A Detailed Study of

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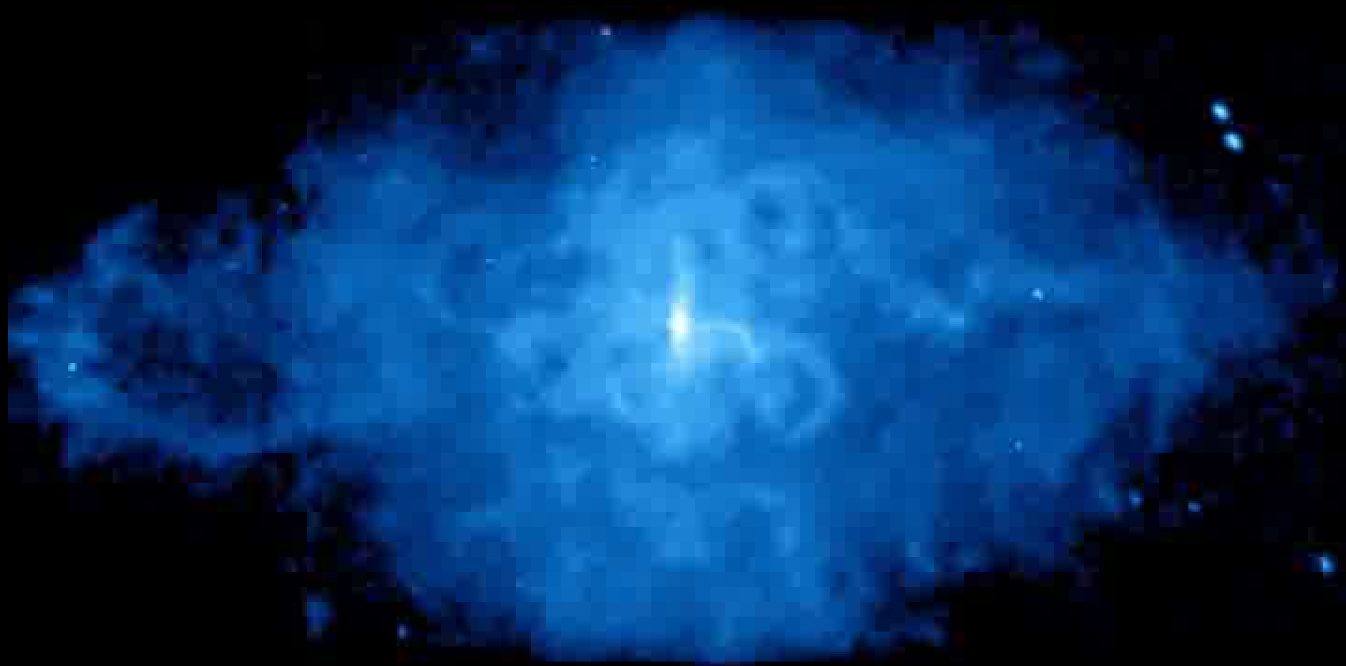

the Pulsar Wind Nebula 3C 58

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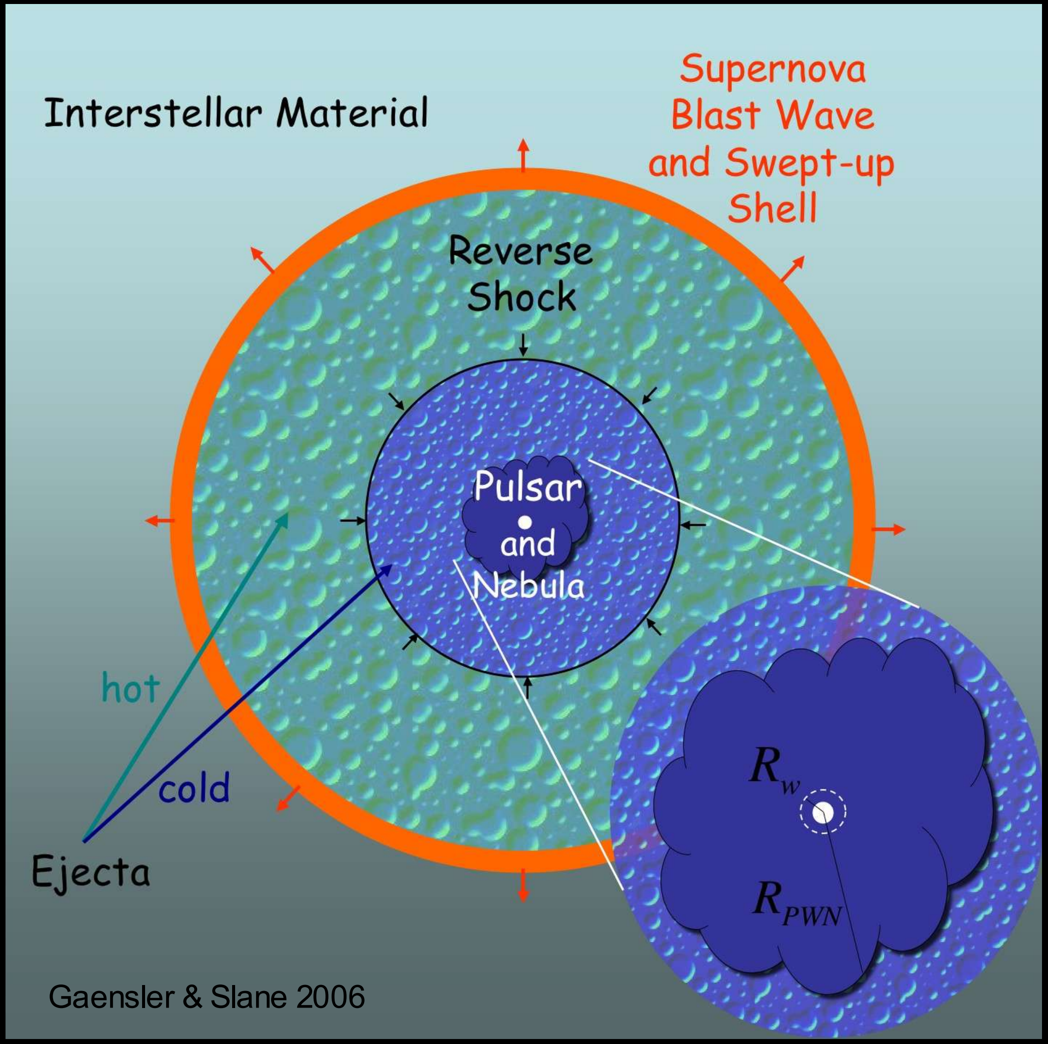
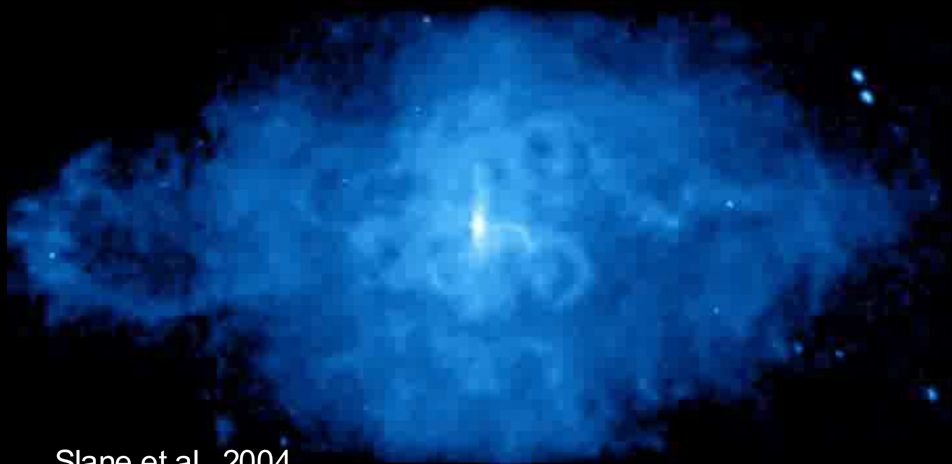
Pulsar Wind Nebulae

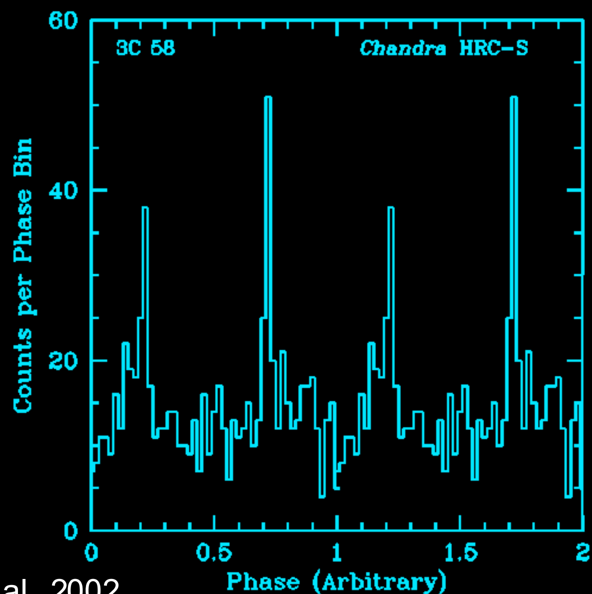


- **Young NS powers a particle/magnetic wind that expands into SNR ejecta**
  - toroidal magnetic field results in axisymmetric equatorial wind
- **Termination shock forms where pulsar wind meets slowly expanding nebula**
  - radius determined by balance of ram pressure and pressure in nebula
- **As PWN accelerates higher density ejecta, R-T instabilities form**
  - optical/radio filaments result
- **As SNR/PWN ages, reverse shock approaches/disrupts PWN**
  - not of interest in context of 3C 58 as no blast-wave component is seen (low n)

