

# Surface emission of neutron stars

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# NS Radii

- A NS with homogeneous surface temperature and local blackbody emission

$$L = 4\pi R^2 \sigma T^4$$

$$F = \frac{L}{4\pi D^2} = \left(R/D\right)^2 \sigma T^4$$

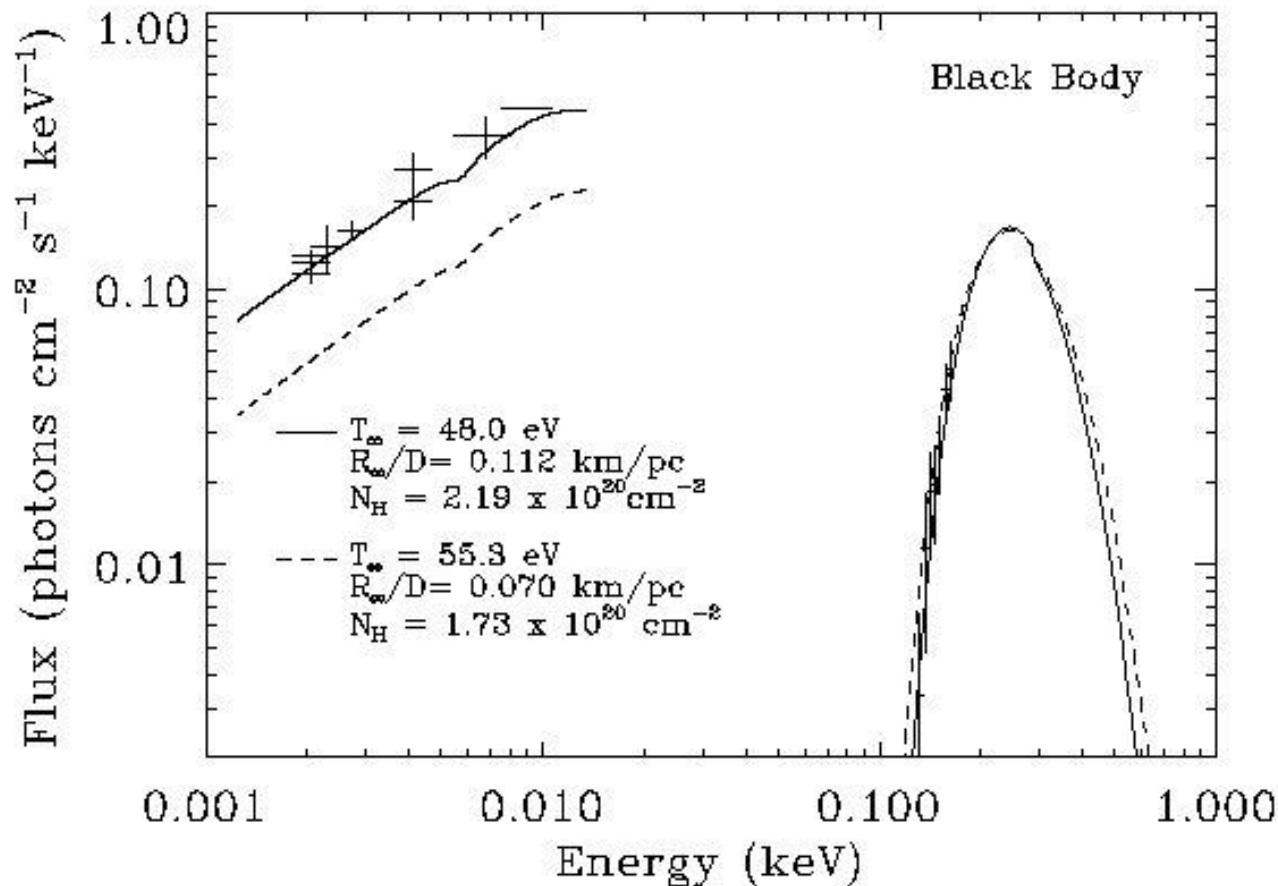
From dispersion  
measure

From X-ray  
spectroscopy

# NS Radii - II

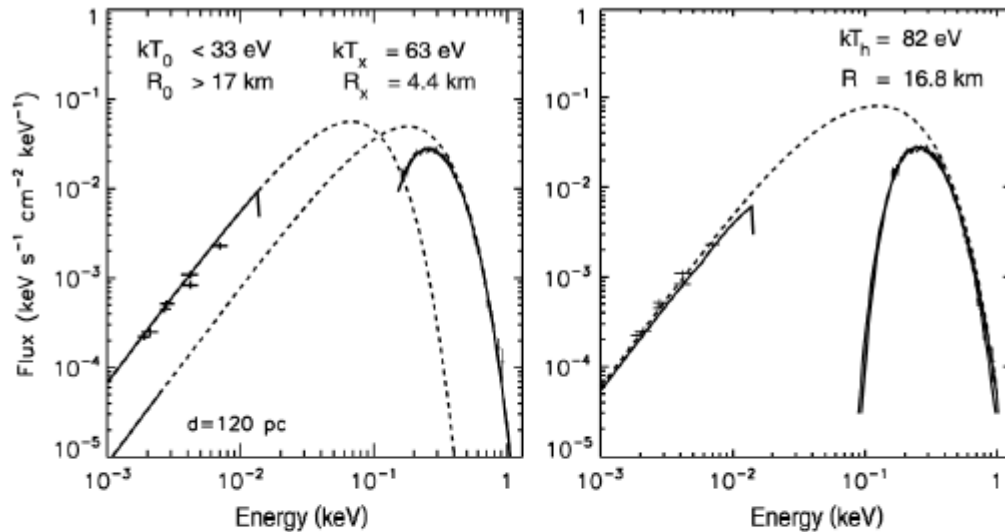
- Real life is a trifle more complicated...  
Atmospheres.
  - Because of the strong B field
    - Photon propagation different
    - Surface temperature is not homogeneous
    - Local emission may be not exactly planckian
  - Gravity effects are important
-

# Uncertainties in temperature

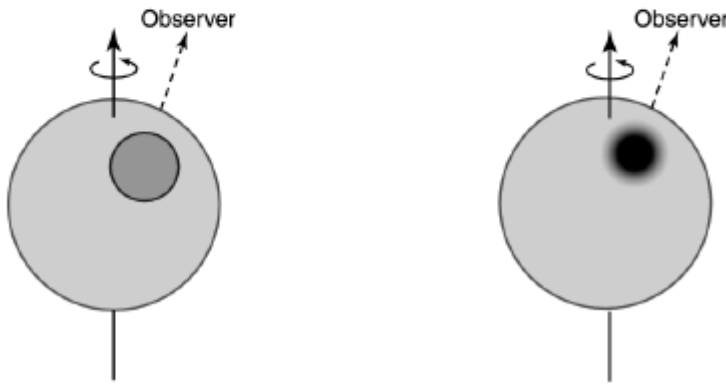


- Atmospheres (composition)
- Magnetic field
- Non-thermal contributions to the spectrum
- Distance
- Interstellar absorption
- Temperature distribution

# Non-uniform temperature distribution

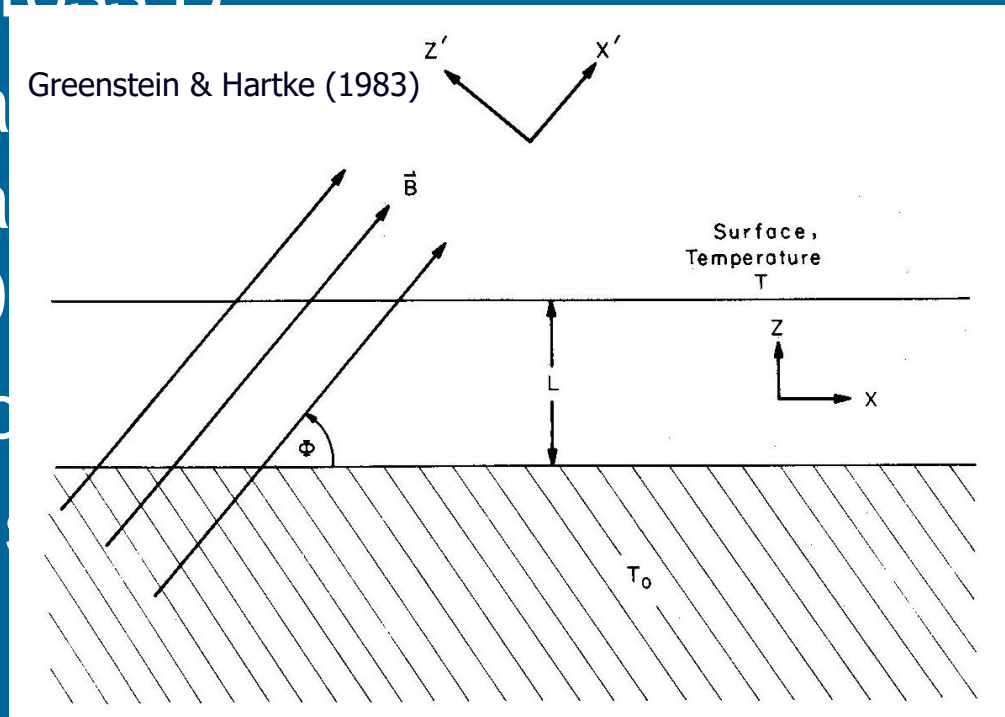


In the case of RX J1856 because of significant ( $\sim 6$ ) optical excess it was proposed that there is a spot, or there is a continuous temperature gradient.



# NS Thermal Maps

- Electrons move much more easily along  $B$  than across  $B$
- Thermal conductivity inside a metal is  $\rho \gg 10^{-8} \Omega \cdot \text{cm}$
- Envelope of the thermal map is  $B \sim \cos \theta$



$$T_s = \left[ \cos^2 \Theta + \left( K_{perp} / K_{par} \right) \sin^2 \Theta \right]^{1/4} T_{pole}$$

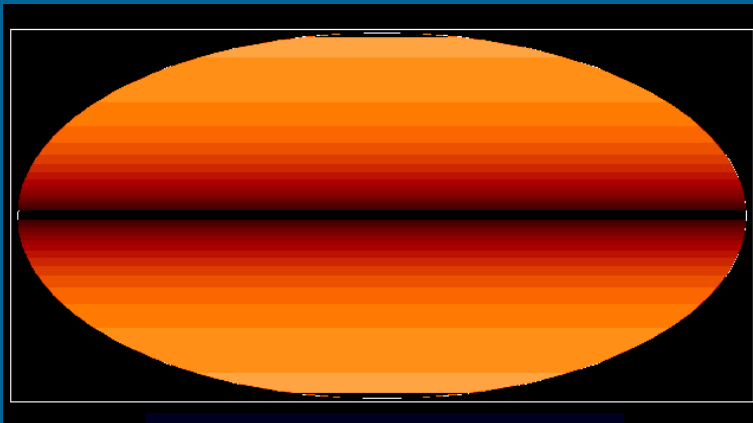
$$K_{perp} / K_{par} \ll 1$$

K - conductivity

$$T_s = |\cos \Theta|^{1/2} T_{pole}$$



Valid for strong fields:  $K_{perp} \ll K_{par}$



Core centered dipole



Core centered quadrupole

# Local Surface Emission

- Much like normal stars NSs are covered by an atmosphere
- Because of enormous surface gravity,  $g \approx 10^{14} \text{ cm/s}^2$ ,  $h_{\text{atm}} \approx 1\text{-}10 \text{ cm}$  ( $h_{\text{atm}} \sim kT/mg$ )
- Spectra depend on  $g$ , chemical composition and magnetic field
- Plane-parallel approximation (locally)



# Atmospheric composition

$A_1$  The lightest

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$A_2$  Light

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$A_3$  Heavy

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$A_4$  The heaviest

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As  $h \ll R$  we can consider only flat layers.

Due to strong gravity an atmosphere is expected to be separated: lighter elements on top.

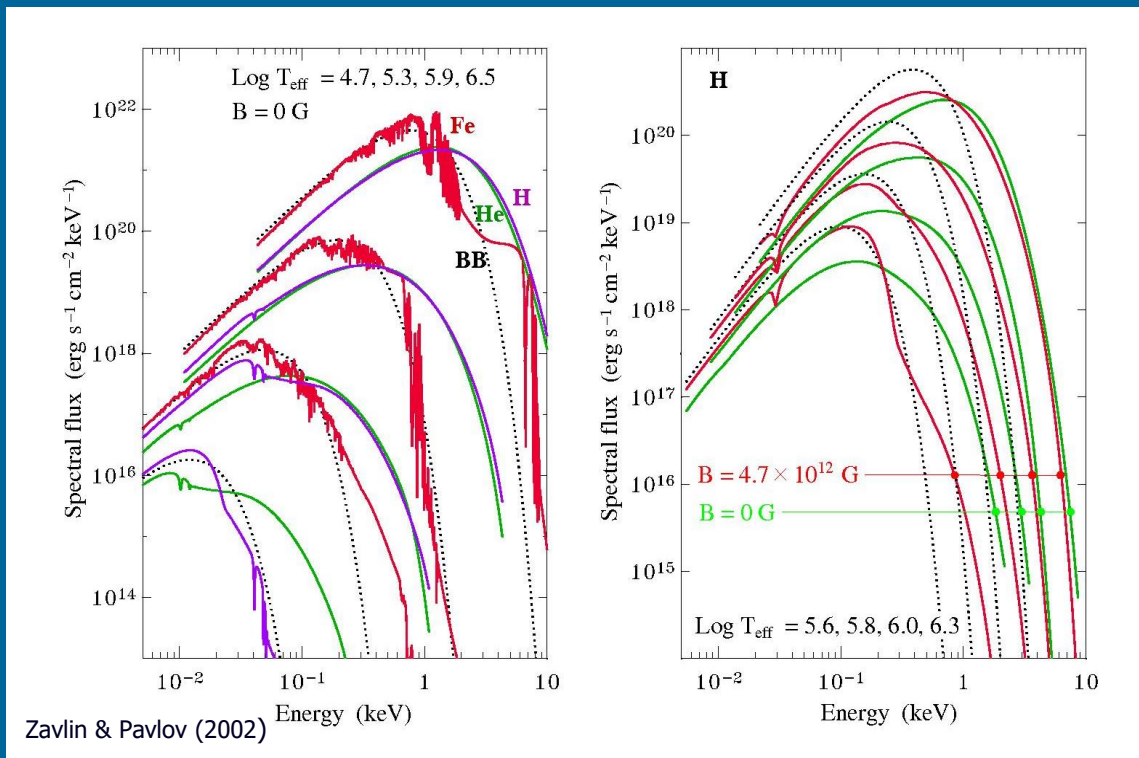
Because of that even a small amount of light elements (hydrogen) results in its dominance in the properties of the atmosphere.

$10^{-20}$  solar mass of hydrogen is enough to form a hydrogen atmosphere.

