Thermal Radiation from Isolated Neutron Stars

George Pavlov	Penn State
Slava Zavlin	MSFC (Huntsville)
Divas Sanwal	Penn State
Oleg Kargaltsev	Penn State
Roger Romani	Stanford

Thermal emission: Why important?

Spectral fit → T, F → R/D = [F/(σ T^4)]$^{1/2}$
→ R → constraints on E.O.S.

T (τ) → cooling history → internal composition, baryon interactions, superfluidity, …

Comparison with **surface emission models** → surface properties (gaseous/condensed), chemical composition, magnetic field, temperature distribution, gravity

Gravitationally redshifted spectral lines → M/R, B

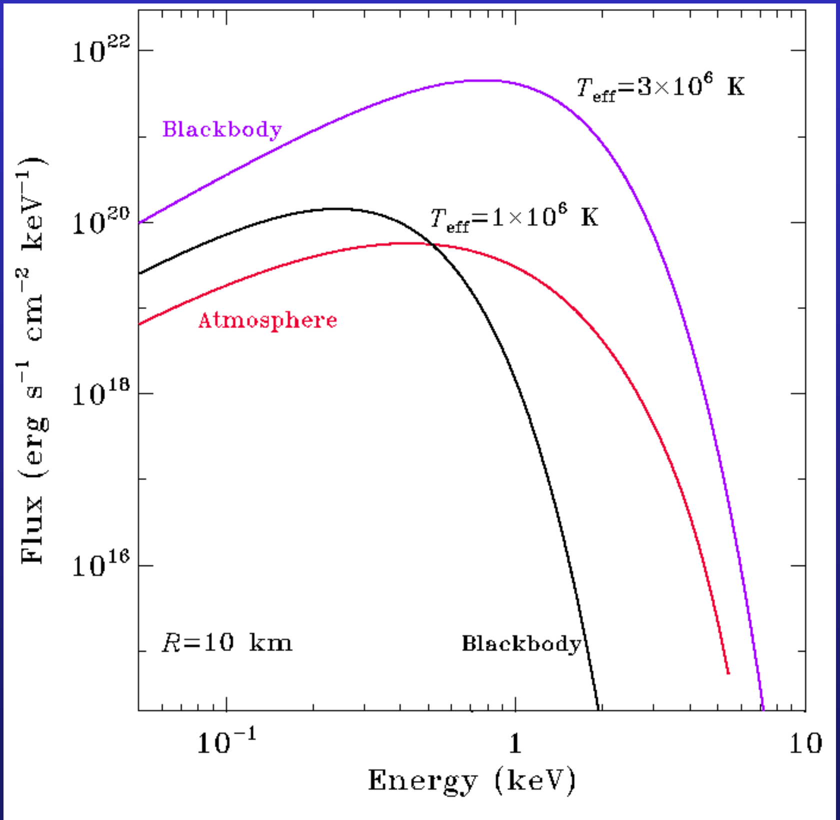
Pulse profiles → M/R, geometry of magnetic field, surface temperature distribution

Surface emission models

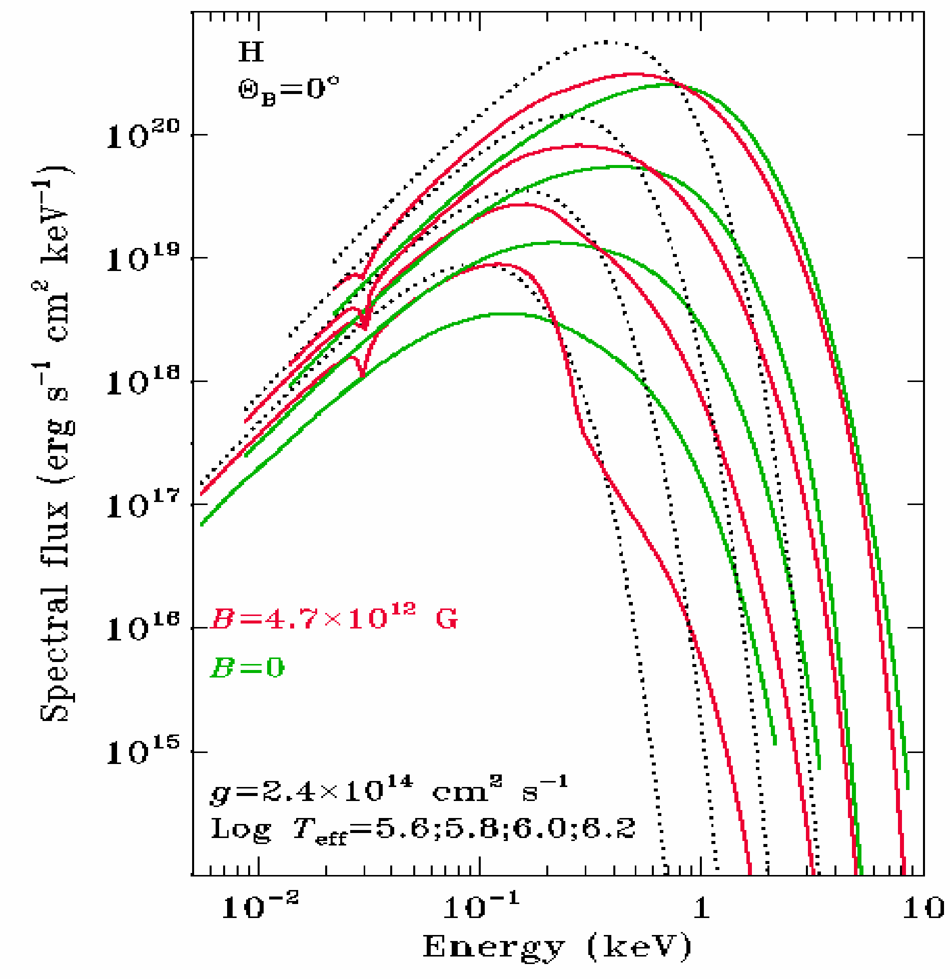
Blackbody: unrealistic

Atmospheres: at higher T, lower B

Low-B Hydrogen atmosphere:
effect of energy-dependent opacity

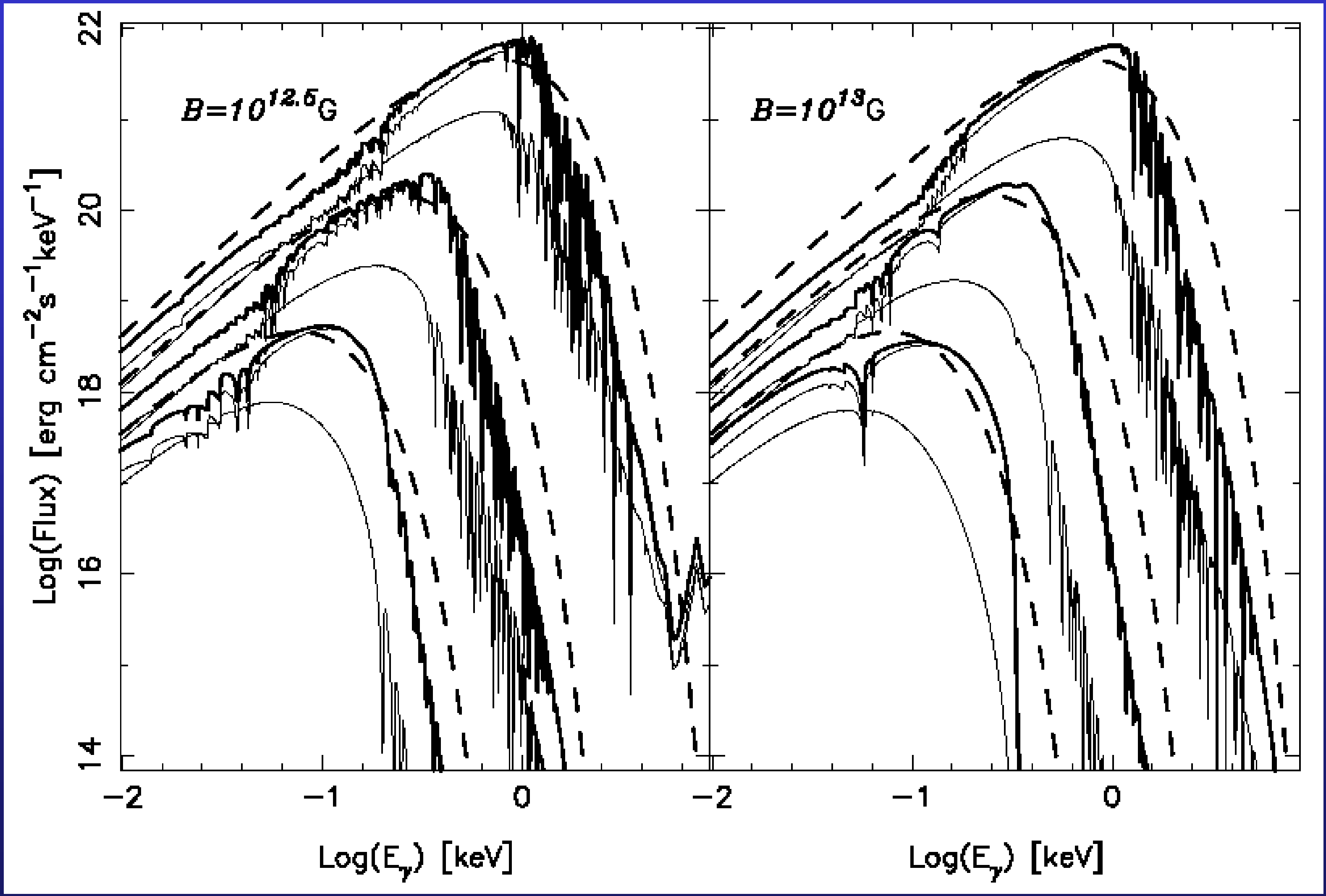


Effect of magnetic field



T_{bb}/T_{atm} = 1.5-3; A_{atm}/A_{bb} = 50-200

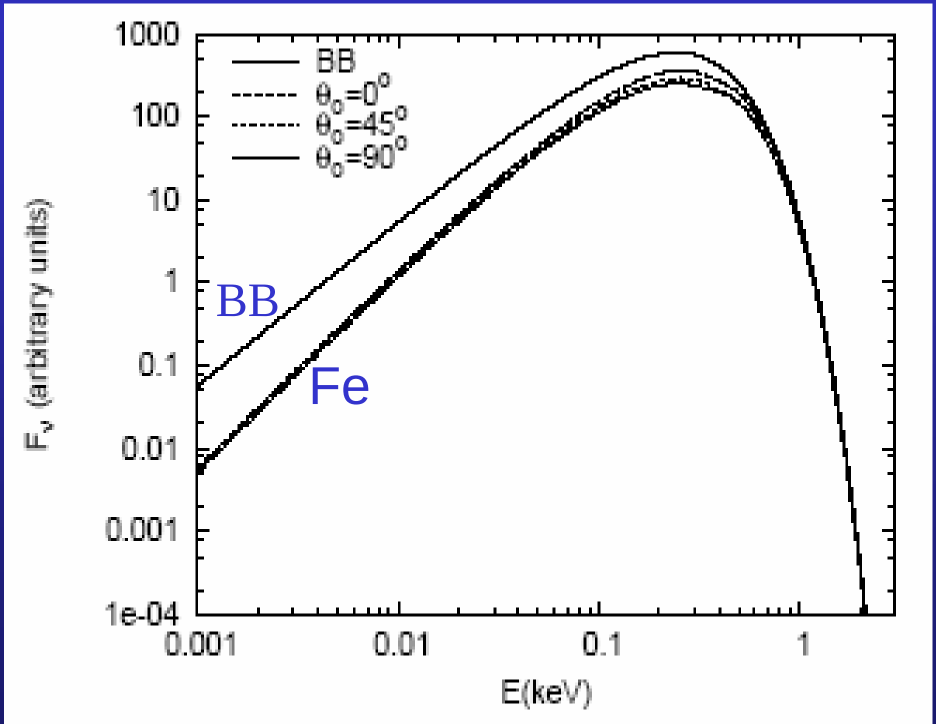
Iron magnetized NS atmosphere models (Rajagopal, Romani, Miller 1997)



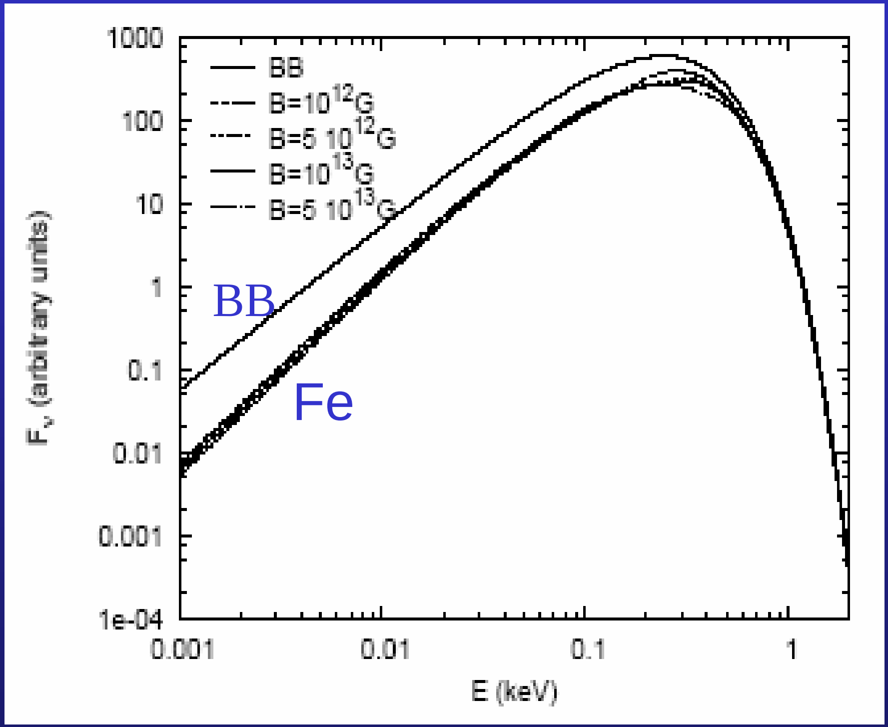
Solid or liquid surface: at lower T, higher B

