Magnetic field decay and unification of young and millisecond pulsar populations

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Physics of Pulsar Magnetospheres
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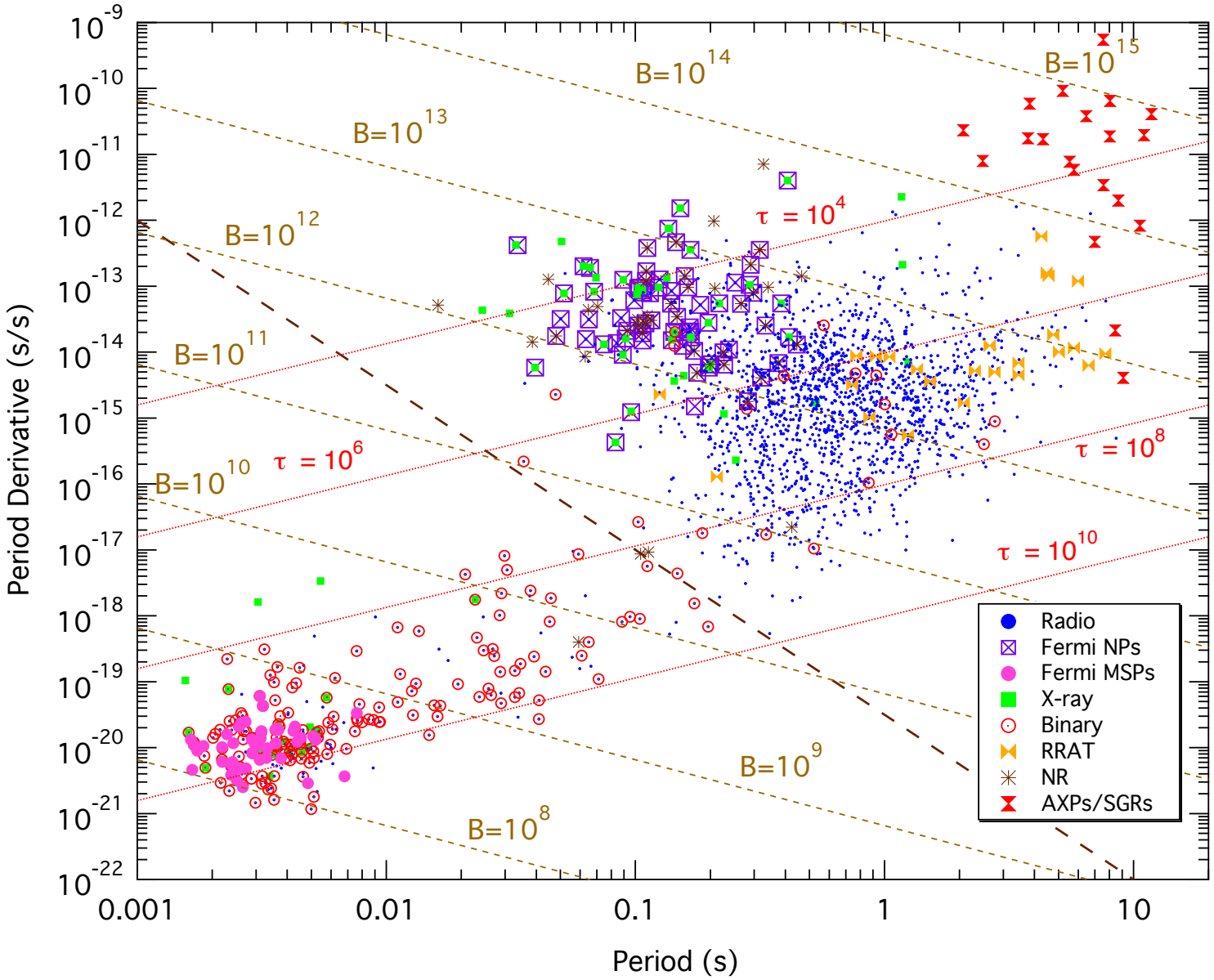
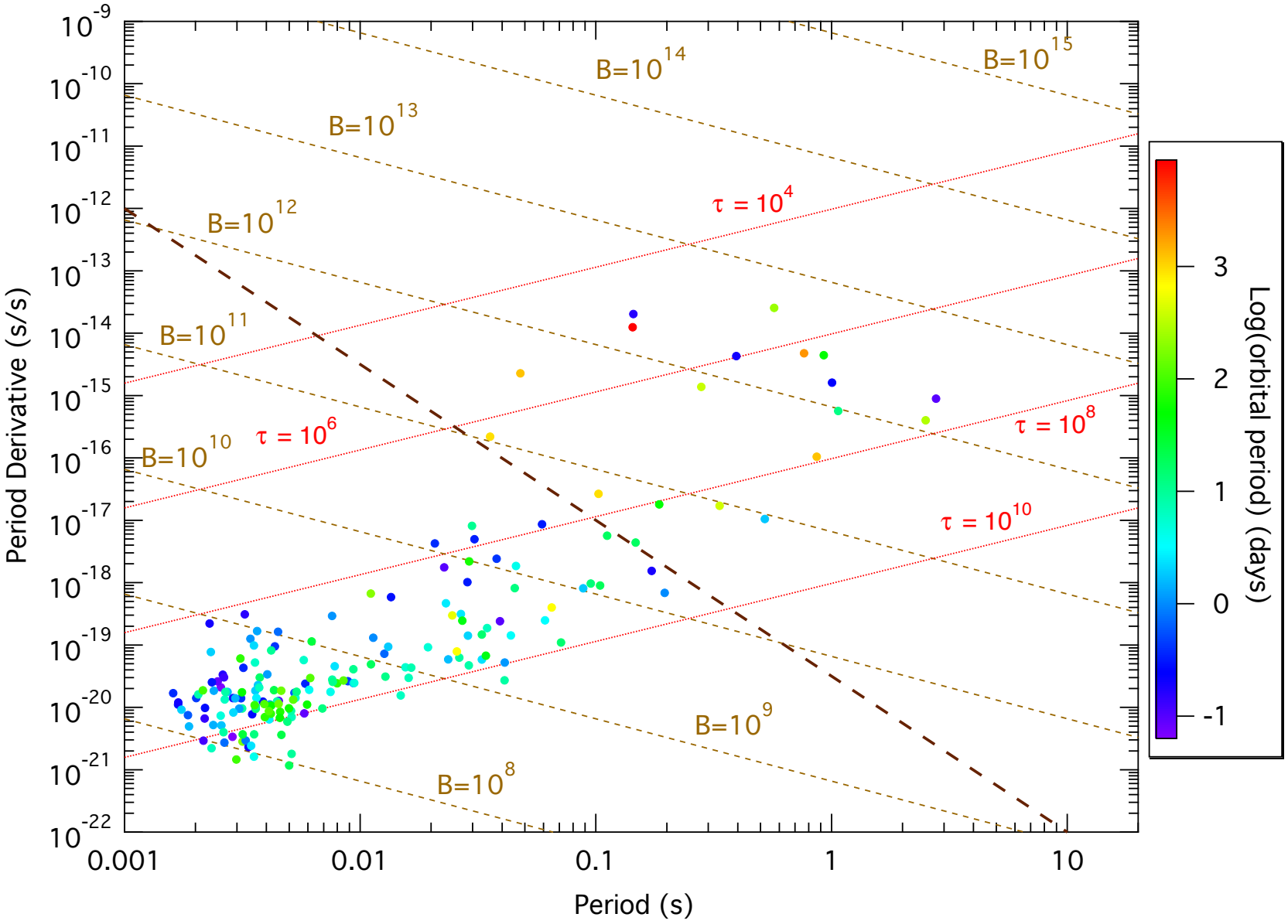
Victoria Merten — Washington and Jefferson College

