The Magnificent Seven – Similarities and Differences

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The discovery of thermal, radio quiet isolated neutron stars

New XMM-Newton and Chandra observations

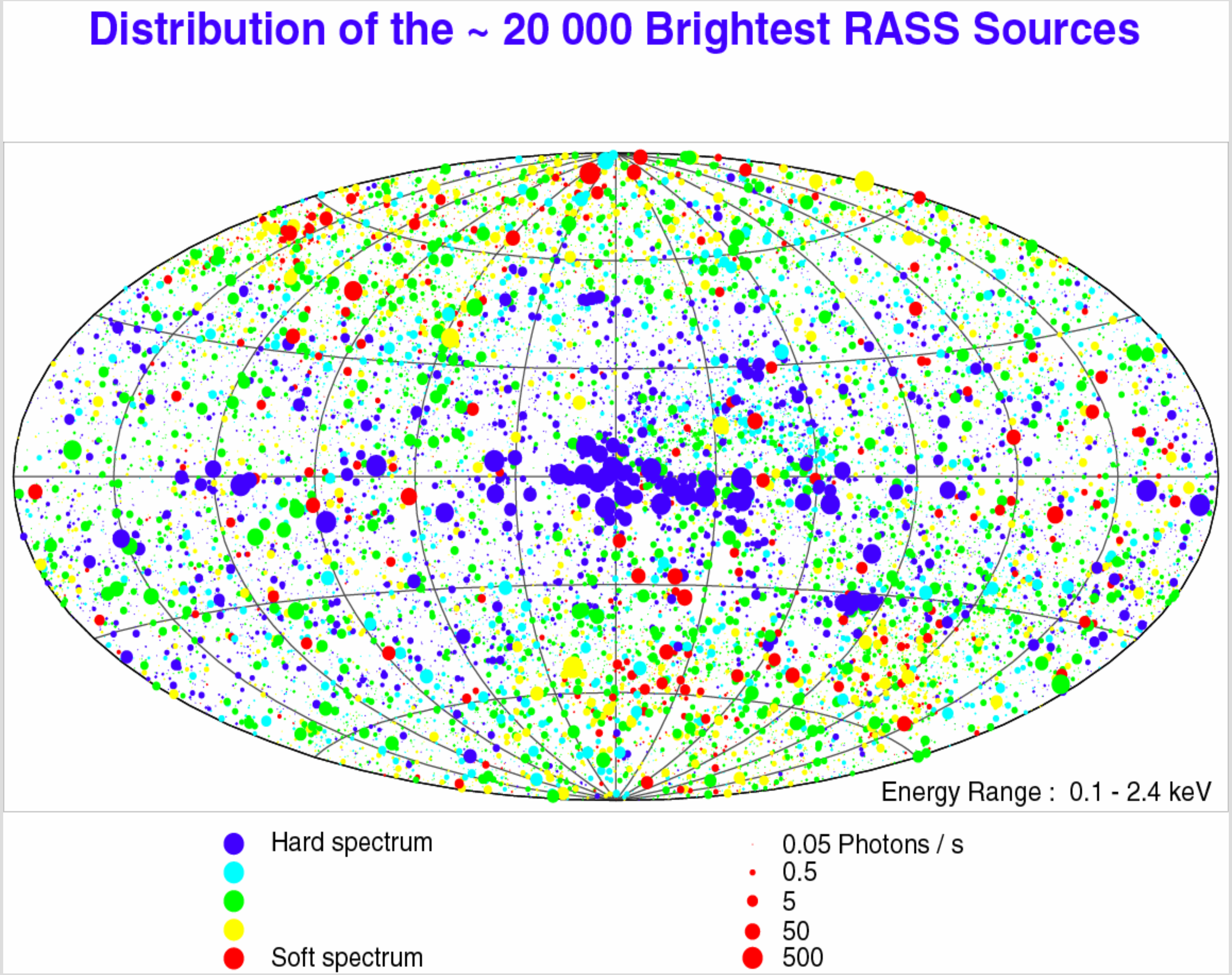
- **The case of RX J1856.5–3754**
- **Absorption features in the X-ray spectra**
    - **Magnetic field estimates**
    - **Pulse phase spectroscopy**
- **The case of RX J0720.4-3125**
    - **Spectral variations on long-term time scales**
    - **Evidence for free precession**

363rd Heraeus-Seminar

Neutron Stars and Pulsars: About 40 years after the discovery

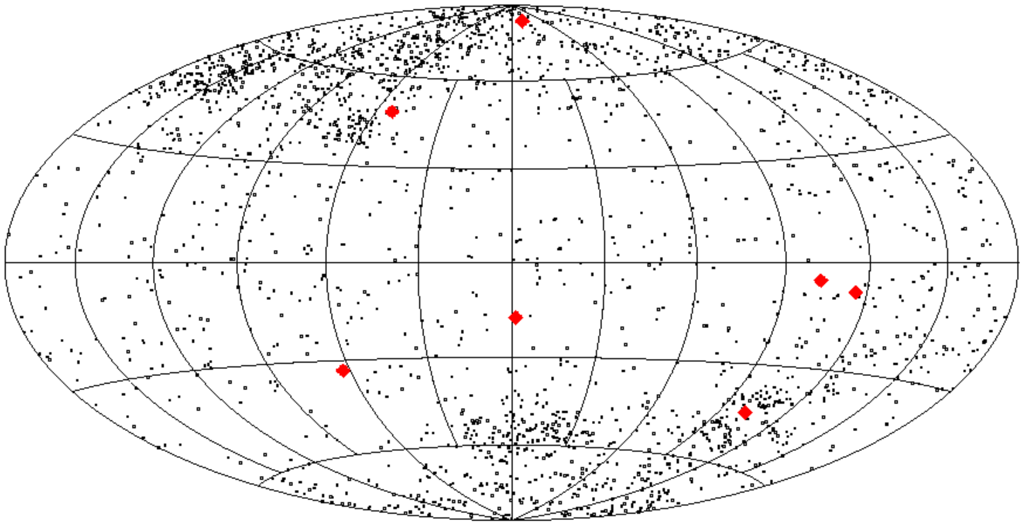
May 14 - 19, 2006 Bad Honnef (Germany)

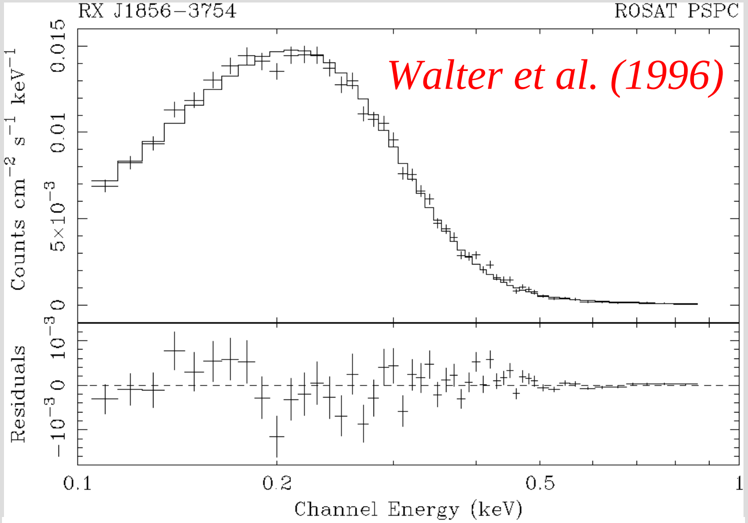
Searching for INSs in the ROSAT All-Sky Survey

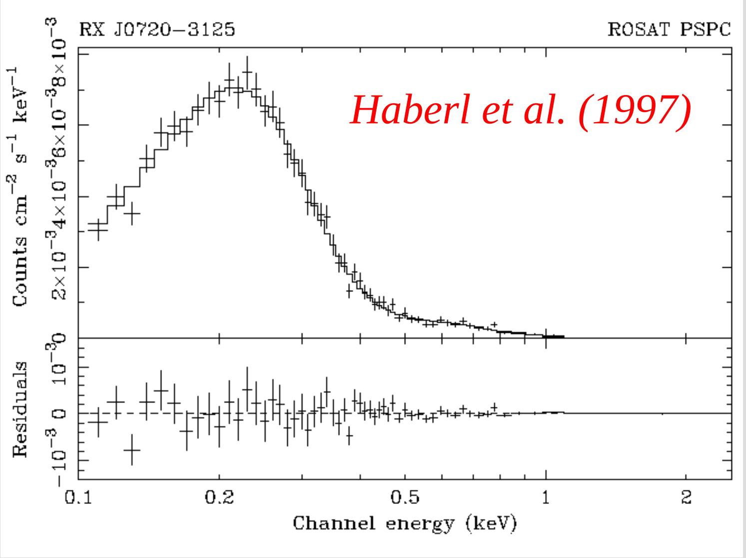


The Magnificent Seven: Thermal, radio-quiet neutron stars

Soft X-ray spectrum + faint in optical







PSPC cts/s	HR1	HR2	Name
0.15 ± 0.01	-0.96 ± 0.03	-0.45 ± 0.73	RX J0420.0-5022
0.23 ± 0.03	-0.06 ± 0.12	-0.60 ± 0.17	RBS1774 = 1RXS J214303.7+065419
0.29 ± 0.02	-0.20 ± 0.08	-0.51 ± 0.11	RBS1223 = 1RXS J130848.6+212708
0.38 ± 0.03	-0.74 ± 0.02	-0.66 ± 0.08	RX J0806.4-4123
0.78 ± 0.02	-0.67 ± 0.02	-0.68 ± 0.04	RBS1556 = RX J1605.3+3249
1.82 ± 0.02	-0.82 ± 0.01	-0.77 ± 0.03	RX J0720.4-3125
3.08 ± 0.02	-0.96 ± 0.01	-0.94 ± 0.02	RX J1856.5-3754

Thermal, radio-quiet isolated neutron stars

- Soft X-ray sources in ROSAT survey
- Blackbody-like X-ray spectra, NO non-thermal hard emission
- Low absorption ~10^{20} H cm^{-2}, nearby (parallax: RX J1856.5-3754, RX J0720.4-3125)
- Luminosity ~10^{31} erg s^{-1}
- Constant X-ray flux on time scales of years
- No obvious association with SNR
- No (faint?) radio emission (RBS1223, RBS1774)
- Optically faint
- Some (all?) are X-ray pulsars (3.45 – 11.37 s)

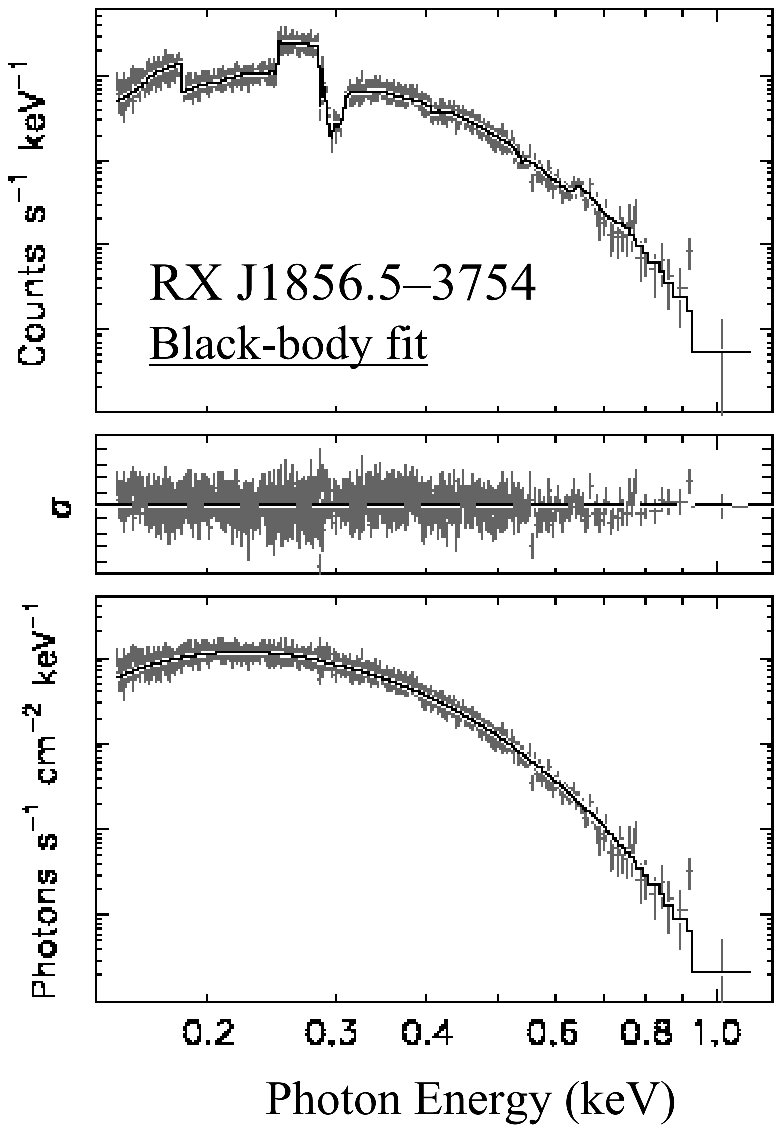
Best candidates for „genuine“ cooling INSs with undisturbed emission from stellar surface

Object	kT/eV	P/s	Optical	
RX J0420.0–5022	44	3.45	B = 26.6	
RX J0720.4–3125	85-95	8.39	B = 26.6	PM = 97 mas/y
RX J0806.4–4123	96	11.37	B > 24	
RBS 1223 (*)	86	10.31	m_{50ccd} = 28.6	
RX J1605.3+3249	96	6.88?	B = 27.2	PM = 145 mas/y
RX J1856.5–3754	62	–	V = 25.7	PM = 332 mas/y
RBS 1774 (**)	102	9.44	B > 26	

(*) 1RXS J130848.6+212708   (**) 1RXS J214303.7+065419

The case of RX J1856.5–3754

Chandra LETGS



$n_H = (9.5 \pm 0.03) \cdot 10^{19}$ cm

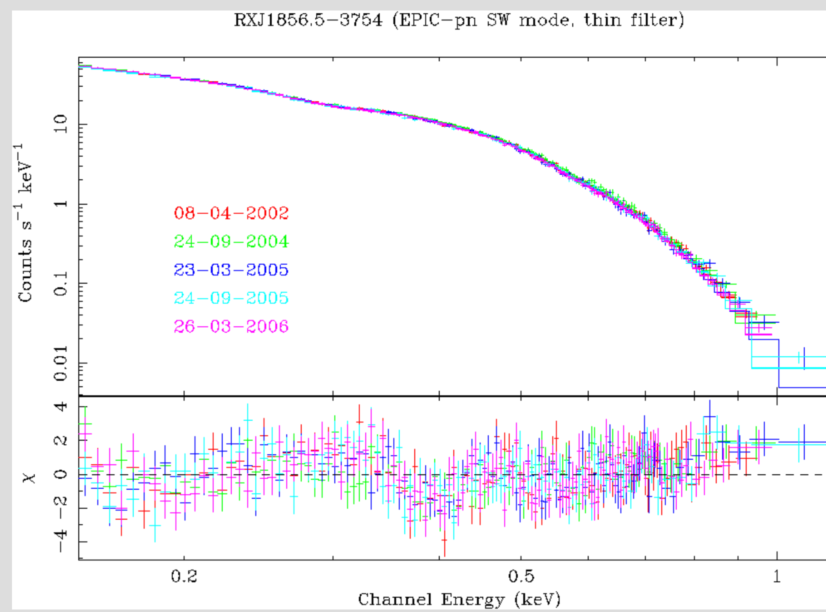
$kT_\infty = 63.5 \pm 0.2$ eV

$R_\infty = 4.4 \pm 0.1$ km (120pc)

$L_{bol} = 4.1 \cdot 10^{31}$ erg s^{-1}

No narrow absorption features !