Spectra from solid Fe surface at T=10^6 K (Perez-Azorin et al 2004):

B = 5 x 10^{13} G, different inclinations



$\Theta_0 = 0$, different magnetic fields



Emission is suppressed at lower energies (models not very reliable)

Different types of isolated neutron stars showing thermal emission

- Active spin-powered pulsars (~1500 in radio, ~60 in X-rays, ~7 in gamma-rays, ~10 in optical, **~10 thermal emission**)

- Central Compact Objects (CCOs) in SNRs (**~7 in X-rays, thermal**)

- “Dim” isolated neutron stars (DINSs) (**7 in X-rays, thermal**)

- Magnetars (AXPs and SGRs) - talks by Kaspi and Hurley **(~10, thermal components in some)**

- NSs in X-ray transients, in quiescence (**>10, thermal**)

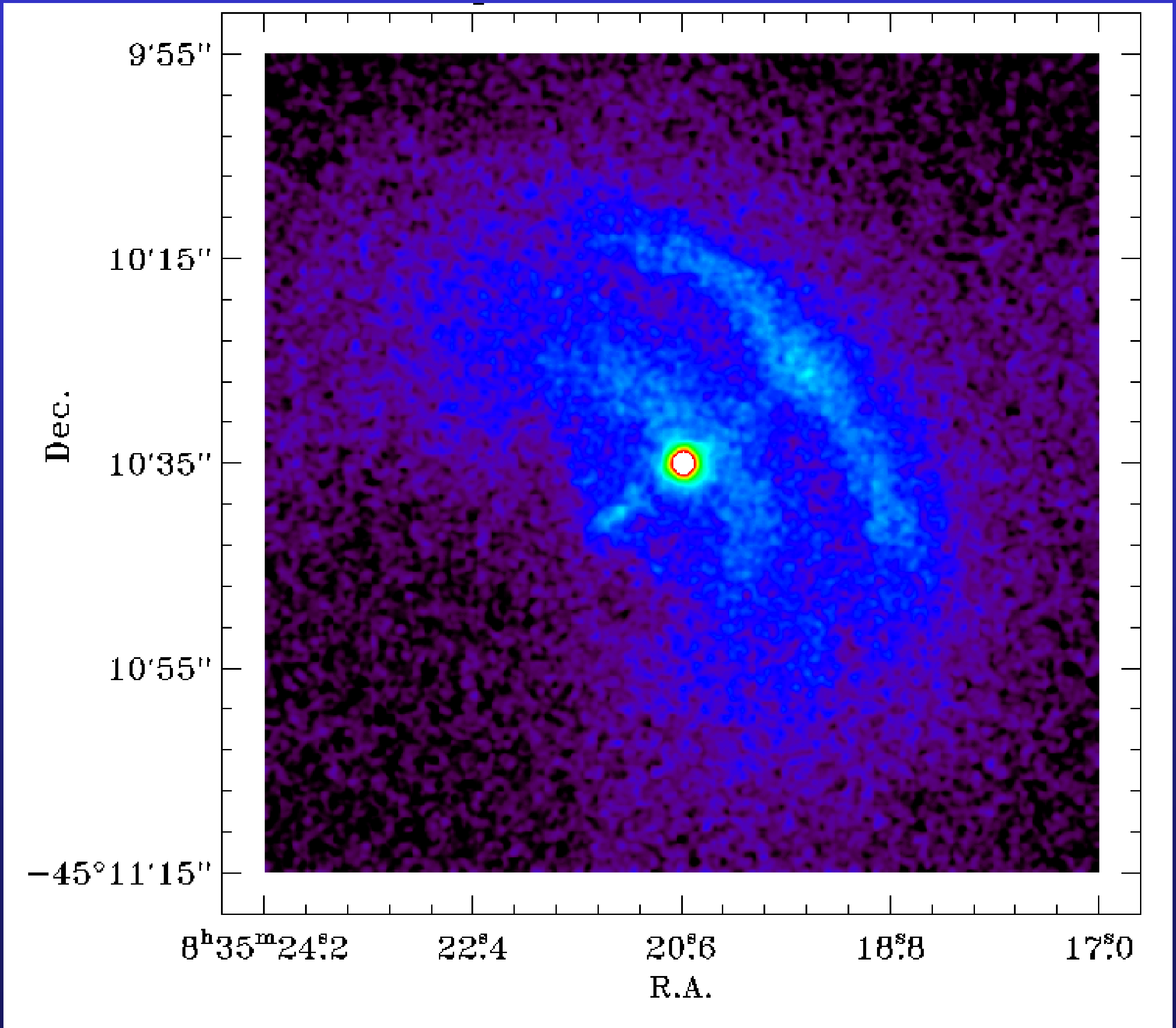
I. ACTIVE, SPIN-POWERED PULSARS

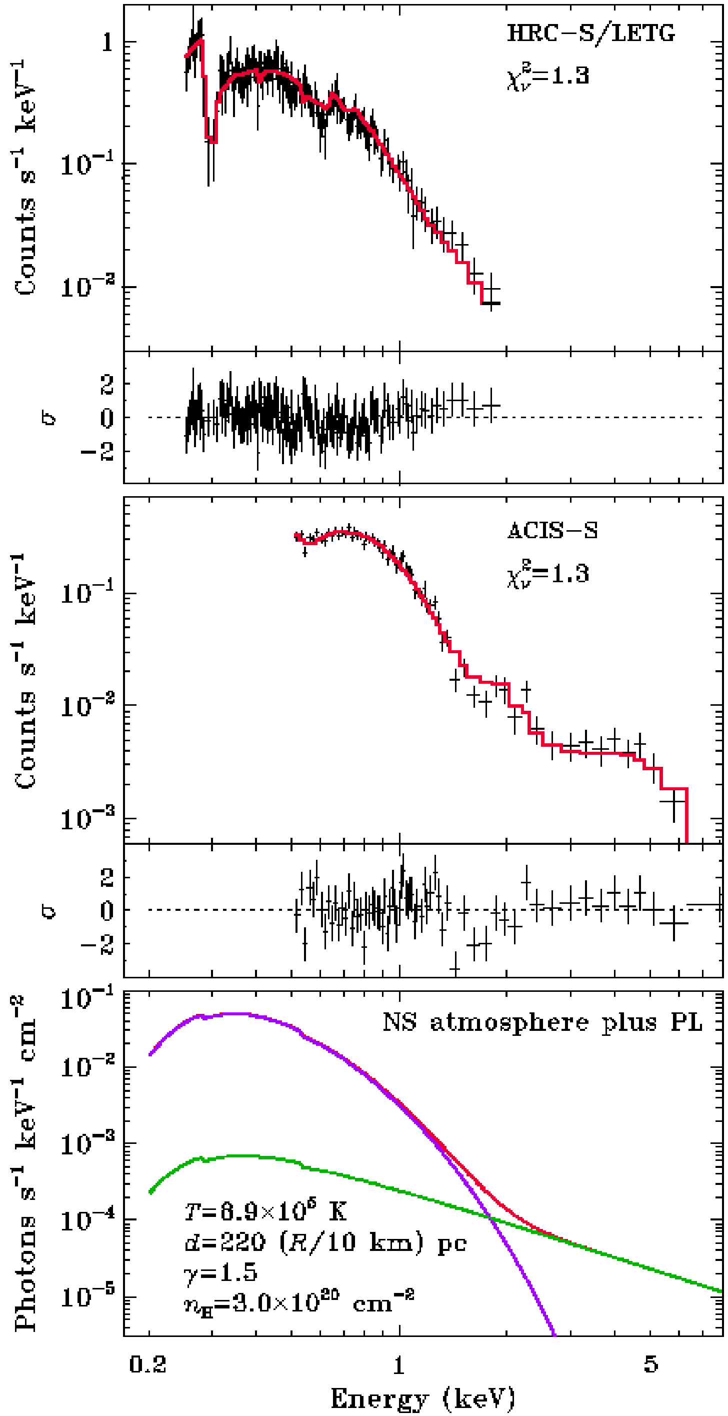
1. Young: Nonthermal emission dominates, upper limits on thermal component from off-pulse radiation (e.g. Crab, 3C58)

2. Middle-aged (10 – 1000 kyr): Thermal from the whole surface (+ polar caps), in soft X-rays, EUV, FUV; nonthermal in hard X-rays, optical

3. Old (including ms-pulsars): Thermal soft X-rays from polar caps (except for those where nonthermal dominates), thermal FUV, nonthermal in optical

Chandra resolves the **Vela pulsar** from its pulsar wind nebula





Chandra spectra of the **Vela pulsar**

($\tau_c \approx$ 11 kyr, d ≈ 300 pc)

LETGS: thermal spectrum at E< 2 keV

ACIS: nonthermal component

Thermal component:

blackbody model:

R ≈ 2.5 km (<< R_{NS})

T ≈ 3.0 MK

with PL of $\Gamma \approx$ 2.8

or

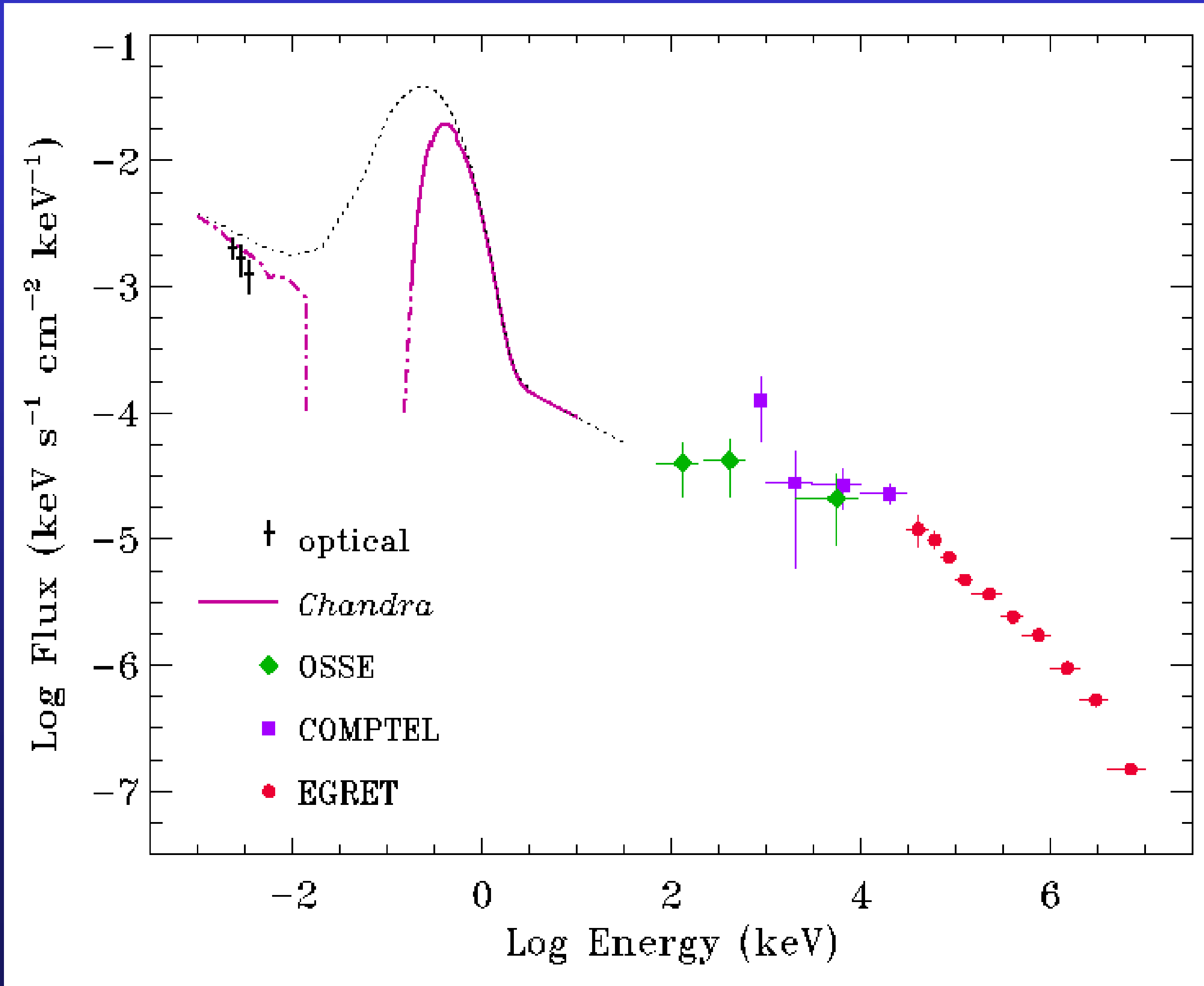
magnetized hydrogen NS atmosphere:

R = 14 km

T ≈ 0.6 MK

with PL of Γ ≈ 1.5

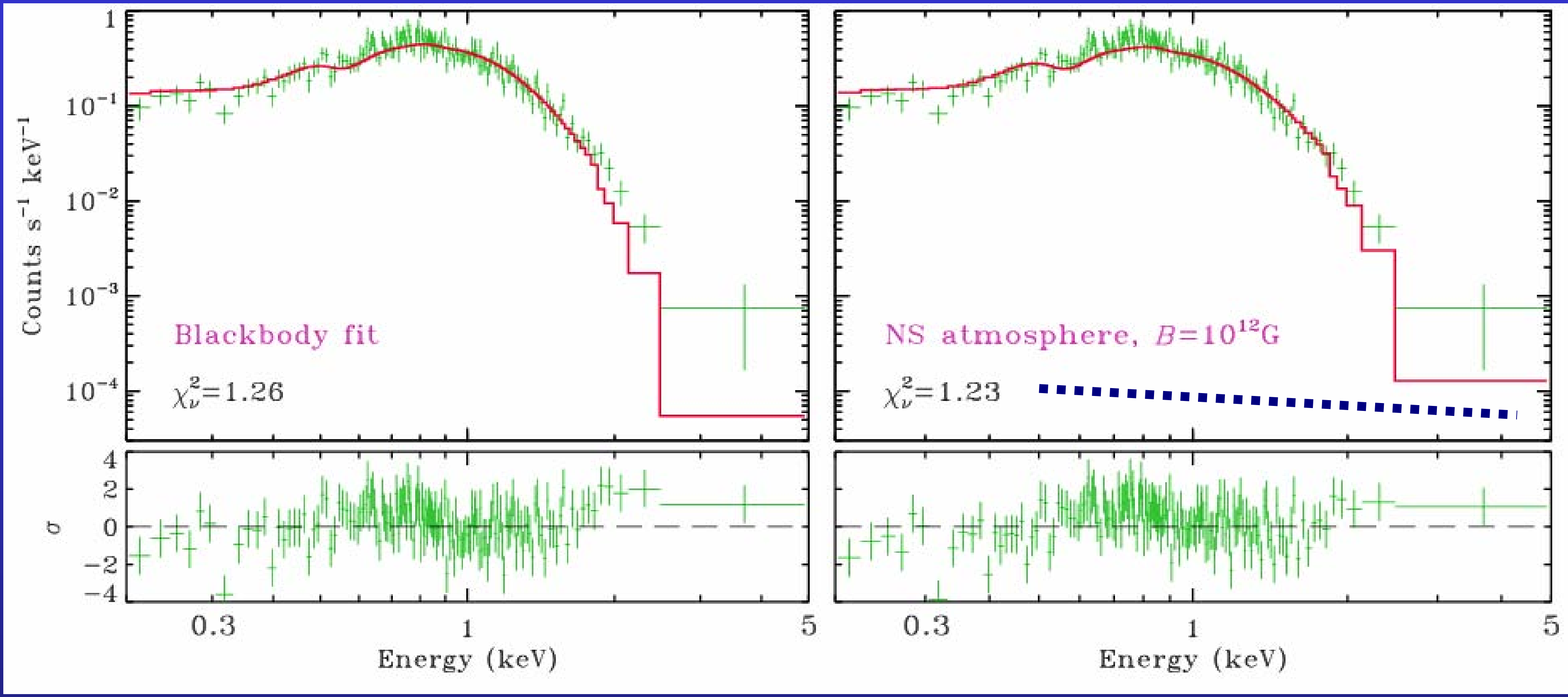
Multiwavelength spectrum of the Vela pulsar with the NS atmosphere model



Thermal emission dominates
at 15 eV - 2 keV

Magnetospheric emission in optical, hard X-rays, γ-rays

XMM-Newton: **PSR J0538+2817** ($\tau \approx 30$ kyr, d $\approx$ 1.2 pc)



Blackbody model:

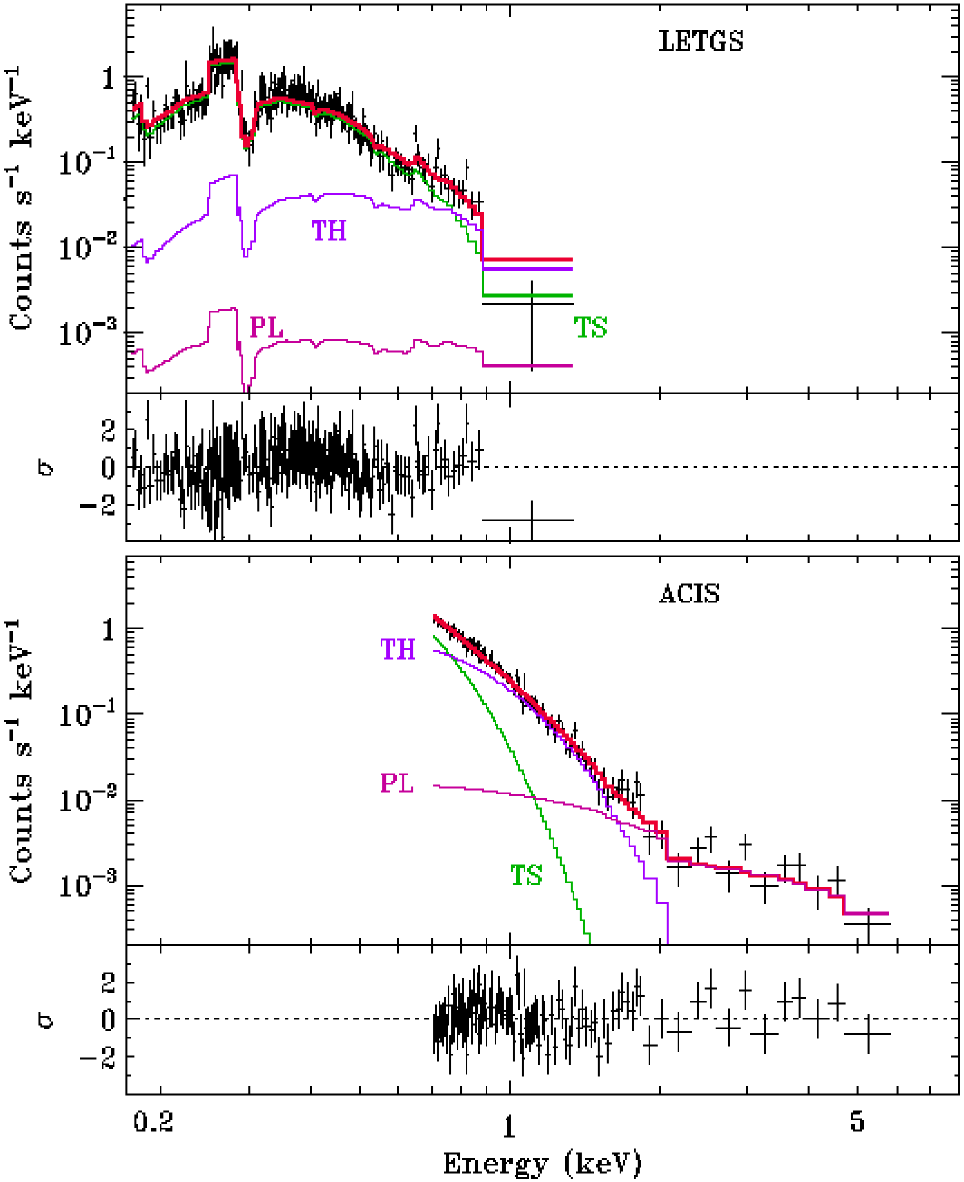
T $\approx$ 2.1 MK
R $\approx$ 1.7 (d/1.2 kpc) km

H atmosphere model:

T $\approx$ 1.2 MK
R $\approx$ 10.5 (d/1.2 kpc) km

Upper limit on a nonthermal component: L^{nonth} **< 0.01** L_{th}

$L_{th} \approx 1.4 \times 10^{33}$ erg/s



Chandra LETGS and ACIS data
(consistent with XMM-Newton data)

Middle-aged **PSR B0656+14**

($\tau_c \approx$ 110 kyr, d $\approx$ 290 pc)

H atmospheres:
too large radius,
R ≈ 30 km for d=290 km

Available metal atmospheres:
do not fit (no lines observed)

