The apparent decay of pulsar magnetic fields

A. Biryukov[1,2], A. Astashenok[3], G. Beskin[4,2] S. Karpov[4,2]

[1] SAI MSU, [2] Kazan Feredal Univ., [3] Baltic Federal Univ., [4] SAO RAS

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Outline

1 Estimating pulsar magnetic fields (*B)*

2 Estimating pulsar ages (*t)*

3 Analyzing the apparent *B(t)*

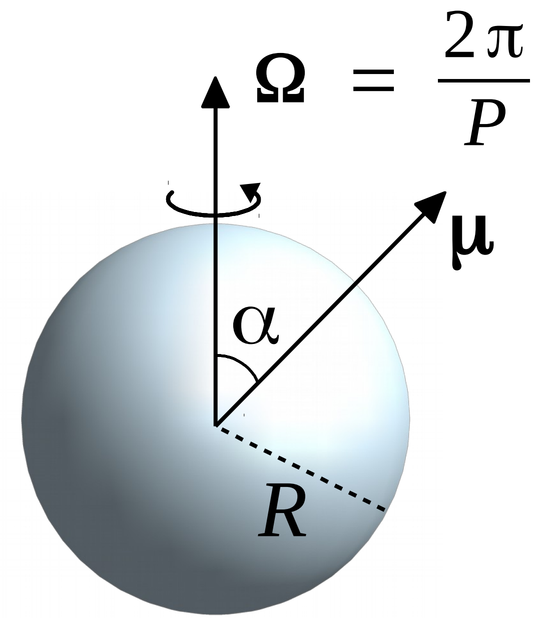
4 Observational selection and the intrinsic *B(t)*

5 Interpretation and conclusions

Estimating the magnetic fields

- Spin-down of a spherical isolated NS:

$$P\dot{P} = \frac{4\pi^2 R^6}{I c^3} \cdot B^2 \cdot \left(k_0 + k_1 \sin^2\alpha\right)$$



- The magnetic field strength (at the magnetic equator):

$$B = \sqrt{\frac{c^3}{4\pi^2}} \times \frac{\sqrt{I(M)}}{R^3(M)} \times \sqrt{\frac{P\dot{P}}{k_0 + k_1 \sin^2\alpha}}$$

equation of state **mass** **magnetic obliquity**

Estimating the magnetic fields

The logarithm of the magnetic field:

$$\log B^{(\mathrm{eos})}(P,\dot{P},M,\alpha) = \log B_{\mathrm{md}}(P,\dot{P}) + \Delta_B^{(\mathrm{eos})}(M,\alpha)$$

additive correction depending on the accepted EOS, NS mass and obliquity

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Standard «magneto-dipolar» formula:

$$\begin{cases} B_{\mathrm{md}}(P,\dot{P}) = \sqrt{\dfrac{3 I_0 c^3}{8\pi^2 R_0^6 \cdot \sin^2\alpha_0} P\dot{P}} = 3.2\times 10^{19}\sqrt{P\dot{P}}\ \ \mathrm{Gs} \\ R_0 = 10\ \mathrm{km},\ \ I_0 = 10^{45}\ \mathrm{g\cdot cm^2},\ \ \alpha_0 = 90^\circ \end{cases}$$

Correction Δ_B constituents

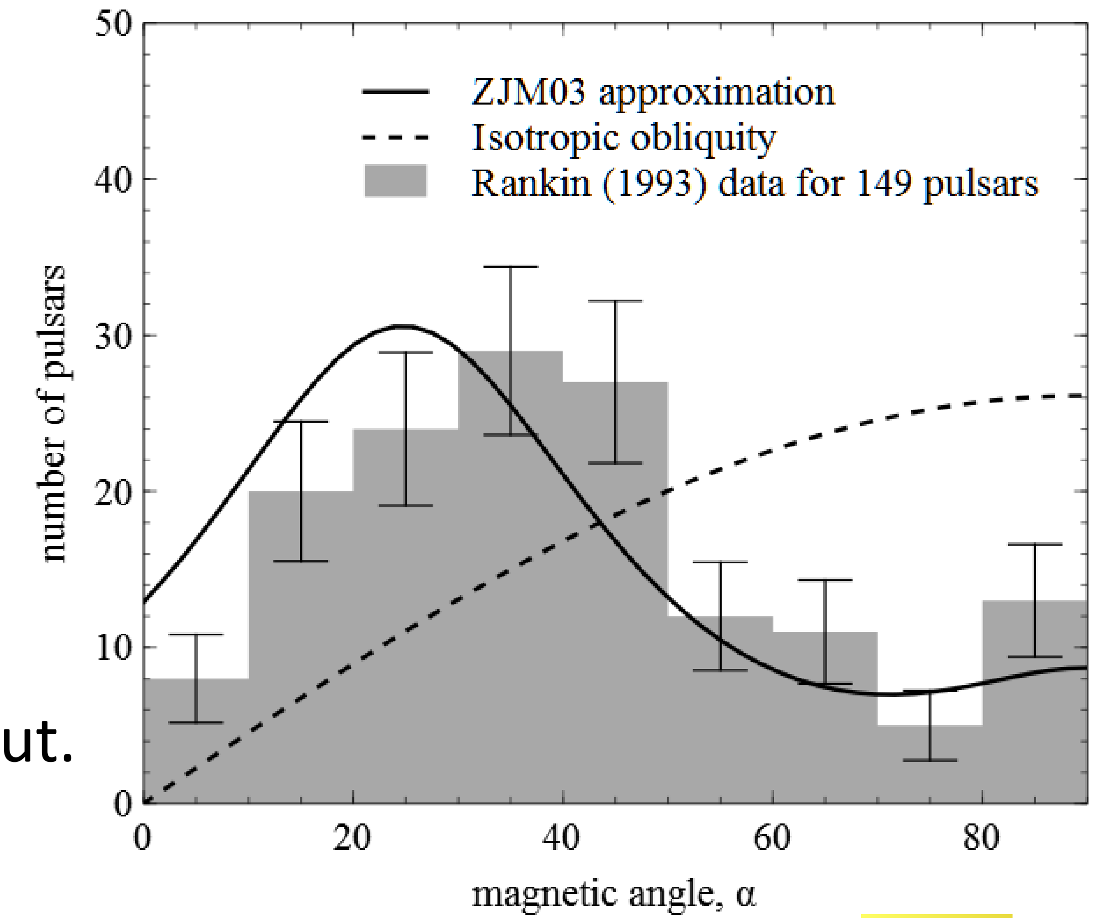
- $$L_{sd} \propto B^2 (k_0 + k_1 \sin^2\alpha)$$
  $$k_0 \approx 1, \quad k_1 \approx 1.4$$

