# 2016 NASSP OTII Pulsars

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# References

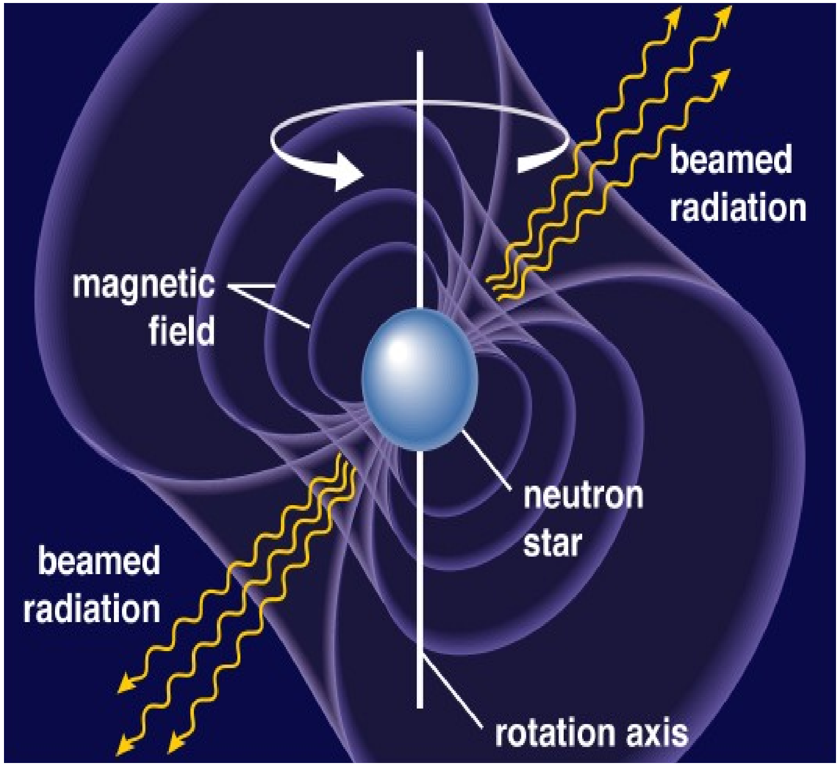
Discovery of pulsars

- http://www.bigear.org/vol1no1/burnell.htm

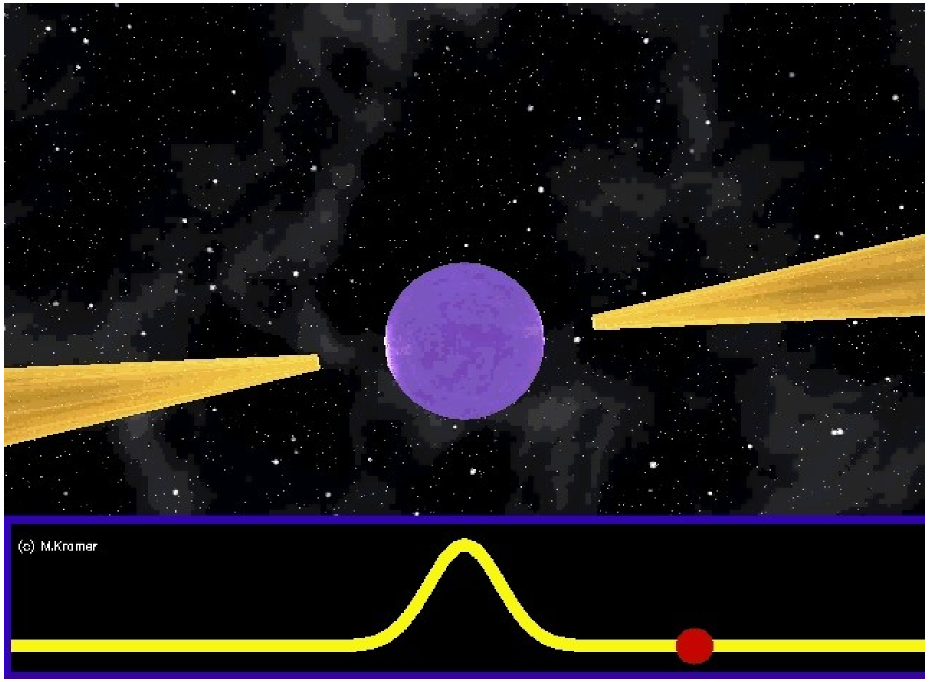
Pulsars from Essential Radio Astronomy

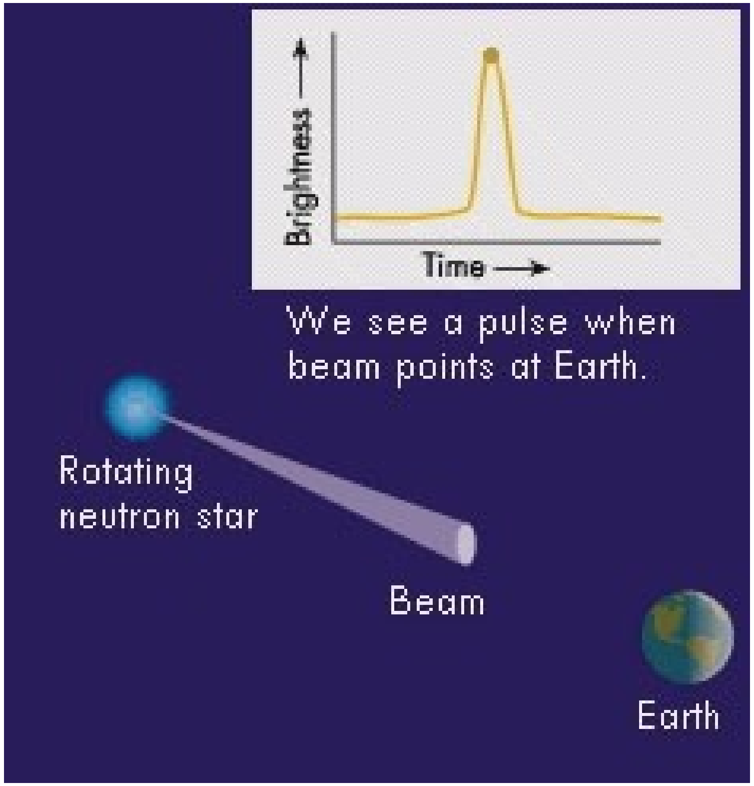
- http://www.cv.nrao.edu/~sransom/web/Ch6.html

# Pulsars

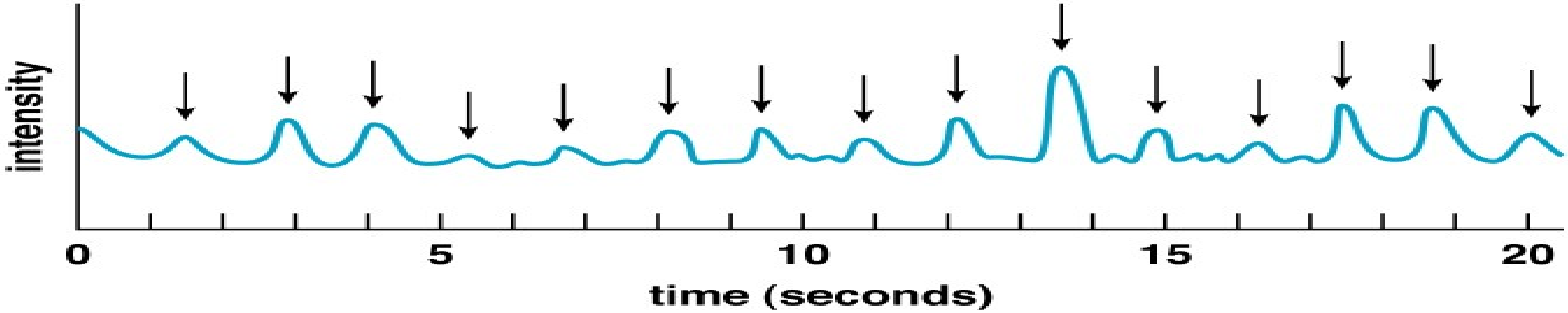

beamed
radiation
magnetic
field
neutron
star
beamed
radiation
rotation axis

# The Pulsar

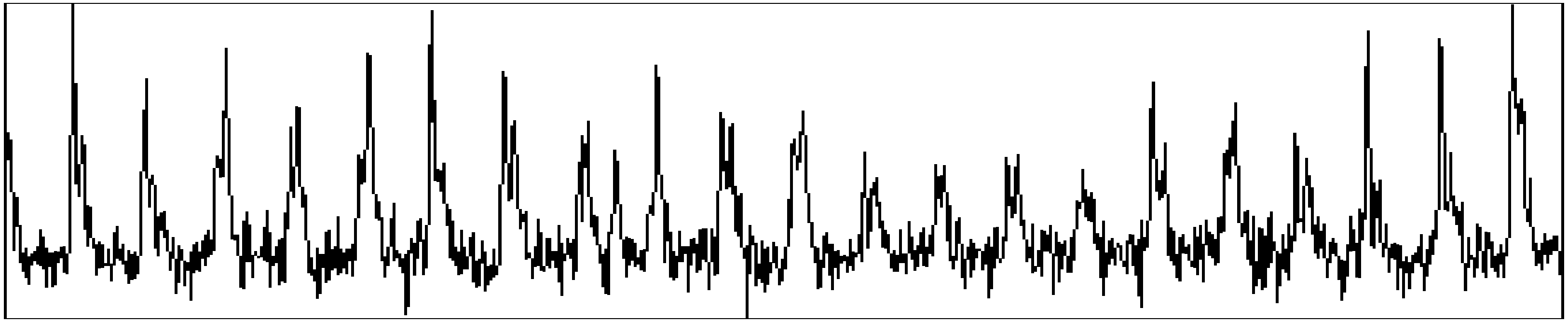




We see a pulse when beam points at Earth.



