Pulsar Astronomy with GLAST

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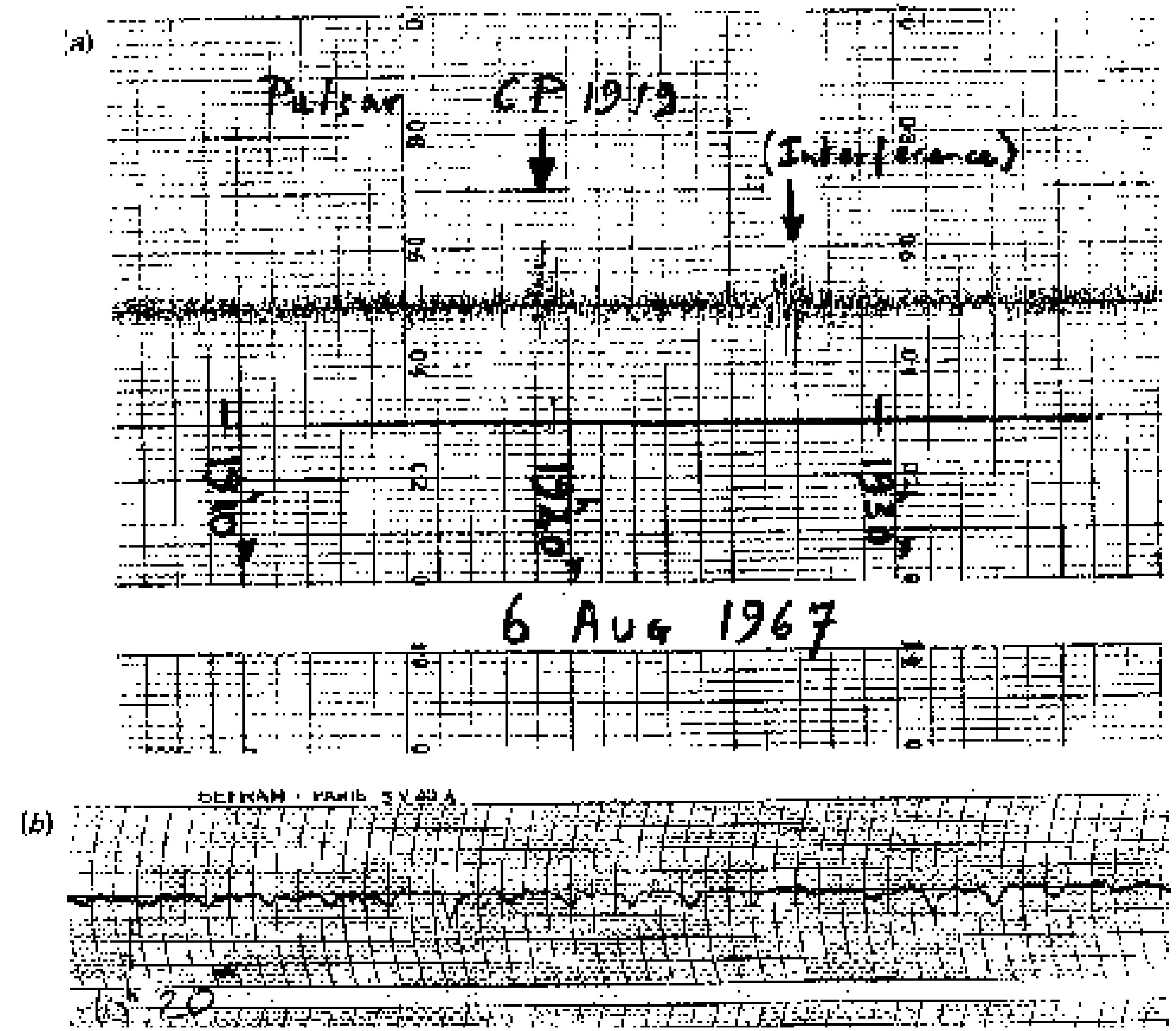
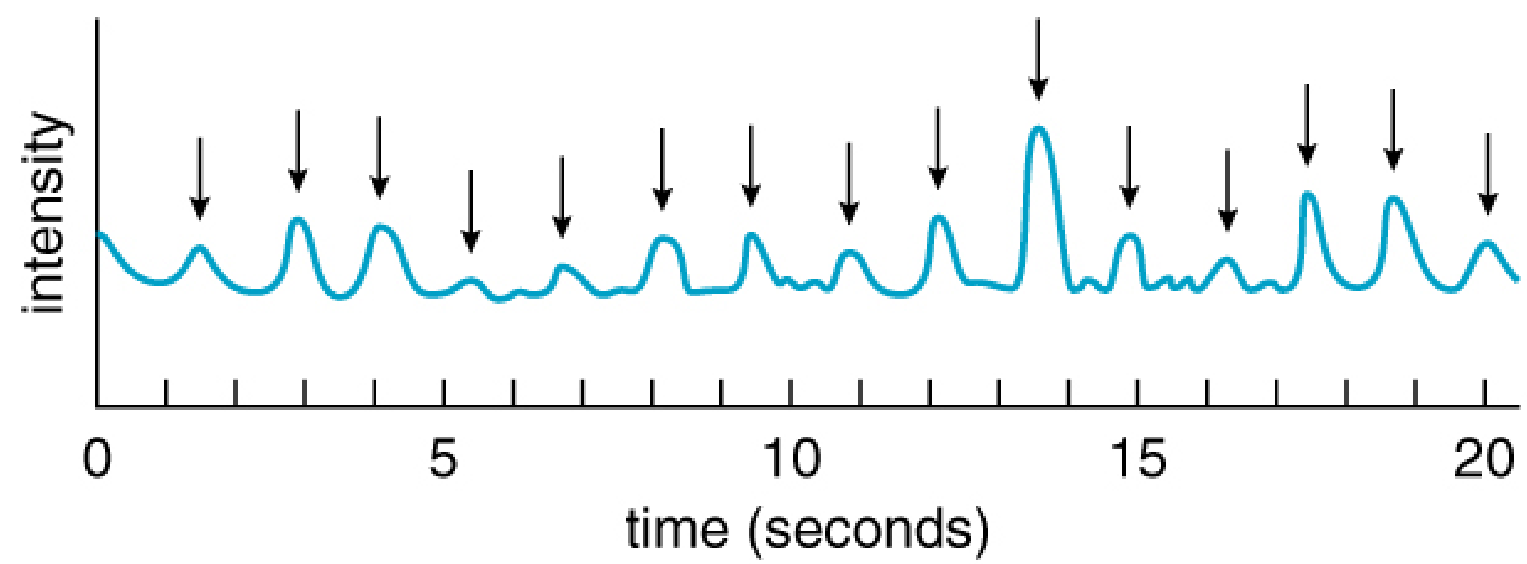
Discovery of Neutron Stars: Pulsars

In 1967, Jocelyn Bell discovered a strange, pulsating radio source (dubbed LGM 1)

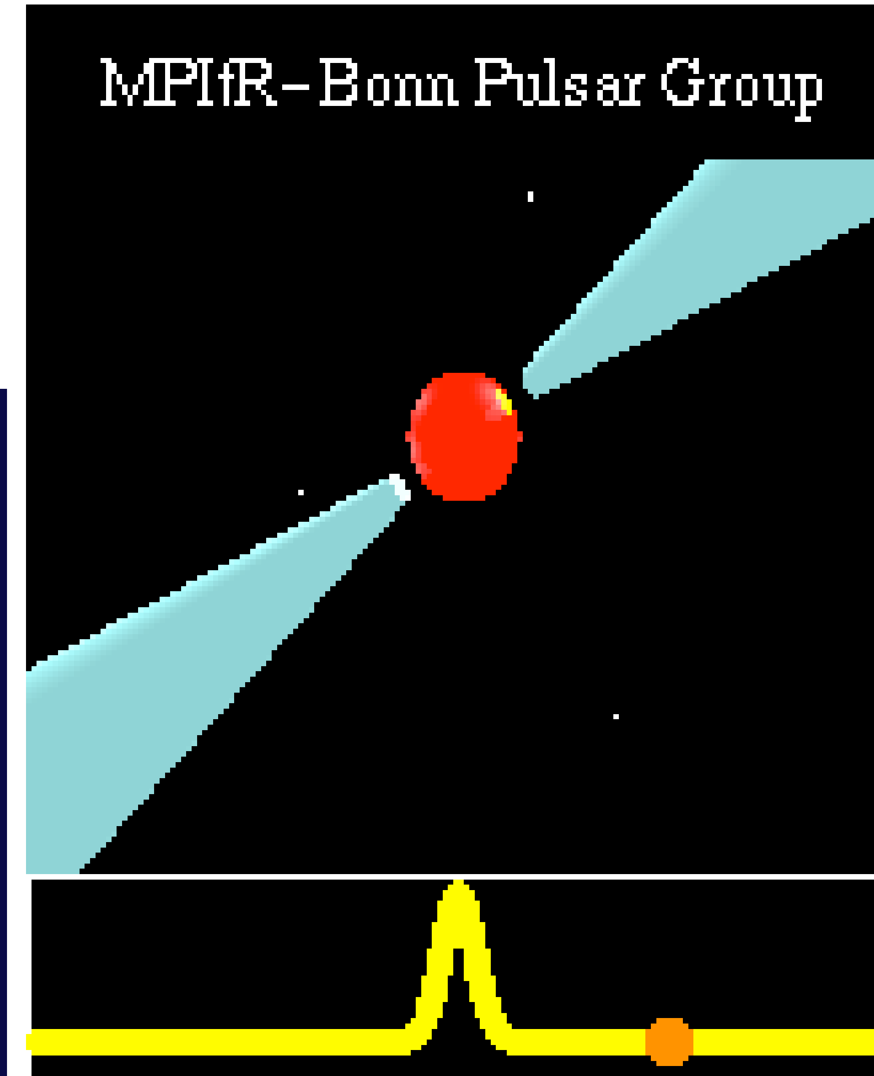


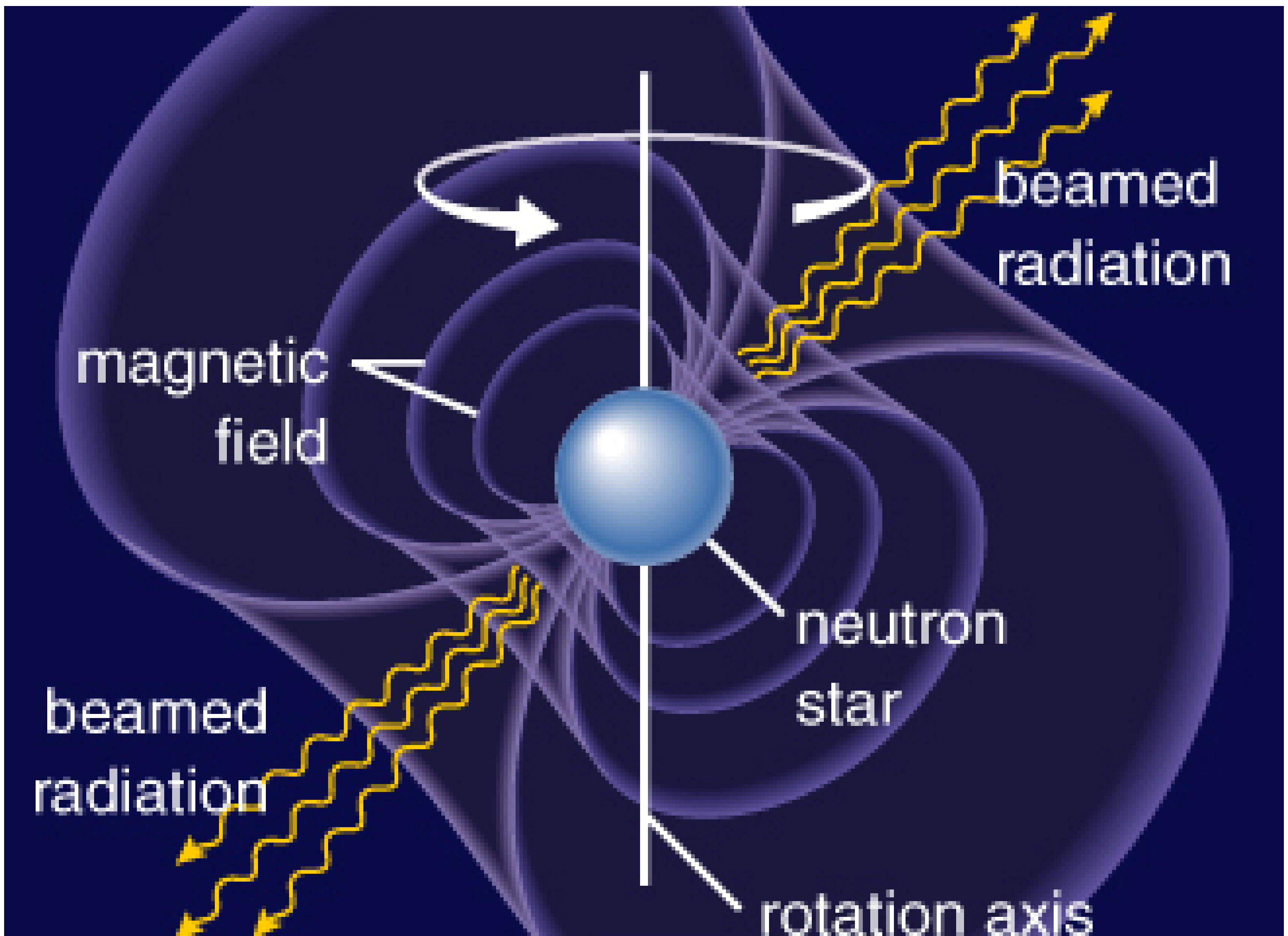


http://www.ggw.org/asras/snimages/

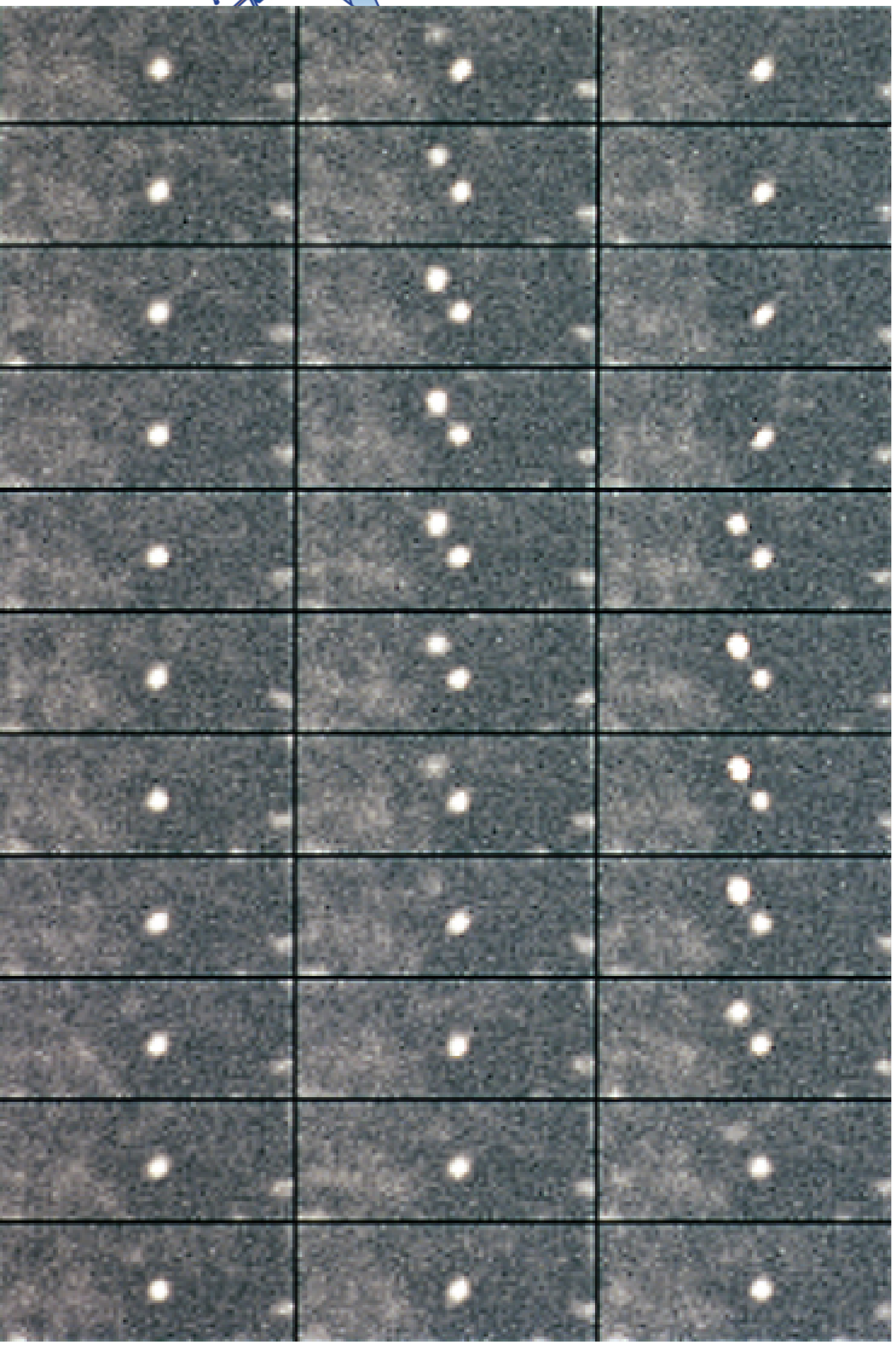
http://www.nordita.dk/~dahle/
Recent_SN.html

