Pulsar Workshop@GSFC, 8 June 2016

X-ray and rotational luminosity correlation and magnetic heating of the radio pulsars

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2016, submitted to ApJ.

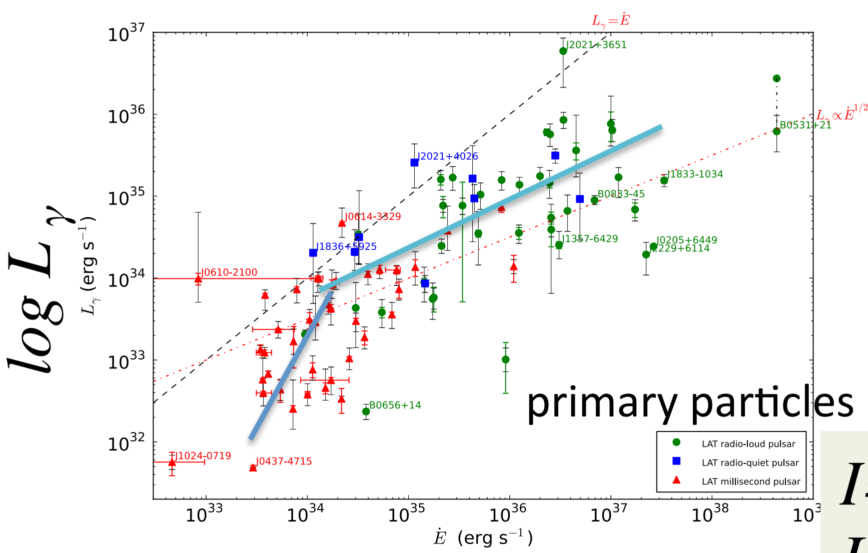
Correlation between
X-ray Luminosity L_x and the spin-down Luminosity L_{rot}
to understand the magnetosphere

$$L_{rot} = I\,\Omega\,(d\Omega/dt) \sim \mu^2\Omega^4/c^3$$

$$L_\gamma \propto L_{rot}^{\;1/2}$$

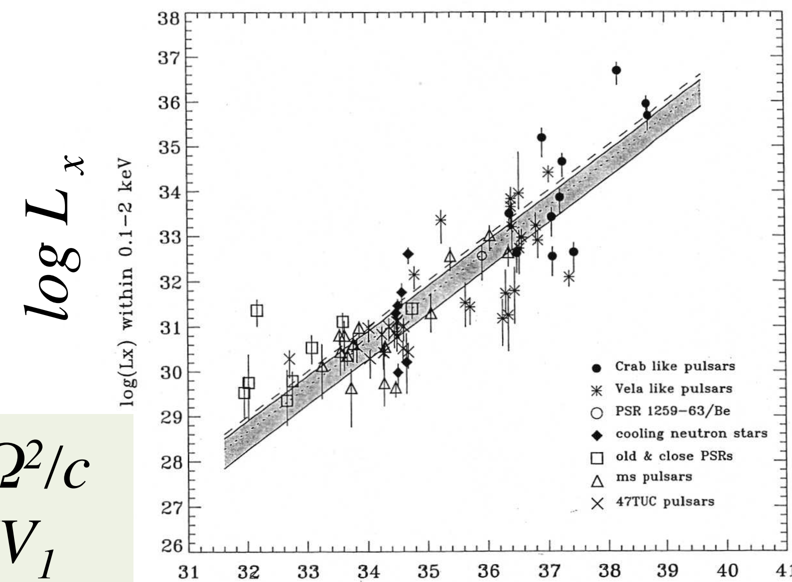
$$L_x \propto L_{rot}$$

secondary particles?



$$I = \mu\Omega^2/c$$
$$L_\gamma = IV_1$$

$\log L_{rot}$



$\log L_{rot}$

The Second Fermi Large Area Telescope Catalog of Gamma-ray Pulsars (The Fermi-LAT collaboration 2013) apjs, 208,2

Becker, W. 2009, Astrophysics and Space Science Library, 357, 91

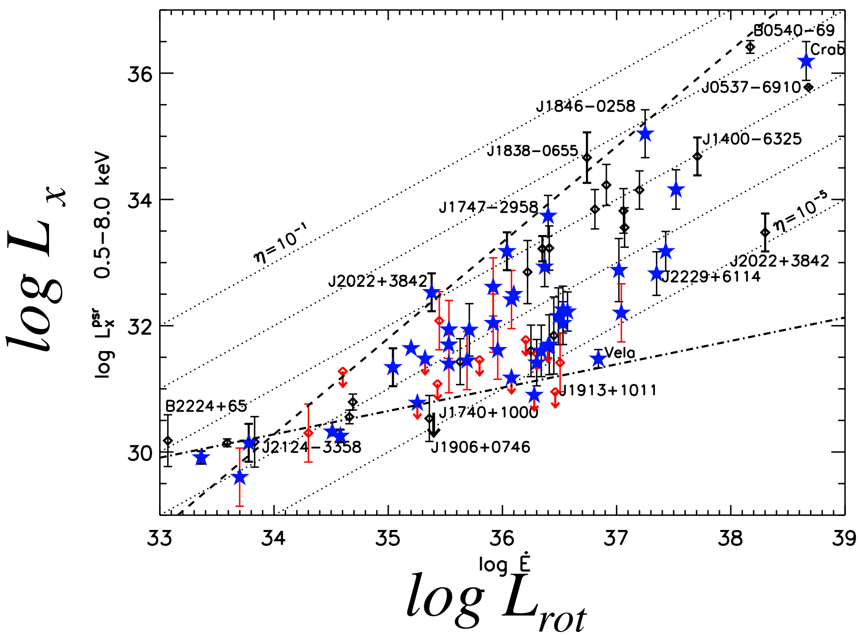
L_x — L_{rot} correlation

- a number of regression lines: $log\ L_x = c_1\ log\ L_{rot} + const.$

- large scatter :
  no statistically acceptable regression lines

Unknown physics/parameter here!

C1	references
1.39	Seward and Wang 1988
1	Becker & Trumper 1997
1.5	Saito 1998
1.34	Possenti et al. 2002
0.92	Li et al 2008
0.997	(0.1-2 keV)Becker 2009
1.336	(2-10 keV)Becker 2009

