Evolution and observational appearance of isolated neutron stars

with decaying magnetic fields

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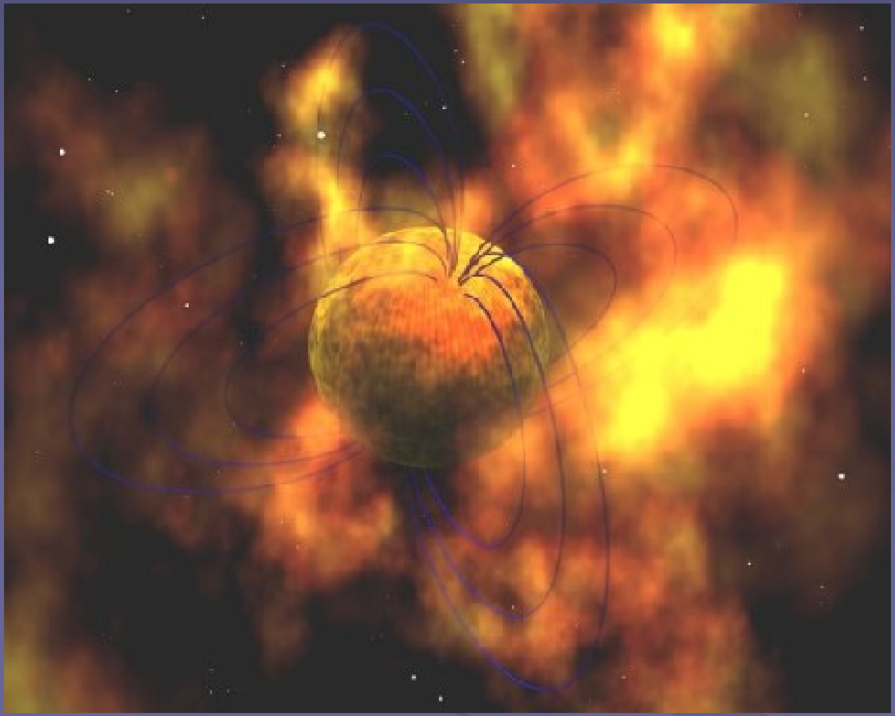
Outline

- Intro
- Extensive population synthesis of isolated neutron stars
- “Public outreach”: a web-tool for population synthesis
- Applications of the results
- P-Pdot diagram, “one second problem” and fine tuning

Diversity of young neutron stars

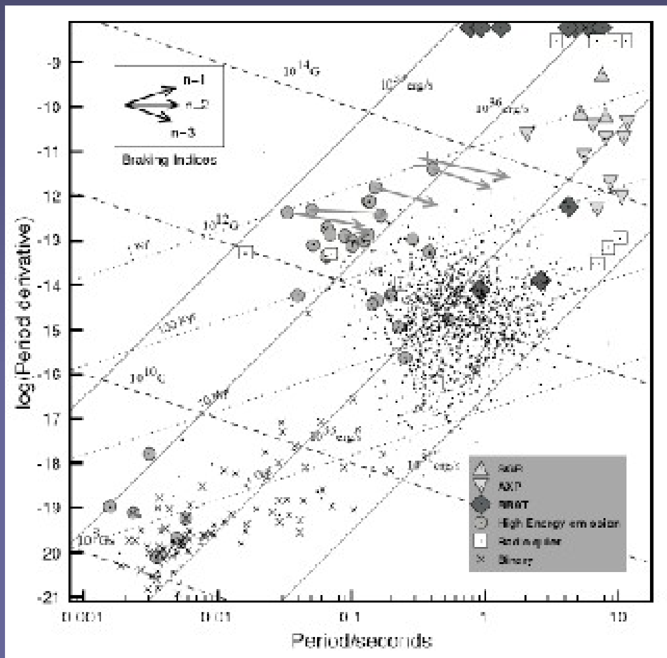
Young isolated neutron stars
can appear in many flavors:

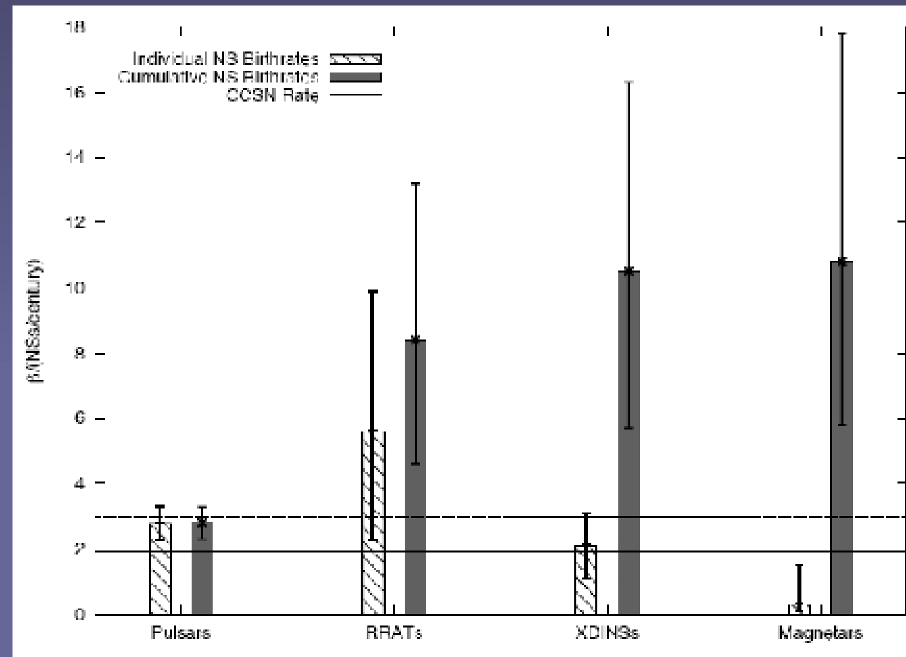
- o Radio pulsars
- o Compact central X-ray sources in supernova remnants.
- o Anomalous X-ray pulsars
- o Soft gamma repeaters
- o The Magnificent Seven & Co.
- o Transient radio sources (RRATs)
- o ....



