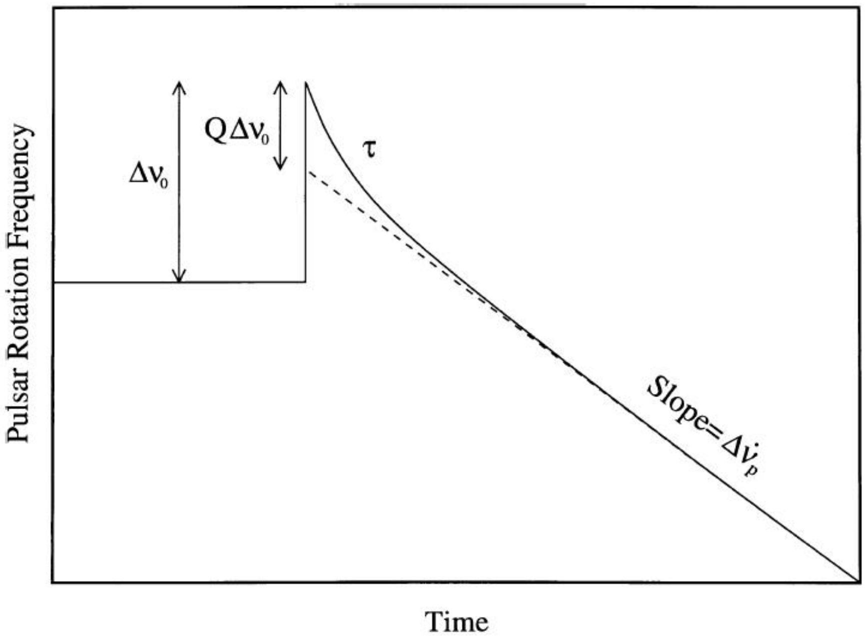
Glitches and precession

What is a glitch?



A sudden increase in rotation rate (limits are down to <12 sec in Vela).

ATNF catalogue gives >200 normal PSRs with glitches.

The most known: Crab and Vela

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

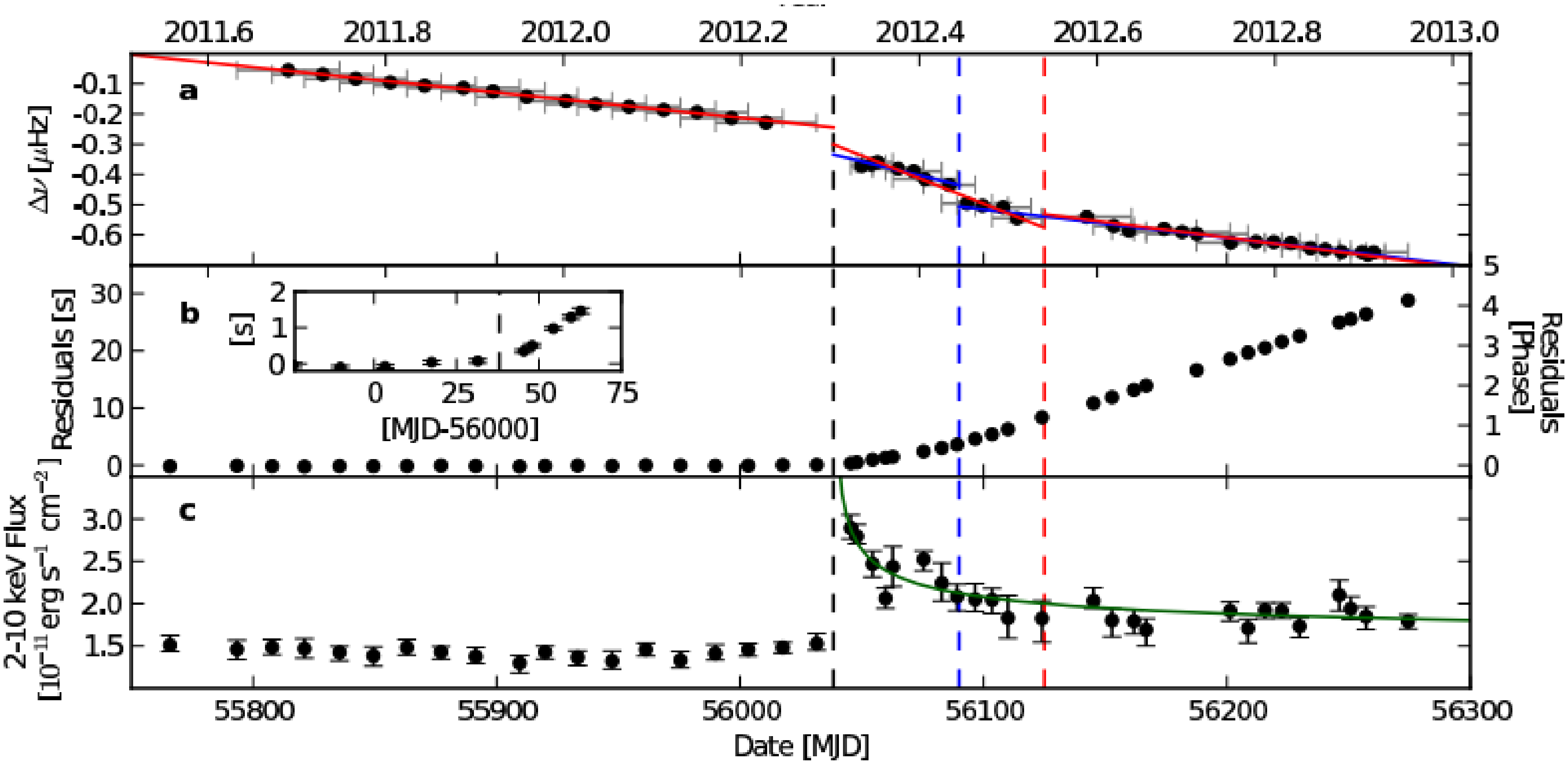
Spin-down rate can change after a glitch. Vela is spinning down faster after a glitch.

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

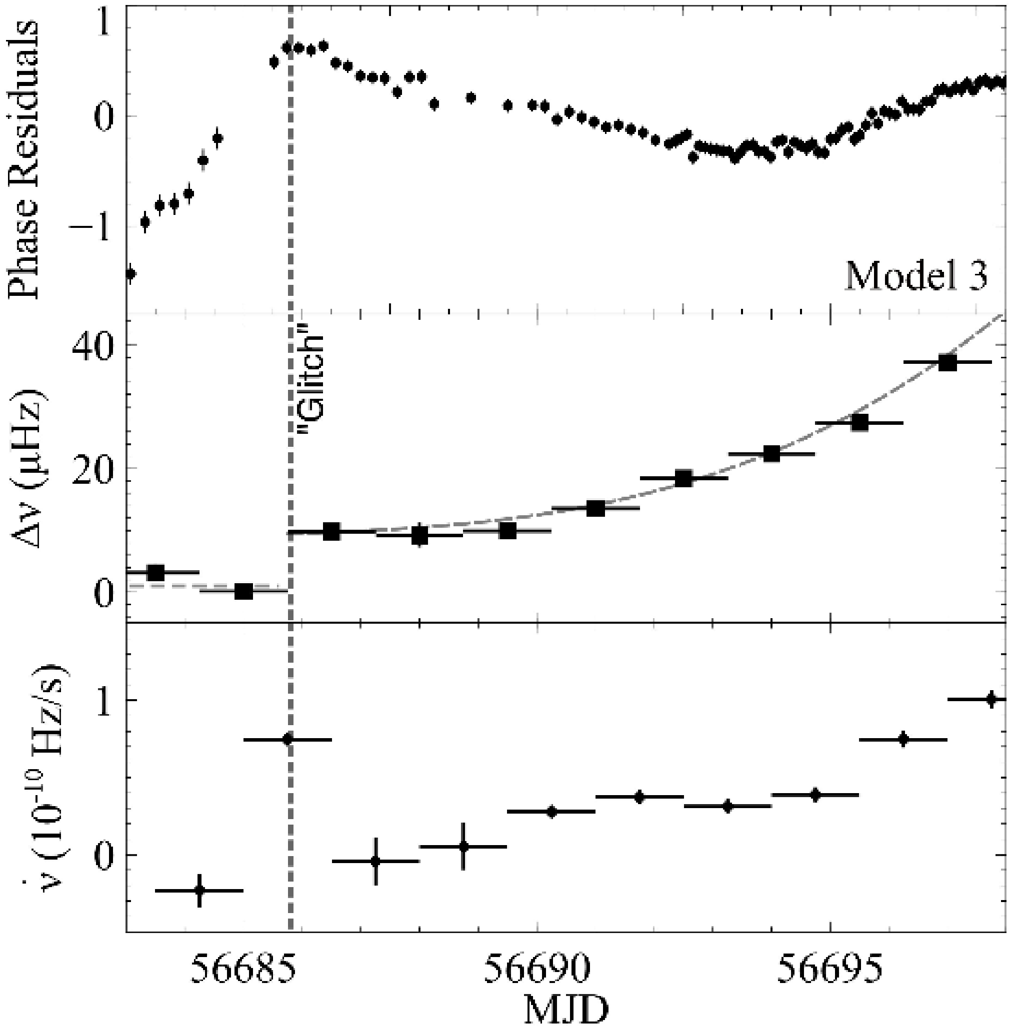
Anti-glitch of a magnetar



AXP 1E 2259+586

1305.6894

Glitches in accreting X-ray binaries



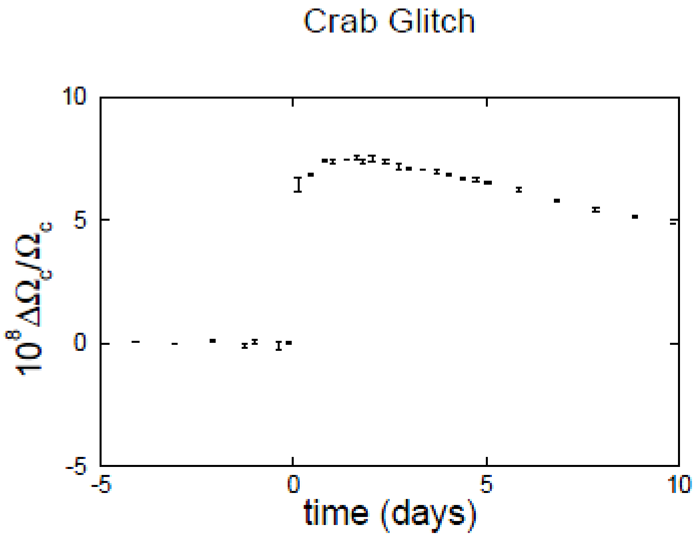
ULX M82 X-2
Pspin=1.4 sec

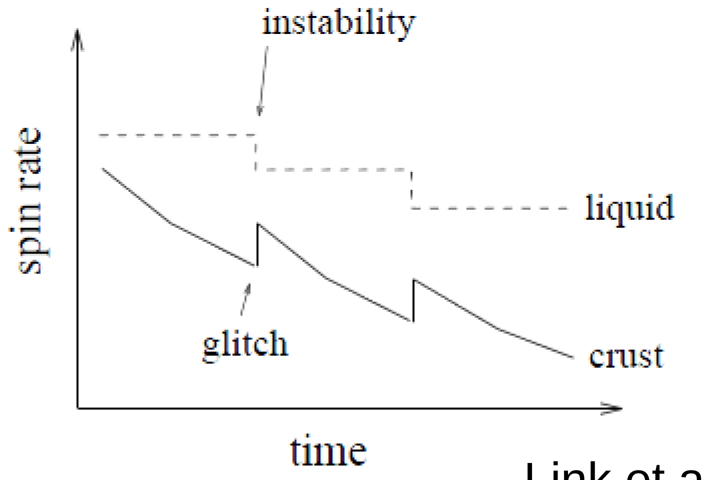
$\Delta\nu/\nu \gtrsim 10^{-5}$

Another anti-glitches in NGC 300 ULX-1. A theory is developed in arXiv: 2205.05896

1905.06423

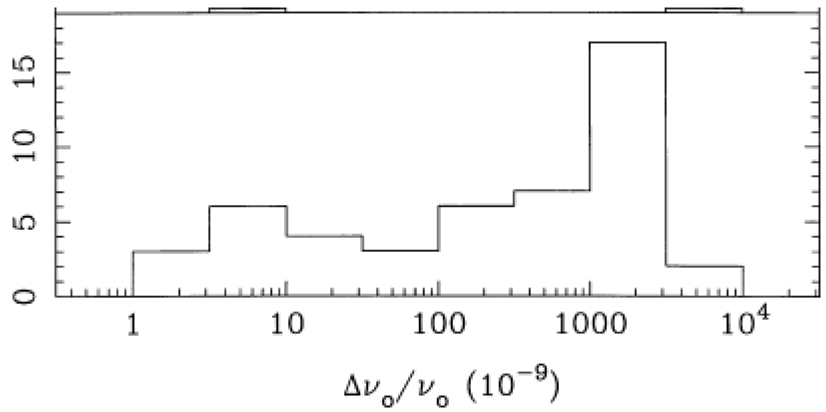
Crab glitch and the general idea





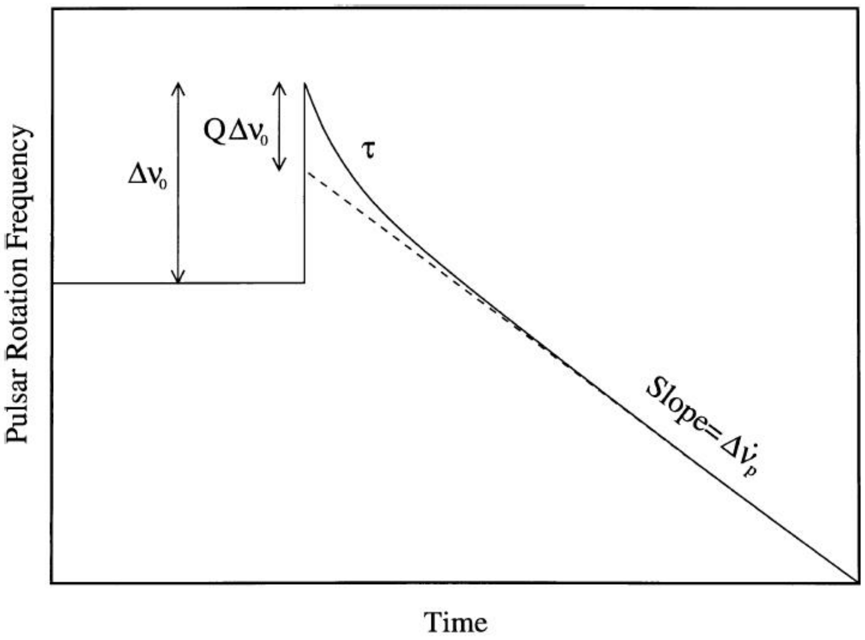
Link et al. (2000)

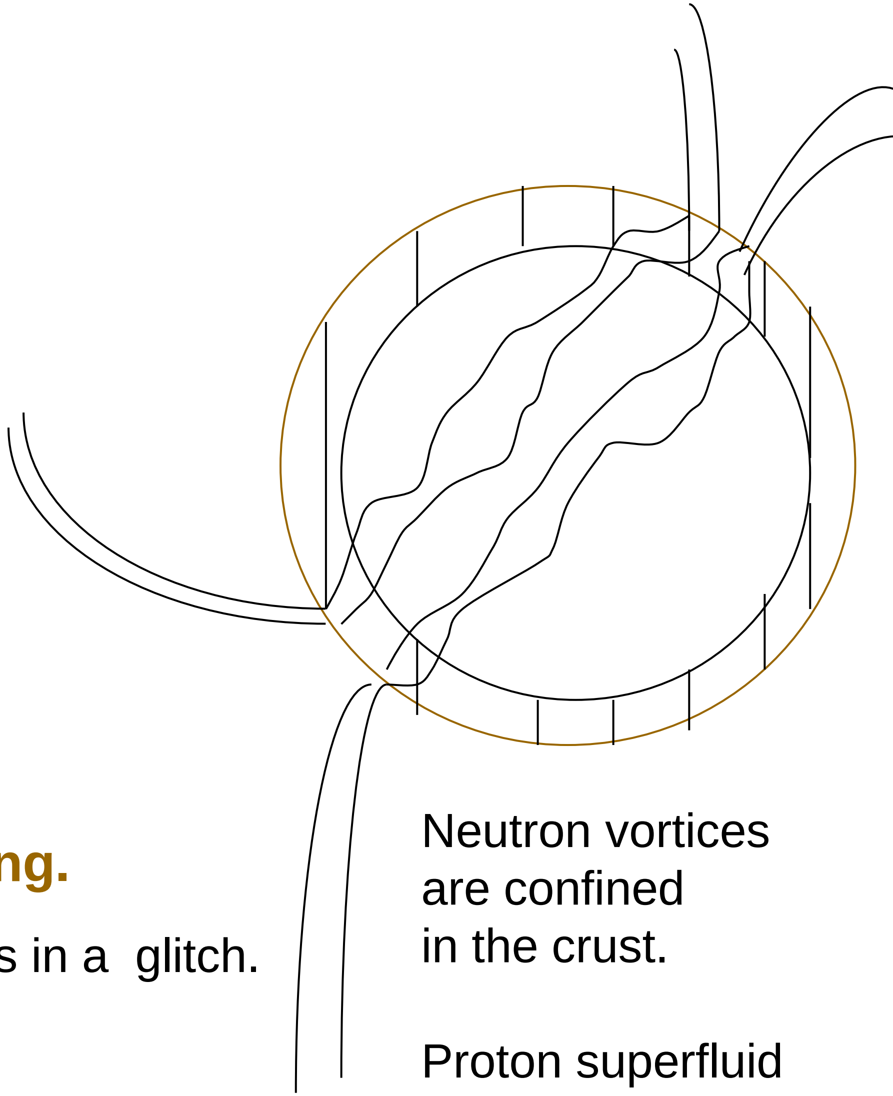
While the crust we see (and all coupled to it)
is slowing down,
some component of a star is not.
Then suddenly (<12 sec) an additional
momentum stored in such a “reservoir”
is released and given to the crust.
The crust spins-up,
up the internal reservoir – down.



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}

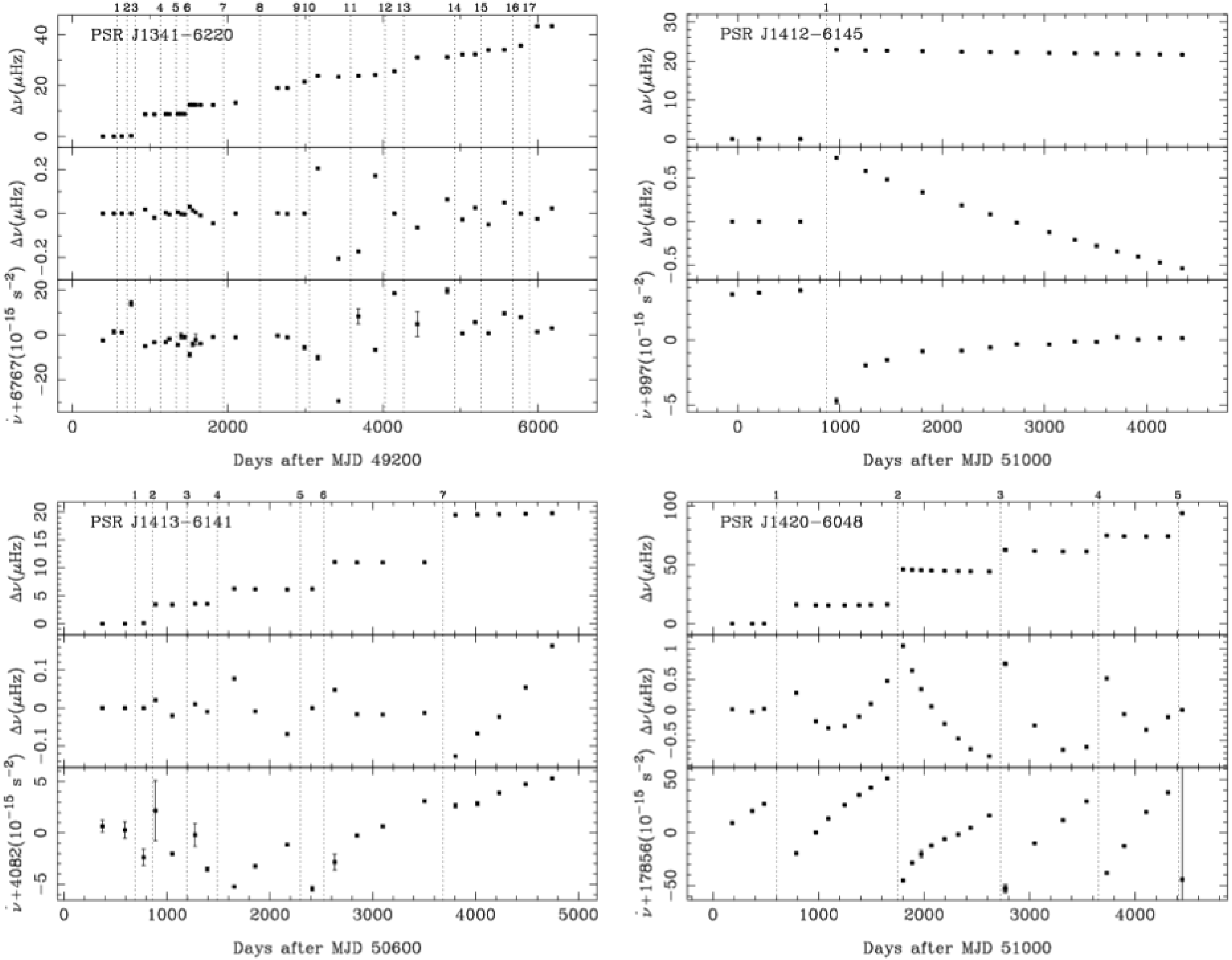
Flux lines density is 5 10^{18} B$_{12}$ cm^{-2}

Neutron vortices
are confined
in the crust.

Proton superfluid
is strongly coupled
to the crust.

Reviews about superfluidity in NS: 1709.10340, 2103.10218

Glitch discovery and observations



1211.2035

The largest glitch of the Crab pulsar

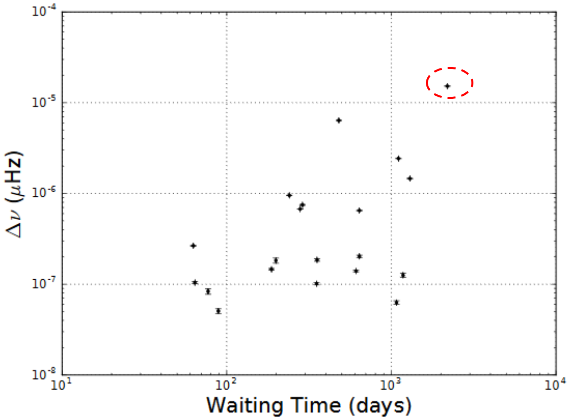
2017 November 8

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

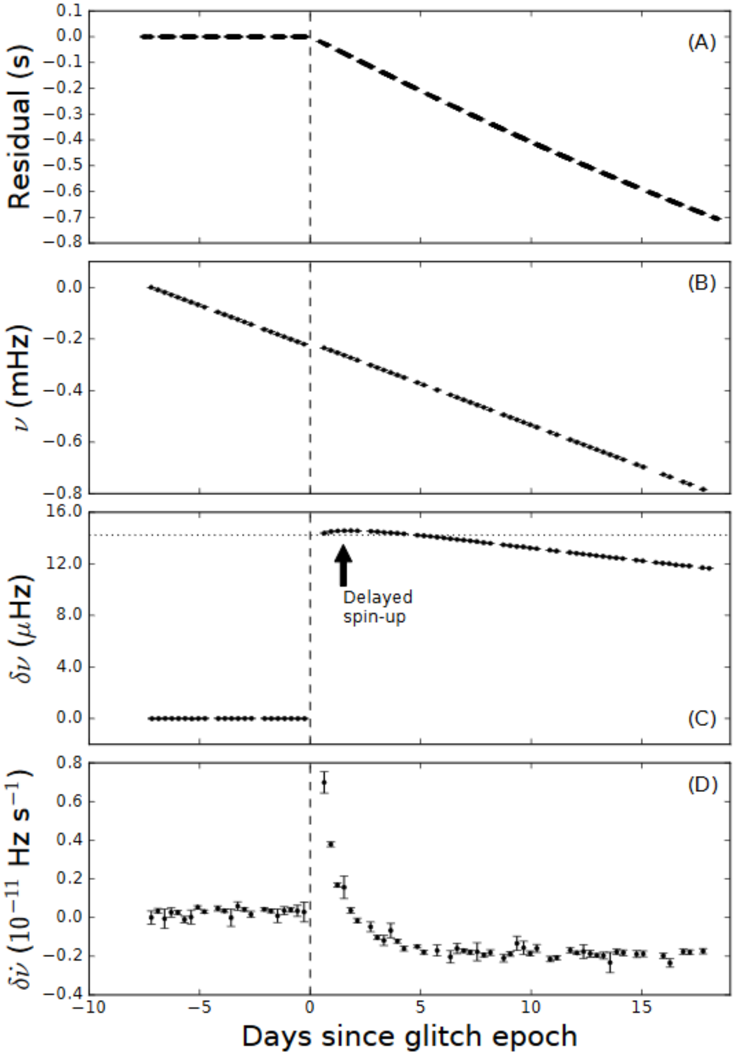
$$\Delta\nu/\nu = 0.516 \times 10^{-6}$$

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

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

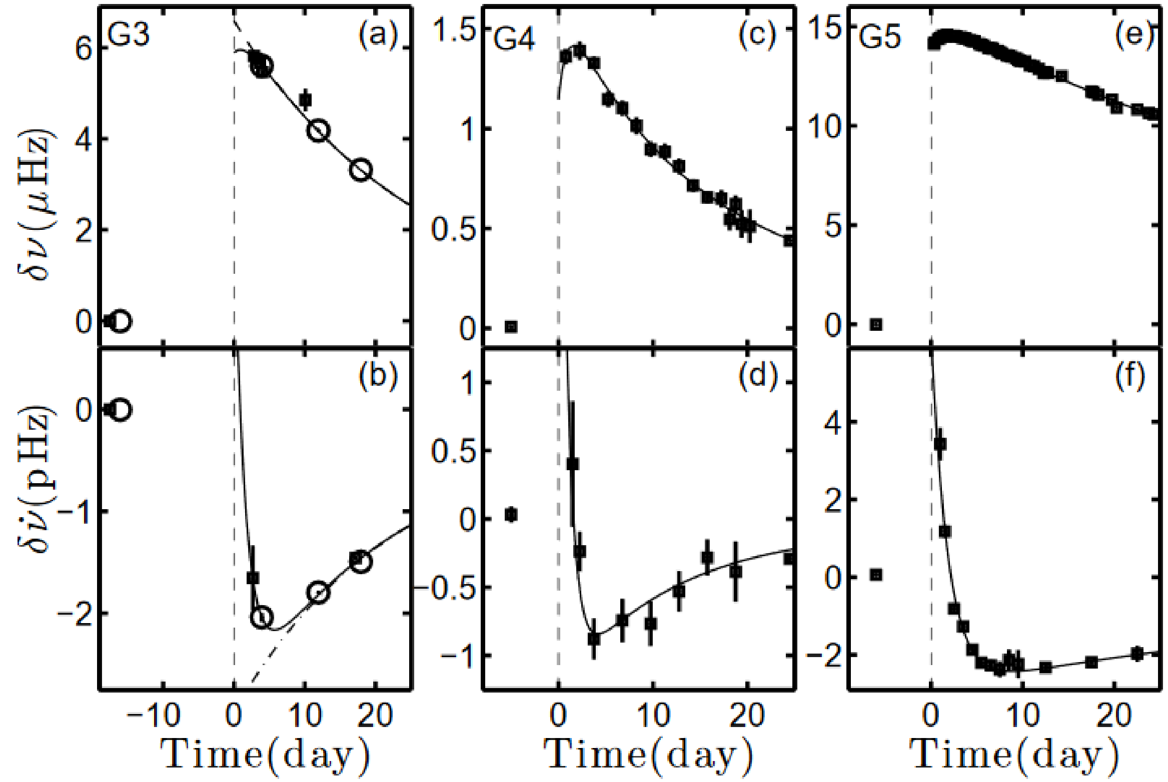
(See theoretical discussion in 1806.10168)

Delayed spin-up in Crab's glitches

Residuals: $$\delta\nu = \Delta\nu_{\rm p} + \Delta\dot{\nu}_{\rm p}\Delta t + \sum_{i=1,2} \Delta\nu_{\rm di}\exp(-\Delta t/\tau_{\rm i})$$

$$\delta\dot{\nu} = \Delta\dot{\nu}_{\rm p} + \sum_{\rm i=1,2} \Delta\dot{\nu}_{\rm di}\exp(-\Delta t/\tau_{\rm i})$$

In delayed spin-up some of $\Delta\nu_{\rm di}$ are negative, as well as $\Delta\dot{\nu}_{\rm di}$

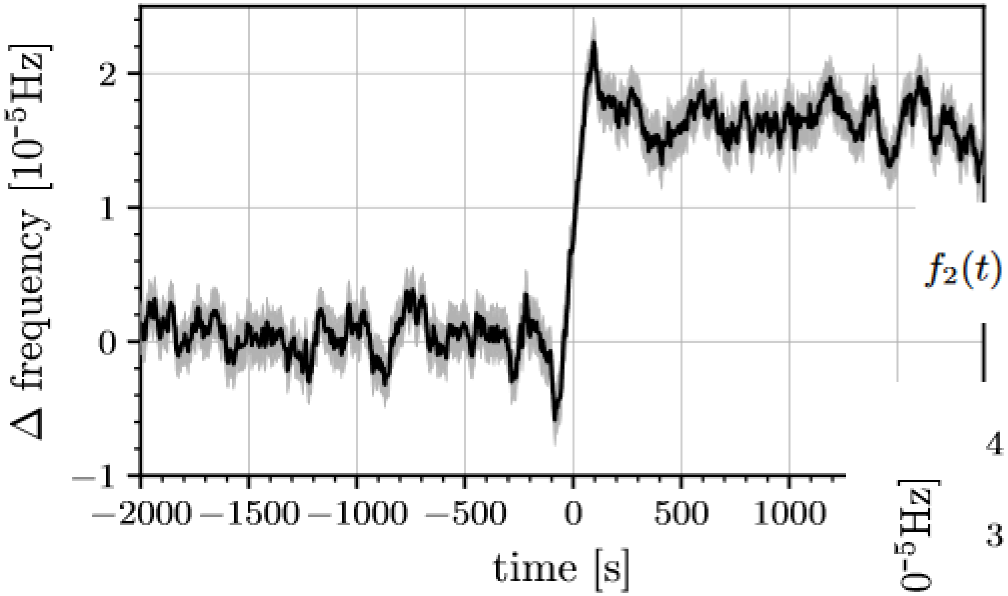


Three glitches with delayed spin-up.

Dot-dashed (panel b) – is the fit without delayed spin-up.

2004.00791. Similar results reported by 2103.13180

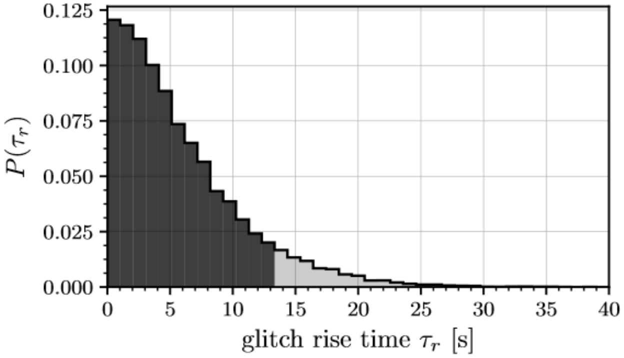
Fastest Vela glitch (and fastest ever!)

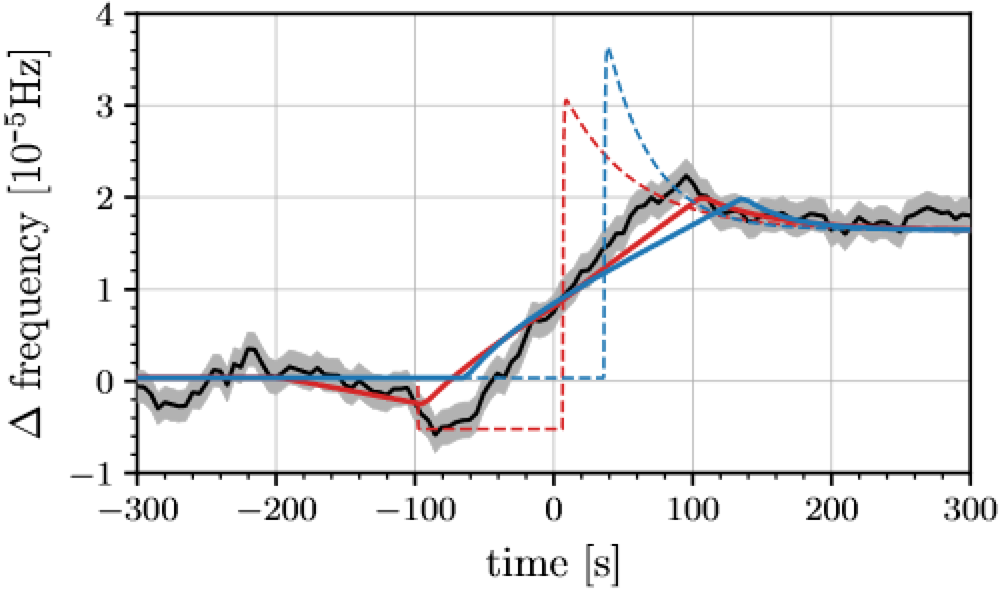


12 December 2016

$$f_2(t) = f_0 + H(t-t_g)\left[\Delta f + \Delta f_r e^{\frac{-(t-t_g)}{\tau_r}} + \Delta f_d e^{\frac{-(t-t_g)}{\tau_d}}\right]$$

Glitch rise time <12 sec





1907.01124, see theoretical discussion in 2003.08724

Phenomenology and the Vela pulsar

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

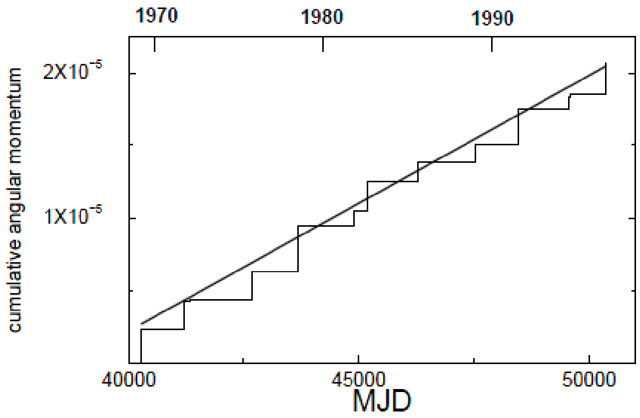
Glitches are driven by the portion of the liquid interior that is differentially rotating with respect to the crust.

