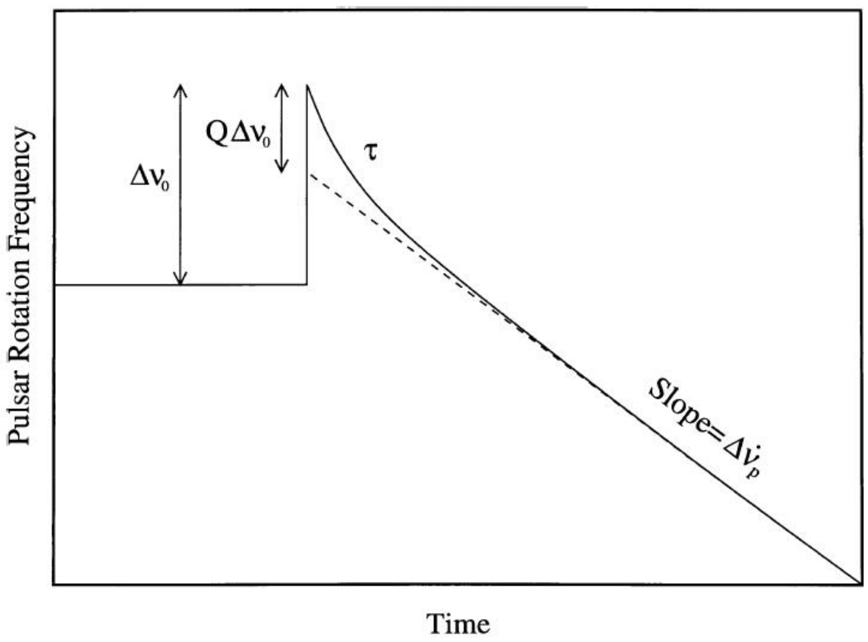
Glitches and precession

What is a glitch?



A sudden increase of rotation rate.

ATNF catalogue gives >130 normal PSRs with glitches.

The most known: Crab and Vela

$\Delta\Omega/\Omega \sim 10^{-9} - 10^{-6}$

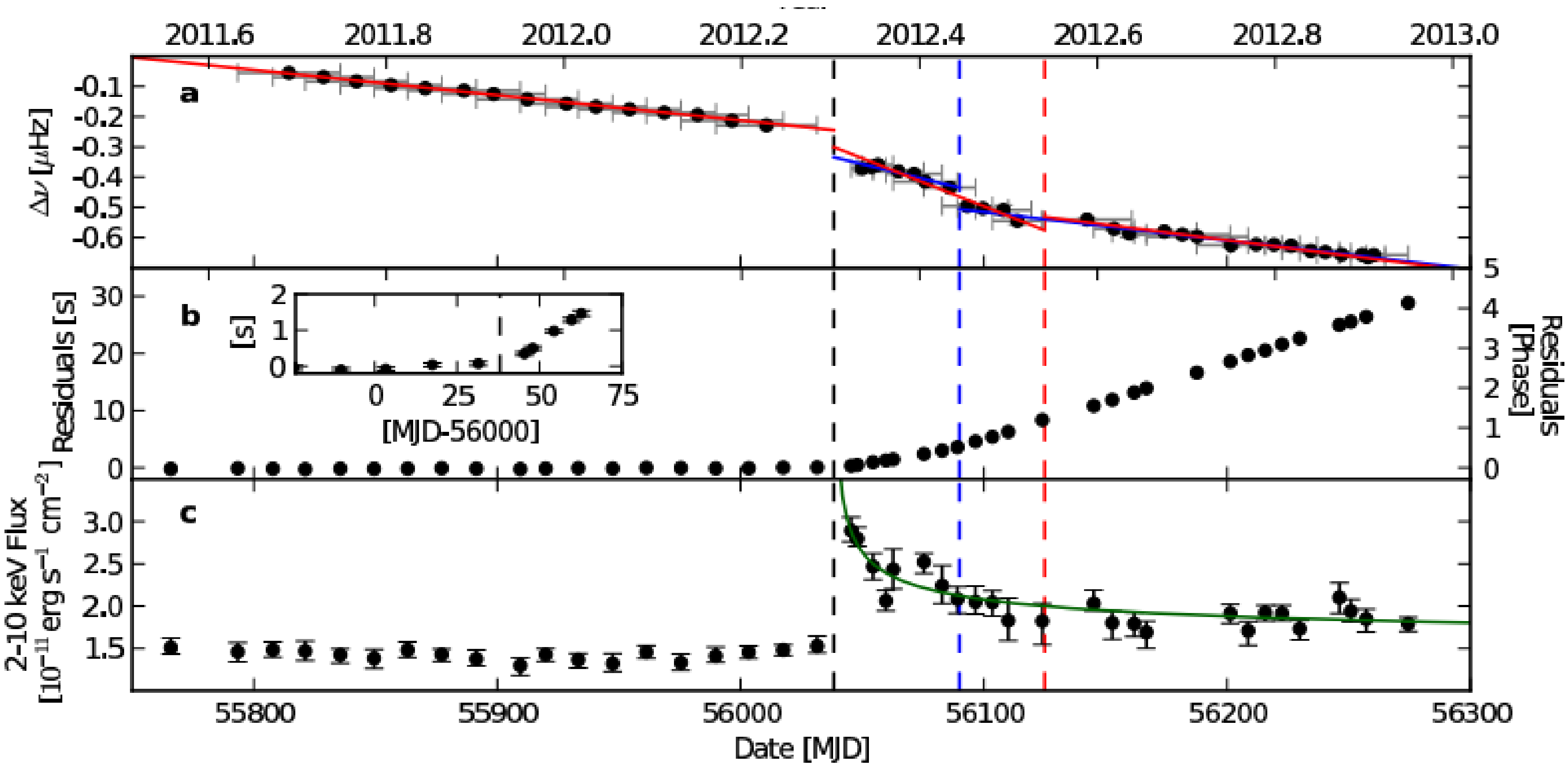
Spin-down rate can change after a glitch.
Vela is spinning down faster after a glitch.

Starquakes or/and vortex lines unpinning -
new configuration or transfer of angular momentum

Glitches are important because they probe internal structure of a NS.

See a review in 1502.07062

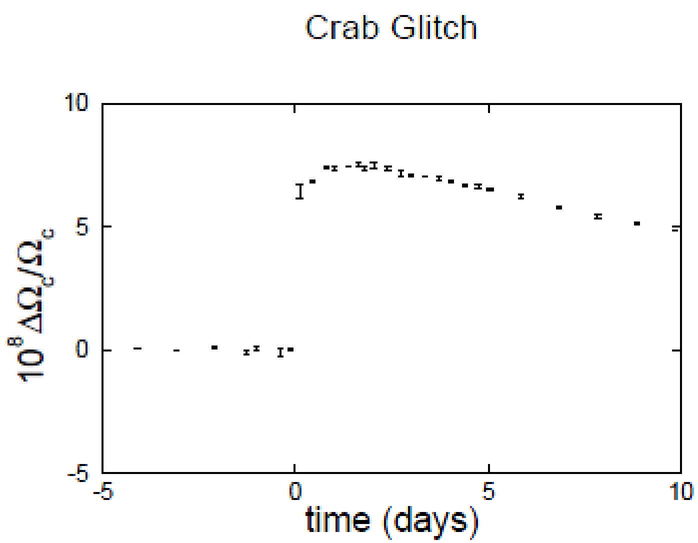
Anti-glitch of a magnetar

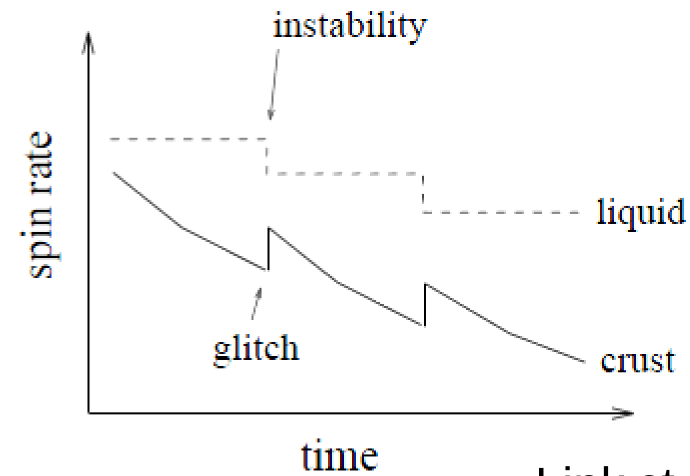


AXP 1E 2259+586

1305.6894

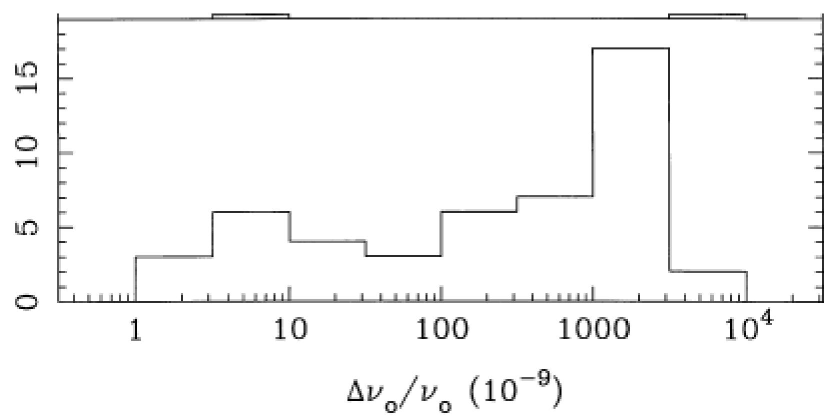
Crab glitch and the general idea





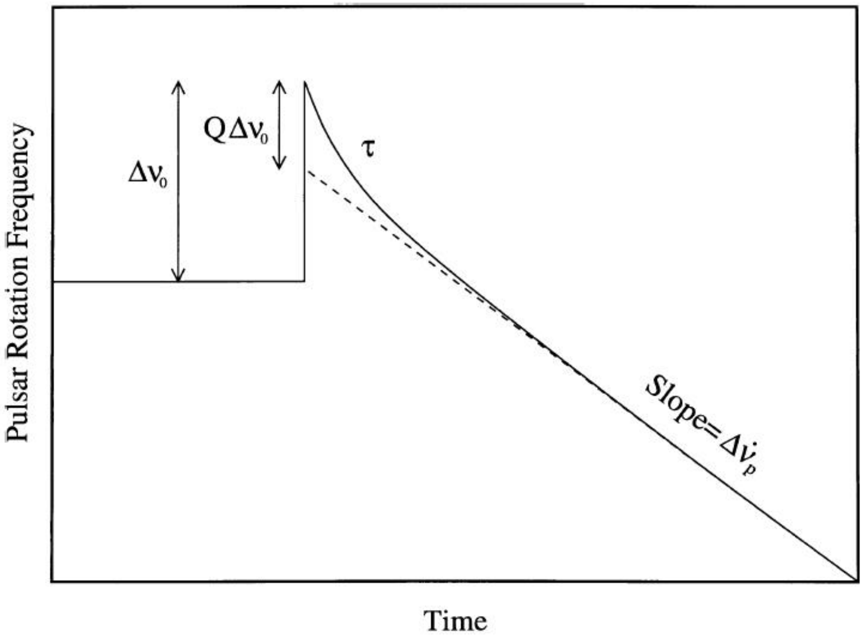
Link et al. (2000)

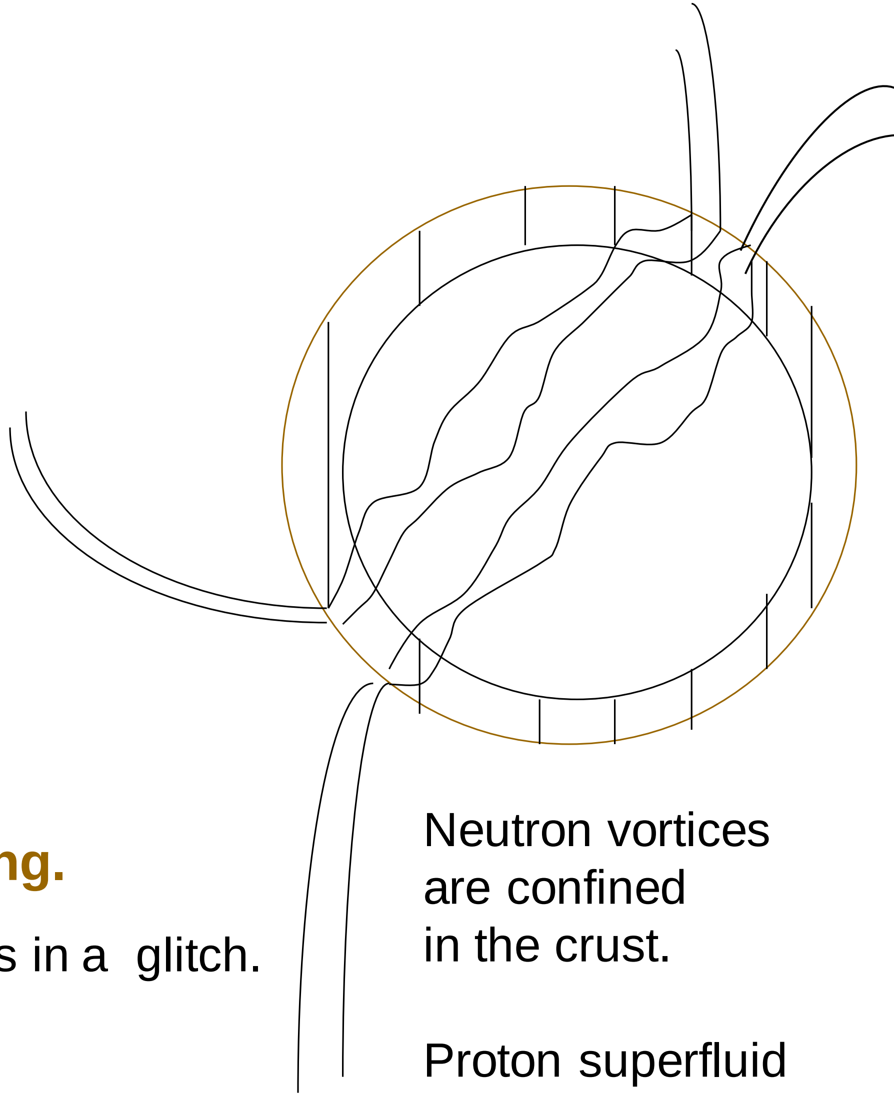
While the crust we see (and all coupled to it)
is slowing down,
some component of a star is not.
Then suddenly an additional
momentum stored in such a “reservoir”
is released and given to the crust.
The crust spins-up,
up the internal reservoir – down.



Lyne et al. (2000)

Glitches





Starquakes or vortex lines unpinning.

Unpinning of superfluid vortex lines results in a glitch.

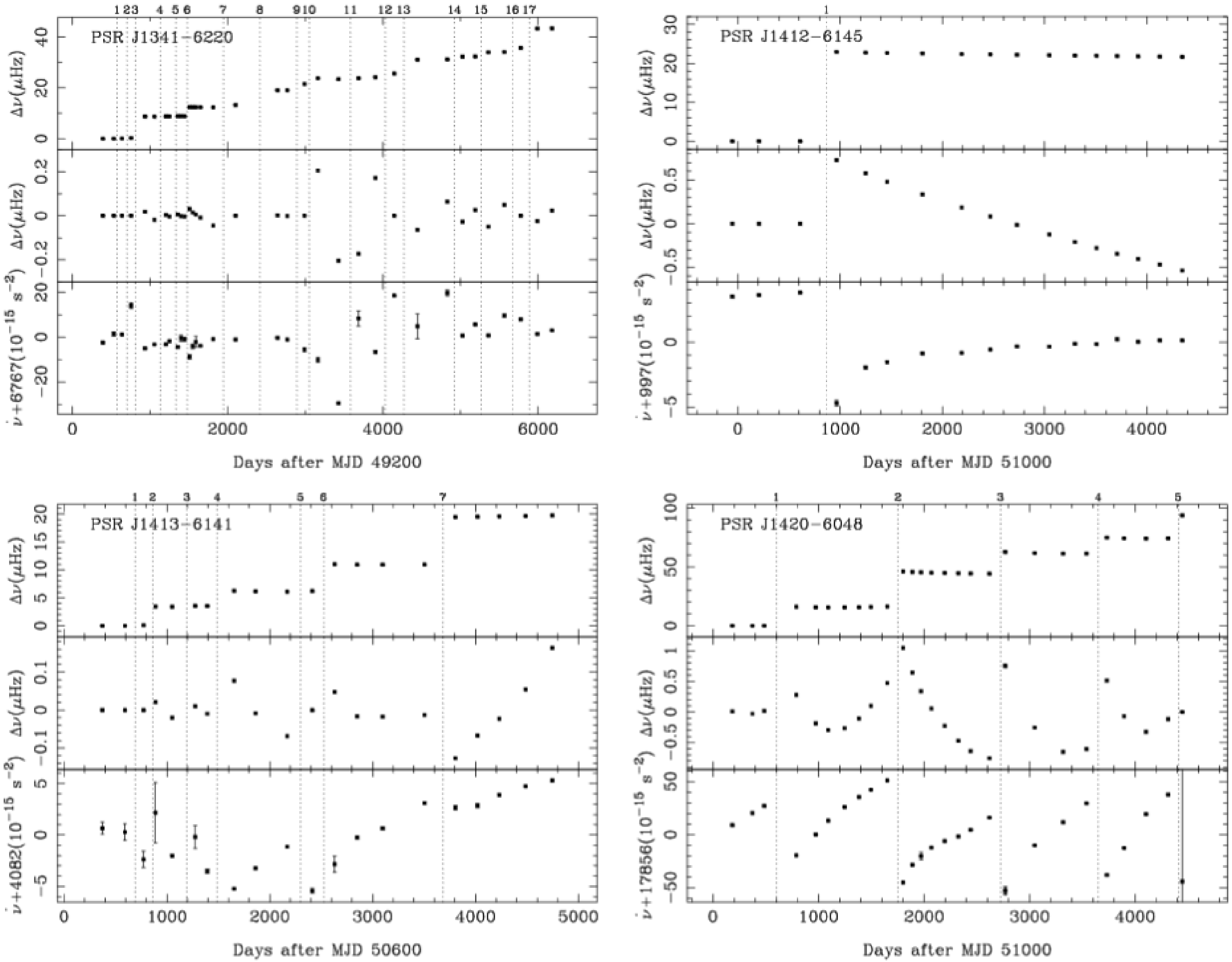
Vortex density is about 10^4 cm^{-2} P^{-1}

Flux lines density is 5 10^{18} B_{12} cm^{-2}

Neutron vortices are confined in the crust.