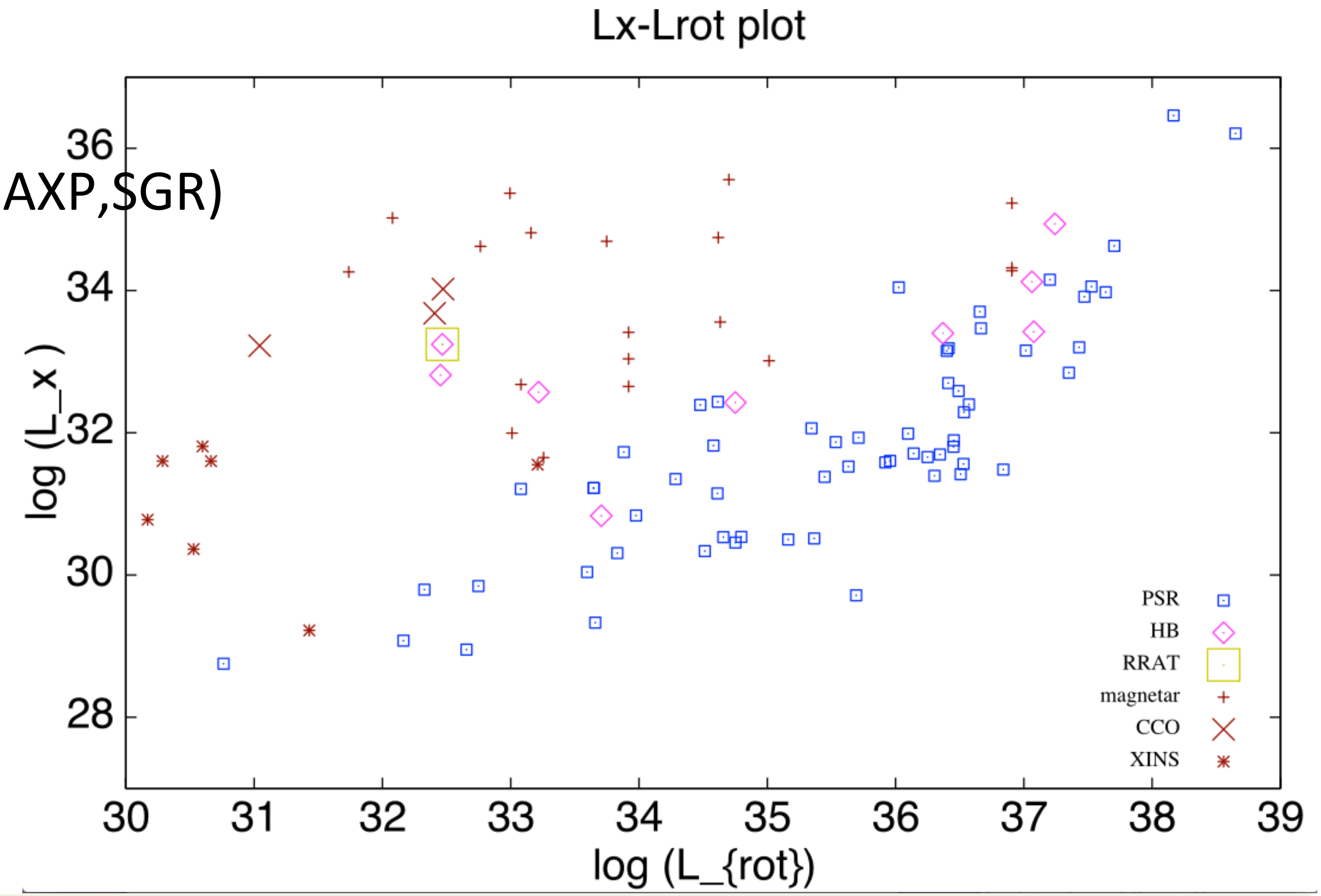


Kargaltsev et al. 2012, apjs, 201, 37

X-ray luminous NS populations!

□ PSR
+ magnetar (AXP,SGR)
X CCO
* XINS

Origin:
magnetic field
dissipation



some population may be mixed into the PSR i.e. magnetic dissipation in RPP ➔ contaminating a simple Lx-Lrot relation ➔scatter

Questions

- inherent Lx-Lrot relation exist?
- origins of large scatter (unknown physics?)
- for large efficiency Lx/Lrot, why?
- for small efficiency Lx/Lrot, why?
- High-B radio pulsars are different?

Sample Preparation

"ordinary radio pulsars"

- Radio pulsars in Parkes ATNF catalog (P, $Pdot$, d known)
- remove magnetars
- remove MSPs ($B_d < 10^{10}$ G)
- remove binary

pick up

remainder

radio pulsar sample

High B pulsar $>10^{13}$ G
Sample HB

log Frot > −9	**Sample S**
−9>log Frot >−10	Sample A
−10>log Frot > −11	Sample B
−11>log Frot > −12	Sample C
−12 > log Frot	Sample F

S+A+B used

where $Frot = L_{rot}/4\pi d^2$

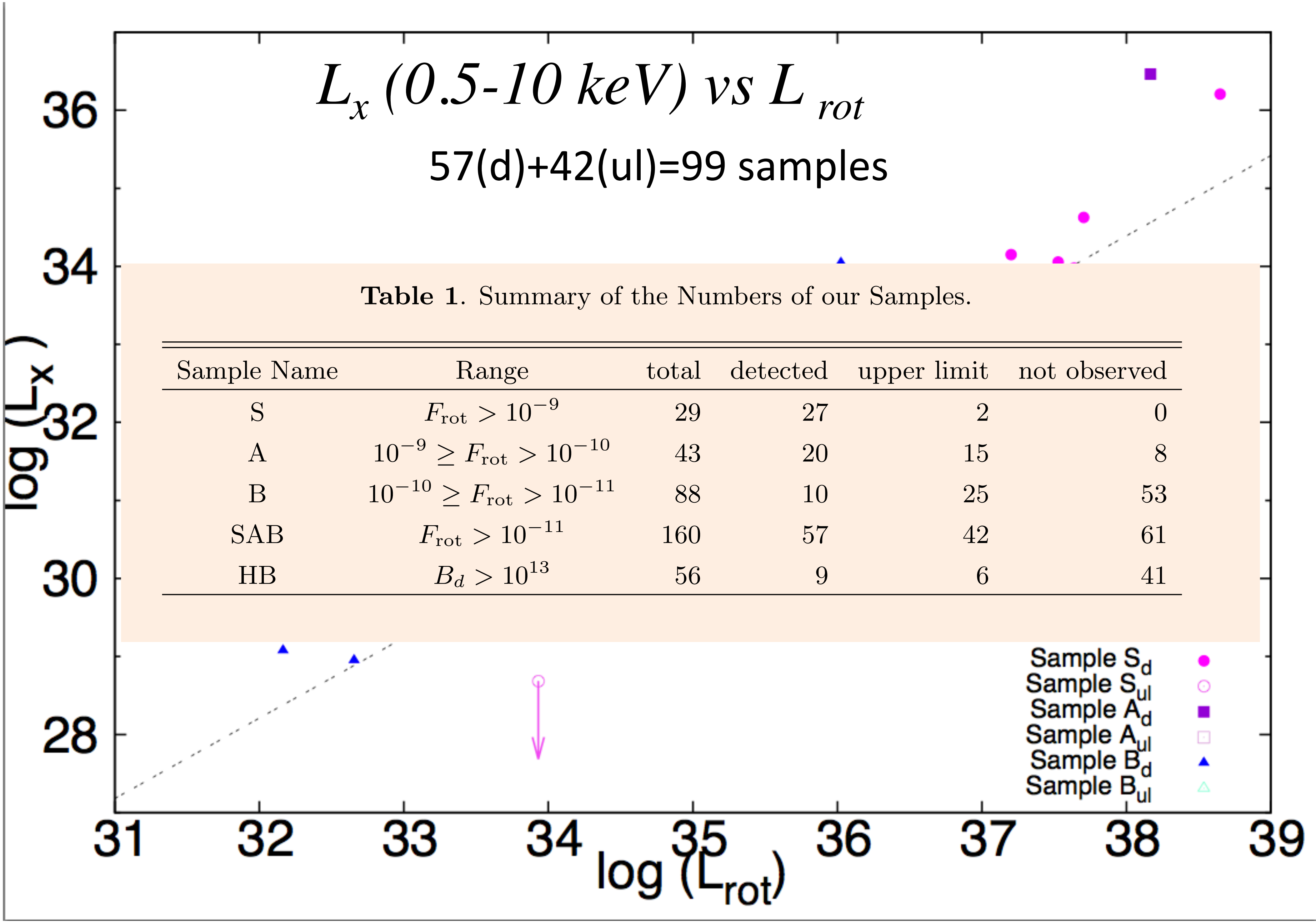
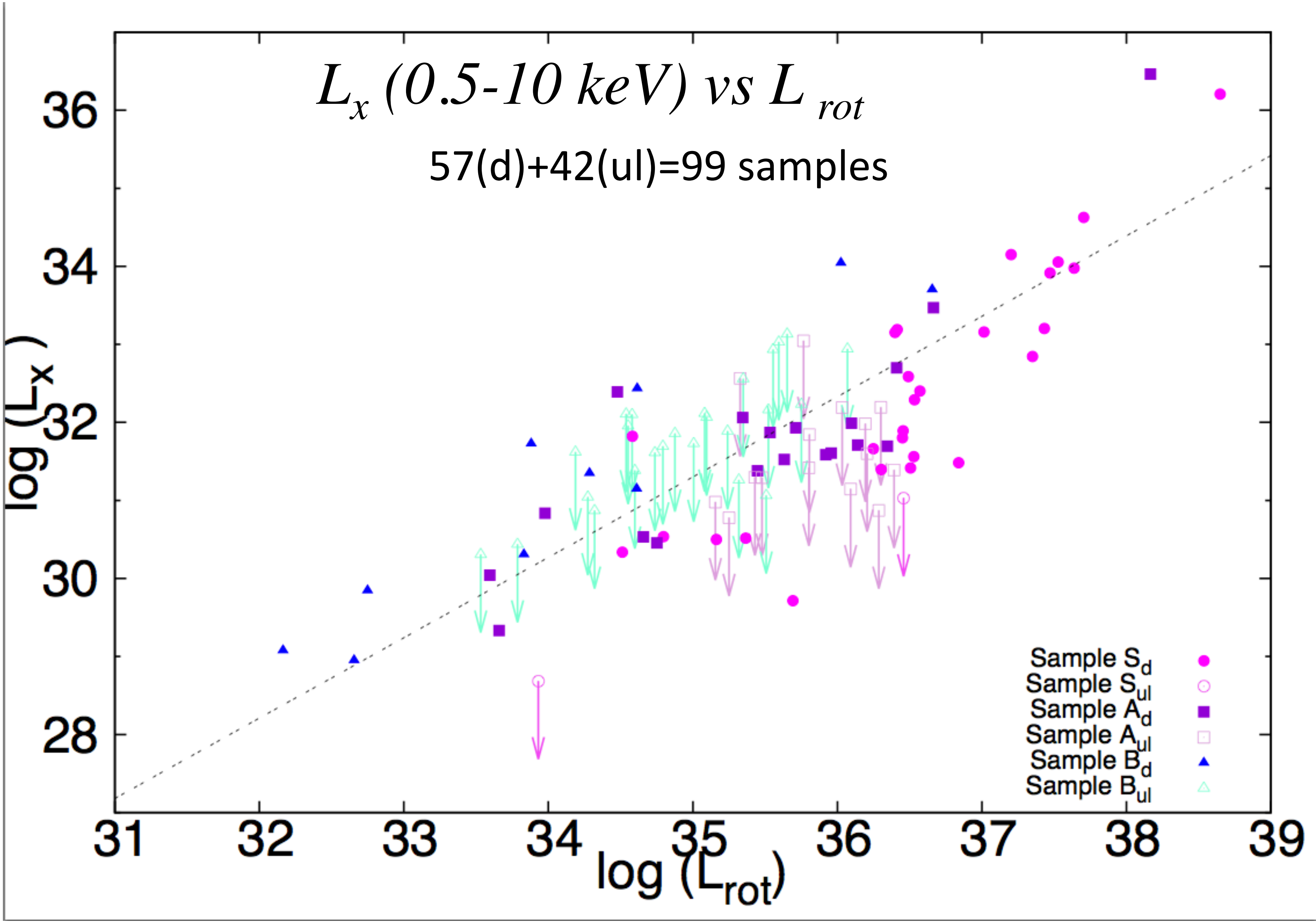