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

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

The average rate of angular momentum transfer (per unit time) due to 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.

(A more sophisticated approach can be found in 2012.01539)

(Values are for the Vela PSR)

In Vela glitches can be related also to the outer core 1806.10168, 2001.09668

Role of the core

Only neutrons in the core are considered.

Three components: $I_n^{pin} + I_n^f + I_p = I$

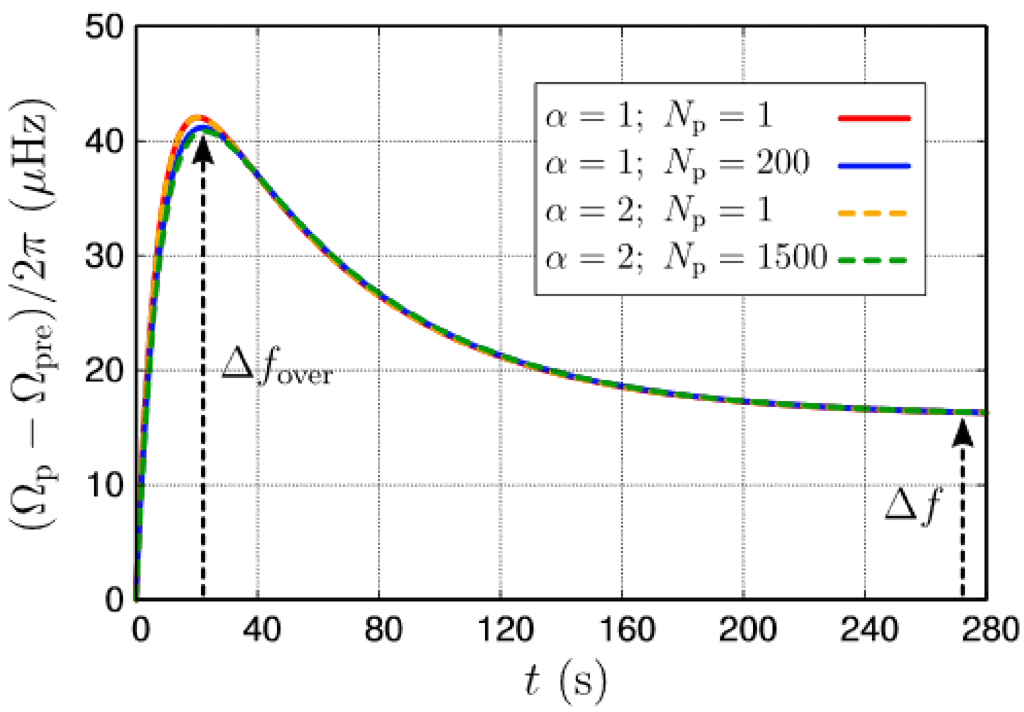
- pinned superfluid neutrons in the outer core;
- free superfluid neutrons in the inner core;
- the rest of the star.

$$\dot{\Omega}_p = -\frac{I_n^f}{I_p}\dot{\Omega}_n^f - \frac{I_n^{pin}}{I_p}\dot{\Omega}_n^{pin} + \frac{\Gamma_{ext}}{I_p}, \quad \Gamma_{ext} = I\dot{\Omega}_\infty$$

$$\dot{\Omega}_n^f = 2\mathcal{B}_f\,\Omega_n^f\left(\Omega_p - \Omega_n^f\right),$$

$$\dot{\Omega}_n^{pin} = 2\mathcal{B}_{pin}\,\Omega_n^{pin}\left(\Omega_p - \Omega_n^{pin}\right),$$

Ω_{pre} extrapolated from the pre-glitch evolution



2001.09668

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).

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

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

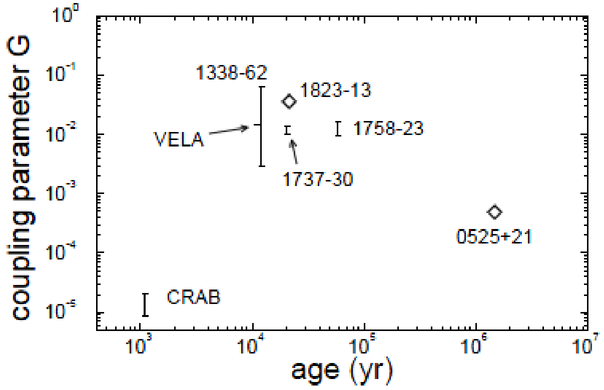
$$\frac{I_{\rm res}}{I_c} \geq \frac{\bar{\Omega}}{|\dot{\Omega}|} A \equiv G,$$

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

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

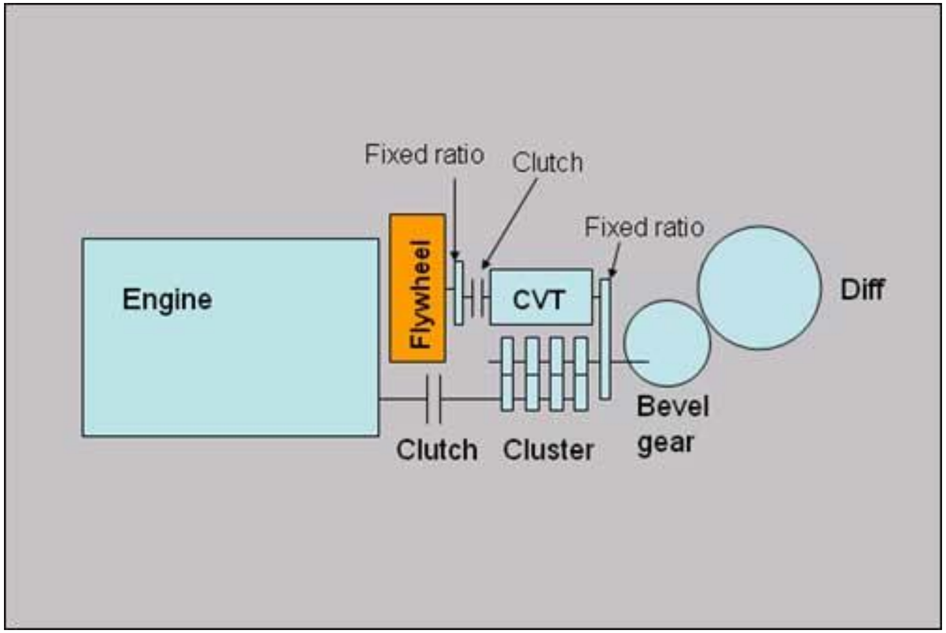
Glitch statistics for Vela provide an estimate for G.

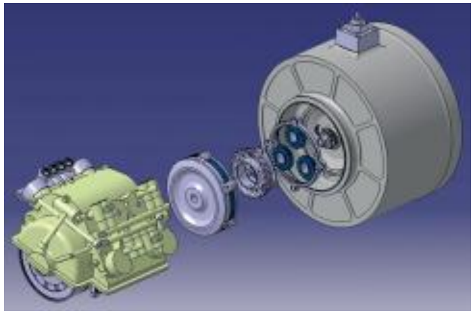
Superfluid is a good candidate to form a “reservoir” because relaxation time after a glitch is very long (~months) which points to very low viscosity.



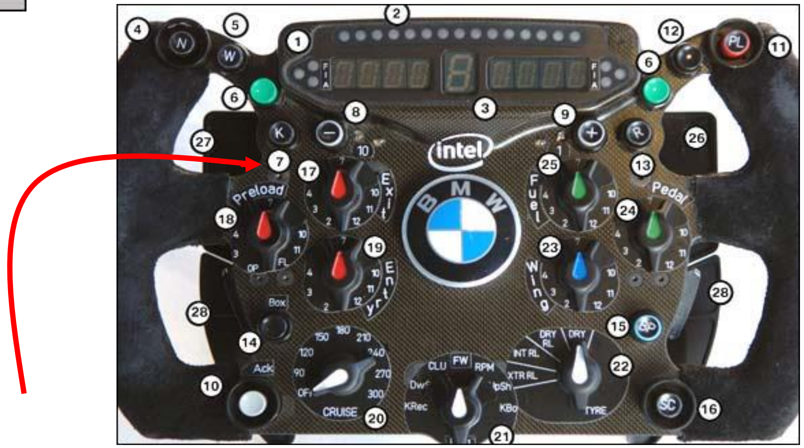
Link et al. 0001245

KERS

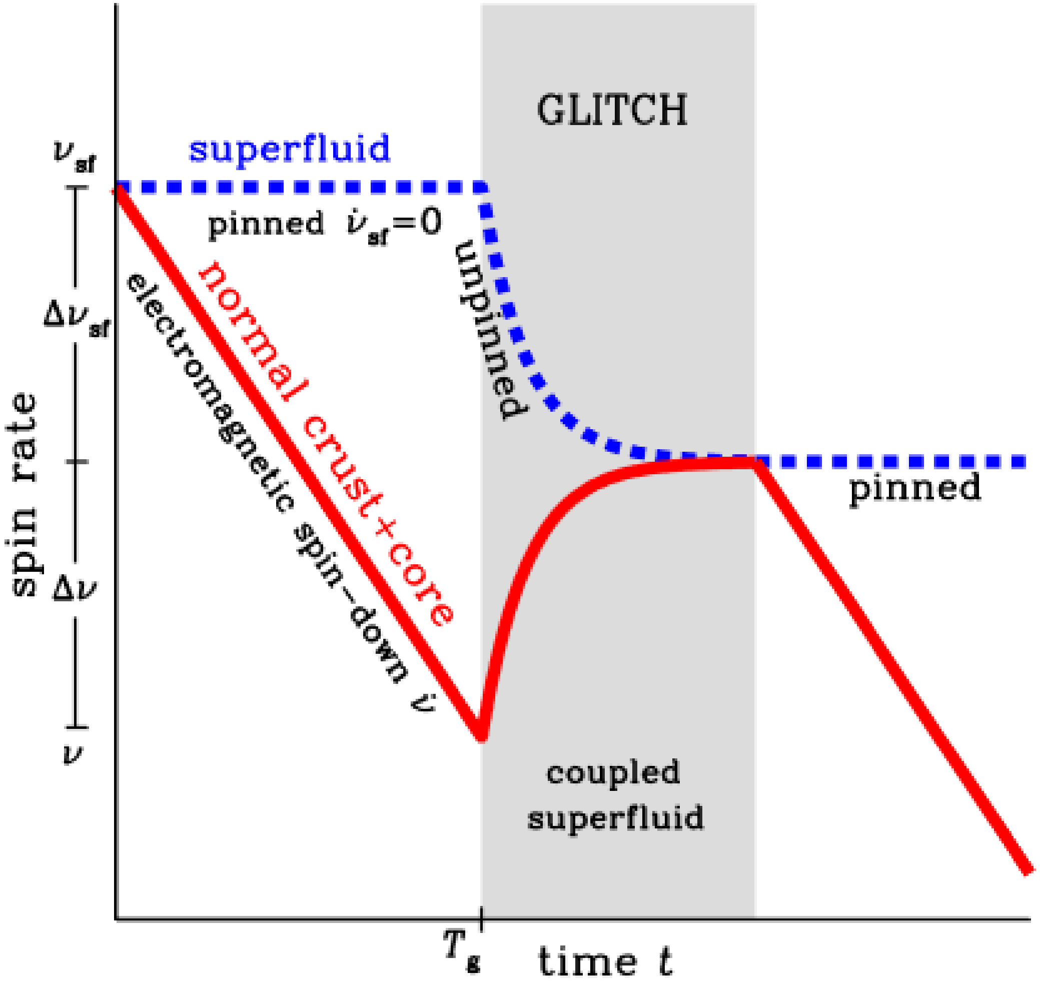




Williams-F1 used mechanical KERS.
Energy is stored in a flywheel.



Evolution between glitches



$$\Delta\nu + |\Delta\nu_{\rm sf}| = \nu_{\rm sf} - \nu = |\dot{\nu}|T_{\rm g},$$

$$|\Delta\nu_{\rm sf}| = \frac{I}{I_{\rm sf}}\Delta\nu,$$

$$\Delta\nu = \frac{I_{\rm sf}}{I}|\dot{\nu}|T_{\rm g},$$

$$T_{\rm obs} \approx N_{\rm g}T_{\rm g}$$

$$\sum\Delta\nu \sim N_{\rm g}\Delta\nu$$

$$\dot{\nu}_{\rm g}/|\dot{\nu}| = I_{\rm sf}/I$$

$$\left|\frac{\Delta\dot{\nu}}{\dot{\nu}}\right| = \frac{I_{\rm sf}}{I}$$

$$|\Delta\dot{\nu}| = \ddot{\nu}_{\rm ig}T_{\rm g}.$$

2205.02865

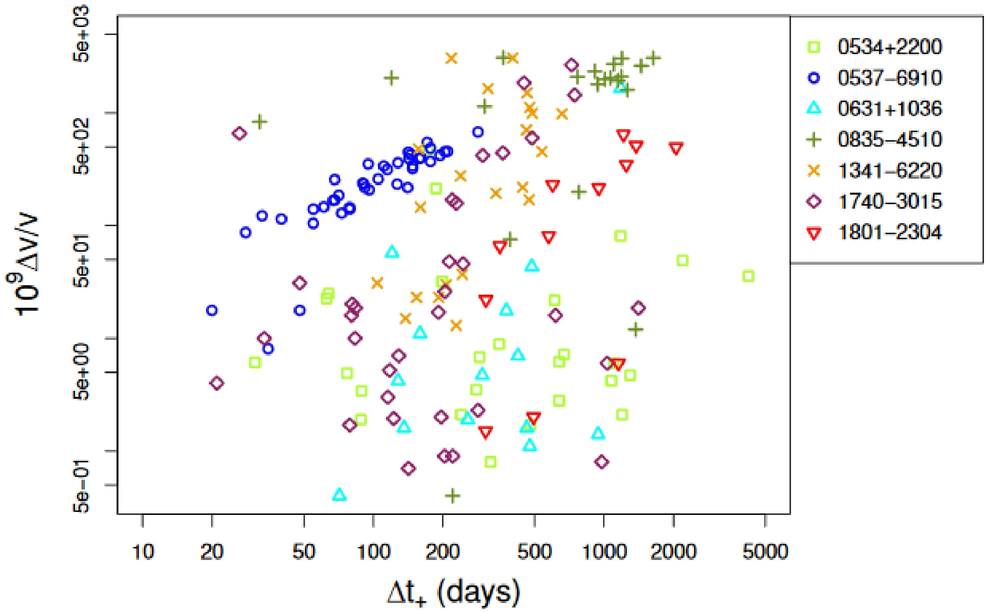
Critical velocity difference

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

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

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

Glitch size – waiting time correlation



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

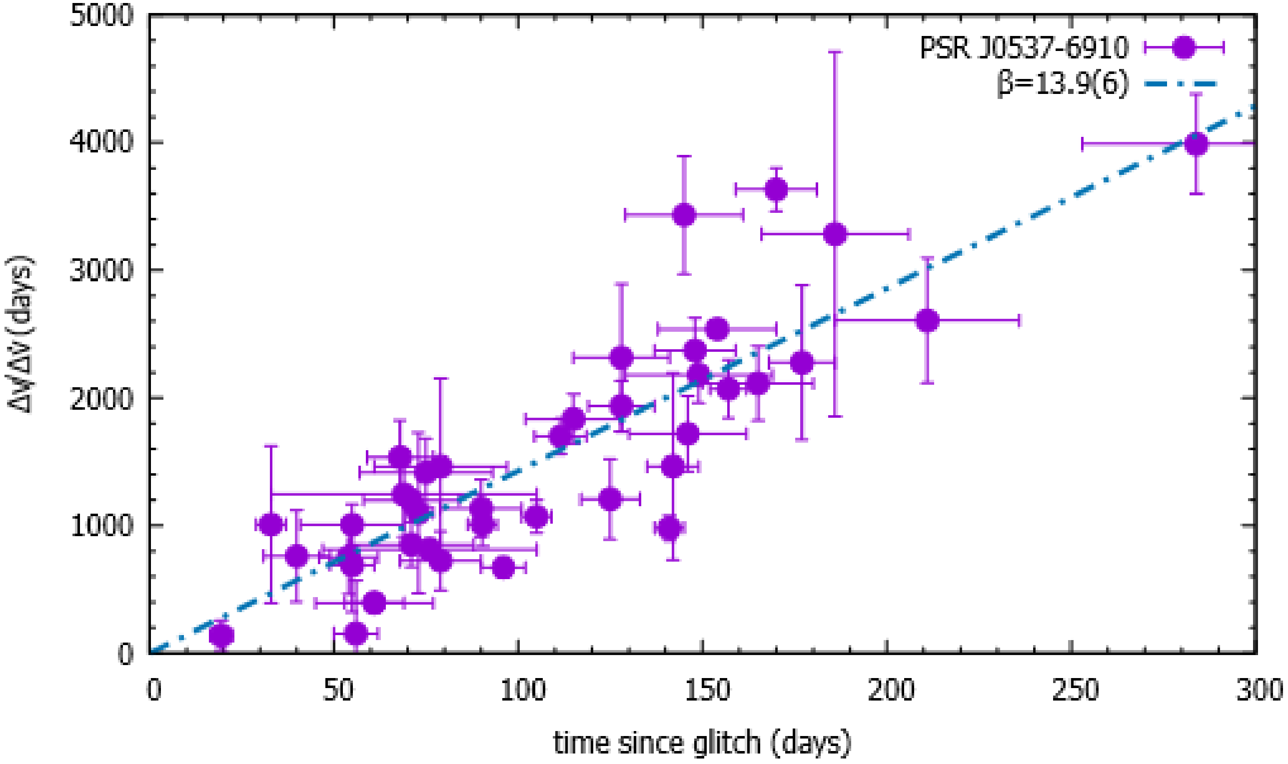
Only for PSR 0537 there is a correlation
(see 1907.09887).
It is observed in X-rays!

1809.03064

Many glitches from PSR J0537-6910

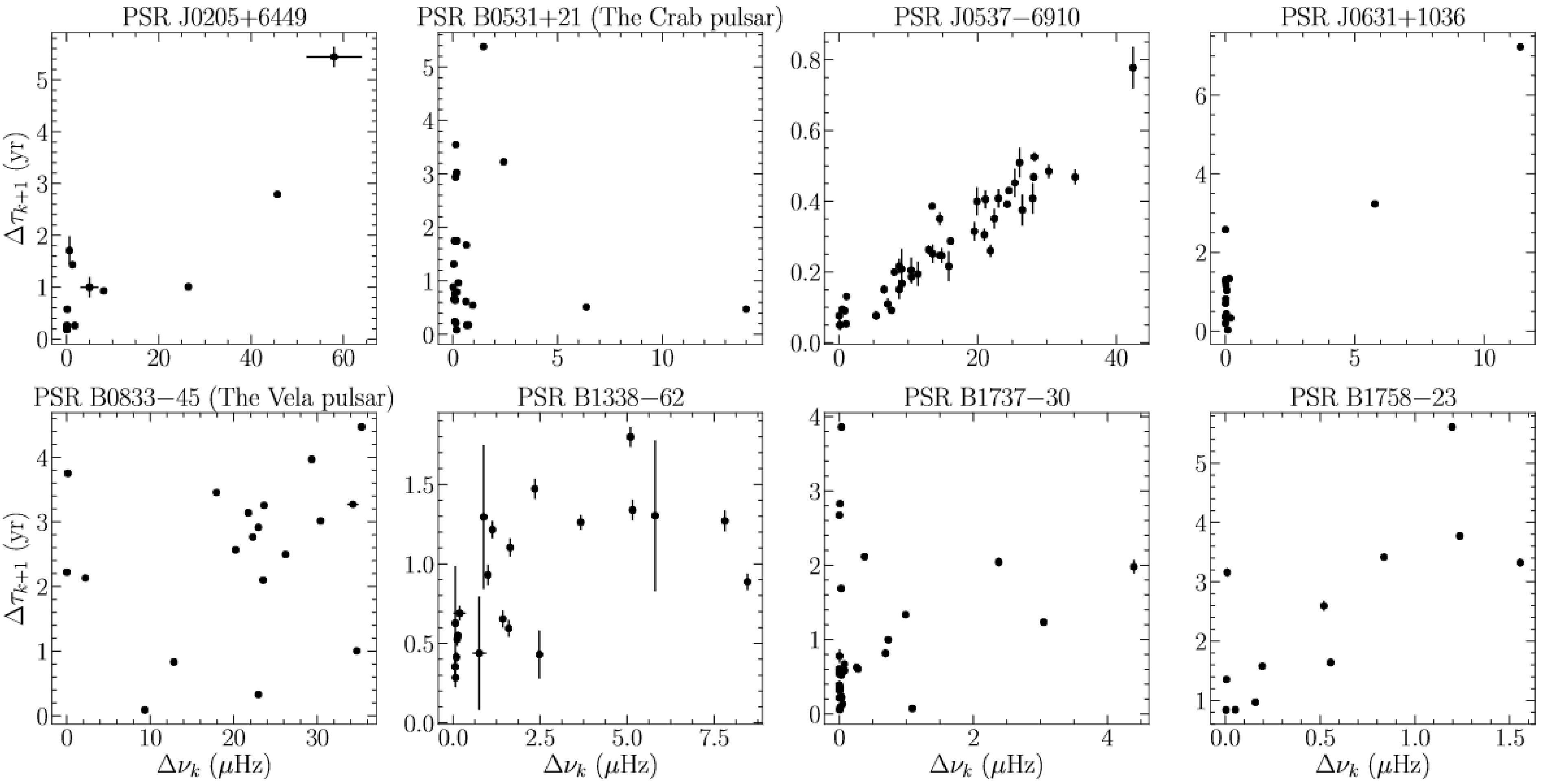
SNR N157B in LMC
Age <5 kyrs
B~10^{12} G
Largest glitch rate (3/yr).

Analysis of 45 glitches.



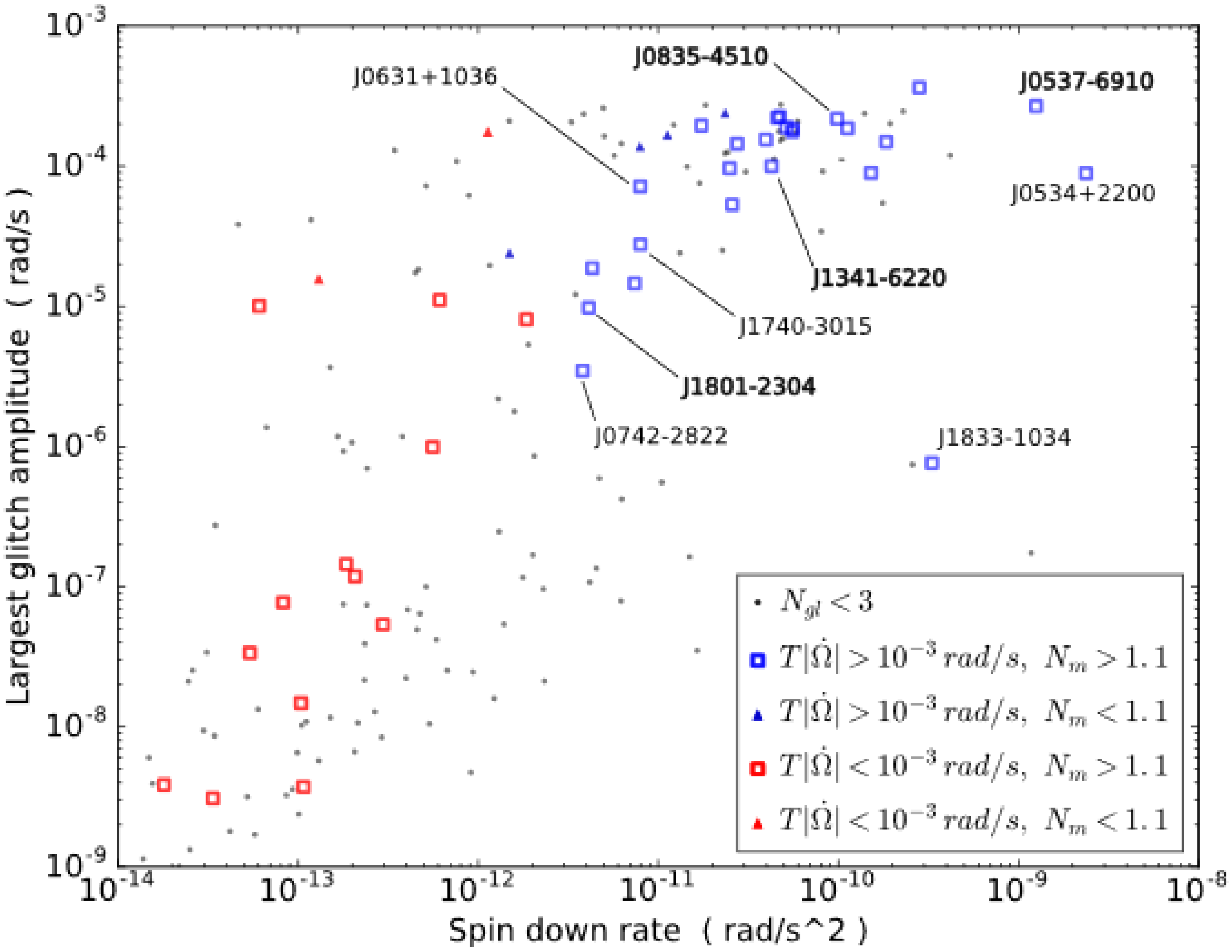
2106.03341

Glitch size vs. time to the next glitch



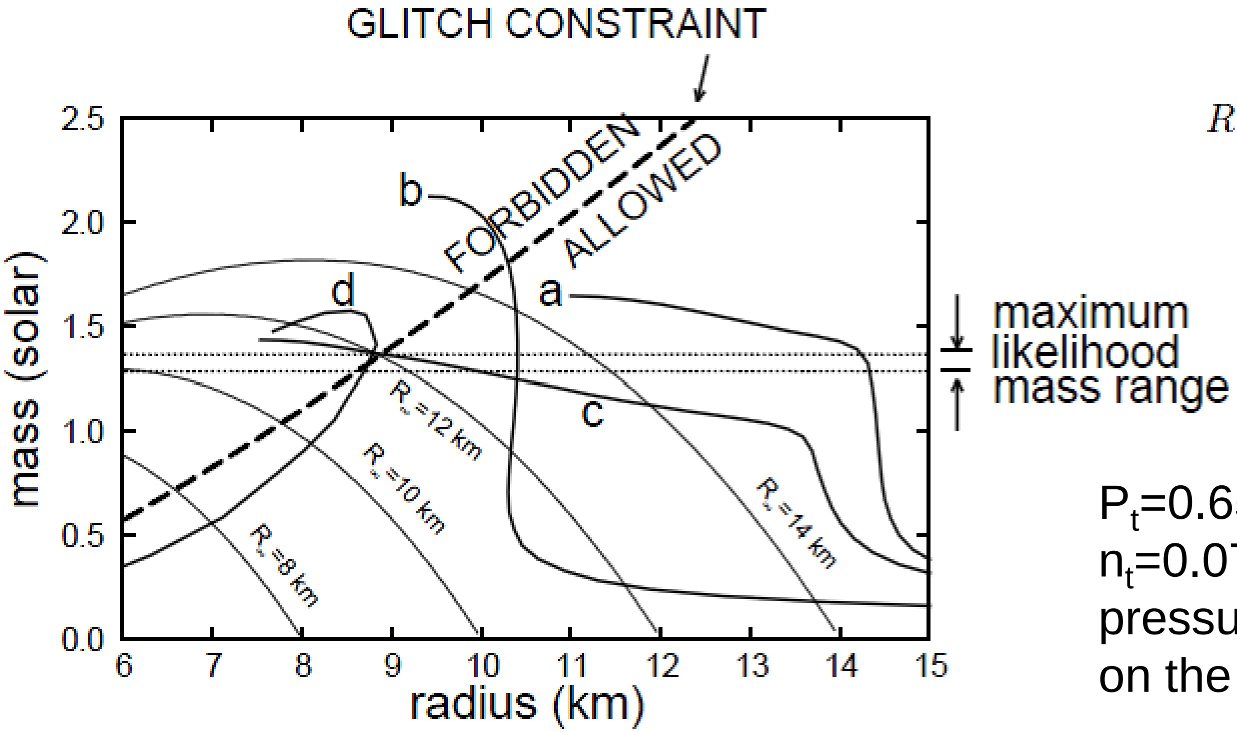
1907.09887

Glitch size – spin down rate correlation



1809.07834. About autocorrelations search see 1907.09143.

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.

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

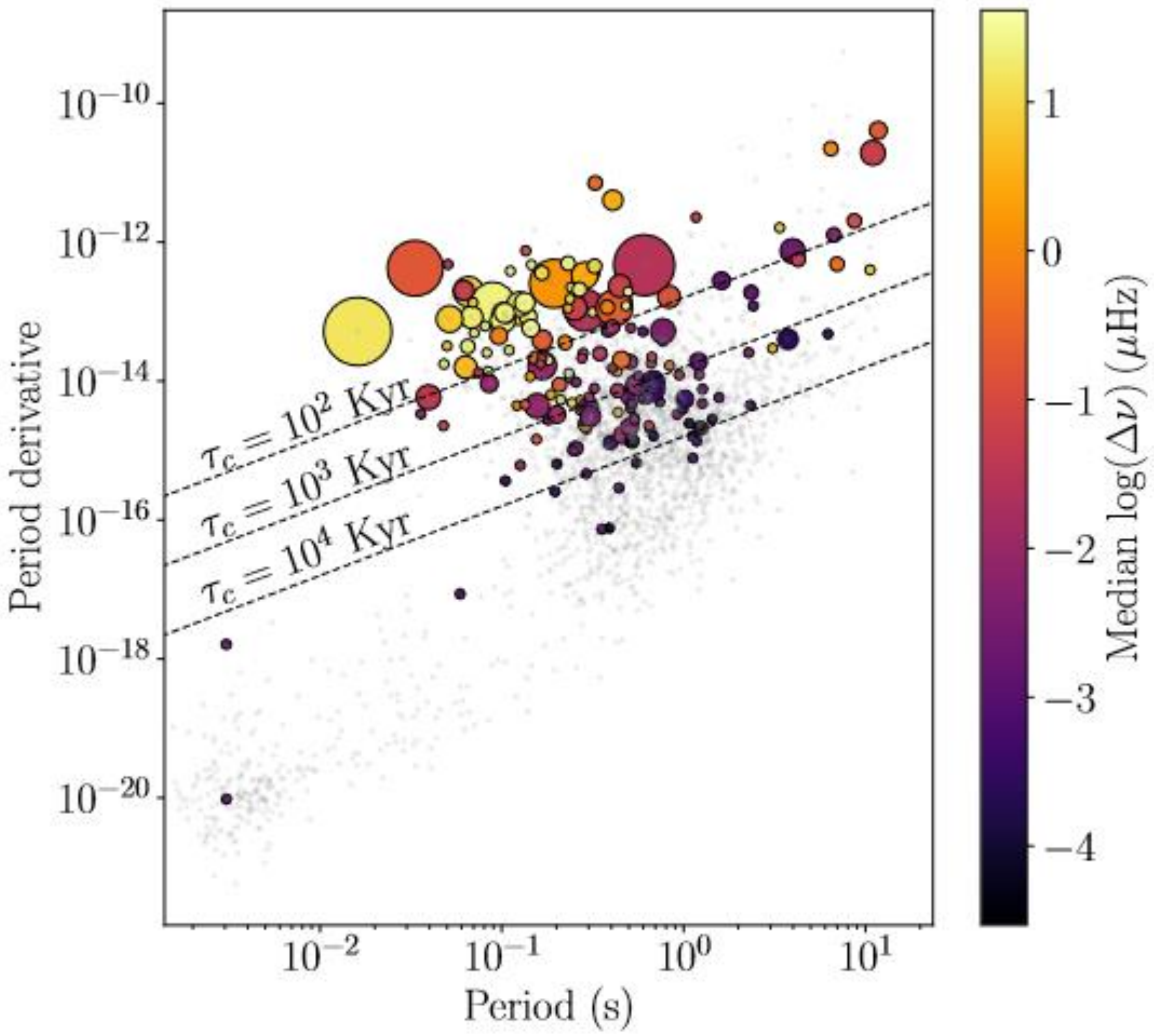
$$\frac{\Delta I}{I} \simeq \frac{28\pi}{3}\frac{P_t R^4}{GM^2}\left[1 + \frac{8P_t}{n_t m_n c^2}\frac{4.5 + (\Lambda - 1)^{-1}}{\Lambda - 1}\right]^{-1}$$

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

Link et al. 0001245

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

Which PSRs do glitch?

