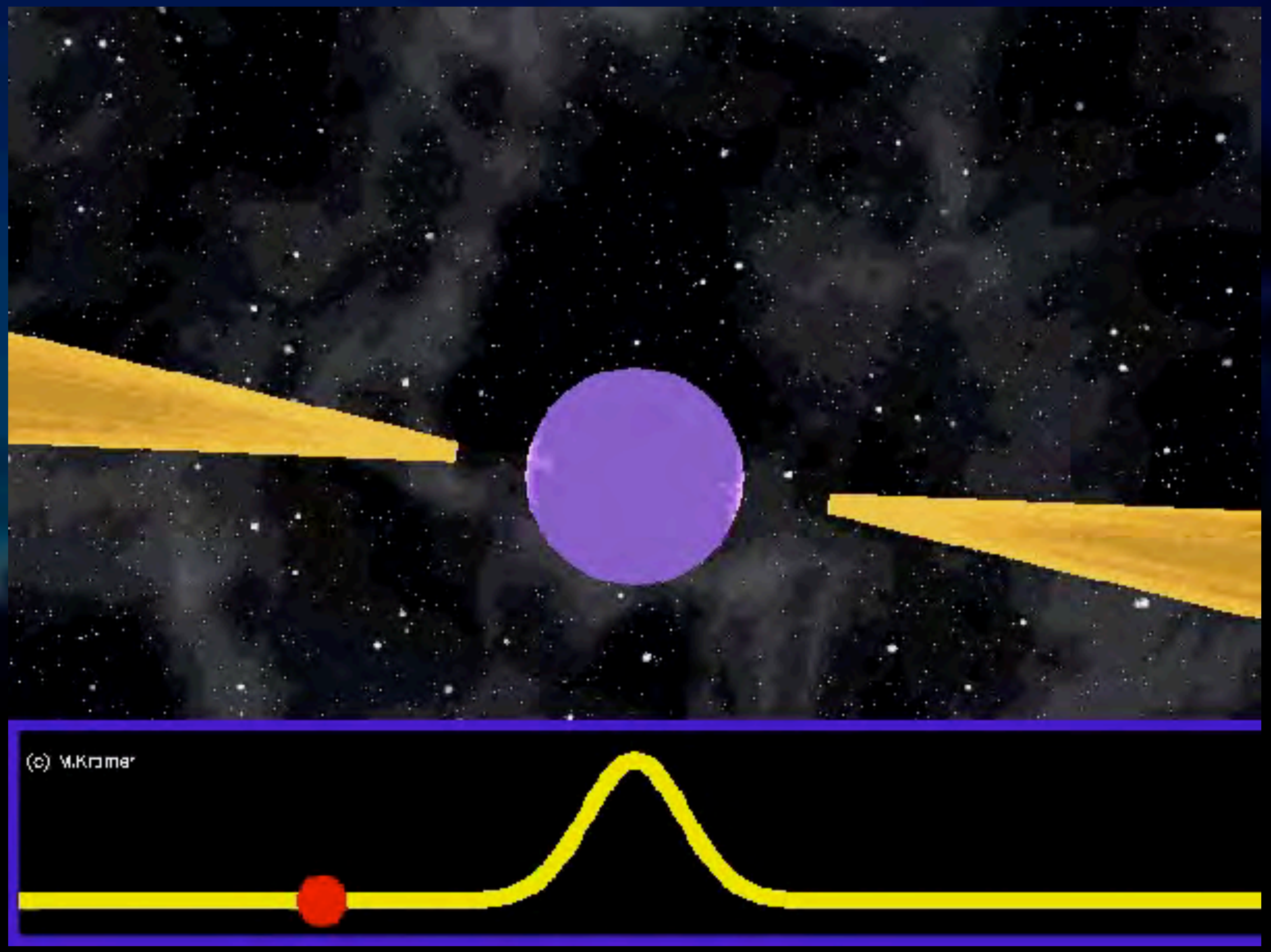
Gravitational Wave Observatories IV: Pulsar Timing Arrays

Neil J. Cornish

Pulsar Timing



Pulsar Timing

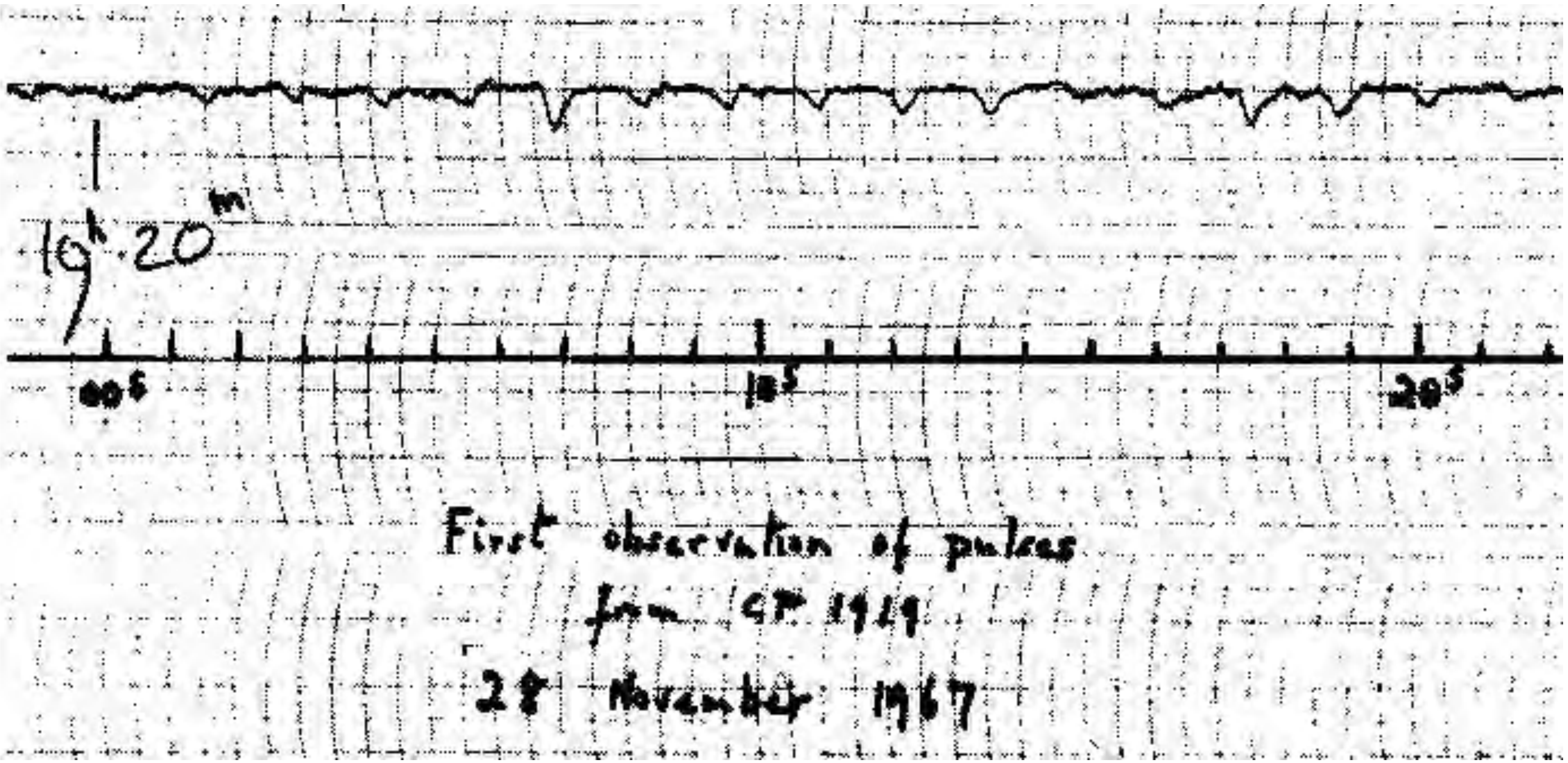
Outline of lecture

- History, status and future of pulsar timing
- What are pulsars? Why use milli-second pulsars?
- Observing pulsars - pulse folding
- Timing model
- Noise sources

Resources

- Duncan Lorimer's review of pulsar timing http://link.springer.com/article/10.12942/lrr-2008-8
- Sarah Burke-Spolar's review https://arxiv.org/pdf/1511.07869.pdf
- Andrea Lommen's review http://iopscience.iop.org/article/10.1088/0034-4885/78/12/124901
- TEMPO2 paper https://academic.oup.com/mnras/article-lookup/doi/10.1111/j.1365-2966.2006.10870.x

The History and Future of Pulsar Timing



Bell & Hewish - discovered first radio pulsar PSR B1919+21 in 1967

Steve Detweiler - Inventor of Pulsar Timing Detection

THE ASTROPHYSICAL JOURNAL, 234:1100–1104, 1979 December 15

PULSAR TIMING MEASUREMENTS AND THE SEARCH FOR GRAVITATIONAL WAVES

STEVEN DETWEILER
Department of Physics, Yale University
Received 1979 June 4; accepted 1979 July 6

ABSTRACT

Pulse arrival time measurements of pulsars may be used to search for gravitational waves with periods on the order of 1 to 10 years and dimensionless amplitudes $\sim 10^{-11}$. The analysis of published data on pulsar regularity sets an upper limit to the energy density of a stochastic background of gravitational waves, with periods ~ 1 year, which is comparable to the closure density of the universe.

Subject headings: cosmology — gravitation — pulsars — relativity

1948-2016

Uses spacecraft doppler tracking GW response formula from Estabrook and Walhquist (1975)

Mentions earlier paper by Sazhin (1978) that considered a particular line-of-sight detection PTA geometry

Steve Detweiler - Inventor of Pulsar Timing Detection

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PULSAR TIMING MEASUREMENTS AND THE SEARCH FOR GRAVITATIONAL WAVES

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Under some circumstances it is possible to differentiate with certainty the effects on the residual caused by a gravitational wave from those caused by some pulsar phenomenon. For example, the cross-correlation of the signals from a number of pulsars could determine that an anomalous residual was produced by an event in the solar system rather than on the pulsar.

1948-2016

Suggests cross-correlation of pulsar signals to detect GWs

The paper discusses possible sources and sets the first upper limits. Limits were weak since pulsars then were poorly timed $\delta t \sim 100\,\mathrm{ms}$

1982 - Discovery of the first milli-second Pulsar, PSR B1937+21

letters to nature

Nature **300**, 615 - 618 (16 December 1982); doi:10.1038/300615a0

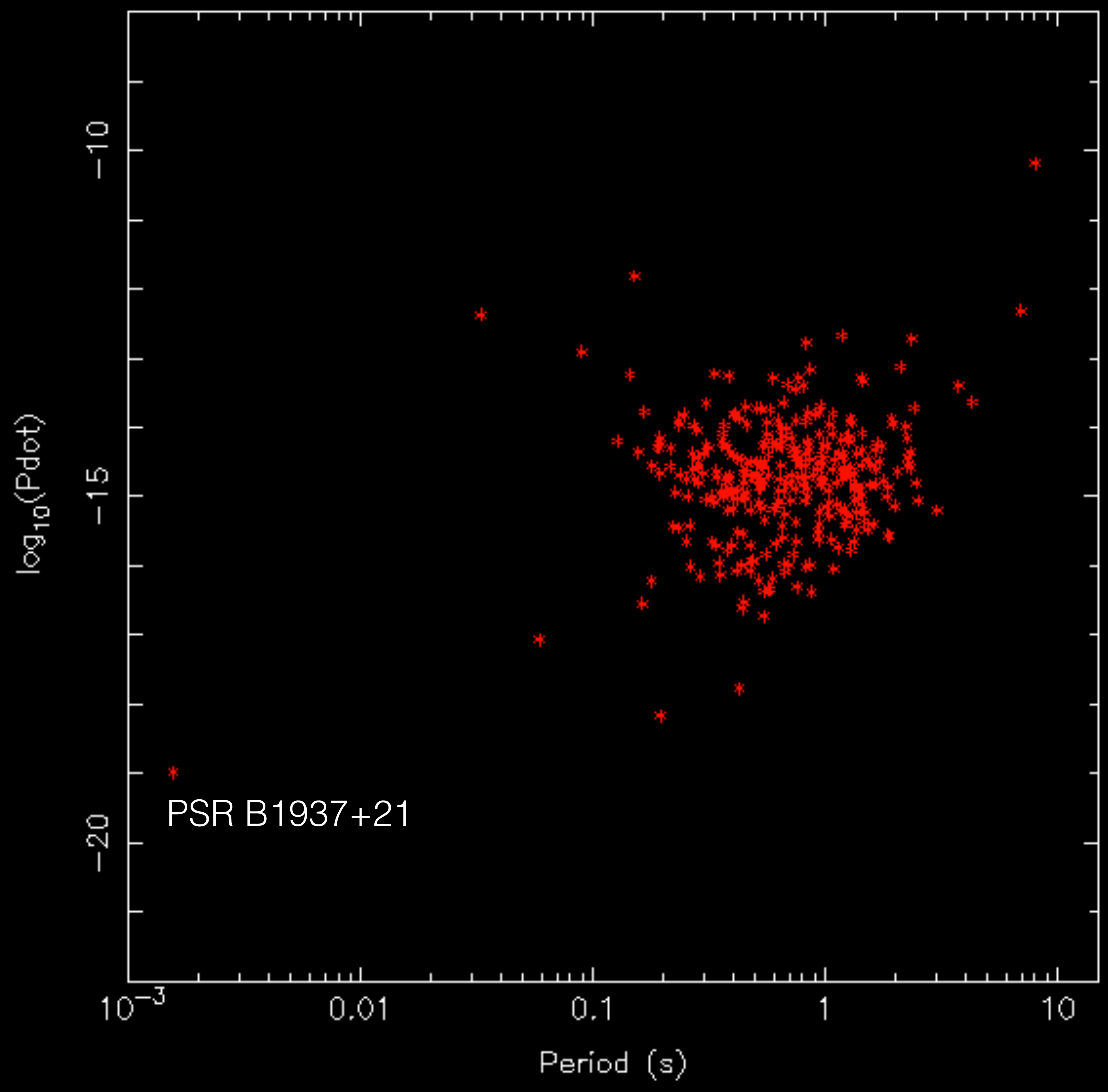
A millisecond pulsar

D. C. BACKER[*], SHRINIVAS R. KULKARNI[*], CARL HEILES[*], M. M. DAVIS[†] & W. M. GOSS[‡]

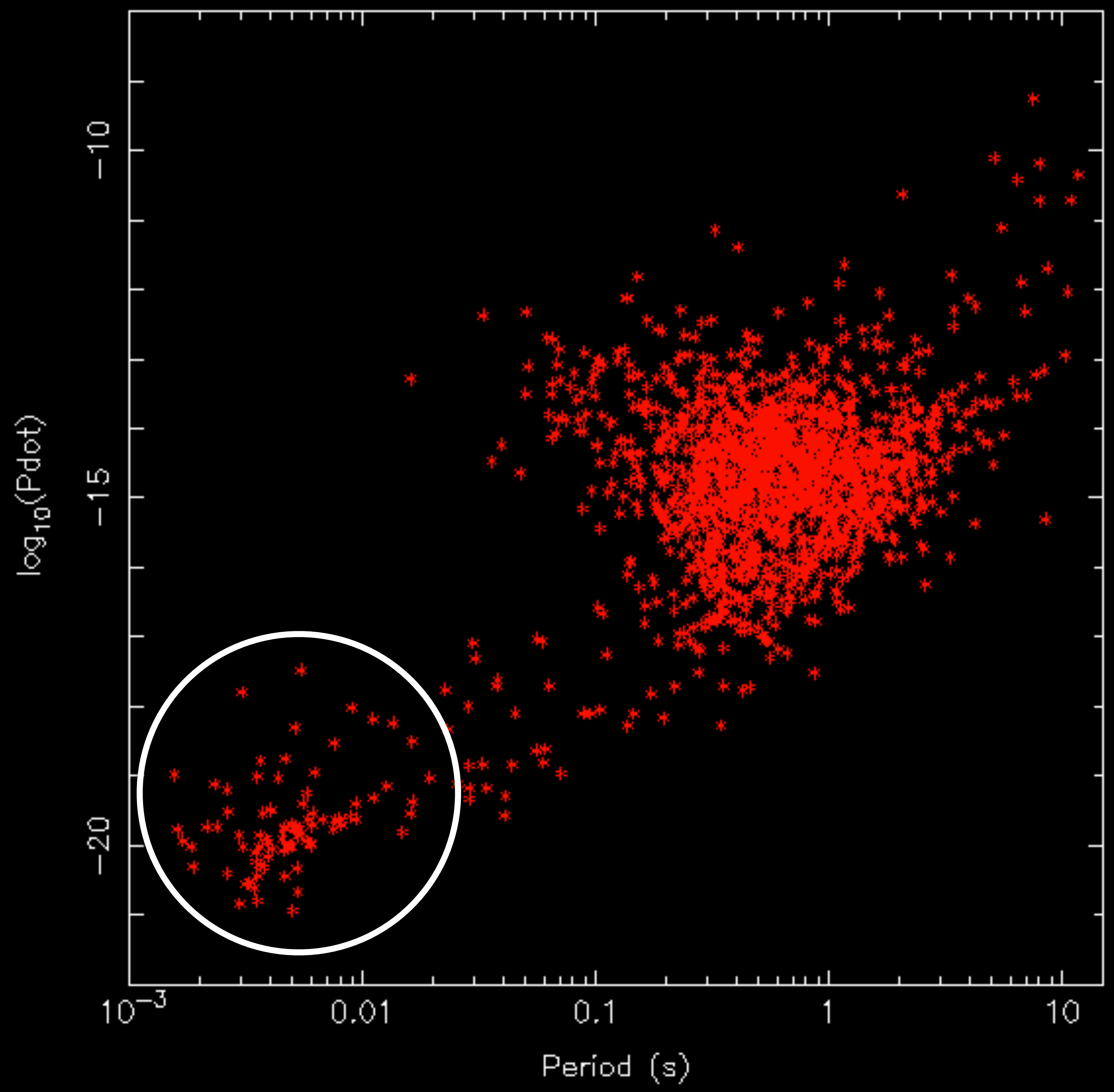
[*]Radio Astronomy Laboratory and Astronomy Department, University of California, Berkeley, California 94720, USA
[†]National Astronomy and Ionosphere Center, Arecibo, Puerto Rico
[‡]Kapteyn Laboratorium, Groningen, The Netherlands

The radio properties of 4C21.53 have been an enigma for many years. First, the object displays interplanetary scintillations (IPS) at 81 MHz, indicating structure smaller than 1 are s, despite its low galactic latitude (–0.3°)[1]. IPS modulation is rare at low latitudes because of interstellar angular broadening. Second, the source has an extremely steep ($\sim\nu^{-2}$) spectrum at decametric wavelengths[2]. This combination of properties suggested that 4C21.53 was either an undetected pulsar or a member of some new class of objects. This puzzle may be resolved by the discovery and related observations of a fast pulsar, 1937+214, with a period of 1.558 ms in the constellation Vulpecula only a few degrees from the direction to the original pulsar, 1919+21. The existence of such a fast pulsar with no evidence either of a new formation event or of present energy losses raises new questions about the origin and evolution of pulsars.

Milli-second Pulsars, 1982 to now



1982



Now

Hellings & Downs, 1983

THE ASTROPHYSICAL JOURNAL, **265**:L39–L42, 1983 February 15

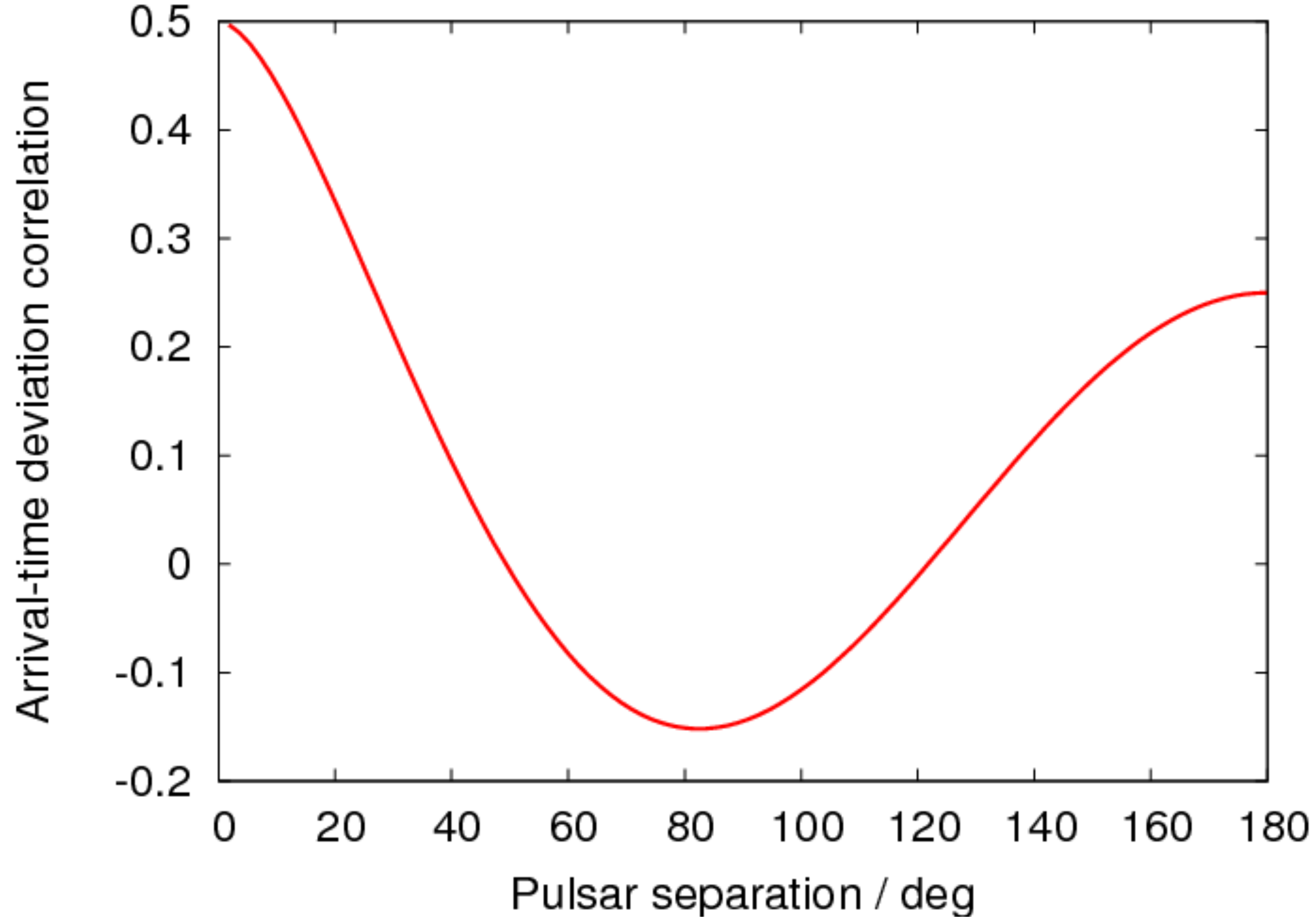
UPPER LIMITS ON THE ISOTROPIC GRAVITATIONAL RADIATION BACKGROUND FROM PULSAR TIMING ANALYSIS[1]

R. W. HELLINGS AND G. S. DOWNS
Jet Propulsion Laboratory, California Institute of Technology
Received 1982 October 1; accepted 1982 October 20

ABSTRACT

A pulsar and the Earth may be thought of as end masses of a free-mass gravitational wave antenna in which the relative motion of the masses is monitored by observing the Doppler shift of the pulse arrival times. Using timing residuals from PSR 1133+16, 1237+25, 1604−00, and 2045−16, an upper limit to the spectrum of the isotropic gravitational radiation background has been derived in the frequency band 4×10^{-9} to 10^{-7} Hz. This limit is found to be $S_E = 10^{21} f^3$ ergs cm^{-3} Hz^{-1}, where S_E is the energy density spectrum and f is the frequency in Hz. This would limit the energy density at frequencies below 10^{-8} Hz to be 1.4×10^{-4} times the critical density.

Subject headings: cosmology — gravitation — pulsars



Bound used classic (un-recylced) pulsars $\delta t \sim 10\,\mu\mathrm{s} \rightarrow 2\,\mathrm{ms}$

Indirect Detection of Gravitational Waves (by mid '80s)

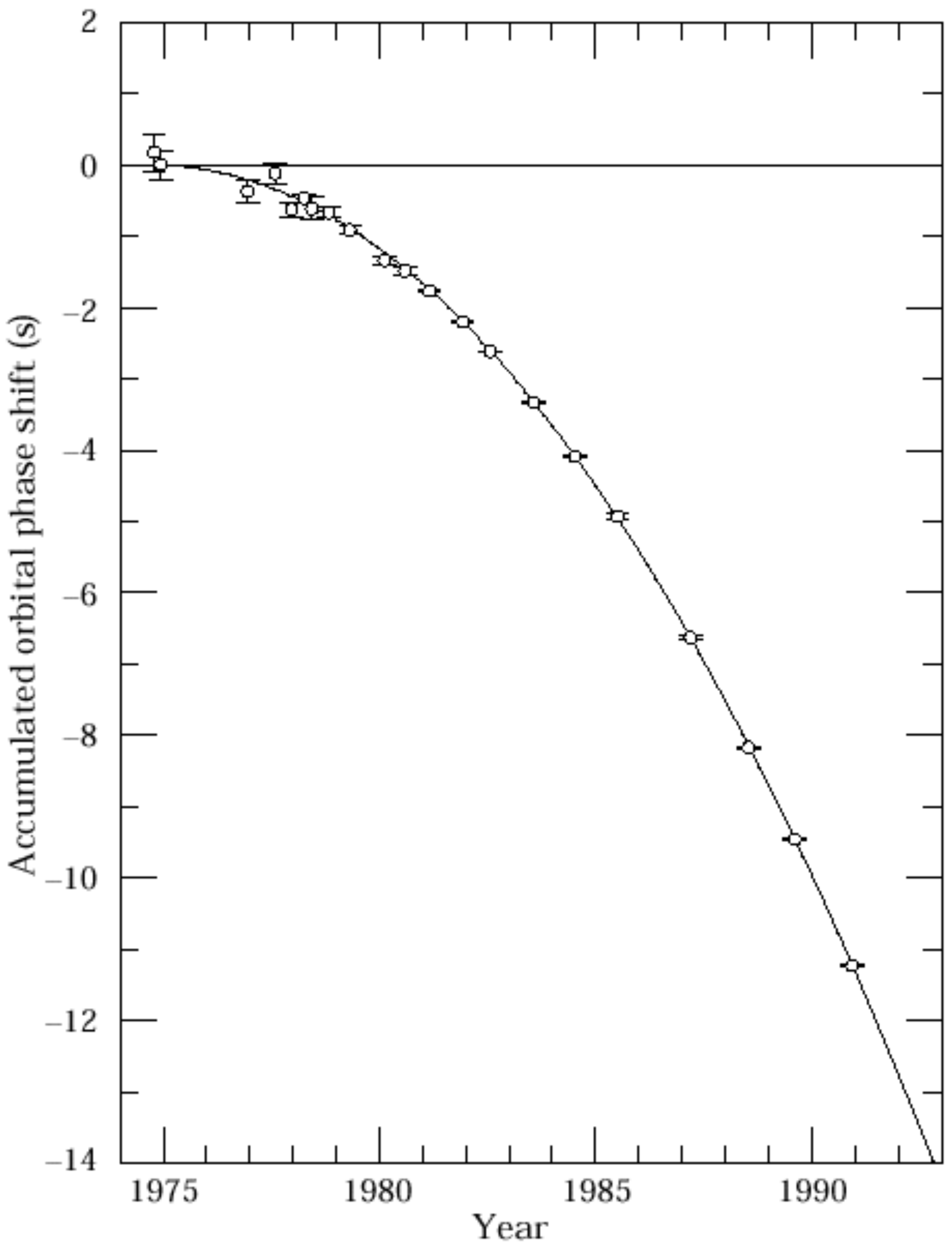


Figure 14.1: Accumulated shift of the times of periastron passage in the PSR 1913+16 system, relative to an assumed orbit with a constant period. The parabolic curve represents the general relativistic prediction, modified by Galactic effects, for orbital period decay from gravitational radiation damping forces.

