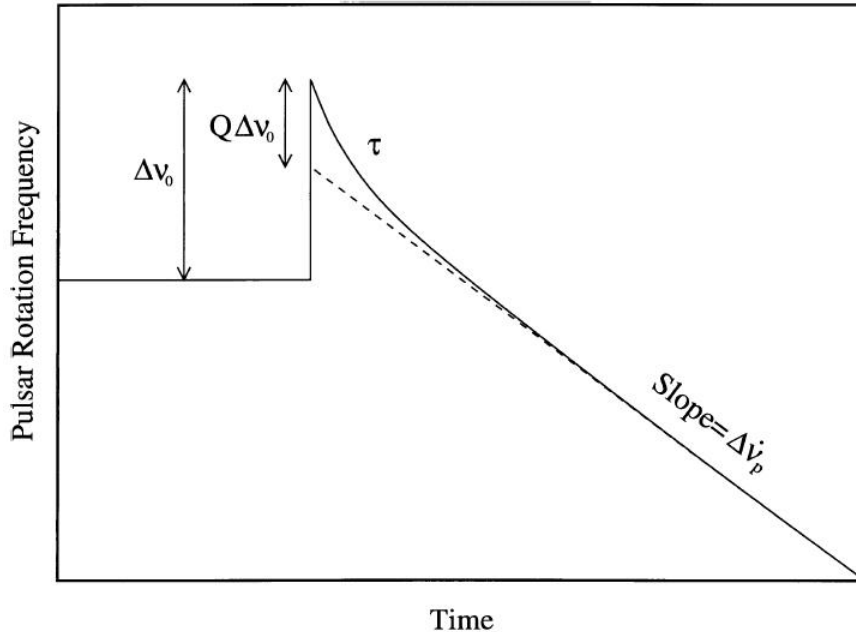# Glitches and precession

What is a glitch?

A sudden increase of rotation rate (limits are down to <40 sec in Vela).

ATNF catalogue gives >130 normal PSRs with glitches.

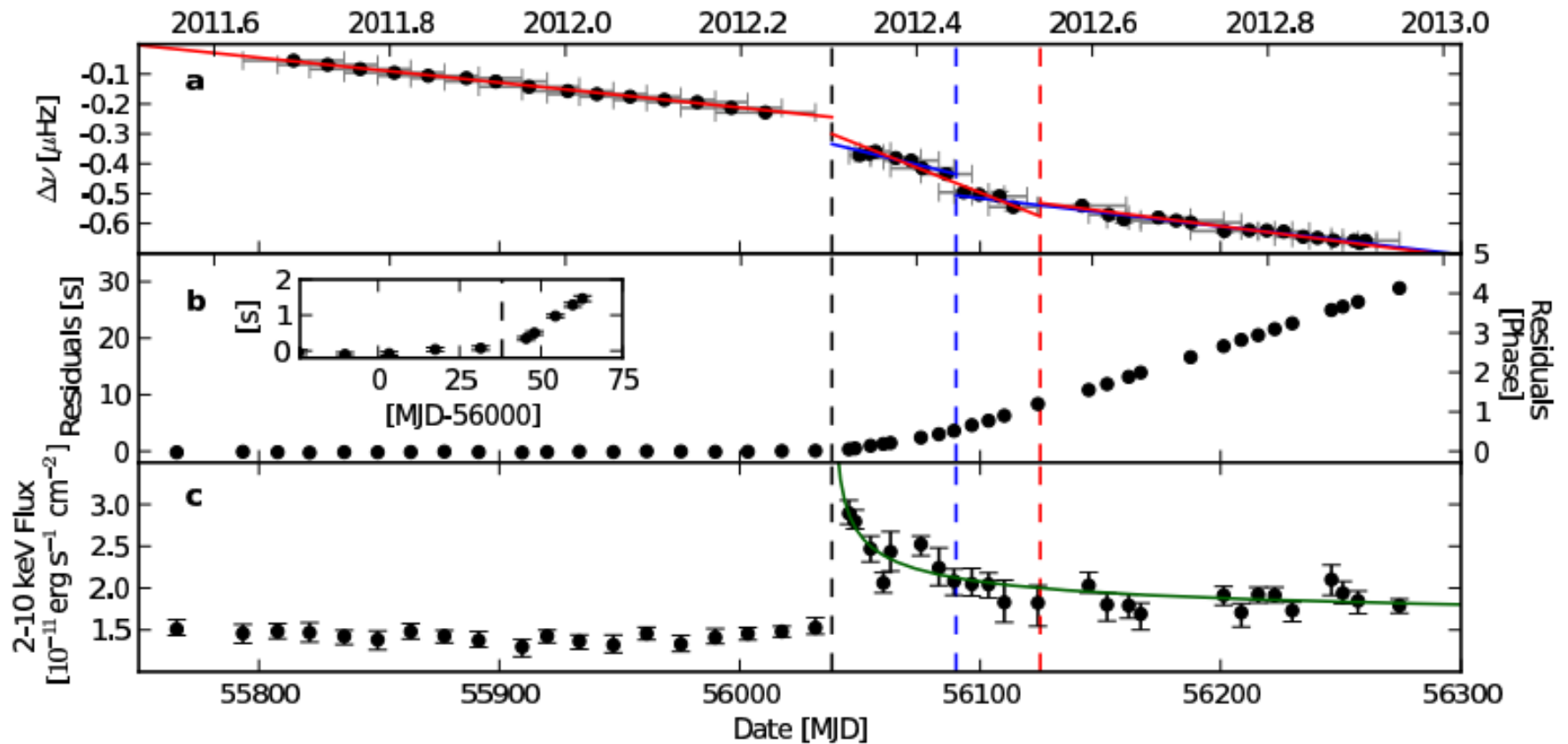The most known: Crab and Vela

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

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

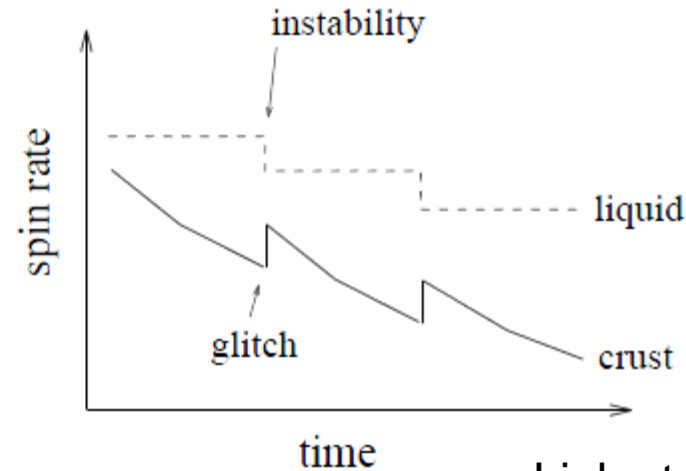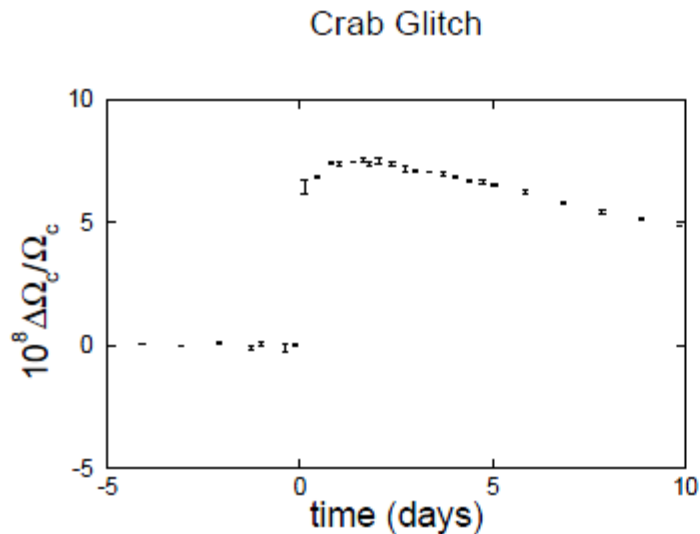**Starquakes or/and vortex lines unpinning - new configuration or transfer of angular momentum**

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

See a review in 1502.07062
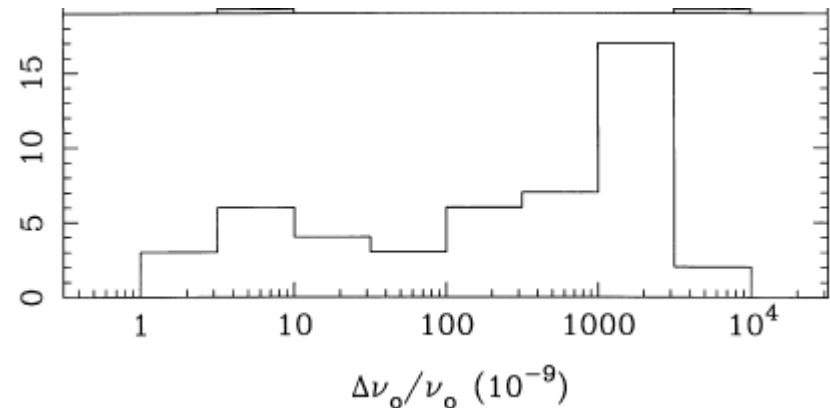
Anti-glitch of a magnetar

AXP 1E 2259+586

1305.6894

Crab glitch and the general idea
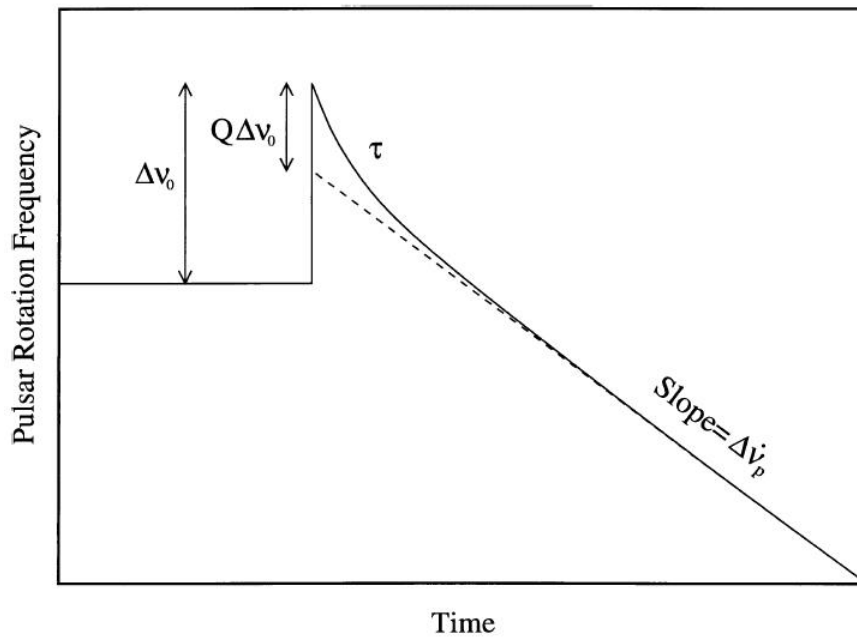
Crab Glitch

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 (<40 sec) an additional
momentum stored in such a "reservoir"
is released and given to the crust.
The crust spins-up,
up the internal reservoir – down.
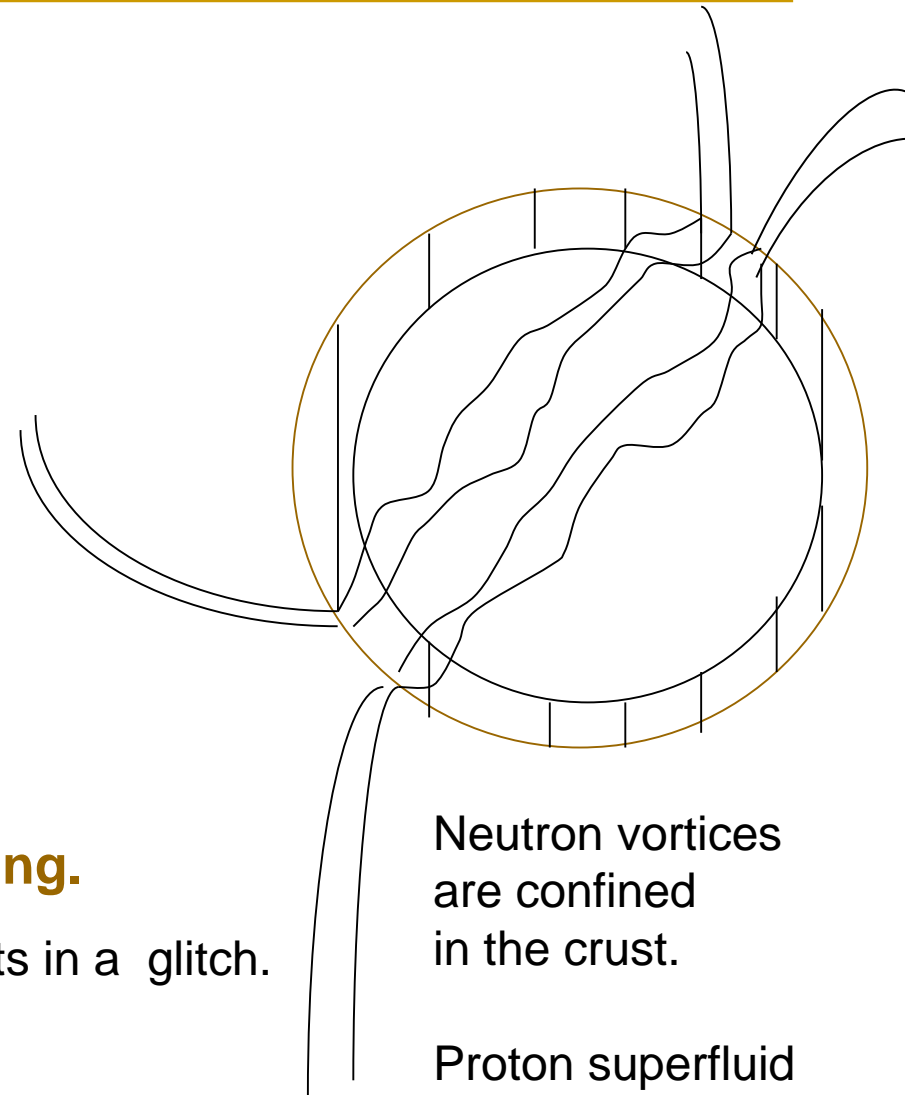

Lyne et al. (2000)

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}
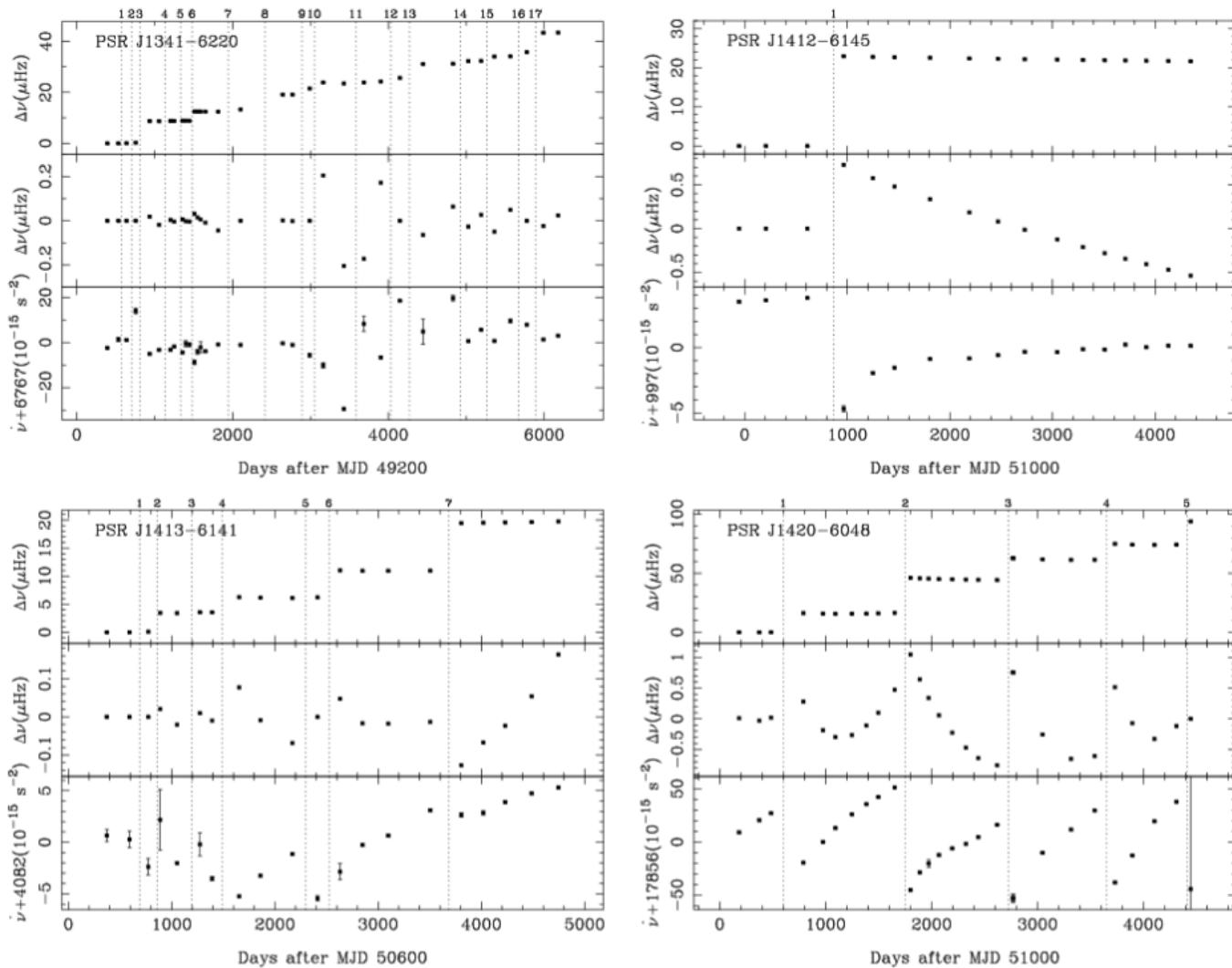
Flux lines density is $5 \cdot 10^{18}$ B$_{12}$ cm^{-2}

Neutron vortices are confined in the crust.

Proton superfluid is strongly coupled to the crust.

A recent review about superfluidity in NS and its relation to glitches, etc.: 1709.10340

Glitch discovery and observations

The largest glitch of the Crab pulsar
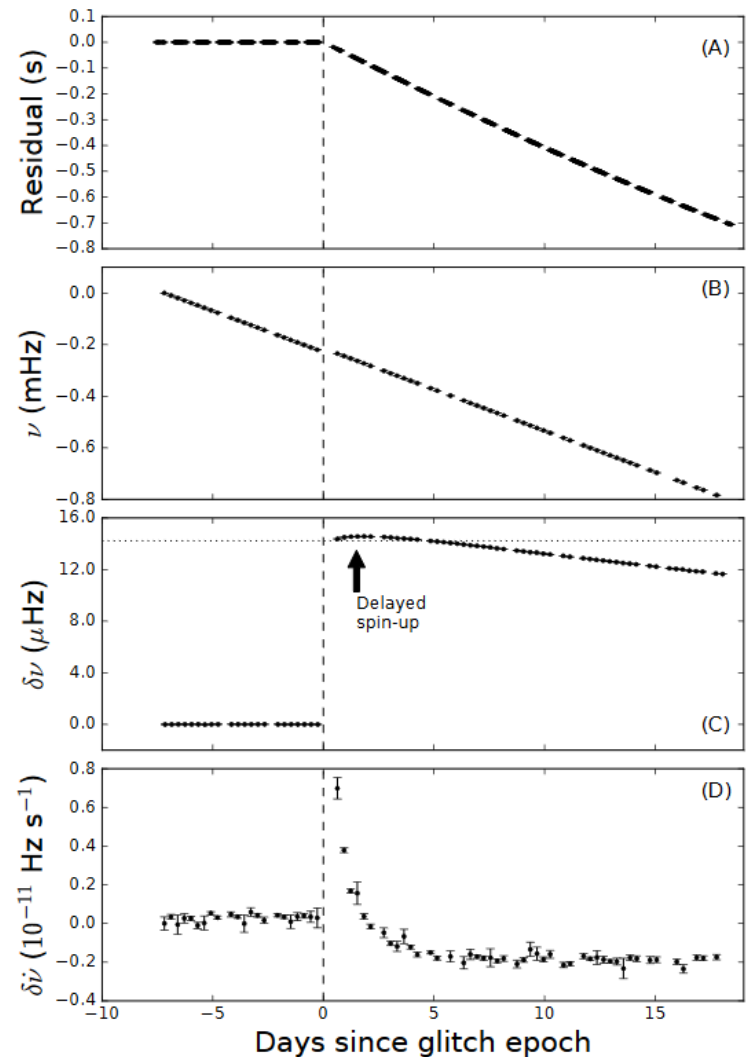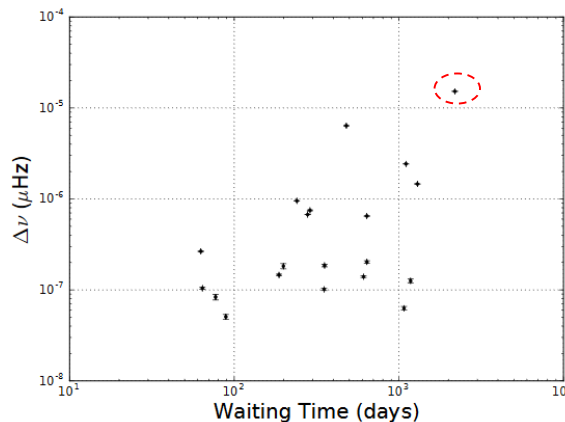
2017 November 8

$$\Delta\nu = 1.530 \times 10^{-5} \text{ Hz}$$

$$\Delta\nu/\nu = 0.516 \times 10^{-6}$$

$$\Delta\dot{\nu}/\dot{\nu} = 7 \times 10^{-3}$$

The glitch occurred
after the longest period
of glitch inactivity –
6 years, -
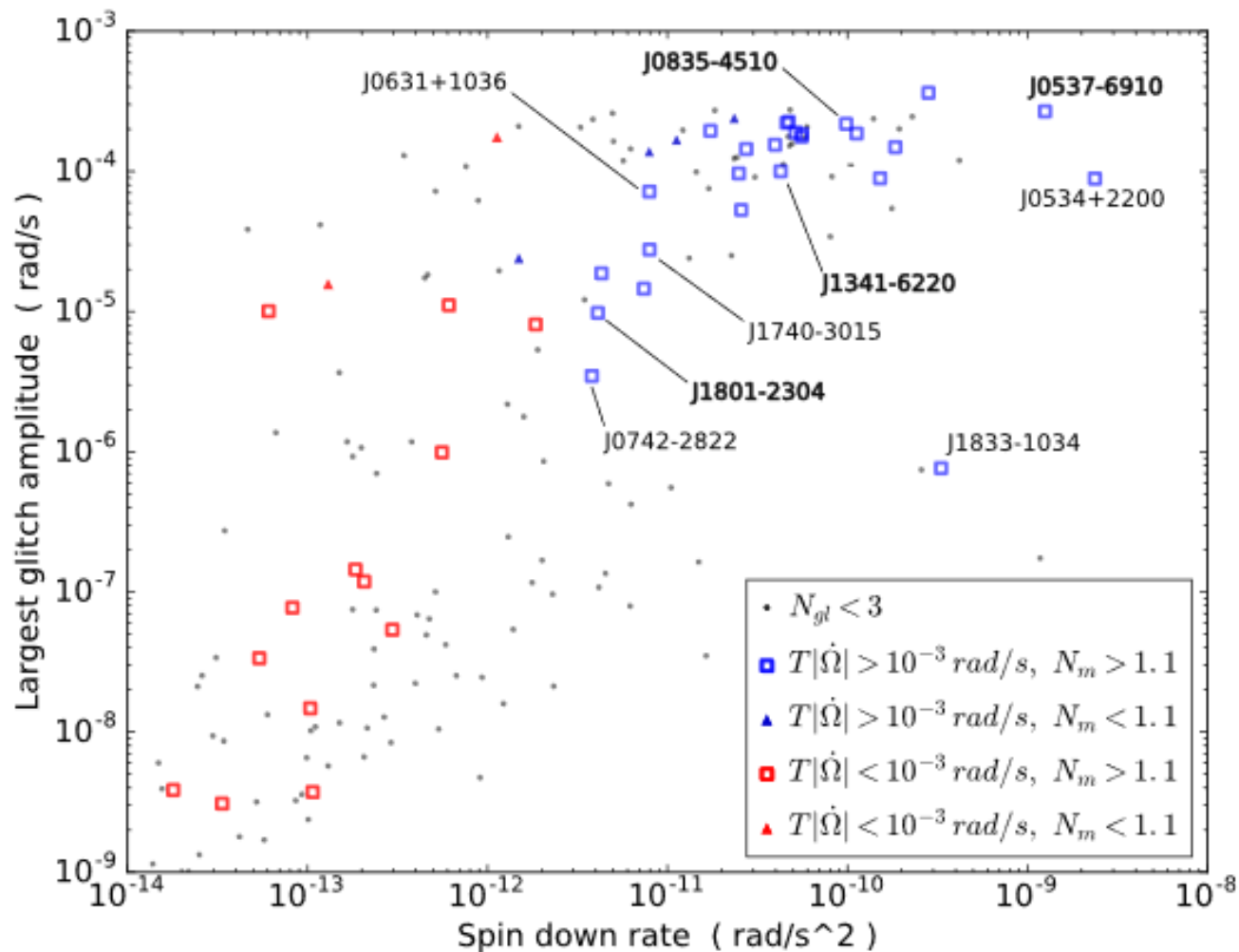since beginning
of daily monitoring
in 1984.

