
# Pulsars: what we have seen

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*On behalf of many (and even more)*

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# Pulsars

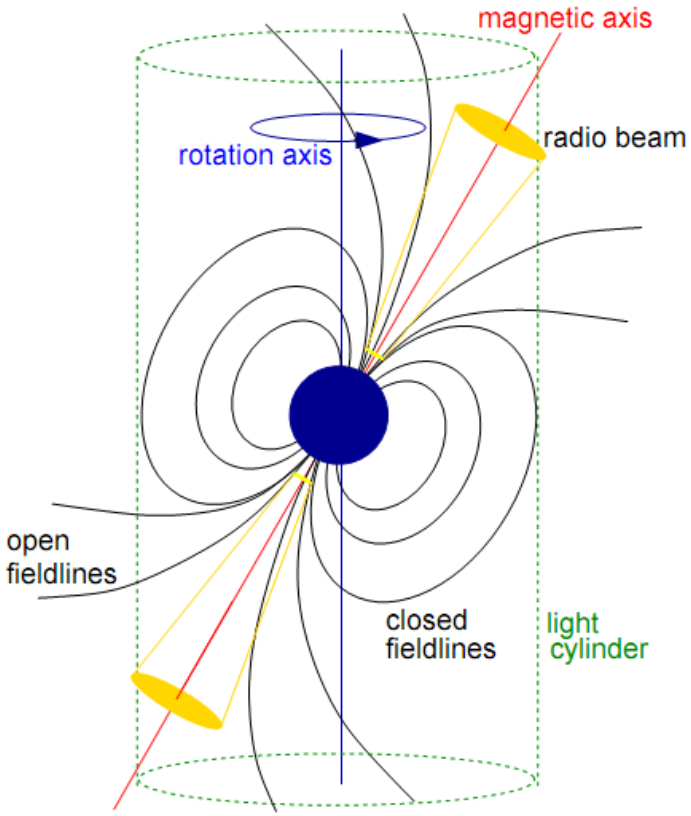
Pulsars are rapidly rotating, highly magnetized neutrons stars, born in supernova explosions of massive stars.

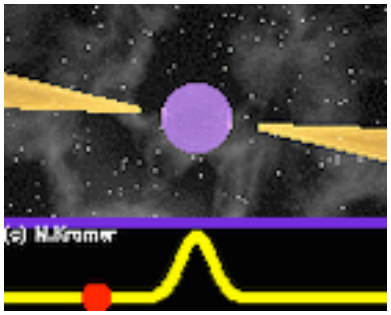
Typically, M ~ 1.4 $M_{sun}$ and R ~ 10 km

A dense plasma is co-rotating with the star. The magnetosphere extends to the "light cylinder", where the rotation reaches the speed of light.

Emission (radio, optical, X-ray …) can be produced in beams around the pulsar, which acts like a cosmic light-house.

~ 1900 pulsars known today. Vast majority in radio!



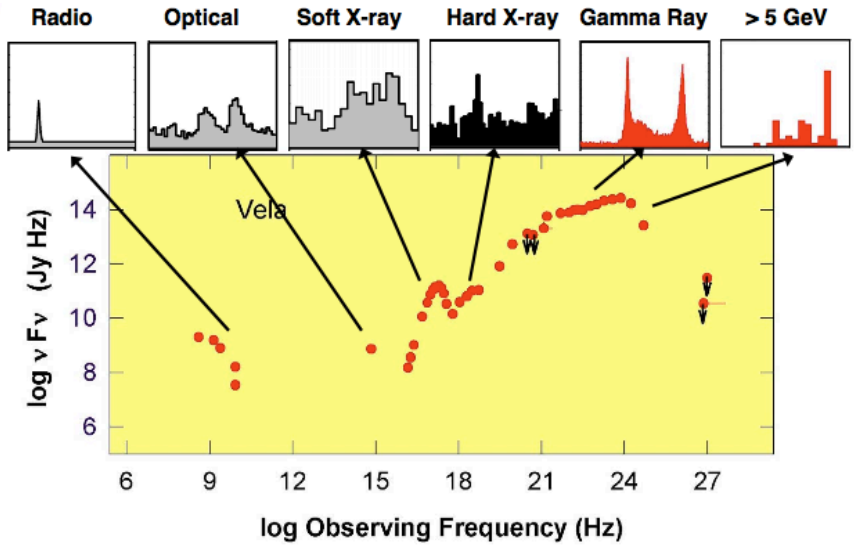



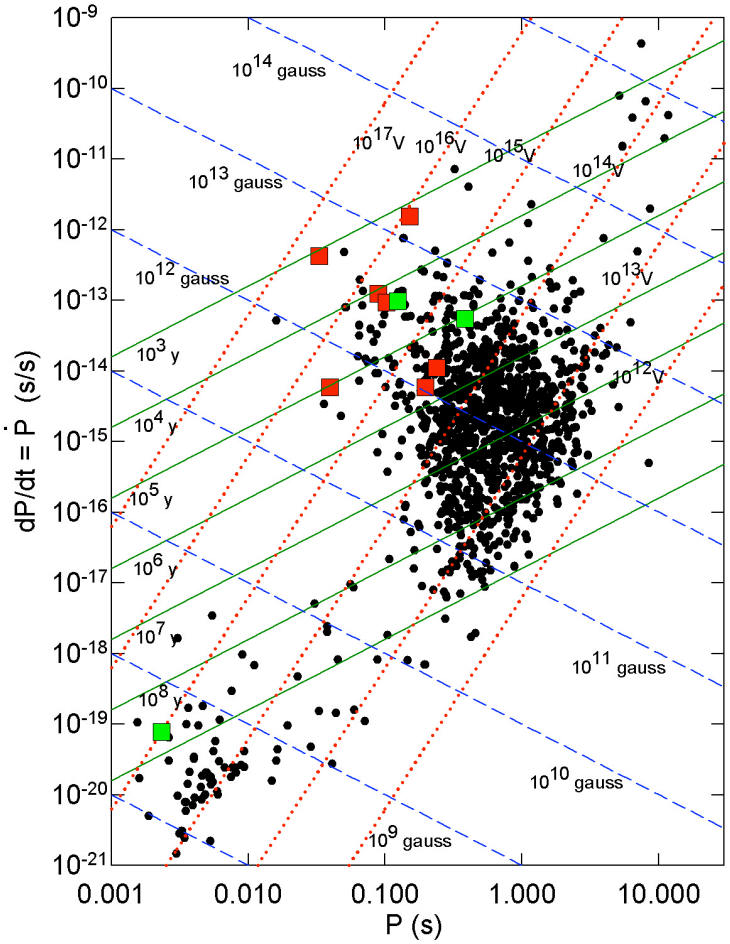
# Gamma-ray pulsars before Fermi

Before Fermi and AGILE: 6 detections by EGRET, 1 by COMPTEL (all normal energetic pulsars),