Proton superfluid is strongly coupled to the crust.

Glitch discovery and observations



1211.2035

Phenomenology and the Vela pulsar

$$\Delta J_i = I_c \Delta\Omega_i,$$

$$J(t) = I_c \bar{\Omega} \sum_i \frac{\Delta\Omega_i}{\bar{\Omega}},$$

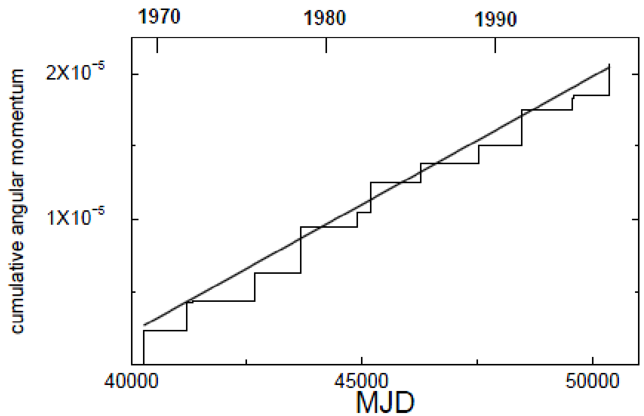
Glitches are driven by the portion of the liquid interior that is differentially rotating with respect to the crust.

I_c – crust + everything coupled with (i.e., nearly all the star, except superfluid neutrons).

The average rate of angular momentum transfer associated with glitches is $I_c \bar{\Omega} A,$

$$A = (6.44 \pm 0.19) \times 10^{-7}\ \mathrm{yr}^{-1}.$$

- Pulsar activity parameter



Vela glitches are not random, they appear every ~840 days.

A – the slope of the straight line in the figure.

(Values are for the Vela PSR)

General features of the glitch mechanism

Glitches appear because some fraction (unobserved directly) rotates faster than the observed part (crust plus charged parts), which is decelerated (i.e., which is spinning-down).

$\dot{J}_{\rm res} \le I_{\rm res} |\dot{\Omega}|,$

The angular momentum is "collected" by the reservoir, related to differentially rotating part of a star (SF neutrons)

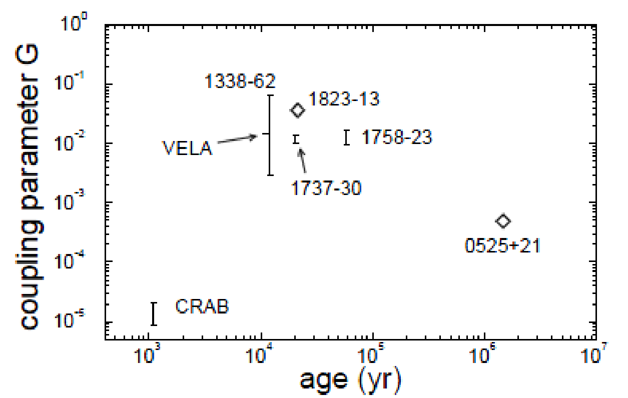
$$\frac{I_{\rm res}}{I_c} \ge \frac{\bar{\Omega}}{|\dot{\Omega}|} A \equiv G,$$

G – the coupling parameter. It can be slightly different in different sources.

$$\frac{I_{\rm res}}{I_c} \ge G_{\rm Vela} = 1.4\%.$$

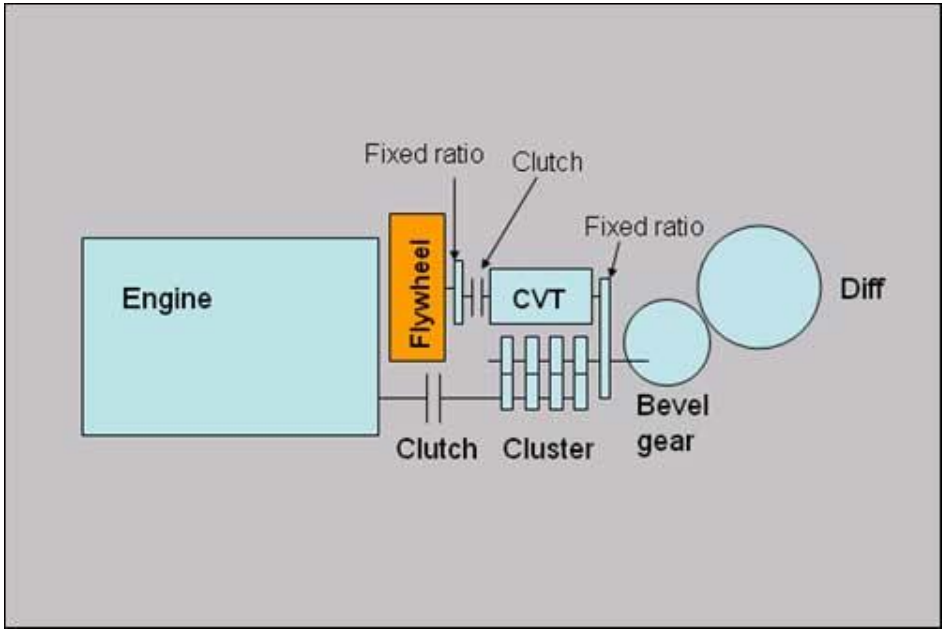
Glitch statistics for Vela provide an estimate for G.

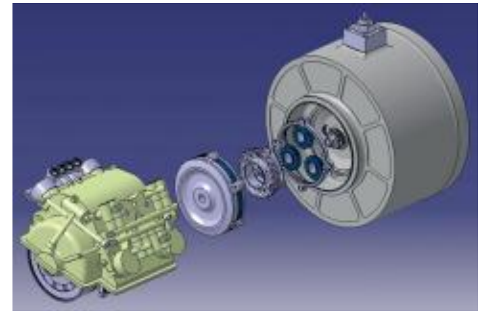
Superfluid is a good candidate to form a "reservoir" because relaxation time after a glitch is very long (~months) which points to very low viscosity.



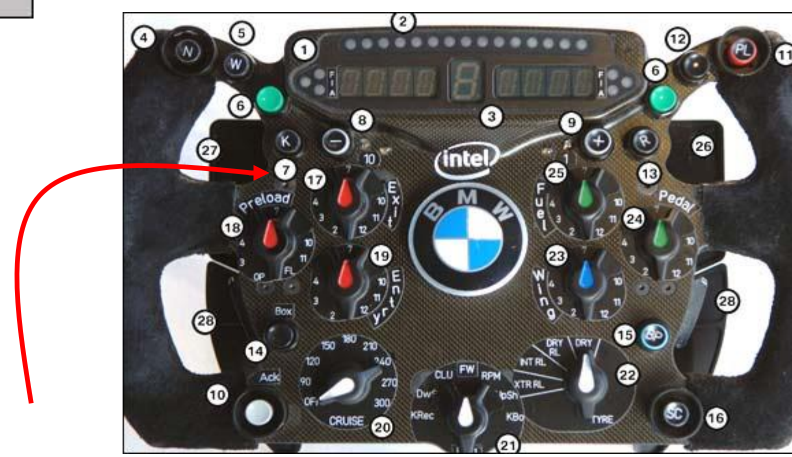
Link et al. 0001245

KERS





Williams-F1 used mechanical KERS.
Energy is stored in a flywheel.



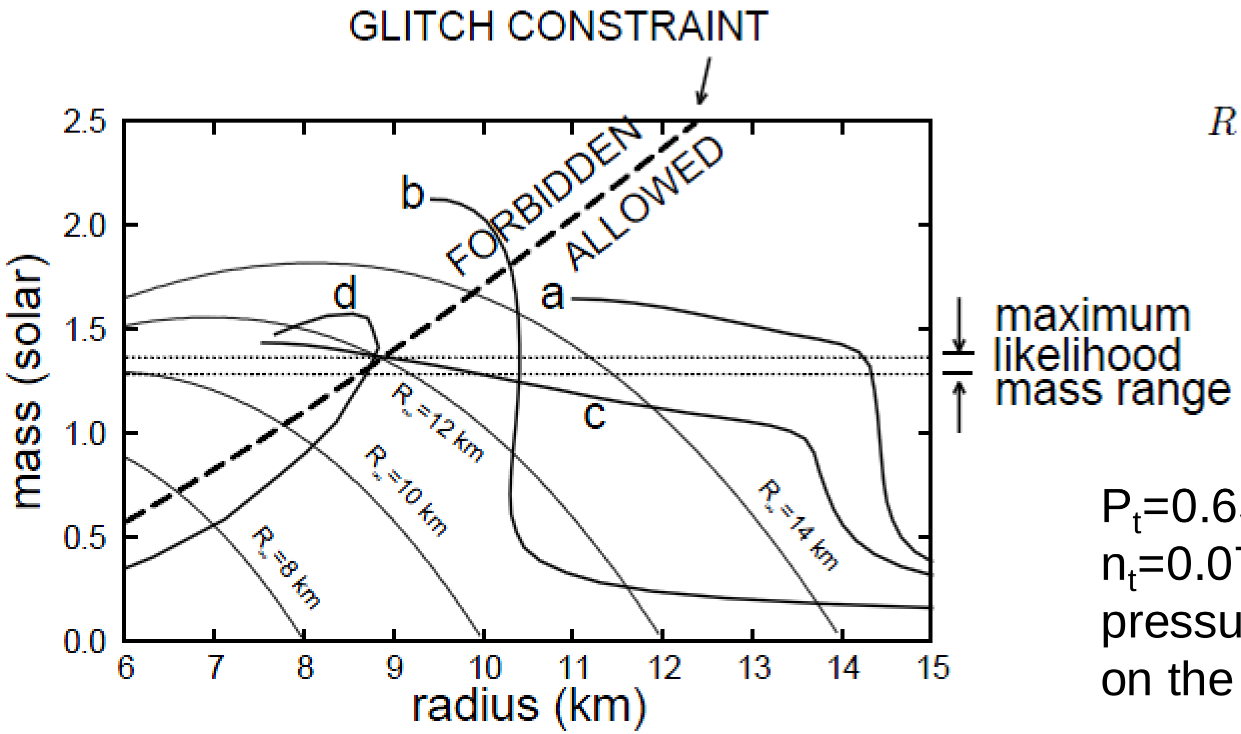
Critical velocity difference

In most popular models glitches appear when the difference in angular velocity between the crust and the superfluid reaches some critical value.

$I_{super}/I_{crust} \sim 10^{-2}$
$\Delta\Omega/\Omega \sim 10^{-6}$
$\Delta\Omega$ – is for the crust (we see it!)
$\Delta\Omega\ I_{crust} = \Delta\Omega_{super}\ I_{super}$

$\Delta\Omega_{super}=\Delta\Omega\ I_{crust}/I_{super} = \Omega\ 10^{-6}\ 10^{2} = 10^{-4}\ \Omega$

EoS and glitches



$$R = 3.6 + 3.9 M/M_{\odot}\,.$$

P_t=0.65 MeV fm^{-3}
n_t=0.075 fm^{-3}
pressure and density
on the core-crust boundary.

$$\Lambda \equiv (1 - 2GM/Rc^2)^{-1}$$

$$\frac{\Delta I}{I} \simeq \frac{28\pi}{3}\frac{P_t R^4}{GM^2}\left[1 + \frac{8P_t}{n_t m_n c^2}\frac{4.5 + (\Lambda-1)^{-1}}{\Lambda - 1}\right]^{-1}$$

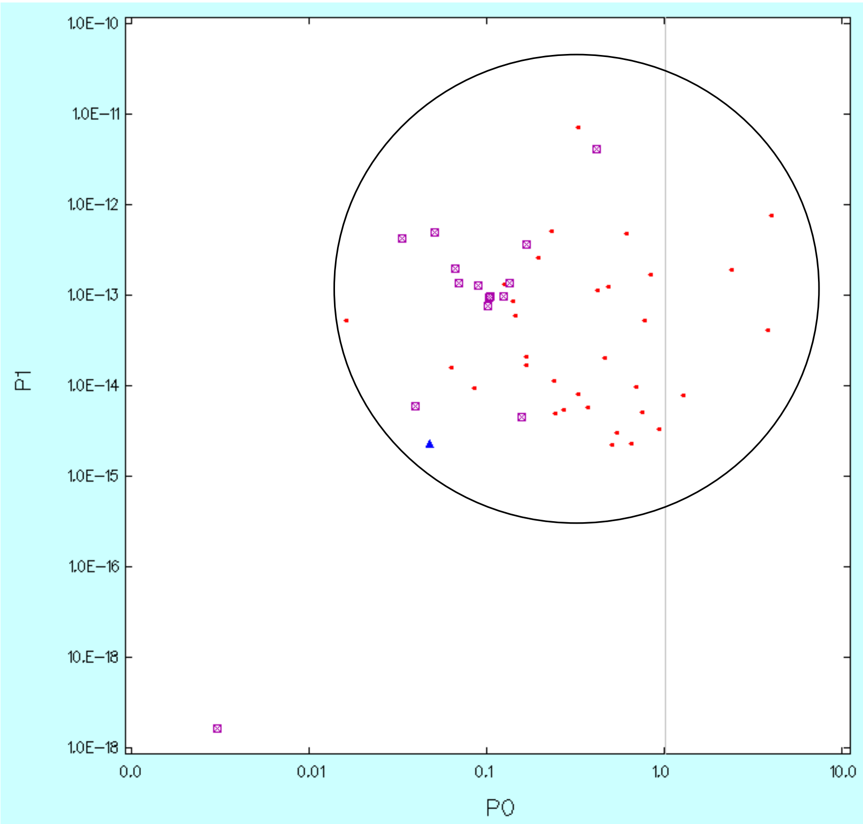
$$\Delta I/(I - \Delta I) \geq \Delta I/I_c \geq I_{\rm res}/I_c \geq 0.014.$$

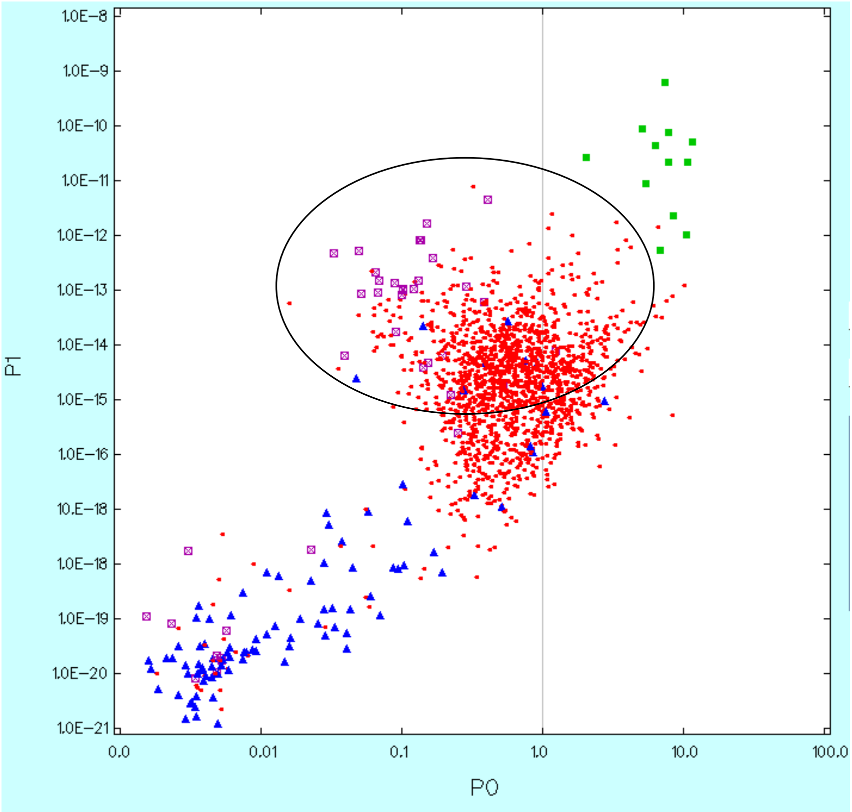
Link et al. 0001245

See some critics in 1207.0633 “Crust is not enough” and 1210.8177
Further discussion – in 1404.2660.

