Magneto-rotational and thermal evolution of near-by young neutron stars

Sergei Popov
(SAI MSU)

Collaborators:
- J.A. Pons (Univ. Alicante)
- P.A. Boldin (Space Res. Inst. and SAI)
- B. Posselt (PennState)
- J.A. Miralles (Univ. Alicante)
- D. Blaschke (Wrozlaw and Dubna)
- H. Grigorian (Yerevan and Dubna)

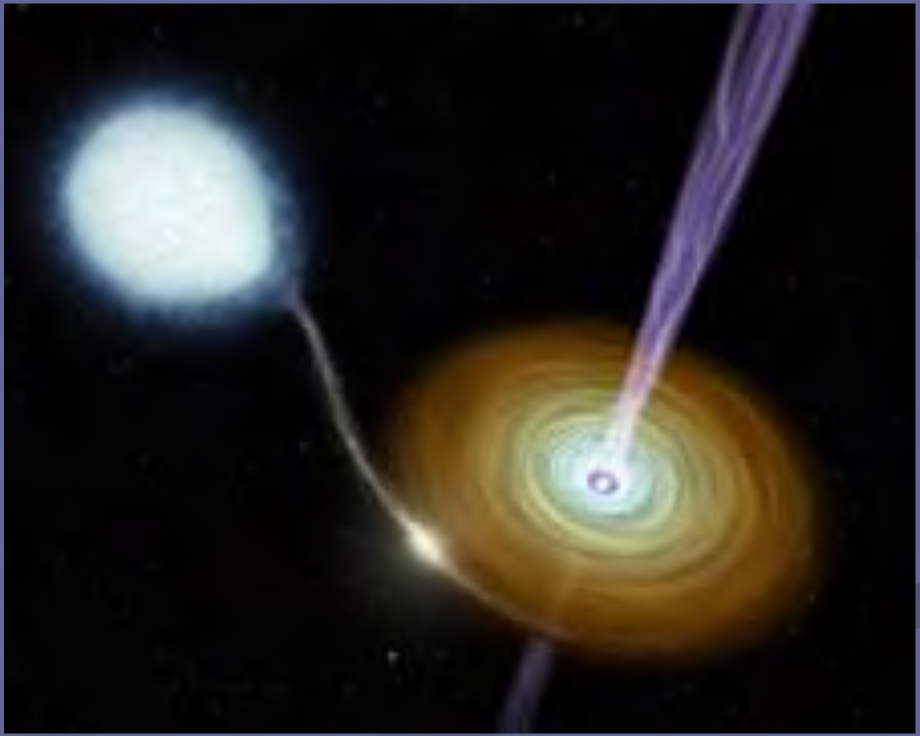
Outline

- Intro. Isolated neutron stars in the sky
- Population synthesis approach
- First population synthesis of near-by cooling neutron stars
- Extensive population synthesis of isolated neutron stars
- P-Pdot diagram, "one second problem" and fine tuning

Good old classics

For years two main types of NSs have been discussed: radio pulsars and accreting NSs in close binary systems

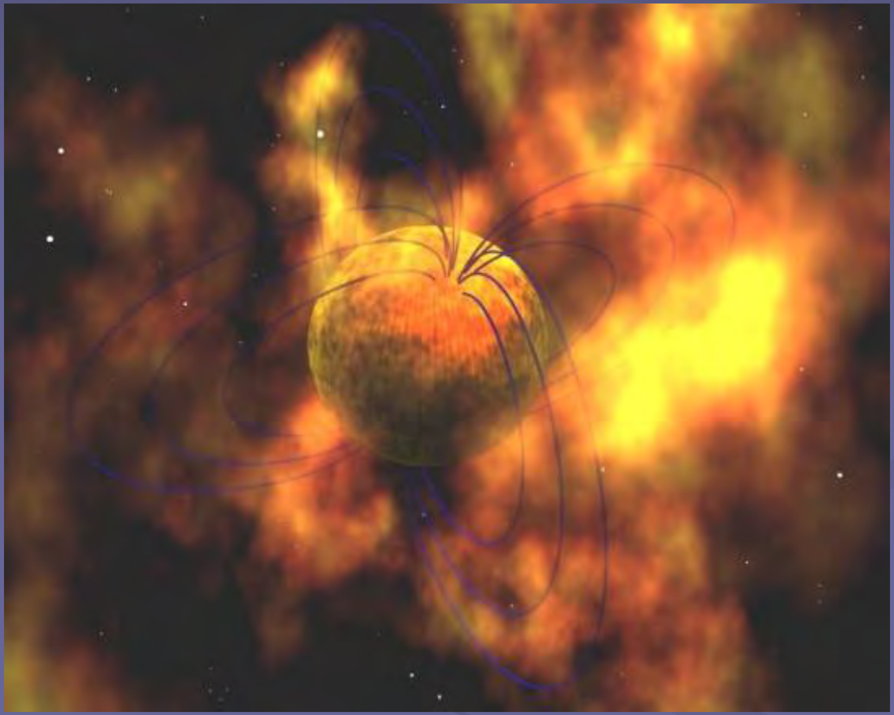
Pulsar in the Crab nebula



A binary system

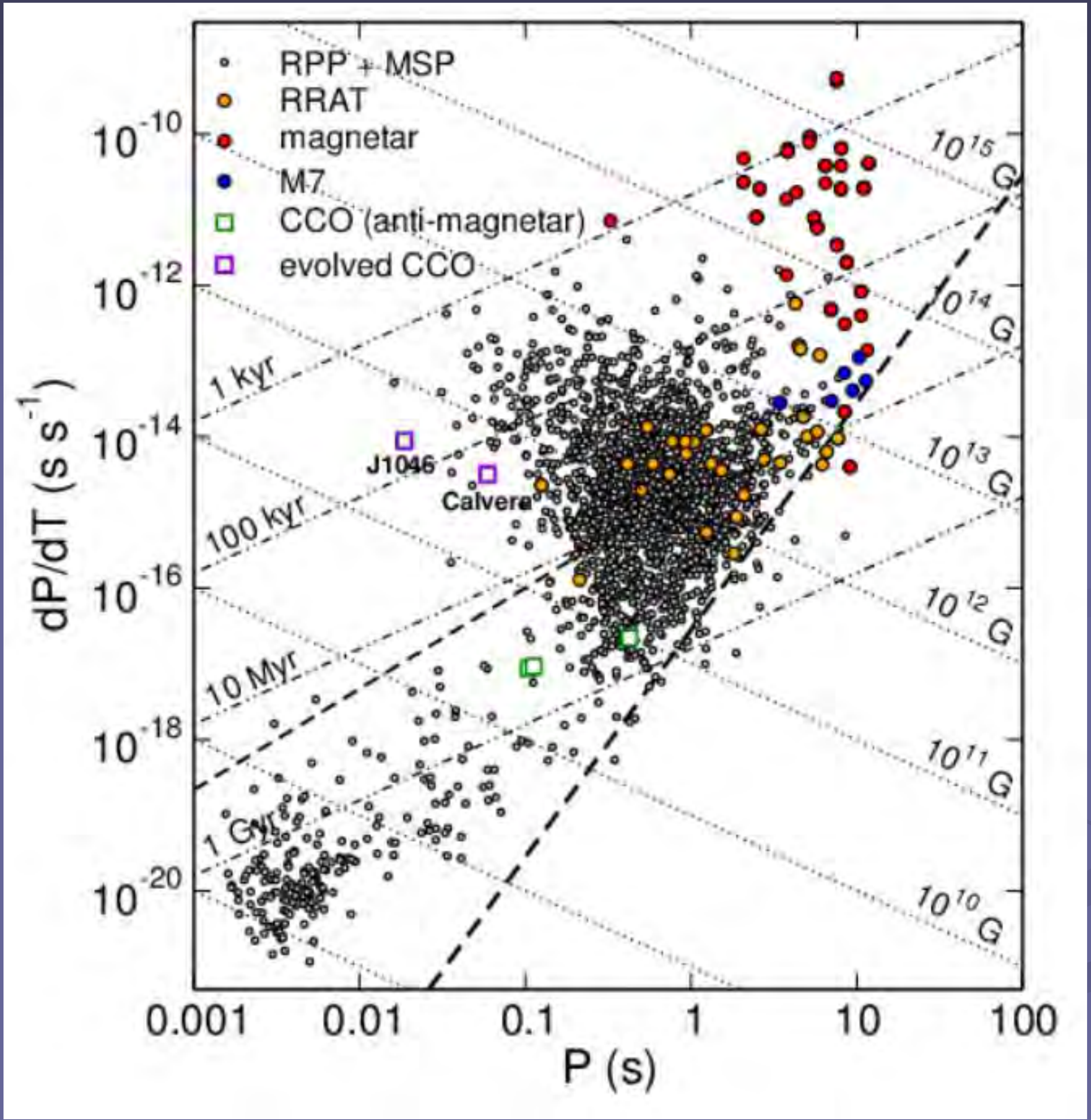
Diversity of young neutron stars

Young isolated neutron stars can appear in many flavors:



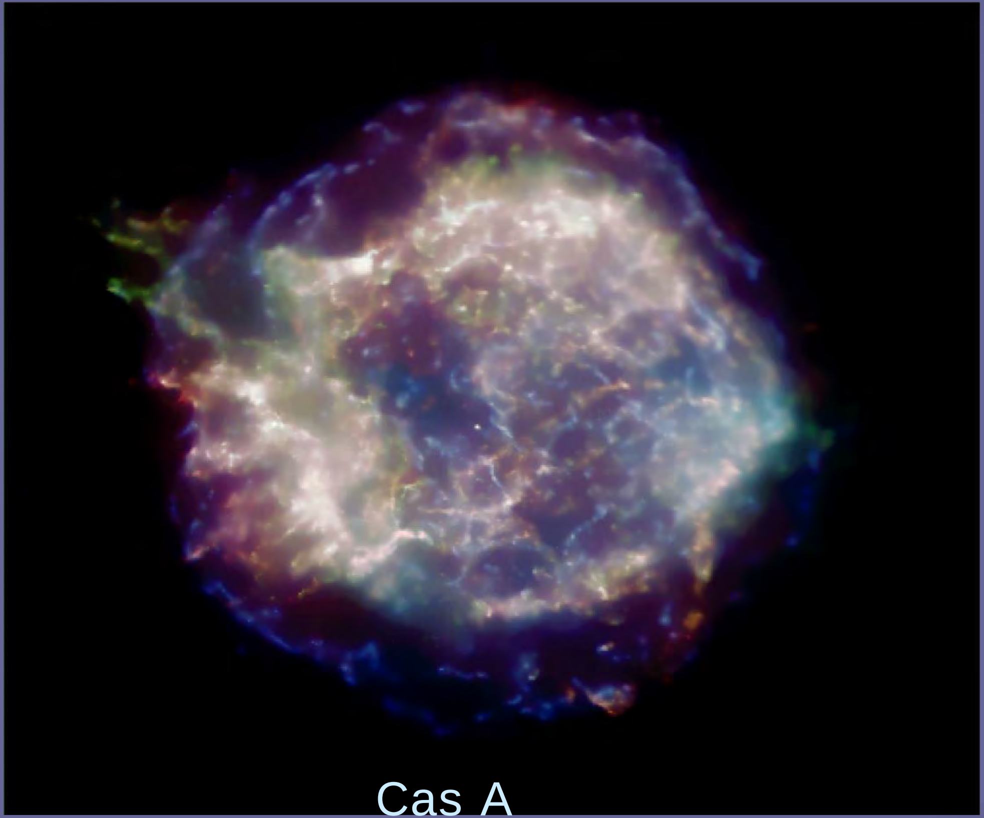
- o Radio pulsars
- o Compact central X-ray sources in supernova remnants._
- o Anomalous X-ray pulsars
- o Soft gamma repeaters
- o The Magnificent Seven & Co.
- o Transient radio sources (RRATs)
- o ....

“GRAND UNIFICATION” is welcomed!
(Kaspi 2010)

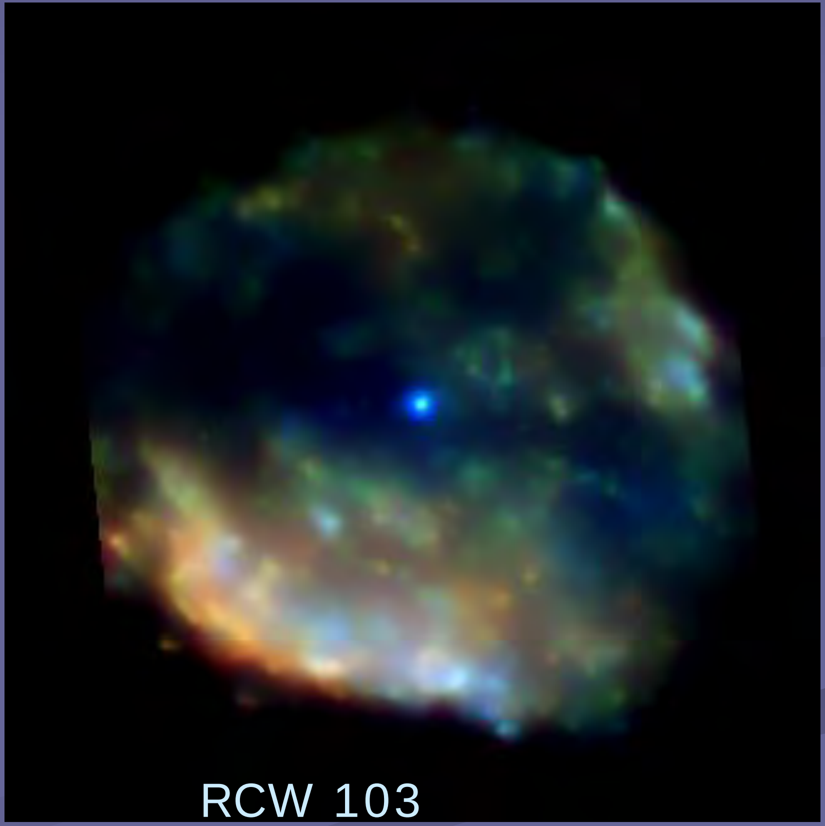


Pires et al. (2015)

Compact central X-ray sources in supernova remnants



Cas A



RCW 103

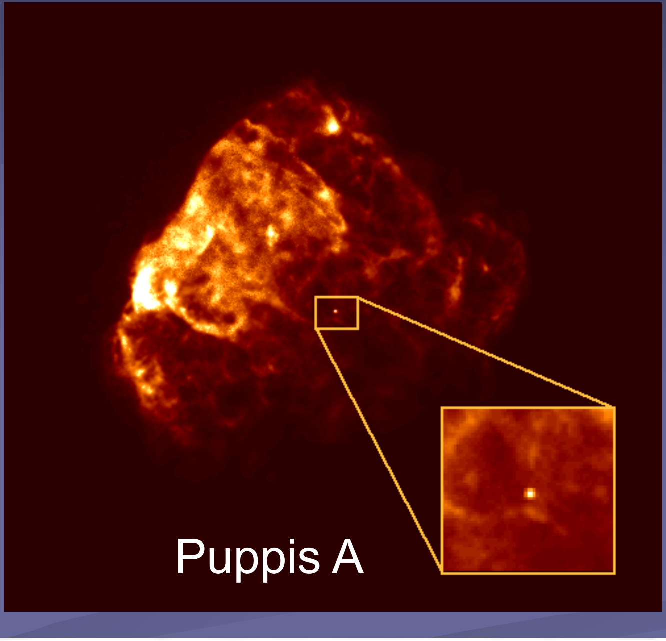
Rapid cooling
(Heinke et al. 1007.4719)

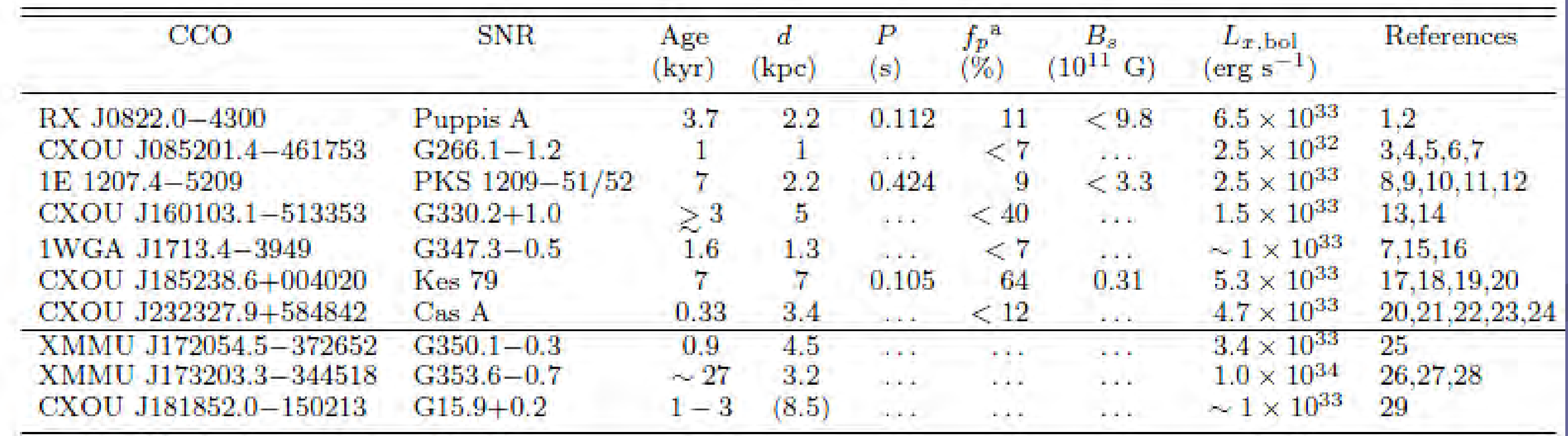
6.7 hour period
(de Luca et al. 2006)

CCOs

For two sources there are strong indications for large (>~100 msec) initial spin periods and low magnetic fields:
1E 1207.4-5209 in PKS 1209-51/52 and
PSR J1852+0040 in Kesteven 79
[see Halpern et al. arxiv:0705.0978]

Recent list in: 0911.0093





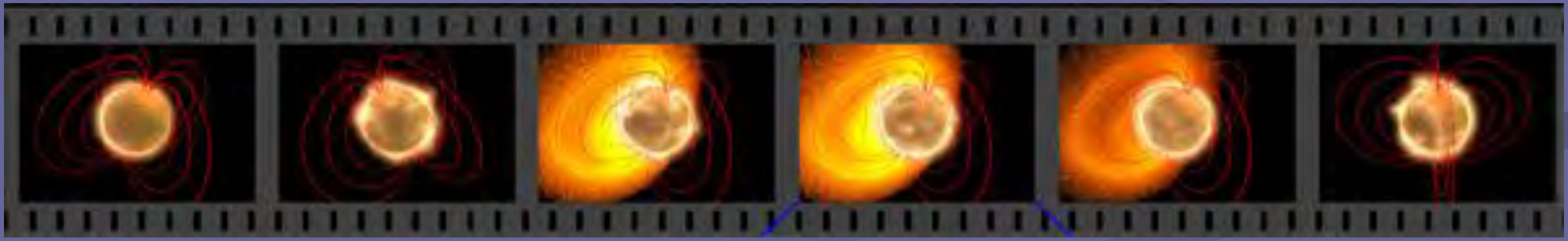
CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p [a] (%)	B_s (10^{11} G)	$L_{x,\mathrm{bol}}$ (erg s^{-1})	References
RX J0822.0−4300	Puppis A	3.7	2.2	0.112	11	< 9.8	6.5×10^{33}	1,2
CXOU J085201.4−461753	G266.1−1.2	1	1	…	< 7	…	2.5×10^{32}	3,4,5,6,7
1E 1207.4−5209	PKS 1209−51/52	7	2.2	0.424	9	< 3.3	2.5×10^{33}	8,9,10,11,12
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim 3$	5	…	< 40	…	1.5×10^{33}	13,14
1WGA J1713.4−3949	G347.3−0.5	1.6	1.3	…	< 7	…	$\sim 1 \times 10^{33}$	7,15,16
CXOU J185238.6+004020	Kes 79	7	7	0.105	64	0.31	5.3×10^{33}	17,18,19,20
CXOU J232327.9+584842	Cas A	0.33	3.4	…	< 12	…	4.7×10^{33}	20,21,22,23,24
XMMU J172054.5−372652	G350.1−0.3	0.9	4.5	…	…	…	3.4×10^{33}	25
XMMU J173203.3−344518	G353.6−0.7	~ 27	3.2	…	…	…	1.0×10^{34}	26,27,28
CXOU J181852.0−150213	G15.9+0.2	$1 - 3$	(8.5)	…	…	…	$\sim 1 \times 10^{33}$	29

Anti-magnetars!

