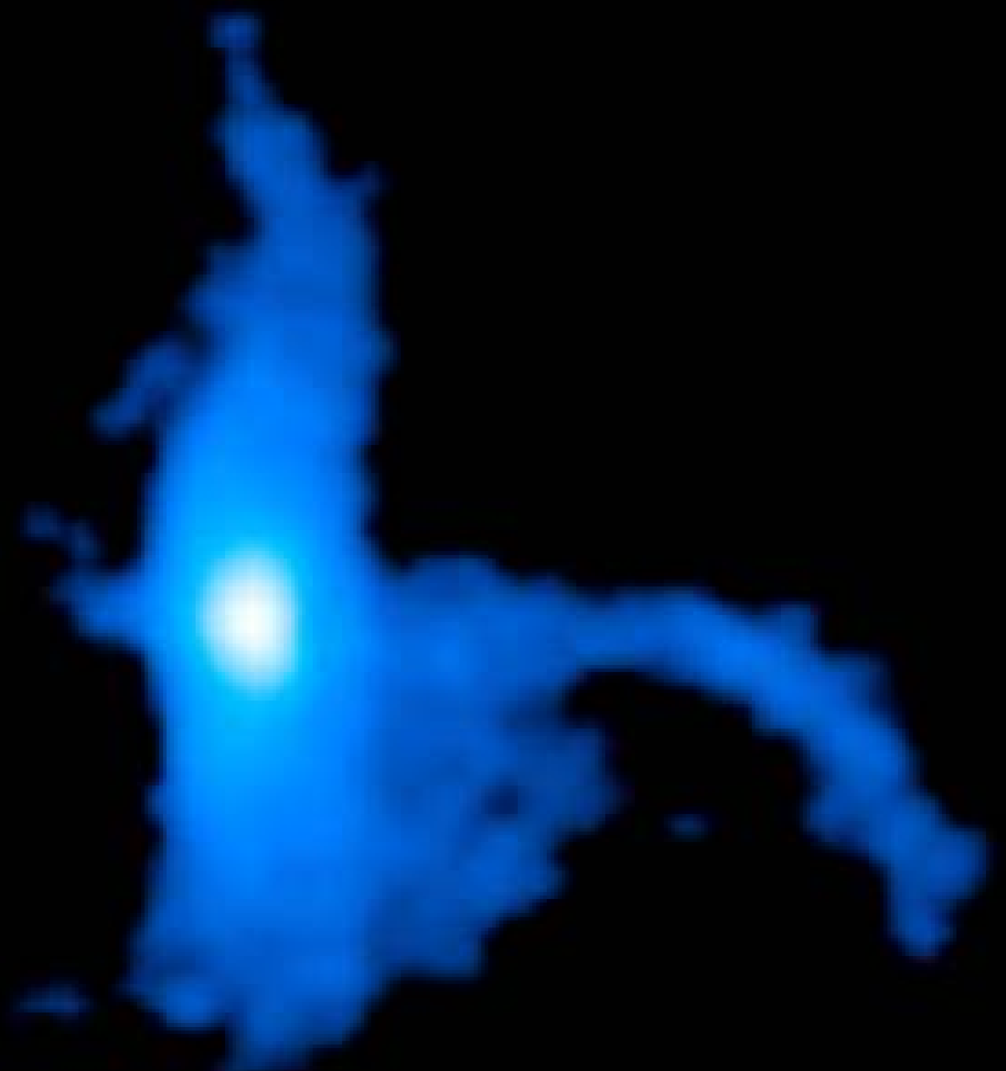
Cooling Limits for the

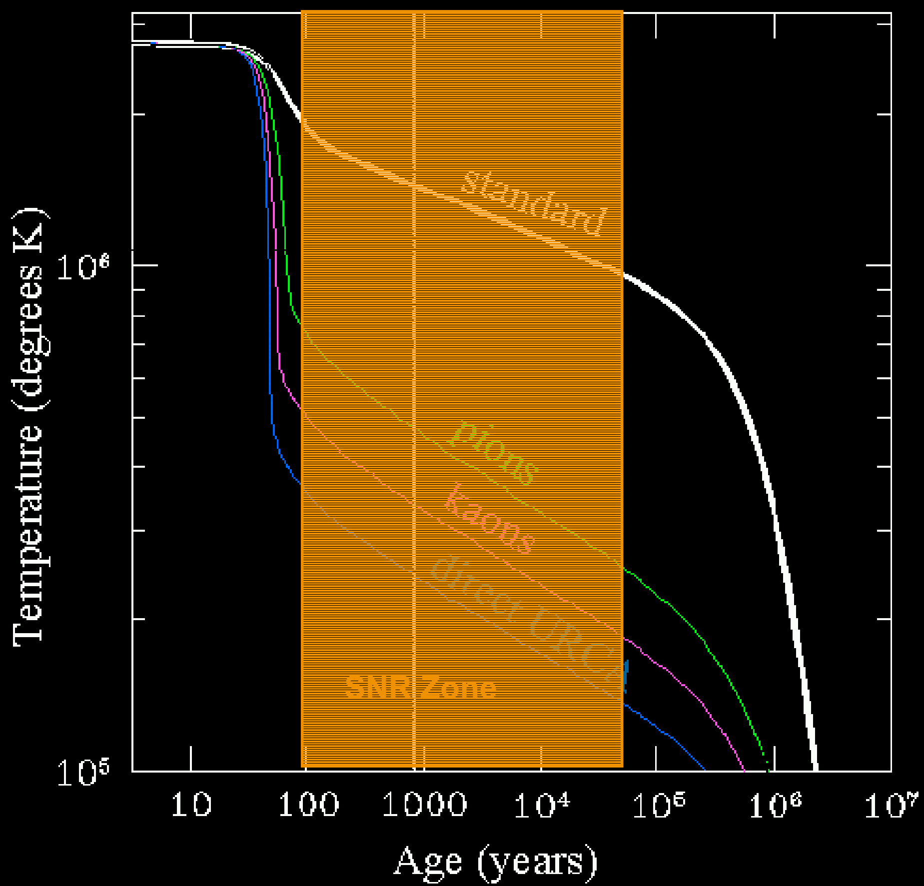


Youngest Neutron Stars

Patrick Slane

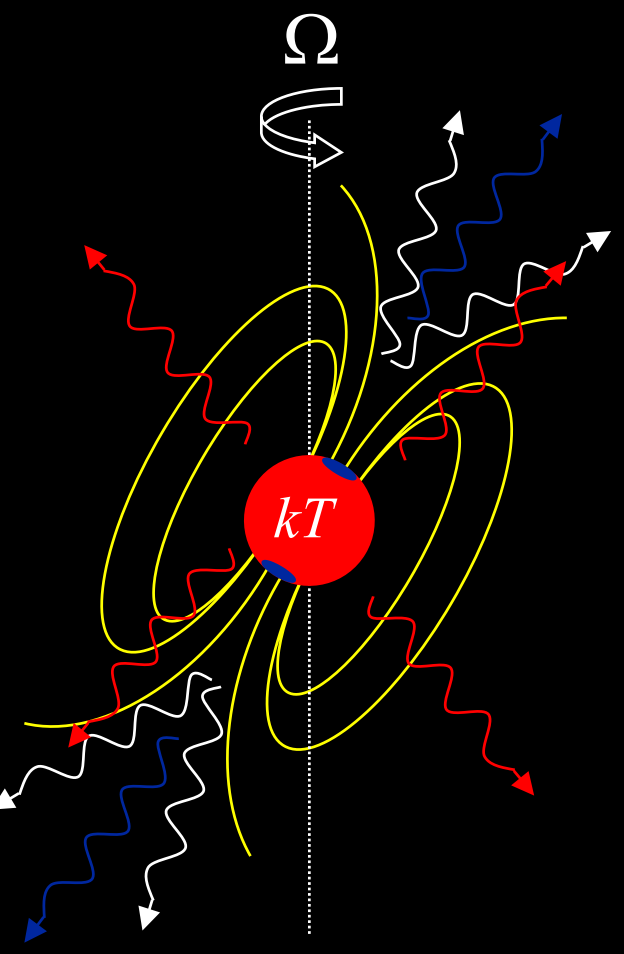
Harvard-Smithsonian Center for Astrophysics

Cooling from the Youngest NSs



- **NSs younger than ~50 kyr offer strong constraints on rapid cooling**
  - the associated physical processes have been reviewed at this meeting
  - Note: this is also about how long SNRs live as X-ray emitters
- **SN rate suggests that there should be 150-200 such SNRs in Galaxy**
- **Accounting for Type Ia and BH-forming events, expect >100 YNSs**
  - we see far fewer; this is partially due to detection limitations (Nh, D) but also appears to be because many of these NSs are intrinsically faint, apparently due to rapid cooling
  - searching for NSs in nearby SNRs is of particular importance

X-ray Emission from Young Neutron Stars

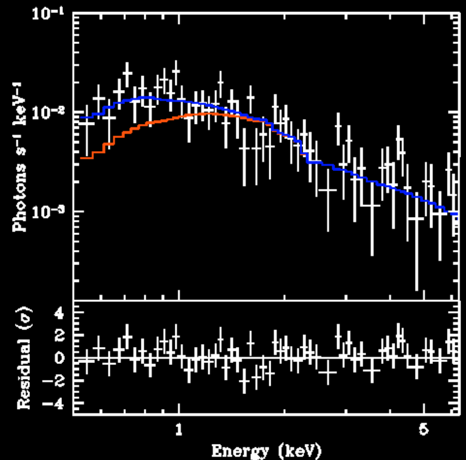


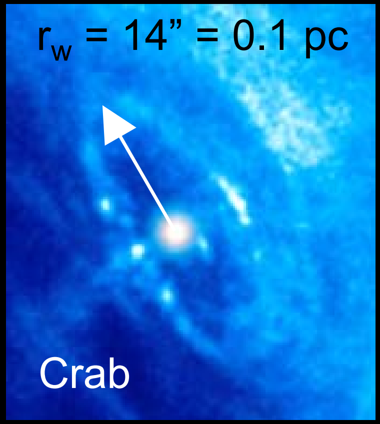
- **Thermal emission from surface**
  - cooling of interior
  - particle heating of surface (caps)
  - accretion from ISM

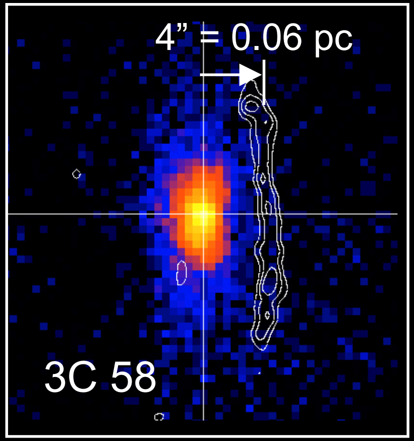
- **Nonthermal emission**
  - pulsed, from magnetosphere
  - unpulsed, from wind (e.g. PWN)

Our interest here is in the cooling emission, which probes interior structure and processes, but we observe this in the presence of some or all of these other components

