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Pulsars @ Jodrell Bank

Patrick Weltevrede

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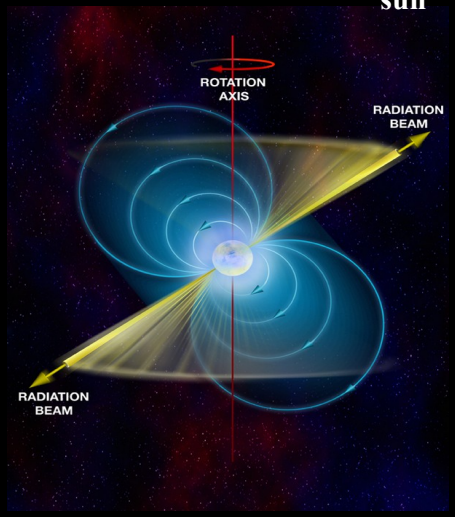
Pulsars

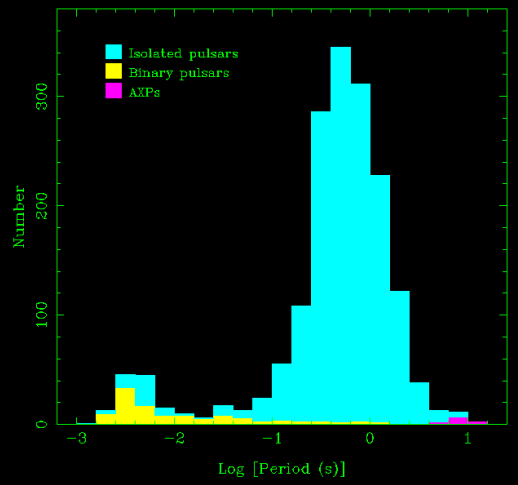
- What are pulsars?
- Pulsars: cosmic clocks.
- Pulsars: tools to study the ISM.
- Pulsars: laboratories of extreme plasma physics.

Pulsars

Rotating neutron stars – the aftermath of supernova explosions

Mass ~ 1.4 M_{sun} Radius ~15 km → Density ~ > atomic nucleus !!



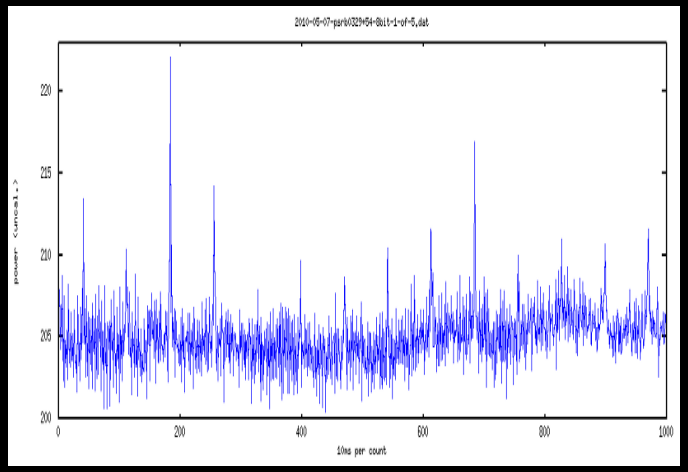


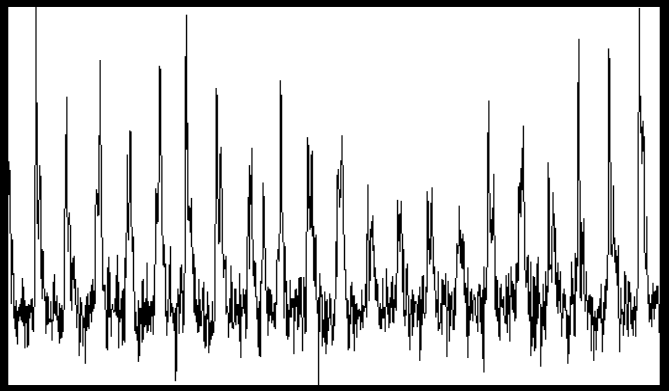
Number known: ~2000

P ~1.5 msec → 8 seconds

Most in the range 0.2-2 sec

http://www.nrao.edu/pr/2007/pulsarcollab/pulsargraphic.jpg http://www.atnf.csiro.au/research/pulsar/psrcat



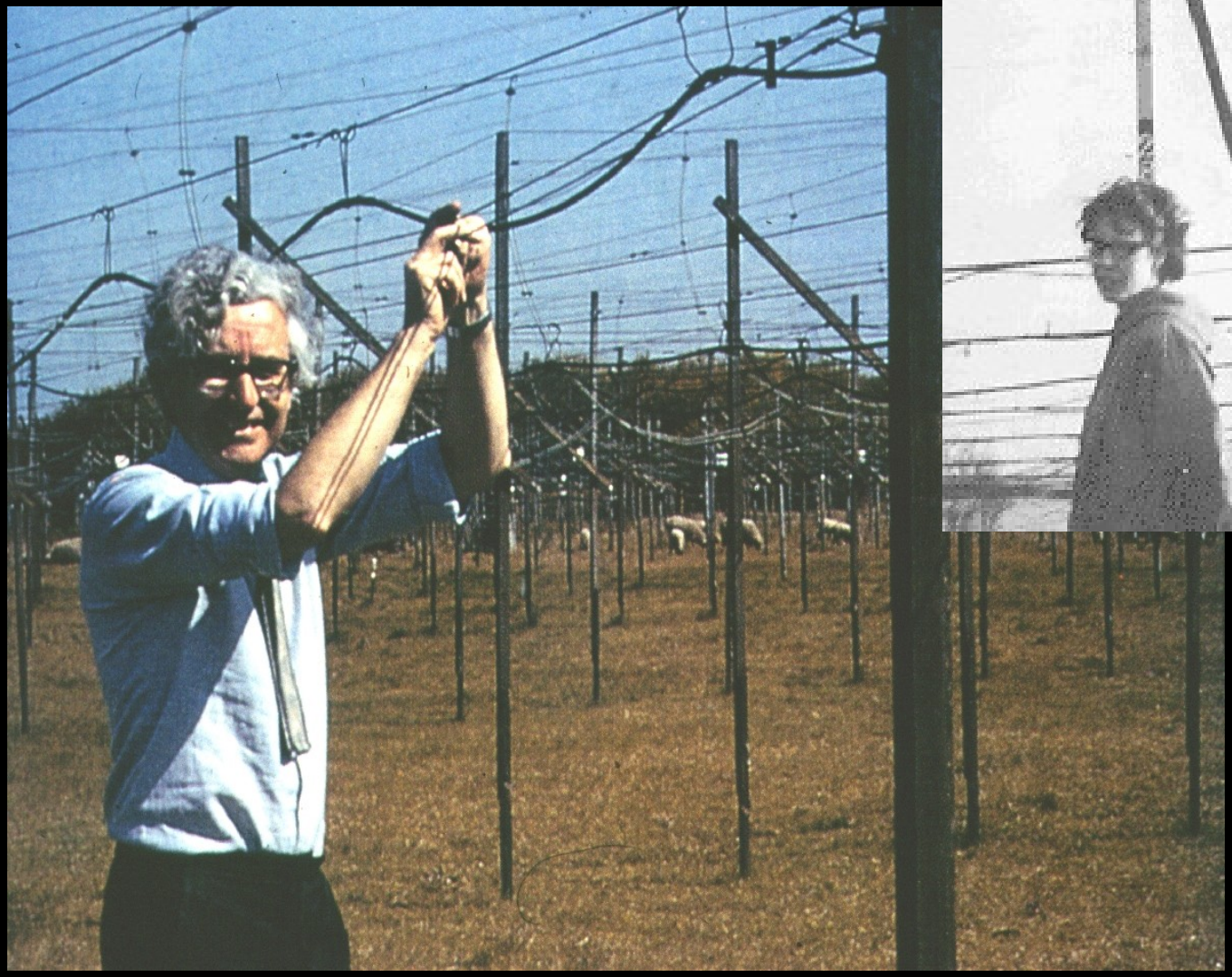


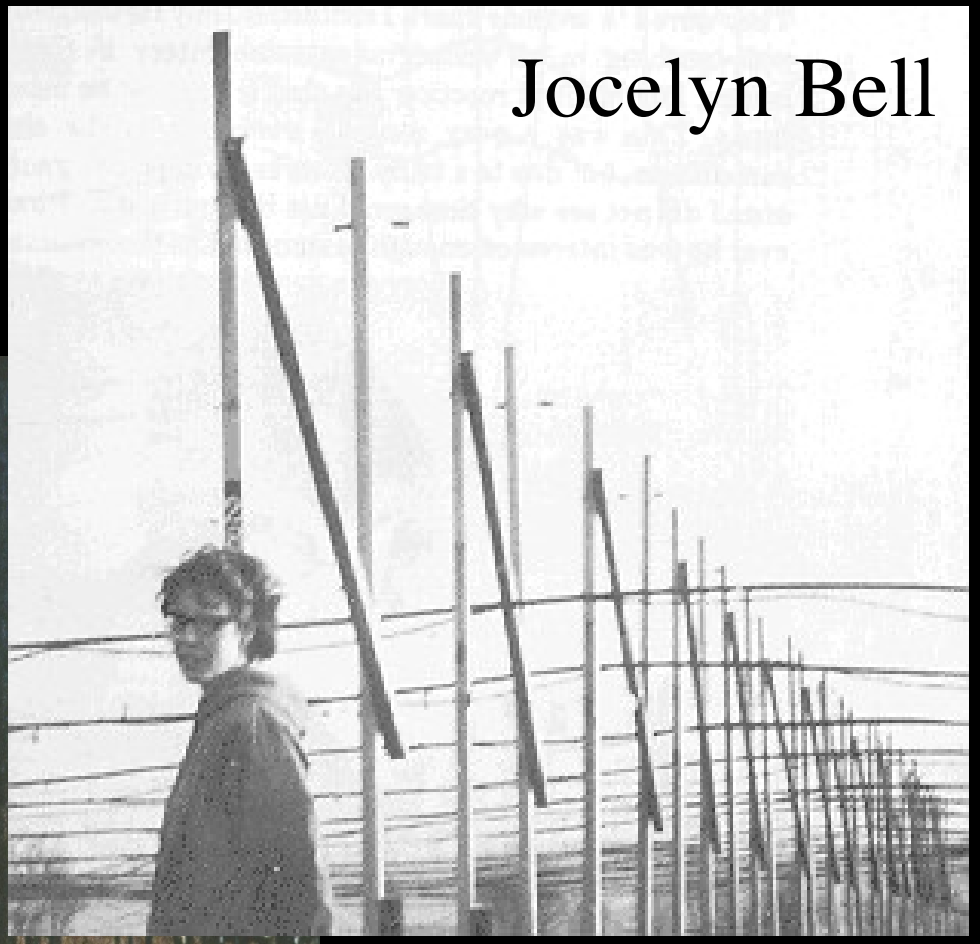
They are *weak* radio sources when integrated over a period → need big telescopes to study them (pulse widths range from 0.1 -10% of period.)

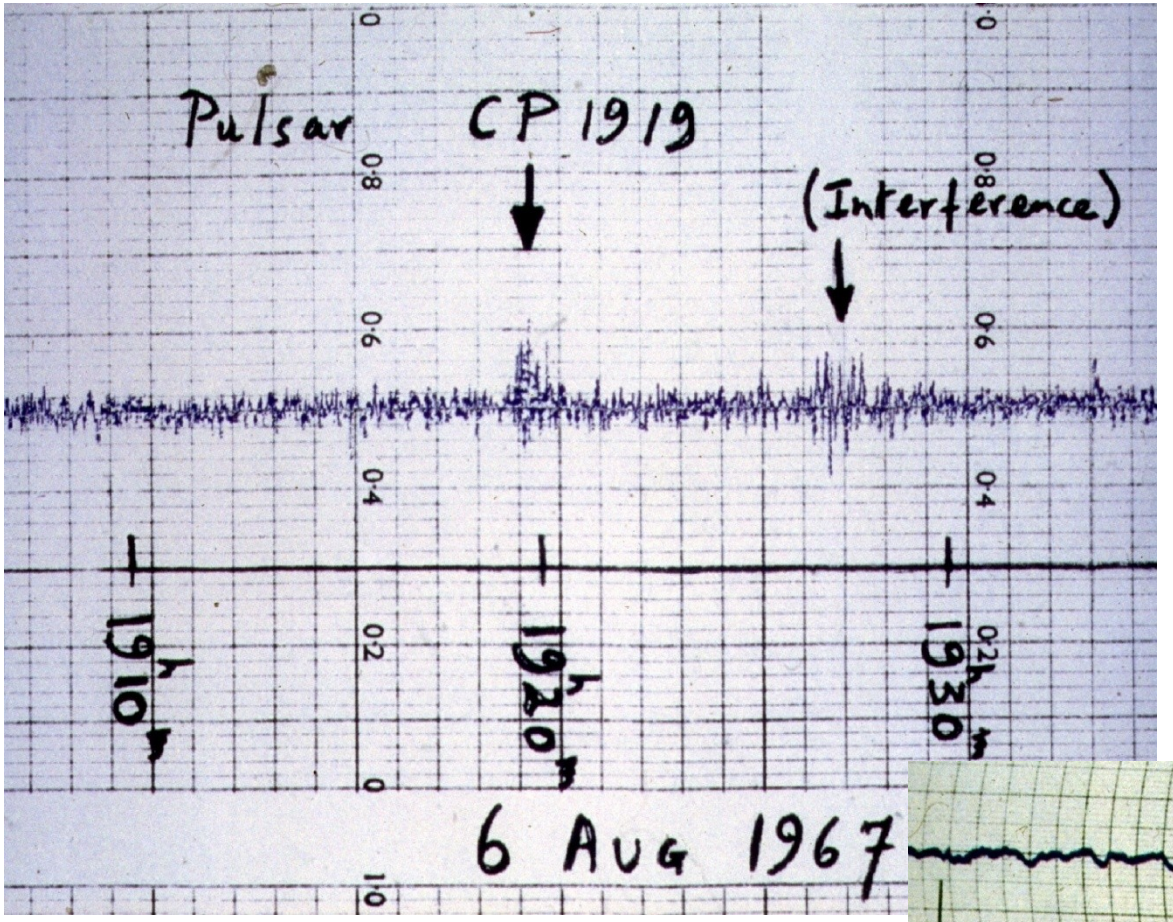
http://setiquest.org/forum/topic/baudline-analysis-psr-b032954

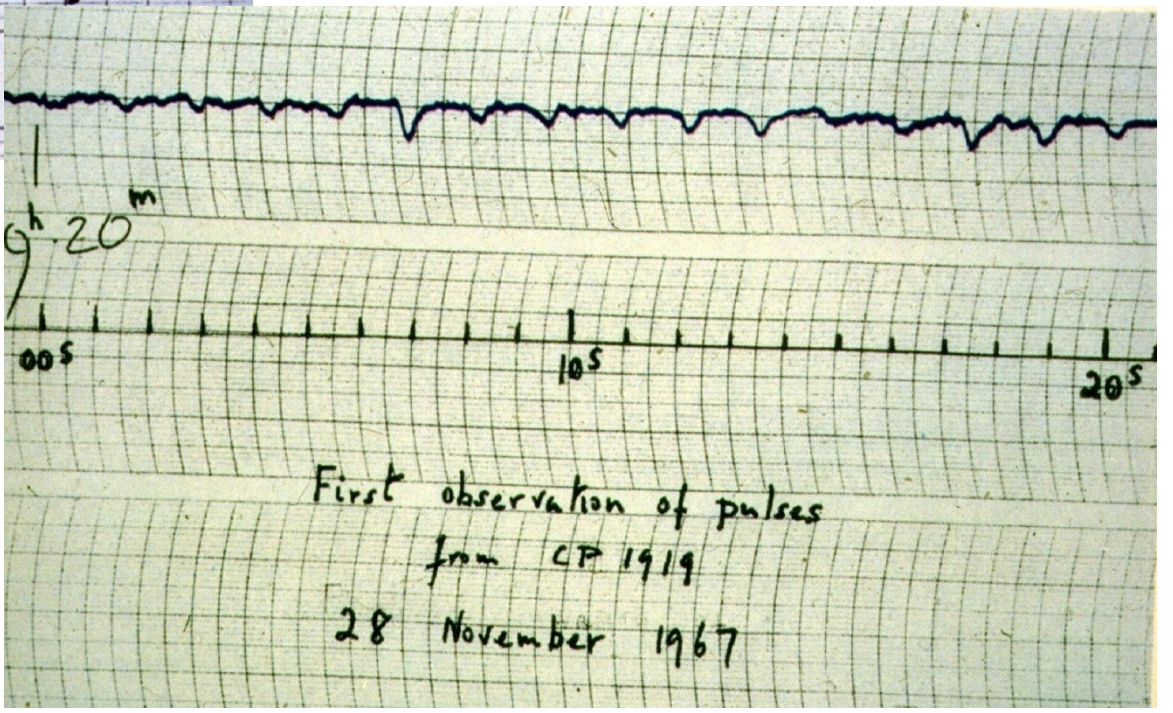
http://outreach.atnf.csiro.au/education/pulseatparkes/images2/pulsar_pulses.gif

Antony Hewish






Pulsar CP 1919
(Interference)
1910h
1920h
1930h
6 Aug 1967


9h.20m
00s
10s
20s
First observation of pulses
from CP 1919
28 November 1967

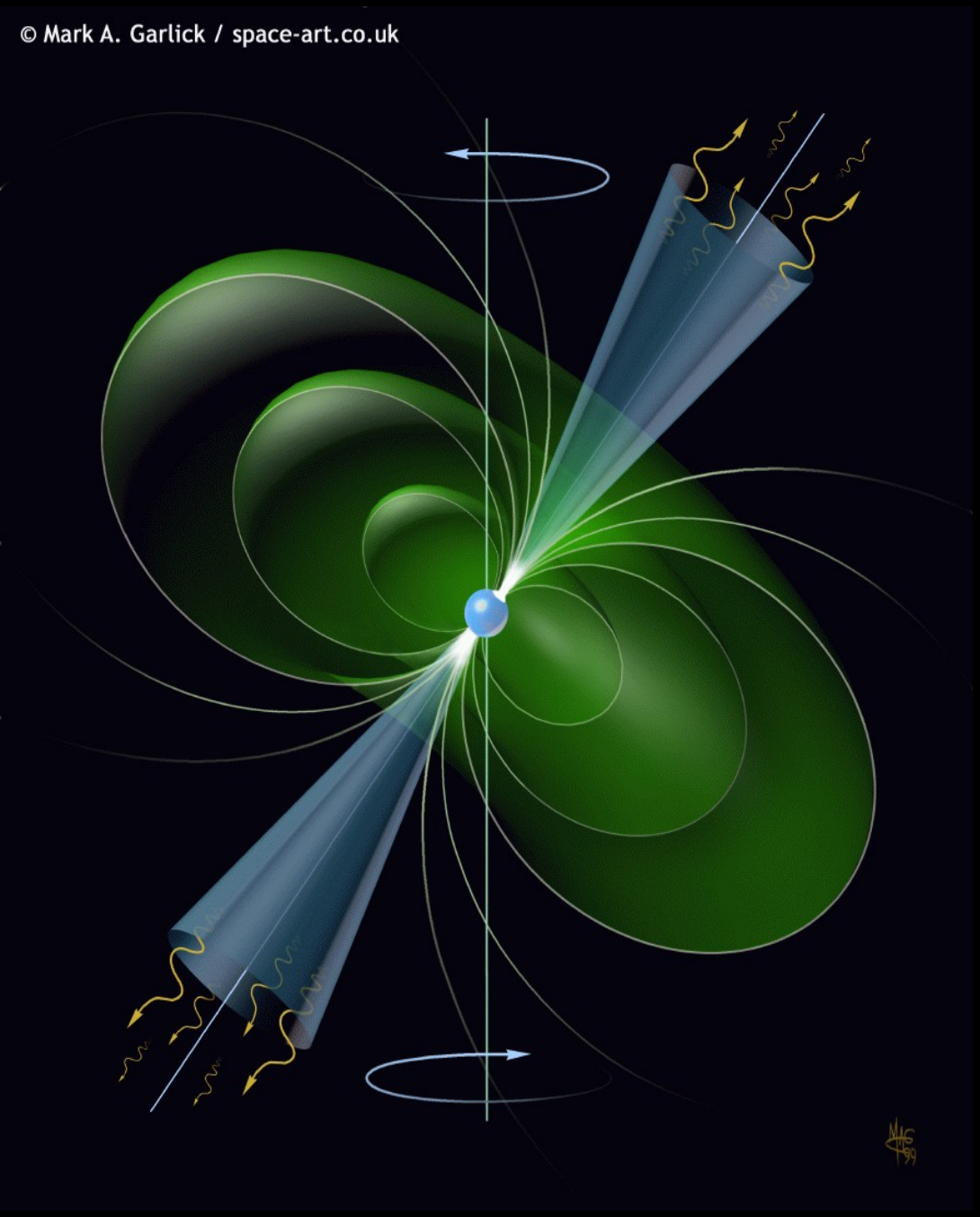
Little green men?

