Pulsar Timing

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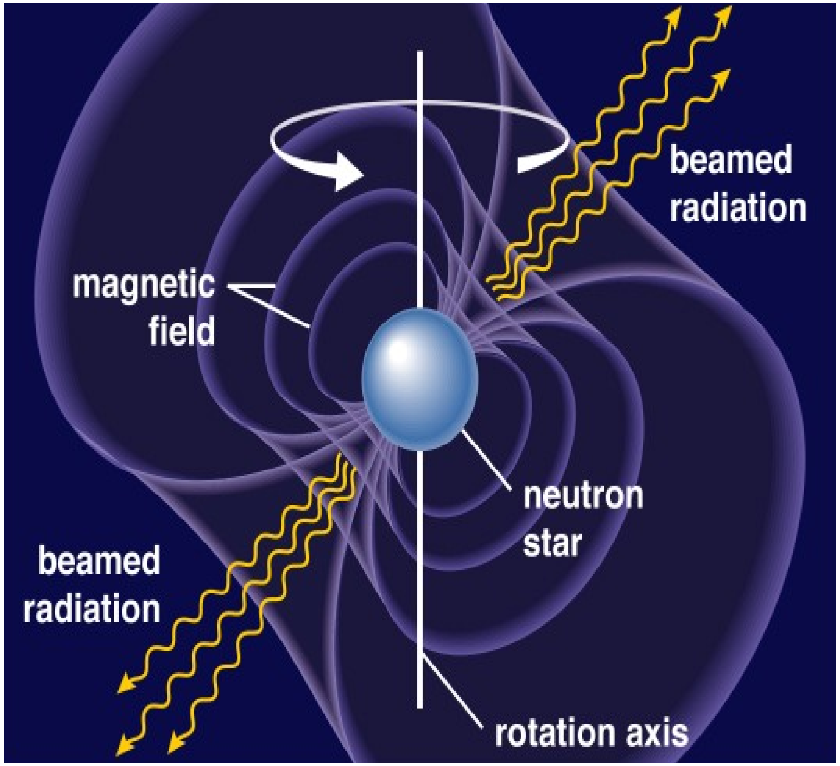
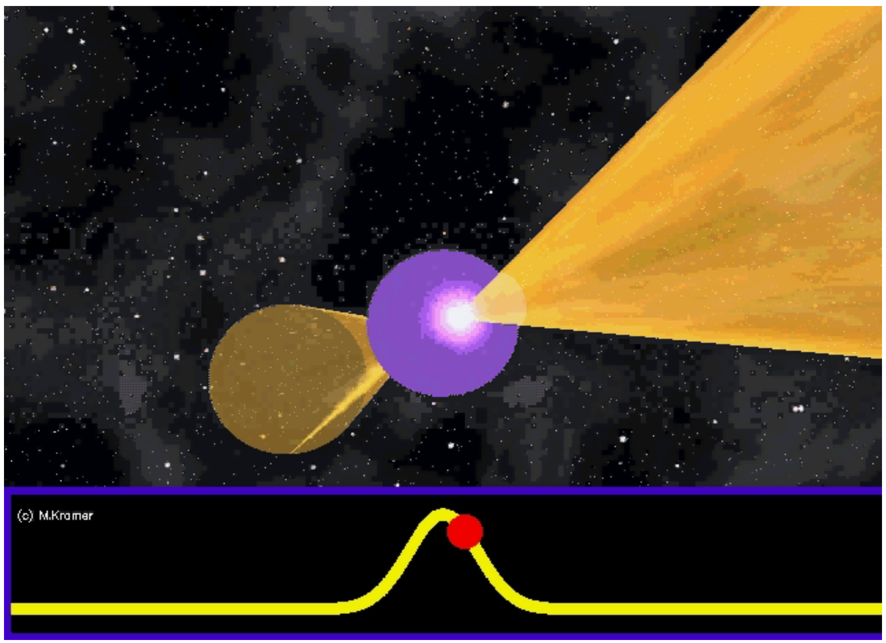
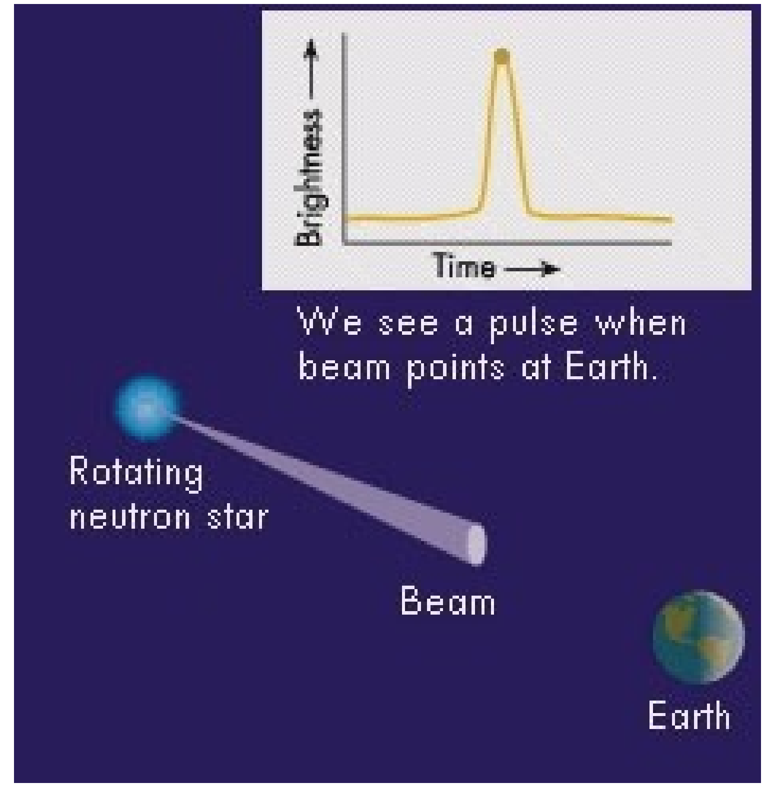
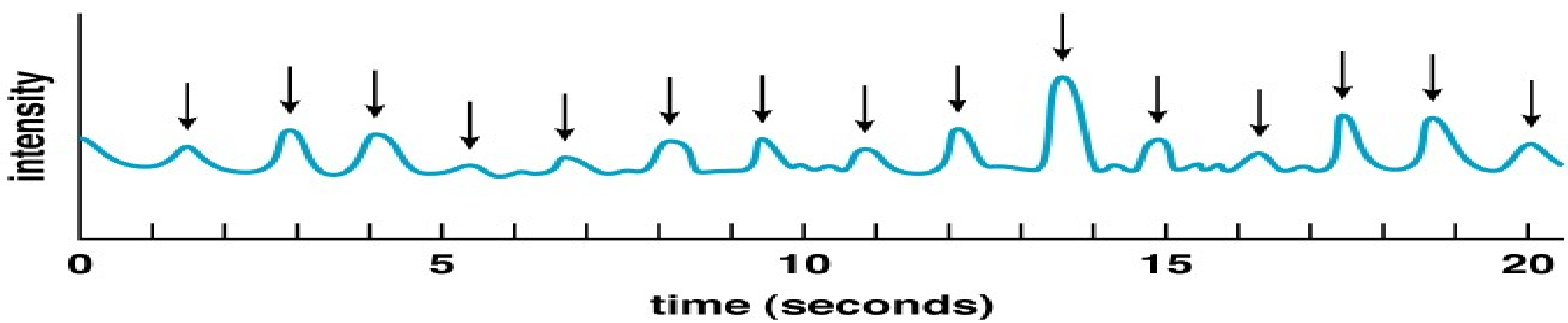
Pulsars


beamed
radiation
magnetic
field
neutron
star
beamed
radiation
rotation axis

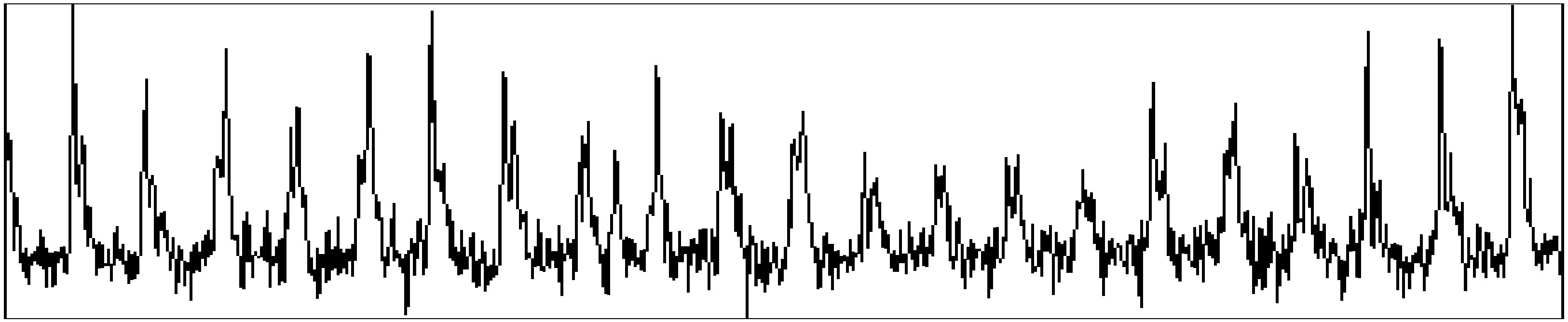
The Pulsar


(c) M.Kramer


Brightness
Time
We see a pulse when beam points at Earth.
Rotating neutron star
Beam
Earth


intensity
0
5
10
15
20
time (seconds)

