EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Mathematisch-Naturwissenschaftliche
Fakultät
Institute of Astronomy and Astrophysics

Discovery of the First Anti-Glitch in rotation-powered pulsar

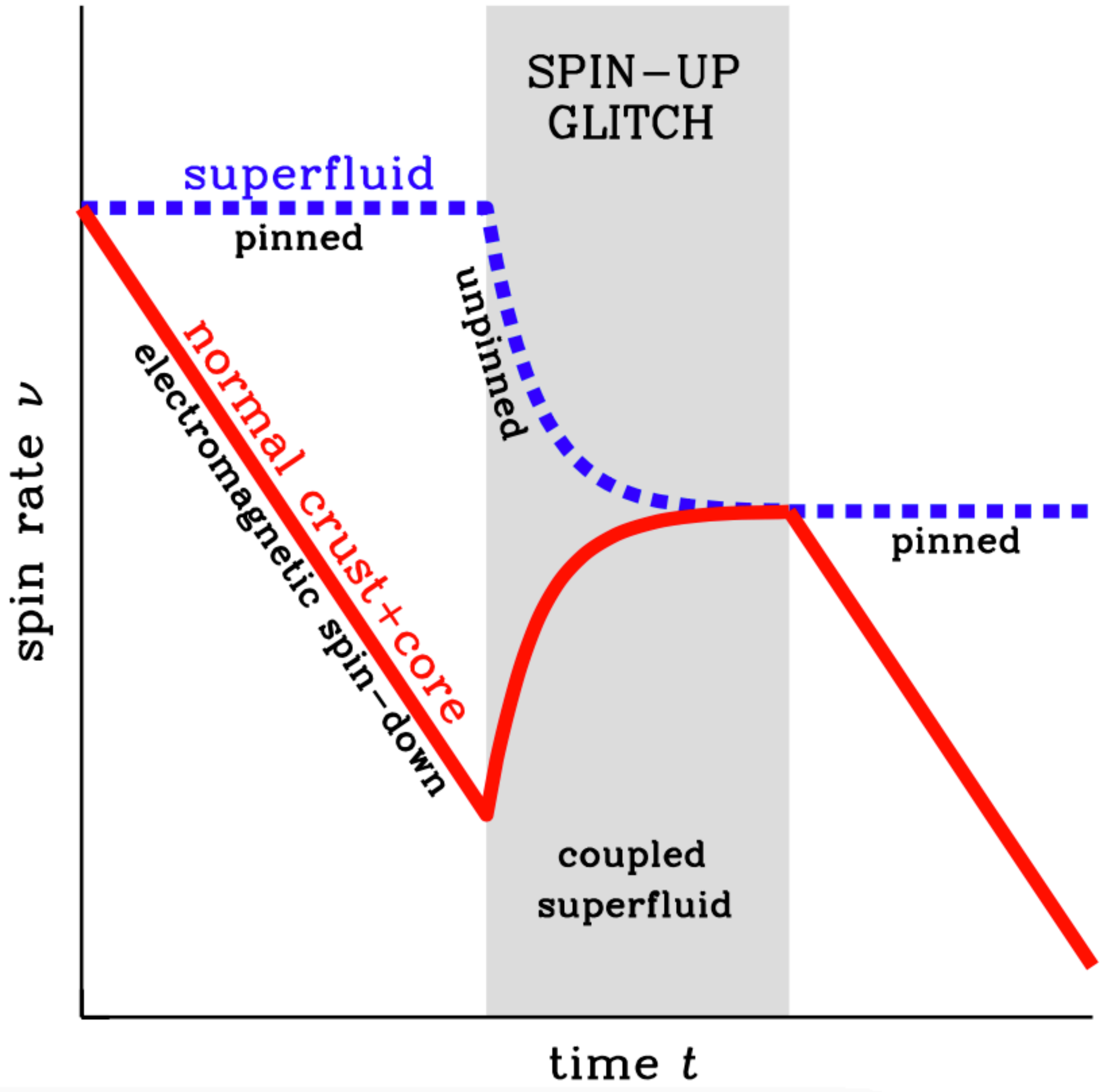
Youli Tuo *et al* 2024 *ApJL* 967 L13

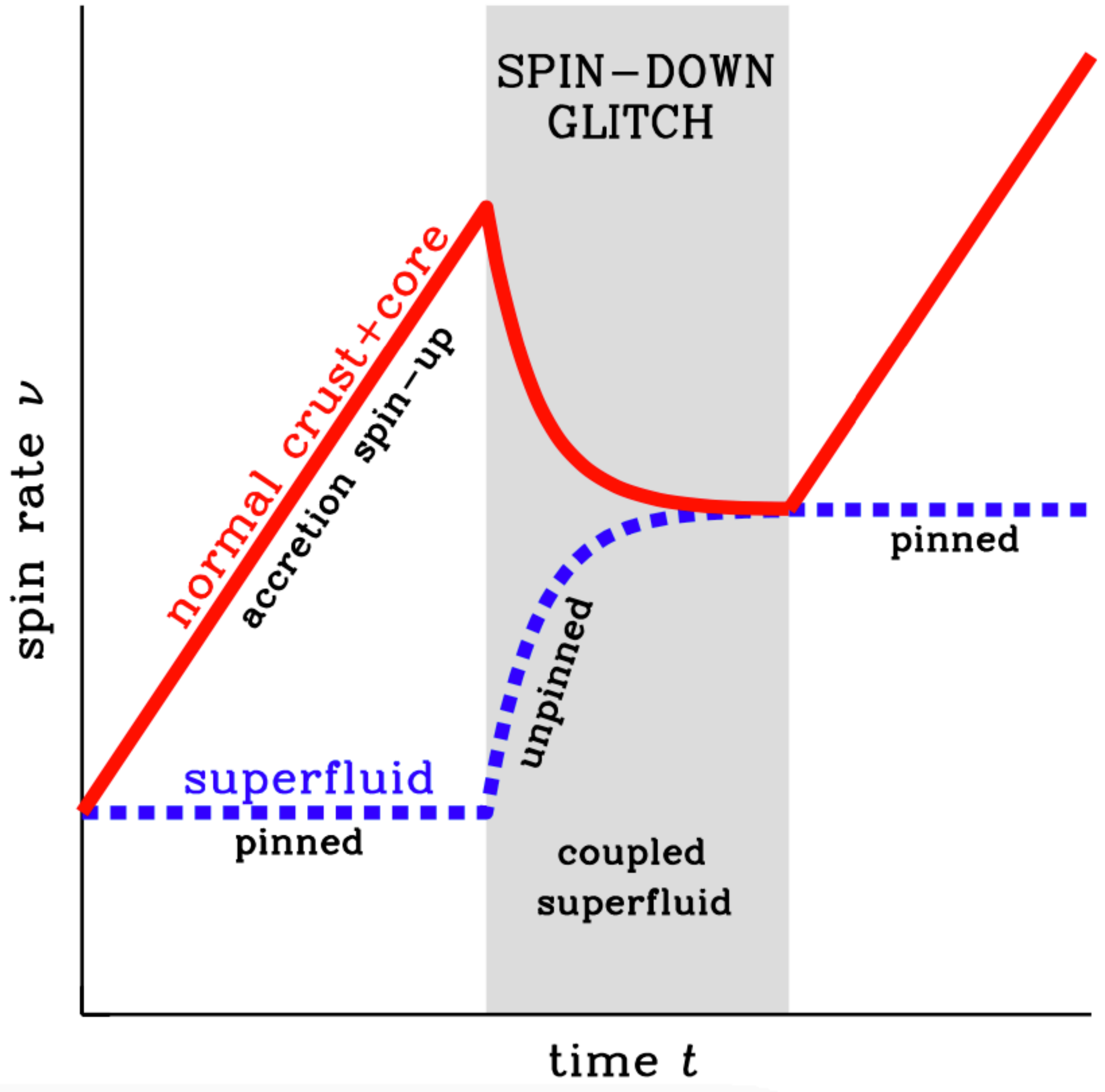
Speaker: **Dr. Youli Tuo 庹攸隶 (IAAT, Tuebingen University, *tuo@astro.uni-tuebingen.de*)**
Collaborators: **Dr. M. Mirac Serim (IAAT), Dr. Lorenzo Ducci (IAAT), Dr. Marco Antonelli (CNRS, France), Dr. Armin Vahdat (IAAT), Prof. Mingyu Ge 葛明玉 (IHEP), Prof. Andrea Santangelo (IAAT), Prof. Fei Xie 谢斐 (GXU)**

Glitch and Anti-glitch phenomena

- Crust: electromagnetic braking
- lag between crust and superfluid
- pin --> unpin: glitch

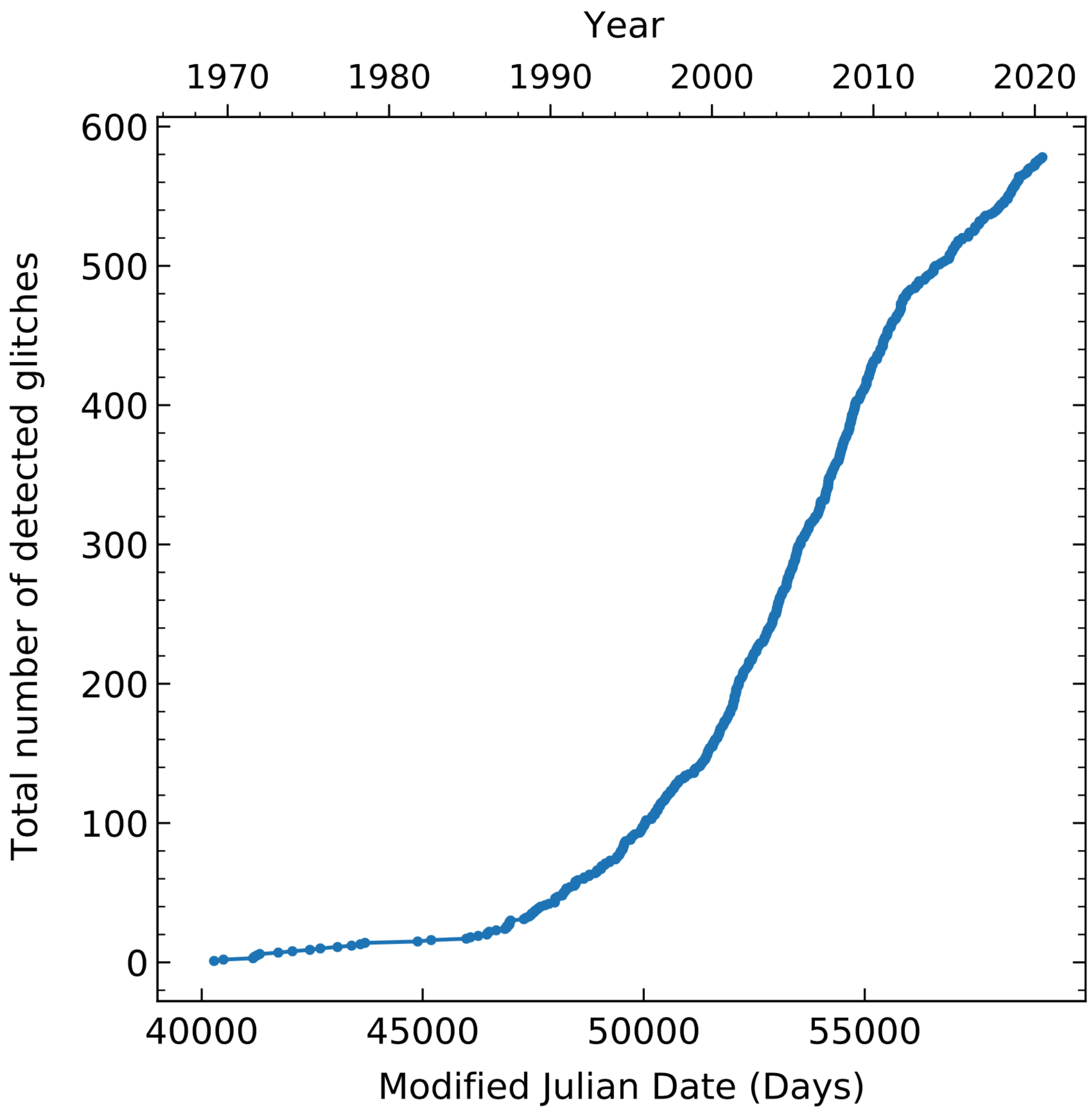
[credit: Ray et al., 2019]