- Source visible 4 min earlier every day
- Distance was ~20 pc (~65 ly)
- No doppler effect measured
- Month later 2nd pulsar was found

Supernova 1987A

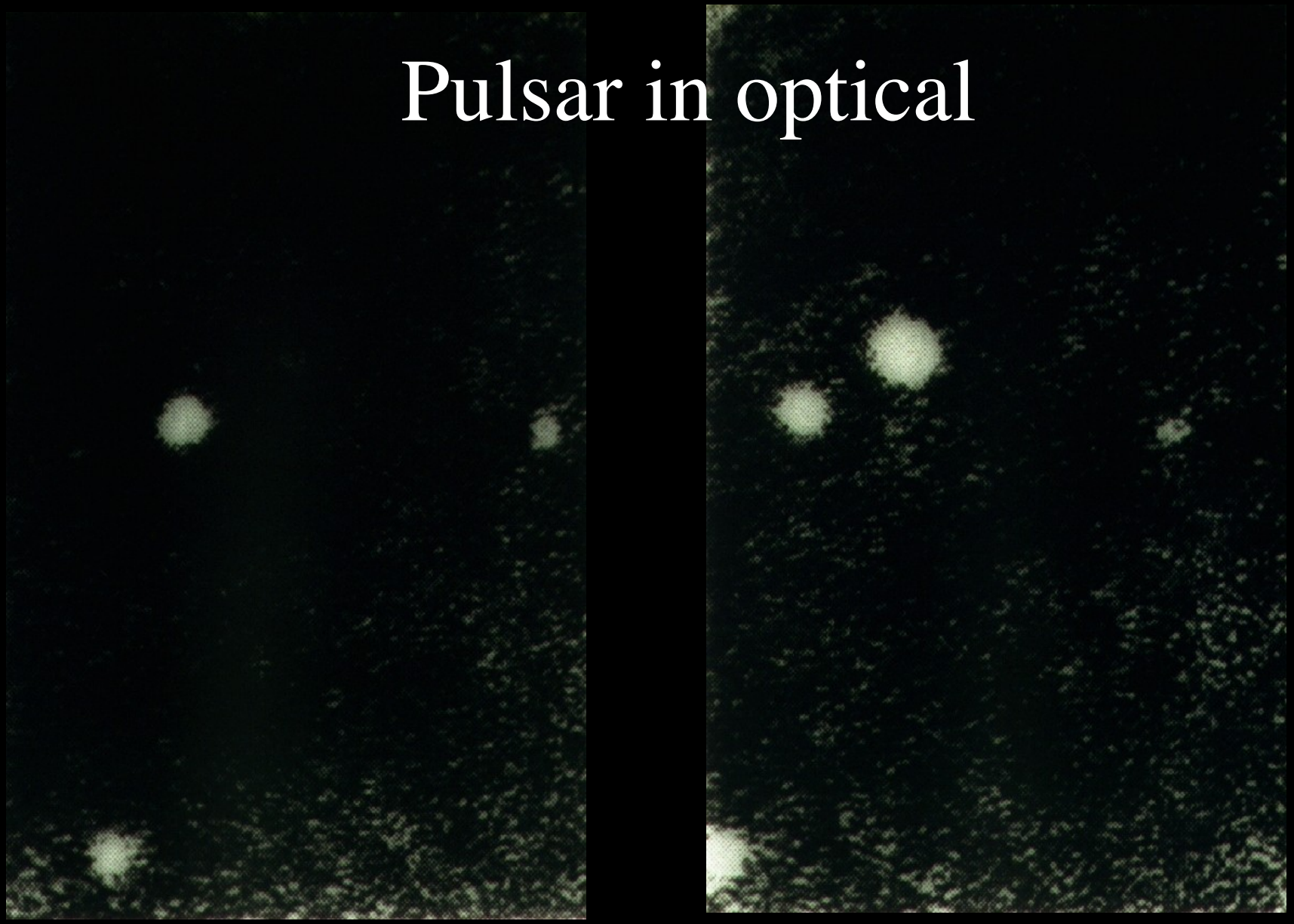
Supernova 1987A

Pulsars



- Neutron stars
- $M = 1.4M_{sun}$
- R = 10 km
- P = 0.0013 – 8.5 sec
- $B = 10^{8} – 10^{14}$ G
- 2000 pulsars known
- Most of them are radio pulsars (but some optical, X-ray or γ-ray)

Pulsar in optical



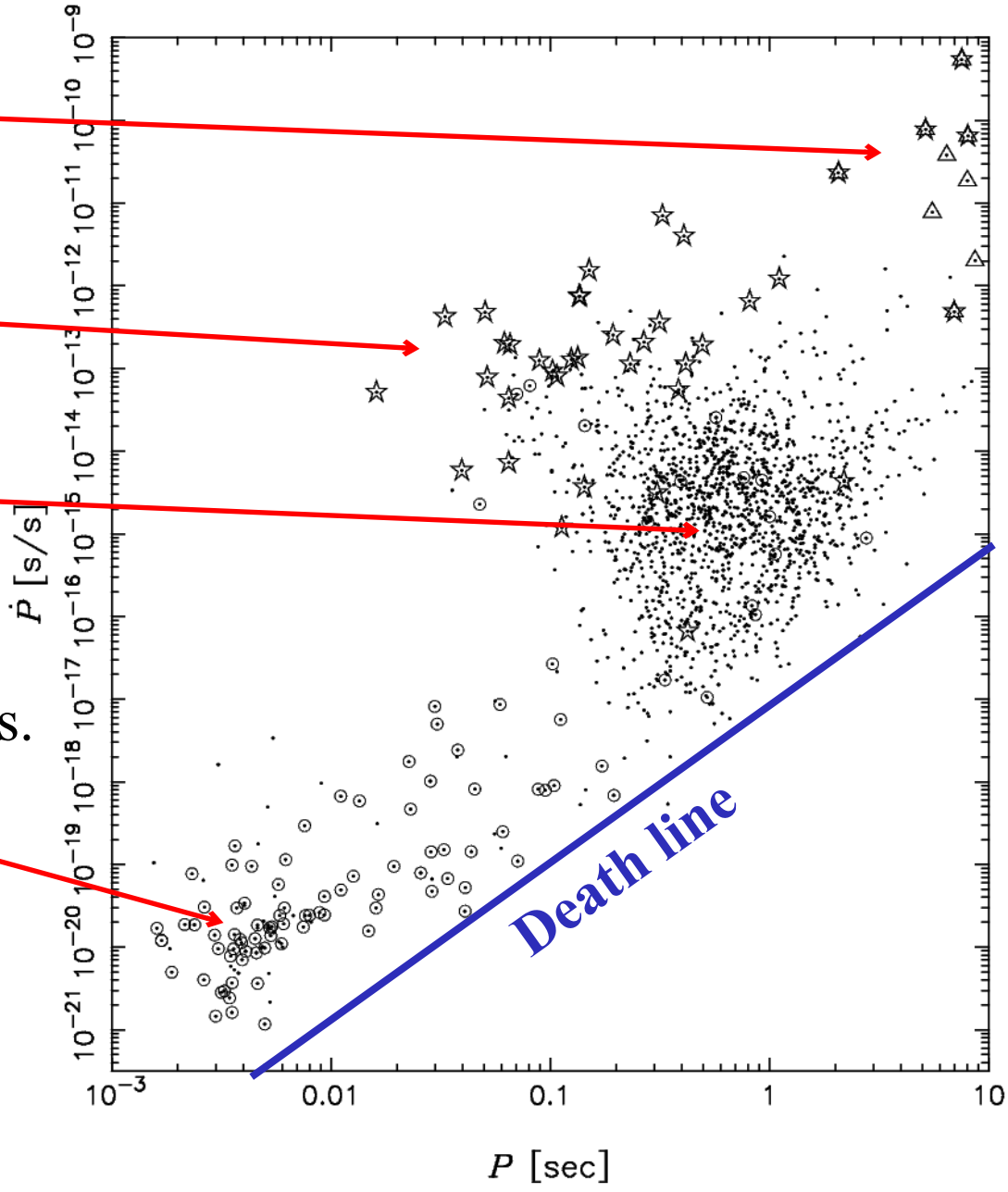
P-Pdot diagram

Magnetars.
Slow, strong B,
Not rotation powered.

Young pulsars
Energetic, fast, often in SNR.

"Normal" pulsars
Bulk of population.

MSPs
Very fast, recycled, often binaries.



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Pulsars

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Pulsars are extremely good clocks

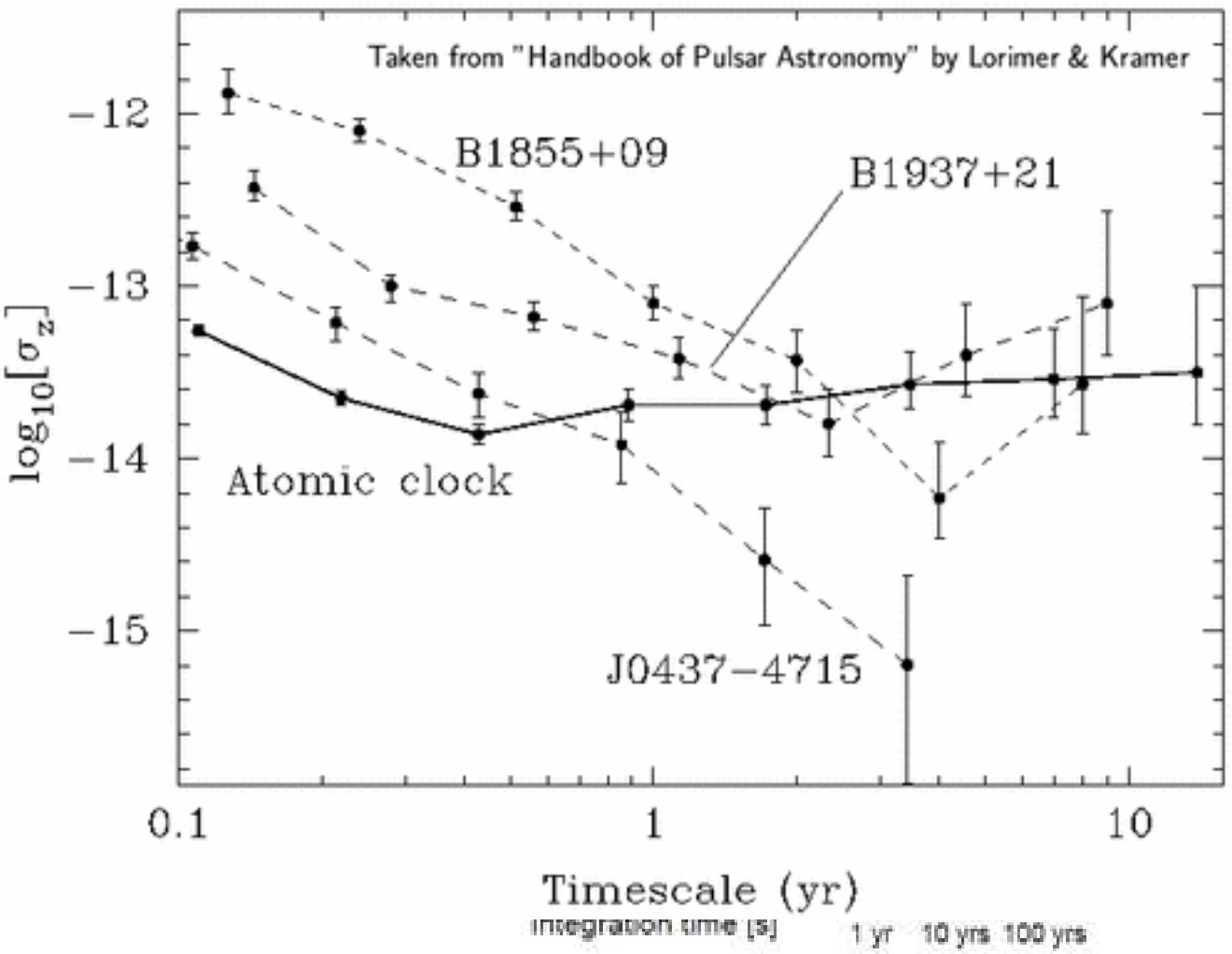
Today at 16:00 the predicted rotational period of pulsar J0437-4715 is: 0.005757451932418 0±0.000000000000001 seconds

Pulsars are extremely good clocks

Some of the effects that were taken into account:

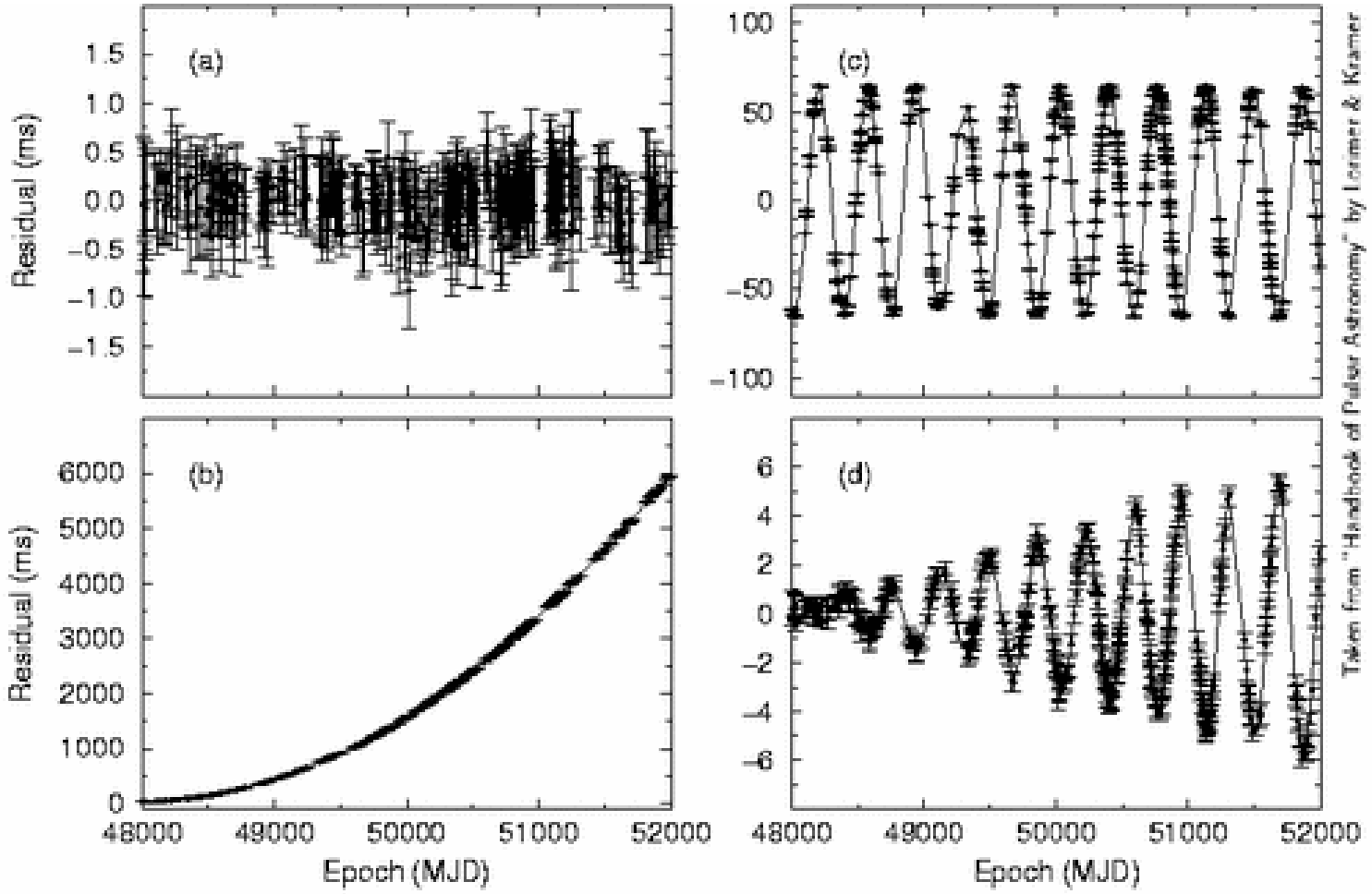
- Römer dalay: barycentric correction
- Shapiro delay: curvature of space-time by the Sun
- Einstein delay: Time dilation caused by motion Earth & gravitational redshift solar system bodies.
- Keplerian binary motion
- Post-Keplerian binary motion (e.g. periastron precession)

Are pulsars best clocks in the universe?