Pulsars – stable clocks

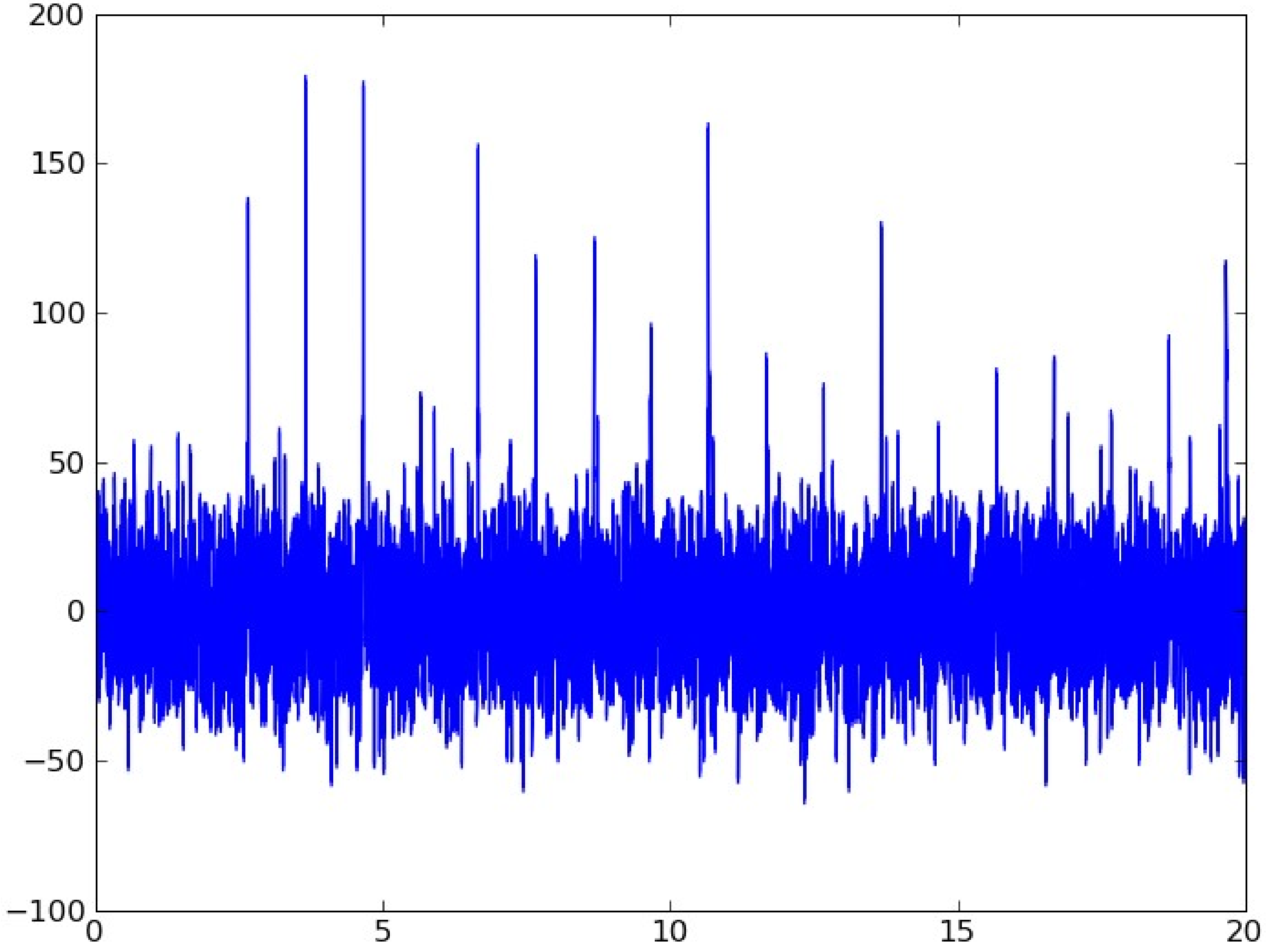


Unambiguously number each pulse

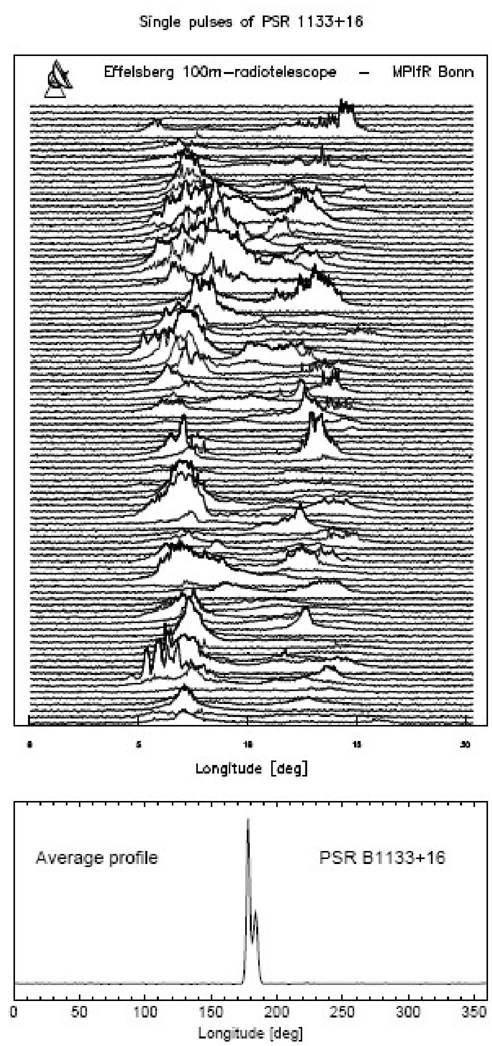
Between
11 Mar 2009 20:55:37
and
29 Apr 2009 21:41:37

There were exactly **47 414 570** pulses

Actual pulse train



Integrate many pulses



Dispersion

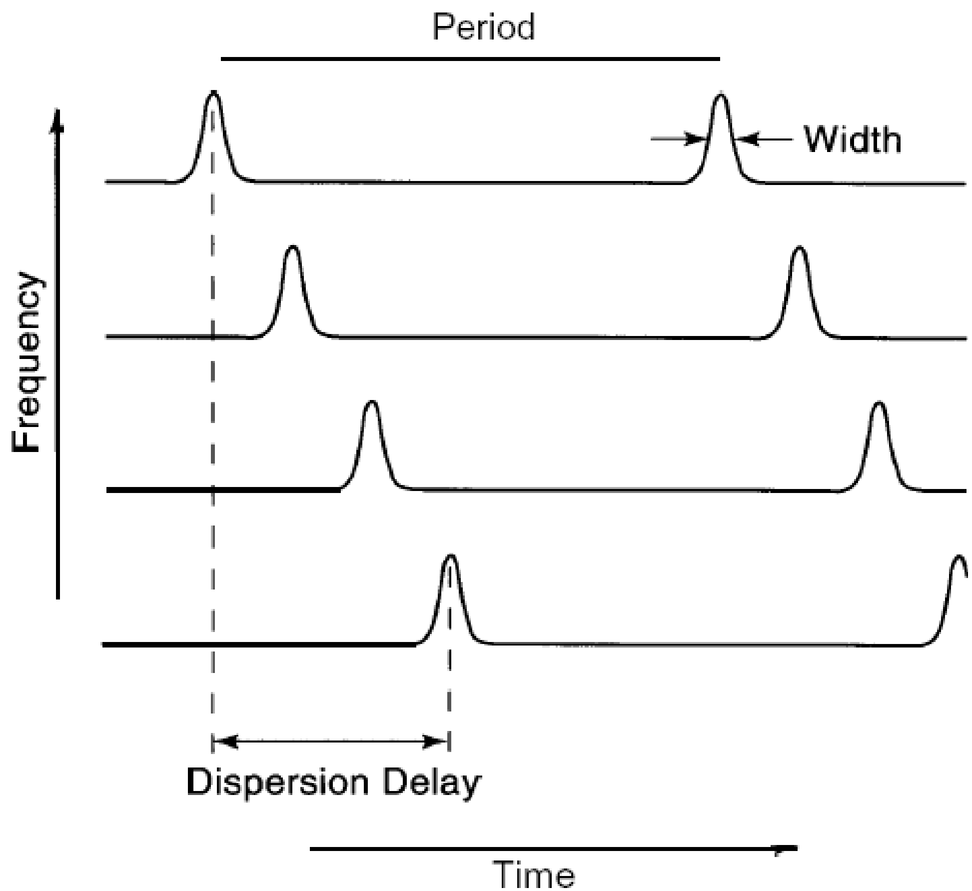
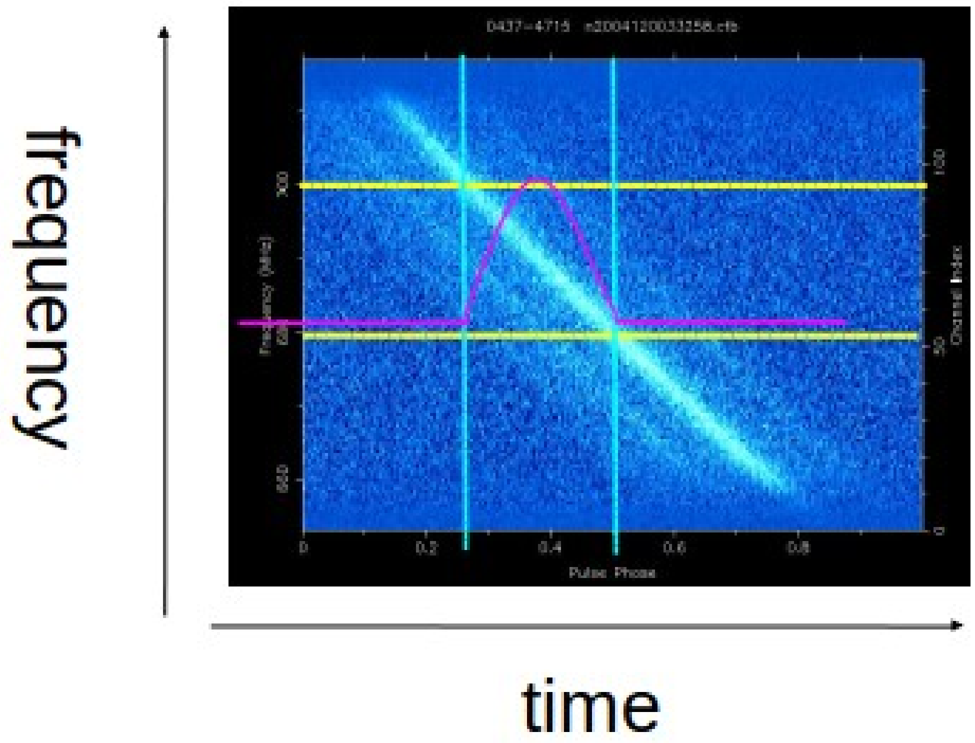


