Tenth International Fermi Symposium

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Population Synthesis of canonical pulsars

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Outline

1 Galactic pulsar population

2 Model

3 Results

4 Summary

1 Galactic pulsar population

Observations

- ~ 3000 pulsars detected in radio (Manchester et al. 2005).
- Also bright in X-rays, optical and gamma-rays.
- Over 250 gamma-ray pulsars discovered with Fermi-LAT (Abdo et al. (2013), Smith et al. (2019)).

→ Statistical treatment of the γ-ray population in combination with deep radio surveys of the Galactic plane.

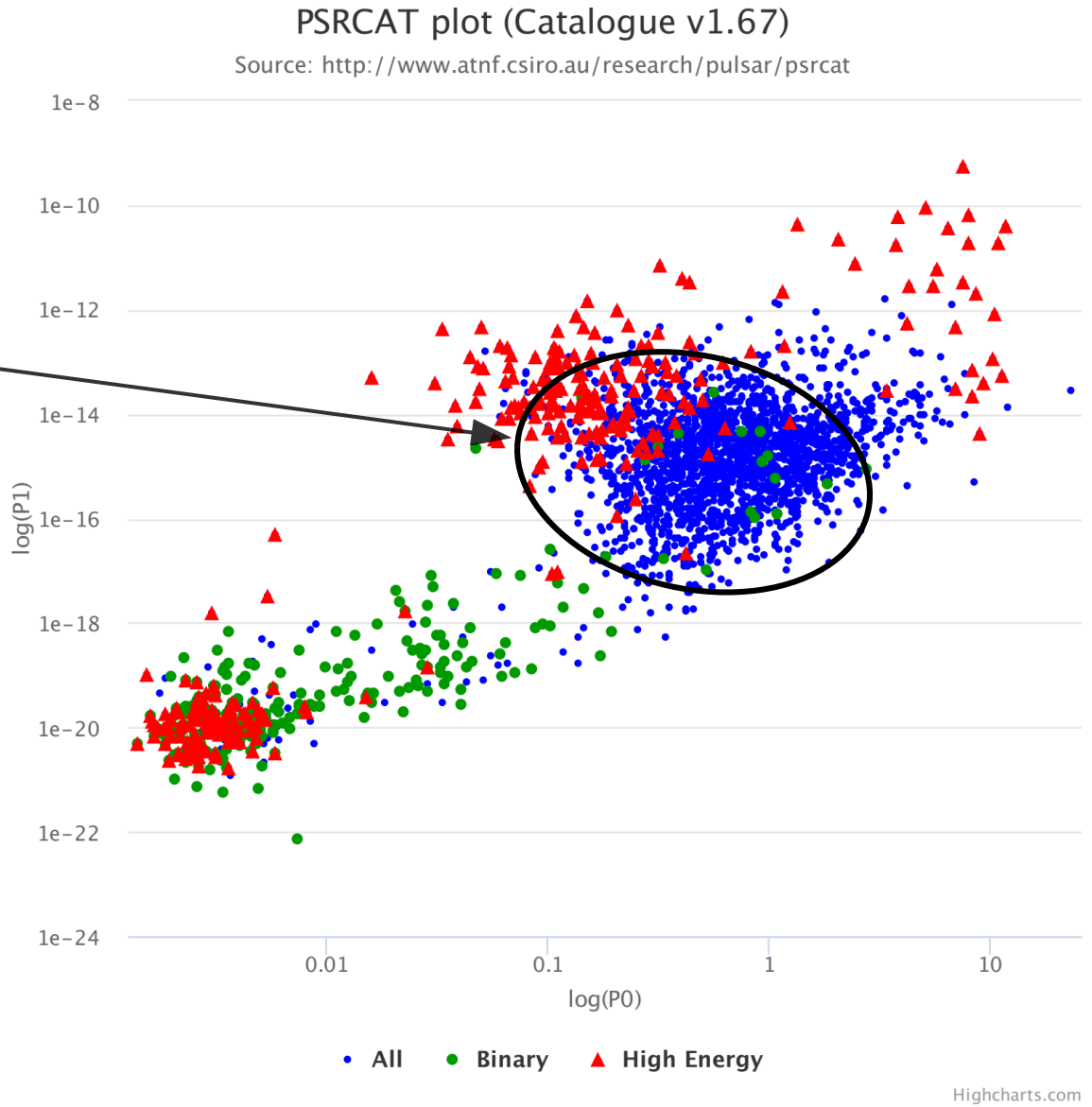
1 Pulsar population synthesis
Observations

Canonical population:

- Non-binaries
- P > 20 ms
- No magnetars

$\log(\dot{E})$ (in W)	$N_{\rm tot}$	$N_{\rm r}$	$N_{\rm g}$	$N_{\rm rg}$
> 31	2	0	0	2
> 28	197	101	35	61
total	2665	2553	63	84

Ė: spin-down luminosity



1 Galactic pulsar population

Pulsar population synthesis (PPS)

Goals:

- Inferring the underlying properties of pulsar population (P,$\dot{P}$,B,d)
- Predictions for future surveys (SKA)

2 approaches:

- Snapshot (Taylor & Manchester (1977), Lyne et al. (1985))
- Evolution (Faucher-Giguère & Kaspi (2006))

Model:

Magnetosphere

- Force-free magnetosphere + evolution of the inclination angle + magnetic field decay applied to both radio and gamma-ray pulsars

Emission:

New

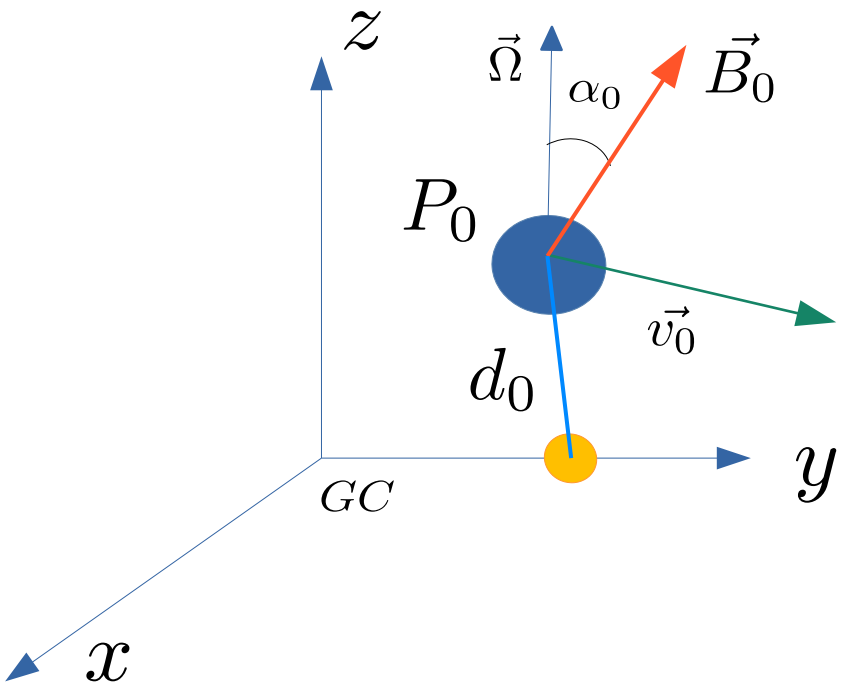
- Polar cap model for radio emission
- Striped wind model for the pulsed gamma ray emission

