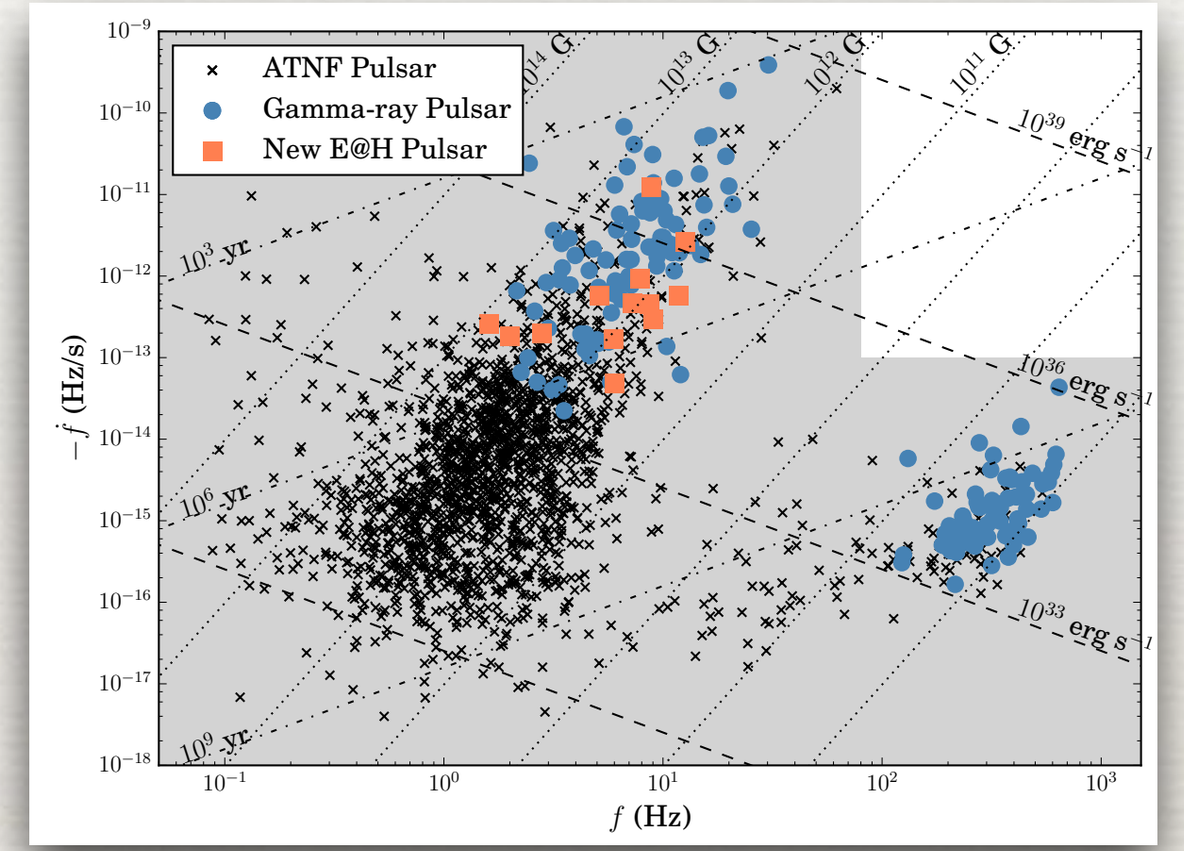
Pletsch et al. 2013: multistage search now done with the Einstein@Home volunteer computing system.

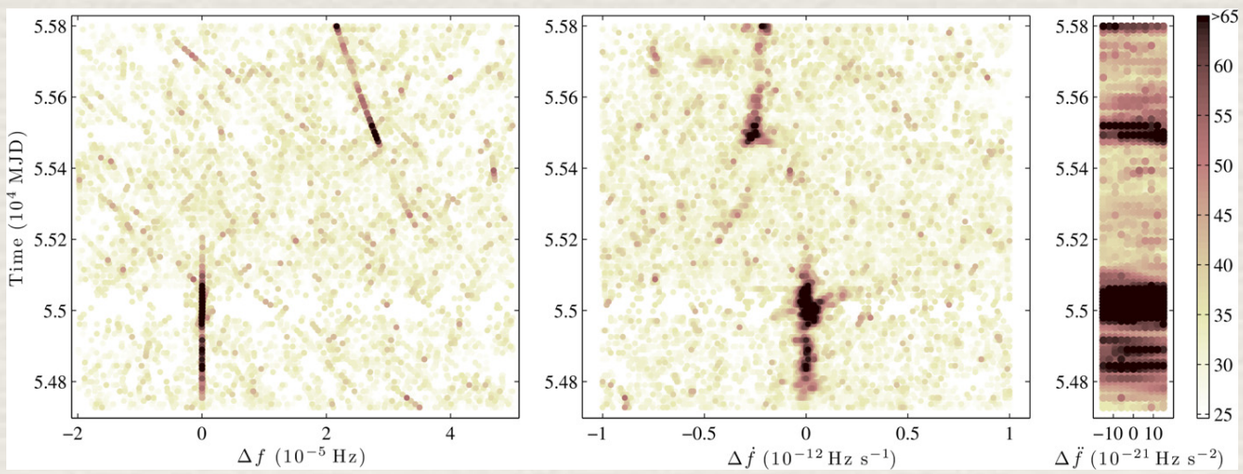
About 60 pulsars discovered up to now!

(Abdo et al. 2009, Saz Parkinson et al. 2010, Pletsch et al. 2012, 2013; Clark et al. 2015, 2016, etc).

Several have glitches (J1838-0537: glitch of ~40μs among the largest observed!).

Very few (<10) have been detected in radio!
Discoveries made significantly easier by *Fermi*.





Pletsch et al., ApJ Lett. 755, 20 (2012)

The first radio-quiet MSP?

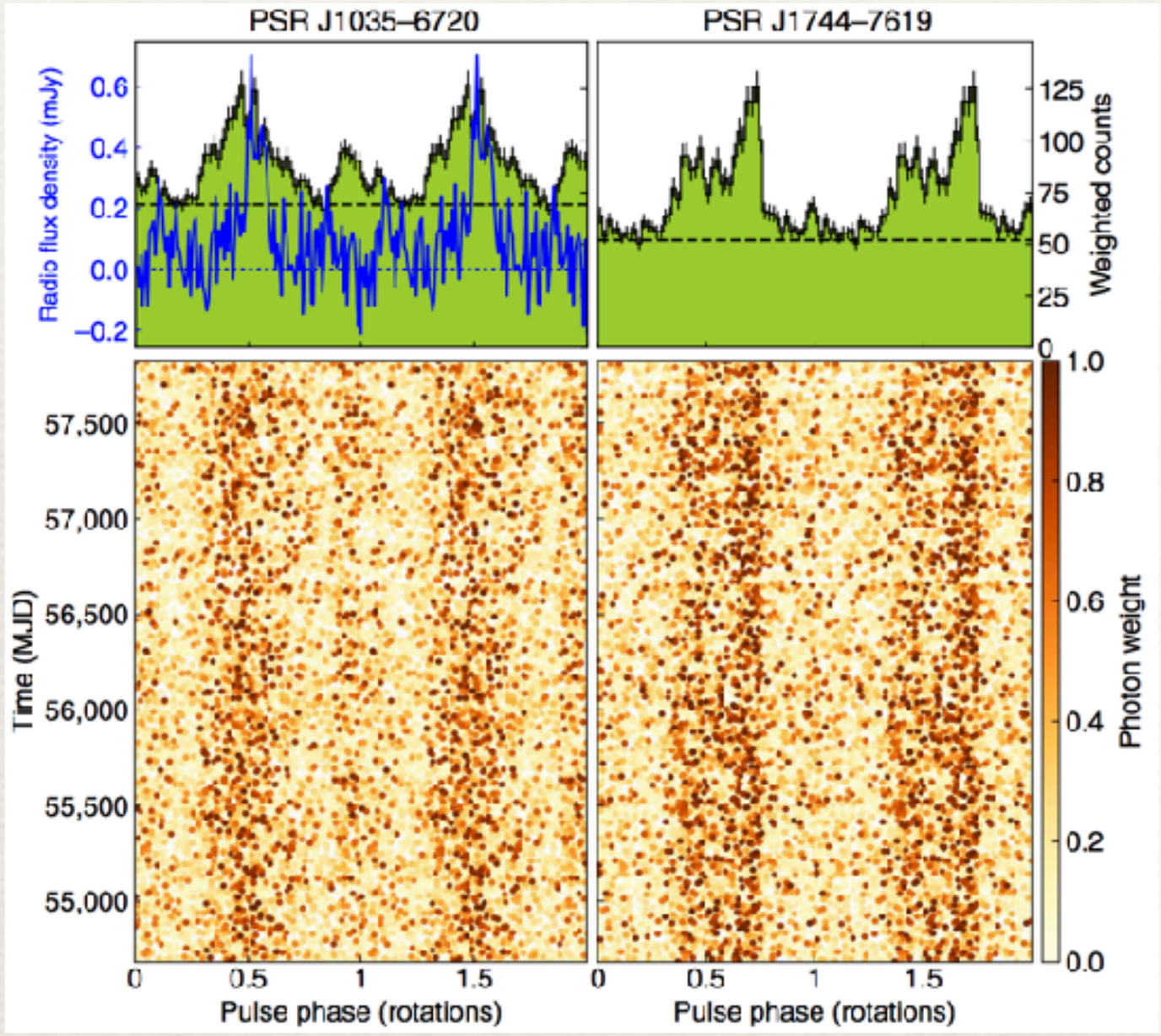
Gamma-ray pulsar searches with Einstein@Home found 17 new pulsars (Clark et al. 2017, Wu et al. 2018).