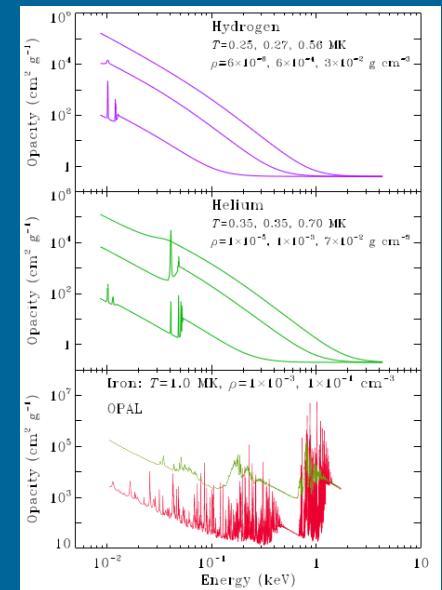
- Free-free absorption dominates

$$\kappa_\nu \propto \nu^{-3}, h\nu \gg kT$$

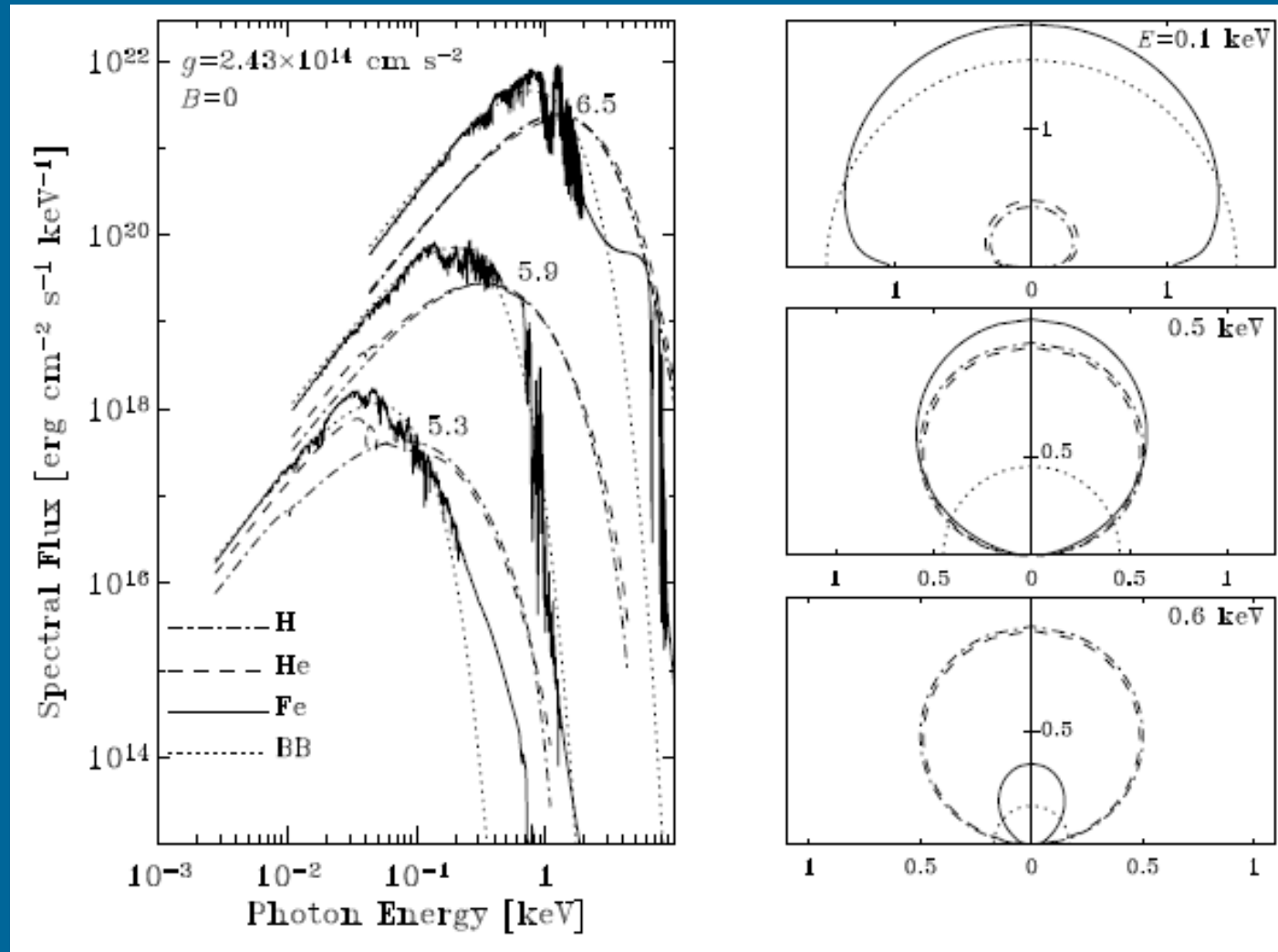
- High energy photons decouple deeper in the atmosphere where T is higher



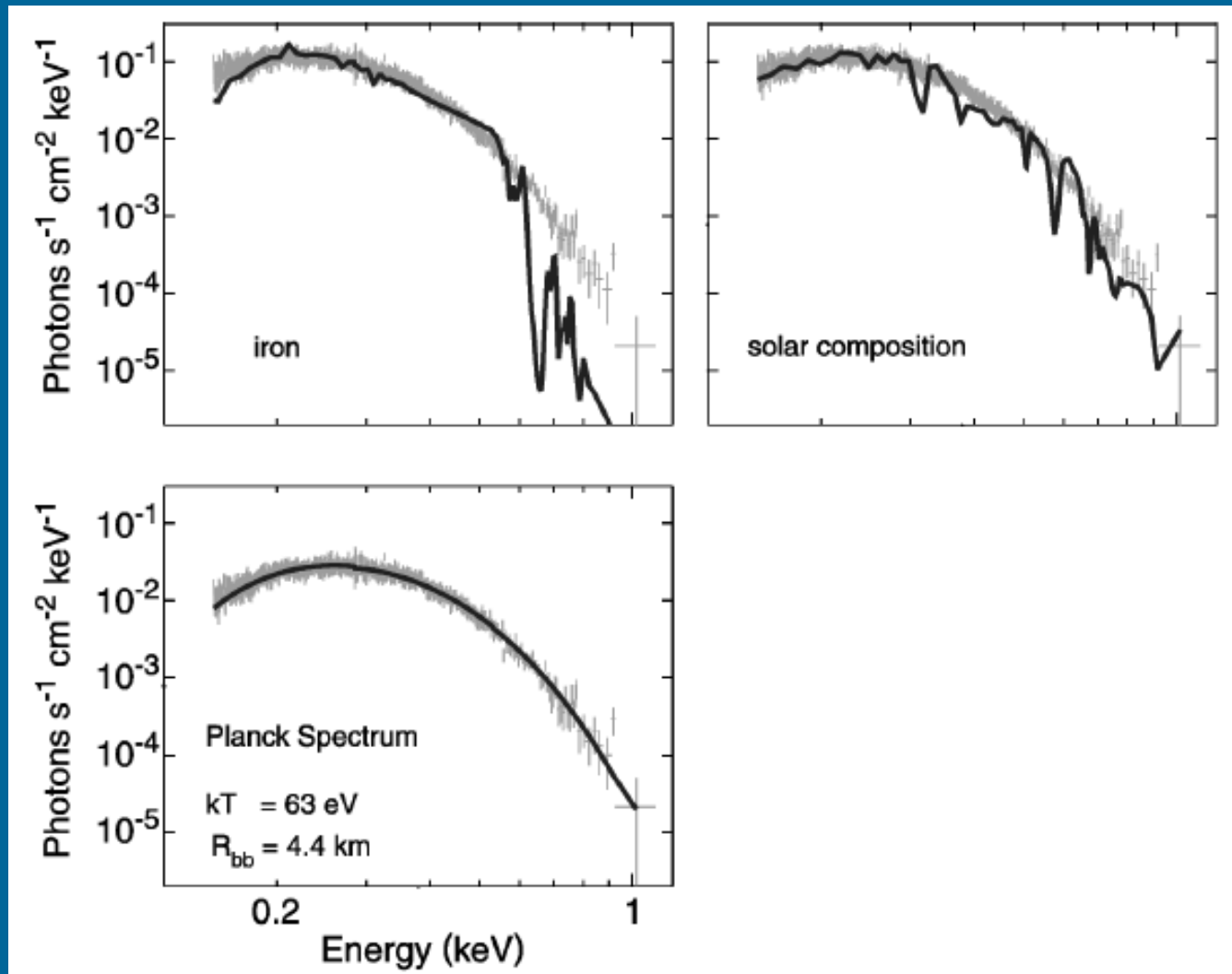
Rapid decrease of the light-element opacities with energy ( $\sim E^{-3}$ )



# Emission from different atmospheres



# Fitting the spectrum of RX J1856



# Different fits

PARAMETERS FROM MULTIWAVELENGTH FITS<sup>a</sup>

Model	$n_{\text{H}}$ ( $10^{20} \text{ cm}^{-2}$ )	$T_{\infty}$ (eV)	$R_{\infty}/D$ (km pc <sup>-1</sup> )	$T_{\infty}(R_{\infty}/D)^2$ [eV (km pc <sup>-1</sup> ) <sup>2</sup> ]	Luminosity <sup>b</sup> ( $10^{31} \text{ ergs s}^{-1}$ )	$P_{\text{ox}}^c$
BB .....	$2.2^{+0.3}_{-0.4}$	$48 \pm 2$	$0.11 \pm 0.01$	$0.60^{+0.05}_{-0.4}$	$1.55^{+0.23}_{-0.17}$	$3 \times 10^{-4}$
H .....	$1.0 \pm 0.1$	$26 \pm 1$	$0.27 \pm 0.01$	$1.94 \pm 0.01$	$0.6 \pm 0.01$	$< 10^{-14}$
Fe.....	$1.8 \pm 0.2$	$44 \pm 1$	$0.13 \pm 0.01$	$0.75 \pm 0.05$	$1.41^{+0.08}_{-0.06}$	$7 \times 10^{-7}$
Si-ash.....	$1.9^{+0.3}_{-0.2}$	$45^{+2}_{-1}$	$0.13 \pm 0.01$	$0.74^{+0.04}_{-0.05}$	$1.63^{+0.14}_{-0.21}$	0.53

<sup>a</sup> 3  $\sigma$  ranges, assuming  $z = 0.305$ . Weighting of the data is discussed in the text.

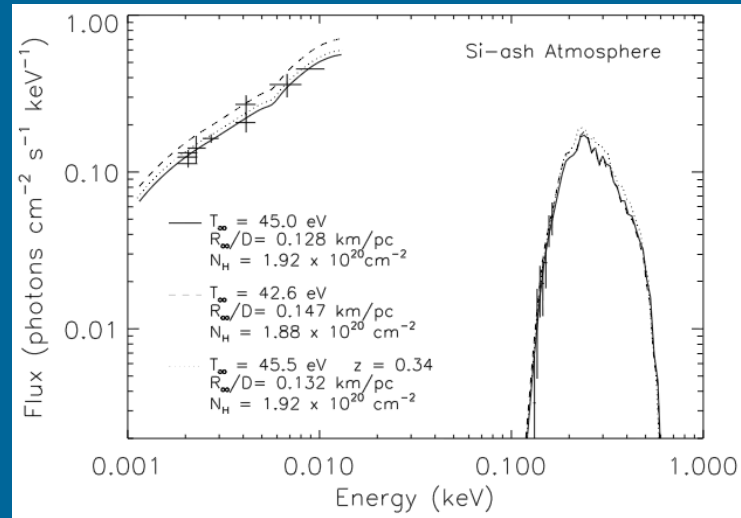
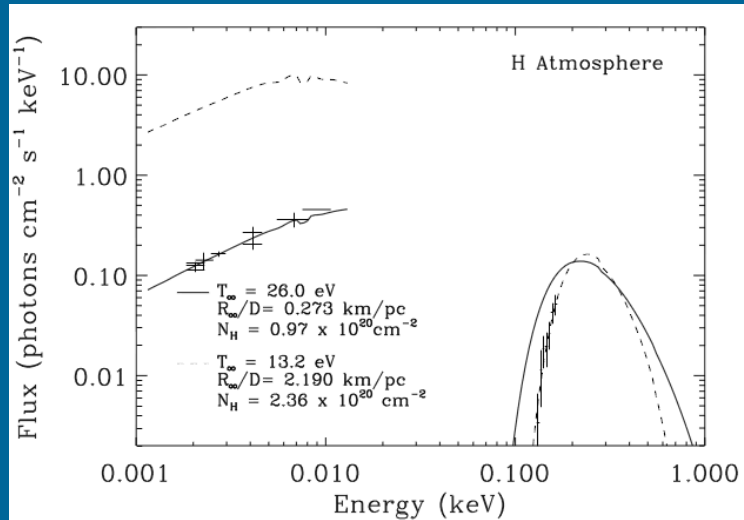
<sup>b</sup> Uncertainty does not include uncertainty in distance.

<sup>c</sup> The likelihood that the X-ray and optical parameters are the same.

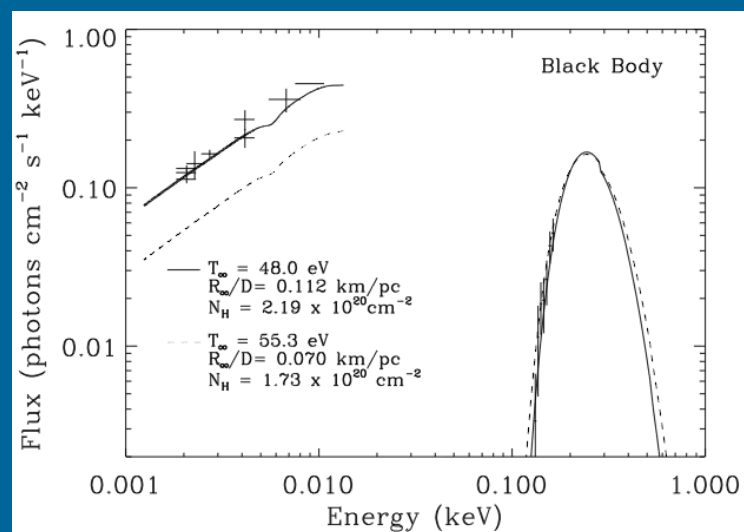
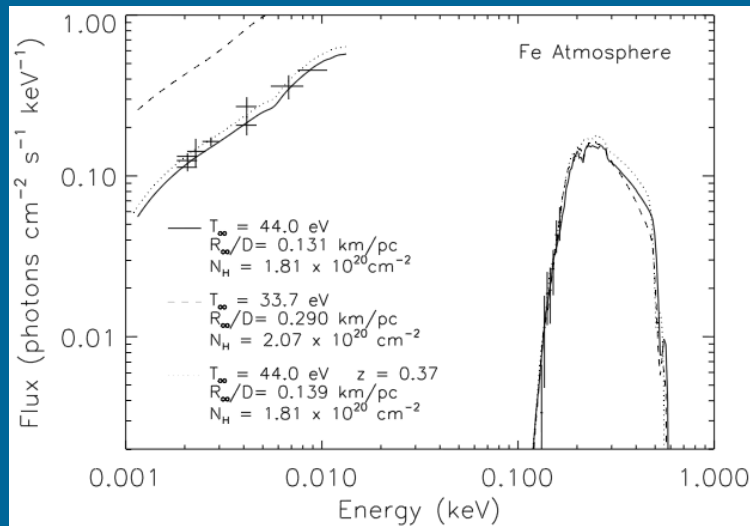
Fits of realistic spectra of cooling NSs give higher temperature (and so smaller emitting surfaces) for blackbody and heavy element atmospheres (Fe, Si).