Lighthouse model for pulsars





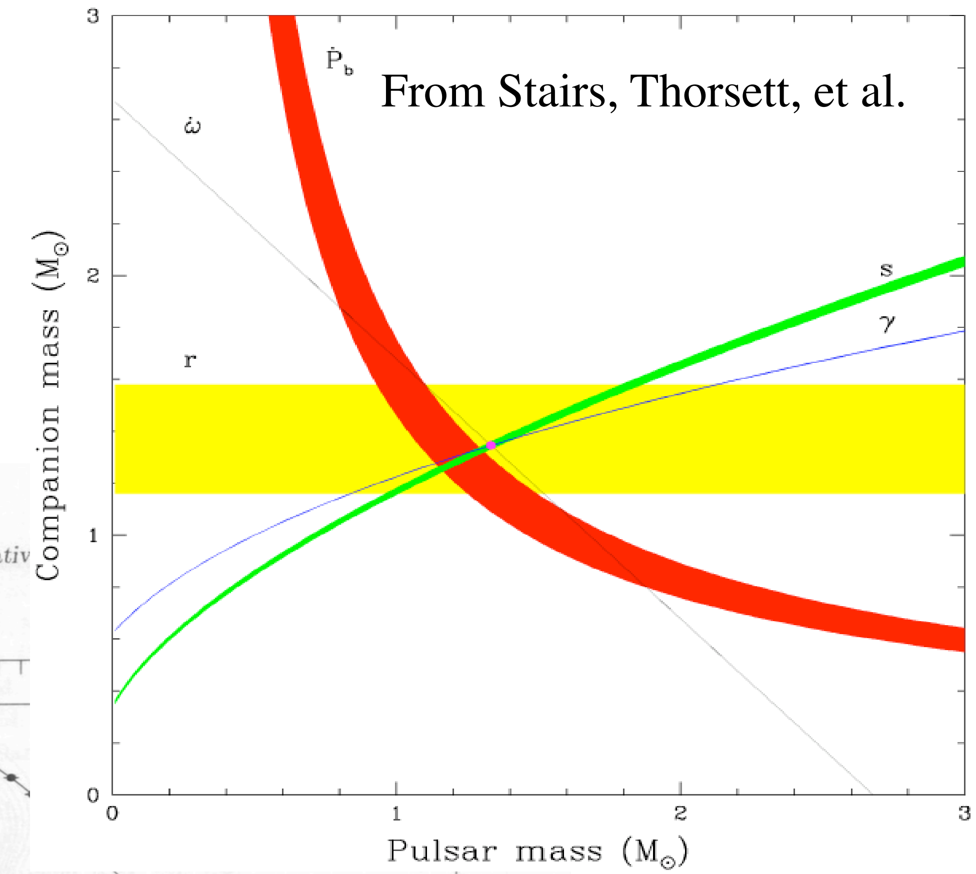
Crab pulsar



- Pulsar in core of Crab nebula is spinning 30 times per second
- Slowing down since 1054 AD

Radio pulsar greatest hits: I

- Tests of General Relativity
  - post-Keplerian corrections to binary equations of motion can be used to test predictions of GR
  - Predicted orbital energy loss to gravitational radiation can be directly measured to better than 1%
  - The "speed of gravity" is c



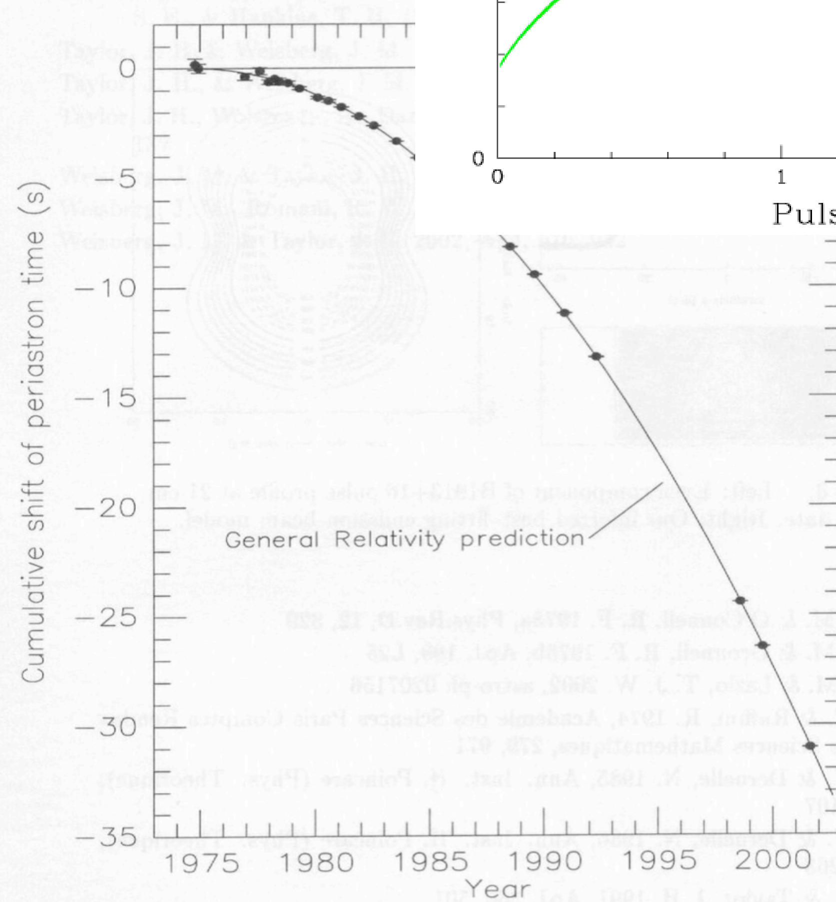
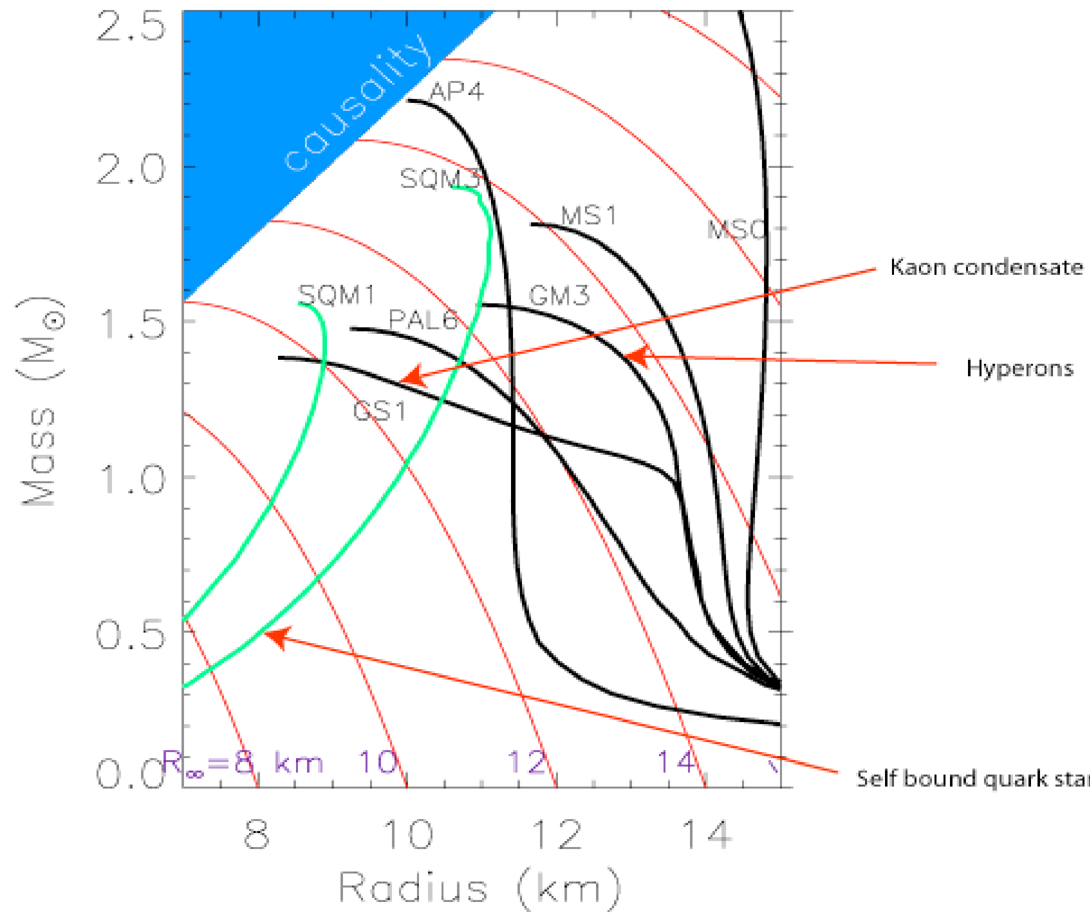
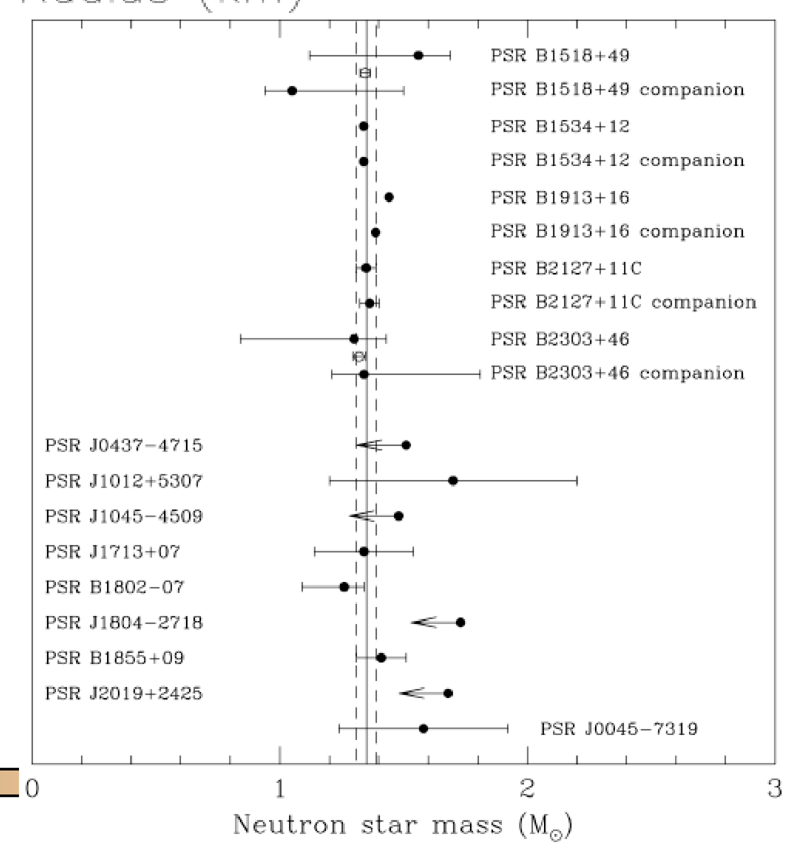


Figure 2. Gravitational radiation damping should cause orbital decay which leads to an accumulating shift in epoch of periastron. The parabola illustrates the general relativistically predicted shift, while the observations are marked by data points. In most cases (particularly in the later data), the measurement uncertainties are smaller than the line widths.

Radio pulsar greatest hits: II

- Nuclear equation of state
  - the properties of neutron stars depend sensitively on the e.o.s. at densities a few times above nuclear
  - We've now measured masses for dozens of stars - most are within a few percent of 1.35 solar, but they range from ~1.2 to ~2.0
  - Radii are harder, but can be done for thermal sources: our best case is 12-20 km



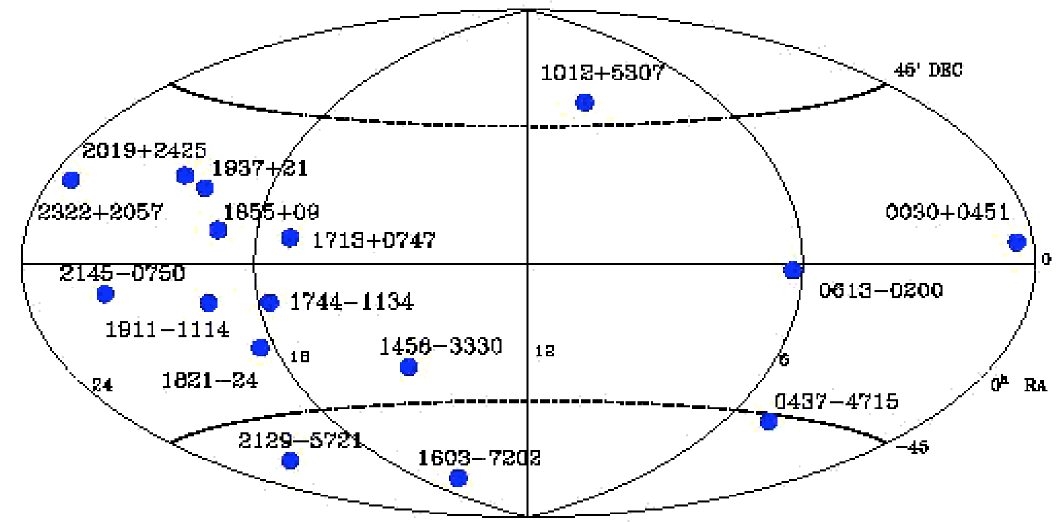


Radio pulsar greatest hits: III

- Cosmological gravitational wave background
  - gravitational red/blueshifting of clocks due to a GW background leads to apparent phase fluctuations in pulsar timing experiments
  - Limits of a few 10^-9 of closure density were enough to apparently rule out some cosmic string models a few years ago
  - Considerable new interest in a large experiment to push these limits downward

MILLISECOND PULSAR TIMING ARRAY – 2001

from D. Backer



If the GWB has a constant energy density per octave Ω_g relative to the closure density then the power spectrum (power per octave bandwidth) of the resulting pulse arrival time residuals will be [23]

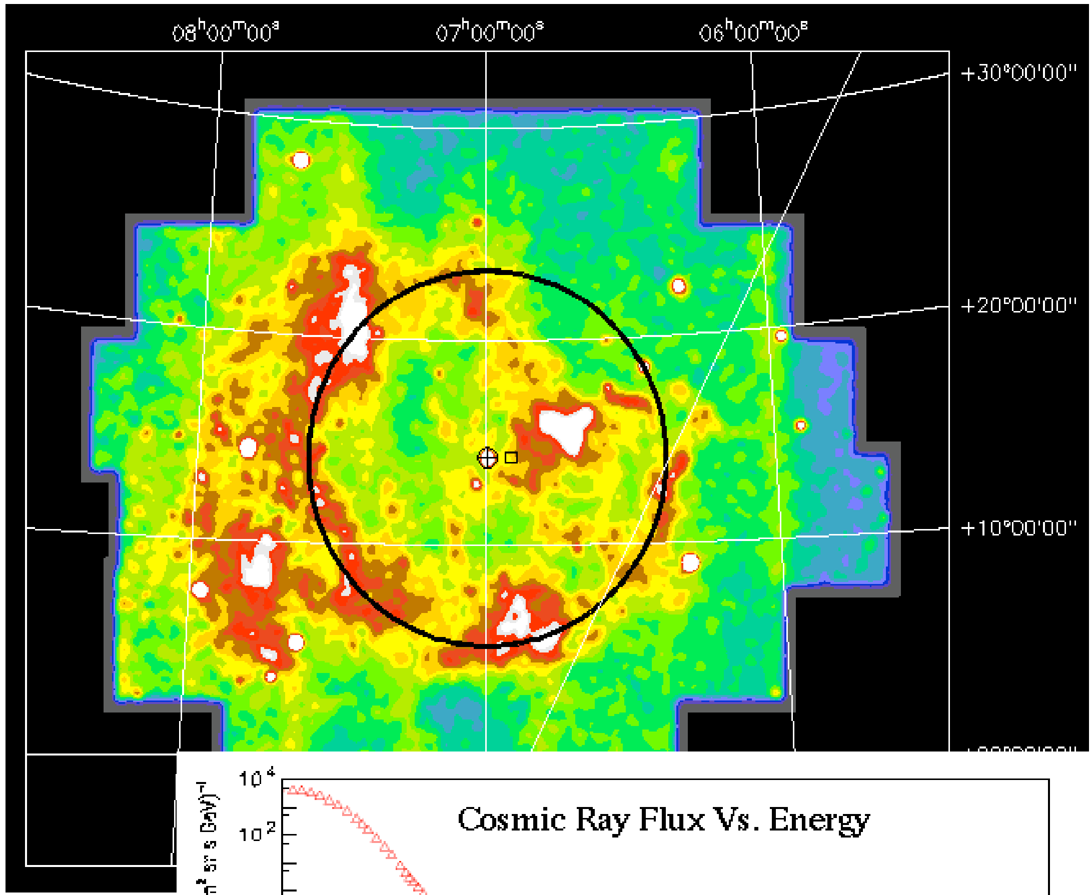
$$S_g(f)=\frac{H_0^2}{8\pi^4}\Omega_g f^{-5}=1.34\times 10^4\Omega_g h^2 f_{\mathrm{yr}^{-1}}^{-5}\mu\mathrm{s}^2\mathrm{yr}, \quad (1)$$

