

# Population synthesis of INNs

# 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](https://arxiv.org/abs/astro-ph/0411792))

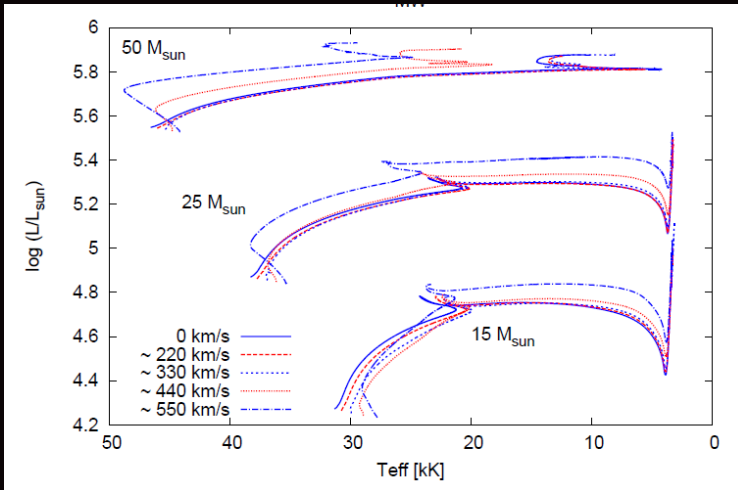
# Two variants

## 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

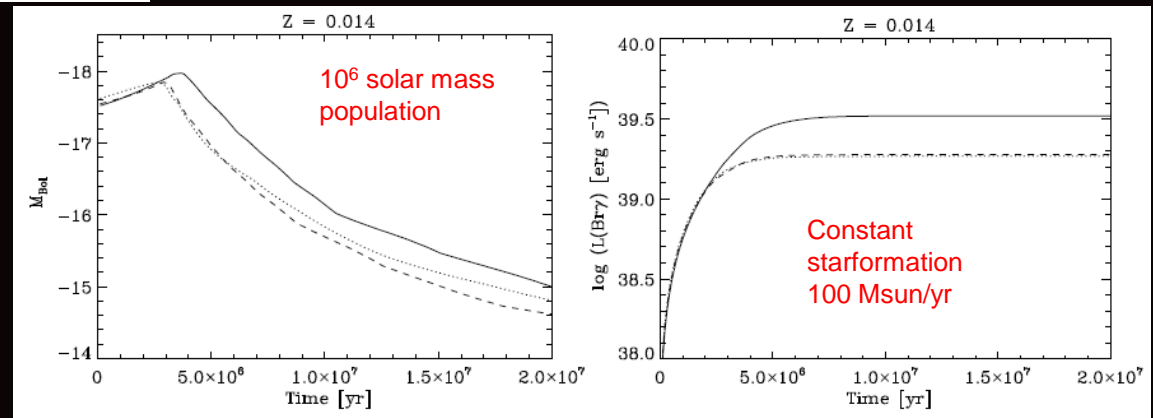
A review can be found in 1111.5204  
The authors present several examples.



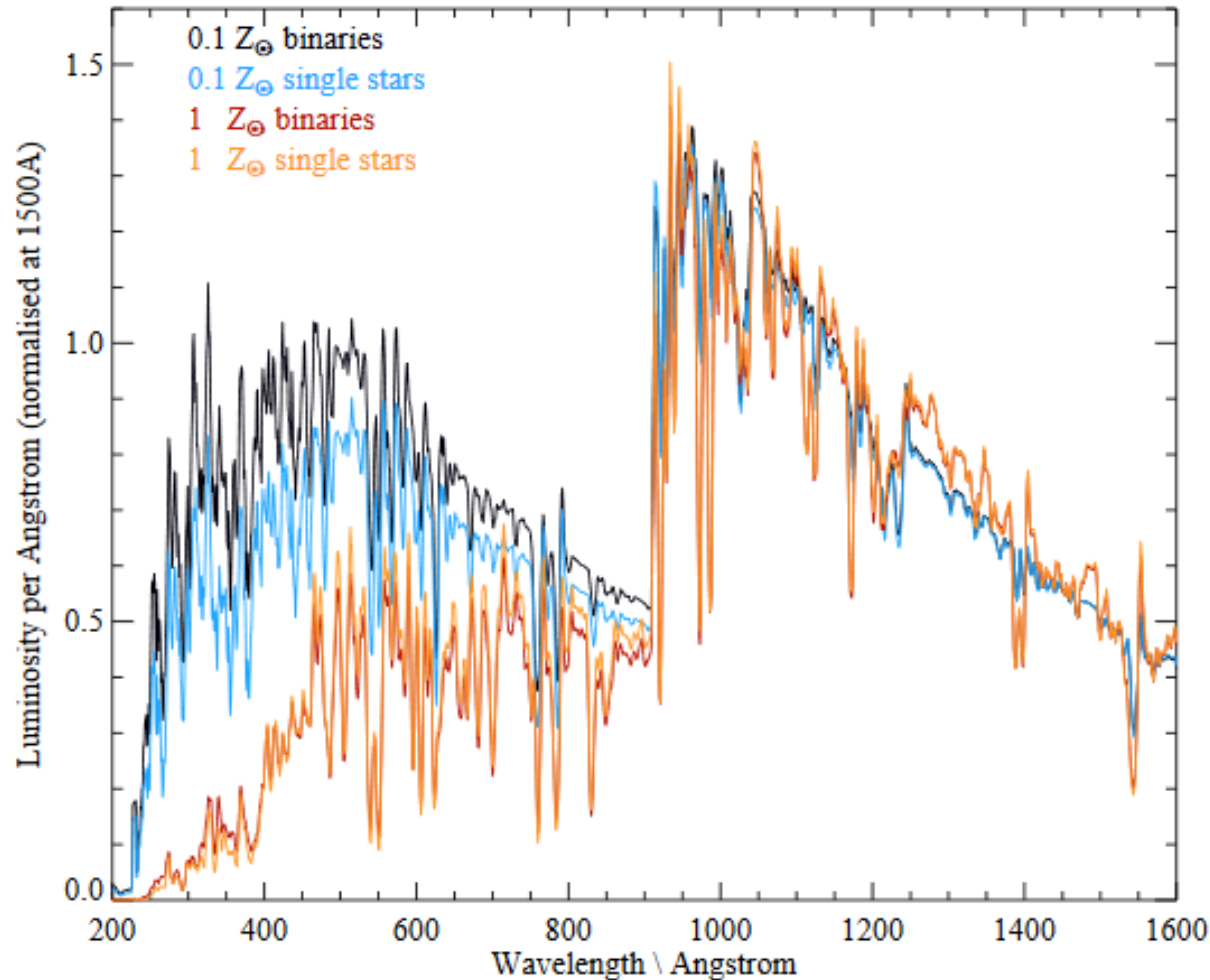
More reviews on popsynthesis  
in application to stellar populations  
and integrated spectra:  
2005.11883, 2005.11881.  
A brief general review: 2009.08611

Solid lines: new tracks with rotation;  
dashed: new tracks with zero rotation velocity

Effects of rotation on  
integrated characteristics  
of stellar populations

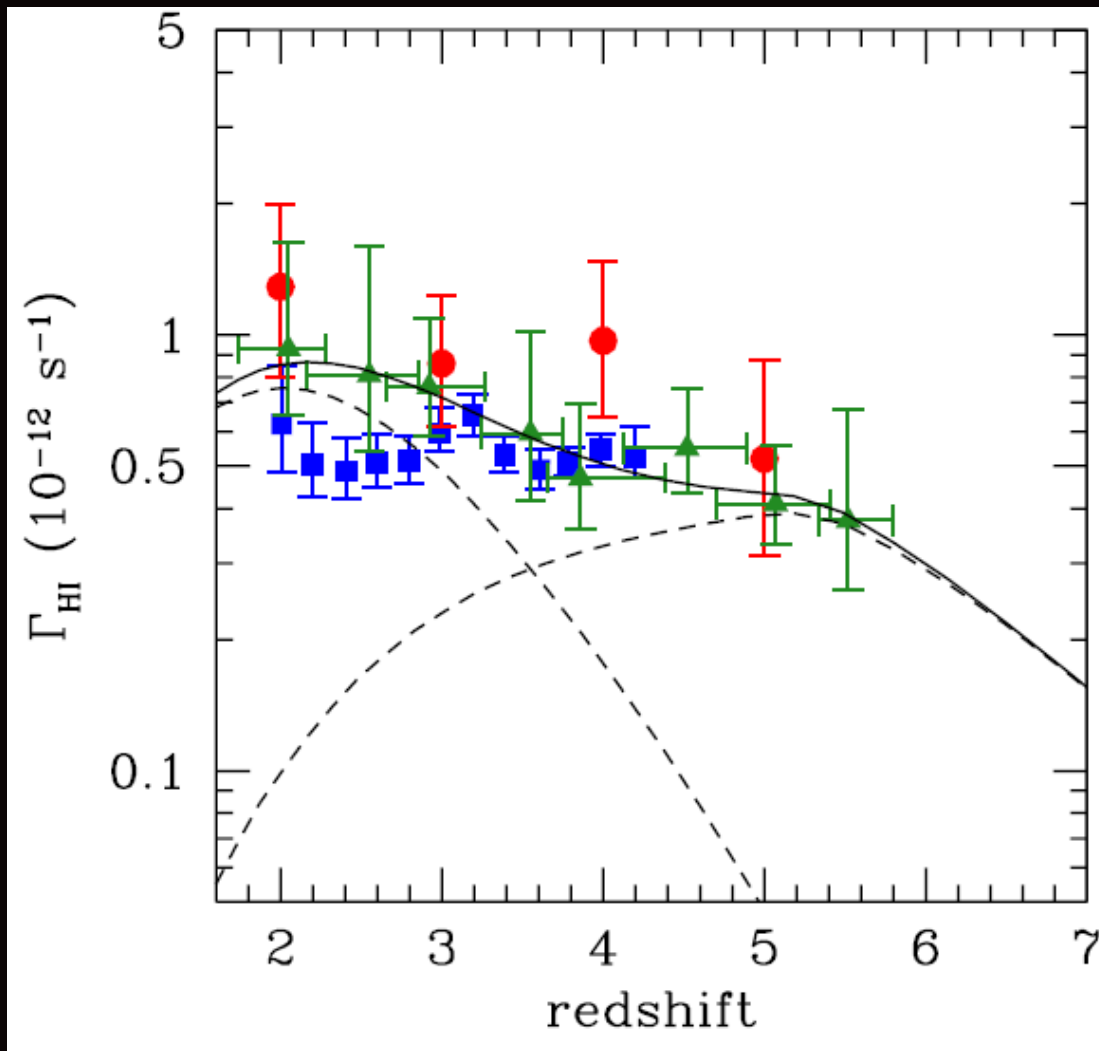


# Integrated synthetic stellar spectra



Parameters of binary population are uncertain, and their variations are important in such calculations, see 2004.11913, 2004.13040, and 2005.01759.

# Empirical population synthesis

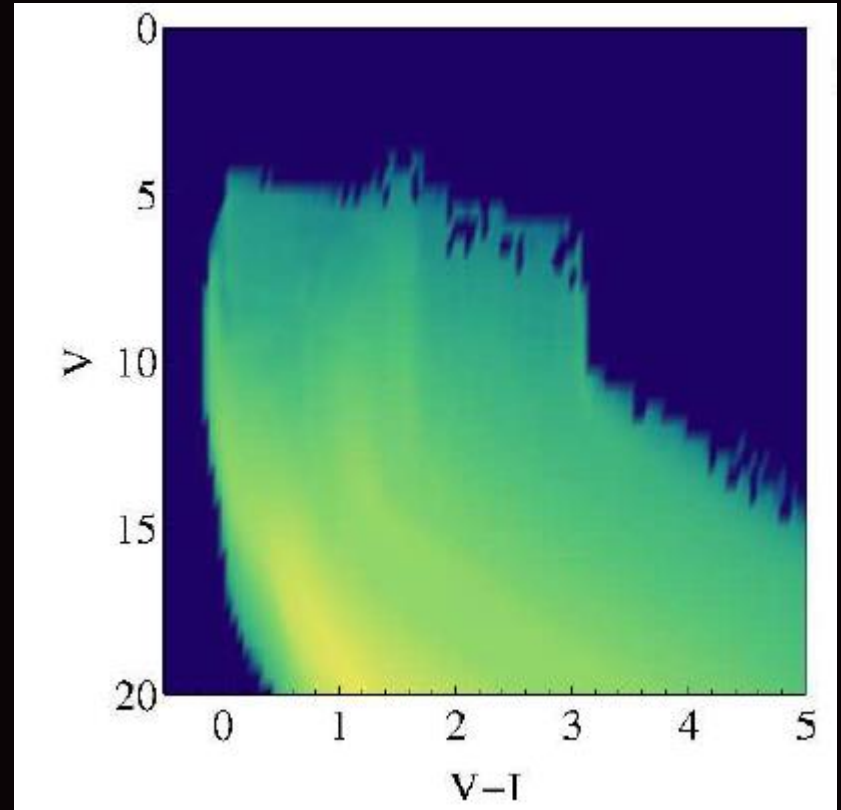
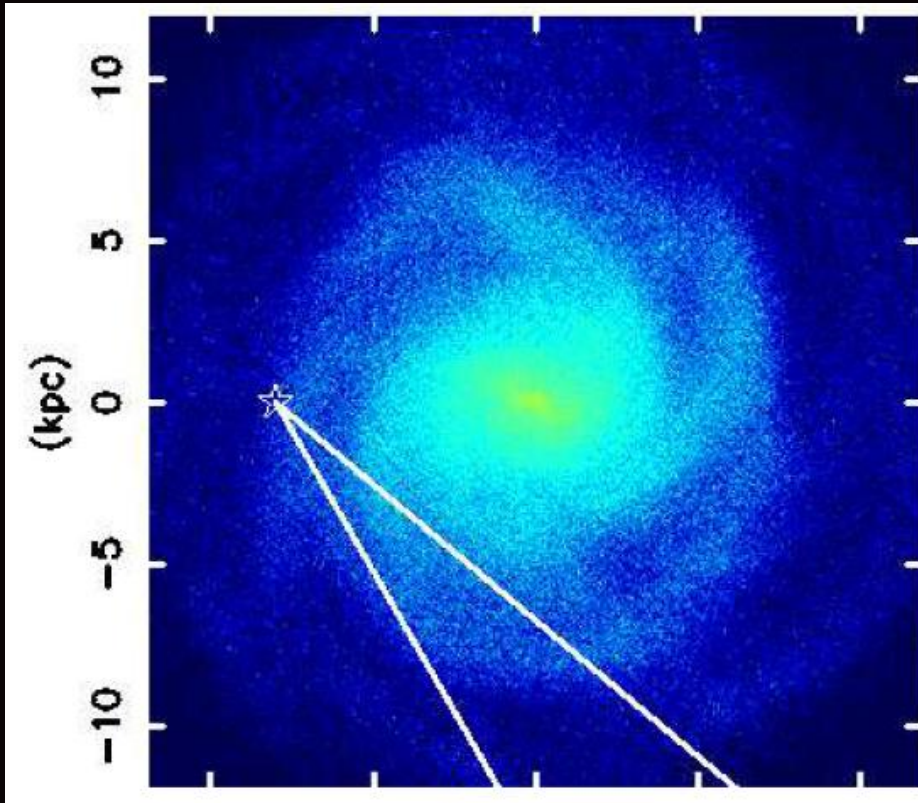


Hydrogen photoionization rate  
as a function of redshift

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

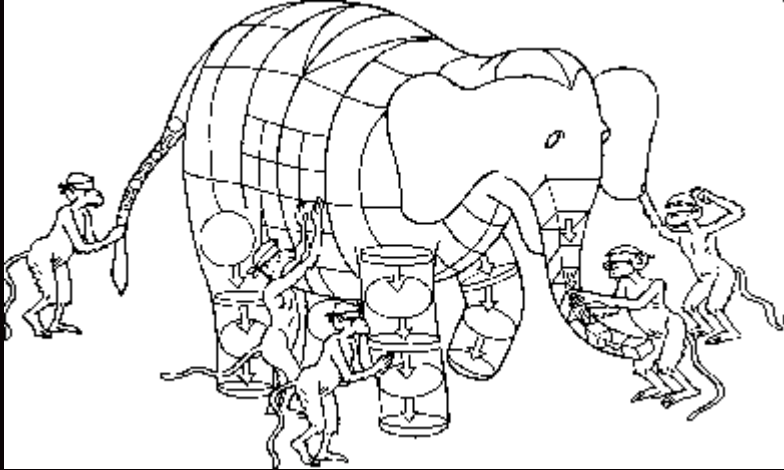
Data corresponds to the  
Ly-alpha forest observations.

# 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 popsynth. approach is applied to calculated colours.

# Population synthesis



## Ingredients:

- initial condition
- evolutionary laws



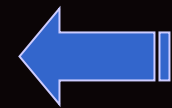
«Artificial  
observed  
universe»



*Modeling  
observations*



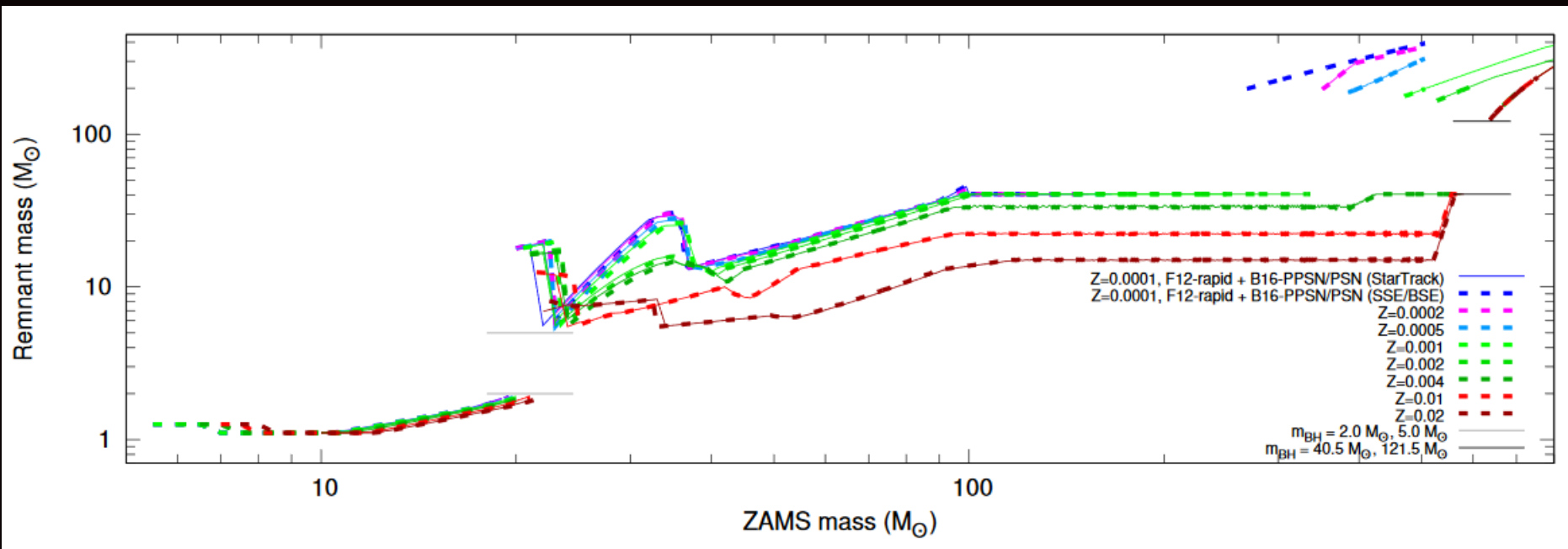
«Artificial universe»





