X-ray observations of old pulsars & the example of PSR B1451-68

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X-ray observations of old pulsars

"Old pulsar": non-recycled pulsar
characteristic age $\tau > 1$ Myr

ATNF pulsar database: ~ 50 old pulsars at d < 1 kpc
only 9 X-ray detected so far

Why interesting ?

evolution of magnetospheres
study of polar cap heating mechanisms
cooling/re-heating of whole surfaces ?

➡ Talks by I.Contopoulus , S. Mereghetti, D. Yakovlev (session 5)

X-ray observations of old pulsars

Pulsar	τ Myr	$\dot{E}$ 10^{30} erg s^{-1}	D pc [π Y/N]	PWN	Pulsar X-ray counts (instrument with most)
J0108-1431	166	6	240 $^{+120}_{-61}$ LK	N	~50 cts in 30 ks, ACIS
B0628-28	2.8	150	332 $^{+52}_{-42}$	N	~670 cts in 32 ks, EPIC-pn
B0823+26	4.9	450	357 $^{+97}_{-63}$	N	~120 cts in 34 ks, EPIC-pn
B0943+10	5.0	100	980 [N]	N	~80 cts in 33 ks, ACIS
B0950+08	17.5	560	262 ±5	N	~1400 cts in 49 ks, EPIC-pn
B1133+16	5.0	88	350 ±20	N	~30 cts in 18 ks, ACIS
B1813-36	3	1400	3780 [N]	N	n.d. in 30 ks, ACIS
B1929+10	3.1	3900	361 $^{+10}_{-8}$	Y	~1900 cts in 24 ks, EPIC-pn
B2224+65	1.1	1200	~2000 [N]	Y	~100 cts in 12 ks, EPIC-pn

LK: 625 $^{+375}_{-313}$ pc

Talk by O. Kargaltsev (session 2)

Pavlov et al. 2009, Hu & Becker 2005,2007, Kargaltsev et al. 2006, Zhang & Pavlov 2005, Becker et al. 2006/4
Ögelman & Tepedelenlioglu 2004, Zavlin & Pavlov 2004, Deller et al. 2009, Brisken et al. 2002,
Chatterjee et al. 2004, Gwinn et al. 1986, ATNF – Manchester et al. 2005

X-ray spectra of old pulsars
- a summary -

- **describable by power laws** with photon indices $\Gamma = 2\text{–}4$
  (reminder typical PL slopes of younger pulsars $\Gamma = 1\text{–}2$)

➡ N(H) sometimes exceeds expectations from DM

- **blackbody-only spectra** can be excluded for some pulsars

- **two components** – power law and blackbody – OK,
but statistically in most cases not required

➡ PL indices $\Gamma = 1\text{–}2$, blackbody temperatures $kT = 0.1 - 0.3$ keV

➡ inferred polar cap area smaller than conventional PC area

- **X-ray efficiencies** $\eta = L_X / \dot{E} \sim 10^{-3} - 10^{-4}$

➡ on average higher than those of younger pulsars (10^{-4} –10^{-5})

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X-ray spectra of old pulsars
an example with “many” counts - B1929+10

Becker et al. 2006: ~3900 counts EPIC-MOS/pn + ~460 counts ROSAT

- single power law sufficient $\Gamma = 2.7 \pm 0.1$, $N(H) = 1.6\ 10^{21}\ cm^{-2}$
- thermal contribution of heated polar caps < 7%

phase-resolved spectral anlaysis:
- PLs at peak ($\Gamma = 3.1 \pm 0.1$) and off-puse ($\Gamma = 3.1 \pm 0.1$)

Misanovic et al. 2008: 2x ~700 counts ACIS + XMM EPIC counts

- single power law $\Gamma = 2.95 \pm 0.14$, $N(H) = (2.2 \pm 0.3)\ 10^{21}\ cm^{-2}$
- add thermal component: 99.98% F-test prob. for improved fit