+ a few marginal detections.

Gamma-ray emission: important part of the total energy budget.




*Above: slowdown – period diagram.*

*Left: emitted power vs. frequency for the Vela pulsar.*

# Emission geometry

Different theoretical models try to explain the observed gamma-ray emission.

They assume different origin in the magnetosphere => different emission geometry.

Depending on:

α: angle between magnetic and rotation axis

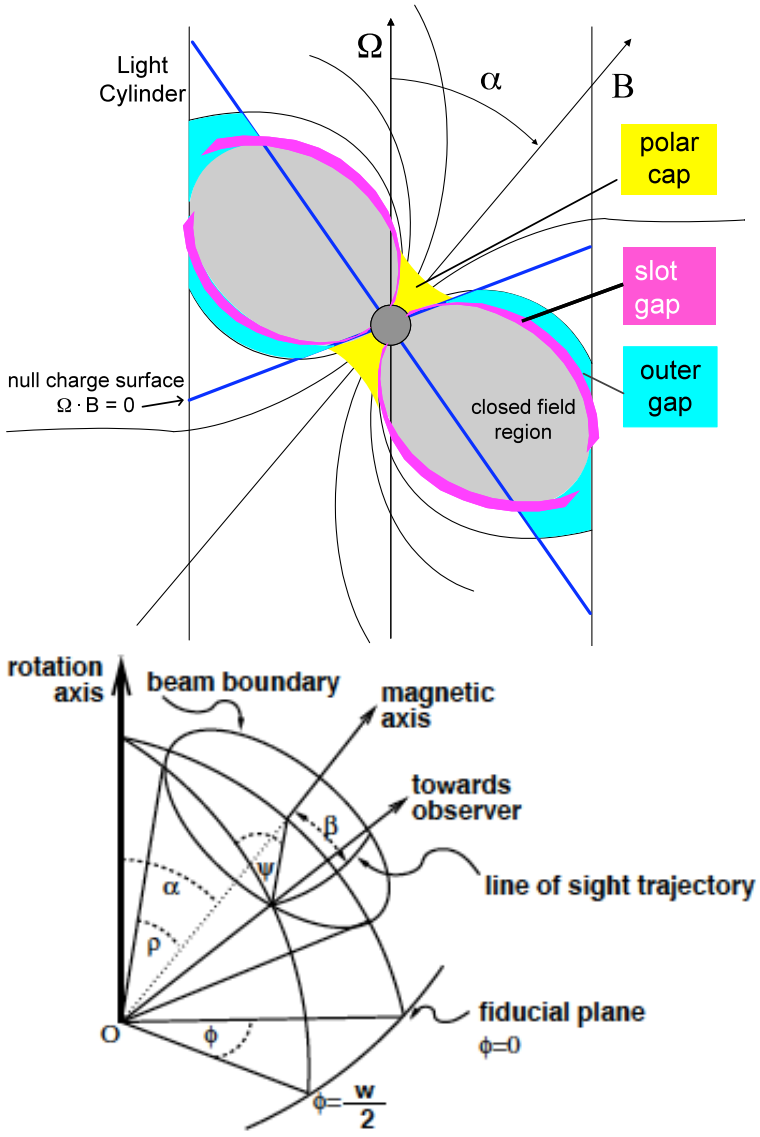
β: angle between line-of-sight and magnetic axis

Different emission patterns are expected (number of peaks, separation, radio/gamma lag, ratio of radio-loud/radio-quiet).

Gamma-ray observations can help disentangle the geometry of pulsars.

***Some open questions:***

- What mechanisms produce the emission of pulsars, from radio to gamma rays ?
- Where do these phenomena take place ?
- Are there gamma-ray millisecond pulsars ?
- What is the fraction of radio-loud and radio-quiet pulsars ?
- What is the contribution of gamma-ray pulsars to the diffuse galactic emission ?



# Observing pulsars with the Fermi LAT

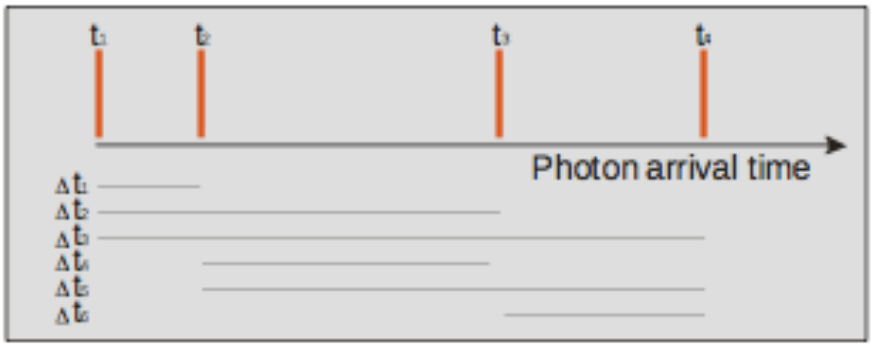
Two different approaches:

- Blind search of the rotational parameters in the gamma-ray data (new pulsars)
- Using rotational parameters obtained in radio or X rays (known pulsars)

***Time differencing technique:***

Datasets are large and direct FFTs are time-consuming and computer-intensive.