Spitkovsky, astro-ph/0603147

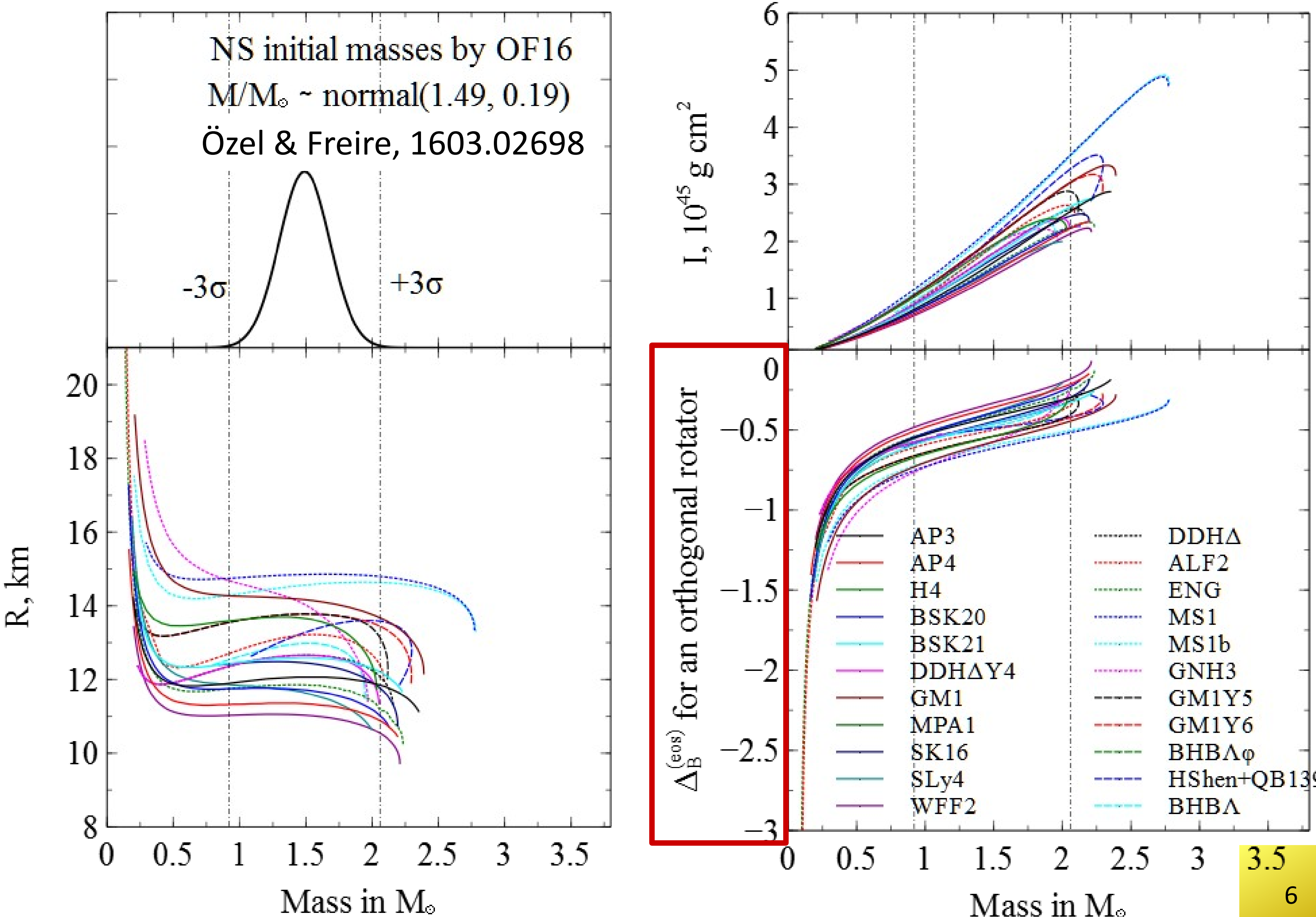
Philippov, Tchekhovskoy & Li, 1311.1513

- Distribution of the magnetic angles is based on the data by Rankin (1993) with their parametrization by Zhang et al. (2003)

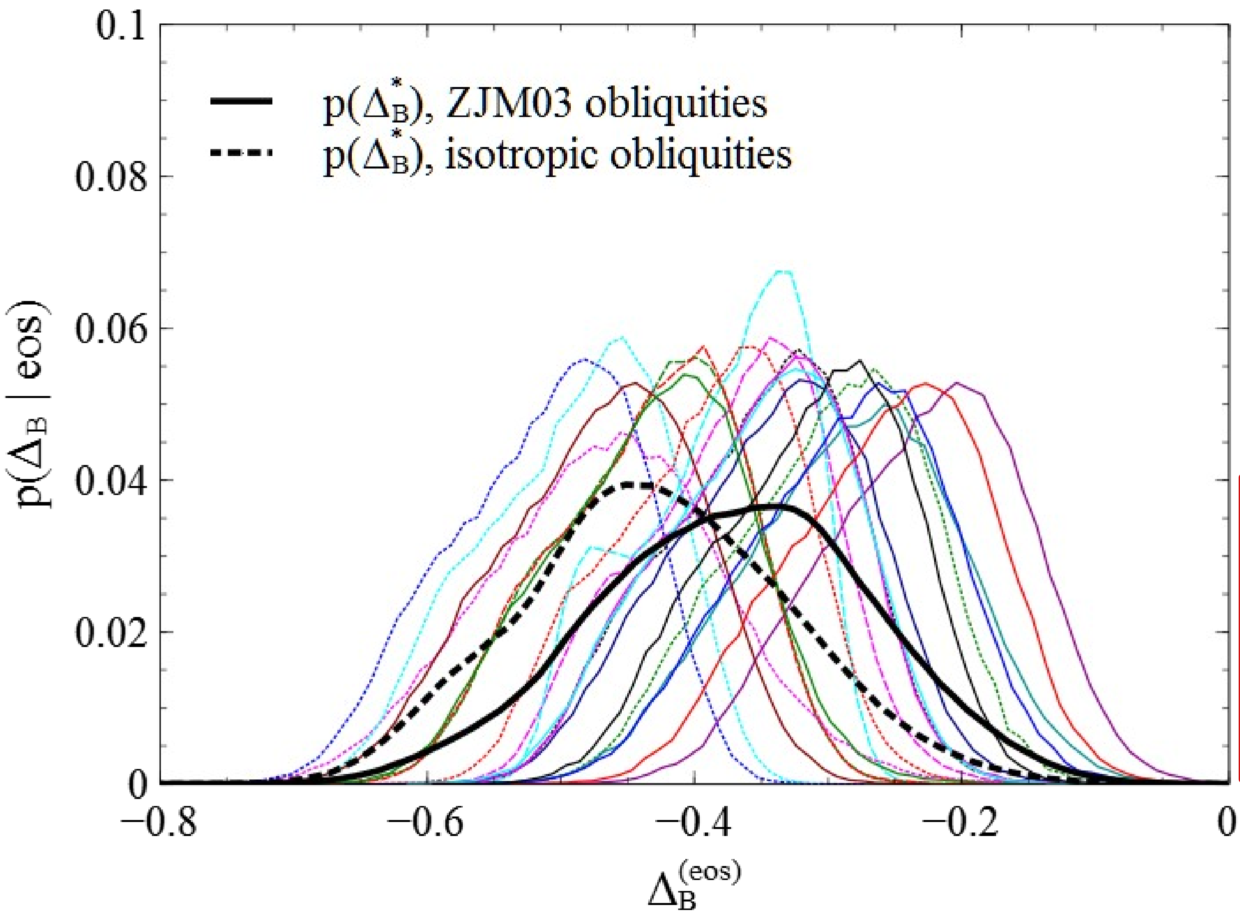
- Isotropic α was also checked out.



NS masses and equation(s) of state



Δ_B distribution(s)



Distributions averages:

$$\left\langle \Delta_B^{(eos)} \right\rangle \approx -0.55 \ldots -0.25 \text{ dex}$$

Distributions widths:

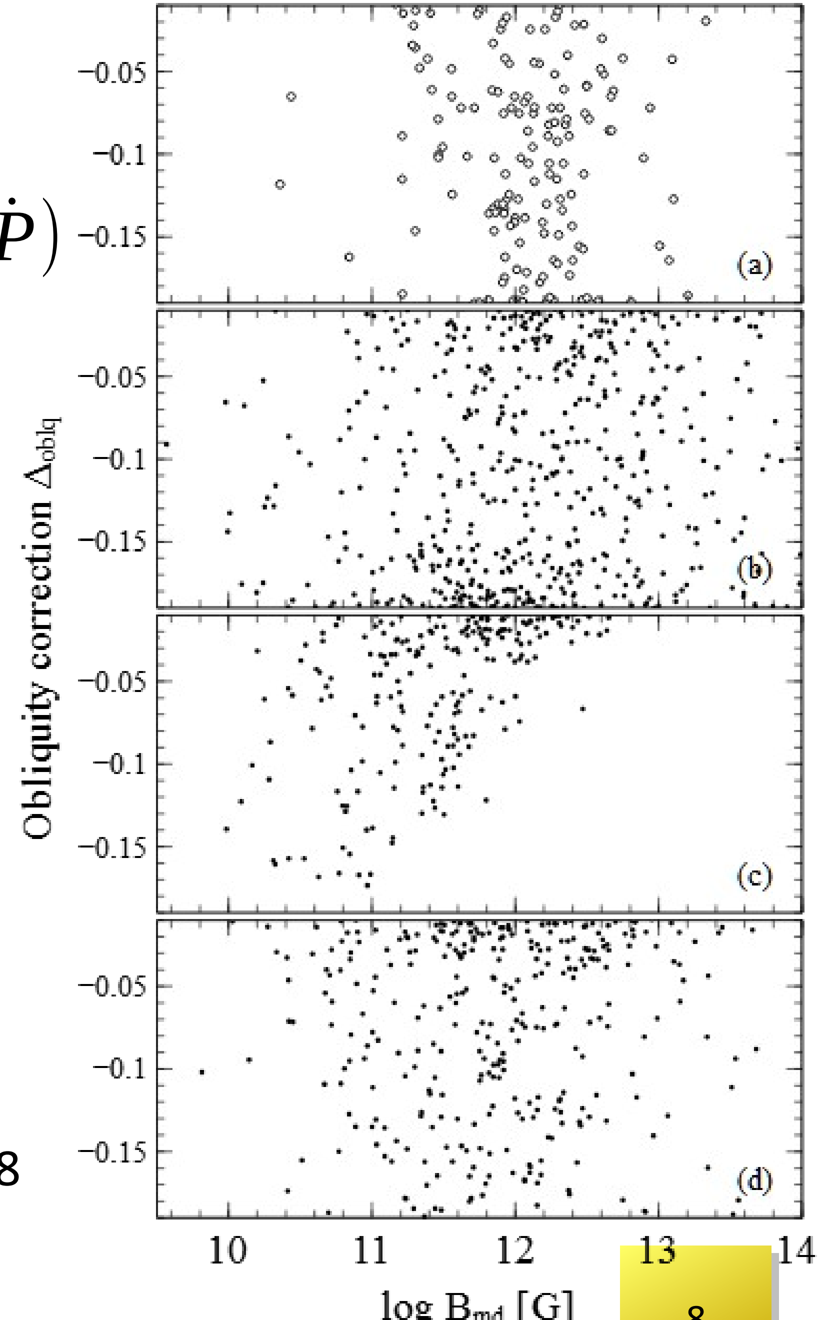
$$\sigma\left[\Delta_B^{(eos)}\right] \approx 0.06 \ldots 0.09 \text{ dex}$$