2 Model

Generating a synthetic pulsar population

- 10^7 pulsars simulated with constant birth rate

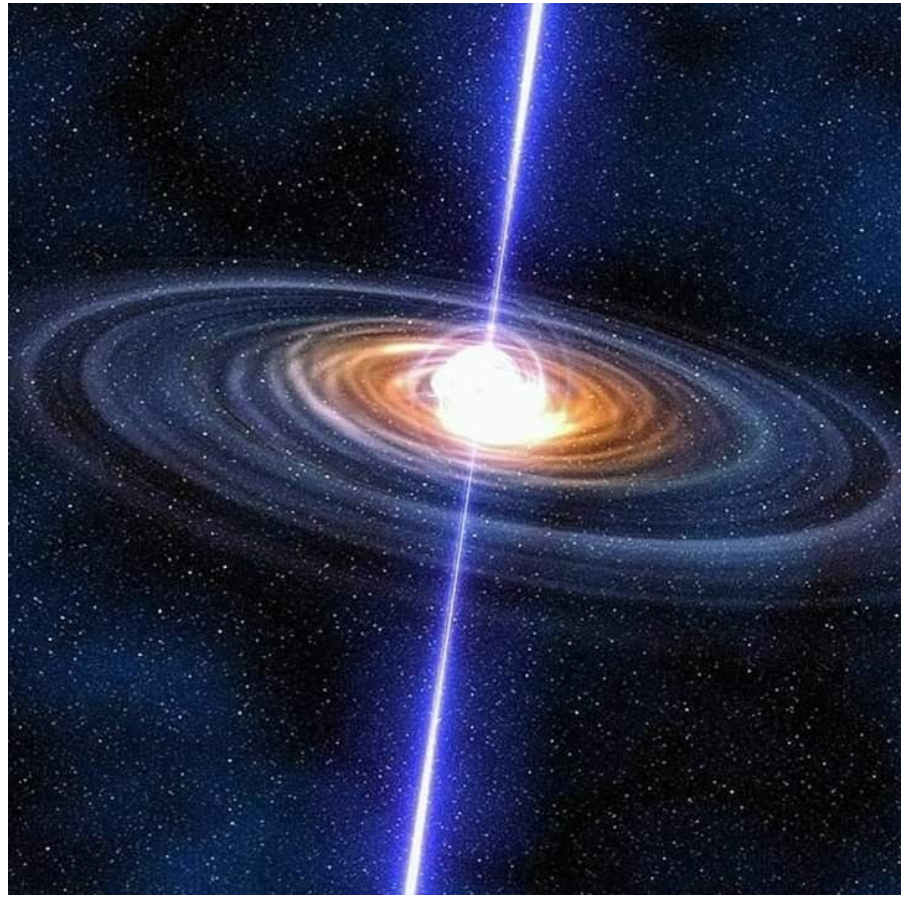
- Initial intrinsic parameters:
  - B_0: initial magnetic field (constant)
  - P_0: initial period
  - α_0: inclination angle at birth
  - n_Ω: unit vector along the rotation axis
  - v_0: initial kick velocity
  - (x_0,y_0,z_0): initial position



- Pulsars are evolved from their birth to the present $(P, \dot{P}, \alpha, B, d)$

2 Model
Detection

- Luminosity of the pulsar
  - Radio (Johnston et al. (2020))
  - Gamma (Kalapotharakos et al.(2019))



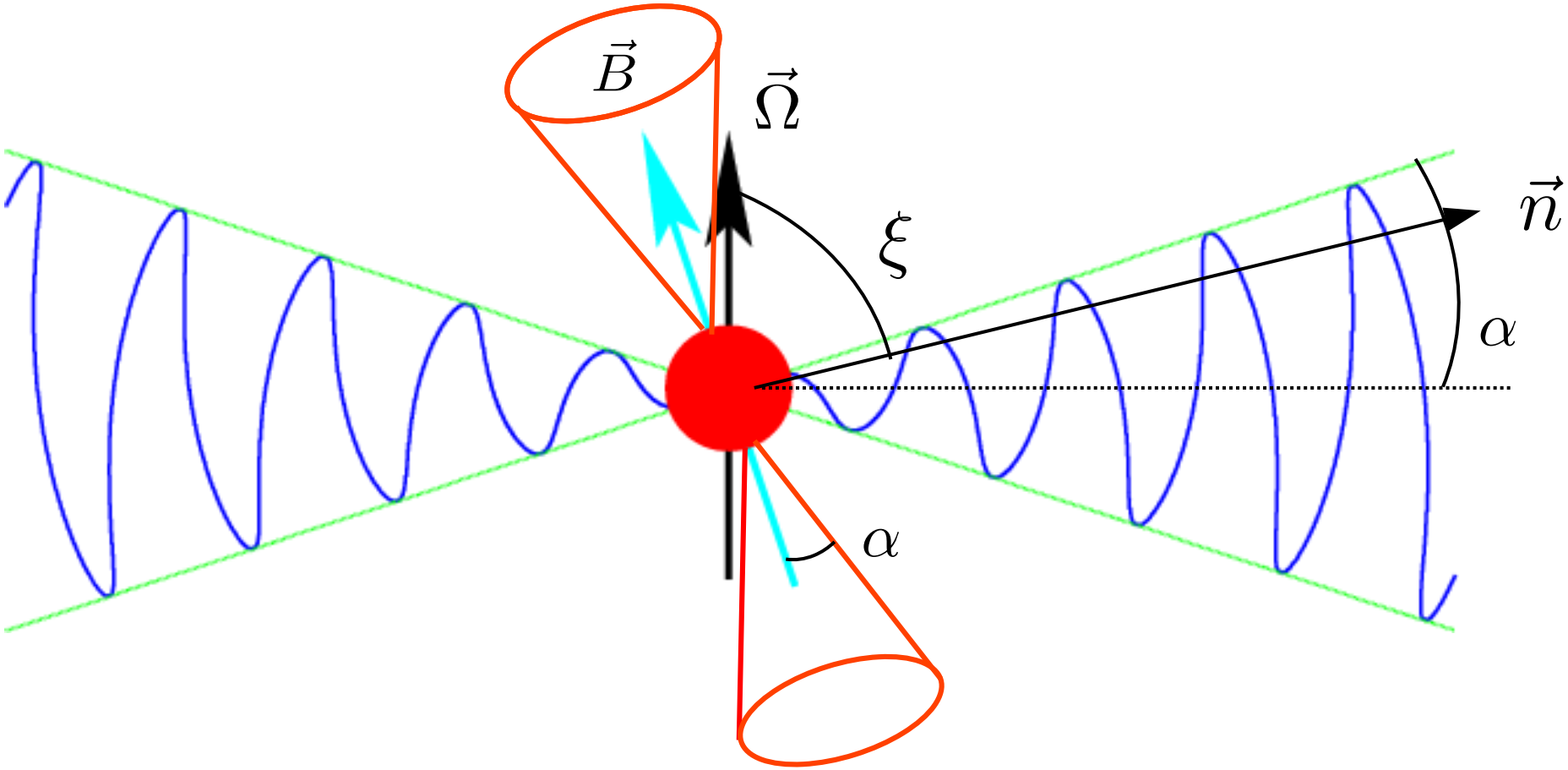
- Sensitivity of the instruments:
  - Fermi/LAT (gamma)
  - Radio ~0.15 mJy (Parkes and Arecibo)

- Beaming fraction:
  - Emission beaming toward us in radio and/or gamma

2 Model
Beaming fraction

Striped wind

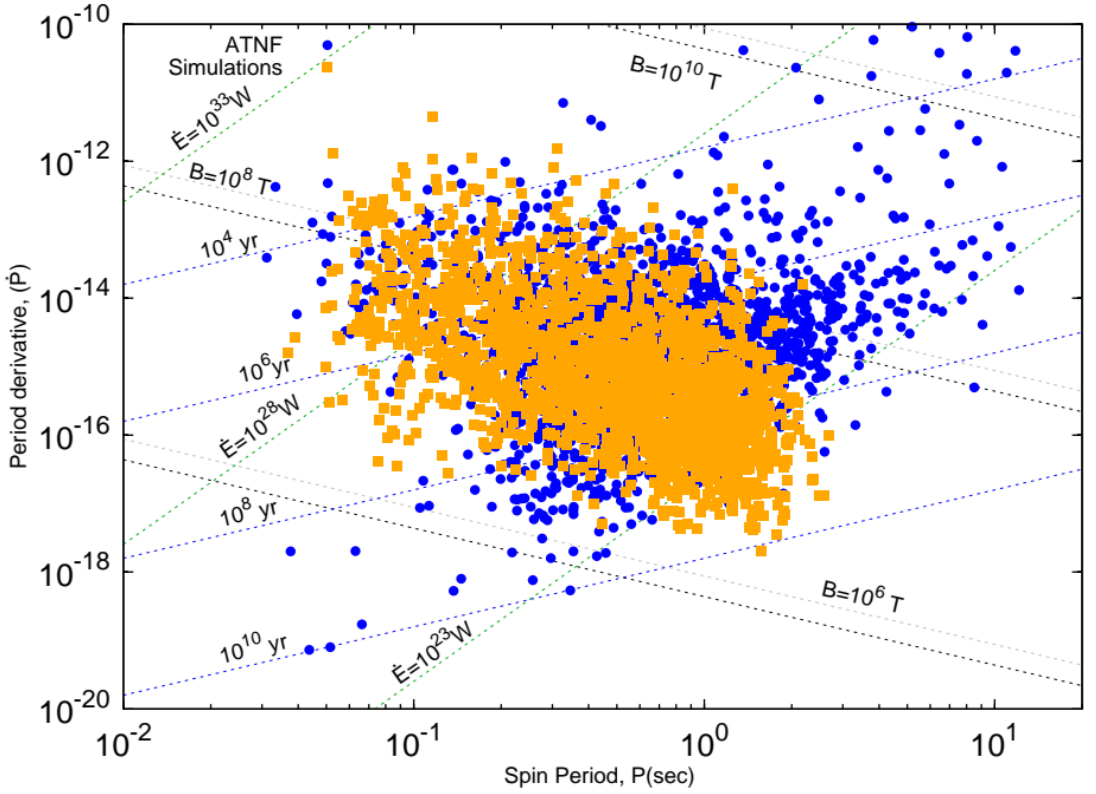
Polar cap model



2 Model
P-Ṗ diagram

τ_{birth} (1/yr)	P_{mean} (ms)	B_{mean} (T)	$\bar{\tau}_d$
70	60	2.5×10^8	4.6×10^5 yr

