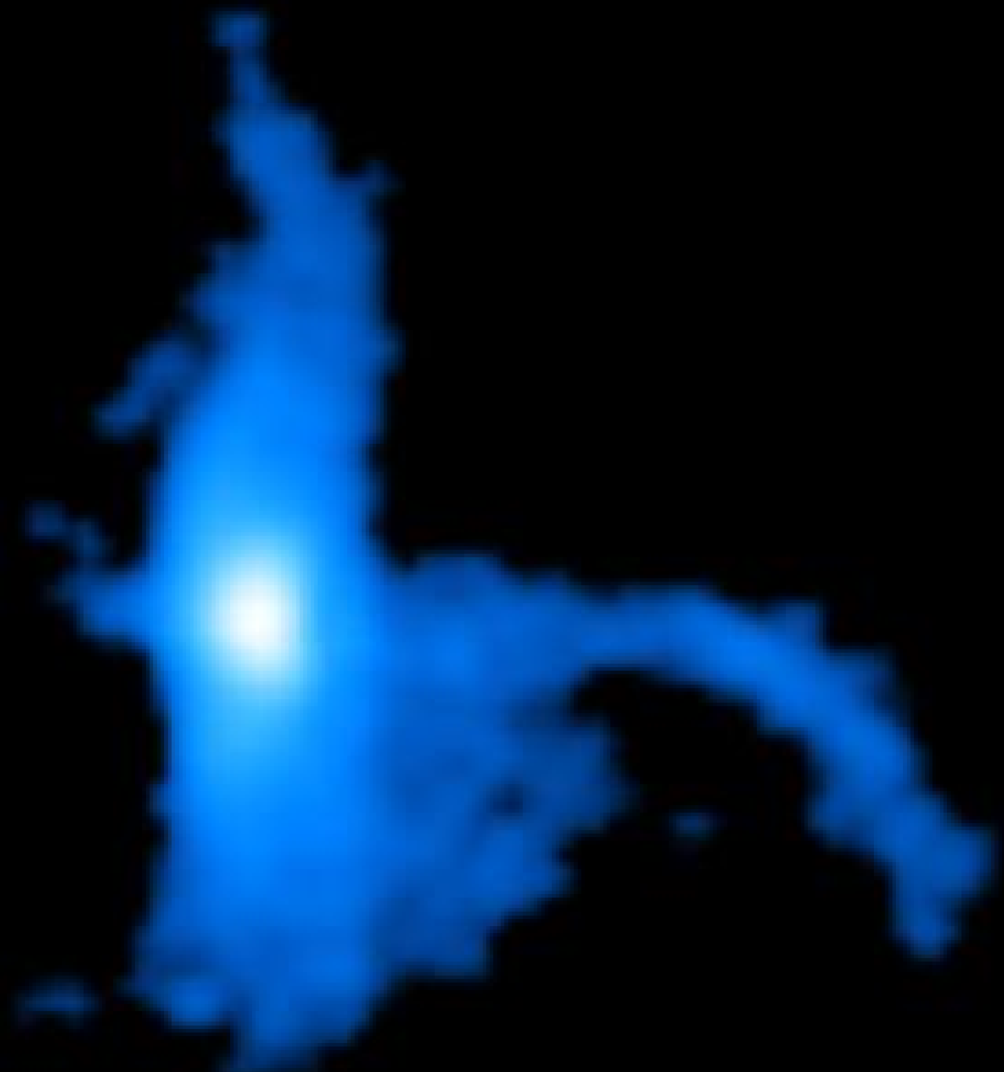
X-ray Observations

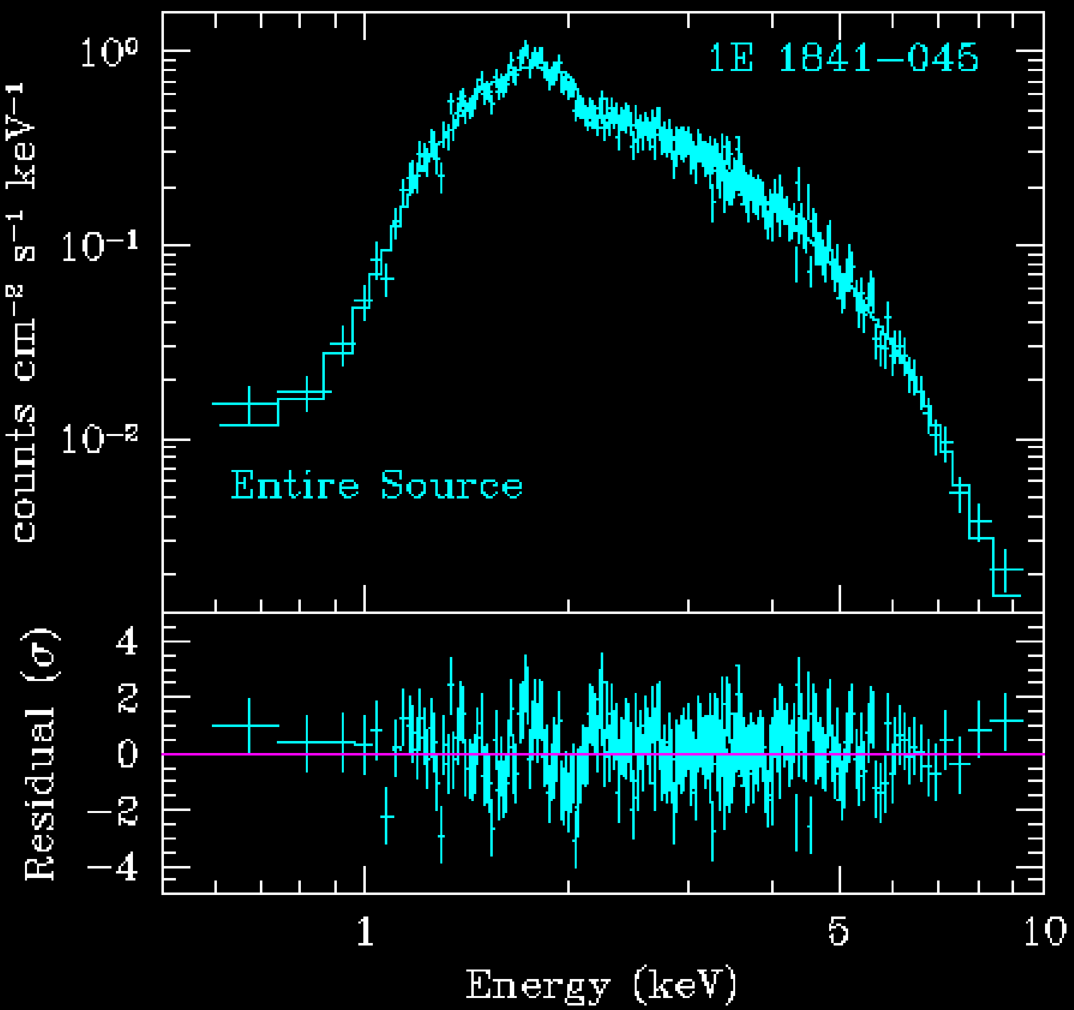


# of Neutron Stars

Patrick Slane

Harvard-Smithsonian Center for Astrophysics

Temperature Limits from X-ray Observations



• **Observe:**

$$T_s^\infty = T_s\sqrt{1-\frac{2GM}{c^2 r}}$$

$$L_\gamma^\infty = L_\gamma\left[1-\frac{2GM}{c^2 R}\right]$$

• **Calculate:**

$$R_\infty^2 = \frac{L_\gamma^\infty}{4\pi\sigma(T_s^\infty)^4}$$

- or fix R_∞ and calculate T_s^∞ based on flux

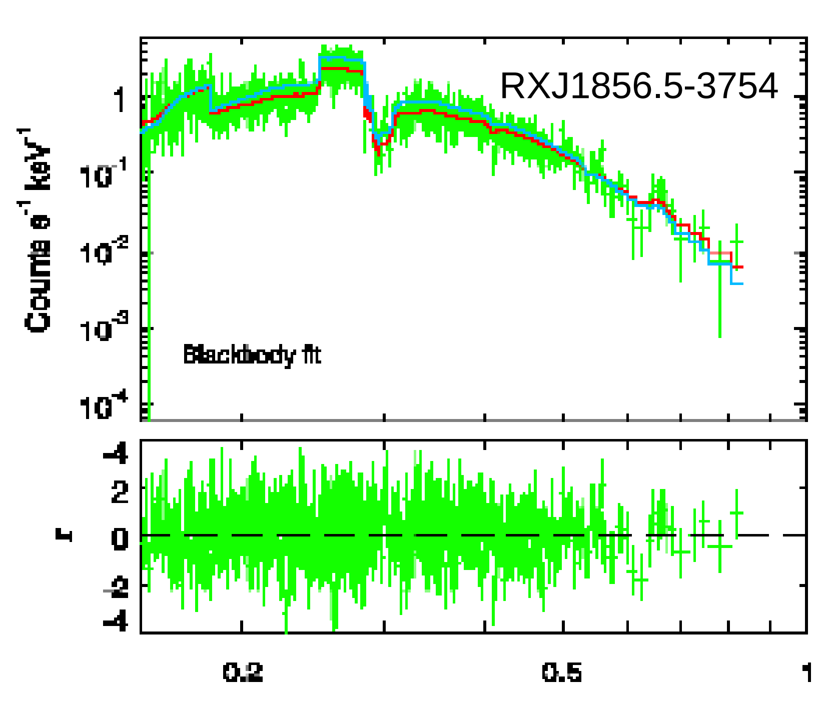
• **Effects of Atmosphere**

- emission is not a blackbody
- for light atmosphere (H, He), spectrum extends beyond Wein tail; temperature inferred from BB fit exceeds T_s^∞
- for Fe atmosphere, kT similar to BB; absorption features evident

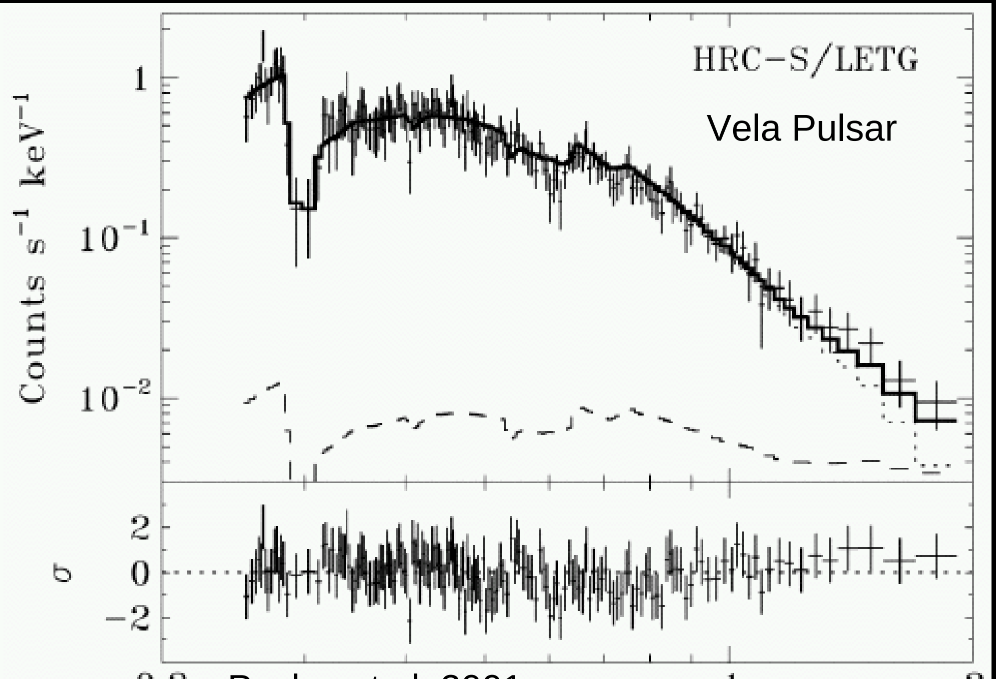
• **Complications**

- absorption, flux, power law components

Featureless X-ray Spectra from NSs



Burwitz et al. 2001



Pavlov et al. 2001

- As discussed in previous lecture, one expects spectral signatures of the atmosphere and/or magnetic field on the surface of the NS
  - Chandra gratings observations of RX J1856-3754 (500 ks!) and Vela reveal no evidence of such spectral features
  - can definitely rule out any heavy element atmospheres for these sources

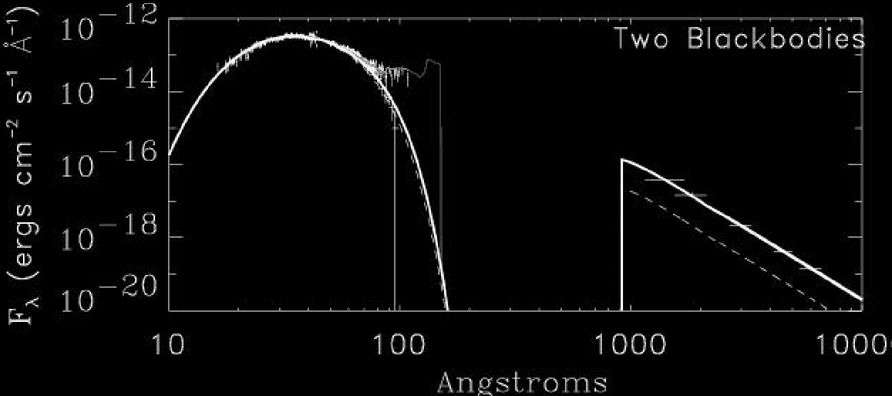
RX J185635-3754: An Old Isolated NS(?)