$$T_{\text{BB}} \sim 2T_{\text{H}}$$

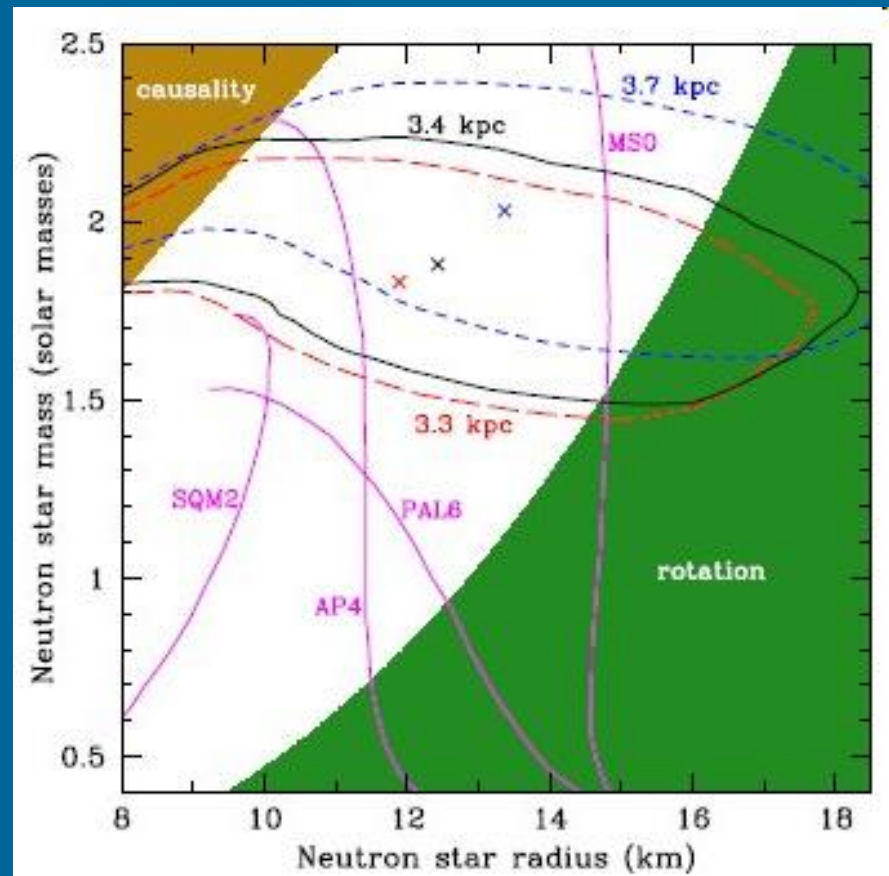
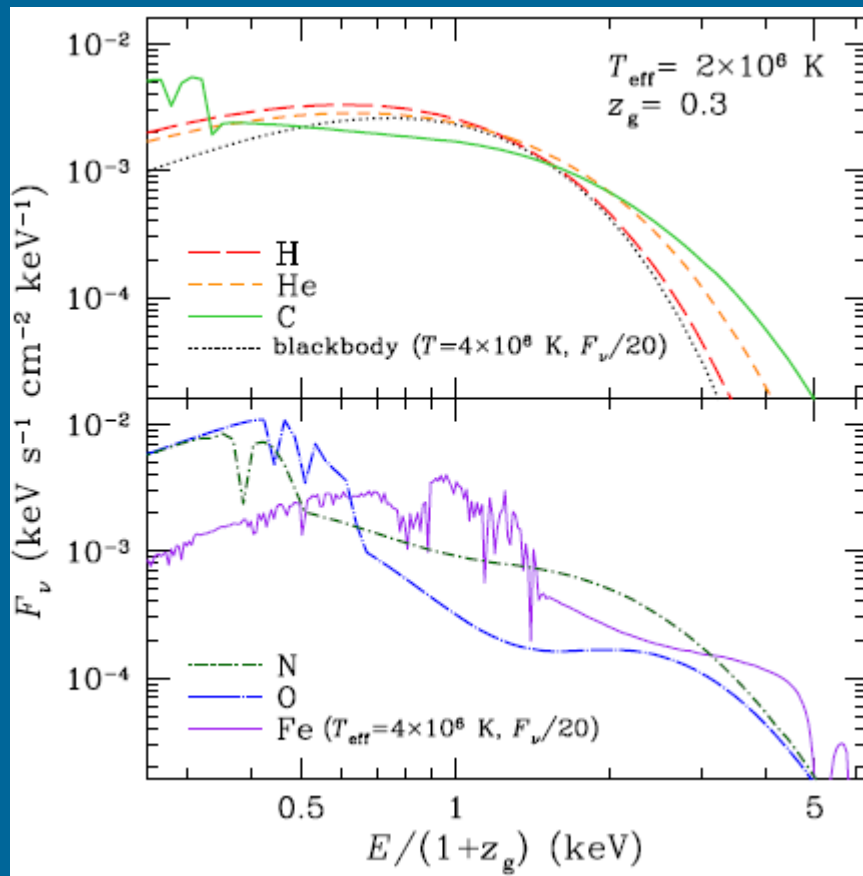
# Different fits



$$T_{\text{bb}} \sim T_{\text{Fe}} > T_{\text{H}}$$



# Cas A carbon atmosphere



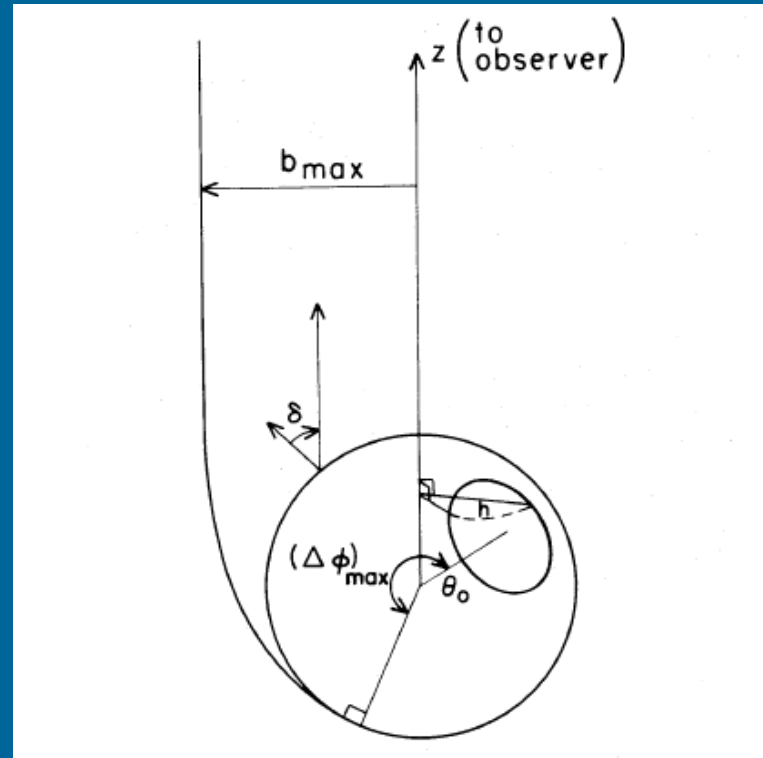
Low-field carbon atmosphere can fit the data.  
Before all fits provided a very small emitting area.

# Gravity Effects

- Redshift
- Ray bending

$$L_{\infty} = 4\pi R_{\infty}^2 \sigma T_{\infty}^4$$

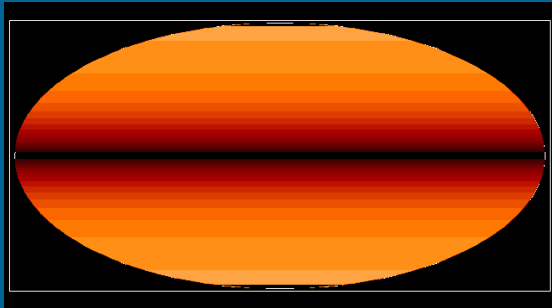
$$4\pi\sigma T_{\infty}^4 \rightarrow \int_0^{2\pi} d\gamma \int_0^{2\pi} d\Phi \int_0^1 du^2 \int_{E_{\infty,1}}^{E_{\infty,2}} dE_{\infty} I(E, B, \cos \Theta, T_s, \gamma)$$





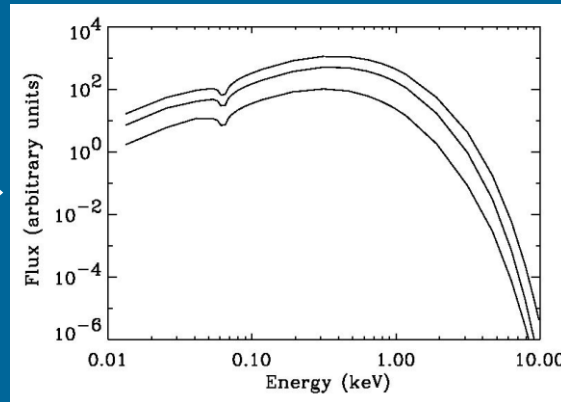
### STEP 1

Specify viewing geometry and B-field topology; compute the surface temperature distribution



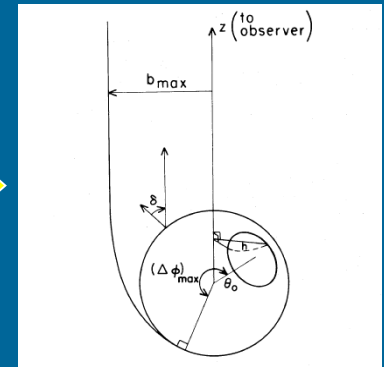
### STEP 2

Compute emission from every surface patch



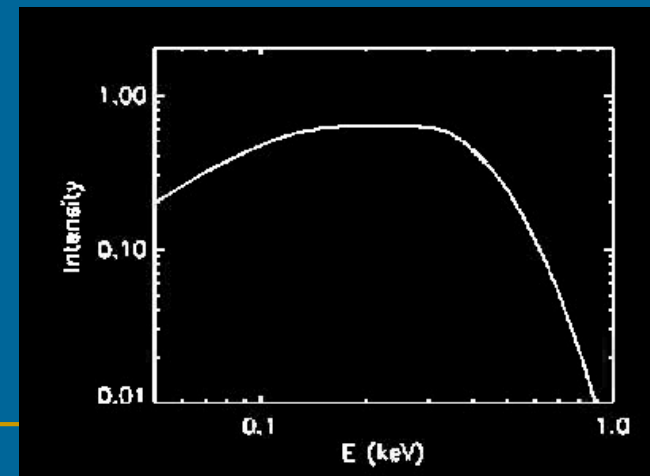
### STEP 3

GR ray-tracing to obtain the spectrum at infinity



### STEP 4

Predict lightcurve and phase-resolved spectrum  
Compare with observations



# The Seven X-ray dim Isolated NSs

- Soft thermal spectrum ( $kT \approx 50\text{-}100$  eV)
- No hard, non-thermal tail
- Radio-quiet, no association with SNRs
- Low column density ( $N_H \approx 10^{20}$  cm<sup>-2</sup>)
- X-ray pulsations in all (but one?) sources ( $P \approx 3\text{-}10$  s)
- Very faint optical counterparts
- Broad spectral features

# ICoNS: The Perfect Neutron Stars

ICoNS are key in neutron star astrophysics:  
these are the only sources for which we have  
a “clean view” of the star surface

- Information on the thermal and magnetic surface distributions
- Estimate of the star radius (and mass ?)
- Direct constraints on the EOS

# ICoNS: What Are They ?

- ICoNS *are* neutron stars
- Idea number 1: Powered by ISM accretion?  
 $\dot{M}_{\text{Bondi}} \sim n_{\text{ISM}}/v^3$  if  $v < 40$  km/s and  $D < 500$  pc  
(e.g. Treves et al 2000)
- Measured proper motions imply  $v > 100$  km/s
- Just cooling NSs

# Simple Thermal Emitters ?

Recent detailed observations of ICoNS allow direct testing of surface emission models

**“STANDARD MODEL”** thermal emission from the surface of a neutron star with a dipolar magnetic field and covered by an atmosphere

The optical excess

ICoNS lightcurves

The puzzle of RX J1856.5-3754

Spectral evolution of RX J0720.4-3125

Note a claim for an excess at harder (keV) X-rays: 1703.05995

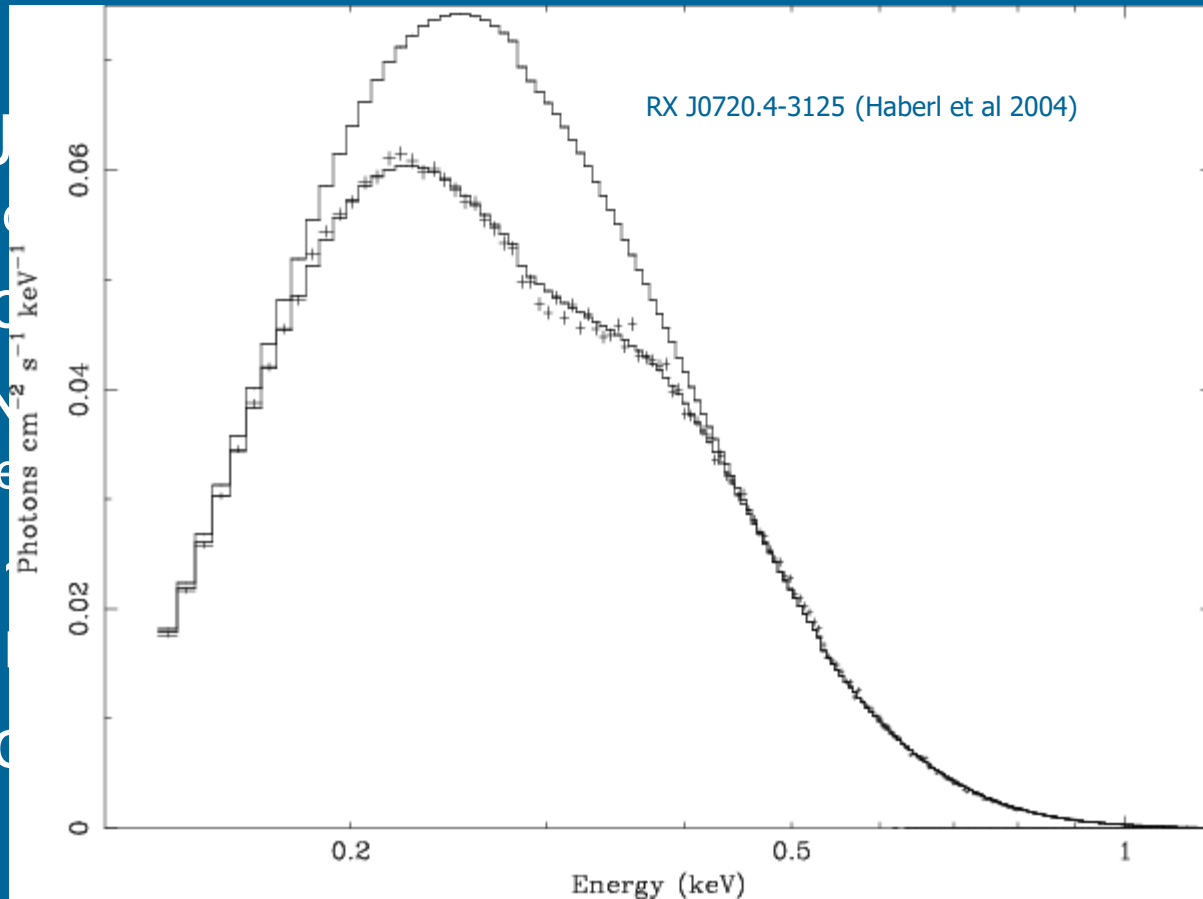
# The Magnificent Seven

Source	kT (eV)	P (s)	Amplitude/2	Optical
RX J1856.5-3754	60	7.06	1.5%	V = 25.6
RX J0720.4-3125 (*)	85	8.39	11%	B = 26.6
RX J0806.4-4123	96	11.37	6%	UV
RX J0420.0-5022	45	3.45	13%	B = 26.6
RX J1308.6+2127 (RBS 1223)	86	10.31	18%	m <sub>50CCD</sub> = 28.6
RX J1605.3+3249 (RBS 1556)	96	-----	??	m <sub>50CCD</sub> = 26.8
1RXS J214303.7+065419 (RBS 1774)	104	9.43	4%	B=27.4

(\*) variable source

# Featureless ? No Thanks !

- RX J0720.4-3125 (Chandra)
- A broad peak  
ICoN model  
Zane et al 2004
- $E_{\text{line}} = 2E_2$  in  
Proton
- ?