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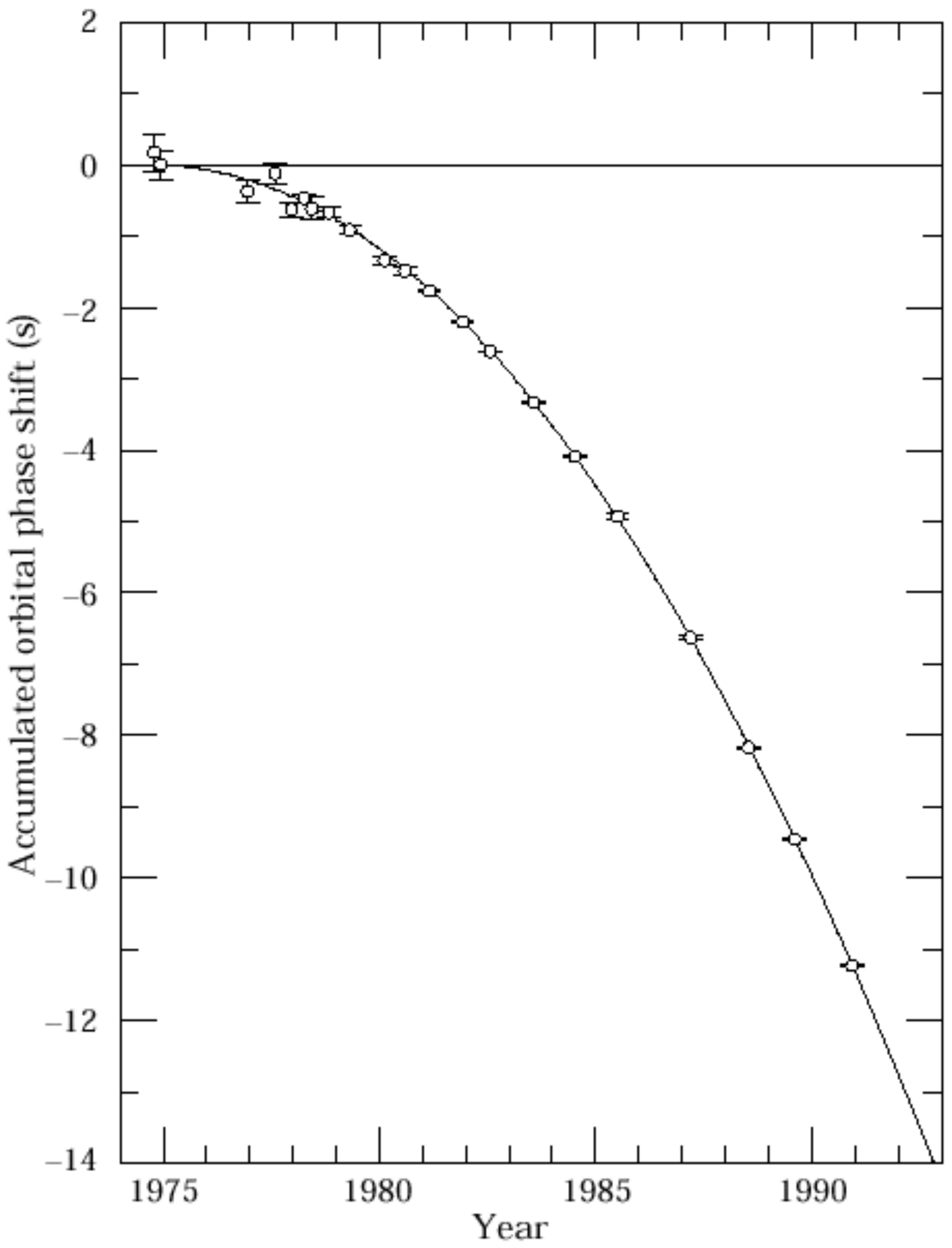

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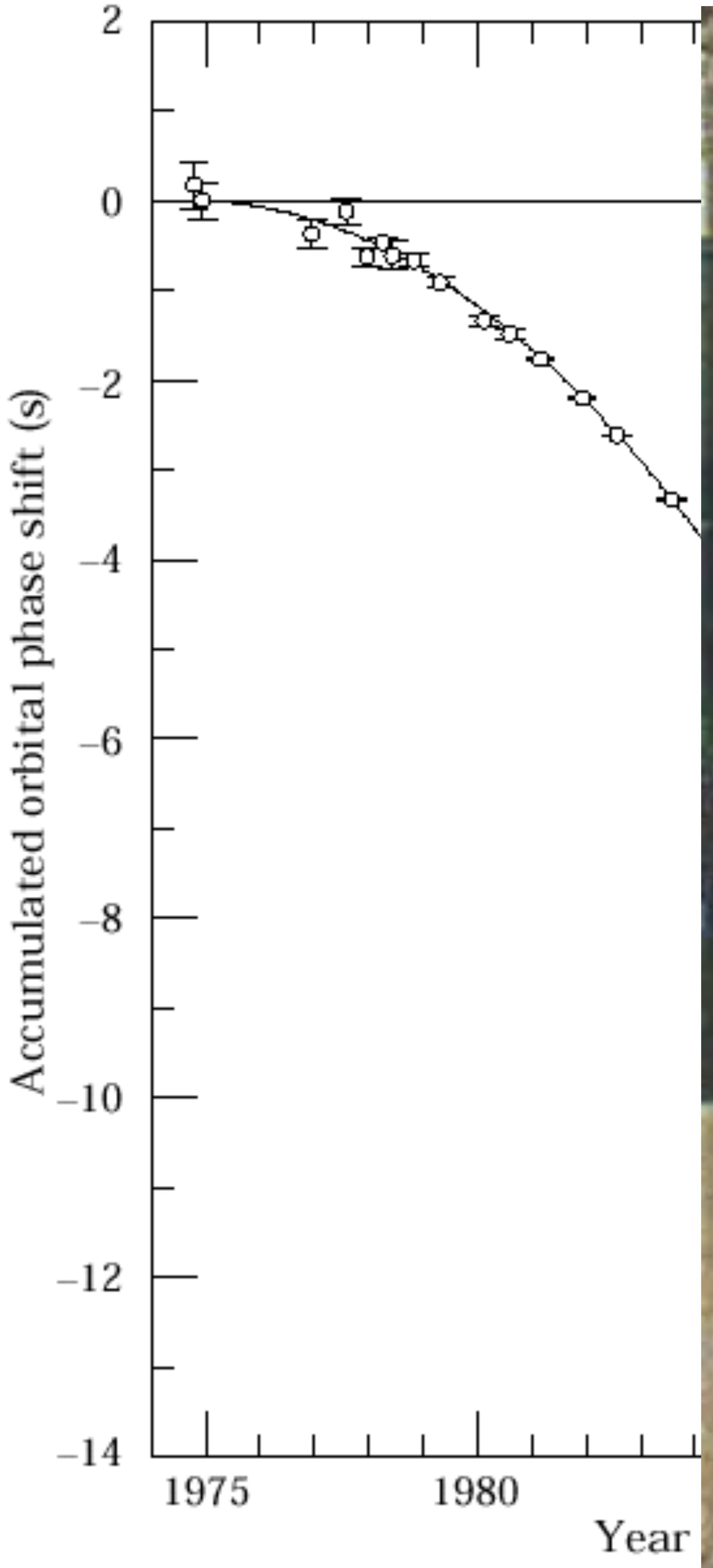

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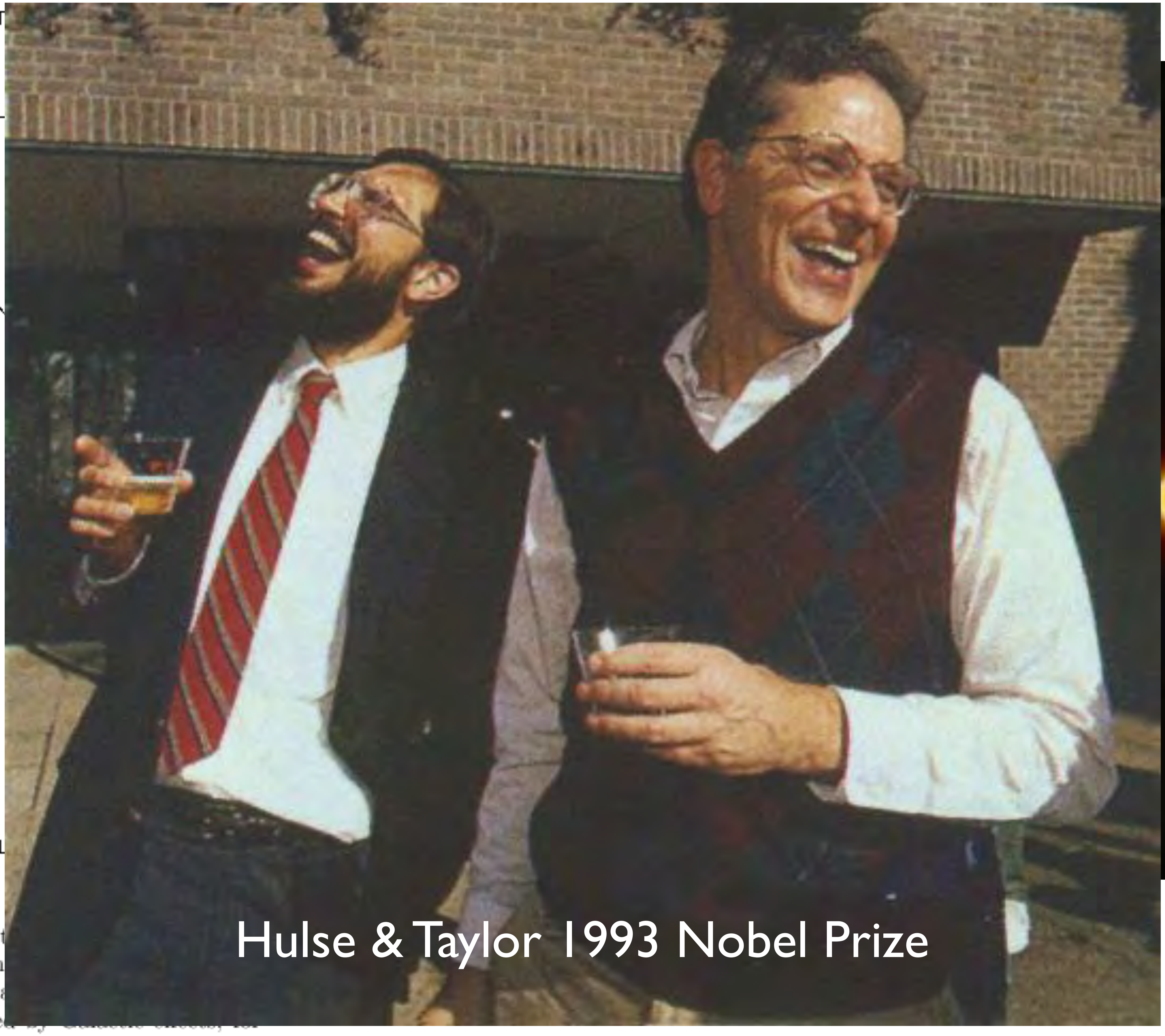
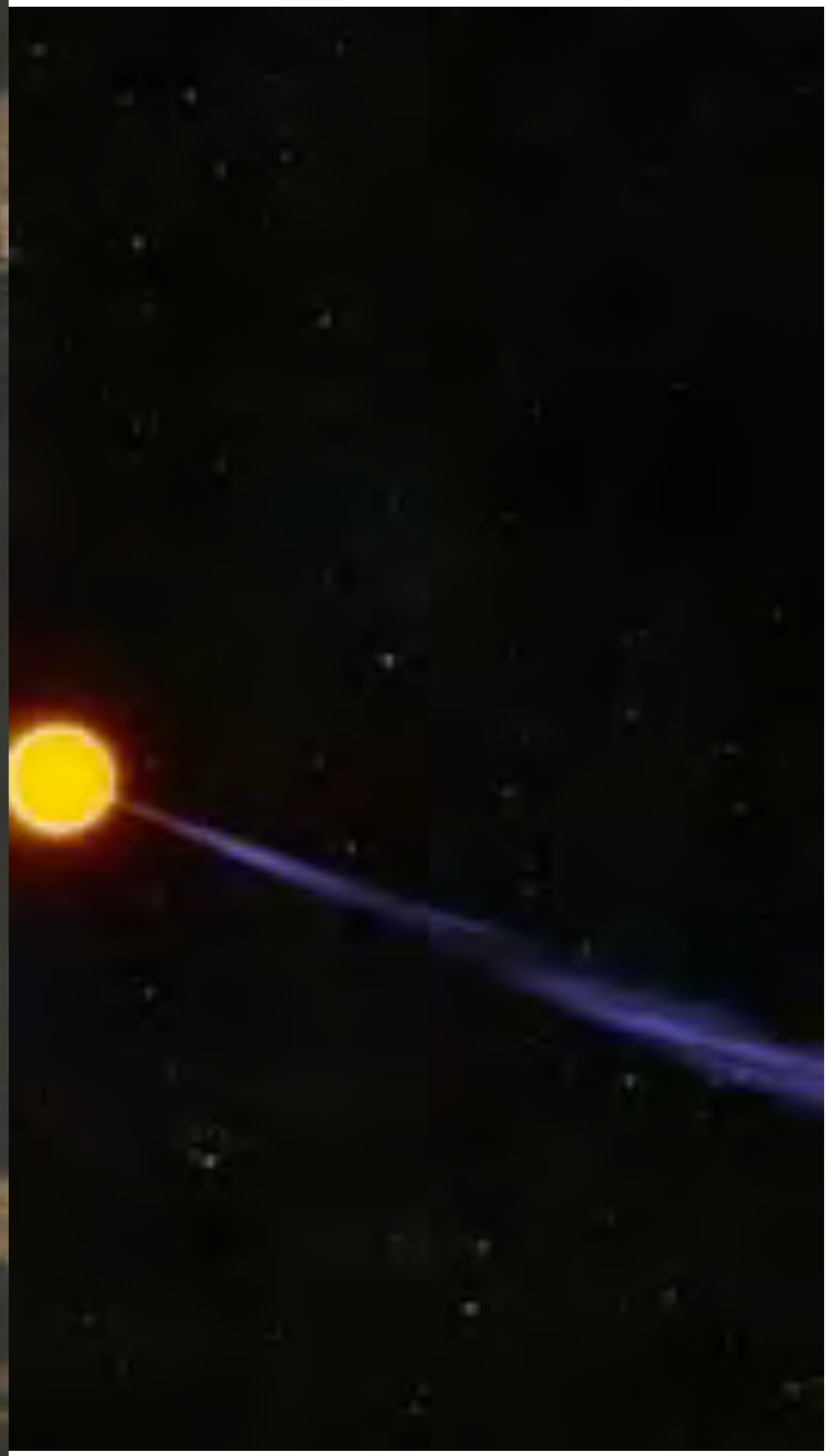
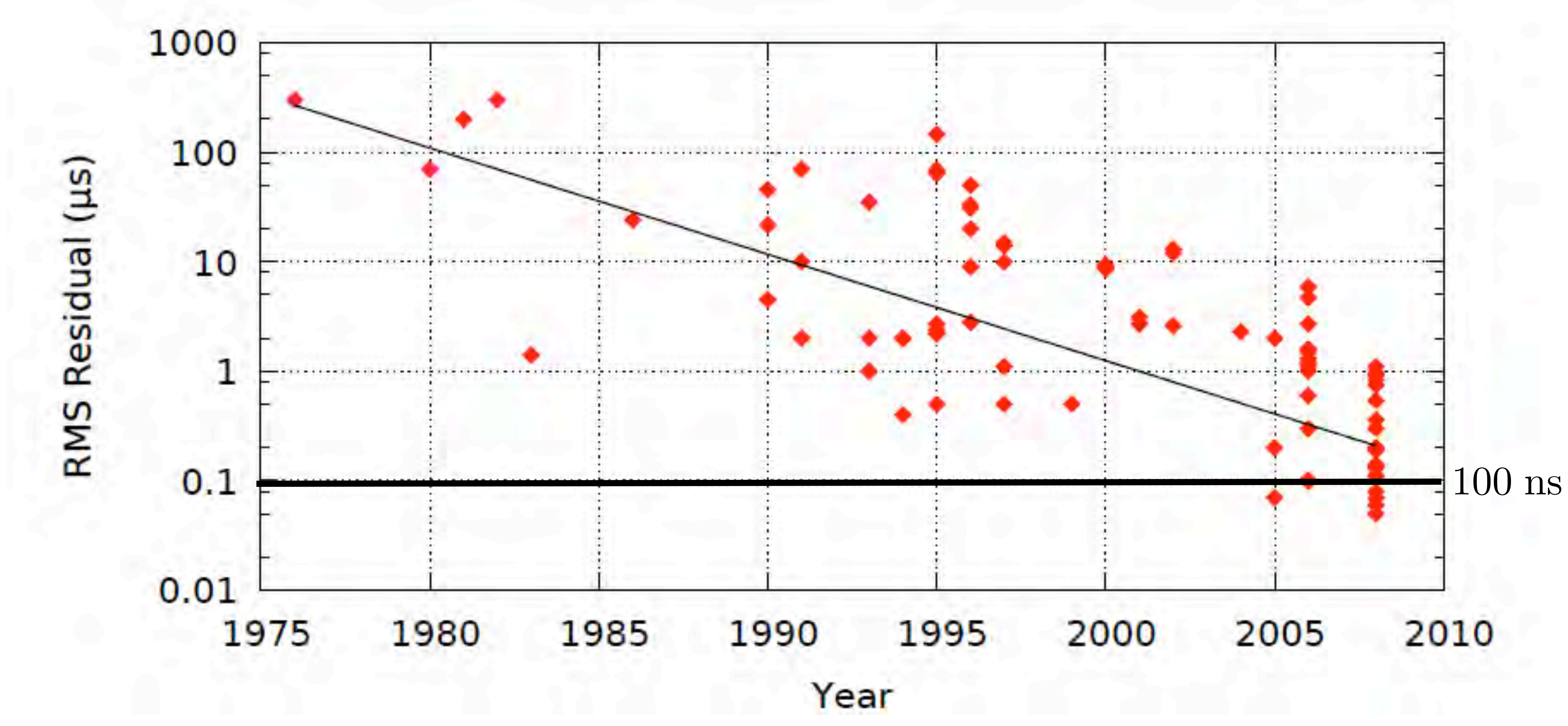
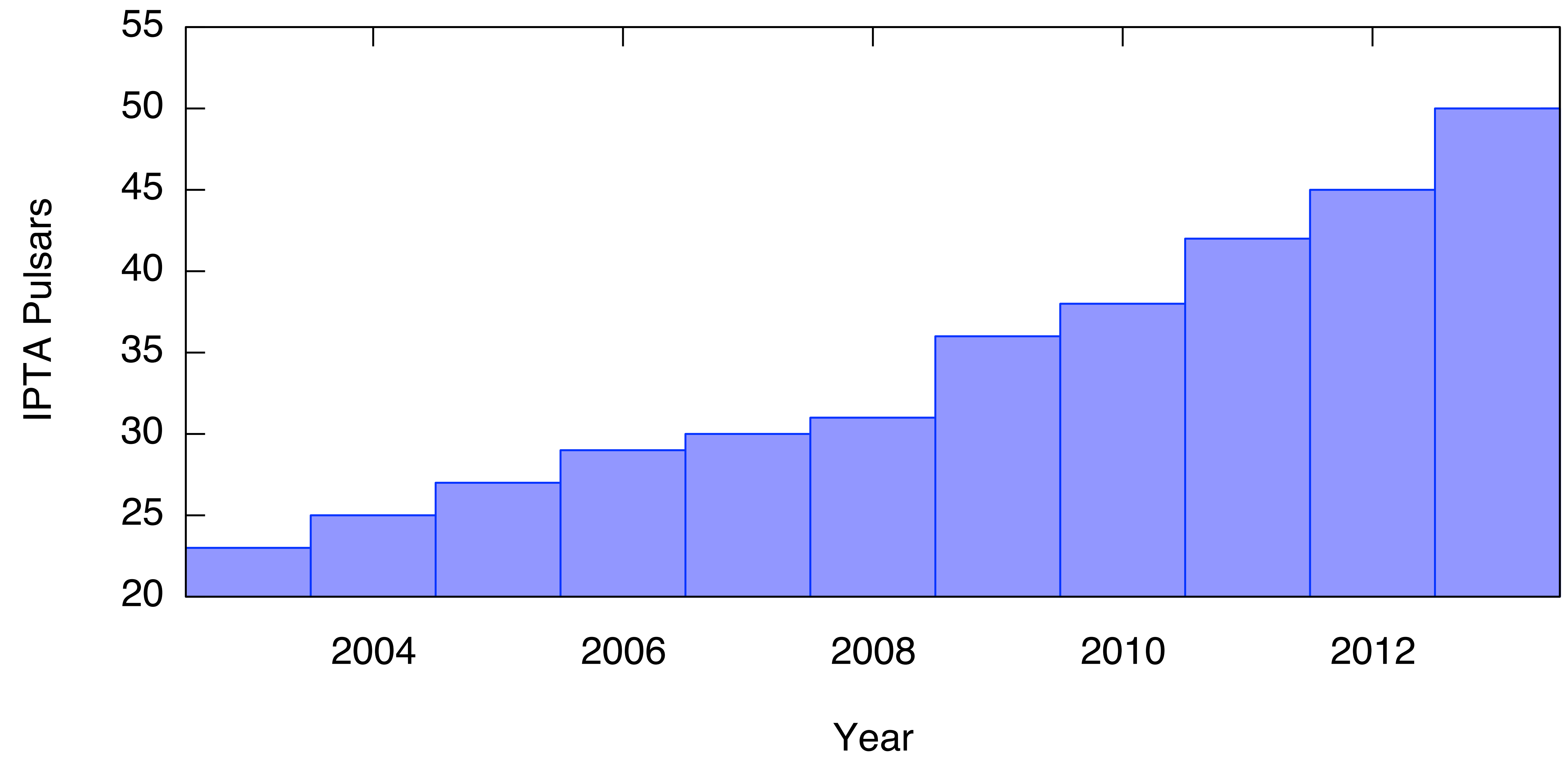
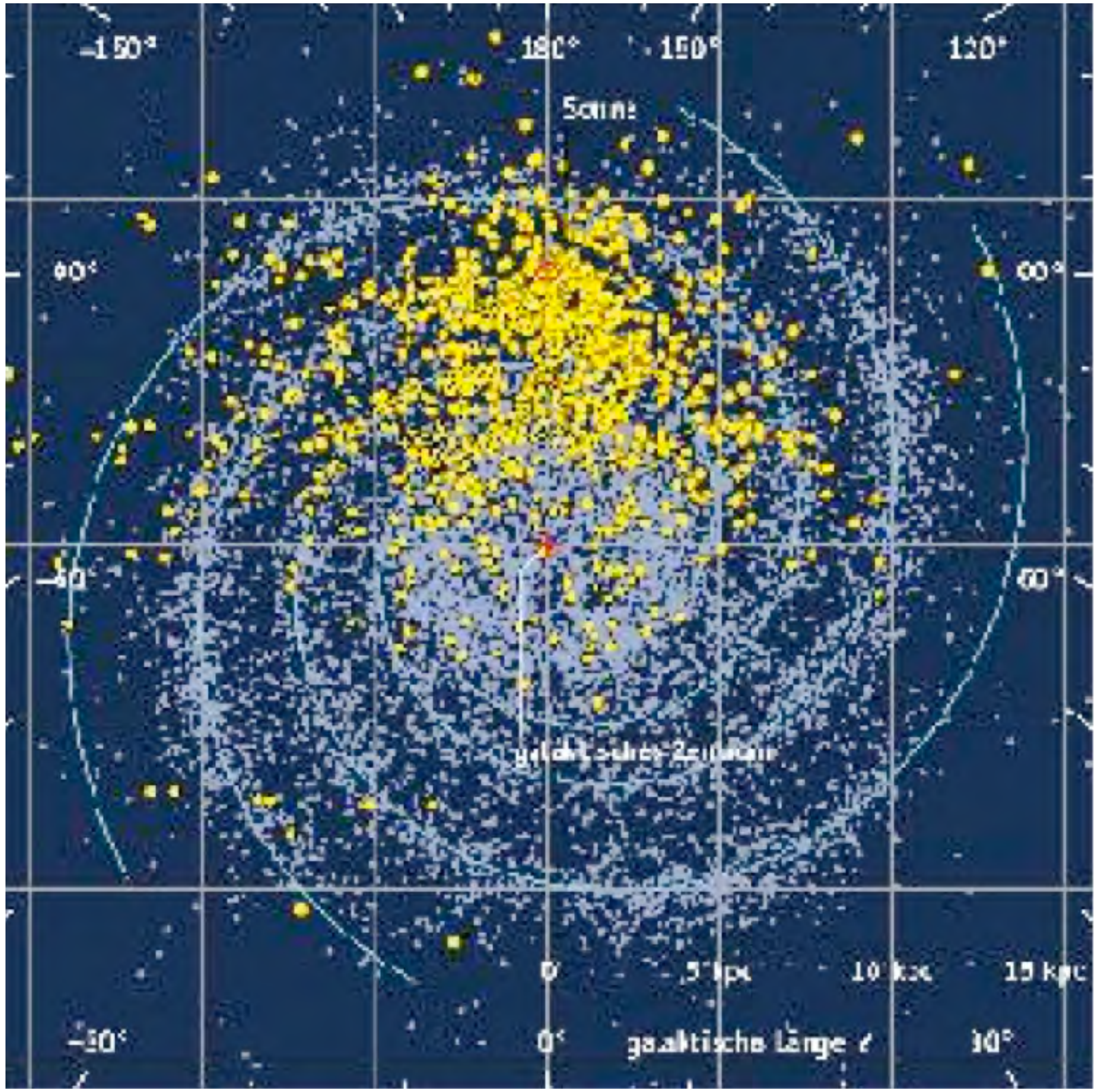