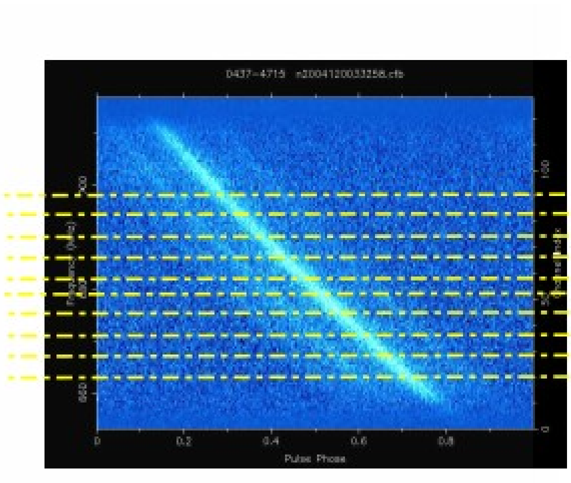
Fig. 3: A depiction of a received pulsar signal as a function of frequency and time, showing the three parameters employed in the pulsar search analysis: dispersion, pulse period, and pulse width.

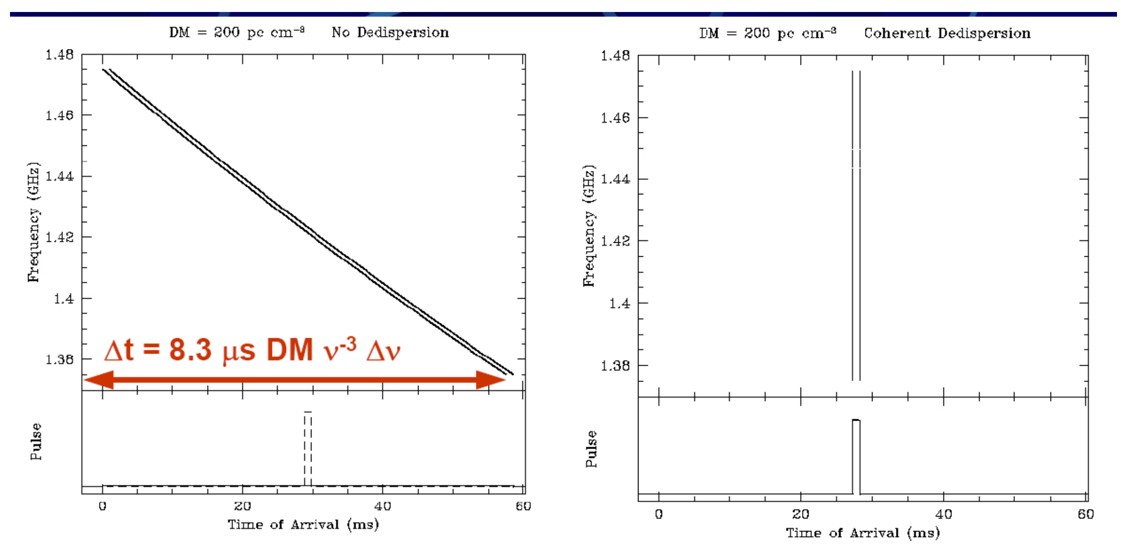
Dispersion smearing

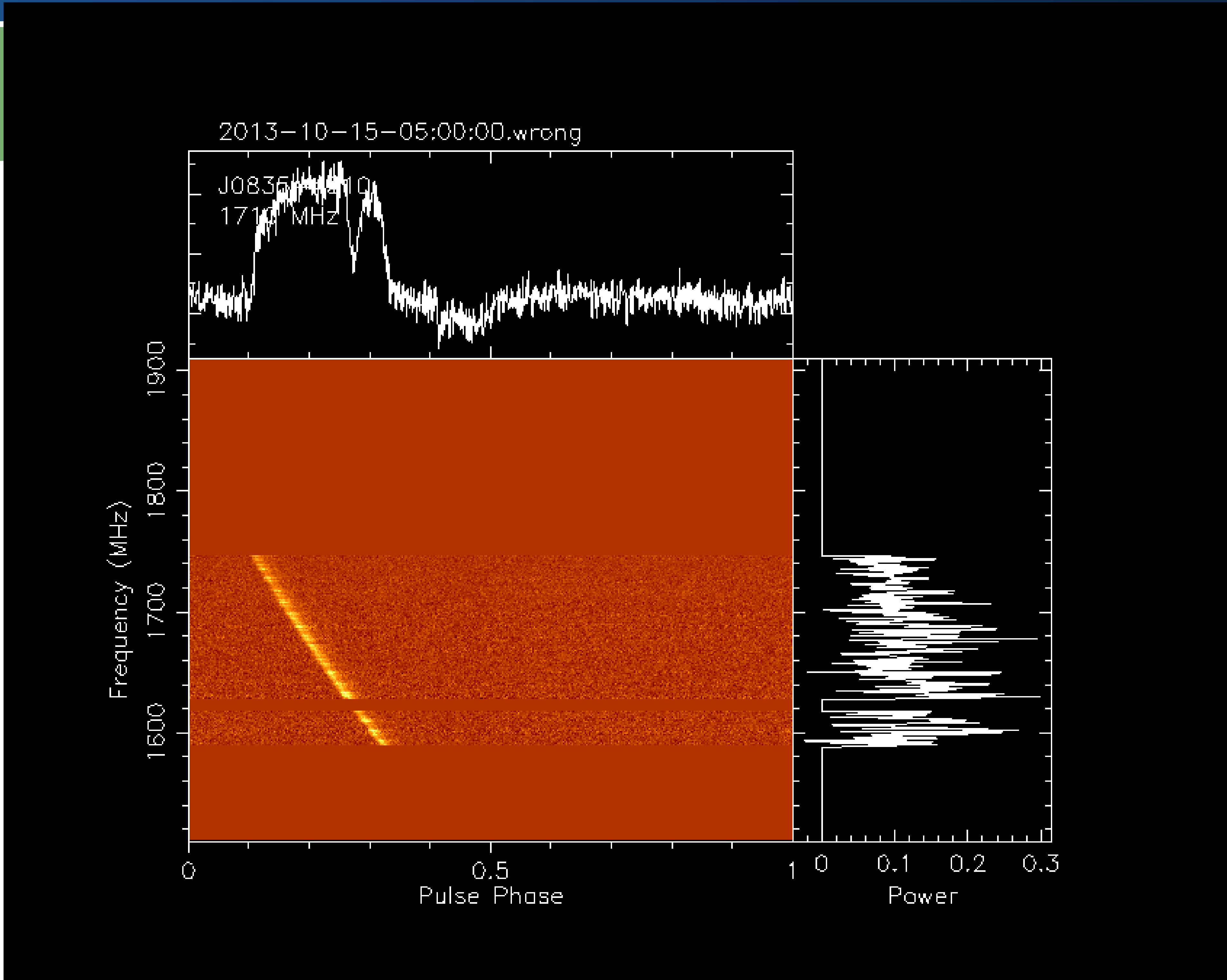