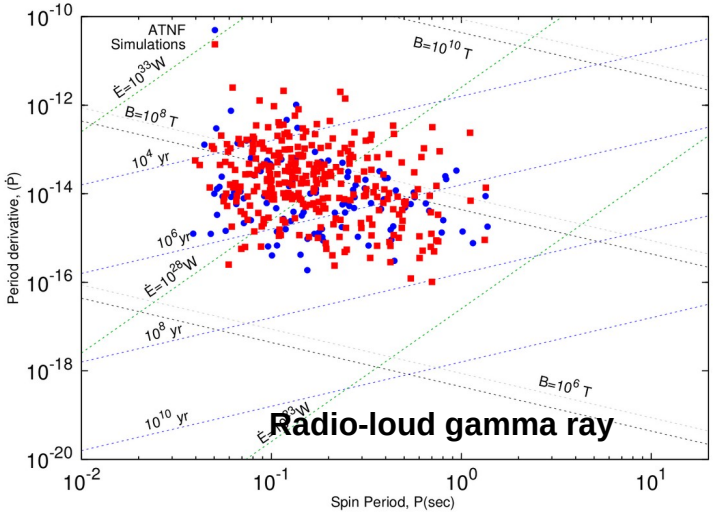
- More pulsars for lower Ṗ.
- Long period pulsars slow down less rapidly.
- Sensitive to the initial distributions of P, Ṗ and B. (Igoshev et al. 2022)
- Modelling the ISM

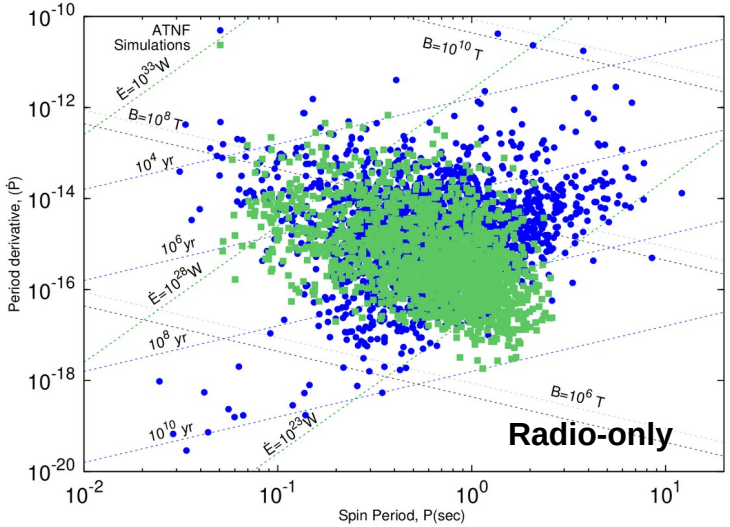


3 Results
Pulsar types

Simulations

$\log(\dot{E})$ (in W)	$N_{\rm tot}$	$N_{\rm r}$	$N_{\rm g}$	$N_{\rm rg}$
> 31	3	0	1	2
> 28	238	87	47	104
total	2155	1864	122	169





Observations

$\log(\dot{E})$ (in W)	$N_{\rm tot}$	$N_{\rm r}$	$N_{\rm g}$	$N_{\rm rg}$
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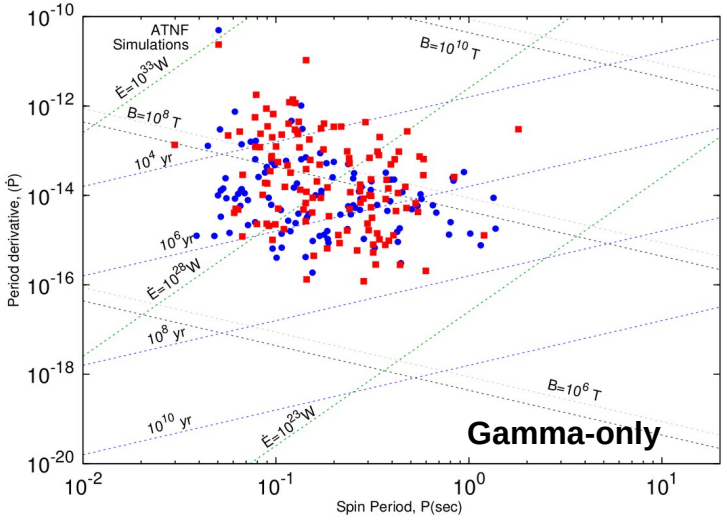
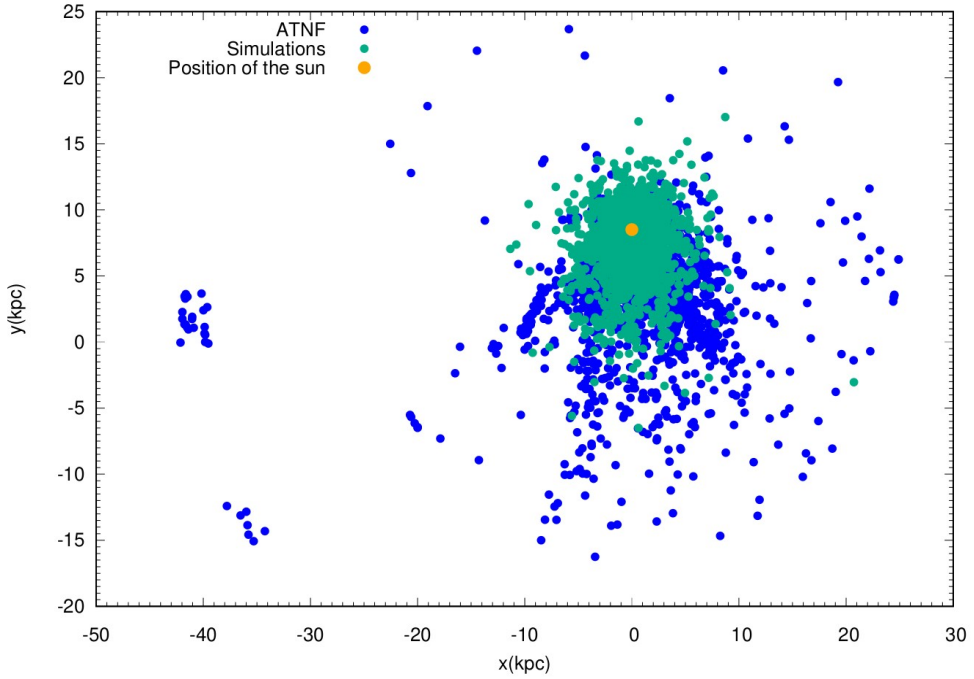
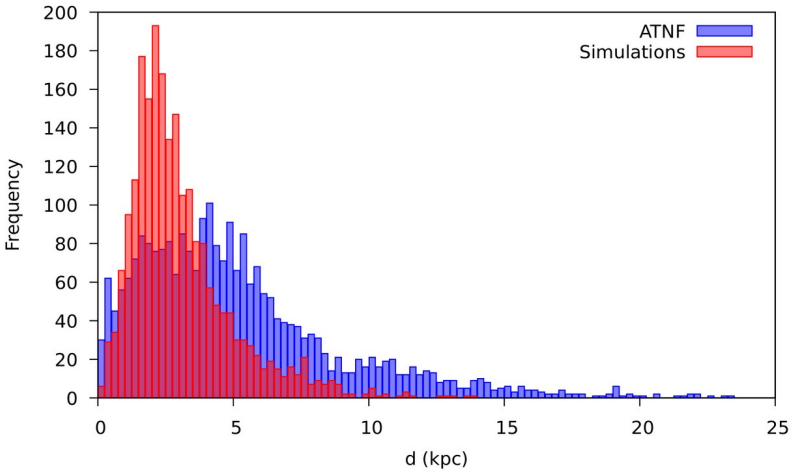
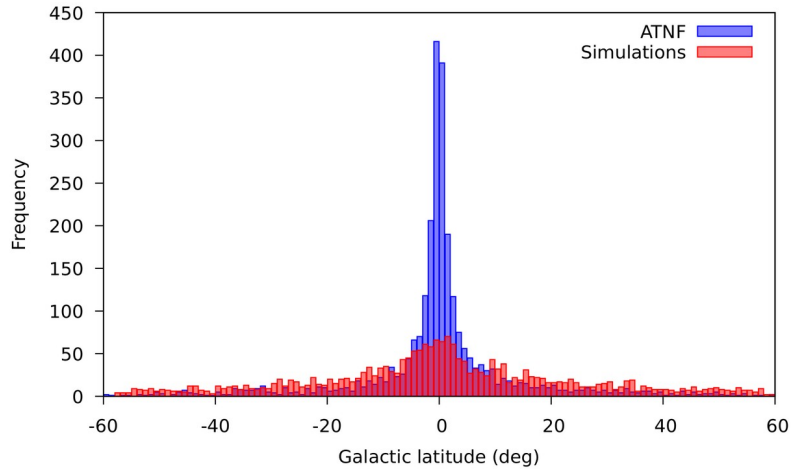


