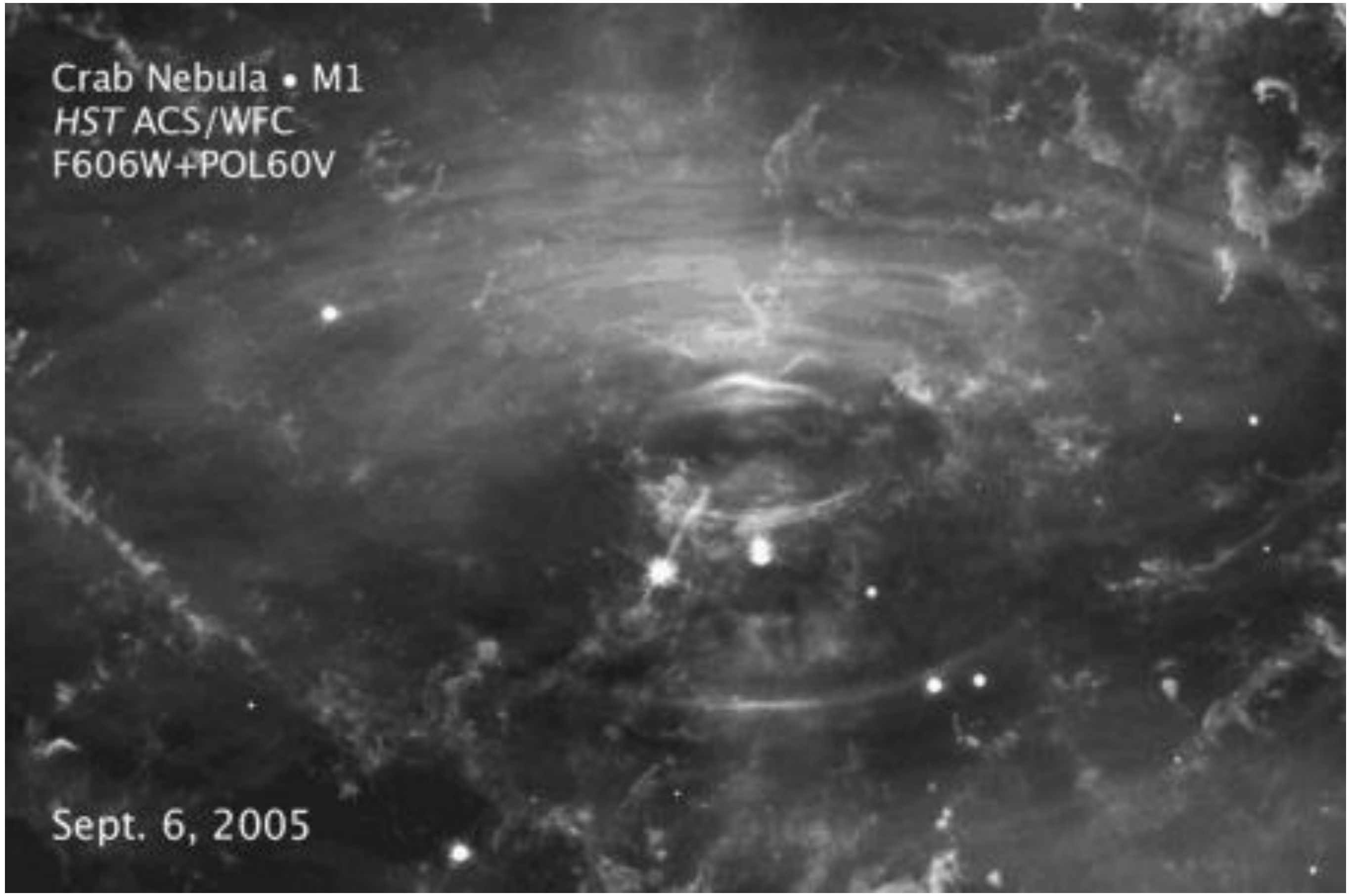
Resolving the bow shock and tail of the cannonball pulsar PSR J0002+6216

Pratik Kumar
University of New Mexico

Frank Schinzel(NRAO/UNM), Greg Taylor(UNM), Matthew Kerr(NRL), Daniel Castro(Harvard/CfA), Urvashi Rau(NRAO) and Sanjay Bhatnagar(NRAO)

Pulsar Wind Nebula (PWN)

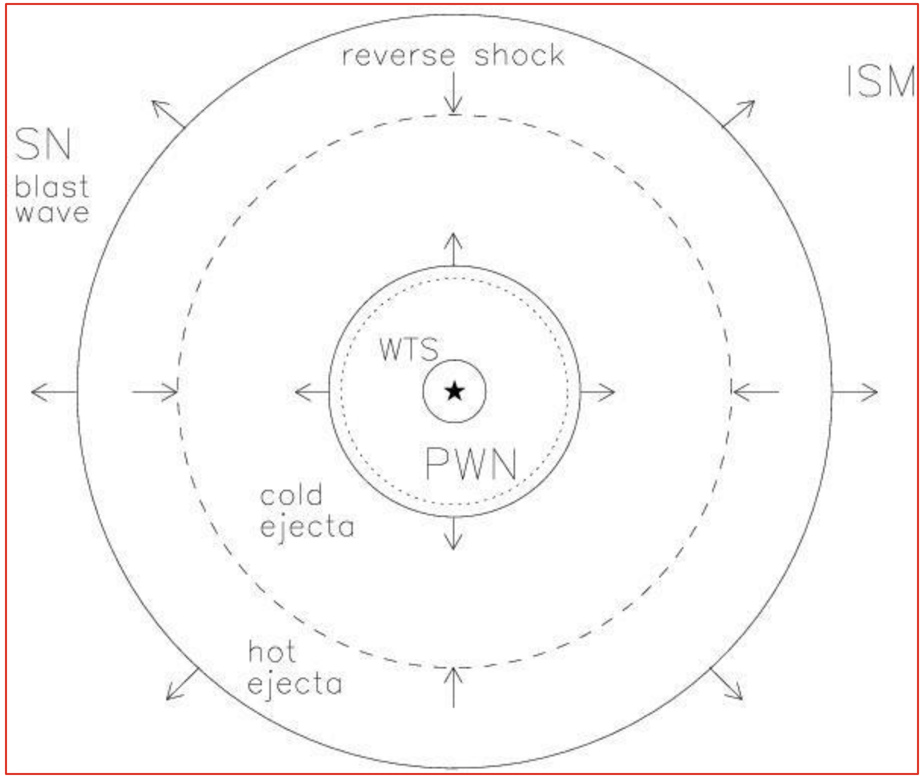


- Cold, magnetized, ultra-relativistic outflow with Lorentz factor in range $10^4 – 10^7$ (Goldreich & Julian 1969)
- Ram pressure of Pulsar wind balanced by surrounding ISM
- Broadband emission
- Galactic Accelerators: study the properties of relativistic shocks

