Thermal Emission from Isolated Neutron Stars

- Theoretical aspects
- Observations and model applications

Slava Zavlin (MPE, Garching)

A Short History

- Chi & Salpeter (1964) and Tsuruta (1964):
  thermal radiation from the surface of a hot NS
  may be a source of cosmic X-rays

- First detections with Einstein (1978-81) and EXOSAT (1983-86):
  middle-aged PSRs B0656+14 and B1055-52
  old PSRs B0950+08 and B1929+10
  central compact sources in the SNRs RCW 103, Puppis A, Kes 73 and PKS 1209-52

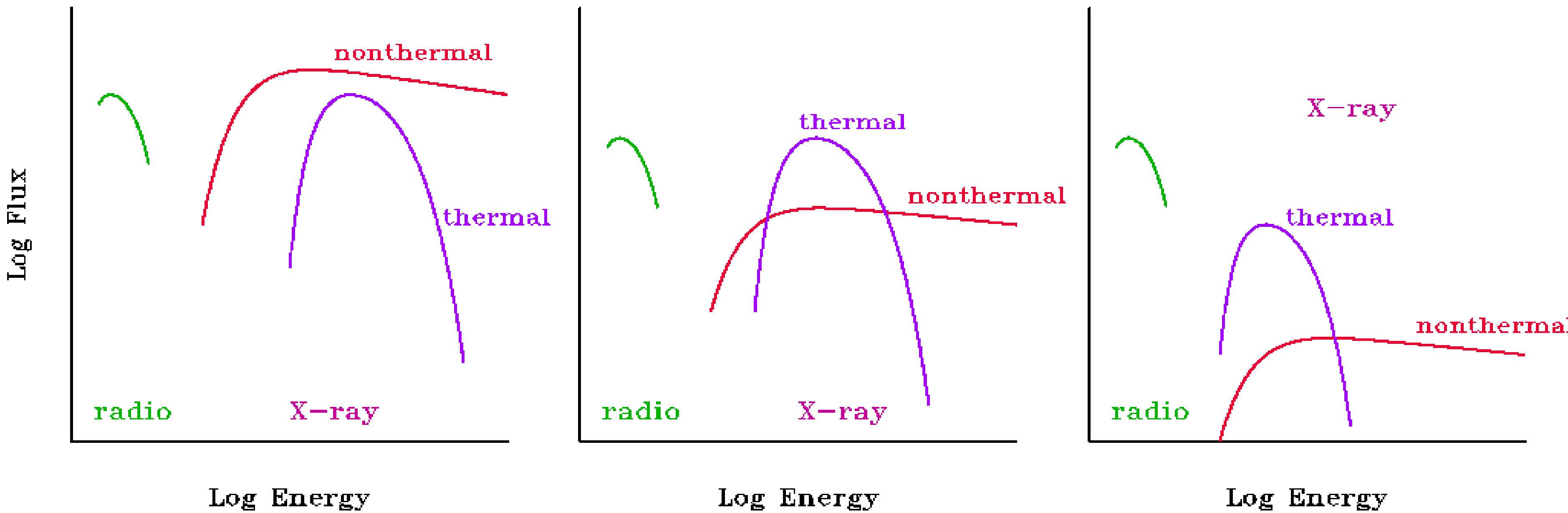
- X-ray studies in the "Decade of Space Science" since 1991 with ROSAT, ASCA, EUVE, BeppoSax, Chandra and XMM-Newton

In total thermal emission detected from about a dozen of isolated NSs:

- from the whole surface - atmosphere – of cooling NSs

- from polar caps heated by relativistic particles streaming down into the surface from pulsar's magnetosphere

Thermal vs. Nonthermal Emission in Pulsars of Different Ages



Young active (<1 kyr): nonthermal radiation dominates

Middle-aged (10-10² kyr): thermal component in soft EUV and soft X-rays

Old (>10³ kyr): thermal emission in optical-UV and/or soft X-rays

- No nonthermal radiation is seen in "**dead**" pulsars

First Questions

- Why studying thermal emission is needed?
- Why not to take the blackbody model?
- What is the state of the NS surface?
  Isn't it just solid?
- What is the chemical composition of the NS surface?
  Is it hydrogen?
  Or it's composed of heavier elements?

- Why studying thermal emission is needed?

Comparing observed emission with theoretical models $\Rightarrow$

T_{sur}, B, R, M

T_{sur} $\Rightarrow$ thermal evolution

R, M $\Rightarrow$ constraints on **EOS** and internal structure

surface chemical composition $\Rightarrow$
formation of NSs and their interaction with environment

- Why not to take the blackbody model?

Stars are not black bodies

Thermal radiation $\neq$ blackbody radiation

- What is the state of the NS surface? Isn't it just solid?

It depends on T_{sur}, B and chemical composition.
For hydrogen, the surface is in a condensed state if:

$T_{sur} < 1 \times 10^5$ K at $B = 1 \times 10^{13}$ G
$T_{sur} < 5 \times 10^5$ K at $B = 1 \times 10^{14}$ G
$T_{sur} < 1 \times 10^6$ K at $B = 5 \times 10^{14}$ G (Lai & Salpeter 1997)

- What is the chemical composition of the NS surface?
  Is it hydrogen? Or it's composed of heavier elements?

A small amount of H, $\rho \approx 10^{-3} - 10^{-1}$ g/cm^2 due to accretion from ISM or fallback of material ejected during the SNR explosion, determines properties of the atmosphere.

Nuclear spallation reactions may destroy heavy elements (Bildsten et al. 1992, 1993).

Othewise, other elements may be present.

Main Aspects of the NS Atmosphere Modeling

- What's special about NS atmospheres?
  Why not to use standart stellar atmosphere models?

1. Enormous gravity at the surface ($M \approx 1.4\ M_\odot$, $R \approx 10$ km)

$$g \approx 10^{14} \quad \text{vs.} \quad 10^{4} \ \ \mathrm{cm^2/s} \ \text{ for usual stars}$$

$\Rightarrow$ NS atmospheres are strongly compressed

$$\rho \approx 10^{-2} - 10^{1} \quad \text{vs.} \quad 10^{-7} \ \ \mathrm{g/cm^3}$$

$$H \approx kT_{sur}/m_p g \approx 10^{-1} - 10^{1} \quad \text{vs.} \quad 10^{8} \ \mathrm{cm}$$

$\Rightarrow$ stratification of chemical elements

$\Rightarrow$ nonideality effects (pressure ionization, smoothed spectral features)

2. Huge magnetic fields, $B \approx 10^{10} - 10^{14}$ G

$\Rightarrow$ $E_{CE} = 11.6\ (B/10^{12}\ G)$ keV $\gg kT_{sur} \approx 0.1 - 1$ keV

$\Rightarrow$ NS atmospheres are essentially anisotropic

$\Rightarrow$ opacities depend on the direction and polarisation of radiation

$\Rightarrow$ radiation is polarized

$\Rightarrow$ $\gamma = E_{CE}/(Z^2\ Ry) = 850\ Z^{-2}\ (B/10^{12}\ G) \gg 1$

$\Rightarrow$ atomic structure is distorted by B

$\Rightarrow$ increase of binding (ionization) energies of bound states

$I/(Z^2 Ry) \approx \ln^2(\gamma/Z^2) \gg 1$, $I_H \approx 0.2$ keV at $B = 10^{13}$ G

$\Rightarrow$ altered ionisation equilibrium

$\Rightarrow$ radiation depends on B

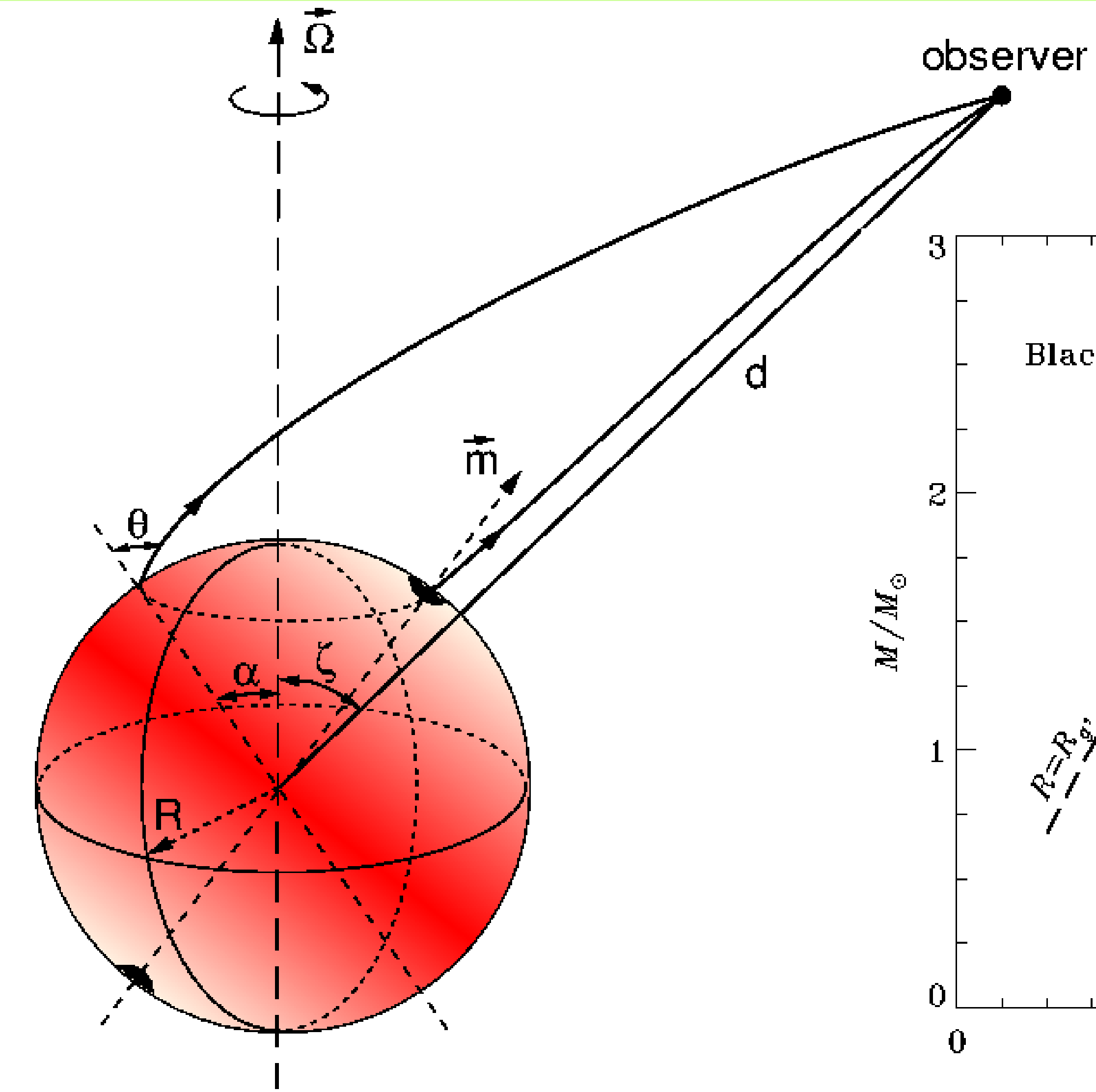
$\Rightarrow$ proton cyclotron line at $E_{CP} = 63\ (B/10^{14}\ G)$ eV

3. Nonuniform magnetic field $\Rightarrow$
nonuniform surface temperature distribution $\Rightarrow$
thermal radiation is pulsed

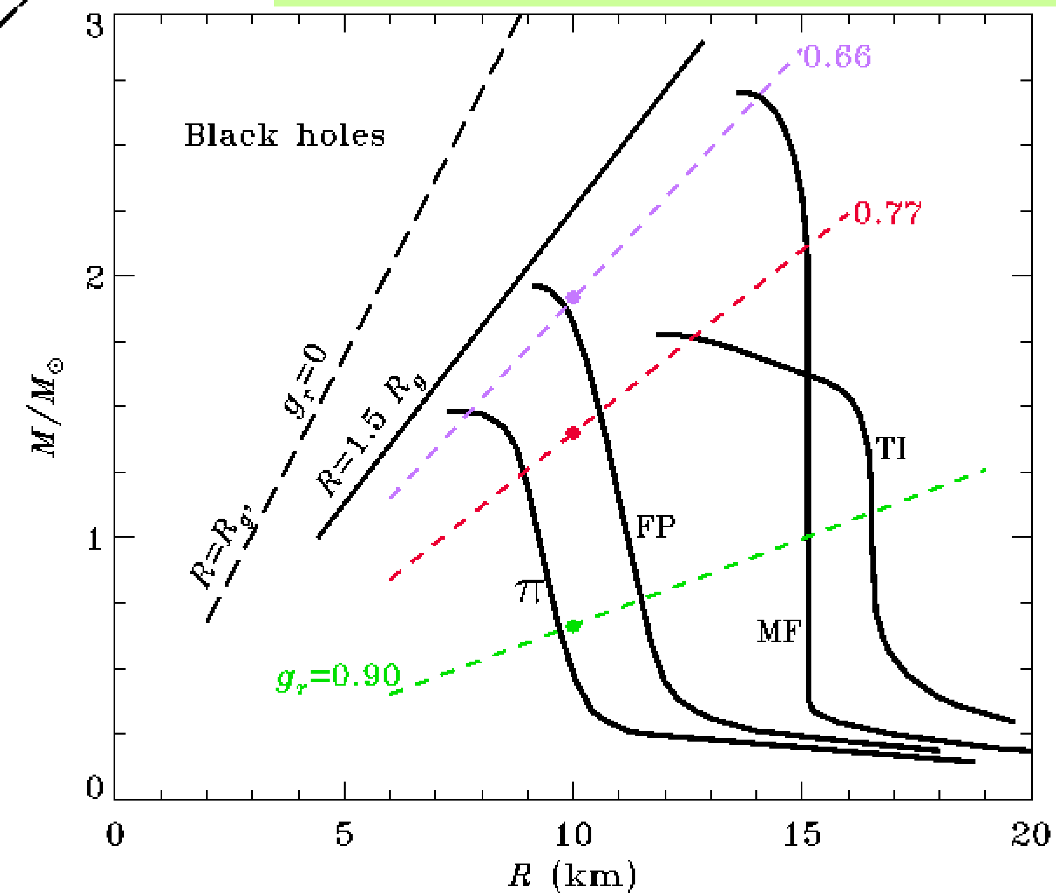
4. Gravitational bending of photon trajectories srongly affects the shape of pulsations