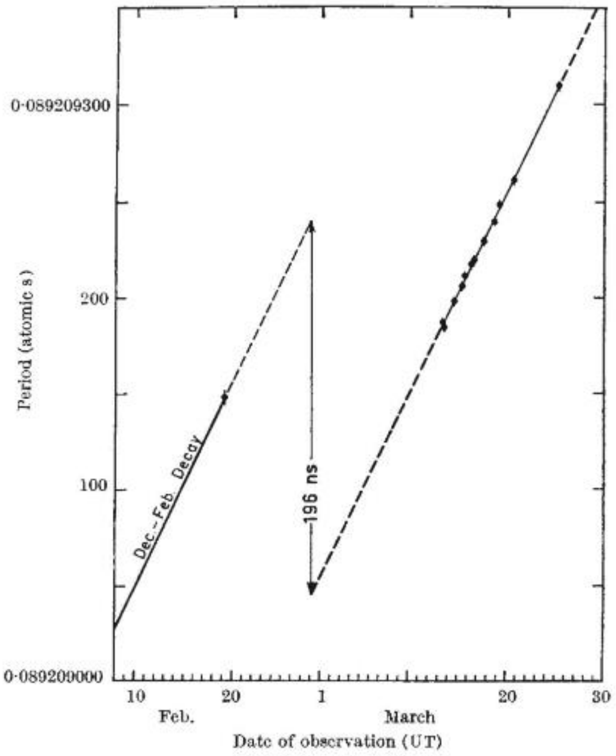


On average young pulsars with larger spin-down glitch more frequently

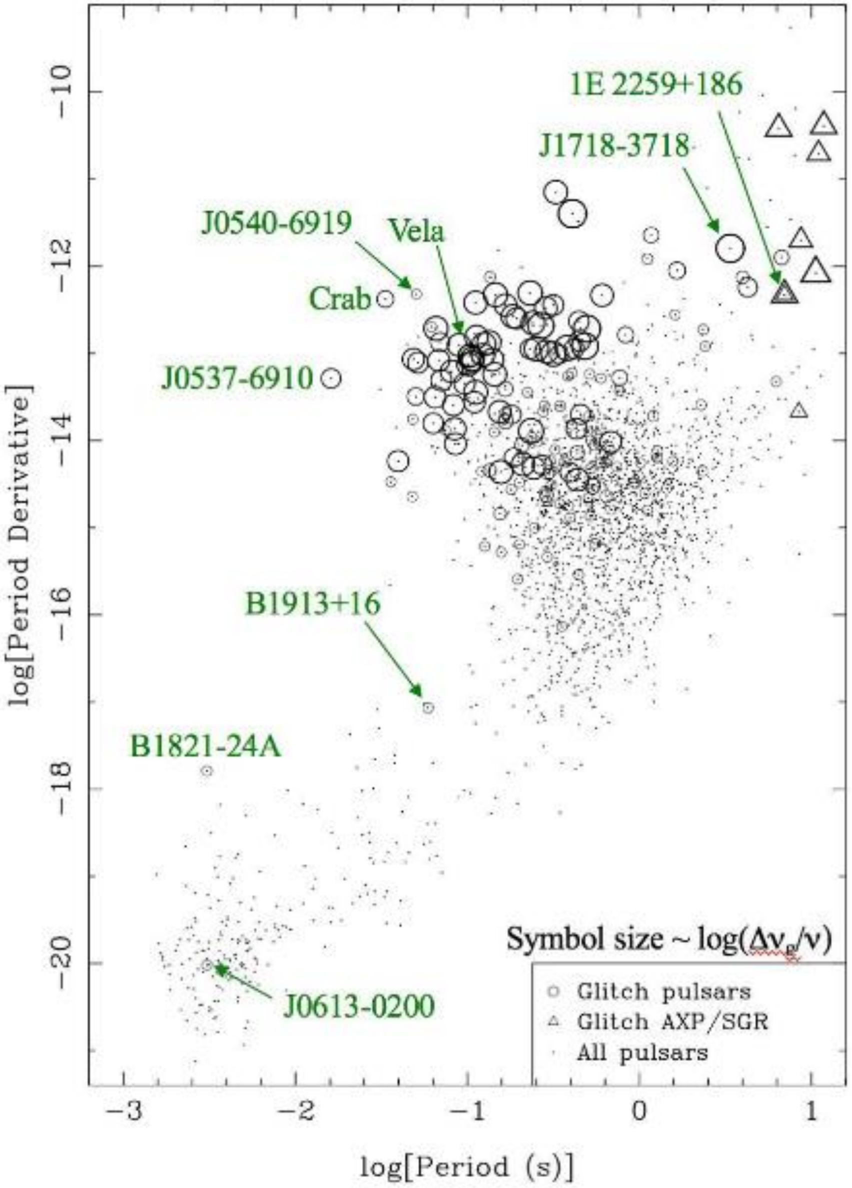
2111.06835

P-Pdot

>520 glitches
in >180 PSRs



Vela glitch in 1969

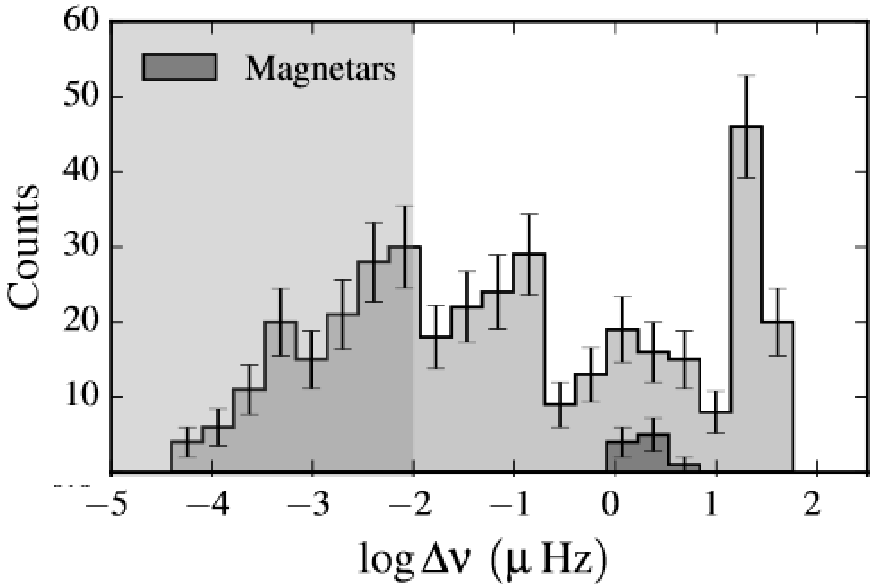


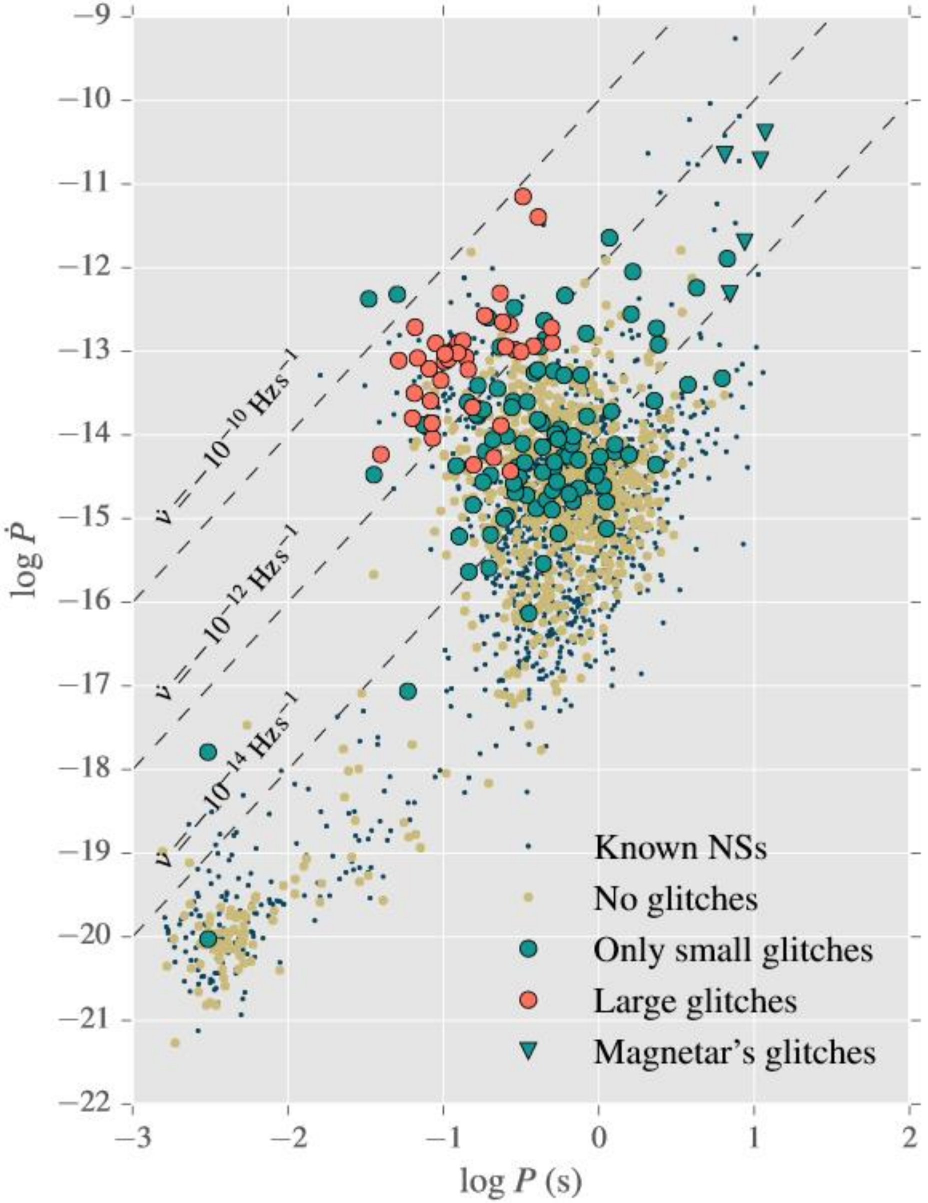
1801.04332

In 2020: ~600 glitches in ~200 PSRs
In 2022: >800 glitches

Statistics

384 glitches in 141 NSs

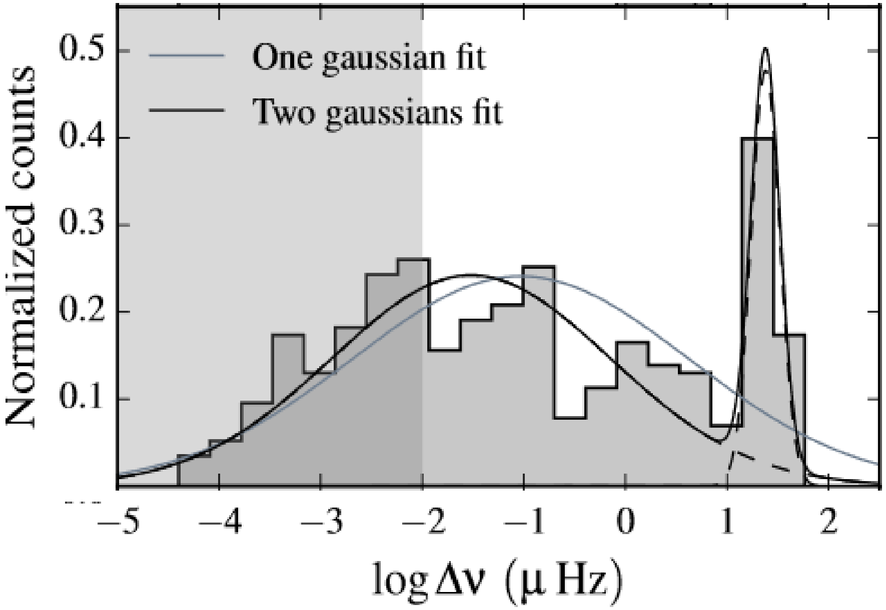




1710.00952

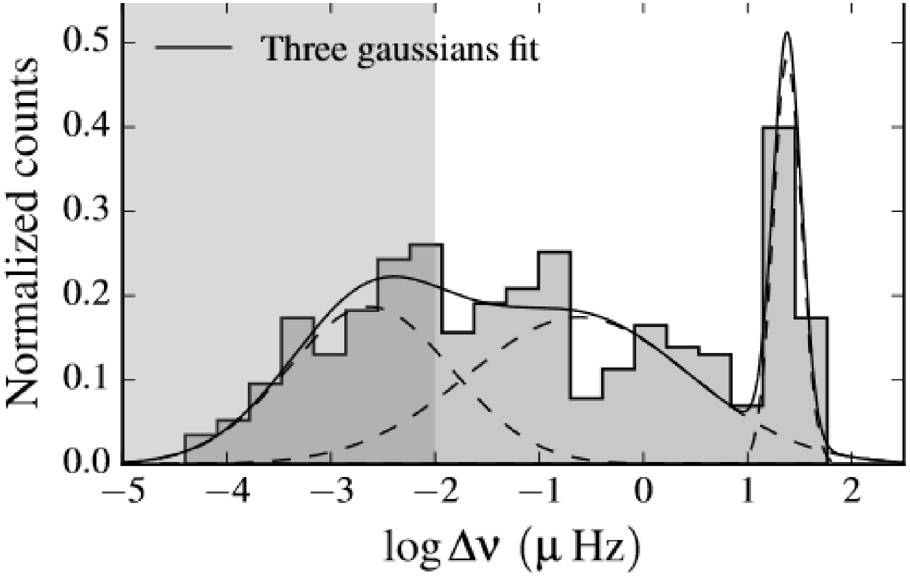
Catalogue http://www.jb.man.ac.uk/pulsar/glitches.html
New additions: 2111.06835. 543 glitches in 178 PSRs.

Glitches properties

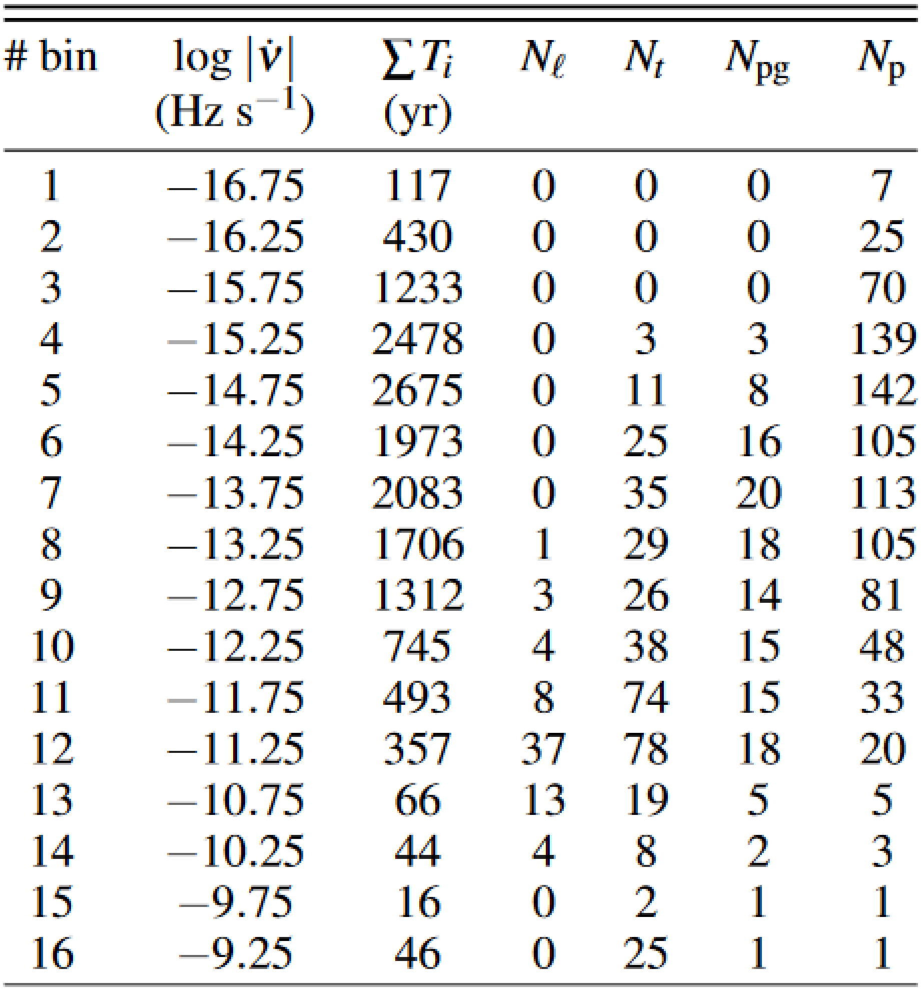


384 glitches in 141 NSs

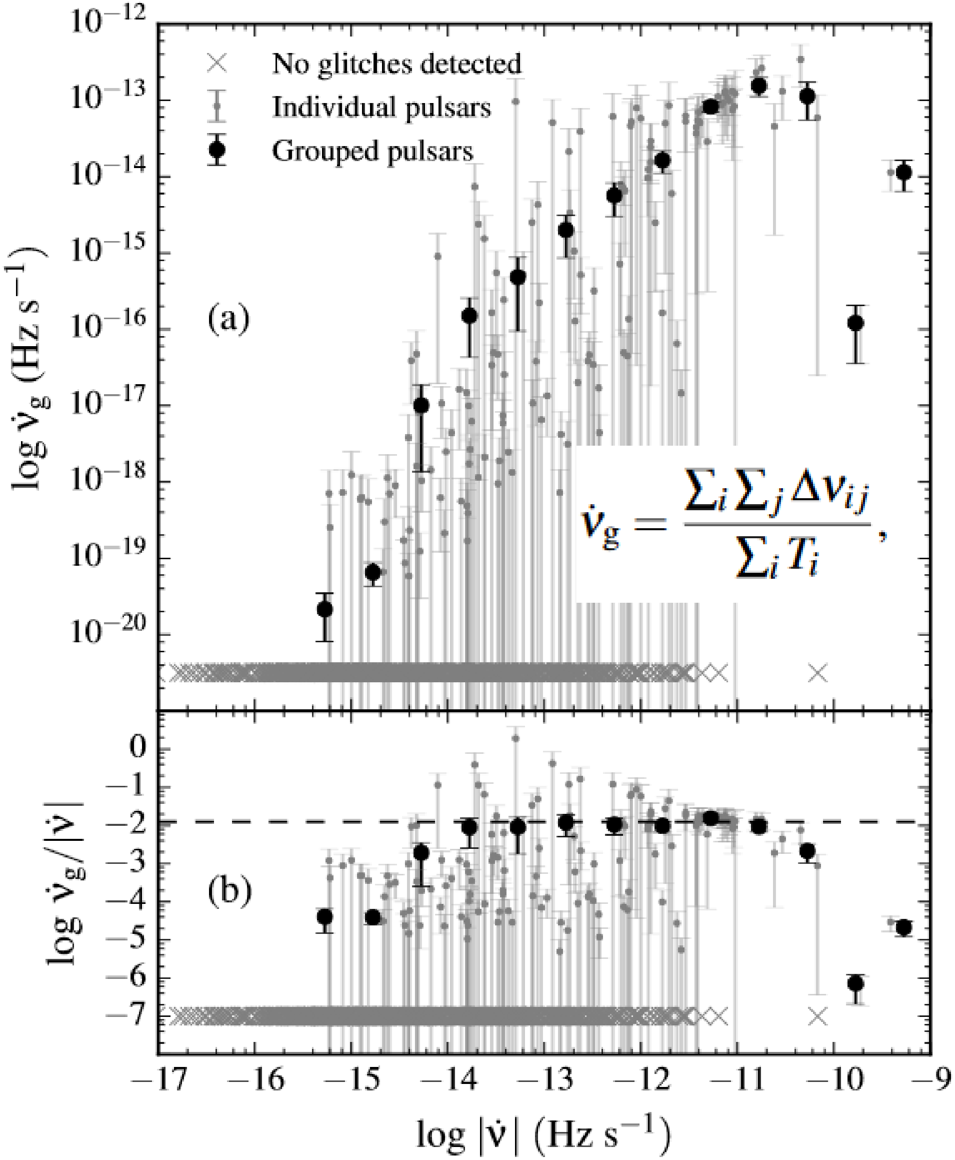
Three gaussian
is not needed any more
(2111.06835).



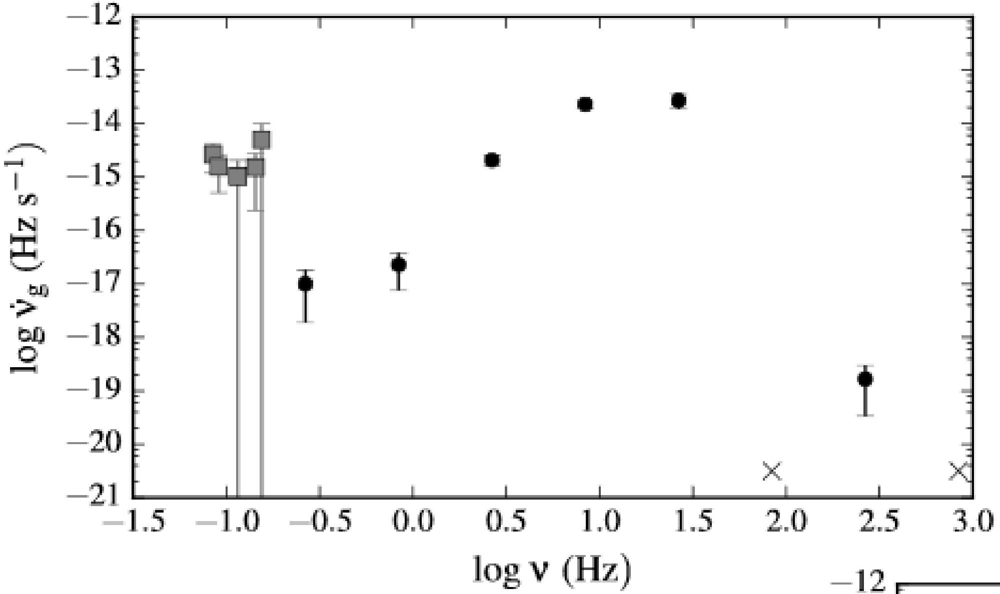
1710.00952. Statistics is growing: 2109.07612, 2111.06835.



# bin	$\log \lvert\dot{\nu}\rvert$ (Hz s^{-1})	$\sum T_i$ (yr)	N_ℓ	N_t	$N_{\rm pg}$	$N_{\rm p}$
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



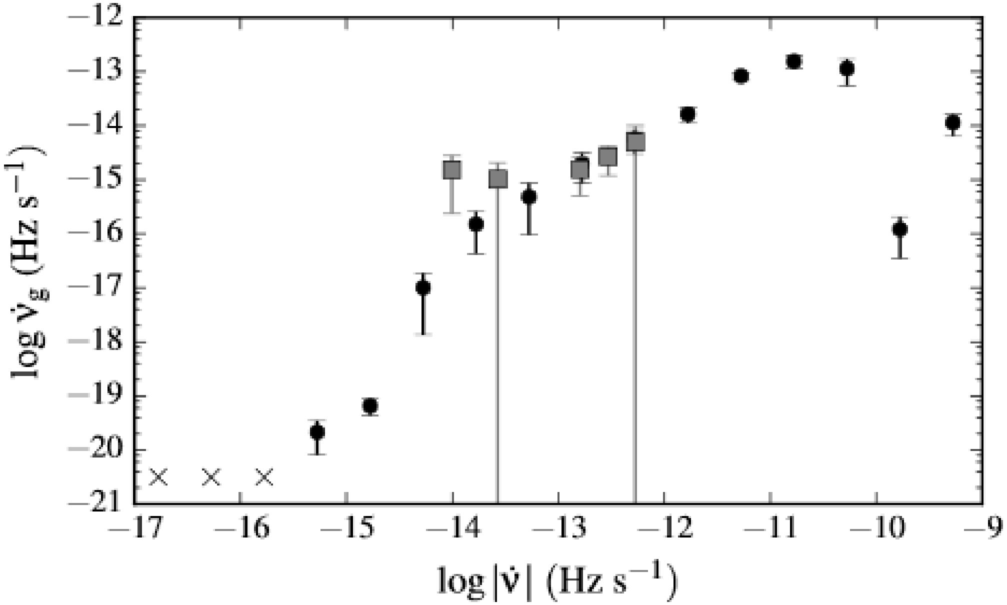
1710.00952



All PSRs in the survey are included, also those with no detected glitches.

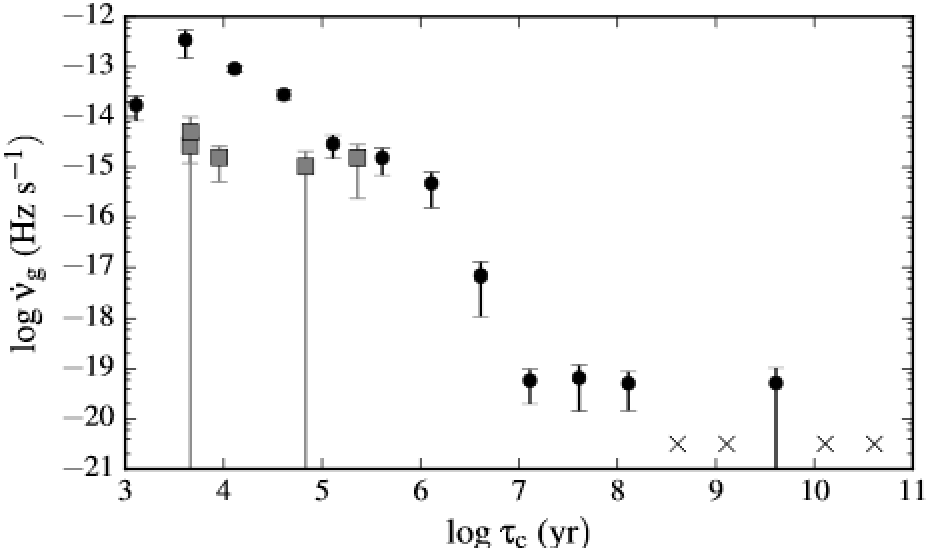
$$\dot{\nu}_g = \frac{\sum_i \sum_j \Delta\nu_{ij}}{\sum_i T_i},$$

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.

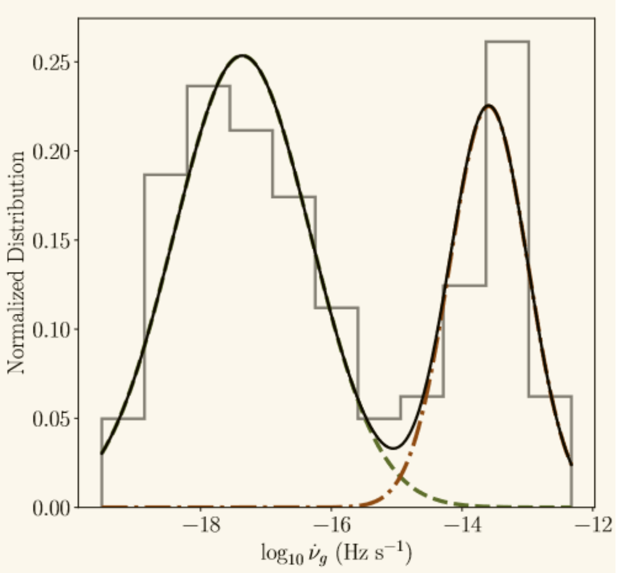


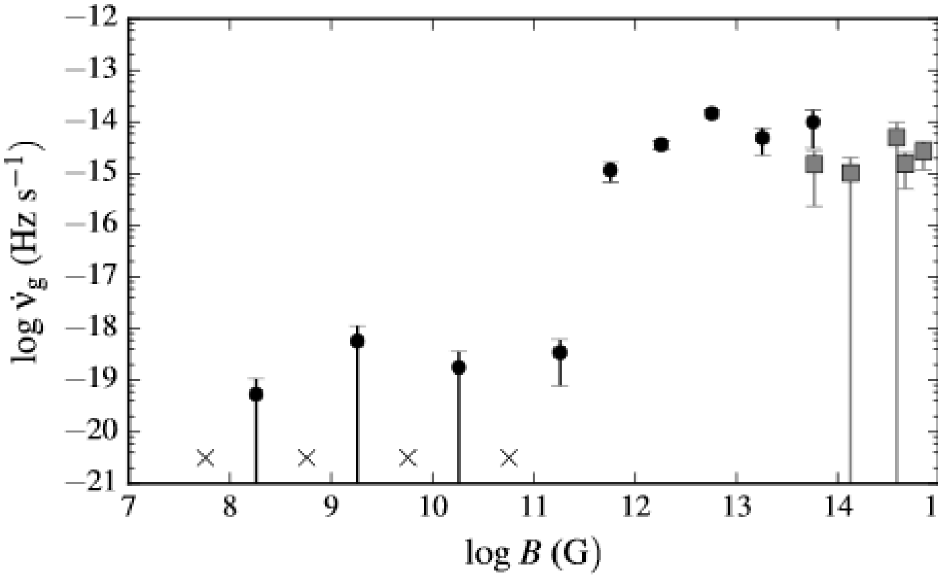
1710.00952

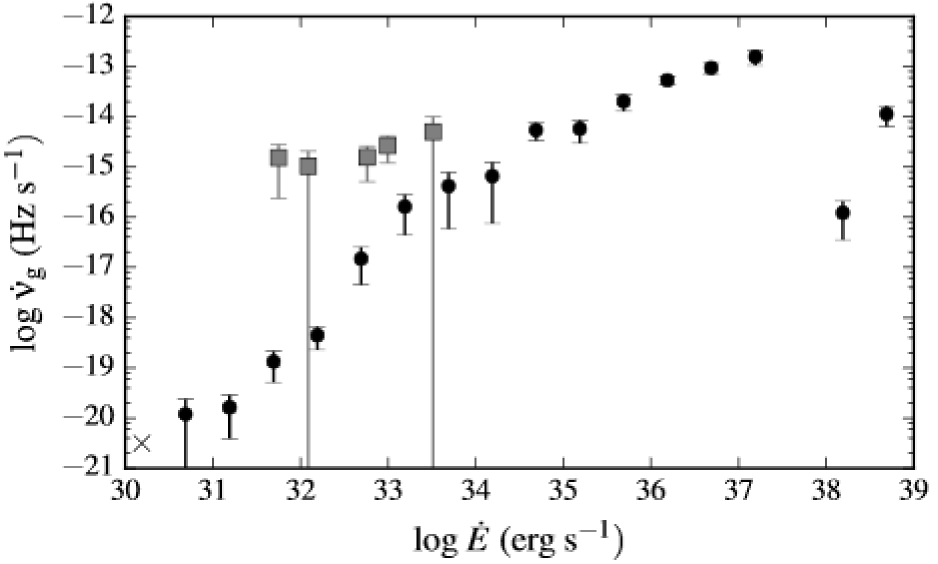
$$\dot{\nu}_{\rm g} = \frac{\sum_i \sum_j \Delta\nu_{ij}}{\sum_i T_i},$$



2111.06835

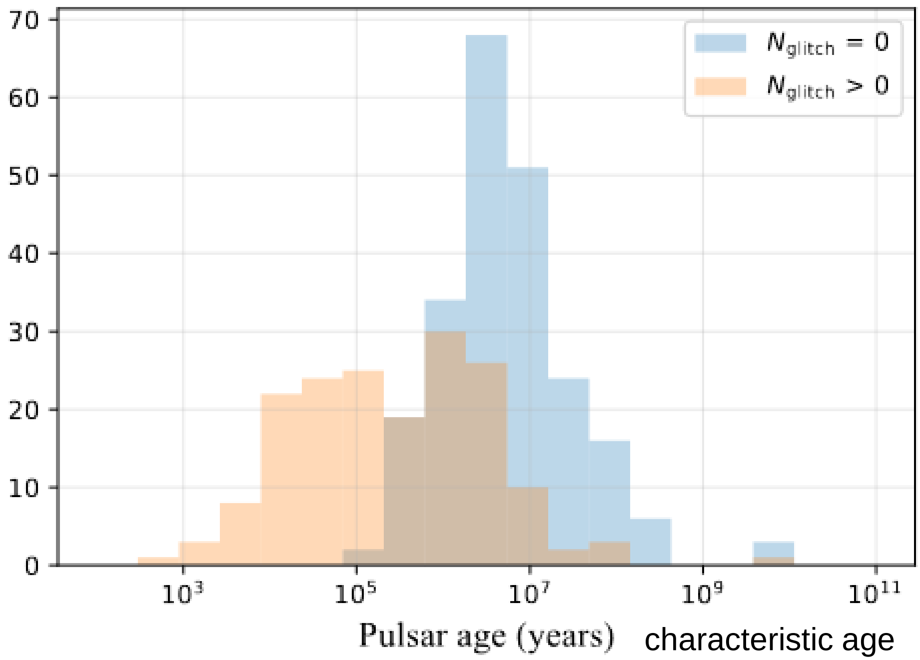






1710.00952

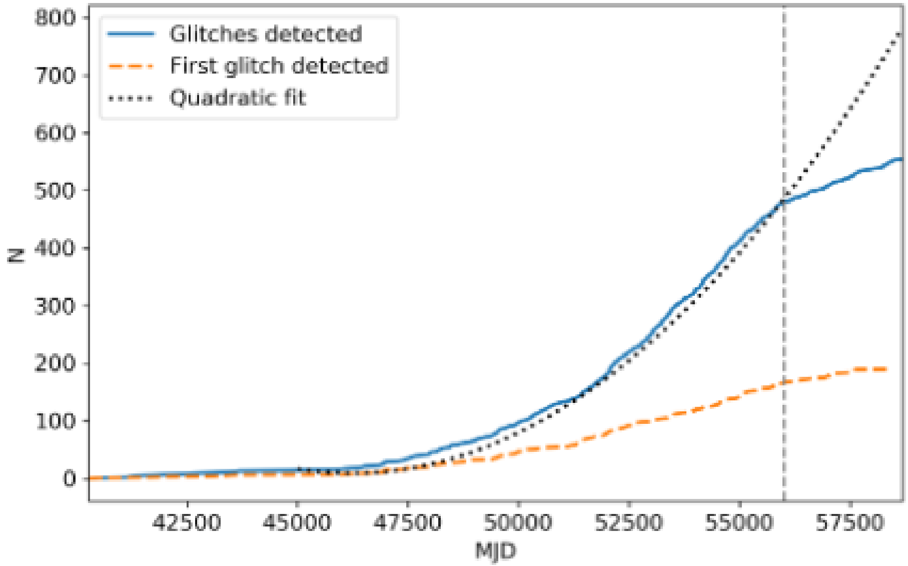
Glitch rate analysis



characteristic age

$$\lambda_A = A\,(\tau/\tau_{ref})^{-\gamma} \qquad \tau_{ref} = 1\ \text{yr}$$

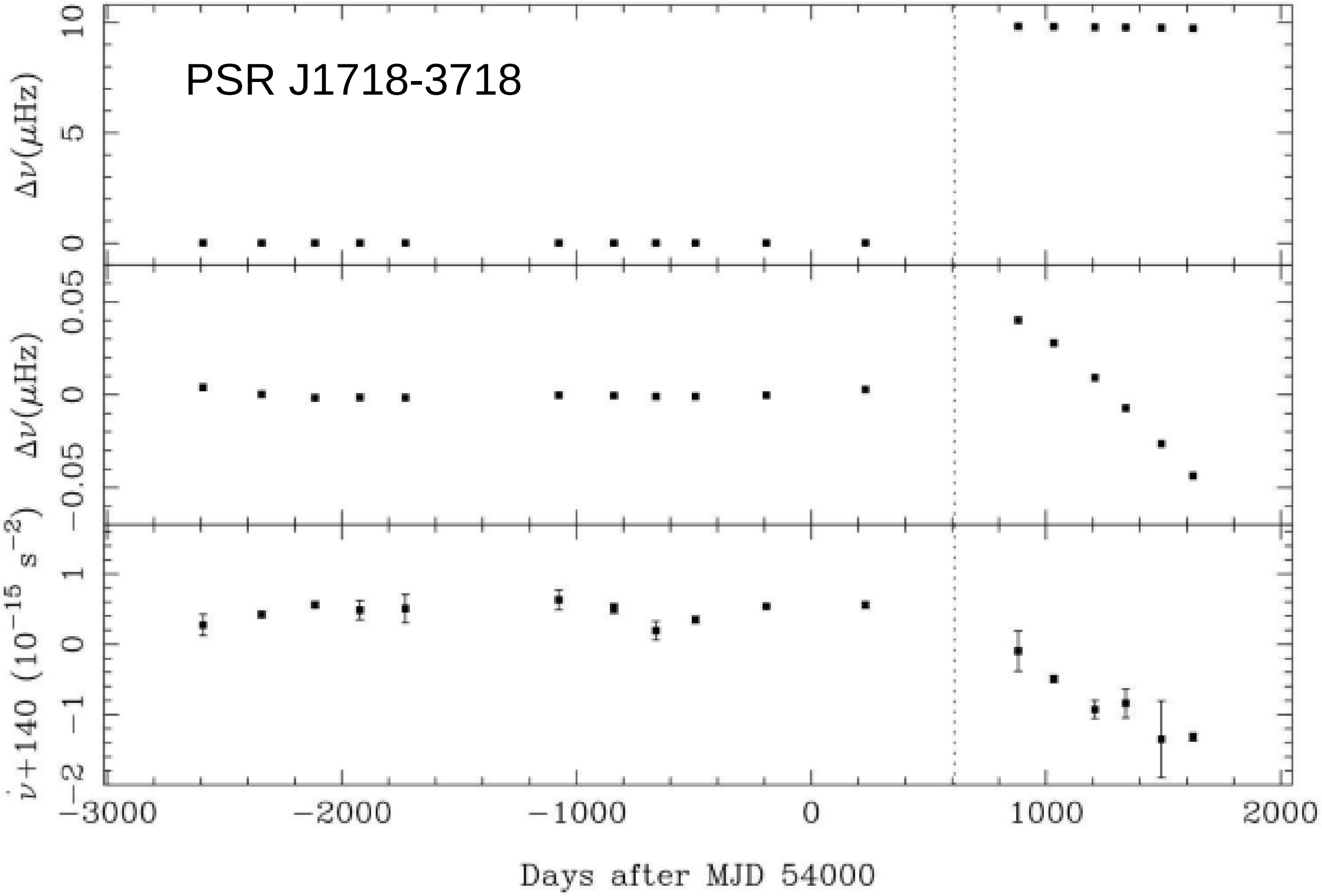
$$A = 0.0099^{+0.004}_{-0.003}\ \text{yr}^{-1},\ \gamma = 0.31^{+0.03}_{-0.03}$$



2202.01930

Analysis of the glitch rate allows for obtaining model-dependent estimates of micro- and mesoscopic parameters, 2302.11079.