Magnetars

- $dE/dt > dE_{rot}/dt$
- By definition: The energy of the magnetic field is released

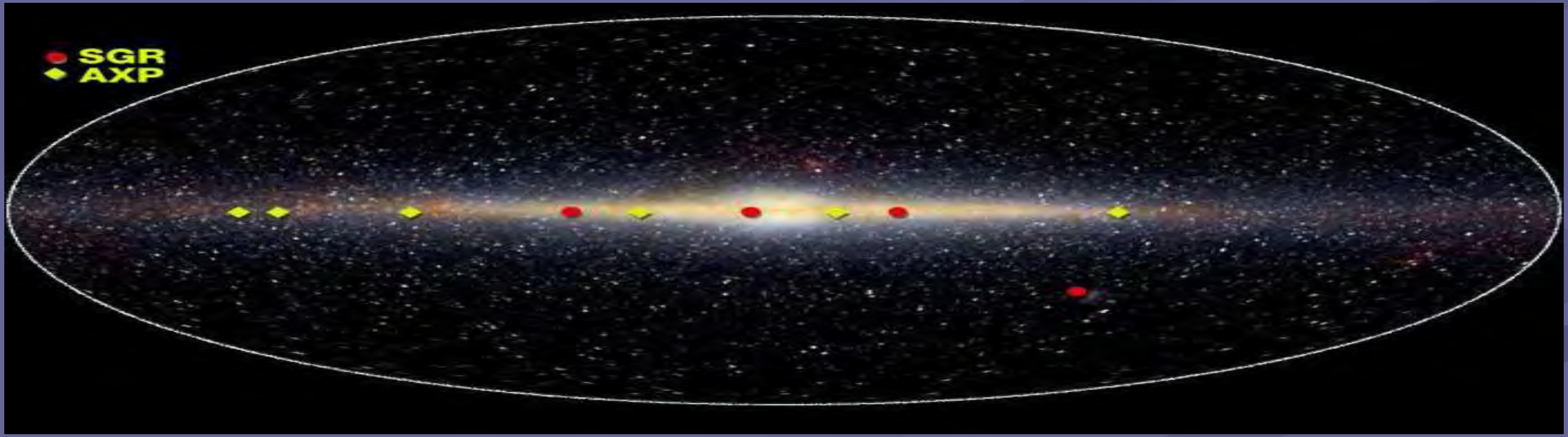
Magnetic fields 10^{14}–10^{15} G



Magnetars in the Galaxy

- ~11 SGRs, ~12 AXPs, plus 5 candidates, plus radio pulsars with high magnetic fields (about them see arXiv: 1010.4592)…
- Young objects (about 10^4 year).
- About 10% of all NSs

Catalogue: http://www.physics.mcgill.ca/~pulsar/magnetar/main.html

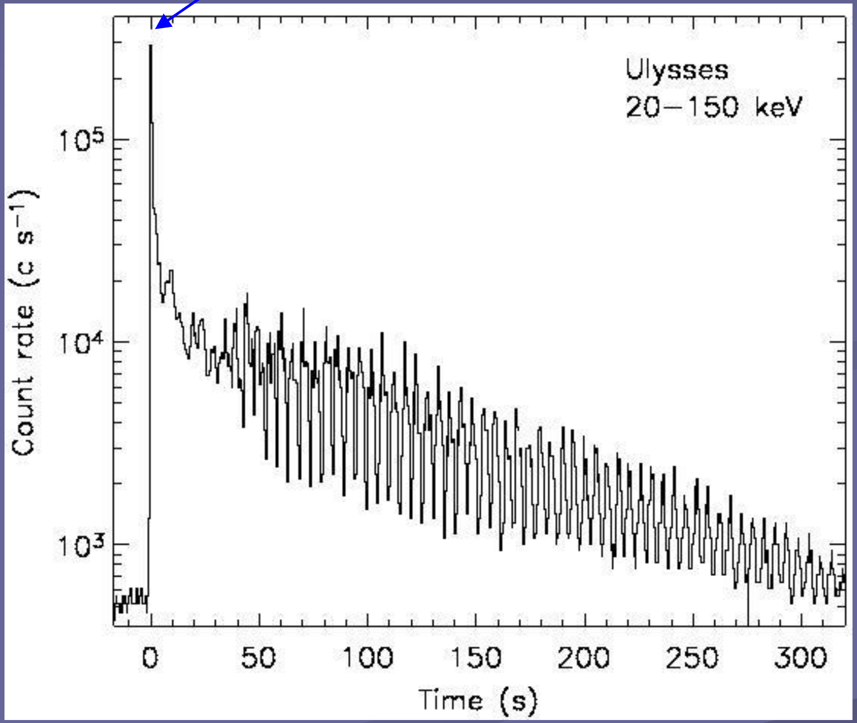


(see a recent review in arXiv:1503.06313 and catalogue description in 1309.4167)

Soft Gamma Repeaters: main properties

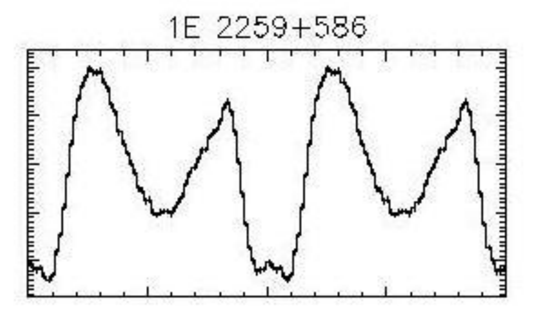
- Energetic “Giant Flares” (GFs, L ≈ 10^{45}-10^{47} erg/s) detected from 3 (4?) sources
- No evidence for a binary companion, association with a SNR at least in one case
- Persistent X-ray emitters, L ≈ 10^{35} - 10^{36} erg/s
- Pulsations discovered both in GFs tails and persistent emission, P ≈ 5 -10 s
- Huge spindown rates, $\dot{P}/P \approx 10^{-10}\ s^{-1}$

Saturation of detectors

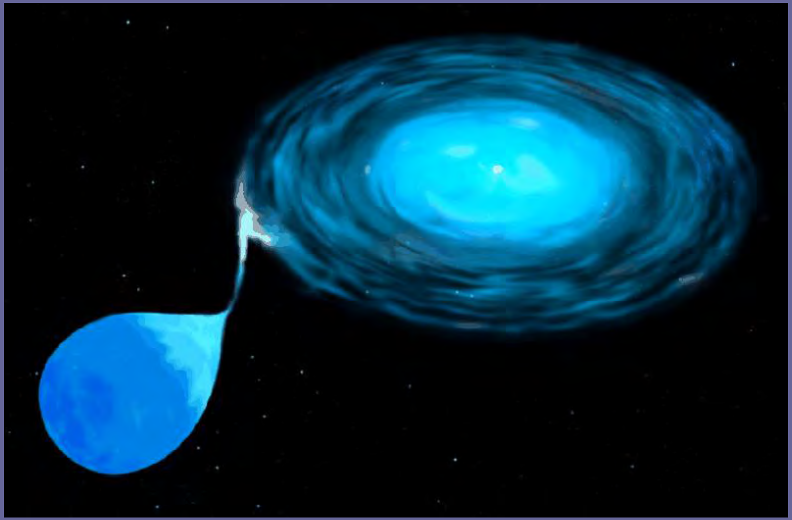


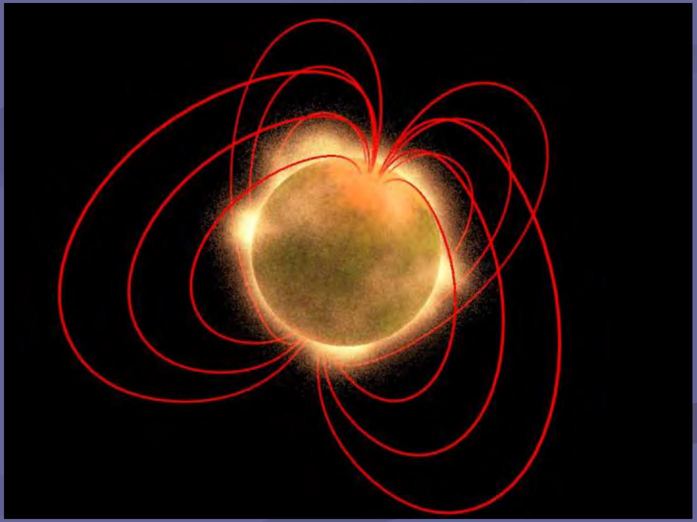
Anomalous X-ray pulsars

Identified as a separate group in 1995.
(Mereghetti, Stella 1995 Van Paradijs et al.1995)



- Similar periods (5-10 sec)
- Constant spin down
- Absence of optical companions
- Relatively weak luminosity
- Constant luminosity



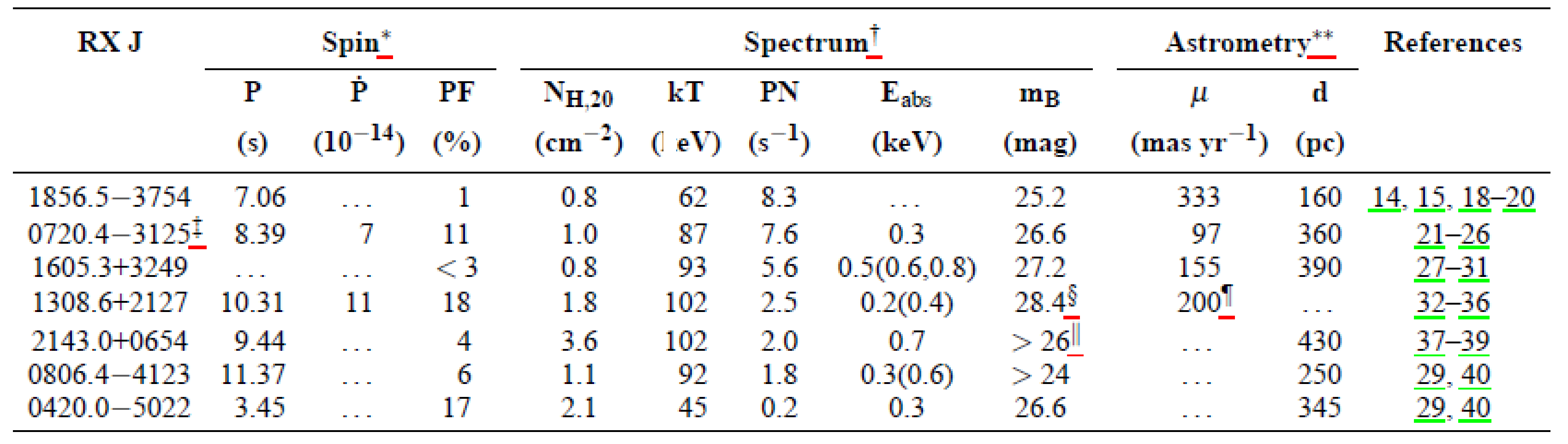


Magnificent Seven

Name	Period, s
RX 1856	7.05
RX 0720	8.39
RBS 1223	10.31
RBS 1556	6.88?
RX 0806	11.37
RX 0420	3.45
RBS 1774	9.44

Radioquiet
Close-by
Thermal emission
Absorption features
Long periods

Spin properties and other parameters



RX J	Spin[*]			Spectrum[†]					Astrometry[**]		References
	P (s)	$\dot{P}$ (10^{-14})	PF (%)	$N_{H,20}$ (cm^{-2})	kT (eV)	PN (s^{-1})	E_{abs} (keV)	m_B (mag)	μ (mas yr^{-1})	d (pc)	
1856.5−3754	7.06	…	1	0.8	62	8.3	…	25.2	333	160	14, 15, 18–20
0720.4−3125[‡]	8.39	7	11	1.0	87	7.6	0.3	26.6	97	360	21–26
1605.3+3249	…	…	< 3	0.8	93	5.6	0.5(0.6,0.8)	27.2	155	390	27–31
1308.6+2127	10.31	11	18	1.8	102	2.5	0.2(0.4)	28.4[§]	200[¶]	…	32–36
2143.0+0654	9.44	…	4	3.6	102	2.0	0.7	> 26[‖]	…	430	37–39
0806.4−4123	11.37	…	6	1.1	92	1.8	0.3(0.6)	> 24	…	250	29, 40
0420.0−5022	3.45	…	17	2.1	45	0.2	0.3	26.6	…	345	29, 40

Kaplan arXiv: 0801.1143

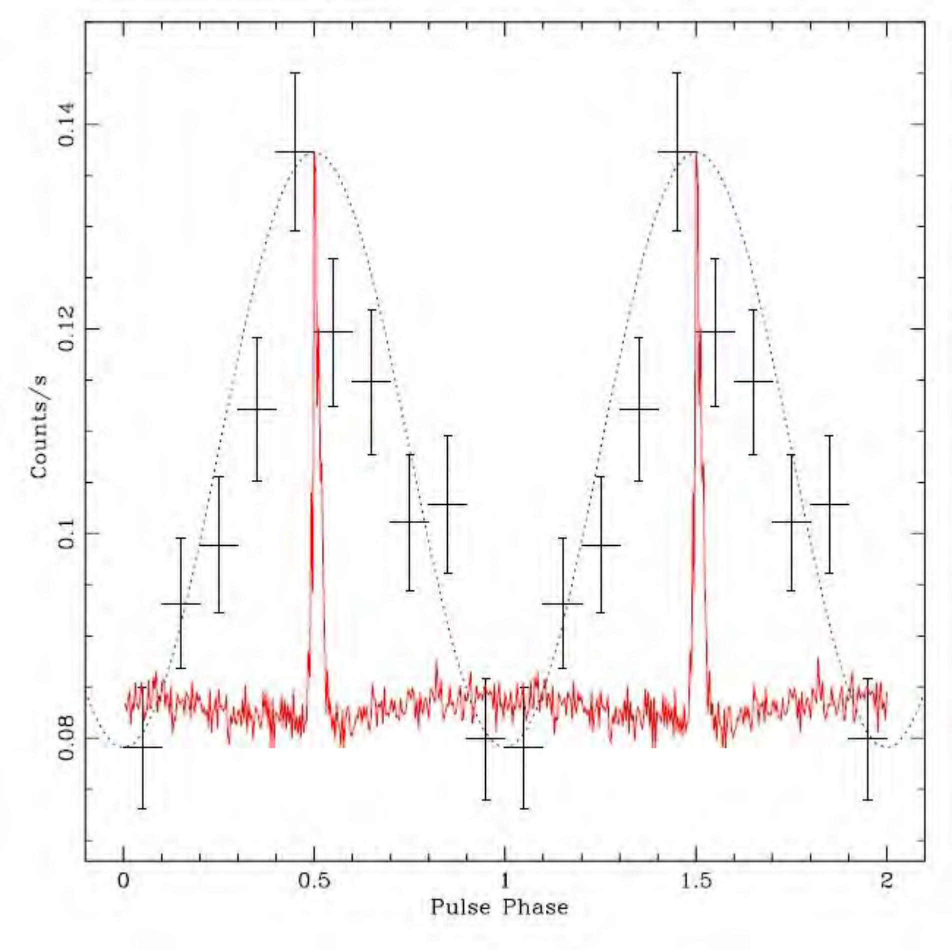
Updates:

- 1856. vdot=-6 10^{-16} (| vdot|<1.3 10^{-14}) van Kerkwijk and Kaplan arXiv: 0712.3212
- 2143. vdot=-4.6 10^{-16} Kaplan and van Kerkwijk arXiv: 0901.4133
- 0806. |vdot|<4.3 10^{-16} Kaplan and van Kerkwijk arXiv: 0909.5218
- 0420. vdot=-2.3+/-0.2 10^{-15} Kaplan and van Kerkwijk arXiv:1109.2105

Discovery of radio transients

McLaughlin et al. (2006) discovered a new type of sources – RRATs (Rotating Radio Transients).
For most of the sources periods
about few seconds were discovered.
The result was obtained during
the Parkes survey of the Galactic plane.