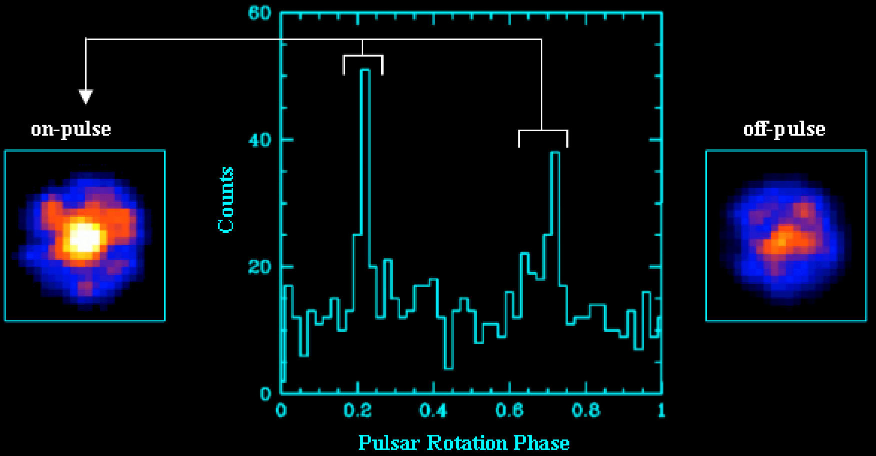
Finding the Cooling Emission



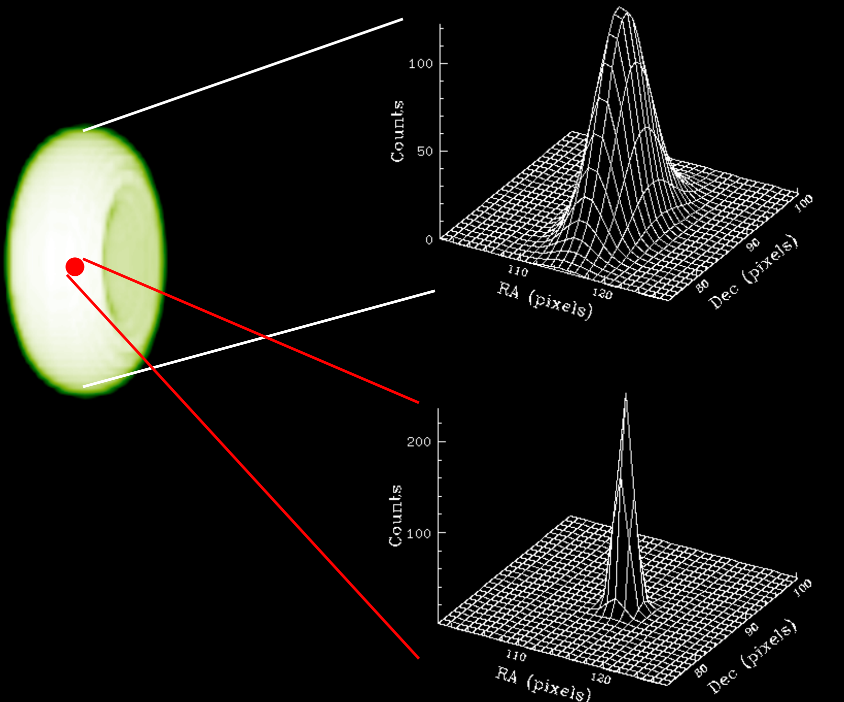




Spectral fitting: model thermal emission
Mixed with power law component

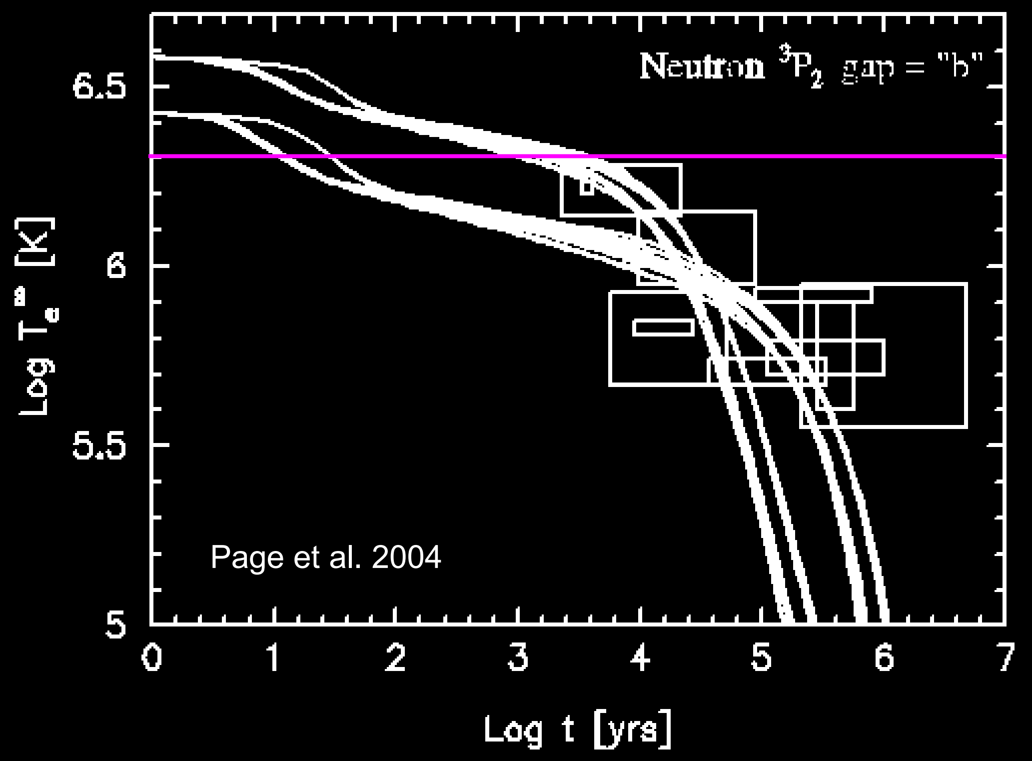


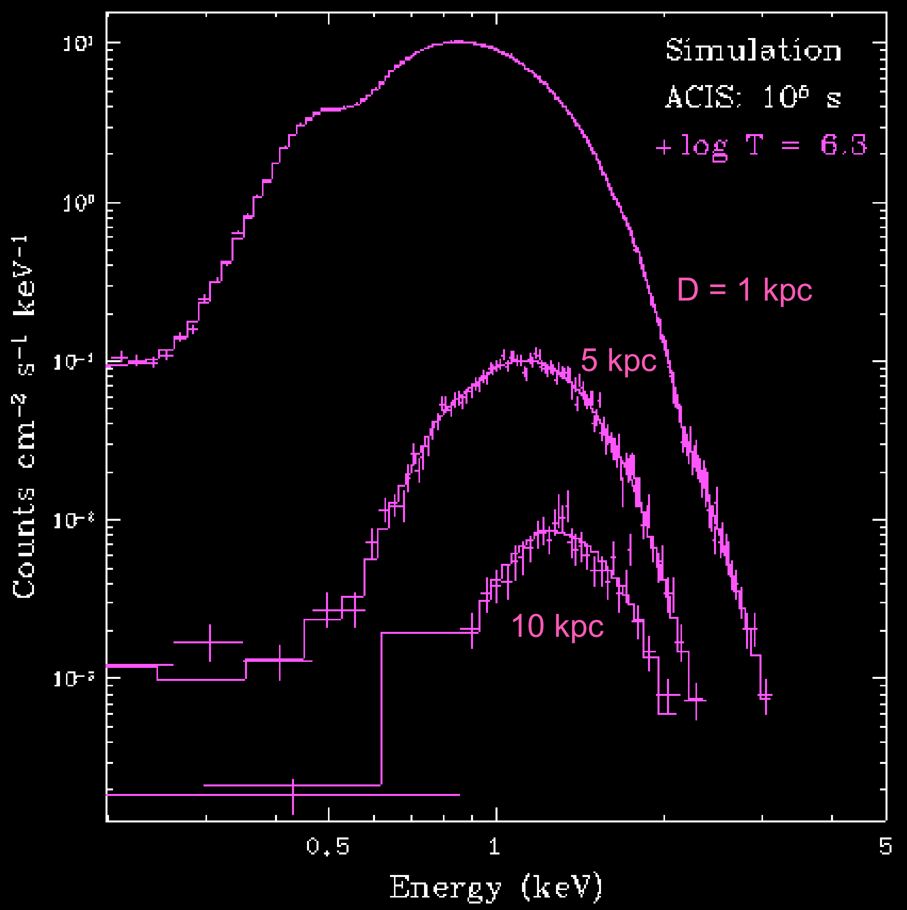
Pulse gating: get limit from off-pulse count rate



Spatial modeling: get limit from point-like component in extended emission profile