About 3C 58



Slane et al. 2004



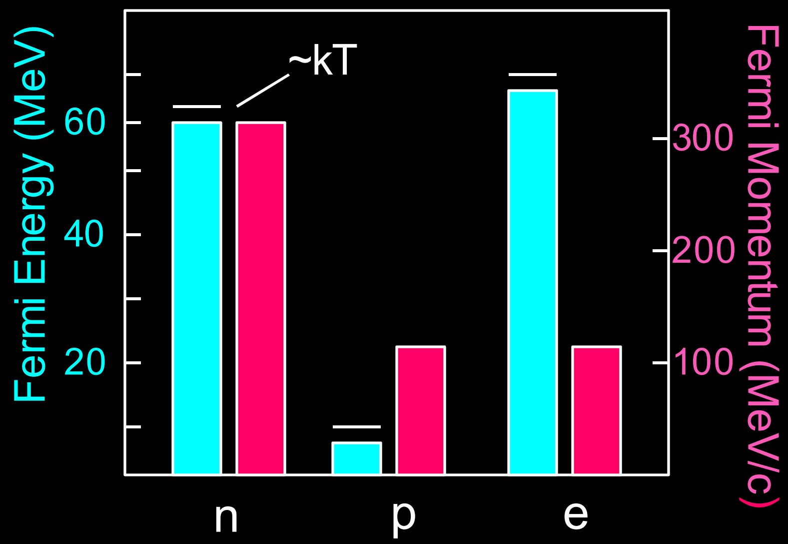
Murray et al. 2002

- **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)

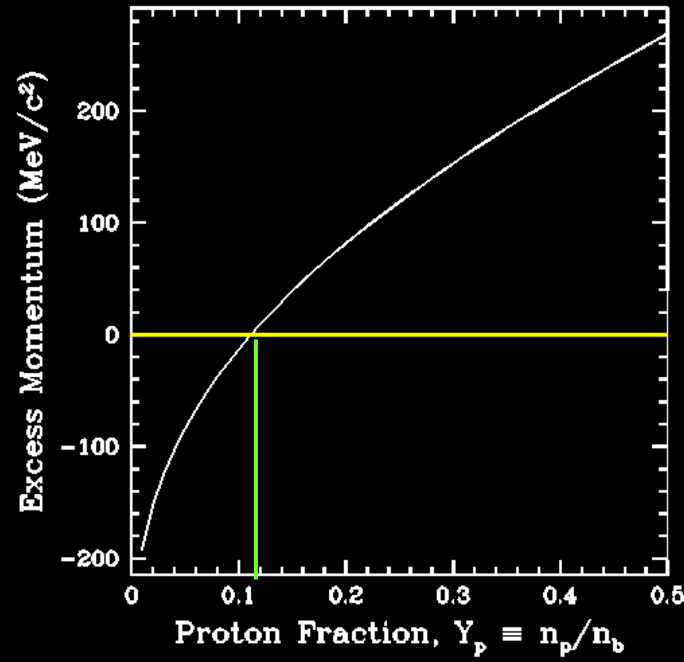
- **Believed to be associated w/ SN 1181 based on historical records**
  - pulsar has 3rd highest spin-down power of Galactic pulsars $\dot{E} = 3 \times 10^{37}$ erg s^{-1}

    ==> very young
  - however, PWN expansion velocity observed in optical filaments is too low to explain large size, making association troublesome

How Does the Neutron Star Interior Cool?



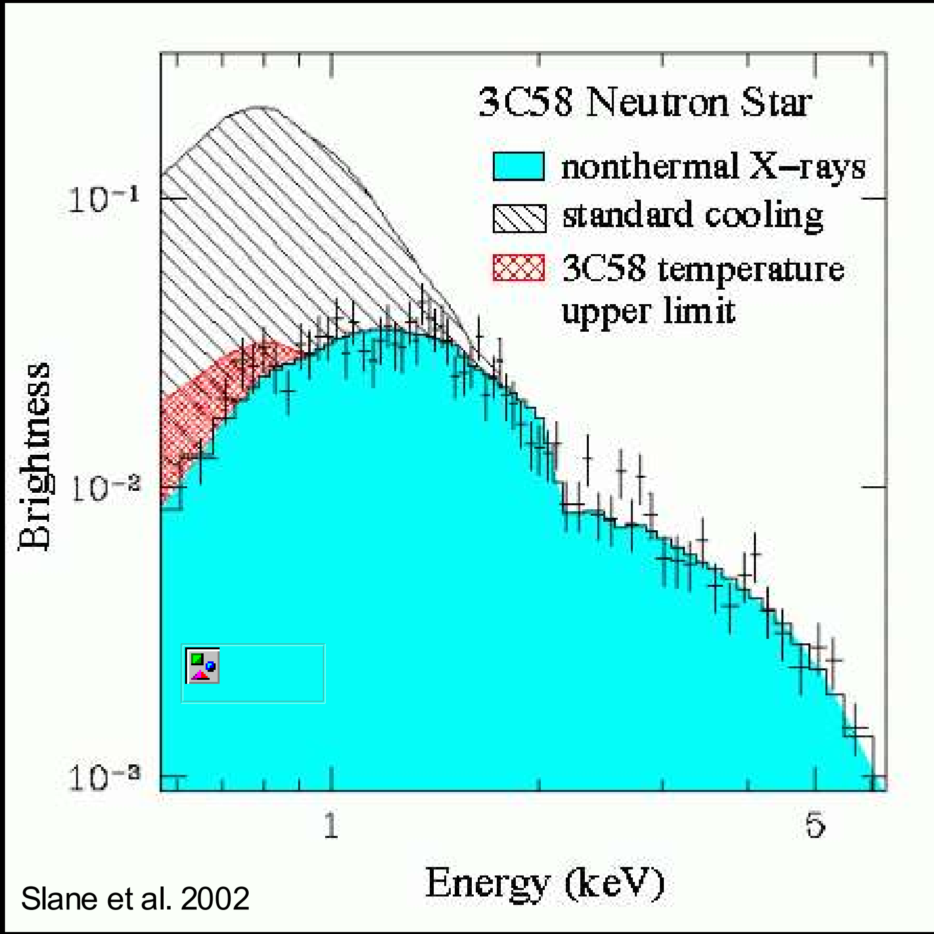
Urca process:

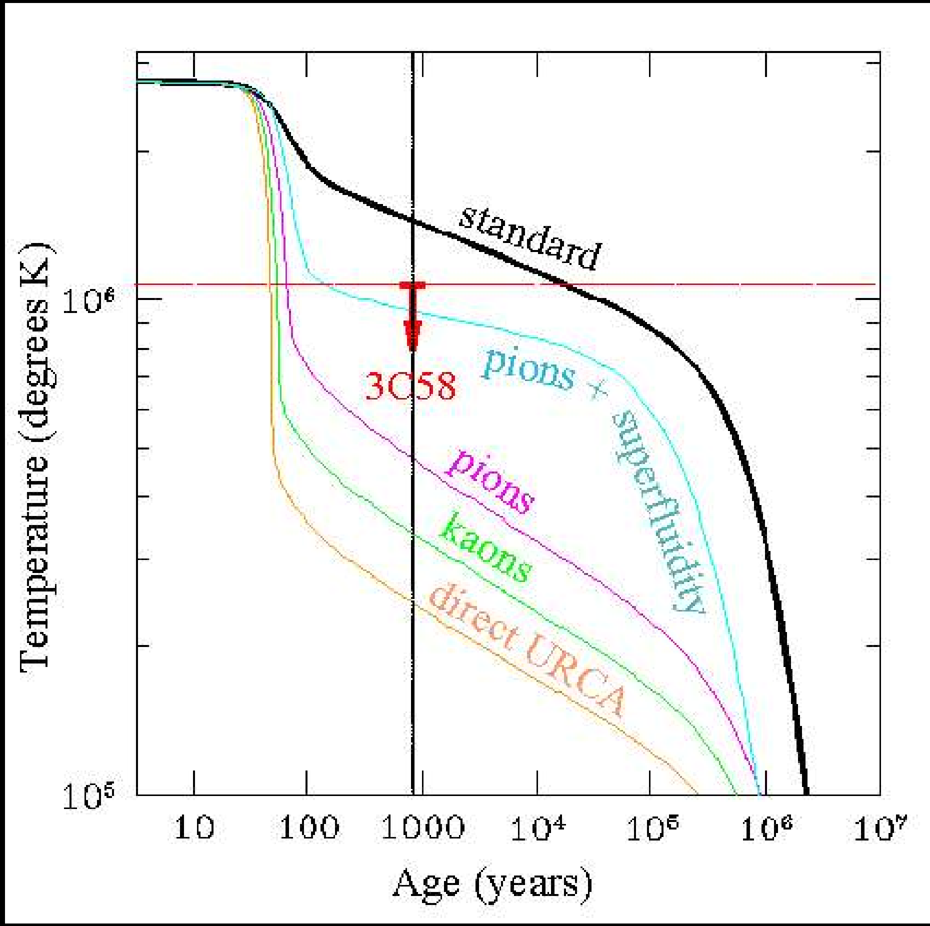


- **Charge neutrality requires:**
- **NS matter is highly degenerate**
- **Momentum conservation requires**

- **We thus require**
  - momentum can only be conserved for Urca reactions if proton fraction is >0.12
  - for lower values, need bystander particle to conserve momentum