Burwitz et al. (2003)

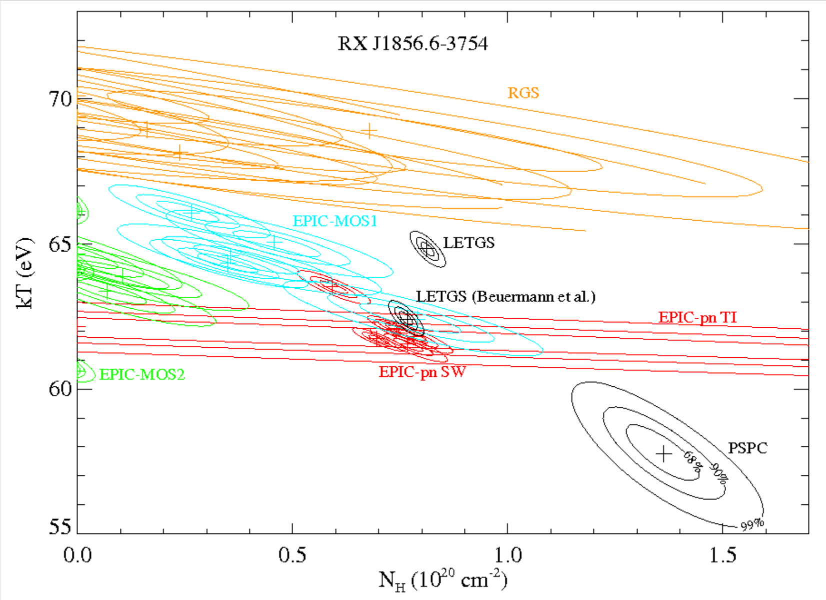


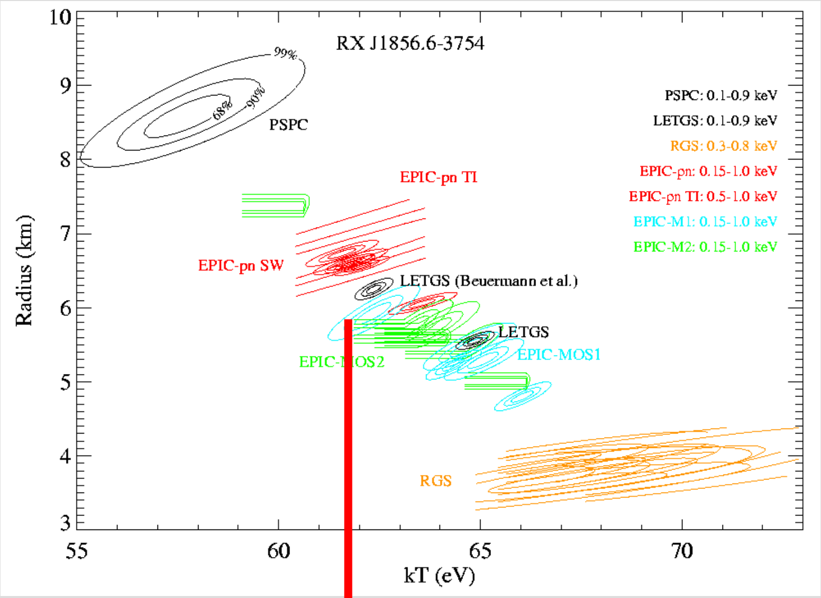
XMM EPIC-pn

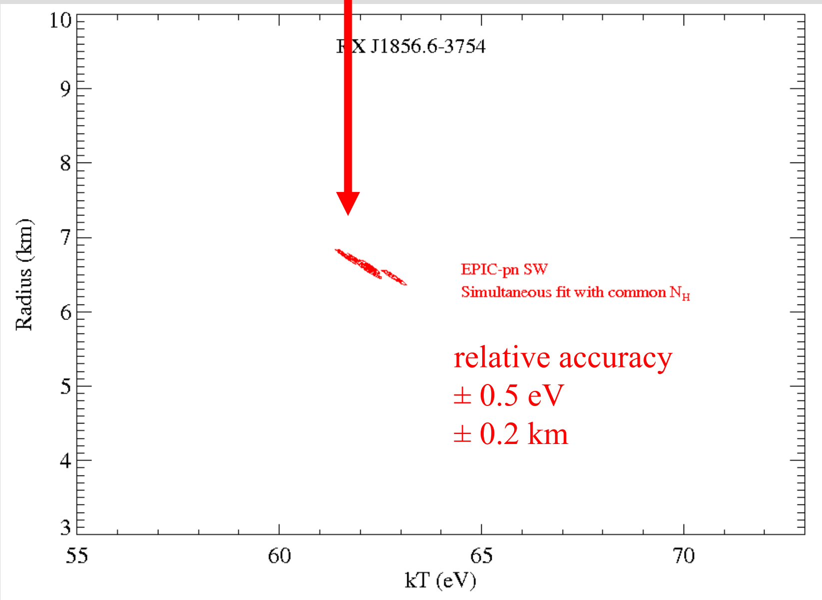
Spectrum constant over time scales of years

Haberl (2006)

The case of RX J1856.5–3754 (II)

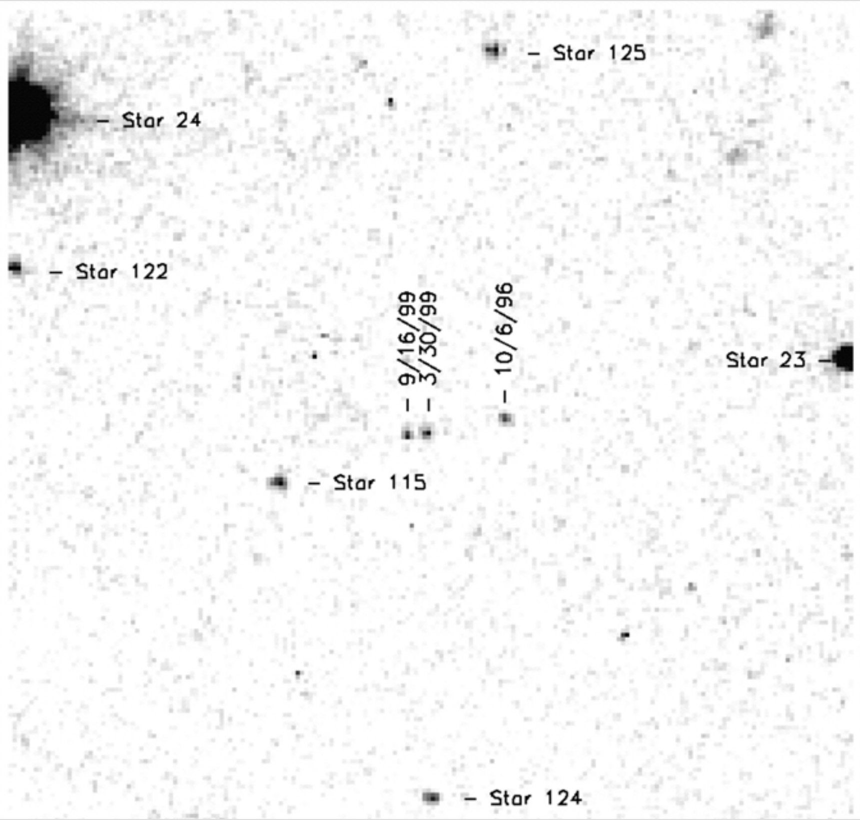






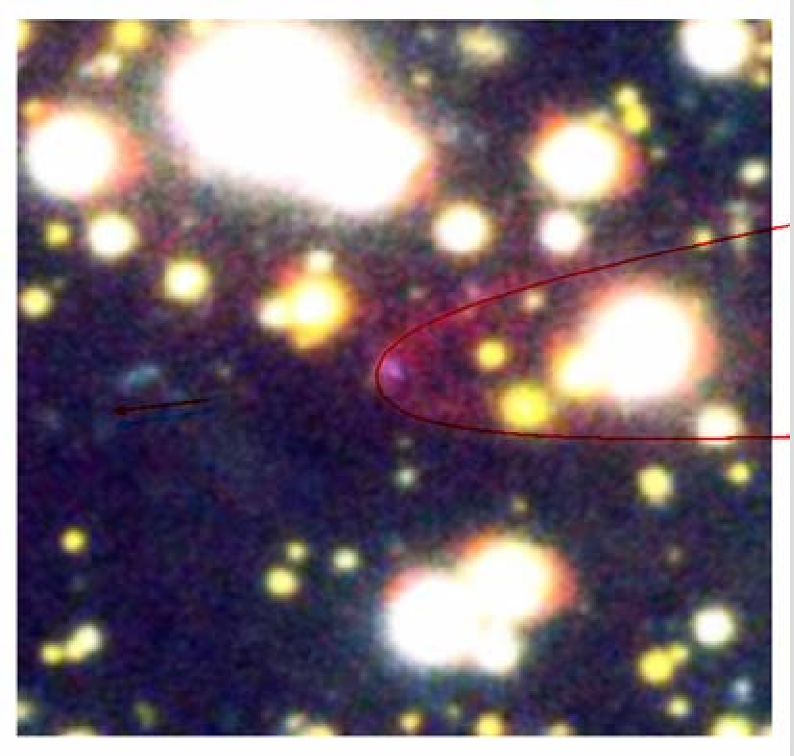
- Low column density requires energies down to 0.1-0.15 keV
- No full agreement between different instruments yet
- For broad band spectroscopy EPIC-pn has largest sensitivity and is the most stable instrument

RX J1856.5-3754: optical



Distance 117 ± 12 pc HST

High proper motion:
Not heated by accretion of ISM !!
Cooling isolated neutron star



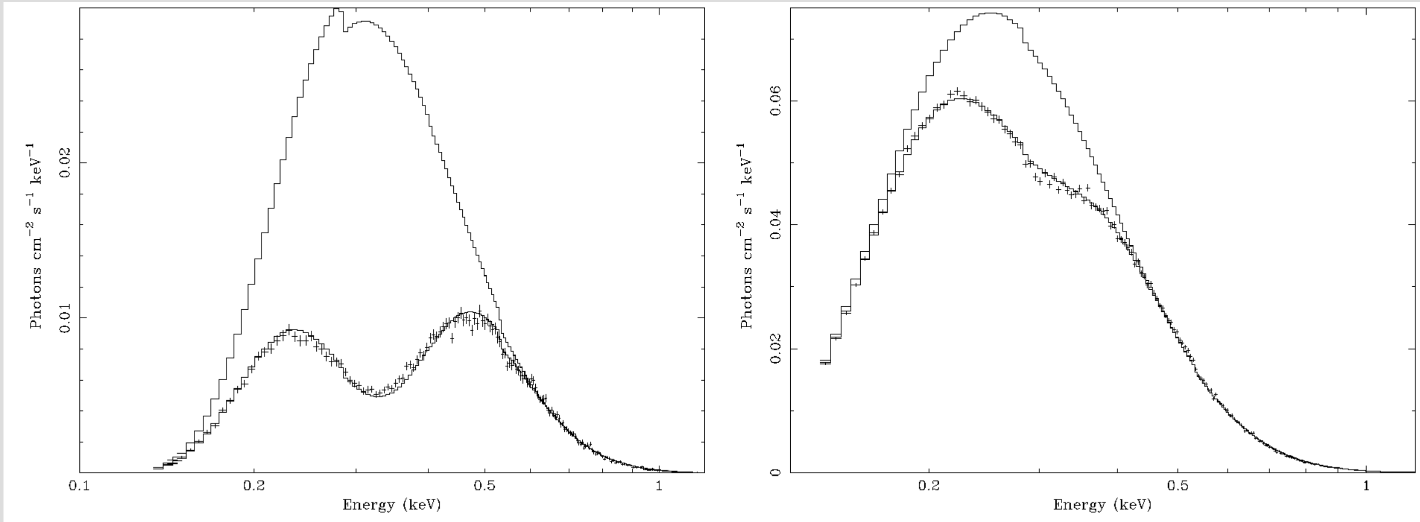
Bowshock Nebula VLT

Powered by magnetic dipole braking:
$dE/dt = 4.5 \times 10^{32}$ erg s^{-1}, $t = 5 \times 10^{5}$ y
$B \approx 10^{13}$ G

Braje & Romani (2002)
Trümper et al. (2004)