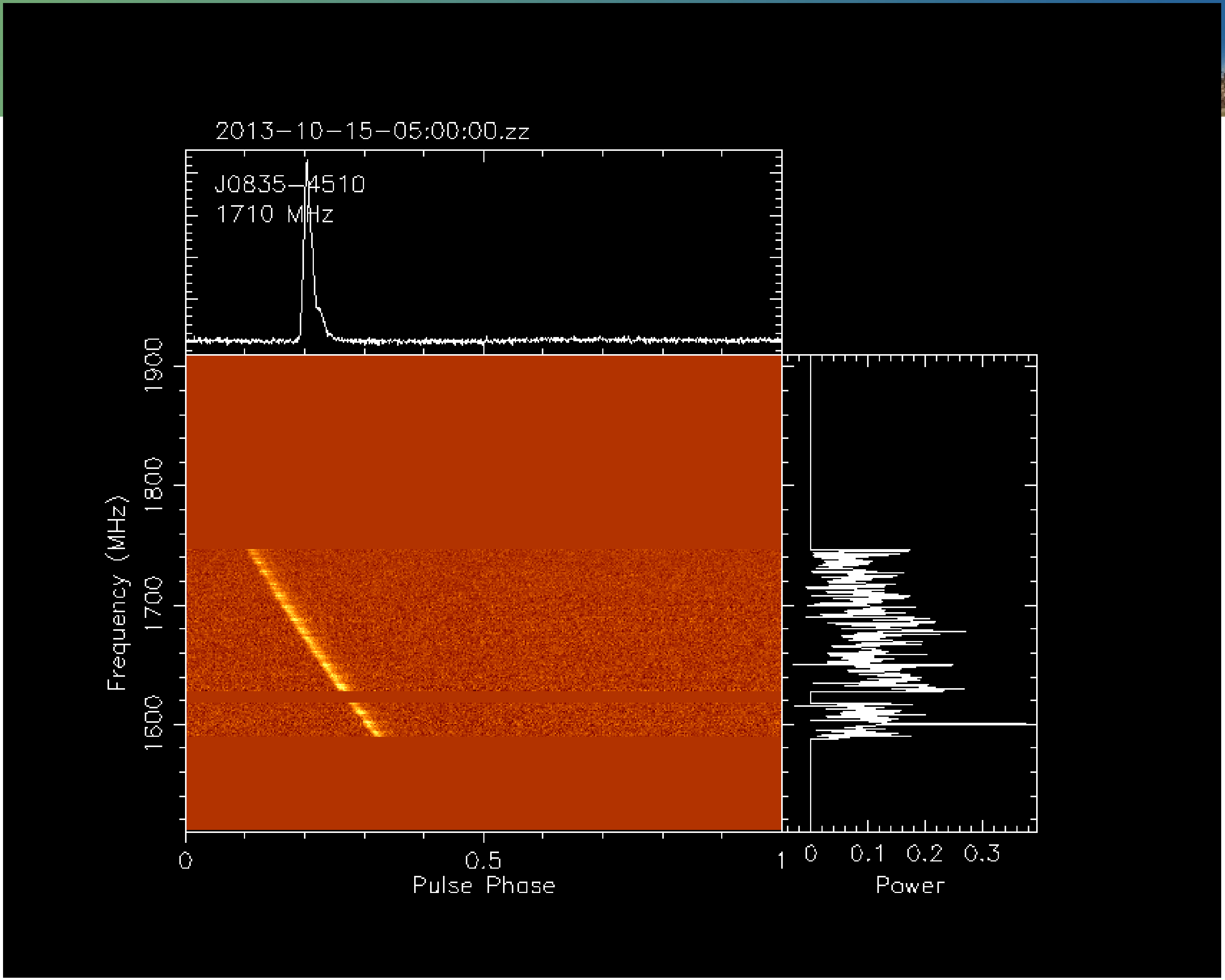
$$Smear = 8.3\mu s \frac{B}{MHz}\left(\frac{\nu}{GHz}\right)^{-3} DM$$

Incoherent dedispersion

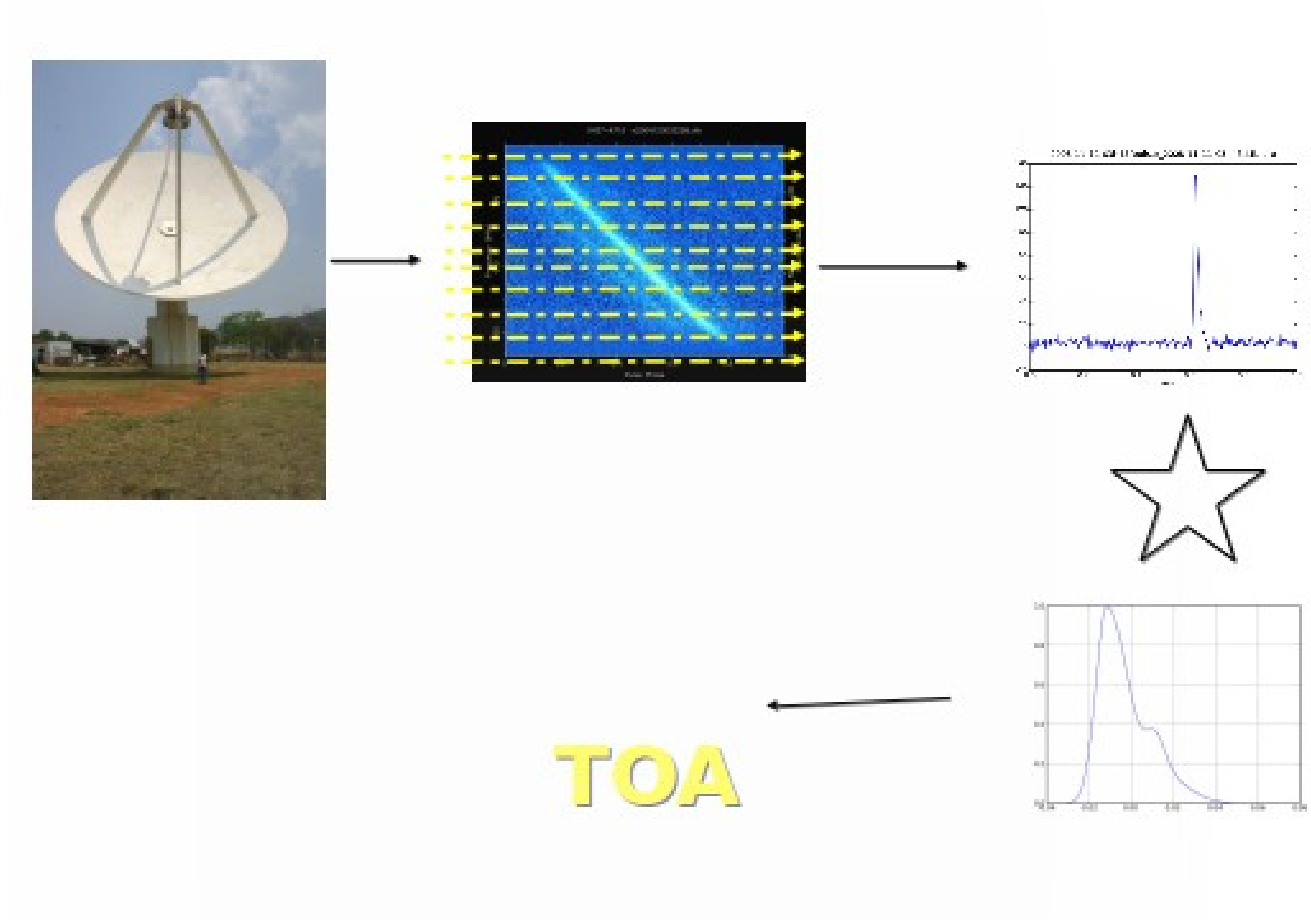




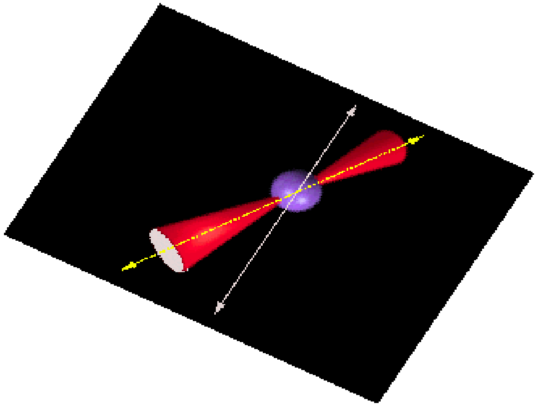

2013-10-15-05:00:00.wrong
Frequency (MHz)
1900
1800
1700
1600
0
0.5
1
Pulse Phase
0
0.1
0.2
0.3
Power