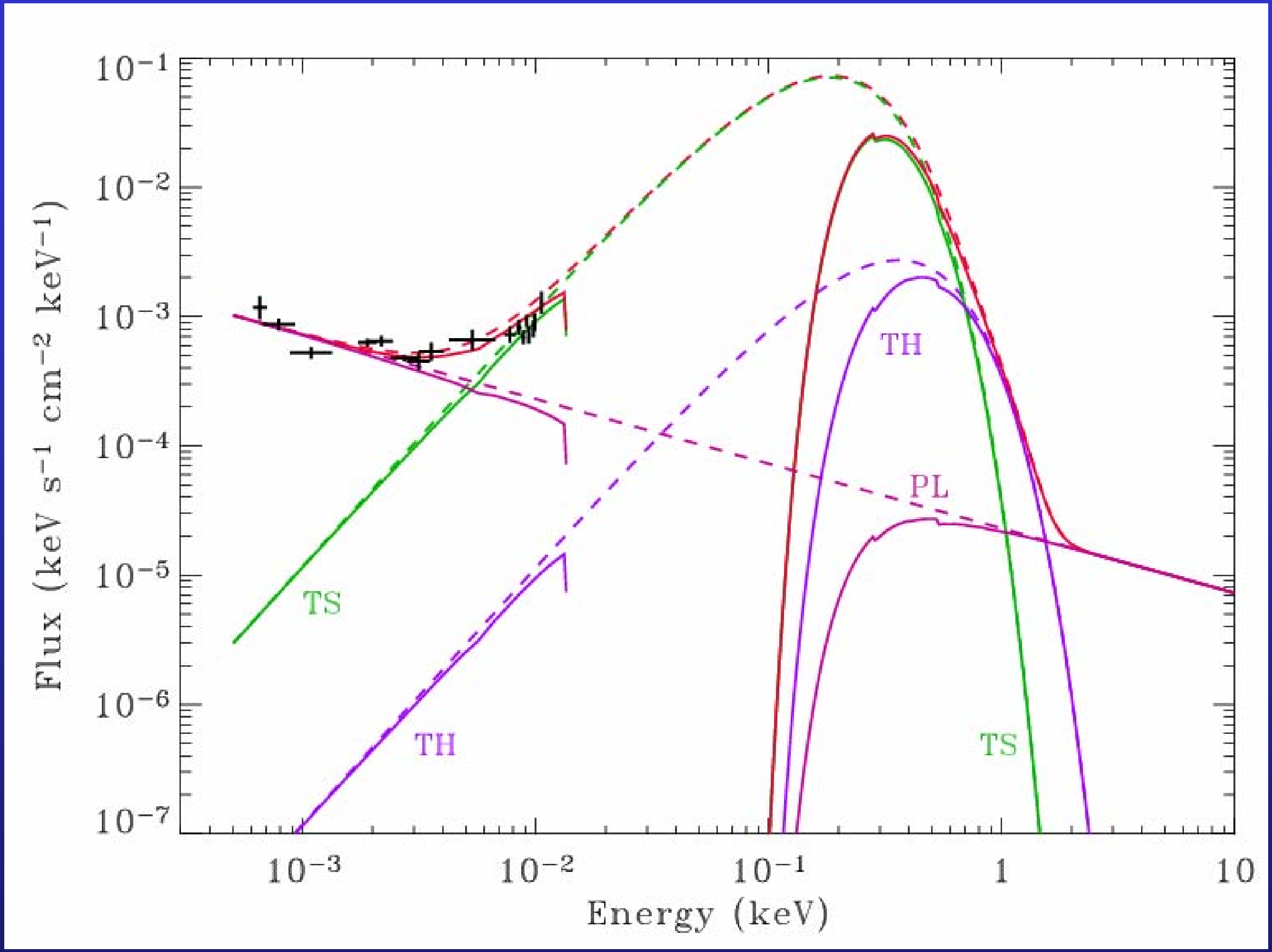
Blackbody model: two thermal components

	"Soft"	"Hard"
T ≈	0.9 MK	1.7 MK
R ≈	7 km	0.6 km

plus PL of $\Gamma \approx 1.5$

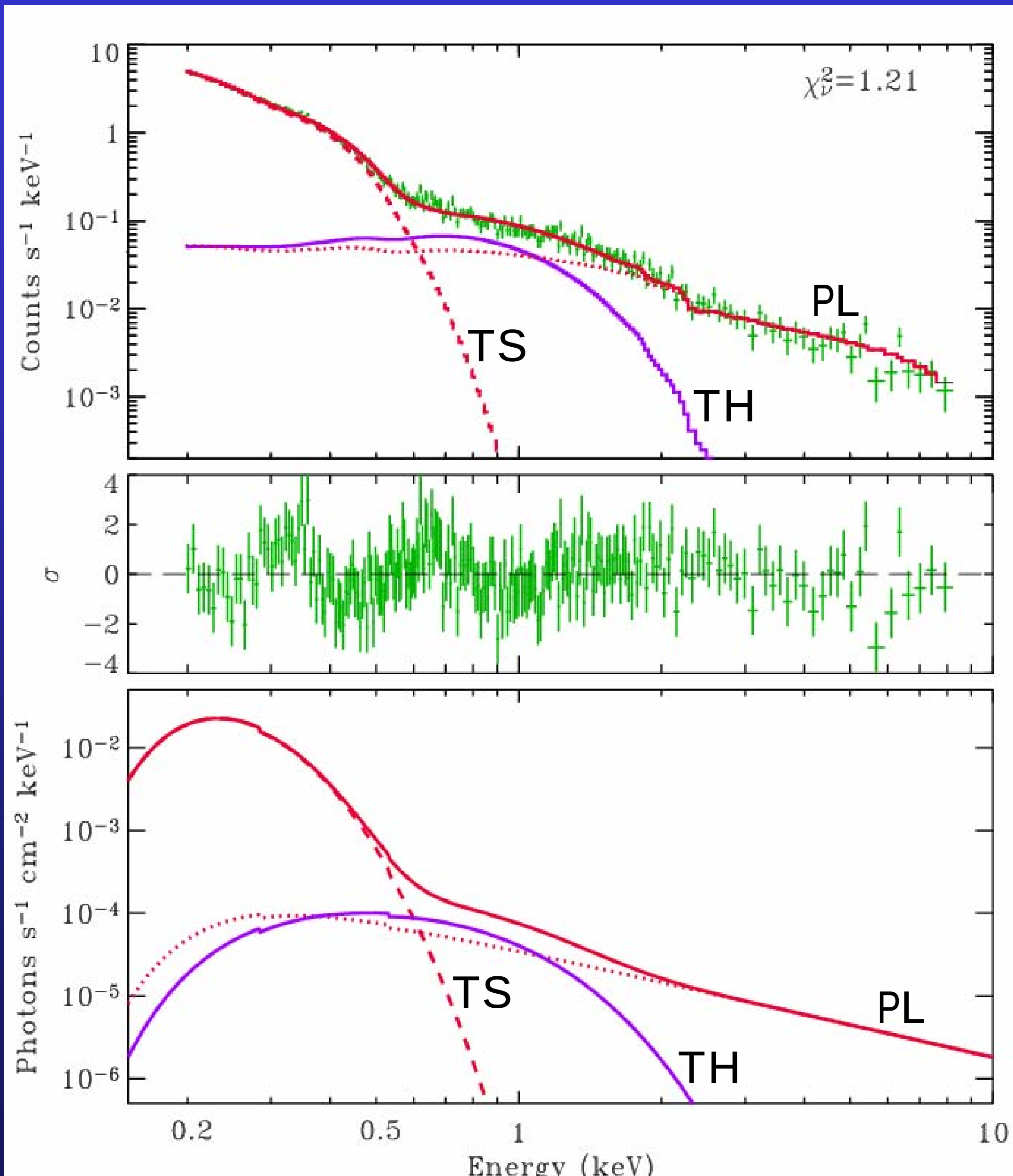
too small R →
nonuniform surface temperature?

Multiwavelength spectrum of **PSR B0656+14**



The TS+TH+PL model fits well the X-ray and optical-UV data

X-ray spectrum of **Geminga**: (τ_c = 340 kyr)



Three-component model

PL: Γ = 1.5

TS: T = 0.49 MK
R = 12 km @ 200 pc

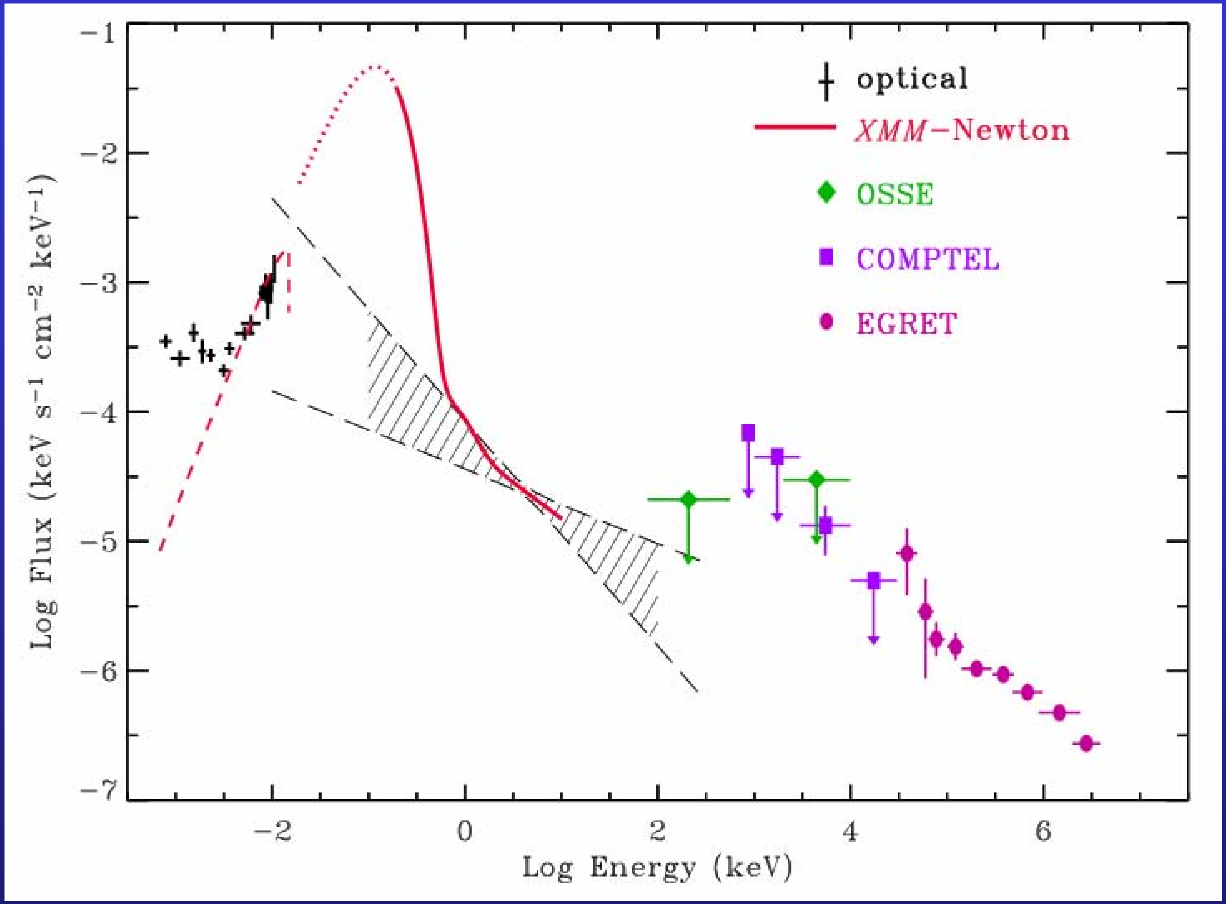
TH: T ≈ 2.4 MK
R ≈ 40 m @ 200pc

TS+TH+PL models for the brightest middle-age PSRs

B0656+14
Geminga
B1055-52

(not enough counts to fit spectra of other middle-aged pulsars with three-component models)

Multiwavelength spectrum of **Geminga**

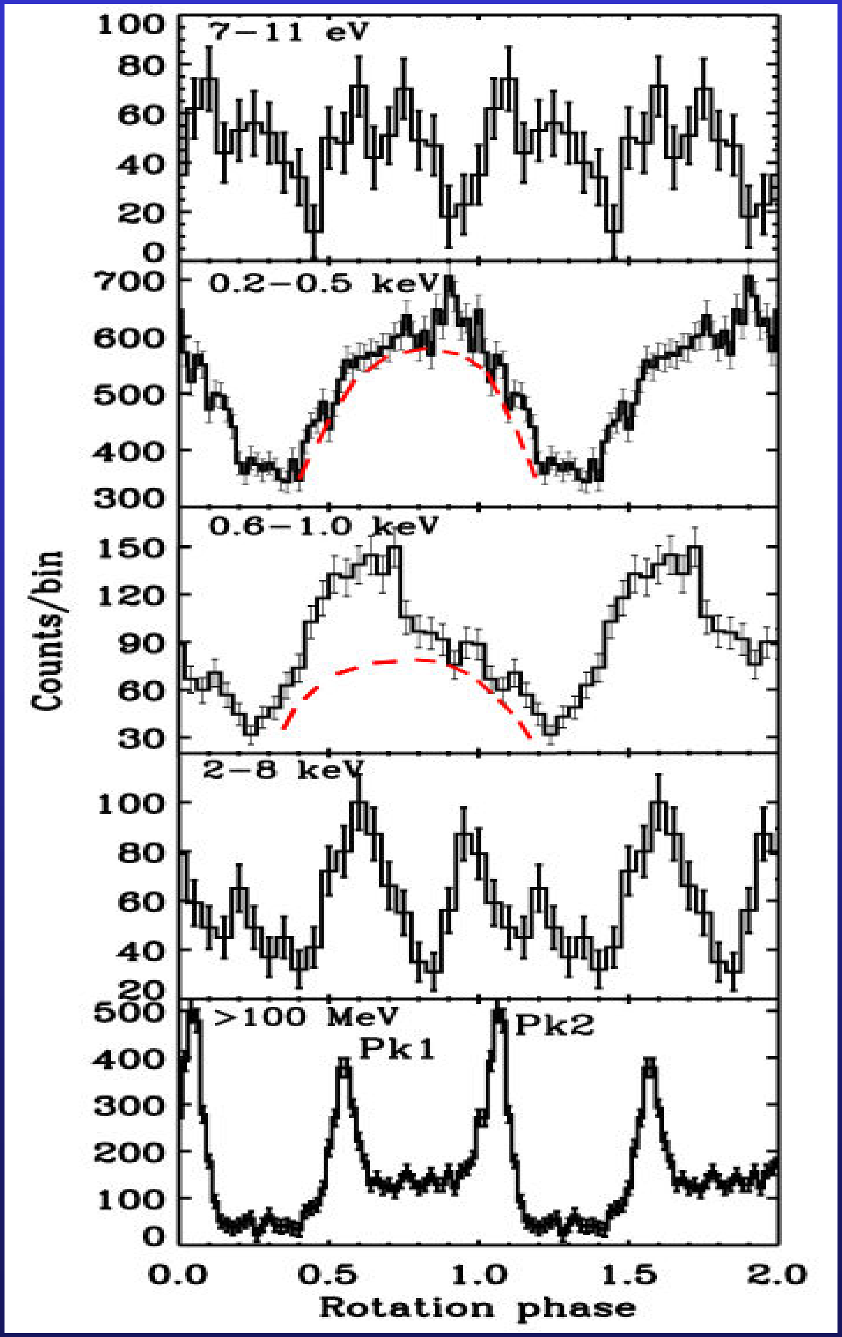


Far-UV points (7-11 eV; HST STIS observations) lie on extrapolation of TS component

Thermal emission dominates in 5 – 500 eV

Optical, hard X-ray and gamma-ray emission from the magnetosphere

Pulsations of **Geminga** from FUV to gamma-rays



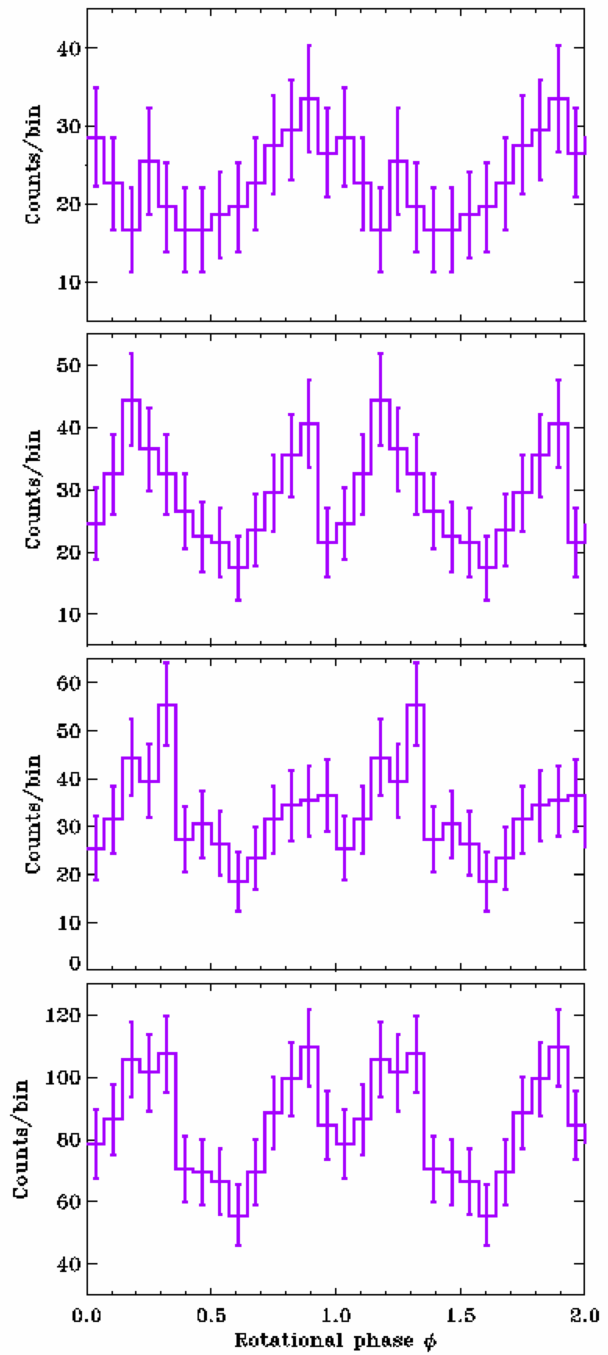
Far-UV: Thermal emission with unusual pulsations (narrow dip at $\phi = 0.45$), pf ~40%, eclipsed by magnetosphere?

