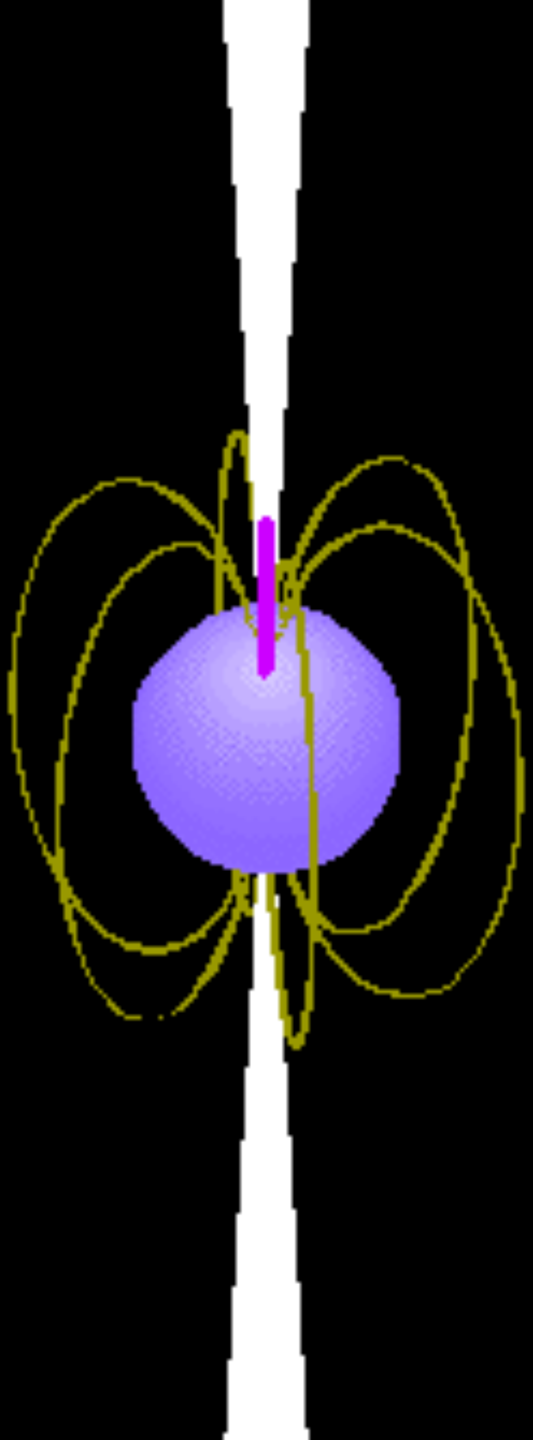
Pulsar astronomy in γ-rays: a revolution

Patrizia Caraveo



REVIEWS IN ADVANCE

Gamma-Ray Pulsar Revolution

Patrizia A. Caraveo

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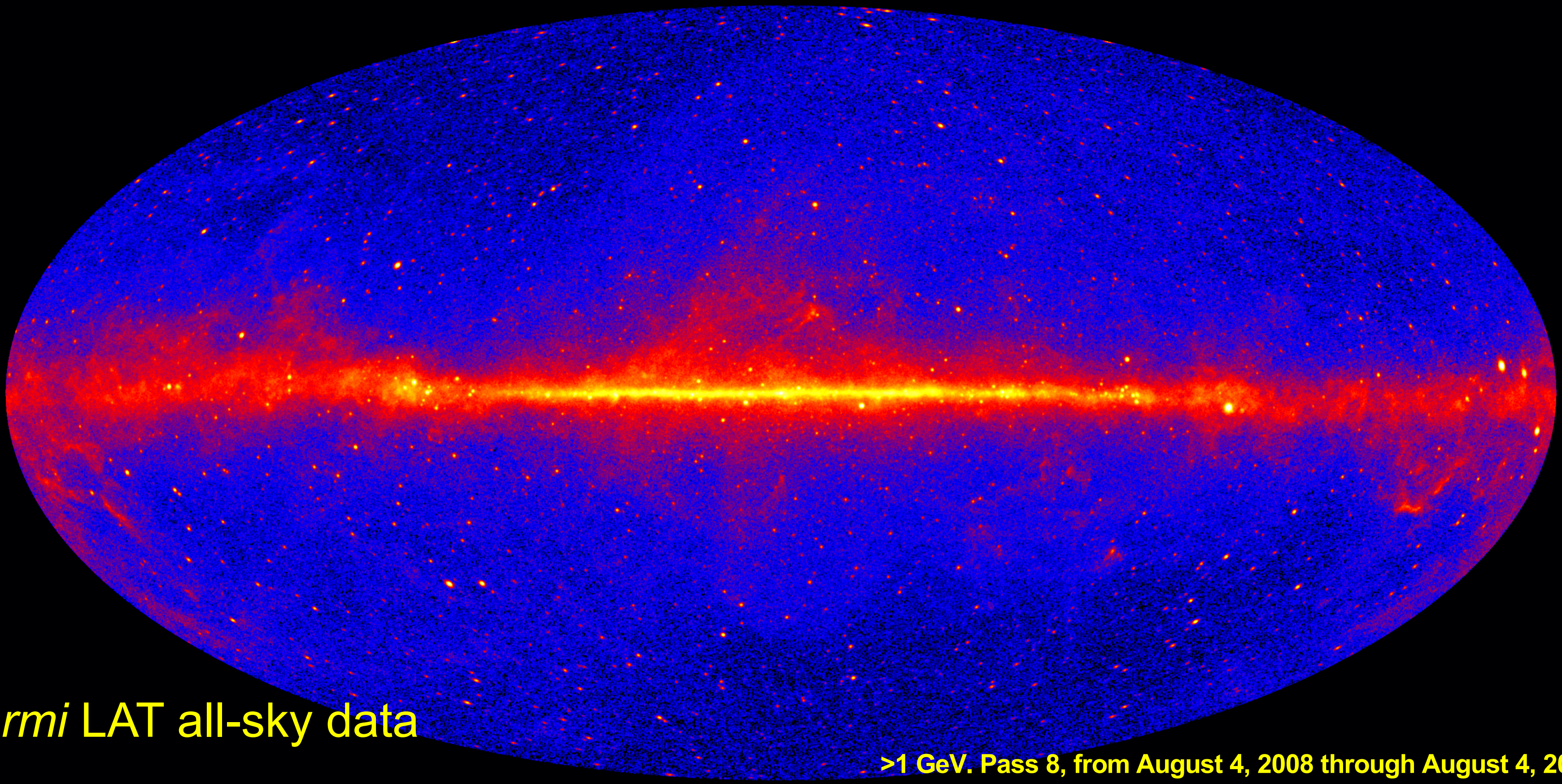
Updated thanks to many colleagues and friends **(David Smith)**

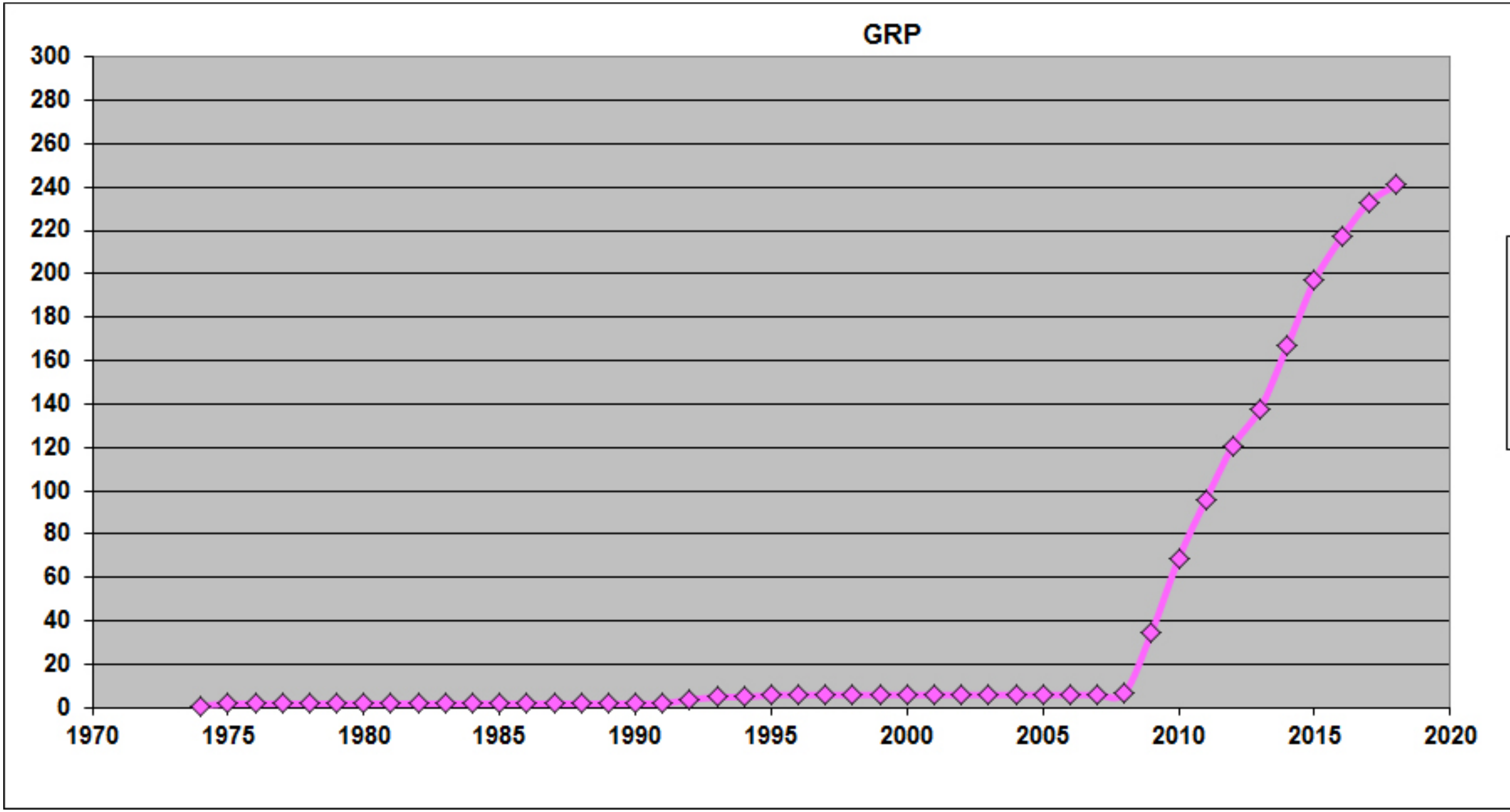


Fermi LAT all-sky data

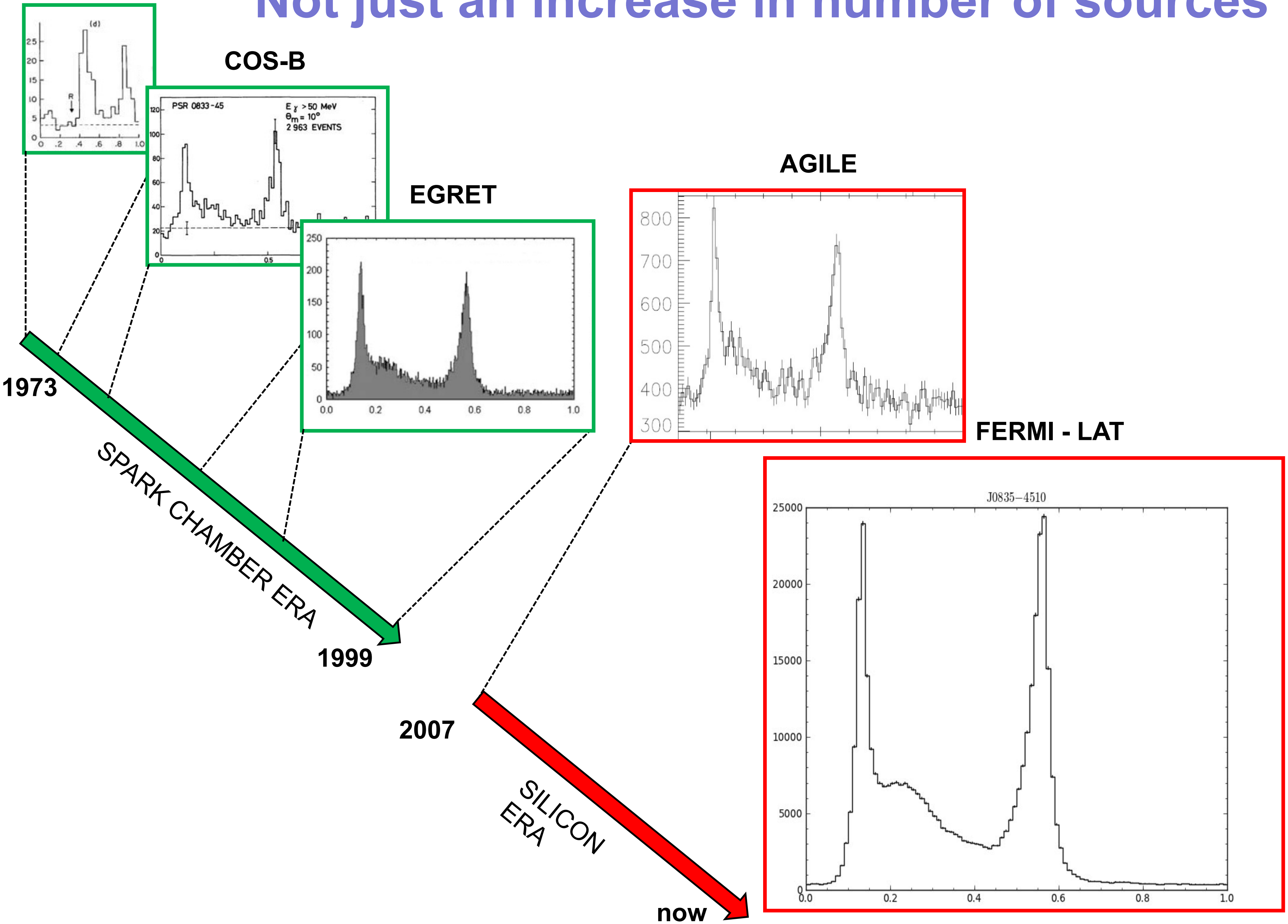
>1 GeV. Pass 8, from August 4, 2008 through August 4, 2017.
LAT rocking angle <52° and zenith angle <100°. 6.25 Mphotons.

Point sources in the plane are mostly pulsars.
Off the plane, mostly blazars (and some MSP)

γ-ray PULSAR CENSUS



Not just an increase in number of sources



SAS-2

COS-B

EGRET

AGILE

FERMI - LAT

1973

SPARK CHAMBER ERA

1999

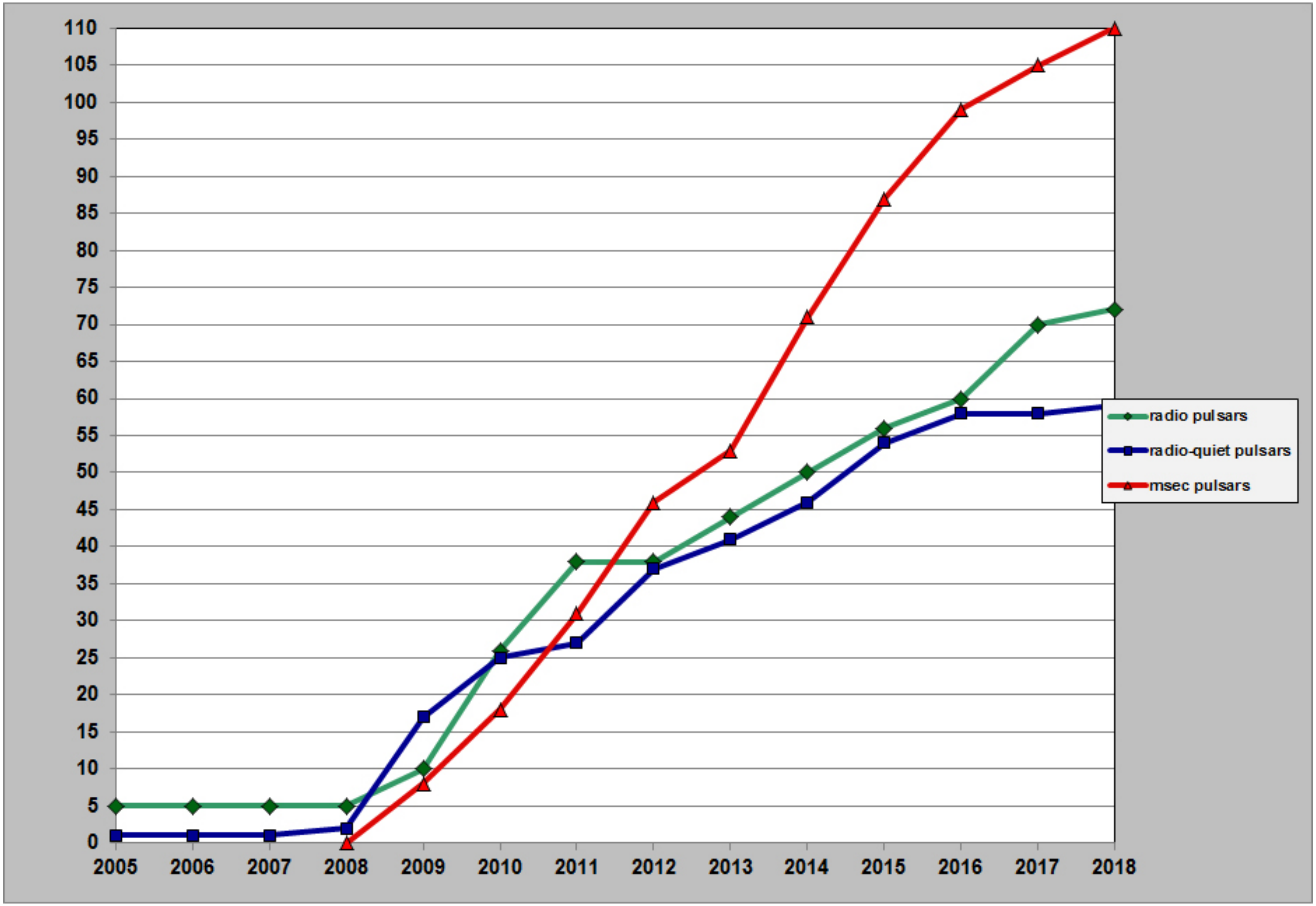
2007

SILICON ERA

now

Not just an increase in number

Diverse Family



3 ways to discover gamma-ray pulsars

1. Phase-fold gammas using ***known*** rotation parameters.

*Weight using spectrum⊗point-spread-function** ➔ *O(1) trials, highest sensitivity.*

~1000 ephemerides provided by radio astronomers (x-rays too) Smith et al, A&A (2008)

2. Deep radio searches at positions of pulsar-like **unid. gamma sources**..

e.g. Cromartie et al ApJ (2016)

- Rotation ephemeris ➔ phase-fold as above. 59+5 gamma MSPs so far.