3 Results
Spatial distribution



$$F_r \propto \left(\frac{1}{d}\right)^2 \left(\dot{E}\right)^{1/4}$$





- Observed distance not accurately determined (model dependent).
- More refined treatment of the sensibility depending on the latitude
- Better description of the initial spatial distribution + birth kick velocity should be implemented.
- Take into account the galactic potential.

3 Results

Effects of geometry and Smin on the detection of gamma pulsars

Pulsar type	Model	Geometry	Observations
N_r/N_{tot}	84%	6%	95%
N_g/N_{tot}	7%	84%	2%
N_r/N_{tot}	9%	9%	3%

Still a lot of gamma-ray pulsars to be detected!!

Pulsar type	S_{min}	$S_{min}/2$	$S_{min}/5$
N_r/N_{tot}	84%	76%	57%
N_g/N_{tot}	7%	12%	26%
N_r/N_{tot}	9%	12%	17%

Deep follow-up surveys at 1.4 GHz of gamma-ray sources:

$\text{if glat} < 2^\circ, S_{min} = 4 \times 10^{-15}\ \text{Wm}^{-2}$

Blind survey

$S_{min} = 16 \times 10^{-15}\ \text{Wm}^{-2}$

Summary

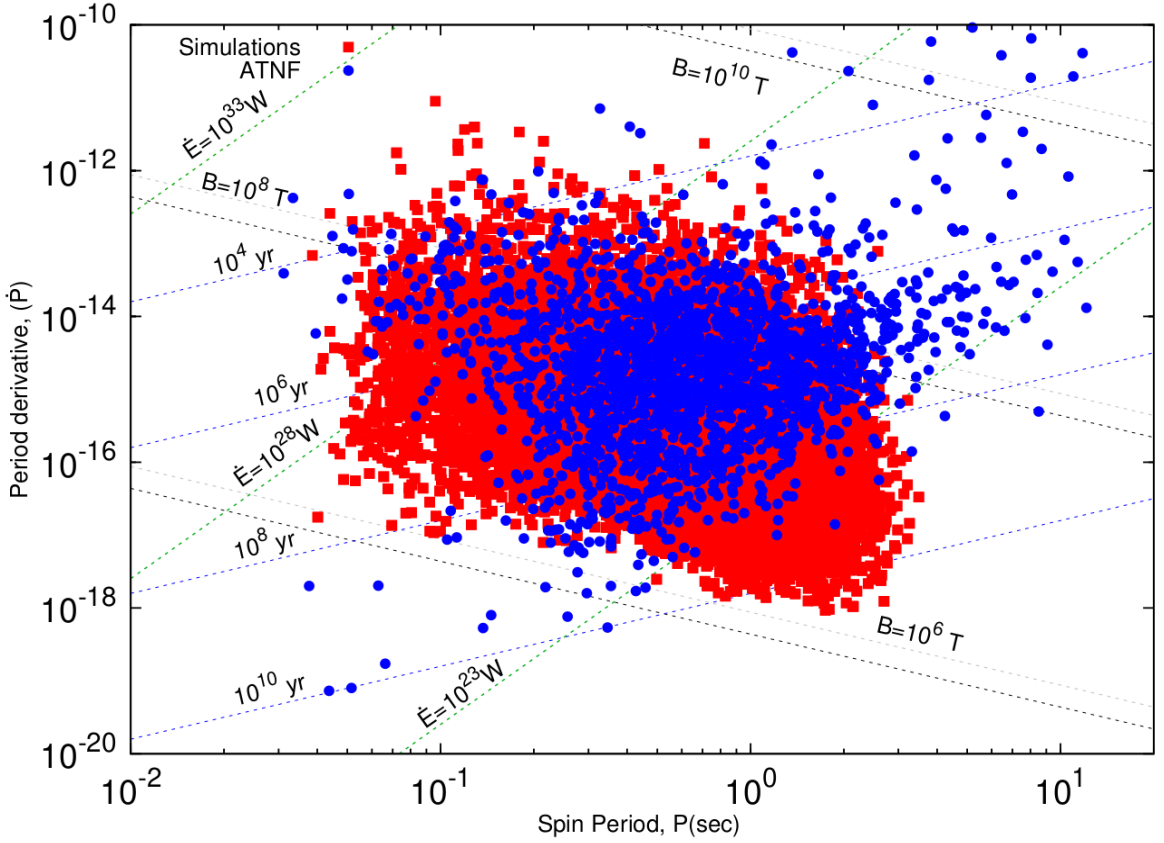
- Force-free evolution scenario + magnetic field decay + striped wind emission model for gamma-rays.

  ➡ reproduce satisfactorily P-Ṗ diagram and the number of detected pulsars.

- PPS are valuable and reliable tool to constrain the basic physics of neutron star electrodynamics and for **predictions.**

- Future prospects:
  - Galactic potential
  - Effect of the ISM
  - Radio emission death line

Prediction for SKA (50 times more sensitive): ~ 27000 detected pulsars



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Thank you for your attention!

Ludmilla Dirson

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Backup

Model

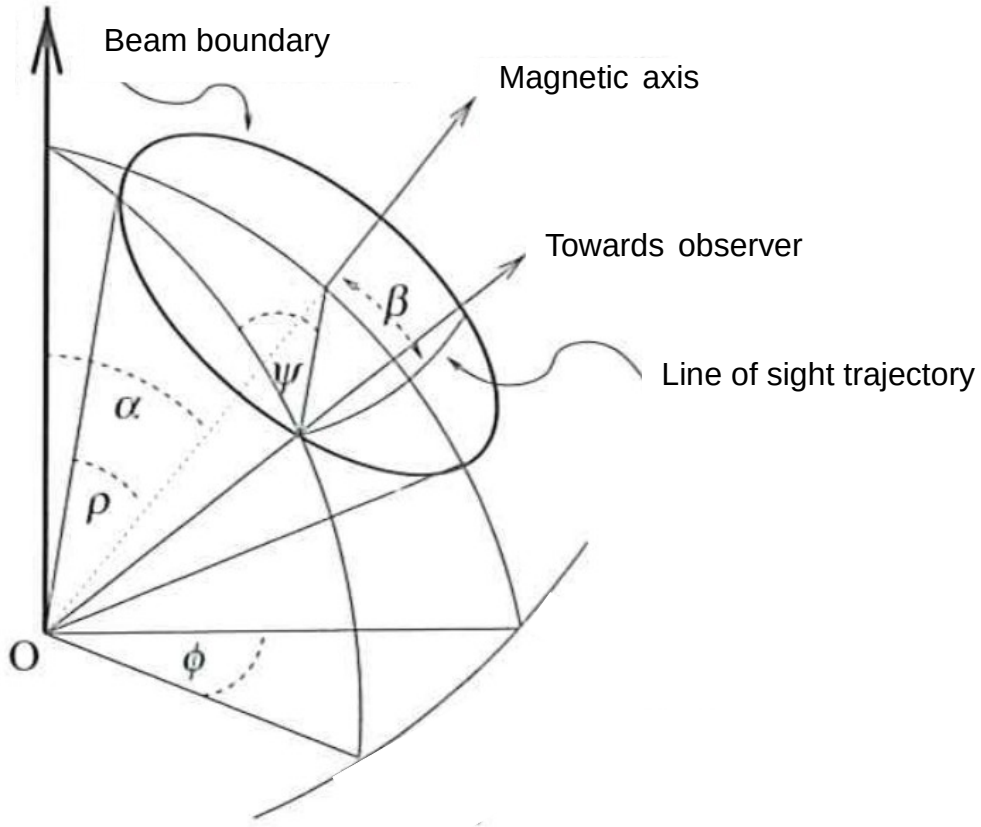
Generating a synthetic pulsar population