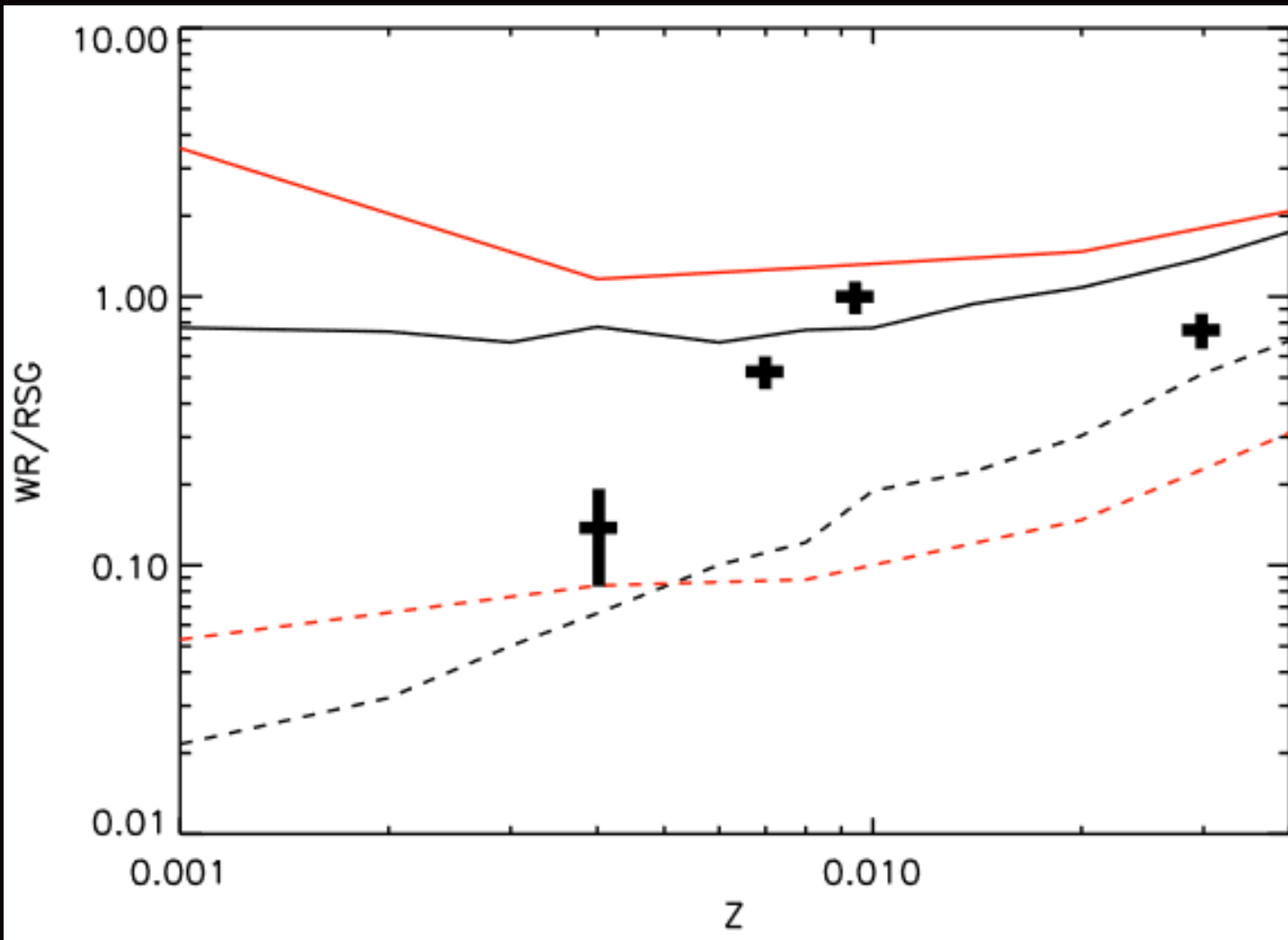
# Binary population synthesis

There are many codes (starting from models by Tutukov, Yungelson and Lipunov et al.). Recent comparison of BSE and StarTrack can be found in 1902.07718



For example, recently appeared many papers related to popsynth calculations of properties of binary BH and NS systems in relation to GW observations, see 1902.01419, 2011.13503 and references therein (and a review in 2107.14239).

# Example of binary vs. single model

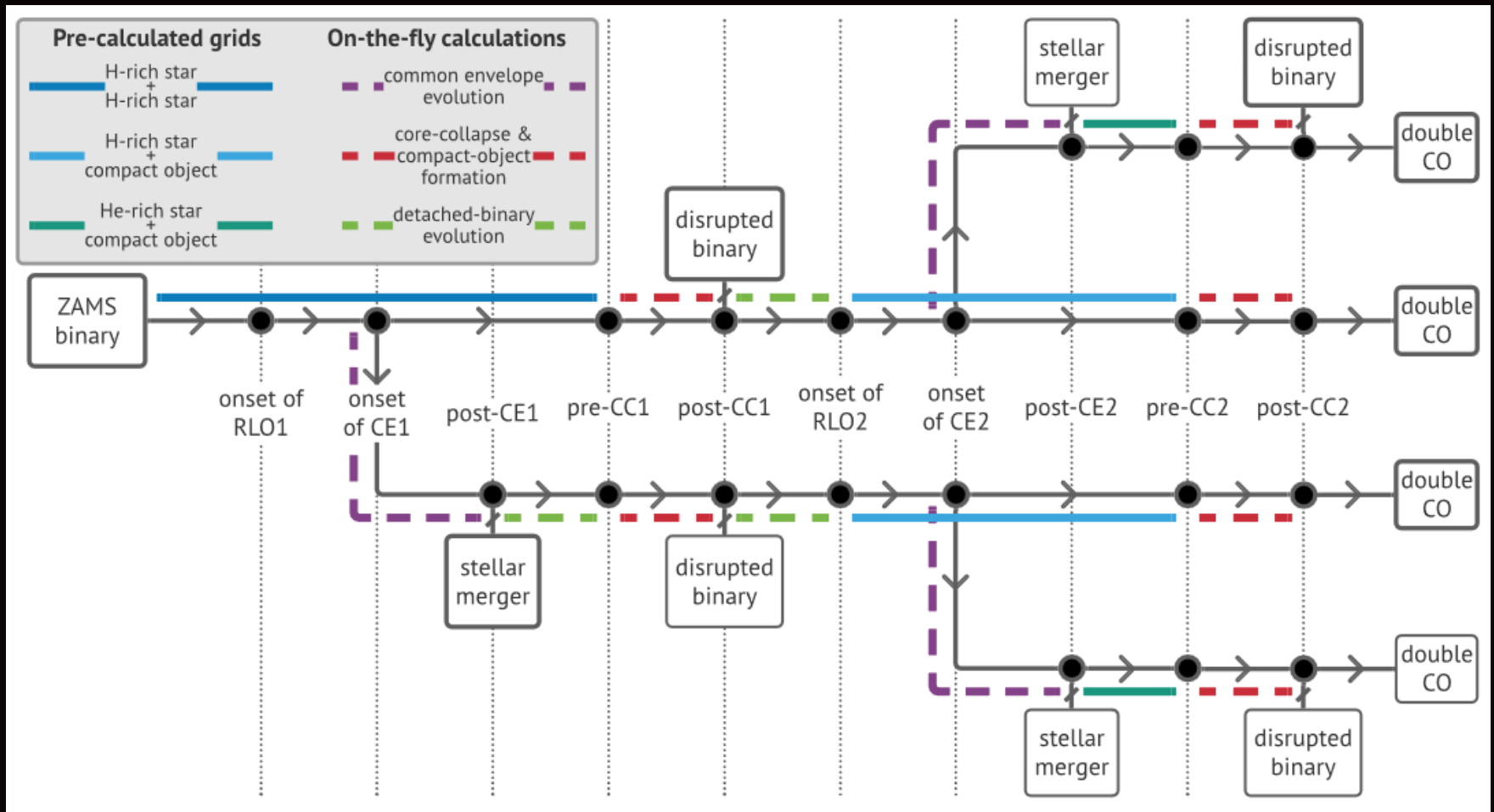


Solid – binaries,  
dashed – singles.

Red and black  
are two different  
models.

Crosses –  
observations.

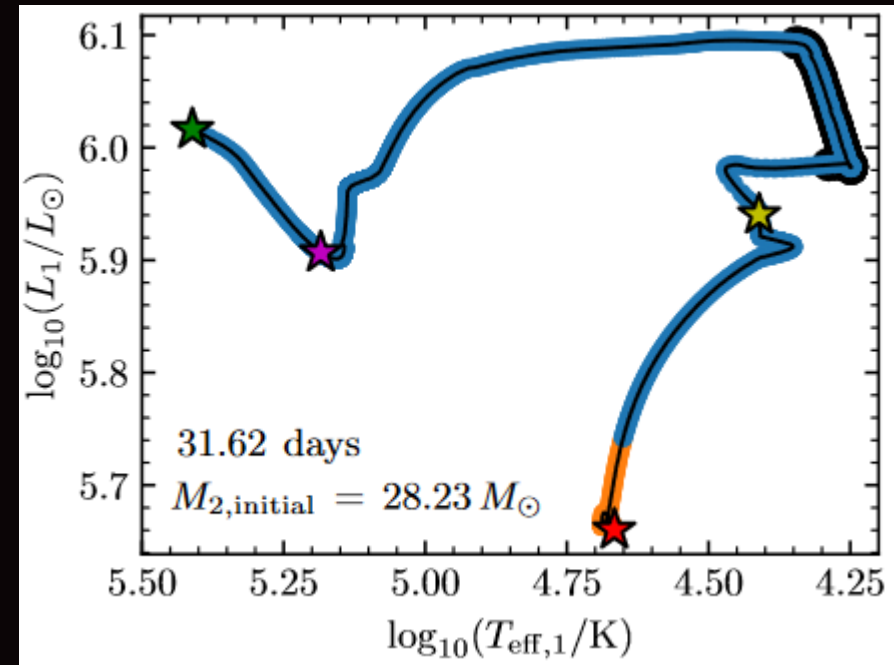
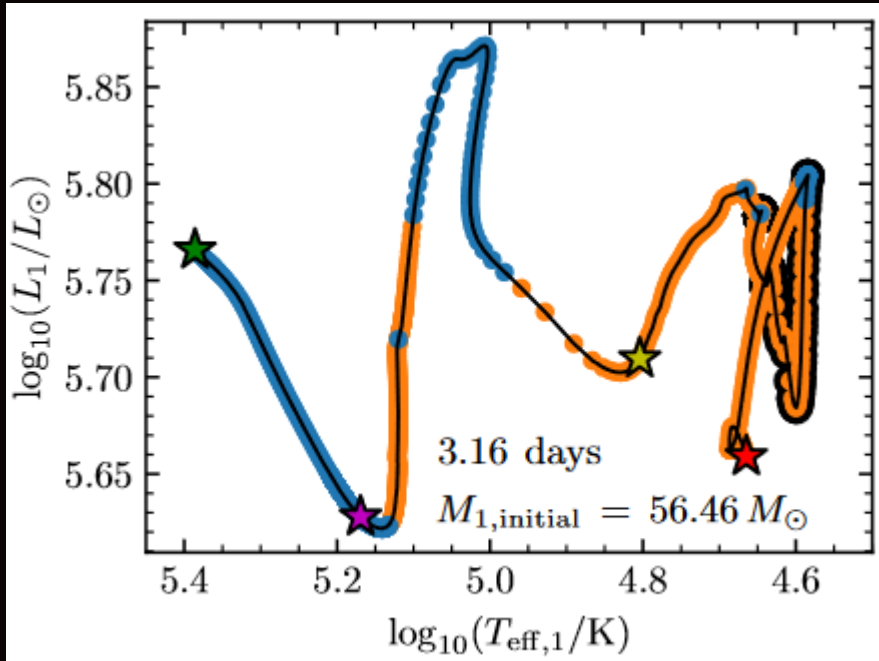
# A new code: POSYDON



Includes MESA calculations of stellar evolution.

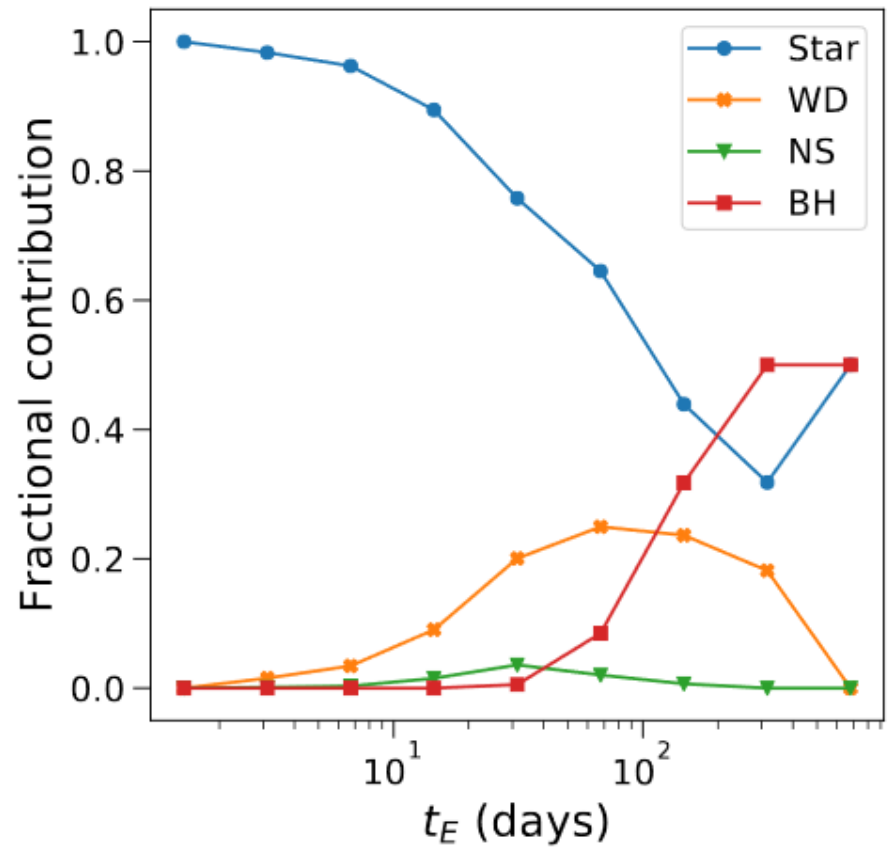
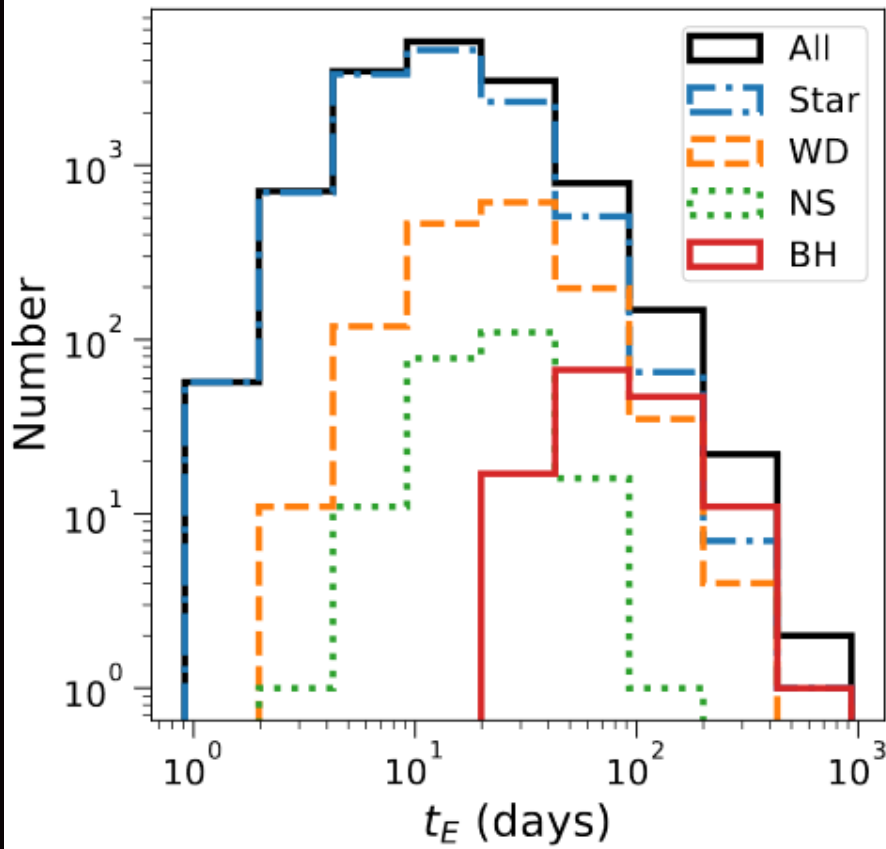
# Donor evolution

- Dynamical tides
- Equilibrium tides
- ★ ZAMS
- ★ End of MS
- ★ Core-He depletion
- ★ Core-C depletion
- RLO



# Population synthesis of isolated BHs and NSs to predict microlensing events

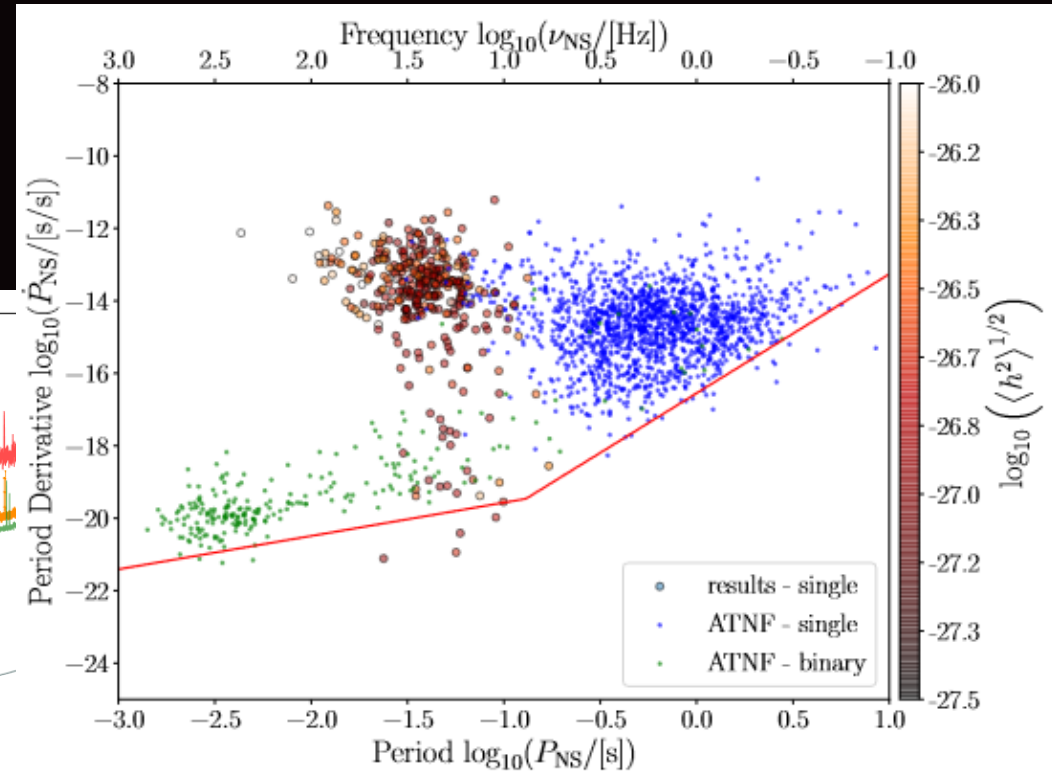
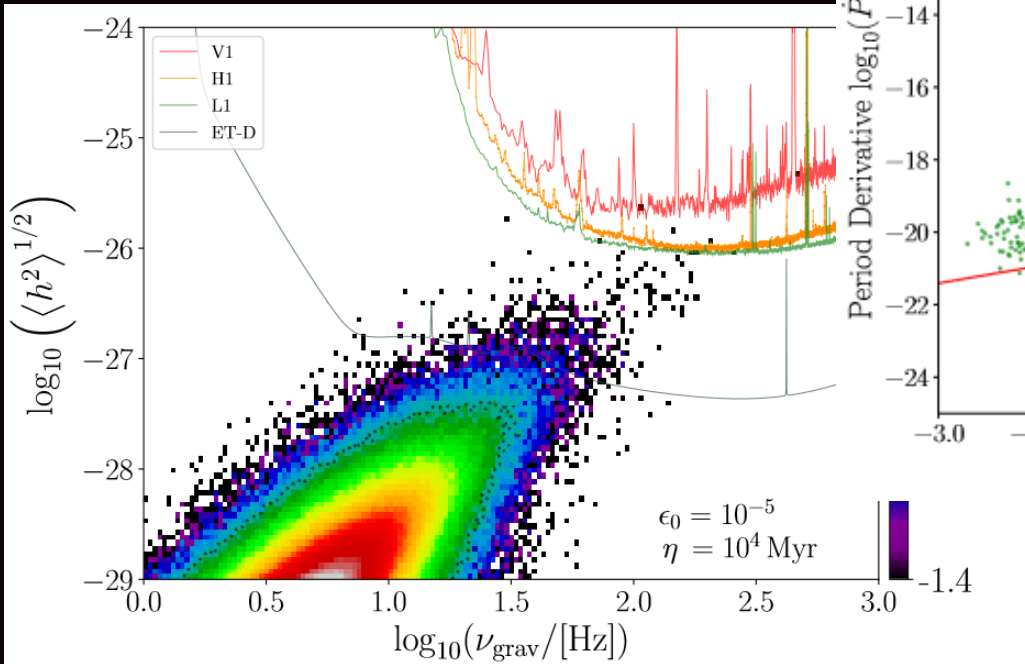
PopSvCLE:



# Population synthesis of GWs from NSs

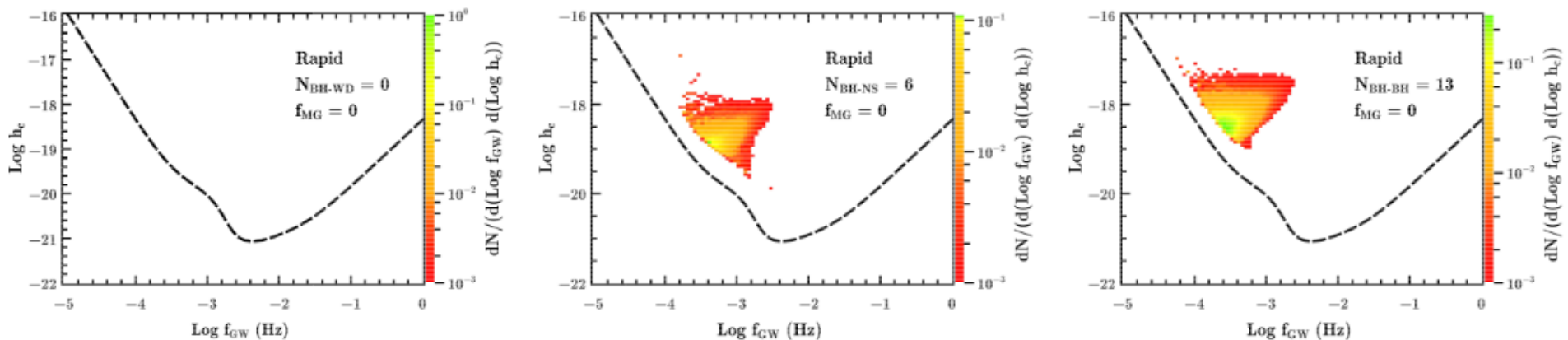
$$\epsilon = \epsilon_0 \exp\left(\frac{-t}{\eta}\right)$$

Simple model of ellipticity evolution



# Population synthesis of BH+CS binaries for space-based GW detectors

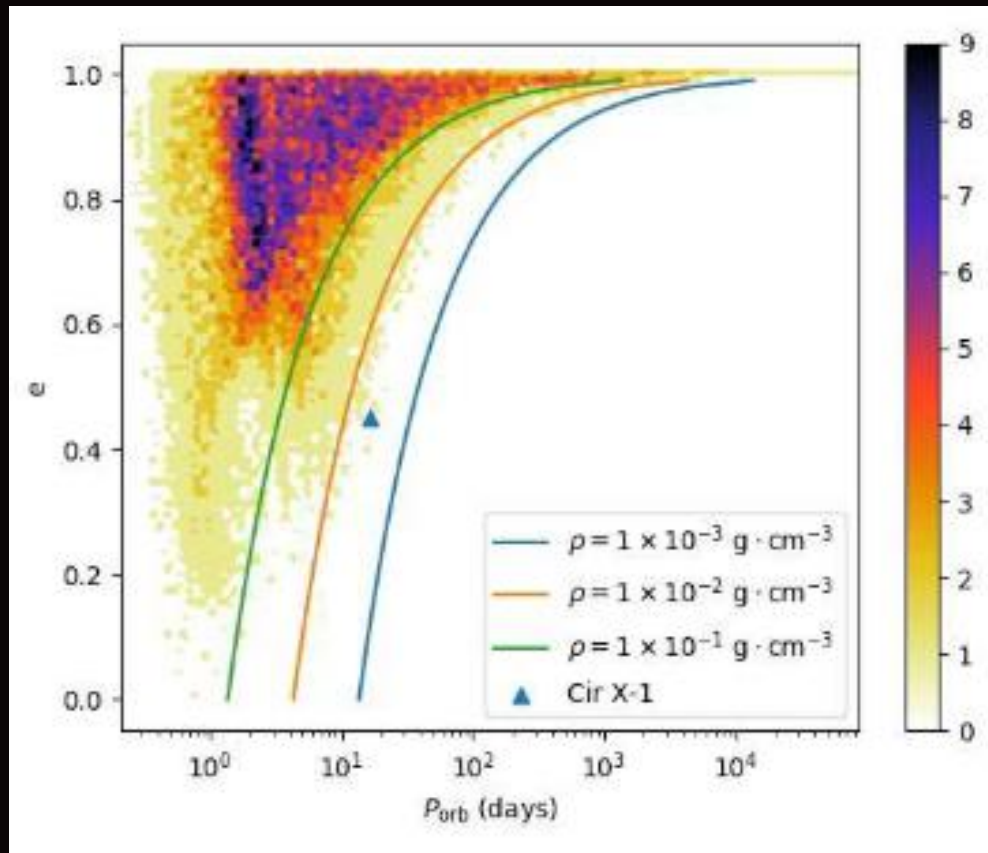
Future space GW antennae (LISA, Taiji, TianQin, Decigo) will be able to detect compact binaries long before their coalescence.



Assumptions about mass distributions and kick velocity are very important. With other (realistic) assumptions all numbers in the plot can be increased.

# PS of NSs in X-ray binaries in SNRs


Distribution of Roche-lobe overflow systems with a MS companion  
for kick dispersion 150 km/s at ages <100 000 yrs



In this study the authors ignore NS magneto-rotational evolution. Thus, their results are not applicable to wind-fed systems.



# 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

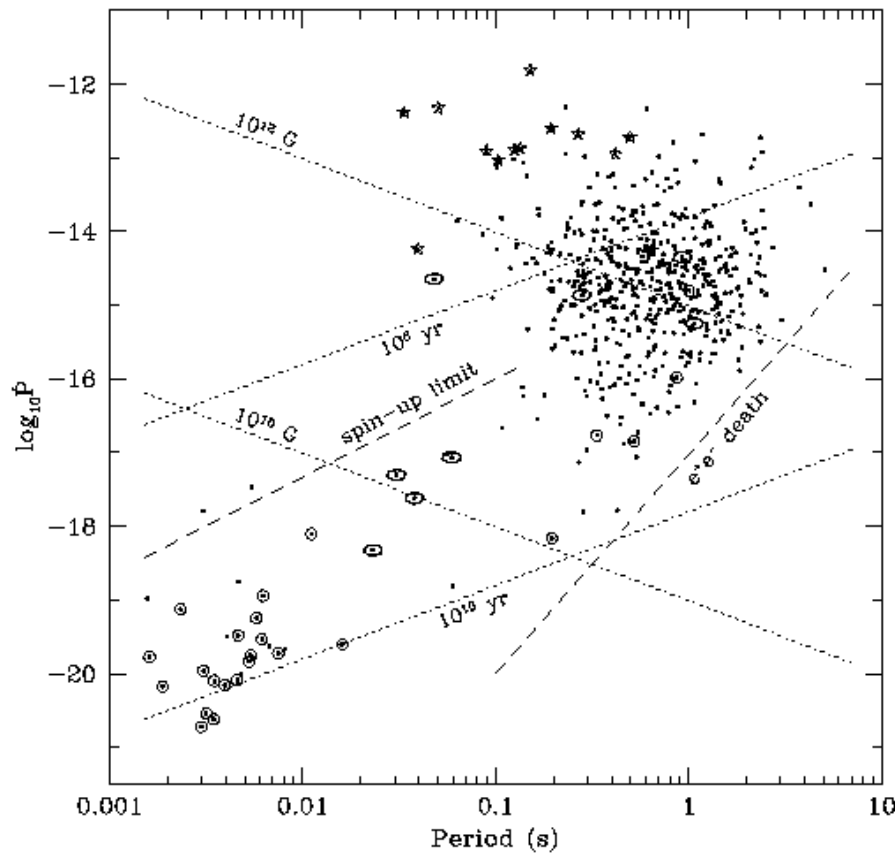
# Tasks

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



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

$$B \sim 3.2 \times 10^{19} (PdP/dt)^{1/2} \text{ G.}$$

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 pulsars 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.*

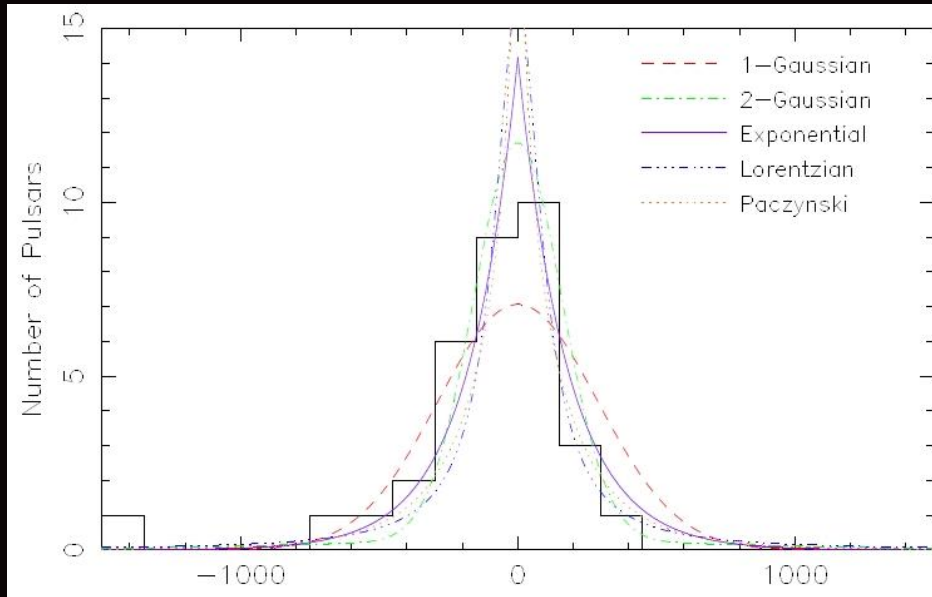
*A synthetic PSR is detected if it appears in the area covered by one of the surveys, and if its radio flux exceeds some limit.*

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

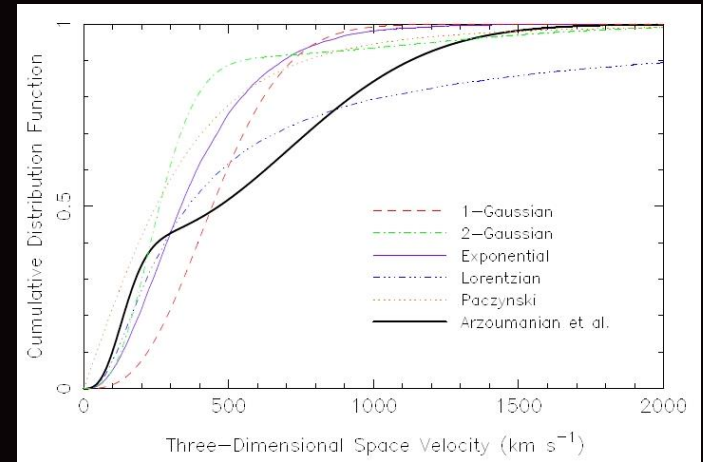
---

(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

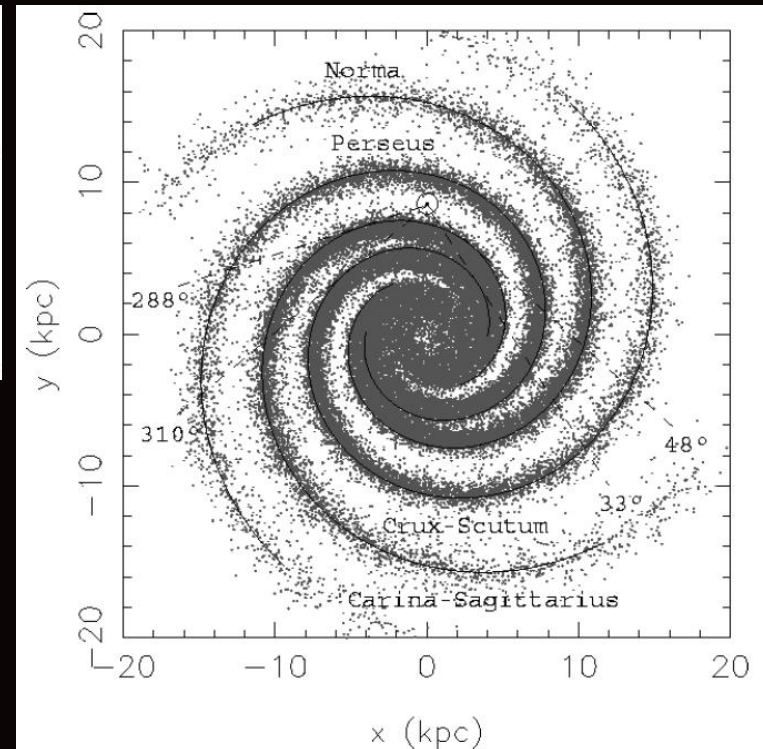
Initial spatial distribution of PSRs was calculated in a complicated realistic way.

- 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)	$\theta_0$ (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

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

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

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

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

Constant	Disc-Halo (dh)	Bulge (b)	Nucleus (n)
$M$	$1.45 \times 10^{11} M_\odot$	$9.3 \times 10^9 M_\odot$	$1.0 \times 10^{10} M_\odot$
$\beta_1$	0.4		
$\beta_2$	0.5		
$\beta_3$	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  $\sin \chi=1$  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:

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

# Radio luminosity and beaming

Model I

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

$$\begin{aligned} L_{\text{to}} &= 2 \text{ mJy kpc}^2 \\ \alpha_1 &= -19/15 \\ \alpha_2 &= -2 \\ L_{\text{low}} &= 0.1 \text{ mJy kpc}^2 \end{aligned}$$

[Shown to be bad]

Model II

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

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

Average beaming fraction is about 10%

# Optimal model and simulations

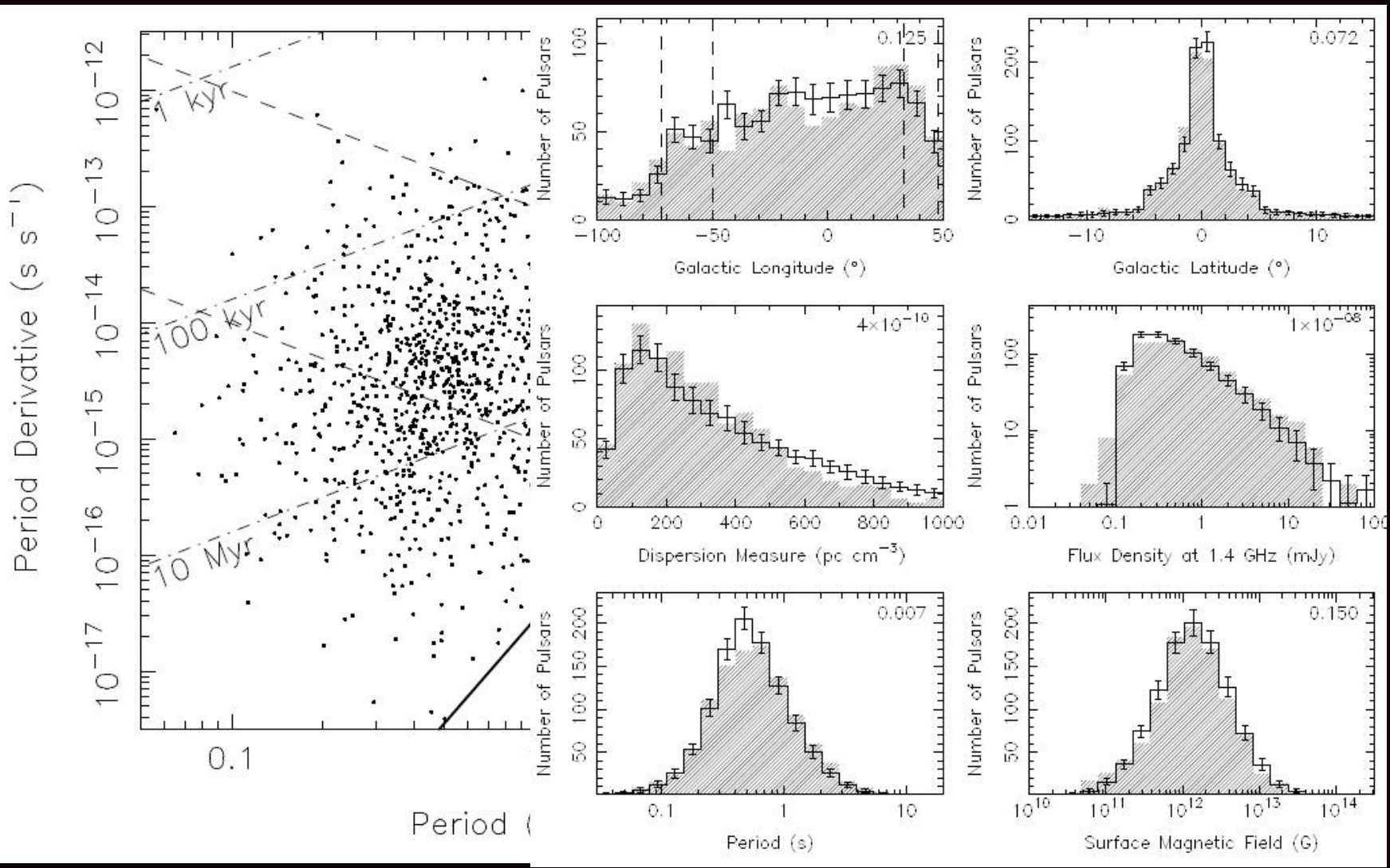
Model Parameter	Value
Radial Distribution Model	Yusifov & Küçük
$R_1$	0.55 kpc
$a$	1.64
$b$	4.01
Birth Height Distribution	Exponential
$\langle z_0 \rangle$	50 pc
Birth Velocity Distribution	Exponential
$\langle v_{3D} \rangle$	380 km s <sup>-1</sup>
Birth Spin Period Distribution	Normal
$\langle P_0 \rangle$	300 ms
$\sigma_{P_0}$	150 ms
Magnetic Field Distribution	Log-Normal
$\langle \log(B/G) \rangle$	12.65
$\sigma_{\log B}$	0.55
Luminosity Model	$P - P$ Power Law
$L_0$	0.18 mJy kpc <sup>2</sup>
$\epsilon_P$	-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



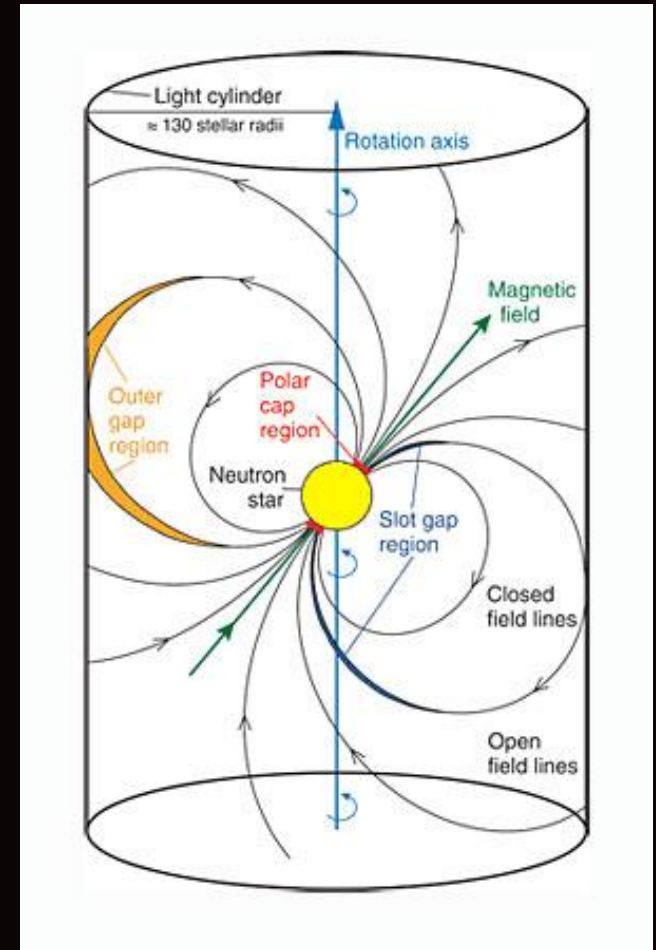
Solid lines – calculation, hatched diagrams - real observations

# 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  $2.8 \pm 0.1$  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 of emission generation