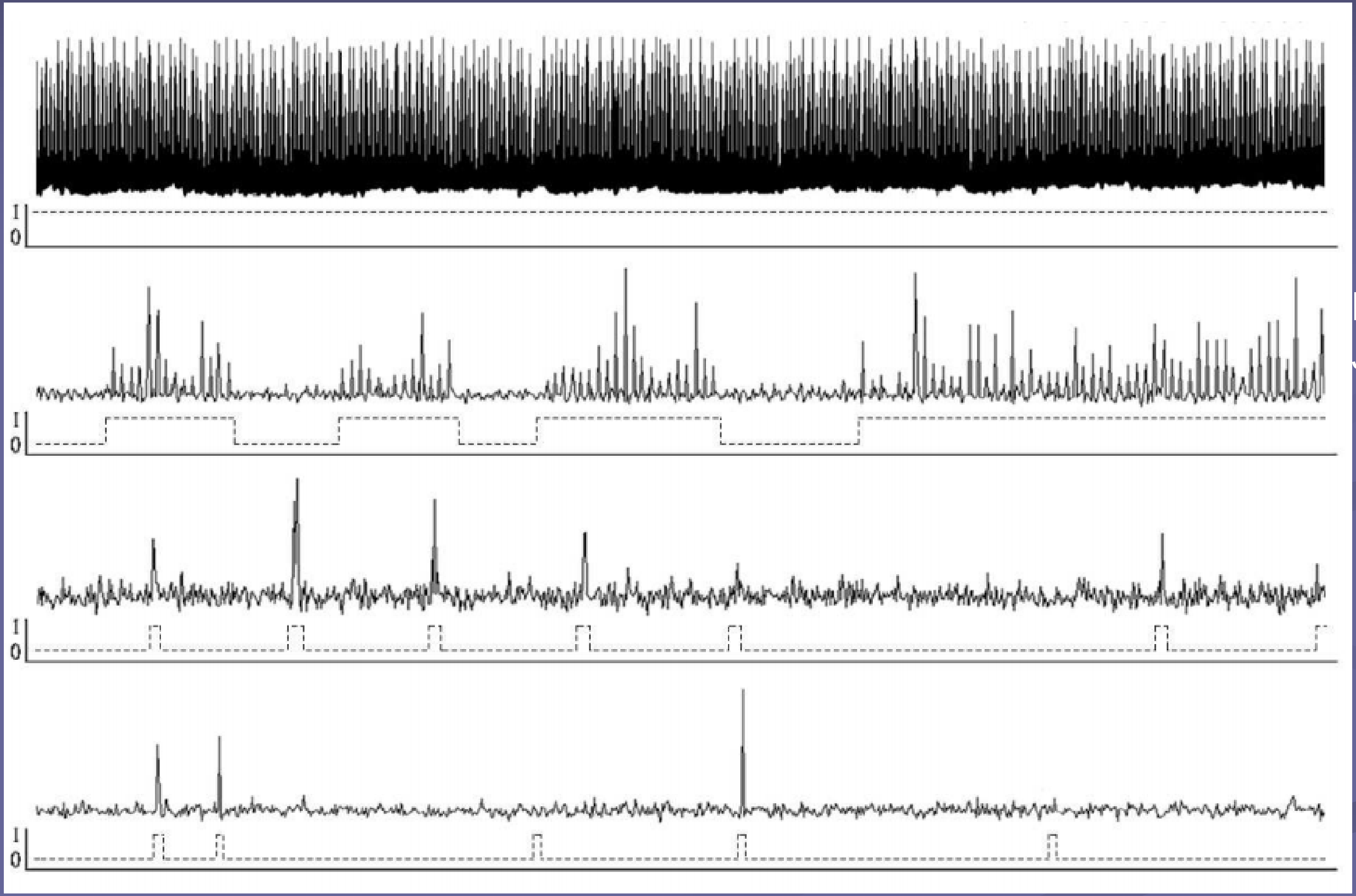
Burst duration 2-30 ms,
interval 4 min-3 hr
Periods in the range 0.4-7 s



Thermal X-rays were observed
from one of the RRATs
(Reynolds et al. 2006).
This one seems to be the youngest.

arXiv: 0710.2056

Most of RRATs are PSRs?



Vela

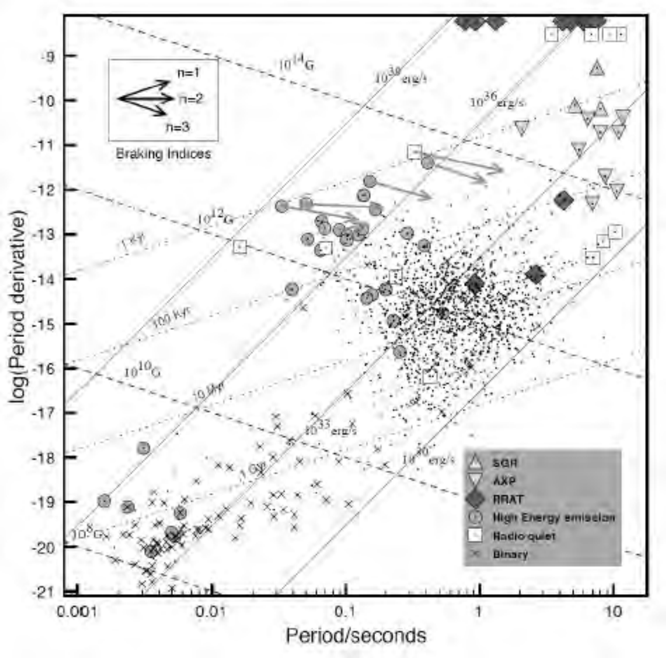
PSR J1646–6831

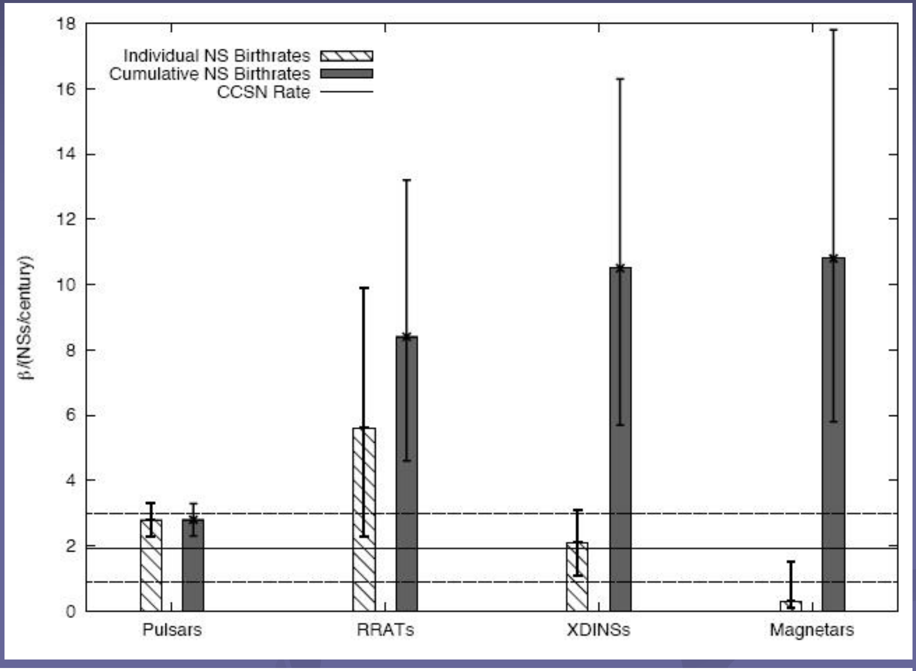
J1647–36

J1226–32

1212.1716

NS birth rate





β_{PSR}, n_{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

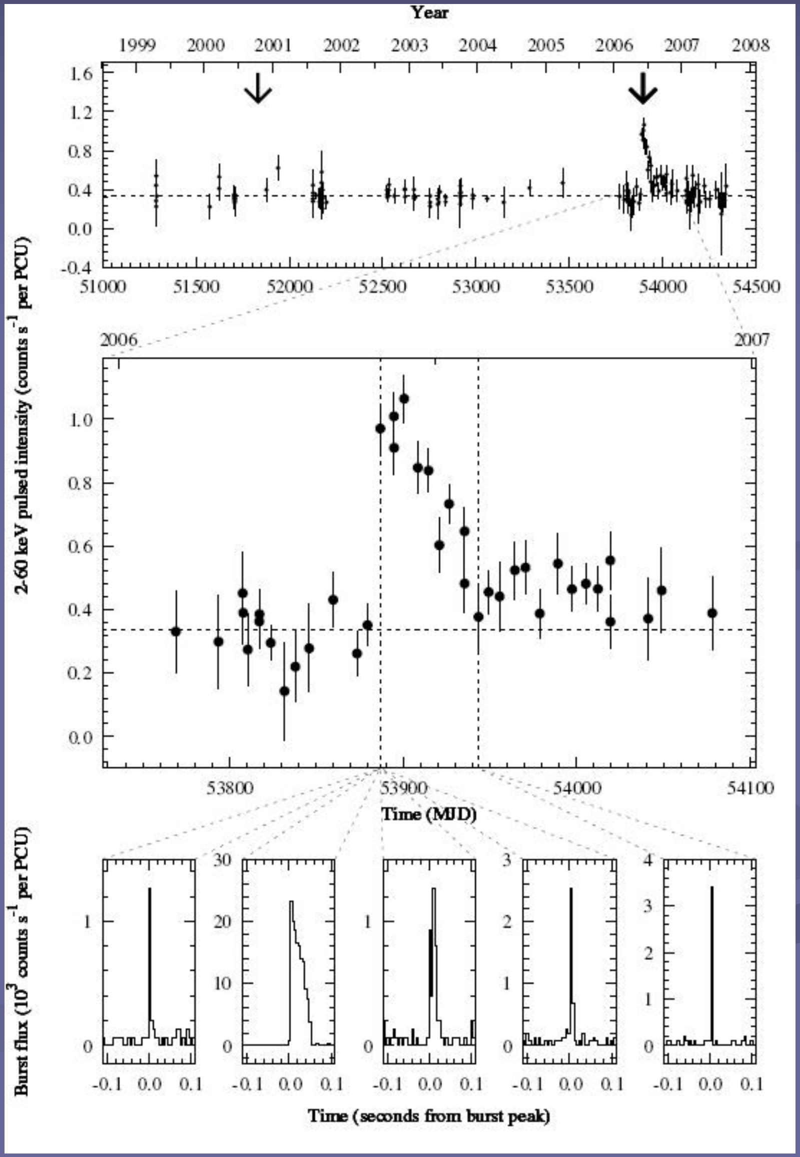
[Keane, Kramer 2008, arXiv: 0810.1512]

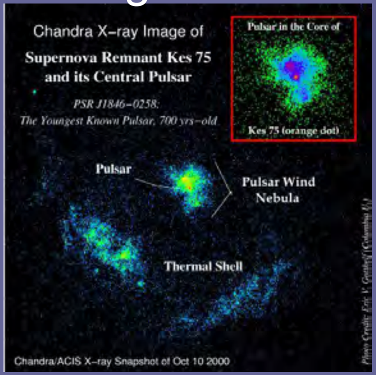
Transient radiopulsar

PSR J1846-0258
P=0.326 sec
B=5 10^{13} G

Among all rotation powered PSRs it has the largest Edot. Smallest spindown age (884 yrs).

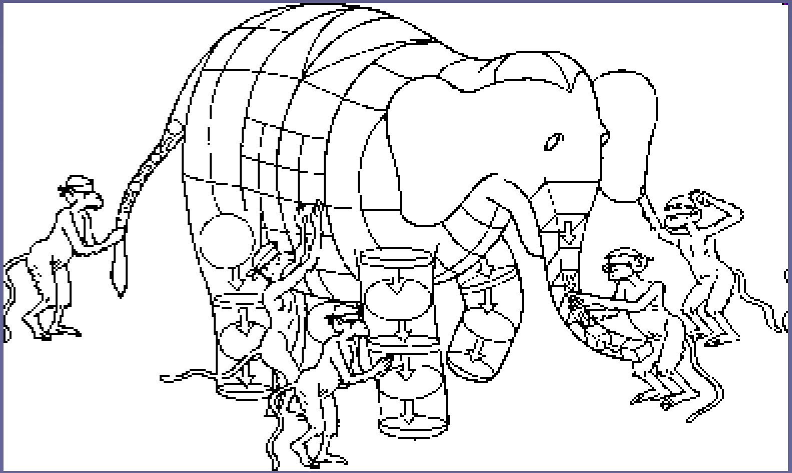
The pulsar increased
its luminosity in X-rays.
Increase of pulsed X-ray flux.
Magnetar-like X-ray bursts (RXTE).
Timing noise.



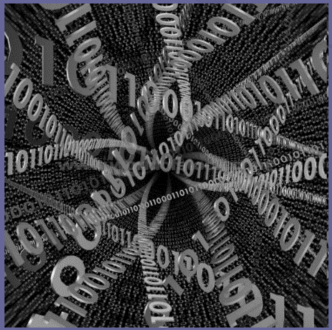


0802.1242, 0802.1704

Population synthesis



Ingredients:
- initial conditions
- evolutionary laws



«Artificial universe»

Modeling of observations

«Artifitial
observed universe»

Population synthesis of cooling NSs: ingredients

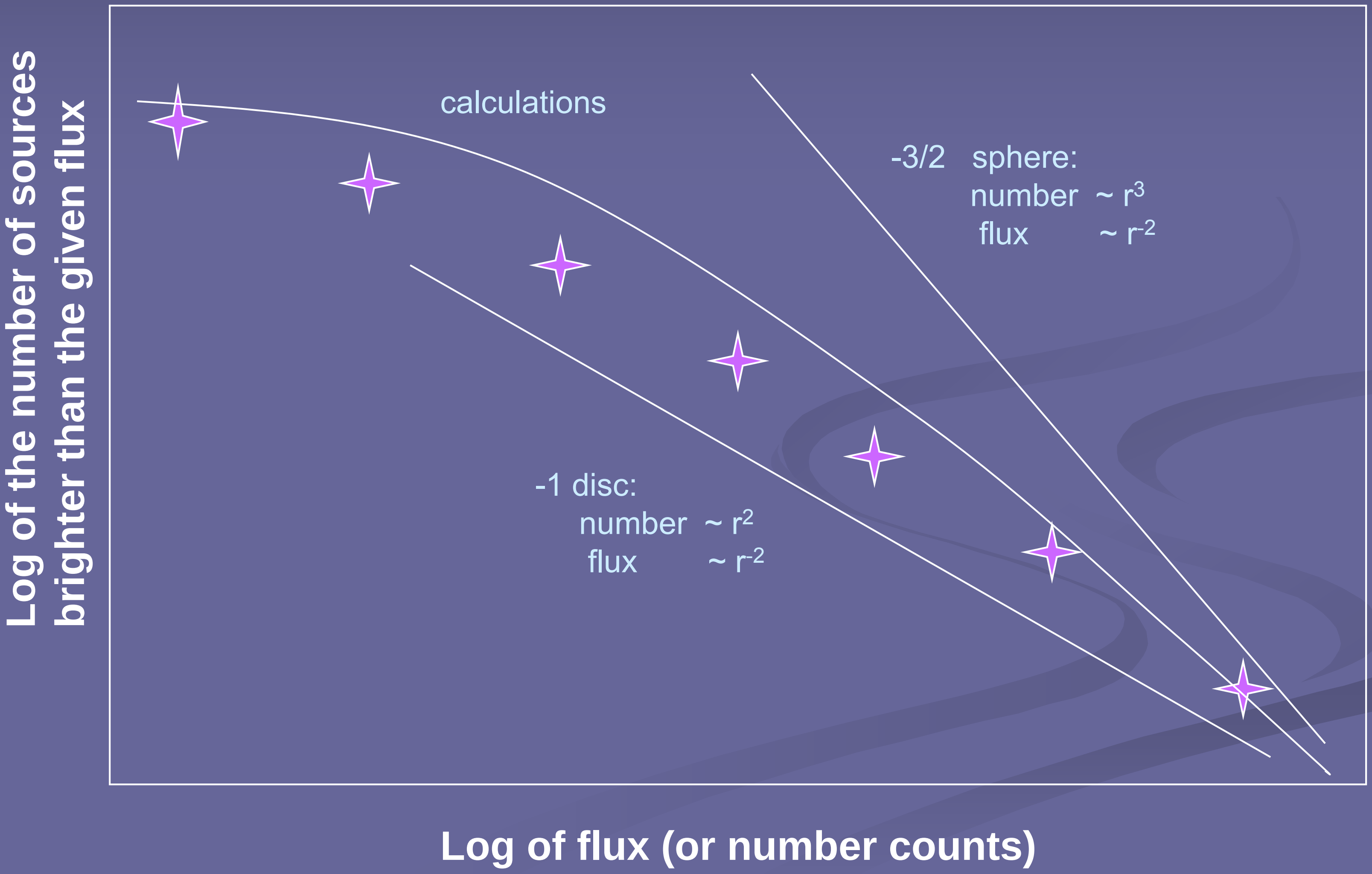
- Birth rate of NSs
- Initial spatial distribution
- Spatial velocity (kick)
- Mass spectrum
- Thermal evolution
- Interstellar absorption
- Detector properties
- …….