The periodicity can also be seen in differences of arrival times!




*(credit: M. Ziegler)*

*Atwood et al., ApJL 652, 49 (2006)*

*Ziegler et al., ApJ 680, 620 (2008)*

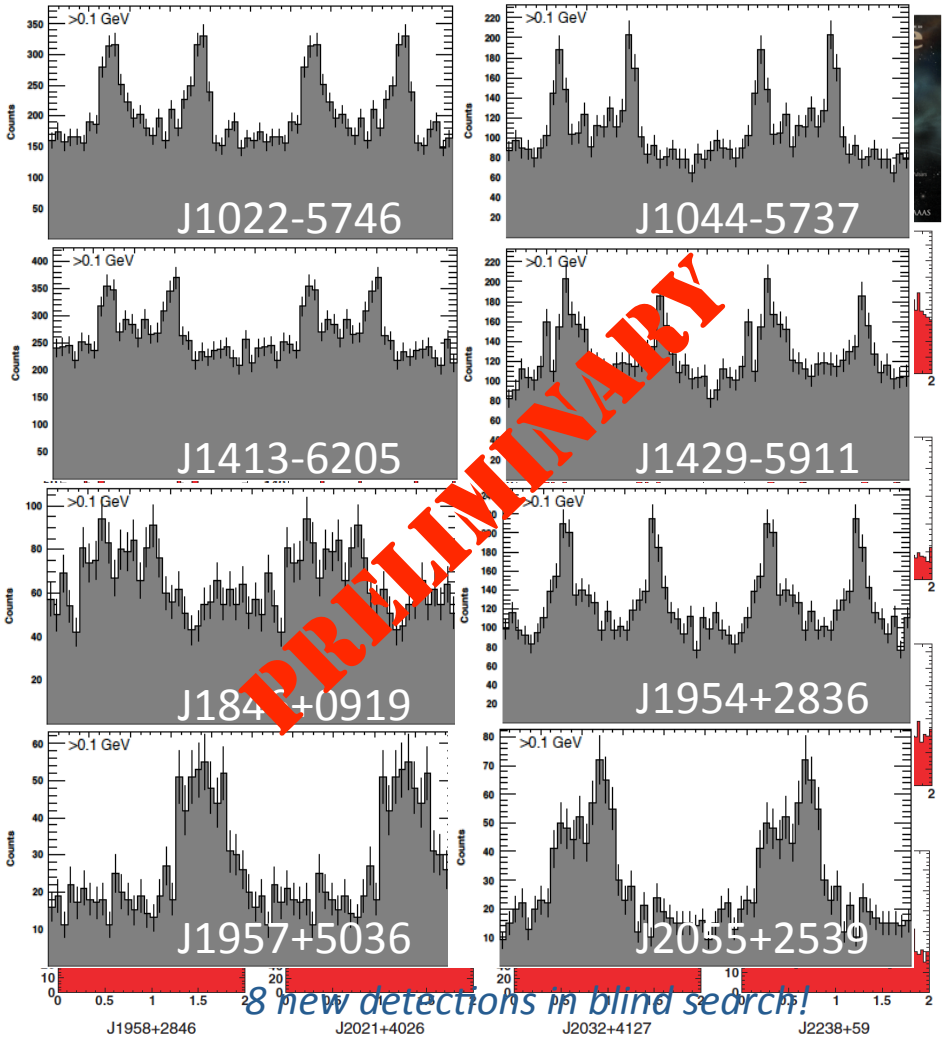
# Gamma-ray selected pulsars

Where to search ?

- Geminga candidates: CTA1, 3EG J1835+5918 (« next Geminga »), compact objects …
- Unidentified Fermi sources.

The first "blind search" detection was a 317 ms pulsar in CTA1, coincident with unidentified X-ray and gamma-ray sources.
(Abdo et al., Science 322, 1218, 2008).

After 4 months of data taking, 16 pulsars have been found with the same technique!
(Abdo et al., Science 325, 840, 2009).




*8 new detections in blind search!*
*(Abdo et al., in prep)*

*(See talks and posters by Aous Abdo, Pablo Saz Parkinson, Andrea Belfiore, Megan DeCesar, Paul Ray)*

# Pulsar timing campaign

*Jodrell Bank (UK)*

*Nançay (France)*

*RXTE (in space)*

*Parkes (Australia)*

*Green Bank (USA)*

*+ other contributions: Arecibo, Hartebeesthoek, etc.*

*=> Timing for ~ 230 energetic pulsars, of interest for Fermi.*

*(Smith, Guillemot, Camilo et al., A&A 492, 923, 2008)*

# EGRET pulsars with Fermi

EGRET pulsars generally are prime targets for spectral analyses with unprecedented details, because of their brightness.

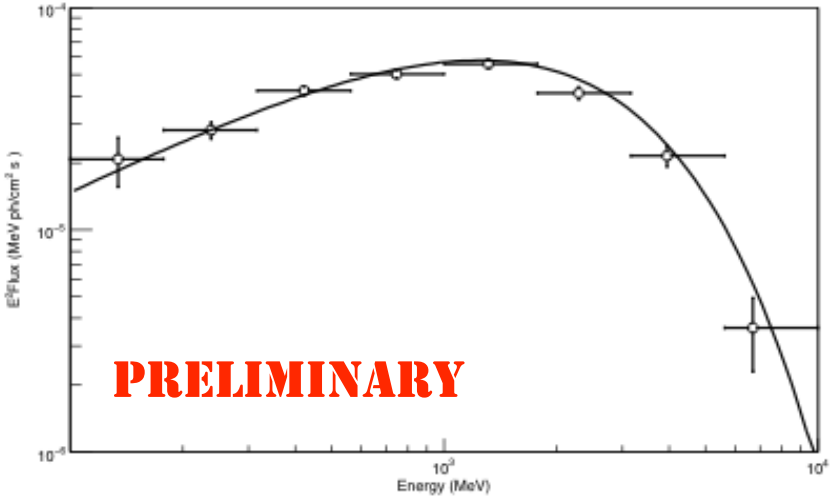
Important variation is seen in spectral properties across the rotation.