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



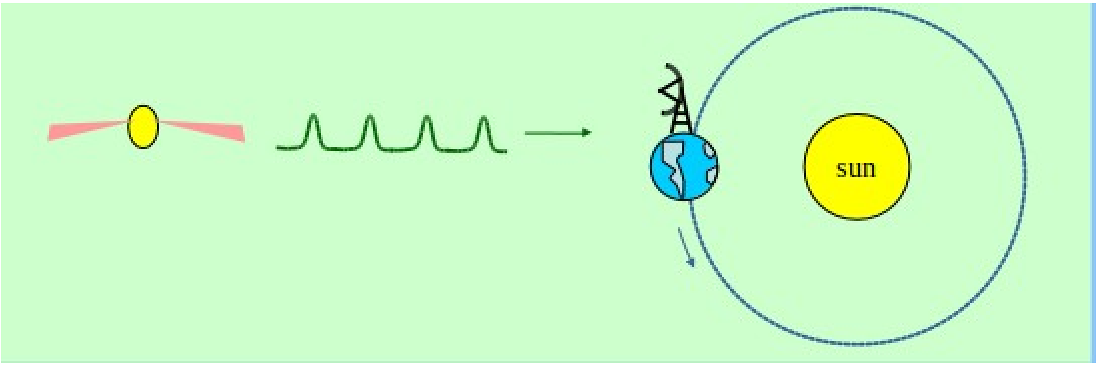
Pulsar Timing



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

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

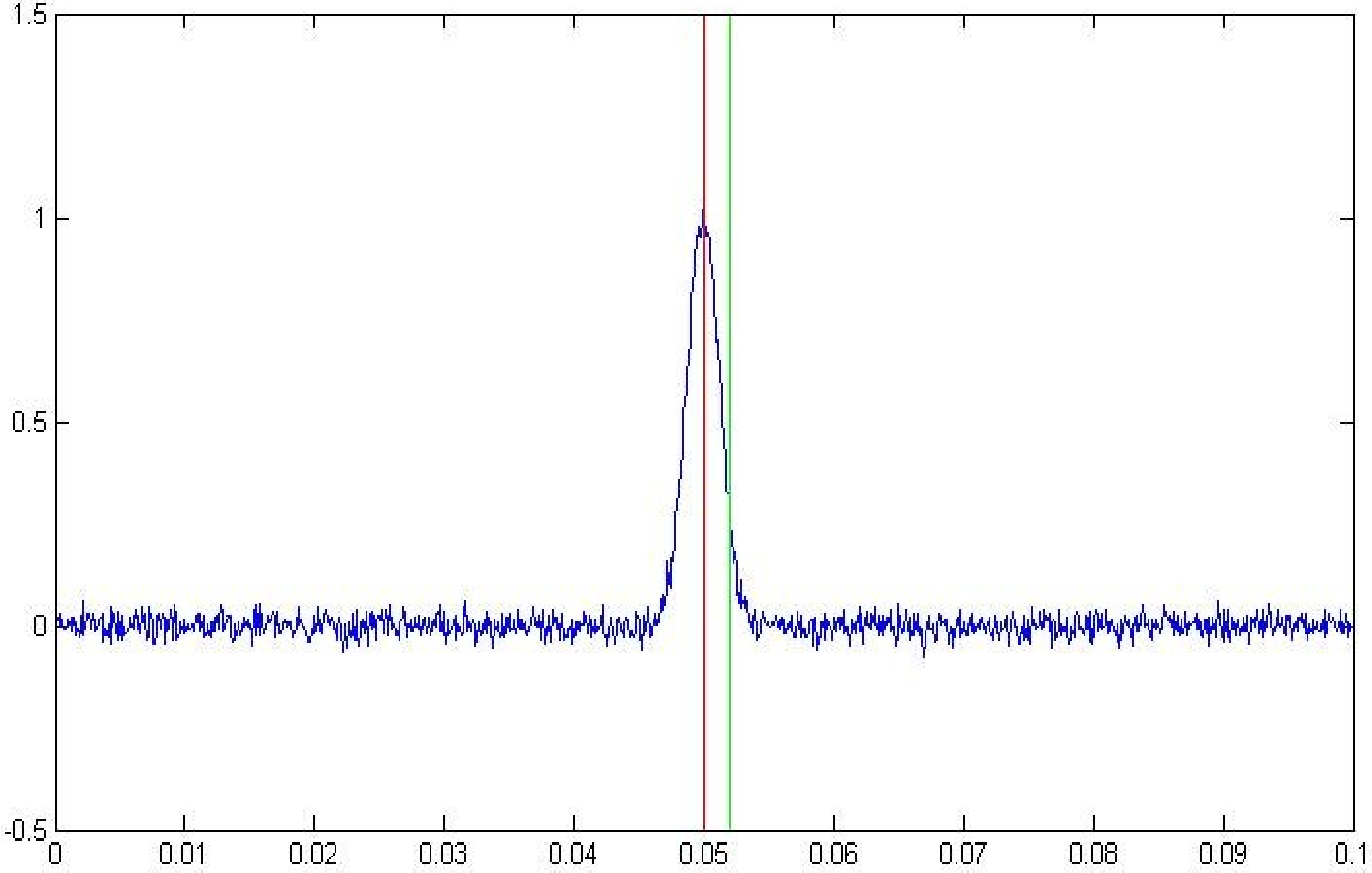
As before, t_0 is a reference epoch, Δ_{clock} represents a clock correction that accounts for differences between the observatory clocks and terrestrial time standards, and Δ_{DM} is the frequency-dependent dispersion delay caused by the ISM. The other Δ terms are delays from within the Solar System 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 β 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 Δ_{R} is the corresponding delay across the orbit of a pulsar in a binary or multiple system. The **Einstein delay** Δ_{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** Δ_{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

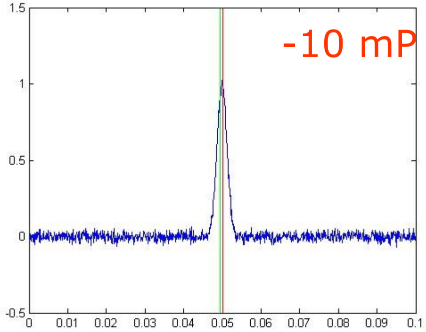
- Pulsars gradually lose energy – spin slower
- Model the spin-down as

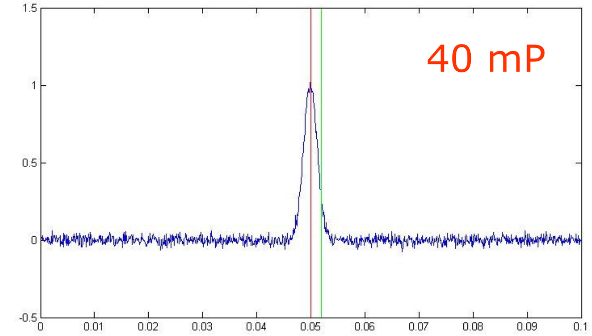
$$\phi_S(t - t_0) = \phi_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}_0(t - t_0)^2 + \frac{1}{6}\ddot{\nu}_0(t - t_0)^3$$