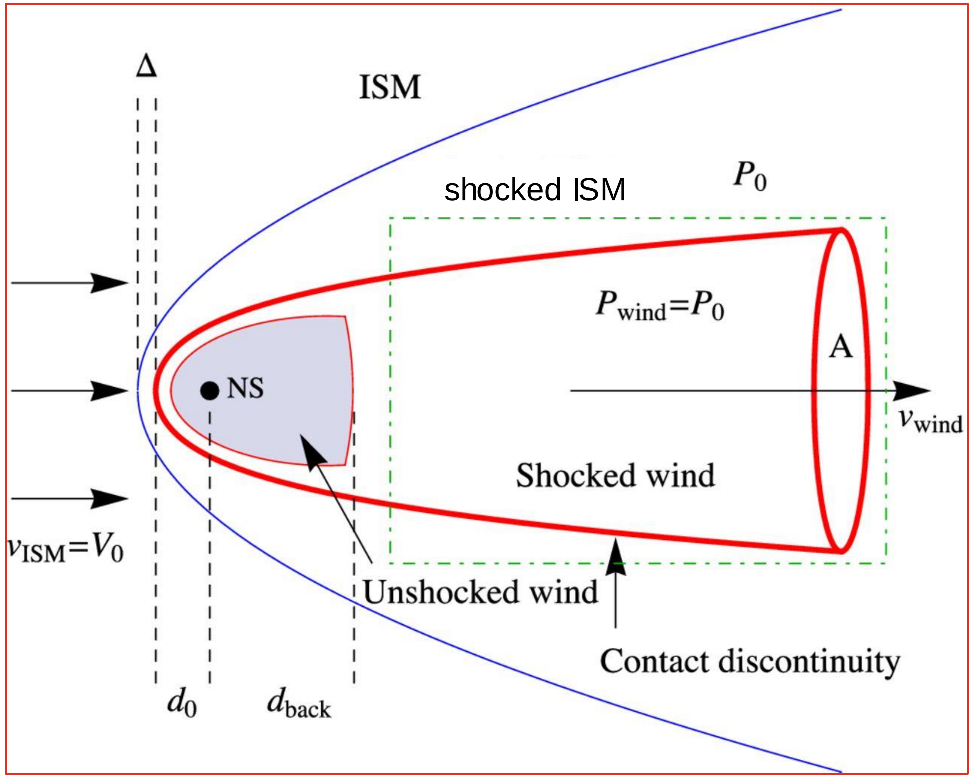
Crab Nebula in Optical, dissipating energy and creating wave like structures
NASA/ESA/ASU/J.Hester

PWN Primer

Zajczk et al. (2011)

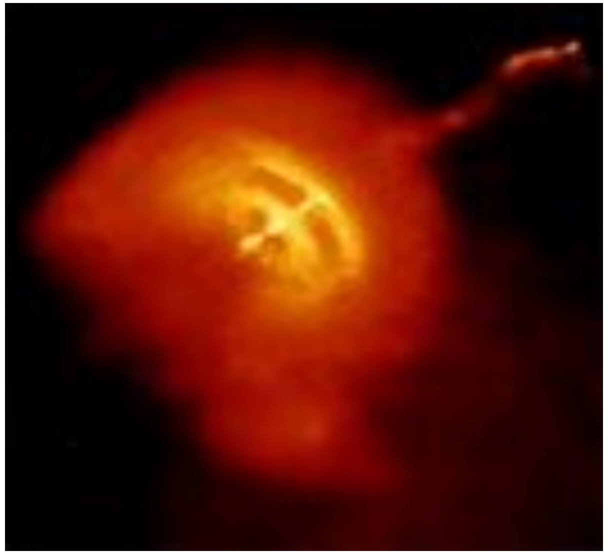


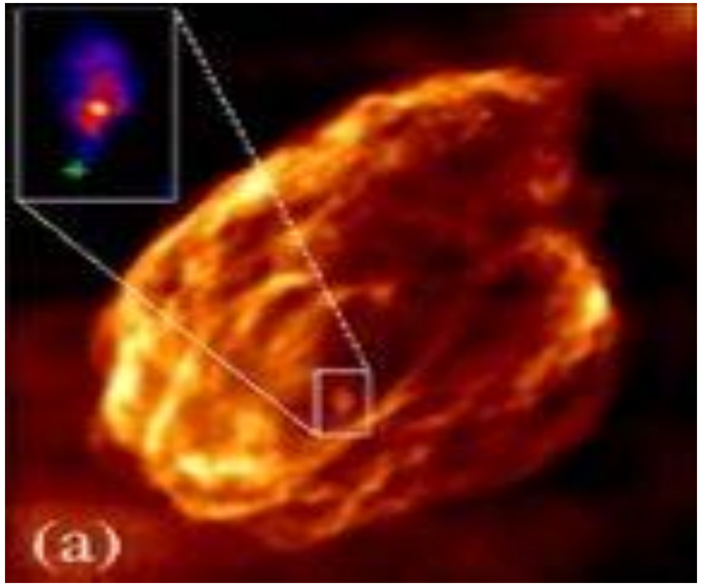
Morlino, Lyutikov & Vorster (2015)