Table 1. Summary of the Numbers of our Samples.

Sample Name	Range	total	detected	upper limit	not observed
S	$F_{\rm rot} > 10^{-9}$	29	27	2	0
A	$10^{-9} \geq F_{\rm rot} > 10^{-10}$	43	20	15	8
B	$10^{-10} \geq F_{\rm rot} > 10^{-11}$	88	10	25	53
SAB	$F_{\rm rot} > 10^{-11}$	160	57	42	61
HB	$B_d > 10^{13}$	56	9	6	41



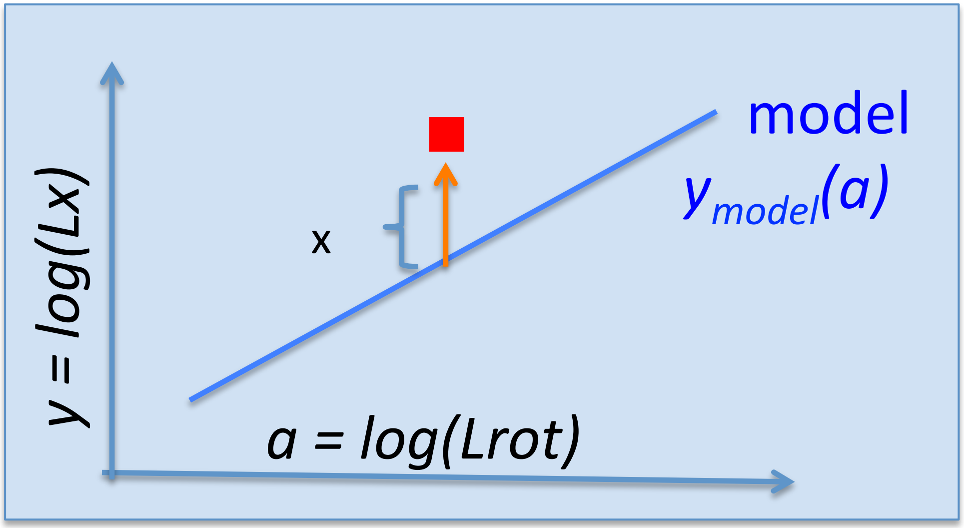
L_x (0.5-10 keV) vs L_{rot}
57(d)+42(ul)=99 samples
log (L_x)
log (L_{rot})
36
34
32
30
28
31
32
33
34
35
36
37
38
39
Sample S_d
Sample S_{ul}
Sample A_d
Sample A_{ul}
Sample B_d
Sample B_{ul}

Method of Statistical Analysis

assume a model relation

$$y_{model}(a) = c_1\,(a\text{-}37) + c_2$$

$y = \log L_x,\; a = \log L_{rot}$



random variable:
residual

$$x = y - y_{model}(a)$$

p.d.f. $f(x)$ is calculated by the simulator which have some parameters to be determined.

➔obtain the best-fit model (c_1, c_2) + the p.d.f. parameters (non-parametric test). KS test & χ^2 test

How our simulator works

$$y_{model}(a) = c_1\,(a\text{-}37) + c_2$$

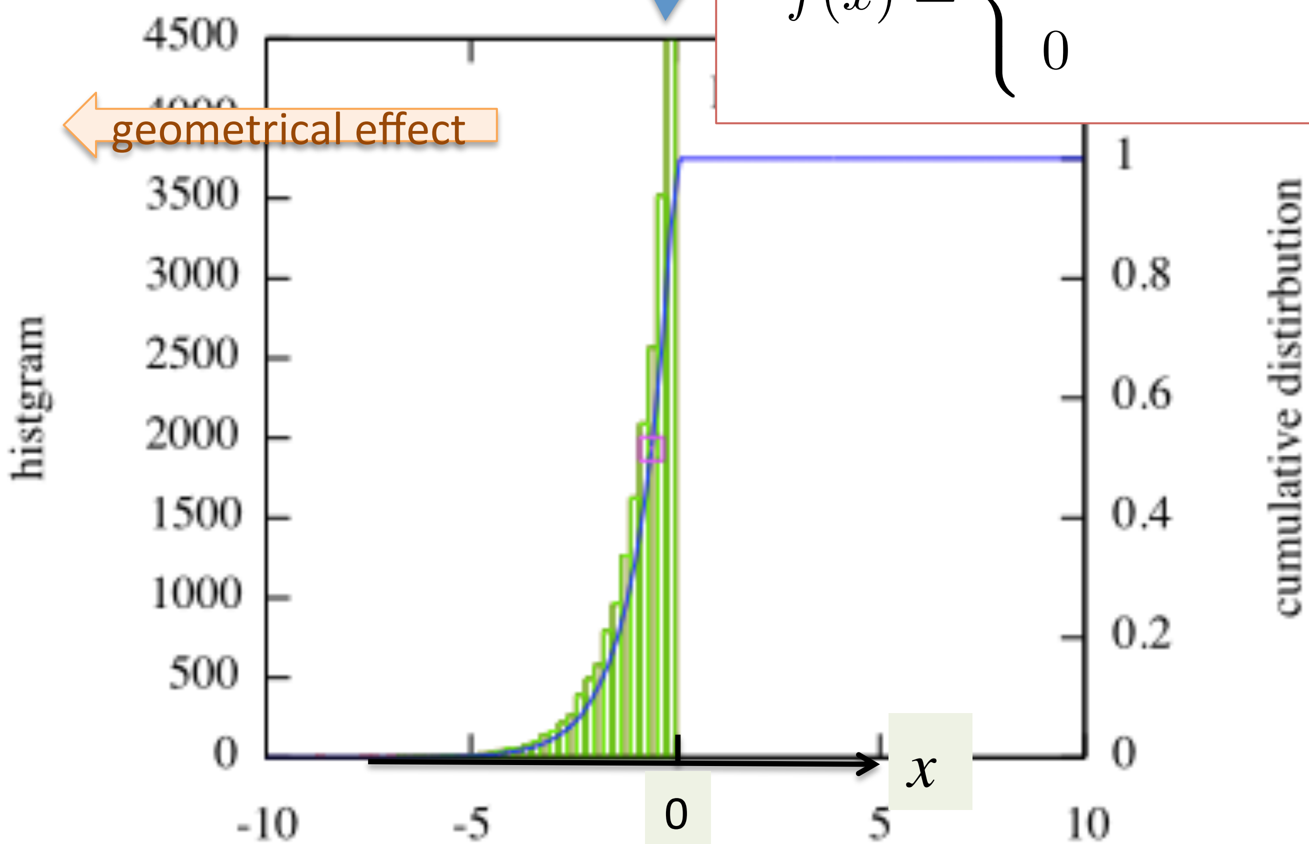
parameters of the simulator

parameter	base line	meaning
n	3	anisotropy of radiation
Pr_maggy	0	Probability of occurrence the crustal magnetic field decay. if exits, $L_{x,mag}=10^{33}$ erg/s
σ_{obs}	0.7	scatter by distance, nH, other observational uncertainty, provided log-normal distribution
log $F_{x,limit}$	-14	observation limit (in erg/cm2 sec)

How our simulator works (cont.)