Timing accuracy and number of good pulsars have been increasing with time

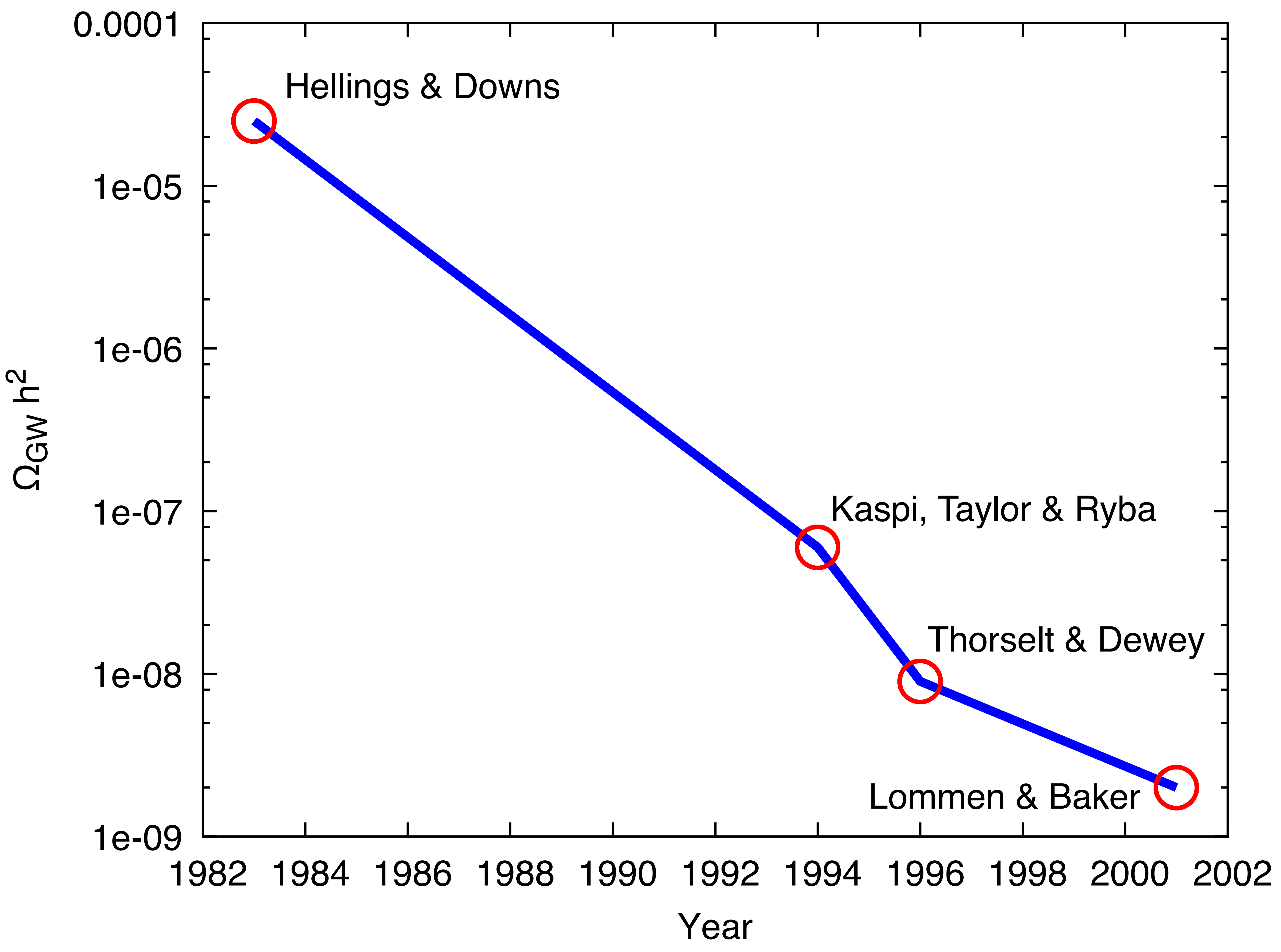


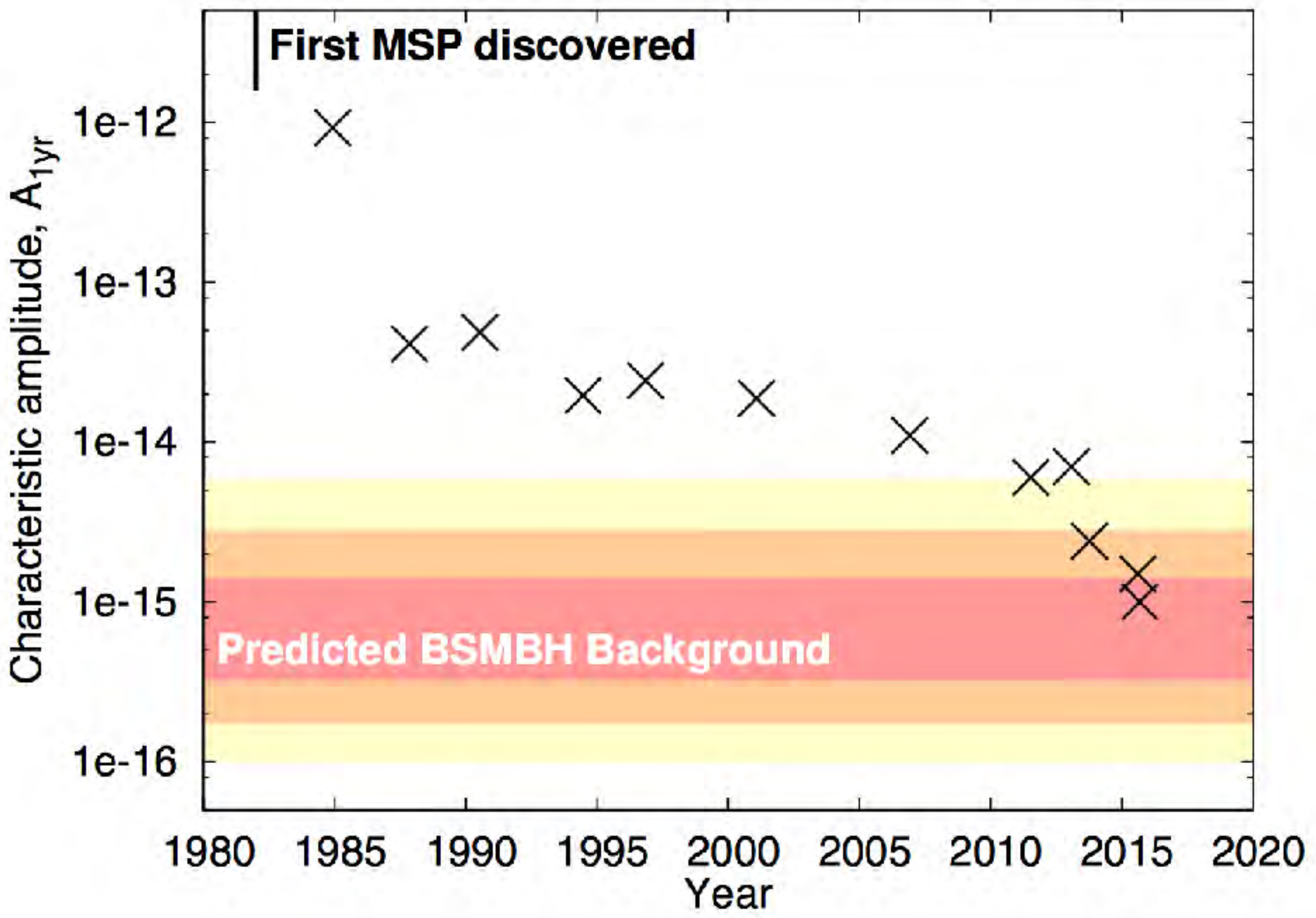




Galactic Scale Detector

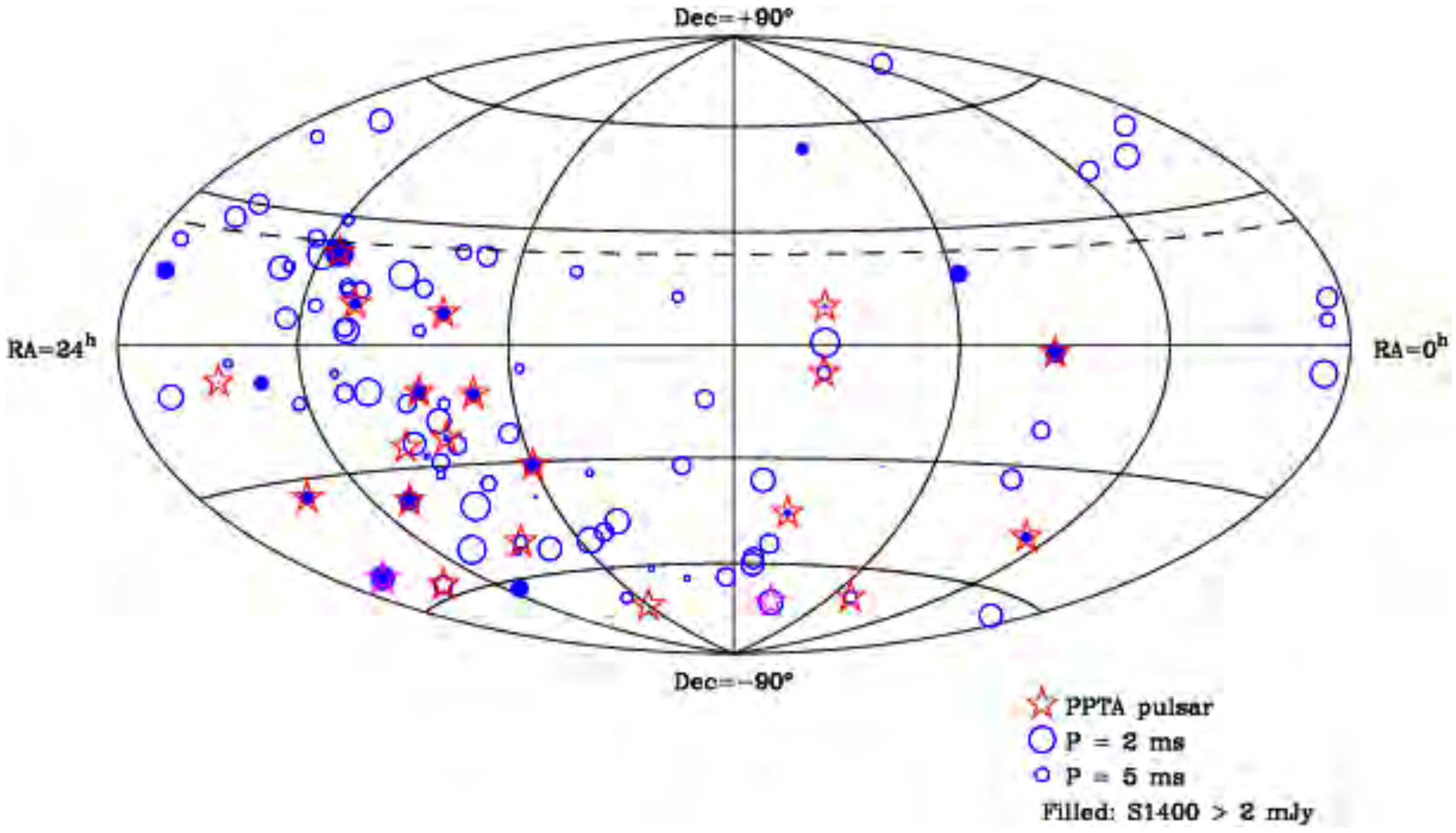
Improving upper bounds

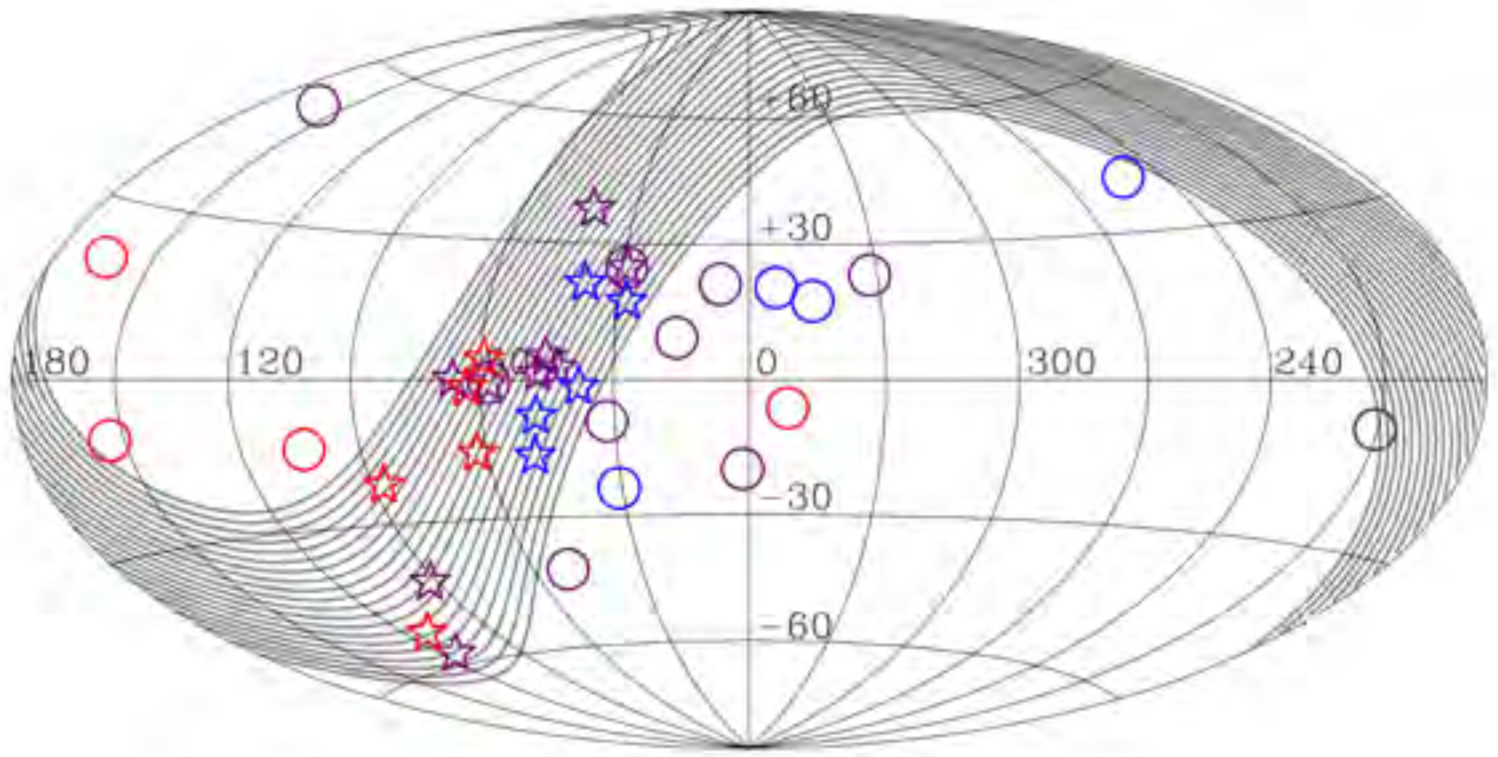




Parkes Pulsar Timing Array

PPTA





NANOGrav

European Pulsar Timing Array

EPTA

The International Pulsar Timing Array

EPTA

PPTA

NANOGrav

Next steps: Chime, FAST, MeerKAT, and the SKA

Outline of lecture

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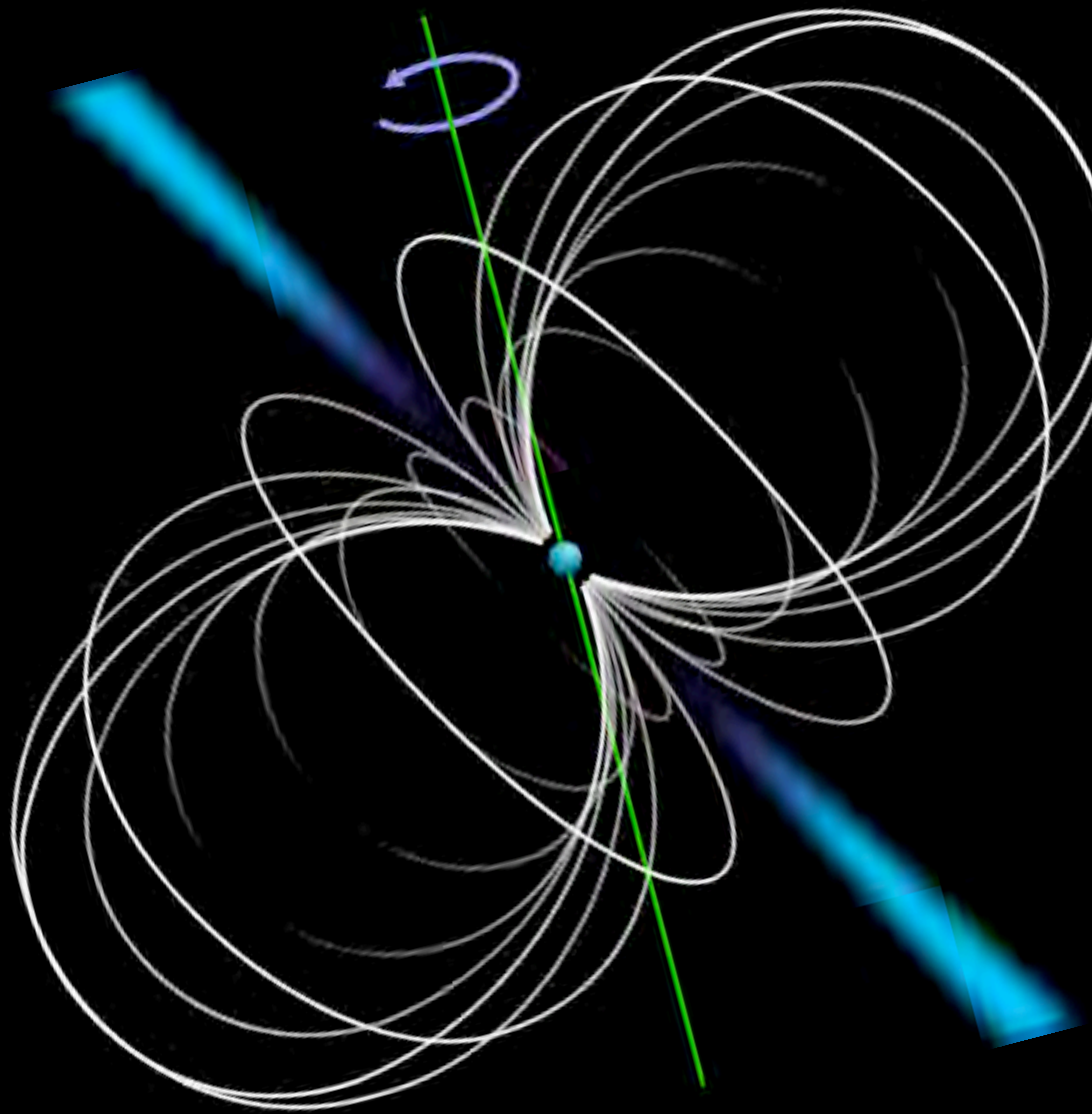
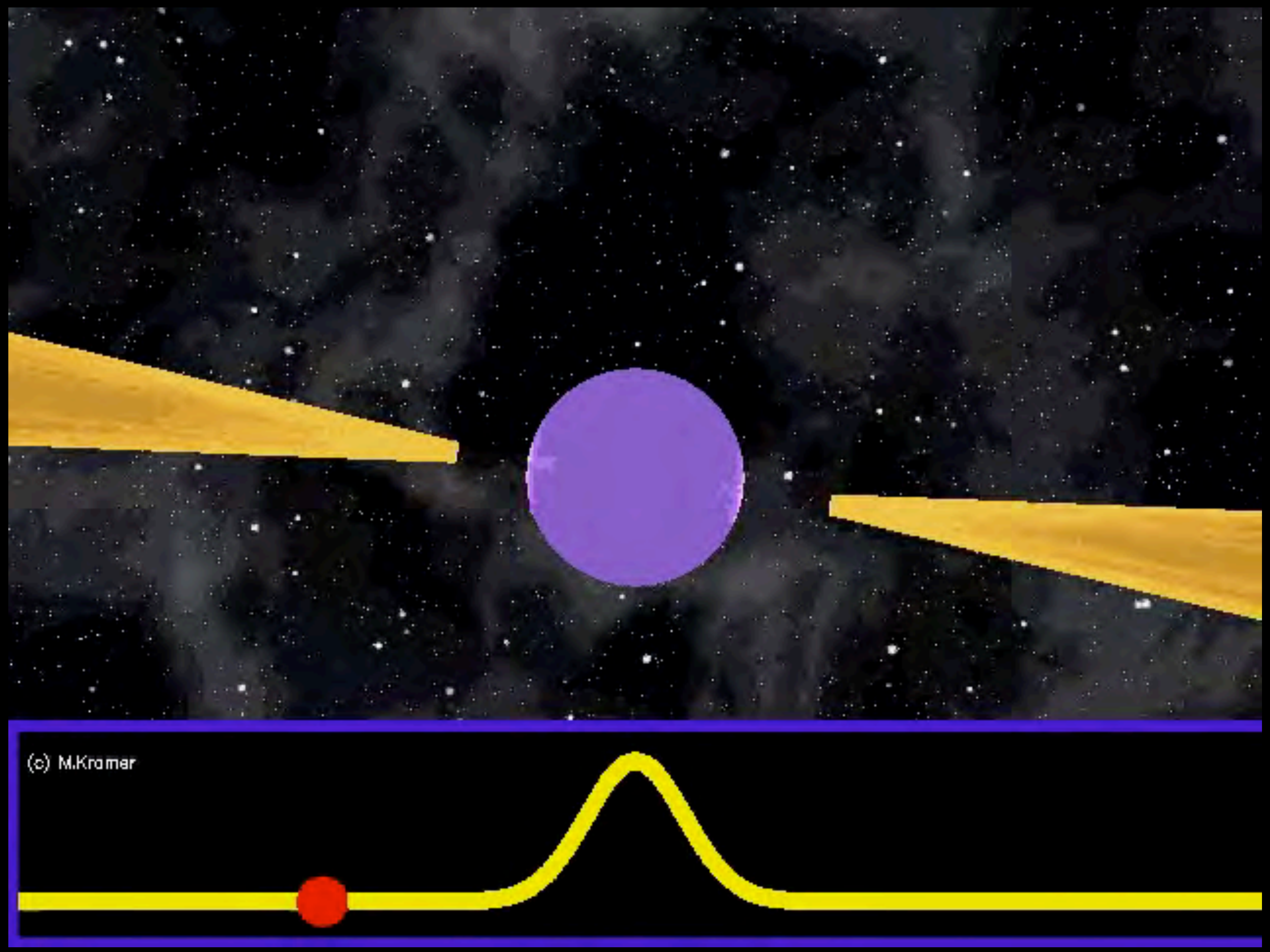
- What are pulsars? Why use milli-second pulsars?
- Observing pulsars - pulse folding
- Timing model
- Noise sources

Lighthouse model





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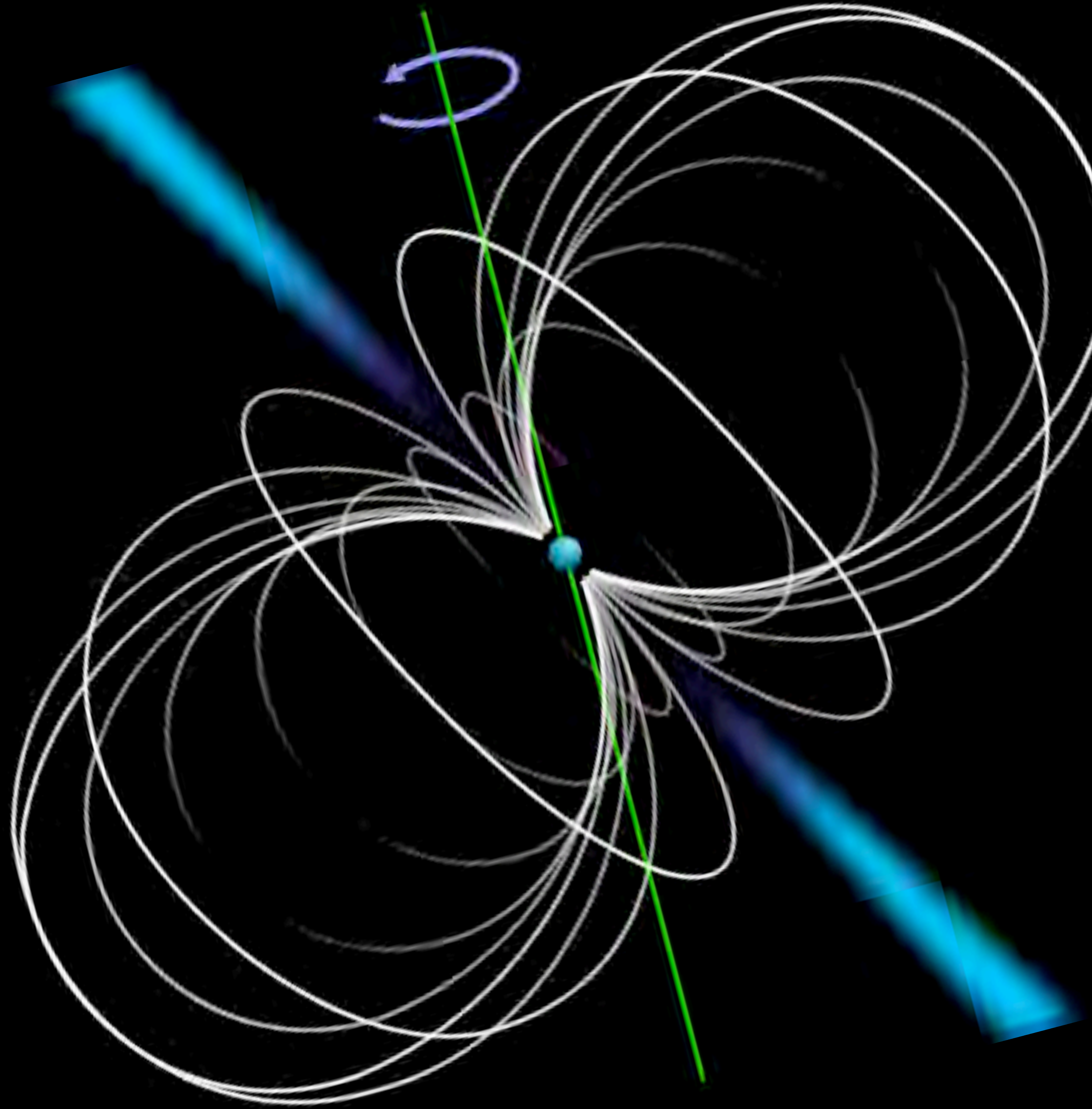
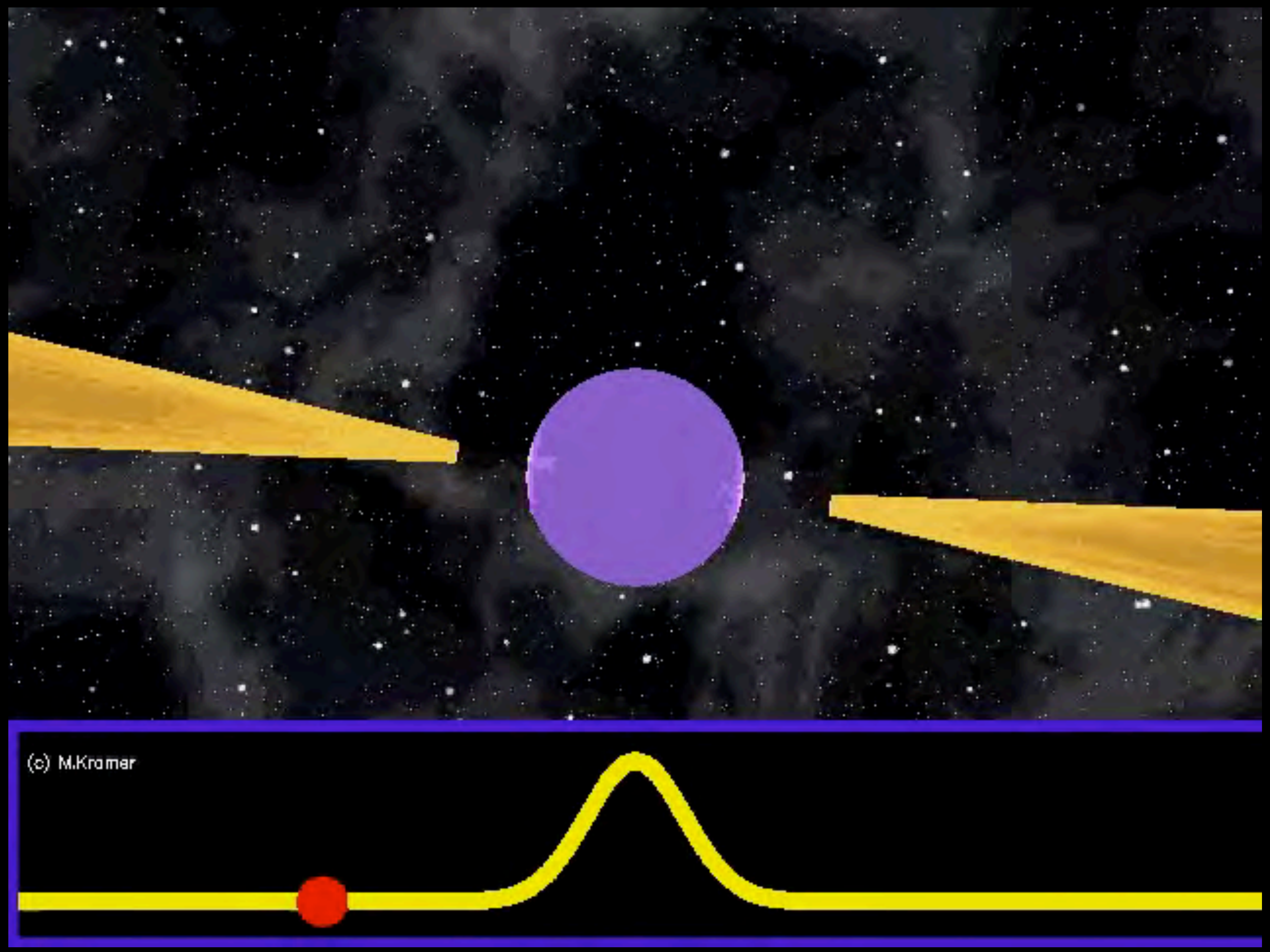
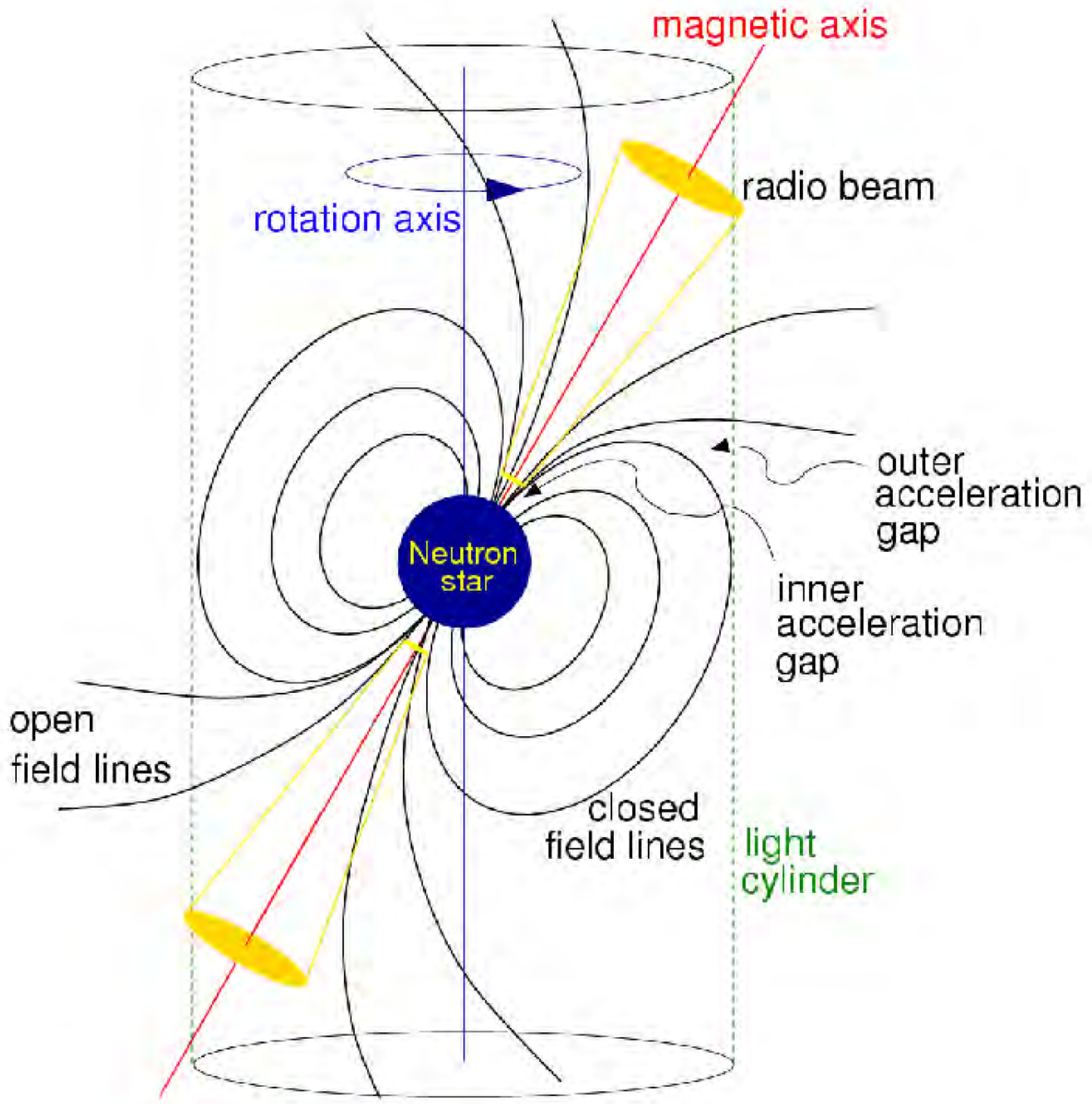
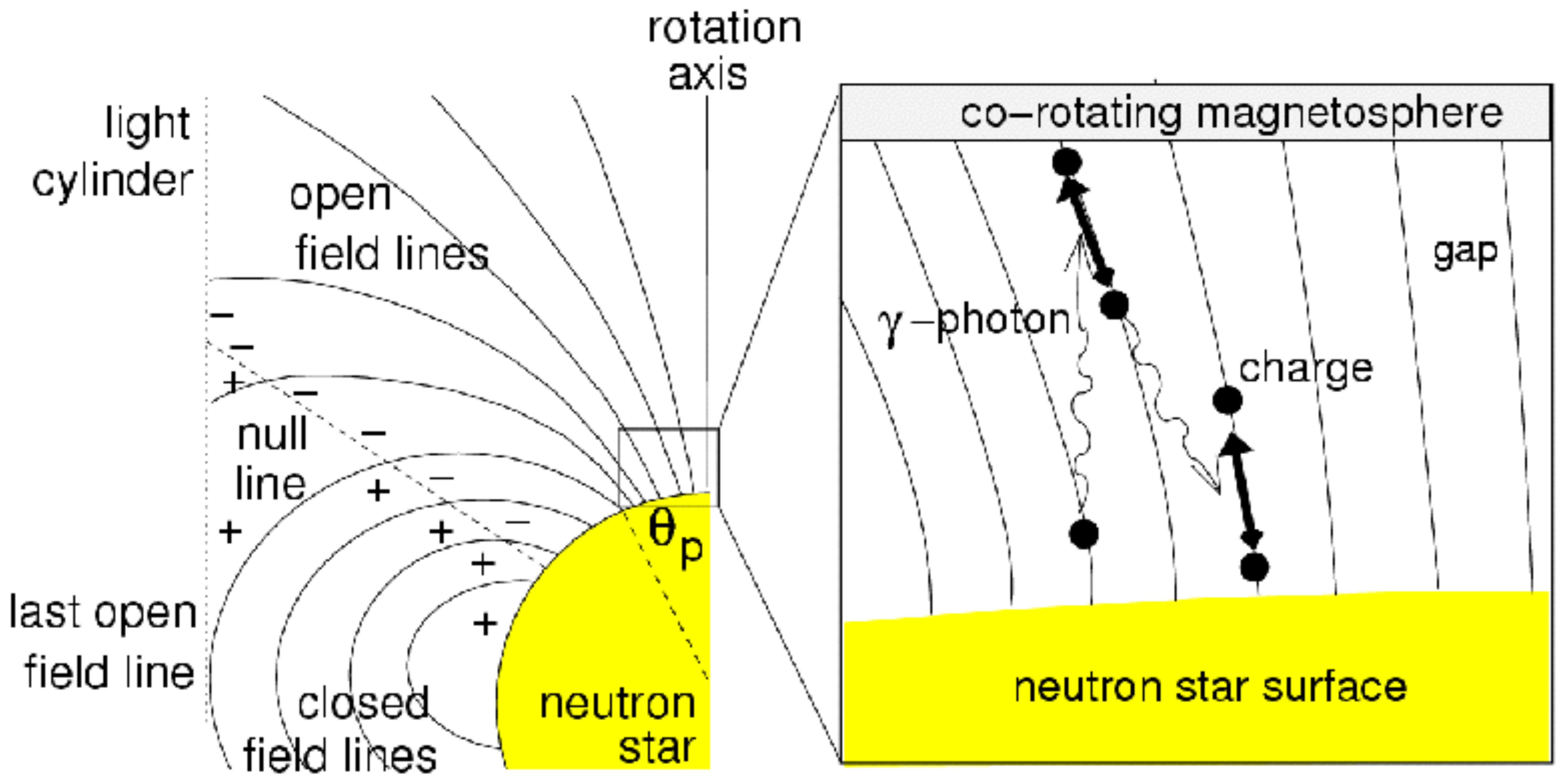