# Pulsars – stable clocks

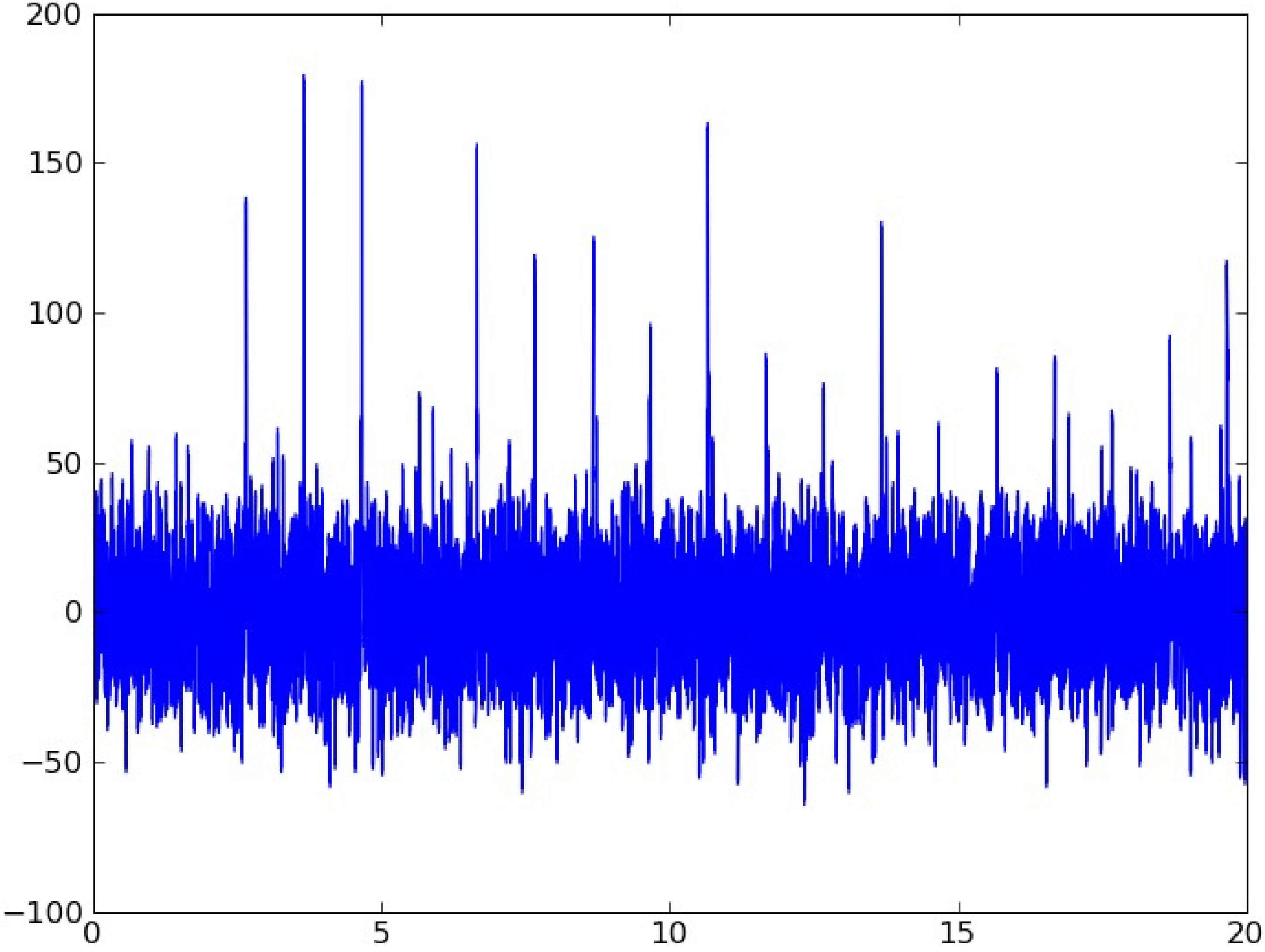


Unambiguously number each pulse

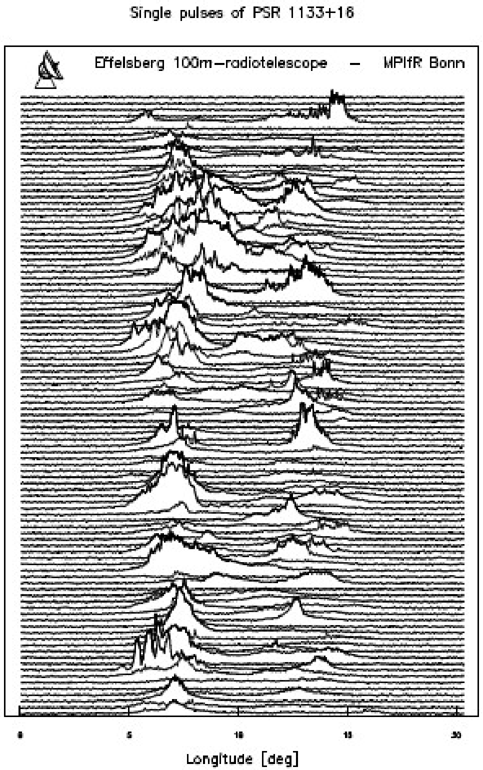
Between
11 Mar 2009 20:55:37
and
29 Apr 2009 21:41:37

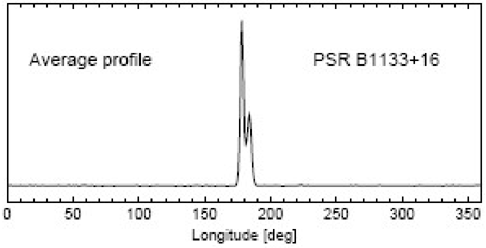
There were exactly **47 414 570** pulses

# Actual pulse train



# Integrate many pulses





# Dispersion

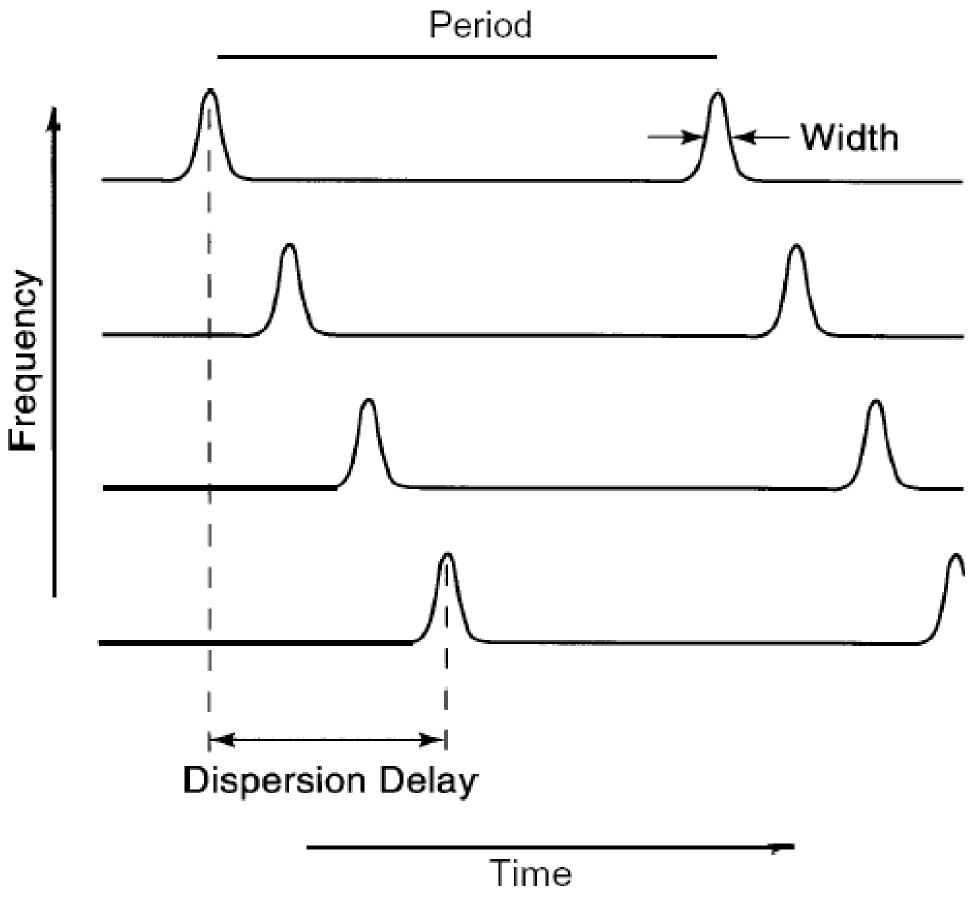
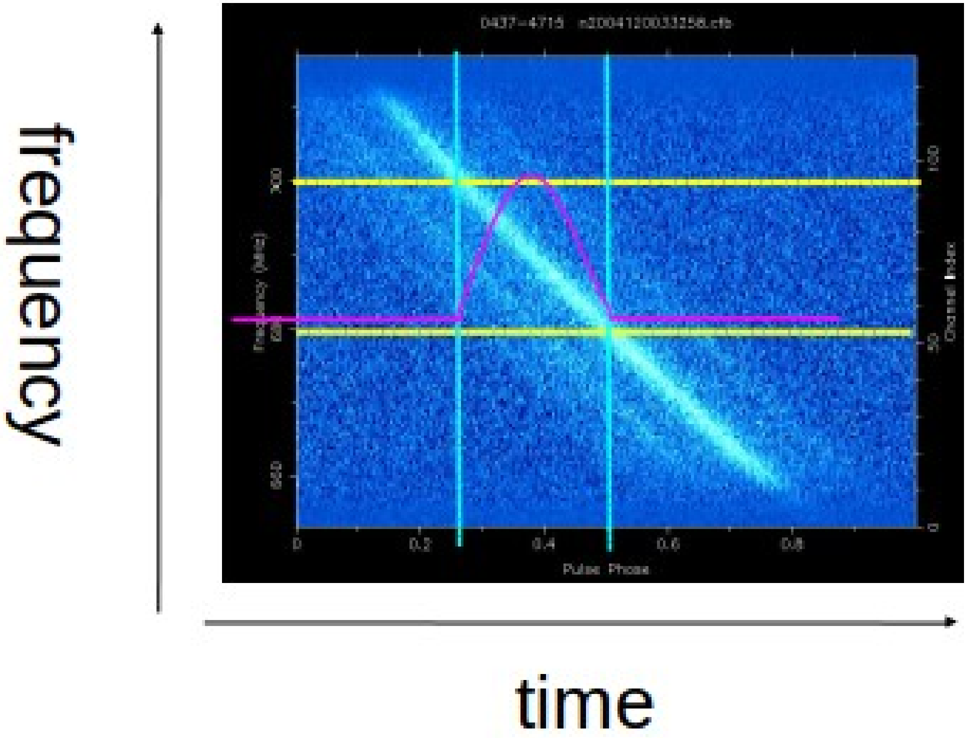


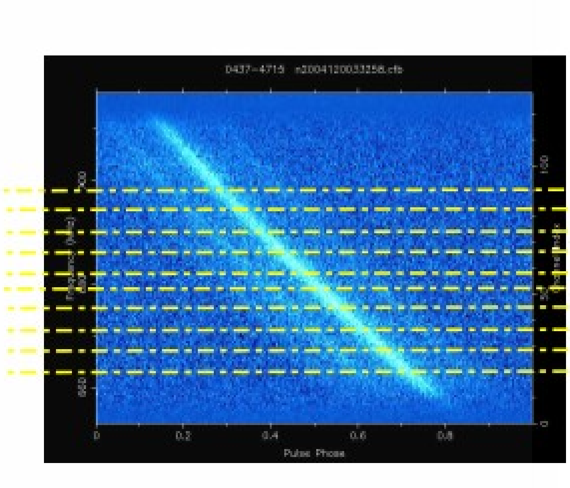
*Fig. 3:* A depiction of a received pulsar signal as a function of frequency and time, showing the three parameters employed in the pulsar search analysis: dispersion, pulse period, and pulse width.

