Population synthesis of INSs

Population synthesis in astrophysics

A population synthesis is a method
of a direct modeling of
relatively large populations of
weakly interacting objects
with non-trivial evolution.
As a rule, the evolution of the objects
is followed from their birth
up to the present moment.

(see astro-ph/0411792)

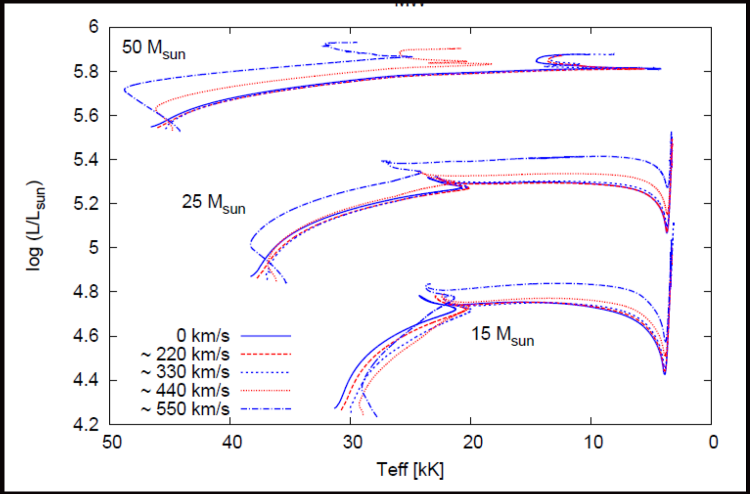
Two variants

Evolutionary and Empirical

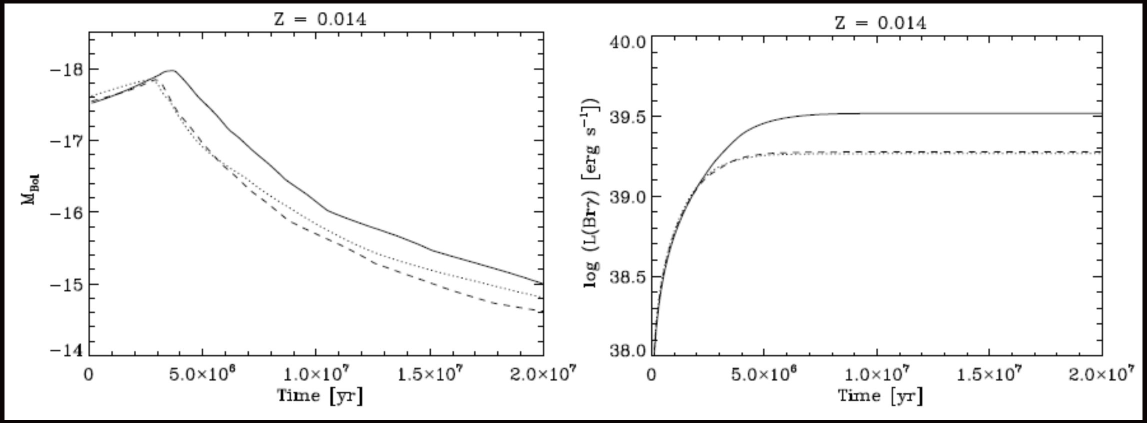
1. Evolutionary PS.
   The evolution is followed from some early stage.
   Typically, an artificial population is formed (especially, in Monte Carlo simulations)
2. Empirical PS.
   It is used, for example, to study integral properties (spectra) of unresolved populations.
   A library of spectra is used to predict integral properties.

Empirical population synthesis

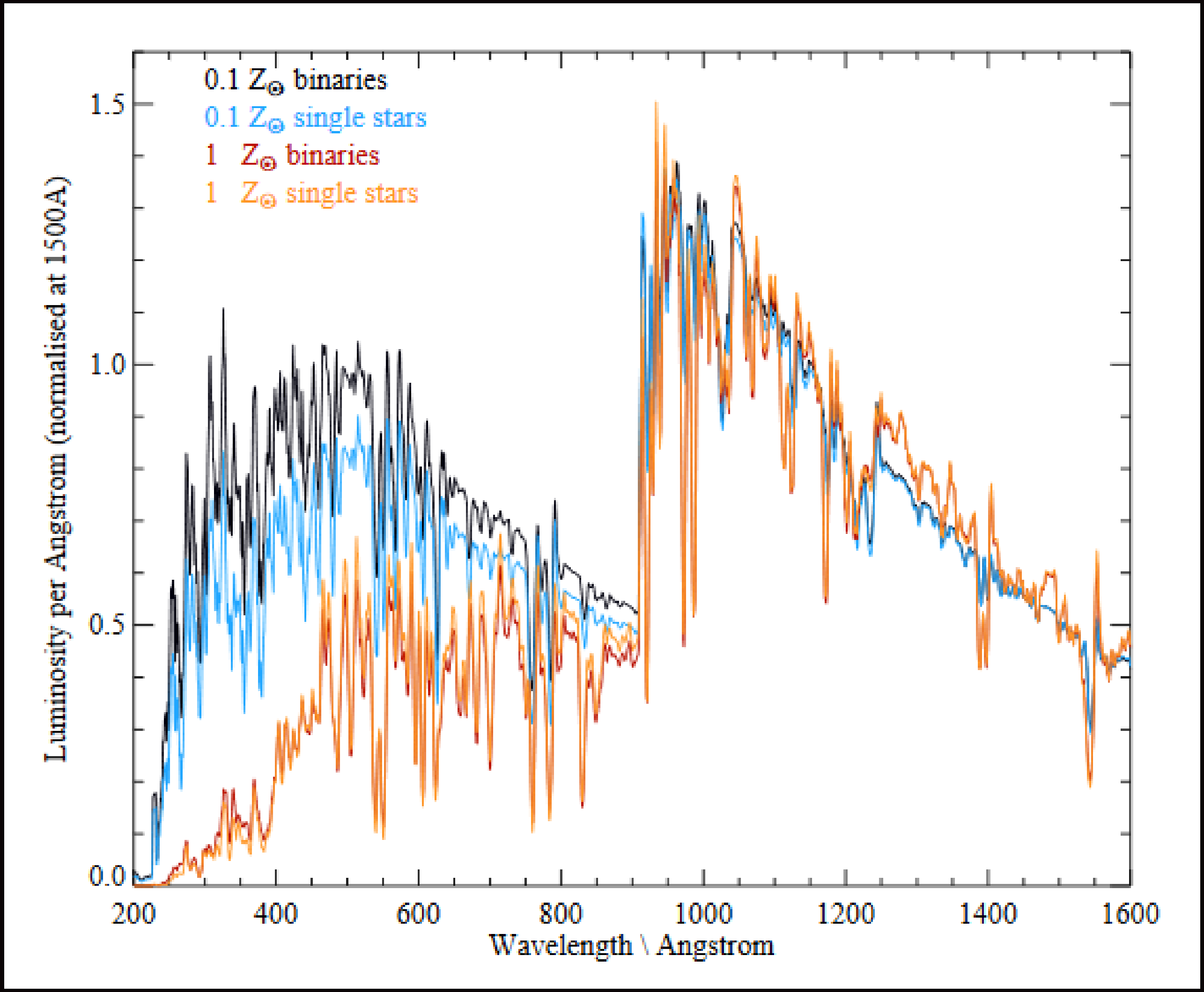
A recent review can be found in 1111.5204
The authors present several examples.



Effects of rotation on integrated characteristics of stellar populations



Integrated synthetic stellar spectra



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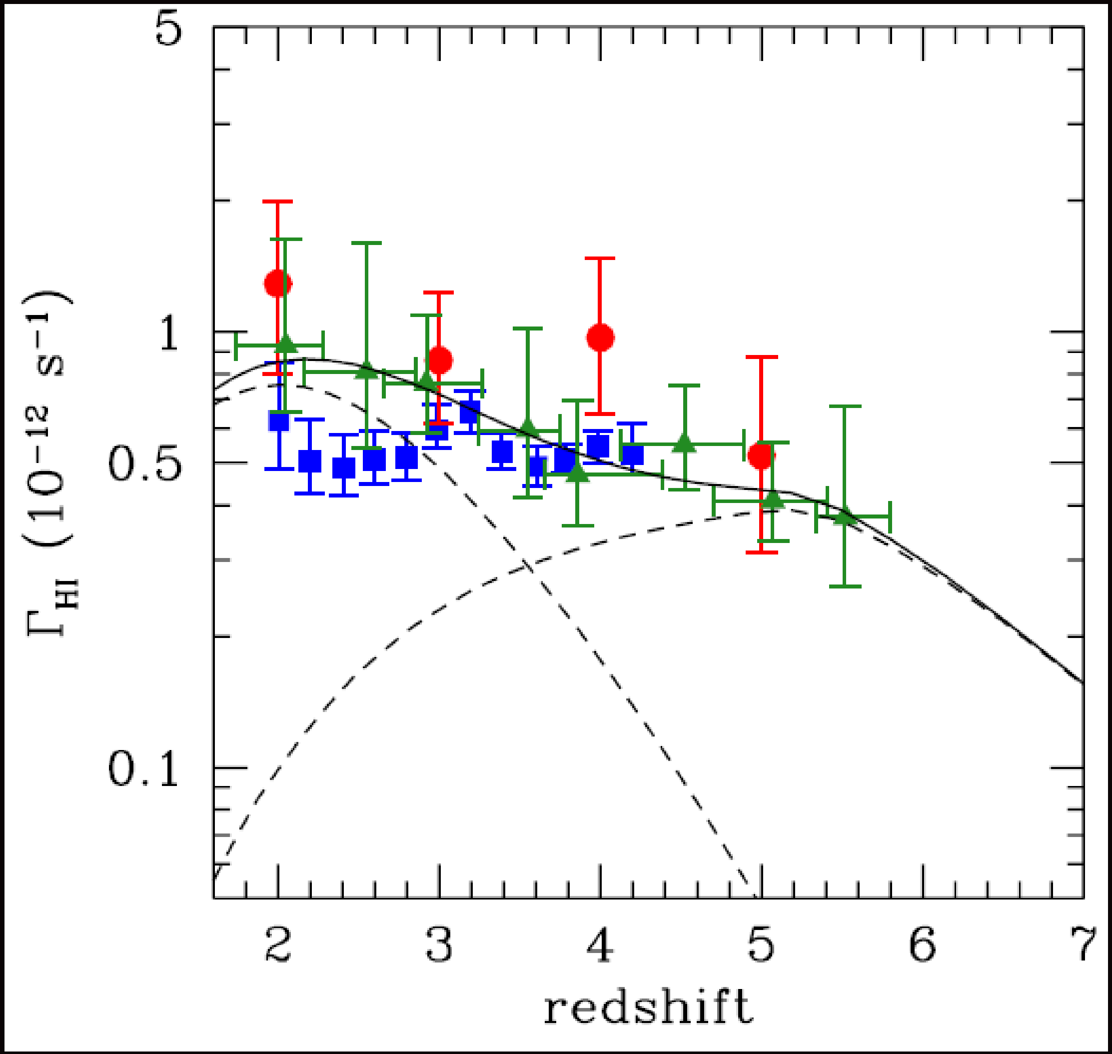
Empirical population synthesis



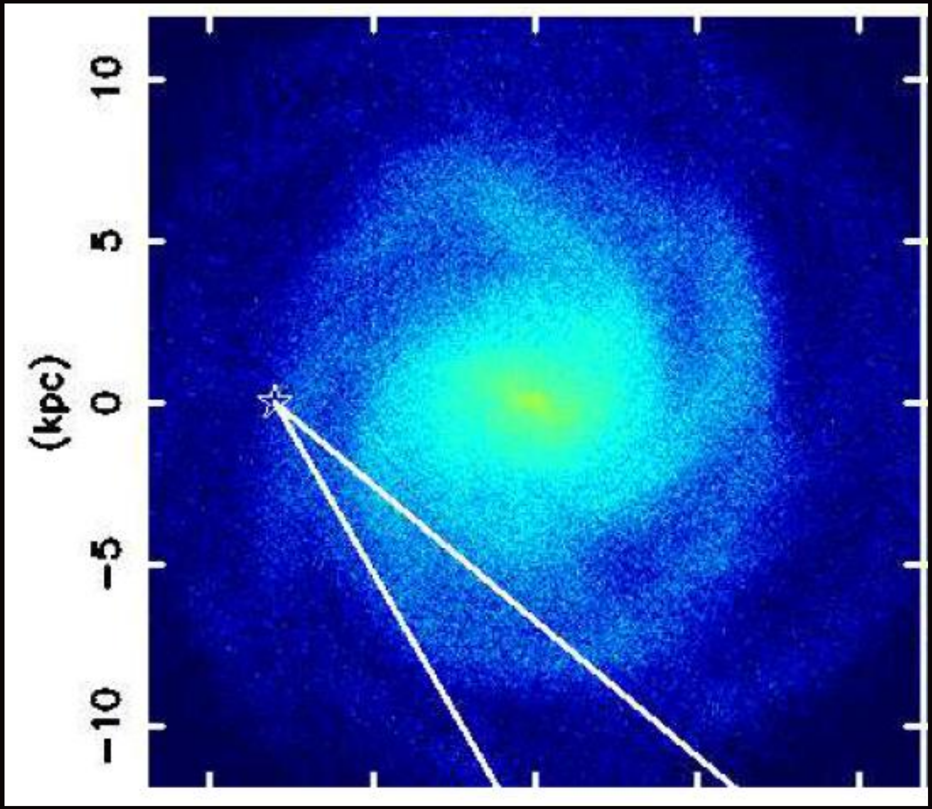
Hydrogen photoionization rate as a function of redshift

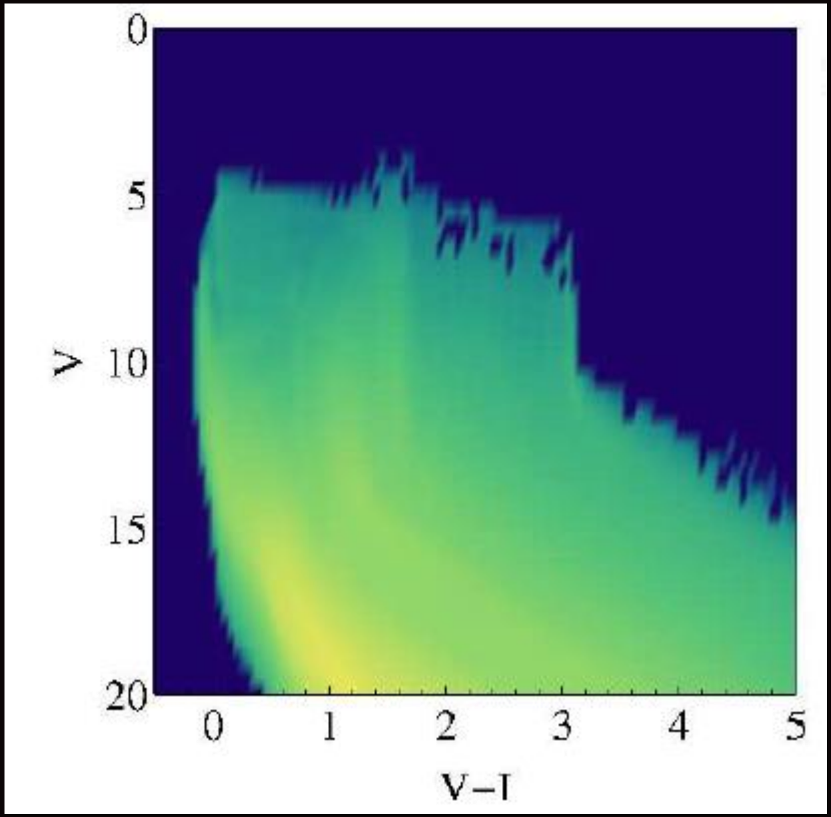
Ionizing background from QSO (left dashed) and galaxies (right dashed).

Data corresponds to the Ly-alpha forest observations.

1103.5226

PopSynth + N-body

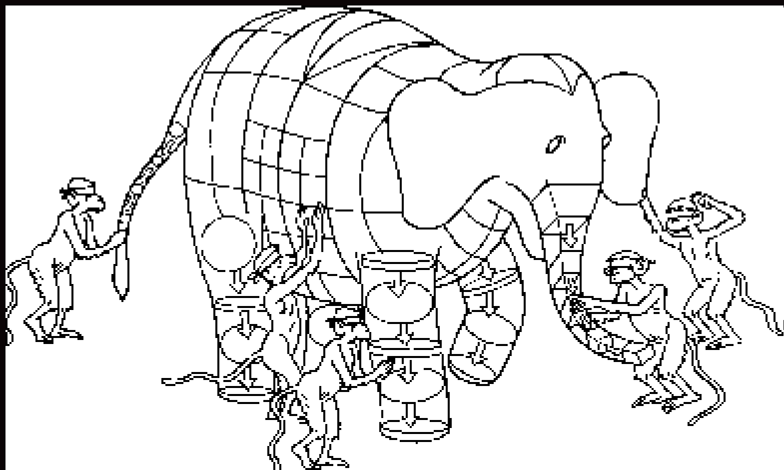




Evolution of the galaxy (stellar+gas disc, feedback etc.) is modeled with an N-body code. Then for a selected region a pop.synth. Approach is applied to calculated colours.

1207.5048

Population synthesis



Ingredients:
- initial condition
- evolutionary laws

«Artificial universe»

Modeling observations

«Artificial observed universe»

Why PS is necessary?

1. No direct experiments → computer experiments
2. Long evolutionary time scales
3. Selection effects. We see just a top of an iceberg.
4. Expensive projects for which it is necessary to make predictions

Tasks

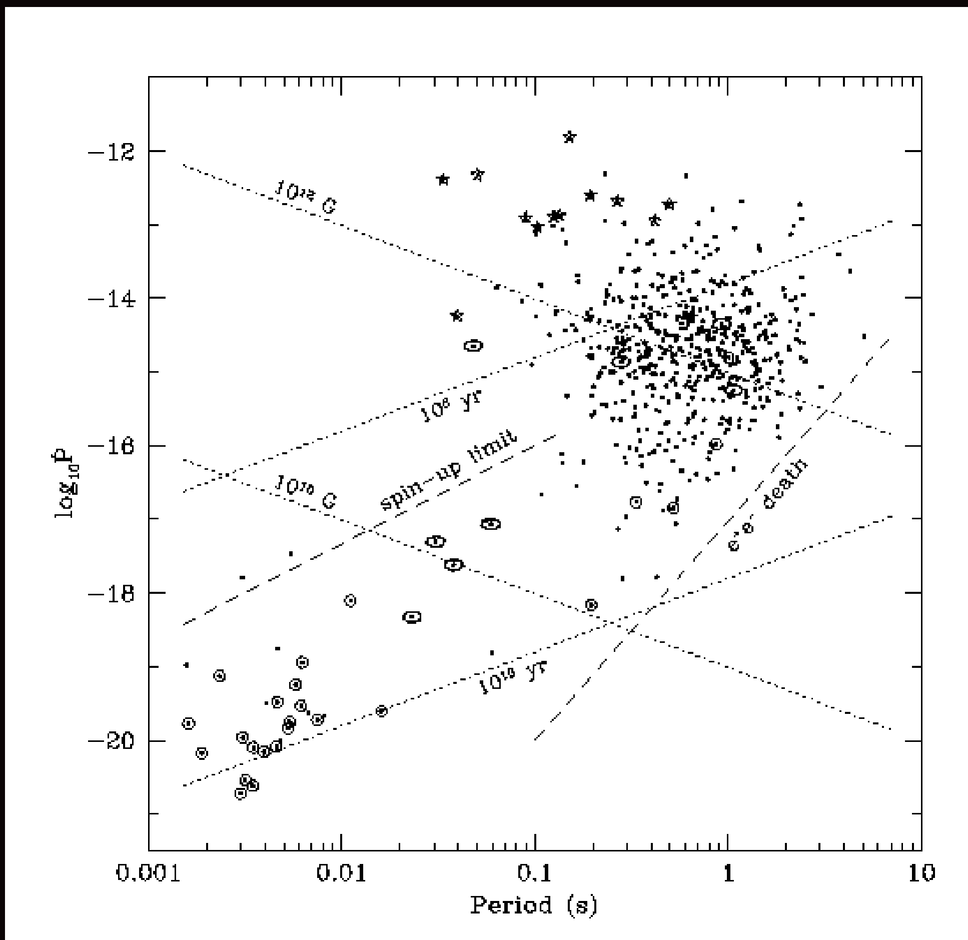
1. To test and/or to determine initial and evolutionary parameters.
   To do it one has to compare calculated and observed populations.
   This task is related to the main *pecularity* of astronomy:
   we cannot make direct experiments under controlled conditions.