Soft X-rays: Thermal soft dominates, one broad peak with (magnetospheric) ripples, pf = 30%

Intermediate X-rays: Mixture of TS, TH, and PL components, pf = 62%

Hard X-rays: Magnetospheric, two broad peaks, pf = 34%

Gamma-rays: Two sharp peaks with a bridge, 100% pulsed



Old PSR B0950+08 (τ_c = 17 Myr; d = 262 pc)

X-ray pulsations (XMM observations):

0.2—0.5 keV: pf = 33%, single broad pulse,
thermal emission from a polar cap?

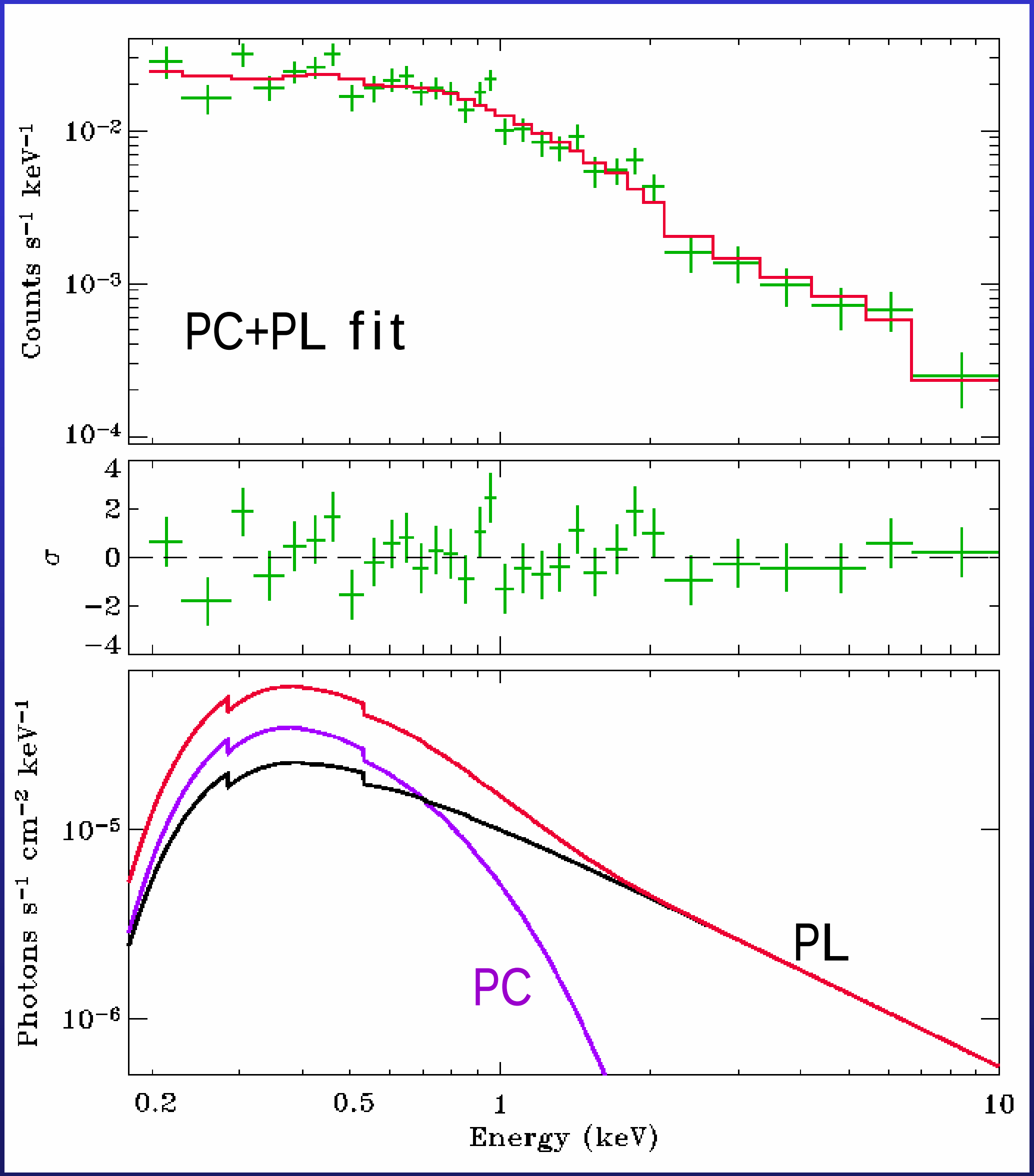
0.5—1 keV: pf = 60%, double-peaked structure,
separated by ~0.4 of P (as in radio)
→ magnetospheric emission

1—5 keV: pf = 57%,
resembles the pulse in 0.5—1 keV

0.2—5 keV: pf = 41%

Pulse shape depend on E →
multi-component radiation

PSR B0950+08: X-ray spectrum



Two-component PC+PL fit:

$\Gamma \approx 1.3$

Blackbody model for PCs:

$T \approx 1.8$ MK

$R \approx 50$ m

Hydrogen NSA for PCs:

$T_{pc} \approx 1.1$ MK

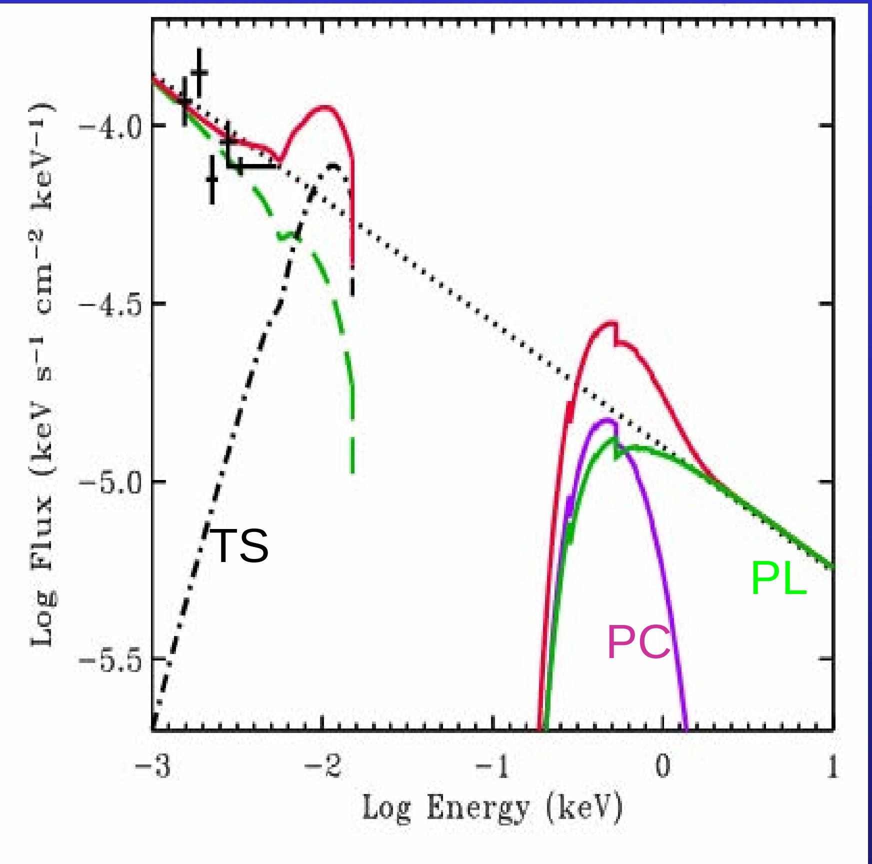
$R_{pc} \approx 250$ m

$L_{pc} \approx 3\times10^{29}$ erg/s

Pulsar models: $R_{pc} = (2\pi R^3/cP)^{1/2} = 290$ m (for R=10 km)

PSR B0950+08:
X-rays vs. optical

Optical fluxes in I, R, V, B, UV bands



PC+PL model,
plus a TS component
(emitted from the bulk of the surface):

same PL of Γ=1.3-1.4 in optical/X-rays

same PC fitting the „soft“ light curve

TS temperature < 0.15 MK

Summary on thermal emission from active pulsars:

- thermal emission has been observed in X-rays and far-UV from ordinary pulsars with ages in a broad range, ~ 10 kyr — 20 Myr, as well as from some millisecond pulsars
- for younger pulsars (10-30 kyr) it can be interpreted as radiation from the whole NS surface covered with a lihgt-element atmosphere; heated PCs are not seen (buried under the brighter surface emission?)
- thermal X-ray emission from middle-aged pulsars likely consists of two components: emission from the whole surface and heated PCs
- for old pulsars emission from the whole surface can only be observed in the UV range; in X-rays emission from hot PCs is detectable
- NS thermal radiation is anisotropic; observed pulsations suggest that NSs have nonuniform surface temperature; some may have decentered dipole or multipole magnetic field

II. Radio-quiet neutron stars (“dead pulsars”)

Expect purely thermal emission,
not contaminated by magnetospheric activity

“The only good pulsar is a dead one”

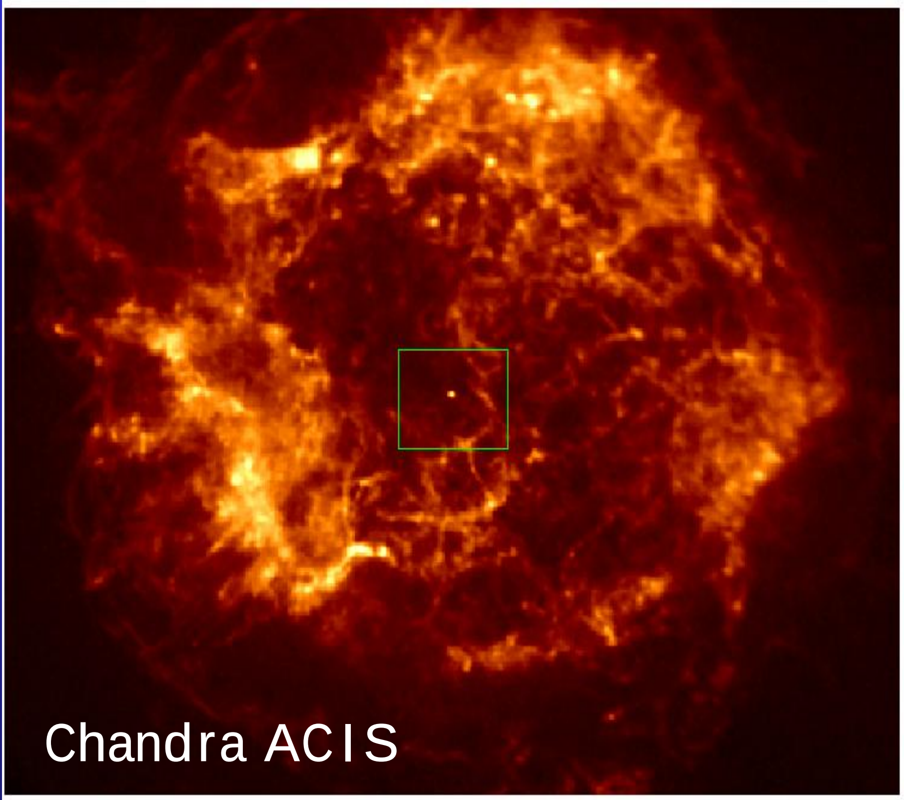
(G. Pavlov 1999)

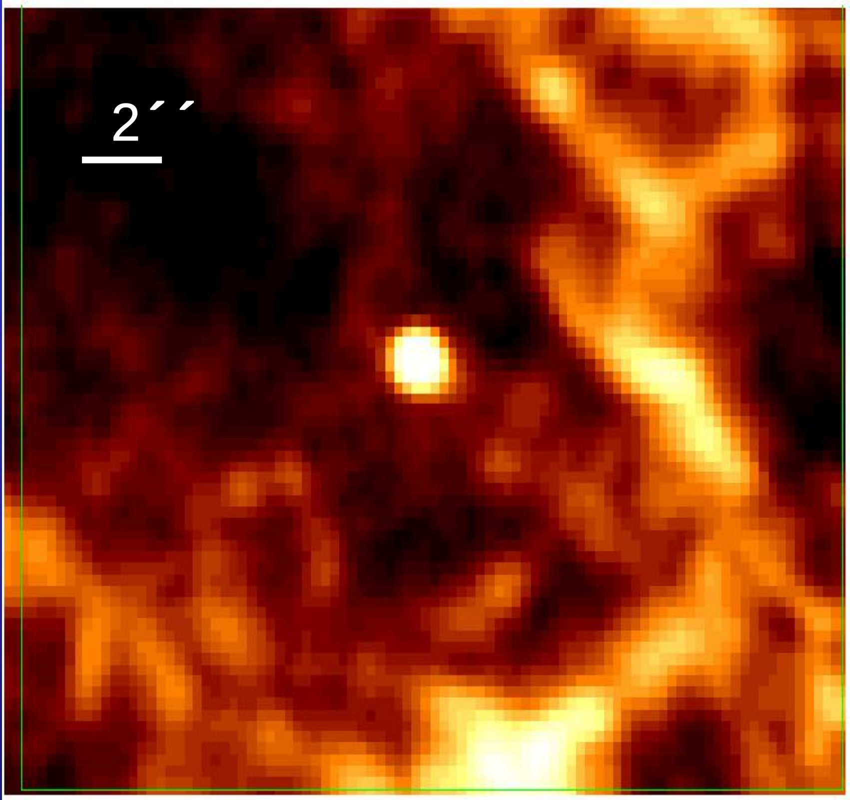
1. Compact central objects (CCOs) in SNRs

