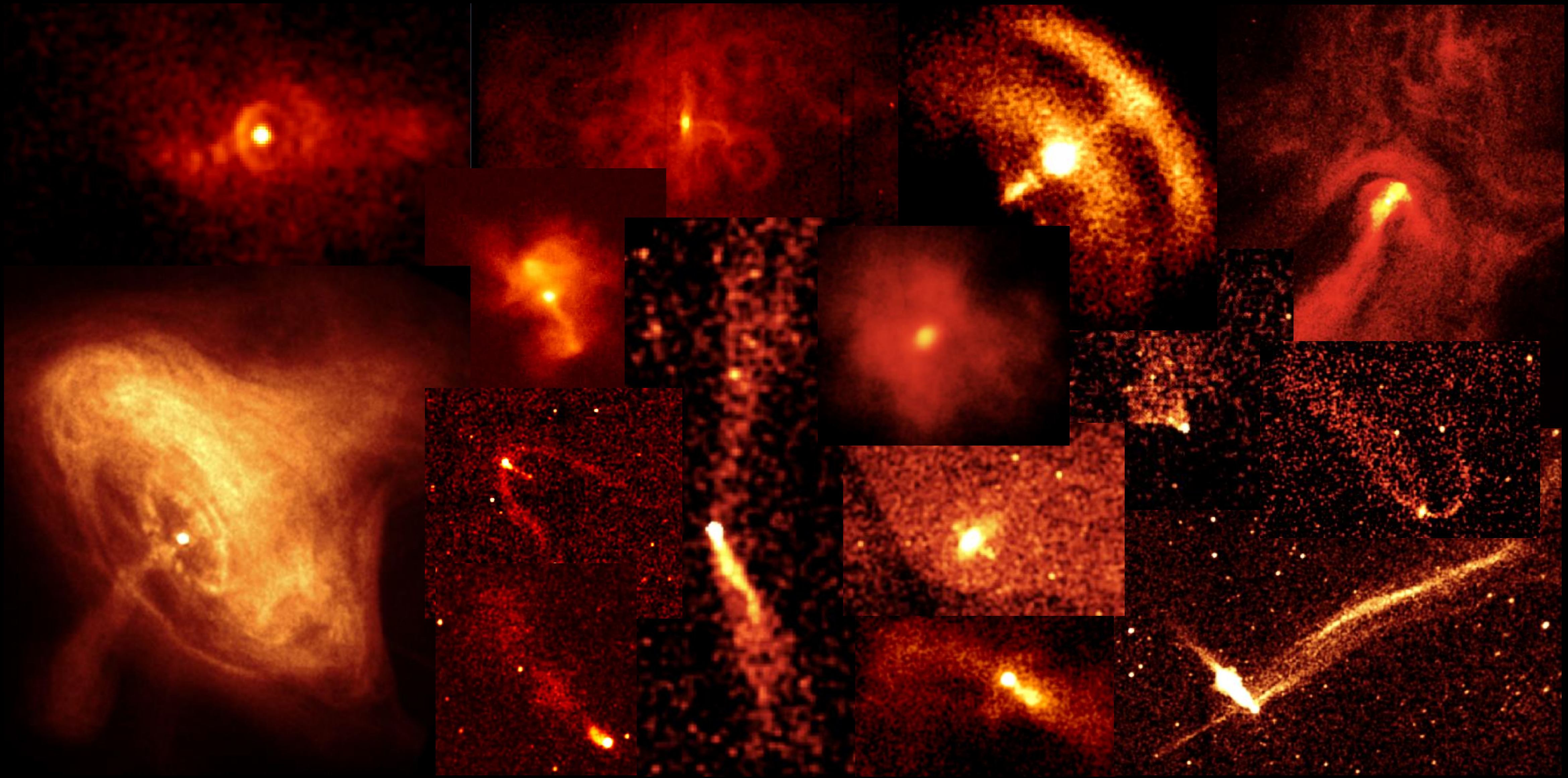
Deep CXO Imaging of Pulsar Wind Nebulae

Oleg Kargaltsev, The George Washington University

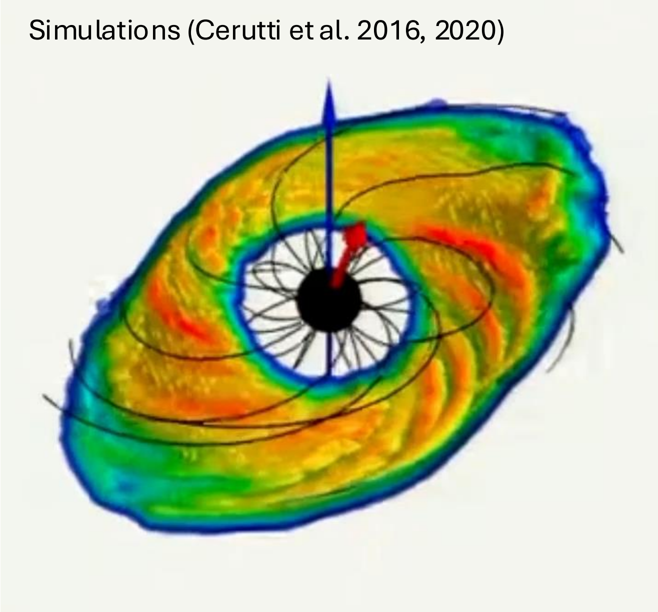


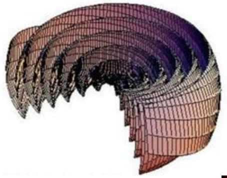
Pulsar wind nebulae as high-energy plasma astrophysics laboratories

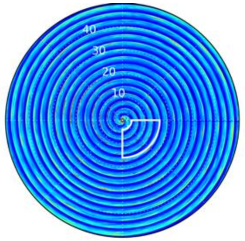
Big Question: *How do magnetized neutron stars convert their rotational kinetic energy into a magnetized wind of ultra-relativistic particles whose energies reach PeV?*

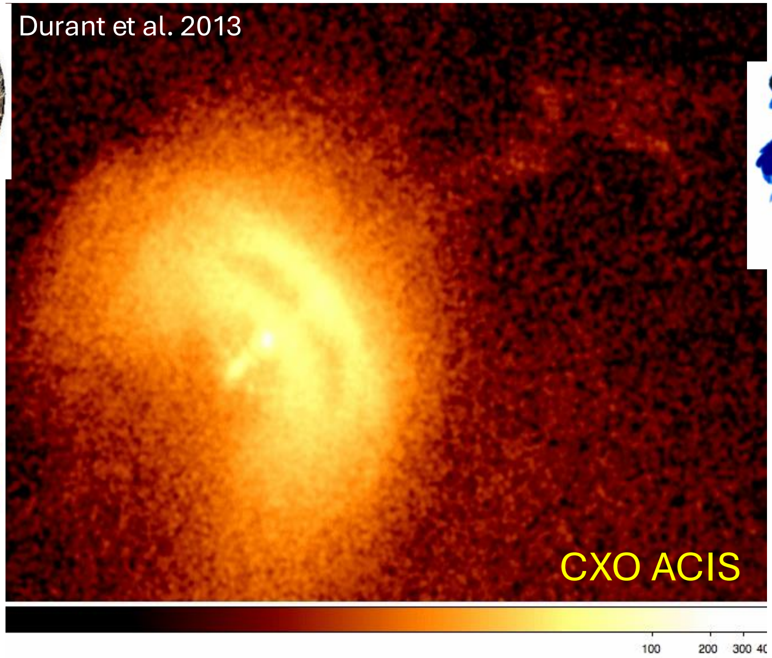
- Particle acceleration mechanism and its connection to pulsar magnetosphere geometry
- Physics of relativistic magnetized outflows (turbulence, reconnection, collimation)
- Interaction of pulsar winds with surrounding medium and ultra-relativistic particle escape from PWNe
- NS kick direction with respect to NS spin axis and magnetic dipole axis

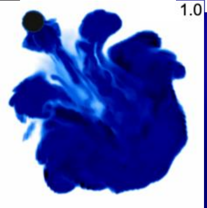
See also poster by Seth Gagnon.

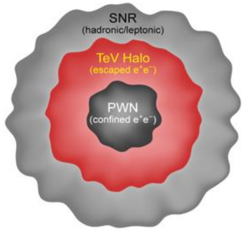


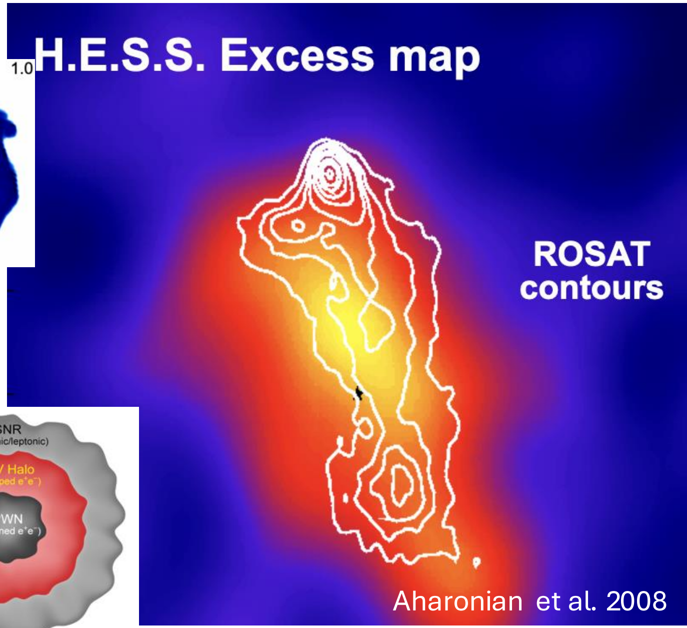




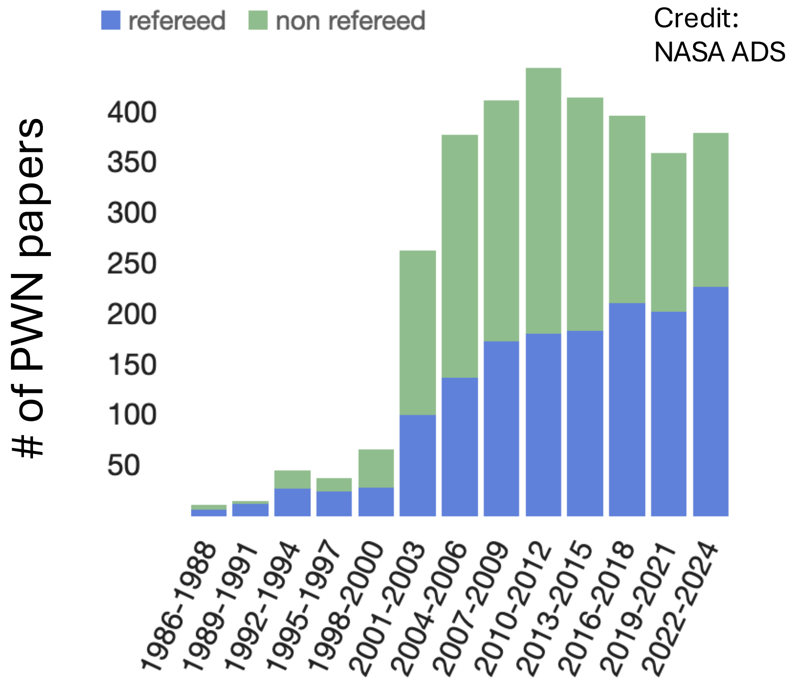








What have we learned in 25 years of Chandra observations of PWNe?



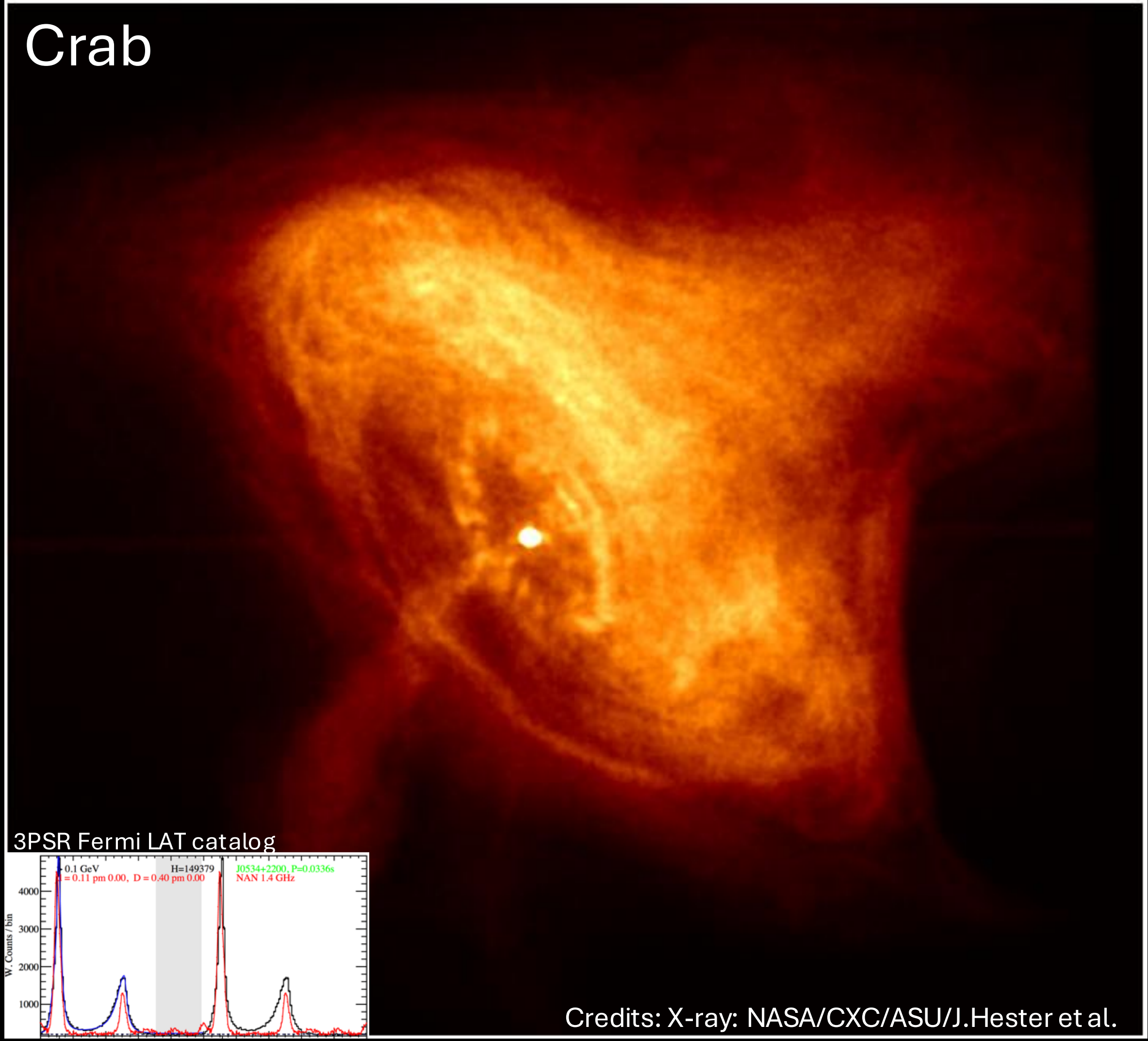
Chandra is ideally suited for PWN studies because:

- its angular resolution is comparable to the termination shock angular size (for a young pulsar at a few kpc distance)
- PWNe have hard spectra whose evolution with distance from the pulsar can be studied using low-resolution <u>spatially-resolved</u> spectroscopy
- characterizing faint extended emission on large angular scales requires extremely low ACIS background and substantial effective area above 1 keV (since many PWNe are strongly absorbed below 1 keV)

A very young PWN inside a shell-less SNR

$\dot{E} = 4.5 \times 10^{38}$ erg s^{-1}
$\tau_c = 1.2$ kyrs
$B_s = 3.8 \times 10^{12}$ G

Dominated by torus (equatorial outflow), rich dynamics



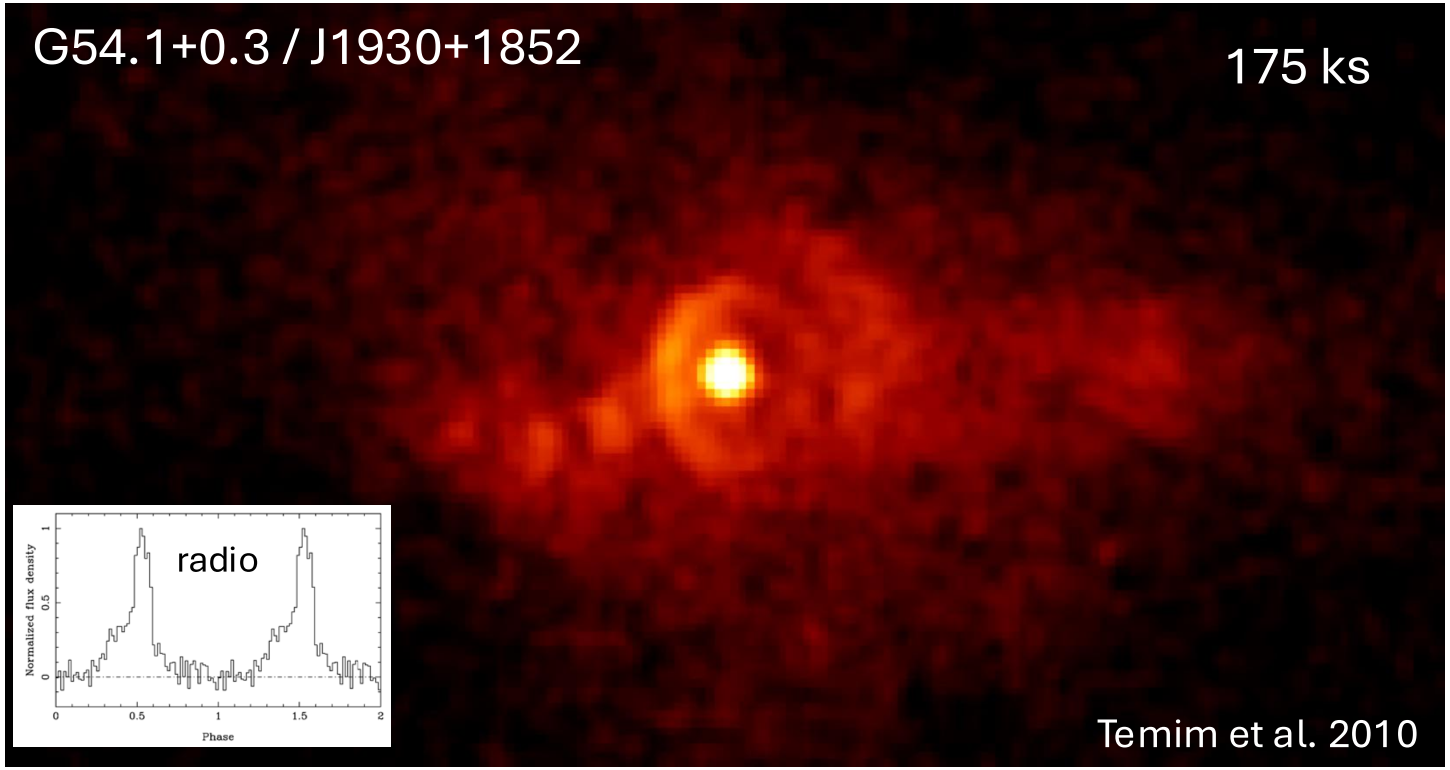
Credit: G. Dubner (IAFE, CONICET-University of Buenos Aires) et al.; NRAO/AUI/NSF; A. Loll et al.; T. Temim et al.; F. Seward et al.; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; and Hubble/STScI

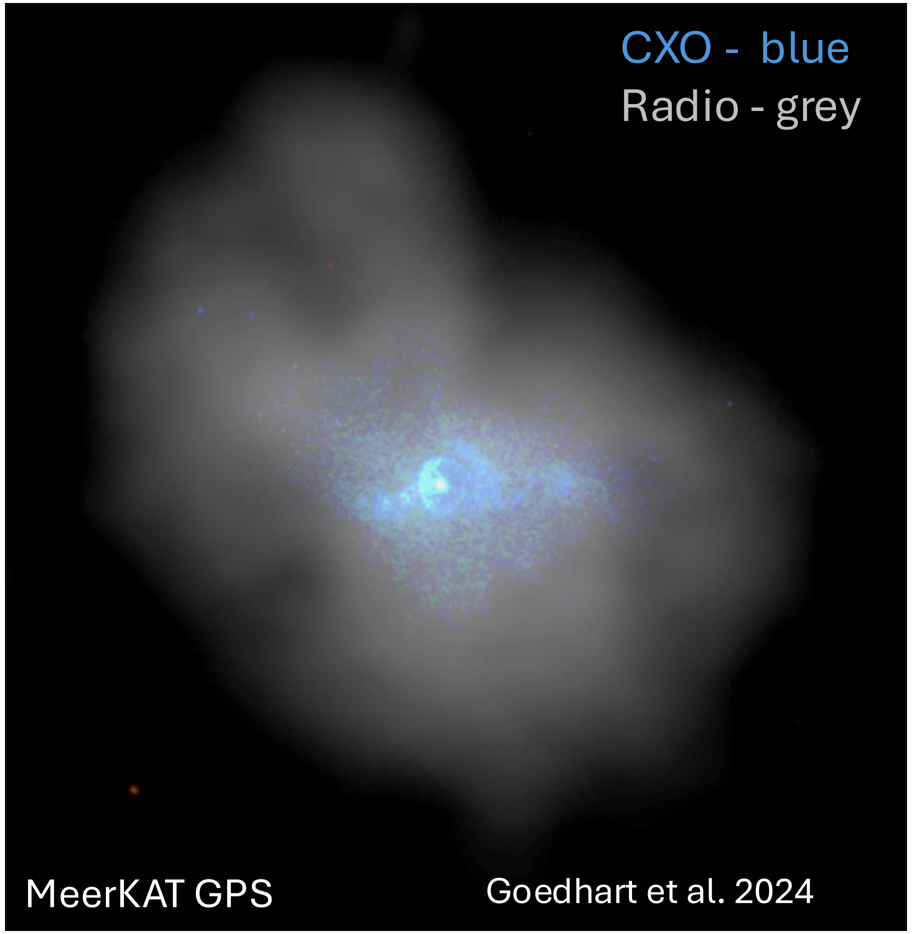
A young PWN inside a shell-less SNR

$\dot{E} = 1.2 \times 10^{37}$ erg s^{-1}
$\tau_c = 2.9$ kyrs
$B_s = 1.0 \times 10^{13}$ G

A lower efficiency and weak torus could be due to the pulsar being closer to an aligned rotator.
The jets are surprisingly poorly collimated.