Two of the new pulsars are isolated MSPs, one of which being still undetected in radio!

J1744-7619: undetected in two 3-hr Parkes observations at 1.4 GHz.

J1035-6720: 348 Hz, S_{1400} ~ 40 μJy,
DM ~ 84 pc cm^{-3}
J1744-7619: 213 Hz, S_{1400} < 23 μJy, DM?

Both have extremely low radio luminosities. How many radio-quiet gamma-ray MSPs among LAT sources?



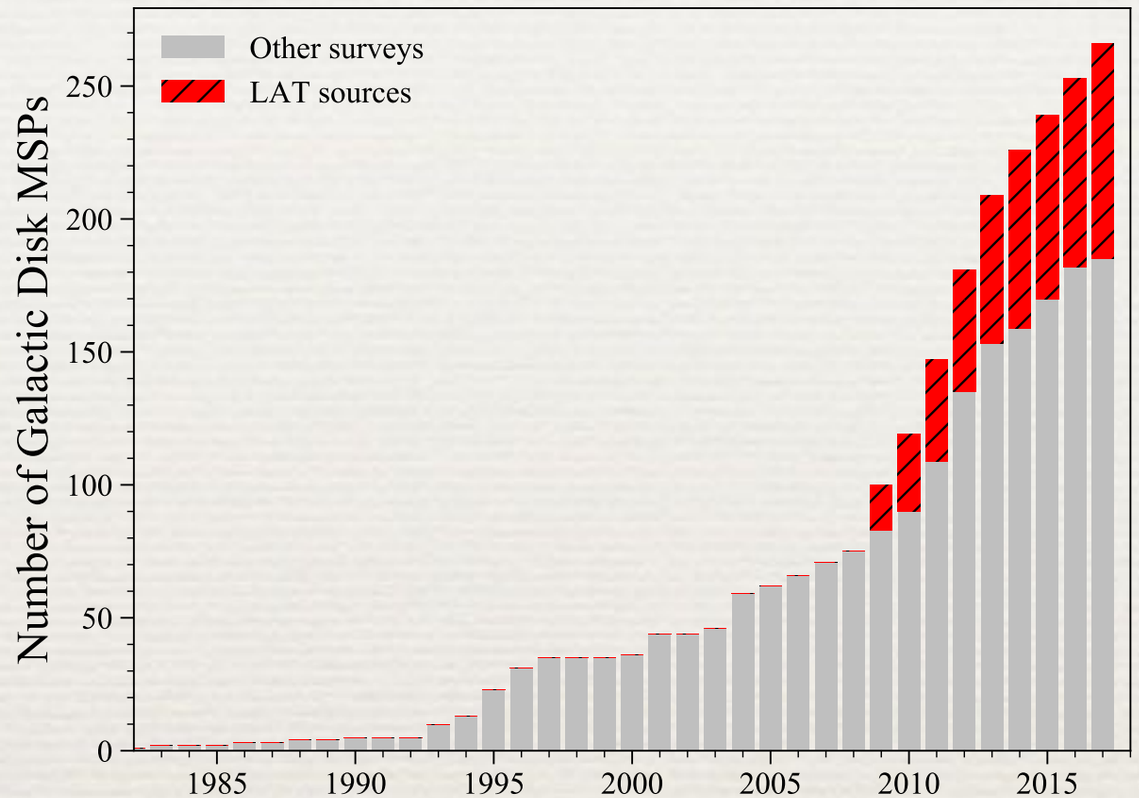
See Clark et al., Sci Adv. 2018.

Radio searches of LAT unassociated sources

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

More than 80 pulsars discovered, mostly MSPs.

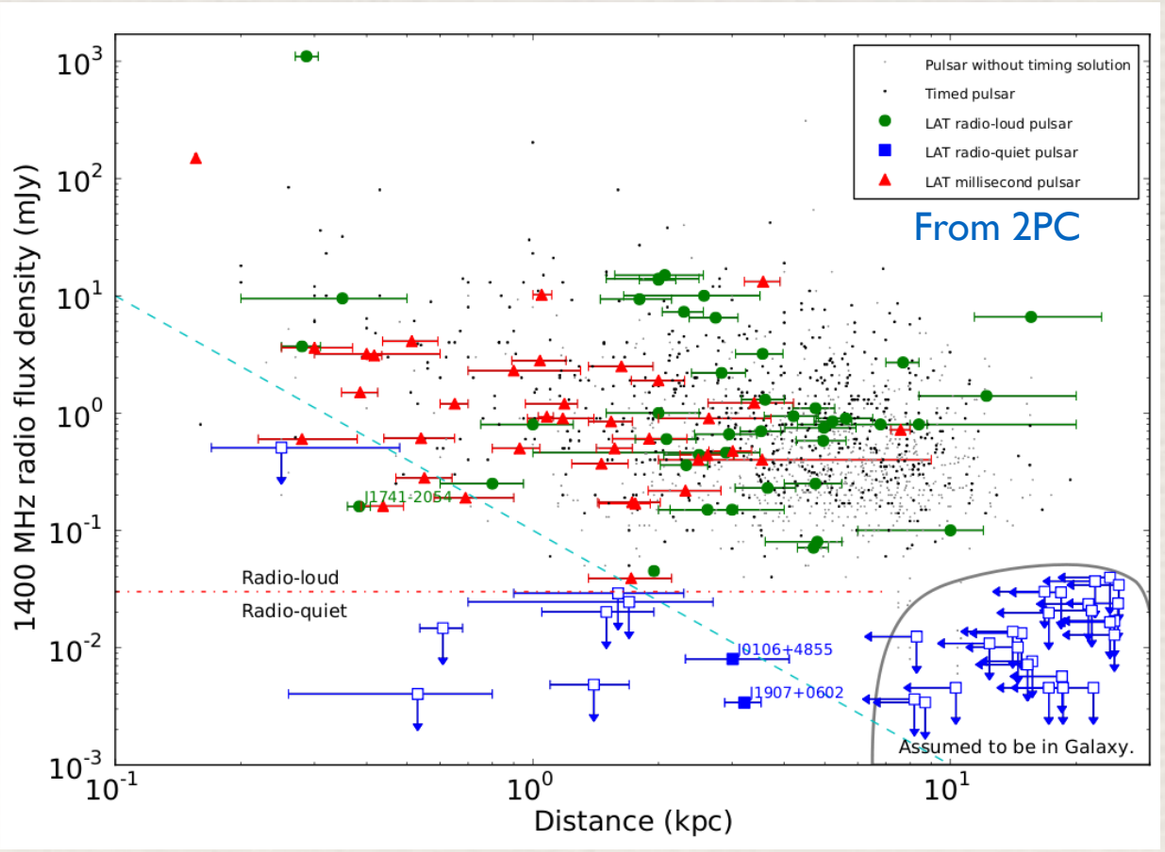
Significant contribution to the hunt for Galactic-disk MSPs!



MANY new redback and black widow systems.