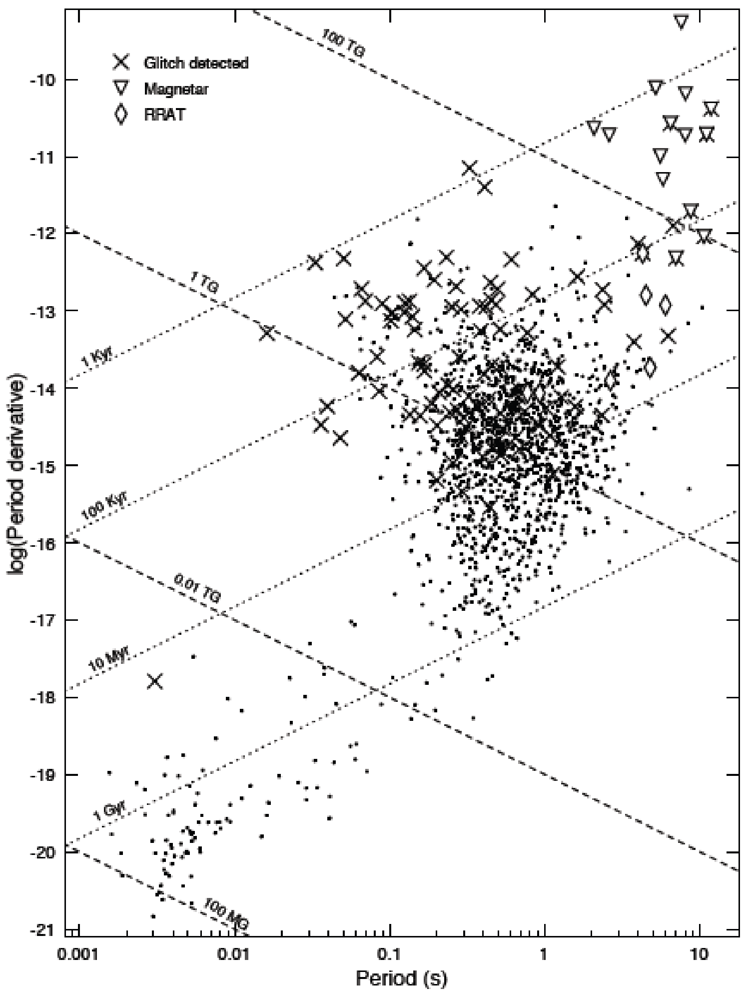
Which PSRs do glitch?

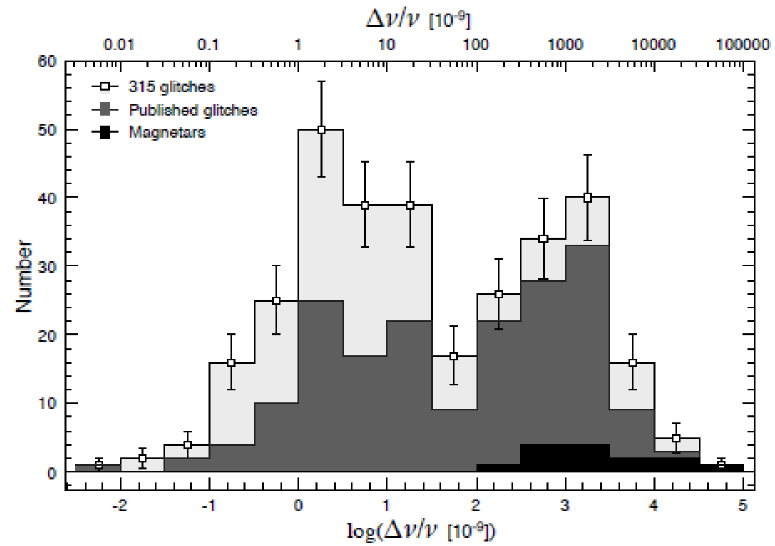
On average young pulsars with larger spin-down glitch more frequently

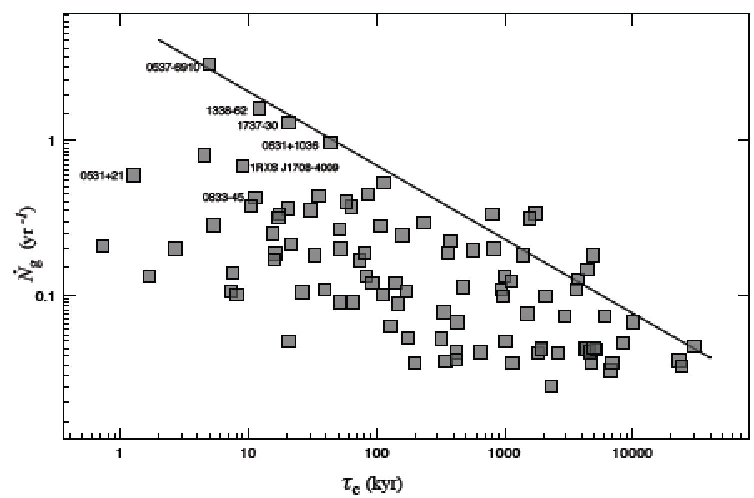




Many-many glitches …



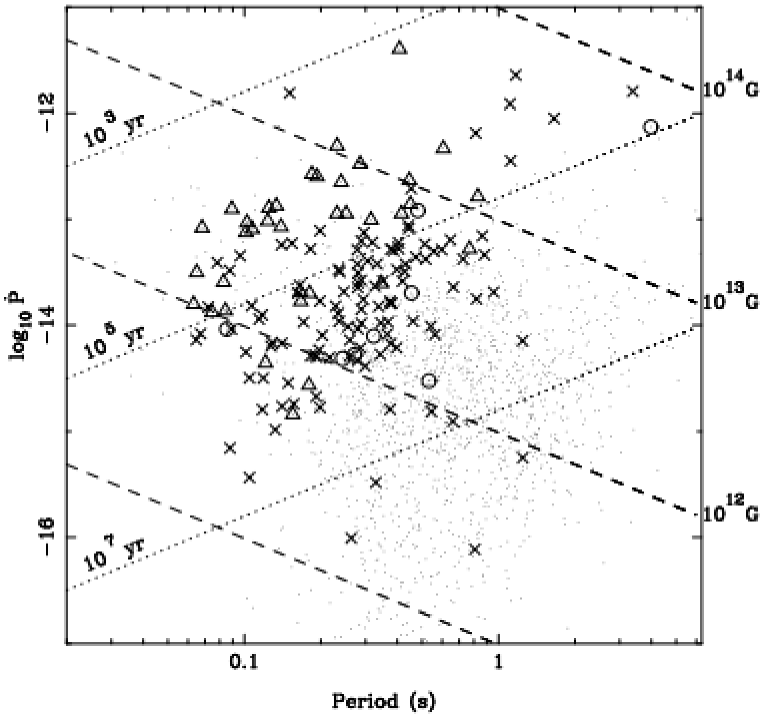


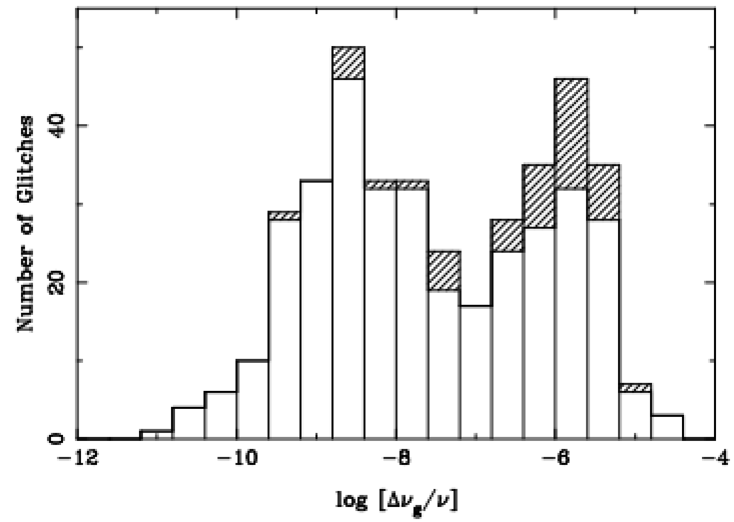


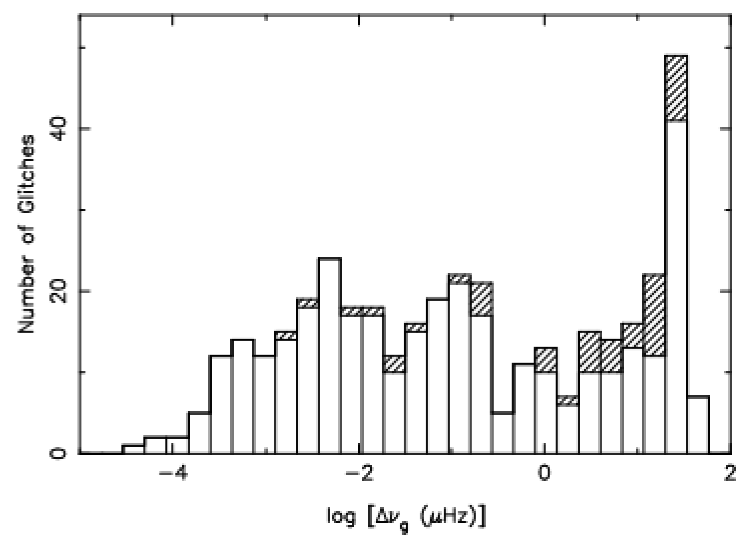
1102.1743

315 glitches in 102 PSRs

107 new glitches in 36 pulsars

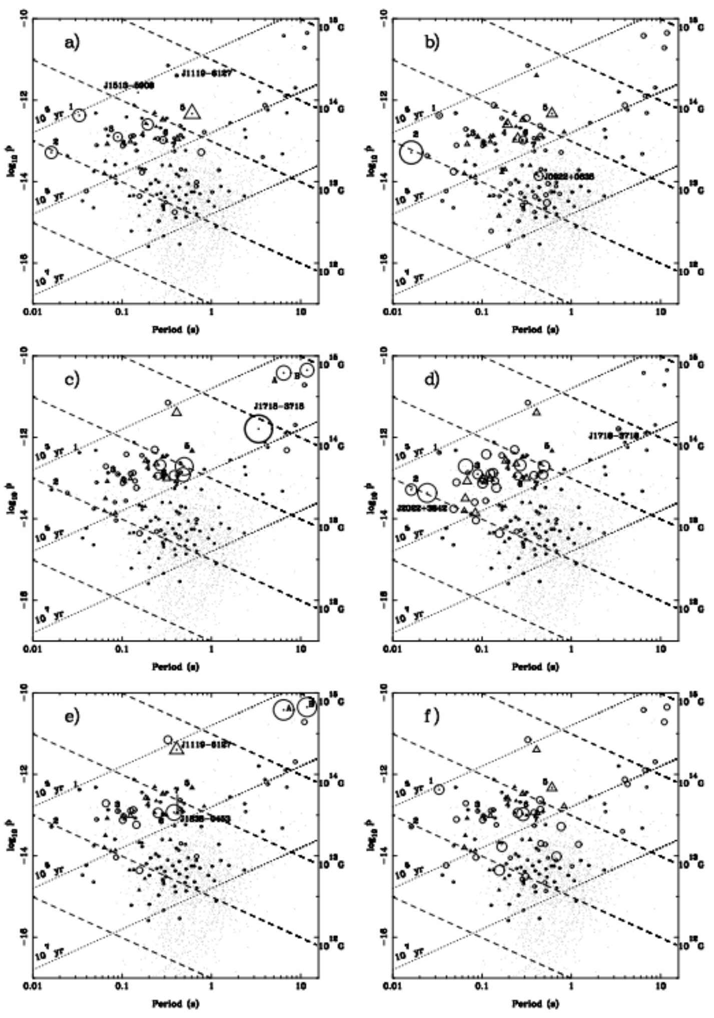






1211.2035

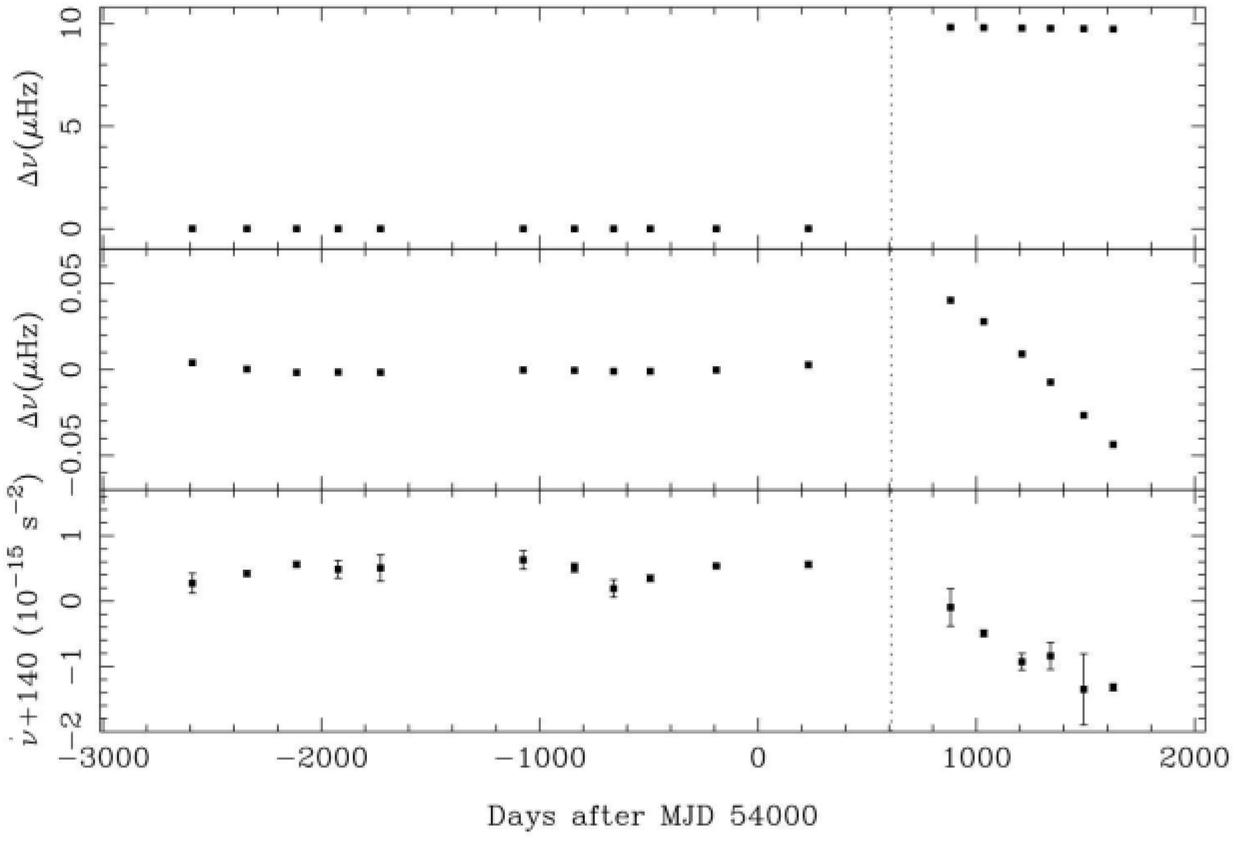
P–Pdot diagrams for glitch-related quantities



a) number of detected glitches; b) average number of glitches per year;
c) maximum fractional glitch size; d) maximum glitch size; e) rms fractional glitch size; and f) rms fractional size normalised by the mean. A circle indicates the parameter was obtained from the ATNF Pulsar Catalogue glitch table, whereas a triangle symbol indicates a parameter from this work. In the various plots, the seven pulsars exhibiting ten or more glitches are marked: 1 – PSR B0531+21 (Crab pulsar); 2 – PSR J0537−6910; 3 – PSR B0833−45 (Vela pulsar); 4 – PSR J1341−6220; 5 – PSR J1740−3015; 6 – PSR J0631+1036; 7 – PSR J1801−2304; and two magnetars: A – PSR J1048−5937 (1E 1048.1−5937) and B – PSR J1841−0456 (1E 1841−045).