2. To predict properties of unobserved populations.
   Population synthesis is actively use to define programs for future observational projects: satellites, telescopes, etc.

Examples

1. PS of radiopulsars
2. PS of gamma-ray pulsars
3. PS of close-by cooling NSs
4. PS of isolated NSs

Magnetorotational evolution of radio pulsars



$$L_m = \frac{2}{3}\frac{\mu^2\omega^4}{c^3}\sin^2\beta = \kappa_t\frac{\mu^2}{R_l^3}\omega\,,$$

$$B \sim 3.2\times10^{19}\,(P dP/dt)^{1/2}\ \mathrm{G}.$$

Spin-down.
Rotational energy is released.
The exact mechanism is still unknown.

Population synthesis of radio pulsars

The idea was to make an advance population synthesis study of normal radio pulsar to reproduce the data observed in PMBPS and Swinburne. Comparison between actual data and calculations should help to understand better the underlying parameters and evolution laws.

Only normal (non-millisecond, non-binary, etc.) pulsars are considered.
Note, however, that the role of pulsars originated in close binaries can be important.

Ingredients

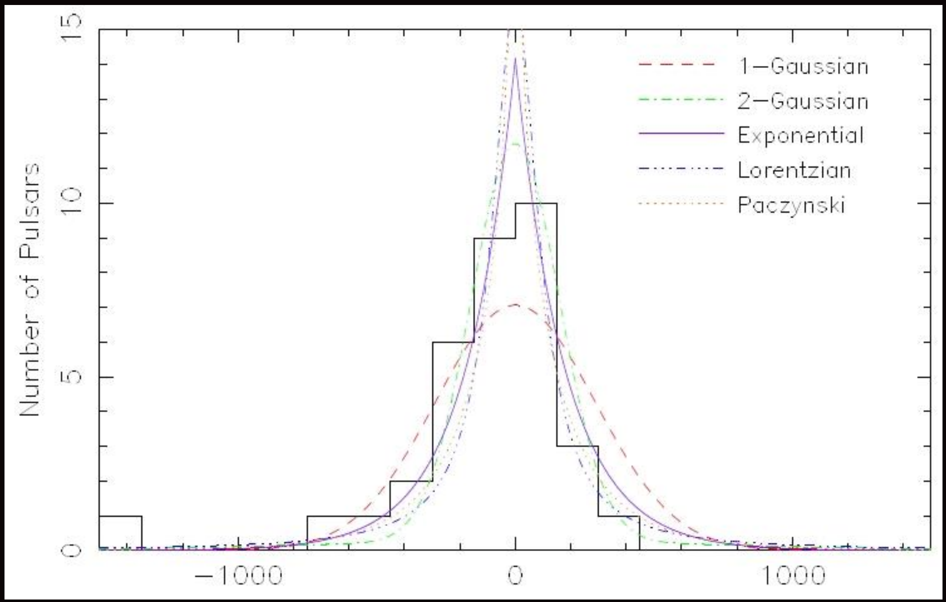
- Velocity distribution
- Spatial distribution
- Galactic model
- Initial period distribution
- Initial magnetic field distribution
- Field evolution (and angle)
- Radio luminosity
- Dispersion measure model
- Modeling of surveys

The observed PSR sample is heavily biased. It is necessary to model the process of detection, i.e. to model the same surveys in the synthetic Galaxy.
A synthetic PSR is detected if it appears in the area covered by on pf the survey, and if its radio flux exceeds some limit.

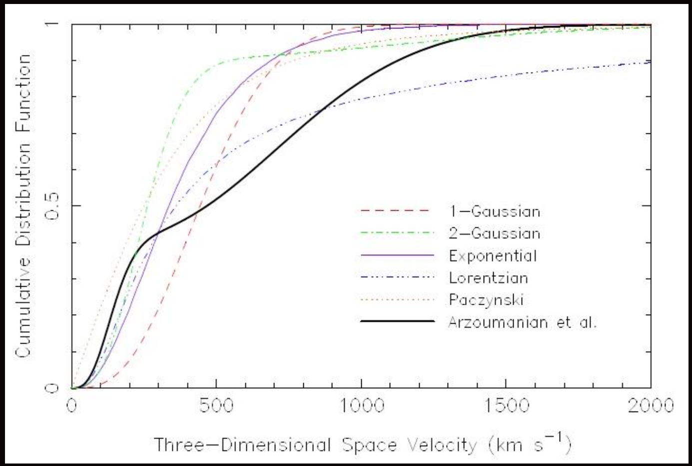
2/3 of known PSRs were detected in PMBPS or/and SM (914 and 151).

(following Faucher-Giguere and Kaspi astro-ph/0512585)

Velocity distribution



Observational data for 34 PSRs.
V_{max}=1340 km/s (PSR B2011+38).



The authors checked different velocity distributions: single maxwellian, double maxwellian, lorentzian, paczynski mode, and double-side exponential. The last one was takes for the reference model.
Single maxwellian was shown to be inadequate.

$$p(v_l) = \frac{1}{2\langle v_l\rangle}\exp\left(-\frac{|v_l|}{\langle v_l\rangle}\right),$$

$v_l = D\mu_l \cos b - \Delta v_l$ is the component of the pulsar's transverse velocity parallel to the plane, relative to its LSR, where $\Delta v_l(D, l, b)$ is the contribution to the observed velocity due to differential Galactic rotation and the motion of the Sun relative to its own LSR

Spatial distribution

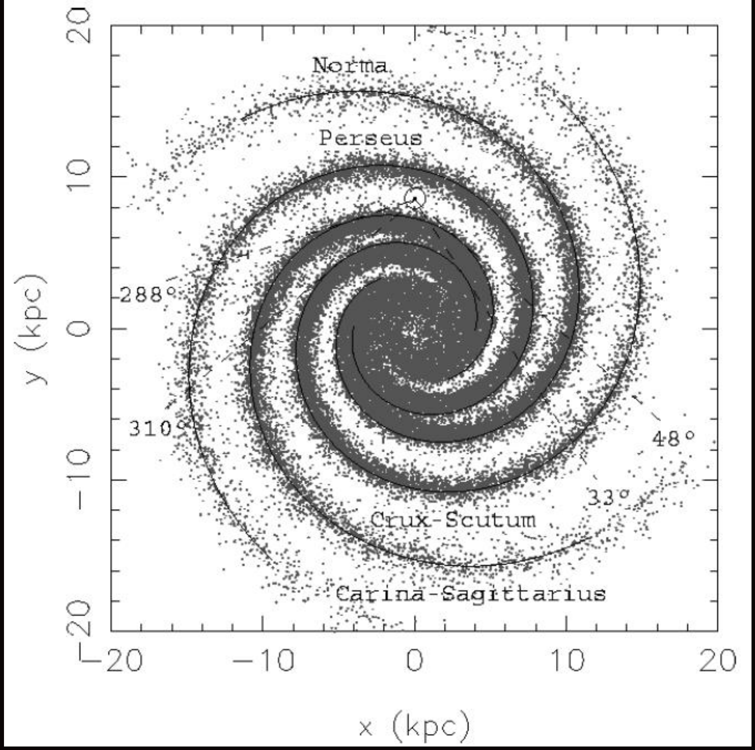
Initial spatial distribution of PSRs was calculated in a complicated realistic way.

- exponential dependences (R and Z) were taken into account
- Spiral arms were taken into account
- Decrease of PSR density close to the Galactic center was used

Arm Number	Name	k (rad)	r_0 (kpc)	θ_0 (rad)
1	Norma	4.25	3.48	1.57
2	Carina-Sagittarius	4.25	3.48	4.71
3	Perseus	4.89	4.90	4.09
4	Crux-Scutum	4.89	4.90	0.95

$$\theta(r) = k \ \ln(r/r_0) + \theta_0.$$

However, some details are still missing. For example, the pattern is assumed to be stable during all time of calculations (i.e. corotating with the Sun).



Galactic potential

The potential was taken from Kuijken and Gilmore (1989):

- disc-halo
- bulge
- nuclei

$$\phi_G(r,z) = \phi_{dh}(r,z) + \phi_b(r) + \phi_n(r),$$

$$\phi_{dh}(r,z) = \frac{-GM_{dh}}{\sqrt{(a_G + \sum_{i=1}^{3}\beta_i\sqrt{z^2+h_i^2})^2 + b_{dh}^2 + r^2}}$$

$$\phi_{b,n}(r) = \frac{-GM_{b,n}}{\sqrt{b_{b,n}^2 + r^2}}.$$

$$\ddot{\boldsymbol{x}} = -\boldsymbol{\nabla}\phi_G,$$

Constant	Disc-Halo (dh)	Bulge (b)	Nucleus (n)
M	1.45×10^{11} M$_\odot$	9.3×10^{9} M$_\odot$	1.0×10^{10} M$_\odot$
β_1	0.4		
β_2	0.5		
β_3	0.1		
h_1	0.325 kpc		
h_2	0.090 kpc		
h_3	0.125 kpc		
a_G	2.4 kpc		
b	5.5 kpc	0.25 kpc	1.5 kpc

Initial spin periods and fields

Spin periods were randomly taken from a normal distribution.
Magnetic fields – also from a normal distribution for log B.

The authors do not treat separately the magnetic field and inclination angle evolution.

Purely magneto-dipole model with n=3 and sin χ=1 is used.
$R_{NS}=10^6$ cm, $I=10^{45}$.

$$P\dot{P} = \left(\frac{8\pi^2 R^6}{3Ic^3}\right) B^2 \sin^2\chi,$$

$$P \sim (P_0^2 + K\,t)^{1/2}$$

The death-line is taken in the usual form:

$$\frac{B}{P^2} = 0.17 \times 10^{12}\ \mathrm{G\ s^{-2}}$$

Radio luminosity and beaming

Model I

$$p(L) \propto \begin{cases} L^{\alpha_1} & \text{for } L \in [L_{low}, L_{to}) \\ L^{\alpha_2} & \text{for } L \in [L_{to}, \infty) \\ 0 & \text{otherwise} \end{cases}$$

L_{to} = 2 mJy kpc^2
α_1=-19/15
α_2=-2
L_{low}= 0.1 mJy kpc^2

[Shown to be bad]

Model II

$$\log L = \log\left(L_0 P^{\epsilon_P} \dot{P}_{15}^{\epsilon_{\dot{P}}}\right) + L_{corr},$$

$$f(P) = 0.09[\log(P/s) - 1]^2 + 0.03.$$

Average beaming fraction is about 10%

Optimal model and simulations

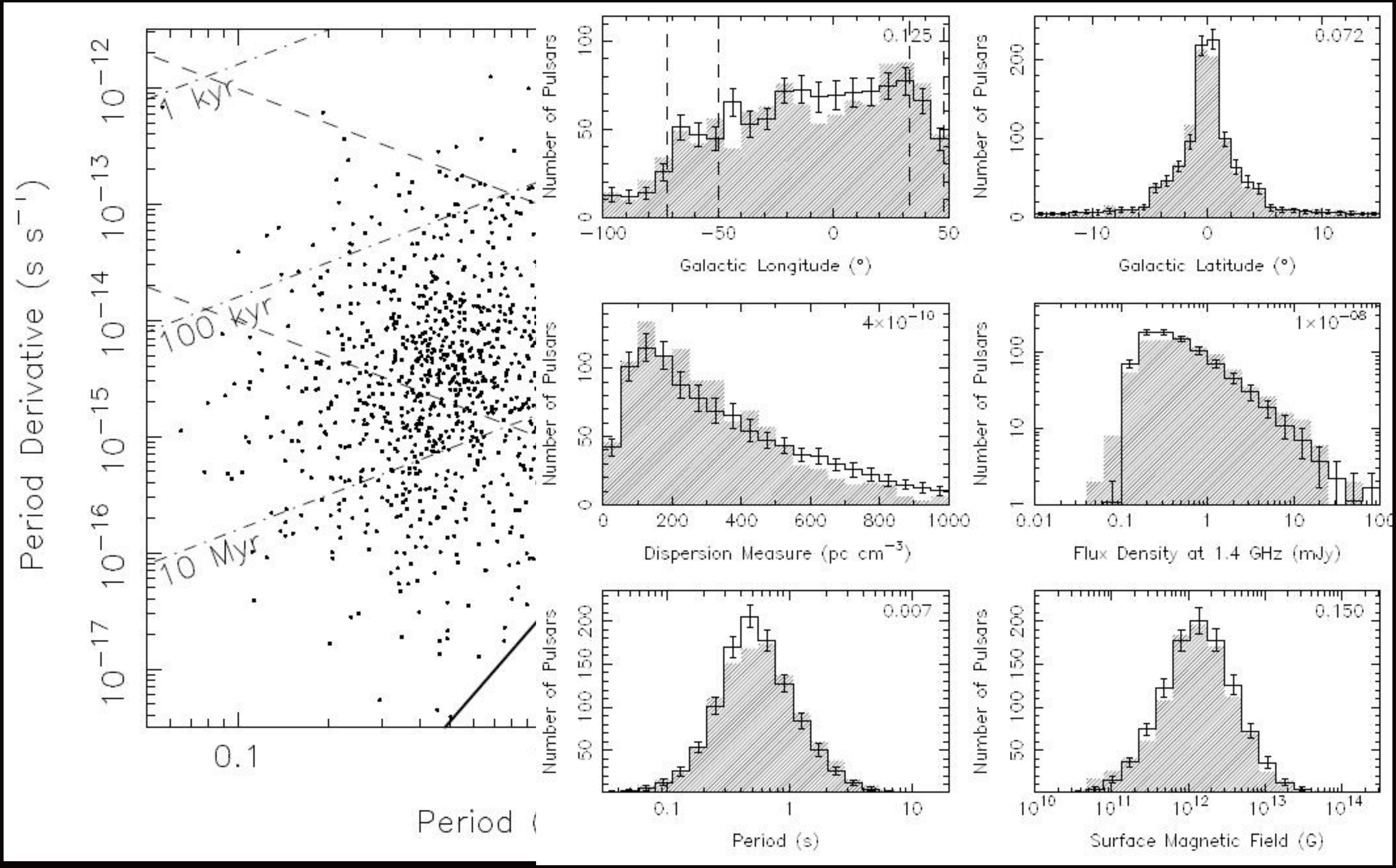
Model Parameter	Value
Radial Distribution Model	Yusifov & Küçük
R_1	0.55 kpc
a	1.64
b	4.01
Birth Height Distribution	Exponential
$\langle z_0 \rangle$	50 pc
Birth Velocity Distribution	Exponential
$\langle v_{3D} \rangle$	380 km s^{-1}
Birth Spin Period Distribution	Normal
$\langle P_0 \rangle$	300 ms
σ_{P_0}	150 ms
Magnetic Field Distribution	Log-Normal
$\langle \log (B/\mathrm{G}) \rangle$	12.65
$\sigma_{\log B}$	0.55
Luminosity Model	$P - \dot{P}$ Power Paw
L_0	0.18 mJy kpc^2
ϵ_P	-1.5
$\epsilon_{\dot{P}}$	0.5
$\sigma_{L_{corr}}$	0.8

The code is run till the number of “detected” synthetic PSR becomes equal to the actual number of detected PSRs in PMBPS and SM.

For each simulation the “observed” distributions of *b,l, DM,* S_{1400}, P, and B, are compared with the real sample.

It came out to be impossible to to apply only statistical tests.
Some human judgement is necessary for interpretation.

Results



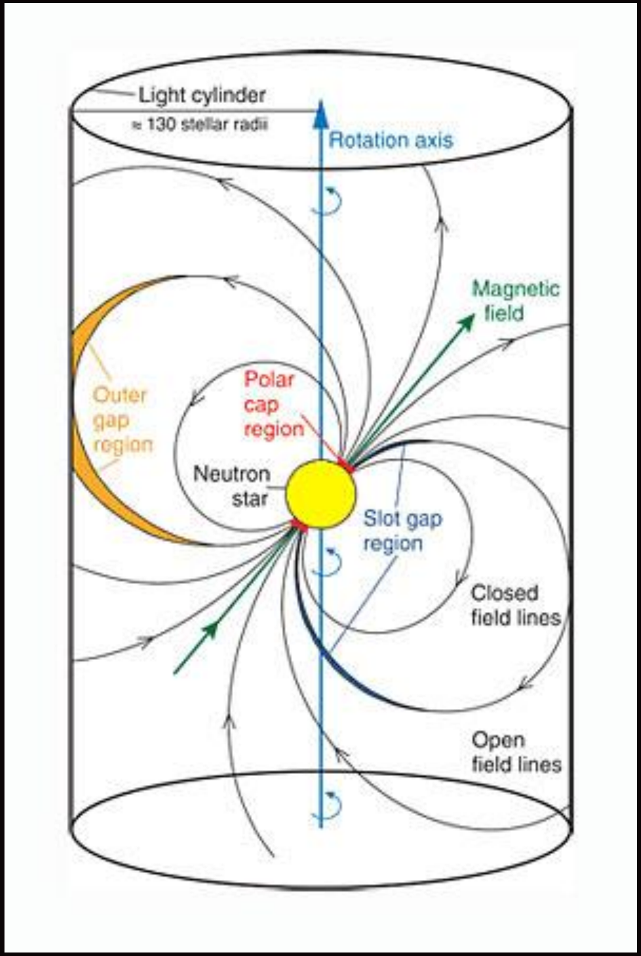
Solid lines – calculation, hatched diagrams - real observations

Discussion of the results

1. No significant field decay (or change in the inclination angle) is necessary to explain the data.
2. Results are not very sensitive to braking index distribution
3. Birthrate is 2.8+/-0.1 per century.
   If between 13% and 25% of core collapse SN produce BHs, then
   there is no necessity to assume a large population of radio quiet NSs.
   120 000 PSRs in the Galaxy

Several models

- Polar cap (inner gap or space-charge limited flow)
- Outer gap
- Slot gap and TPC
- Striped wind



Population synthesis of gamma-ray PSRs

Ingredients

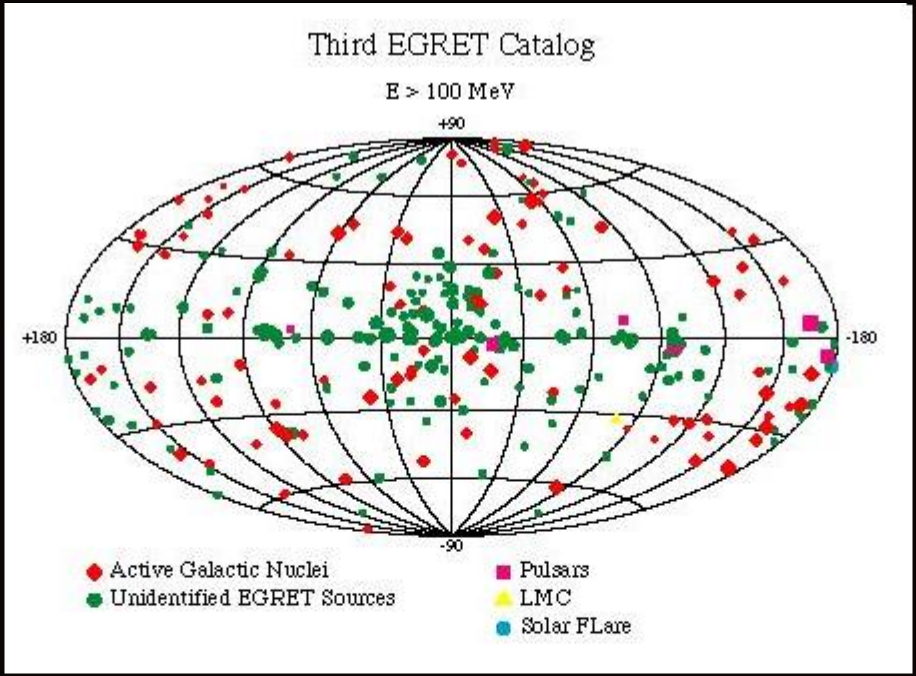
1. Geometry of radio and gamma beam
2. Initial period distribution
3. Initial magnetic field distribution
4. Period evolution
5. Initial spatial distribution
6. Initial velocity distribution
7. Radio and gamma spectra
8. Radio and gamma luminosity
9. Properties of gamma detectors
10. Radio surveys to compare with.