No changes in
the shape of
the pulse profile,
no changes
in the X-ray flux.

1805.05110

(See theoretical discussion in 1806.10168)

Glitch size – spin down rate correlation

Phenomenology and the Vela pulsar
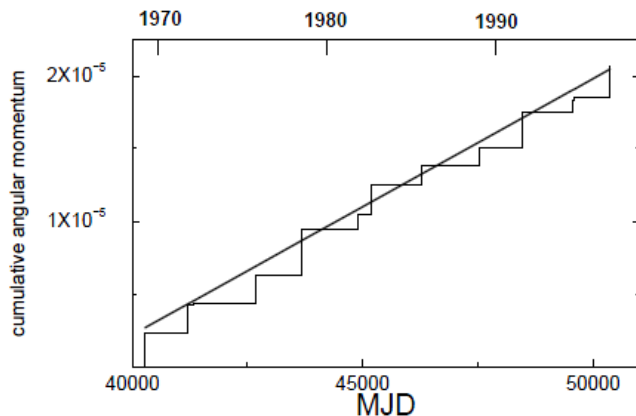
$$\Delta J_i = I_c \Delta \Omega_i,$$

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

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 $I_c \bar{\Omega} A,$

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

In Vela glitches can be related also to the outer core 1806.10168

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).

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

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

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

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

$$\frac{I_{res}}{I_c} \geq G_{Vela} = 1.4\%.$$
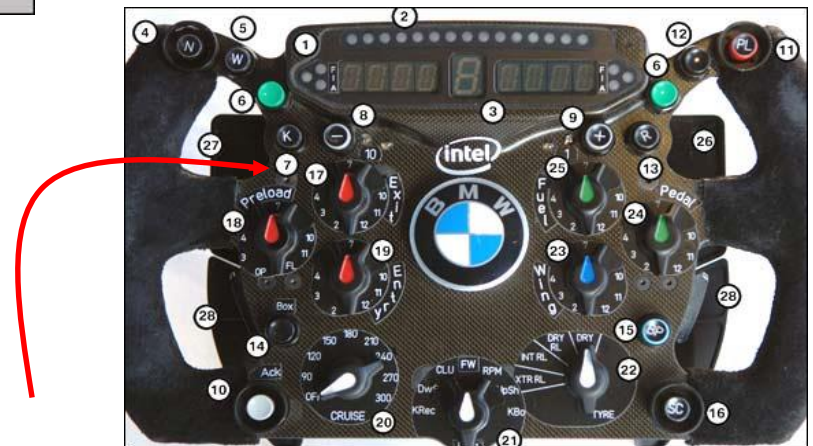
Glitch statistics for Vela provide an estimate for G.

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
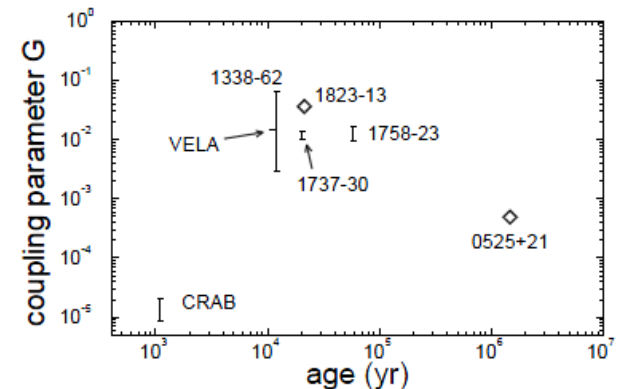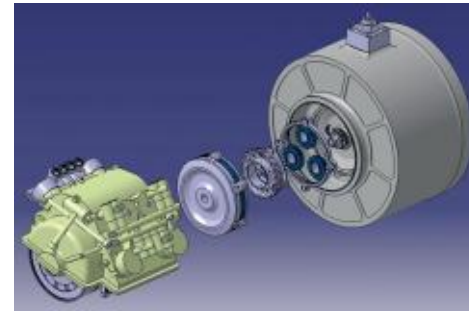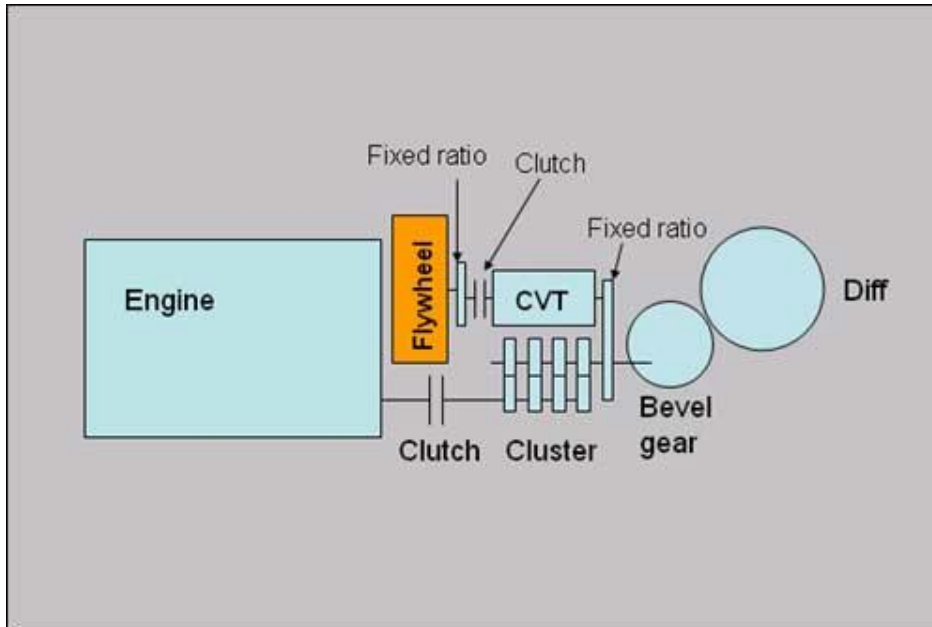
KERS

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.

$I_{super}/I_{crust} \sim 10^{-2}$

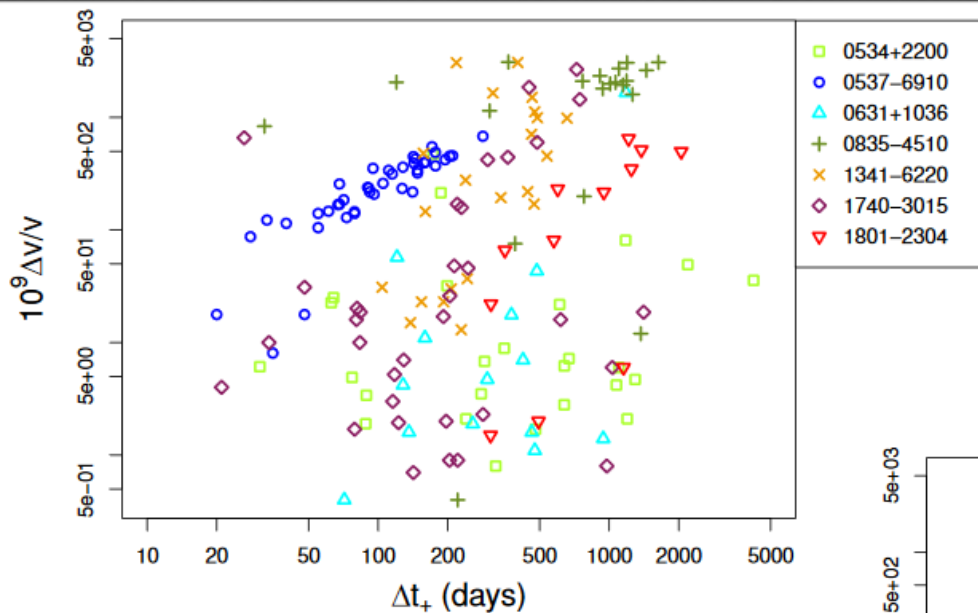$\Delta\Omega/\Omega \sim 10^{-6}$
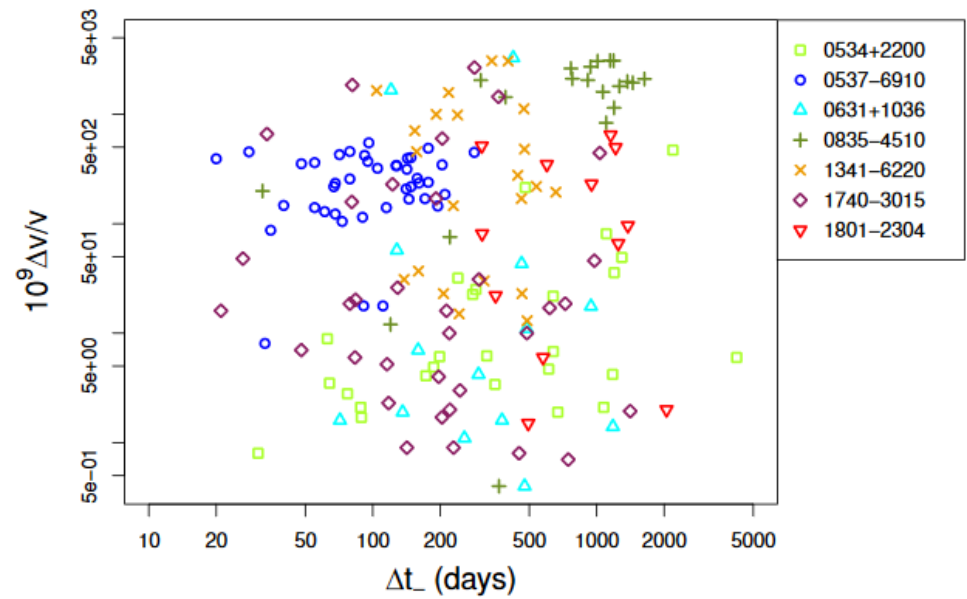
$\Delta\Omega$ – is for the crust (we see it!)

$\Delta\Omega\, I_{crust} = \Delta\Omega_{super}\, I_{super}$

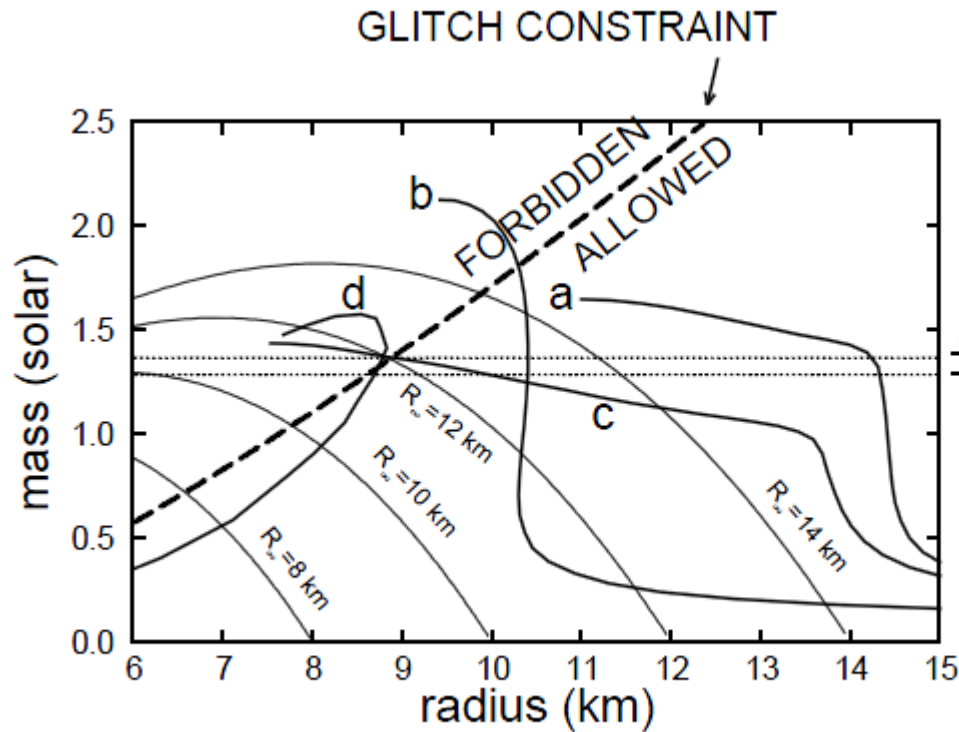$\Delta\Omega_{super} = \Delta\Omega\, I_{crust}/I_{super} = \Omega\, 10^{-6}\, 10^{2} = 10^{-4}\, \Omega$

Glitch size – waiting time correlation

No correlation of a glitch size with time since the previous glitch, or with time before the next one.

1809.03064

EoS and glitches

FORBIDDEN

ALLOWED

b

d

a

c

$R_* = 12$ km

$R_* = 10$ km

$R_* = 8$ km

$R_* = 14$ km

mass (solar)

radius (km)

maximum
likelihood
mass range

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

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

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

$$\frac{\Delta I}{I} \simeq \frac{28\pi}{3} \frac{P_t R^4}{GM^2} \left[1 + \frac{8P_t}{n_t m_n c^2} \frac{4.5 + (\Lambda - 1)^{-1}}{\Lambda - 1} \right]^{-1}$$
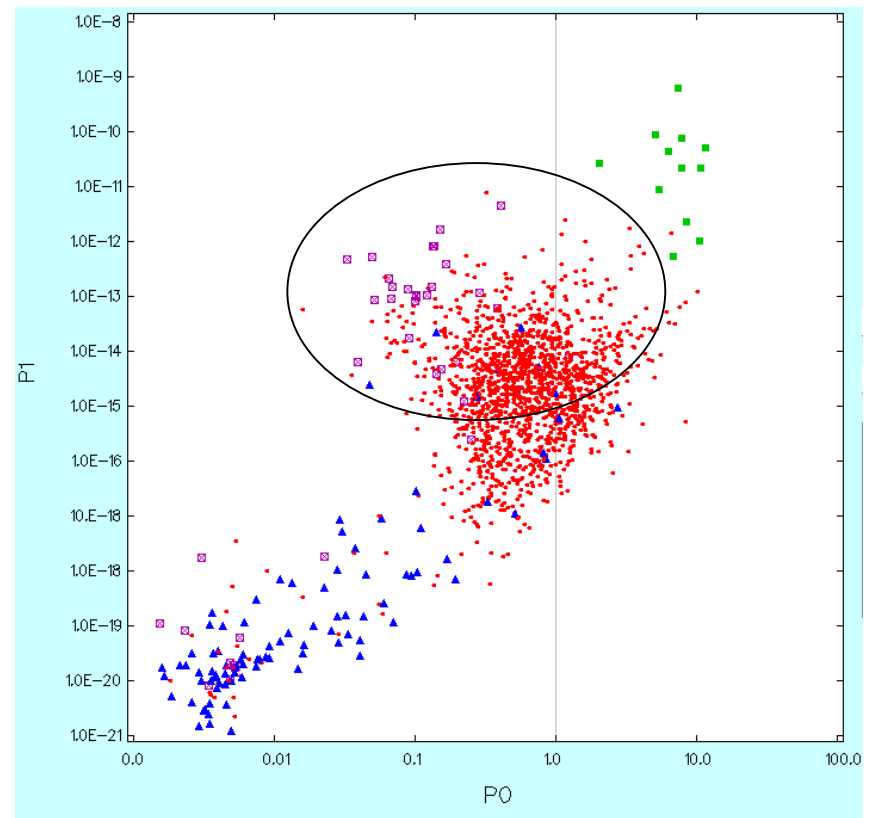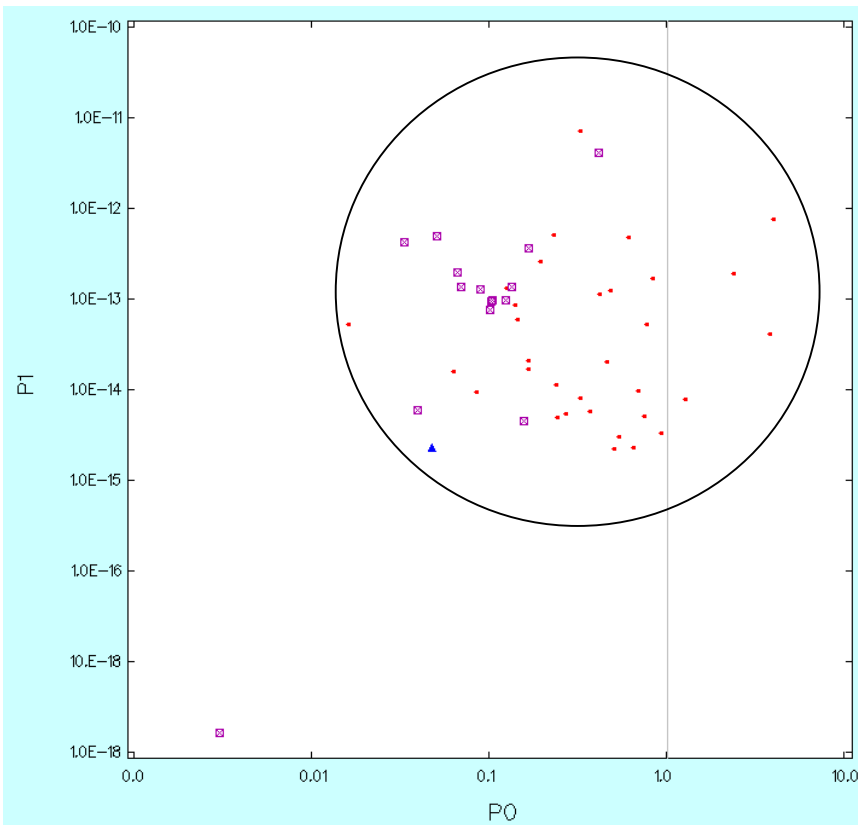
$$\Delta I/(I - \Delta I) \geq \Delta I/I_c \geq I_{res}/I_c \geq 0.014.$$

Link et al. 0001245

See some critics in 1207.0633 "Crust is not enough" and 1210.8177
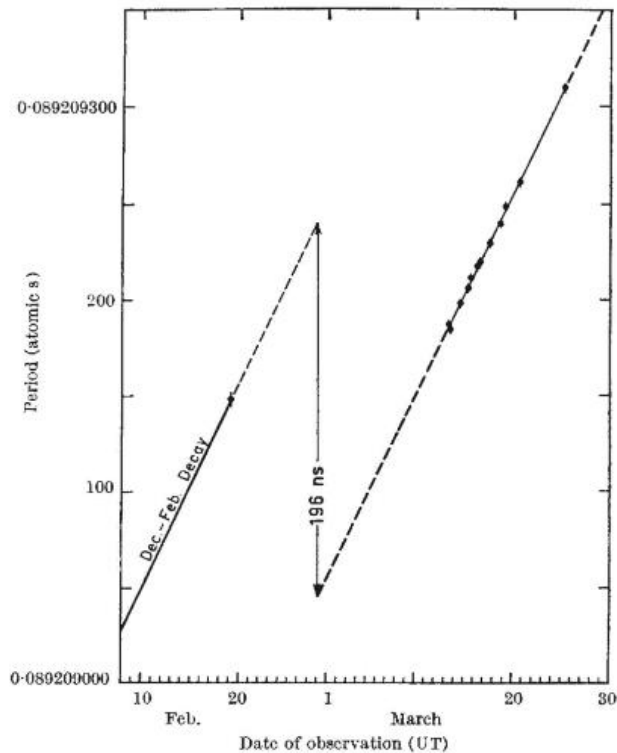Further discussion – in 1404.2660, 1809.07834.

Which PSRs do glitch?