Vela: complex P1 and P2 behaviors. A shift of P3 with energy has been observed (Abdo et al., ApJ 696, 1084, 2009)!

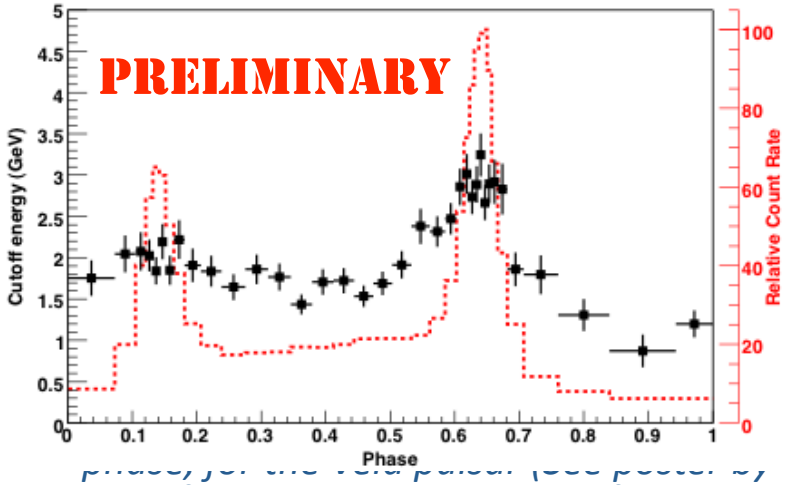
Spectral index and cutoff energy variations are thought to be due to emission altitude changes with energy (see e.g. Geminga).

In general, pulsar spectra are consistent with simple-exponential cutoffs, indicative of absence of magnetic pair attenuation.

*(See posters by Tyrel Johnson, Ozlem Çelik, Massimiliano Razzano)*




*PSR B1055-52 spectrum*



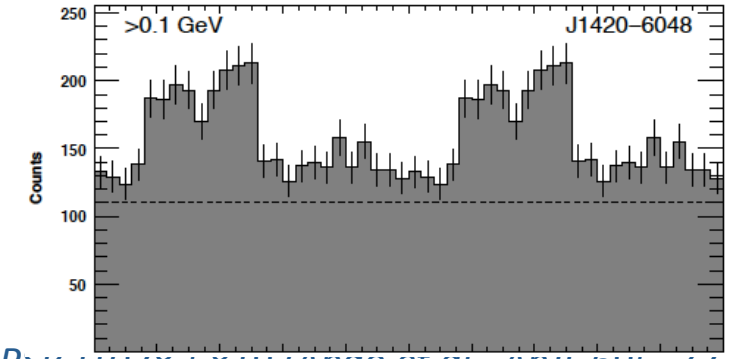

*Cutoff energy vs. pulse phase, for the Geminga pulsar*

# Young radio-loud pulsars

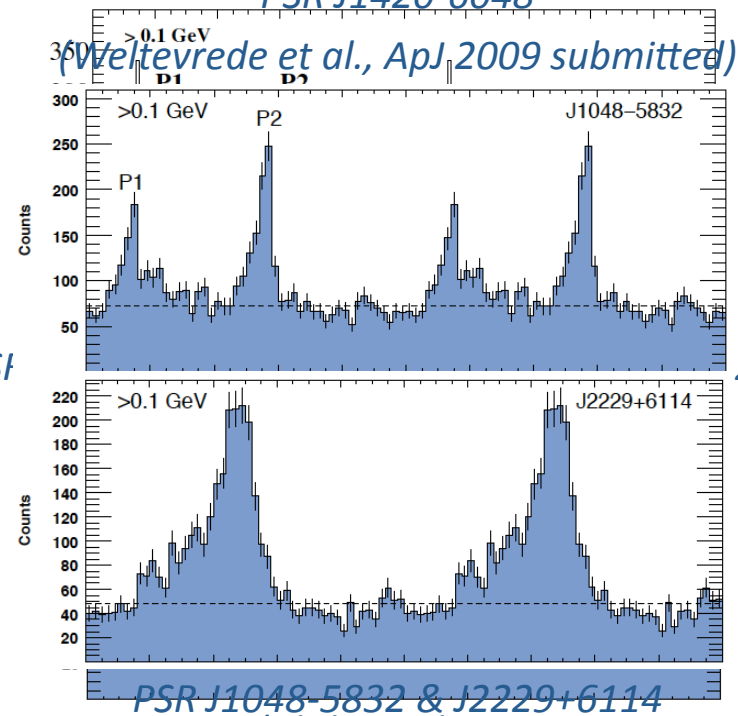
Fermi detected a number of young radio-loud gamma-ray pulsars, all highly energetic ($\dot{E} > 3\ 10^{33}$ erg/s).

Many are seen in unidentified EGRET sources: 3EG J1027-5817, 3EG J2021+3716, 3EG J1048-5840, 3EG J2227+6122, …

*(See posters by Andrea Caliandro and Damien Parent)*




*PSR J1028-5819 (Abdo et al., ApJL 695, 72, 2009)*
*PSR J1420-6048*
*(Weltevrede et al., ApJ 2009 submitted)*




*PSR J1048-5832 & J2229+6114*
*PSR J0205+6449 (Abdo et al., ApJL 699, 102, 2009)*
*(Abdo et al., ApJ 2009 accepted)*