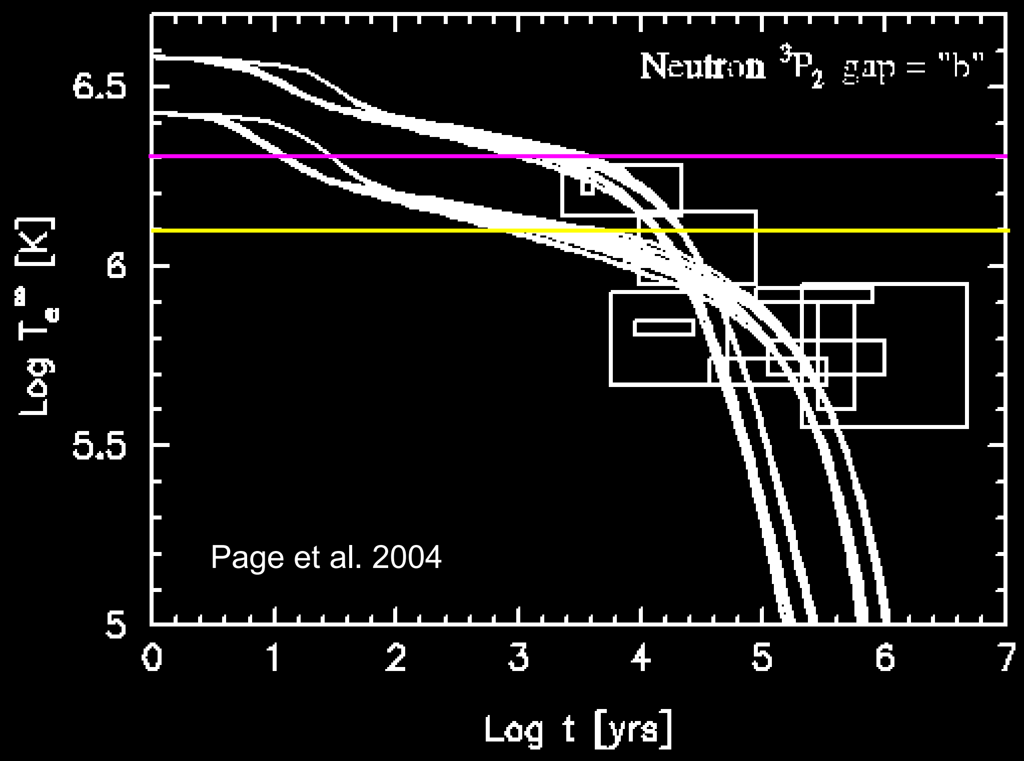
NS Cooling: X-ray Flux Considerations

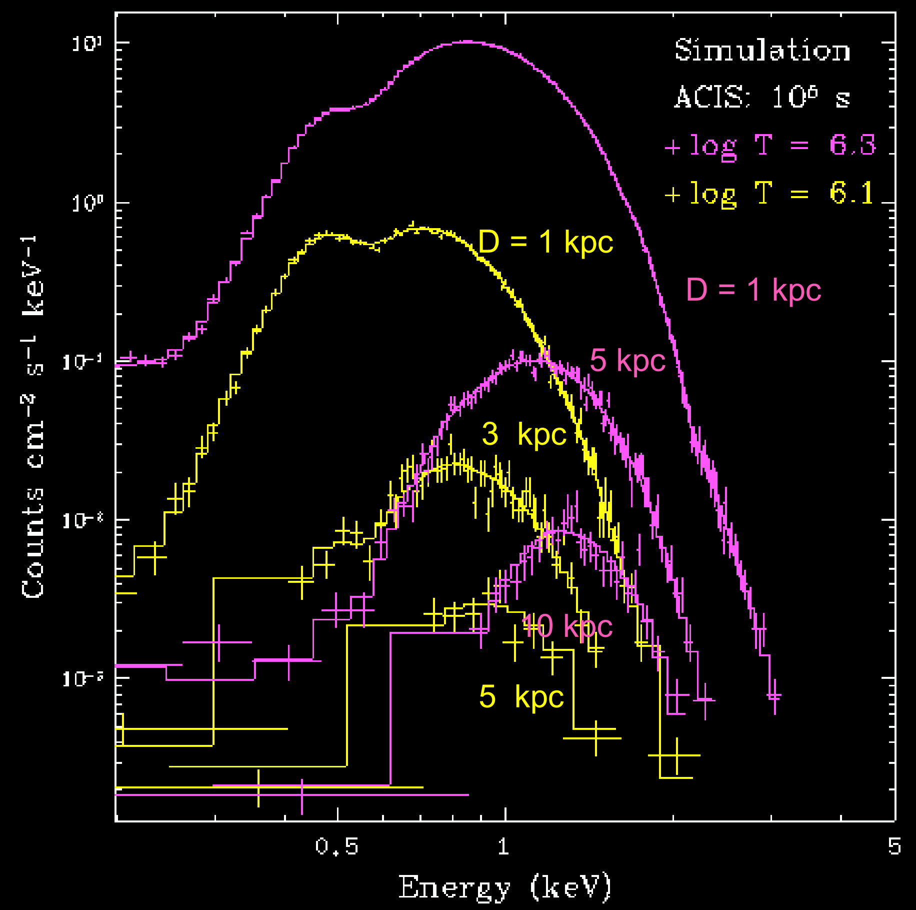




- Cooling emission from young NSs is primarily in the soft X-ray band
  - a hot, cooling NS can be detected at a large distance

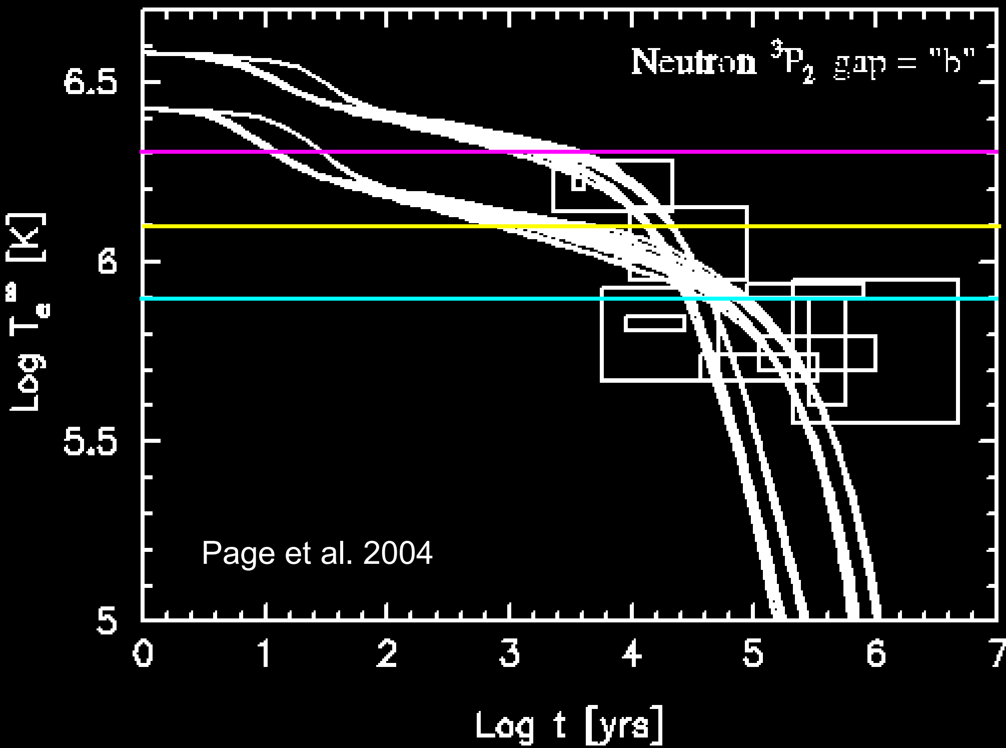
NS Cooling: X-ray Flux Considerations

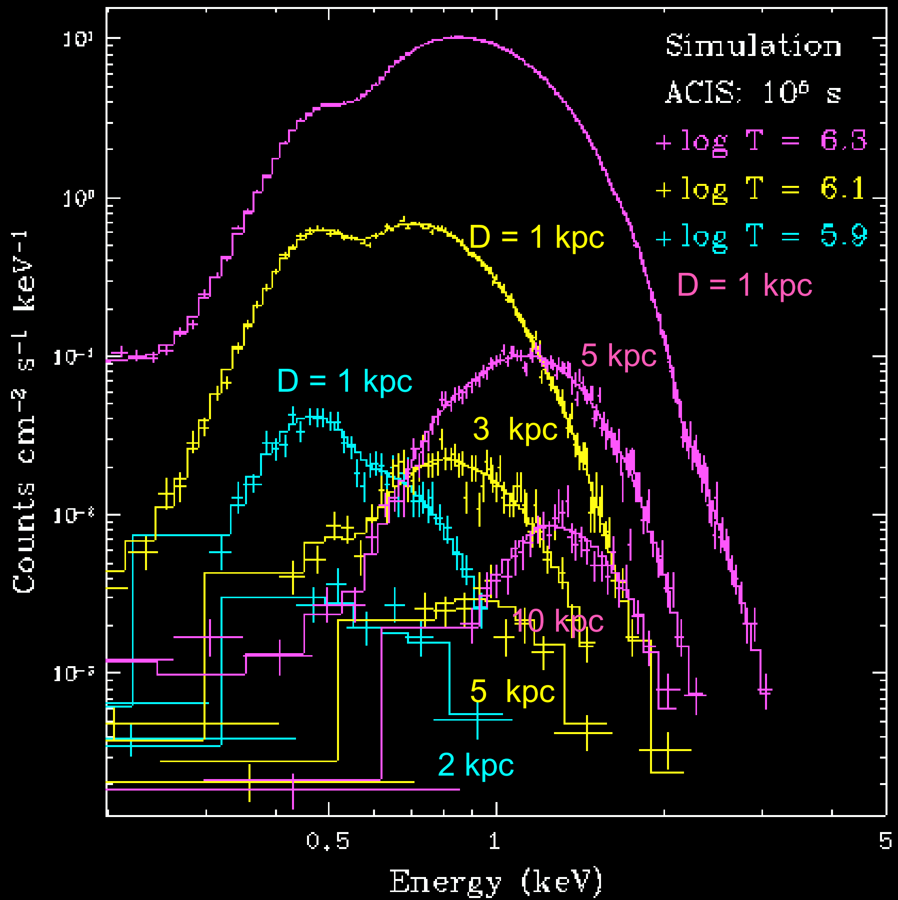




- Cooling emission from young NSs is primarily in the soft X-ray band
  - a hot, cooling NS can be detected at a large distance
- For more rapid cooling, things are harder…
  - even nearby NSs require long exposures

NS Cooling: X-ray Flux Considerations

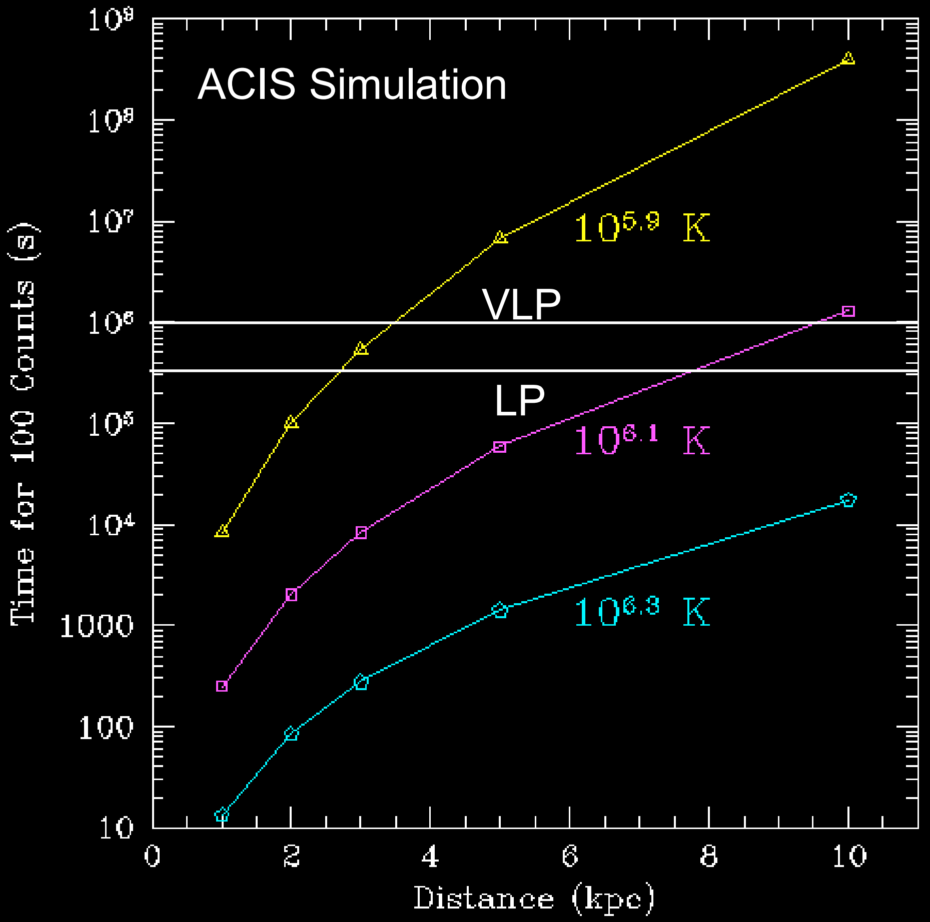




- Cooling emission from young NSs is primarily in the soft X-ray band
  - a hot, cooling NS can be detected at a large distance
- For more rapid cooling, things are harder…
  - even nearby NSs require long exposures