- Distance known well from parallax
  - d = 117 +- 12 pc (Walter & Lattimer 2002)

- X-ray emission consistent with blackbody
  - no lines seen despite 450 ks Chandra LETG observation; rules out heavy element atmosphere
  - kT = 63 eV; R = 4.3 km at d = 117 pc
  - this is too small for a neutron star! (quark star??!!)

- X-ray BB spectrum under-predicts optical/UV flux
  - model with two BBs needed; 27 eV and 64 eV
  - then $R_\infty = 17 \pm 1.9$ km
  - but smaller size still needed for X-rays; hot spot
  - no quark star needed…

- No pulsations observed
  - pulsed fraction < 5%; how can this be?
  - GR bending (hard to reconcile with optical radius)



- Recent atmosphere model holds promise (Ho et al. 2006)
  - emission from partially-ionized H yields reasonable NS size and log B ~ 12.6
  - but, need very thin atmosphere so that not optically thick at all temp; how does this arise???

NSs With X-ray Absorption Features

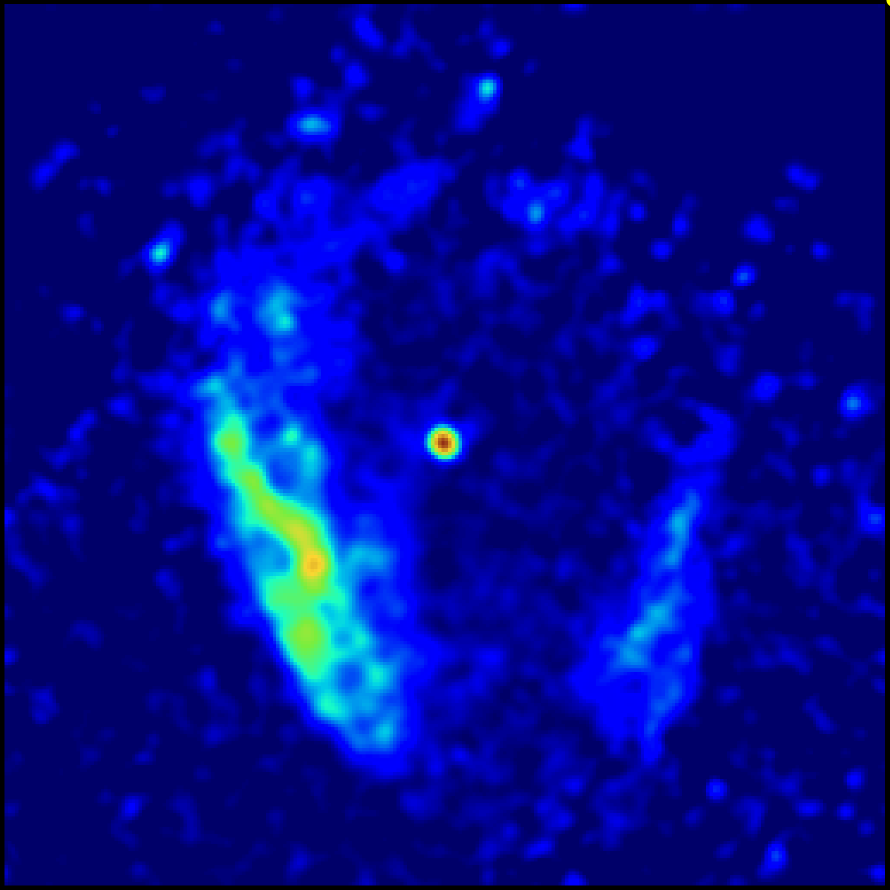
Source Name	Absorption Energy (keV)	Period (s)	B (TG)
RX J1308.6+2127	~0.2-0.3	10.31	34
RX J0720.4-3125	~0.27	8.39	24
1E 1207.4-5209	0.7, 1.4	0.42	2-4
RX J1605.3+3249	~0.45		
RX J0420-5022	~0.3?		
RX J0806.4-4123	~0.5?		
RBS 1774	~0.7?		

- Nearby, thermally-emitting NSs offer the best opportunity for measuring spectra directly from NS surface
  - low absorption provides X-ray spectra to low energies
  - sources are faint; must be nearby

- Several sources show thermal emission with no evidence of any features from a NS atmosphere
  - PSR B0656+14 and Vela Pulsar show featureless BB spectra with an additional power law component; both pulse in X-rays
  - RX J1856-3754 is perfectly fit by a blackbody; no pulsations observed

- Four (perhaps 7) nearby NSs show evidence for absorption in X-ray spectra
  - may be associated with cyclotron absorption by either ions or electrons; independent magnetic field estimates available for 3 sources; no pulses from the rest
  - may be absorption from bound states of neutral hydrogen in atmosphere

1E 1207.4-5209: Probing The Atmosphere of a Neutron Star



- **Associated w/ SNR PKS 1209-51/52**

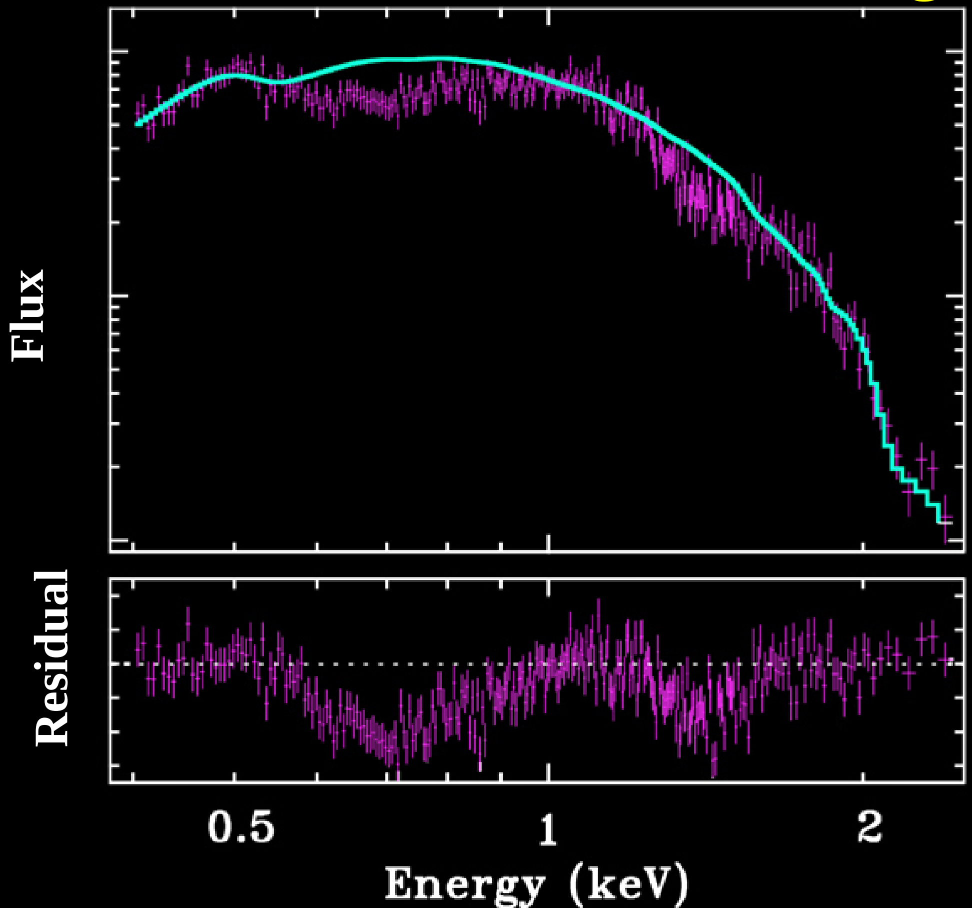
$$d = 2.1^{+1.8}_{-0.8} \text{ kpc} \ \ (\text{H}\,\text{I absorption})$$

$$P = 424 \text{ ms}; \tau > 200 \text{ kyr (too old for SNR)}$$

$$\Rightarrow \text{presumably } P \approx P_0$$

$$B = 2 - 4 \times 10^{12} \text{ G (from spin-down)}$$

1E 1207.4-5209: Probing the Atmosphere of a Neutron Star



- **Associated w/ SNR PKS 1209-51/52**

$$d = 2.1^{+1.8}_{-0.8}\ \text{kpc (HI absorption)}$$

$$P = 424\ \text{ms}; \tau > 200\ \text{kyr (too old for SNR)}$$

$$\Rightarrow \text{presumably } P \approx P_0$$

$$B = 2-4\times10^{12}\ \text{G (from spin-down)}$$

- **X-ray spectrum shows broad absorption features (Sanwal et al. 2002)**
  - features centered at ~0.7 and ~1.3 keV
  - continuum gives R ~ 1.6 km for emission region

- **Cyclotron absorption (1st & 2nd harmonic)?**

Electrons:

$$E_{ce} = \frac{11.6}{1+z} B_{12}\ \text{keV} \Rightarrow B_{12} = 0.06(1+z)$$ **too small**

Protons:

$$E_{cp} = \frac{0.63}{1+z} B_{14}\ \text{keV} \Rightarrow B_{14} = 1.1(1+z)$$ **too large**