Tasks

1. To explain the Fermi data
2. Prediction for further observations
3. Checking the model

(following Takata et al 1010.5870 and 1102.2746)

EGRET legacy



Just 6 pulsars:

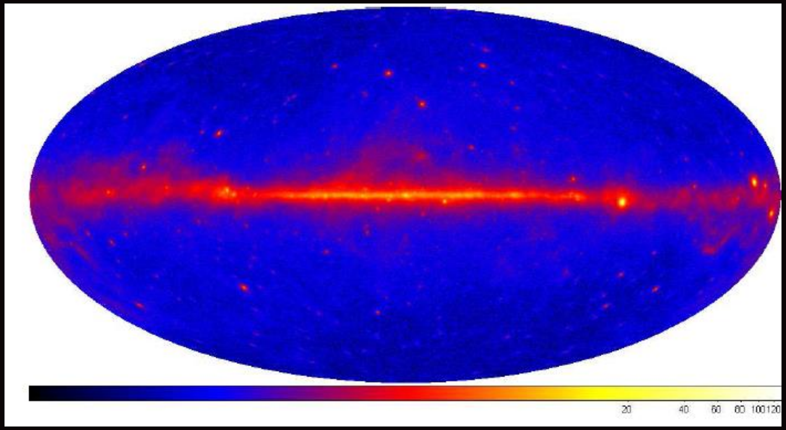
- Crab
- Geminga
- Vela
- PSR B1055-52
- PSR B1706-44
- PSR B1951+32

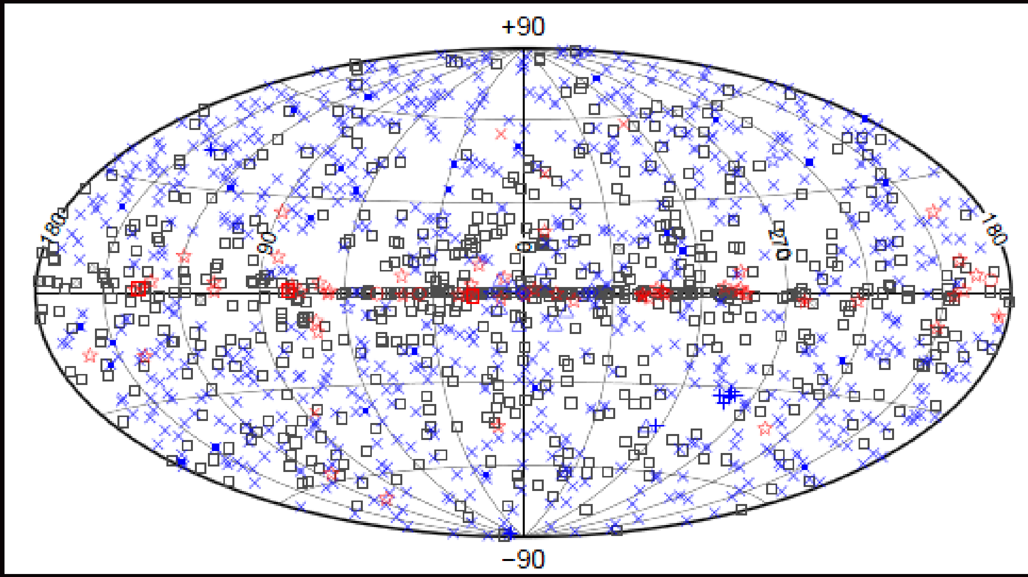
(plus one by COMPTEL)

Nolan et al. 1996
astro-ph/9607079

The first Fermi catalogue

56 pulsating sources out from 1451 sources in total

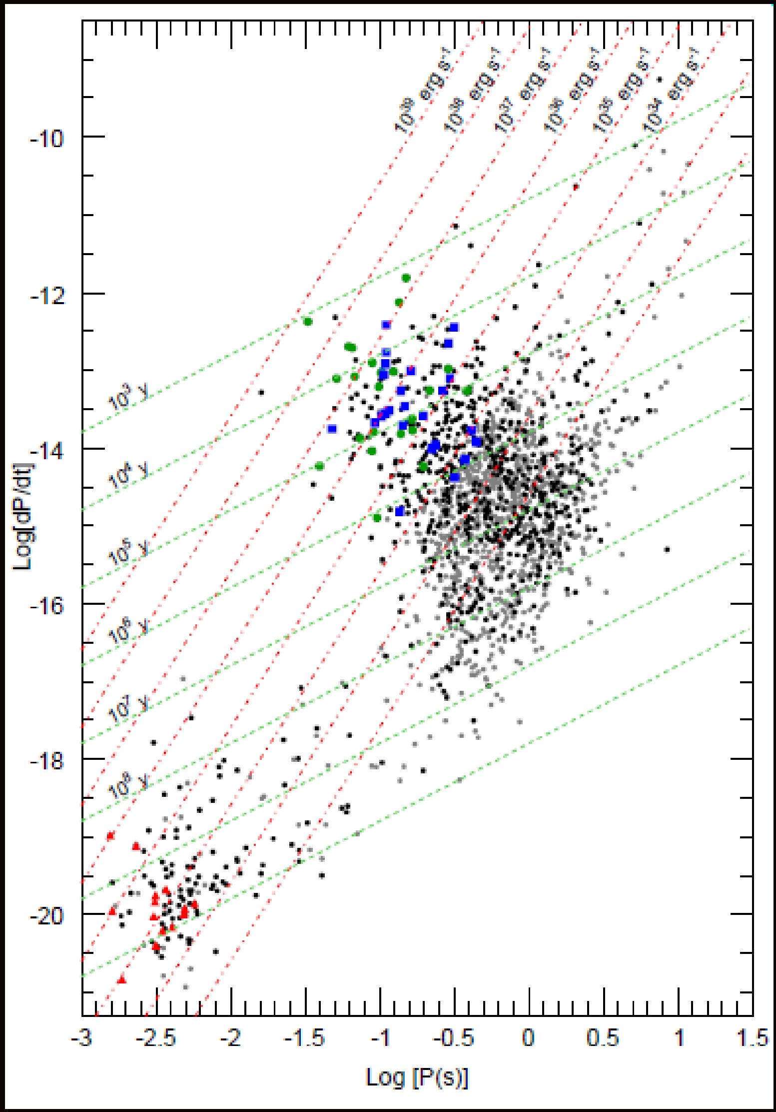




arXiv: 1002.2280

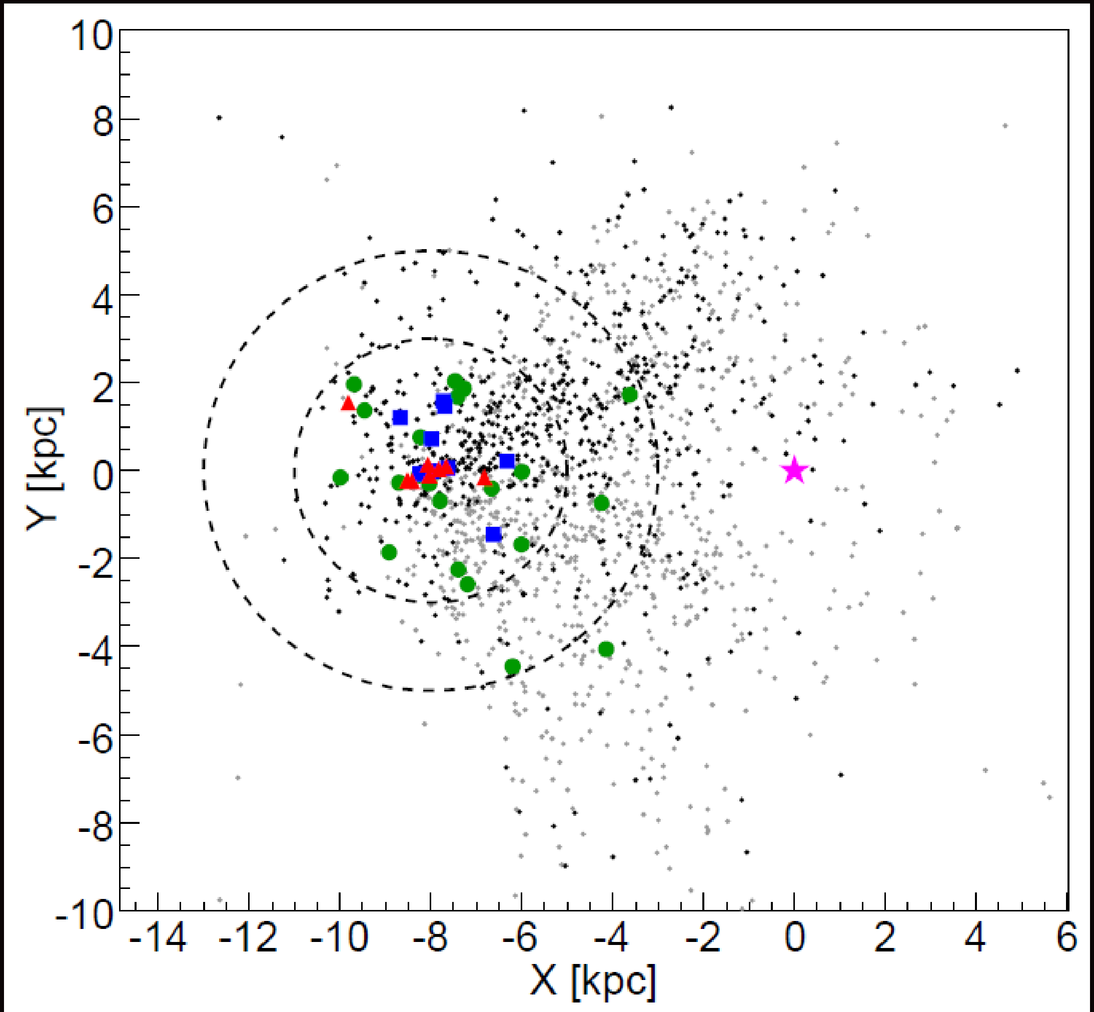
P-Pdot diagram

63 PSRs detected by Fermi



arXiv: 1007.2183

Galactic map



arXiv:0910.1608

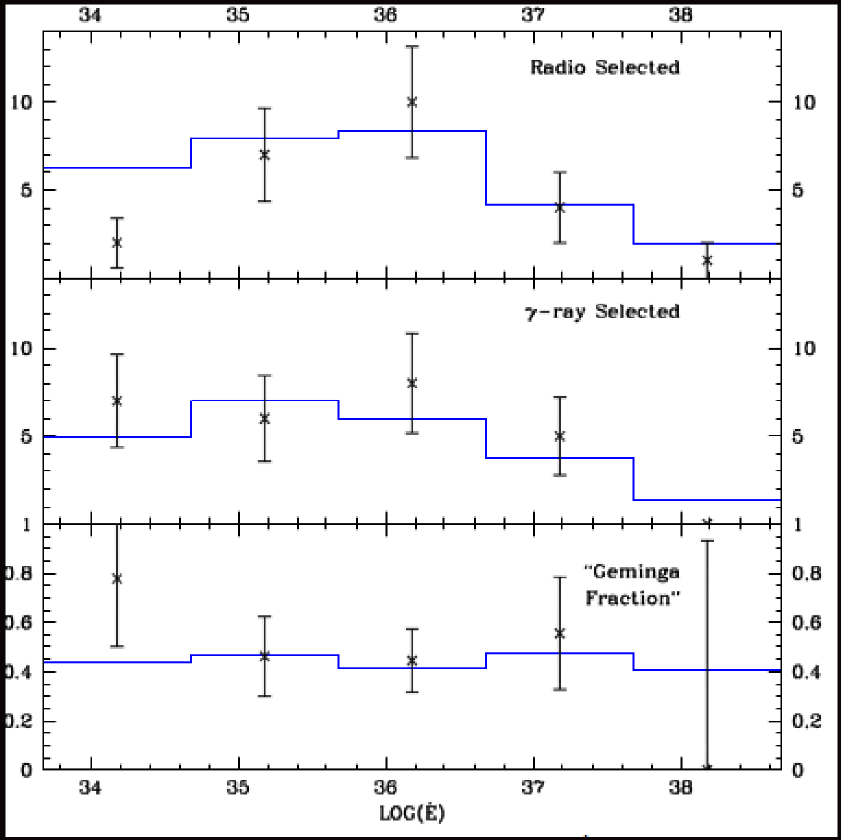
Fermi data: summary

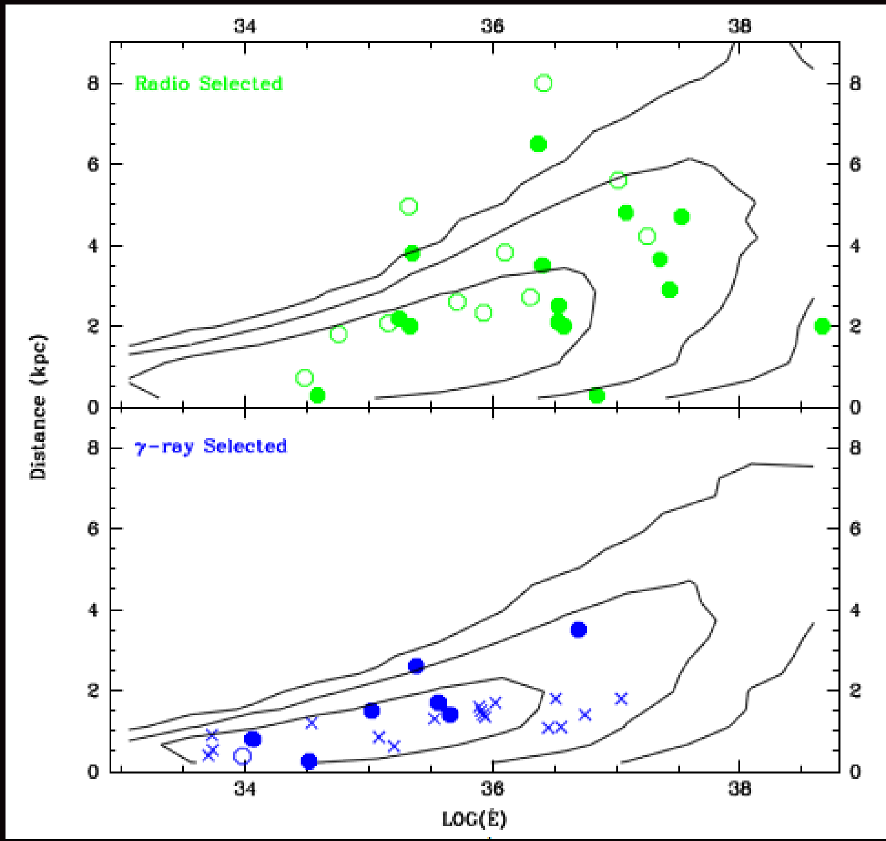
- 63 clearly detected pulsating PSRs:
  ~20 radio selected (with 7 known from CGRO time)
  24 – in blind searches (several detected also in radio)
  27 - mPSRs
- 18 mPSRs candidates from radio (non-pulsating in gamma)

The outer gap models seems to be more probable on the base of Fermi data.