Glitch observations

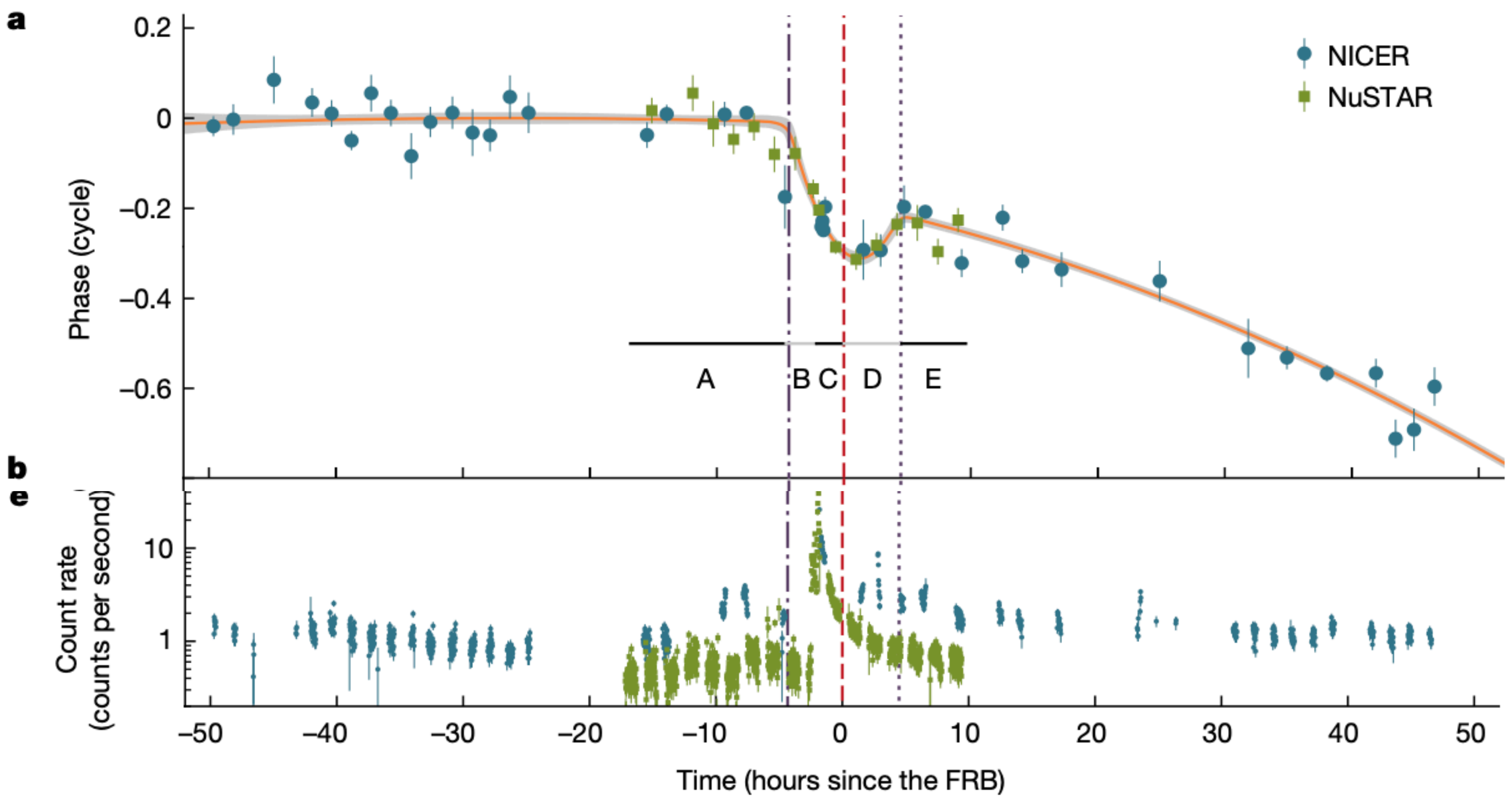
- **over 500 glitches observed in radio pulsar**
  - radio glitches
  - JBO (Espinoza et al., 2011)
  - Parkes Observatory (Yu et al., 2013)
- **ALL of them are glitch**
  - spin-up after the glitch
- **Anti-glitch**
  - 7 anti-glitches
  - Only 2 magnetars + 2 accreting pulsar
- **magnetar, rotating NS with high magnetic field**
  - more burst activities
  - prolate shape --> spherical shape



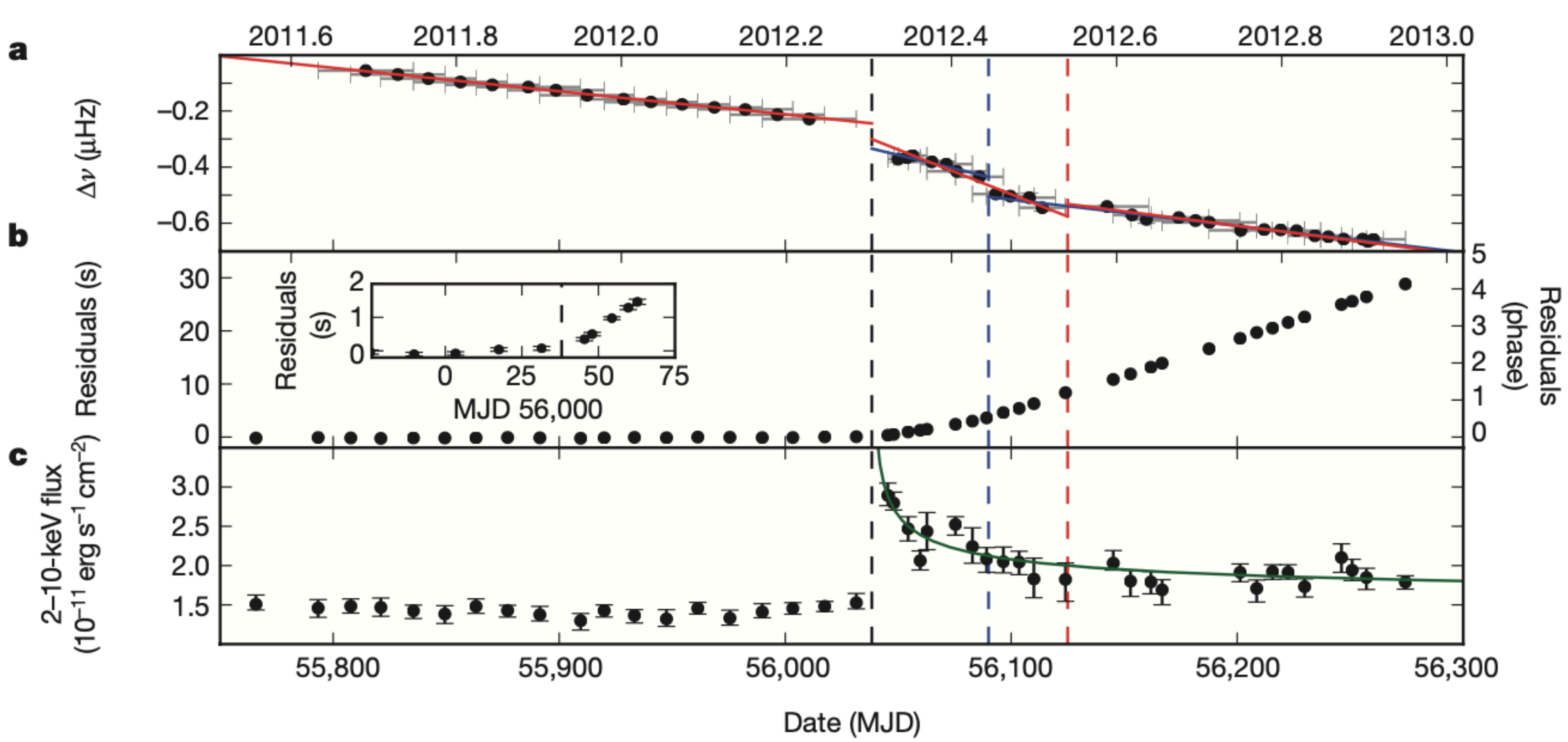
Glitch observations

- **Magnetar + glitch**
  - 1E 2259+586 spin-up glitch (Younes et al., 2020)
  - SGR 1935 giant glitch before FRB (Ge et al., 2022)
  - SGR 1935 glitch associate with FRB (Hu et al., 2024 Nature, 626, 500)
- **Magnetar + anti-glitch**
  - 1E 2259+586 first discovered anti-glitch (Archibald et al., 2013, Nature, 497, 591)
  - SGR 1935+2154 spin-down glitch associated with FRB (Younes et al., 2022, NatAst, 7, 339)
- **RPP + Spin-up glitch**
  - most of the ordinary pulsar endure such glitch (Yu et al., 2013, MNRAS, 429, 688)

SGR 1935 credit: Archibald et al., 2013]