Pulsar Zoo with over 2530 subjects



ATNF - http://www.atnf.csiro.au/research/pulsar/psrcat

Binary Pulsars



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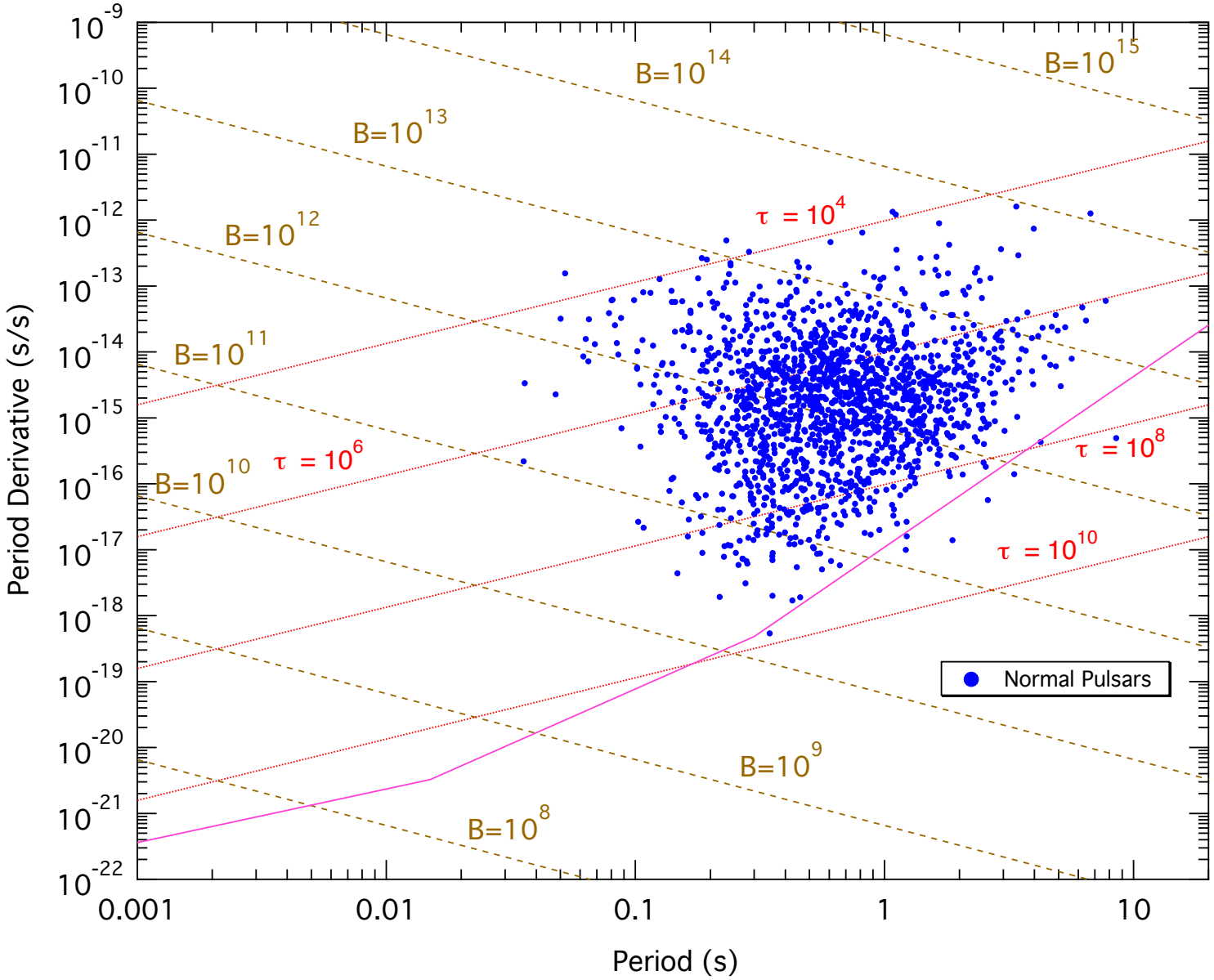
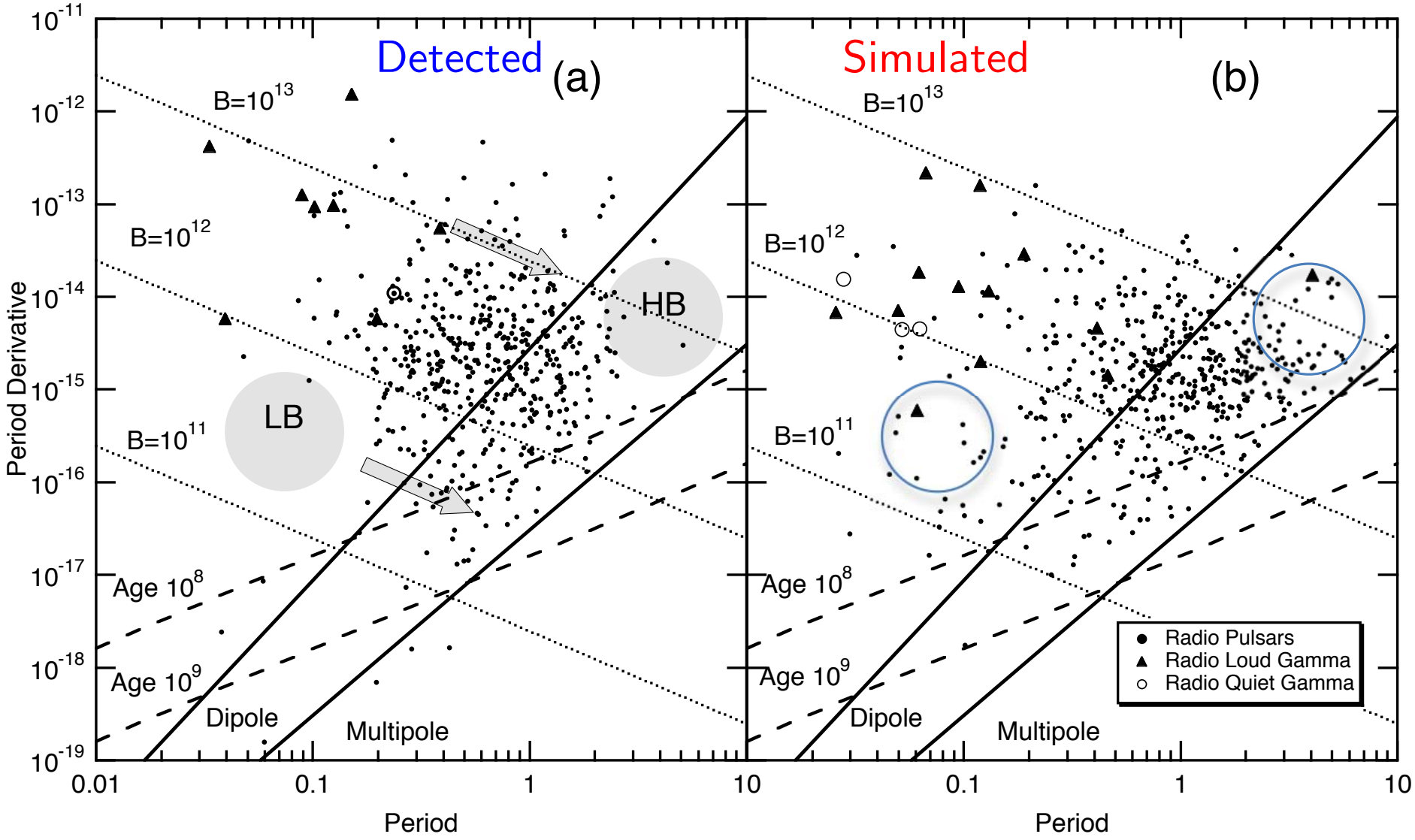
Normal Pulsars



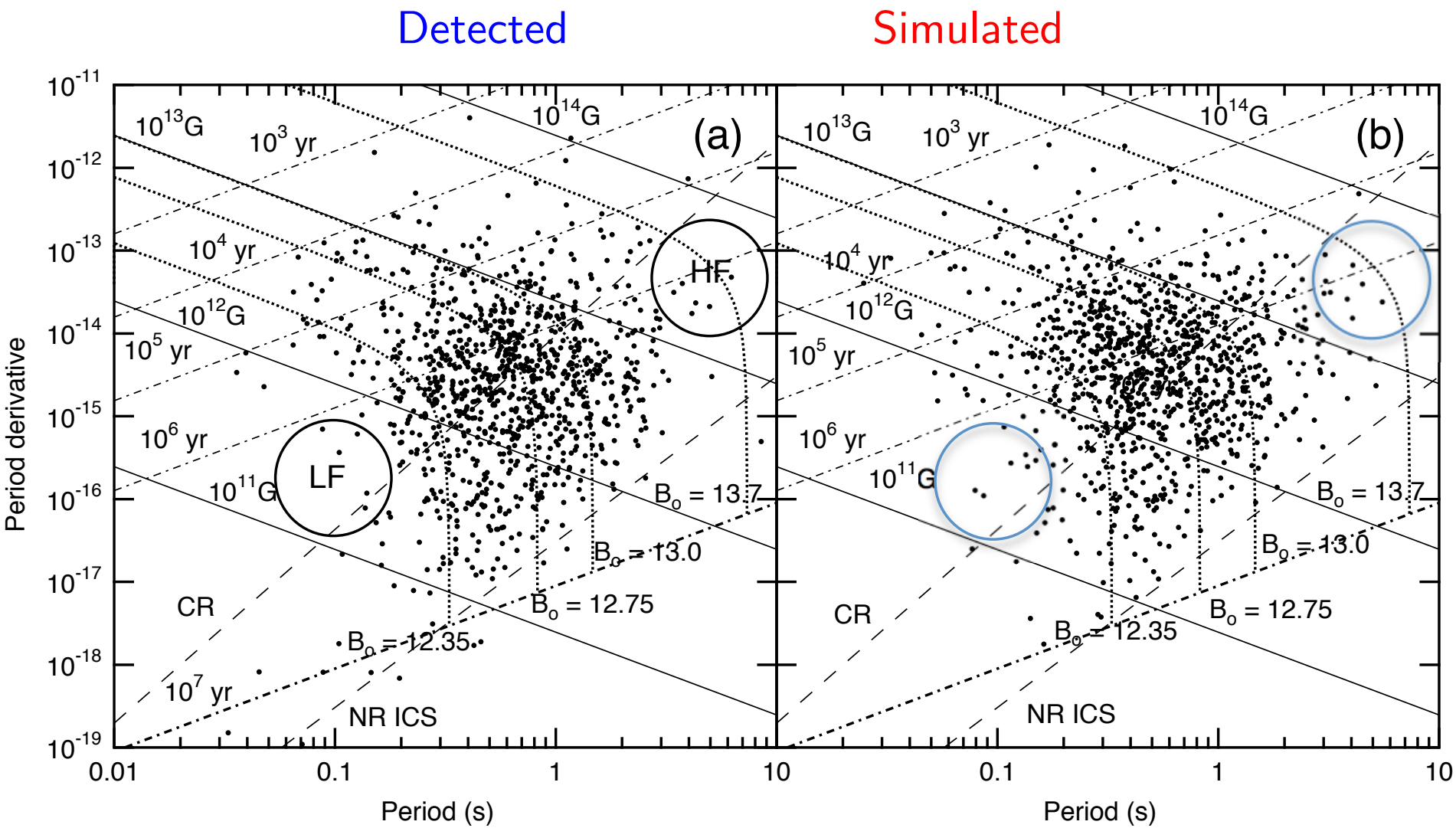
ATNF - `http://www.atnf.csiro.au/research/pulsar/psrcat`