1211.2035

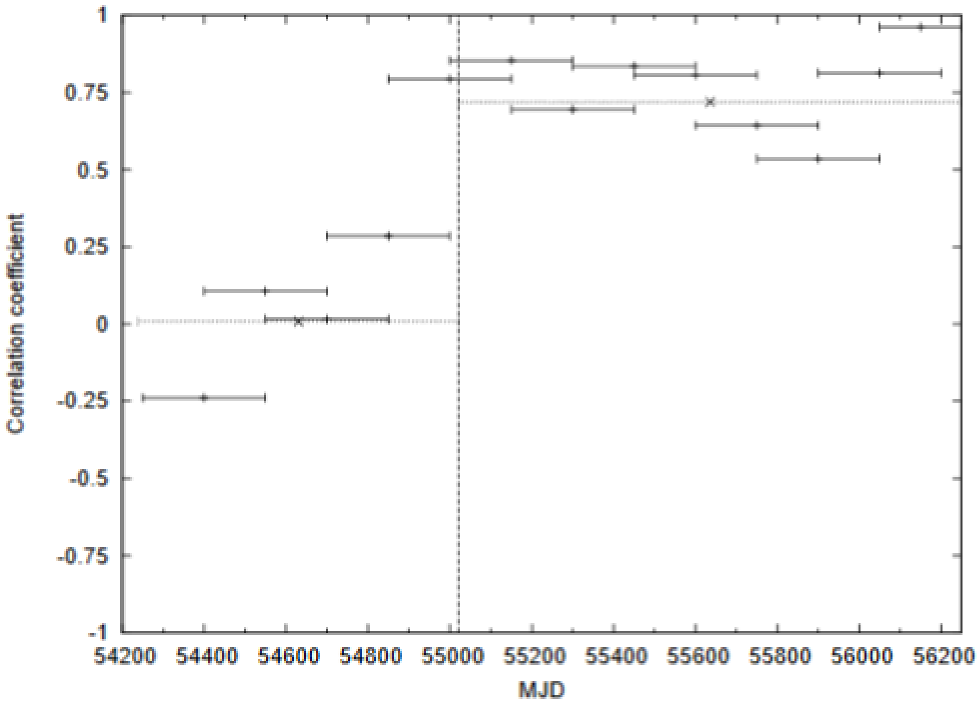
The largest glitch



$33\ 10^{-6}$

1106.5192

Glitch and radio properties

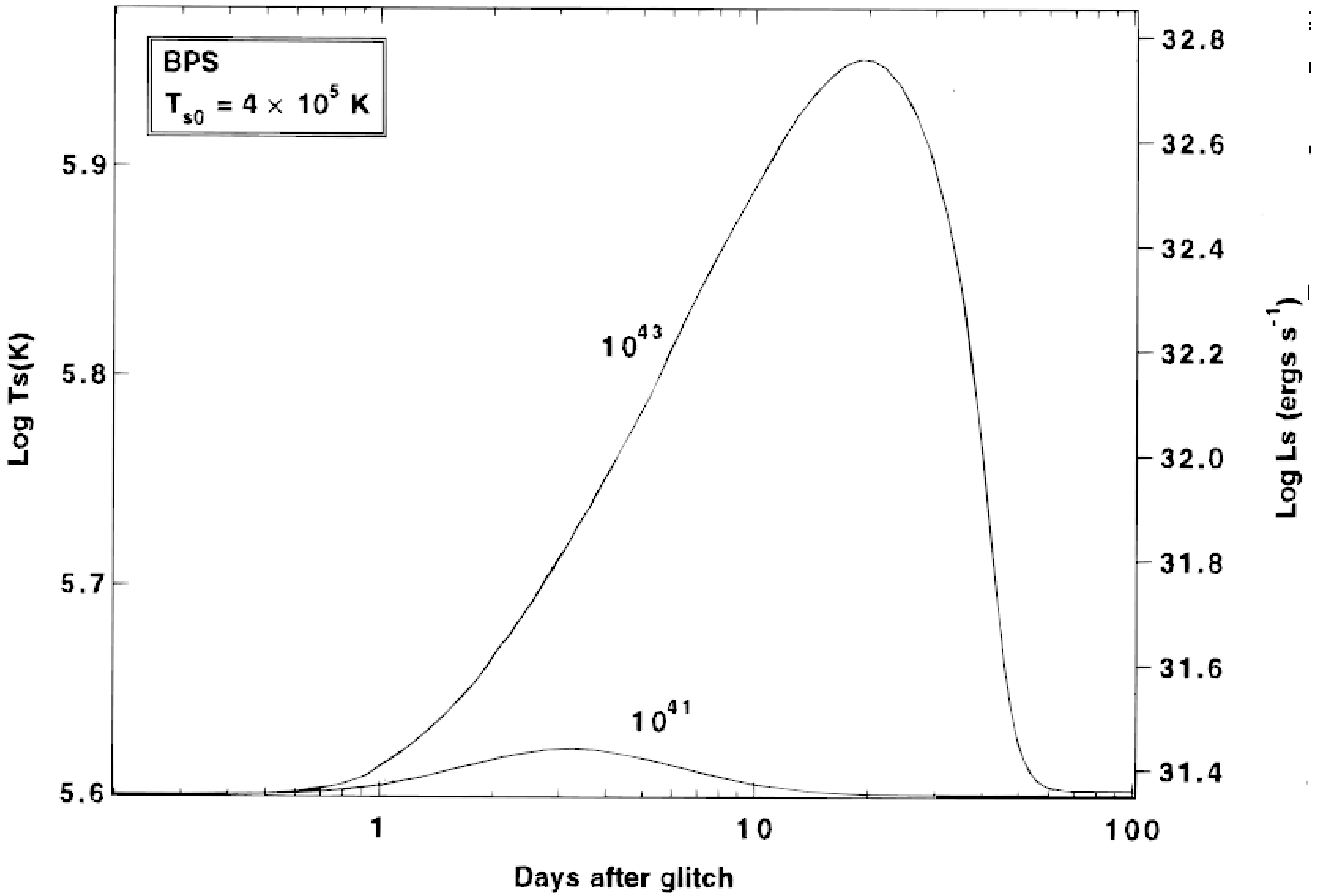


PSR J0742−2822
exhibits two distinct emission states that are identified by discrete changes in the observed pulse profile.

Correlation between frequency derivative and smoothed pulse shape parameter for overlapping 300-day intervals. The vertical dashed line at MJD 55022 indicates the epoch of a glitch.
Also shown with dotted bars is the same correlation when computed for the entire pre and post-glitch epochs.

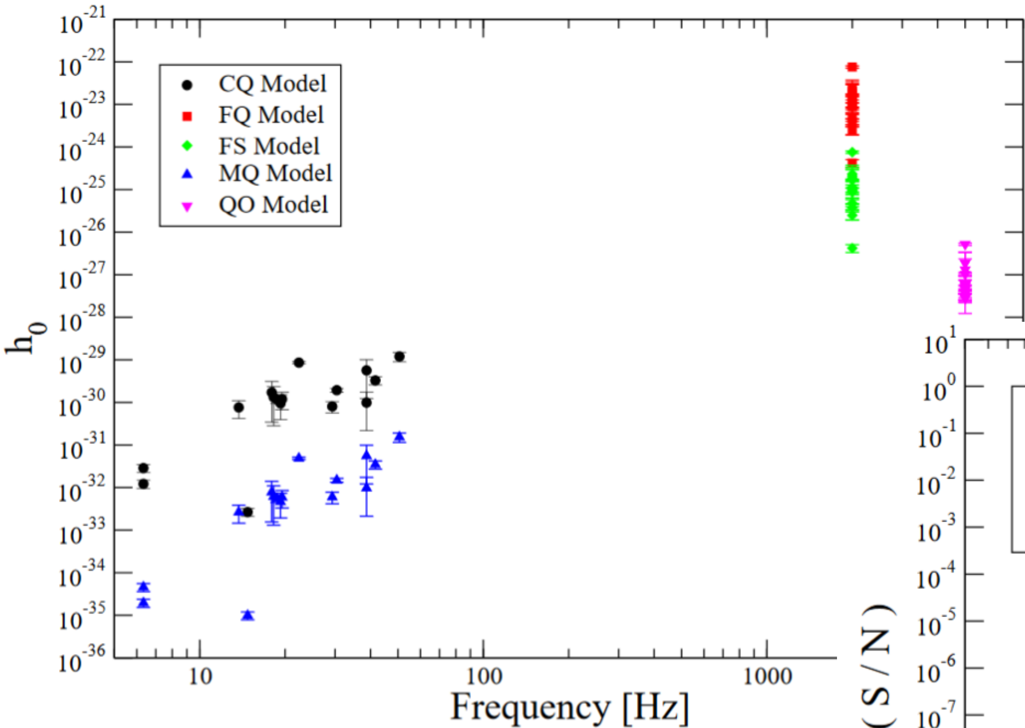
1304.4644

Thermal effect of a glitch

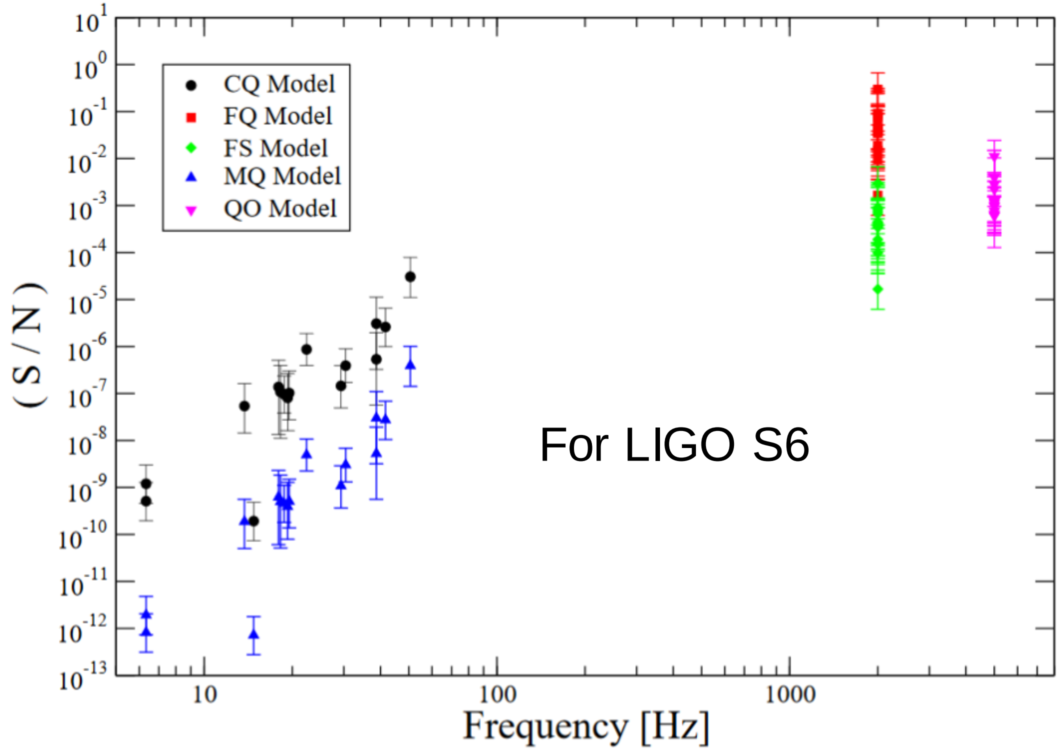


Hirano et al. 1997

Gravitational waves from glitches



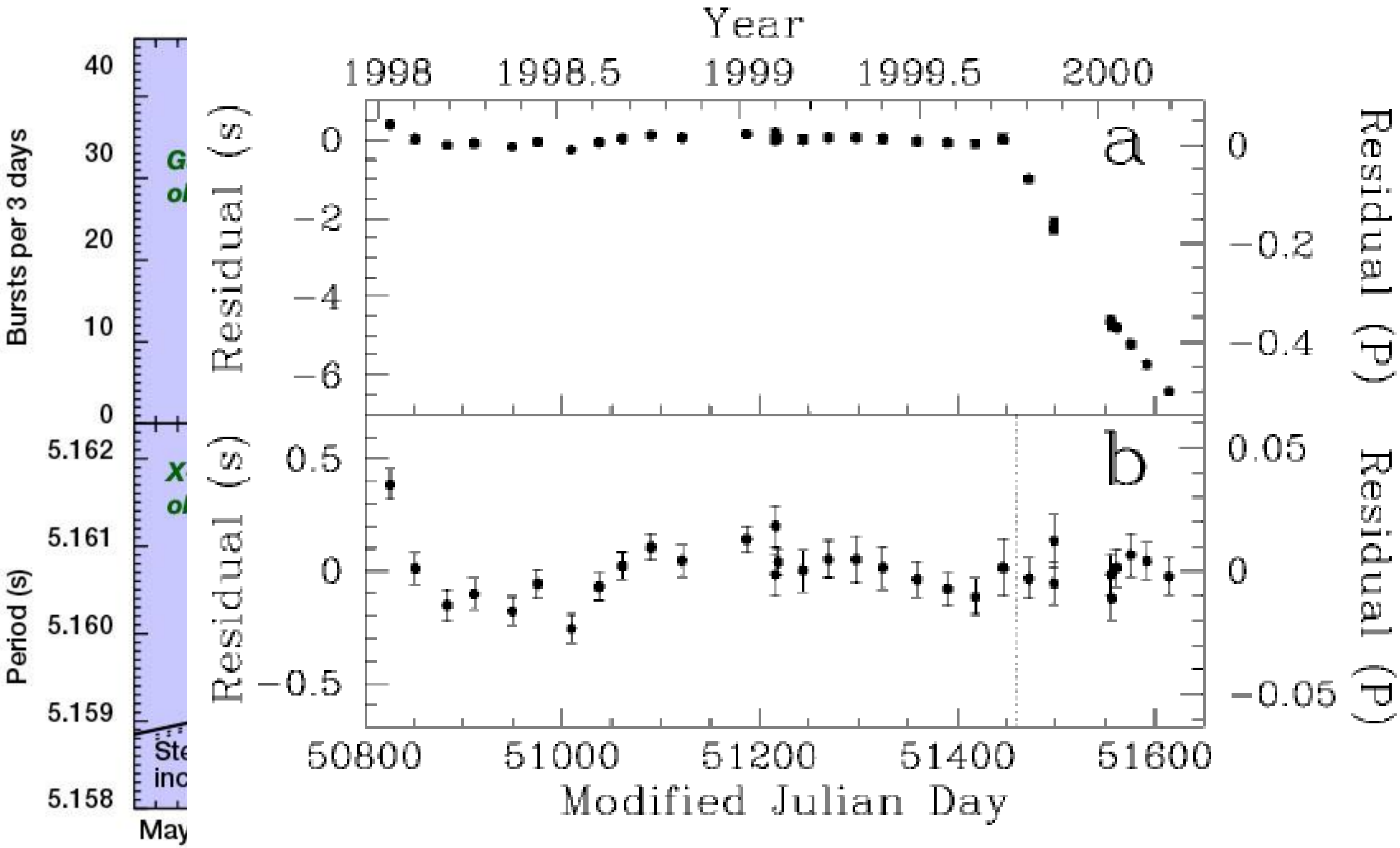
In some very optimistic models GW signals from PSRs glitches can be detected already with existing detectors (aLIGO, adVIRGO).



For LIGO S6

1305.2466

Glitches of magnetars



es.

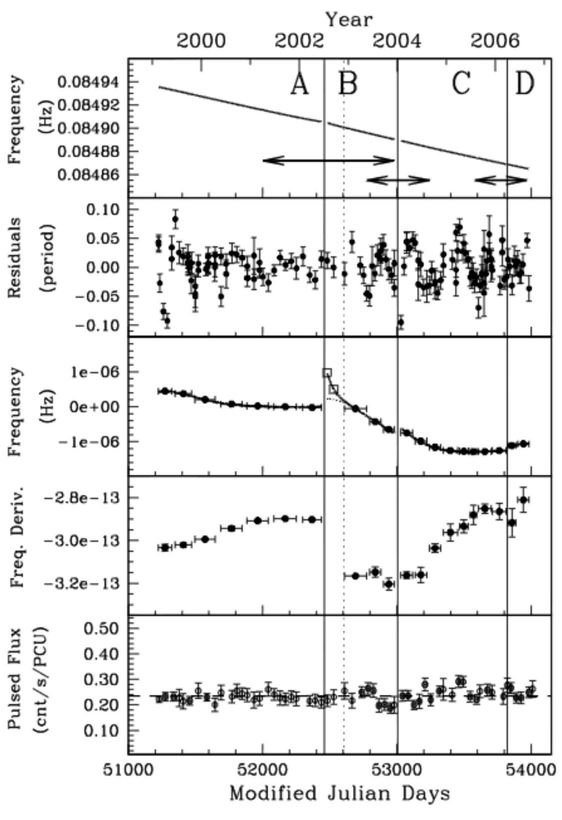
Rs'.

)00:

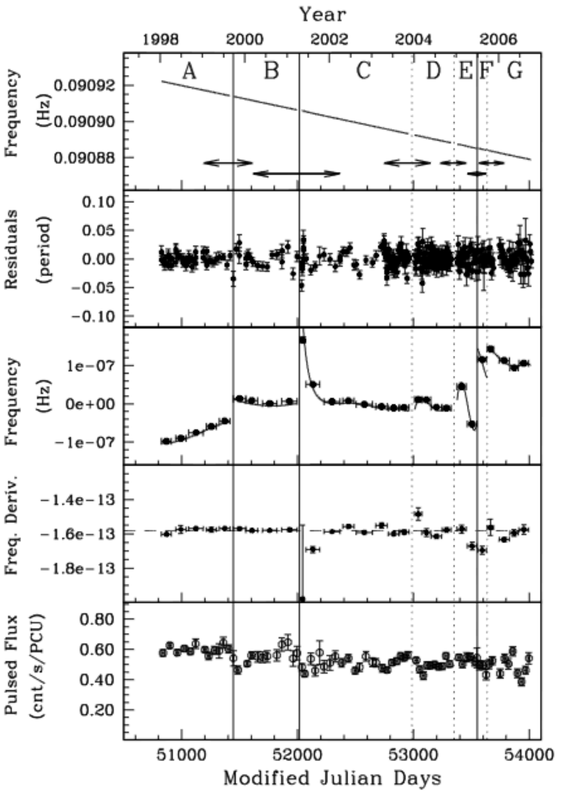
About modeling of magnetar bursts see 1203.4506:
glitches always are accompanied by energy release.

Glitches and bursts

Sometime magnetar glitches are related to bursts, sometime – not.

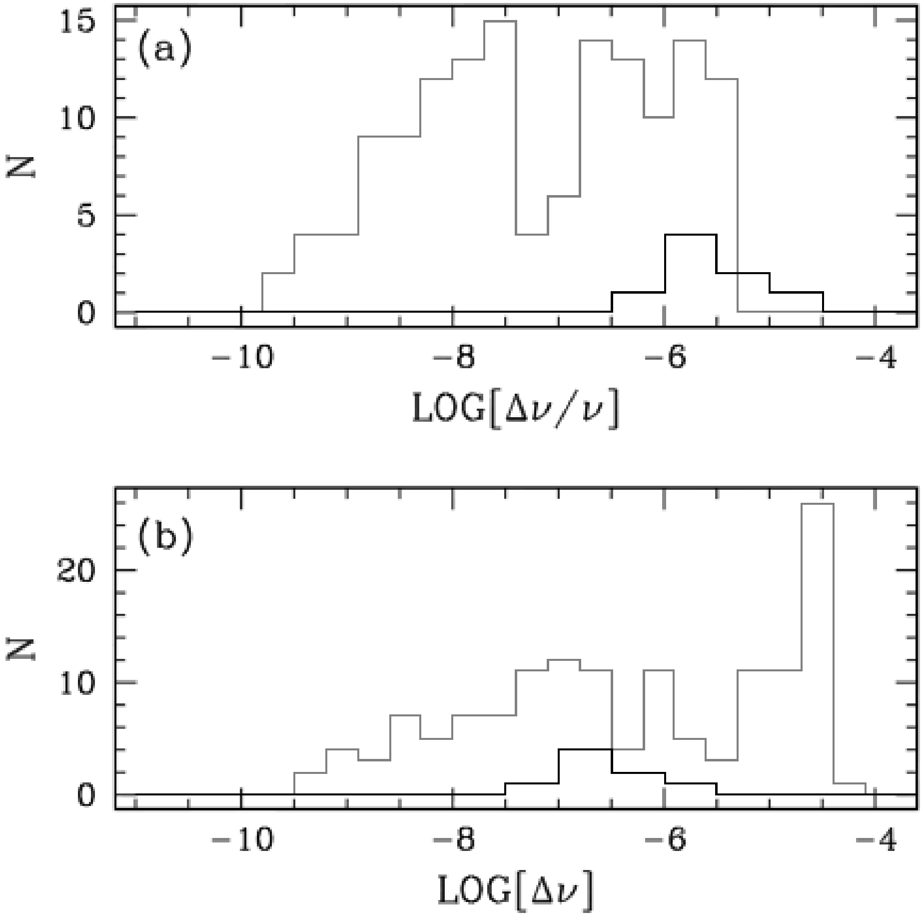


The pulsed flux was nearly constant during glitches.



