The pulsars among the Magnificent Seven

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- **The discovery of thermal, radio quiet isolated neutron stars**
- **New XMM-Newton and Chandra observations**
  - **Magnetic field estimates**
    - **Spin period history + Spectral absorption features**
  - **Multiple absorption lines – Cyclotron harmonics?**
  - **Spectral variations**
    - **With pulse phase**
    - **On long-term time scales**
    - **Properties of the magnetic poles**
  - **Precession -The case of RX J0720.4-3125**

Isolated Neutron Stars: from the Surface to the Interior

April 24-28, 2006 London (UK)

Thermal, radio-quiet isolated neutron stars

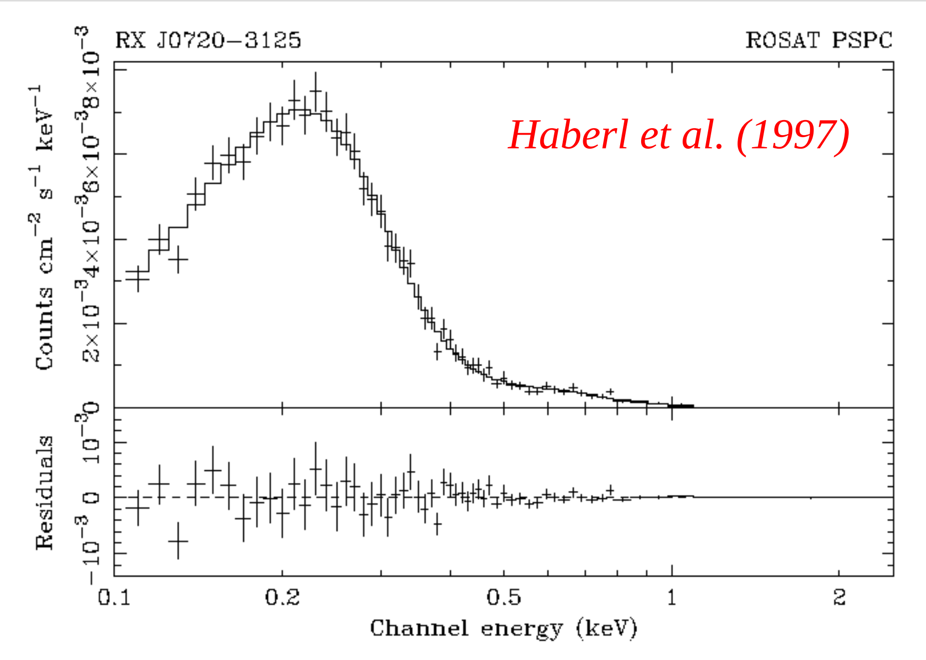
- Soft X-ray sources in ROSAT survey
- Blackbody-like X-ray spectra, NO non-thermal hard emission
- Low absorption ~10^{20} H cm^{-2}, nearby (parallax for RX J1856.5-3754)
- Luminosity ~10^{31} erg s^{-1} (X-ray dim isolated neutron stars)
- Constant X-ray flux on time scales of years
- No obvious association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

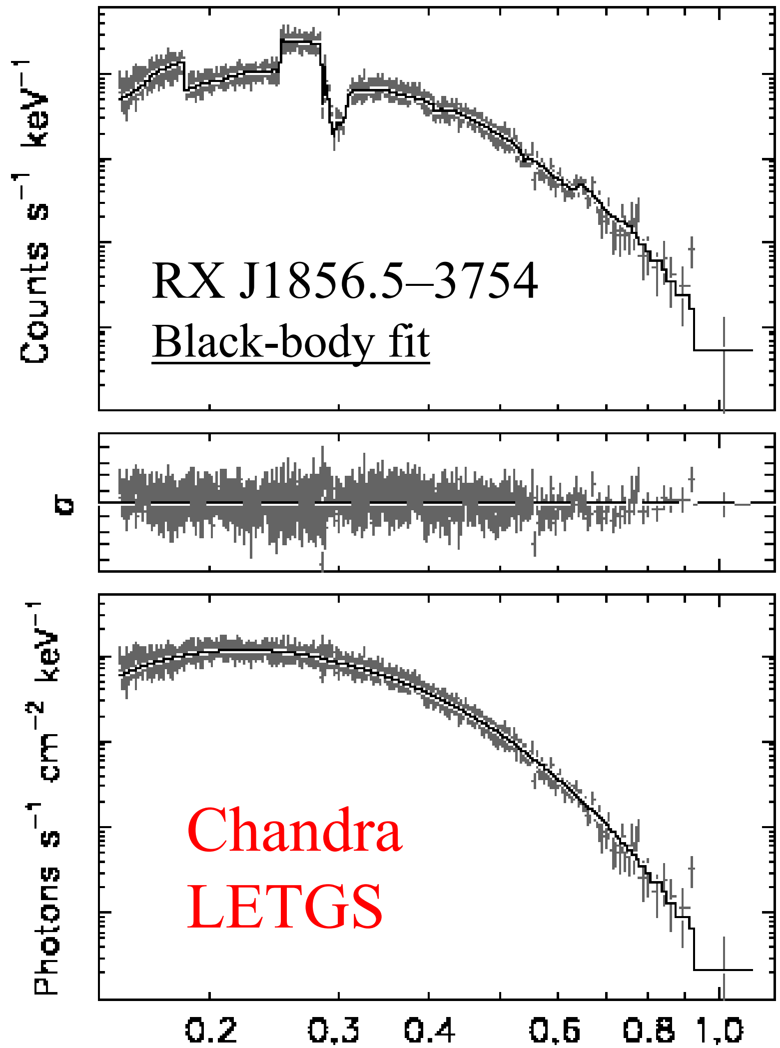
best candidates for „genuine“ INSs with undisturbed emission from stellar surface

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 (*)	80-92	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 (see poster A7)	

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

Soft, thermal X-ray spectra



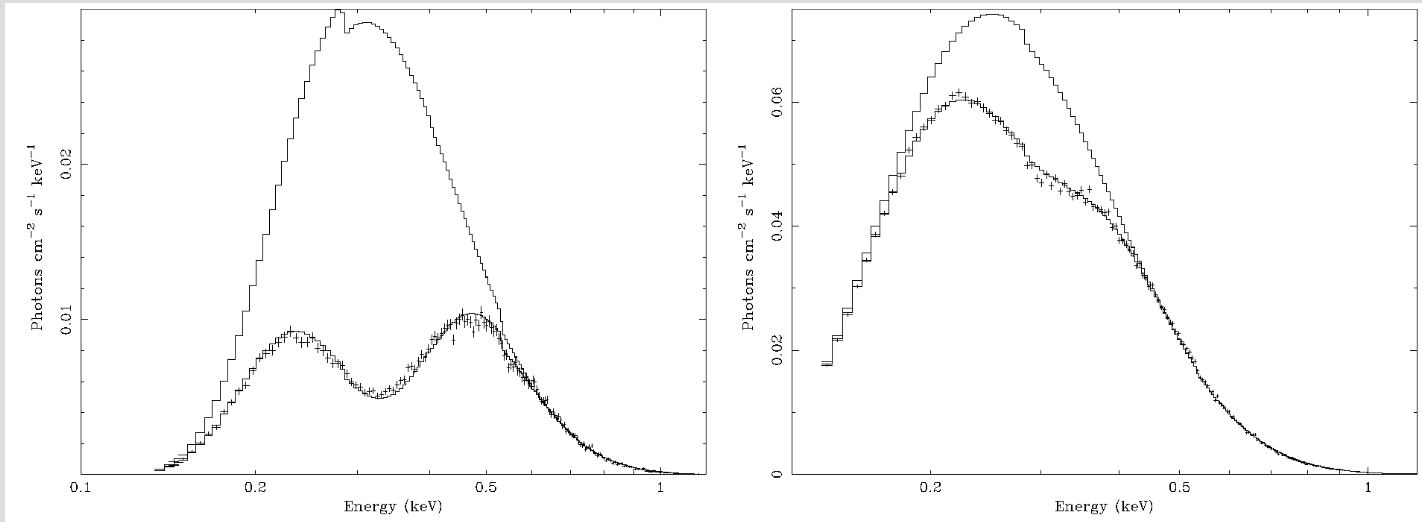


$$n_H = (9.5 \pm 0.03) \cdot 10^{19}\ \mathrm{cm}$$
$$kT_\infty = 63.5 \pm 0.2\ \mathrm{eV}$$
$$R_\infty = 4.4 \pm 0.1\ \mathrm{km}\ (120\mathrm{pc})$$
$$L_{bol} = 4.1 \cdot 10^{31}\ \mathrm{erg\ s^{-1}}$$

Burwitz et al. (2003) Photon Energy (keV)

XMM-Newton follow-up: absorption features

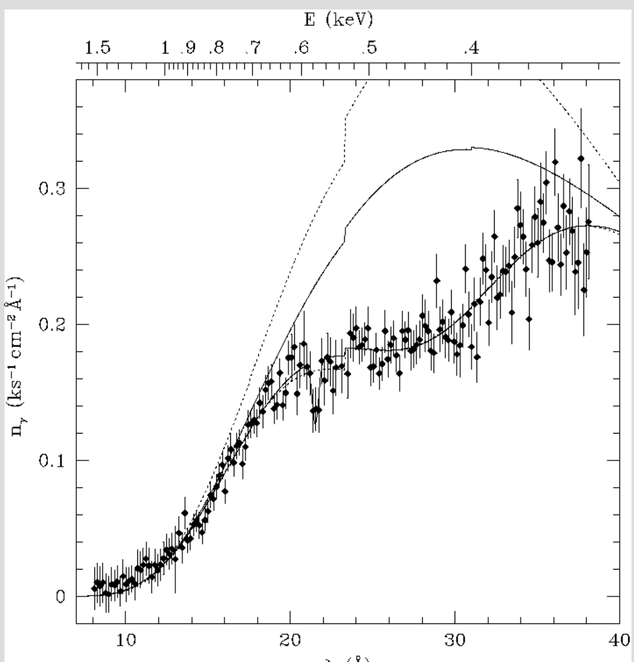
RBS 1223
EW = 150 eV
Pulse phase variations



XMM-Newton EPIC-pn

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

XMM-Newton RGS

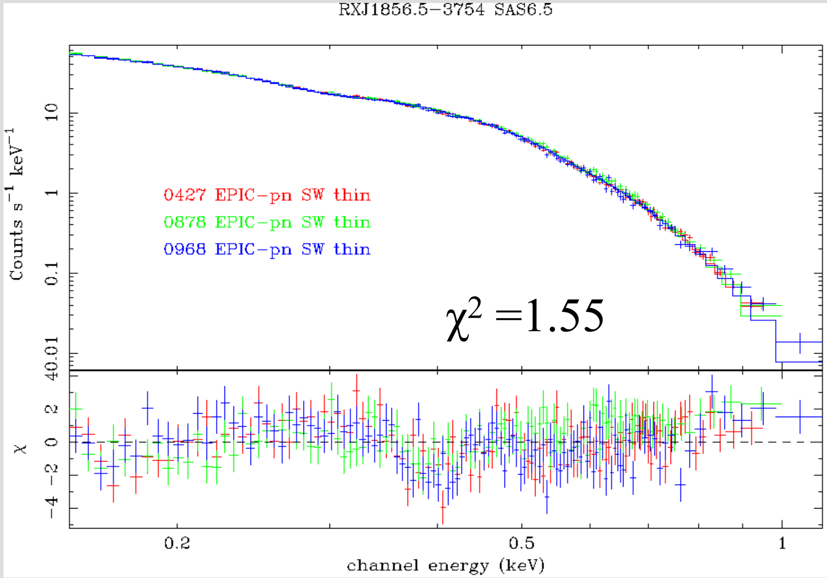


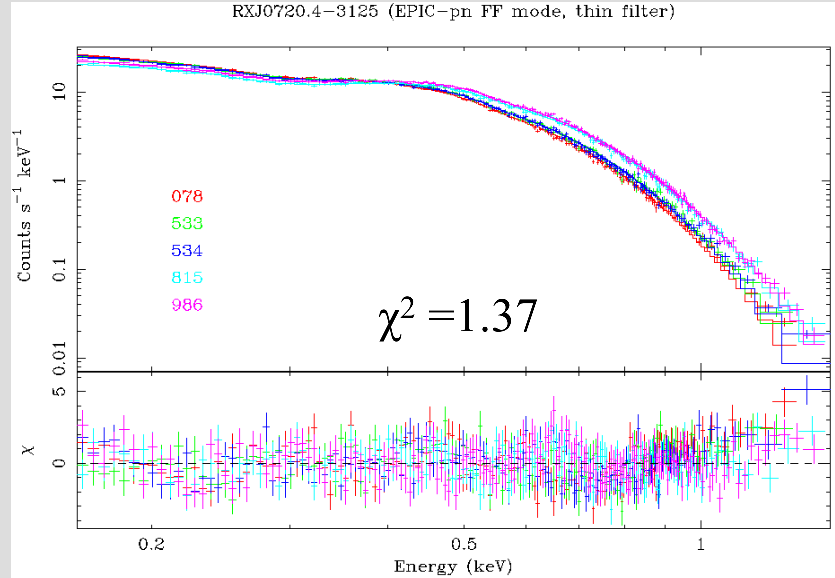
RX J1605.3+3249
RGS
kT = 95 eV
$N_H = 0.8 \cdot 10^{20}$ cm^{-2}
E_{line} = 450 – 480 eV