Gonthier et al. (2002) — no field decay



Death lines - Zhang, Harding & Muslimov (2000)

Gonthier et al. (2004) — Exponential B field decay



$\tau = 2.8$ million years

Death lines - Harding, Muslimov & Zhang (2002)

Birth distributions — a more recent study

- Born in the spiral arms using the electron density model NE2001 — Cordes & Lazio (2003). Spiral arm system rotates with the speed of the density waves
- Trajectories are evolved in the Galactic potential — Paczyński (1990)
- For $B_{\rm o}$ — Log normal distribution

$$< \log B_{\rm o} > = 12.8$$
$$\sigma_{\log B_{\rm o}} = 0.46$$

- For $P_{\rm o}$ — Gaussian distribution — need to explore other distributions

$$< P_{\rm o} > = 0.11 \text{ with } P_{\rm o_{min}} \text{ of } 1.3 \text{ ms}$$
$$\sigma_{P_{\rm o}} = 0.14$$

- Four free parameters to define the means and widths — searched in MCMC chains

Spin-down and field decay

- Spitkovsky (2006)
- Contopoulos, Kalapotharakos & Kazanas (2014)
- Tchekhovskoy, Philippov & Spitkovsky (2016)

$$L = \left(1 + \sin^2 \chi\right) L_{\rm o}$$

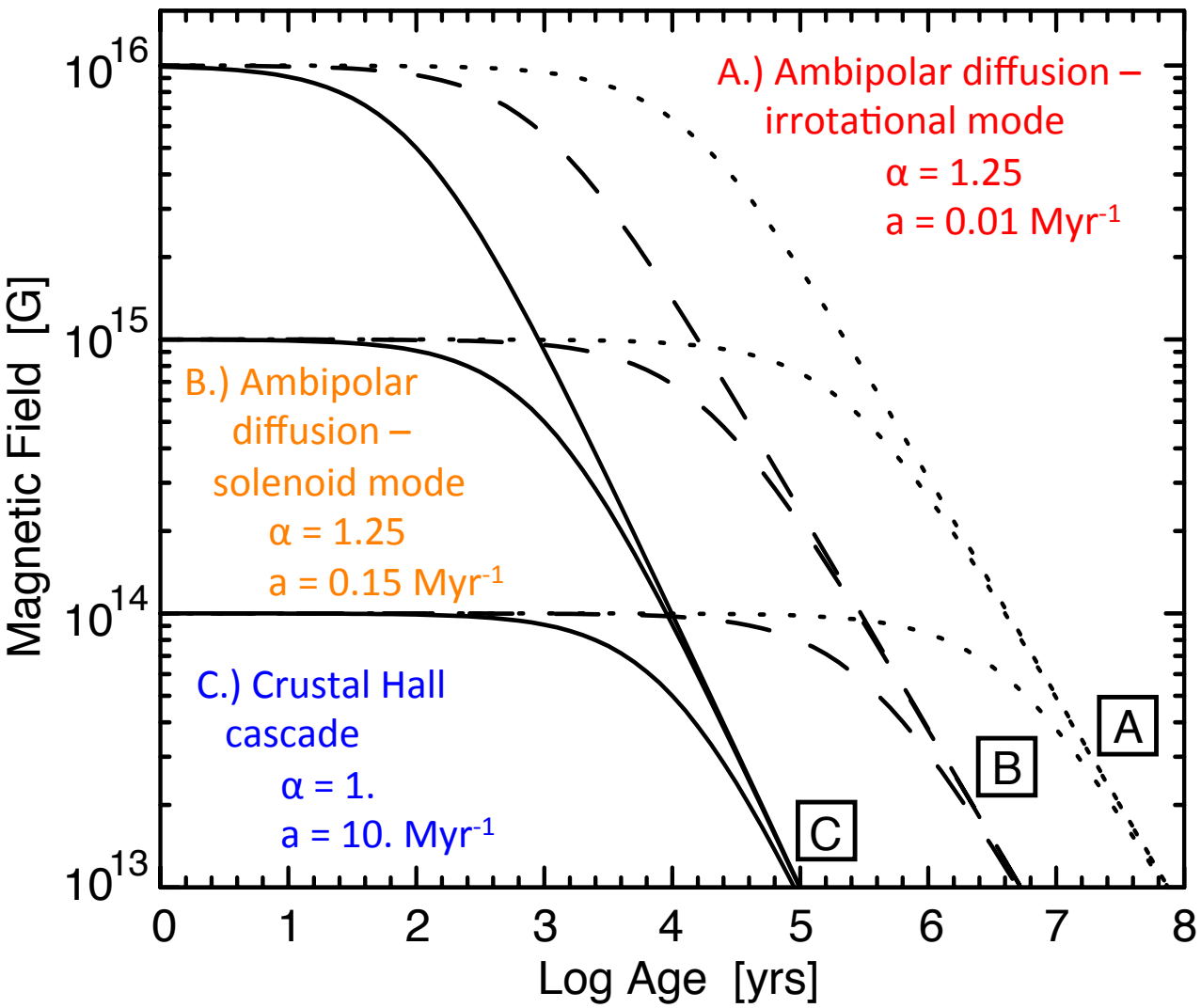
- Magnetic field decay model — Colpi, Geppert & Page (2000)

$$\frac{d\,B_{13}}{d\,t} = -a\,B_{13}^{1+\alpha} \qquad \text{(Eq. 2)}$$

$$a = \frac{1}{\tau_{\rm Myr}}$$

$$B_{13}(t) = \frac{B_{13_{\rm o}}}{\left[1 + a\,\alpha\,B_{13_{\rm o}}^{\alpha}\,t_6\right]^{1/\alpha}} \qquad \text{(Eq. 3)}$$