PSR J0205+6449: Cooling Emission

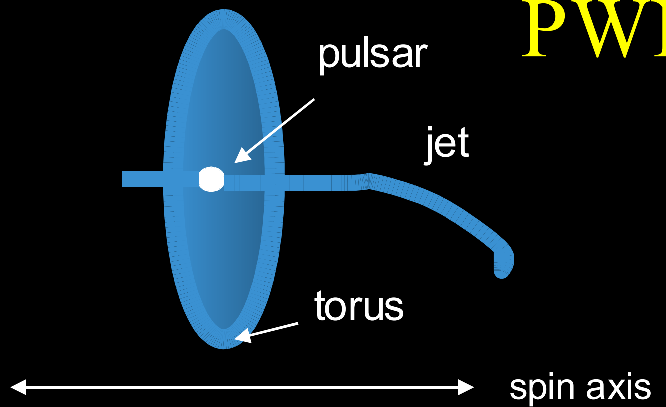


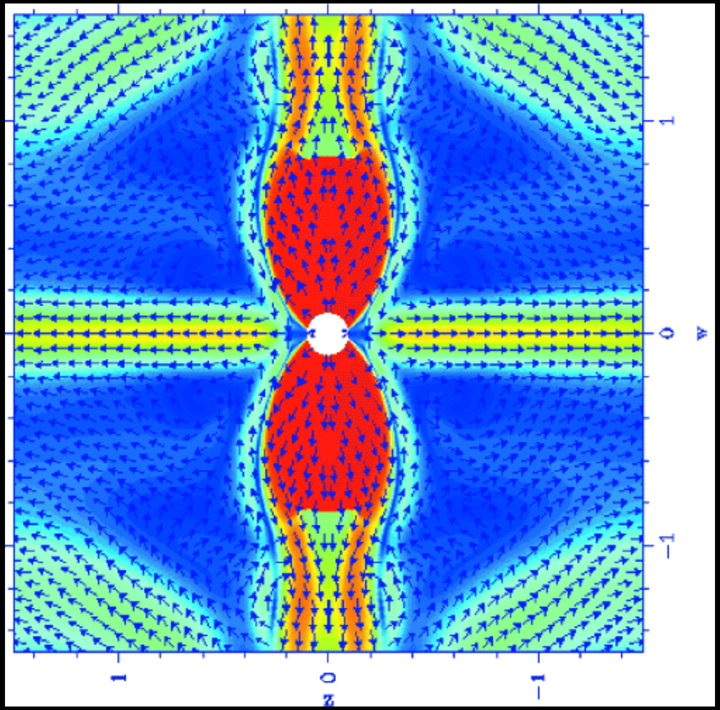


- **Point source spectrum is a power law; adding blackbody component leads to limit on surface cooling emission**
  - since atmosphere effects harden spectrum, limit on surface temperature is conservative

- **For NS w/ *R* = 10 km,**
  - standard cooling models predict higher temperature for this age
  - may indicate direct Urca or pion cooling

PWN Jet/Torus Structure





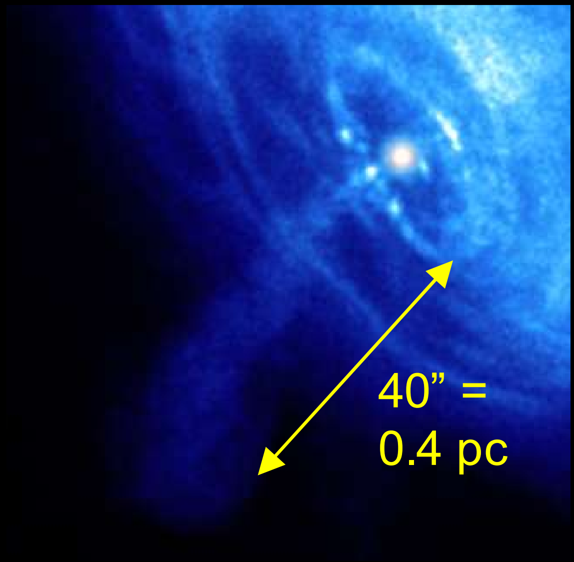
Komissarov & Lyubarsky 2003

- **Poynting flux from outside pulsar light cylinder is concentrated in equatorial region due to wound-up B-field**
  - termination shock radius decreases with increasing angle from equator

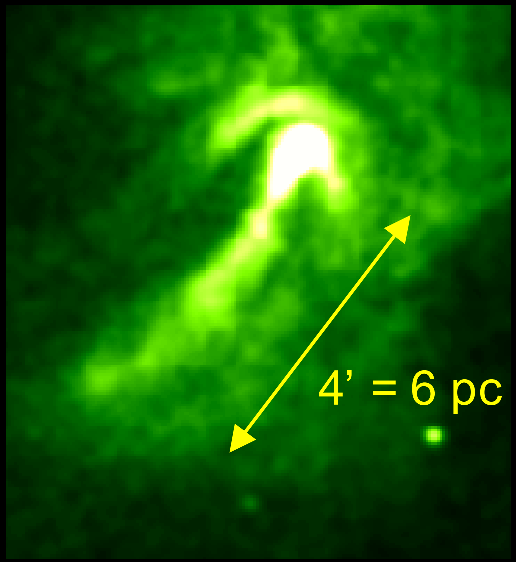
- **For sufficiently high magnetization parameter ($\sigma \sim 0.01$), magnetic stresses can divert particle flow back inward**
  - collimation into jets may occur
  - asymmetric brightness profile from Doppler beaming

- **Collimation is subject to kink instabilities**
  - magnetic loops can be torn off near TS and expand into PWN (Begelman 1998)
  - many pulsar jets are kinked or unstable, supporting this picture

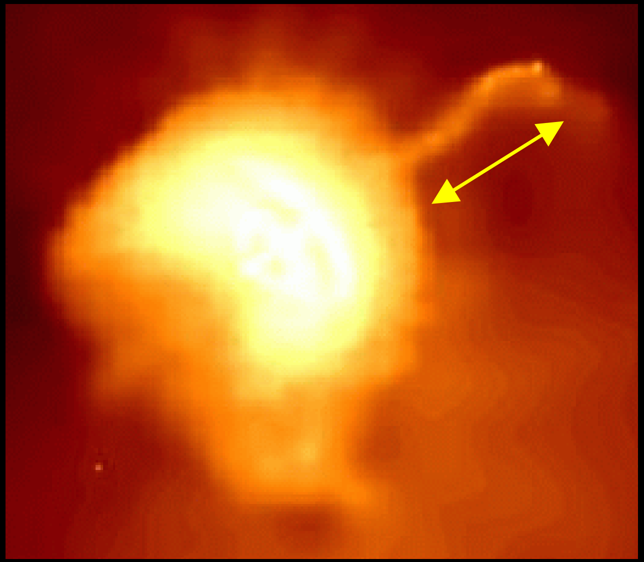
Inner Structure in PWNe: Jets



Crab Nebula (Weisskopf et al 2000)

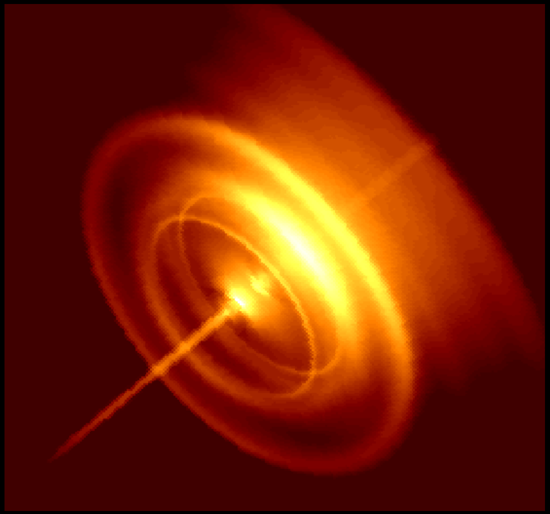


PSR B1509-58 (Gaensler et al 2002)



Vela PWN (Pavlov et al 2003)