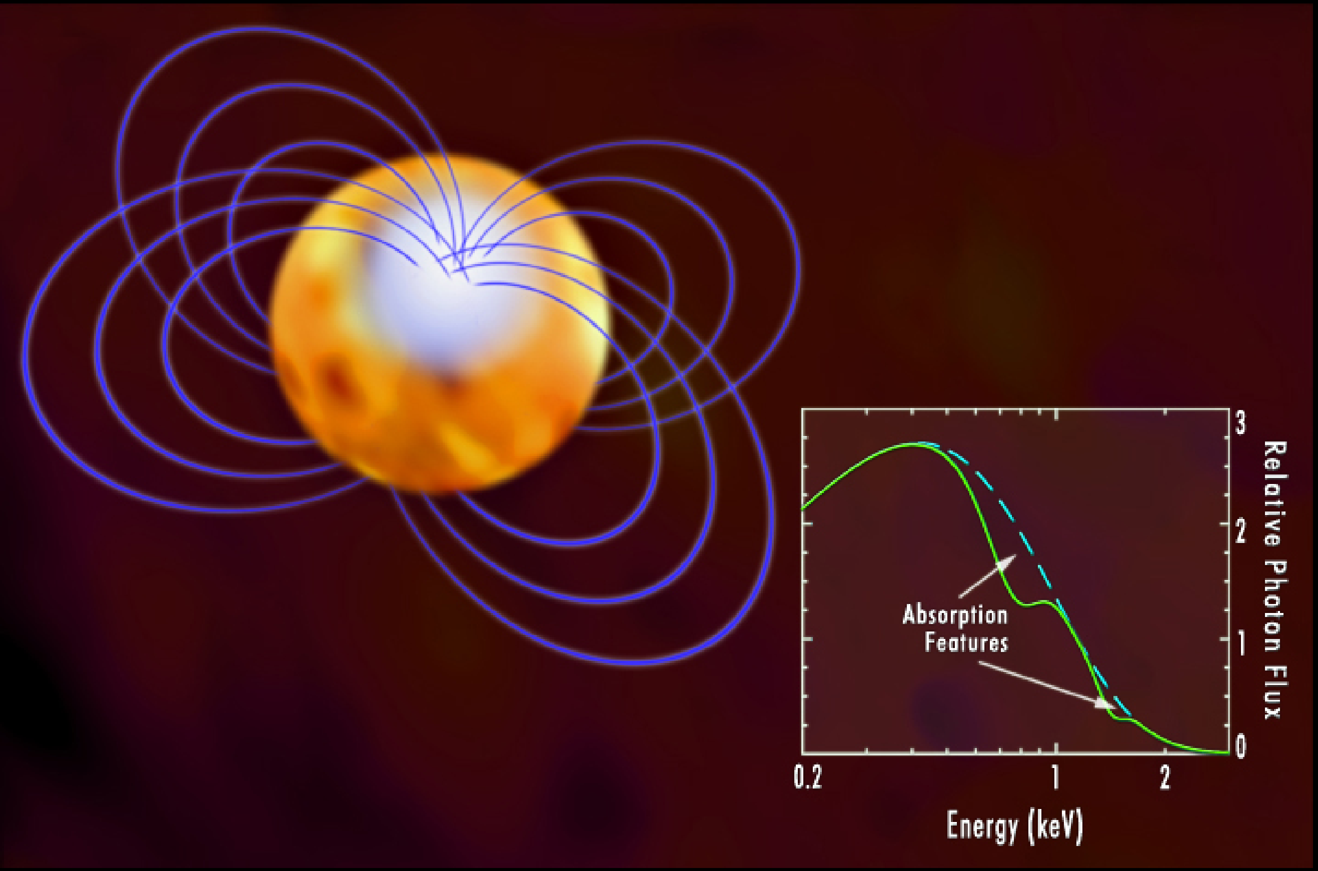
oscillator strengths for 1st/2nd are also very different

-Bignami et al. 2003 who claim to see 3rd/4th harmonics; Mori et al. 2005 dispute this claim

- **Atomic absorption lines?**
  - gravitational redshift can give mass-radius ratio

$$1+z = \frac{1}{\sqrt{1-\left(2MG/c^2R\right)}}$$

1E 1207.4-5209: Probing the Atmosphere of a Neutron Star



- **Light element ionization edges:**

$$E_Z \approx 4.4 Z^2 \left[\ln\left(\frac{426 B_{12}}{Z^2} \right) \right]^2 \text{ eV}$$

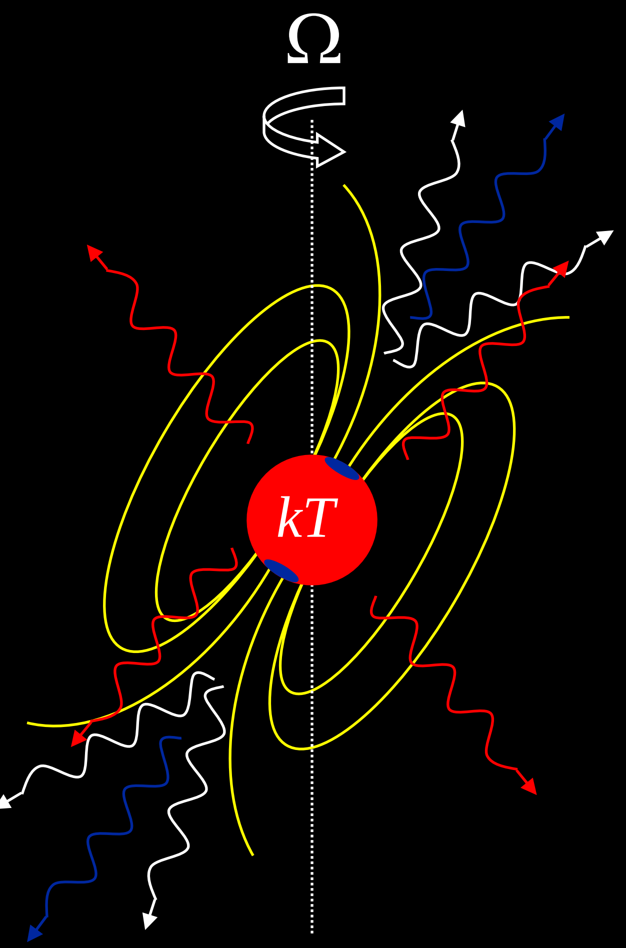
- e.g. 160 eV for H (compare with 13.6 eV for B=0)

- **Can't be hydrogen**
  - no pair of lines like this at any B value (Sanwal et al. 2002)

- **May be once-ionized He (Pavlov et al. 2002)**
  - this gives $R / M = 8.8 - 14.2 \text{ km M}$
  - details of model not yet published

- **Hailey & Mori (2002) suggest He-like oxygen or neon in 10^{12} G magnetic field**
  - need more detailed substructure in lines to fully constrain model and measure *z*
  - assuming a 1.4 solar mass star rules in favor of oxygen lines
  - redshift then leads to very stiff equation of state

X-ray Emission from Young Neutron Stars



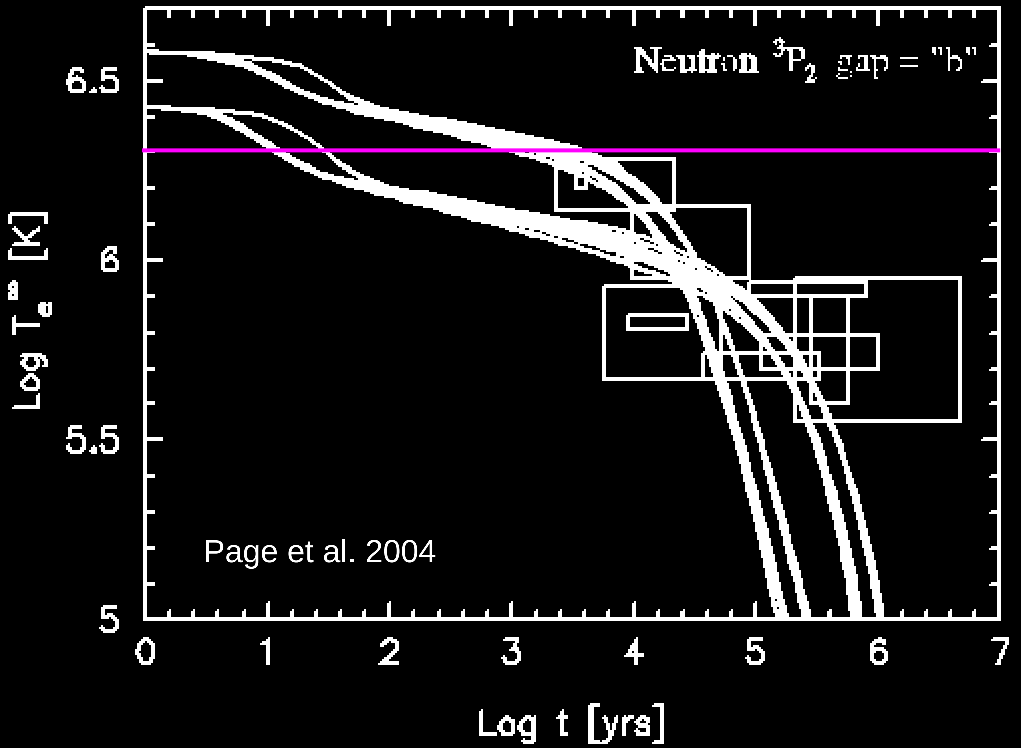
- **Thermal emission from surface**
  - cooling of interior
  - particle heating of surface (caps)
  - accretion from ISM

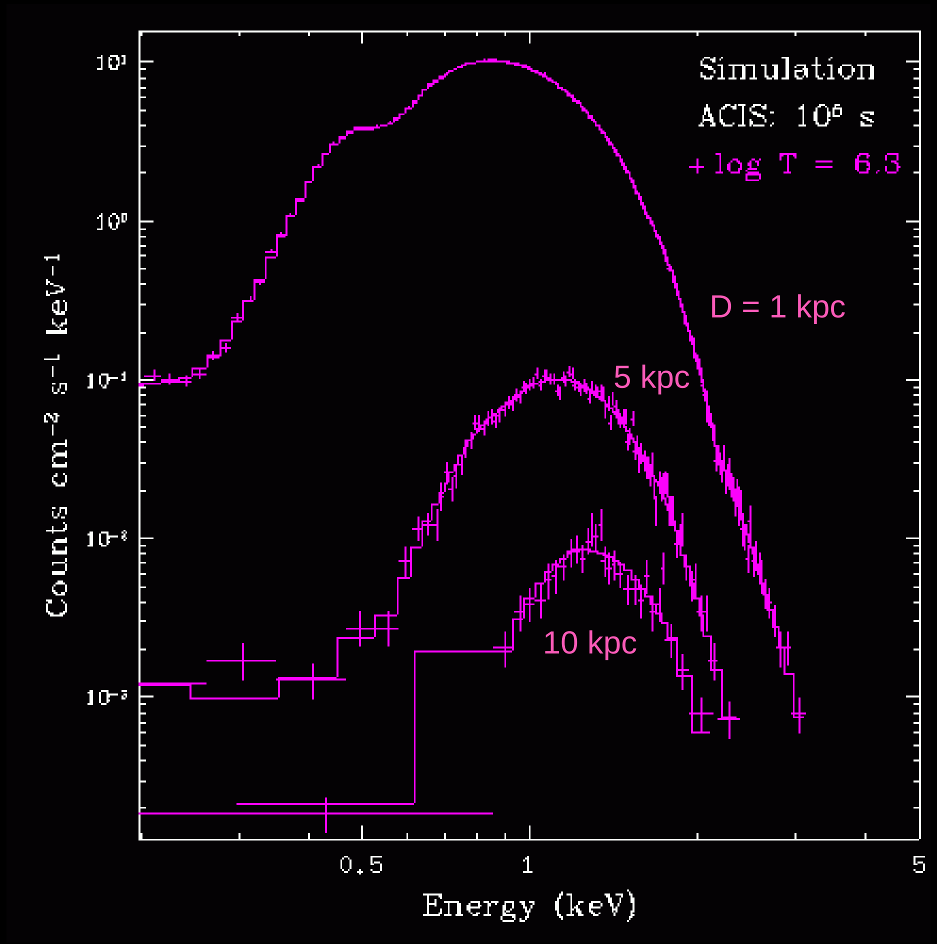
- **Nonthermal emission**
  - pulsed, from magnetosphere
  - unpulsed, from wind (e.g. PWN)

- **Timing analysis**
  - provides information on spin, magnetic field, and age
  - comparing spin-down age with independent estimate can constrain spin period at birth

- **Imaging**
  - can provide information about kick velocities, emission structure near pulsar, and emission geometry (more on this in PWN lecture)