Pulsar timing

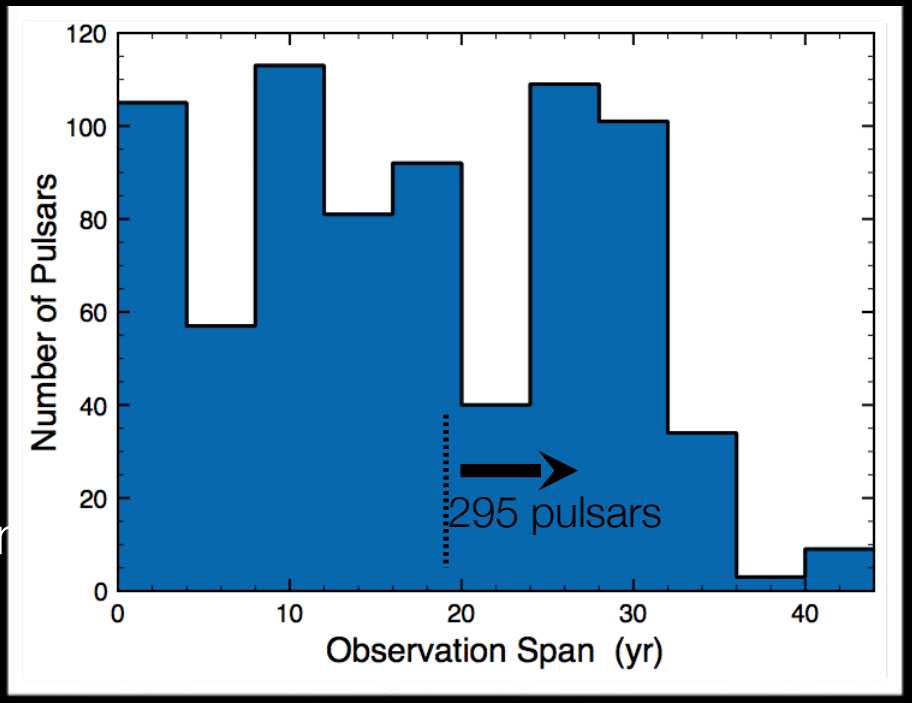
$$\phi(t) = \phi_0 + \nu(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \ldots$$

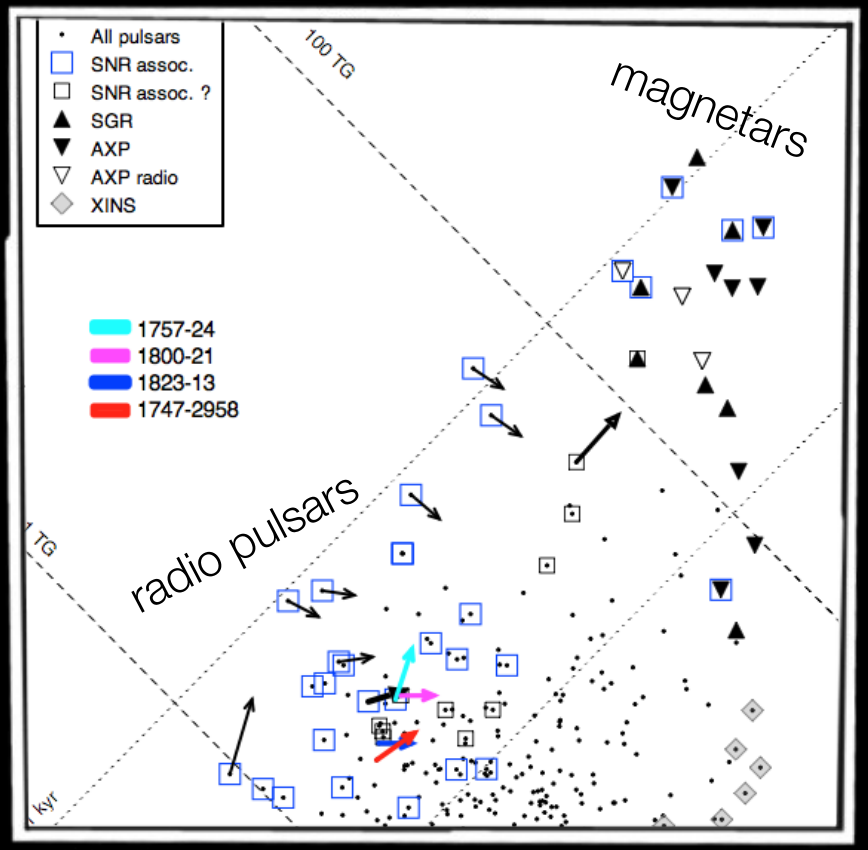


JBO Pulsar Timing database

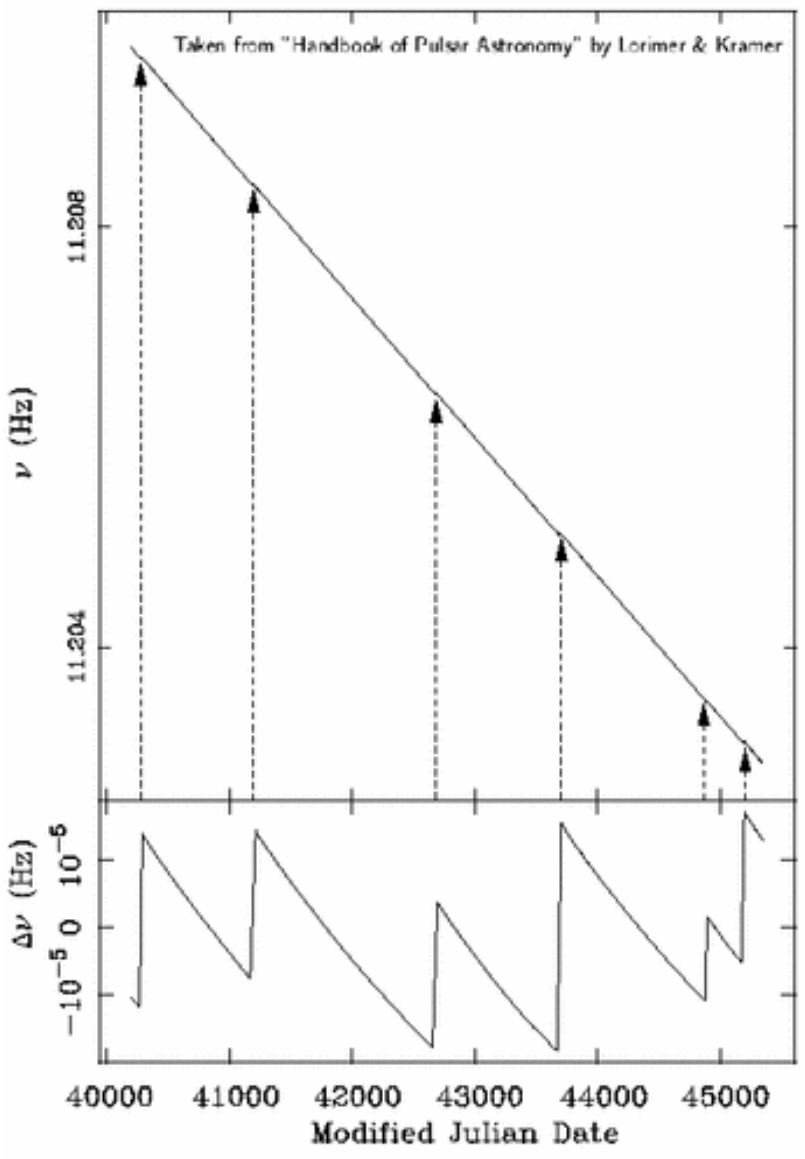
Unique monitoring of more than 700 pulsars/100 MSPs

- Long-term spin evolution: B-evolution, population studies.
- Glitches: large database, interior physics.
- Timing irregularities, transient phenomena.
- Support to other projects (GW/high-energy)

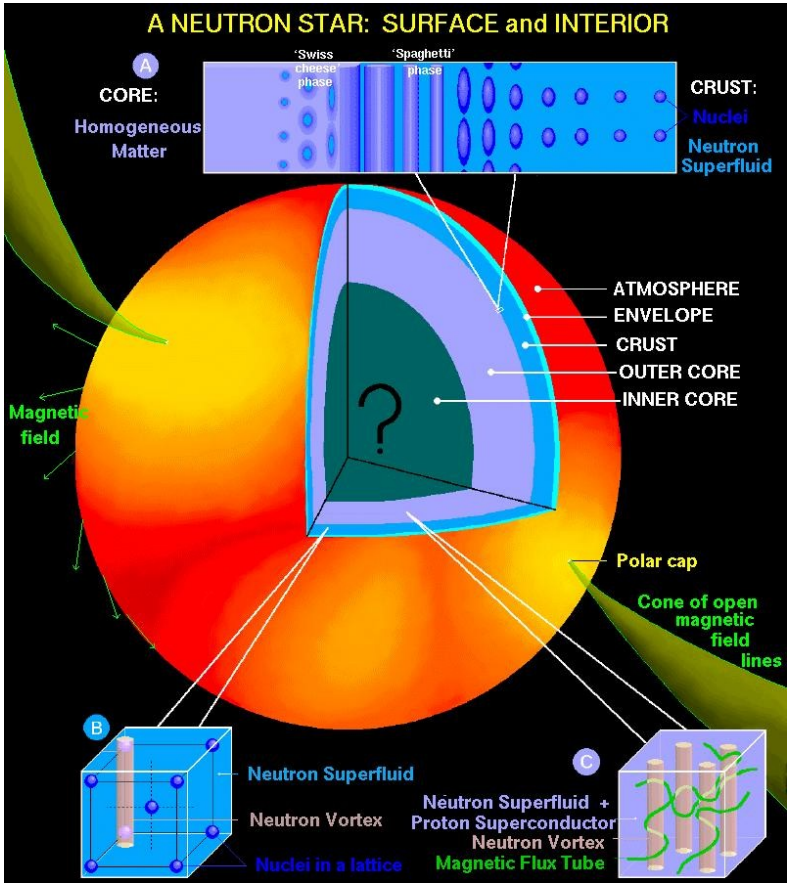




Timing "Glitches"



- Jumps in spin frequency.
- Interaction between superfluid interior and crust?

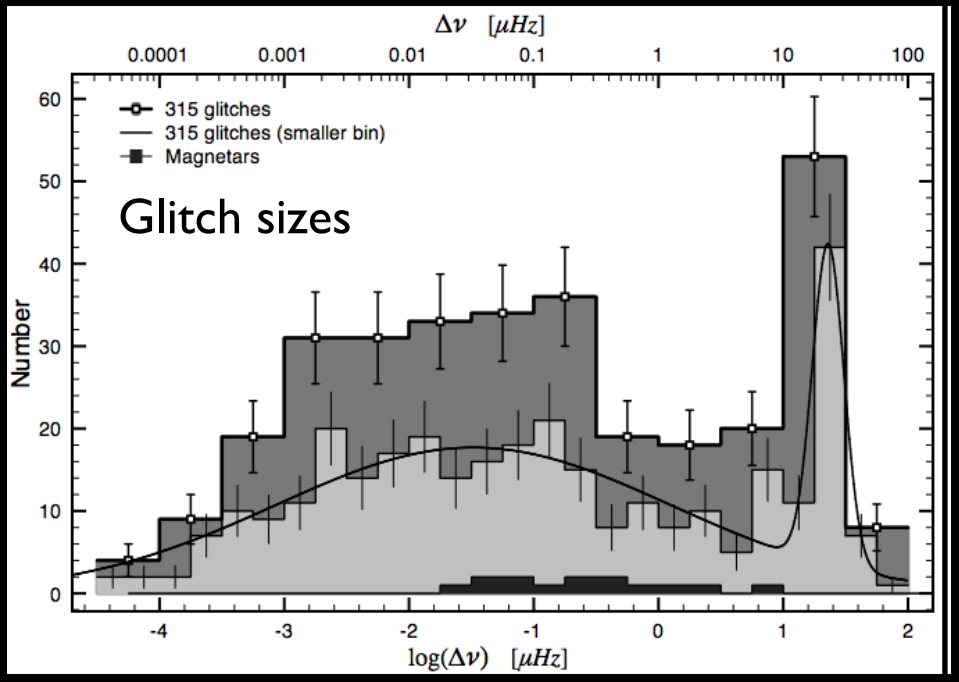


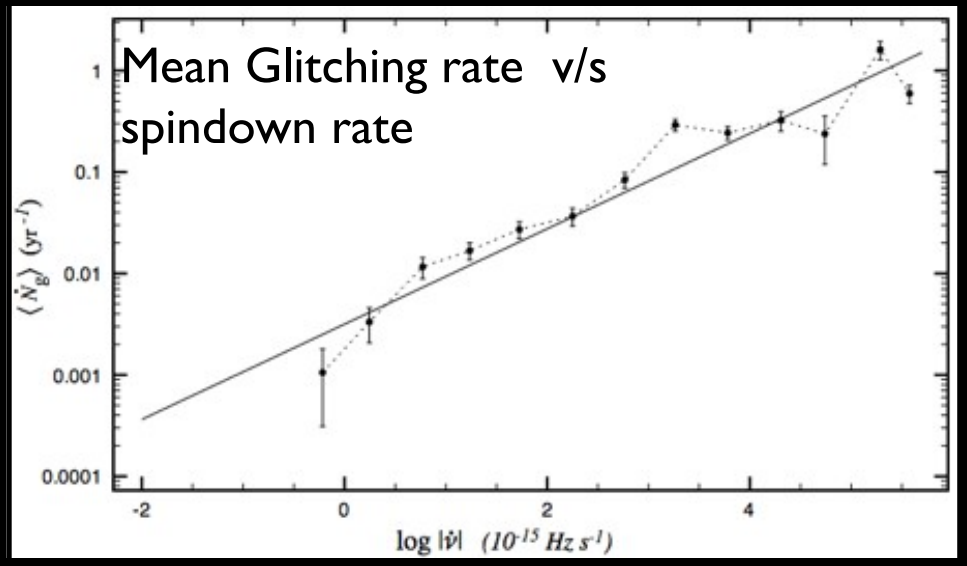
Largest glitch database comes from Jodrell Bank

- 378 glitches in 130 pulsars

  http://www.jb.man.ac.uk/pulsar/glitches.html

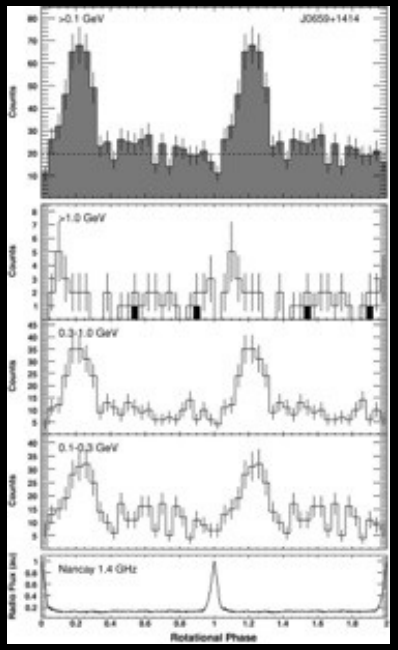
- Glitch size distribution is bimodal; some pulsars only exhibit large glitches.
- Glitch activity is larger for pulsars with higher spindown rates.

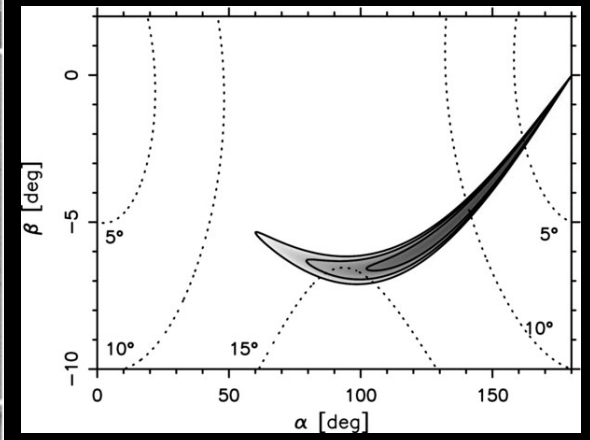




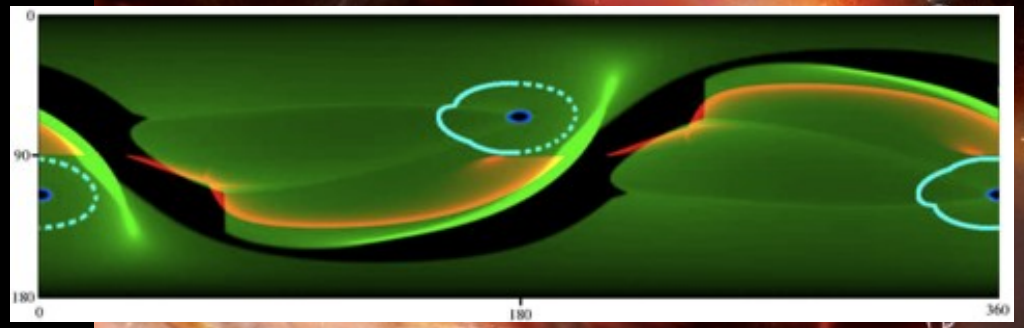
The gamma-ray/radio connection

- Fermi can detect gamma-ray pulsations, especially if rotation history is already known.
- Shape of gamma-ray light curves can be predicted for a given model, if viewing geometry is known.
- So if viewing geometry is known, the models can be constrained.
- Radio polarization measurements can constrain the viewing geometry.