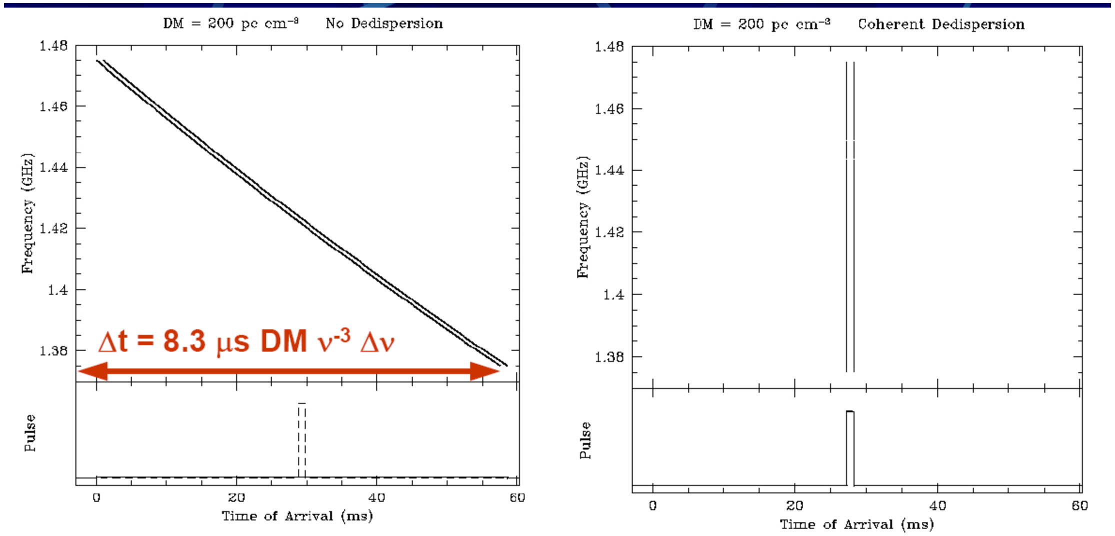
# Dispersion smearing



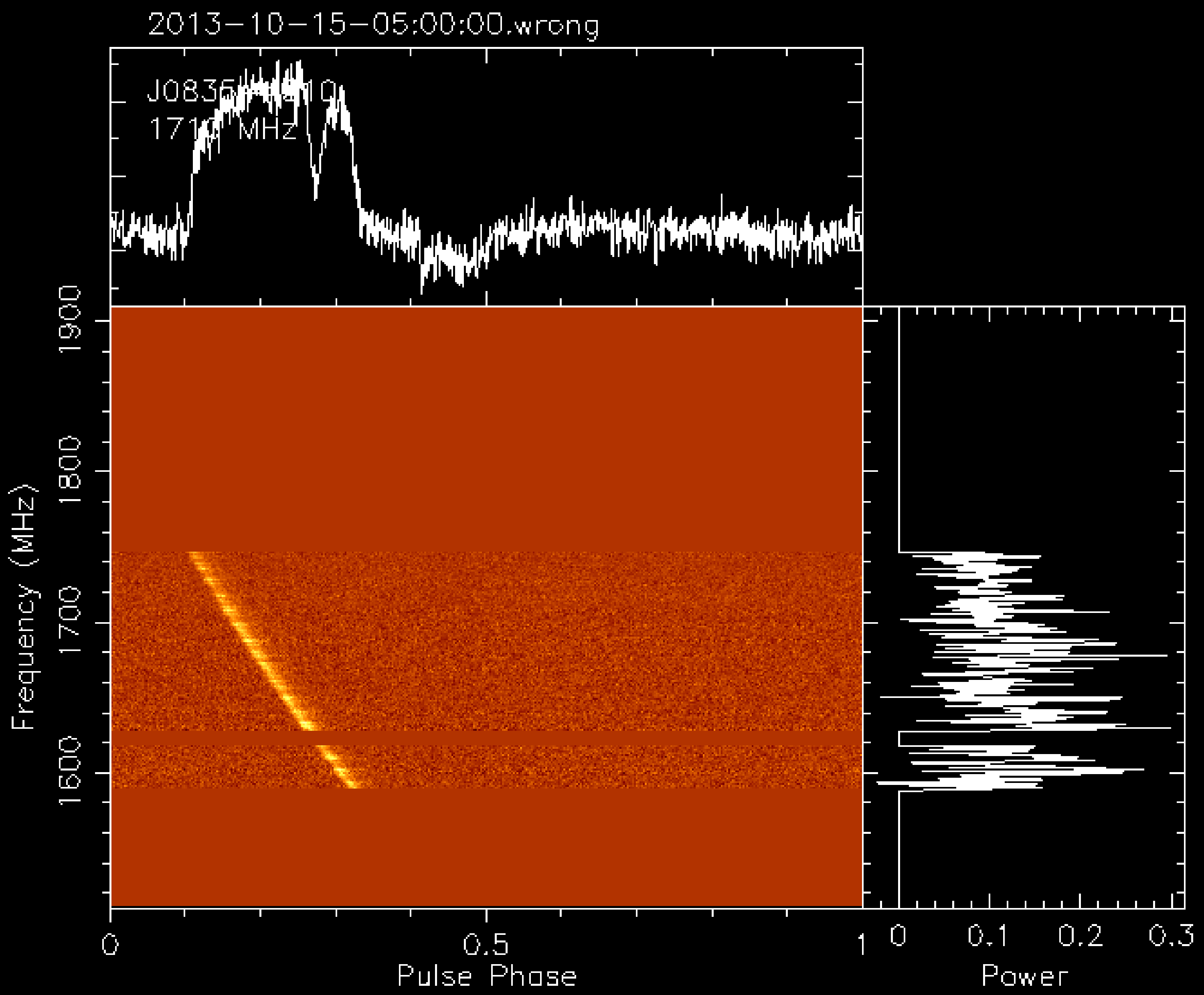
$$Smear = 8.3\mu\text{s}\,\frac{B}{\text{MHz}}\left(\frac{\nu}{\text{GHz}}\right)^{-3} DM$$