LOFAR found fastest (707 Hz) field MSP in a *Fermi* source Bassa et al, ApJ Lett (2017)

Looking forward to Meerkat and SKA

3. **Blind period search** in gamma-rays at **those same positions**.

59 young PSRs e.g. Clark et al ApJ (2017), 5 MSPs.

~4 radio detections.

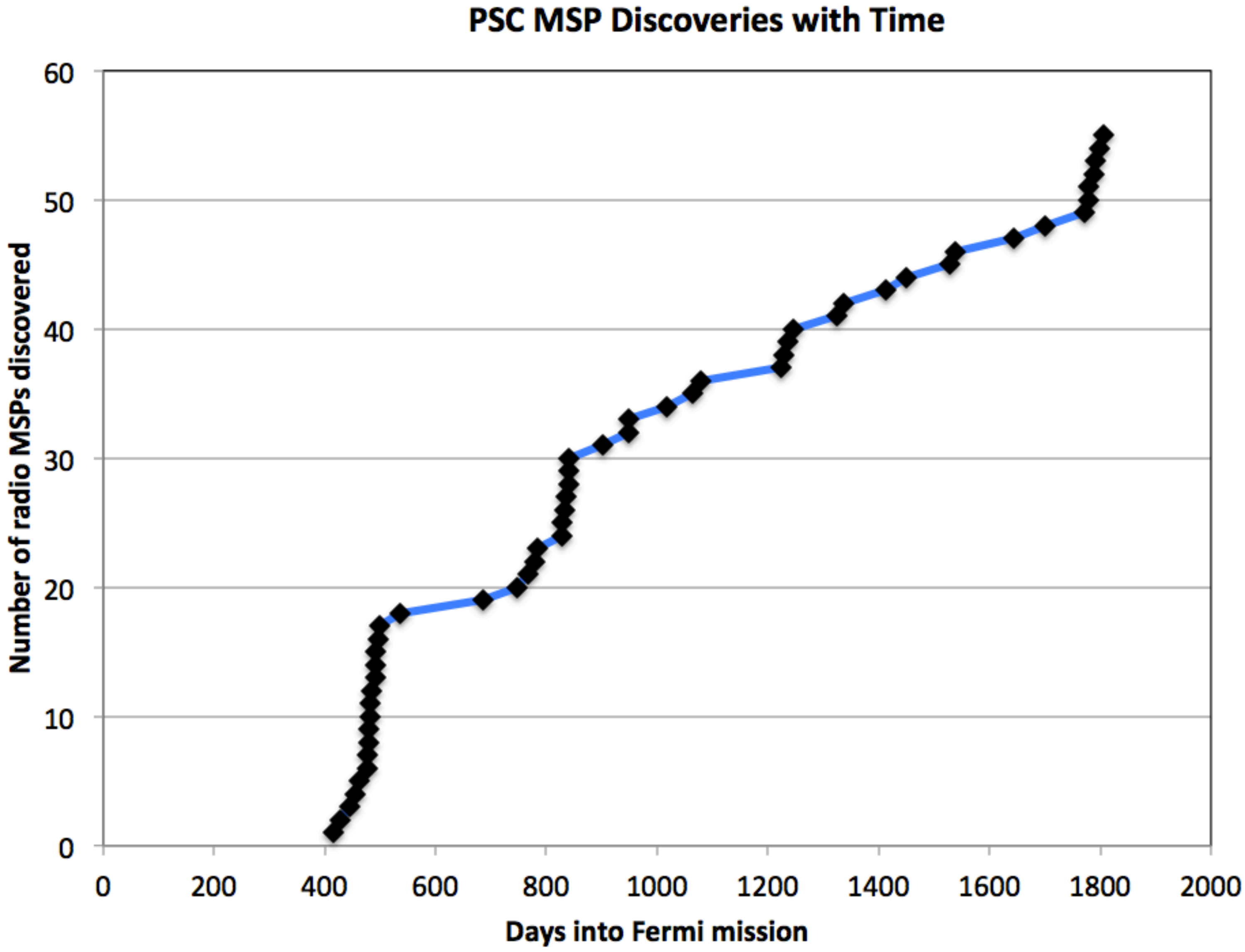
Einstein@Home searches very successful.

1st radio quiet MSP discovered! **Clark et al,**

Courtesy of David Smith

*M. Kerr, ApJ (2011)

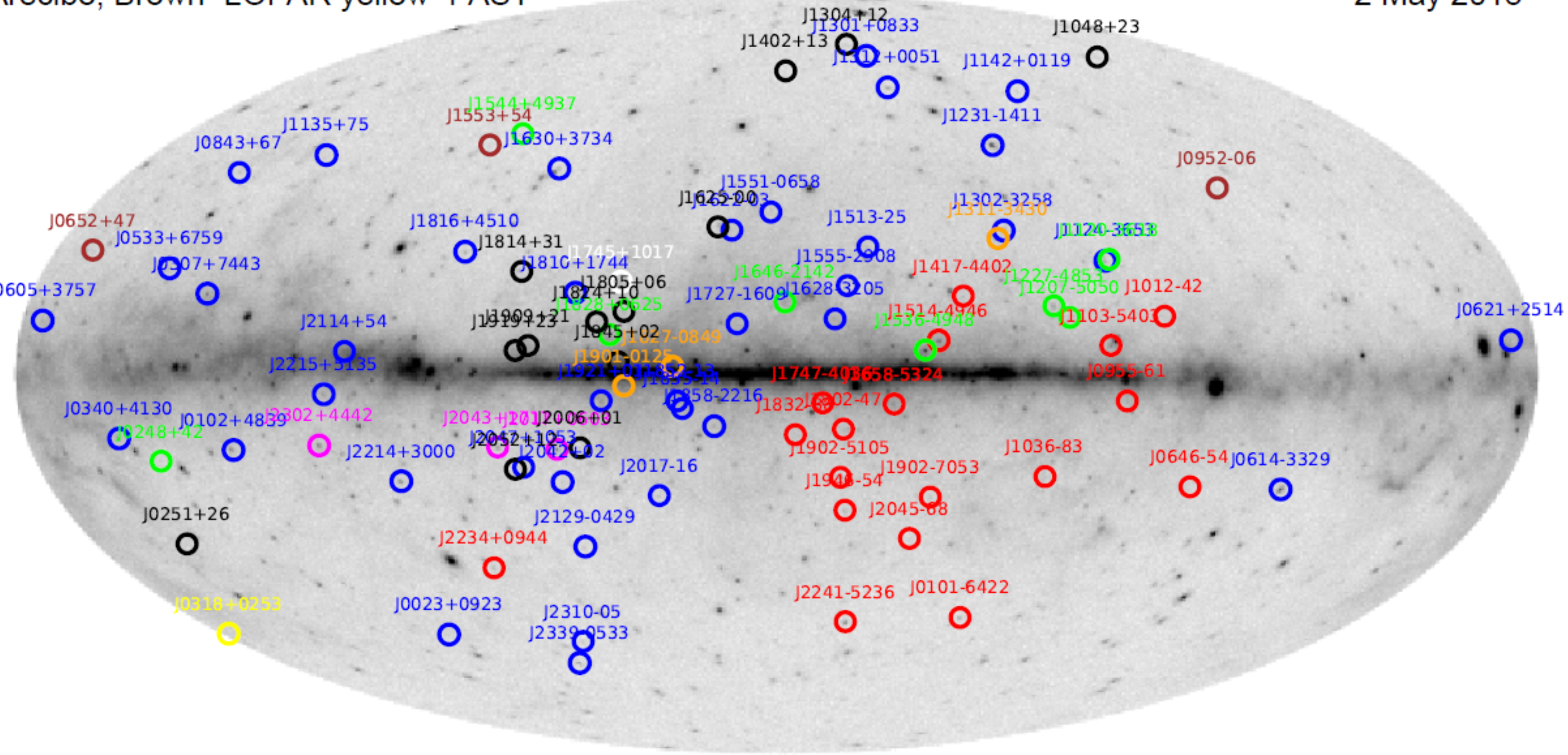
MSPs discovered in Fermi sources



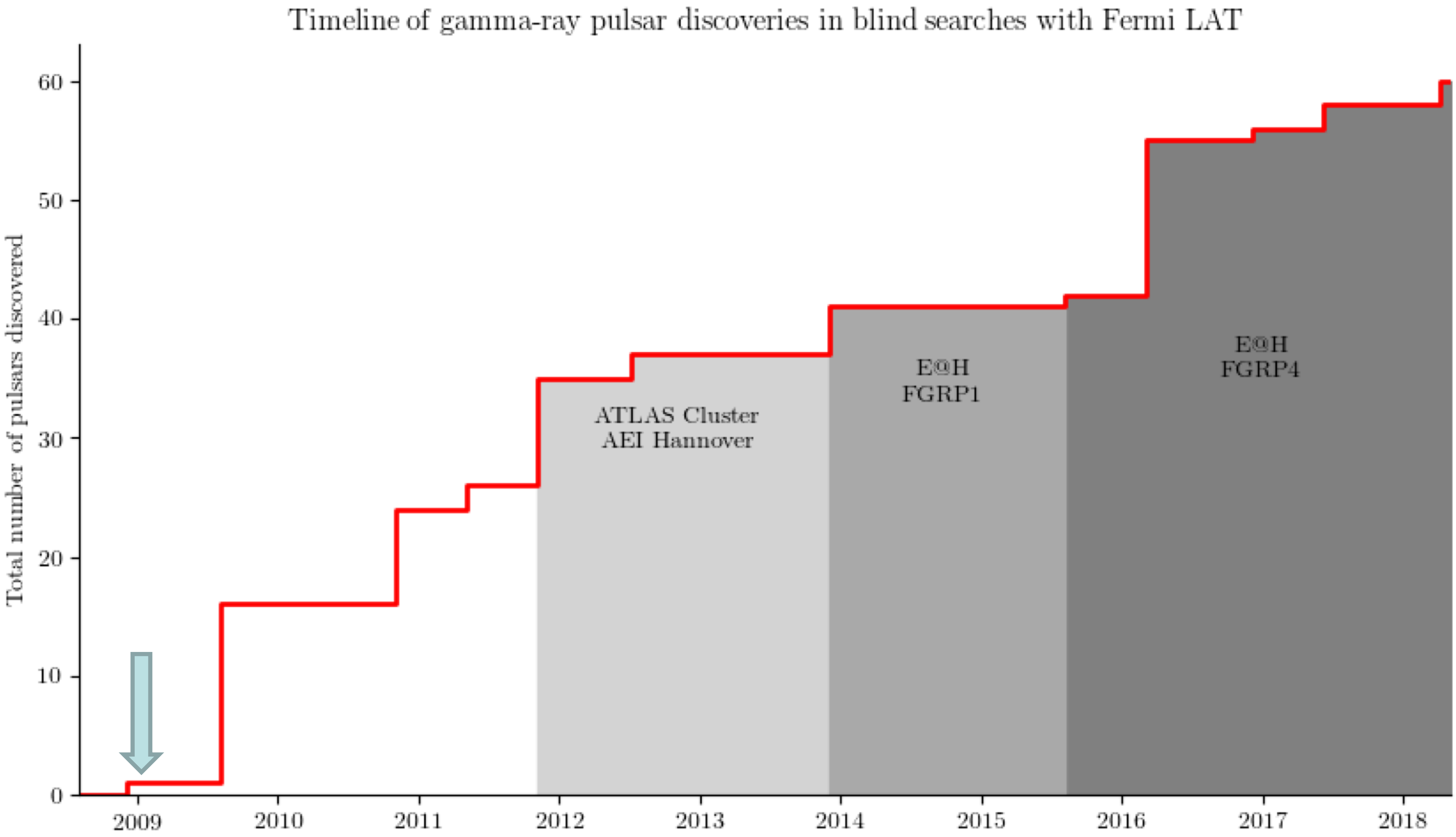
MSP gold mine

Blue=GBT, Red=Parkes, Green=GMRT White=Eff Magenta=Nancay Orange=LAT
Black=Arecibo, Brown=LOFAR yellow=FAST

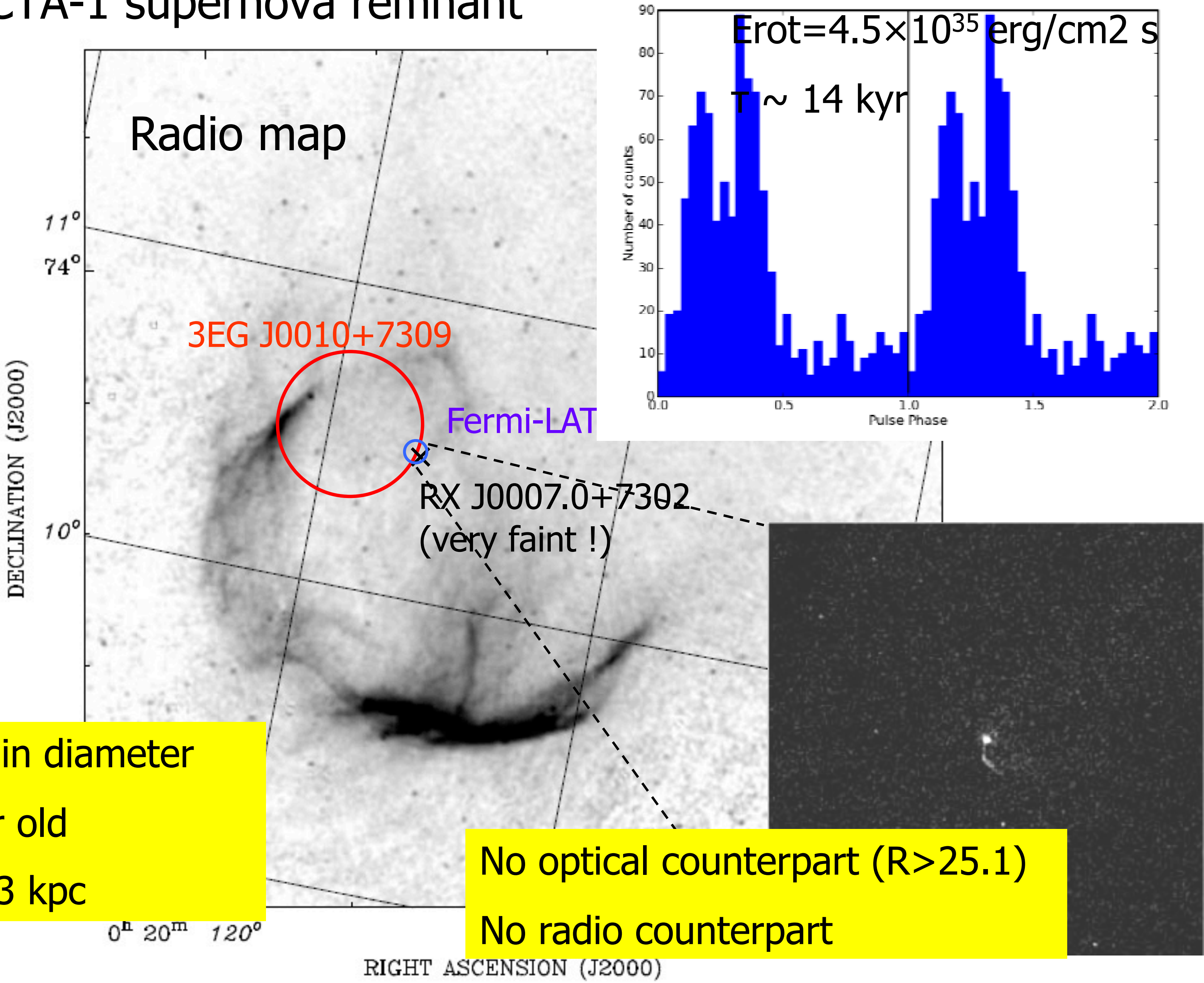
88 PSC MSPs
2 May 2018



The hunt for radio quiet pulsars



The CTA-1 supernova remnant



$E_{rot} = 4.5 \times 10^{35}$ erg/cm2 s

$\tau \sim 14$ kyr

RX J0007.0+7302
(very faint !)