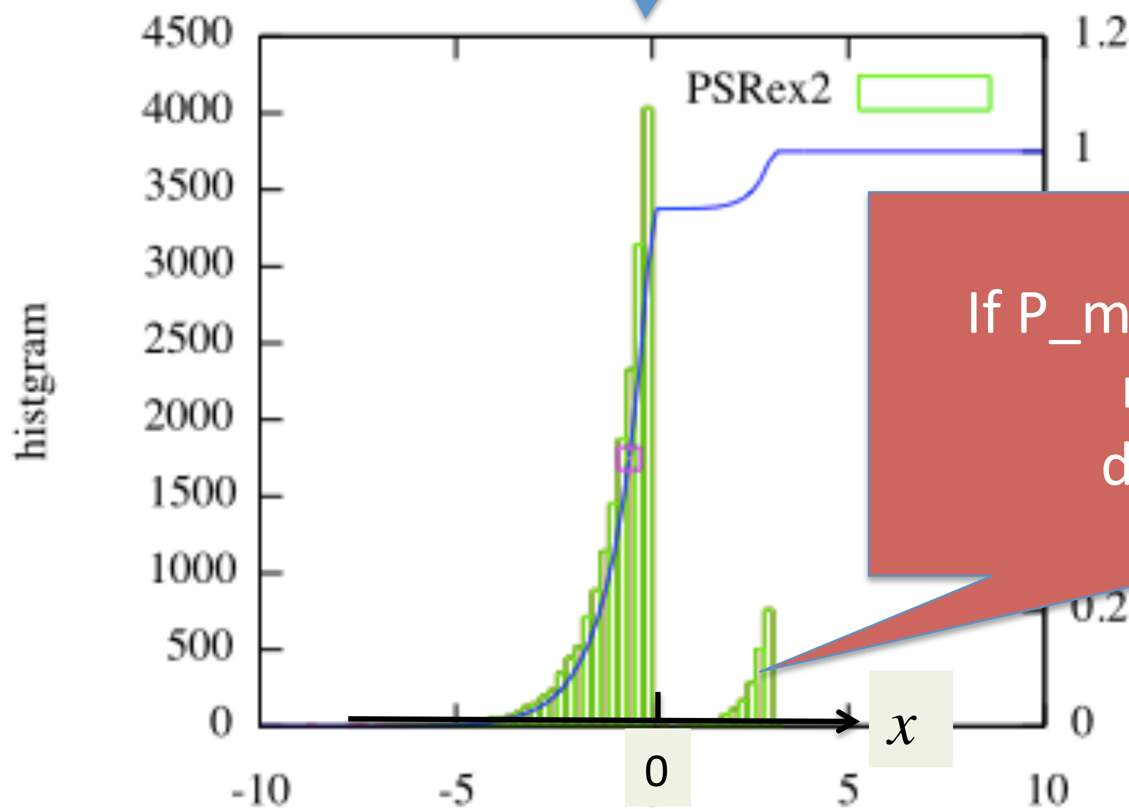
model luminosity

$$f(x) = \begin{cases} (1/n)\exp(x/n) & \text{if} \quad x \leqq 0 \\ 0 & \text{if} \quad x > 0. \end{cases}$$



How our simulator works (cont.)