XMM-Newton observations of the Mag7: absorption features

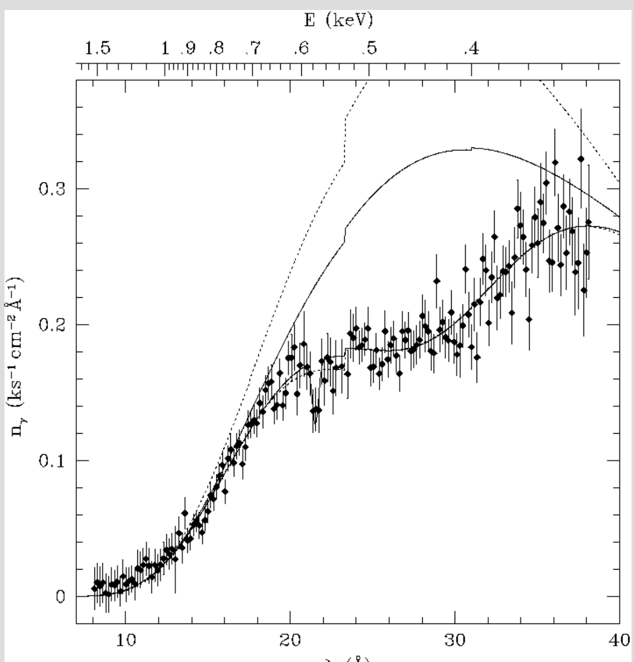
RBS 1223
EW = 150 eV
Pulse phase variations



XMM-Newton EPIC-pn

RX J0720.4-3125
EW = 40 eV variable with pulse phase and over years

XMM-Newton RGS

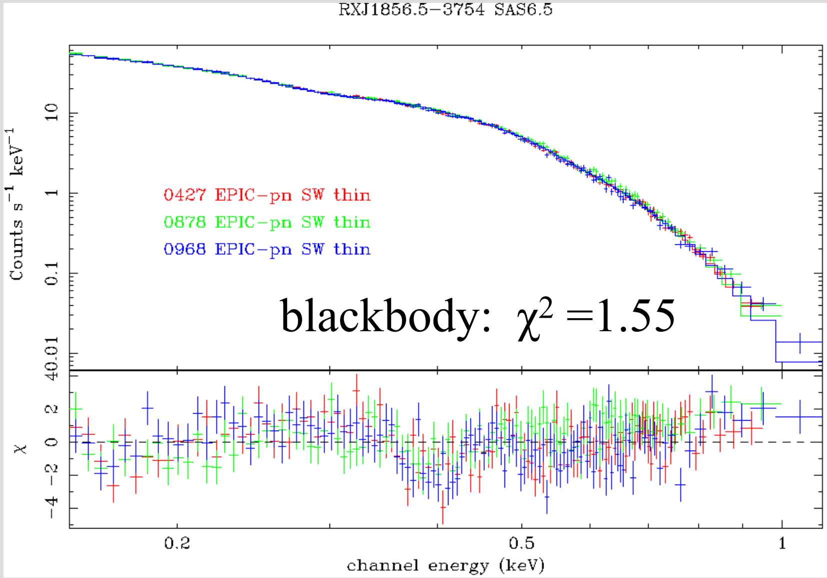


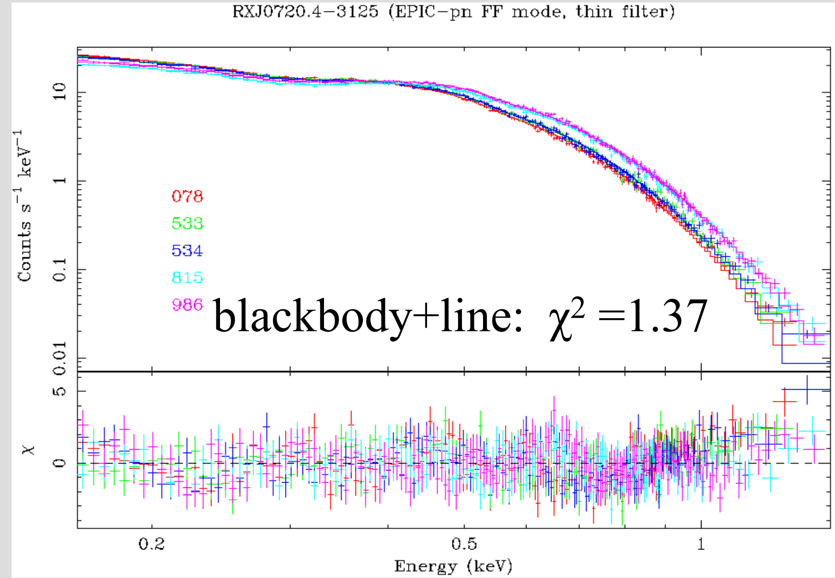
RX J1605.3+3249
RGS
kT = 95 eV
$N_H = 0.8 \cdot 10^{20}$ cm^{-2}
$E_{line} = 450 - 480$ eV

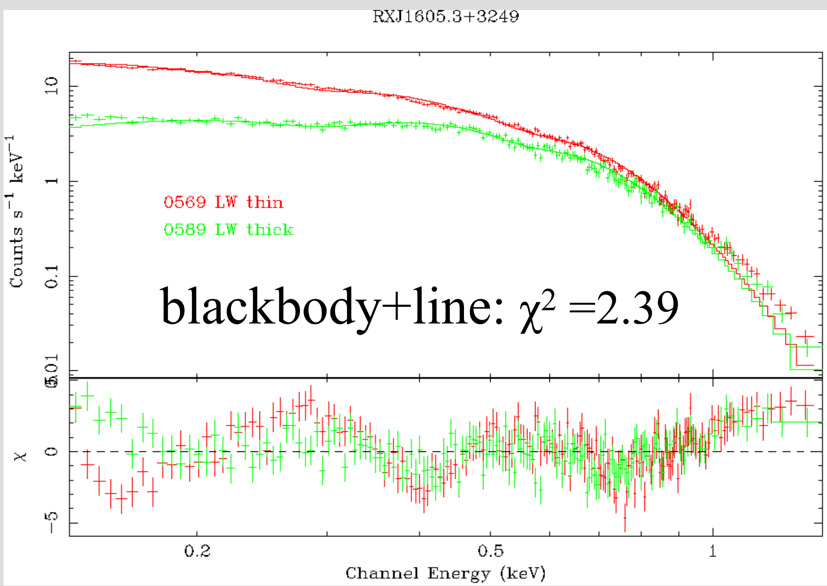
Van Kerkwijk et al. (2004)

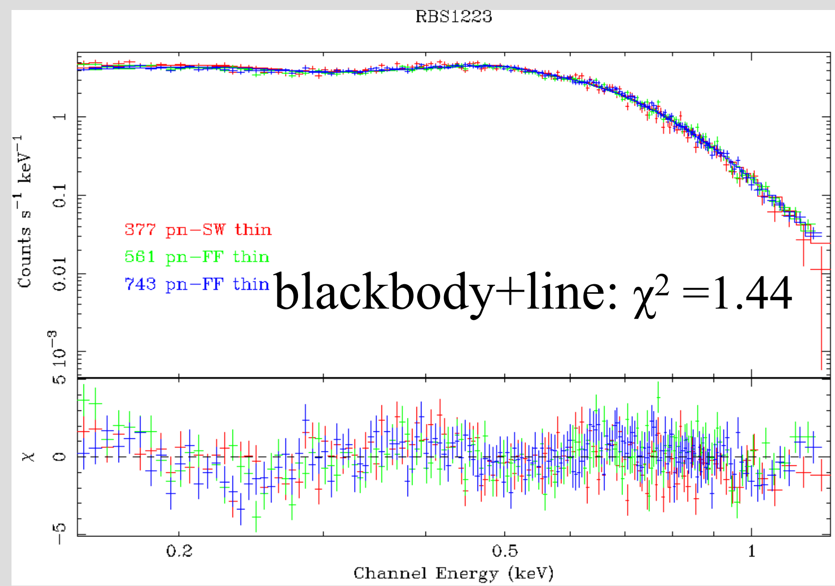
Proton cyclotron absorption lines ?
Atomic line transitions ?
Mixture ?
In any case $B \approx 10^{13} - 10^{14}$ G

Evidence for multiple lines:

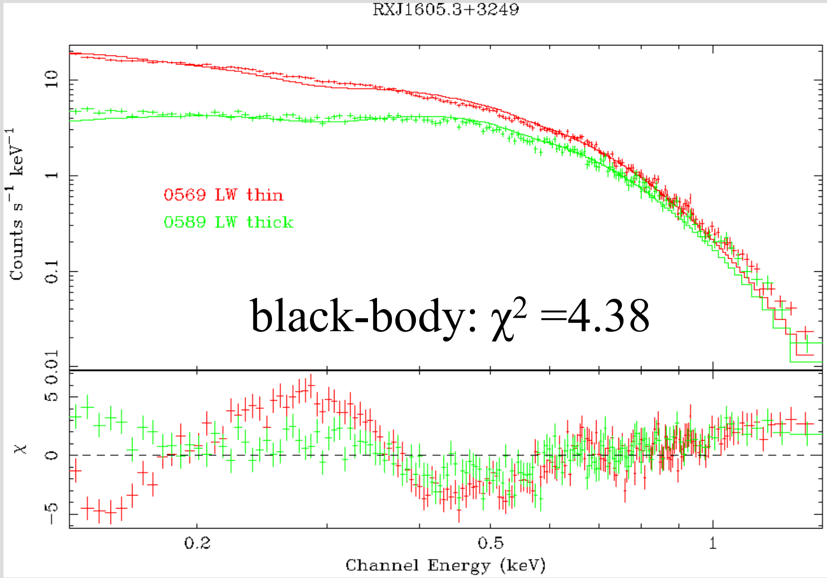


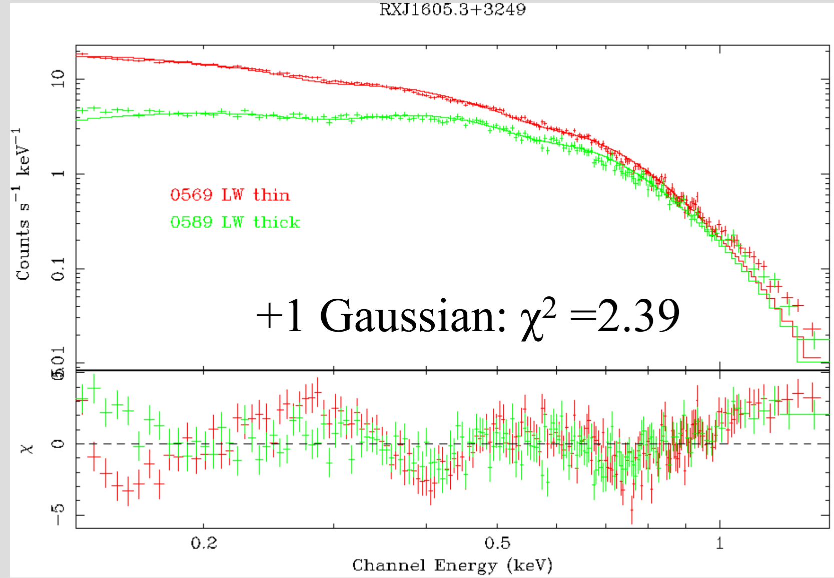


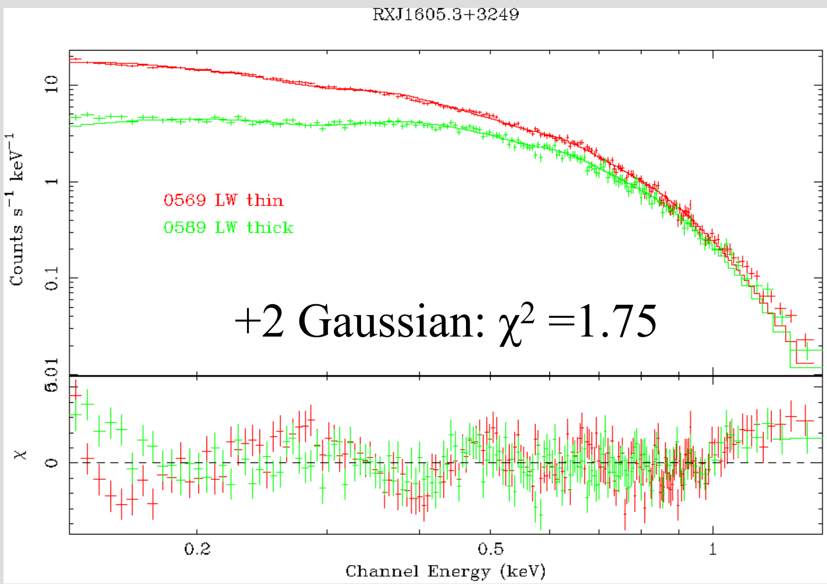


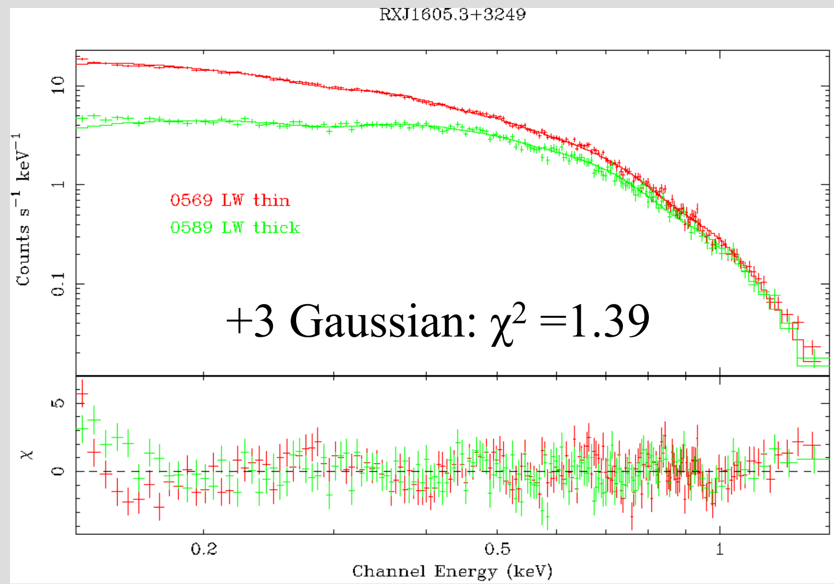


RX J1605.3+3249: Evidence for three lines









RX J1605.3+3249: Three absorption lines with regular energy spacing

Line energies:

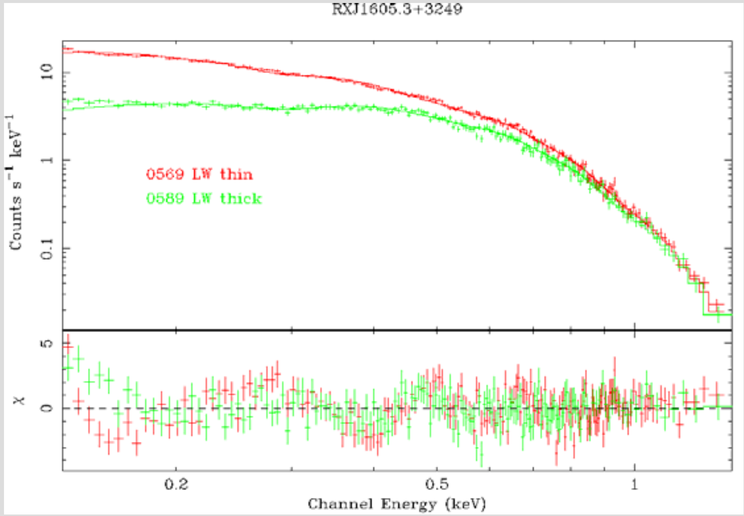
$E_1 = 403 \pm 2$ eV
$E_2 = 589 \pm 4$ eV
$E_3 = 780 \pm 24$ eV
$E_2/E_1 = 1.46 \pm 0.02$
$E_3/E_1 = 1.94 \pm 0.06$
$E_3/E_2 = 1.32 \pm 0.04$

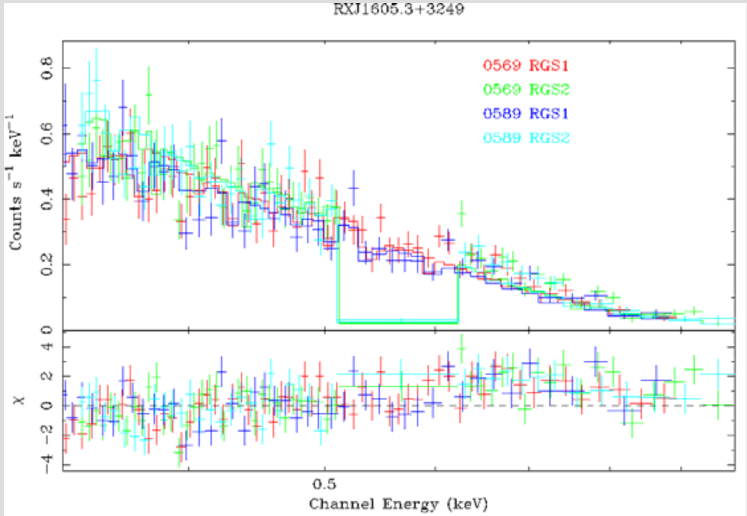
$E_1 : E_2 : E_3 = 1 : 1.5 : 2$

Absorbed line fluxes:

$N_1 = -(4.3 \pm 0.1) \cdot 10^{-3}$ ph/cm²/s $EQW_1 = 96$ eV
$N_2 = -(8.0 \pm 0.8) \cdot 10^{-4}$ ph/cm²/s $EQW_2 = 76$ eV
$N_3 = -(1.6 \pm 0.4) \cdot 10^{-5}$ ph/cm²/s $EQW_3 = 67$ eV
$N_1/N_2 = 5.38 \pm 0.54$
$N_2/N_3 = 5.00 \pm 1.35$

$N_1 : N_2 : N_3 \sim 25 : 5 : 1$
(common line $\sigma = 87$ eV)



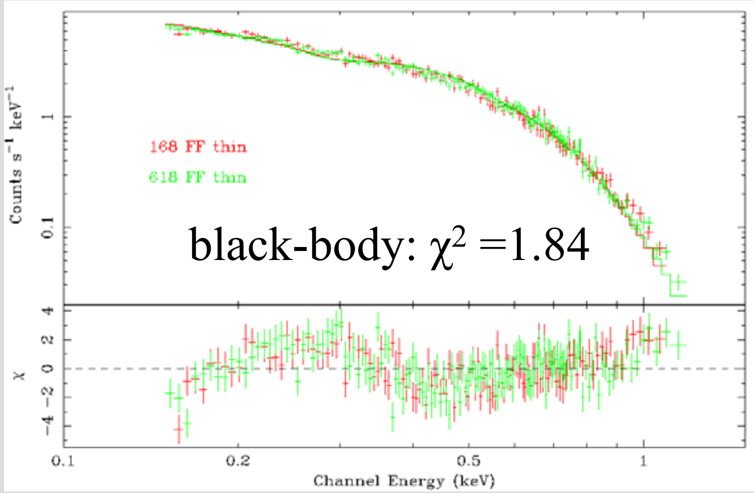


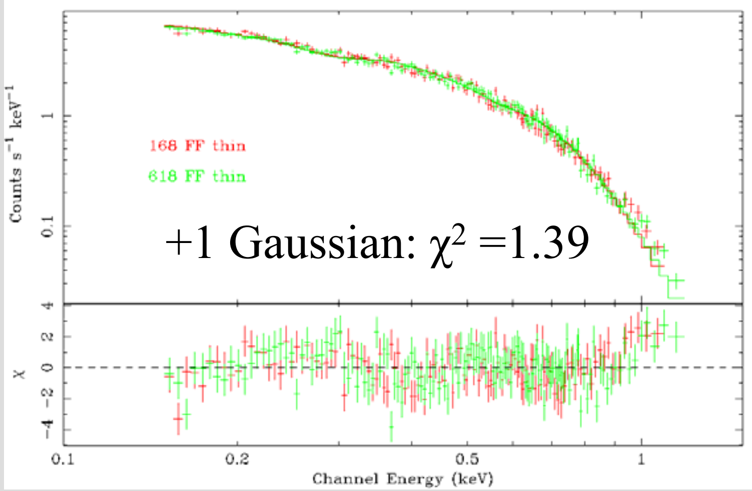
Proton cyclotron absorption: the deepest line?
(in the case of proton scattering harmonics should be greatly suppressed)
In addition atomic line transitions?
Pure hydrogen ruled out?

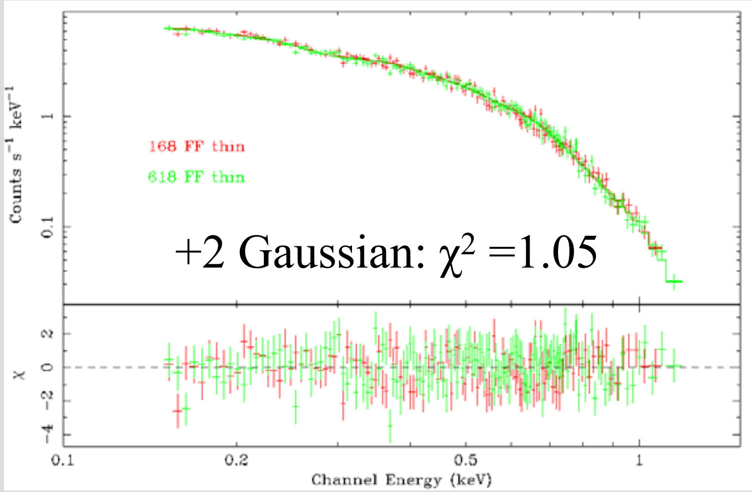
More multiple lines ?

RBS1223: Evidence for lines at 230 eV and at 460 eV (Schwope et al. 2006, London)

RX J0806.4-4123:







One line:

E_1 **= 433 ± 16 eV**

σ_1 **= 100 eV fixed**

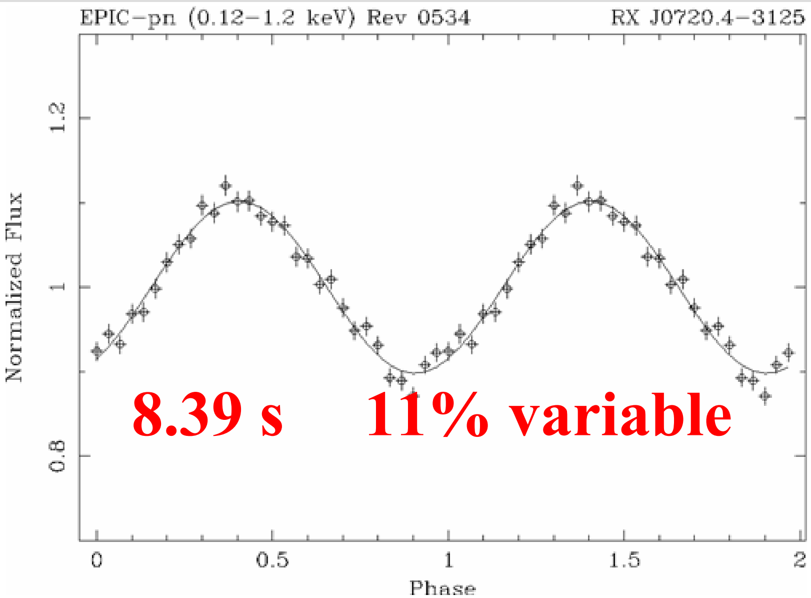
Two lines:

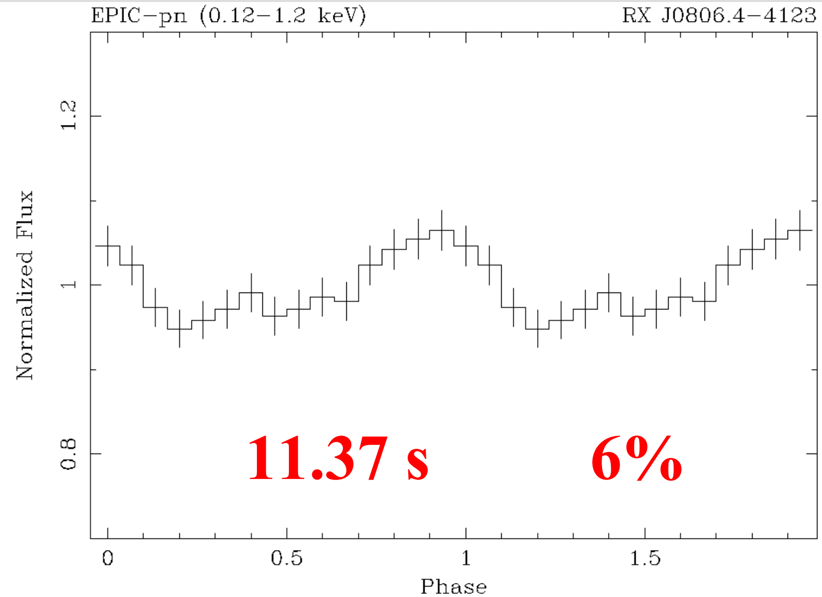
E_1 **= 306 ± 3 eV** E_2 **= 612 eV (linked to** E_1**)**