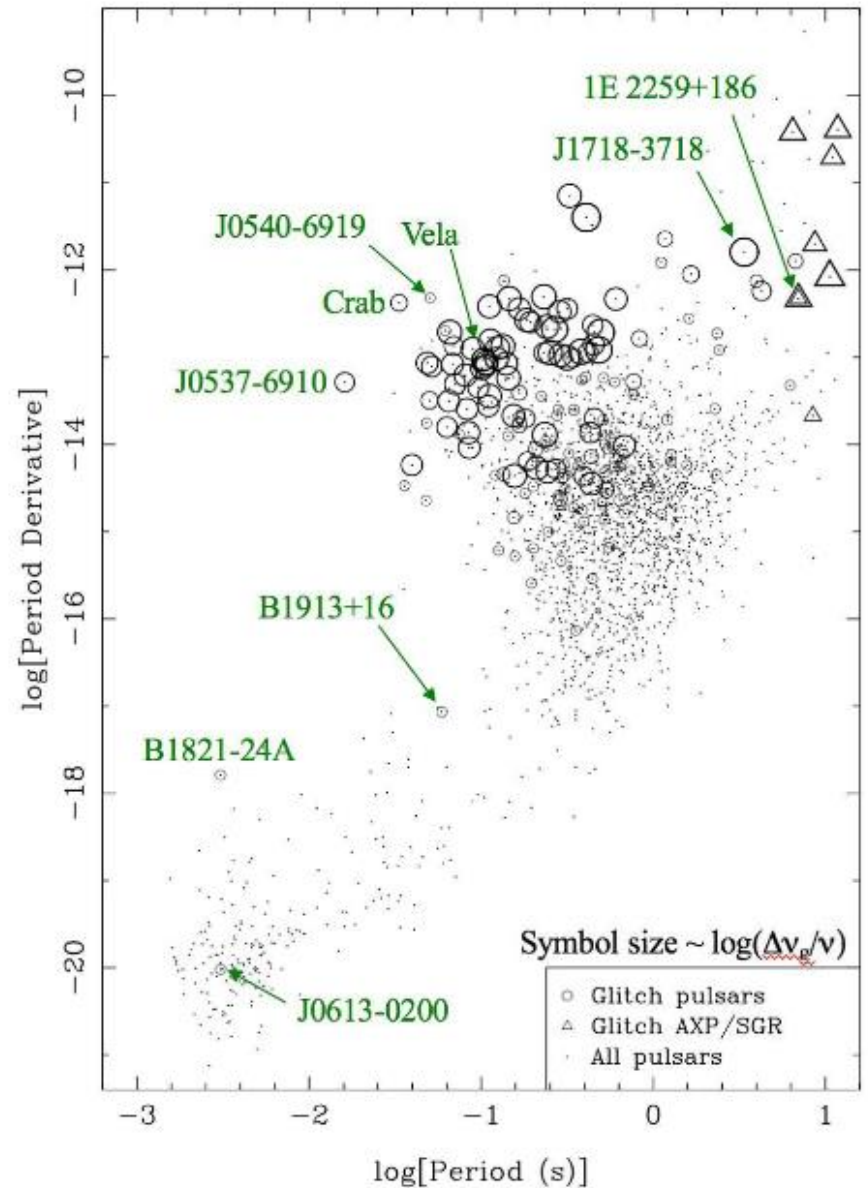On average young pulsars with larger spin-down glitch more frequently
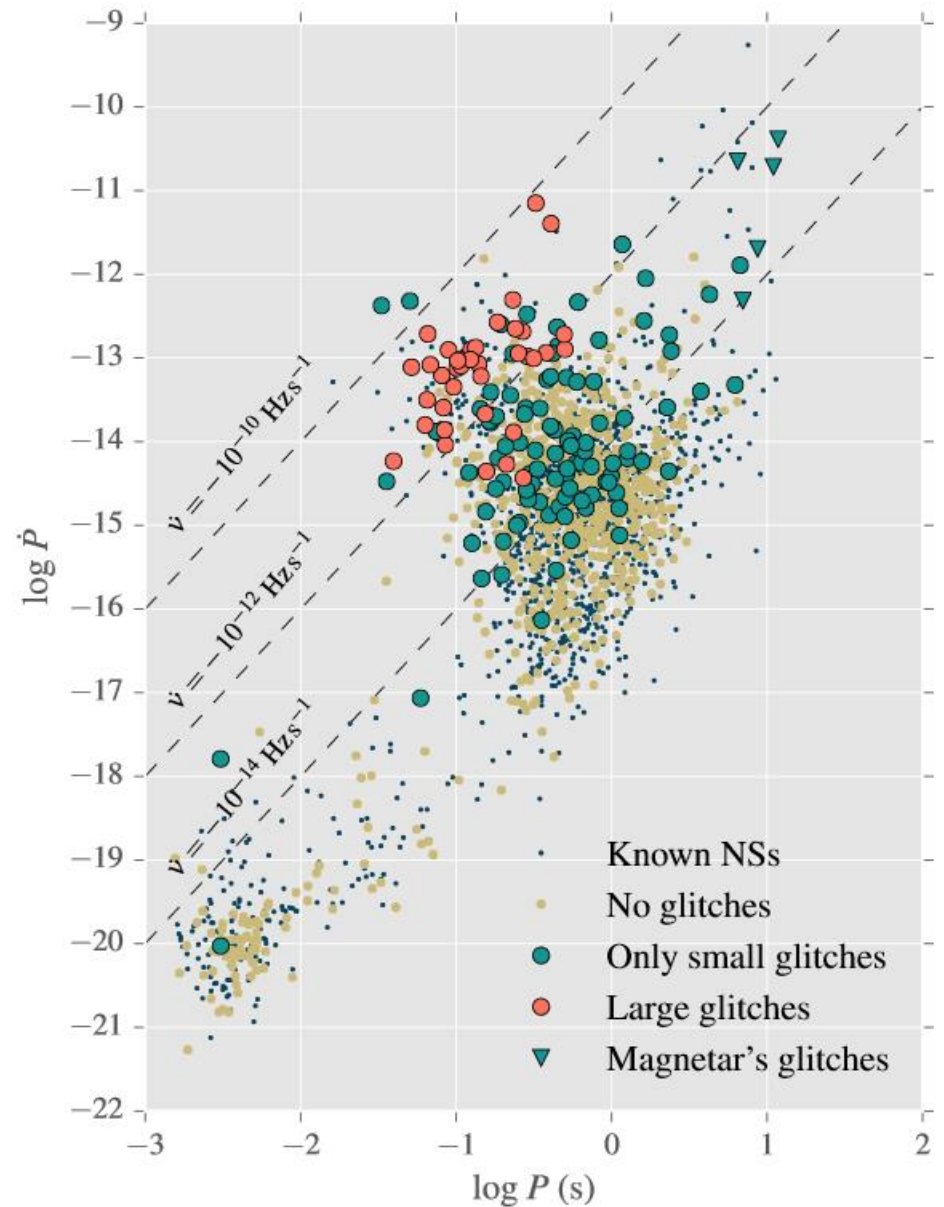
P-Pdot

>520 glitches
in >180 PSRs

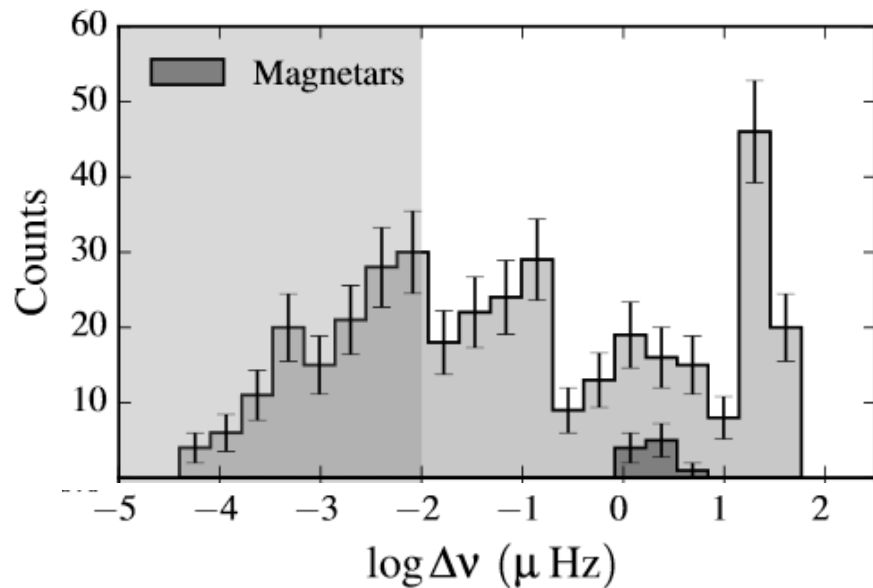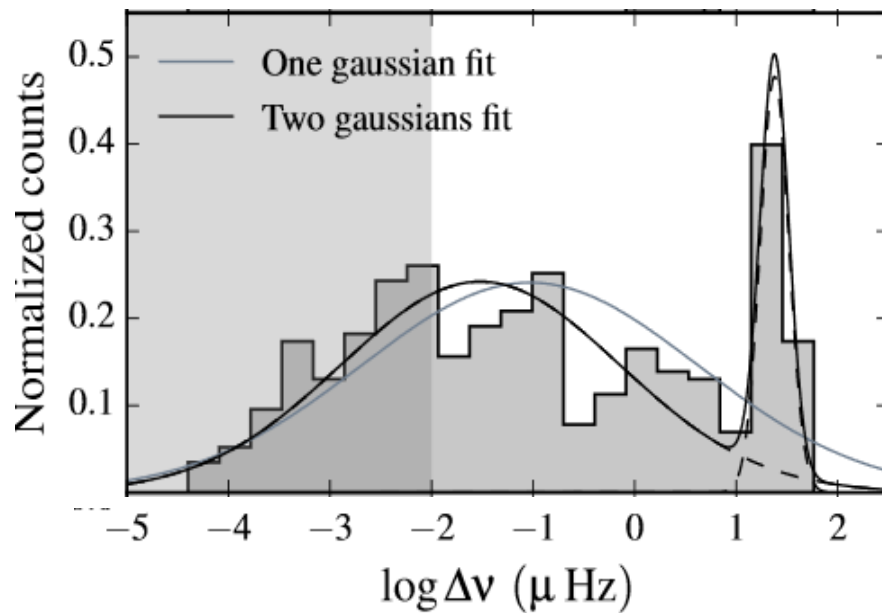Vela glitch in 1969

1801.04332

Statistics

384 glitches in 141 NSs

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

Glitches properties

384 glitches in 141 NSs

1710.00952
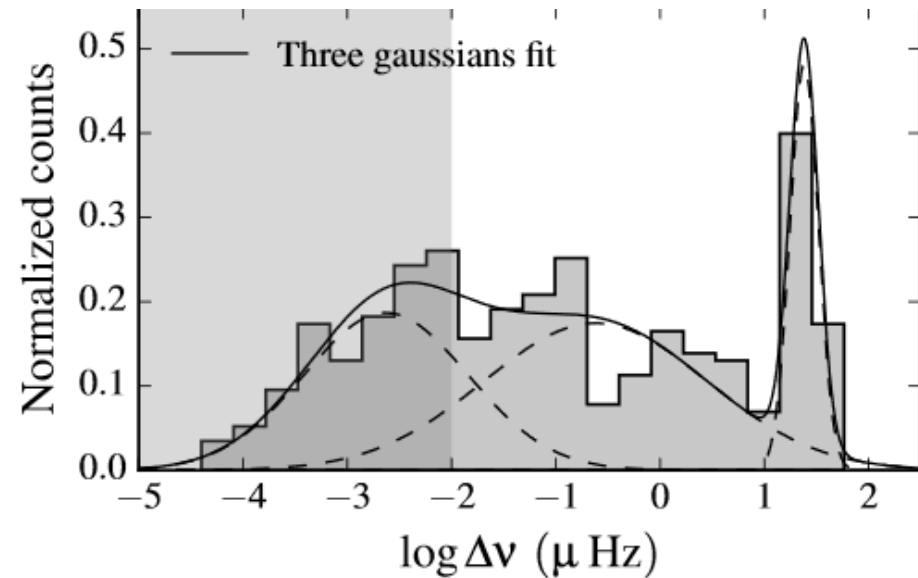
# bin	log $|\dot{\nu}|$ (Hz s^{-1})	$\sum T_i$ (yr)	N_ℓ	N_t	N_{pg}	N_p
1	-16.75	117	0	0	0	7
2	-16.25	430	0	0	0	25
3	-15.75	1233	0	0	0	70
4	-15.25	2478	0	3	3	139
5	-14.75	2675	0	11	8	142
6	-14.25	1973	0	25	16	105
7	-13.75	2083	0	35	20	113
8	-13.25	1706	1	29	18	105
9	-12.75	1312	3	26	14	81
10	-12.25	745	4	38	15	48
11	-11.75	493	8	74	15	33
12	-11.25	357	37	78	18	20
13	-10.75	66	13	19	5	5
14	-10.25	44	4	8	2	3
15	-9.75	16	0	2	1	1
16	-9.25	46	0	25	1	1

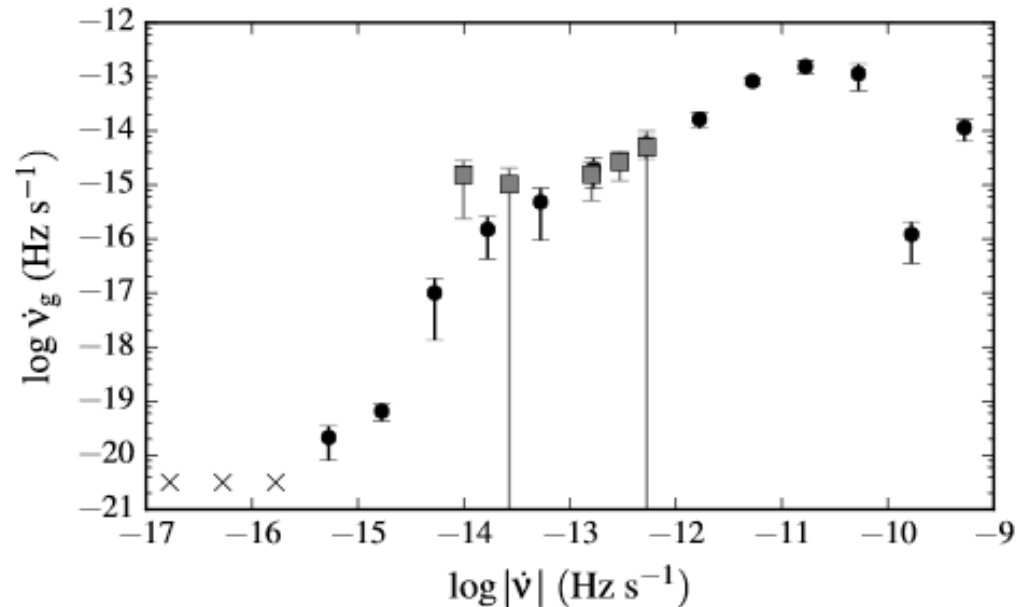$$\dot{\nu}_g = \frac{\sum_i \sum_j \Delta\nu_{ij}}{\sum_i T_i},$$
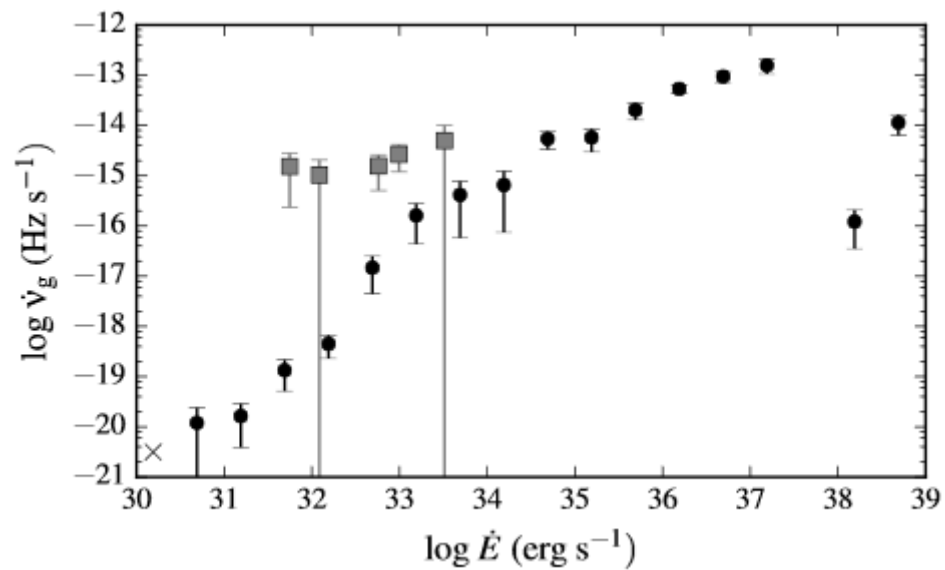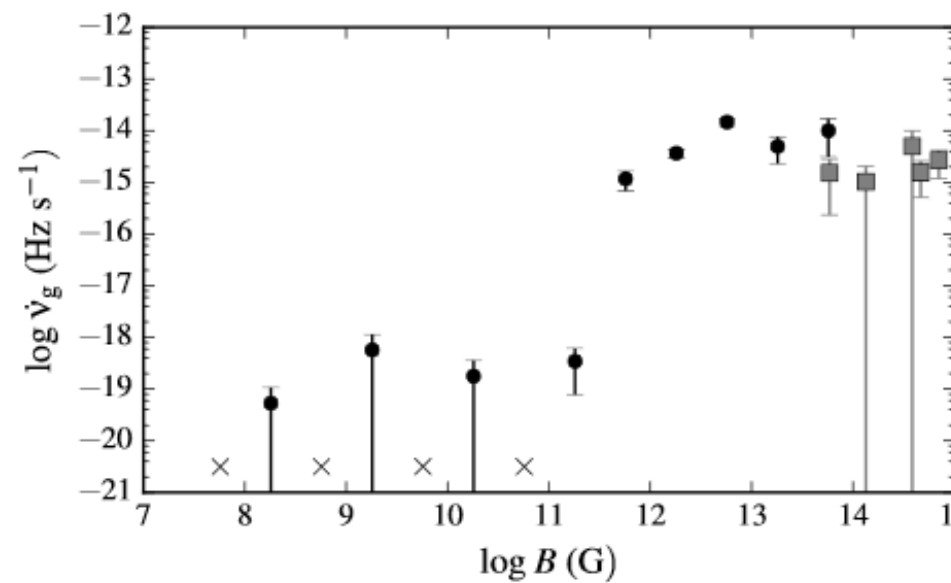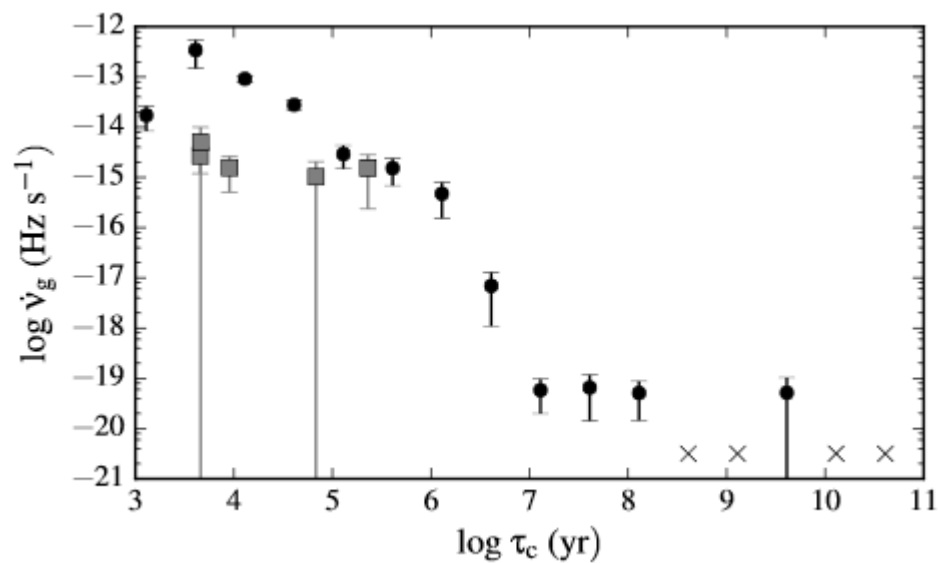
1710.00952
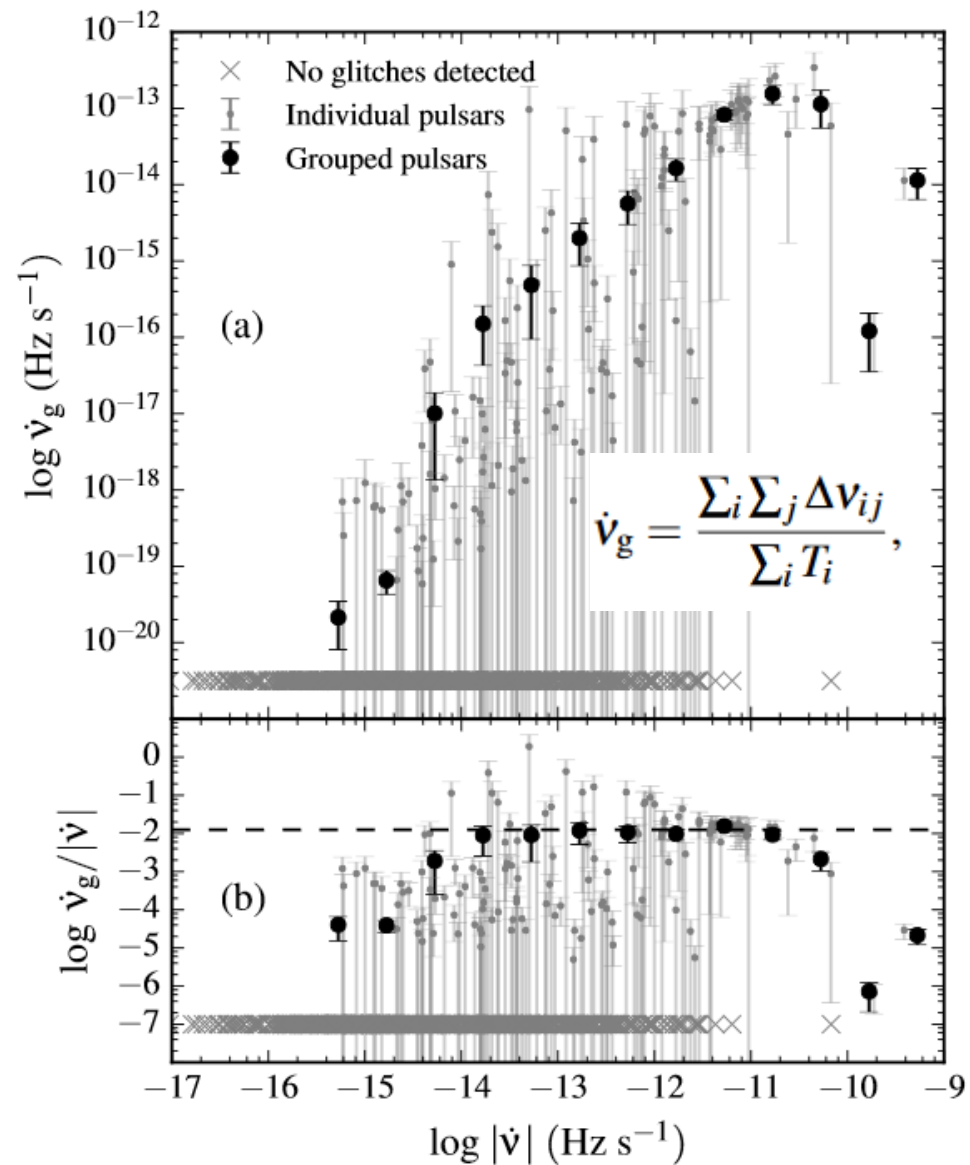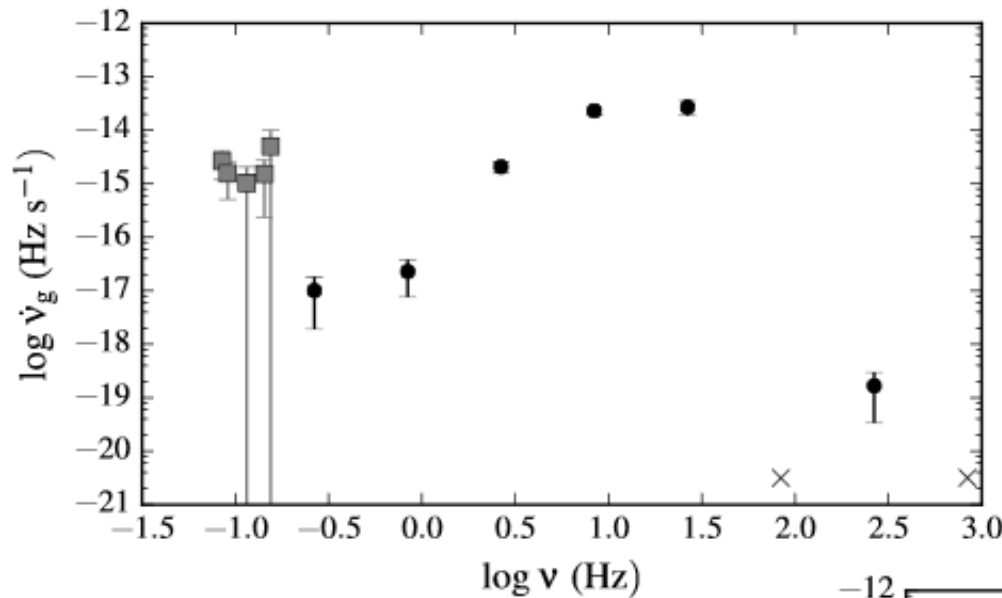
All PSRs in the survey are included, also those with no detected glitches.