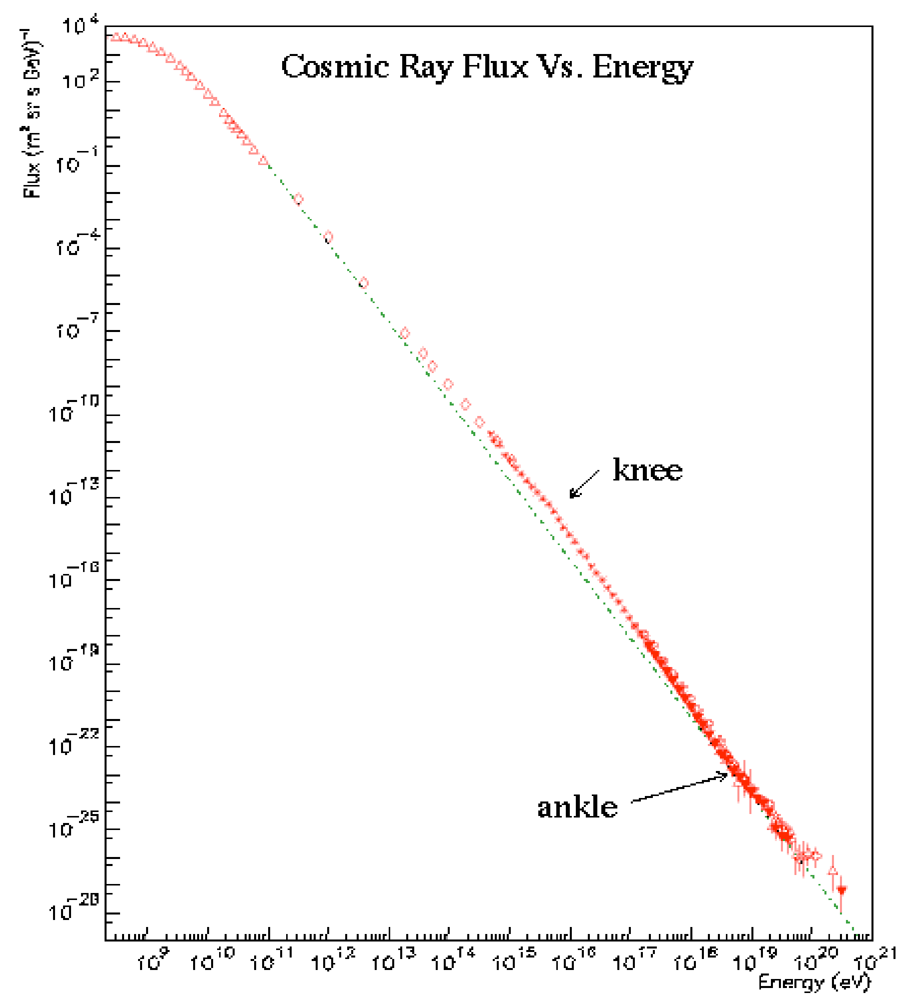
Thorsett & Dewey '96

GLAST

Radio pulsar "greatest" hits: IV

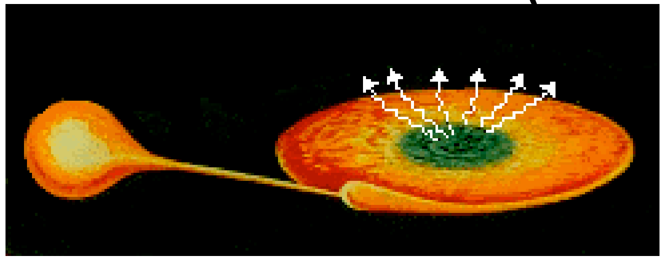
- The origin of the cosmic rays
  - Our recent parallax for B0656+14 shows it is 288 pc away, at the center of the Monogem ring SNR (and we know it is ~110,000 years old)
  - Erlykin & Wolfendale have argued from the amplitude and energy of the "knee" in the CR spectrum that it may be dominated by a single SNR 300-350 pc away and 90-100 kyr old

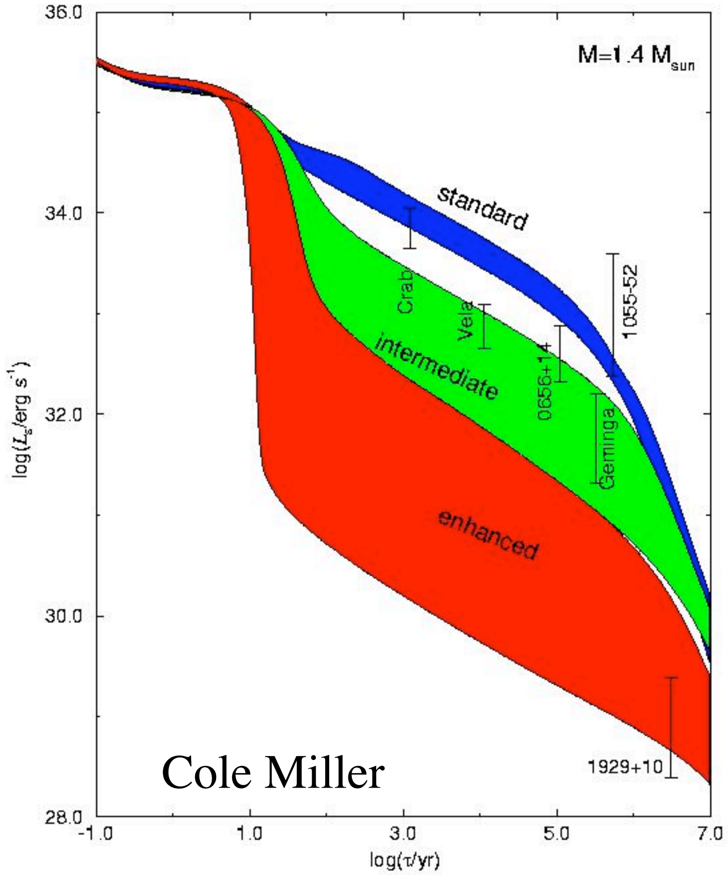




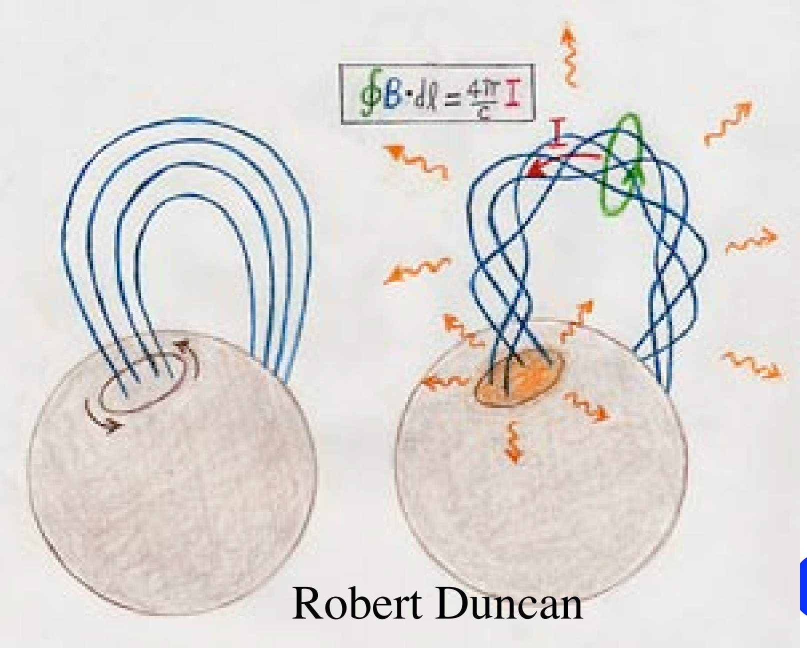
Energy sources

- A neutron star has four potential energy sources:
  - accretion (from the interstellar medium or from a companion star)





  - residual thermal energy
  - energy stored in the magnetic field
  - rotational kinetic energy



Rotational energy

- Energy stored at birth is substantial:

$$E = \frac{1}{2} I\omega^2 \sim \frac{1}{2}\left(10^{45}\mathrm{g\,cm}^2\right)\left(\frac{2\pi}{10\mathrm{ms}}\right)^2 \sim 2\times 10^{50}\mathrm{erg}$$

(comparable to the total energy radiated by the Sun in its history)

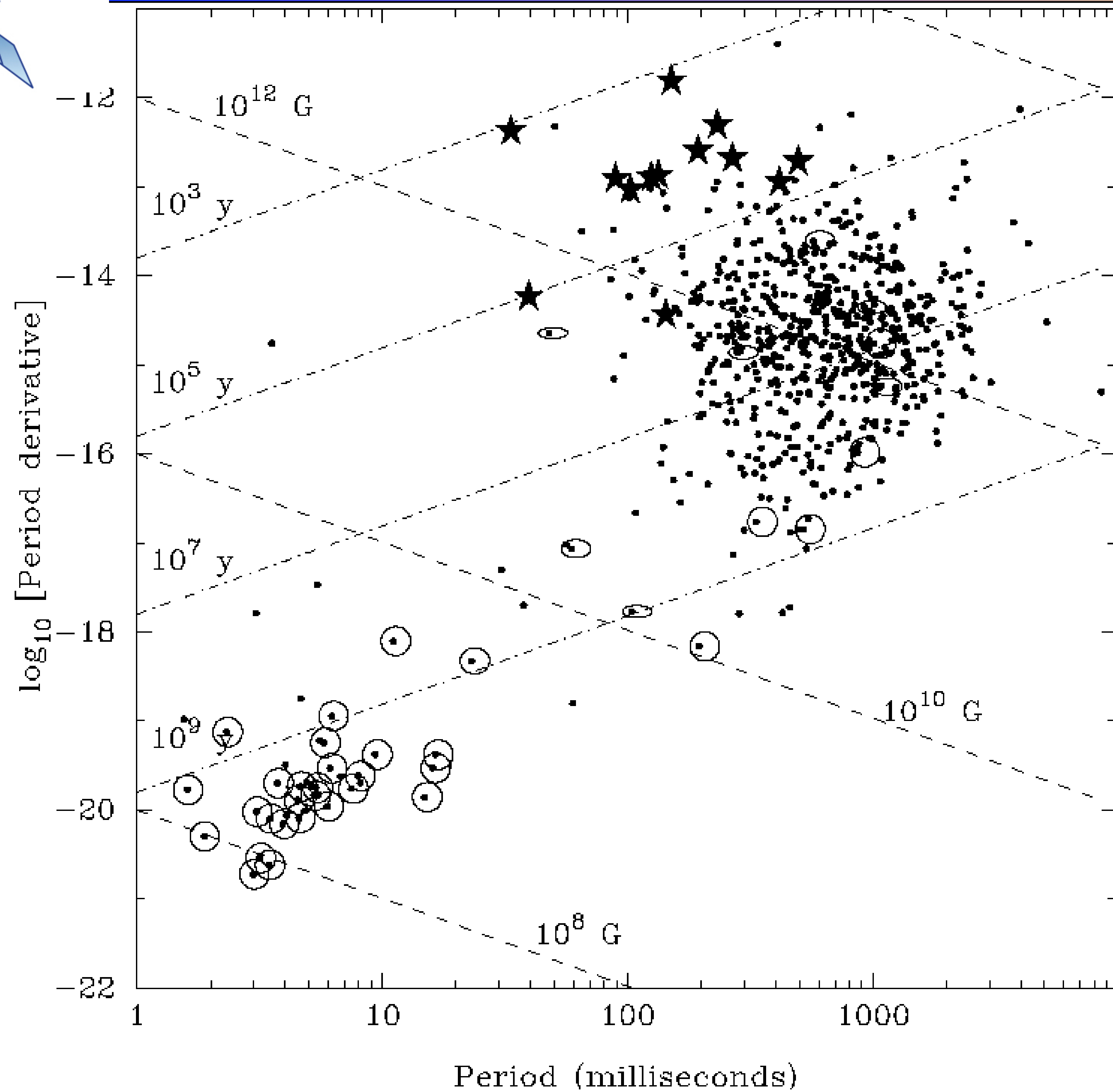
- Energy loss causes observed slow-down of pulsar spin:

$$\dot{E} = I\omega\dot{\omega} = \frac{4\pi^2 I\dot{P}}{P^3}$$

Magnetic dipole model

- Identifying magnetic dipole radiation as energy loss mechanism gives $P\dot{P} \propto B^2$
- An "age" can also be estimated (time to spin down to observed frequency, assuming fast initial spin and fixed magnetic field): $\tau \approx P/2\dot{P}$

The pulsar population

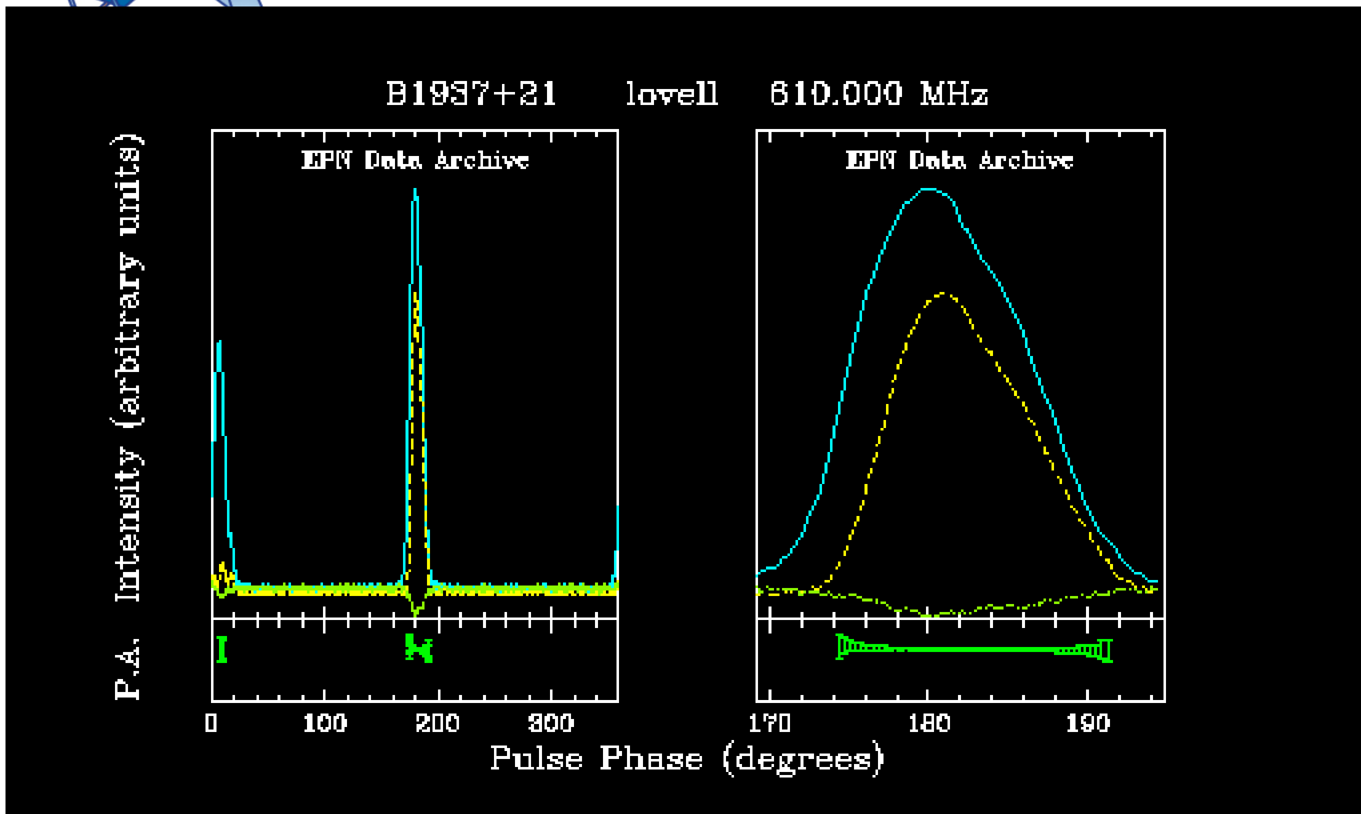


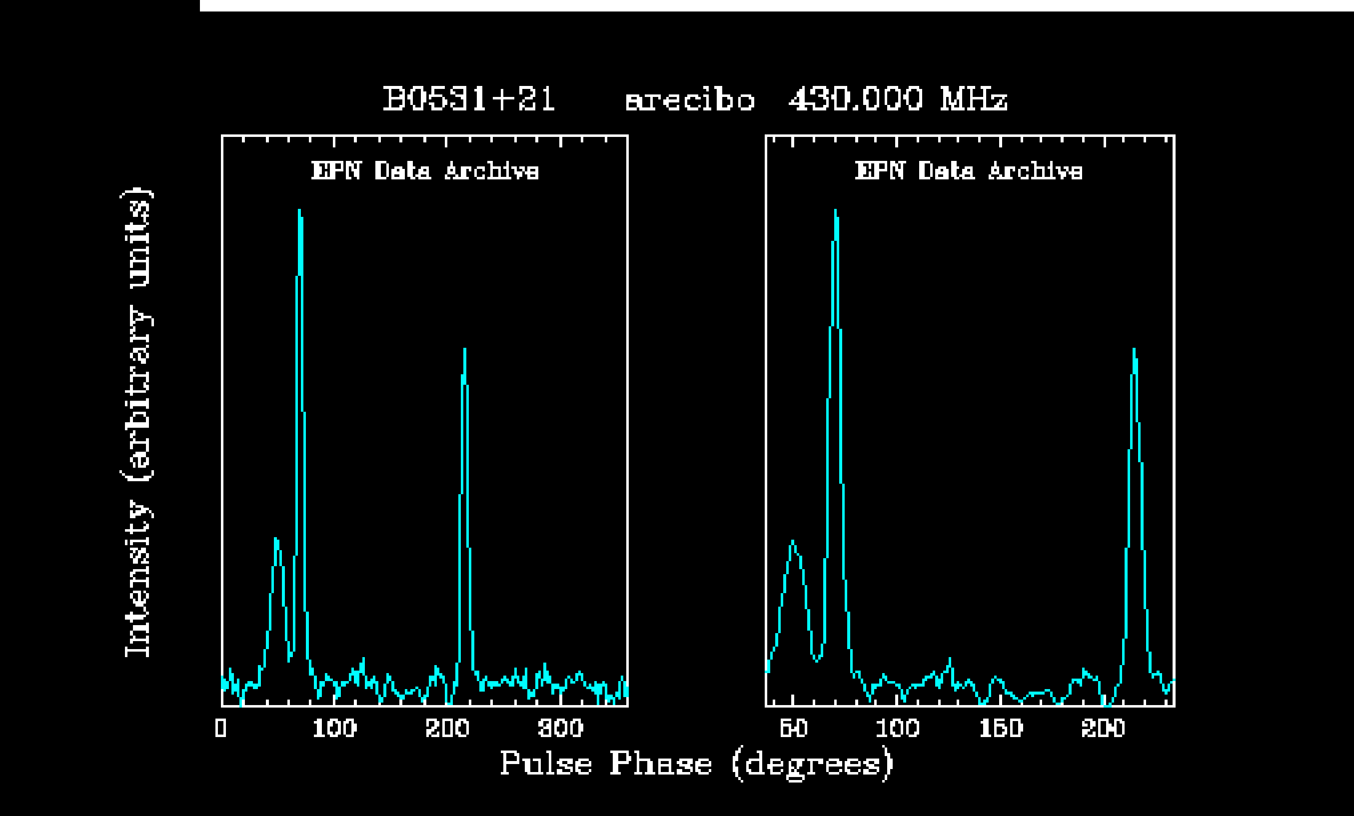
http://relativity.livingreviews.org/Articles/lrr-2001-5/fig07.gif