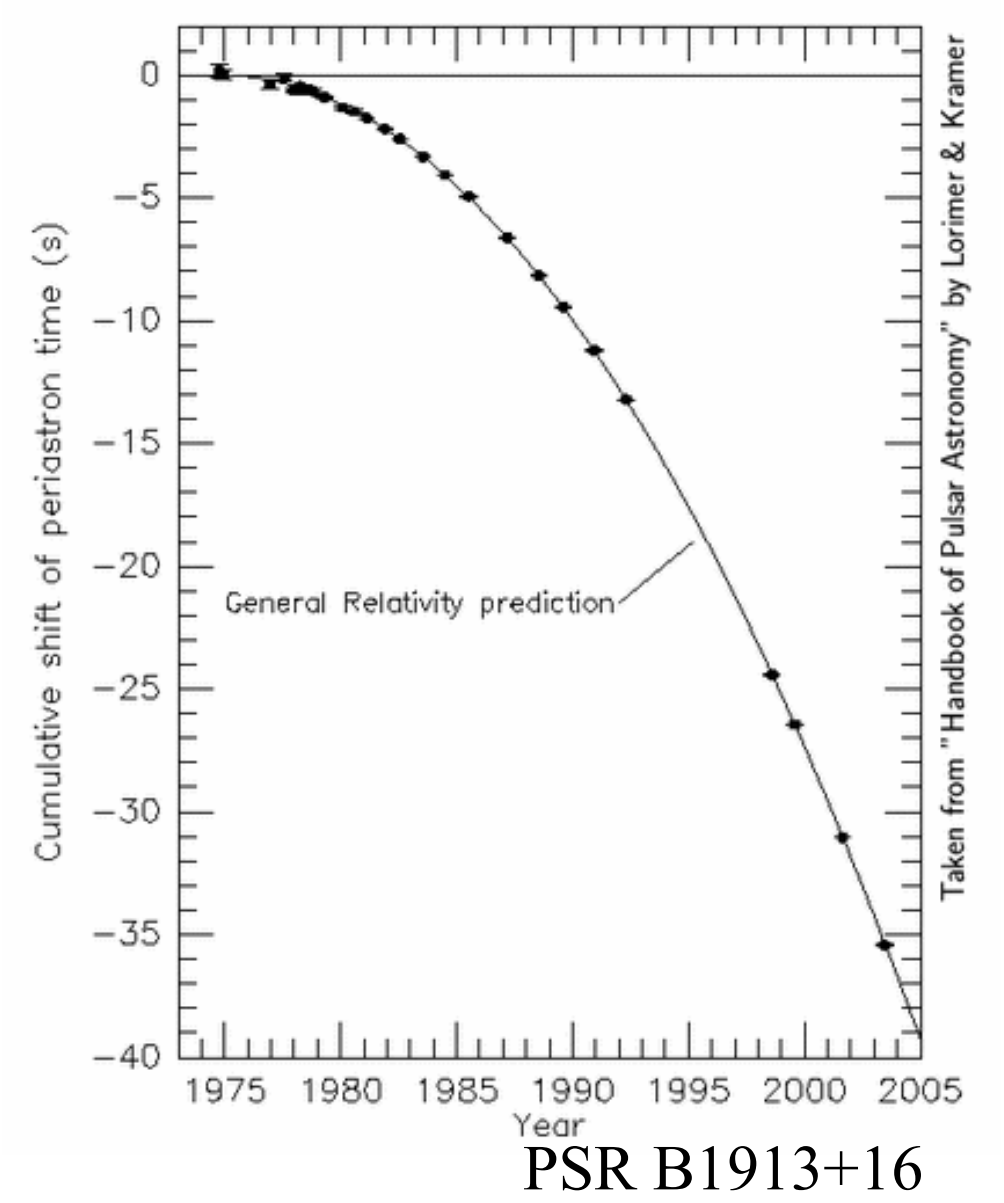


Weltevrede et al. 2010



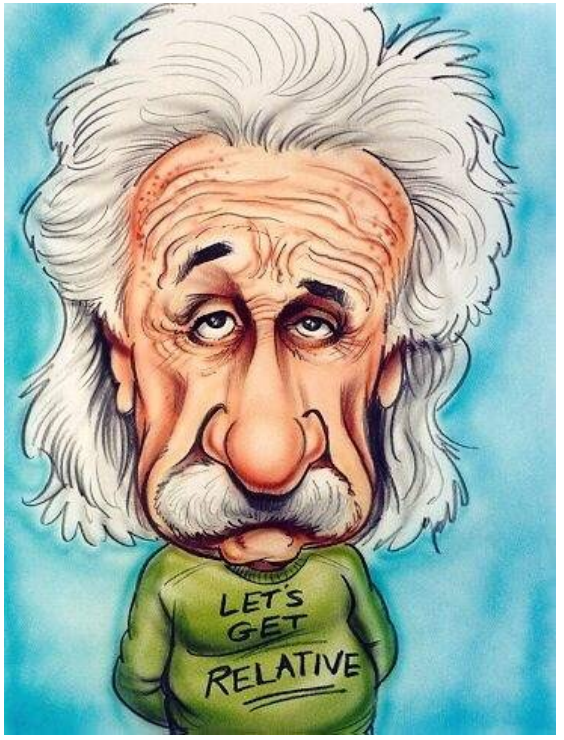
Watters et al. 2009

Double NS binaries

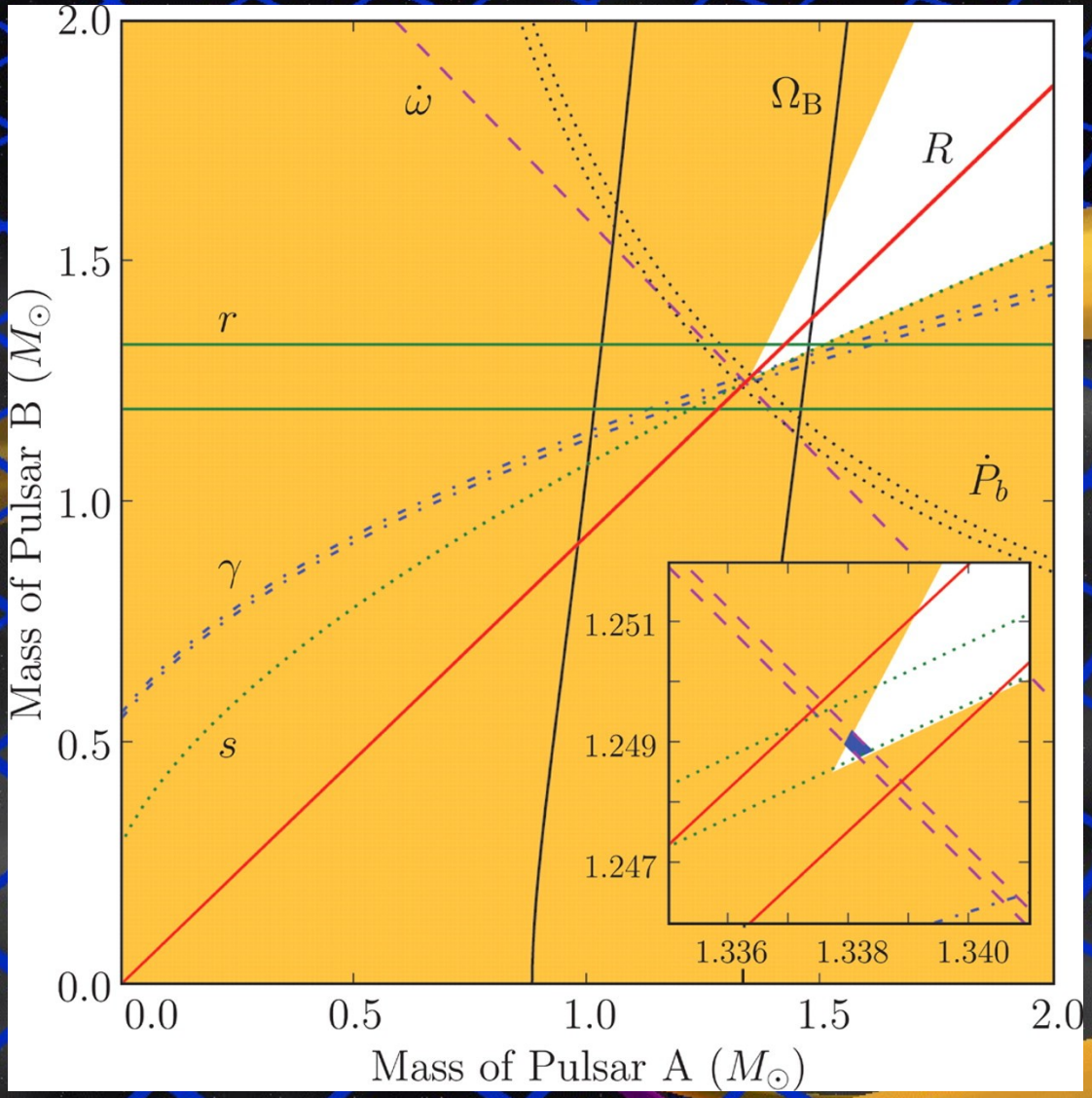


PSR B1913+16

- PSR B1913+16: orbit shrinks with ~1 cm/day
- Best indirect evidence for GW.



Double pulsar



- GR effects orbit, depending on the masses of the stars.
- Different GR parameters agree at 99.95% level.

Kramer et al. 2006

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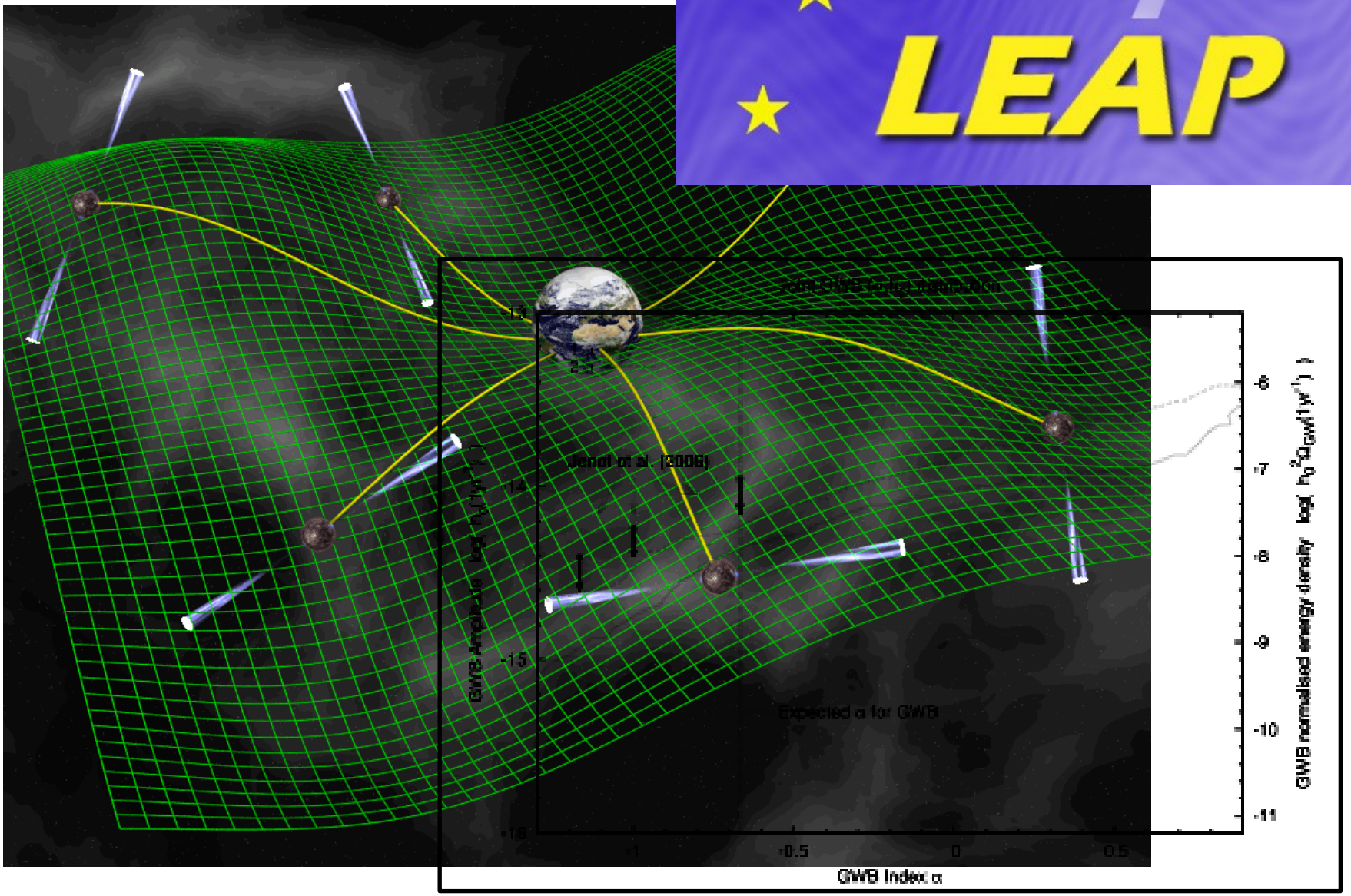
EPTA

LEAP



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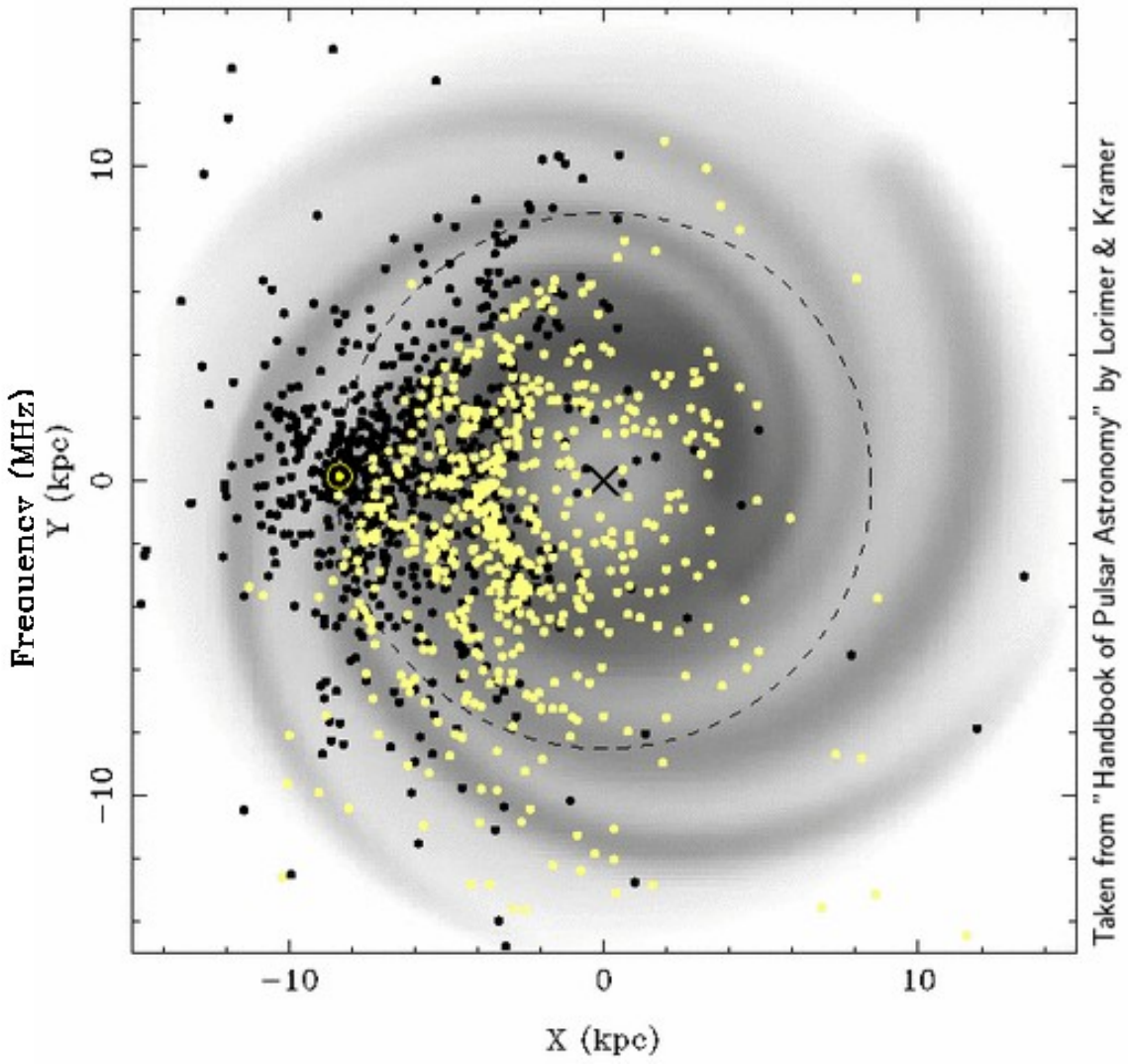
Interstellar medium: dispersion of radio signals

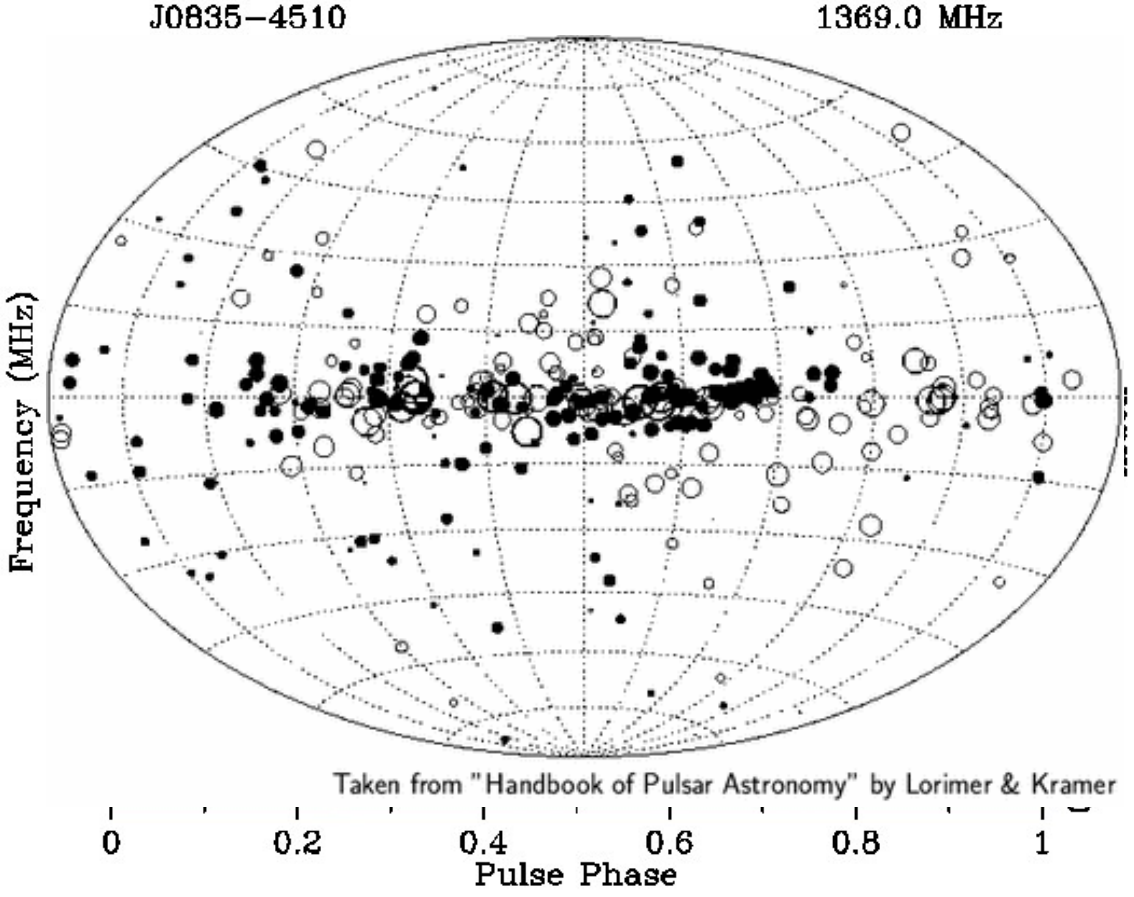


$$\Delta t = 4.15 \times 10^6 \text{ ms} \times \frac{\text{DM}}{f^2_{\text{MHz}}}$$

$$\text{DM} = \int_0^d n_e \, \text{d}l$$

- Knowledge of n_e gives you the distance.
- Knowledge about distance gives you n_e.

Interstellar medium: Faraday rotation of radio signals



$$\Delta\psi_{\mathrm{PPA}} = \lambda^2 \times \mathrm{RM}$$

$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^d n_e B_{||}\, \mathrm{d}l$$

- Can be used to measure magnetic field.