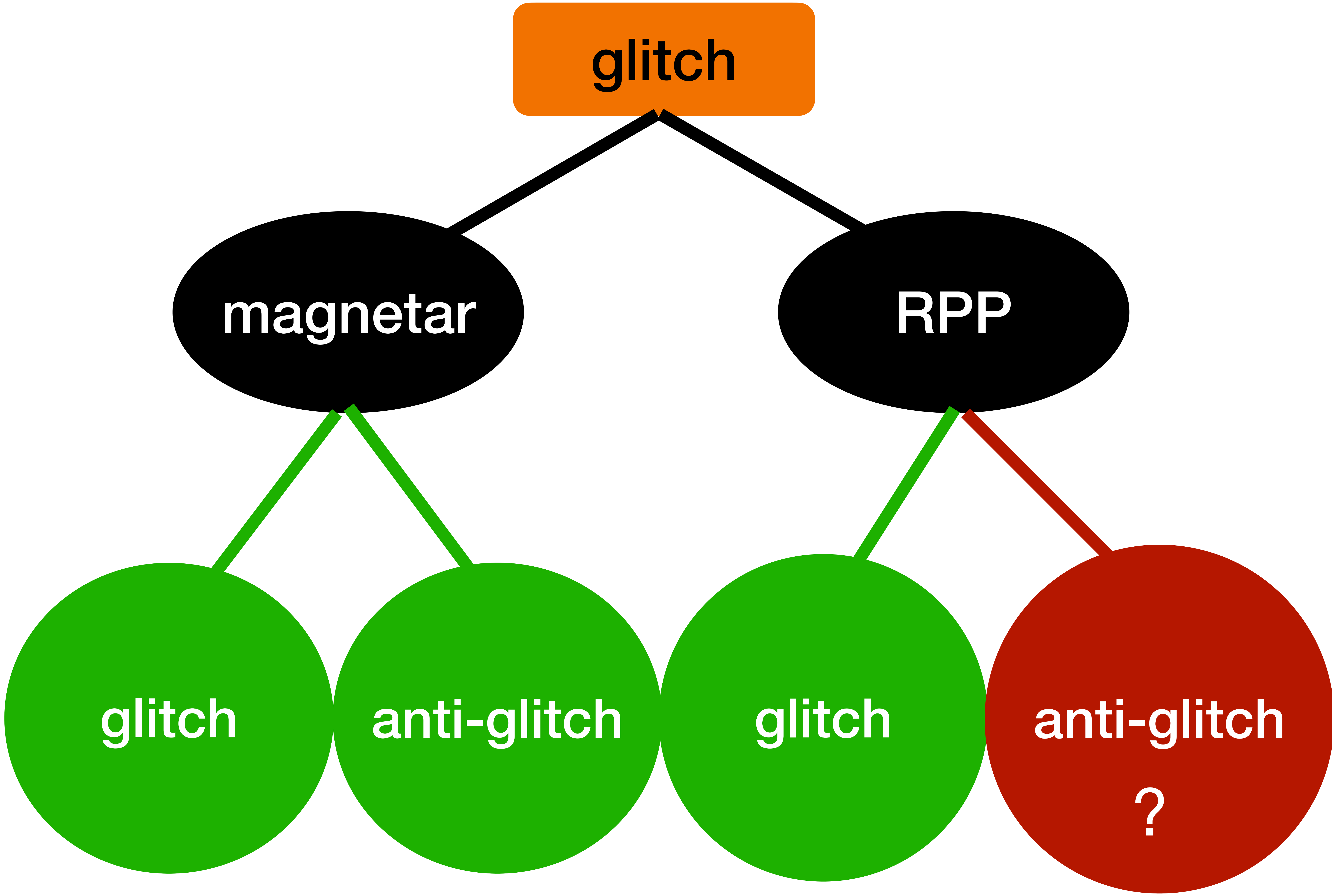


1E 2259+586 [credit: Archibald et al., 2013]



Glitch observations

- **Magnetar + glitch**
  - 1E 2259+586 spin-up glitch (Younes et al., 2020)
  - SGR 1935 giant glitch before FRB (Ge et al., 2022)
  - SGR 1935 glitch associate with FRB (Hu et al., 2024 Nature, 626, 500)
- **Magnetar + anti-glitch**
  - 1E 2259+586 first discovered anti-glitch (Archibald et al., 2013, Nature, 497, 591)
  - SGR 1935+2154 spin-down glitch associated with FRB (Younes et al., 2022, NatAst, 7, 339)
- **RPP + Spin-up glitch**
  - most of the ordinary pulsar endure such glitch (Yu et al., 2013, MNRAS, 429, 688)

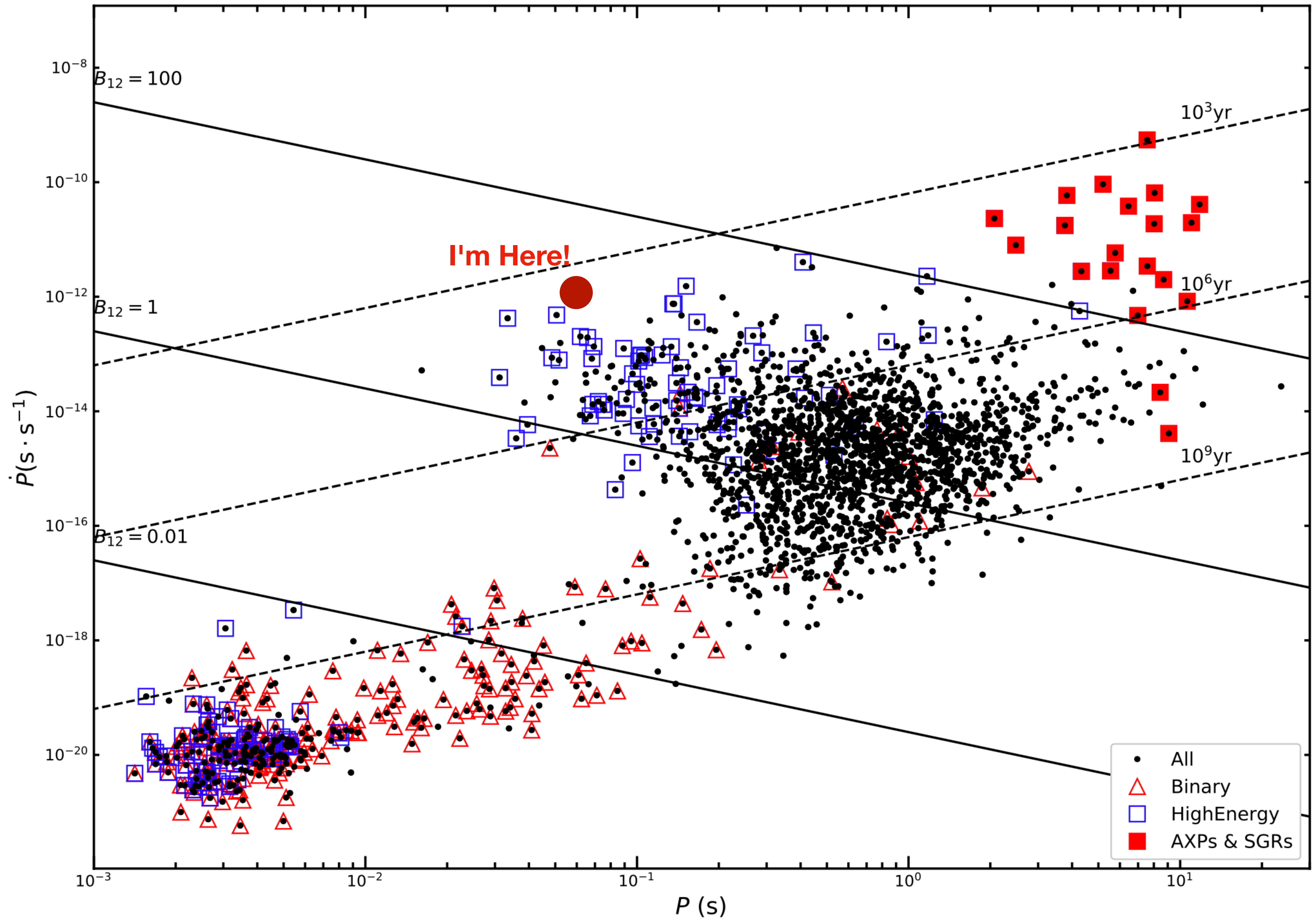


PSR B0540-69 properties

- **Discovery:** early 1980s through the Einstein X-ray Observatory.
- **Location:** supernova remnant SNR 0540–693 (1140 yr-old), within the Large Magellanic Cloud
- age: ~1100 yr-old;
- **magnetic field**: ~B12-B13

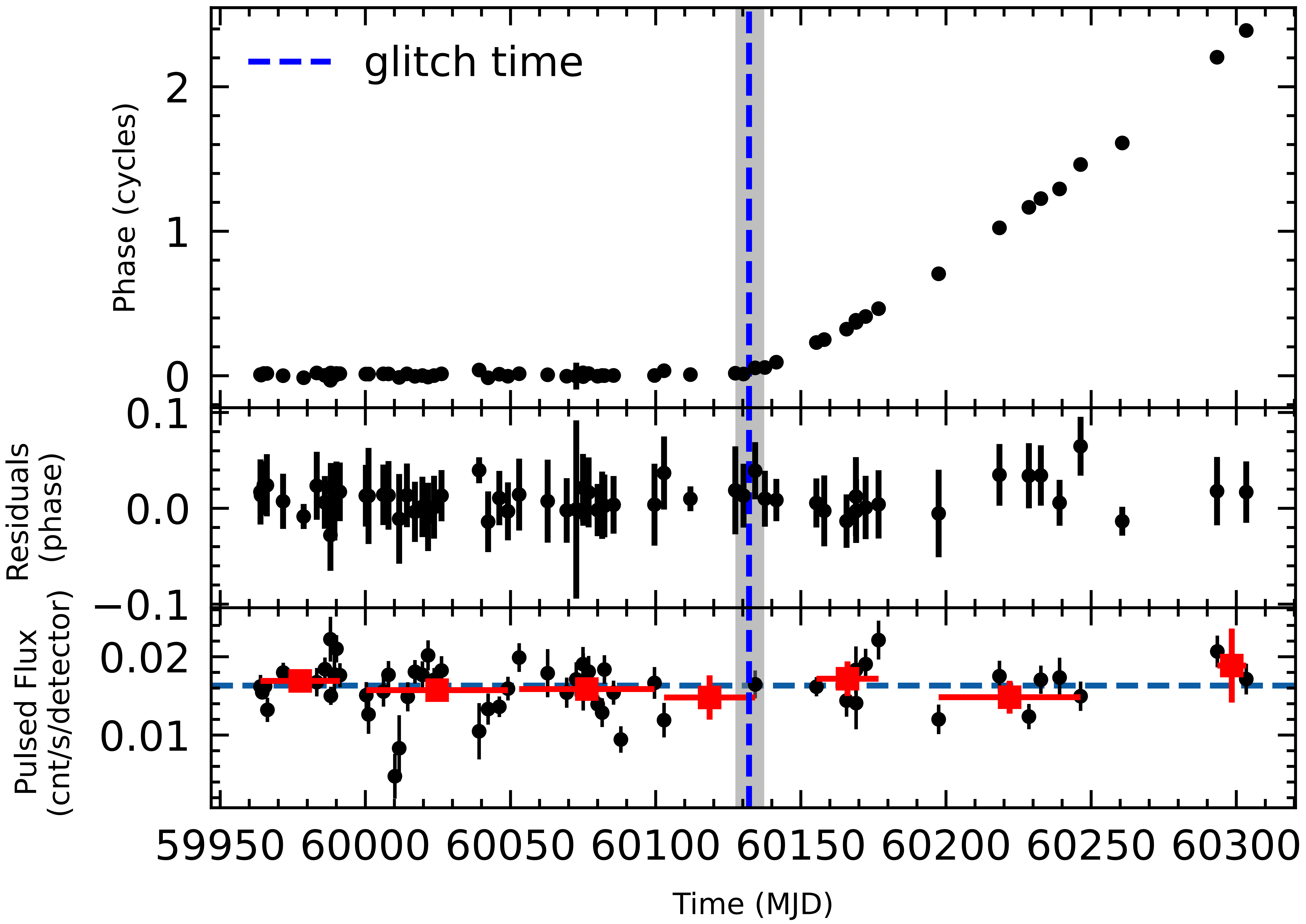
- **Timing properties**
  - Spin Period: ~50 milliseconds
  - Large Spin-down rate :