Gravitational bending of photon trajectories

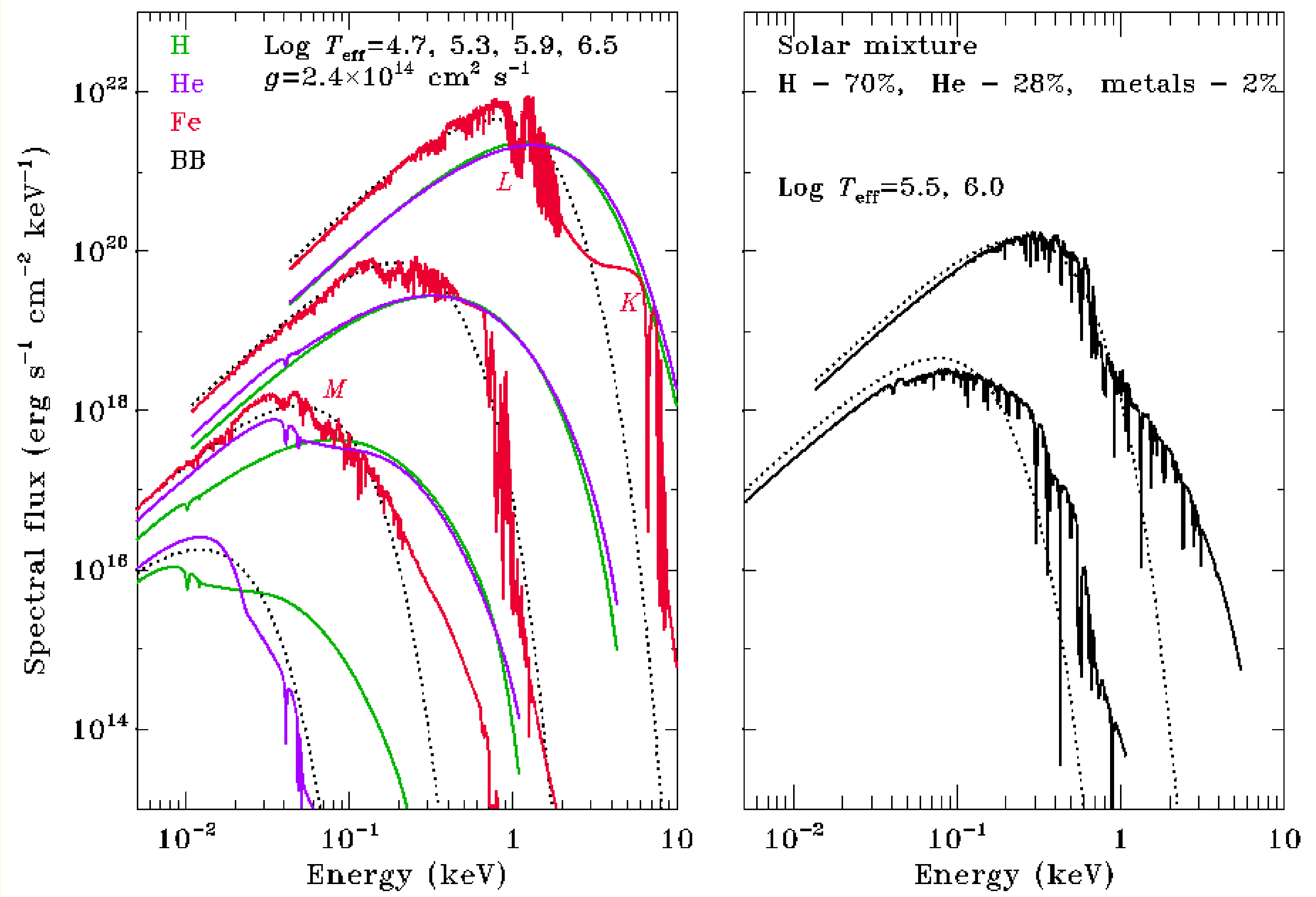
$g_r = (1 - R_G/R)^{1/2}$, $R_G = 2GM/c^2$

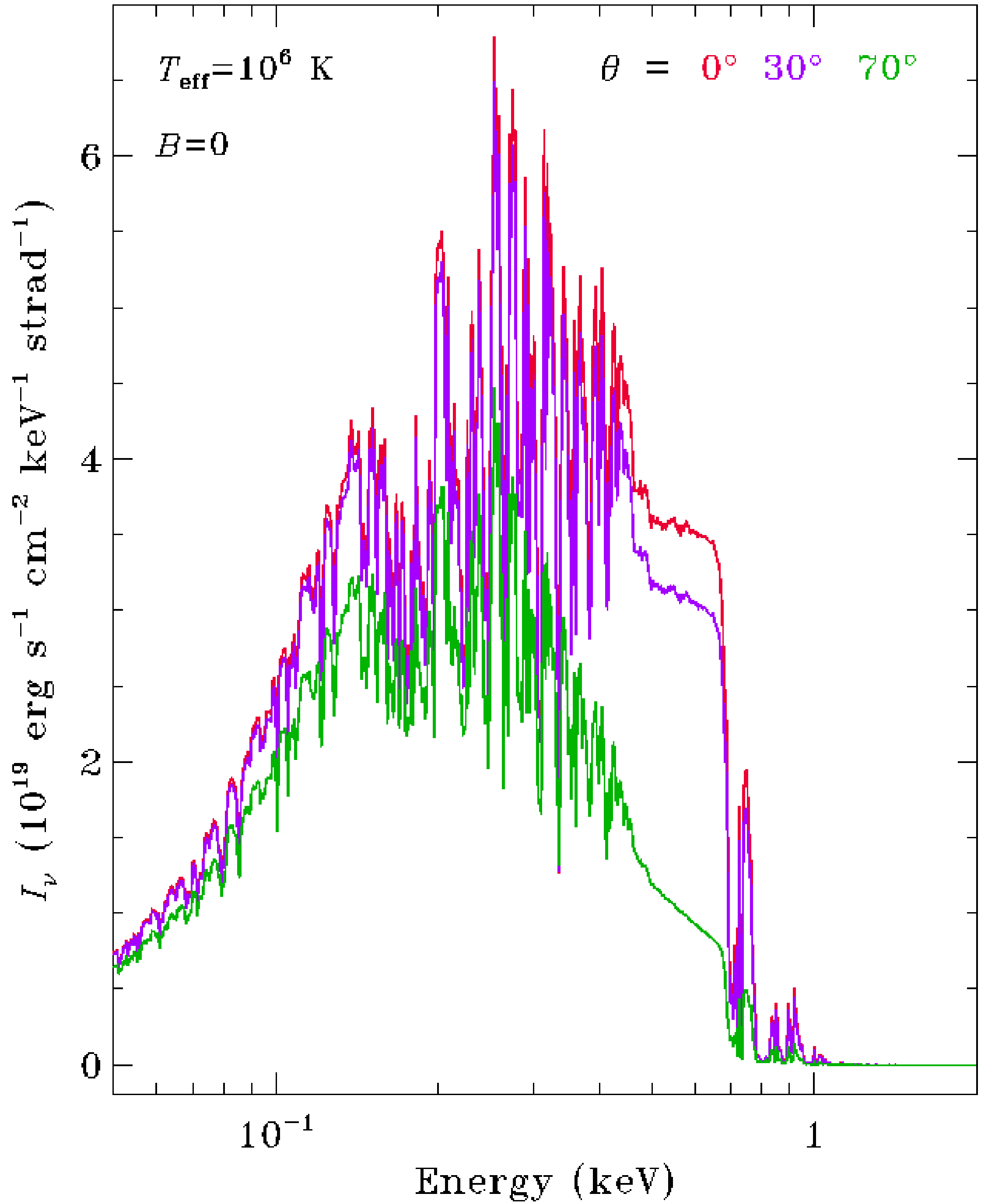


the whole surface
is visible if
$g_r < 0.69$



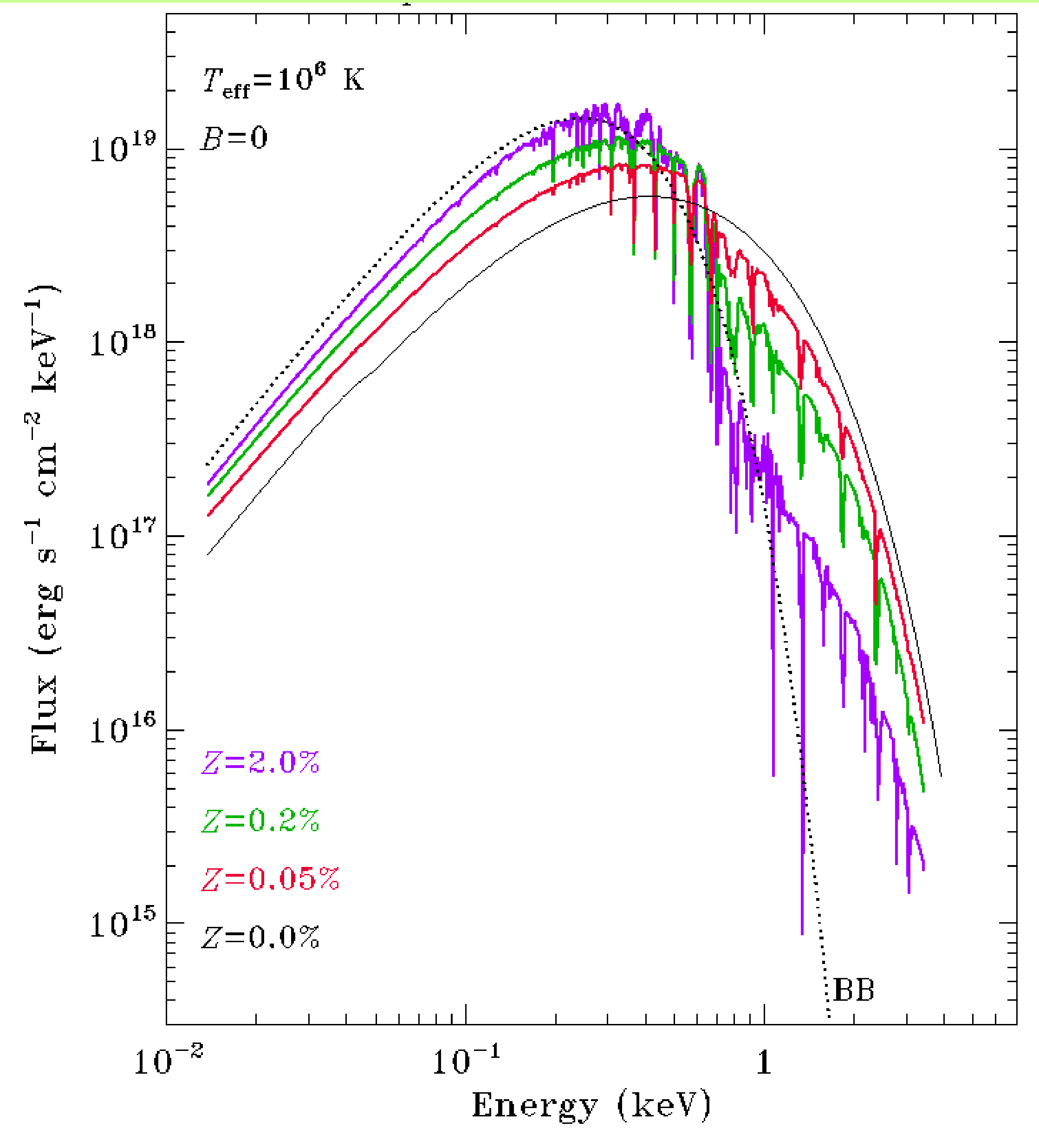
NS atmosphere models with low magnetic fields, $B < 10^8 - 10^9$ G