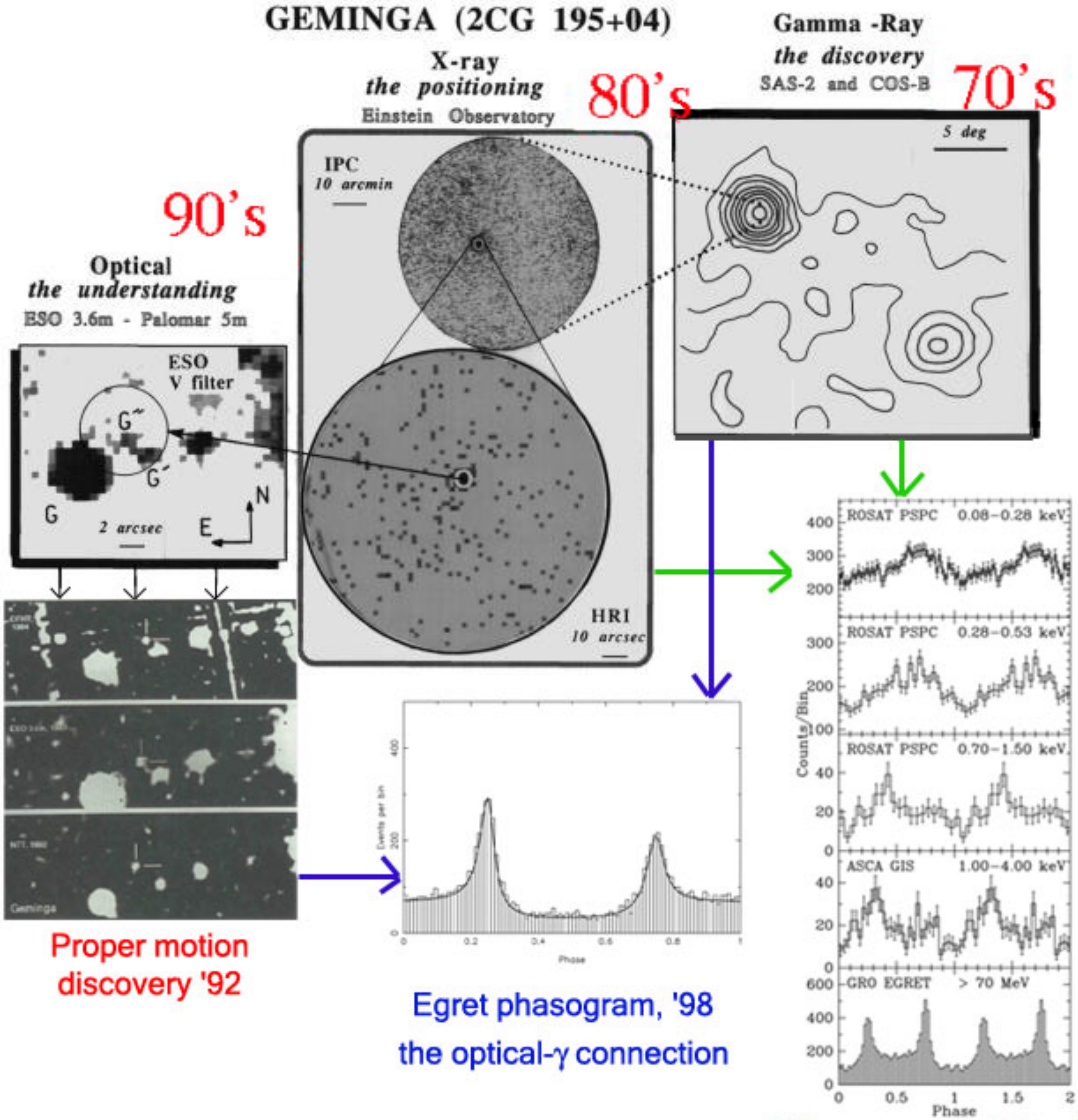
90 arcmin diameter

5-15 kyr old

1.4 ± 0.3 kpc

No optical counterpart (R>25.1)

No radio counterpart



Proper motion discovery '92

Egret phasogram, '98
the optical-γ connection

237 msec periodicity, '92
the x-γ connection

It took 20+ years to understand Geminga.

GEMINGA GEMINi GAmma

Gh’è minga

Nanni Bignami

Nanni's commentary in Science on the first post-launch discovery paper: the pulsar in CTA1

Only Galileo was quicker. After discovering the satellites of Jupiter on 10 January 1610 in Padua, he wrote up his results in elegant Latin, personally did the artwork, allowed time for refereeing (by the Inquisition) and for printing (by hand), and had the Sidereus Nuncius hit the streets, or the canals, of Venice on 10 March. The NASA-led, international GLAST mission, now called the Fermi Observatory, was launched on 11 June 2008, deployed flawlessly into orbit, started taking in gamma rays from the sky and routing them through an impressive data-crunching machine, allowed time for a minimum of thinking, and just 4 months later, its first important result was reported online [Abdo *et al.*, see p. 1218 of this issue (*1*)]. Even Galileo would have been impressed, and so should we: Here is a new way of doing science, right on the eve of the International Year of Astronomy.

ASTRONOMY

Gamma Rays and Neutron Stars

Satellite and ground observations provide new insights into gamma-ray emissions from neutron stars.

Giovanni F. Bignami

Only Galileo was quicker. After discovering the satellites of Jupiter on 10 January 1610 in Padua, he wrote up his results in elegant Latin, personally did the artwork, allowed time for refereeing (by the Inquisition) and for printing (by hand), and had the Sidereus Nuncius hit the streets, or the canals, of Venice on 10 March. The NASA-led, international GLAST mission, now called the Fermi Observatory, was launched on 11 June 2008, deployed flawlessly into orbit, started taking in gamma rays from the sky and routing them through an impressive data-crunching machine, allowed time for a minimum of thinking, and just 4 months later, its first important result was reported online [Abdo *et al.*, see p. 1218 of this issue (*1*)]. Even Galileo would have been impressed, and so should we: Here is a new way of doing science, right on the eve of the International Year of Astronomy.

As Abdo *et al.* report, the Fermi Observatory has—for the first time in gamma-ray astronomy—discovered a rotating neutron star purely through its gamma-ray emission: Fewer than 1000 photons, collected over 2 months, are shown to have a convincing periodicity of about a third of a second. The star is not seen to emit at all at radio and optical wavelengths, and the weak x-ray emissions from the star are not pulsed. In short, Fermi has found a pure gamma-ray star, a "gamstar," or, if you will, the second Geminga (*2*). Only, it took 20 years (from 1973 to 1993) to understand the unidentified gamma-ray source that we had called Geminga, and which until today, was the only known rotating gamma-ray neutron star invisible in radio.

The new gamstar, as yet unnamed, is close to the center of CTA1, a diffuse remnant of a supernova that exploded about 10,000 years ago (see the figure). The gamstar's age, estimated by the slowing of its rotation, is consistent with its being the hard-core remnant of that explosion. A nice, coherent association—if a little déjà vu: It brings to mind the Vela pulsar and the diffuse emission surrounding it, remnants of a supernova explosion that took place around the time of the CTA1 supernova. However, the Vela pulsar is much closer to us and could be observed at the dawn of gamma-ray astronomy in 1975 (*3*), using radio data to clock the sparse gamma-ray photons. In fact, scientists continued to find gamma-ray pulsars using radio data, with the remarkable, if laborious, exception of Geminga. Fermi's little brother, the Italian gamma-ray mission AGILE, has just found another Vela-like gamma-and-radio pulsar (*4*), the sixth of its kind.

Herein lies the importance of the Fermi gamstar discovery: From now on, given half-decent photon statistics, no radio data will be required for finding pulsating gamma-ray sources. Known gamstars, now numbering two, are not only here to stay but are likely to quickly increase in number.

A third one may already be coming up: a previously discovered gamma-ray source officially called 3EG J1835+5918, which Jules Halpern (co-discoverer of Geminga) has called the "next Geminga." This gamma-ray source lacks a radio counterpart, but otherwise has all the markings of a neutron star. AGILE has now found interesting time variability for the source (*5*). CTA1 ended up being the real "next Geminga," but this one may be next in line.

Many more Geminga-like gamstars may soon be discovered by Fermi (and AGILE) by looking at the position of unidentified gamma-ray objects (UGOs), which represent the majority of known gamma-ray sources in our Galaxy. Interpreting UGOs as gamstars would provide a natural explanation for the quarter-of-a-century UGO mystery: Gamstars are simply pulsars that emit gamma rays in a fan beam geometrically different from the radio one, which may well exist but does not intercept the Earth. Gamstars would then be neutron stars with a somewhat different physics (and geometry) from that of the gamma-and-radio pulsars (like Vela and the Crab), for which both beams sweep the Earth.

But neutron stars and gamma rays seem to have even more in common. On page 1221 of this issue, The MAGIC Collaboration (*6*) shows that the Crab pulsar—our prototype of the well-behaved neutron star, known to judiciously emit pulsed radiation from radio photons to gigaelectron volt (GeV) gamma rays—reaches its peak emission energy at 25 GeV and quickly fades afterwards. This is a brilliant result of the MAGIC Collaboration, who lowered the energy threshold of their ground-based telescope to around 25 GeV and for the first time detected pulsed gamma rays from the Crab at that energy.

Detecting 25 GeV gamma rays from the ground requires careful discrimination between signal and noise. By doing so, the authors bridged the decade-long gap between ground- and space-based gamma-ray astronomies, because the upper energy limit of Fermi photons will be close to 20 GeV. Since the 1970s, gamma-ray energies detected from the Crab have increased from tens of MeV (*7*) to several GeV (*8*, *9*), and now 25 GeV from MAGIC—an increase by an energy decade per calendar decade.

The MAGIC data show that even young neutron stars, like the Crab, less than 1000 years old, have their limitations in producing higher and higher energy photons. Above 25 GeV, MAGIC sees a sharp cut-off in the Crab spectrum. This has immediate implications for neutron star physics, because it discrimi-

A new gamstar. The CTA1 supernova remnant has a well-formed radio shell, with a diameter of about 1.5°. Close to its center, the Fermi gamstar (blue dot) discovered by Abdo *et al.* (*1*) emits trains of pulsed gamma radiation.

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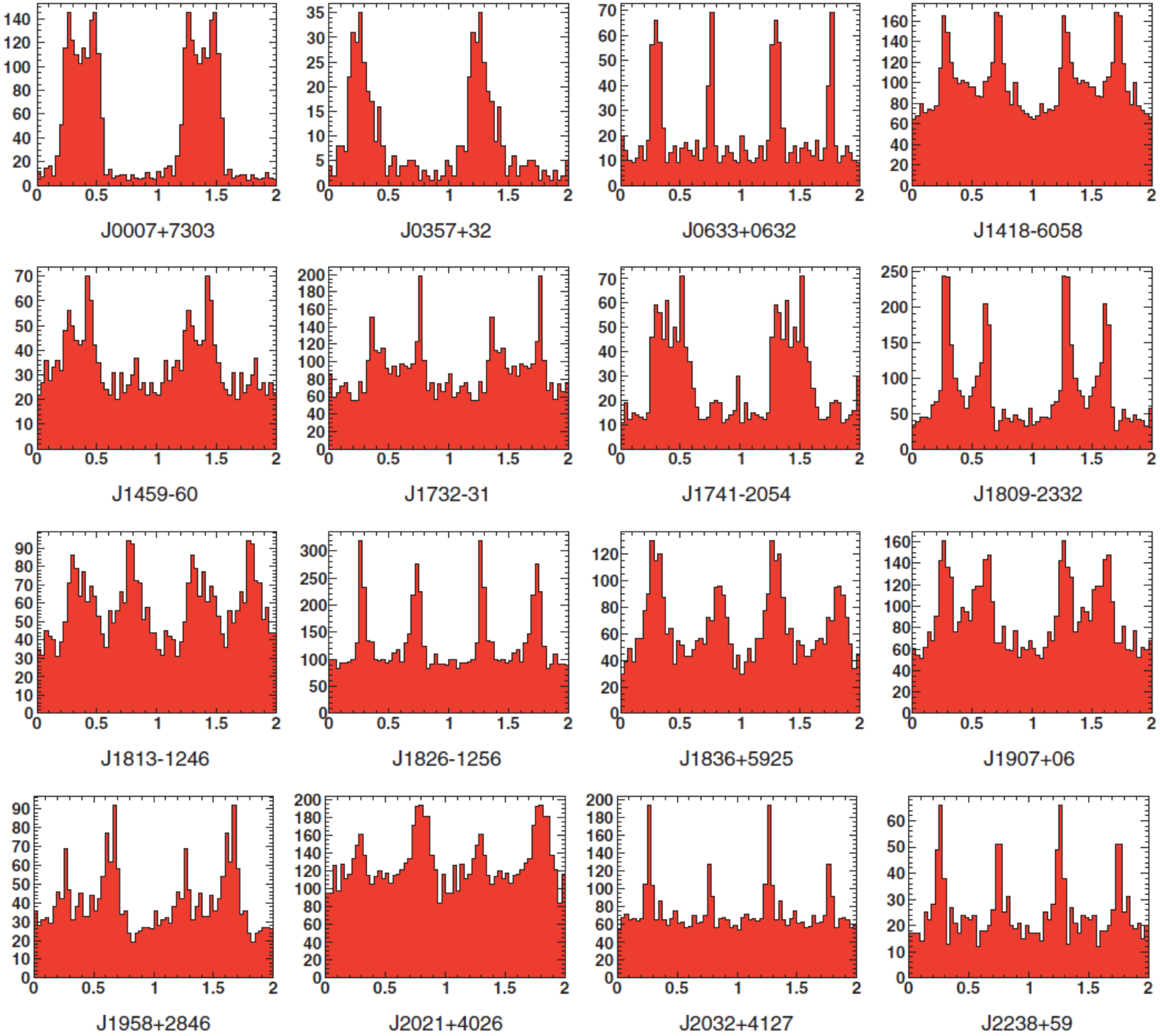
Geminga-like pulsars

Abdo et al 2009 Science

- **The first one in the CTA1 SNR**
- **4 later found also in radio**



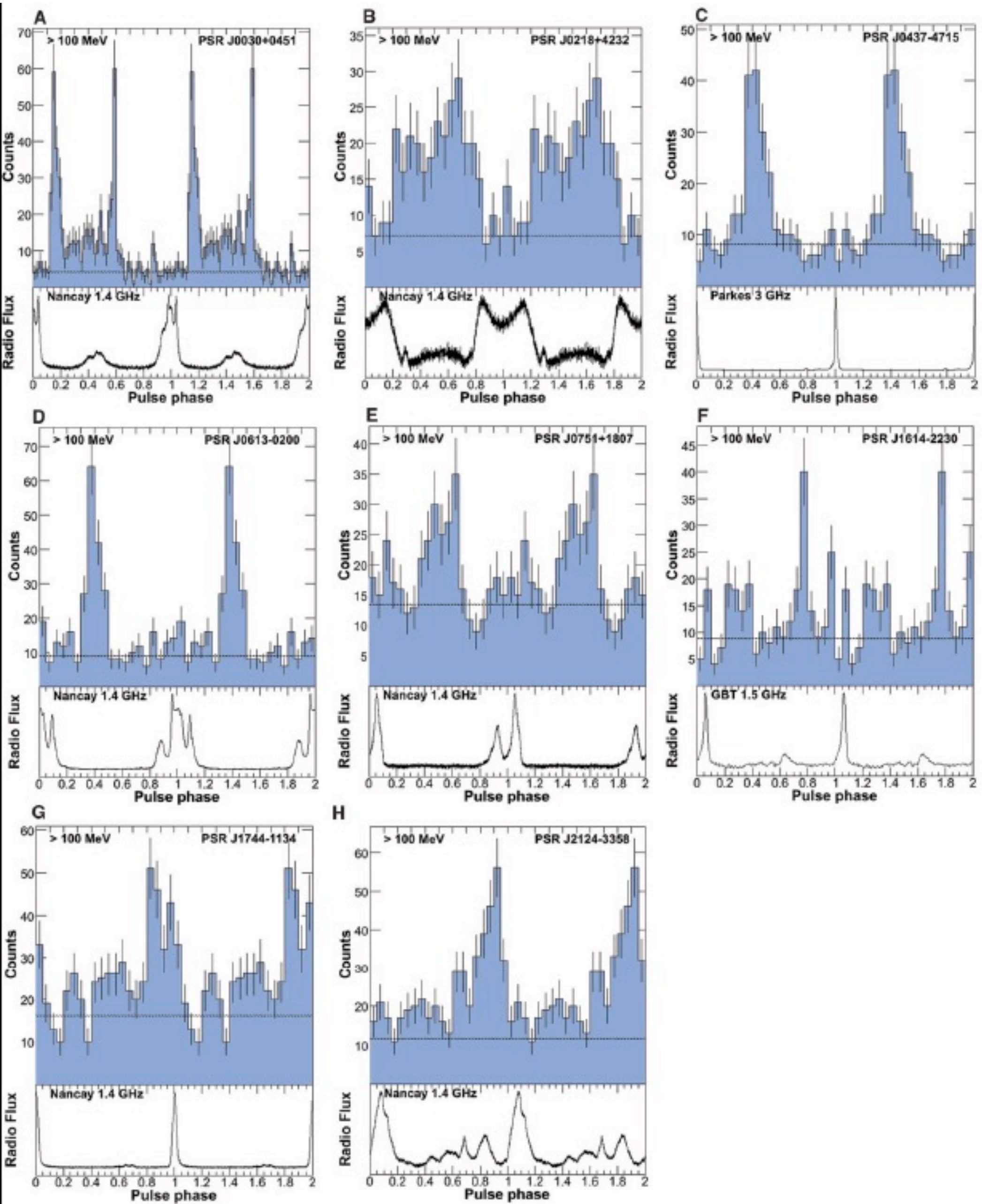
J0007+7303 J0357+32 J0633+0632 J1418-6058

J1459-60 J1732-31 J1741-2054 J1809-2332

J1813-1246 J1826-1256 J1836+5925 J1907+06

J1958+2846 J2021+4026 J2032+4127 J2238+59

Gamma-ray millisecond pulsars !