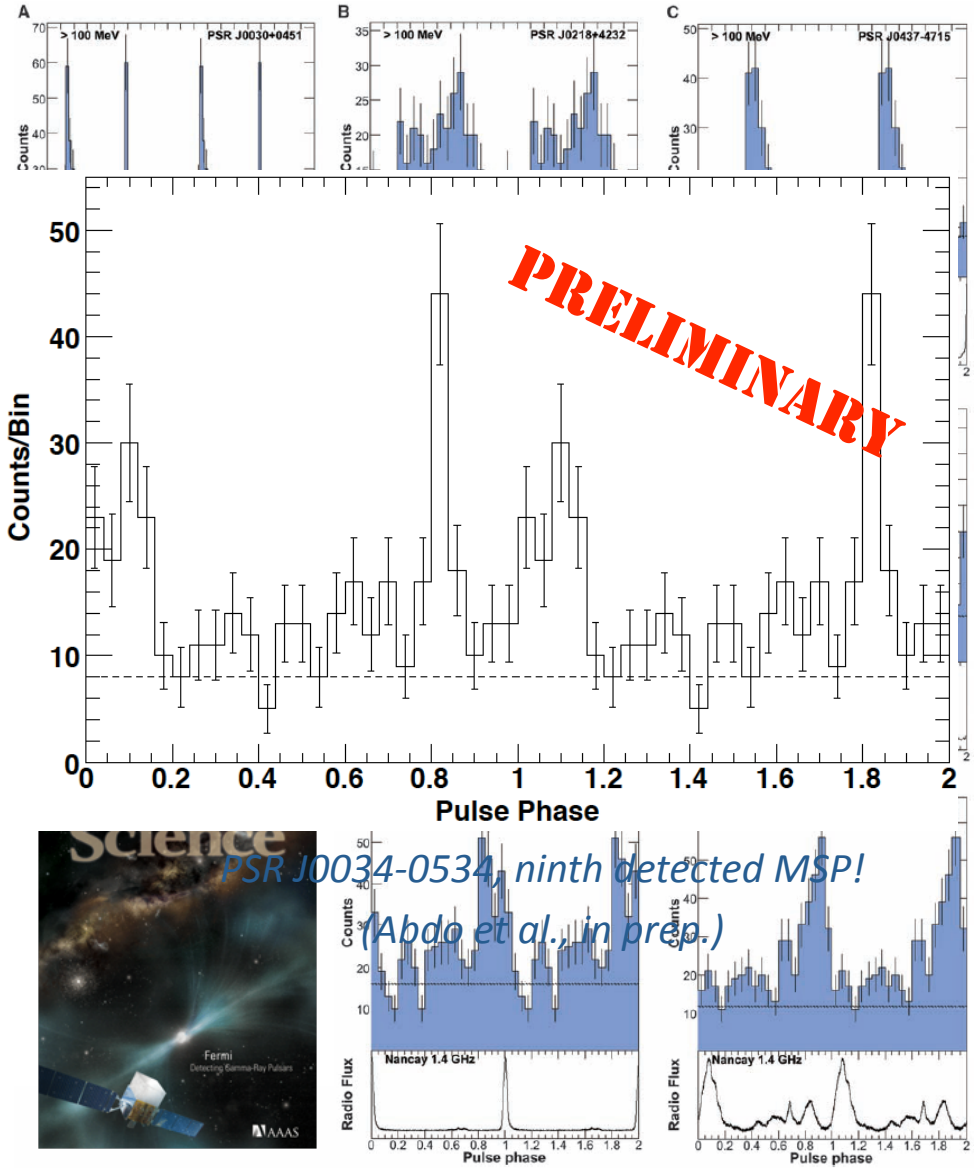
# Radio-loud millisecond pulsars

The LAT detected pulsed gamma-ray emission from J0030+0451, making it the first firm detection of an MSP in gamma rays (Abdo et al., ApJ 699, 1171, 2009).

After 9 months of data taking, the LAT had detected 8 gamma-ray MSPs (Abdo et al. Science 325, 848, 2009).

For the first time, a population of gamma-ray MSPs has been observed.