1E 1841-045 From Dib et al. 2008 RXS J170849.0-400910

PSRs vs. magnetars



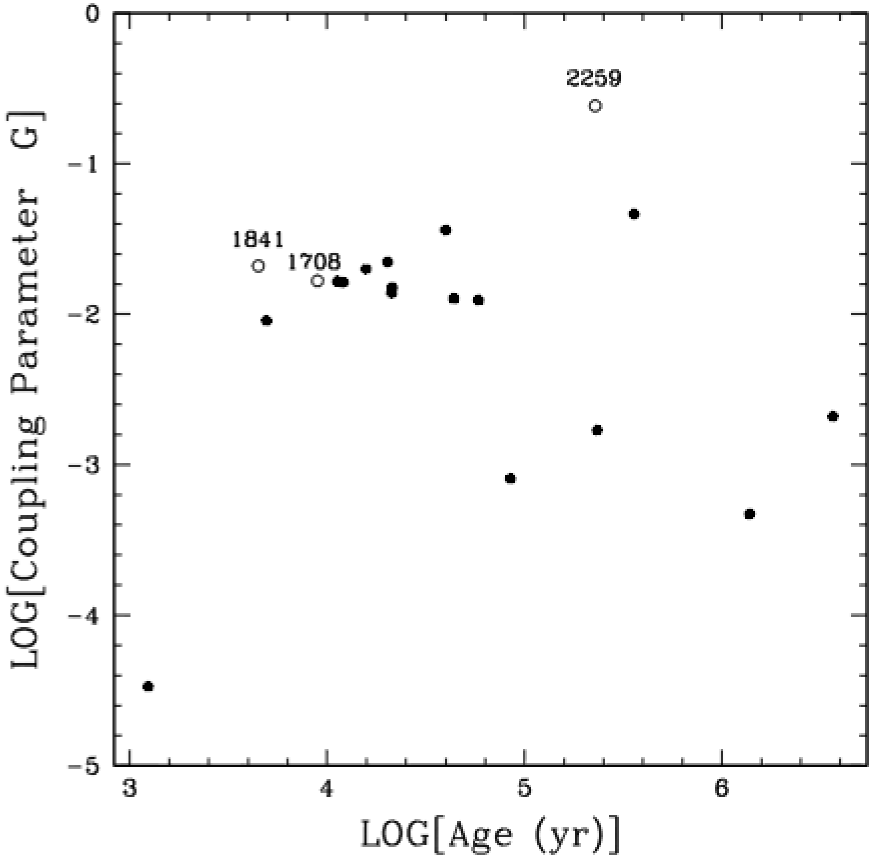
Nearly all known persistent AXPs now seem to glitch.

In terms of fractional frequency change, AXPs are among the most actively glitching neutron stars, with glitch amplitudes in general larger than in radio pulsars.

However, in terms of absolute glitch amplitude, AXP glitches are unremarkable.

Dib et al. 2008

Are PSRs and magnetar glitches similar?



$$\dot{J}_{\rm res} \leq I_{\rm res}|\dot{\Omega}|, \quad \frac{I_{\rm res}}{I_c} \geq \frac{\bar{\Omega}}{|\dot{\Omega}|} A \equiv G,$$

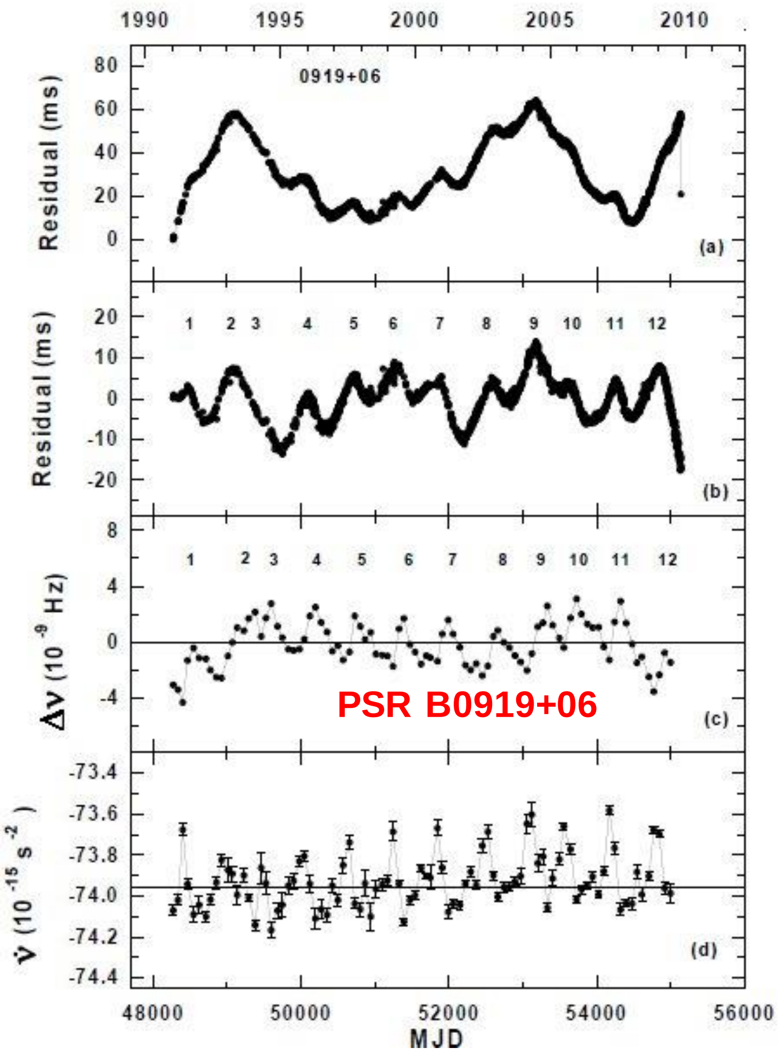
$$\frac{I_{\rm res}}{I_c} \geq G_{\rm Vela} = 1.4\%.$$

It seems that for some AXP glitches G is much larger than for PSRs. Dib et al. propose that it can be related to the role of core superfluid.

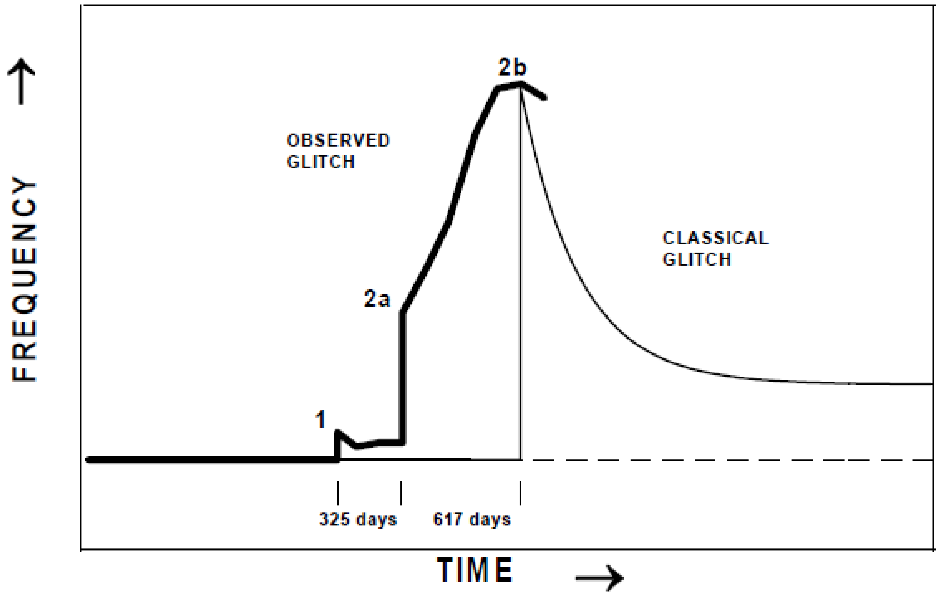
Many others proposed that glitches of magnetars can be related to magnetic field dissipation in the crust. As the field can be dynamically important there, its decay can result in crust cracking.

Dib et al. (2008), see arXiv: 0706.4156

Slow glitches

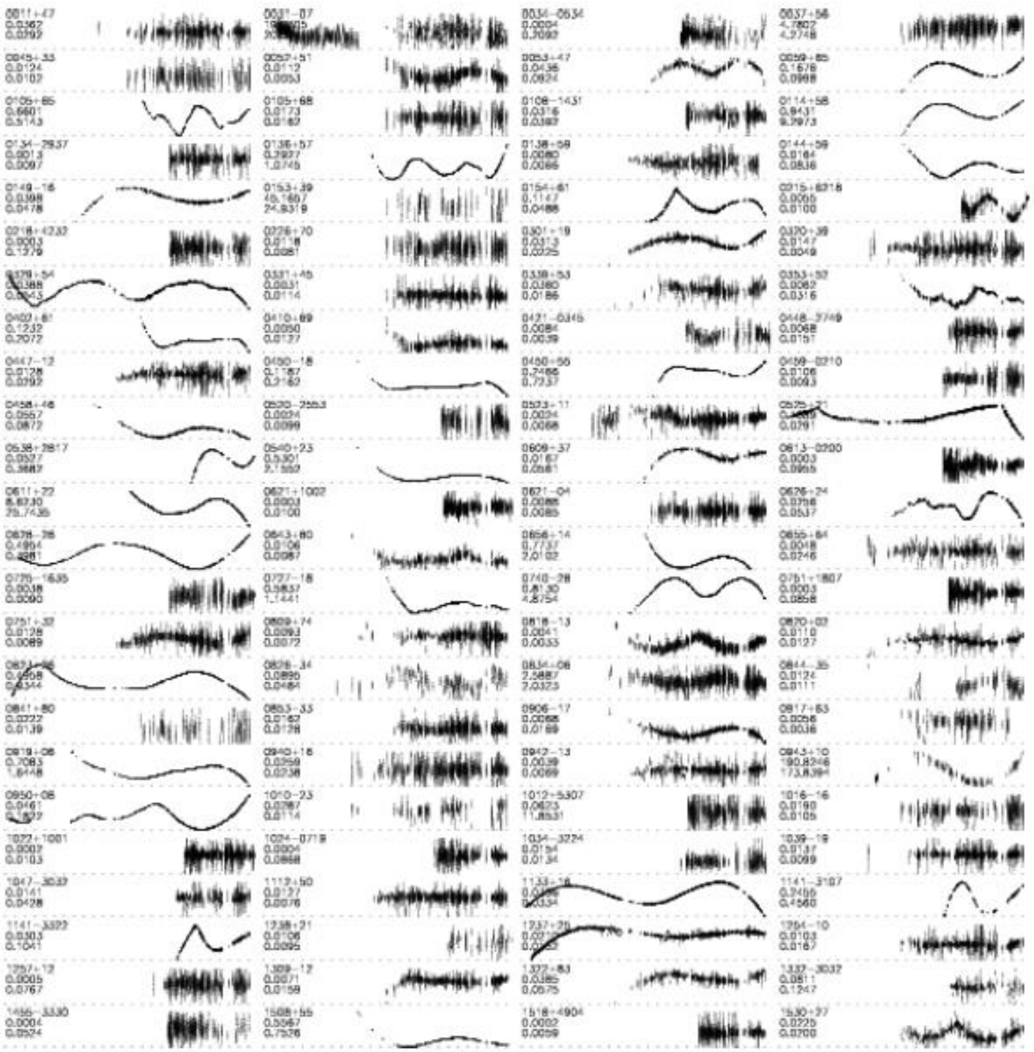


Below: a slow glitch by PSR B1822-09 (Shabanova 1998)



1007.0125

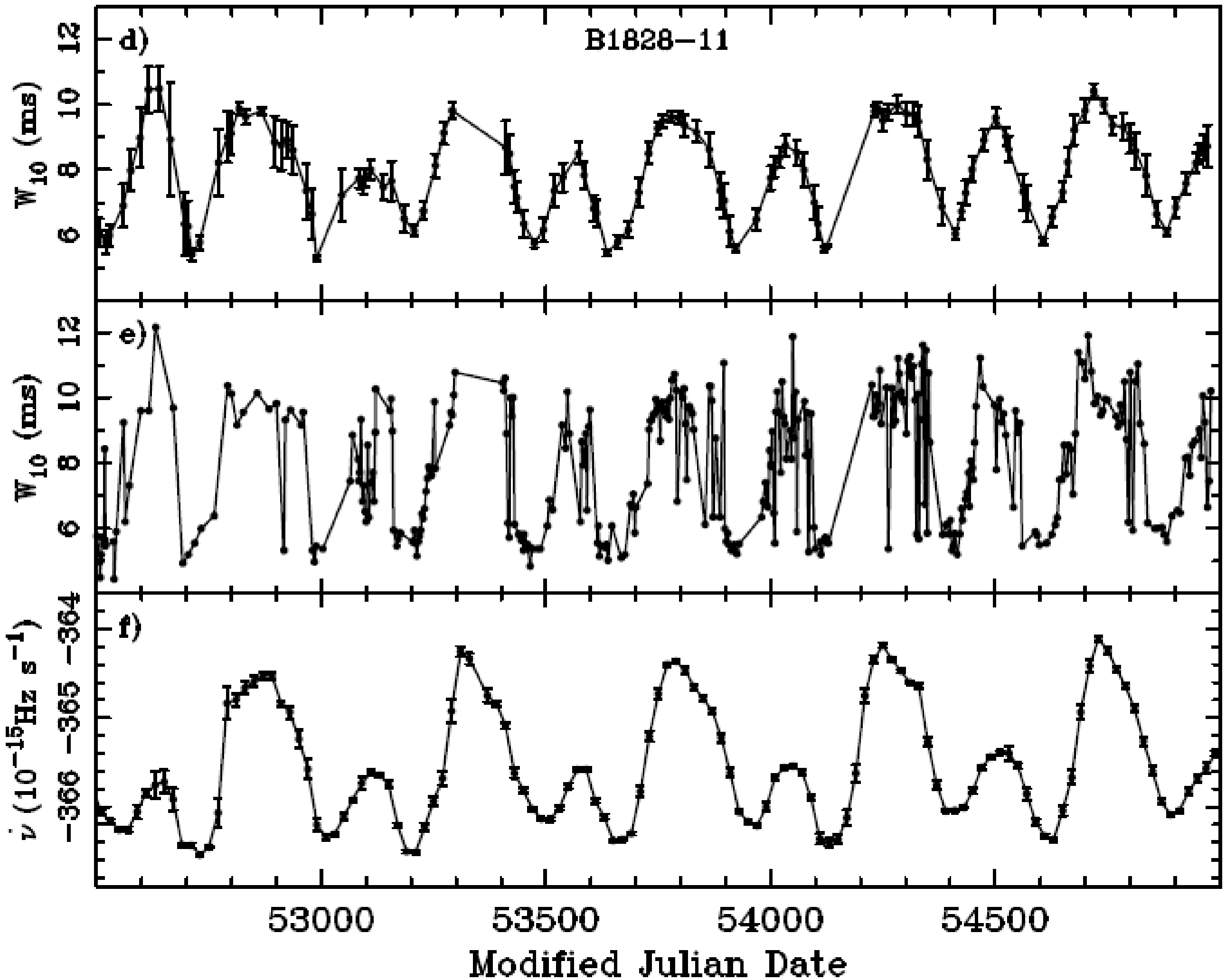
Timing irregularities



Analysis demonstrates different type of irregularities including quasi-periodic.

0912.4537

Possible explanation?



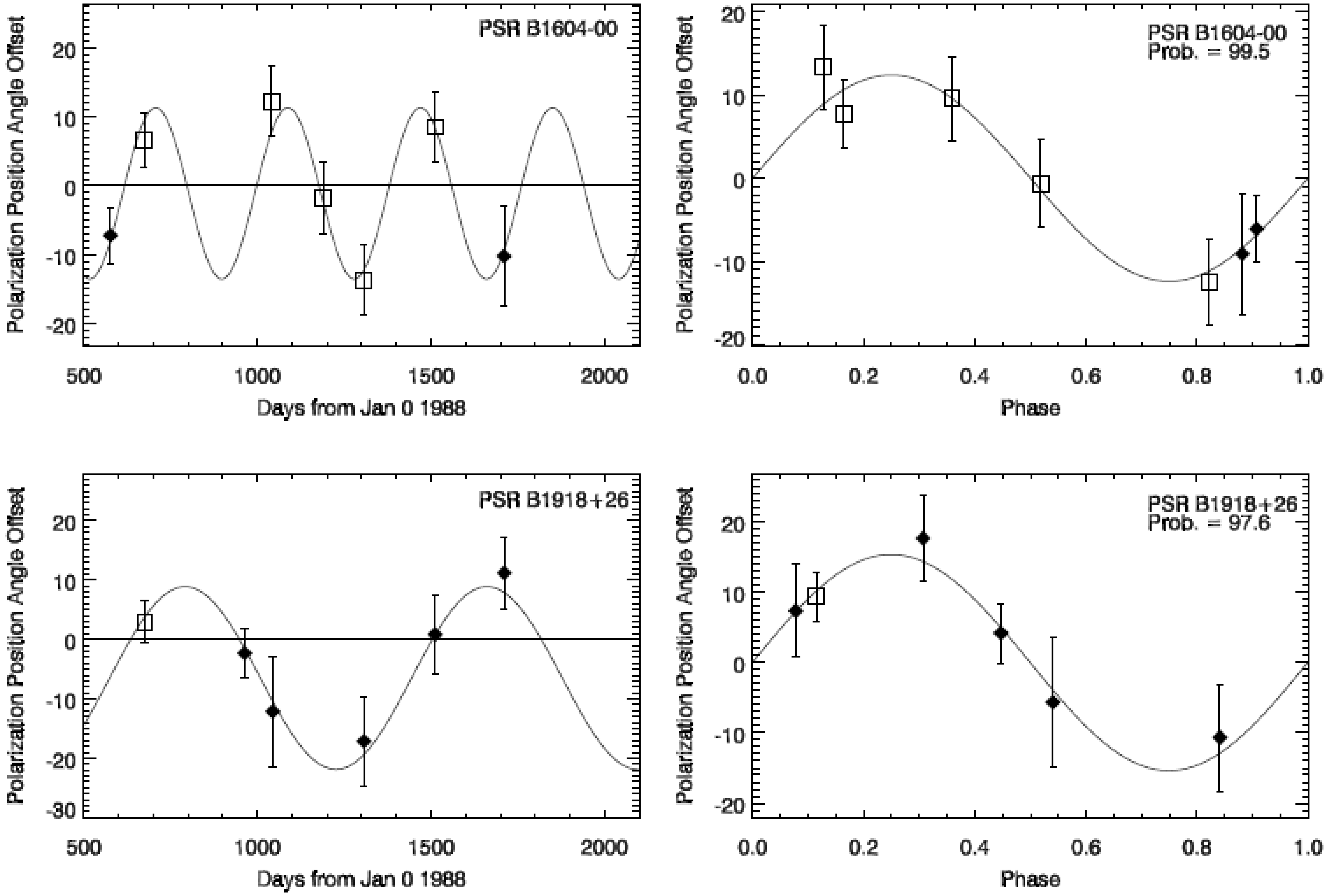
Magnetospheric effect?