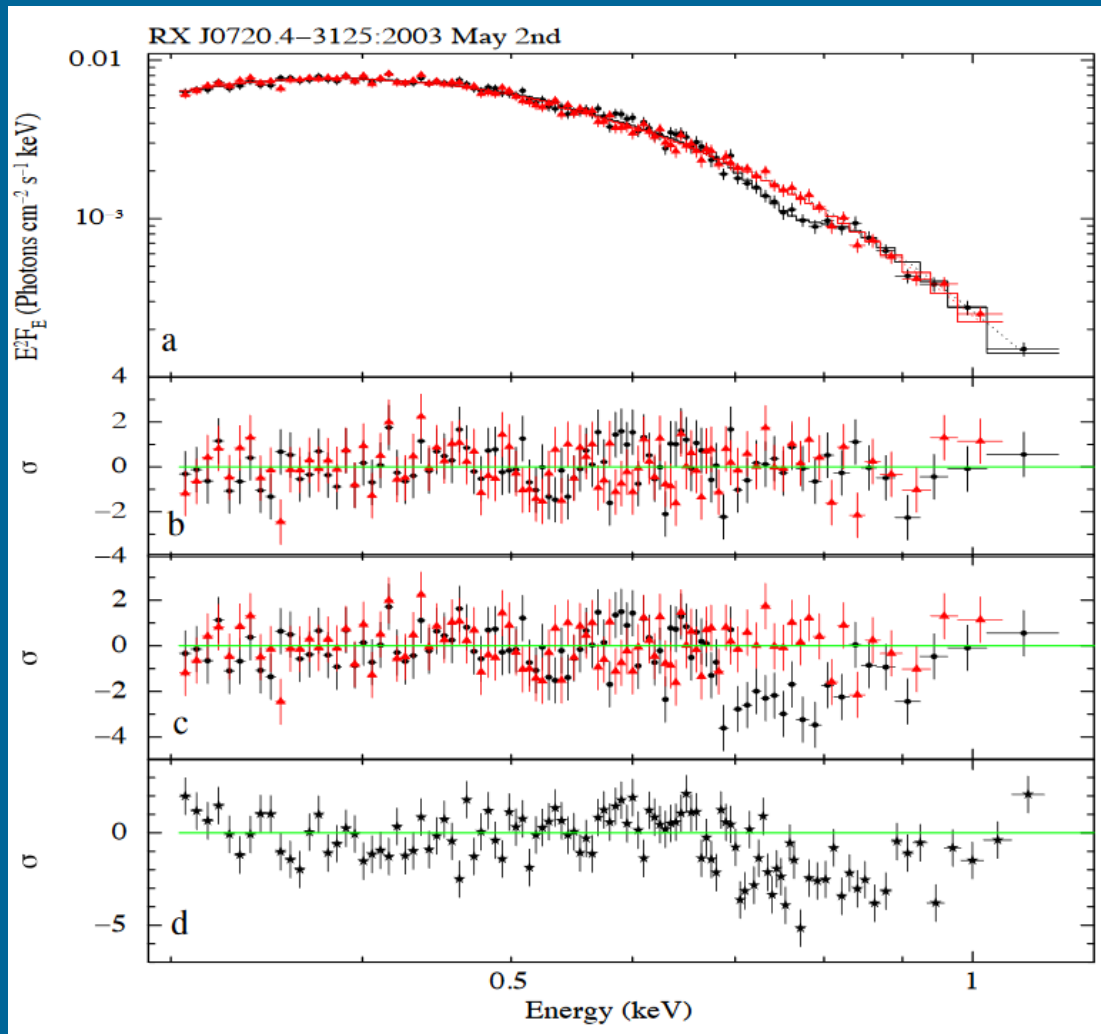


S  
her  
al 2004;  
th  $E_1 \sim$   
high B

Source	Energy (eV)	EW (eV)	$B_{\text{line}}$ ( $B_{\text{sd}}$ ) ( $10^{13}$ G)	Notes
RX J1856.5-3754	no	no	?	-
RX J0720.4-3125	270	40	5 (2)	Variable line
RX J0806.4-4123	460	33	9	-
RX J0420.0-5022	330	43	7	-
RX J1308.6+2127	300	150	6 (3)	-
RX J1605.3+3249	450	36	9	-
1RXS J214303.7+065419	700	50	14	-

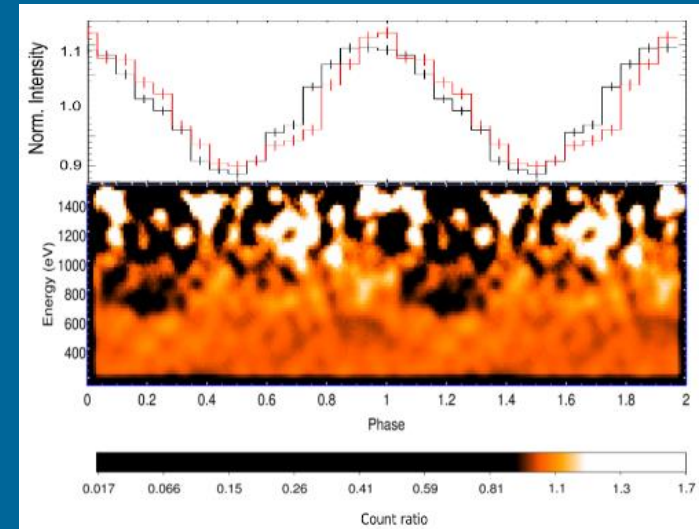


# Phase variable spectral feature



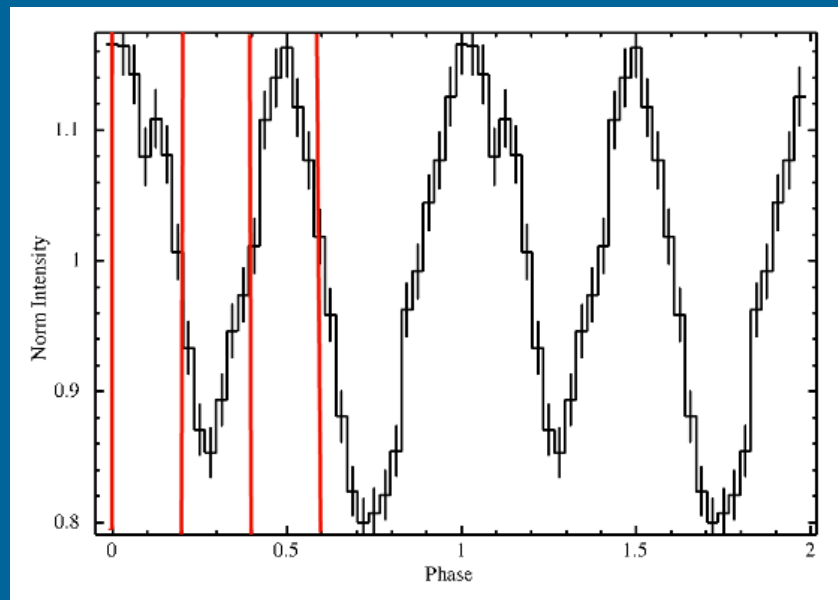
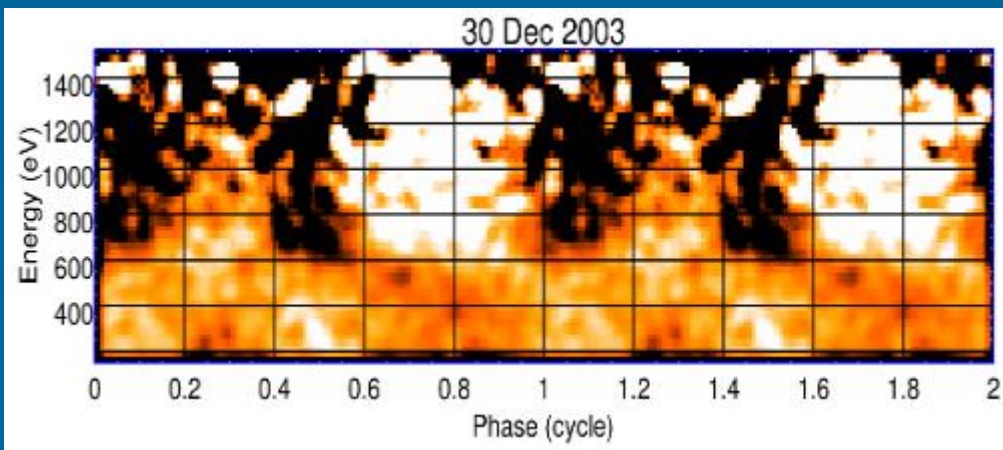
RX J0720.4-3125

Black: phase 0.1-0.3  
red: phase 0.5-0.7



# More phase-dependent features in M7

RX J1308.6+2127

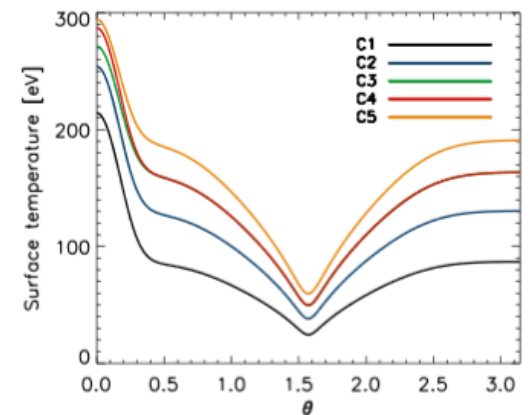
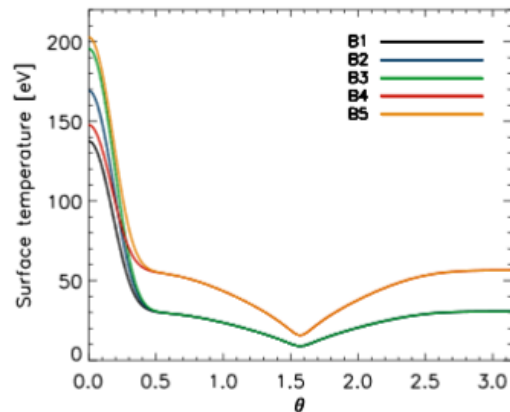
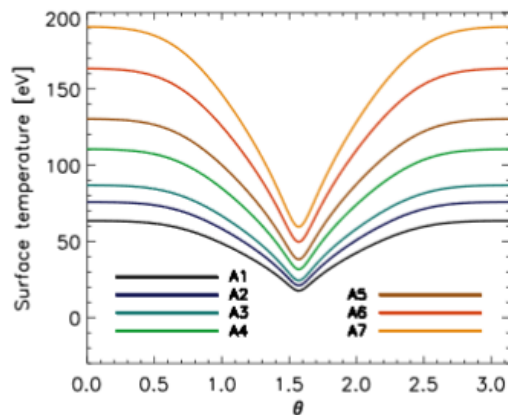


Parameter <sup>a</sup>	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1
BB+GAUSS					
kT <sub>BB</sub> (eV)	77.7 <sup>+1.8</sup> <sub>-2.0</sub>	75.4 <sup>+2.2</sup> <sub>-2.5</sub>	84.9 <sup>+1.3</sup> <sub>-1.4</sub>	75.6 <sup>+2.1</sup> <sub>-2.7</sub>	84.9 <sup>+1.8</sup> <sub>-2.0</sub>
R <sub>BB</sub> (km)	4.3±0.5	5.6±1.0	2.6±0.1	5.8±1.1	3.4±0.3
Flux <sup>b</sup>	3.34 <sup>+0.04</sup> <sub>-0.09</sub>	3.67 <sup>+0.15</sup> <sub>-0.09</sub>	3.10 <sup>+0.05</sup> <sub>-0.07</sub>	3.68 <sup>+0.07</sup> <sub>-0.06</sub>	3.69±0.06
Unabs. Flux <sup>b</sup>	7.42±1.10	7.69 <sup>+1.70</sup> <sub>-1.01</sub>	6.63 <sup>+0.63</sup> <sub>-0.36</sub>	8.26 <sup>+1.35</sup> <sub>-1.39</sub>	7.77 <sup>+0.55</sup> <sub>-0.76</sub>
E <sub>1</sub> (eV)	173 <sup>+32</sup> <sub>-39</sub>	107 <sup>+44</sup> <sub>-54</sub>	256 <sup>+22</sup> <sub>-28</sub>	109 <sup>+41</sup> <sub>-59</sub>	198 <sup>+30</sup> <sub>-36</sub>
σ <sub>1</sub> (eV)	143 <sup>+13</sup> <sub>-12</sub>	169 <sup>+15</sup> <sub>-14</sub>	105 <sup>+11</sup> <sub>-11</sub>	168 <sup>+16</sup> <sub>-13</sub>	146 <sup>+14</sup> <sub>-12</sub>
Eq Width <sub>1</sub> (eV)	182 <sup>+2</sup> <sub>-8</sub>	204 <sup>+2</sup> <sub>-35</sub>	128 <sup>+10</sup> <sub>-14</sub>	203 <sup>+2</sup> <sub>-5</sub>	171 <sup>+11</sup> <sub>-29</sub>
NHP <sup>c</sup>	1.6×10 <sup>-1</sup>	1.5×10 <sup>-1</sup>	5.4×10 <sup>-2</sup>	1.3×10 <sup>-1</sup>	2.8×10 <sup>-3</sup>
χ <sub>ν</sub> <sup>2</sup>	1.12	1.12	1.20	1.13	1.35
dof	141	149	139	147	150

1703.05336

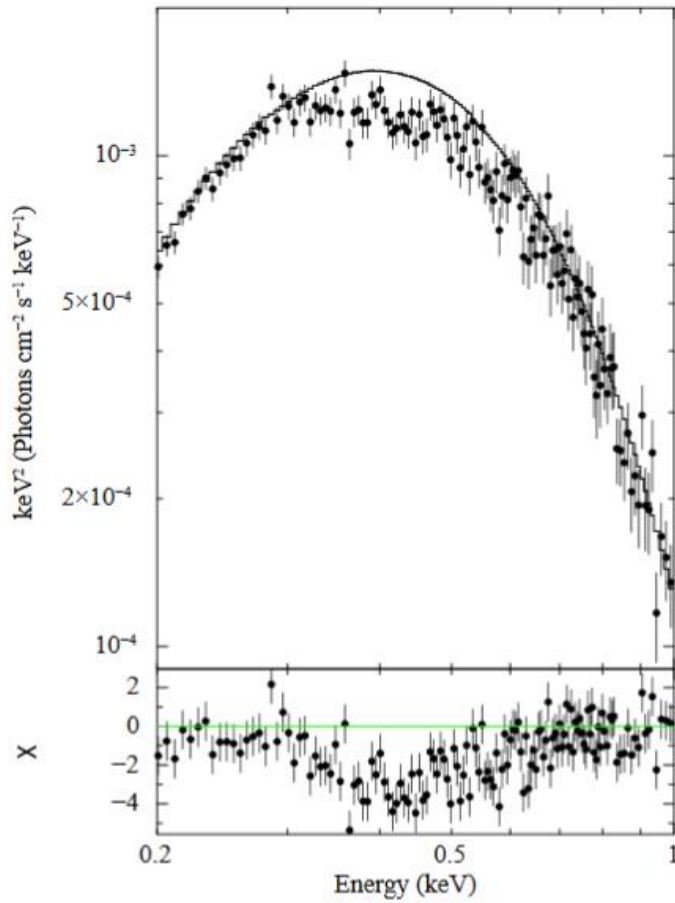
# Non-uniform temperature distribution

Source	Class	$B_{dip}$ [ $10^{12}$ G]	$N_H$ [ $10^{20}$ cm $^{-2}$ ]	$kT_{bb}$ [eV]	$E_0$ [eV]	$ E_w $ [eV]	PF %	Refs.
RX J0720.4-3125	XINS	49	1.0	84-94	311*	0-70	11	[1]
RX J0806.4-4123	XINS	51	0.9	95	486*	30	6	[2]
RX J1308.6+2127	XINS	68	3.7	93	390*	150	18	[3]
RX J1605.3+3249	XINS	148 <sup>†</sup>	0	99	400*	70	5 <sup>†</sup>	[4]
RX J2143.0+0654	XINS	40	2.3	104	750	50	4	[5]
2XMM J1046-5943 <sup>‡</sup>	?	?	26	135	1350*	90	<4	[6]
1E 1207.4-5209	CCO	0.2	13	155,290	740,1390	60,100	4-14**	[7]
PSR J1740+1000	RPP	37	9.7	94	550-650	50-230	30	[8]
PSR J1819-1458	RPP	100	124	112	1120*	400	34	[9]
XTE J1810-197	MAG	410	73	300	1150	35	17-47**	[10]