*(See talk by Christo Venter)*

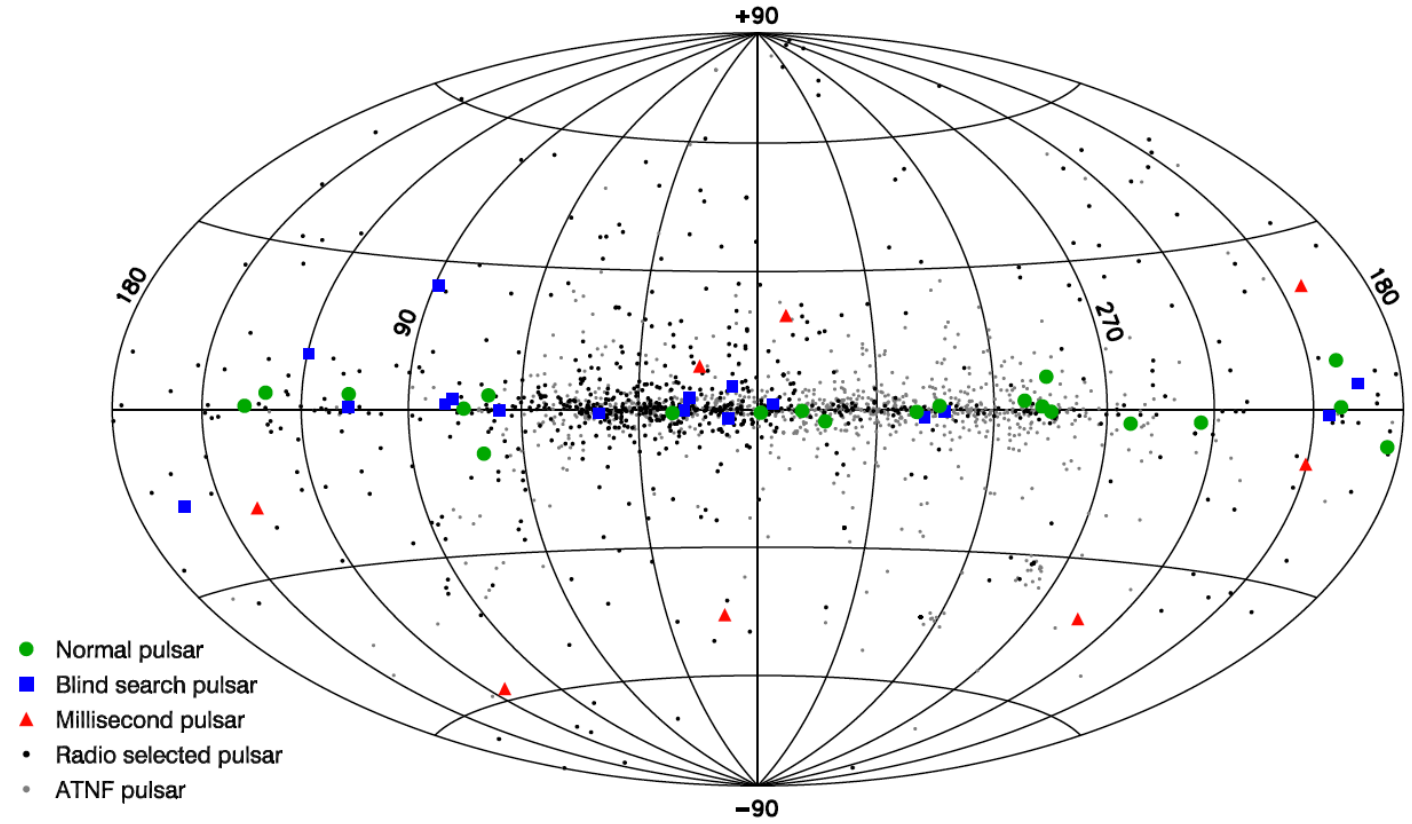



*PSR J0034-0534, ninth detected MSP!*
*(Abdo et al., in prep.)*

# The pulsar catalog

In addition to the search for new pulsars, 762 known pulsars with ephemerides were searched for pulsations in nine months of data.

=> 46 pulsars were detected: 16 blind search PSRs, 8 radio-loud MSPs, 22 radio-loud normal PSRs.




*Abdo et al., ApJ 2009 submitted, arXiv:0910.1608.*

*(See poster by Andrea Caliandro)*

# What do we learn ?

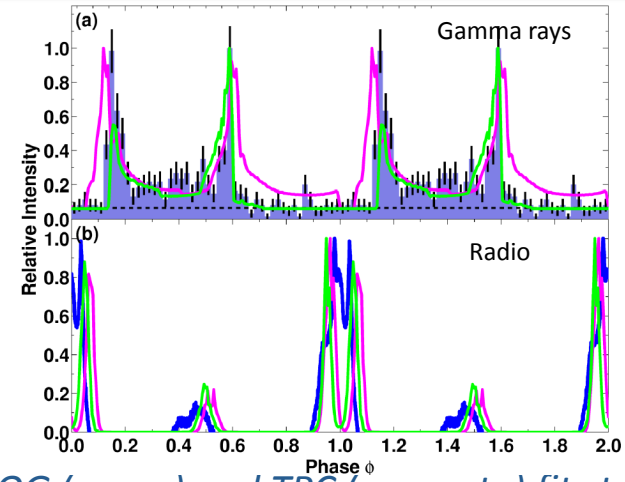
The gamma-ray profiles typically are two-peaked; the first one lagging the radio by 0.1 to 0.2 (with a few exceptions, e.g. J2229+6114).

The Two-Pole Caustic (TPC) or the Outer Gap (OG) models generally provide good fits to the observed profiles.

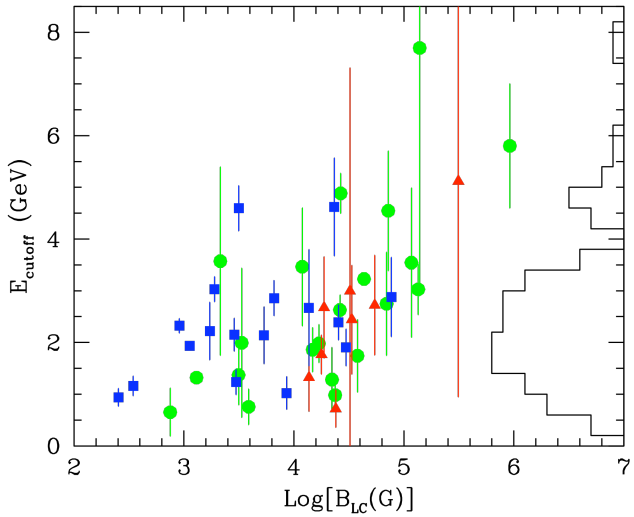
Polar Cap emission remains plausible for some pulsars.

Spectra are consistent with exponentially cutoff power-laws, with cutoff energies below 10 GeV.

*(See talks by Anatoly Spitkovsky, Kyle Watters & Christo Venter)*




*OG (green) and TPC (magenta) fits to J0030+0451's light curve (Venter, Harding & Guillemot, ApJ 2009, accepted)*




*Cutoff energy vs. $B_{LC}$ for the 46 catalog PSRs*

# What do we learn ?

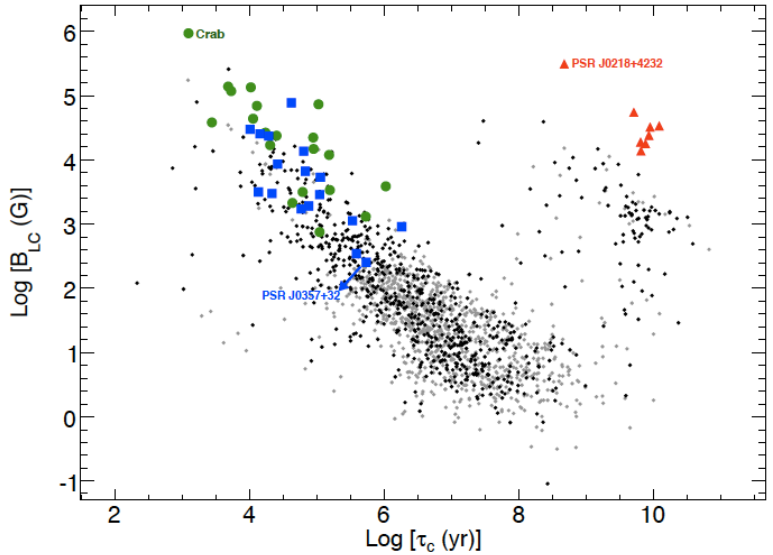
As for EGRET, the detected pulsars are relatively close and highly energetic.