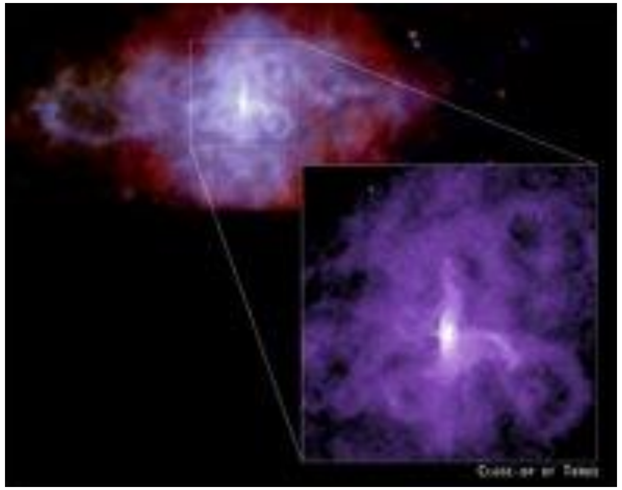


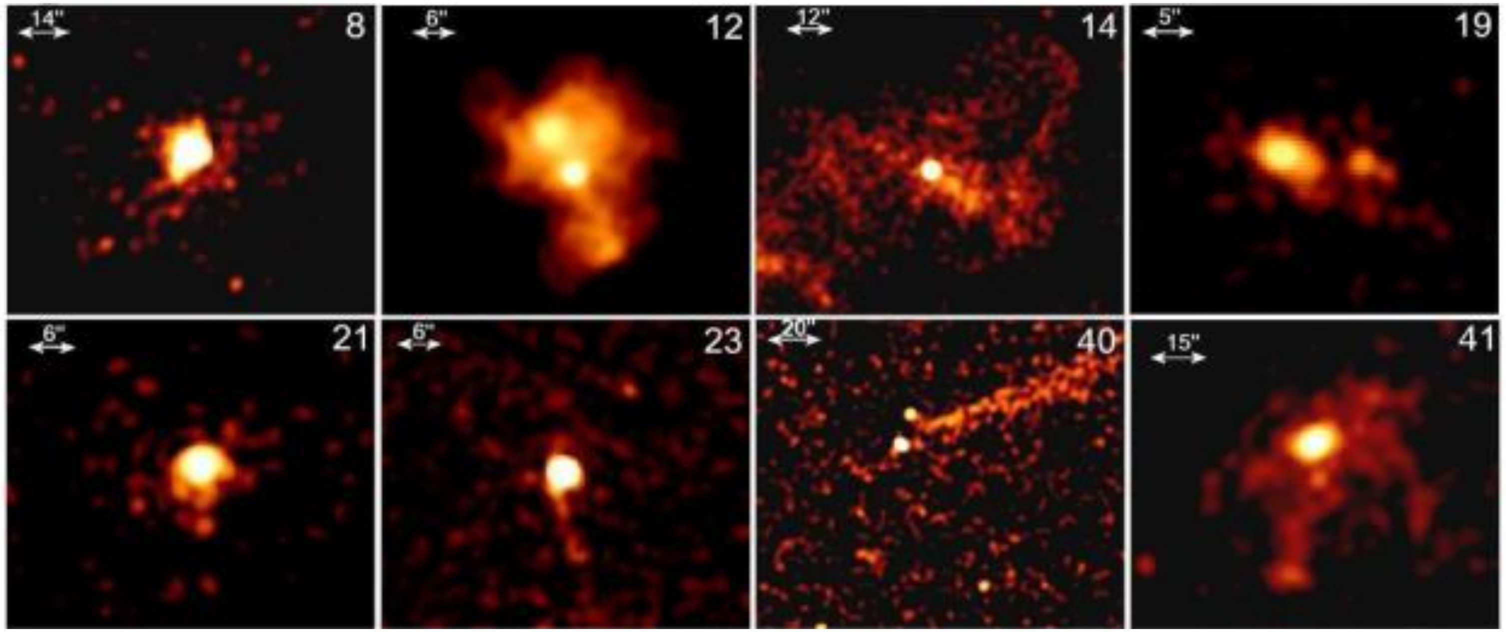
- Spectrally resolved X-ray and Radio images
  - Electron energy distribution
  - Evidence of in situ particle acceleration
  - Synchrotron cooling