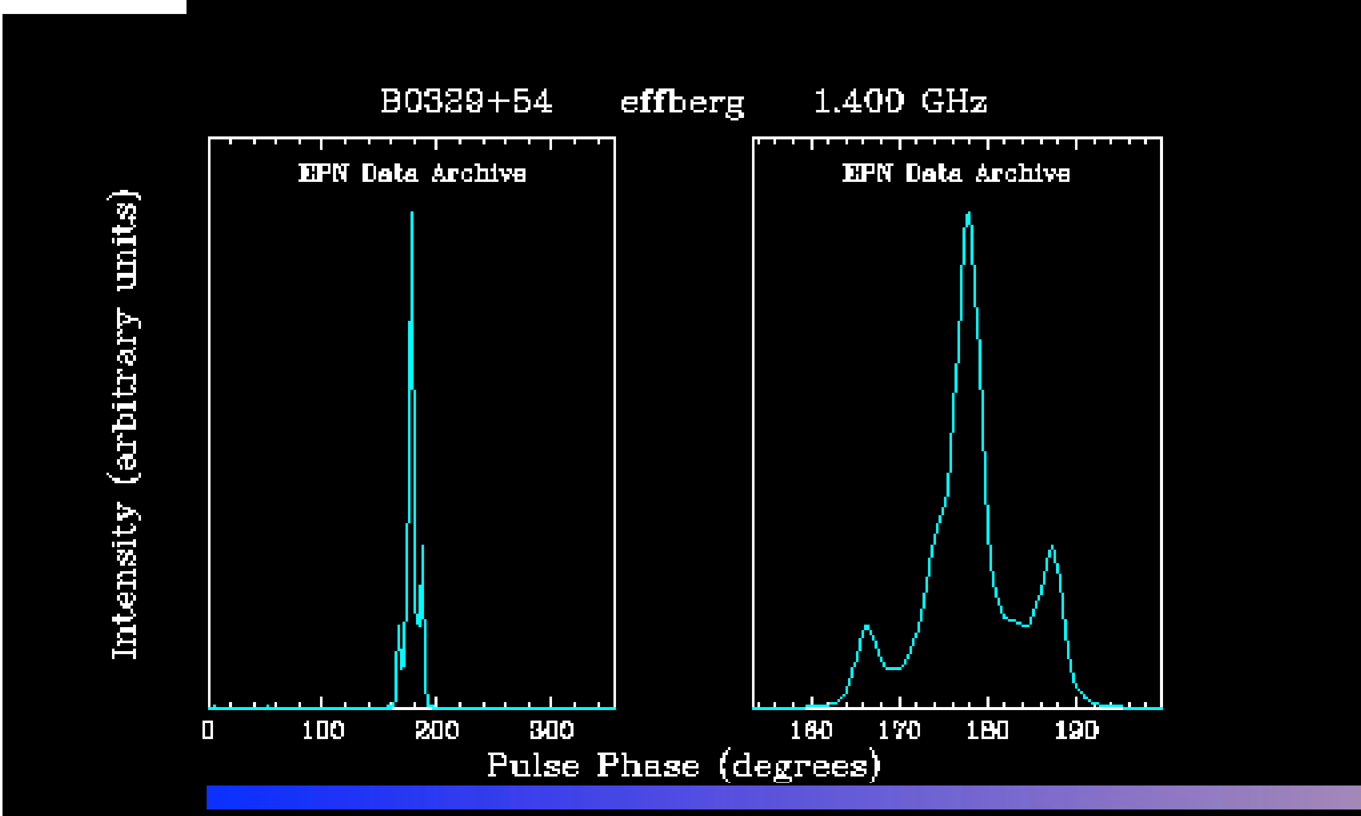
The radio pulsar population

- There are now over 1500 radio pulsars known
- Magnetic fields range from ~10^8 to ~10^13G
- Ages range from 10^3 to 10^10 years
- Periods range from 1.5 milliseconds to 8 seconds
- Distances range from ~10^2 pc to ~50 kpc
- Radio phenomenology is extremely complex (giant pulses, nulling, drifting subpulses, mode changing, orthogonal polarization models, ...)

Some radio profiles



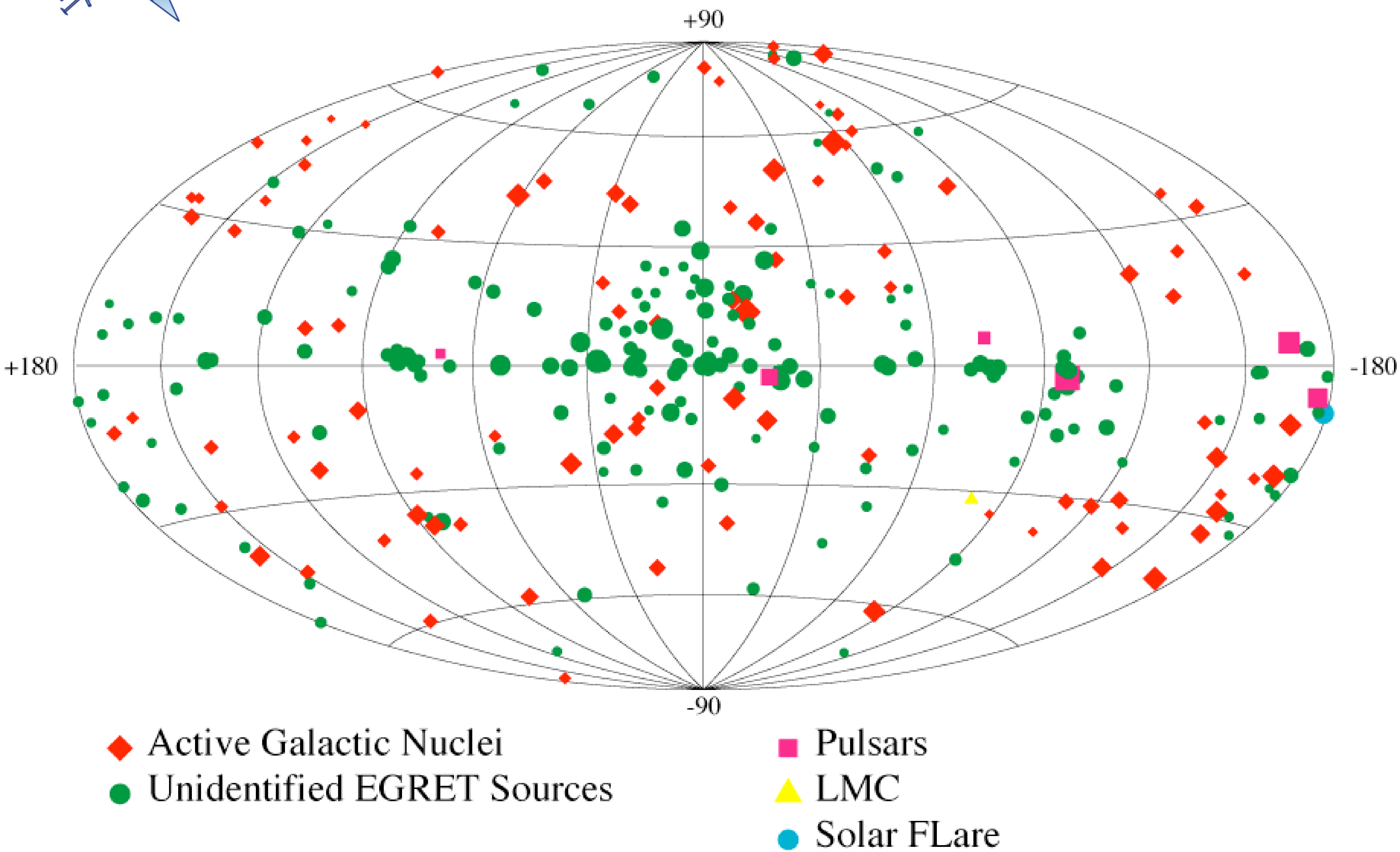




High energy emission from pulsars

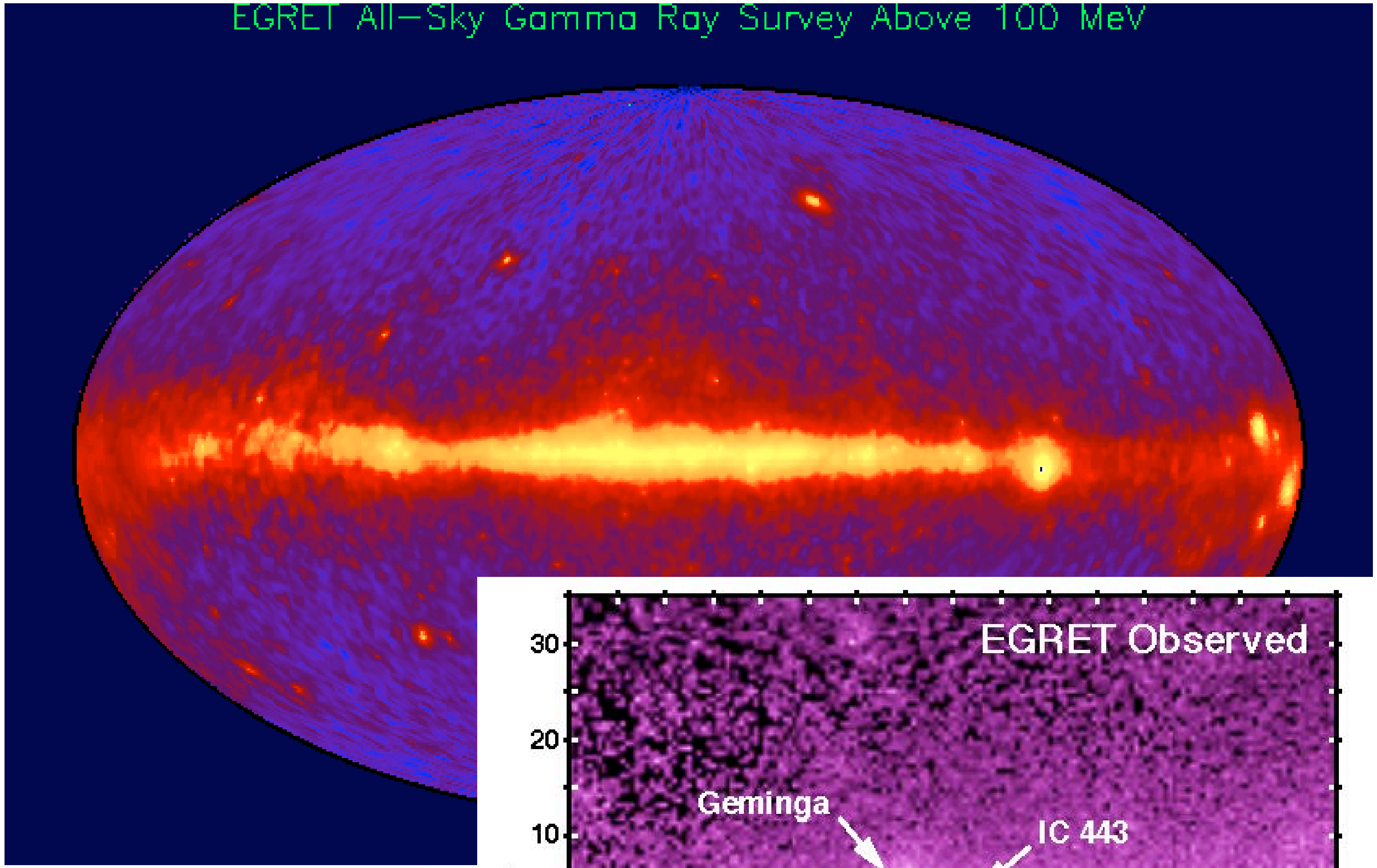
- Pulsars were first gamma-ray detections
  - Pulsars in the Crab and Vela supernova remnants were detected as pulsed sources by SAS-2 and COS-B in late 1970s
  - No other successes until:
- EGRET on the Compton Gamma-Ray Obs.
  - Had three additional pulsars (Geminga, B1055-52, and B1706-44) in source catalog
  - Found B1951+32 with additional analysis (and probably B1046-58)
  - Detected B1509-58 in hard X-ray/soft gamma-ray bands only (below 30 GeV)

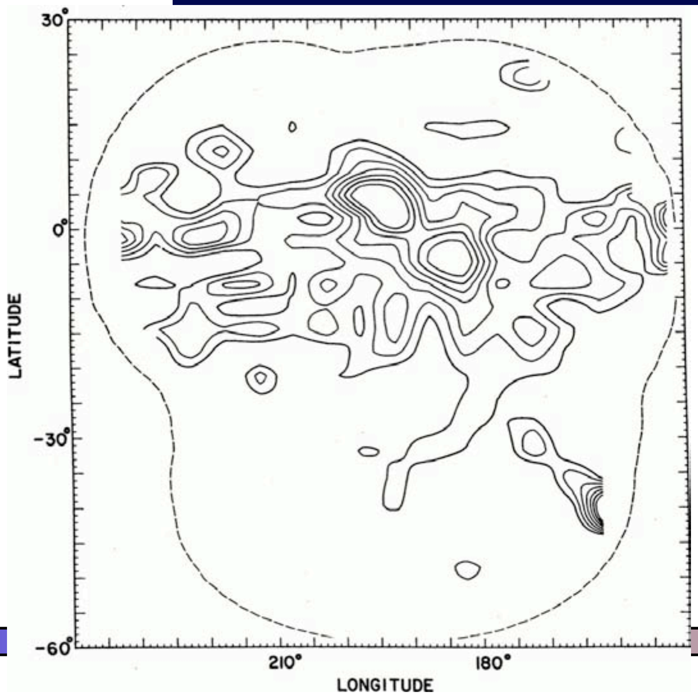
3rd Egret catalog (E>100 MeV)

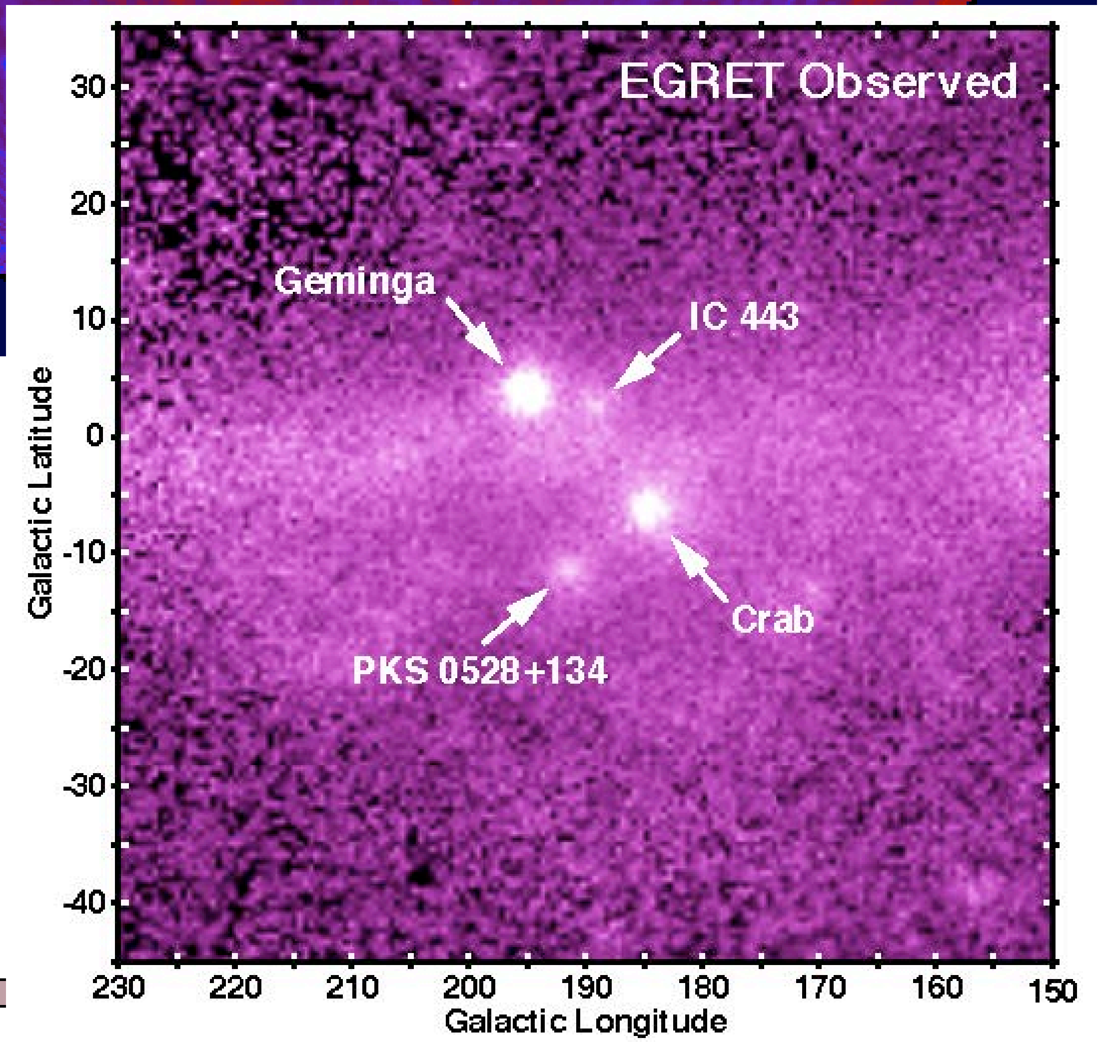


Interlude: the story of Geminga

- Geminga was discovered by SAS-2 in 1972
- Second brightest gamma-ray source
- No long-wavelength counterpart (faint x-ray)