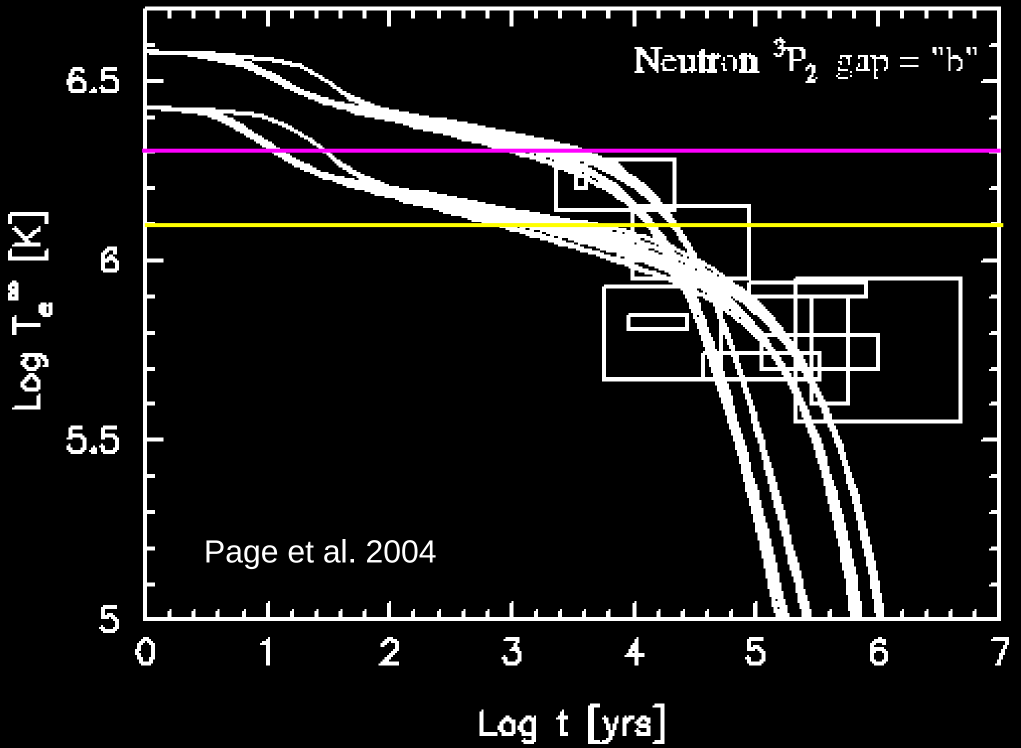
NS Cooling: X-ray Flux Considerations

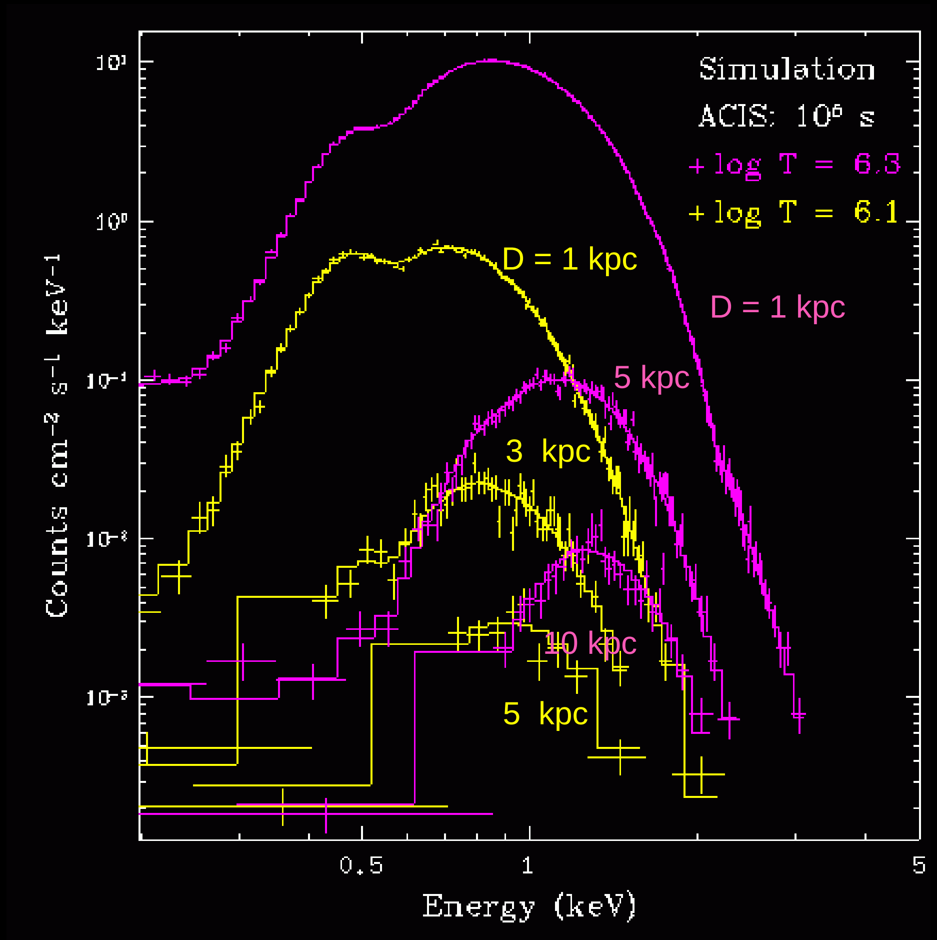




- Cooling emission from young NSs is primarily in the soft X-ray band
  - a hot, cooling NS can be detected at a large distance

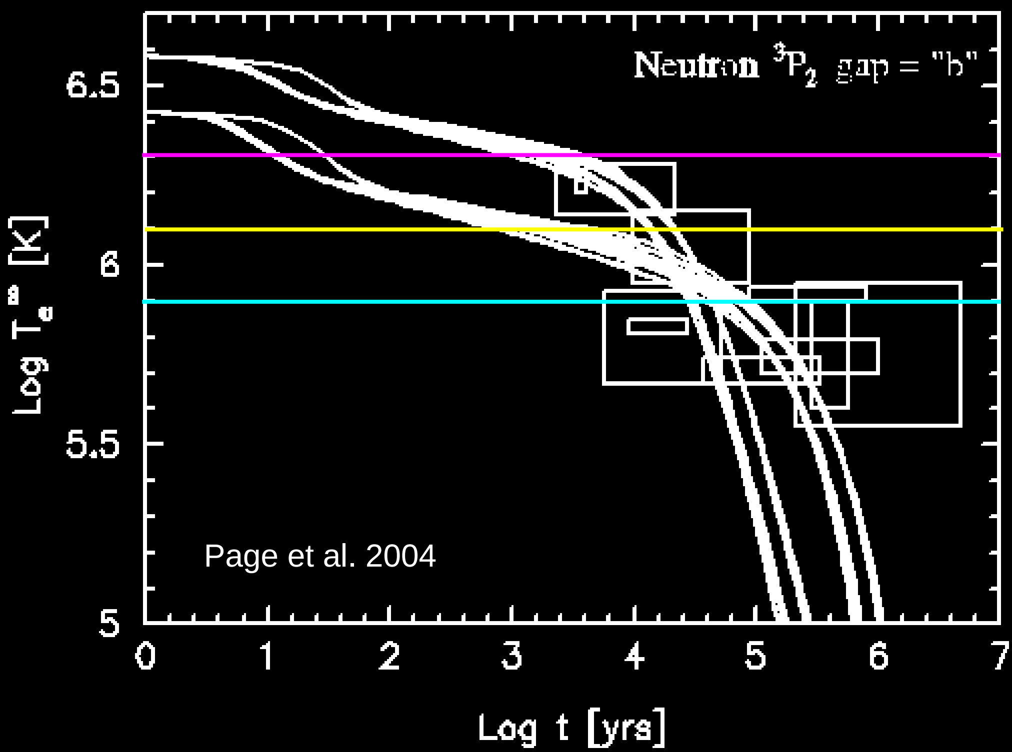
NS Cooling: X-ray Flux Considerations

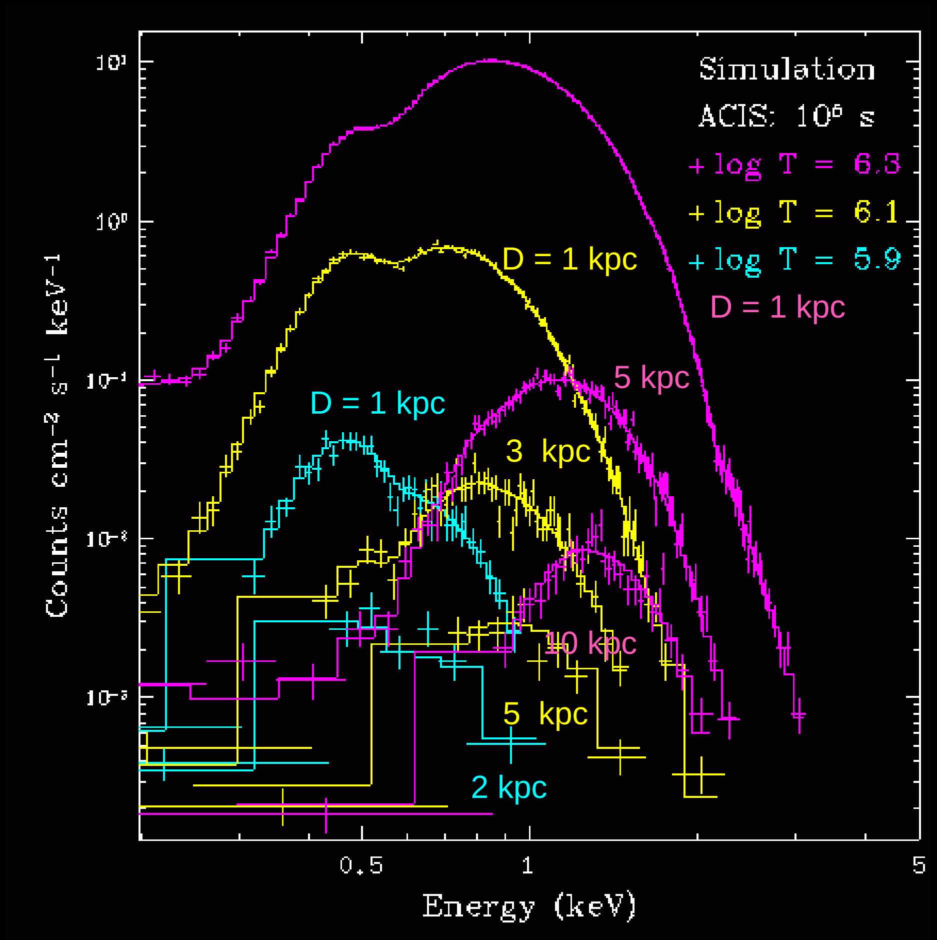




- Cooling emission from young NSs is primarily in the soft X-ray band
  - a hot, cooling NS can be detected at a large distance
- For more rapid cooling, things are harder…
  - even nearby NSs require long exposures

NS Cooling: X-ray Flux Considerations



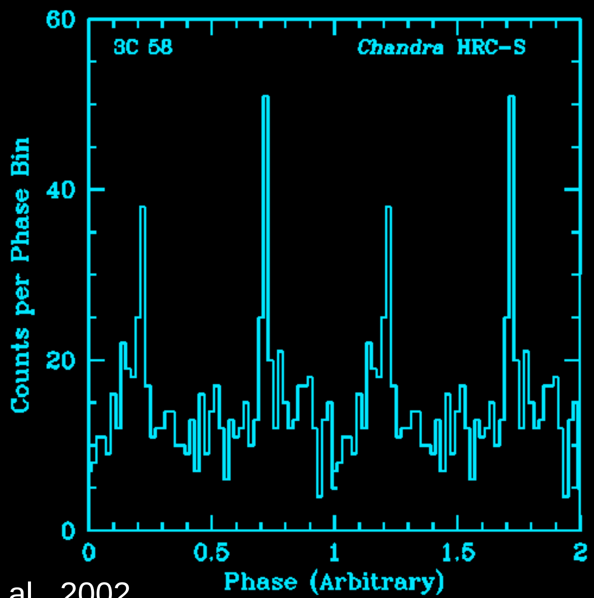


- Cooling emission from young NSs is primarily in the soft X-ray band
  - a hot, cooling NS can be detected at a large distance
- For more rapid cooling, things are harder…
  - even nearby NSs require long exposures