8 Millisecond pulsars

Abdo et al 2009 Science 325 848

- **5 are in binary orbits**
- **Similar lightcurves and spectra as in the young pulsars**
- **These MSP suggest the same emission mechanism as the young pulsars**

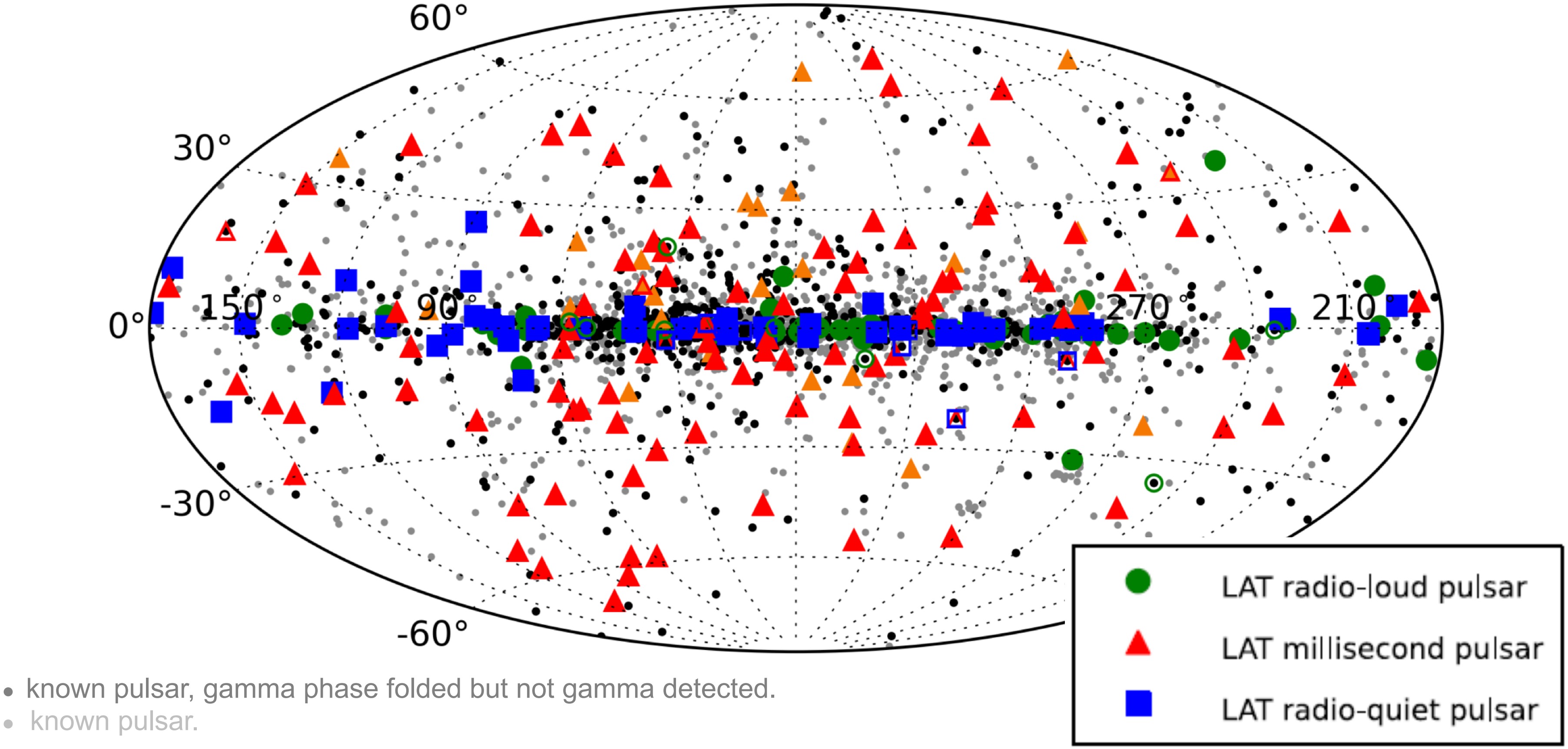
«2nd most relevant discovery in 2009» ***(Science)***

Bruno Rossi Prize 2014

Now over 240 *Fermi* LAT pulsars.

Update of Fig 2 from **2PC** = *2nd Pulsar Catalog*: ApJ Suppl. 208 17 (2013)

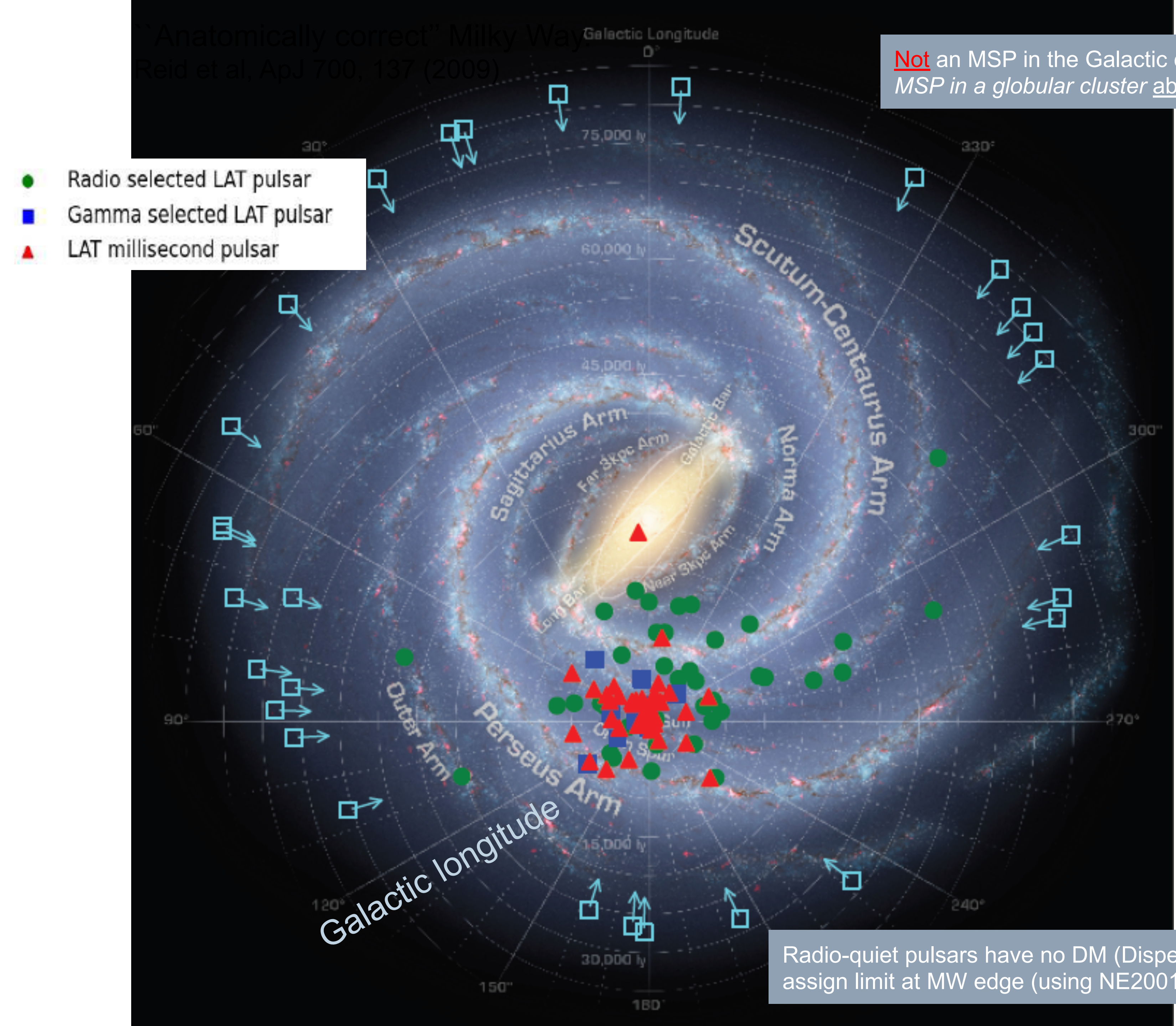
3PC in preparation for late 2018.



- known pulsar, gamma phase folded but not gamma detected.
- known pulsar.

Courtesy of David Smith

``Anatomically correct'' Milky Way: Reid et al, ApJ 700, 137 (2009)

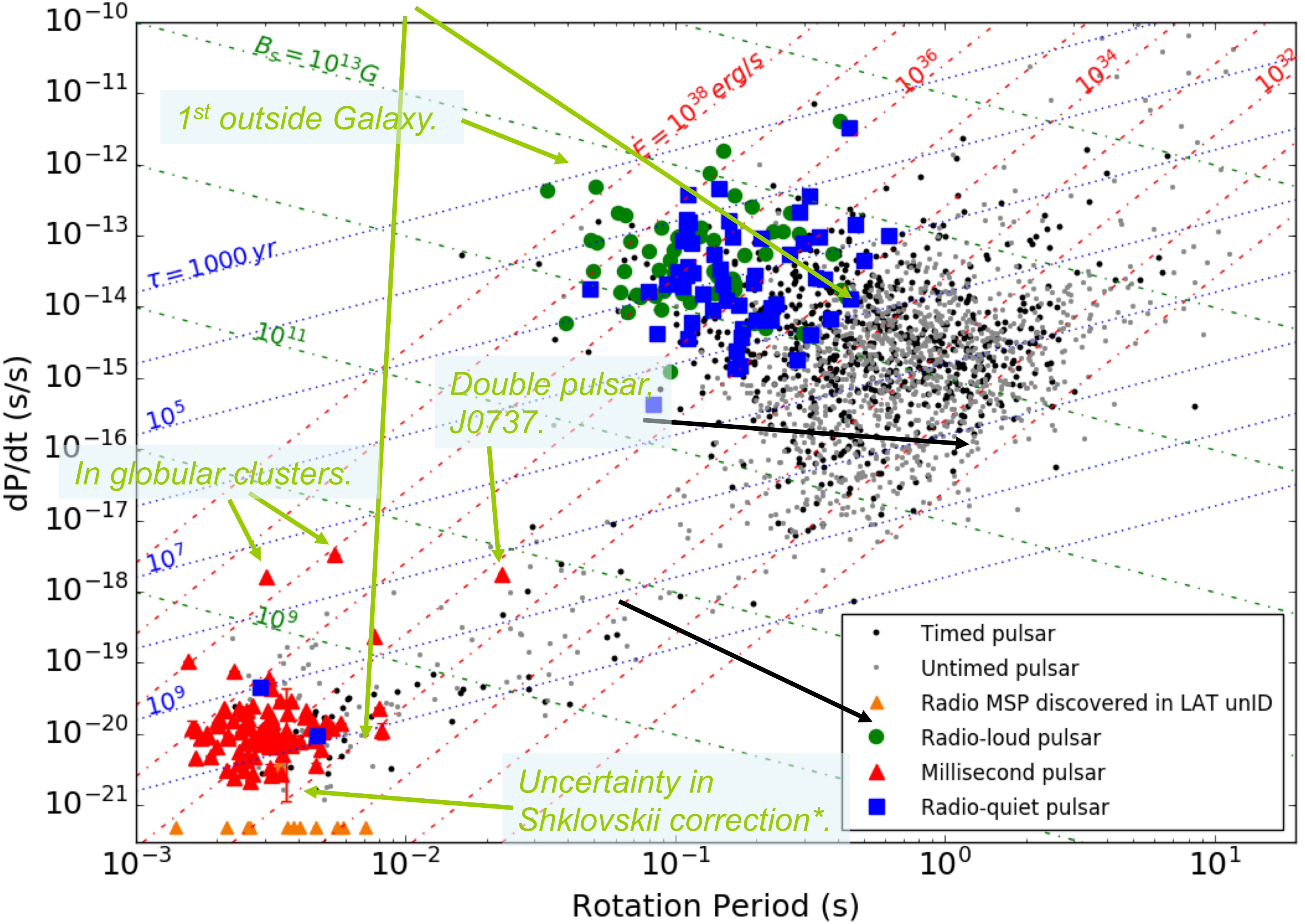


Not an MSP in the Galactic center.
MSP in a globular cluster above the center.

Radio-quiet pulsars have no DM (Dispersion Measure): assign limit at MW edge (using NE2001).

Gamma-ray deathline near spin-down power
$\dot{E} = 4I\pi^2 \dot{P}/P^3$ of ~3E33 erg/s. ($I \equiv$ 1E45 gm cm^2 depends on EoS.)

Update of 2PC Fig 1.



1st outside Galaxy.

Double pulsar, J0737.

In globular clusters.

Uncertainty in Shklovskii correction.*

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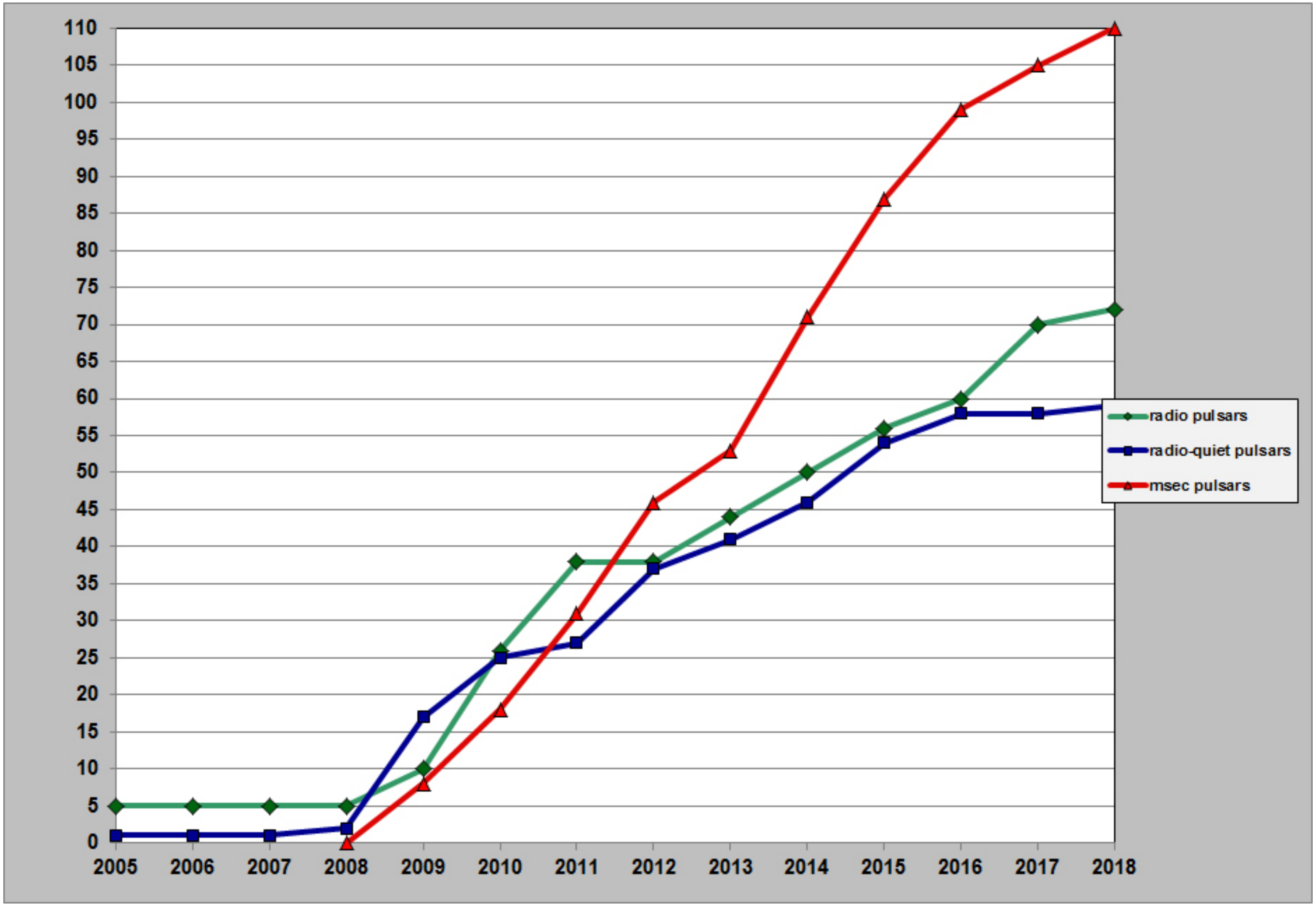
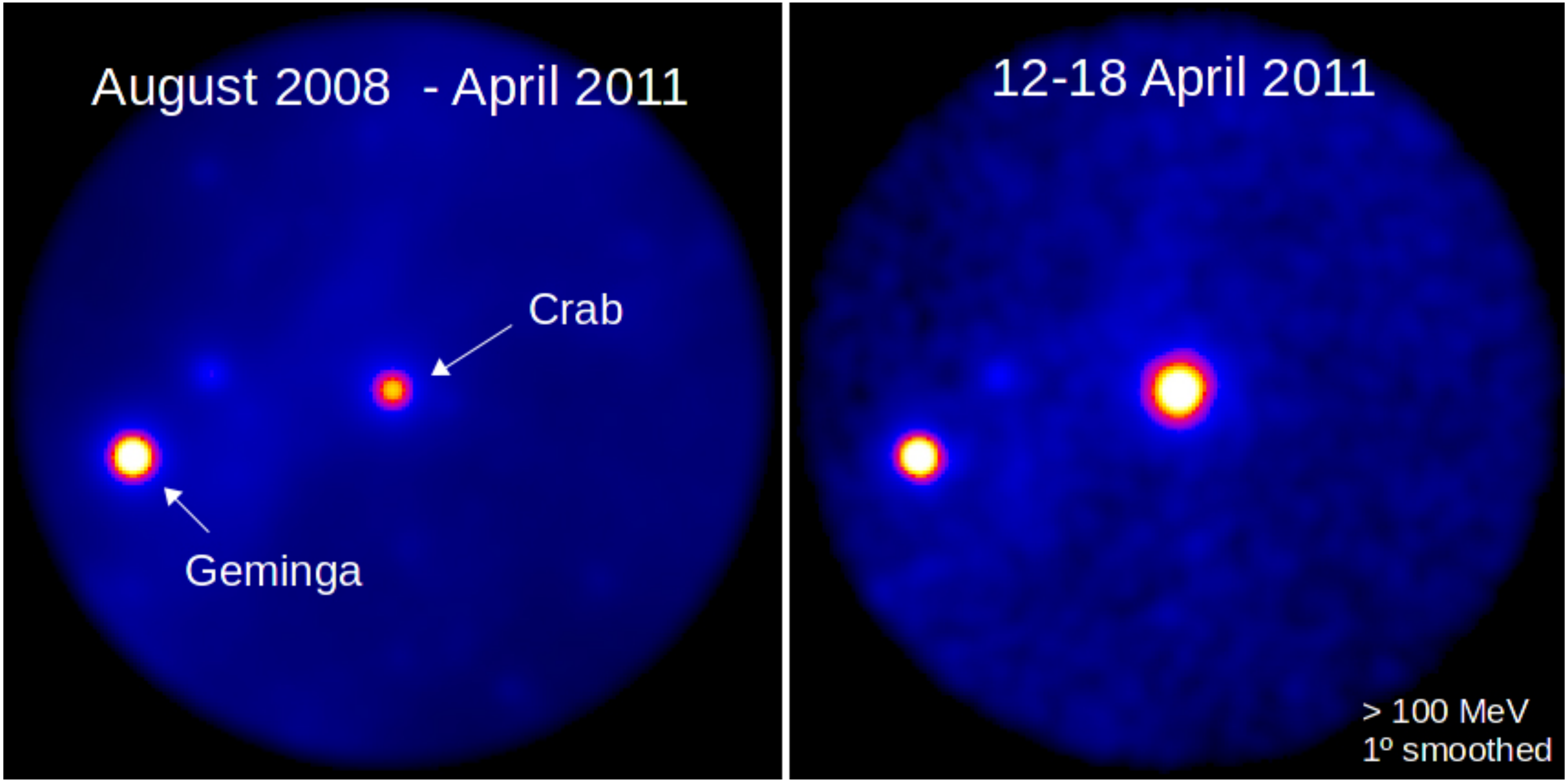
*See e.g. *γ MSP Deathline, revisited*, Guillemot et al. A&A (2016)