Mixture PDF for all 22 considered EOSs:

$$p\left(\Delta_B^*\right) = \sum w_i\, p\left(\Delta_B | \text{eos}\right) \Rightarrow \Delta_B^* \approx -0.37 \pm 0.10 \quad \text{or} \quad B^* \approx \frac{3}{7} B_{md}$$

Properties of Δ_B

- Δ_B(M, α) does not correlate with $B_{\rm md}\left(P,\dot{P}\right)$
- <Δ_B> is the same for all pulsars (when a particular EOS is adopted)
- σ[Δ_B] can be considered as a formal precision of the magnetic field estimation for an individual pulsar

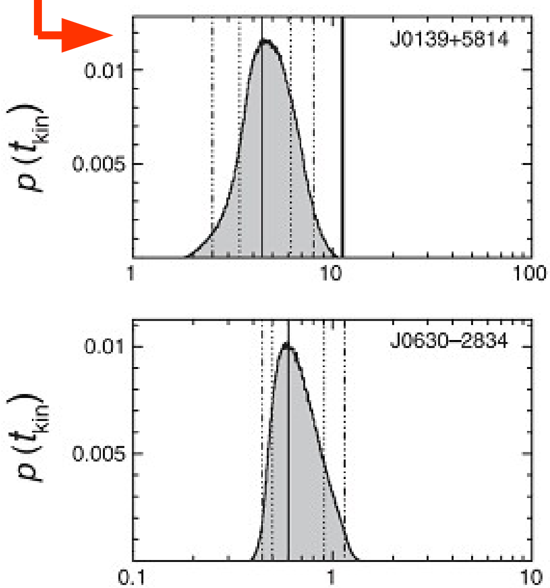


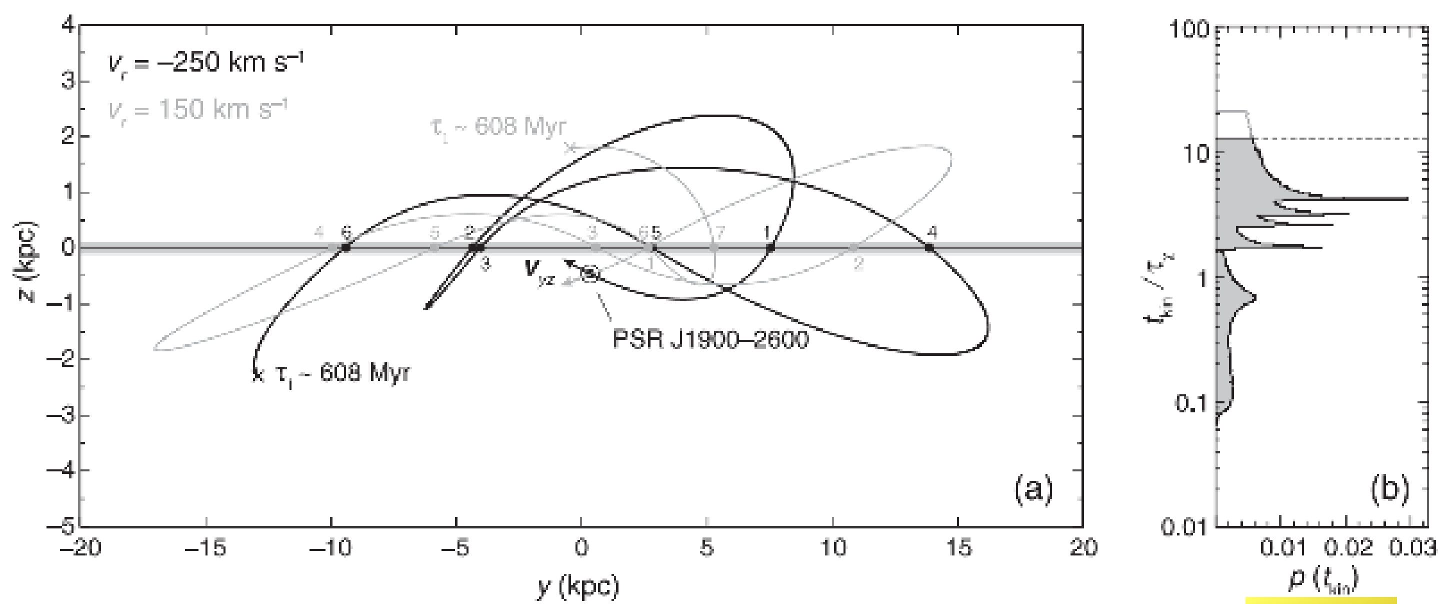
AB, Astashenok, G. Beskin, 1702.00018

Pulsar ages

- 22 PSR-SNR associations with ages within $10^3 \ldots 10^5$ years (mostly from Popov & Turolla, 1204.0632 and Gill & Heyl, 1305.0930);

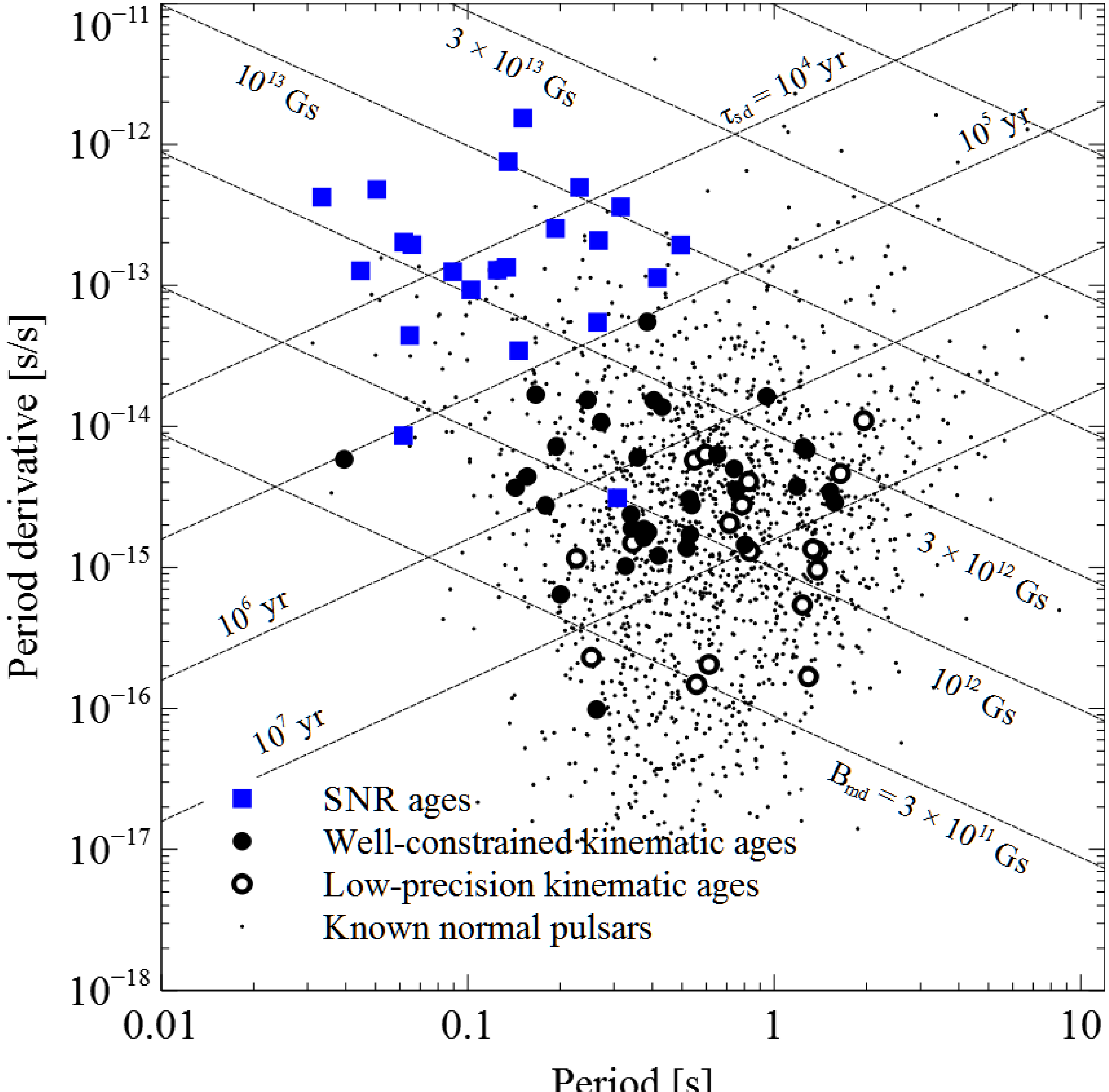
- 54 pulsars with kinematic ages within $10^5 \ldots 10^8$ years (mostly from Noutsos+, 1301.1265; also: Chmyreva, G. Beskin, AB, 1203.2836; Tetzlaff+, 1401.4678)
  - 36 pulsars with «well-constrained» t_{kin}
  - 18 pulsars with «low-precision» t_{kin}