➡ $\Gamma = 1.73\ ^{+0.46}_{-0.66}$, $kT = 0.30\ ^{+0.02}_{-0.03}$ keV, $N(H) = (1.7\ ^{+2.3}_{-1.7})\ 10^{20}\ cm^{-2}$

expected $N(H) \sim 10^{20}\ cm^{-2}$
from DM=3.178 pc cm^{-3} and 10% ISM ionisation

Power law fits and the N(H)

Pulsar	counts	Γ	N(H) in 10^{20} cm^{-2}	expected N(H) in 10^{20} cm^{-2}	total N(HI) in 10^{20} cm^{-2}
J0108-1431	~50	$3.4^{+1.0}_{-0.8}$	23^{+17}_{-12}	~ 0.7	~ 2.1
B0628-28	~670	2.6 ± 0.2	$6.0^{+3.1}_{-1.8}$	~ 11	~ 4.9
B0823+26	~120	$2.5^{+0.9}_{-0.5}$	≤ 8.8	~ 6	~ 3.4
B0943+10	~80	$2.6^{+0.7}_{-0.5}$	frozen	~ 5	~ 2.4
B0950+08	~1400	1.8 ± 0.2	2.9 ± 2.1	~ 0.9	~ 3.0
B1133+16	~ 30	$2.5^{+0.4}_{-0.3}$	frozen	~ 1.5	~ 2.8
B1929+10	~1900	$2.95^{+0.14}_{-0.13}$	22 ± 3	~ 1	~35
B2224+65	~100	$1.7^{+0.5}_{-0.2}$	≤ 9	~ 11	~50

DM-inferred 10% ionisation

LAB HI survey

Johnson & Wang 2010, Pavlov et al. 2009, Hu & Becker 2005,2007, Kargaltsev et al. 2006, Zhang & Pavlov 2005, Becker et al. 2006, 2004, Ögelman & Tepedelenlioglu 2004, Zavlin & Pavlov 2004, Deller et al. 2009, Brisken et al. 2002, Chatterjee et al. 2004, Gwinn et al. 1986, ATNF – Manchester et al. 2005, Kalberla et al. 2005

Assuming a polar cap contribution...

	effective radius r_{PC}	$R_{PC}=(2R^3_{NS}/cP)^{1/2}$
B1929+10:	r_{PC} ~ 33 m (@361 pc) (*kT*=0.15 keV blackbody *component*)	R_{PC} ~ 300 m
B0950+08:	r_{PC} ~ 50 m (@262 pc) (*kT*=0.30 keV, blackbody *component*)	R_{PC} ~ 290 m
B1133+16:	r_{PC} ~ 19 m (@357 pc) (*kT*=0.24 keV, blackbody fit only)	R_{PC} ~ 130 m
B0108-1431:	r_{PC} ~ 8 m (@240 pc) (*kT*=0.28 keV, blackbody fit only)	R_{PC} ~ 170 m

Possible explanations:

- Hydrogen atmosphere increases effective radii (Zavlin & Pavlov 2004)
- "sparks" footprints caused by infalling particles from above the PC (Zhang et al. 2005, Ruderman & Sutherland 1975)

Pavlov et al. 2009, Misanovic et al. 2008, Kargaltsev et al. 2006, Zhang & Pavlov 2005, Zavlin & Pavlov 2004

PSR B1451-68

PSR B1451-68

$P = 0.263$ s

$dE/dt = 2.1\ 10^{32}$ ergs s^{-1}

inferred $B = 1.6\ 10^{11}$ G

inferred $\tau = 43$ Myr

(ATNF pulsar data base)

Proper motion

$\mu_\alpha = -39.5 \pm 0.7$ mas yr^{-1}

$\mu_\delta = -12.3 \pm 0.6$ mas yr^{-1}

Parallactic distance: 450 ± 60 pc

(Bailes et al. 1990)

LK: $480\ ^{+80}_{-60}$ pc

PSR B1451-68

Re-analysis of Parkes data
(400, 600 & 1400 MHz)