Task:

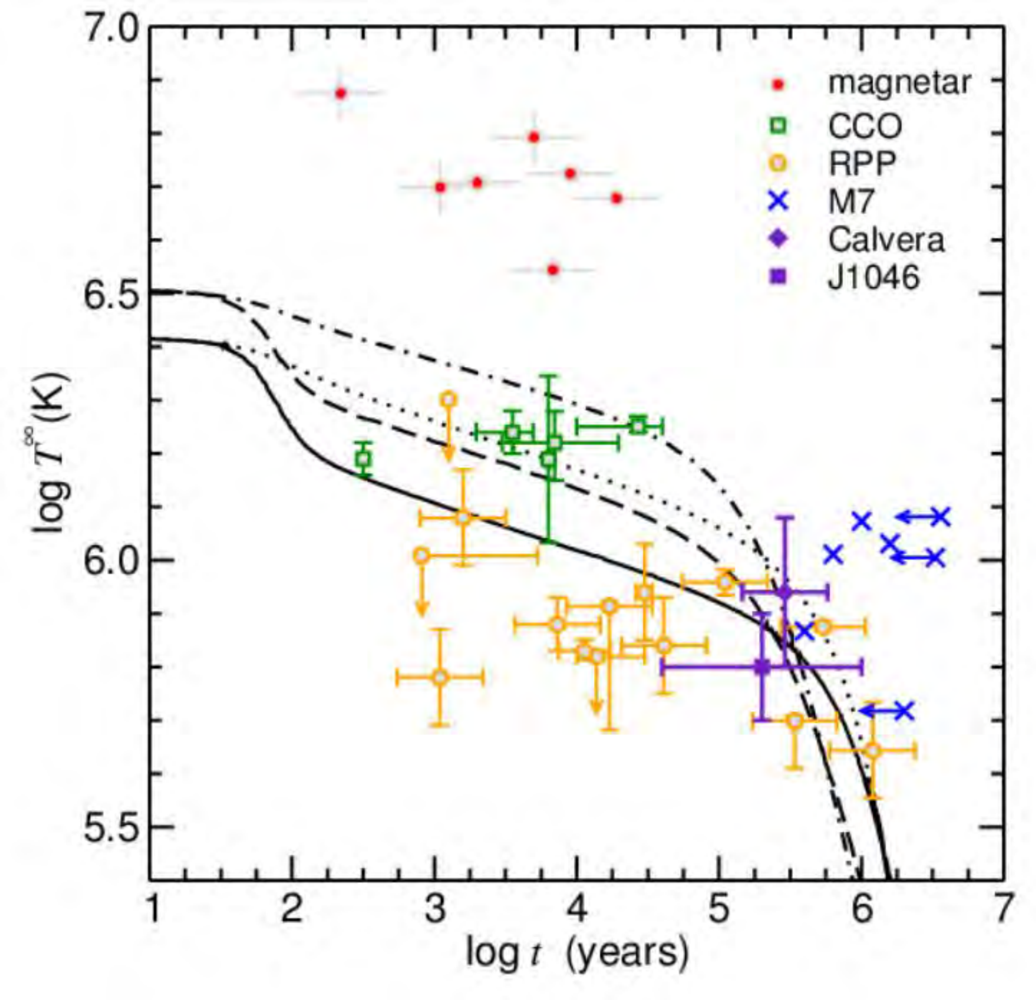
To build an artificial model of a population of some astrophysical sources and to compare the results of calculations with observations.

A brief review on population synthesis in astrophysics can be found in astro-ph/0411792 and in Physics-Uspekhi (2007).

Log N – Log S


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

Thermal evolution



$$\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma$$

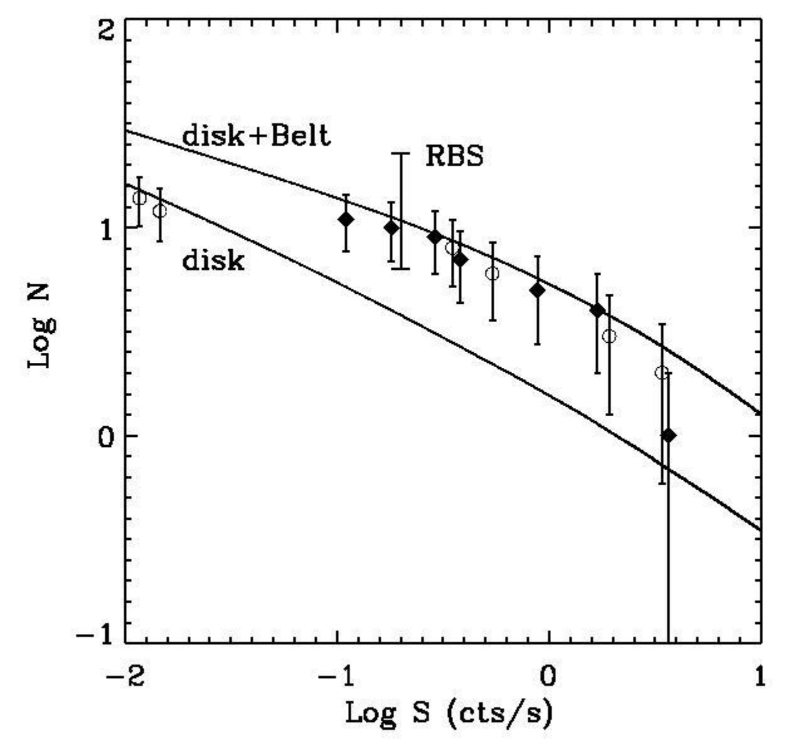
Neutrino luminosity

Photon luminosity

For magnetars additional heating is necessary.

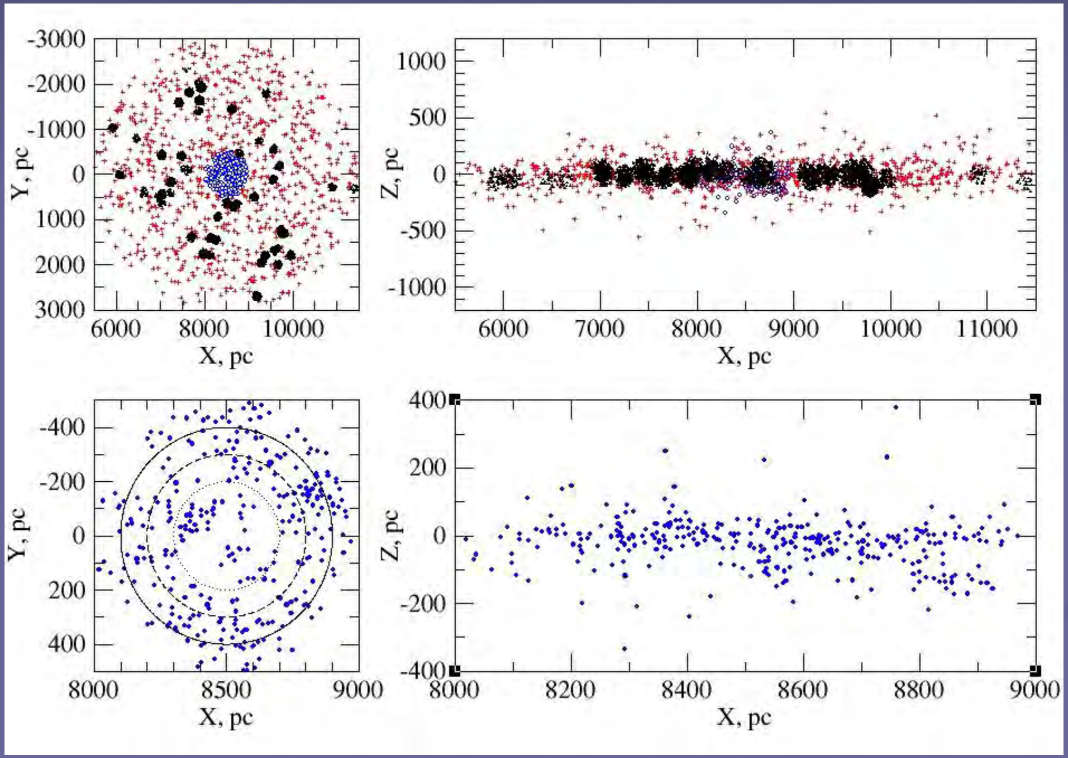
Results – 2003: Log N – Log S

- Task: to understand the Gould Belt contribution
- Calculate separately disc (without the Belt) and both together
- Cooling curves from Kaminker et al. (2001)
- Flat mass spectrum
- Single maxwellian kick
- R_{belt}=500 pc



astro-ph/0304141

Spatial distribution



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.

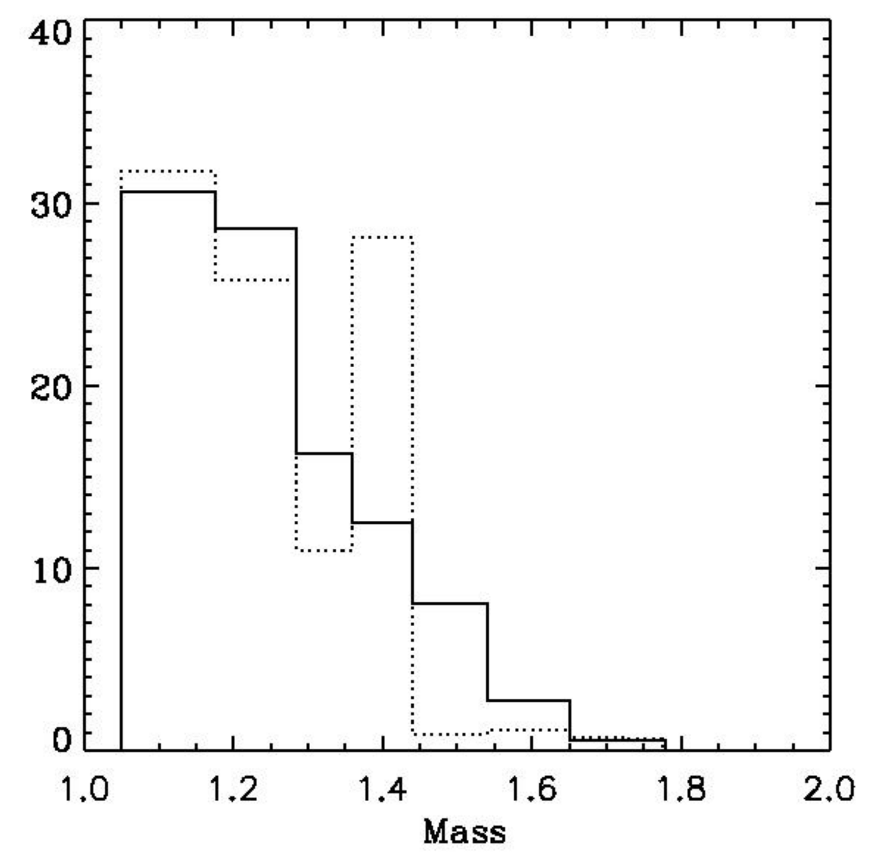
Mass distribution

- 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);

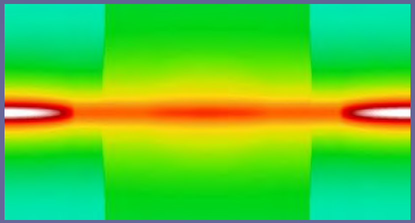
  Woosley et al. (2002)

Low mass progenitors for the dotted mass spectrum are treated following astro-ph/0409422.



Spatial distribution of ISM

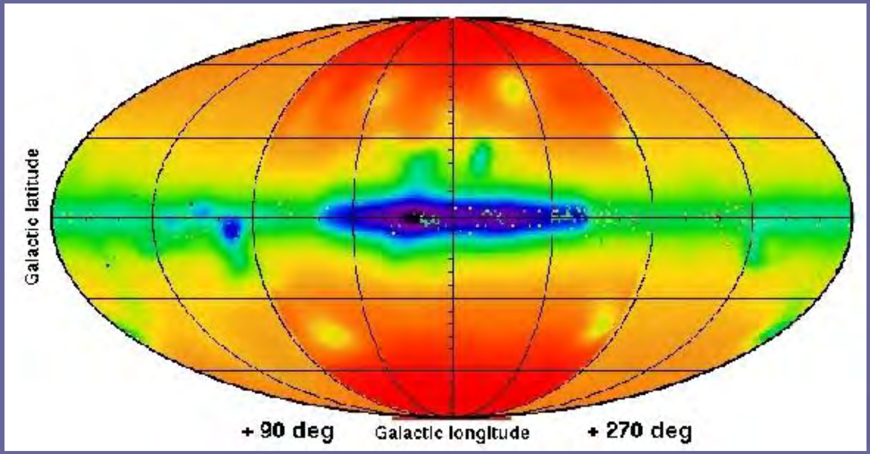
instead of :



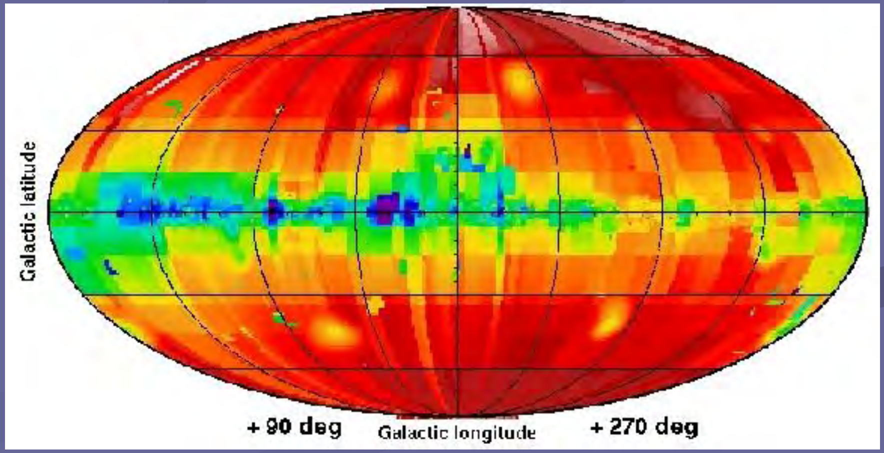
N_H inside 1 kpc

(see astro-ph/0609275 for details)

now :