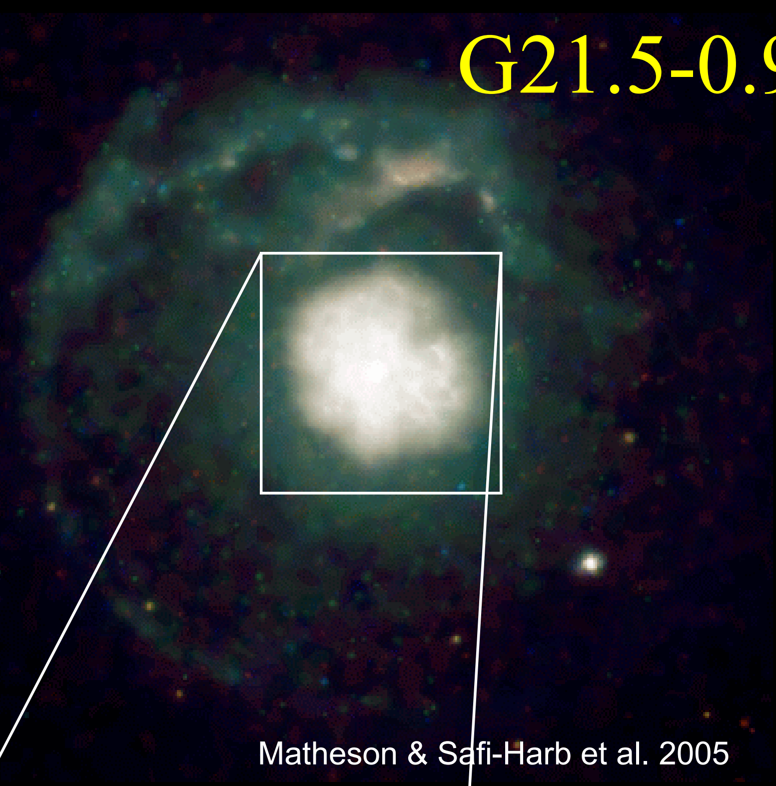
- The combination of increased distance, higher column density, and lower kT can render young NSs virtually undetectable

NS Cooling: X-ray Flux Considerations

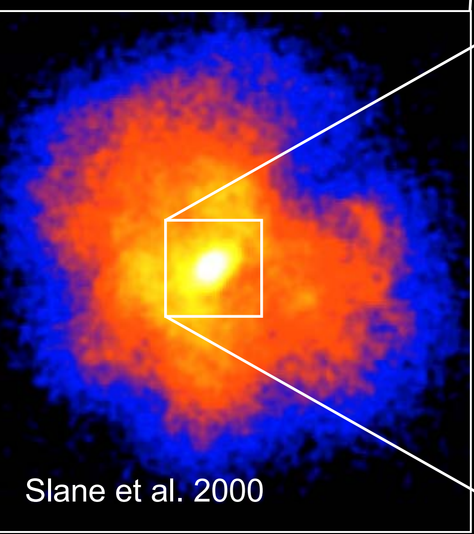


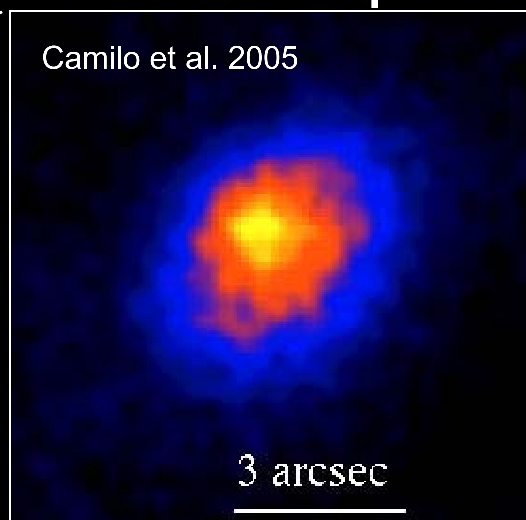
- The exposure times required to detect rapidly cooling NSs with current X-ray telescopes are very large
  - for reference, a 100 ks Chandra observation is considered fairly long; a 300 ks observation is in the “Large Project” category
- Obtaining decent spectra, for which models for magnetized atmospheres can be confronted, is possible only for nearby, hot NSs
  - these don’t seem to be the most typical
- For the youngest NSs, nonthermal emission provides an additional complication
  - the nonthermal flux can be large
  - an associated pulsar wind nebula can present difficulties in separating NS emission from that associated with the wind

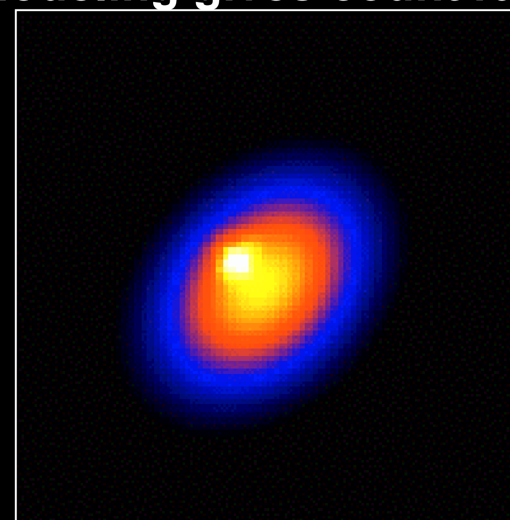
G21.5-0.9: Home of a Young Pulsar



- **G21.5-0.9 is a composite SNR for which a radio pulsar with the 2nd highest spin-down power has recently been discovered (Camilo et al. 2005)**
  - $P = 61.8\ \text{ms};\ \dot{E} = 3.3\times10^{37}\ \text{ergs s}^{-1}$
  - τ ~ 4.8 kyr; true age more likely < 1 kyr
- **Merged 351 ks HRC observation reveals point source embedded in compact nebula (torus?)**
  - no X-ray pulsations observed
  - column density is > 2 x 10^{22} cm^{-2}, distance ~5 kpc
- **Spatial modeling gives count rate of 1.5 - 4 cnts/ks**

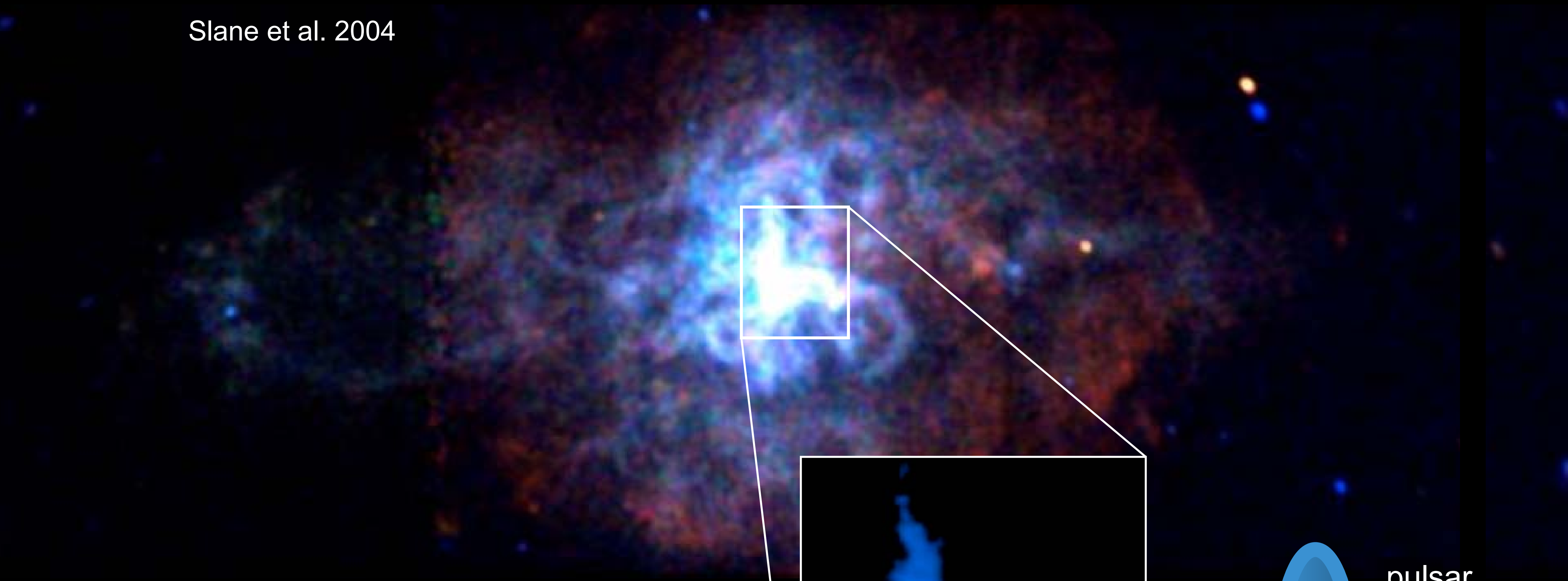


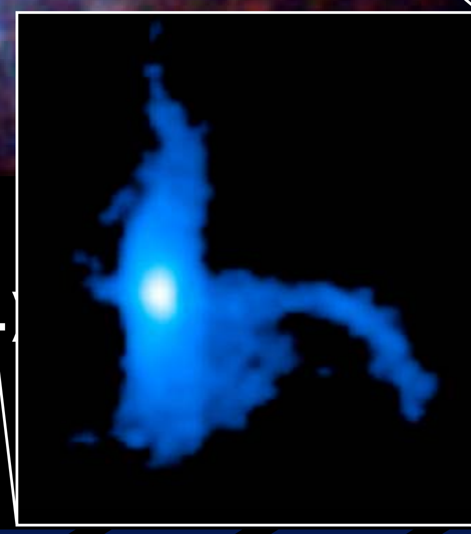


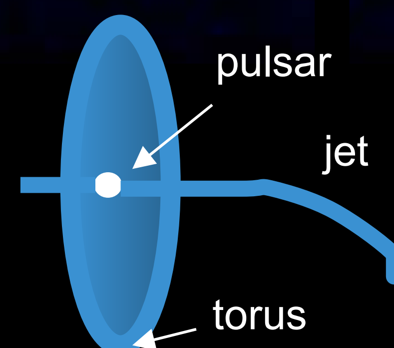


- standard cooling would give a rate of 0.2 cnts/ks
- thus, **we have no interesting cooling limit for this very young NS!**