Sometimes called the **Crab twin** but notice a **relatively weak torus and lack of gamma-ray emission**.

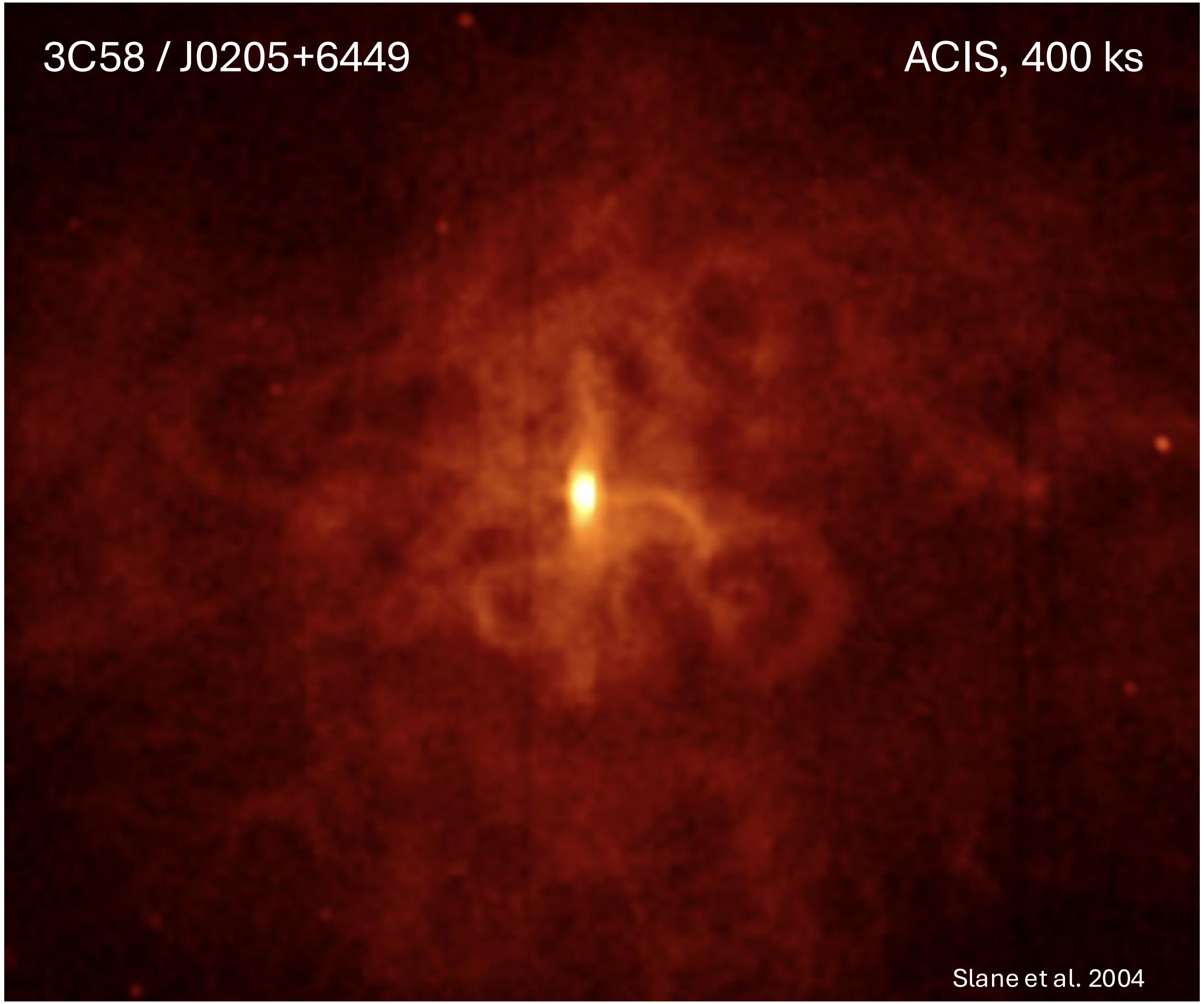


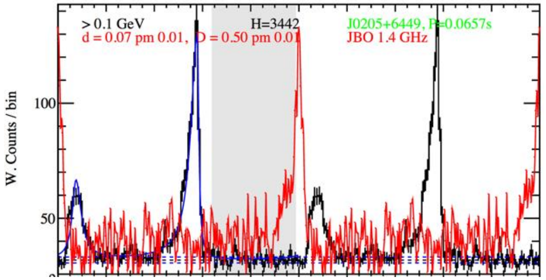


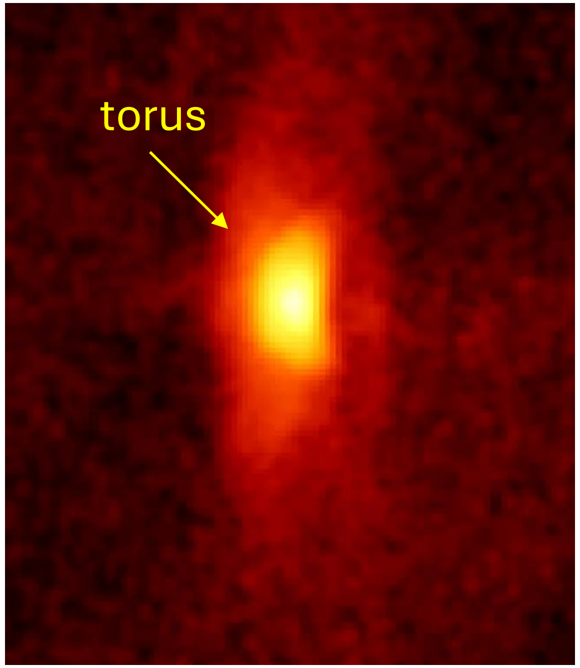
A young PWN inside a shell-less SNR

$\dot{E} = 2.7 \times 10^{37}$ erg s^{-1}
$\tau_c = 5.4$ kyrs
$B_s = 3.6 \times 10^{12}$ G

Numerous loops possibly reflecting large scale B-field structure
Jets are weak and difficult to identify, torus is only seen at the highest CXO resolution





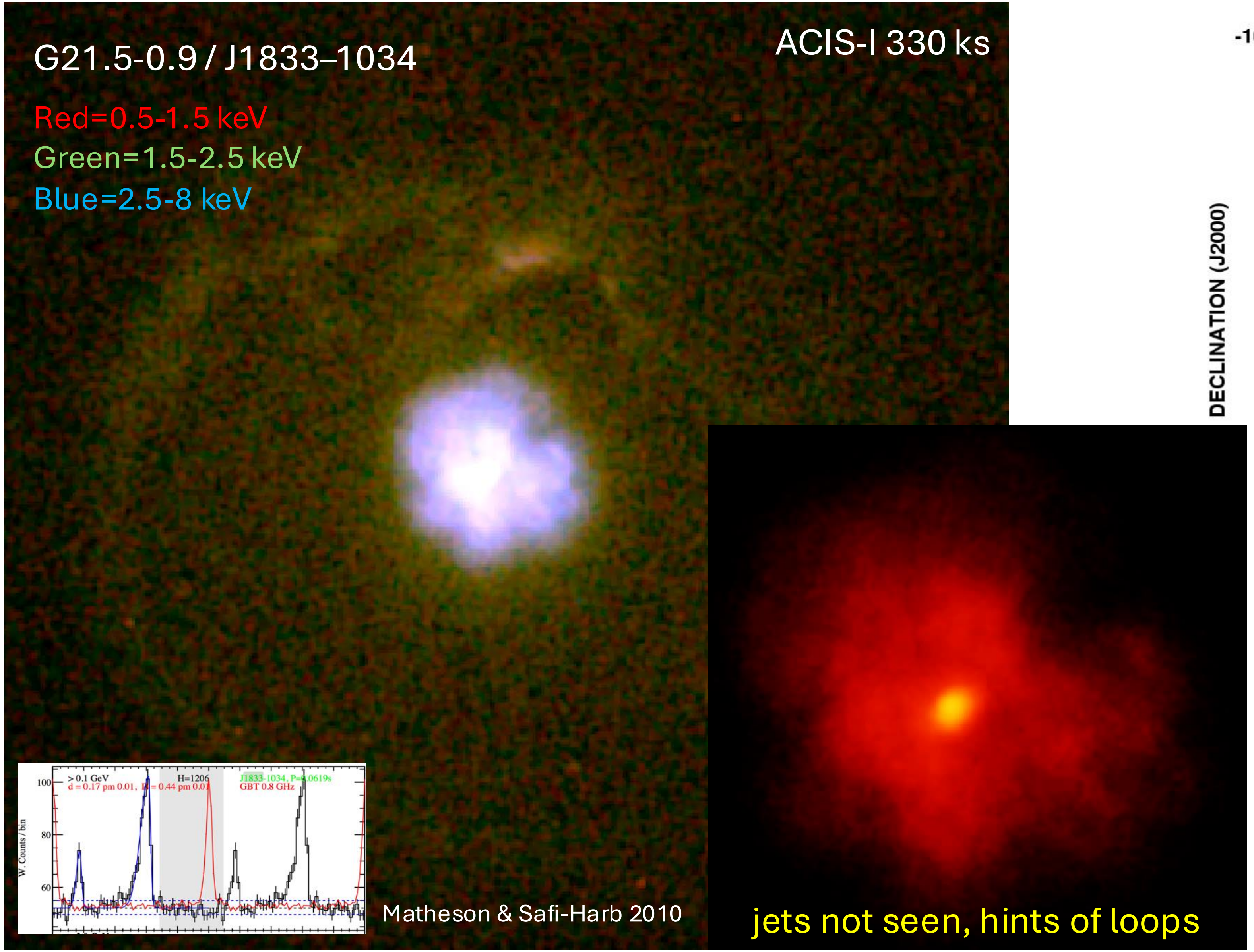


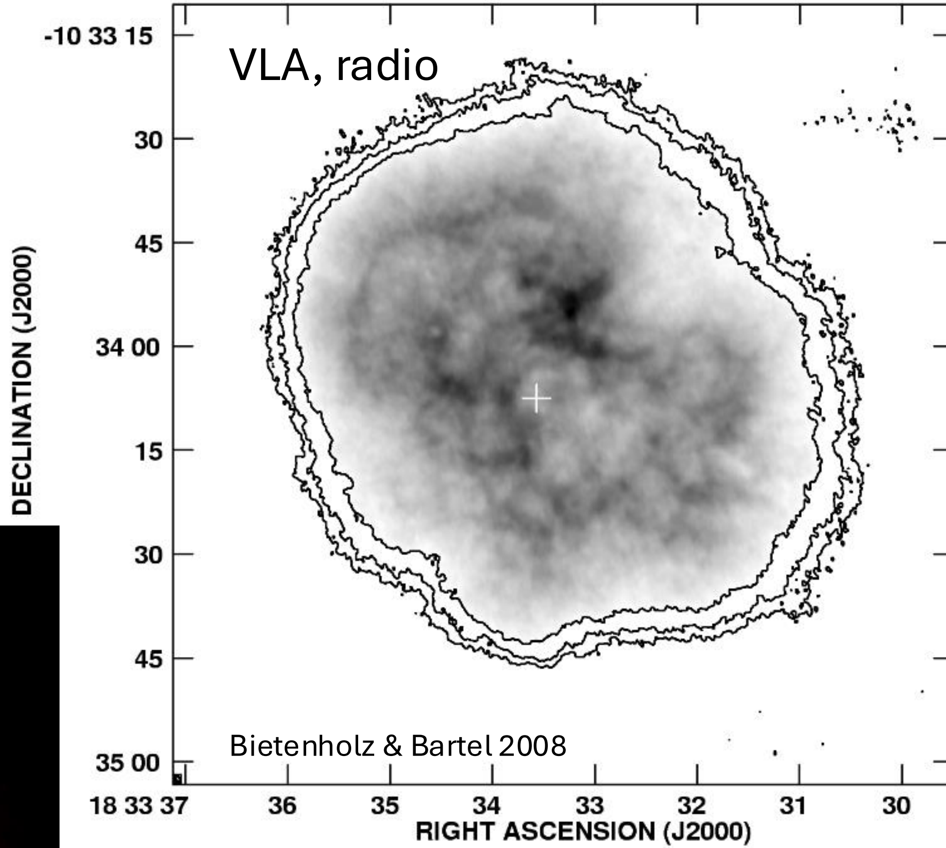
Changes in 3C58 can be seen over 20-yr timescale

The jet gives itself away but having significant motion and developing similar helical structure to those of Vela, Crab, and PSR J1811-1925 jets.

Young PWN inside the faint SNR shell

Compact torus, no traces of jets, they are not pointing to the observer due to the gamma-ray pulse
Deep image shows hints of loops similar to those in 3C58



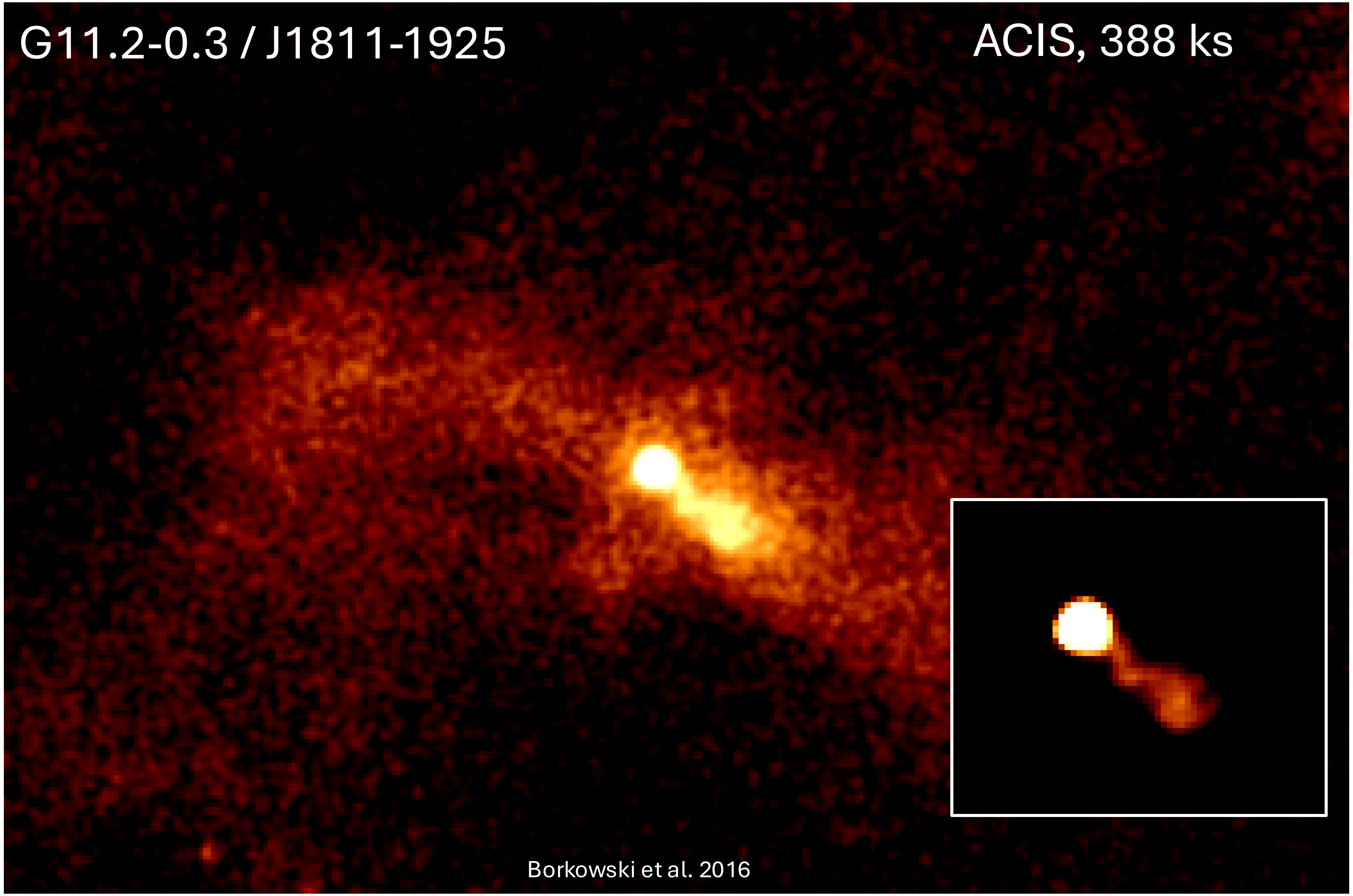


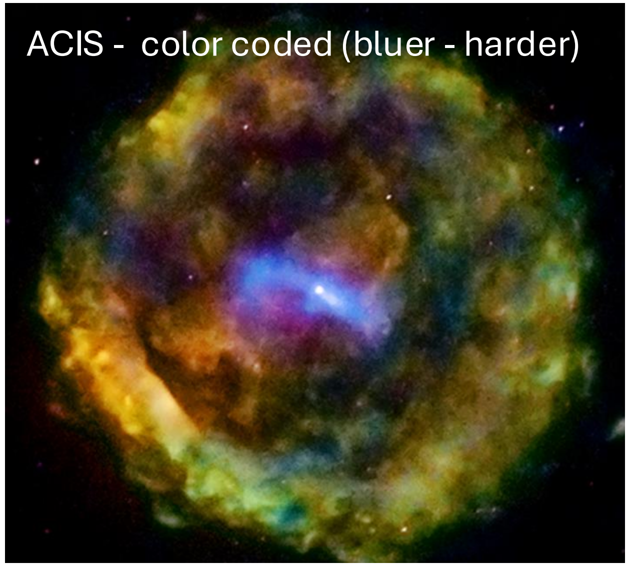
$\dot{E} = 3.4 \times 10^{37}$ erg s^{-1}
$\tau_c = 4.8$ kyrs
$B_s = 3.6 \times 10^{12}$ G

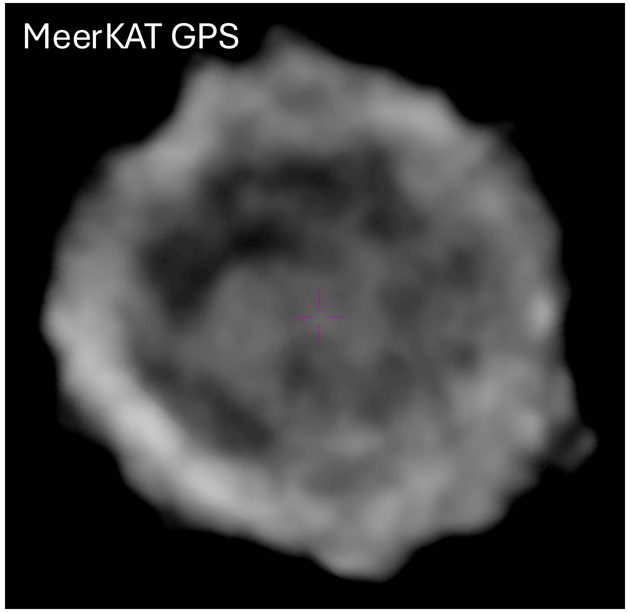
Young PWN inside SNR with shell

$\dot{E} = 6.4 \times 10^{36}$ erg s
$\tau_c = 23$ kyrs
$B_s = 1.7 \times 10^{12}$ G