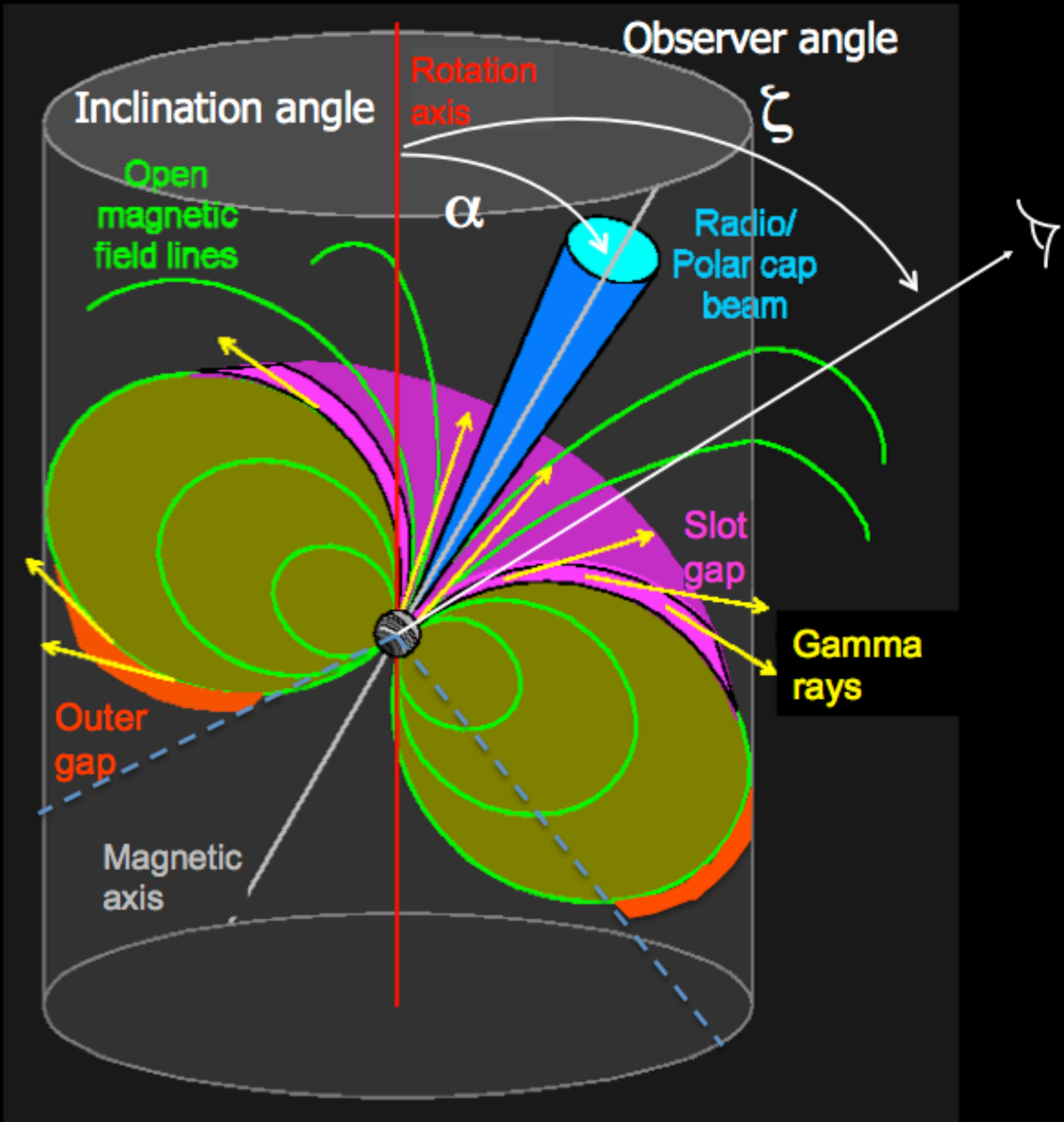
Also a radio pulsar can surprise you

The Crab that roared



Variable Nebular emission!

Gamma-ray emission sites



Key Observables: Energy spectrum

The energy spectrum can be described by a power law with an (hyper) exponential cutoff :

Spectral Index

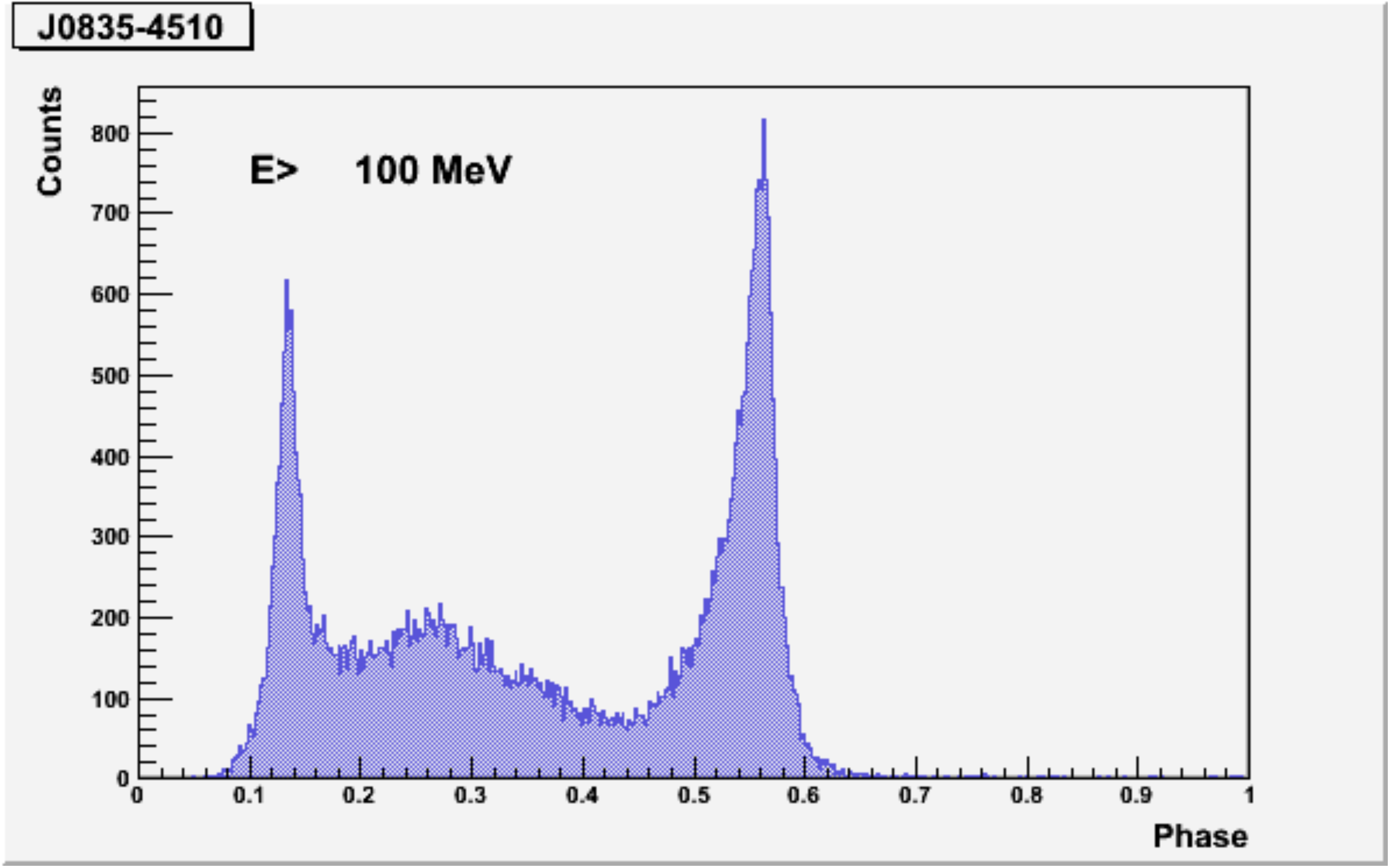
$$\frac{dN}{dE} = N_0 \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-\Gamma} \exp\left(-\frac{E}{E_c}\right)^{\beta}$$

Cutoff Energy

β : cutoff index

~ 1 : Slot Gap and Outer Gap models (high altitude emission)

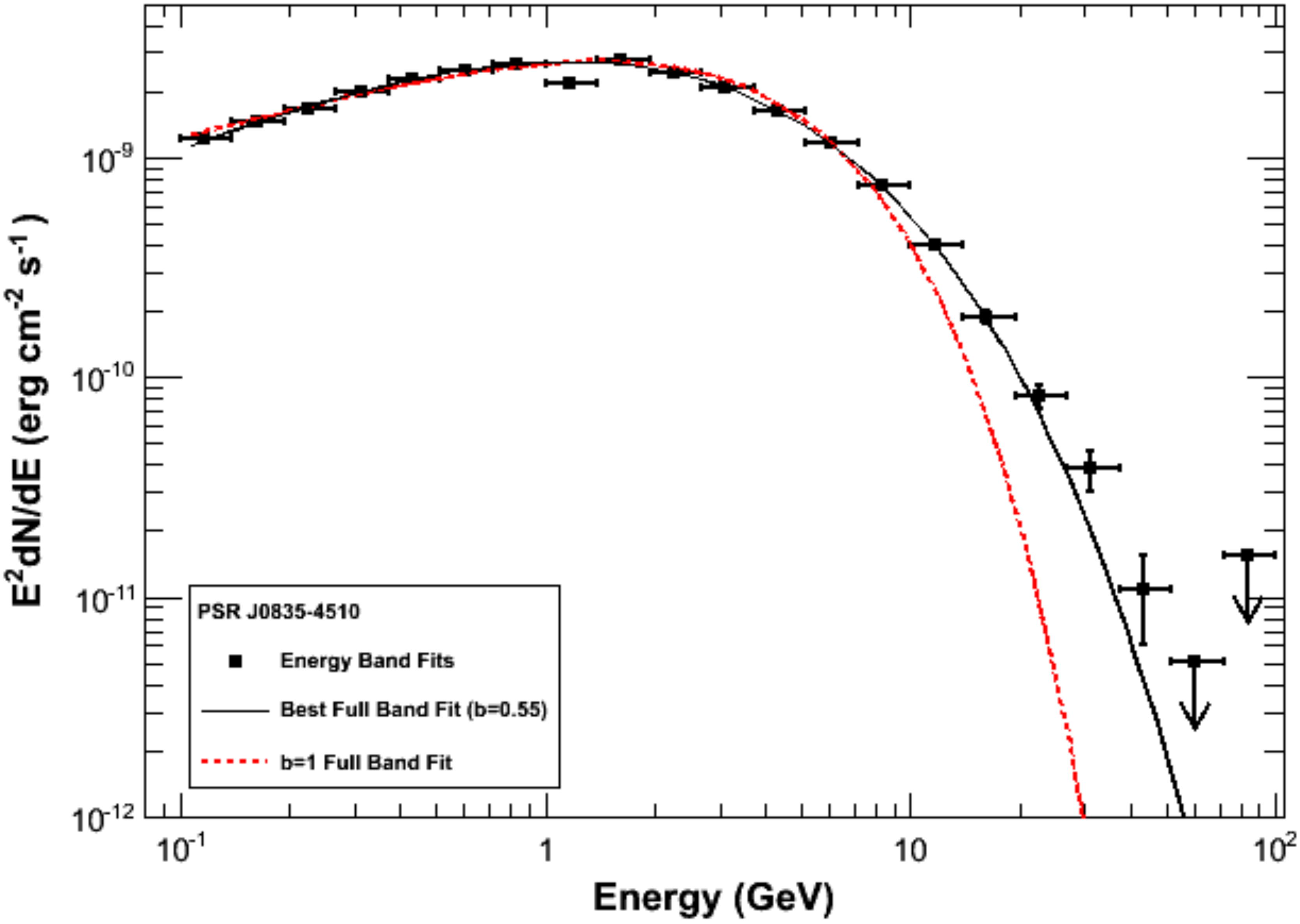
~ 2 : Polar Cap model (low altitude emission)



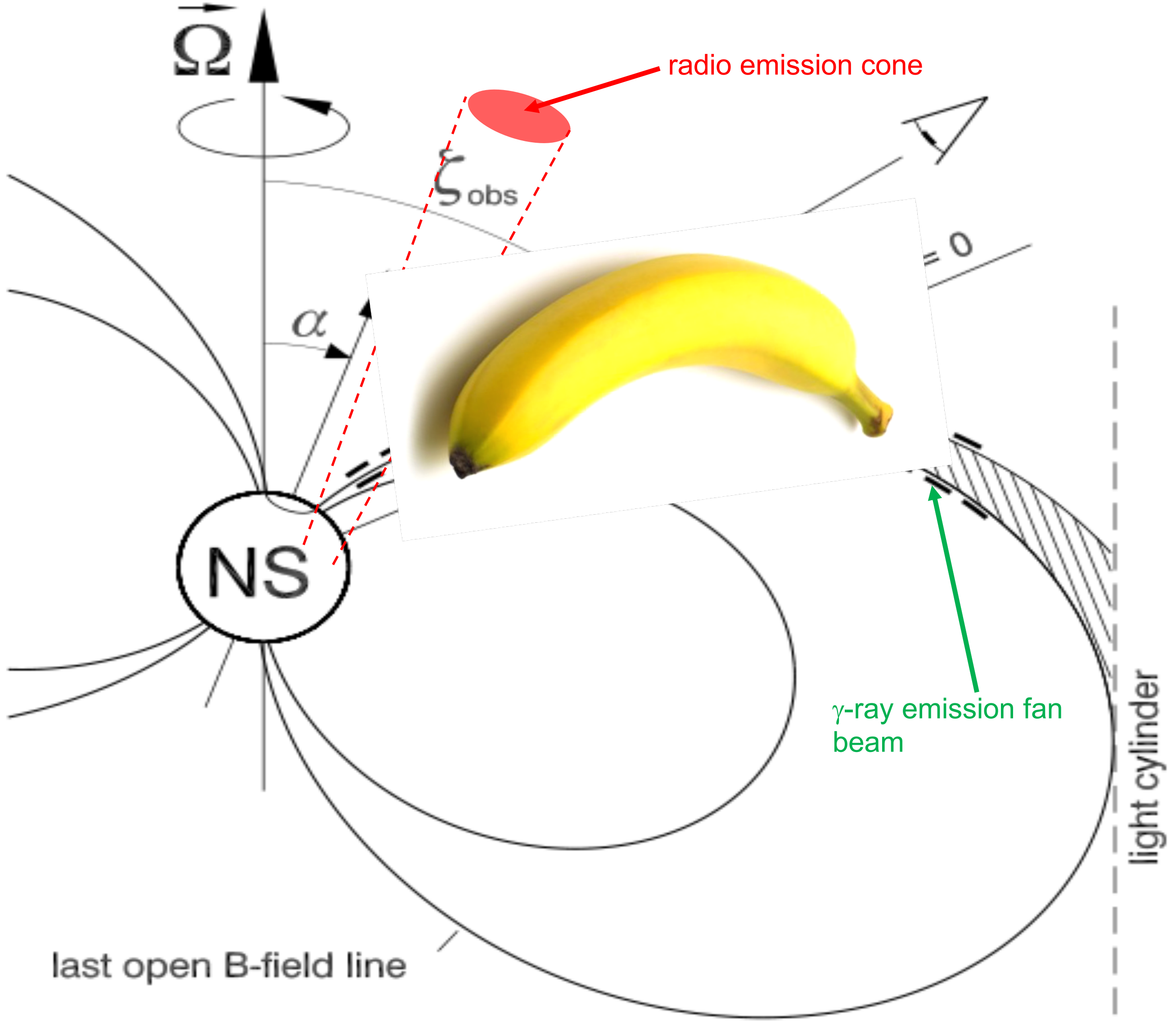
Vela pulsar. Abdo, A. A. et al. 2009, ApJ, 696, 1084

Atypical 3rd peak ("shoulder") drifts with phase. Two main peaks are typical.
(here, 3 years of data.)