Two stages characterized by particular pulse profile and spin-down rate.

Switching between these states happens rapidly.

1006.5184

Polarization angle variations

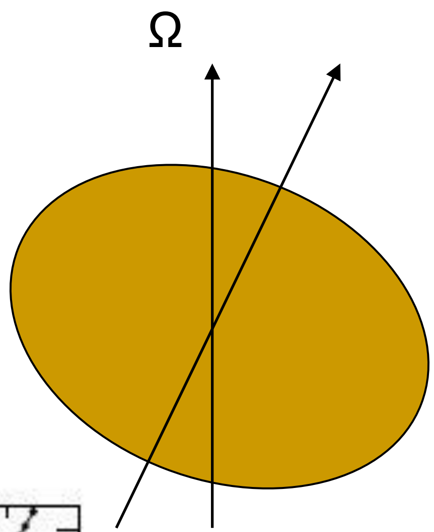


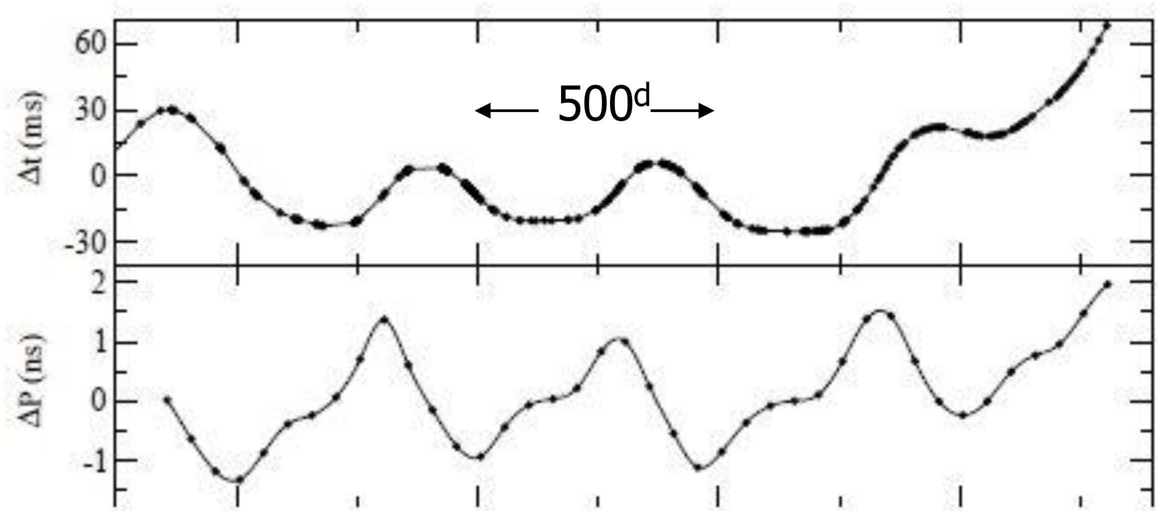
Weisberg et al. 2010

Precession in NSs

$P_{prec}=P/\varepsilon$,
ε-oblateness: $\varepsilon \sim 10^{-8}$ ⇒ $P_{prec} \sim$ year

(More complicated models are developed, too.
See Akgun, Link, Wasserman, 2005)





Time of arrival
and period residuals
for PSR B1828-11.
Wobbling angle is ~3-5^o

But why among ~1500
there are just 1-2
candidates… ?

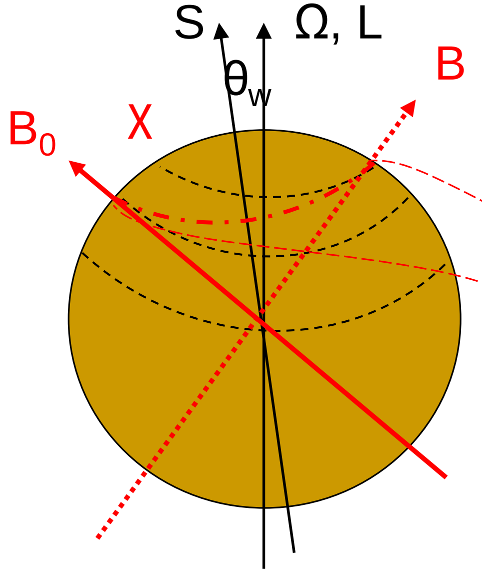
New analysis confirms that PSR 1826-11 can have precession (1510.03579).
Still, it is difficult to bring it in correspondence with glitches from this PSR (1610.03509).

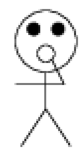
Precession (nutation)

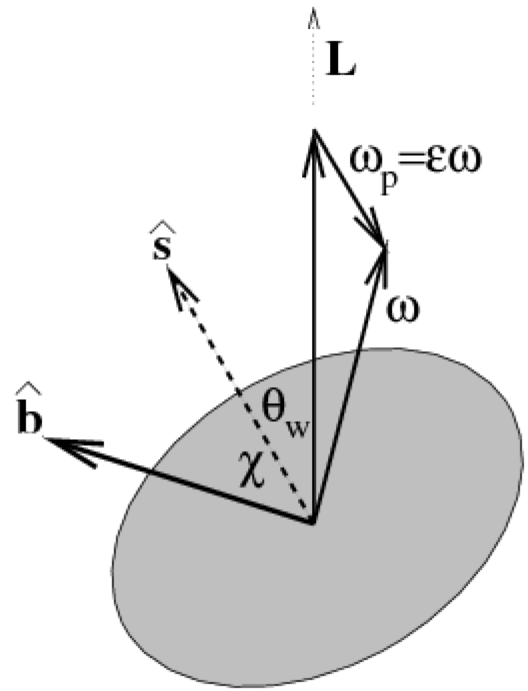
Θ_w – is small
Ω and L are very close

If we consider the free precession,
then we have a superposition of two motions:

1. Rapid (~Ω) rotation around total angular momentum axis – L
2. Slow (Ω_p) retrograde rotation around the symmetry axis (s)





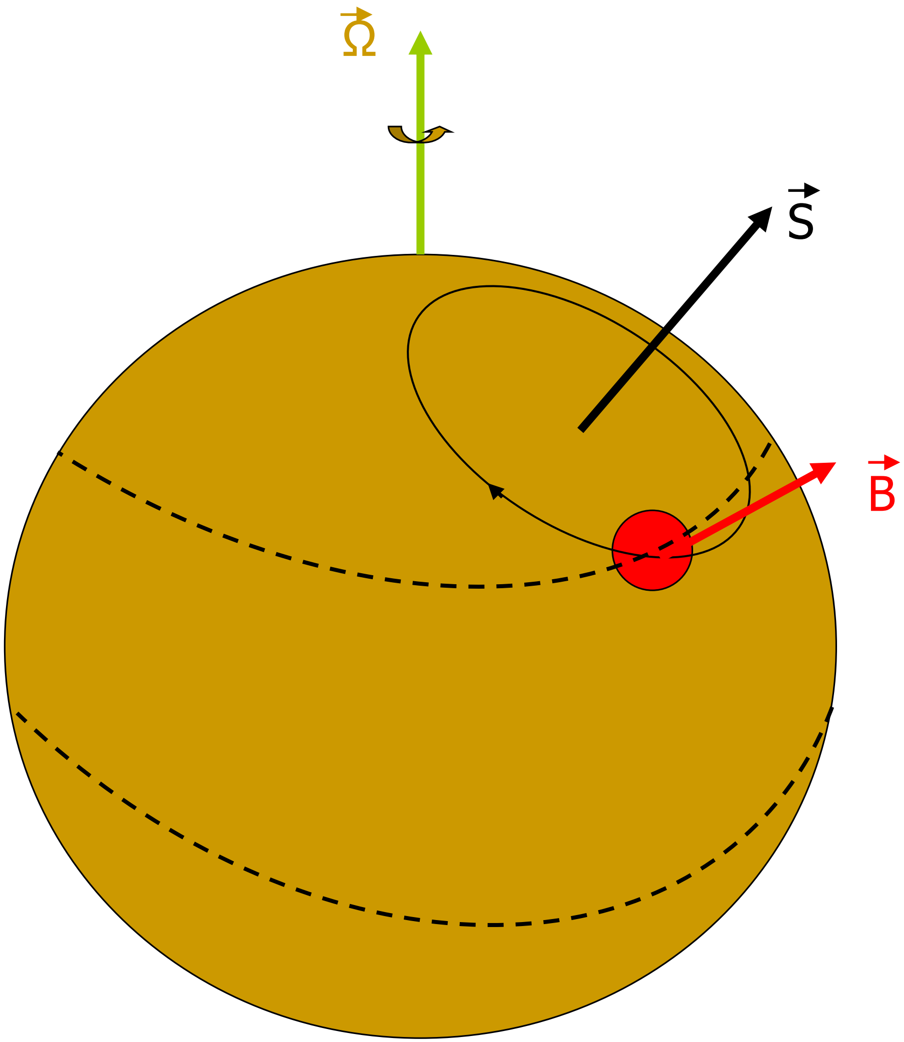


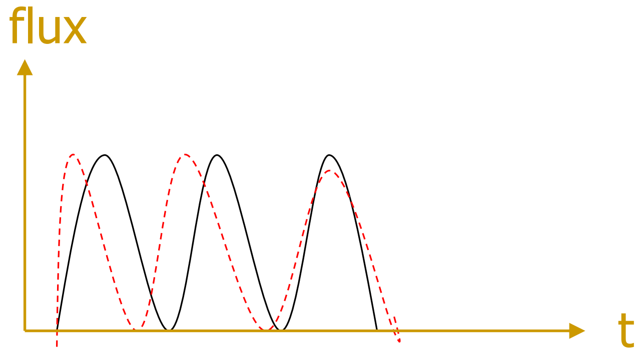
$\Delta\varphi=\varphi_{max}-\varphi_{min}=(\chi+\theta_w)-(\chi-\theta_w)=2\theta_w$

Beam width variation

See B. Link astro-ph/0211182

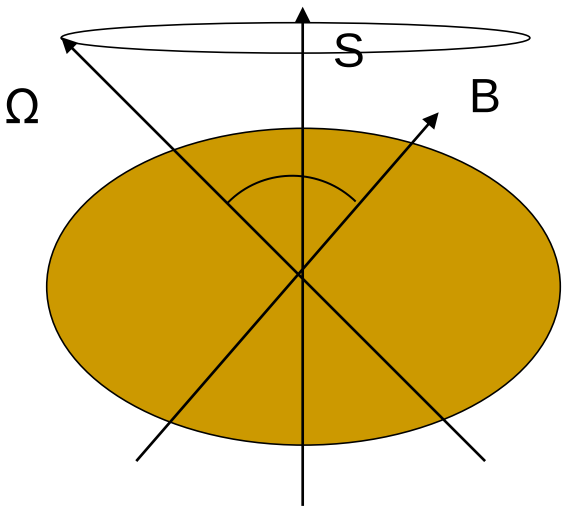
A toy model





This is a picture seen
by an external observer.

In the coordinate frame of the body

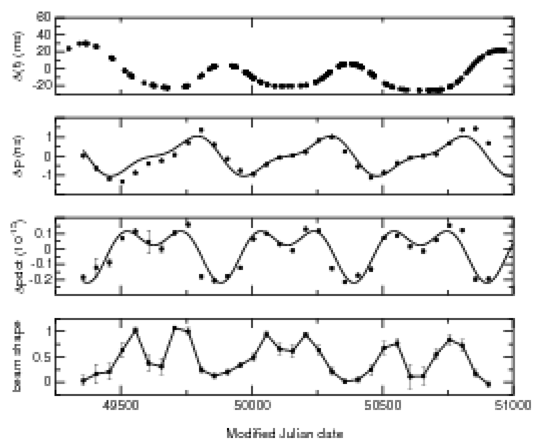


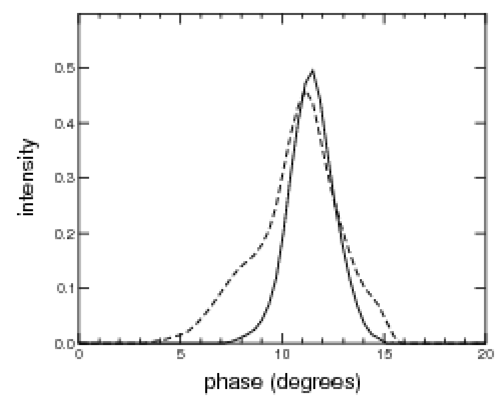
In this system the rotation axis is rotating around the symmetry axis.
So, it is clear that the angle between spin axis and the magnetic axis changes.

This results in an additional effect in timing:
Now the spin-down rate changes with the period of precession.

$$\frac{1}{2} I_1 \frac{d\omega^2}{dt} \simeq \boldsymbol{\omega} \cdot \mathbf{N},$$

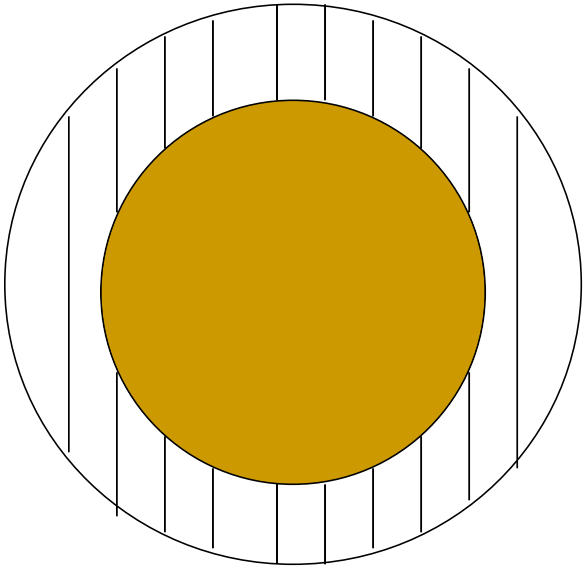
$$\mathbf{N} = \frac{2\omega^2}{3c^3} (\boldsymbol{\omega} \times \mathbf{m}) \times \mathbf{m},$$





Complications …

A neutron star is not a solid body …
At least crust contains superfluid neutron vortices.
They are responsible for I_p~0.01 of the total moment of inertia.



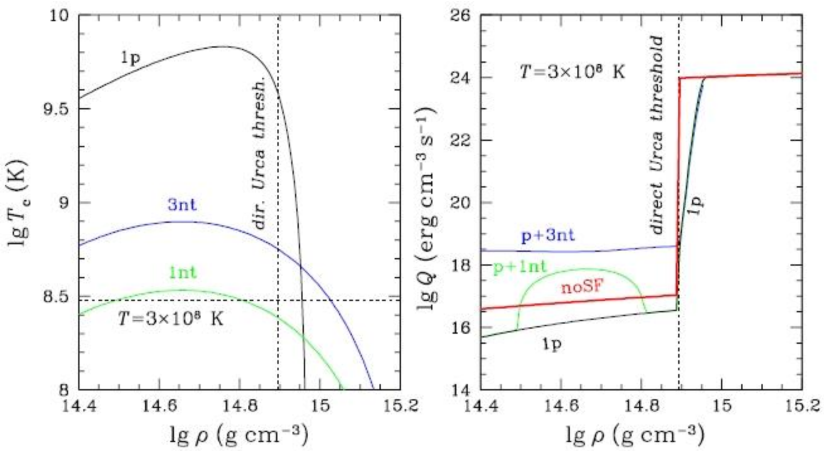
There are several effects related to vortices.

Neutron vortices can interact with the crust.
So-called "pinning" can happen.

The vortex array works as a gyroscope.
If vortices are absolutely pinned to the crust then $\omega_{prec}=(I_p/I)\Omega\sim10^{-2}\Omega$ (Shaham, 1977).
But due to finite temperature the pinning is not that strong, and precession is possible (Alpar, Ogelman, 1987).

Superfluidity in NSs

50 years ago it was proposed (Migdal, 1959) that neutrons in NS interiors can be *superfluid*.