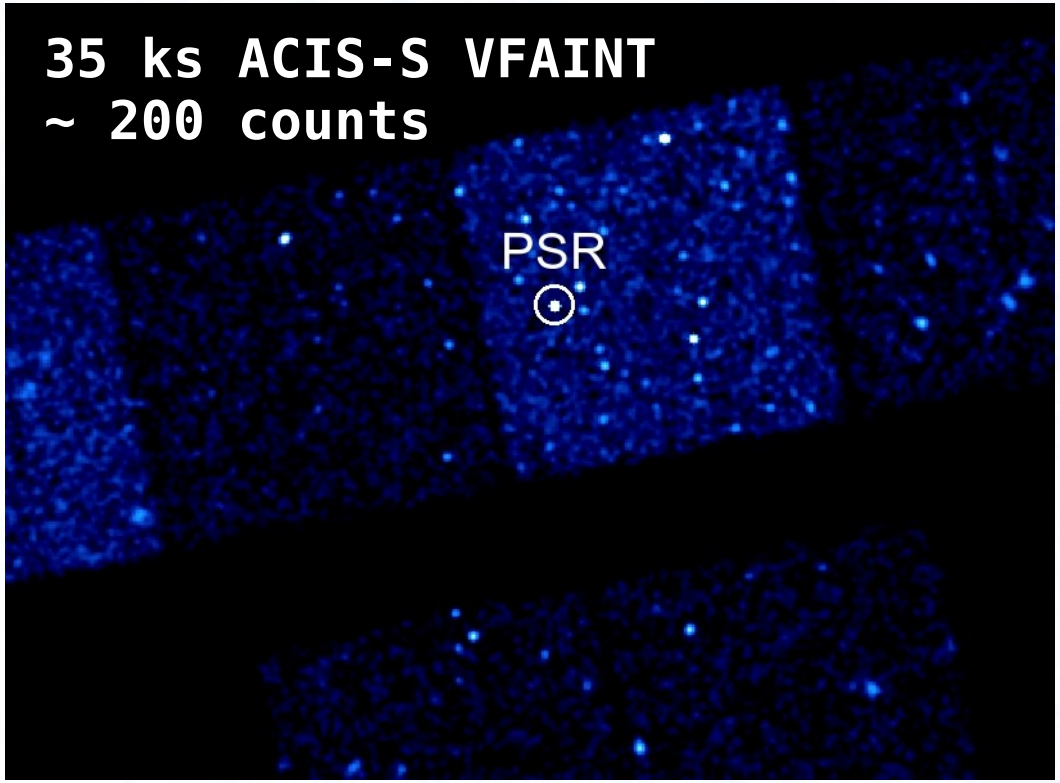
RA (J2000)= 14:56:00.071(6)
DEC(J2000)= -68:43:39.25(5)