$$\dot{\nu} \approx -2.52 \times 10^{-10}\,\mathrm{Hz} \cdot \mathrm{s}^{-1}$$



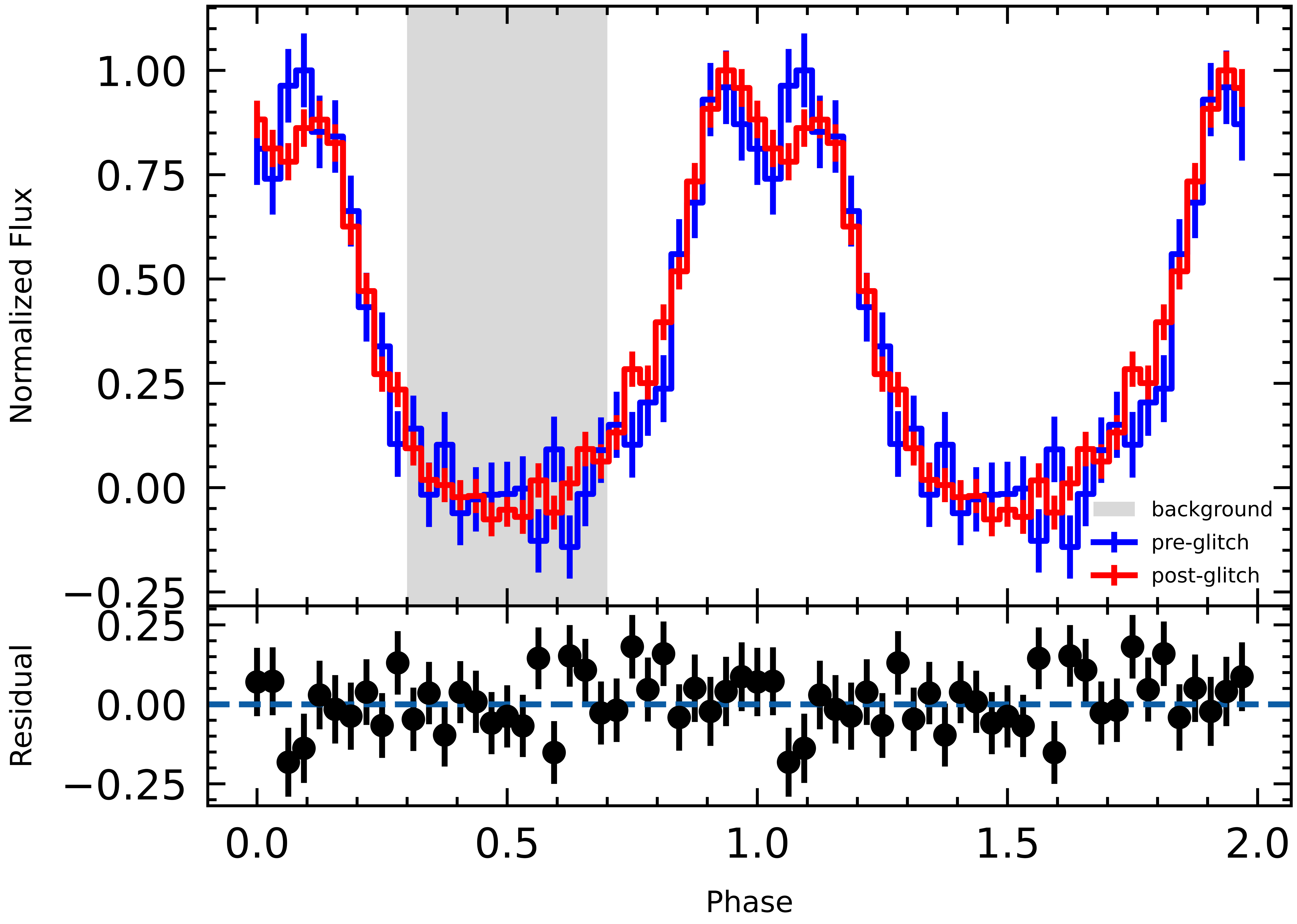
Results: glitch properties

- **phase evolution of pre-glitch timing solution**
- **glitch model fitting residuals**
  - $\phi_g = \Delta\nu(t - t_g) + \frac{1}{2}\Delta\dot{\nu}(t - t_g)^2 + [1 - e^{-(t-t_g)/\tau d}] \cdot \Delta\nu_d\tau_d$
  - $\Delta\nu = (-1.04 \pm 0.07) \times 10^{-7}\,\mathrm{Hz}$
  - $\Delta\dot{\nu} = (-7.4 \pm 6.2) \times 10^{-15}\,\mathrm{Hz} \cdot \mathrm{s}^{-1}$
  - $|\Delta\nu/\nu| = 5.28 \times 10^{-9}$: micro-glitch
  - **NO** exponential term observed
- **pulsed flux remain constant**
- **no associated triggered burst**
  - NICER
  - GBM
- **No pulse profile variation**



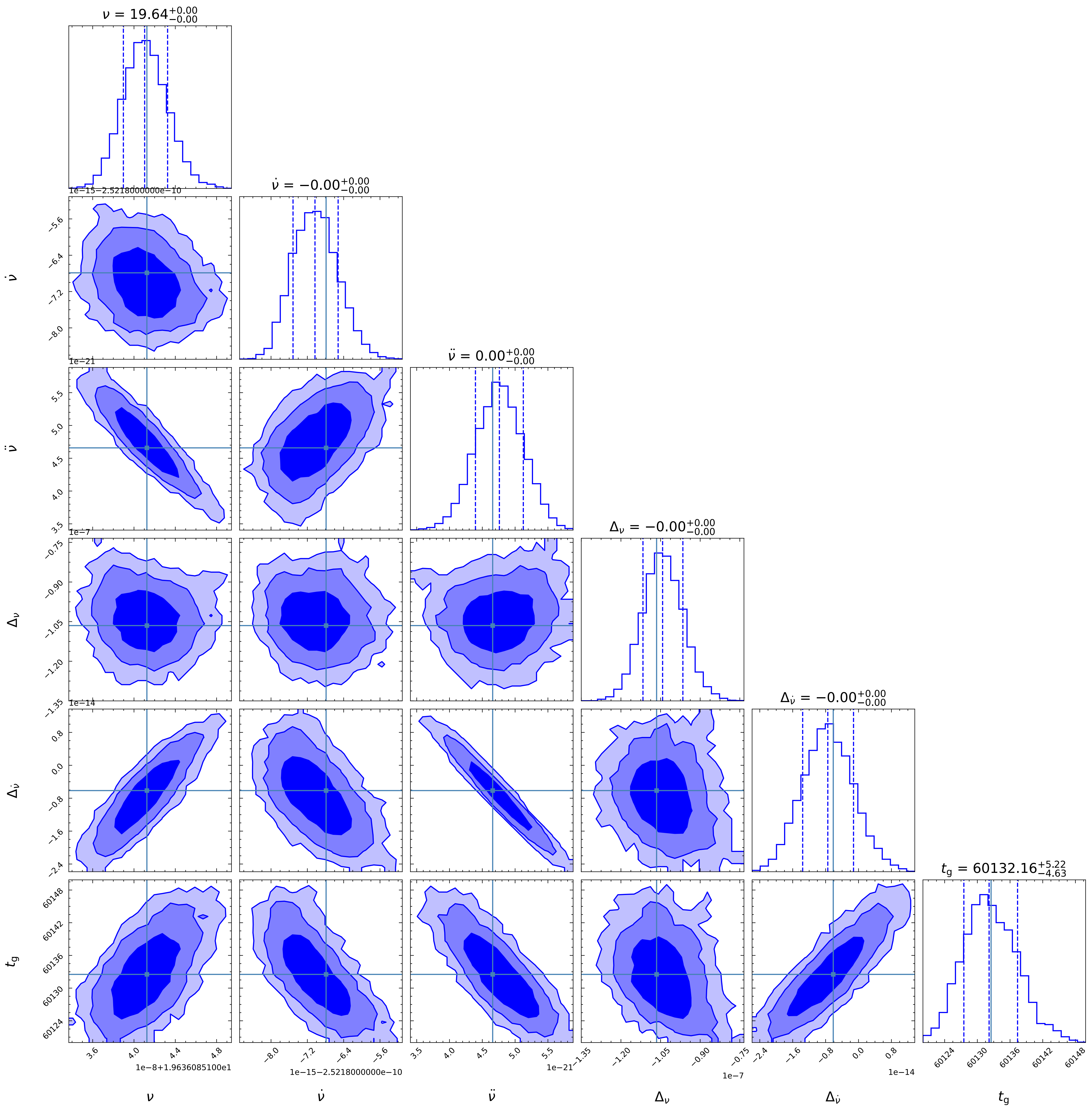
Results: glitch properties

- **phase evolution of pre-glitch timing solution**
- **glitch model fitting residuals**
  - $\phi_g = \Delta\nu(t - t_g) + \frac{1}{2}\Delta\dot{\nu}(t - t_g)^2 + [1 - e^{-(t-t_g)/\tau d}] \cdot \Delta\nu_d \tau_d$
  - $\Delta\nu = (-1.04 \pm 0.07) \times 10^{-7}\,\mathrm{Hz}$
  - $\Delta\dot{\nu} = (-7.4 \pm 6.2) \times 10^{-15}\,\mathrm{Hz \cdot s^{-1}}$
  - $|\Delta\nu/\nu| = 5.28 \times 10^{-9}$: micro-glitch
  - **NO** exponential term observed
- **pulsed flux remain constant**
- **no associated triggered burst**
  - NICER
  - GBM
- **No pulse profile variation**



Results: glitch properties

Parameters	Values
R.A. (J2000)	$05^{\mathrm{h}}40^{\mathrm{m}}10.84^{\mathrm{s}}$
Decl. (J2000)	$-69°19'54.2''$
ν (Hz)	19.636085141(2)
$\dot{\nu}$ ($\times10^{-10}$ Hz · s^{-1})	−2.521868(3)
$\ddot{\nu}$ ($\times10^{-21}$ Hz · s^{-2})	4.6(1)
Epoch (MJD)	60041.21699
Valid Range (MJD)	59901–60318
Ephemeris	JPL-DE430
$\Delta\nu$ ($\times10^{-7}$ Hz)	$-1.042^{+0.076}_{-0.074}$
$\Delta\dot{\nu}$ ($\times10^{-15}$ Hz · s^{-1})	$-7.4^{+6.2}_{-6.1}$
t_g (MJD)	$60132.158^{+5.224}_{-4.633}$
$\Delta\nu/\nu$ ($\times10^{-9}$)	$5.306^{+0.038}_{-0.037}$
r.m.s residual (µs)	829.8