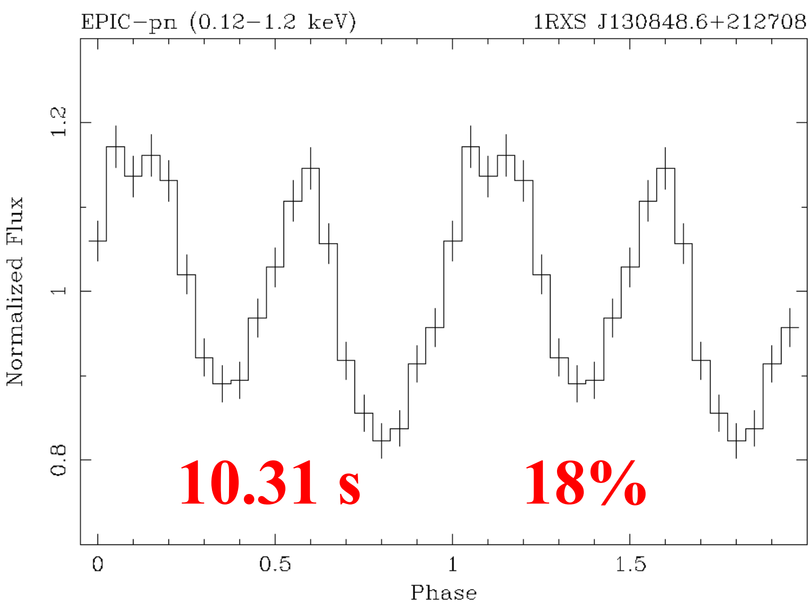
$\sigma_1 = \sigma_2$ **= 139 ± 6 eV**

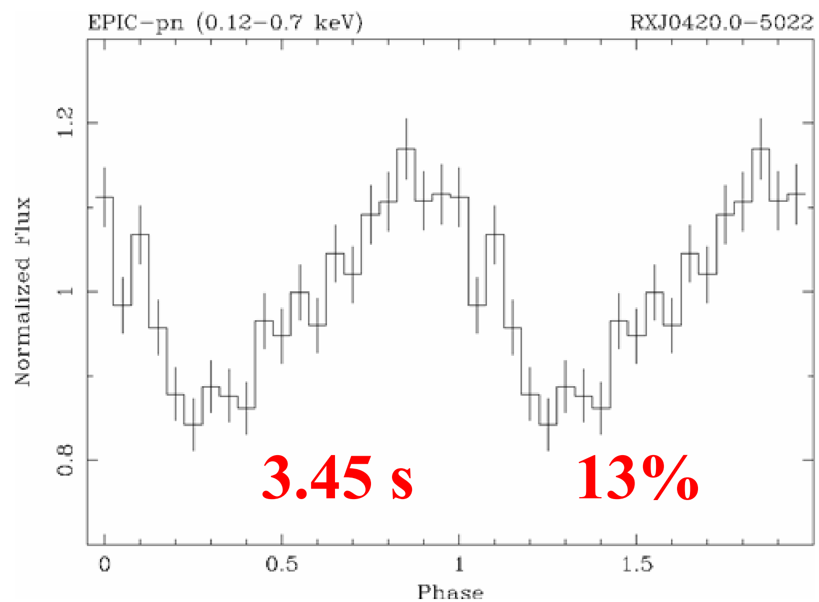
N_1/N_2 **= 16.6**

X-ray pulsations

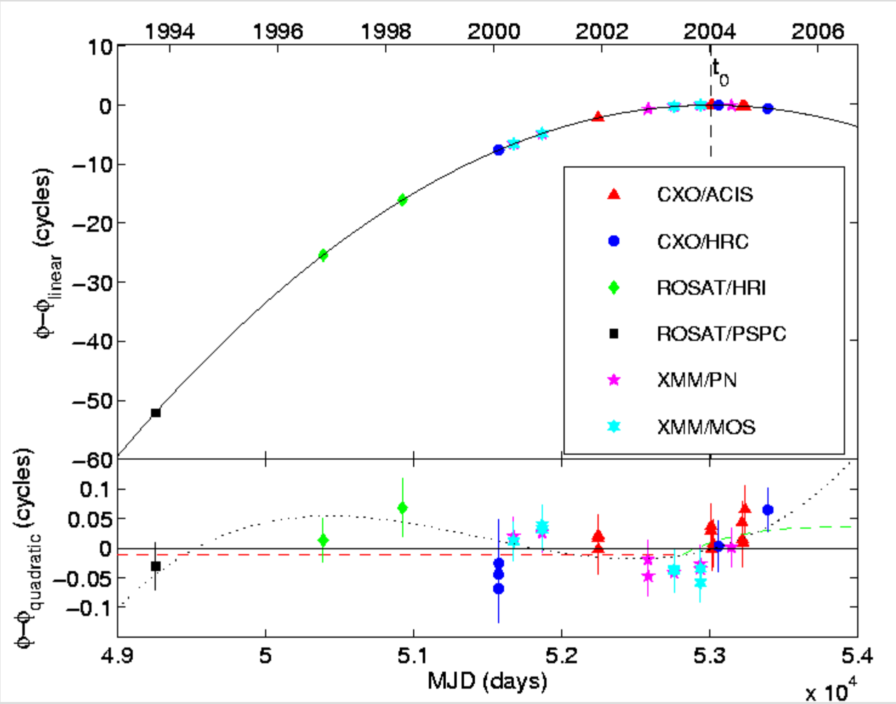


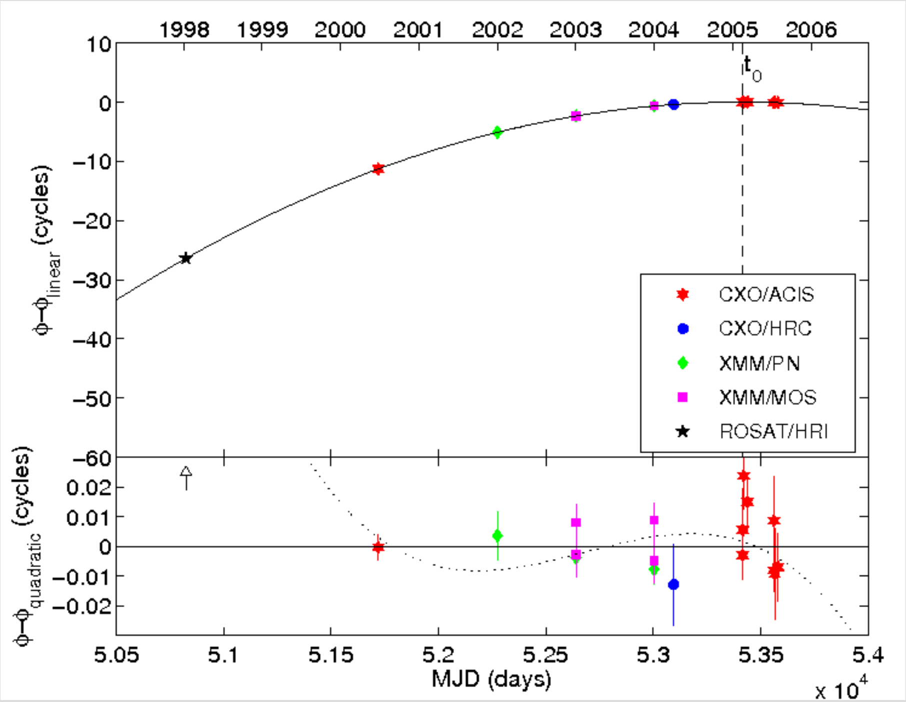






Period history: RX J0720.4–3125 and RBS 1223





P = 8.39 s

dP/dt = $(0.698 \pm 0.002) \cdot 10^{-13}$ s s^{-1}

τ = P/2(dP/dt) = $1.9 \cdot 10^{6}$ y

B = $2.4 \cdot 10^{13}$ G

Kaplan & van Kerkwijk 2005
ApJ 628, L45

P = 10.32 s

dP/dt = $(1.120 \pm 0.003) \cdot 10^{-13}$ s s^{-1}

τ = P/2(dP/dt) = $1.5 \cdot 10^{6}$ y

B = $3.4 \cdot 10^{13}$ G

Kaplan & van Kerkwijk 2005
ApJ 635, L65

Magnetic fields

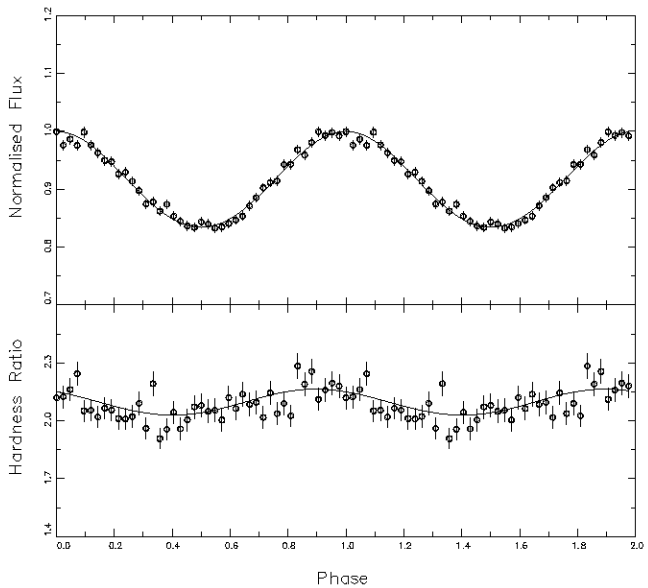
Unique opportunity to estimate B in two independent ways:

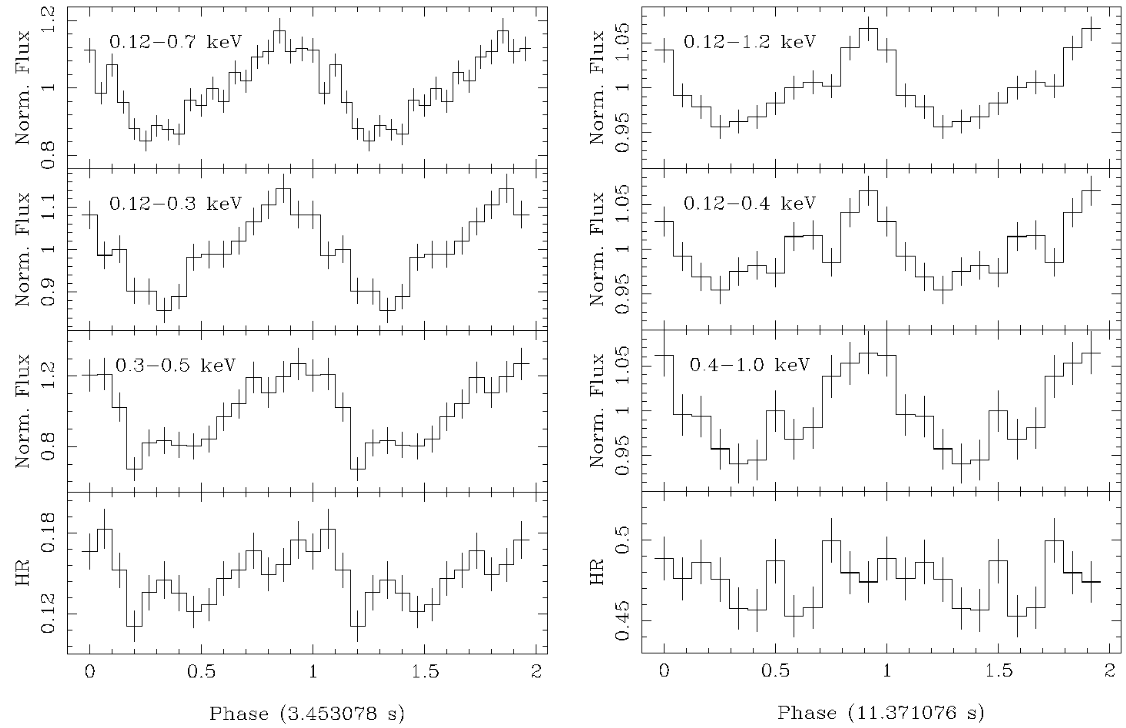
- **Magnetic dipole braking → $B = 3.2 \times 10^{19} (P \times dP/dt)^{1/2}$**
  Spin-down rate (P, dP/dt)
  Spin-down luminosity required to power the Hα nebula (dE/dt, τ)
- **Proton cyclotron absorption → $B = 1.6 \times 10^{11} E(eV)/(1-2GM/c^2R)^{1/2}$**

Object	P [s]	Semi Ampl.	dP/dt [10^{-13} ss^{-1}]	E_{cyc} [eV]	B_{db} [10^{13} G]	B_{cyc} [10^{13} G]
RX J0420.0–5022	3.45	13%	< 92	?	< 18	
RX J0720.4–3125	8.39	8-15%	0.698(2)	280	2.4	5.6
RX J0806.4–4123	11.37	6%	< 18	430/306[a)]	< 14	8.6/6.1
1RXS J130848.6+212708	10.31	18%	1.120(3)	300/230[a)]	3.4	6.0/4.6
RX J1605.3+3249				450/400[b)]		9/8
RX J1856.5–3754				–	~1[c)]	
1RXS J214303.7+065419	9.43	4%	<60[d)]	750	< 24[d)]	15

a) Spectral fit with single line / two lines
b) With single line / three lines at 400 eV, 600 eV and 800 eV
c) Estimate from Hα nebula assuming that it is powered by magnetic dipole breaking
d) Radio detection: Malofeev et al. 2006, ATEL 798

Spectral variations with pulse phase





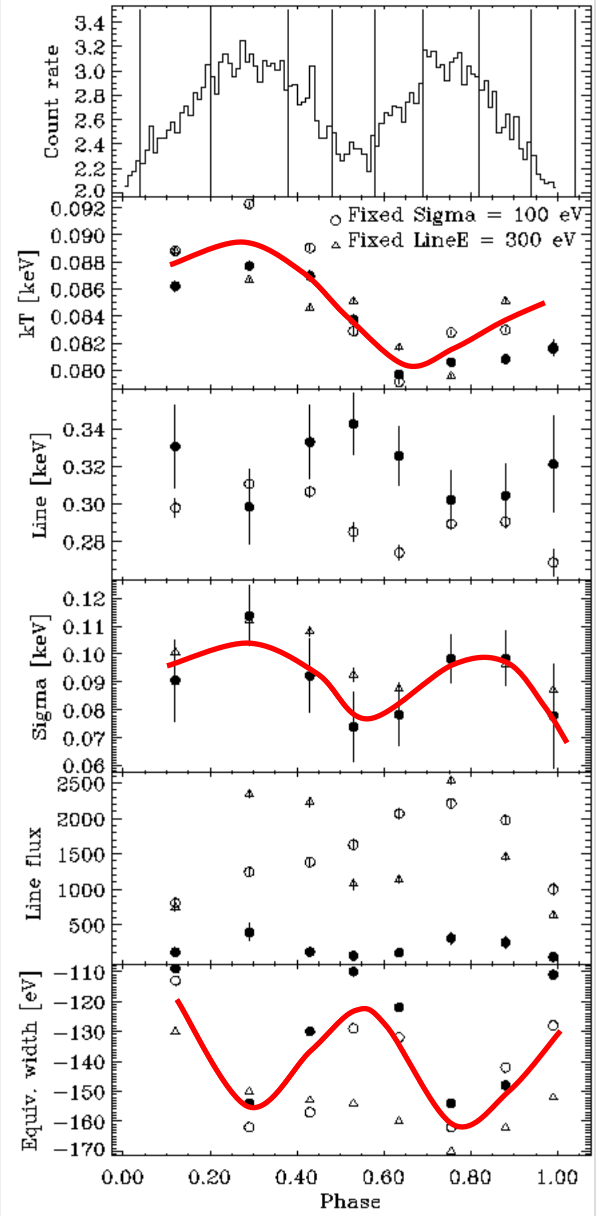
RX J0720.4-3125

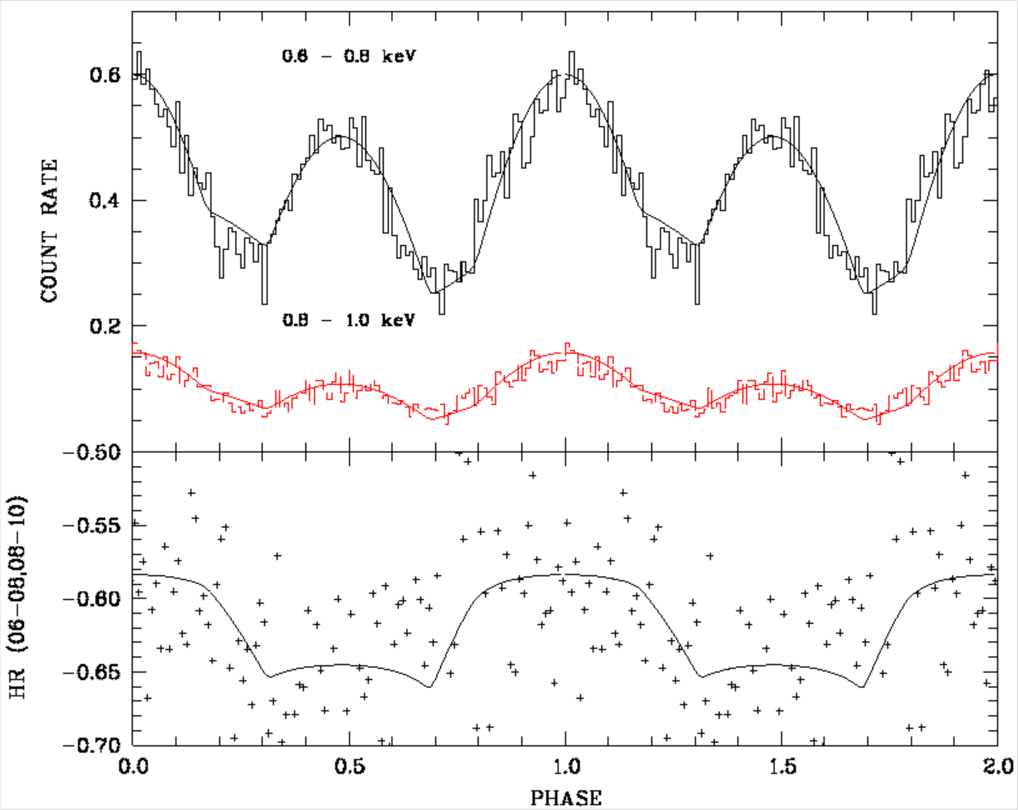
Cropper et al. (2001)