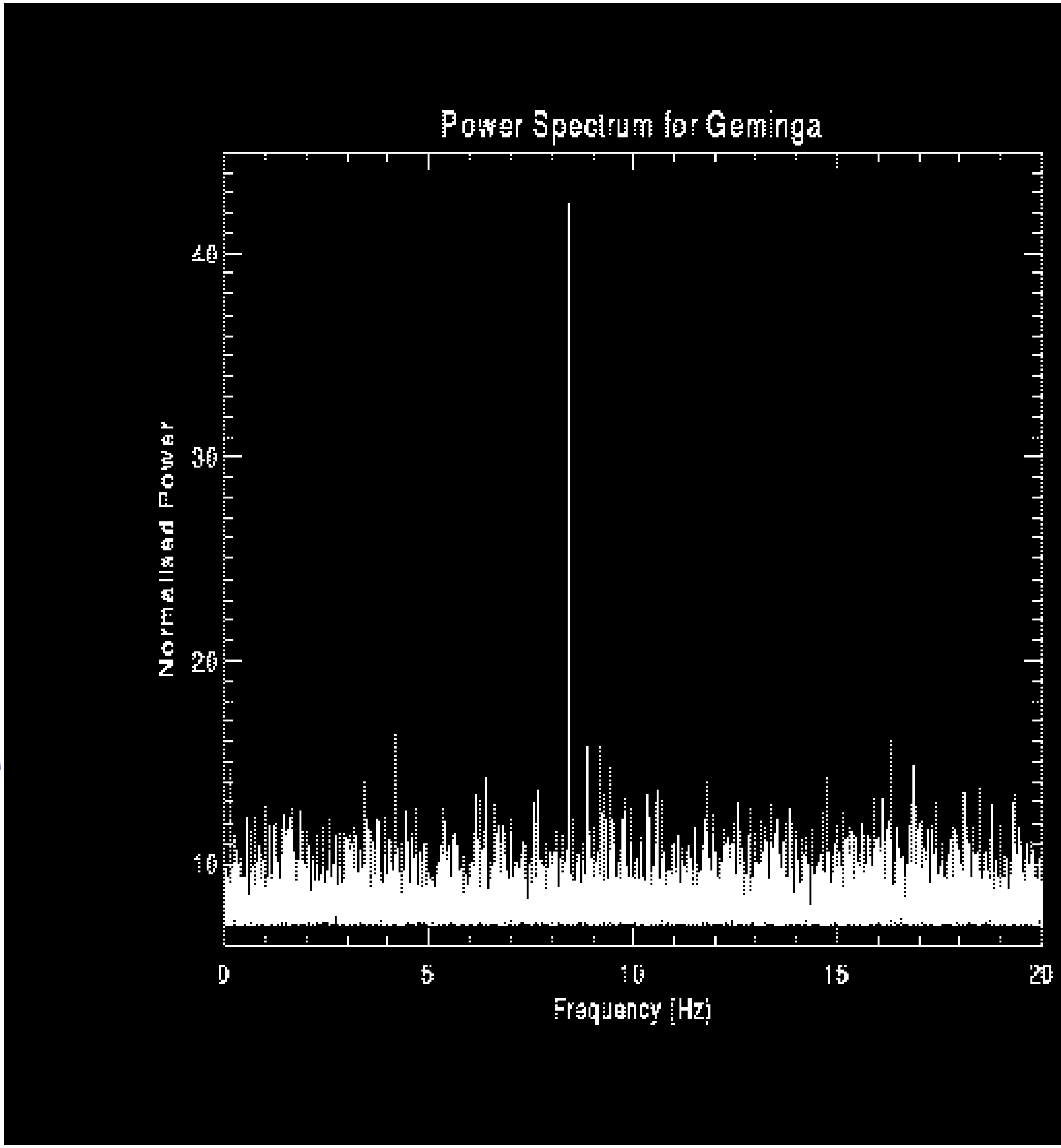


The Geminga pulsar

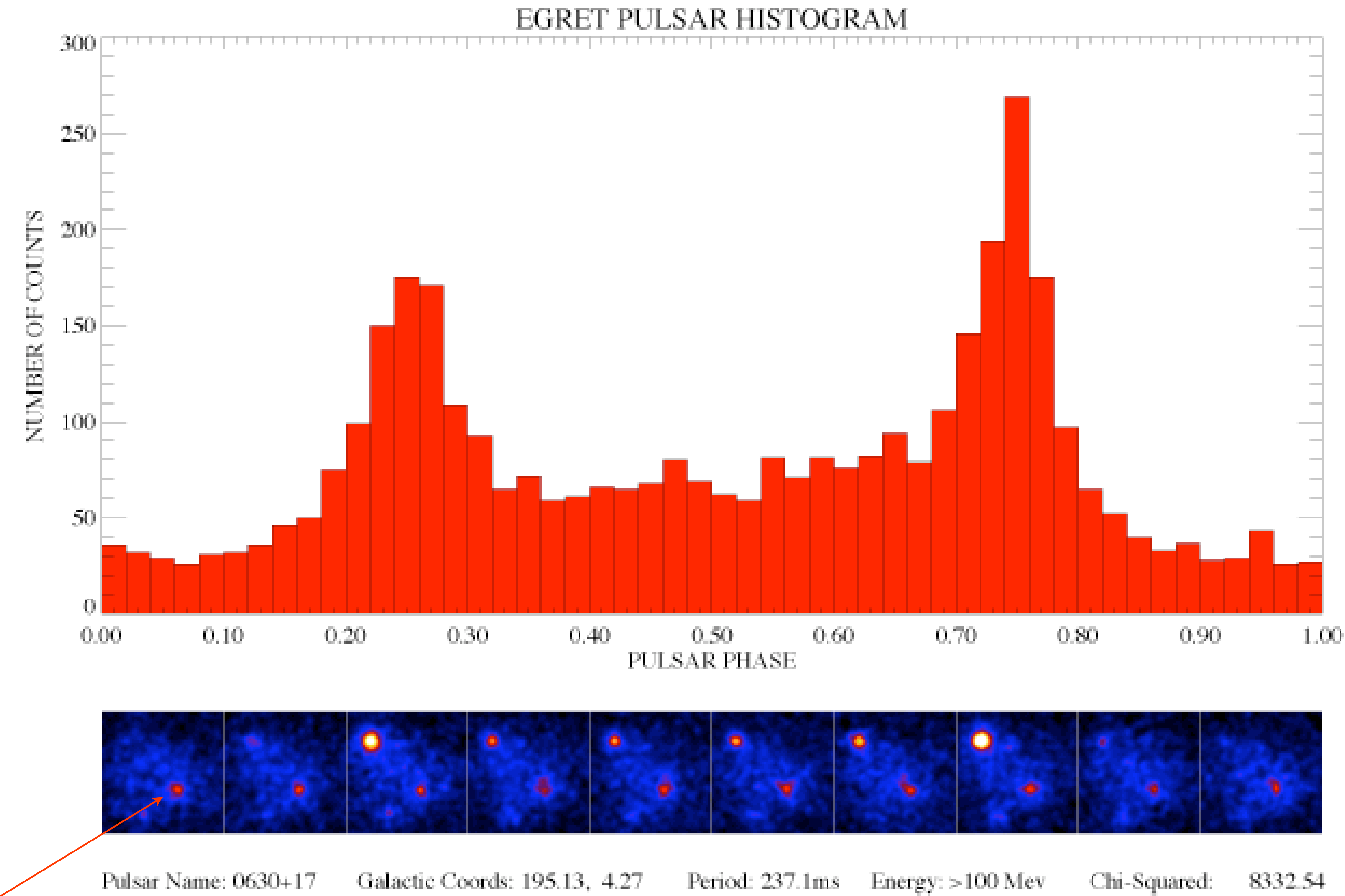
- 20 years later, Halpern et al. were able to find a 237 millisecond period in 7000 photons detected by ROSAT
- The period was confirmed by EGRET (showing that the x-ray source and gamma-ray source were the same)
- (almost certainly) not detectable at radio wavelengths
  - two claimed detections around 100 MHz, with different profiles, and claims for unique variability and other properties
  - apparently inconsistent upper limits at both higher and lower freqs.

Geminga: a missed EGRET opportunity

- The pulsar was detectable by EGRET
- This is a 2^28 point FFT
- The (largely Caltech based) EGRET pulsar search team was scooped while waiting for data to be publicly released



The Geminga light curve

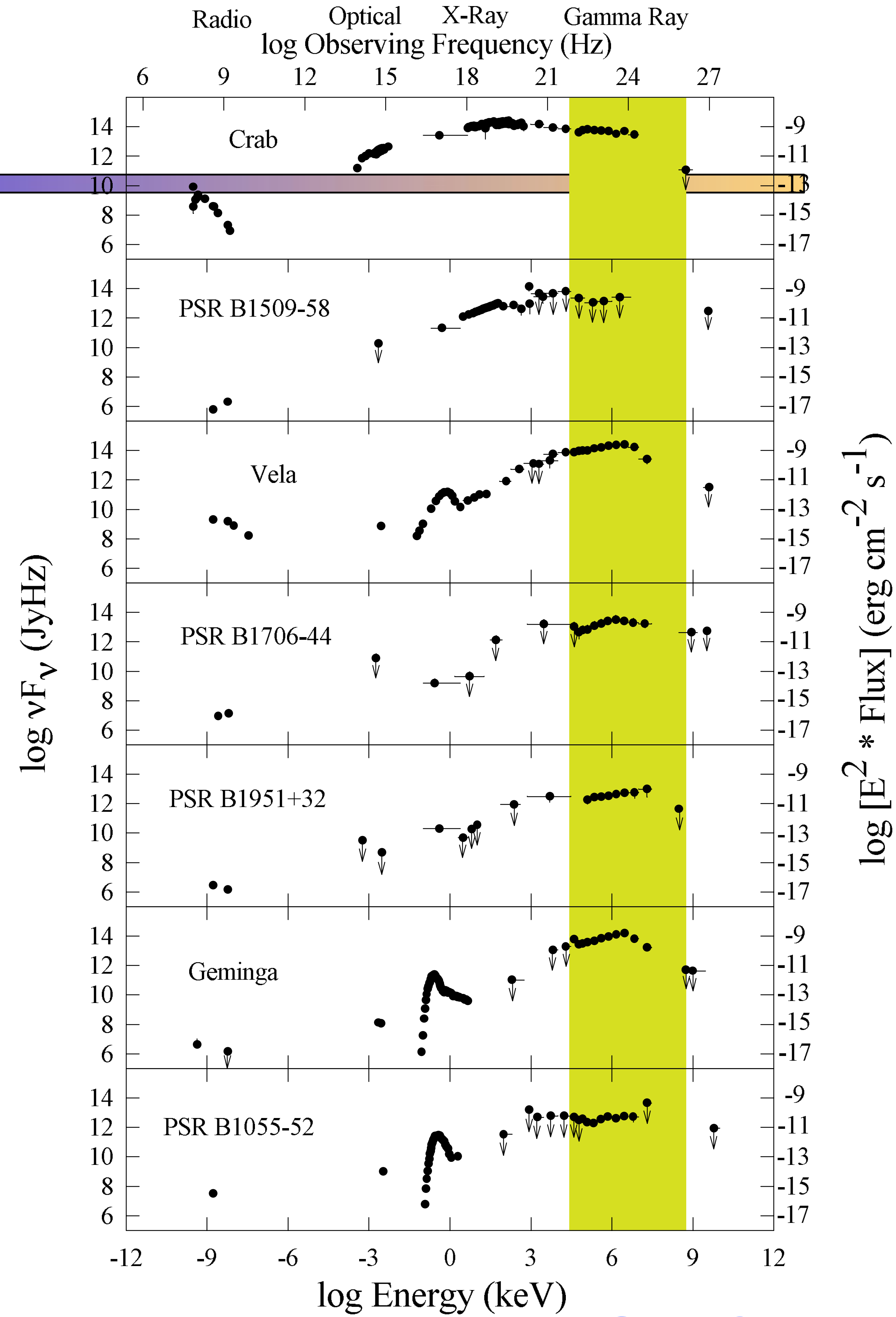


Note the Crab pulsar too!

Credit: P. Sreekumar (NASA/GSFC)

Spectra

- In power per log energy band, spectra peak in hard x-ray to gamma-ray
- GLAST sensitivity is near spectral peak
- Radio band is energetically unimportant



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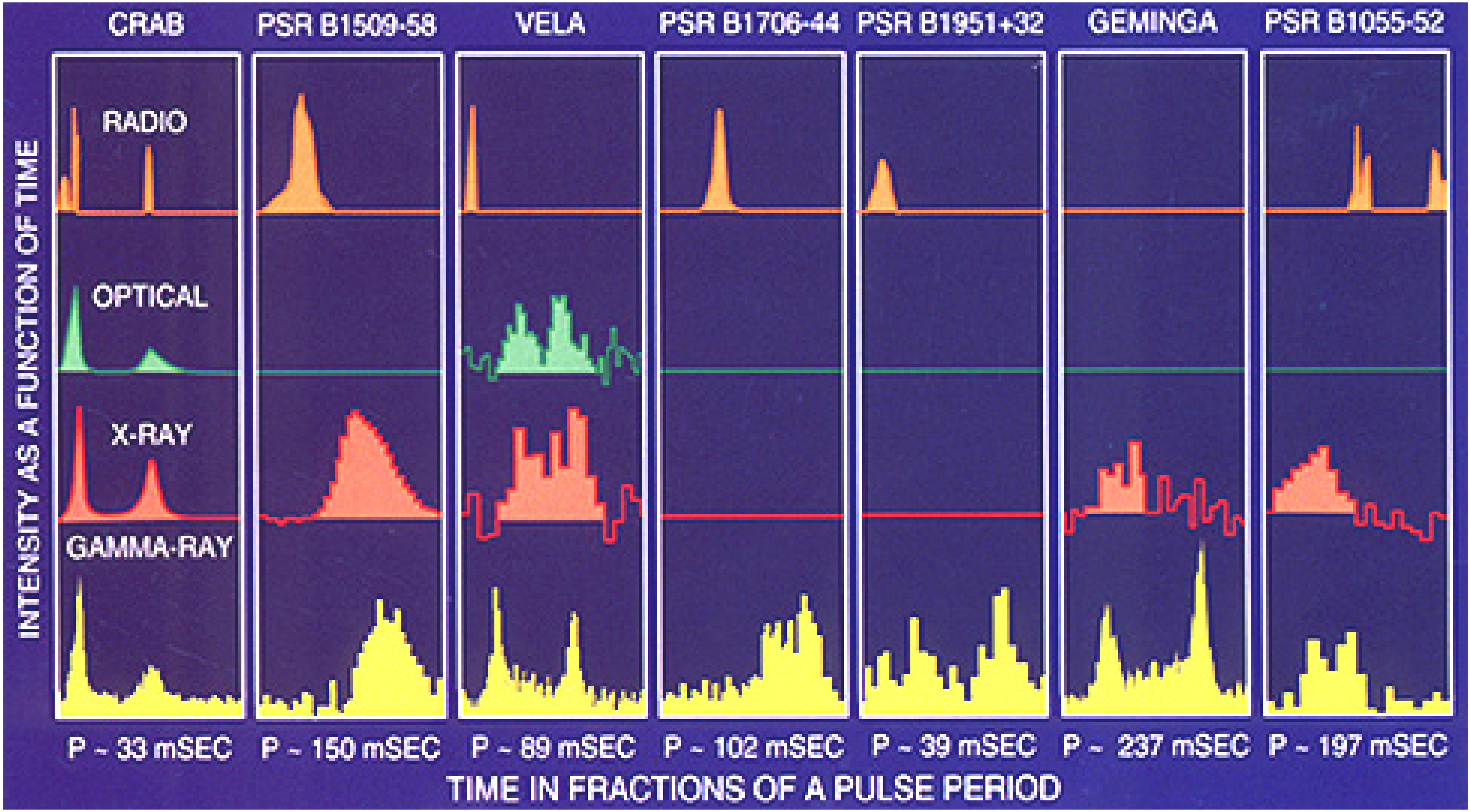
The "gamma-ray pulsars"

Pulsar	P s	τ yr	$\dot{E}$ erg s^{-1}	F_E erg cm^{-2}s^{-1}	d kpc	L_{HE} erg s^{-1}	η
Crab	0.033	1300	4.5×10^{38}	1.3×10^{-8}	2.0	5.0×10^{35}	0.001
B1509−58	0.150	1500	1.8×10^{37}	8.8×10^{-10}	4.4	1.6×10^{35}	0.009
Vela	0.089	11,000	7.0×10^{36}	9.9×10^{-9}	0.5	2.4×10^{34}	0.003
B1706−44	0.102	17,000	3.4×10^{36}	1.3×10^{-9}	2.4	6.9×10^{34}	0.020
B1046−58	0.124	20,000	2.0×10^{36}	2.5×10^{-10}	3.0	2.1×10^{34}	0.011
B1951+32	0.040	110,000	3.7×10^{36}	4.3×10^{-10}	2.5	2.5×10^{34}	0.007
Geminga	0.237	340,000	3.3×10^{34}	3.9×10^{-9}	0.16	9.6×10^{32}	0.029
B1055−52	0.197	530,000	3.0×10^{34}	2.9×10^{-10}	1.5	6.2×10^{33}	0.20

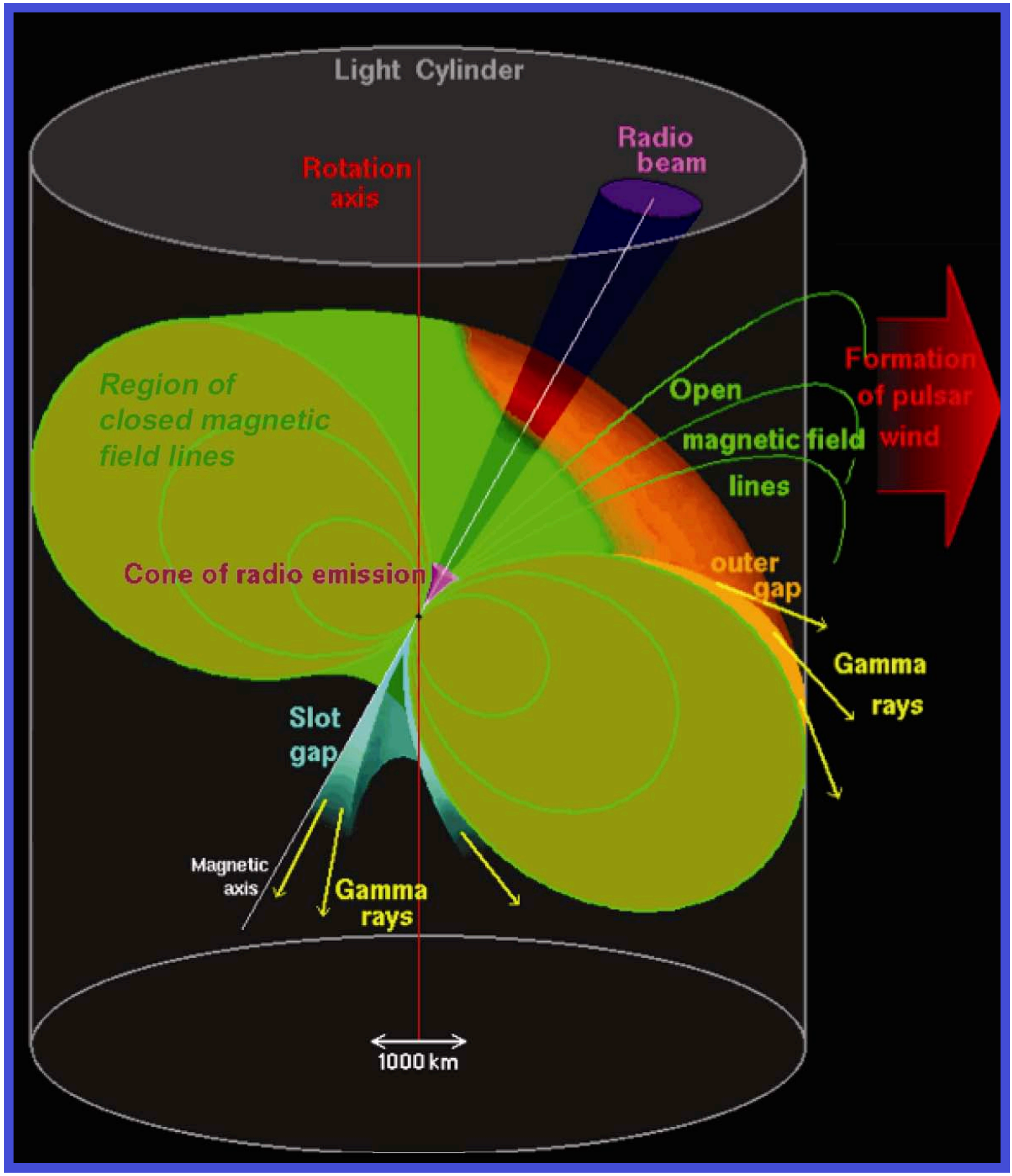
Table 1: *Summary of properties of known γ-ray pulsars, from refs. [14, 16]. Pulsars are ordered by increasing characteristic age τ. The high-energy luminosity L_{HE} is estimated assuming the pulsars radiate into 1 sr; true luminosity may be smaller than or up to 4π larger than this estimate. The efficiency η is the ratio of L_{HE} to the total spin-down luminosity $\dot{E}$.*