Colpi, Geppert, & Page 2000 - Figure 1



Colpi, Geppert, & Page 2000, ApJ, 529, L29 – Figure 1

Magnetic field decay — Viganò, Pons, & Miralles 2012

Viganò et al. (2013) — Figure 10

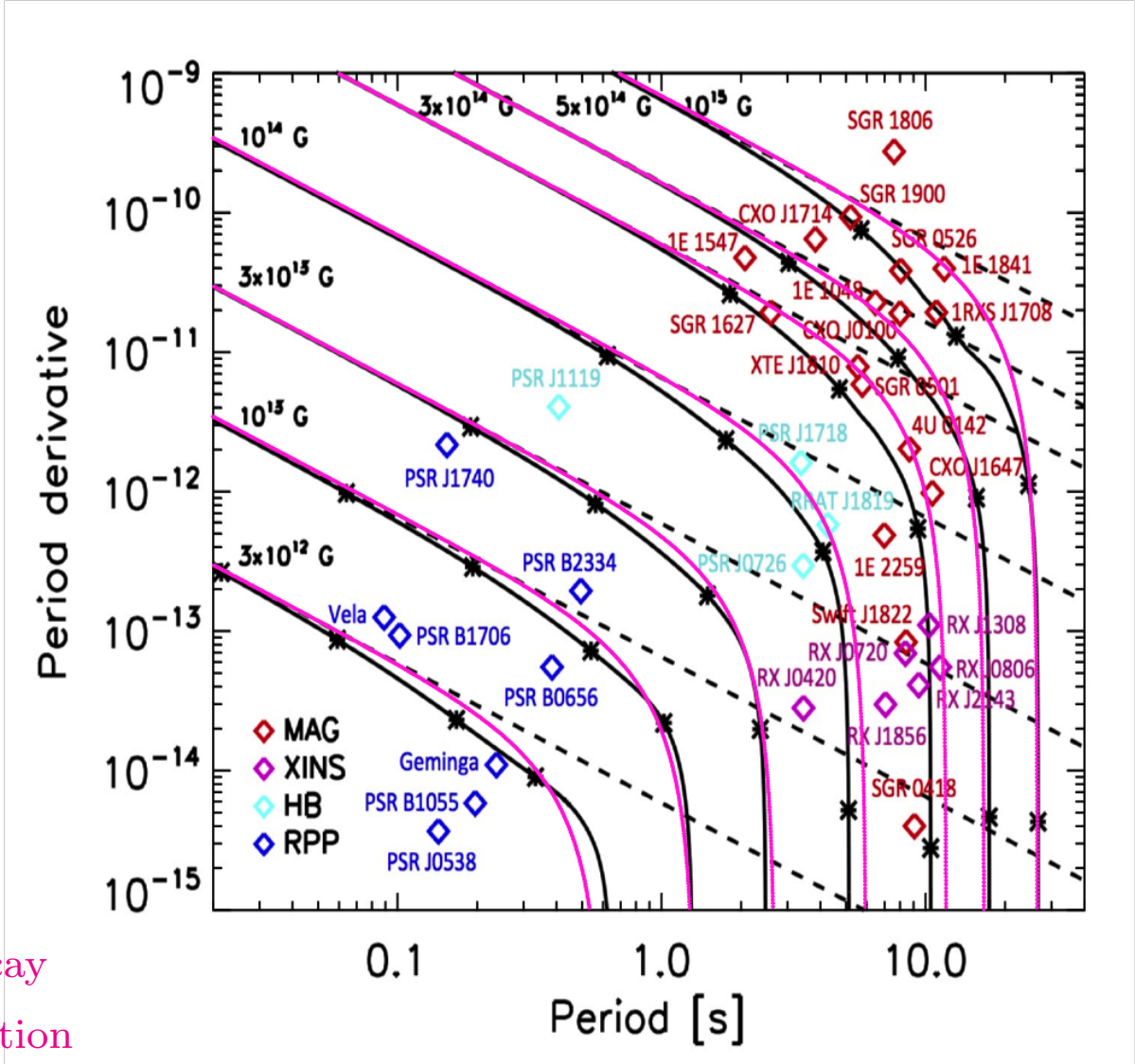
$$a = 1\ \mathrm{Myr}^{-1}$$

$$\tau_{\mathrm{Myr}} = 1\ \mathrm{Myr}$$

$$\alpha = 0.7$$

$$\frac{d\,B_{13}}{d\,t} = -a\,B_{13}^{1+\alpha}$$

$$\alpha = \begin{cases} 0 \rightarrow \text{Ohmic decay} \\ 1 \rightarrow \text{Hall induction} \\ 2 \rightarrow \text{Ambipolar diffusion} \end{cases}$$



private communication, José Pons

Radio and γ-ray beam geometry and emission

- Harding, Grenier & Gonthier (2007) and
- Pierbattista, Grenier, Harding, & Gonthier (2012)
- Core and conal beams
  - Conal — altitude dependent — Kijak & Gil (2003)
  - Empirical radio luminosity — P and $\dot{P}$ dependence Arzoumanian, Chernoff, Cordes (2002)

$$\mathcal{L}_\nu \;=\; \mathcal{L}_{\rm o}\, P^{\alpha_\nu}\, \dot{P}^{\beta_\nu}\ \mathrm{mJy}\cdot\mathrm{kpc}^2\cdot\mathrm{MHz}$$

  - Exponents α_ν and β_ν are free parameters searched by MCMC

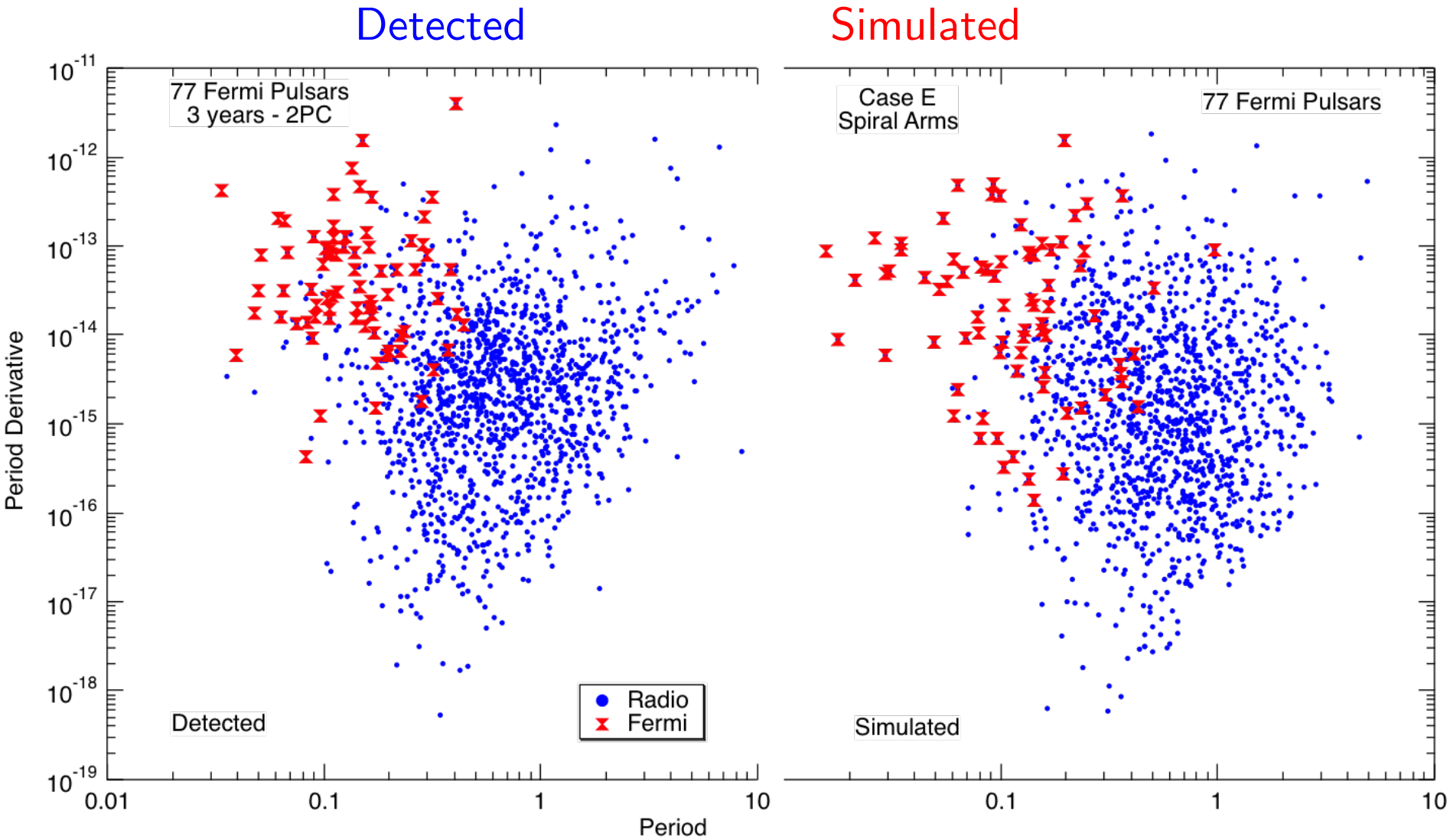
$$\alpha_\nu \;=\; -0.94, \quad \beta_\nu \;=\; 0.41$$

- Threshold characteristics of a select group of ten radio surveys
- γ-ray sky maps — Extended Slot Gap emission — Muslimov & Harding (2004)
  - Empirical γ-ray luminosity

$$\mathcal{L}_\gamma \;=\; f_\gamma\, P^{\alpha_\gamma}\, \dot{P}^{\beta_\gamma}\ \mathrm{eV/s}$$