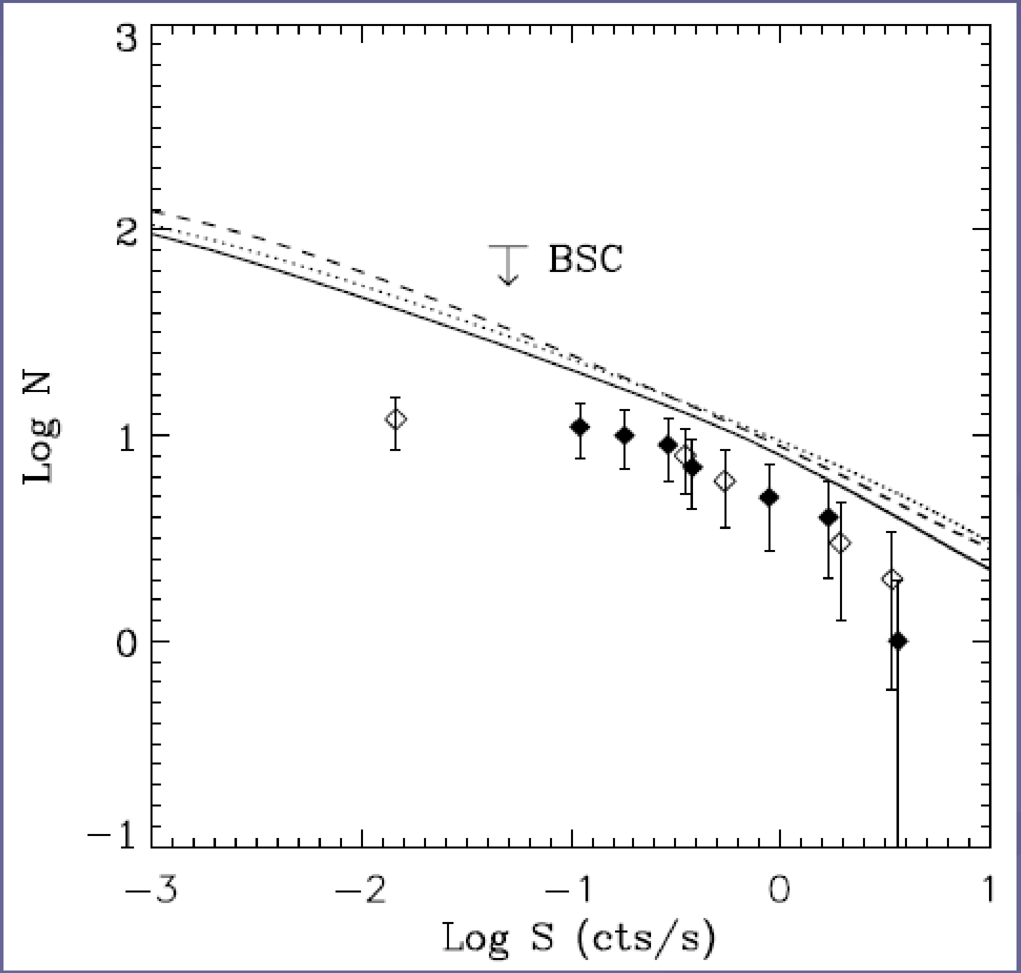


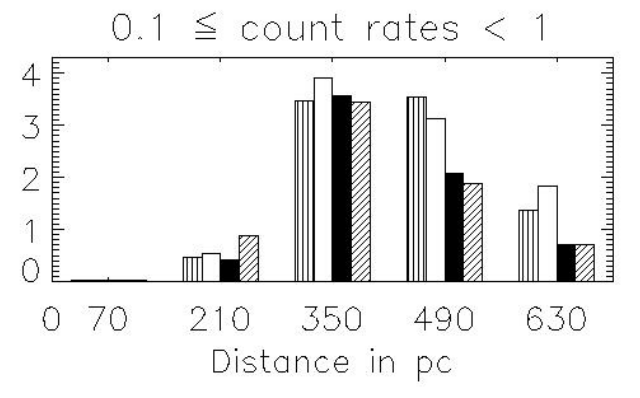
Modification of the old one



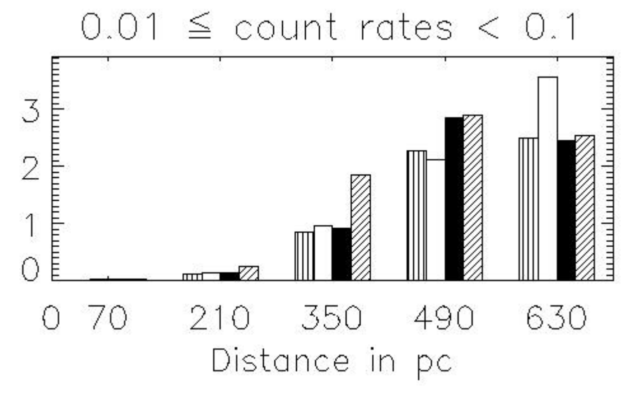
Hakkila

Results for the new model



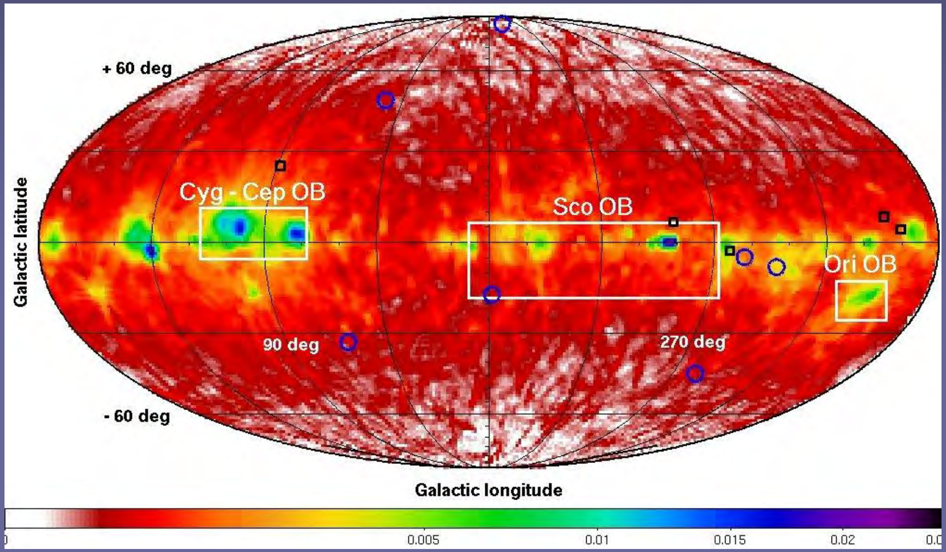


Known – from the Gould Belt
Weaker – behind the Belt



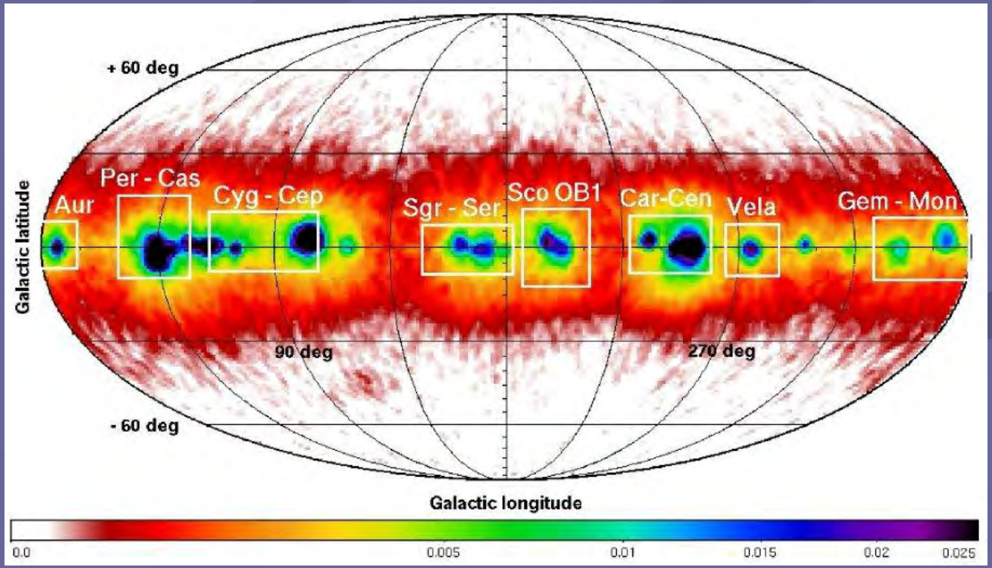
A&A 2008, 2010

Sky distributions



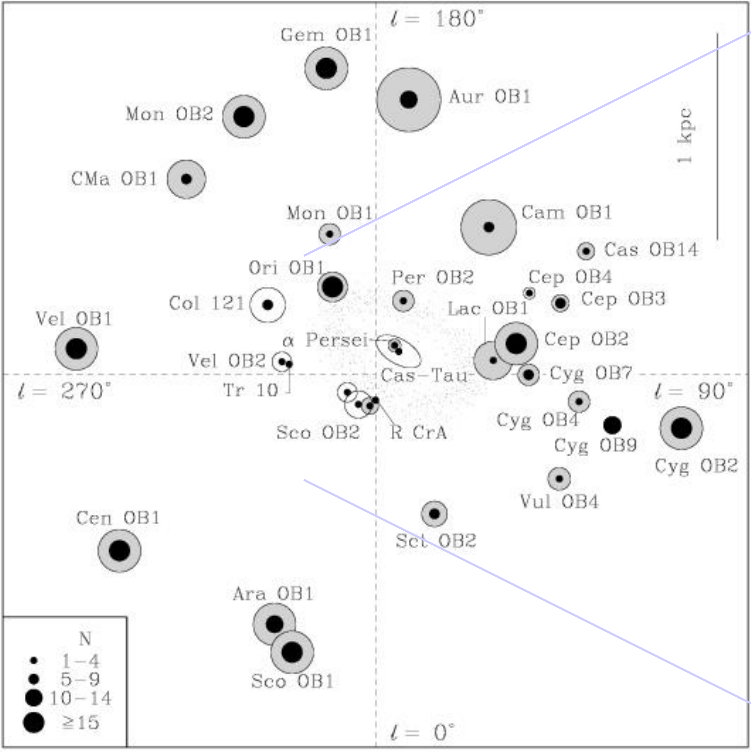
Weak sources

Bright sources

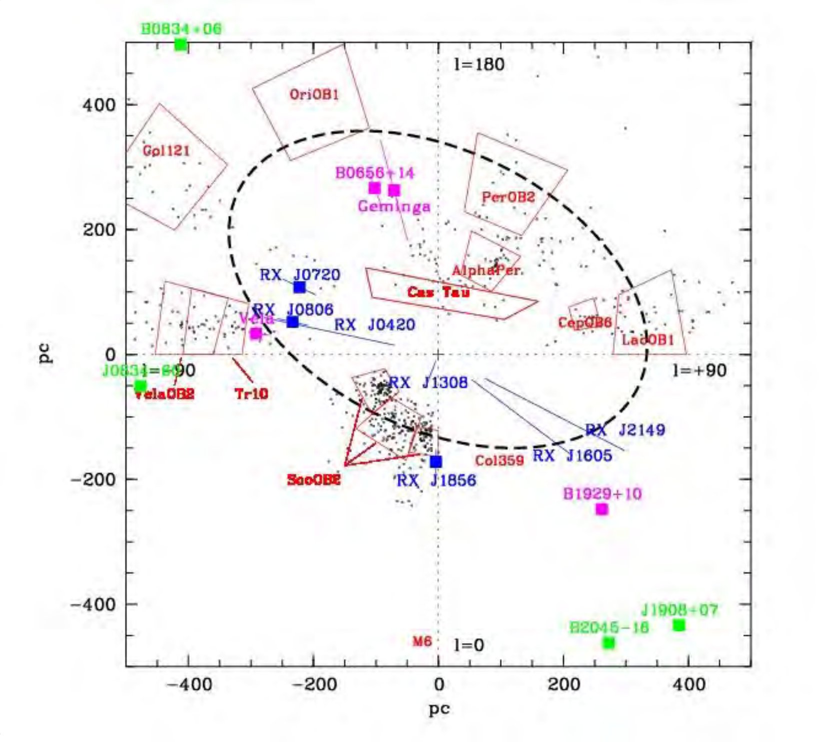


INSs and local surrounding

Massive star population in the Solar vicinity (up to 2 kpc) is dominated by OB associations.
Inside 300-400 pc the Gould Belt is mostly important.

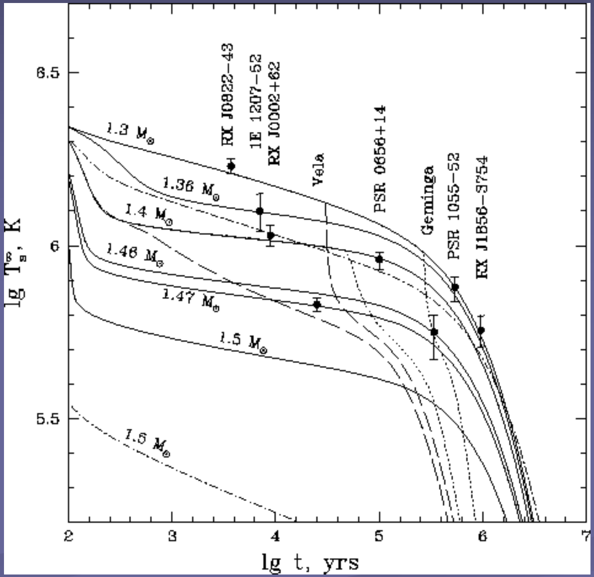


De Zeeuw et al. 1999

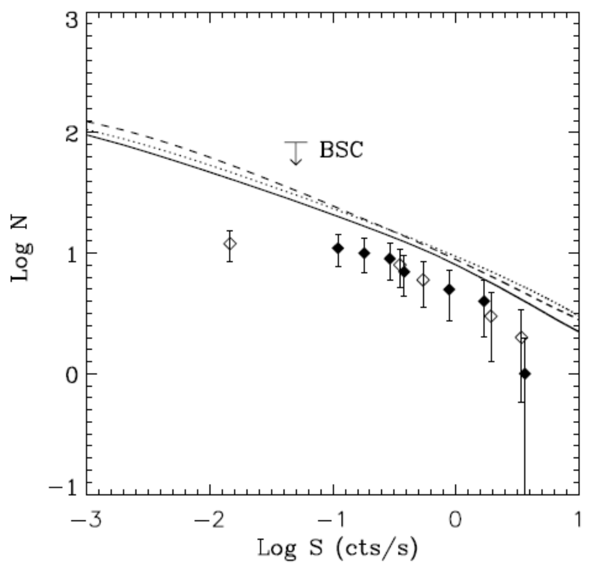


Motch et al. 2006

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

List of models (Blaschke et al. 2004)

Blaschke et al. used 16 sets of cooling curves.

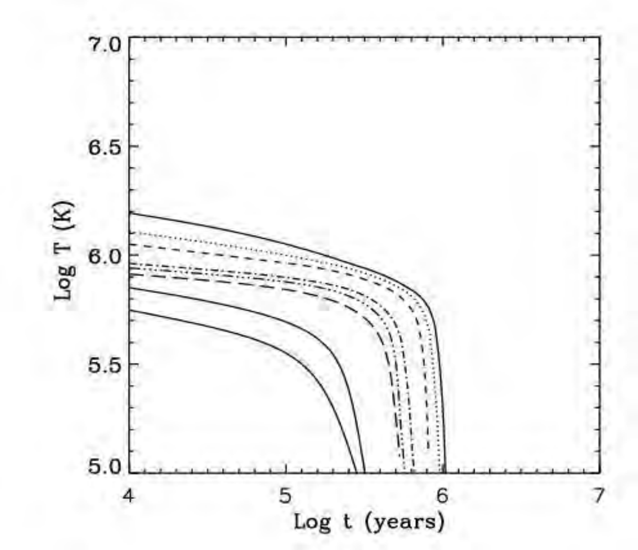
They were different in three main respects:

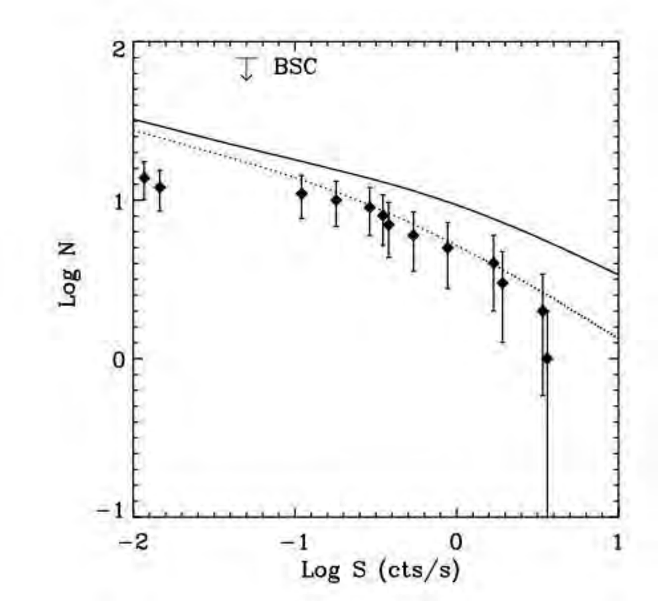
1. Absence or presence of pion condensate
2. Different gaps for superfluid protons and neutrons
3. Different T_s-T_{in}

	Pions	Crust	Gaps
Model I.	Yes	C	A
Model II.	No	D	B
Model III.	Yes	C	B
Model IV.	No	C	B
Model V.	Yes	D	B
Model VI.	No	E	B
Model VII.	Yes	C	B’
Model VIII.	Yes	C	B”
Model IX.	No	C	A

Model I

- Pions.
- Gaps from Takatsuka & Tamagaki (2004)
- T_s-T_{in} from Blaschke, Grigorian, Voskresenky (2004)

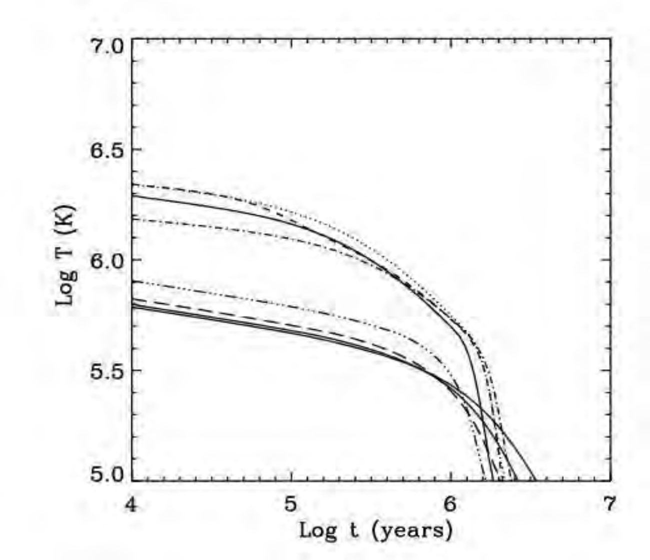


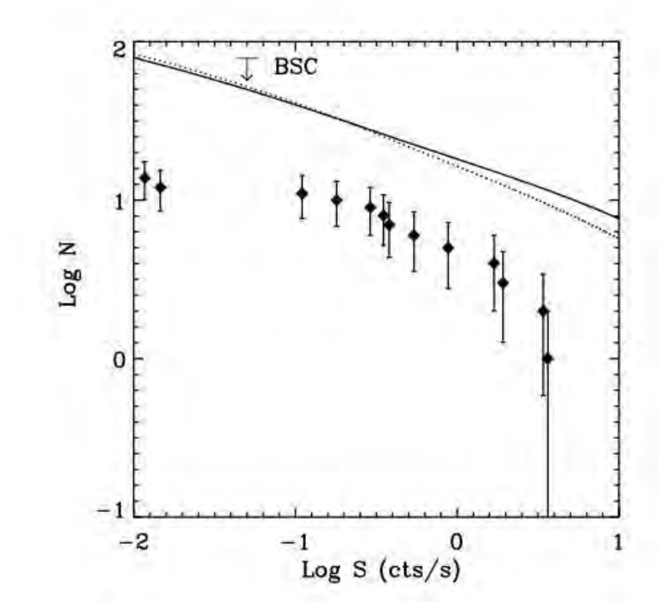


Can reproduce observed Log N – Log S

Model II

- No Pions
- Gaps from Yakovlev et al. (2004), $^3P_2$ neutron gap suppressed by 0.1
- T_s-T_{in} from Tsuruta (1979)





Cannot reproduce observed Log N – Log S

Sensitivity of Log N – Log S

- Log N – Log S is very sensitive to gaps
- Log N – Log S is not sensitive to the crust if it is applied to relatively old objects (>10^{4-5} yrs)
- Log N – Log S is not very sensitive to presence or absence of pions

Model I (YCA) Model II (NDB) Model III (YCB)
Model IV (NCB) Model V (YDB) Model VI (NEB)
Model VII(YCB') Model VIII (YCB'') Model IX (NCA)

We conclude that the two test complement each other

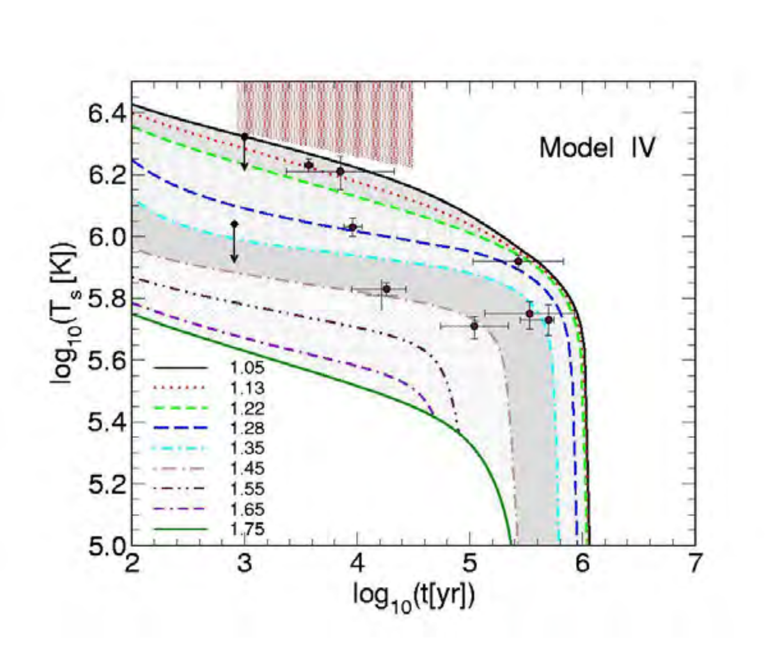
Popov et al. (2006) A&A astro-ph/0411618

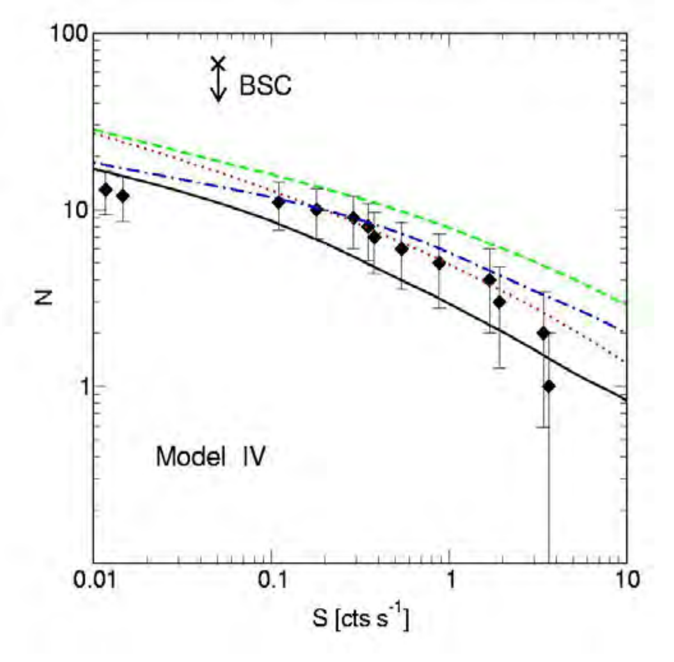
Hybrid stars

We use models of HySs introduced by Grigorian et al. (2005)

Model	Δ_0 [MeV]	α	BC	T – t	Log N – Log S	$M_{typ} \leq 1.5\ M_\odot$	All tests
I	1	10	+	+	○	-	-
II	0.1	0	+	-	+	-	-
III	0.1	2	+	○	+	-	-
IV	5	25	+	+	+	+	+

One model among four was able to pass all tests.