Pulsar's intrinsic parameters:

- B_0: initial magnetic field (constant) **(Gaussian in log space)**
- P_0: initial period **(Gaussian)**
- α_0: inclination angle at birth **(Isotropic)**
- n_Ω: unit vector along the rotation axis **(Isotropic)**
- v_0: initial kick velocity **(Maxwellian)**
- (x_0,y_0,z_0): initial position
- d: distance to Earth
- P and $\dot{P}$: current period and its time derivative
- α, current inclination angle

Model

Beaming fraction: radio



$$\rho \propto \frac{1}{\sqrt{P}}$$

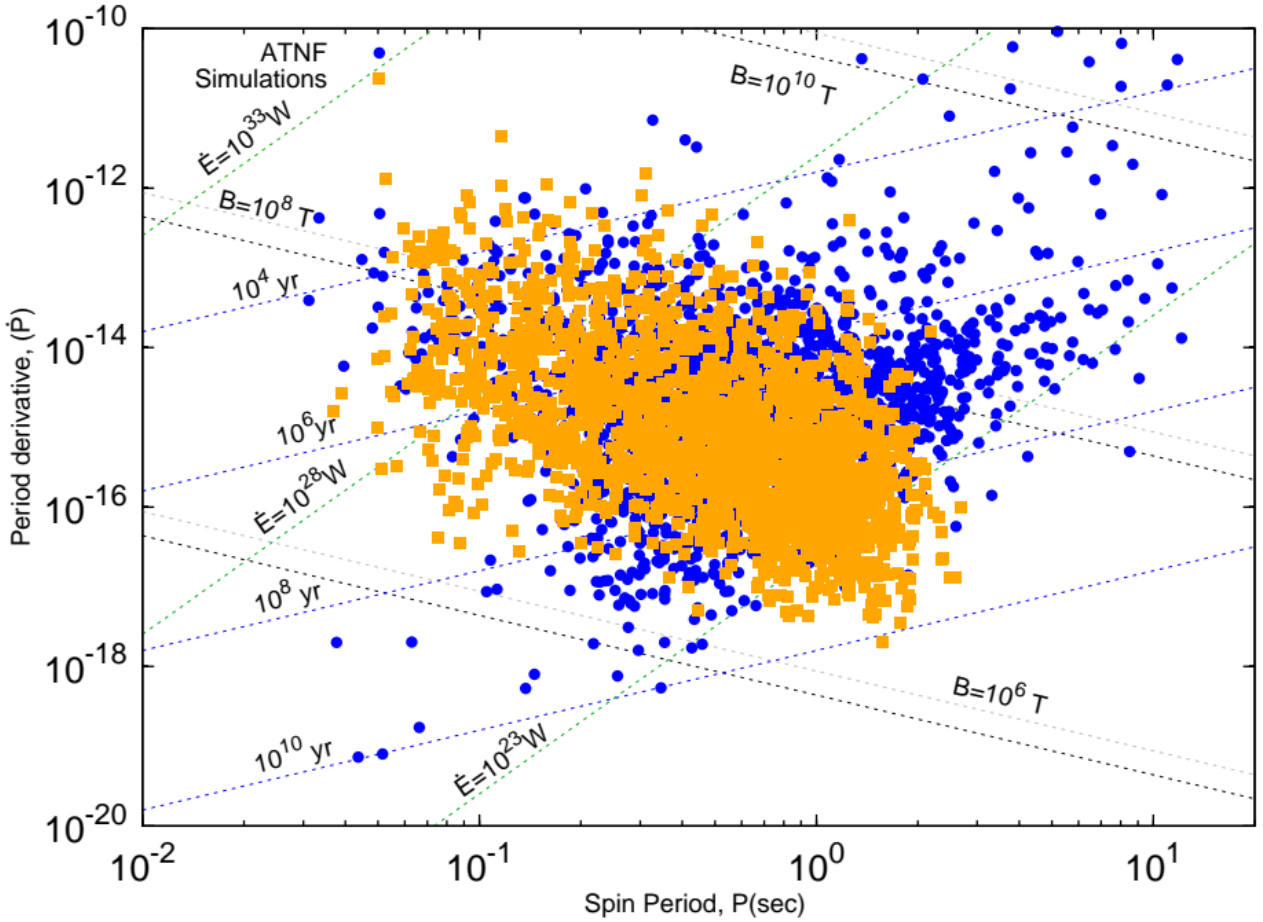
- Pulsar *can* be detected if $\beta = |\xi - \alpha| \leq \rho$

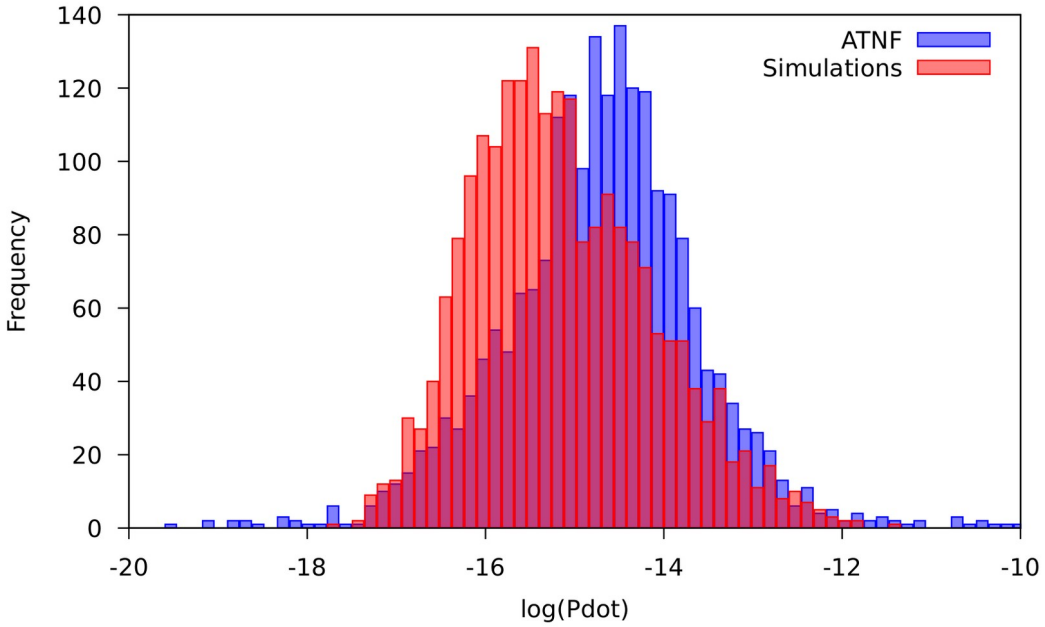
  or $|\xi - (\pi - \alpha)| \leq \rho$

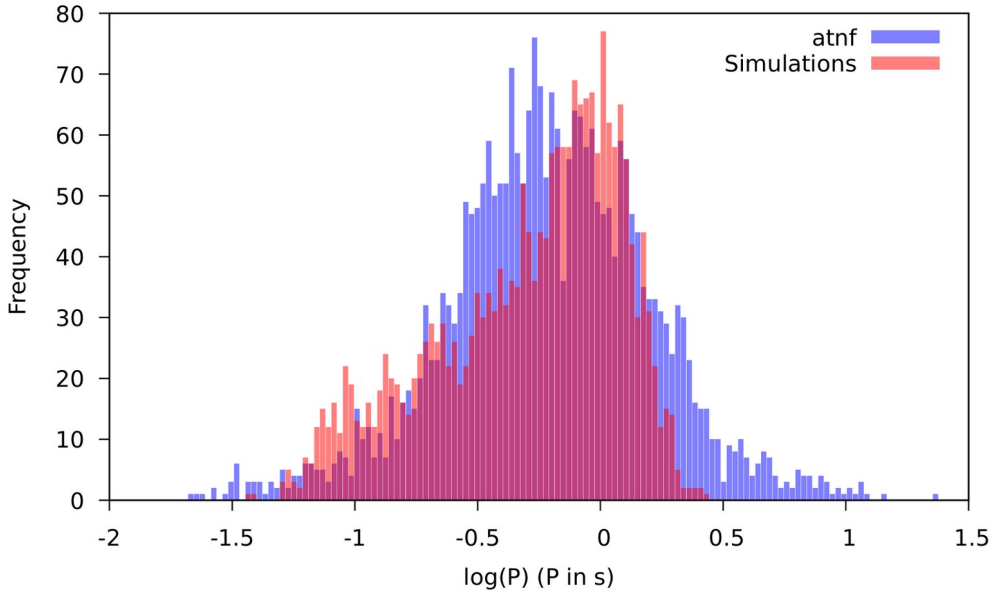
Lorimer, D. R. & Kramer, M. 2004, Handbook of Pulsar Astronomy