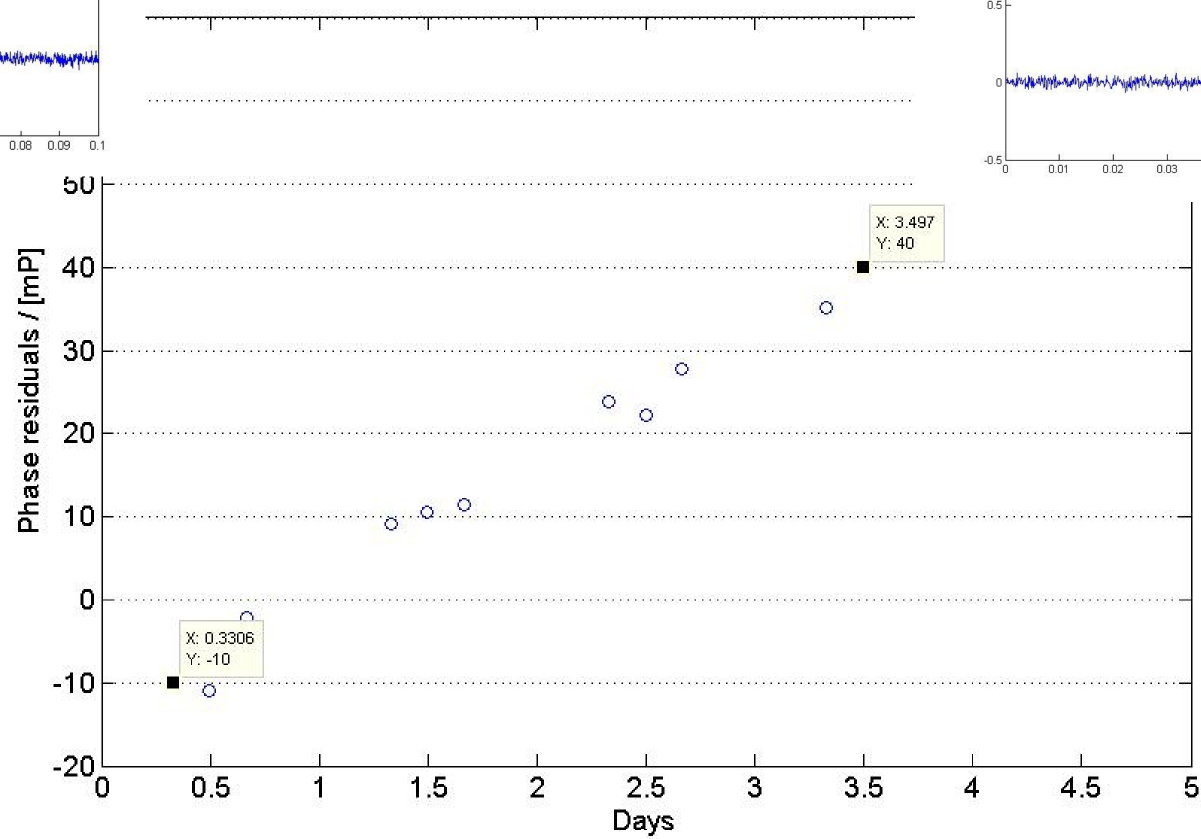
Phase Residuals



Phase residuals

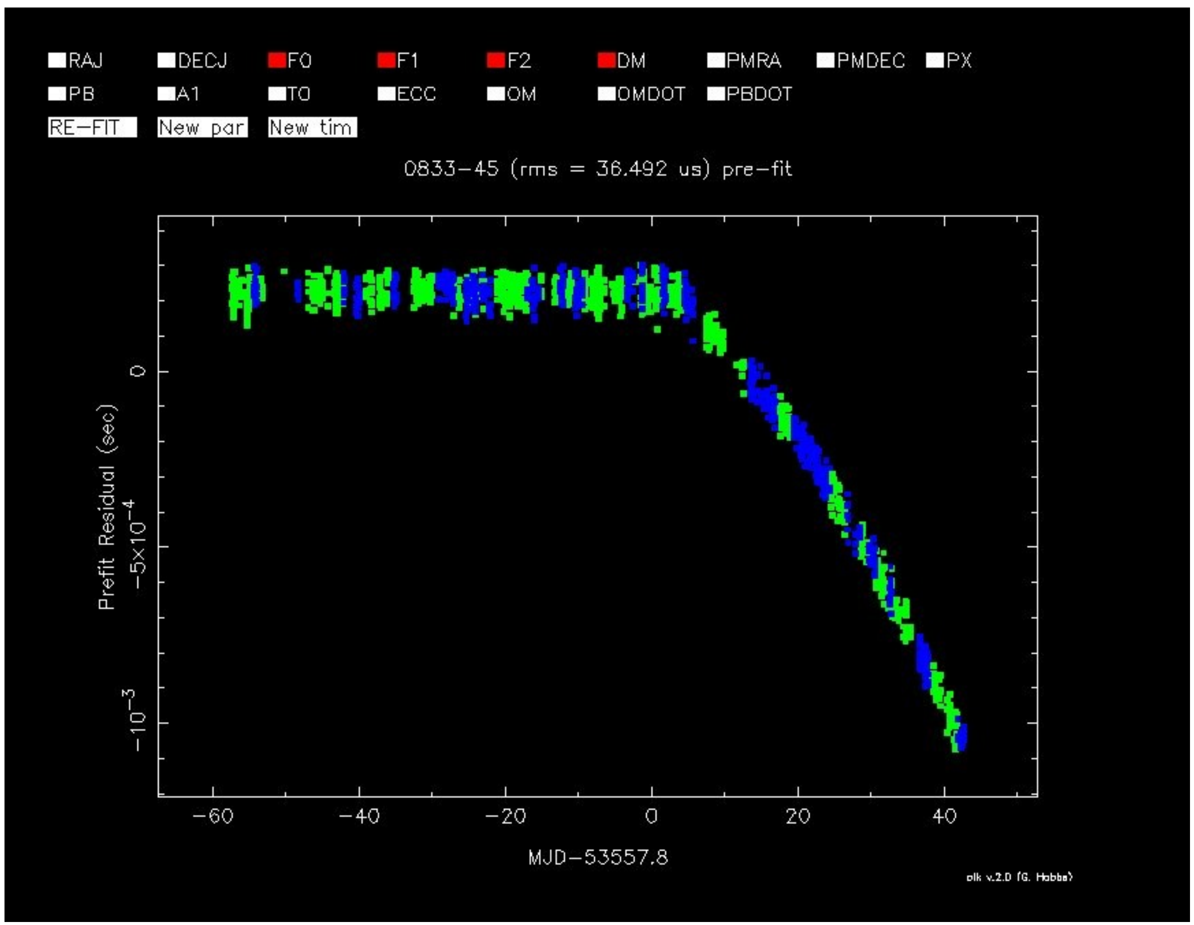






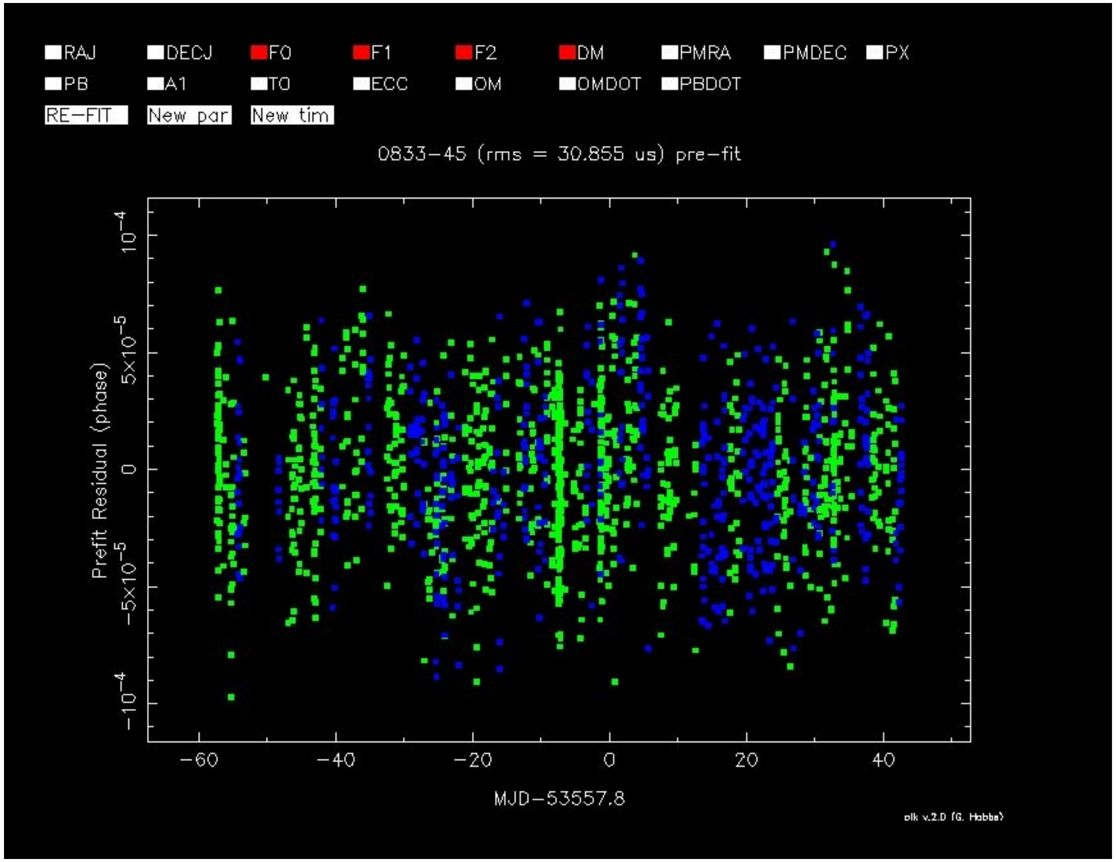
Fit a model

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



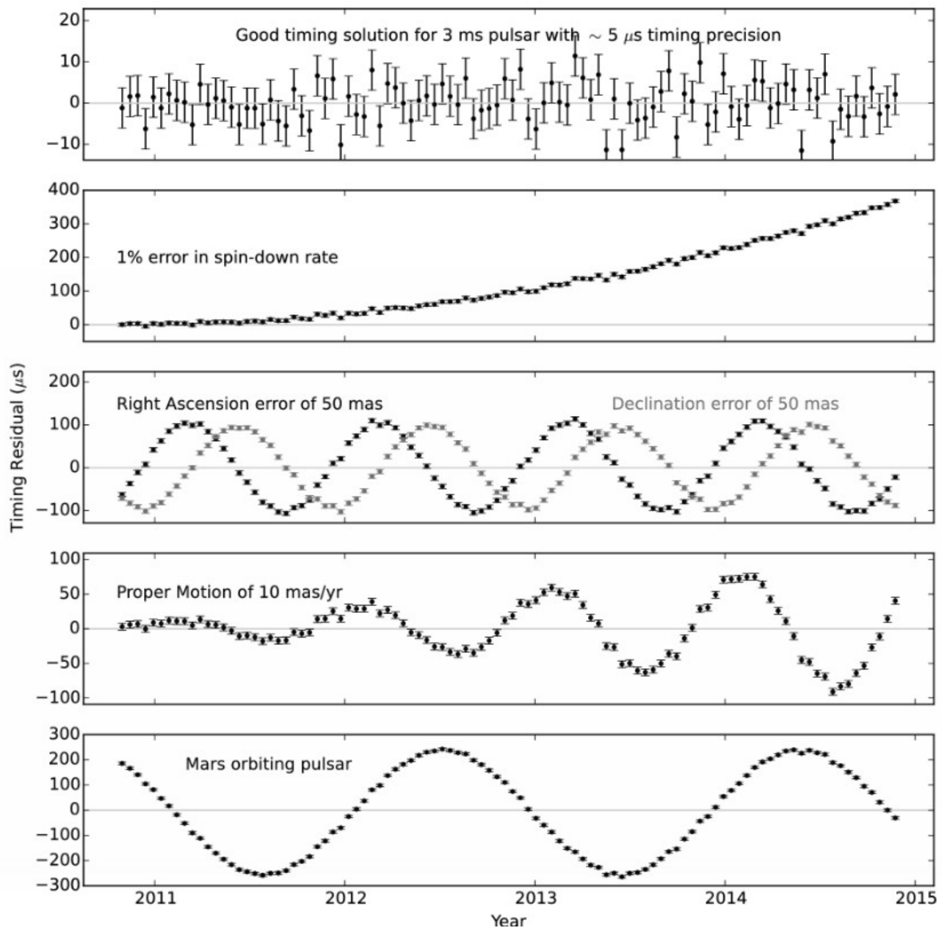
Fit a model

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