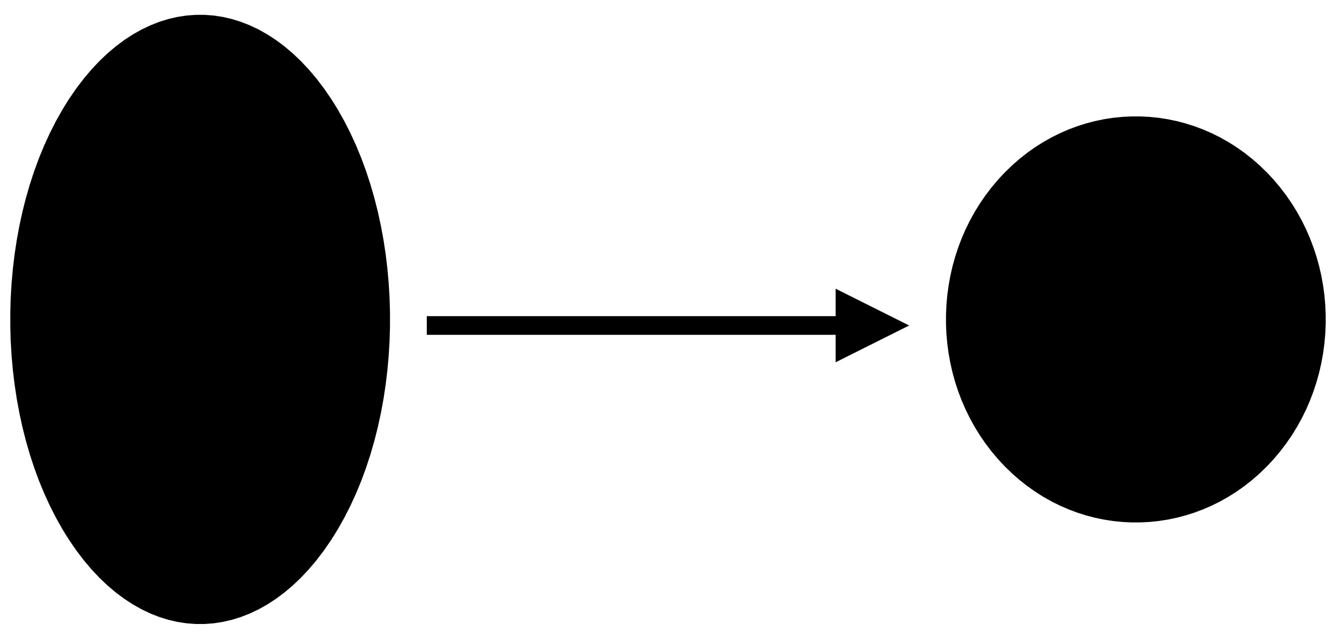
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Possible Anti-glitch Interpretation

- **External processes or Internal processes?**
- **External processes**
  - Change in internal magnetization [Mastrano et al. 2015] → **Strong B**
    - decay of its internal toroidal magnetic field: prolate --> spherical
  - Outflow along the open field lines [Thompson 2000; Granot 2006]
  - Wind braking model for magnetar [Tong 2016]
  - Meteoroid hit [Huang and Geng 2014]

  } **Radiatively Loud**
- **Internal process**
  - **trapped ejecta model [Yim et al., 2024]**
  - **Crust-superfluid exchange under certain conditions [Kantor 2014]**

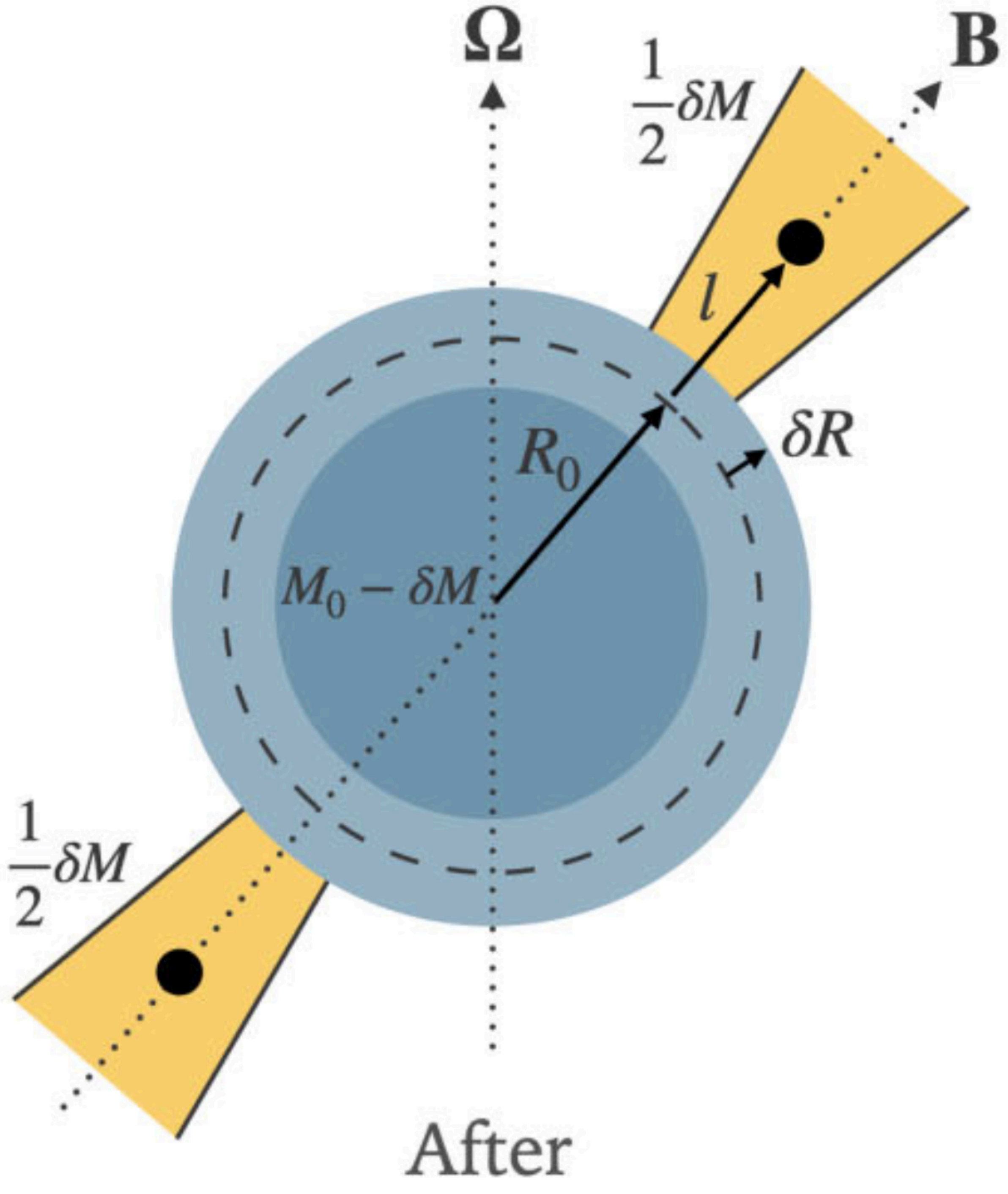
magnetar configuration

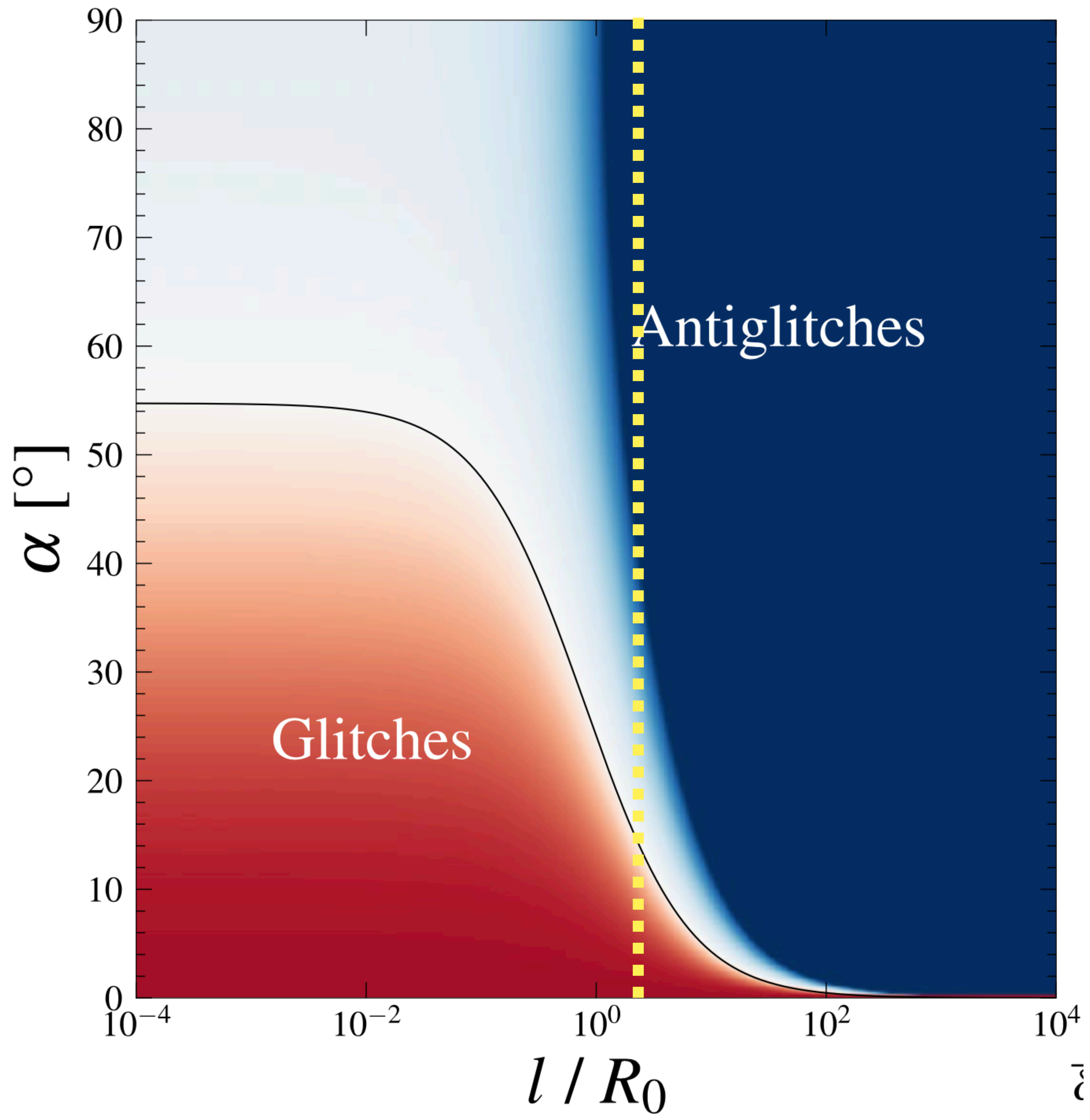


Trapped ejecta Model

- ejecta M_0 emitted from magnetic pole
- trapped within co-rotation radius R_{co}
- moment of inertia decrease