The detected pulsars also have the highest values of magnetic field at the light cylinder, $B_{LC}$.

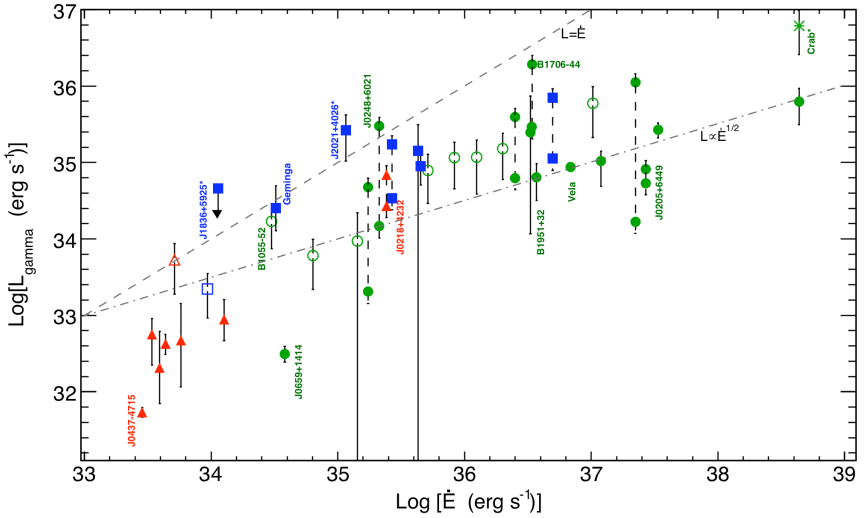
Both detected normal PSRs and MSPs have comparable $B_{LC}$ values. Similar emission mechanisms operating?

Luminosities are affected by distance uncertainties. However, the luminosity seems to grow with spin-down energy; with a $L \propto \dot{E}$ at low $\dot{E}$, $L \propto \sqrt{\dot{E}}$ at high $\dot{E}$.

*(See poster by Andrea Caliandro)*




*$B_{LC}$ vs. characteristic age for the catalog PSRs*




*Gamma-ray luminosity vs. spin-down energy for the catalog PSRs*

# Follow-up of Fermi sources

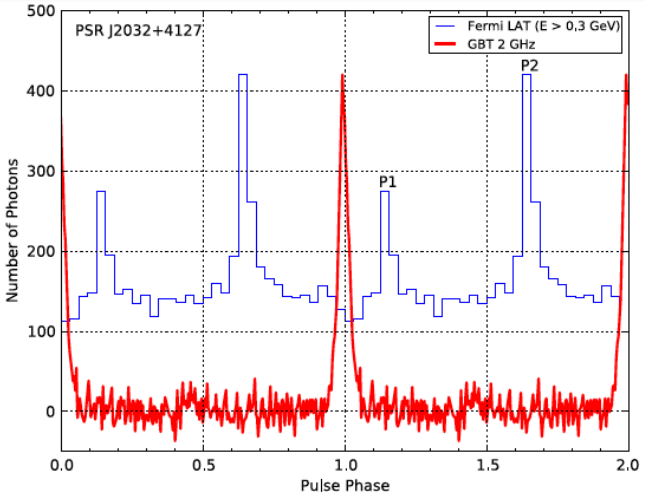
There is much to expect from the study of Fermi pulsars across the spectrum.

Fermi pulsar timing gives precise pulsar positions => sensitive pulse searches in (archival or new) radio or X-ray data! *(see talk by Paul Ray)*

PSRs J1741-2054, J1907+0602 & J2032+4127 are first radio detections among gamma-ray selected pulsars.

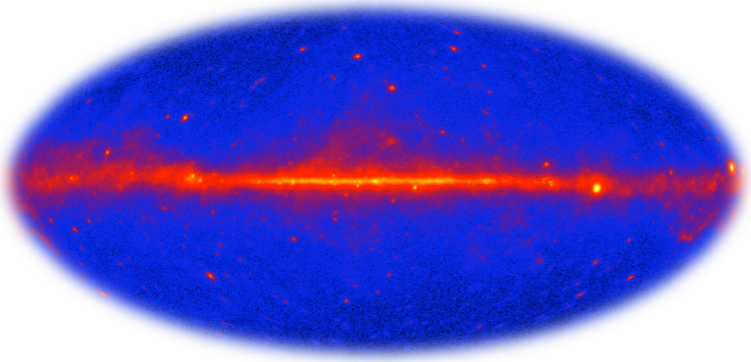
More generally, unknown pulsars must be powering many Fermi unidentified sources, like those seen in Abdo et al., ApJS 183, 46 (2009).

Counterpart searches are underway in telescopes around the world! *(see talks by Scott Ransom & Nobu Kawai)*