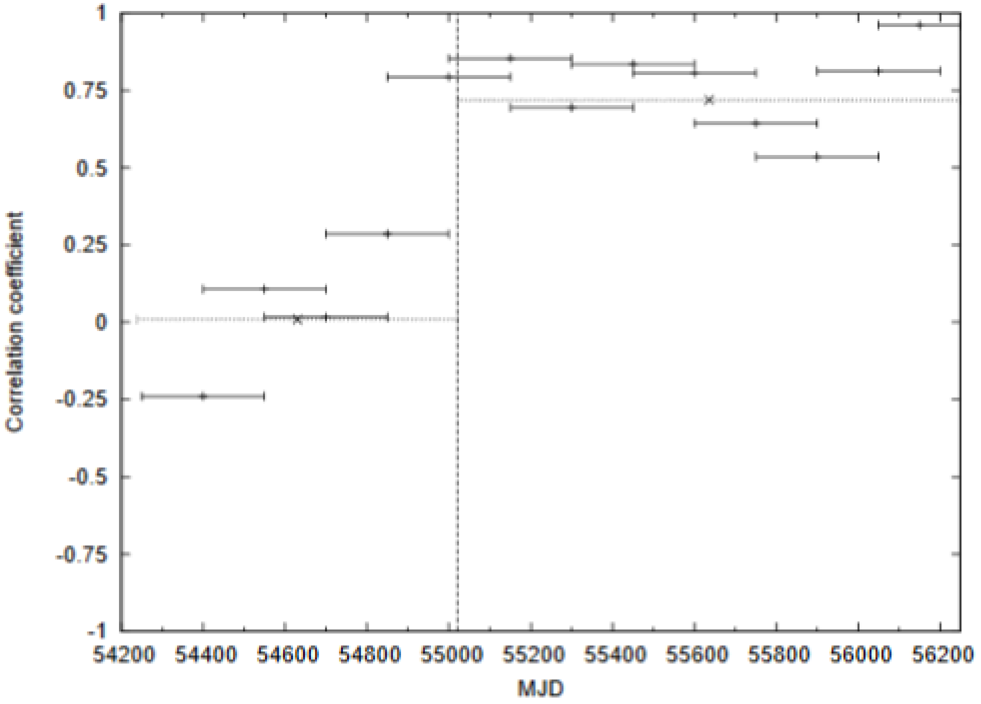
The largest glitch



$33\ 10^{-6}$

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.

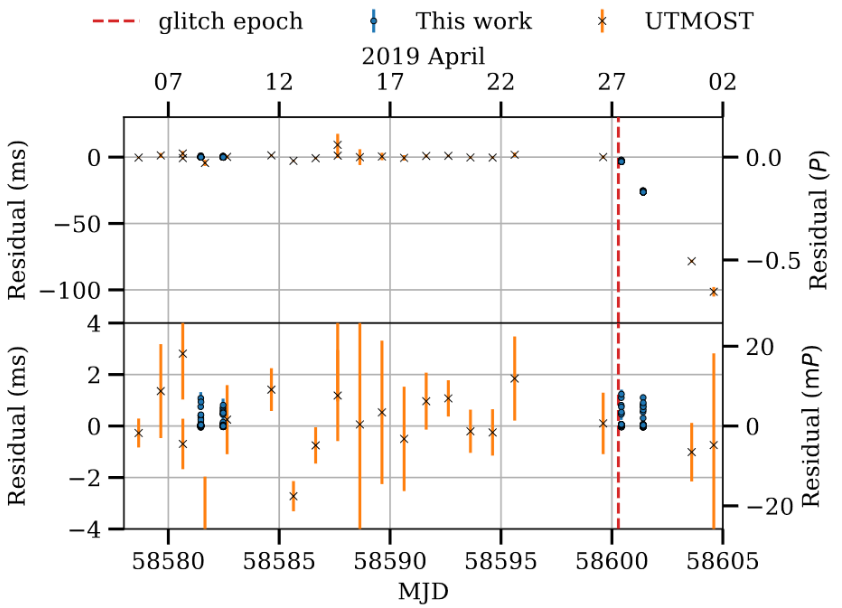
Also shown with dotted bars is the same correlation
when computed for the entire pre and post-glitch epochs.

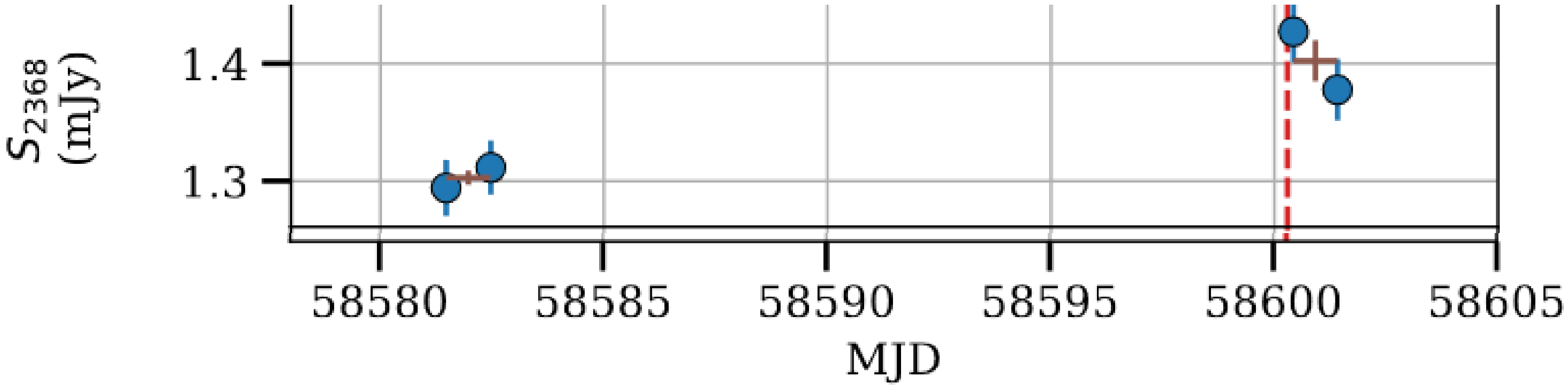
1304.4644

Flux density increase

PSR J1452−6036

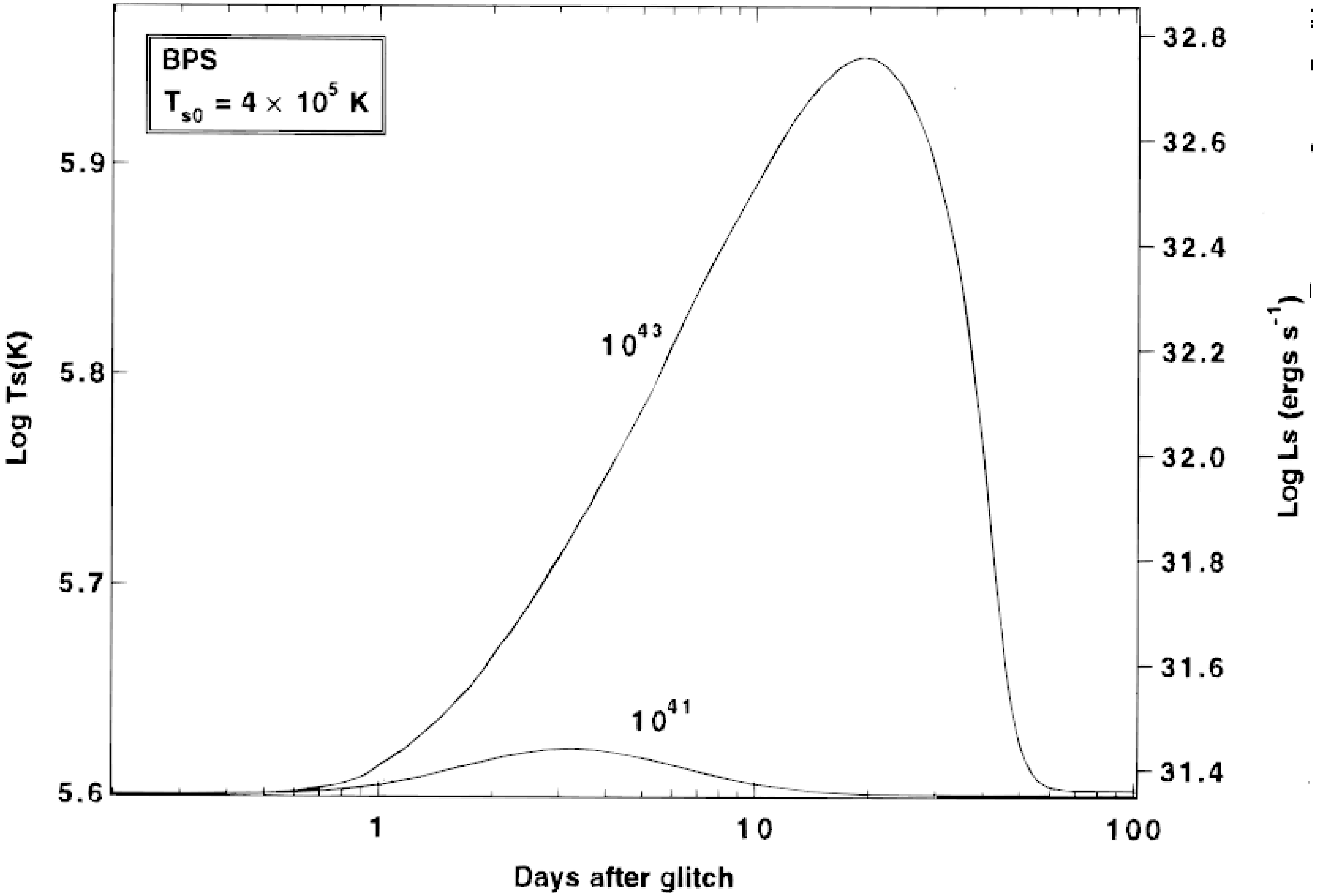
Occasional observations just hours after a glitch.





2103.09869

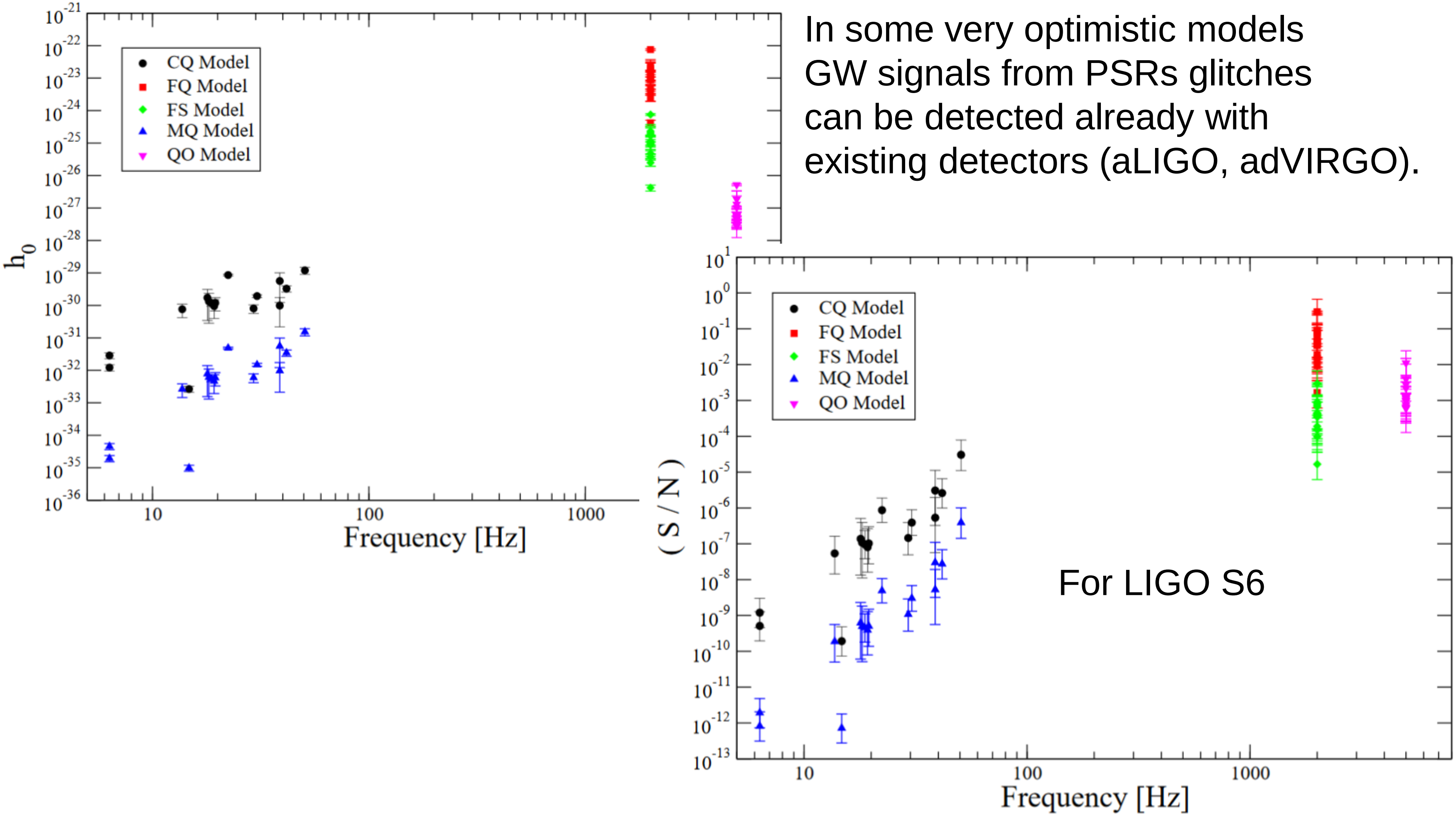
Thermal effect of a glitch



Hirano et al. 1997

Gravitational waves from glitches

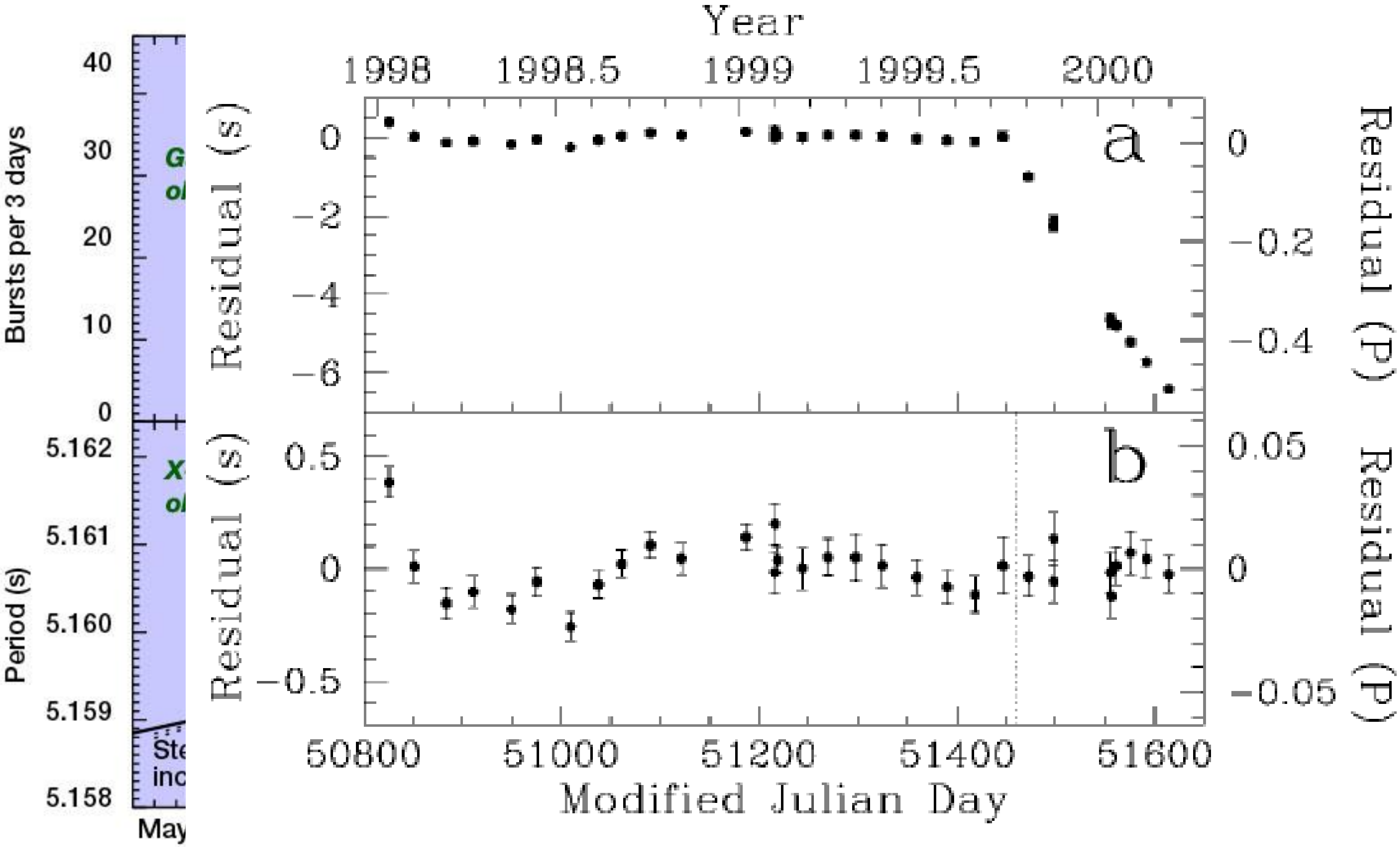
In some very optimistic models GW signals from PSRs glitches can be detected already with existing detectors (aLIGO, adVIRGO).



For LIGO S6

1305.2466

Glitches of magnetars



es.

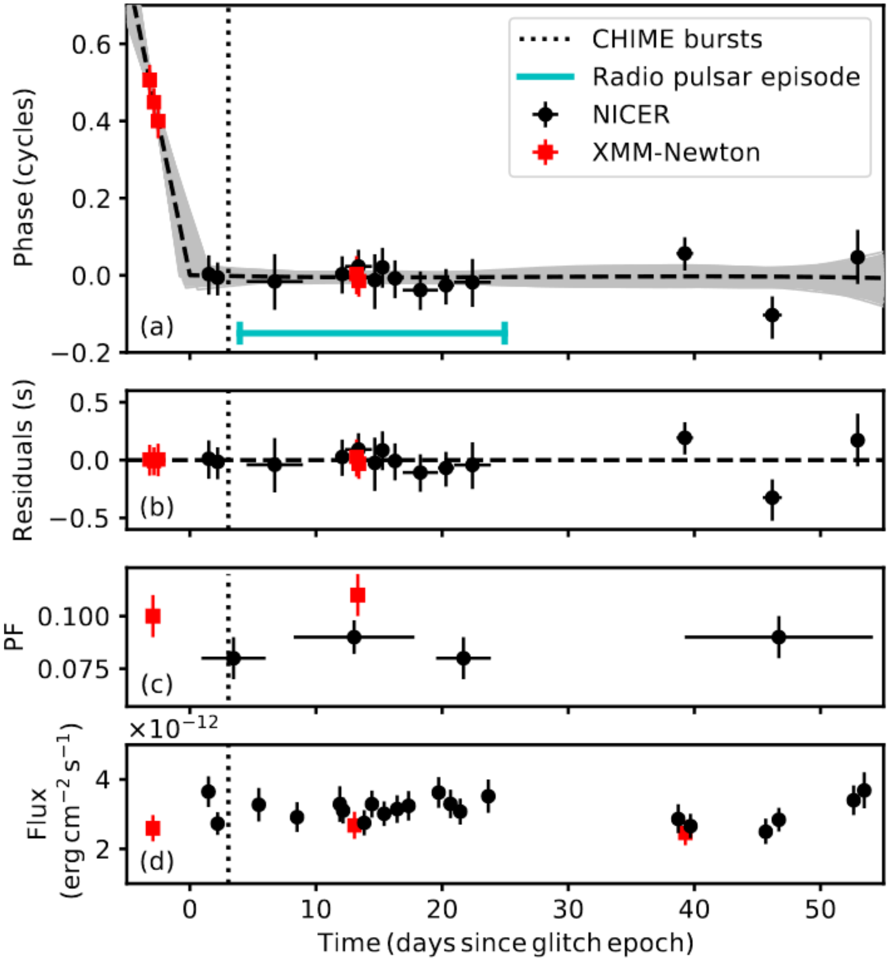
Rs'.

00:

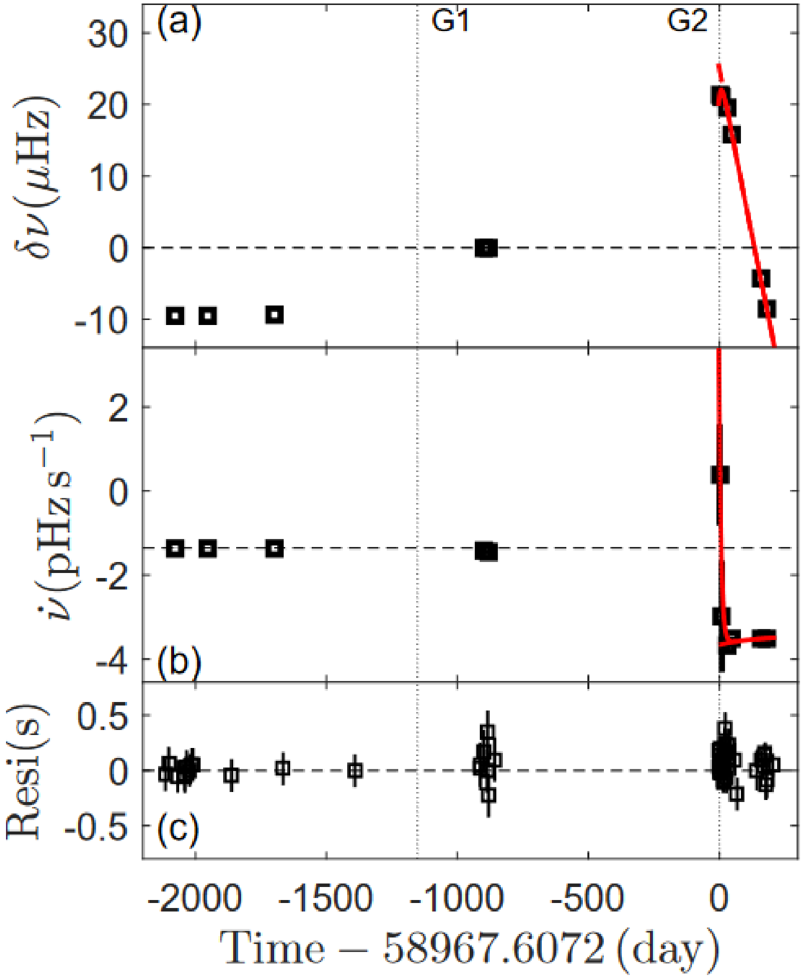
About modeling of magnetar bursts see 1203.4506:
glitches always are accompanied by energy release.

A glitch before FRB-like bursts

SGR 1935+2154, Oct. 2020



April 2020



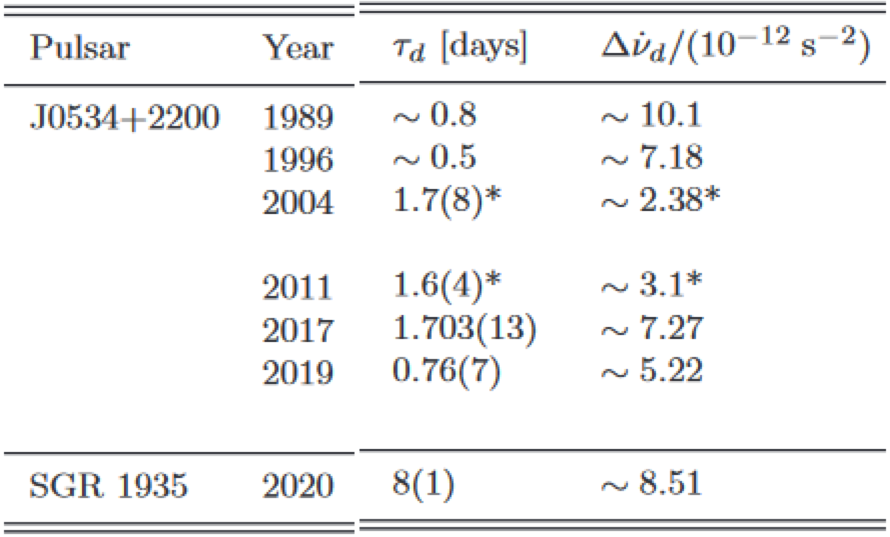
2210.11518.

2211.03246

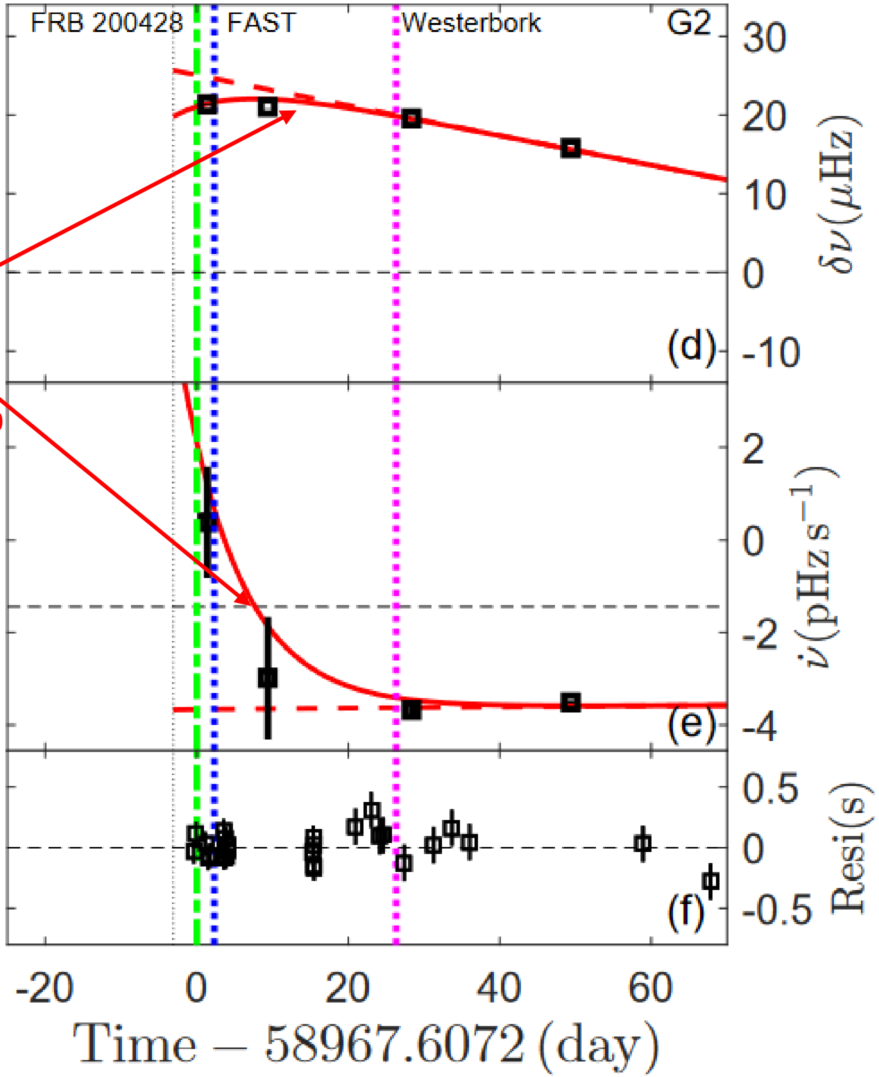
Delayed spin-up in G2

The April glitch demonstrated a behavior similar to some giant glitches of the Crab pulsar: the delayed spin-up.