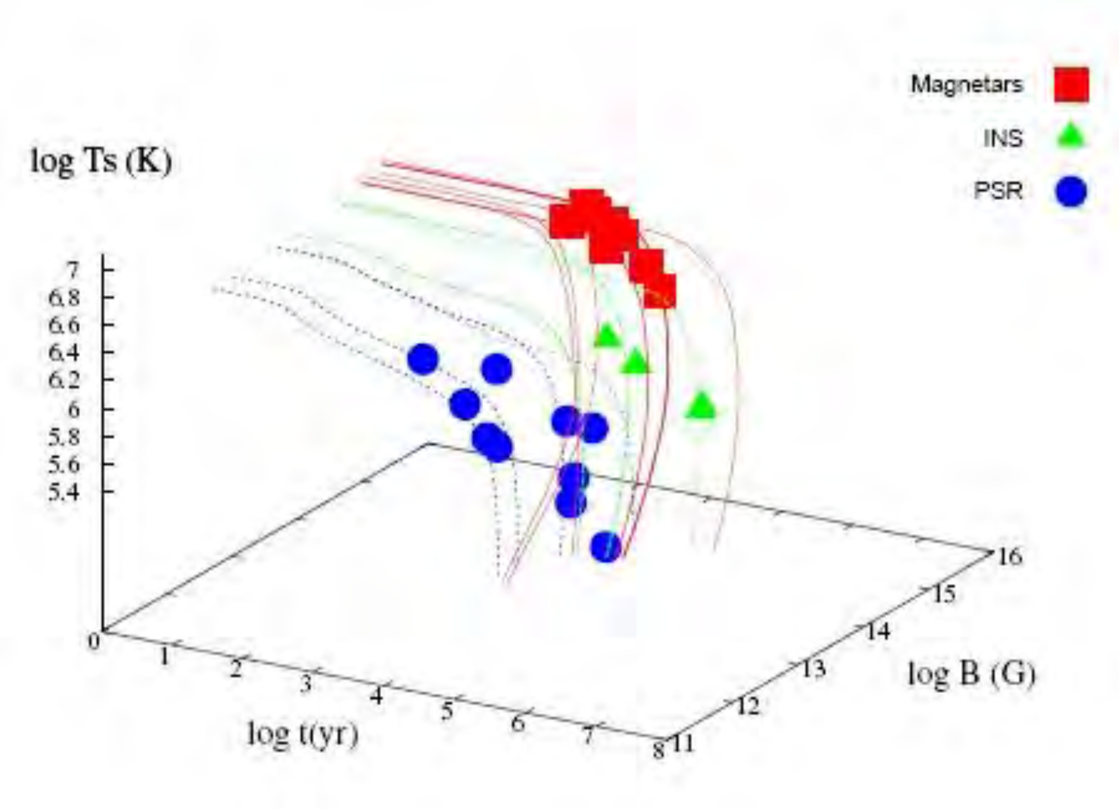




nucl-th/0512098

Magnetic field decay

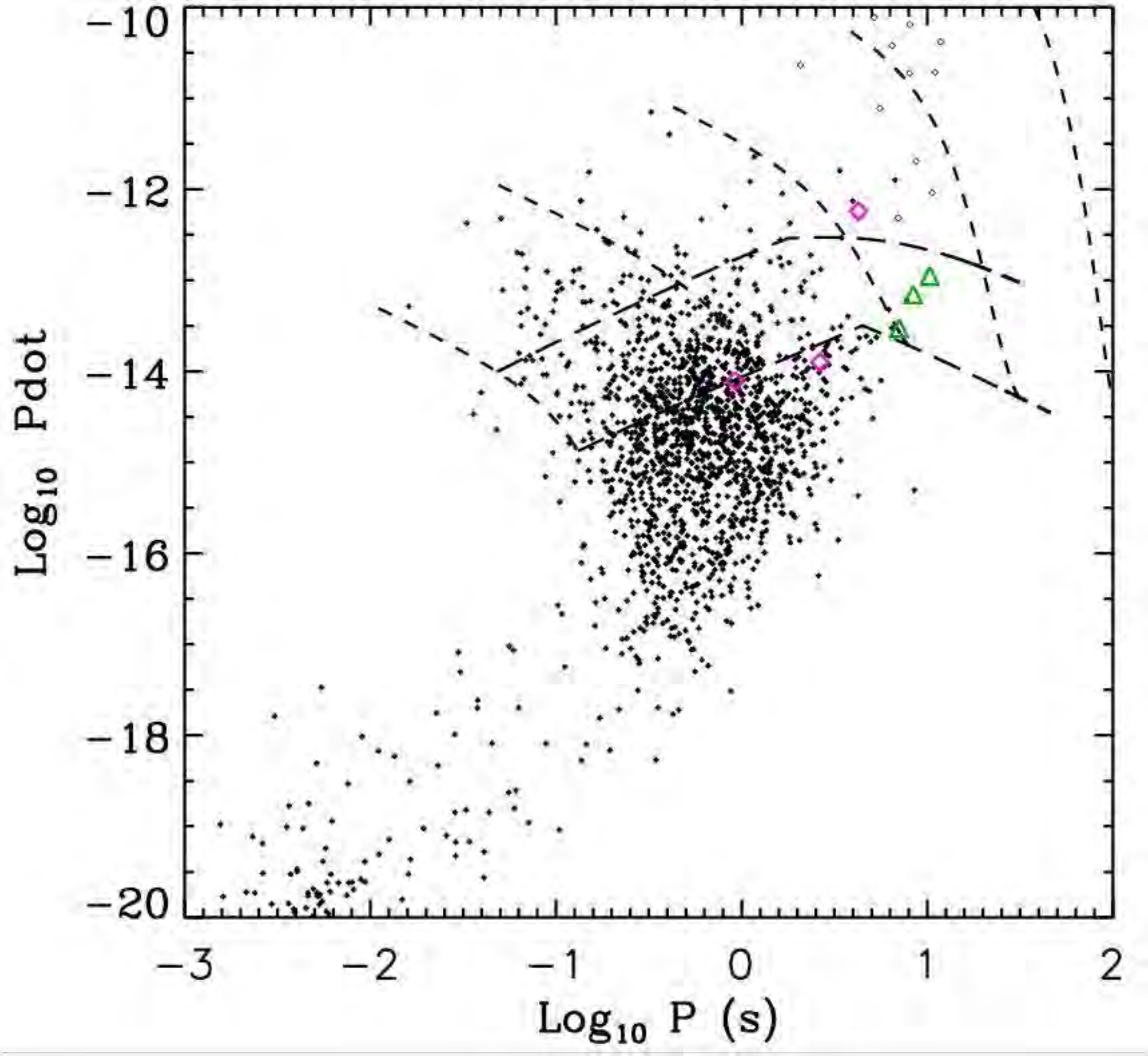
A model based on the initial field-dependent decay
can provide an evolutionary link between different populations (Pons et al.).



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

arXiv: 0710.4914 (Aguilera et al.)

P-Pdot diagram and field decay



Let us try to see how PSRs with decaying magnetic fields evolve in the P-Pdot plot.

At first we can use a simple analytical approximation to the evolutionary law for the magnetic field.

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

$\tau_{\mathrm{Ohm}} = 10^6$ yrs
$\tau_{\mathrm{Hall}} = 10^4/(B_0/10^{15}\ \mathrm{G})$ yrs

Extensive population synthesis

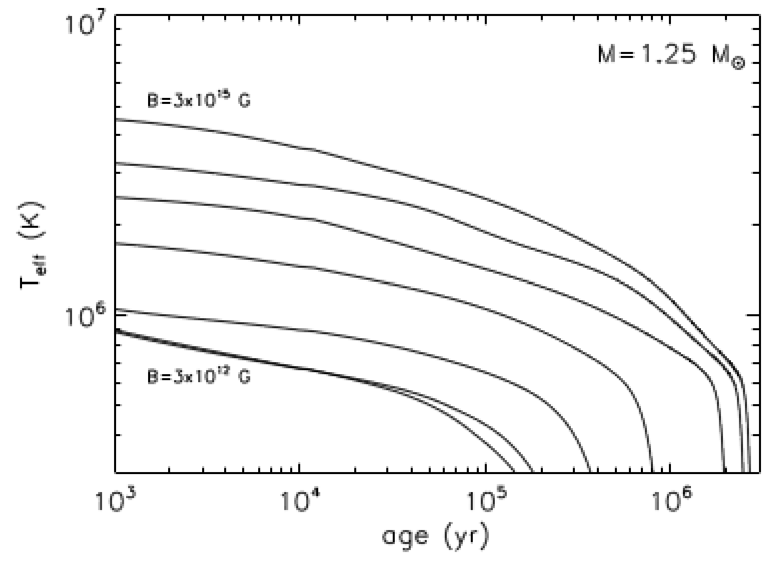
We want to make extensive population synthesis studies using as many approaches as we can to confront theoretical models with different observational data

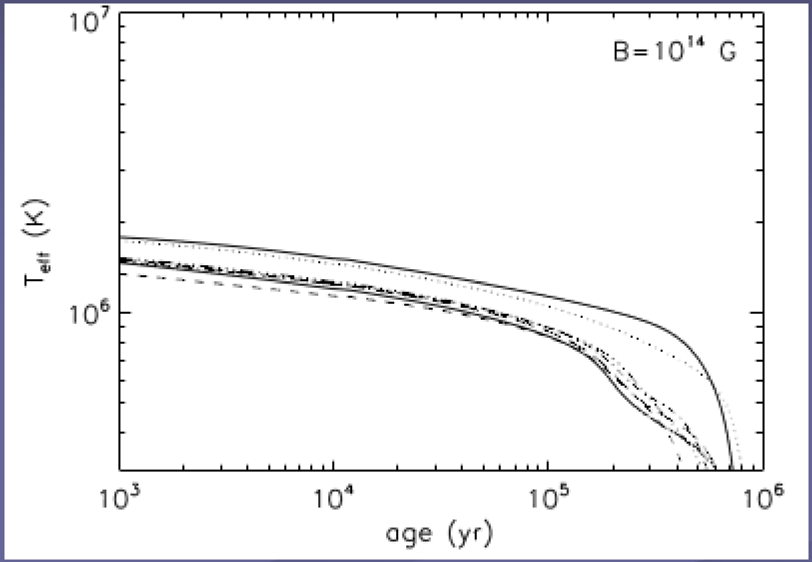
- Log N – Log S for close-by young cooling isolated neutron stars
- Log N – Log L distribution for galactic magnetars
- P-Pdot distribution etc. for normal radio pulsars

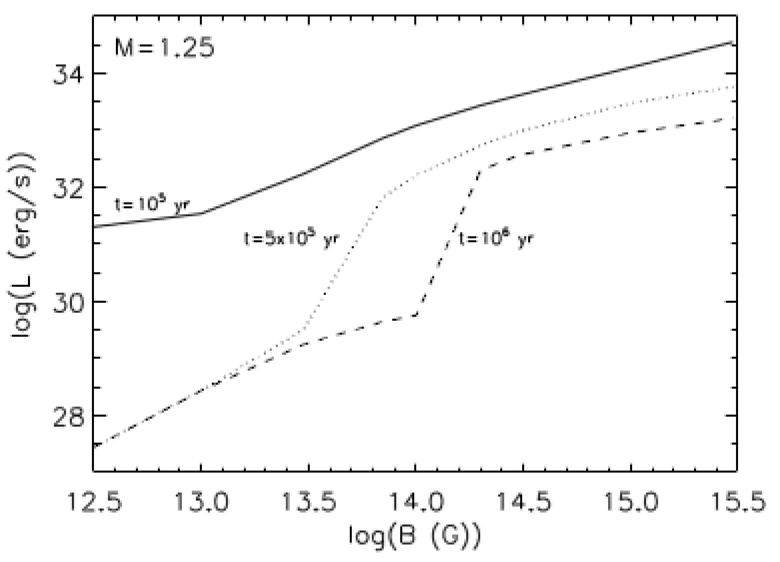
MNRAS 401, 2675 (2010)
arXiv: 0910.2190

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

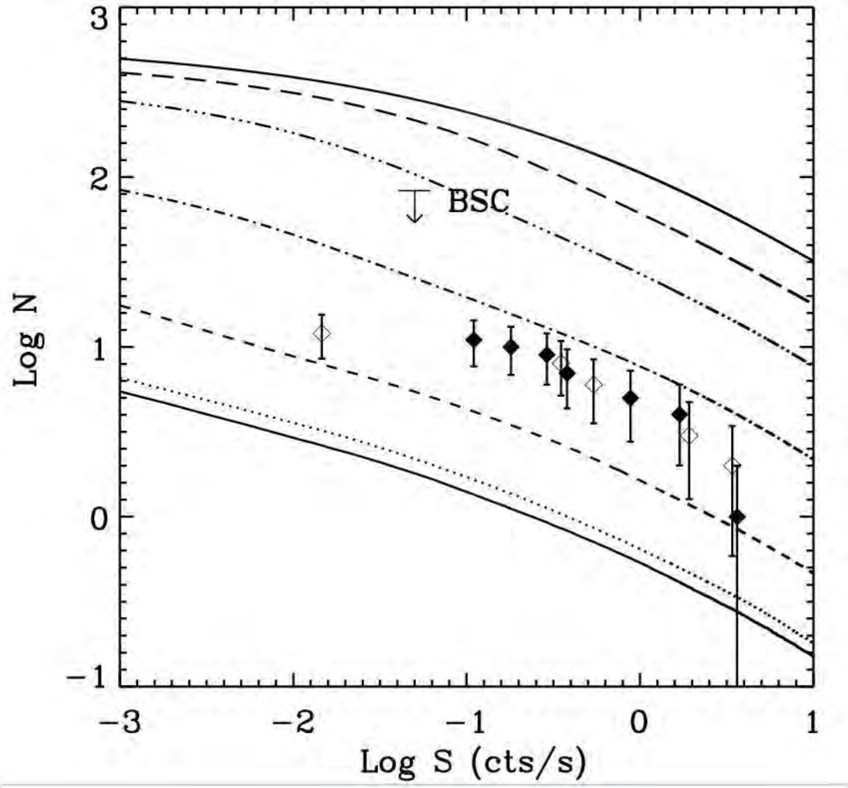






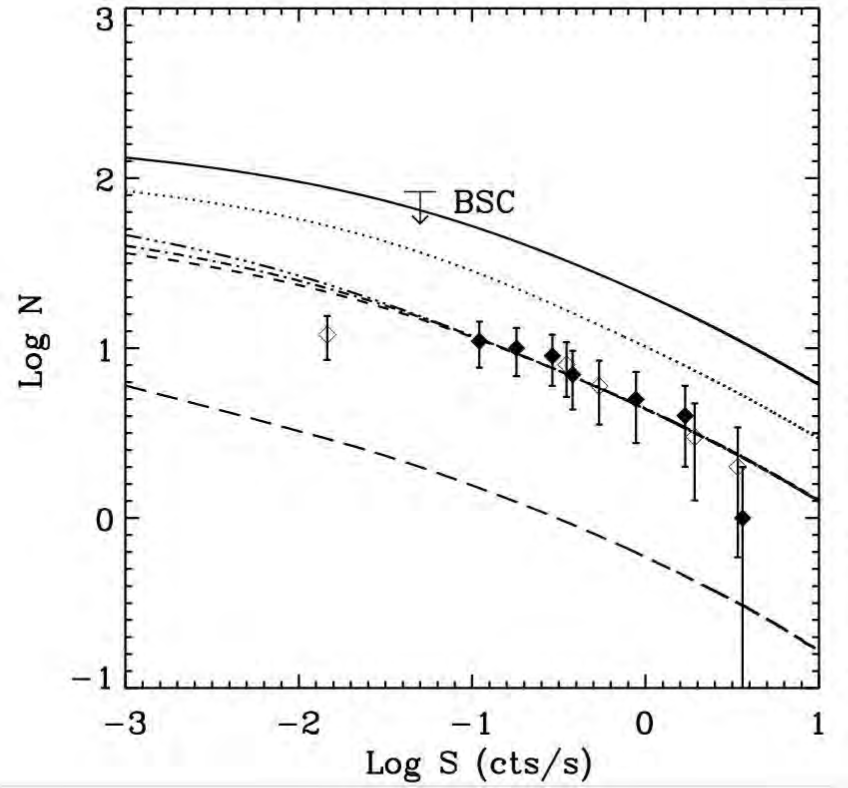
Magnetic field distribution is more important than the mass distribution.

Log N – Log S with heating



Log N – Log S for 7 different magnetic fields.