model luminosity

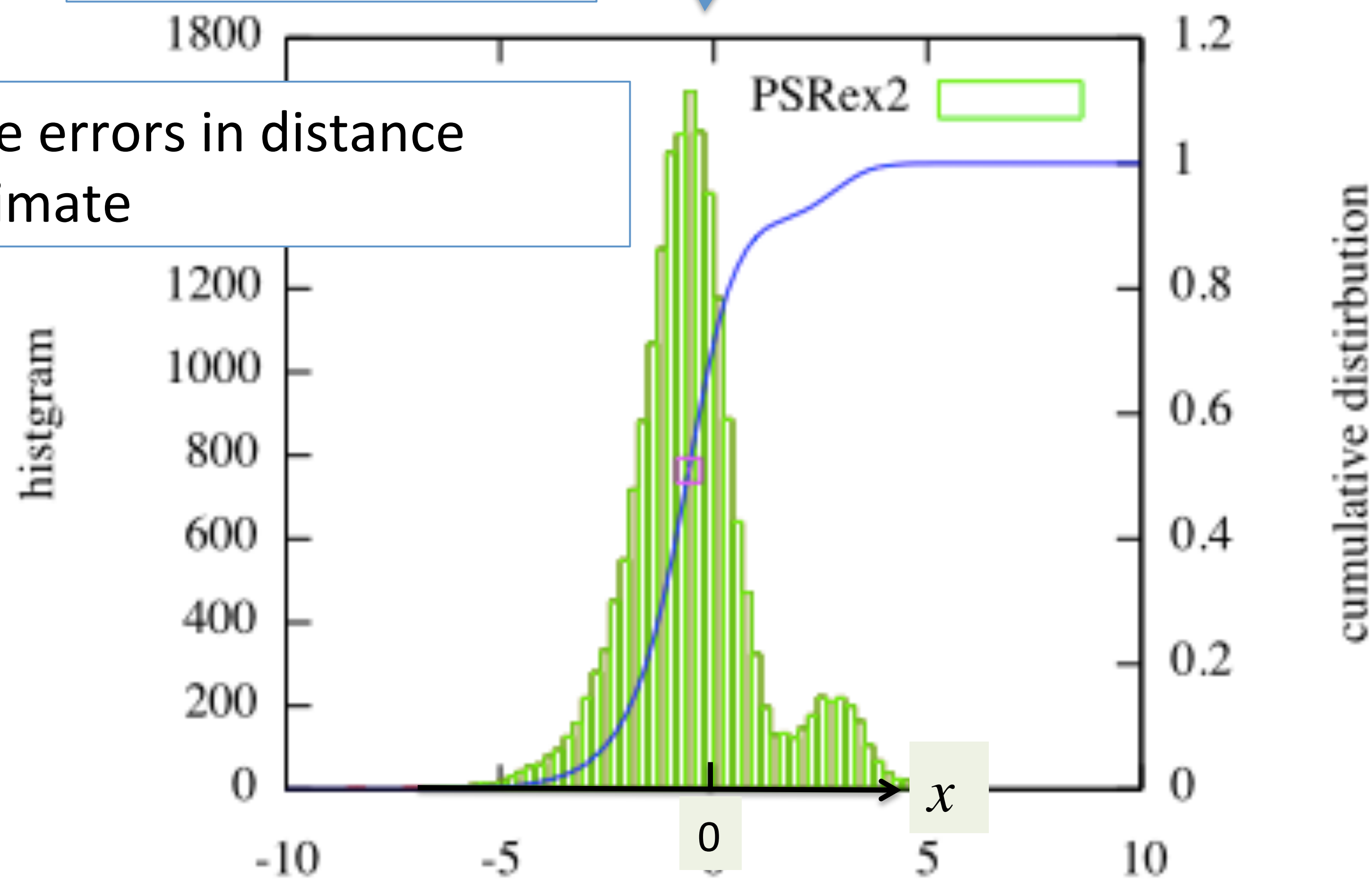


If P_maggy is no zero magnetic dissipation

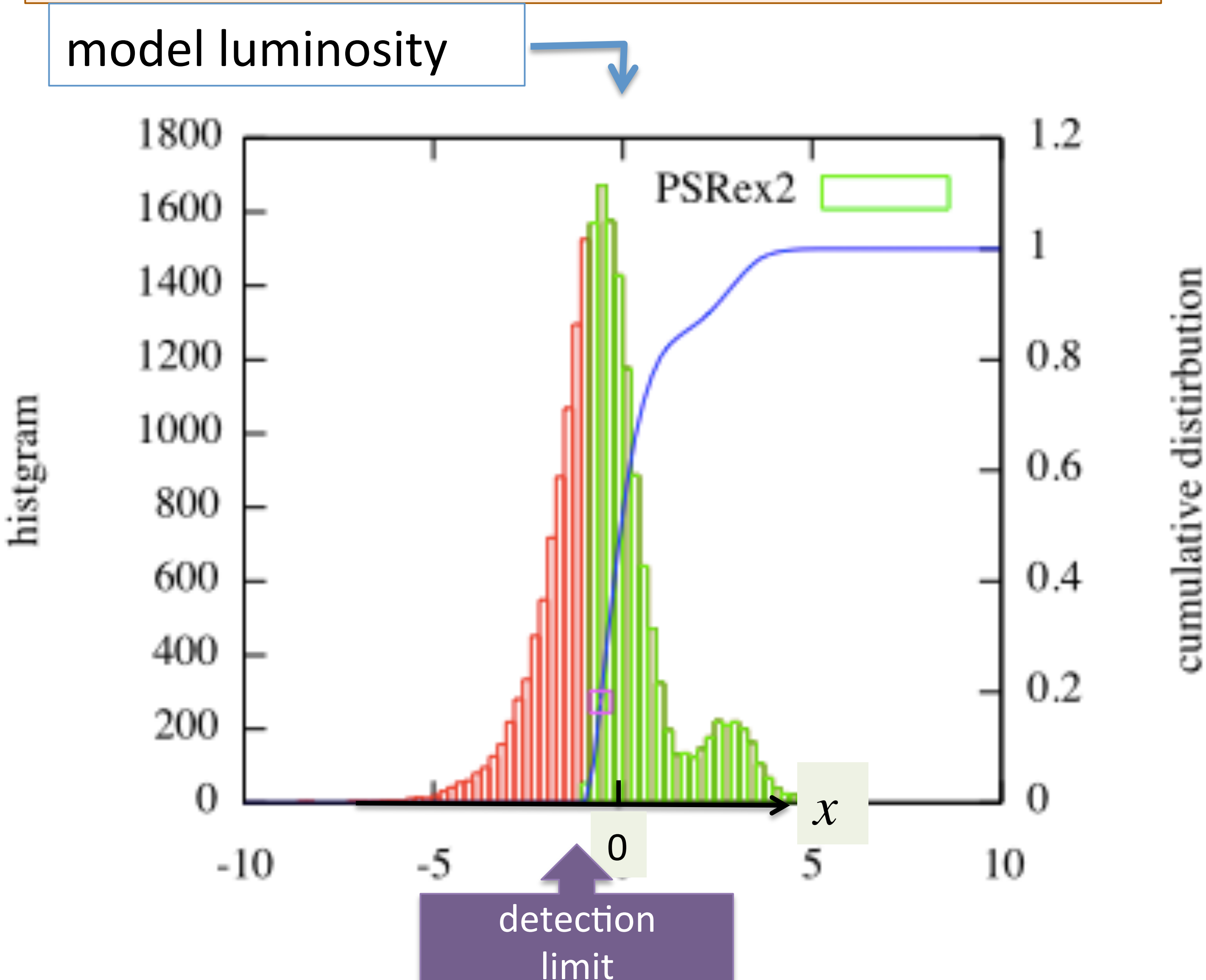
How our simulator works (cont.)

model luminosity

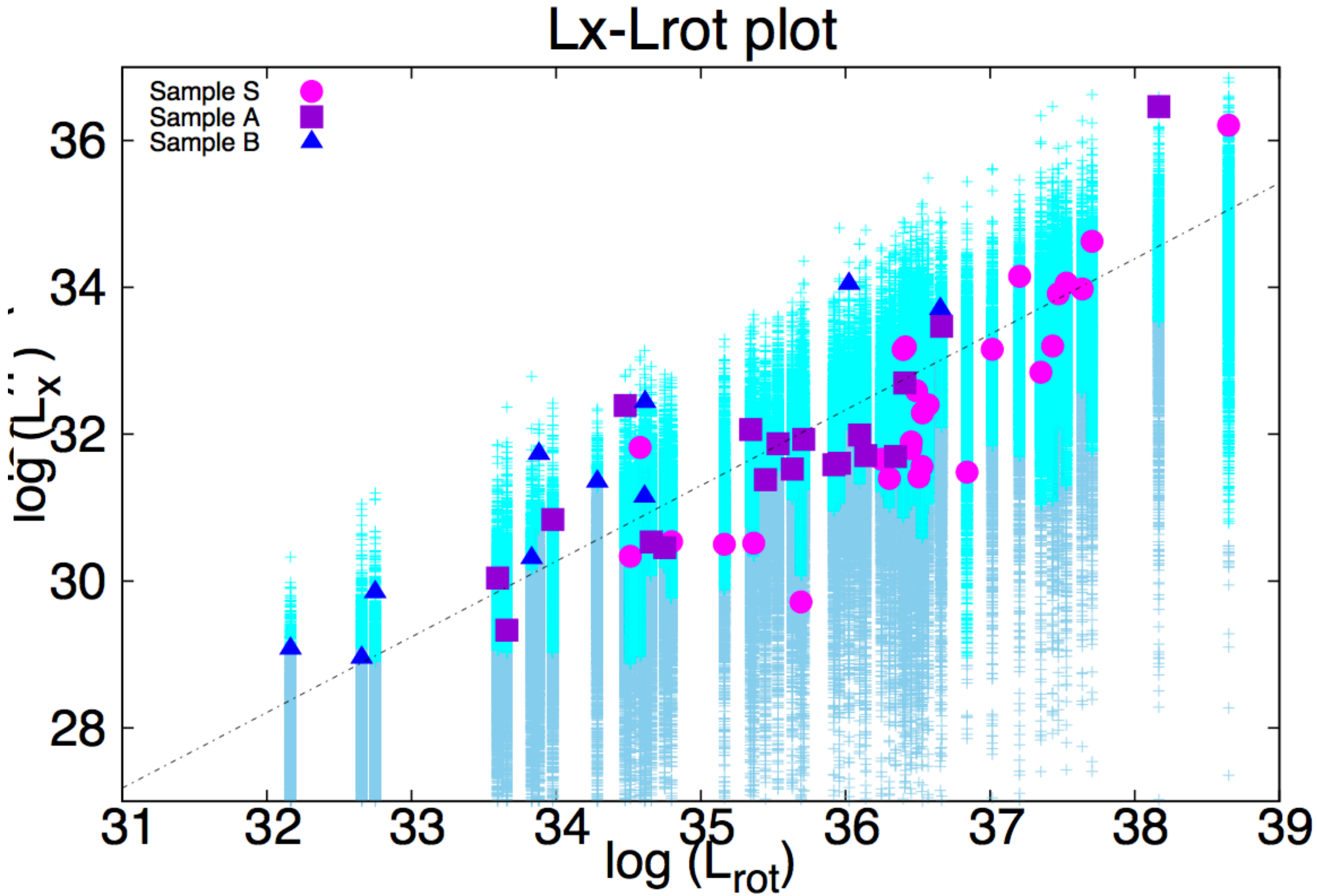
take errors in distance estimate



How our simulator works (cont.)