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



# Population synthesis of gamma-ray PSRs

## Ingredients

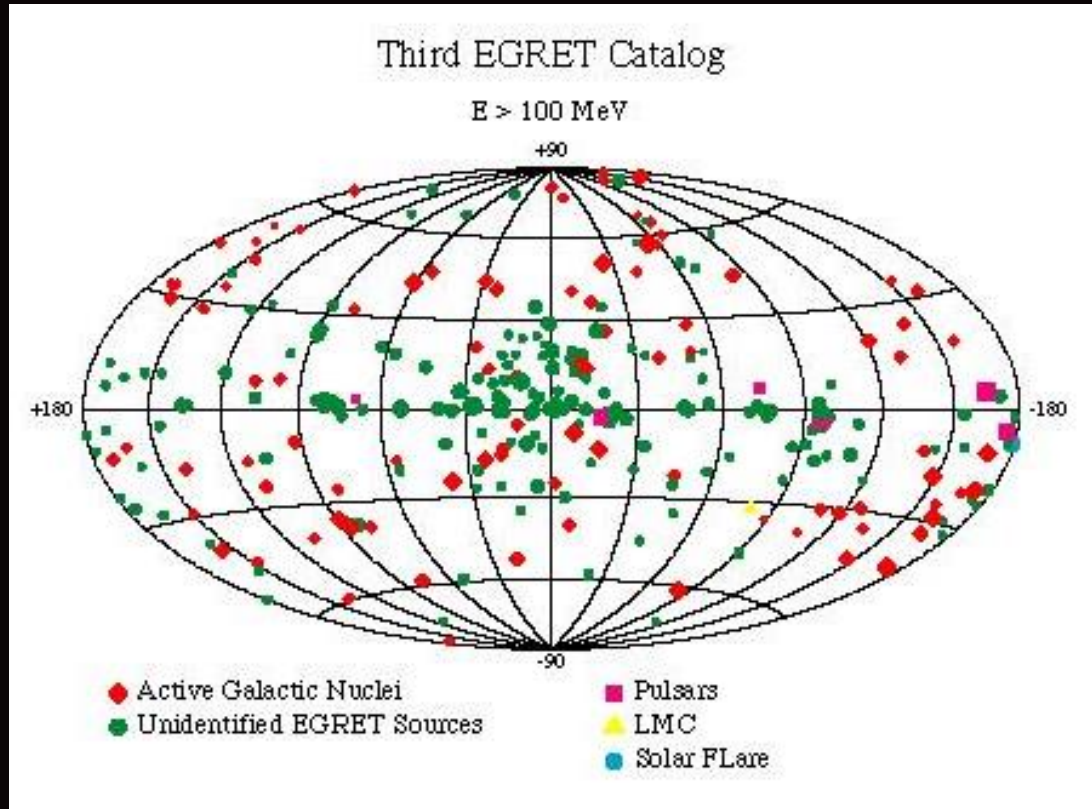
1. Geometry of radio and gamma beam
2. Initial period distribution
3. Initial magnetic field distribution
4. Period evolution
5. Initial spatial distribution
6. Initial velocity distribution
7. Radio and gamma spectra
8. Radio and gamma luminosity
9. Properties of gamma detectors
10. Radio surveys to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

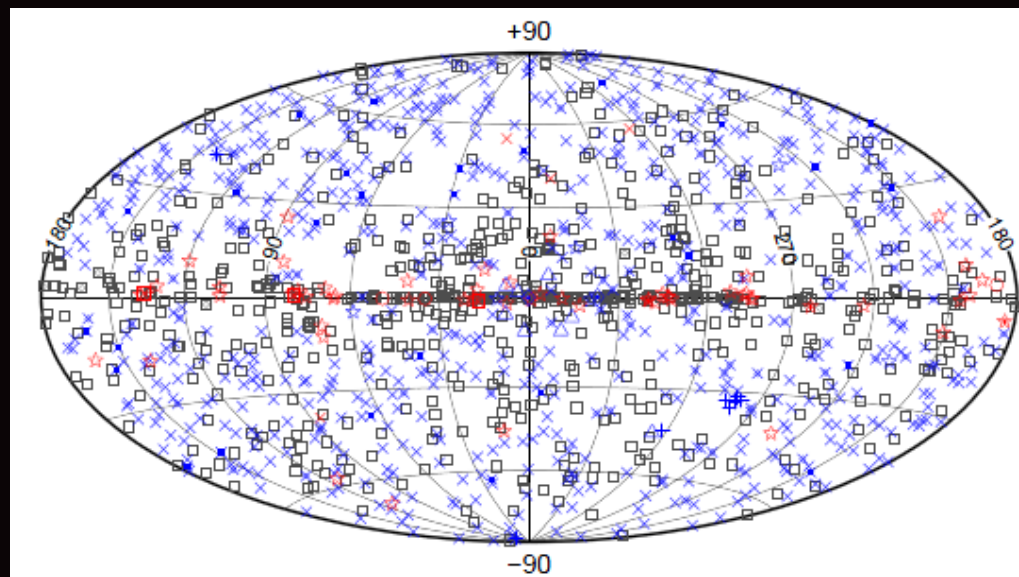
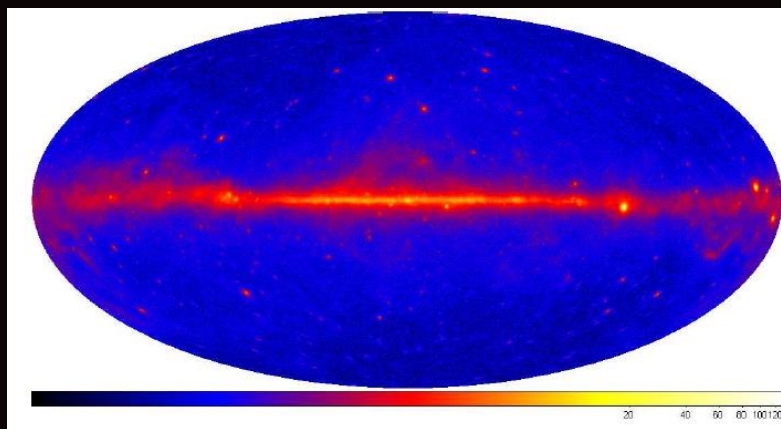
- Crab
  - Geminga
  - Vela
  - PSR B1055-52
  - PSR B1706-44
  - PSR B1951+32
- (plus one by COMPTEL)

Nolan et al. 1996  
astro-ph/9607079



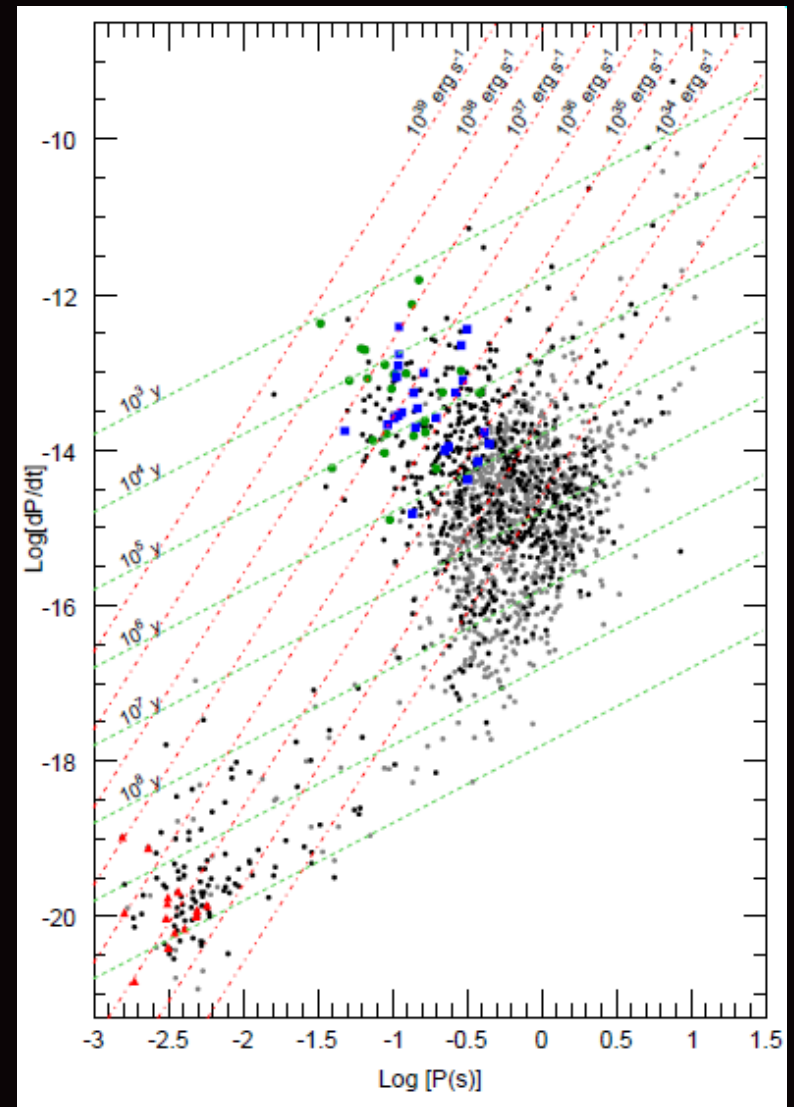
# The first Fermi catalogue

56 pulsating sources out from 1451 sources in total

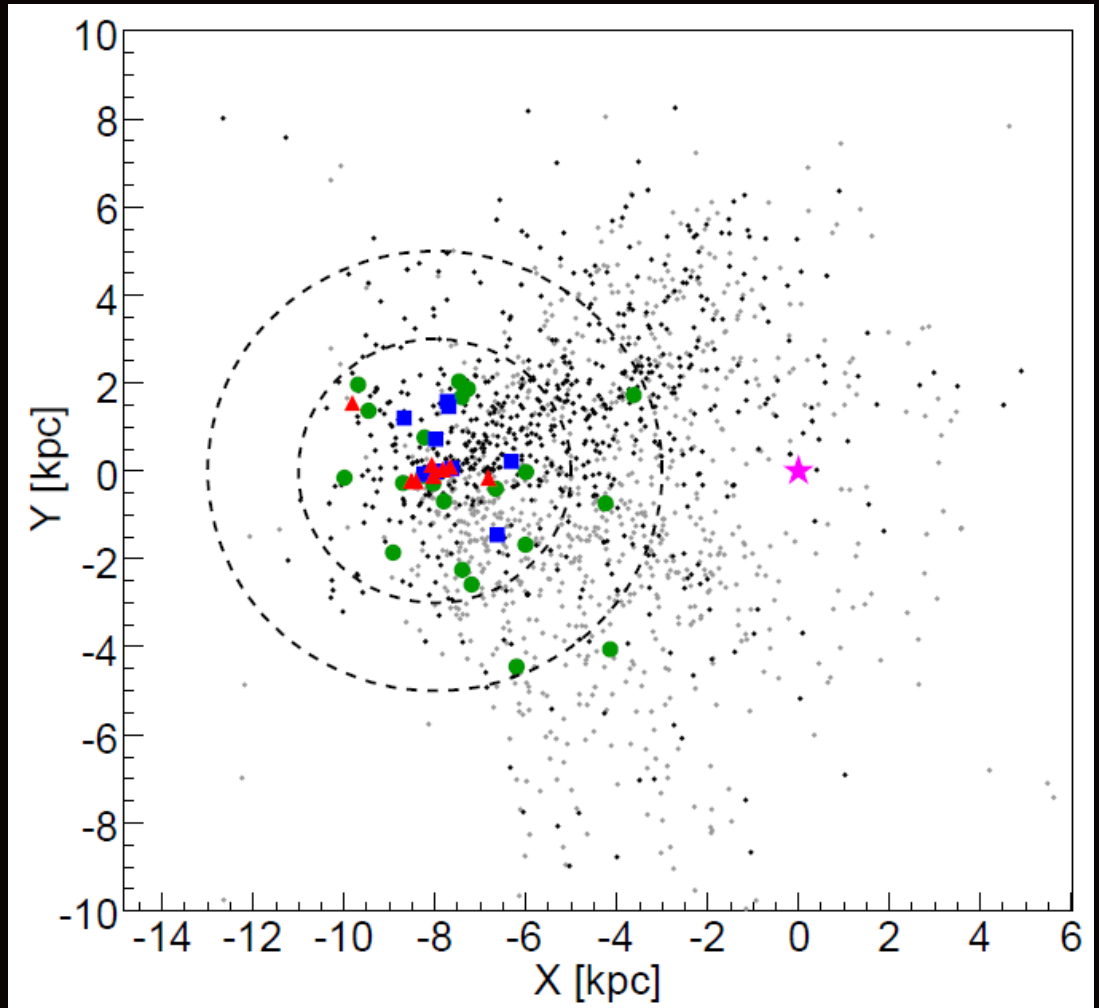


# P-Pdot diagram

63 PSRs detected by Fermi



# Galactic map



# Fermi data: summary

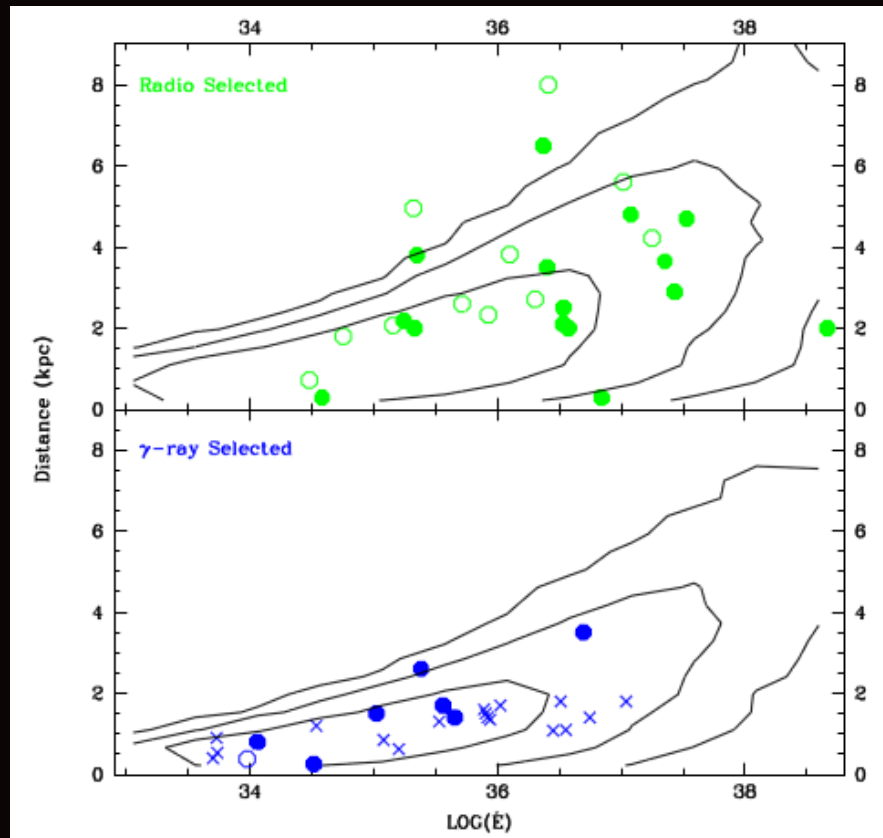
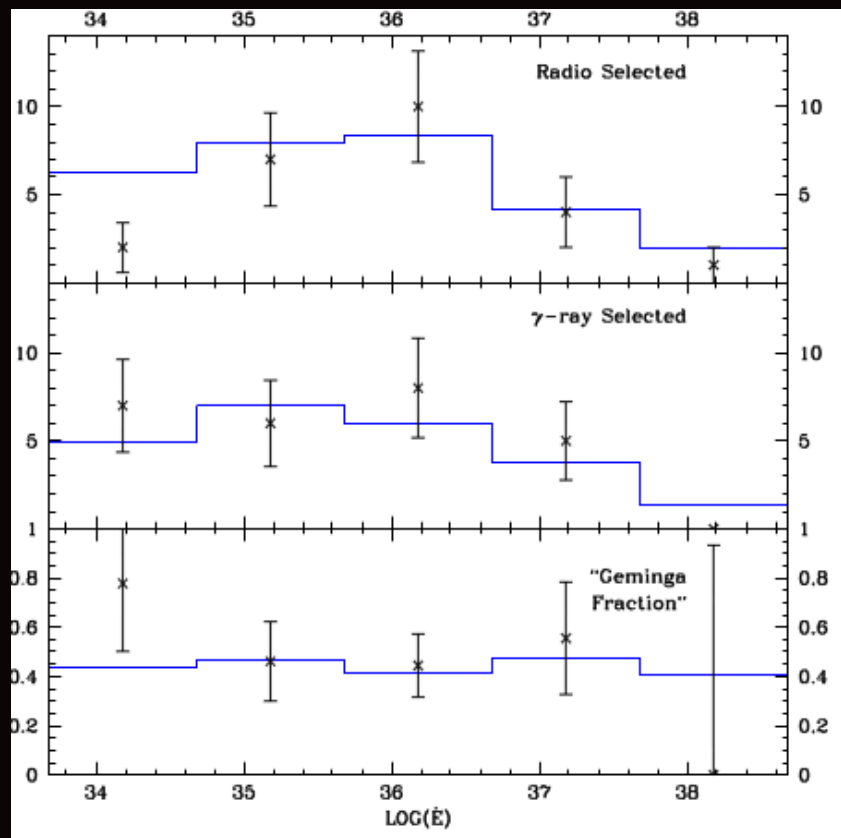
- 63 clearly detected pulsating PSRs:
  - ~20 radio selected (with 7 known from CGRO time)
  - 24 – in blind searches (several detected also in radio)
  - 27 - mPSRs
- 18 mPSRs candidates from radio (non-pulsating in gamma)



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

About radio pulsar population  
see Lorimer arXiv: 1008.1928

# Population synthesis for Fermi: young PSRs



Outer gap model (for gamma) is preferred

# 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

# Initial spatial and velocity distributions

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

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

Plus galactic potential and circular velocity

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

# Radio emission and beaming

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

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

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

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

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

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

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

Survey	Gain (KJy <sup>-1</sup> )	$C_{thres}$	$T_{rec}$ (K)	$\nu$ (MHz)	$t_i$ (s)	$\tau_{samp}$ (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

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

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

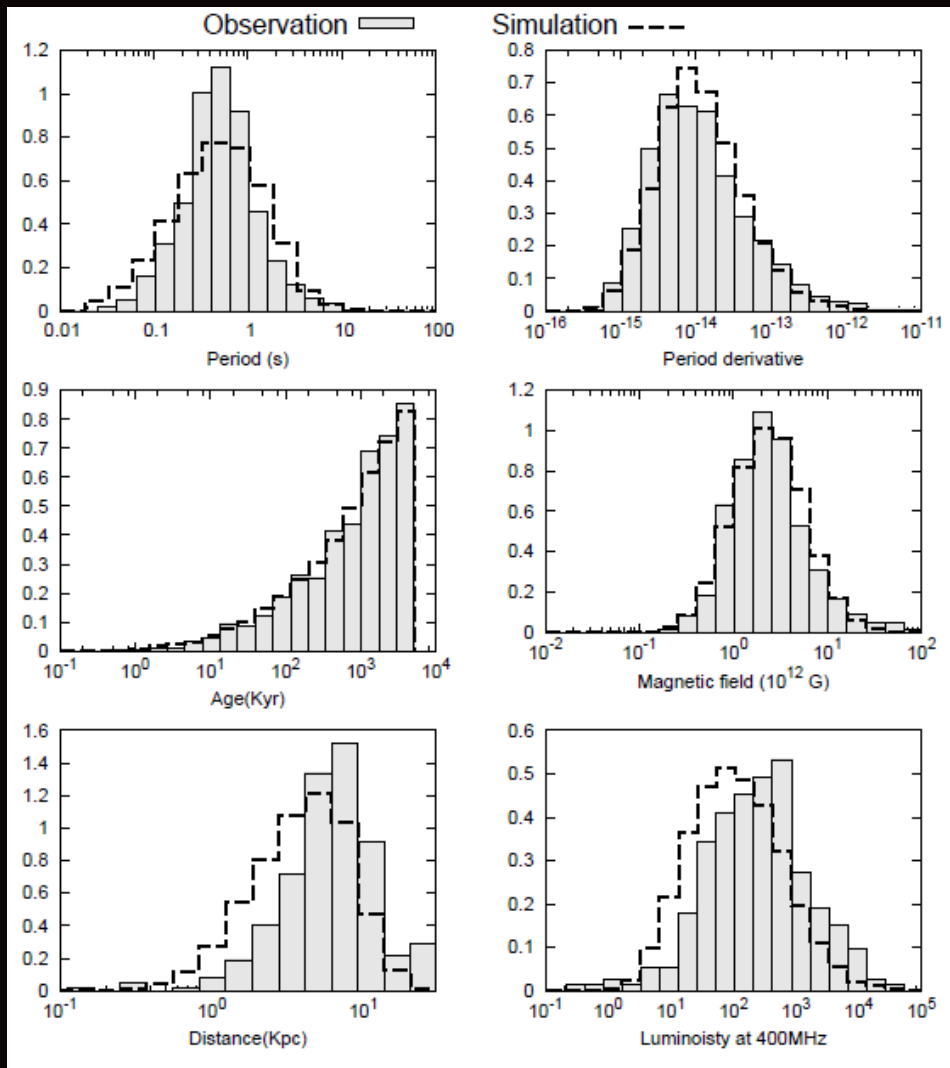
$$L_{\gamma} \sim 1.1 \times 10^{34} K^3 B_{12}^{3/4} L_{sd,36}^{5/8} \text{ erg/s.}$$