Torus (equatorial component) is very weak, bright jet, no gamma-ray pulsations





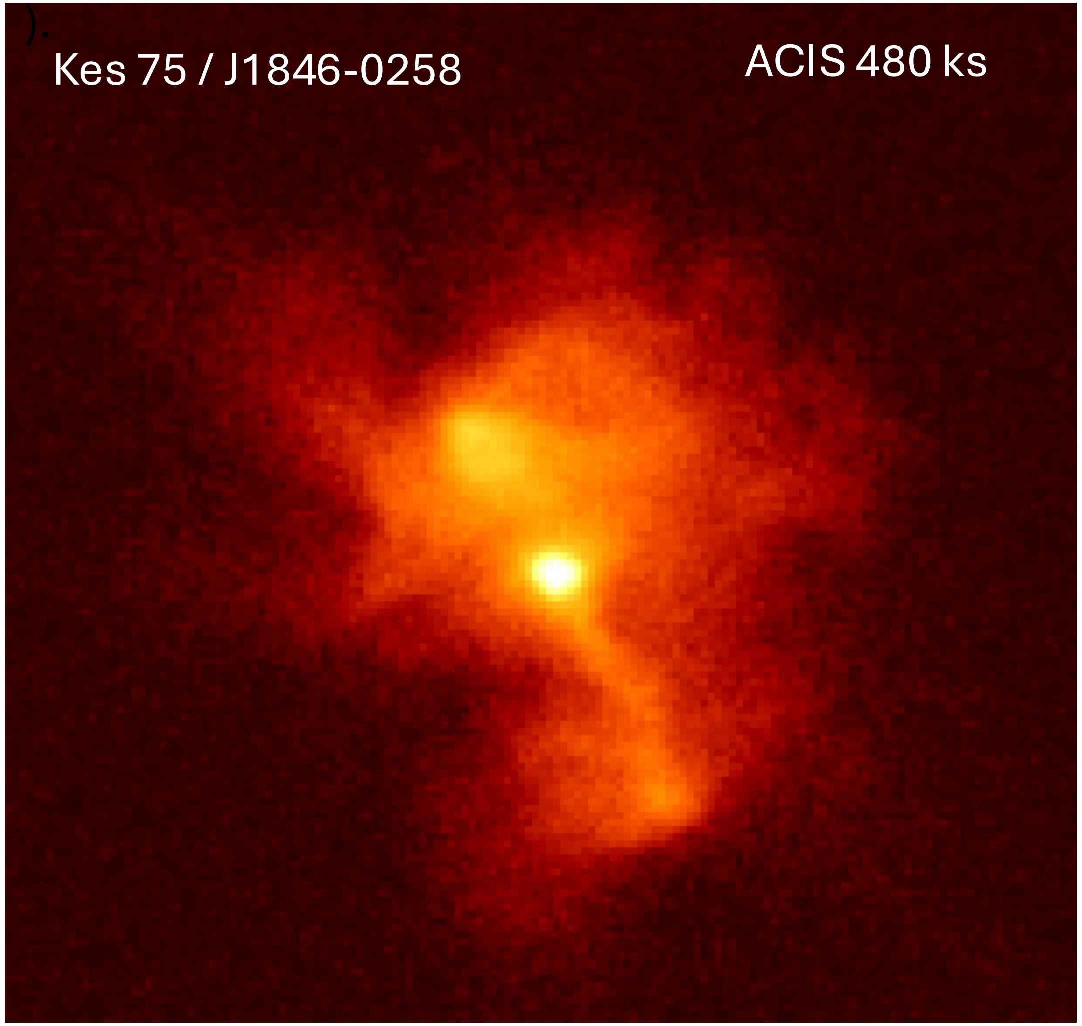


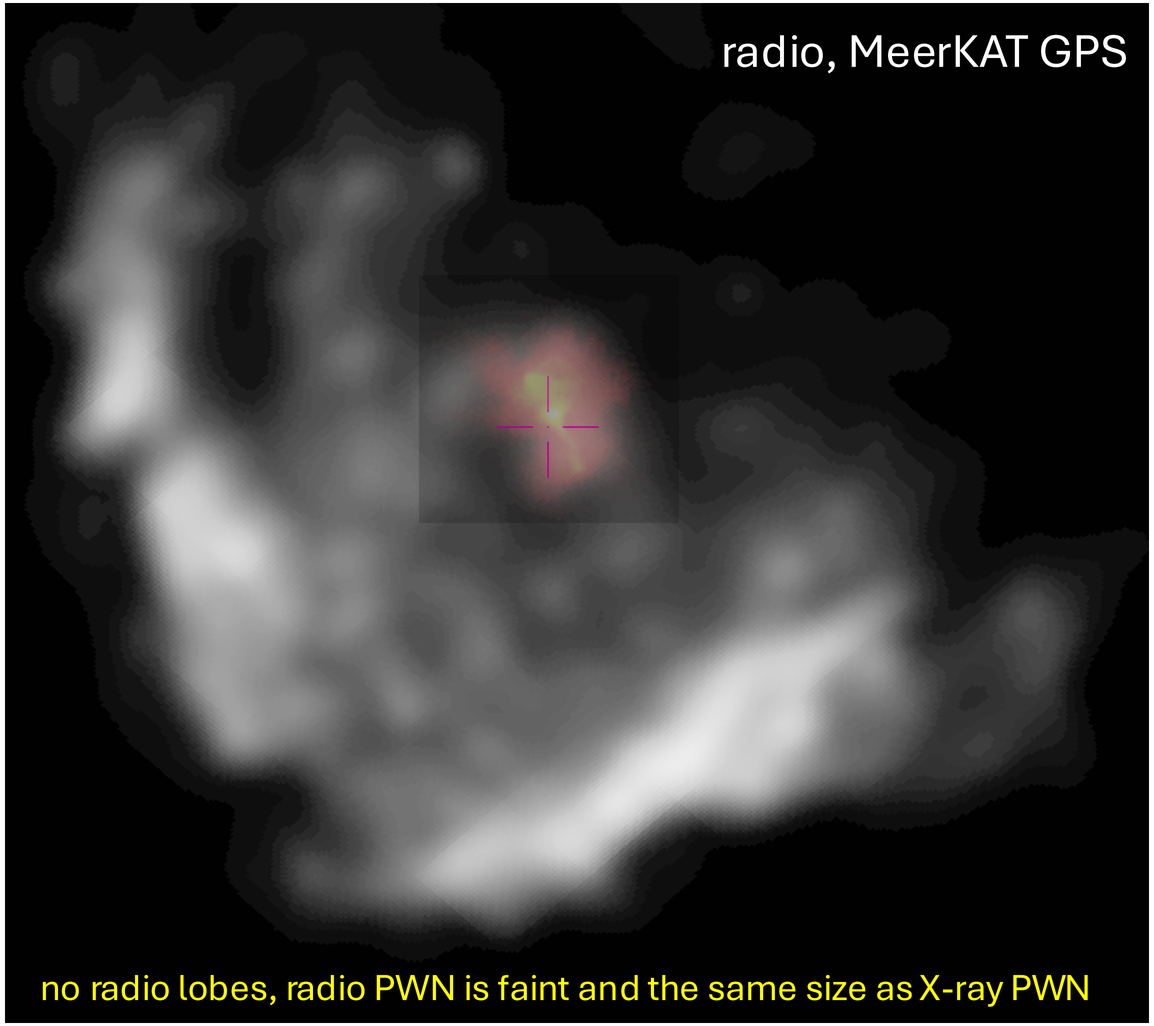
A very young PWN inside SNR with shell

$\dot{E} = 8.1 \times 10^{36}$ erg s^{-1}
τ_c = **700 yrs**
$B_s = 4.9 \times 10^{12}$ G

The PWN appears to be jet-dominated with a weak torus, no gamma-ray (> 1 GeV) pulsations

Expansion measurements with multi-epoch CXO images suggest an age of ~**400 years** (Reynolds et al. 2018)
).



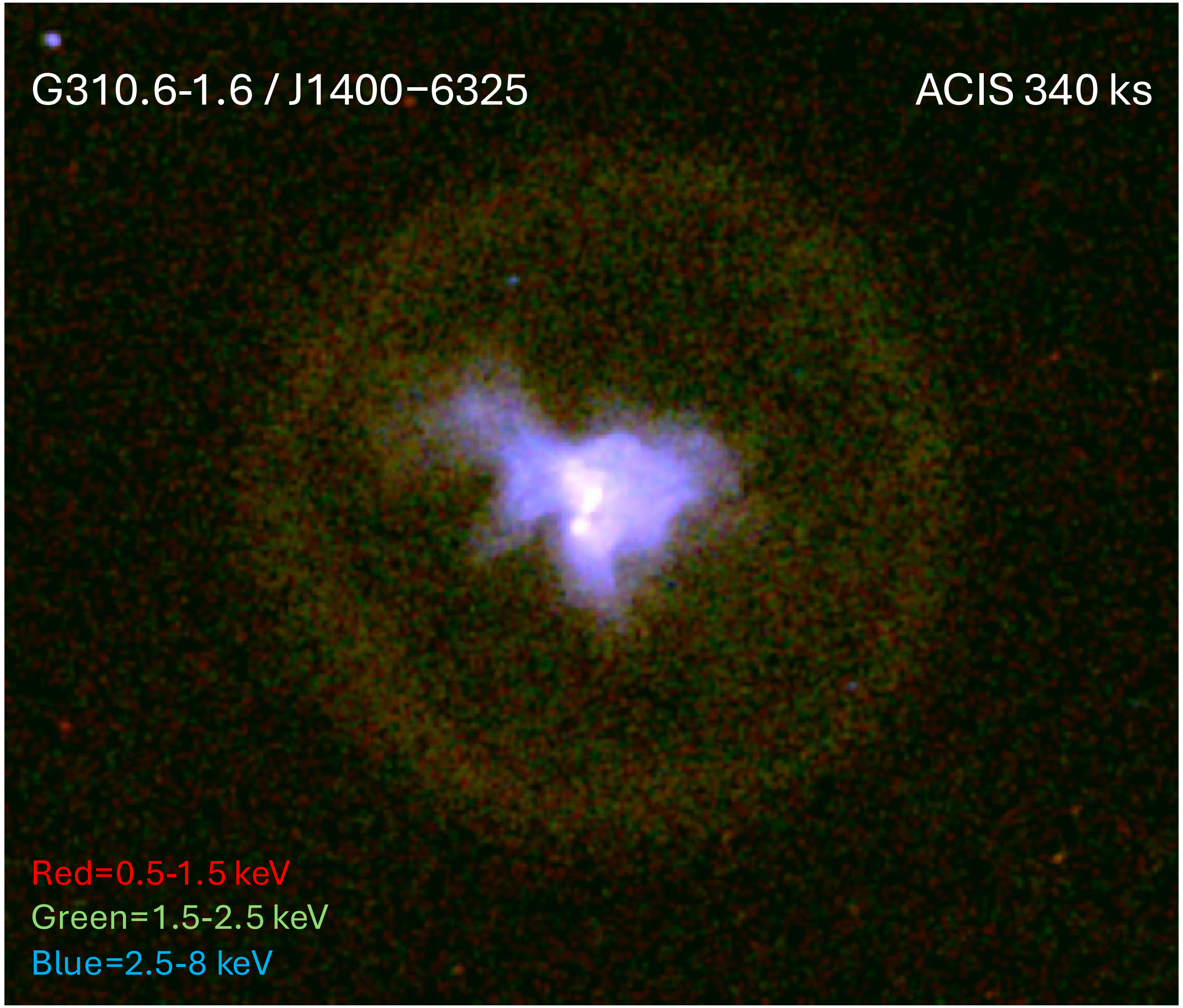


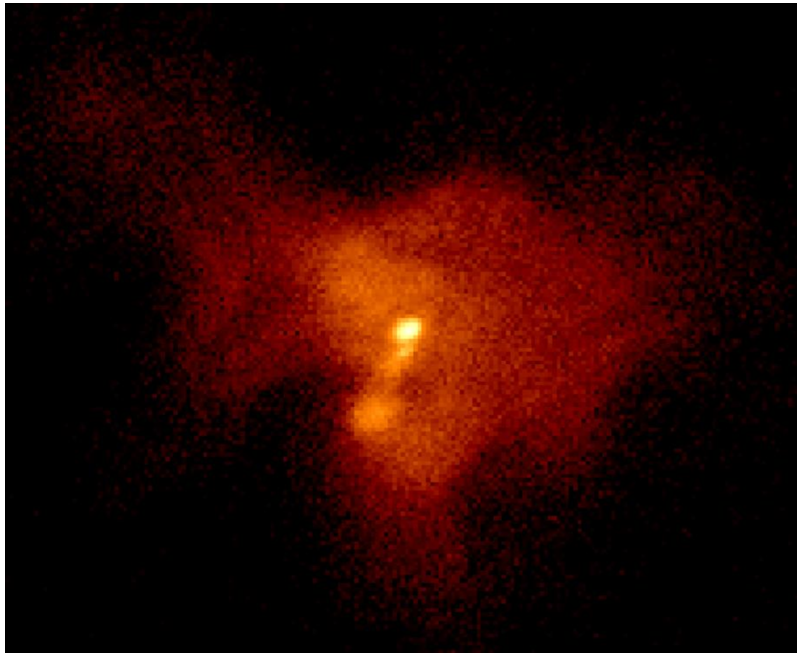
This pulsar showed magnetar-like flares.

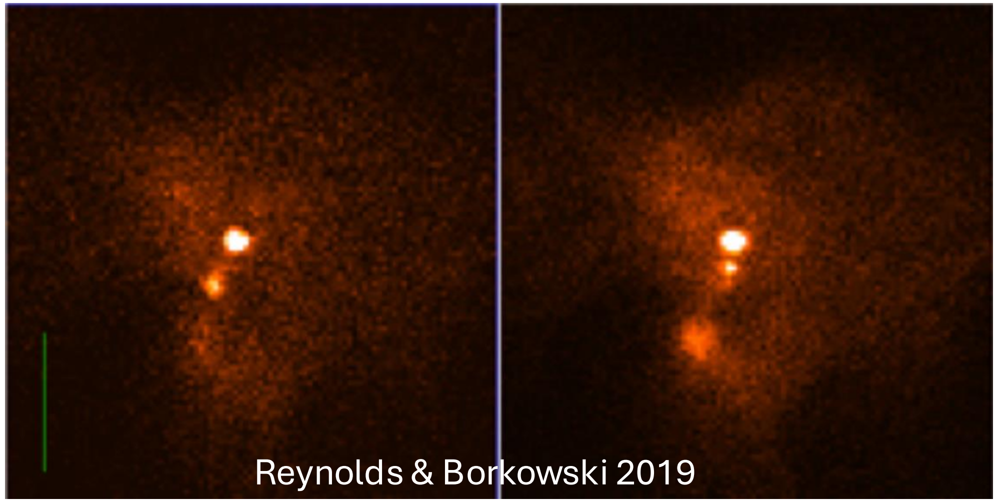
Young PWN inside SNR with a shell(?)

$\dot{E} = 5.1 \times 10^{37}$ erg s^{-1}
$\tau_c = 13$ kyrs
$B_s = 1.1 \times 10^{12}$ G

Likely jet-dominated with only weak torus, no gamma-ray (GeV) pulsations



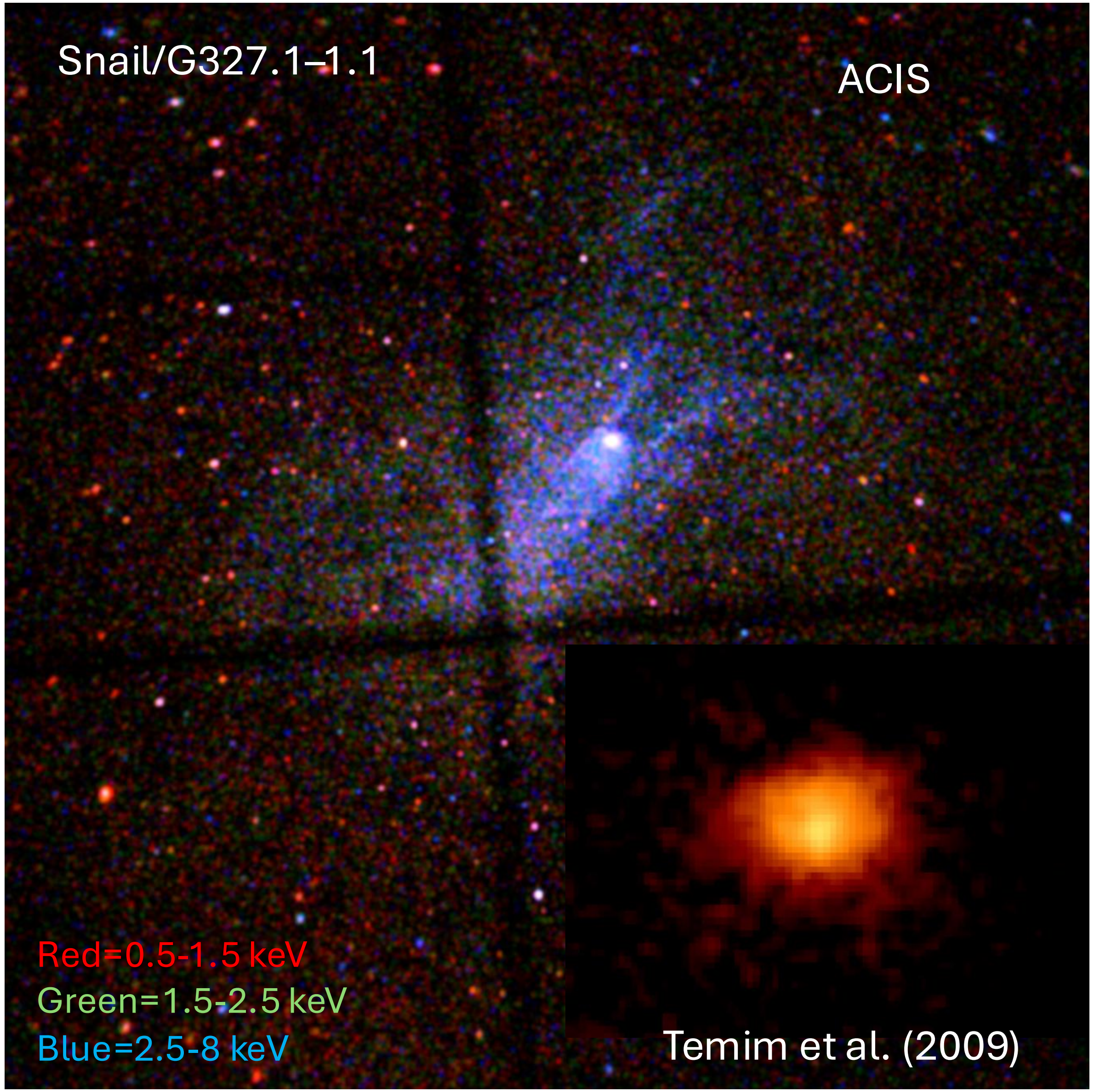


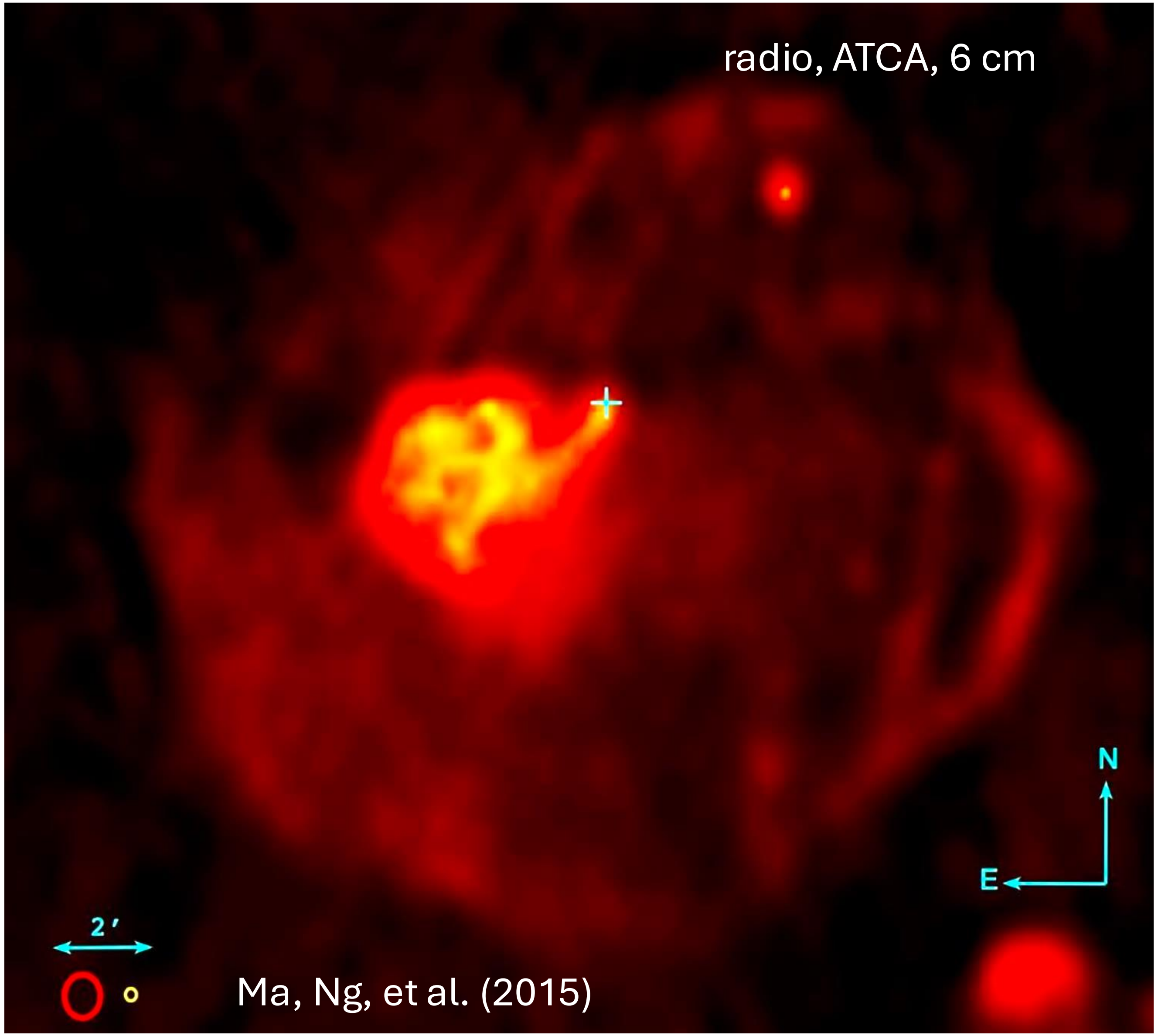


Young PWN inside SNR with shell

No pulsations found yet.