About radio pulsar population see Lorimer arXiv: 1008.1928

New population synthesis: young PSRs





Outer gap model is prefered

Watters, Romani arXiv: 1009.5305

Gamma-ray pulsar population synthesis with the outer gap model: spin periods

$$\rho_B(\log_{10} B_s) = \frac{1}{\sqrt{2\pi}\sigma_B} \exp\left[-\frac{1}{2}\left(\frac{\log_{10} B_s - \log_{10} B_0}{\sigma_B}\right)^2\right],$$

$$P(t) = \left(P_0^2 + \frac{16\pi^2 R_s^6 B^2}{3Ic^3} t\right)^{1/2},$$

$$\dot{P}(t) = \frac{8\pi^2 R_s^6 B^2}{3Ic^3 P}.$$

Standard constant field magneto-dipole formula with constant angle

1010.5870

Initial spatial and velocity distributions

$$\rho_R(R) = \frac{a_R \mathrm{e}^{-R/R_{\mathrm{exp}}} R}{R_{\mathrm{exp}}^2},$$

$$\rho_z(z) = \frac{1}{z_{\mathrm{exp}}} \mathrm{e}^{-|z|/z_{\mathrm{exp}}},$$

$$\rho_v(v) = \sqrt{\frac{\pi}{2}} \frac{v^2}{\sigma_v^3} \mathrm{e}^{-v^2/2\sigma_v^2}.$$

Plus galactic potential and circular velocity

Radio emission and beaming

$L_{400}=d^2\,S_{400}$

$$\rho_{L_{400}} = 0.5\lambda^2 e^{\lambda},$$

where $\lambda = 3.6[\log_{10}(L_{400}/ < L_{400} >) + 1.8]$ with $\log < L_{400} >= 6.64 + \frac{1}{3}\log_{10}(\dot{P}/P^3)$,

Beaming:

$$f_r(\omega) = (1 - \cos\omega) + (\pi/2 - \omega) + \sin\omega,$$

$$\omega_{KG} \sim 0.02 r_{KG}^{1/2} P^{-1/2},$$

$$r_{KG} = 40\nu_{GHz}^{-0.26}\dot{P}_{-15}^{0.07} P^{0.3},$$

Radio detection and surveys

$$S_{min} = \frac{C_{thres}[T_{rec} + T_{sky}(l,b)]}{G\sqrt{2B_{BD}t_i}}\sqrt{\frac{W}{P-W}},$$

$$T_{sky}(\nu) = 25 + \left\{\frac{275}{[1+(l/42)^2)][1+(b/3)^2]}\right\}\left(\frac{408\ \mathrm{MHz}}{\nu}\right)^{2/6}\ \mathrm{K}.$$

$$W^2 = W_0^2 + \tau_{samp}^2 + \tau_{DM}^2 + \tau_{scat}^2,$$

Survey	Gain (KJy^{-1})	C_{thres}	T_{rec} (K)	ν (MHz)	t_i (s)	τ_{samp} (ms)	B_{BD} (MHz)	$\delta\nu$ (MHz)	l (degree)	b (degree)	References
Molonglo 2	5.1	5.4	210	408	40.96	40	3.2	0.8	[0,360]	[-85,20]	Manchester et al. (1978)
Green Bank 2	0.89	7.5	30	390	137	33.5	16	2	[0,360]	[-18,90]	Dewey et al. (1985)
Green Bank 3	0.95	8	30	390	131	2.2	8	0.25	[0,360]	[-18,90]	Stokes et al. (1986)
Arecibo 2	10.9	8	90	430	39.3	0.4	0.96	0.06	[40,65]	[-10,10]	Stokes et al. (1986)
Arecibo 3	13.35	8.5	75	430	68.2	0.5	10	0.078	[35,65]	[-8,8]	Nice et al. (1993)
Parkes 1	0.24	8	45	1520	157	2.4	320	5	[270,20]	[-4,4]	Johnston et al. (1992)
Parkes 2	0.43	8	50	436	157	0.6	32	0.125	[0,360]	[-90,0]	Manchester et al. (1996)
Parks MB	0.735	24	21	1374	2100	0.250	285	3	[260,50]	[-5,5]	Manchester et al. (2001)
Jordell Bank 2	0.4	6	40	1400	524	4	40	5	[355,105]	[-1,1]	Clifton et al. (1992)
Swinburne IL	0.64	15	21	1374	265	0.125	288	3	[260,50	[5,15]	Edwards et al. (2001)

Gamma-ray emission

$$L_\gamma \propto L_{sd}^{\beta} \begin{cases} \beta \sim 0, & \text{for } L_{sd} \gtrsim 10^{36} \text{ erg/s} \\ \beta \sim 0.5, & \text{for } L_{sd} \lesssim 10^{36} \text{ erg/s.} \end{cases}$$

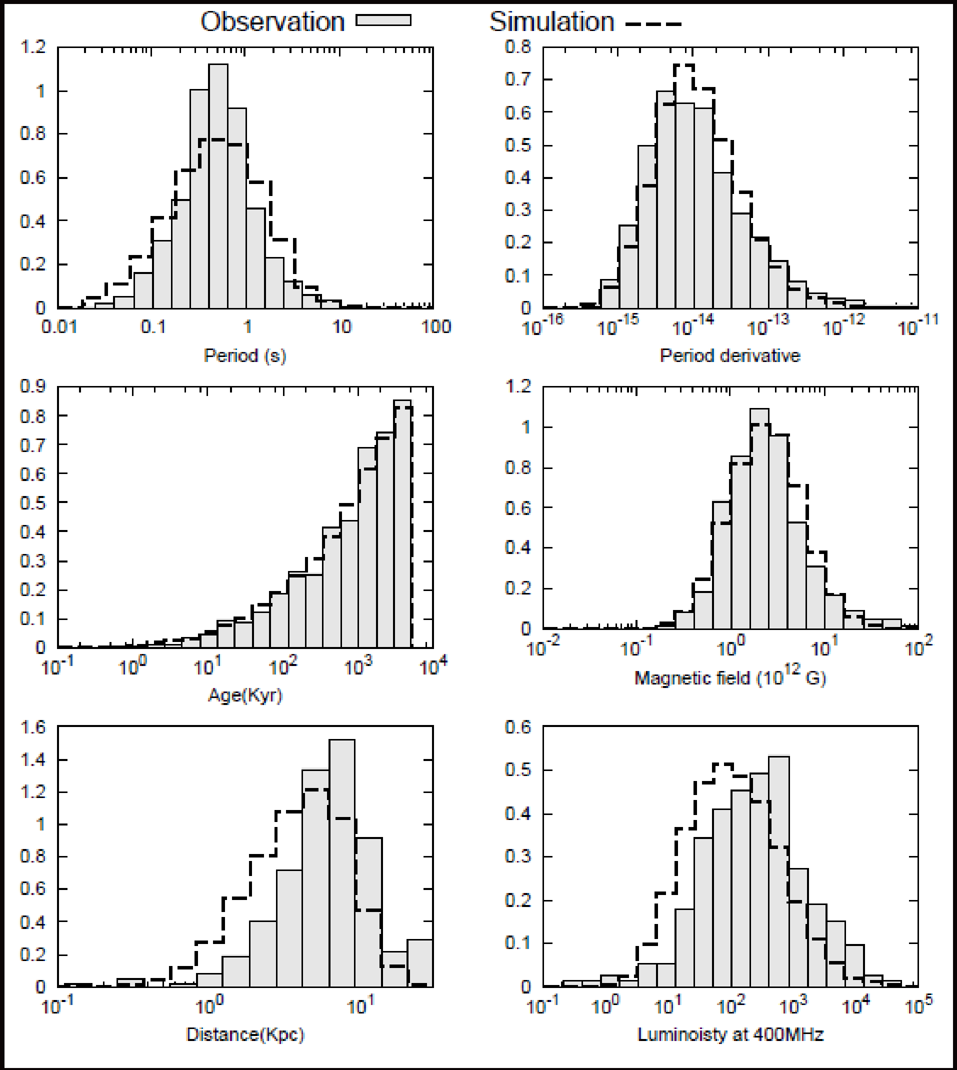
$$L_\gamma \sim 1.3 \times 10^{34} B_{12}^{1/7} L_{sd,36}^{1/14} \text{ erg/s,}$$

$$L_\gamma \sim 1.1 \times 10^{34} K^3 B_{12}^{3/4} L_{sd,36}^{5/8} \text{ erg/s.}$$