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.



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 fi

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

Neutron stars & Black Holes:

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

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

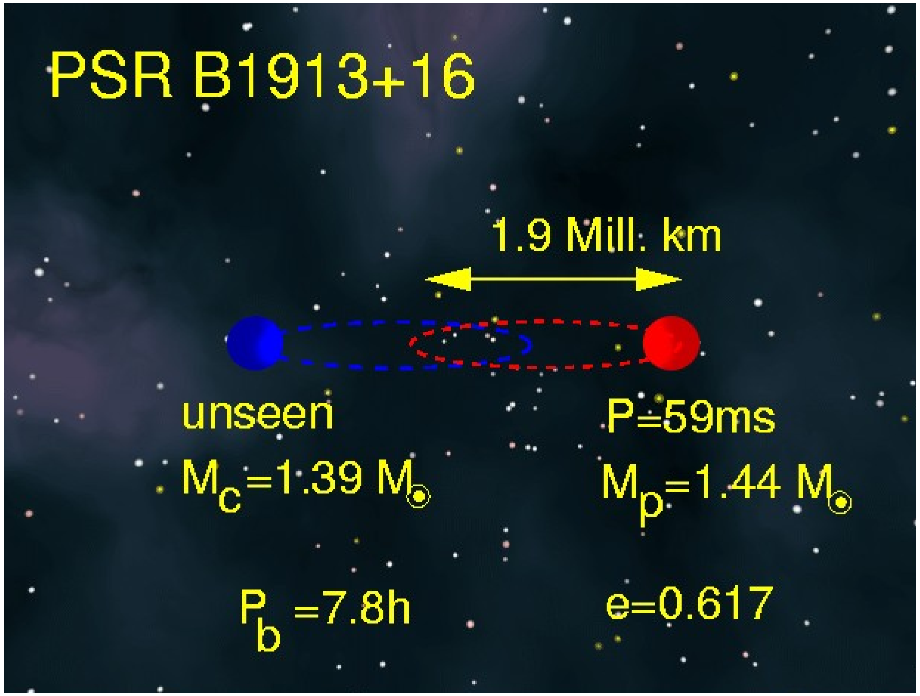
Solar system:

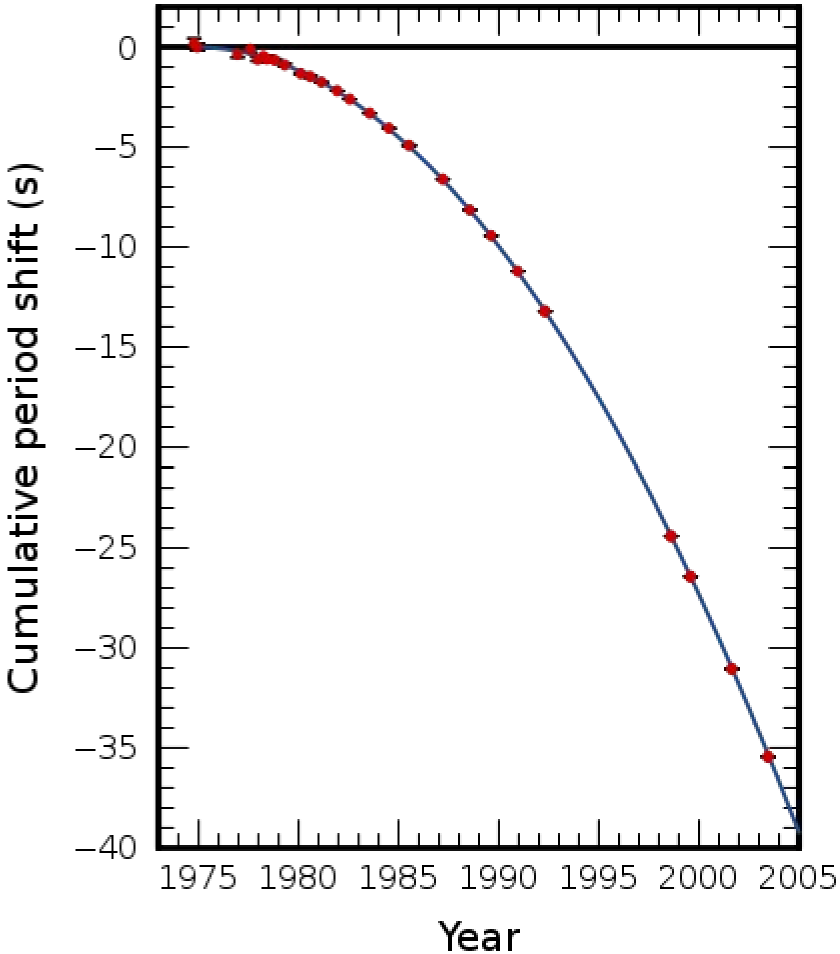
$$\varepsilon_{Sun} \approx 0.000001$$

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

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

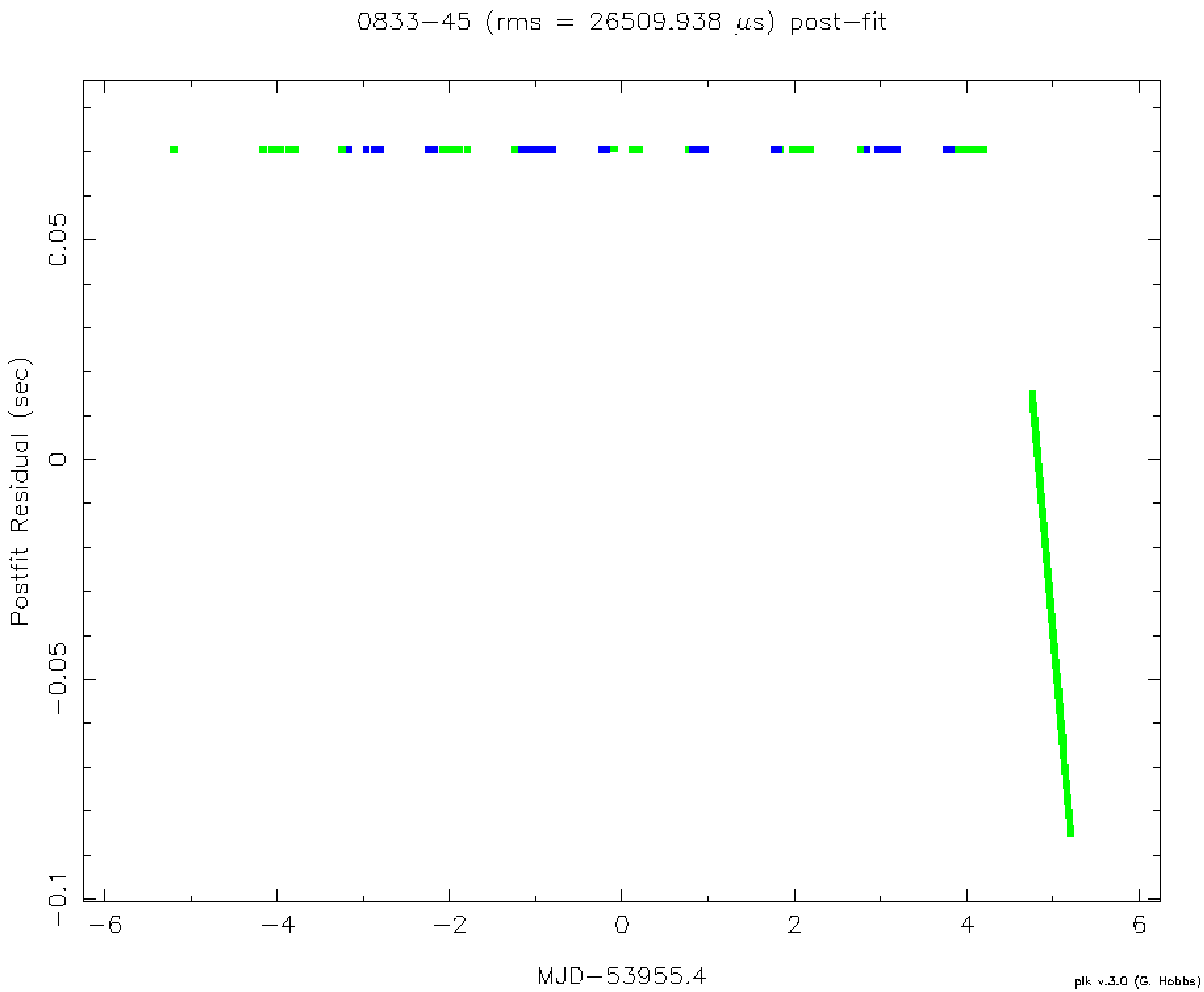
First binary pulsar





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 Glitches

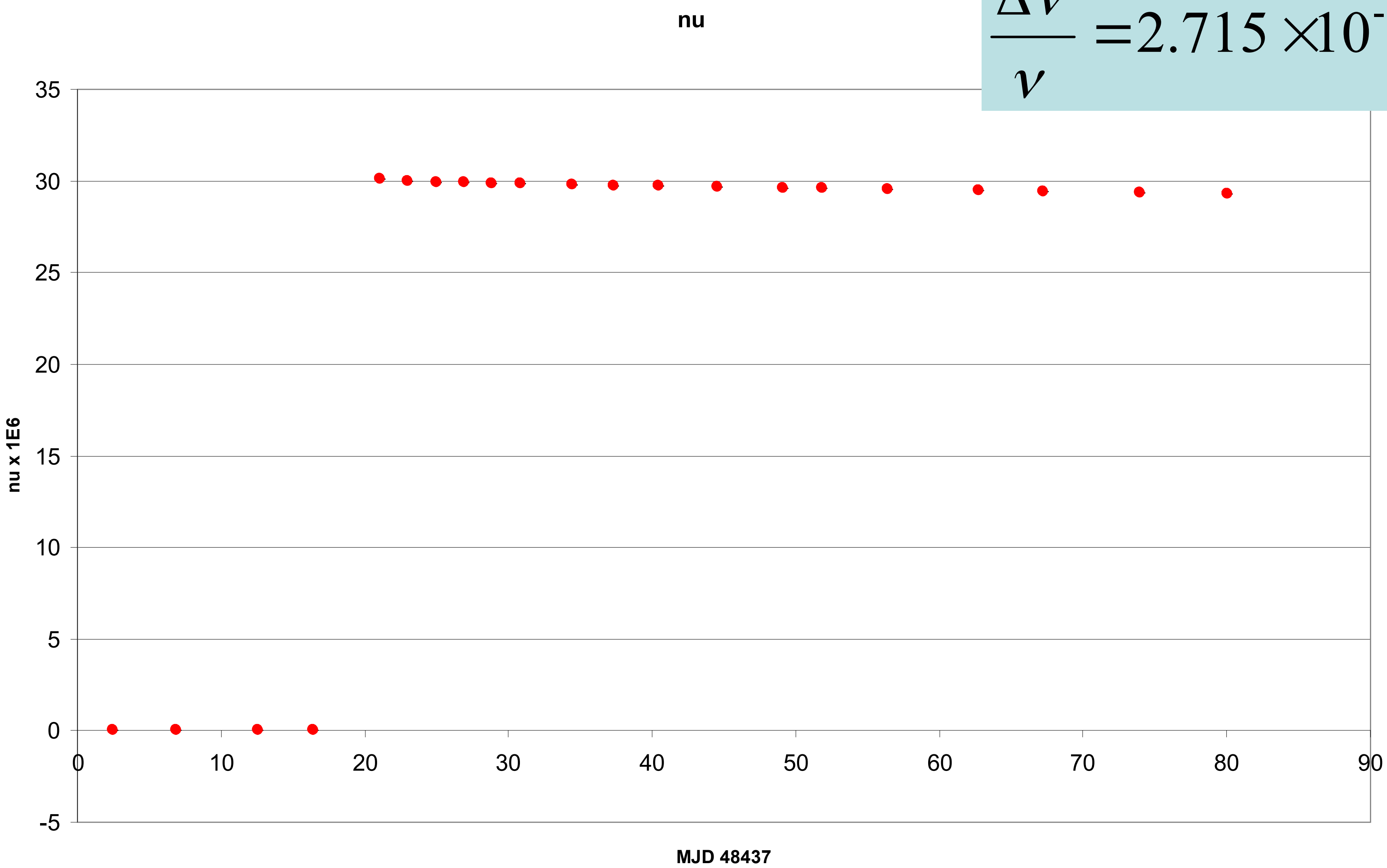


Gltich

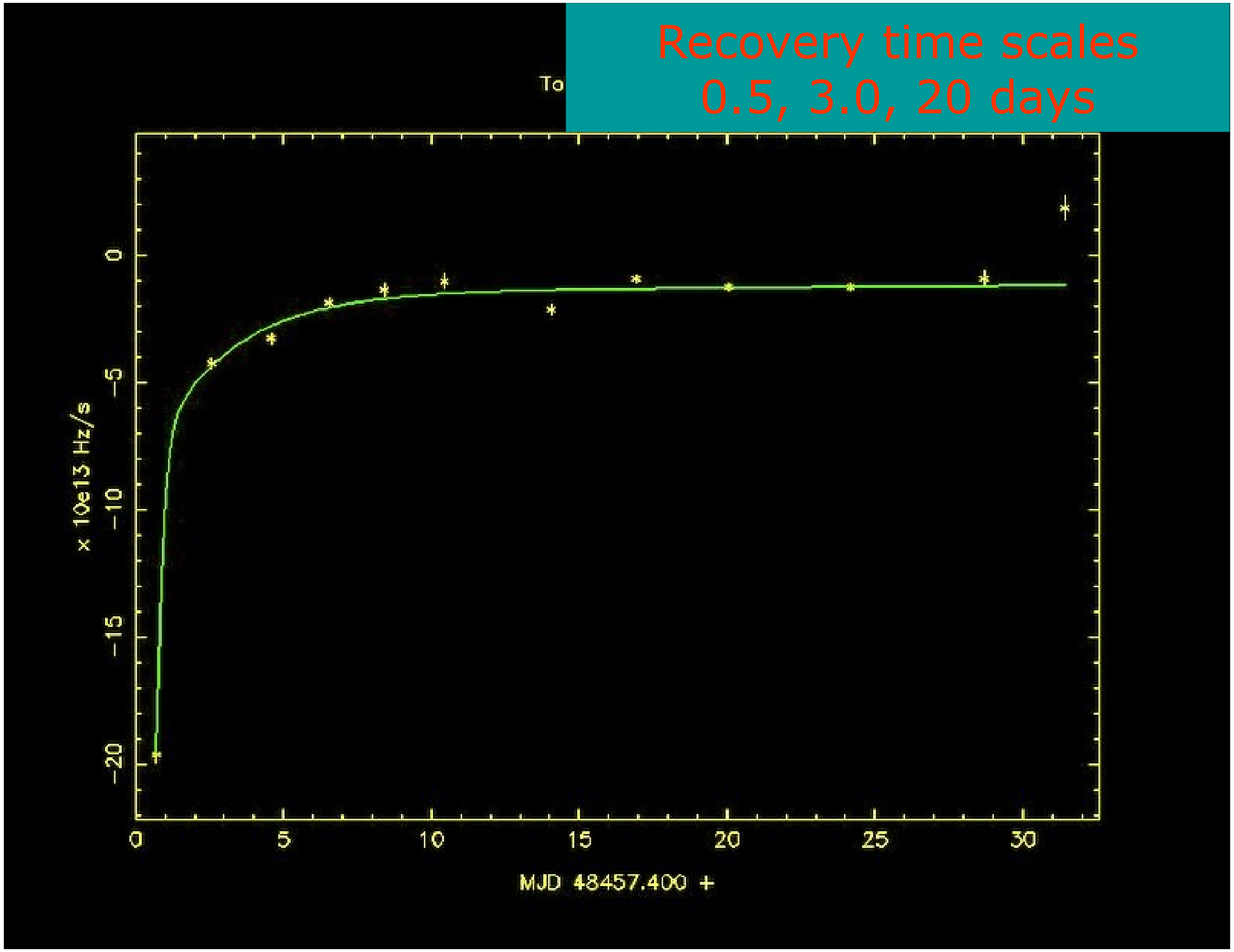
- Sudden increase in frequency or “spin-up”
- Frequency increases by few parts per million

Sudden spin-up

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



Gradual recovery in nudot



Vela Pulsar Glitches