Peculiar prongs suggesting recent interaction with SNR reverse shock, possibly, kinetic particle escape.

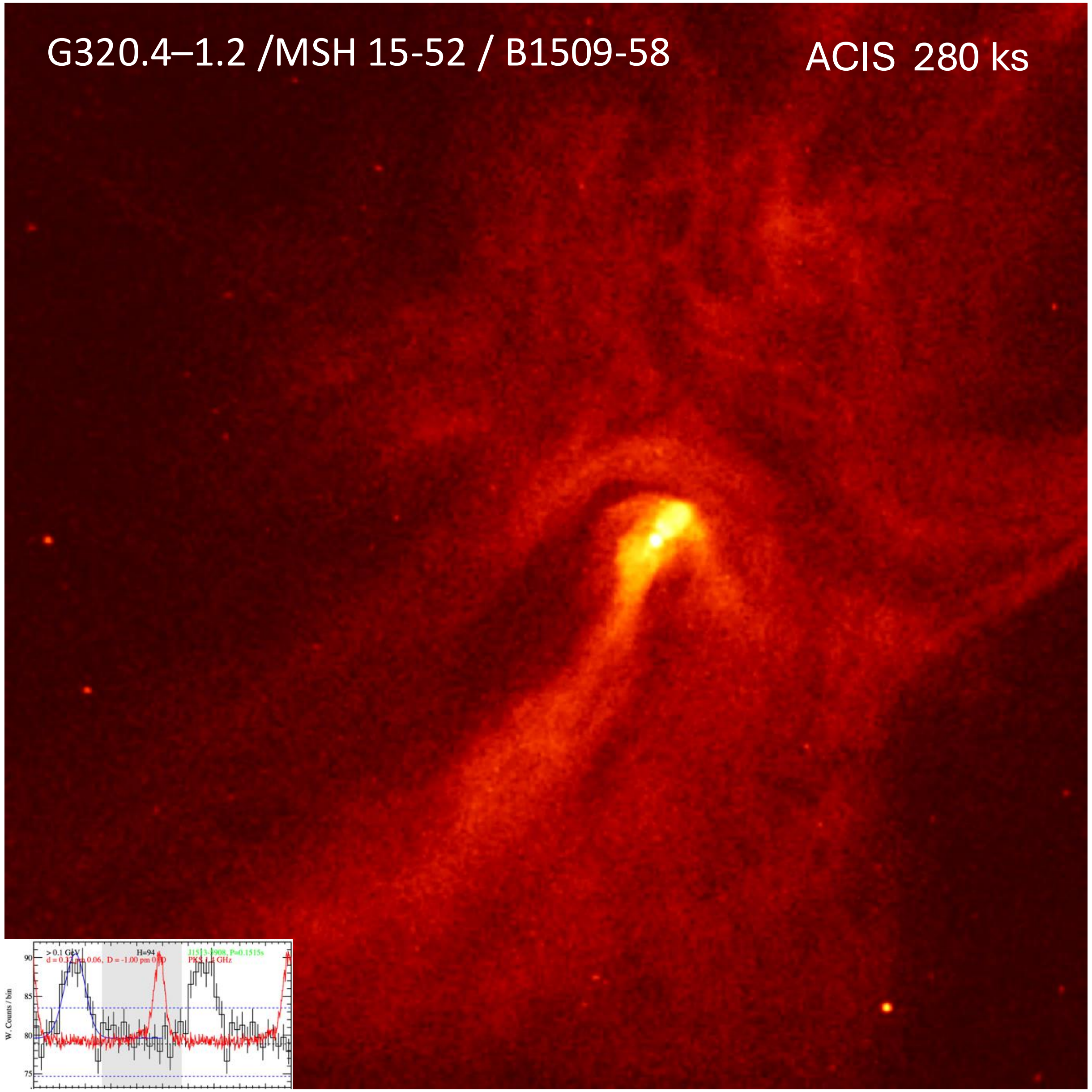


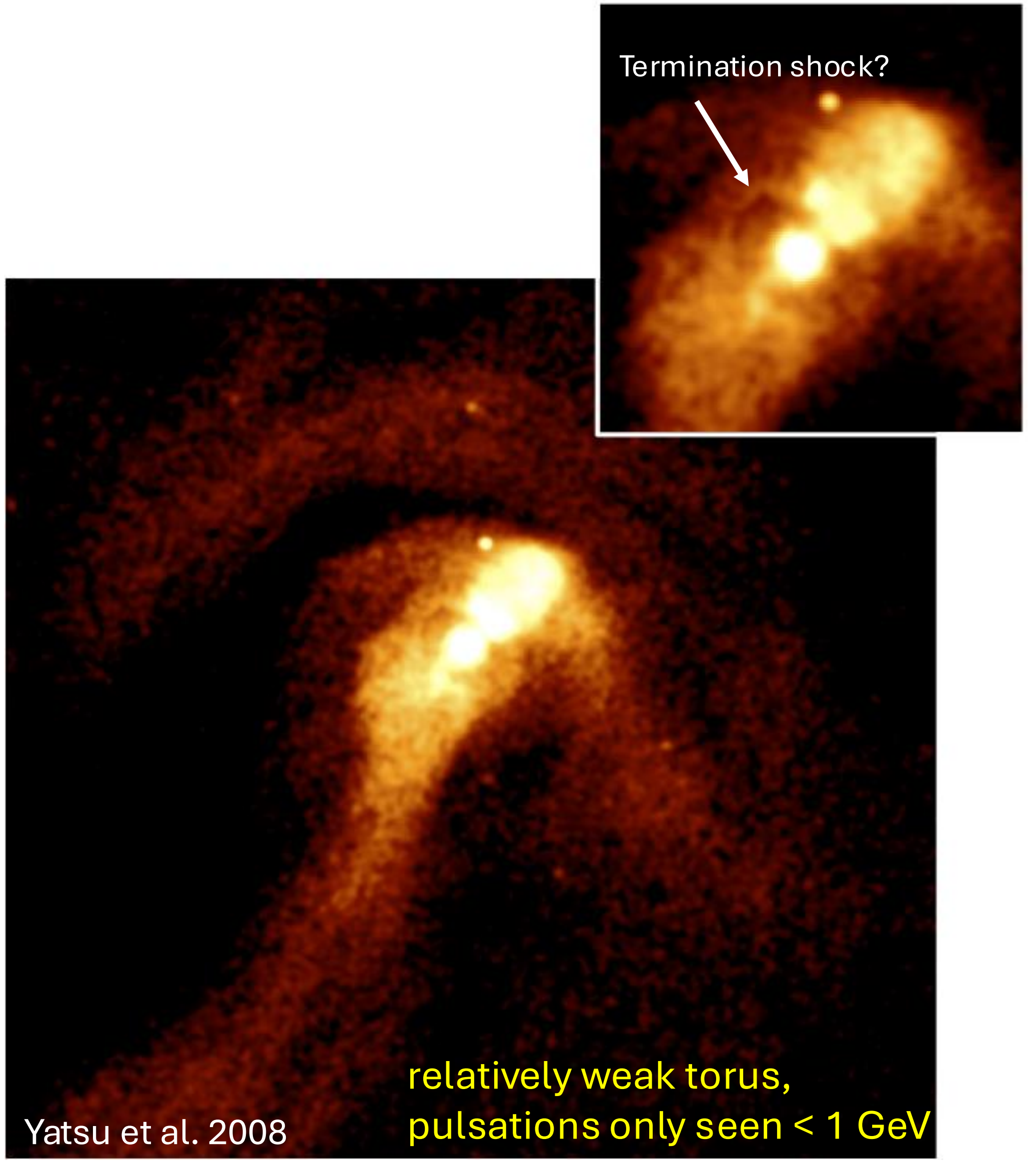


Young PWN inside the SNR with uncertain morphology

Dominated by polar outflows which are, however, not strongly collimated.
Loops and weak inner ring appear in the deep CXO image. Unusually soft gamma-ray pulsations (<1 GeV).

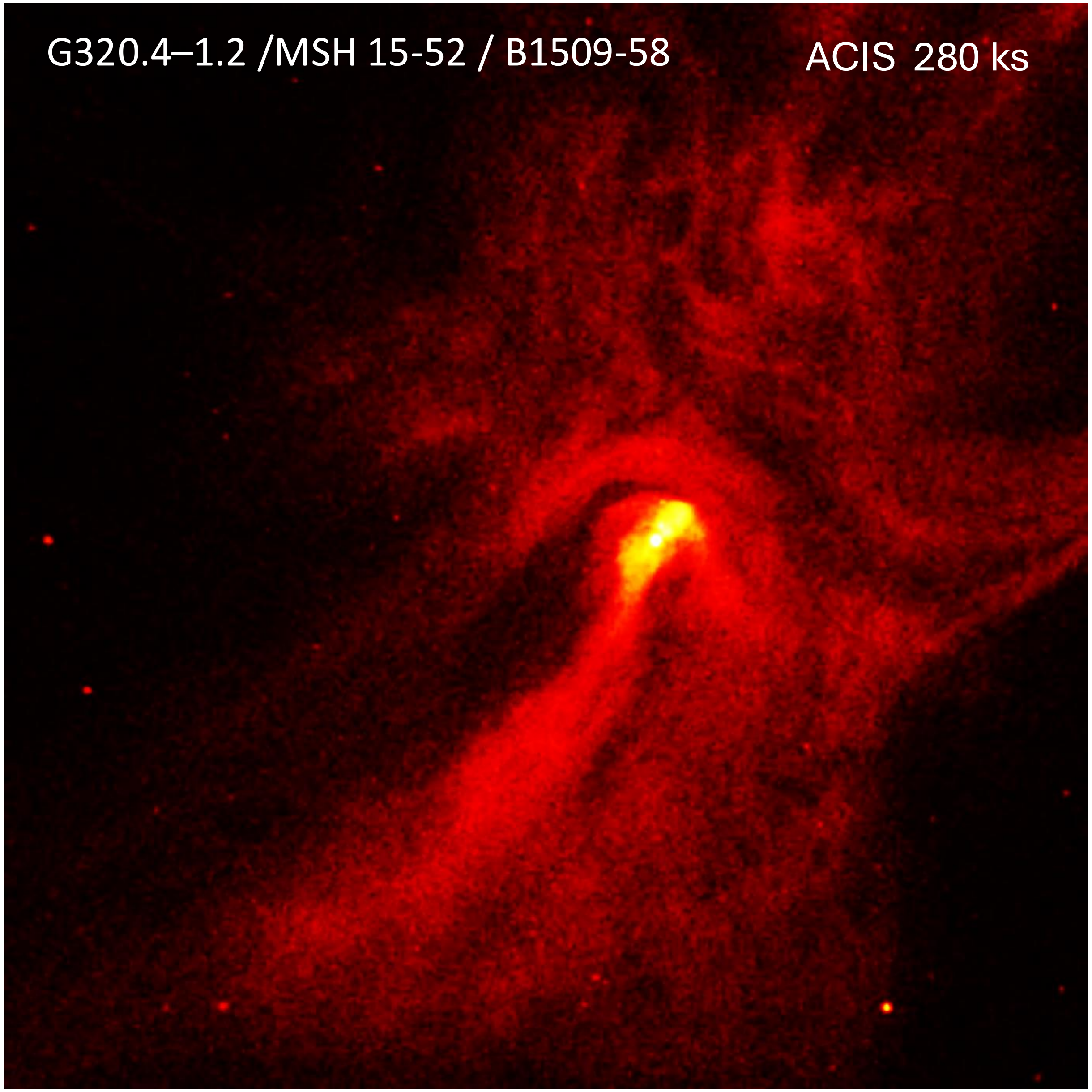
$\dot{E} = 1.7 \times 10^{37}$ erg s^{-1}
$\tau_c = 1.5$ kyrs
$B_s = 1.5 \times 10^{13}$ G

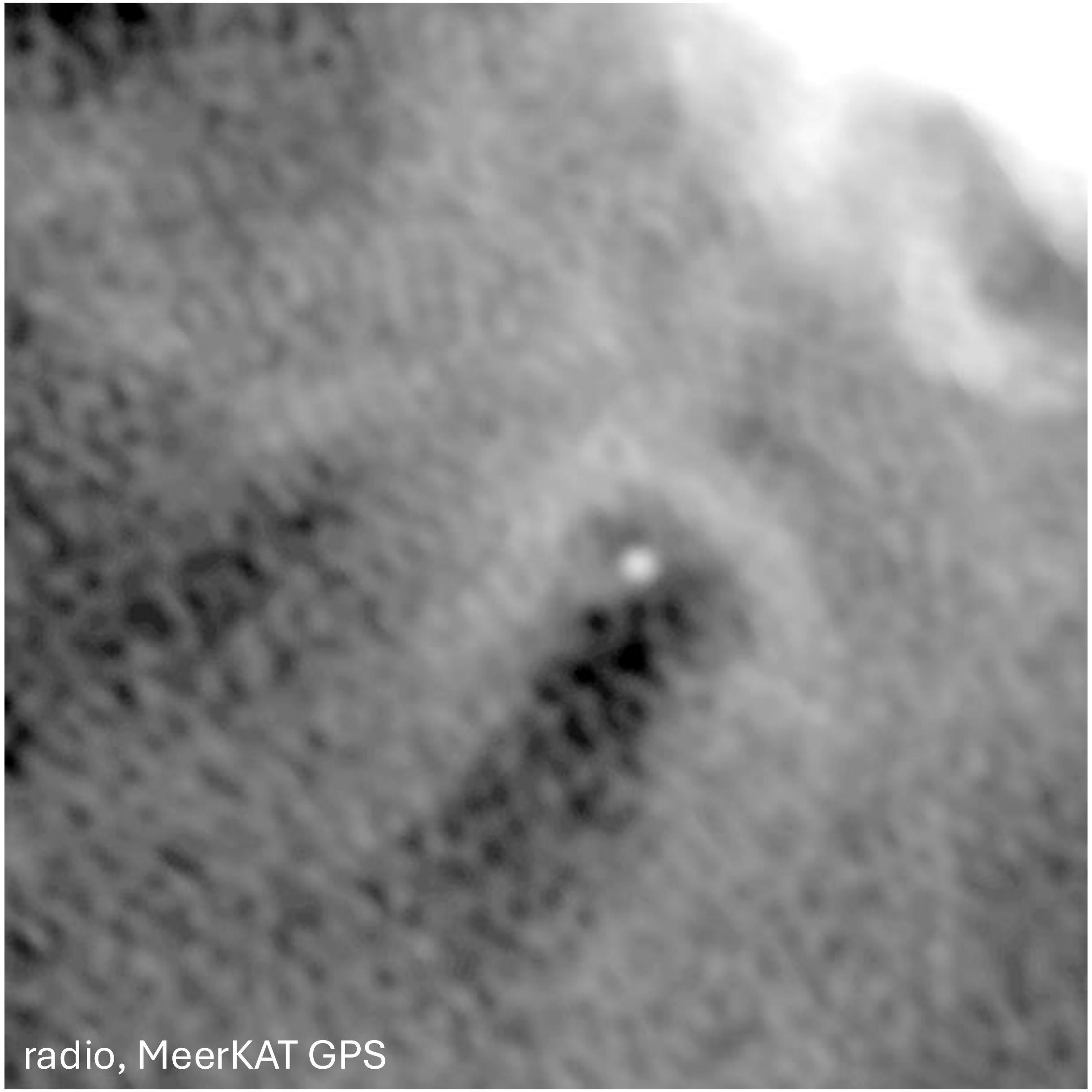




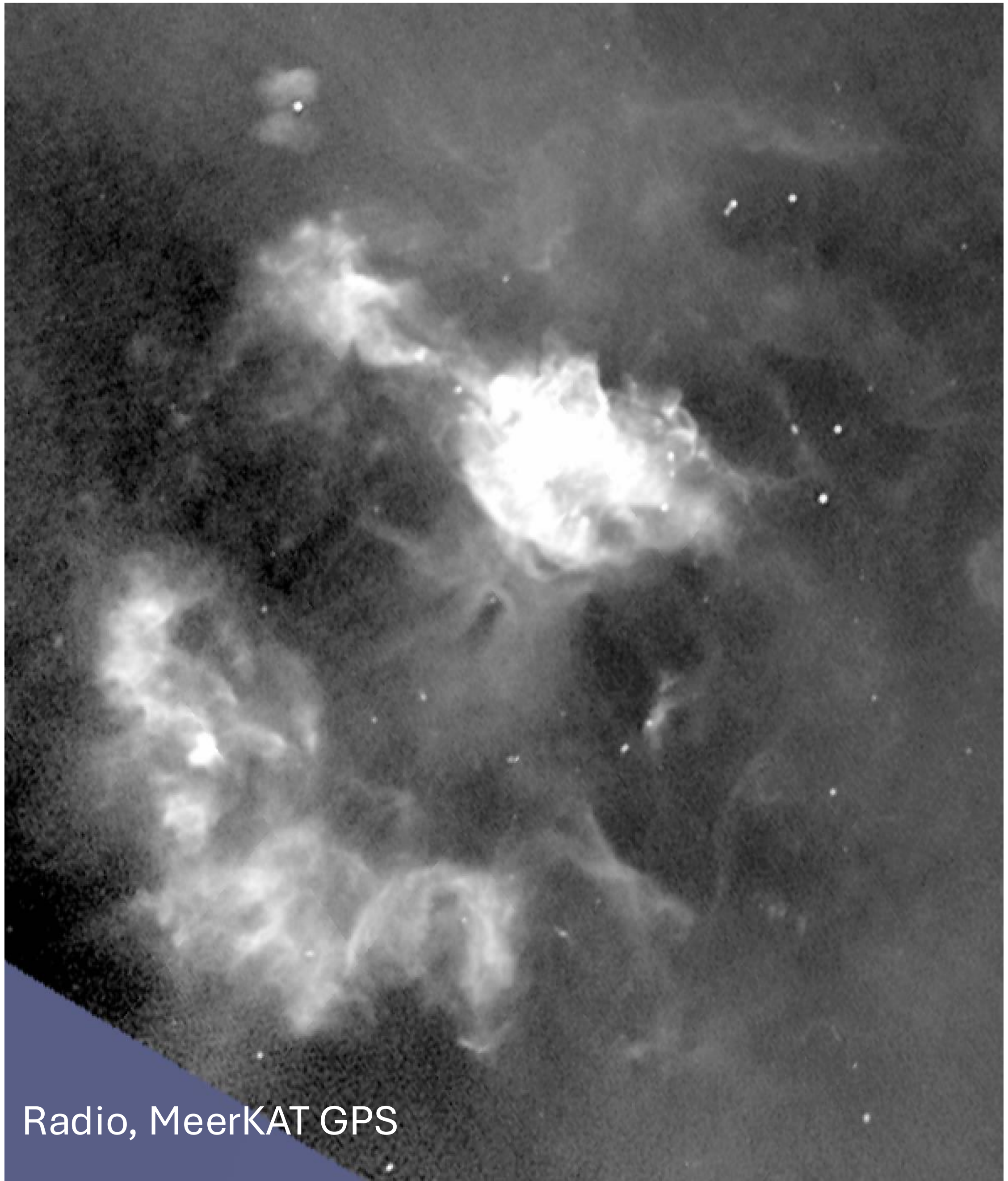
Young PWN inside SNR

Deficit of radio emission at the place of bright X-ray PWN similar to Vela PWN and some others.





