THE GEORGE WASHINGTON UNIVERSITY
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# Deep Chandra Observations Nebulae Produced by Three Supersonic Pulsars


Physics of Neutron Stars 2017

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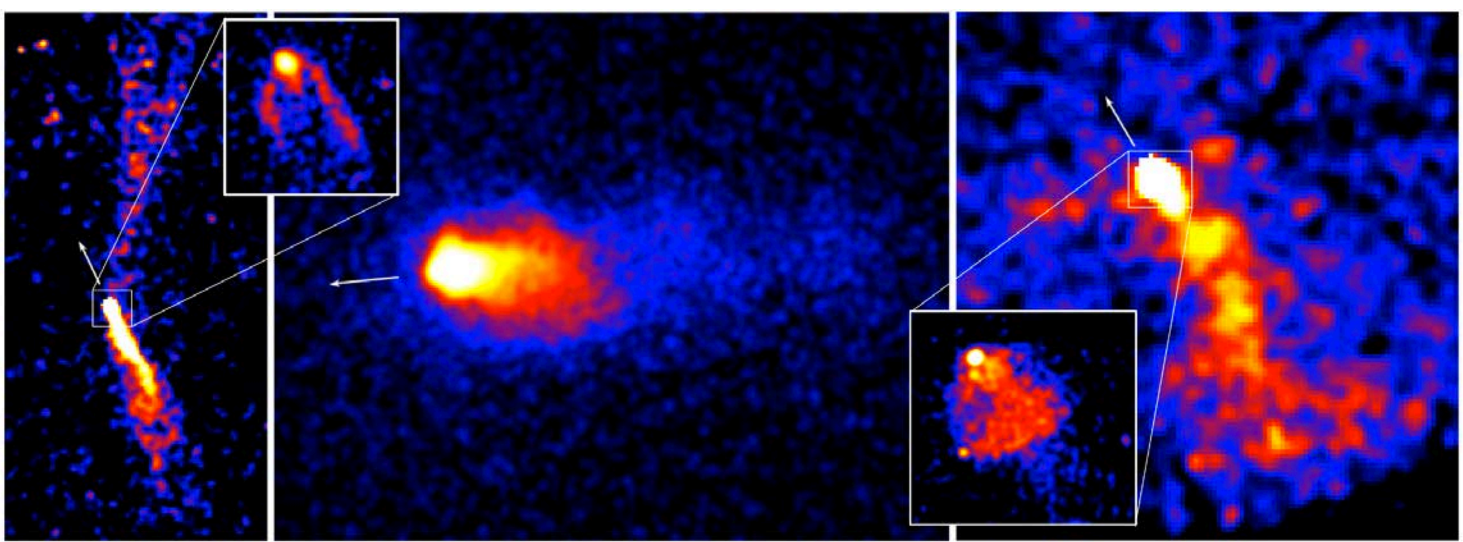


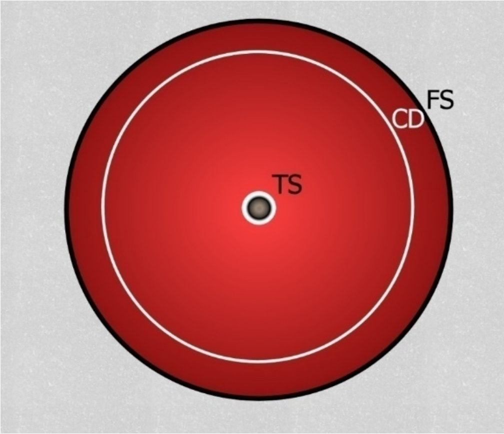
# Overview

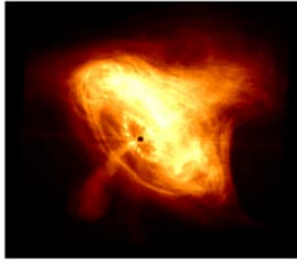
- Supersonic pulsars & SPWNe
- Objects of interest: key features
  - J1509-5850
  - B0355+54
  - J1747-2958 (the Mouse)
- Compact Nebulae (CN) Morphology
  - connection to pulsar geometry and light curves
- Misaligned outflows
- Spatially-resolved spectroscopy
  - spectral cooling, multiwavelength analysis, tail properties
- Comparison of pulsar tails and trends

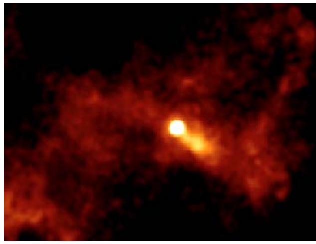
# PWN & Pulsar Velocity

- PWN morphologies depend on pulsar velocity $v_{PSR}$, ISM sound speed $c_{S,ISM}$, and intrinsic outflow anisotropy
  - Most important parameter: Mach number $M = v_{PSR} / c_{S,ISM}$

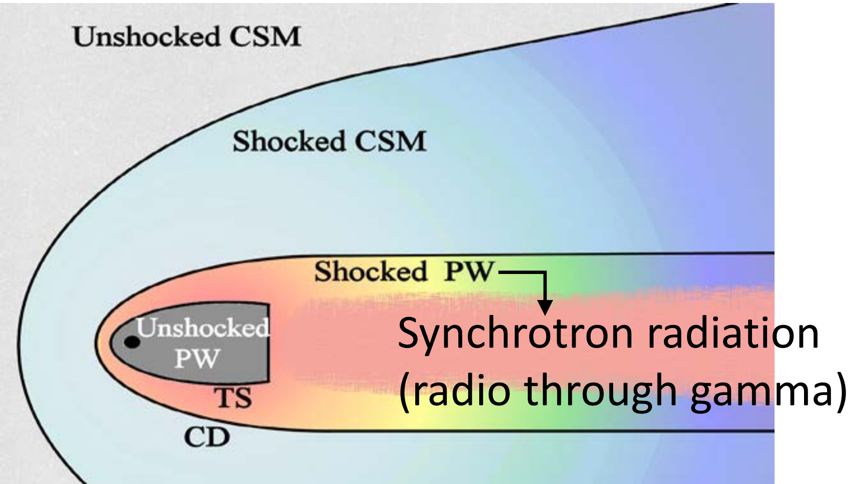
- Subsonic velocity: sphere (isotropic) or torus + jets (anisotropic)
- Supersonic velocity: ISM pressure confines pulsar wind (PW) to direction behind PSR

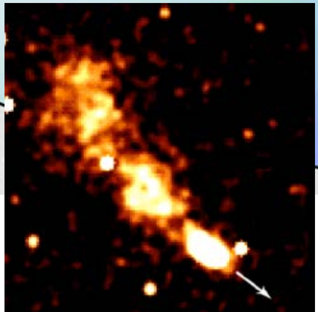


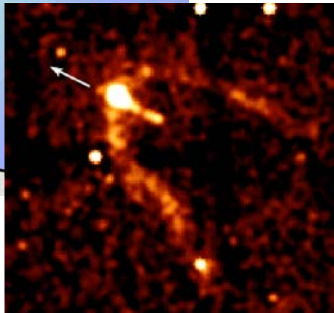





TS – termination shock
CD – contact discontinuity
FS – forward shock (i.e., BS)