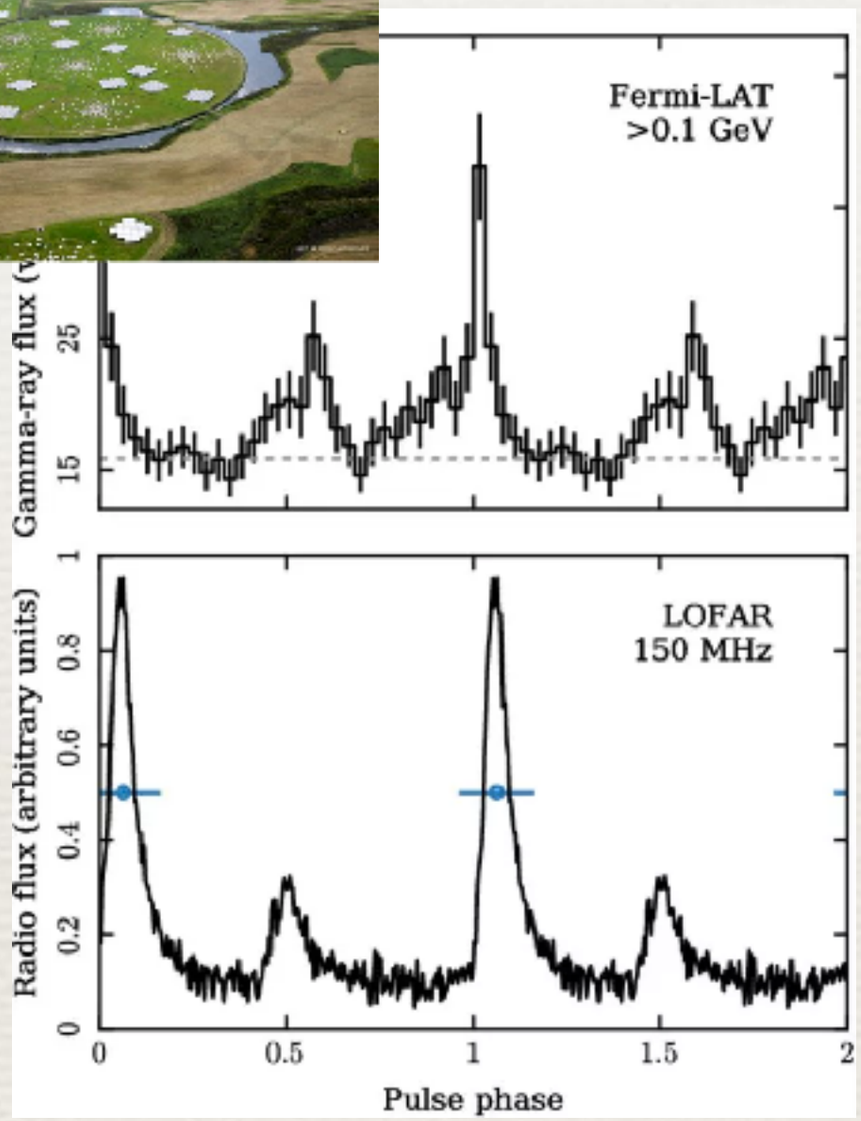
Some of the new MSPs are being added to pulsar timing arrays (PTAs) to search for GWs.

Still probably more to be found in future LAT catalogs: gamma-ray and radio fluxes uncorrelated!



L. Guillemot, 13/08/18

Some recent highlights



J1552+5437 (above), J0952-0607 & J0652+47: 3 MSPs discovered by LOFAR at 150 MHz! (see Pleunis et al. 2017 & Bassa et al. 2017)

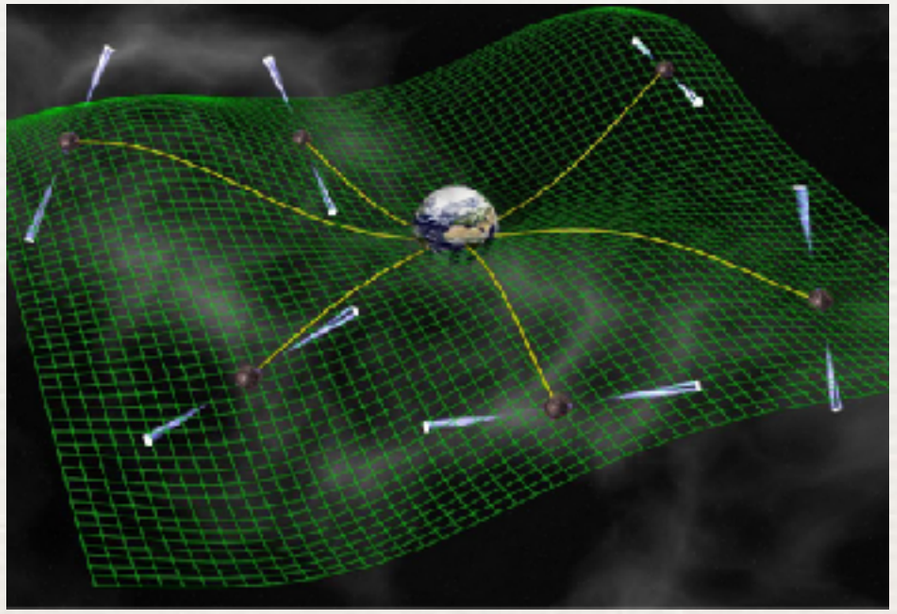
J0318+0253: first MSP discovered by FAST, in a LAT source! (Wang et al., ATEL11584).

L. Guillemot, 13/08/18

PTAs: cosmic-scale GW detectors

In a « Pulsar Timing Array » (PTA), pulsars act as the arms of a cosmic GW detector.

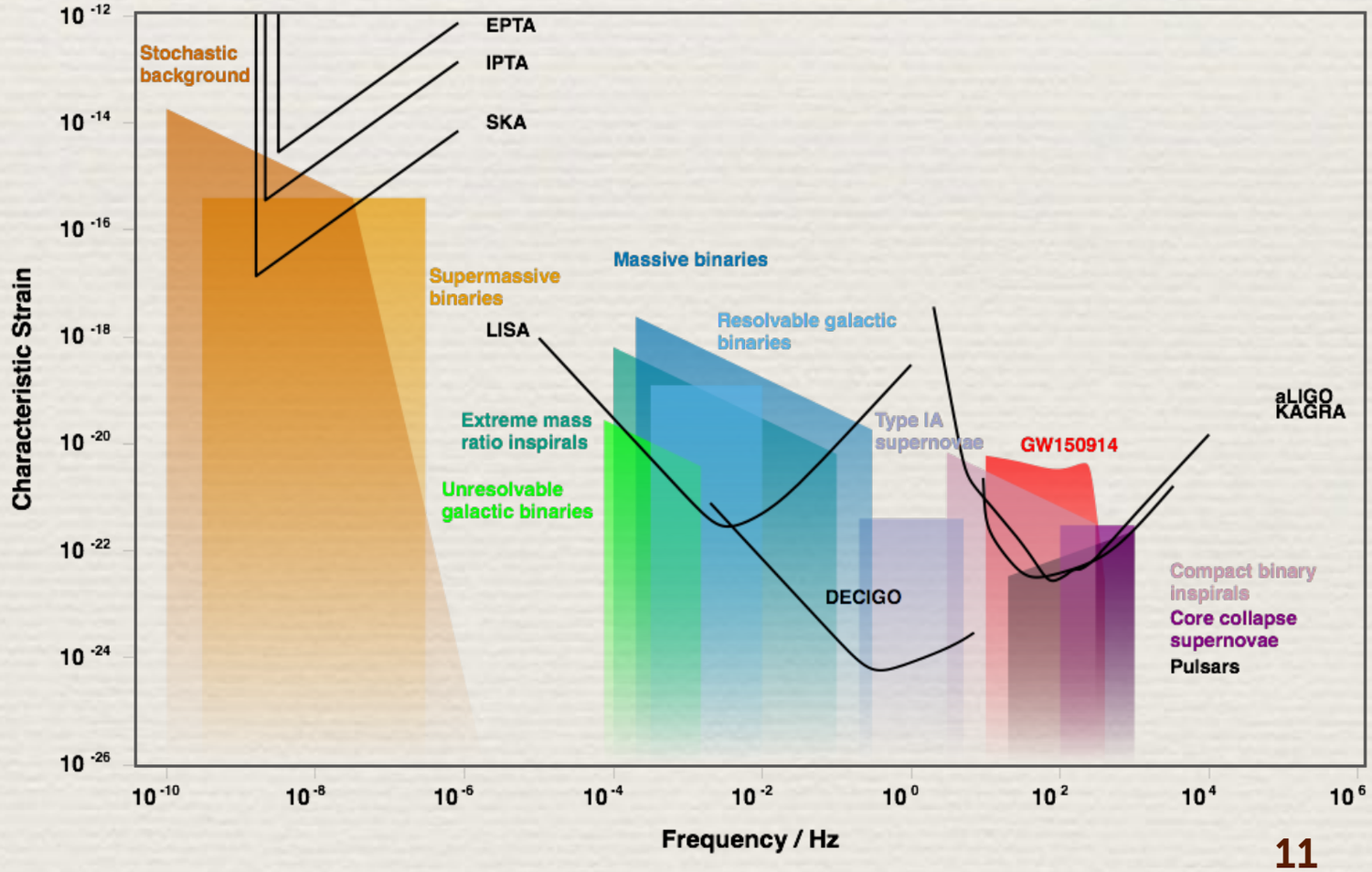
Sources: supermassive black hole binaries, cosmic strings, stochastic background.



Current efforts: EPTA (Europe), PPTA (Australia), NANOGrav (North Am.), IPTA (International).