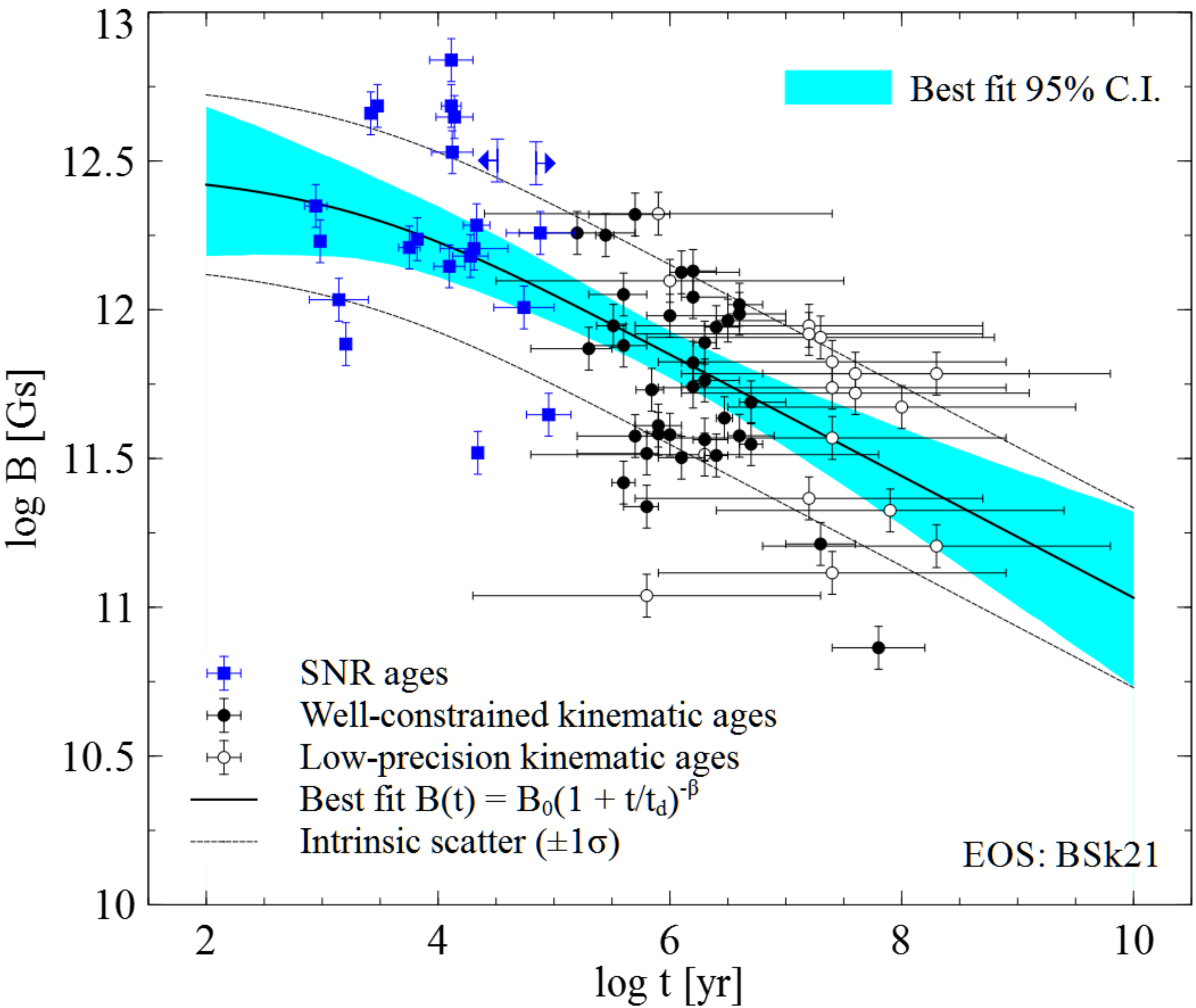
Figures from Noutsos+ 2013

76 pulsars



10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
Period derivative [s/s]
0.01
0.1
1
10
Period [s]
10^{13} Gs
3×10^{13} Gs
$\tau_{sd} = 10^4$ yr
10^5 yr
10^6 yr
10^7 yr
3×10^{12} Gs
10^{12} Gs
$B_{md} = 3 \times 10^{11}$ Gs
SNR ages
Well-constrained kinematic ages
Low-precision kinematic ages
Known normal pulsars

Apparent field evolution

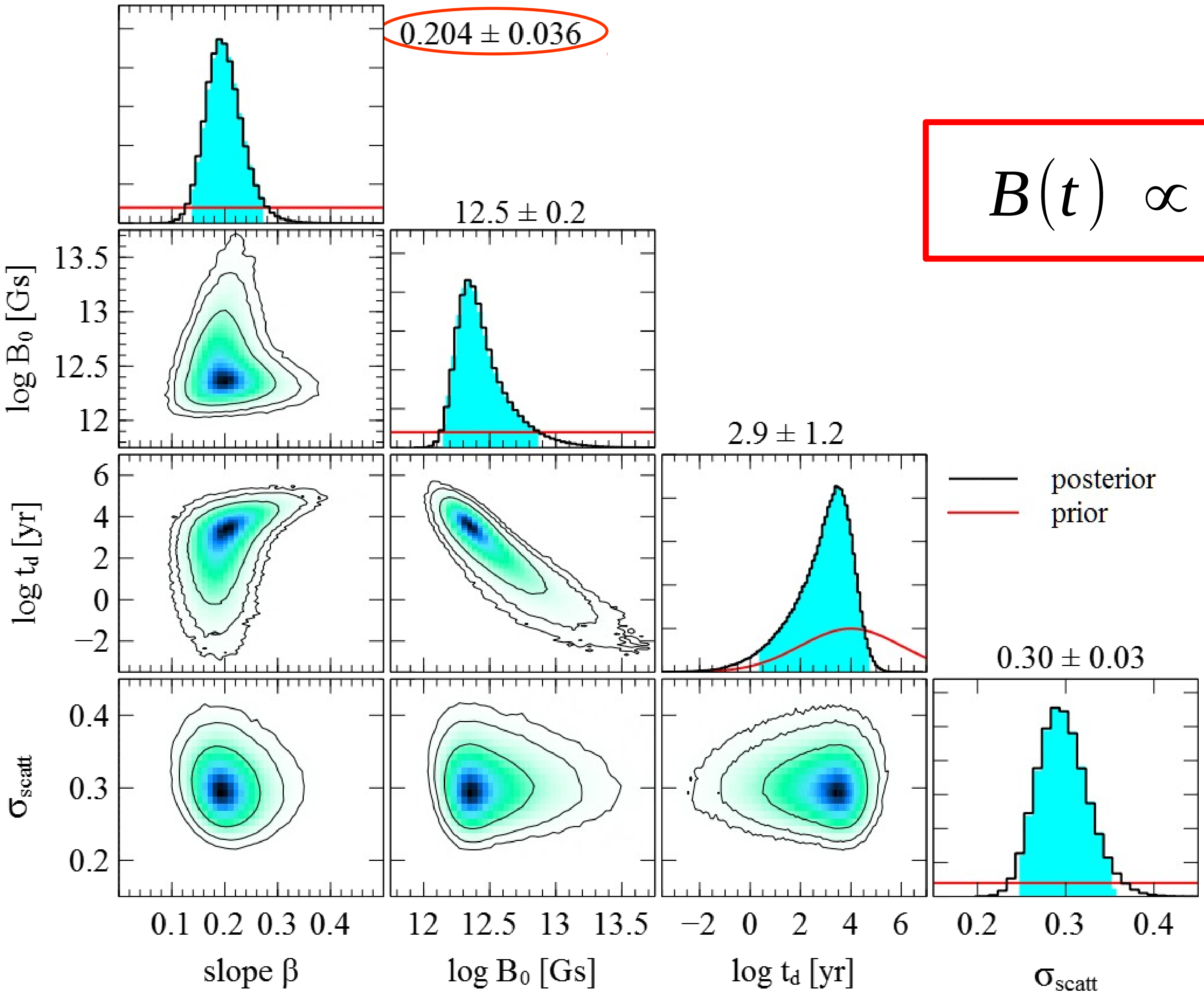


Bayesian fit by the model:

$$B(t) = B_0 \left(1 + \frac{t}{t_\mathrm{d}}\right)^{-\beta}$$

The shape and the slope of the cloud are independent on the choice of EOS

Apparent field evolution



$$B(t) \propto t^{-1/5}$$

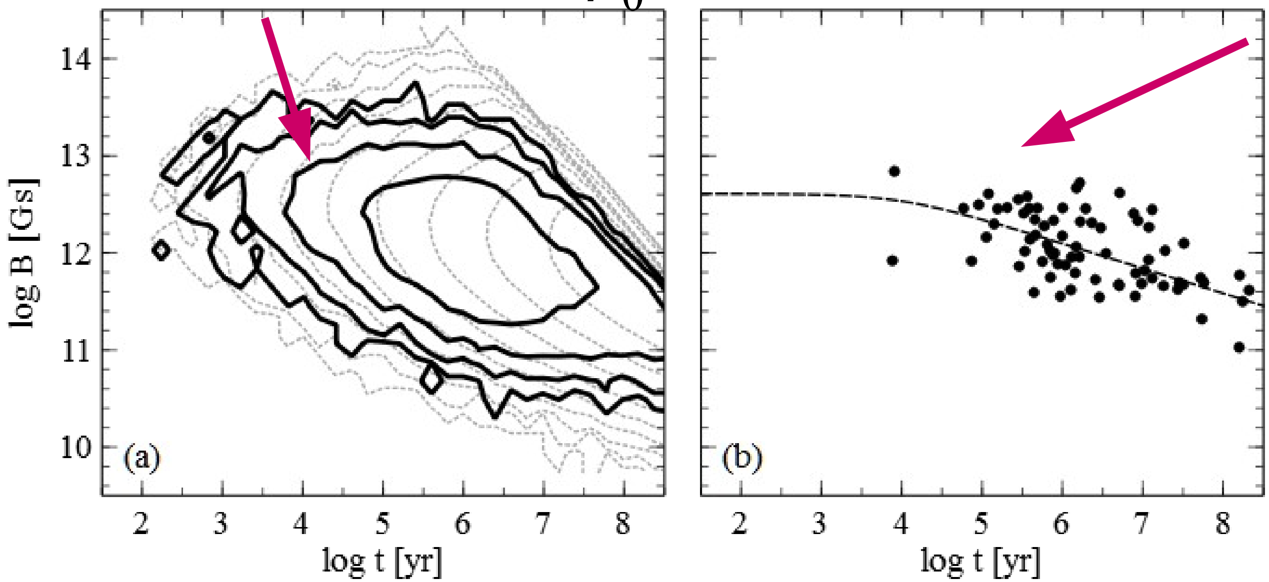
Population synthesis

- Based on the best model derived by Faucher-Giguere & Kaspi, astro-ph/0512585 (including initial P_0, B_0, luminosities, kinematics etc.), death line equation: $\dot{P} = \left(2.82\times10^{-17}\ \mathrm{sec}^{-3}\right)\cdot P^3$

- Some extensions of the model:
  - Direct modeling of pulsar beam direction to the observer and pulse width W_{10}. Assume beam half-width $\rho = 5.7^\circ P^{-1/2}$
  - Modeling of the magnetic angle evolution (from isotropic α_0)
  - Spin-down + field decay: $P\dot{P} \propto B_0^2\left(1+\frac{t}{10^3\ \mathrm{yr}}\right)^{-2\beta_0}\cdot\left[1+1.4\sin^2\alpha(t)\right]$
  - α-dependend death line: $\cos\alpha < \left(P/\mathrm{sec}\right)^{15/7}\left(B/10^{12}\ \mathrm{Gs}\right)^{-8/7}$
    Beskin, Gurevich & Istomin 1993
    (see also Arzamasskiy, Beskin & Pirov, 1612.04820)