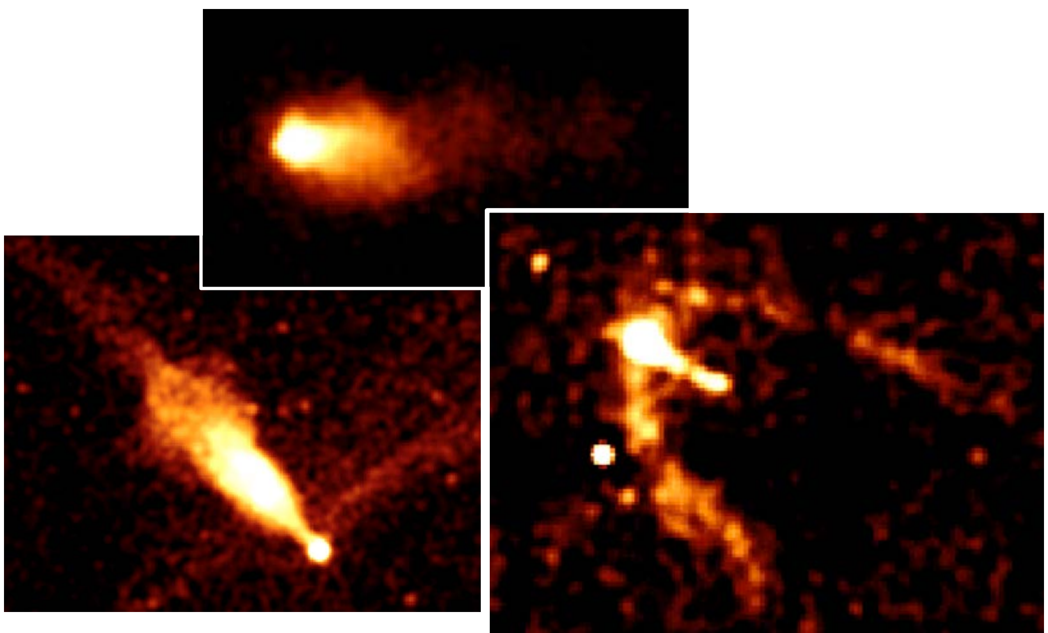


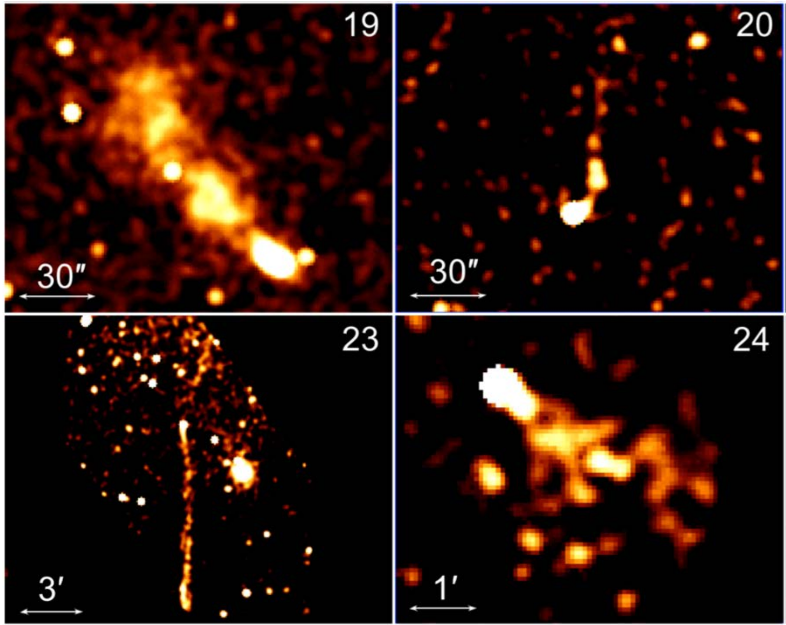





# Supersonic Pulsars

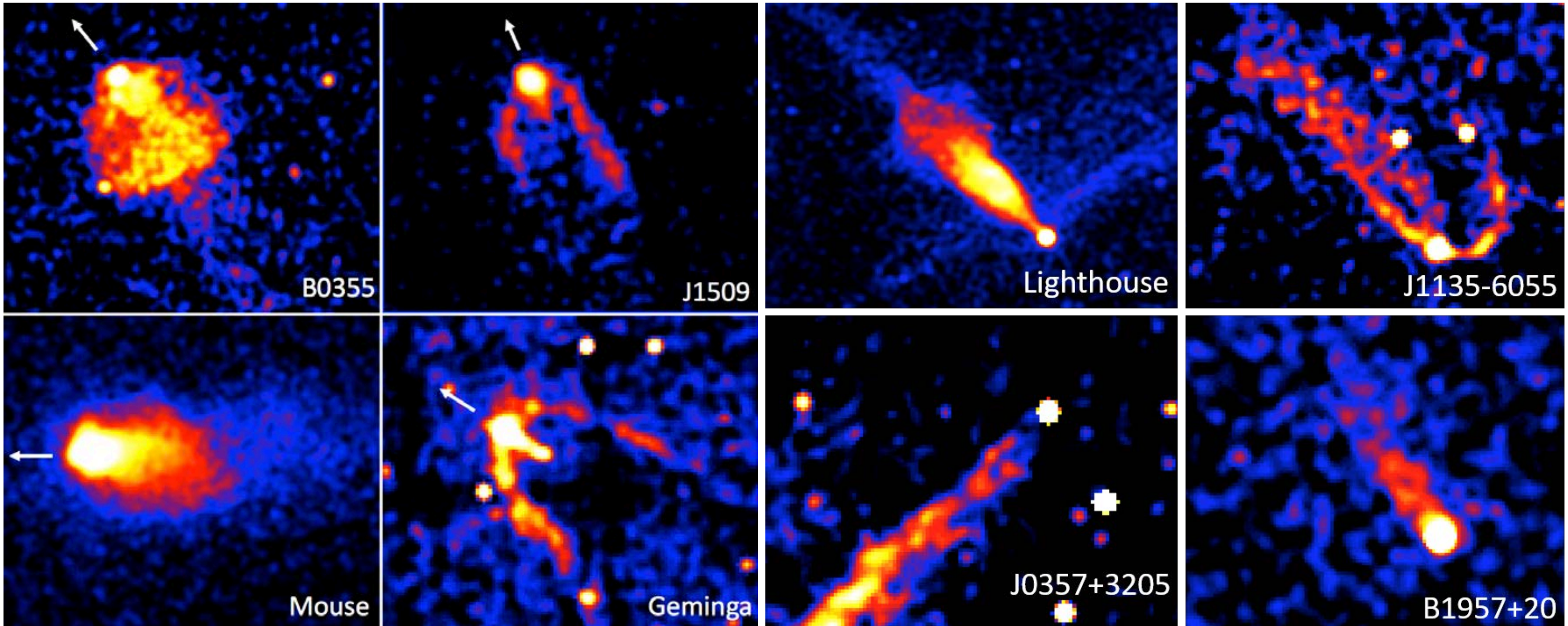
- SNR birth kicks → typical $v_{PSR}$ ~ 400 km/s (Hobbs 2005)
- PSRs usually escape SNR within a few ~10 kyr
- $c_{S,ISM}$ ~ 1 – 10 km/s → Pulsar Mach M ~ 1 – 10
- Supersonic PWNe (SPWNe) usually display a bow shock compact nebula (<1 pc) + long tail (~few pc)





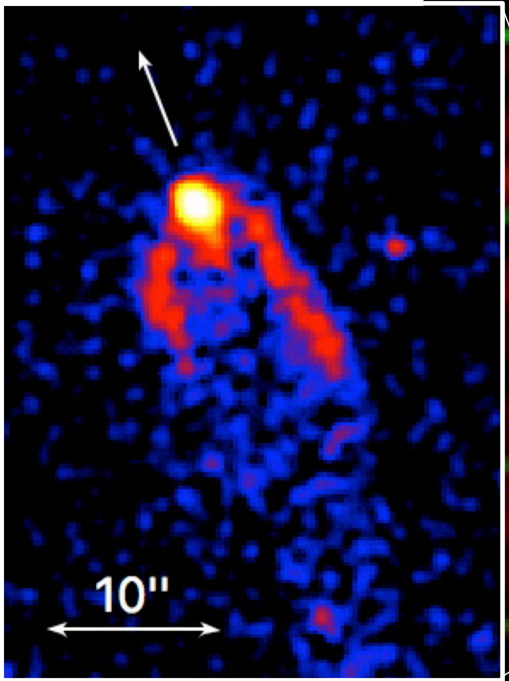
# SPWNe Population

- >230 pulsars with measured proper motion
- ~30 fast-moving pulsars with PWNe seen in X-ray (see Kargaltsev et al. 2017 for review)
  - even fewer seen in radio
  - Typically, only PSRs with $\tau < 1$ Myr can produce synchrotron nebulae
- Morphologies highly varied
  - Filled, hollow, tail without CN, combined tail + CN, asymmetrical, and many more:

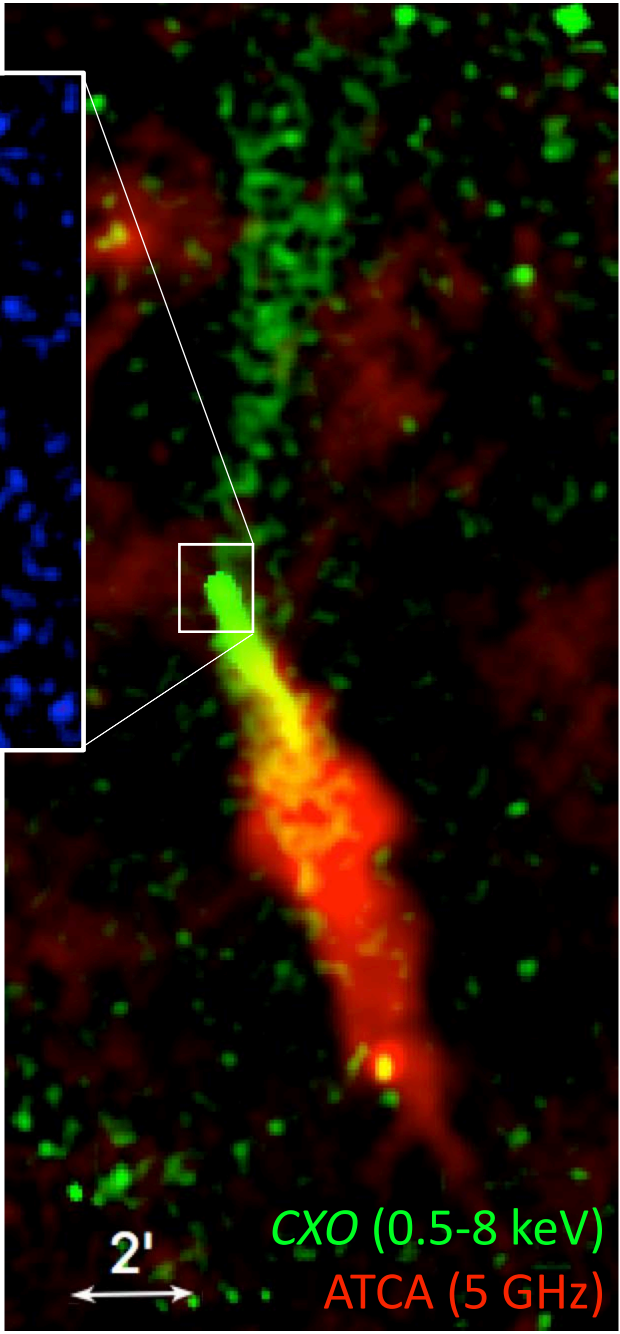


# J1509–5850

- d ~ 3.8 kpc
- Middle-aged ($\tau_{SD}$ ~ 154 kyr)
- $v_{\perp,PSR}$ ~ 400 km/s
- $\dot{E} = 5.1 \times 10^{35}$ erg/s
- P = 89 ms
- radio + γ-ray pulsar
- 370 ks ACIS-I exposure



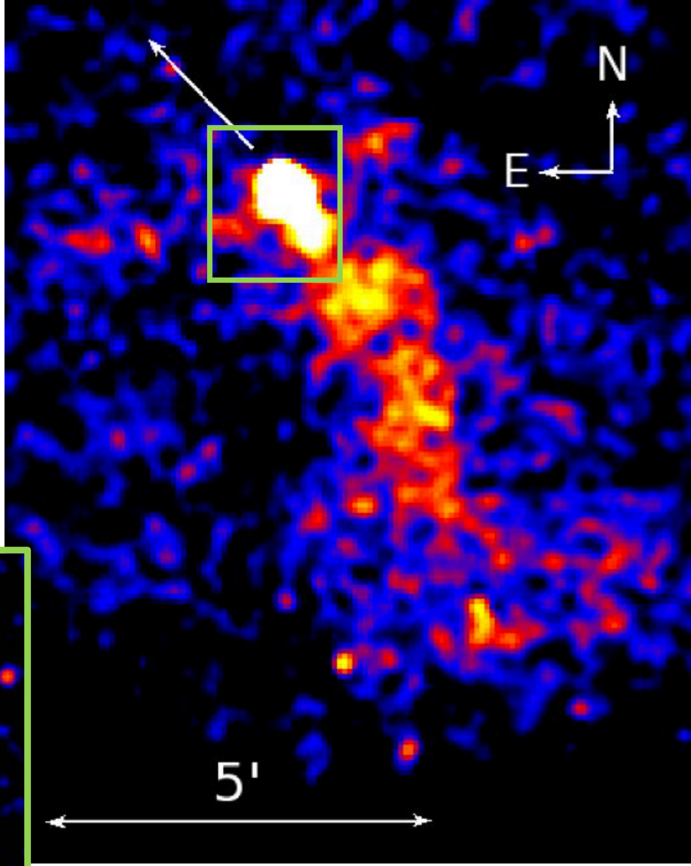
Klingler et al. (2016)

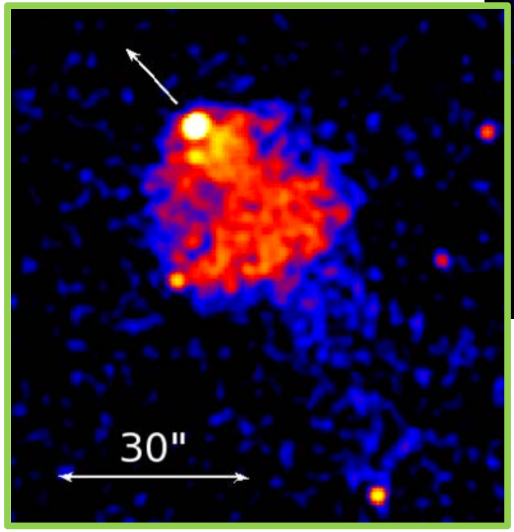



- Features:
    - “hollow” compact nebula (CN): jets + deformed equatorial outflow,
    - tail: X-ray tail dims with distance, 11 pc radio tail reaches peak brightness in the middle; CN not seen in radio
    - misaligned outflow

# B0355+54

- Nearby (d = 1.04 kpc)
- Middle-age ($\tau_{SD}$ ~ 560 kyr)
- $v_{\perp,PSR}$ = 61 km/s (Chatterjee et al. 2004)
  - Mach 6-60
- $\dot{E} = 4.5 \times 10^{34}$ erg/s
- P = 156 ms
- Not seen by Fermi,
  no radio PWN
- 395 ks ACIS-I exposure



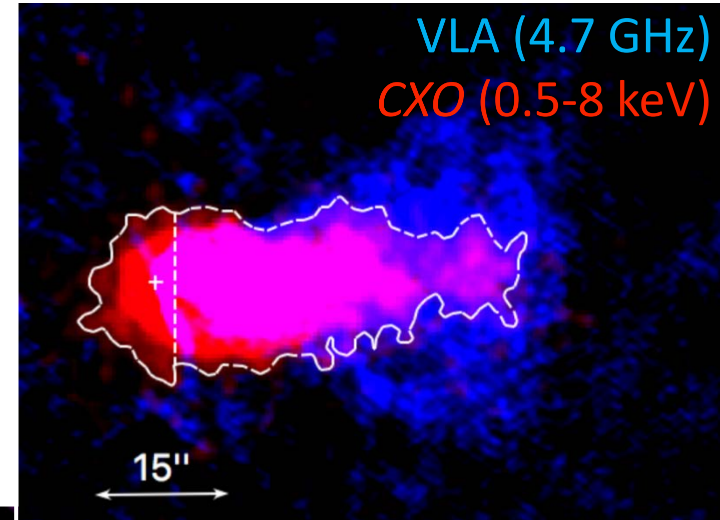



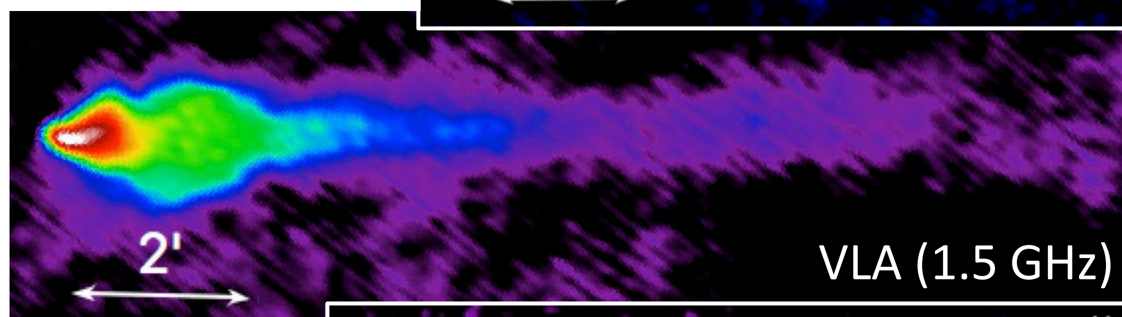

Klingler et al. (2016)