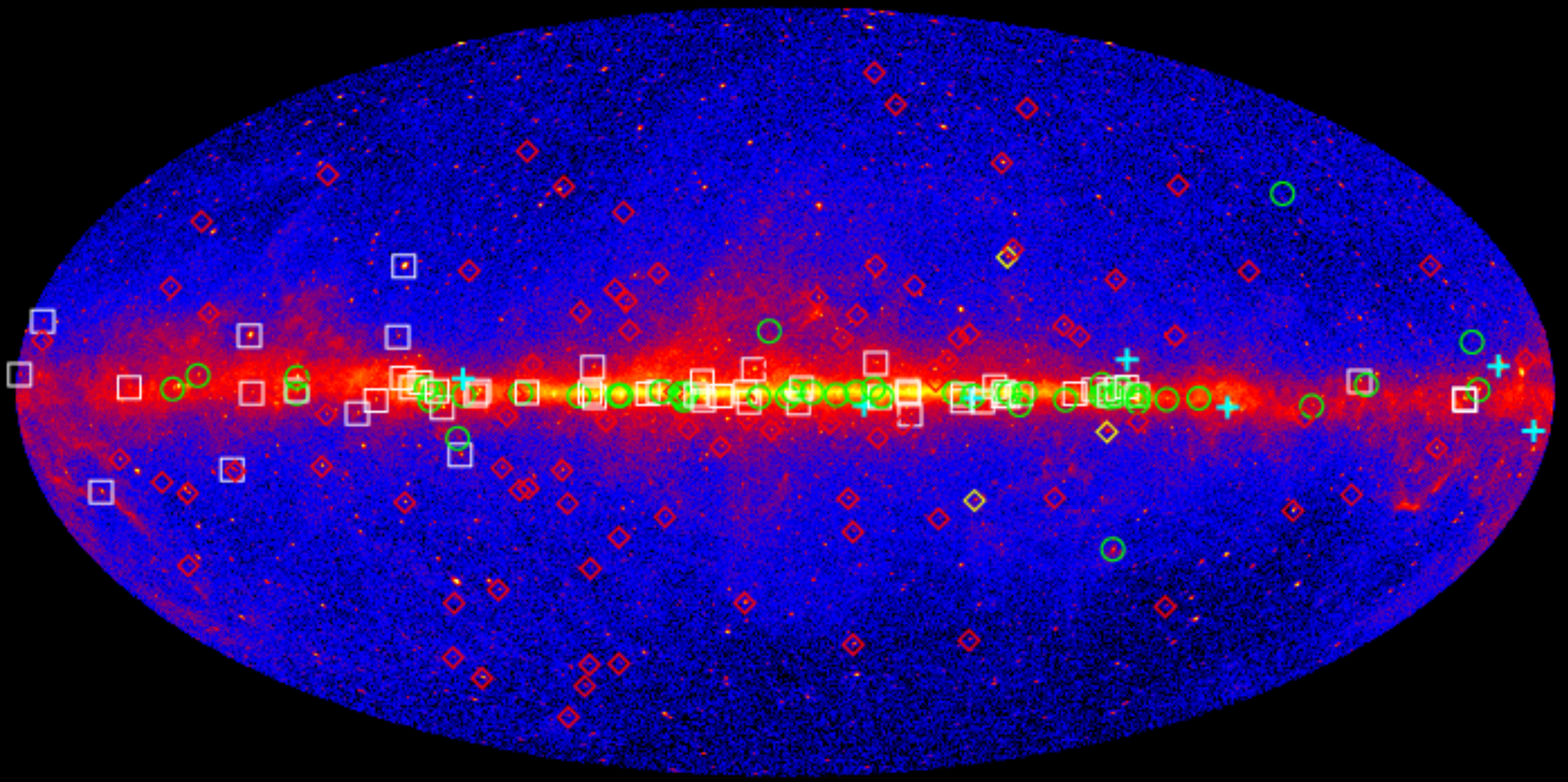
Need 5 to 10 years of timing of 20 pulsars with <100 ns accuracy.

Several MSPs found in LAT sources are bright, stable, and have sharp profiles!



LAT pulsars

Public list of LAT-detected pulsars available at: https://confluence.slac.stanford.edu/x/5JI6Bg



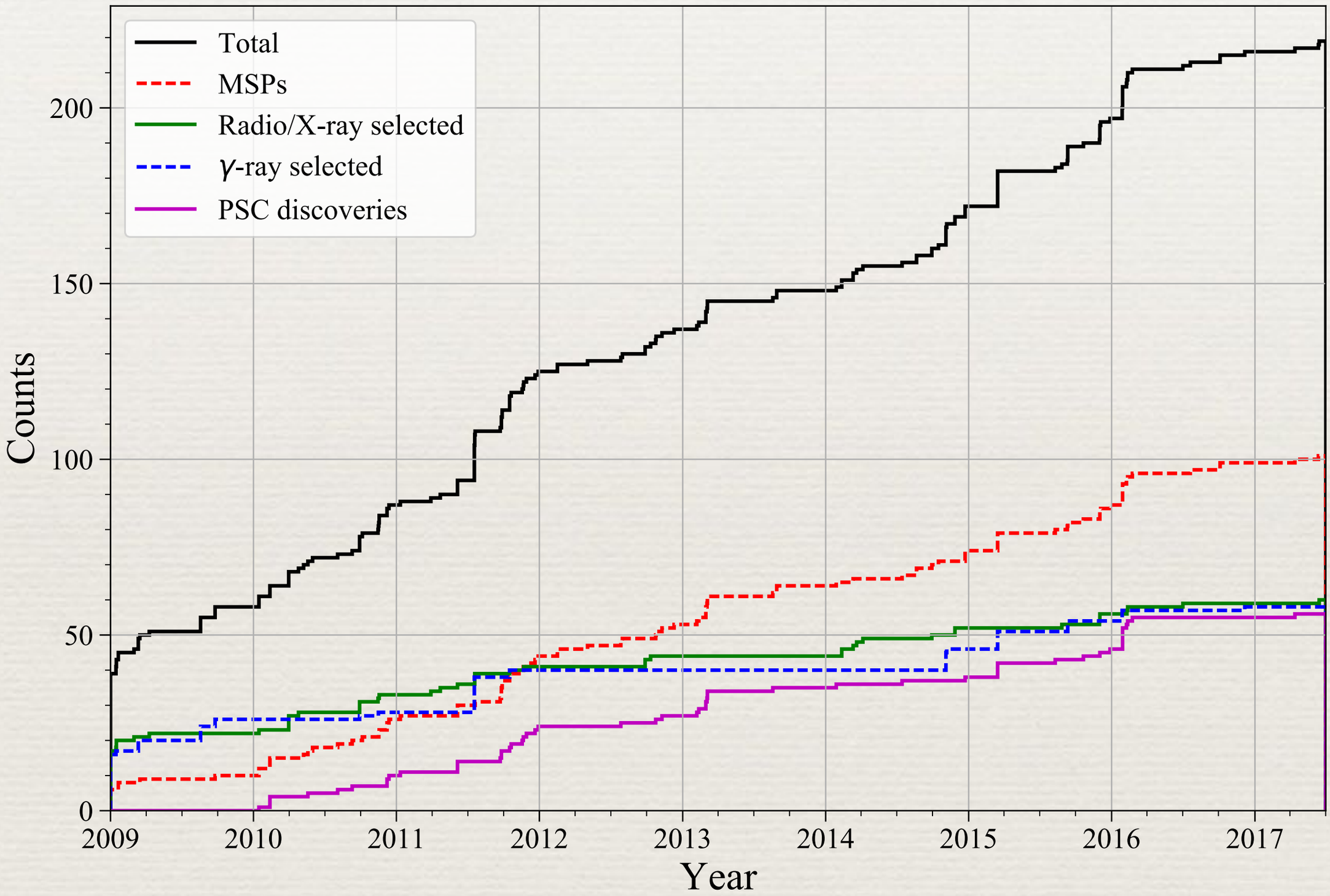
60 young radio- and X-ray-selected (green circles, cyan crosses: EGRET pulsars)

57 young gamma-ray-selected (white squares)

96 radio-selected MSPs (red diamonds), 3 gamma-ray-selected MSP (yellow diamonds)