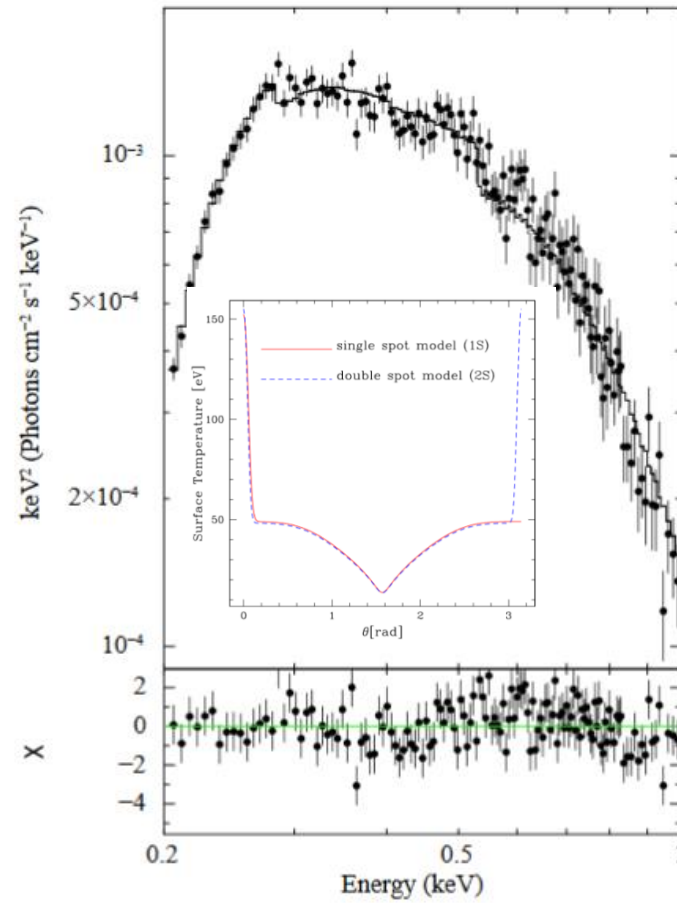


# RX J0806.4-412

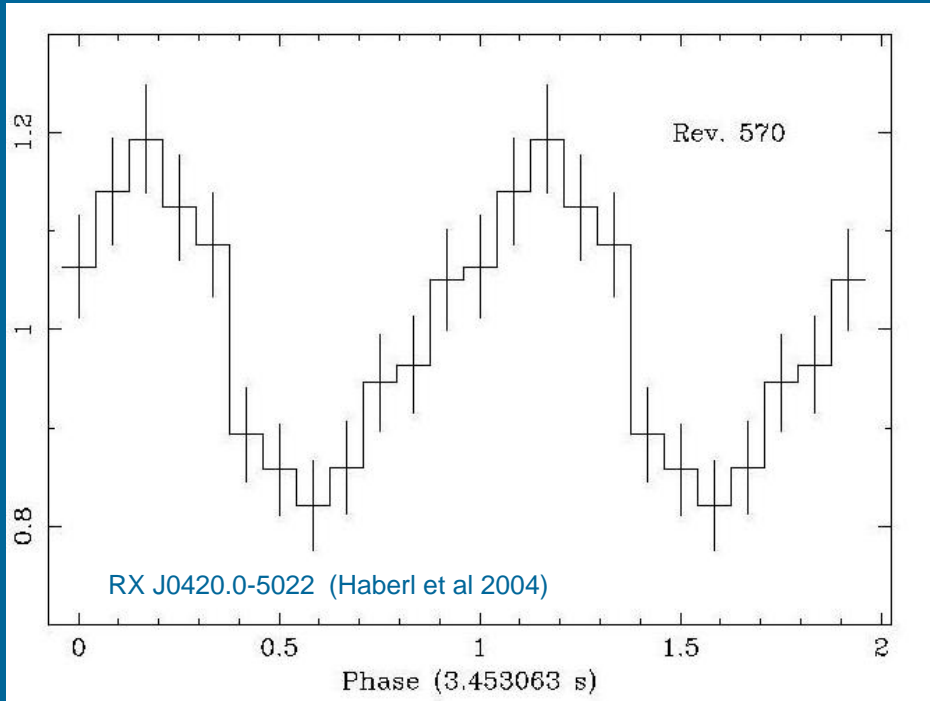
BB+line



Non-uniform distribution



# Pulsating ICoNS - I



- Quite large pulsed fractions
- Skewed lightcurves
- Harder spectrum at pulse minimum
- Phase-dependent absorption features

# Pulsating ICoNS - II

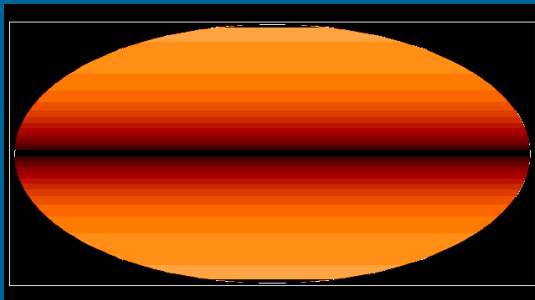
Core-centred  
dipole field

+

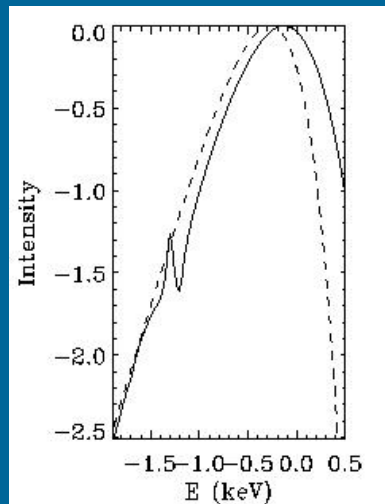
Atmosphere  
emission

=

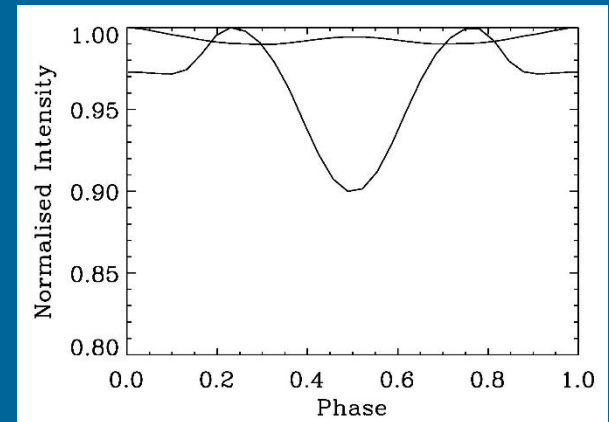
Too small  
pulsed fractions  
Symmetrical  
pulse profiles  
(Zane & Turolla 2006)



+



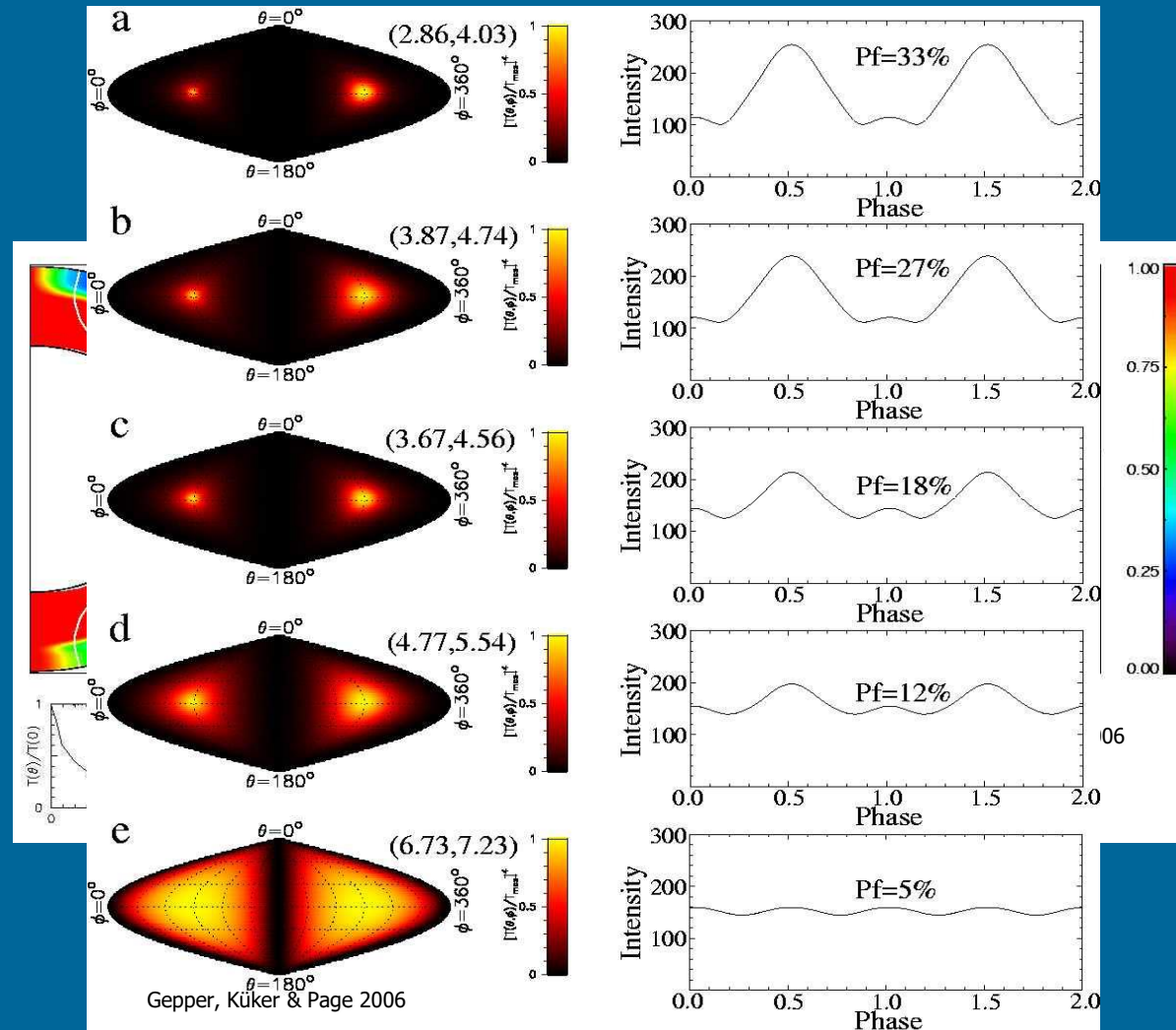
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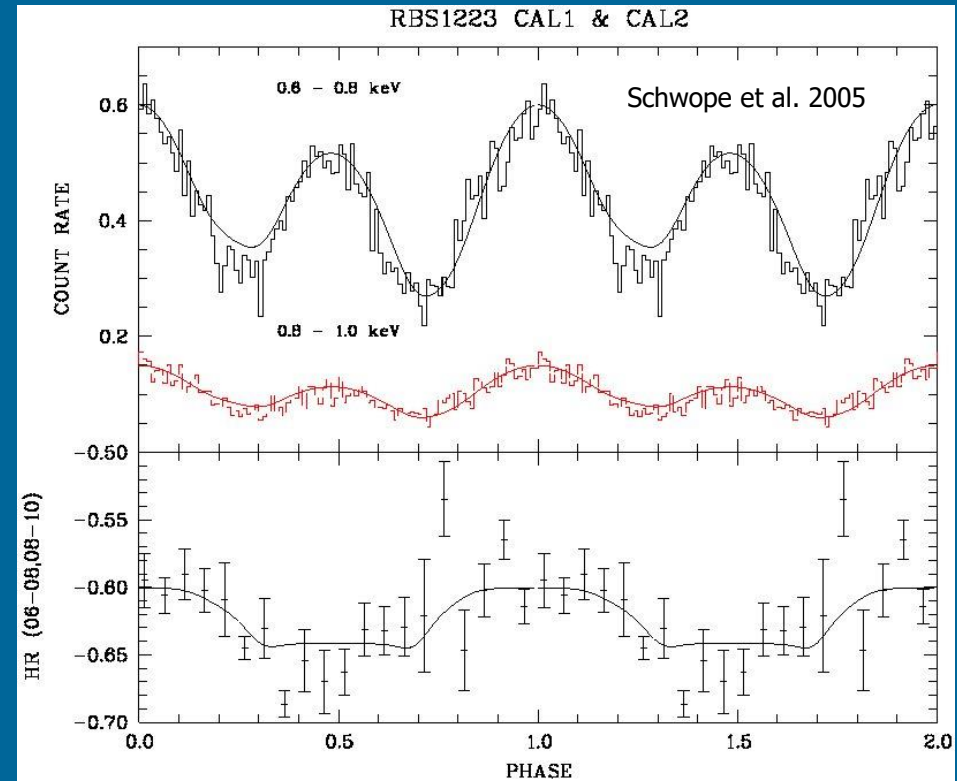
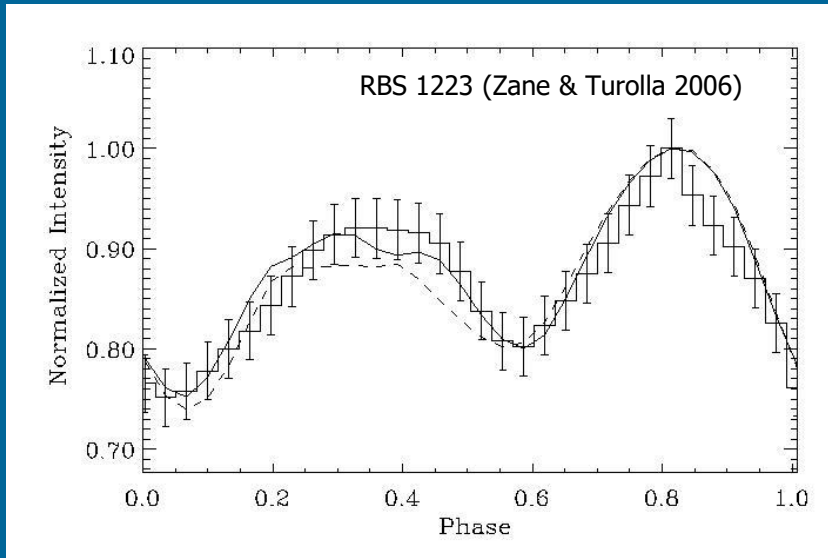




# Crustal Magnetic Fields

- Star centred dipole + poloidal/toroidal field in the envelope (Geppert, Küker & Page 2005; 2006)
- Purely poloidal crustal fields produce a steeper meridional temperature gradient
- Addition of a toroidal component introduces a N-S asymmetry





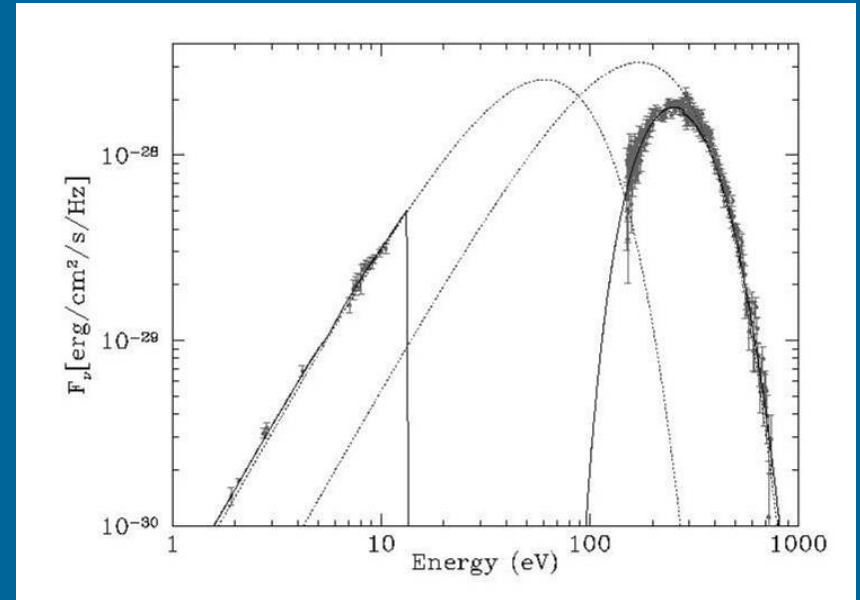
Indications for non-antipodal caps (Schwope et al 2005)

Need for a non-axisymmetric treatment of heat transport



# RX J1856.5-3754 - I

Blackbody featureless spectrum in the 0.1-2 keV band (Chandra 500 ks DDT, Drake et al 2002); possible broadband deviations in the XMM 60 ks observation (Burwitz et al 2003)



RX J1856 multiwavelength SED (Braje & Romani 2002)

Thermal emission from NSs is not expected to be a featureless BB !  
H, He spectra are featureless but only blackbody-like (harder).  
Heavy elements spectra are closer to BB but with a variety of features

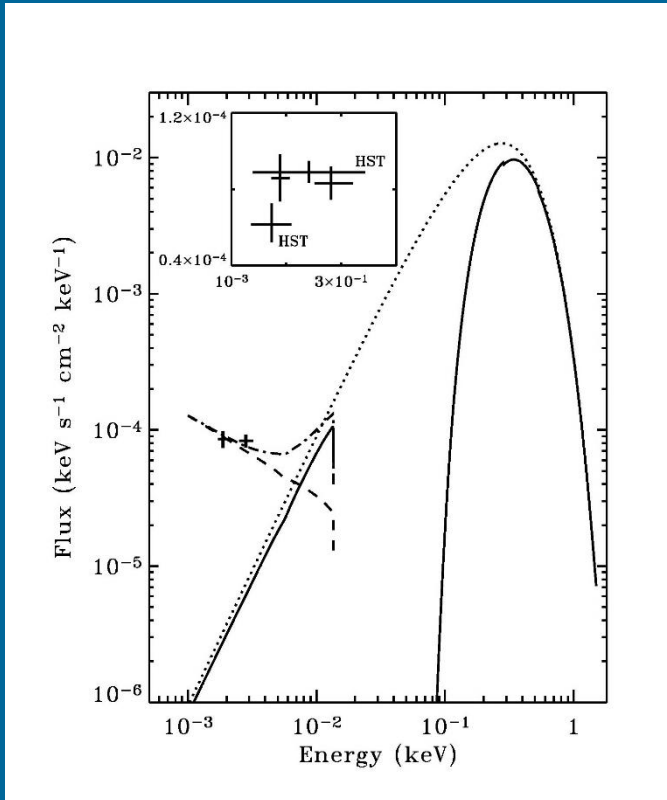
# RX J1856.5-3754 - II

What spectrum ?  
The optical excess ?