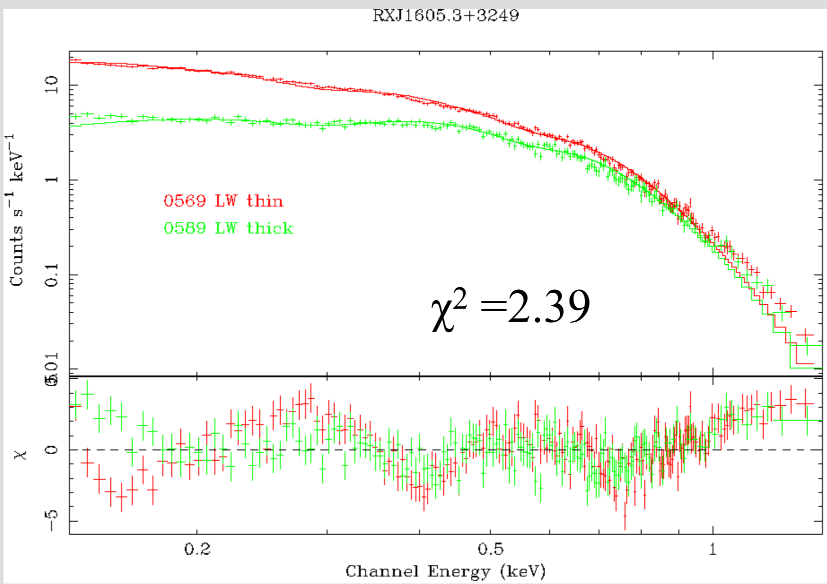
Van Kerkwijk et al. (2004)

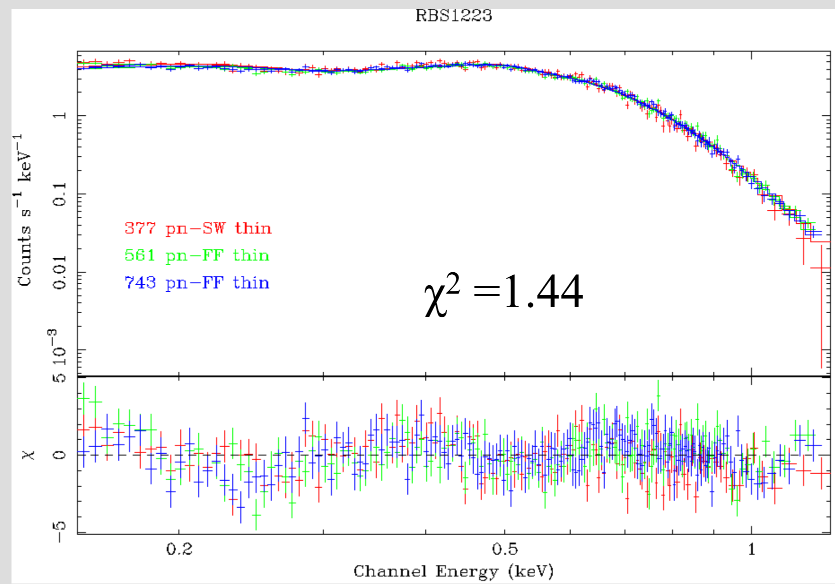
Proton cyclotron absorption lines ?
Atomic line transitions ?
Mixture ?
In both cases B ≈ $10^{13} - 10^{14}$ G

Evidence for multiple lines:

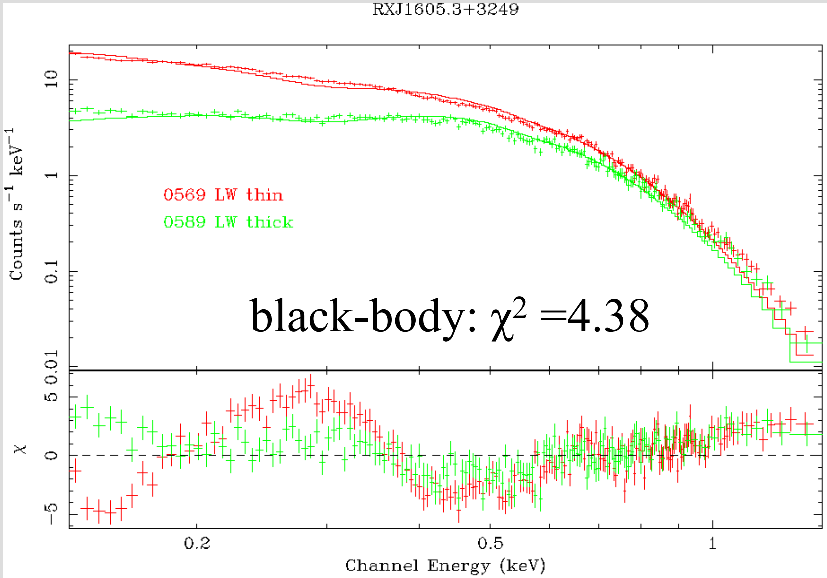


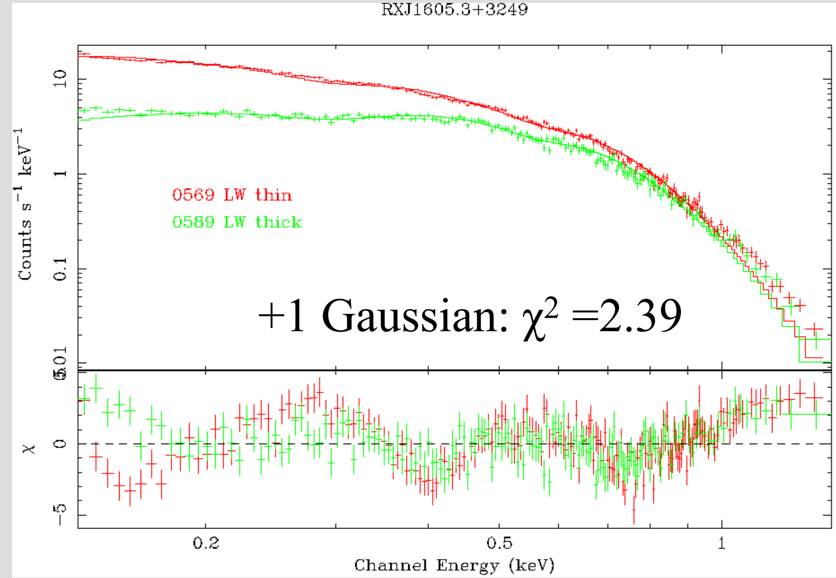


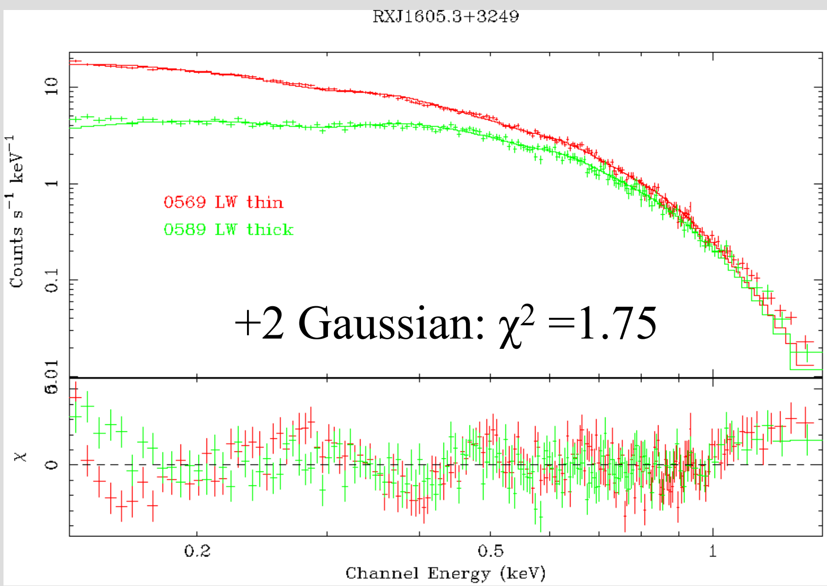


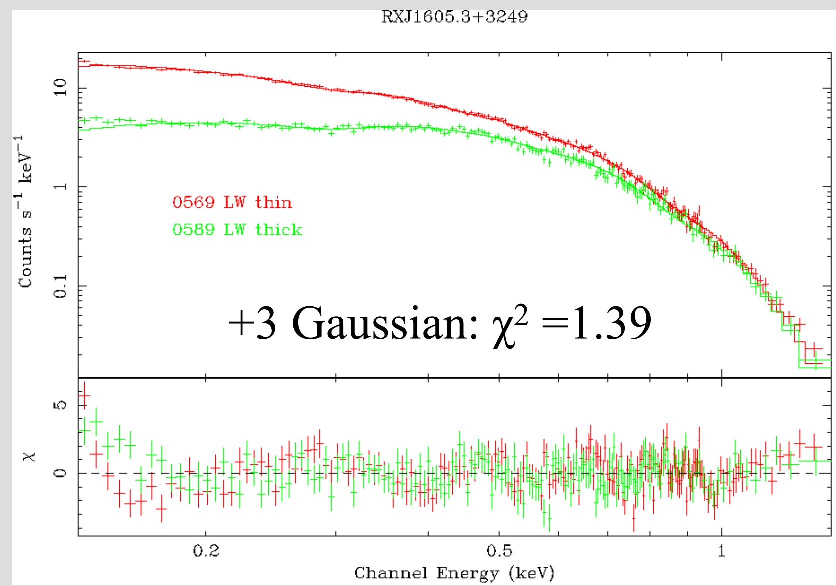


RX J1605.3+3249: Evidence for three lines









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

Line energies:

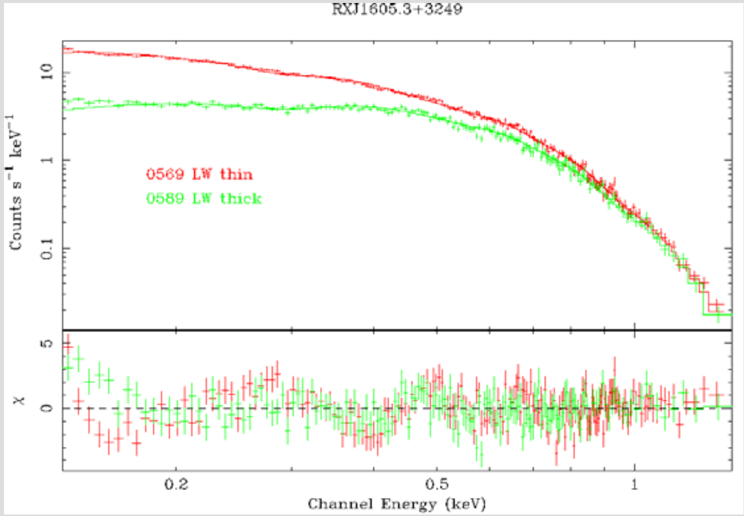
$E_1 = 403 \pm 2$ eV
$E_2 = 589 \pm 4$ eV
$E_3 = 780 \pm 24$ eV
$E_2/E_1 = 1.46 \pm 0.02$
$E_3/E_1 = 1.94 \pm 0.06$
$E_3/E_2 = 1.32 \pm 0.04$