Zooming out on SNR MSH 15-52

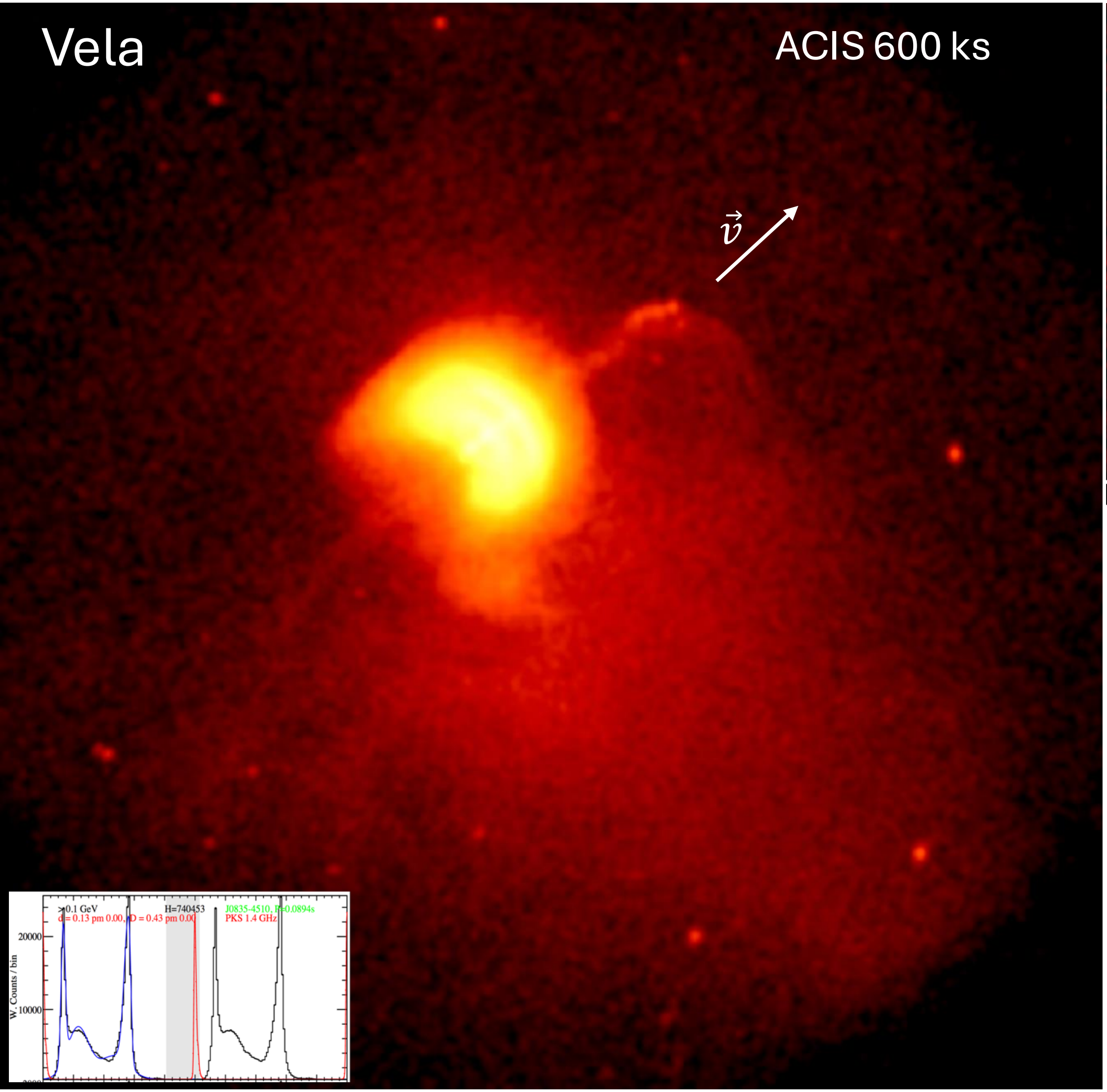


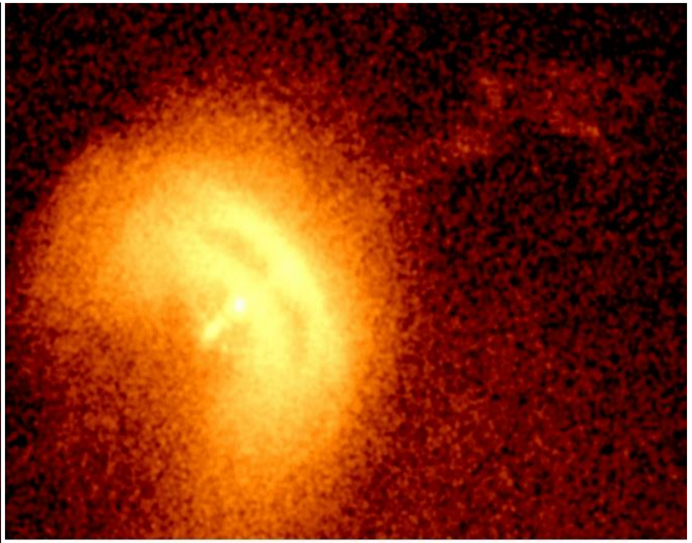
The SNR type
is difficult to define.

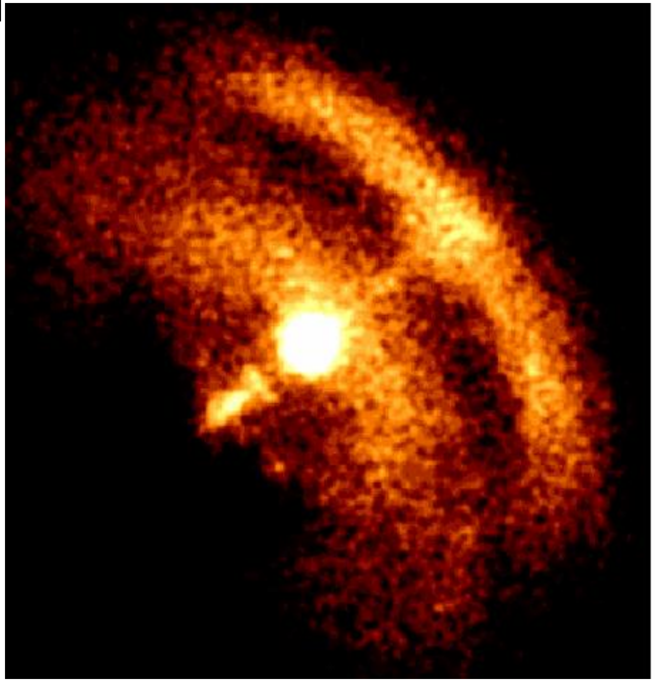
Young PWN inside the SNR with a shell

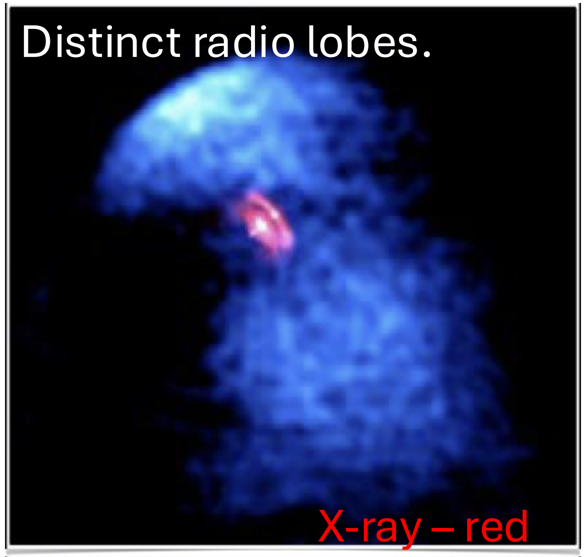
$\dot{E} = 6.9 \times 10^{36}$ erg s
$\tau_c = 11$ kyrs
$B_s = 3.4 \times 10^{12}$ G

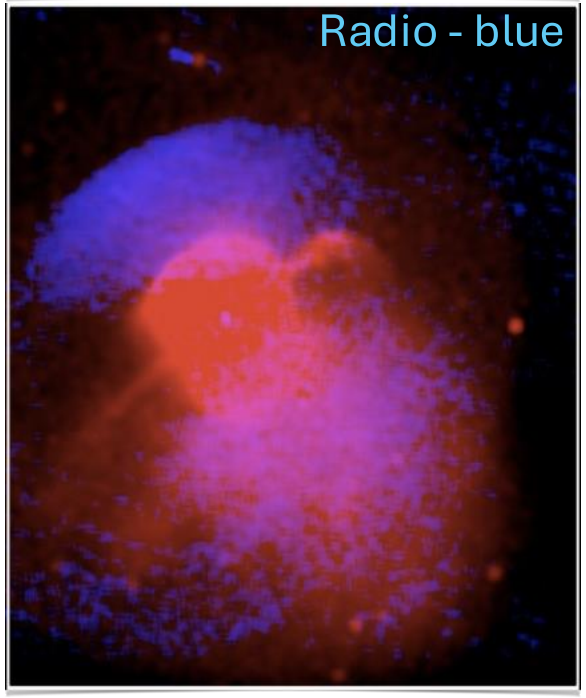
Torus dominated morphology, one of the few PWNe with double torus.









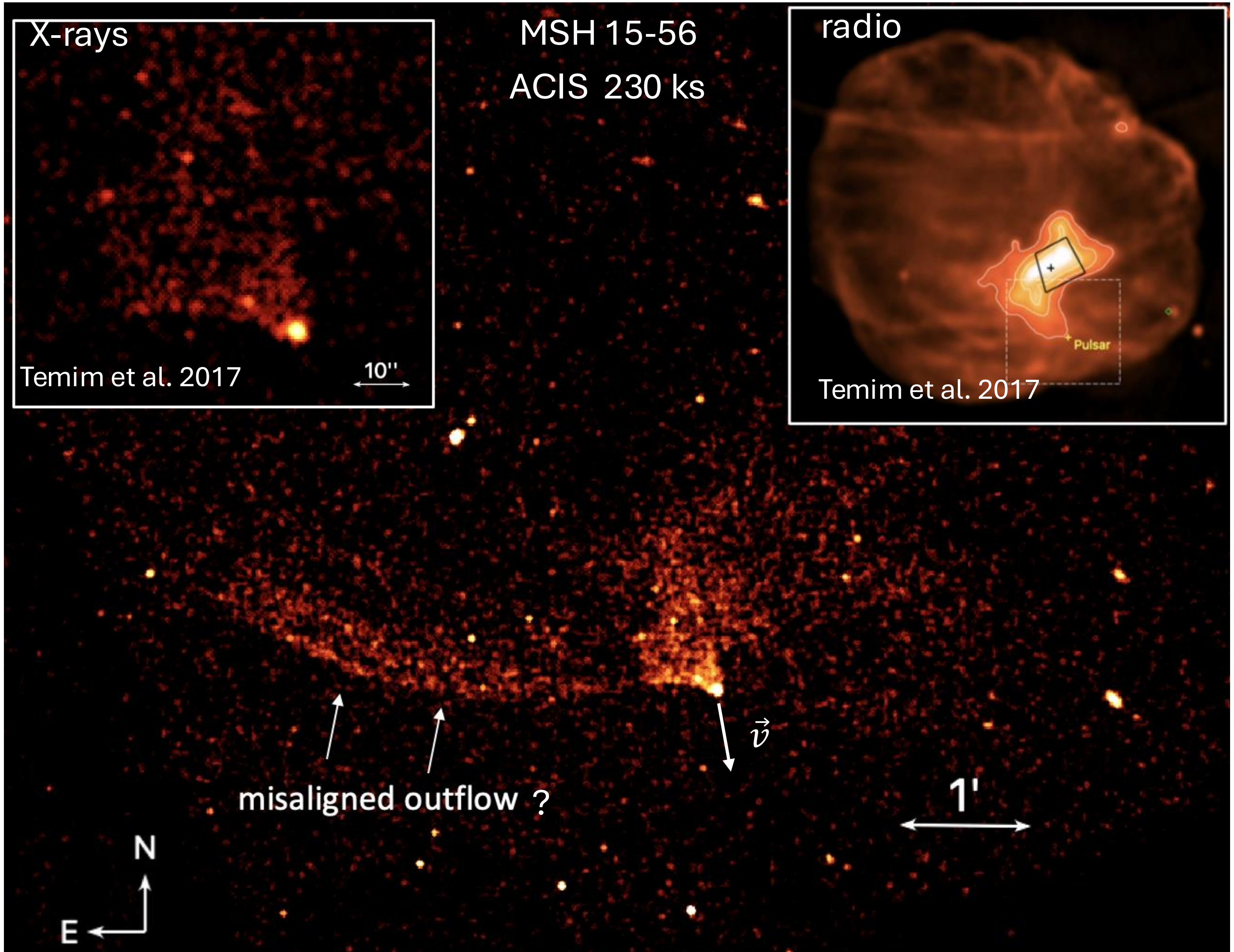


A likely young PWN inside the SNR with a shell

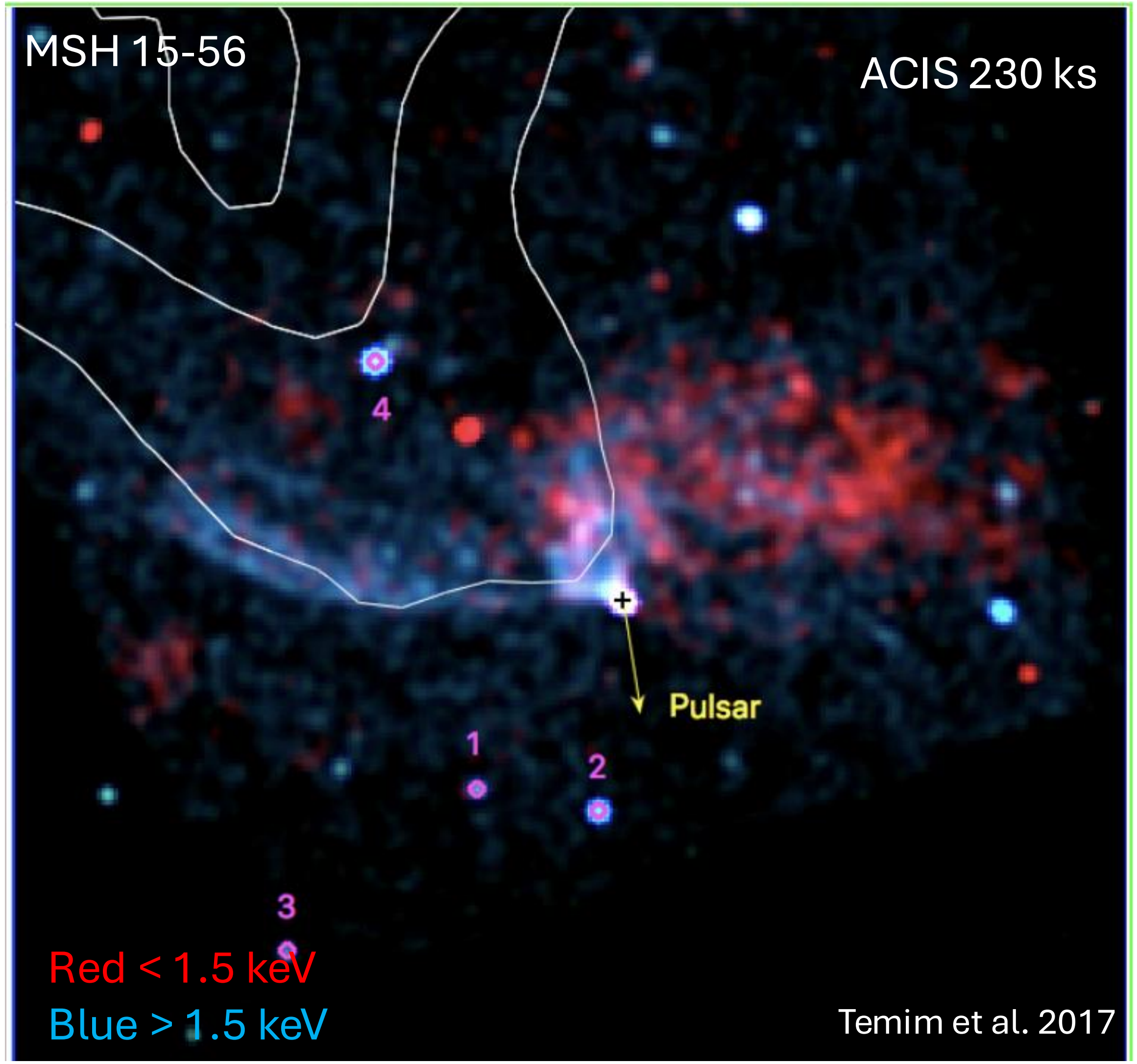
No pulsations found

PWN morphology suggest significant ram-pressure impact, either due to very fast pulsar motion or the SNR reverse shock

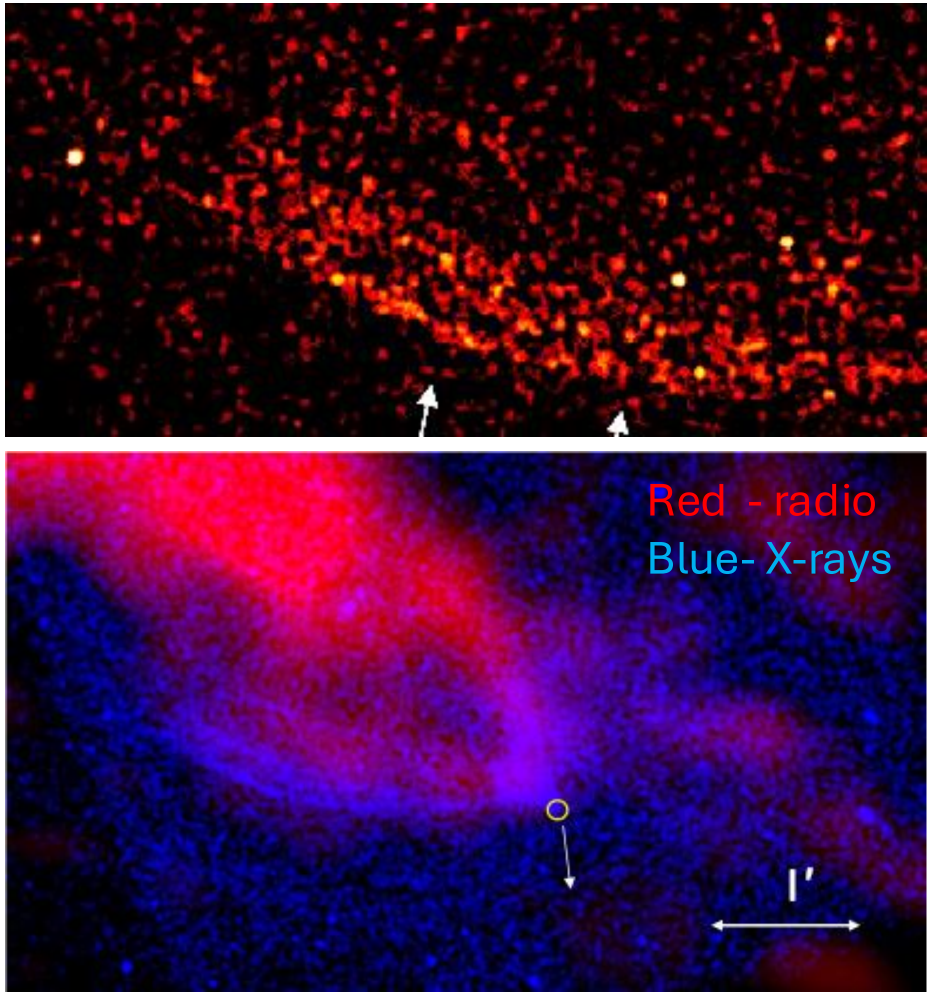
Asymmetric extended emission suggest misaligned (with pulsar motion) outflow (kinetic particle escape from bowshock)



Limited existing CXO data suggest a hard spectrum, typical for a **misaligned outflow**, implying rapid particle transport away from the pulsar.