3C 58: A Young Pulsar Wind Nebula

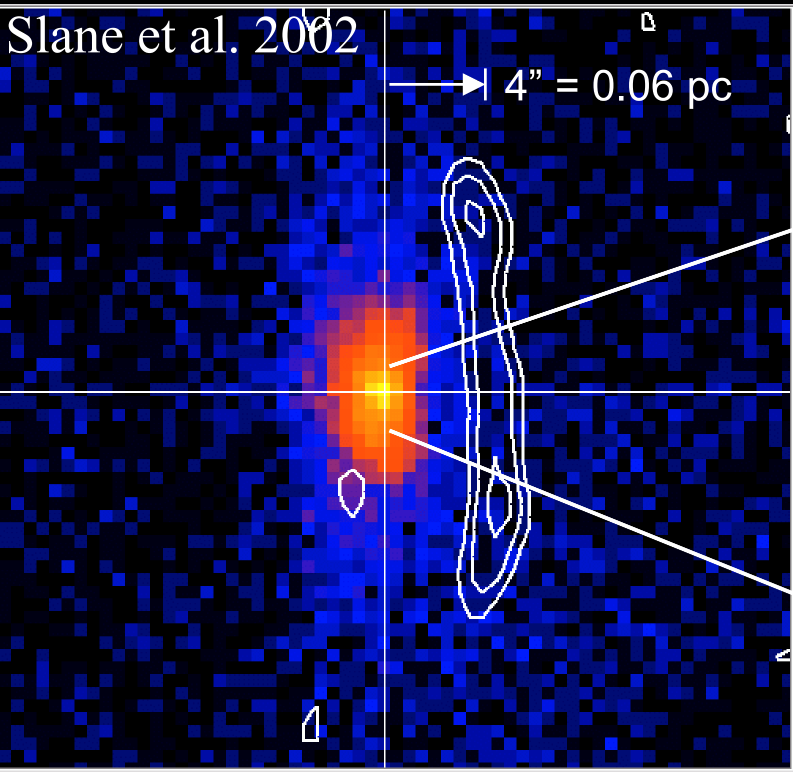


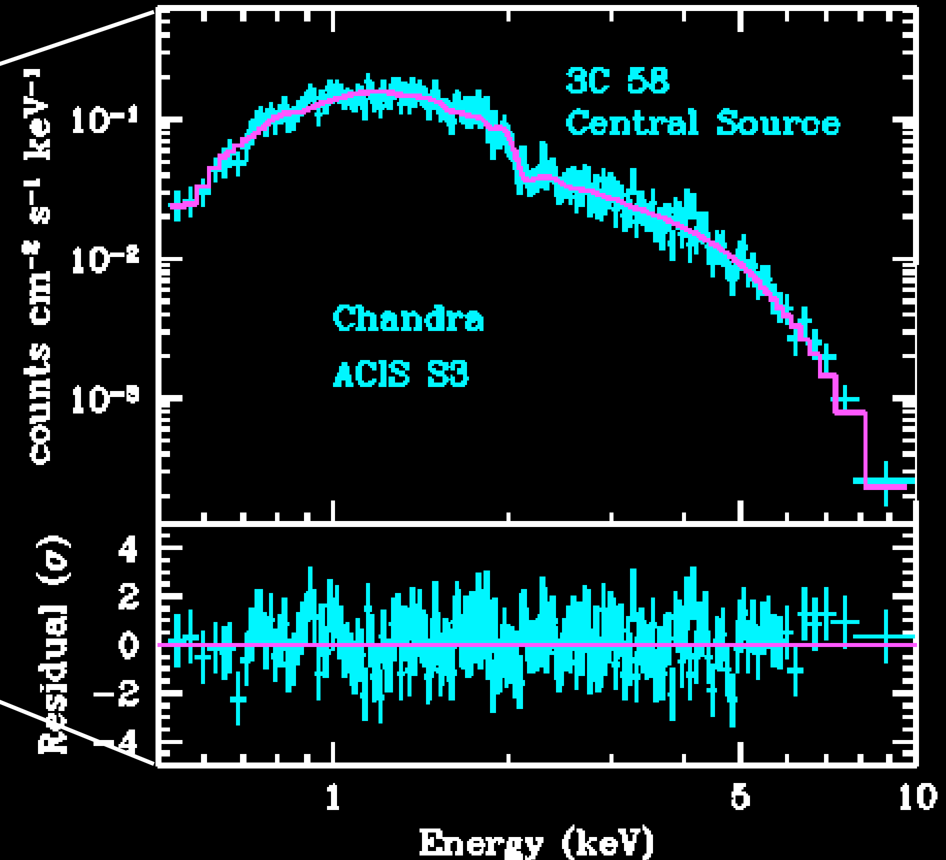




- **Believed to be associated with SN 1181 (but there are some problems with this…)**
- **Rapid (62 ms) high spin-down pulsar observed**
  - jet-torus morphology

3C 58: Neutron Star Spectrum



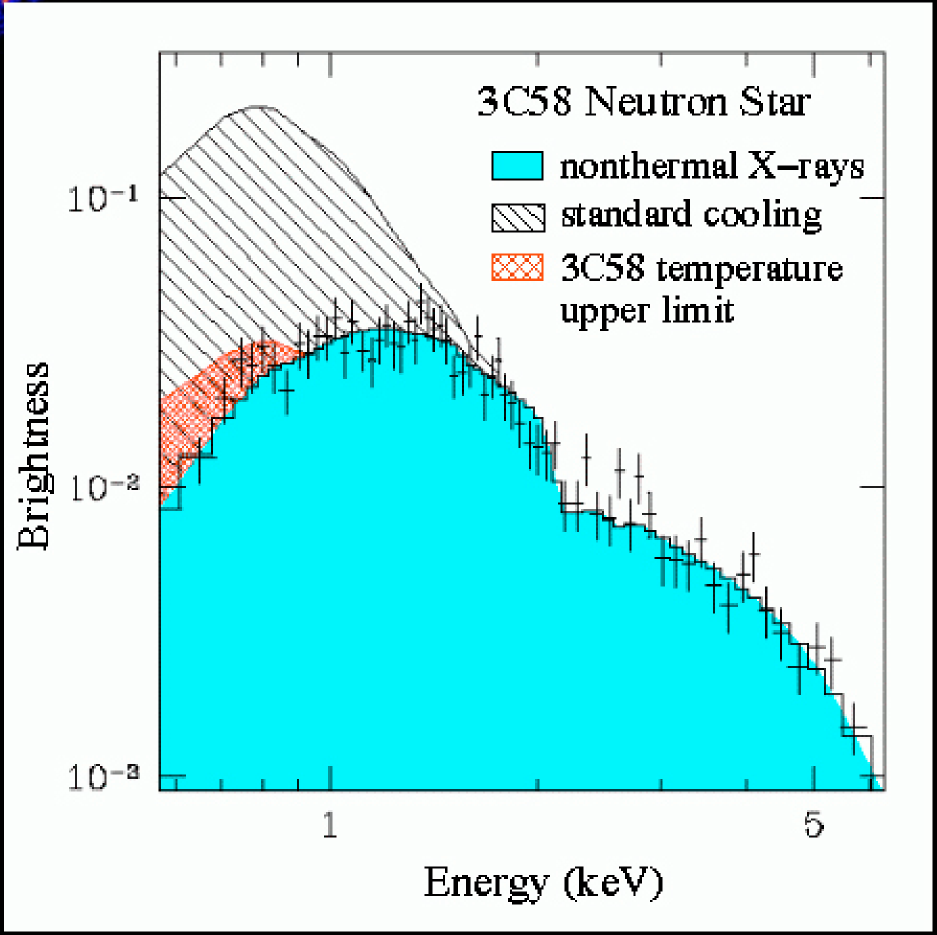


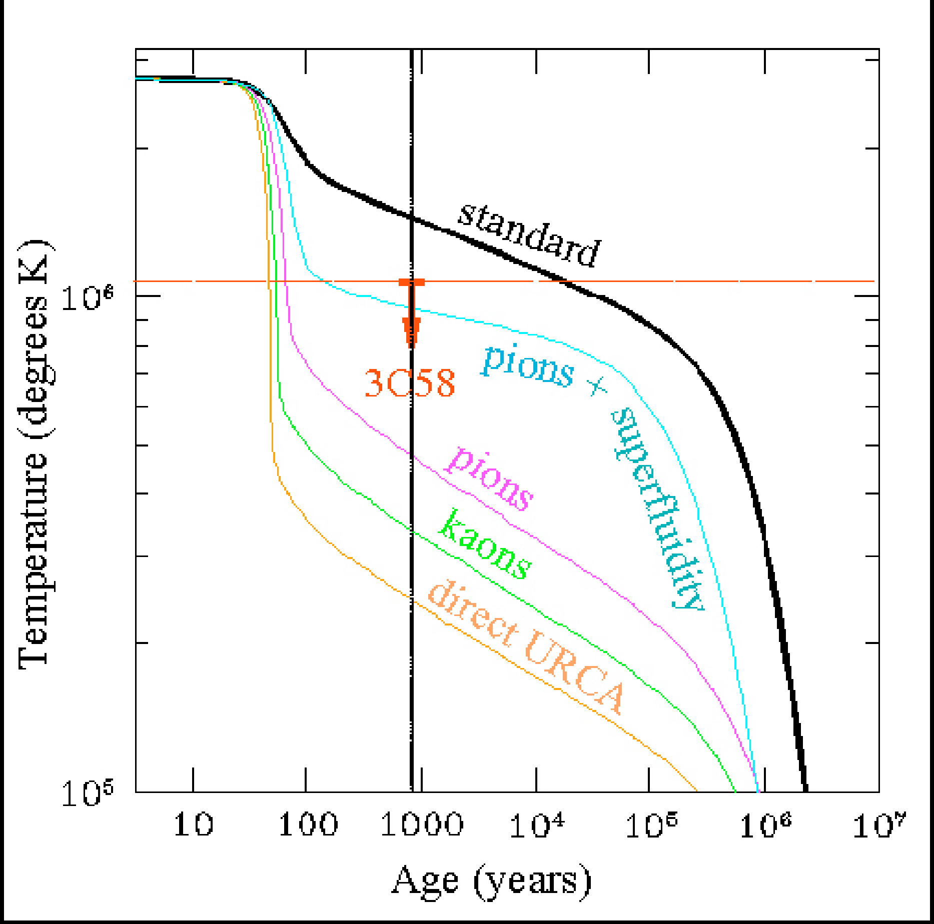
- **Central spectrum is completely dominated by a power law**

$$\Gamma = 1.6 \pm 0.1,$$
$$L_x = 9.0 \times 10^{32} d_{3.2}^2 \text{erg s}^{-1}$$

- **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

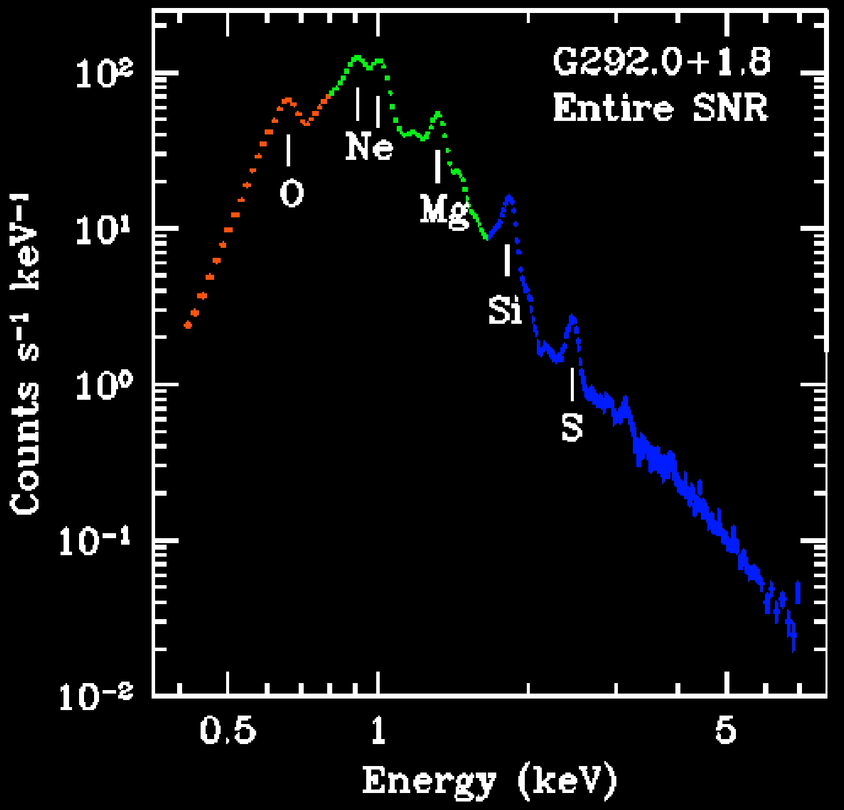




- **Adding blackbody component leads to limit on surface cooling emission**
  - since atmosphere effects harden spectrum limit on surface temperature is conservative