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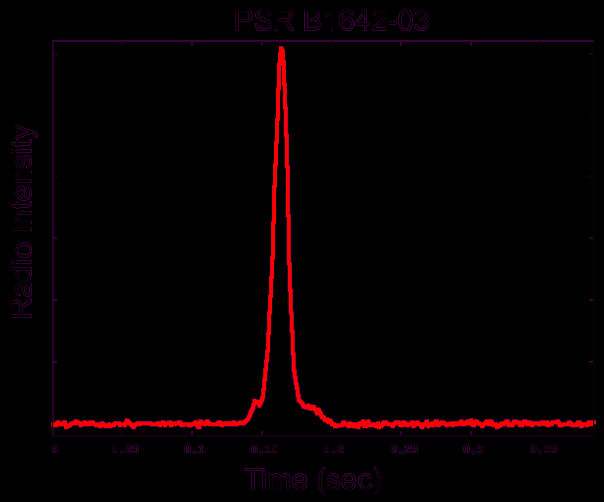
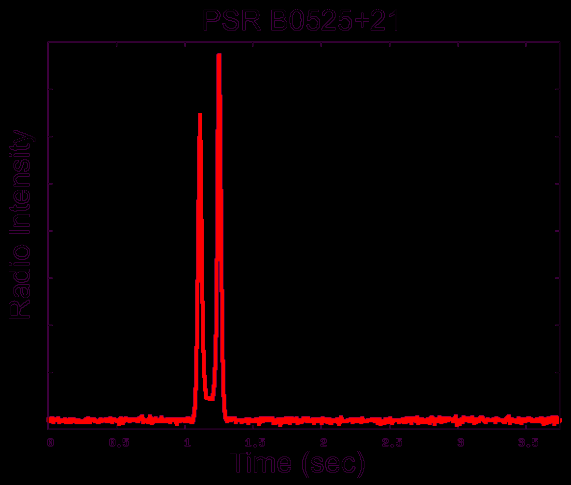
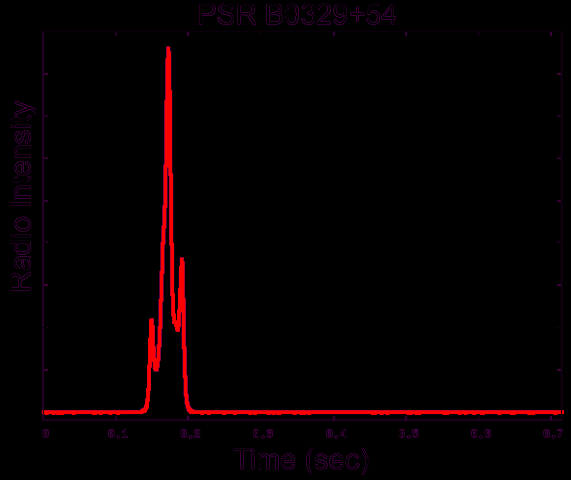
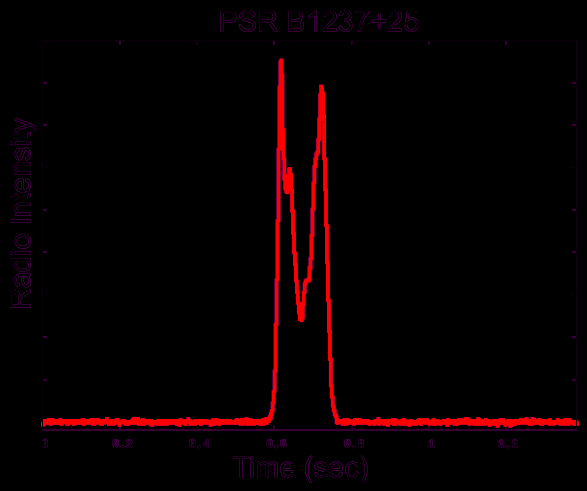
Conclusions

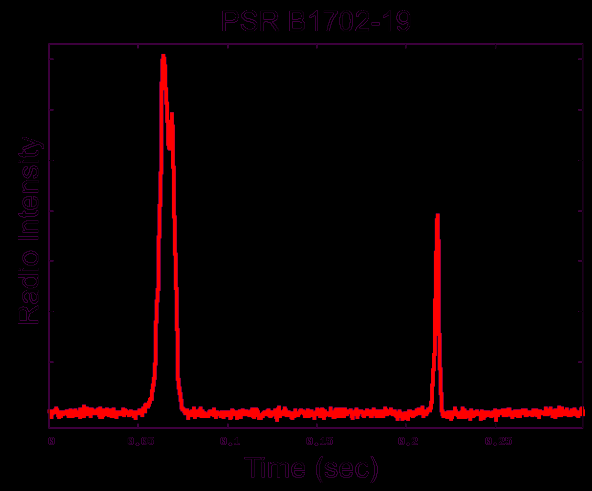
- Pulsars are great to test fundamental physics
  - General relativity
  - Matter under extreme conditions
  - Plasma physics under extreme conditions
- UK is a big player in field of pulsar astronomy.
- GHANA telescope equipped with pulsar equipment from U.Manchester Jodrell Bank Observatory

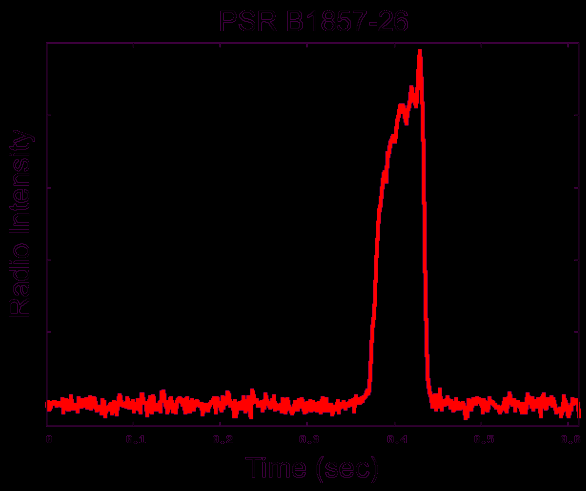

PSR B1642-03
Radio Intensity
Time (sec)


PSR B0525+21
Radio Intensity
Time (sec)

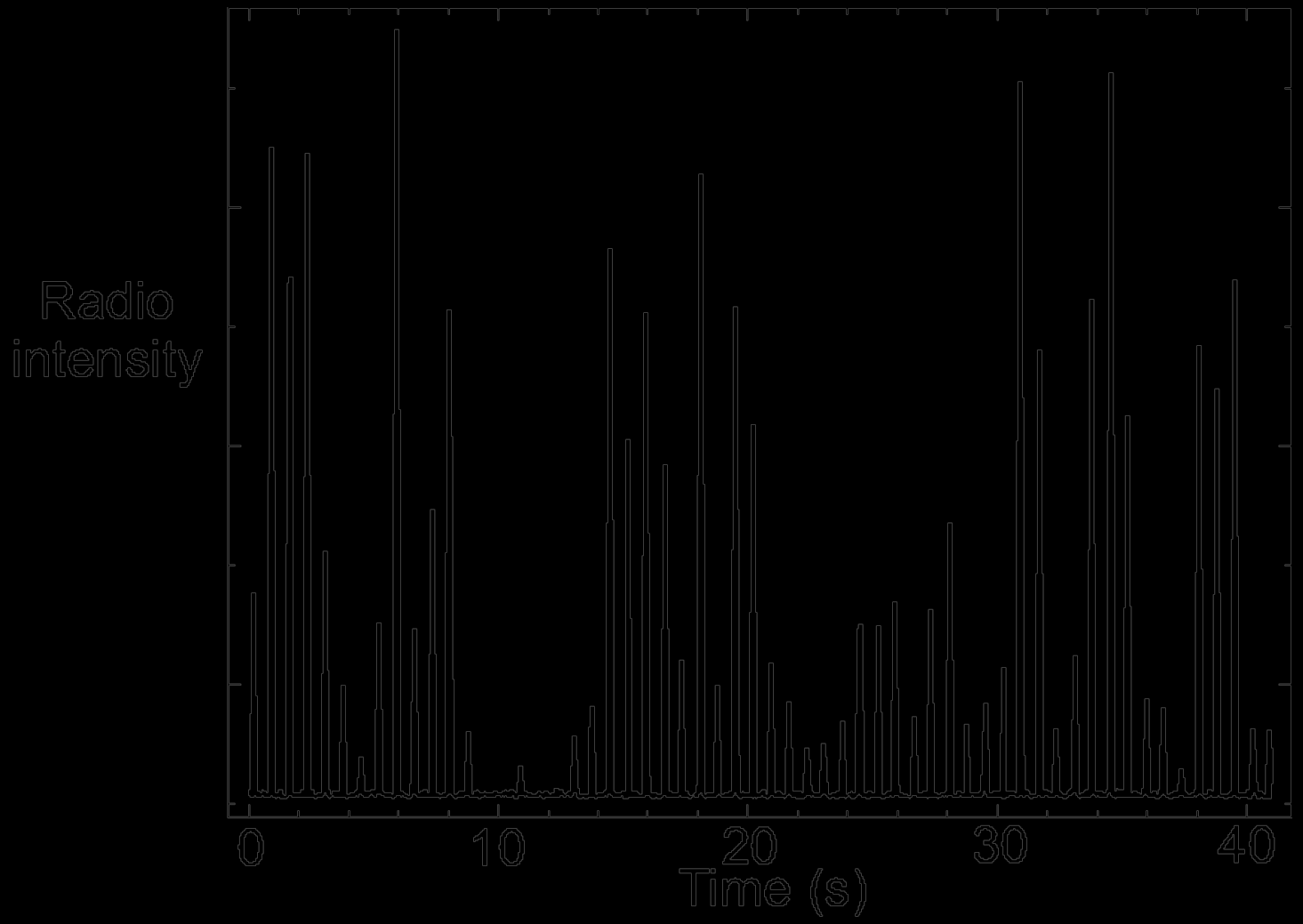

PSR B0329+54
Radio Intensity
Time (sec)

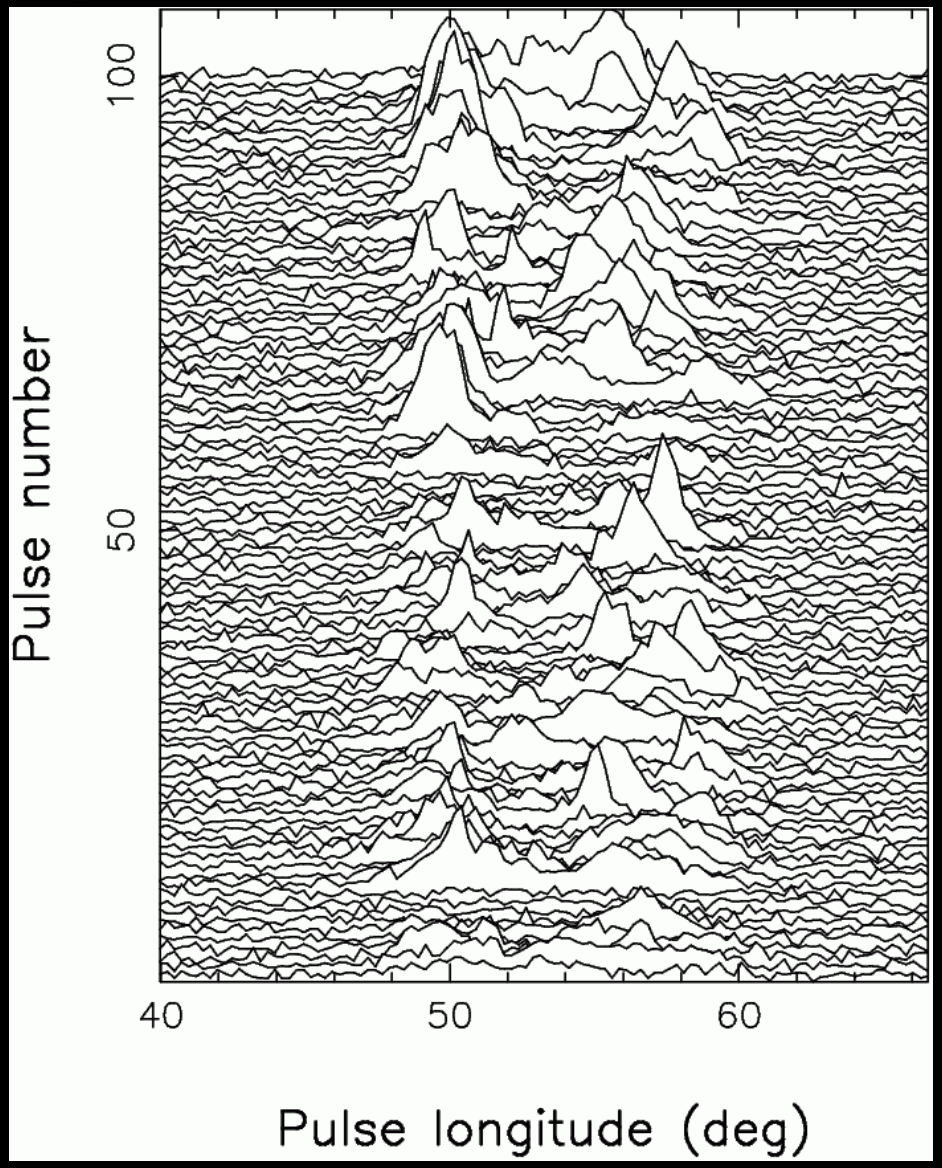

PSR B1237+25
Radio Intensity
Time (sec)

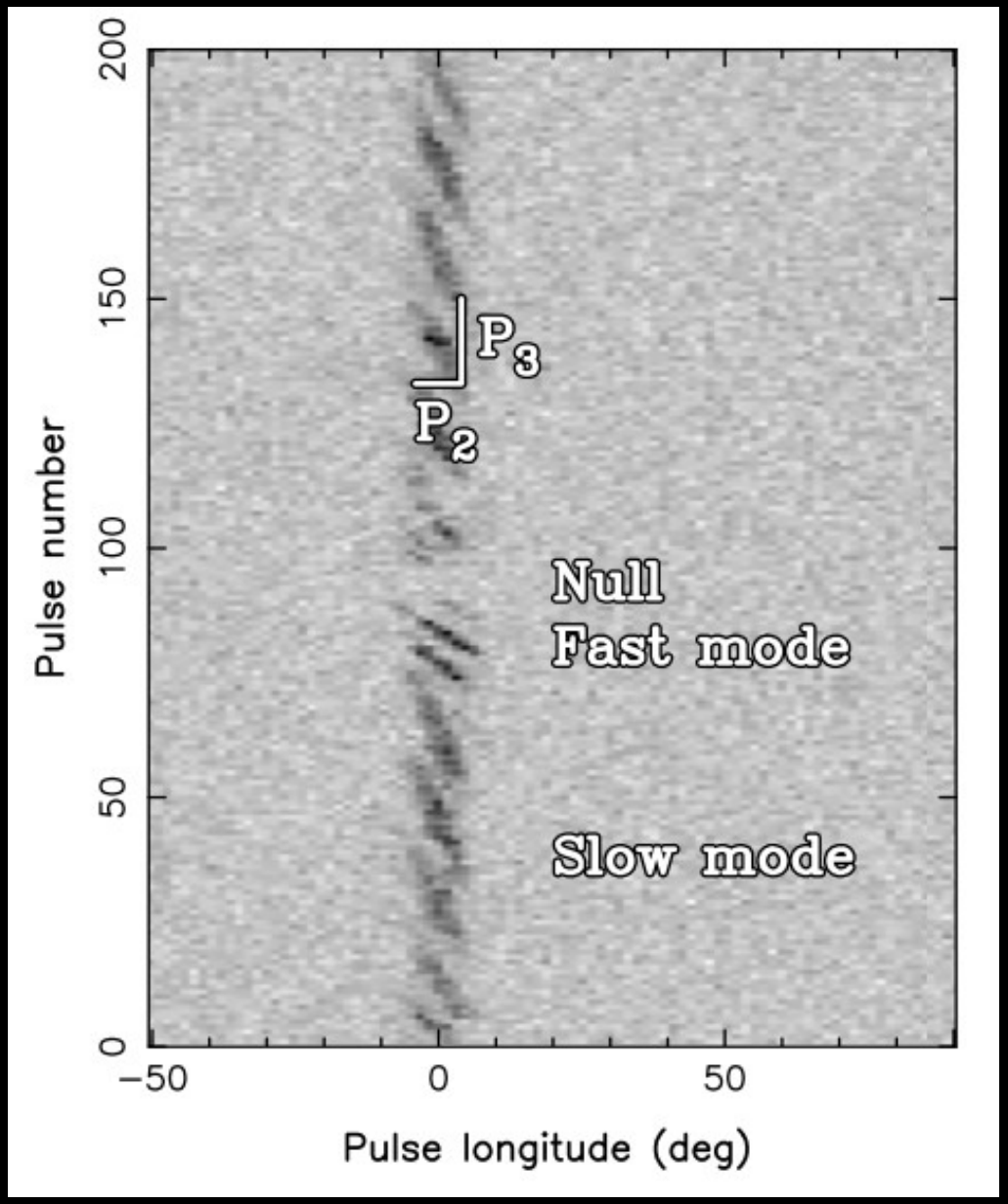

PSR B1702-19
Radio Intensity
Time (sec)

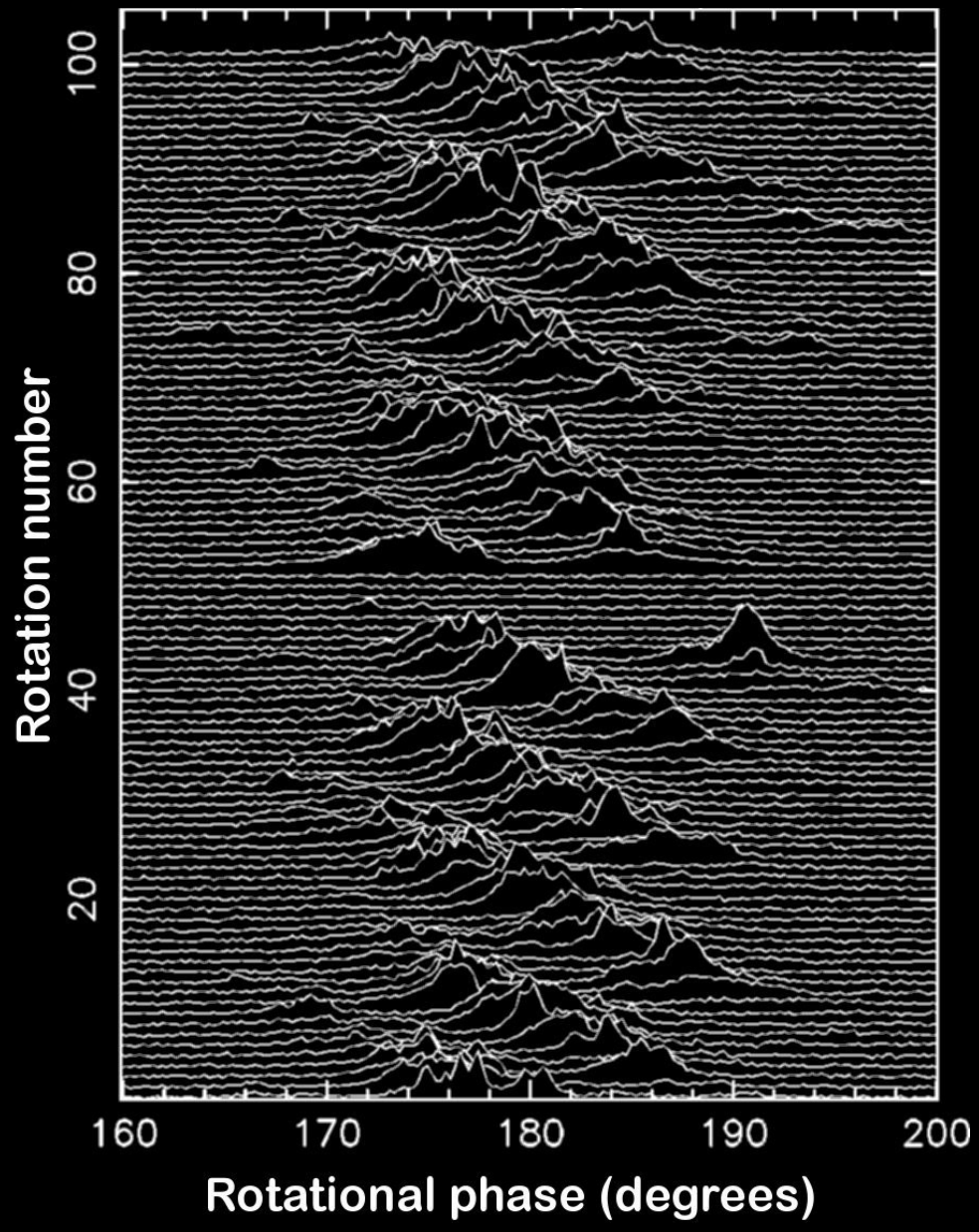

PSR B1857-26
Radio Intensity
Time (sec)