- The combination of increased distance, higher column density, and lower kT can render young NSs virtually undetectable

About 3C 58

Slane et al. 2004

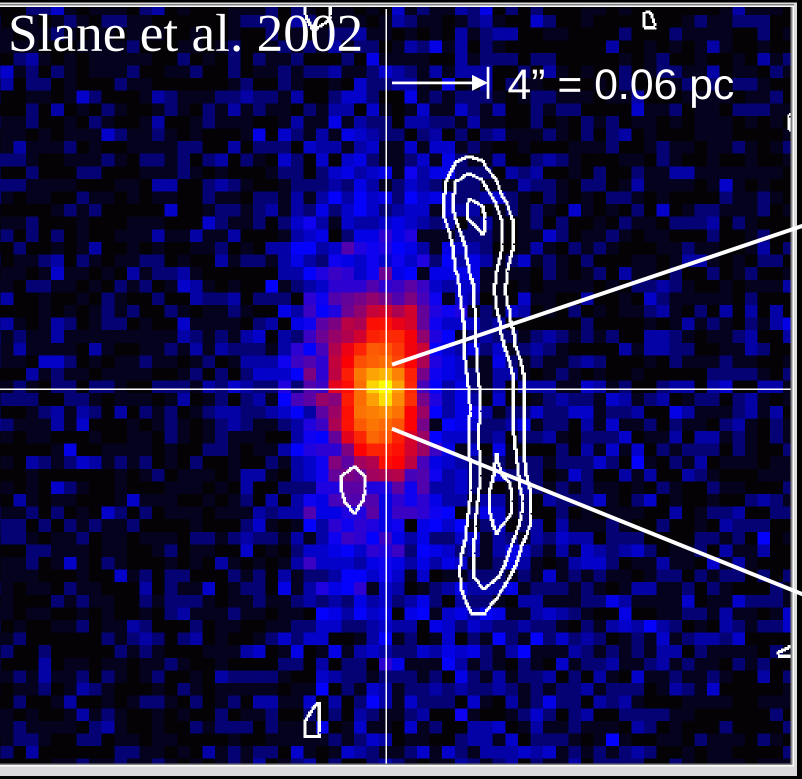


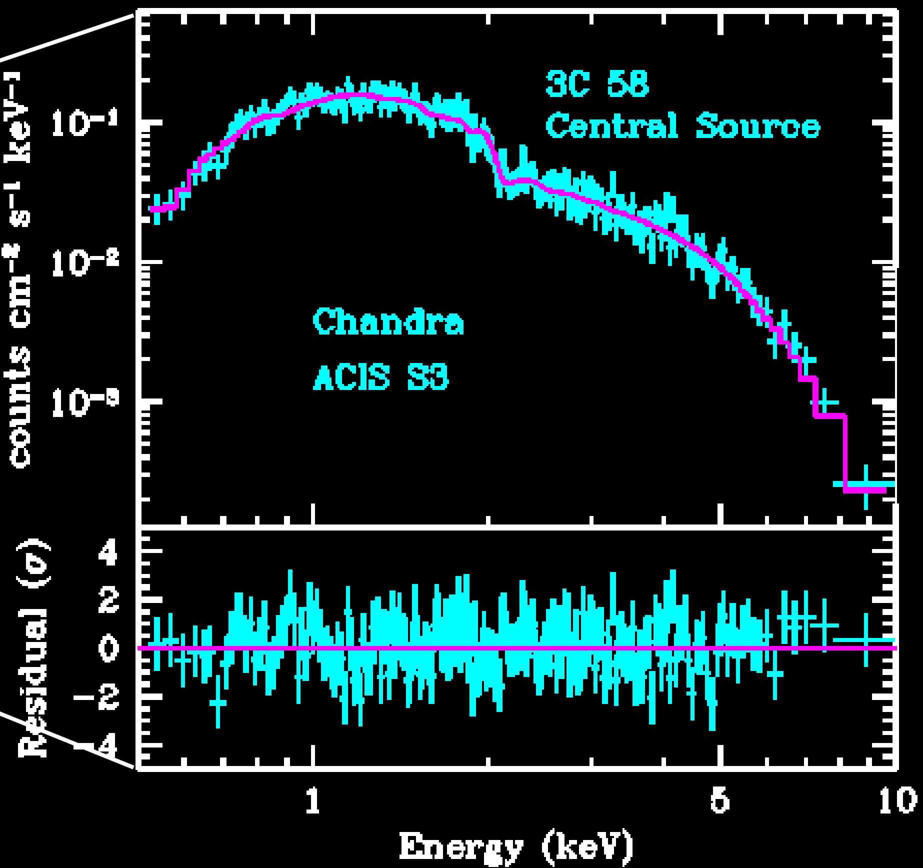
Murray et al. 2002

- **Wind nebula produced by PSR J0205+6449**
  - D = 3.2 kpc (HI absorption)
  - size: 9 x 5 arcmin ==> 8.4 x 4.7 pc
  - P = 62 ms (Camilo et al. 2002)

- **Believed to be associated w/ SN 1181 based on historical records**
  - pulsar has 3rd highest spin-down power of Galactic pulsars $\dot{E} = 3 \times 10^{37}$ ergs s^{-1}
    ==> very young
  - however, PWN expansion velocity observed in optical filaments is too low to explain large size, making association troublesome

3C 58: Neutron Star Spectrum





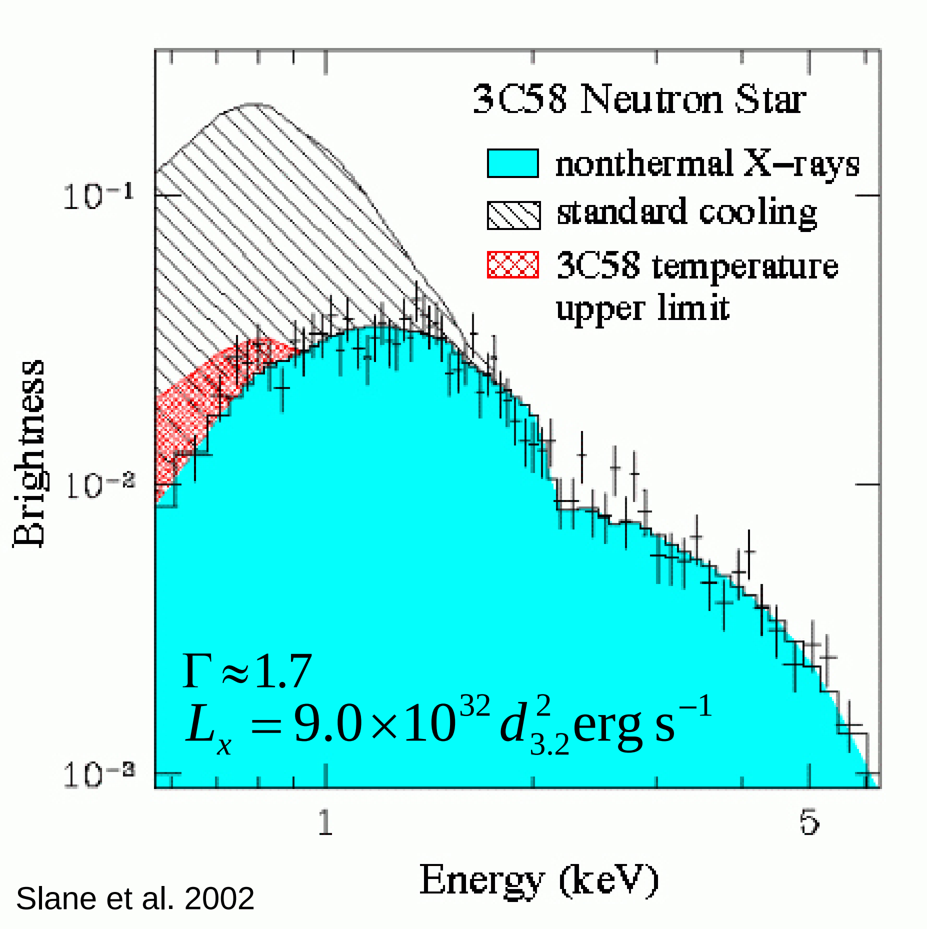
- **Central spectrum is completely dominated by a power law**

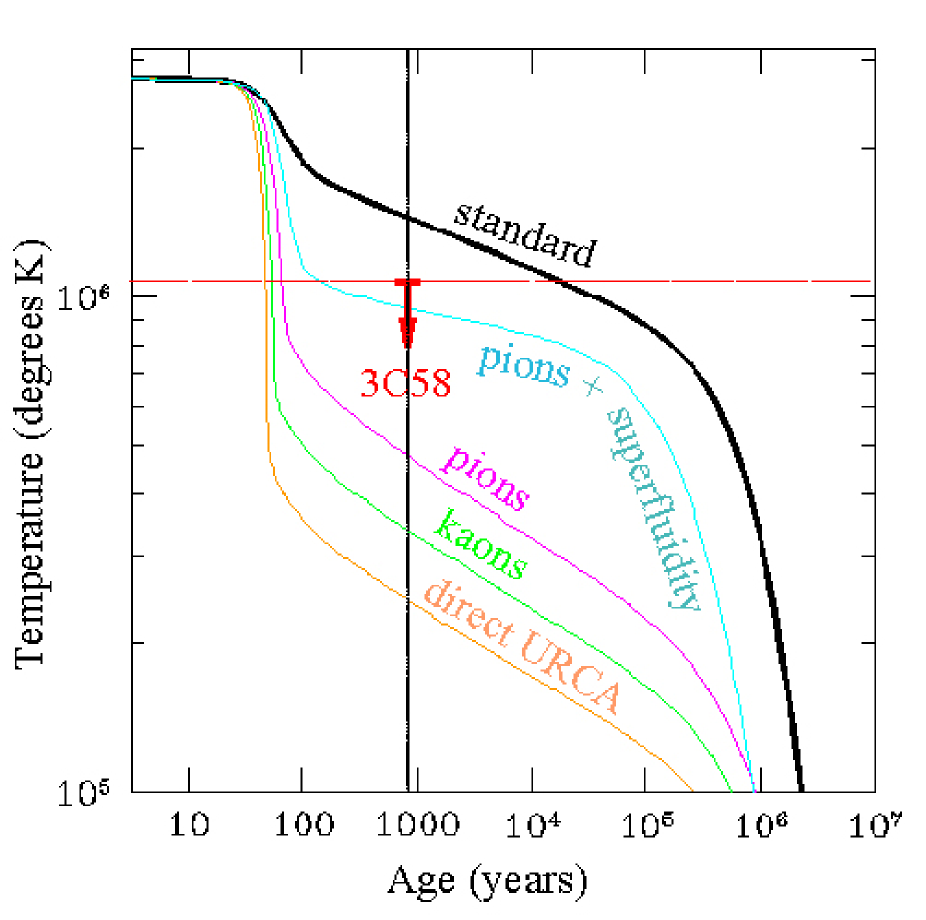
$$\Gamma = 1.6 \pm 0.1,$$

$$L_x = 9.0 \times 10^{32}\, d_{3.2}^2\, \mathrm{erg\ s^{-1}}$$

- **Best fit includes a 10 km NS w/ H atmosphere and log T = 5.97**
  - this is a statistical improvement over a power law, but not a huge one; if we assume no detection, the upper limit is log T < 5.99