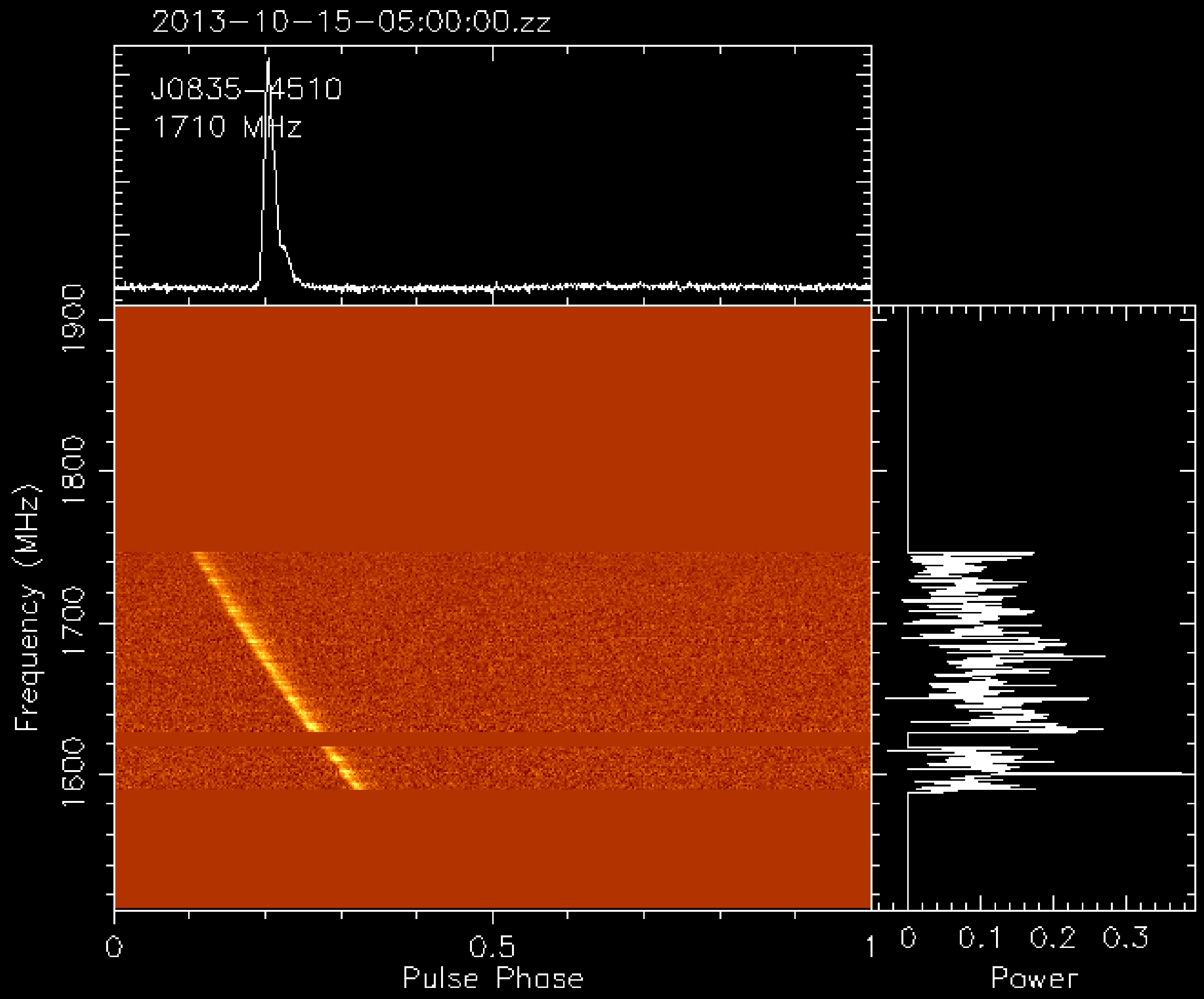
# Incoherent dedispersion



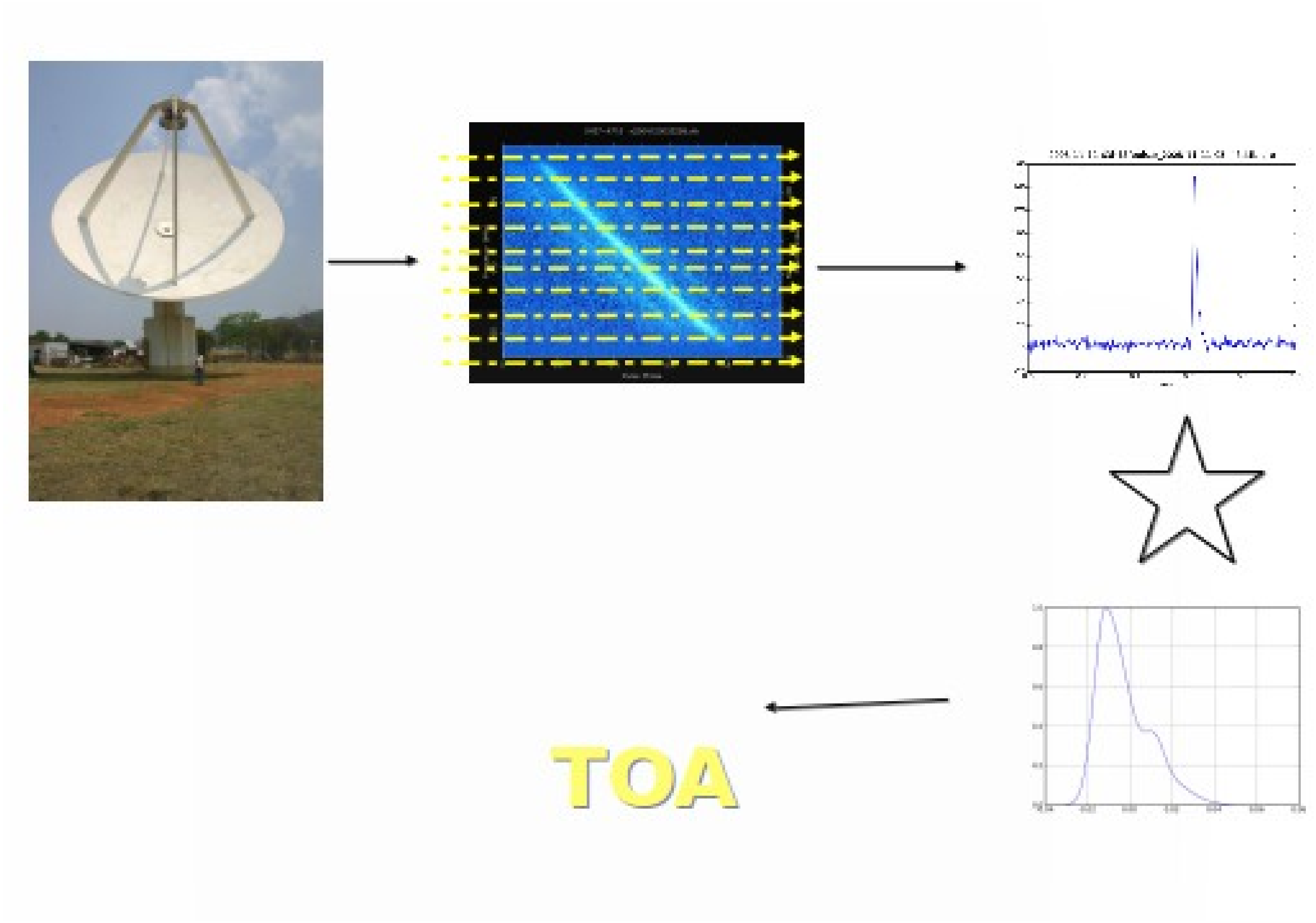


$\Delta t = 8.3\ \mu s\ DM\ \nu^{-3}\ \Delta\nu$

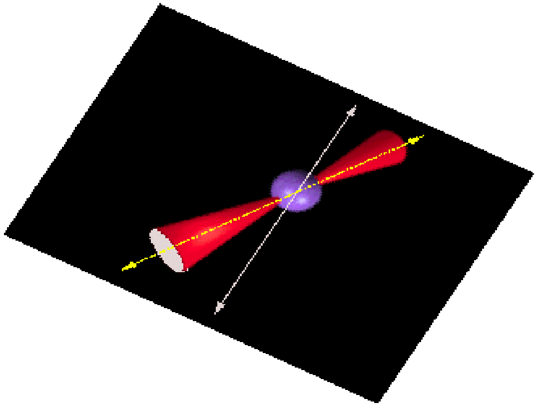

2013-10-15-05:00:00.wrong
J0835-4510
1710 MHz
Frequency (MHz)
1900
1800
1700
1600
0
0.5
1
Pulse Phase
0
0.1
0.2
0.3
Power


2013-10-15-05:00:00.zz
J0835−4510
1710 MHz
Frequency (MHz)
1900
1800
1700
1600
0
0.5
1
Pulse Phase
0
0.1
0.2
0.3
Power

# Observing with XDM



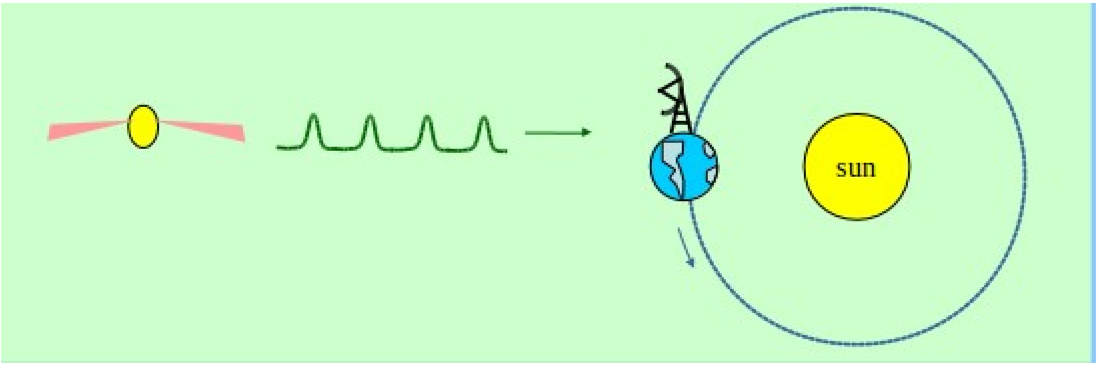
# Pulsar Timing



Record arrival times

53075.8716014048
53076.6068099029
53076.6315093162
53076.6352589534
53076.6390085897
53076.7453055512
53076.7728053205
53076.8144370828
53076.8440091993

# Transform to SSB



Measurement of a pulse time of arrival at the observatory is a relativistic event.
It must be transformed to an inertial frame: that of the solar system barycenter.

Time transfer:

Observatory clock → GPS → UT → TDB

Position transfer:

For Earth and Sun positions, use a solar system ephemeris, e.g., JPL ‘DE405’

For earth orientation (UT1, etc.), use IERS bulletin B

# Timing equation

$$t = t_\mathrm{t} - t_0 + \Delta_\mathrm{clock} - \Delta_\mathrm{DM} + \Delta_{\mathrm{R}\odot} + \Delta_{\mathrm{E}\odot} + \Delta_{\mathrm{S}\odot} + \Delta_\mathrm{R} + \Delta_\mathrm{E} + \Delta_\mathrm{S}.$$

As before, $t_0$ is a reference epoch, $\Delta_\mathrm{clock}$ represents a clock correction that accounts for differences between the observatory clocks and terrestrial time standards, and $\Delta_\mathrm{DM}$ is the frequency-dependent dispersion delay caused by the ISM. The other $\Delta$ terms are delays from within the Solar System and, if the pulsar is in a binary, from within its orbit. The **Roemer delay** $\Delta_{\mathrm{R}\odot}$ is the classical light travel time across the Earth's orbit. Its magnitude is $\sim 500 \cos\beta$ s, where $\beta$ is the **ecliptic latitude** of the pulsar (the angle between the pulsar and the **ecliptic plane** containing the Earth's orbit around the Sun), and $\Delta_\mathrm{R}$ is the corresponding delay across the orbit of a pulsar in a binary or multiple system. The **Einstein delay** $\Delta_\mathrm{E}$ accounts for the time dilation from the moving pulsar (and observatory) and the gravitational redshift caused by the Sun and planets or the pulsar and any companion stars. The **Shapiro delay** $\Delta_\mathrm{S}$ is the extra time required by the pulses to travel through the curved space–time containing the Sun, planets, and pulsar companions. Errors in any of these parameters, as well as other parameters such as $f$, $\dot{f}$, and proper motion, give very specific systematic signatures in plots of **timing residuals** (see Figure 6.7), which are simply the differences between the observed TOAs and the predicted TOAs based on the current timing model parameters.