1. $3\ 10^{12}$ 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]

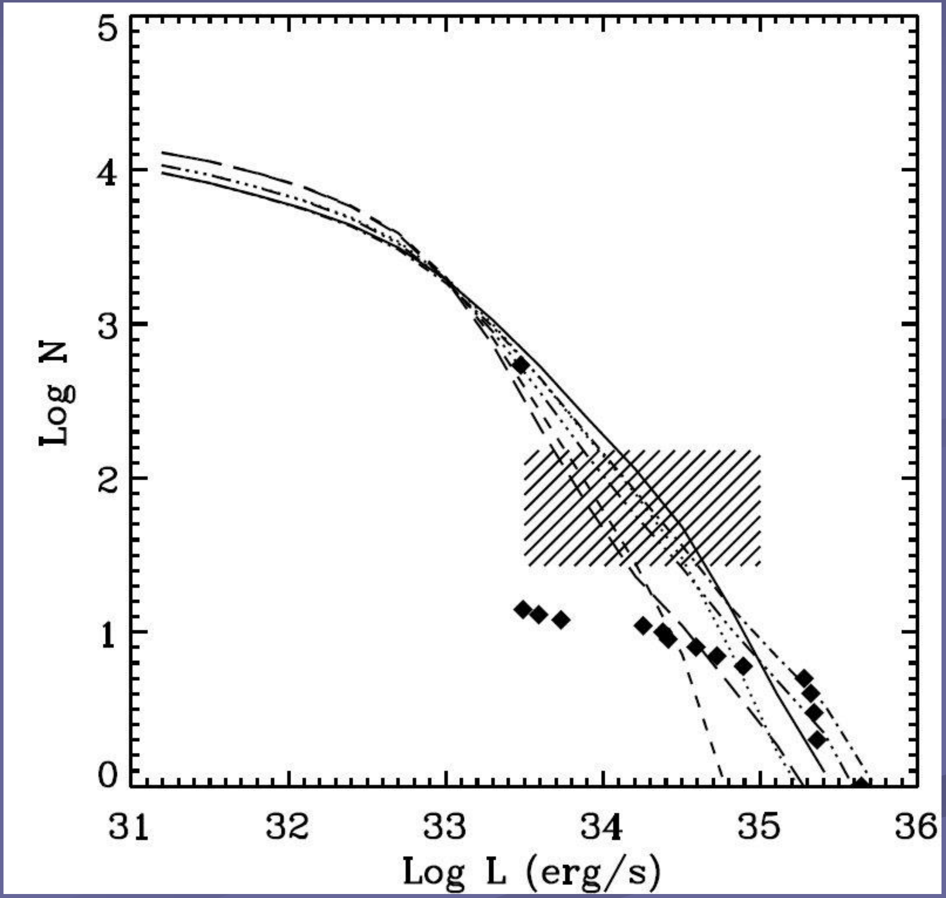
Log N – Log L for magnetars

We used the same initial magnetic field distributions.

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

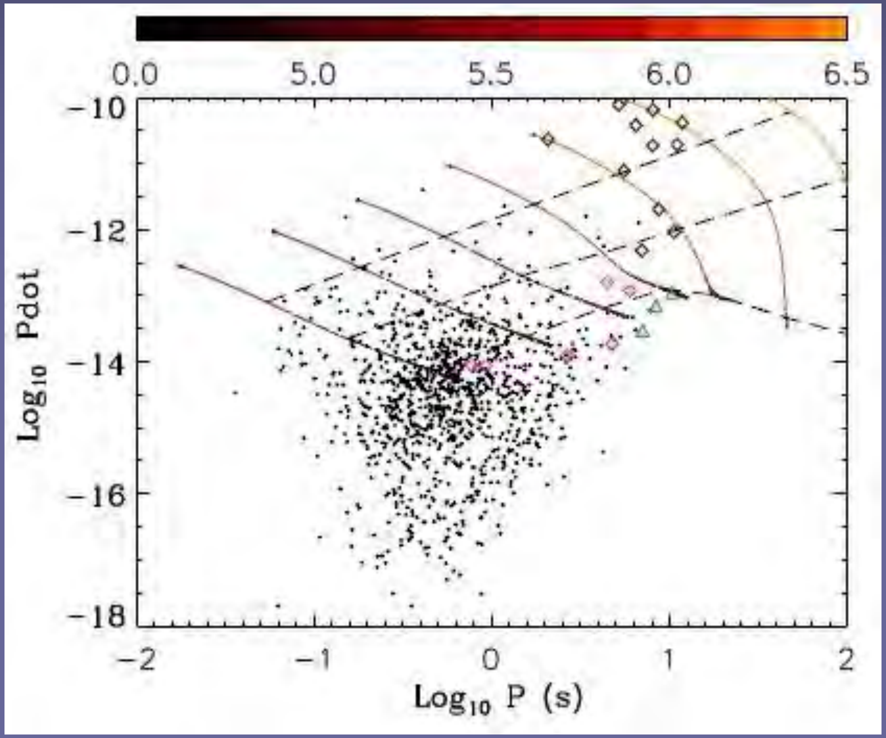
It is assumed that the total luminosity can be well approximated by the energy release due to field decay.

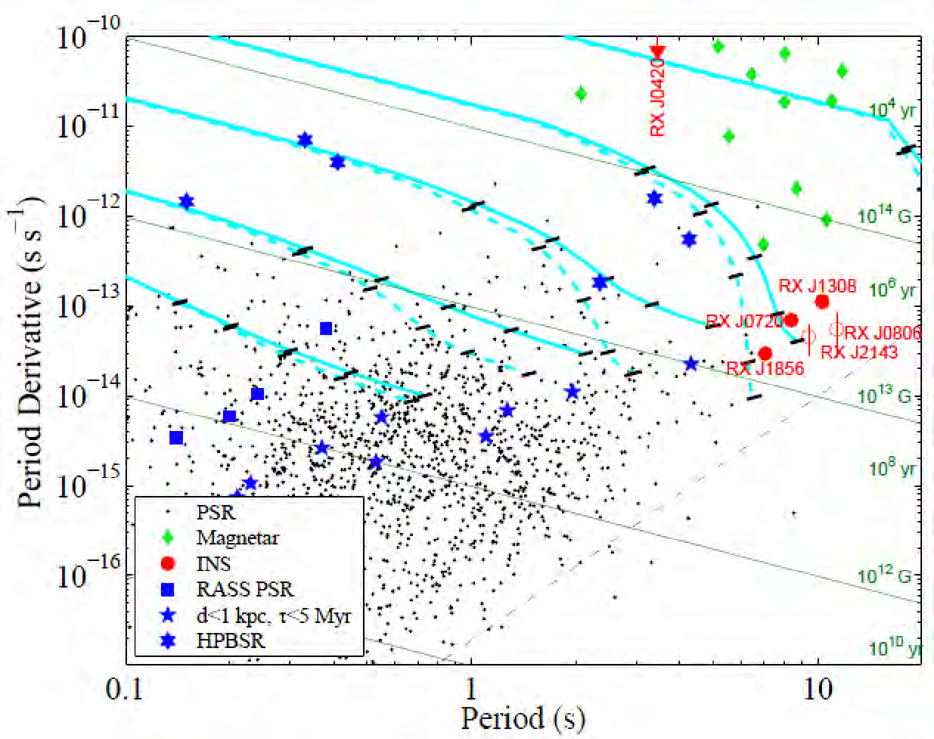
It is seen that the same log-normal distributions can reasonably well describe the data for magnetars.



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

P-Pdot tracks



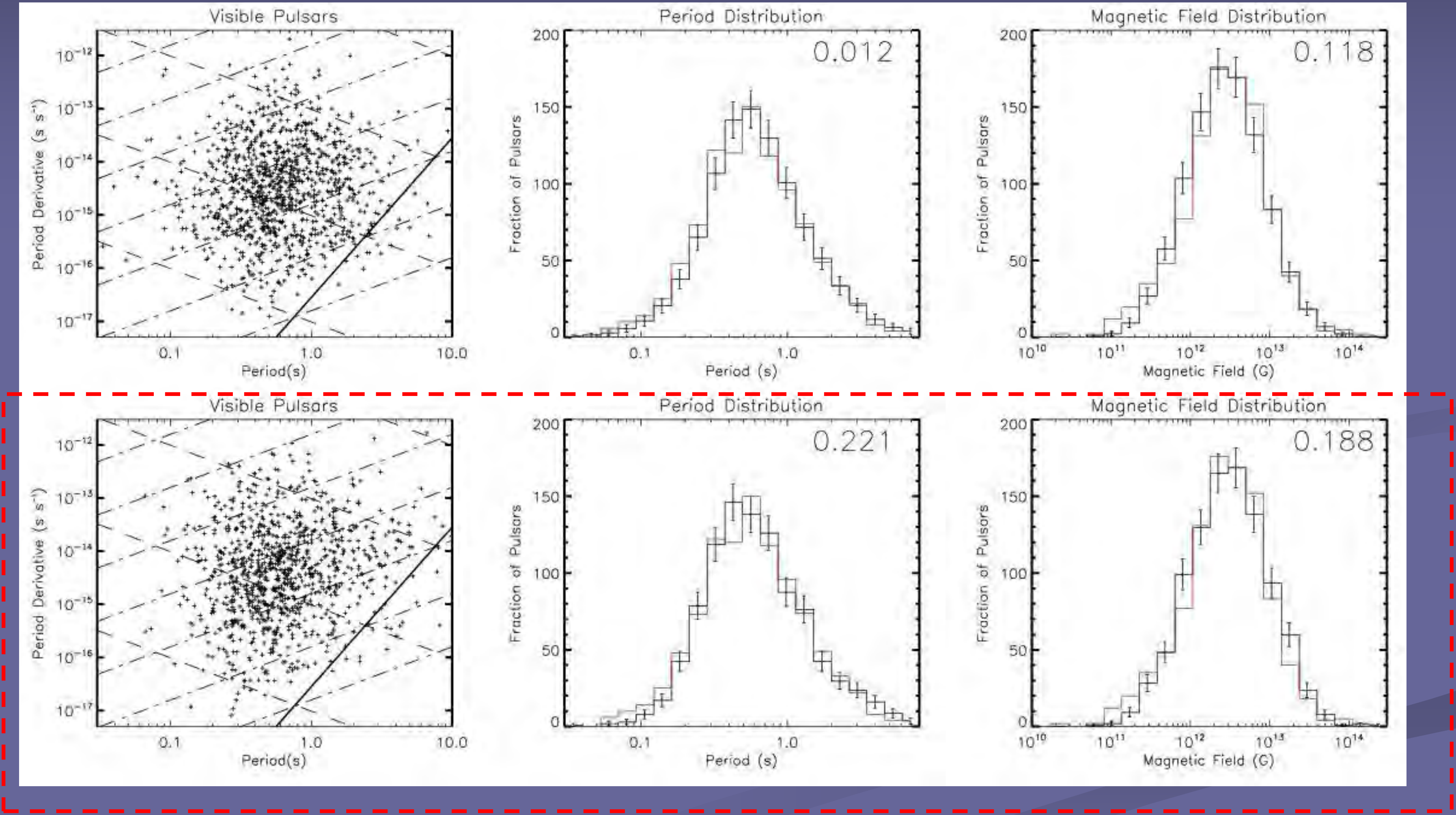


Kaplan & van Kerkwijk arXiv: 0909.5218

Color on the track encodes surface temperature.

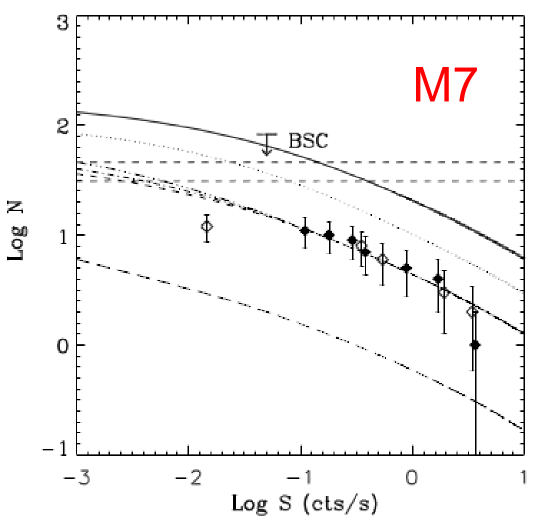
Tracks start at 10^3 years, and end at ~3 10^6 years.

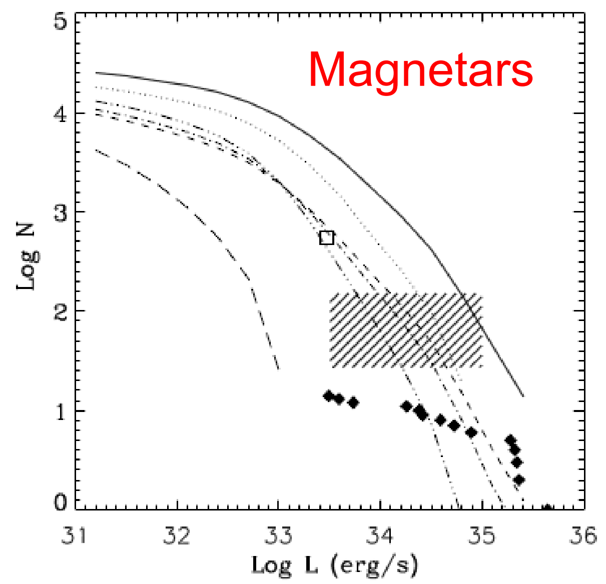
Population synthesis of PSRs

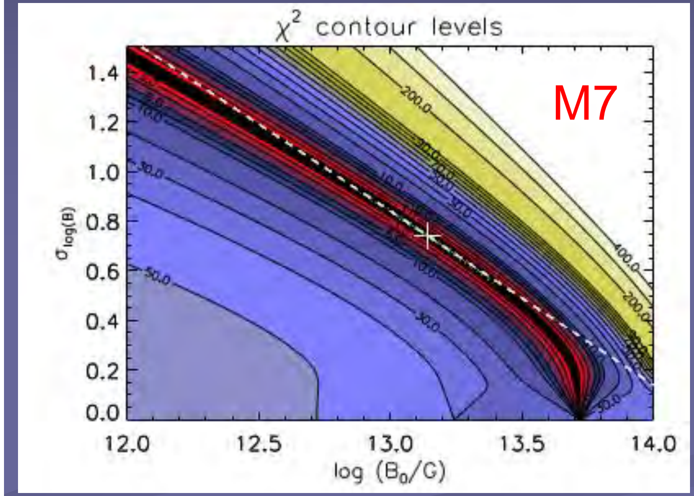


Best model: $<\log(B_0/[G])> = 13.25$, $\sigma_{\log B0}=0.6$, $<P_0> = 0.25$ s, $\sigma_{P0} = 0.1$ s
(recently, Gullon et al. 2014 obtained similar results with an updated model)

Extensive population synthesis: M7, magnetars, PSRs

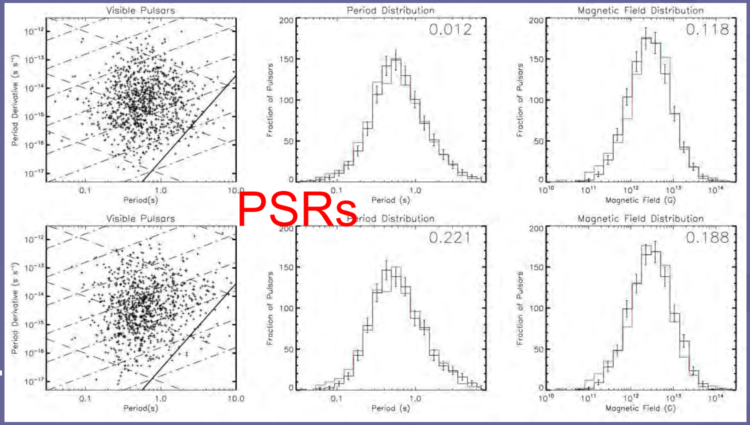


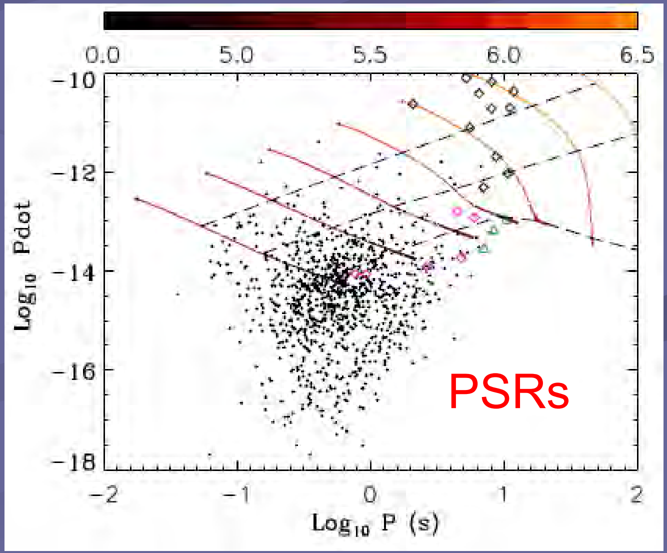




Using one population it is difficult or impossible to find unique initial distribution for the magnetic field

All three populations are compatible with a unique distribution. Of course, the result is model dependent.