Solid red line:
with the delayed spin-up



Pulsar	Year	τ_d [days]	$\Delta\dot{\nu}_d/(10^{-12}\,\mathrm{s}^{-2})$
J0534+2200	1989	~ 0.8	~ 10.1
	1996	~ 0.5	~ 7.18
	2004	1.7(8)*	~ 2.38*
	2011	1.6(4)*	~ 3.1*
	2017	1.703(13)	~ 7.27
	2019	0.76(7)	~ 5.22
SGR 1935	2020	8(1)	~ 8.51

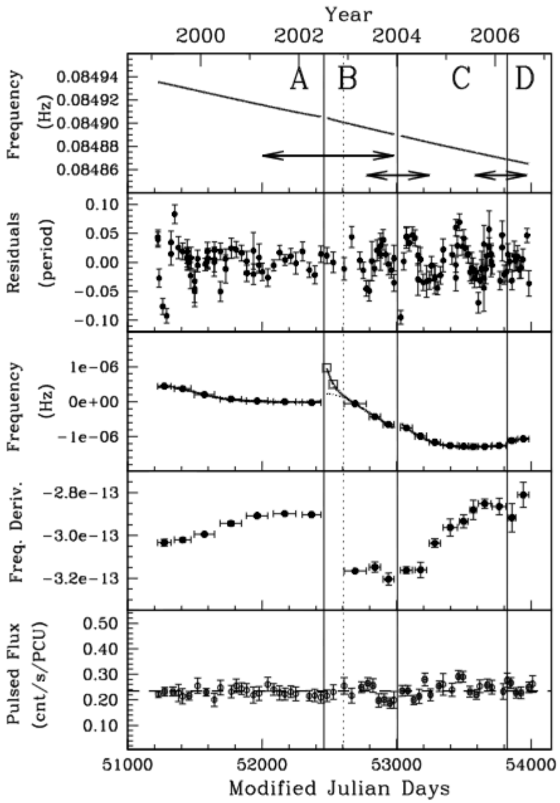


2211.03246

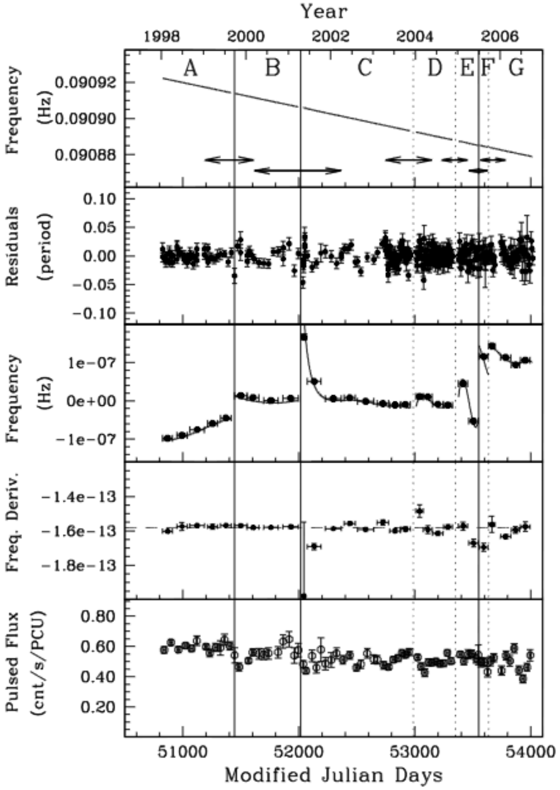
Theoretical analysis in 2211.08151

Glitches and bursts

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



The pulsed flux was nearly constant during glitches.

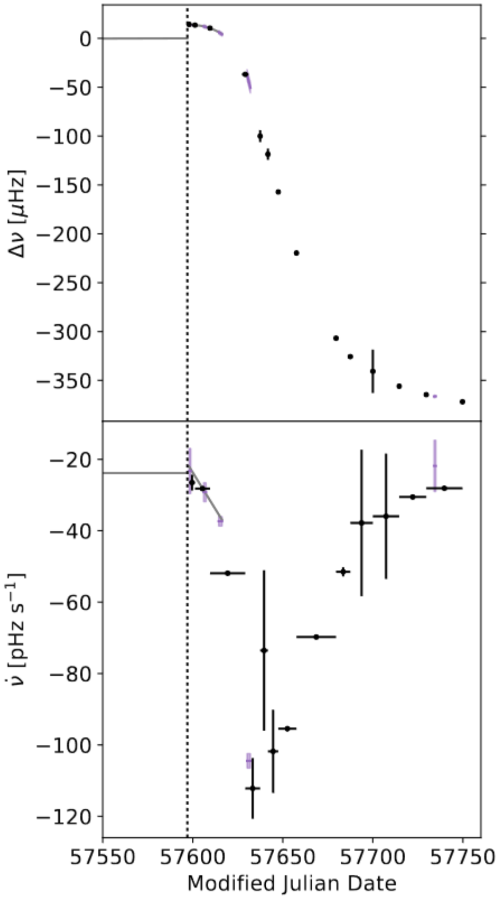


1E 1841-045

From Dib et al. 2008

RXS J170849.0-400910

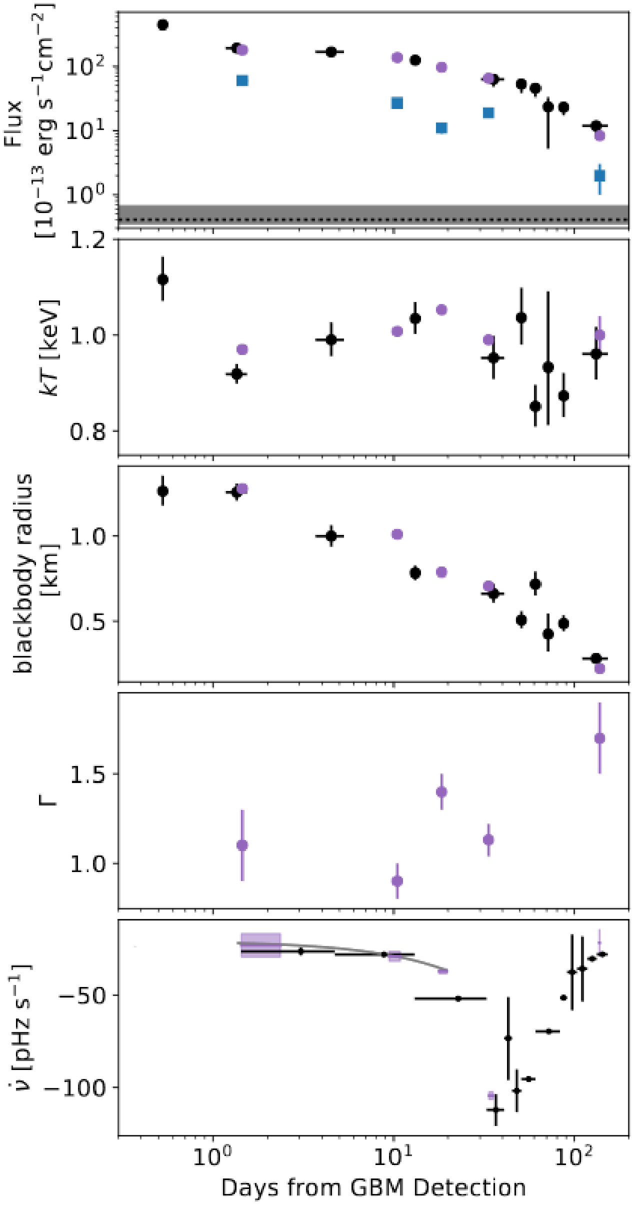
Glitch and bursts from PSR J1119−6127



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.

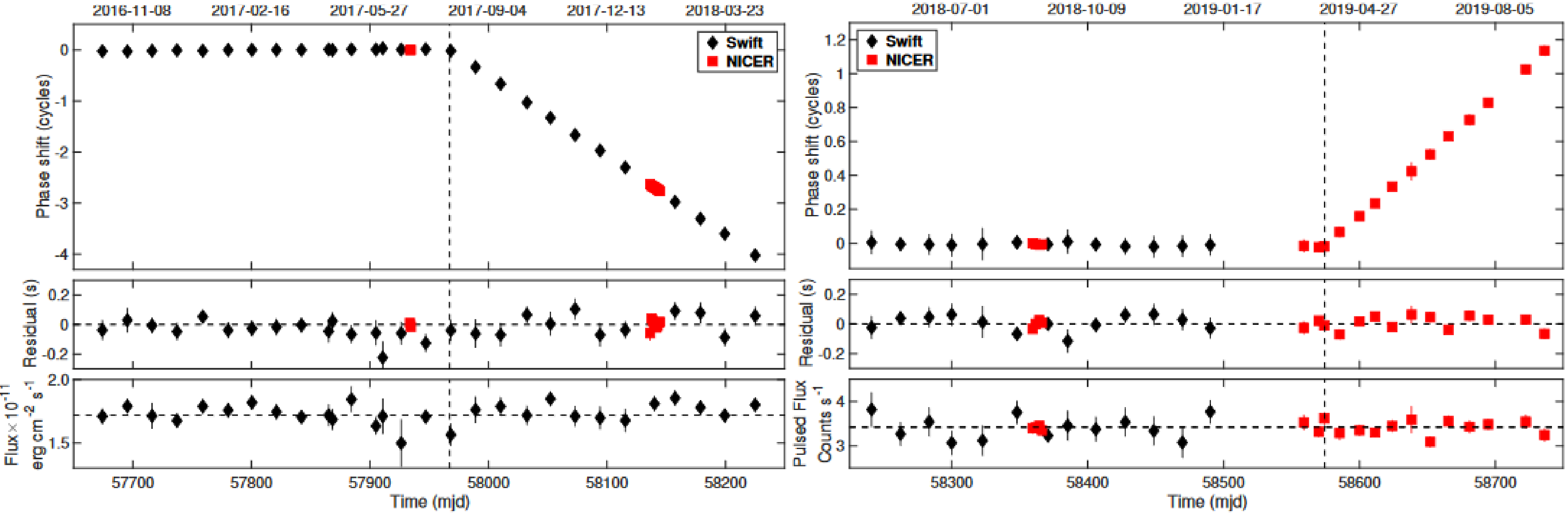


1806.01414 (see also 1806.05064)

Quiet magnetar glitches and anti-glitches

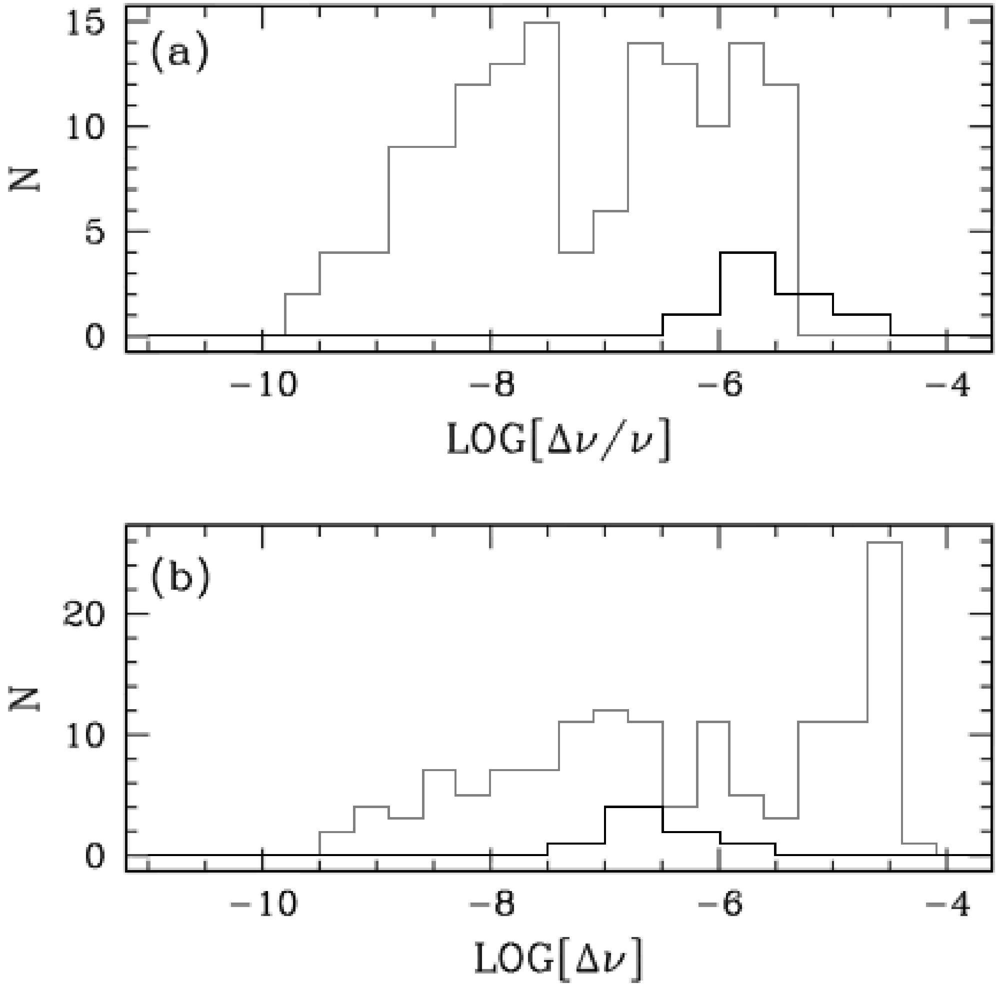
1E 2259+586 – the magnetar that anti-glitched.
The new anti-glitch is similar to the original one.
But no changes in flux or/and pulse profile are observed.

A new glitch also was not accompanied with any changes in flux or/and profile.



2006.04854

PSRs vs. magnetars



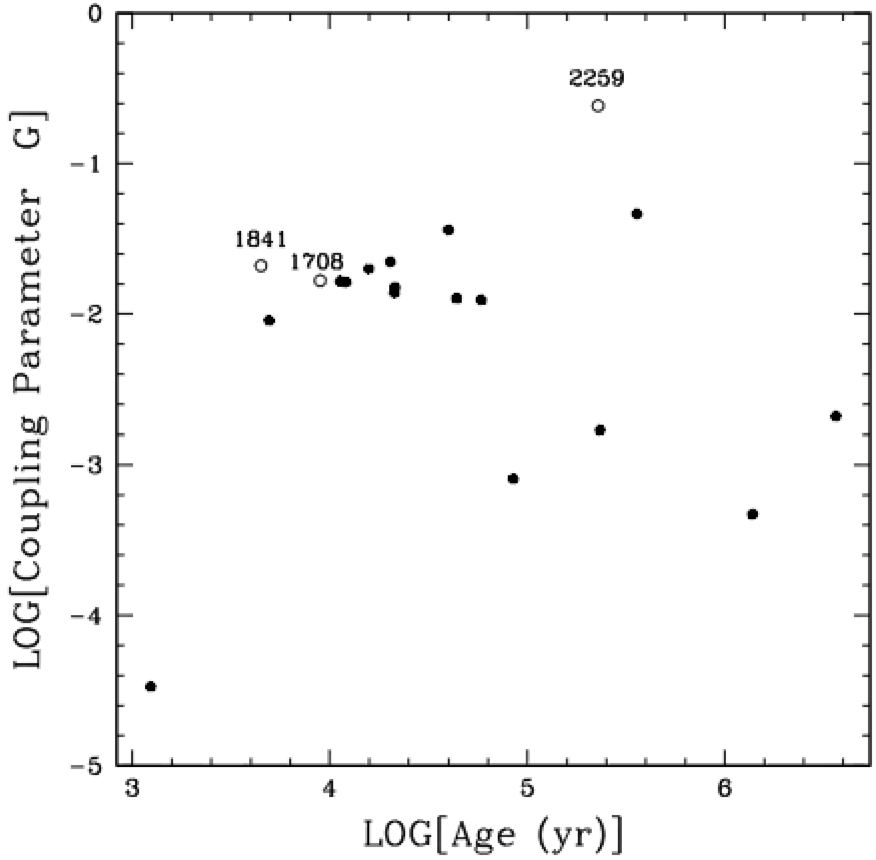
Nearly all known persistent AXPs now seem to glitch.

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?



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

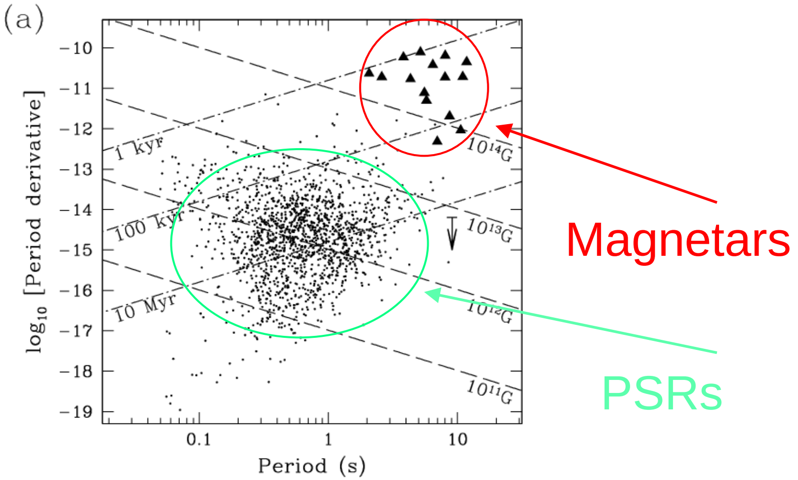
$$\frac{I_{\rm res}}{I_c} \ge G_{\rm Vela} = 1.4\%.$$

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.

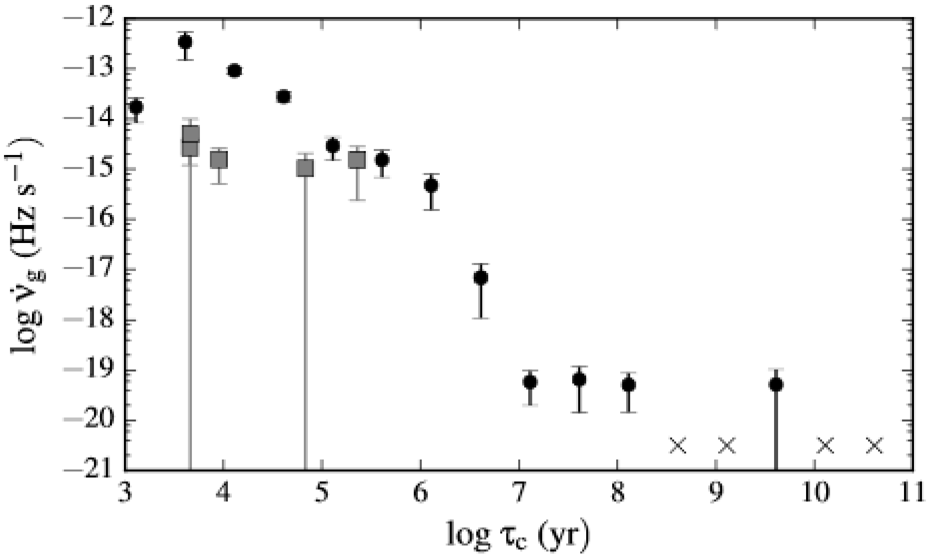
Many others proposed that glitches of magnetars can be related to magnetic field dissipation in the crust. As the field can be dynamically important there, its decay can result in crust cracking.

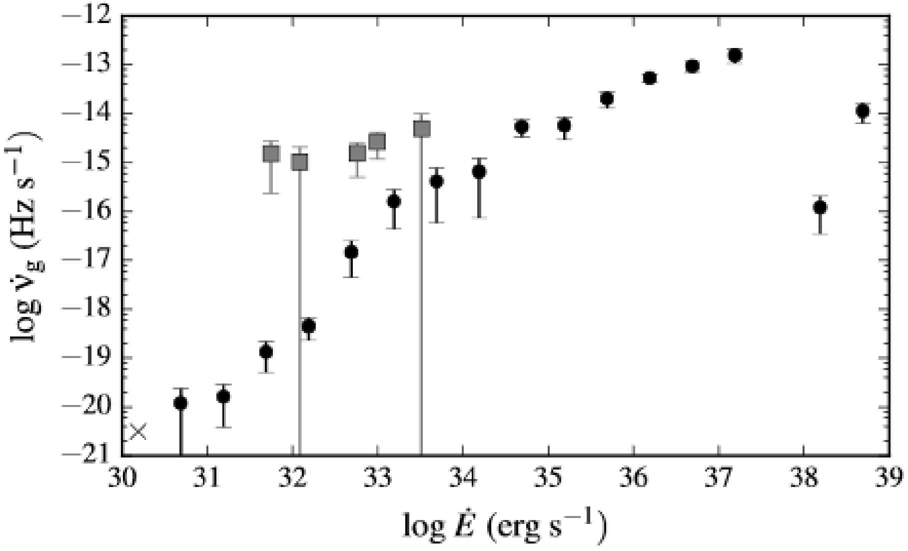
Dib et al. (2008), see arXiv: 0706.4156

PSRs vs. Magnetars



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.





1710.00952

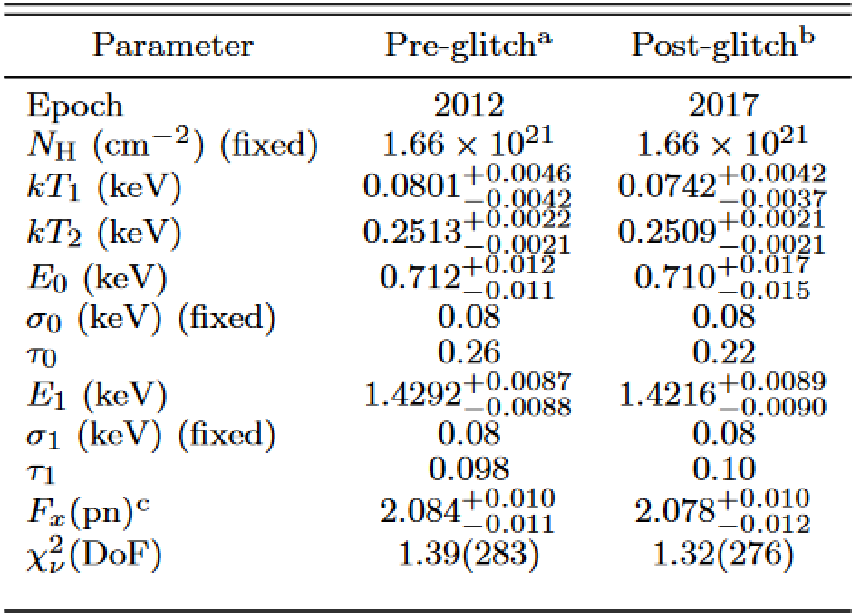
CCOs also glitch!

1E 1207.4–5209

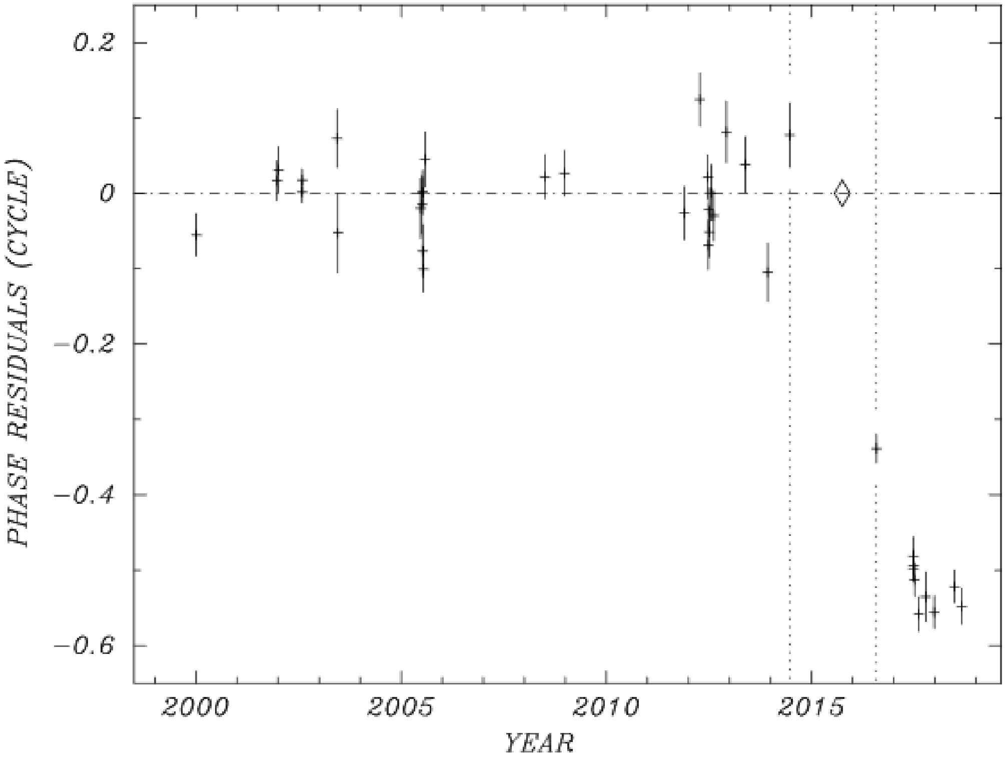
0.424 s

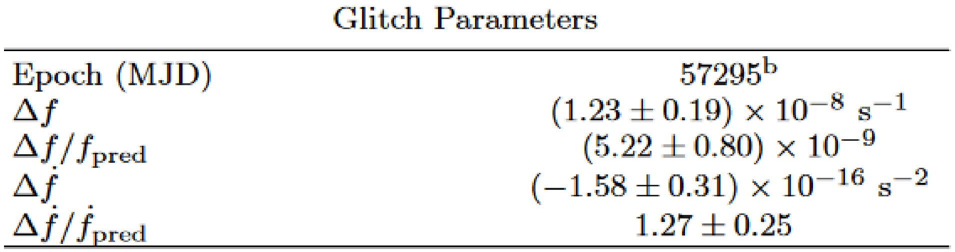
$B_s \approx 9 \times 10^{10}$ G

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



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)



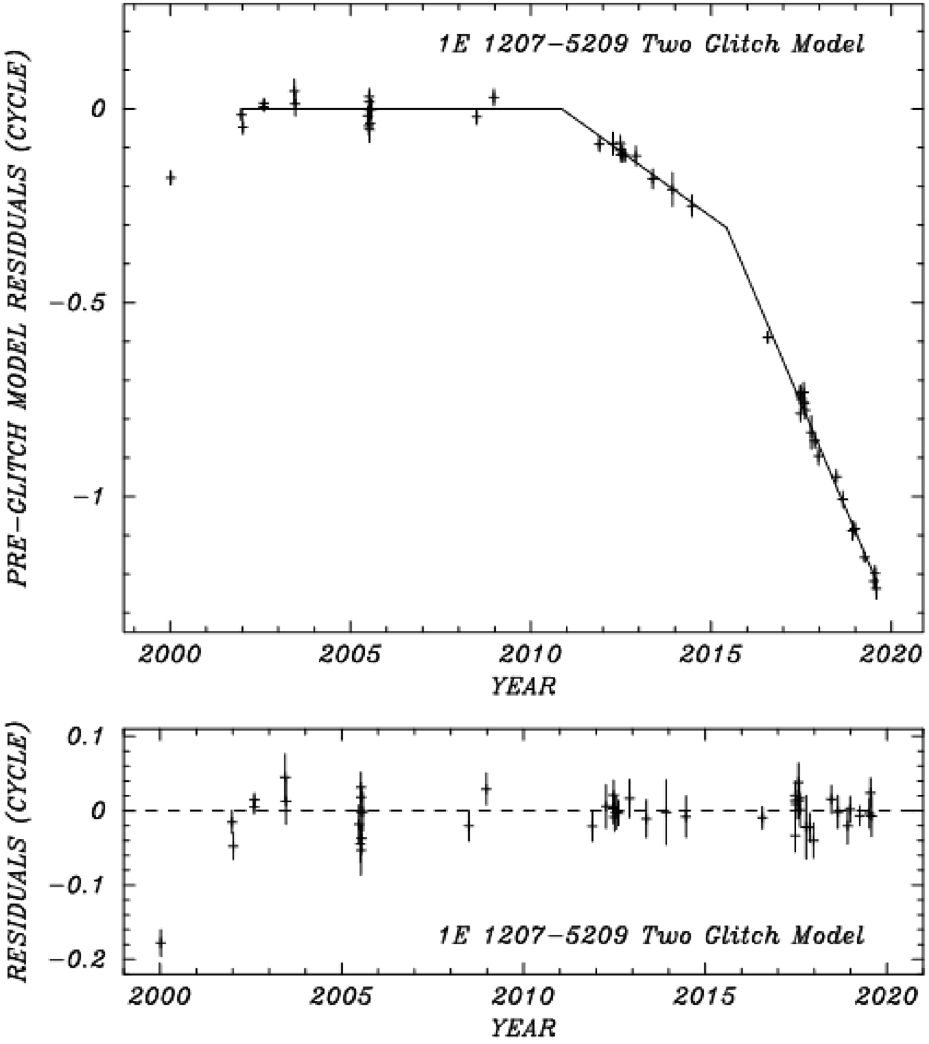


Glitch Parameters

Epoch (MJD)	57295[b]
Δf	$(1.23 \pm 0.19) \times 10^{-8}$ s^{-1}
$\Delta f / f_{\rm pred}$	$(5.22 \pm 0.80) \times 10^{-9}$
$\Delta \dot{f}$	$(-1.58 \pm 0.31) \times 10^{-16}$ s^{-2}
$\Delta \dot{f} / \dot{f}_{\rm pred}$	1.27 ± 0.25

1809.04678

Even more than once!

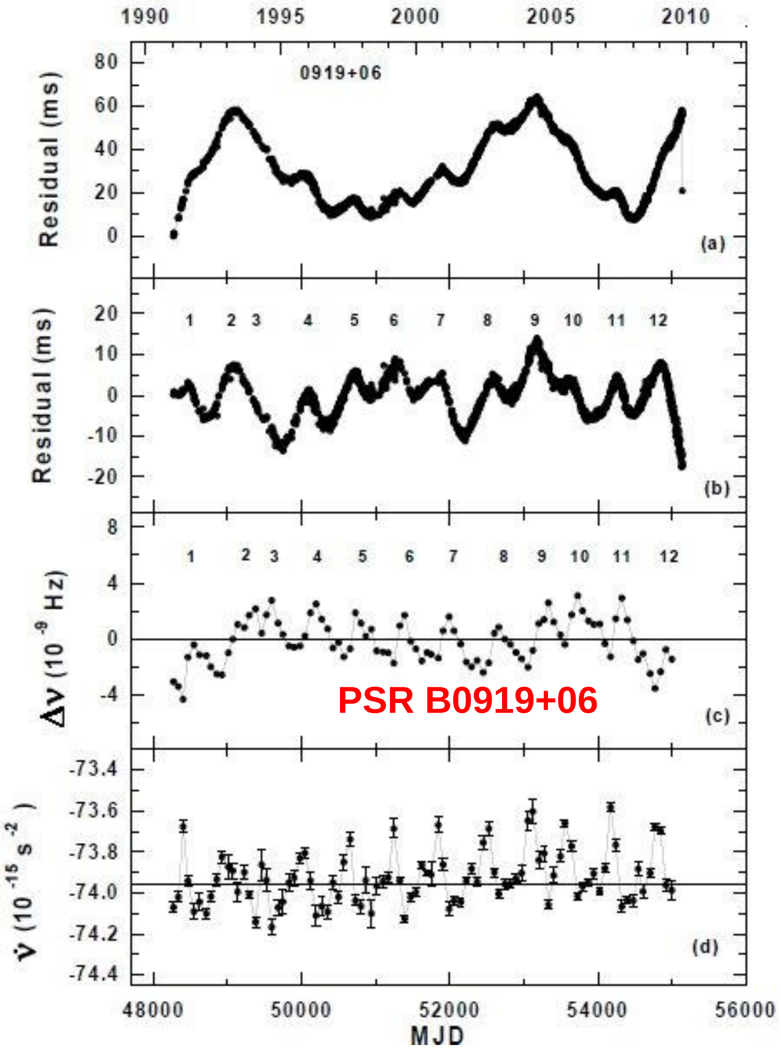


And maybe another between 2000 and 2002.

High glitch activity
for such a low spin-down rate!