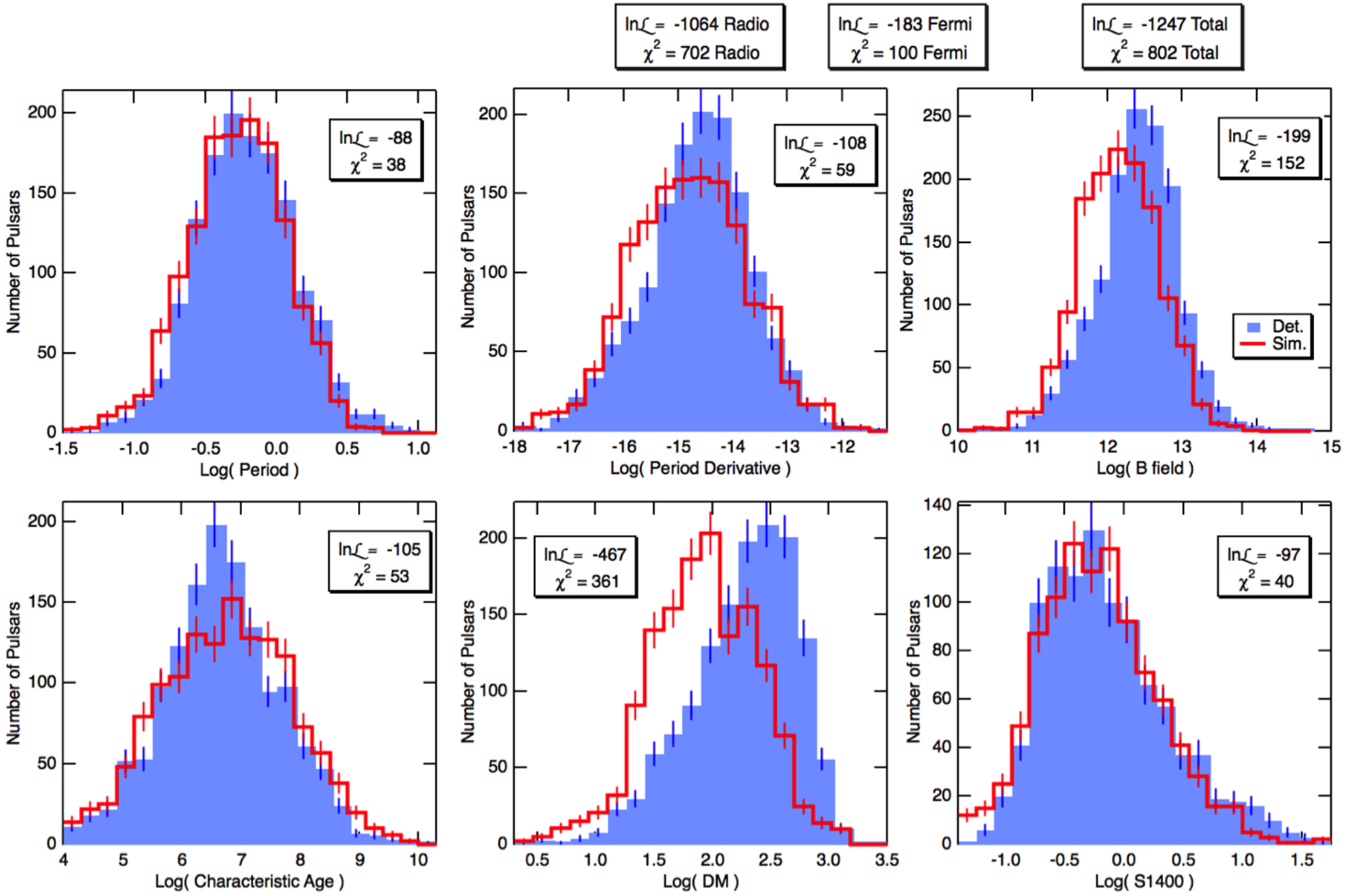
$$\alpha_\gamma \;=\; -2.55, \quad \beta_\gamma \;=\; 0.63$$

B field power-law decay model

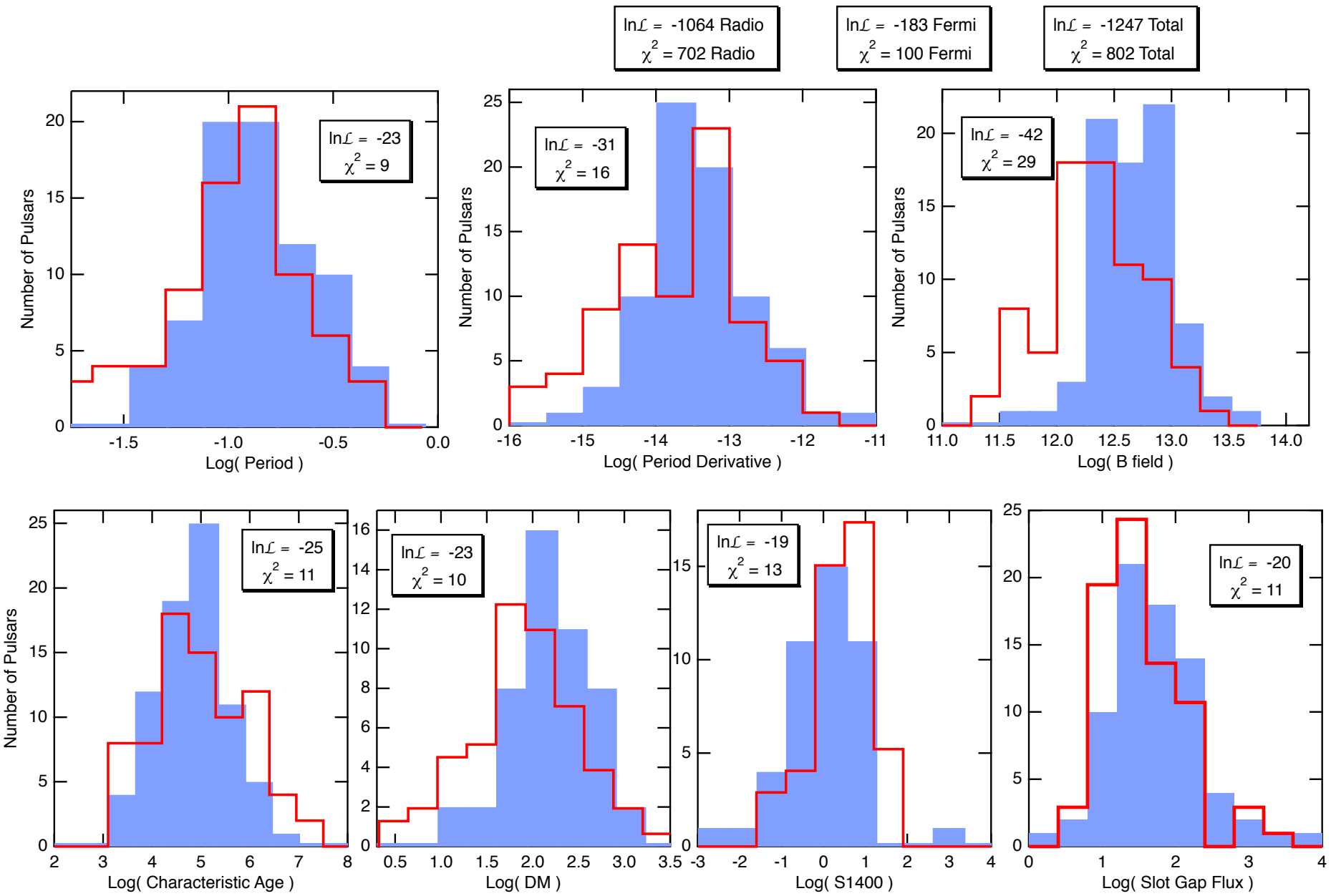


The Structure and Signals of Neutron Stars, from Birth to Death, March 24 - 28, 2014, Florence, Italy