Pulsar Emission Mechanism

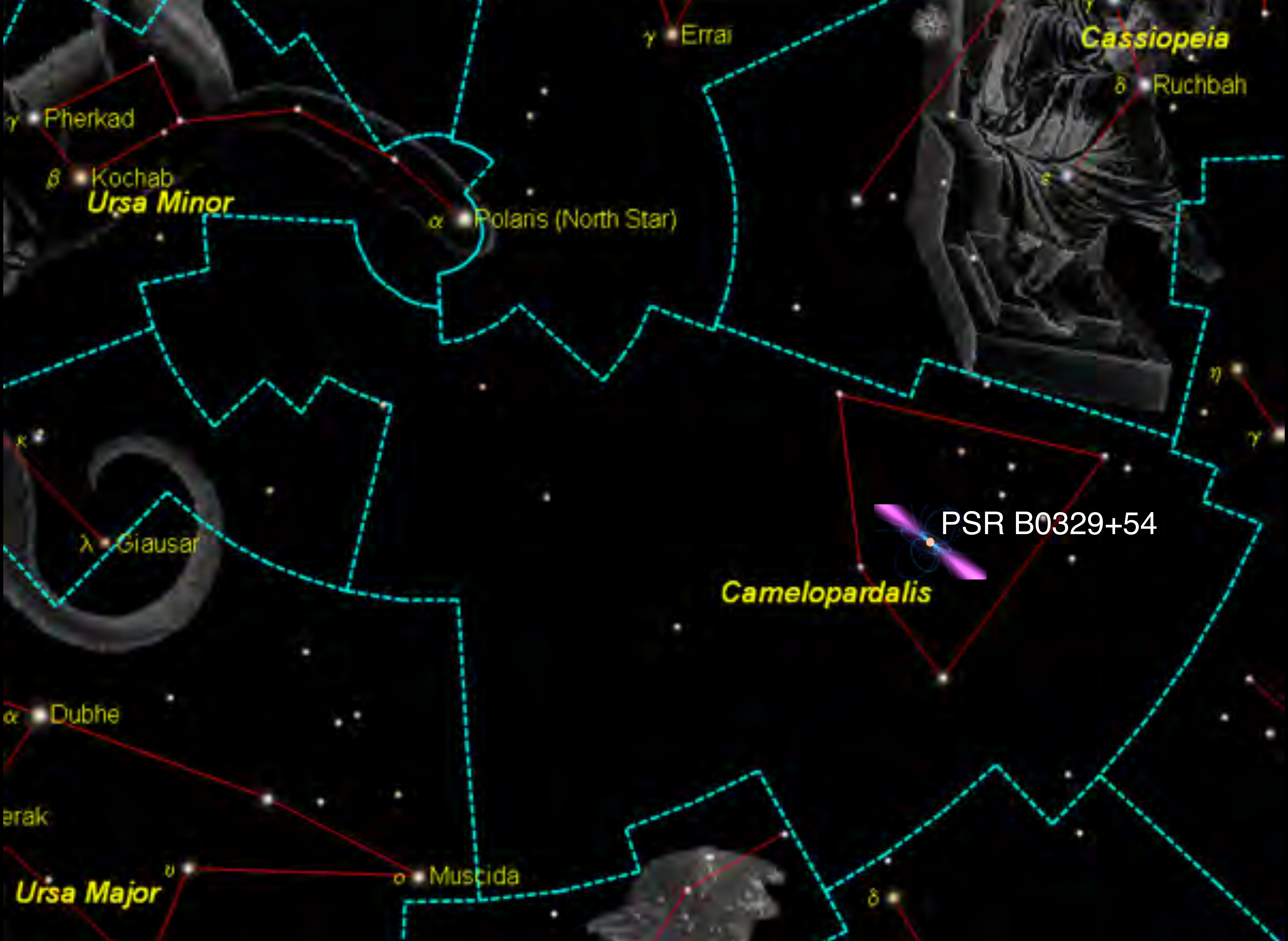
Still an active area of research
(no one really knows)

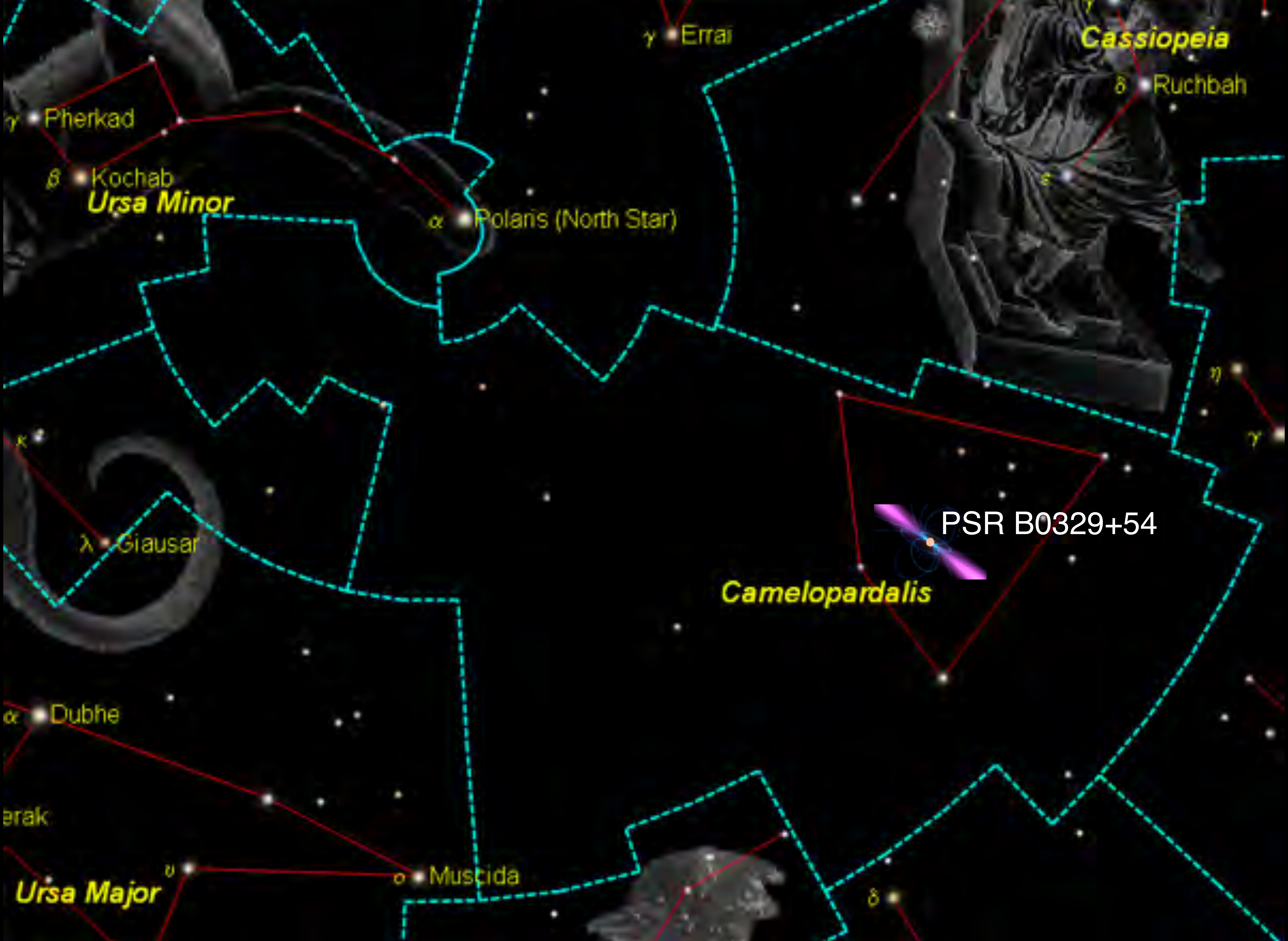




Basic picture:

- Time varying B produces large E, sets up a pair cascade
- Charged particles accelerated to relativistic velocities in magnetosphere
- Light cylinder or polar caps may be site of emission


Errai
Cassiopeia
Ruchbah
Pherkad
Kochab
Ursa Minor
Polaris (North Star)
PSR B0329+54
Giausar
Camelopardalis
Dubhe
erak
Muscida
Ursa Major



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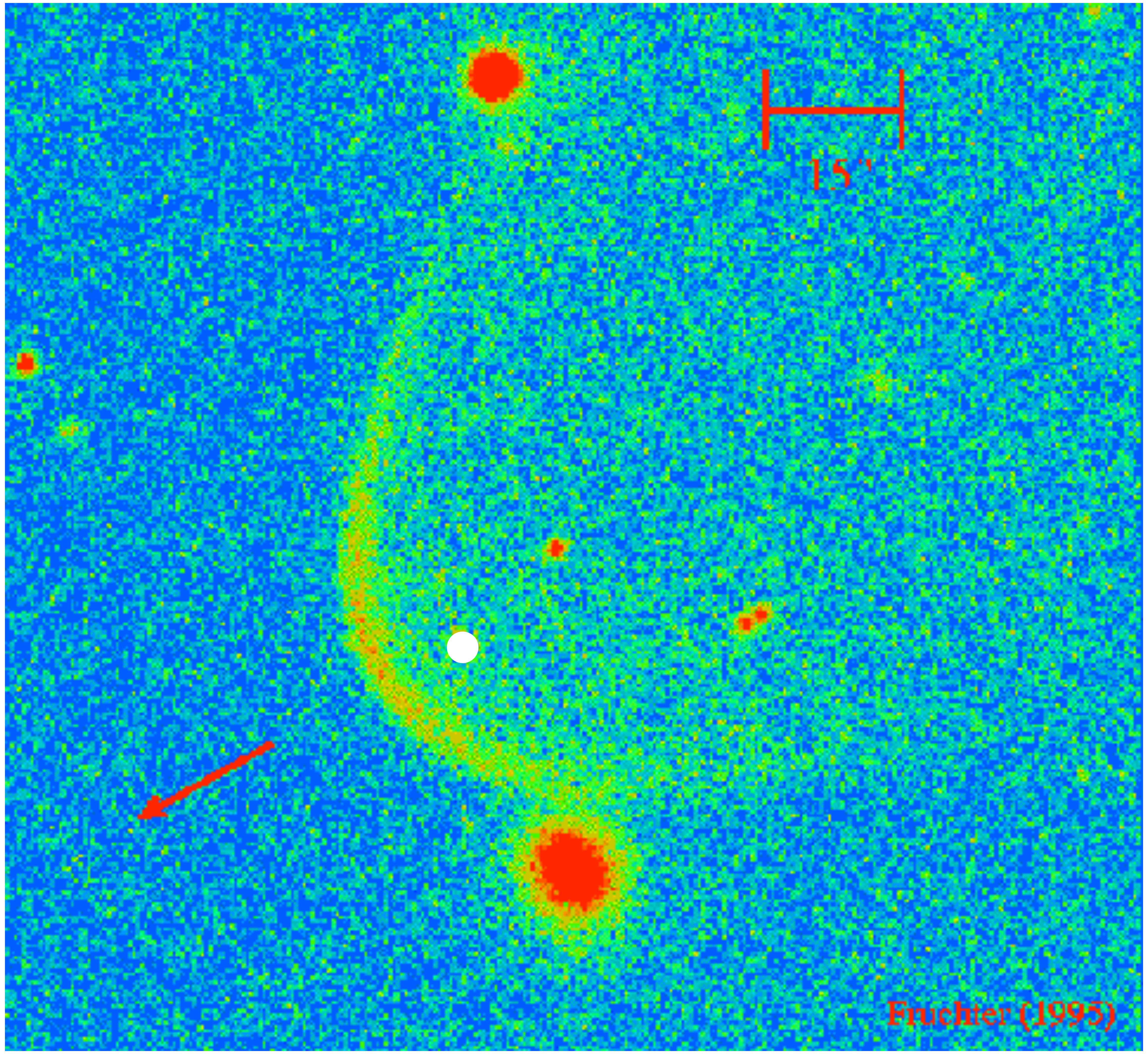
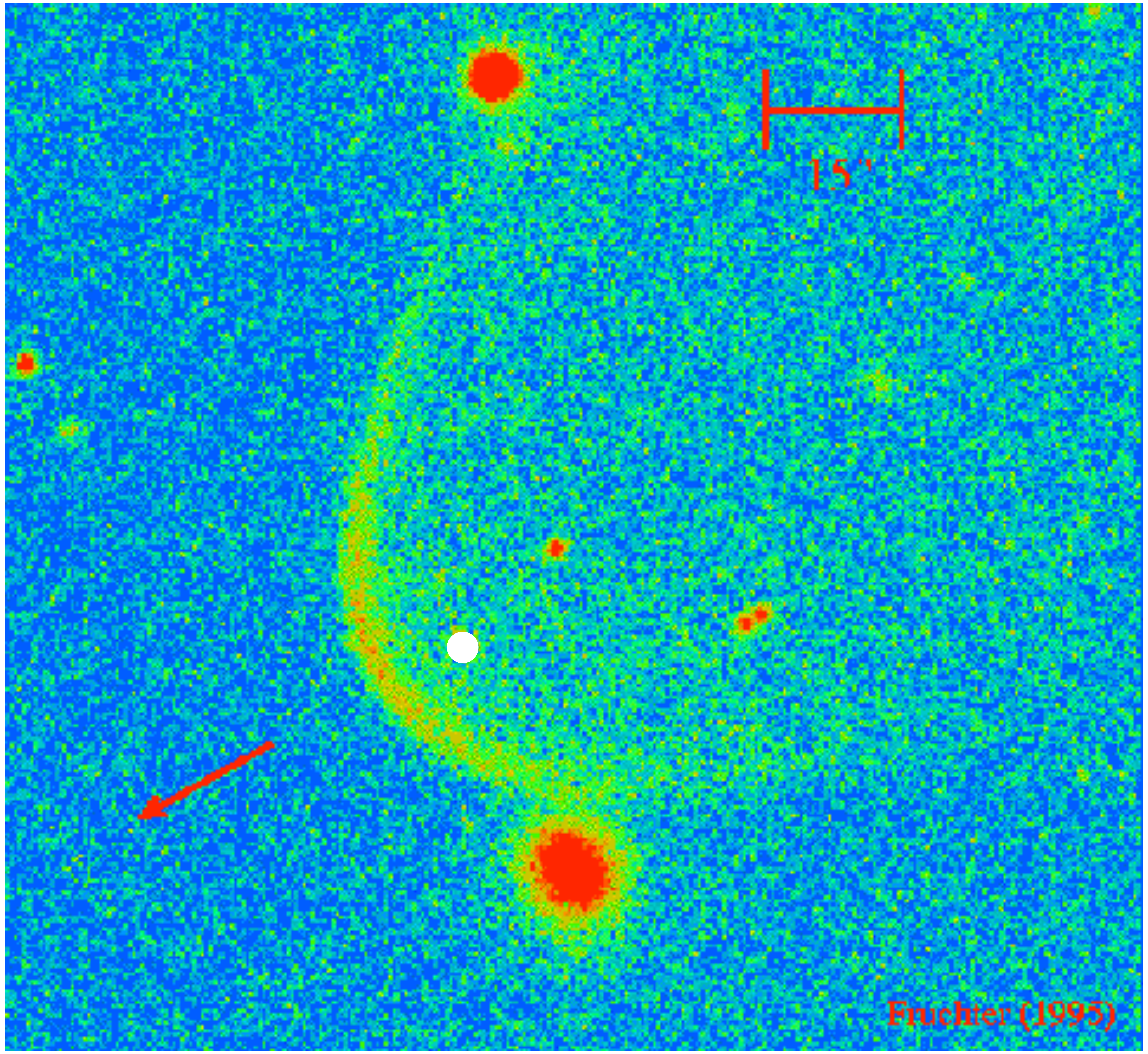
Milli-Second Pulsar PSR J0437-4715



At 9 am CEST on June 9, 2017 it was rotating at 173.68794xxxxx times per second

At 7 pm MST on Jan 31, 2014 it was rotating at 173.6879481784(6). times per second

Milli-Second Pulsar PSR J0437-4715



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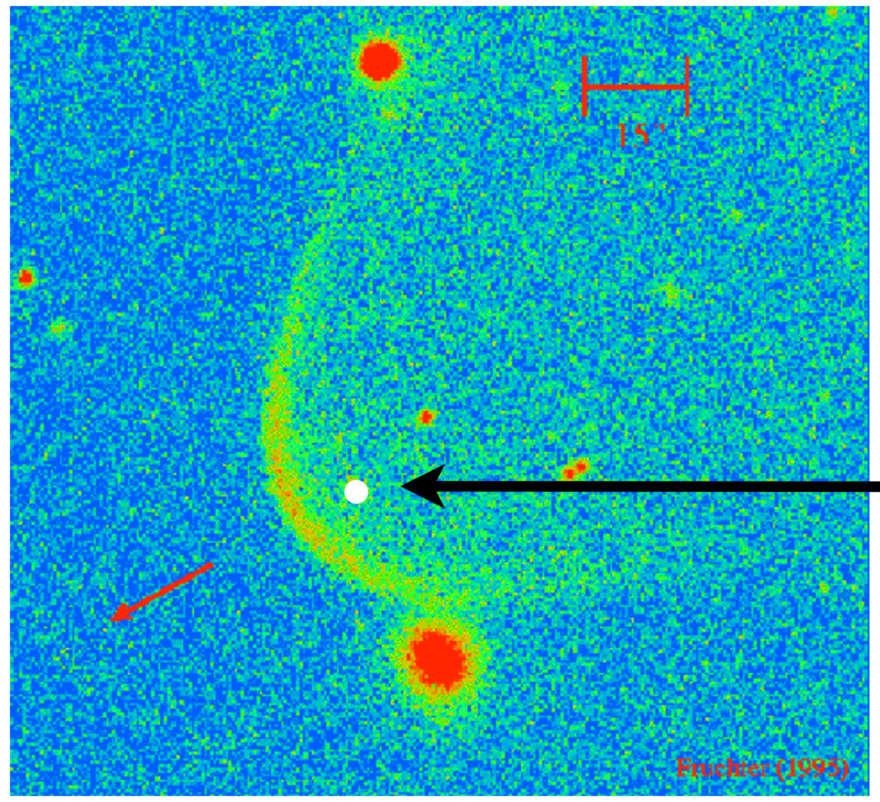
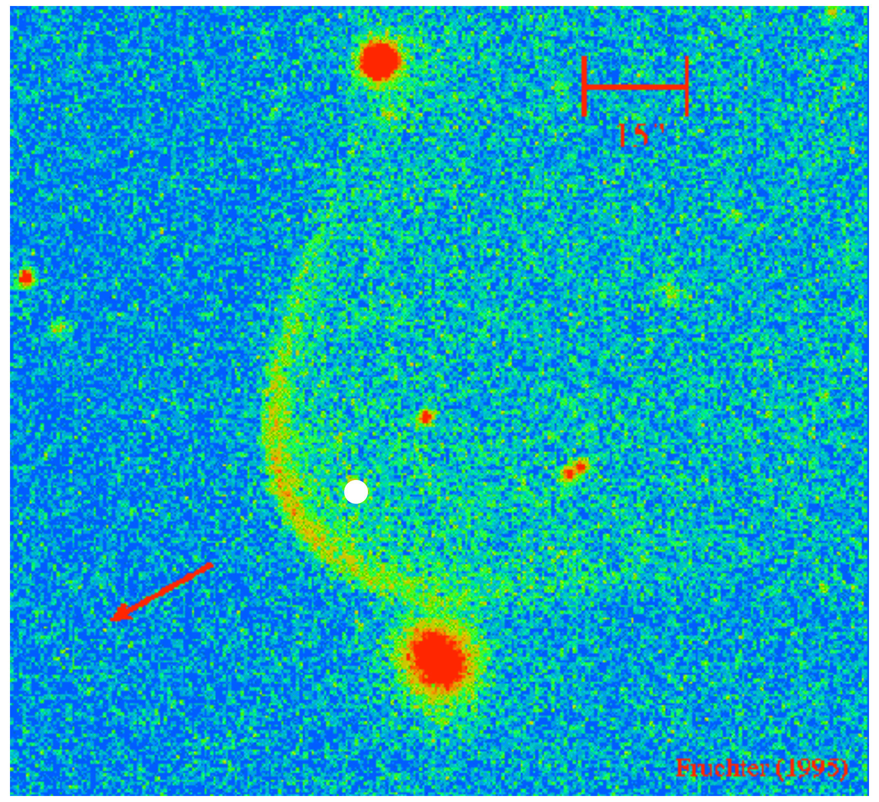


4,823,000,000,000,000,000 meters

(4.8 Billion Billion meters)

For over a decade we have tracked the distance to this Pulsar to a accuracy of 30 meters!

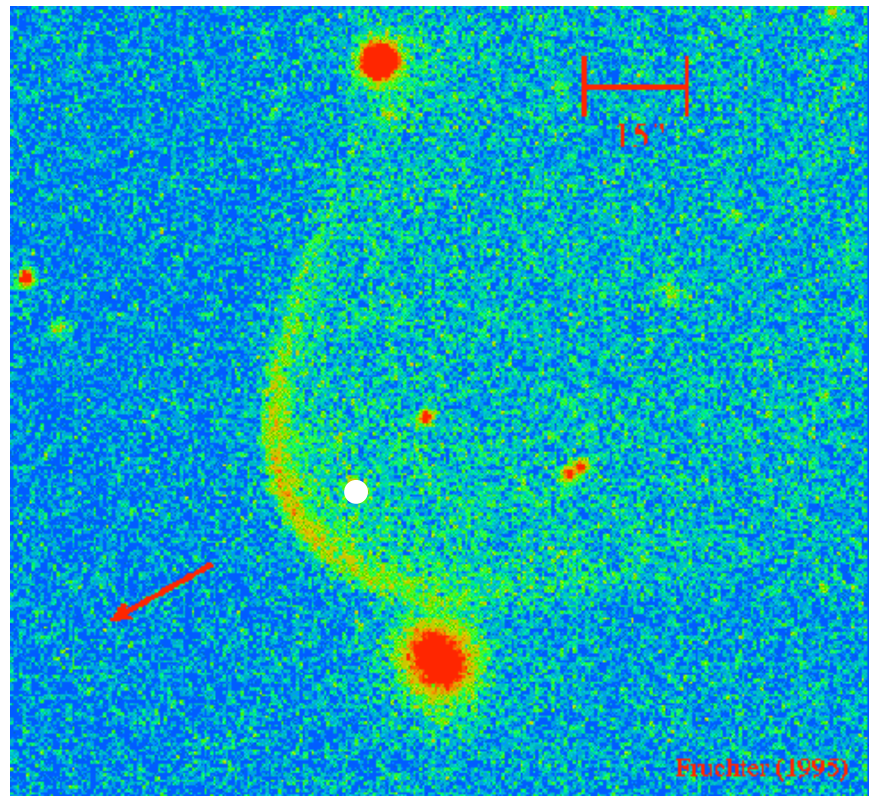
Milli-Second Pulsar PSR J0437-4715



We only observe each Pulsar every few weeks
In two weeks have will completed 210,092,942 revolutions

We know exactly which one is the 210 millionth pulse!

Milli-Second Pulsar PSR J0437-4715



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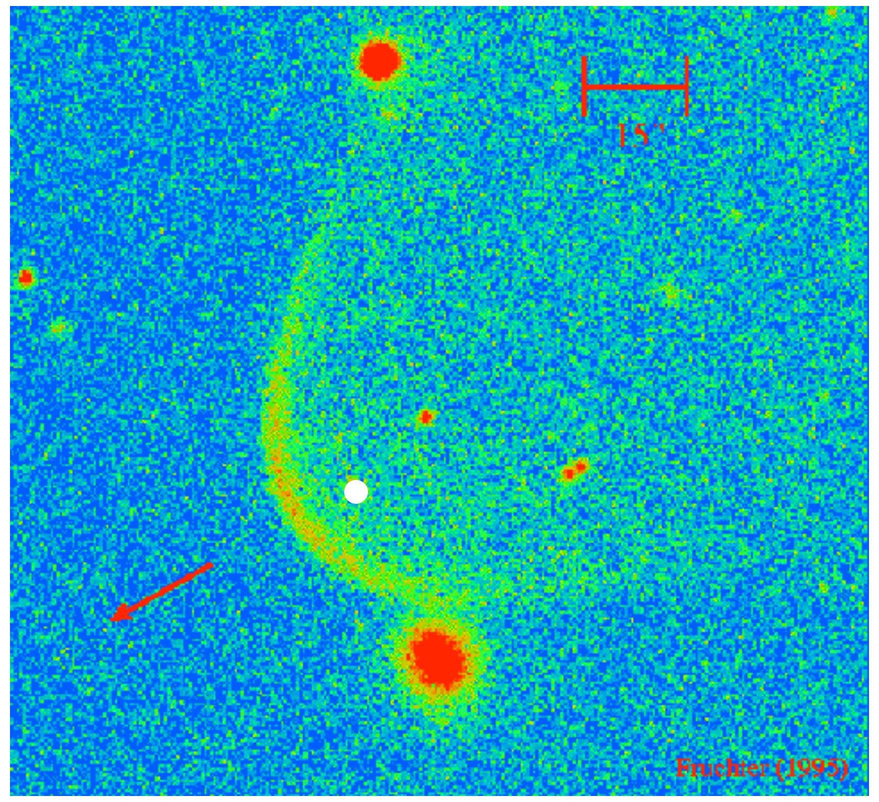
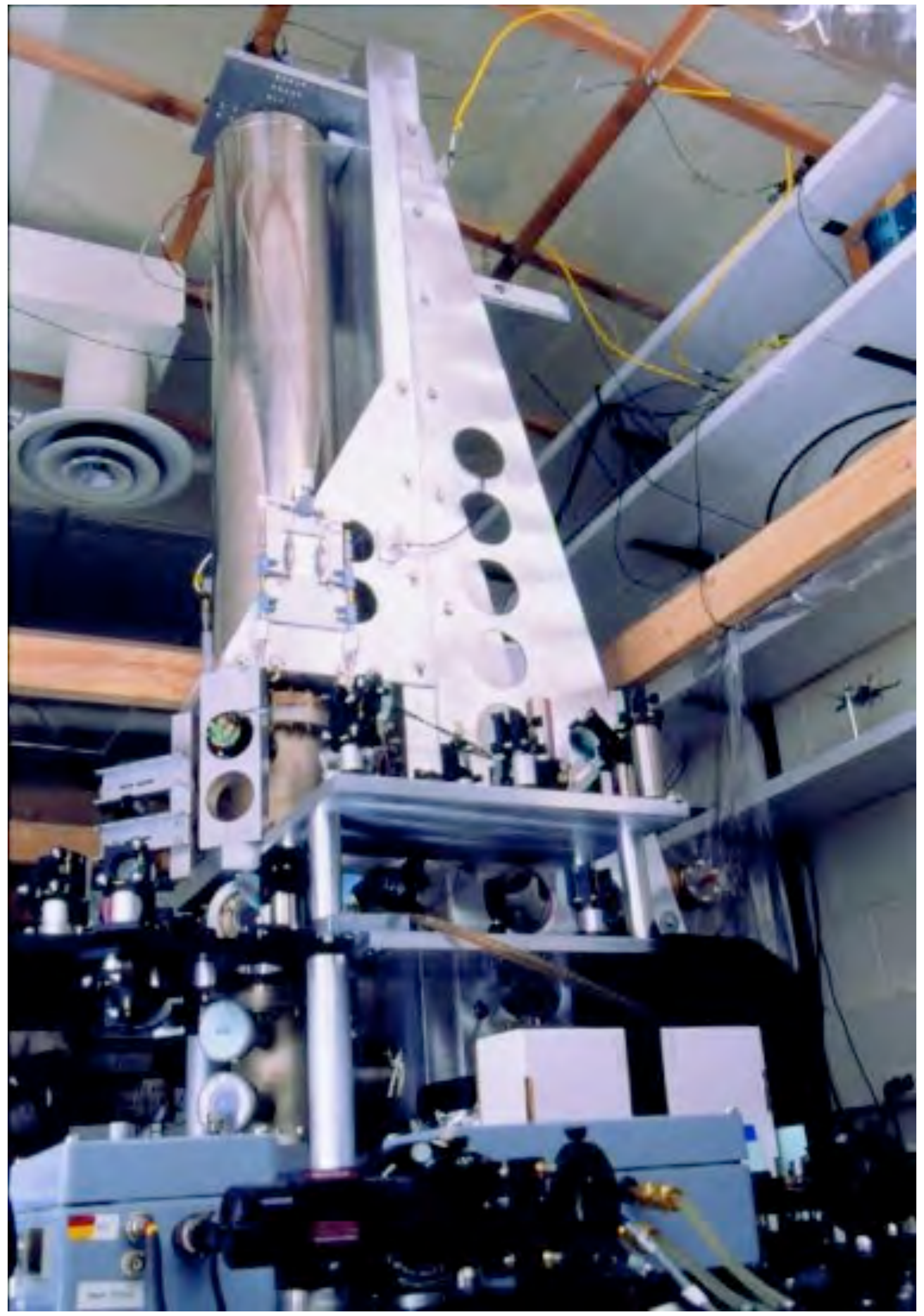
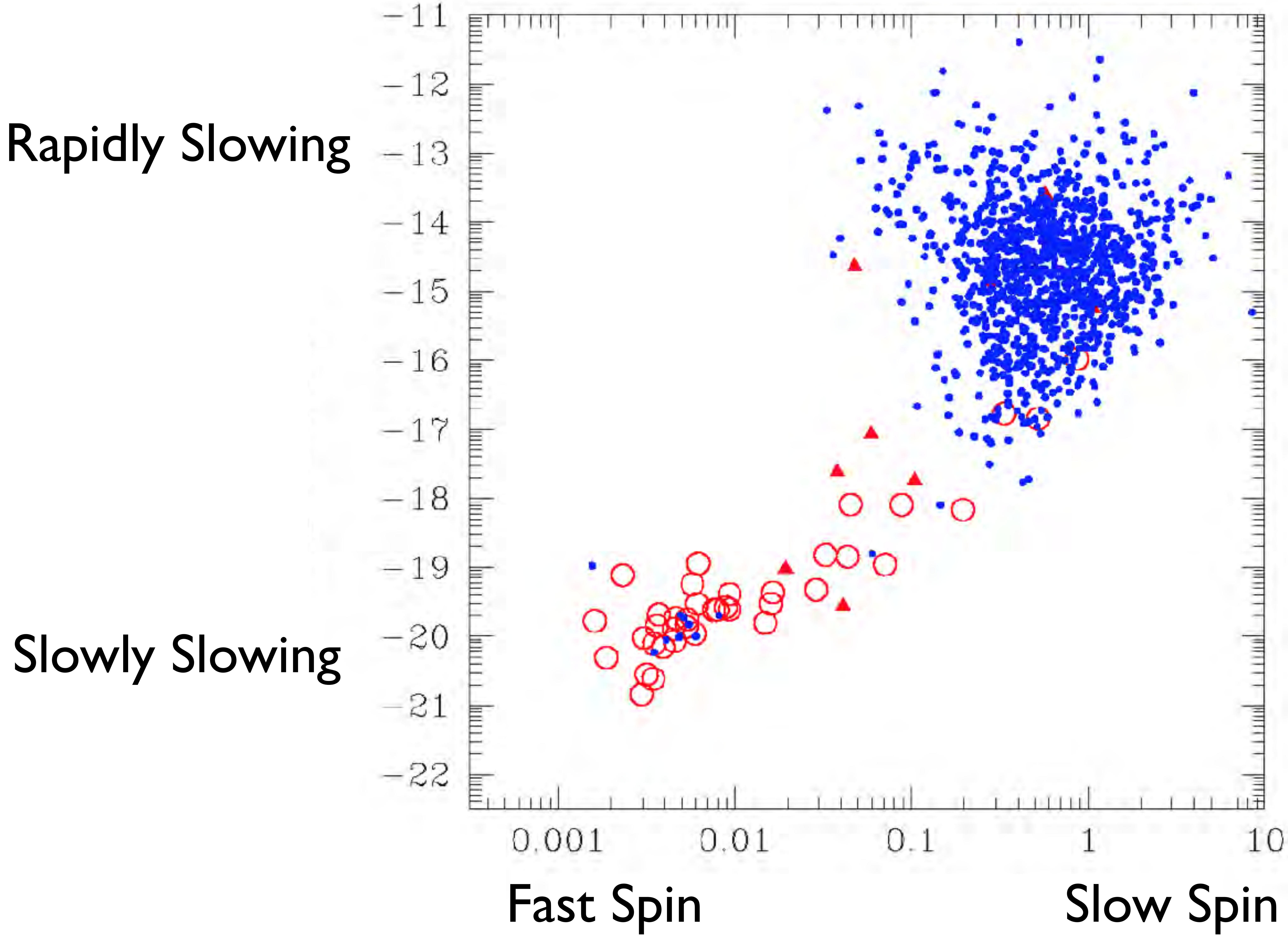