Multiwavelength pulsar profiles



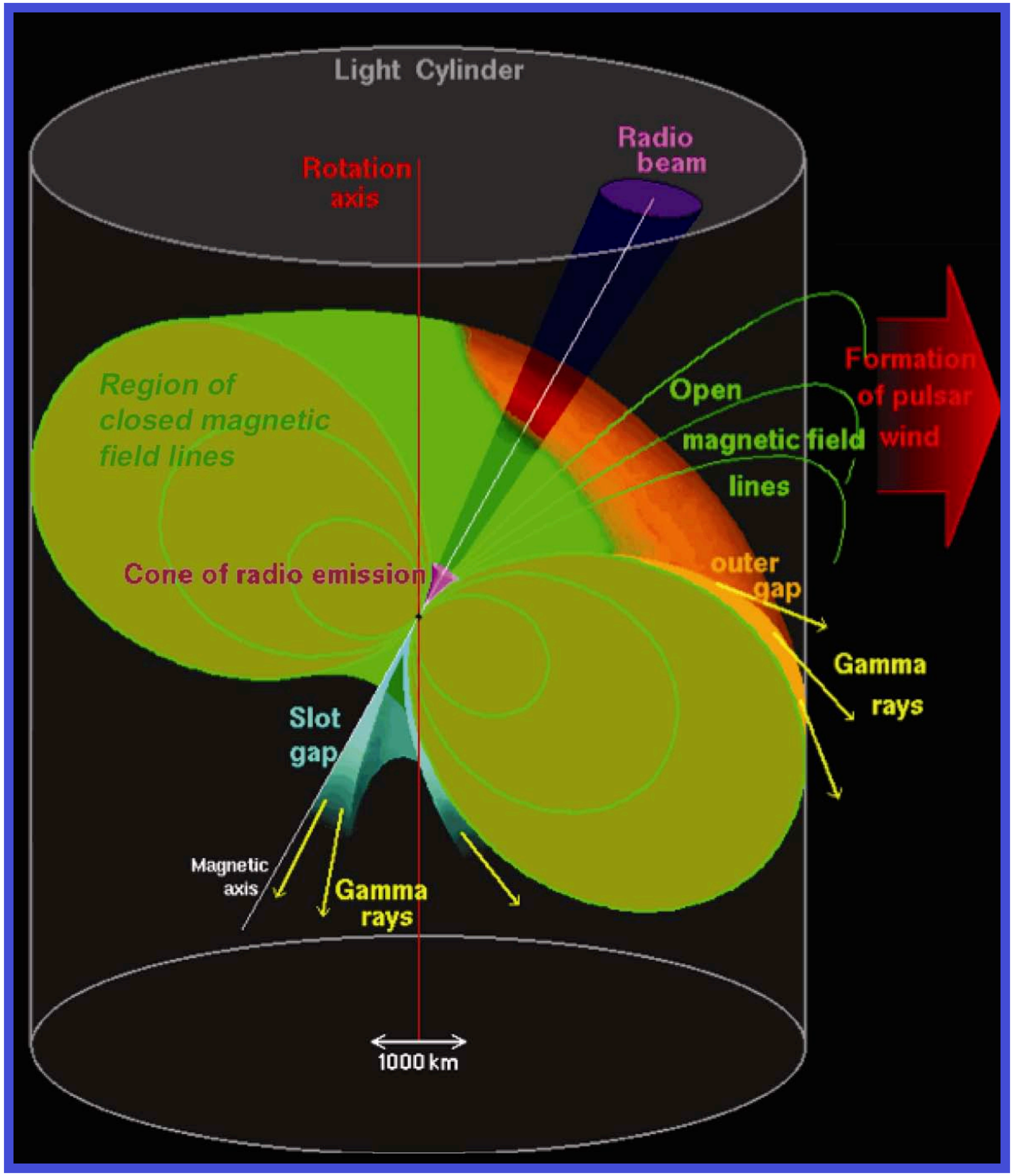
Polar cap models

- Acceleration of particles along curved field lines above poles produces curvature radiation or inverse Compton
- Predict sharp high energy attenuation by pair production on B field at a few GeV



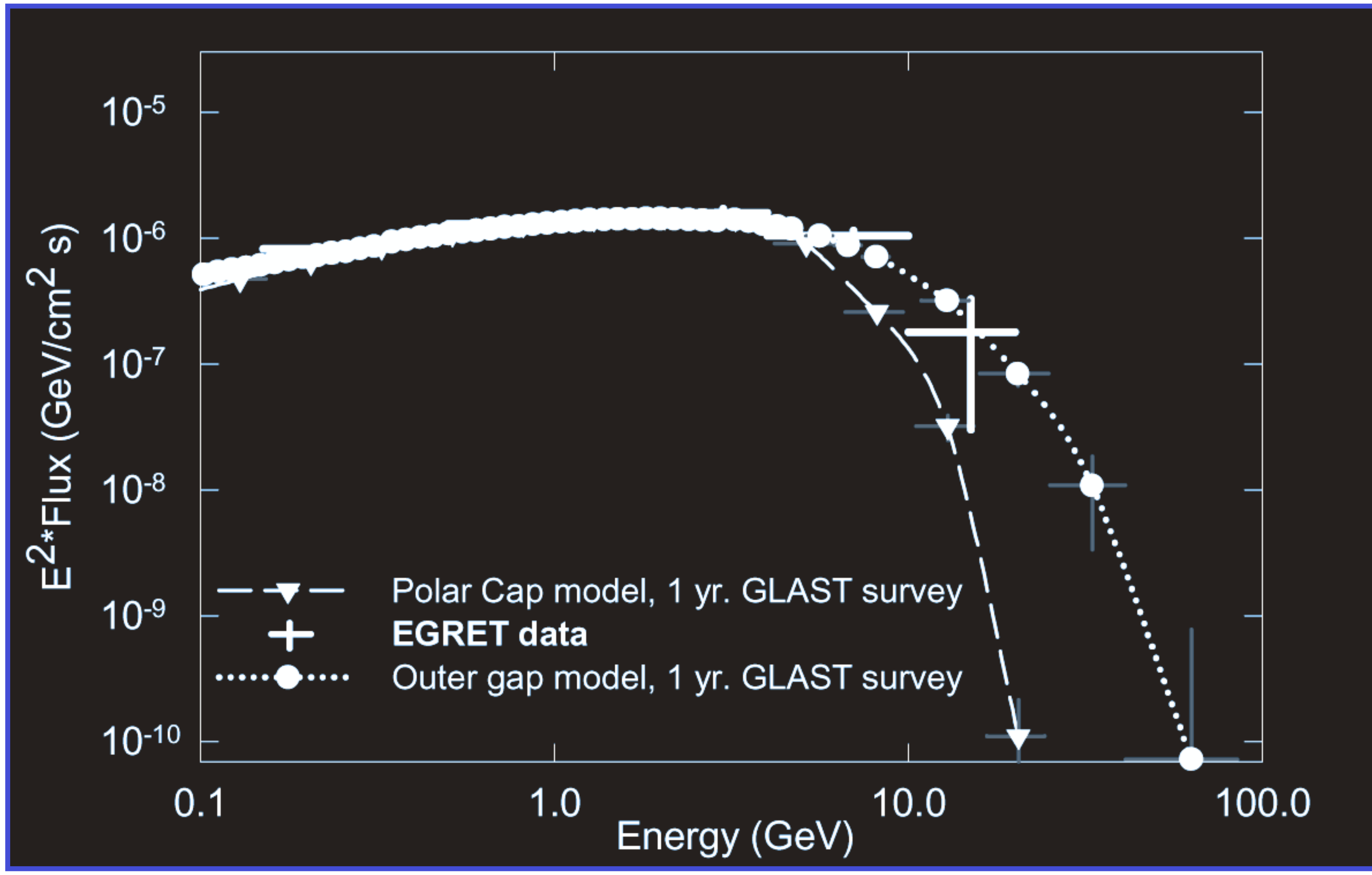
Outer gap models

- particles accelerated across vacuum gaps in outer magnetosphere
- cascades seeded by photon-photon pair production
- predict more gradual high energy cutoffs



Model predictions

- Polar cap and outer gap models are both rich, well-developed theories (subject for different talk)
- They make different predictions for high energy spectra:



- They make different predictions for beam geometries:

A beaming prediction example

- This is an example calculation (from Yadigaroglu and Romani 1995) for an outer gap model
- Polar cap models have much more overlap between radio and gamma-ray bright pulsars

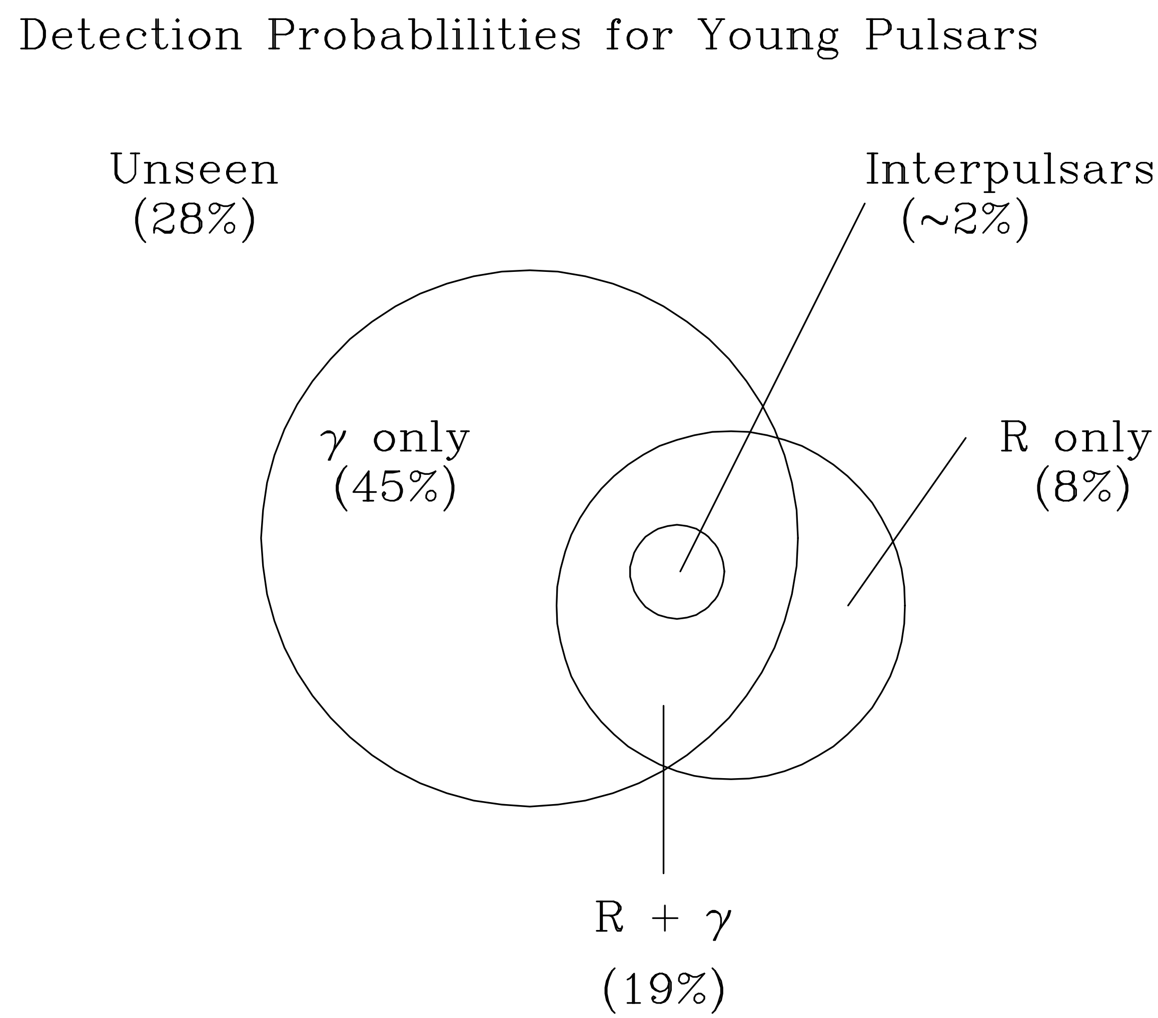


Figure 4: *The fraction of pulsars beaming towards the Earth in radio and γ-ray bands, in one outer-gap model (figure from ref. [43]). In this model, wide γ-ray emission beams imply that nearly 2/3 of pulsars are detectable in γ-rays, while just over a quarter are radio-detectable.*

Mid-course summary

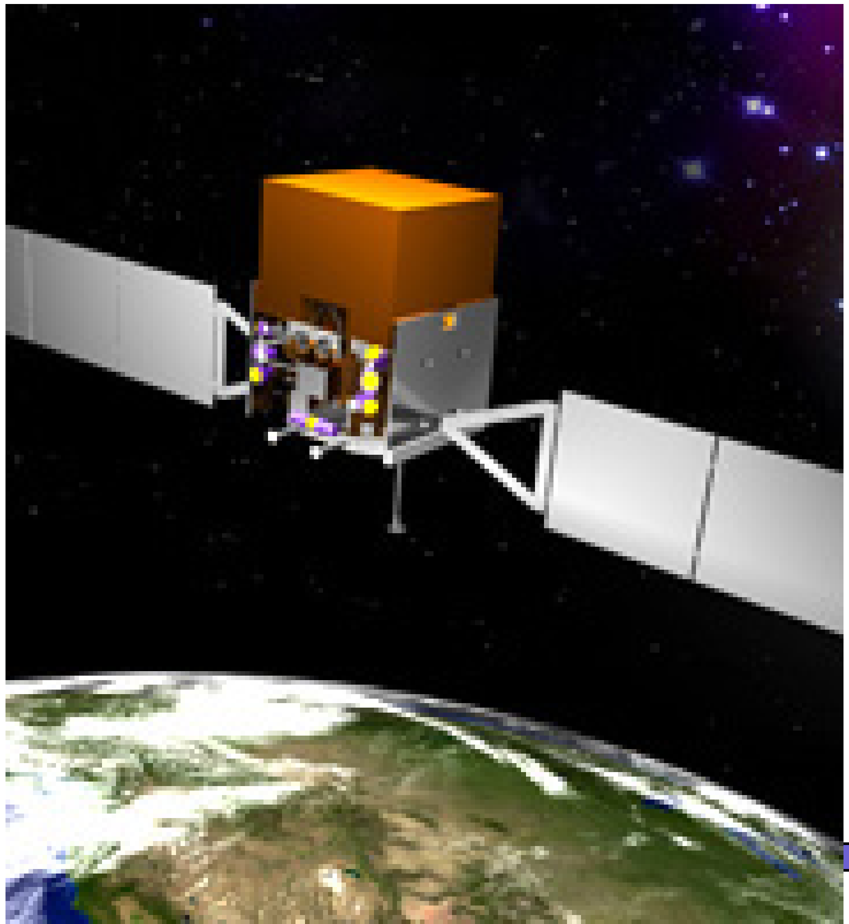
- Why study pulsars at high energy?
  - Pulsars are prodigious high energy particle accelerators
  - Gamma-rays are the "natural" energy band for so-called radio pulsars, around the spectral peak
  - Gamma-ray emission is "simple" in a way radio emission isn't:
    - —radio emission is a coherent process, not dependent in a simple way on primary particle energies and densities
    - —gamma-ray models make relatively straightforward predictions about spectral properties
    - —those of us who fear we are studying "weather" in the radio might hope to be studying "climate" at high energy