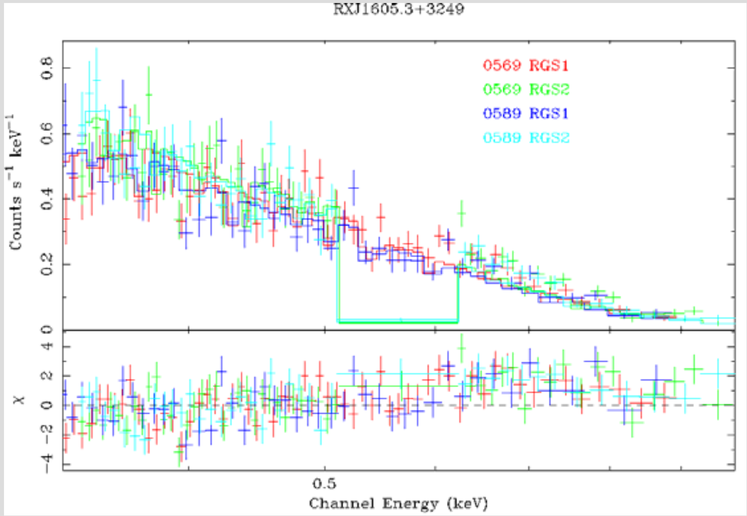
$E_1 : E_2 : E_3 = 1 : 1.5 : 2$

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)



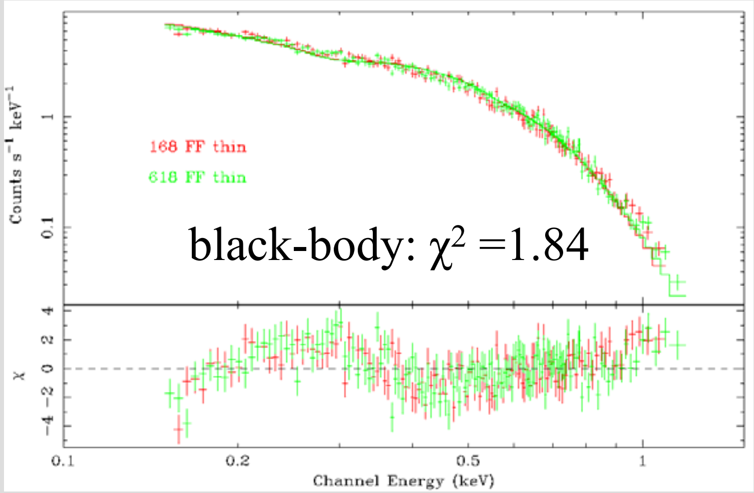


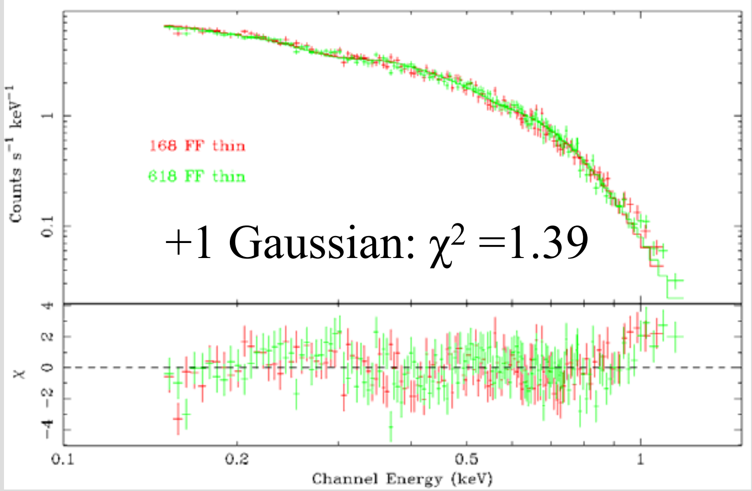
Proton cyclotron absorption: the deepest line ?
In addition atomic line transitions ?
Pure hydrogen ruled out?

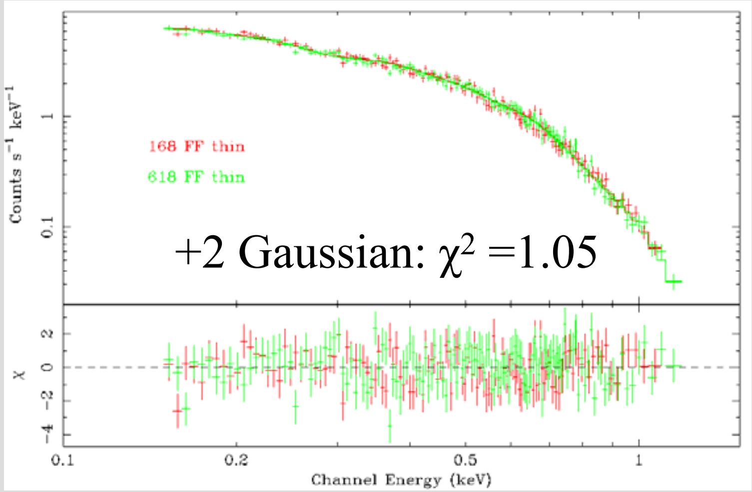
More multiple lines ?

RBS1223: Evidence for lines at 230 eV and at 460 eV (see poster B22, Schwope et al.)

RX J0806.4-4123:







One line:

E_1 = 433 ± 16 eV

σ_1 = 100 eV fixed

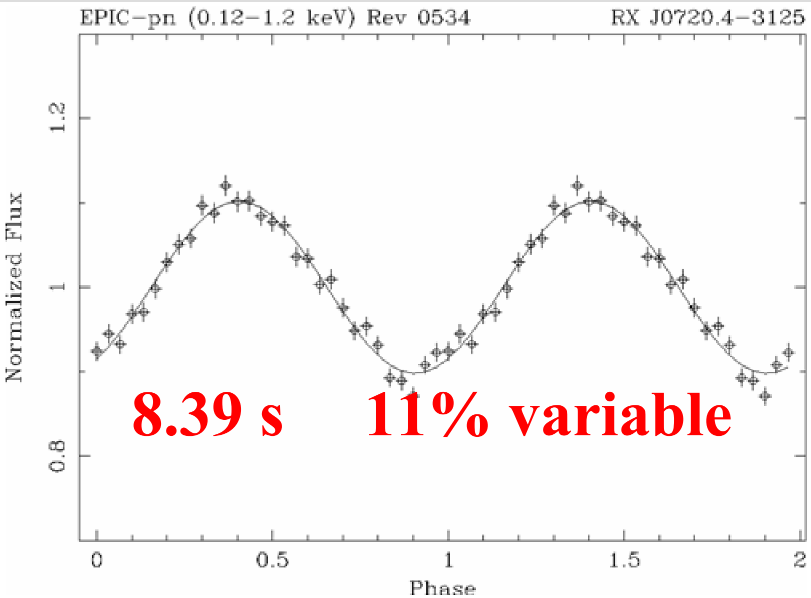
Two lines:

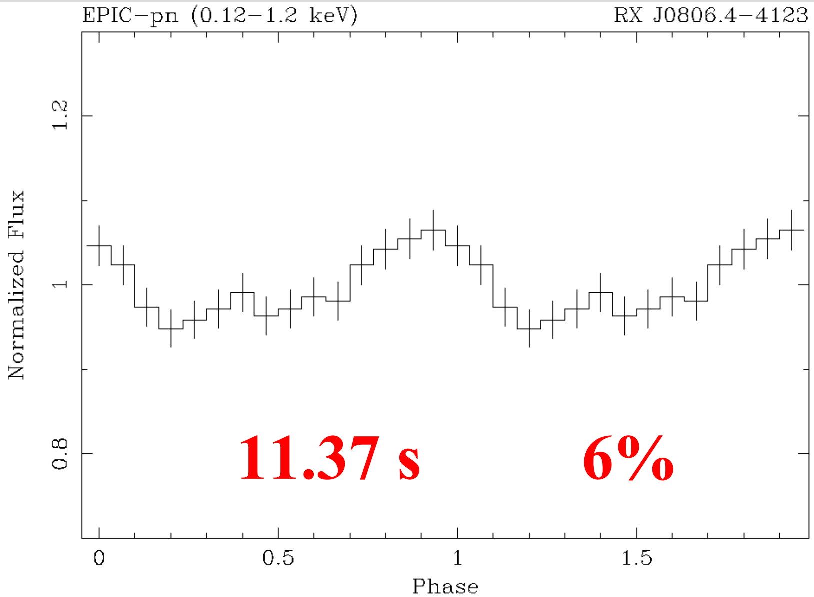
E_1 = 306 ± 3 eV E_2 = 612 eV (linked to E_1)