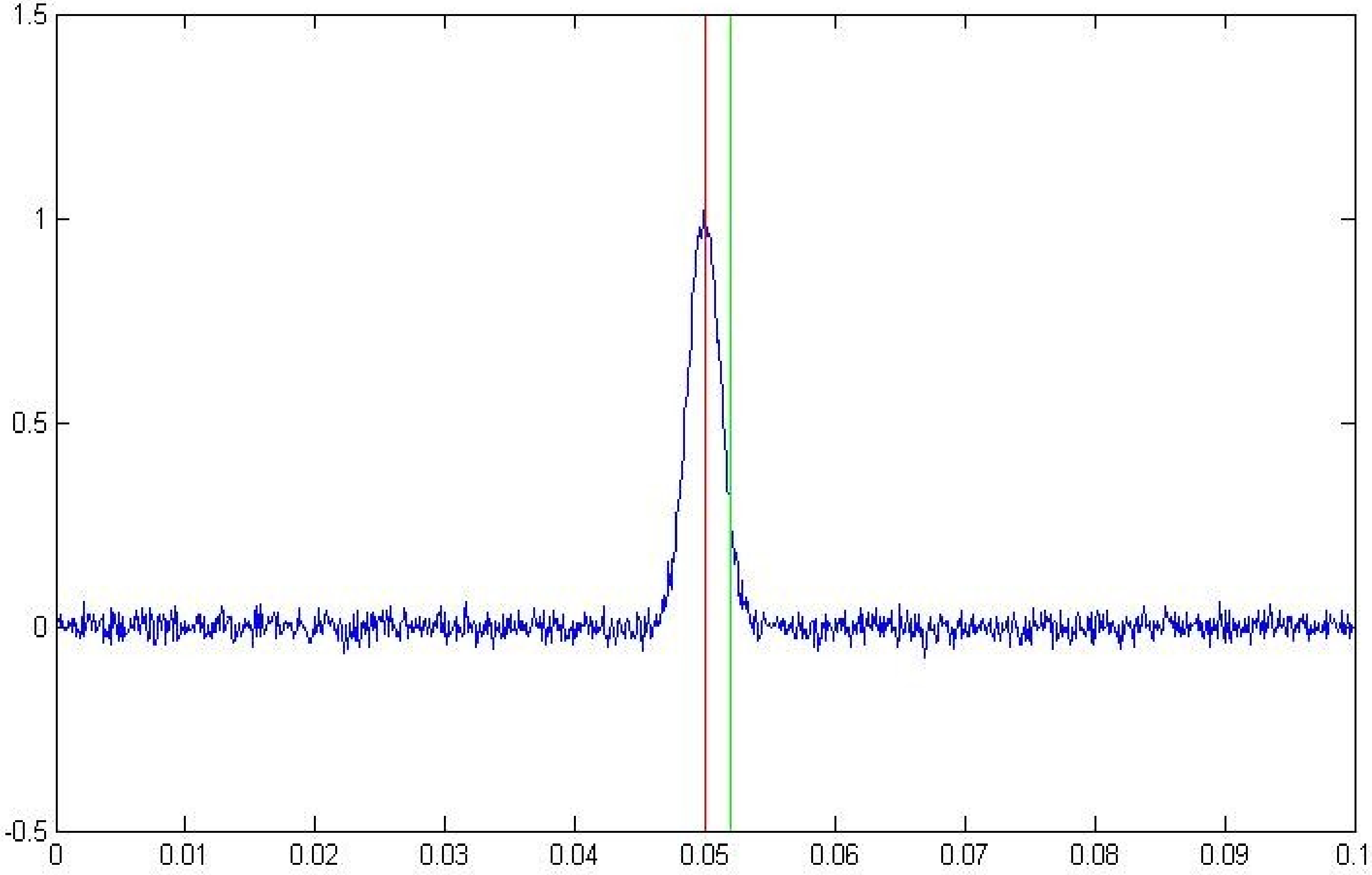
# Model arrival times

- Pulsars gradually lose energy – spin slower

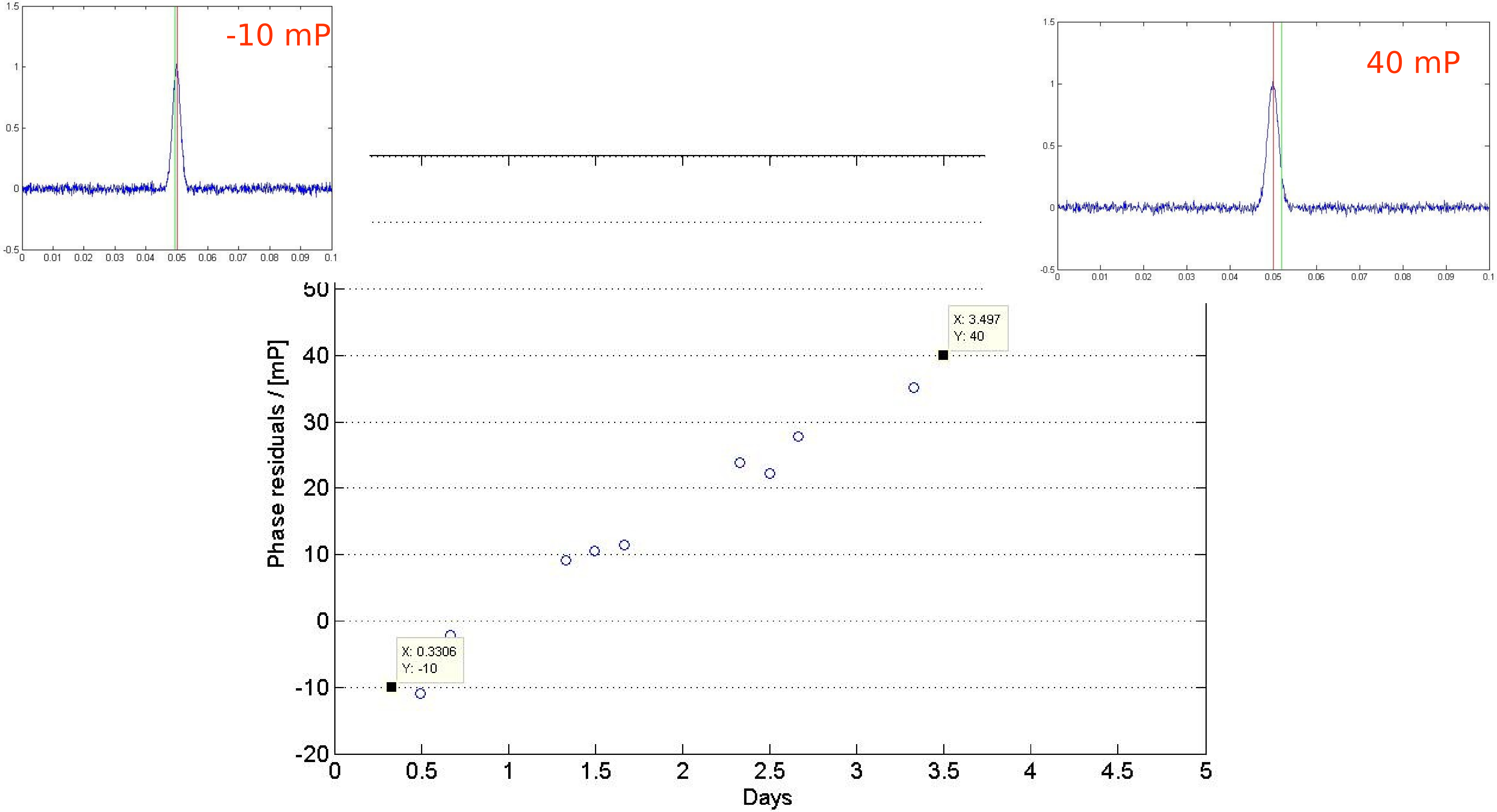
- Model the spin-down as

$$\phi_S(t-t_0)=\phi_0+\nu_0(t-t_0)+\frac{1}{2}\dot{\nu}_0(t-t_0)^2+\frac{1}{6}\ddot{\nu}_0(t-t_0)^3$$