Radio pulsars

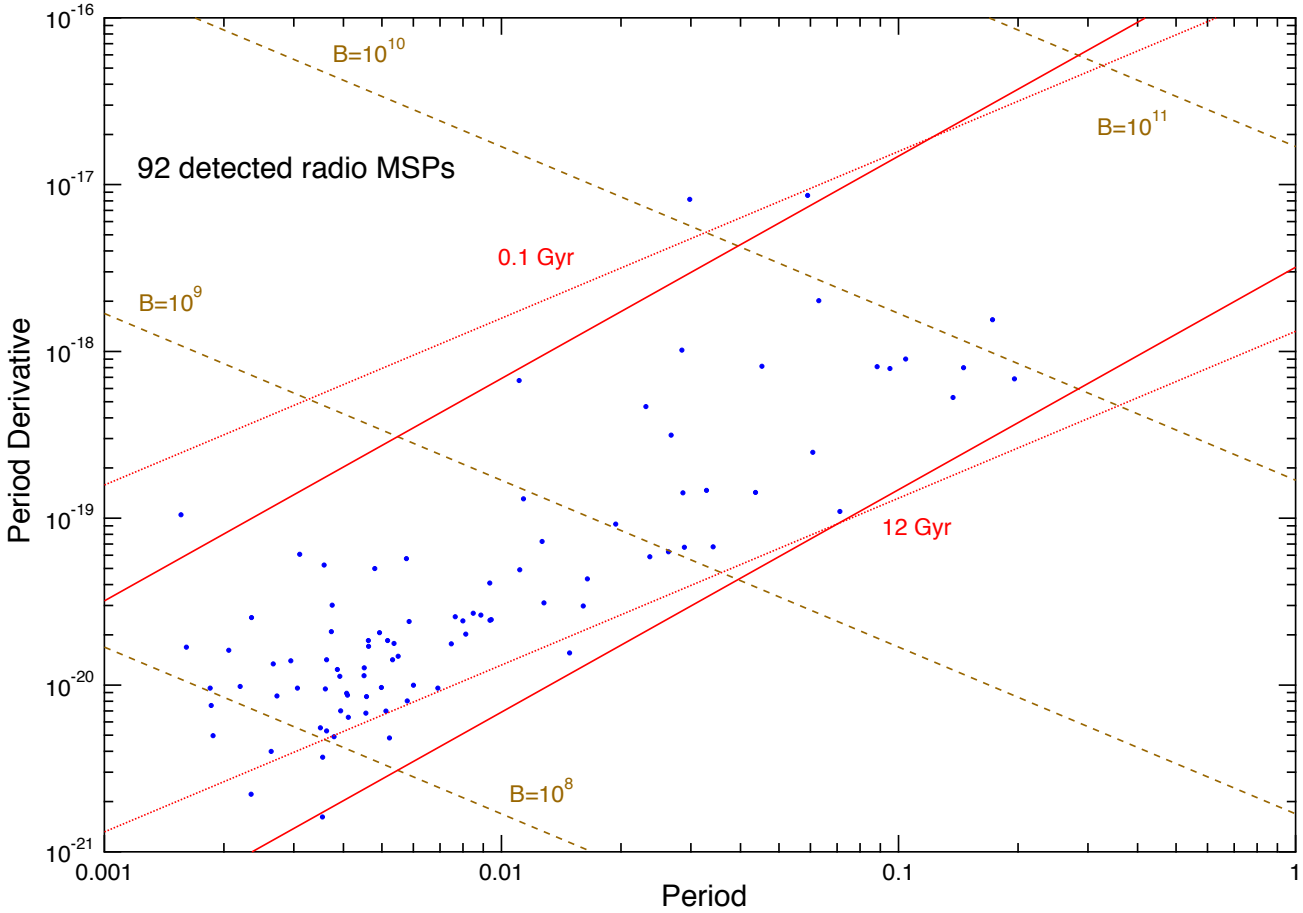


Fermi pulsars



Population synthesis of millisecond pulsars
Initial Magnetic Field and Period

- $P(B_8) \propto B_8^{-1.3}$
- $B_{\rm min} = 0.9 B_8$
- $P_{\rm o_{min}} = 1.3$ ms



Mass accretion lines — $P_{\rm o} = 0.18 \times 10^{3\delta/7} \times B_8^{6/7}$ ms where δ dithered between 0 and 2.8 — Lamb & Yu (2005)

MCMC - Radio and γ-ray Luminosities

- Assuming empirical radio and γ-ray luminosities as it the case of NPs

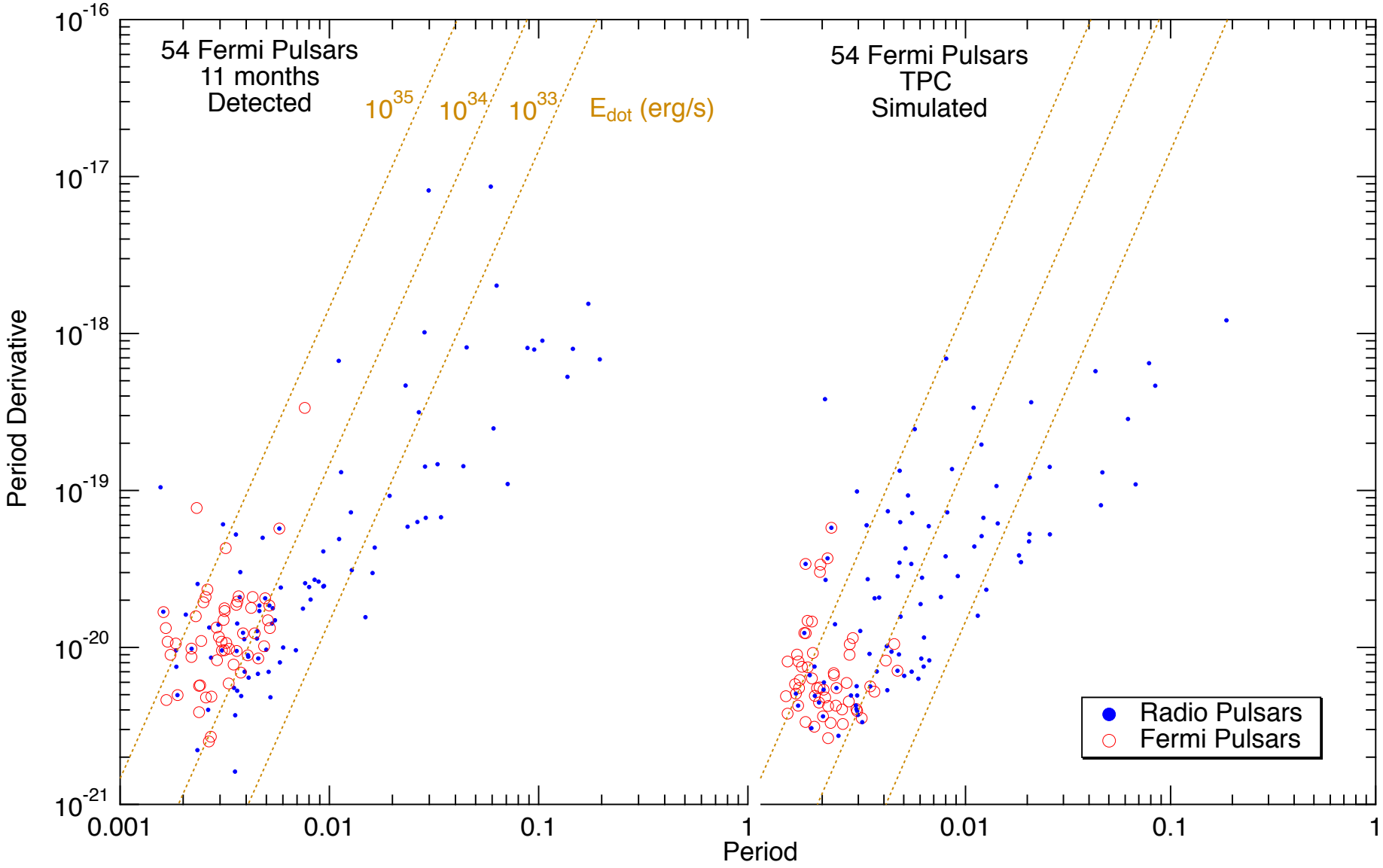
$$L \propto P^{\alpha} \dot{P}^{\beta}$$

- MCMC searches a 4D model parameter space selecting

$$\alpha_{\nu} = -1.07 \pm 0.17, \quad \beta_{\nu} = 0.59 \pm 0.12$$

$$\alpha_{\gamma} = -2.7 \pm 1.0, \quad \beta_{\gamma} = 1.1 \pm 0.4$$

$\dot{P} - P$ - TPC

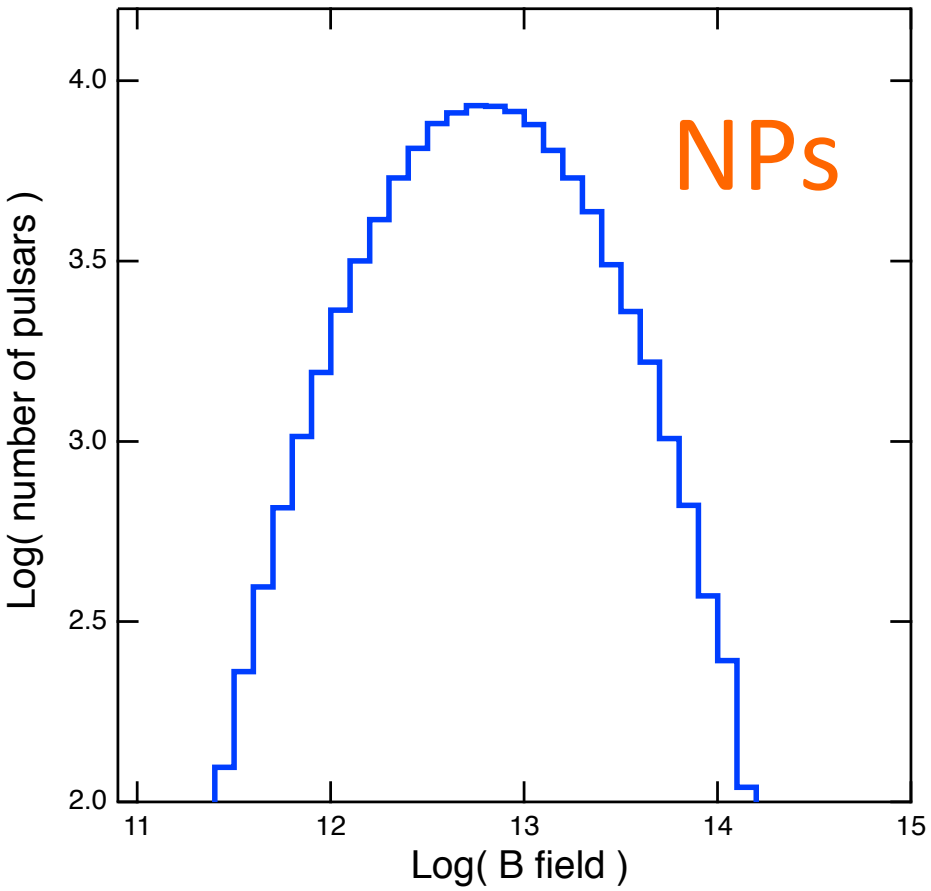

54 Fermi Pulsars
11 months
Detected
10^{35}
10^{34}
10^{33}
E_{dot} (erg/s)
54 Fermi Pulsars
TPC
Simulated
Radio Pulsars
Fermi Pulsars
Period Derivative
Period
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
0.001
0.01
0.1
1