MJD 50135

Refined Dispersion Measure:
DM = 8.557 ± 0.014 (2σ) cm^{-3} pc

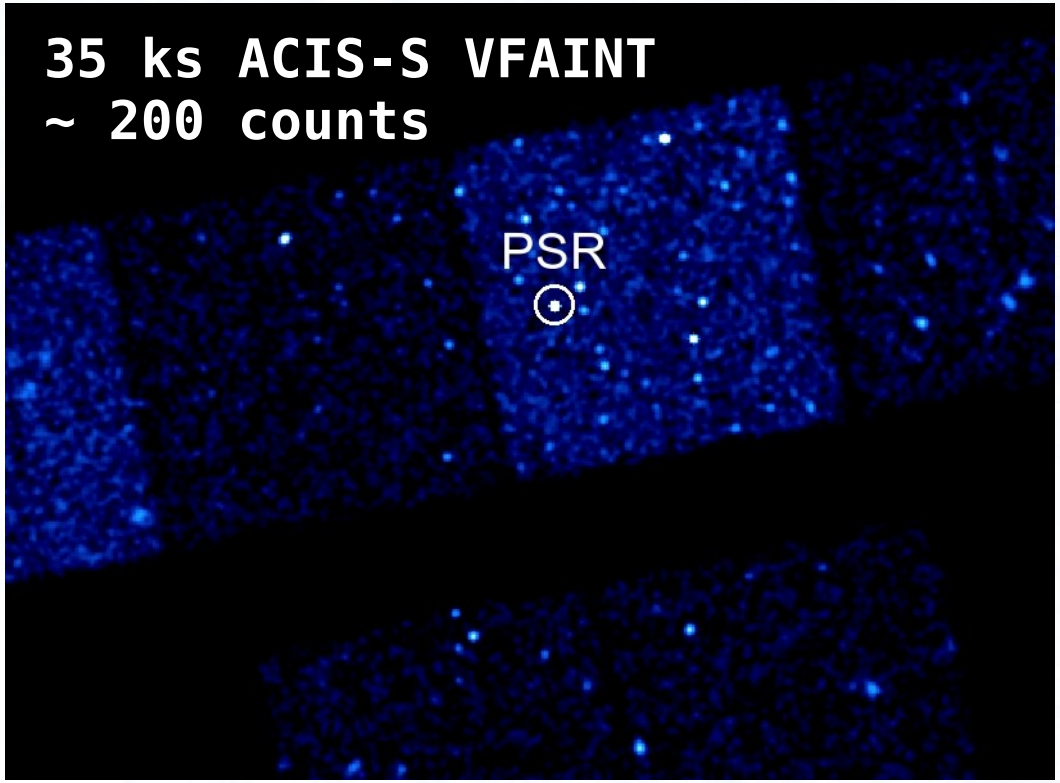
Expected $N(H)_{DM}$ = 2.6 10^{20} cm^{-2}

Chandra observations



ACIS time resolution not enough for timing (3.2 sec frame time)

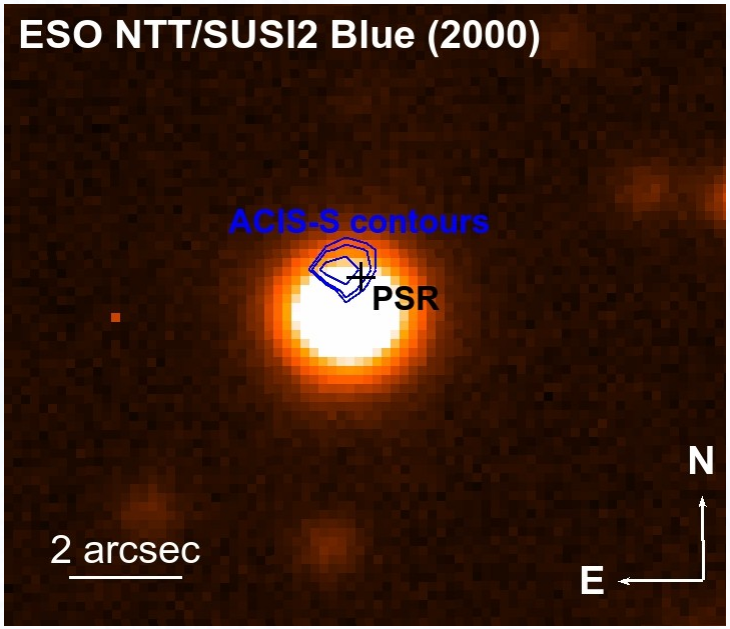
Chandra observations



Problem:

at ~0.7”

B ~ 17 mag
from colors (*JHKBV*)
probably G4-K2



Proper motion (Roeser et al. 2010)