# Phase Residuals

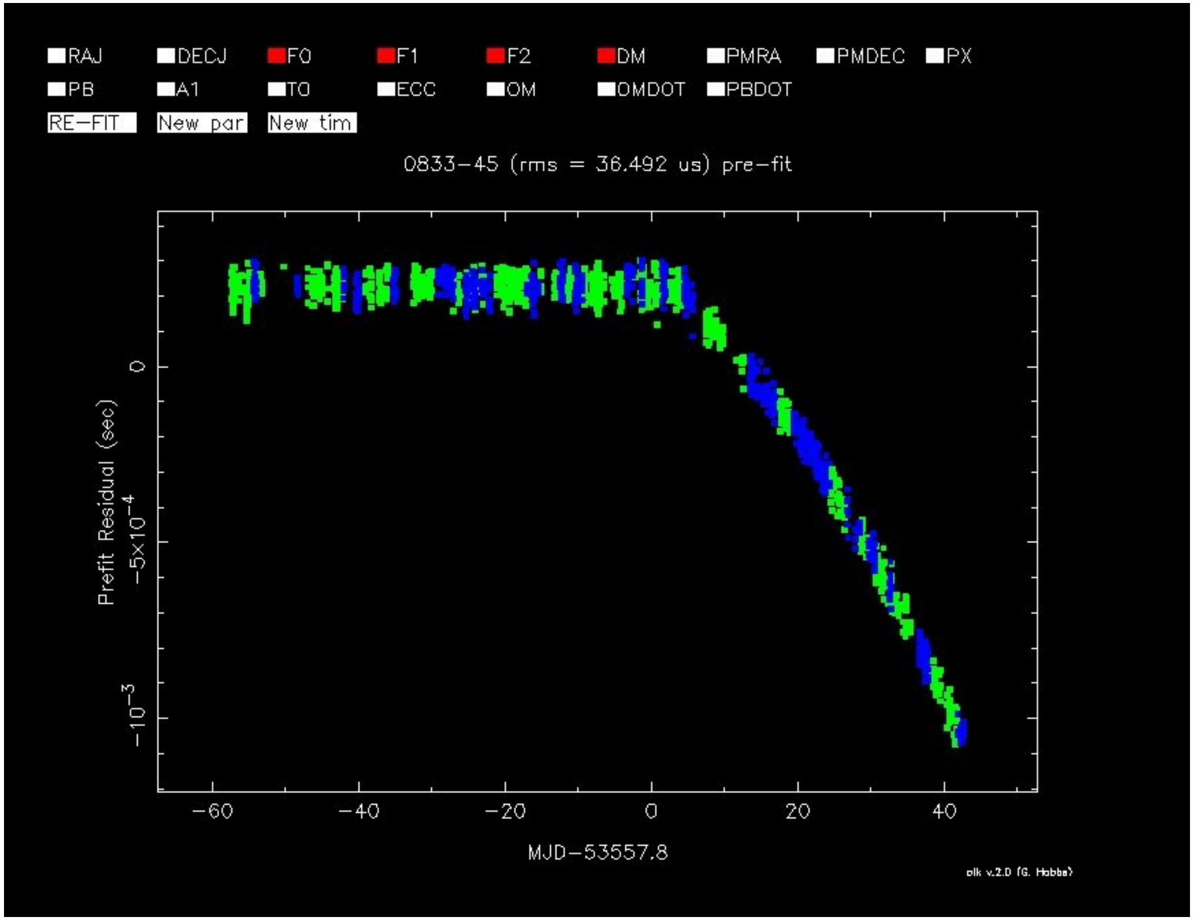


# Phase residuals



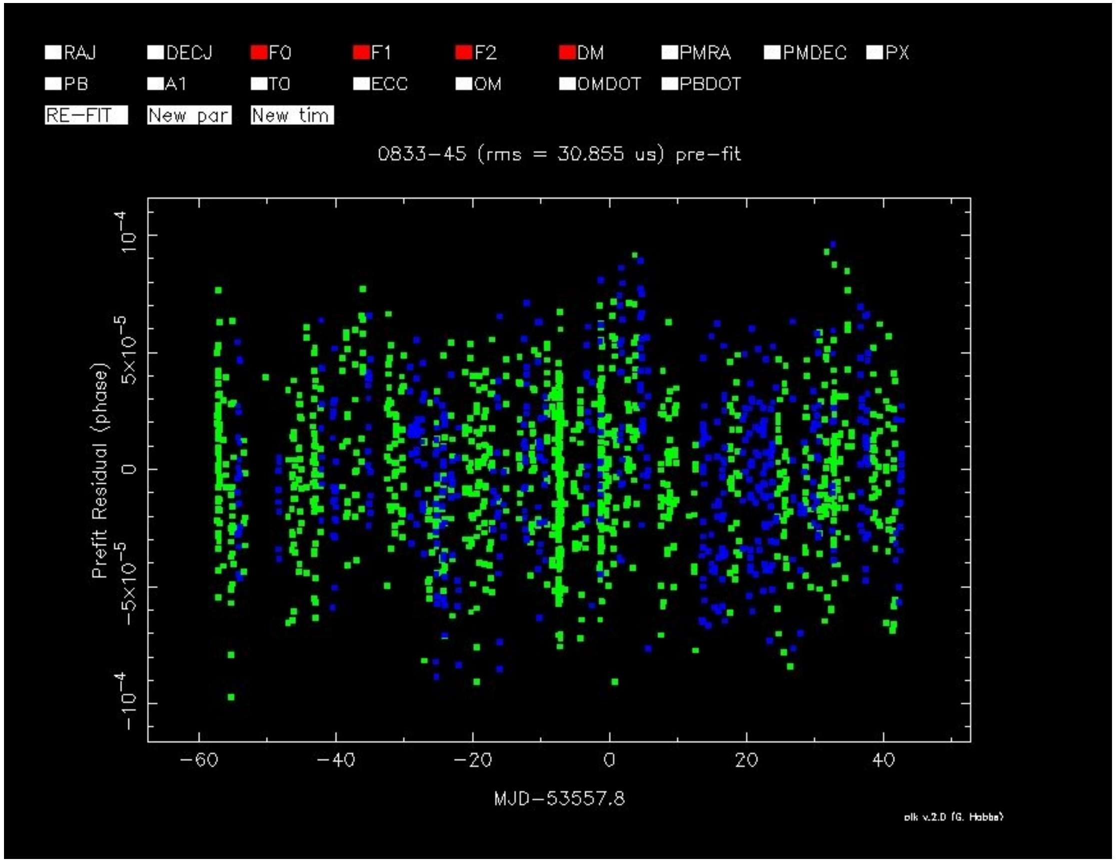
# Fit a model

$$\phi_S(t-t_0)=\phi_0+\upsilon_0(t-t_0)+\frac{1}{2}\dot{\upsilon}_0(t-t_0)^2+\frac{1}{6}\ddot{\upsilon}_0(t-t_0)^3$$



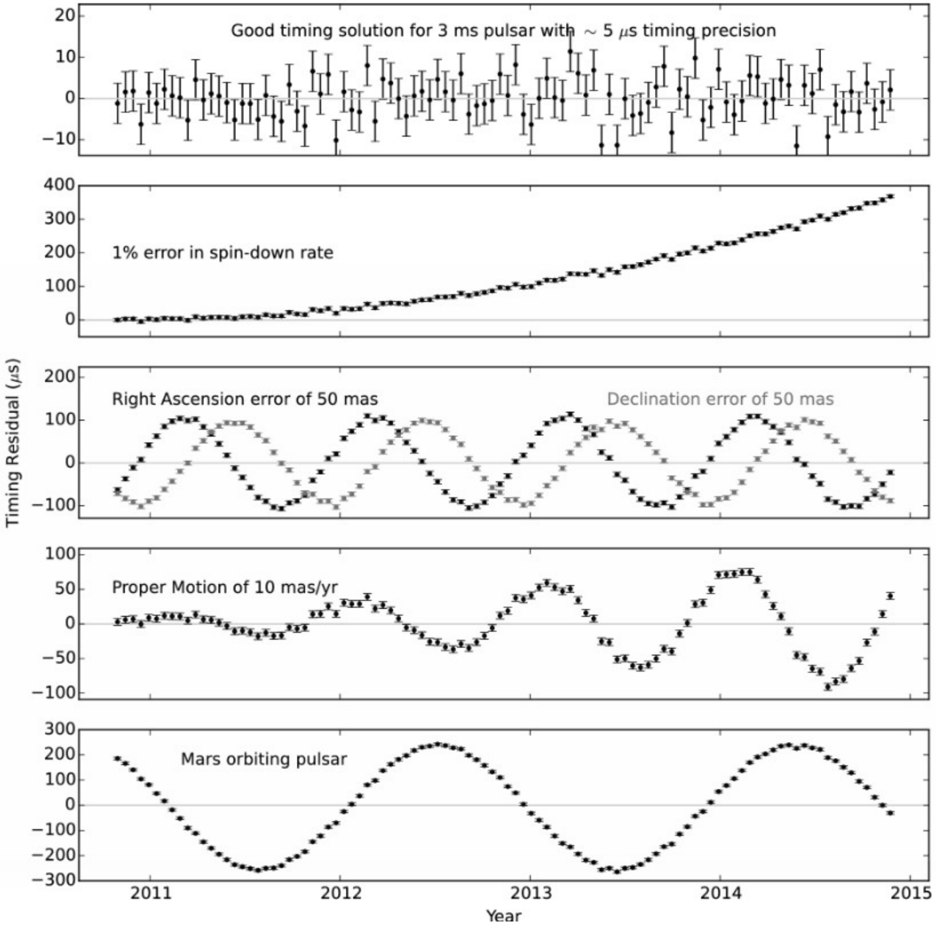
# Fit a model

$$\phi_S(t-t_0)=\phi_0+\upsilon_0(t-t_0)+\frac{1}{2}\dot{\upsilon}_0(t-t_0)^2+\frac{1}{6}\ddot{\upsilon}_0(t-t_0)^3$$



# Timing residuals

- Figure 6.7: Pulsar timing residuals. The top panel shows a “good” timing solution for a fairly average millisecond pulsar with an rms timing precision of about 5 µµs over 4 years. The four remaining panels show how the timing residuals are affected by various timing parameter errors. From top to bottom, an error of 1% in the spin-down rate of the pulsar (causing a quadratic drift in pulsar phase), a position error in either right ascension or declination of only 50 mas (an annual sinusoid reflecting the Earth’s motion), a pulsar proper motion of 10 mas/yr (an annual sinusoid growing linearly with time), or the presence of a planet with the mass and orbital period of Mars around the pulsar.



# TOA uncertainty

$$\Delta\mathrm{TOA} \propto \frac{\mathrm{W}}{\mathrm{S/N}}$$

The arrival time can be measured to ΔTOA given above – where W is the pulse width (typically a few hundred micorseconds and S/N is the signal to noise For the best timing pulsars TOA can be measured to a few microseconds.

The residuals can have an RMS of 100 nanoseconds

# Science Questions

- Testing GR in strong fields
- Detecting gravitational waves using pulsar timing arrays
- Pulsar interiors
  - Glitches

# Testing Einstein

- Experiments in the solar system test GR but in weak gravitational fields
- Does GR apply in strong gravitational fields
- Energy in gravitational field