“GRAND UNIFICATION” is welcomed!
(Kaspi 2010)

NS birth rate



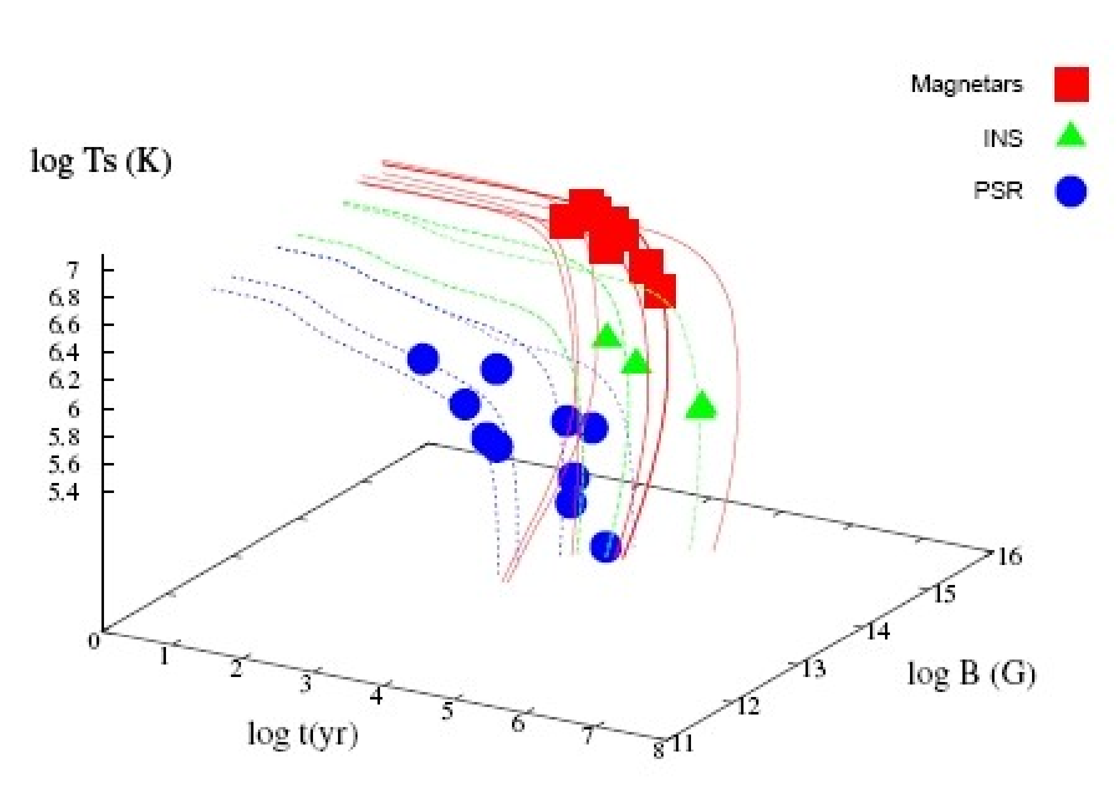


$\beta_{\rm PSR}$, $n_{\rm e}$	PSRs	RRATs	XDINSs	Magnetars	Total	CCSN rate
FK06, NE2001	2.8 ± 0.5	$5.6^{+4.3}_{-3.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$10.8^{+7.0}_{-5.0}$	1.9 ± 1.1
L+06, NE2001	1.4 ± 0.2	$2.8^{+1.6}_{-1.6}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$6.6^{+4.0}_{-3.0}$	1.9 ± 1.1
L+06, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1
V+04, NE2001	1.6 ± 0.3	$3.2^{+2.5}_{-1.9}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$7.2^{+5.0}_{-3.4}$	1.9 ± 1.1
V+04, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1

[Keane, Kramer 2008, arXiv: 0810.1512]

Magnetic field decay

A model based on the initial field-dependent decay
can provide an evolutionary link between different populations (Pons et al.).



$$B = B_0 \frac{\exp\left(-t/\tau_{\mathrm{Ohm}}\right)}{1 + \frac{\tau_{\mathrm{Ohm}}}{\tau_{\mathrm{Hall}}}\left(1 - \exp\left(-t/\tau_{\mathrm{Ohm}}\right)\right)}$$

arXiv: 0710.4914 (Aguilera et al.)

Extensive population synthesis

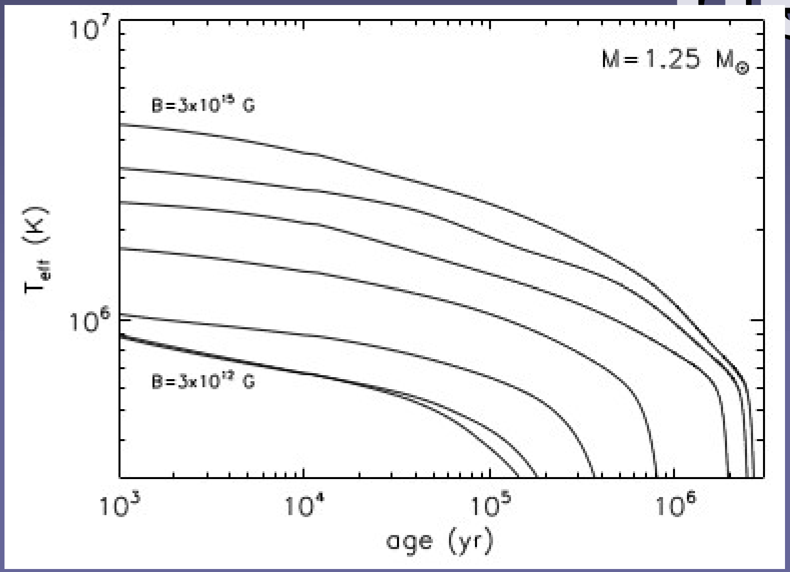
We want to make extensive population synthesis studies using as many approaches as we can to confront theoretical models with different observational data

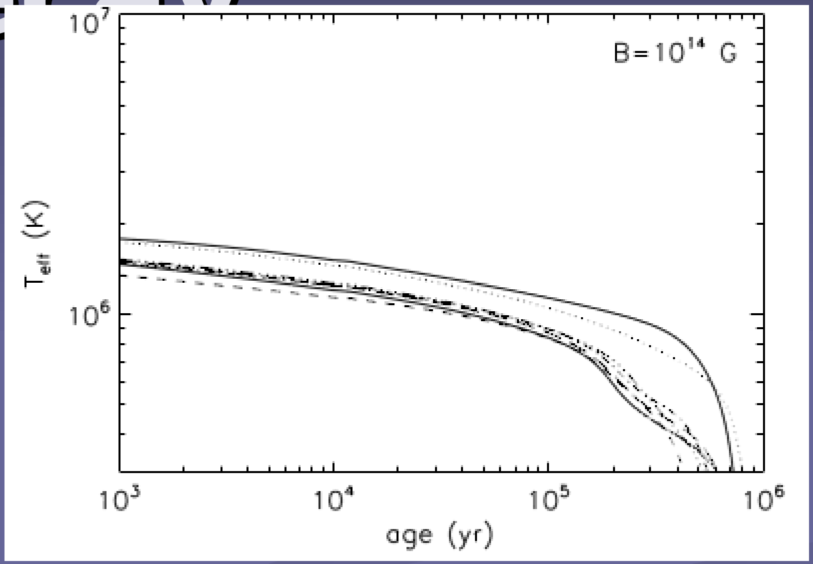
- Log N – Log S for close-by young cooling isolated neutron stars
- Log N – Log L distribution for galactic magnetars
- P-Pdot distribution etc. for normal radio pulsars