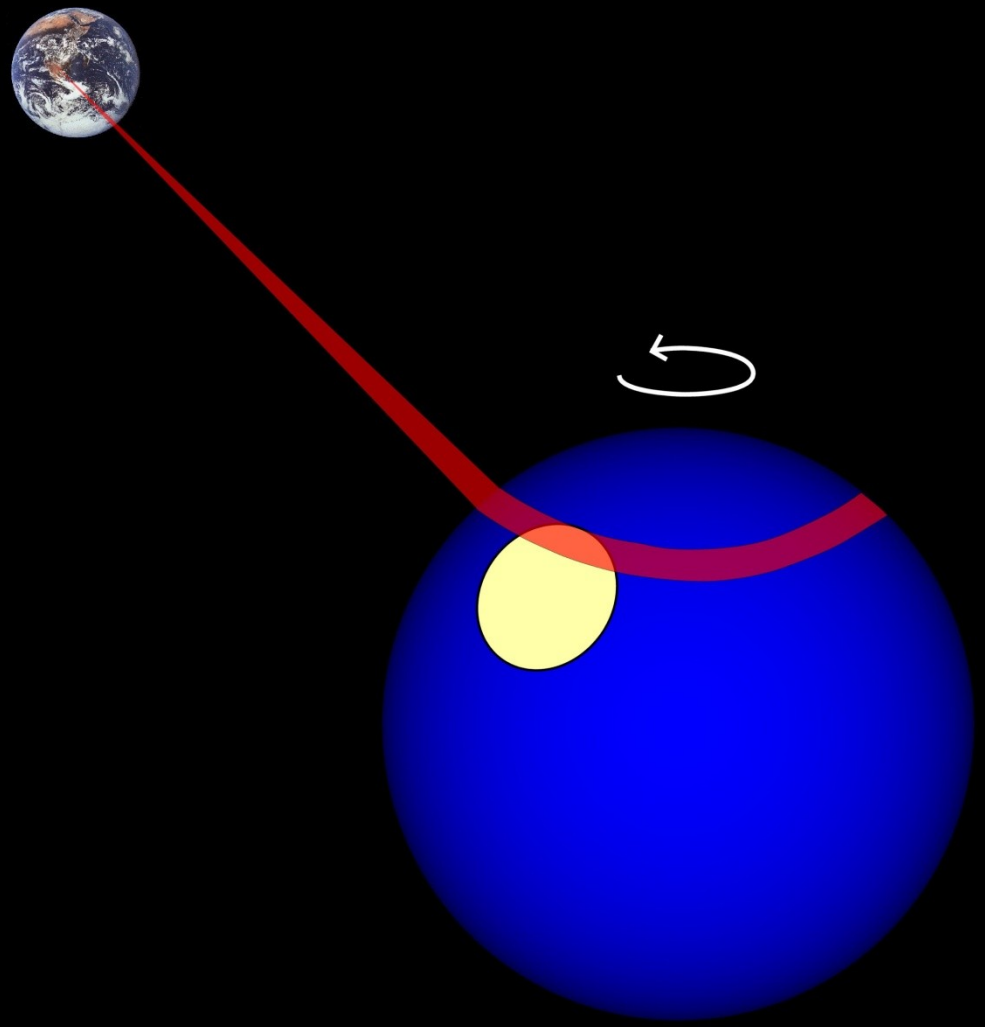
A signal of a bright pulsar



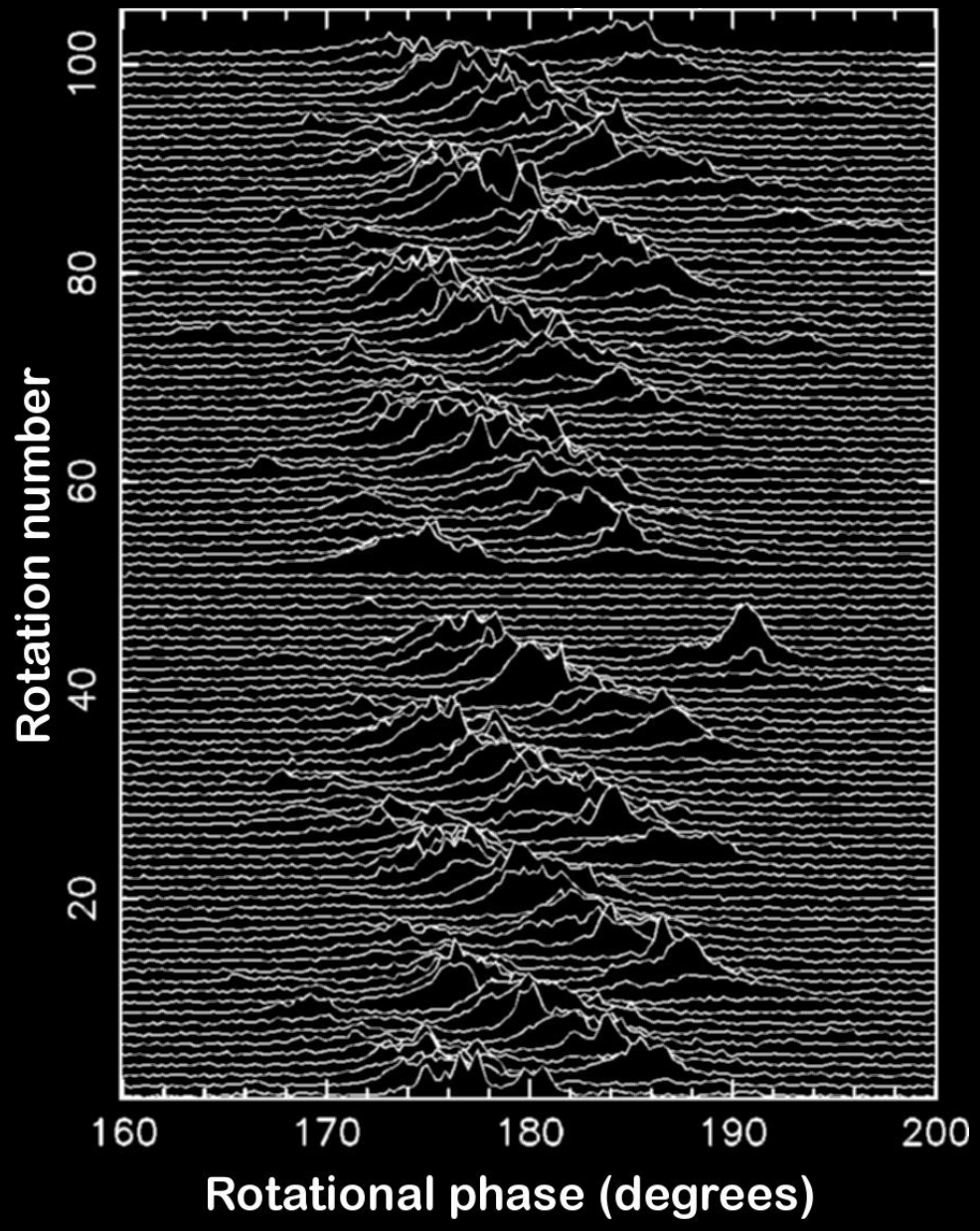

Pulse number
100
50
40
50
60
Pulse longitude (deg)

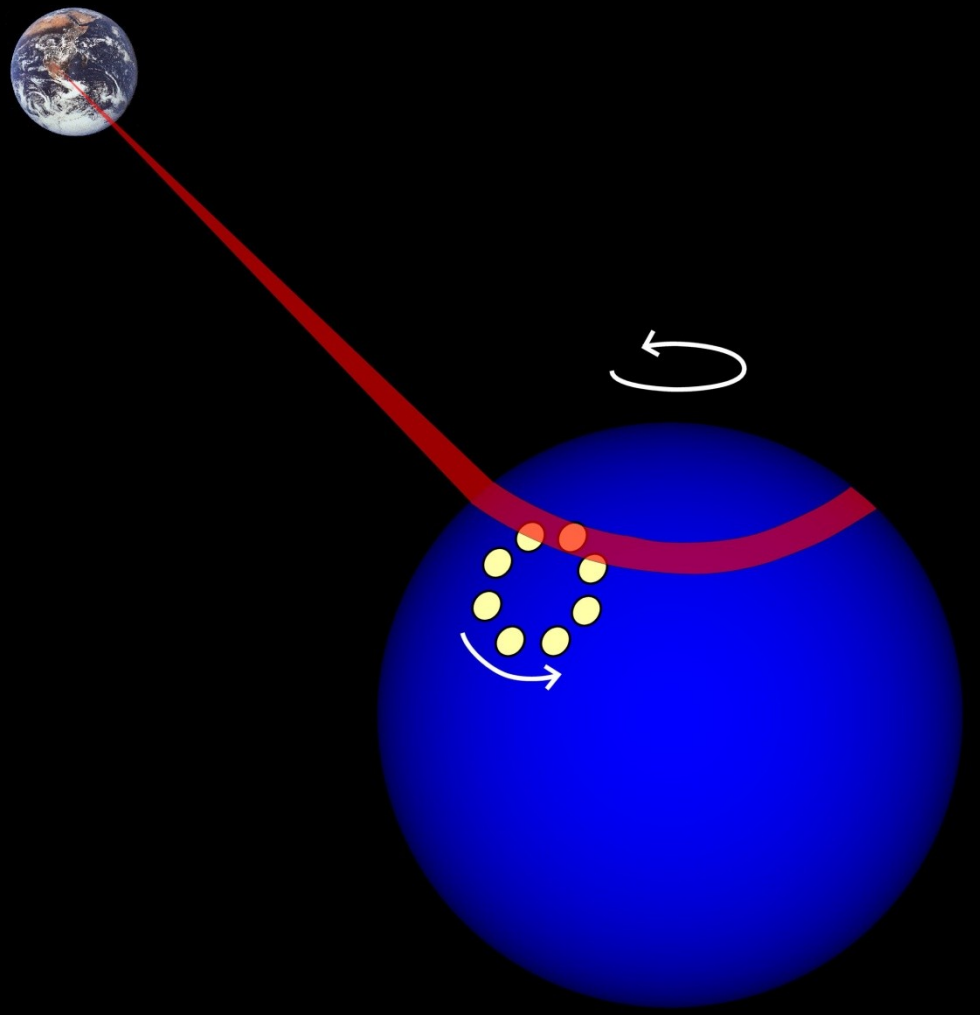

Pulse number
200
150
100
50
0
−50
0
50
Pulse longitude (deg)
P3
P2
Null
Fast mode
Slow mode


Rotation number
100
80
60
40
20
160
170
180
190
200
Rotational phase (degrees)