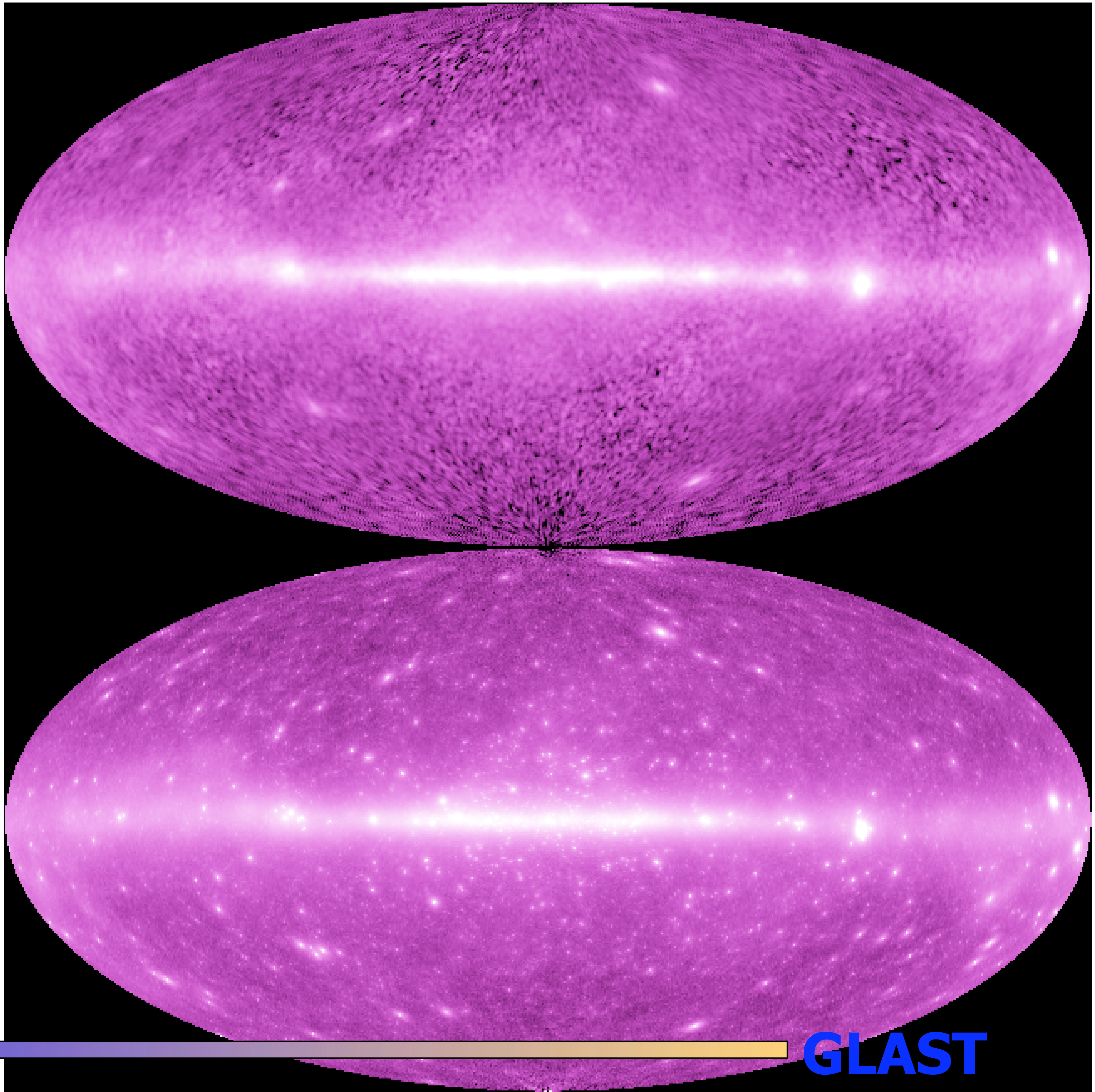
Mid-course summary

- Why study pulsars at high energy?
  - Beaming properties are different
    - —we believe gamma-ray beams are larger
    - —in any case, comparisons of radio and gamma-ray beaming fractions will give us a better estimate of the fraction of pulsars that is observed
  - Gamma-rays are penetrating
    - —radio telescopes are “more sensitive” in the sense that they detect (and will continue to detect) far more pulsars
    - —however, radio observations near the Galactic center are difficult because of dispersion and scattering
  - We get a better estimate of the pulsar birth rate/core collapse supernova rate/massive star birth rate/nucleosynthesis rate both locally and near the Galactic center

So what will GLAST actually see?

- GLAST will be roughly a factor 30 more sensitive than EGRET





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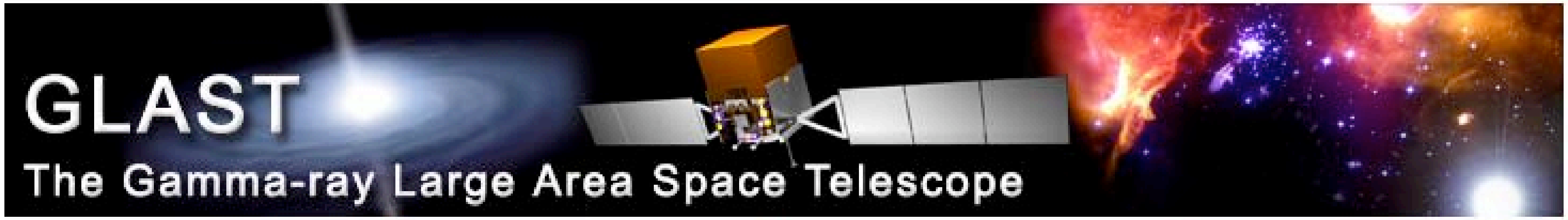

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Science Info

Overview
Instruments
+ Large Area Telescope
+ Burst Monitor
Science Support Center
Science Working Group
Users' Committee
Multiwavelength Observations
GRB/SF Science Team
Resources

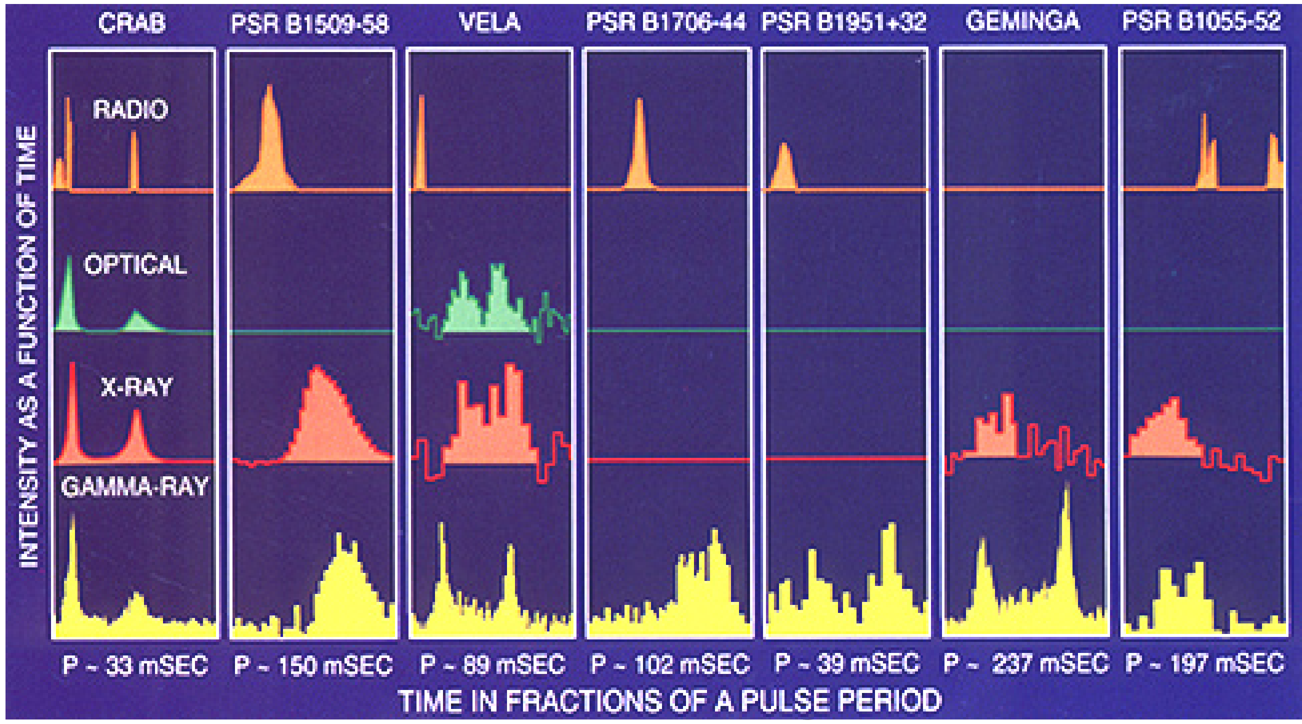
LAT Specifications and Performance Compared with EGRET

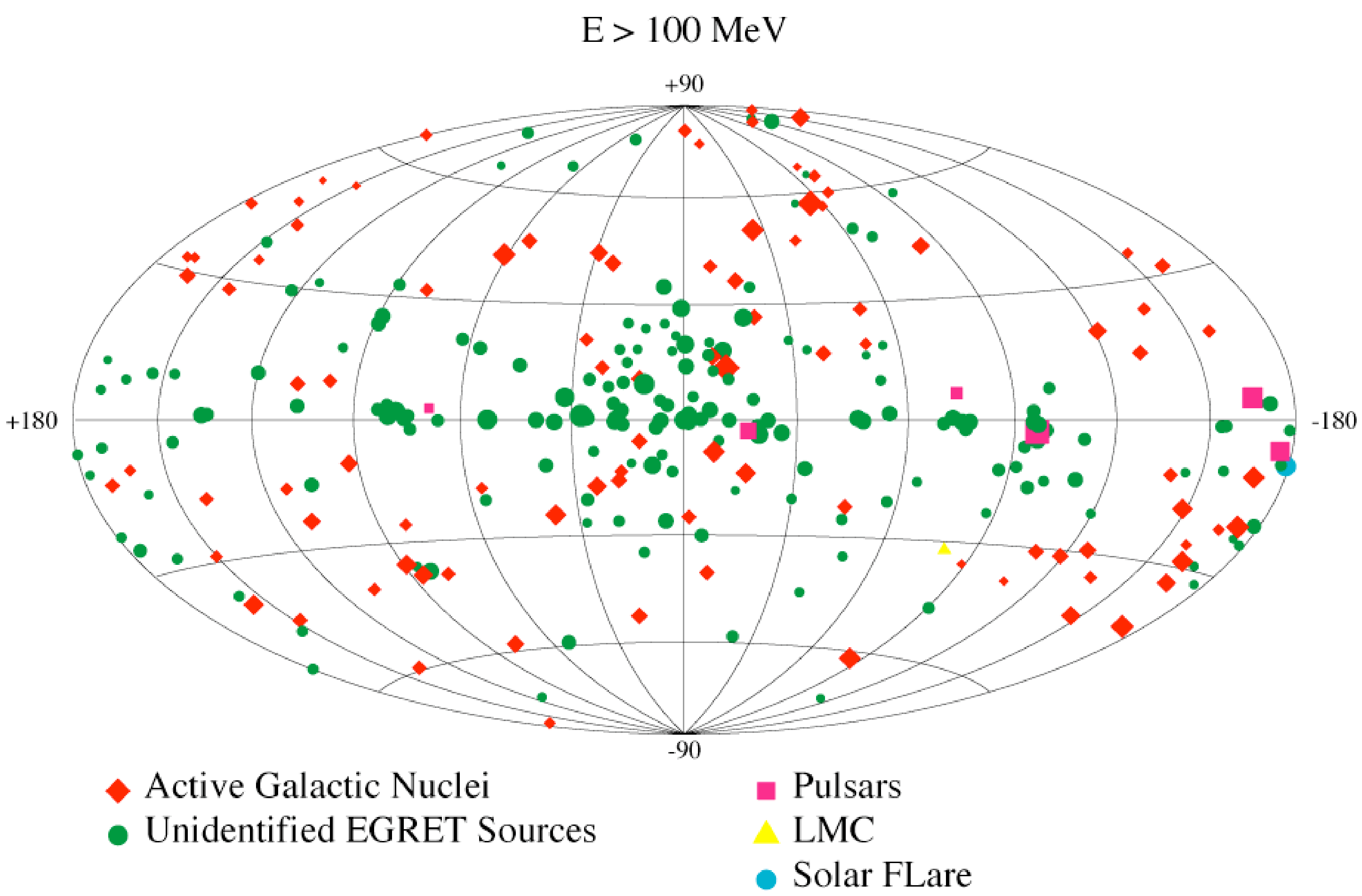
Quantity	LAT (Minimim Spec.)	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area[1]	> 8000 cm^2	1500 cm^2
Field of View	> 2 sr	0.5 sr
Angular Resolution[2]	< 3.5° (100 MeV) < 0.15° (>10 GeV)	5.8° (100 MeV)
Energy Resolution[3]	< 10%	10%
Deadtime per Event	< 100 μs	100 ms
Source Location Determination[4]	< 0.5'	15'
Point Source Sensitivity[5]	$< 6 \times 10^{-9}\ cm^{-2}\ s^{-1}$	$\sim 10^{-7}\ cm^{-2}\ s^{-1}$

[1] After background rejection
[2] Single photon, 68% containment, on-axis
[3] 1-σ, on-axis
[4] 1-σ radius, flux $10^{-7}\ cm^{-2}\ s^{-1}$ (>100 MeV), high $|b|$
[5] > 100 MeV, at high $|b|$, for exposure of one-year all sky survey, photon spectral index -2

For known sources...

- GLAST will have high signal-to-noise on known gamma-ray pulsars, allowing phase resolved spectroscopy
- GLAST can do blind pulsation sources roughly to the EGRET detection limit



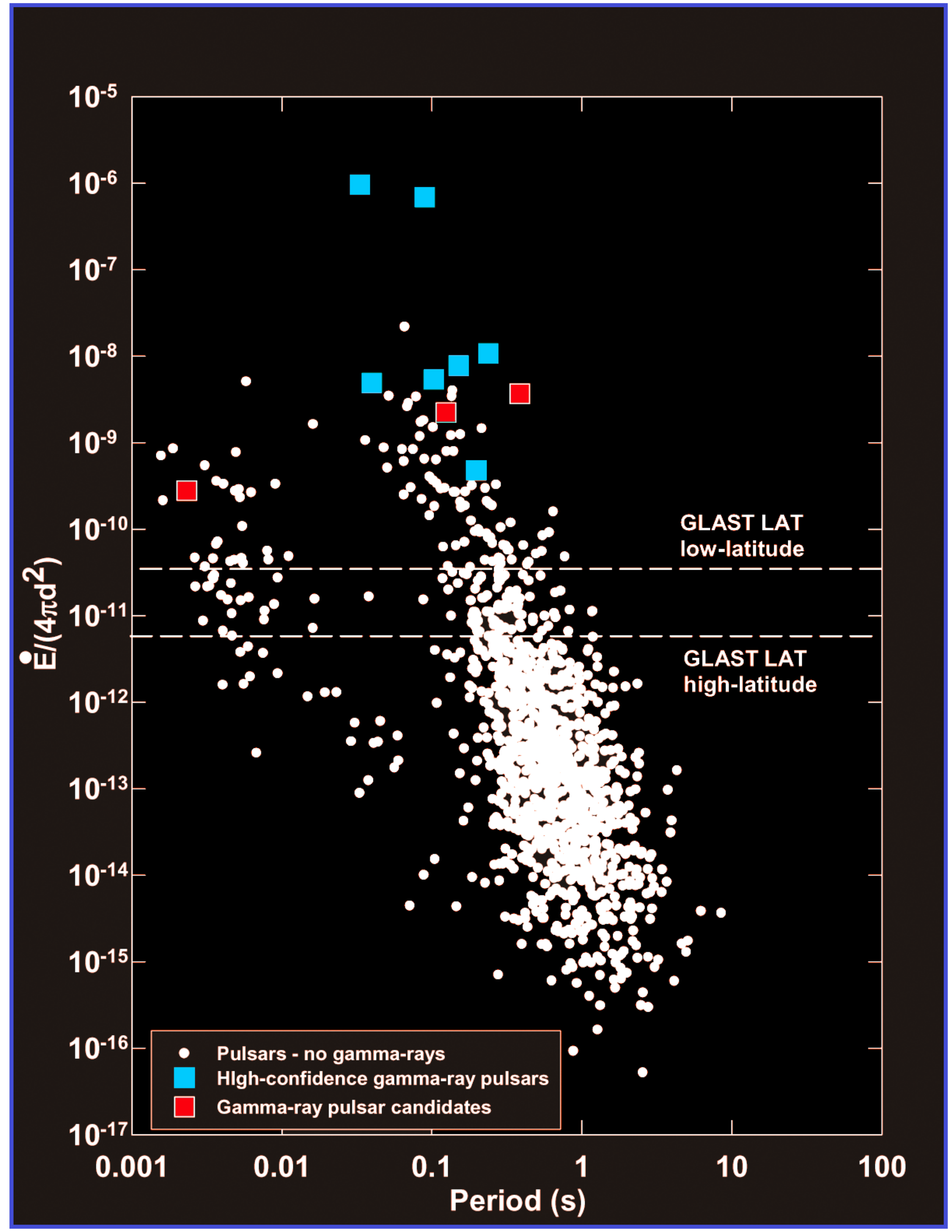


What other pulsars might GLAST see?