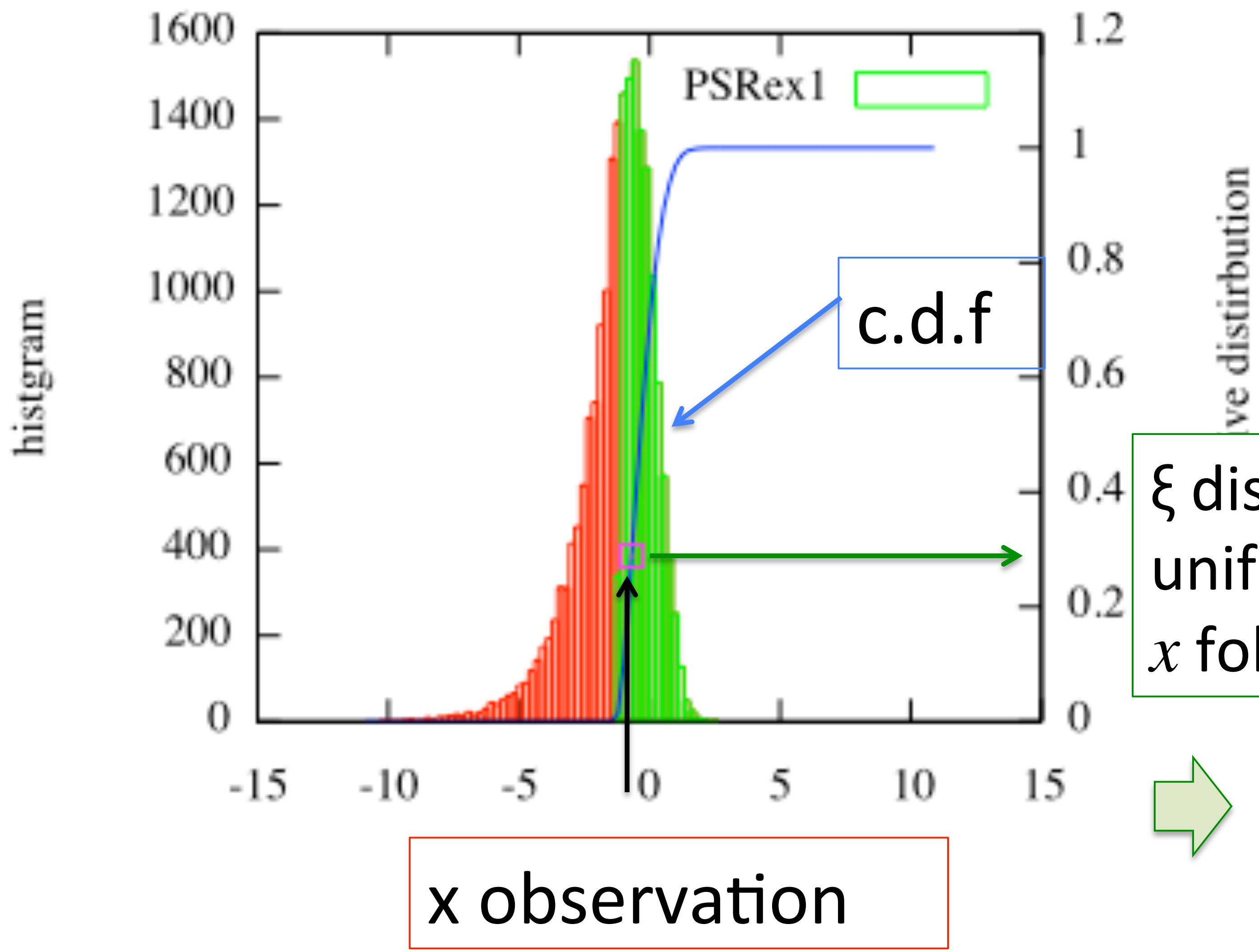


How our simulator works (cont.)



Statistical Analysis

We have p.d.f. $f(x)$ and its c.d.f. for each pulsar.



ξ distributes uniformly if x follows $f(x)$

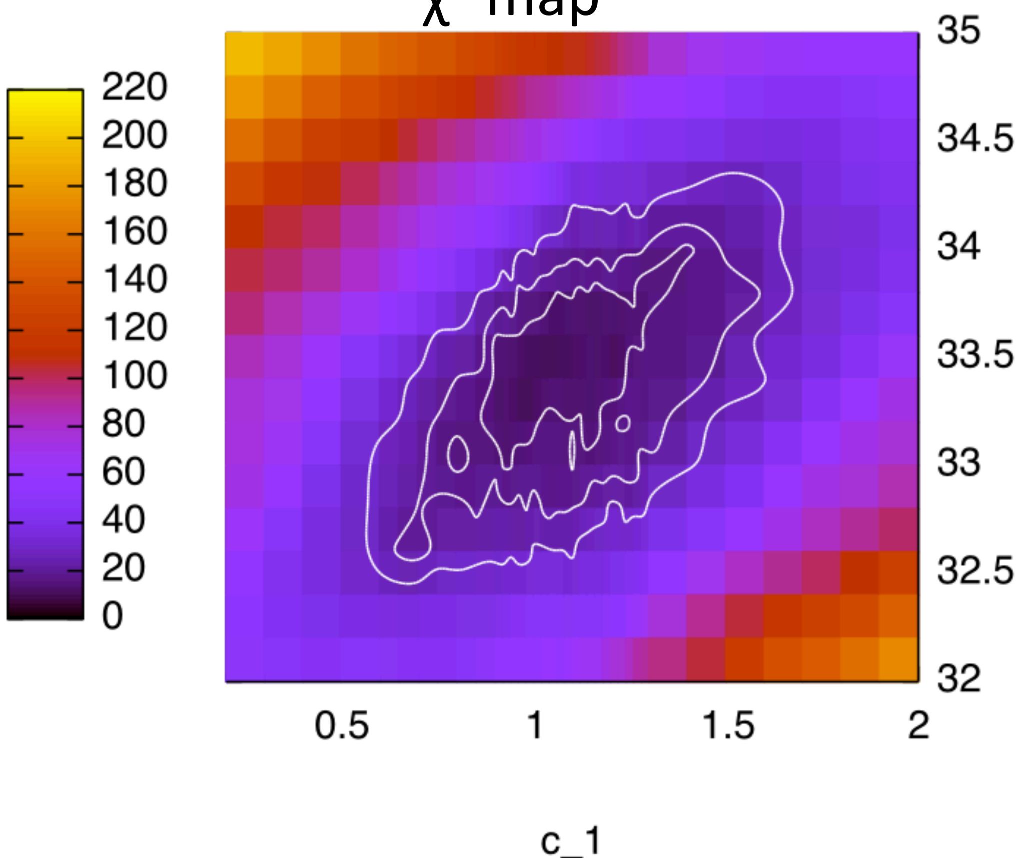
KS test

χ^2 test

Result

Q1 inherent Lx-Lrot relation exist?

χ^2 map



$$L_{\rm x} = 10^{-4.75} L_{\rm rot}^{1.03}$$

$$y_{model}(a) = c_1\,(a\text{-}37) + c_2$$

$C_1=1.03\pm0.27$

$C_2=33.36\pm0.43$

f(x) fits very well

χ^2 /dof = 9.0/13

KS D=0.104 (56.6%)

We have simply

$$\log \eta_{\rm psr} = \log(L_{\rm x}/L_{\rm rot}) \approx -3.7$$

next page

Q2. large scatter (unknown physics?)

non-parametric test : very good!

the best fit p.d.f. $f_i(x)$:

- n=2,3, we have exponential tail in p.d.f.

$$f(x) = \begin{cases} (1/n)\exp(x/n) & \text{if} \quad x \leqq 0 \\ 0 & \text{if} \quad x > 0. \end{cases}$$

▪There are dim pulsars (Lx: almost uniform dist.)

geometrical model
(anisotropy + viewing angle)

not necessarily so, ,,,,

- The best model gives σ=0.7. It is just the expected value.
- We do not need extra heating P_maggy = 0
- $log\ F_{xllim}$ = -14.0 (±3%)

Q3. for large efficiency L_x/L_{rot}, why?

The list of high ξ (>0.9) pulsars

Table 5. Large efficiency pulsars $\xi > 0.9$.

pulsar name	ξ	log $L_{\rm rot}$	log $F_{\rm rot}$	Fermi LAT	Hard X	Type	Spectral Properties BB	Spectral Properties PL	PWN $\eta_{\rm pwn}$
B0540-69	0.998	38.17	-9.37	Yes	Yes	VE	-	PL(2.05)	-0.89
J0855-4644	0.994	36.02	-10.04	no	-	L,nth	-	PL(1.24)	-2.01
B1055-52	0.992	34.48	-9.97	Yes	-	L,th	2BB(68 eV)	-	-5.28
B0531+21	0.986	38.65	-6.03	Yes	Yes	VE	-	PL(1.63)	-1.64
B0656+14	0.969	34.58	-8.39	Yes	-	H,th	2BB(56 eV)	-	-5.68
J1301-6310	0.956	33.88	-10.82	no	-	L,?	?	?	-
B1822-14	0.931	34.61	-10.93	no	-	L,th?	BB(200 eV)	-	-
J1617-5055	0.922	37.20	-8.49	No	Yes	H,nth	-	PL(1.15)	-3.41
J1400-6325	0.918	37.70	-8.06	No	Yes	H,nth	-	PL(1.22)	-2.76
J1741-2054	0.901	33.98	-9.05	Yes	-	H,th	BB(60 eV)	-	-4.58

Q3. for large efficiency L_x/L_{rot}, why? (cont.)