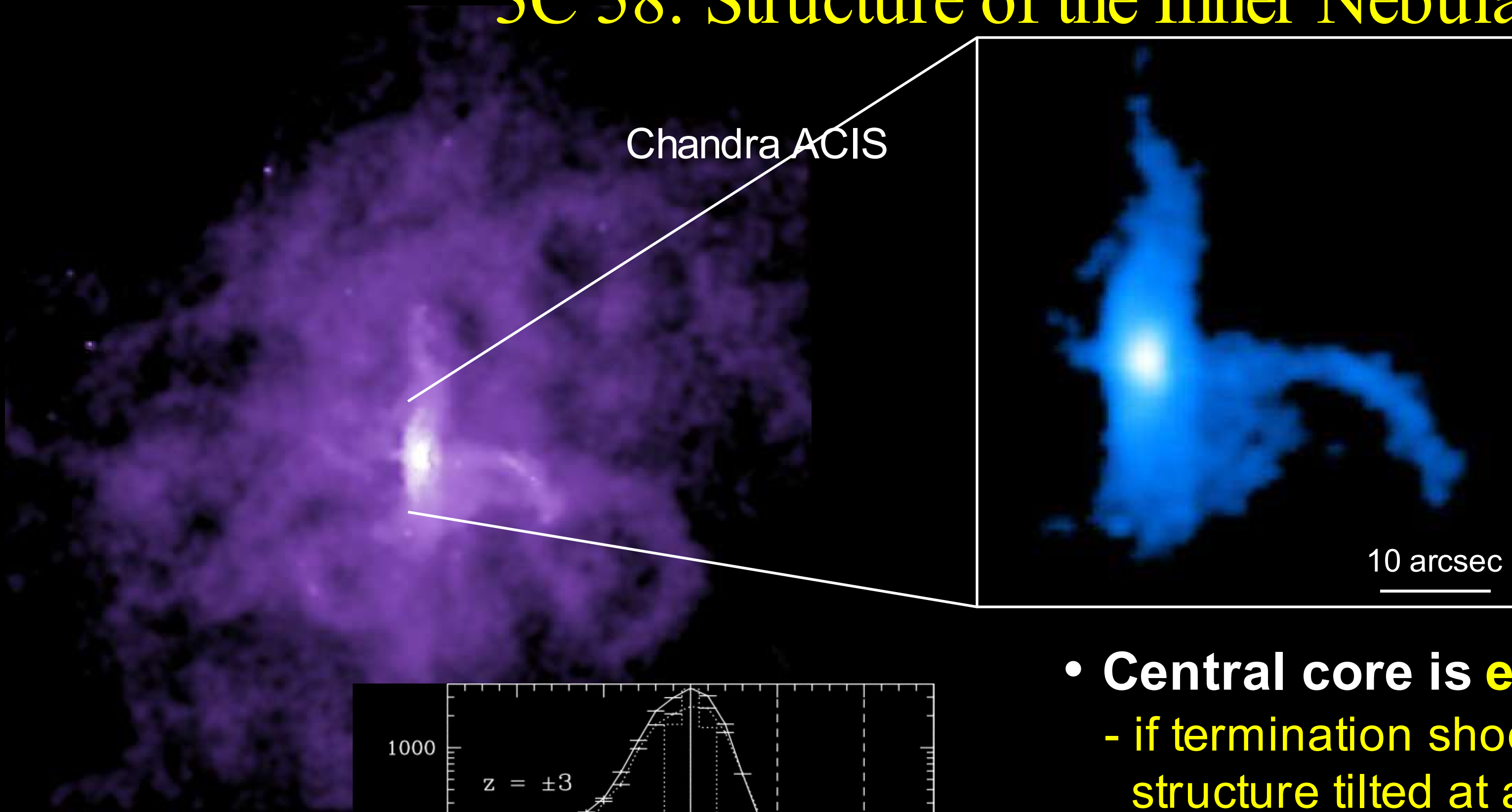
- **Collimated features**
  - some curved at ends – why?
- **Wide range in brightness and size (0.01–6 pc)**
  - how much energy input?
- **Perpendicular to inner ring**
  - directed along spin axis?

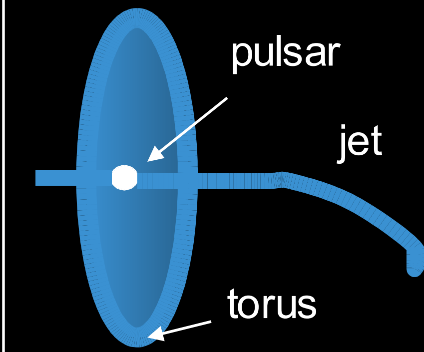


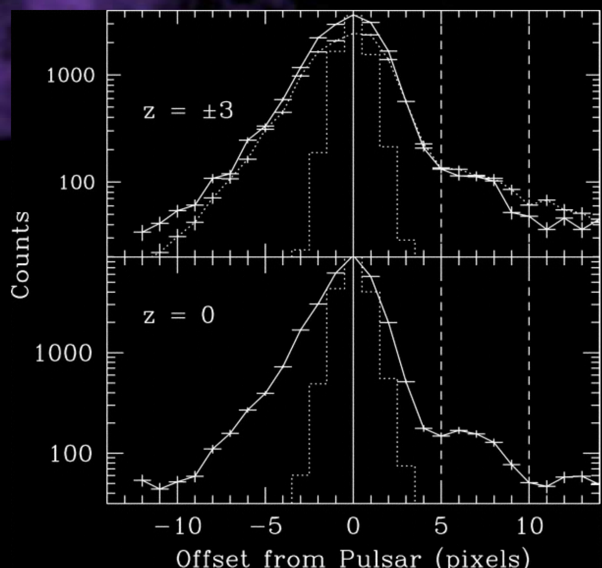
Kommisarov & Lyubarsky (2003)

- **Relativistic flows:**
  - motion, spectral analysis give v/c ~ 0.3–0.6
- **Primarily one-sided**
  - Doppler boosting?
- **Magnetic collimation / hoop stress?**

3C 58: Structure of the Inner Nebula

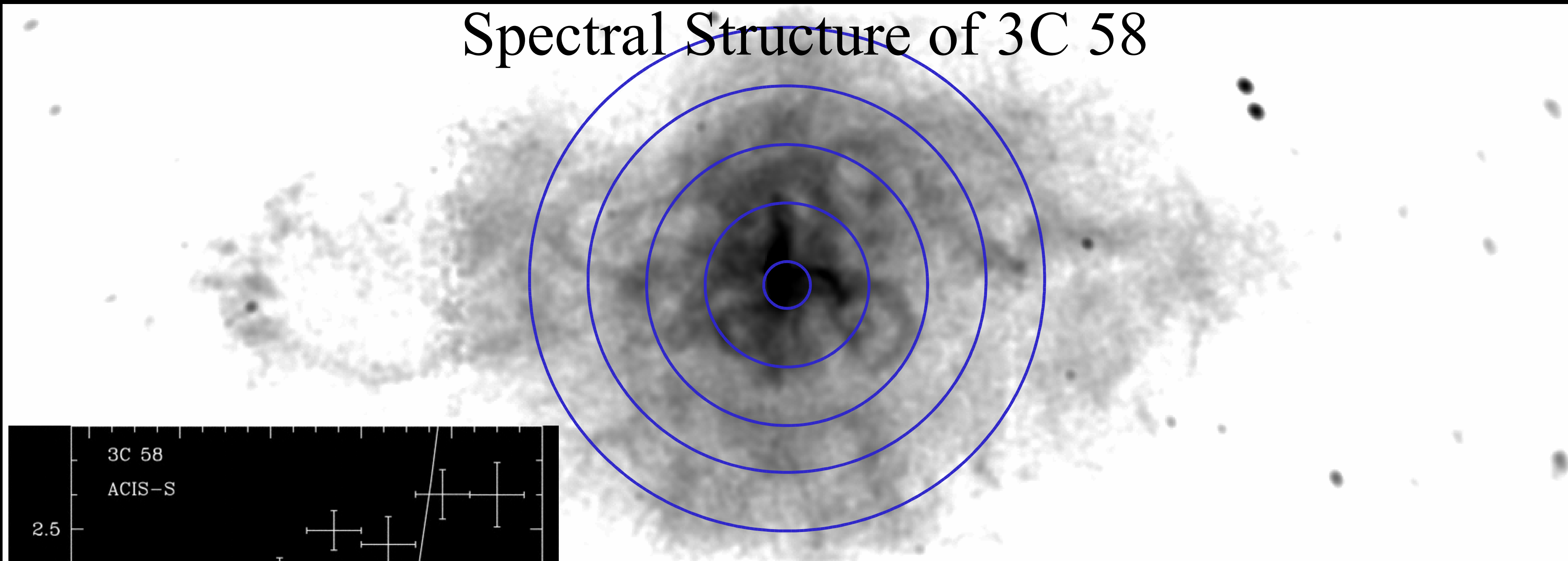


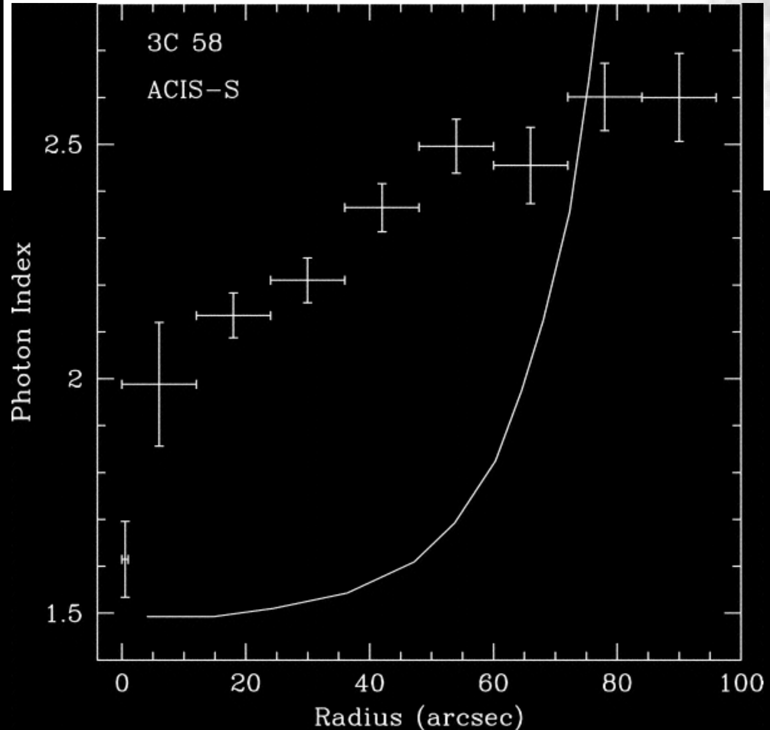




- **Central core is extended N/S**
  - if termination shock, suggests ring-like structure tilted at about 70 degrees
  - agrees w/ spindown
  - profile shows bump from torus
- **Suggests E-W axis for pulsar**
  - consistent with E-W elongation of 3C 58 itself due to pressure from toroidal field (van der Swaluw 2003)