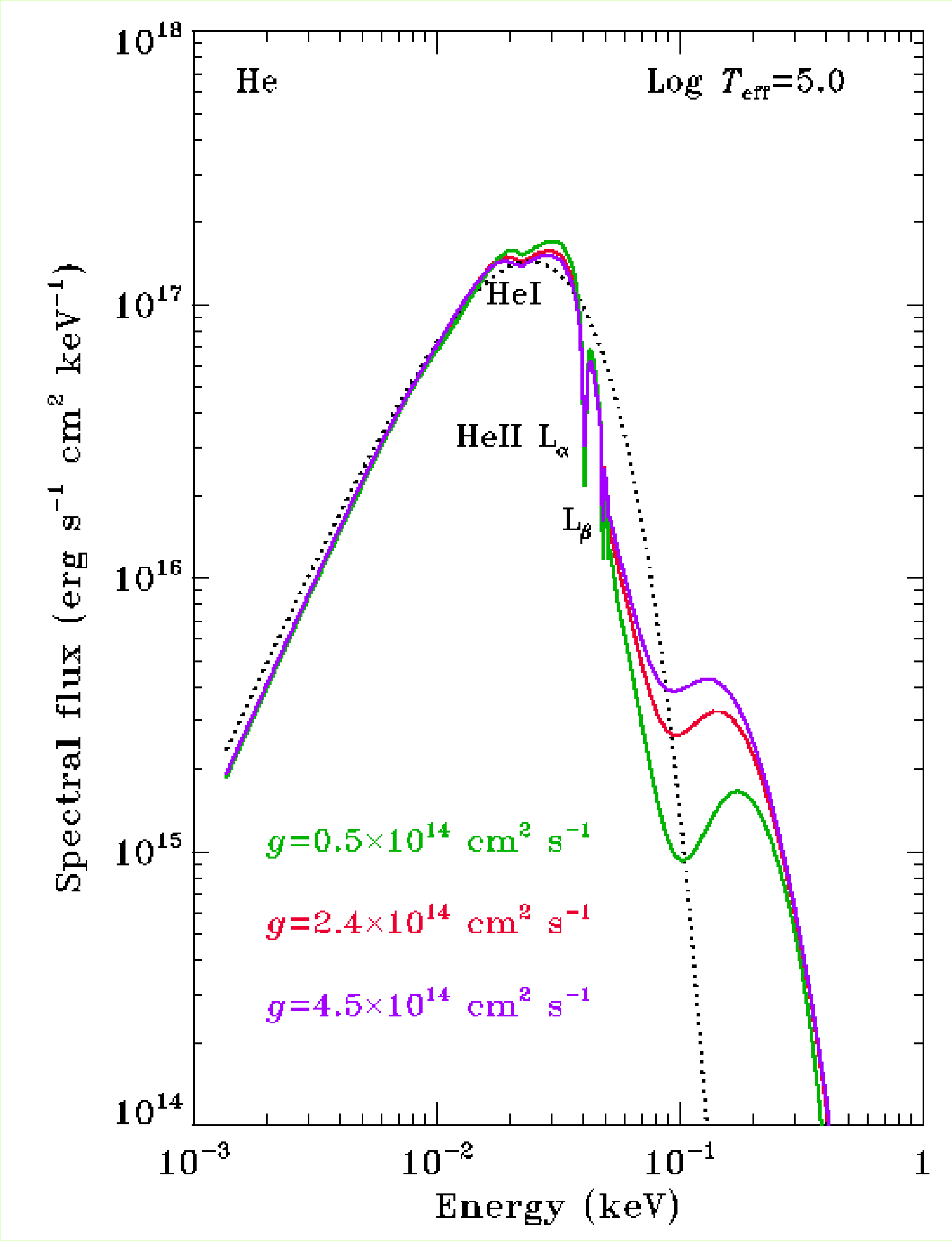


- radiation is essentially anisotropic
- anisotropy depends on energy

Spectra of nonmagnetic NS atmospheres with various abundances of heavy elements



Effect of the surface gravity g



larger g $\Rightarrow$

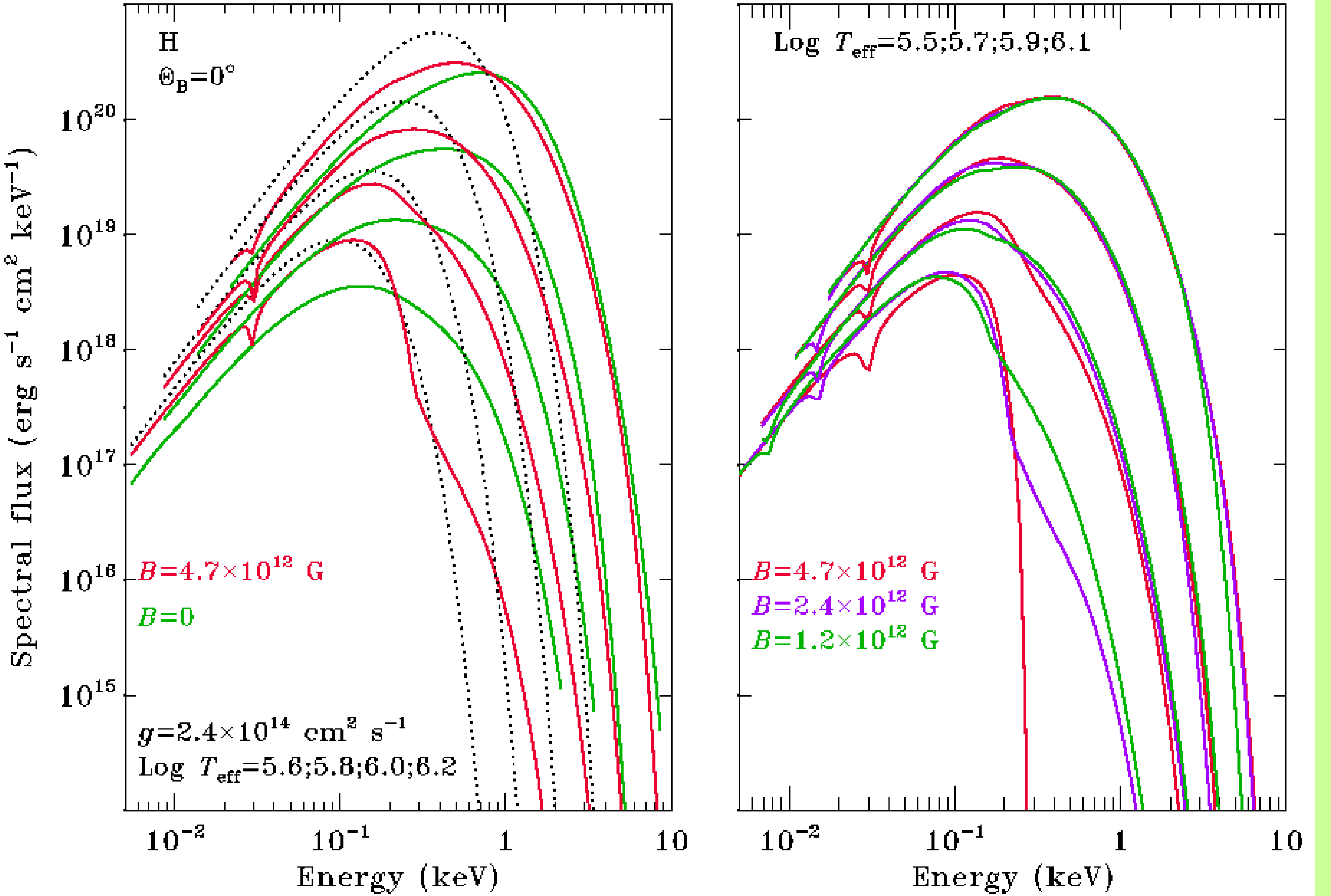
higher density ρ $\Rightarrow$

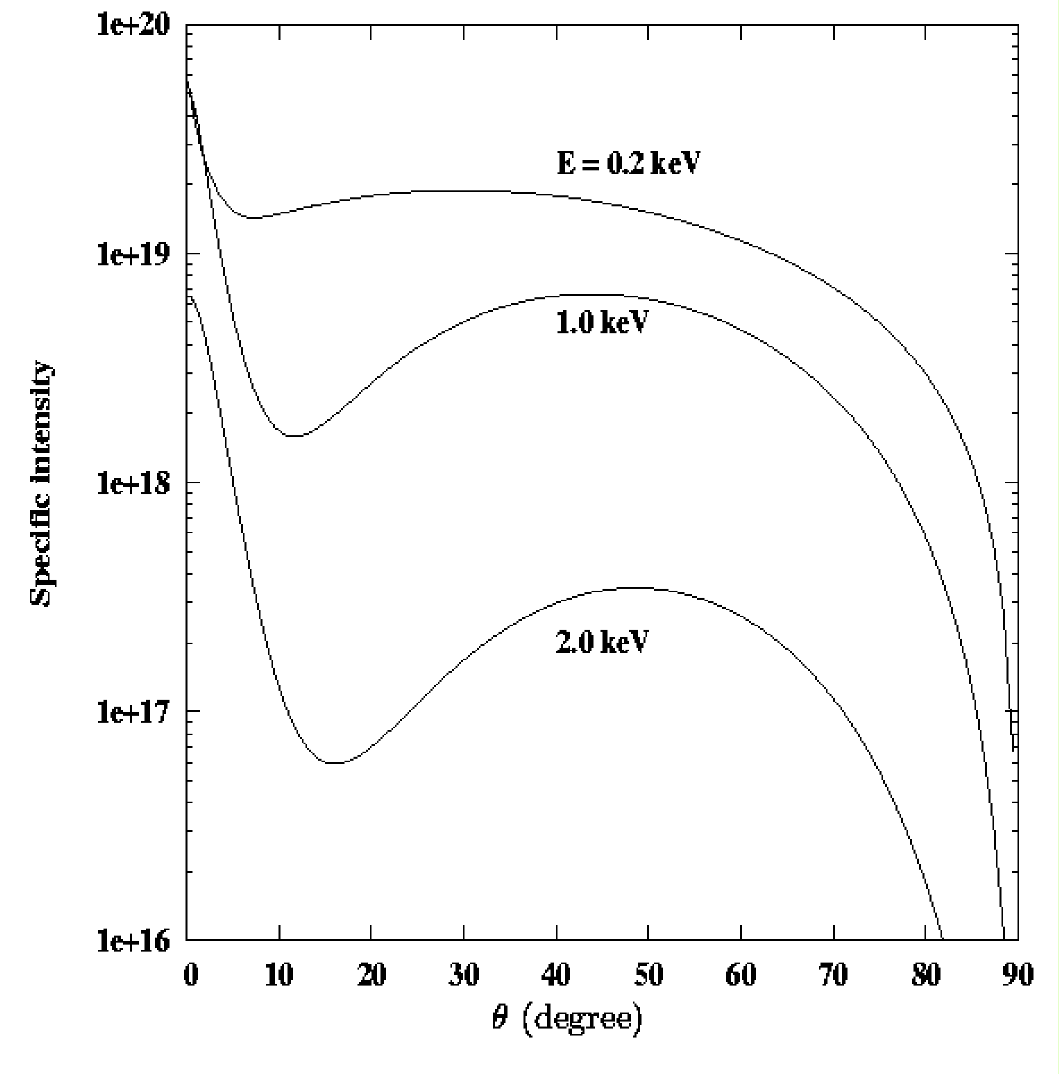
stronger ionization $\Rightarrow$

weaker features

(important at low T_{eff})

NS atmosphere models with strong magnetic fields, B > 10^{11} G



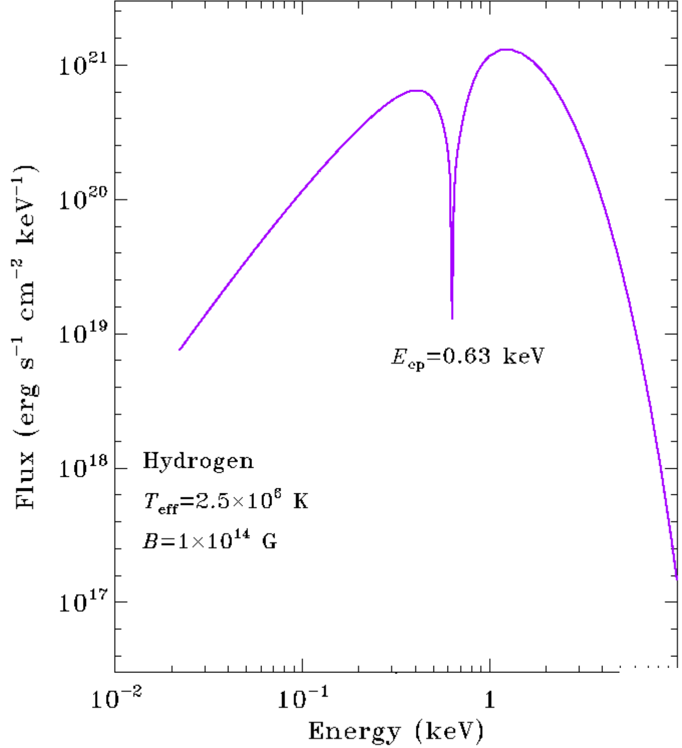


Angular dependence of emitted radiation:

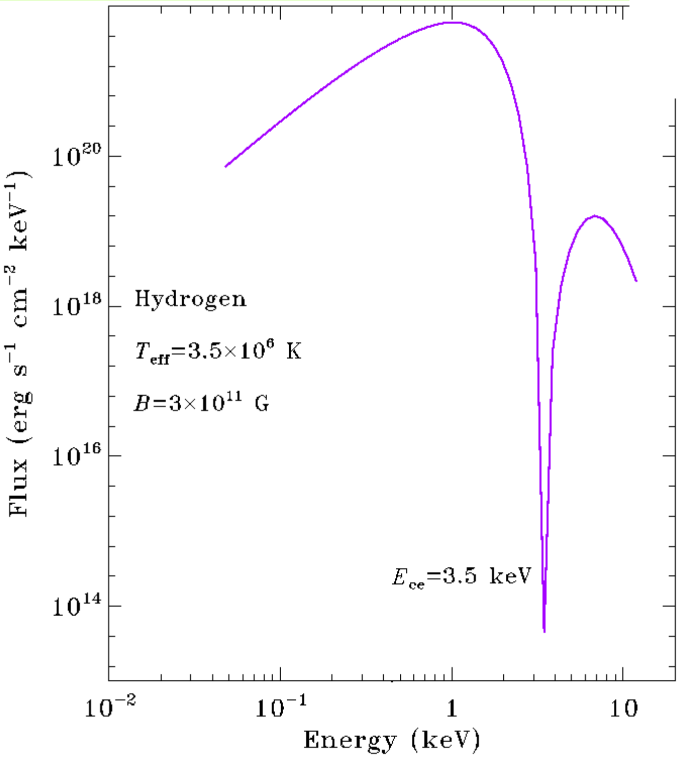
"pencil"-like structure along B

"fan"-like structure across B

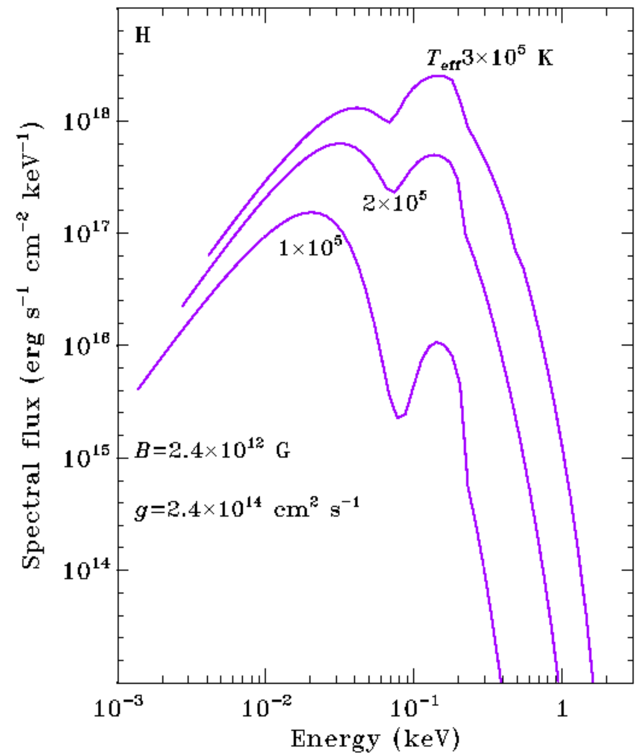
proton cyclotron line
$B = 10^{14}$ G



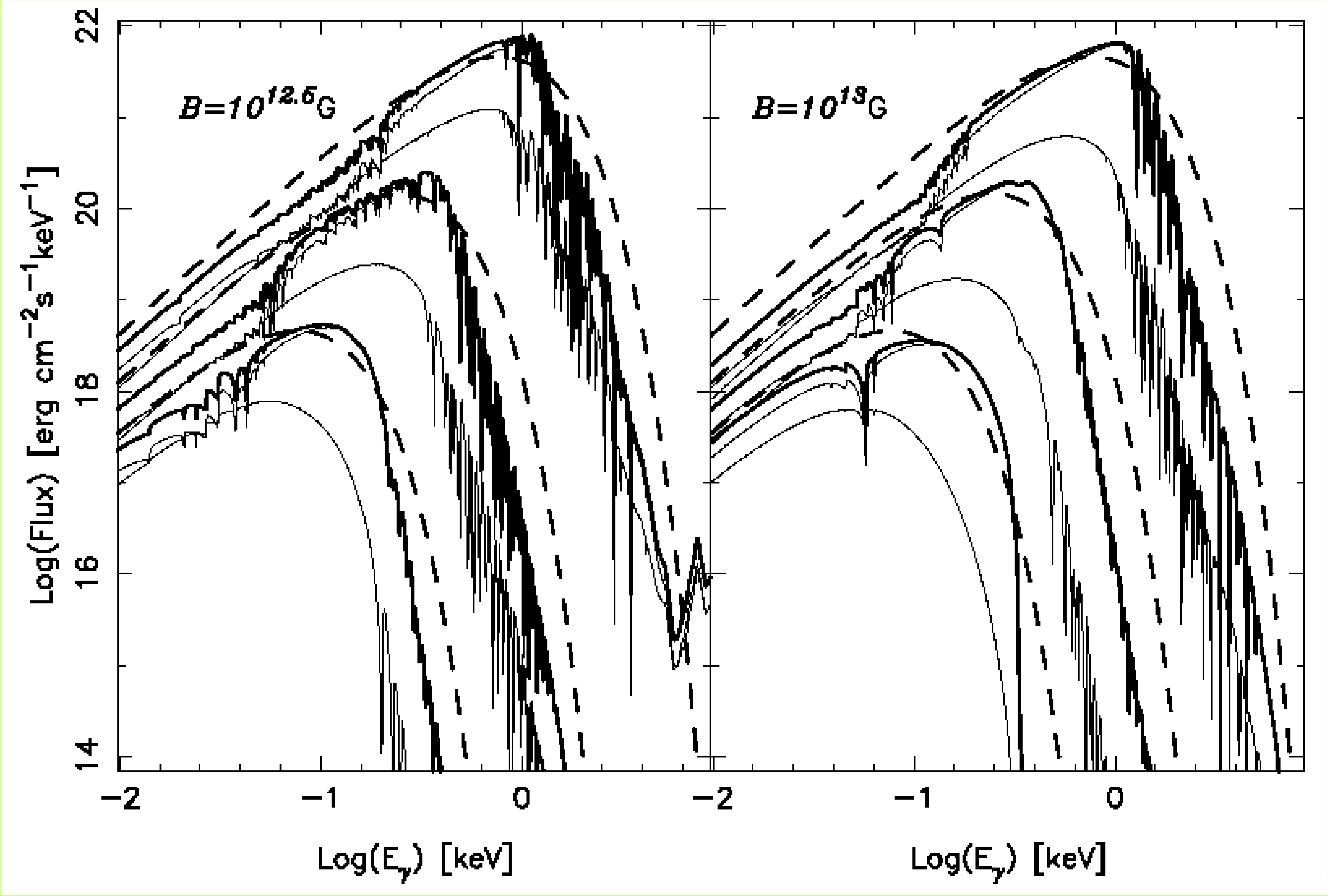
electron cyclotron line
$B = 3 \times 10^{11}$ G



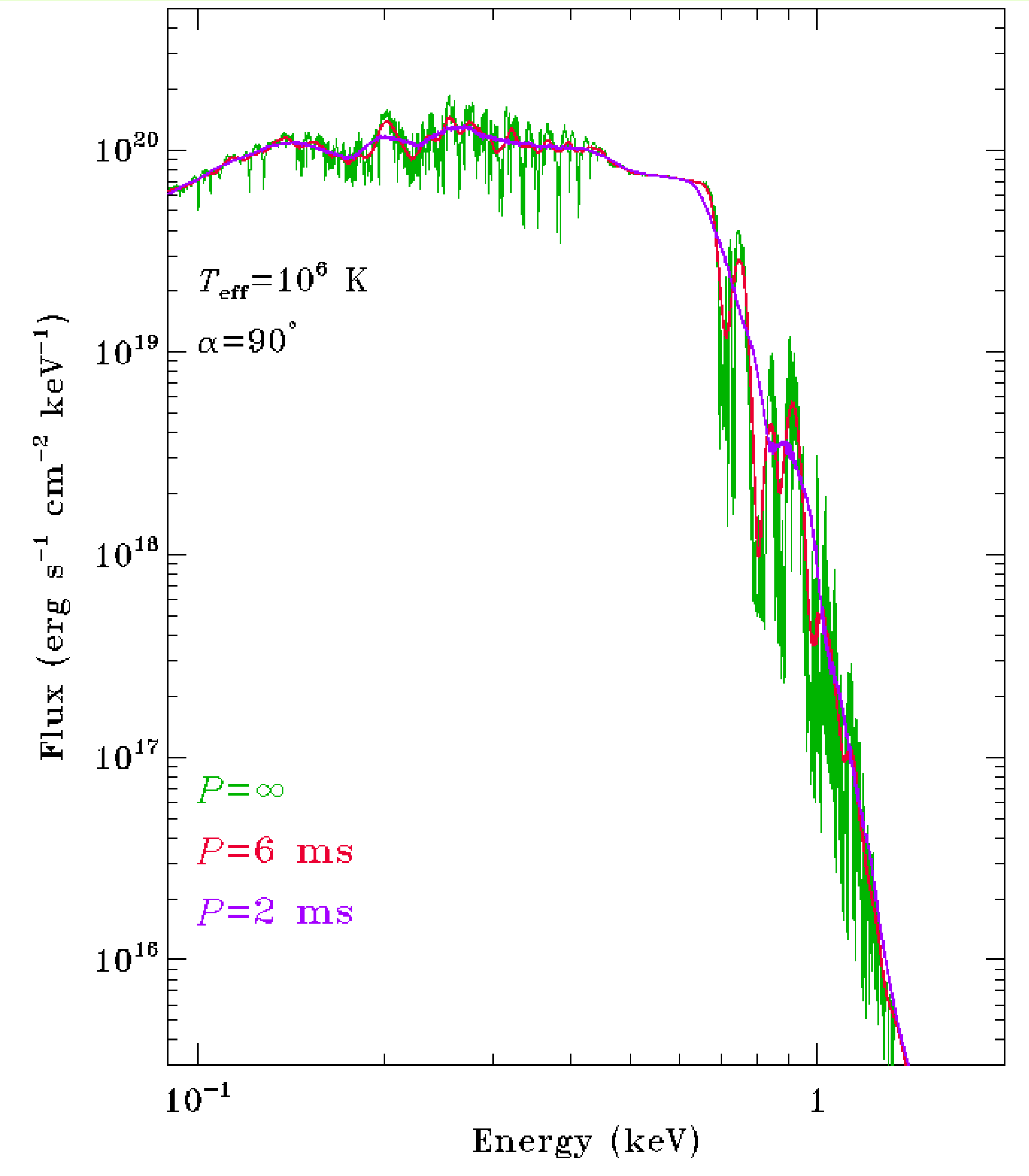
atomic transitions
$T_{eff} < 10^6$ K



Magnetic iron spectra (Rajagopal et al. 1997)