- A quark star (Drake et al 2002; Xu 2002; 2003)
- A NS with hotter caps and cooler equatorial region (Pons et al 2002; Braje & Romani 2002; Trümper et al 2005)
- A bare NS (Burwitz et al 2003; Turolla, Zane & Drake 2004; Van Adelsberg et al 2005; Perez-Azorin, Miralles & Pons 2005)

A perfect BB ?

# The Optical Excess

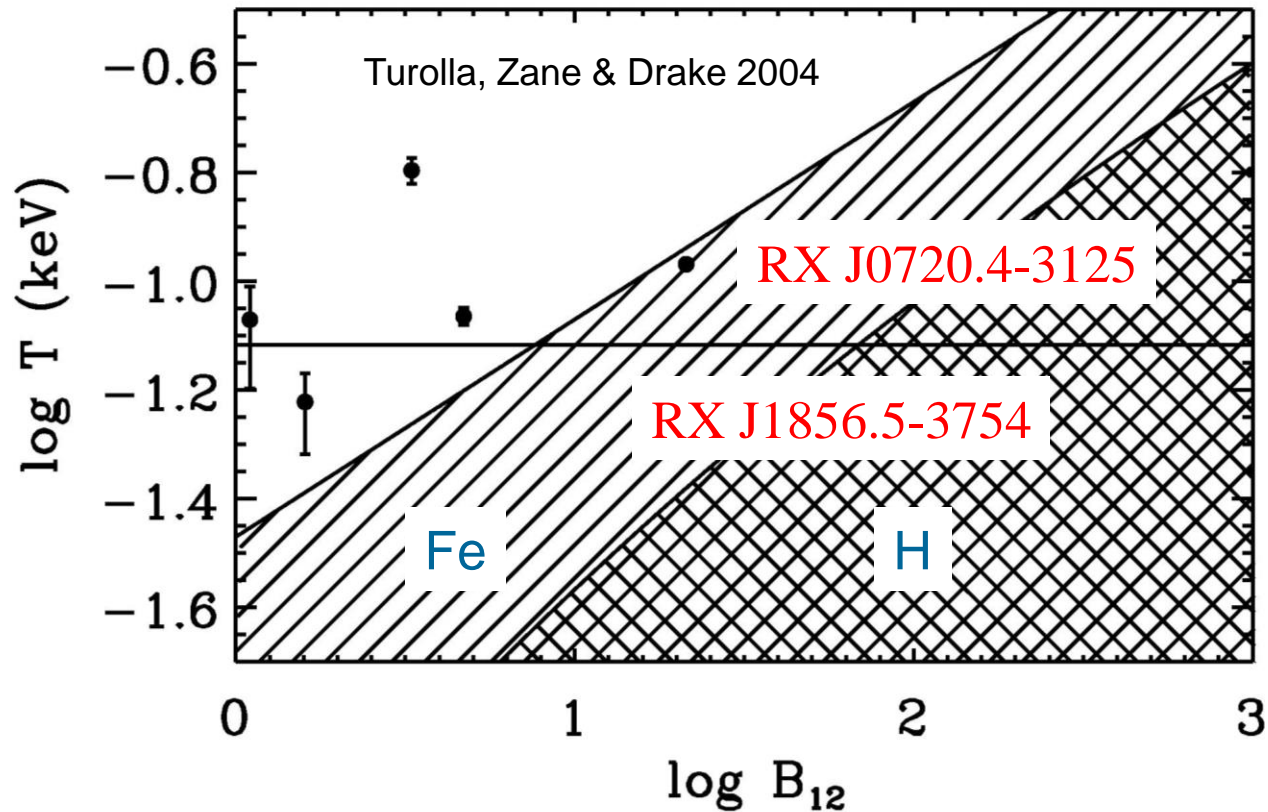
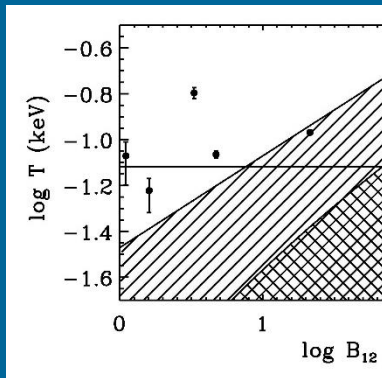


RX J1605 multiwavelength SED (Motch et al 2005)

- In the most of the sources with a confirmed optical counterpart  $F_{\text{opt}} \approx 5-10 \times B_{\nu}(T_{\text{BB},X})$
- $F_{\text{opt}} \approx \nu^2$  ?
- Deviations from a Rayleigh-Jeans continuum in RX J0720 (Kaplan et al 2003) and RX J1605 (Motch et al 2005). A non-thermal power law ?

# Bare Neutron Stars

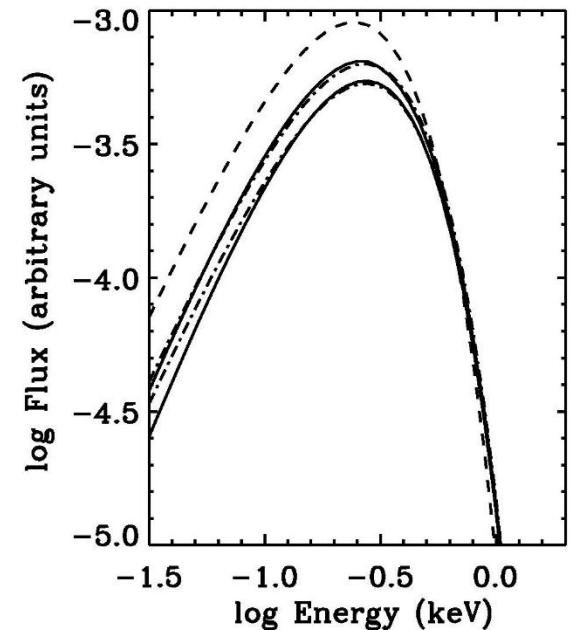
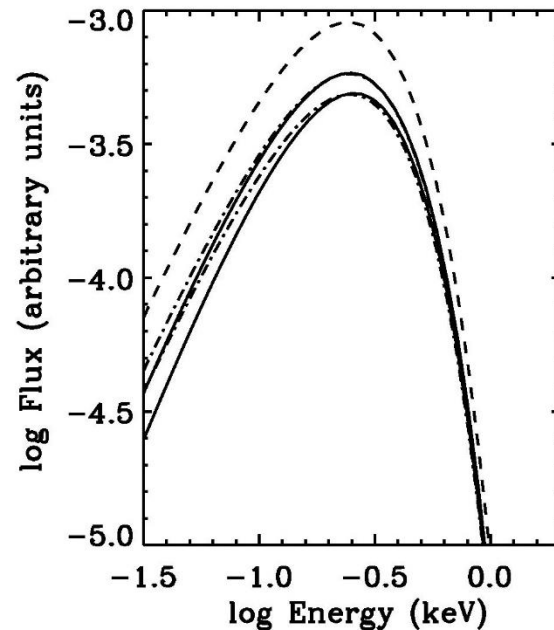
- At  $B \gg B_0 \sim 2.35 \times 10^9$  G atoms



# Spectra from Bare NSs - I

The cold electron gas approximation.  
Reduced emissivity expected below  $\omega_p$   
(Lenzen & Trümper 1978; Brinkmann 1980)

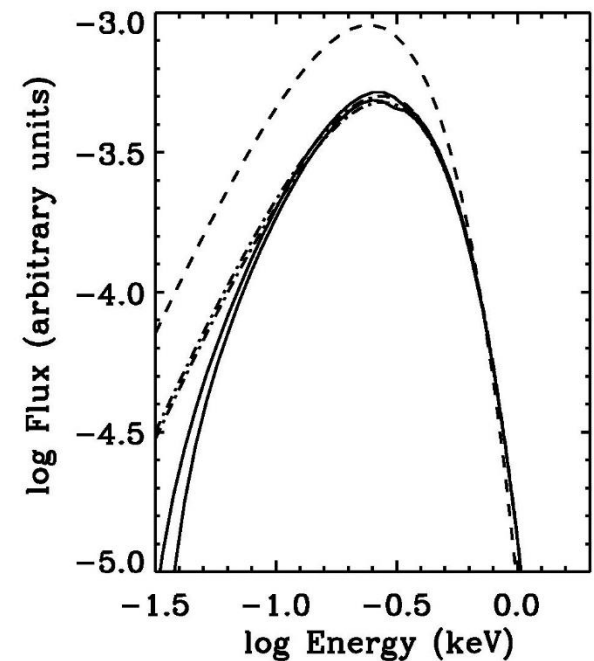
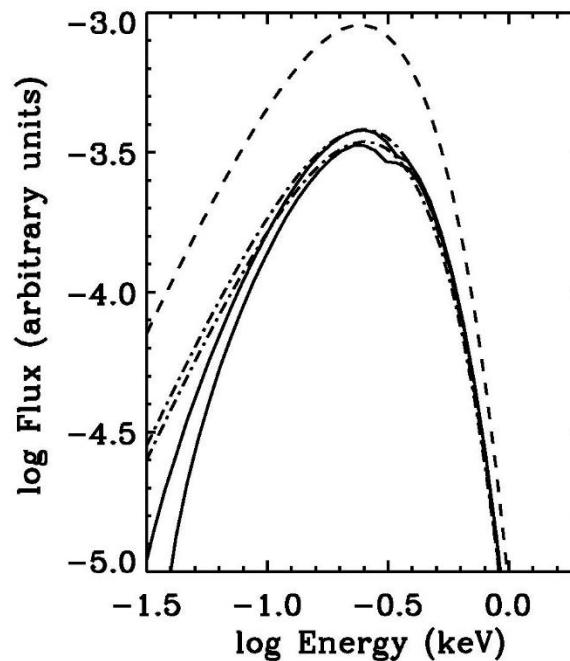
Spectra are  
very close to BB  
in shape  
in the 0.1 - 2 keV range,  
but depressed  
wrt the BB at  $T_{\text{eff}}$ .  
Reduction factor  $\sim 2 - 3$ .



# Spectra from Bare NS - II

Proper account for damping  
of free electrons by lattice interactions  
(e-phonon scattering; Yakovlev & Urpin 1980; Potekhin 1999)

Spectra deviate  
more from BB.  
Fit in the 0.1 – 2 keV  
still acceptable.  
Features  
may be present.  
Reduction factors  
higher.



# Is RX J1856.5-3754 Bare ?

- Fit of X-ray data in the 0.15-2 keV band acceptable
- Radiation radius problem eased
- Optical excess may be produced by reprocessing of surface radiation in a very rarefied atmosphere (Motch, Zavlin & Haberl 2003; Zane, Turolla & Drake 2004; Ho et al. 2006)
- Details of spectral shape (features, low-energy behaviour) still uncertain

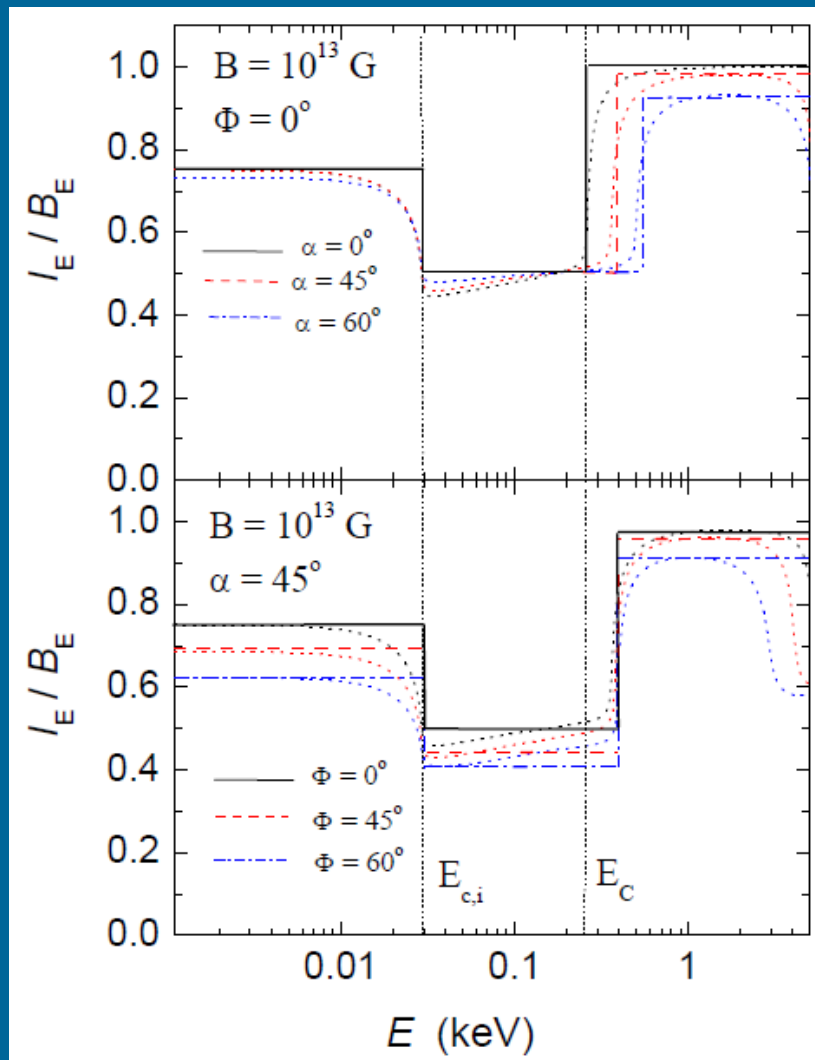
$$R_{\infty} = 4.25 f_E^{-1/2} \left( \frac{D}{100 \text{ pc}} \right) \left( \frac{T_{BB}}{60 \text{ keV}} \right)^{-2} \text{ km}$$

Does the atmosphere keep the star surface temperature ?