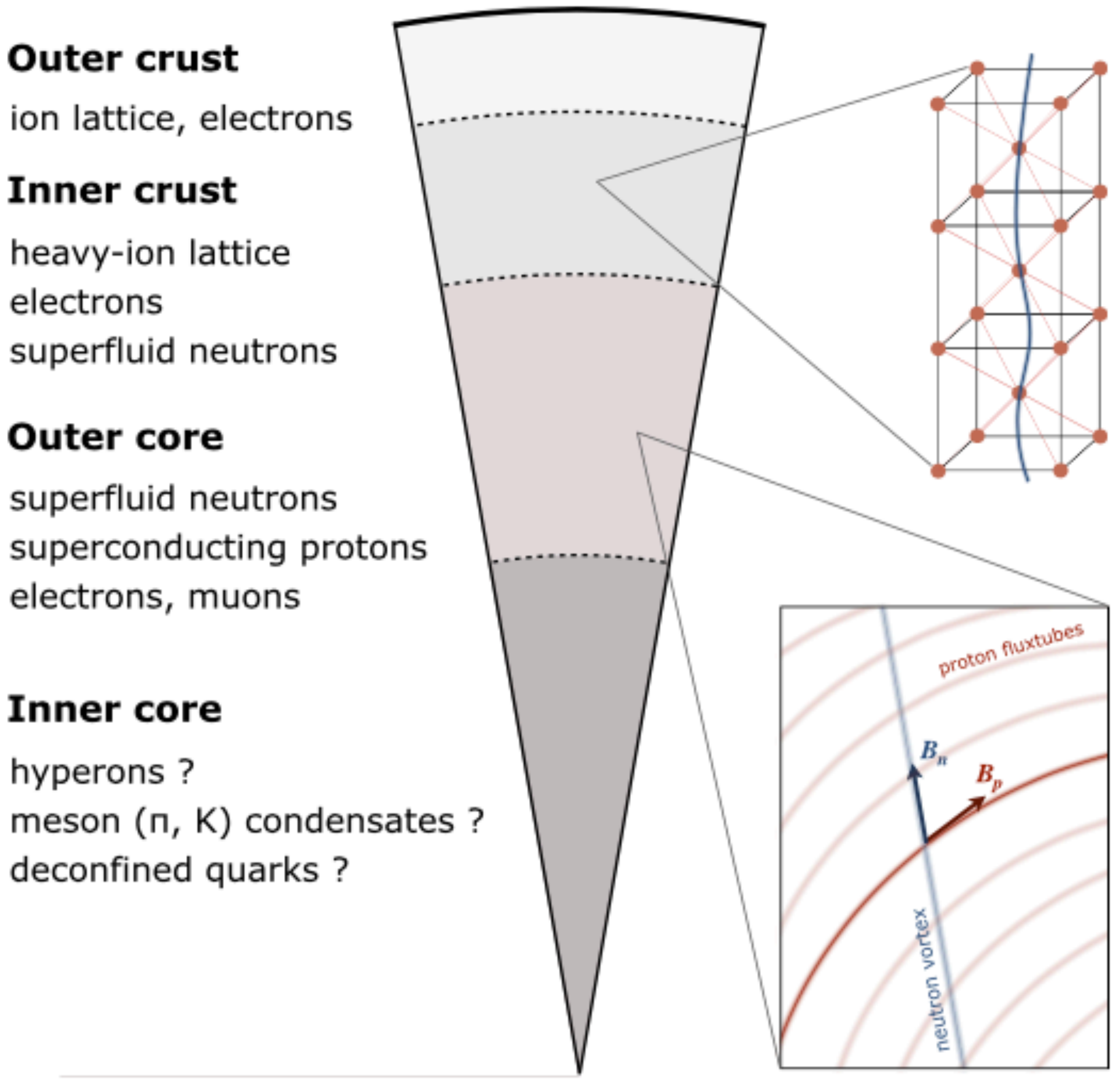
- PSR B0540-69:
  - $R_{co} = 23R_0$
  - magnetic inclination angle α?
- Possible
  - requires large α
  - expels to large height
- Problem
  - free precession of NS
  - polarization/timing/pulse profile modulation/GW





Crust-superfluid exchange

- **Angular momentum exchanges** + **Mass exchanges**
- **Angular momentum conservation**
  - $I_{c0}\Omega_{c0} + I_{s0}\Omega_{s0} = I_{c1}\Omega_{c1} + I_{s1}\Omega_{s1}$ (0: pre-glitch, 1: post-glitch, s: superfluidity, c: crust)
- **Taylor expansion**
  - $I_{c0}\Omega_{c0} + I_{s0}\Omega_{s0} = [I_{c0} + \dot{I}_c(\delta\Omega_s - \delta\Omega_c)](\Omega_{c0} + \delta\Omega_c) + [I_{s0} + \dot{I}_s(\delta\Omega_s - \delta\Omega_c)](\Omega_{s0} + \delta\Omega_s)$
  - where $\dot{I}_c = -\dot{I}_s = dI_c/d(\Delta\Omega)$ (over rotation lag $\Delta\Omega$)
- **yields the variation of crust angular velocity**
  - $\delta\Omega_c = -\dfrac{I_{s0} - \dot{I}_c\Delta\Omega_0}{I_{c0} + \dot{I}_c\Delta\Omega_0}\delta\Omega_s$
    - $\delta\Omega_c > 0$: 'normal' glitch
    - $\delta\Omega_c < 0$: anti-glitch = $|\dot{I}_s|\Delta\Omega_0 > I_{s0}$

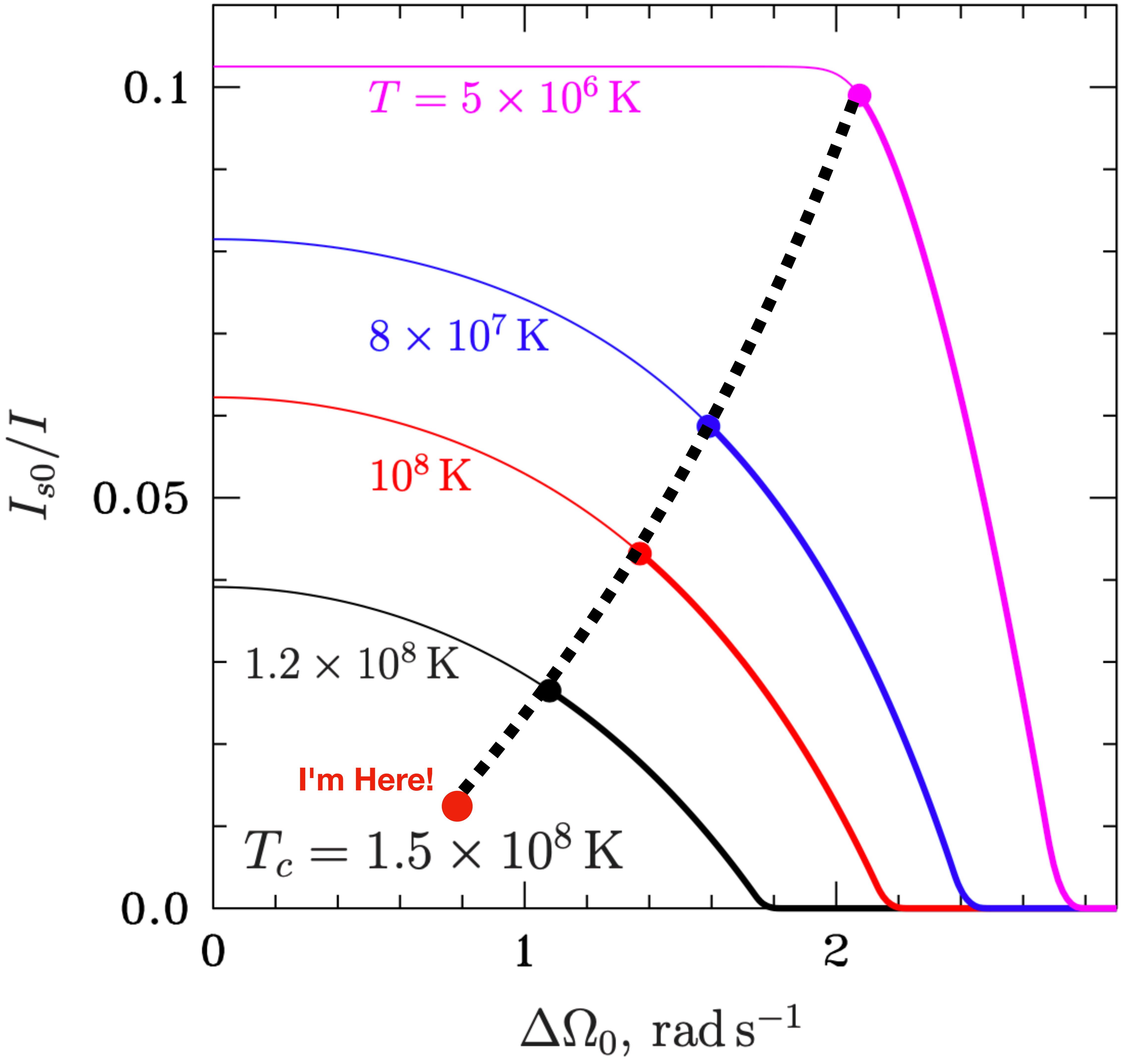


Physical Conditions

- **Spin-down glitch requires 2 condition**
  - high temperature
    - young pulsar, hot surface -> T_{core} ~$10^8 - 10^9$K
  - large lag between superfluid and crust
    - spin-down rate transition event
    - lag established since the previous glitch
      - $\Delta\Omega_0 \sim 0.88\,\mathrm{rad\,s^{-1}}$

- **This model is plausible**
  - rarity of anti-glitch
  - imply the high core temperature of NS

[credit: Kantor et al., 2014]