PSR J0205+6449: Cooling Emission

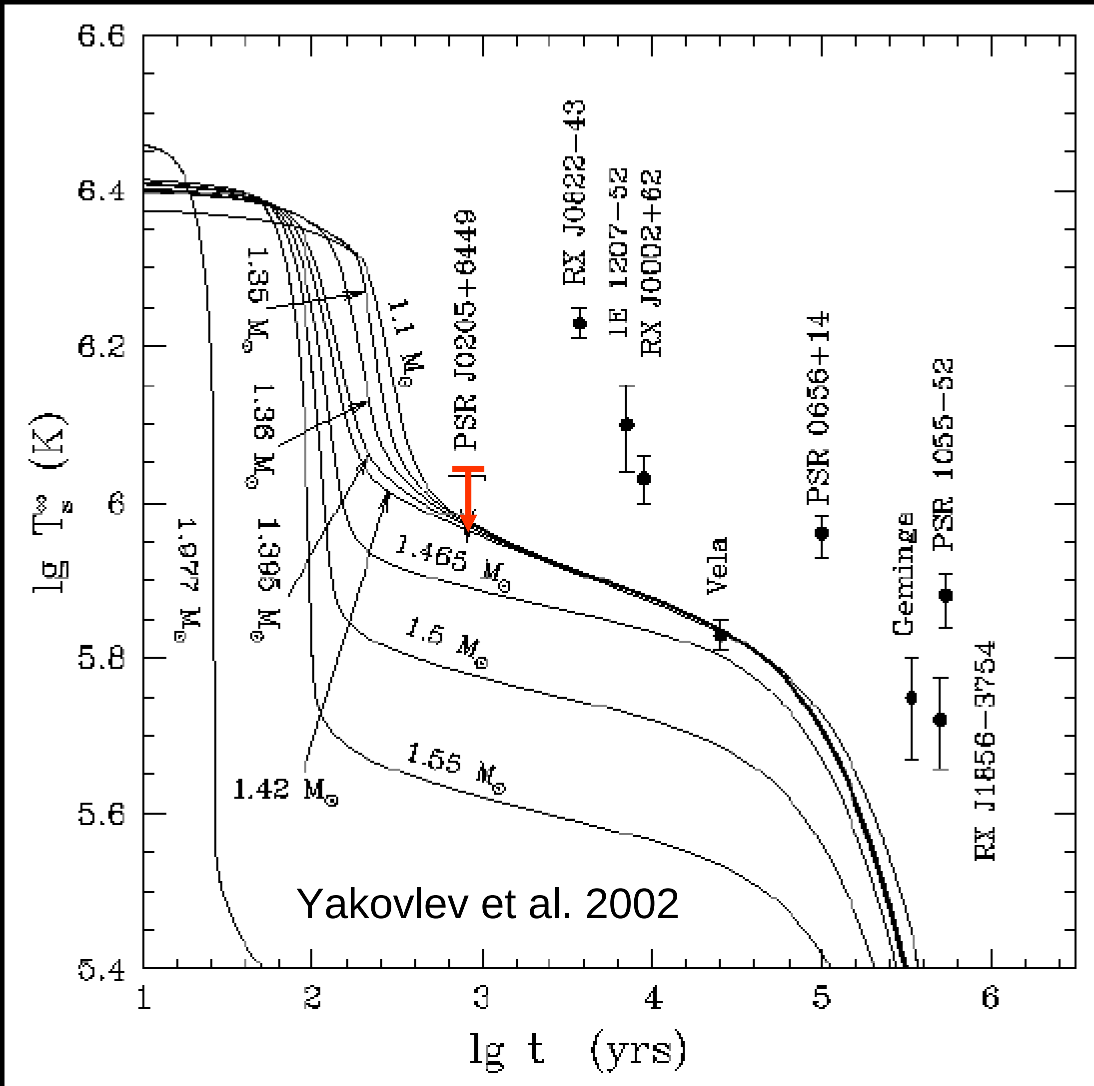




- **Point source spectrum is a power law; adding blackbody component leads to limit on surface cooling emission**
  - since atmosphere effects harden spectrum, limit on surface temperature is conservative

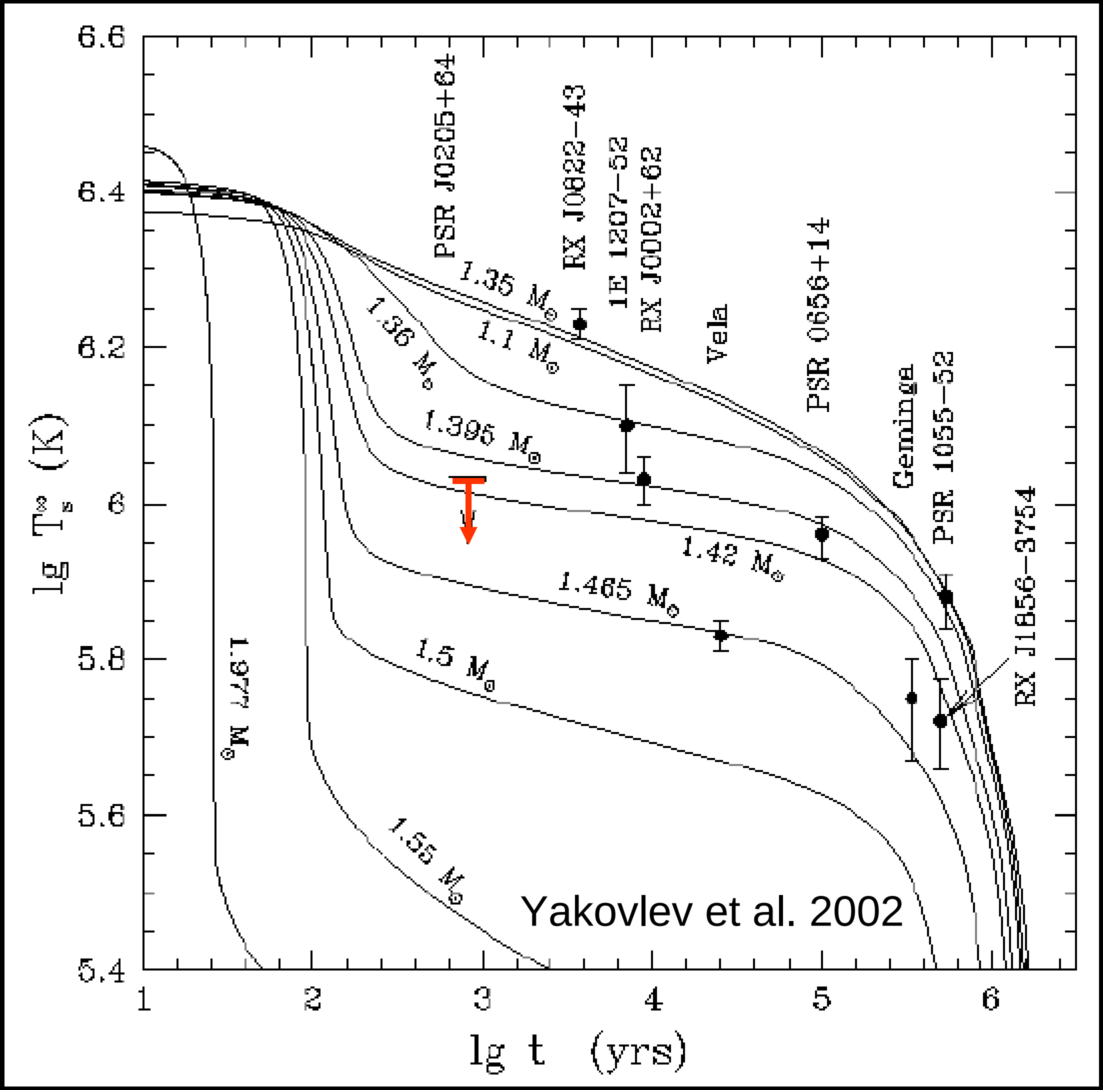
- **For NS w/ *R* = 10 km,** $T < 1.1 \times 10^6 \, \text{K}$
  - standard cooling models predict higher temperature for this age
  - may indicate direct Urca or pion cooling

PSR J0205+6449: Standard or Non-Standard Cooling?



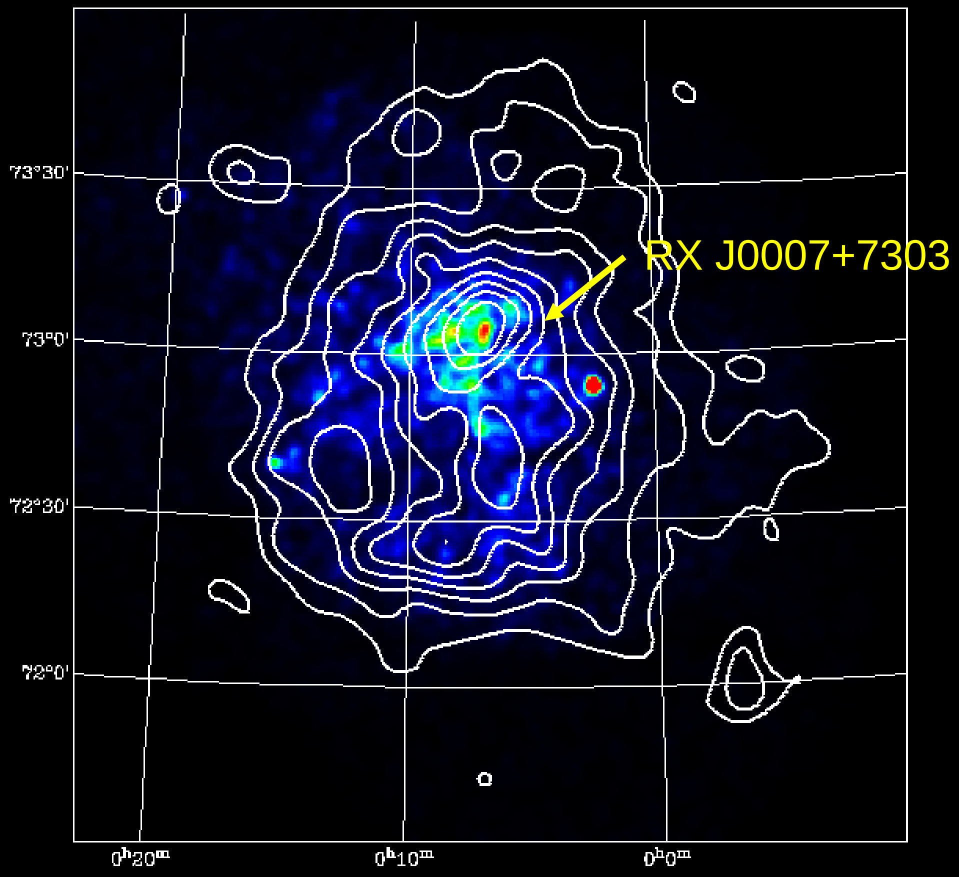
- **Recent calculations yield rapid cooling without "exotic" processes (e.g. Kaminker et al. 2001)**
  - EOS has direct Urca turn-on for M > 1.358 Mo
  - requires particular superfluidity assumptions to allow fast cooling to persist
  - explains J0205+6449 result, but requires different core structure for other NSs

PSR J0205+6449: Standard or Non-Standard Cooling?