$$L_{sd,c} \sim 10^{36} K^{-168/31} B_{12}^{-34/31} \text{ erg/s,}$$

Beaming=0.4

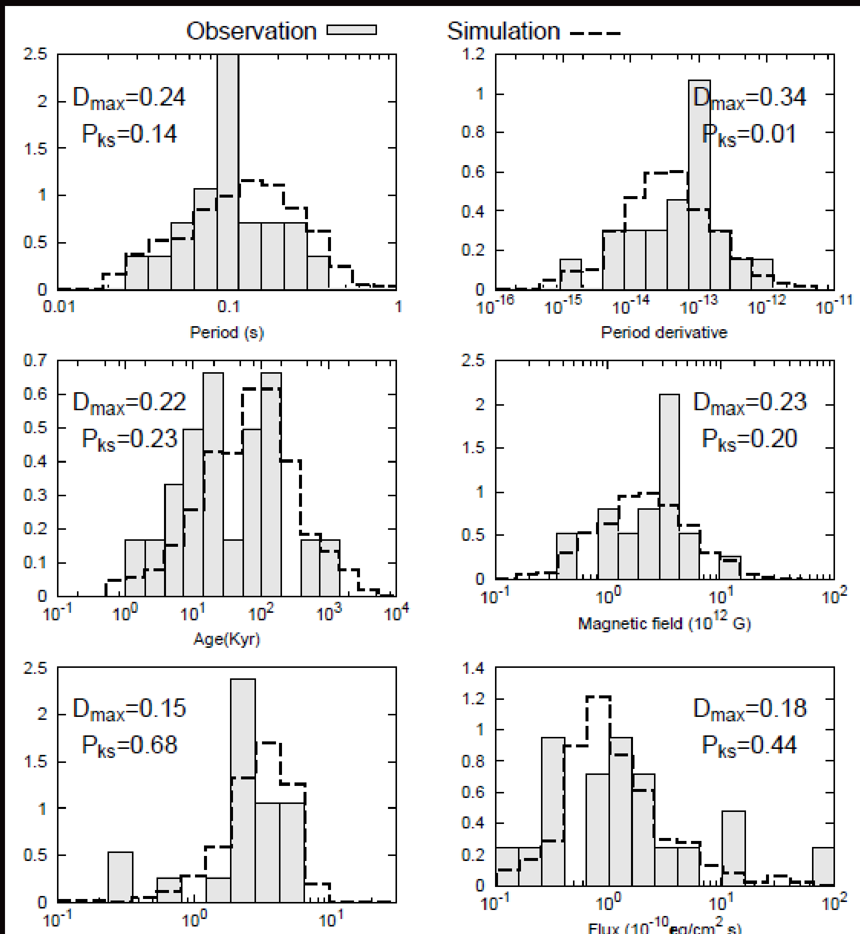
Results



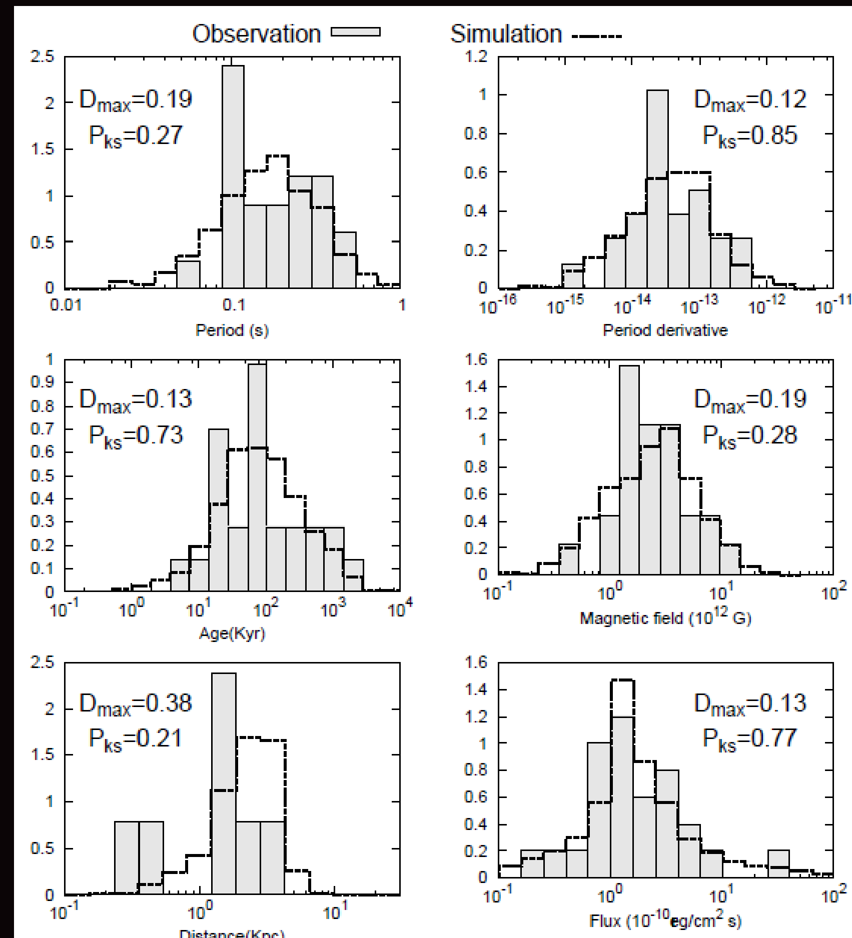
Birth rate: ~1.3 per century

Results

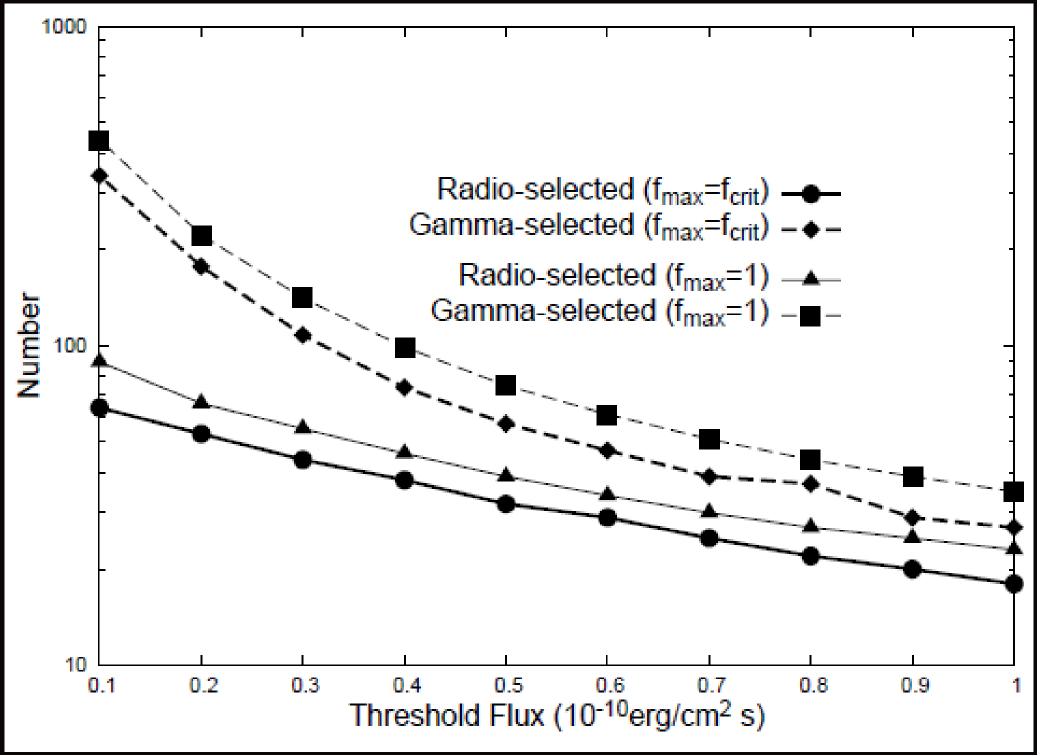
Radio selected

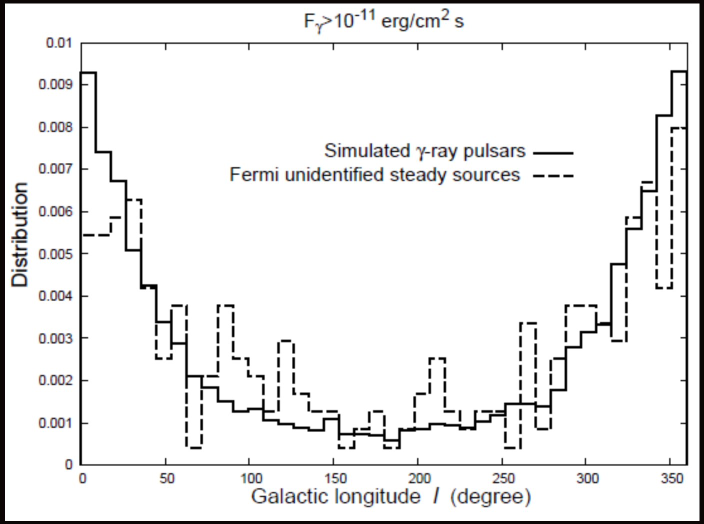


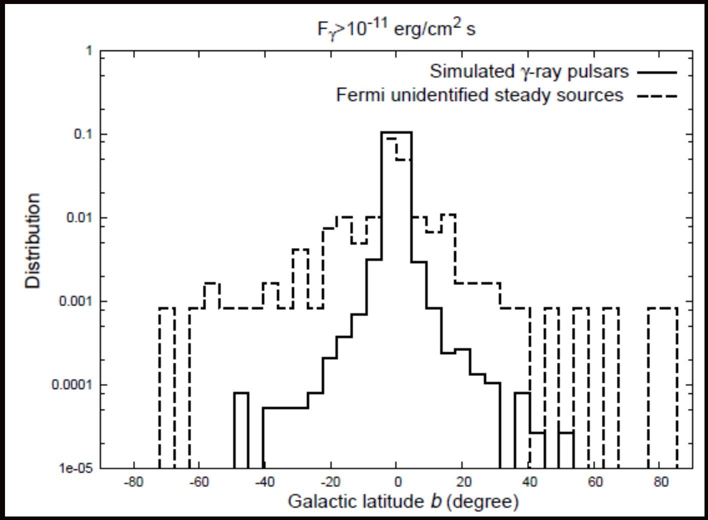
Gamma-ray selected



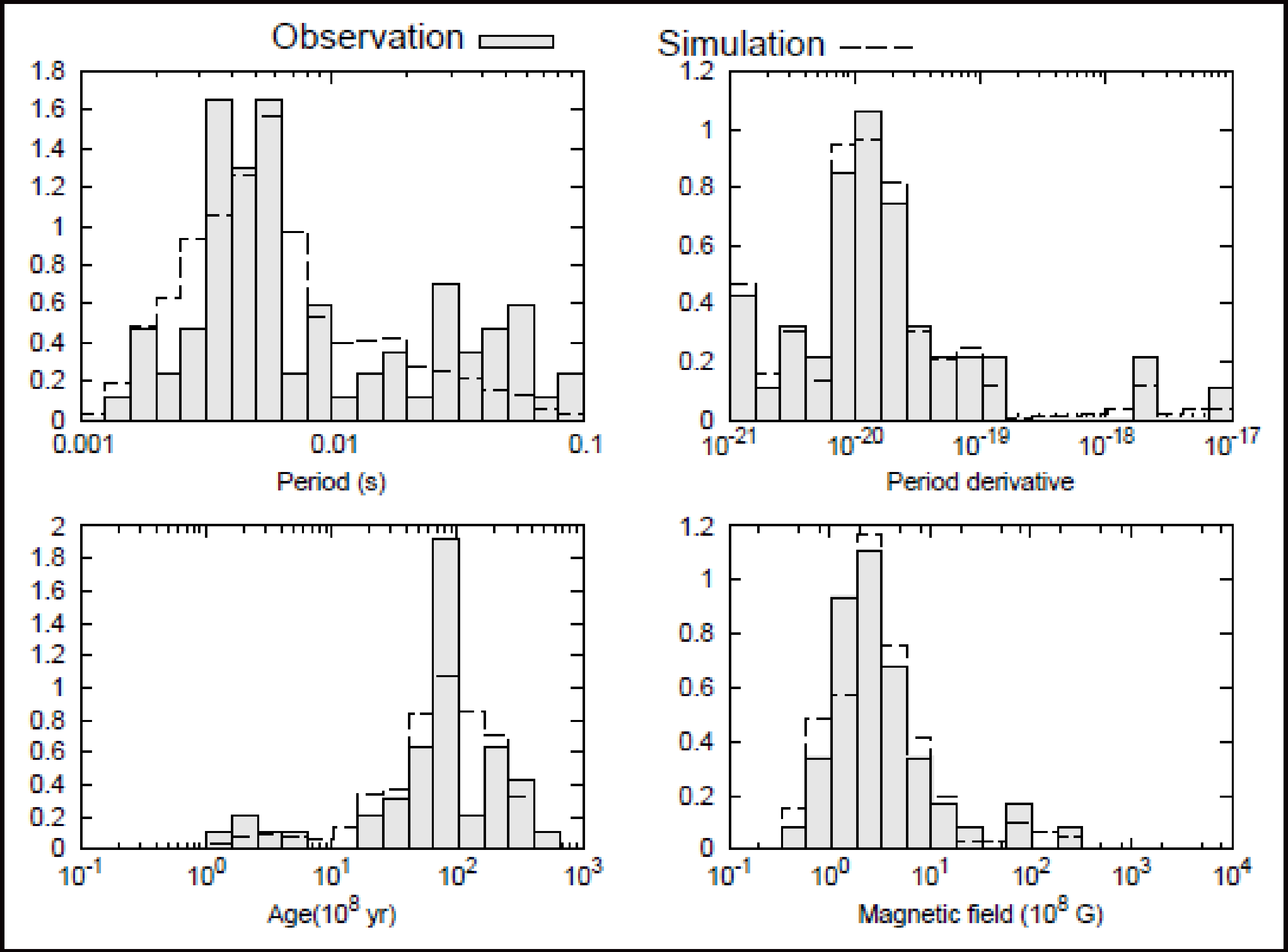
Predictions for lower fluxes







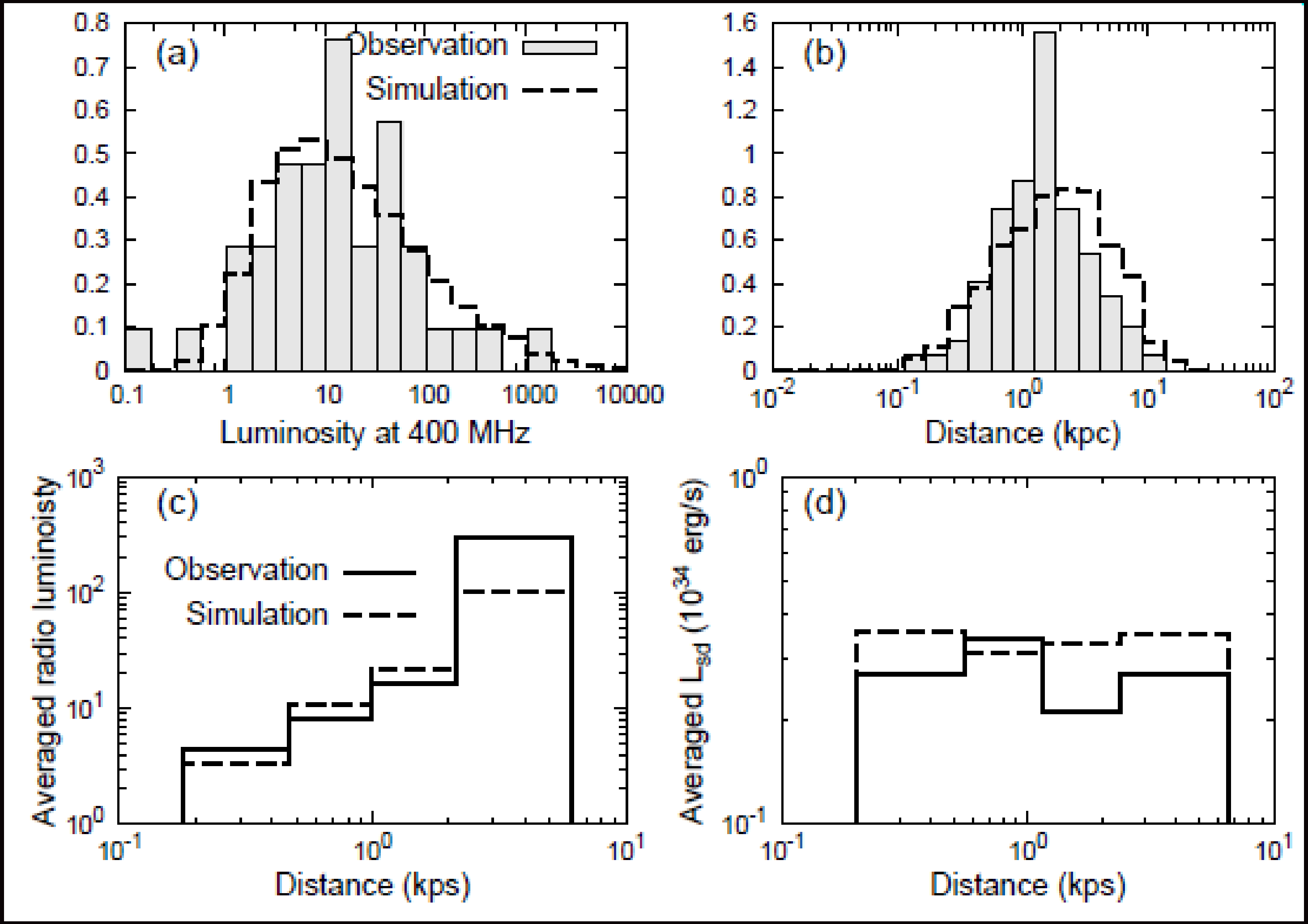
Millisecond pulsars



Radio observed

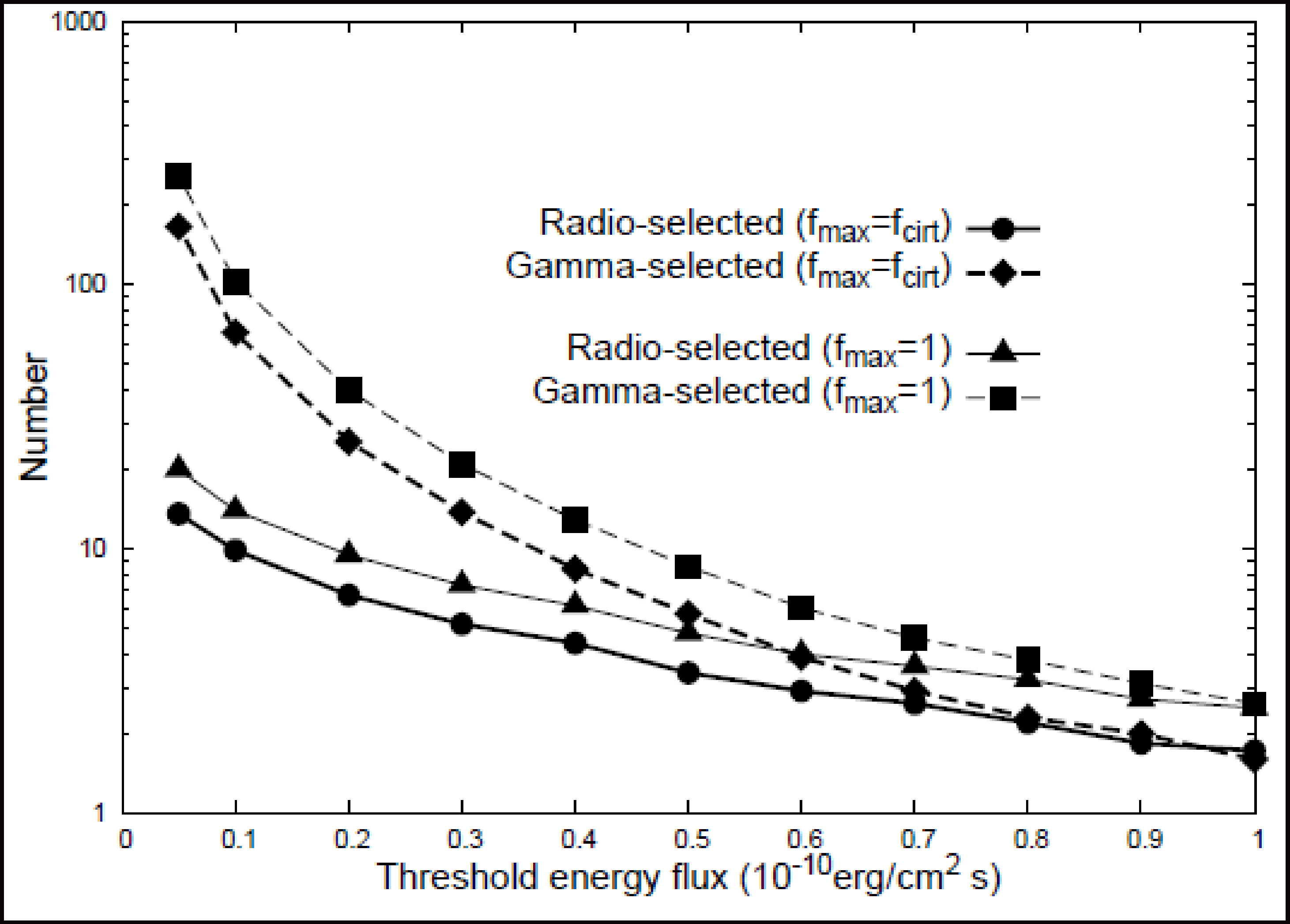
1102.2746 (see also 1110.5401)

Millisecond pulsars



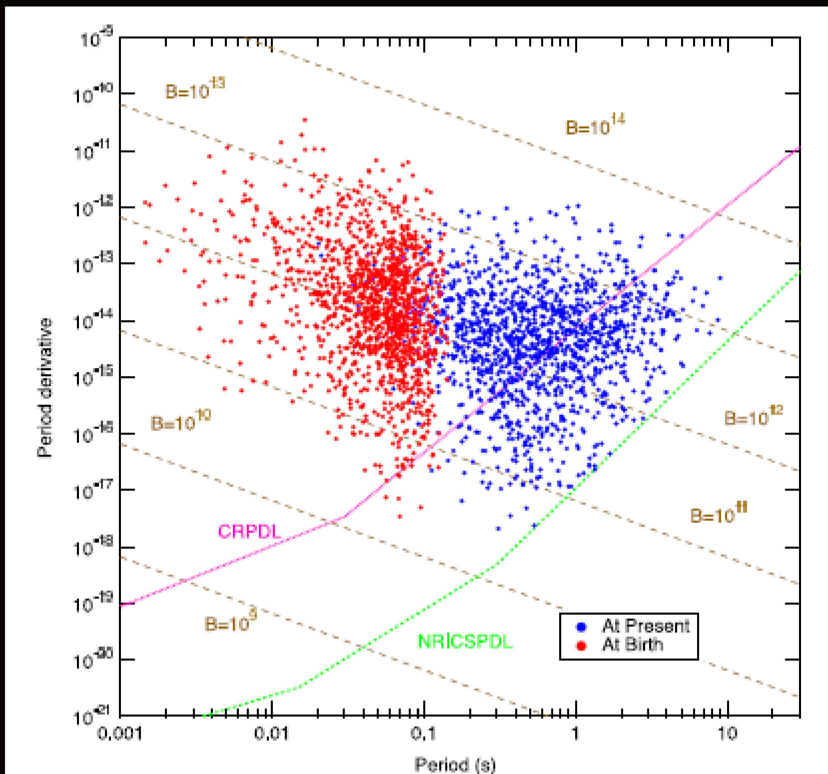
Radio detected

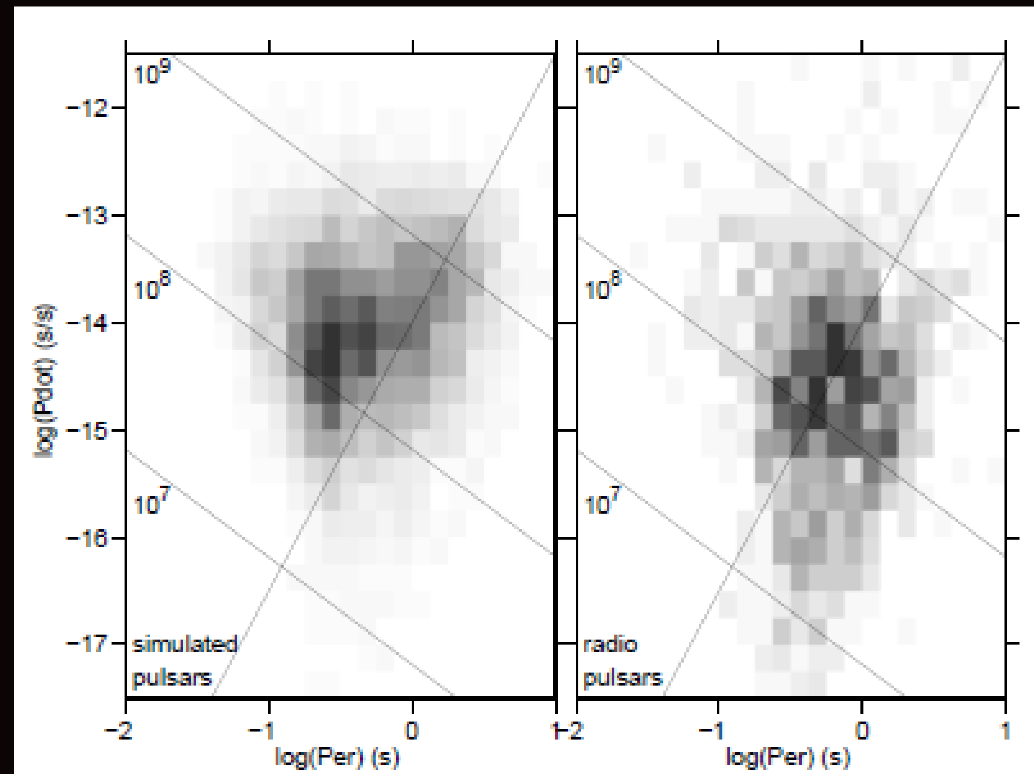
Prediction for low fluxes



Gap models study

Four models: Polar cap, slot gap, outer gap, one pole caustic.

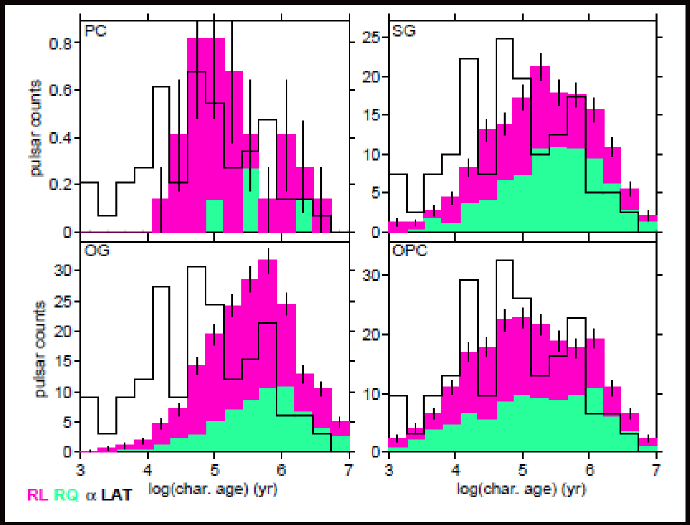


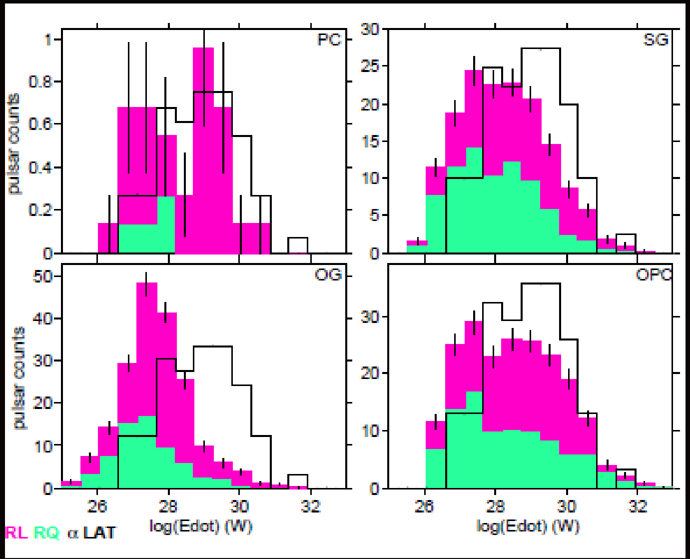


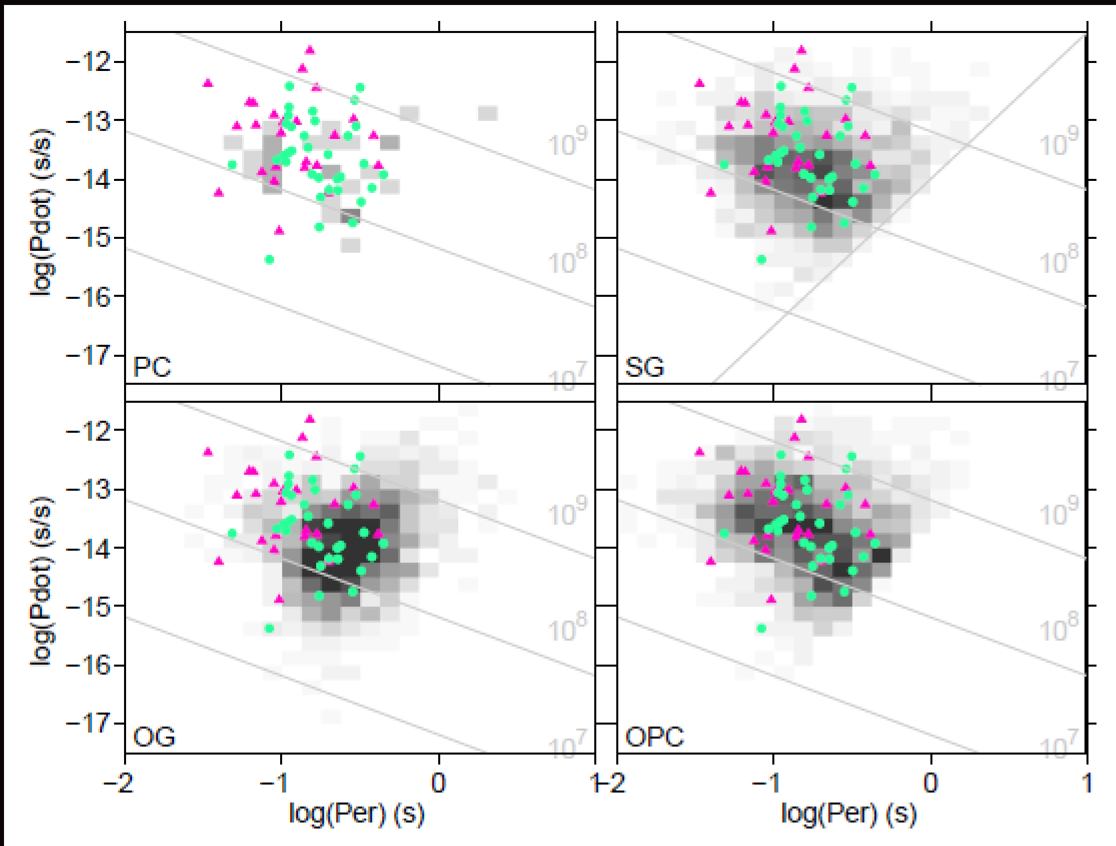
Radio data is OK

1206.5634

Problems of the model





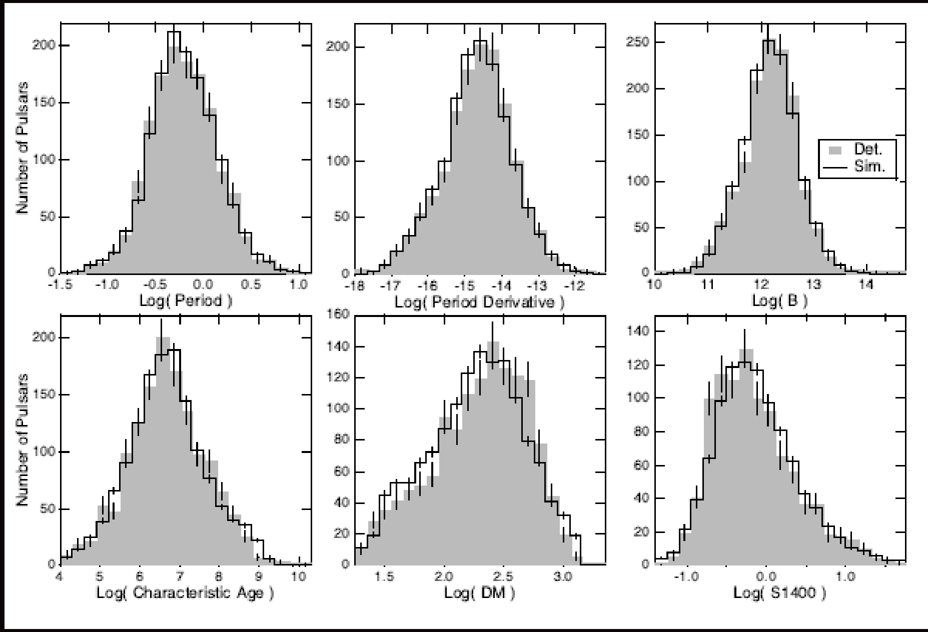


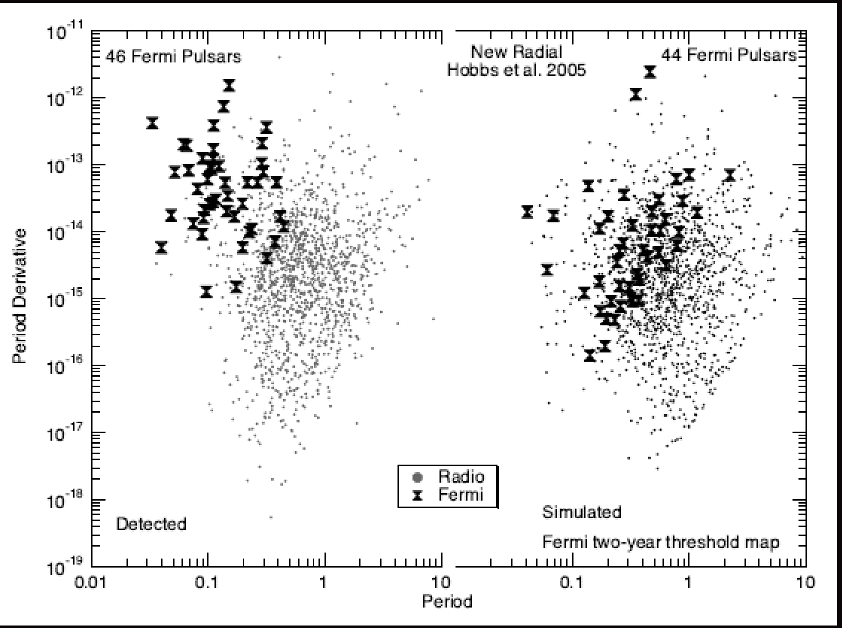
All model underpredict
the number of Fermi detections
for large rotation energy losses.