$\mu_\alpha = -0.6 \pm 8.2$ mas yr^{-1}

$\mu_\delta = -1.9 \pm 8.2$ mas yr^{-1}

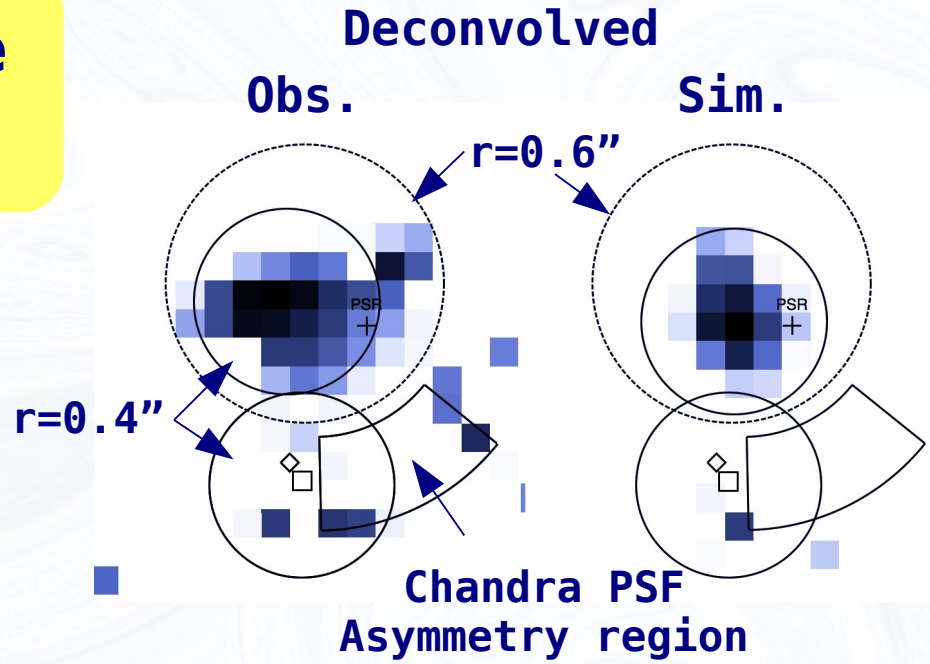
Chandra data analysis

- Refinement of astrometric solution
- Spatial distribution of count energies
- Deconvolution of subpixelised images
- Comparison with MARX simulations

star 0.78” from X-ray source
(rel. ast. unc. = 0.28”)

source too hard for G4-K2

flux contribution < 7%



Simple X-ray model fits for the pulsar