- One might expect $\dot{E}/d^2$ to be a useful predictor
- If pulsars are sorted by this metric, the eight EGRET pulsars are ranked 1-6, 9, and 24
- (Remember that distance is only very poorly known in the vast majority of cases)

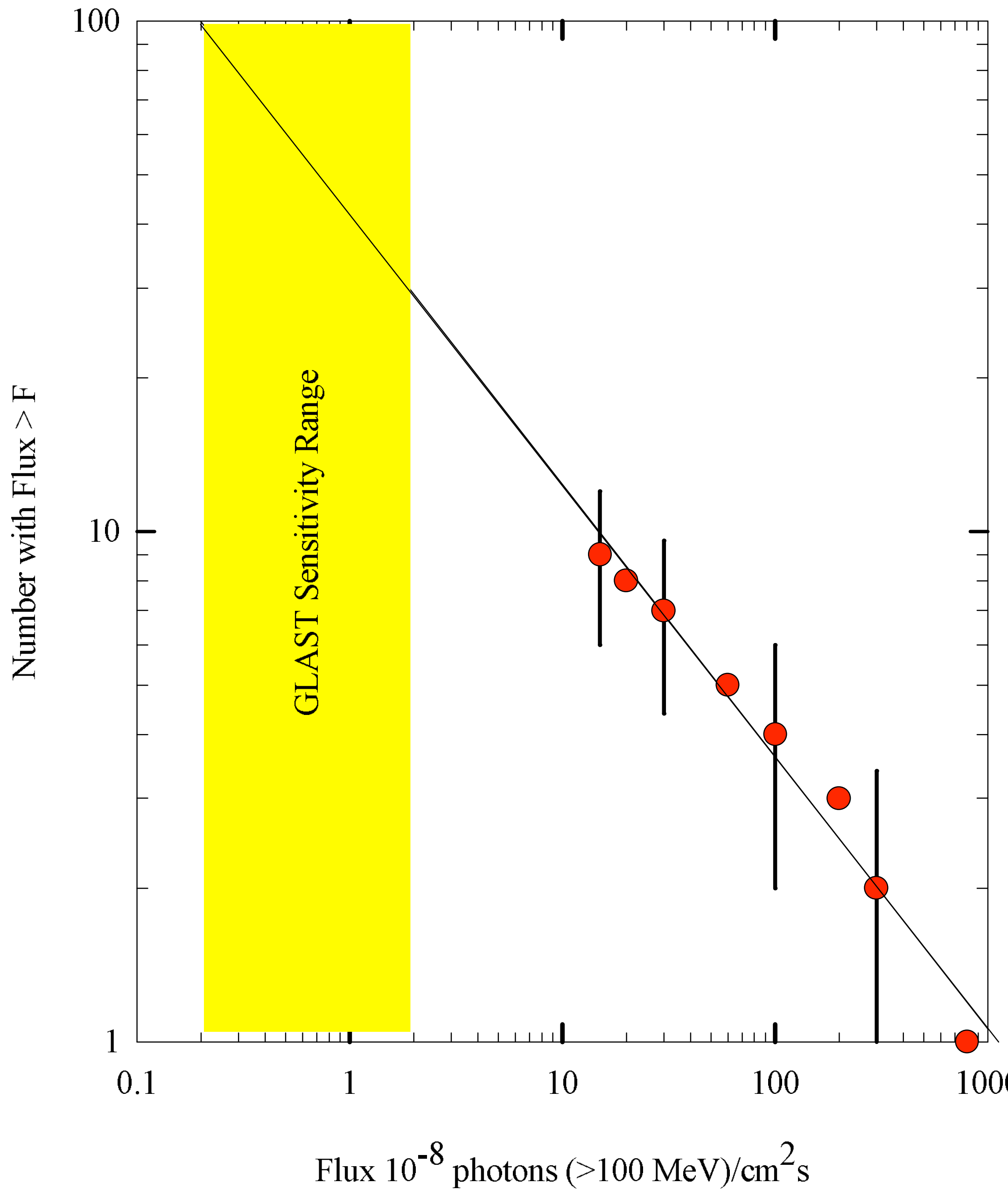
Below the tip of the iceburg

- EGRET is clearly seeing only the very most luminous (e.g., Crab) and closest (e.g., Geminga) pulsars
- The number of expected detectable targets increases very steeply as sensitivity improves



Some predictions

- Estimates depend sensitively on beam geometry assumptions
  - Gonthier et al. (2004, polar cap): 276 radio quiet, 344 radio loud
  - McLaughlin and Cordes (2000): 750, of which 120 are currently known radio pulsars
- Thompson (2001) predicts roughly 100 based on simple extrapolation



BUT

- These pulsars won't be trivial to find
- Most will be near threshold, so will require integrating over years (even the full 10 year mission)
- Pulsars exhibit both phase wobble and glitches

left. The average period is about 0.8 s. (Figure from Taylor, Manchester, and Lyne, *Ap. J. Suppl.*, *88*, 529, 1993.)

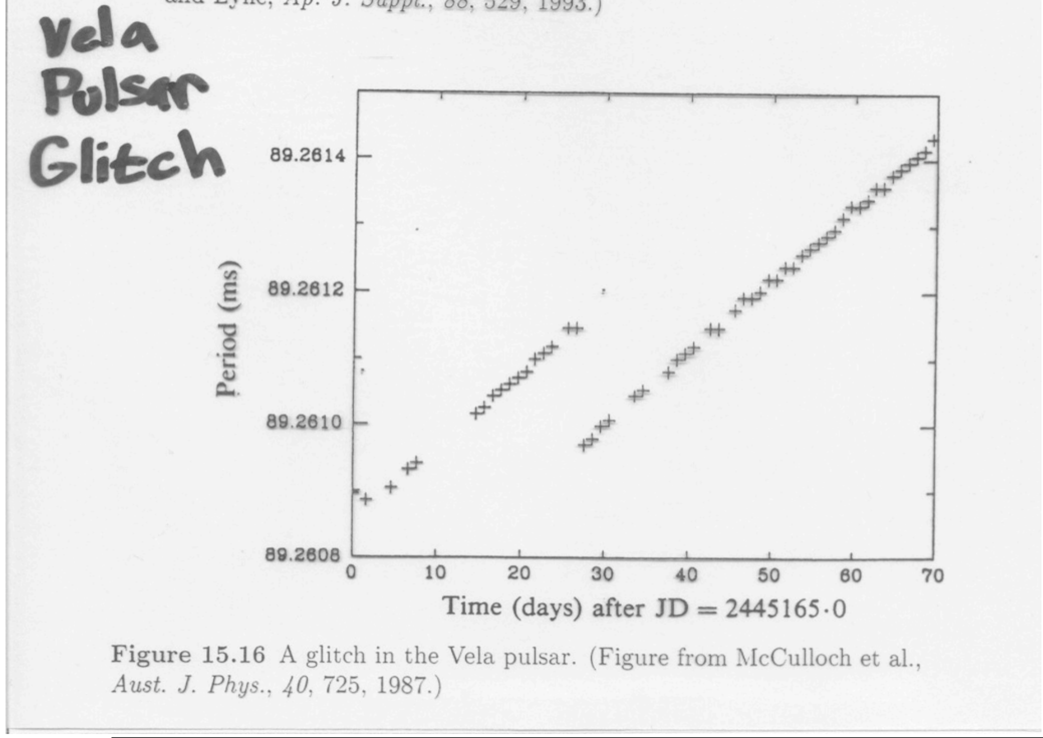
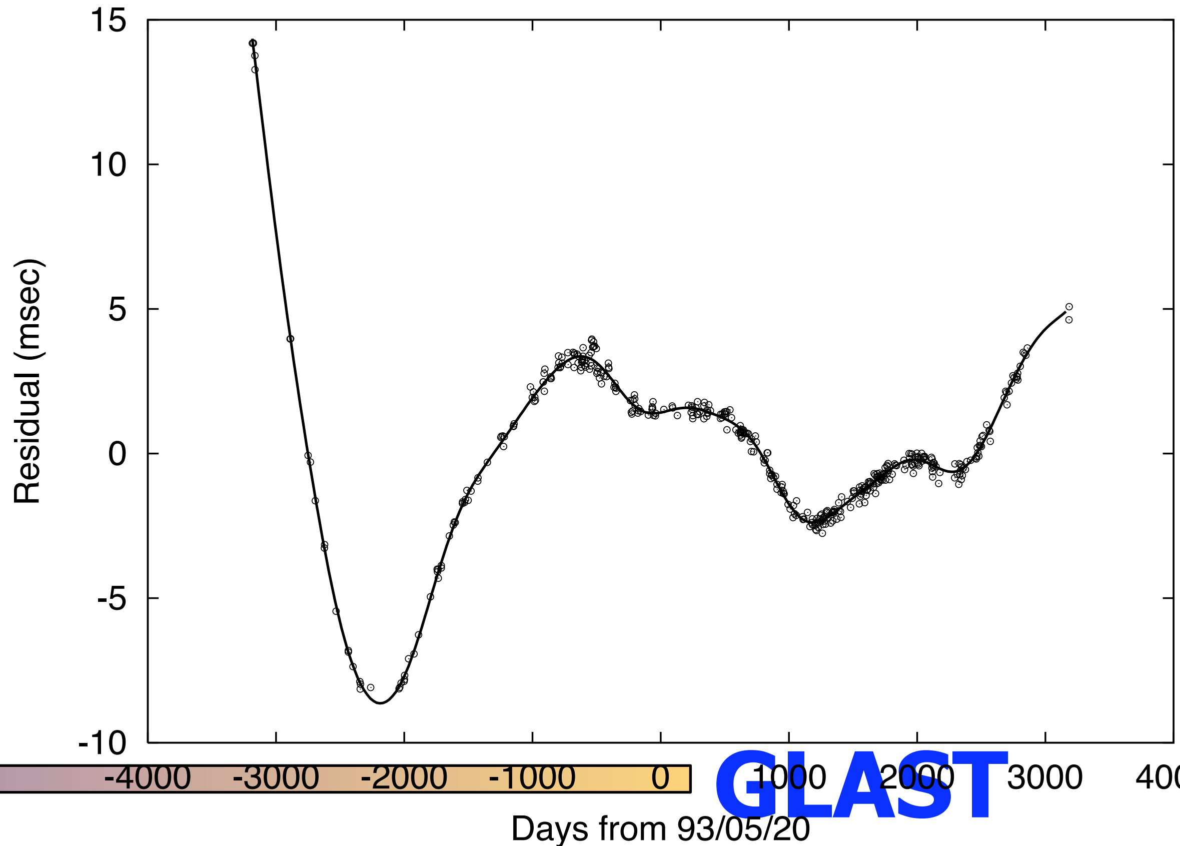


Figure 15.16 A glitch in the Vela pulsar. (Figure from McCulloch et al., *Aust. J. Phys.*, *40*, 725, 1987.)

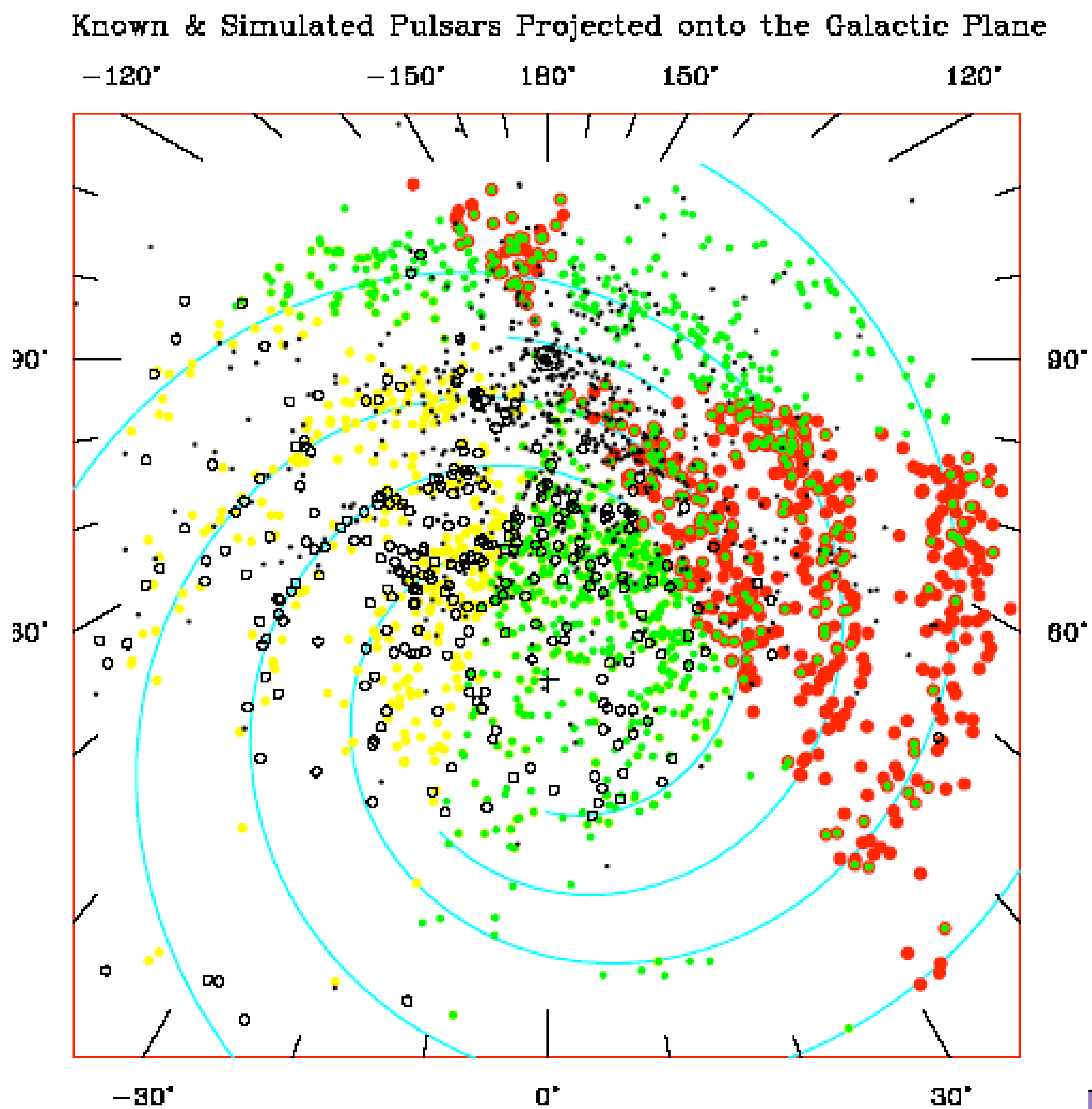


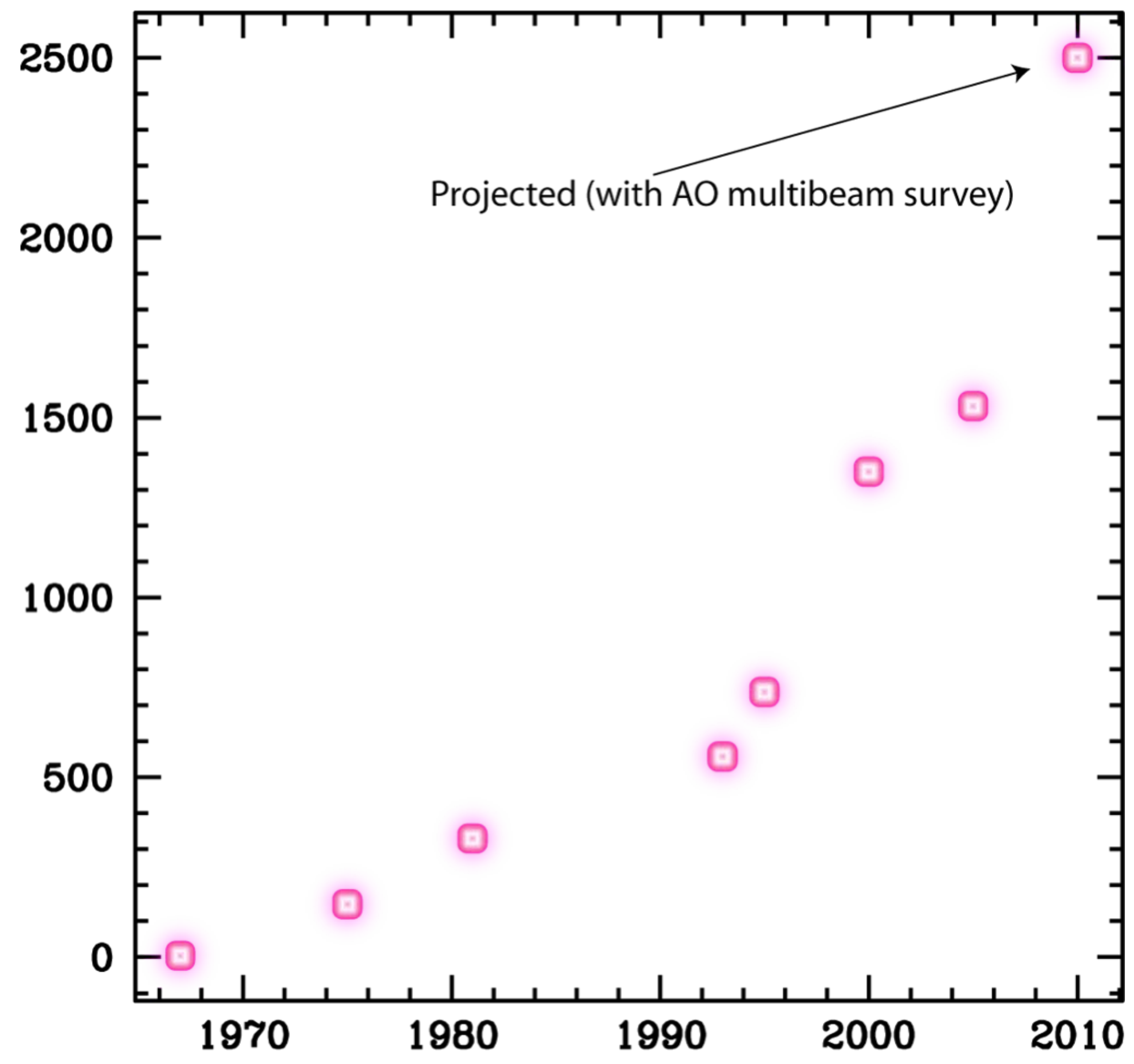
Contemporaneous radio timing...

- ...is needed to allow gamma-ray photons to be folded synchronously
- ...was relatively easy when targeting only the brightest pulsars for EGRET
- ...is very hard when the number of potentially interesting sources is much higher
- Must be carried out on the very biggest radio telescopes (Arecibo, GBT, Parkes, Jodrell) in the vast majority of cases

Scope of the problem

- Number of known pulsars has jumped enormously (remember, this is a good thing!)





The advantage of 21-cm

- Most surveys at 430 MHz
  - Pulsars are strong/beams are big
  - But sky is bright and dispersion limits distance
- Parkes survey was at 1400 MHz
  - 13 beams simultaneously/long dwell (2100s per pointing)
  - BIG advantages in Galactic plane (where the youngest pulsars are)
  - discovered ~700 new pulsars
- Arecibo ALFA system:
  - 7 beams at 1400 MHz
  - 10 times raw sensitivity of Parkes beams
  - New, very broadband (300 MHz) spectrometer (soon)
  - 1.8 times as deep/6 times the volume (50 times for fast pulsars)

P-ALFA Summary

- Search:
  - Proposal is for ~140 hrs/trimester for five years
  - This is about 1/3 of Galactic center time at Arecibo!
  - Expectation (with large unknowns about source population) is roughly 1000 new pulsars
- Followup:
  - All new pulsars must be timed to determine p-dot, E-dot, and detect binary motion
  - It takes about a year of observations to separate position from p-dot
  - It is roughly 2.6 hours/pulsar, or ~2600 hours!
- This doesn't include longer term monitoring!

Conclusions

- Although useful tools for fundamental physics, pulsars are physical “black boxes.” GLAST is our best hope for progress on understanding pulsar emission physics
- GLAST will open a less (or differently) biased window on the pulsar birthrate/supernova rate
- GLAST’s enormous sensitivity increase brings challenges for observers at other wavelengths
  - GLAST will benefit from large recent and ongoing radio surveys
  - GLAST needs new observations for target characterization and prioritization, and will need follow-up searches
  - GLAST needs population studies incorporating recent radio survey data