CXO image hints at the thread-like structure more clearly visible in the Lighthouse PWN.

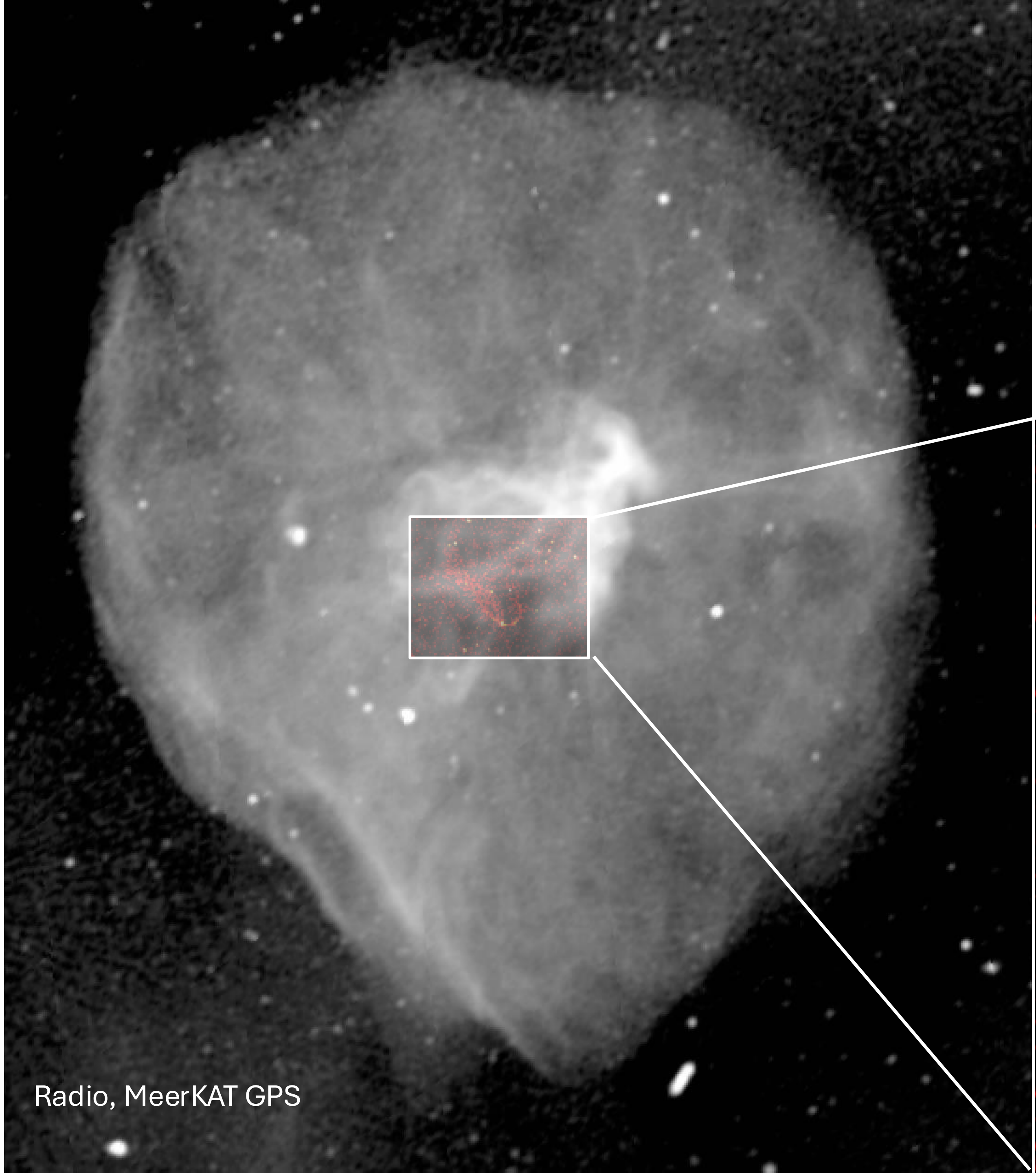


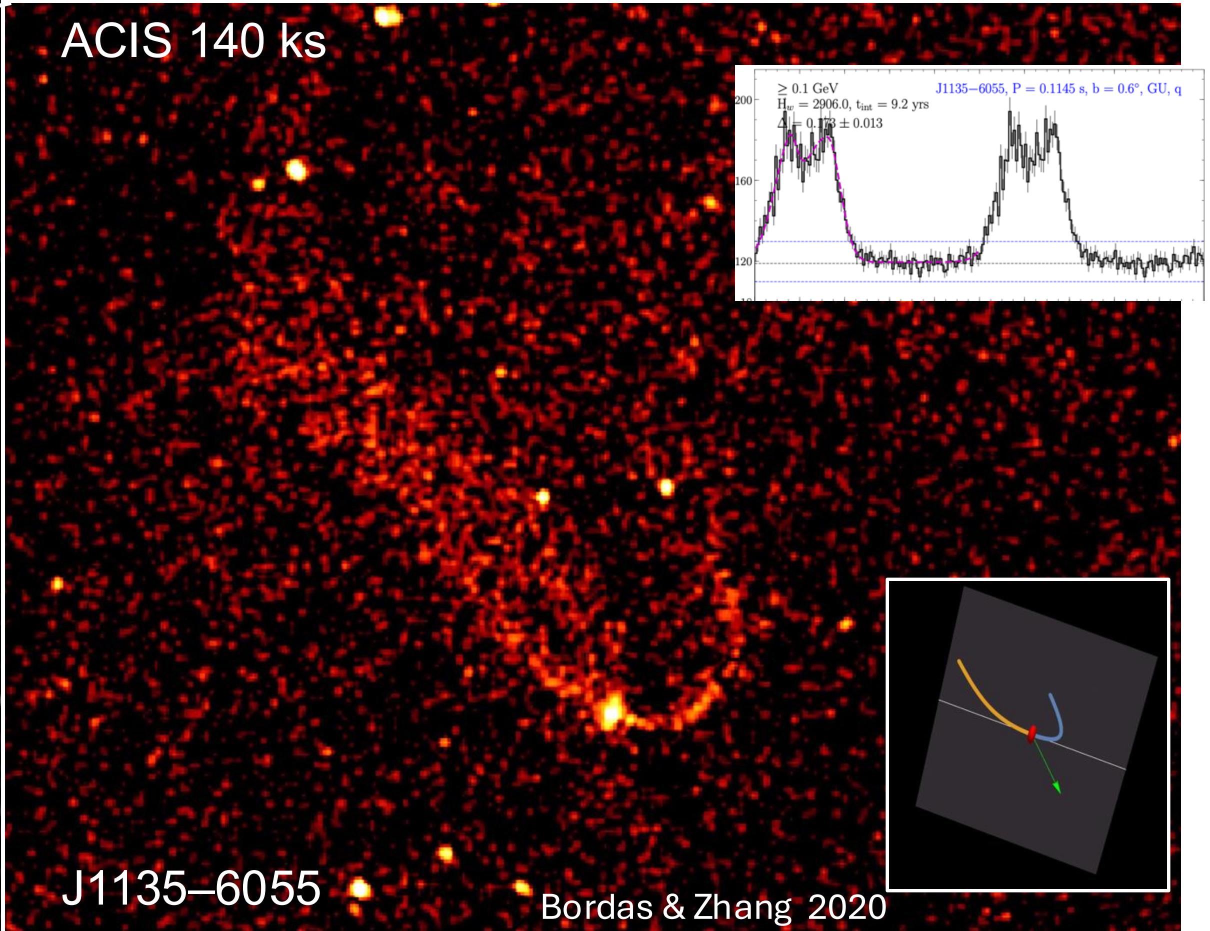
PWN inside SNR

$\dot{E} = 2.0 \times 10^{36}$ erg s^{-1}
$\tau_c = 23$ kyrs
$B_s = 3.0 \times 10^{12}$ G

Toroidal component is evident at the highest CXO resolution.

Western jet may be brightened due to the compression caused by pulsar motion (or the SNR reverse shock passage) also responsible for bending of the jets.



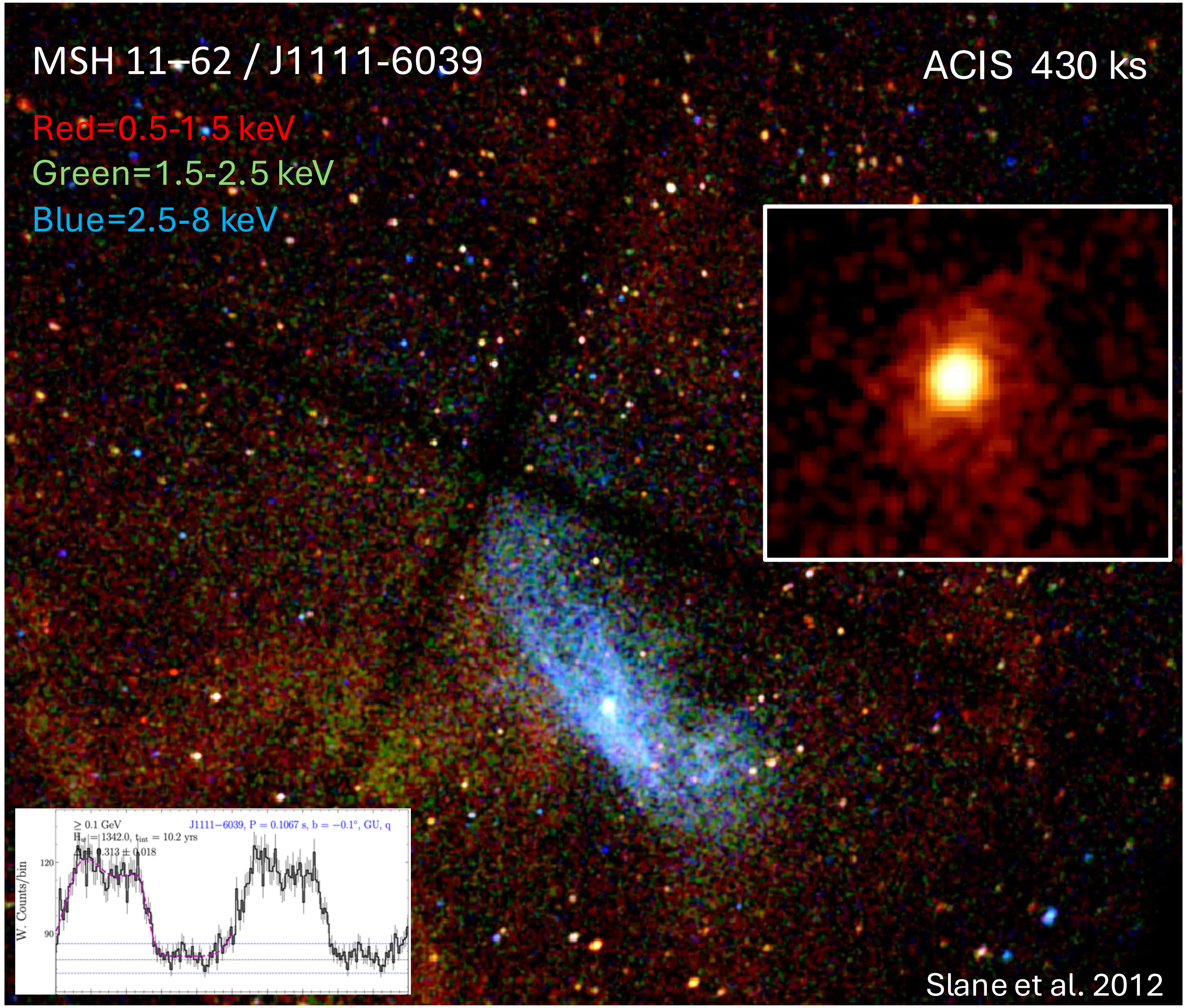


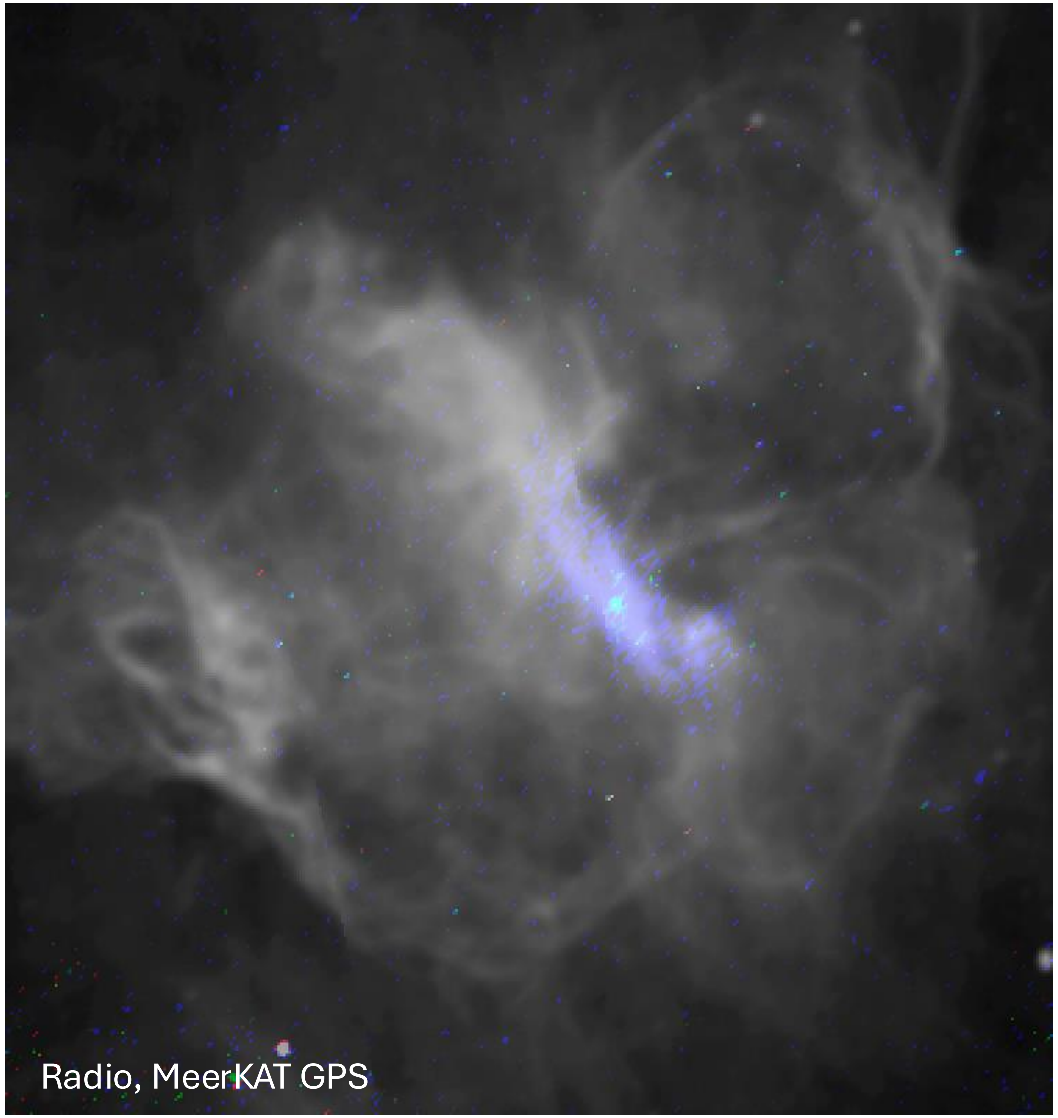
Bordas & Zhang 2020

Young PWN inside SNR

$\dot{E} = 6.4 \times 10^{36}$ erg s^{-1}
$\tau_c = 8.6$ kyrs
$B_s = 4.6 \times 10^{12}$ G

Uncertain PWN morphology at any scales, possibly small torus, unusually broad gamma-ray pulse.

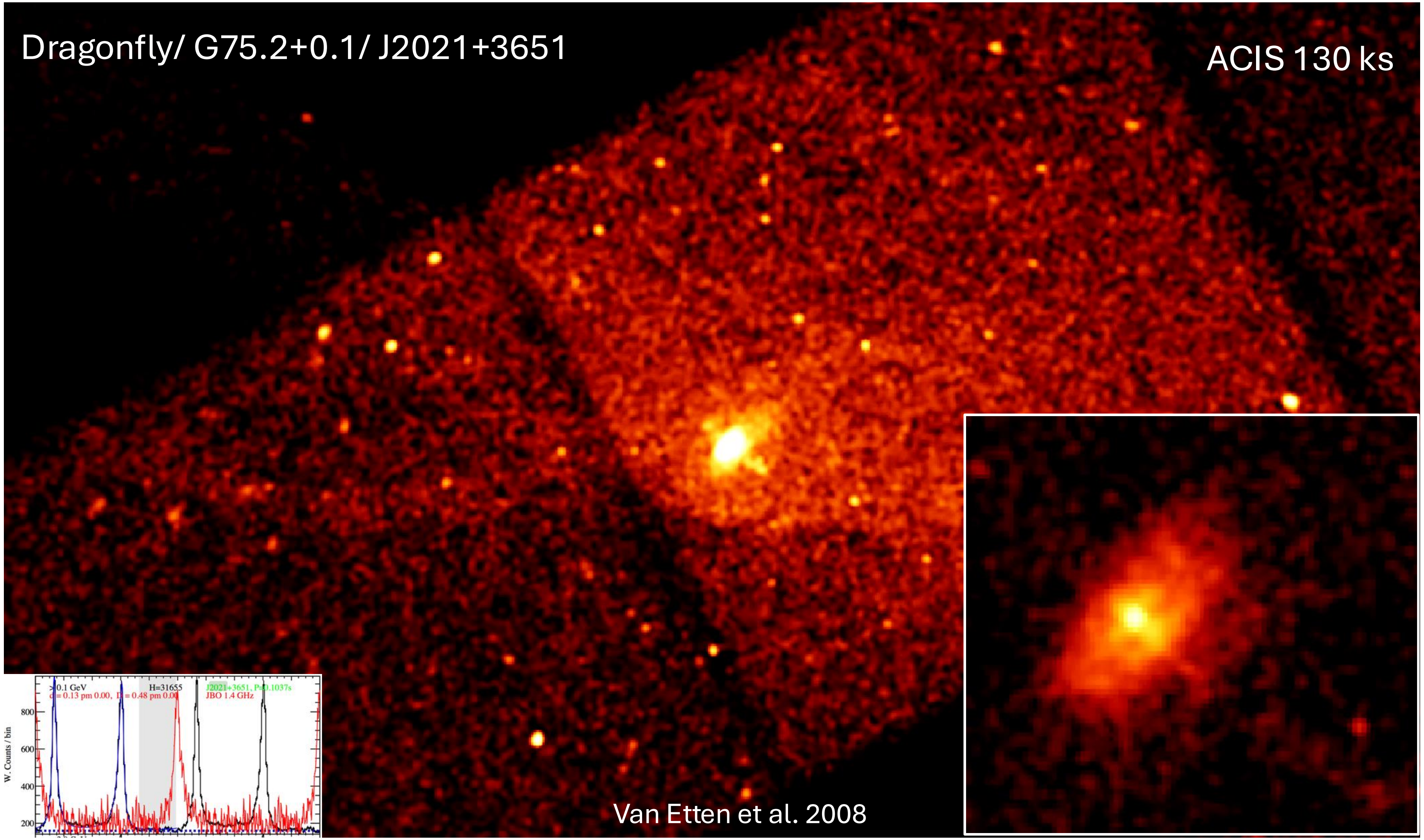




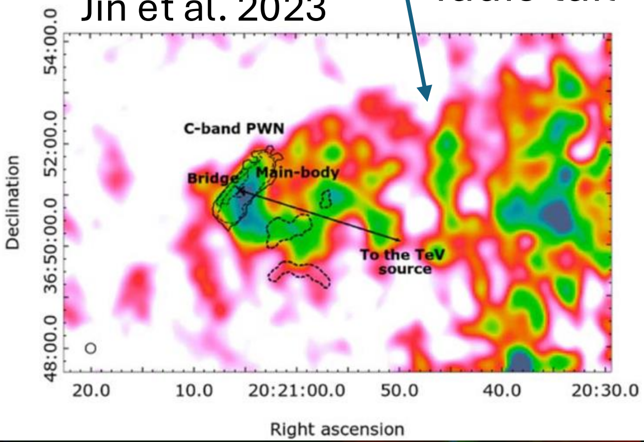
A possibly still young PWN lacking an obvious host SNR