Results

P-Ṗ diagram

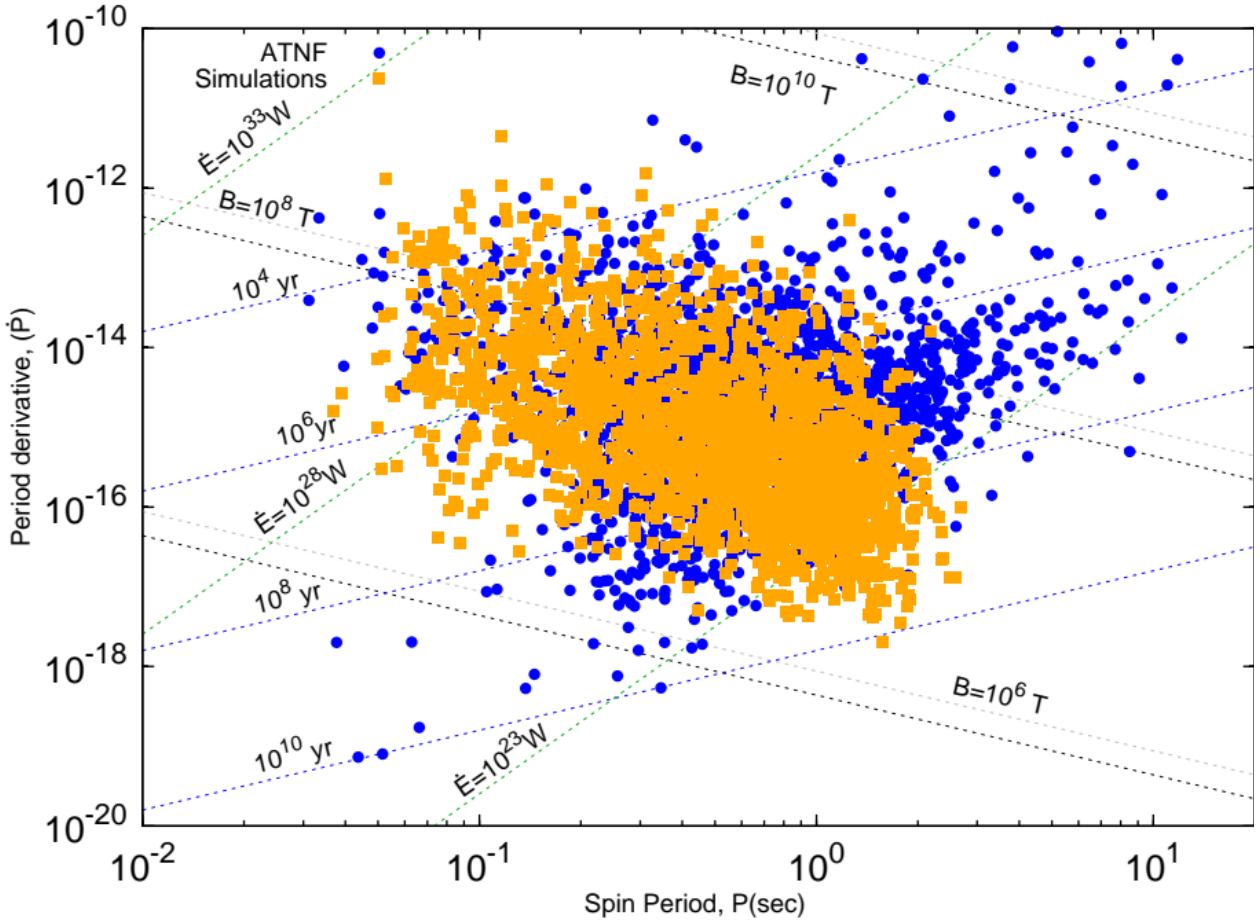


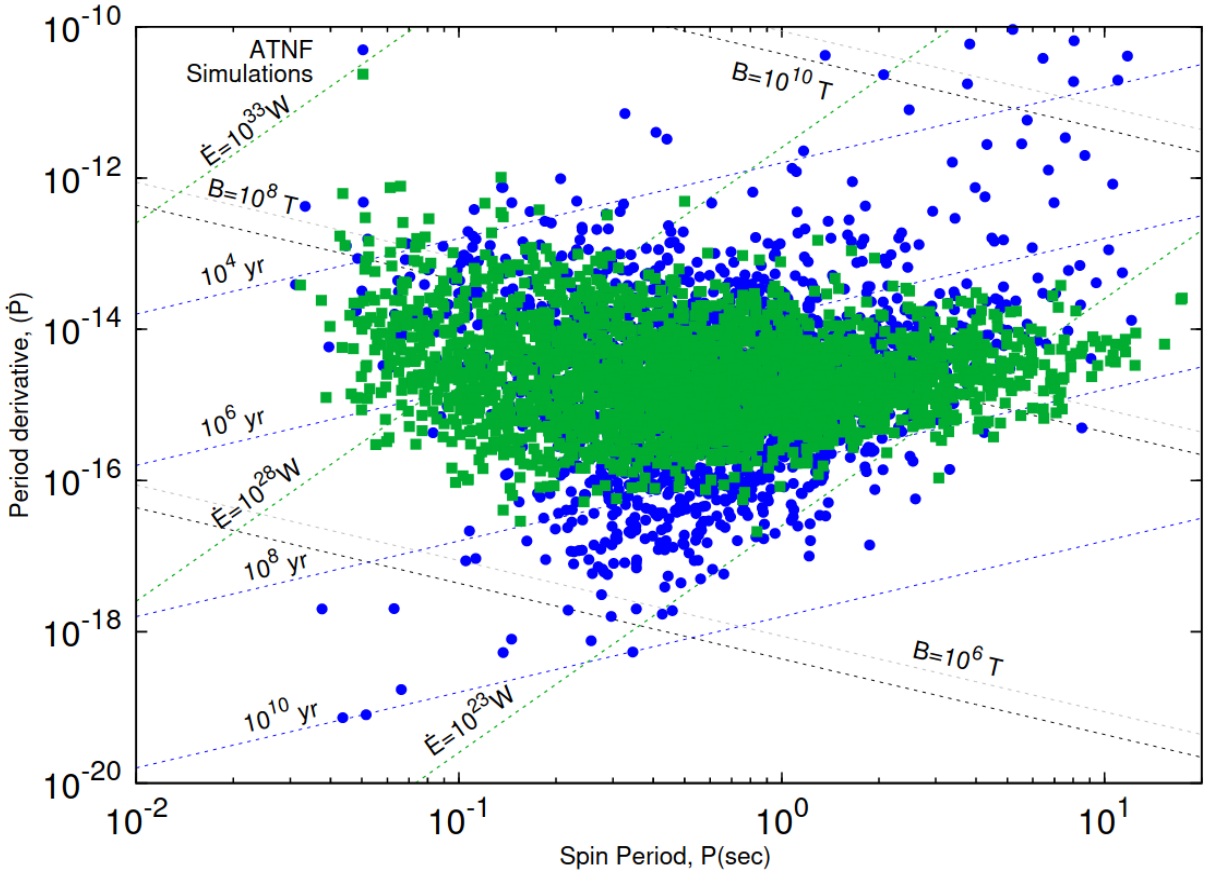




Results

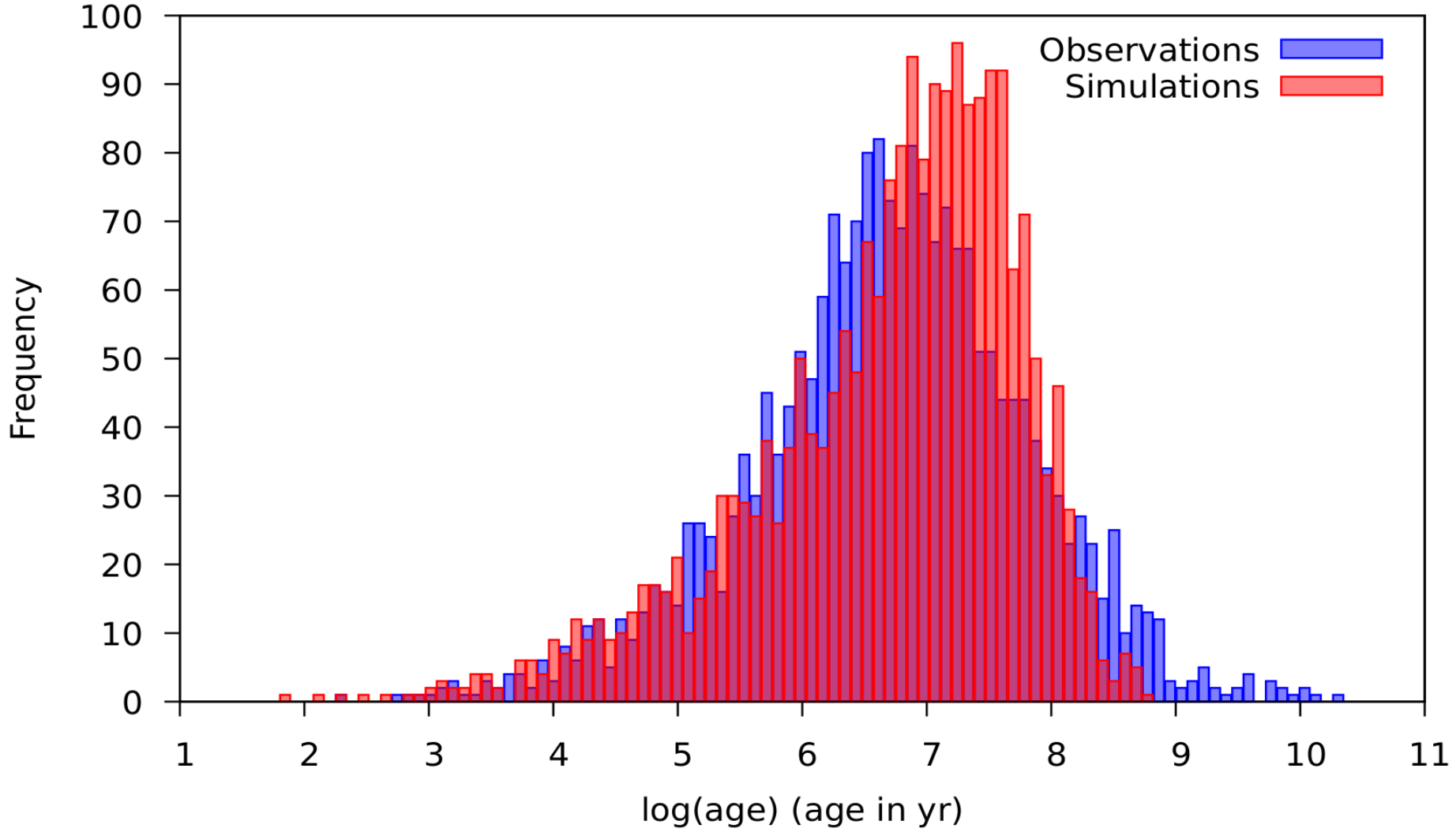
P-Ṗ diagram





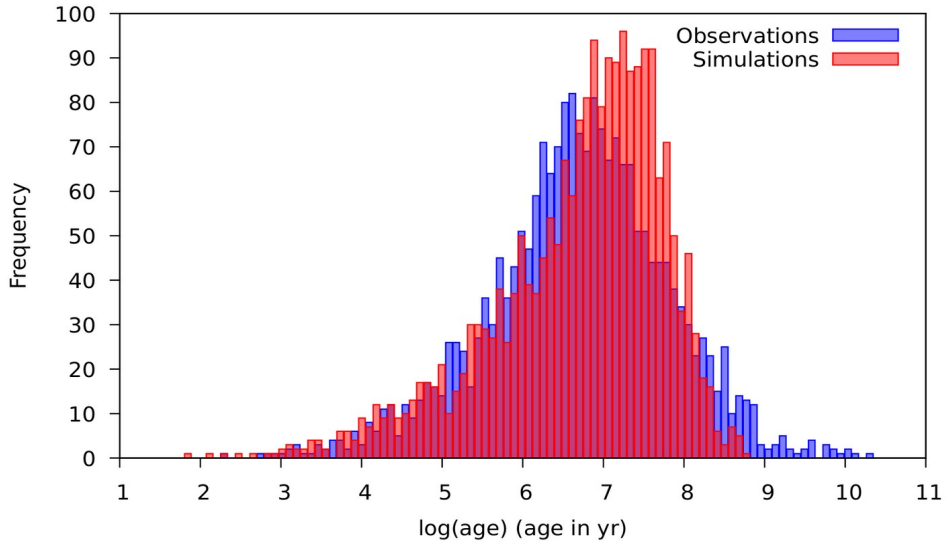
Results

Age of detected pulsars



Results

Age of detected pulsars



Model

Radio luminosity and sensitivity

- Radio flux density at 1.4 GHz:

$$F_r = 9\,\mathrm{mJy}\left(\frac{d}{1\ \mathrm{kpc}}\right)^{-2}\left(\frac{\dot{E}}{10^{29}\ \mathrm{W}}\right)^{1/4} 10^{F_j}$$

- Signal-to-noise ratio:

$$S/N = \frac{F_r}{S^{\min}_{\mathrm{survey}}}$$

- Minimum detectable flux of a pulsar survey:

$$S^{\min}_{\mathrm{survey}} = S_0\sqrt{\frac{\tilde{w}_r}{P-\tilde{w}_r}}$$