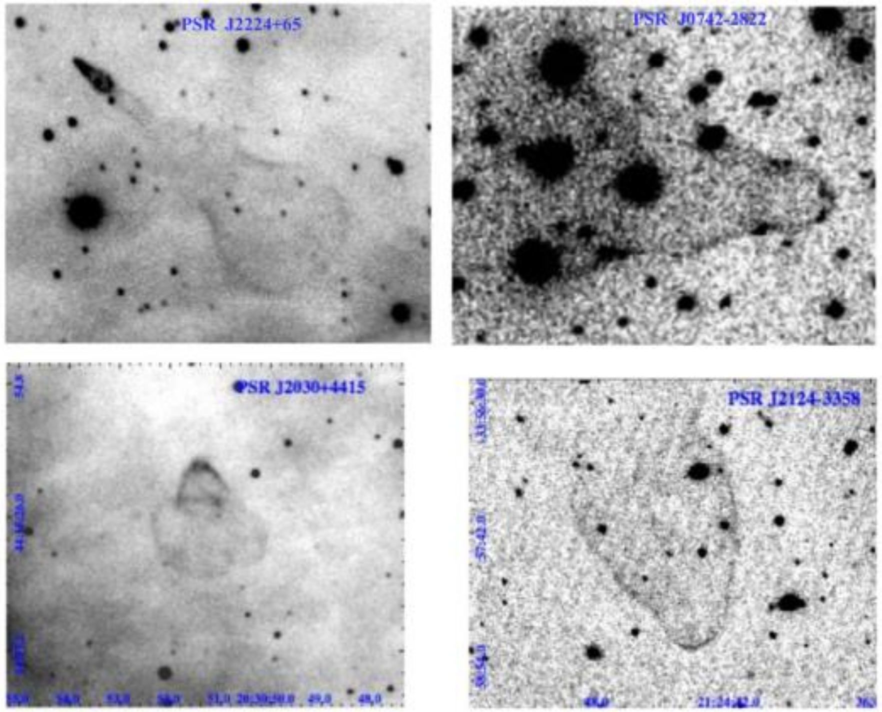
PWN Morphology Zoo









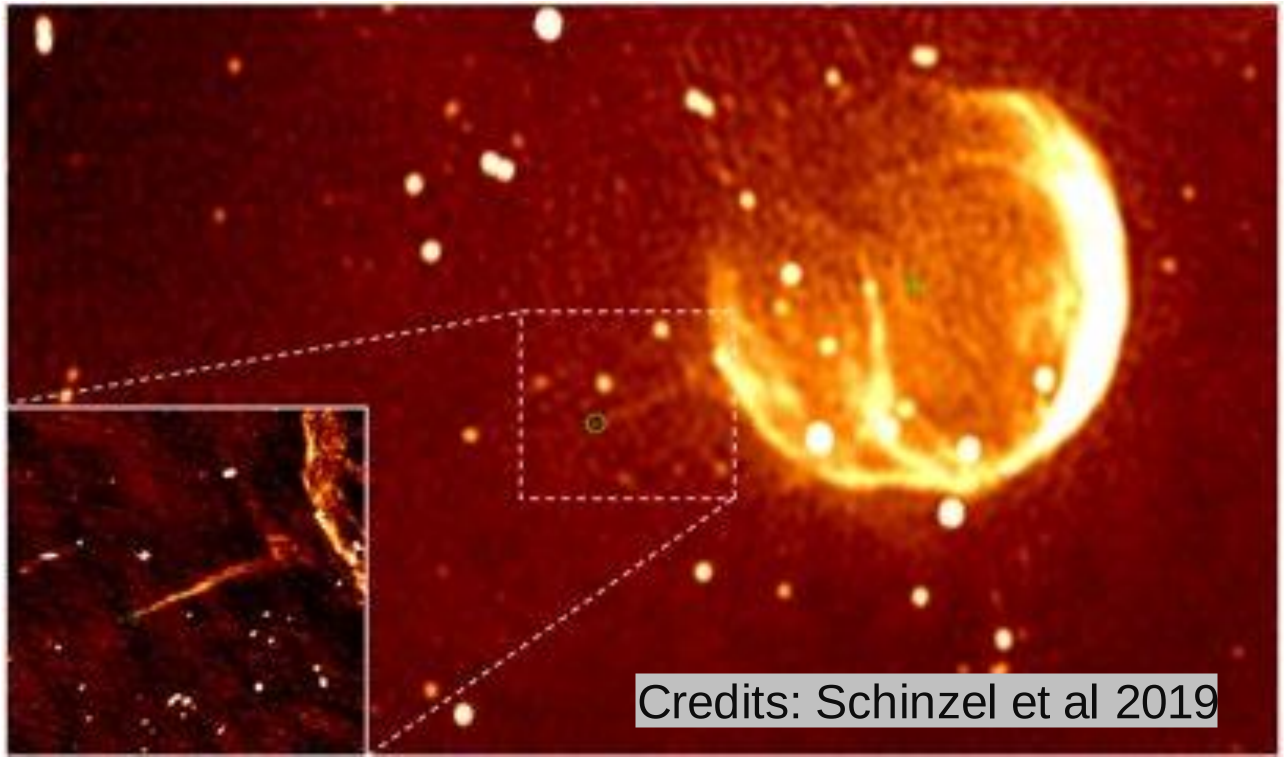


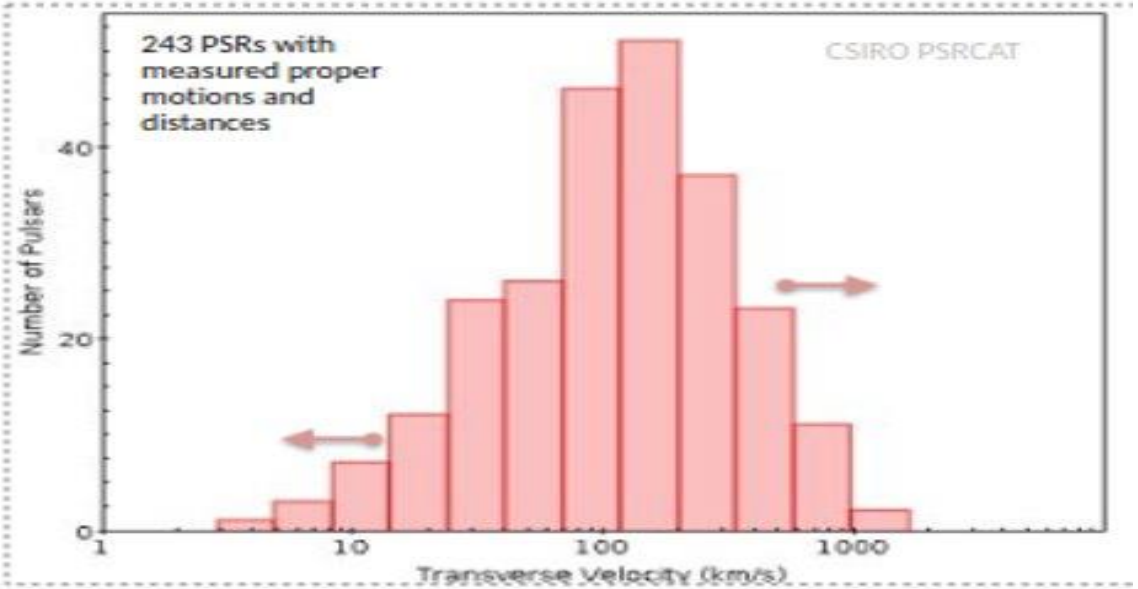
J0002+6216 : Cannonball

- Observed during 17B-348: VLA

- PSR+PWN+SNR

- High Kick velocity: outlier (see Hobbs et al 2009)
  - Velocity ~ 1100 km/s, maybe slower
  - Period ~ 115 ms : Fermi
  - Distance ~ 2 kpc
  - Mach number ~ 200



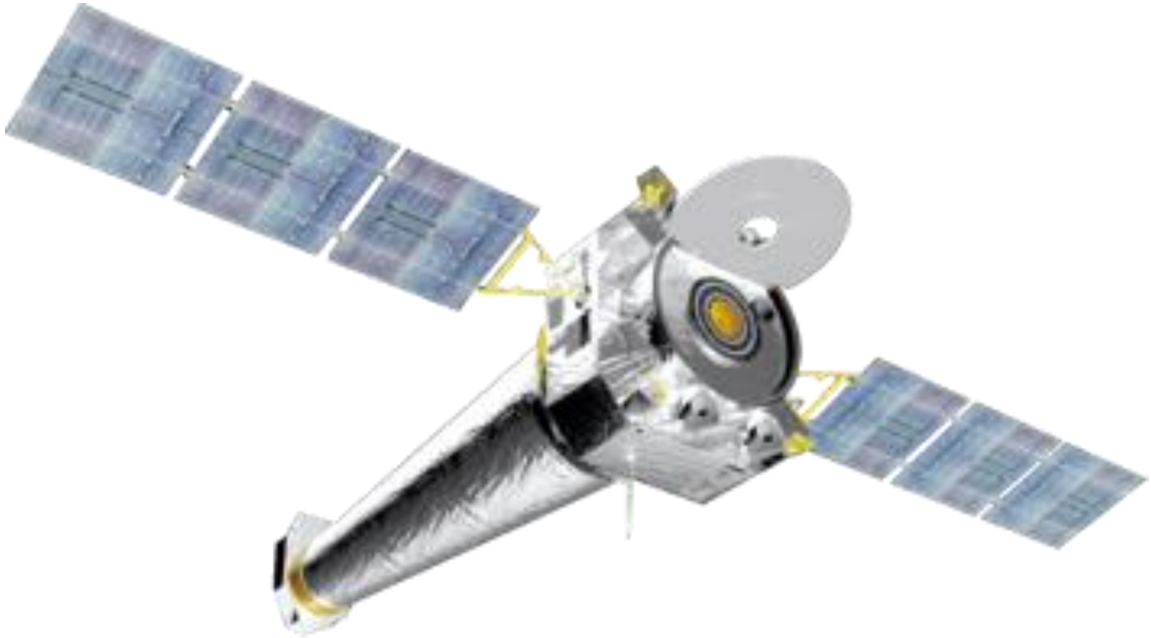


Follow ups:

- Bow shock : X-ray + Radio
- Parallax: VLBI

X-ray Observations

- Chandra Observations
- ACIS S3 Instrument
  - High resolution Imaging
  - Resolution ~ 0.5 arcsec
- Observations in 0.5-7 Kev energy band
- 2 observing epochs: ~16ks and 30ks exposures
- Data processing and model fitting using CIAO and Sherpa



Credit: NASA spacecraft icons

Radio Observations

- Observations in B, C and D configurations

- In two Frequency band
  - C : 4-8 GHz
  - X : 8-12 GHz

- Highest resolution 0.6" comparable to our X-ray observations

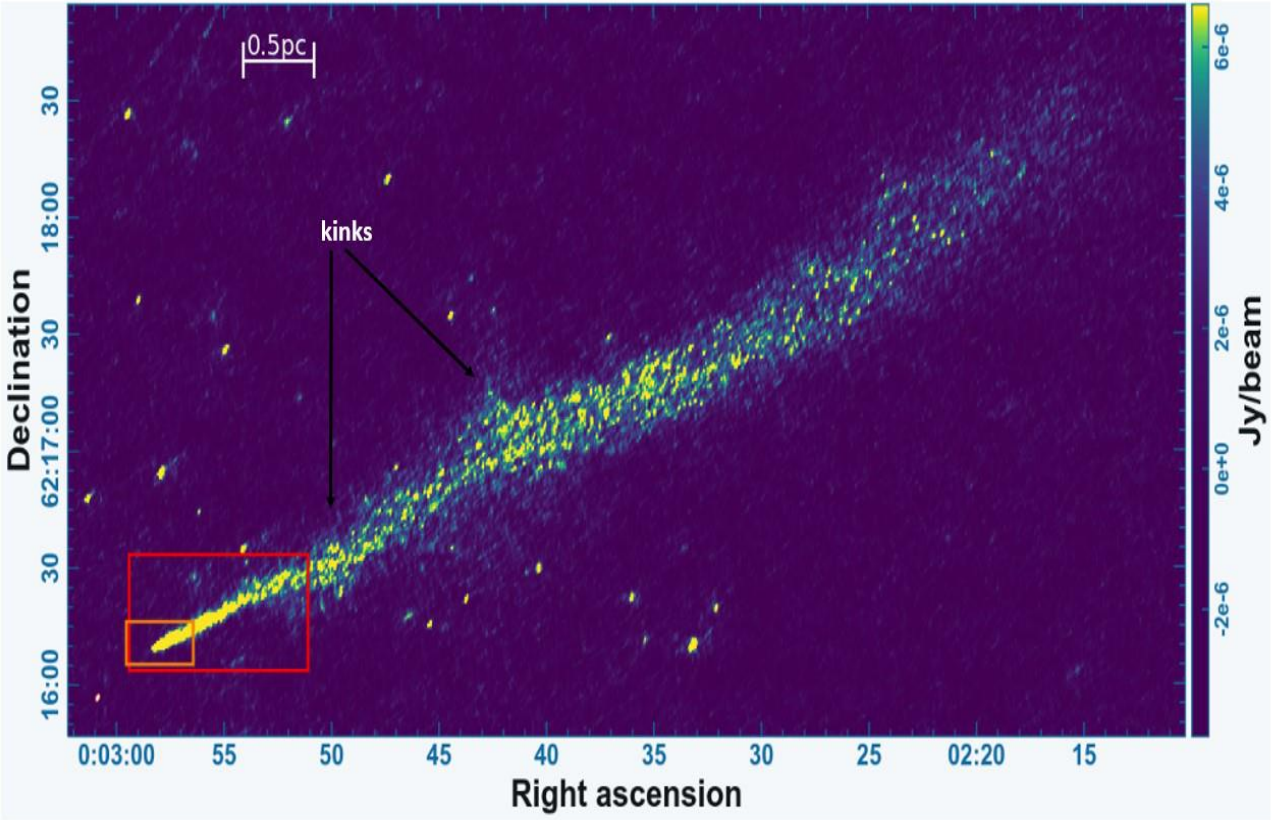
- Imaging and data processing using CASA 6.2.1.7 together with the automated VLA data reduction pipeline

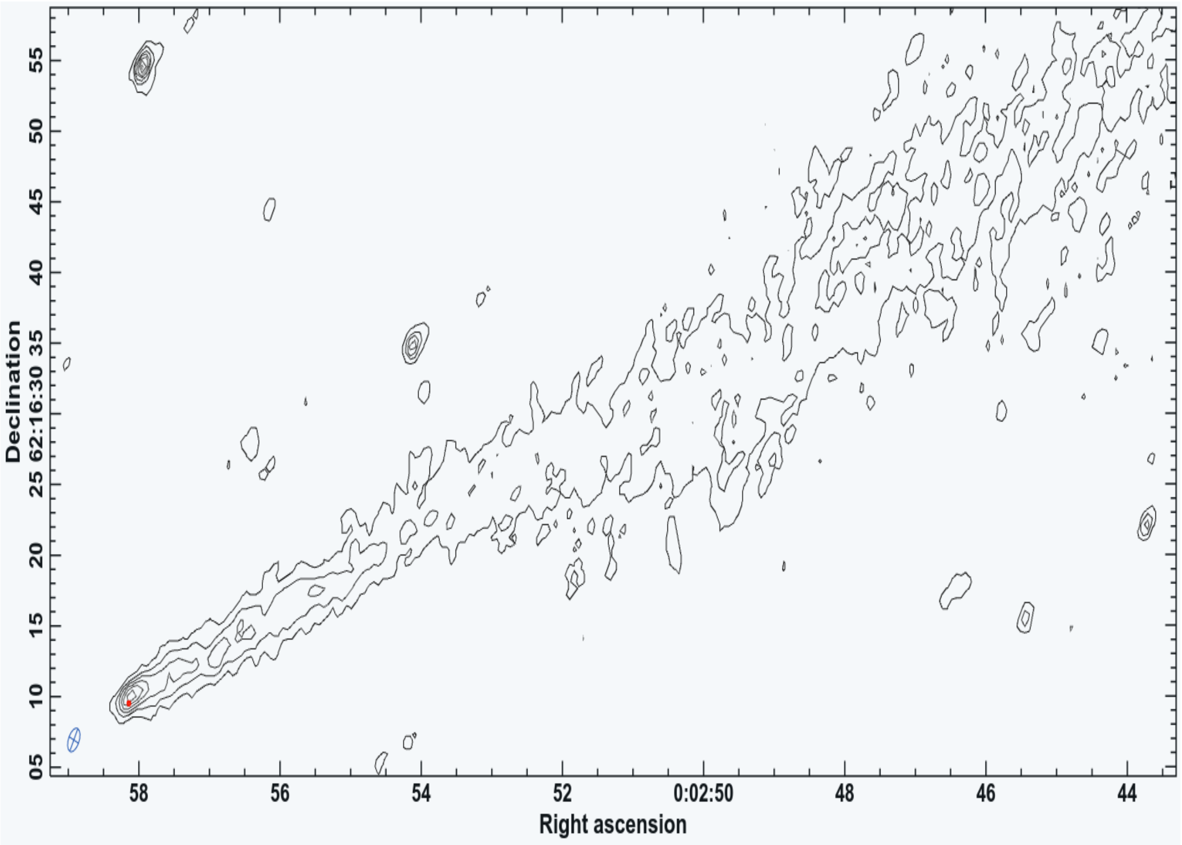
- 4 observing epochs, on source time
  - C : B(95 min) C(104 min)
  - X : B(290 min) C (140 min)