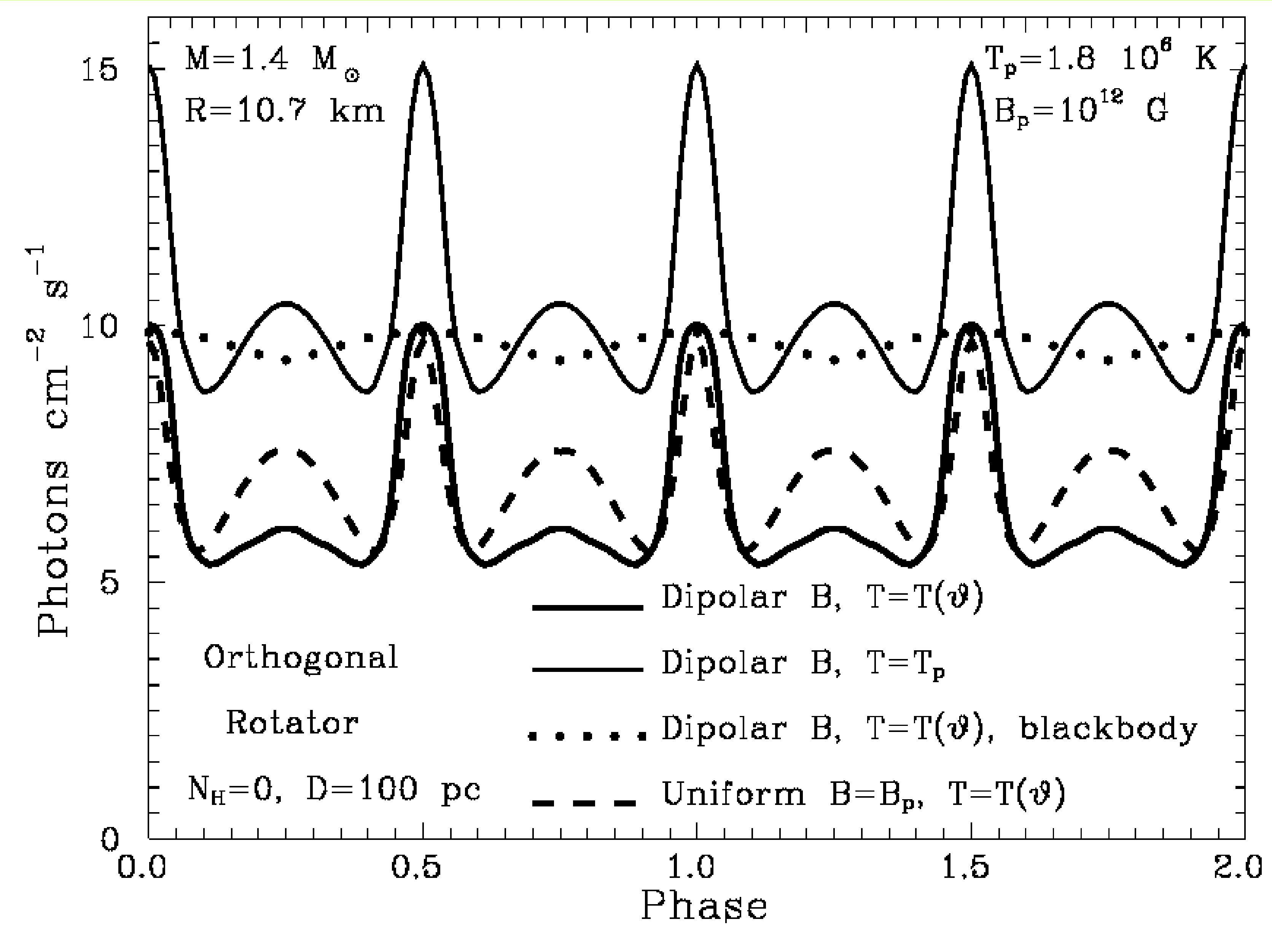


Emission from the whole NS surface:
smearing of spectral features due to fast rotation

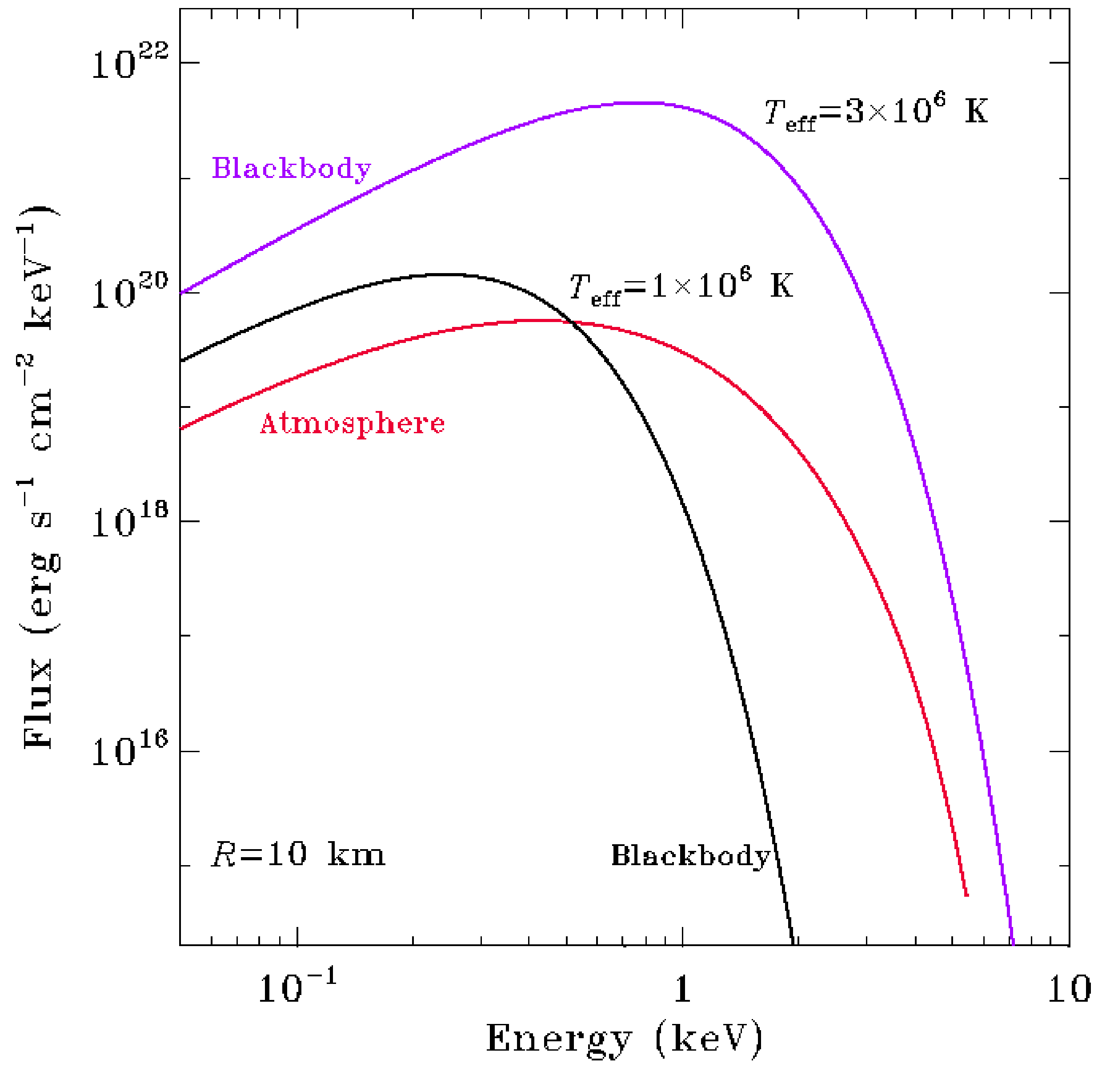


P < 10 ms

Light curves of radiation from a magnetized NS



NS atmosphere vs. blackbody model

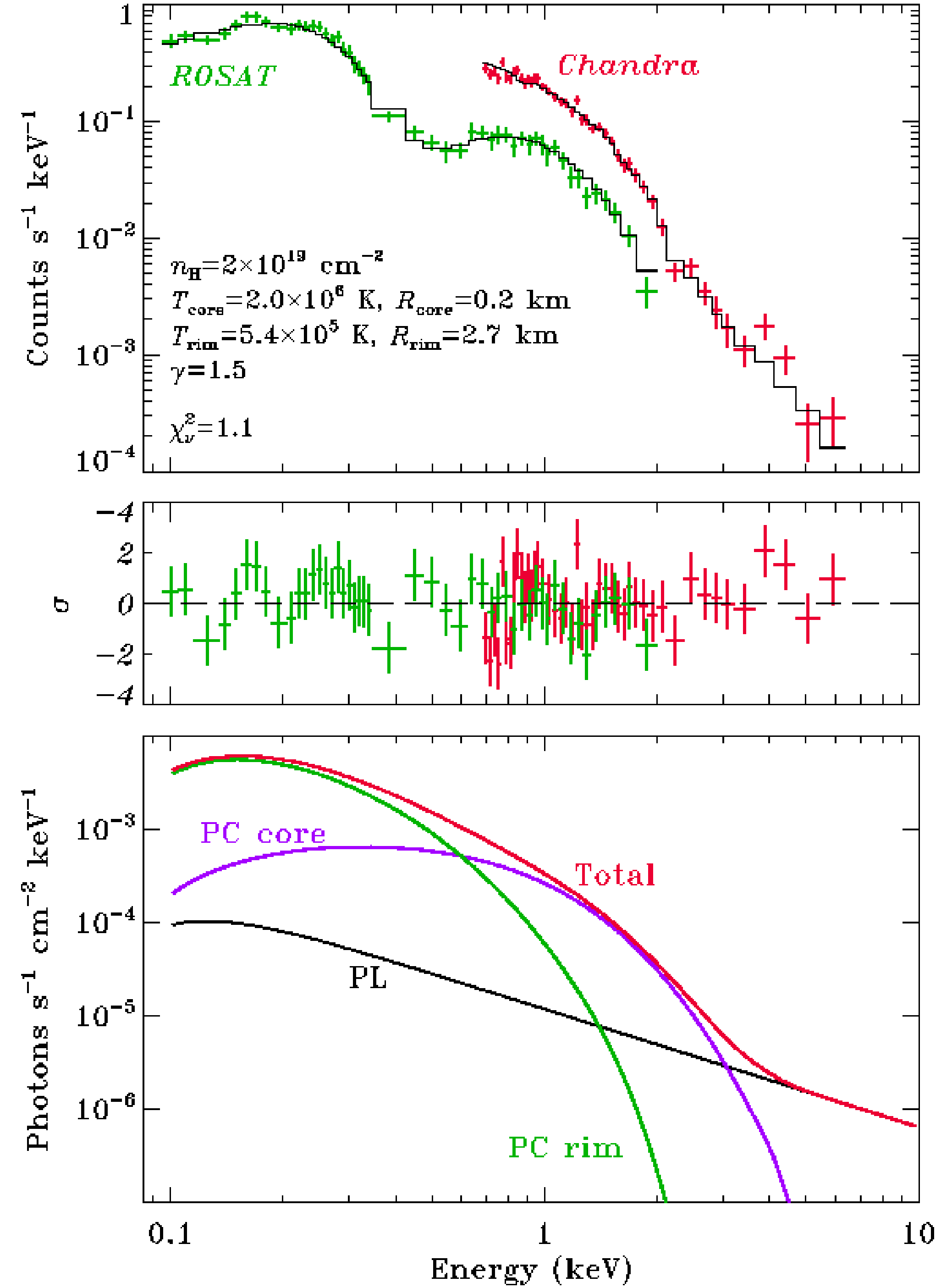


$T_{bb} > T_{atm}$

$S_{bb} < S_{atm}$

Atmosphere Models vs. Multiwavelength Observational Data on Isolated Neutron Stars

- the millisecond pulsar J0437-4715
- the Vela pulsar
- the middle-aged pulsars B0656+14 and B1055-52
- the X-ray pulsar 1E 1207.4-5209 in the SNR PKS 1209-51
- some others...



ROSAT and Chandra on
ms-pulsar J0457-4715:

thermal emission from PCs with
nonuniform temperature ⇒
bulk of X-rays

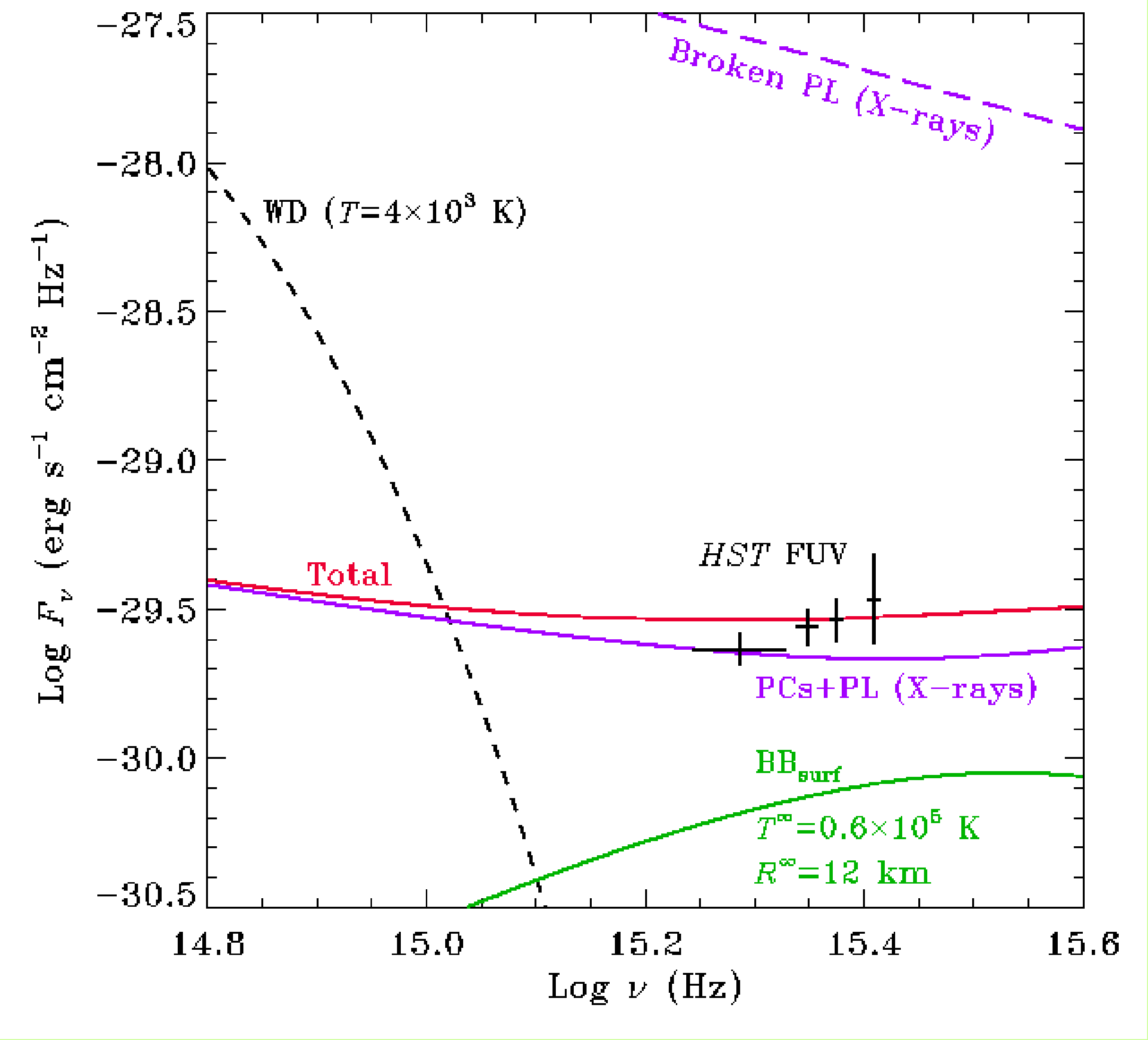
plus

nonthermal PL (E > 2 keV)

or

a single broken PL
with $E_{br} \approx 1.7$ keV ?