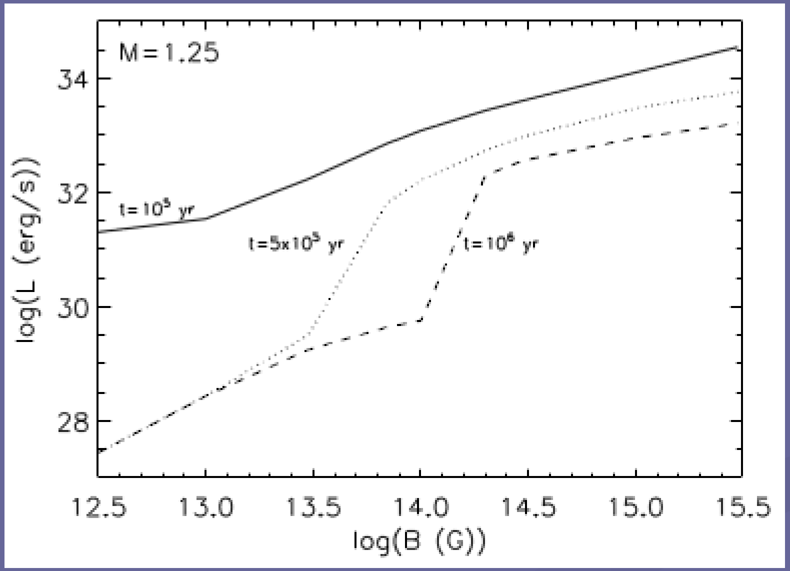
MNRAS 401, 2675 (2010)
arXiv: 0910.2190

See a review of the population synthesis technique in
Popov, Prokhorov *Physics Uspekhi* vol. 50, 1123 (2007)
[ask me for the PDF file, if necessary - it is not in the arXiv]

Cooling curves with decay

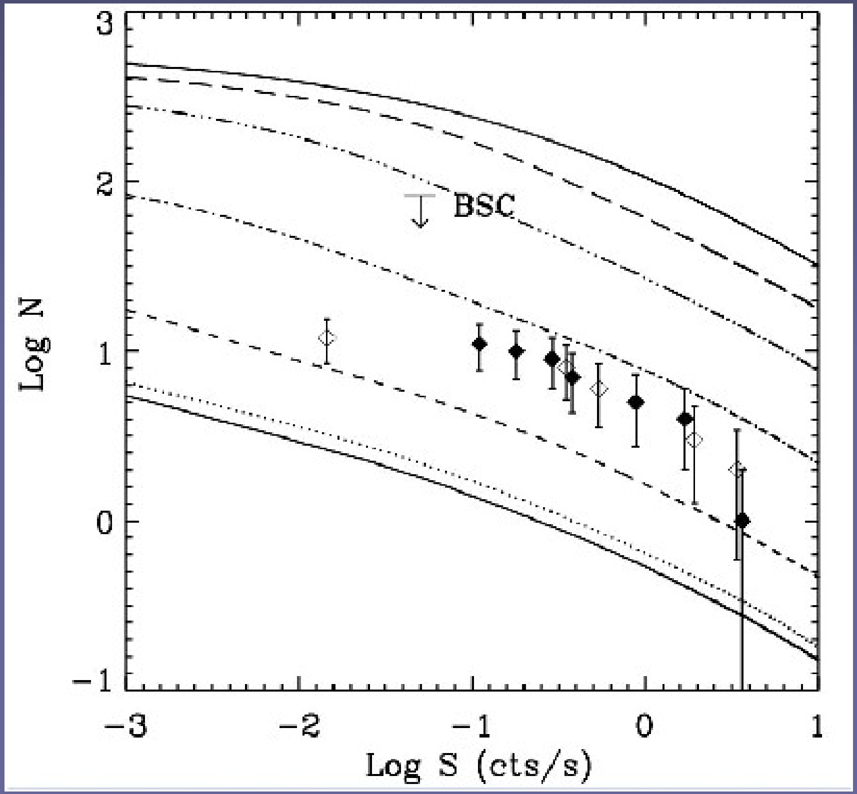


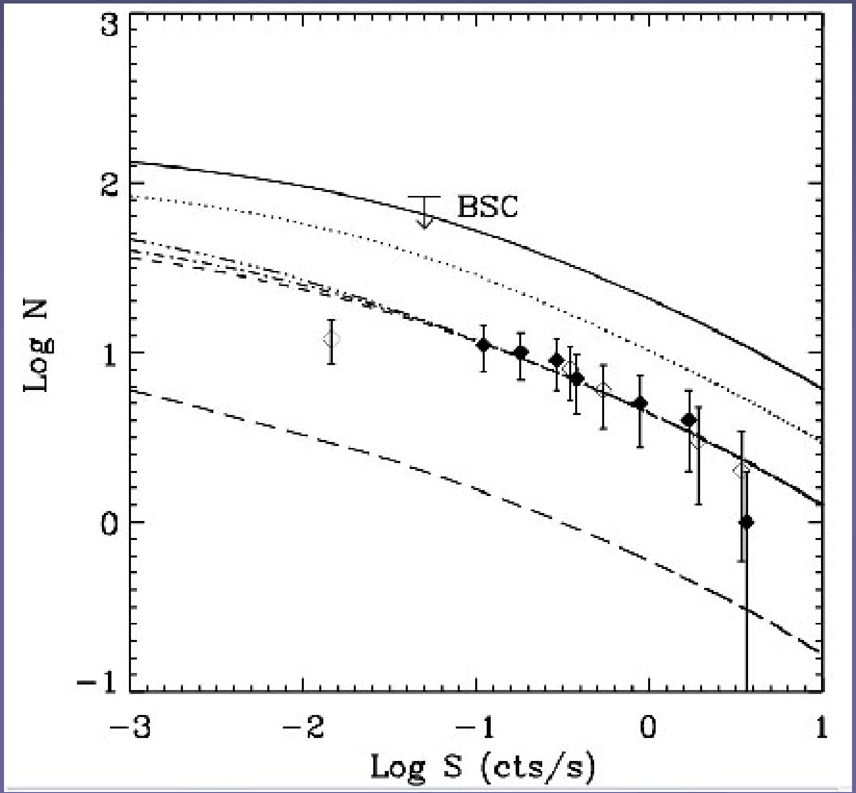




Magnetic field distribution is more important than the mass distribution.