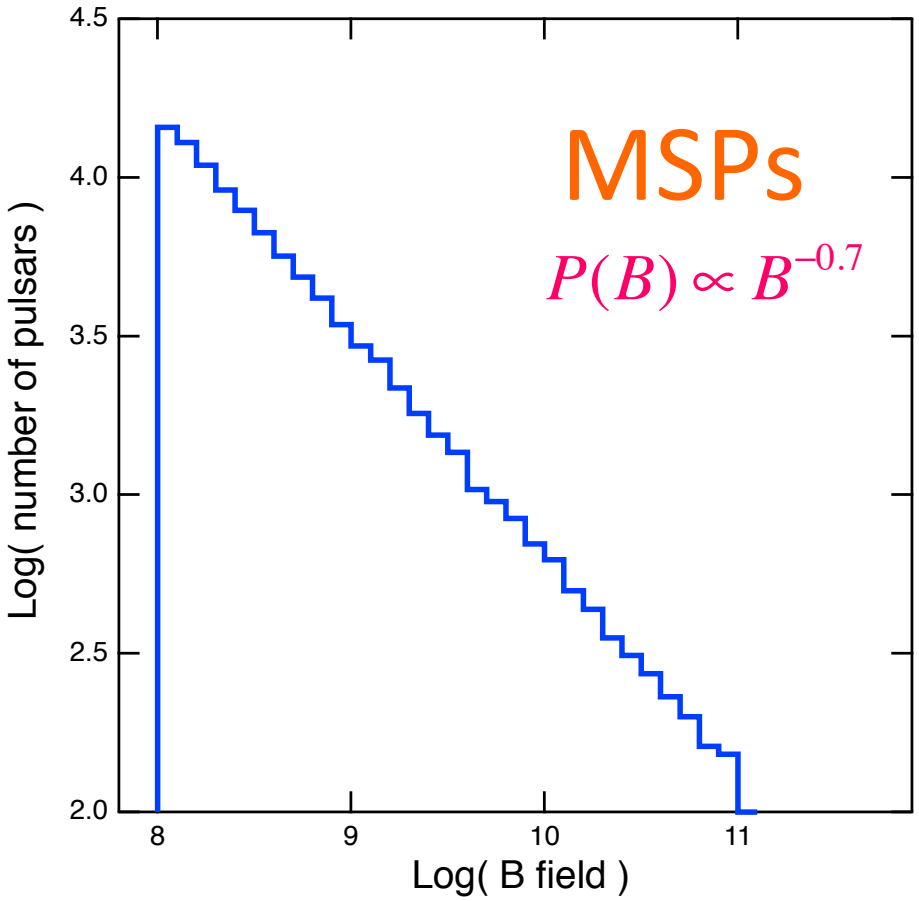
Summary of Population Synthesis of MSPs

Catalog	Period	Detected	Simulated			
			TPC	OG	RALTPC	PSPC
BSL	3 months	13	29	30	27	29
1FGL	11 months	54	54	54	54	54
2FGL	2 years	68	76	77	80	80
3FLG	4 years	82	107	106	110	109
	5 years		119	118	121	122
	10 years		162	153	170	160

The Alicante connection: NPs to MSPs - field decay

How do we go from a log-normal B distribution (NPs) to a power law B distribution (MSPs)?





A natural consequence of the power-law decay of the magnetic field!

$$B = \frac{B_{\rm o}}{[1 + a\,\alpha\,B_{\rm o}^{\alpha}\,t_6]^{1/\alpha}}$$

For large times $(a\,\alpha\,B_{\rm o}^{\alpha}\,t_6) >> 1$

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We are assuming a constant birth rate, therefore the number of present pulsars at time t is

$$N = c\,t_6$$

where c is the constant birth rate of MSPs — $c = 4$ to 5 per Myr

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$$N = \frac{B^{-\alpha}}{a\,\alpha\,c}$$

Issues based on previous simulations

$$B_{\rm min}^{\alpha} = \frac{1}{a\,\alpha\,t_{6_{\rm max}}} = \left(9\times10^{-6}\right)^{\alpha}$$

If we assume, $P(B_8) \propto B_8^{-1.3}$ — as we have in previous simulations

- $\alpha = 1.3$ does not work!

$$a = \frac{1}{1.3\times\left(9\times10^{-6}\right)^{1.3}\times12000} = 232\ {\rm Myr}^{-1}$$

- So we take $a = 1\ {\rm Myr}^{-1}$ and $\alpha = 0.7$ for NPs (Viganò et al. 2013) and apply them to MSPs

$$t_{6_{\rm max}} = \frac{1}{0.7\times1\ \ {\rm Myr}^{-1}\times\left(9\times10^{-6}\right)^{0.7}} = 4900\ {\rm Myr}$$

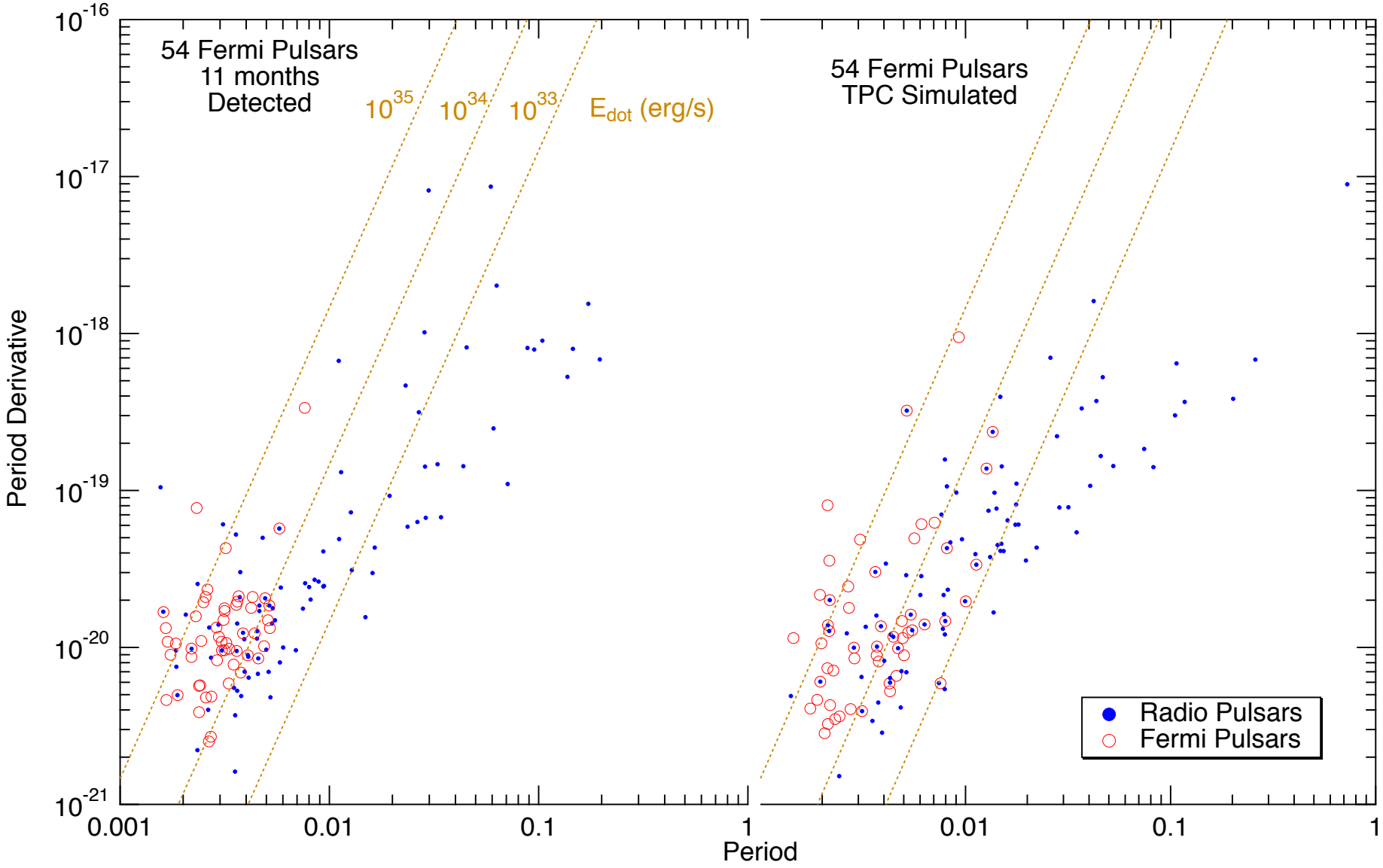
Proposed new simulation

- From NPs $\alpha = 0.7$ and $a = 1\ \mathrm{Myr}^{-1}$ to describe Hall induction and Ohmic decay of crustal field
- Switch to $\alpha = 1.3$ and $a = 0.01\ \mathrm{Myr}^{-1}$ to describe ambipolar diffusion of the core field — pure guess, but not sensitive
- Theoretical details pending and the code development
- Redo the MSP simulation to test the scenario with