$$\dot{\nu}_g = \frac{\sum_i \sum_j \Delta \nu_{ij}}{\sum_i T_i},$$
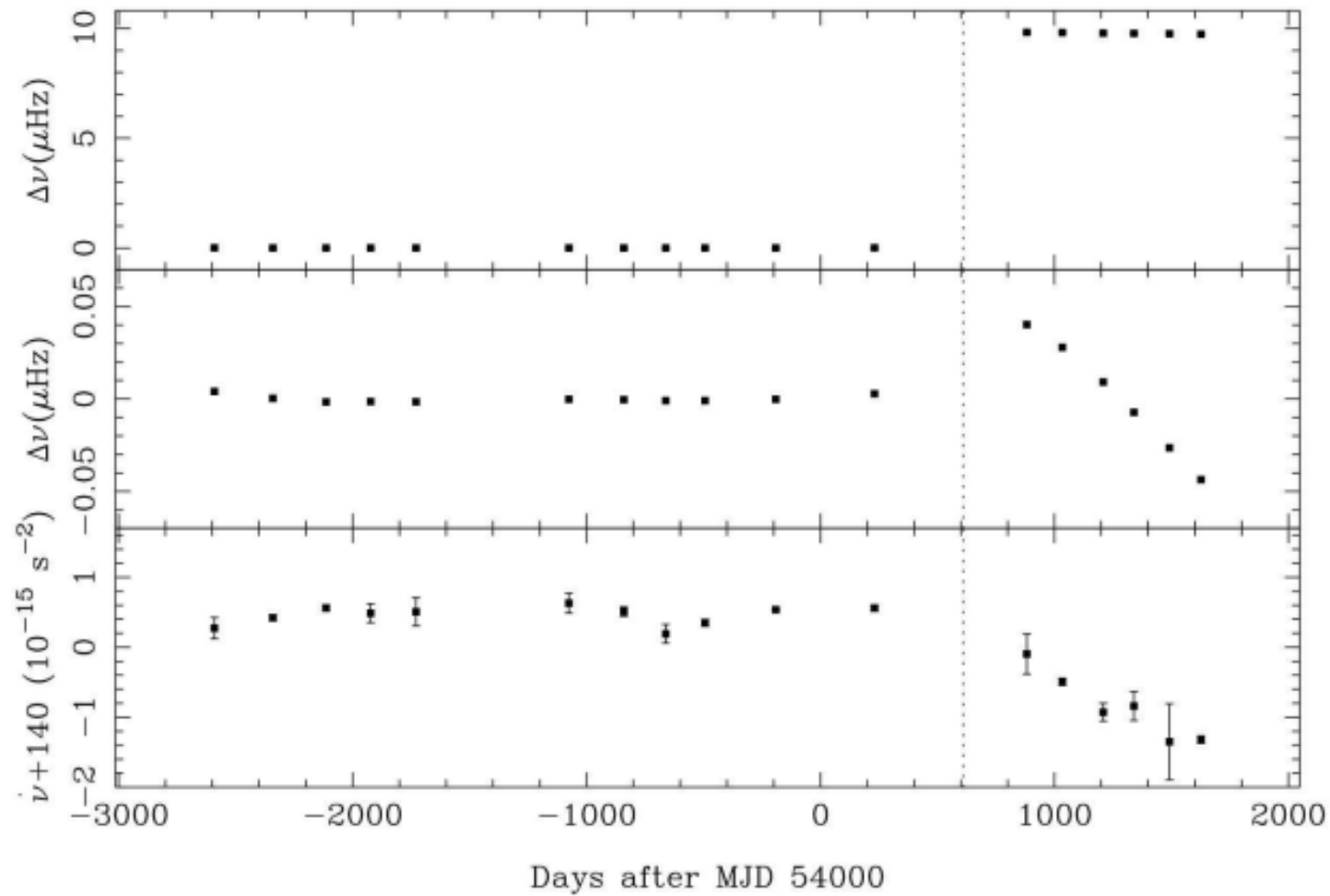
The double sum runs over every change in frequency $\Delta \nu_{ij}$ due to the glitch j of the pulsar i, and T_i is the time over which pulsar i has been searched for glitches.

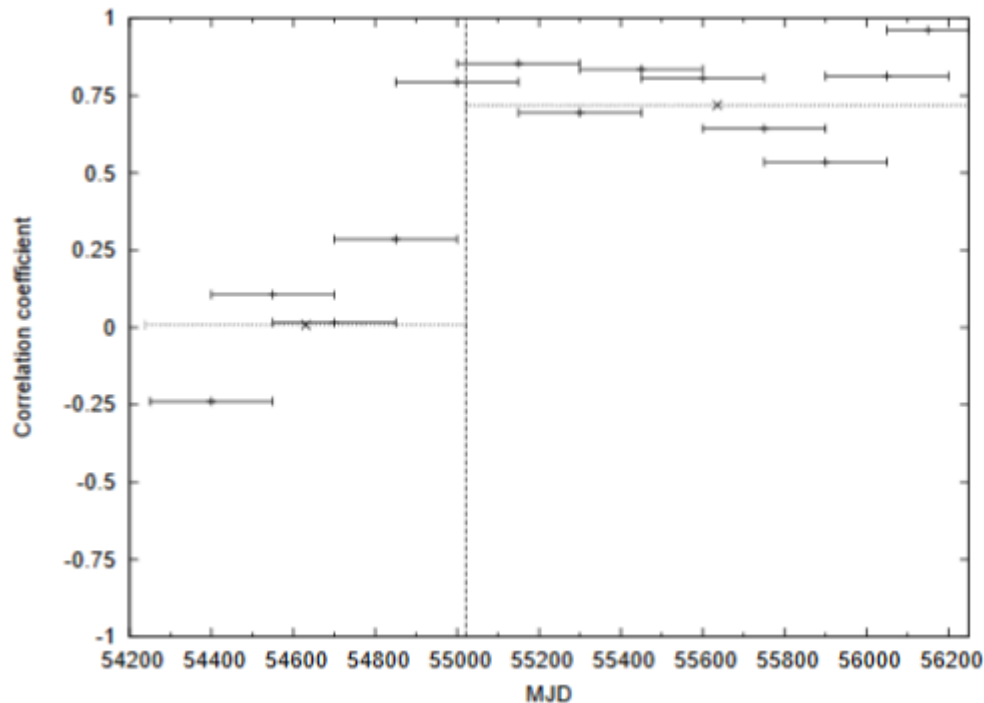1710.00952

$$\dot{\nu}_g = \frac{\sum_i \sum_j \Delta \nu_{ij}}{\sum_i T_i},$$

1710.00952

The largest glitch

33 10⁻⁶

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.

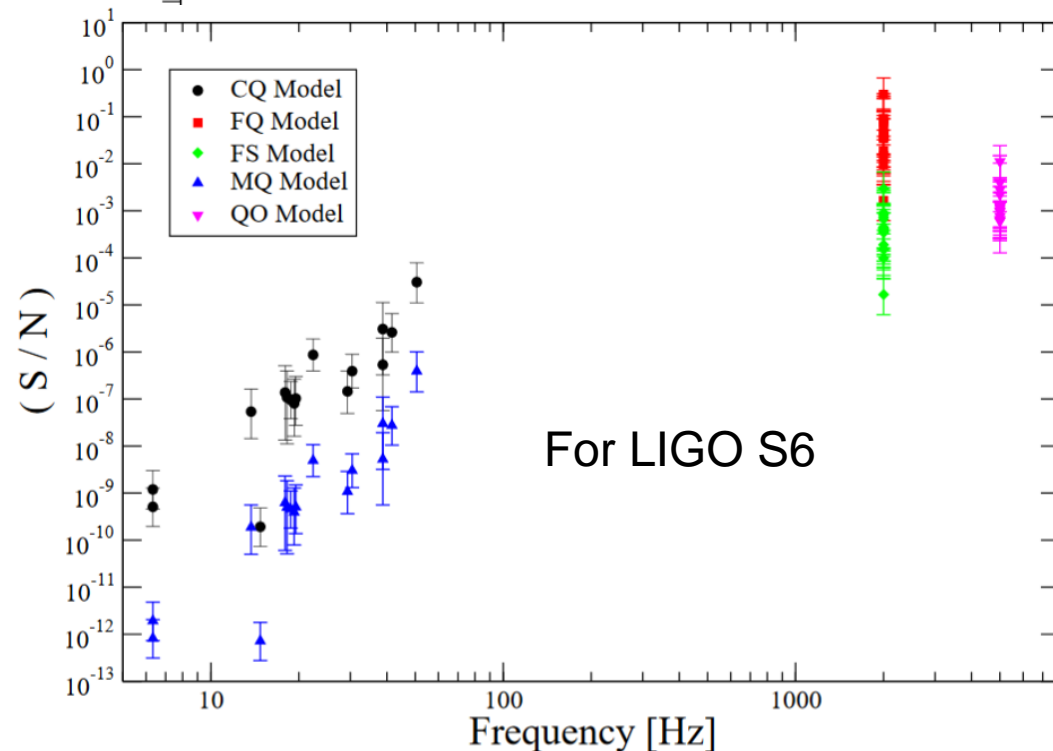1304.4644

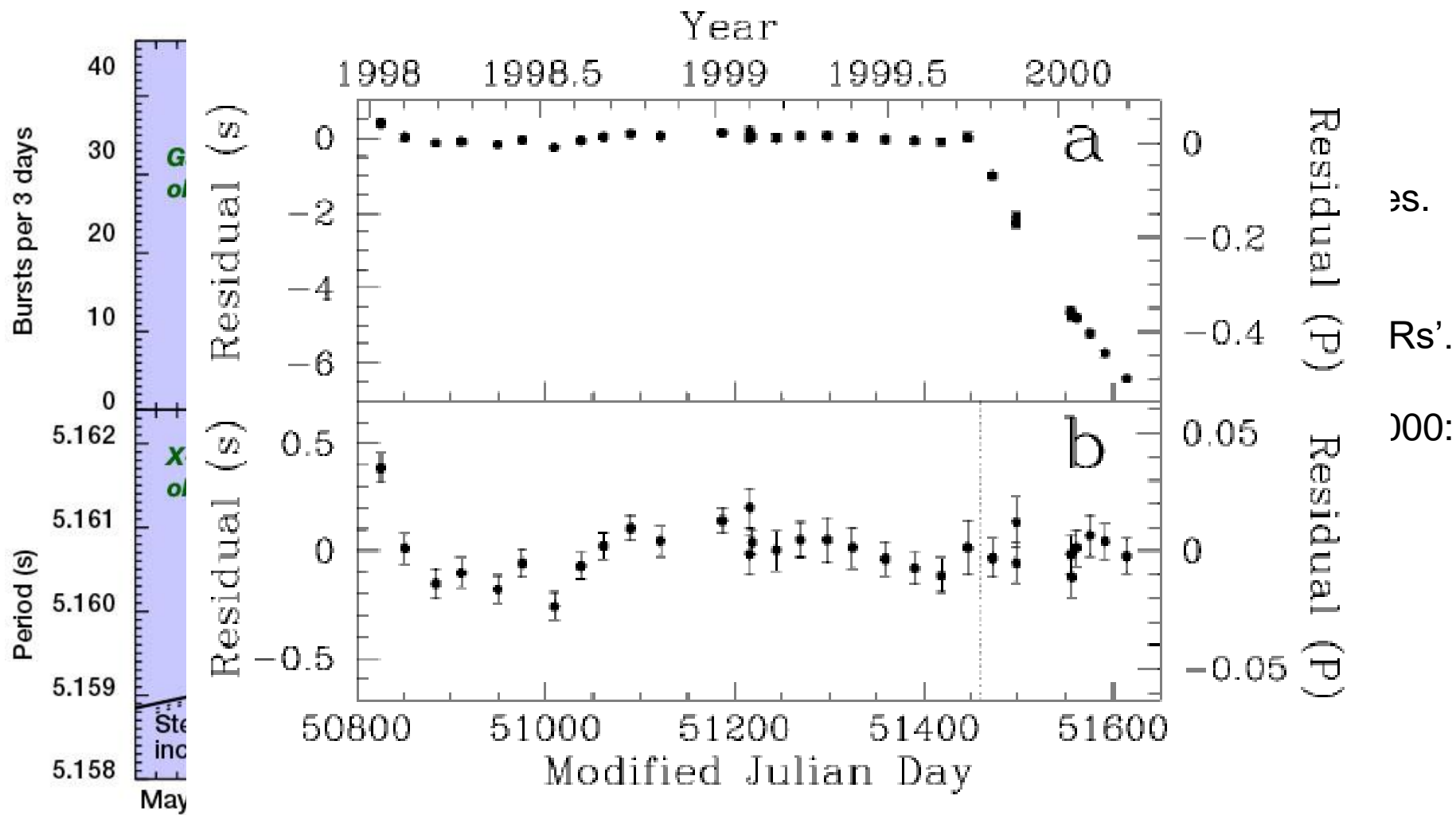# Thermal effect of a glitch

Hirano et al. 1997
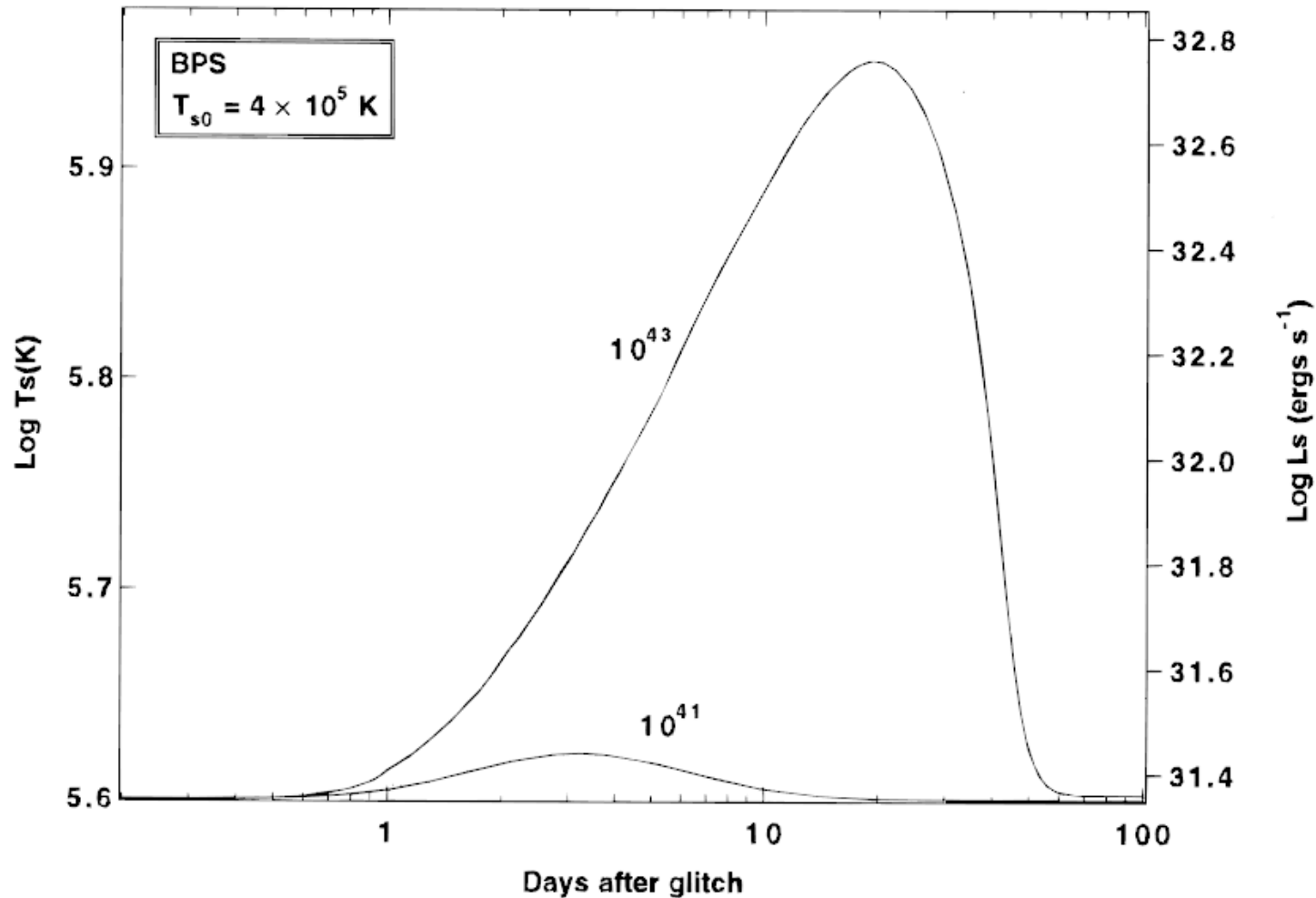
Gravitational waves from glitches
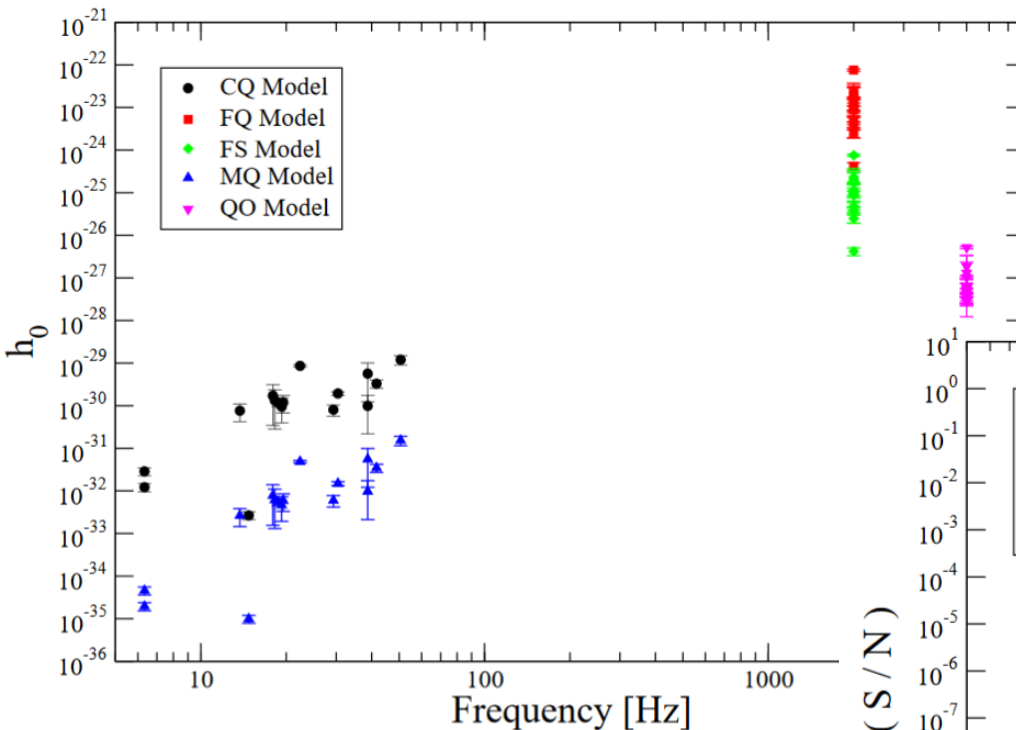
In some very optimistic models GW signals from PSRs glitches can be detected already with existing detectors (aLIGO, adVIRGO).
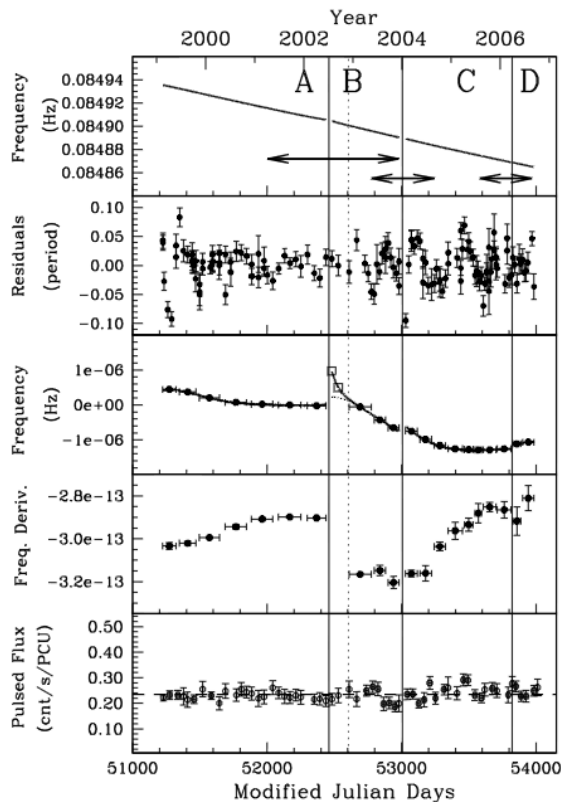
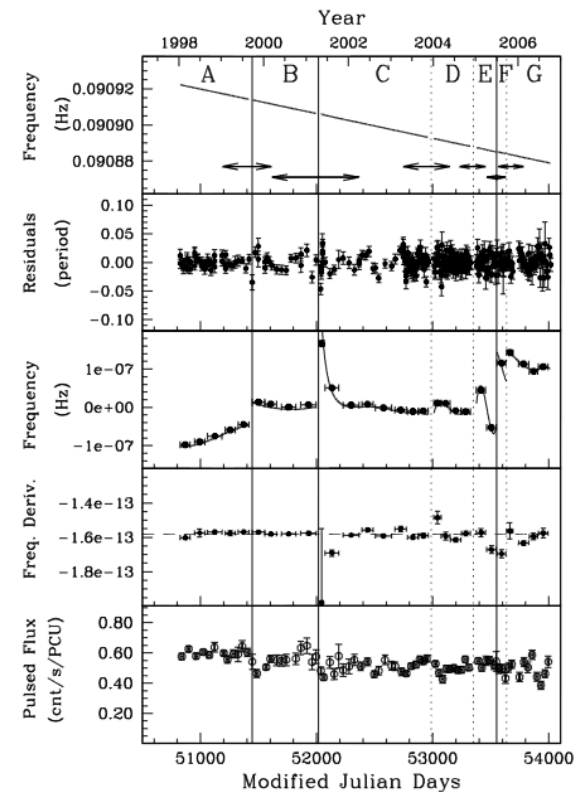For LIGO S6

1305.2466

Glitches of magnetars

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
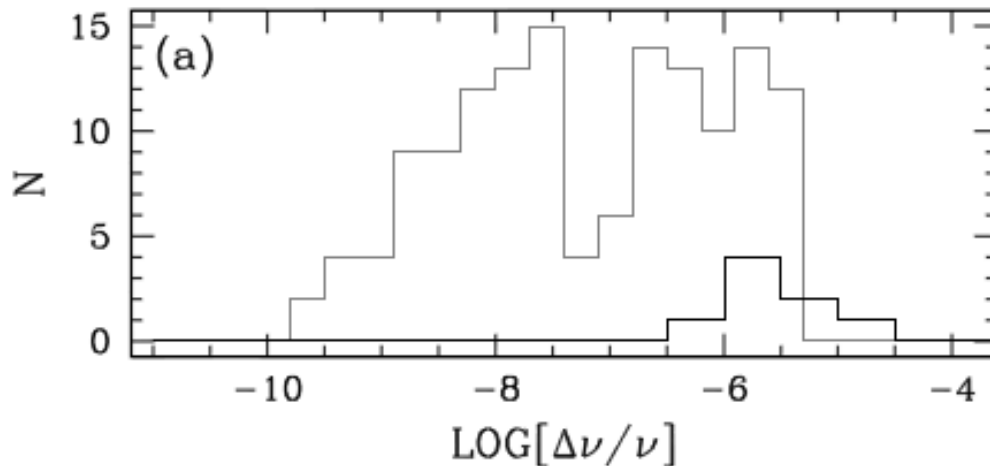
Glitch and bursts from PSR J1119−6127

Young highly magnetizes radio pulsar.