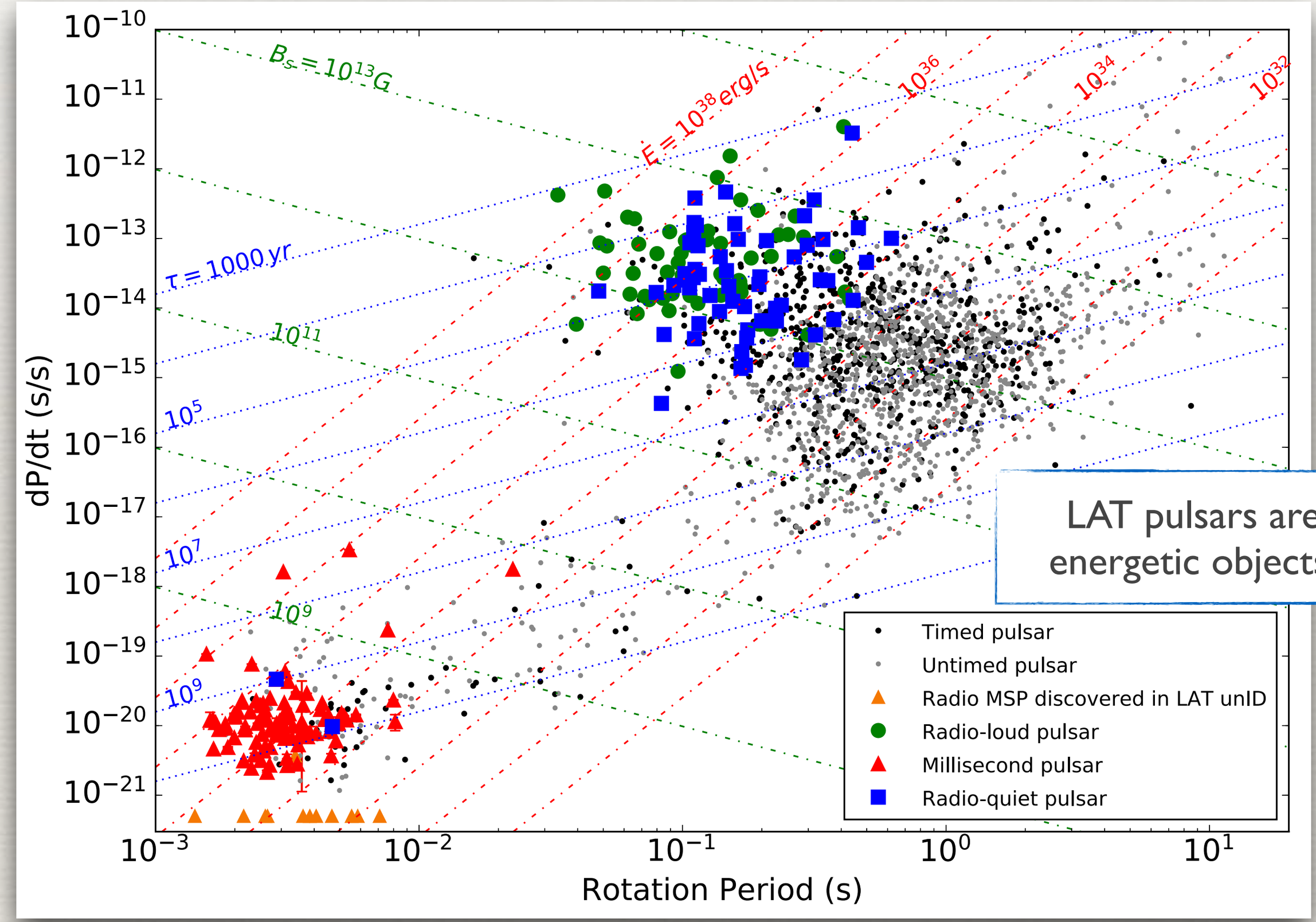
216 in total!

Detection rate



Gamma-ray pulsar detection rate surprisingly steady!

The 200+ pulsars in the P-Ṗ diagram



LAT pulsars are energetic objects.

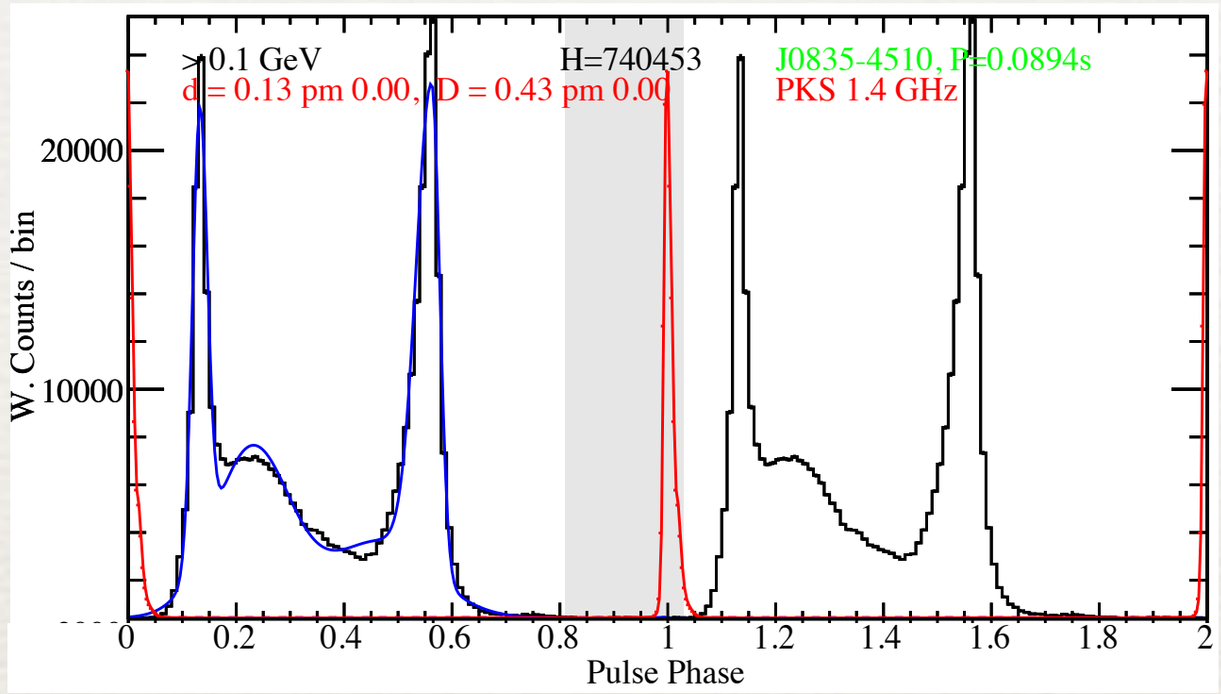
What is a gamma-ray pulsar like?

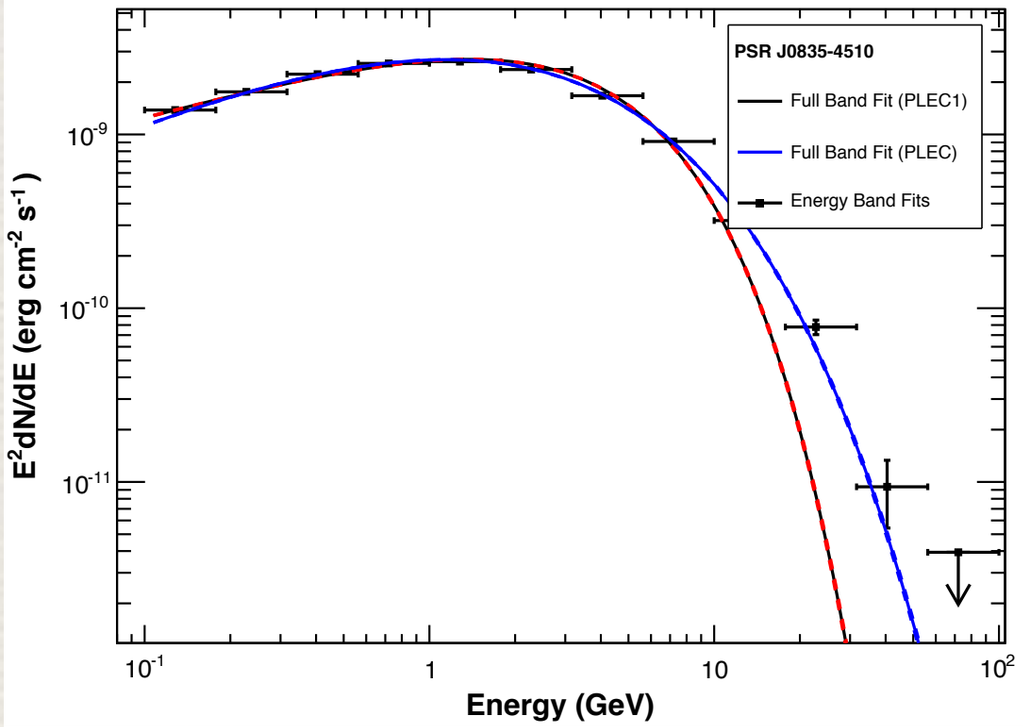
Vela = archetypal γ-ray pulsar.

- two sharp peaks separated by Δ ~ 0.4, with bridge emission in between.
- first peak lagging the radio peak (red arrow) by ~ 0.15.
- Spectrum well modeled with an exponentially cut off power law, with Γ~1.37, and E_c ~ 3.15 GeV.
- Spectral properties vary with phase.