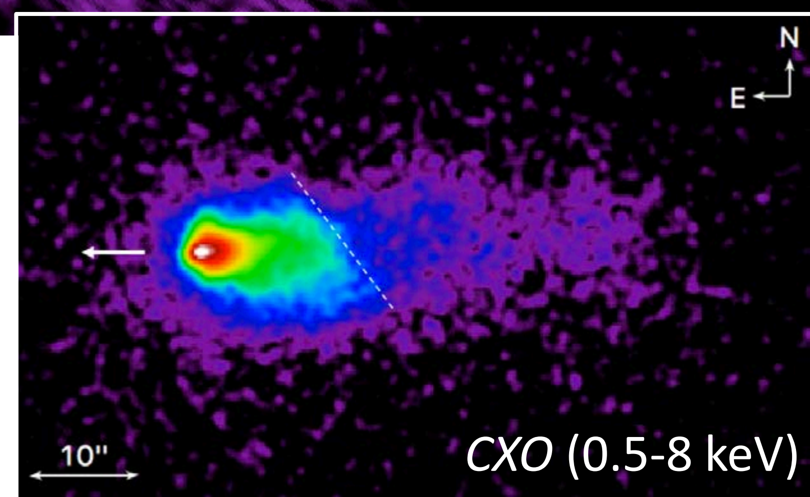
- Features:
  - "filled" bow shock ("the mushroom" PWN): bright along axis, well-defined boundary, dimmer "stem" (bent back jets), ~2 pc tail (bends, slightly widens), misaligned outflow

# J1747–2958 (the Mouse)

- d ~ 5 kpc
- $v_{⍰,PSR} \approx 300$ km/s (Hales et al. 2009)
- $\tau_{SD}$ ~ 25 kyr,
  - $v_{⍰,PSR}$, radio tail → true age > 160 kyr
- $\dot{E} = 2.5 \times 10^{36}$ erg/s
- P = 99 ms
- γ-ray pulsar
- 154 ks ACIS-I
  + 58 ks HRC-I
- Features: “filled” CN, 45” X-ray tail that narrows with distance, 12’ (17 pc) radio tail: initially widens, then narrows



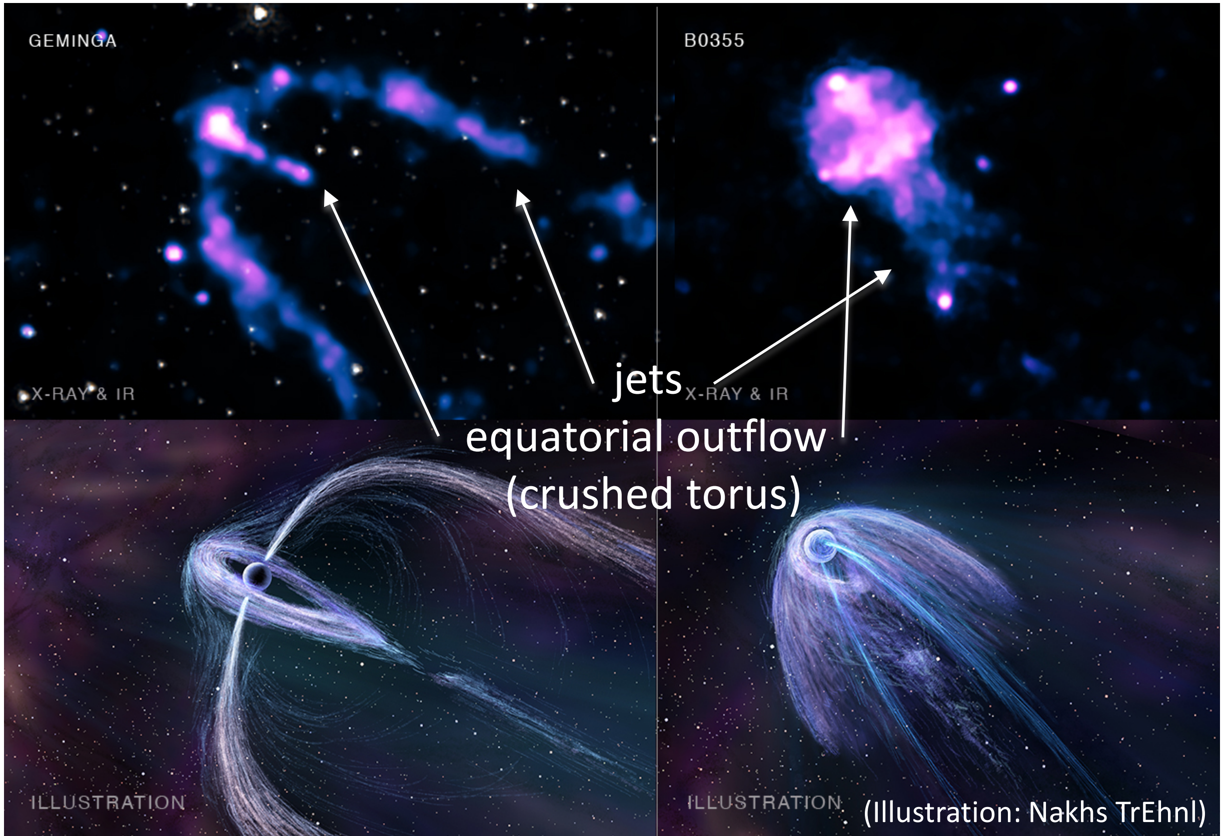
# CN Morphologies: connection to pulsar geometry

Geminga: not seen in radio
image → viewed from equatorial plane;
jets oriented into plane of sky

B0355+54: not seen in γ-rays
image → viewed from near spin axis;
jets oriented toward us

Posselt et al. (2017)

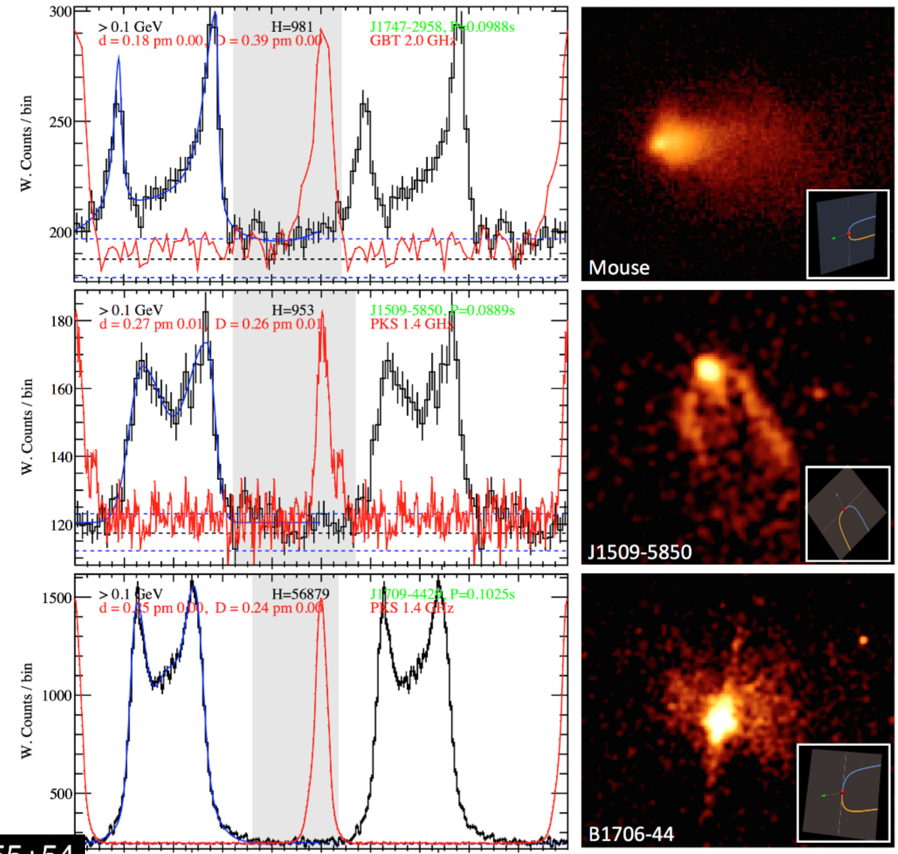
Klingler et al. (2016)