Outburst with many flares.

Glitch properties confirm the model of magnetospheric perturbation and energy release. Spin behavior correlates with pulse profile and spectral changes.

1806.01414 (see also 1806.05064)
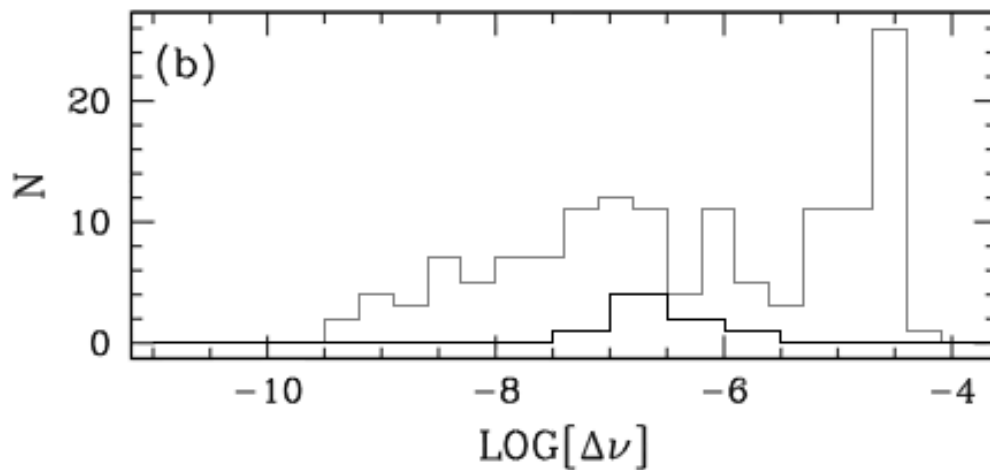
PSRs vs. magnetars
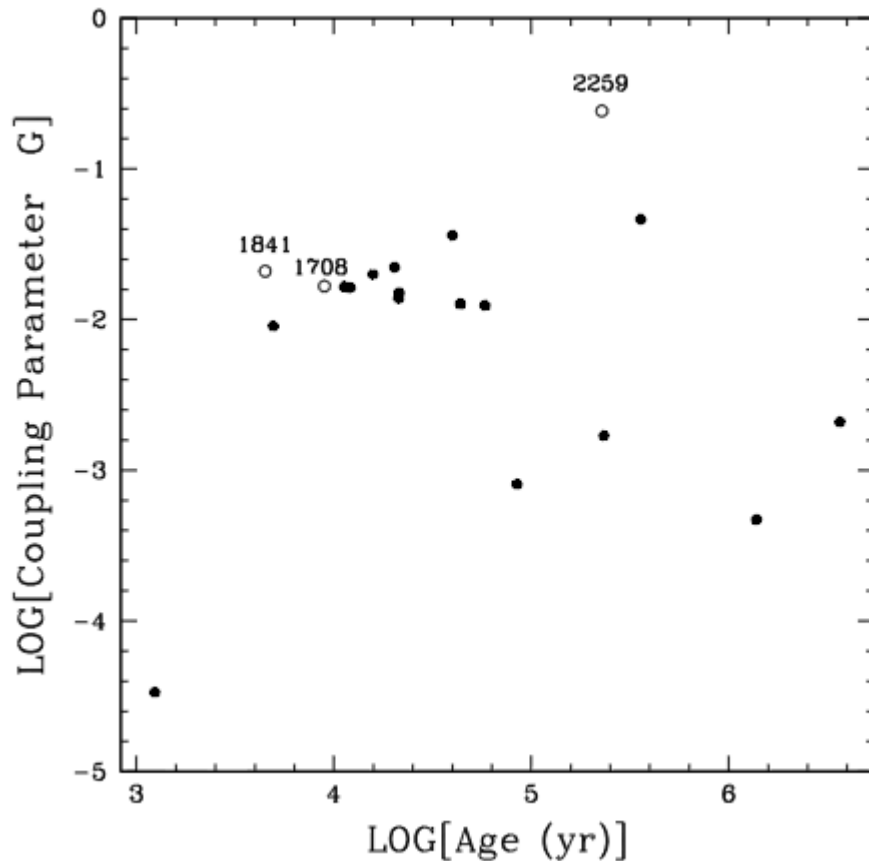

(a)

LOG[$\Delta\nu/\nu$]

(b)

LOG[$\Delta\nu$]
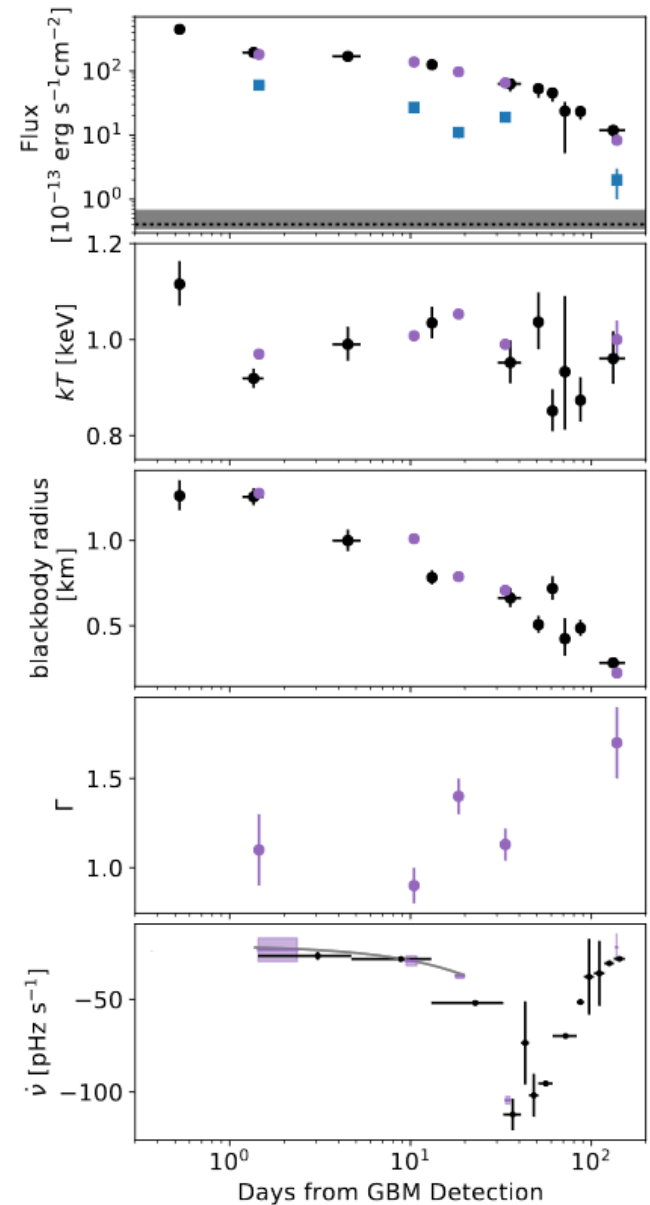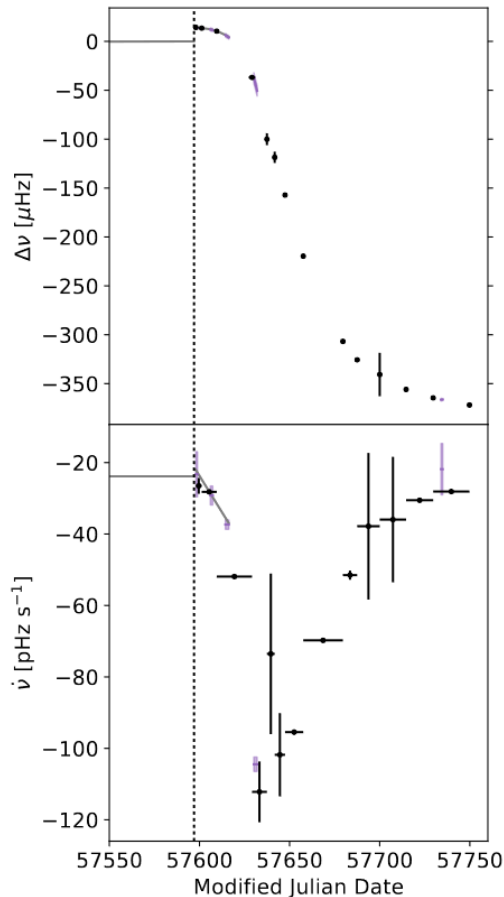
Nearly all known persistent AXPs now seem to glitch.

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

PSRs vs. Magnetars

Magnetars

PSRs

Glitch activity of the magnetars with the smallest characteristic ages is lower than that of the rotation-powered pulsars with similar characteristic ages.

However, their activity is larger than that of pulsars of equal spin-down power.
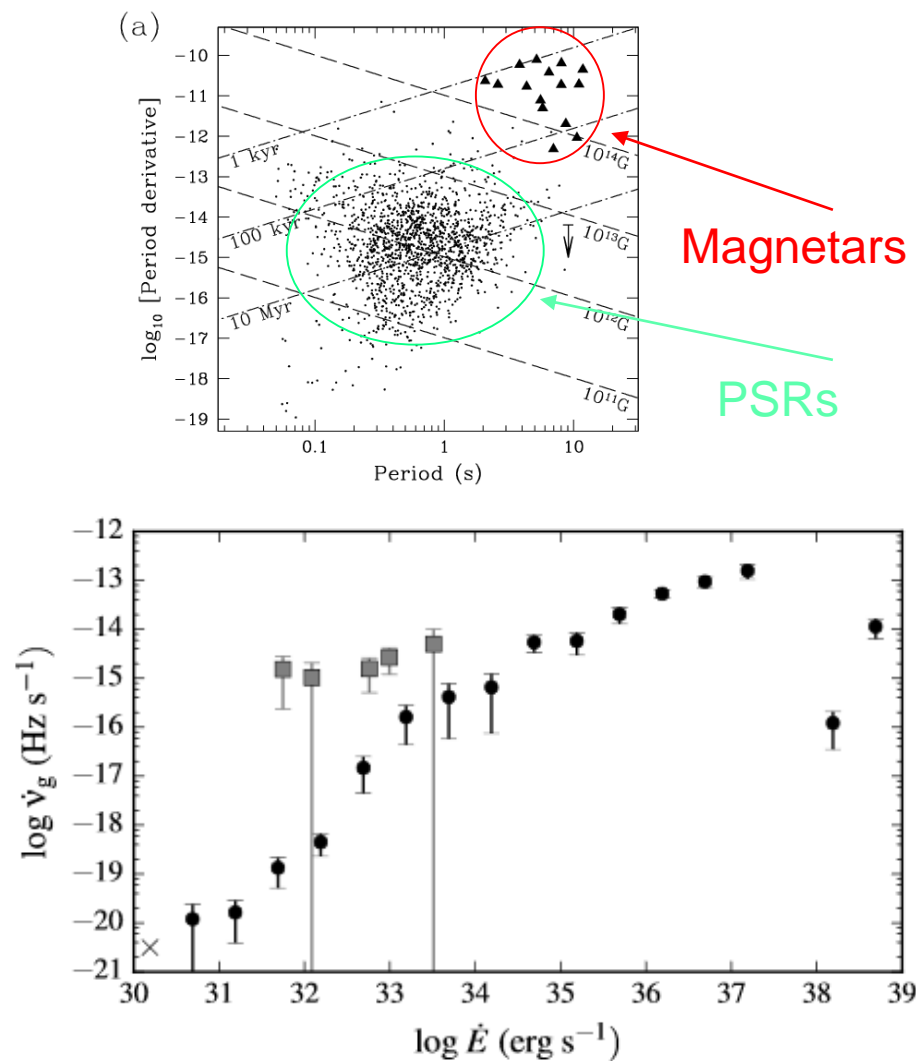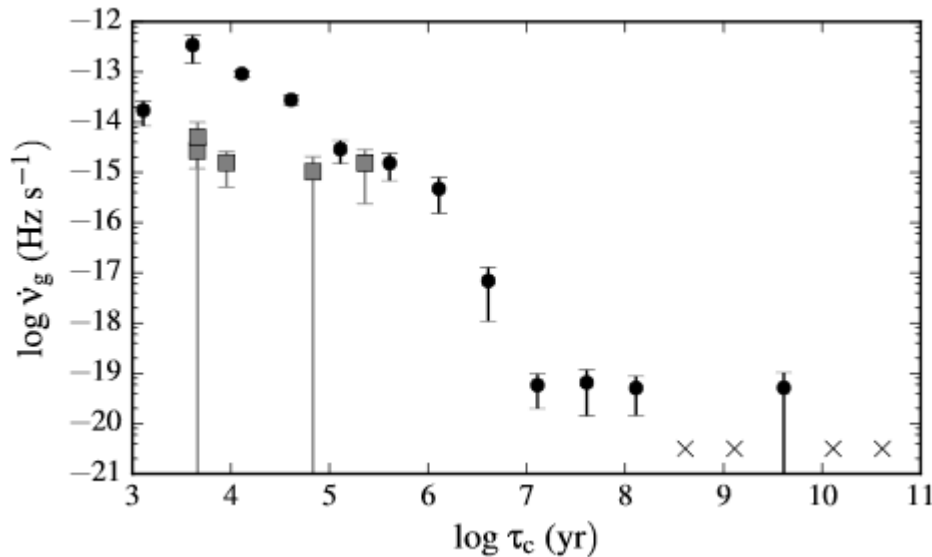
CCOs also glitch!

1E 1207.4−5209

0.424 s

$B_s \approx 9 \times 10^{10}$ G

$\Delta f/f = (2.8 \pm 0.4) \times 10^{-9}$

Parameter	Pre-glitch[a]	Post-glitch[b]
Epoch	2012	2017
N_H (cm^{-2}) (fixed)	1.66×10^{21}	1.66×10^{21}
kT_1 (keV)	$0.0801^{+0.0046}_{-0.0042}$	$0.0742^{+0.0042}_{-0.0037}$
kT_2 (keV)	$0.2513^{+0.0022}_{-0.0021}$	$0.2509^{+0.0021}_{-0.0021}$
E_0 (keV)	$0.712^{+0.012}_{-0.011}$	$0.710^{+0.017}_{-0.015}$
σ_0 (keV) (fixed)	0.08	0.08
τ_0	0.26	0.22
E_1 (keV)	$1.4292^{+0.0087}_{-0.0088}$	$1.4216^{+0.0089}_{-0.0090}$
σ_1 (keV) (fixed)	0.08	0.08
τ_1	0.098	0.10
F_x(pn)[c]	$2.084^{+0.010}_{-0.011}$	$2.078^{+0.010}_{-0.012}$
χ^2_ν(DoF)	1.39(283)	1.32(276)
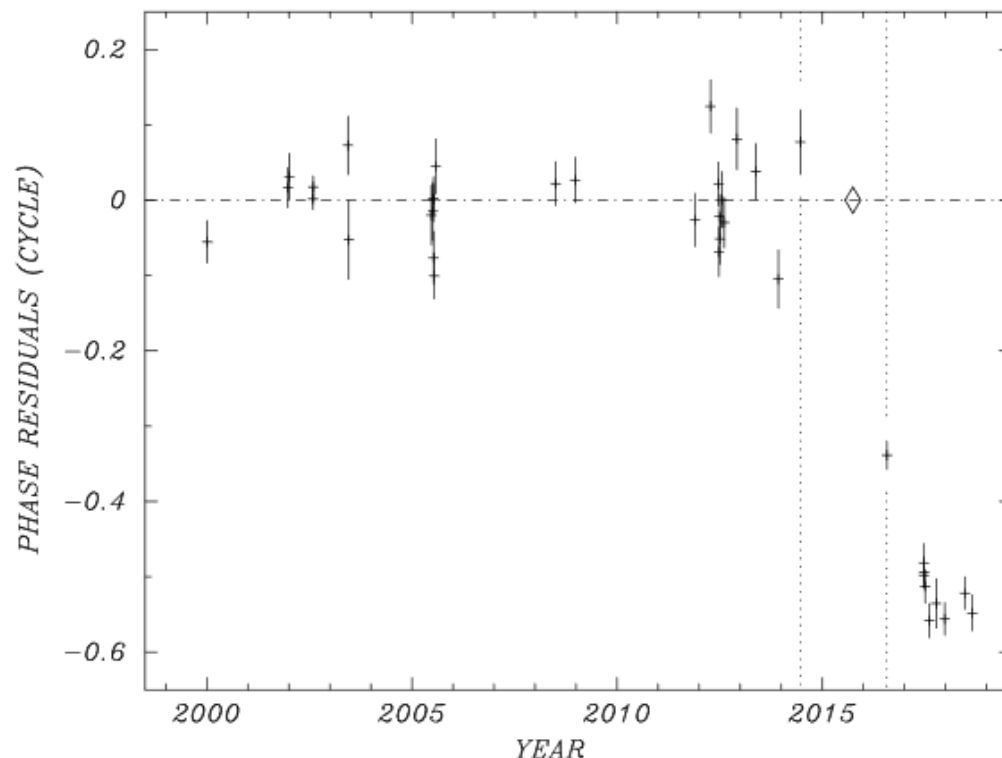
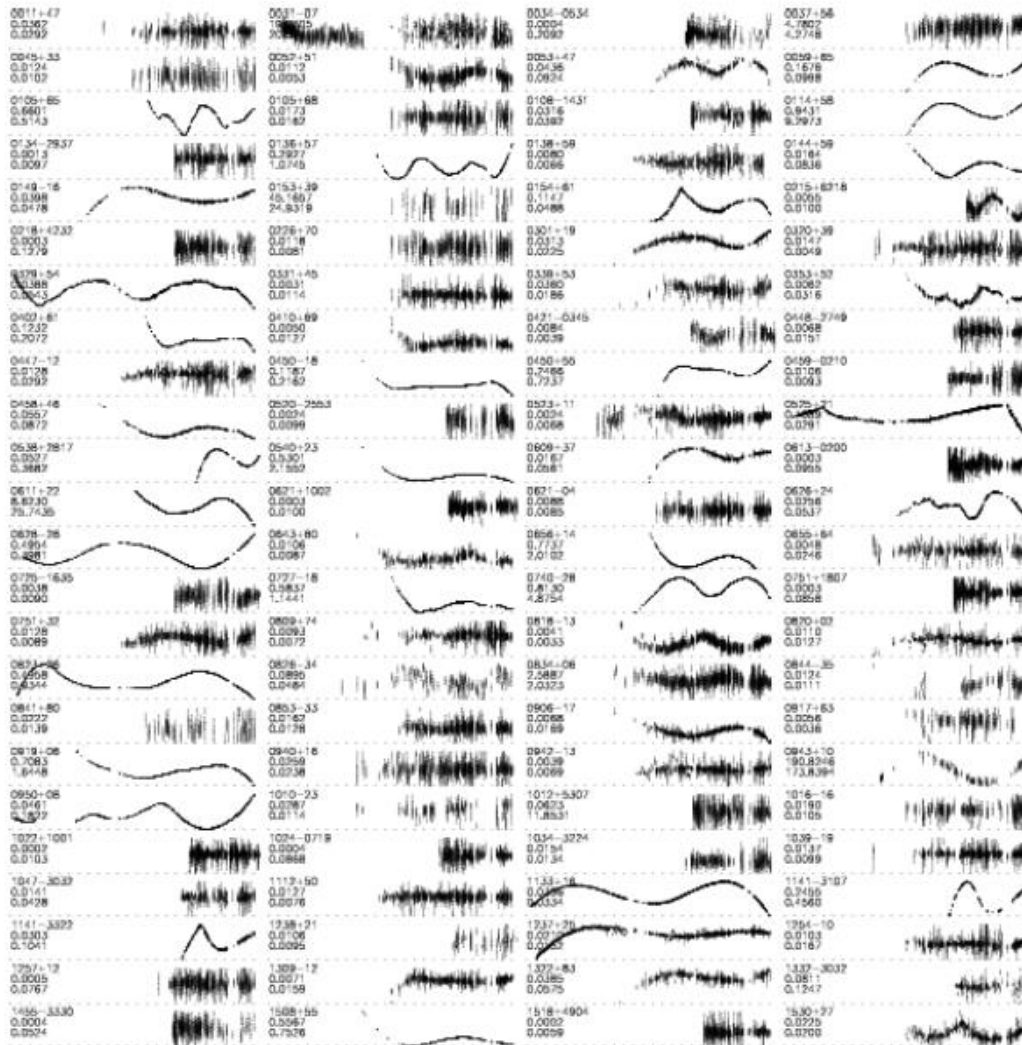| Glitch Parameters	
Epoch (MJD)	57295[b]
Δf	$(1.23 \pm 0.19) \times 10^{-8}$ s^{-1}
$\Delta f/f_{pred}$	$(5.22 \pm 0.80) \times 10^{-9}$
$\Delta \dot{f}$	$(-1.58 \pm 0.31) \times 10^{-16}$ s^{-2}
$\Delta \dot{f}/\dot{f}_{pred}$	1.27 ± 0.25