1206.5634

Markov Chain Monte Carlo for PSRs

A new approach in PSR PS. Just preliminary results have been presented.





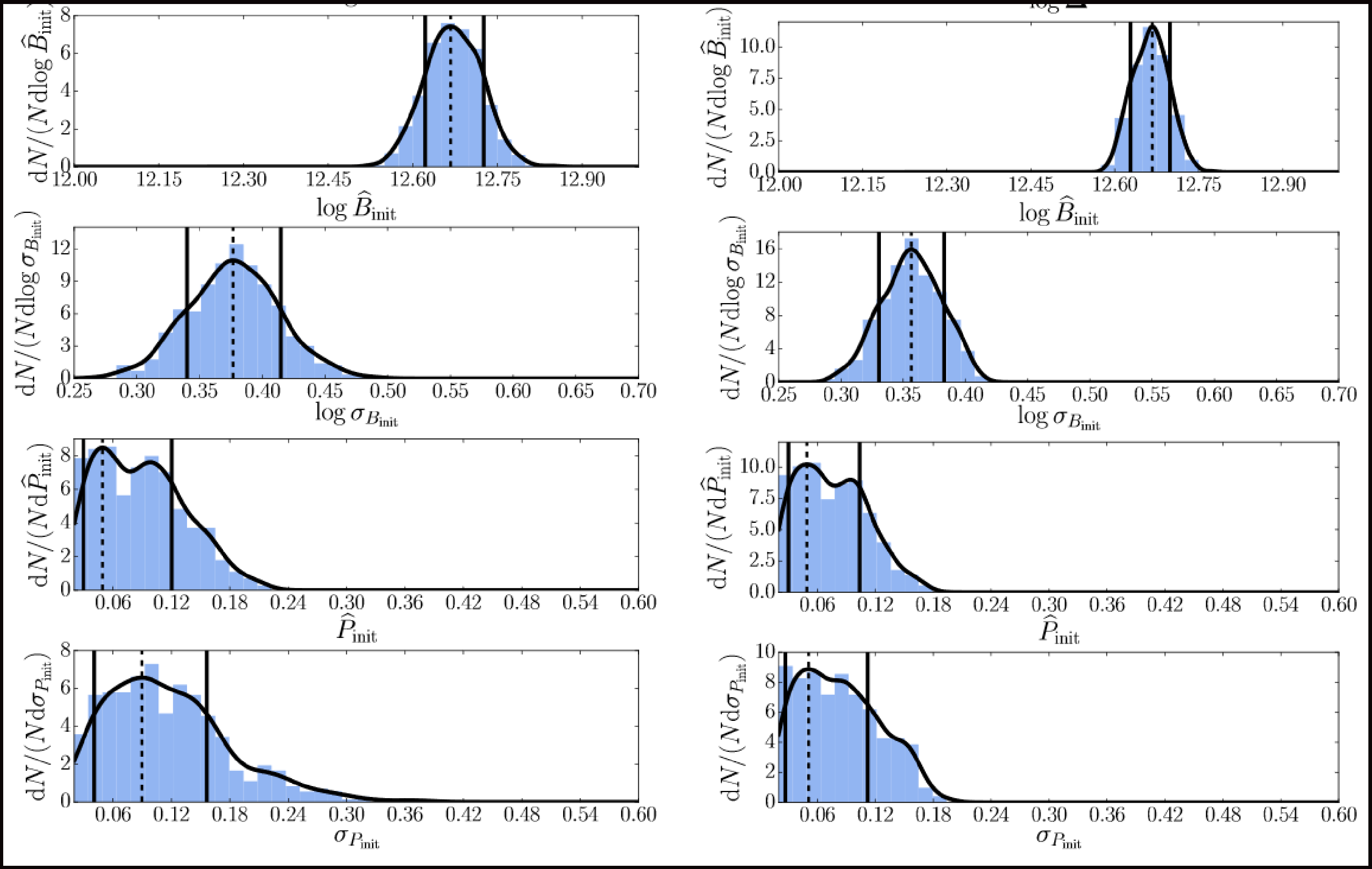
Main findings:

- Anti-correlation P_0-B_0
- Alignment on the time-scale 10^7 yrs

Some problems in explaining the Fermi data appeared (see 1206.5634)

1206.5958

New Markov chain synthesis



1803.02397

Population of close-by young NSs

- Magnificent seven
- Geminga and 3EG J1853+5918
- Four radio pulsars with thermal emission (B0833-45; B0656+14; B1055-52; B1929+10)
- Seven older radio pulsars, without detected thermal emission.

To understand the origin of these populations and predict future detections it is necessary to use population synthesis.

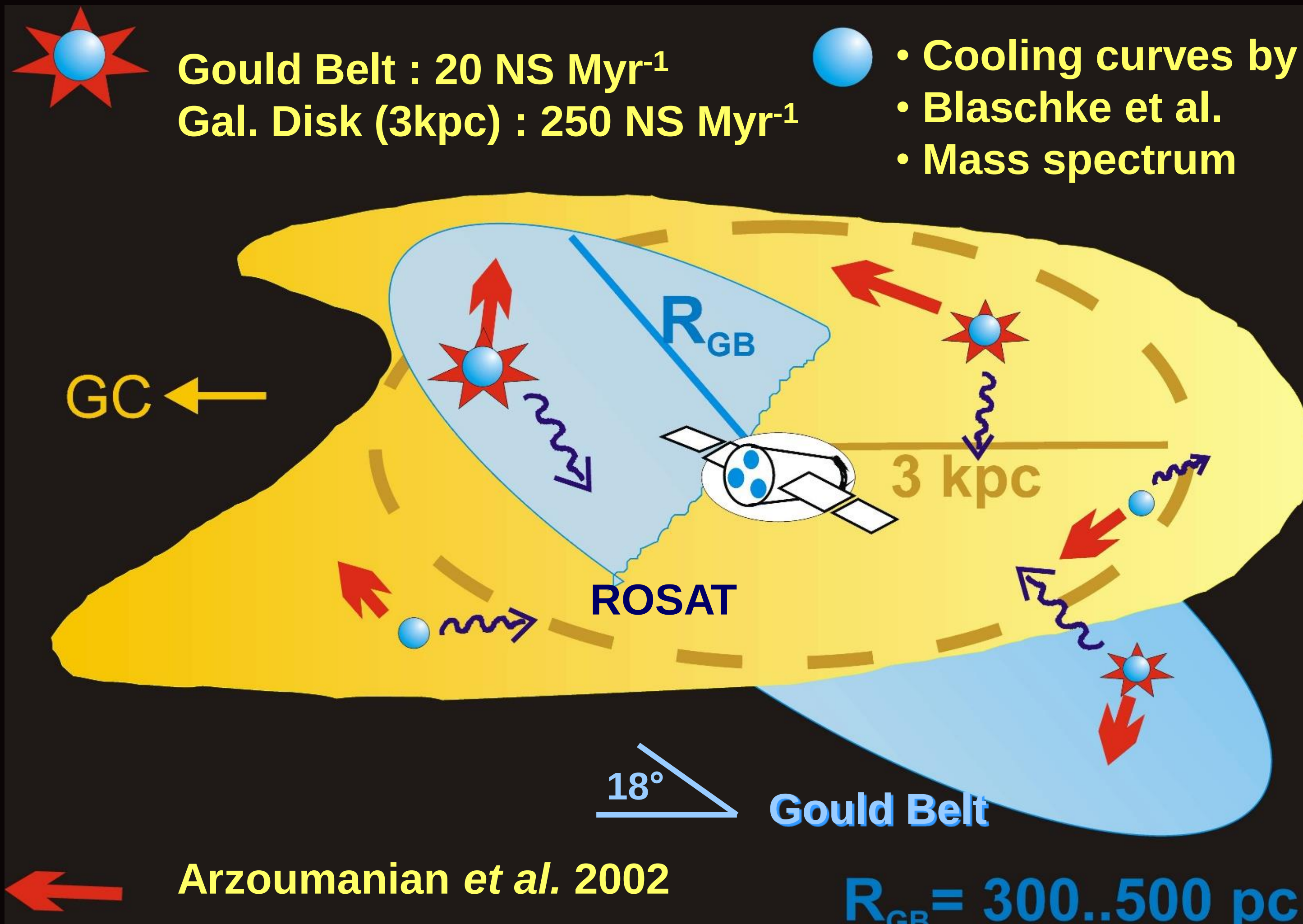
Population synthesis: ingredients

- Birth rate of NSs
- Initial spatial distribution
- Spatial velocity (kick)
- Mass spectrum
- Thermal evolution
- Interstellar absorption
- Detector properties

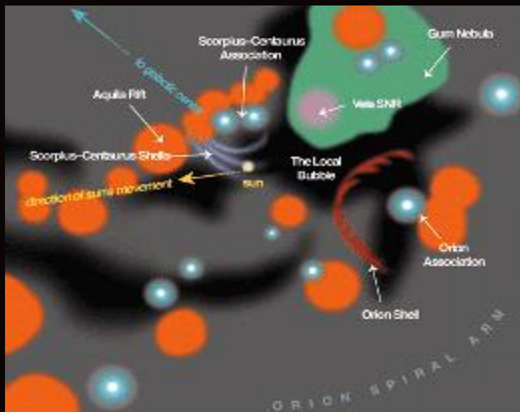
Task:

To build an artificial model of a population of some astrophysical sources and to compare the results of calculations with observations.

Population synthesis – I.



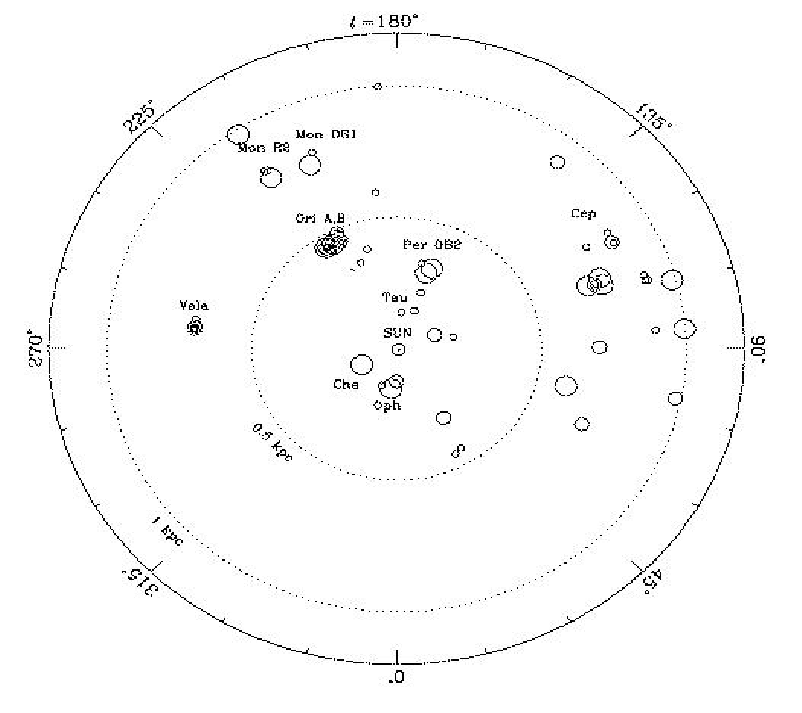
Solar vicinity

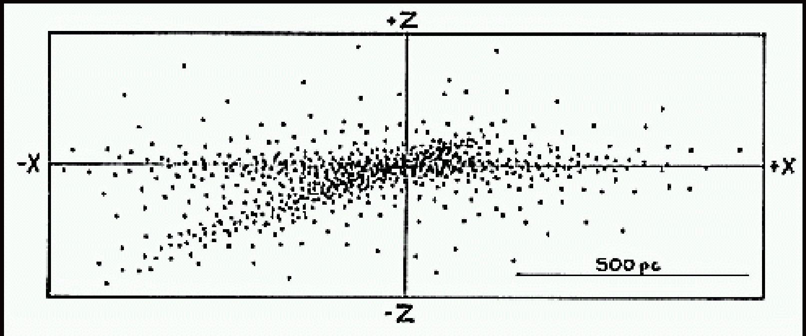


- Solar neighborhood is not a typical region of our Galaxy
- Gould Belt
- R=300-500 pc
- Age: 30-50 Myrs
- 20-30 SN per Myr (Grenier 2000)
- The Local Bubble
- Up to six SN in a few Myrs

The Gould Belt

- Poppel (1997)
- R=300 – 500 pc
- Age 30-50 Myrs
- Center at 150 pc from the Sun
- Inclined respect to the galactic plane at 20 degrees
- 2/3 massive stars in 600 pc belong to the Belt



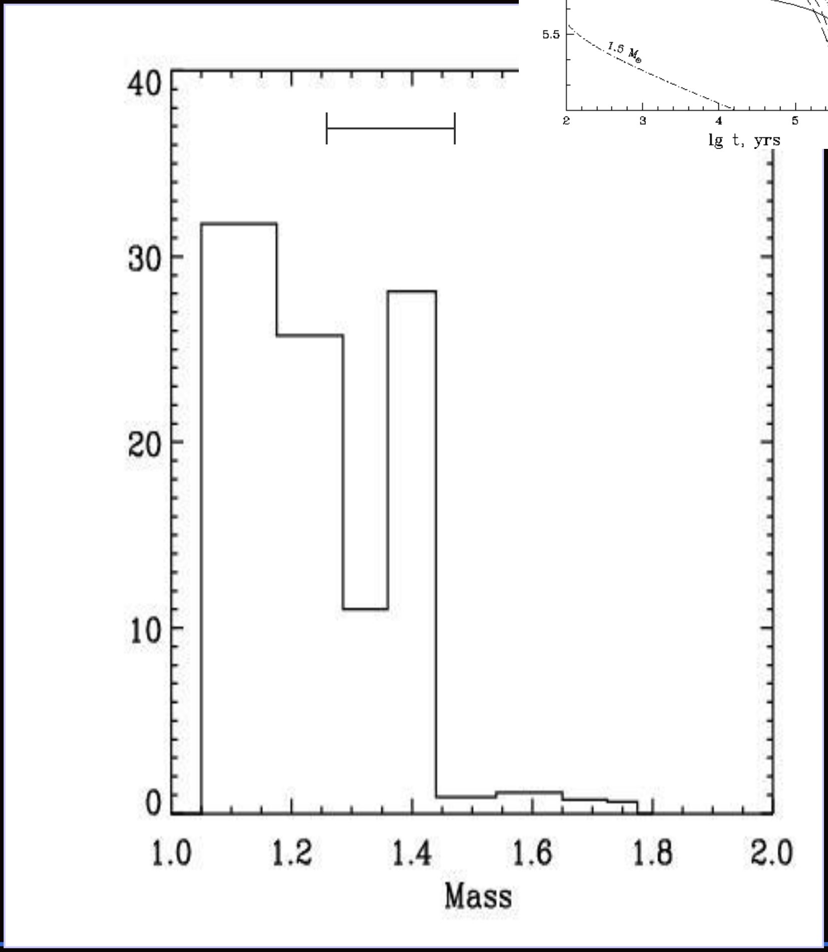


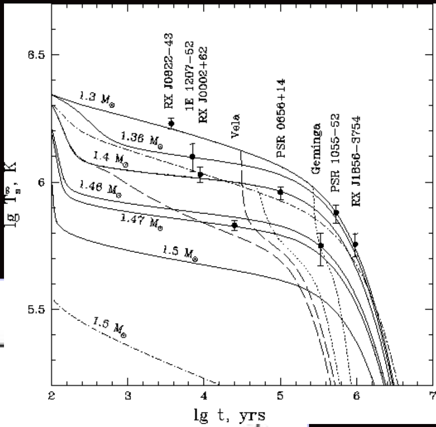
Mass spectrum of NSs

- Mass spectrum of local young NSs can be different from the general one (in the Galaxy)
- Hipparcos data on near-by massive stars
- Progenitor vs NS mass:

  Timmes et al. (1996);