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

Beaming=0.4

# Results

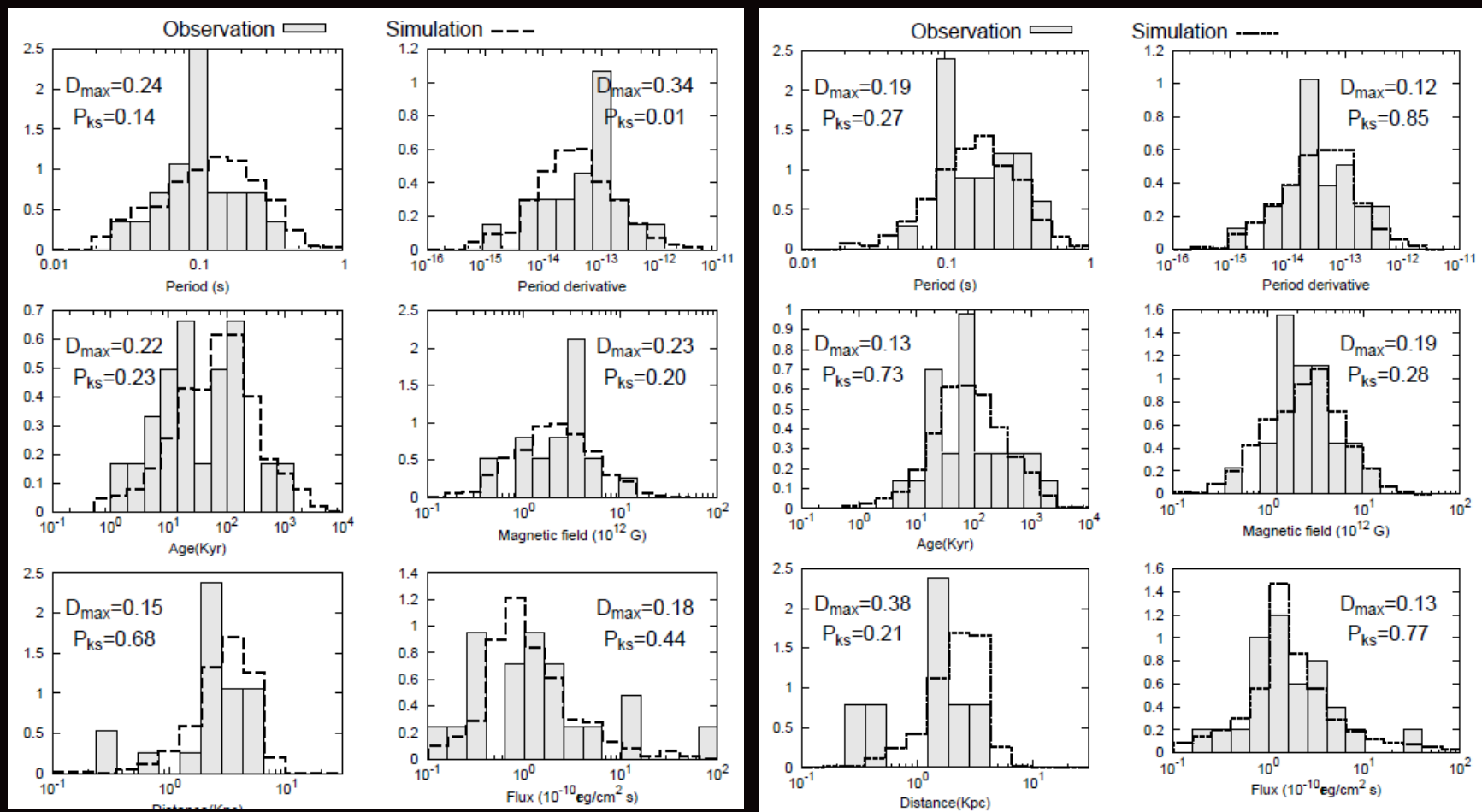
Birth rate:  $\sim 1.3$  per century



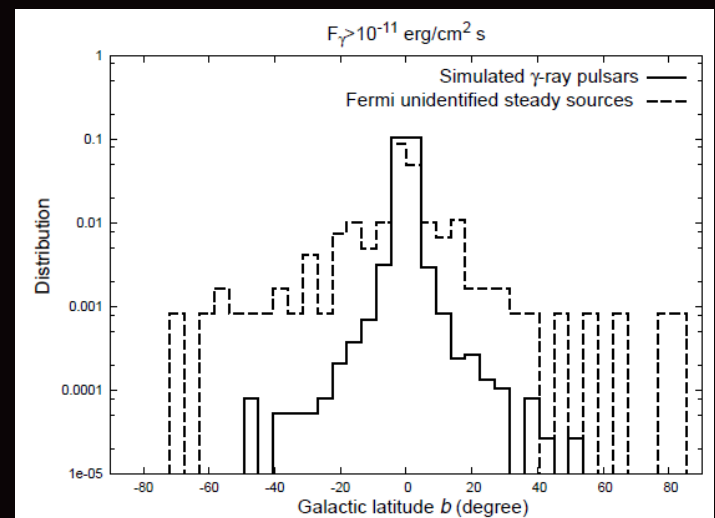
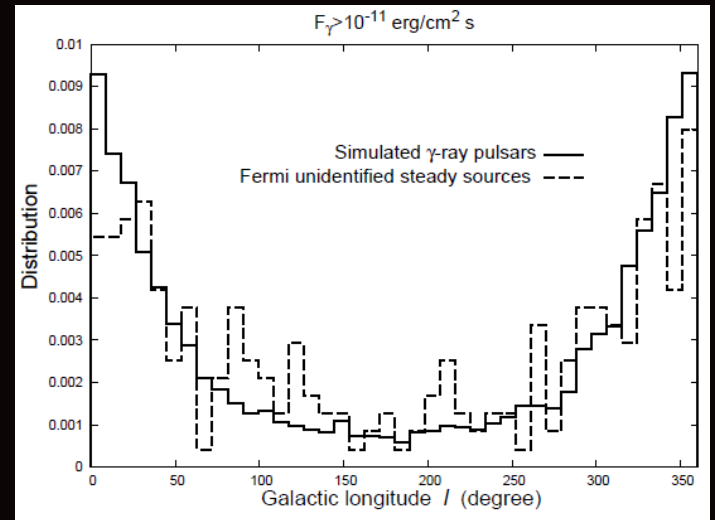
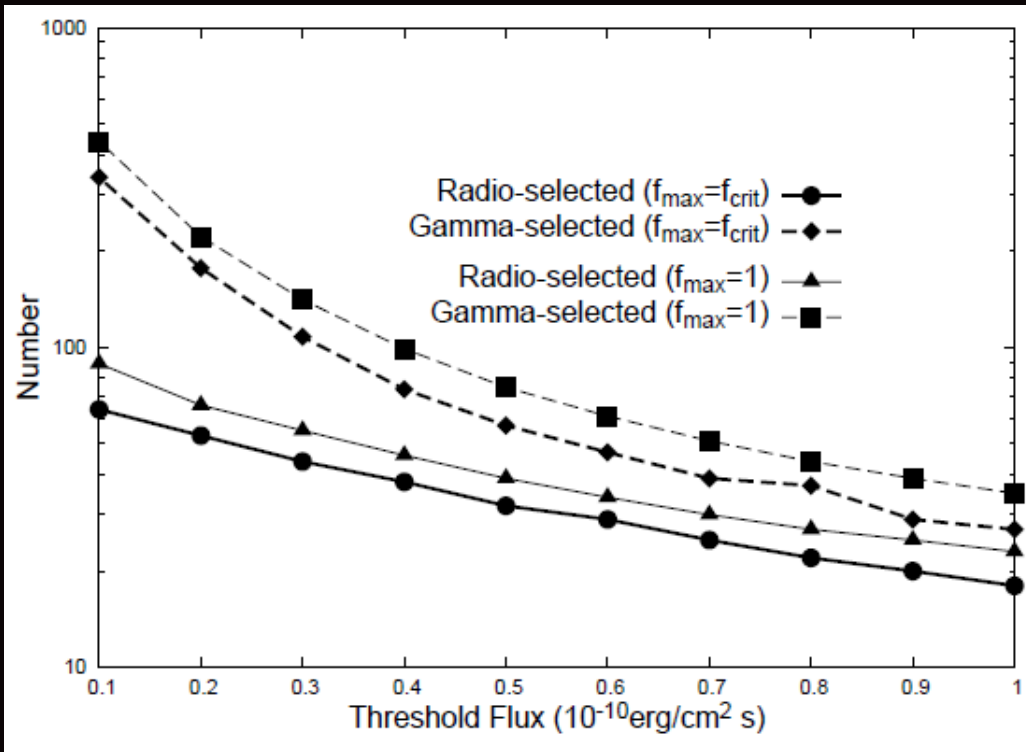
# Results

## Radio selected

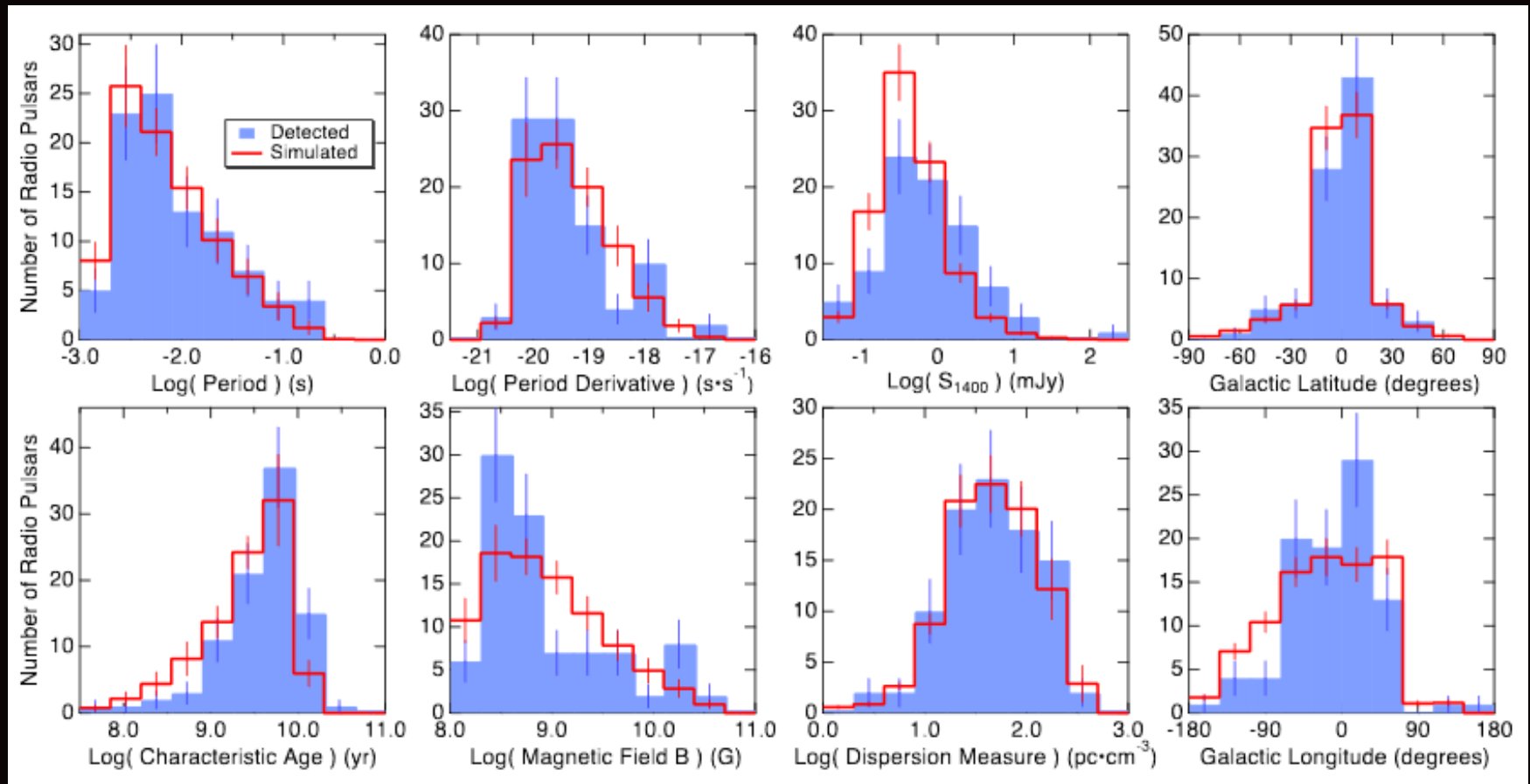
## Gamma-ray selected



# Predictions for lower fluxes

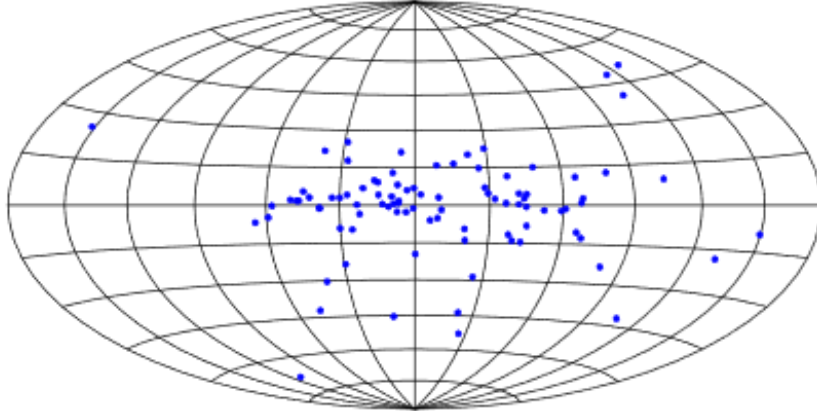


# Millisecond PSRs

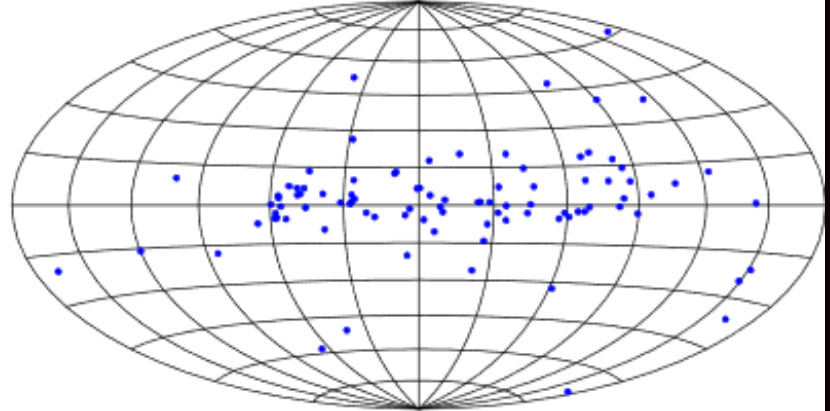


# Millisecond PSRs

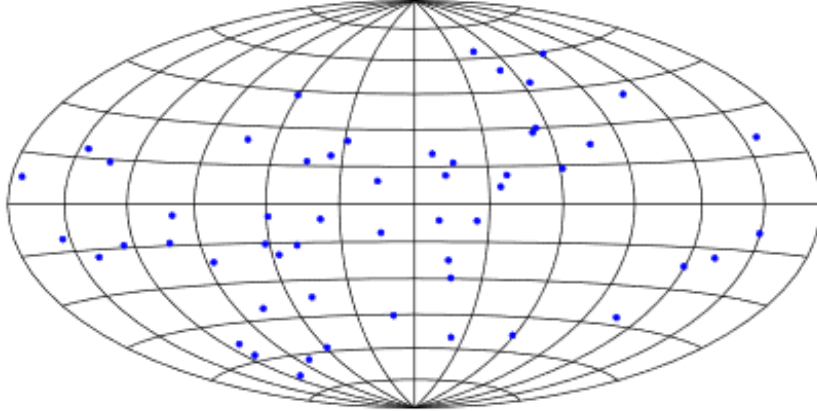
Detected Radio Pulsars



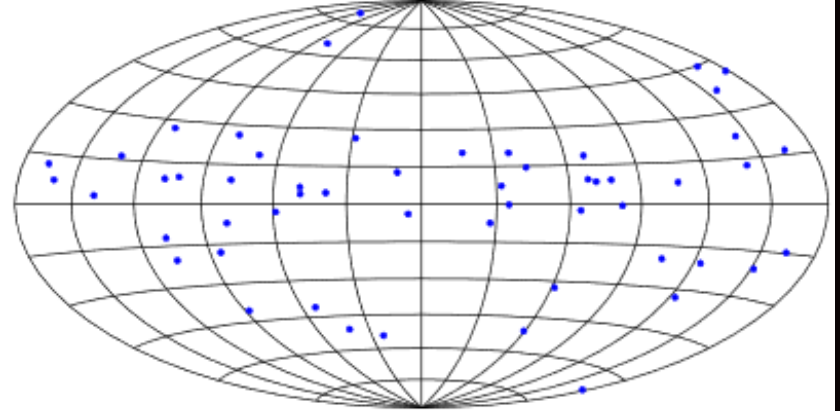
Simulated Radio Pulsars



Detected Fermi Pulsars

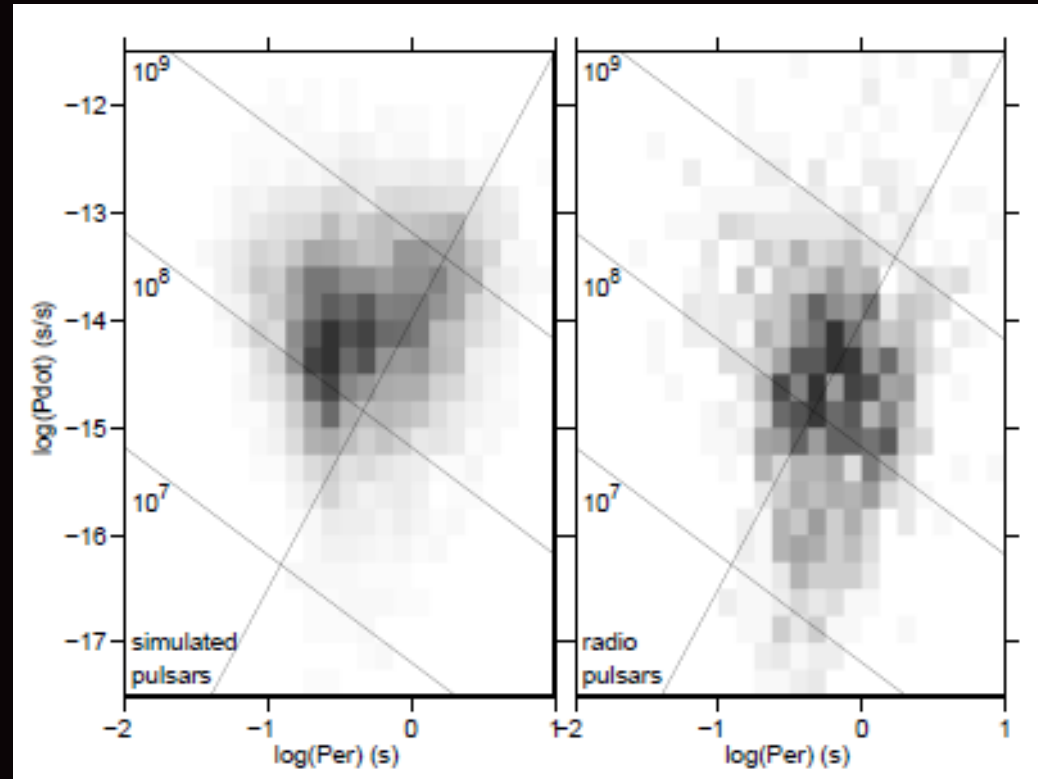
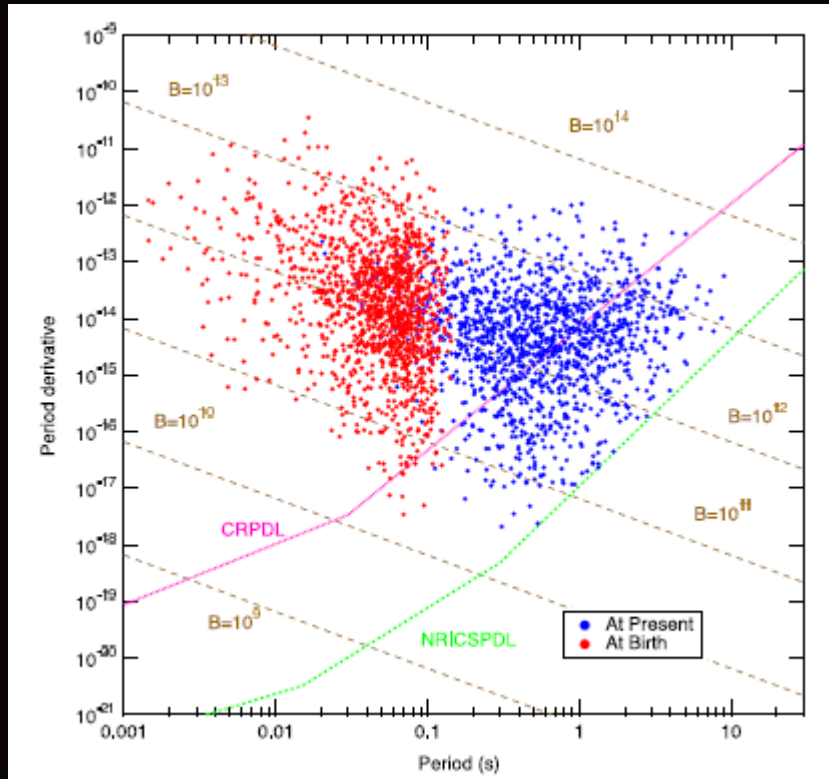