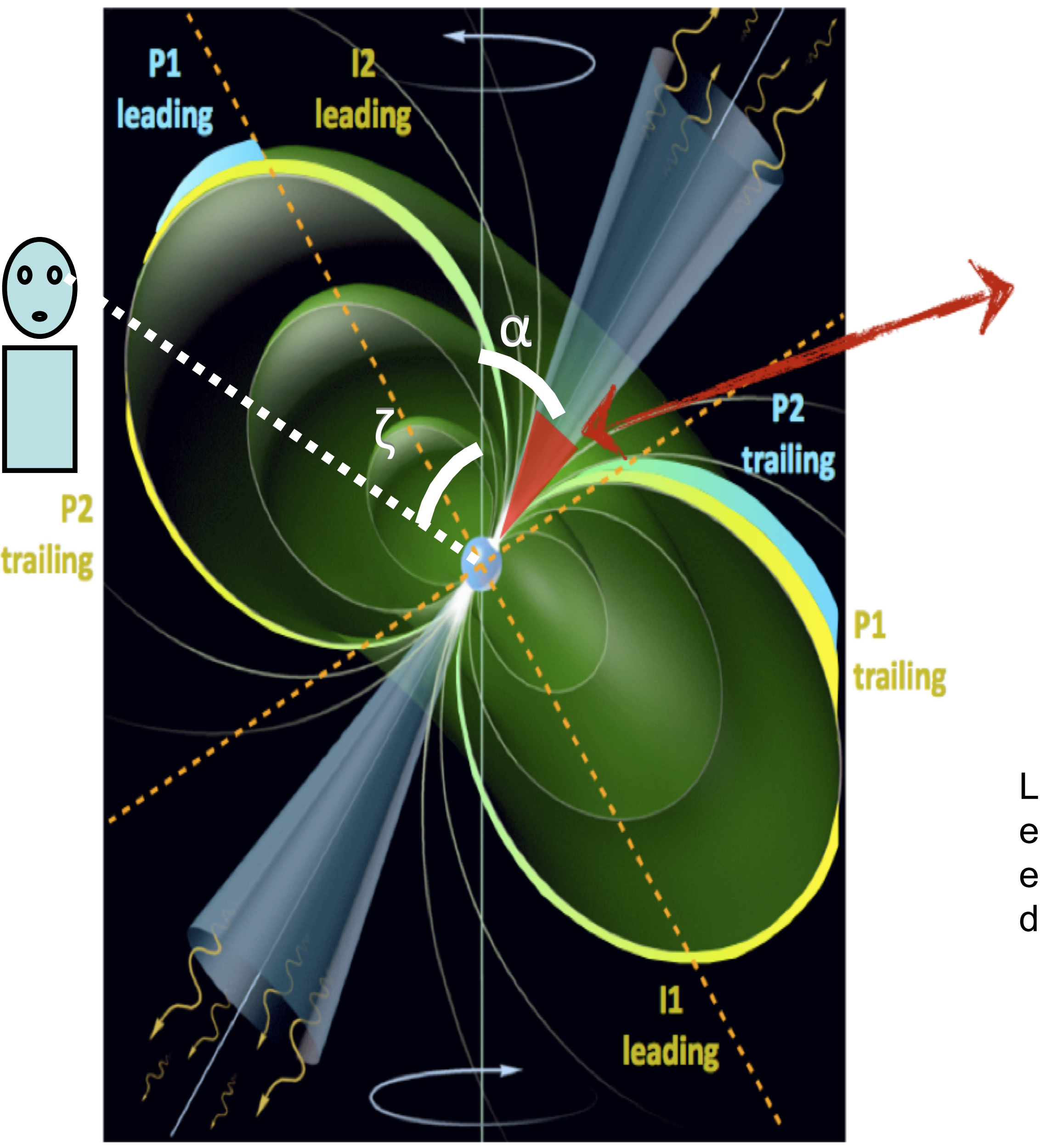
By Thierry Reposeur, Bordeaux.


E^2dN/dE (erg cm^{-2} s^{-1})
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-1}
1
10
10^{2}
Energy (GeV)
PSR J0835-4510
■ Energy Band Fits
Best Full Band Fit (b=0.55)
b=1 Full Band Fit

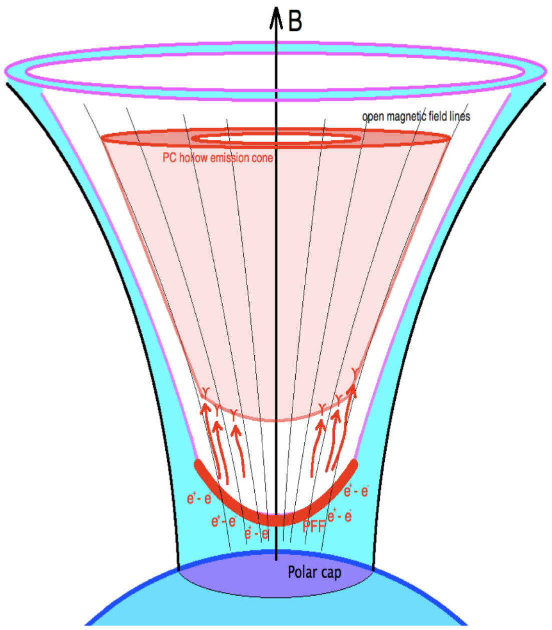
How to use light-curves to constrain pulsar geometry and emission models



Gap regions: location and energetics



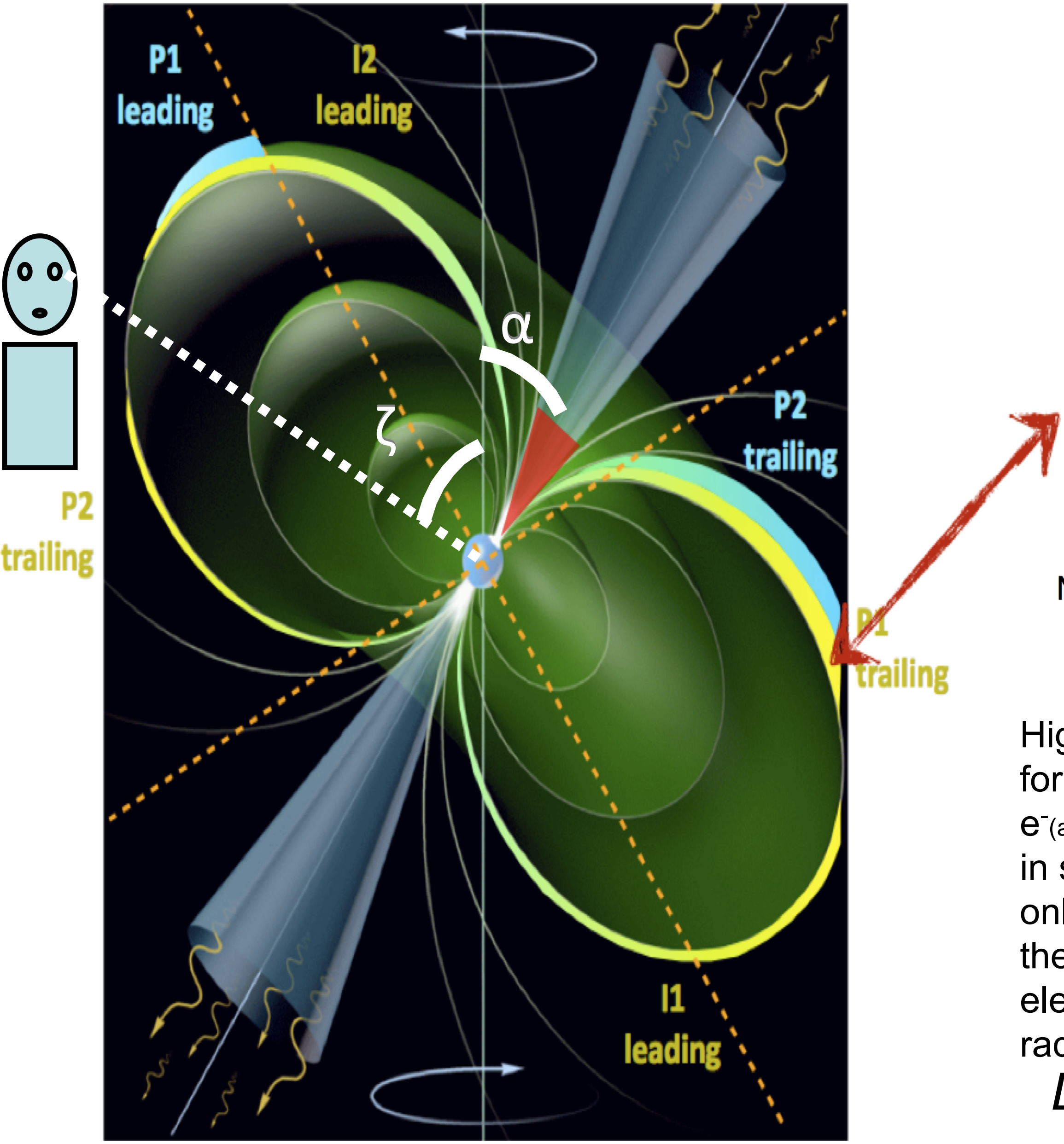
Polar Cap model (PC)
Muslimov & Harding
2003



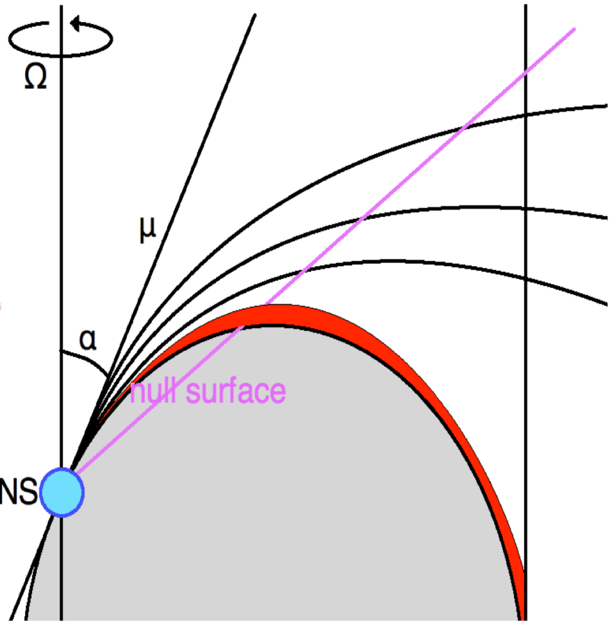
Low altitude emission, PFF formation,
e^-(accelerated by E) ⟶ γ (+B)⟶ $e^{+/-}$
$e^{+/-}$ increase→E screened in a short distance

$$L_\gamma \propto \dot{E}\,\Delta\xi^3 \quad \Delta\xi = f(B,P)$$

Gap regions: location and energetics



Slot gap model (SG)
Muslimov & Harding
2004



High altitude emission, PFF formation,

e^{-}(accelerated by E) ⟶ γ (+B)⟶ $e^{+/-}$

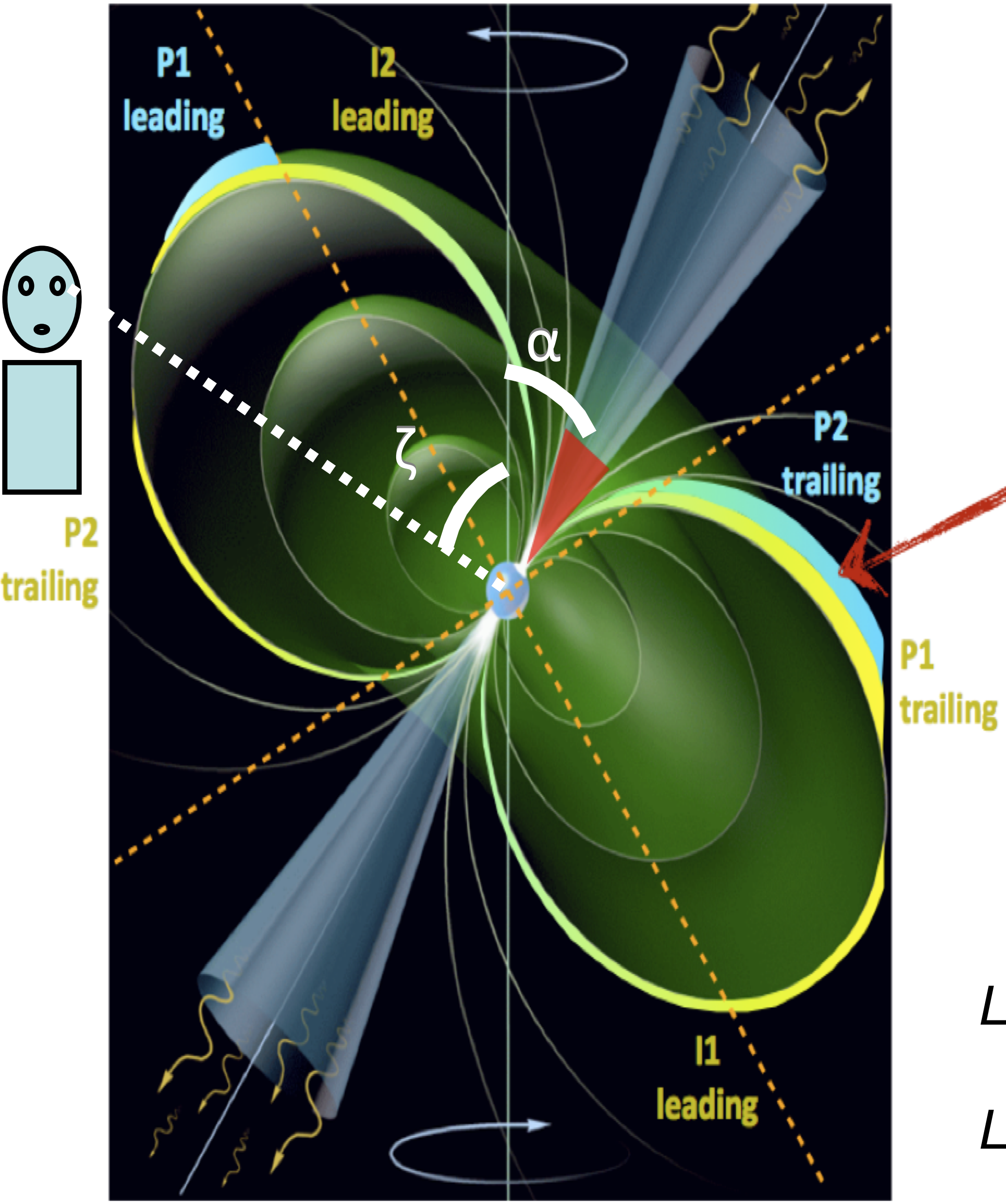
in slot gap regions→no screening

only the primary e^{-} are accelerated in the SG

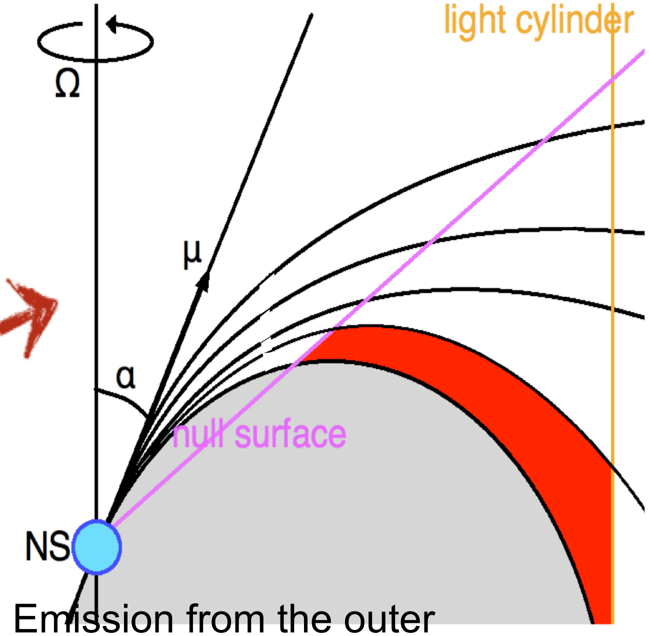
electron's energy limited by curvature radiation reaction

$$L_\gamma \propto \dot{E}\,\Delta\xi^3 \qquad \Delta\xi = f(B,P)$$

Gap regions: location and energetics



Outer gap model (OG) Cheng et al. 2000
One Pole Caustic (OPC) Watters et al. 2009

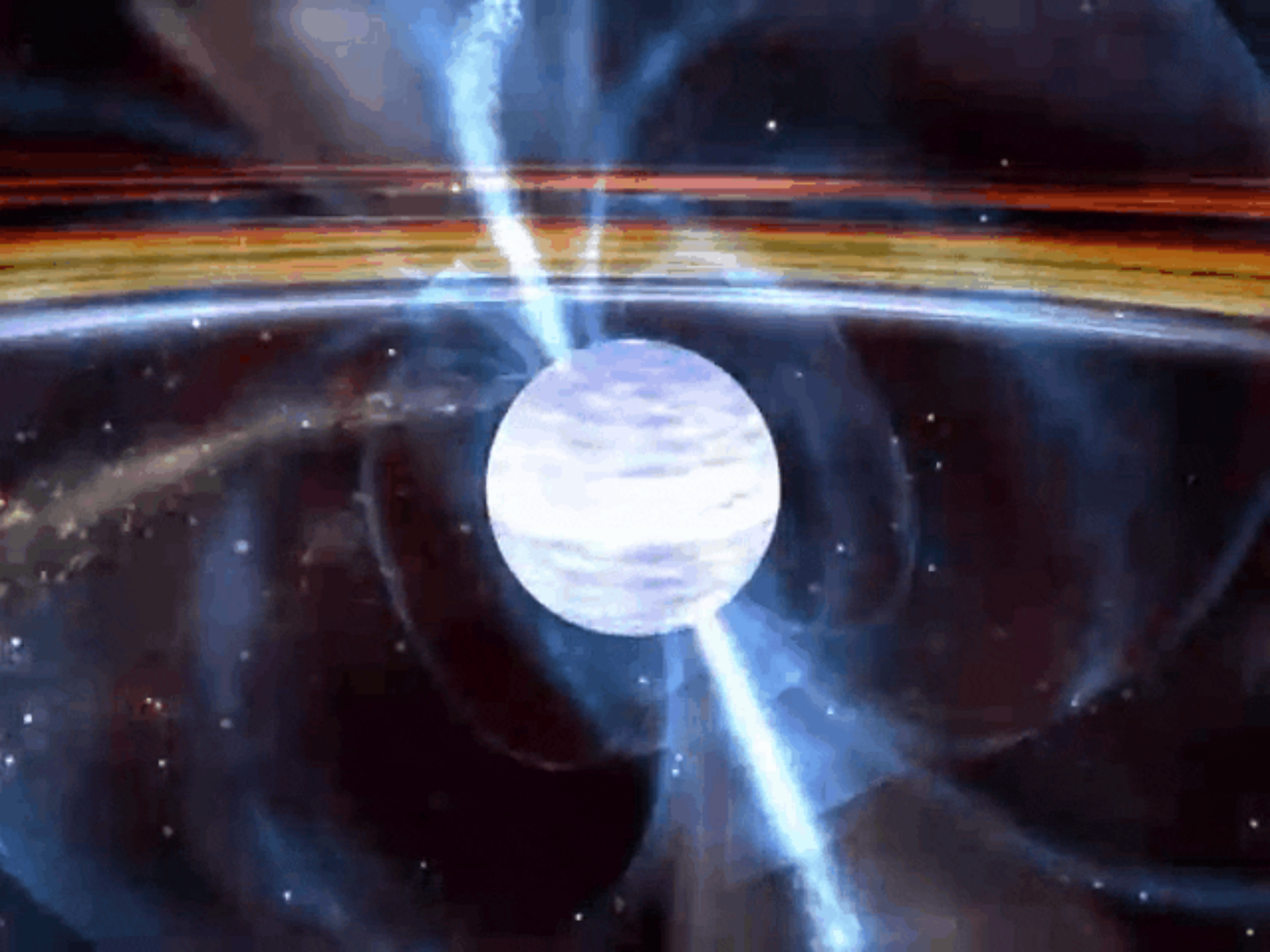


Emission from the outer magnetosphere
empty OG gaps form→ $\Delta\rho_{GJ}$→strong E
$e^{+/-}$ accelerated up to very high energy