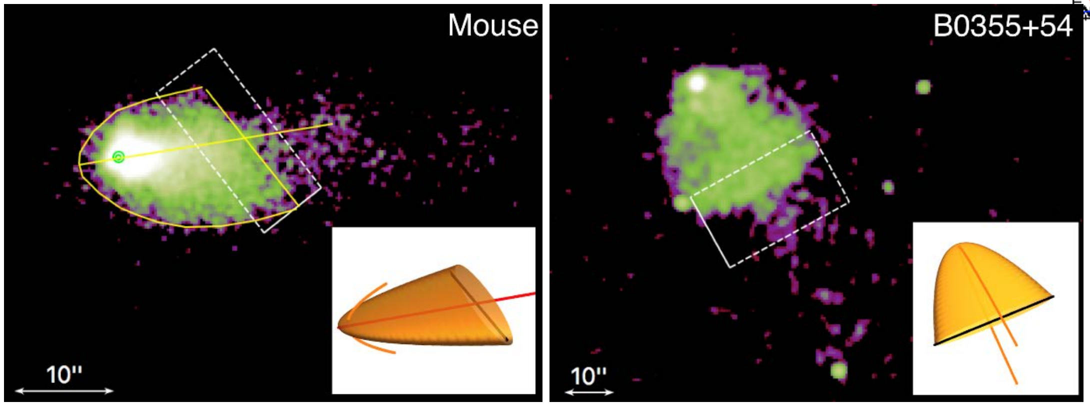



(Illustration: Nakhs TrEhnl)

# Morphologies, light curves, and geometries

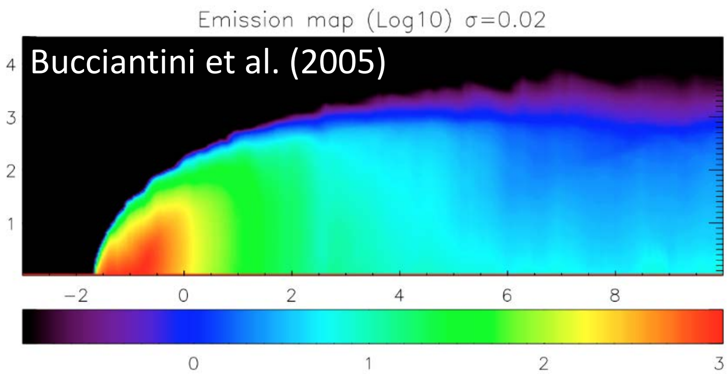
- The geometry of the CN and light curves can be used to obtain viewing angle
  - Mouse viewed from ζ ~ 70° from equatorial plane
  - γ-ray/radio lightcurves → magnetic offset/inclination angle α ~ ζ ~ 70°
- Similar angles for J1509, and B1706
- All cases: v perpendicular to spin axis

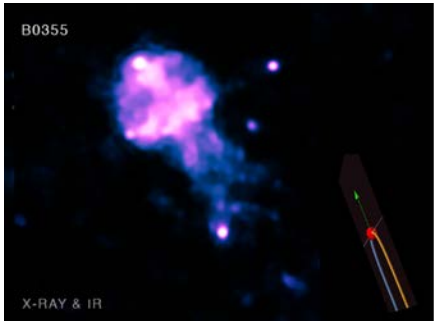


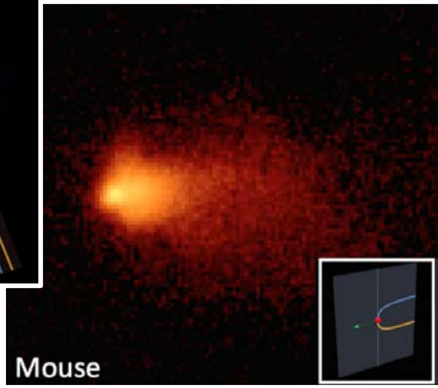



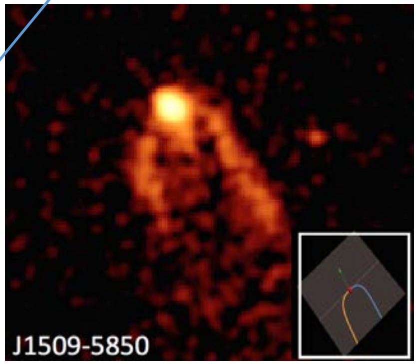
# Compact Nebulae

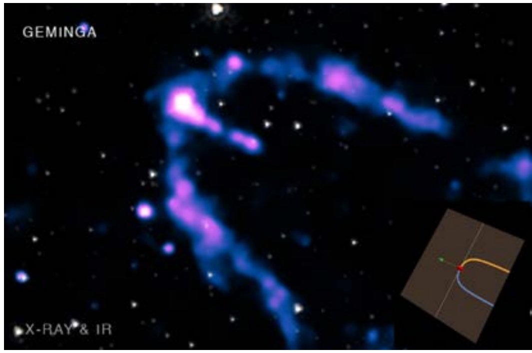
- Simple (isotropic) MHD simulations don’t always describe SPWNe morphologies
  - Anisotropic winds, misaligned outflows