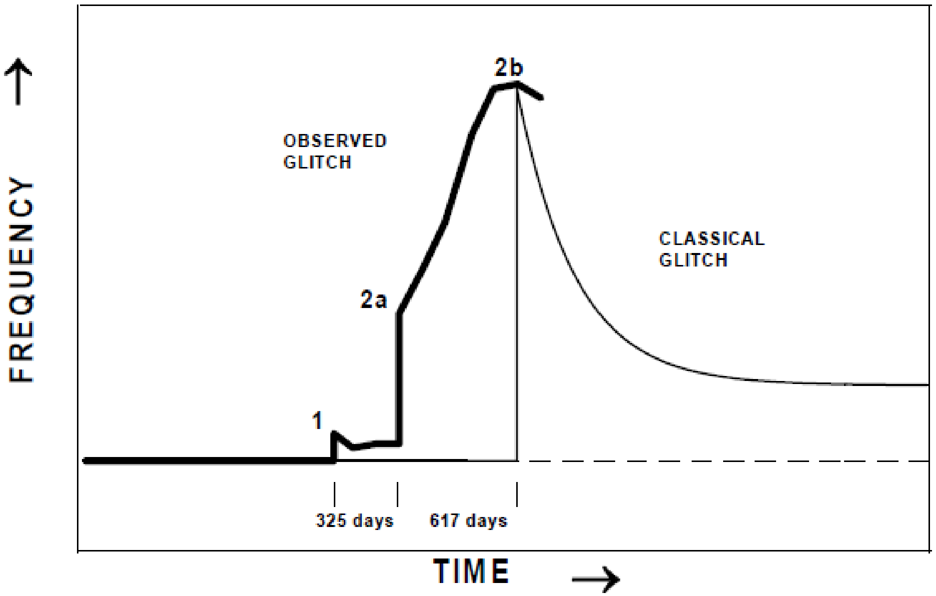
2007.10431

Slow glitches



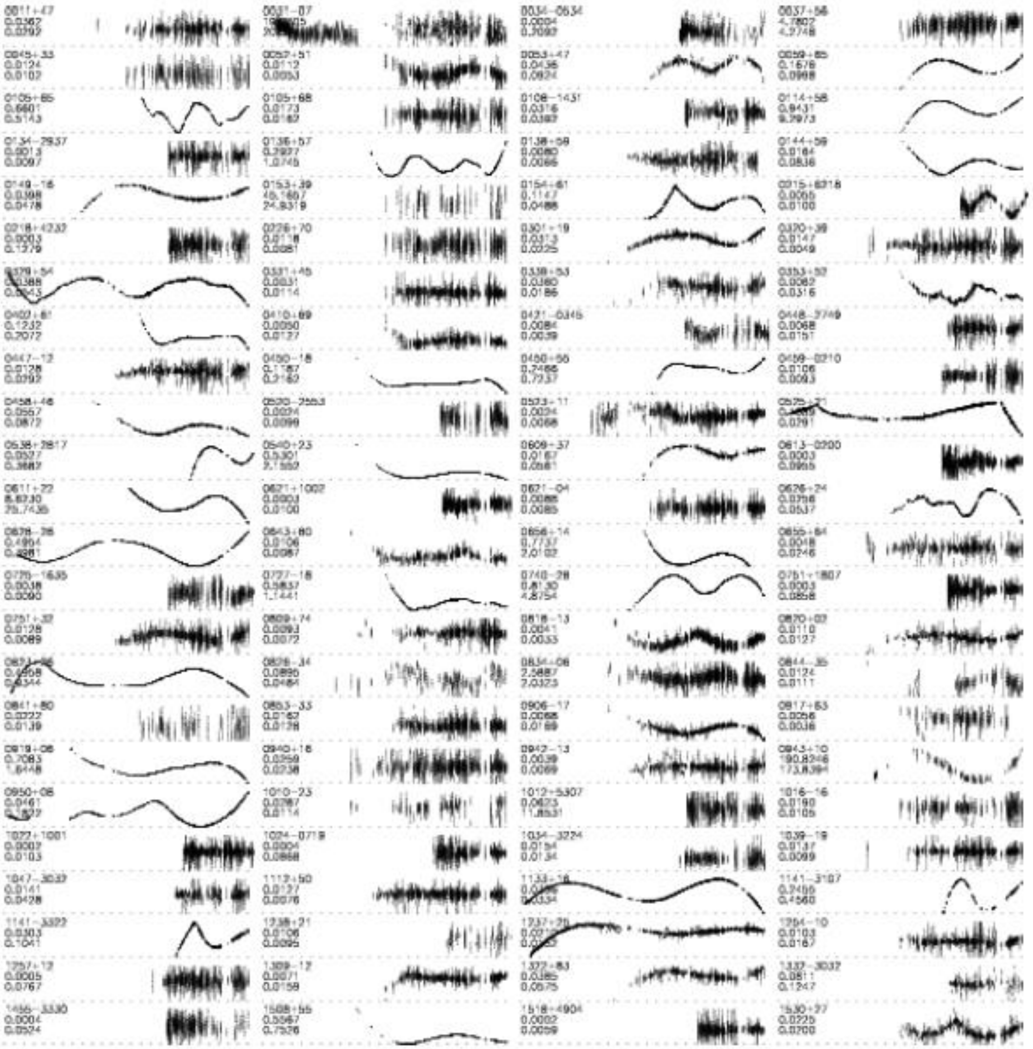
PSR B0919+06

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



1007.0125

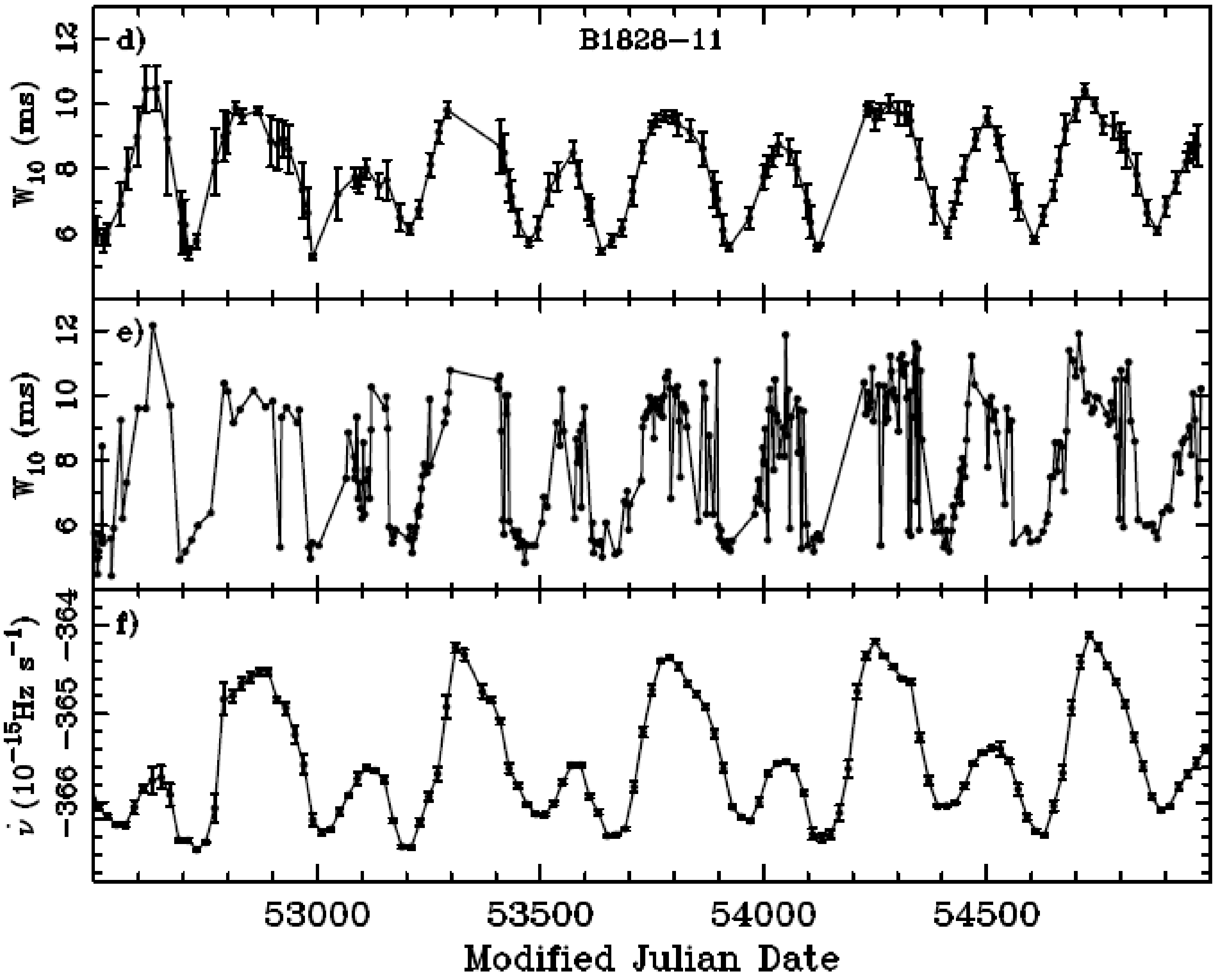
Timing irregularities



Analysis demonstrates different type of irregularities including quasi-periodic.

0912.4537

Possible explanation?



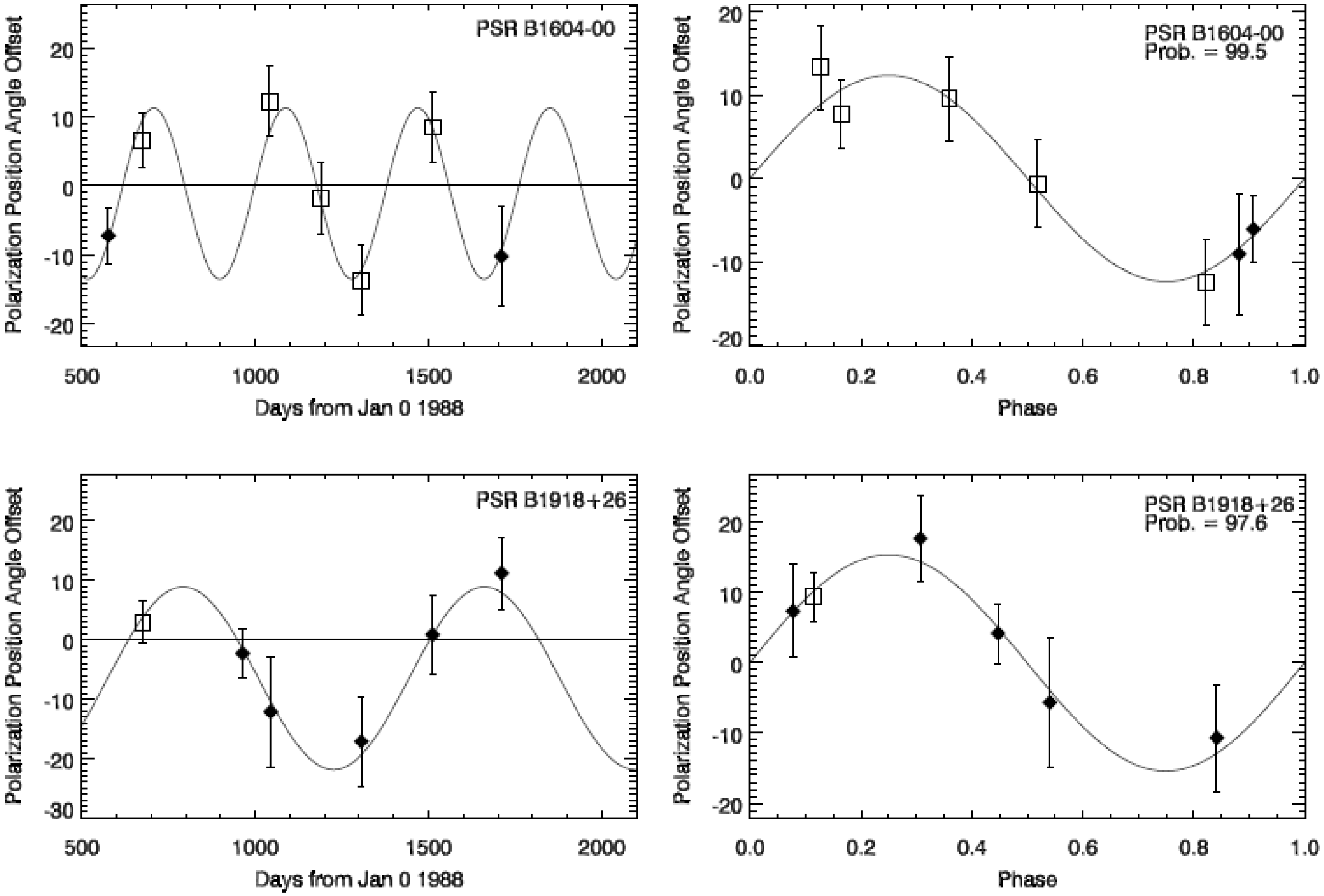
Magnetospheric effect?

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

Switching between these states happens rapidly.

1006.5184, see new results in 1903.01573

Polarization angle variations



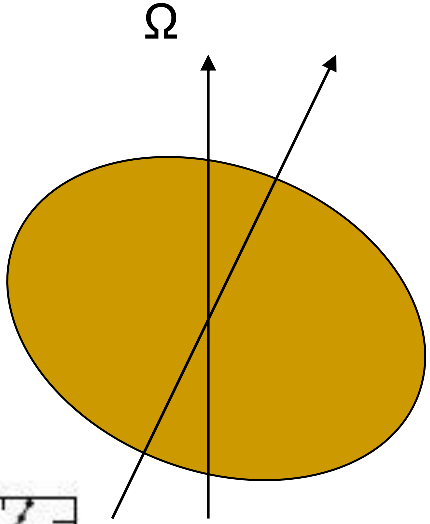
Such variations could be caused by precession

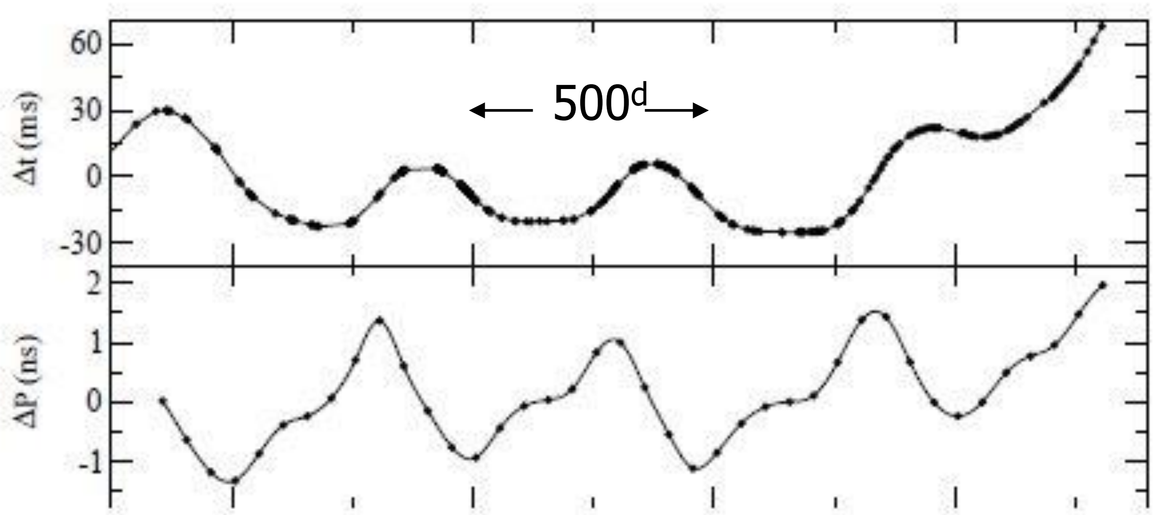
Weisberg et al. 2010 1008.0454

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)





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

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

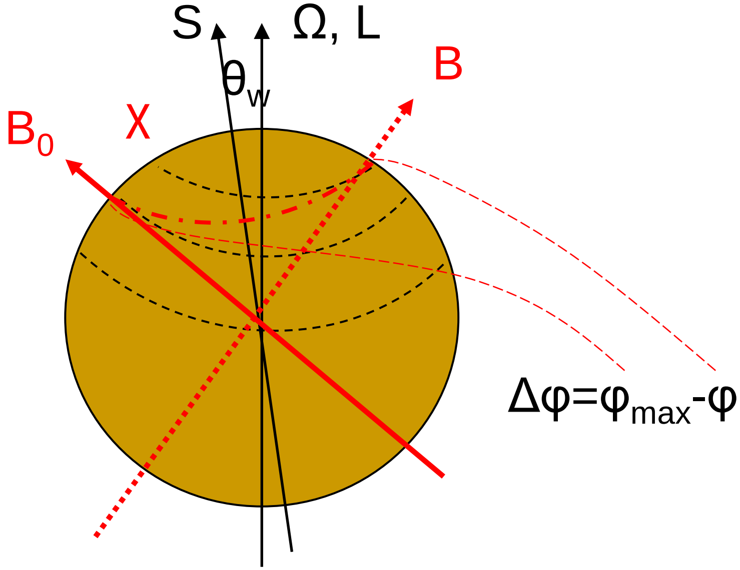
New analysis confirms that PSR 1826-11 can have precession (1510.03579).
Still, it is difficult to bring it in correspondence with glitches from this PSR (1610.03509).

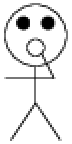
Precession (nutation)

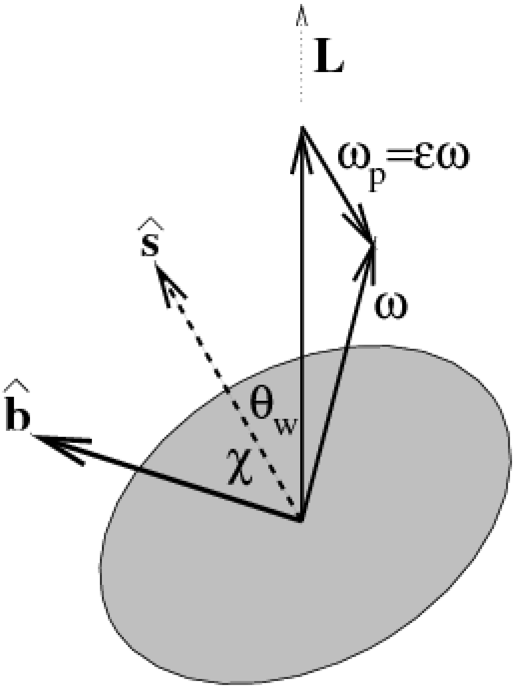
Θ_w – is small
Ω and L are very close

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)





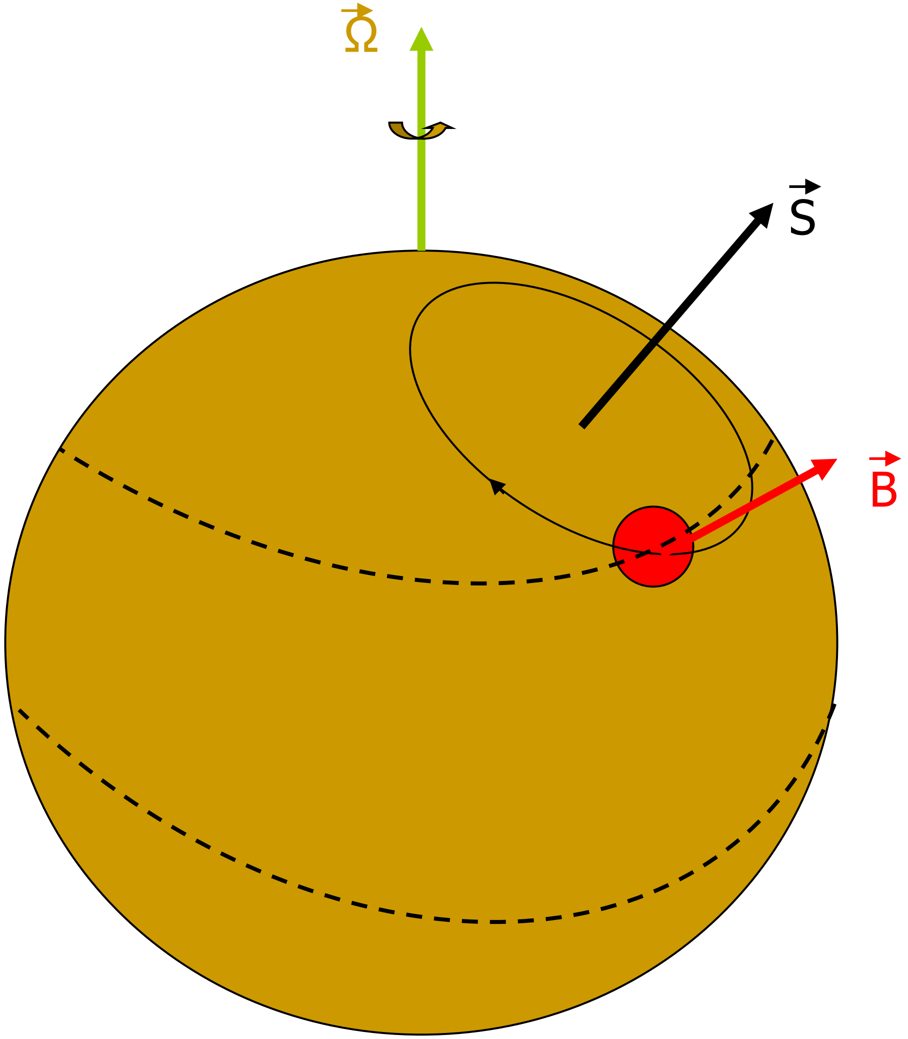


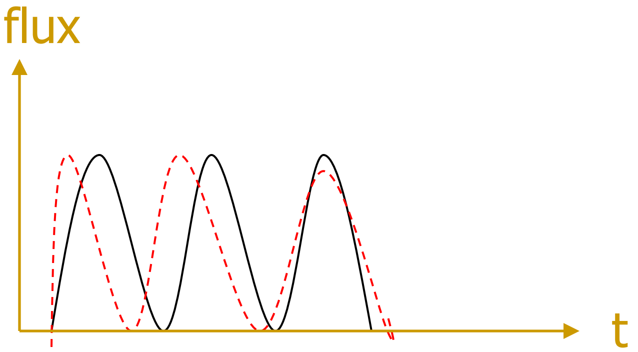
$\Delta\varphi=\varphi_{max}-\varphi_{min}=(\chi+\theta_w)-(\chi-\theta_w)=2\theta_w$

Beam width variation

See B. Link astro-ph/0211182

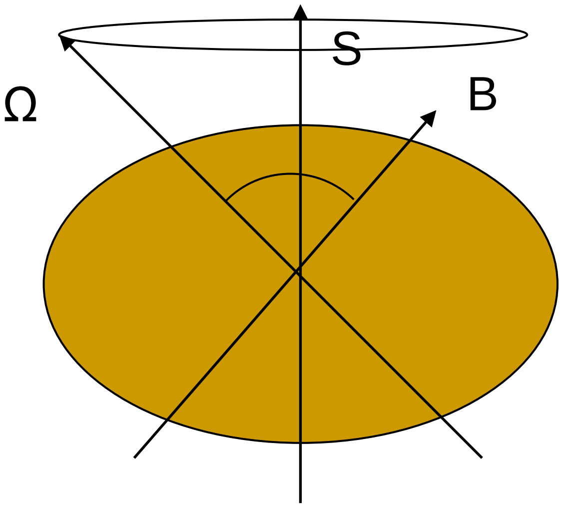
A toy model





This is a picture seen
by an external observer.

In the coordinate frame of the body

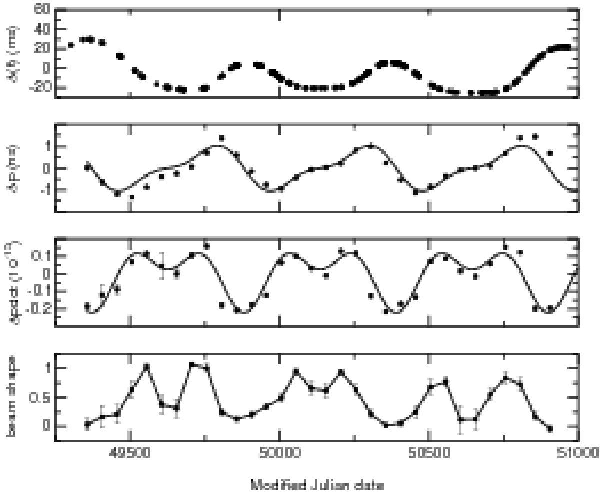


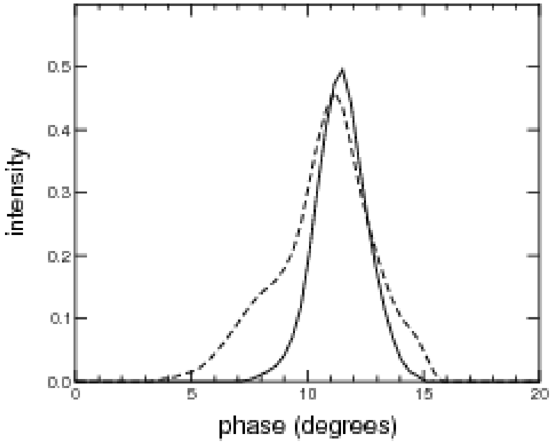
In this system the rotation axis is rotating around the symmetry axis.
So, it is clear that the angle between spin axis and the magnetic axis changes.

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

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

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

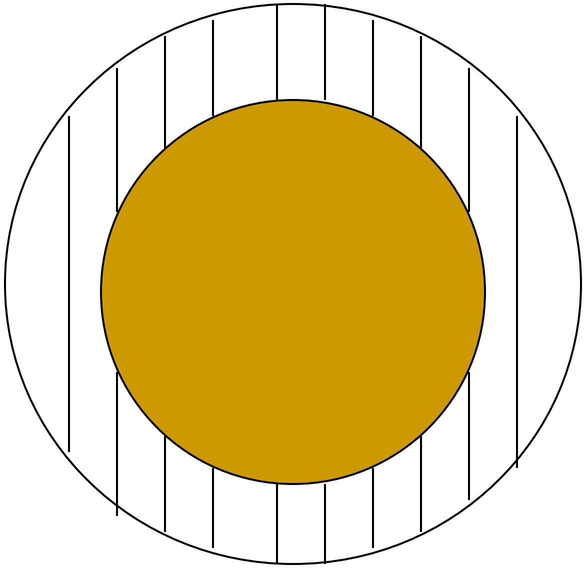




astro-ph/0211182

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.



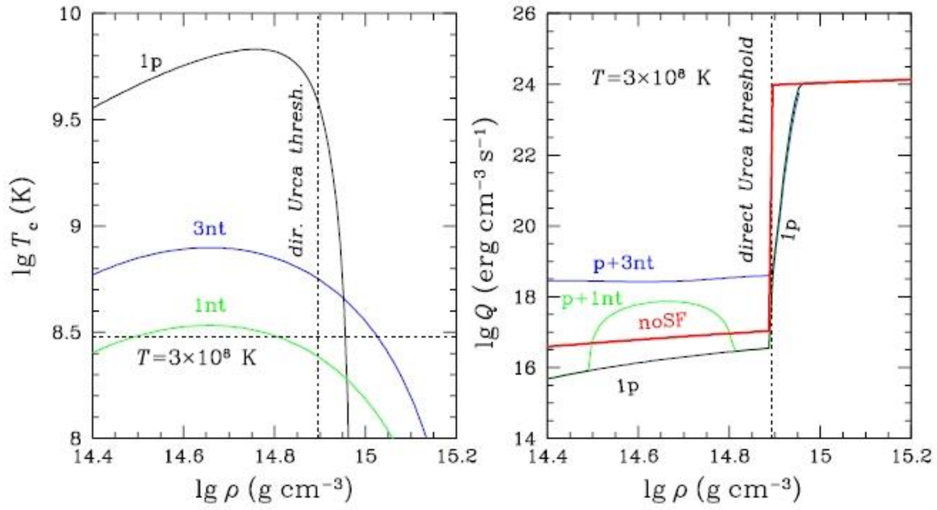
There are several effects related to vortices.

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*.



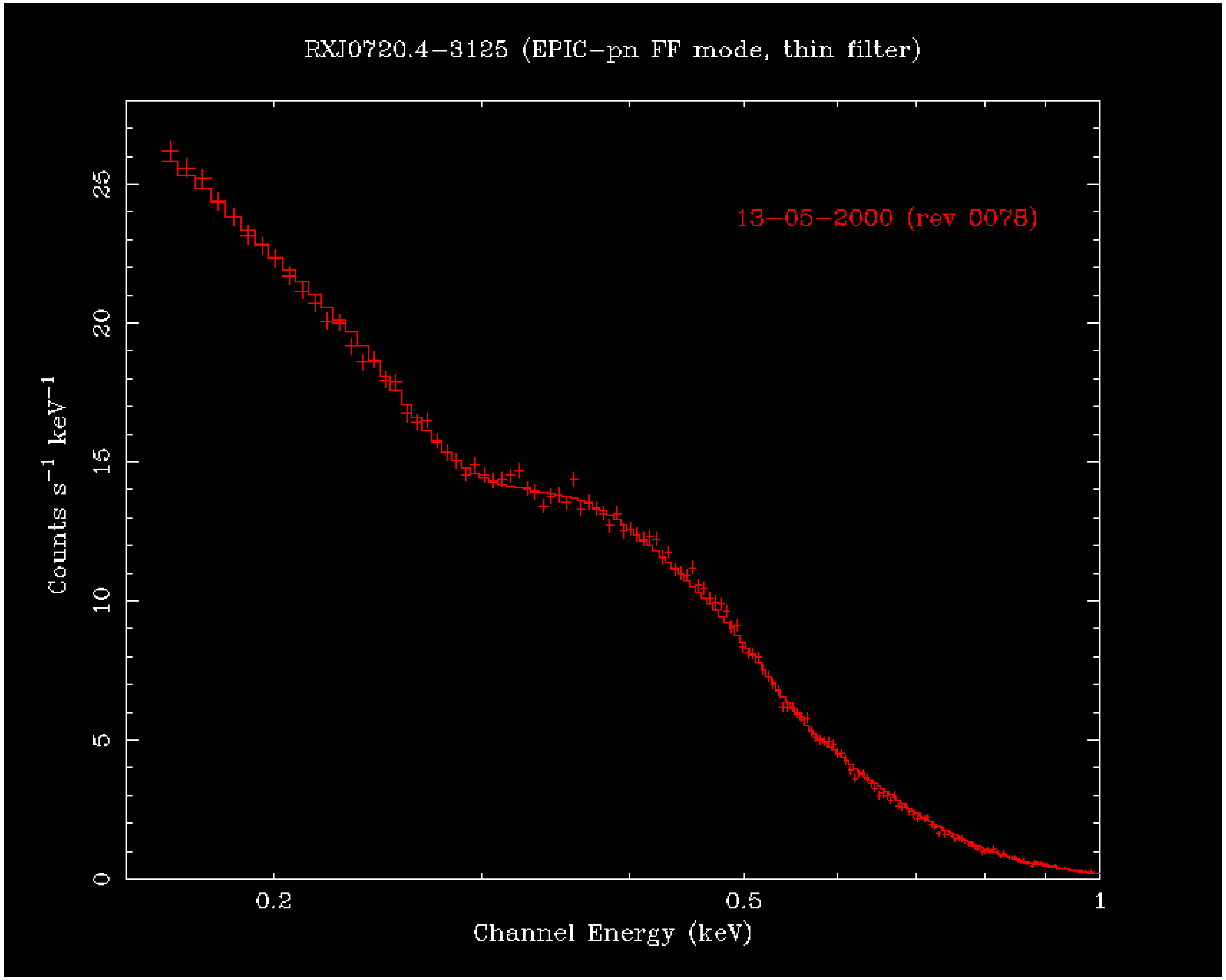
Various baryons in neutron star matter can be in *superfluid* state produced by Cooper pairing of baryons due to an attractive component of baryon-baryon interaction.

Now it is assumed that

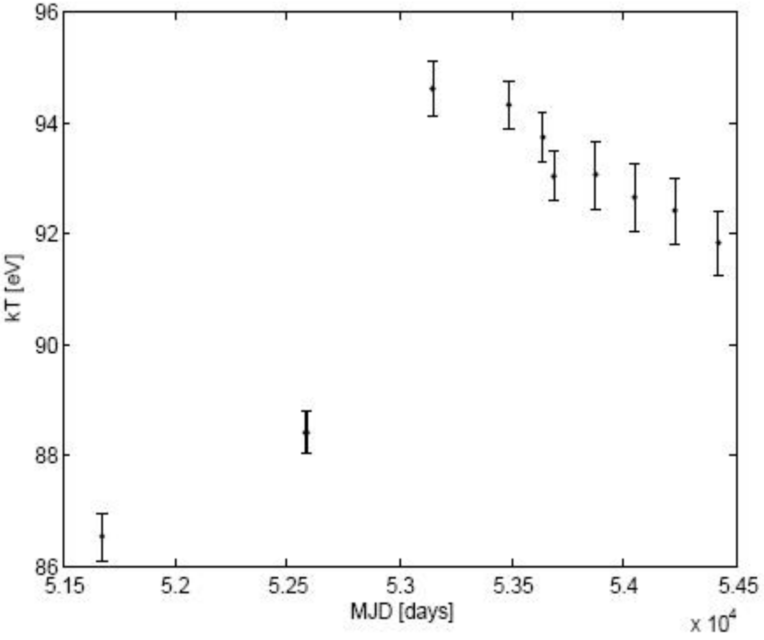
- neutrons are supefluid in the crust (singlet)
- protons are superfluid in the core (singlet)
- neutrons can also be superfluid in the core (triplet)

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

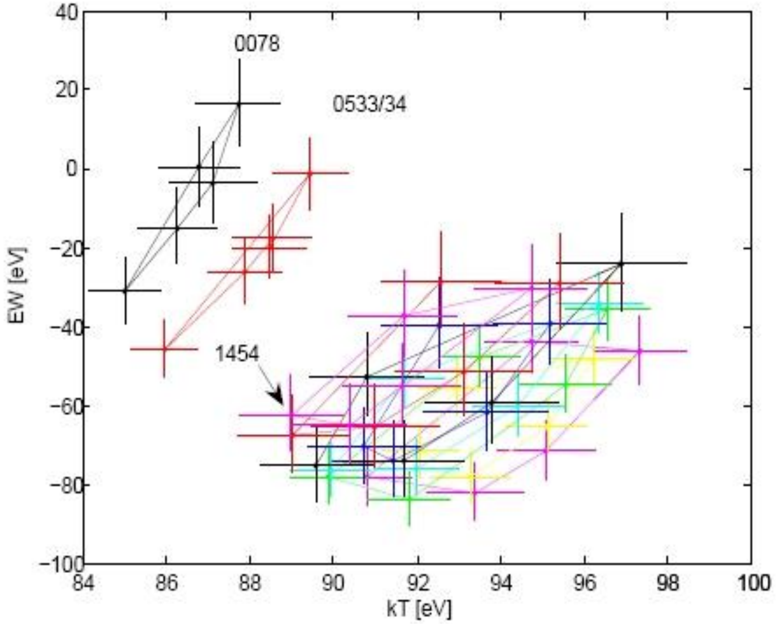
Peculiar behavior of RX J0720



RX J0720.4-3125 as a variable source



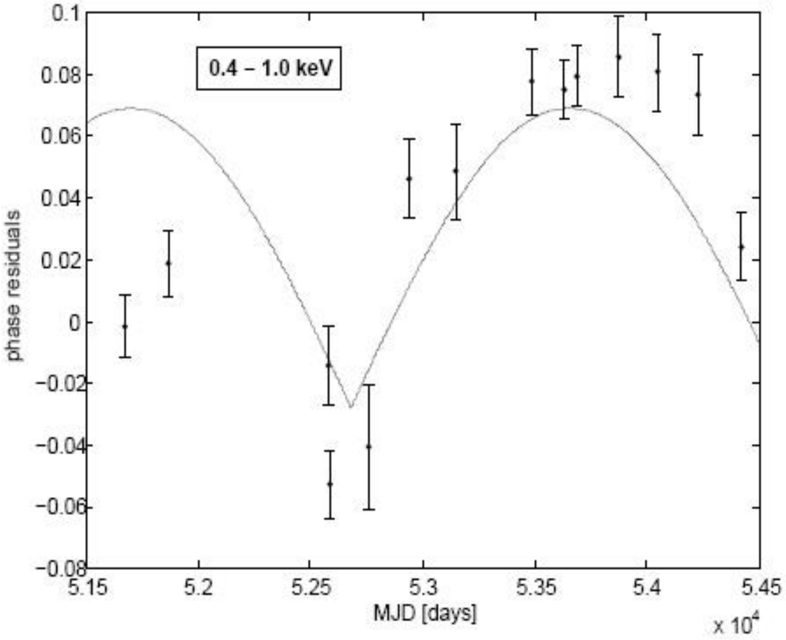
Long term phase averaged spectrum variations



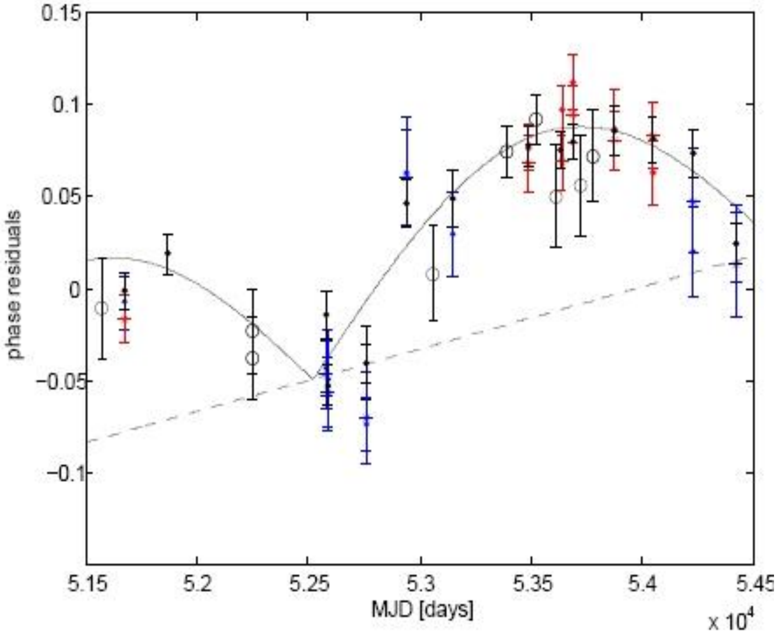
Phase dependent variations during different observations.