$$L_{\gamma,OG} \propto \dot{E}\, w_{OG}^3 \quad w_{OG} = f(B,P,\alpha)$$

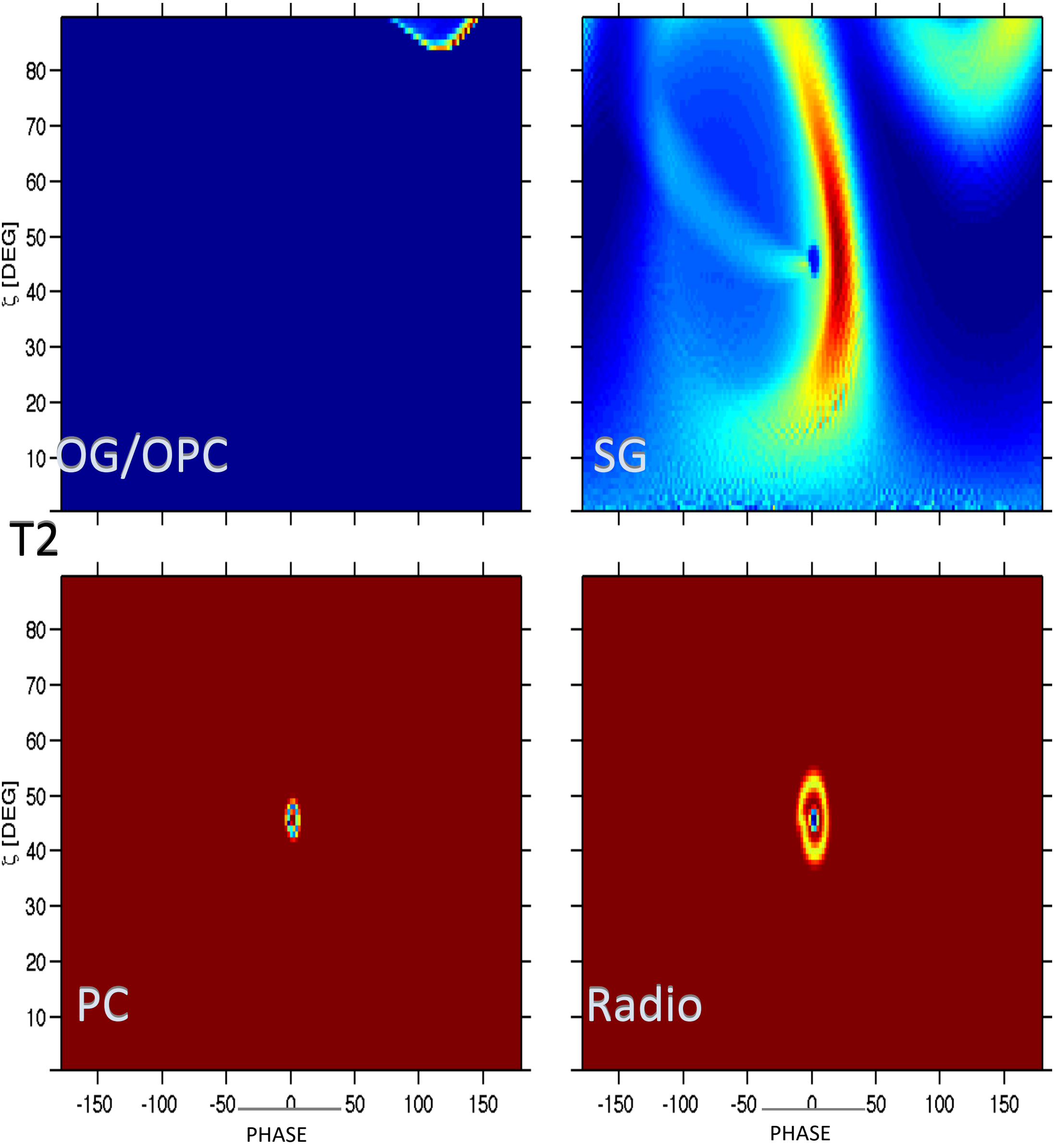
$$L_{\gamma,OPC} \propto \dot{E}\, w_{OPC} \quad w_{OG} = (10^{-26} W \dot{E})^{0.5}$$

Phenomenological model



Pulsar emission geometry: the phase plot

A pulsar phase-plot is a two-dimensional matrix, containing the pulsar emission at all rotational phases (light curve) for all the possible values of the observer line of sight ζ, and obtained for the specific set of pulsar parameters: P,, B, gap width, and α.



Geometrical emission model from Dyks et al. 2004

1- dipole magnetic field
2- photon tangent to B lines
3- effects due to the star rotation

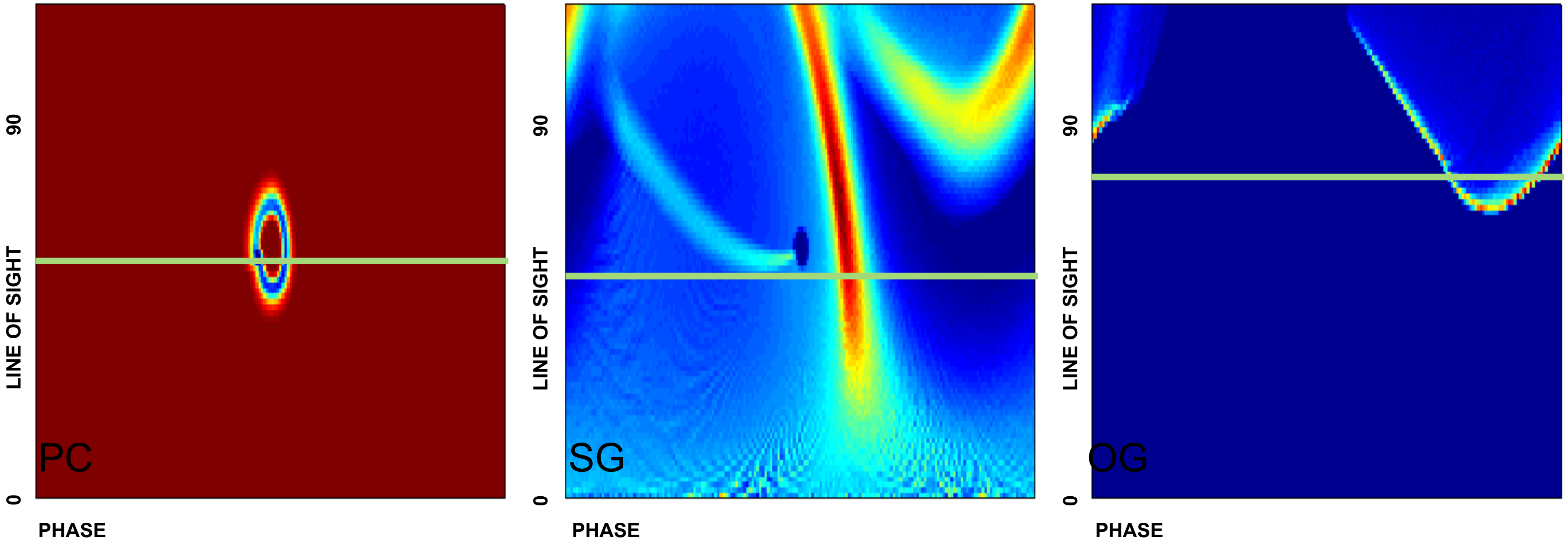
When the pulsar ages the spin period increases
so the light cylinder radius increase

$R_{LC} = c/\Omega = c\,P/2\pi$

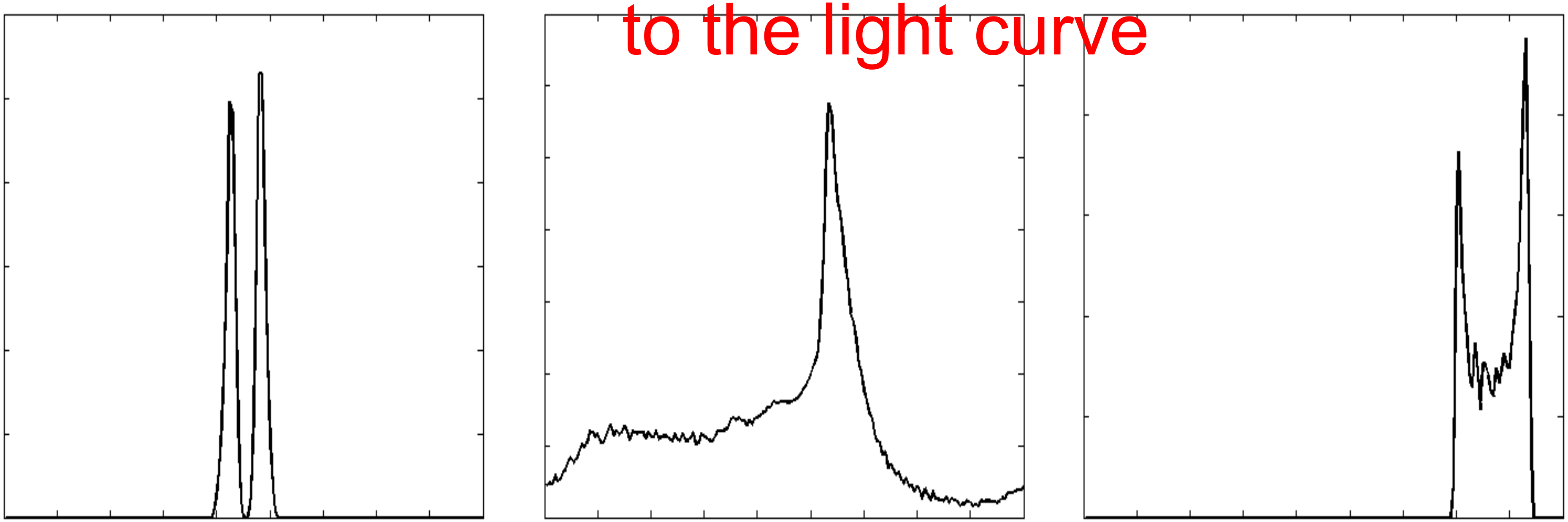
as a consequence, the magnetosphere structure changes: the open magnetic field line region becomes smaller

PC, OG, and Radio emission beams become smaller. SG case more complicated

Pulsar emission geometry: from the phase plot



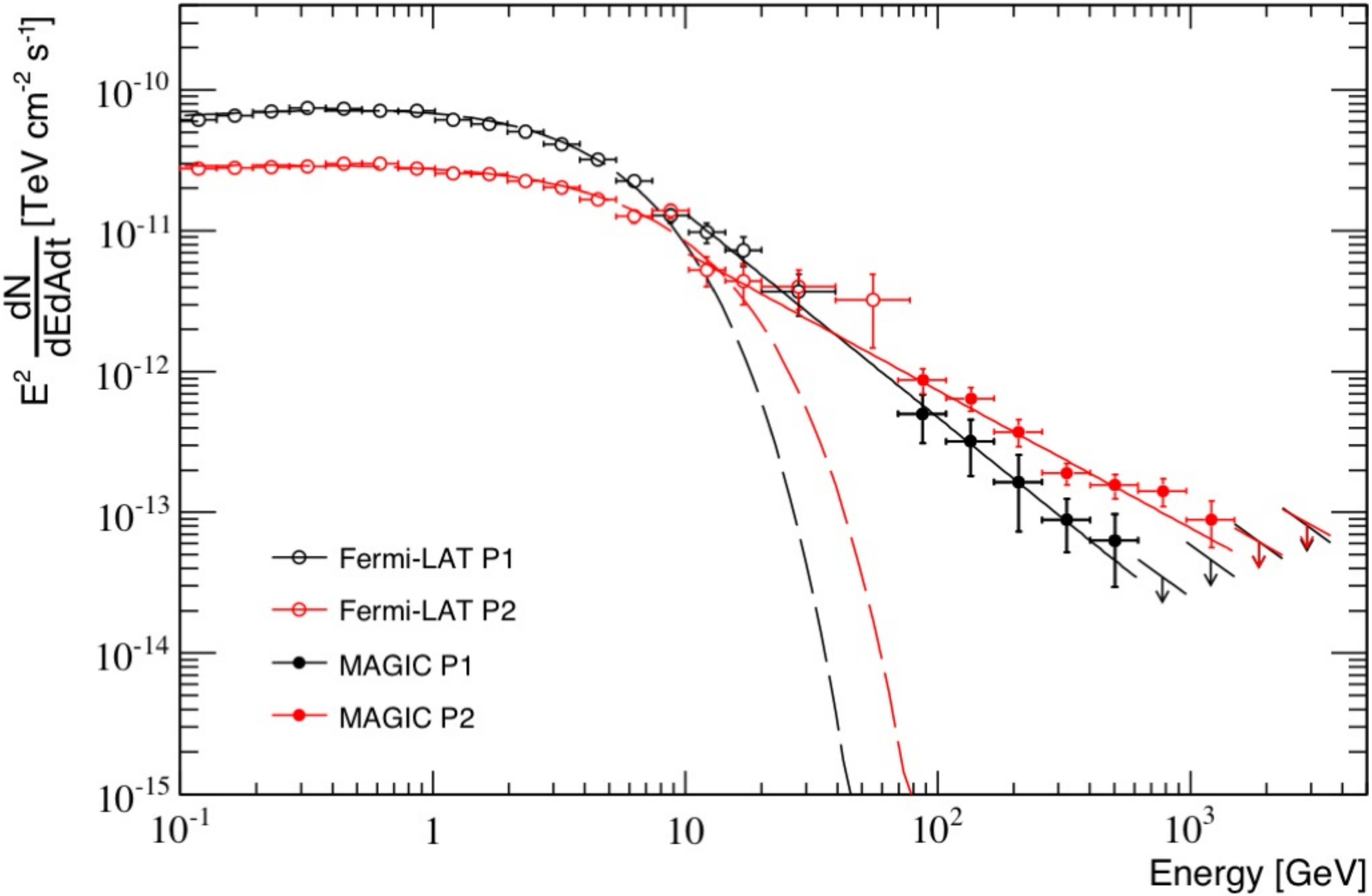
to the light curve



The light-curve Atlas

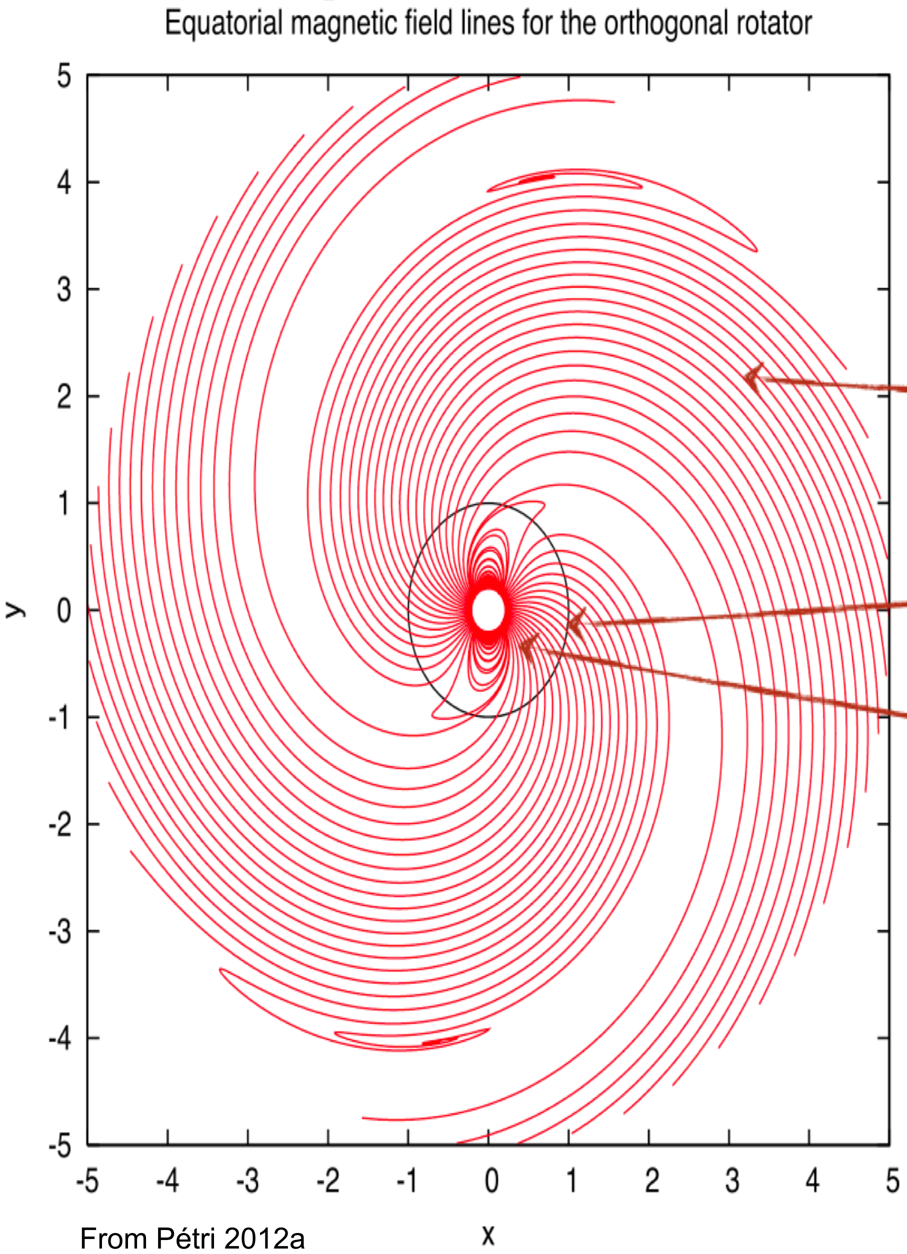
- The OG/SG models are generally better but not adequate to fit all objects
- PC can only account for a few pulsars
- SG need a boost in efficiency to account for the observed set of LAT detections.
- NONE of the models is able to account for the phenomenology of LAT pulsars
- Some pulsars can be fitted by more than one model, some by none.