- **Recent calculations yield rapid cooling without "exotic" processes (e.g. Kaminker et al. 2001)**
  - EOS has direct Urca turn-on for M > 1.358 $M_\odot$
  - requires particular superfluidity assumptions to allow fast cooling to persist
  - explains J0205+6449 result, but requires different core structure for other NSs
- **Alternatively, different superfluidity model allows same EOS to explain variations as due to NS mass**
  - requires direct Urca (i.e. "nonstandard") cooling for J0205+6449, Vela, and other pulsars
- **Note that Tsuruta et al. (2002) argues that above models do not actually achieve superfluid state**
  - argue proton fraction is too small for direct Urca
  - suggest pion cooling as nonstandard process

CTA 1: A Central Compact Source



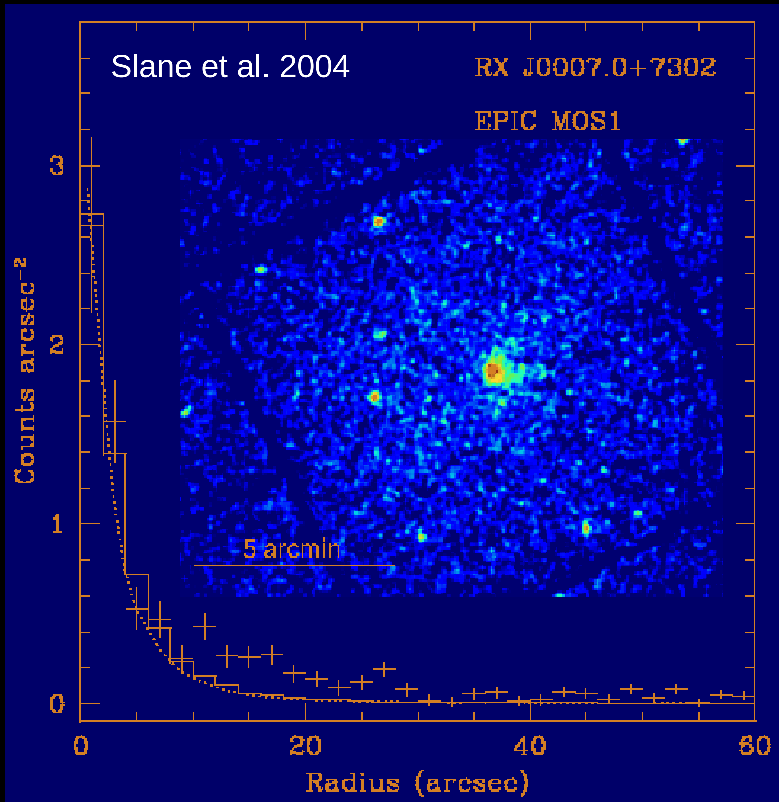
ROSAT PSPC image showing the position of RX J0007.0+7303.

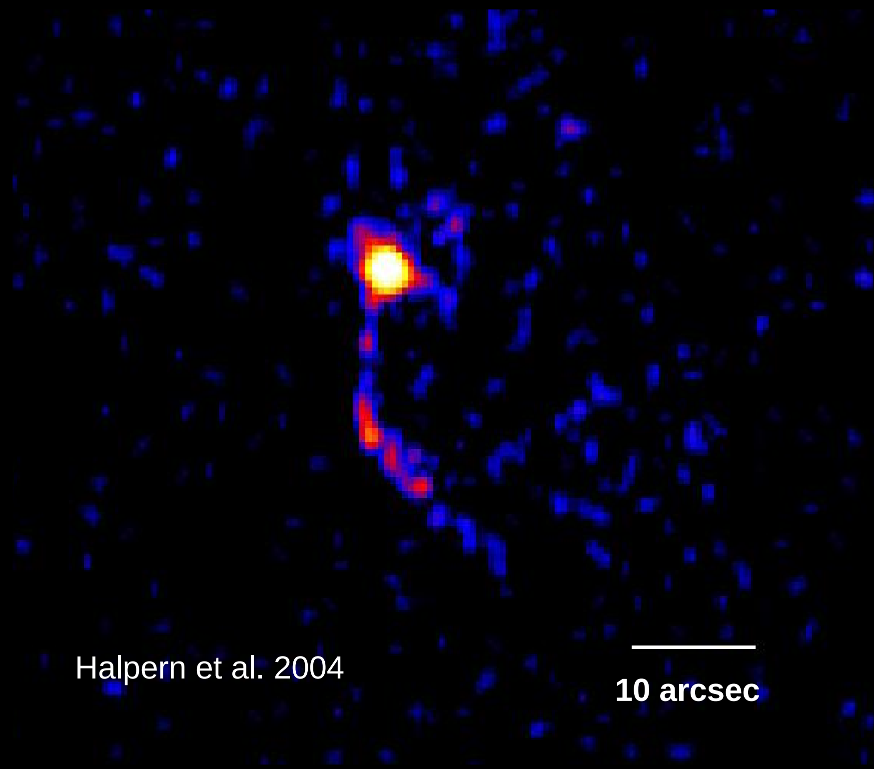
- CTA 1 is a high-latitude SNR whose central X-ray emission is dominated by synchrotron radiation
  - indicative of a PWN, and thus a young NS
  - Sedov solution gives SNR age of about 20 kyr

- The faint unresolved X-ray source RX J0007.0+7303 resides at the center of the diffuse emission
  - presumably the NS counterpart

- An unidentifed EGRET source contains the X-ray source in its error circle
  - another indicator of a young NS

J000702+7302.9: Extended Emission

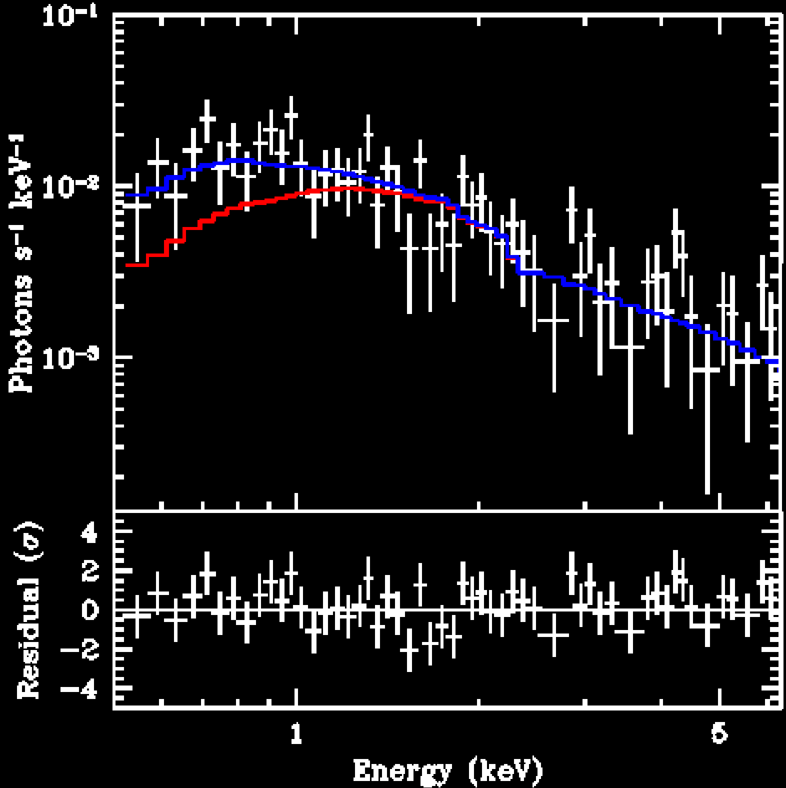




- XMM observations reveal soft spectrum typical of young NS
- Slight evidence of extended emission
  - structure from pulsar outflows?

- Chandra observation reveals extended source and jet-like structure
  - source is unquestionably the pulsar powering the PWN; pulsation searches underway

RX J0007.0+7302: Spectrum



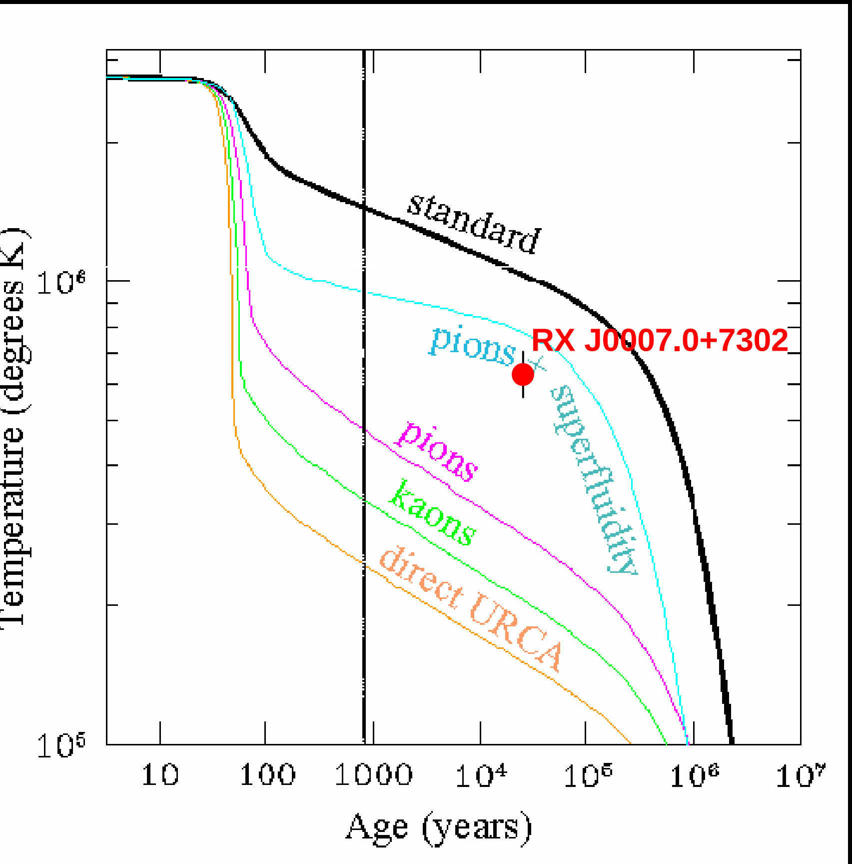
- For $N_H = 2.8 \times 10^{21}\ \mathrm{cm}^{-2}$ (fixed at that for CTA 1), power law fit requires additional **soft component**

- **Power law:**

  $$\Gamma = 1.5 \pm 0.2 \quad L_x = 4.7 \times 10^{31} D_{1.4}^2\ \mathrm{erg\ s}^{-1}$$

  - low for a young pulsar, but not extremely so
  - ~0.1% of PWN Lx (similar to 3C 58, G54.1+0.3 and G292.3+0.8)
  - assuming $L_x \approx 10^{-3} \dot{E}$, RX J0007.0+7302 would have an $\dot{E}/d^2$ ratio larger than the faintest known γ-ray pulsars
  - extrapolation of X-ray spectrum to EGRET band reproduces γ-ray spectrum without need for a spectral break

RX J0007.0+7302: Spectrum



- **Soft Component:**

Blackbody:

$$\log T = 6.20^{+0.03}_{-0.04}\ \mathrm{K} \qquad R = 0.63\, D_{1.4}\ \mathrm{km}$$

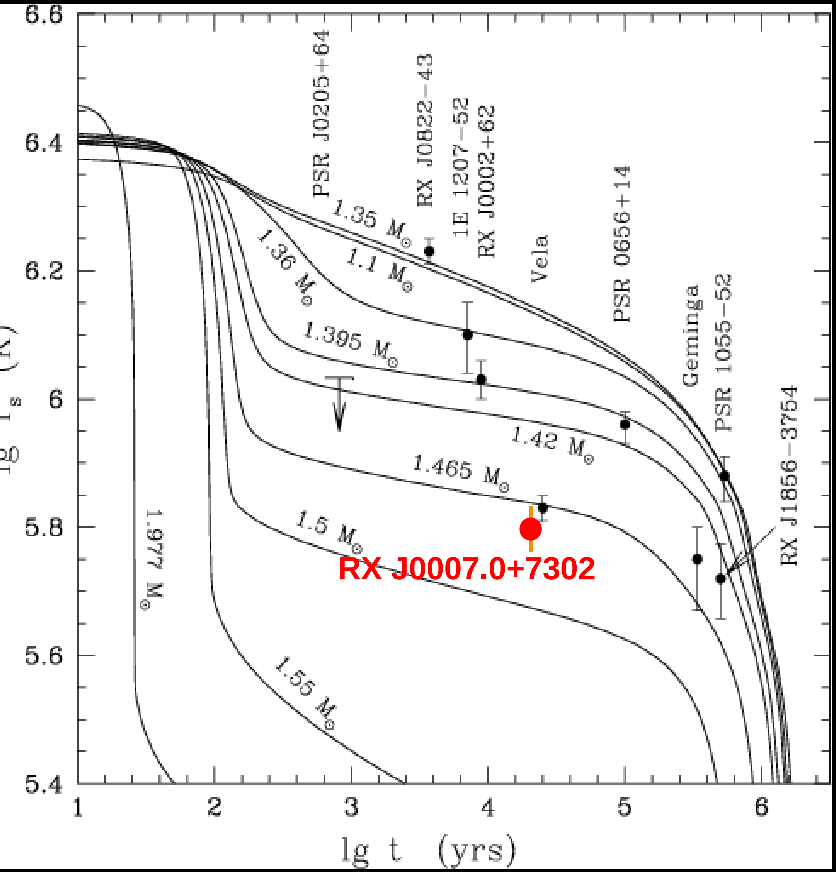
- temperature too high, and radius too small for cooling from entire NS surface
- suggestive of **hot polar cap emission**