[Hohle et al. 2009 arXiv:0810.5319]

~10 years period: precession???



10.711 +/-0.058 yrs



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

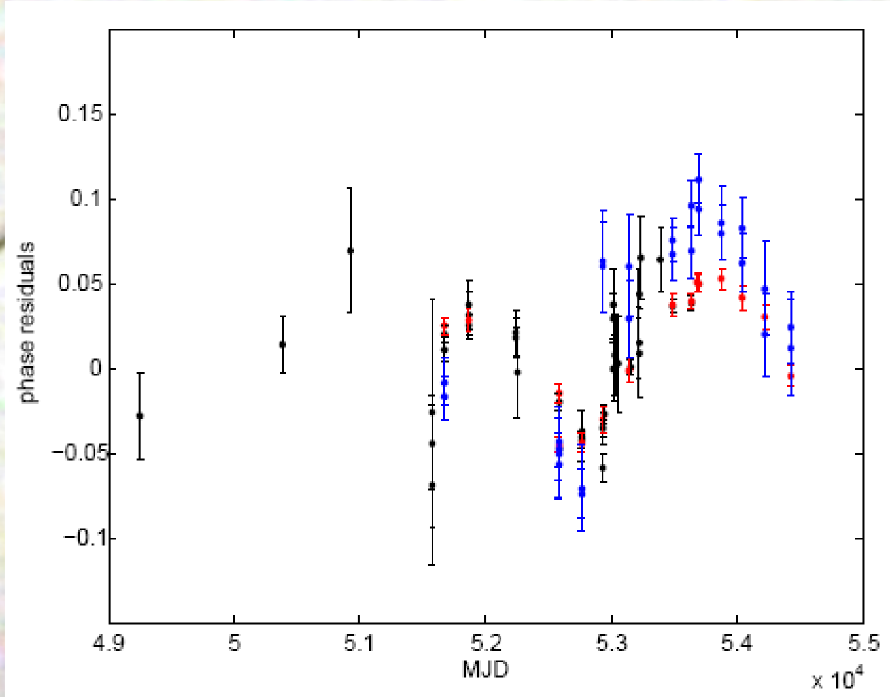
-for $P(t_0)$ and *dP/dt* : phase coherent timing
-in Kaplan & van Kerkwijk (2005) and van Kerkwijk 2007, without energy restriction

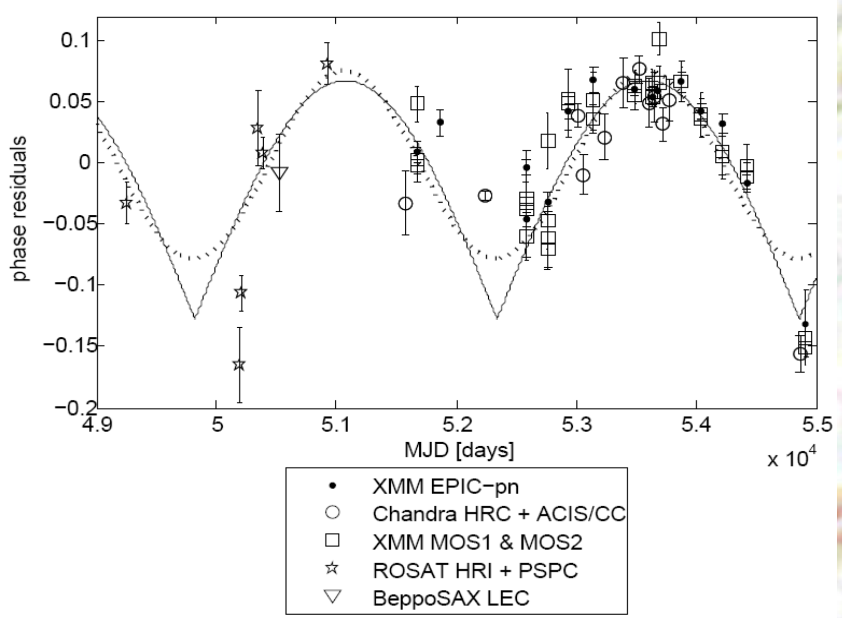
-now: restricting to the hard band (except for ROSAT and Chandra/HRC)
+five new XMM-Newton
+two new Chandra/HRC observations

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

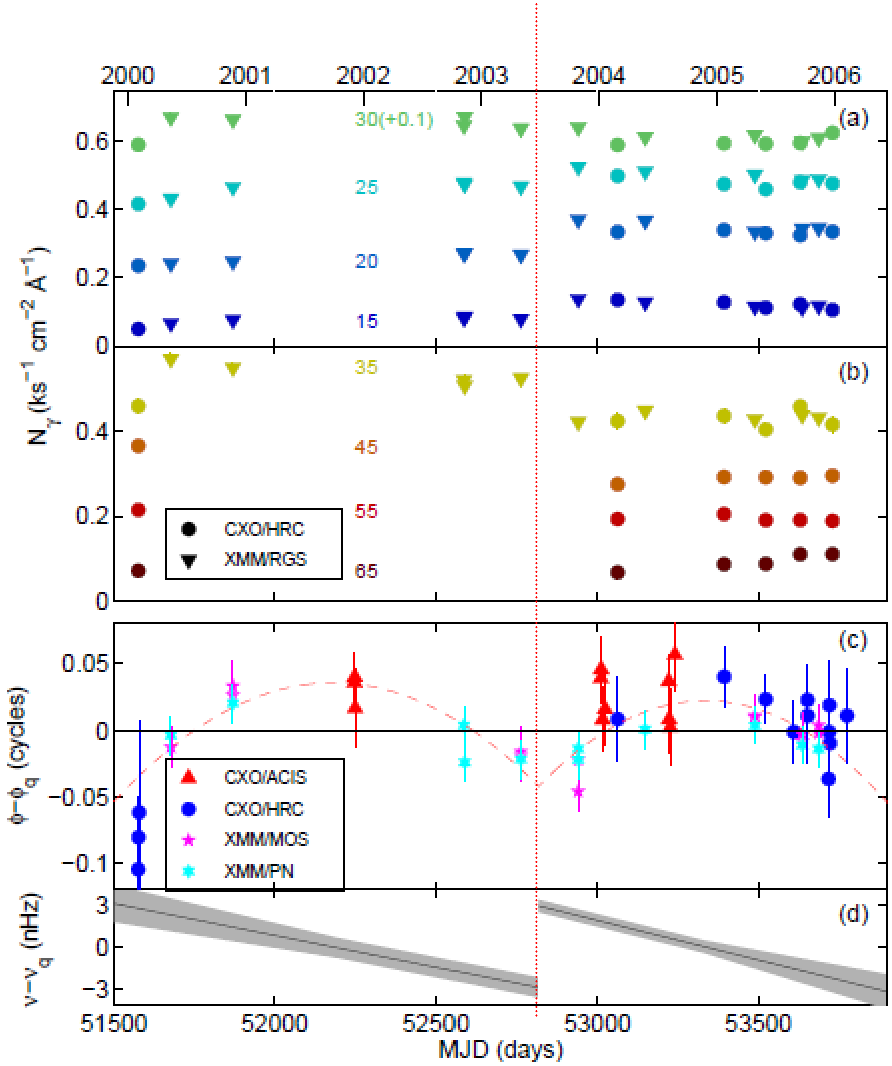
-long term period: (6.91 +/- 0.17) yrs
Haberl (2007): (7.70 +/- 0.60) yrs
for two hot spots: abs(sine)
with 13-15.5yrs period

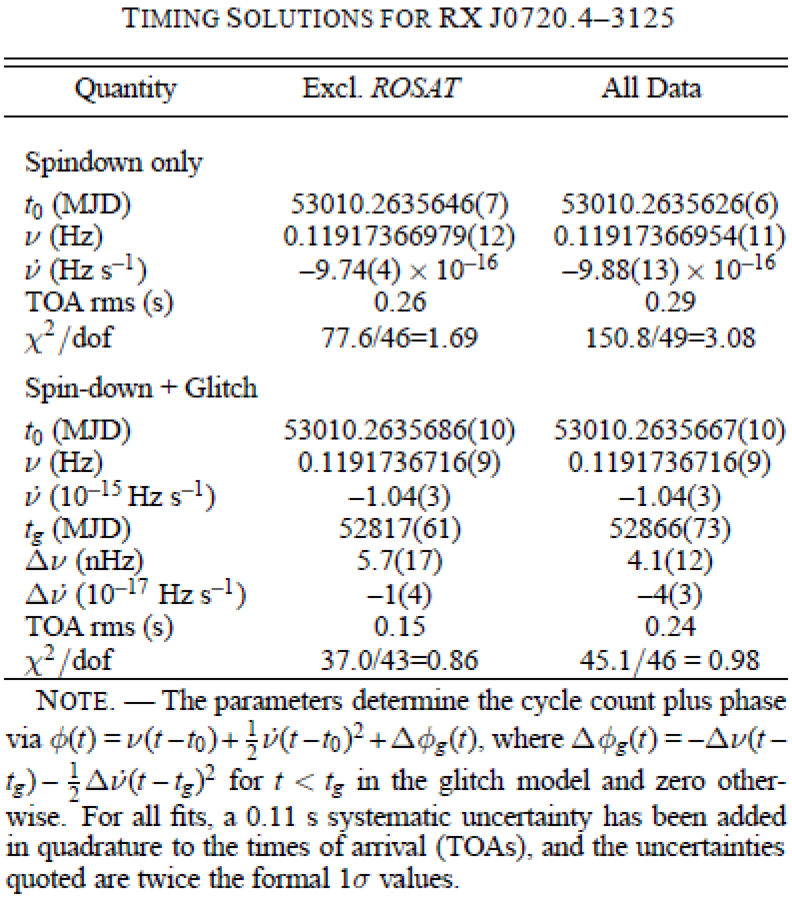
The slide from a talk by
Markus Hohle (Jena observatory).





Another interpretation: glitch + ?





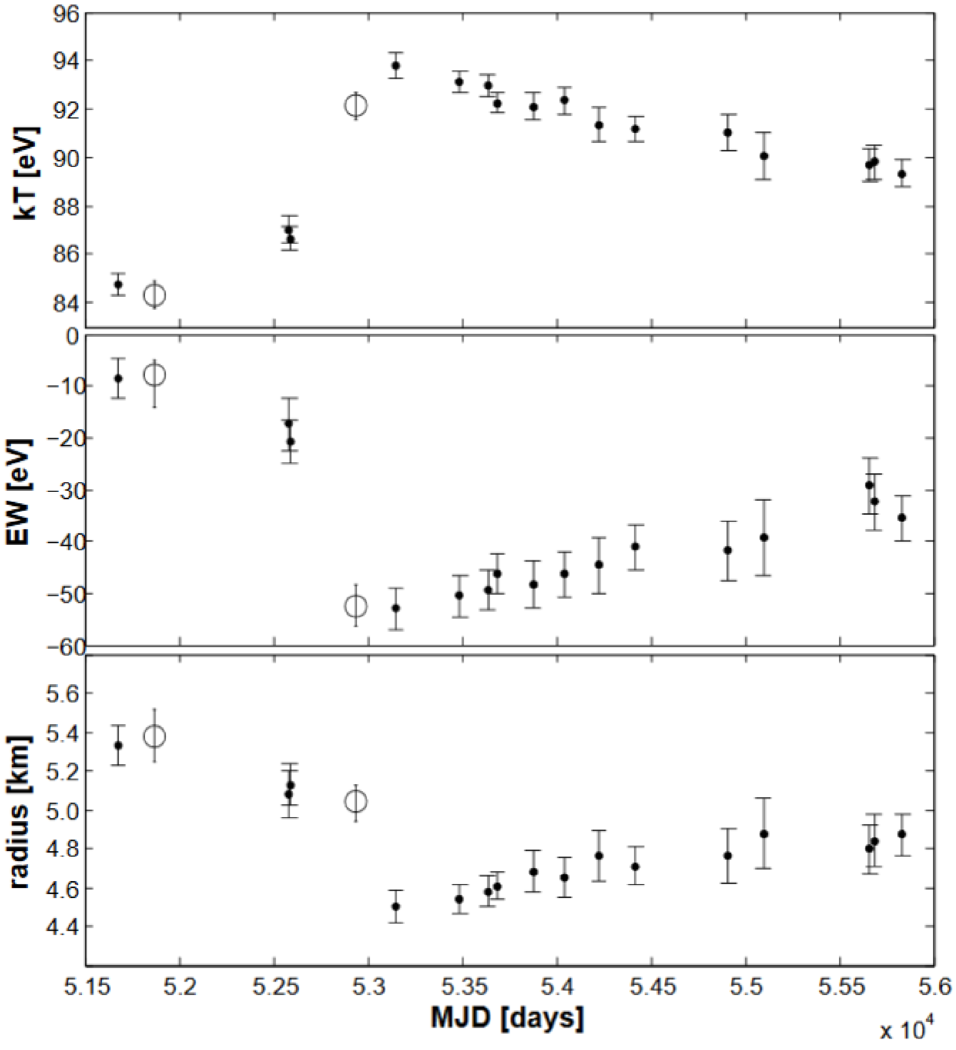
TIMING SOLUTIONS FOR RX J0720.4–3125

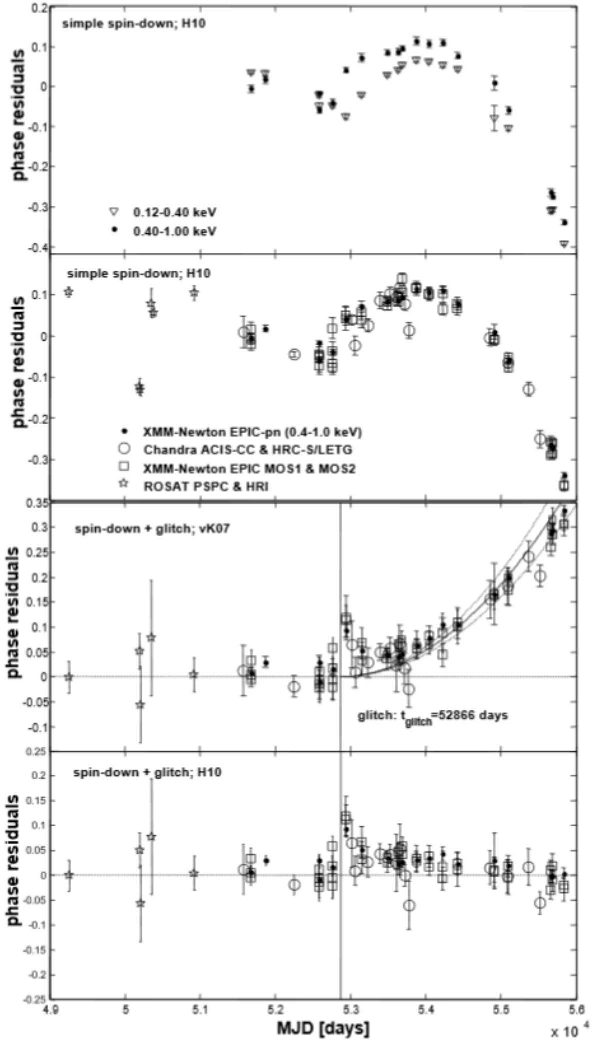
Quantity	Excl. *ROSAT*	All Data
Spindown only		
t_0 (MJD)	53010.2635646(7)	53010.2635626(6)
ν (Hz)	0.11917366979(12)	0.11917366954(11)
$\dot{\nu}$ (Hz s^{-1})	$-9.74(4) \times 10^{-16}$	$-9.88(13) \times 10^{-16}$
TOA rms (s)	0.26	0.29
χ^2/dof	77.6/46=1.69	150.8/49=3.08
Spin-down + Glitch		
t_0 (MJD)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

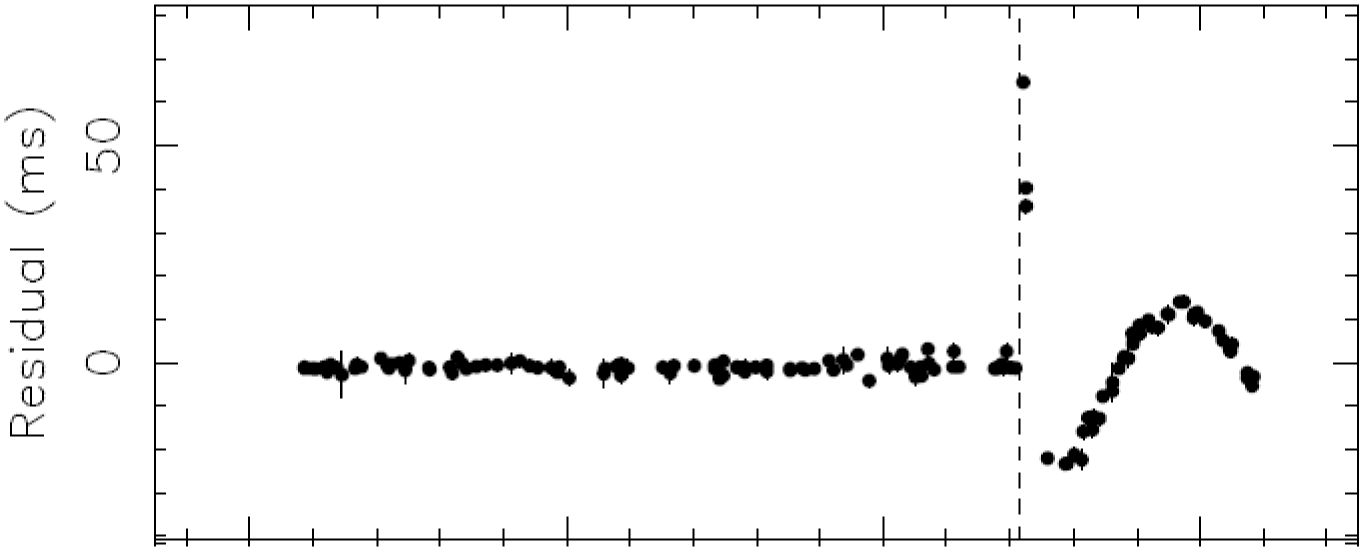
RX J0720.4-3125: a glitch





1203.3708

Glitch+? in a PSR



PSR B2334+61

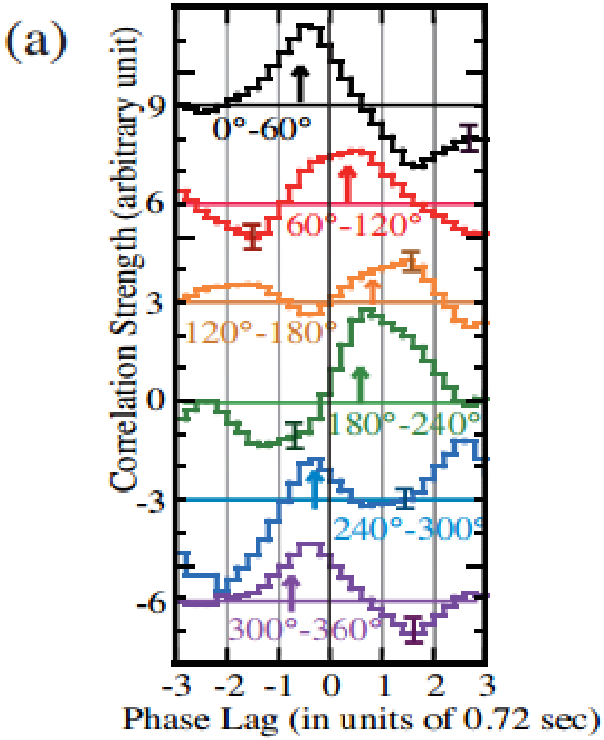
arXiv: 1007.1143

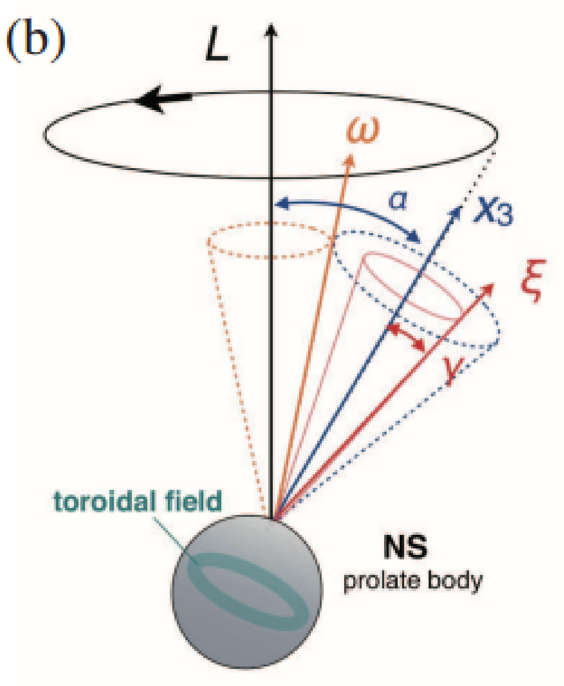
Precession after a glitch was proposed as possible feature due to Tkachenko waves excitation (arXiv: 0808.3040).

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

Free precession of a magnetar?

4U 0142+61
Slow phase modulations in hard X-rays





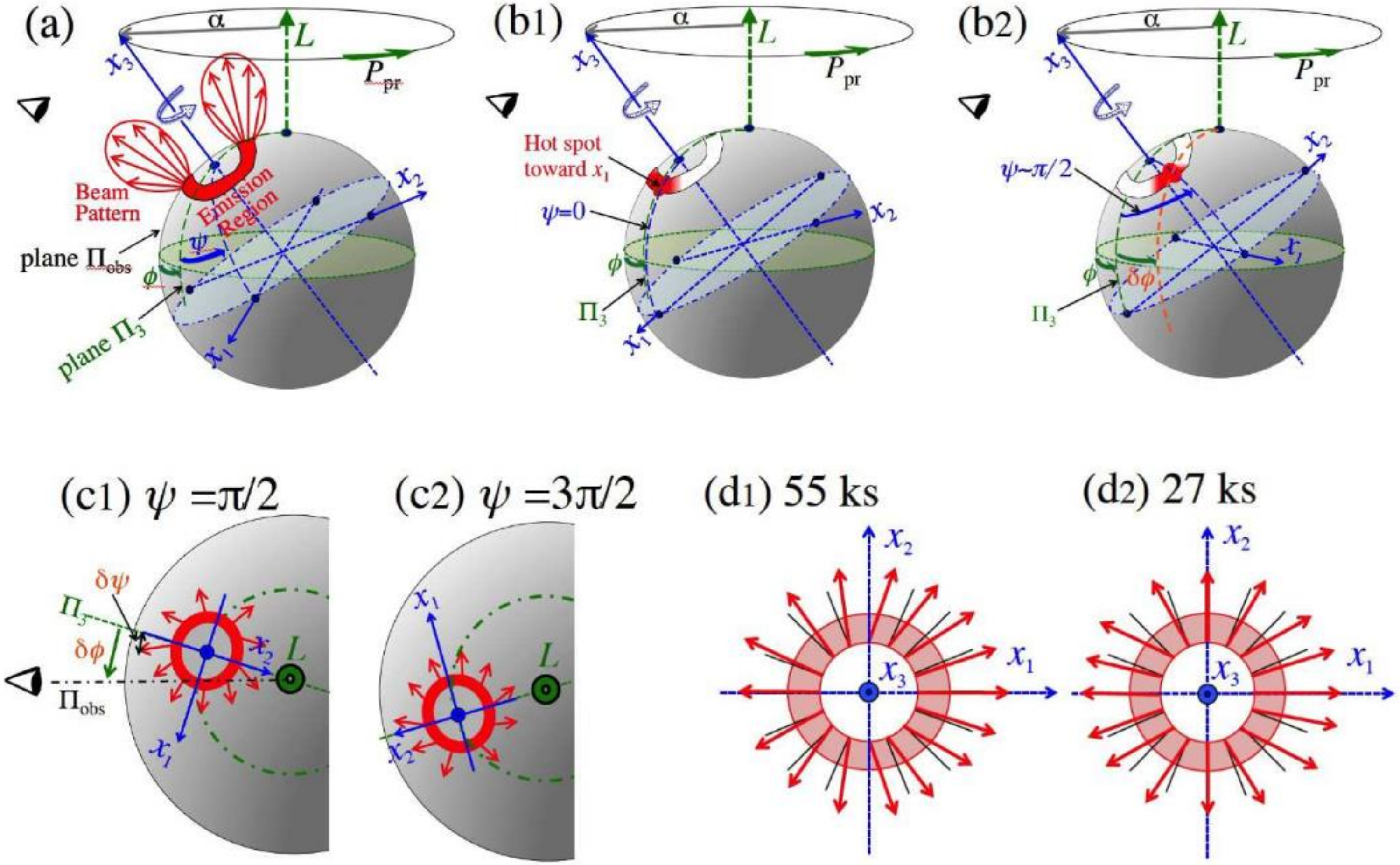
The authors observe modulation of the pulse profile with a period ~15 hours.
If it is interpreted by a free precession, than the NS is significantly deformed which can be due to strong toroidal field.
This field might be $\sim 10^{16}$ G.

See new results and analysis in 1810.11147

1404.3705

More X-ray data confirms modulation

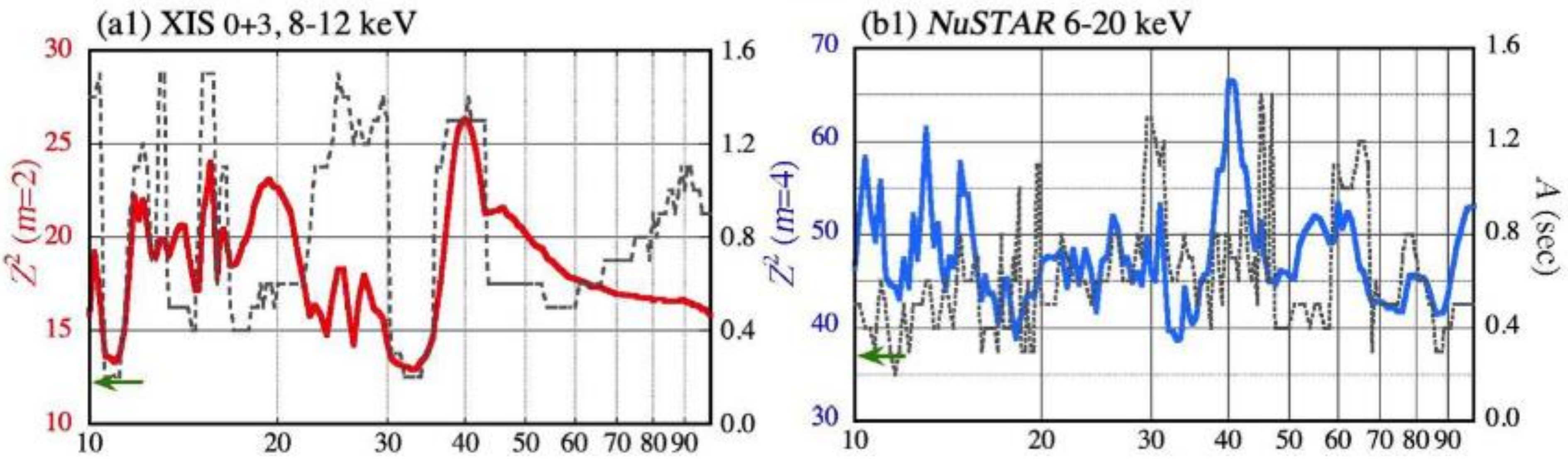
4U 0142+61



1810.11147

Energy-dependent pulse fraction modulation with the period 36 ks were also suspected for 1E 1547−5408, 2102.00153

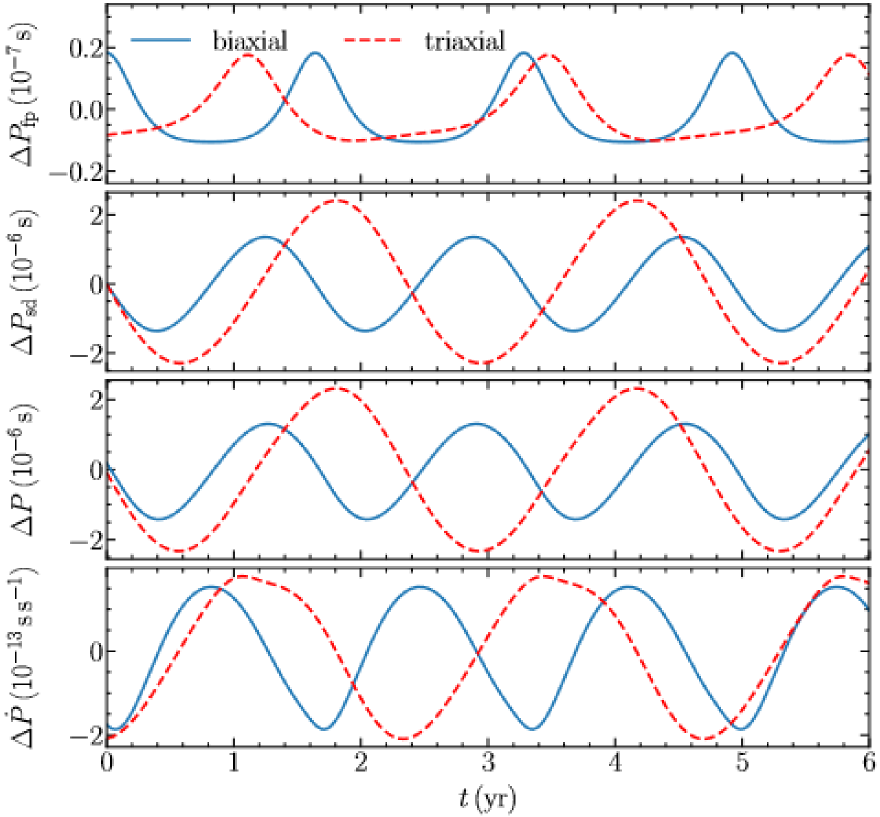
40 ksec modulation in SGR 1900+14

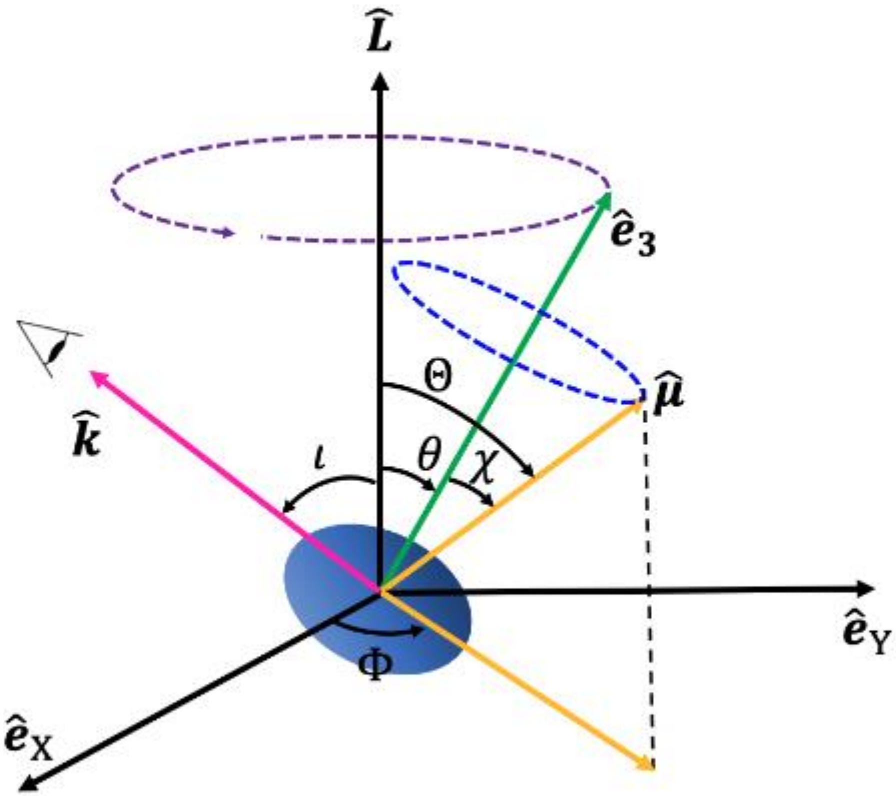


Can be explained by toroidal field ~10^{16} G

2109.11150

Theory of magnetar precession



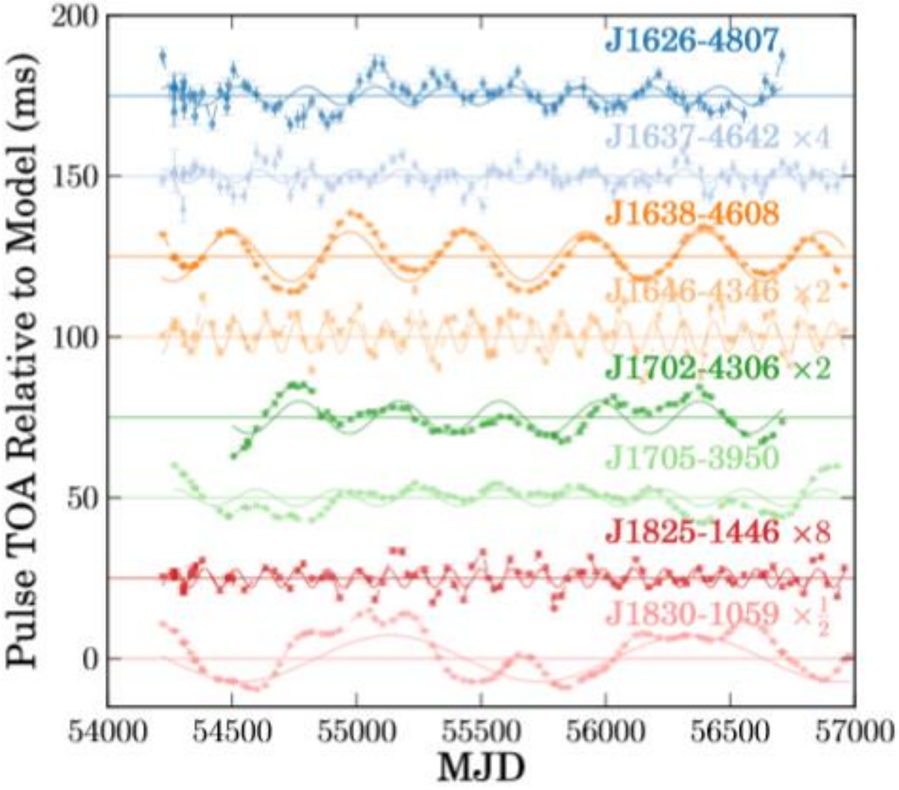


Case	Intrinsic parameters							Effective parameters					
	P_0 (s)	B (G)	ϵ	δ	θ_0 (°)	χ (°)	η (°)	$\epsilon_{\rm eff}$	$\delta_{\rm eff}$	$\theta_{\rm eff,0}$ (°)	$\chi_{\rm eff}$ (°)	$\eta_{\rm eff}$ (°)	$T_{\rm eff}$ (yr)
I	5	10^{14}	10^{-7}	0	15	45	0	1.00×10^{-7}	7.61×10^{-3}	15.4	45.4	0	1.65
II	5	10^{14}	10^{-7}	1	15	45	45	9.96×10^{-8}	1.01	15.3	45.6	44.8	2.38