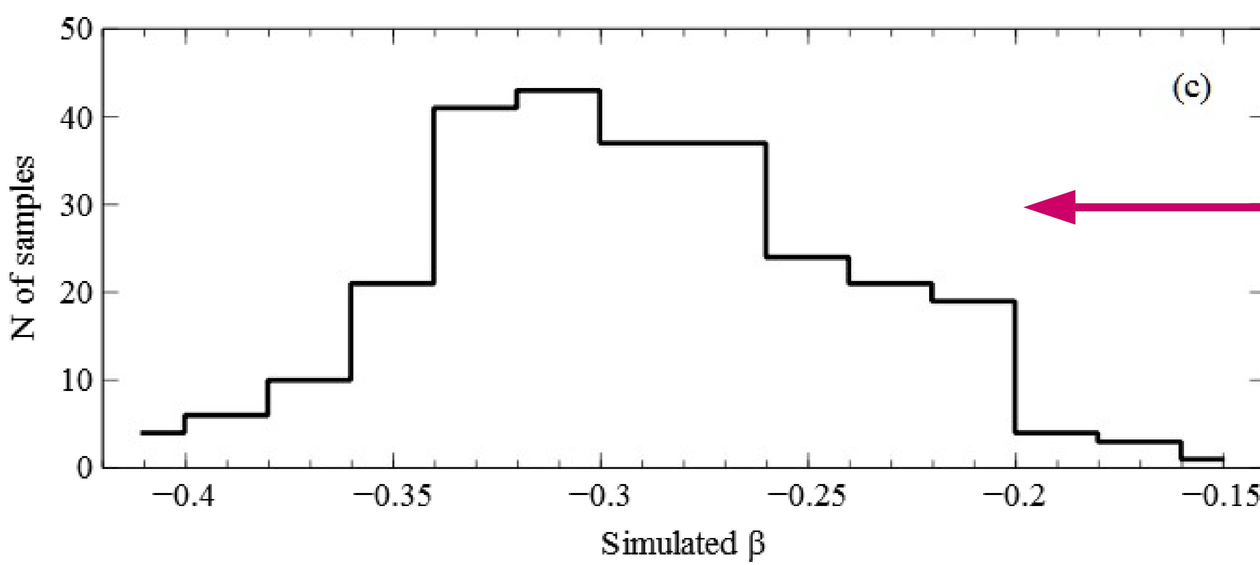
Modeling the observational selection

Modeling *log B-log t* for synthetic pulsars assuming a particular β_0



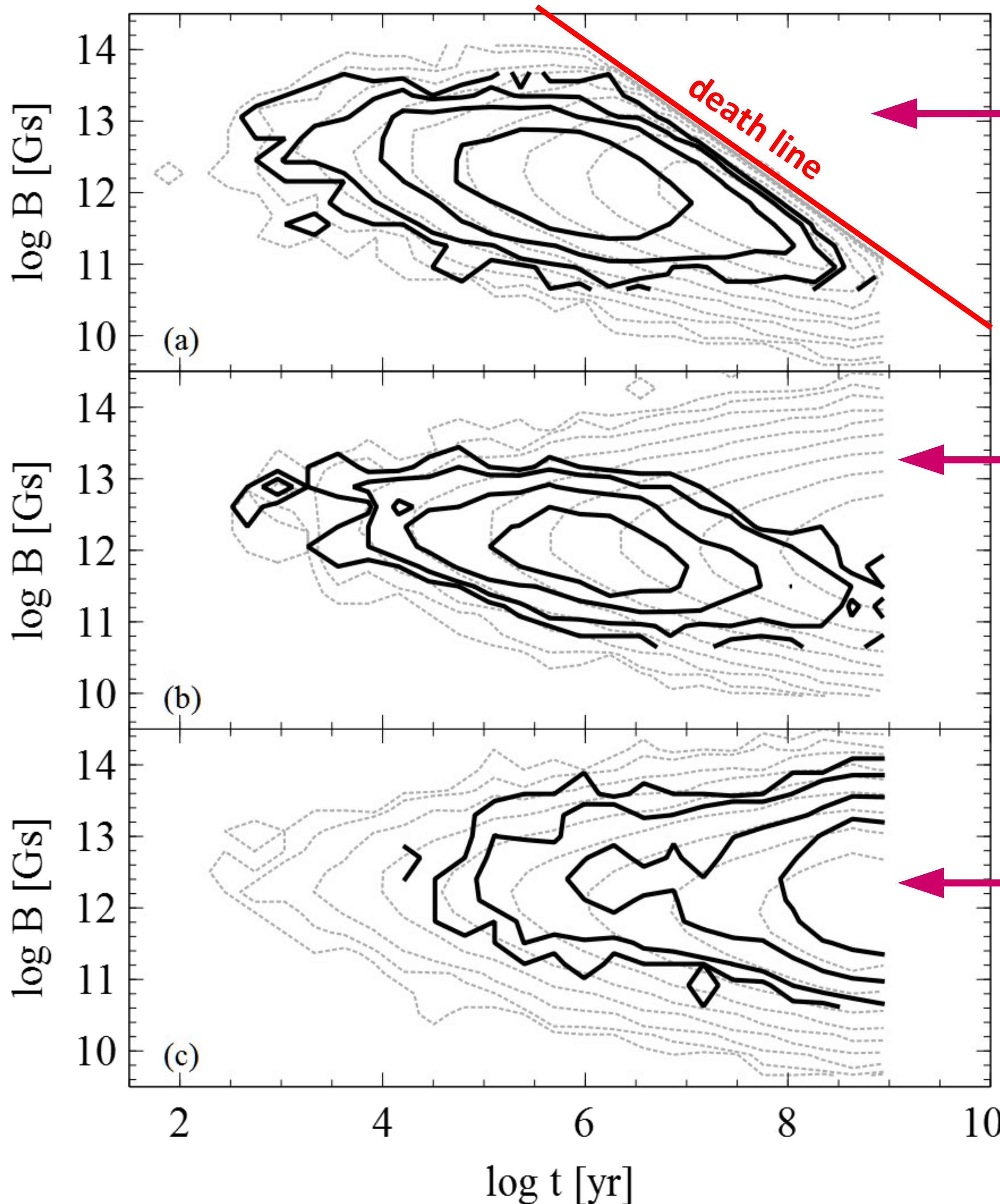
Extracting and fit the independent samples of 76 pulsars with

$$B = B_0\left(1 + \frac{t}{10^3\ \mathrm{yr}}\right)^{-\beta}$$



Plot the distribution of simulated β

Selectional effects (for $\beta_0 = 0$)