HST data on PSR J0437-4715 in far-UV

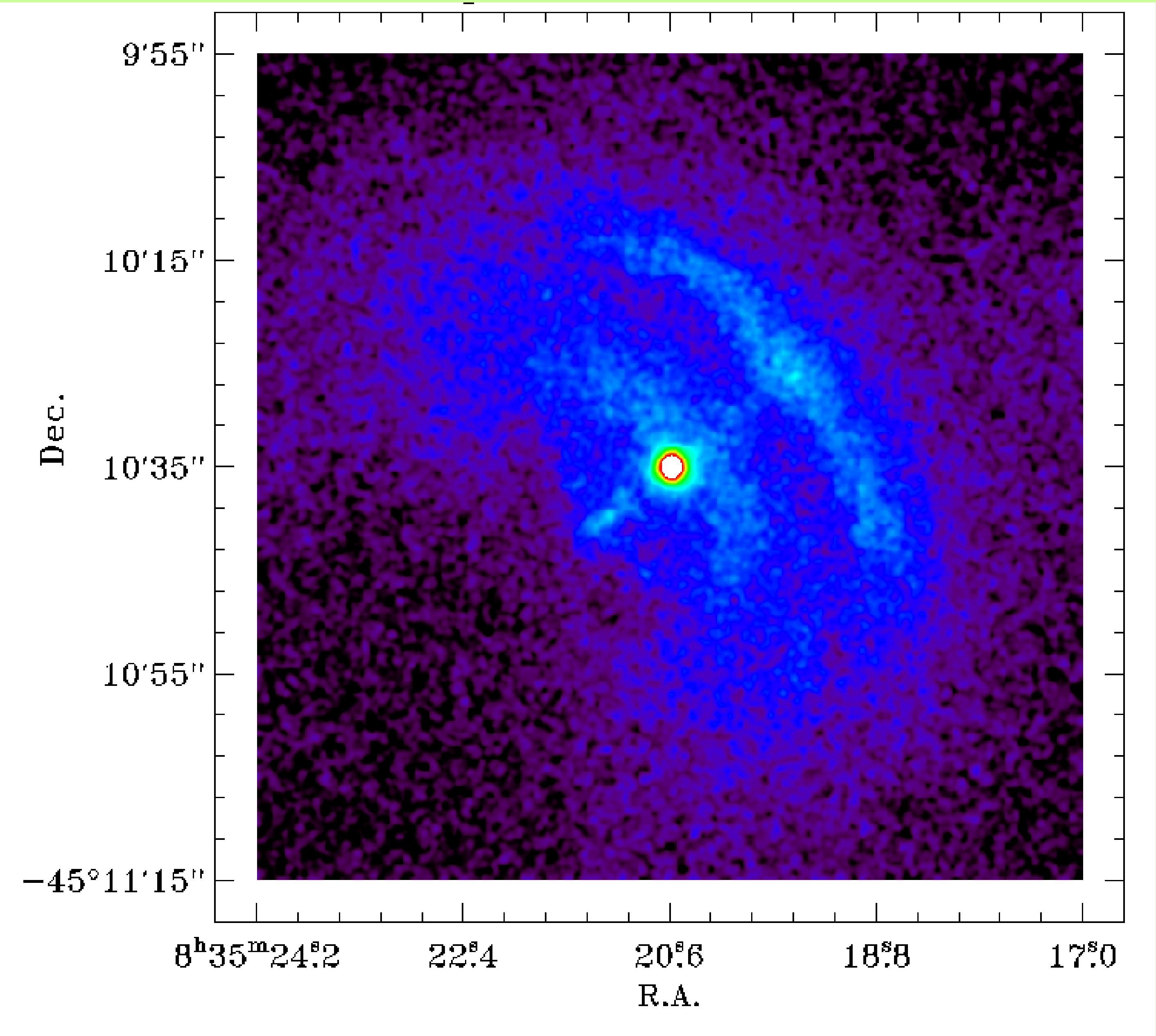


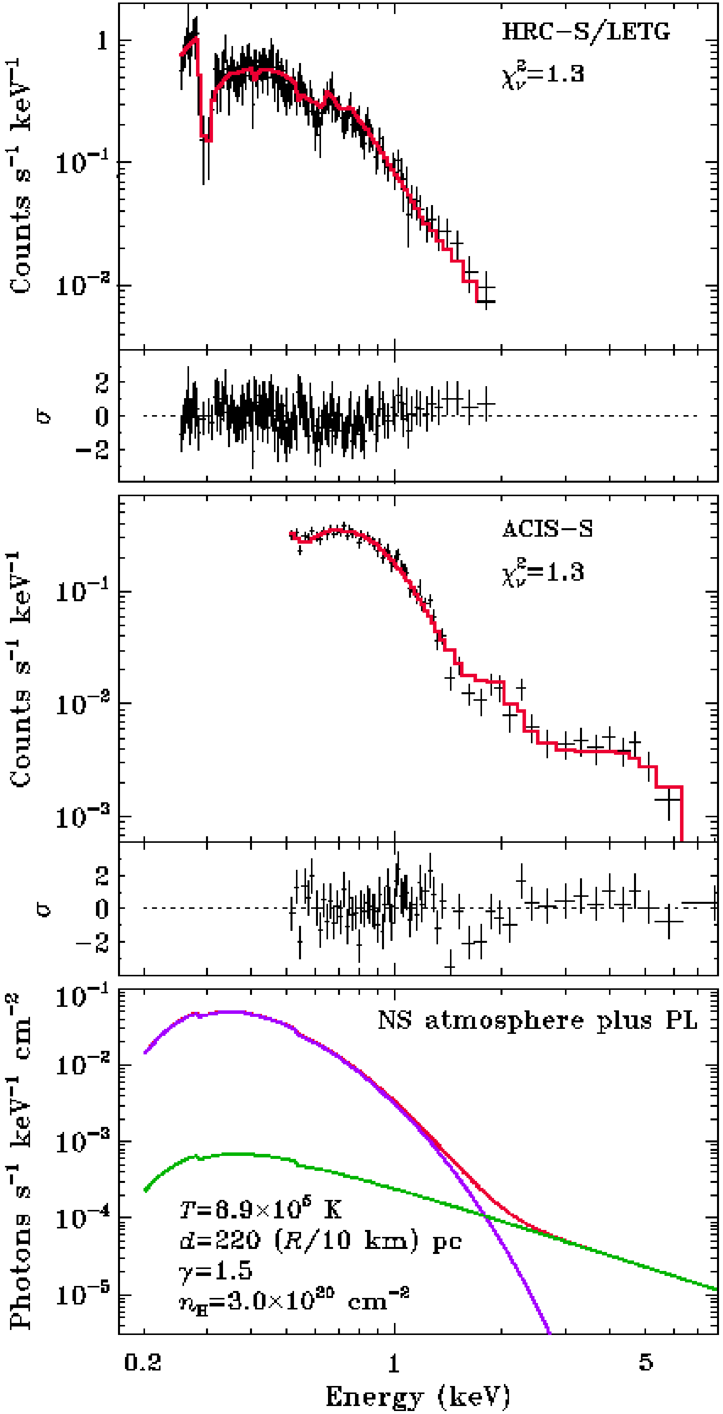
suppot:
X-ray PCs+PL plus emission from the rest surface of $T_{sur} \approx 6\times10^4$K

rule out:
the broken PL model

PSR J003+0451:
optical data rule out the nonthermal interpretation of the X-ray emission (Koptsevich et al. 2003)

Chandra Resolves the Vela Pulsar from Its Nebula





The Vela pulsar

LETGS: a smooth thermal spectrum at E< 2 keV

ACIS: second nonthermal component

Thermal componet:

blackbody model —

$R_{bb} \approx$ 2.5 km at $d \approx$ 300 pc (parallax)

$T_{bb} \approx 3{\times}10^6$ K

with PL of $\gamma \approx$ 2.8

or

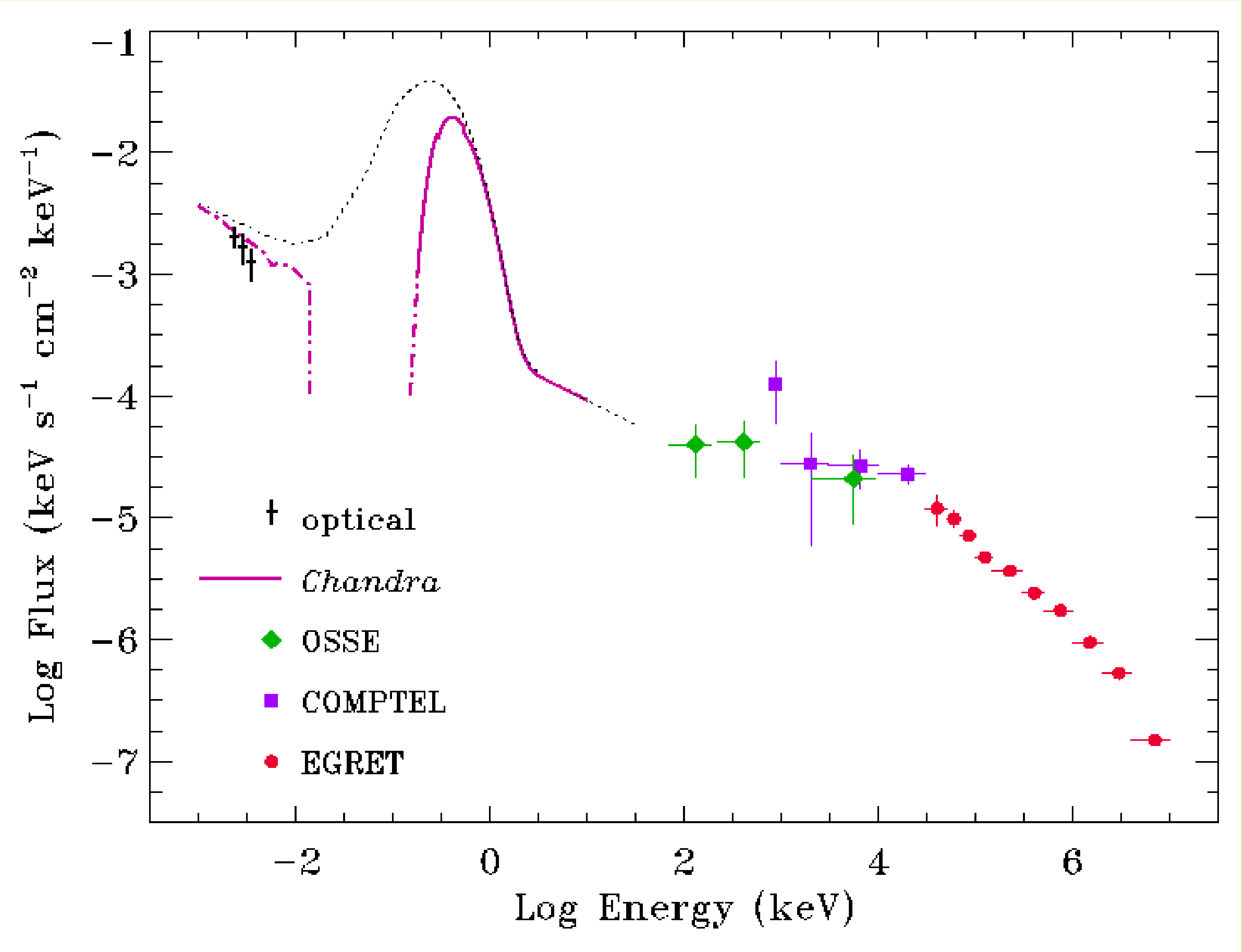
hydrogen magnetized NS atmosphere —

$d \approx$ 250 pc at R = 10 km

$T \approx 9{\times}10^5$ K

with PL of $\gamma \approx$ 1.5

The multiwavelength spectrum of the Vela pulsar: interpretation involving the NS atmosphere model