RX J0420.0-5022 **RX J0806.4-4123**

Haberl et al. (2005)

Spectral variations with pulse phase: RBS 1223





RBS 1223 (10.31s) ***Schwope et al. 2005***

Two-spot model: kT_{∞} **= 92 eV and 84 eV**

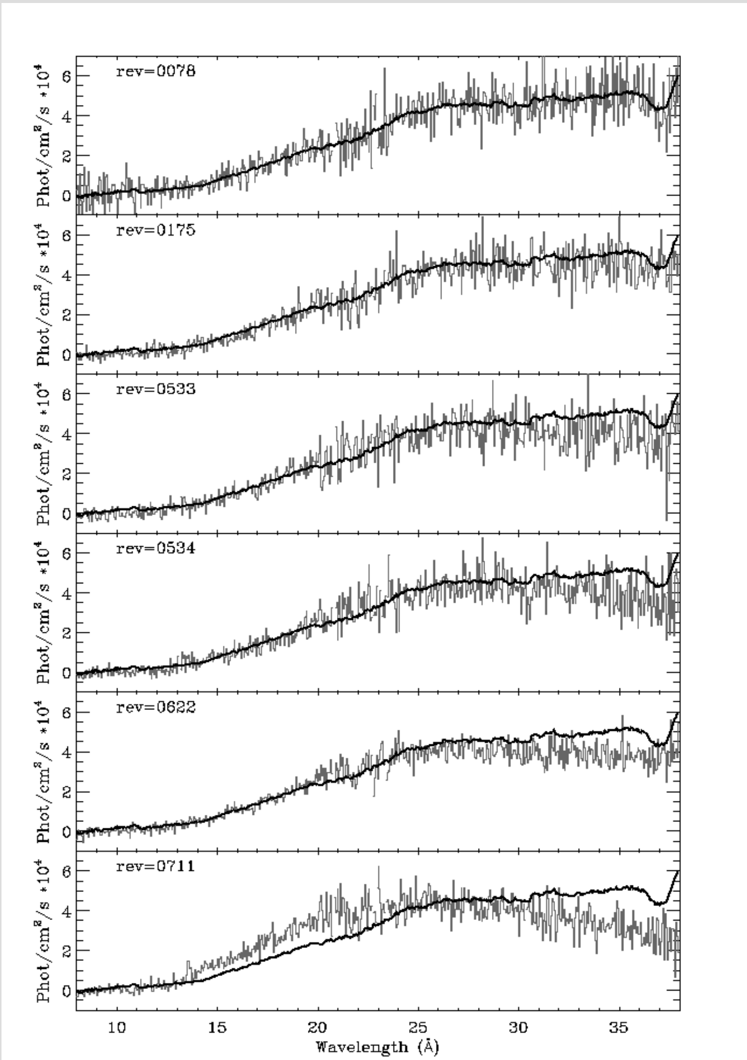
$2\Phi \sim 8^{o}$ **and** $\sim 10^{o}$

offset $\sim 20^{o}$

Long-term spectral changes from RX J0720.4-3125

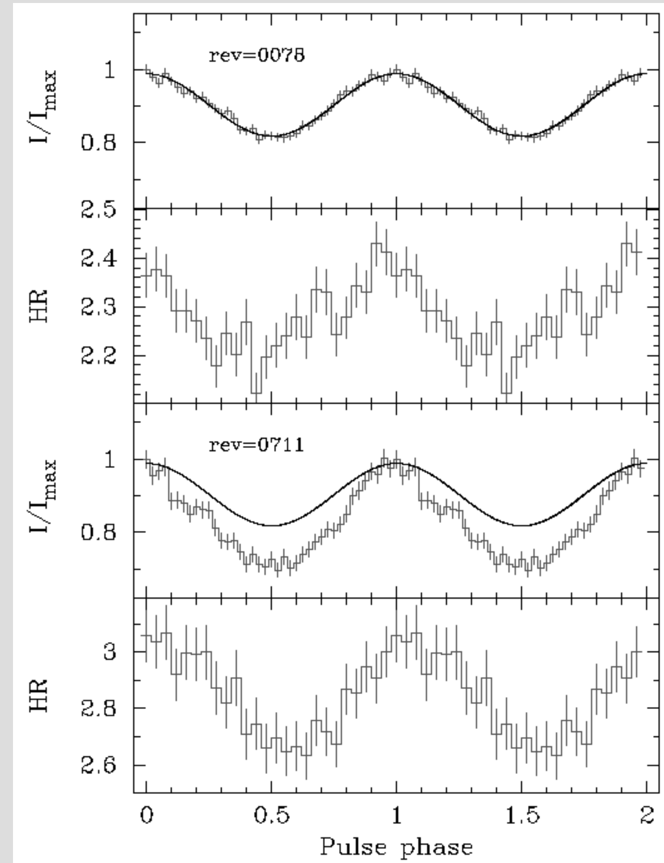
Increase at short wavelength: temperature increase
Decrease at long wavelength: deeper absorption line

XMM-Newton RGS



Increase in pulsed fraction

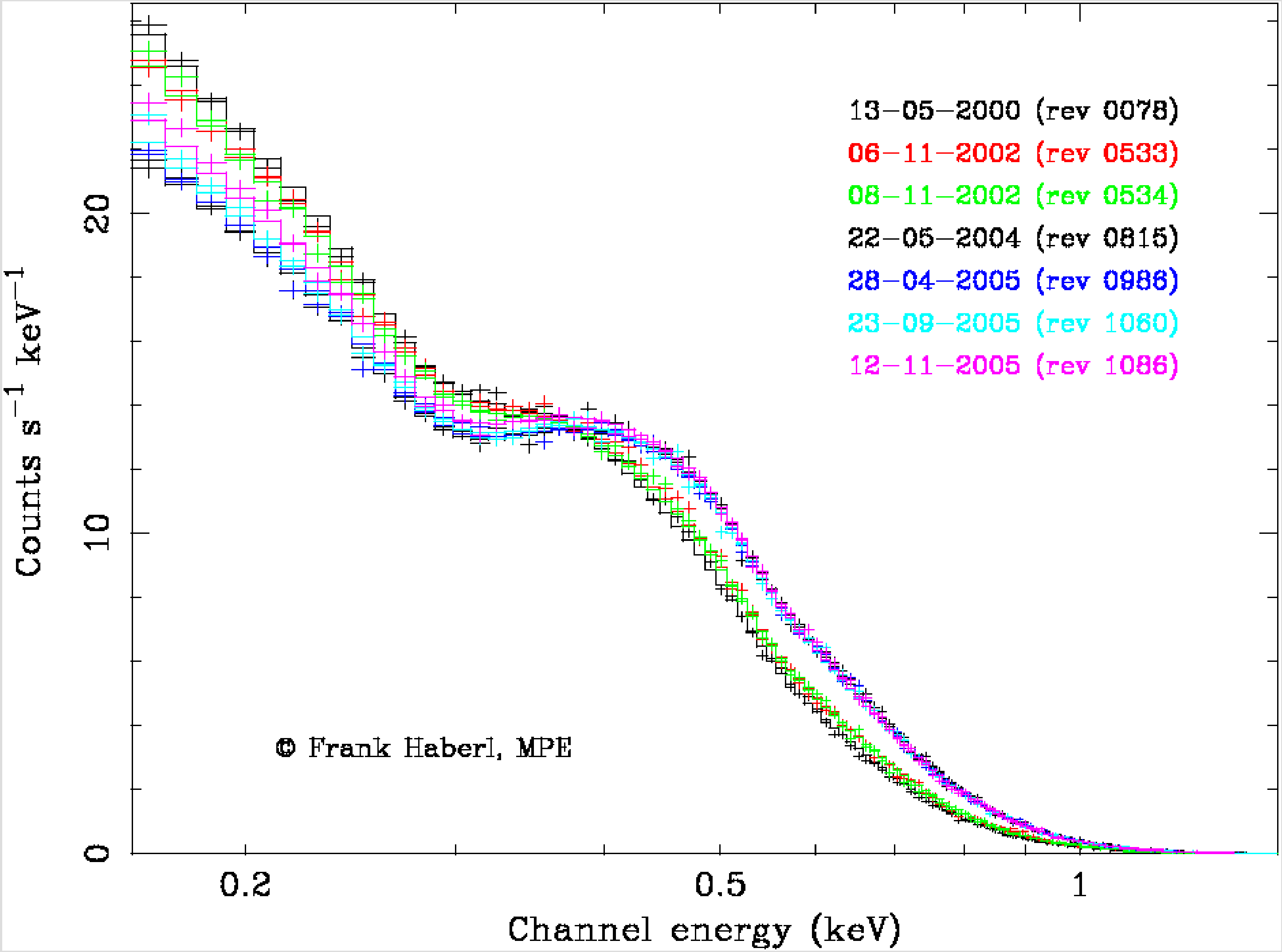
XMM-Newton EPIC-pn



Precession of the neutron star?

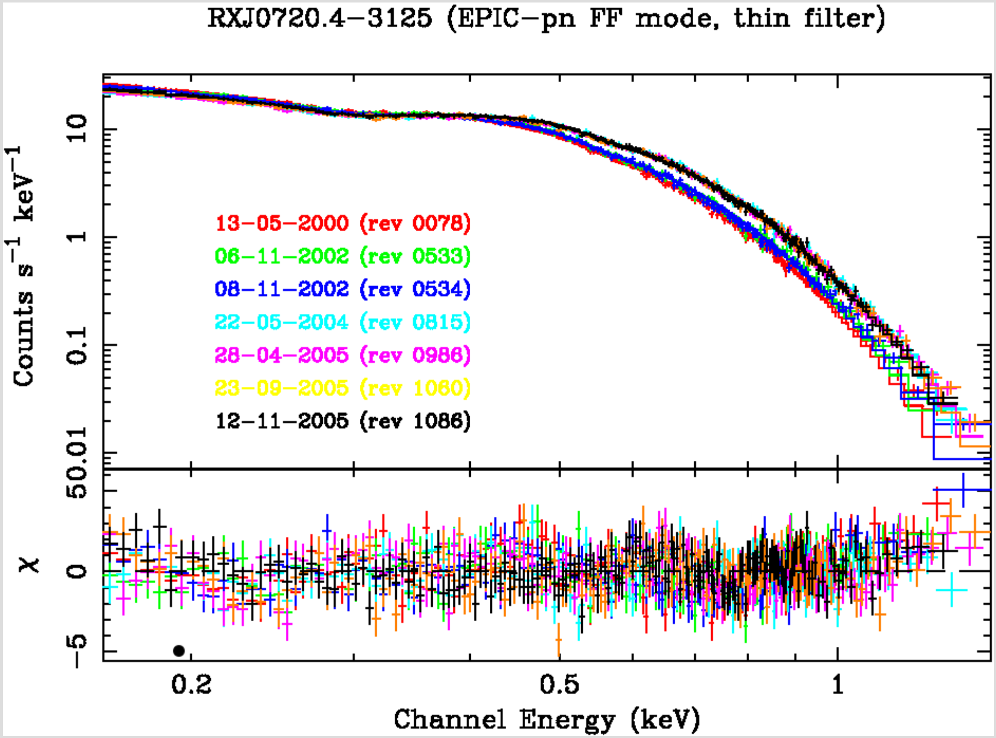
de Vries et al. (2004)

RX J0720.4-3125 longterm spectral variations



RX J0720.4-3125: Spectral variations over 4.5 years

XMM-Newton EPIC-pn



Rev.	kT(eV)	EW(eV)
•0078	86.6 ± 0.4	–5.02 ± 4.5
0175	86.5 ± 0.5	+8.68 ± 7.7
•0533/534	88.3 ± 0.3	–21.5 ± 2.6
0711/711	91.3 ± 0.6	–73.7 ± 4.9
•0815	93.8 ± 0.4	–72.4 ± 4.7
•0986	93.5 ± 0.4	–68.3 ± 5.2
•1060	93.2 ± 0.4	–67.4 ± 4.3
•1086	92.6 ± 0.4	–67.5 ± 3.5

• FF mode + thin filter

common line energy: 280 ± 6 eV
common line width: σ = 90 ± 5 eV

Long-term variations over 4.5 years:

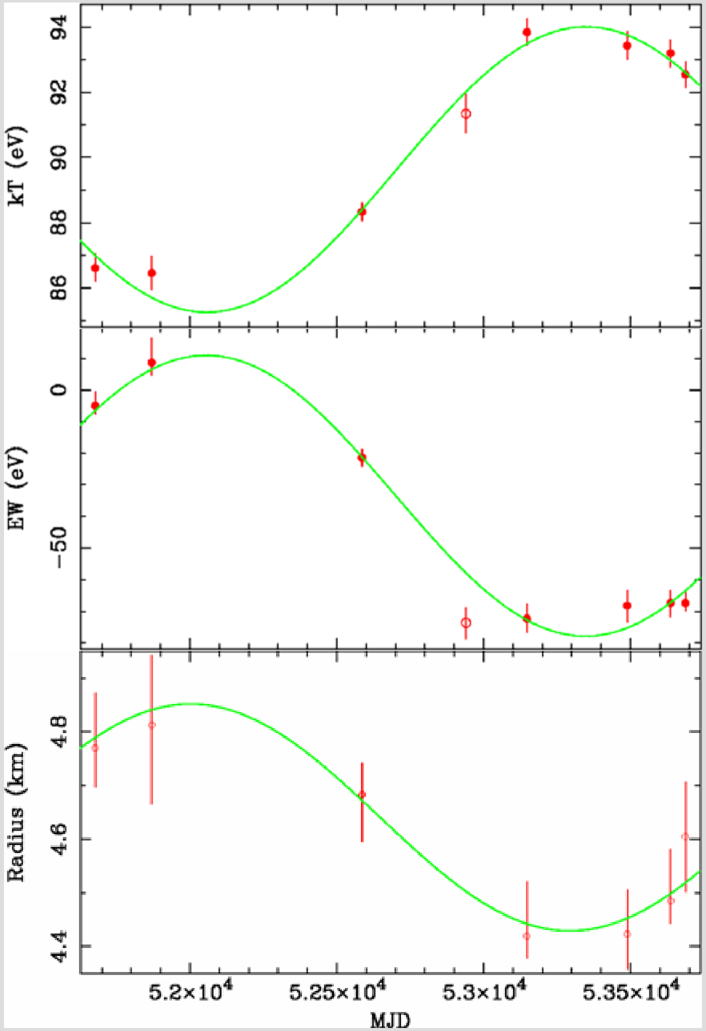
Temperature by ~7 eV

Absorption line equivalent width by ~70 eV

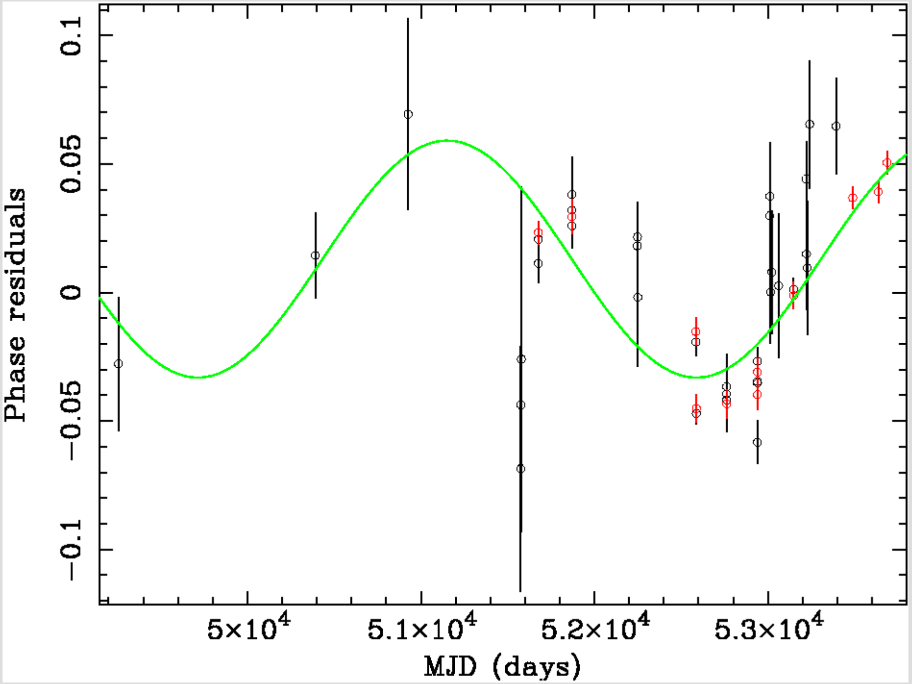
Radius of emission area from 4.4 km to 4.8 km (d=300pc)

But flux is constant within ±2%

RX J0720.4-3125 longterm spectral variations



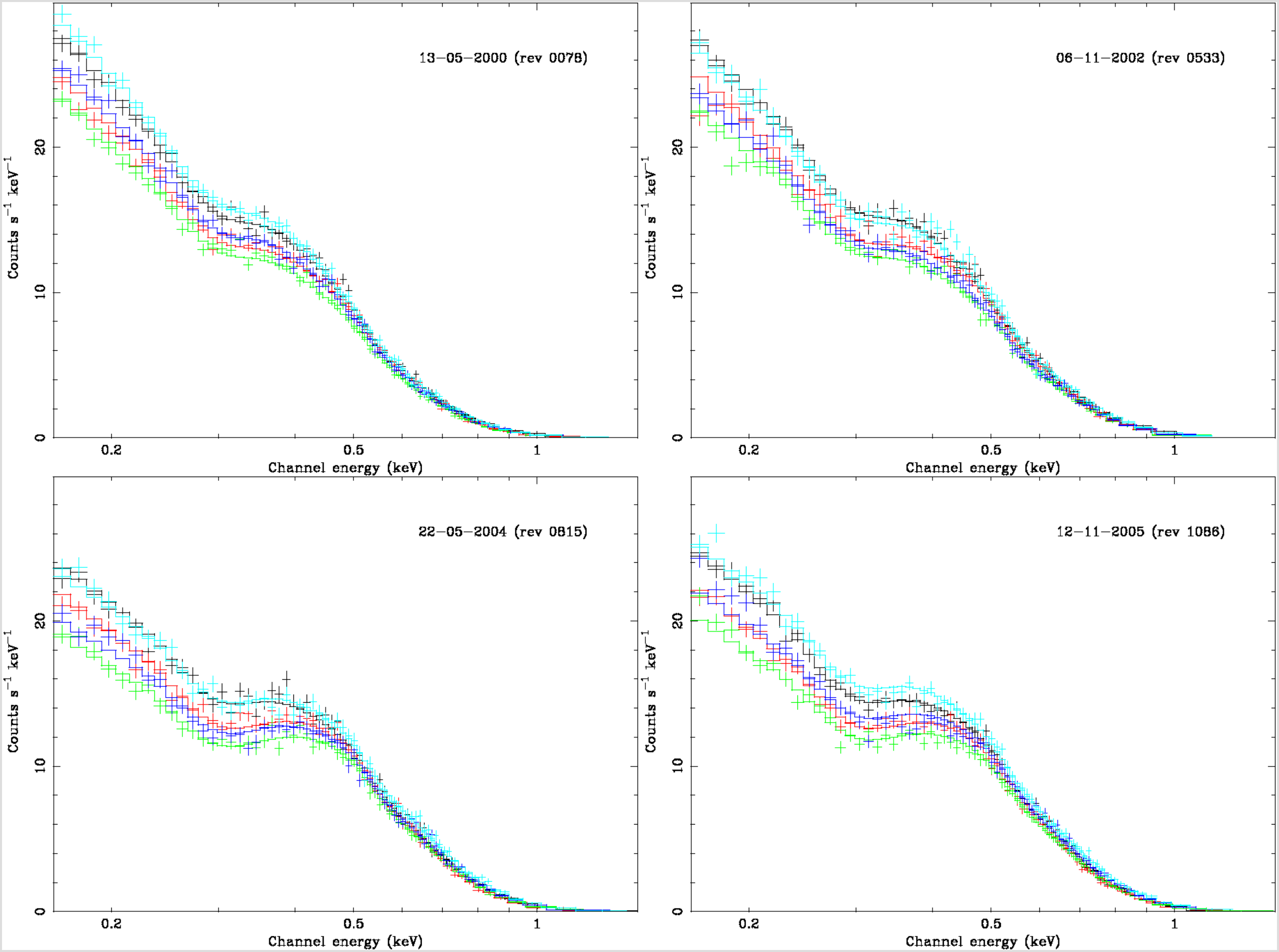
Sinusoidal variations in spectral parameters
Period 7.1 ± 0.5 years



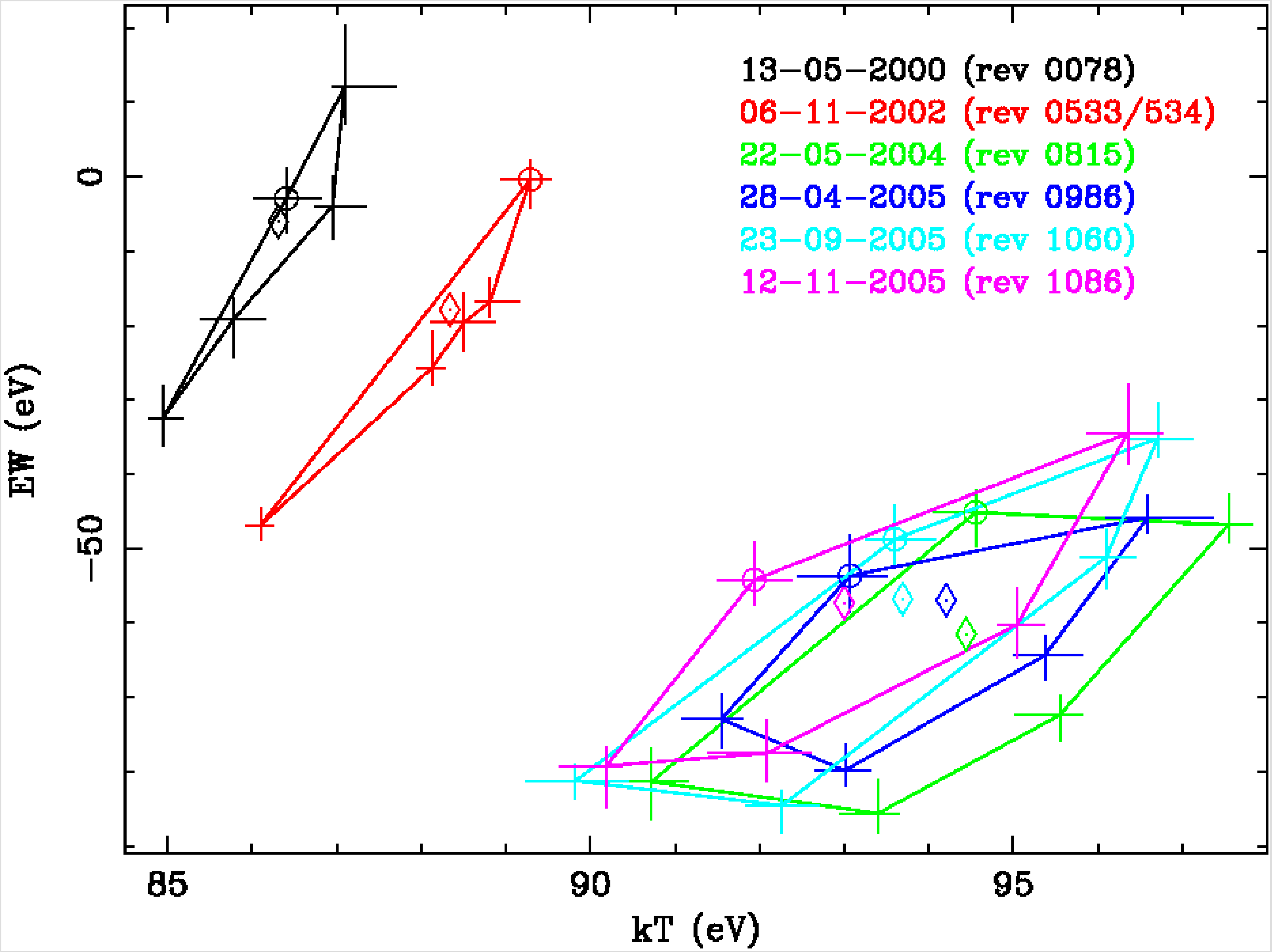
Sinusoidal variations in pulse timing
Period 7.7 ± 0.6 years

Free precession of an isolated neutron star with period 7–8 years
$\varepsilon = (I_3 - I_1) / I_1 = P_{spin} / P_{prec} \approx 4 \cdot 10^{-8}$ (moments of inertia for a rigid body)
between that reported from of radio pulsars and Her X-1

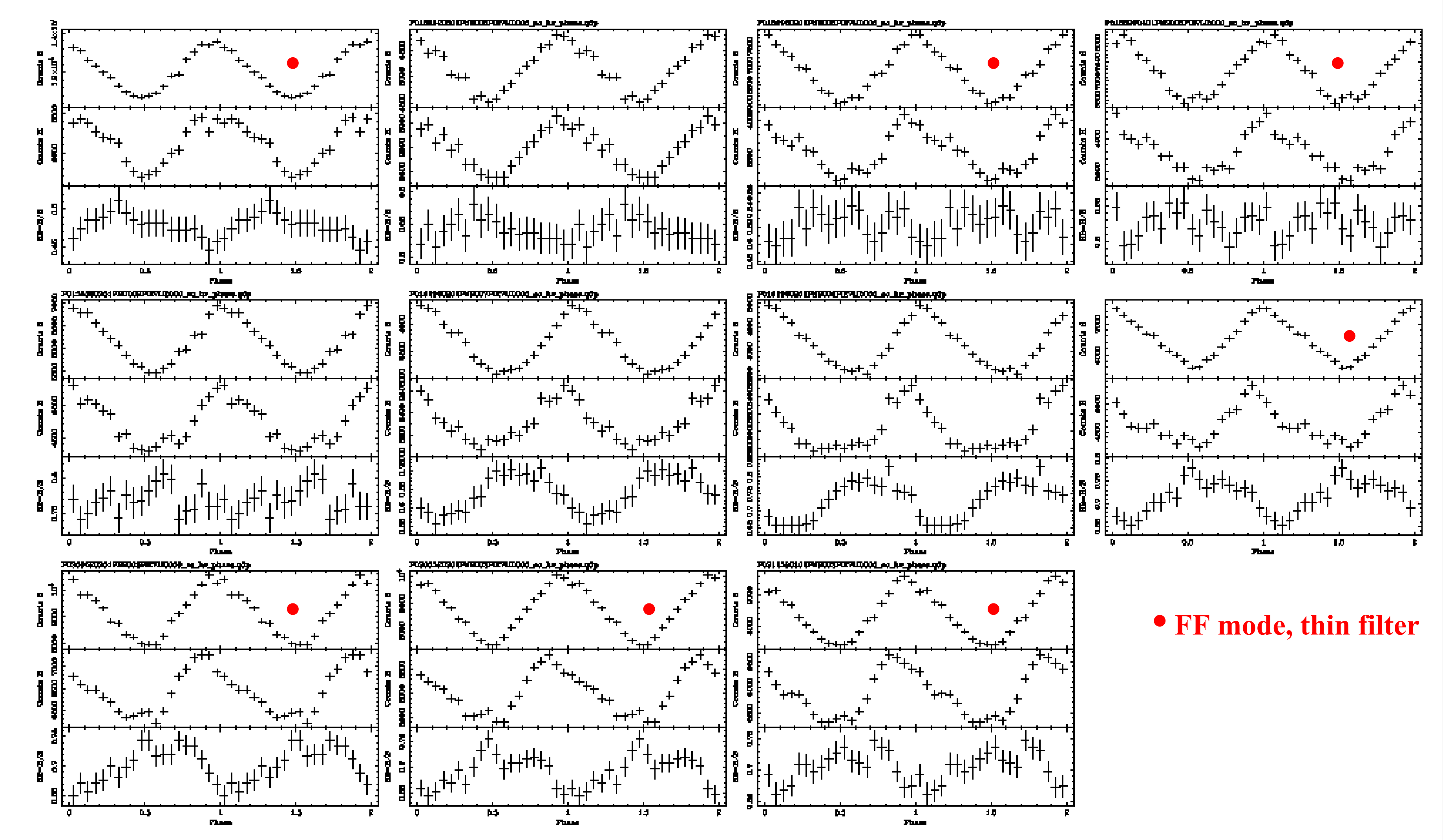
RX J0720.4-3125 pulse phase spectral variations