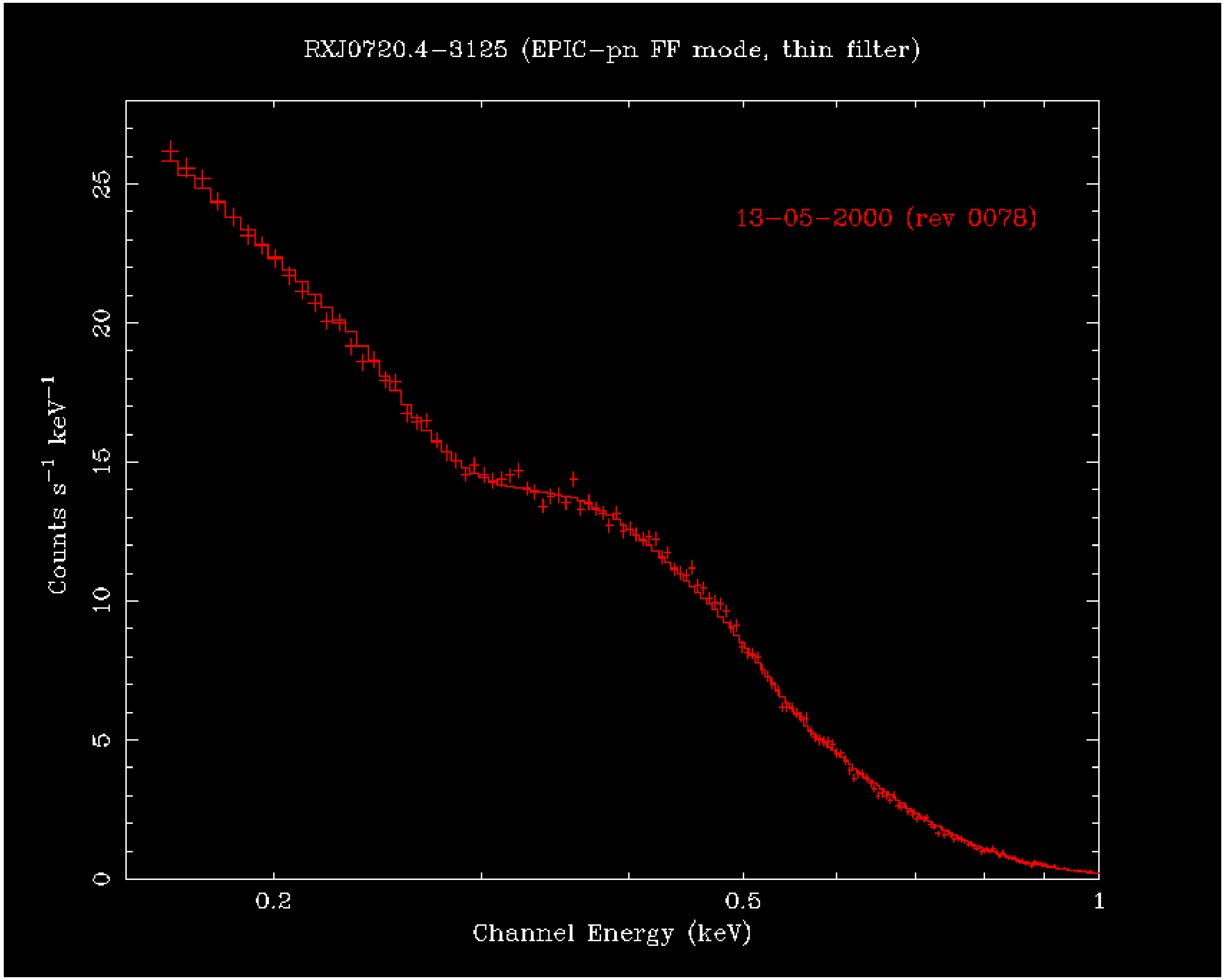
Various baryons in neutron star matter can be in *superfluid* state produced by Cooper pairing of baryons due to an attractive component of baryon-baryon interaction.

Now it is assumed that

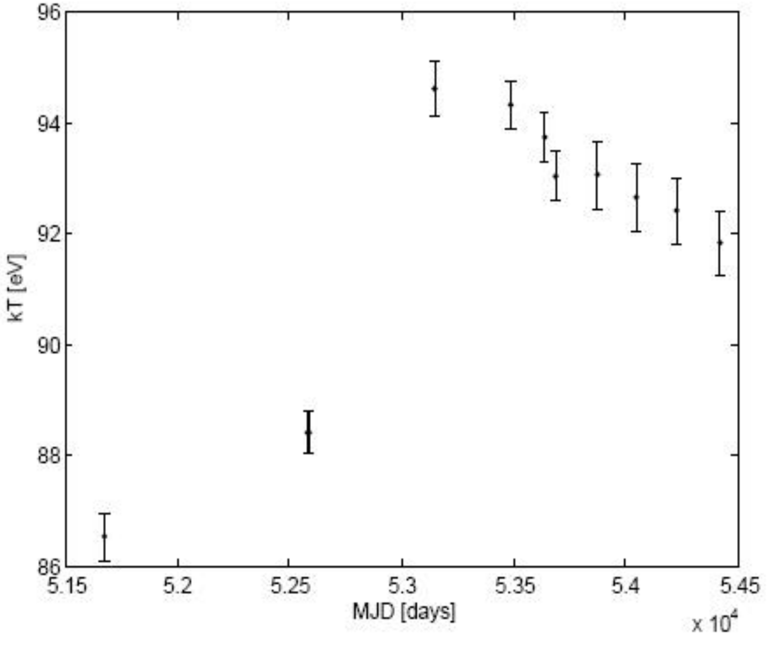
- neutrons are supefluid in the crust (singlet)
- protons are superfluid in the core (singlet)
- neutrons can also be superfluid in the core (triplet)

Onsager and Feynman revealed that rotating superfluids were threaded by an array of quantized vortex lines.

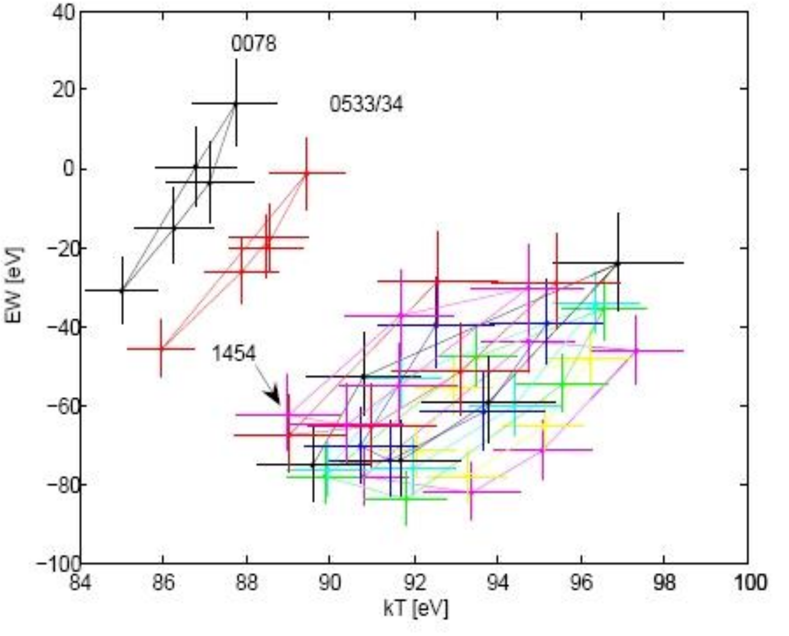
Peculiar behavior of RX J0720



RX J0720.4-3125 as a variable source



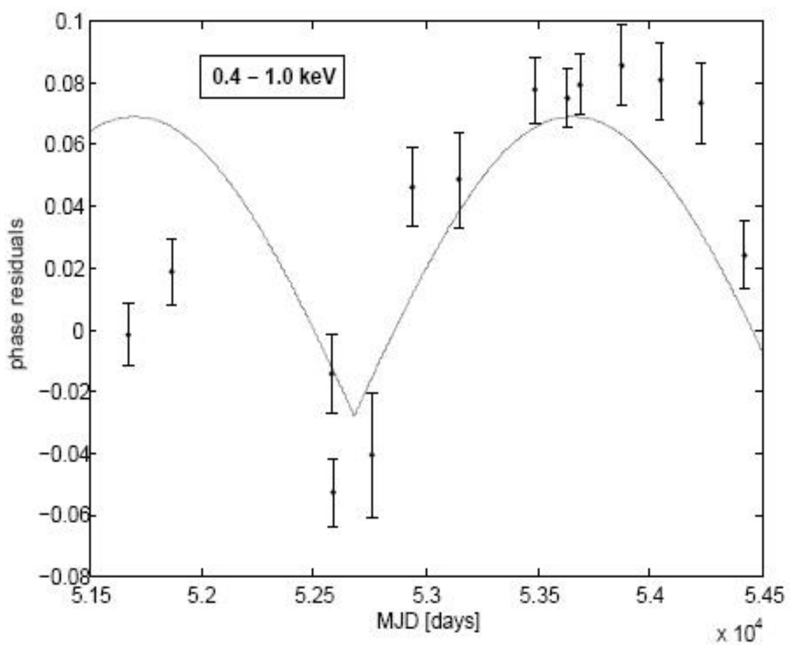
Long term phase averaged spectrum variations

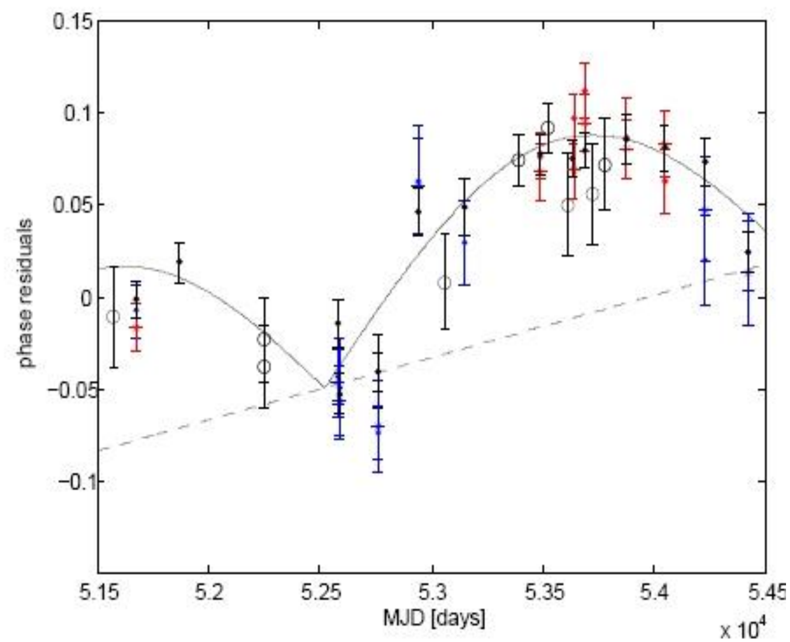


Phase dependent variations during different observations.

[Hohle et al. 2009 arXiv:0810.5319]

~10 years period: precession???





10.711 +/-0.058 yrs

[Hohle et al. 2009]

However, the situation is not clear.
New results and a different timing solution.
The estimate of the period of precession slightly changed down to ~7 years.

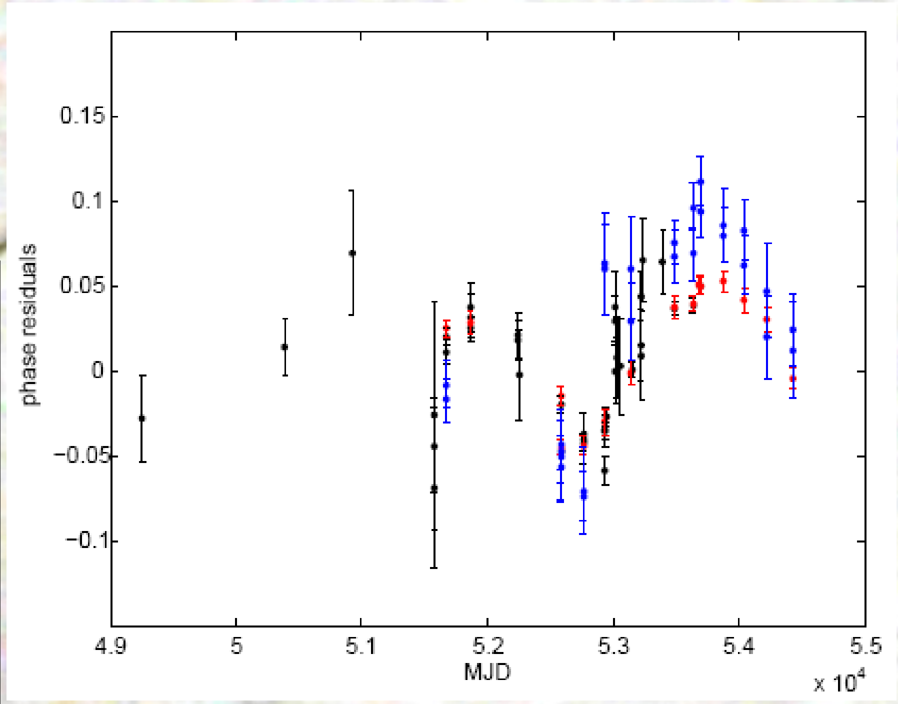
RX J0720.4-3125: timing residuals

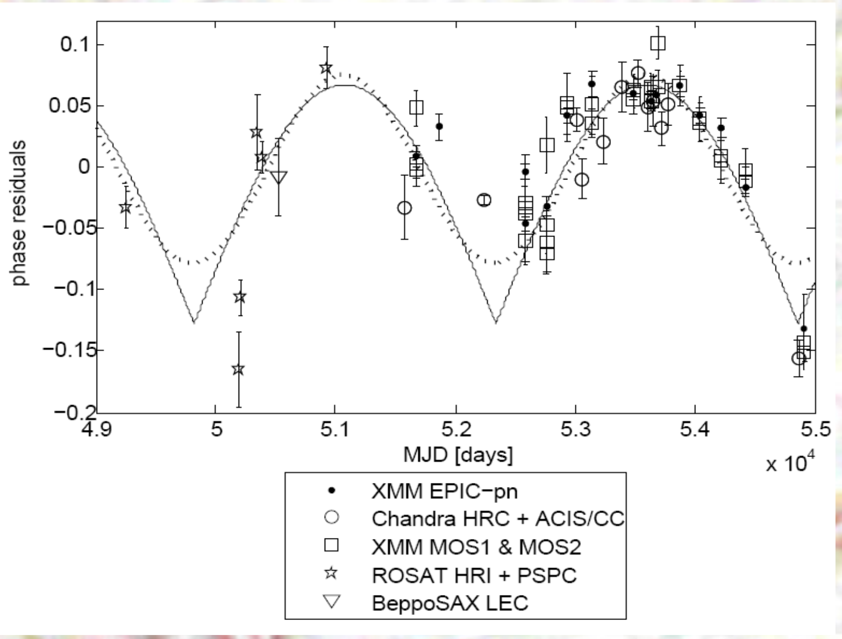
-for $P(t_0)$ and *dP/dt*: phase coherent timing
-in Kaplan & van Kerkwijk (2005) and van Kerkwijk 2007, without energy restriction

-now: restricting to the hard band (except for ROSAT and Chandra/HRC)
+five new XMM-Newton
+two new Chandra/HRC observations

$P(t_0)$=8.3911132650(91)s
dP/dt=6.9742(19) 10^{-14} s/s

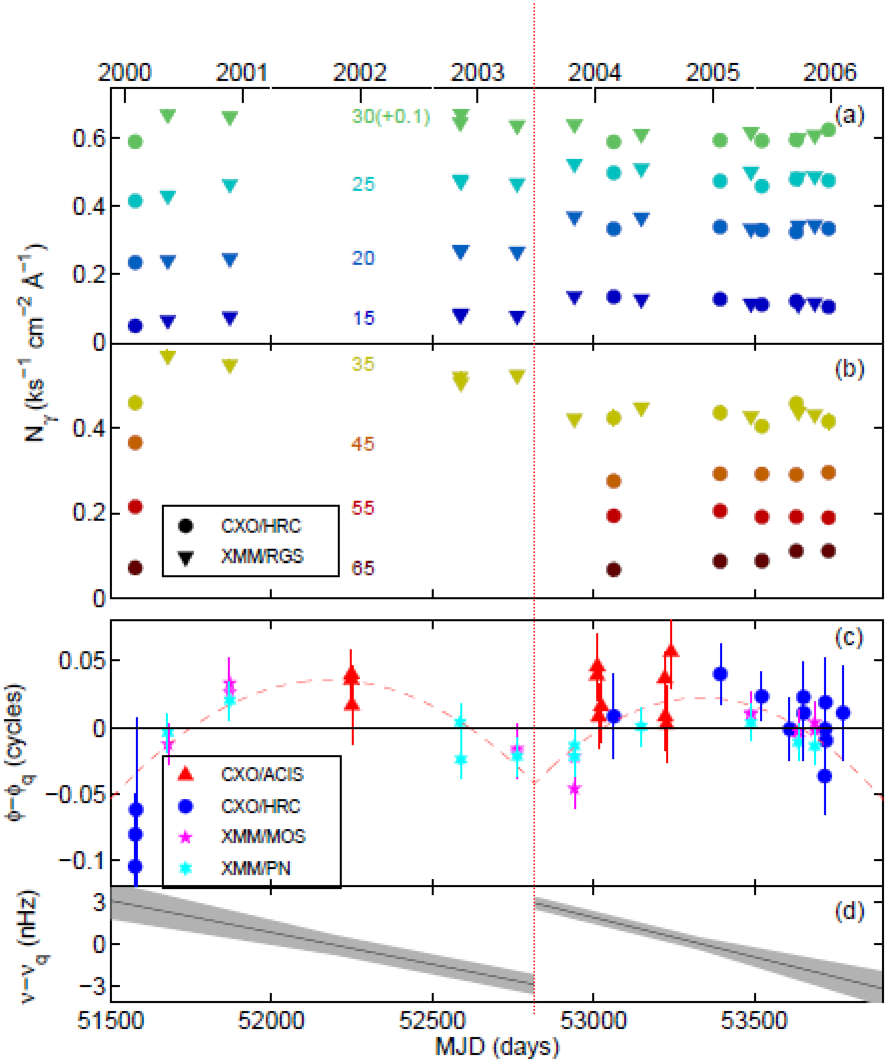
-long term period: (6.91 +/- 0.17) yrs
Haberl (2007): (7.70 +/- 0.60) yrs
for two hot spots: abs(sine)
with 13-15.5yrs period





The slide from a talk by Markus Hohle (Jena observatory).