$$P(B_8) \propto B_8^{-0.7}$$

- and $\alpha = 1.3$ and $a = 0.01\ \mathrm{Myr}^{-1}$

$\dot{P} - P$ - TPC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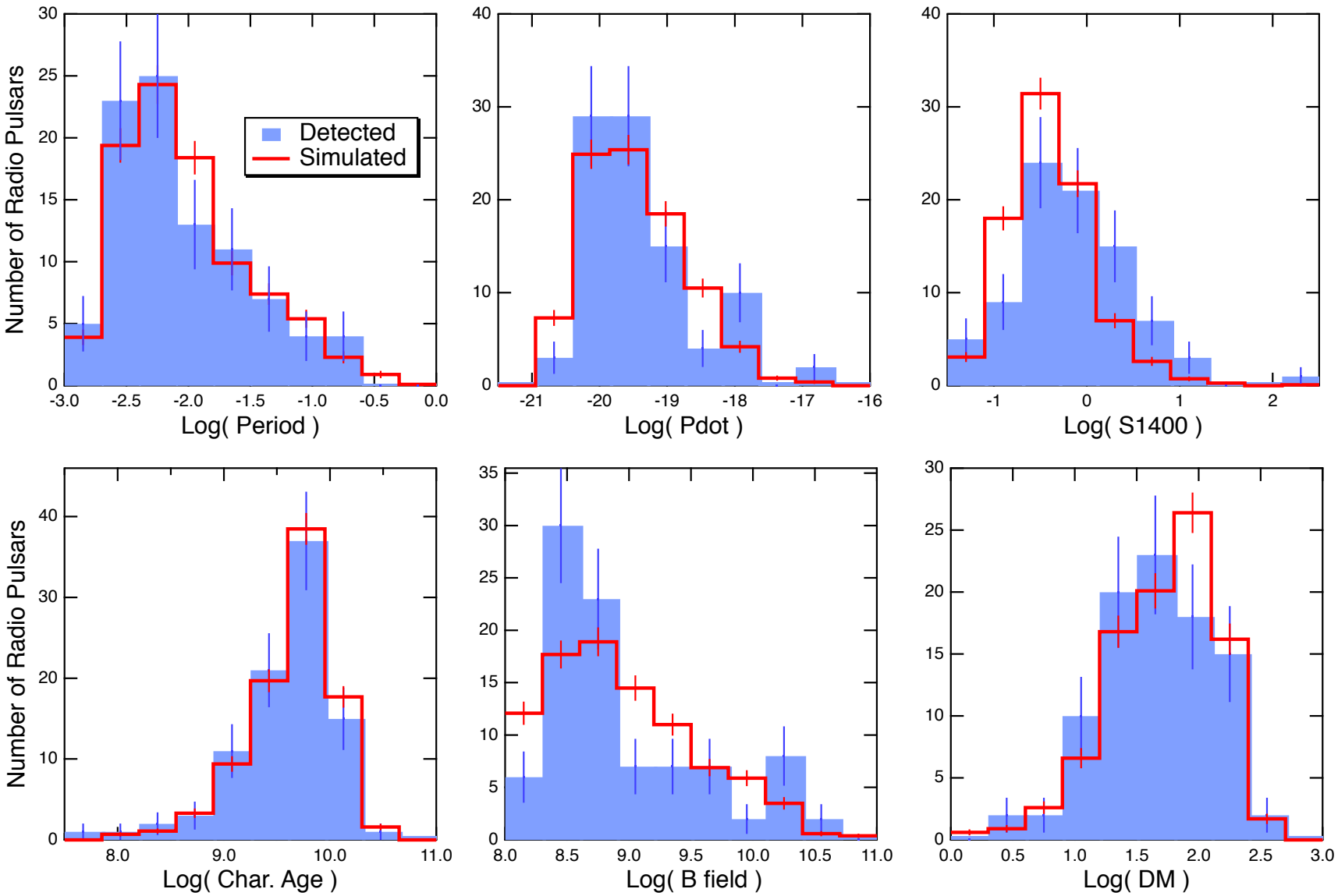
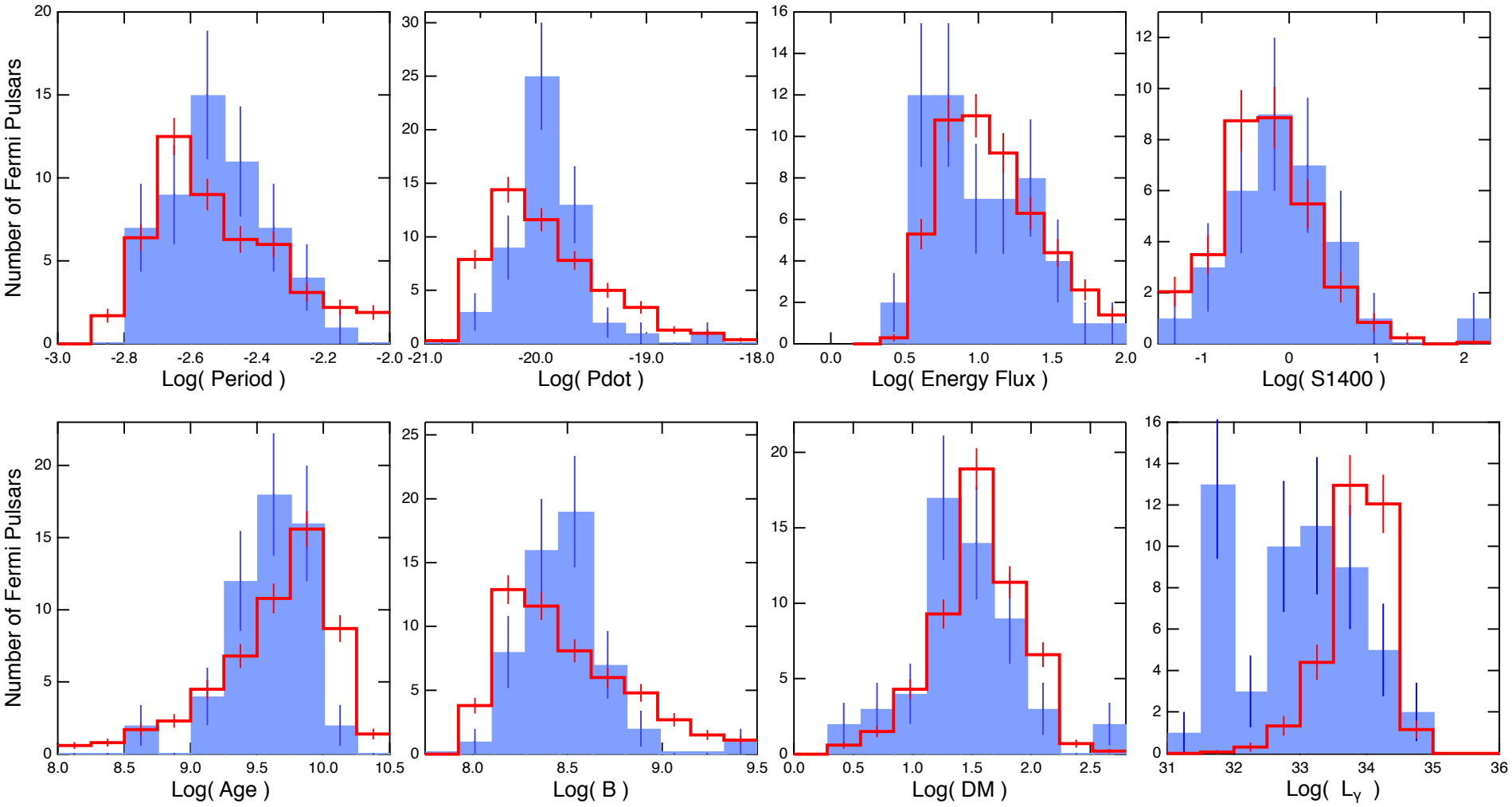
10^{-18}
10^{-19}
10^{-20}
10^{-21}
0.001
0.01
0.1
1

Radio pulsars



From $\alpha_\nu = -1.07, \quad \beta_\nu = 0.59,$ to $\alpha_\nu = -0.94, \quad \beta_\nu = 0.05$

Fermi pulsars



From $\alpha_\gamma = -2.7, \quad \beta_\gamma = 1.1,$ to $\alpha_\gamma = -1.77, \quad \beta_\gamma = 0.23$

Conclusions

- Normal pulsars and binary pulsar systems may come from a similar parent distribution of magnetized neutron stars.
- A log-normal B field distribution of young (normal, isolated) pulsars can be converted into a power-law B field distribution via standard crustal Hall induction and Ohmic field decay leaving ambipolar diffusion to later play a role within the neutron star core of old dead pulsars that can then be recycled into millisecond pulsars via mass accretion from a stellar companion spinning up the neutron star.
- The cutoff $B_{\rm min}$ in the assumed B field birth distribution of MSPs may be an indication of maximum age and minimum period of active MSPs.
- Detailed theoretical work is pending as well as code development for an adequate full population simulation.