1809.04678
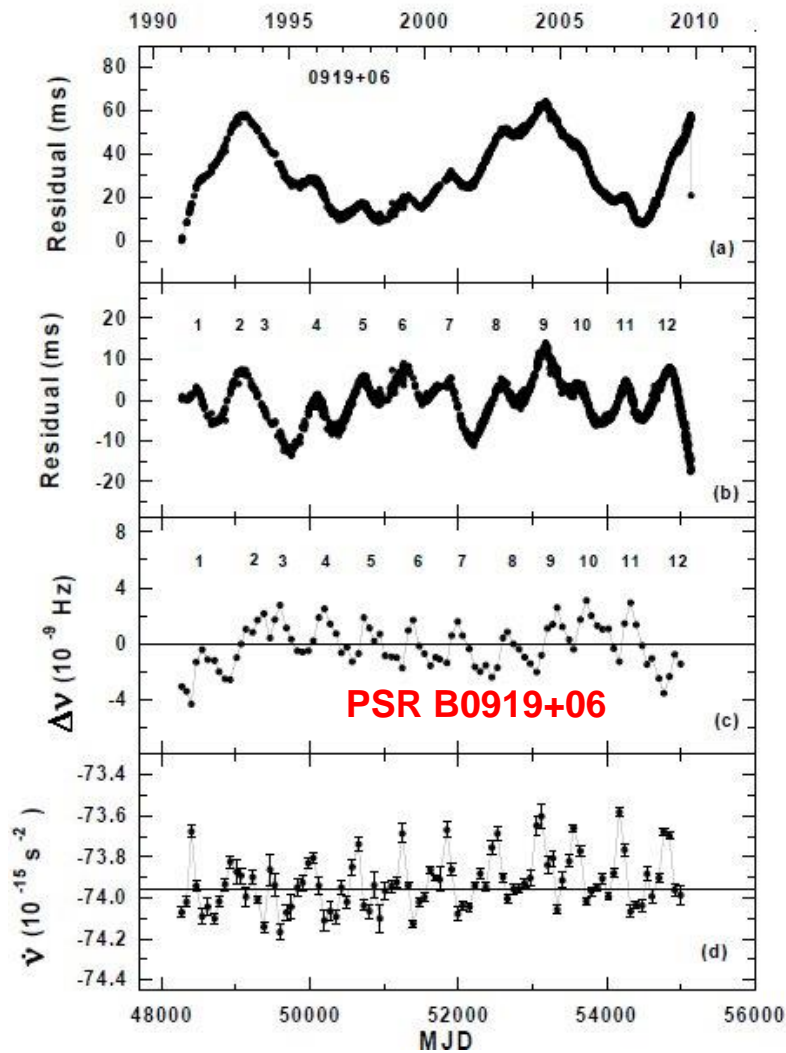
Slow glitches

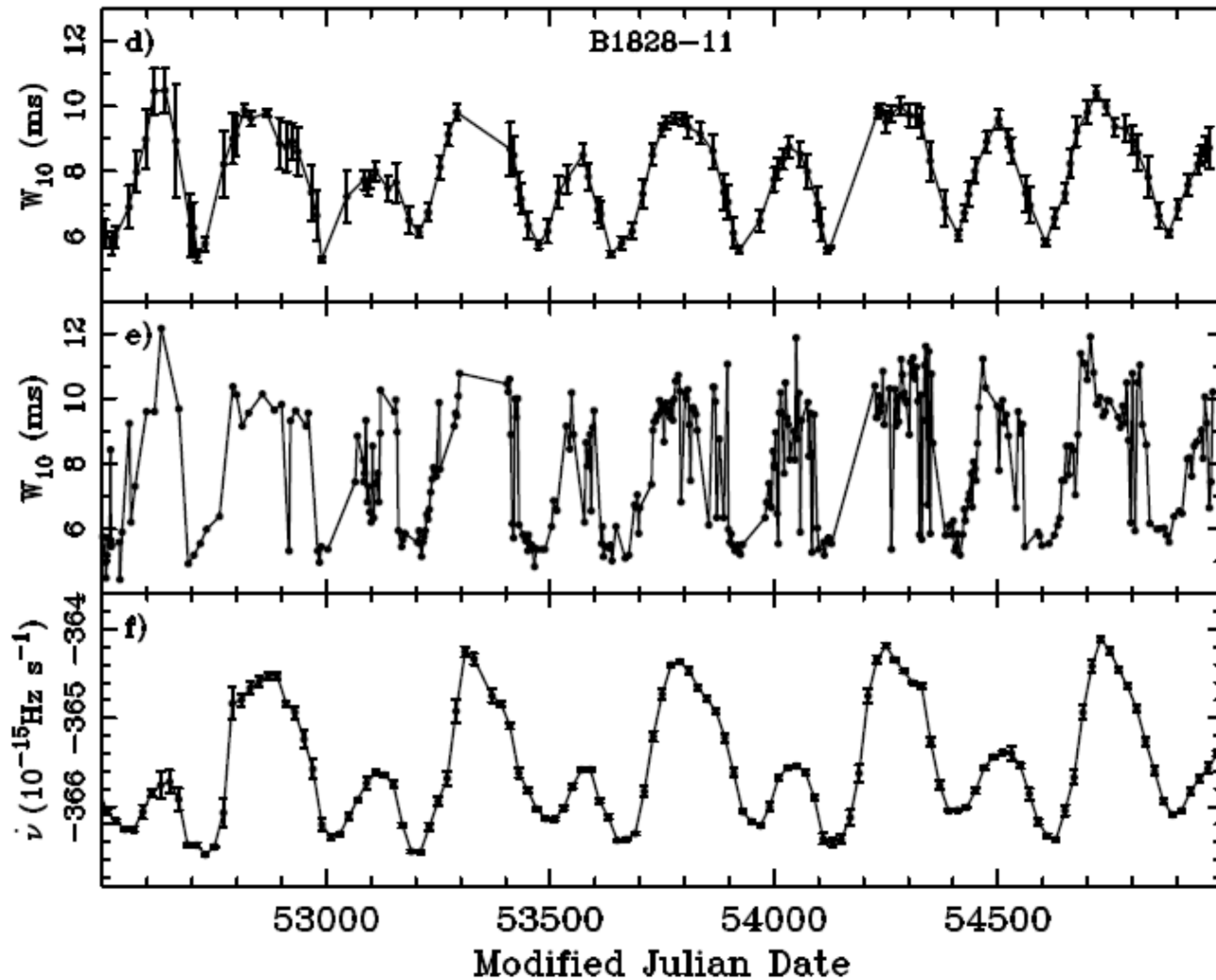Below: a slow glitch by PSR B1822-09 (Shabanova 1998)
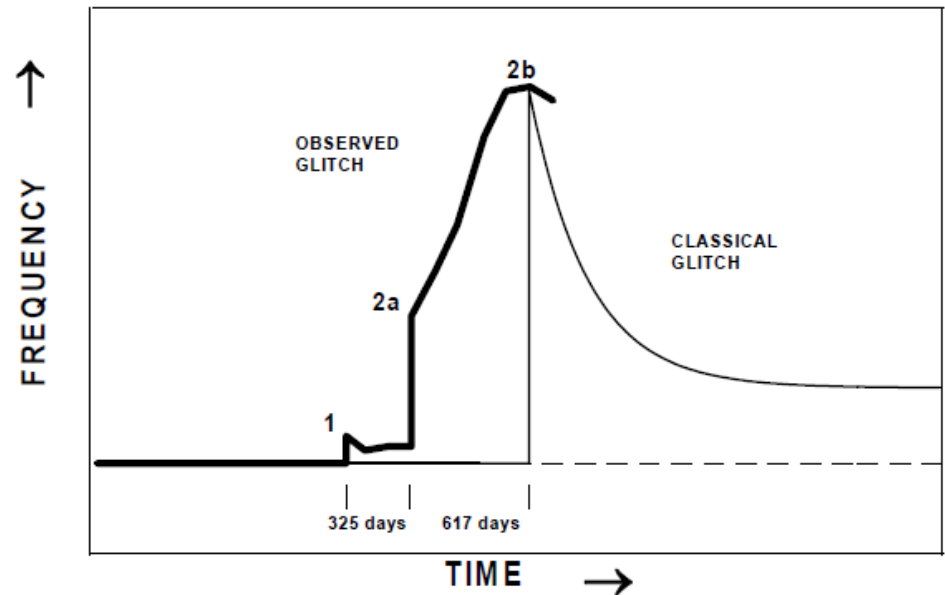
Timing irregularities

Analysis demonstrates different type of irregularities including quasi-periodic.

0912.4537
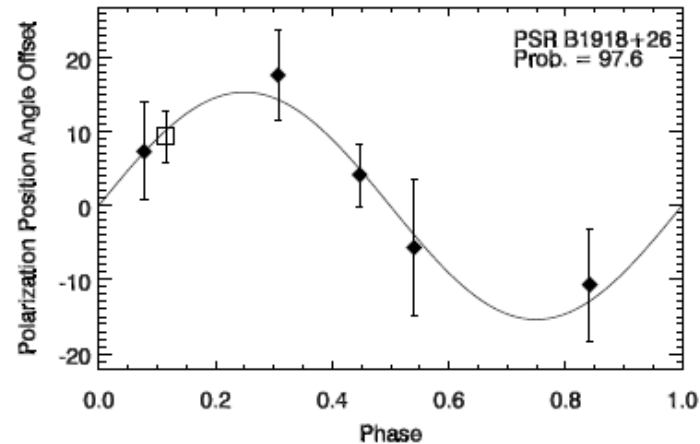
Possible explanation?

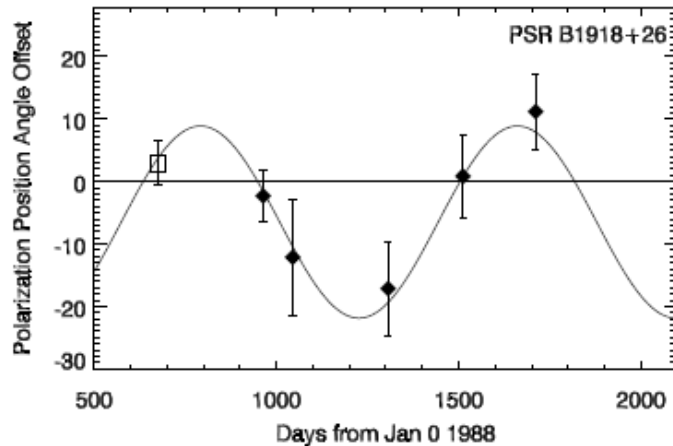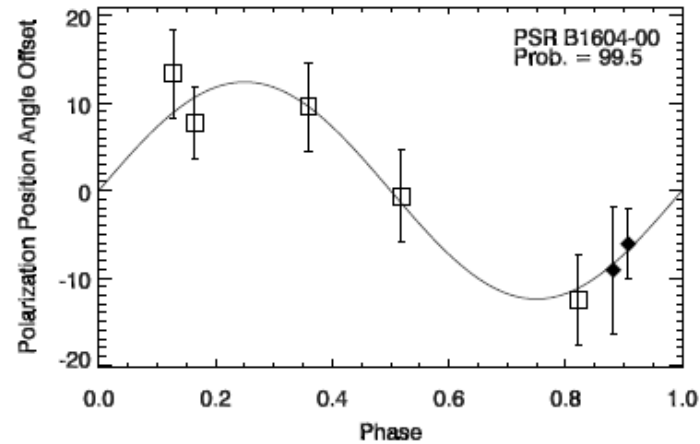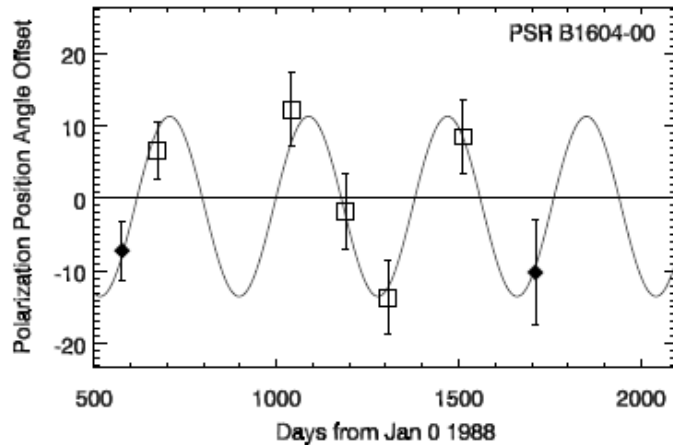Magnetospheric effect?

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

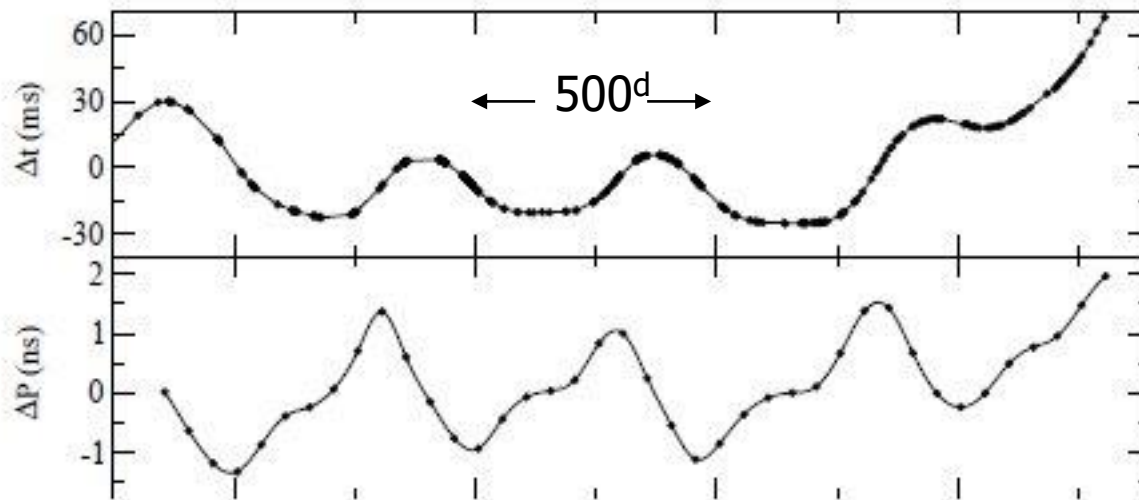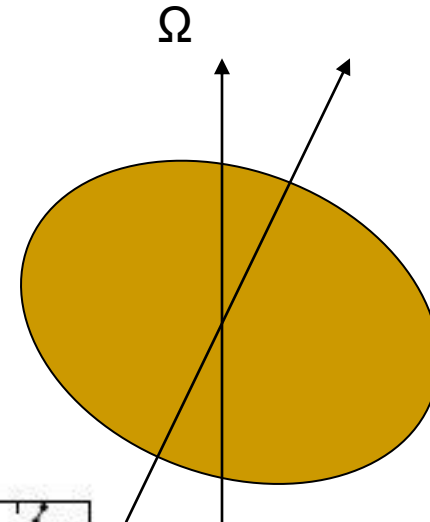Switching between these states happens rapidly.

1006.5184

Polarization angle variations

Such variations could be caused by precession

Weisberg et al. 2010   1008.0454

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)

Ω

←— 500^d —→

Δt (ms)

ΔP (ns)

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

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)

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

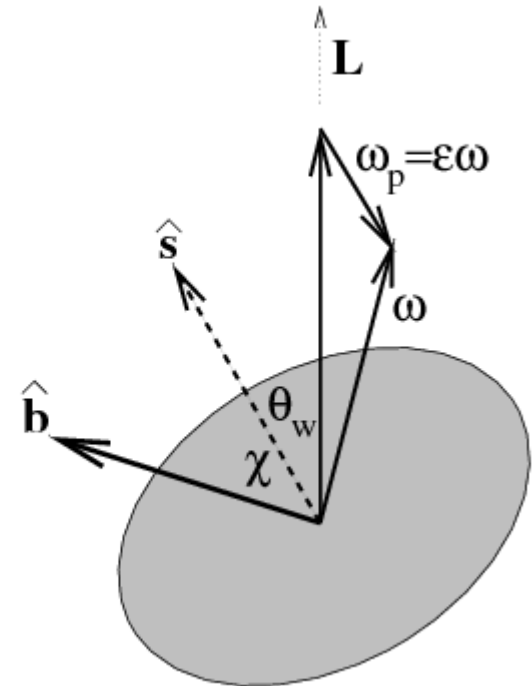1. Rapid ($\sim\Omega$) rotation around total angular
     momentum axis – L
2. Slow (Ω_p) retrograde rotation around
   the symmetry axis (s)

Θ_w – is small
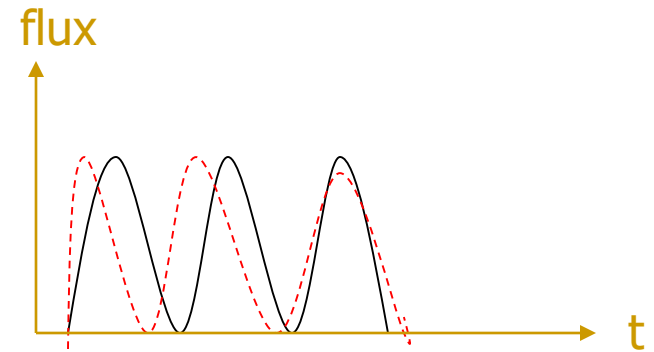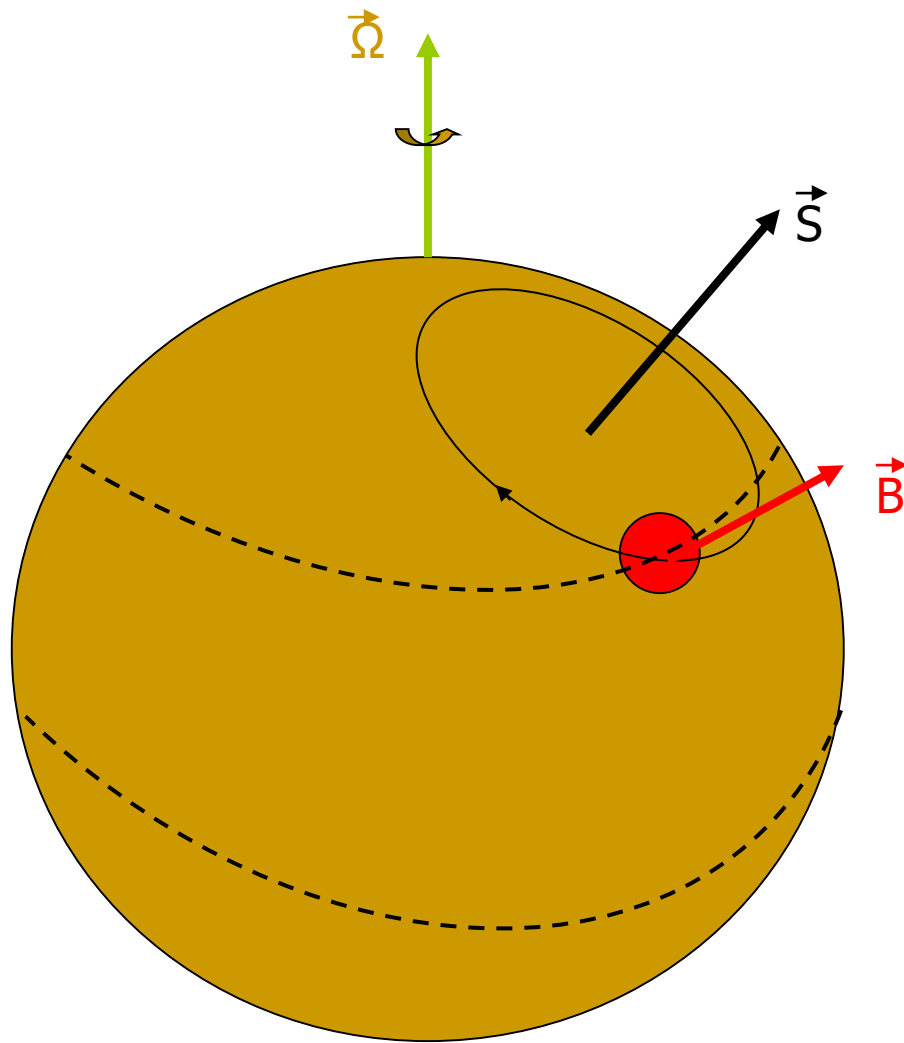Ω and L are very close
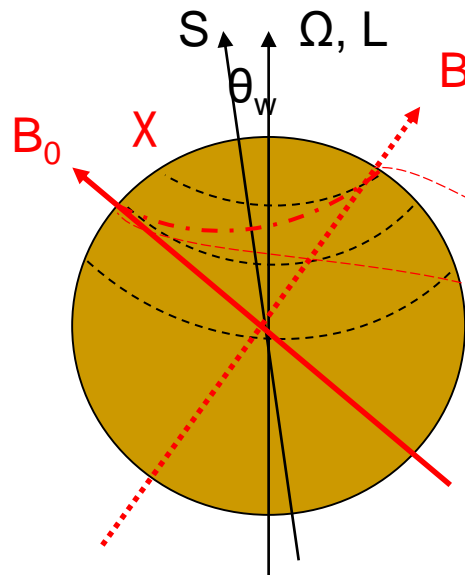
$$\Delta\varphi=\varphi_{max}-\varphi_{min}=(\chi+\theta_w)-(\chi-\theta_w)=2\theta_w$$

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

S

Ω

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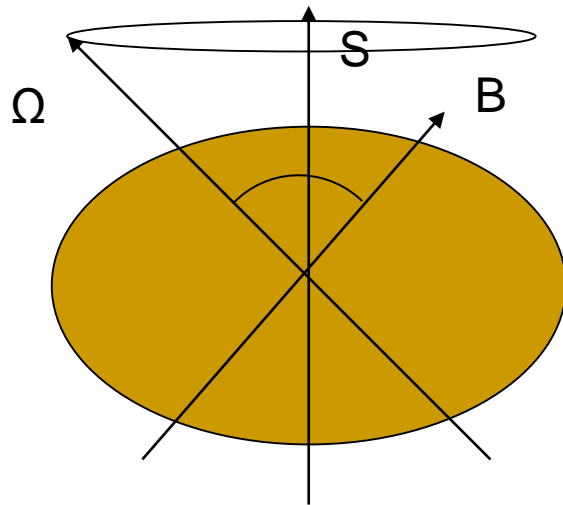
In this system the rotation axis is rotating around the symmetry axis.
So, it is clear that the angle between spin axis and the magnetic axis changes.

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

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

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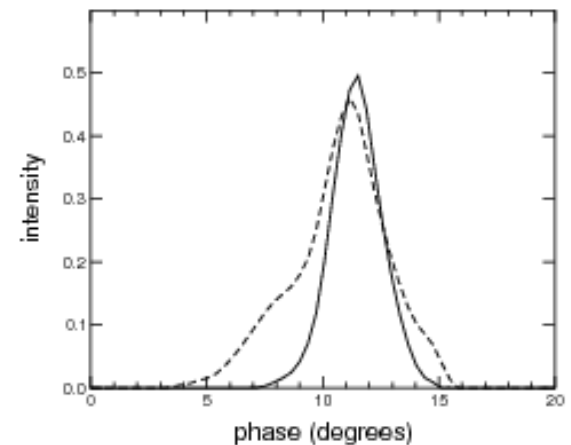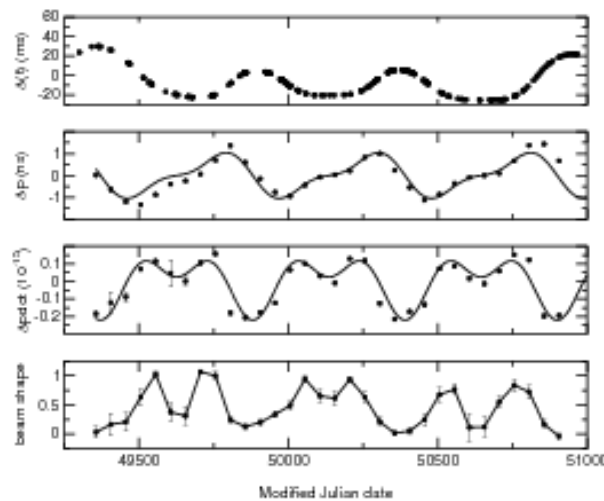
Complications …

A neutron star is not a solid body …
At least crust contains superfluid neutron vortices.
They are responsible for $I_p \sim 0.01$ of the total moment of inertia.
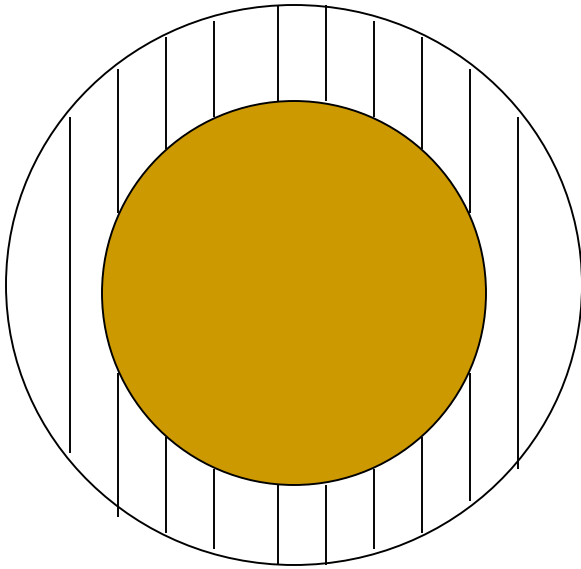
There are several effects related to vortices.