Pulsar Demographics



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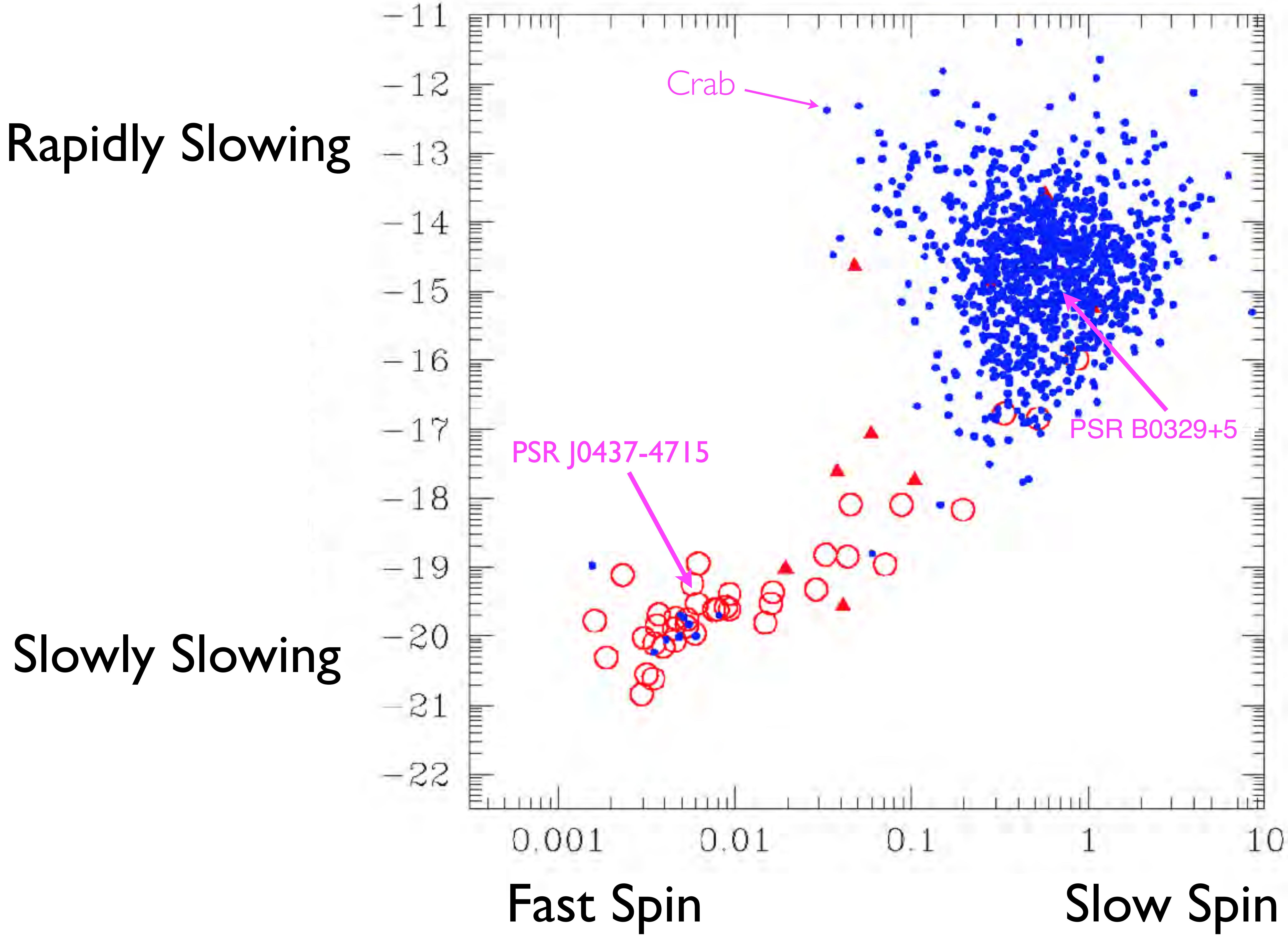
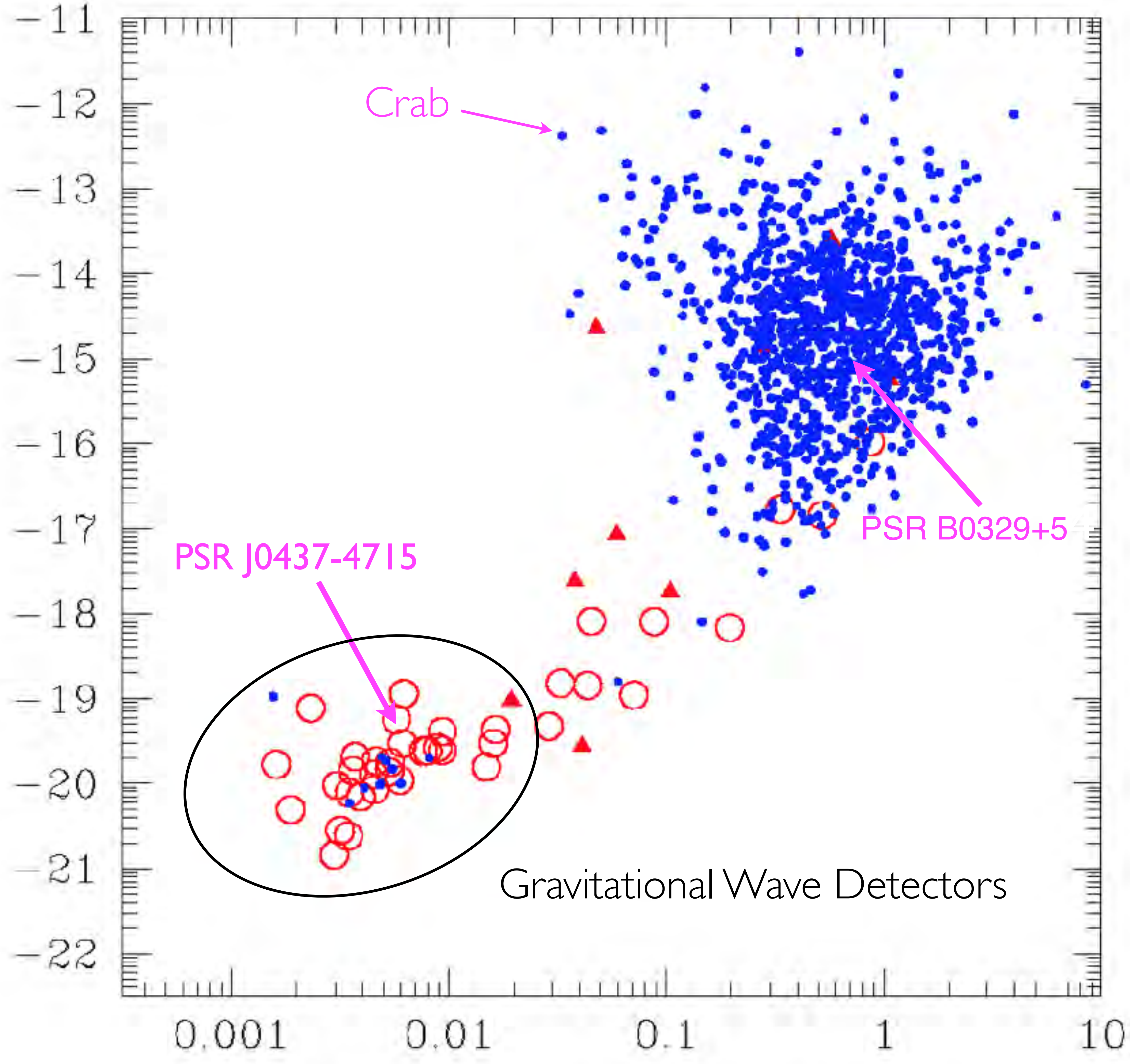


Pulsar Demographics

Rapidly Slowing

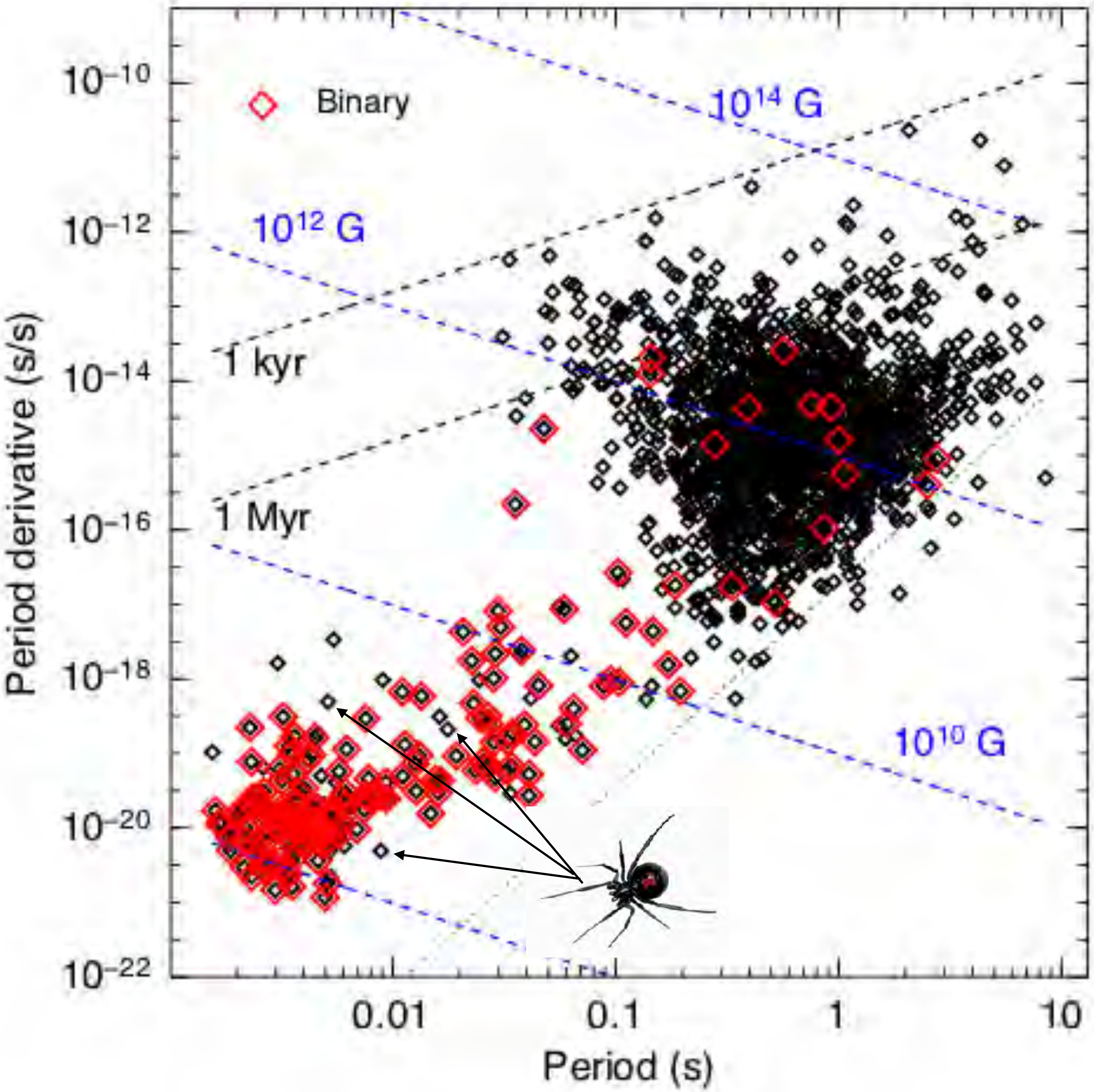
Slowly Slowing



Fast Spin

Slow Spin

Recycled pulsars



Most milli-second pulsars are in binary systems (WD or NS). Consistent with spin-up via recycling

Black widows - ablated their companions

Outline of lecture

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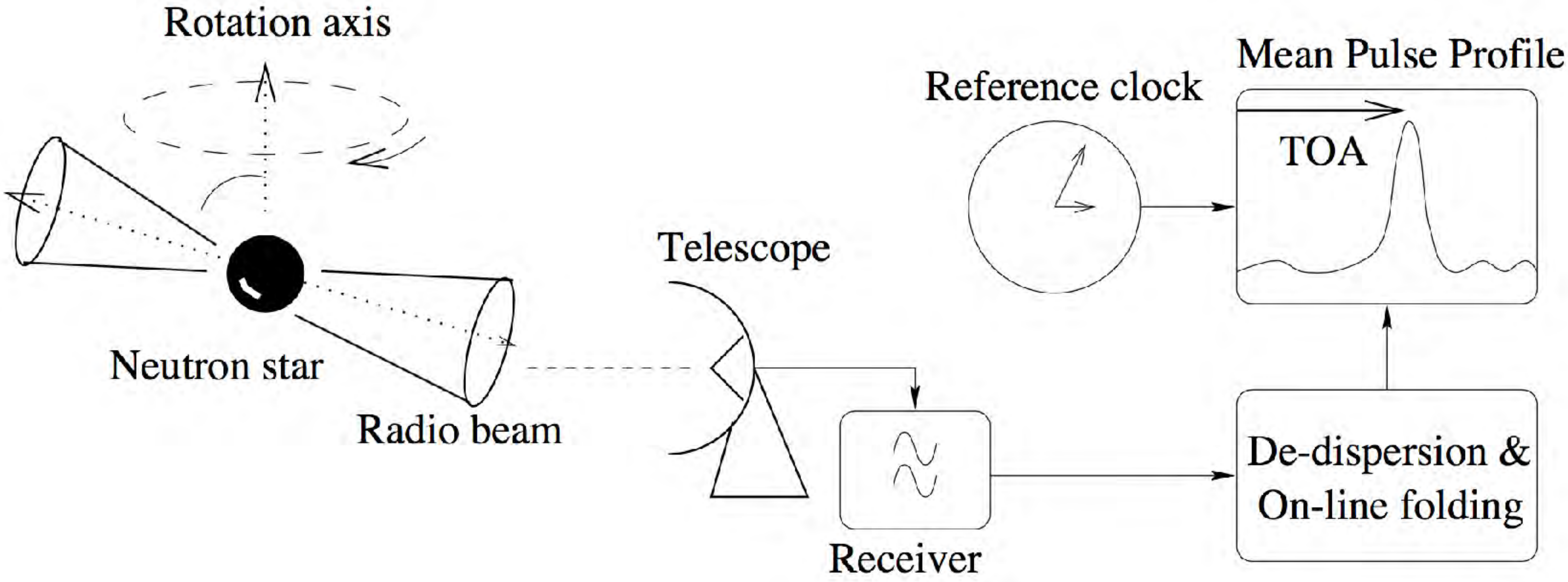
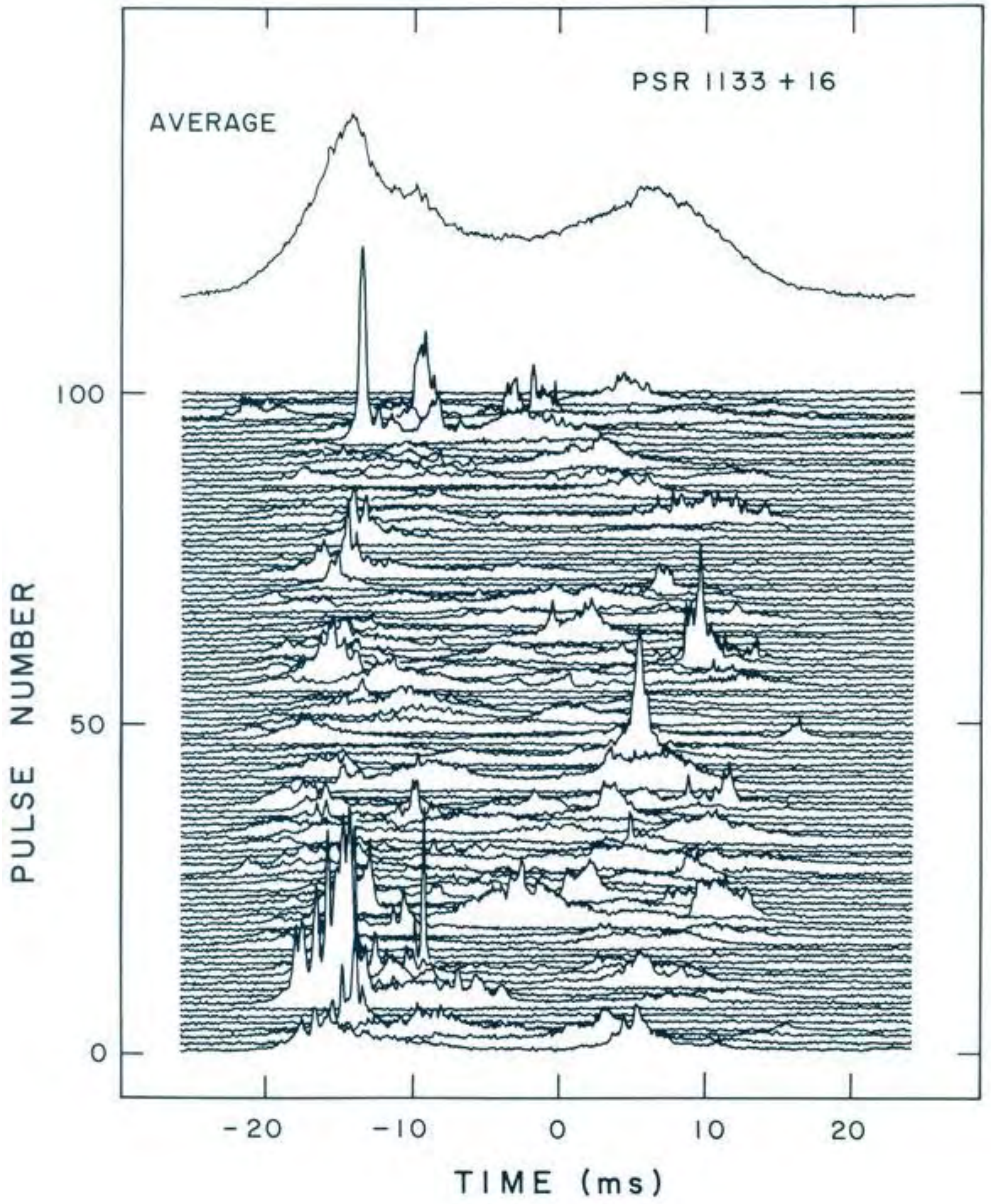
Pulsar timing 101

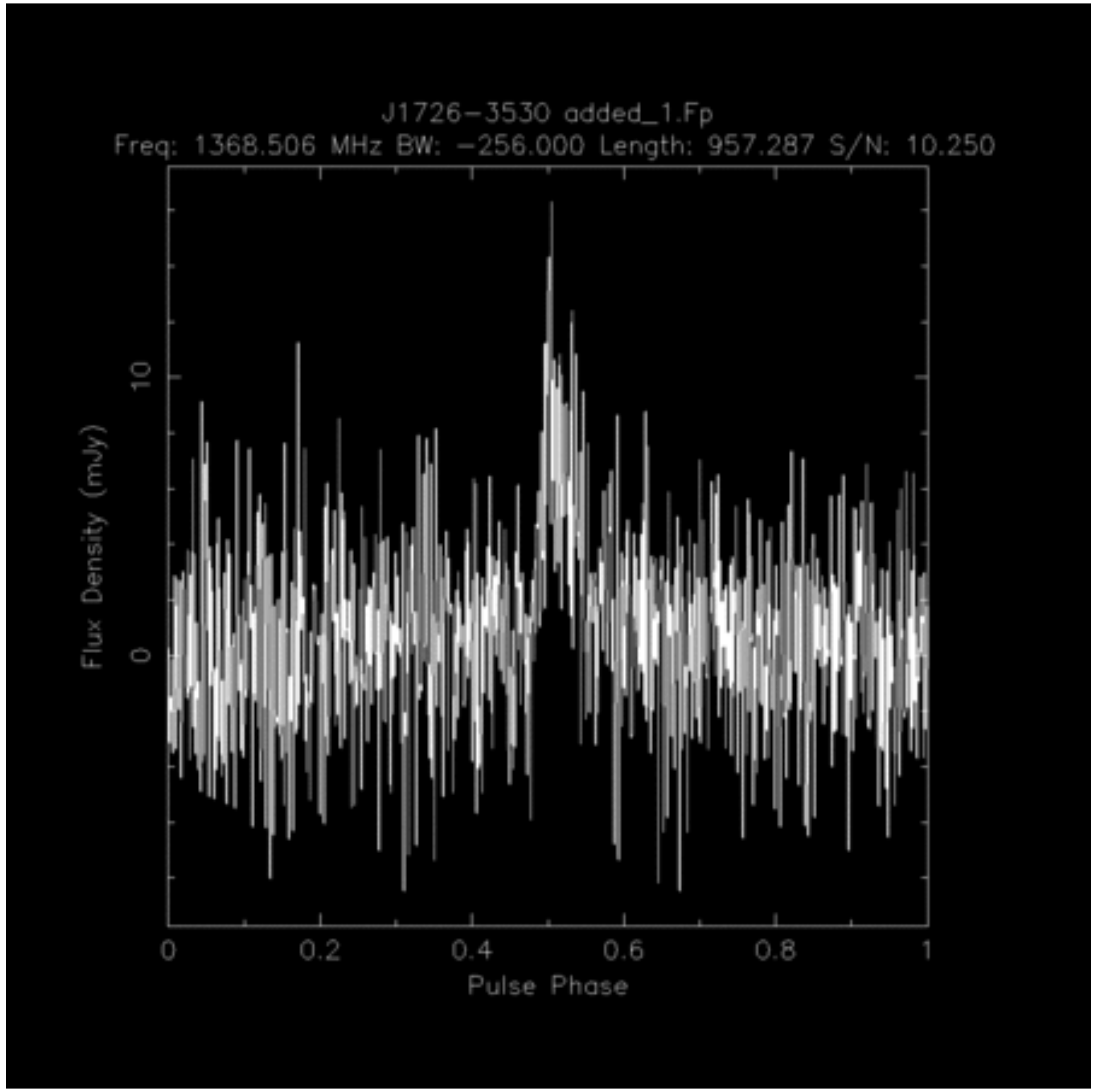


Pulse folding

Individual pulses are irregular in shape, and often not individually detectable



Average profile is remarkably stable



Average usually taken over tens of minutes - hundreds of thousands of pulses

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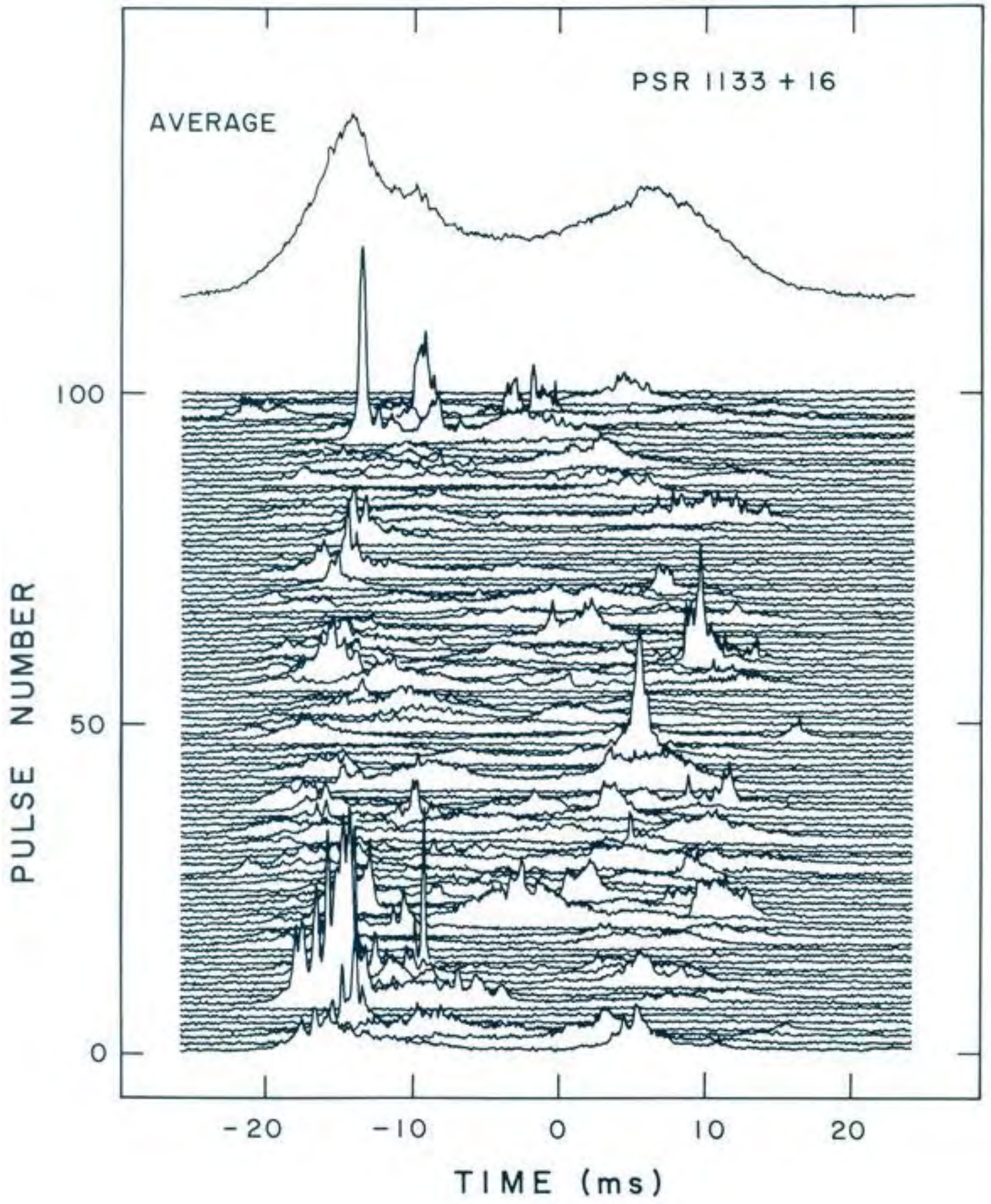