- **For NS w/ *R* = 10 km,** $T < 1.1\times10^{6}\,\mathrm{K}$
  - standard cooling models (e.g. Tsuruta 1998) predict higher temperature for this age
  - indicates direct Urca (or pion?) cooling

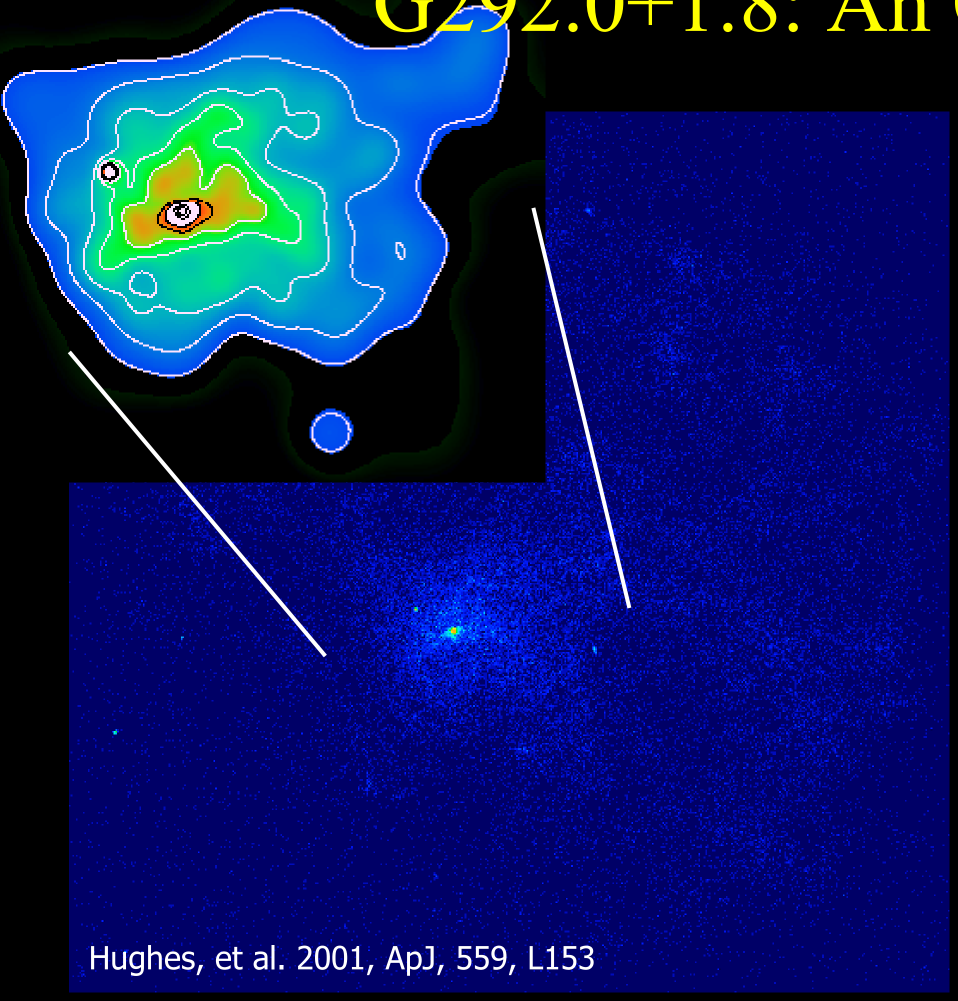
G292.0+1.8: An O-Rich Composite SNR



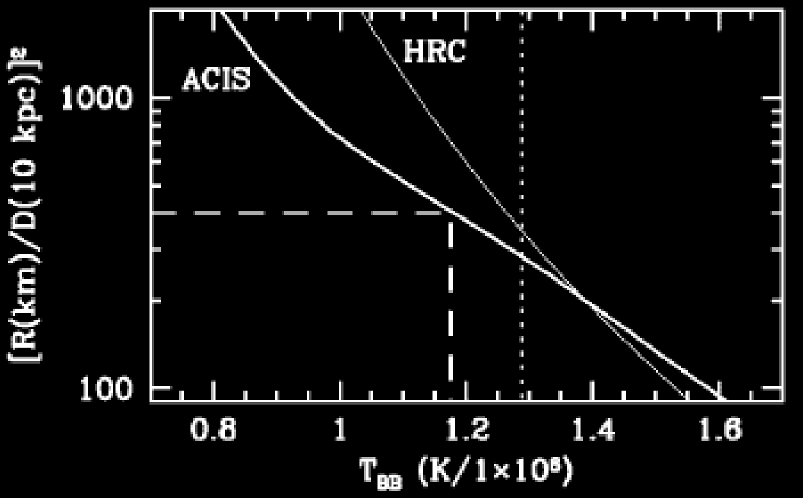
- Oxygen-rich SNR; massive star progenitor
  - dynamical age ~2000 yr
  - O & Ne dominate Fe-L, as expected

Park, et al. 2002, ApJ, 564, L39

G292.0+1.8: An O-Rich Composite SNR



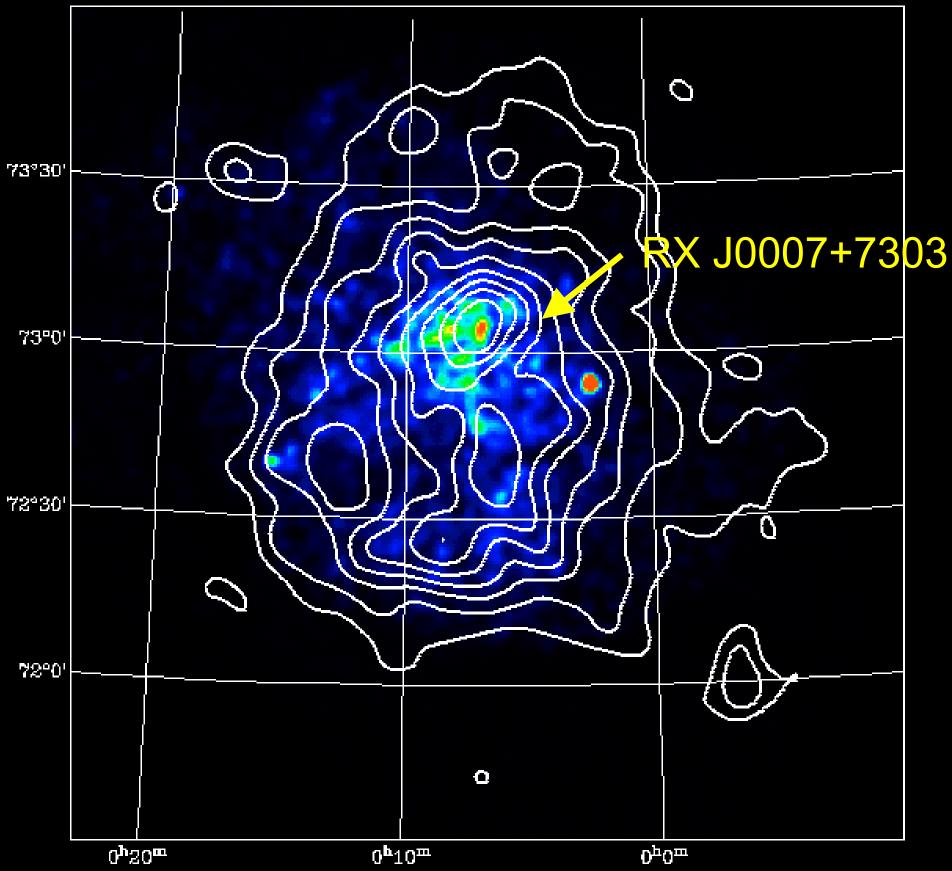
Hughes, et al. 2001, ApJ, 559, L153



Hughes, Slane, Roming, & Burrows 2003, ApJ

- Compact source surrounded by diffuse emission seen in hard band
  - 135 ms radio pulsations confirmed in X-rays
- Compact source extended; jets/torus?
- Spectral fitting gives log T < 6.07
  - slightly below standard cooling
  - consistent with (slightly more constraining than) inferred from pulse-gated count rate

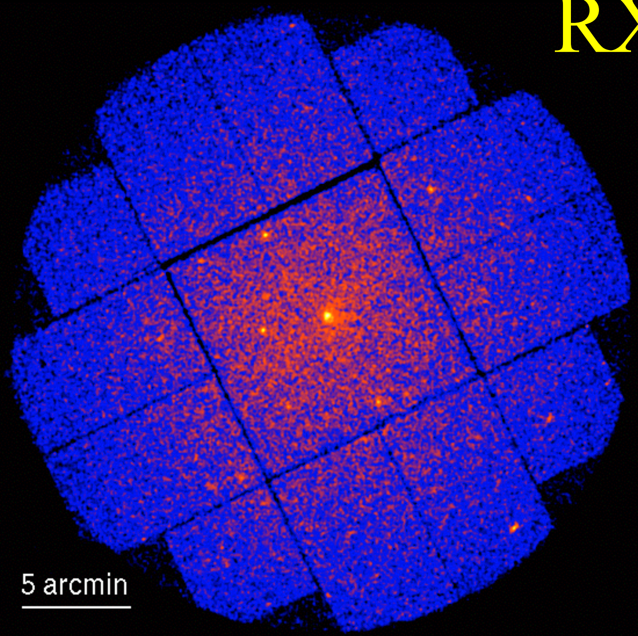
CTA 1: A Central Compact Source

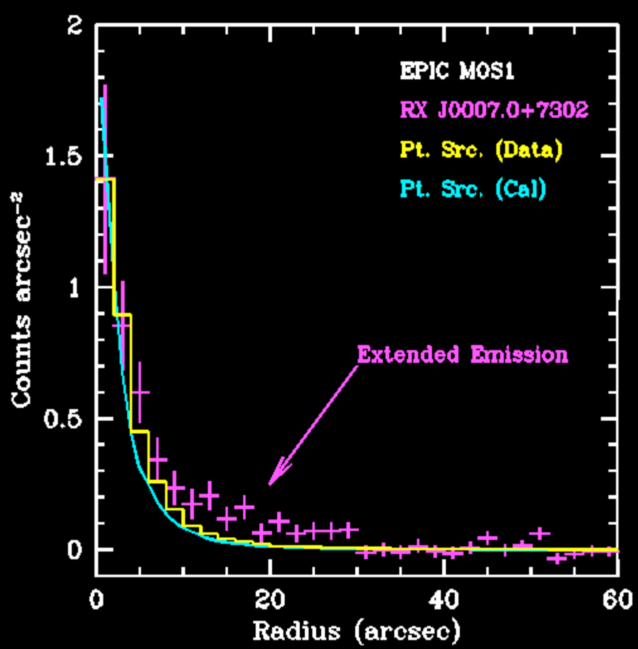


ROSAT PSPC image showing the position of RX J0007.0+7303.