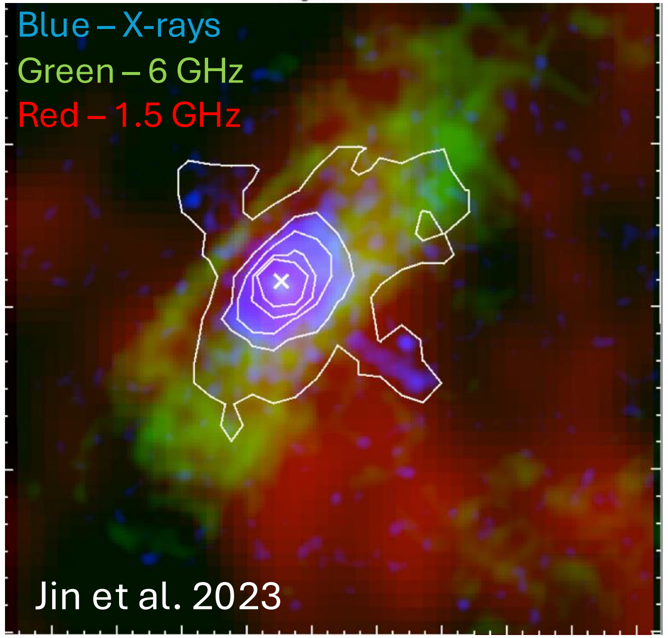
$\dot{E} = 3.4 \times 10^{36}$ erg s
$\tau_c = 17$ kyrs
$B_s = 3.2 \times 10^{12}$ G

A torus-dominated PWN which appears to be surrounded by large scale faint X-ray emission with X-ray morphology being different from that of the radio emission



A possible radio tail

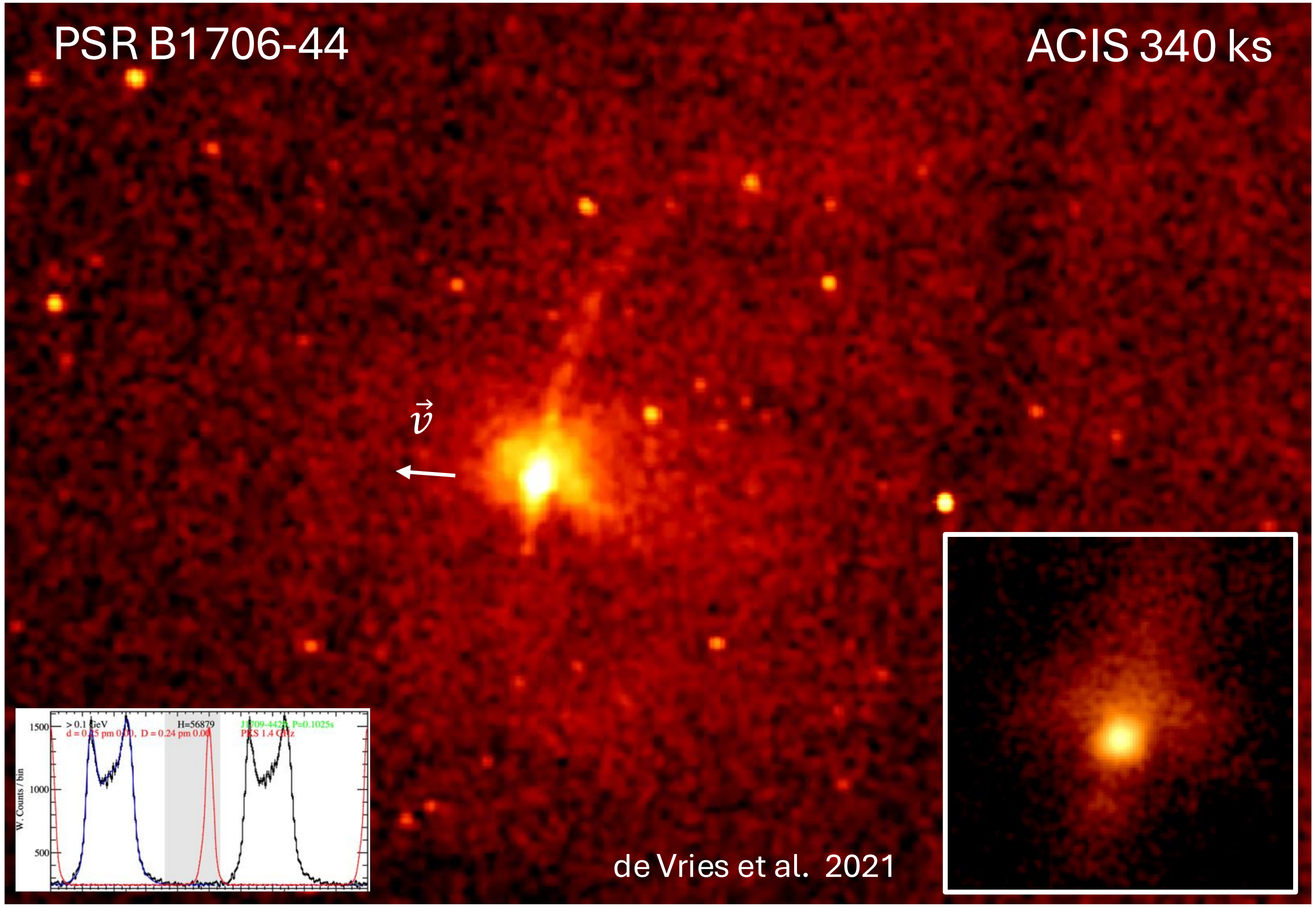


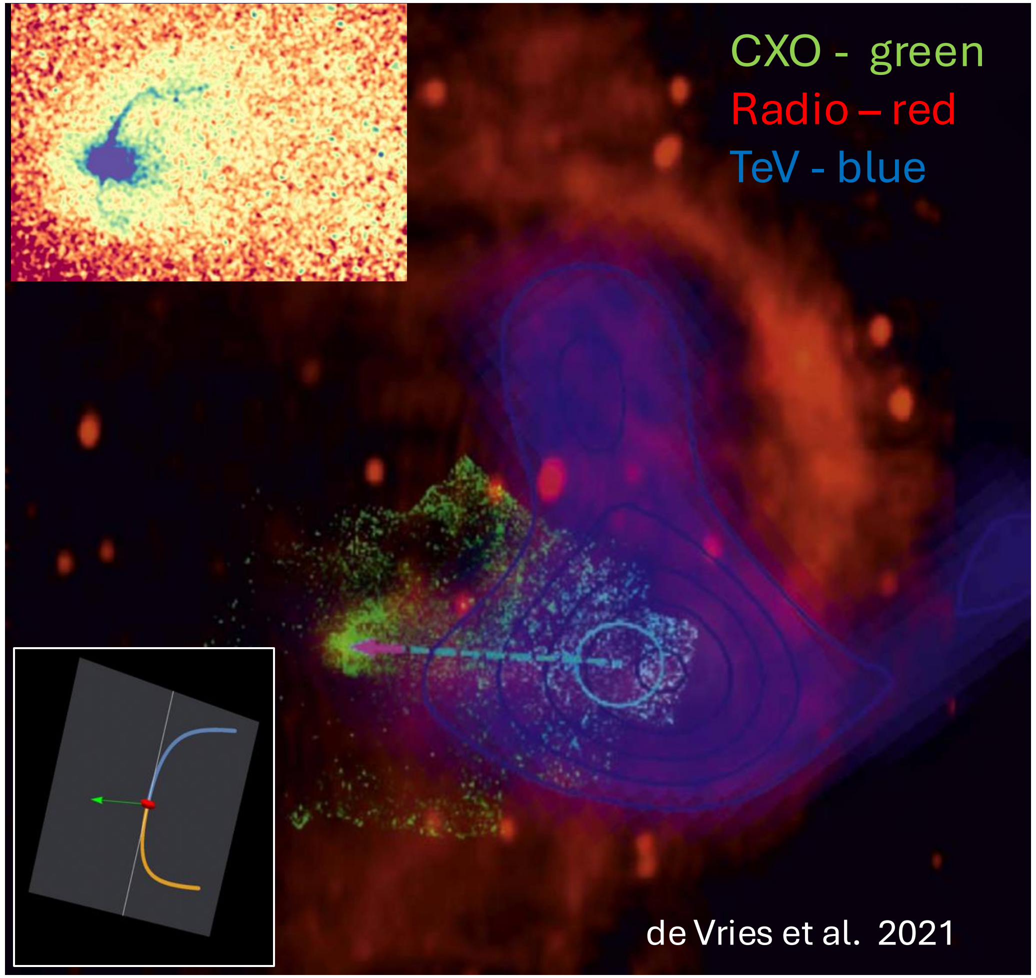


Older PWN escaping from its host SNR

$\dot{E} = 3.4 \times 10^{36}$ erg s^{-1}
$\tau_c = 17$ kyrs
$B_s = 3.1 \times 10^{12}$ G

A torus-dominated PWN which appears to be surrounded by large scale faint X-ray emission which is offset from an even larger TeV emission region located behind the moving pulsar which still may be within its host SNR.

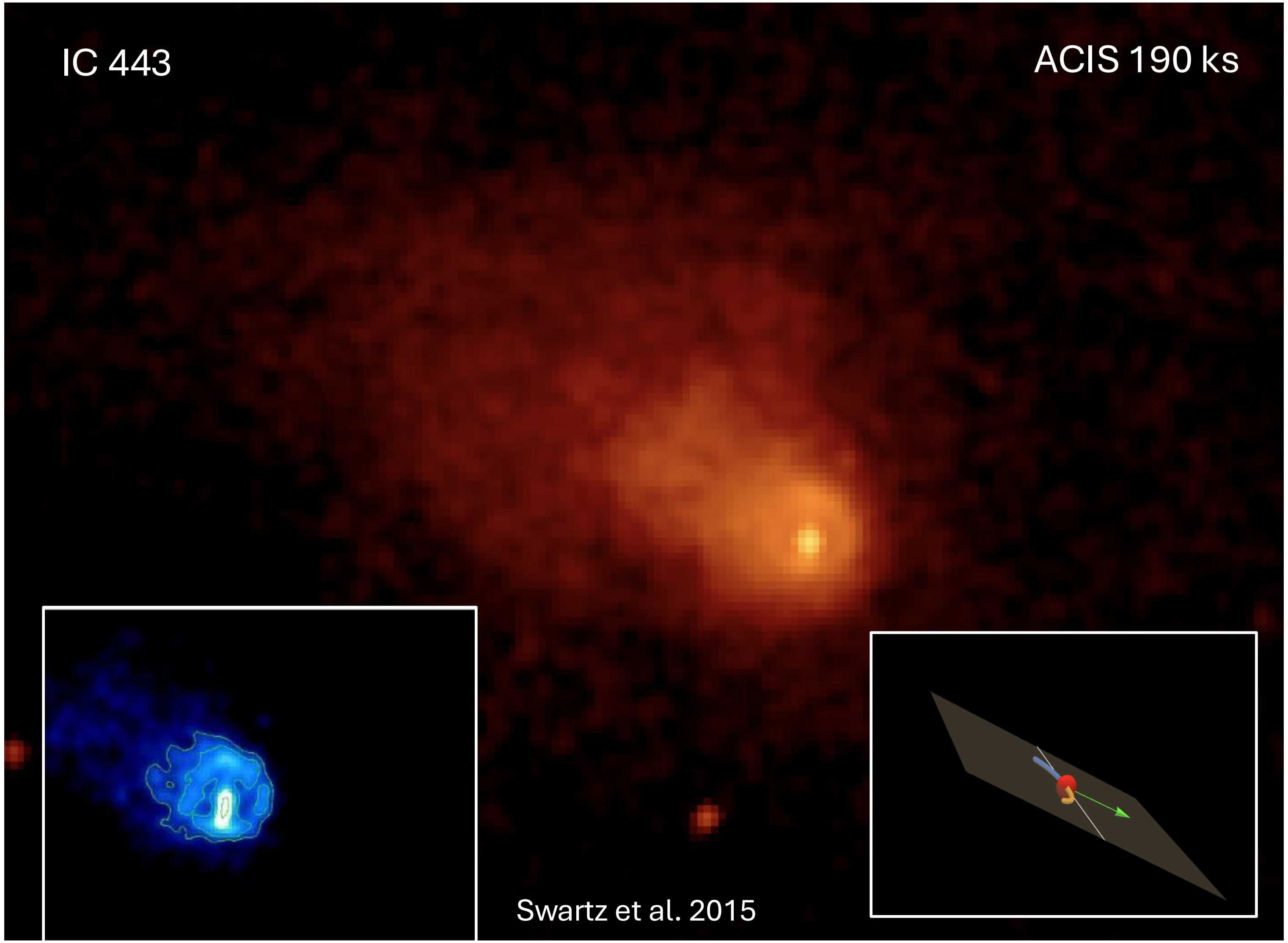


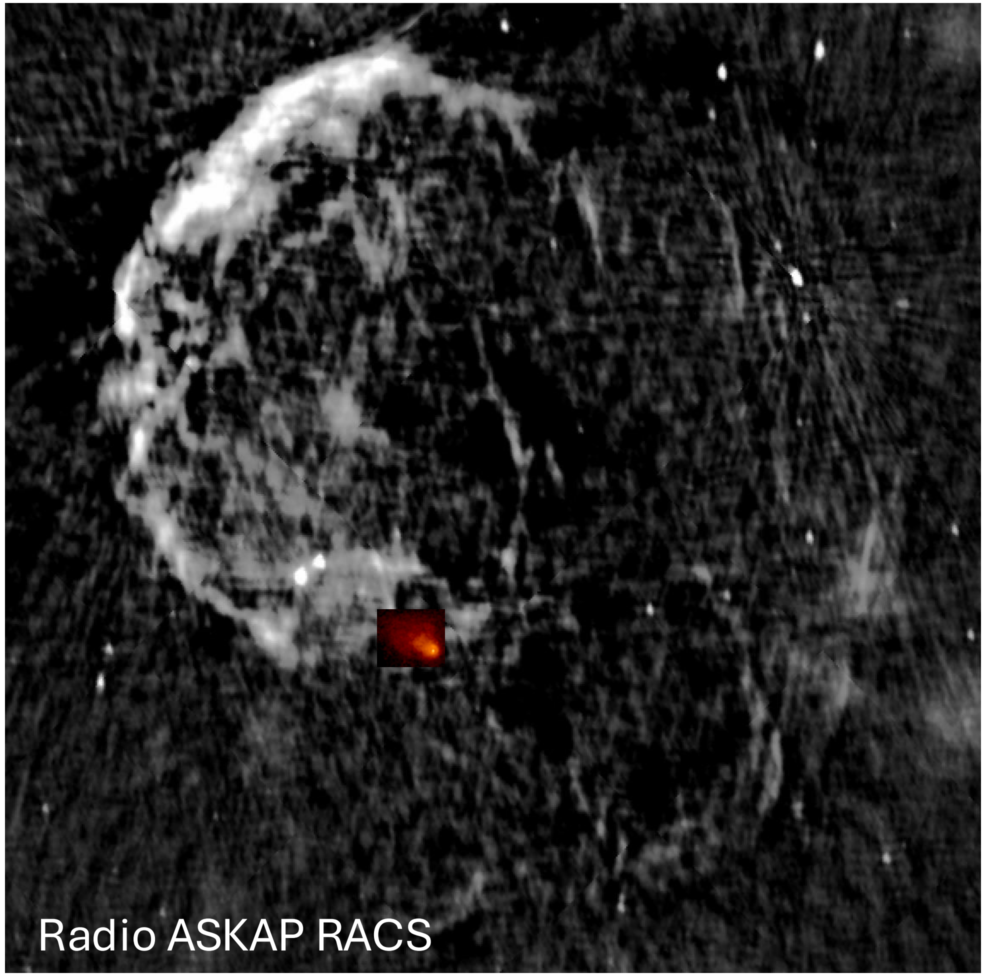


An uncertain age PWN with an uncertain SNR (IC 443) association

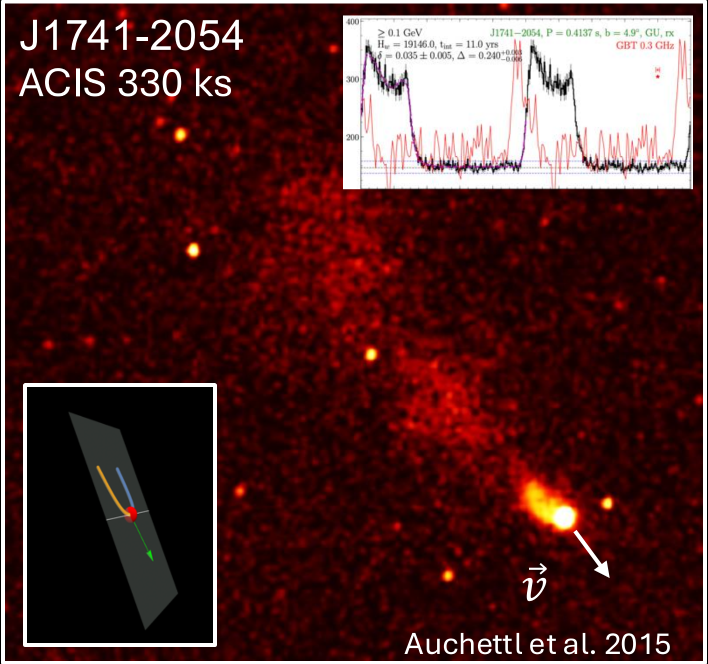
No pulsations found

Effect of pulsar motion (due to ram pressure) can be seen but the compact PWN structure (torus-jet) is preserved.



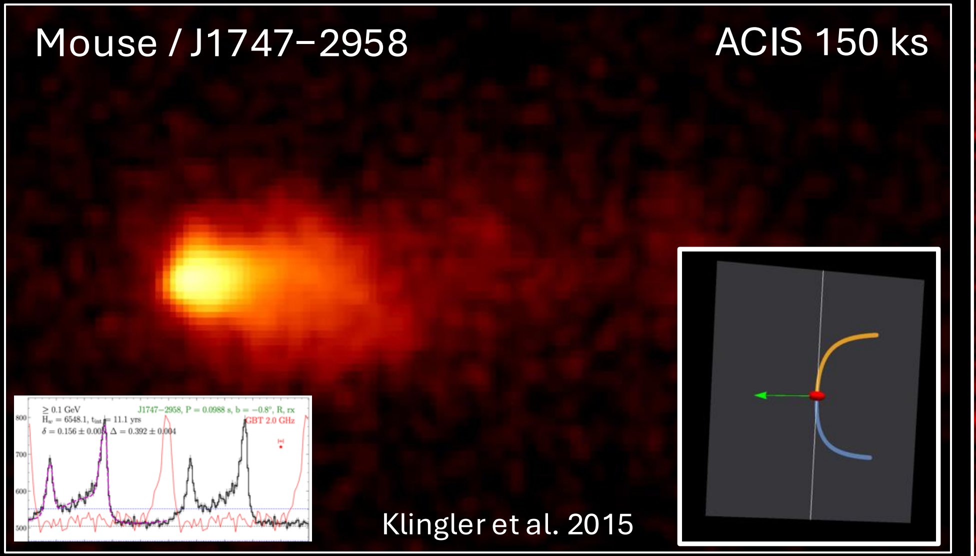


Highly Supersonic PWNe

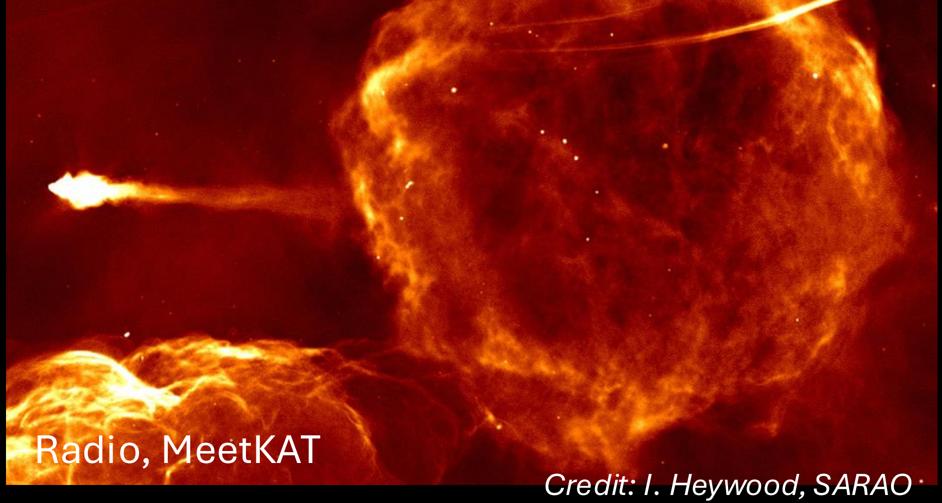


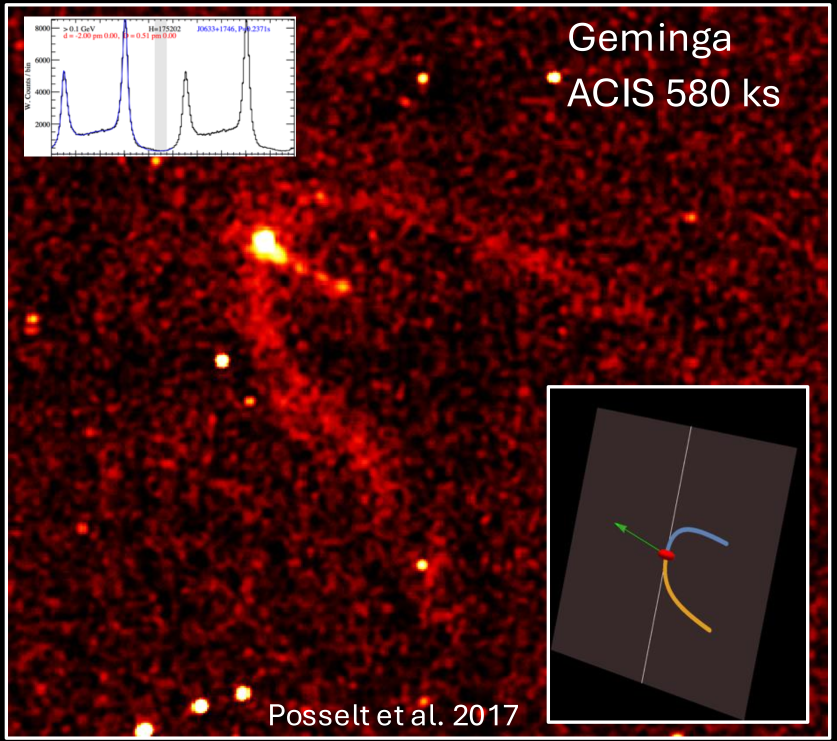
$\dot{E} = 9.5 \times 10^{33}$ erg s^{-1}
$\tau_c = 386$ kyrs
$B_s = 2.7 \times 10^{12}$ G

Radio ?