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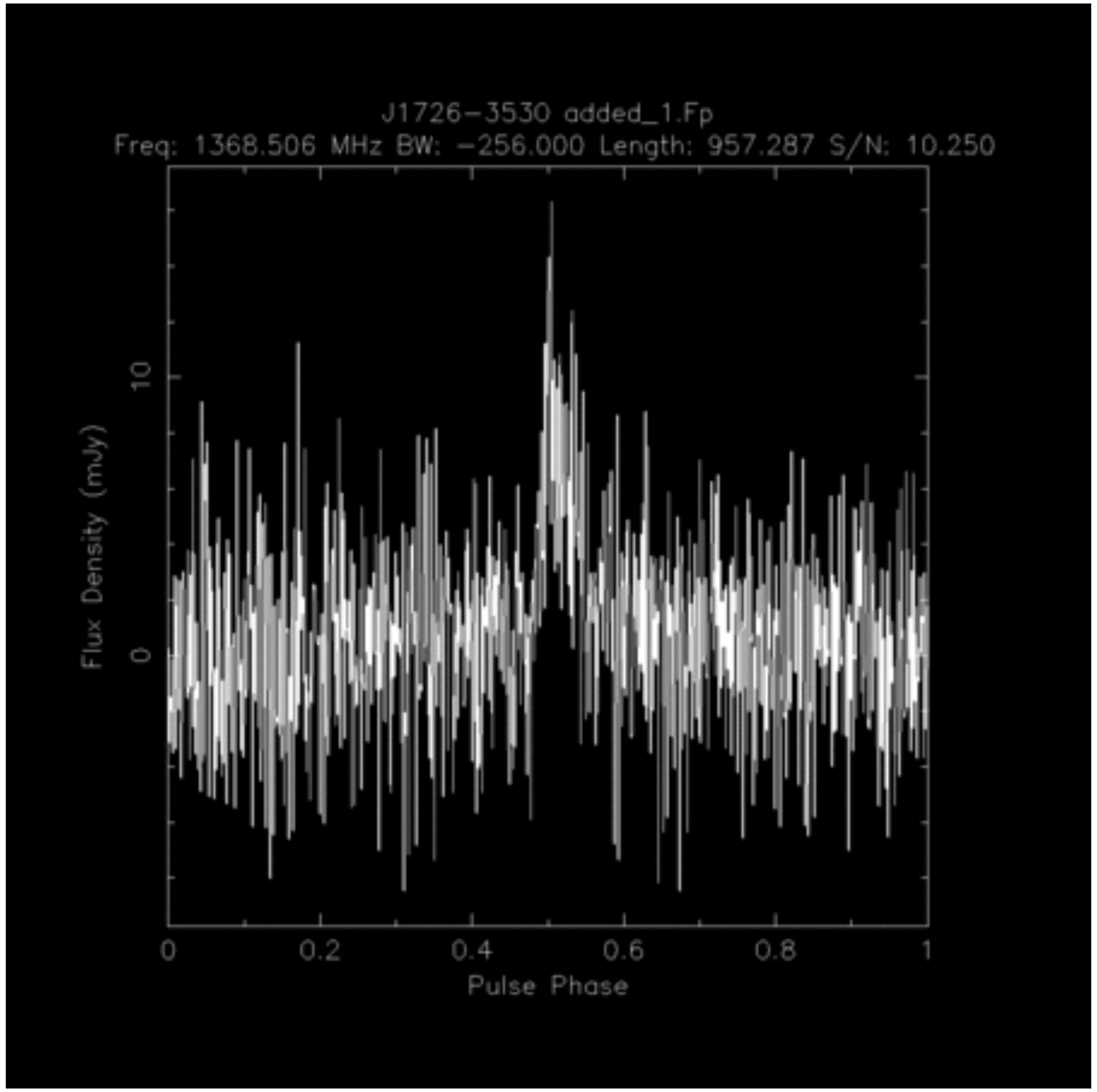

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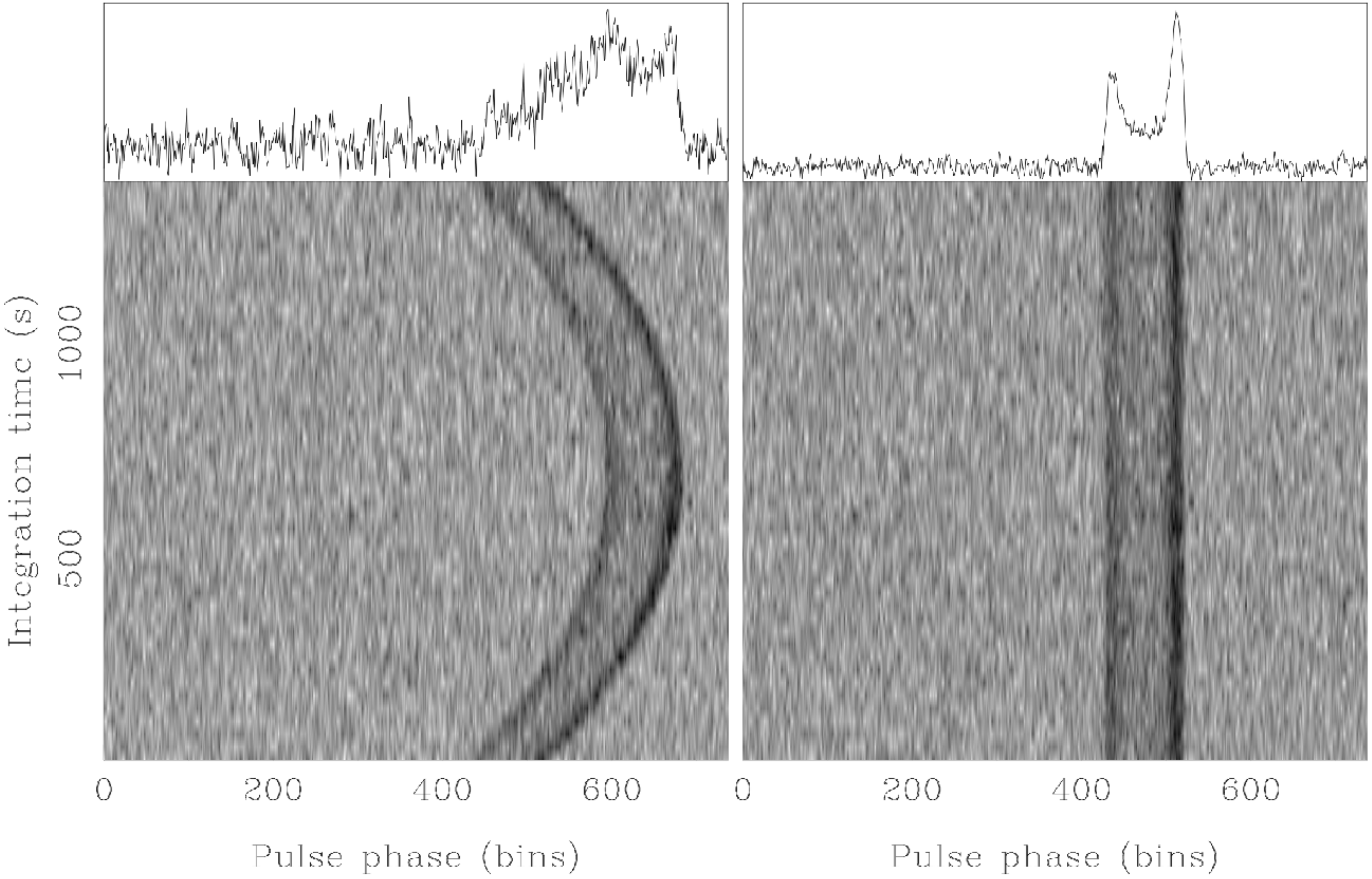
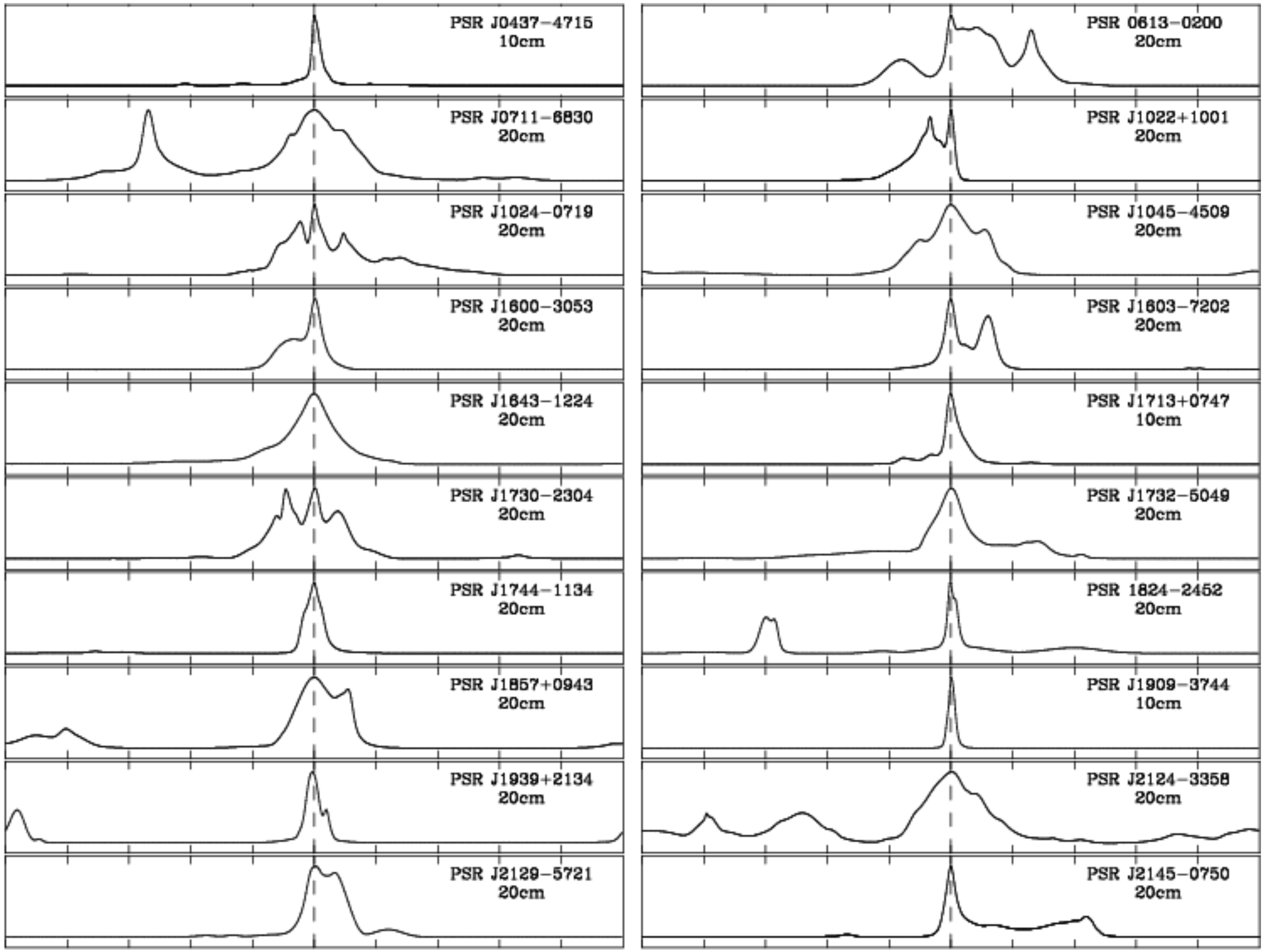
Pulse folding - binary pulsars



Orbital motion of PSR B1913+16 in just 20 minutes causes significant Doppler shift. Need to include this in the folding model

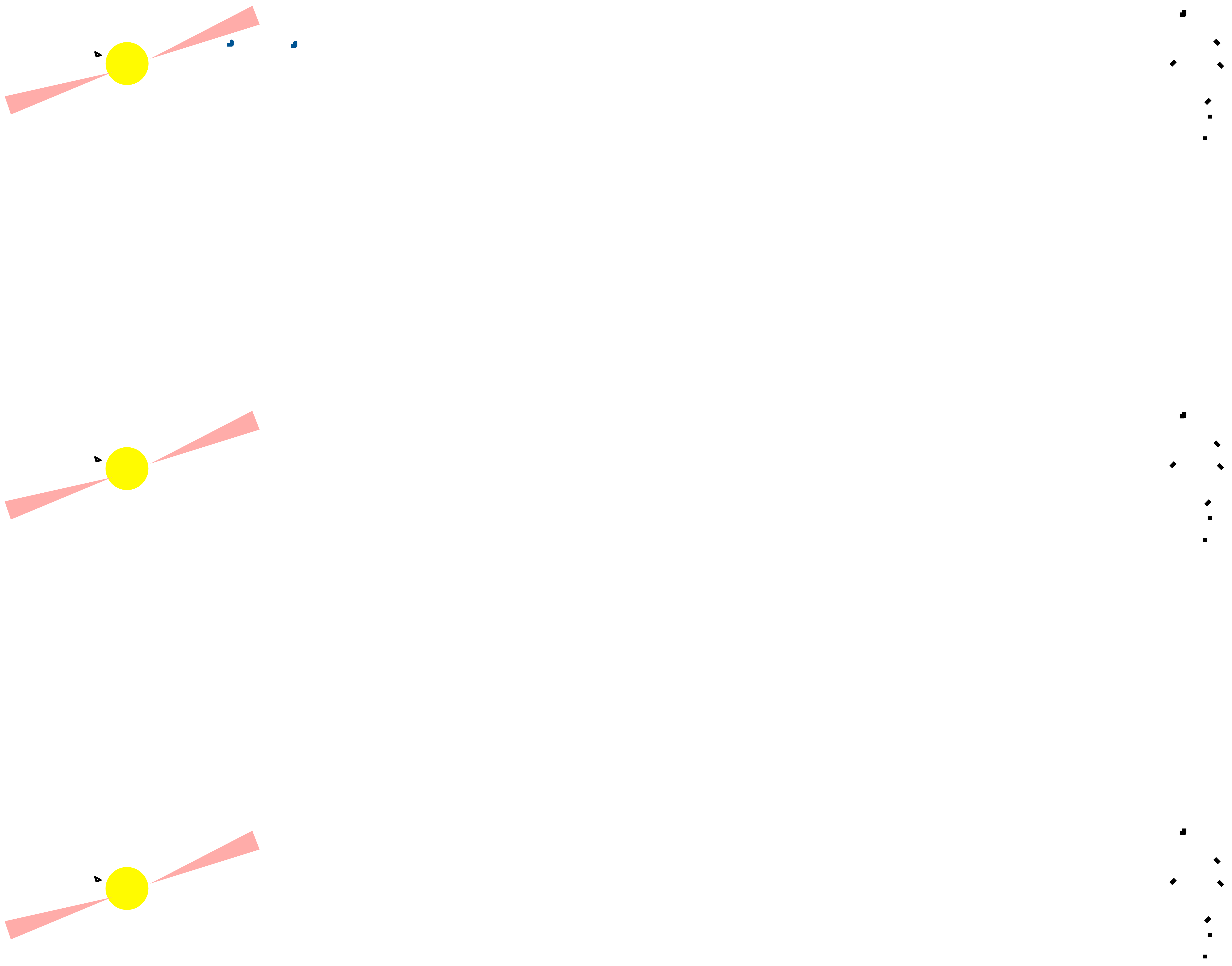
Pulse profiles



Pulse profile templates for 20 PPTA pulsars

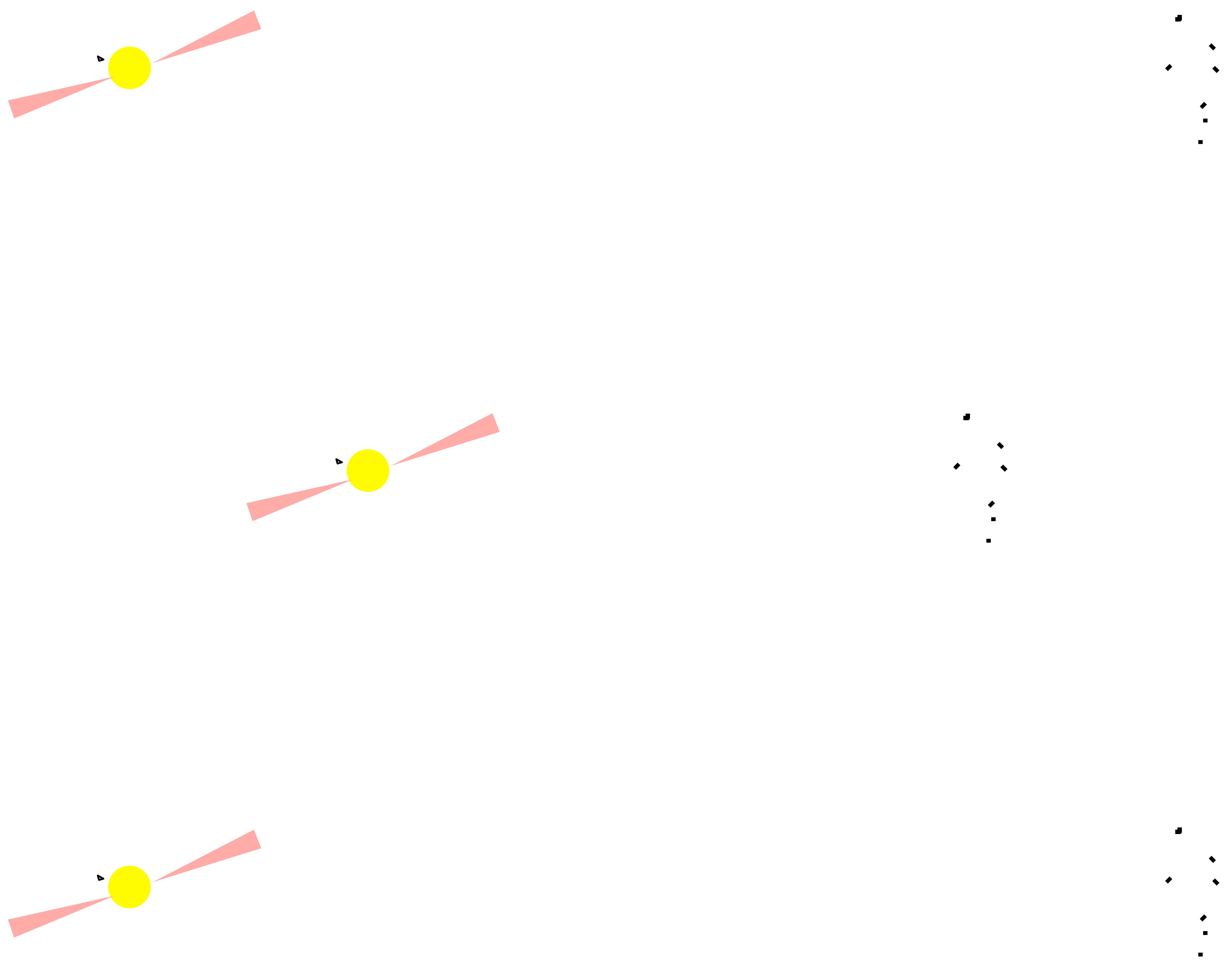
Wide variety of pulse shapes

Pulsar timing and GW detection



Pulsar timing and GW detection

Pulsar timing and GW detection



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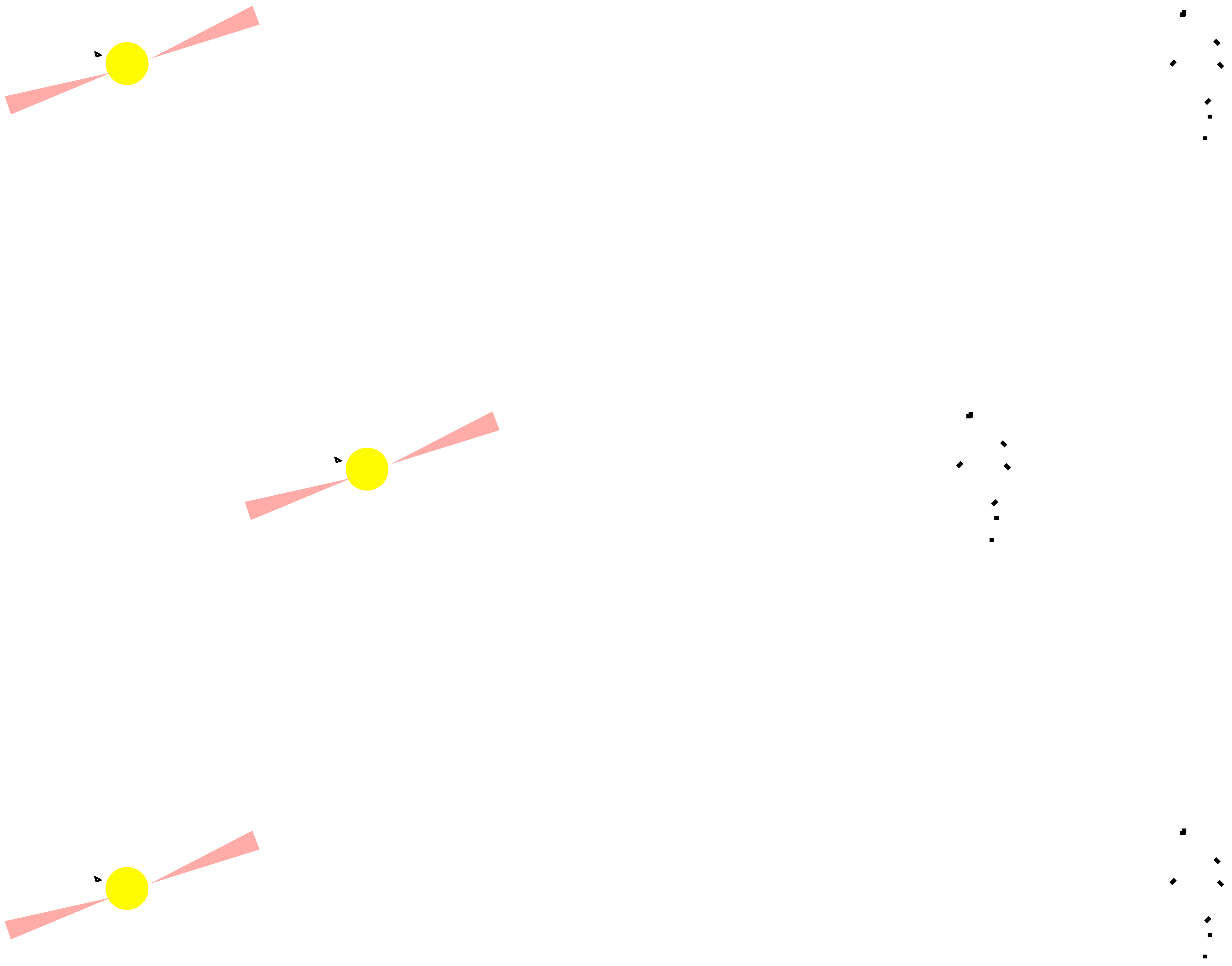

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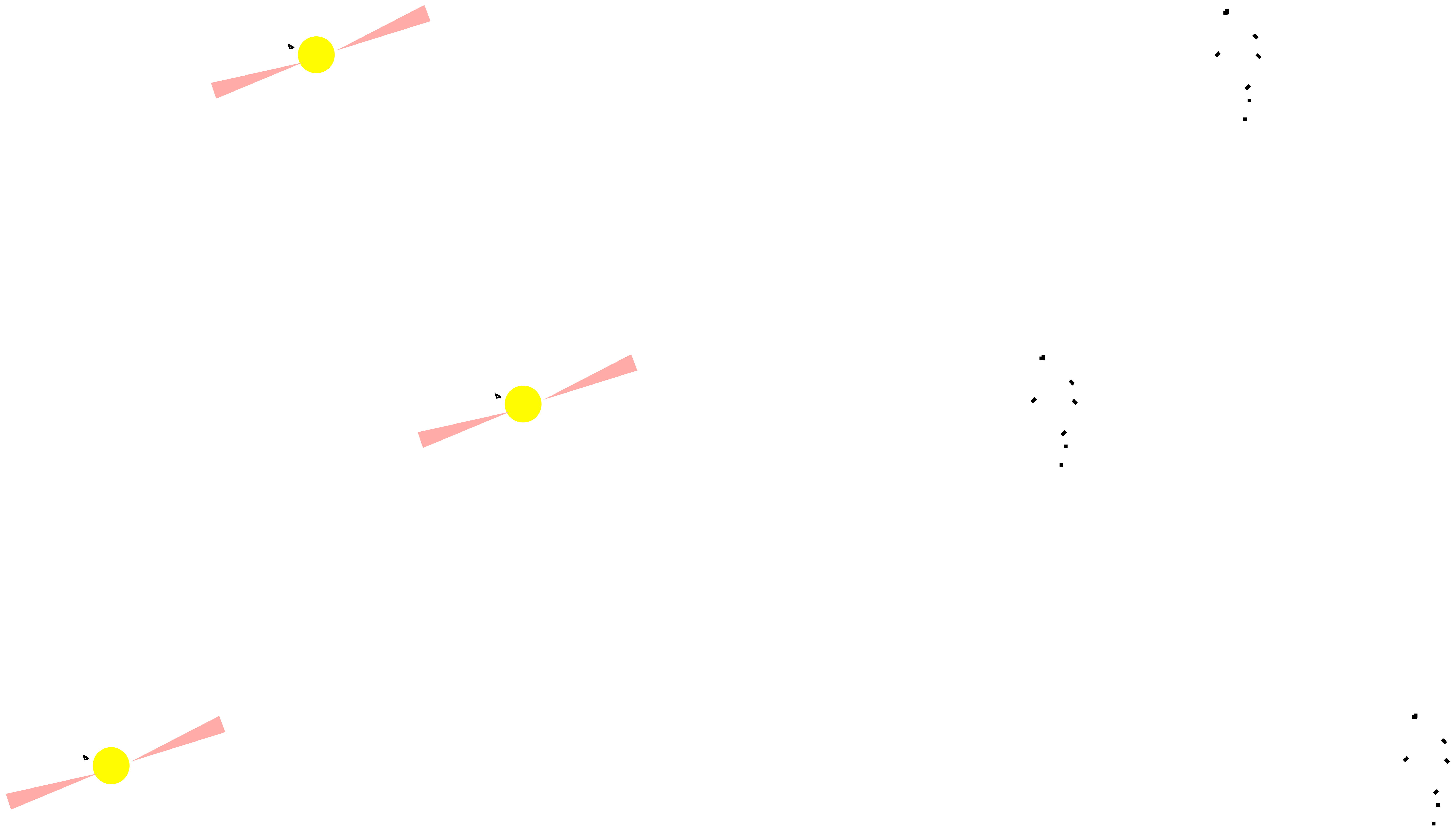

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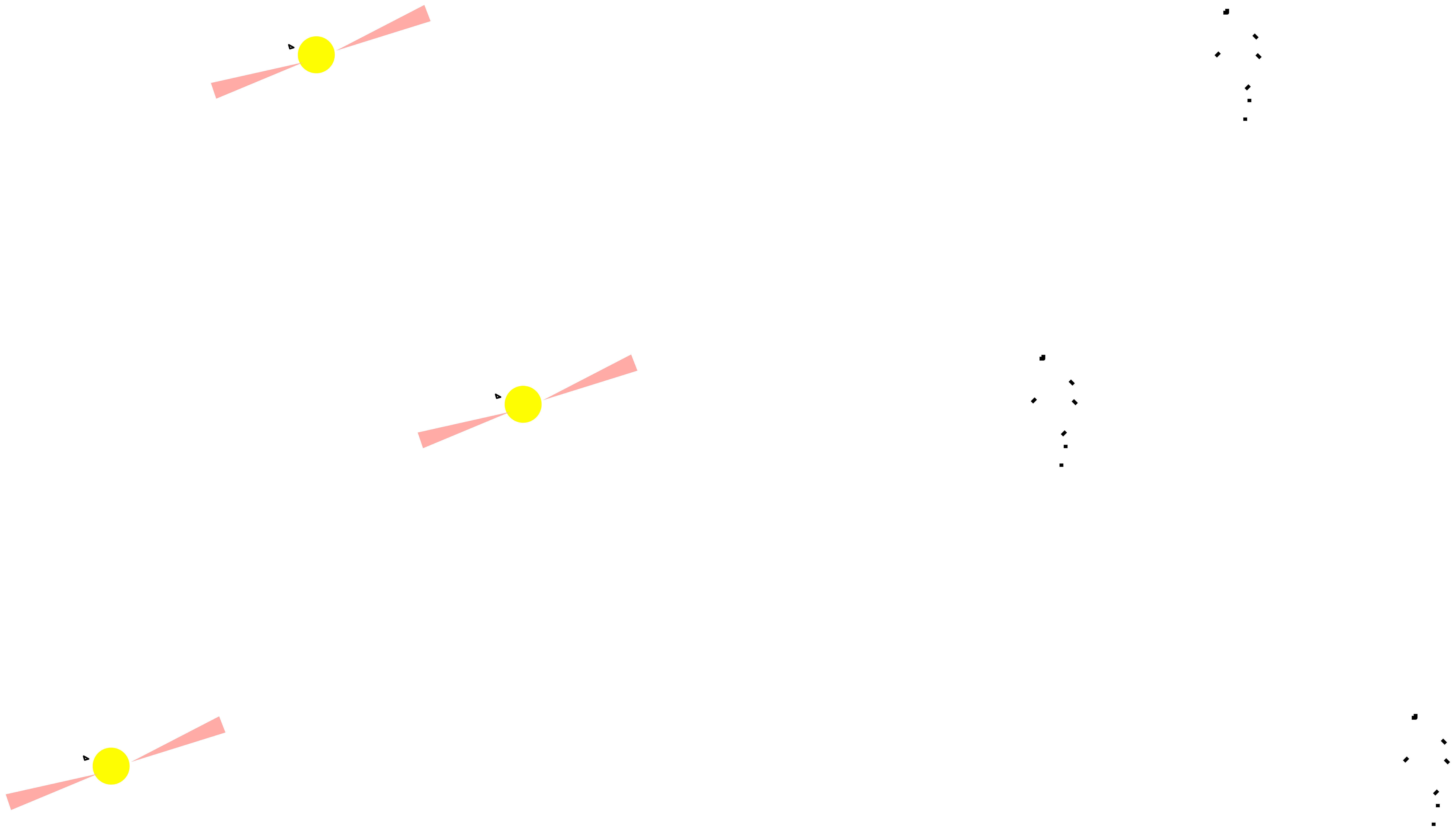