The challenge of VHE emission



Are there other γ-ray emission models? The striped wind model

Pétri 2012a and b



From Pétri 2012a

Striped pulsar wind introduced from Coroniti 1990. The γ-ray emission is generated outside the pulsar light cylinder in the striped wind region, where the magnetic field switches from dipolar to toroidal.

Striped win sheet, opened toroidal magnetic field

Light cylinder (black circle)

Dipolar magnetic field region, closed dipolar magnetosphere

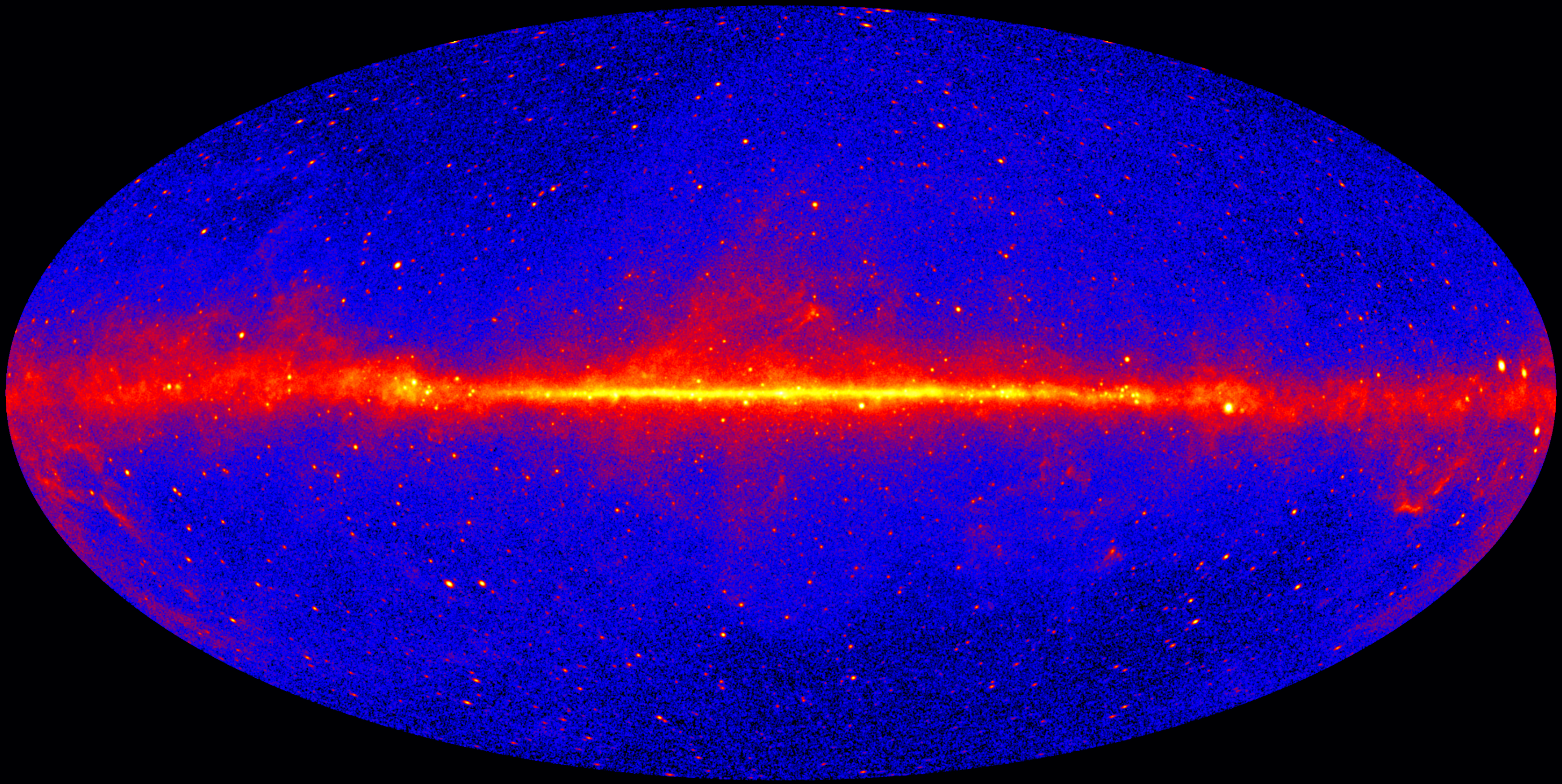
$L_\gamma \propto (\dot{E}/P)^{0.5}$ Synchrotron, Pétri 2012b

Emission is due to the current flowing in the toroidal striped wind sheets.

Lessons learned from a Revolution

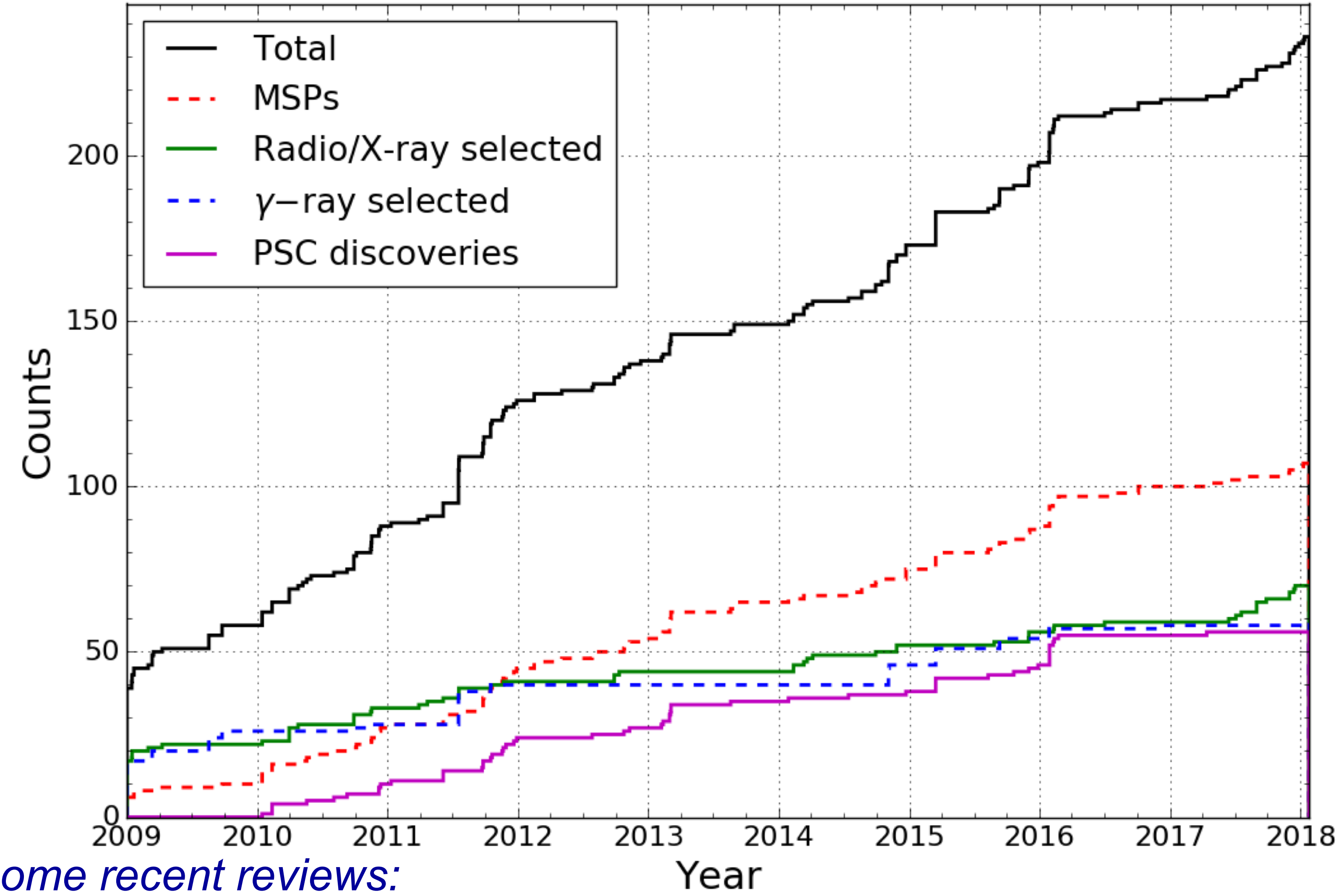
FERMI is a remarkable pulsar hunter

- INSs are indeed responsible for A LOT of previously unidentified γ-ray sources
- MSPs are the winner in the γ-ray pulsar race
- Models are still… in progress



Is it worth continuing the search for more pulsars?

Fermi LAT still detecting ~25 gamma pulsars per year.



Some recent reviews:

γ-ray Pulsar Revolution, P. Caraveo, Annual Review of Astronomy and Astrophysics 52, 2014.
γ-ray Pulsars: a Gold Mine, I. Grenier & A.K. Harding, Compte rendus Physique 16, 2015
The Soft γ-ray Pulsar Population: a High-Energy Overview, L. Kuiper & W. Hermsen, MNRAS 449, 2015
γ-ray Pulsars with *Fermi*, D.A. Smith et al., arXiv:1706.03592

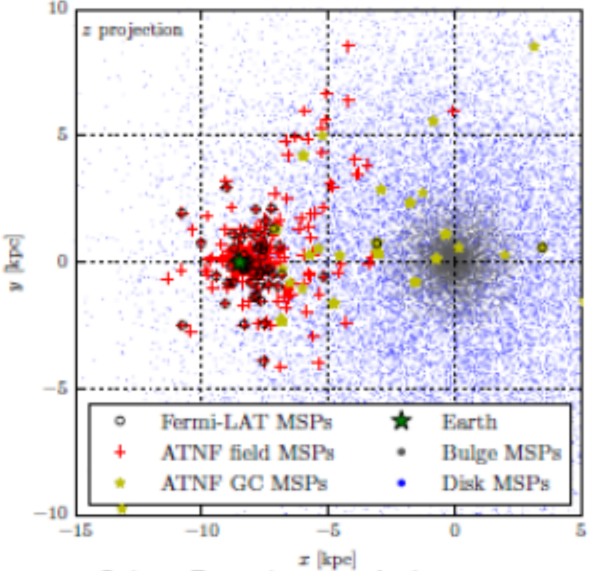
Another reason to care about *faint* γ pulsars:

Dark Matter *versus* Pulsars

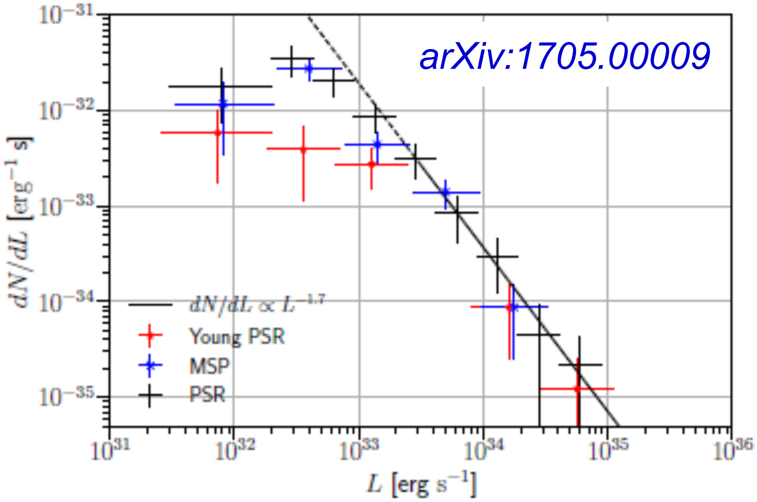
~10% more diffuse GeV emission towards the Galactic center than naïvely expected.

Spectrum as for neutralino annihilation (and pulsars). *Abundant literature…*

A key : Extrapolate log N-log S to estimate the contribution of unresolved pulsars.



Calore, F., et al., 2016, ApJ, 827, 143



arXiv:1705.00009

Figure 9. Observed luminosities for young PSRs (red data), MSPs (blue data) and the whole population of PSRs with $d < 1.5$ kpc (black data). The best fit to the luminosity distribution for $L > 3 \times 10^{33}$ erg s^{-1} is also reported (black line). The luminosity is integrated over the energy range [0.3, 500] GeV.

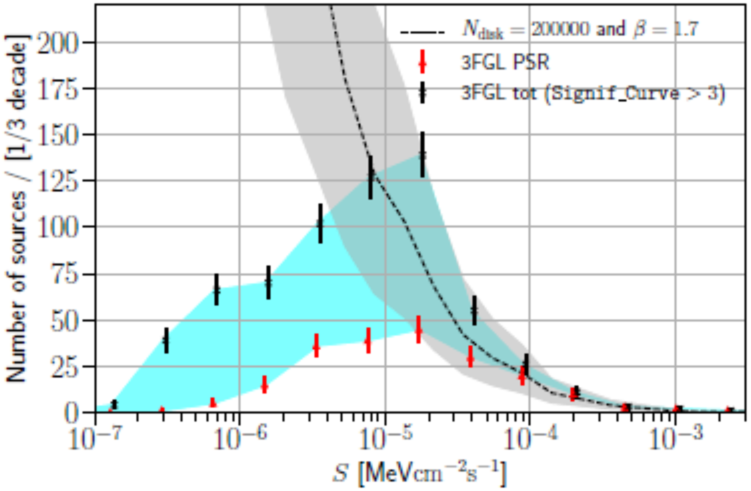
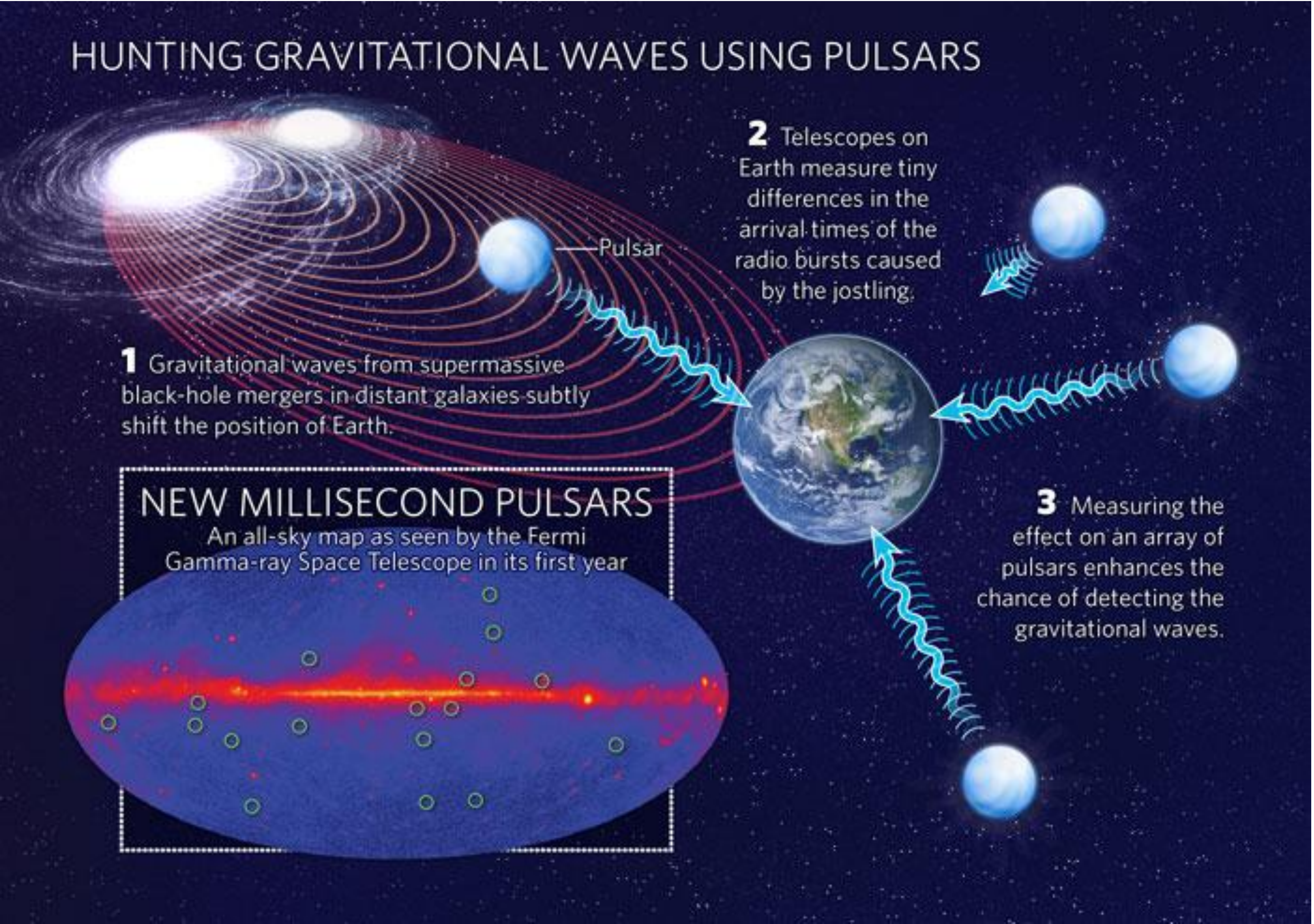


Figure 10. Flux histogram of 3FGL PSRs alone (red triangles) or added to the flux distribution of unassociated 3FGL sources with curvature `Signif_Curve` > 3 (black points). The cyan band represents the region between the lower limit (already detected PSRs) and upper limit (3FGL PSRs plus unassociated 3FGL sources with detected spectral curvature). Finally the black curve (gray band) represents the benchmark (band between the minimum and maximum) number of disk PSRs. The flux is integrated over the energy range [0.3, 500] GeV.

MSP Bonanza BONUS: Gravitational waves ?



HUNTING GRAVITATIONAL WAVES USING PULSARS

1 Gravitational waves from supermassive black-hole mergers in distant galaxies subtly shift the position of Earth.

2 Telescopes on Earth measure tiny differences in the arrival times of the radio bursts caused by the jostling.

3 Measuring the effect on an array of pulsars enhances the chance of detecting the gravitational waves.

NEW MILLISECOND PULSARS

An all-sky map as seen by the Fermi Gamma-ray Space Telescope in its first year