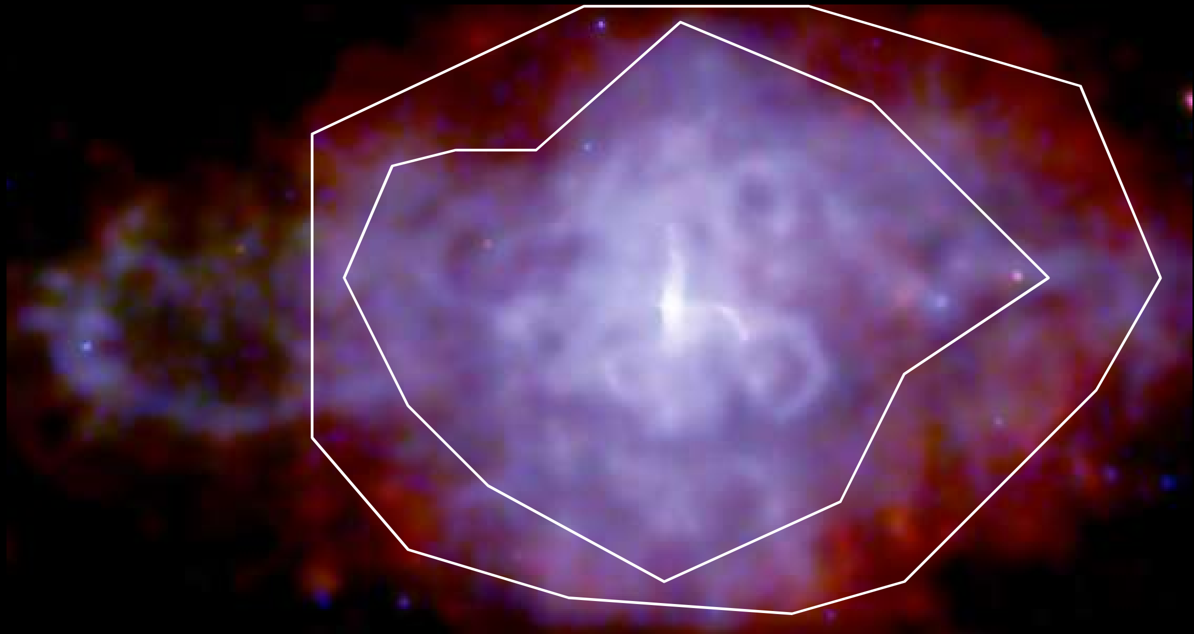
Spectral Structure of 3C 58



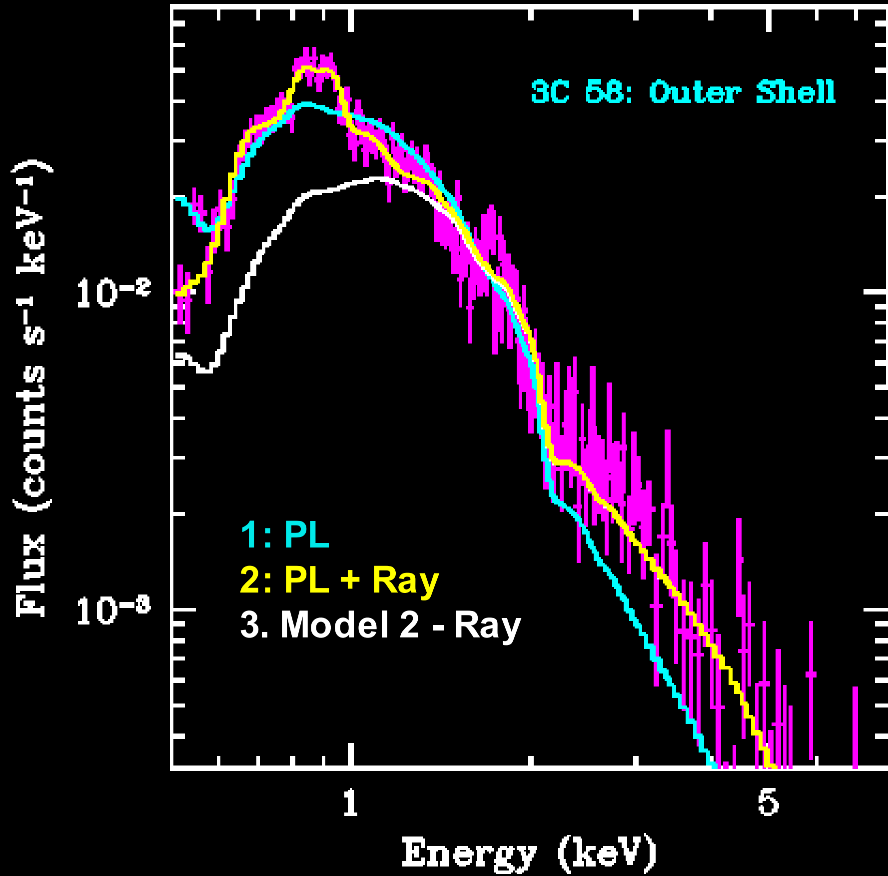


- **Radial steepening of spectral index shows aging of synchrotron-emitting electrons**
  - consistent with injection from central pulsar
- **Modeling of spectral index in expected toroidal field is <u>unable</u> to reproduce the observed profiles**
  - model profile has much more rapid softening of spectrum (Reynolds 2003)
  - diffusive particle transport and mixing may be occurring

3C 58: A Thermal Shell



Slane et al. 2004

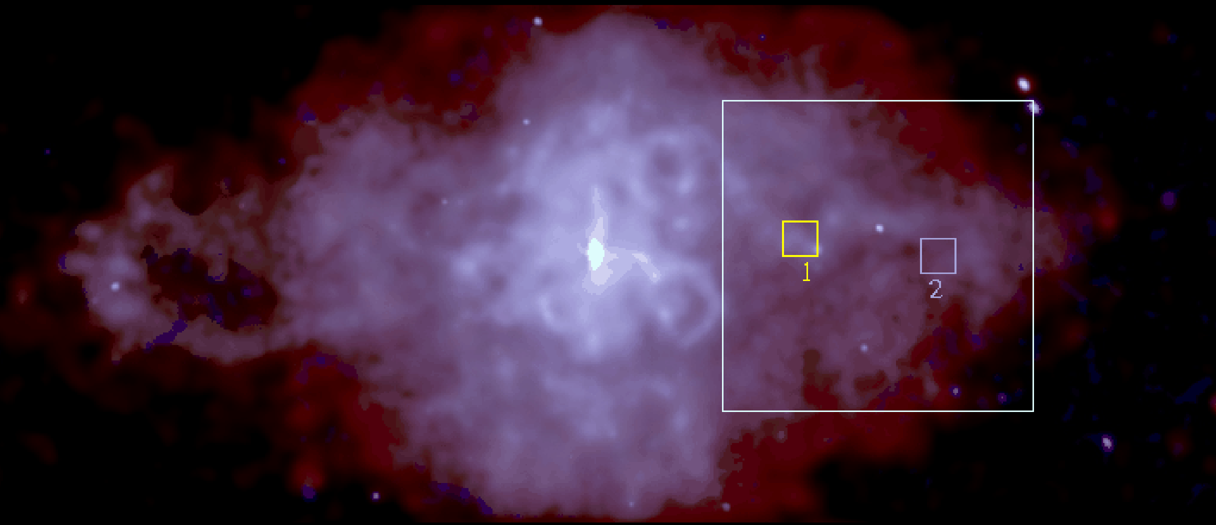


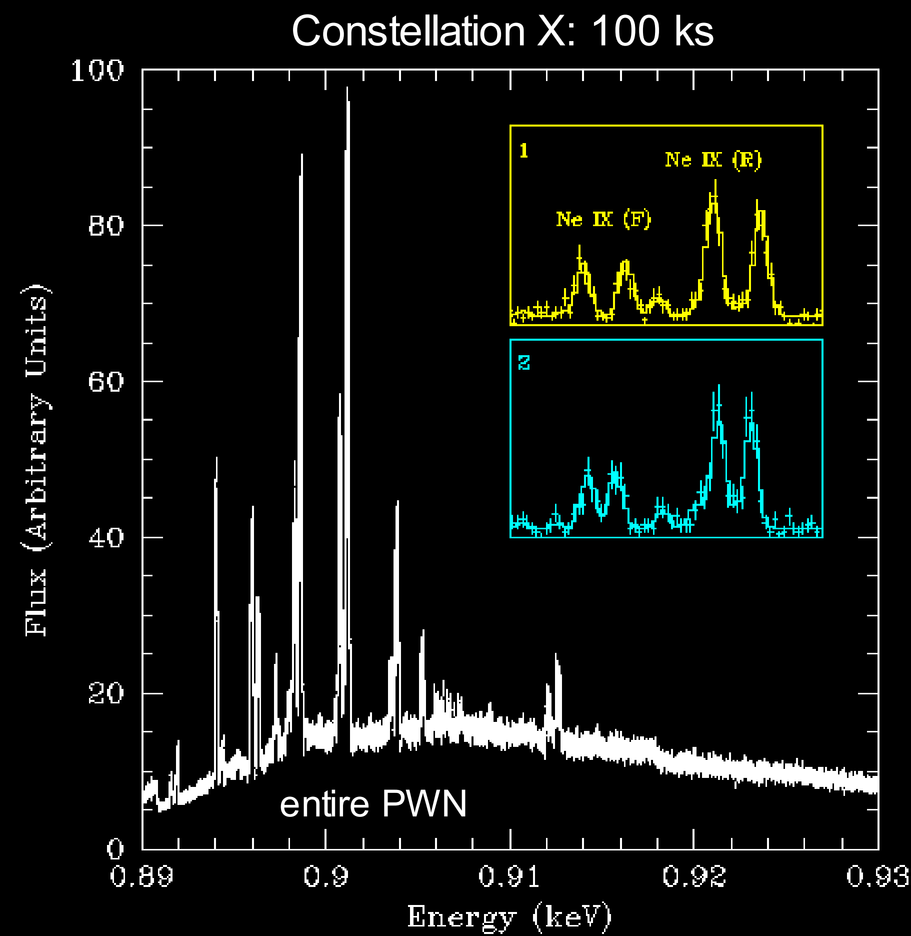
- Outer region shows thermal emission (Bocchino et al. 2001)