2211.17087

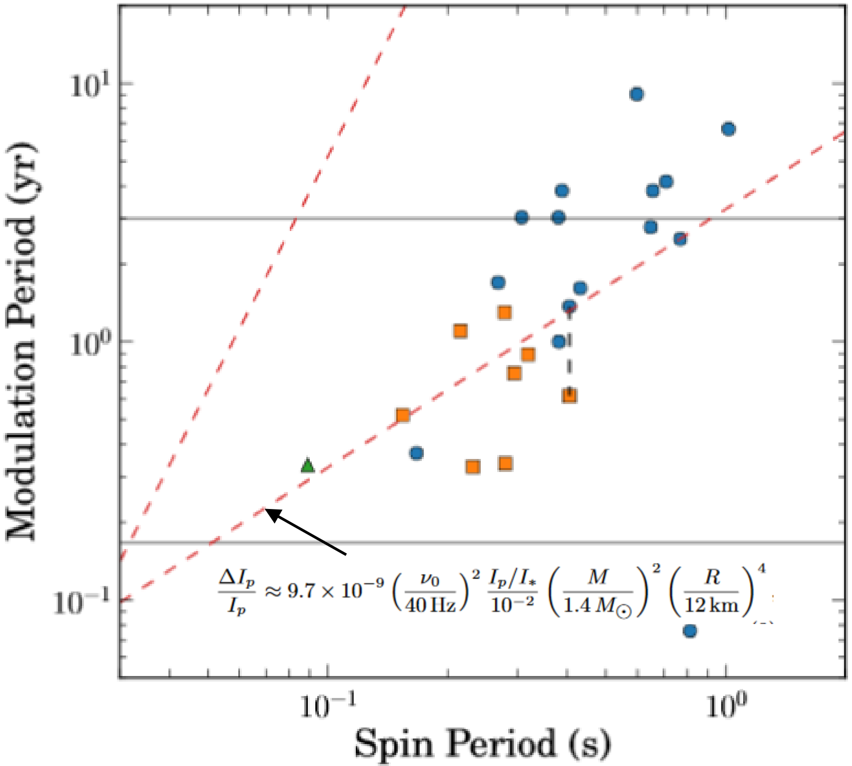
Modulation of polarization properties are also expected.

More precession candidates among PSRs



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

Periodic modulations which can be interpreted as free precession.



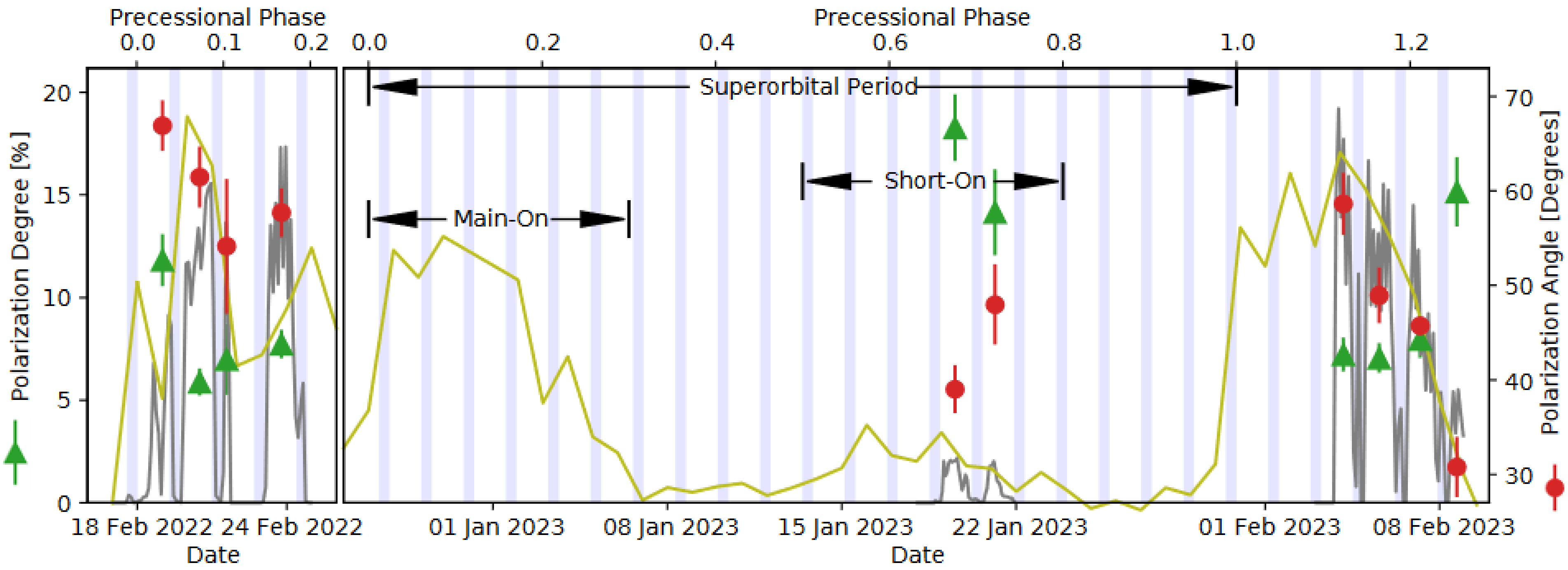
$$\frac{\Delta I_p}{I_p} \approx 9.7 \times 10^{-9} \left(\frac{\nu_0}{40\,\mathrm{Hz}}\right)^2 \frac{I_p/I_*}{10^{-2}} \left(\frac{M}{1.4\,M_\odot}\right)^2 \left(\frac{R}{12\,\mathrm{km}}\right)^4$$

1510.06078

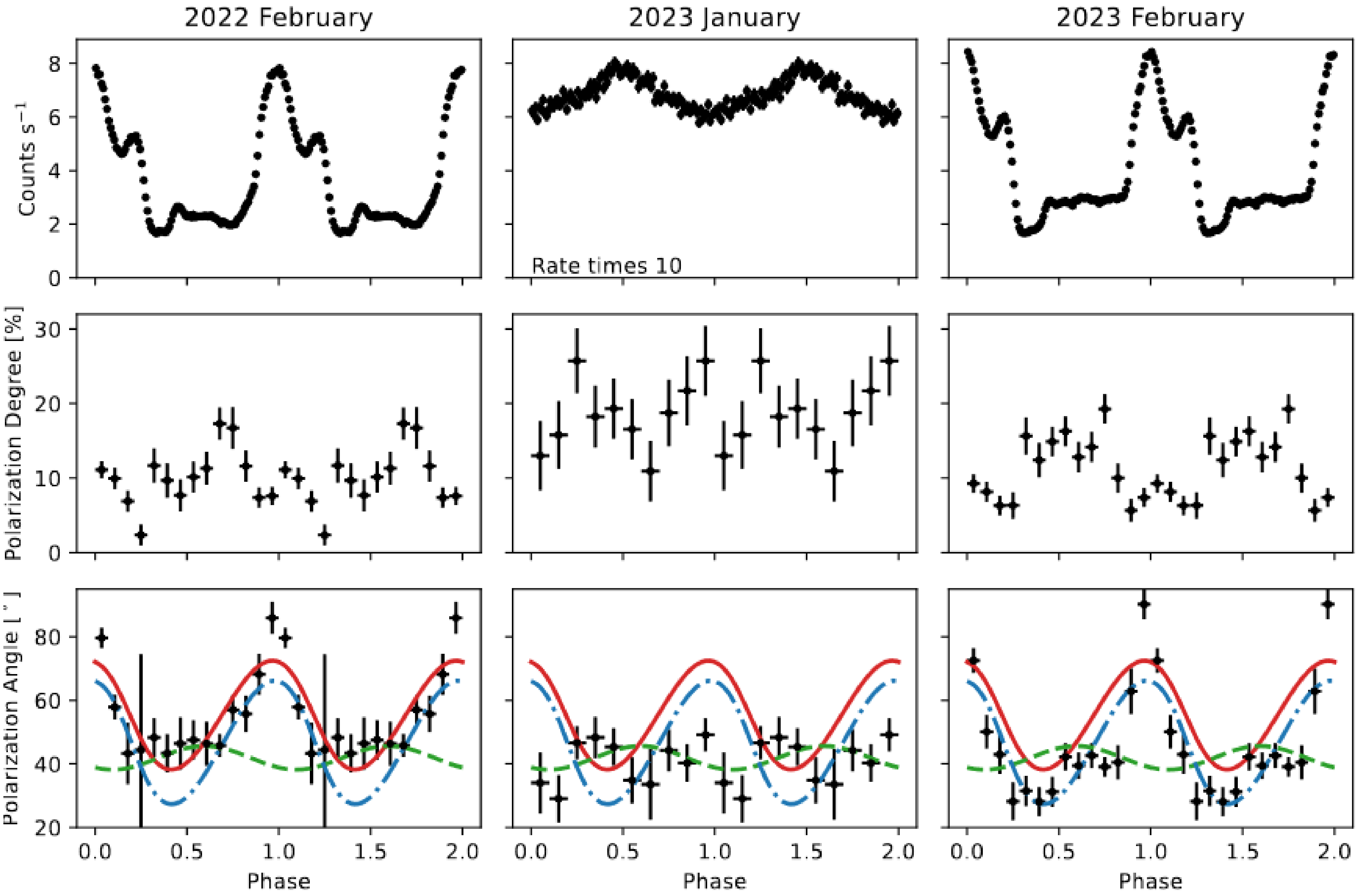
Precession of the NS in Her X-1

IXPE observations

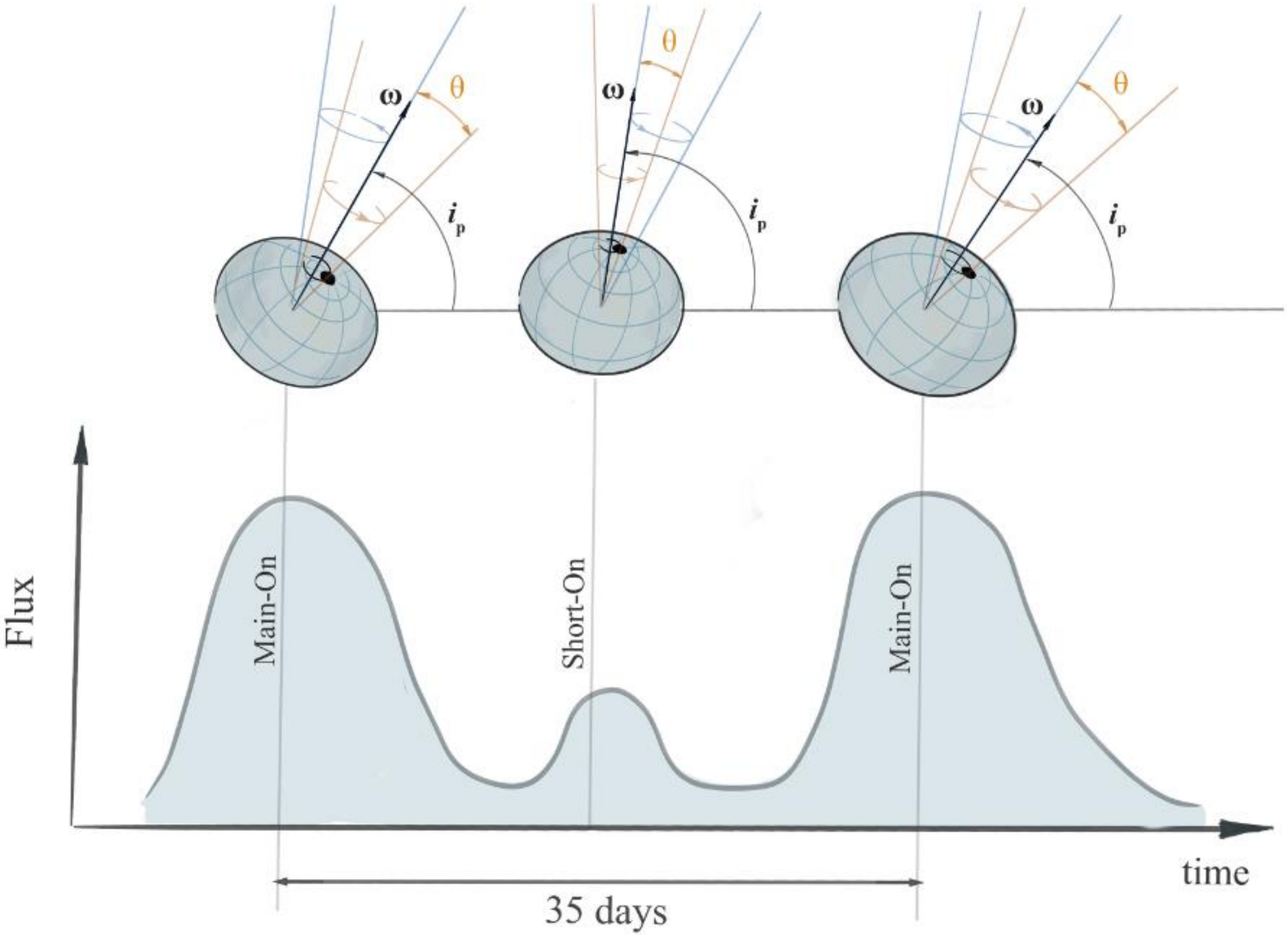
Spin 1.2 s
Superorbital period ~35 days



2311.03667


2022 February
2023 January
2023 February
Counts s^{-1}
Polarization Degree [%]
Polarization Angle [°]
Rate times 10
Phase
Phase
Phase
0
2
4
6
8
0
10
20
30
20
40
60
80
0.0
0.5
1.0
1.5
2.0

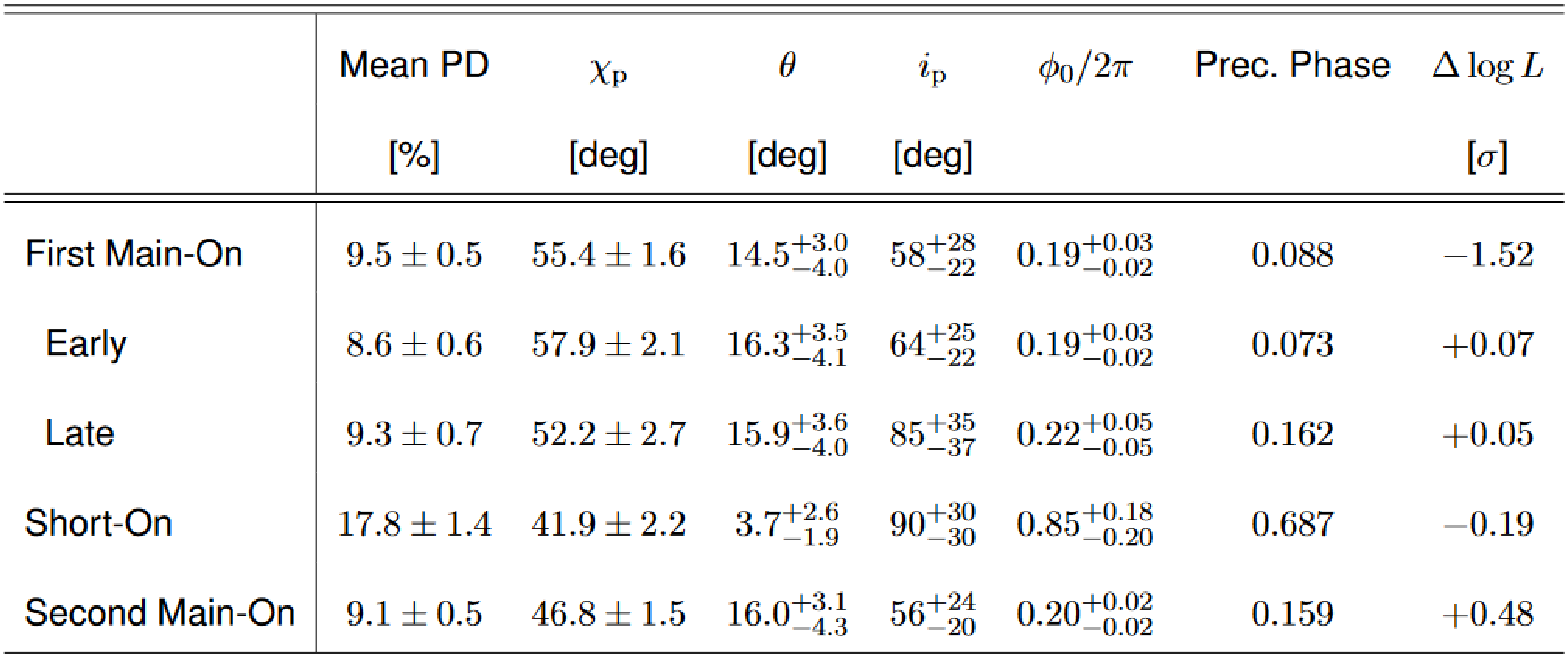
2311.03667



2311.03667

$\chi_{\rm p}$ positional angle of the spin axis
θ the angle between the spin and dipole axes

Two effects are observed:
θ is changing from Main-on to short on
$\chi_{\rm p}$ is changing between two Main-on phases



	Mean PD [%]	$\chi_{\rm p}$ [deg]	θ [deg]	$i_{\rm p}$ [deg]	$\phi_0/2\pi$	Prec. Phase	$\Delta \log L$ [σ]
First Main-On	9.5 ± 0.5	55.4 ± 1.6	$14.5^{+3.0}_{-4.0}$	58^{+28}_{-22}	$0.19^{+0.03}_{-0.02}$	0.088	-1.52
Early	8.6 ± 0.6	57.9 ± 2.1	$16.3^{+3.5}_{-4.1}$	64^{+25}_{-22}	$0.19^{+0.03}_{-0.02}$	0.073	$+0.07$
Late	9.3 ± 0.7	52.2 ± 2.7	$15.9^{+3.6}_{-4.0}$	85^{+35}_{-37}	$0.22^{+0.05}_{-0.05}$	0.162	$+0.05$
Short-On	17.8 ± 1.4	41.9 ± 2.2	$3.7^{+2.6}_{-1.9}$	90^{+30}_{-30}	$0.85^{+0.18}_{-0.20}$	0.687	-0.19
Second Main-On	9.1 ± 0.5	46.8 ± 1.5	$16.0^{+3.1}_{-4.3}$	56^{+24}_{-20}	$0.20^{+0.02}_{-0.02}$	0.159	$+0.48$

2311.03667

Conclusion

Many observed phenomena are related to internal dynamics of NSs.

- Glitches
- Precession

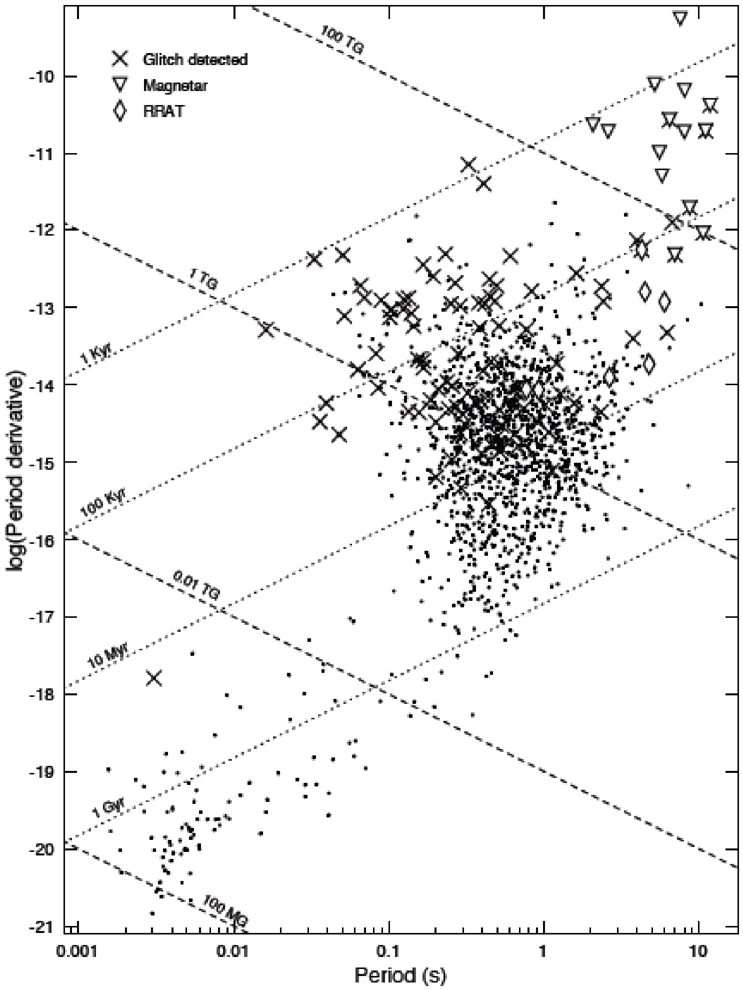
Glitches are related to the existence of some reservoir for angular momentum. Most probably, it is a layer of superfluid neutrons in the inner crust.

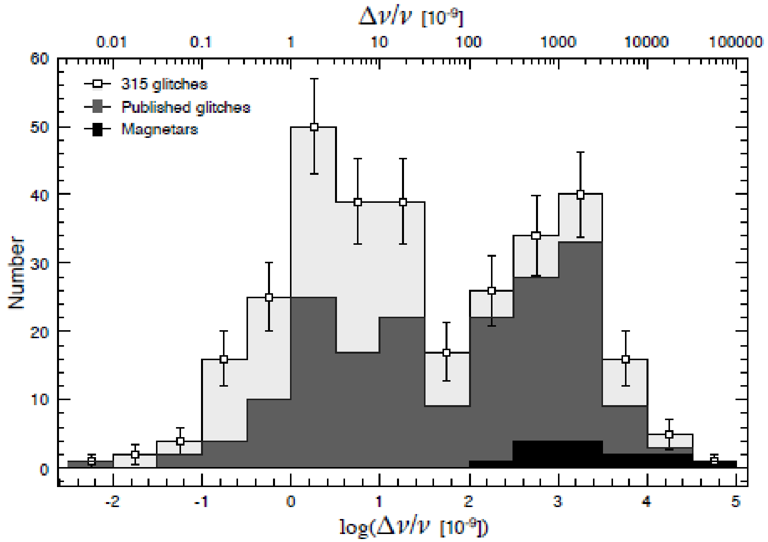
Some glitches of magnetars can be related to a different process.

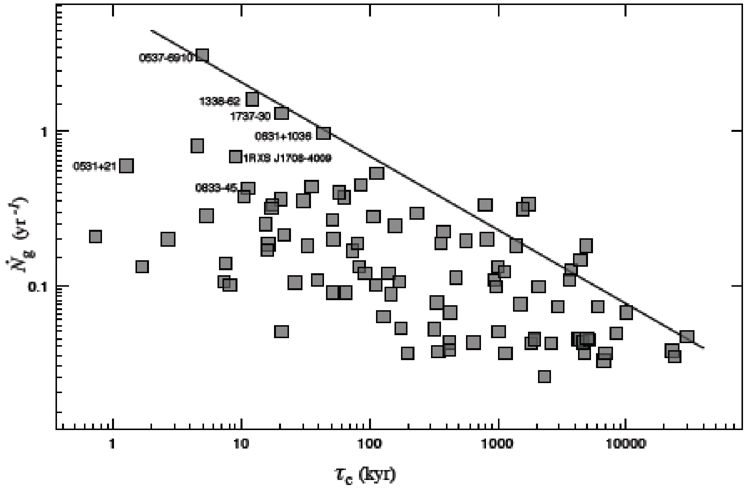
Main papers

- Link et al. astro-ph/0001245 Glitches
- Link astro-ph/0211182 Precession
- Jones, Andersson astro-ph/0011063 Precession
- Haskell, Sedrakian arXiv: 1709.10340 Big review on superfluidity
- Andersson arXiv: 2103.10218 Good brief review on superfluidity in NSs
- Zhou et al. arXiv: 2211.13885 A large review on glitches
- Antonelli et al. arXiv: 2301.12769 Review of the physics of glitches

Many-many glitches …



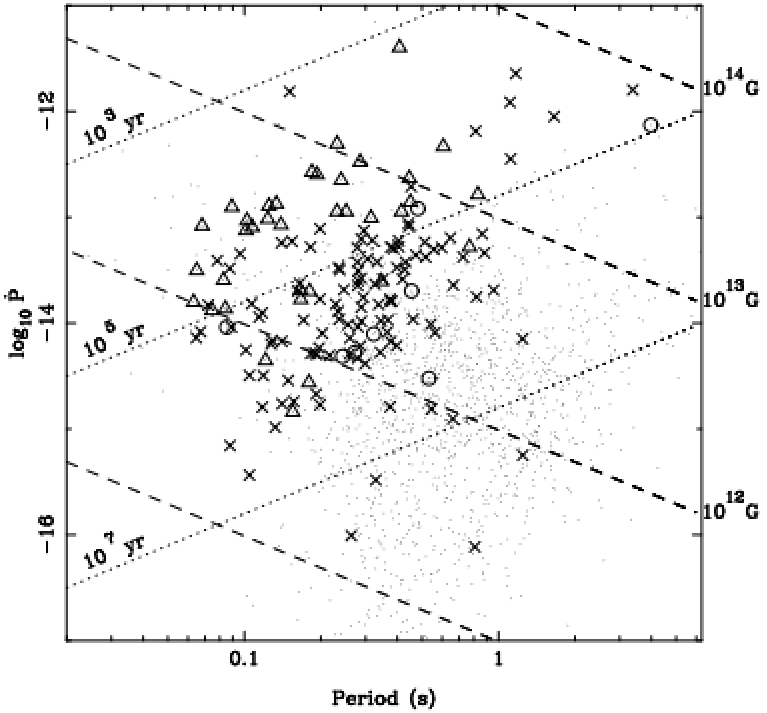


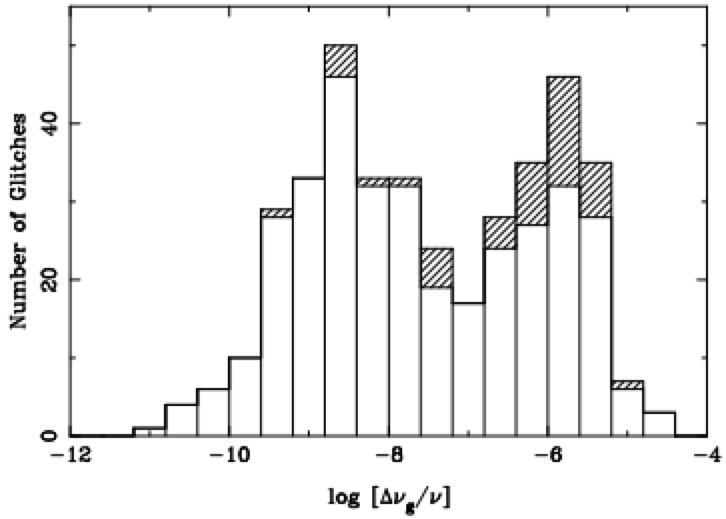


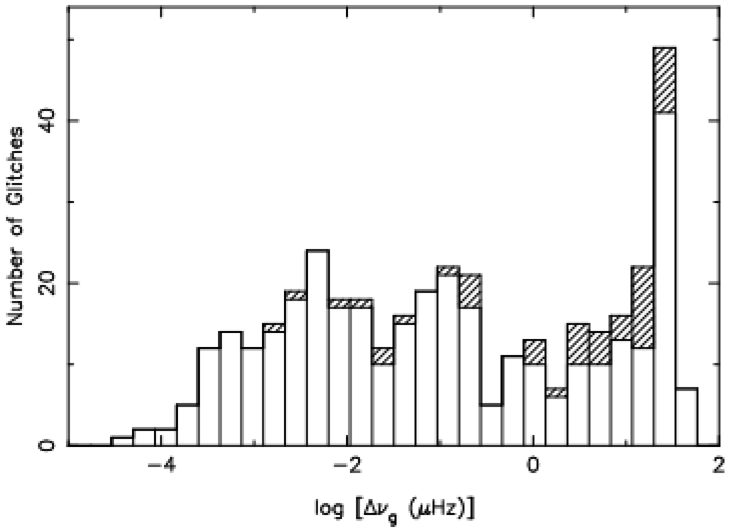
1102.1743

315 glitches in 102 PSRs

107 new glitches in 36 pulsars

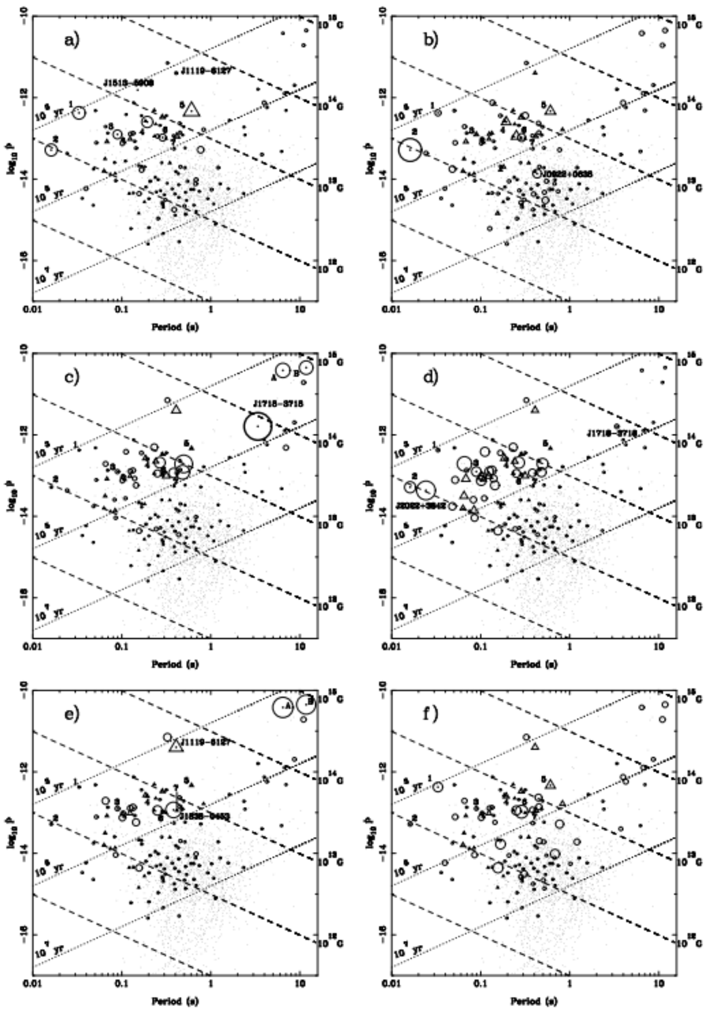






1211.2035

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

1801.01413