Another interpretation: glitch + ?



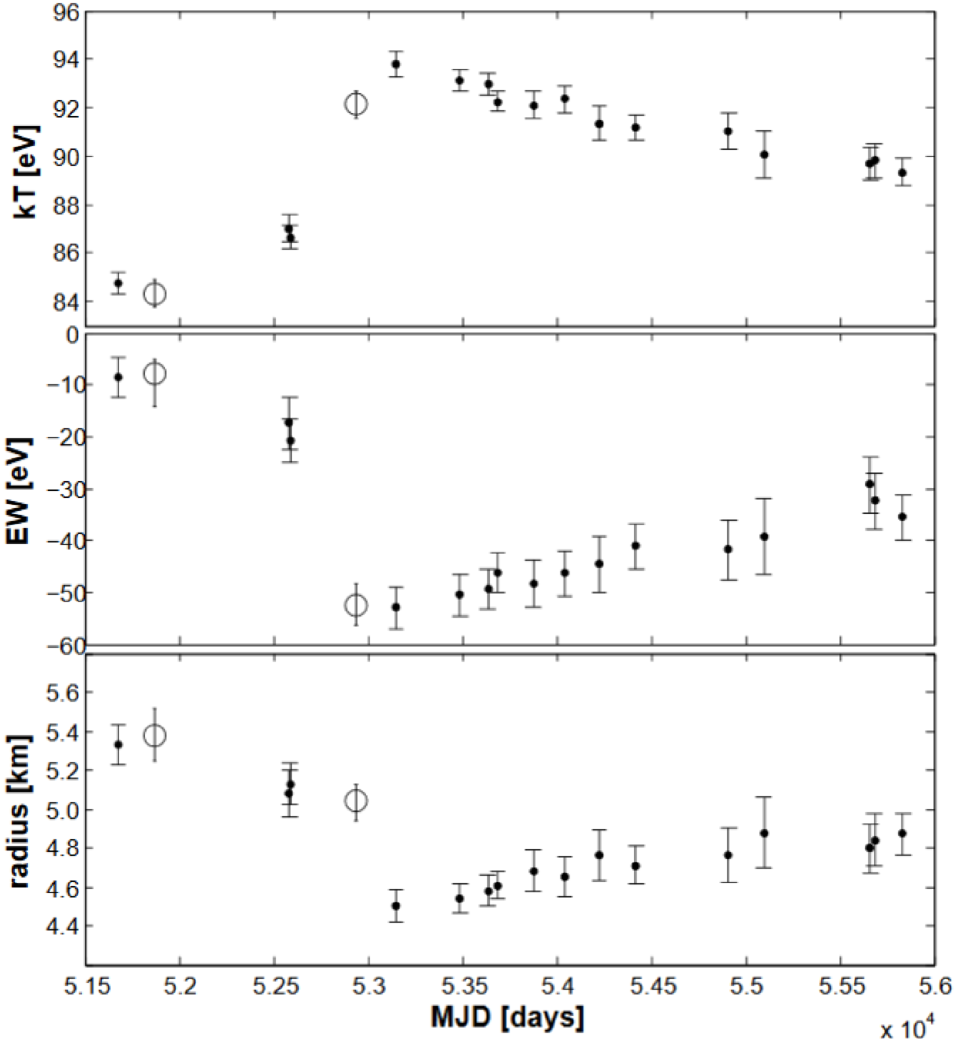
TIMING SOLUTIONS FOR RX J0720.4−3125

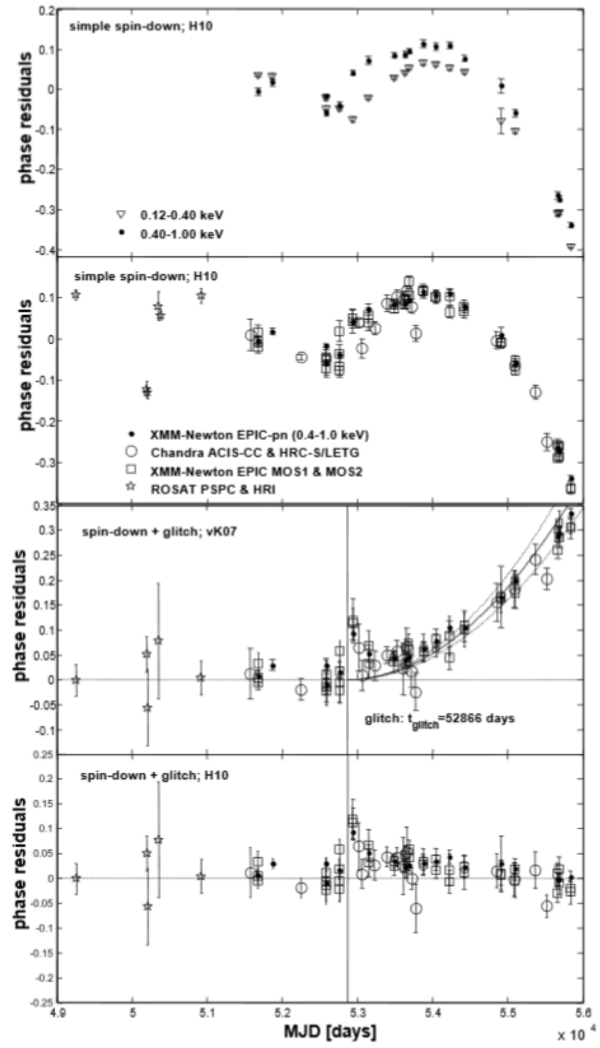
Quantity	Excl. *ROSAT*	All Data
Spindown only		
t_0 (MJD)	53010.2635646(7)	53010.2635626(6)
ν (Hz)	0.11917366979(12)	0.11917366954(11)
$\dot\nu$ (Hz s^{-1})	$-9.74(4)\times10^{-16}$	$-9.88(13)\times10^{-16}$
TOA rms (s)	0.26	0.29
χ^2/dof	77.6/46=1.69	150.8/49=3.08
Spin-down + Glitch		
t_0 (MJD)	53010.2635686(10)	53010.2635667(10)
ν (Hz)	0.1191736716(9)	0.1191736716(9)
$\dot\nu$ (10^{-15} Hz s^{-1})	−1.04(3)	−1.04(3)
t_g (MJD)	52817(61)	52866(73)
$\Delta\nu$ (nHz)	5.7(17)	4.1(12)
$\Delta\dot\nu$ (10^{-17} Hz s^{-1})	−1(4)	−4(3)
TOA rms (s)	0.15	0.24
χ^2/dof	37.0/43=0.86	45.1/46 = 0.98

NOTE. — The parameters determine the cycle count plus phase via $\phi(t)=\nu(t-t_0)+\frac{1}{2}\dot\nu(t-t_0)^2+\Delta\phi_g(t)$, where $\Delta\phi_g(t)=-\Delta\nu(t-t_g)-\frac{1}{2}\Delta\dot\nu(t-t_g)^2$ for $t<t_g$ in the glitch model and zero otherwise. For all fits, a 0.11 s systematic uncertainty has been added in quadrature to the times of arrival (TOAs), and the uncertainties quoted are twice the formal 1σ values.

Van Kerkwijk et al. astro-ph/0703326

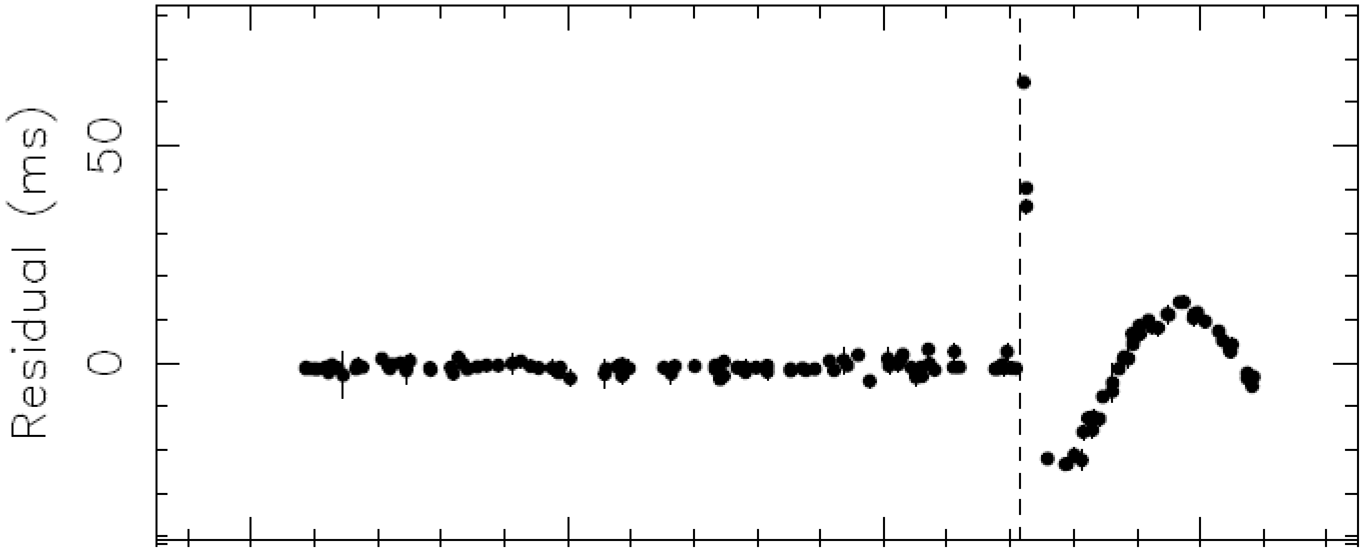
RX J0720.4-3125: a glitch





1203.3708

Glitch+? in a PSR



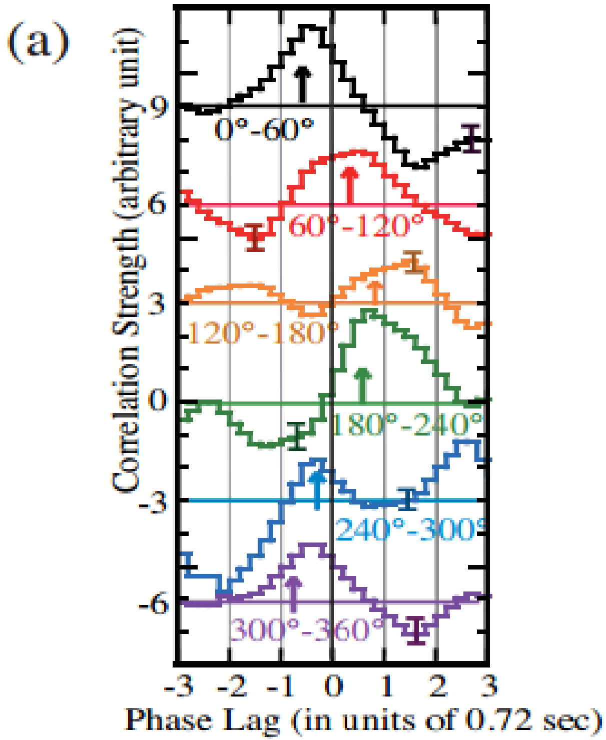
PSR B2334+61

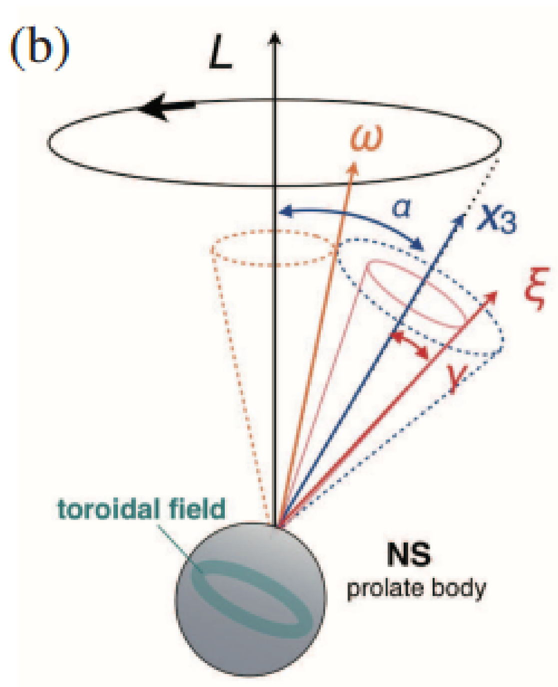
arXiv: 1007.1143

Precession after a glitch was proposed as possible feature due to Tkachenko waves excitation (arXiv: 0808.3040).

Precession as a viable mechanism for long-term modulation was recently discussed in details in 1107.3503.

Free precession of a magnetar?



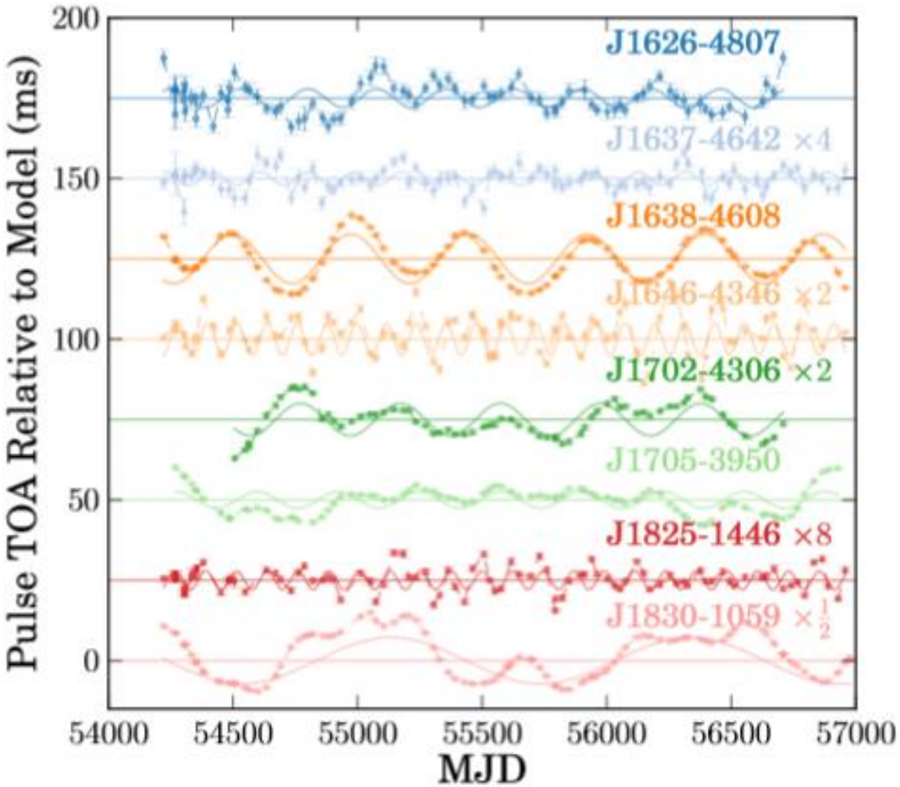


The authors observe modulation of the pulse profile with a period ~15 hours.

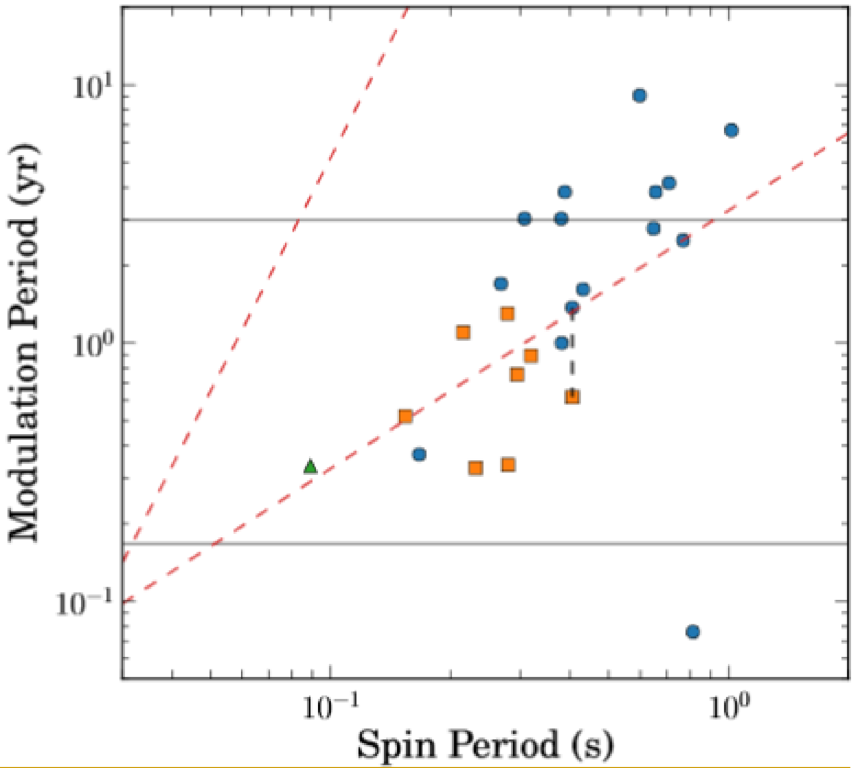
If it is interpreted by a free precession, than the NS is significantly deformed which can be due to strong toroidal field. This field might be ~10^{16} G.

1404.3705

New precession candidates among PSRs



Periodic modulations which can be interpreted as free precession.



Correlations of the modulation period with spin period, characteristic age and spin-down power.

1510.06078

Conclusion

Many observed phenomena are related to internal dynamics of NSs.

• Glitches
• Precession

Glitches are related to the existence of some reservoir for angular momentum. Most probably, it is a layer of superfluid neutrons in the inner crust.

Some glitches of magnetars can be related to a different process.

Main papers

- Link et al. astro-ph/0001245 Glitches
- Link astro-ph/0211182 Precession
- Jones, Andersson astro-ph/0011063 Precession
- Dib et al. arXiv: 0706.4156 AXP glitches
- Haskell, Melatos arXiv: 1502.07062 Big review