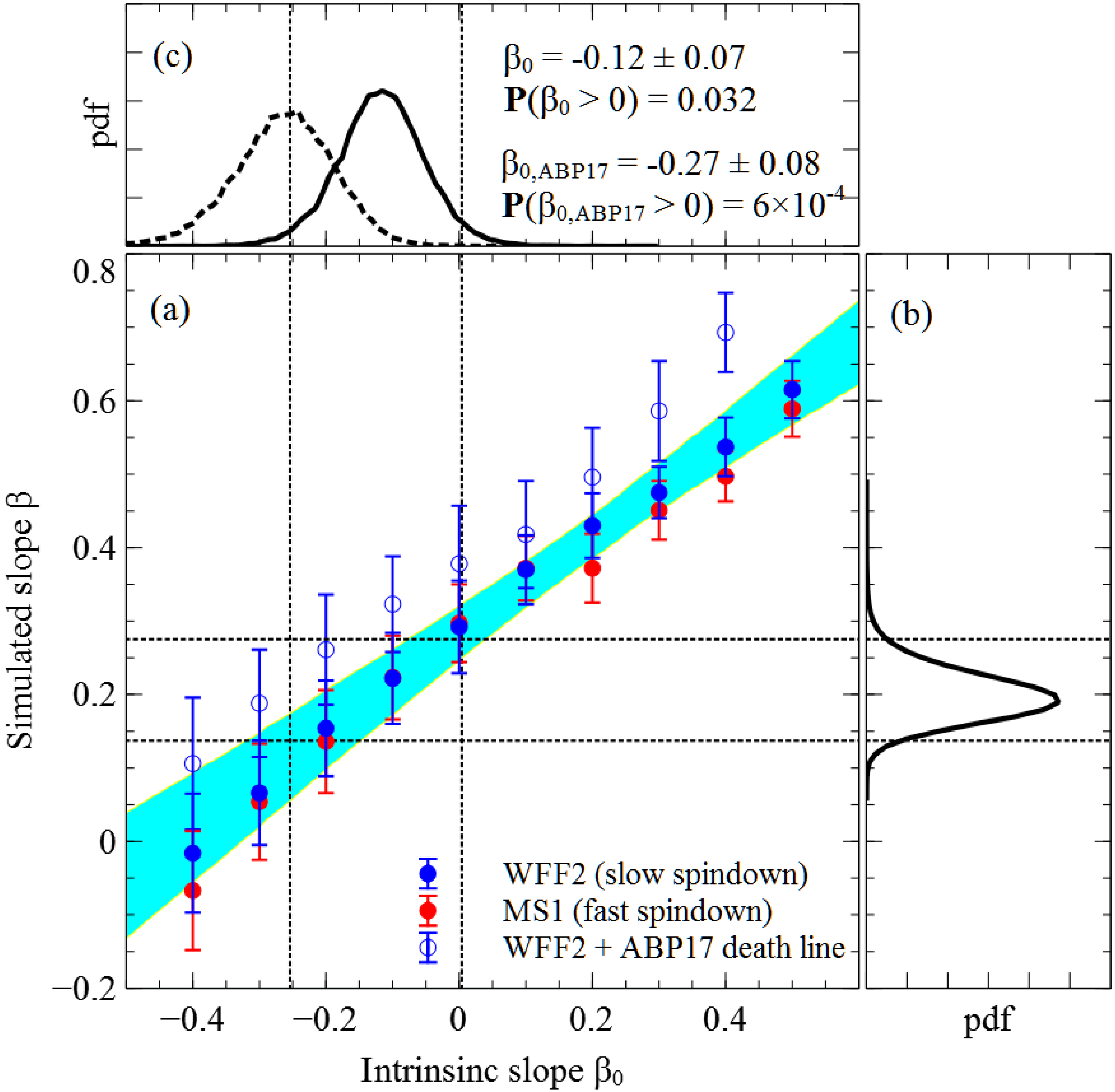


Death line exist and luminosity is period-dependent

No death line and luminosity is period-dependent

No death line and constant luminosity

Intrinsic field decay



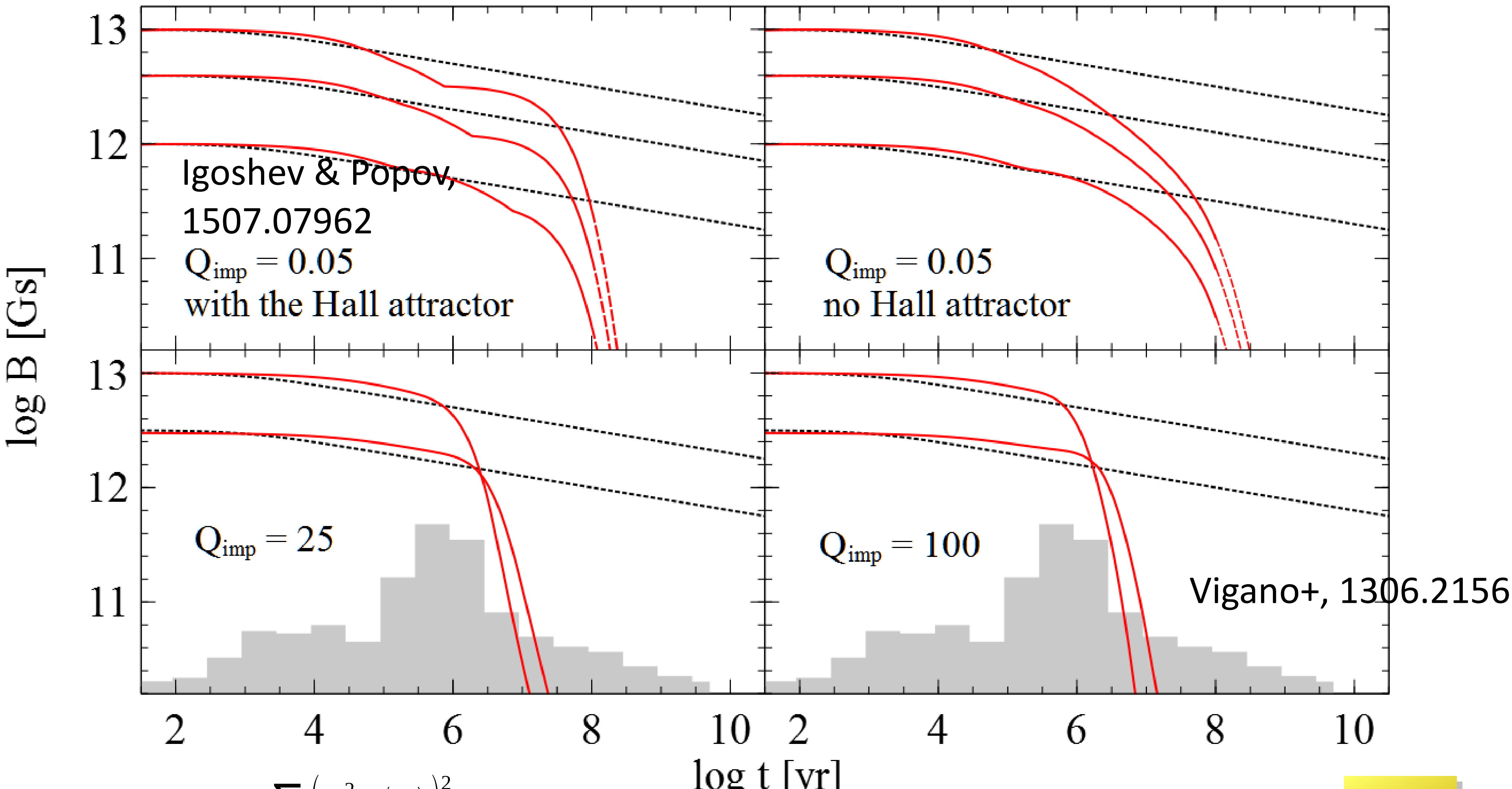
Intrinsic slope β_0 in

- [-0.33…0.09] @ 3σ C.L. for an α-**in**dependend death line
- [-0.51…-0.03] @ 3σ C.L. for an α-dependend death line

Discussion

Observerd *B(t)* **rejects:**

moderate decay with $\beta > 0.1$ (at 3σ confidence)

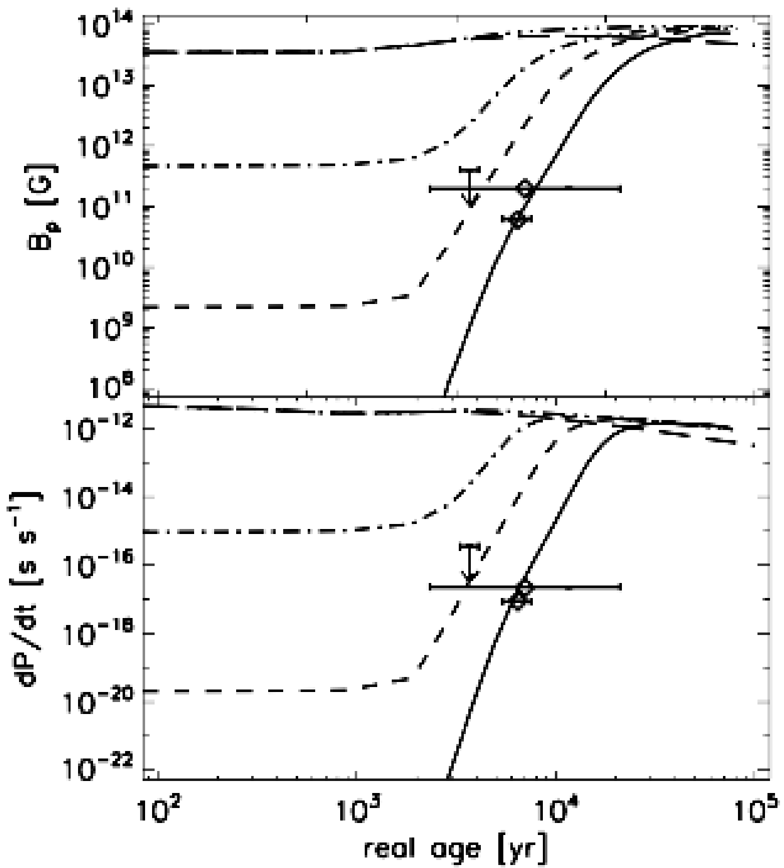


$$Q_{\rm imp} \propto \sum_i \left(Z_i^2 - \langle Z \rangle\right)^2$$

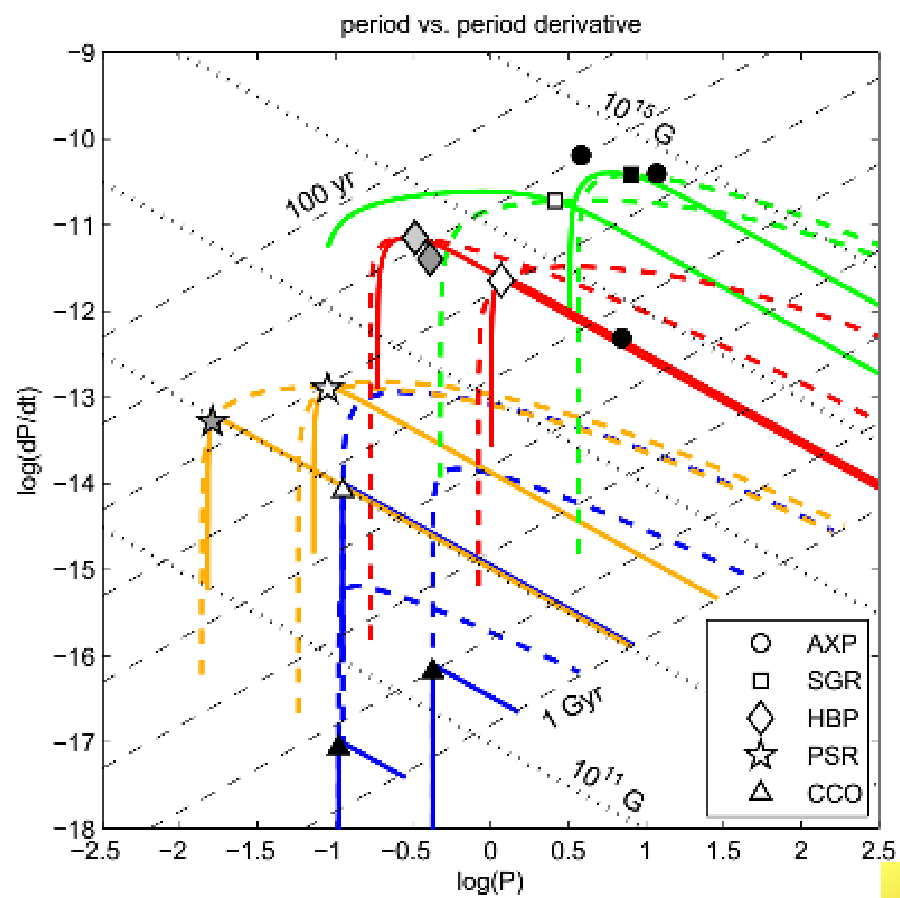
Discussion

Apparent *B(t)* does not **formally** reject @ < 3.2% C.L.:

- neithter the absence of the field evolution (β = 0) nor its moderate growth (β < -0.1) (**but** Pons+, astro-ph/0607583; Kaspi, 1005.0876; Xie & Zhang, 1110.3869; Pons, Vigano & Geppert, 1209.2273; Igoshev, Popov, 1407.6269 etc.)



Vigano & Pons, 1206.2014



Rogers & Safi-Harb, 1601.00949

Conclusions

- The timing-based value of *B* can be estimated with ~15-30% accuracy for a given pulsar within the state-of-the-art constrains on the NS masses, magnetic angles and EOS

- $B_{\rm md} = 3.2\times10^{19}\sqrt{P\dot{P}}\ \ {\rm Gs}$ is good, but biased. Use your favorite EOS when calculating *B*, or adopt $B^* = 3B_{\rm md}/7$ at least.

- There is a significant apparent trend $B(t) \propto t^{-1/5}$, which is consistent with the field decay models that assume a low amount of impurities in a NS crust.