  - Chandra confirms presence of a thermal shell
  - corresponds to ~0.06 solar masses
  - 3C 58 has evolved in a very low density region

- Thermal component requires enhanced neon
  - consistent with ejecta being swept up by PWN

Getting Ahead of Ourselves…

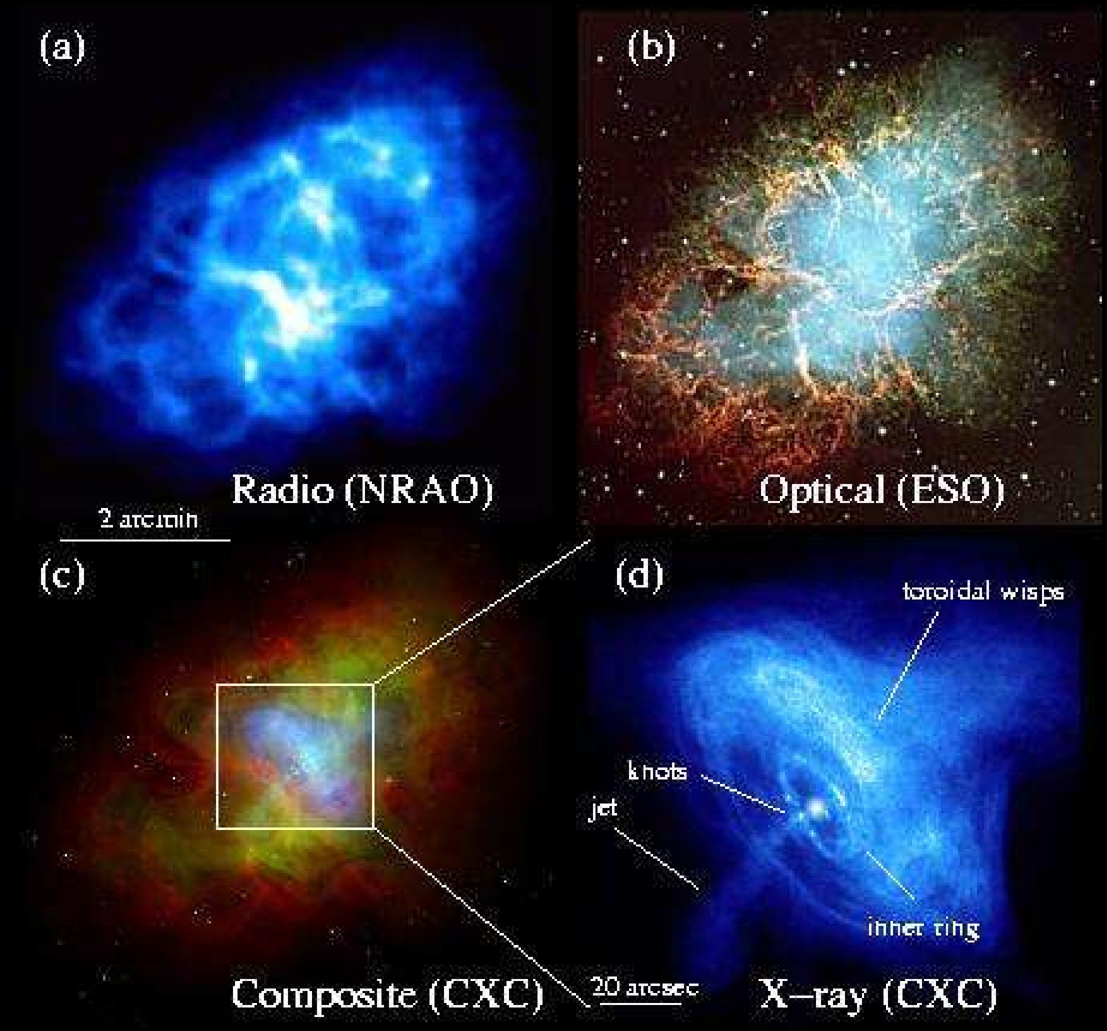




- **Current Con-X baseline gives ~16000 counts in Ne line in a 100 ks observation**

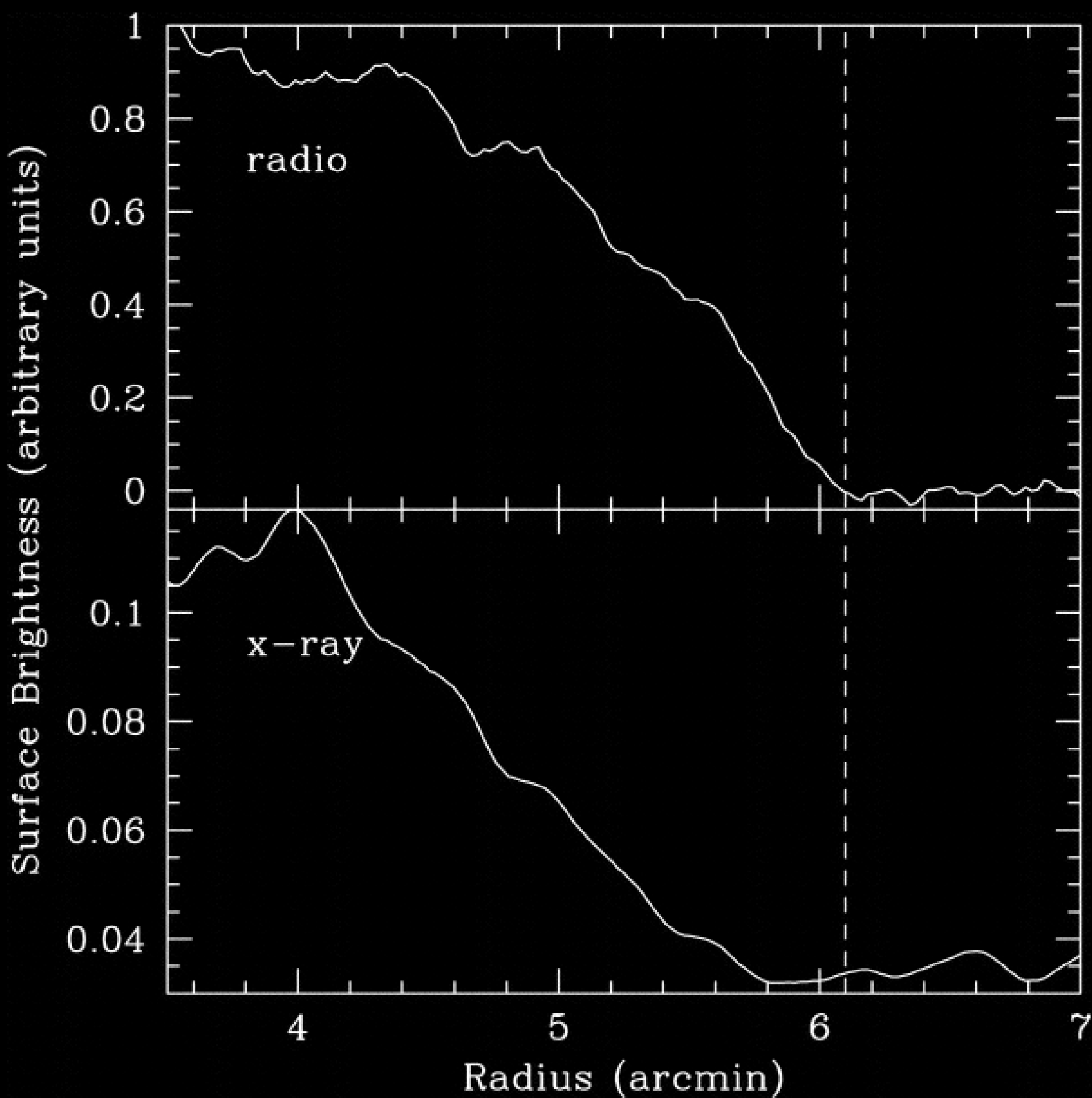
- **Can measure velocity shift of front/back shell to address discrepancy in expansion**
  - variation in projected velocity with radius easily measured as well

Filaments in PWNe



- **As PWN expands, it encounters and accelerates denser ejecta**
  - Rayleigh-Taylor instabilities form a network of optical line-emitting filaments
  - compressed magnetic field enhances synchrotron emission as well, creating radio filaments
- **In Crab Nebula, velocities show that filaments form a shell**
  - X-ray filaments not seen because B-field is too large for energetic particles to reach outskirts of nebula

3C 58: Radio vs X-ray Size



- **The X-ray emission from 3C 58 extends virtually all the way to the radio boundary**
  - magnetic is smaller than in Crab; synchrotron break must be just below X-ray band

- **In this case, we might expect to see X-ray filaments as well**

Filamentary Structure in 3C 58


Slane et al. 2004

- **X-ray emission shows considerable filamentary structure**
  - particularly evident in higher energy X-rays
- **Radio structure is <u>remarkably</u> similar, both for filaments and overall size**