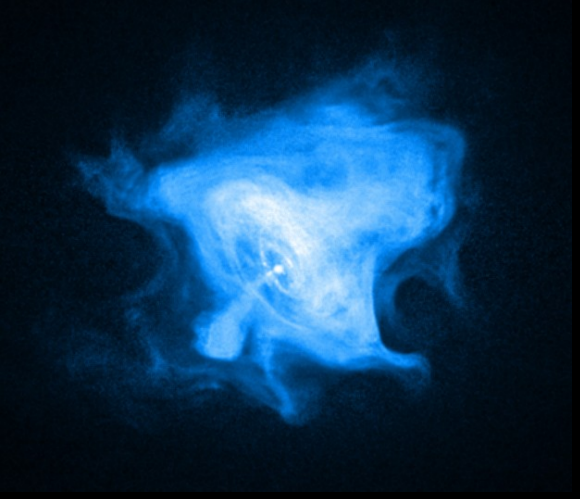


Carousel model

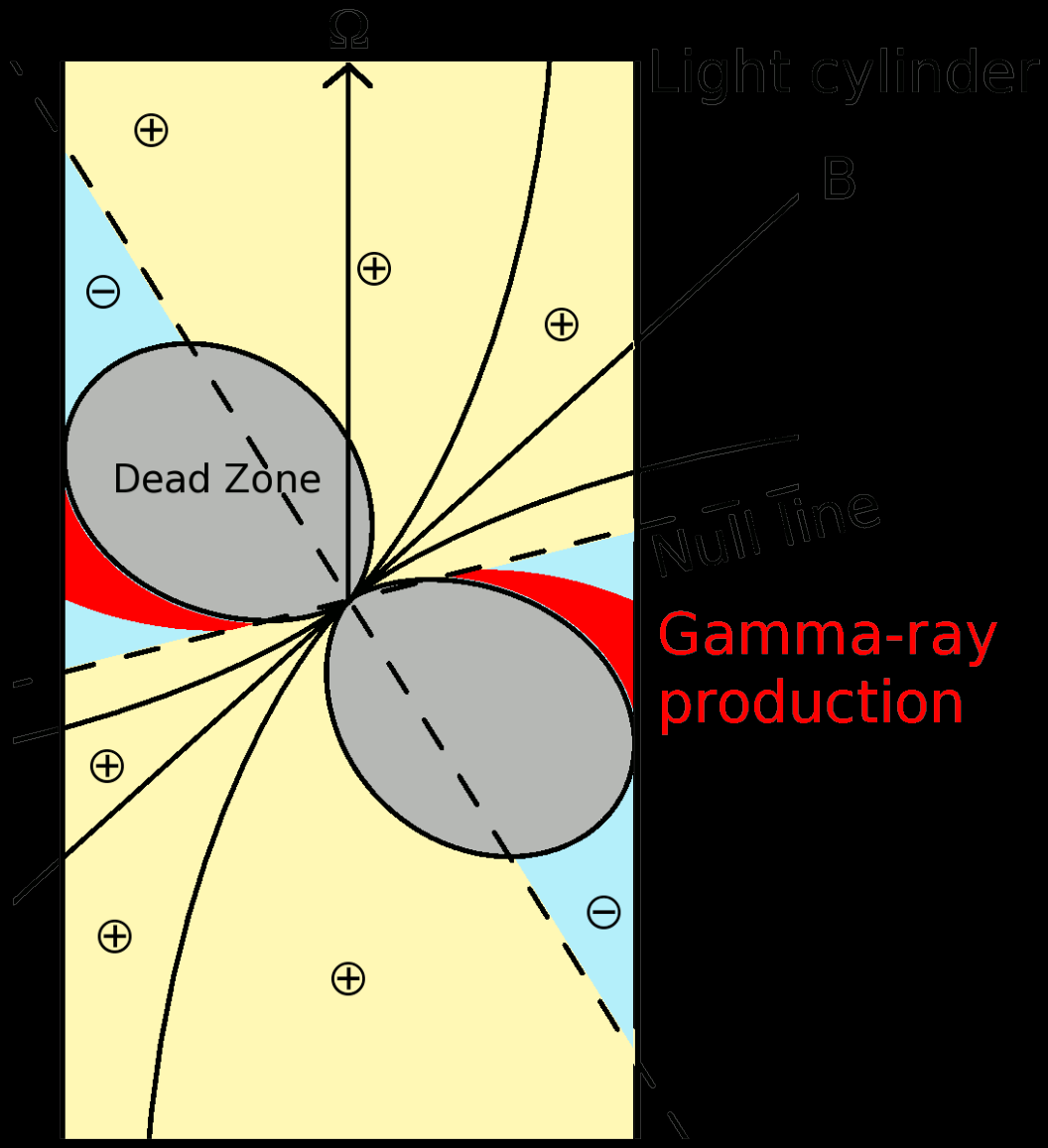


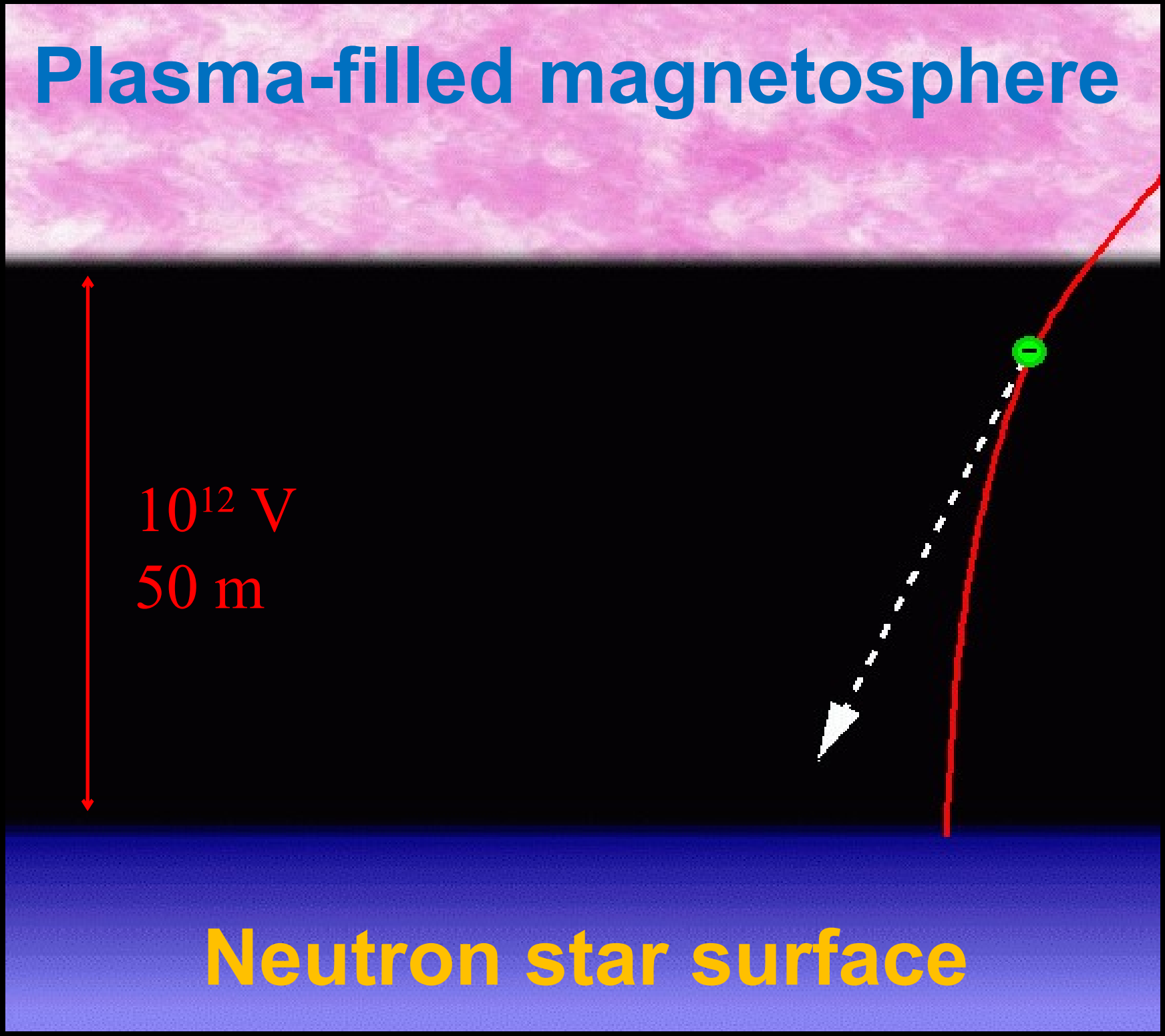


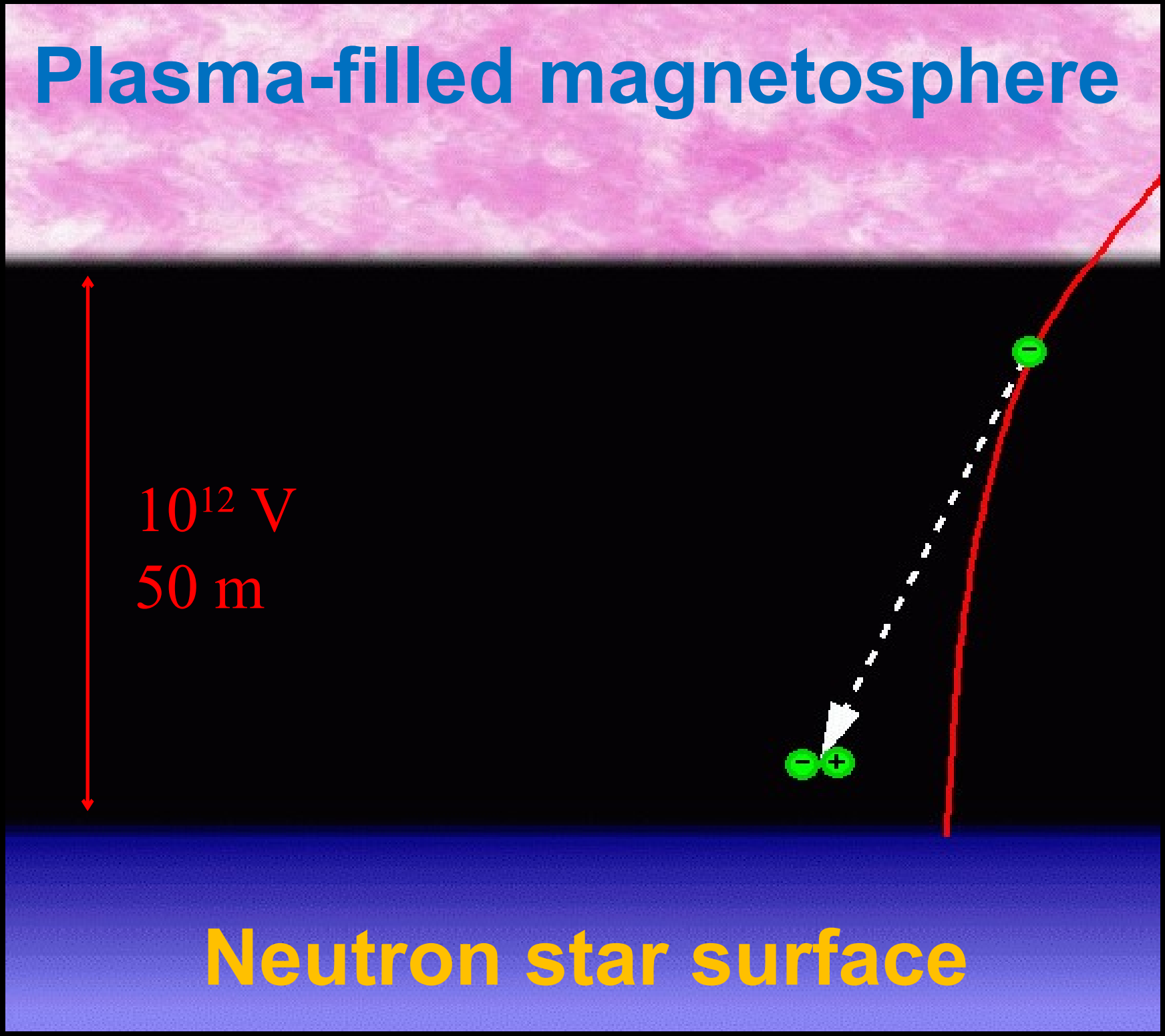
Ruderman & Sutherland 1975



Pulsar magnetospheres




Plasma-filled magnetosphere
10^{12} V
50 m
Neutron star surface


Plasma-filled magnetosphere
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50 m
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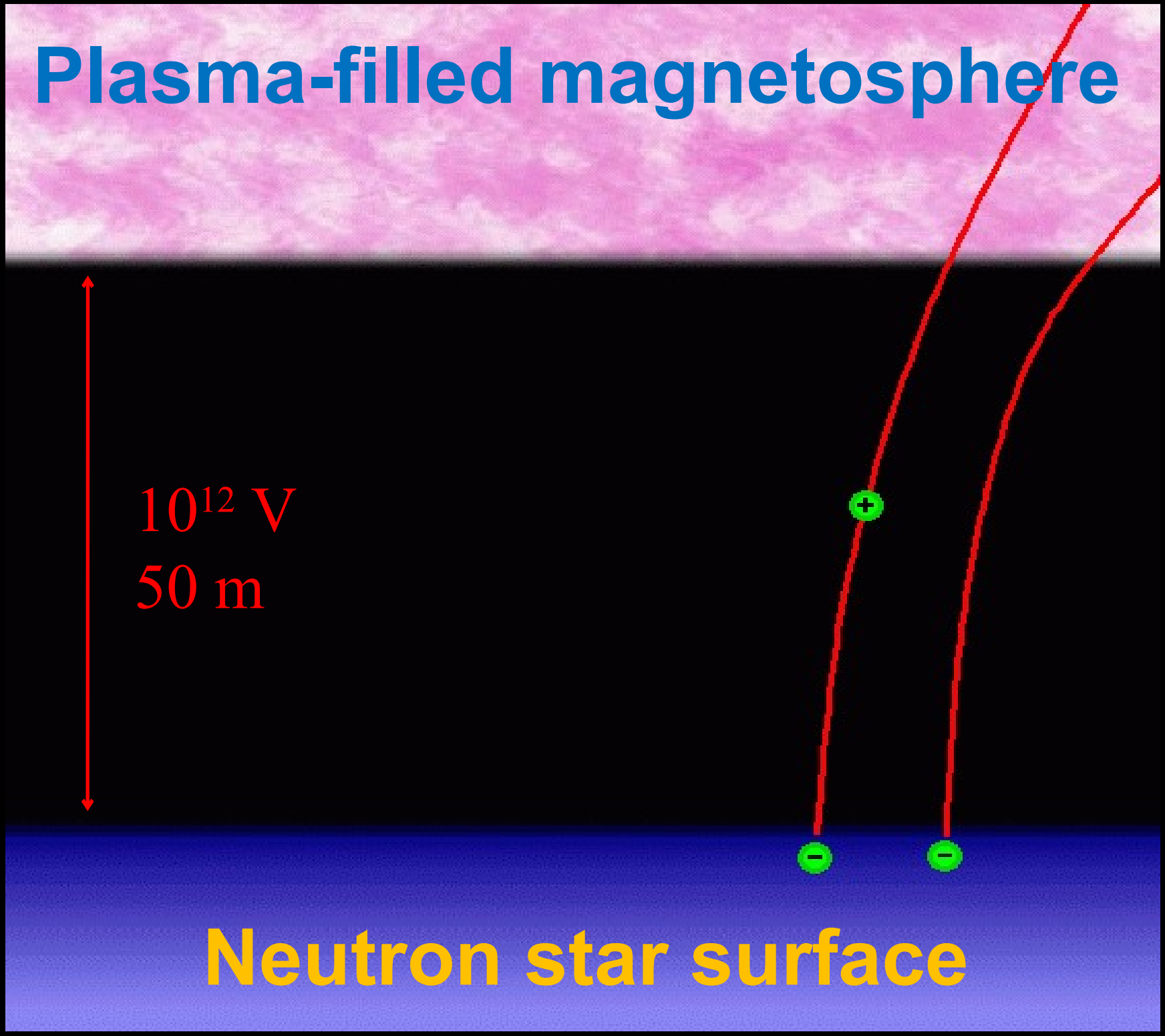
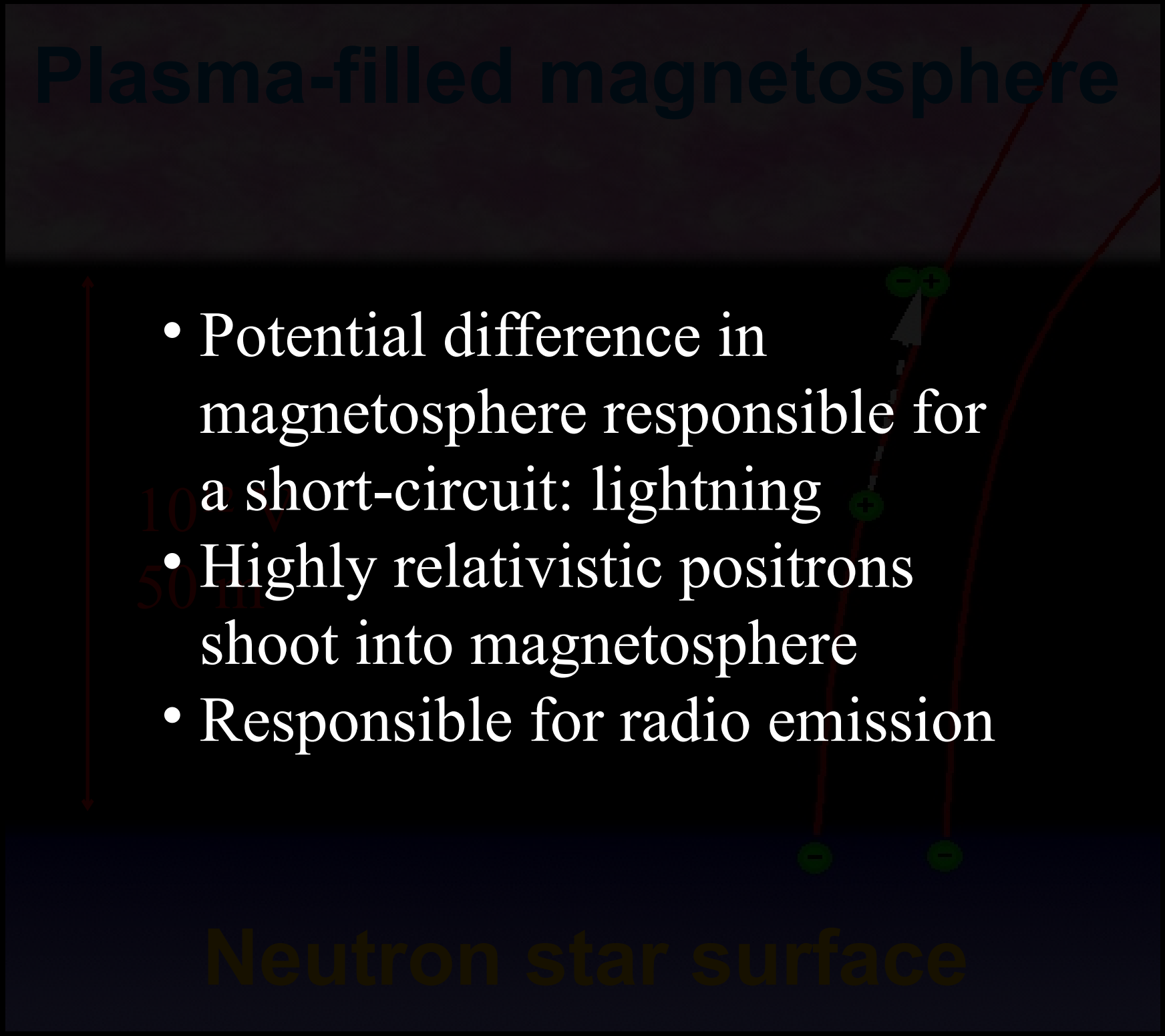
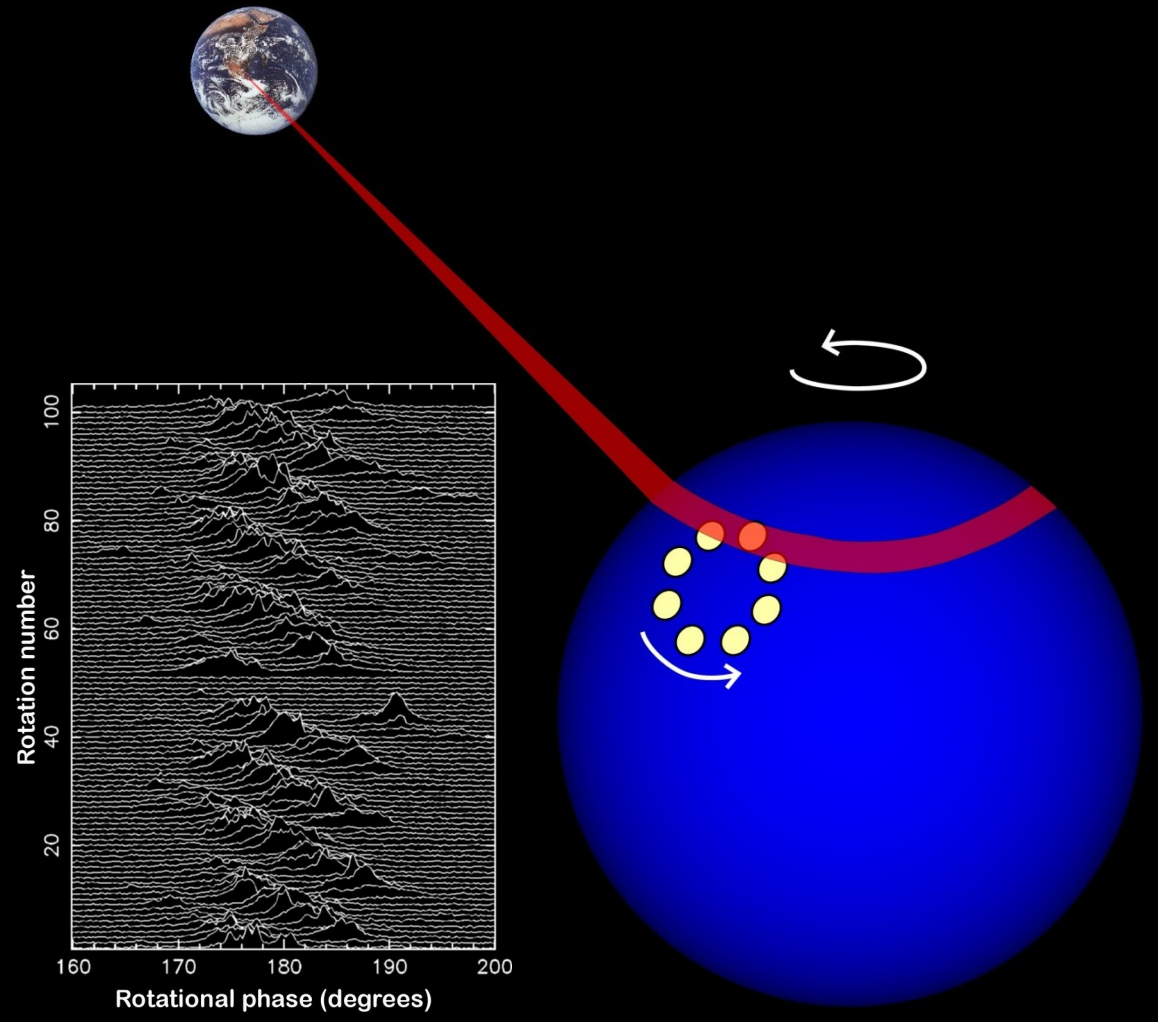
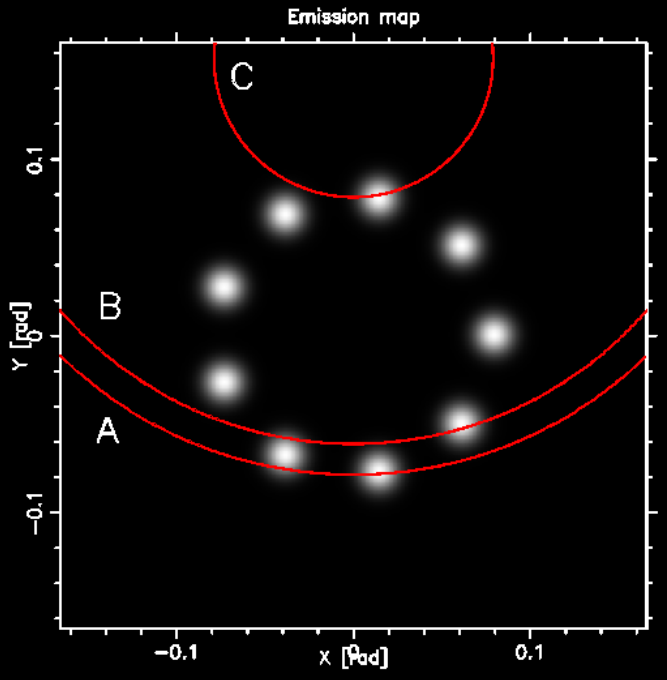