(See Abdo et al., ApJ 713, 154, 2010)

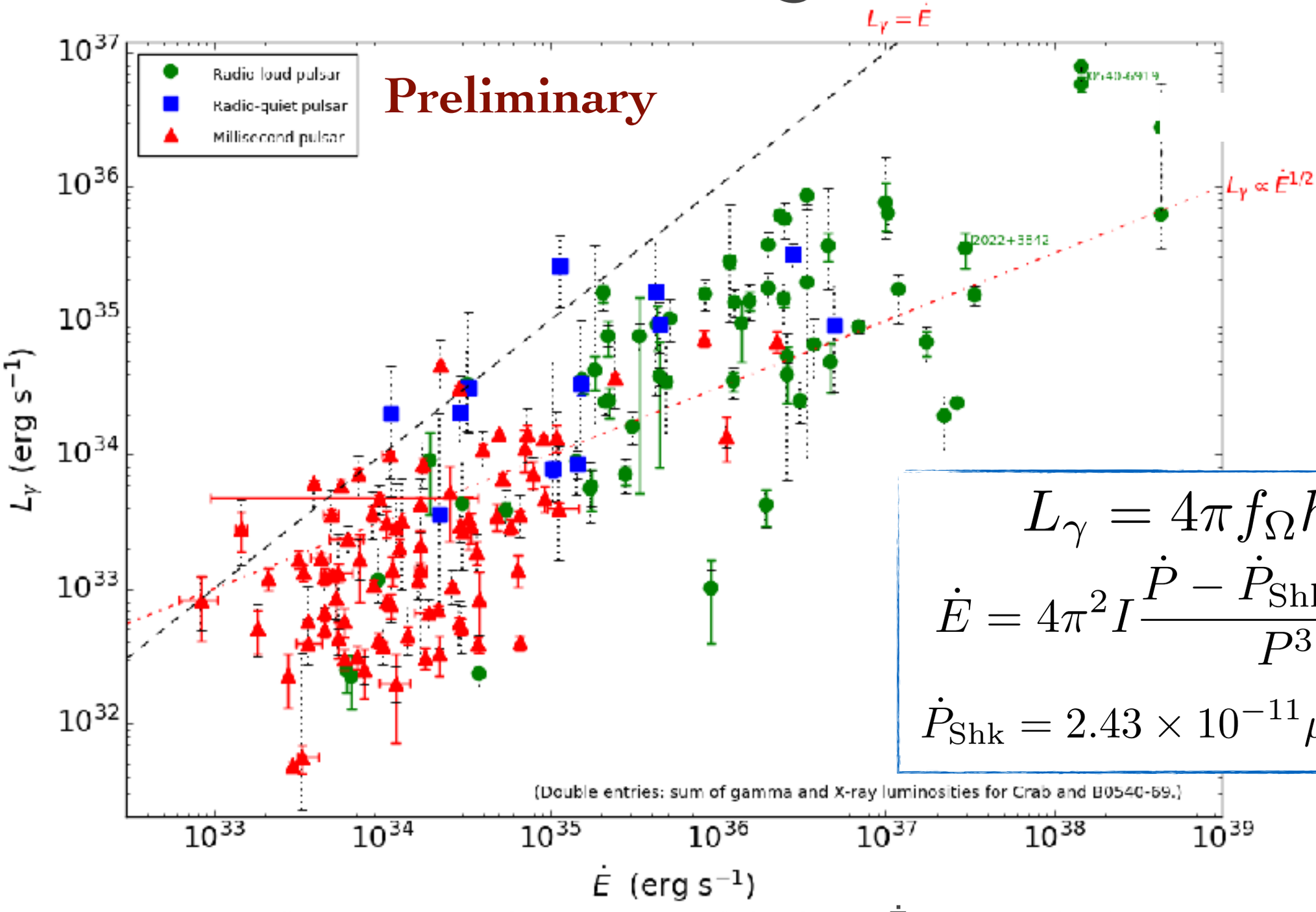
Outer magnetospheric models are preferred. Emission likely due to curvature radiation in high-altitude gaps, or beyond the light cylinder.





From the Second Fermi LAT Catalog of Gamma-ray Pulsars (2PC), ApJ Suppl. 208, 17 (2013)

Pulsar energetics



$$L_\gamma = 4\pi f_\Omega h d^2$$

$$\dot{E} = 4\pi^2 I \frac{\dot{P} - \dot{P}_{\rm Shk} - \cdots}{P^3}$$

$$\dot{P}_{\rm Shk} = 2.43 \times 10^{-11} \mu_\perp^2 \; d \; P$$

Can we get a clearer view of the L_γ vs $\dot{E}$ relationship?

Where does the deathline for gamma-ray emission (if there's any) lie?

Need accurate $\dot{P}$ measurements, proper motions, distances, and beaming estimates!

Understanding outliers is important!

J1024-0719: distance and proper motion very accurately measured, but $\dot{E}_{int} < 0$!

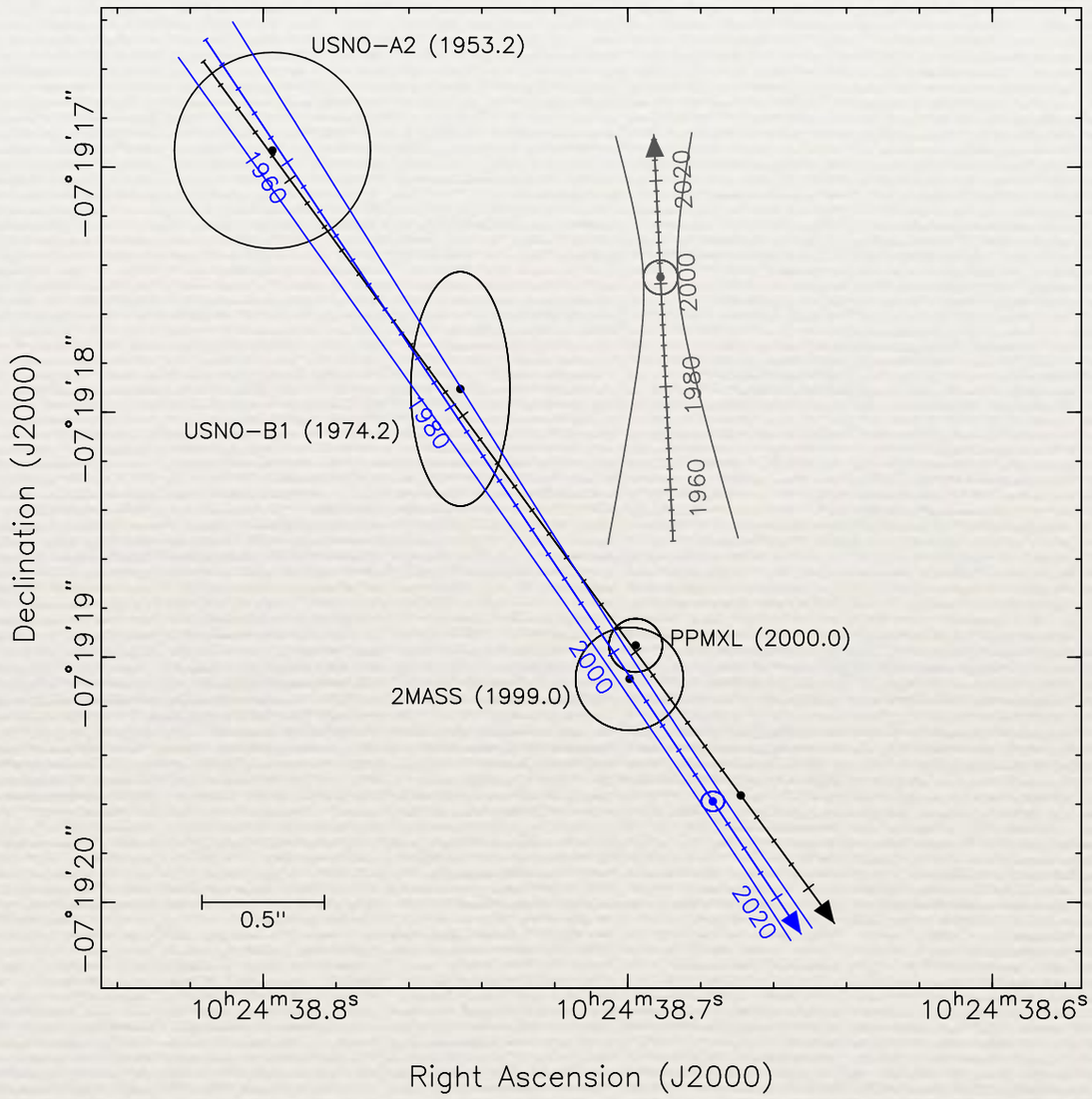
Bassa et al. (2016): P0… P4 with ~20 yrs of timing!

High-order period derivatives extremely unusual for MSPs.

Bassa et al. (2016): J1024-0719 and 2MASS J10243869−0719190 are in a wide (> 200 yr) orbit. Acceleration along the line of sight!

Unknown $\dot{E}_{int}$ for this one at present!

Another example: is J1823-3021A orbiting an intermediate-mass BH at the center of its host cluster? (Perera et al. MNRAS 2017).