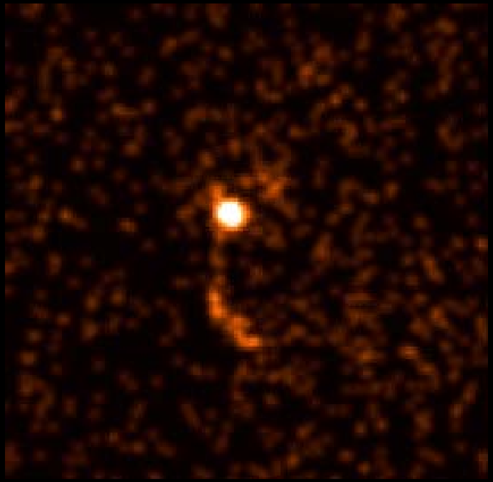
- CTA 1 is a high-latitude SNR whose central X-ray emission is dominated by synchrotron radiation
  - indicative of a PWN, and thus a young NS
  - Sedov solution gives SNR age of about 20 kyr
- The faint unresolved X-ray source RX J0007.0+7303 resides at the center of the diffuse emission
  - presumably the NS counterpart
- An unidentifed EGRET source contains the X-ray source in its error circle
  - another indicator of a young NS

RX J0007.0+7302: Imaging



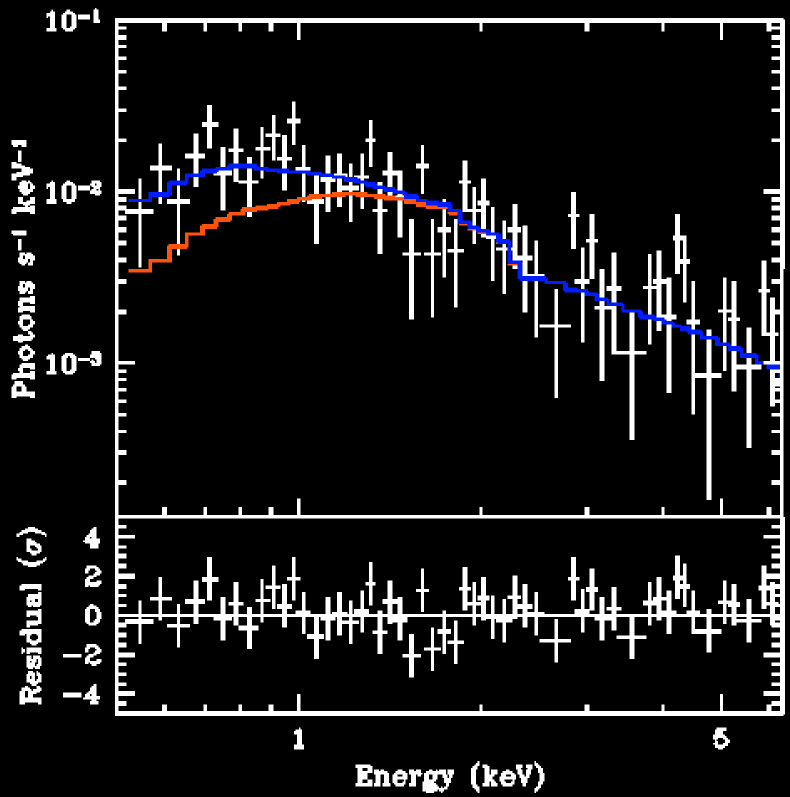


- RX J0007.0+7302 appears **slightly extended** in EPIC/MOS images
  - possible **structure in inner nebula** as seen in recent studies of other PWNe
- Radial profile exceeds PSF at R~10-30”



- Chandra observations (Halpern et al. 2004) reveal structure extending south of source
  - presumably a jet from a young pulsar

RX J0007.0+7302: Spectrum



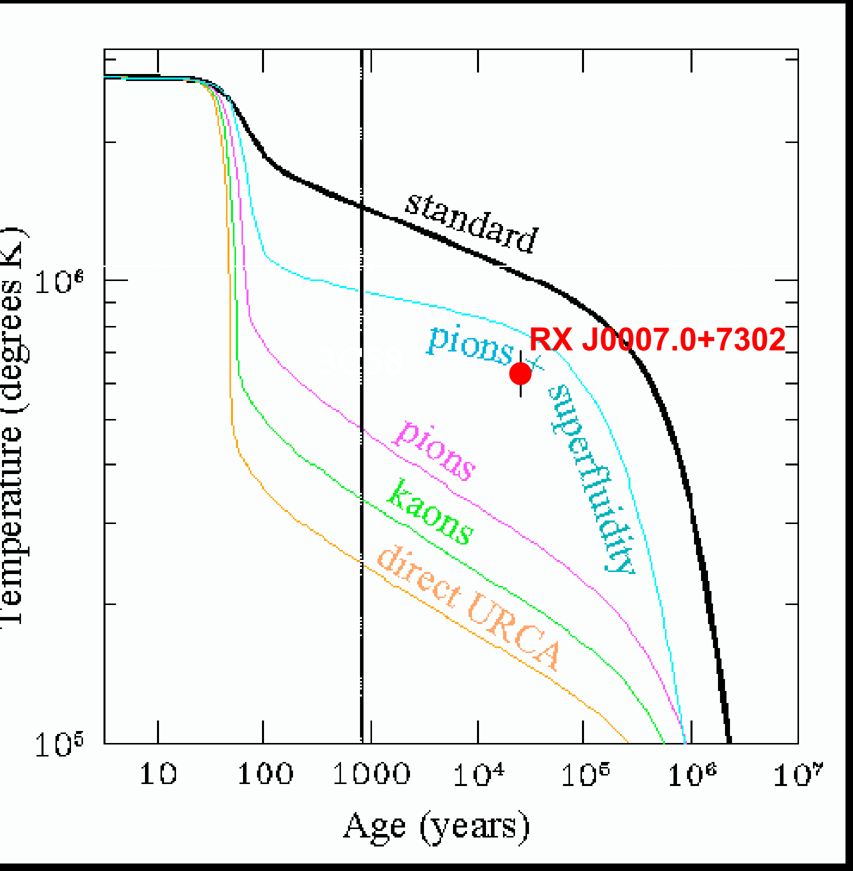
- For $N_H = 2.8 \times 10^{21}$ cm^{-2} (fixed at that for CTA 1), power law fit requires additional **soft component**

- **Power law:**

  $\Gamma = 1.5 \pm 0.2 \quad L_x = 4.7 \times 10^{31} D_{1.4}^2$ 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:

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

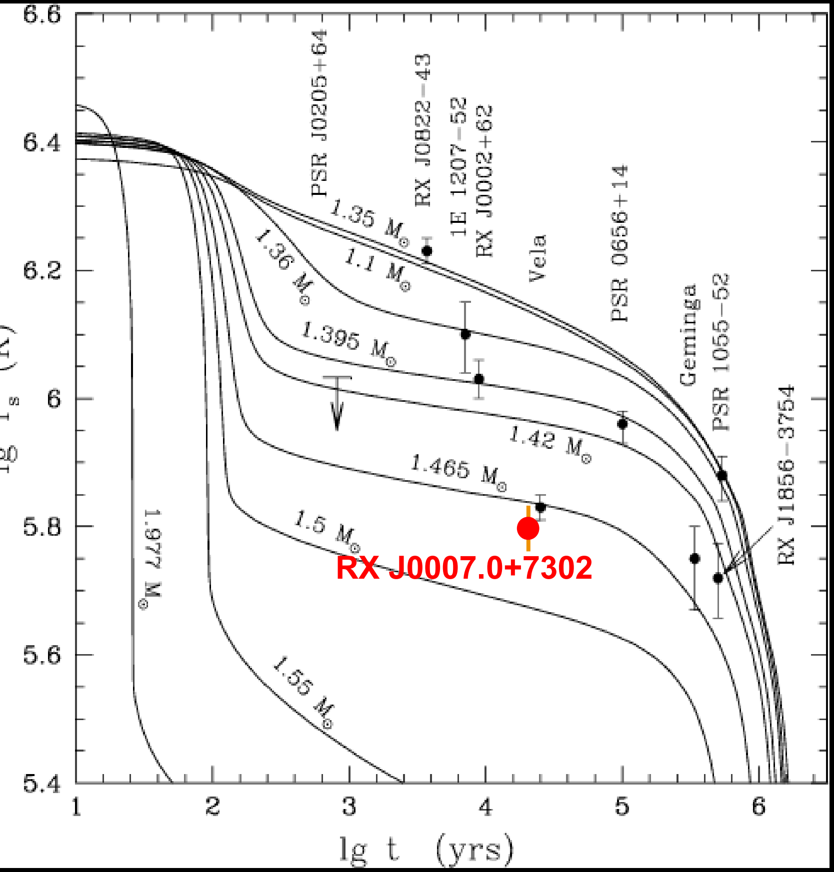
- temperature too high, and radius too small for cooling from entire NS surface
- suggestive of **hot polar cap emission**

Light NS Atmosphere: (Pavlov et al. 1995)
- for $R = 10$ 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:

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

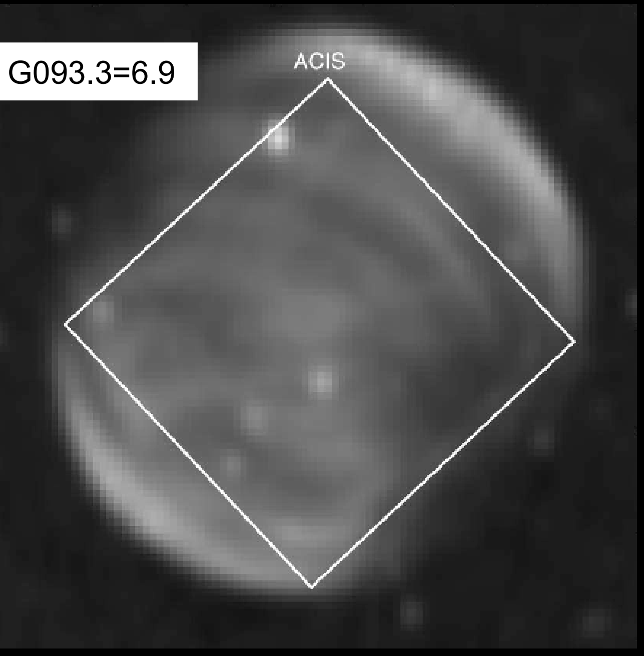
- temperature too high, and radius too small for cooling from entire NS surface
- suggestive of **hot polar cap emission**

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

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

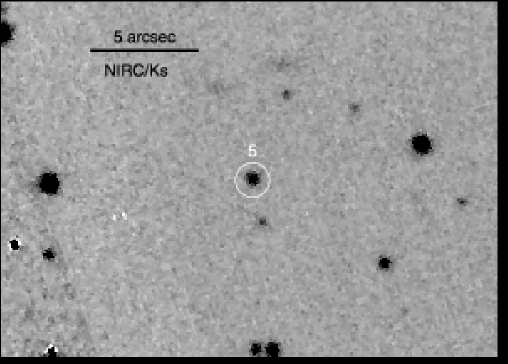
- this falls **below standard cooling** curves for the modified Urca process
- direct Urca cooling is consistent for $M \approx 1.46\, M_{sun}$ (Yakovlev et al. 2002)