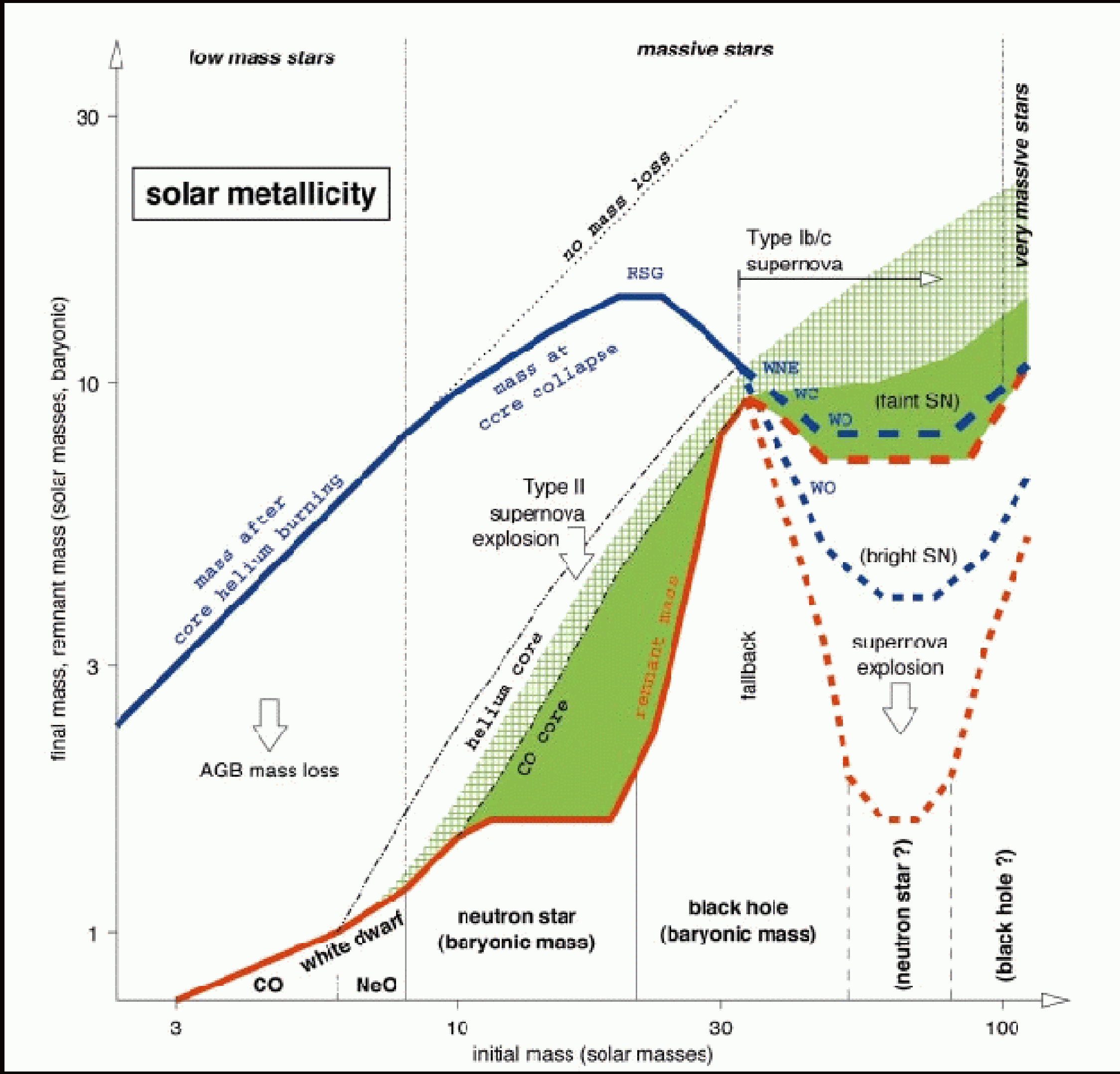
  Woosley et al. (2002)





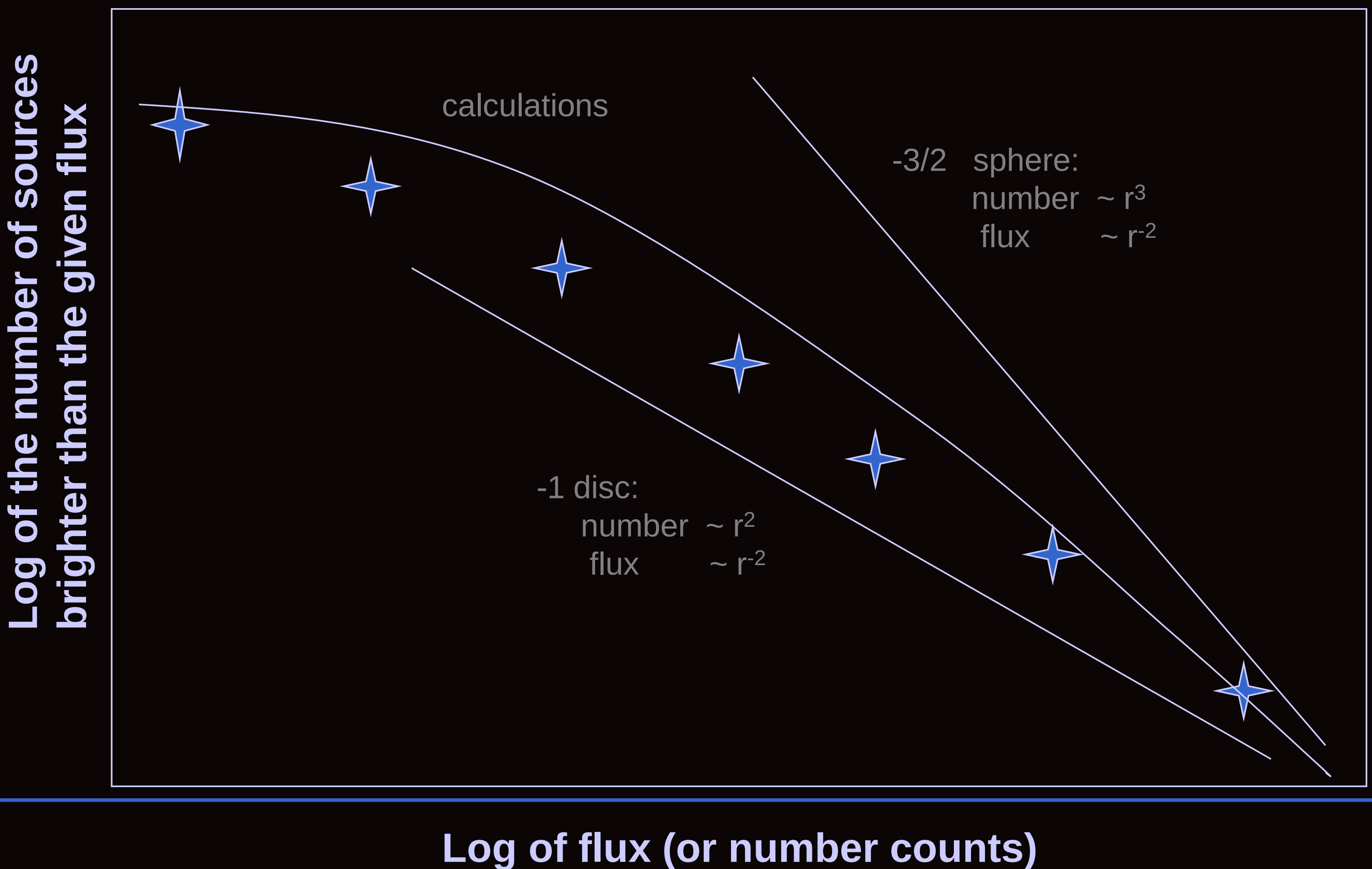
astro-ph/0305599

Progenitor mass vs. NS mass



Woosley et al. 2002

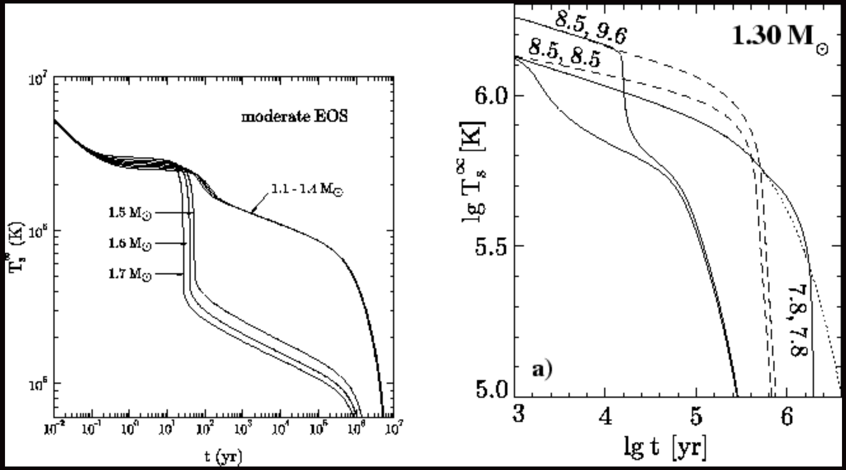
Log N – Log S



calculations
-3/2 sphere:
number ~ r3
flux ~ r-2
-1 disc:
number ~ r2
flux ~ r-2
Log of the number of sources brighter than the given flux
Log of flux (or number counts)

Cooling of NSs

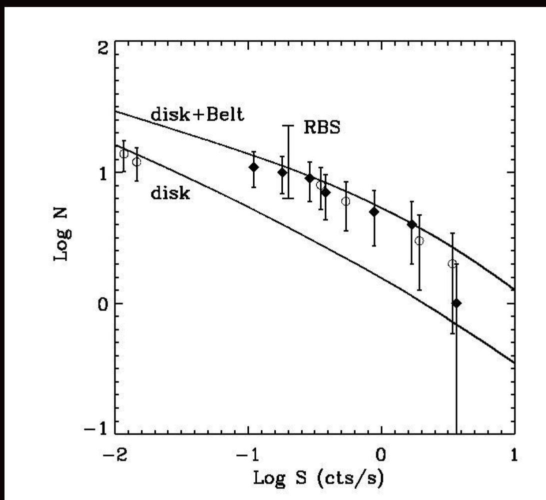
- Direct URCA
- Modified URCA
- Neutrino bremstrahlung
- Superfluidity
- Exotic matter (pions, quarks, hyperons, etc.)

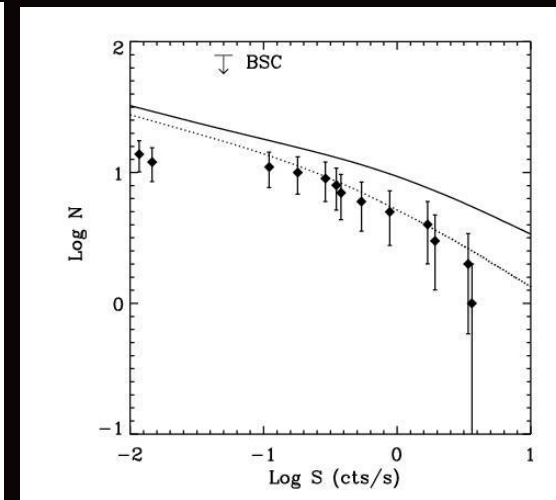


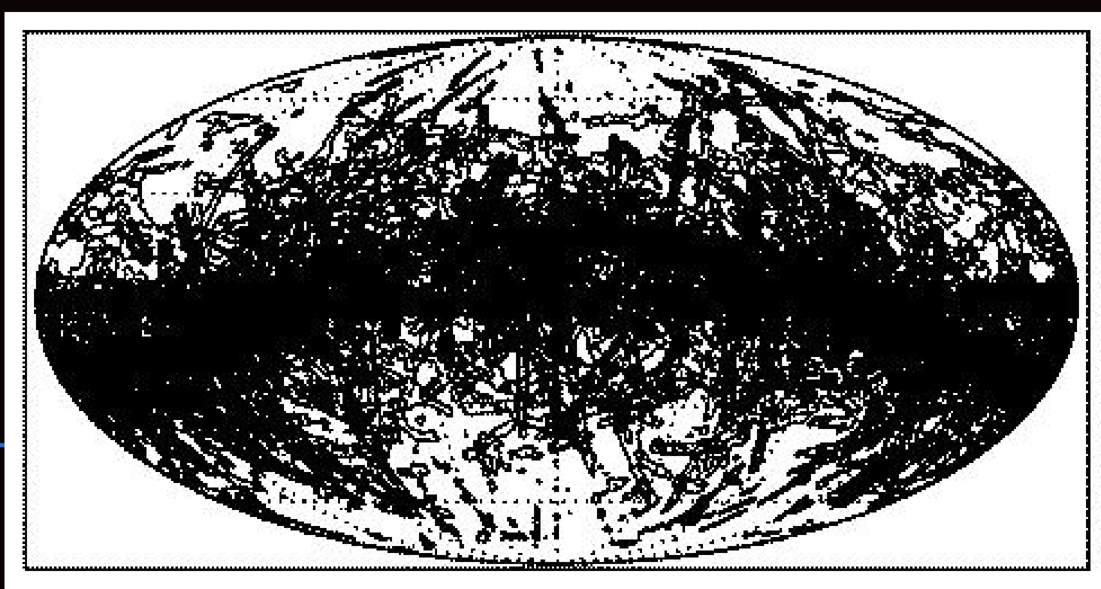
(see a recent review in astro-ph/0508056)

In our study for illustrative purposes we use a set of cooling curves calculated by Blaschke, Grigorian and Voskresenski (2004) in the frame of the *Nuclear medium cooling model*

Some results of PS-I:
Log N – Log S and spatial distribution







Log N – Log S for close-by ROSAT NSs can be explained by standard cooling curves taking into account the Gould Belt.

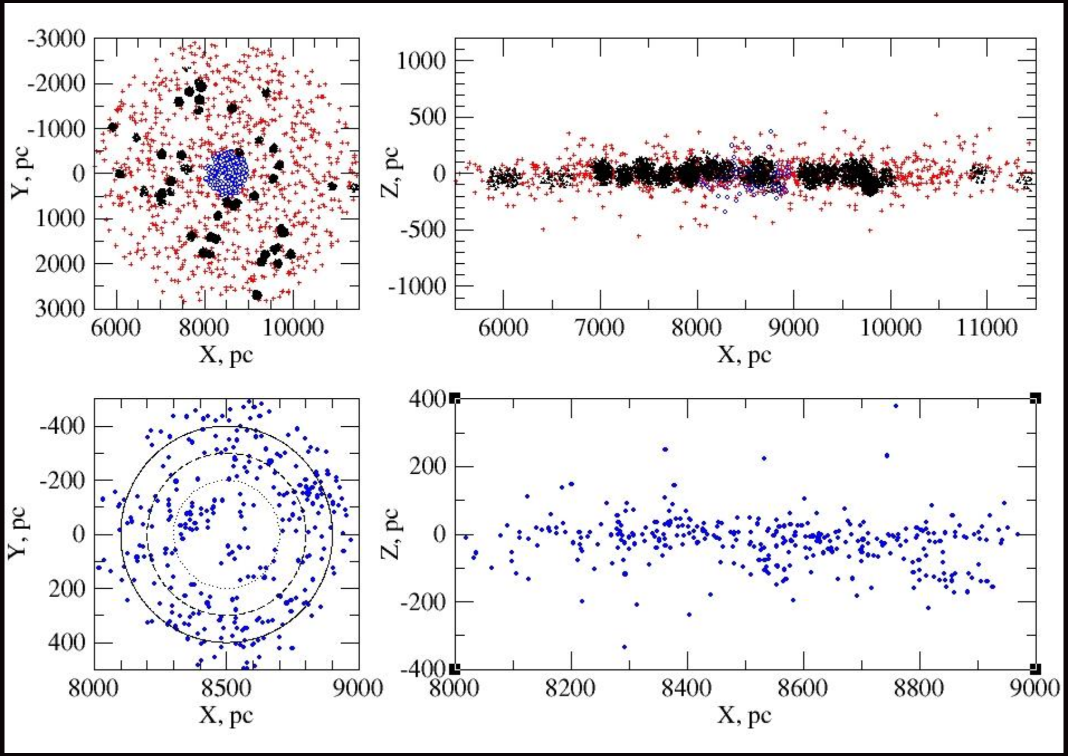
Log N – Log S can be used as an additional test of cooling curves

More than ½ are in +/- 12 degrees from the galactic plane.
19% outside +/- 30^o
12% outside +/- 40^o

(Popov et al. 2005 Ap&SS 299, 117)

Population synthesis – II.
recent improvements

1. Spatial distribution of progenitor stars



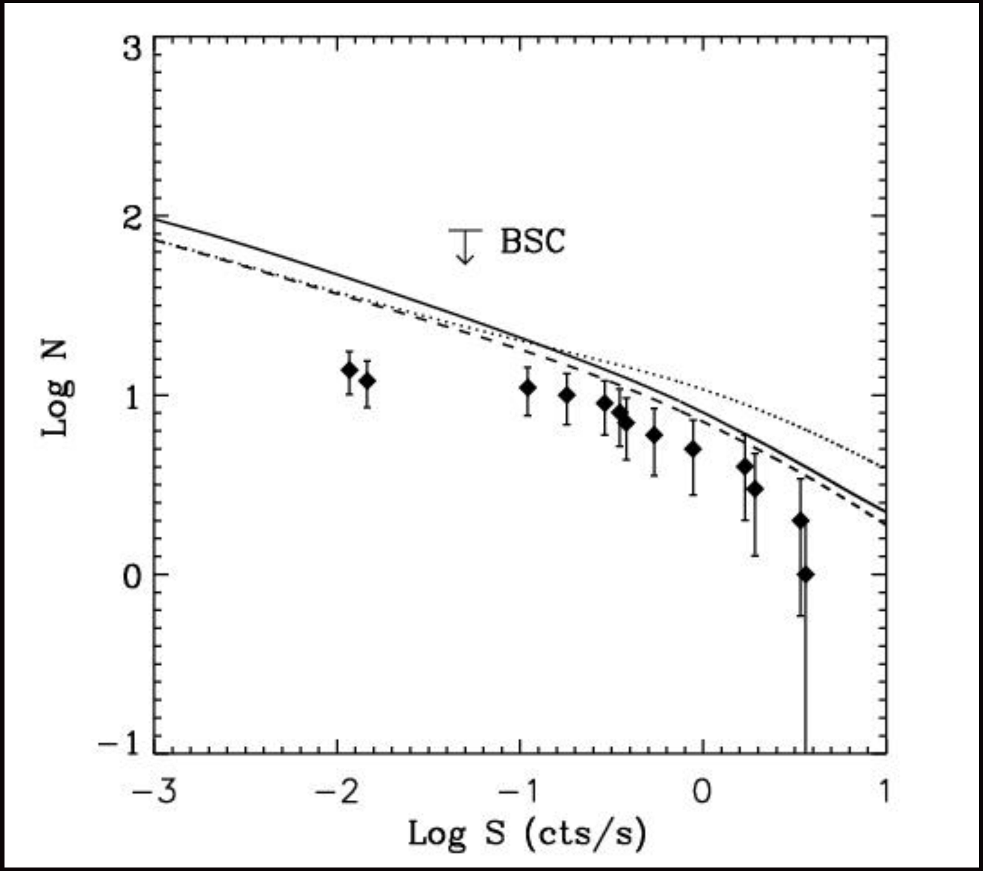
a) Hipparcos stars up to 500 pc
[Age: spectral type & cluster age (OB ass)]
b) 49 OB associations: birth rate ~ N_{star}
c) Field stars in the disc up to 3 kpc

We use the same normalization for NS formation rate inside 3 kpc: 270 per Myr.

Most of NSs are born in OB associations.

For stars <500 pc we even try to take into account if they belong to OB assoc. with known age.