Log N – Log S with heating





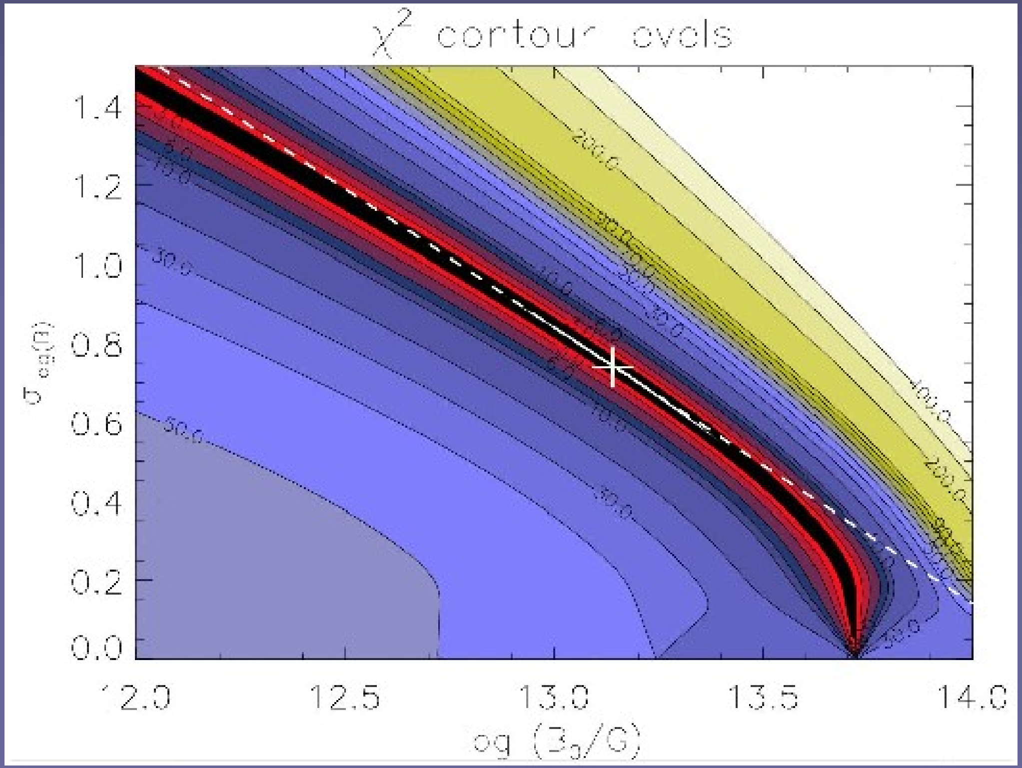
Log N – Log S for 7 different magnetic fields.

- 3 10^{12} G 2. 10^{13} G
3. 3 10^{13} G 4. 10^{14} G 5. 3 10^{14} G
6. 10^{15} G 7. 3 10^{15} G

Different magnetic field distributions.

[The code used in Posselt et al. A&A (2008) with modifications]

Fitting Log N – Log S



We try to fit the Log N – Log S with log-normal magnetic field distributions, as it is often done for PSRs.

We cannot select the best one using only Log N – Log S for close-by cooling NSs.

We can select a combination of parameters.

Model	$\sigma_{\log B}$	x_c	3×10^{12} G	10^{13} G	3×10^{13} G	10^{14} G	3×10^{14} G	10^{15} G	3×10^{15} G	Line
No mag			0.5	0.5	0.0	0.0	0.0	0.0	0.0	Long-dashed
A1			0.3	0.2	0.1	0.1	0.1	0.1	0.1	Solid
A2			0.3	0.2	0.2	0.1	0.1	0.1	0.0	Dotted
G1	1.1	12.5	0.575	0.164	0.114	0.08	0.039	0.019	0.009	Short-dashed
G2	0.84	13.0	0.37	0.244	0.191	0.126	0.049	0.0165	0.0038	Dot-dashed
G3	0.46	13.5	0.045	0.243	0.396	0.263	0.049	0.0039	0.000075	Dot-dot-dashed

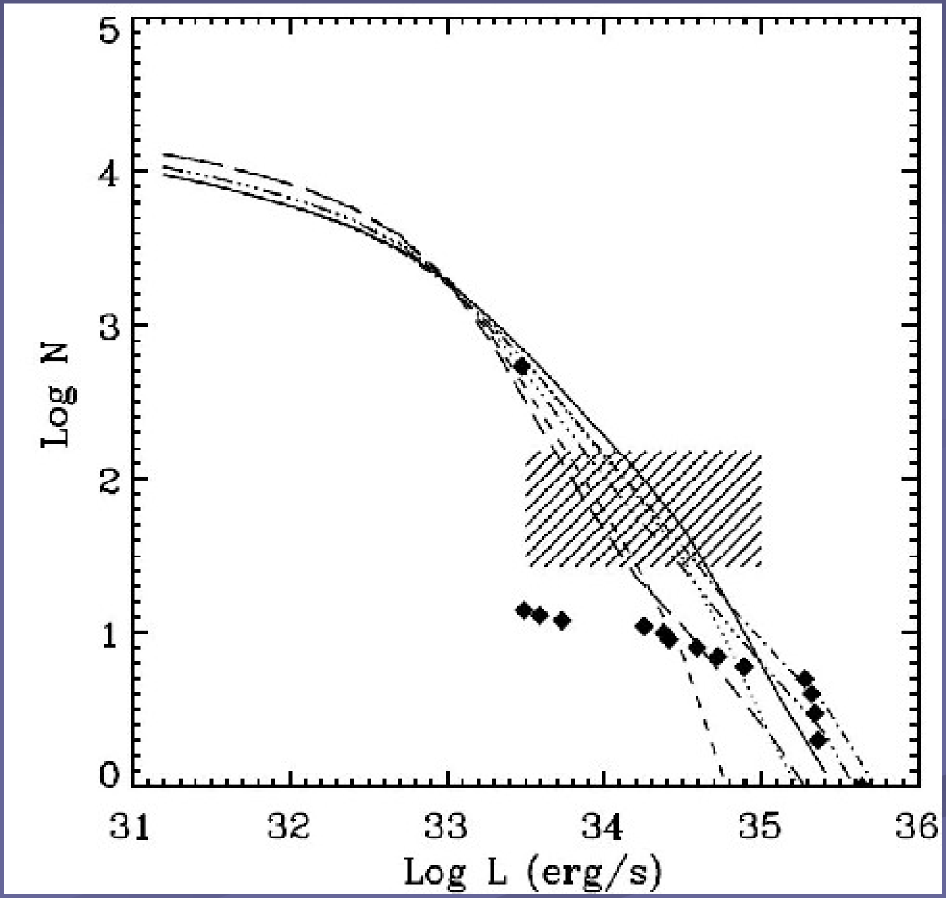
Log N – Log L for magnetars

We used the same initial magnetic field distributions.

Curves are shown for three log-normal distributions with and without a “transient” behaviour.