What is the ion contribution to the dielectric tensor ?  
(Van Adelsberg et al. 2005; Perez-Azorin, Miralles & Pons 2005)

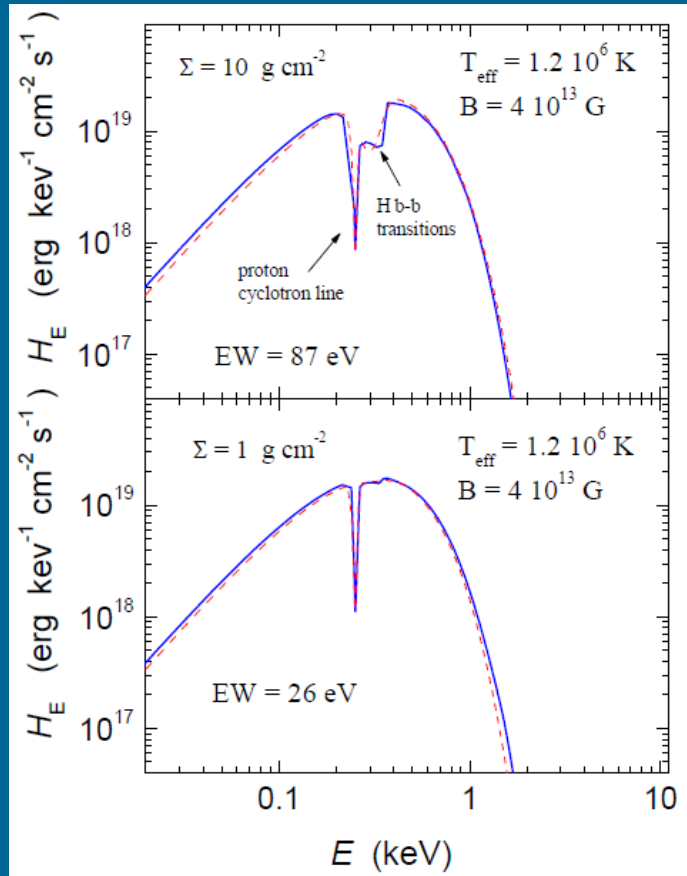
# Condensed iron surface emissivity



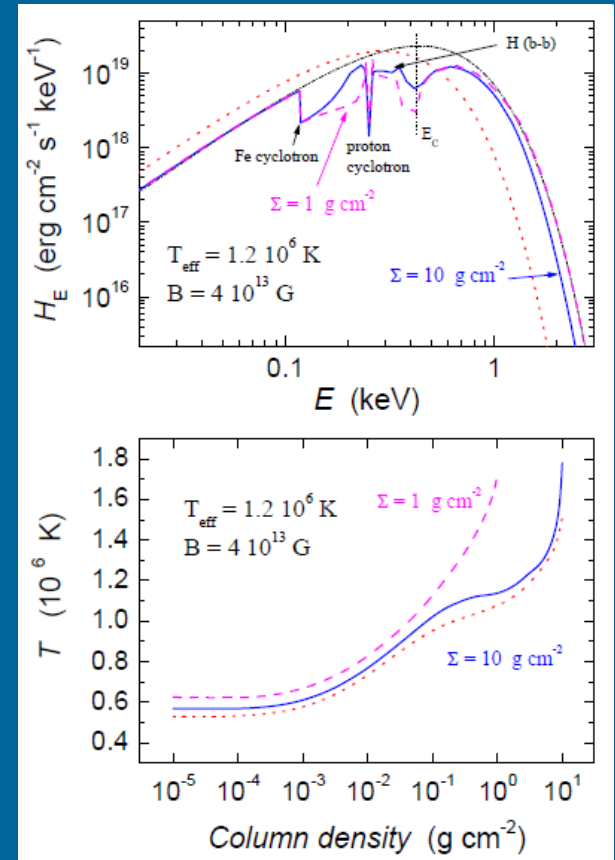
Free ions approximation.



# Thin hydrogen magnetized atmosphere above blackbody and iron condensed surface

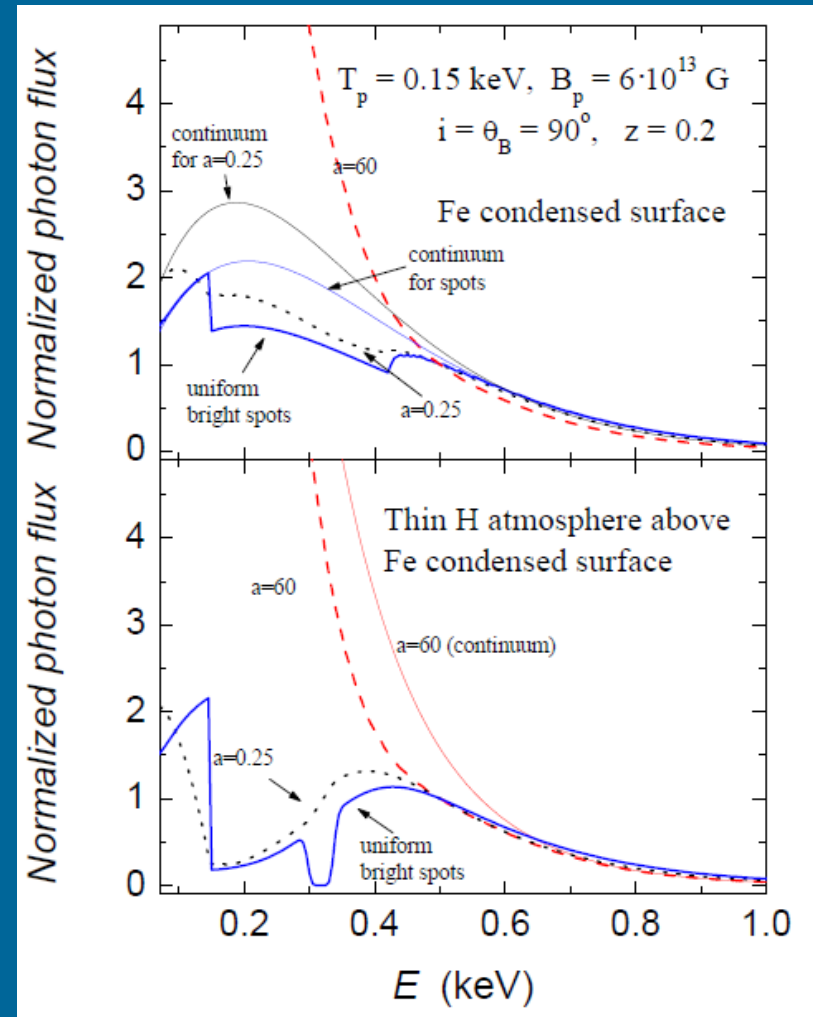
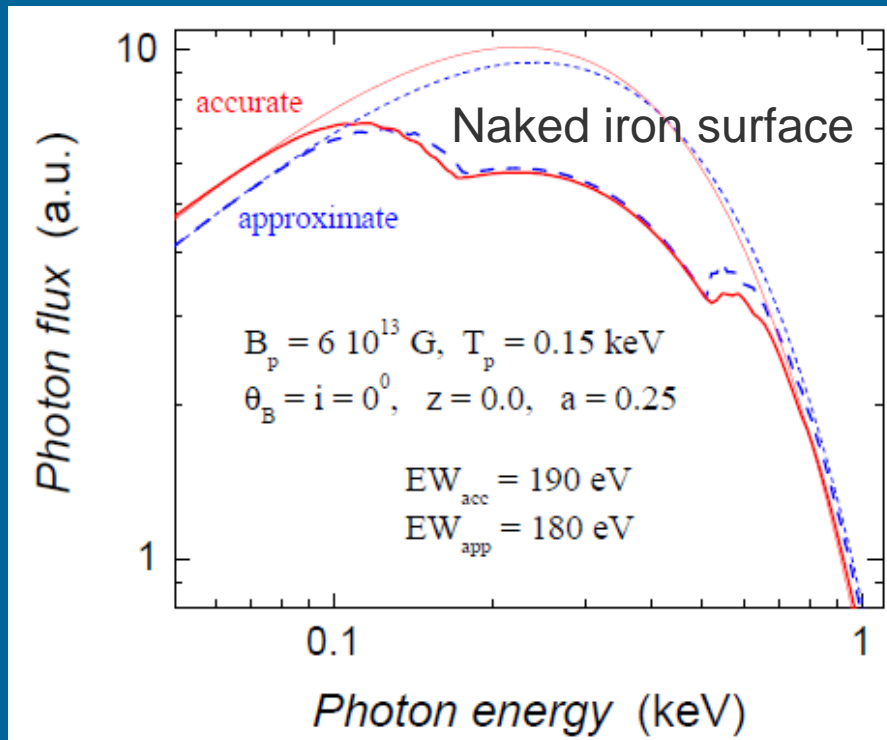


Below atmosphere was a blackbody spectrum



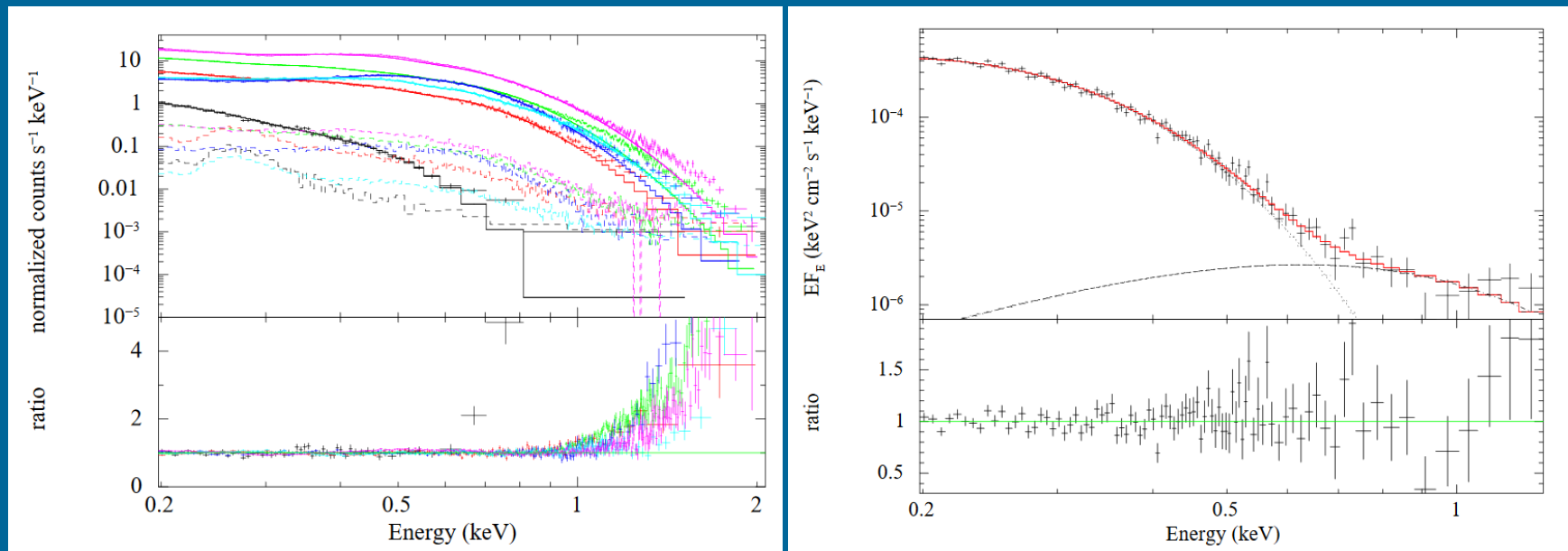
Below – iron condensed surface

# Let us make it realistic

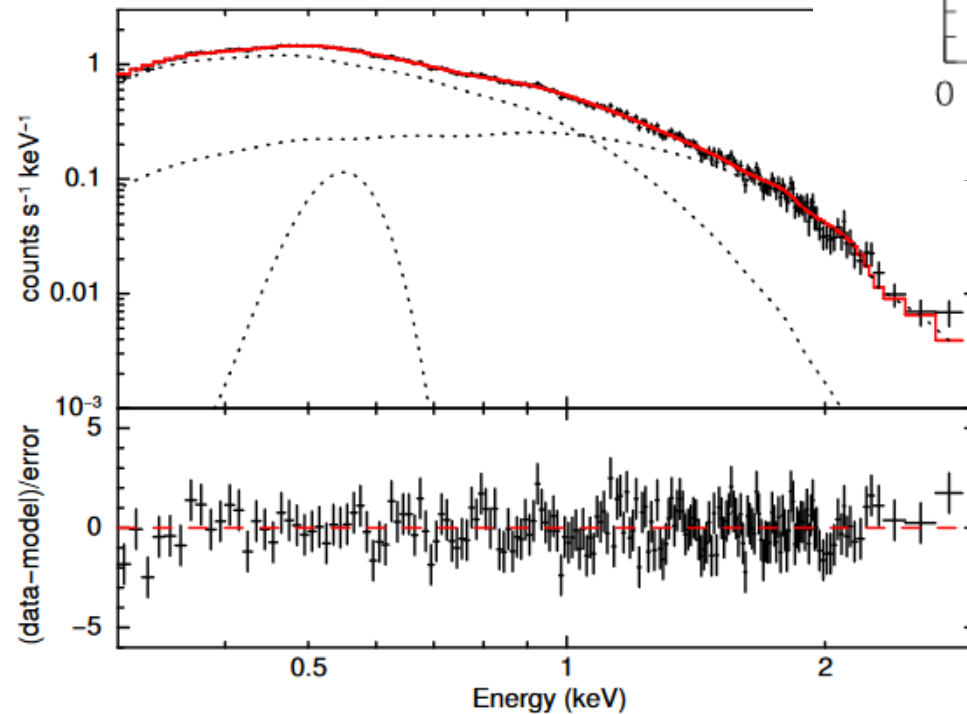
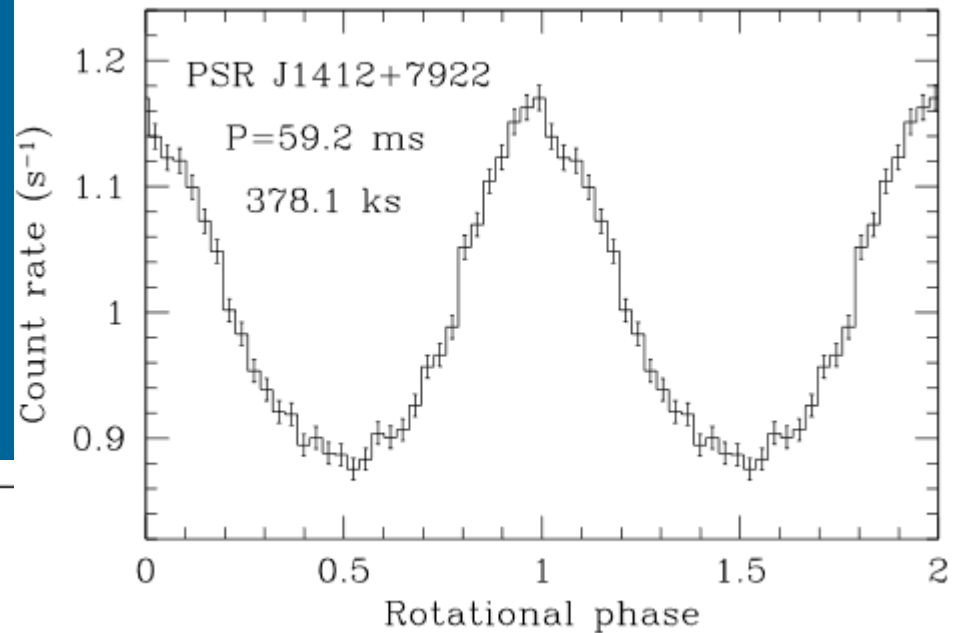


# Excess at $>1$ keV?

Analysis of spectra of M7 demonstrated a strange excess at energies  $> 1$  keV. This is somehow similar to what magnetars demonstrate.