Parkes multibeam survey and Arecibo surveys have a sensitivity of ~ 0.15 mJy

Model

Gamma luminosity and sensitivity

$$L_{\gamma(2D)} = 10^{26.15\pm2.6}\ \mathrm{W} \left(\frac{B}{10^8\ \mathrm{T}}\right)^{0.11\pm0.05} \left(\frac{\dot{E}}{10^{26}\ \mathrm{W}}\right)^{0.51\pm0.09}$$

Kalapotharakos et al. (2019)

Fermi/LAT sensitivity to pulsars:

- at galactic latitude $< 2^\circ$ is $F_{\mathrm{min}} = 4.10^{-15}\mathrm{W.m}^{-2}$
- For blind searches: $F_{min} = 16.10^{-15}\mathrm{W.m}^{-2}$

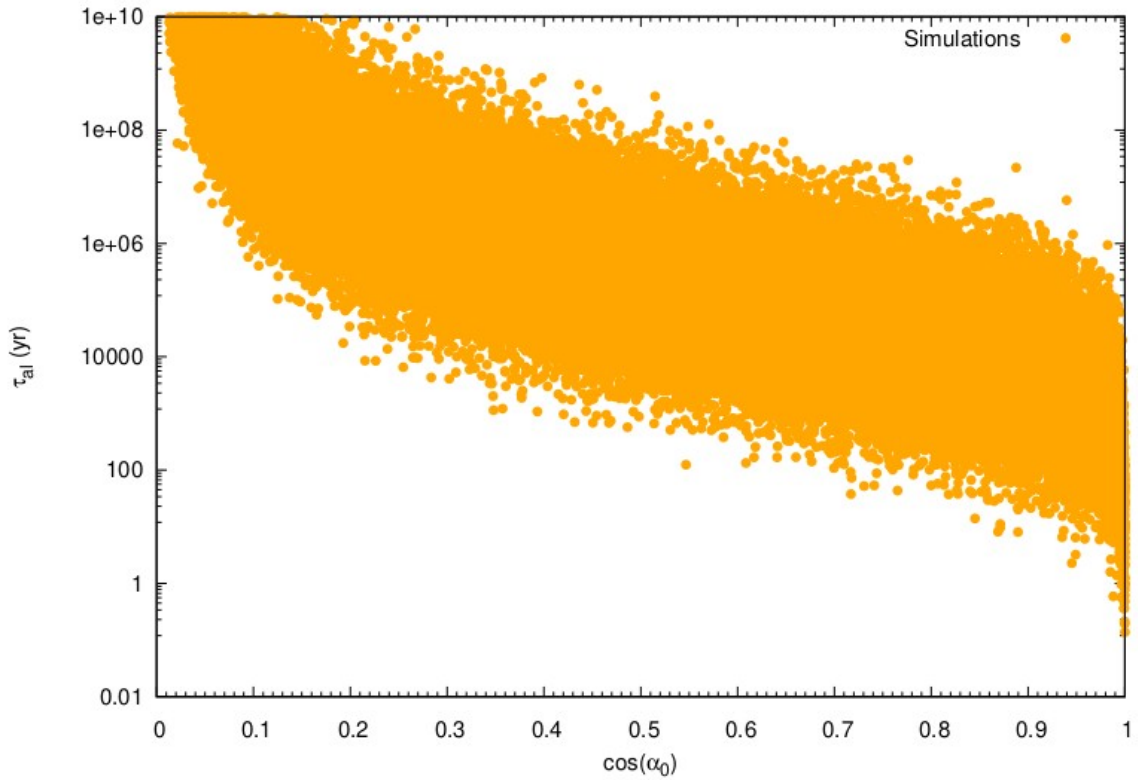
- Vacuum rotator: $$\sin\alpha(t) = \sin\alpha_0 \exp\left(-t/\tau_{align}^{vac}\right)$$
- In the MHD case, $$\alpha \propto t^{-1/2}$$
- For a force-free magnetosphere, integral of motion is:

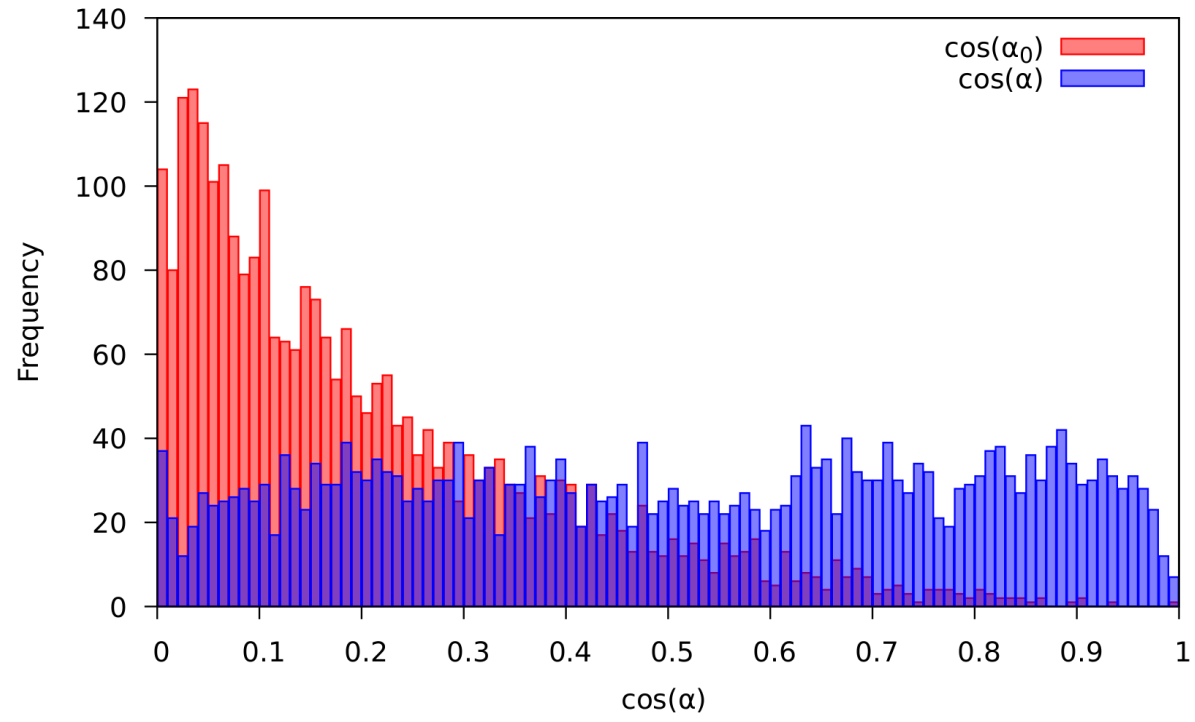
Philippov et al. 2014

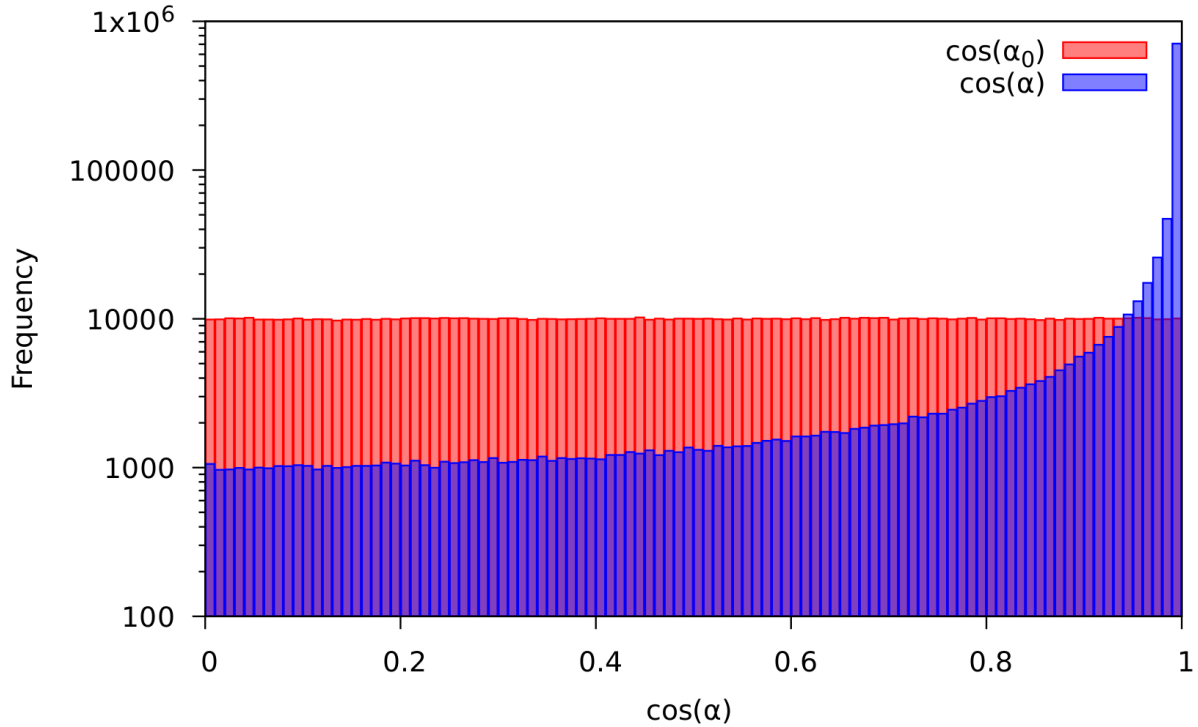
$$\Omega \frac{\cos^2\alpha}{\sin\alpha} = \Omega_0 \frac{\cos^2\alpha_0}{\sin\alpha_0}$$

$$I\,\dot{\Omega} = -\frac{3}{2}\frac{L_\perp}{\Omega}\left(1+\sin^2\chi\right)$$

$$I\,\Omega\,\dot{\chi} = -\frac{3}{2}\frac{L_\perp}{\Omega}\cos\chi\,\sin\chi.$$


Simulations
1e+10
1e+08
1e+06
10000
100
1
0.01
τ_{al} (yr)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
cos(α_0)


140
120
100
80
60
40
20
0
Frequency
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
cos(α)
cos(α0)
cos(α)


1x10^6
100000
10000
1000
100
Frequency
0
0.2
0.4
0.6
0.8
1
cos(α)
cos(α0)
cos(α)

S/N	N_{tot}	N_{r}	N_{g}	N_{rg}
3	6675	6489	109	77
5	4874	4688	109	77
10	2900	2714	109	77
15	2097	1911	109	77

B_{mean} (in T)	N_{tot}	N_{r}	N_{g}	N_{rg}
10^7	23167	22425	370	372
1.5×10^7	17951	17284	334	333
5×10^7	6639	6310	173	156
10^8	3591	3399	123	69
1.5×10^8	2398	2242	104	52

σ_b (in T)	$N_{\rm tot}$	$N_{\rm r}$	$N_{\rm g}$	$N_{\rm rg}$
0.1	1957	1792	100	65
0.2	2204	2051	97	56
0.3	2452	2289	98	65
0.4	2938	2766	104	68
1	8204	7929	151	124

P_{mean} (in s)	$N_{\rm tot}$	$N_{\rm r}$	$N_{\rm g}$	$N_{\rm rg}$
10	1541	1352	121	68
20	2068	1877	115	76
50	2970	2781	113	76
100	3654	3524	84	46

birth rate (in yr^{-1})	$N_{\rm tot}$	$N_{\rm r}$	$N_{\rm g}$	$N_{\rm rg}$
50	17860	16770	707	383
100	8535	8021	324	190
200	4280	3989	181	110
300	2211	2067	89	55