Power law fit: χ^2=0.4 for 10 d.o.f

N(H)= (2.5 ± 1.3) 10^{21} cm^{-2} Γ= 2.4 ± 0.4

Blackbody fit: χ^2=1.4 for 10 d.o.f

N(H) ≤ 1.1 10^{21} cm^{-2}

*k*T= 0.4 ± 0.06 keV r_{bb}(@450pc)= 12.4 ± 2.7 m

Blackbody & power law χ^2=0.5 for 8 d.o.f

N(H)= (1.7 ± 2.6) 10^{21} cm^{-2} Γ= 2.2 ± 1.0

*k*T= 0.3 ± 0.2 keV

expected $N(H)_{DM}$ = 2.6 10^{20} cm^{-2}

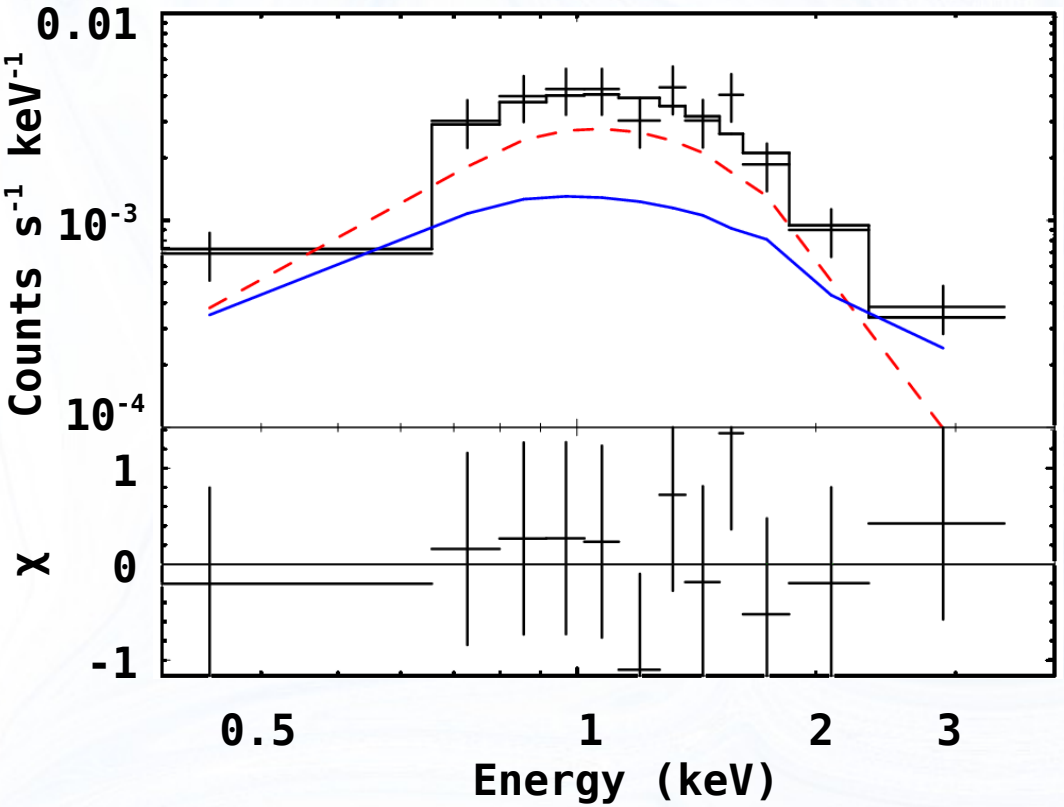
Galactic N(HI) = 1.6 10^{21} cm^{-2} *(Kalberla et al. 2005)*