Simulated Fermi Pulsars



# Gap models study

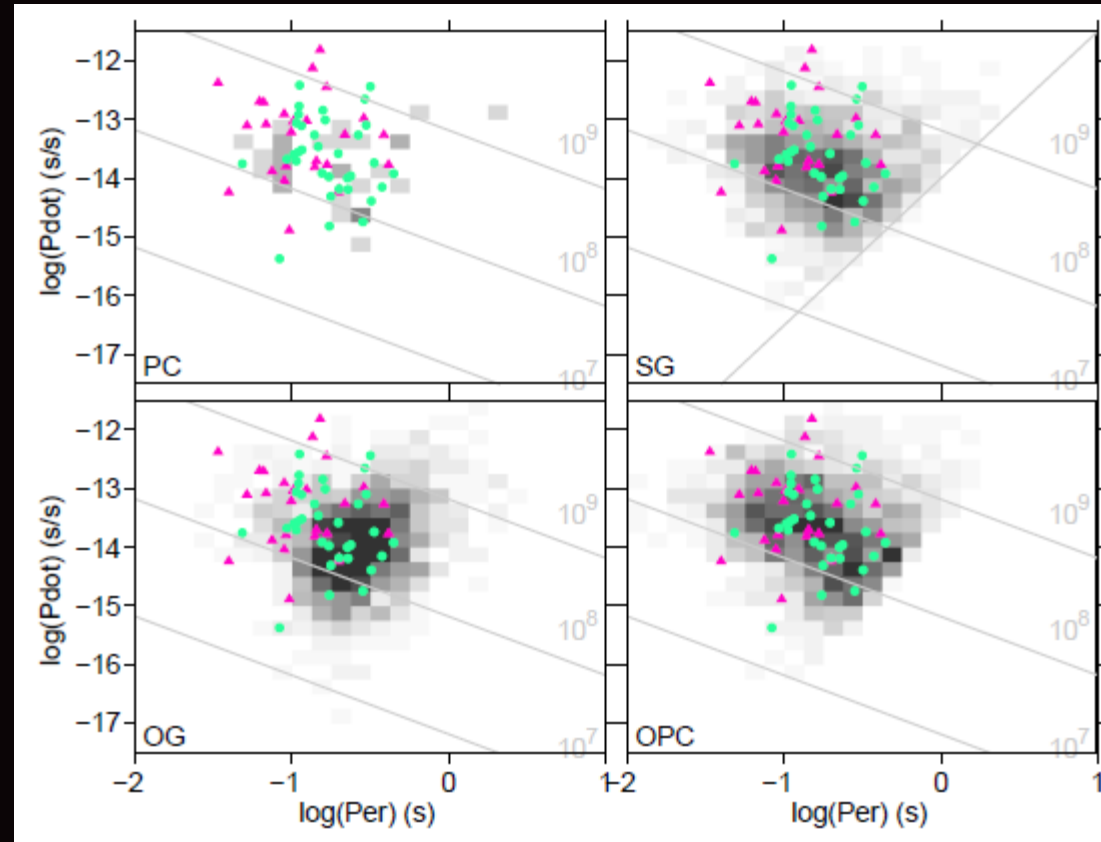
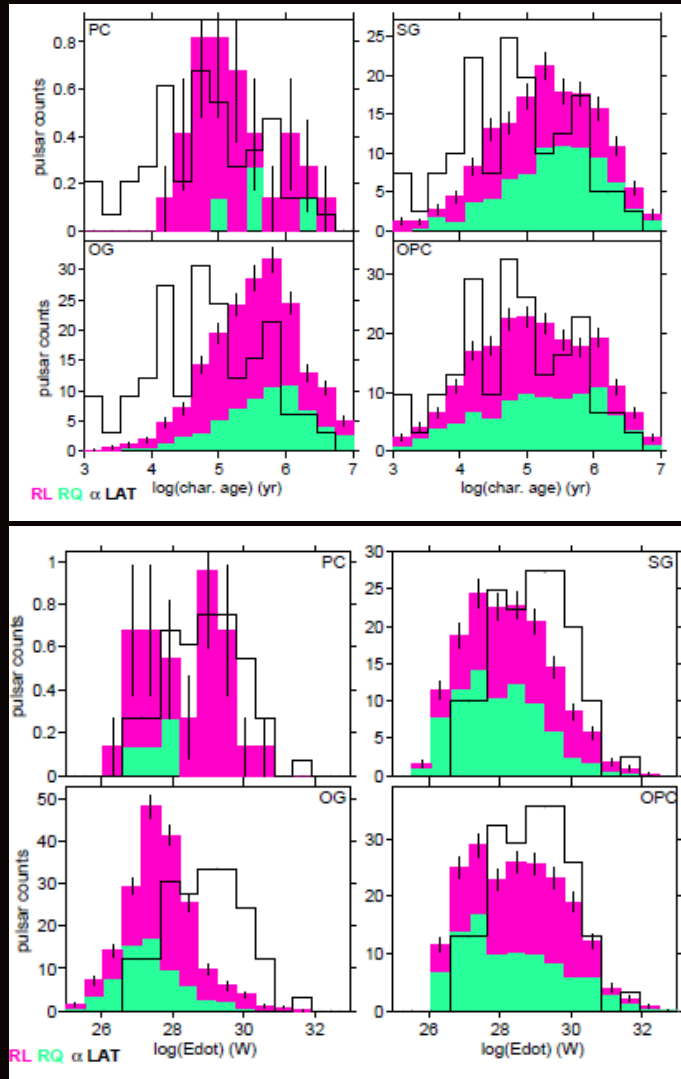
Four models: Polar cap, slot gap, outer gap, one pole caustic.



Radio data is OK



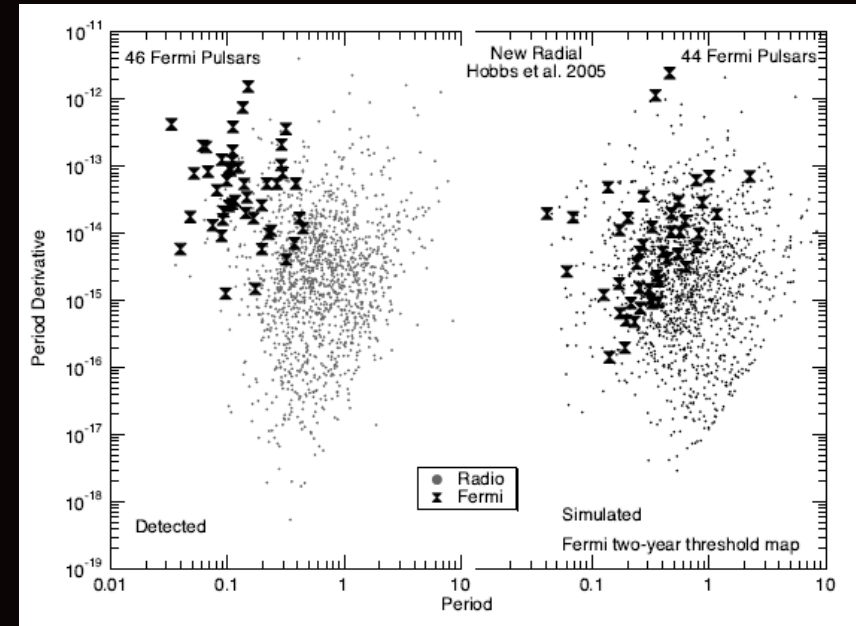
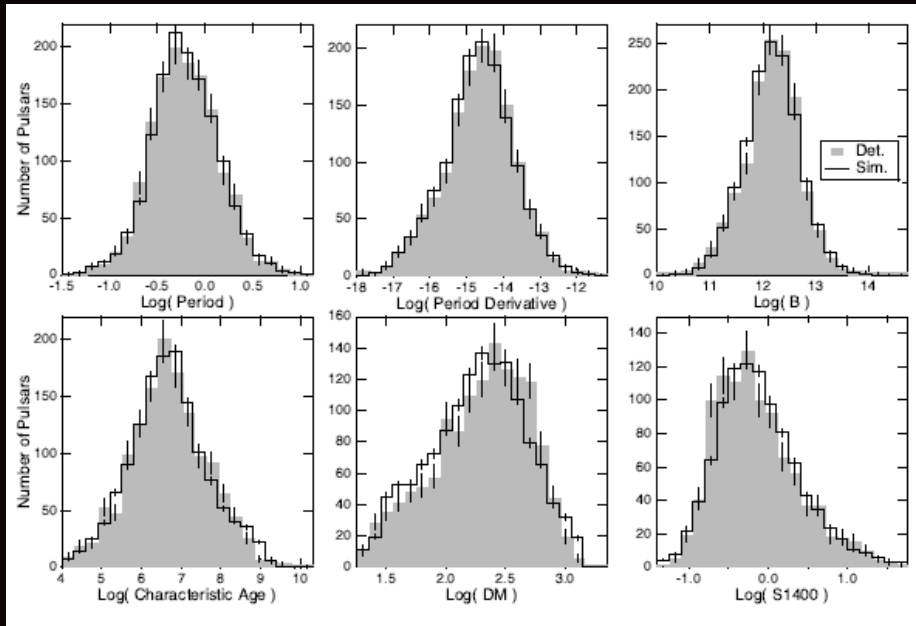
# Problems of the model



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

# 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)

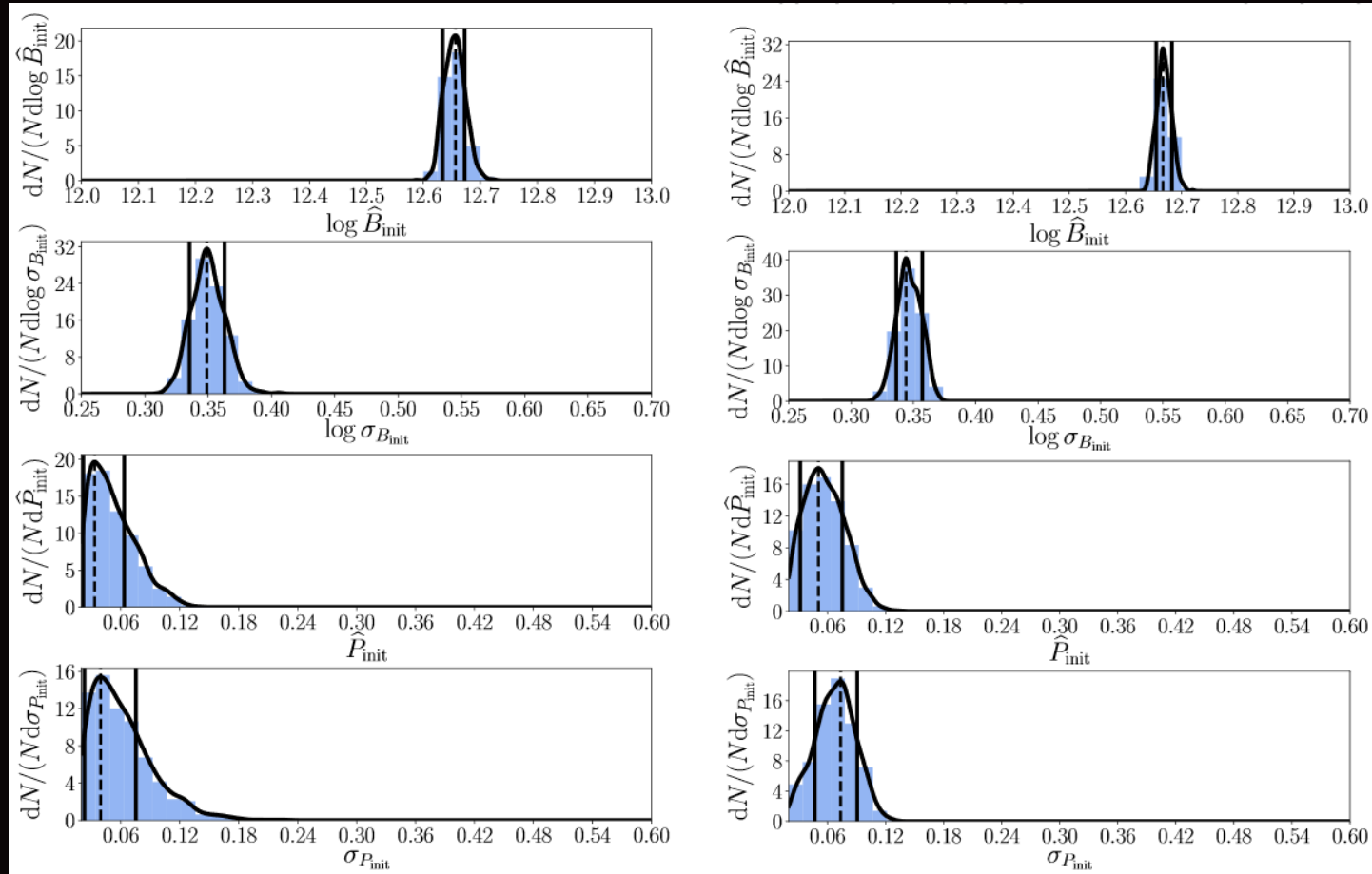
# New Markov chain synthesis

The *power-law model*

$$L_{400} = \gamma P^\alpha P_{15}^\beta \text{ mJy} \times \text{kpc}^2$$

The *rotational model*

$$L_{400} = \gamma \left( \dot{P}_{15}^{\frac{1}{3}} P^{-1} \right)^\kappa$$



1803.02397

The preferred model has a short decay scale of the magnetic field of  $\sim 4\text{-}5$  Myr.

# 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.*

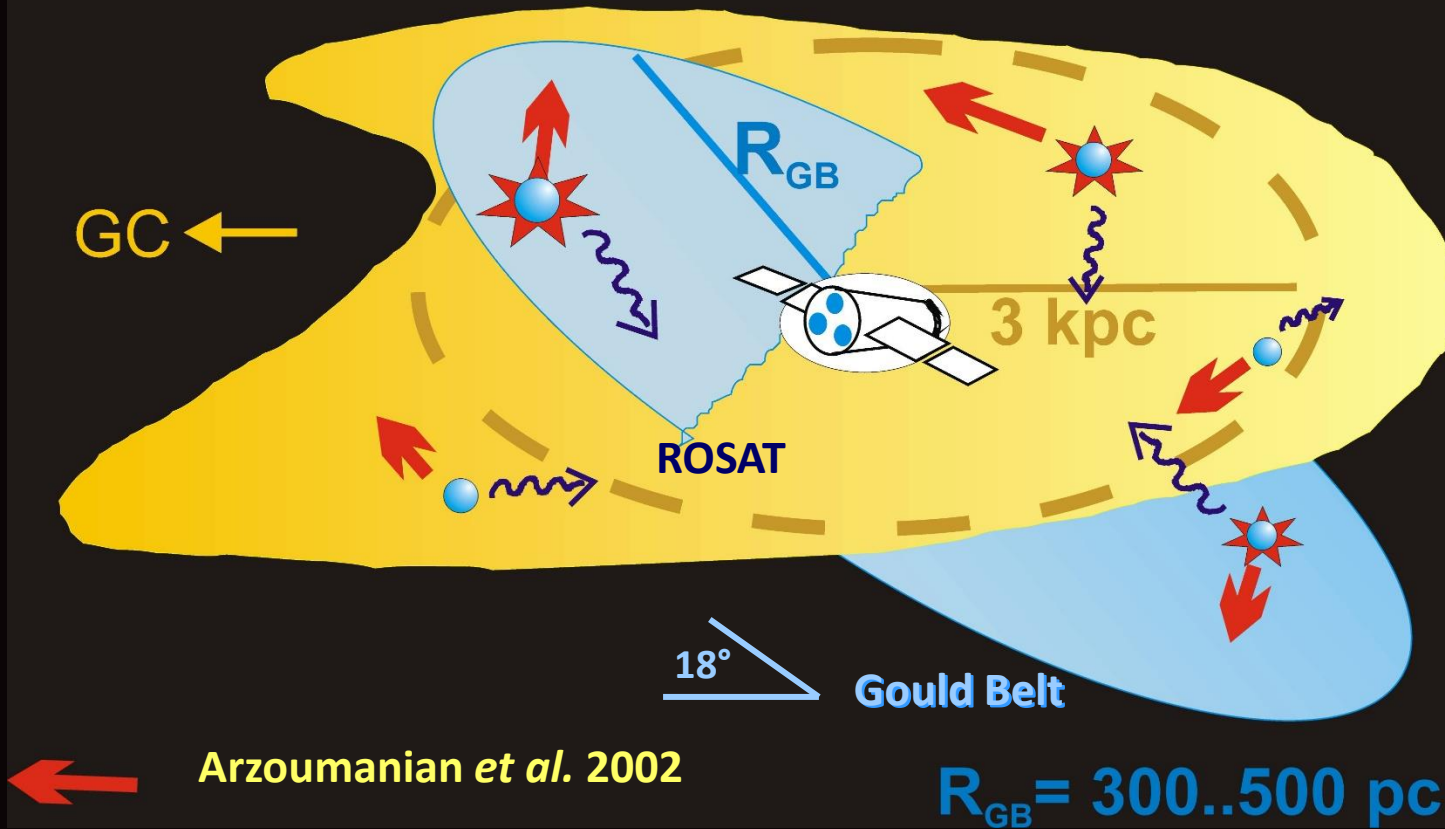
# Population synthesis – I.