Credit: NRAO

Combined 4-12 GHz broadband radio image and contour map

Kumar et. al. 2023
arxiv: 2302.04927

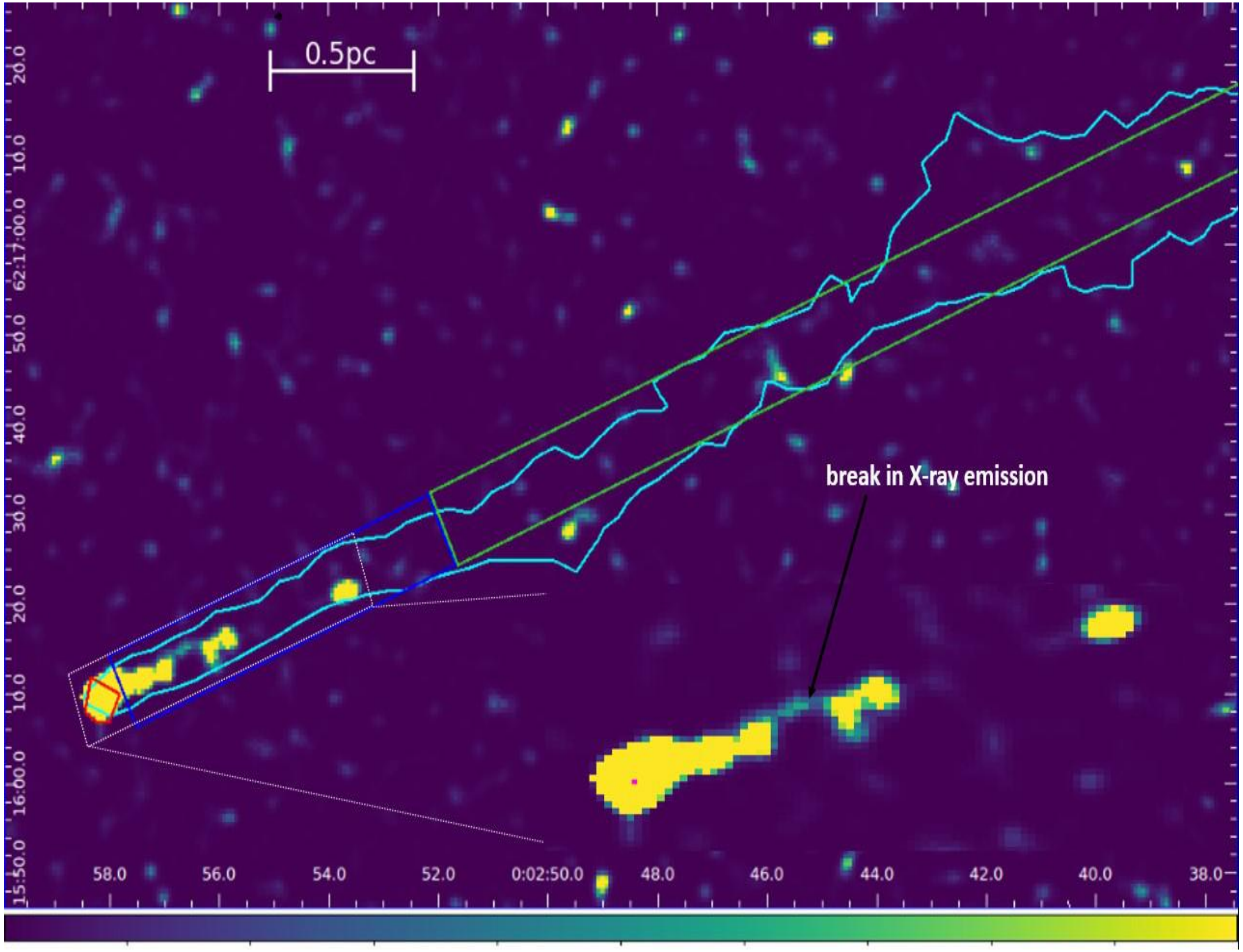




- Synthesized beam: 1.78" x 1.03", Briggs=0.5, resolution=0.45", noise rms=1.08uJy/beam
- Uniformly bright emission near the pulsar and the bow shock region

- Kinks and hotspot along the extended tail of emission
- Contour map indicates a laminar flow near the bow shock and just behind the pulsar