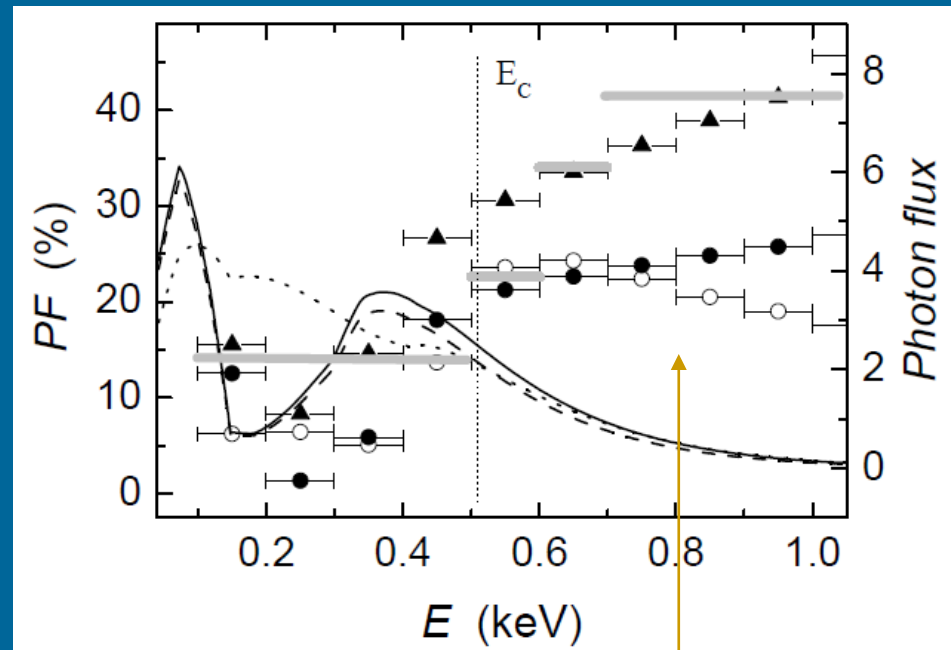
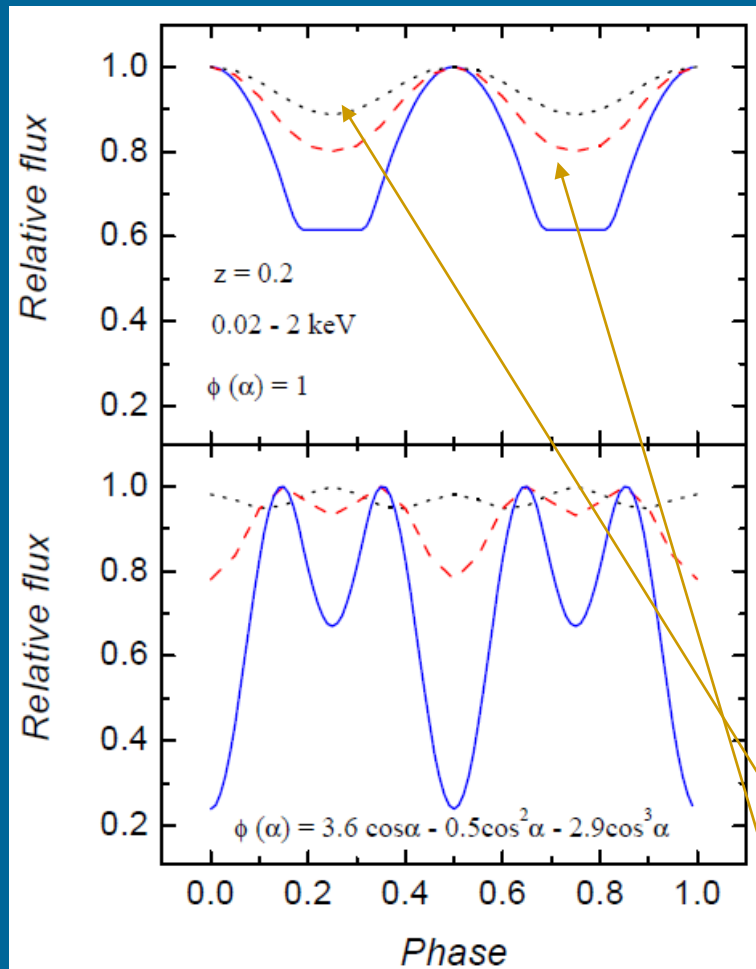


# Calvera spectrum



$kT_1$ (keV)	$0.154 \pm 0.004$
$R_1$ (km) <sup>b</sup>	$2.21^{+0.08}_{-0.07}$
$kT_2$ (keV)	$0.319^{+0.013}_{-0.012}$
$R_2$ (km) <sup>b</sup>	$0.37 \pm 0.04$

# Light curves and pulsed fraction



$$a_{1,2} = (1 + \mu_{1,2}^2 R^2)/4$$

$a_1 = a_2 = 0.25$  (dotted curves)

$a_1 = a_2 = 60$  (dashed curves)

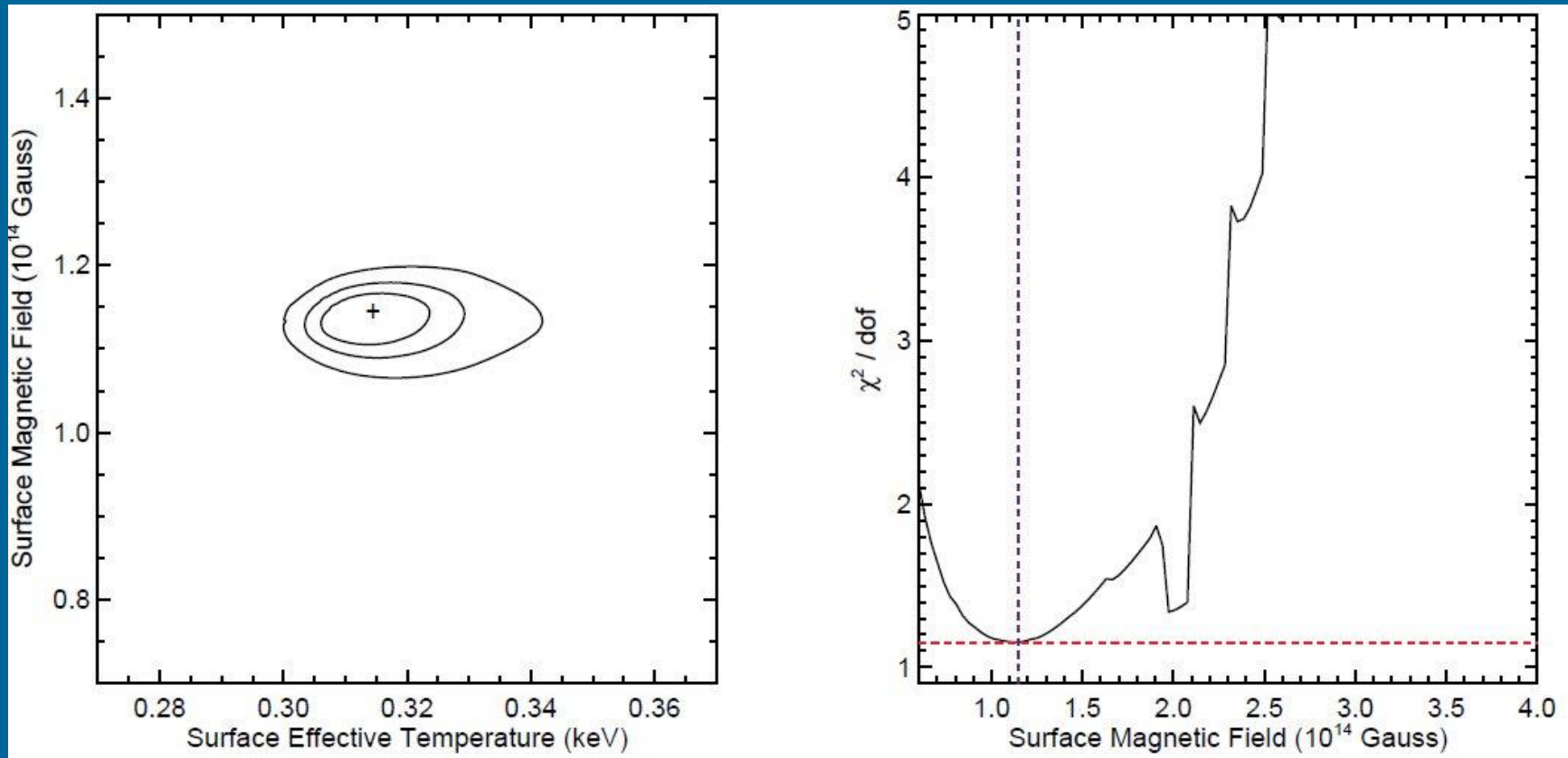
1006.3292

1010.0125

# Low-field magnetar SGR 0418+5729

Fitting parameters of the magnetized atmosphere it is possible to show, that the low-field solution is not acceptable.

This can be due to non-dipolar field components.



# Conclusions

- Emission from cooling NSs is more complicated than a simple blackbody
- Light bending (gravity)
- Atmospheres
- Magnetic field distribution - effects on properties of atmospheres and emission
- Magnetic field (including toroidal) in the crust – non-uniform temp.distr.
- Condensate
- Rotation at  $\sim$ msec periods can smear spectral lines

# Papers to read

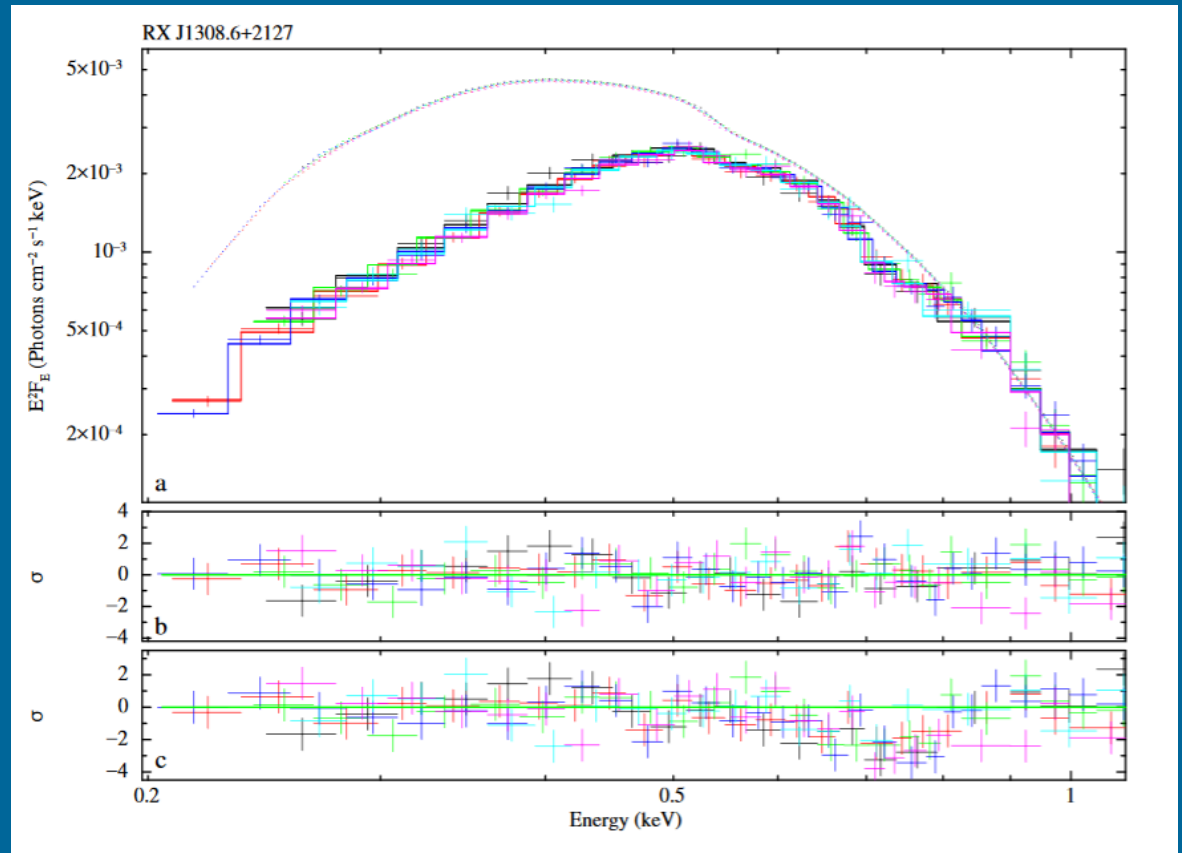
- [astro-ph/0702426](#) ←
- [arXiv: 0801.1143](#)  
or [astro-ph/0609066](#) } Reviews on the M7
- [astro-ph/0206025](#) ←
- [arXiv: 0905.3276](#) } Recent calculations of spectra from magnetized atmos.
- [arXiv: 1006.3292](#) }
- [arXiv: 1210.0916](#) – review
- [arXiv: 1409.7666](#) - review



# Phase-resolved spectra and features

RX J1308.6+2127

A feature at the energy of  $\sim 740$  eV  
and an equivalent width of  $\sim 15$  eV

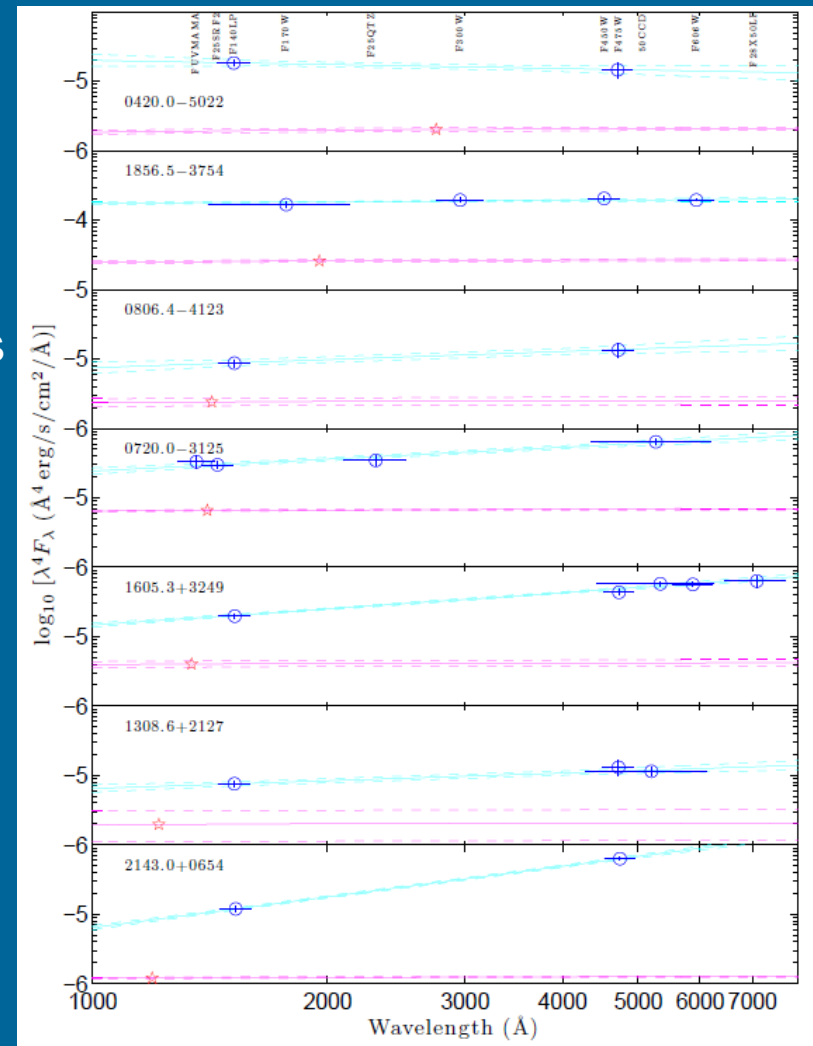


# All in optics and UV

All seven objects have confirmed optical and ultraviolet counterparts.

The Rayleigh-Jeans tail would be flat.  
The best-fit power-laws with  $\pm 1\sigma$  uncertainties are shown by the cyan lines.  
The extrapolations of the X-ray blackbodies with  $\pm 1\sigma$  uncertainties are shown by the magenta lines.

$kT \rightarrow$



New data: Kaplan et al. 1105.4178

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Does the atmosphere keep the star surface temperature ?