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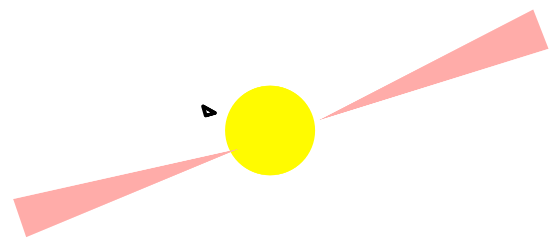
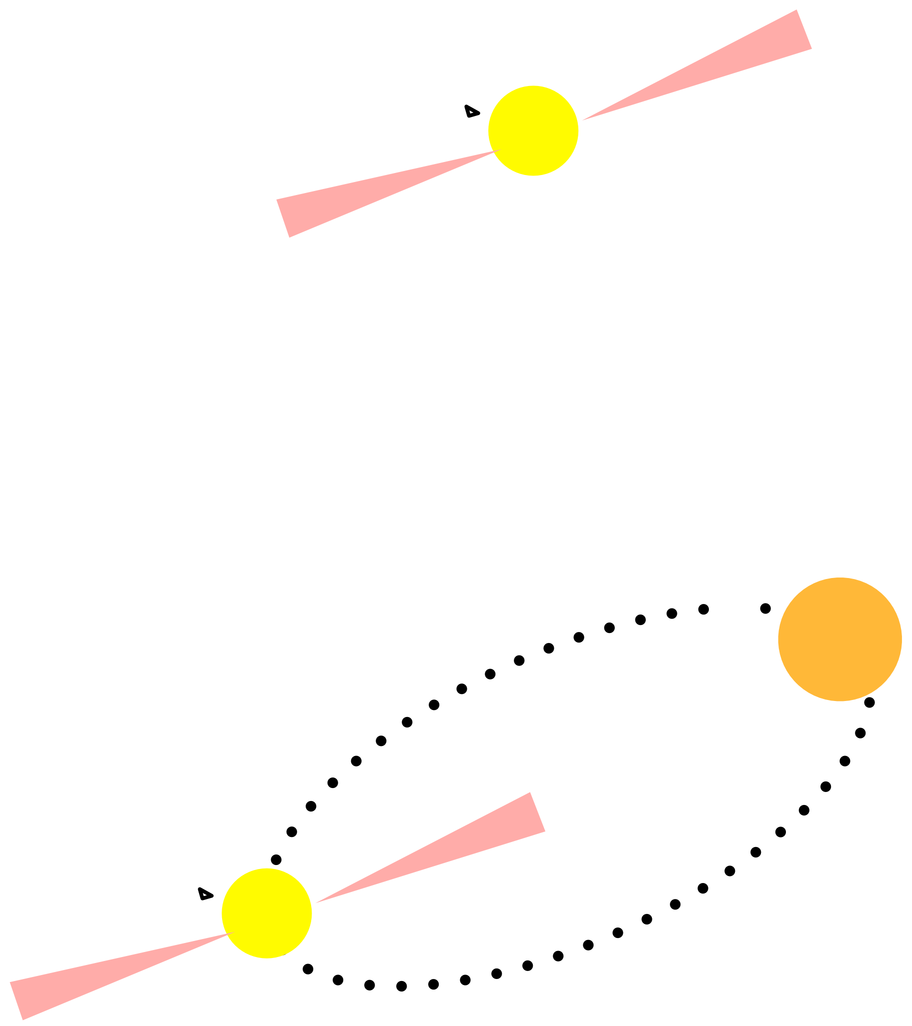
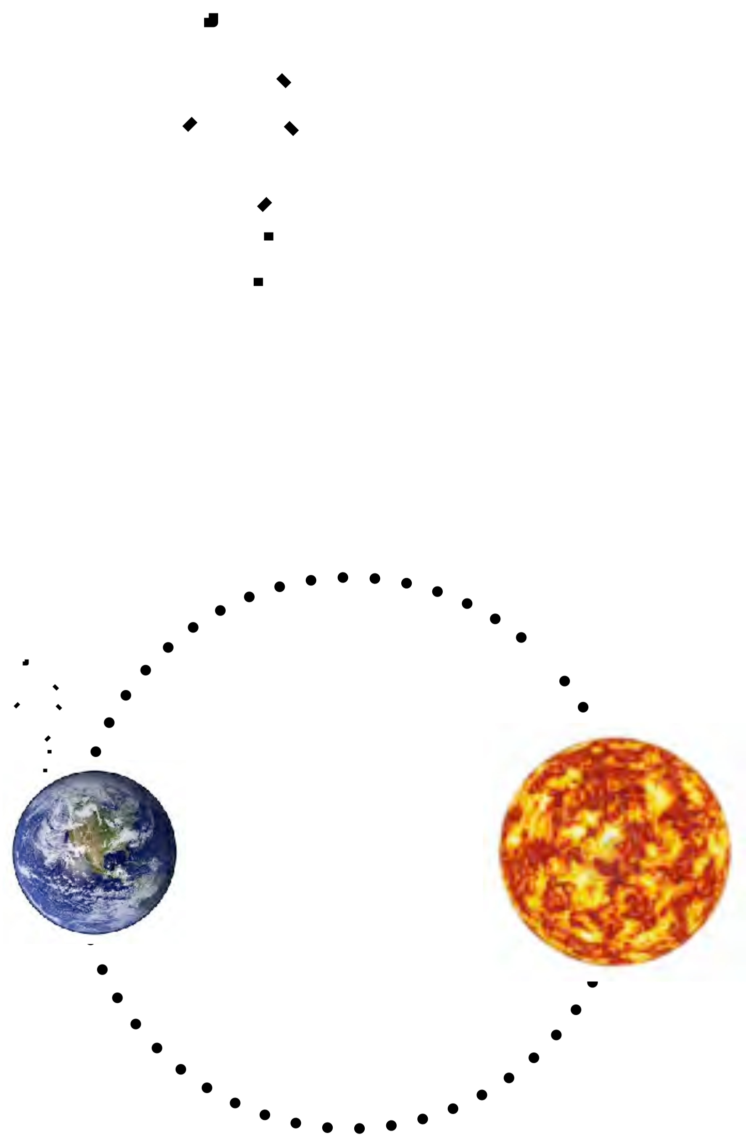
Complications....

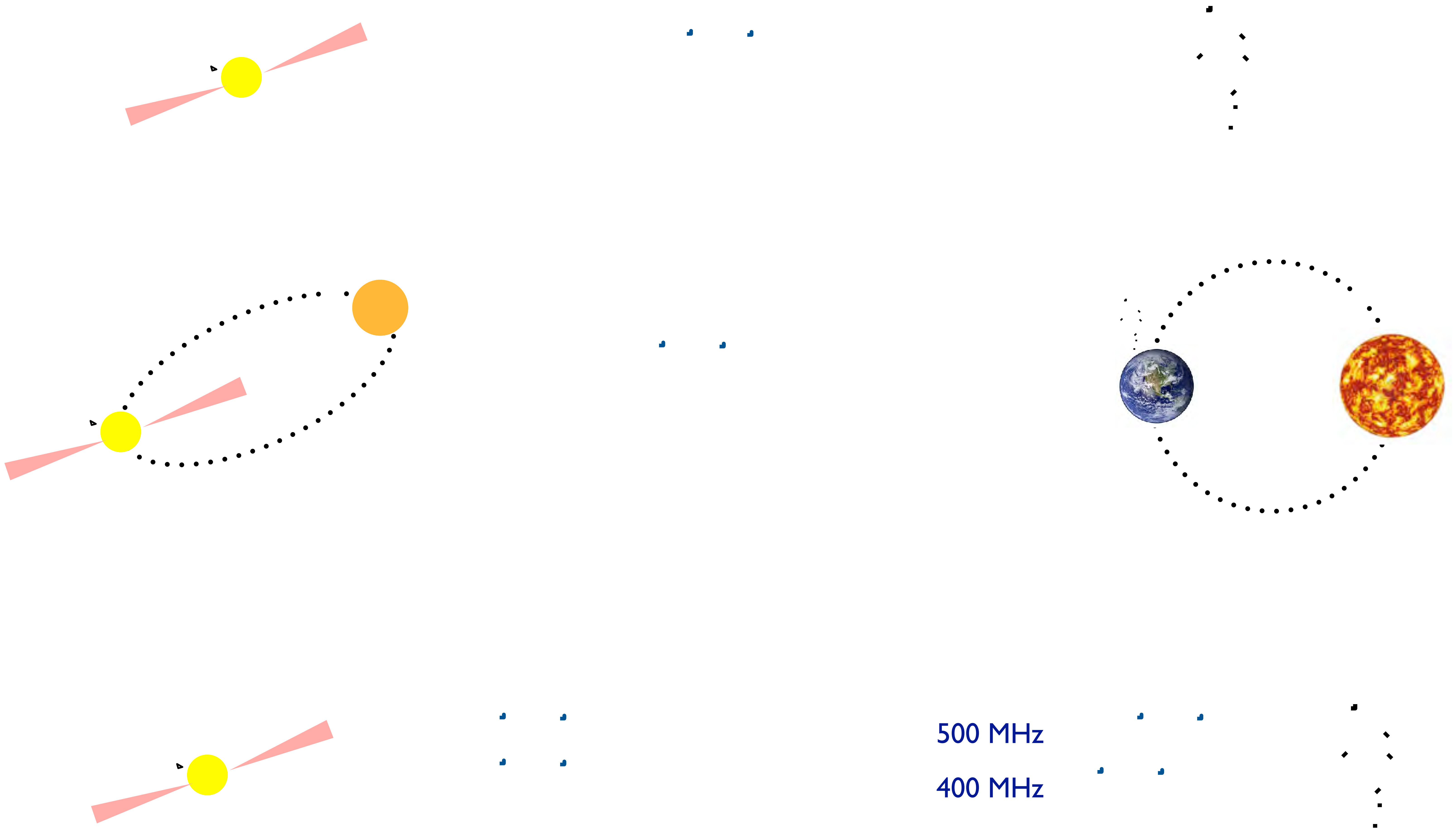


Complications....





Complications....



Timing Model

$$t^{\mathrm{obs}} = t^{\mathrm{PSR}} + \Delta_{\odot} + \Delta_{\mathrm{ISM}} + \Delta_{\mathrm{B}}$$

Observed arrival time

Emission time at pulsar

Barycentering

Propagation delay from pulsar to SSB

Pulsar orbit

Barycentering: Observatory to SSB

$$t^{\rm obs} = t^{\rm PSR} + \Delta_\odot + \Delta_{\rm ISM} + \Delta_{\rm B}$$

Solar system Einstein delay

SS Shapiro delay

$$\Delta_\odot = \Delta_C + \Delta_A + \Delta_{\rm E_\odot} + \Delta_{\rm R_\odot} + \Delta_{\rm S_\odot} + \ldots$$

Clock corrections

Atmospheric delays

SS Roemer delay

Roemer delay - Finite speed of light, time delay between observatory and SSB [Ephermeris model key]

Einstein delay - Clocks run slower in deeper gravitational potentials

Shapiro delay - Time delay due to light propagation in curved spacetime geometry

ISM: Pulsar to SSB

$$t^{\rm obs} = t^{\rm PSR} + \Delta_\odot + \Delta_{\rm ISM} + \Delta_{\rm B}$$

Interstellar dispersion

Einstein delay

$$\Delta_{\rm ISM} = \Delta_{\rm VP} + \Delta_{\rm ISD} + \Delta_{\rm FDD} + \Delta_{\rm ES} + \ldots$$

Vacuum propagation

Additional Frequency dependent delay

Vacuum propagation - Roemer type delay, including changing distance from pulsar to SSB

Interstellar dispersion - Depends on dispersion measure and radio frequency $\Delta_{\rm ISD} = \frac{D}{\nu^2}$

Einstein delay - Special relativistic time dilation due to relative motion of Pulsar-SSB

Binary: Pulsar frame corrections

$$t^{\mathrm{obs}} = t^{\mathrm{PSR}} + \Delta_{\odot} + \Delta_{\mathrm{ISM}} + \Delta_{\mathrm{B}}$$

Aberration

Shapiro delay

$$\Delta_{\mathrm{B}} = \Delta_{\mathrm{RB}} + \Delta_{\mathrm{AB}} + \Delta_{\mathrm{EB}} + \Delta_{\mathrm{SB}}$$

Roemer delay

Einstein delay

Roemer delay - Variations in the distance due to orbital motion. Includes PN effects

Aberration - Apparent direction to pulsar changed by transfer velocity

Einstein delay - Clocks run slower in deeper gravitational potentials

Shapiro delay - Time delay due to light propagation in curved spacetime geometry

Spin down model

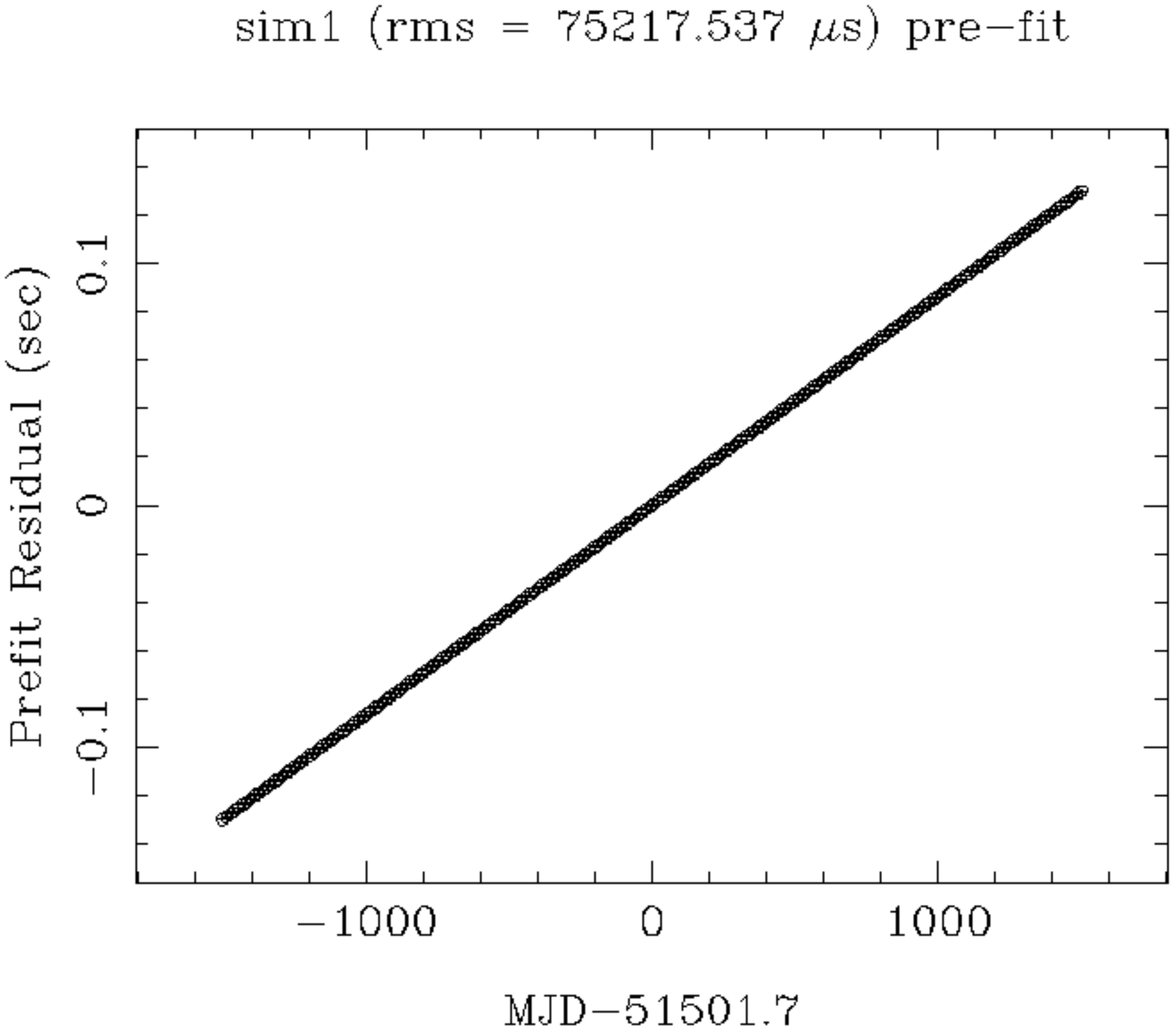
$$t^{\rm obs} = t^{\rm PSR} + \Delta_\odot + \Delta_{\rm ISM} + \Delta_{\rm B}$$

Emission time at pulsar

The time between pulses can undergo intrinsic changes due to the Pulsar spinning down

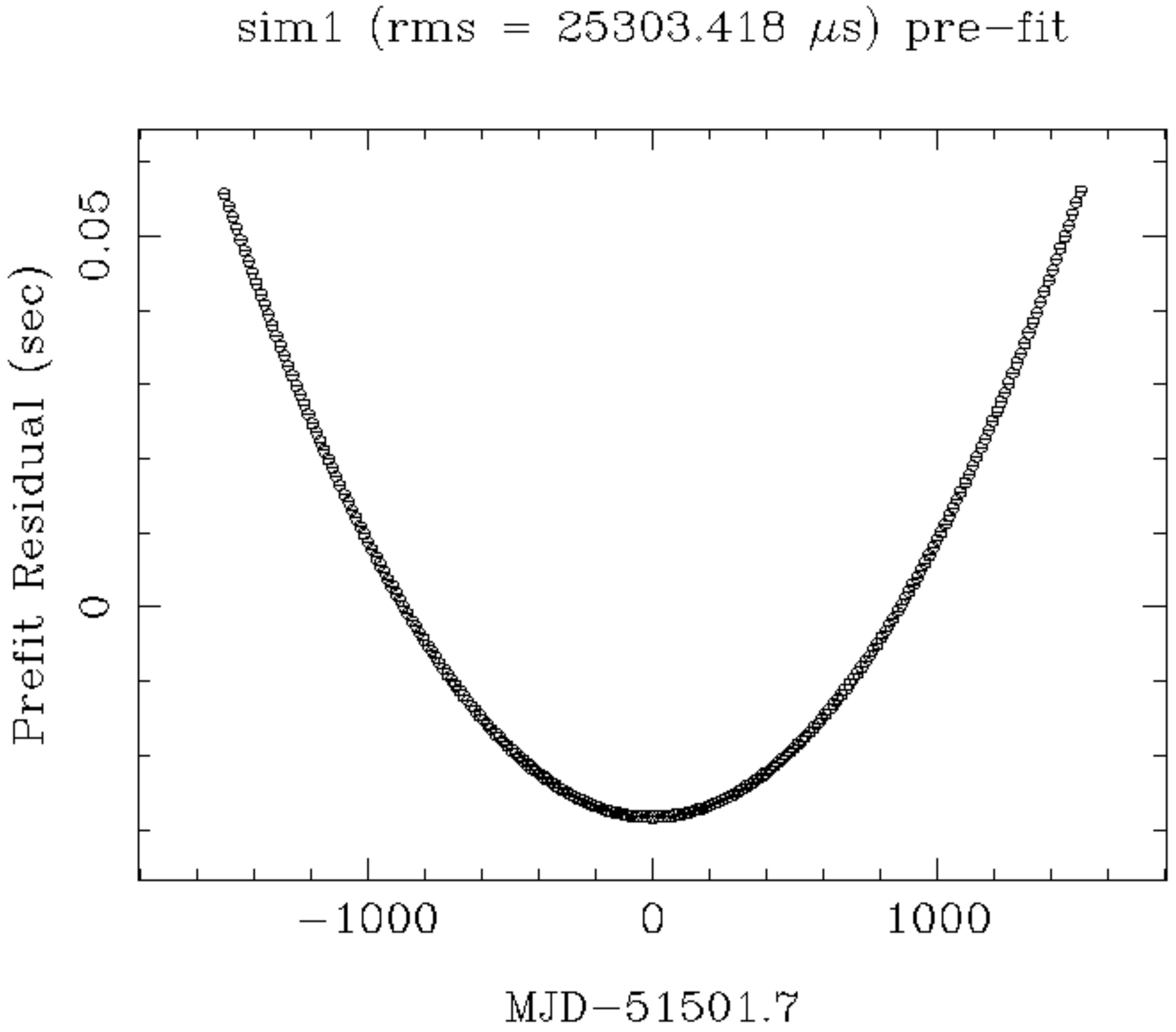
$$P(t) = P_0 + \dot{P}_0 \left(t - t_0\right) + \frac{1}{2}\ddot{P}_0 \left(t - t_0\right)^2 + \ldots$$