Broadband X-ray image: 0.5 - 7 keV



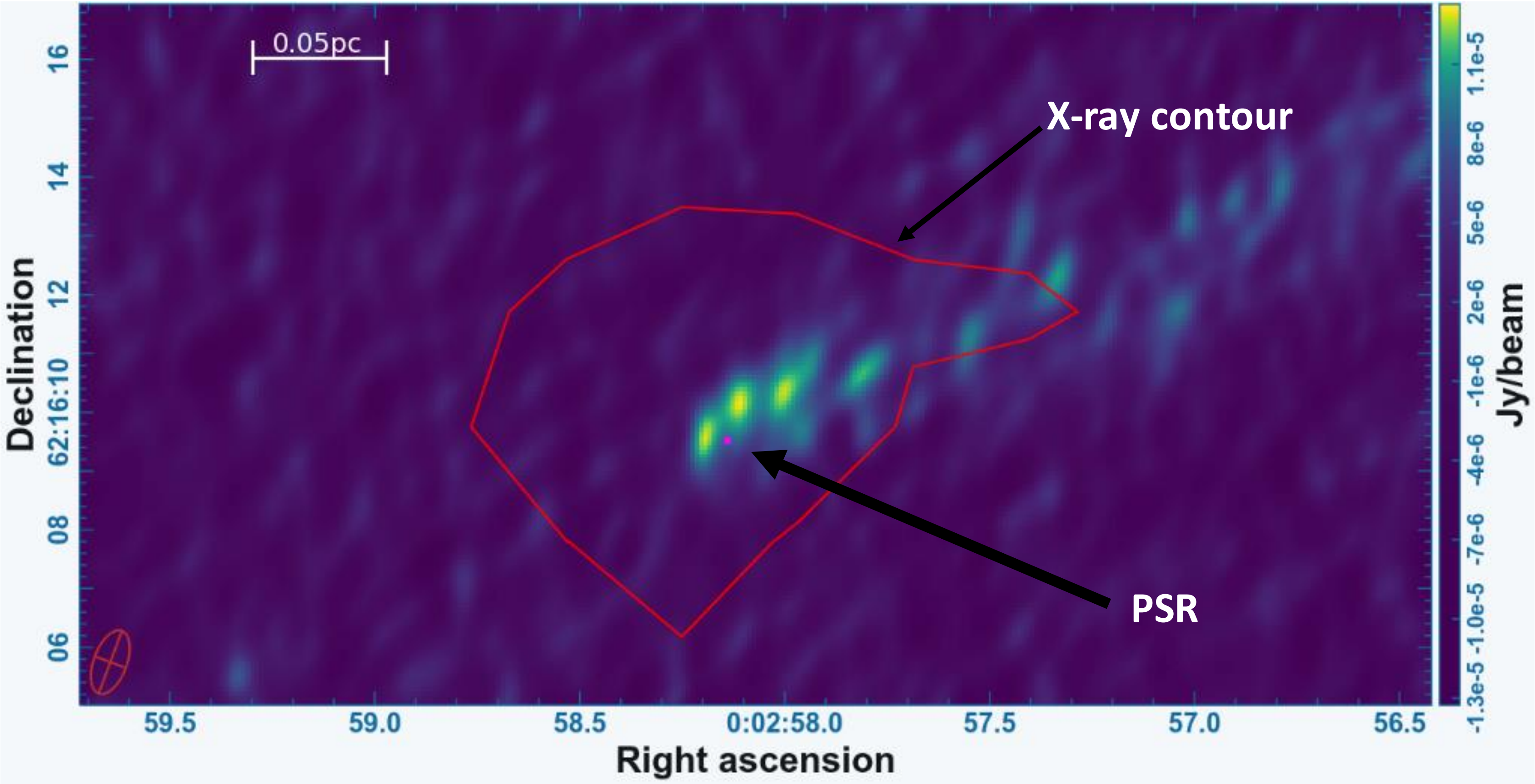
Kumar et. al. 2023, arxiv: 2302.04927

- Cyan= contour from 4-12 GHz radio
- Spatially resolved regions (red, blue, green box) to study spectral evolution
- Size of X-ray emission ~21" with hotspots along the radio emission
- Absorption PL fitting shows some evidence of synchrotron cooling along the tail, although unconstrained
- X-ray gets more collimated like "Mouse" (Klingler et. al. 2018)

	Best Fit	Lower Bound	Upper Bound
R_0(red)	4.12	-1.59	4.72
R_1(blue)	3.23	-1.56	4.83
R_2(green)	5.69	-2.48	6.91

Photon index and 90% bound on the three regions

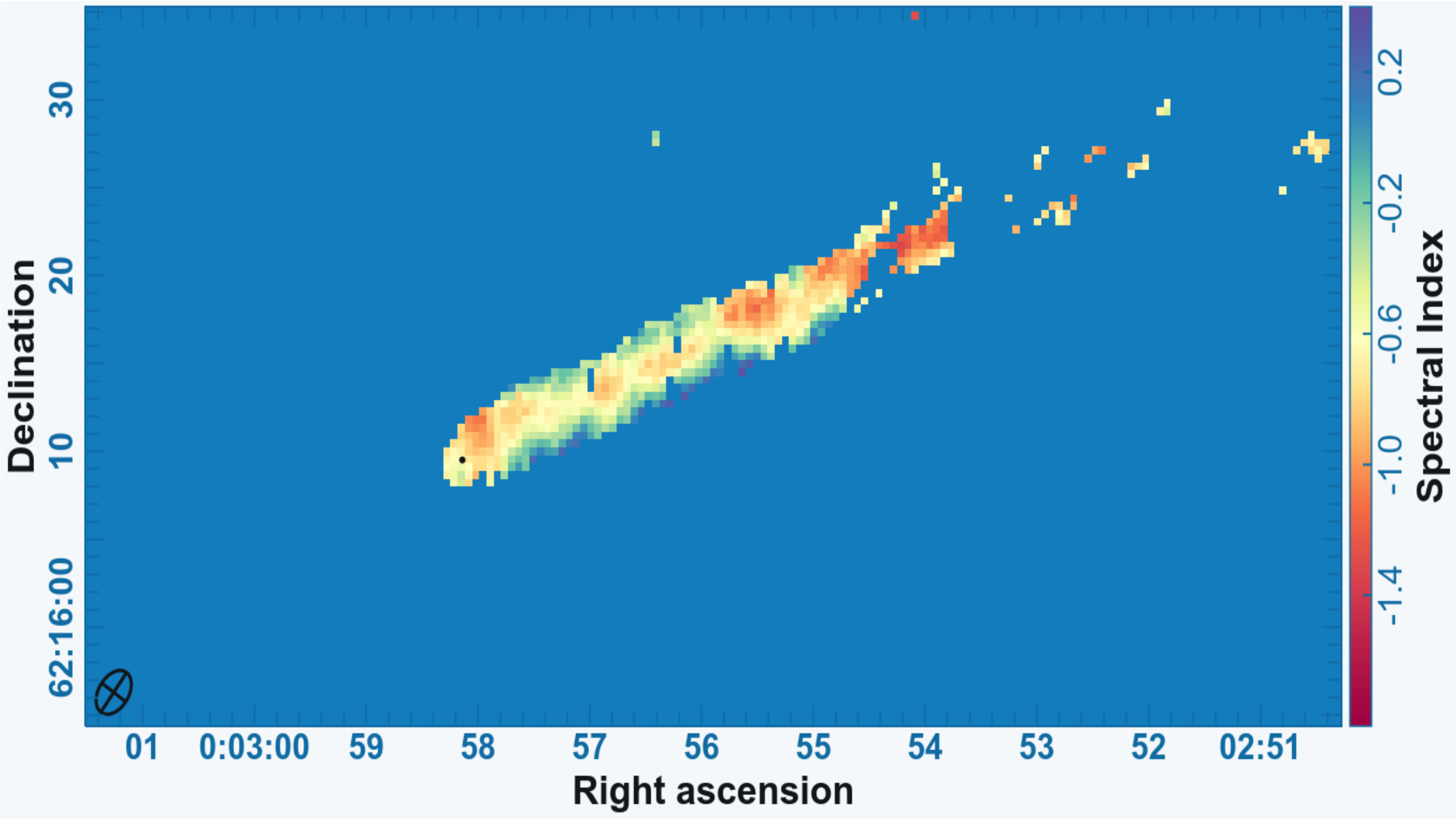
Highest resolution radio image



- From single epoch B config 8-12 GHz data
- Synthesized beam : 1.13" x 0.56" , Briggs : 0.5 resolution: 0.075", noise rms : 2.08 uJy/beam