high ξ pulsars are

1. magnetospheric emission dominated in hard X and soft gamma bands

2. thermally bright pulsars with a high temperature as compared with standard cooling curve

soft gamma-ray pulsars
detected in 20 keV – 30 MeV

Kuiper, L., & Hermsen, W. 2015, mnras, 449, 3827

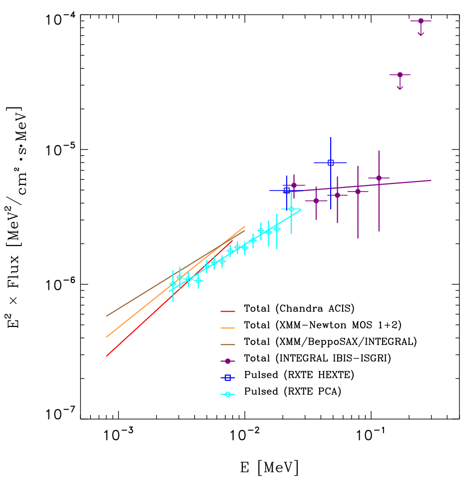


Figure 9. PSR J1617−5055; high-energy (0.8–300 keV) total and pulsed spectra as derived from measurements by *Chandra* ACIS (total pulsar 0.8–8 keV; solid red; Kargaltsev et al. 2009), *XMM–Newton* MOS (total, including compact PWN, 0.8–10 keV; solid orange; Becker & Aschenbach 2002), joint fit *XMM–Newton*/*BeppoSAX*/ISGRI (total, including compact PWN, 0.8–10 keV; solid brown; Landi et al. 2007), *RXTE* PCA (pulsed 2.5–30 keV;

KARPOVA ET AL.

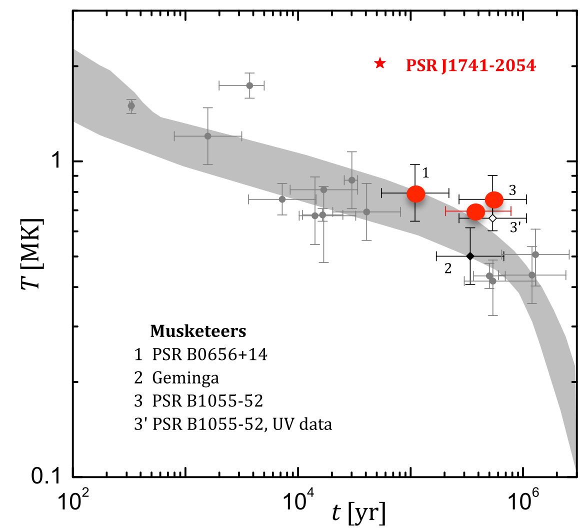


Figure 5. Observations of isolated cooling NSs compared with standard cooling theory predictions (filled region). The PSR J1741−2054 data point is shown by the star symbol. We artificially adopt a factor of two error on its age. The Three Musketeers are indicated with the filled diamonds. The temperature and age error bars for these stars are shown in accordance with Kaminker et al. (2006)

Karpova, A., Danilenko,A., Shibanov, Y., Shternin, P., & Zyuzin, D. 2014, apj, 789, 97

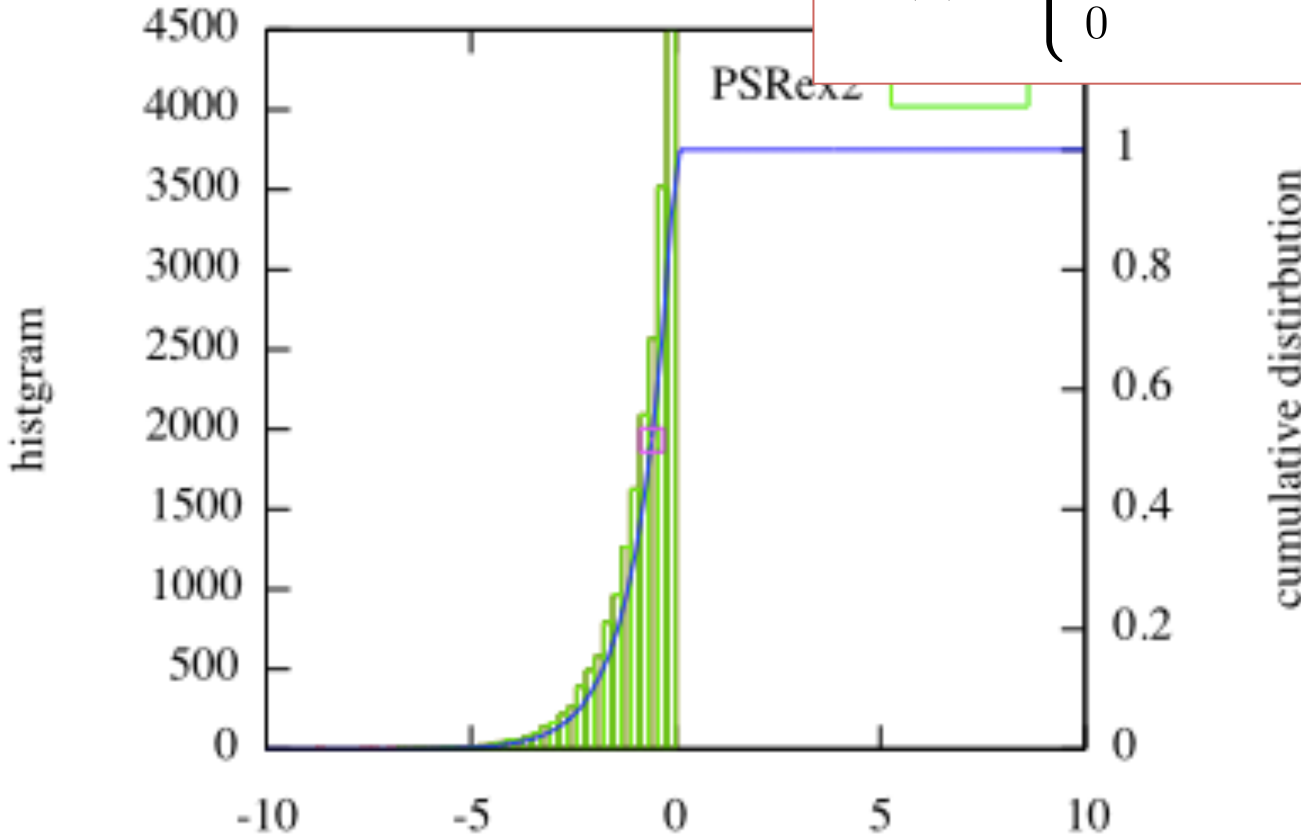
Q4 for small efficiency L_x / L_{rot}, why?

appearance of dim pulsars follows exponential form.

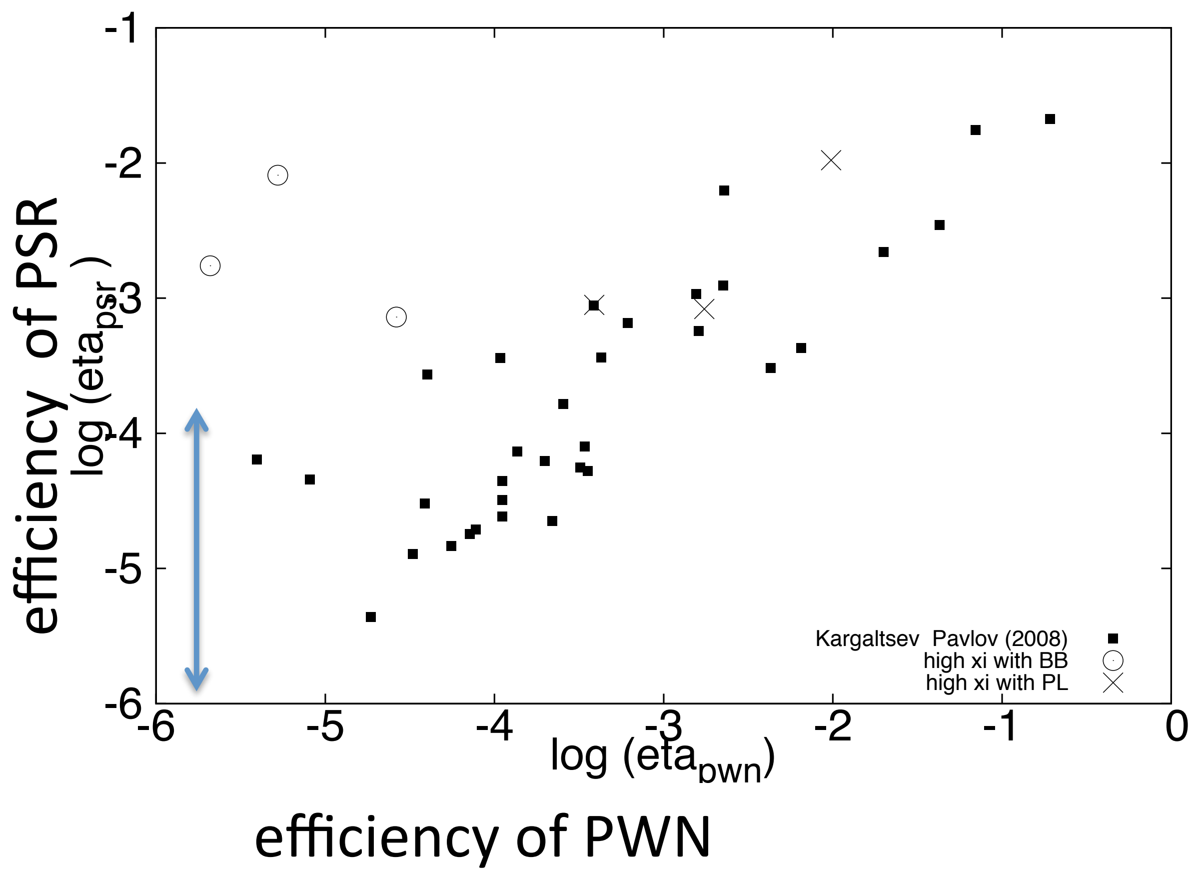
- dim pulsars (almost uniform)