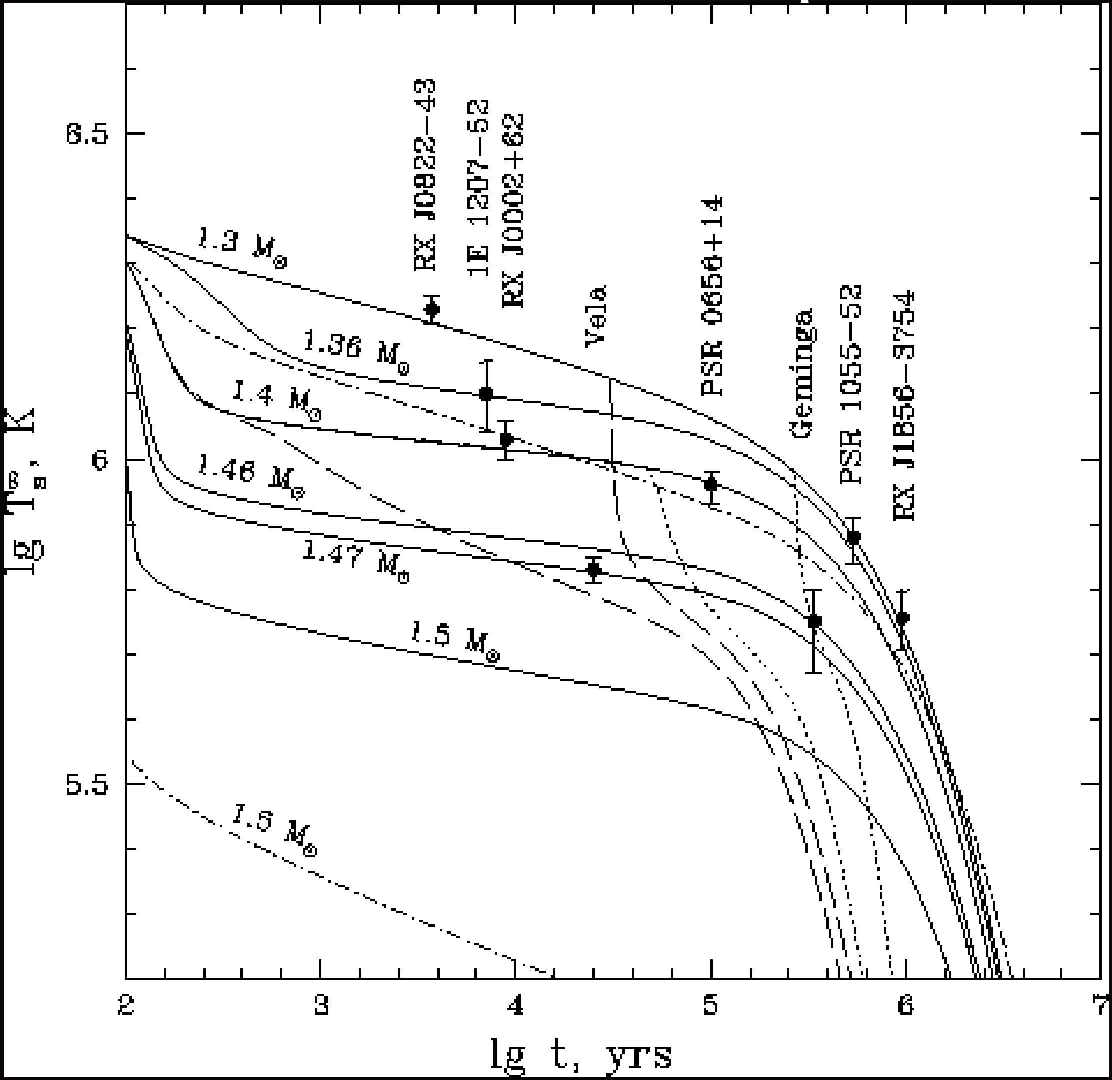
Effects of the new spatial distribution on Log N – Log S



There are no significant effects on the Log N – Log S distribution due to more clumpy initial distribution of NSs.

Solid – new initial XYZ
Dashed – R_{belt} = 500 pc
Dotted – R_{belt} = 300 pc

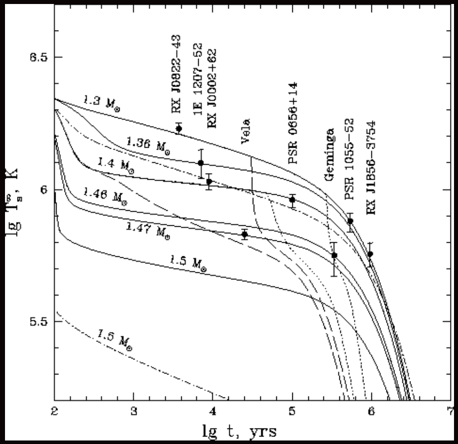
Standard test: temperature vs. age

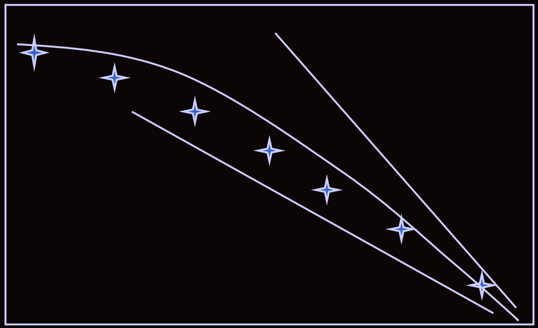


Kaminker et al. (2001)

Log N – Log S as an additional test

- Standard test: Age – Temperature
  - Sensitive to ages <10^5 years
  - Uncertain age and temperature
  - Non-uniform sample
- Log N – Log S
  - Sensitive to ages >10^5 years (when applied to close-by NSs)
  - Definite N (number) and S (flux)
  - Uniform sample
- Two test are perfect together!!!





astro-ph/0411618

Isolated neutron star census

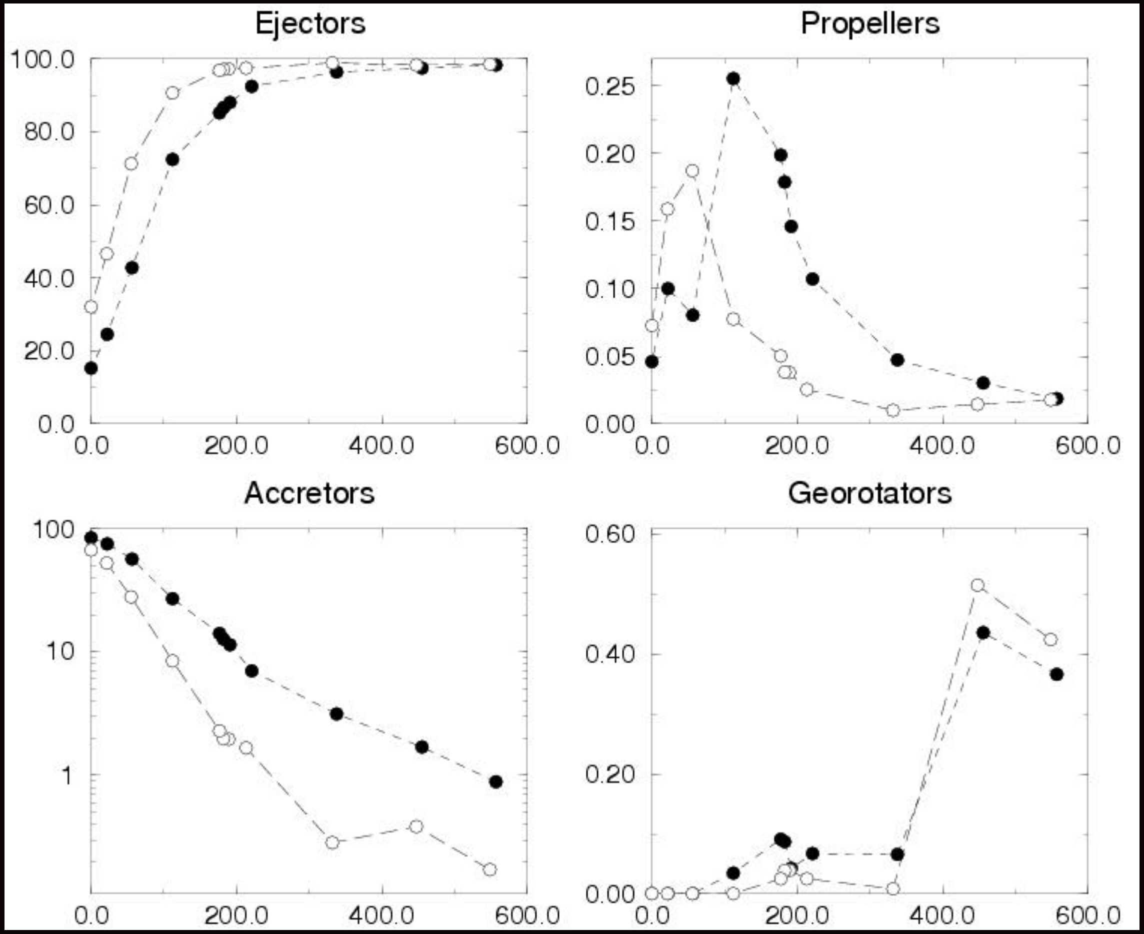
Task.

To calculate distribution of isolated NSs in the Galaxy over evolutionary stages: Ejector, Propeller, Accretor, Georotator

Ingredients.

- Galactic potential
- Initial NS spatial distribution
- Kick velocity
- ISM distribution
- Spin evolution and critical periods
- Magnetic field distribution and evolution

Stages



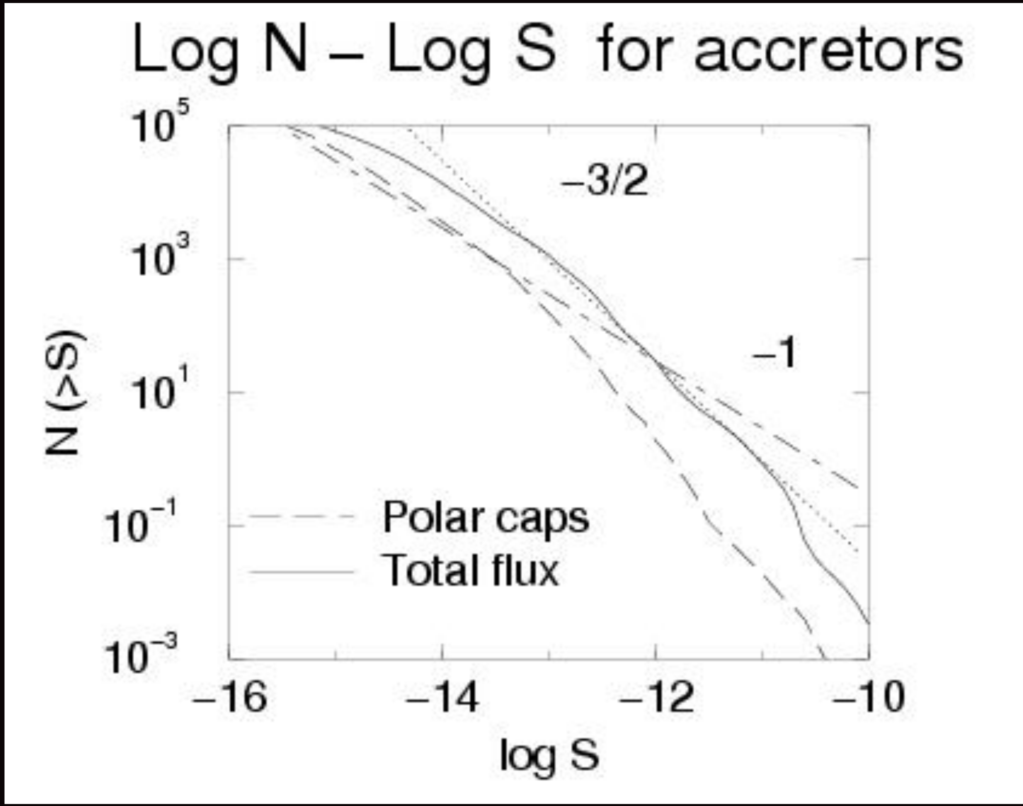
Rather conservative evolutionary scheme was used.

For example,
subsonic propellers
have not been considered
(Ikhsanov 2006).

astro-ph/9910114

Accreting isolated NSs

At small fluxes $<10^{-13}$ erg/s/cm^2 accretors can become more abundant than coolers. Accretors are expected to be slightly harder: 300-500 eV vs. 50-100 eV. Good targets for eROSITA!



From several hundreds up to several thousands objects at fluxes about few **x** 10^{-14}, but difficult to identify.

Monitoring is important.

Also isolated accretors can be found in the Galactic center (Zane et al. 1996, Deegan, Nayakshin 2006).

astro-ph/0009225

New results in 1004.4805

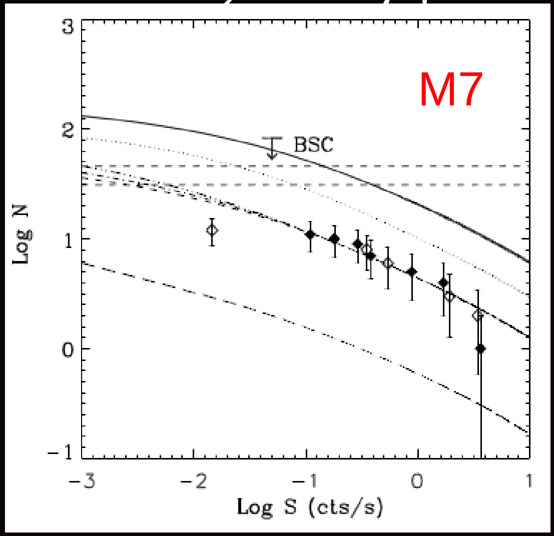
Extensive population synthesis

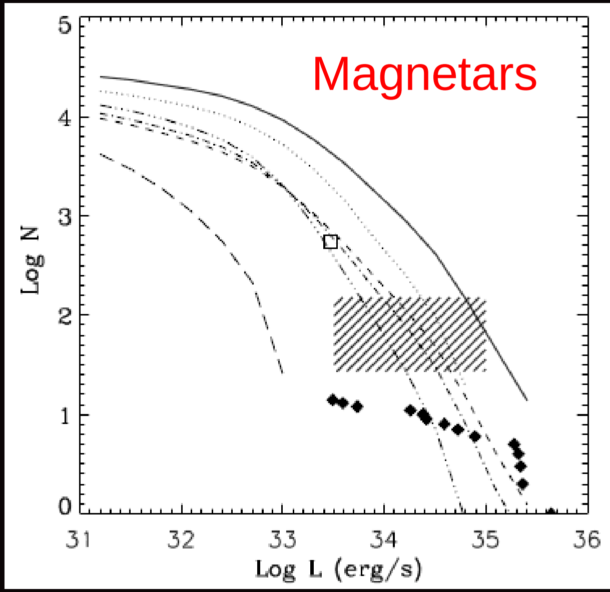
We want to make extensive population synthesis studies using as many approaches as we can to confront theoretical models with different observational data

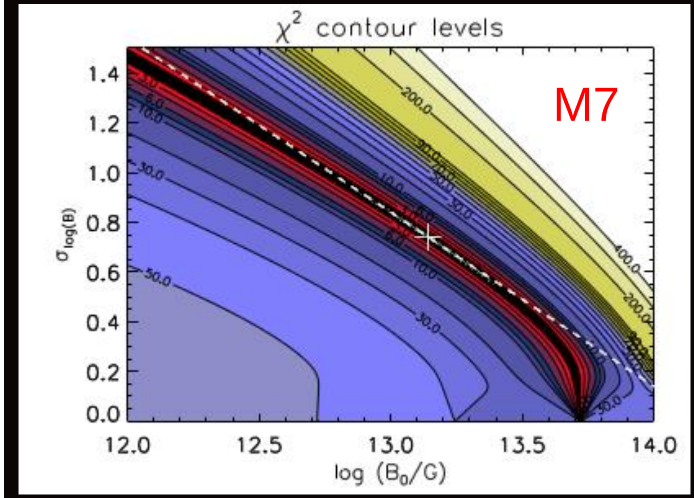
- Log N – Log S for close-by young cooling isolated neutron stars
- Log N – Log L distribution for galactic magnetars
- P-Pdot distribution for normal radio pulsars

MNRAS (2009) arXiv: 0910.2190

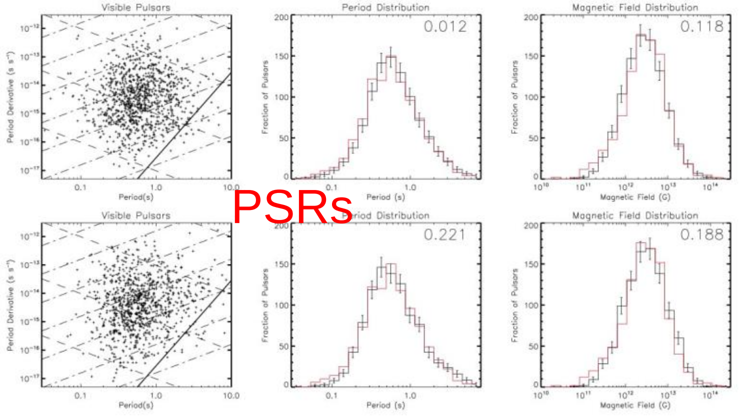
Extensive population synthesis: M7, magnetars, PSRs

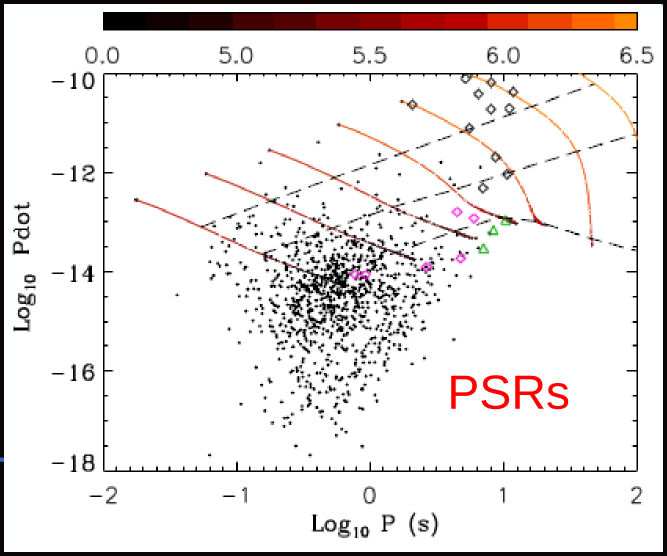






Using one population it is difficult or impossible to find unique initial distribution for the magnetic field





All three populations are compatible with a unique distribution.

Of course, the result is model dependent.

Results

- There are several different populations of neutron stars which must be studied together in one framework
- Population synthesis calculations are necessary to confront theoretical models with observations
- We use different approaches to study different populations using the same parameters distribution
- In the model with magnetic field decay we focused on log-normal distributions of initial magnetic fields
- We can describe properties of several populations
  - ◊ close-by cooling NSs
  - ◊ magnetars
  - ◊ normal PSRs

  with the same log-normal magnetic field distribution

Best model: $\langle \log(B0/[G]) \rangle = 13.25$, $\sigma_{\log B0}=0.6$, $\langle P0 \rangle = 0.25$ s, $\sigma_{P0} = 0.1$ s

- We exclude distributions with >~20% of magnetars
- Populations with ~10% of magnetars are favoured

Conclusions

- Population synthesis is a useful tool in astrophysics
- Many theoretical parameters can be tested only via such modeling
- Many parameters can be determined *only* via PS models
- Actively used to study NSs

Papers to read

- Physics Uspekhi 50, 1123 (2007) – see my web-page http://xray.sai.msu.ru/~polar/html/presentations.html