$$\varepsilon = \frac{E_{gravity}}{mc^2}$$

**Neutron stars & Black Holes:**

$$\varepsilon_{NS} \approx 0.15$$

$$\varepsilon_{BH} \approx 0.5$$

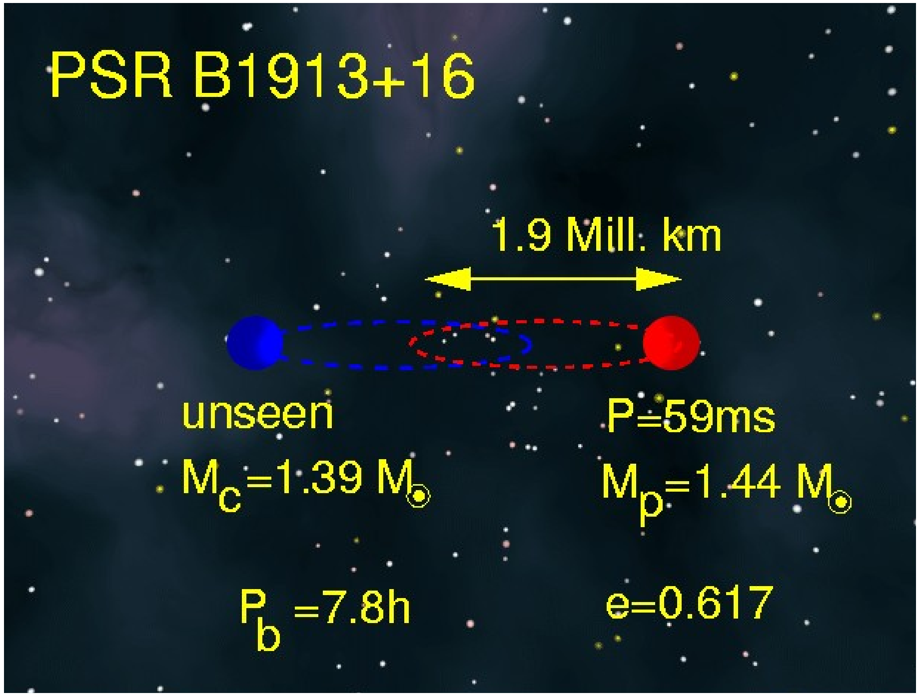
**Solar system:**

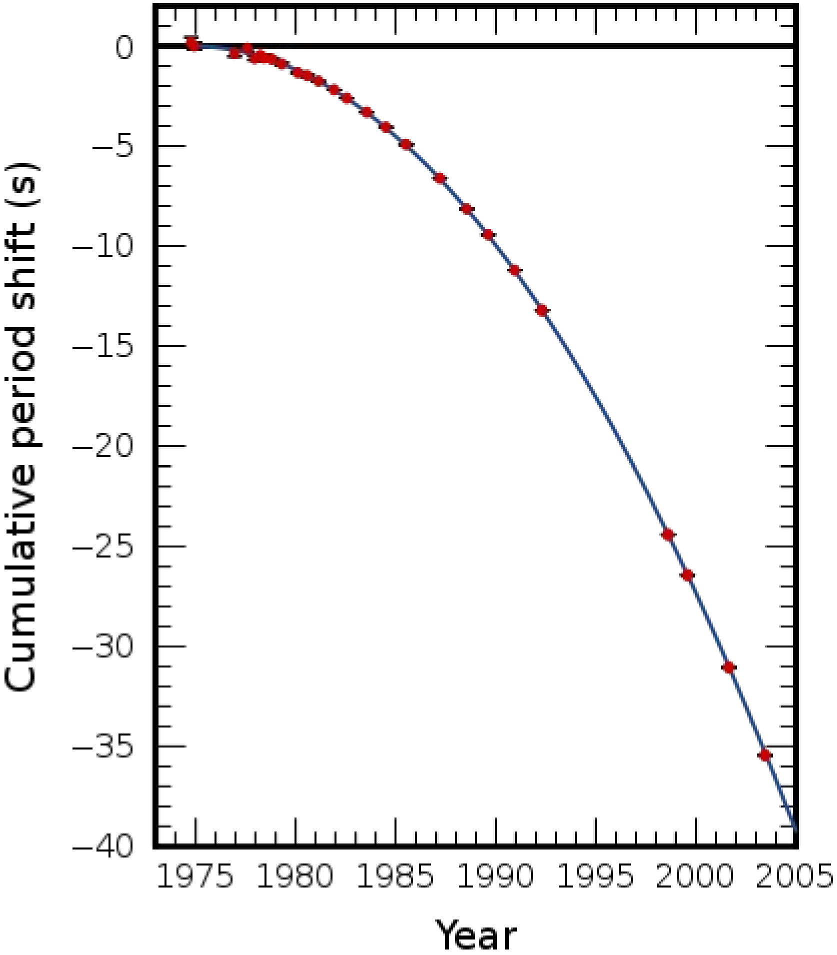
$$\varepsilon_{Sun} \approx 0.000001$$

$$\varepsilon_{Earth} \approx 0.0000000001$$

$$\varepsilon_{Moon} \approx 0.00000000001$$

# First binary pulsar





Orbital decay of PSR B1913+16.[7] The data points indicate the observed change in the epoch of periastron with date while the parabola illustrates the theoretically expected change in epoch according to general relativity.

# Pulsar Timing Arrays

- For reference
- Nanograv website
  - http://nanograv.org/
  -

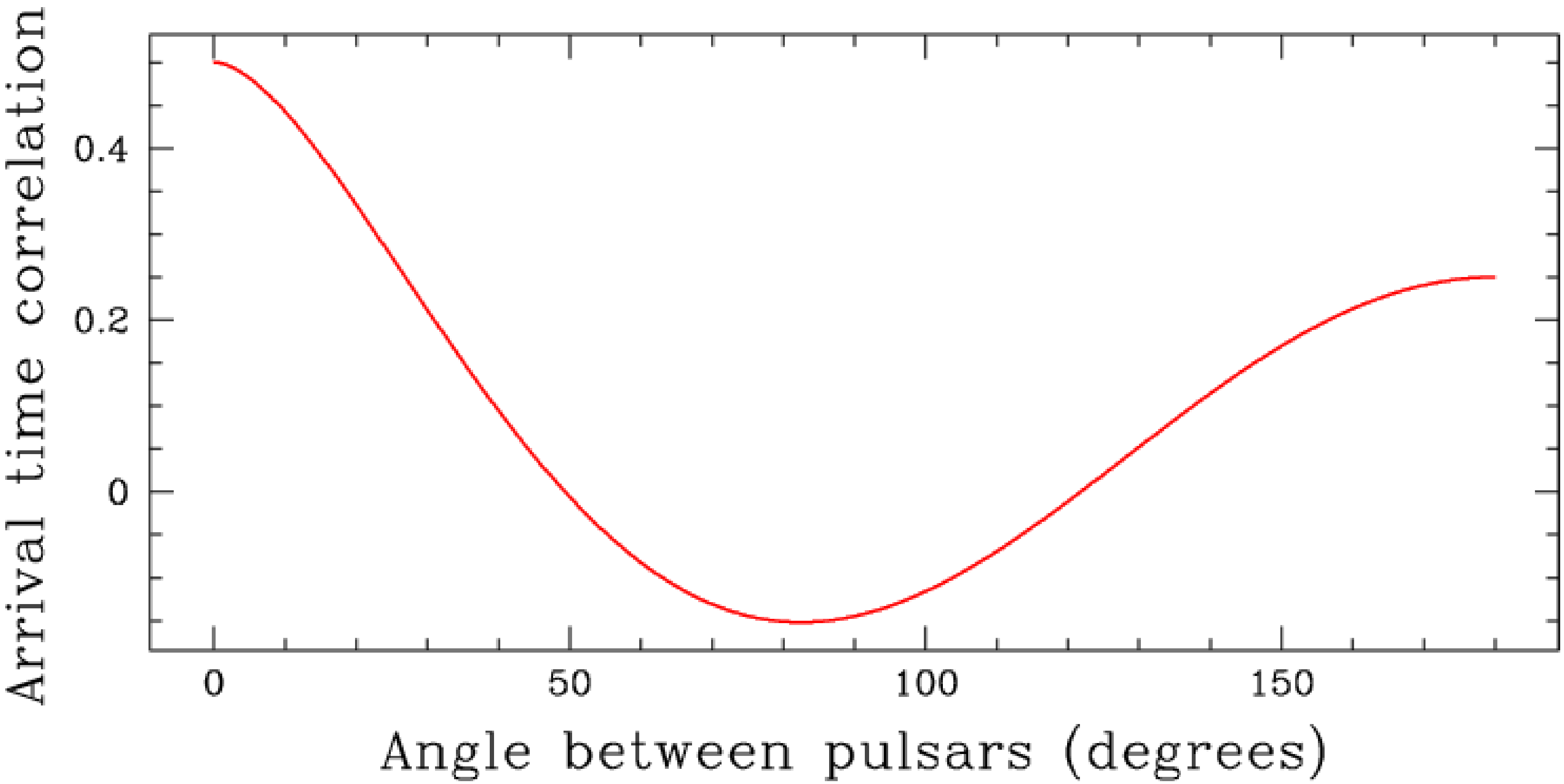
# Binary systems

- The double neutron-star systems have indirectly confirmed the existence of gravitational waves by matching the predicted orbital decays as orbital energy is carried away by gravitational radiation. But over the last decade, one of the driving efforts in pulsar astronomy has become the direct detection of GWs using pulsar timing arrays (PTAs). A PTA is an array of MSPs spread over the sky rather than an array of telescopes, and the goal is to use that pulsar array to detect correlated signals in the timing residuals of dozens of MSPs caused by the distortions of interstellar space from nanohertz (i.e., periods of years) GWs passing through our Galaxy

# Hellings and Downs curve

- Because GW emission and propagation is a quadrupolar process in general relativity, in contrast to the dipolar emission of electromagnetic waves from an accelerating electron, GWs cause specific angular correlations in the timing residuals between pairs of pulsars on the sky. Pulsars close together on the sky will be similarly affected by a passing GW, whereas those much farther apart on the sky will be uncorrelated or even negatively correlated by the same GW. That angular pattern is known as the Hellings and Downs curve [49], and detecting it would be the key to confirming that correlated signals in timing residuals are caused by GWs and not by other effects such as clock or planetary ephemeris errors.