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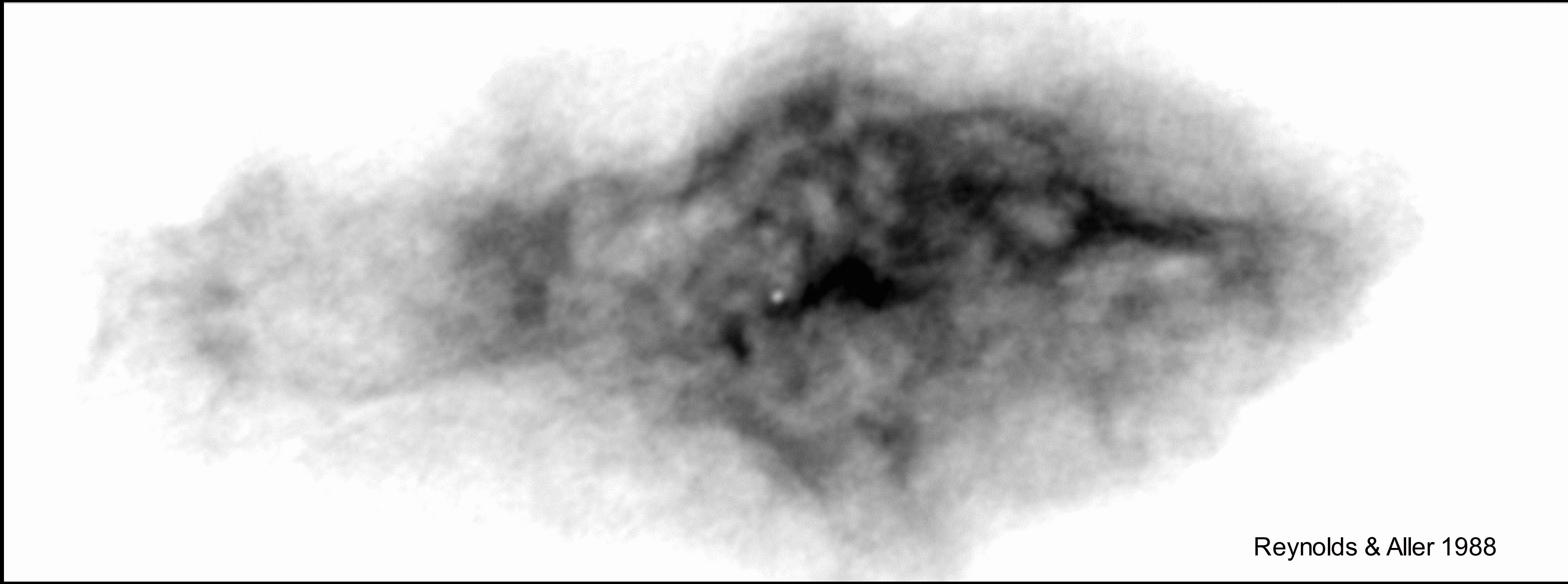

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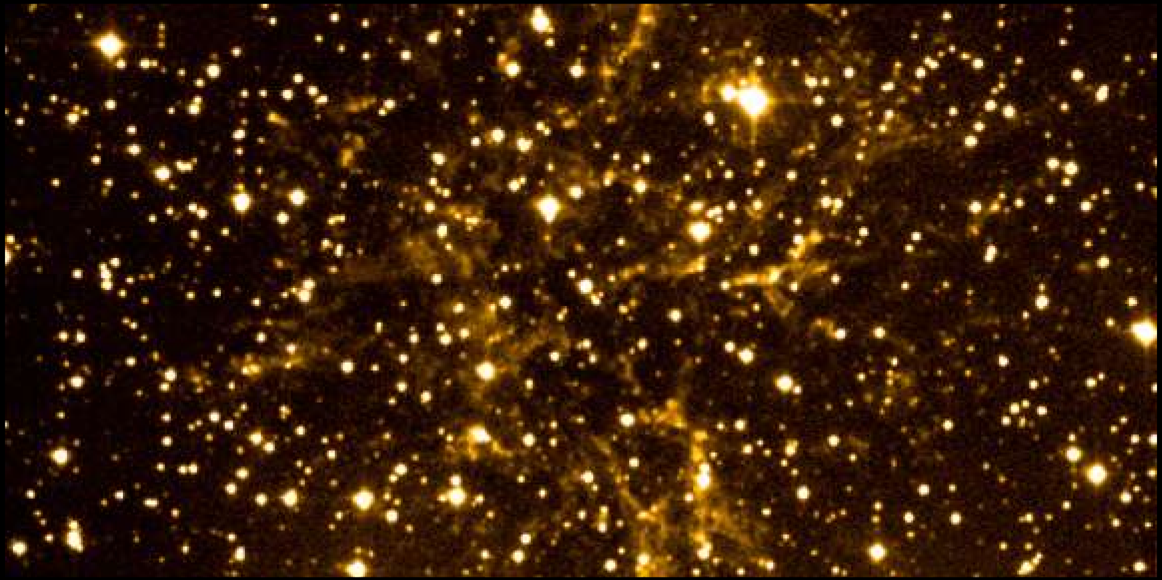
Optical Filaments in 3C 58



- **Considerable filamentary structure is seen in optical images of 3C 58**
  - these are presumably similar in nature to Crab optical filaments; evidence of ejecta encountered by expanding PWN
- **These filaments do not seem to have X-ray counterparts (with a few possible exceptions)**
  - indicative of a different origin?
- **Loop-like structure and lack of thermal emission suggest magnetic structures**
  - produced by kink instabilities in toroidal field (Begelman 1998)?
  - may also be responsible for curved jets seen in Crab, Vela, 3C 58, and others

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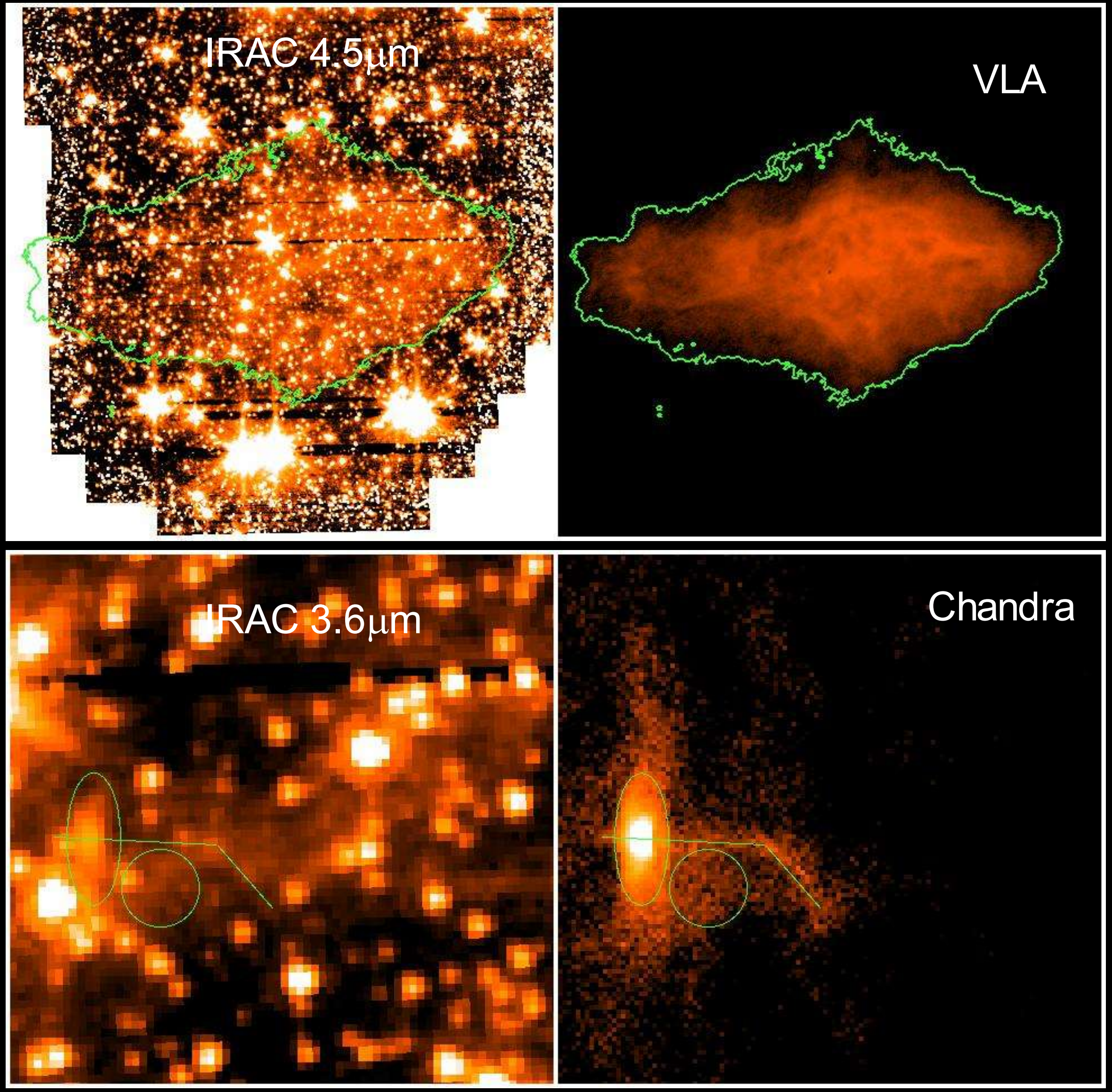
IRAC Observations of 3C 58