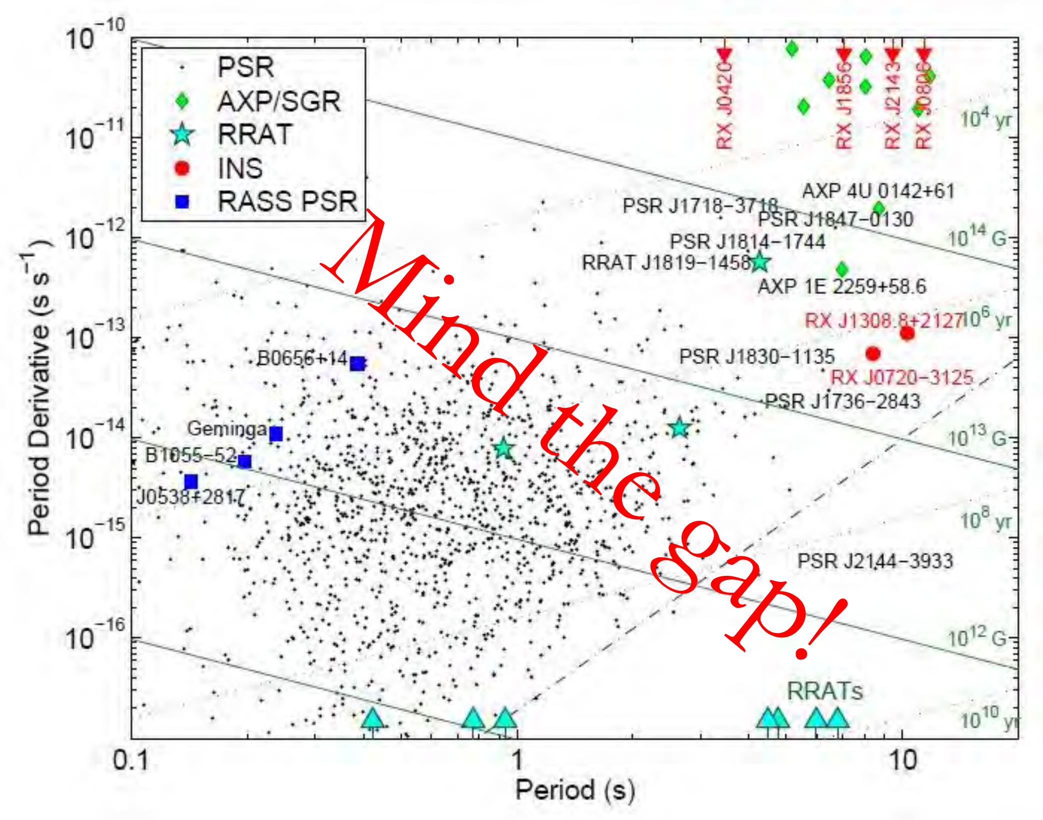


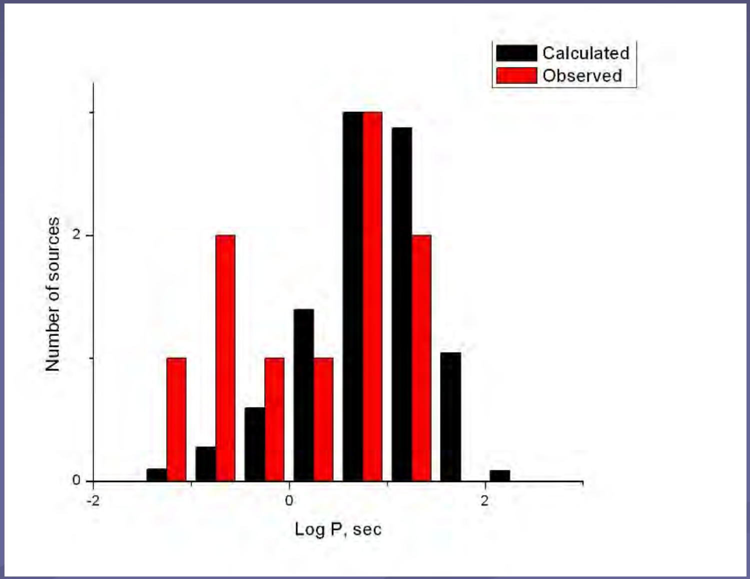


The “one second” problem

Two types of sources are observed:

- Radiopulsars (P<1 sec)
- Magnificent Seven (P>1 sec)





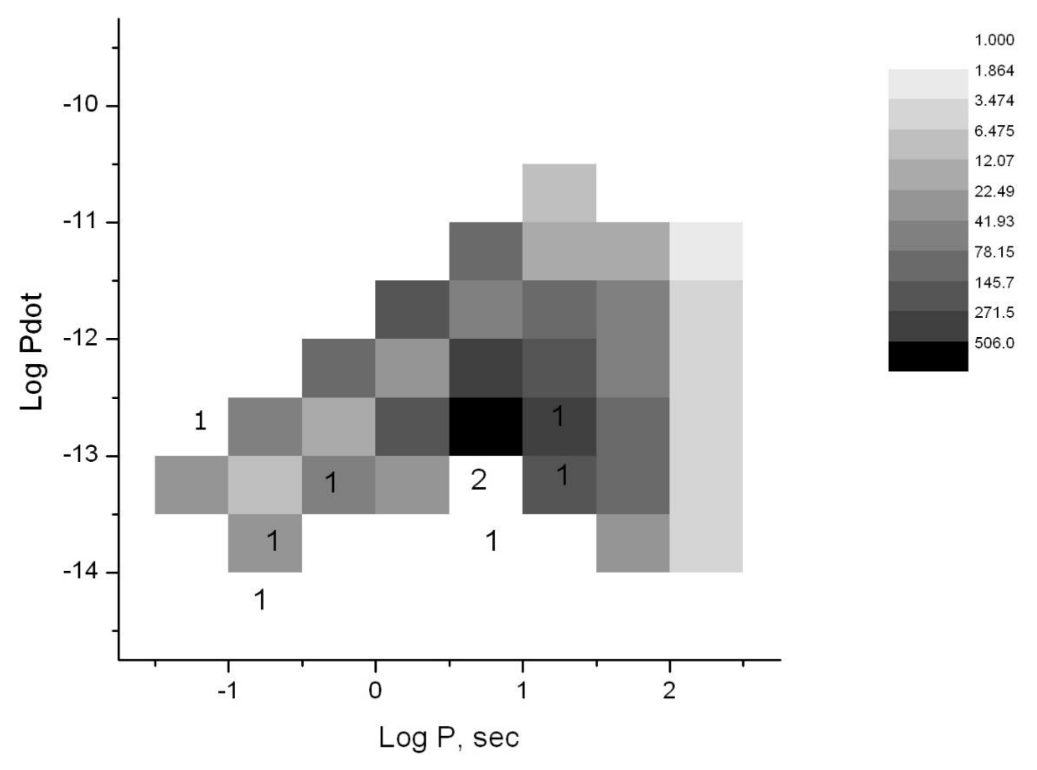
No close-by cooling NSs in the range ~-0.5 <log P< ~0.5

Kaplan arXiv: 0801.1143

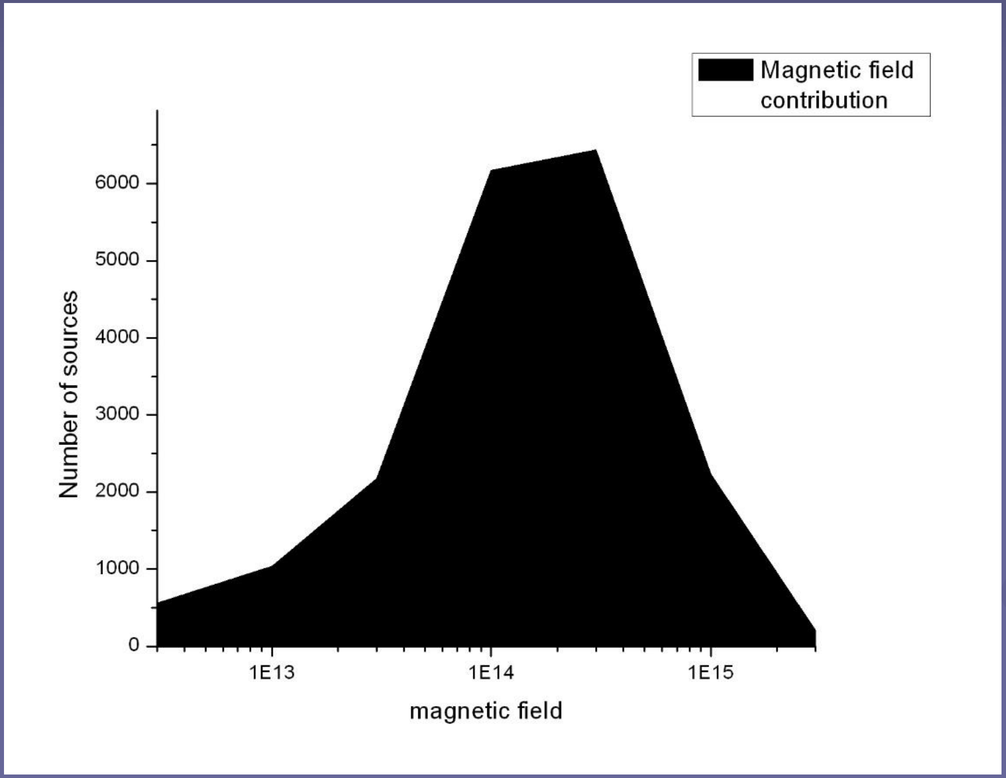
P-Pdot diagram for coolers

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

Numbers correspond to the observed sources.



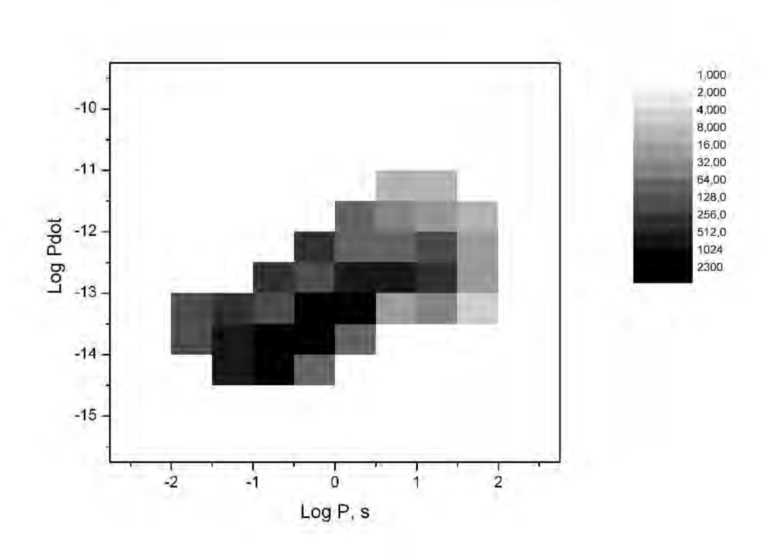
Initial magnetic fields of the modeled coolers



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

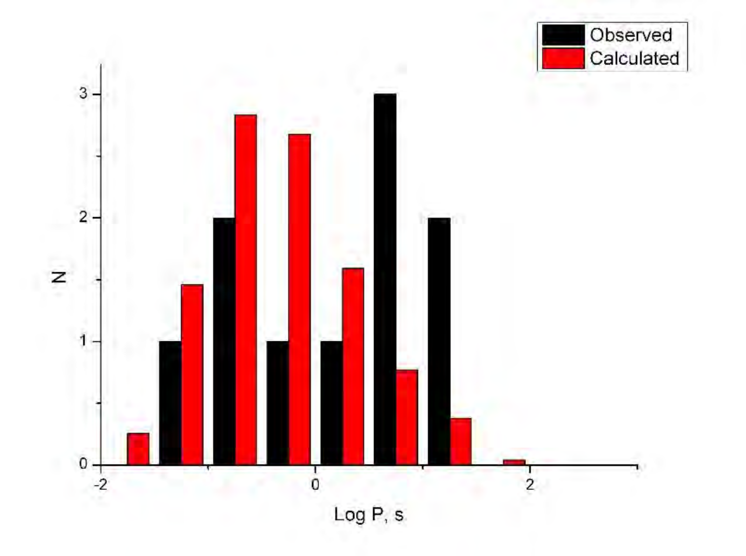
Obviously, there is the same problem as with the period distribution.

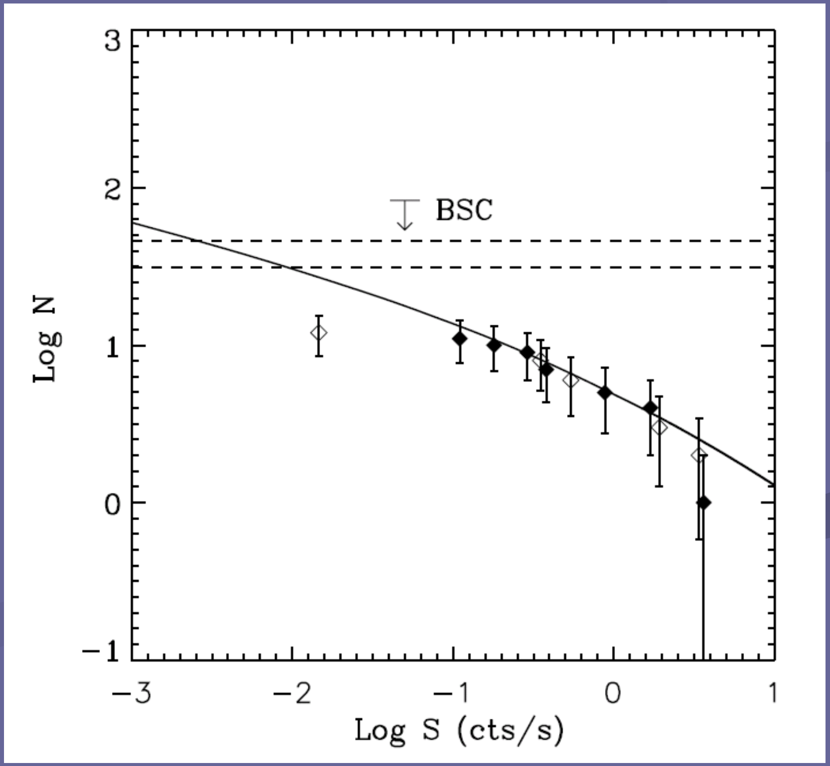
New calculations



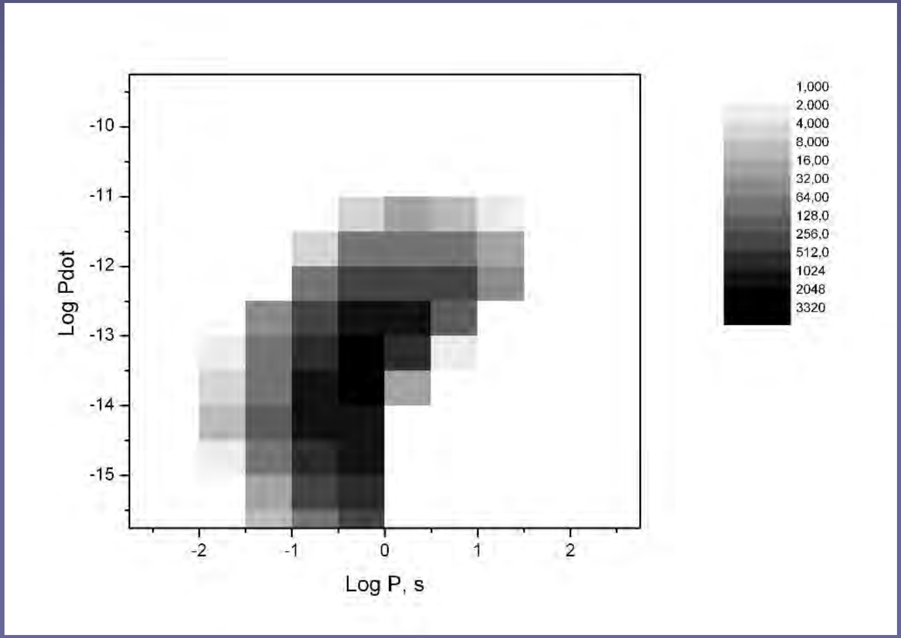
New cooling models (Pons, Vigano).
Now low-B NSs are hotter than before, and high-B NSs are colder.

Still, it is not possible to explain the P-Pdot data.
Fine tuning is necessary.

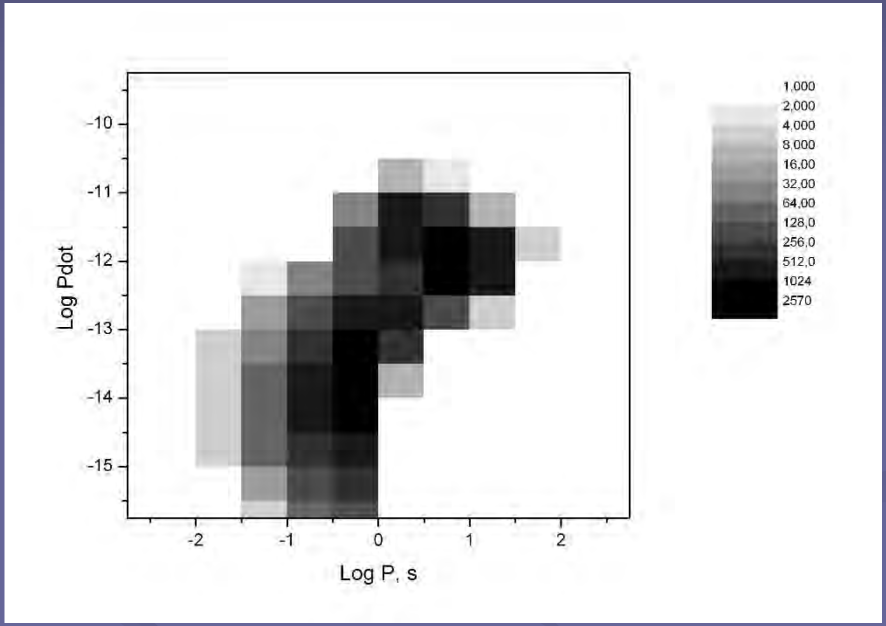




Evolution without heating



Kaspi-like population

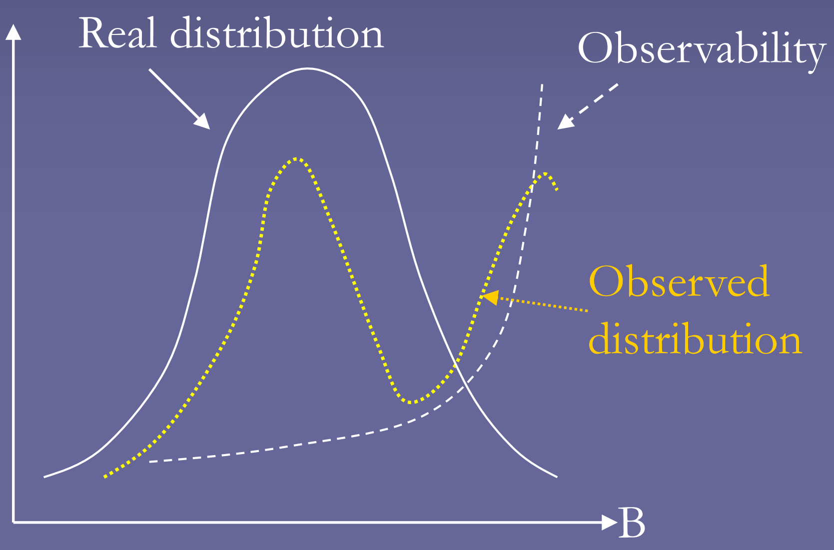


Kaspi-like population with additional peak at B=10^{14} G and small dispersion

Calculations with new cooling curves from the St.Petersburg group (Sternin, Yakovlev et al.) can easily explain the Log N – Log S, but cannot the P-Pdot without finetuning for the B-distribution (curves are not sensitive to B, so it is important only for spin evolution).

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

Most probably,
there is some mechanism
for magnetar field enhancement.
So, there is no single gaussian.
Then selection effects
(and, possibly, low statistics)
might explain the observed
P-Pdot distribution for
near-by cooling neutron stars

Conclusions

- Young isolated neutron stars demonstrate a wide range of astrophysical manifestation. It is tempting to explain all this diversity in a unified model
- Population synthesis is the tool to confront our theoretical models with observational data
- Now we understand well properties of near-by cooling NSs and can use these data to probe models of NS cooling
- 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!