- Point-like X-ray sources close to SNR centers
- No radio and γ-ray emission
- No pulsar-wind nebulae
- No or very faint optical counterparts
- Soft thermal X-ray spectra of T_{BB} = 2.5 —5 MK, some might have PL tails at higher energies
- Small apparent sizes, R_{BB} = 0.3 —3 km
- Currently, 7 CCOs are known

CCO in Cas A: J2323+5848 (τ = 0.32 kyr, d ~ 3.3 kpc)

Chandra ACIS

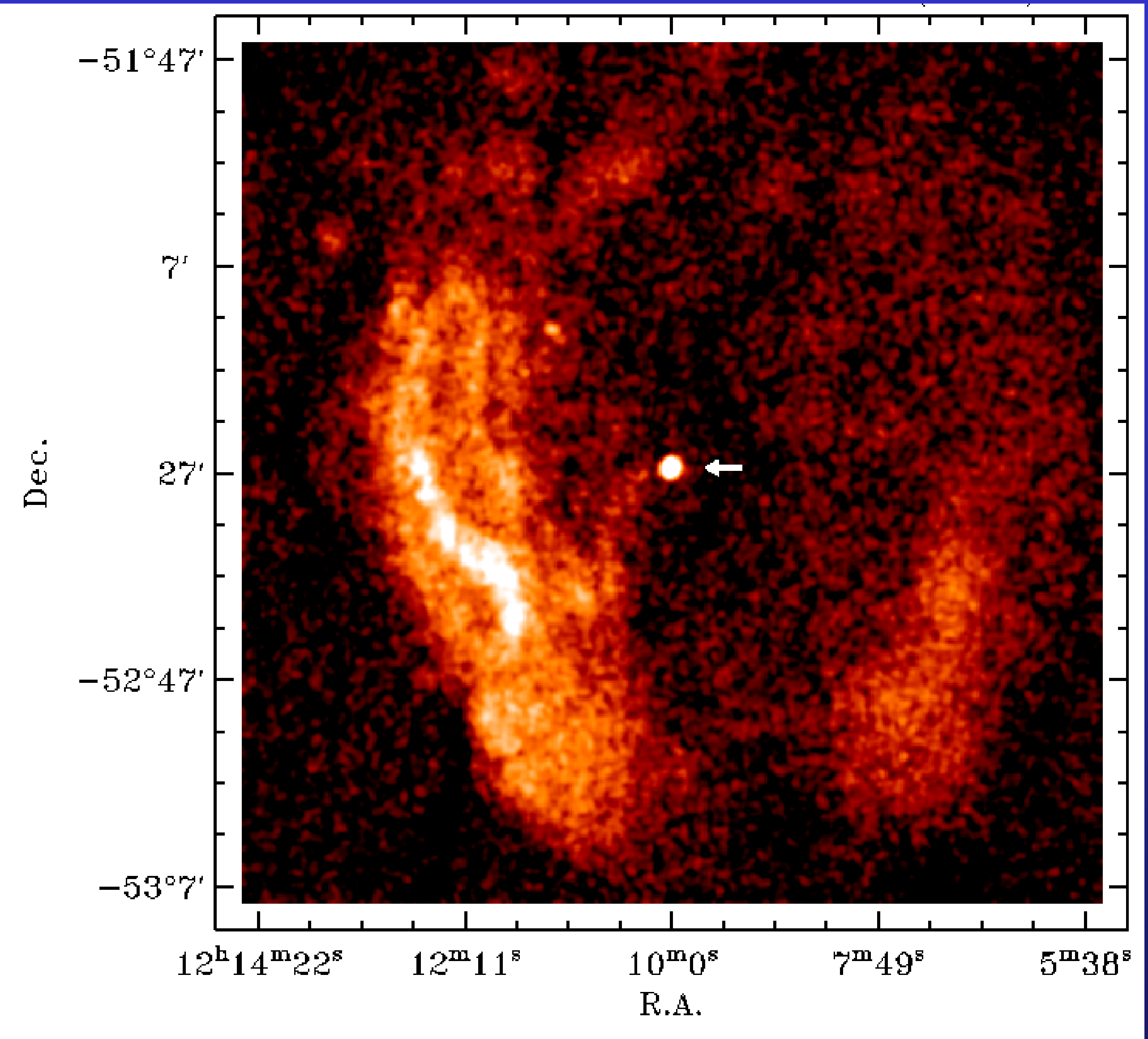




No clear PWN

No period, no clear variability, thermal X-ray spectrum (T_{BB} = 5 MK, R_{BB} = 0.8 km), perhaps with a faint PL tail

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



SNR:

$\tau \approx$ 3-20 kyr

d ≈ 1.3-3.9 kpc

size of ~ 1.5°

CCO:

discovered with Einstein (Helfand & Becker 1984)

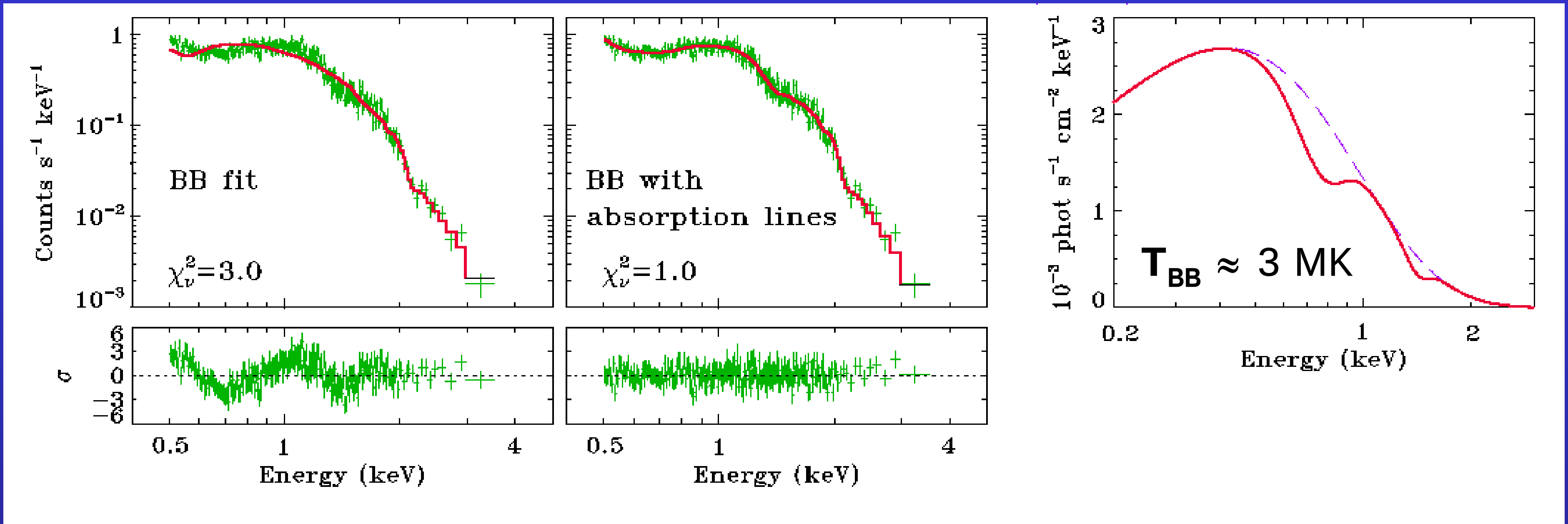
thermal spectrum detected with ROSAT and ASCA

Chandra revealed smooth pulsations of its X-ray flux at

P ≈ 424 ms, pf ≈ 8%

(Zavlin et al. 2000)

Chandra X-ray spectrum of **1E 1207.4-5209**

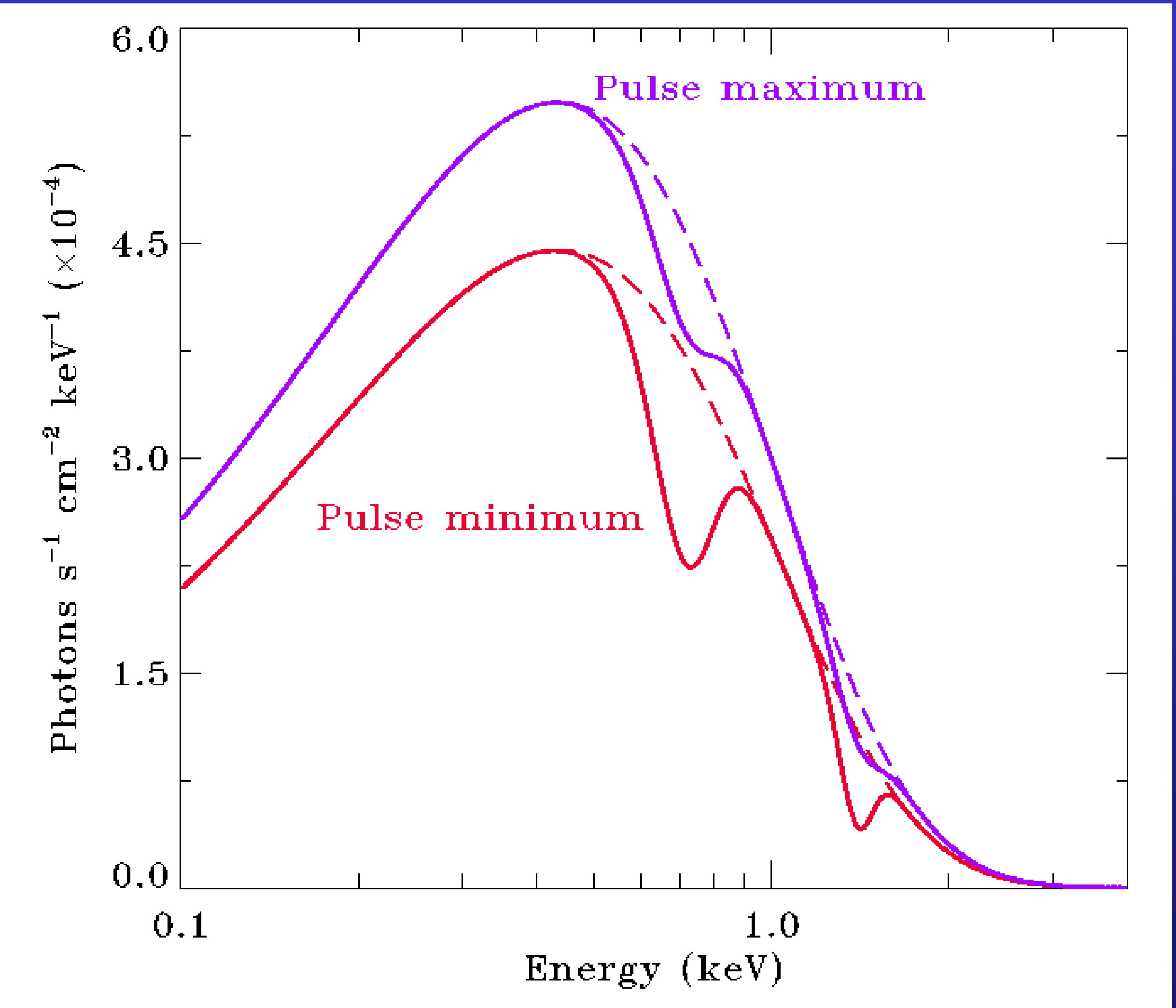


Two absorption lines at 0.7 and 1.4 keV (Sanwal et al. 2002) :
first spectral lines in an INS spectrum, the only case of more than one line, confirmed by XMM-Newton (Mereghetti et al. 2002)

Electron cyclotron lines in B ≈ 10^{11} G ? — unlikely — too strong harmonic for so low temperature, $kT/m_ec^2 \approx 5\times10^{-4}$, and magnetic field, $E_{ce}/m_ec^2 \approx 2\times10^{-3}$