Incorrect Period

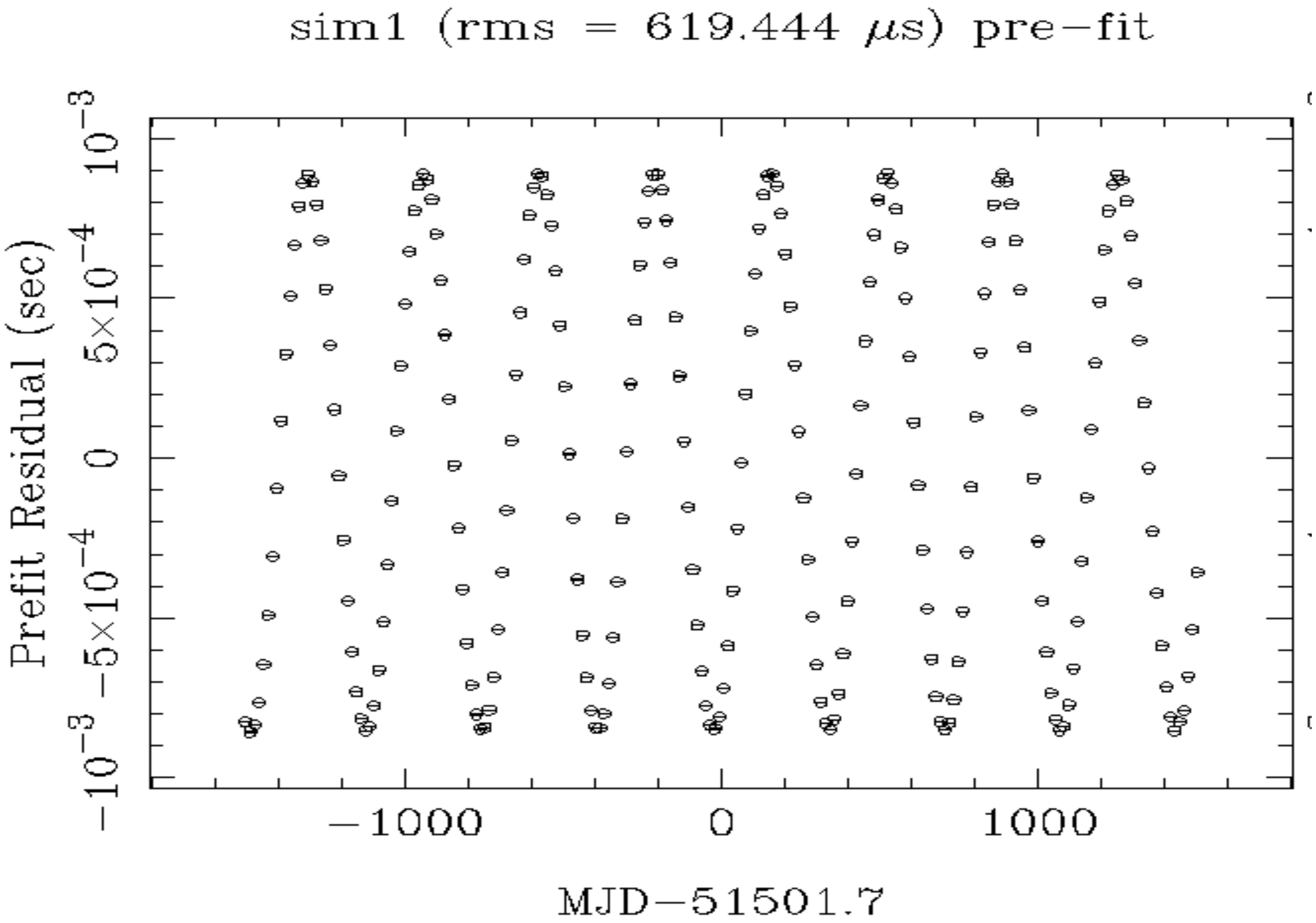


$P_{model} > P_{true}$

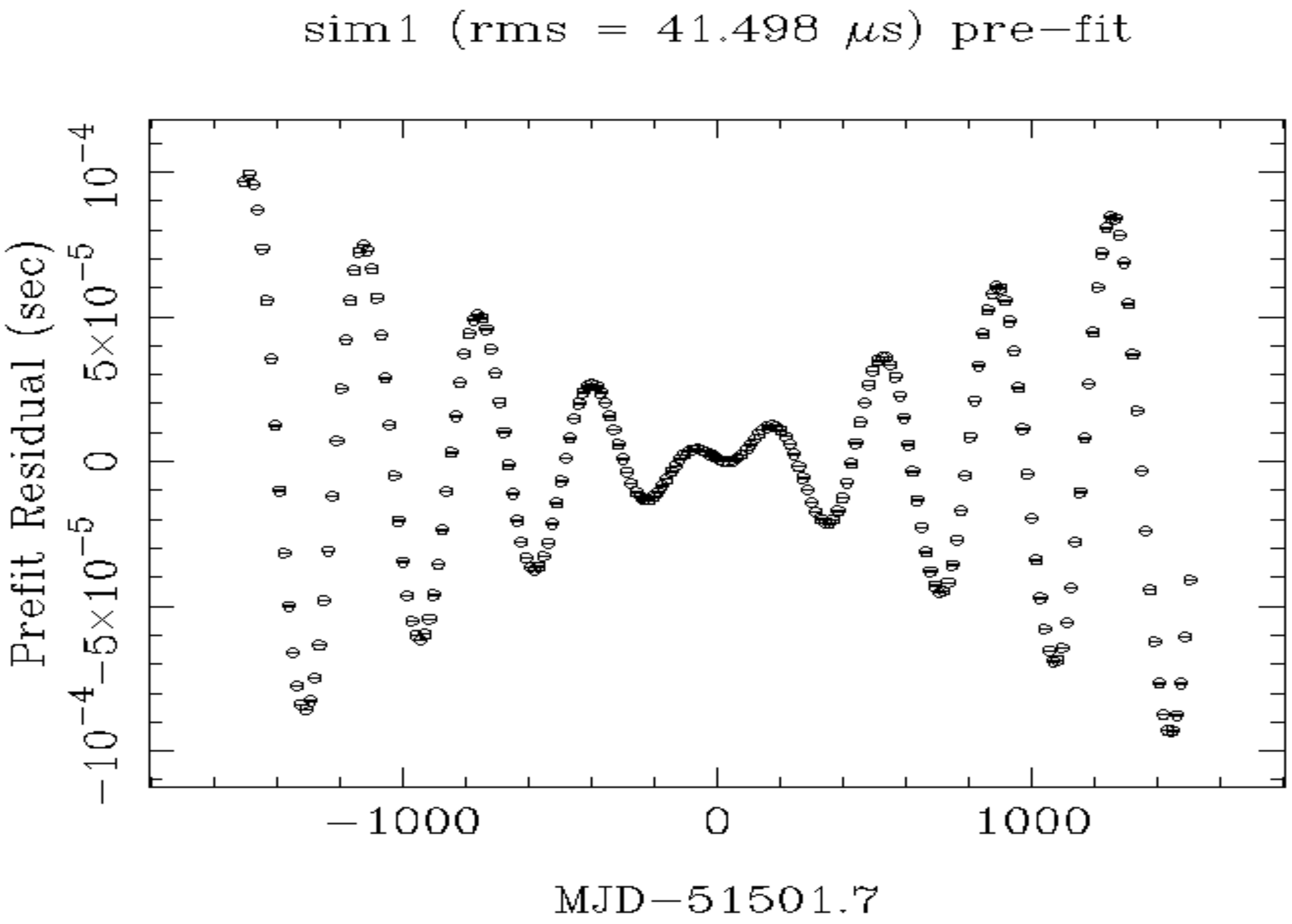
Incorrect Period Derivative



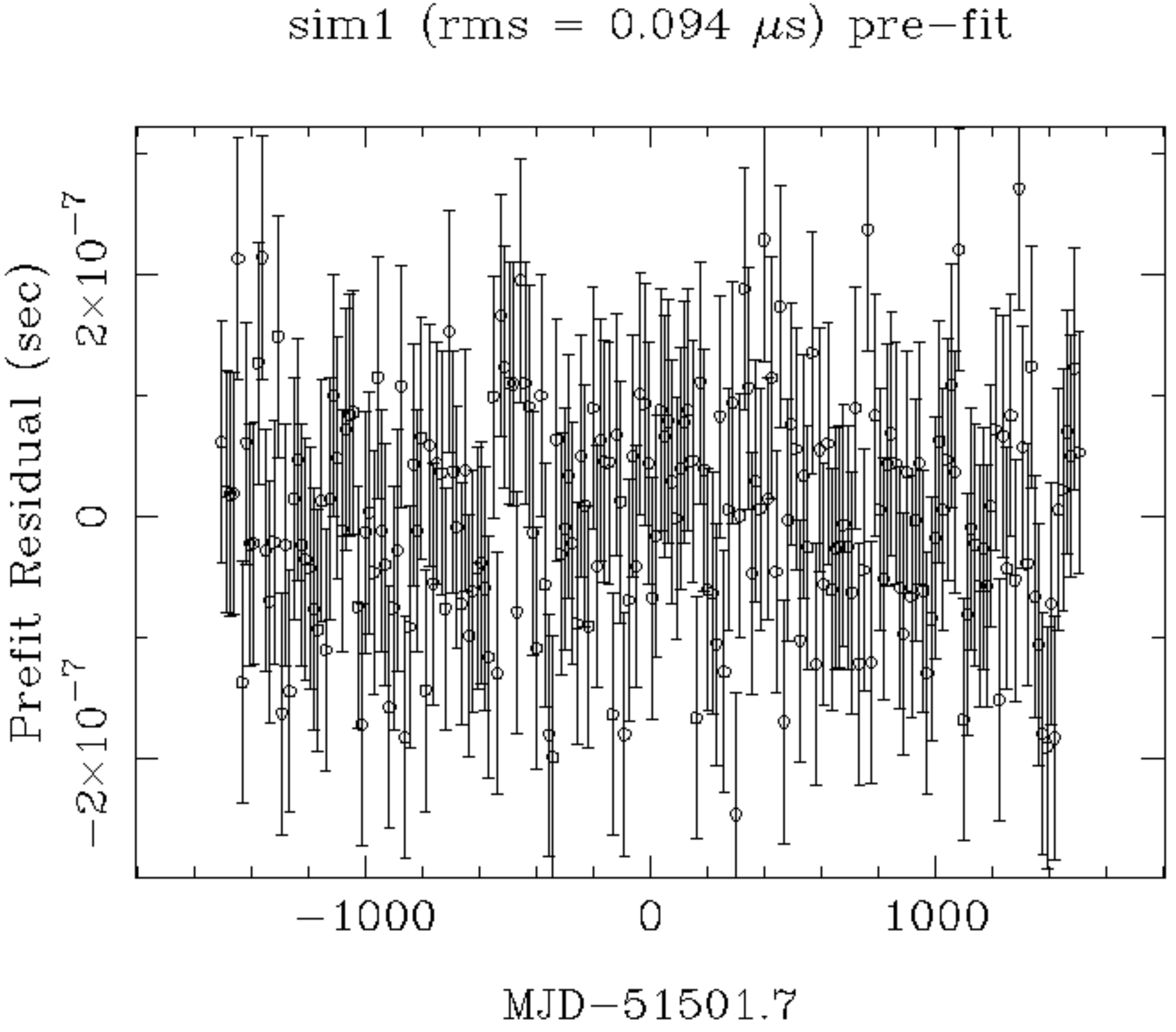
Incorrect Pulsar Sky location



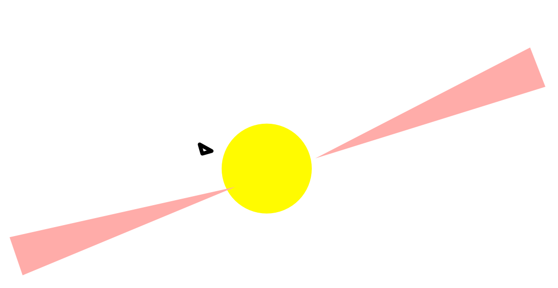
Incorrect Pulsar proper motion

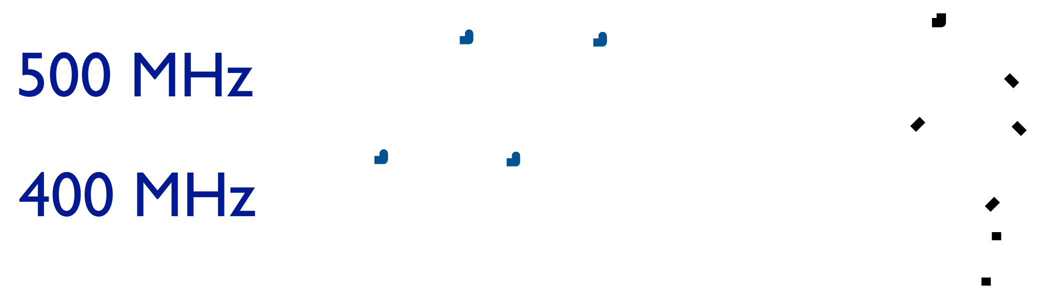


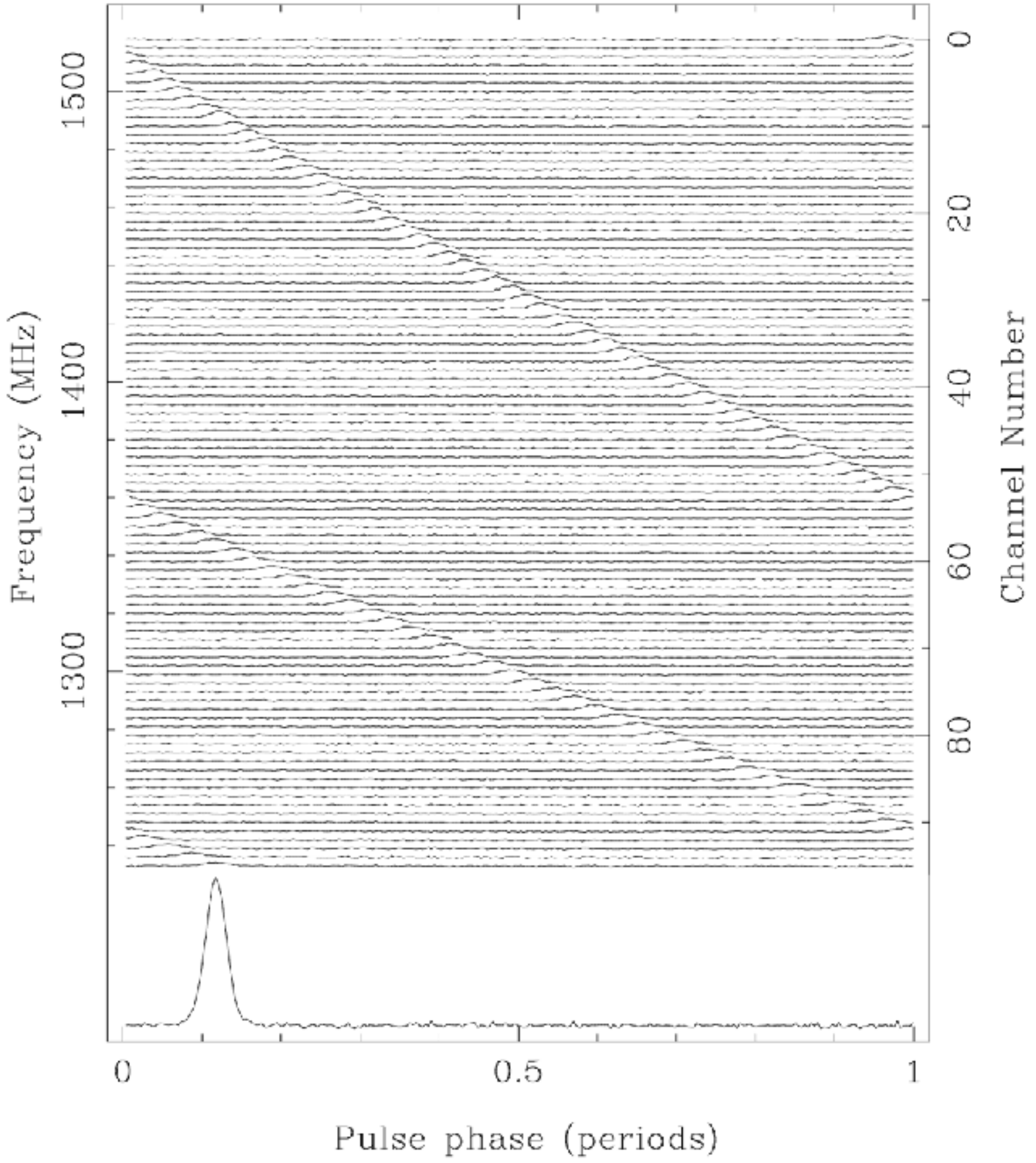
Timing model residuals with a good solution



Dispersion and de-dispersion



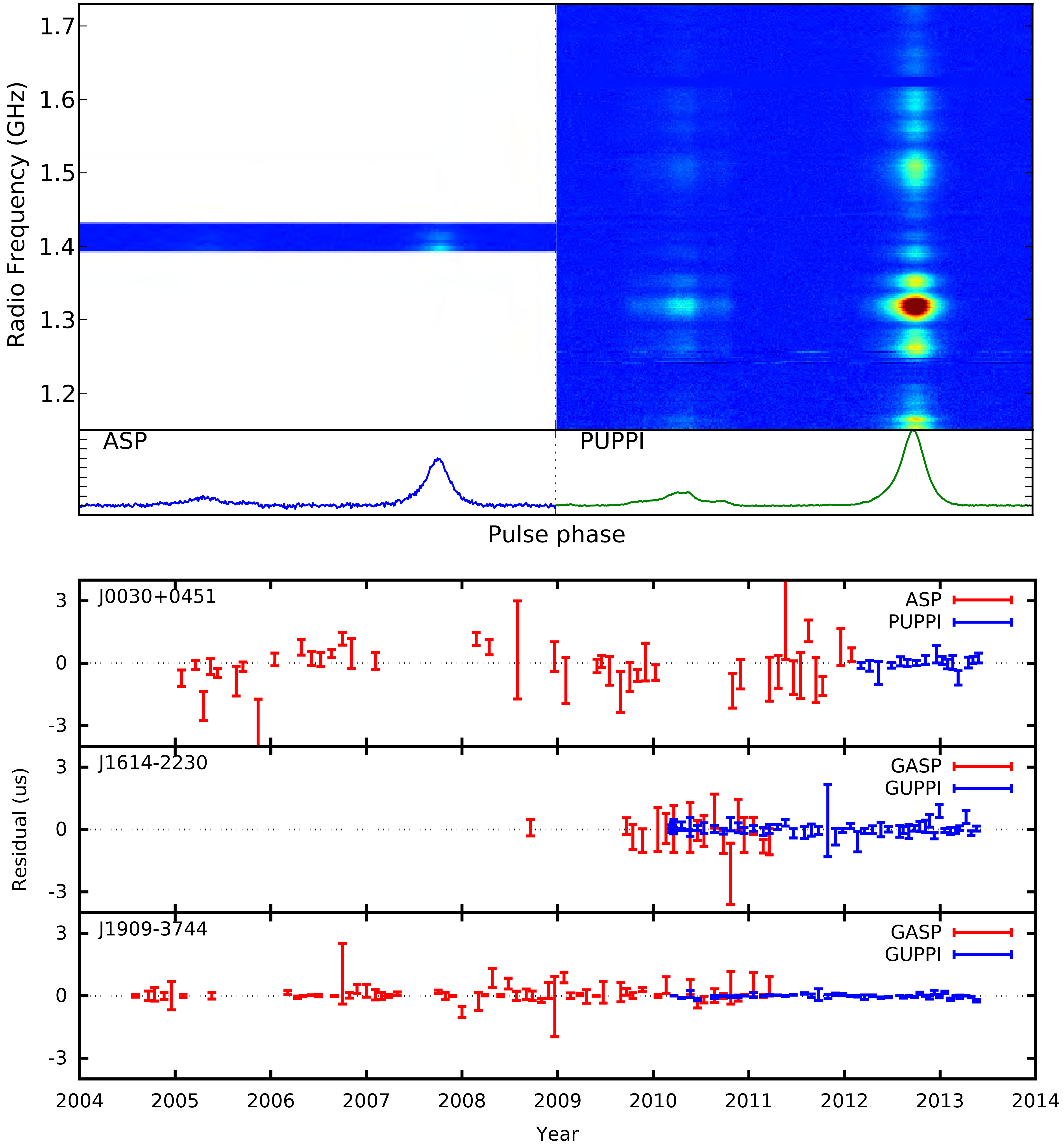




$$\Delta_{\mathrm{ISD}} = \frac{D}{\nu^2}$$

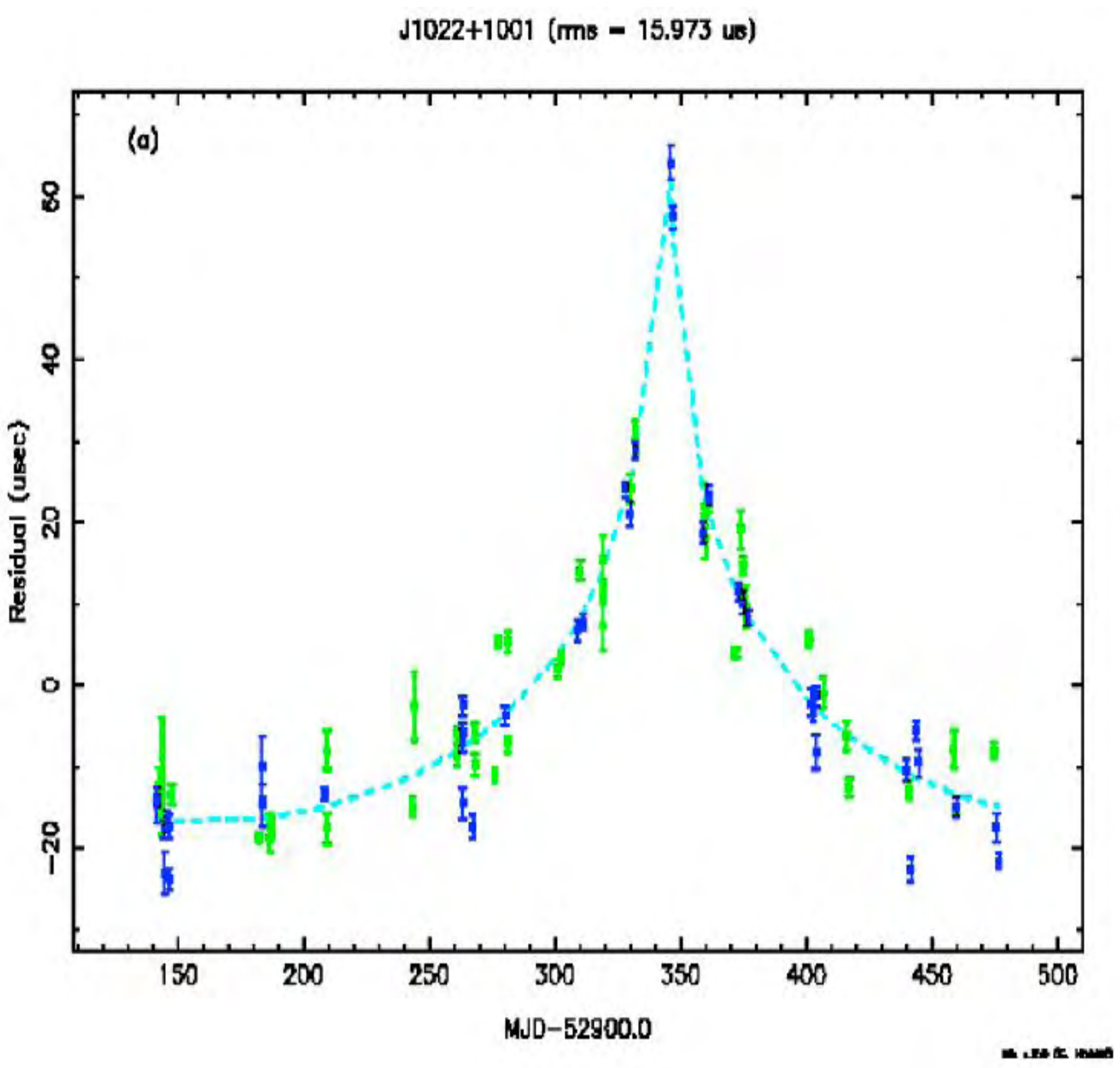
The dispersion measure ***D*** depends on the distance to the pulsar and the column density of electrons along the line of sight. Used as proxy for distance

Wide-band de-dispersion



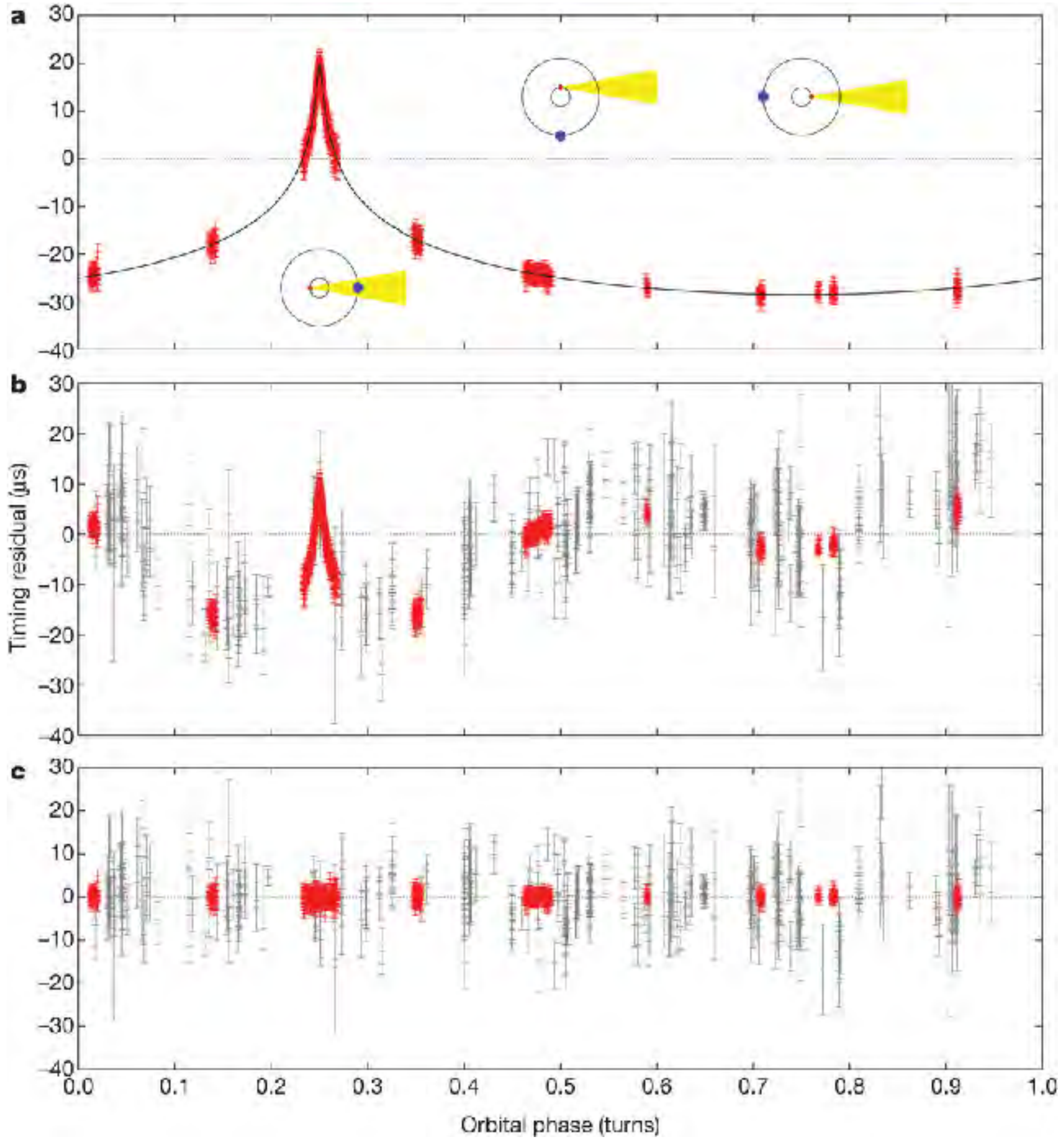
Shapiro delays

$\Delta_{S_\odot}$



Shaprio delay for PSR J1022+1001 from Jupiter

Δ_{SB}



Orbital Shaprio delay seen in PSR J1614-2230

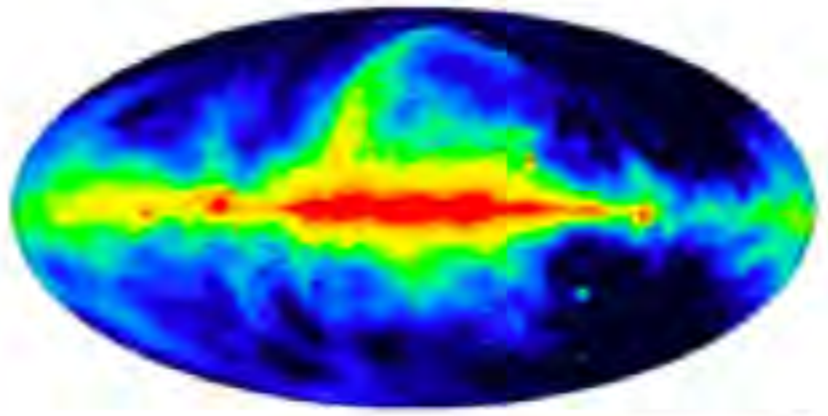
Outline of lecture

- History, status and future of pulsar timing
- What are pulsars? Why use milli-second pulsars?
- Observing pulsars - pulse folding
- Timing model
- Noise sources

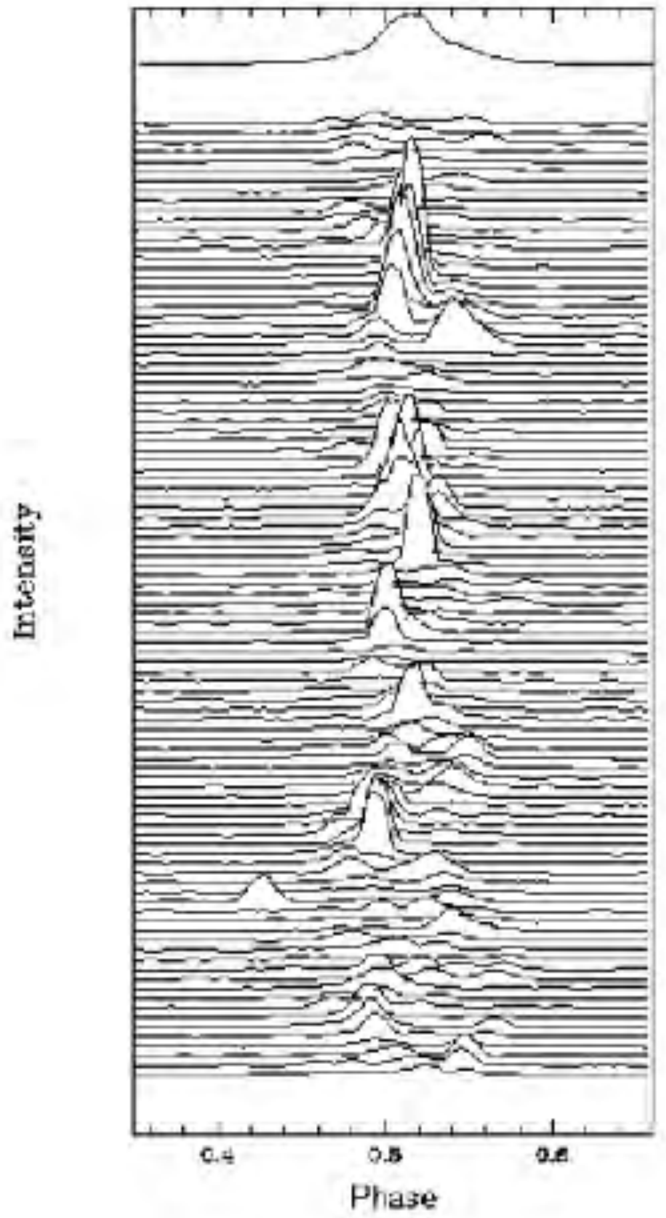
White noise residuals

=

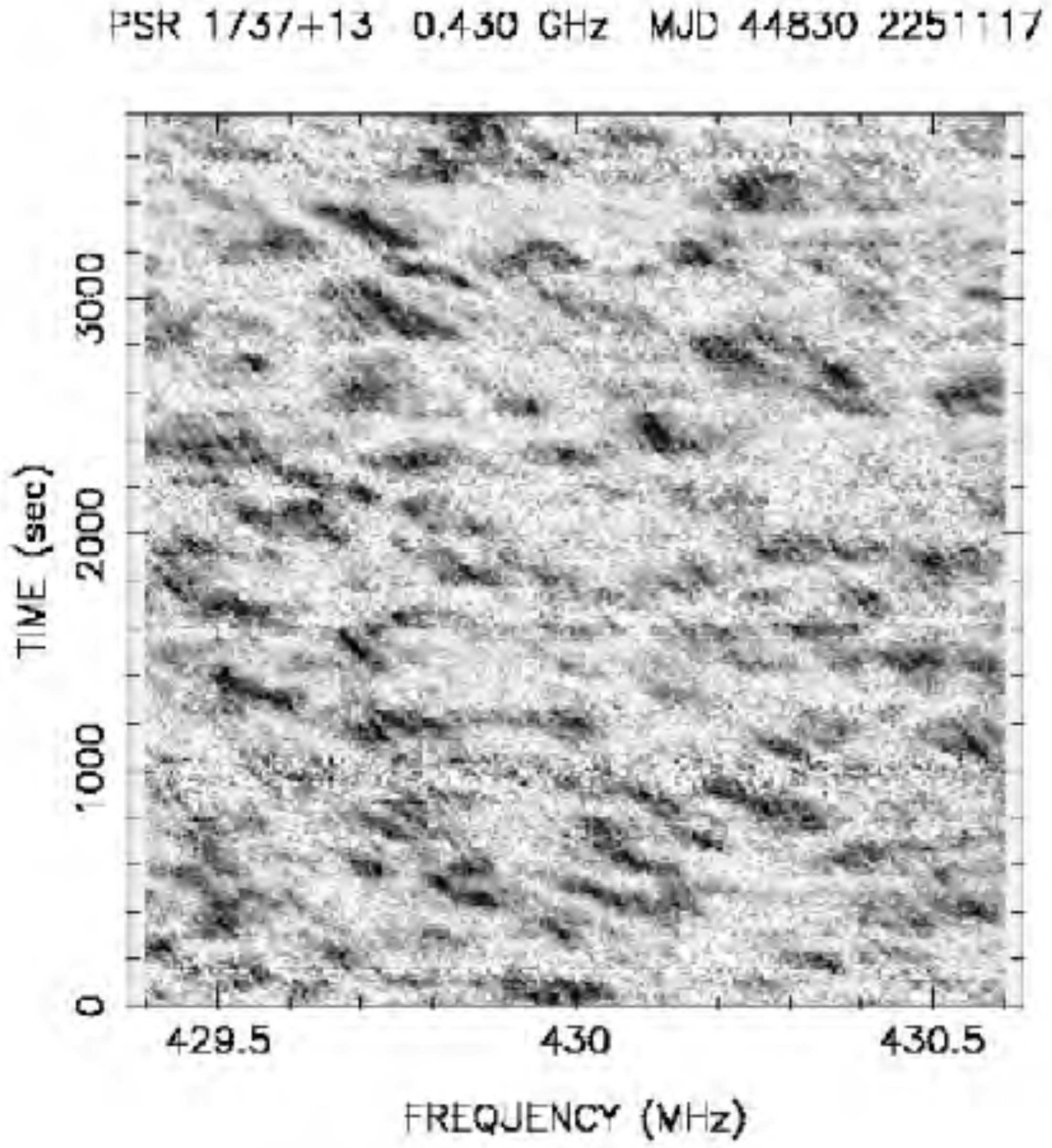
Radiometer noise

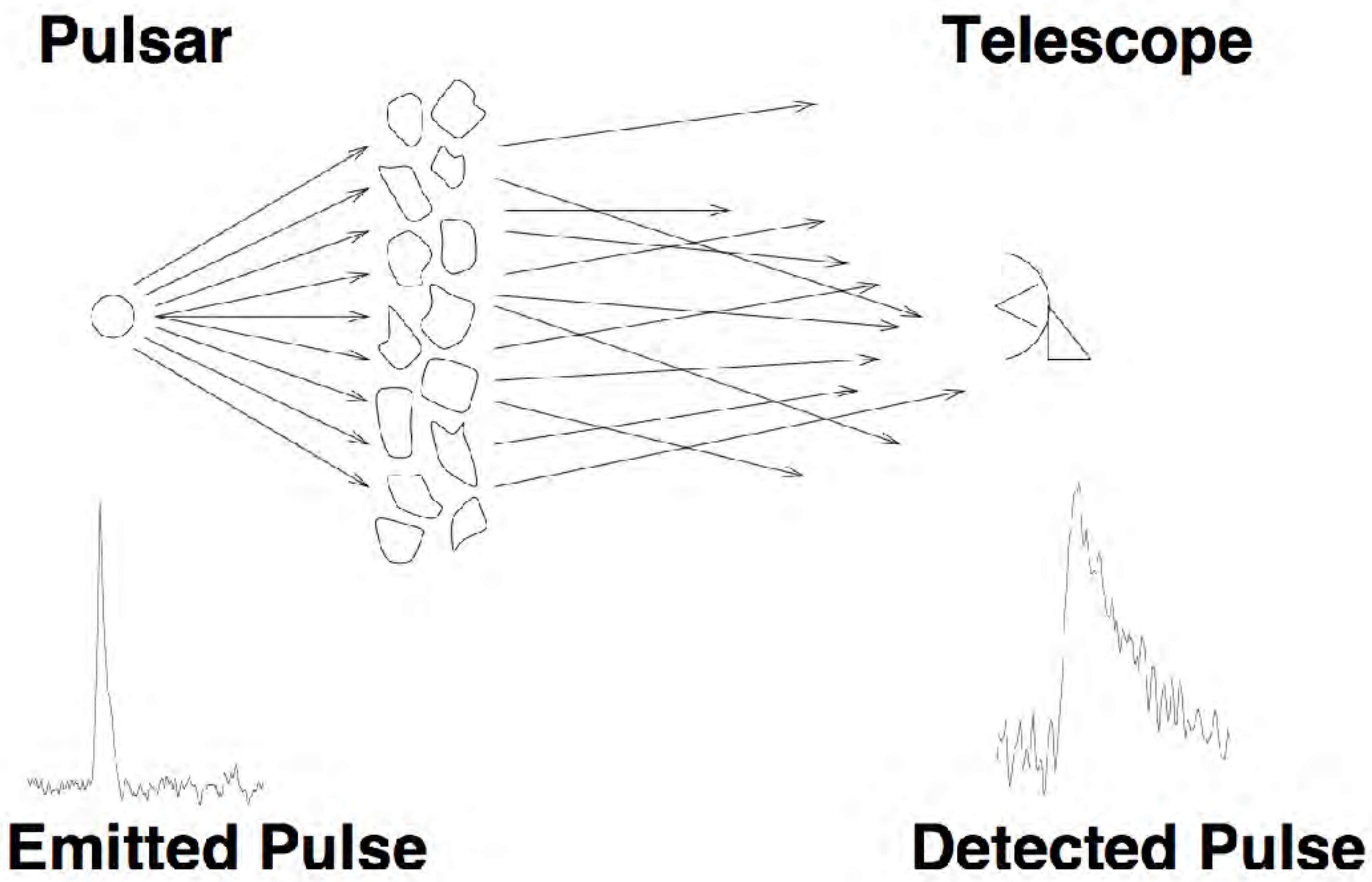


Pulse Jitter



DISS





Pulsar
Telescope
Emitted Pulse
Detected Pulse

Red noise residuals

=

Spin noise + DM variations + GWs (stochastic)

f^{-5} $f^{-8/3}$ $f^{-13/3}$