RX J0720.4-3125: Spectral variations over pulse and precession phase



RX J0720.4-3125: Pulse profile changes



RX J0720.4-3125: A precessing isolated neutron star

The model:

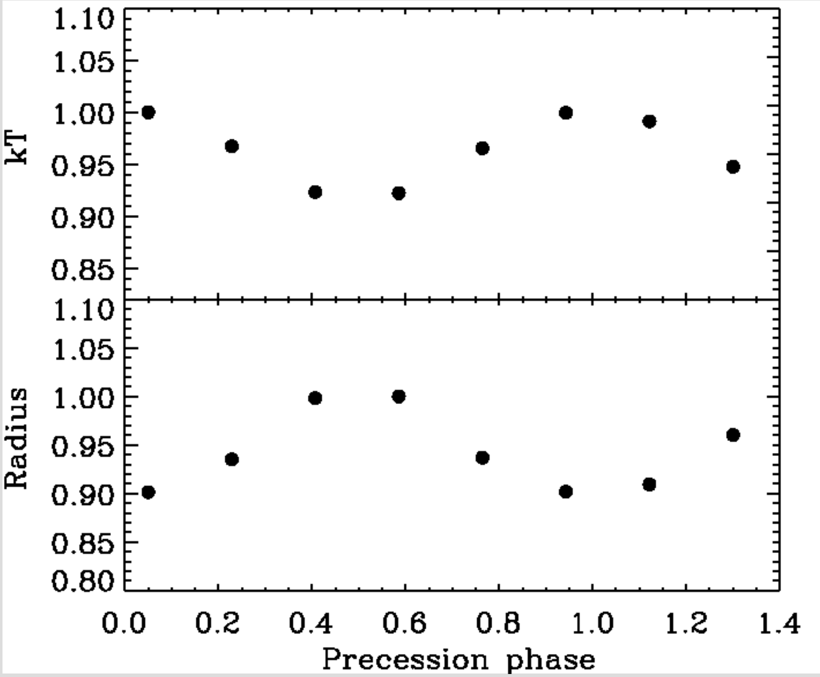
Two hot polar caps
- **with different temperature**
- **with different size**
- **the hotter is smaller: T–R anti-correlation**

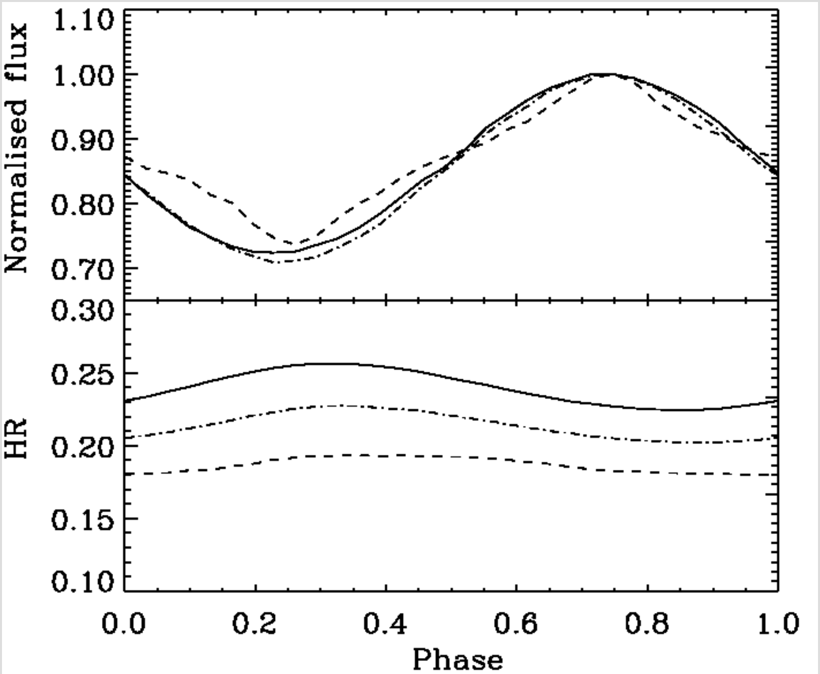
$T_1 = 80$ eV $\sin\theta_1 = 0.8$

$T_2 = 100$ eV $\sin\theta_2 = 0.6$

not exactly antipodal:
phase shift of lag between hard and soft emission

$\theta_0 = 160^o$



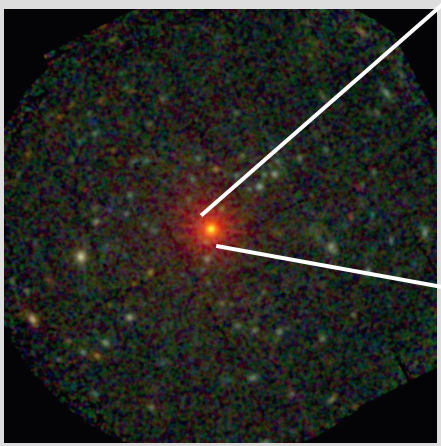


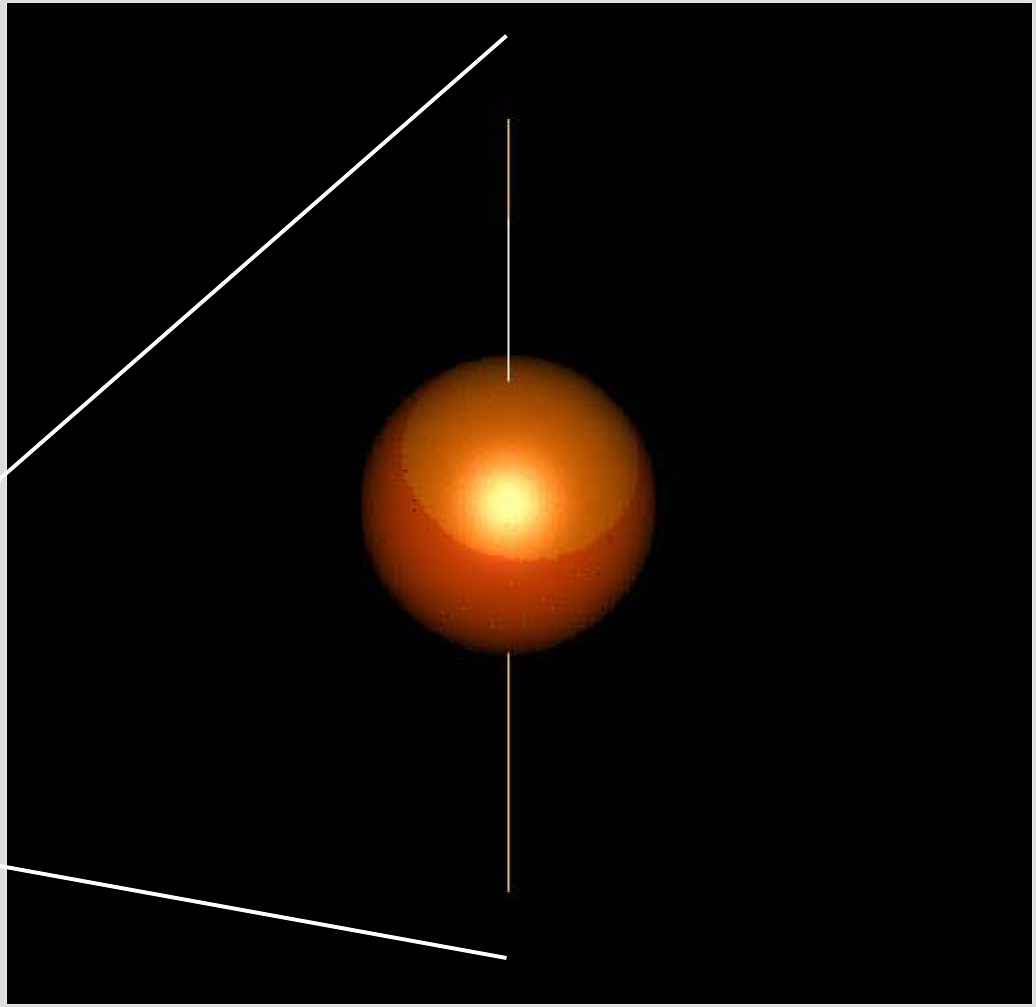
See also: Perez-Azorin et al. (2006) astro-ph/0603752

RX J0720.4-3125: A precessing isolated neutron star

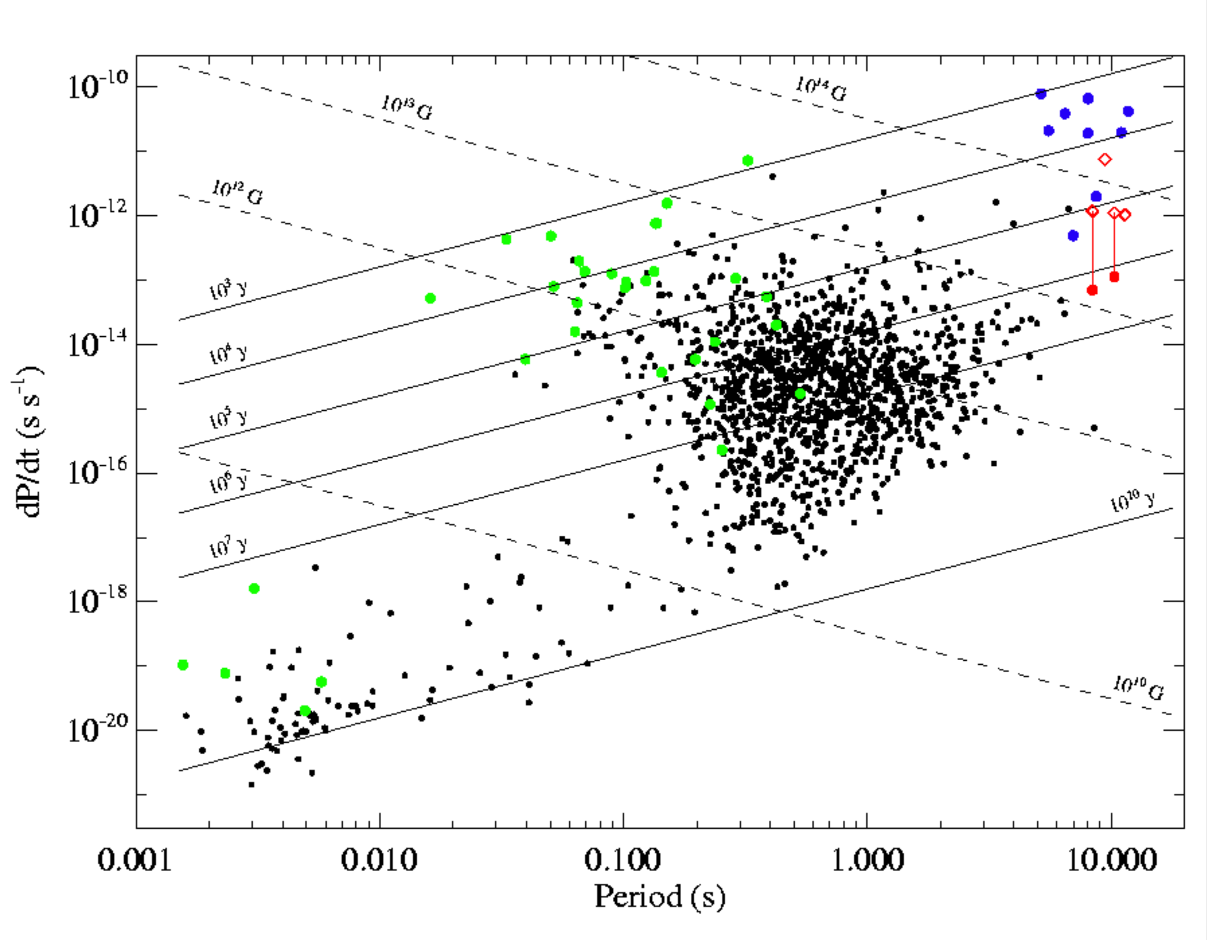
Roberto Turolla
Cor P. De Vries
Silvia Zane
Jacco Fink
Mariano Mendez
Frank Verbunt

Haberl et al. 2006
A&A 451, L17





Pulsars



high-energy detections (incomplete)

AXPs / SGRs (magnetars)

Magnificent Seven:
circles: $P/\dot{P}$
diamonds: cyclotron lines

magnetic dipole braking: age = $P / 2\dot{P}$, B = $3.2 \times 10^{19} (P\dot{P})^{1/2}$

The Magnificent Seven: What have we learned?

$F_x/F_{opt} > 10^4$ → Isolated neutron stars

High proper motion → Nearby, cooling isolated neutron stars

dP/dt + absorption features → Magnetic fields $10^{13\text{-}14}$ G

Evidence for multiple lines → Proton cyclotron absorption
+ Atomic line transitions?

Interesting individuals:

RX J0720.4-3125: Pulsar, absorption feature → B field, kT distribution
Precession → Another probe to the NS interior

RX J1856.4-3754: No pulsations, no absorption feature → Just a viewing effect?

The Magnificent Seven: Open questions

***The* question:**

ICONs – RICONs – RINs – PUTINs – XBINs – XDINs – THEINs … ?

What is the state of the atmosphere (condensed)?
What is the composition of the atmosphere?
What causes the absorption features?
Why are they regularly spaced?
(proton cyclotron absorption should show only the fundamental)
Why does RX J1856.4-3754 not show absorption features?
Why does RX J1856.4-3754 not show pulsations?
Is it a geometrical effect?
How common is precession?

What do we need:
Theoretical work on NS atmospheres including effects of strong B fields
Better energy resolution of X-ray detectors + a large collecting area
More X-ray monitoring
Optical observations with large telecopes: Identification, proper motion, parallax