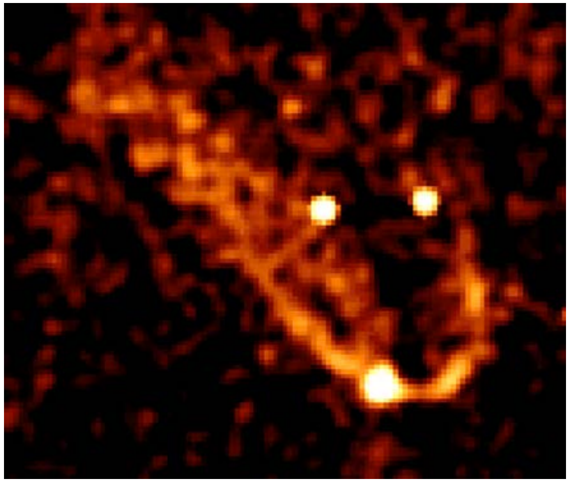


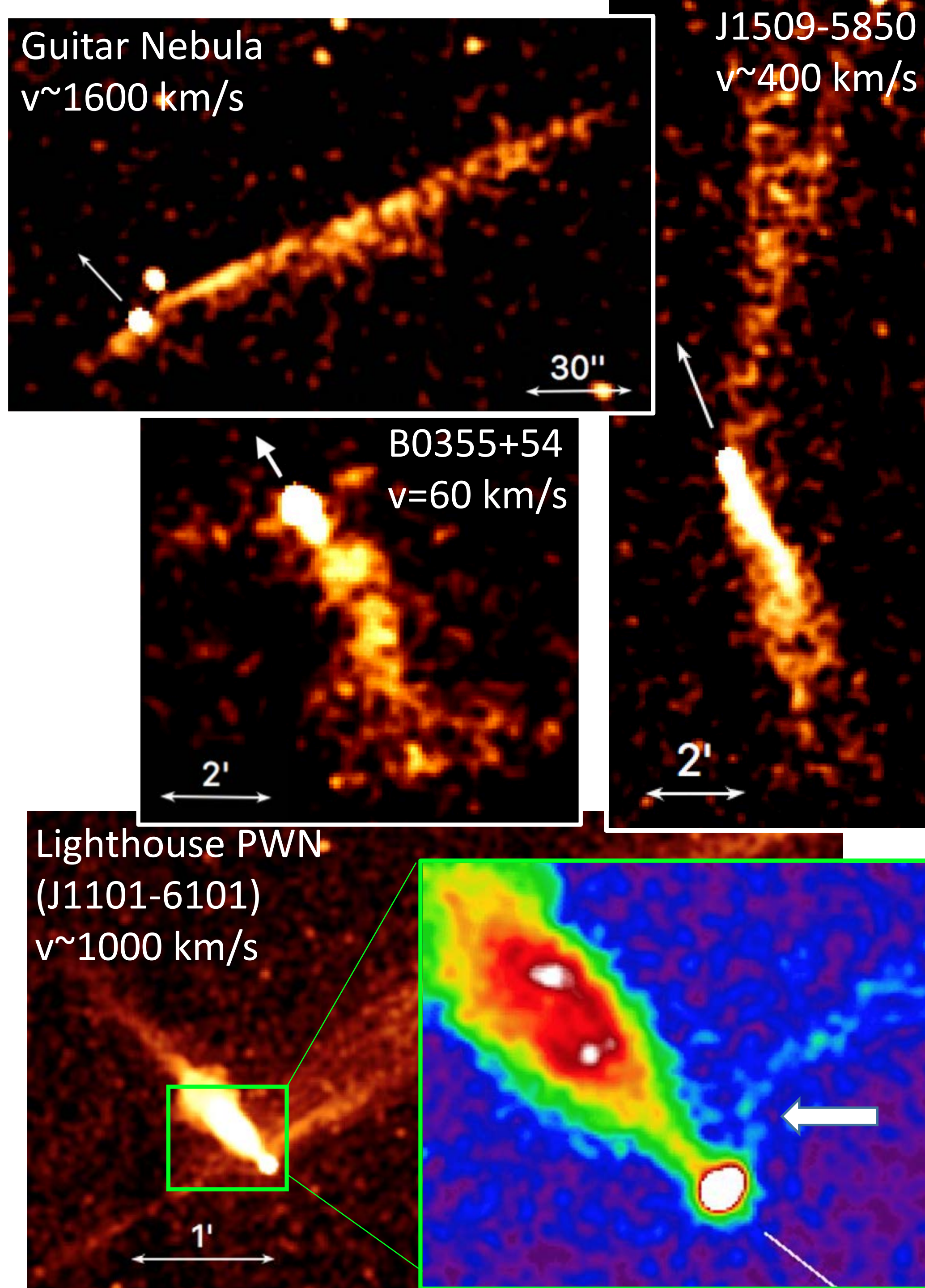



- In many cases, velocity vector appears perpendicular to pulsar velocity; though there are also examples of aligned spin/velocity vectors
  - Challenges previous hypothesis of spin-velocity alignment
  - Can provide clues on pulsar birth kick mechanism in supernovae

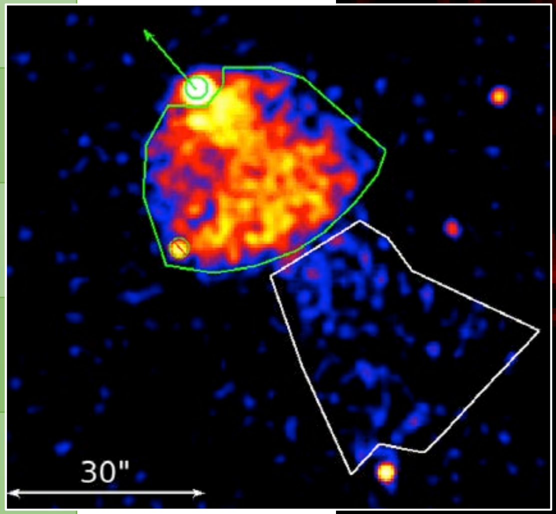
# Misaligned outflows

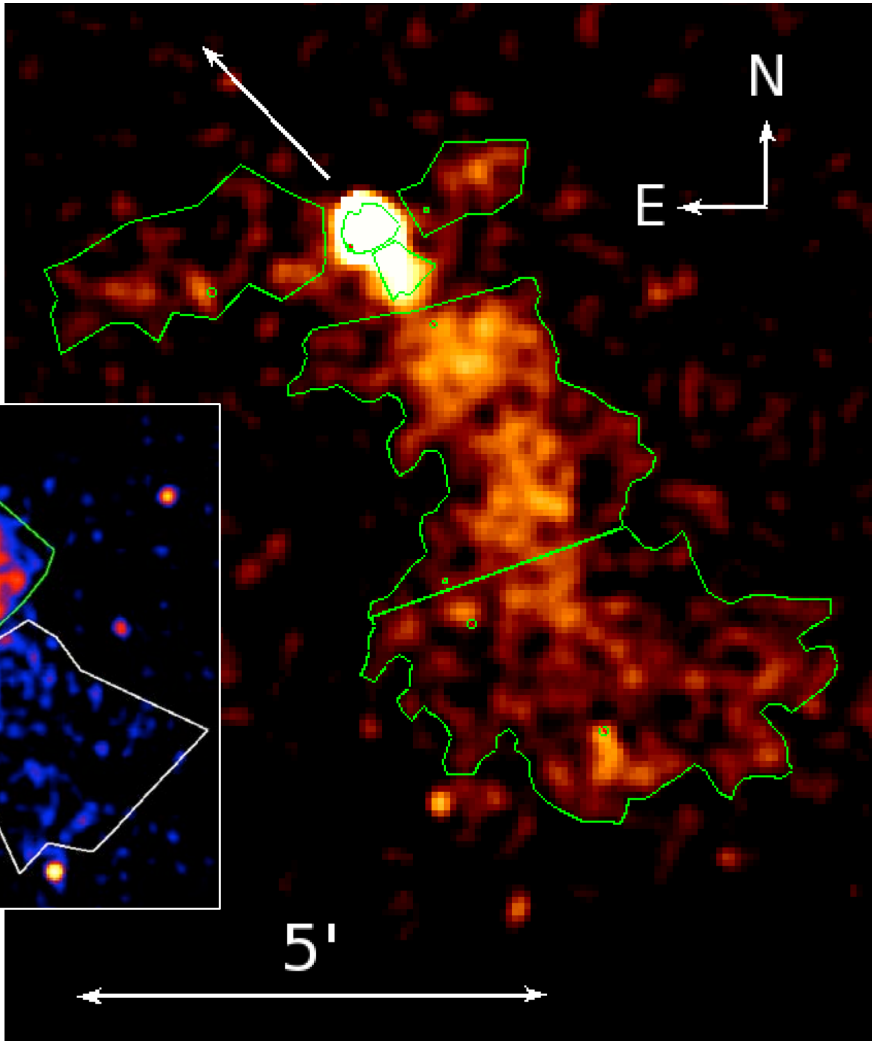
- Puzzling: PW should be confined to tail; not jets – they bend by ram pressure on much smaller scales (and are seen in 2 cases: B0355 and J1509)
- Bandiera (2008): in high Mach pulsars (e.g., Guitar), $e^-$ gyroradius can exceed BS stand-off distance; $e^-$ can't be contained within BS, "leak" into ISM and travel along ambient field
- Ambient B field can "drape" around a bow shock (Lyutikov 2006, Dursi & Pfrommer 2008)
  - Seen in Lighthosue (Pavan et al. 2016)
- Bykov et al. (2017): if ISM B-field reconnects with field in PWN BS (e.g., jets), high-E particles will launch along ISM field; ISM can only reconnect with B-fields oppositely oriented, perhaps explaining the asymmetry



# B0355+54 Tail

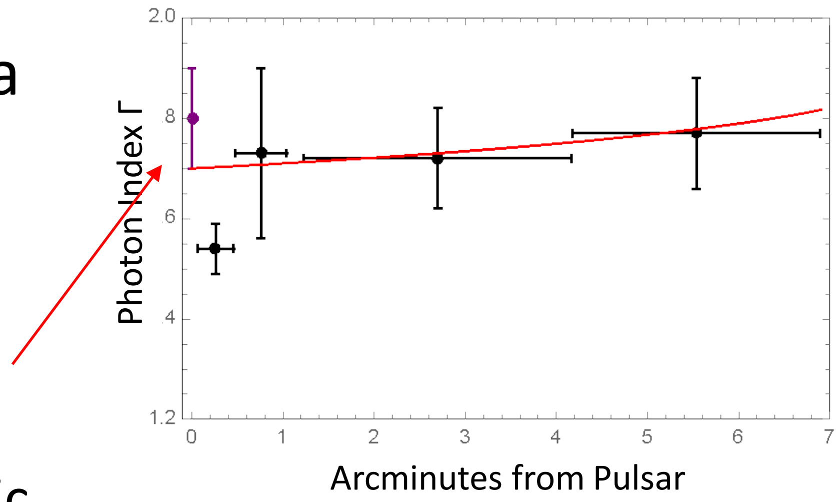
| Region | Photon Index Γ |
|---|---|
| Pulsar | 1.80 ± 0.10 |
| CN | 1.54 ± 0.05 |
| Outflows | 1.6 ± 0.3 |
| Stem (jets) | 1.73 ± 0.17 |
| **Tail (Entire)** | **1.74 ± 0.08** |
| Tail (Near) | 1.72 ± 0.10 |
| Tail (Far) | 1.77 ± 0.11 |



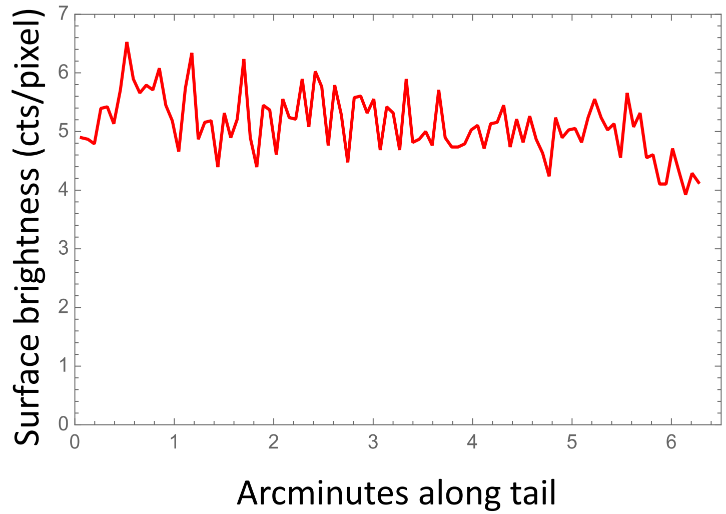



# B0355 tail

- No significant changes in spectra or brightness seen up to 2 pc (limited by *Chandra* FOV)
- Simple (1D) synchrotron cooling model (Chen et al. 2002)
  - Assumes cylindrical tail, constant: width, bulk flow speed u, magnetic field B
  - Data suggests either:
    - fast flow speed u ~ 0.04-0.12c (few*$10^4$ km $s^{-1}$)
    - and/or low magnetic field $B_{tail}$ ~ (4-17) μG
- Particle re-acceleration within tail?