Freezing N(H) at the DM-inferred value: $N(H) = 2.6\ 10^{20}\ cm^{-2}$

Power law fit: $\Gamma = 1.7 \pm 0.2$ χ^2=1.6 for 10 d.o.f

Blackbody fit: $kT = 0.4 \pm 0.06$ keV

r_{bb}(@450pc)$= 14.9 \pm 1.8$ m χ^2=1.4 for 10 d.o.f



Blackbody & power law

$\Gamma = 1.4 \pm 0.4$, and

$kT = 0.35 \pm 0.05$ keV,

r_{bb}(@450pc)$= 13.3^{+4.1}_{-6.1}$m

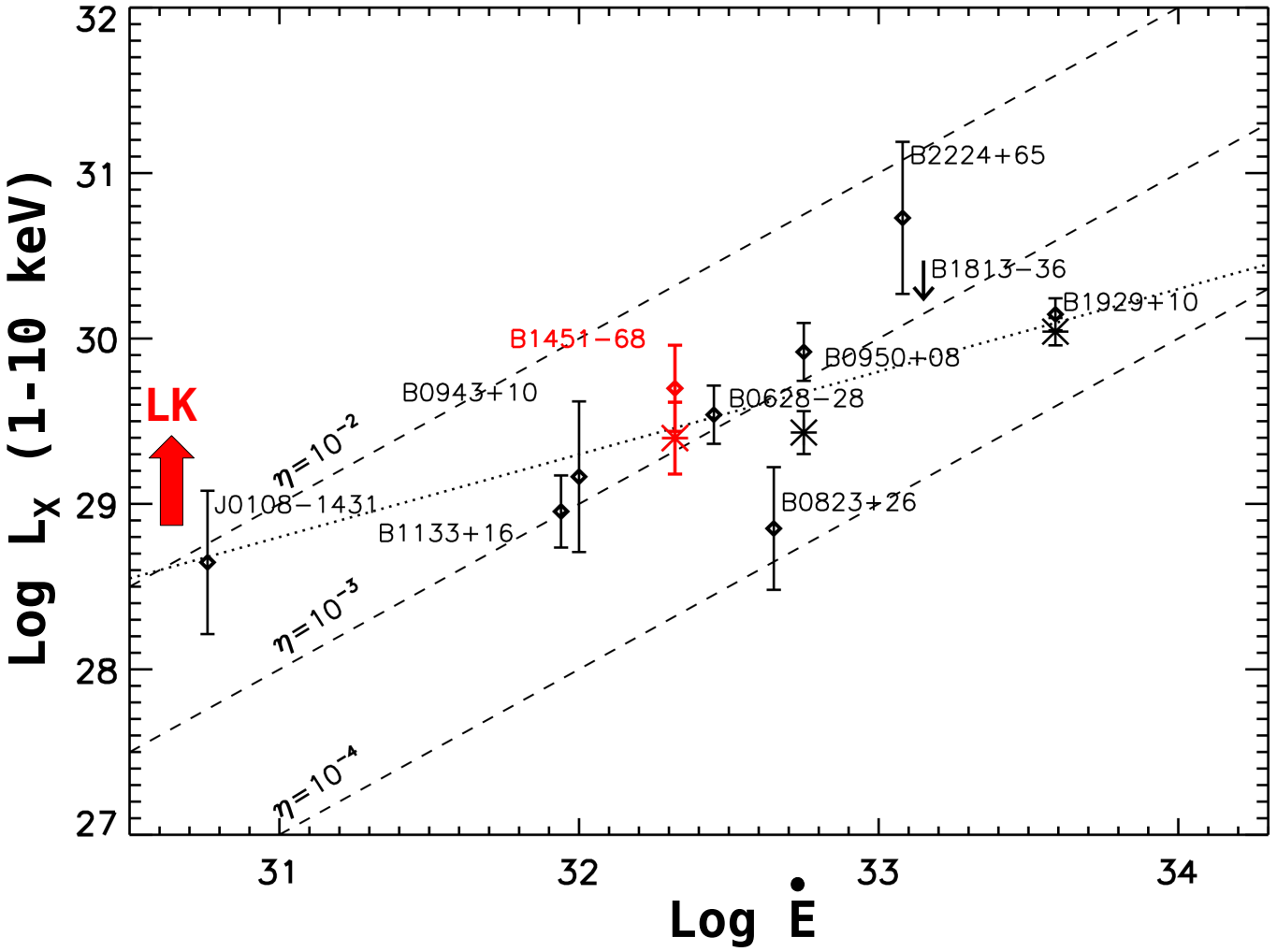
χ^2=0.5 for 9 d.o.f

F-test probability

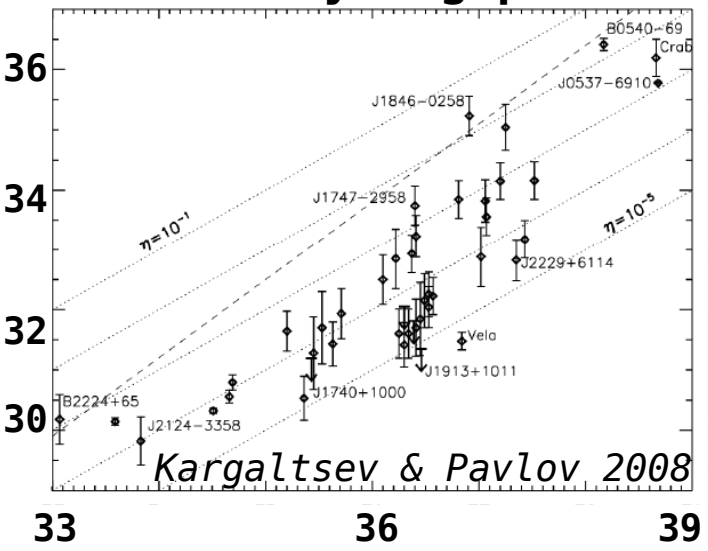
for improvement comparing to PL fit: 99.4%