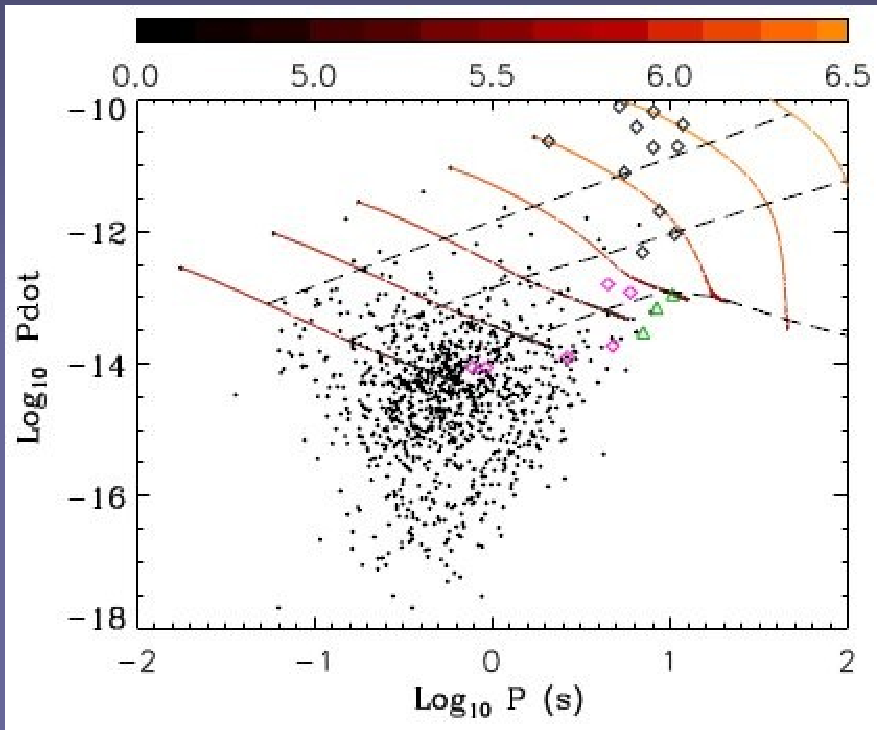
It is assumed that the total luminosity can be well approximated by the energy release due to field decay.

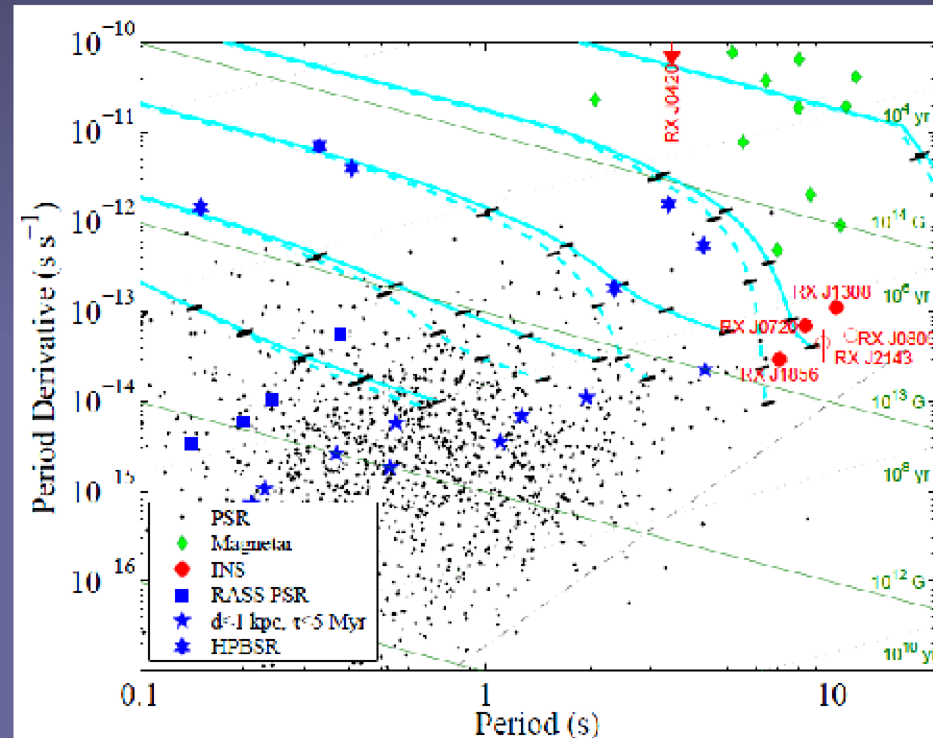
It is seen that the same log-normal distributions can reasonably well describe the data for magnetars.



Data points from the McGill catalogue
Limits from Muno et al. (2008)