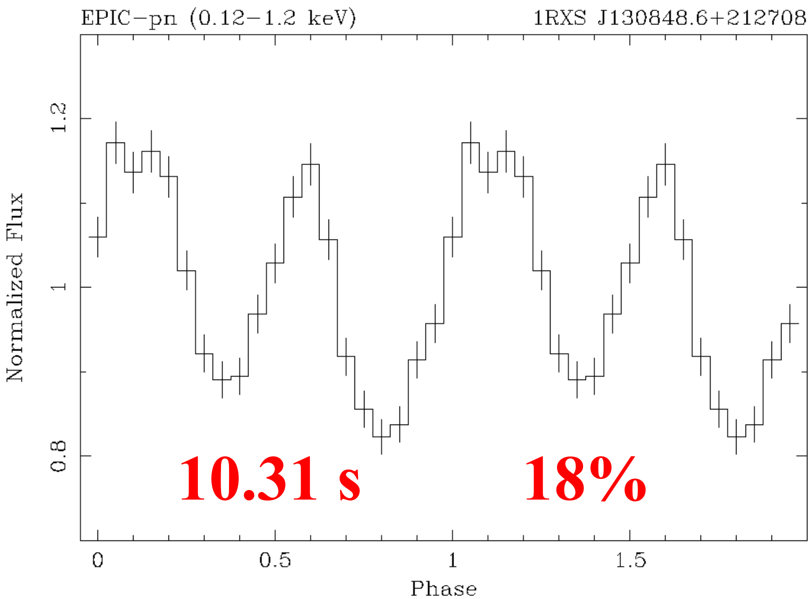
$\sigma_1 = \sigma_2$ = 139 ± 6 eV

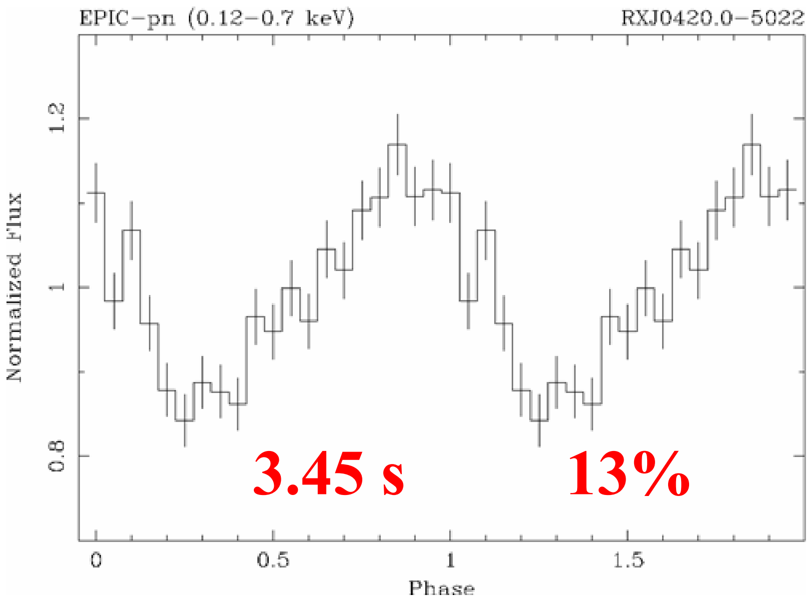
N_1/N_2 = 16.6

X-ray pulsations

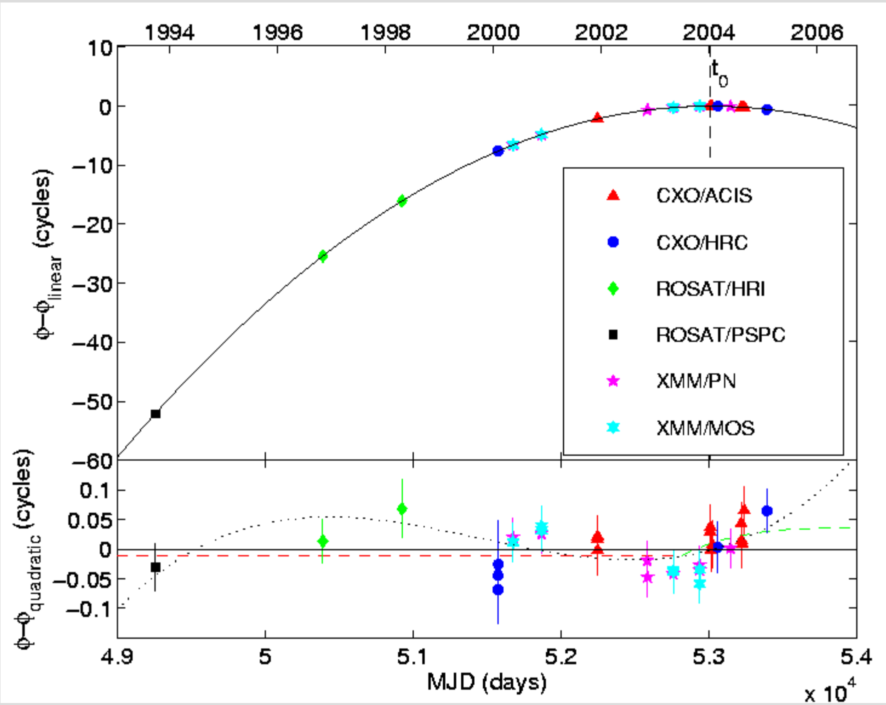


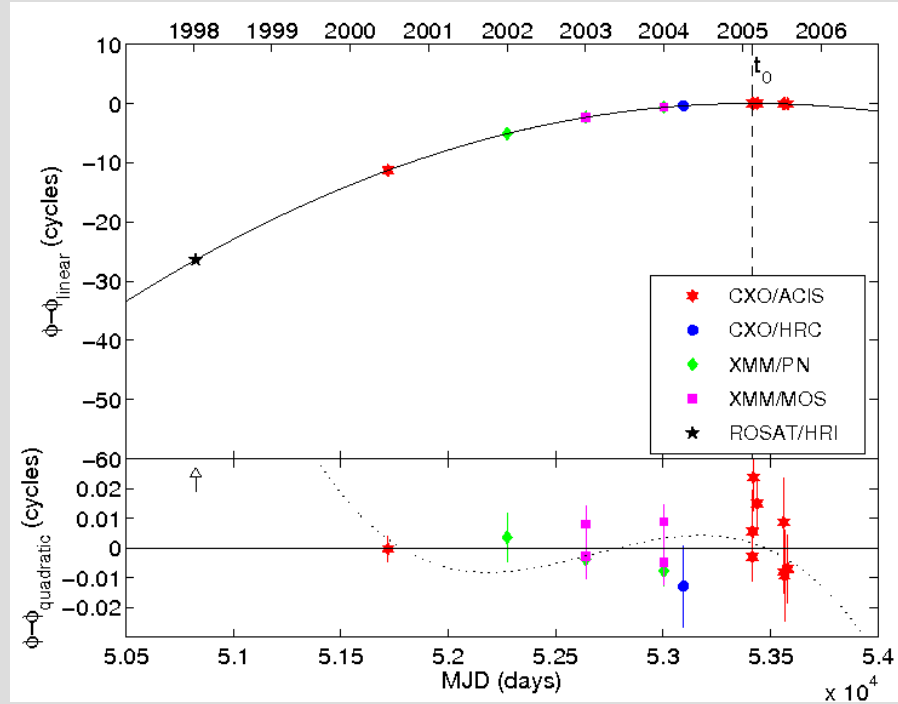






Period history: RX J0720.4–3125 and RBS 1223





RX J0720.4–3125

$P = 8.39$ s

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

$\tau = P/2(dP/dt) = 1.9 \cdot 10^{6}$ y

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

Kaplan & van Kerkwijk 2005
ApJ 628, L45

RBS 1223

$P = 10.32$ s

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

$\tau = P/2(dP/dt) = 1.5 \cdot 10^{6}$ y

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

Kaplan & van Kerkwijk 2005
ApJ 635, L65

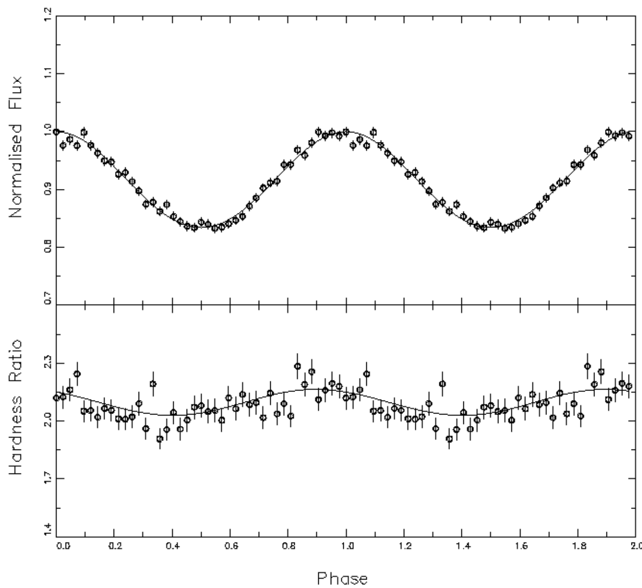
Magnetic fields

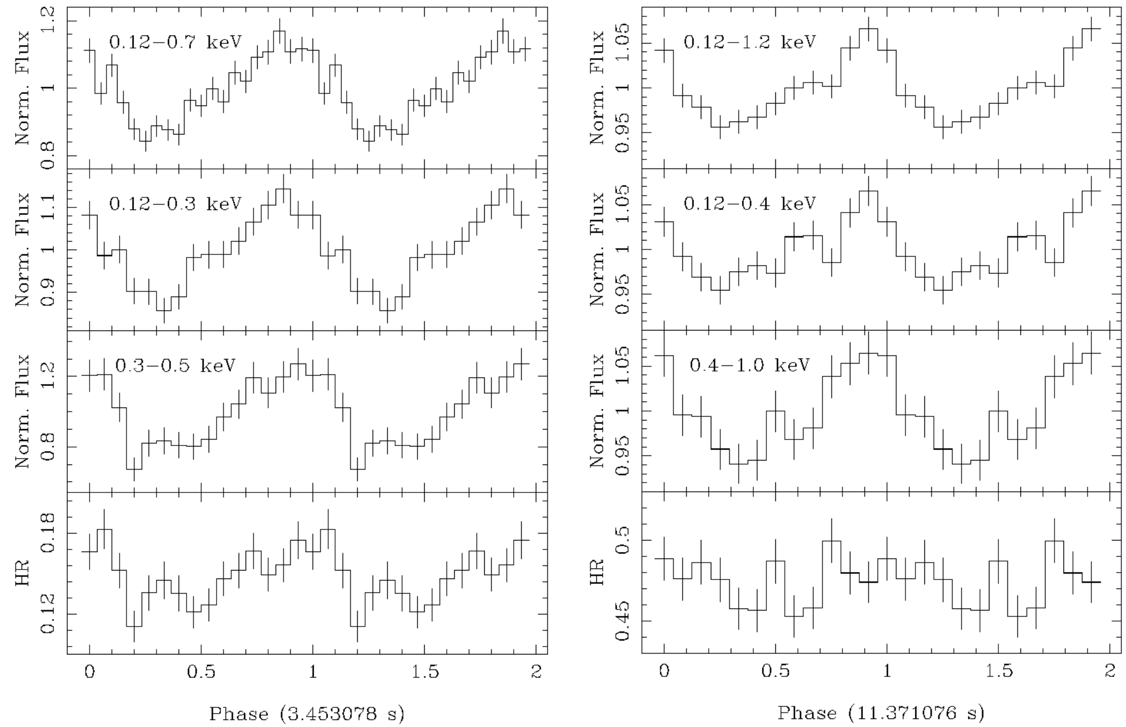
- Magnetic dipole braking → $B = 3.2 \times 10^{19} (P \times dP/dt)^{1/2}$
  Spin-down rate (P, dP/dt)
  Spin-down luminosity required to power the Hα nebula (dE/dt, τ)
- Proton cyclotron absorption → $B = 1.6 \times 10^{11} E(eV)/(1-2GM/c^2R)^{1/2}$