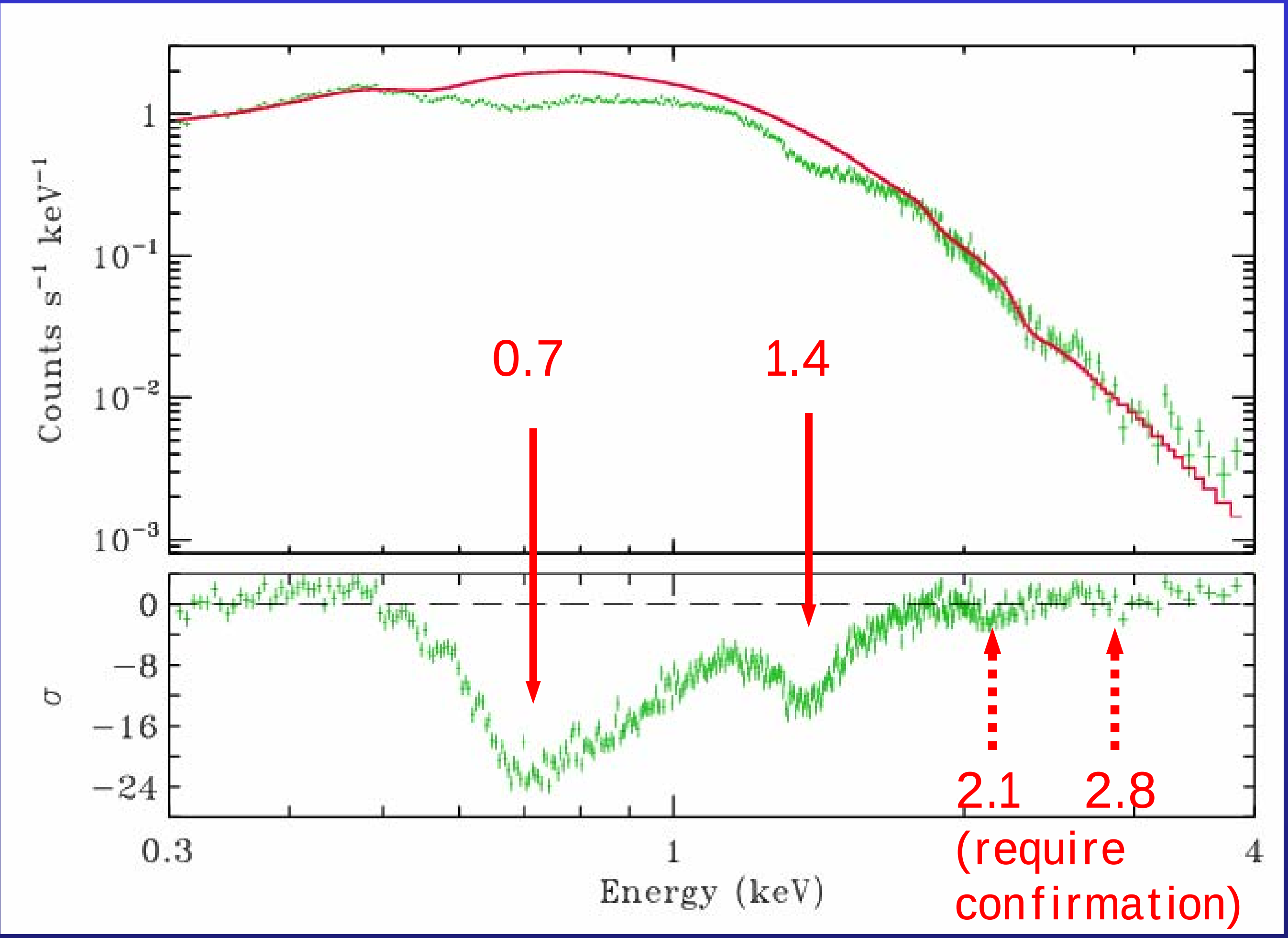
If intepreted as atomic/molecular transitions:
no atomic hydrogen
once-ionized helium at B ≈ 1.5 × 10^{14} G ? (Pavlov et al 2002)
He-like oxygen or neon at B ≈ 10^{12} G? (Mori & Hailey 2002)
Hydrogen molecular ion H_3^{++} at B = 3 × 10^{14} G (Lopez Vieyra & Turbiner 2004)

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



the lines are stronger at the pulse minimum with lower T $\Rightarrow$ supports atomic (or molecular) interpretation (more ions responsible for the lines are available) ?

1E1207.4-5259: XMM-Newton (260 ks; Aug´02)



Bignami et al. (2003): indication of lines at 2.1 and 2.8 keV
electron-cyclotron harmonics $\Rightarrow$ $B \approx 8\times10^{10}$ G

But: the harmonics should be <u>much</u> weaker at such low T and B

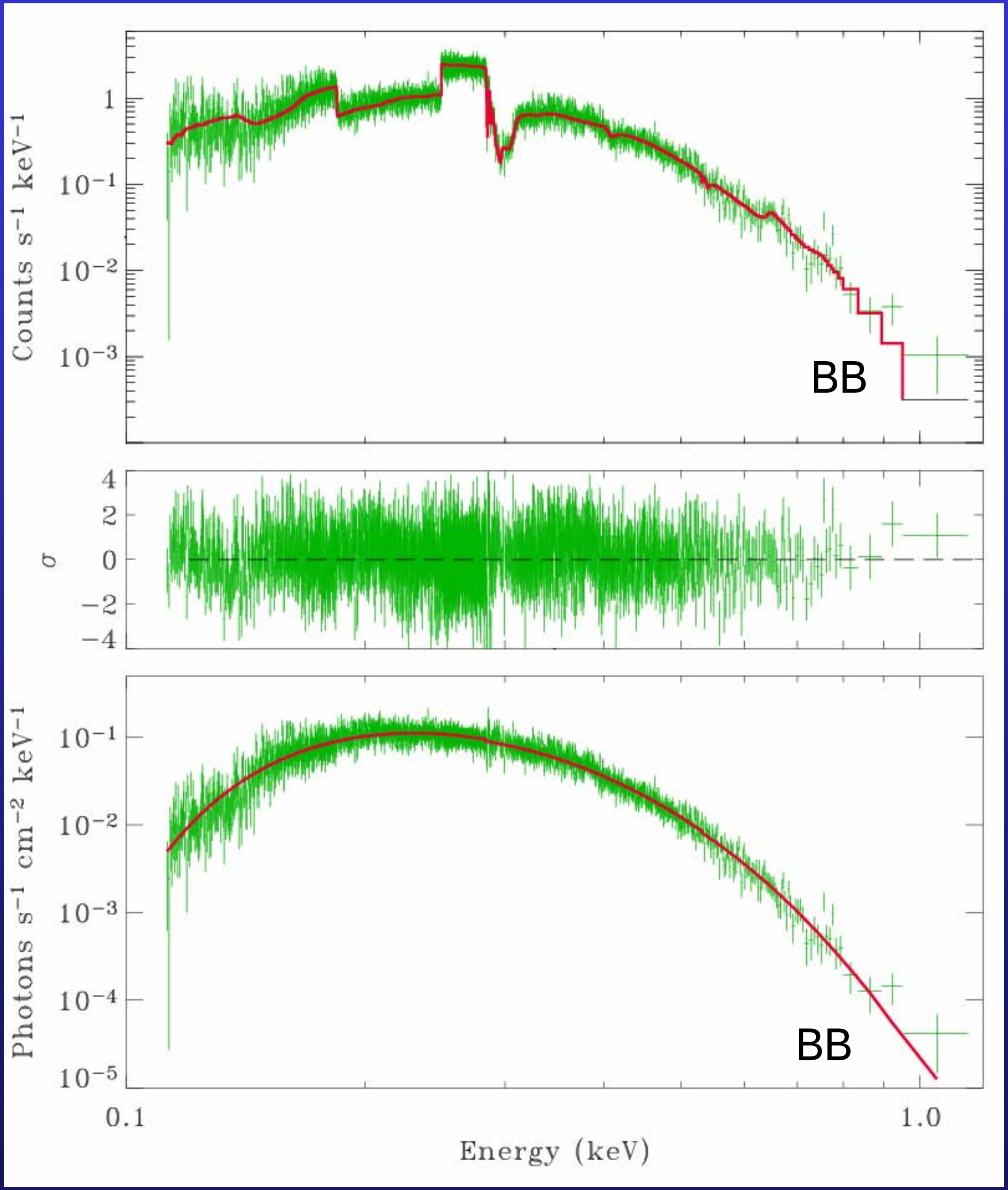
Possibly an instrumental effect (Mori et al. 2004)

2. X-ray “dim“ isolated neutron stars

Seven discovered with ROSAT:

- not associated with SNRs
- no radio, no γ-rays, no PL tails in X-ray spectra
- very soft thermal X-ray spectra ($T_{BB} \approx 0.5$–1 MK)
- spin periods known for 4 objects ($P = 3.4$–11.4 s)
- broad spectral features reported for 3 (4?) objects, around 0.2-0.5 keV
- 4 objects detected in optical ($V = 25$-29, close to Rayleigh-Jeans tails when spectral information available)
- optical fluxes exceed extrapolations of X-ray spectra by a factor of 3–8

500 ks of Chandra LETGS on **RX J1856-3754**



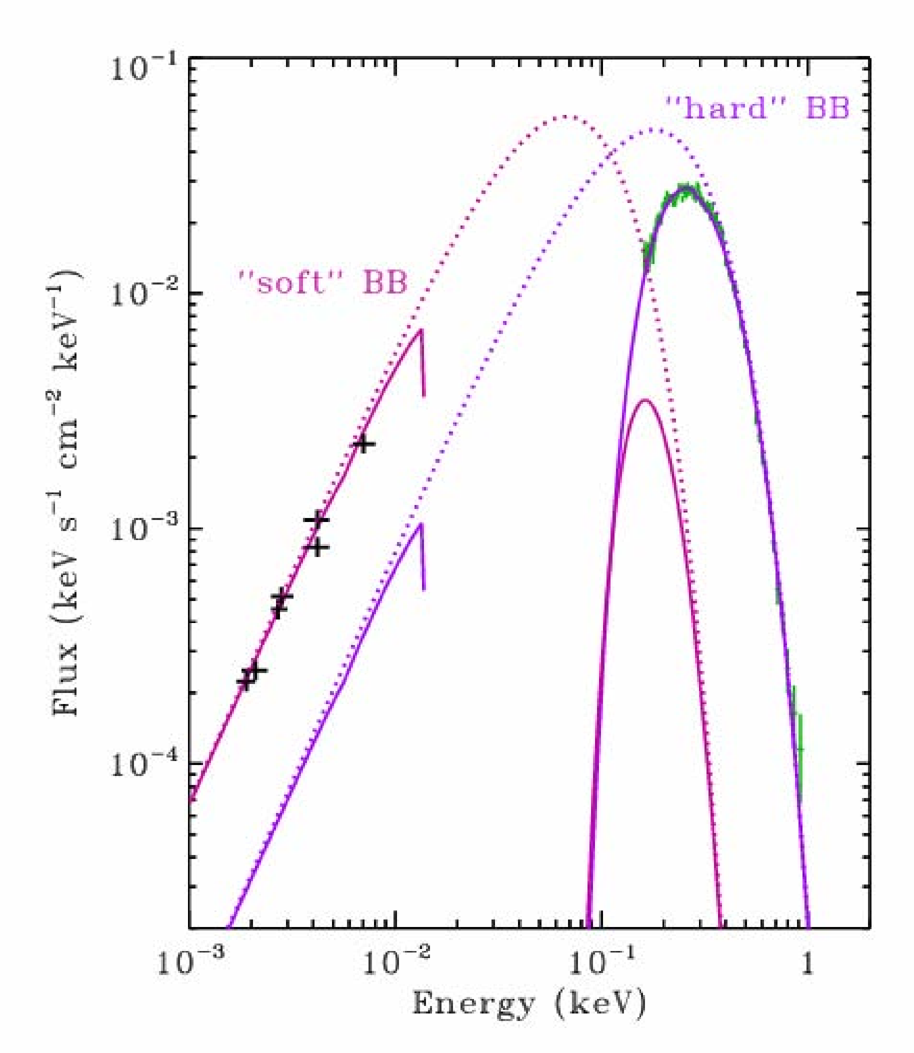
(almost) perfect BB fit:

T ≈ 0.7 MK

R ≈ 4.4 km (for d=120 pc)

Quark star???

no spectral features,
no spin period



RX J1856-3754

distance	~ 120 pc
spin period	**? ? ?**
"hard" T	0.7 MK
"soft" T	0.3 MK
"hard" R	4.4 km
"soft" R	16.4 km

New estimate: d ~ 180 pc $\Rightarrow$
(Kaplan et al. 2004)

"soft" R > 24 km
blackbody model inapplicable?