- Within the assumptions made in the modeling, the trend also does not reject a systematic moderade field growth at the Myr-timescales.

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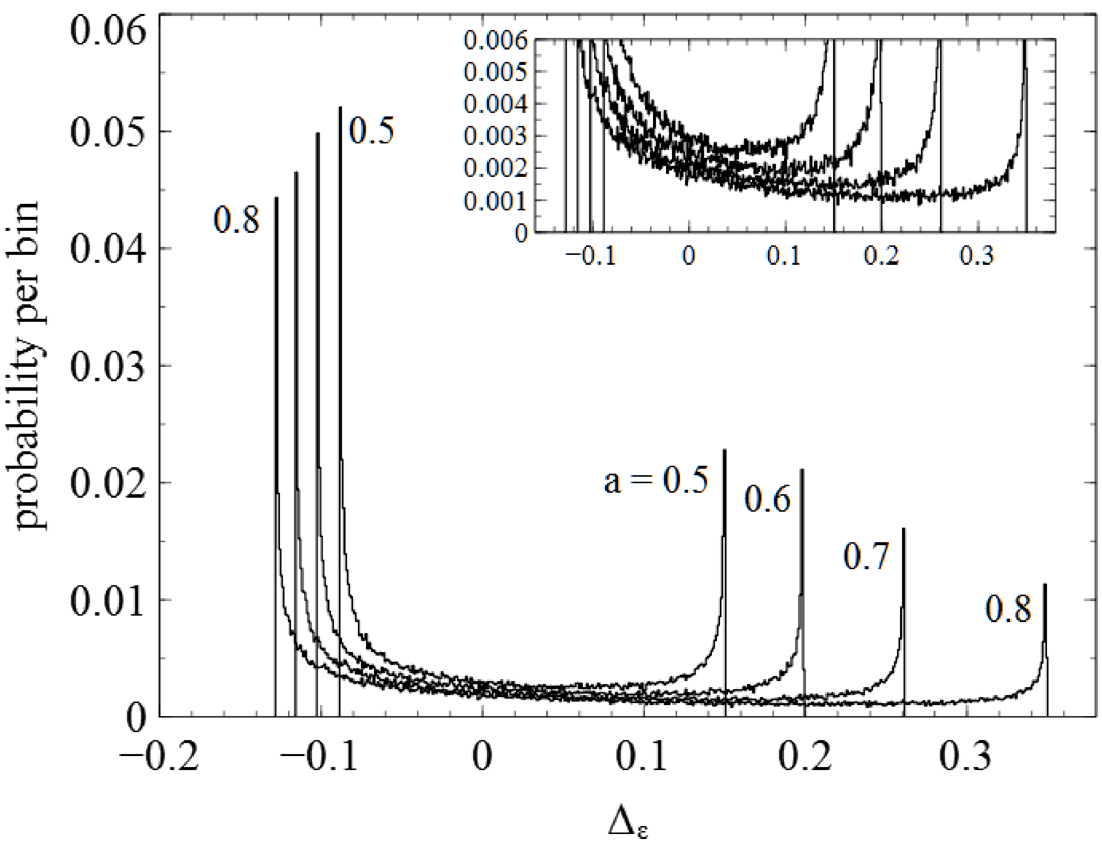
Thank you! :-)

Timing noise effects

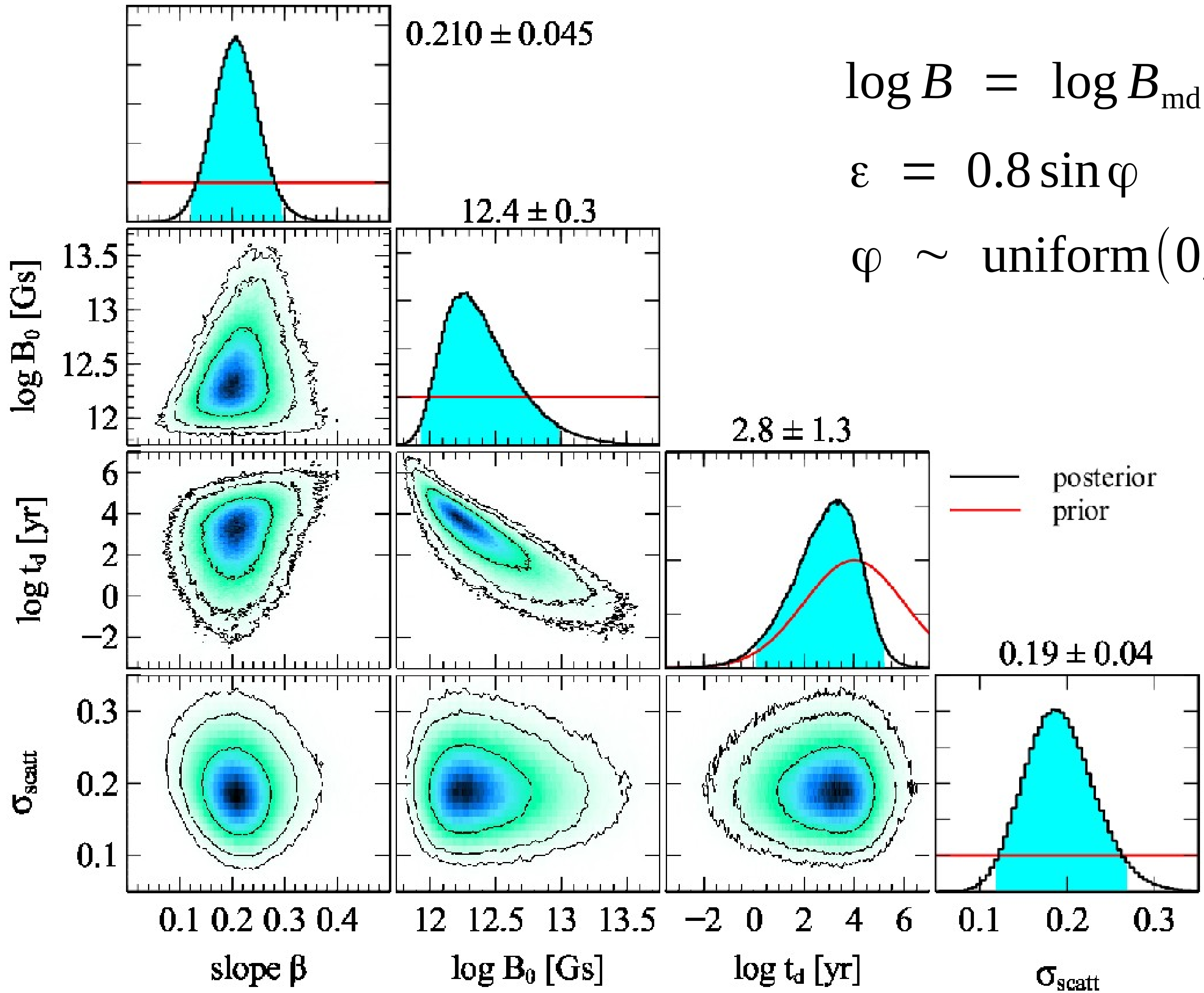
$\dot{P}_{obs} = \dot{P}(1+\varepsilon)$ – functional relationship between *P, dP/dt* и *B* can be broken temporally: $|\varepsilon| < 1$ is exist.

$\Delta_\varepsilon = \frac{1}{2}\log(1-\varepsilon)$ – an additional correction to the *log B*



- Slow variations of *B*, α or *I* → **ε ≡ 0** (Pons+, 1209.2273; Arzamasskiy+, 1504.06626; Hamil+, 1608.01383)
- Additional component in the braking torque → **|ε| < 0.8 ≠ 0** (AB, G. Beskin, Karpov, 1105.5019)

B(t) trend including timing noise



$$\log B = \log B_{\mathrm{md}} + \Delta_{\mathrm{B}}^{\mathrm{BSk21}} + \Delta_{\varepsilon}$$

$$\varepsilon = 0.8 \sin \varphi$$

$$\varphi \sim \mathrm{uniform}(0, 2\pi)$$

GR effects

$$P\dot{P} = \eta_{GR}(x)\times\frac{4\pi^2 R^6}{Ic^3}B^2$$

– aligned rotator in a curved space-time

(Gralla, Lupsasca, Philippov, 1604.04625)

$$\eta_{GR}(x) \approx \frac{0.42\cdot x^6}{[x(x+2)+2\ln(1-x)]^2}$$

$$x = 2GM/Rc^2$$

$$\Delta_{GR}^{(eos)}(x) = -\frac{1}{2}\log\eta_{GR}(x)$$