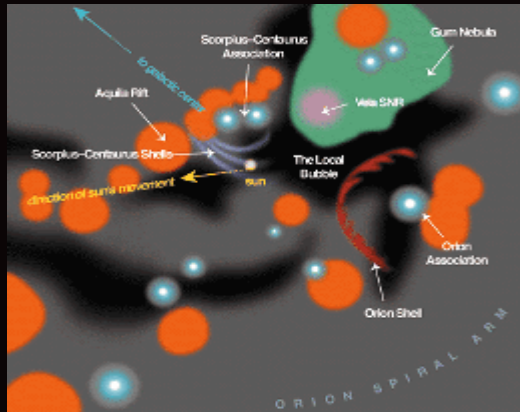
Gould Belt : 20 NS Myr<sup>-1</sup>  
Gal. Disk (3kpc) : 250 NS Myr<sup>-1</sup>



- Cooling curves by Blaschke et al.
- Mass spectrum



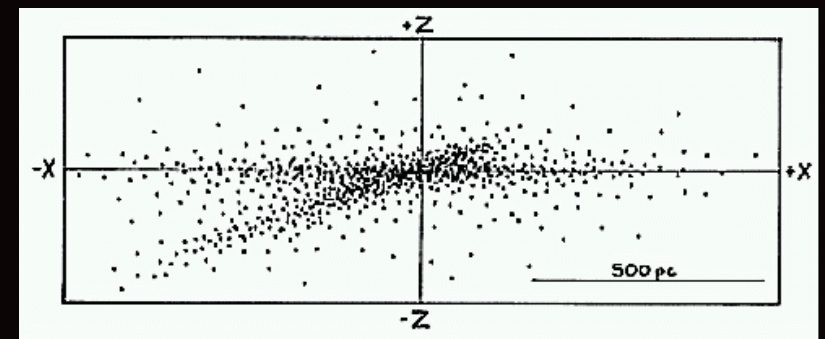
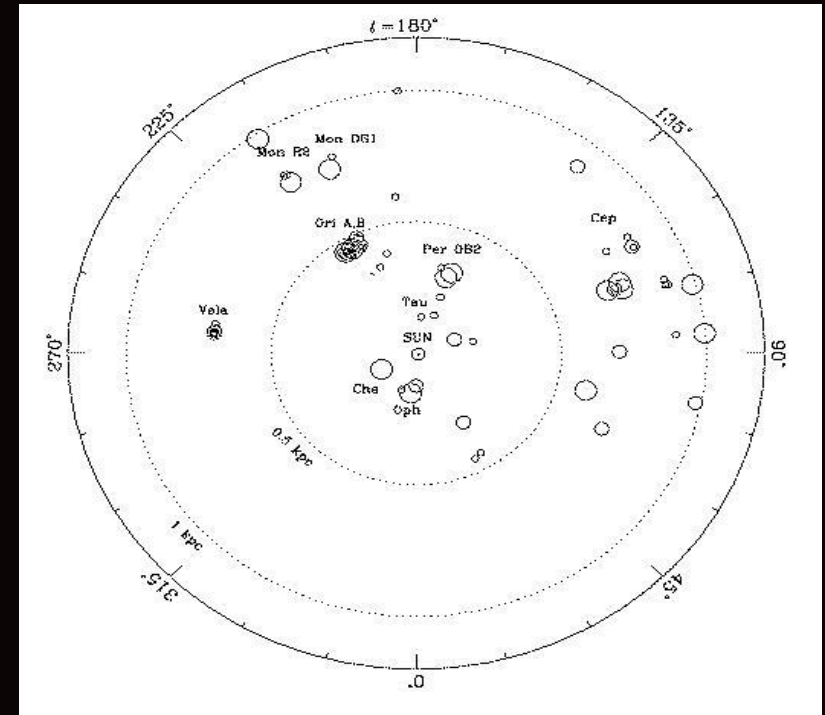
# Solar vicinity



- 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

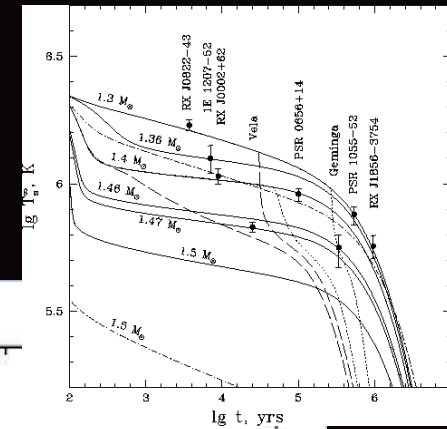
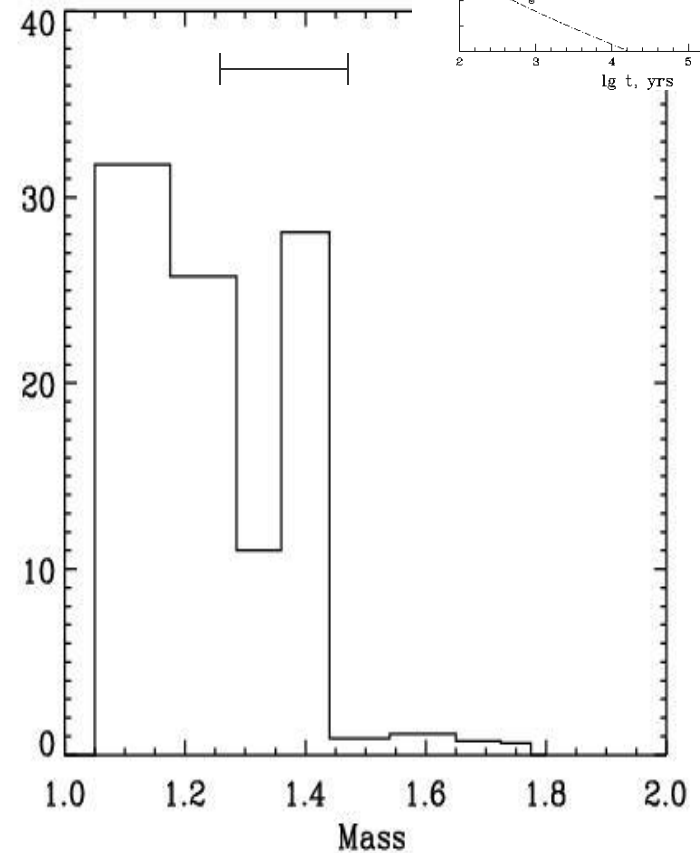
- Poppel (1997)
- $R=300 - 500$  pc
- Age 30-50 Myrs
- Center at 150 pc from the Sun
- Inclined respect to the galactic plane at 20 degrees
- 2/3 massive stars in 600 pc belong to the Belt



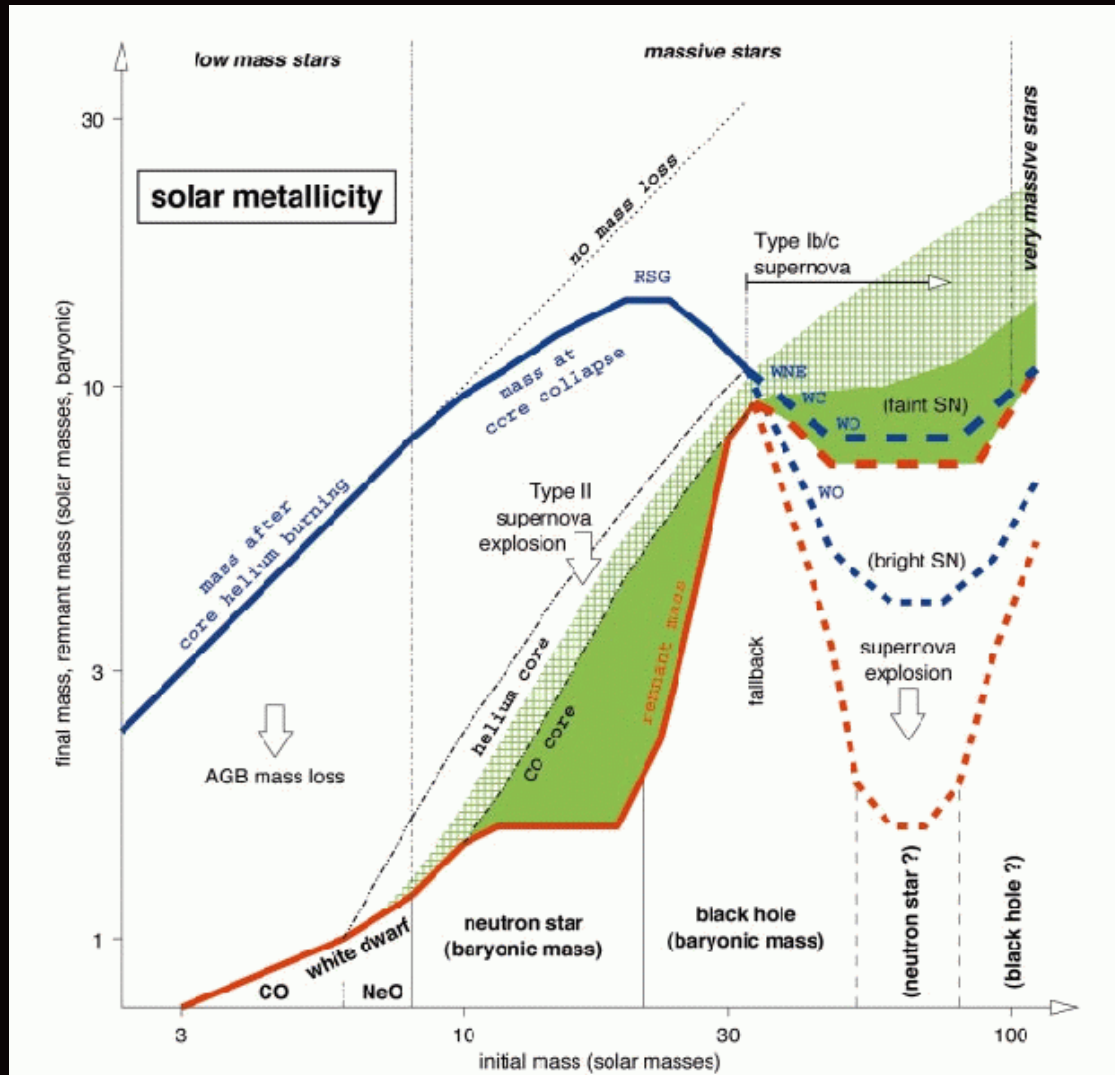


# Mass spectrum of NSs

- 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)

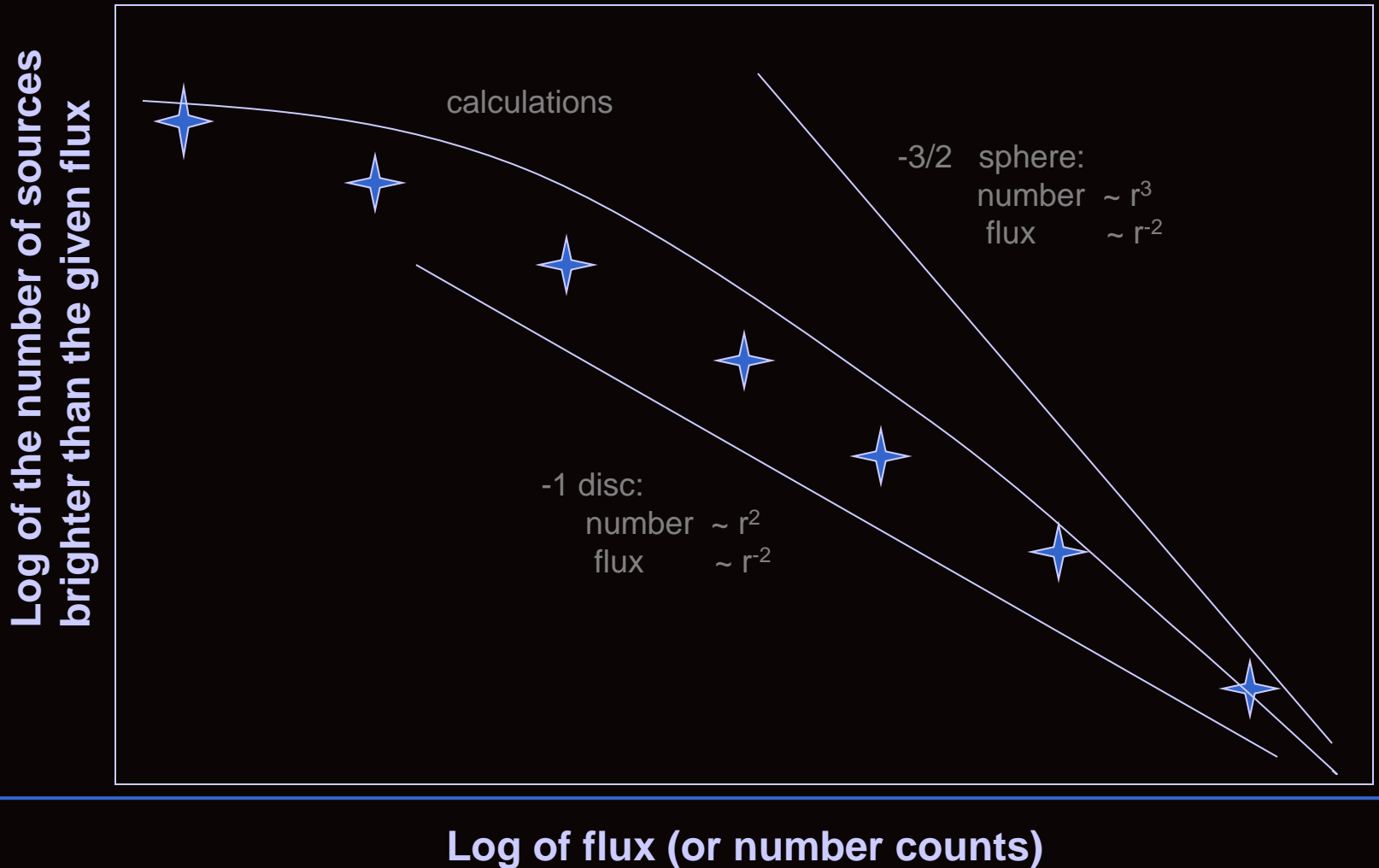


# Progenitor mass vs. NS mass



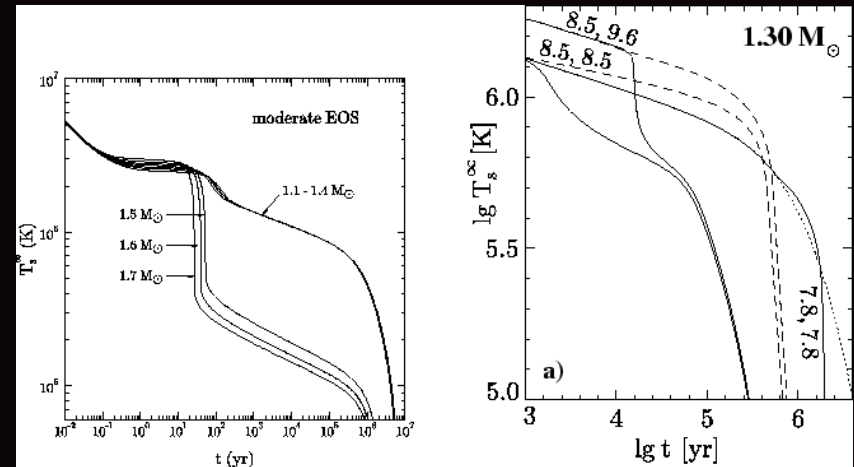
Woosley et al. 2002

# Log N – Log S



# Cooling of NSs

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

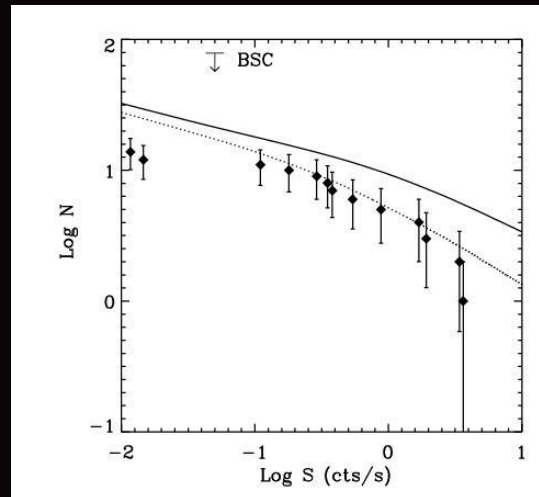
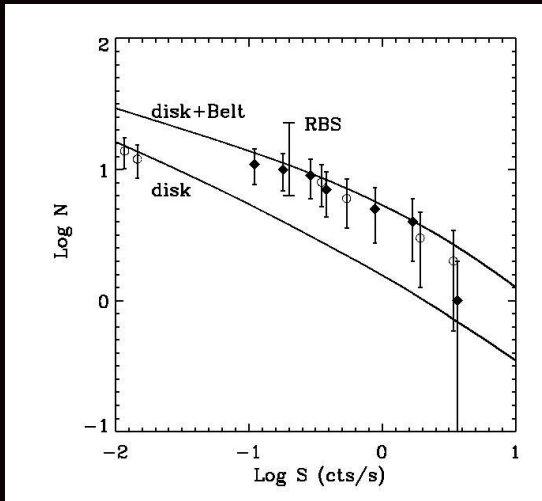


(see a recent review in [astro-ph/0508056](https://arxiv.org/abs/astro-ph/0508056))

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:

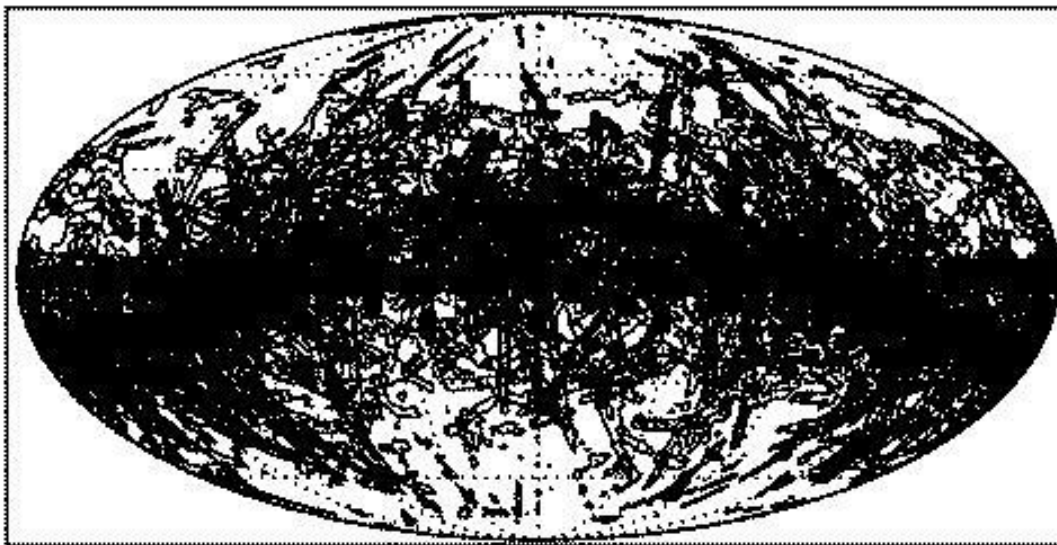
## Log N – Log S and spatial distribution



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

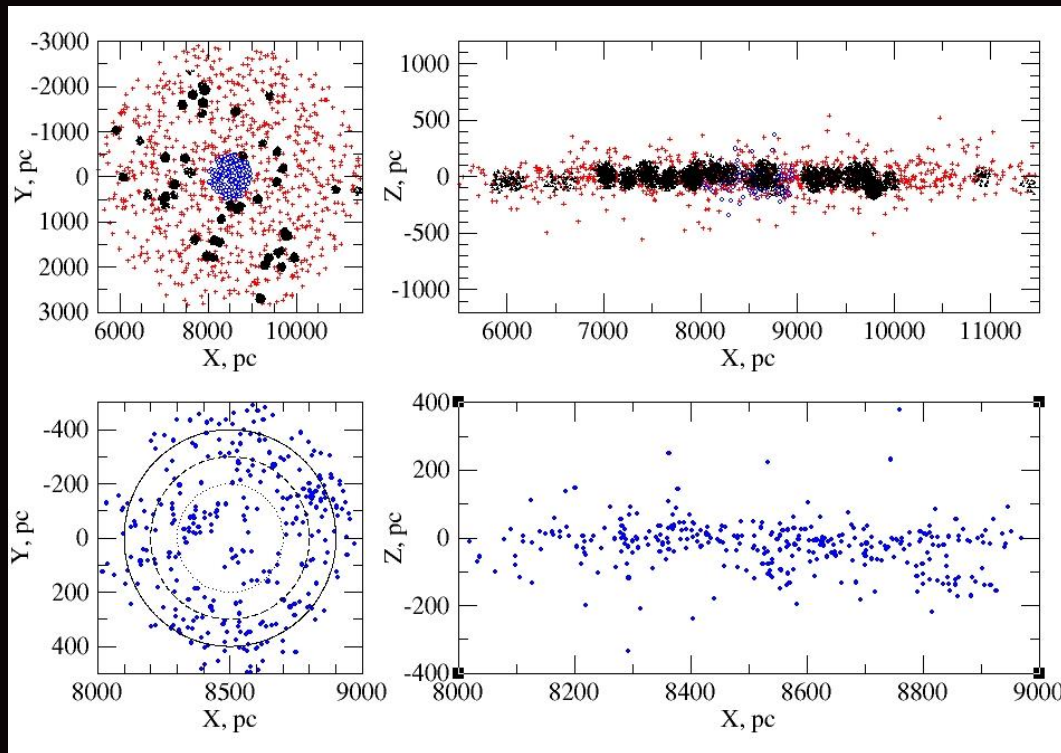
More than 1/2 are in +/- 12 degrees from the galactic plane.  
19% outside +/- 30°  
12% outside +/- 40°



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

# Population synthesis – II. recent improvements

## 1. Spatial distribution of progenitor stars



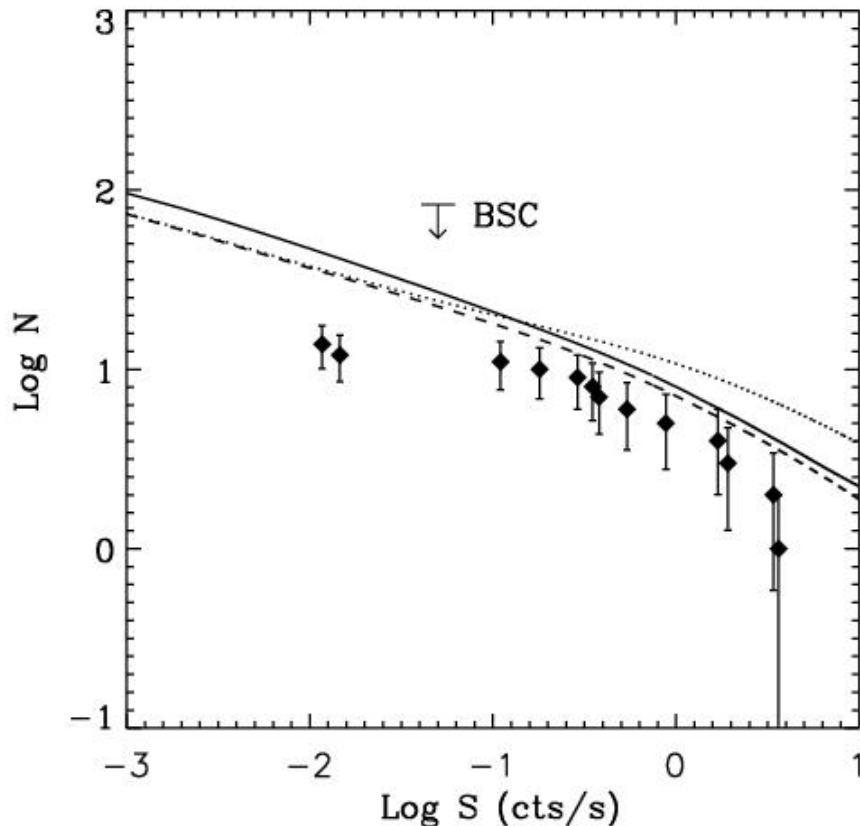
- a) Hipparcos stars up to 500 pc  
[Age: spectral type & cluster age (OB ass)]
- b) 49 OB associations: birth rate  $\sim N_{\text{star}}$
- c) Field stars in the disc up to 3 kpc

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.