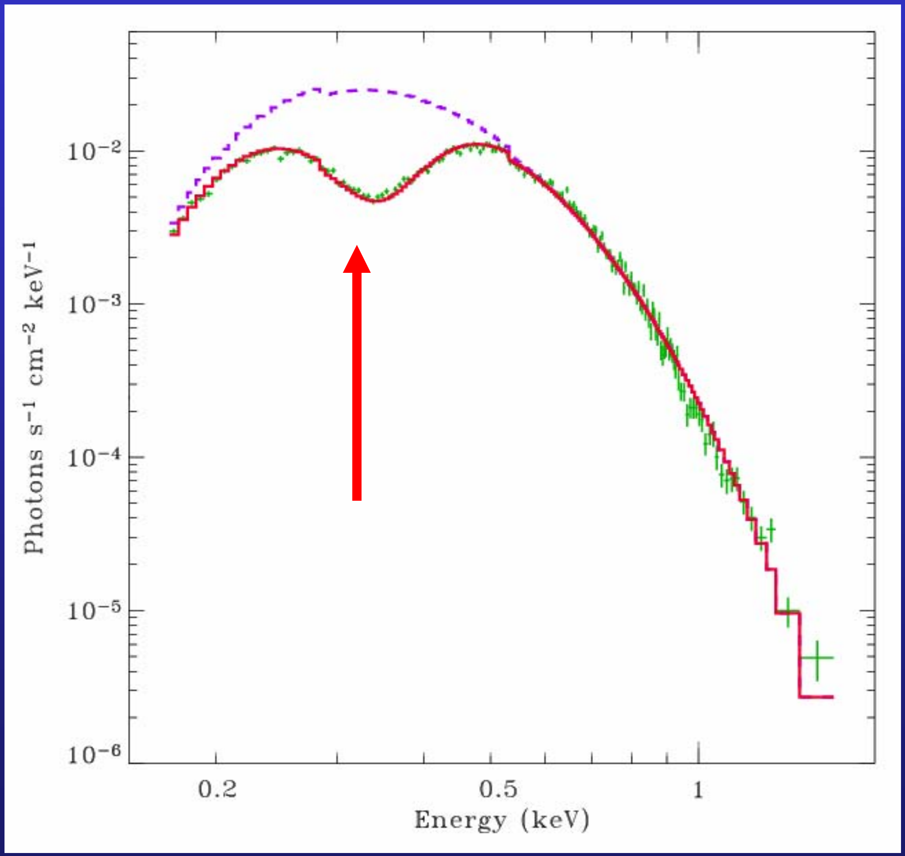
H/He atmospheres: too small distances, too large optical fluxes
Heavy-element atmospheres do not fit the X-ray data

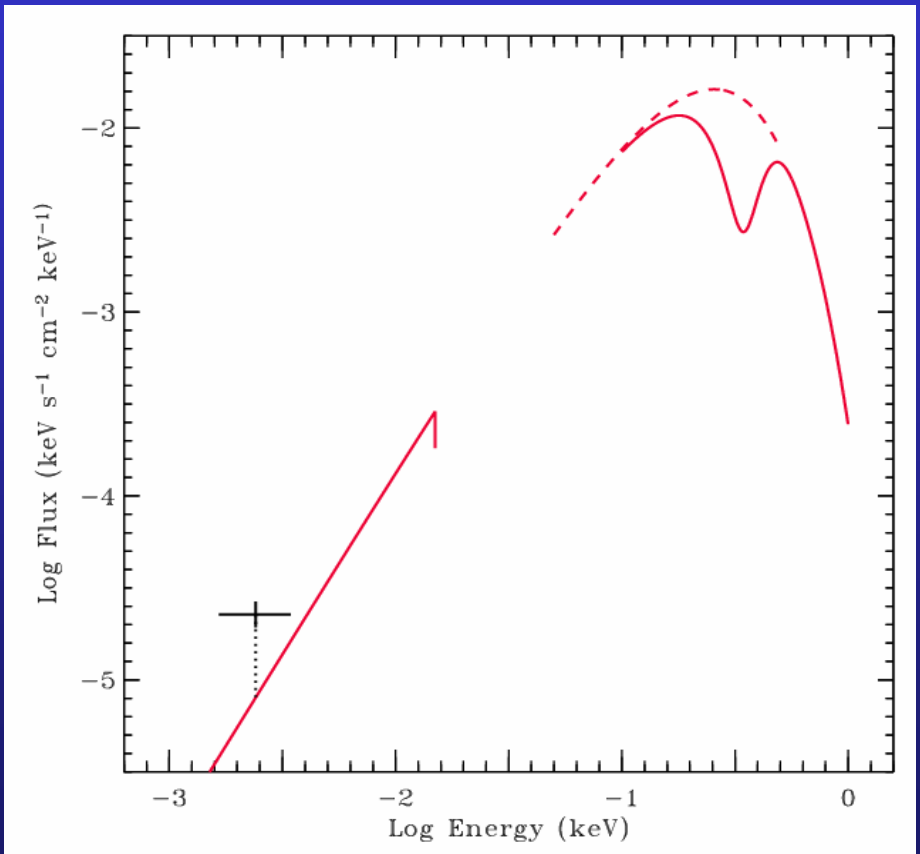
Condensed surface? (Perez-Azorin et al. 2004) $\Rightarrow$ even larger radius ?

RX J1308+2127 (P = 10.3 s, T_X = 1 MK)

XMM: broad absorption feature around 0.3 keV (Haberl et al 2003), Proton cyclotron in B = 5*10^{13} G??

X-rays + optical point (Kaplan et al. 2004), resembles J1856-3754





Similar (fainter) single features in RX J1605+3249 (van Kerkwijk et al 2004), RX J0720-3125 and RX J0420-5022 (Haberl et al 2004a,b)

3. Anomalous X-ray Pulsars [Magnetars]

Details in the talk by V. Kaspi

Spectra in quiescence:

Blackbody [T = 4 – 6 MK, R = 1 – 6 km] + nonthermal

or H atmosphere in a superstrong magnetic field
(T ~ 2 – 3 MK, R ~ 5 – 30 km) + nonthermal

Presence of thermal component is very plausible; can be explained by dissipation of superstrong magnetic field and surface heating from the magnetosphere (Thompson et al. 2002).

No spectral lines found in thermal components

4. NSs in Transient LMXBs, in quiescence

(Cen X-4, Aql X-1, KS 1731-60, 4U 1608-52, ...)

Show thermal components best-described by Hydrogen atmosphere models; T ~ 1 – 3 MK, R ~ 10 – 20 km (e.g., Rutledge et al. 2000-03; Wijnands 2002-04)

Explanation: NS crust heated by pycnonuclear reactions in accreted matter; “incandescent luminosity” proportional to time-averaged accretion rate (Brown, Bildsten, Rutledge 1998).

Useful tool to study superfluidity and fast neutrino emission in NS cores (Yakovlev & Levenfish 2002).

Can lead to rather precise measurements for NS radii (for qLMXBs in globular clusters).

Implications for Neutron Star Cooling

We have reasonable estimates for NS surface temperature and thermal luminosity for a number of NSs of different ages.

What can we infer confronting these results with cooling theories?

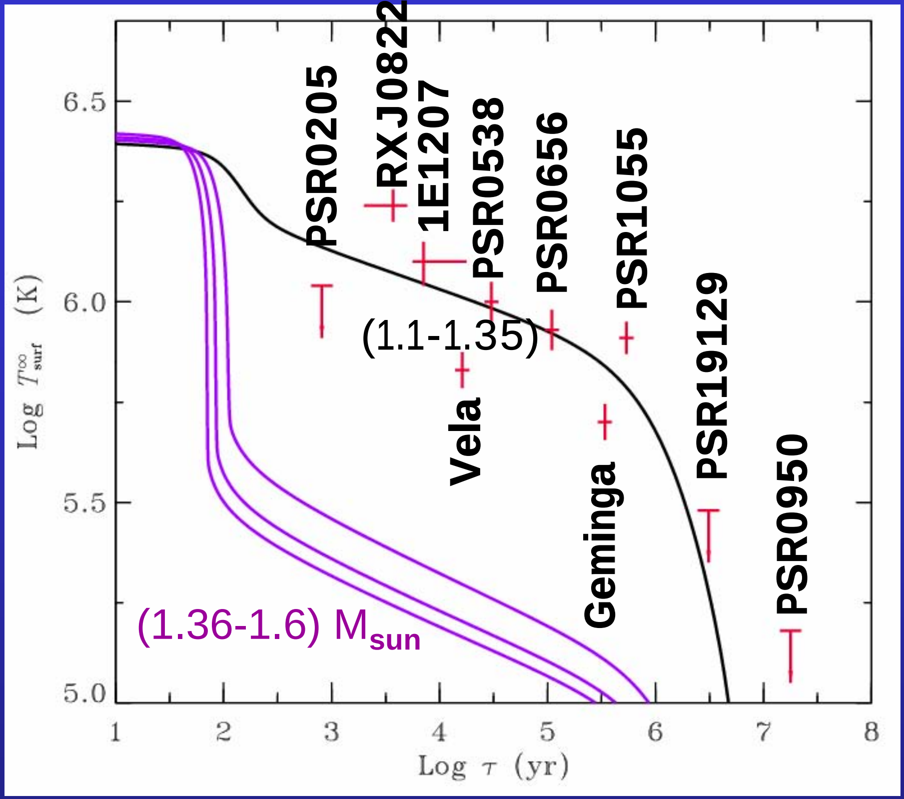
At $\tau = 10^2 - 10^6$ yrs, main cooling regulators are (1) neutrino emission mechanisms and (2) effects of baryon superfluidity on this emission

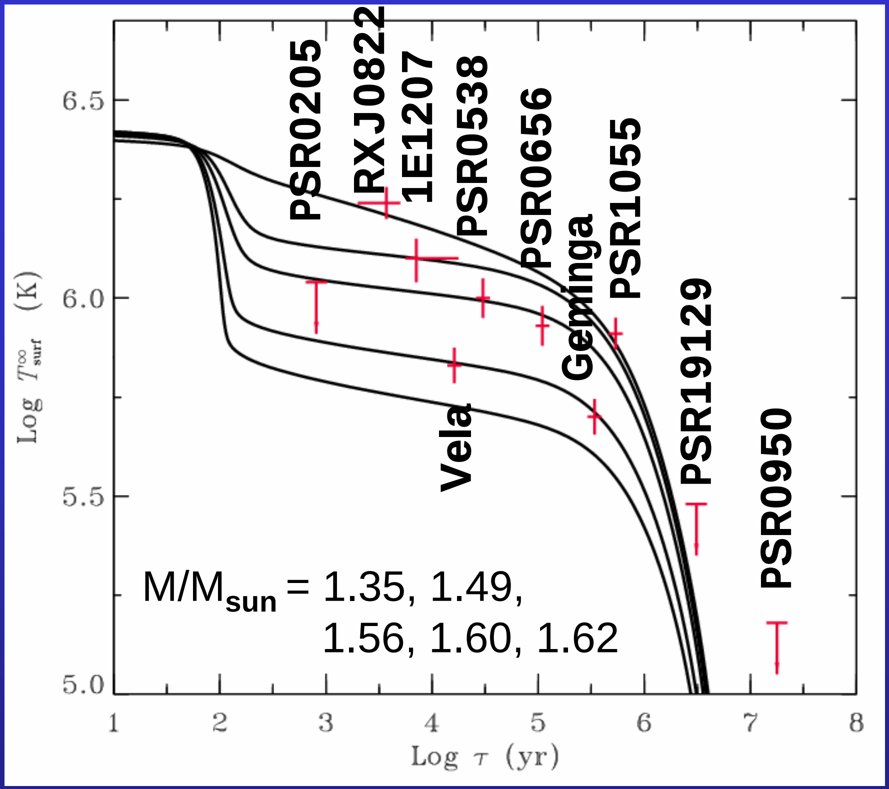
(1) $\rho < \sim 2\rho_{nuc}$: Modified URCA (Murca) + NN Brems.; "weak" mechanisms → slow cooling

$\rho > \sim 2\rho_{nuc}$: Direct URCA (Durca) in nucleon matter or similar mechanisms in hyperon or exotic phases; strong mechanisms → fast cooling

(2) superfluidity: reduces neutrino emission; different types (neutron, proton; triplet, singlet pairing,; ...) with different poorly known critical temperatures $T_c(\rho)$

Observations vs. models of NS cooling (Yakovlev & Pethick 2004)





Nonsuperfluid models:

slow cooling is at $M<1.36\ M_{sun}$,

direct Urca processes (accelerated cooling)

turn on at $M>1.36\ M_{sun}$ →

cannot explain observations

Models with proton superfluidity:

reduced neutrino emission, suppressed Urca processes →

observations can be explained with superfluid models at **different masses**, e.g., $1.3\ M_{sun}$ (PSR 1055-52) and $1.6\ M_{sun}$ (Vela pulsar)

Thermal emission: what we have learned

- observed from ~10 active pulsars and ~25 radio-quiet NSs, temperatures ~ 0.1 – 5 MK (kT ~ 10 – 500 eV)

- investigation of NS thermal evolution, measuring radii ⇒
  NS interiors are superfluid,
  likely, NSs have different masses
  radii, EOS, internal composition are not certain yet (talk by J. Lattimer)

- studying surface layers of NSs ⇒
  surface temperature is nonuniform,
  NS magnetic field can be different from a centered dipole,
  some young NSs likely have H or He atmospheres
  some NSs show puzzling absorption features
  surfaces of older NSs may be in a condenced state

- probing pulsars models through properties of hot PCs ⇒
  models based on vacuum gaps at the NS poles ruled out,
  space charge limited flow models (Arons 1981; Harding & Muslimov 2002-03) are consistent with observations

More efforts required

Observations:

- UV-optical observations to study thermal evolution of older NSs and understand the broad-band thermal emission from younger NSs.
  HUBBLE SERVICING MISSION NEEDED!

- phase-resolved spectroscopy in X-rays and UV-optical to separate the thermal and magnetospheric components and infer distributions of temperature and magnetic field over the NS surface
  DEEPER CHANDRA/XMM/HST OBSERVATIONS NEEDED

Theory/modeling:

- molecules, solids and liquids in strong magnetic fields

- reliable models for partially ionized atmospheres, including molecules, for various chemical compositions

- phase transition from atmospheres to condenced surface

- reliable models for emissivity of condenced surface