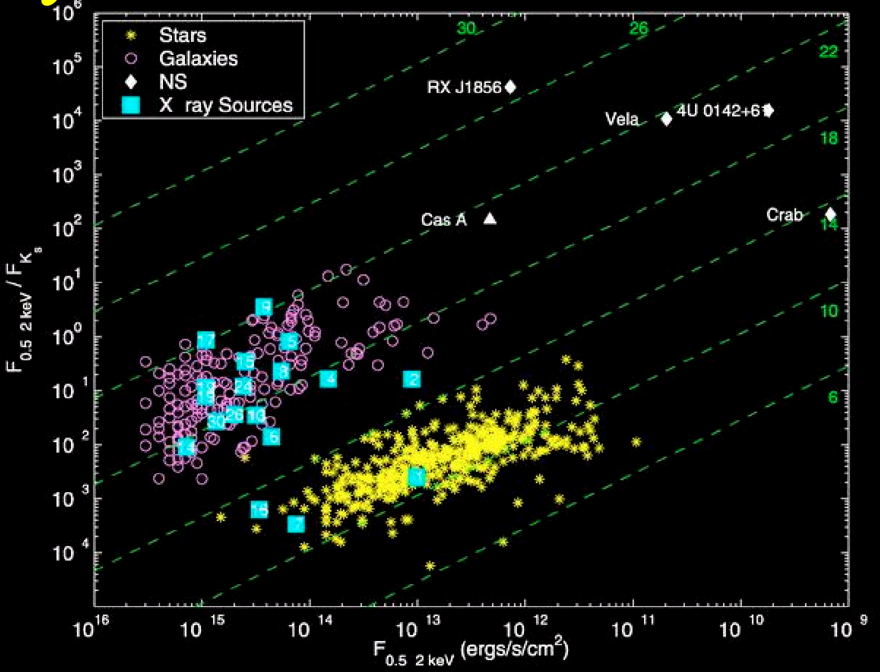
Limits from Nearby SNRs



log t ~ 3.3-4
D ~ 3.5 kpc

if θ > 8 arcmin,
v > 800 km/s





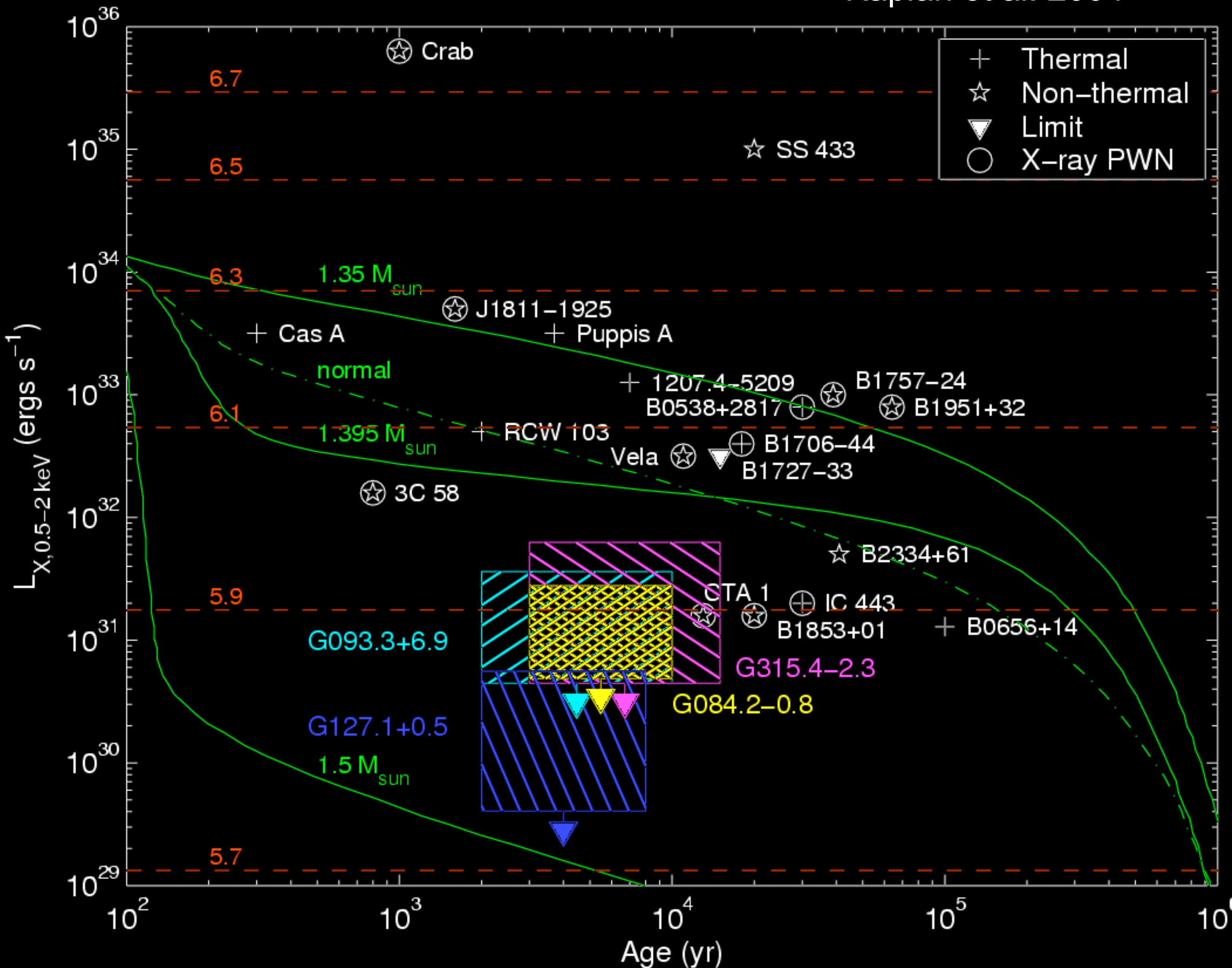
- **Conduct survey of SNRs w/ D < 5 kpc (part of D. Kaplan's thesis)**
  - use Chandra or XMM to detect X-ray sources in field
  - choose field size such that reasonable NS velocities will not move NS from field
  - choose exposures to detect source with luminosities 10x lower than faintest CCOs
  - 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
  - a rapidly cooling NS

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)

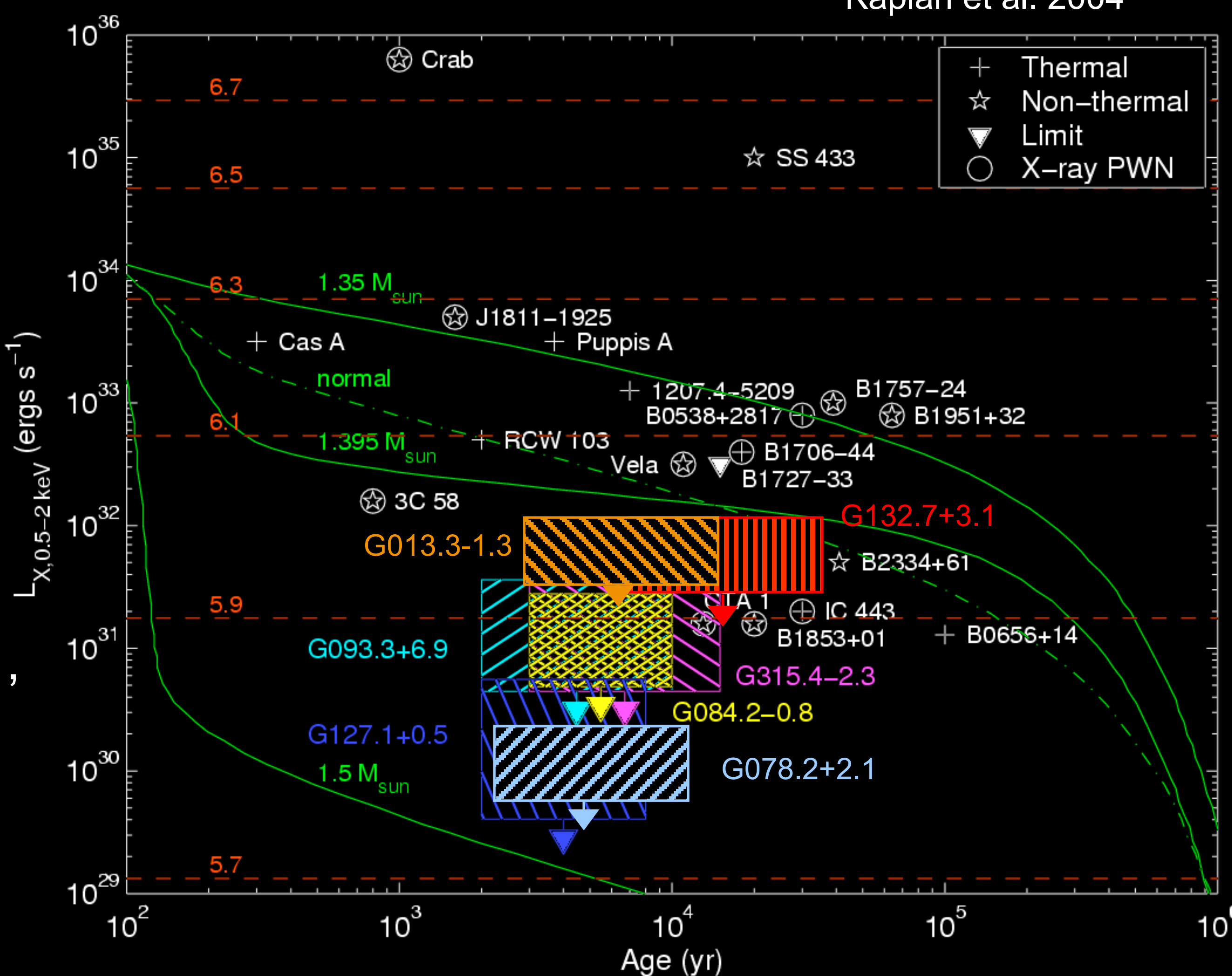
Kaplan et al. 2004



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



Summary

- **X-ray observations of young neutron stars provide strong constraints on cooling**
  - however, such measurements are difficult for a variety of reasons, and sensitivity drops rapidly with distance

- **Newly-discovered young pulsar in G21.5-0.9 has 2nd-highest dE/dt known**
  - large column density and column density, combined with extended emission from associated torus(?), prohibits strong cooling constraint from being determined

- **Neutron stars in 3C 58 and CTA 1 have spectra consistent with a weak H-atmosphere component**
  - temperature upper limits are below standard cooling
  - direct Urca probably required for 3C 58

- **Ongoing survey of nearby SNRs has promise for identifying new YNSs**
  - non-detections in G084.2-0.8, G093.3-6.9, G127.1+0.5, and G078.2+2.1 all provide strong constraints on cooling (assuming that there really are NSs in one or all of these SNRs)