conventional PC radius R_{PC} ~ 280 m

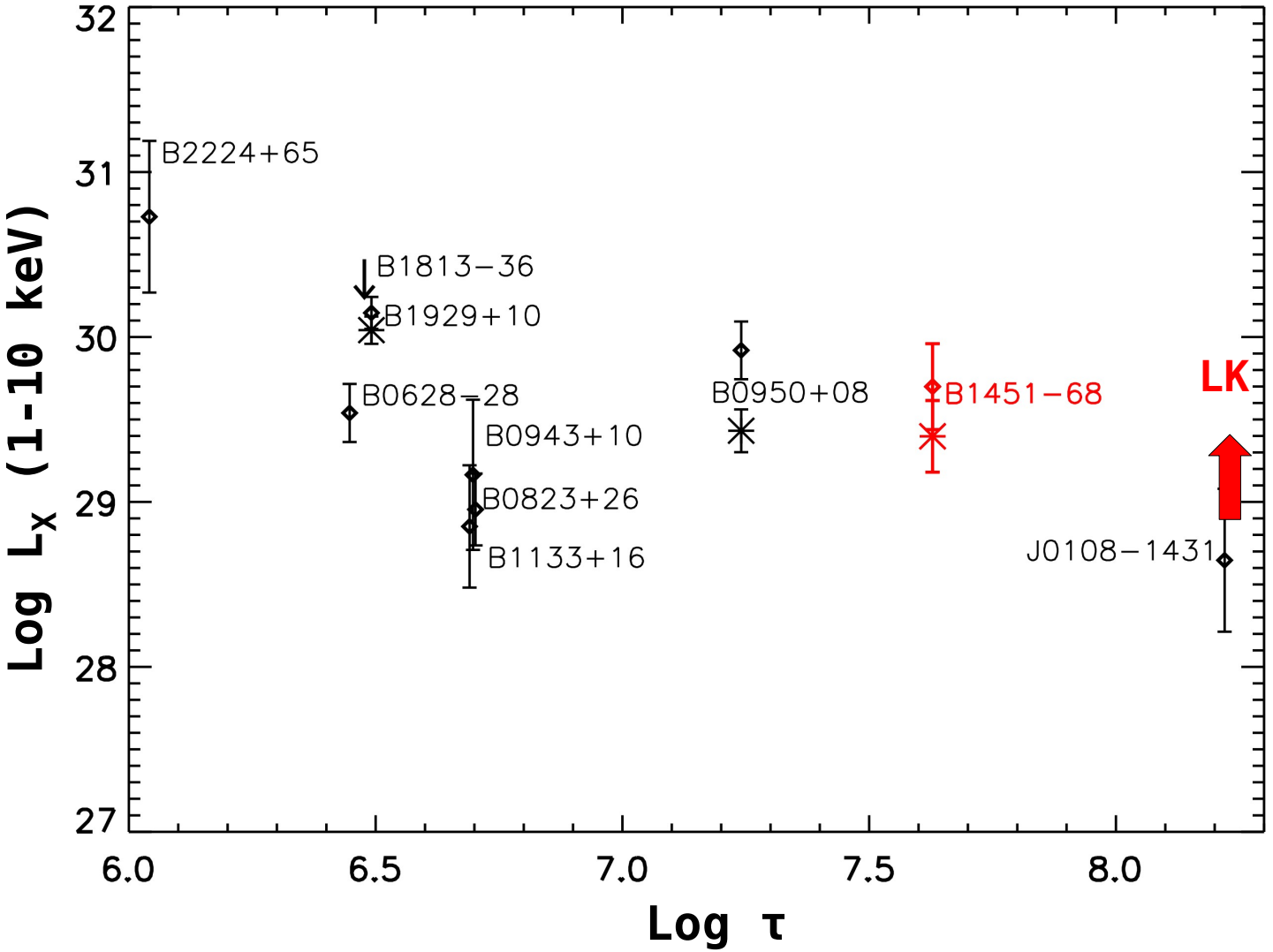
The X-ray efficiency



Reminder: young pulsars



Age dependancy ?



Conclusions

The X-ray spectrum of PSR B1451-68 is consistent with both:

highly absorbed magnetospheric emission
or
reasonably absorbed thermal + non-thermal components

X-ray emission of old pulsars in general

- often – not enough counts to differentiate between models
- $N(H)_{DM}$ & pulsar parallax together provide helpful constraints
- several explanations for $r_{PC} < R_{PC}$ possible
- change towards higher efficiencies / flatter efficiency slope ?
- no obvious age effect on X-ray efficiency

need more X-ray observations / counts of old pulsars !
need more radio parallaxes of old pulsars !