From Bassa et al., MNRAS 460, 2207 (2016)

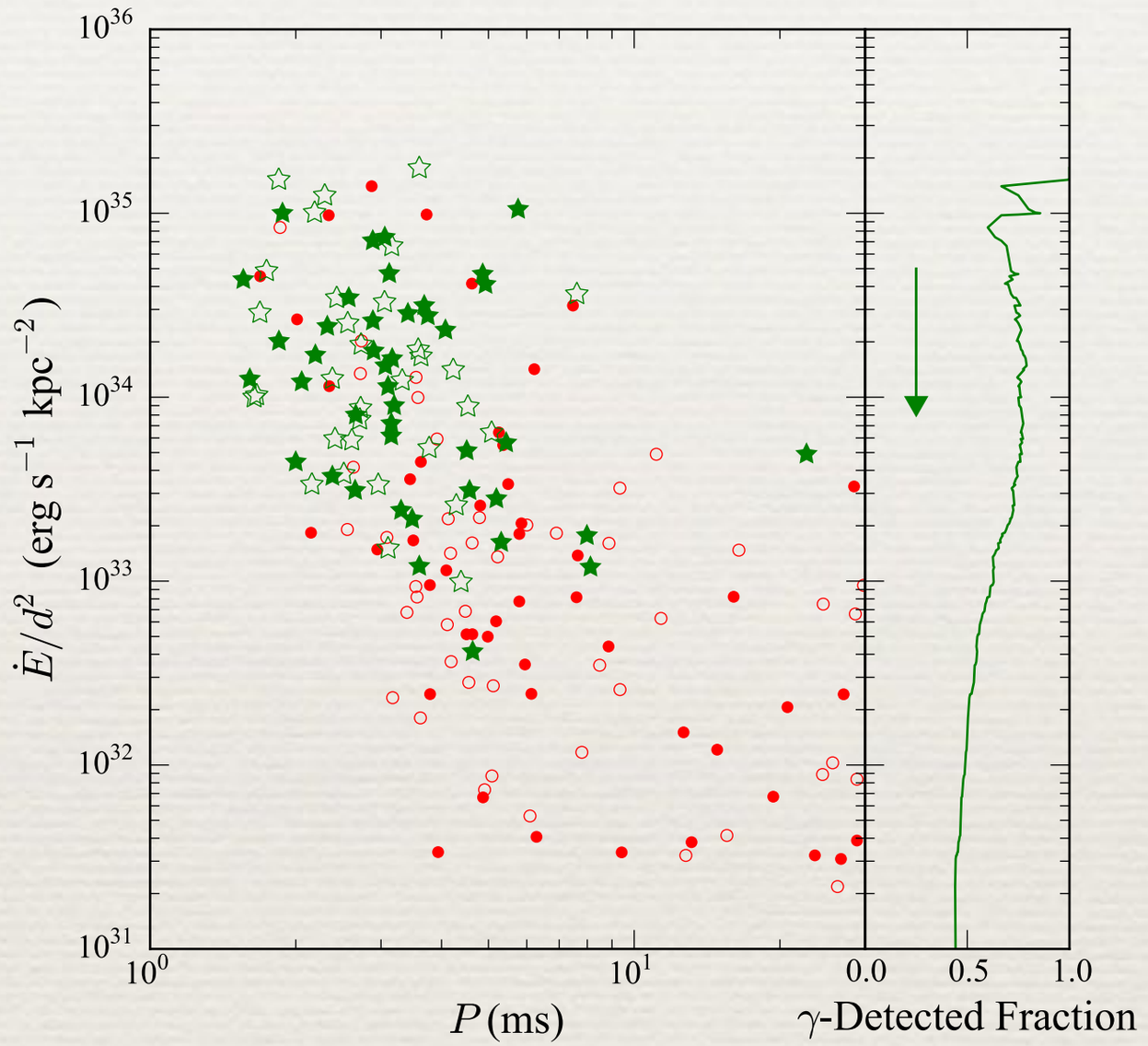
MSP gamma-ray detectability

$\dot{E}/d^2$ versus P for MSPs in the Galactic disk (adding gamma-ray MSPs in GCs, PSR J1823A and J1824A).

A large majority of energetic and nearby MSPs are seen in gamma rays: 75% above $\dot{E}/d^2$ = 5e33 erg/s/kpc^2!

Confirmation that the gamma-ray detectability of MSPs depends crucially on $\dot{E}$ (and the distance).

Non-detections due to unfavorable beaming geometries? (Guillemot & Tauris, 2014)



Green stars: gamma-ray-detected MSPs.

Red circles: undetected ones.

Filled symbols: Shklovskii-corrected.

The brightest known γ-ray pulsar

At the other end of the L_γ vs $\dot{E}$ diagram…

PSRs J0537-6910 and B0540-69 in the LMC: 2nd and 3rd most energetic pulsars known.

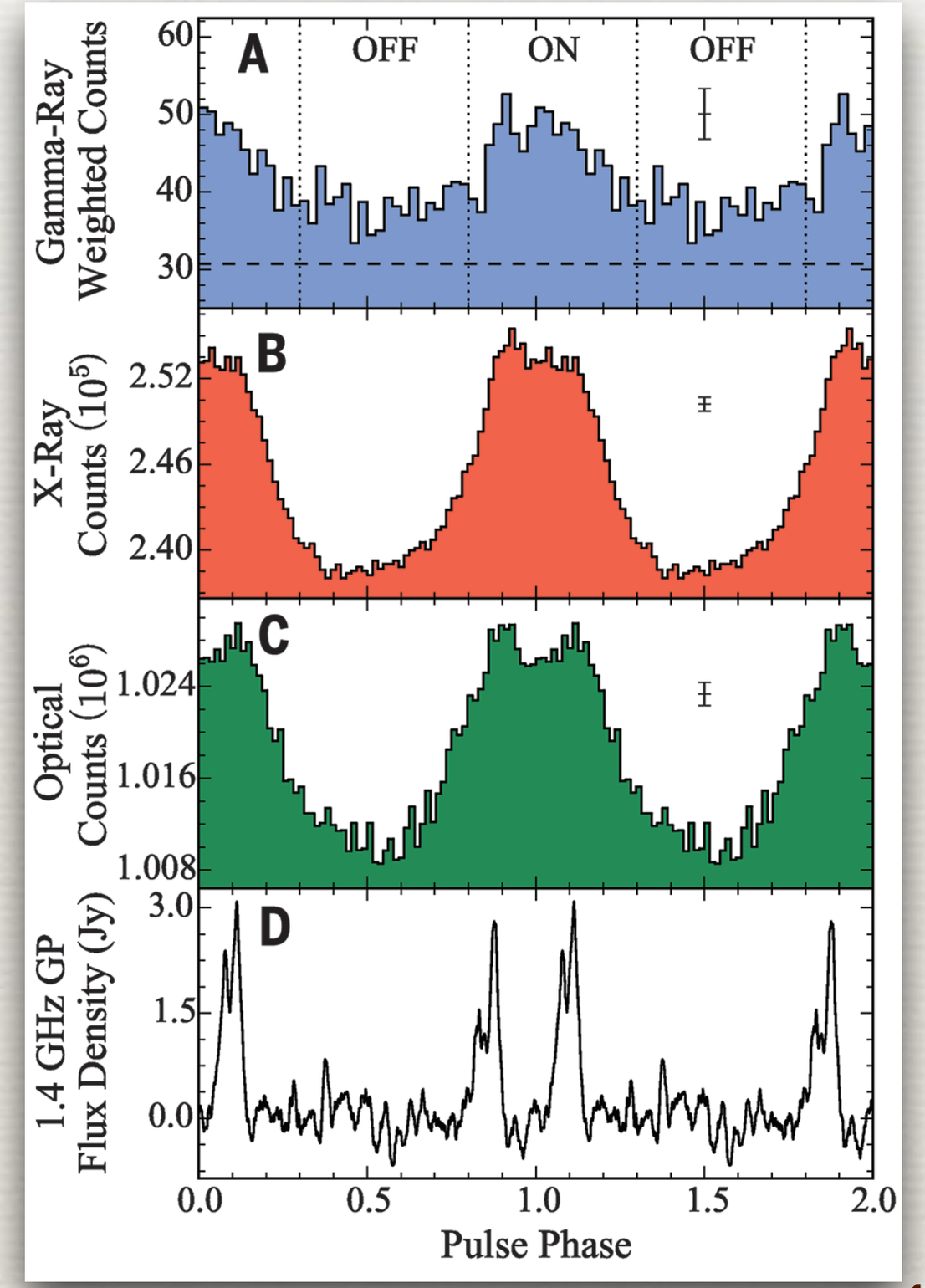
Analysis of 3.5 yrs of Pass 8 LAT data using RXTE X-ray ephemerides (from Frank Marshall):

- no detection of pulsations from J0537.