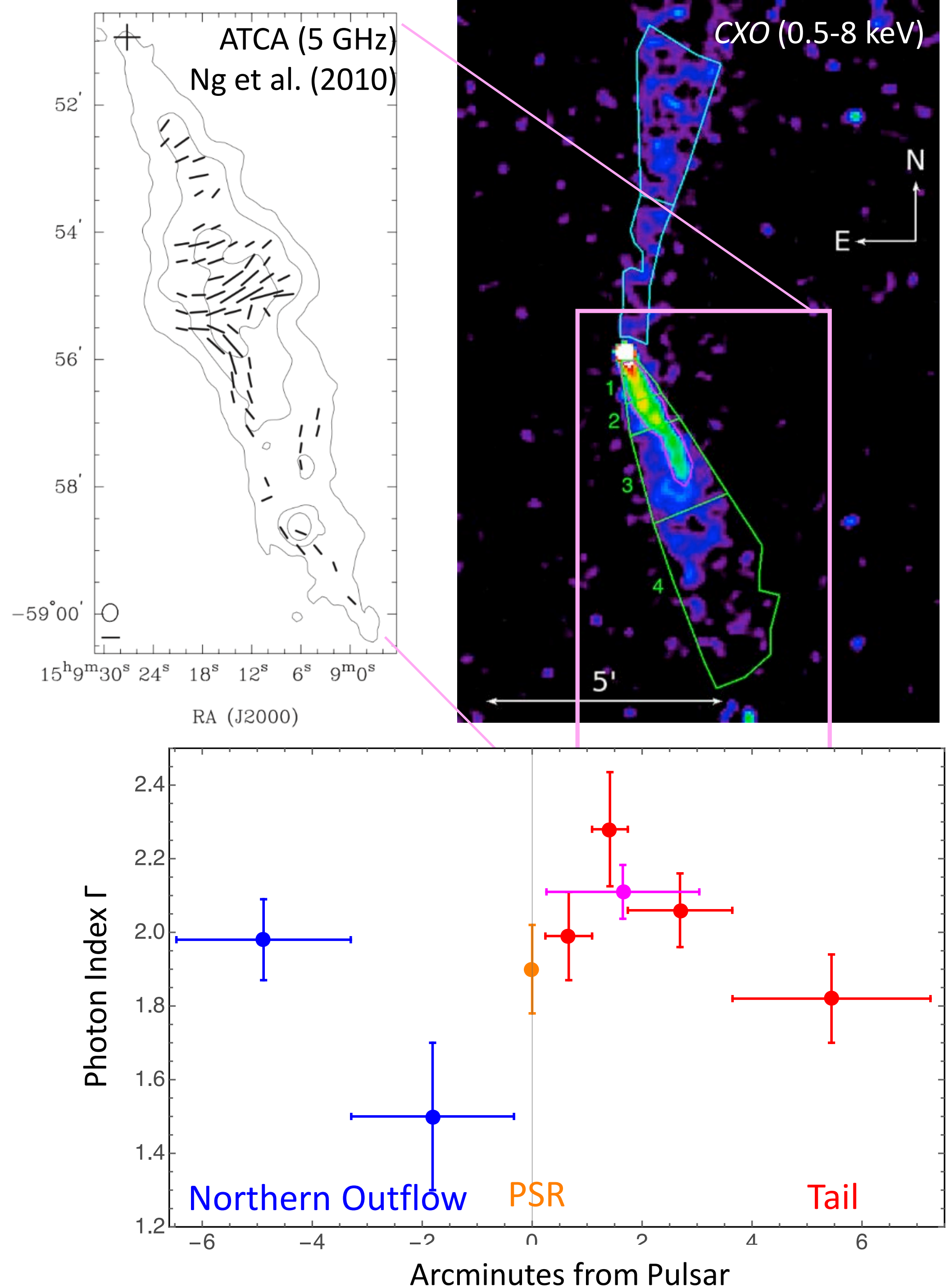

(Klingler et al. 2016)



# J1509 Tail

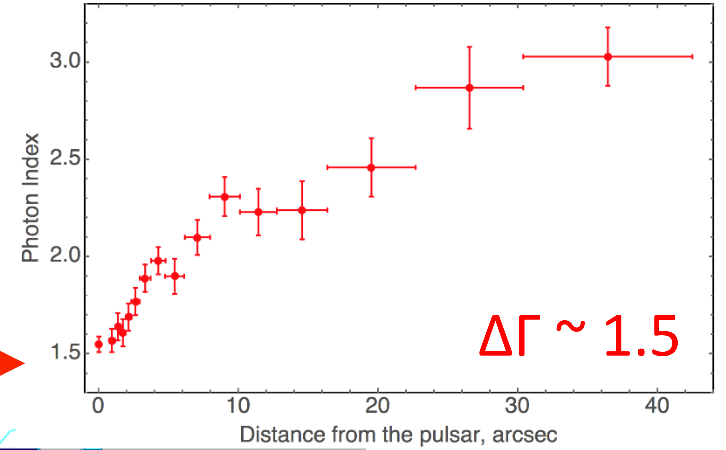
- Initially: Γ softens, radio tail expands + increases in brightness, B field is perpendicular to tail axis
- ~3-4’ downstream:  Γ hardens, B-field becomes parallel + weakens, radio tail narrows + fades
    - Evidence for particle reacceleration, reconnection(?), instabilities (?)
- Misaligned outflow cools

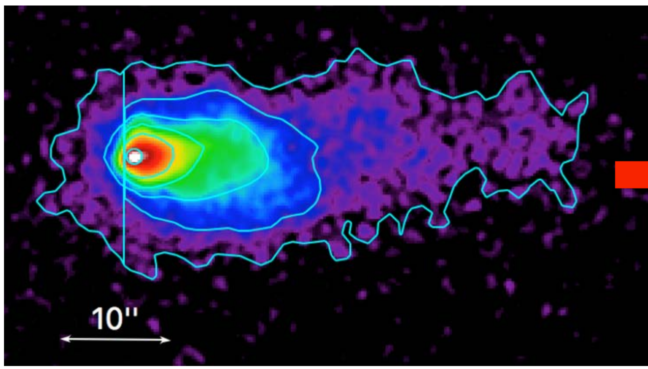
| Region | Γ | B (μG) |
|---|---|---|
| Pulsar | 1.90 ± 0.12 | |
| Jets | 1.80 ± 0.13 | |
| Tail (Entire) | 1.88 ± 0.06 | |
| Tail – sect. 1 | 1.99 ± 0.12 | ~40 |
| Tail – sect. 2 | 2.28 ± 0.16 | ~90 |
| Tail – sect. 3 | 2.06 ± 0.10 | ~30 |
| Tail – sect. 4 | 1.84 ± 0.10 | ~10 |
| Outflow – near | 1.50 ± 0.20 | ~5 |
| Outflow – far | 1.98 ± 0.11 | ~10 |