Light NS Atmosphere: (Pavlov et al. 1995)
- for $R = 10\ \mathrm{km}$ and a 1.4 kpc distance,

$$\log T = 5.79^{+0.03}_{-0.04}\ \mathrm{K}$$

- this falls **below standard cooling** curves for the modified Urca process
- direct Urca cooling is consistent for $M \approx 1.46\, M_{sun}$ (Yakovlev et al. 2002)

RX J0007.0+7302: Spectrum



- **Soft Component:**

  Blackbody:

$$\log T = 6.20^{+0.03}_{-0.04}\ \mathrm{K} \qquad R = 0.63\, D_{1.4}\ \mathrm{km}$$

- temperature too high, and radius too small for cooling from entire NS surface
- suggestive of **hot polar cap emission**

Light NS Atmosphere: (Pavlov et al. 1995)

- for $R = 10\ \mathrm{km}$ and a 1.4 kpc distance,

$$\log T = 5.79^{+0.03}_{-0.04}\ \mathrm{K}$$

- this falls **below standard cooling** curves for the modified Urca process
- direct Urca cooling is consistent for $M \approx 1.46\, M_{sun}$ (Yakovlev et al. 2002)

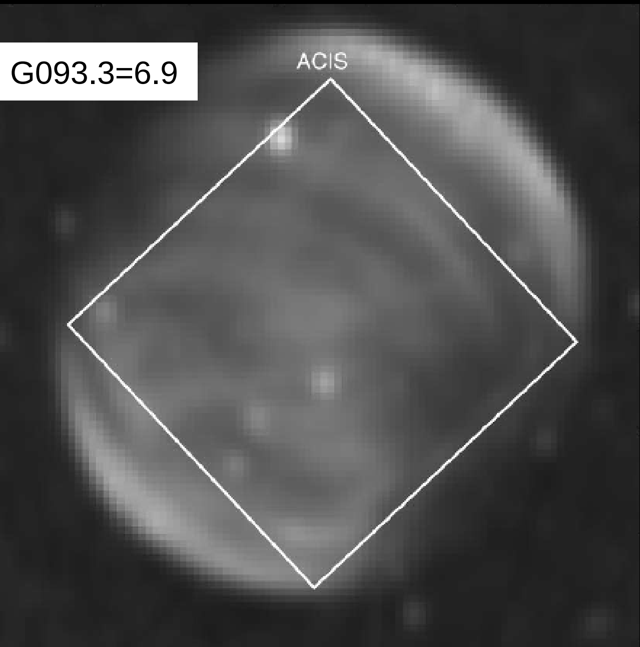
X-ray Searches for Young Neutron Stars

- The youngest neutron stars should still be near the associated SNRs
  - target SNRs to search for young neutron stars
  - studies of SNRs provide addition, independent information about ages, distances, and environment

- Most SNRs should have NSs associated with them
  - ~75-80% are from core-collapse Sne, and only a small fraction of these will form black holes

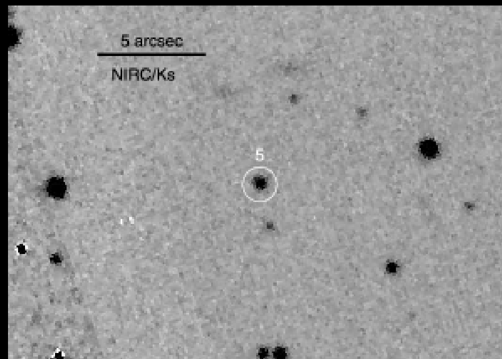
- Yet… there are many SNRs (even very young ones) for which the associated NSs have not yet been identified
  - selection effects can make some hard to find
  - there may be young neutron stars with properties much different from what we currently expect (we've seen this with magnetars and CCOs…); SNRs are the likely places to look for them

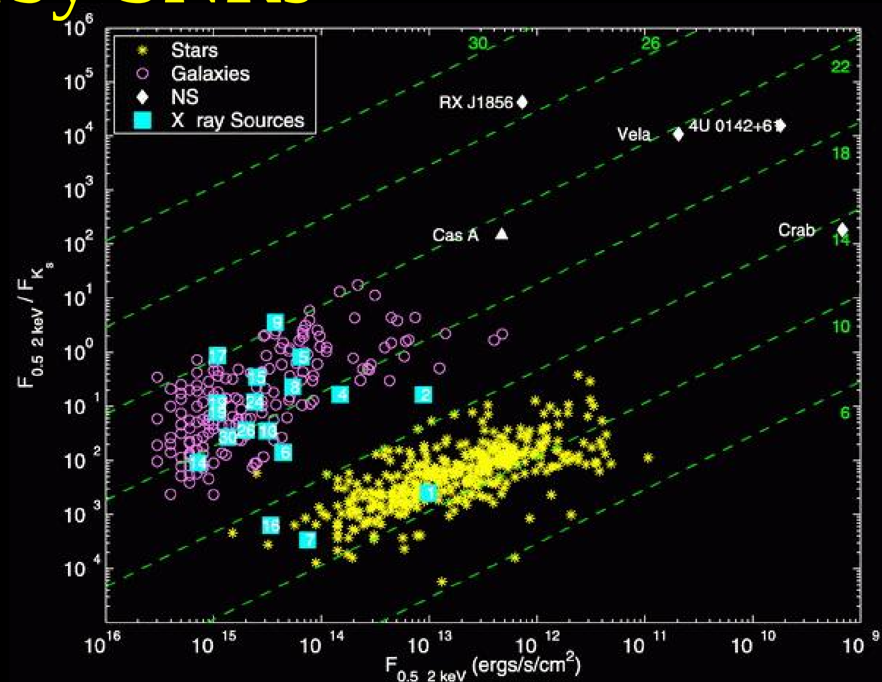
Limits from Nearby SNRs



log t ~ 3.3-4
D ~ 3.5 kpc

if θ > 8 arcmin,
v > 800 km/s





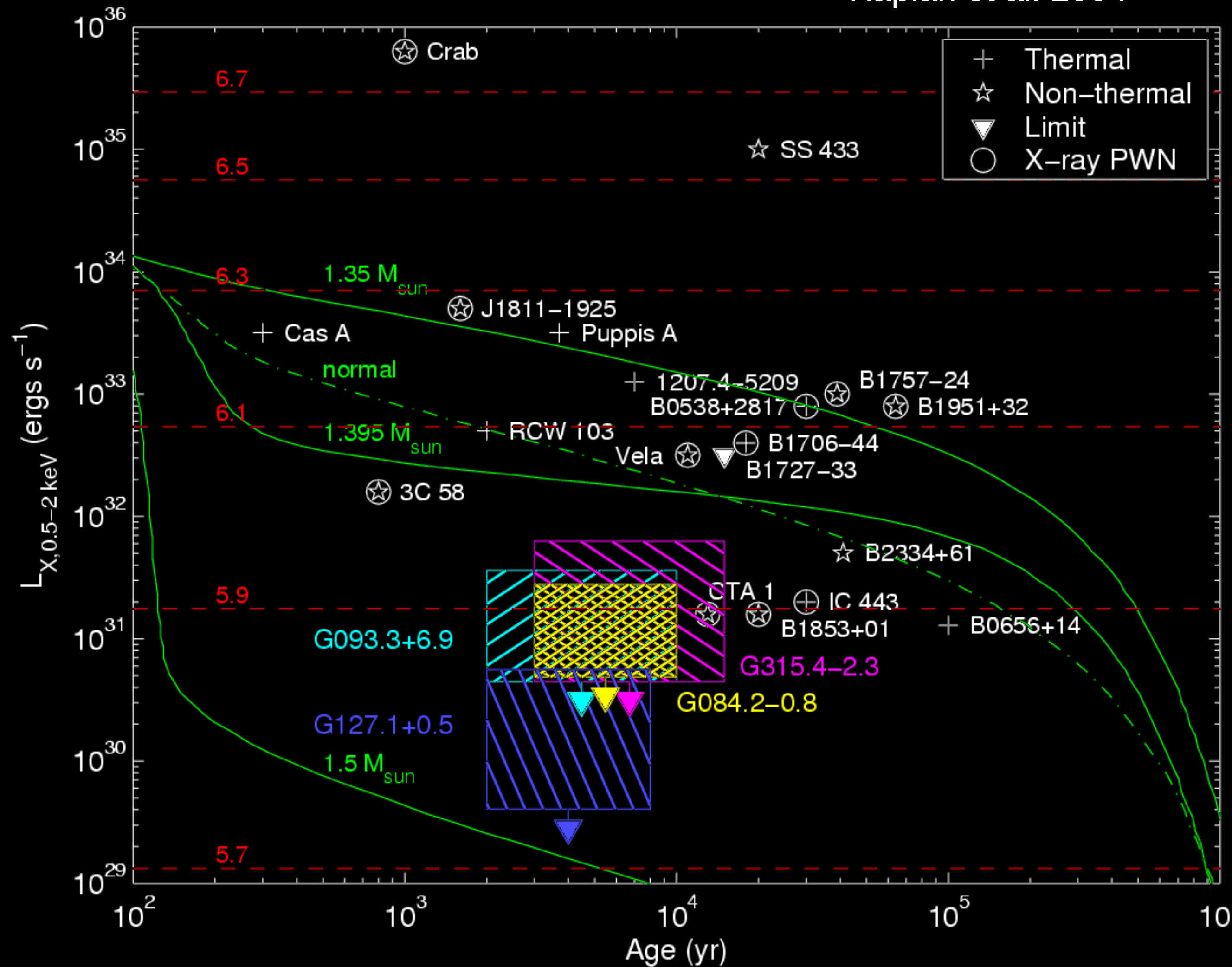
- **Conduct survey of SNRs w/ D < 5 kpc (part of D. Kaplan's thesis)**
  - use Chandra or XMM to detect X-ray sources in field
  - choose field size such that reasonable NS velocities will not move NS from field
  - choose exposures to detect source with luminosities 10x lower than faintest CCOs
  - use optical/IR follow-up for counterpart search to rule out non-NS candidates

- **If no NS is detected, we have:**
  - a Type Ia, a very high-velocity NS, a black hole (none of which should happen often), or
  - <u>a rapidly cooling NS</u>

Searching for Young Neutron Stars in SNRs

- No viable NS candidates identified for G084.2-0.8, G093.3+6.9, G127.1+0.5, or G315.4-2.3
  - upper limits based on detection threshold, or faintest detected source, provide strong cooling constraints (if there is a NS in any of these SNRs)

Kaplan et al. 2004



Searching for Young Neutron Stars in SNRs

- No viable NS candidates identified for G084.2-0.8, G093.3+6.9, G127.1+0.5, or G315.4-2.3
  - upper limits based on detection threshold, or faintest detected source, provide strong cooling constraints (if there is a NS in any of these SNRs)

- Current work on 3 additional SNRs, G013.3-1.3, G078.2+2.1, and G132.7+3.1, has also led to only upper limits (with G078.2+2.1 being quite low)
  - survey work ongoing to increase statistics

Kaplan et al. 2004