- Shows asymmetric emission inside the bow shock region

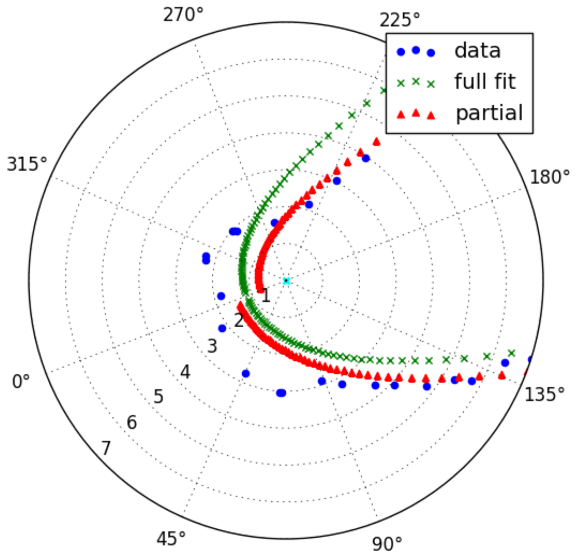
Normally weighted 4 -12 GHz spectrum



- Synthesized beam : 2.77" x 1.84", noise rms : 1.74uJy/beam
- Pixels 5x below corresponding image noise rms and above 0.5 error in spectral index are masked

- Unusually steep spectrum inner channel ~ -1.2 deviating from general PWN –0.5 - 0 (Weiler & Sramek 1988)
- Flat spectrum sheath towards the edge

Bow shock fitting



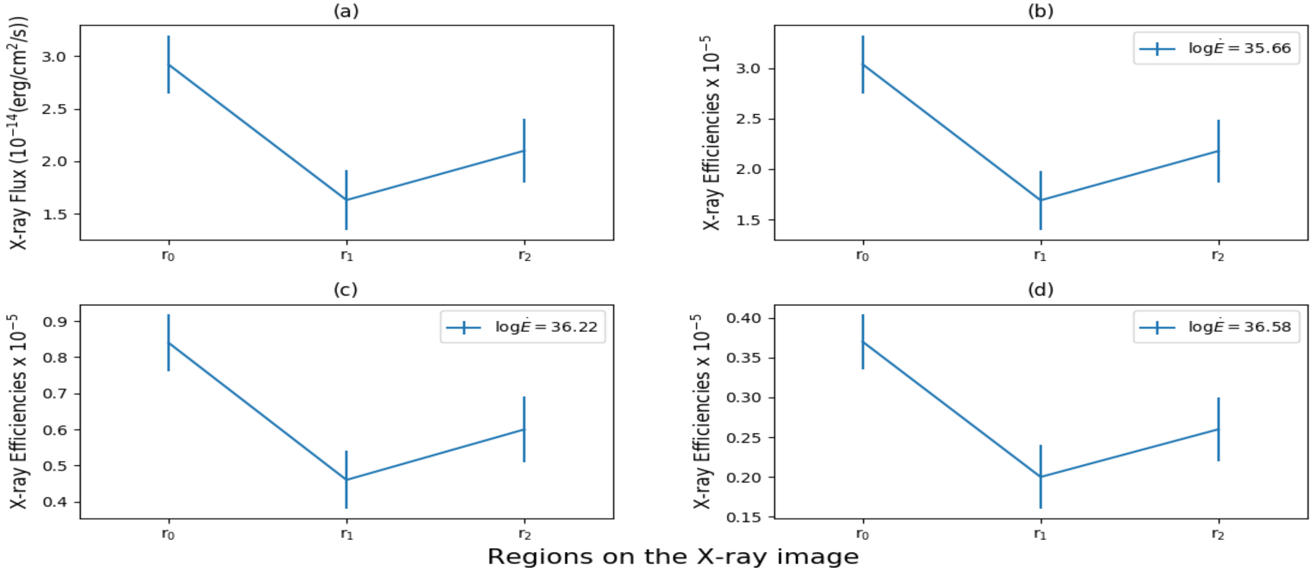
$$R(\theta) = R_o \frac{\sqrt{3(1-\theta\cot\theta)}}{\sin\theta}$$

R_o is the standoff distance (Wilkin 1996)

- Standoff distance of 0.0032 - 0.0092 pc, among the smallest in these systems similar to Frying Pan with M ~200 (Ng. et. al. 2012)
- Edot based on standoff is factor 2-10 from timing, log(Edot)=35.18

- Inconsistencies in Edot can be resolved by a smaller distance to the pulsar

- Calculated X-ray efficiencies are among the lowest reported for such systems (see Kargaltsev & Pavlov 2008)



(a) X-ray flux for the three regions (b,c,d) X-ray efficiency for three regions for different Edot estimates

Discussion

- Hotspots in radio + quick fading of X-ray
  - ISM turbulence -> need magnetic field geometry to confirm
  - Density fluctuations
  - X-ray collimation is possible by efficient cooling -> stronger magnetic field, but X-ray diminished while radio is uniform or a higher velocity of inner channel in contrast to MHD simulations (see Bucciantini 2018b)
- Kinks
  - Density gradient -> unlikely as tail resumes it orientation downstream
  - Flow instability -> would lead to disordered magnetic field, need polarization maps (see Frying Pan, Ng. et. al. 2012)
  - ISM turbulence -> enhanced emission near kinks like in the case of Frying Pan, none here
- Laminar flow and radio spectrum
  - Both, the radio contour and spectral index image indicate a laminar structure as predicted by simulations (see Bucciantini 2018b) with slower inner channel
  - Based on this, flat radio sheath can be explained by less de-boosting of inner region compared to surrounding and so will appear brighter
- Asymmetric emission
  - Evident in both the highest resolution radio and X-ray image
  - Strong turbulence or jets from particle escape collimated by high velocity (see eg Olmi 2018)

Conclusions

- We have detected a bow shock PWN at 10x higher resolution in radio with tail extending up to 5.3' and in X-ray with a short tail of ~21''
- The fit for bow shock provides a very compact size, which is among the smallest in such system and suggest a high velocity for the pulsar as predicted by Schinzel et. al. 2019
- The X-ray efficiency is among the lowest for such systems, suggesting a population not detected by previous X-ray surveys, but will likely be detected in radio
- Apart from the normal behavior it also shows other anomalous features such as a very steep radio spectrum, asymmetric emission inside the nebula, kinks etc., not all of which are explained from the current understanding
- We need follow-up observations in radio to get the polarization information and in X-ray to constrain the spectrum, to better understand some of these features.