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





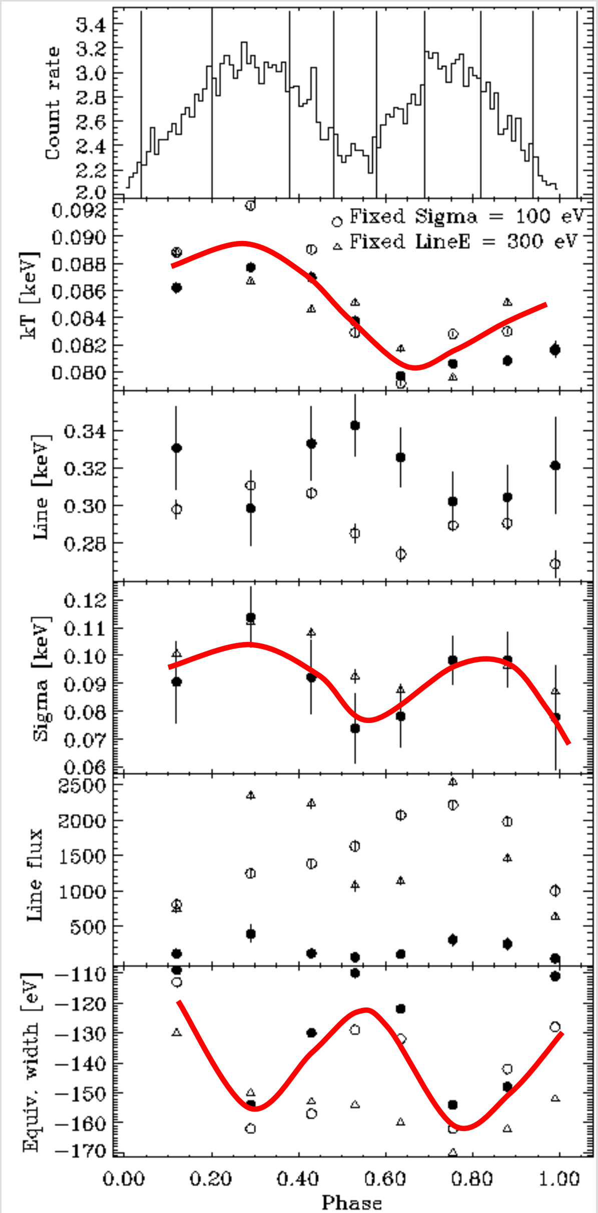
RX J0720.4-3125

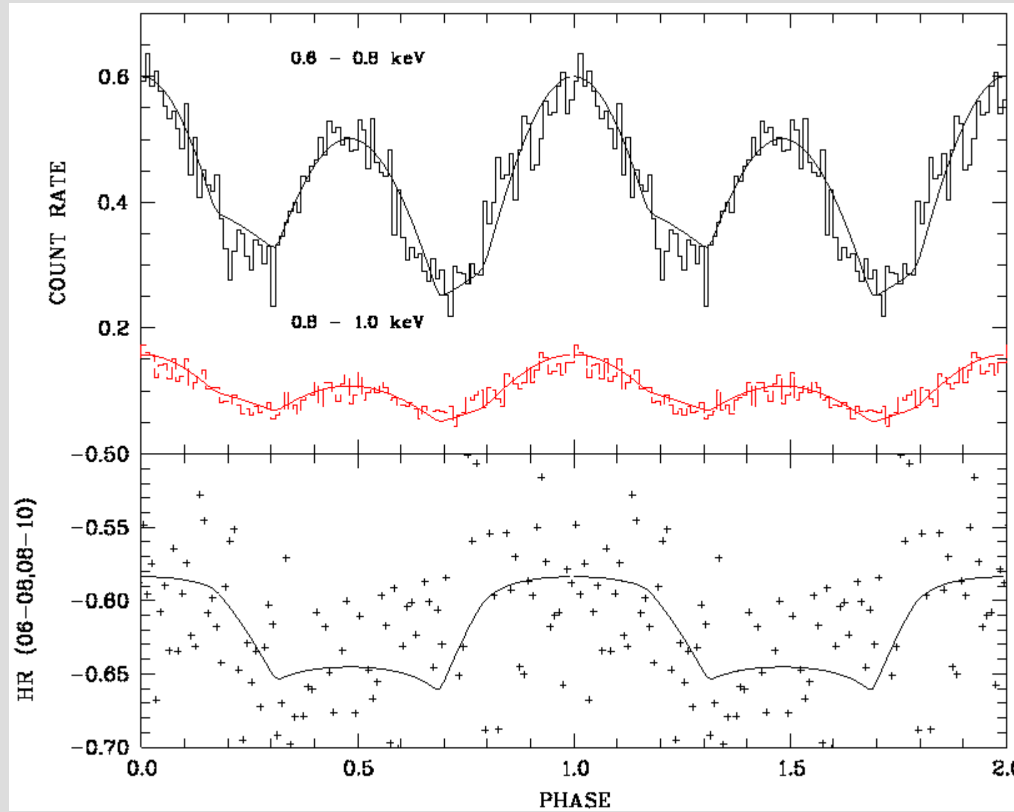
Cropper et al. (2001)

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**

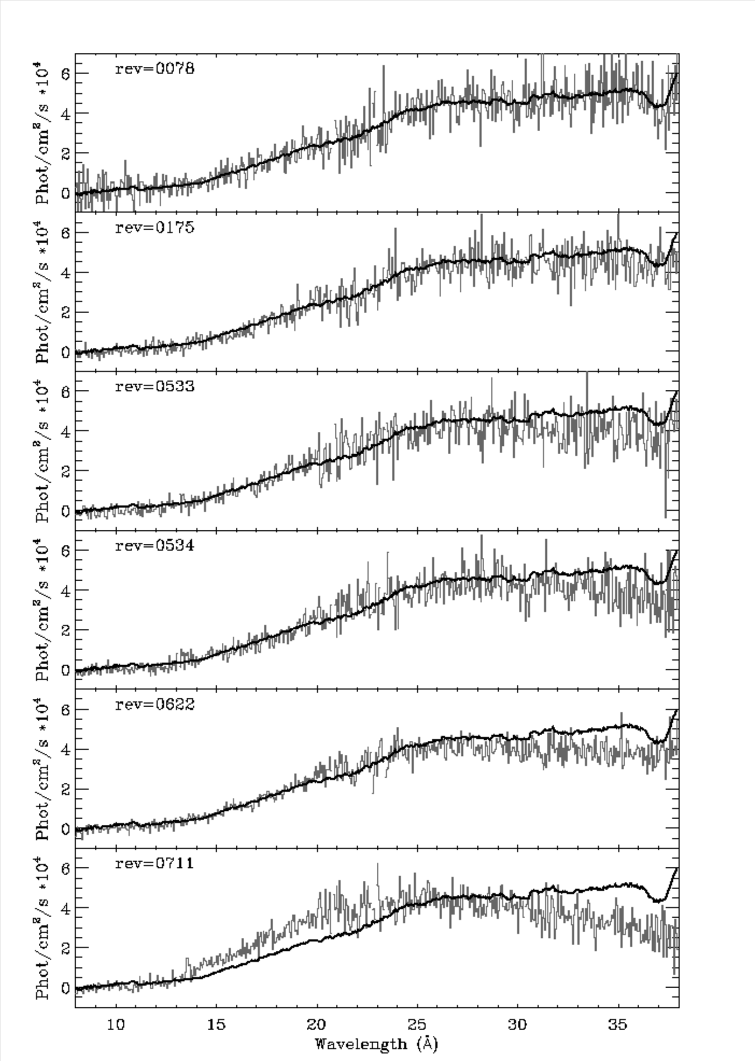
$2\Phi \sim 8^{o}$ **and** $\sim 10^{o}$

offset $\sim 20^{o}$

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

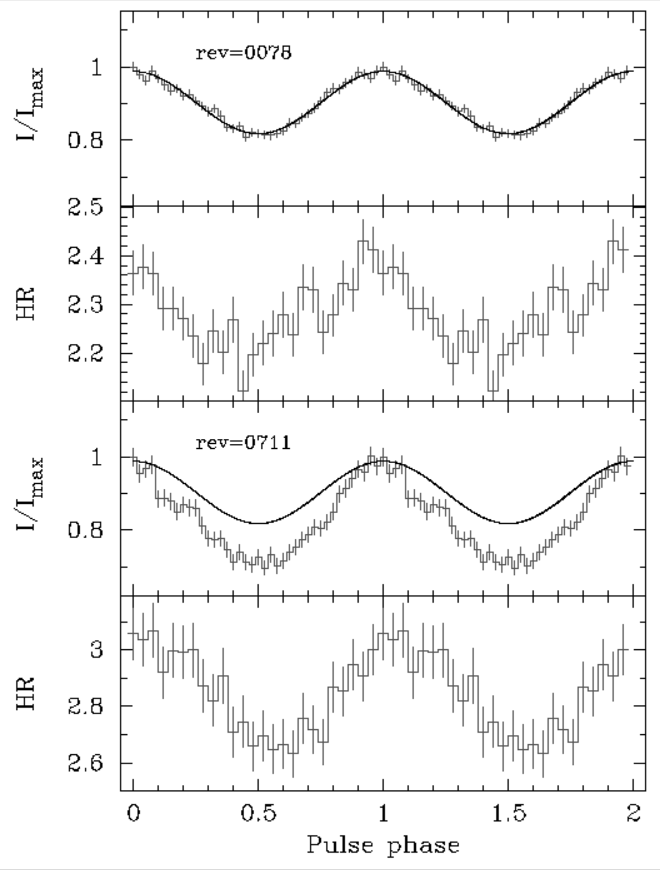
Increase at short wavelength: temperature increase
Decrease at long wavelength: deeper absorption line

XMM-Newton RGS



Increase in pulsed fraction

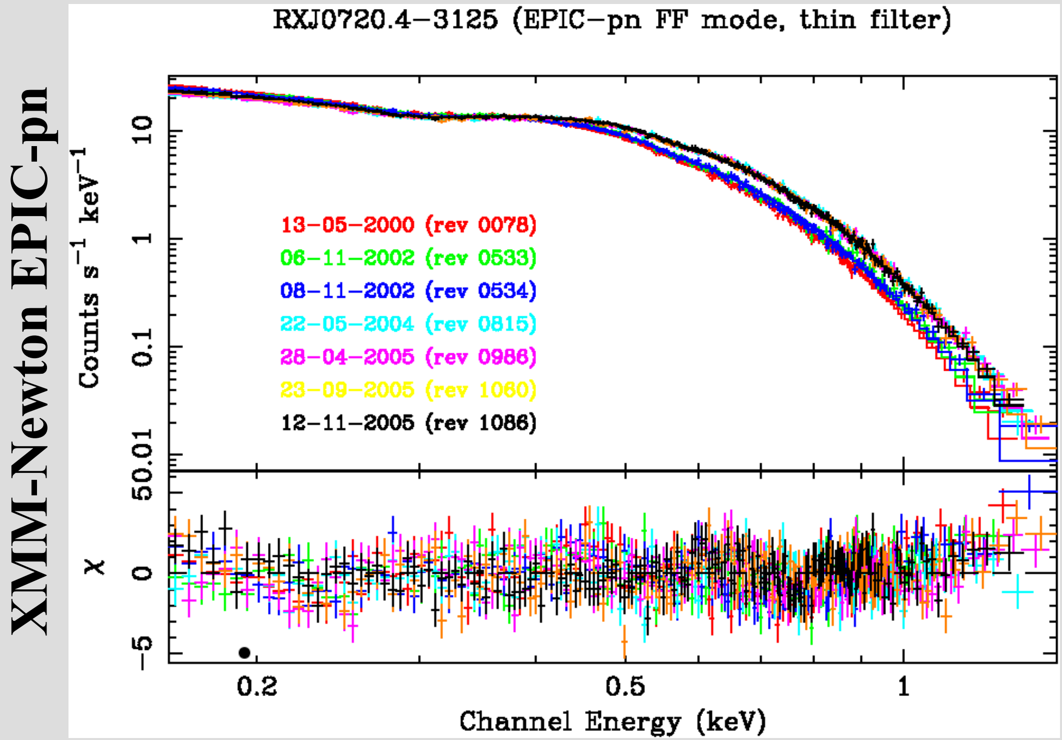
XMM-Newton EPIC-pn



Precession of the neutron star?

de Vries et al. (2004)

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



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:

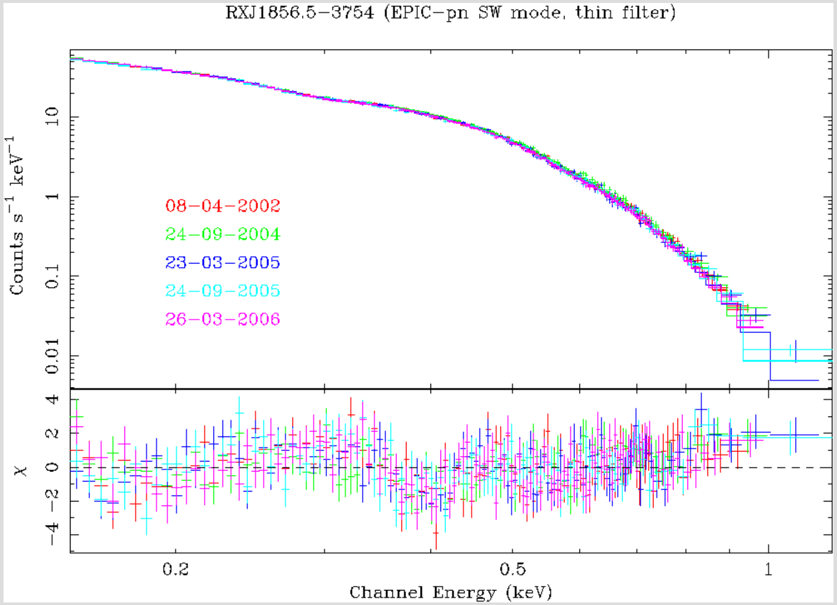
Temperature by ~7eV

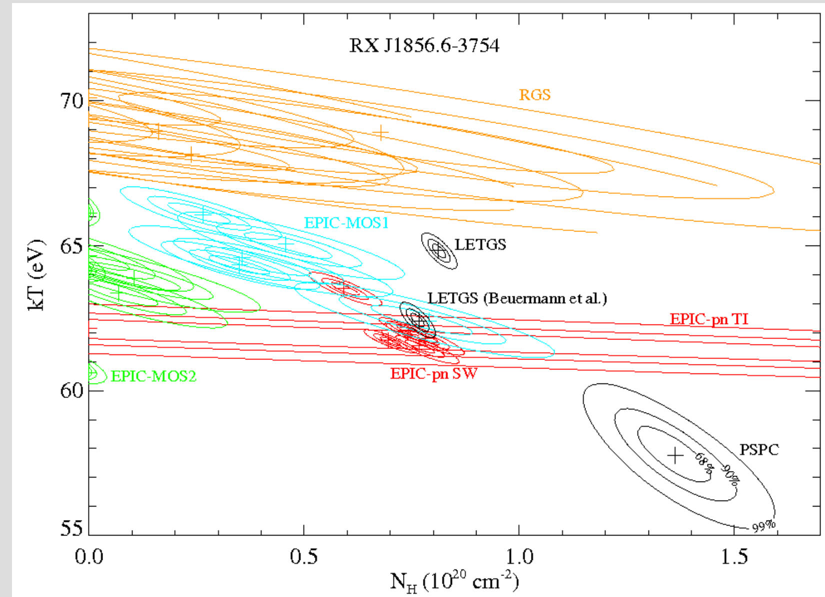
Absorption line equivalent width by a factor of almost 15