*No longer just gamma-ray pulsars!*

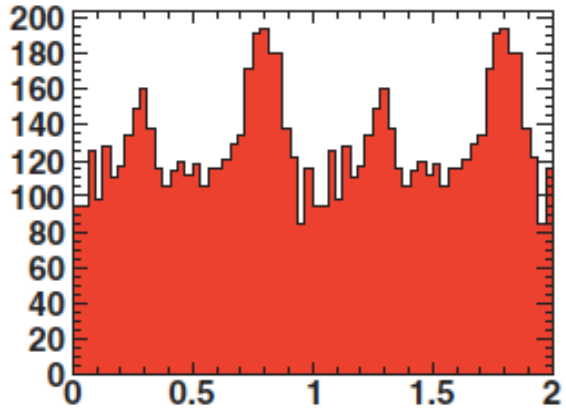
*(Camilo et al., ApJ 705, 1, 2009)*



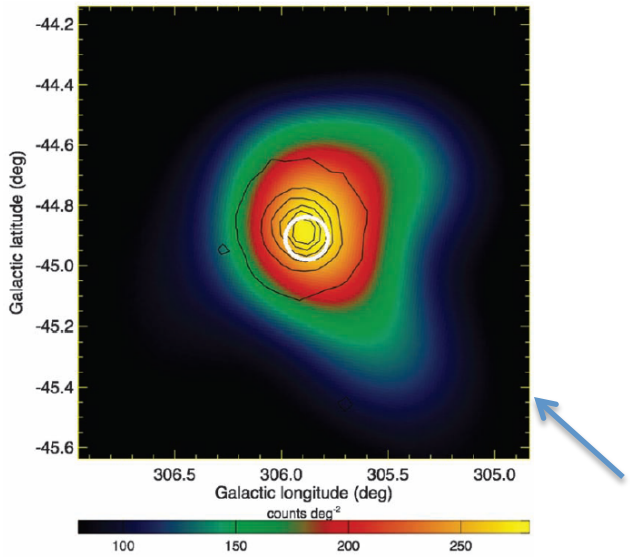
*One year sky map (see talk by Jean Ballet).*

*> 1000 sources!*

# Pulsars everywhere?




*J2021+4026, inside the gamma Cygni Supernova Remnant (Abdo et al., Science 325 840, 2009)*




*47 Tucanae as seen with the Fermi LAT (Abdo et al., Science 325, 845, 2009)*

Pulsars are ubiquitous in the gamma-ray landscape.

The blind searches of gamma-ray pulsars have shown that some are powering TeV nebulae.

The LAT detects the 47 Tucanae globular cluster in gamma rays. Added contribution of internal MSPs? Realistic number predicted (~ 60 objects)!

Contribution of pulsars to the Galactic diffuse emission?

*(See talks and posters by Michael Dormody, Aous Abdo, Adam Van Etten)*

# Search for off-pulse emission

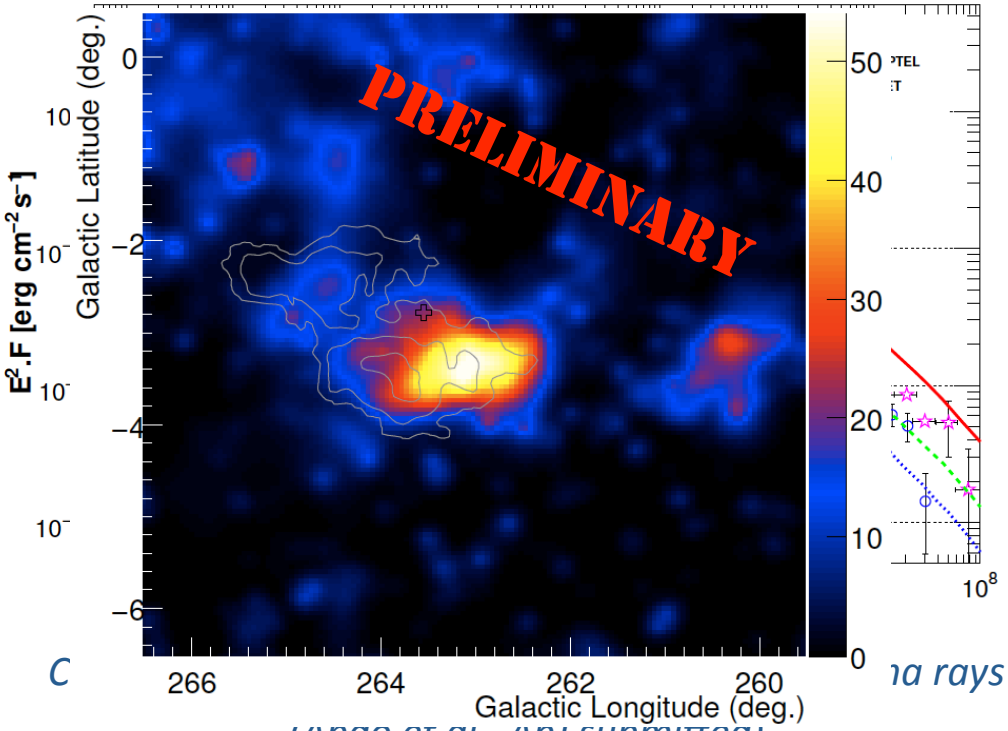
Only one pulsar wind nebula (PWN) has been detected by EGRET (Crab nebula)!

The LAT provided a nice connection of spectral data with results of Earth-based Cerenkov telescopes.

Significant gamma-ray emission is now seen from other PWNe (cf. MSH 15-52 and Vela X)!

Systematic searches in the off-pulse of Fermi-detected pulsars are ongoing.

*(see talks and posters by Marie-Hélène Grondin, Marianne Lemoine-Goumard, Stefan Funk)*




*C* *ıa rays*

*(Abdo et al., ApJ submitted)*

*The Vela X nebula, around the Vela pulsar indicated by a cross*

# Conclusion

*Scott Ransom, 1st GLAST symposium: « The new time-differencing technique […] is promising »*

Indeed! 24 pulsars detected in blind search so far; many others coming.

*Simon Johnston, 1st GLAST symposium: « Without constant monitoring phase cannot be accurately predicted!! ». Steve Thorsett, on the pulsar timing campaign: « We've got to do it right! »*

The timing campaign has been a success; we got ephemerides for more than 700 pulsars. Pulsations seen for 30 of them, including 9 MSPs! => Fermi has detected 55 pulsars so far.

From light curve shapes and spectral properties it is pretty clear that the emission comes from the outer magnetosphere.

Their off-pulse emission is being searched for nebulae. New gamma-ray nebulae have been observed.

# What's next?

Continue follow-up observations at other wavelengths.

Improvement of the analysis methods – increase sensitivity at low energies or using spectral informations *(See posters by Michael Burgess & Matthew Kerr)*

Use Fermi data to improve / constrain / reject theoretical models.

What's the contribution of gamma-ray pulsars to diffuse emission?

While we're talking, data are accumulating. *Stay tuned for other detections!*

**Thanks!**