geometr
(anisotr

$$f(x) = \begin{cases} (1/n)\exp(x/n) & \text{if} \quad x \leqq 0 \\ 0 & \text{if} \quad x > 0. \end{cases}$$



Q4 for small efficiency L_x / L_{rot}, why? (cont.)



(data is taken from Kargaltsev & Pavlov 2008)

Luminosity of the magnetospheric X ray correlates with PWN luminosity. Pair creation rate is a possible link parameter.

Q5 High-B radio pulsars are different?

χ^2 map

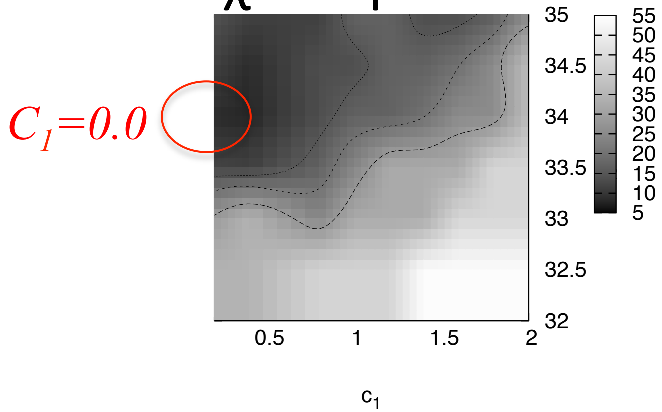


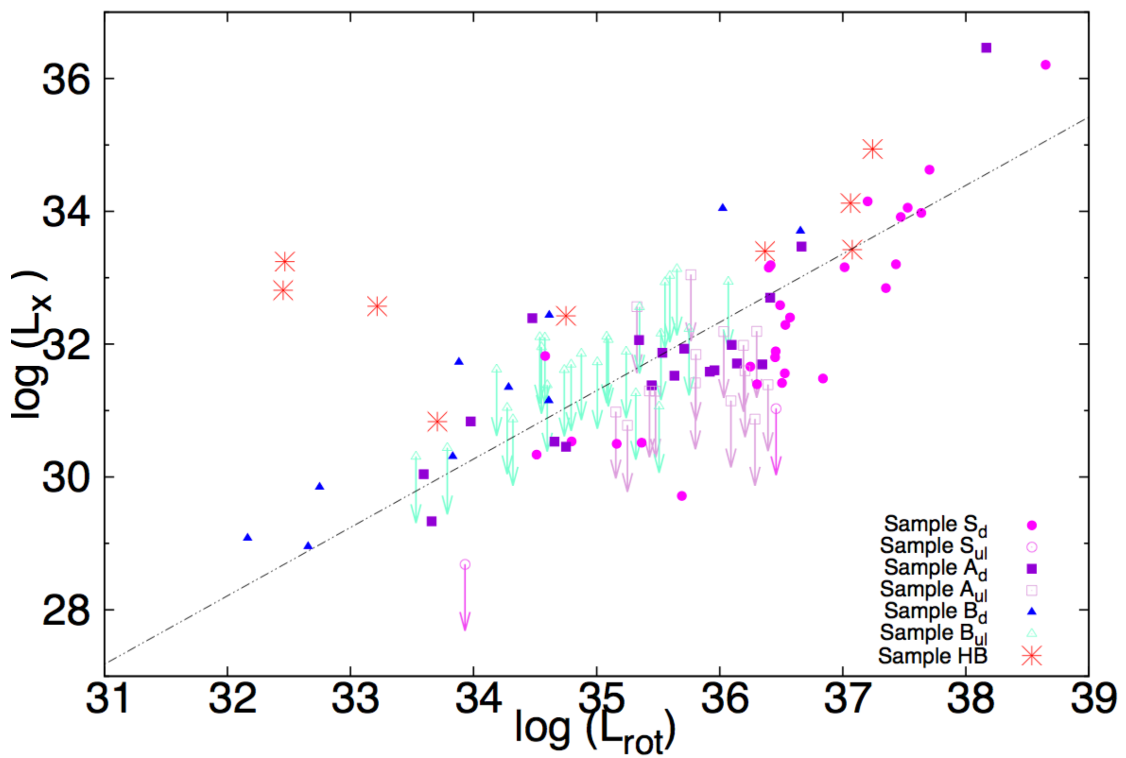
Figure 7. The same as Figure 4 but for Sample HB.

If the best fit model for the ordinary radio pulsars is tested on Sample HB, we have

χ^2 /dof = 23.9/13

KS Pr. 0.09%, i.e.,

C1=0: not correlated to Lrot



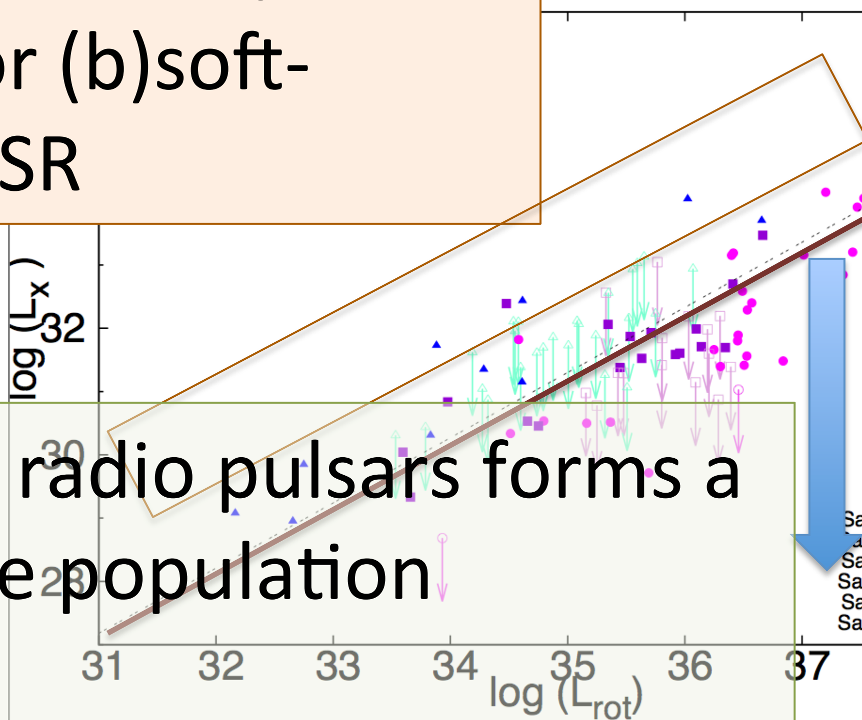
High-B radio pulsars are different from ordinary radio pulsar ($<10^{13}$G)

Conclusion

$L_x - L_{rot}$ scatter plot is so produced :

1. Inherent correlation $L_x = 10^{-3.7} L_{rot}$

2. high efficiency pulsars are (a)high surf. temp. (B-decay?) or (b)soft-gamma PSR



3. uniform distribution of dim pulsars➔ unknown physics that governs Lx and Lx(pwn)

4. High-B radio pulsars forms a distinctive population