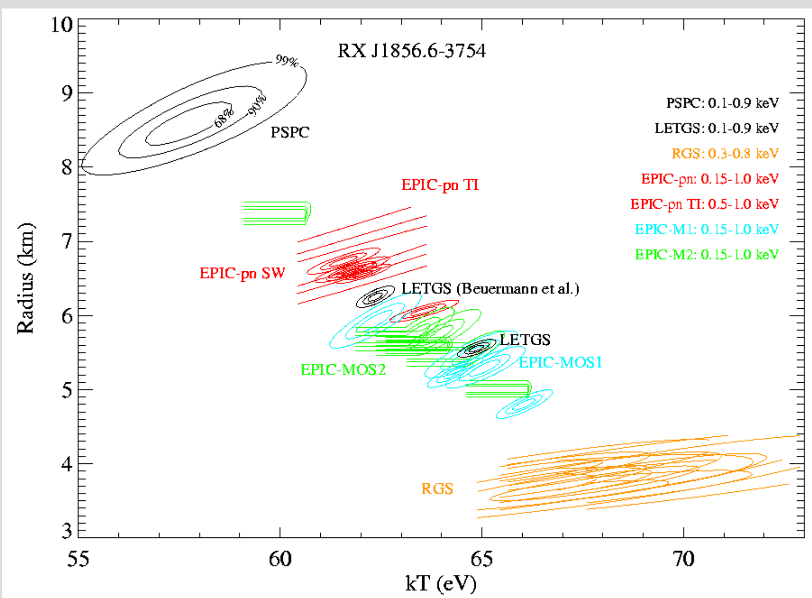
Radius of emission area from 4.4 km to 4.8 km (d=300pc)

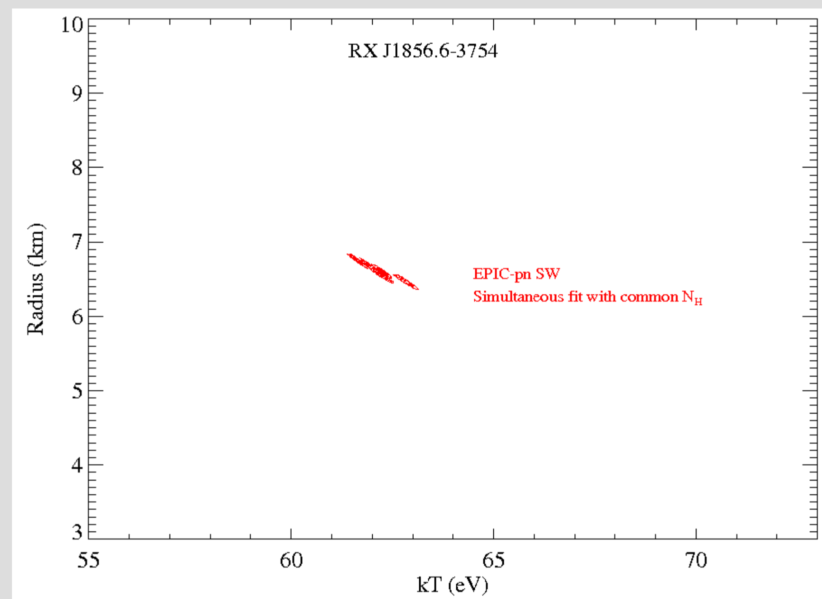
But flux is constant within ±2%

RX J1856.5–3754: A ‚stable‘ neutron star

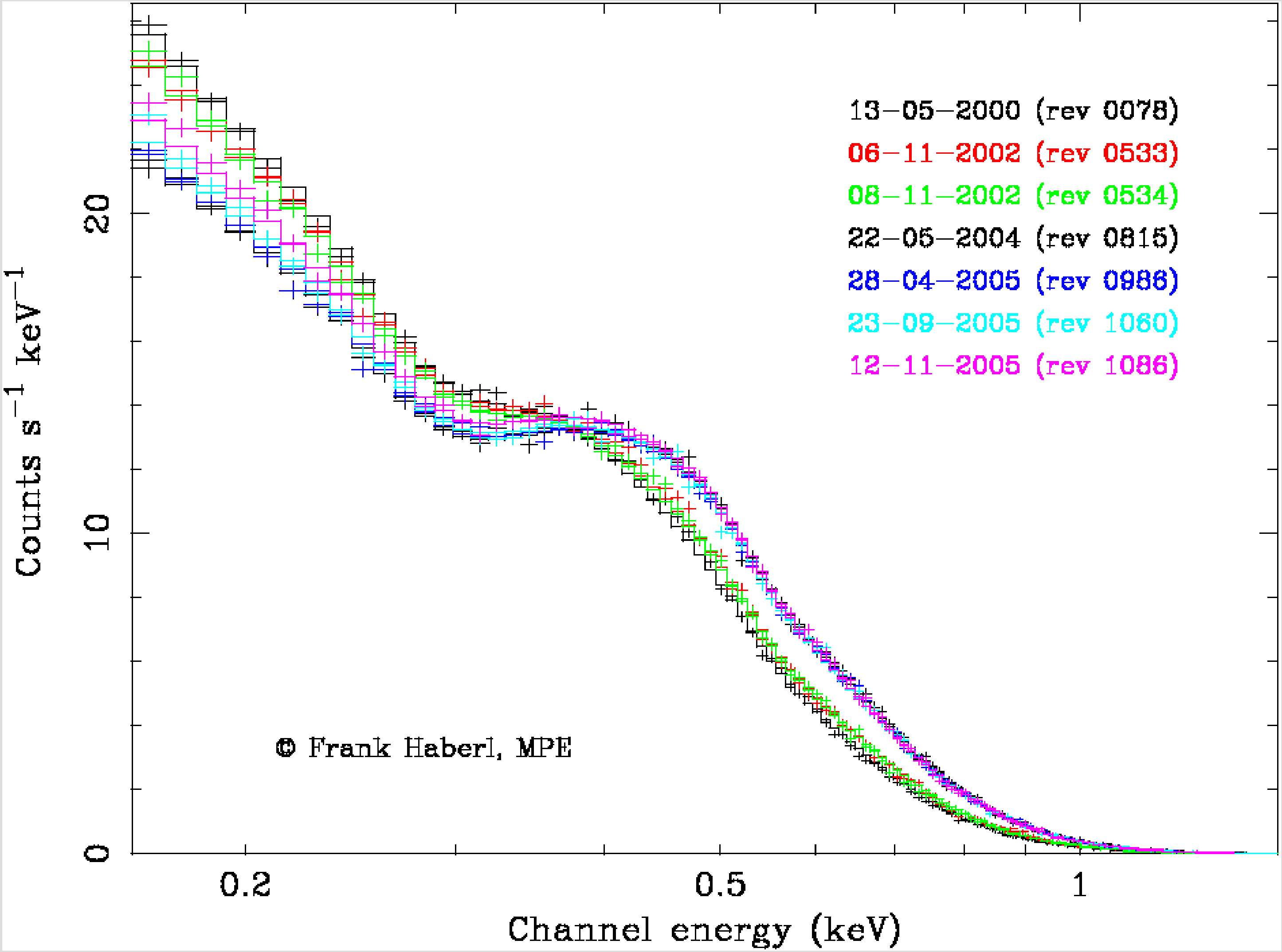




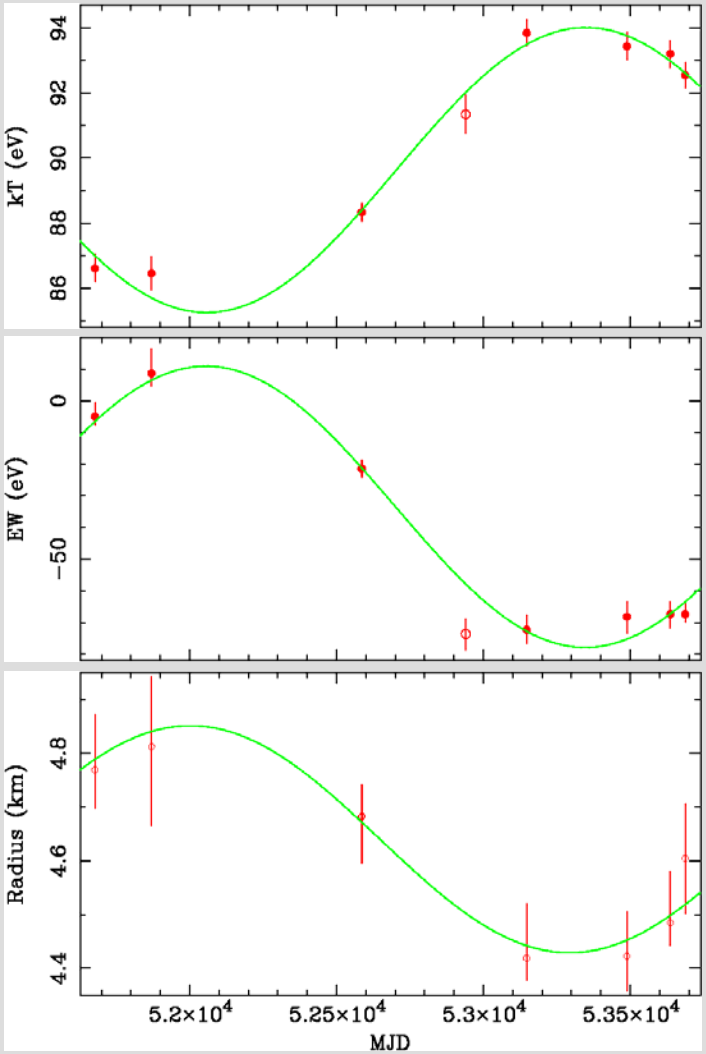




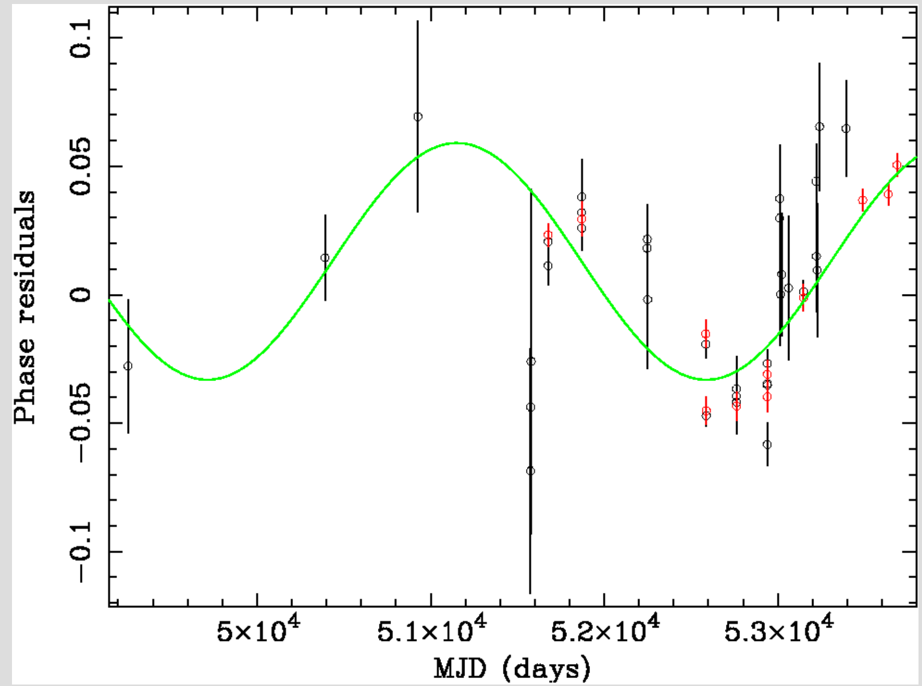
RX J0720.4-3125 longterm spectral variations