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 $\omega_{prec} = (I_p/I)\Omega \sim 10^{-2}\Omega$ (Shaham, 1977).
But due to finite temperature the pinning is not
that strong, and precession is possible
(Alpar, Ogelman, 1987).

Superfluidity in NSs

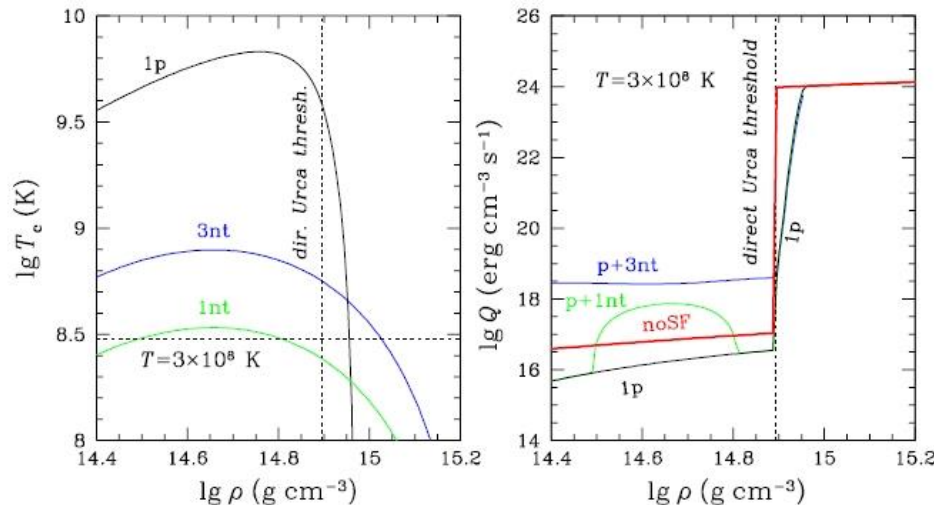50 years ago it was proposed (Migdal, 1959) that neutrons in NS interiors can be *superfluid*.

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
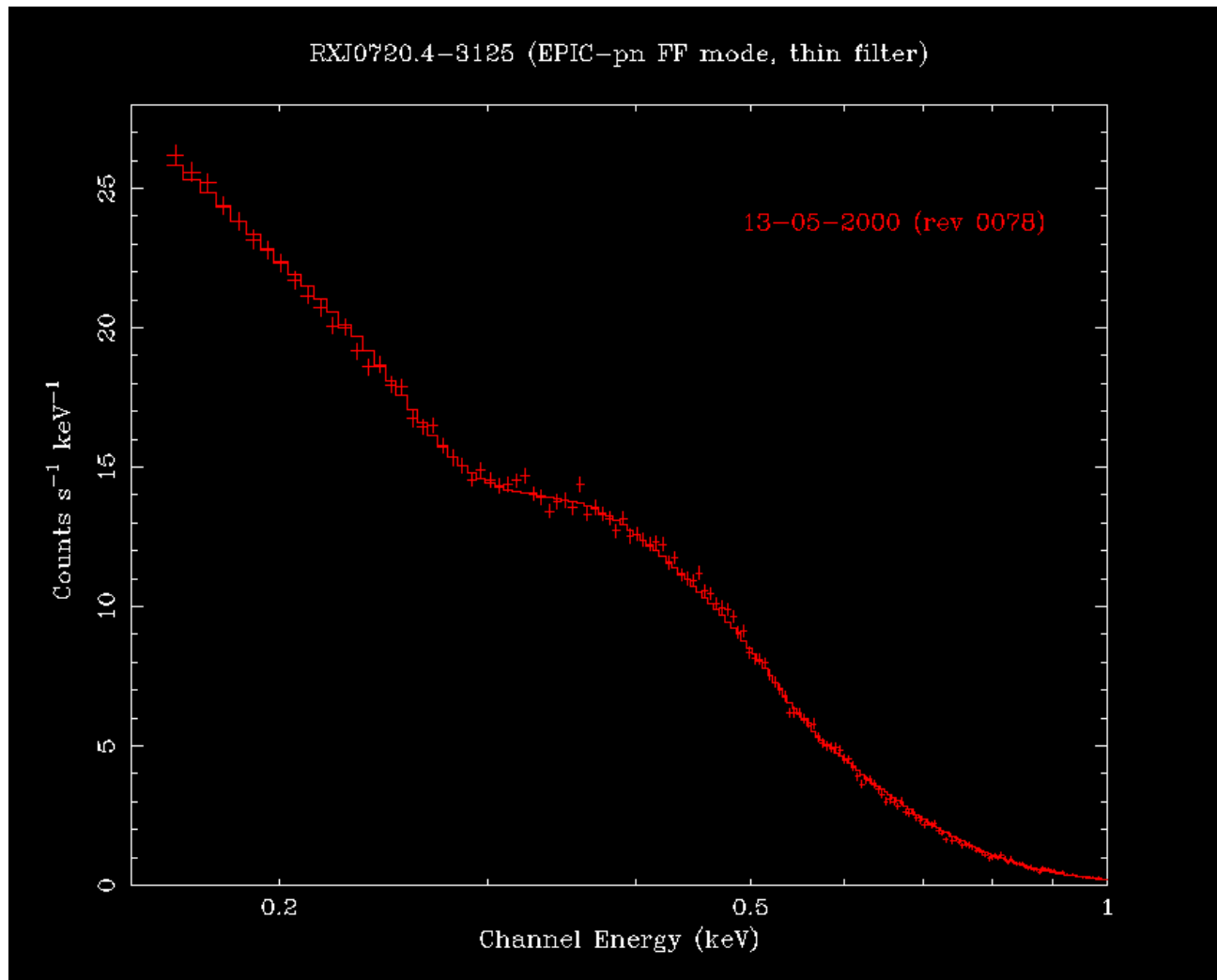
RX J0720.4-3125 as a variable source
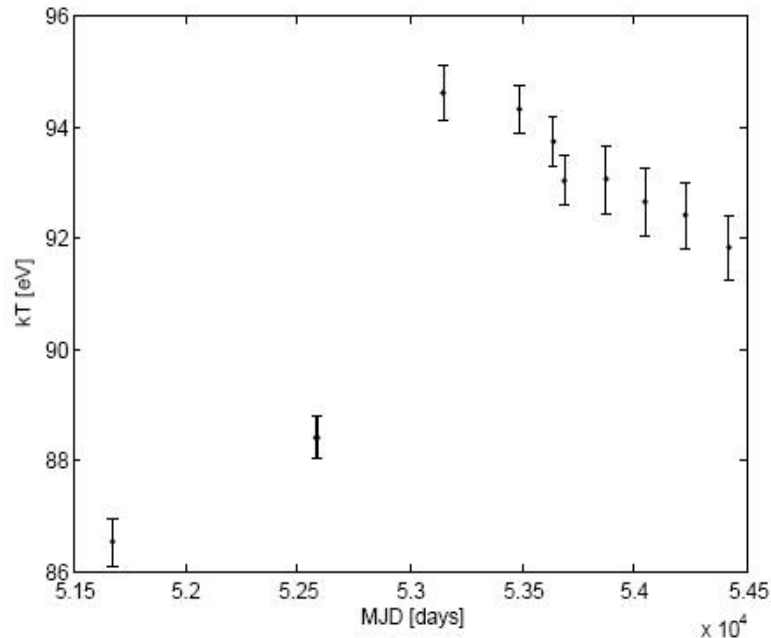
Long term phase averaged
spectrum variations
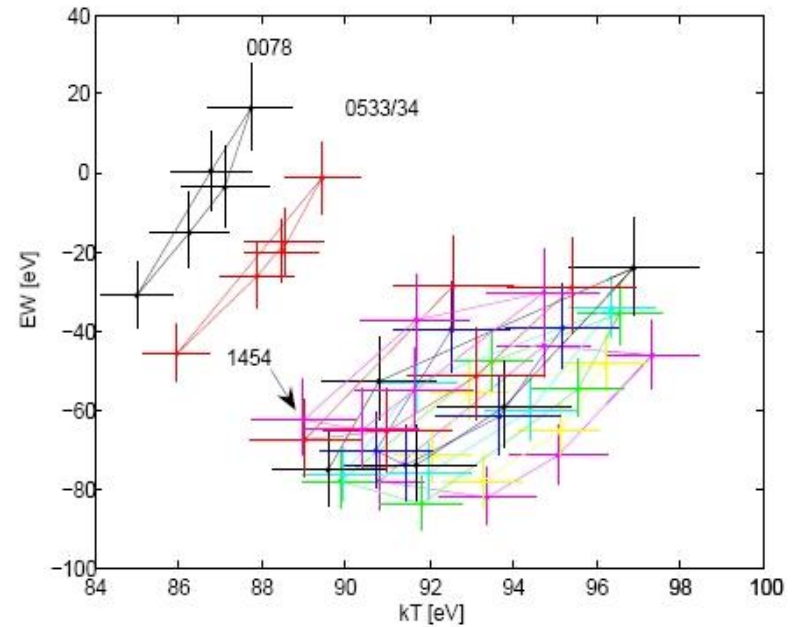
Phase dependent variations
during different observations.

[Hohle et al. 2009 arXiv:0810.5319]

~10 years period: precession???
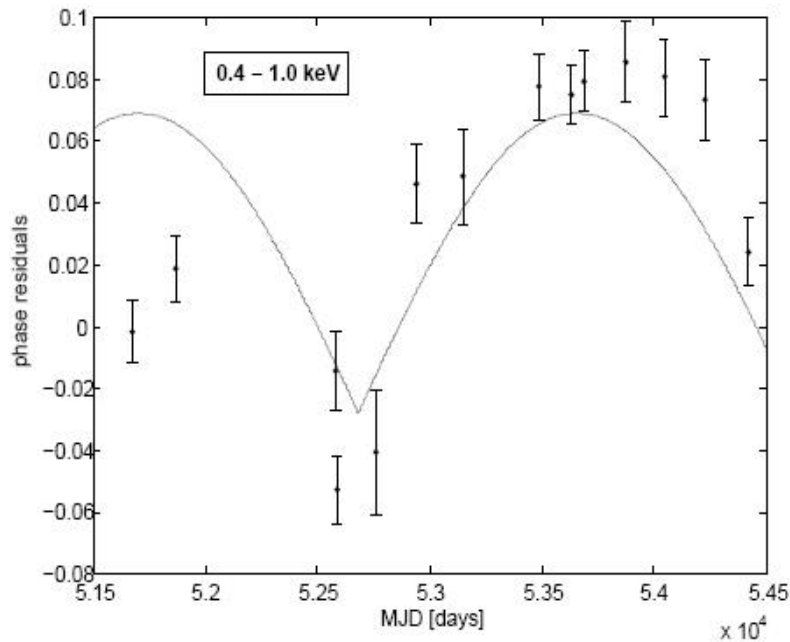
10.711 +/-0.058 yrs
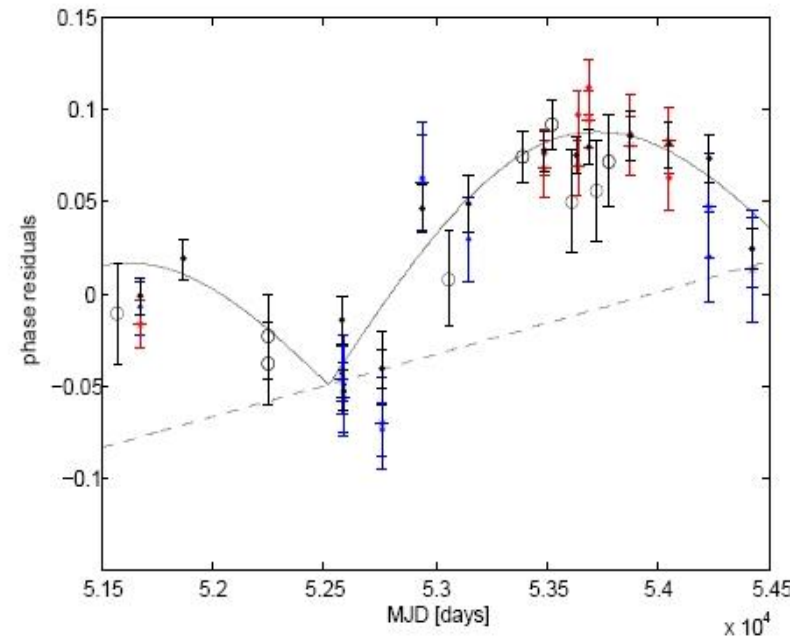
However, the situation is not clear.
New results and a different timing solution.
The estimate of the period of precession
slightly changed down to ~7 years.

[Hohle et al. 2009]

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).
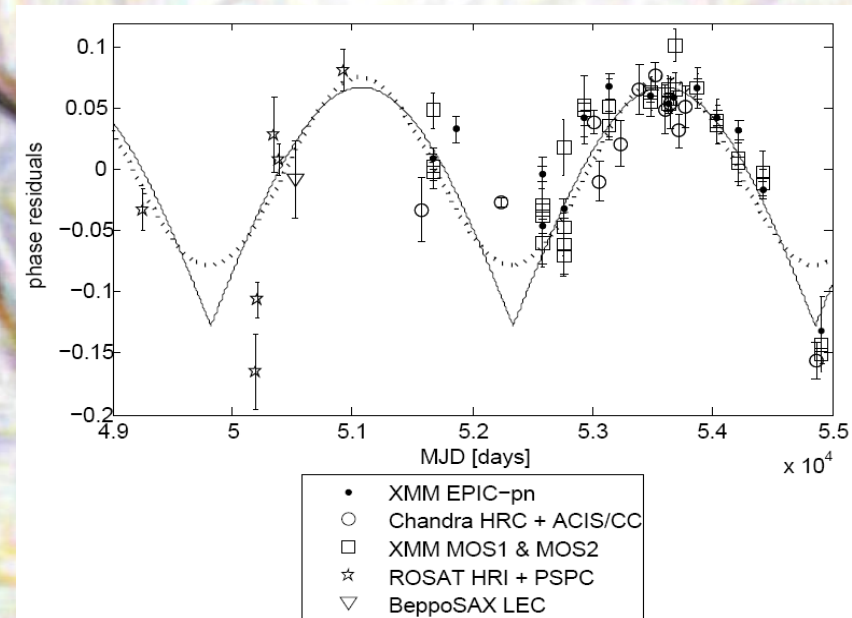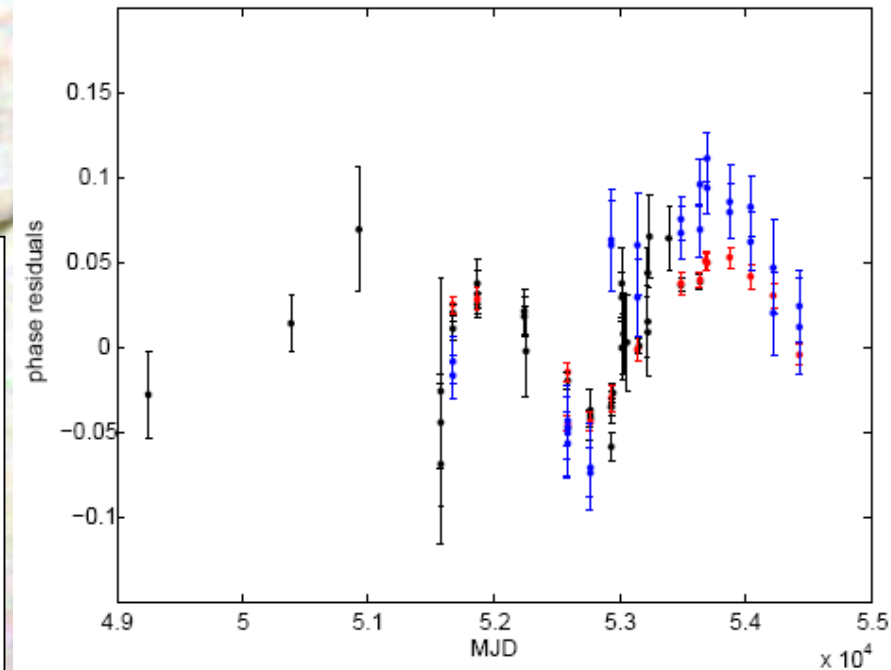
Another interpretation: glitch + ?

TIMING SOLUTIONS FOR RX J0720.4−3125

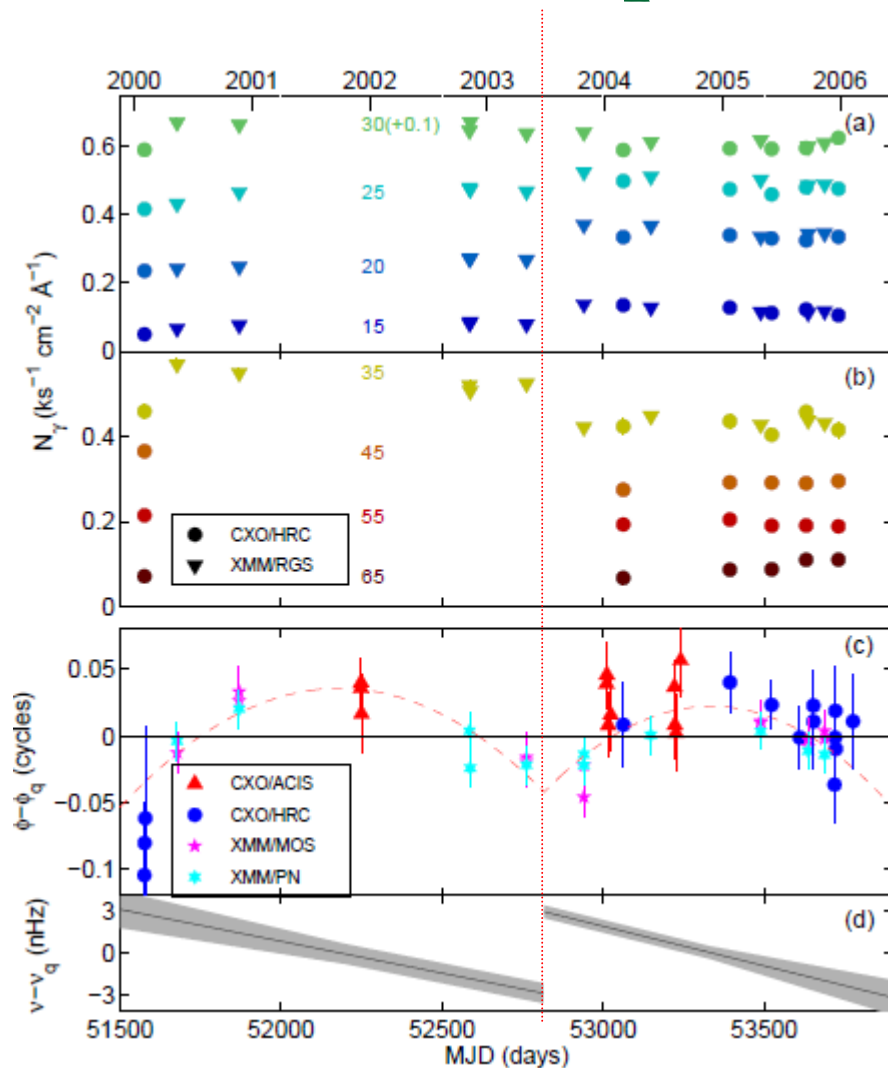| Quantity	Excl. *ROSAT*	All Data
Spindown only		
t_0 (MJD)	53010.2635646(7)	53010.2635626(6)
ν (Hz)	0.11917366979(12)	0.11917366954(11)
$\dot{\nu}$ (Hz s^{-1})	$-9.74(4) \times 10^{-16}$	$-9.88(13) \times 10^{-16}$
TOA rms (s)	0.26	0.29
χ^2/dof	77.6/46=1.69	150.8/49=3.08
Spin-down + Glitch		
t_0 (MJD)	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

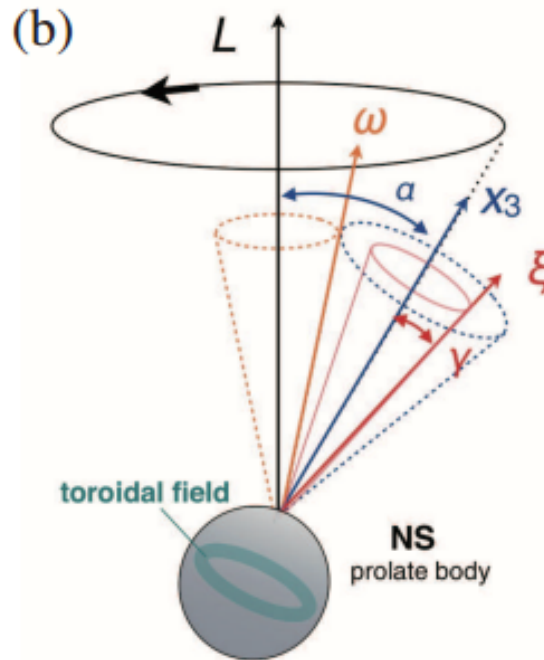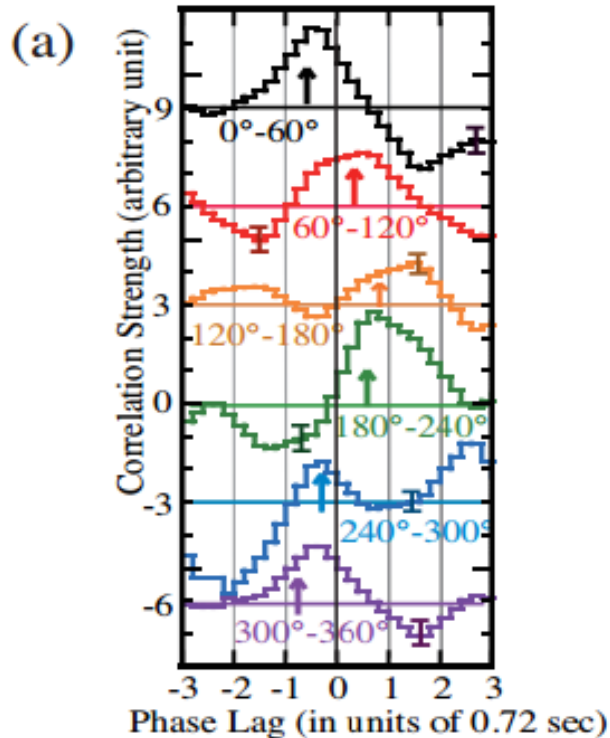# RX J0720.4-3125: a glitch