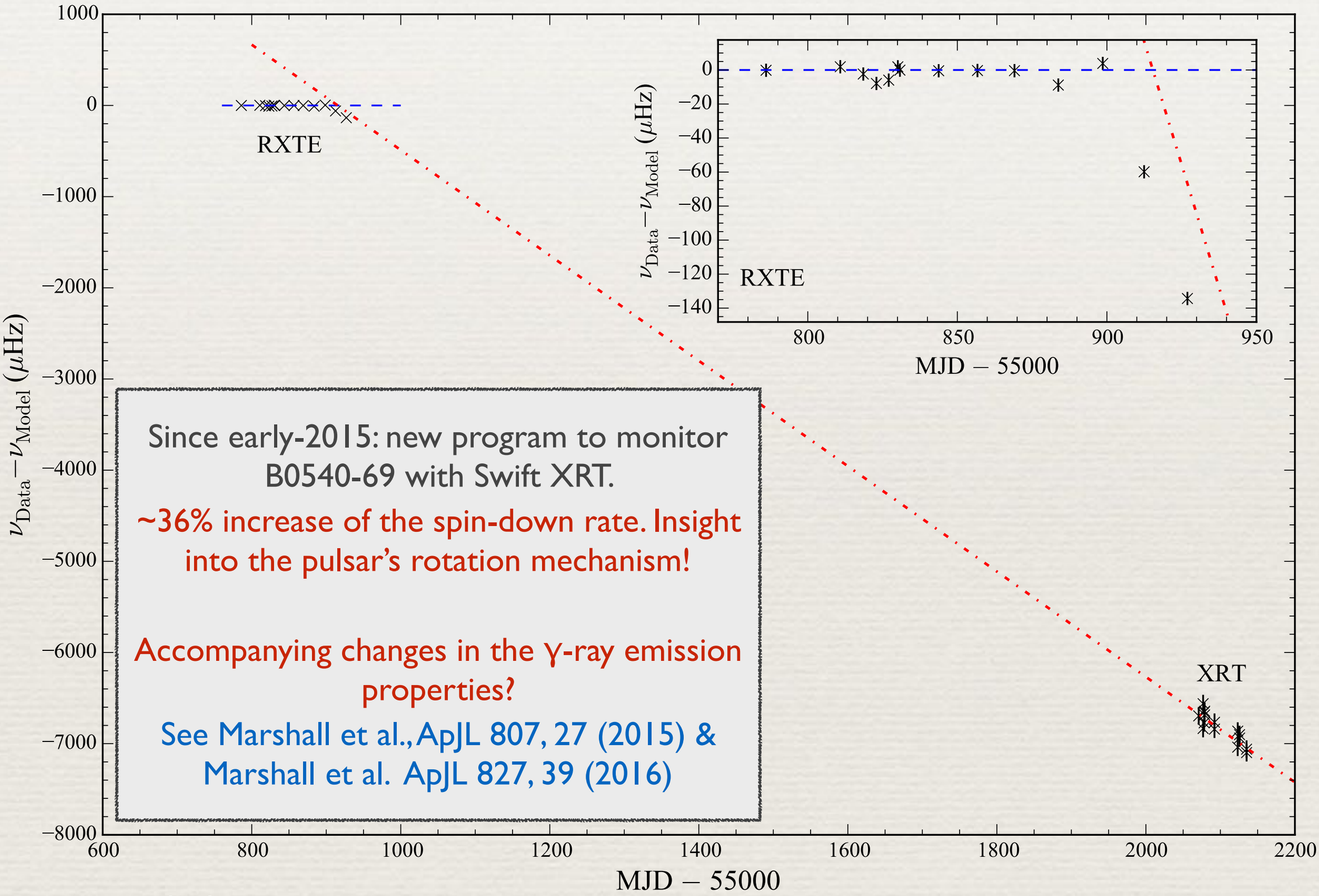
- significant detection of B0540, with γ-ray emission aligned with X-rays, optical and giant radio pulses!

B0540-69: first extragalactic γ-ray pulsar detected, also most luminous known (~20x more luminous than the Crab).

See Ackermann et al., Science 350, 801 (2015)



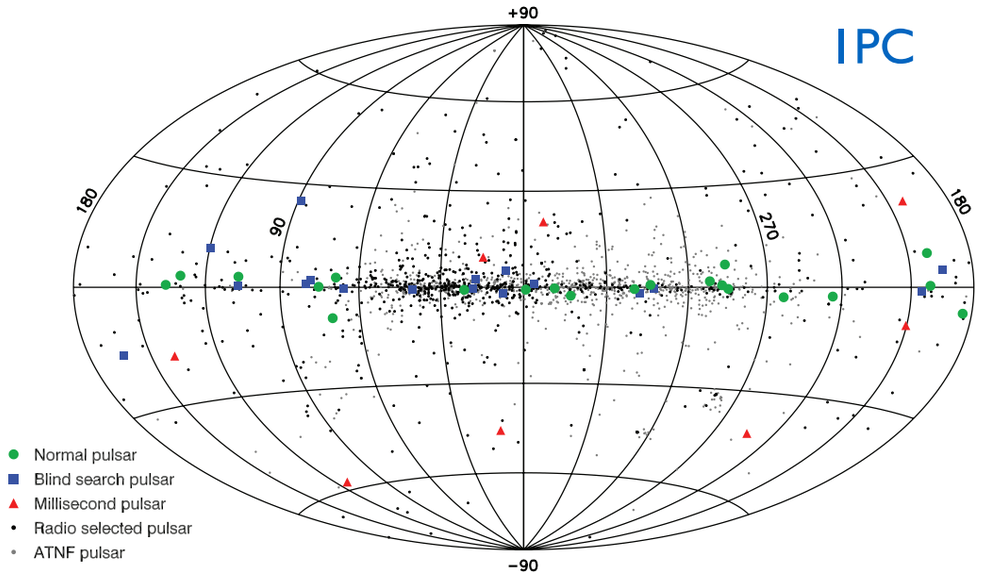
Spin-down state change in B0540-69

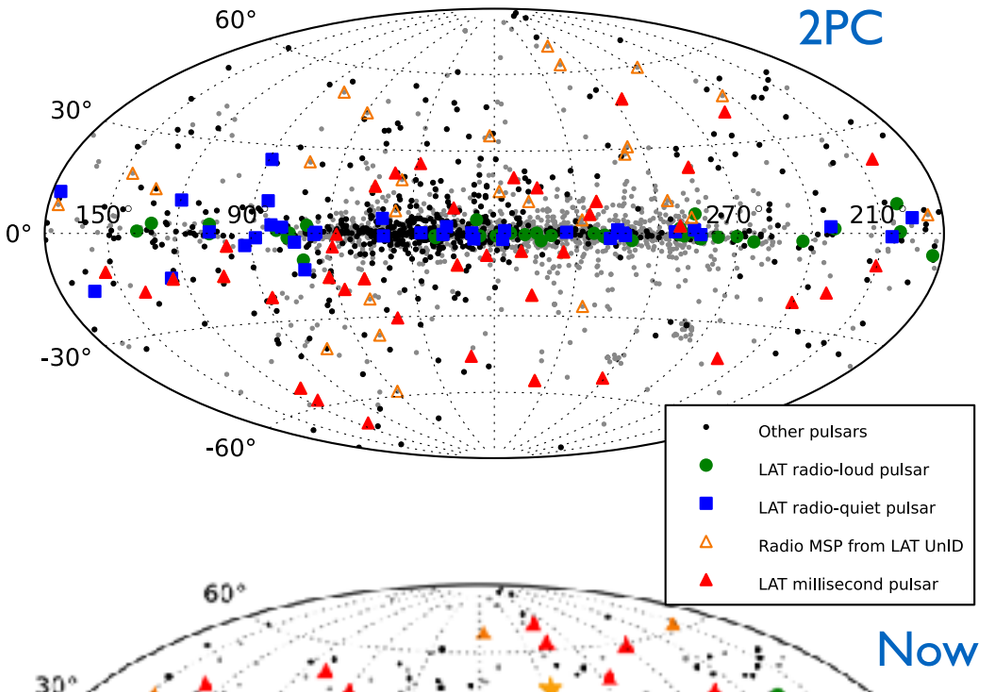


Coming soon: « 3PC »

3PC: Third catalog of LAT-detected pulsars, following 1PC (46 pulsars, Abdo et al. 2010) and 2PC (117 pulsars, Abdo et al. 2013).

3PC will summarize the properties of the >200 LAT-detected pulsars. Will be followed by companion papers on specific aspects.





3PC will include:

- LAT detections, timing and spectral properties
- Pulse profile fits
- Distances, luminosities
- Sensitivity
- etc.

As for 2PC, ephemerides will be made available publicly.

Work on 3PC has begun!

Summary

More than 200 γ-ray pulsars are seen by the LAT. Many of them were found in LAT sources.

Detection rate steady. LAT analyses continue to yield new discoveries and surprises!

Lots of efforts now put in the preparation of 3PC.

Not talked about today:

- Very-high energy pulsar studies (*see talk by Marcos Lopez Moya on Wednesday!*)
- Phase-resolved analyses of bright pulsars
- Pulsar binaries (*see talk by Tyrel Johnson on Thursday!*)
- Redbacks and black-widow pulsars
- Modeling efforts
- X-ray, optical studies of LAT pulsars and LAT sources
- *etc.*

Thank you!