- **PWN clearly detected**
  - extent and morphology similar to radio
  - suggestions synchrotron emission in IR

- **Torus region around pulsar detected as well**

Summary

- 3C 58 is a typical PWN powered by a young, energetic pulsar

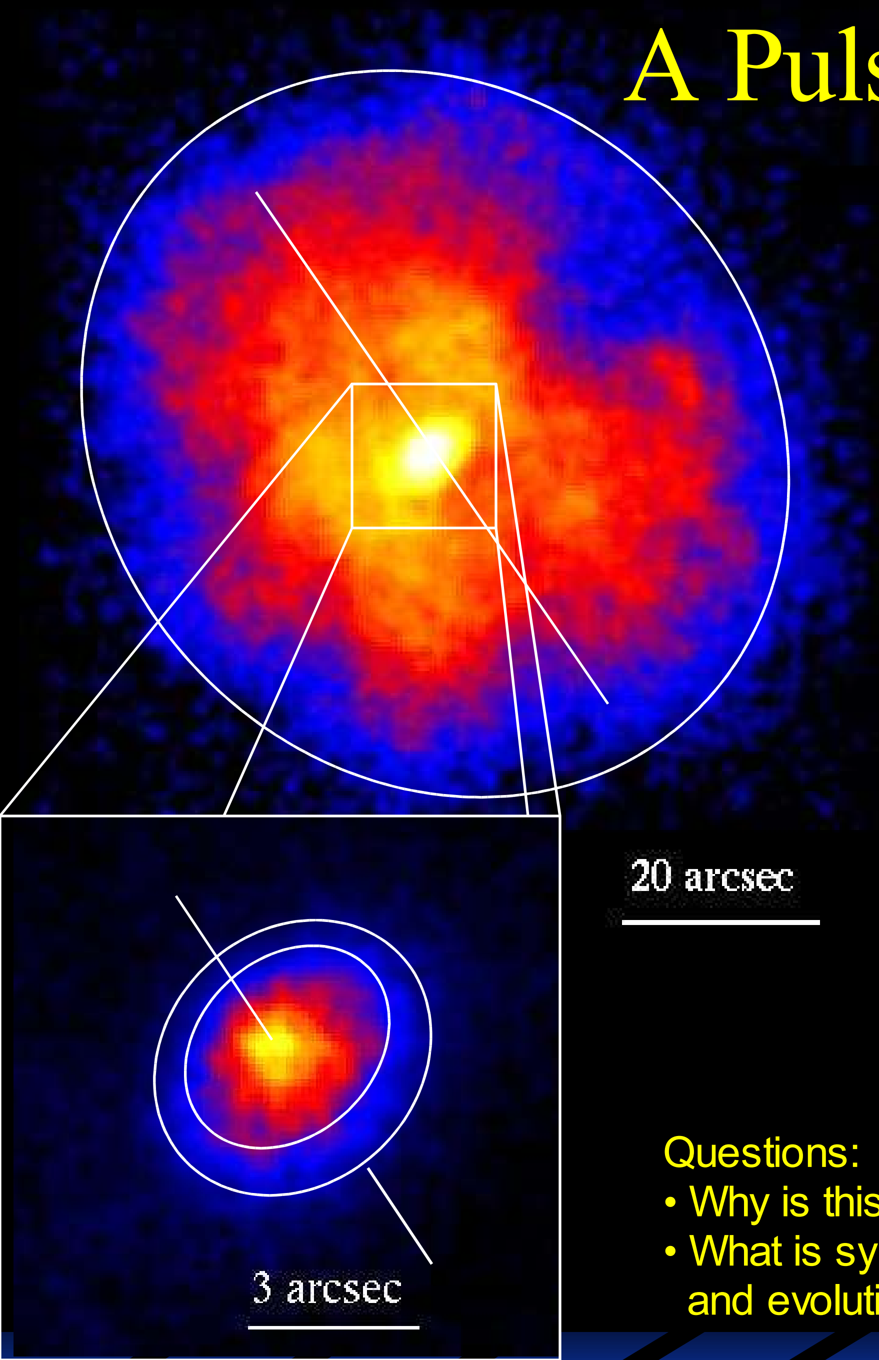
- Limits on blackbody emission from NS indicate nonstandard cooling
  - interpretations with direct Urca processes or pion condensates are suggested

- Central X-ray source is extended in N-S direction
  - consistent with wind termination shock
  - indicates E-W pulsar axis with 70 degree tilt to line of sight
  - deep observation resolves jet/torus structure

- Outer nebula has thermal shell
  - overabundance of Ne indicates ejecta component
  - total mass of shocked gas is small; radius implies small ejecta mass

- Inner nebula shows numerous loop-like and extended structures
  - radio structure is remarkably similar
  - optical filaments do <u>not</u> show good coincidence w/ X-ray features
  - different origin? (kink instability structures?)

A Pulsar in G21.5-0.9



- Camilo et al. (2005 - submitted)

$P = 61.8$ ms, $\dot{E} = 3.3 \times 10^{37}$ erg s^{-1}, $\tau = 4.8$ kyr

  - 2nd highest spin-down power, next to Crab
  - faint in radio: 70 μJy @1.4 GHz

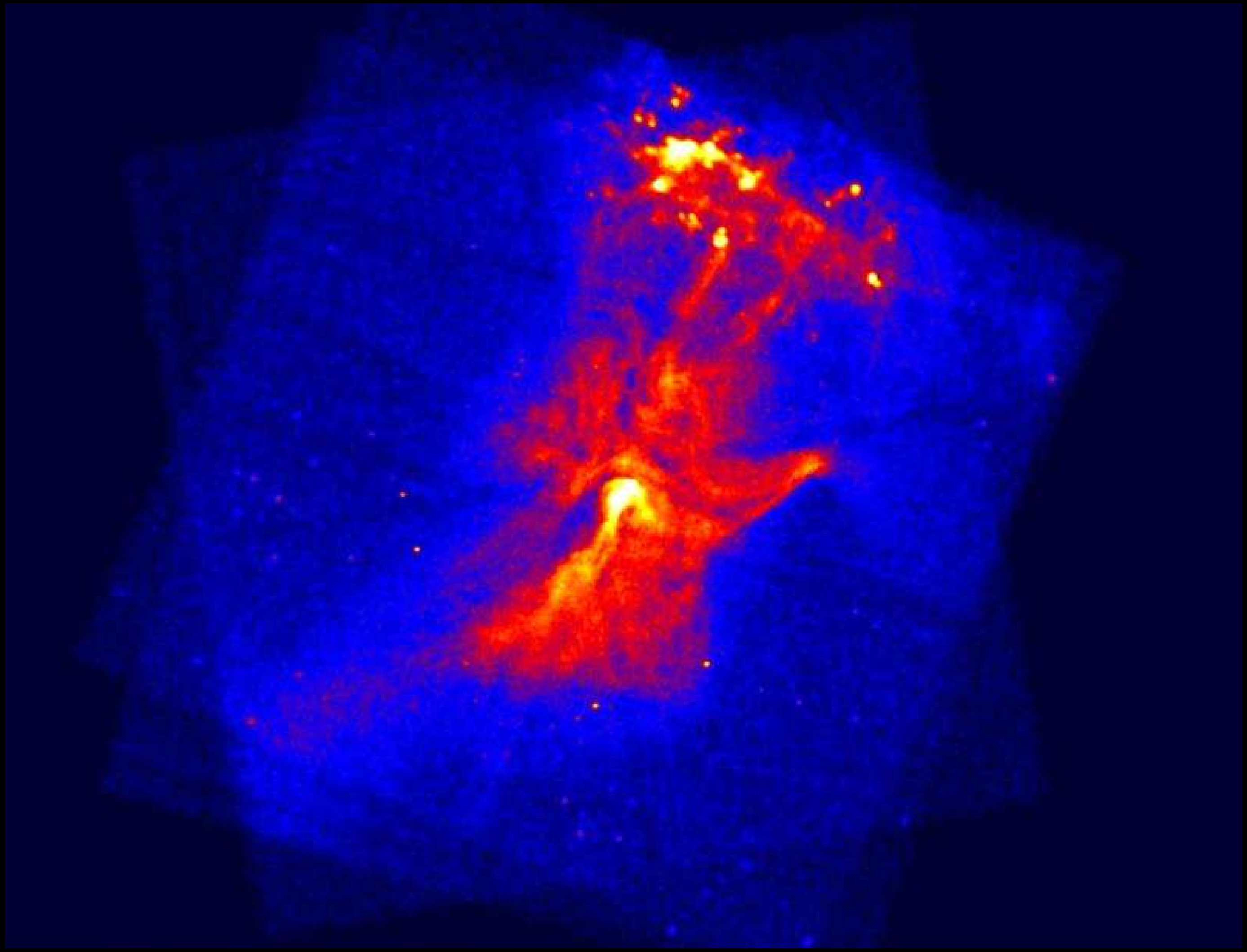
- 350 ks HRC image shows compact object embedded in extended core
  - offset from center suggests tilted torus w/ spin axis in NE/SW direction

- No pulsations seen in 30 ks HRC timing data
  - pulsed fraction may not be extremely low; surrounding core is bright

- PWN is extended along same NE/SW direction, as with other such systems
  - "bay" in NW is along inferred equatorial plane - similar to Crab "bays"

Questions:
- Why is this young, energetic pulsar so faint?
- What is symmetric filamentary structure telling us about the geometry and evolution?

PSR B1509-58



Just Completed…