1203.3708
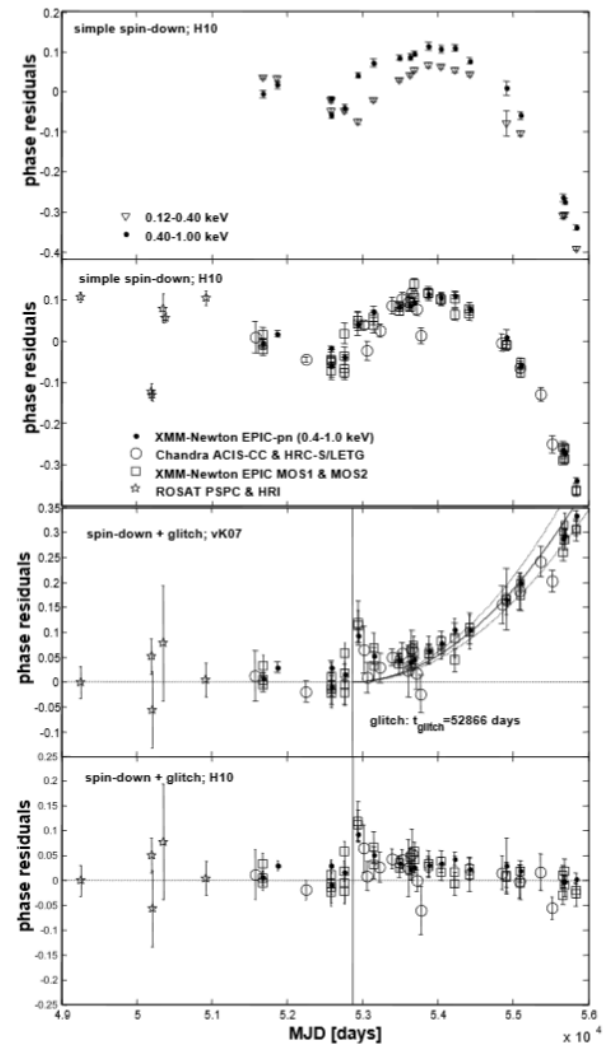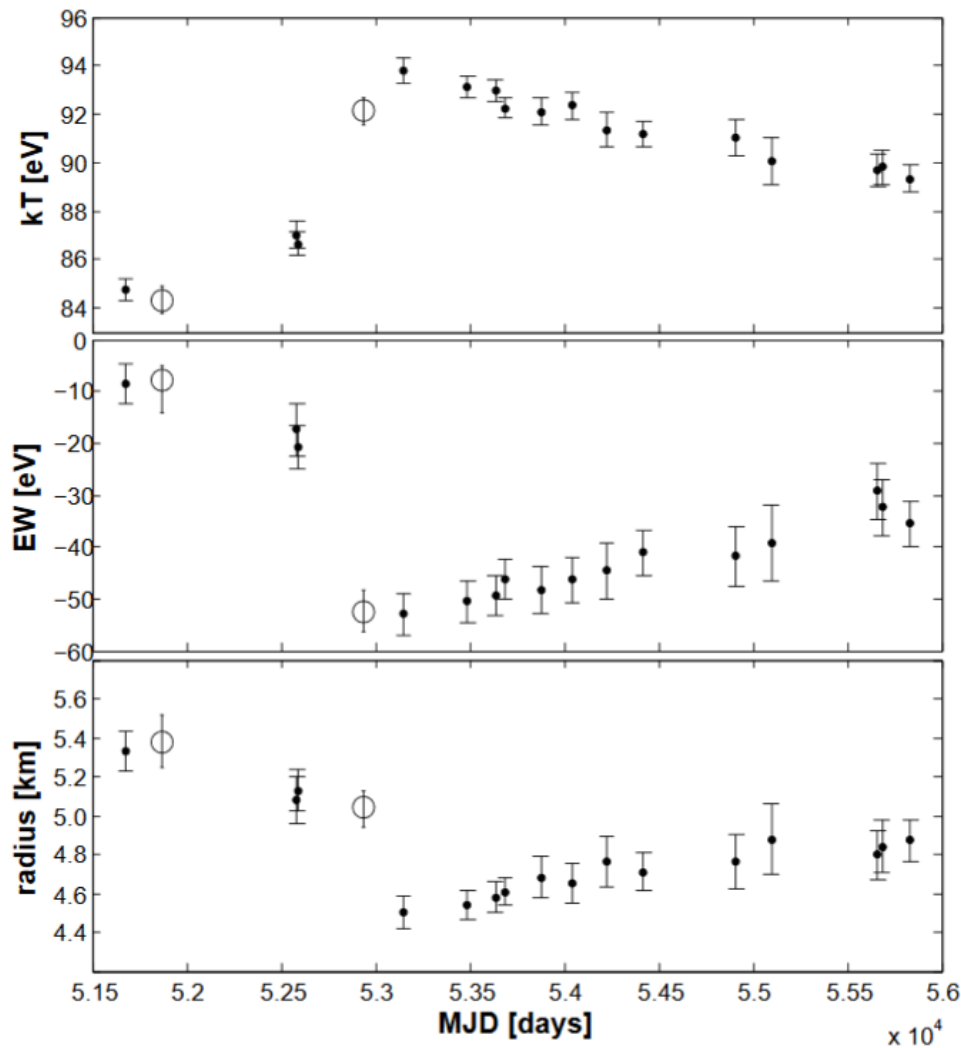
Glitch+? in a PSR
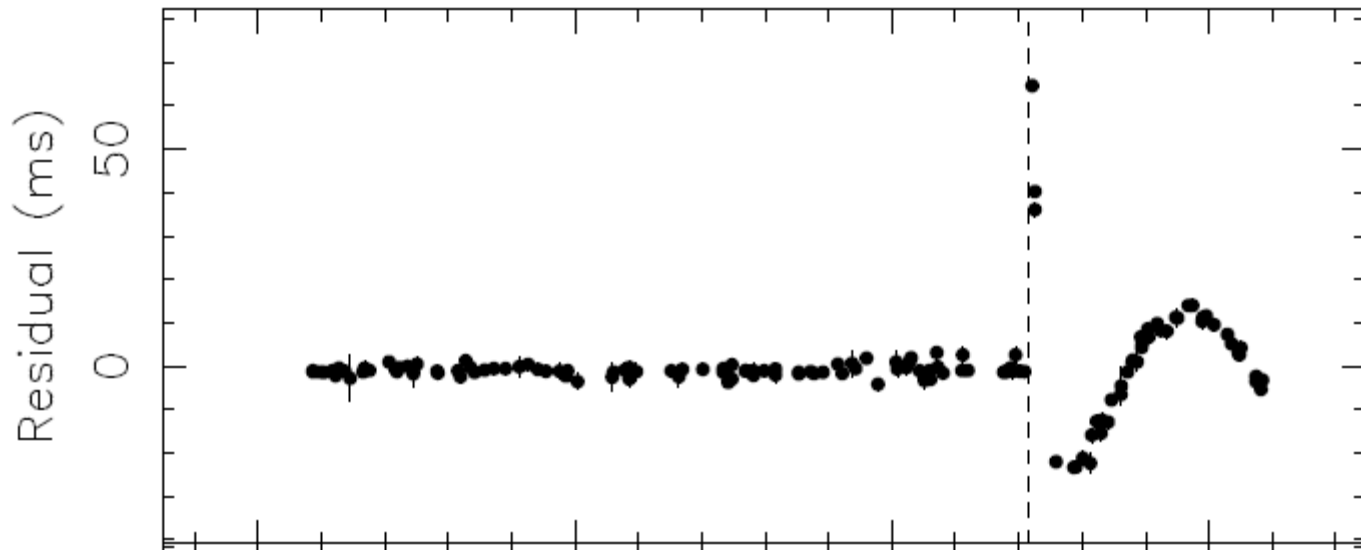
PSR B2334+61

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?

(a) Correlation Strength (arbitrary unit)
0°-60°
60°-120°
120°-180°
180°-240°
240°-300°
300°-360°
Phase Lag (in units of 0.72 sec)

(b) L, ω, a, x_3, ξ, γ
toroidal field
NS prolate body

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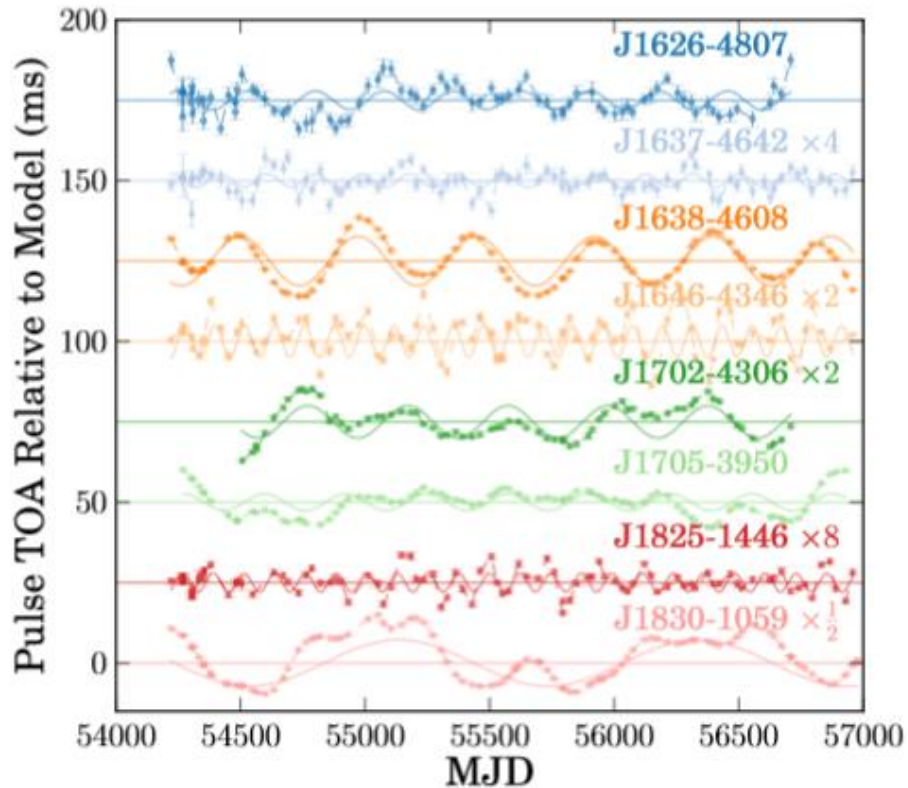
Correlations of the modulation period
with spin period, characteristic age
and spin-down power.

1510.06078
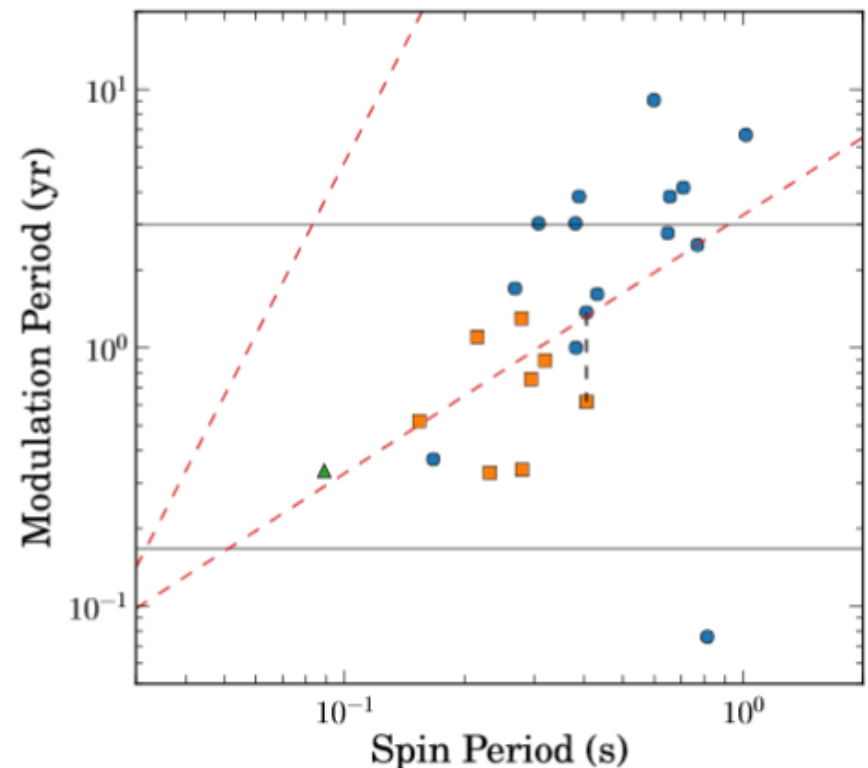
Conclusion

Many observed phenomena are related to internal dynamics of NSs.
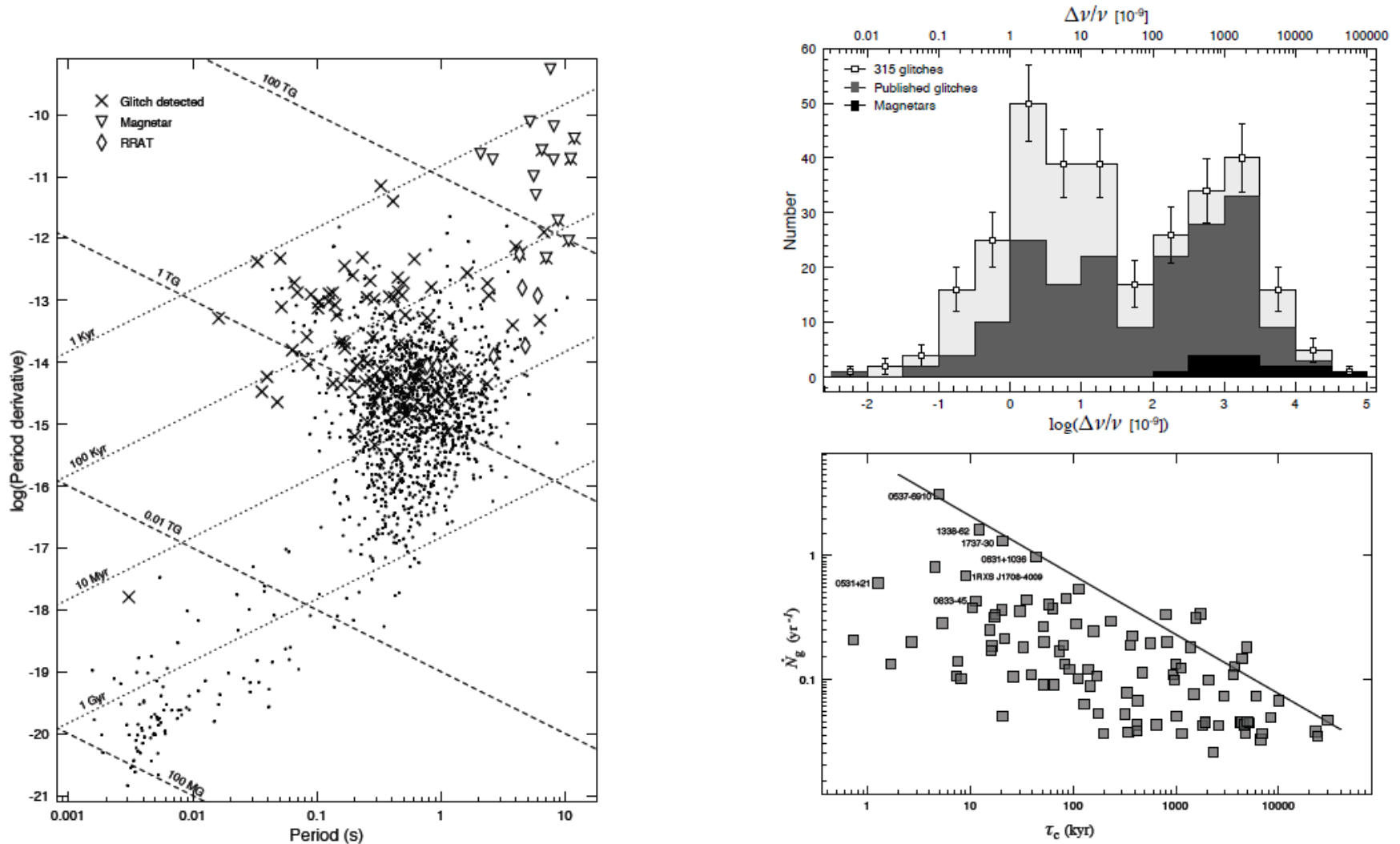
• Glitches
• Precession

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. <u>astro-ph/0001245</u> Glitches
- Link <u>astro-ph/0211182</u> Precession
- Jones, Andersson astro-ph/0011063 Precession
- Dib et al. arXiv: 0706.4156 AXP glitches
- Haskell, Melatos arXiv: 1502.07062 Big review
- Haskell, Sedrakian arXiv: 1709.10340 Big review on superfluidity
- Fuentes et al. arXiv: 1710.00952 Glitch statistics
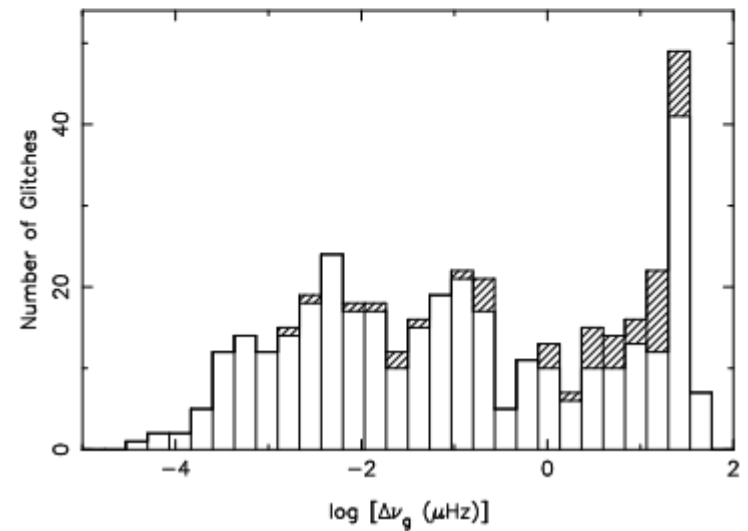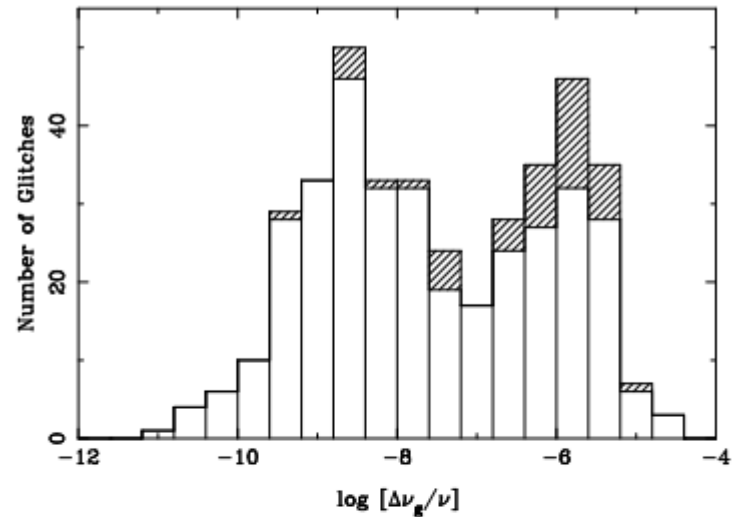- Manchester arXiv: <u>1801.04332</u> Brief review on glitches
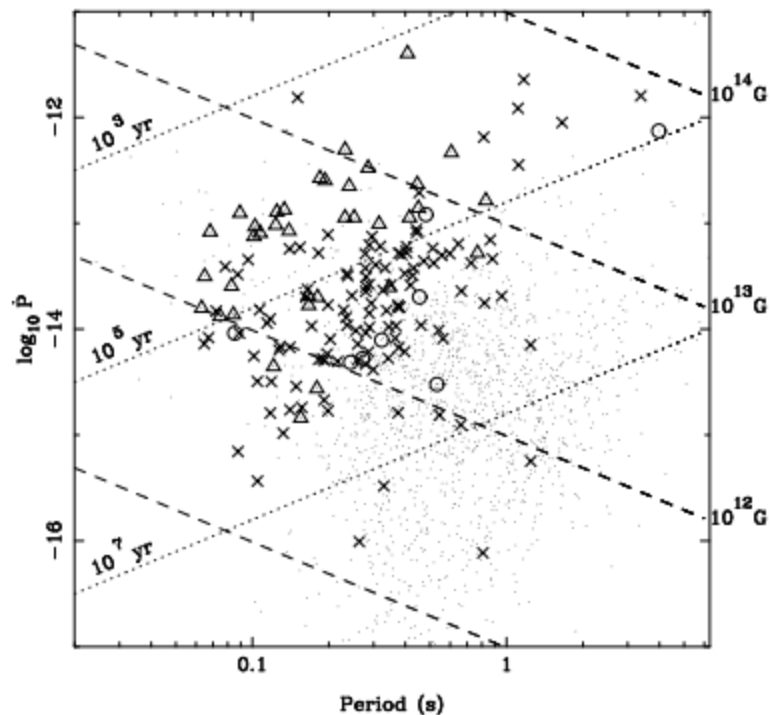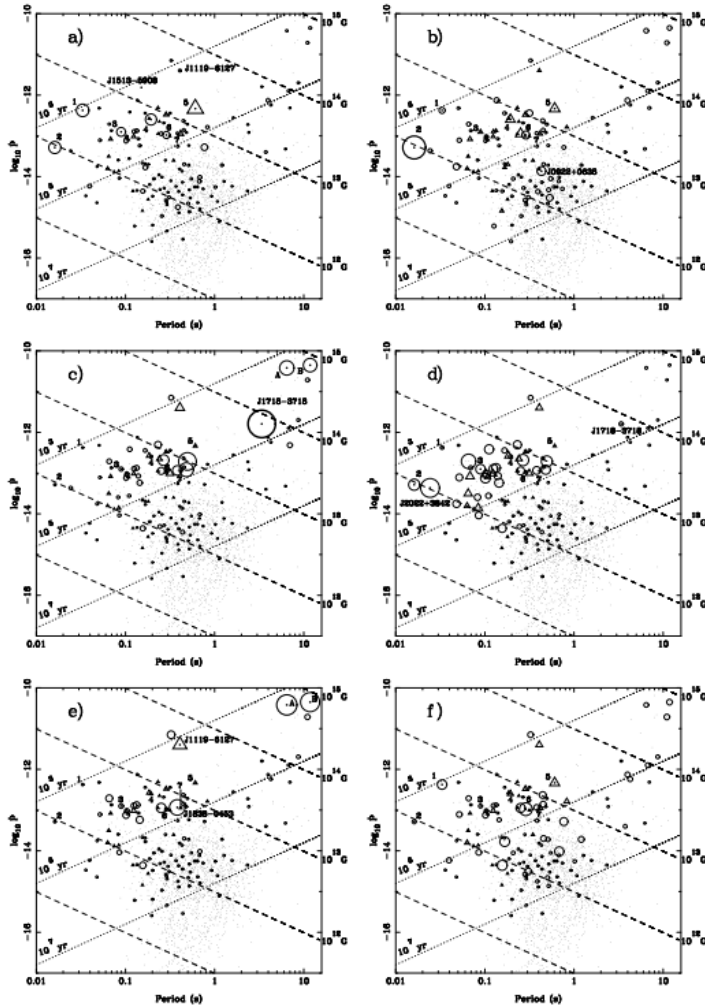
Many-many glitches …

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

Modeling glitches

Mean field approach to describe vortex dynamics