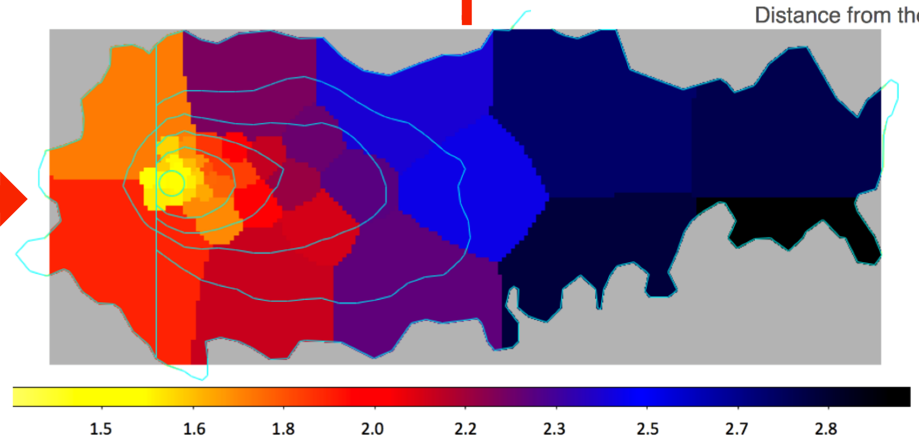


# Mouse Tail

- Adaptively-binned spectral mapping using weighted Voronoi tesselations (Cappellari & Copin 2003, Diehl & Statler 2006)
  - Creates regions to meet a specified S/N maximizing spatial resolution

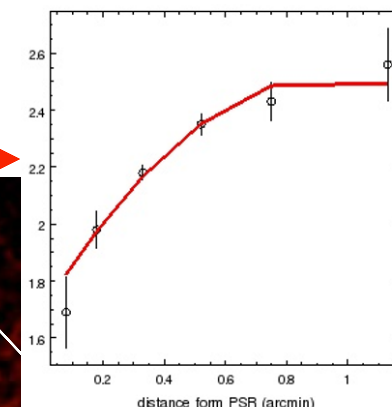


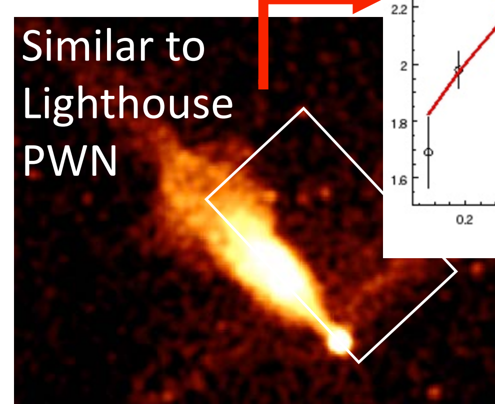




- Rapid synchrotron cooling
- However, tail fits a single PL with Γ=2.09±0.03
  - sum of PLs it not a PL, but here it fits (likely either narrow spectral range, or dominated by bright inner regions)
  - this highlights the danger in obtaining injection spectra from large regions; best to use Γ of the uncooled wind in the immediate vicinity of the pulsar

Photon Index Γ

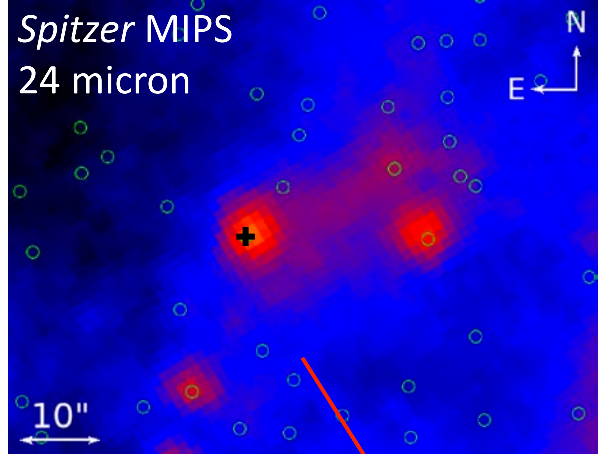


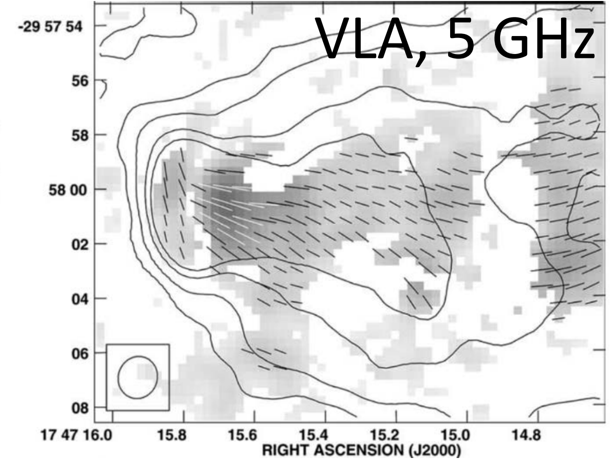




Pavan et al. (2015)

# Mouse Tail

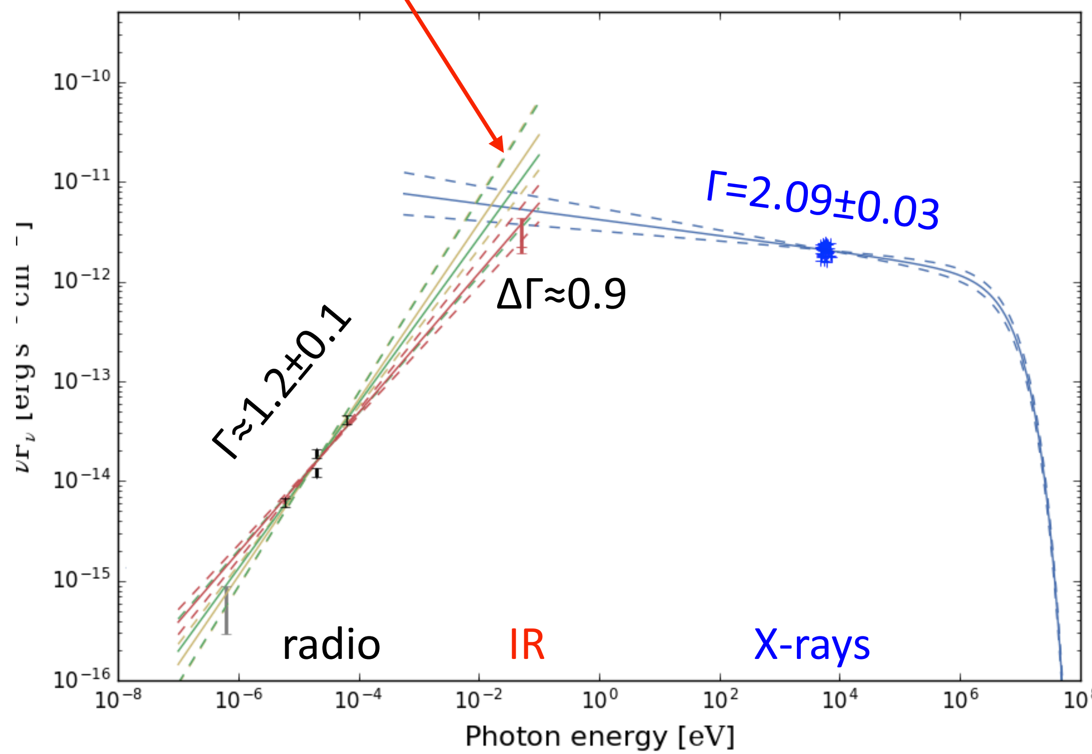
- CN head seen in IR with *Spitzer*, and at 150 MHz with GMRT




Yusef-Zadeh & Gaensler (2005)

- B-field oriented parallel to tail axis (at least in the compact nebula)
- MW spectrum implies very high magnetic field (assuming equipartition): B ≈ 270-300 μG, which then suggests low flow speeds u ⩽ 1000 km/s
- Explains the rapid synchrotron cooling



# Summary

- cooling trends vary can: no cooling over pc-scale distances, rapid cooling, or a hint of reheating parsecs away from pulsar
  - different magnetic field strengths, orientations, degrees of collimation; magnetic reconnection(?)
- tails can: widen with distance, become narrower, bend, etc.; dim or brighten with distance
  - different ISM densities, temperatures, pressures; entrainment of ISM
- surface brightness can: decreasing with distance, or peaking parsecs downstream
- misaligned outflows:
  - link between pulsar $\dot{E}$, v, ISM properties, and outflow characteristics? Why are they so uncommon? (currently only 4 instances seen)
- magnetic field orientations/structure vary: parallel, perpendicular, or switch
  - B-field structure can be different even in the tails of pulsars with same/similar spin-velocity alignment
  - B-fields must depend on other factors, but how?
- X-ray images + MW data can be used to understand structure and morphology of PWNe and their outflows, and place constraints on geometry, viewing angle