Plasma-filled magnetosphere
10^{12} V
50 m
Neutron star surface

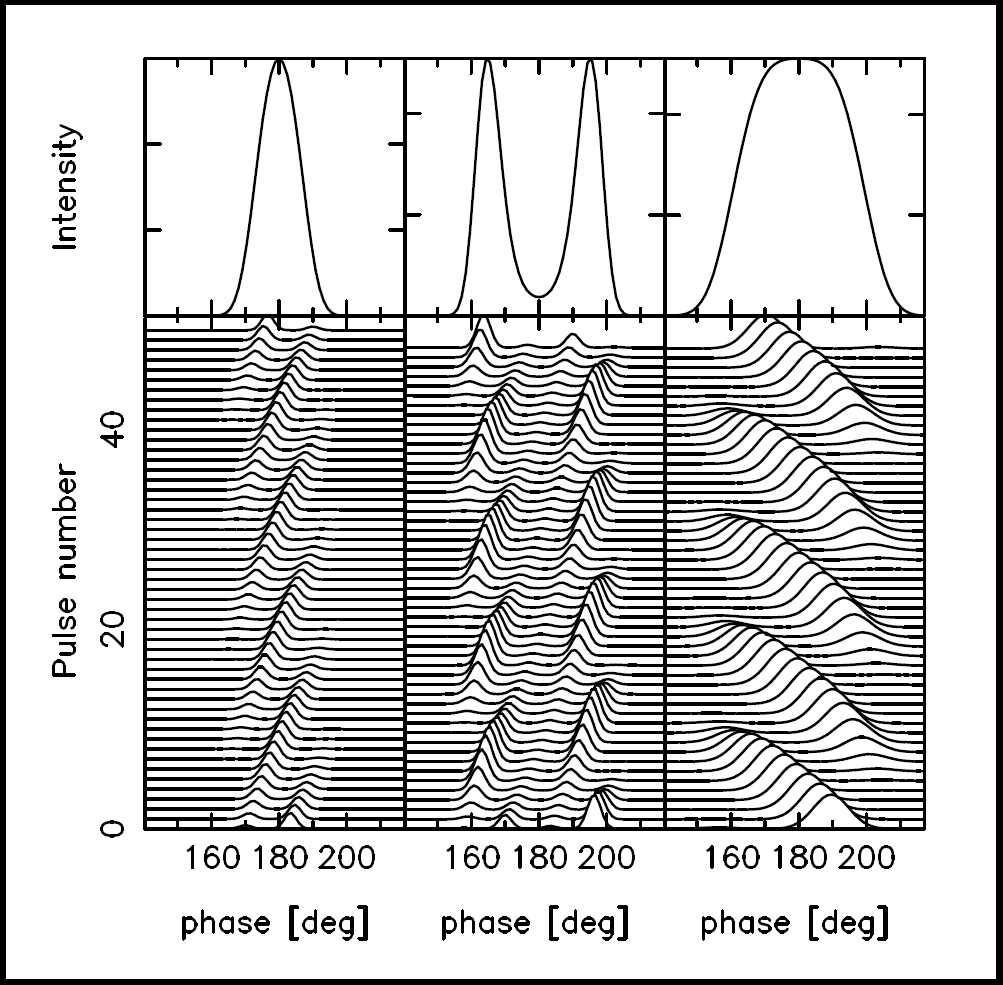


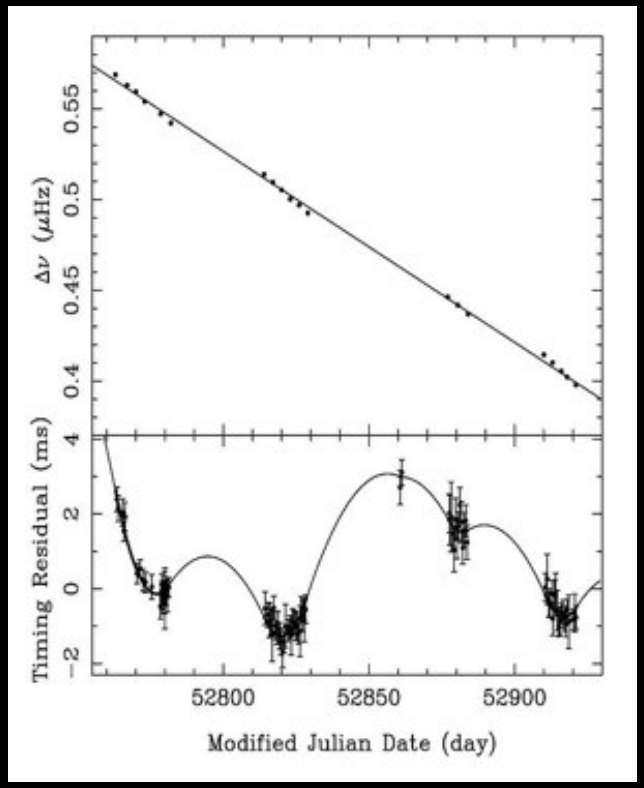
- Potential difference in magnetosphere responsible for a short-circuit: lightning
- Highly relativistic positrons shoot into magnetosphere
- Responsible for radio emission

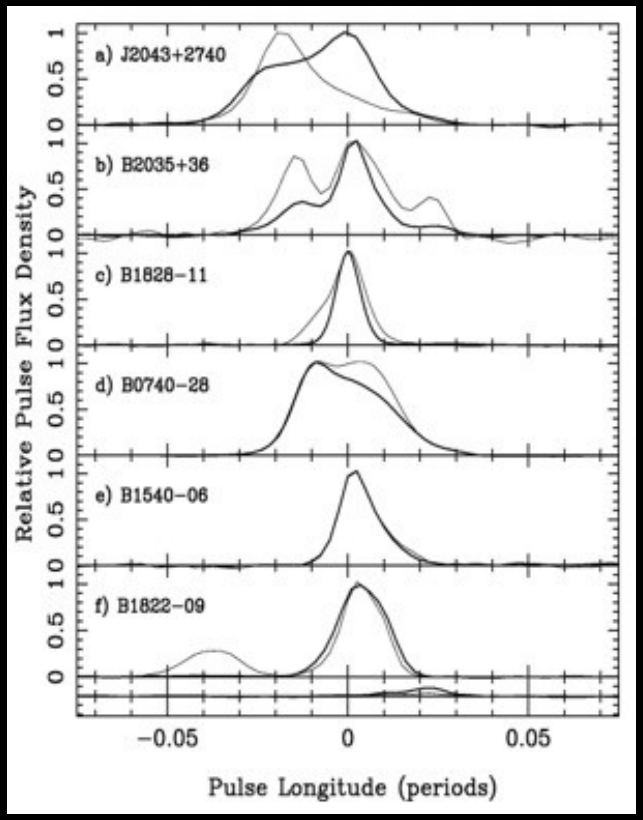
- "Sparks" arranged in a carousel
- Carousel rotates because **E×B** drift.

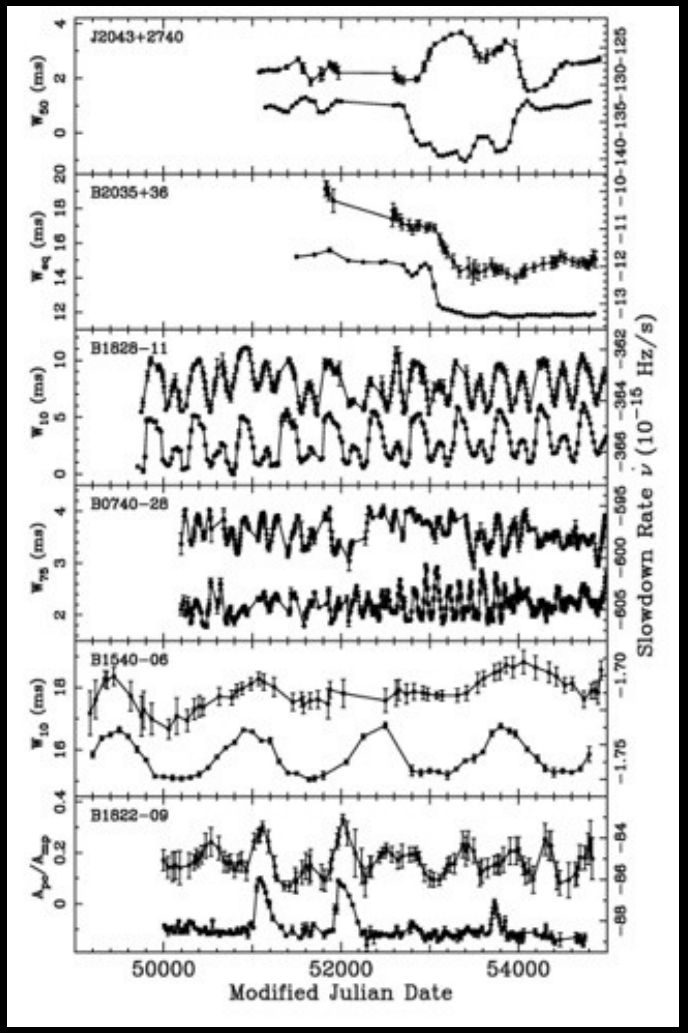


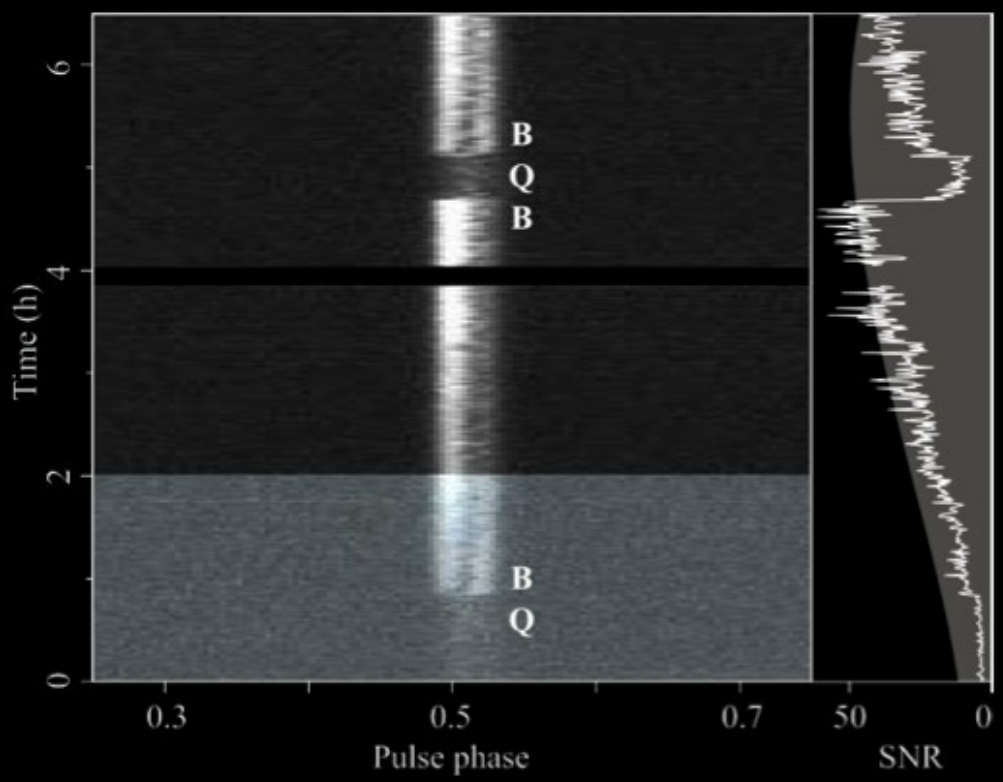

Emission map
C
B
A
0.1
0
−0.1
Y [rad]
−0.1
X [rad]
0.1

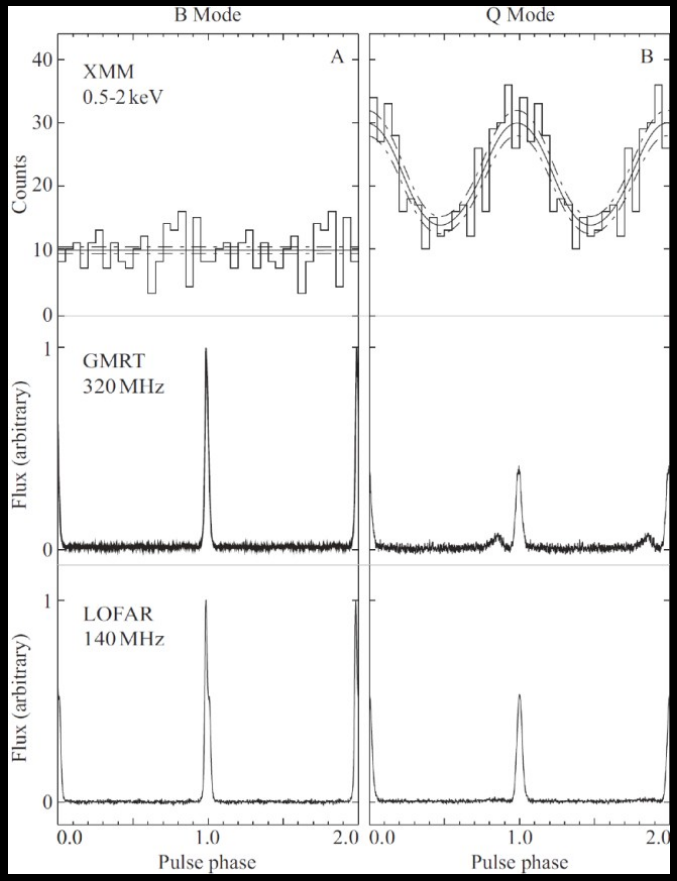

Intensity
Pulse number
0
20
40
160 180 200
phase [deg]
160 180 200
phase [deg]
160 180 200
phase [deg]


Δν (μHz)
0.55
0.5
0.45
0.4
Timing Residual (ms)
4
2
0
−2
52800
52850
52900
Modified Julian Date (day)


a) J2043+2740
b) B2035+36
c) B1828−11
d) B0740−28
e) B1540−06
f) B1822−09
Relative Pulse Flux Density
−0.05
0
0.05
Pulse Longitude (periods)

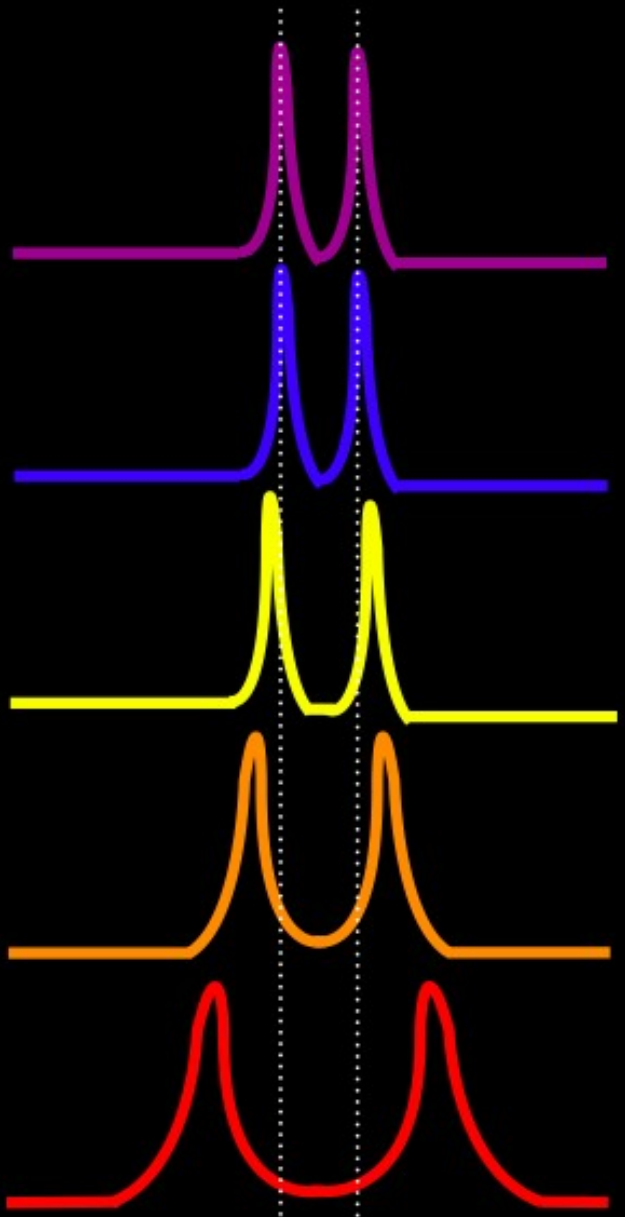

J2043+2740
B2035+36
B1828−11
B0740−28
B1540−06
B1822−09
50000
52000
54000
Modified Julian Date
Slowdown Rate ν̇ (10⁻¹⁵ Hz/s)


Time (h)
0
2
4
6
B
Q
B
B
Q
0.3
0.5
0.7
Pulse phase
50
0
SNR


B Mode
Q Mode
XMM
0.5-2 keV
A
B
Counts
40
30
20
10
0
GMRT
320 MHz
LOFAR
140 MHz
Flux (arbitrary)
1
0
0.0
1.0
2.0
Pulse phase

LOFAR Emission Physics

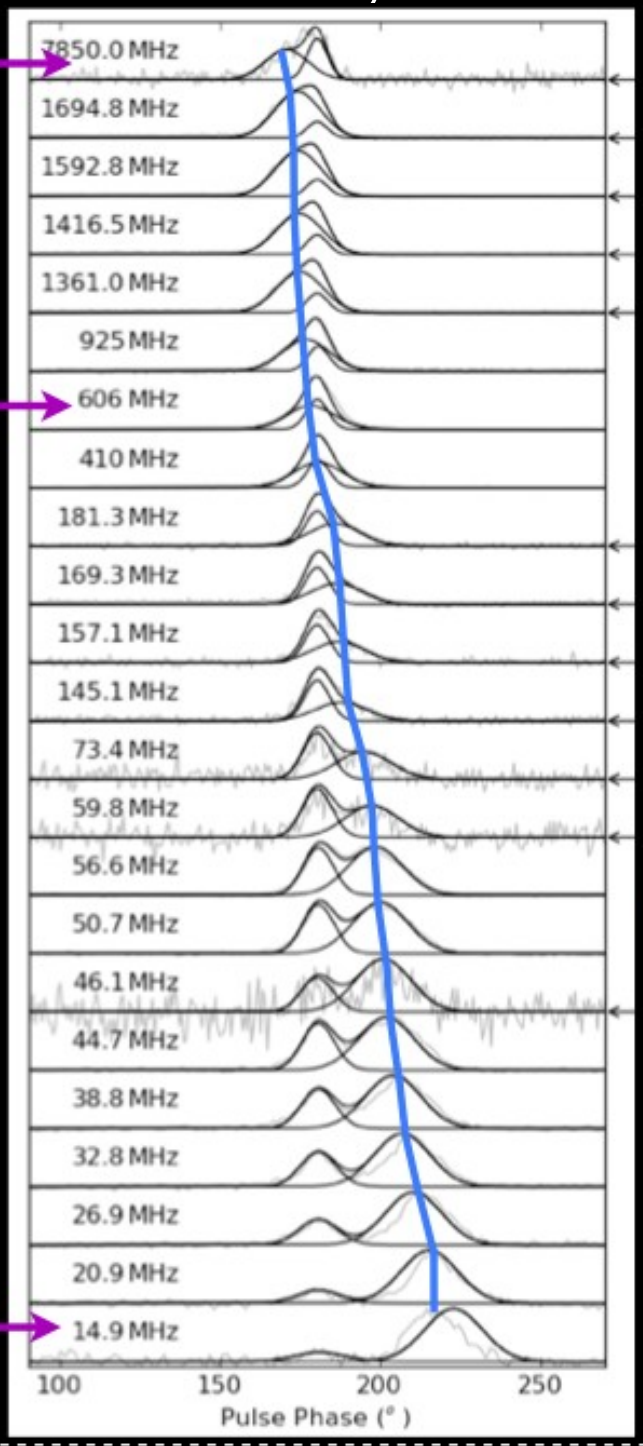
PSR B0809+74



Starts broad

Gets narrower

Broadens again



But this happens in a very smooth way

Looks like one component is moving and one is fixed