RX J0720.4-3125 longterm spectral variations



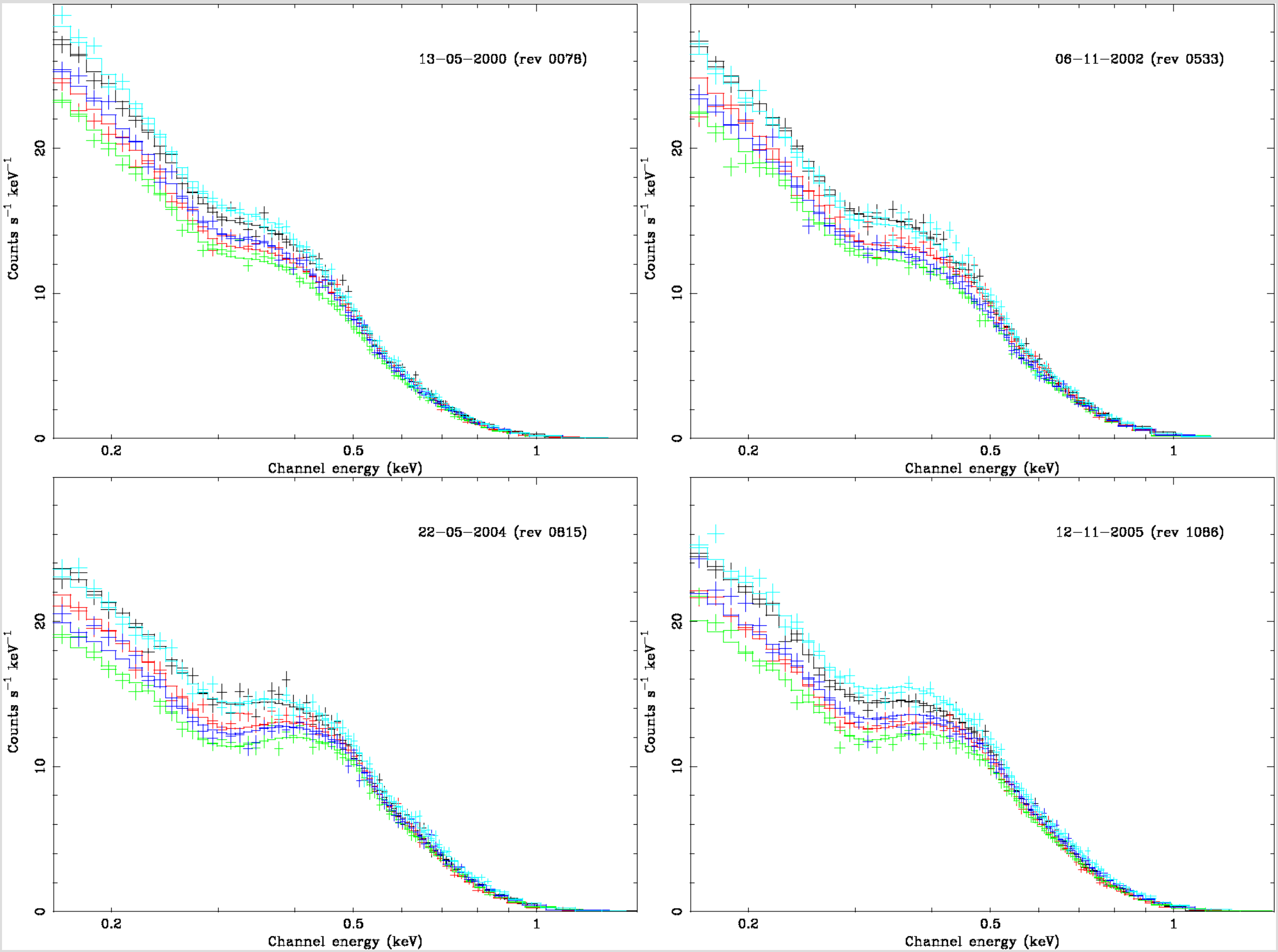
Sinusoidal variations in spectral parameters
Period 7.1 ± 0.5 years



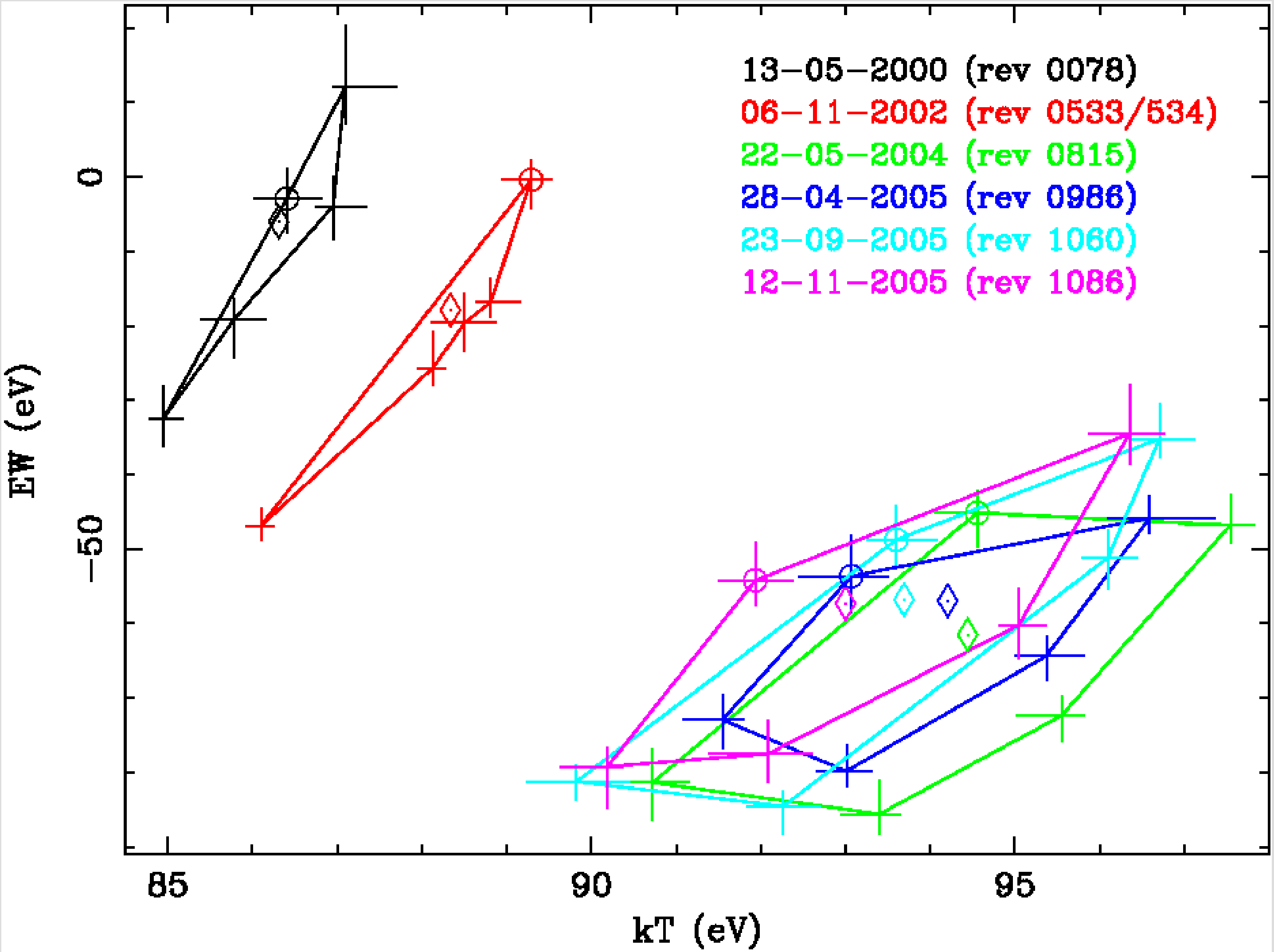
Sinusoidal variations in pulse timing
Period 7.7 ± 0.6 years

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

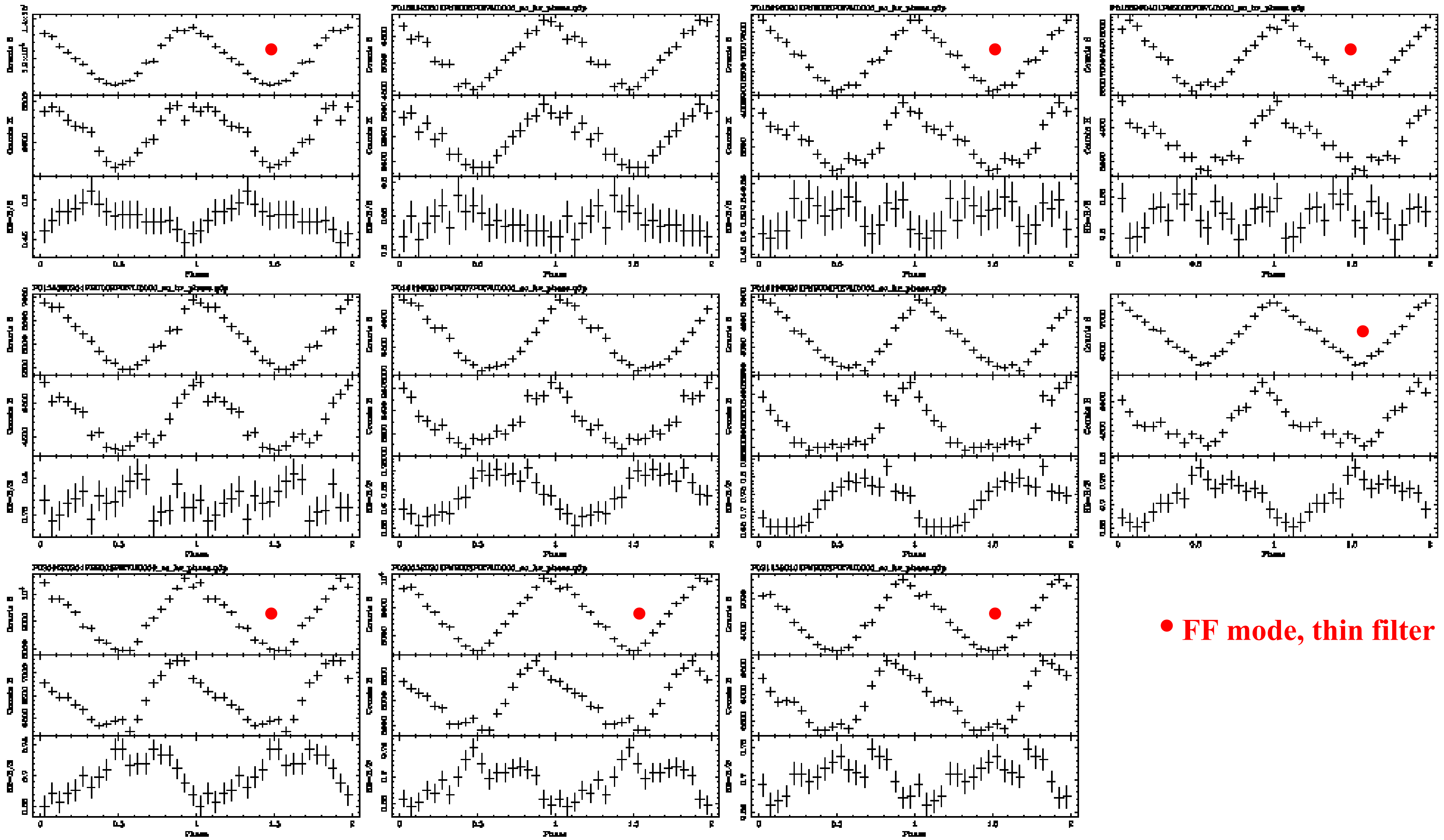
RX J0720.4-3125 pulse phase spectral variations