P-Pdot tracks



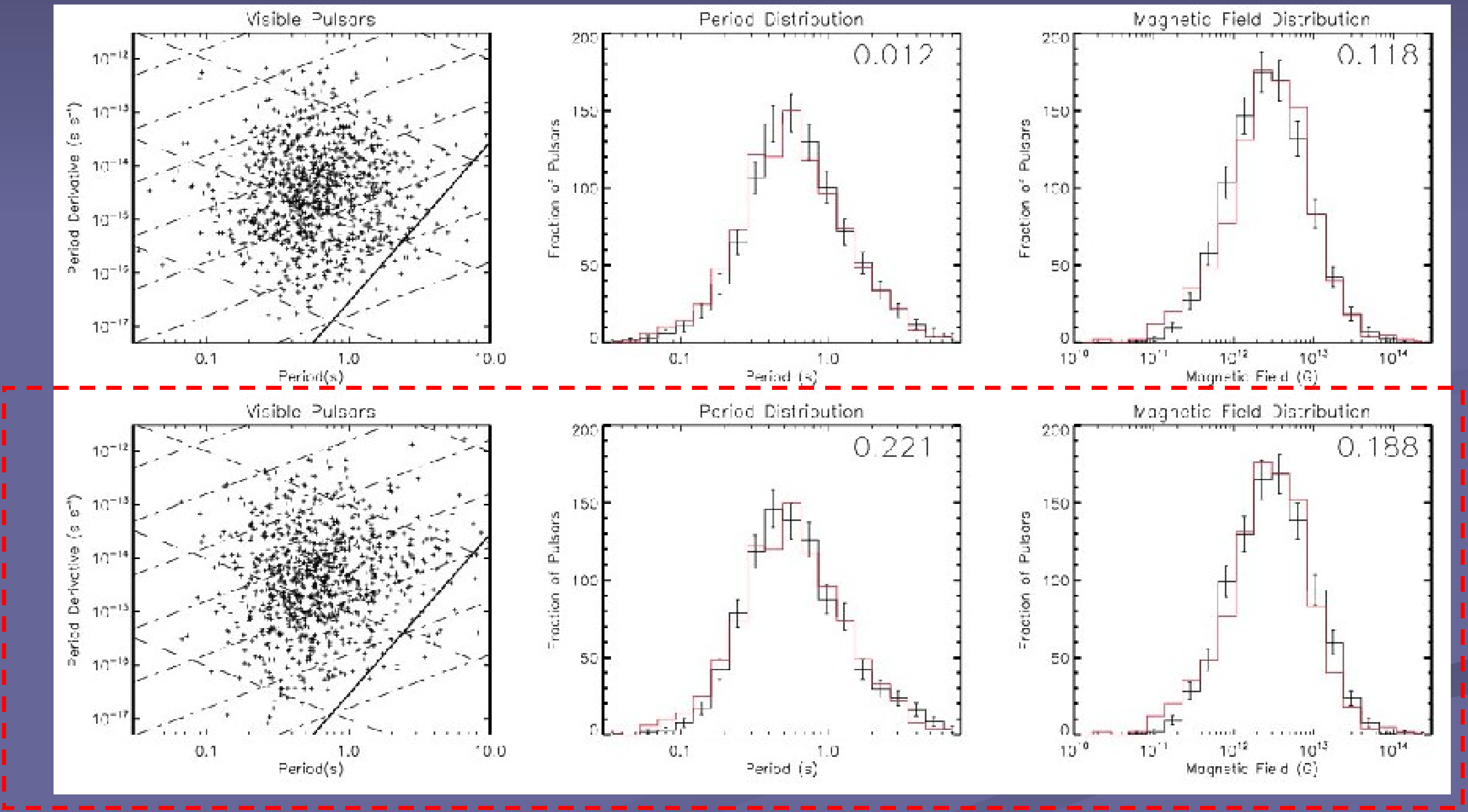


Kaplan & van Kerkwijk arXiv: 0909.5218

Color on the track encodes surface temperature.

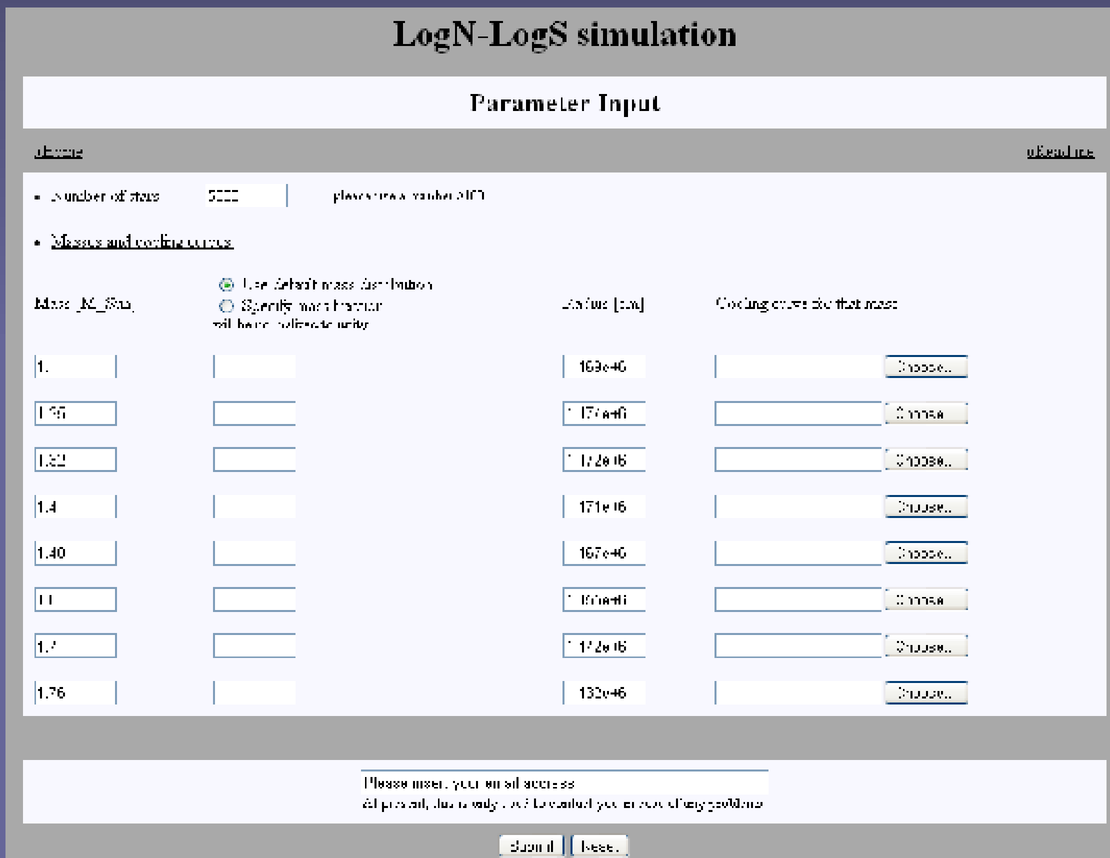
Tracks start at 10^3 years, and end at ~3 10^6 years.

Population synthesis of PSRs



Best model: $\langle \log(B_0/[G]) \rangle = 13.25$, $\sigma_{\log B0} = 0.6$, $\langle P_0 \rangle = 0.25$ s, $\sigma_{P0} = 0.1$ s

PSICoNS: A Web-tool



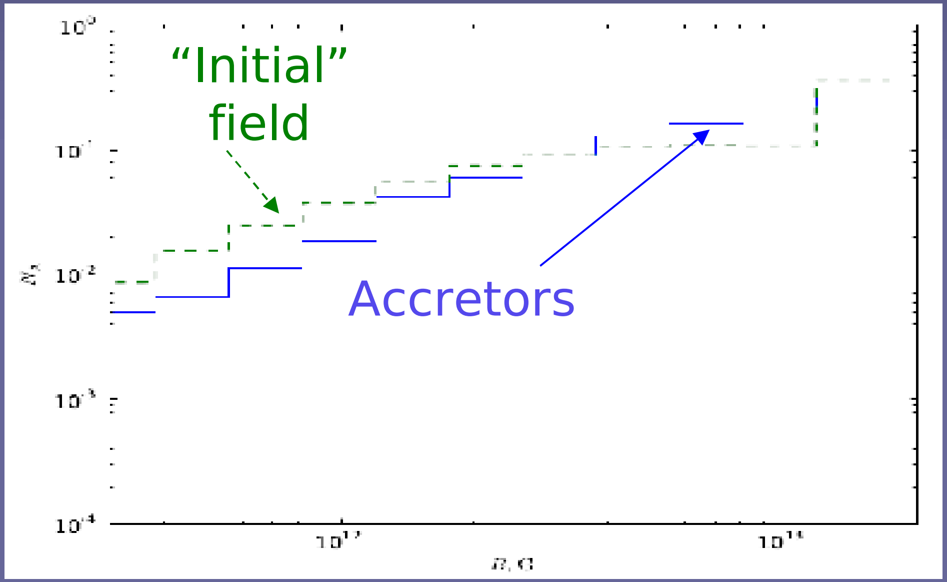
The idea is to make a tool where anybody can download his cooling curves to run a population synthesis model.

http://www.astro.uni-jena.de/Net-PSICoNS/

AN 332, 122 (2011)
arXiv: 1011.4842

Applications of the results

- Population synthesis of old NSs up to the accretion stage (MNRAS vol. 407, p. 1090 (2010) arXiv: 1004.4805)