# Hellings-Downs curve



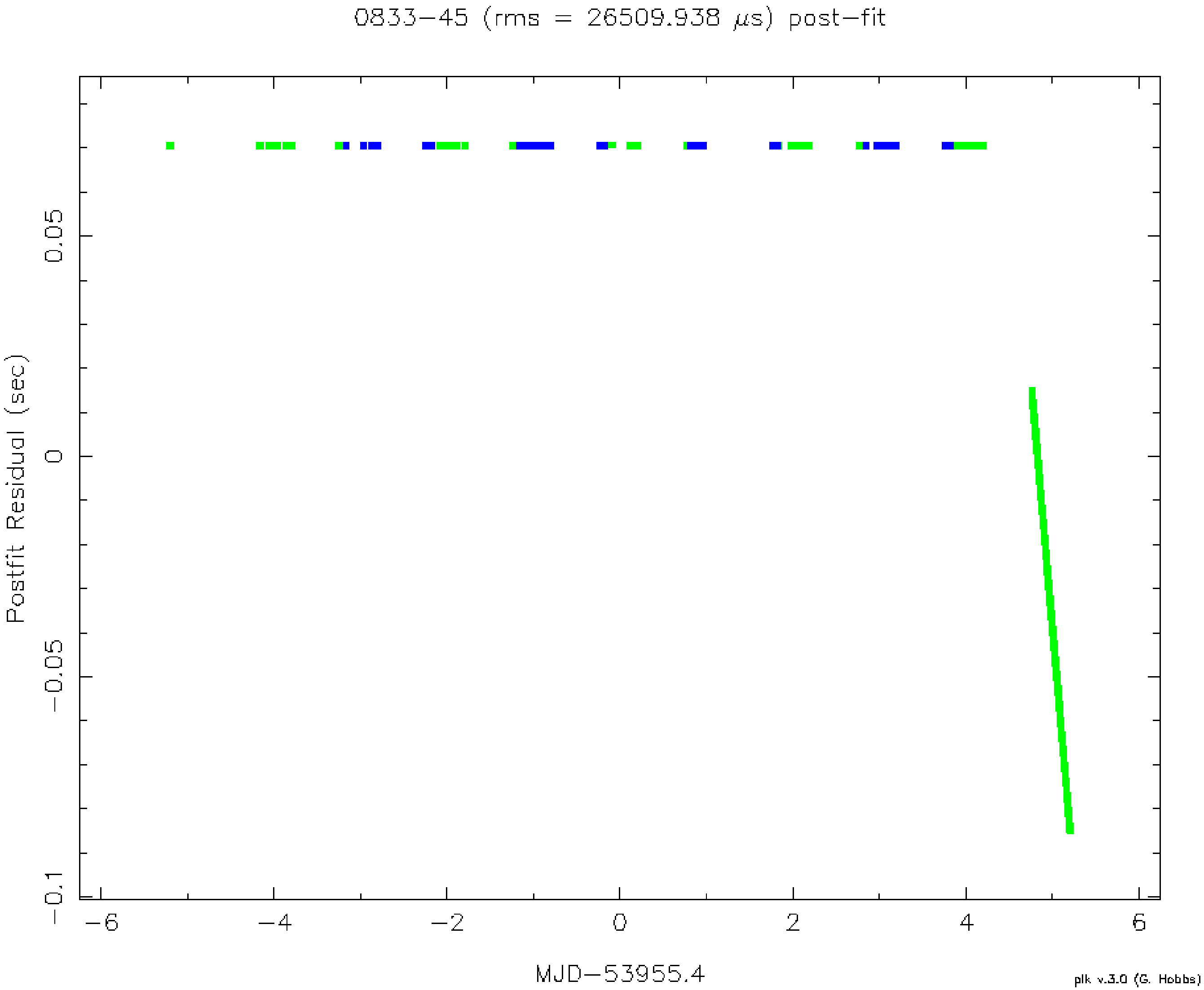
# SMBH

- The most likely sources of detectable nanohertz GWs are supermassive black hole binaries (with total masses of 108108–10101010 M⊙⊙) and years-long orbital periods after their parent galaxies have merged. A single massive nearby system, or an ensemble of more distant, less massive systems (making a “stochastic background” of GWs), will cause tens-of-nanosecond spatially and temporally correlated systematics in PTA timing residuals. This level of long-term timing precision for the best MSPs is now being achieved.

# PTAs

Three PTA experiments have been working on this endeavor: NANOGrav in North America and the Parkes and European PTAs in Australia and Europe, respectively. Together, they are collaborating in the International Pulsar Timing Array (IPTA), and huge progress toward a detection has been made recently. Current PTA limits, based on upper limits for appropriately correlated low-frequency timing residuals, are beginning to constrain models of galaxy mergers throughout the universe. And given continued improvements in pulsar timing capability and many new high-precision MSPs from recent surveys, a direct detection of GWs seems possible or even likely within the next five years.

# Pulsar Glitches



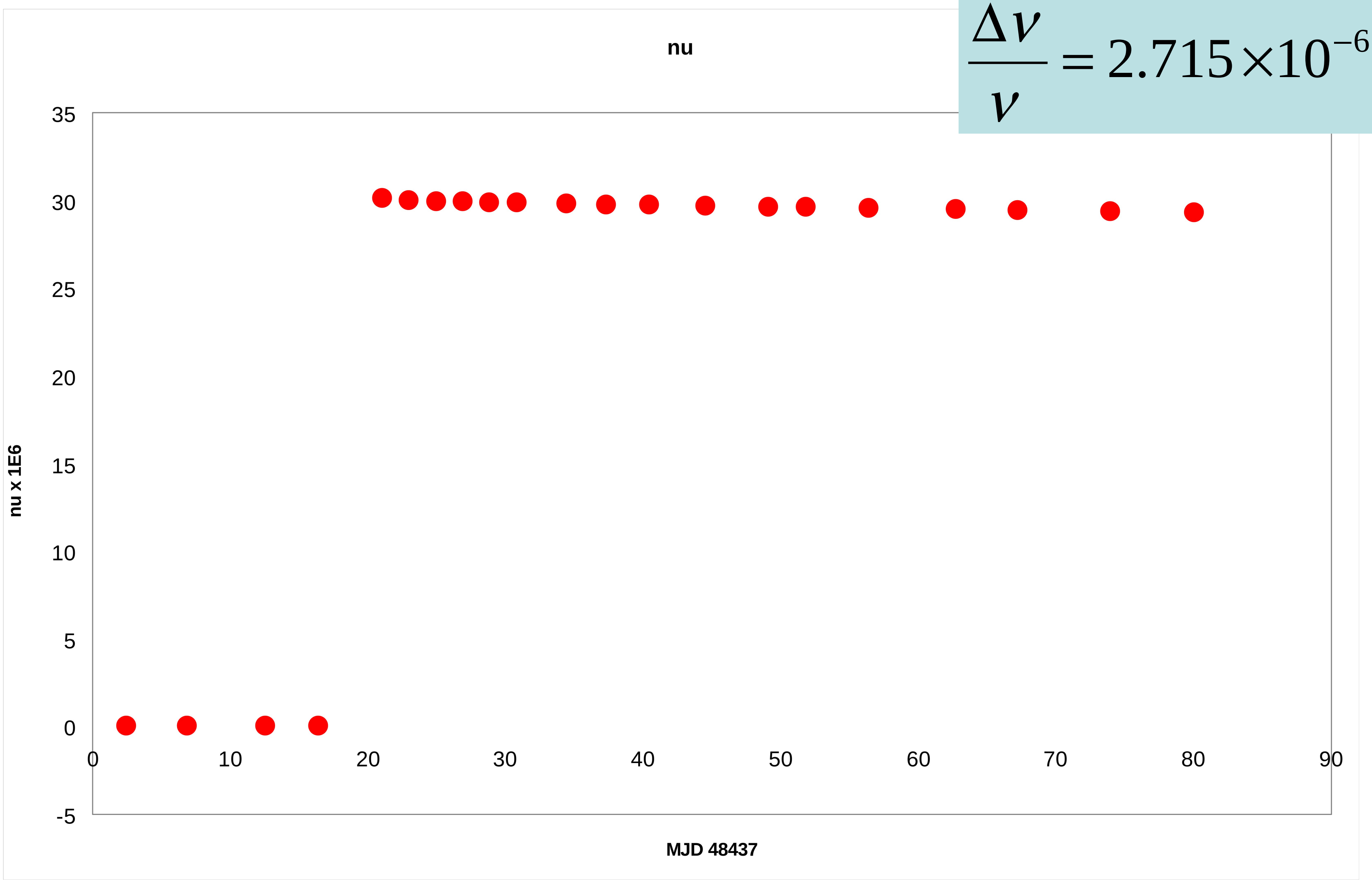
# Gltich

- Sudden increase in frequency or “spin-up”

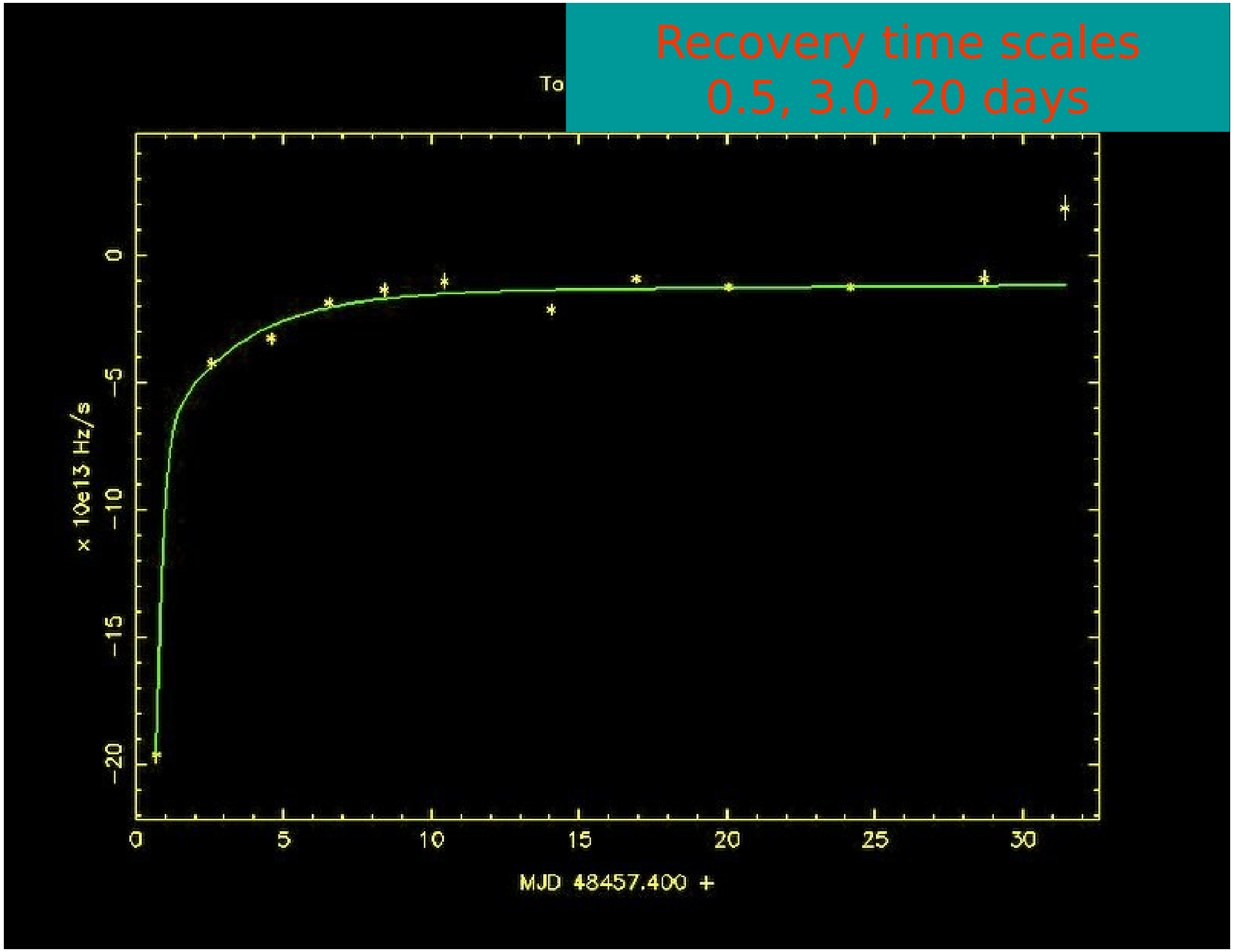
- Frequency increases by few parts per million

# Sudden spin-up

$$\frac{\Delta \nu}{\nu} = 2.715 \times 10^{-6}$$



# Gradual recovery in nudot



Recovery time scales
0.5, 3.0, 20 days

# Vela Pulsar Glitches