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



RX J0720.4-3125: Pulse profile changes



● FF mode, thin filter

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

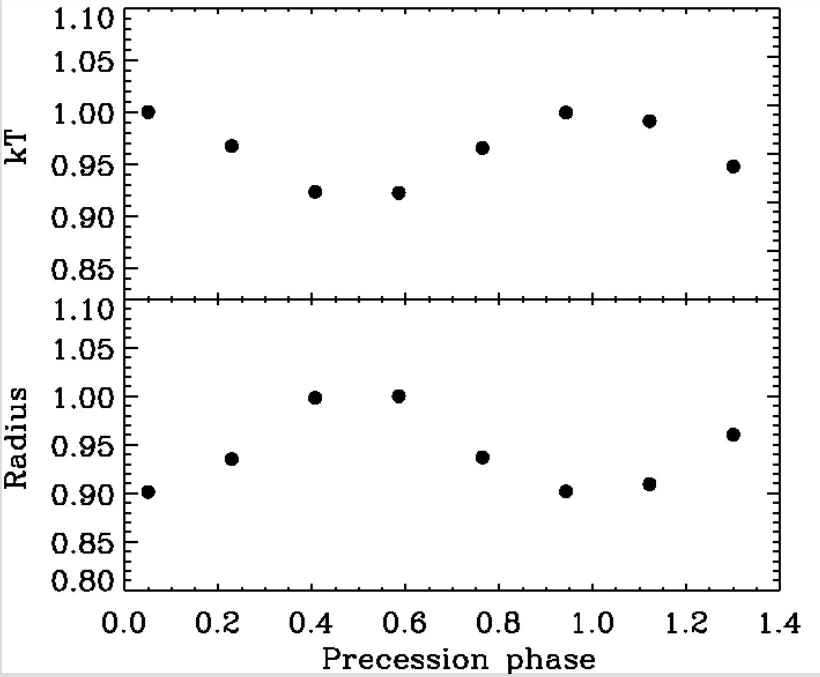
$T_1 = 80$ eV $\sin\theta_1 = 0.8$

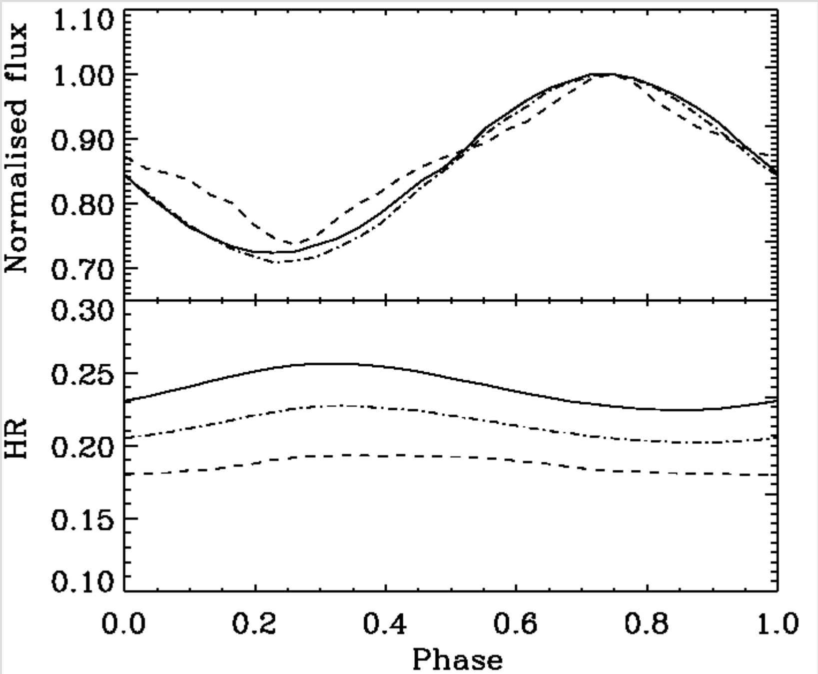
$T_2 = 100$ eV $\sin\theta_2 = 0.6$

not exactly antipodal:

phase shift of lag between hard and soft emission

$\theta_0 = 160^o$



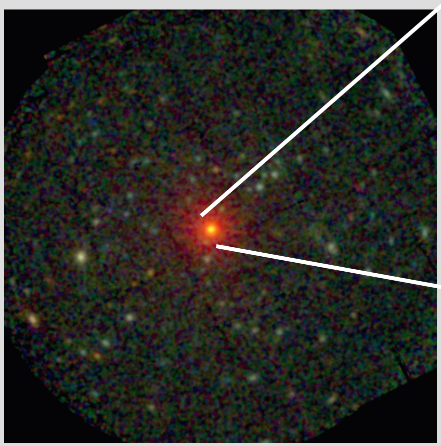


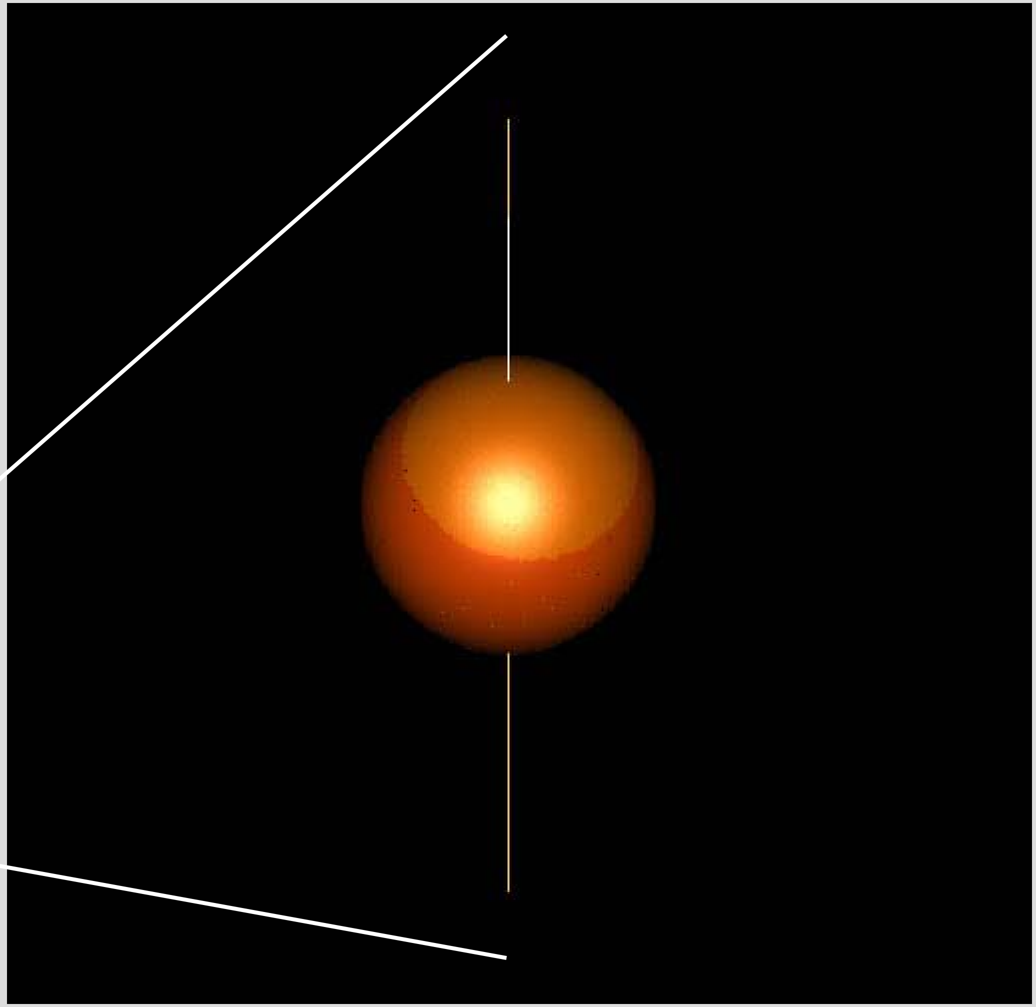
See also: Perez-Azorin et al. (2006) astro-ph/0603752

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

Roberto Turolla
Cor P. De Vries
Silvia Zane (see also her talk)
Jacco Fink
Mariano Mendez
Frank Verbunt

Haberl et al. 2006
A&A in press





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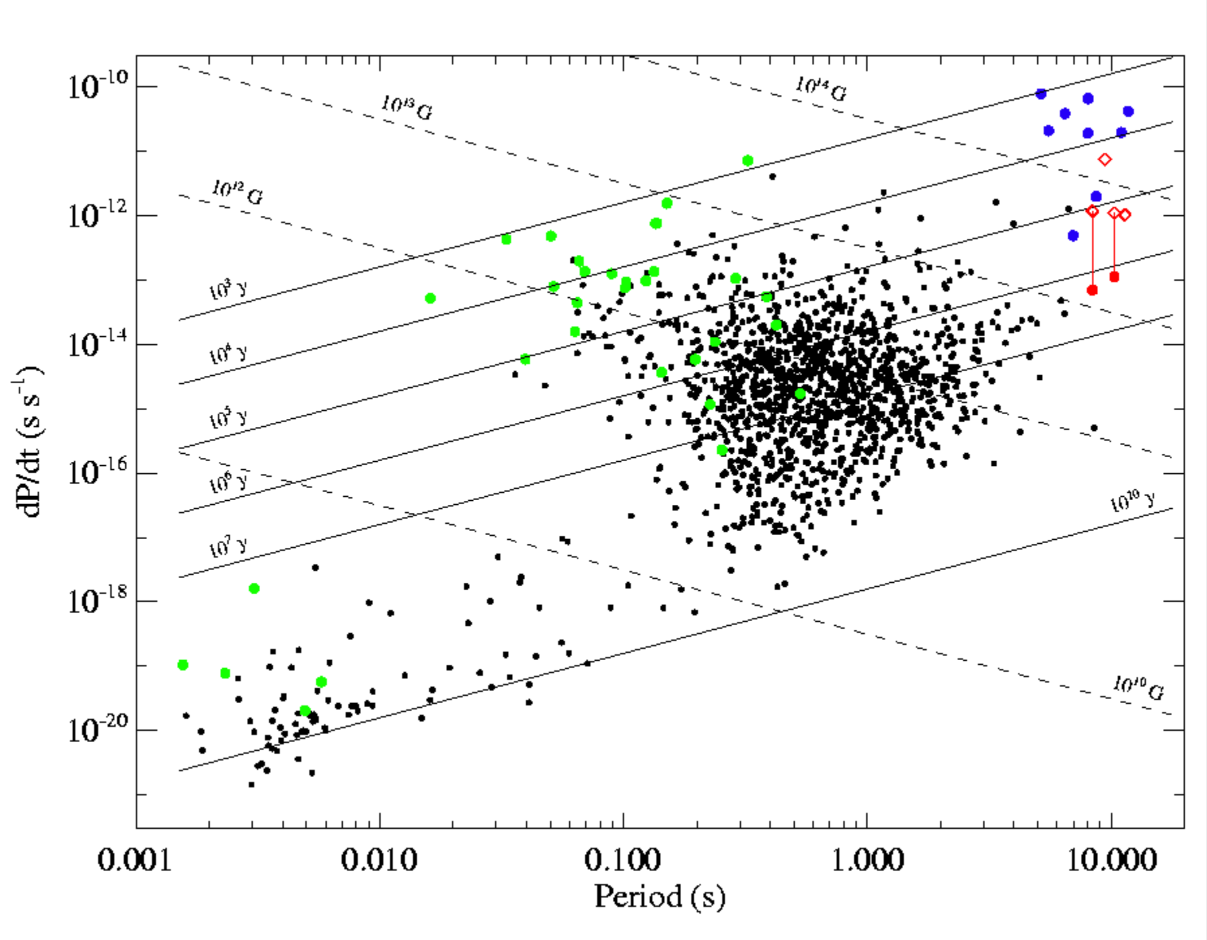
Pulsars



high-energy detections

AXP / γ-ray repeaters (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: Conclusions

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

High proper motion → Nearby, cooling isolated neutron stars

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

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

Interesting individuals:

RX J0720.4-3125: Pulsar
Absorption feature
Precession

RX J1856.4-3754: No pulsations
No absorption feature
Seems to be a special case among the seven (viewing geometry?)