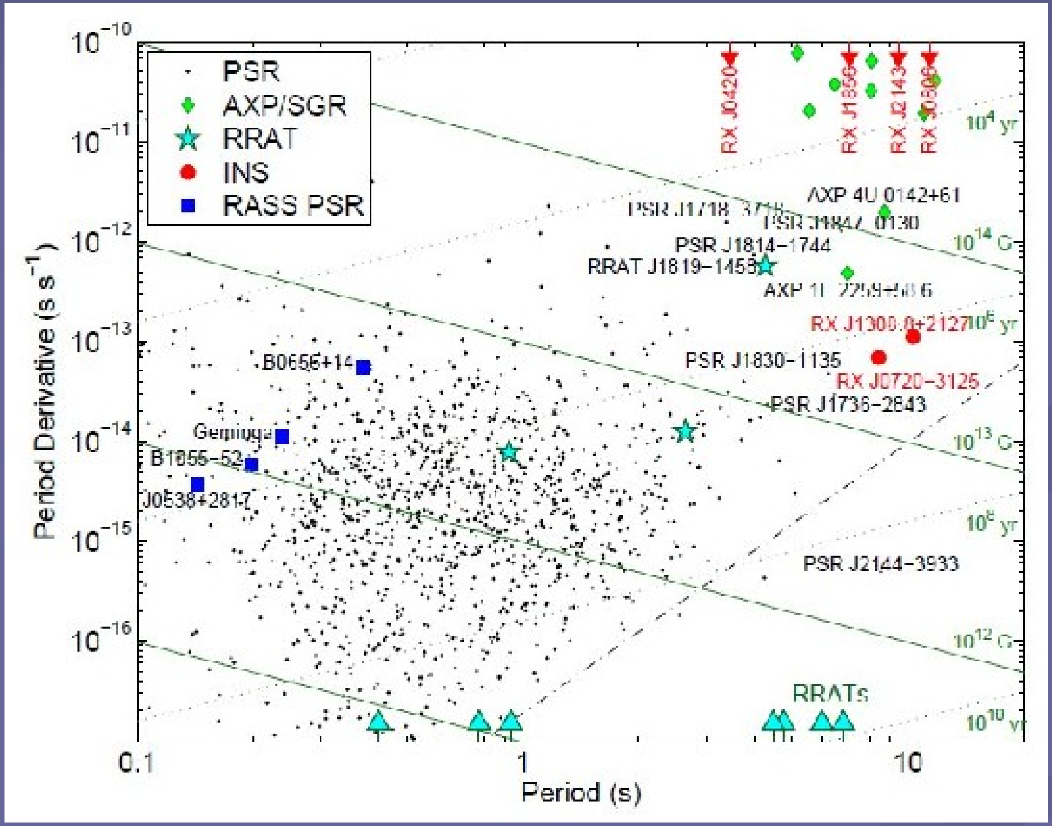


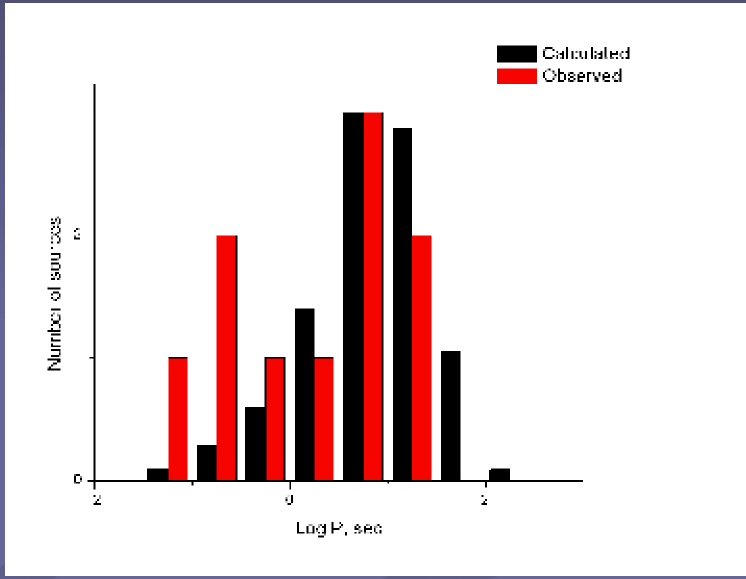
NSs with stronger initial fields form more accretors. Mainly the M7-like NSs will start to accrete.

- Population synthesis of magnetars in application to the ART-XC observations onboard Spektr-RG (see the poster by Pavel Boldin)
- Studies of the field distribution in Be/X-ray binaries (see the poster by Anna Chashkina)

The "one second" problem

Two types of sources are observed:
- Radiopulsars (P<1 sec)
- Magnificent Seven (P>1 sec)





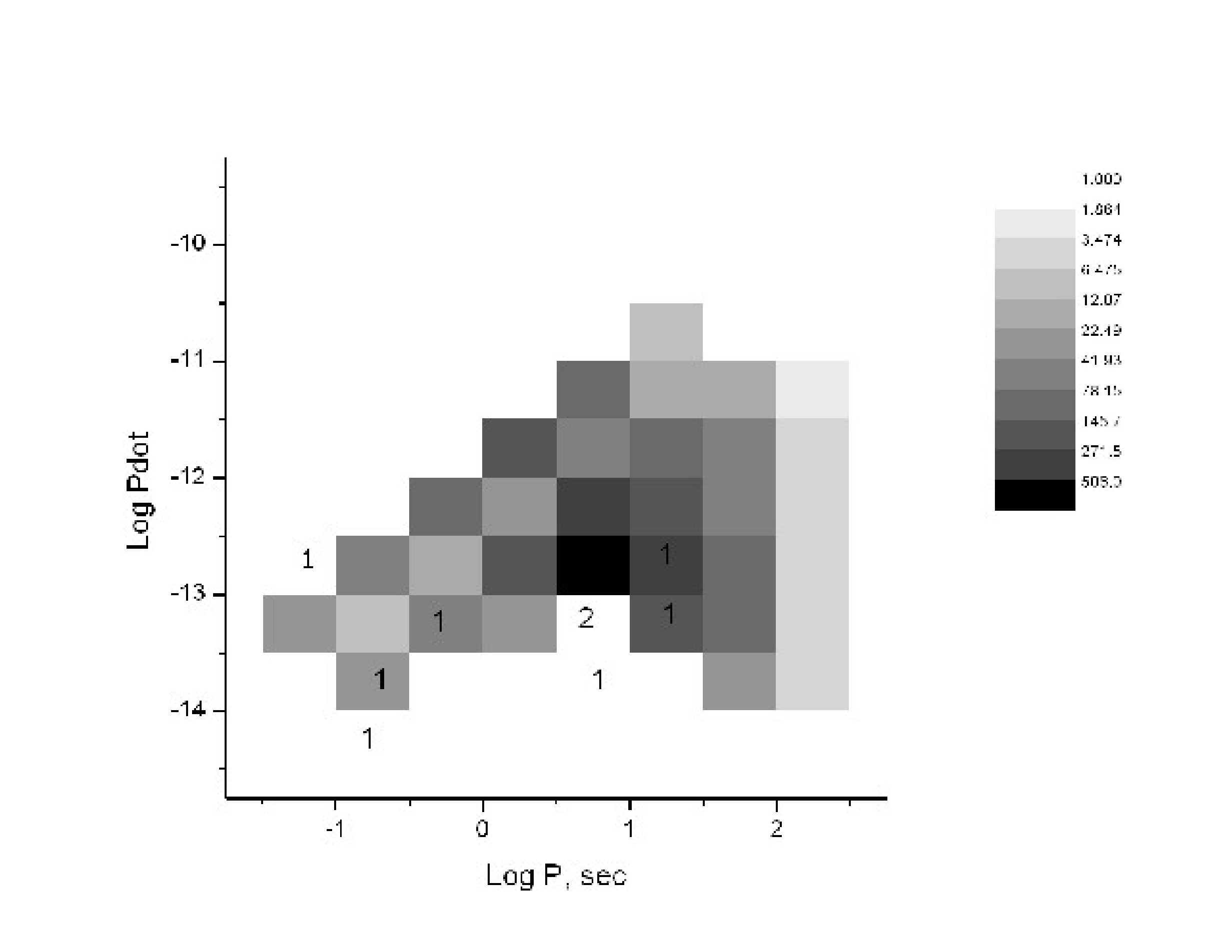
No close-by cooling NSs in the range ~-0.5 <log P< ~0.5