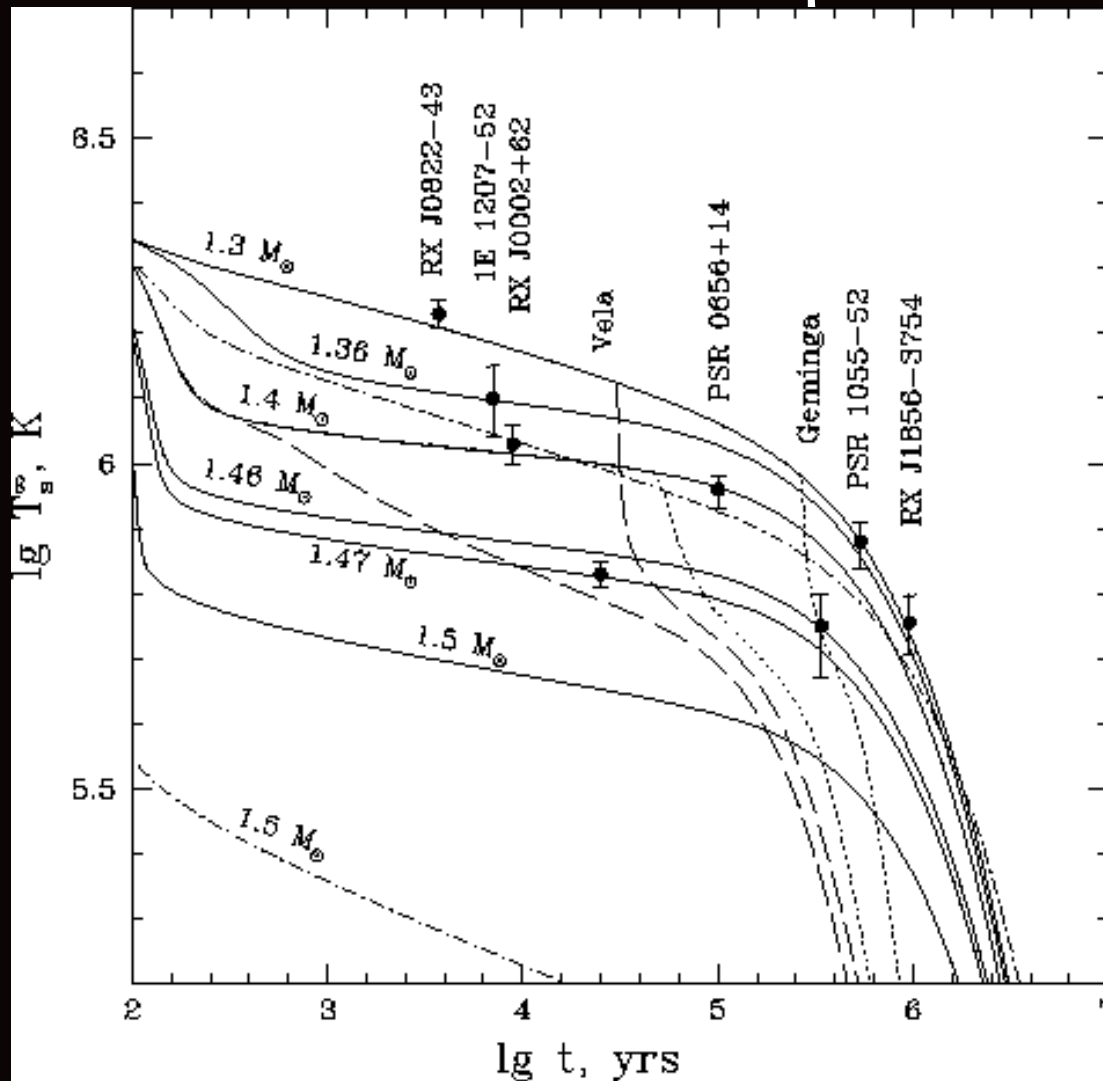
---

Solid – new initial XYZ

Dashed –  $R_{\text{belt}} = 500$  pc

Dotted –  $R_{\text{belt}} = 300$  pc

# Standard test: temperature vs. age

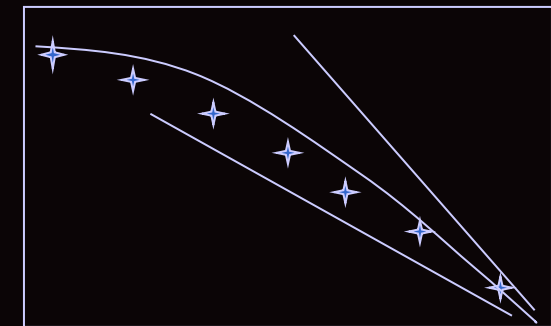
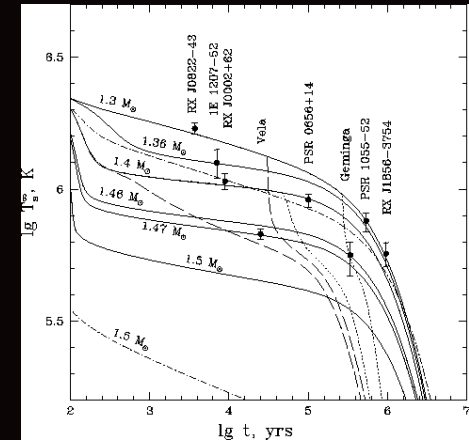


Kaminker et al. (2001)



# 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!!!



# Isolated neutron star census

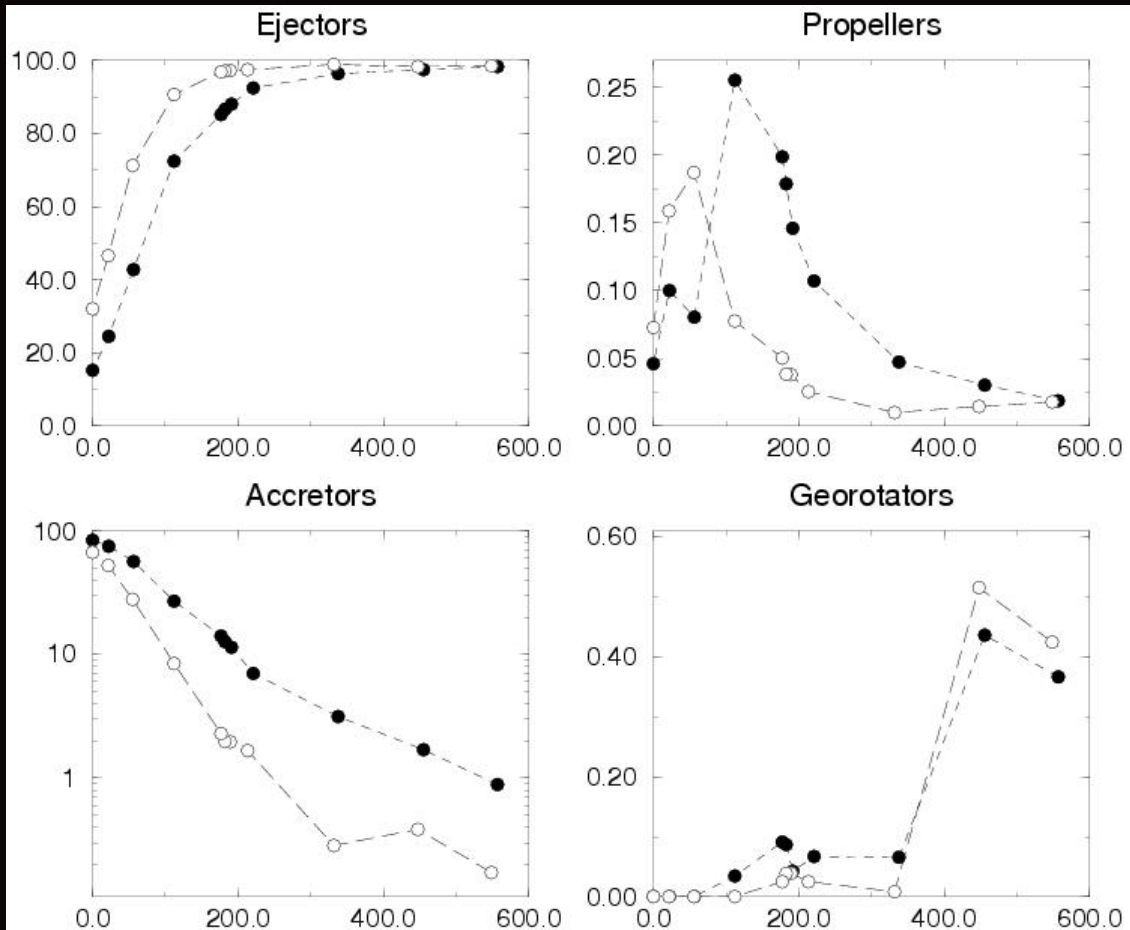
## Task.

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

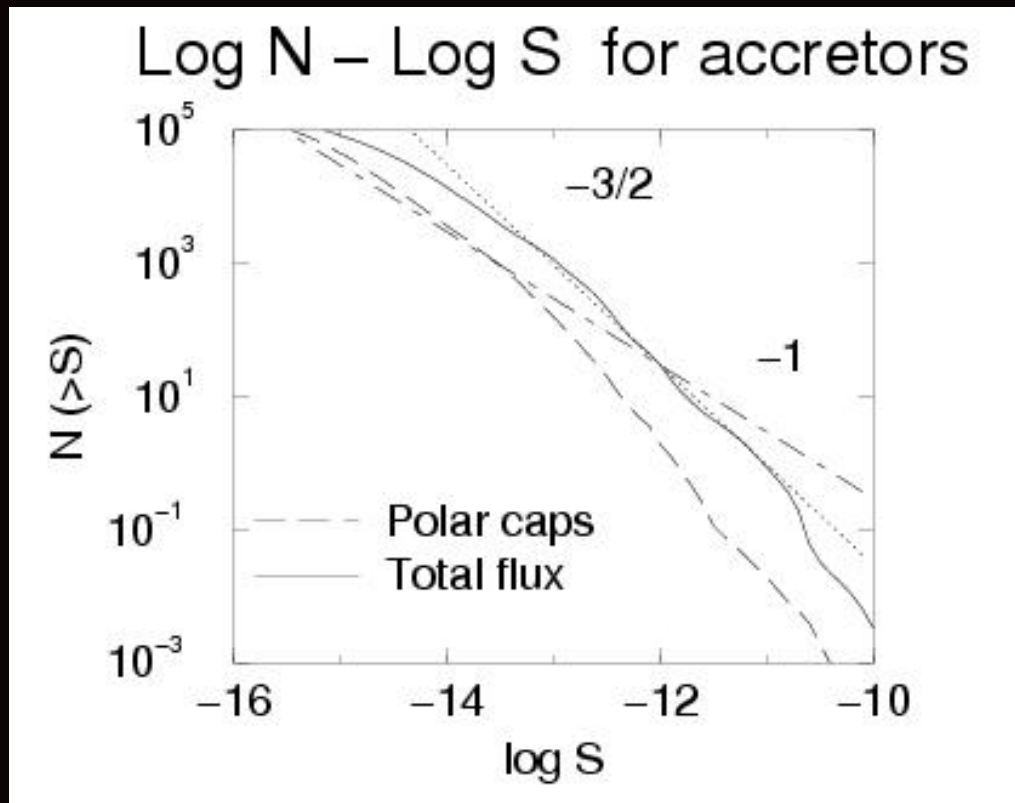


Rather conservative evolutionary scheme was used.

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

# Accreting isolated NSs

At small fluxes  $< 10^{-13}$  erg/s/cm<sup>2</sup> 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  $\times 10^{-14}$ , but difficult to identify.

Monitoring is important.

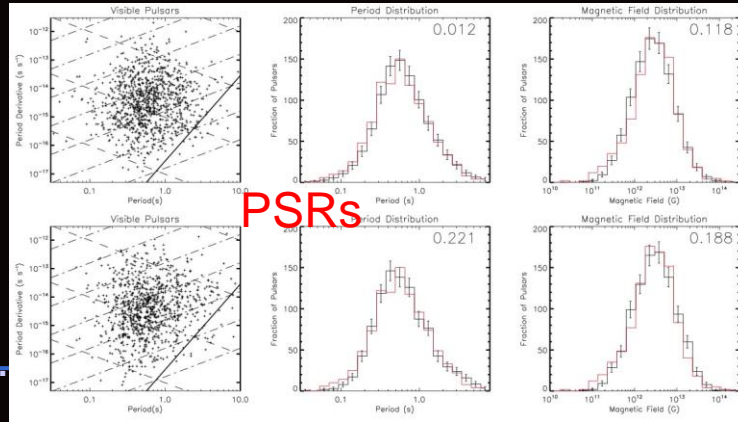
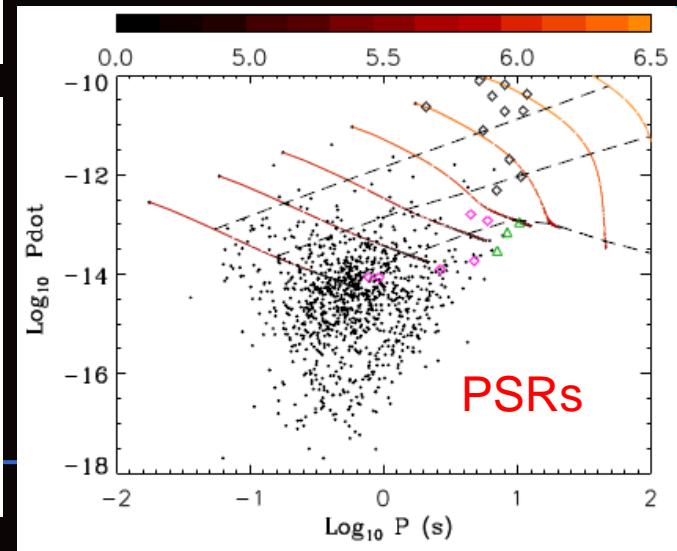
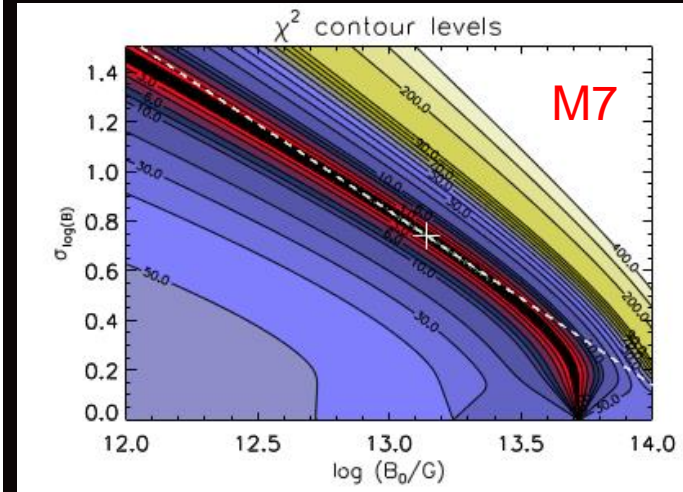
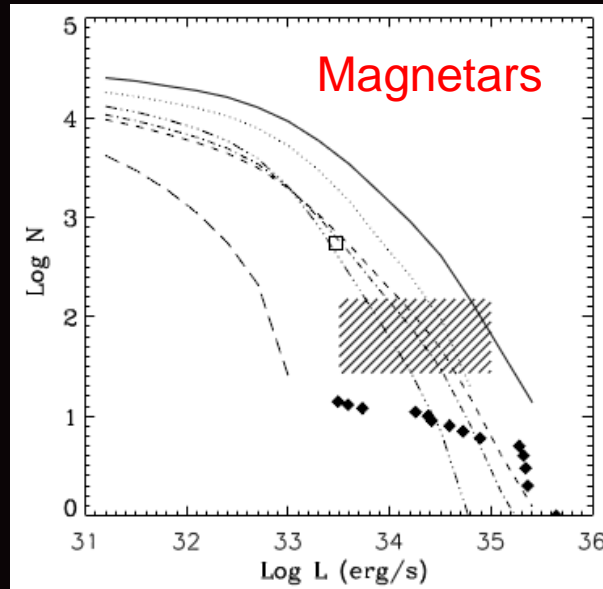
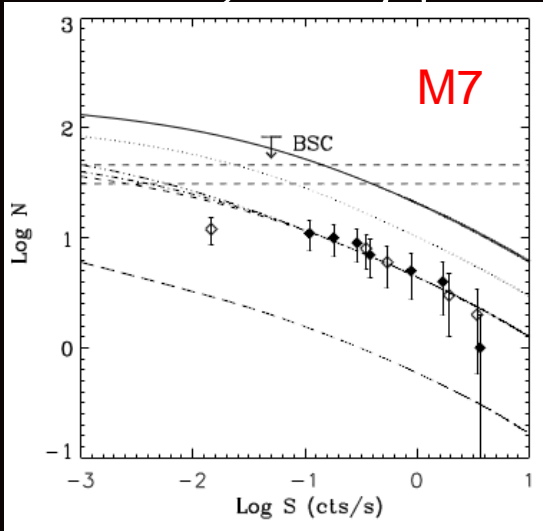
Also isolated accretors can be found in the Galactic center (Zane et al. 1996, Deegan, Nayakshin 2006).

# 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

# 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 PSRswith the same log-normal magnetic field distribution

Best model:  $\langle \log(B_0/[G]) \rangle = 13.25$ ,  $\sigma_{\log B_0} = 0.6$ ,  $\langle P_0 \rangle = 0.25$  s,  $\sigma_{P_0} = 0.1$  s

- ❏ We exclude distributions with  $> \sim 20\%$  of magnetars
- ❏ Populations with  $\sim 10\%$  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)