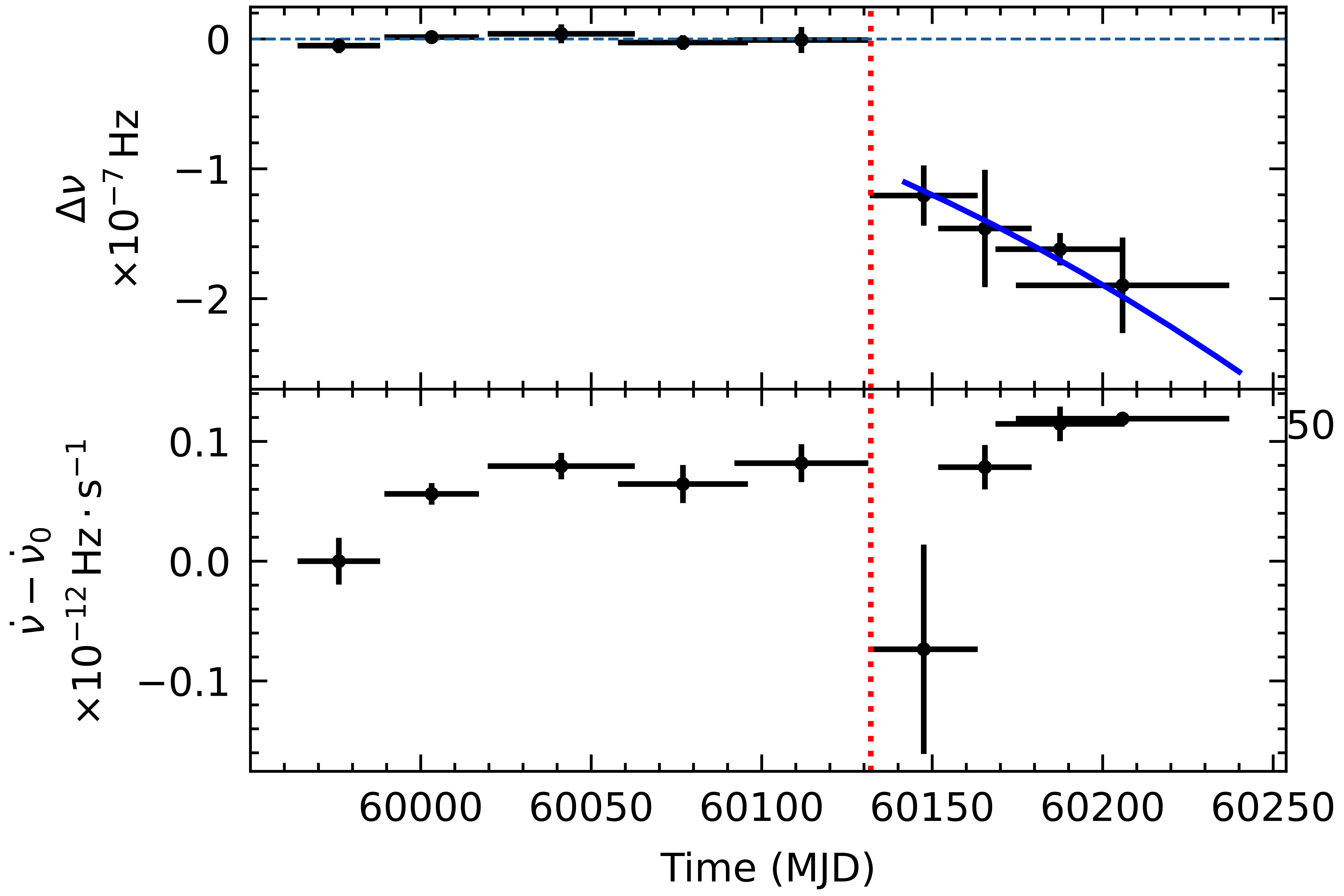


Takeaways

- The **first** anti-glitch discovered in **ordinary (rotation-powered) pulsar**
- Radiatively **quiet** nature of such anti-glitch
- Internal process of Neutron Star
  - angular momentum exchanges
  - **mass redistribution** between the crust and core

Results: glitch properties

- phase evolution of pre-glitch timing solution
- glitch model fitting residuals
  - $\phi_g = \Delta\nu(t - t_g) + \frac{1}{2}\Delta\dot{\nu}(t - t_g)^2 + [1 - e^{-(t-t_g)/\tau_d}] \cdot \Delta\nu_d \tau_d$
  - $\Delta\nu = (-1.04 \pm 0.07) \times 10^{-7}$ Hz
  - $\Delta\dot{\nu} = (-7.4 \pm 6.2) \times 10^{-15}$ Hz $\cdot$ s^{-1}
  - $|\Delta\nu/\nu| = 5.28 \times 10^{-9}$: micro-glitch
  - **NO** exponential term observed
- pulsed flux remain constant
- no associated triggered burst
  - NICER
  - GBM
- No pulse profile variation

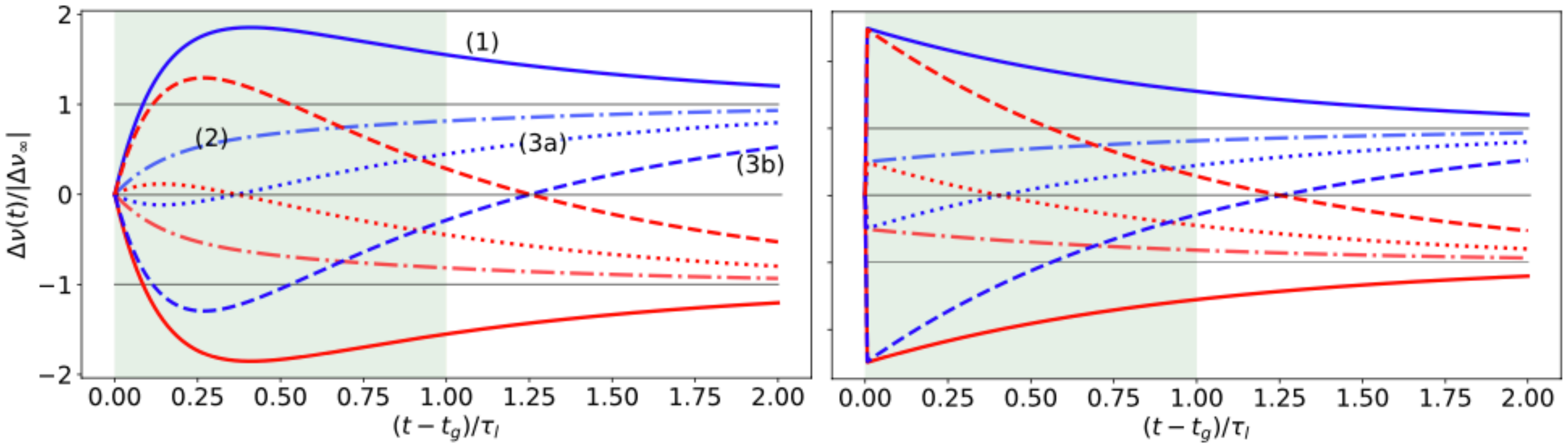


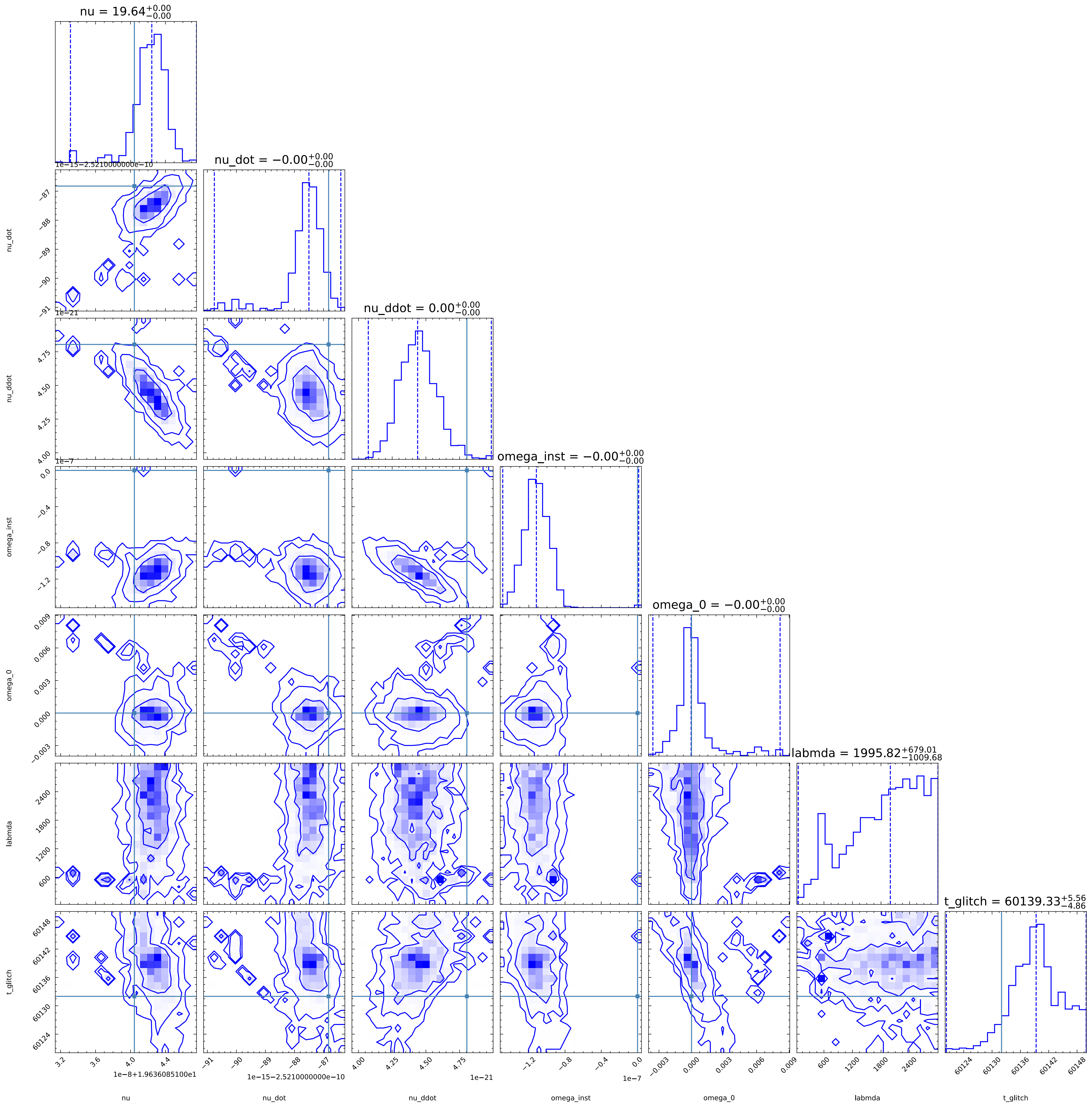
backup: Phenomenological model

- Phenomenological model (Antonelli et al., 2020)

$$\Delta\Phi(t) = \theta(t)\left[\Delta\nu\,\delta t + \Delta\nu_d\,\tau\left(1 - e^{-\delta t/\tau}\right) + \frac{\Delta\dot{\nu}}{2}\delta t^2\right]$$