More (successful) NS atmosphere model applications:

- radio-silent NS RX J0822-4300 in the SNR Puppis A
  $\Rightarrow$ distance consistent with independent measurements
  (blackbody model $\Rightarrow$ 6 times larger distance

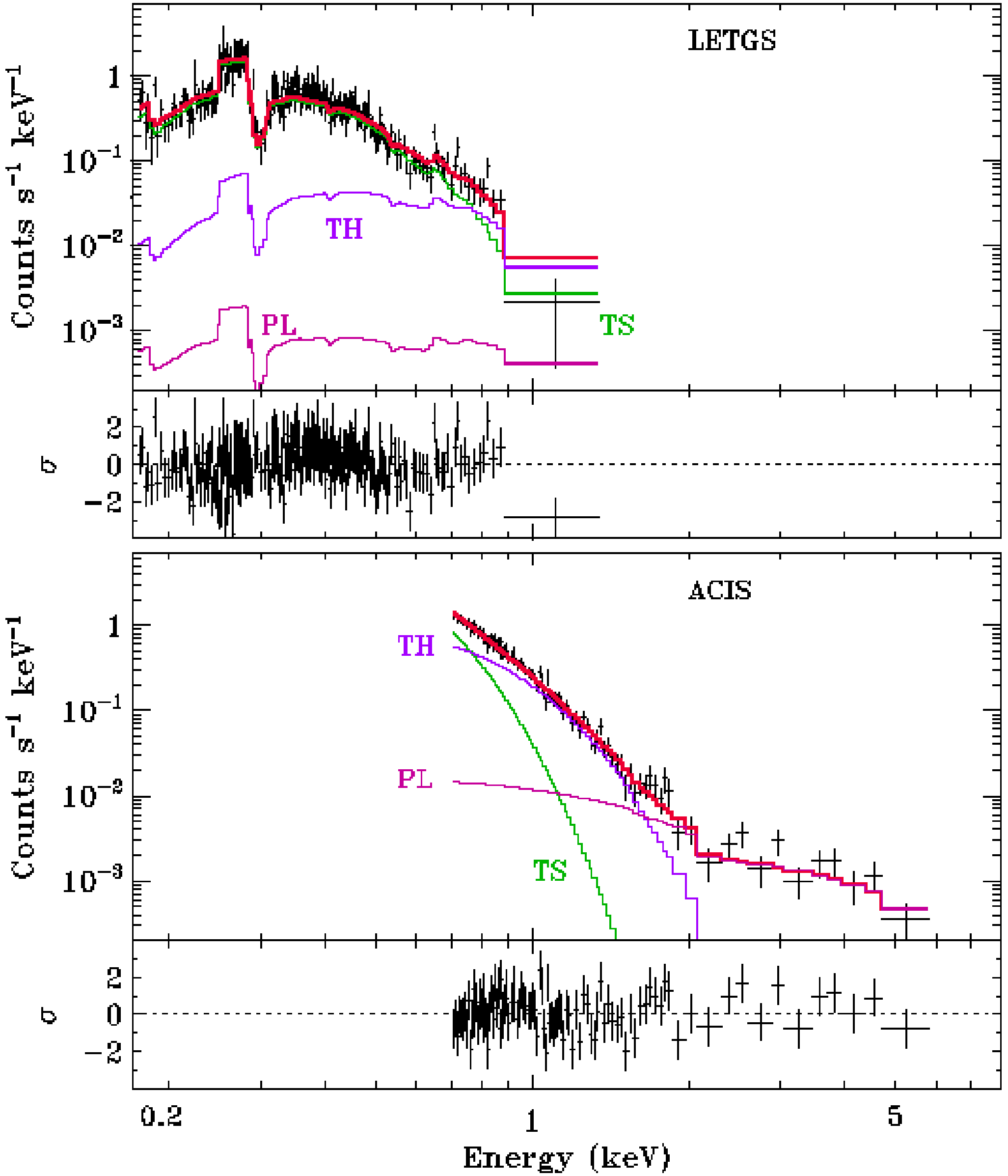
- transiently accreating NSs in X-ray binaries

  Aql X-1, Cen X-4, KS 1713-260, 4U 2129+47

  quiescent radiation from NS hydrogen atmospheres

  (Rutledge et al. 1999-2002; Nowak et al. 2002)

  due to heat released in the compressed material



Chandra LETGS and ACIS data

Middle-aged PSR B0656+14:

two thermal components, blackbody model:

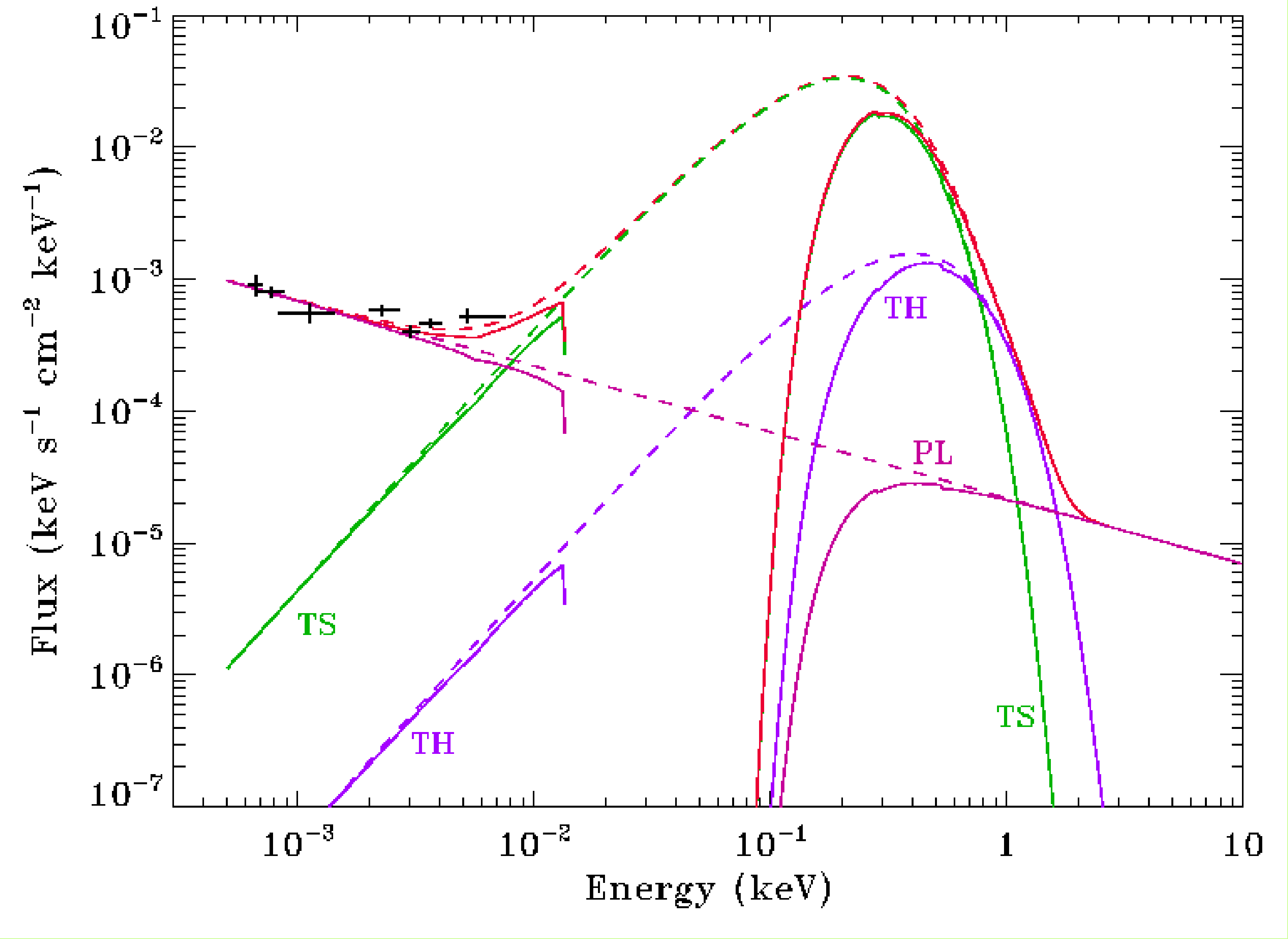
	"soft"	"hard"
T_{bb} ≈	8.5×10^5	1.7×10^6 K
R_{bb} ≈	18	1.5 km

(d ≈ 750 pc)

plus a PL of $\gamma \approx 1.5$

NS atmosphere models: too small distance, d ≈ 100 pc for R=10 km

Multiwavelength spectrum of PSR B0656+14



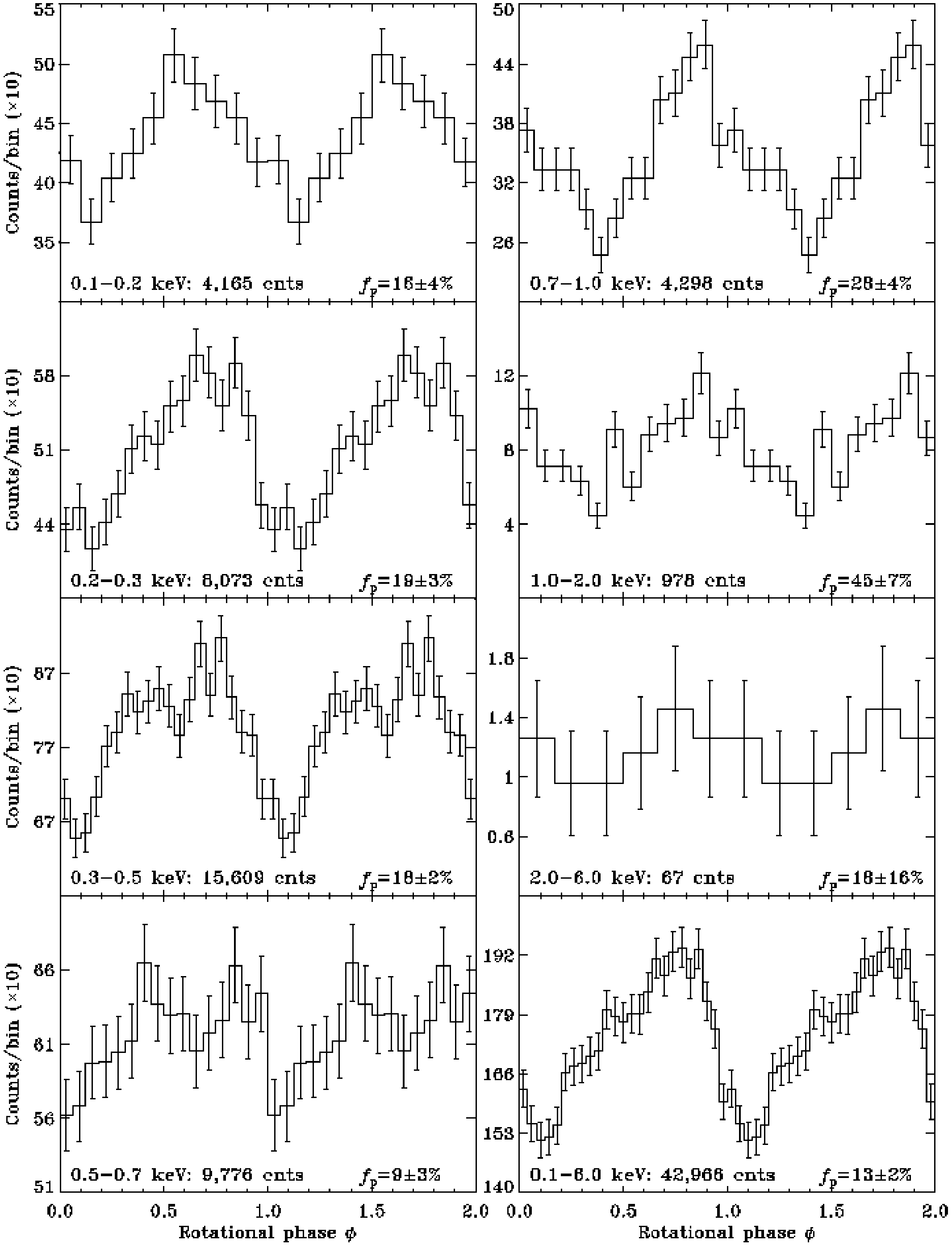
Middle-aged PSR B1055-52

Similar three-componet interpretation, TS+TH+PL:

PL dominates at E>2 keV, fits also the optical and γ-ray fluxes

PSRs	B0656+14	B1055-52
"soft" T_{bb}	8.5×10^5 K	7.5×10^5 K
age $\tau=P/(2dP/dt)$	110 kyr	540 kyr

- the mass of B1055-52 is smaller (Yakovlev et al. 2002) $\Rightarrow$ lower central density and weaker neutrino emission $\Rightarrow$ slower cooling
- characteristic ages are not true ages



Light curves of X-rays from PSR B0656+14:

strong energy dependence of pulse shape and pulsed fraction p_f

p_f ↓ from 18% at 0.2 keV to 9% at 0.6 keV

⇒ blackbody model does not work (Page 1995)

Problems:

- middle-aged PSRs B0656+14 and B1055-52 —

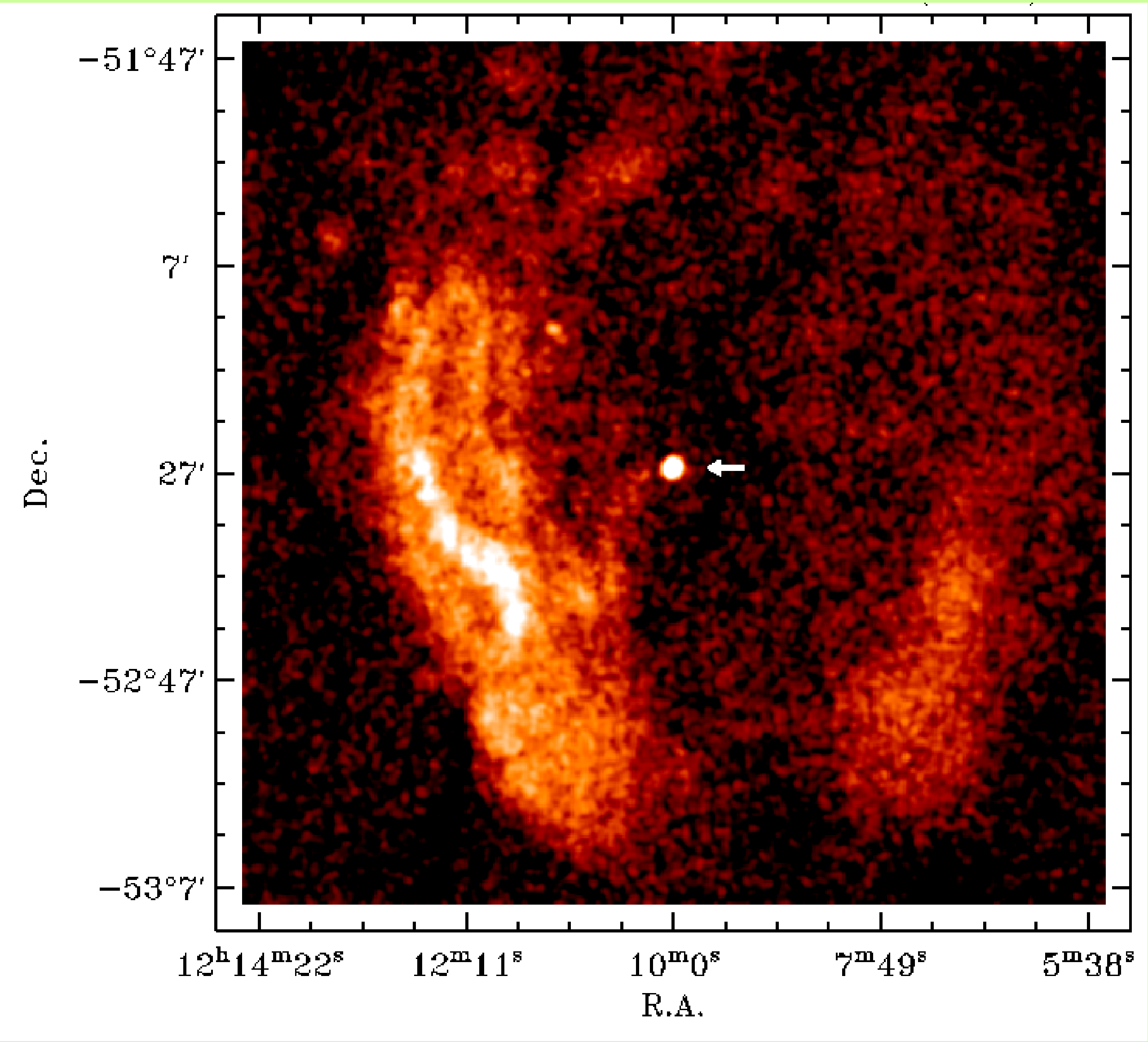
  NS atmosphere models are not applicable ⇒
  no atmospheres ?
  too cold and/or too strong magnetic field?

  blackbody model works on spectral data but
  is not able to explain the temporal bechavior
  (radiation has to be anisotropic)

- “truly“ isolated, “dim“ radio-quiet NSs (old and rather cold)
  RX J1856-3754, J0720-3125 (and a few more)

  none of the standard NS atmosphere works ⇒
  condensed-matter surface? or thin atmosphere?

1E 1207.4-5209 in the SNR PKS 1209-51: ROSAT (1993)



Chandra:

smooth pulsations with

$p_f \approx 6\%$

$P = 0.42$ s

$dP/dt \approx 2 \times 10^{-13}$ s s^{-1}

confirmed with XMM

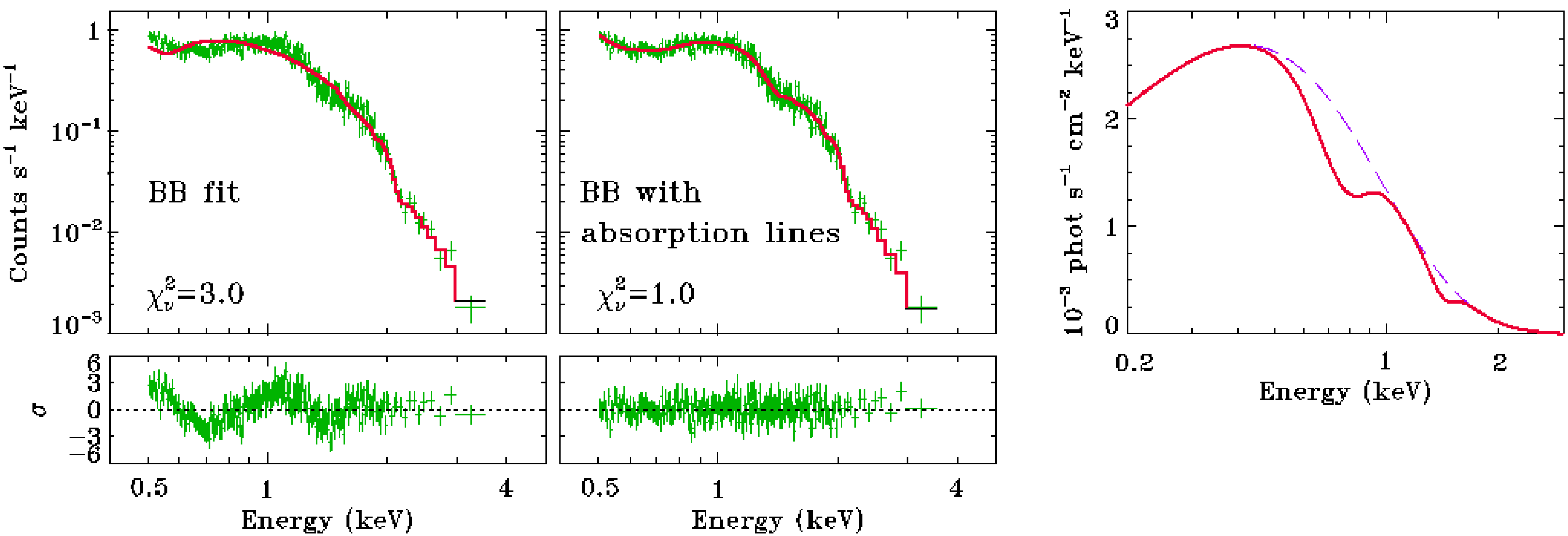
$\Rightarrow$ $B \approx 3 \times 10^{12}$ G

$\tau \approx$ 200-1600 kyr

vs.

7-20 kyr for the SNR

Chandra X-ray spectrum of 1E 1207.4-5209



Two broad absorption lines at 0.7 and 1.4 keV —
first direct evidence of a NS atmosphere:

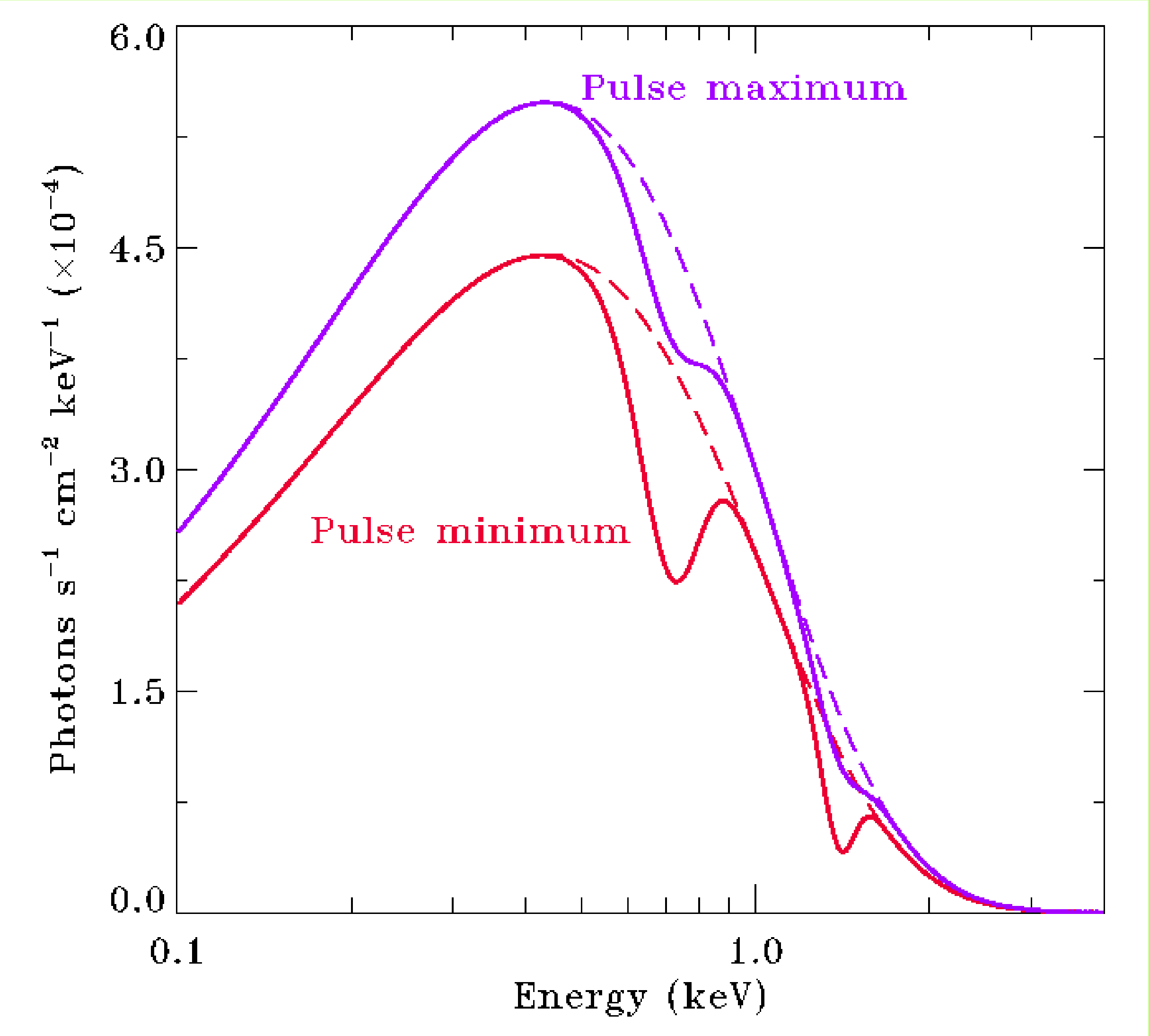
no hydrogen

once-ionized helium at $B \approx 10^{14}$ G?

He-like oxygen or neon at $B \leq 10^{12}$ G (Mori & Hailey 2002)?

new XMM (260 ks, done) and Chandra (300 ks, scheduled) observations

Spectra of 1E 1207.4-5209 at two rotational phases:



the lines are stronger at the pulse minimum

(Some) Conclusions

- More data $\Rightarrow$ more questions:

  true ages of NSs?

  surface temperature and magnetic field distributions?

  actual mechanism(s) of the surface emmision?

  states of the surface matter?

  ....

- Any nonstandard approaches are welcome

  E. g., plate tectonics (Ruderman 1991) —
  magnetized and hot plates on the nonmagnetic and cold surface
  (Page et al. 1995)

  or..........your suggestions?