Kaplan arXiv: 0801.1143

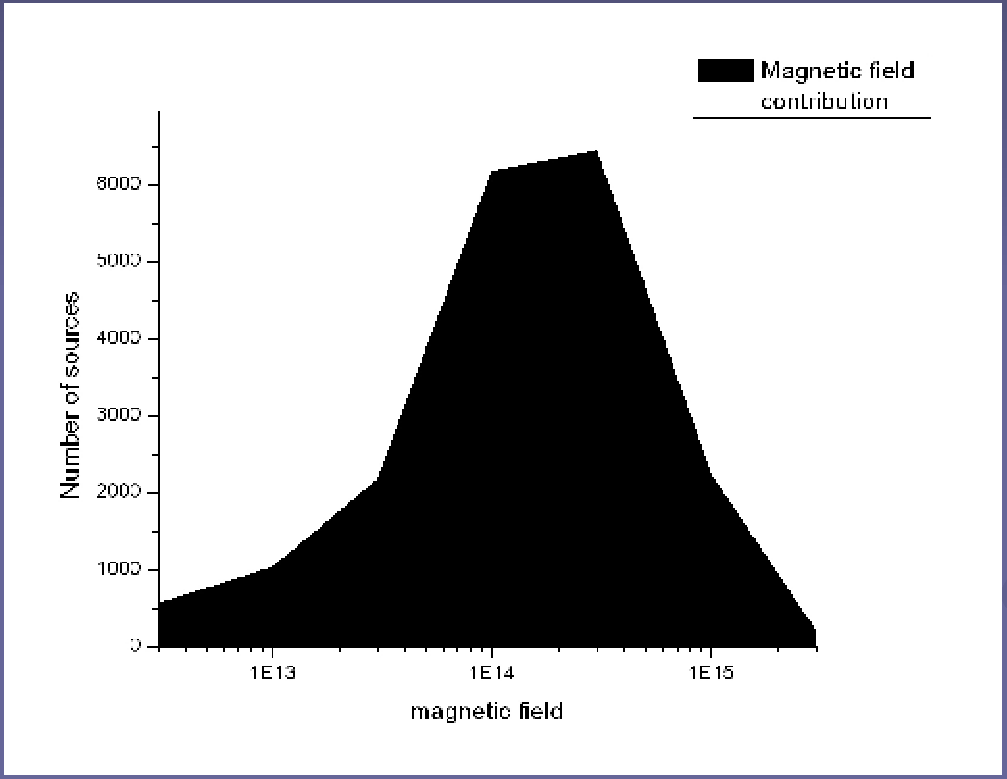
P-Pdot diagram for coolers

This is a P-Pdot diagram for close-by cooling NSs according to our model.

Numbers correspond to the observed sources.



Initial magnetic fields of the modeled coolers

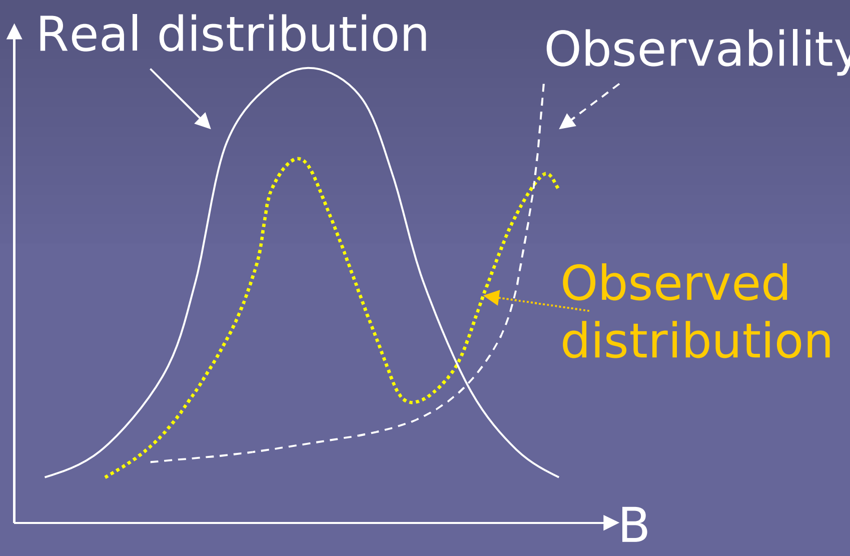


The plot shows the distribution of the initial magnetic fields of NSs which contribute to the Log N – Log S diagram in the range ~0.1-10 cts/s

Obviously, there is the same problem as with the period distribution.

Solutions for the "one second" problem

1



2

Fine-tune the thermal properties of low-field NSs and hope that the gap is due to low statistics

3

Probably, the unique initial magnetic field distribution is a bad assumption, or the whole scenario is wrong

Conclusions

- 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

  The best model:
  $<\log(B_0/[G])>= 13.25$, $\sigma_{\log B0}=0.6$,
  $<P_0>= 0.25$ s, $\sigma_{P0} = 0.1$ s

- We exclude distributions with >~20% of magnetars
- Populations with ~10% of magnetars are favoured
- Some fine tuning is necessary to explain the "one second problem" and the P-Pdot distribution

We are waiting for eROSITA onboard SRG to increase the statistics!