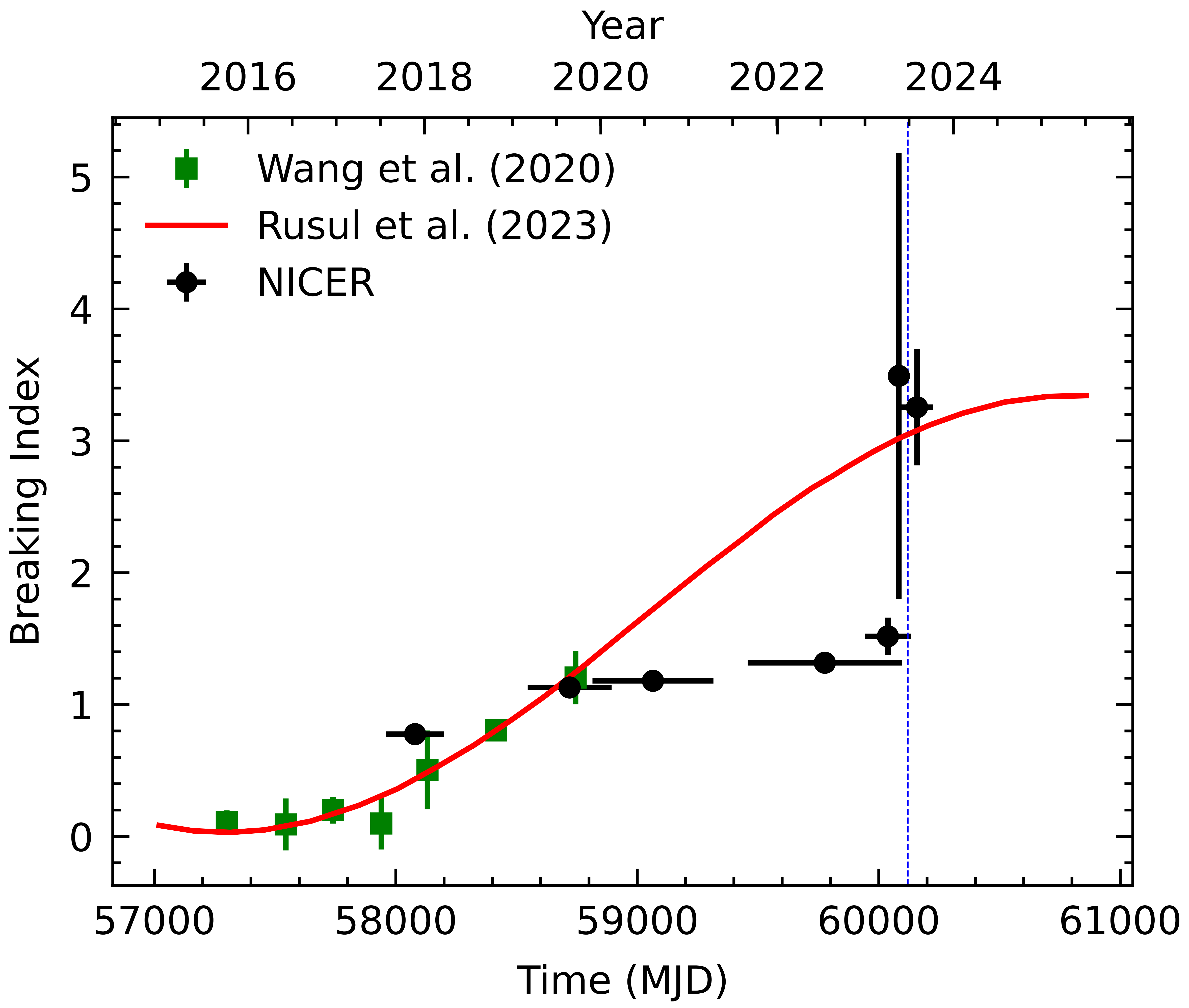
-
- consistent with the previous glitch model
- recovery/overshooting term is marginal

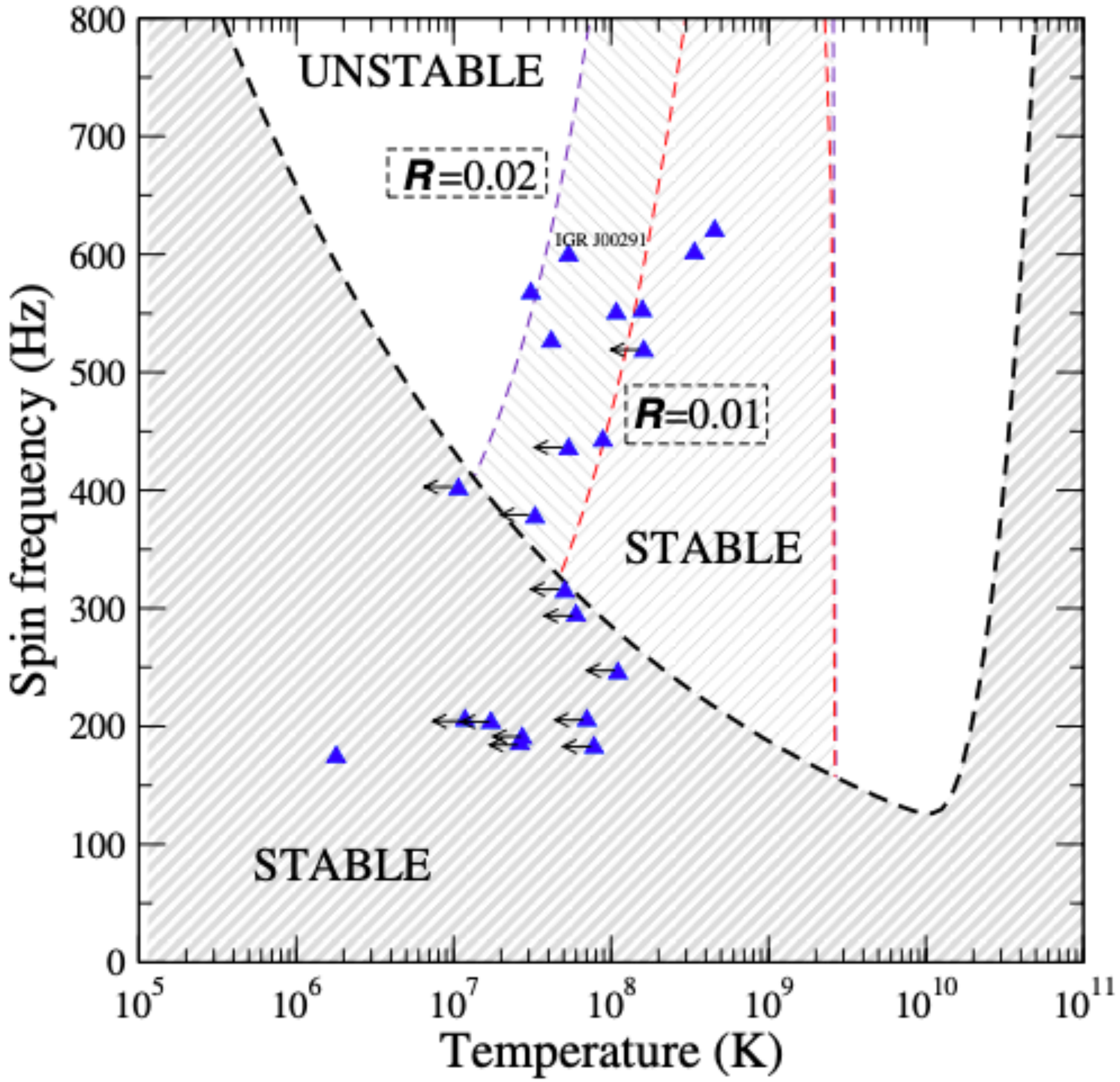




backup: r-mode oscillation

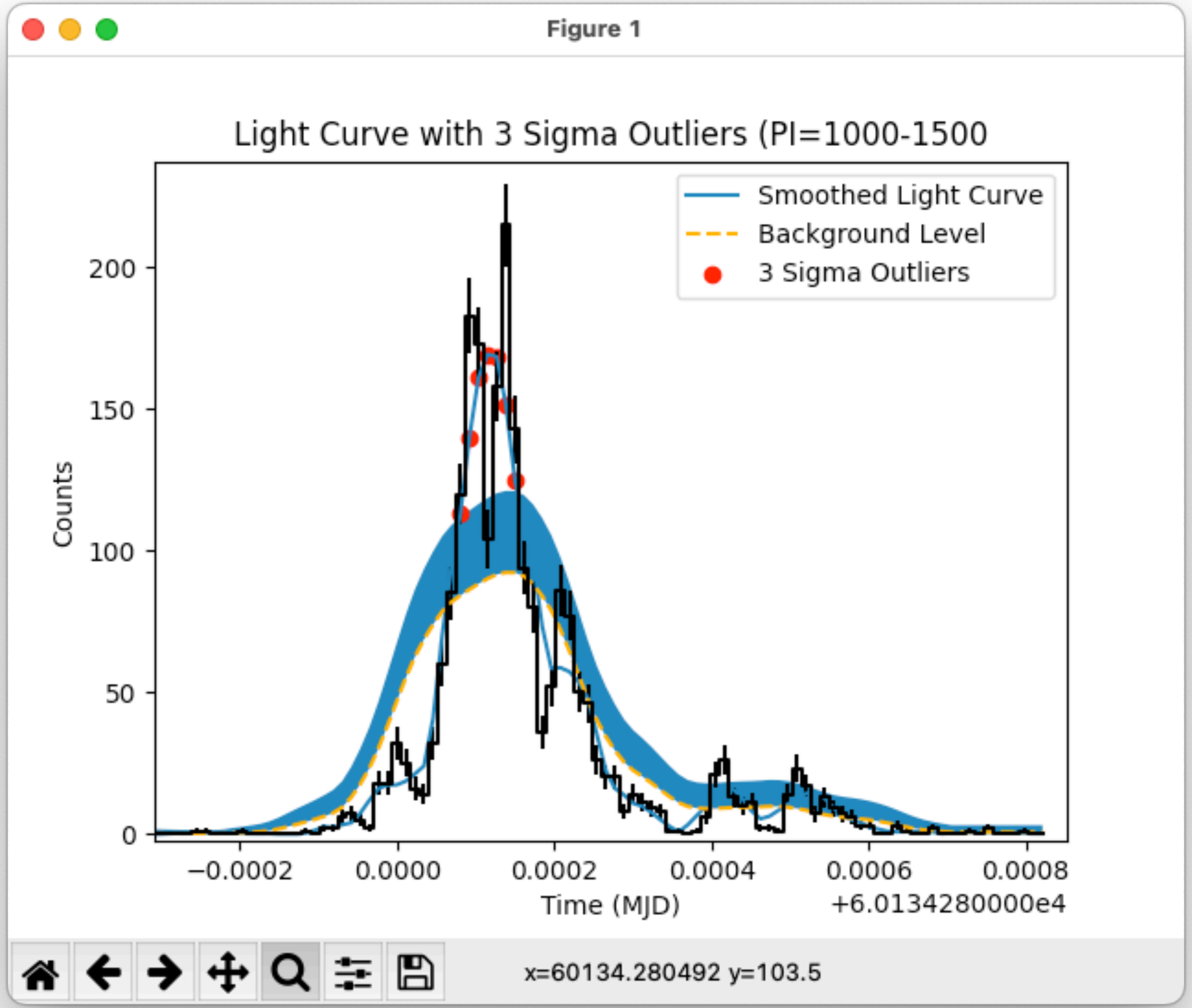
- PSR B0540-69 locates in a STABLE region
- braking index $\neq 7$ (expected for r-modes)





backup: Possible burst

- **NICER burst-like background**



backup: How marginal is exponential term?