$\dot{E} = 2.5 \times 10^{36}$ erg s^{-1}
$\tau_c = 25$ kyrs
$B_s = 2.5 \times 10^{12}$ G





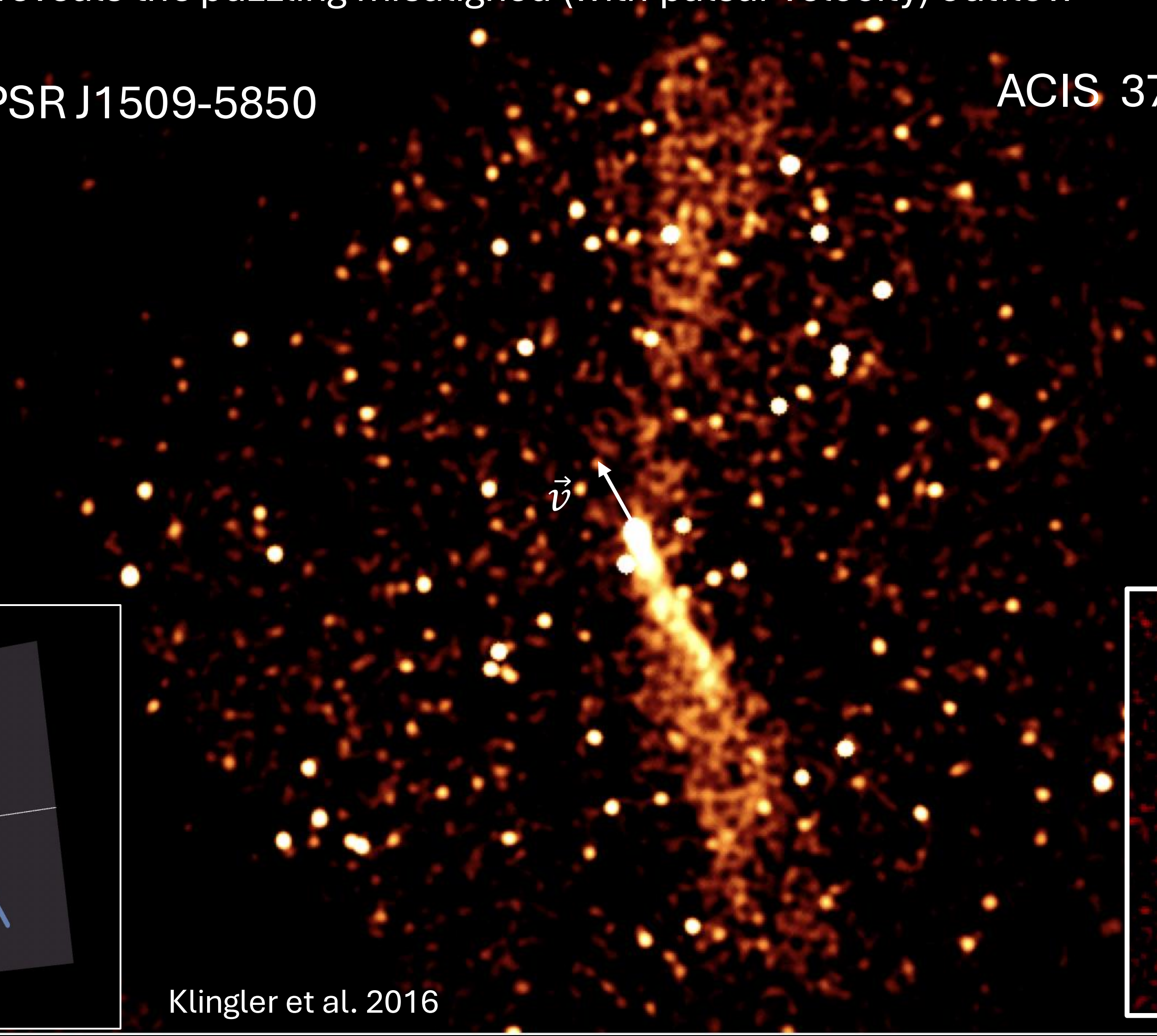
$\dot{E} = 3.2 \times 10^{34}$ erg s^{-1}
$\tau_c = 342$ kyrs
$B_s = 1.6 \times 10^{12}$ G

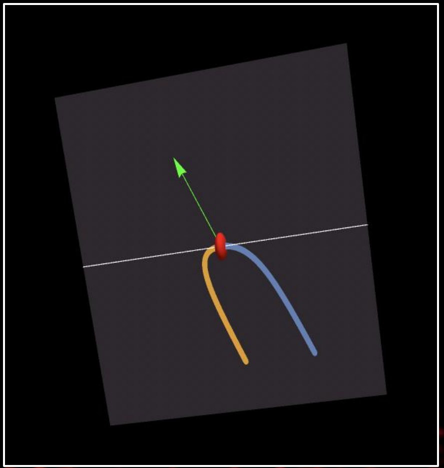
Radio ?

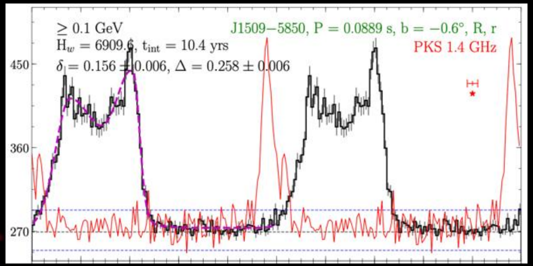
Highly Supersonic PWNe

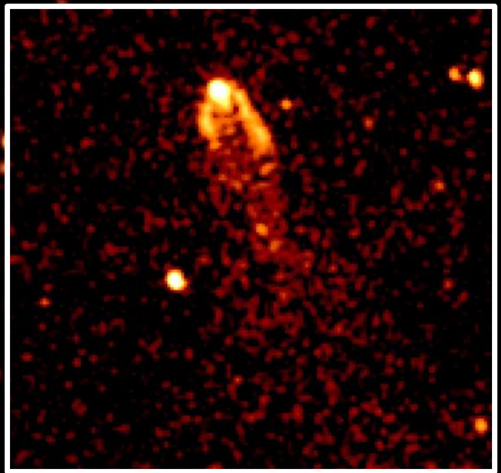
$\dot{E} = 5.1 \times 10^{35}$ erg s
$\tau_c = 154$ kyrs
$B_s = 9.1 \times 10^{11}$ G

A shallow image only showed compact PWN with two tails (similar to Geminga)
Deeper image showed a longer tail behind the moving pulsar.
An even deeper image reveals the puzzling misaligned (with pulsar velocity) outflow



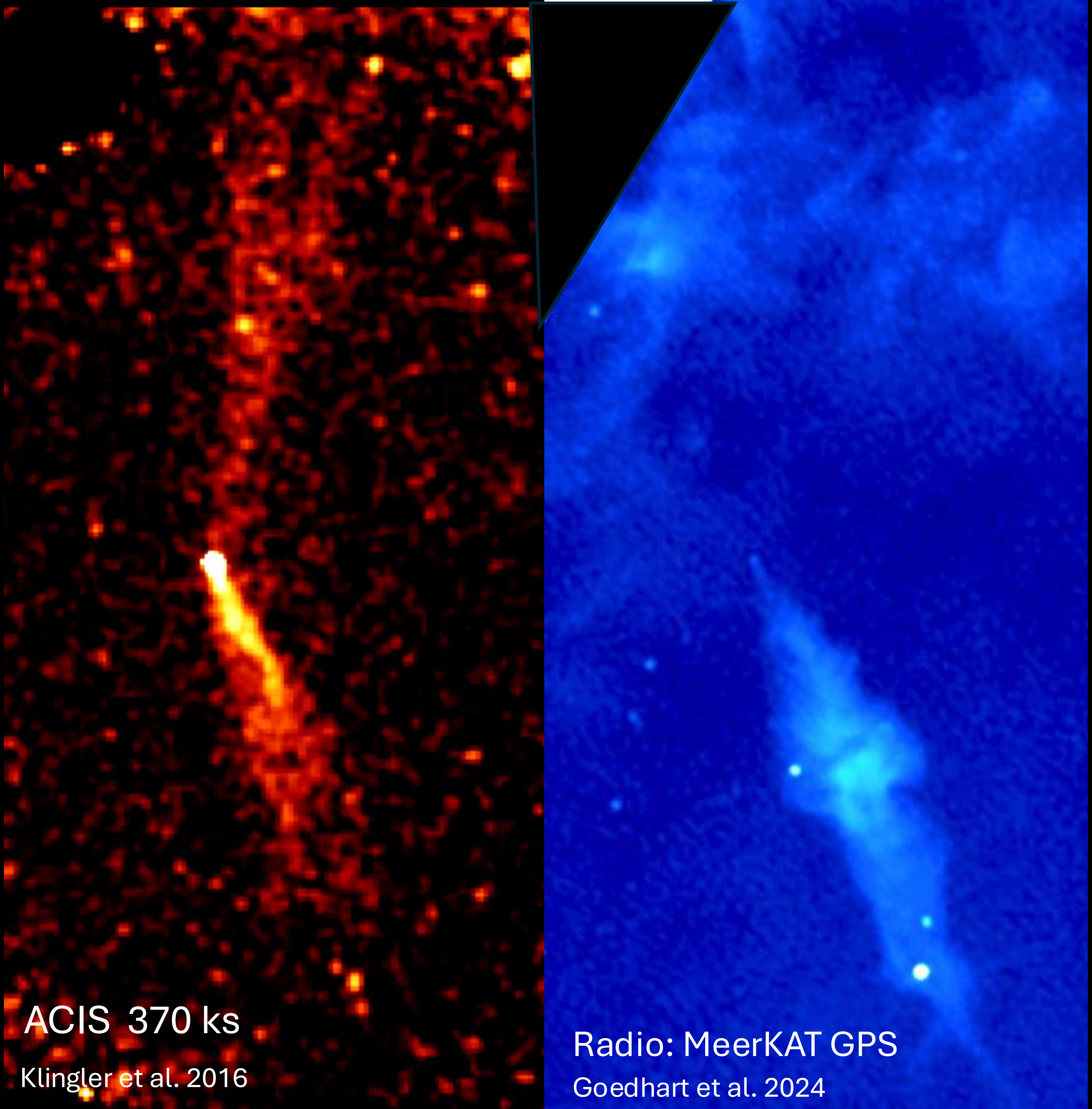






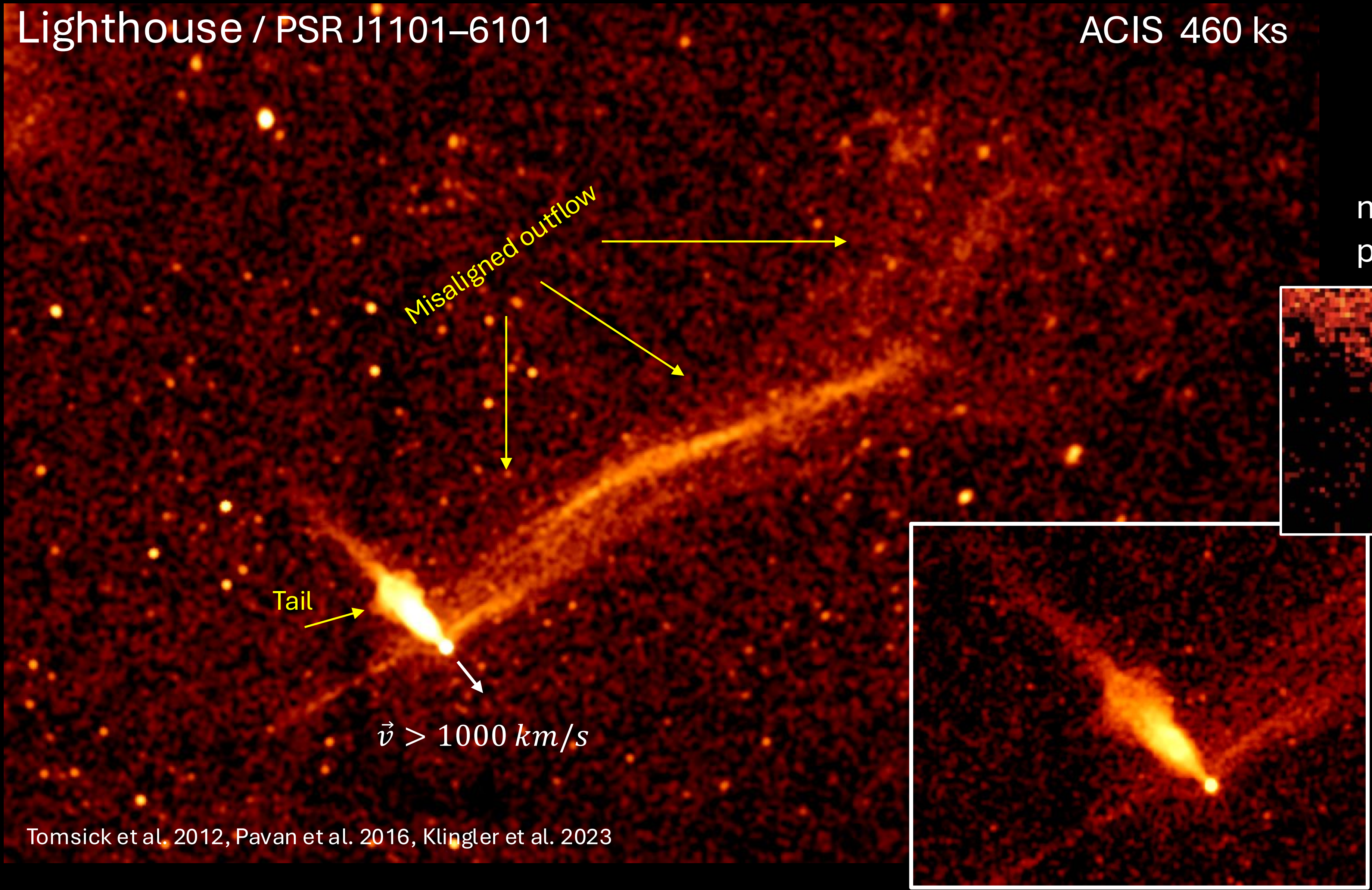
Klingler et al. 2016

Radio images only show tails and not the misaligned outflow



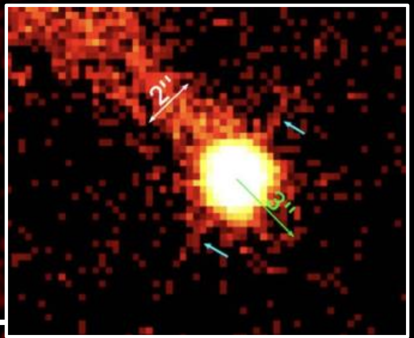
Highly Supersonic PWNe

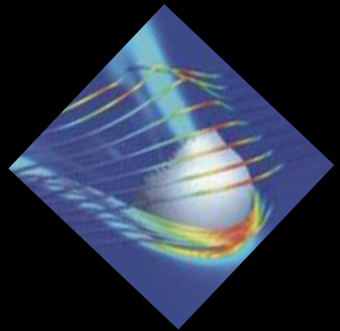
Another spectacular case of the misaligned outflow in a highly supersonic PWN



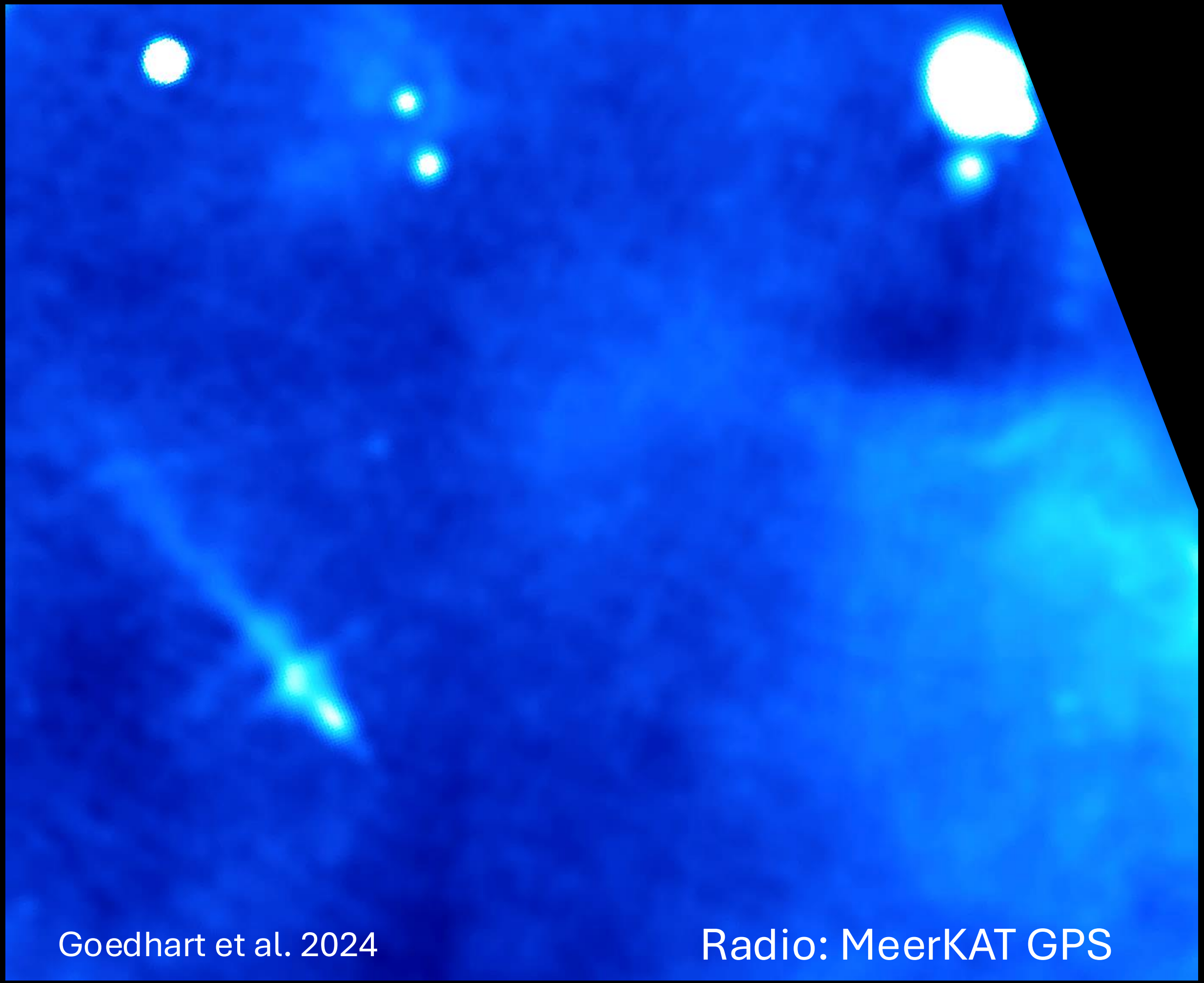
$\dot{E} = 1.4 \times 10^{36}$ erg s^{-1}
$\tau_c = 116$ kyrs
$B_s = 7.4 \times 10^{11}$ G

no gamma-ray pulsations

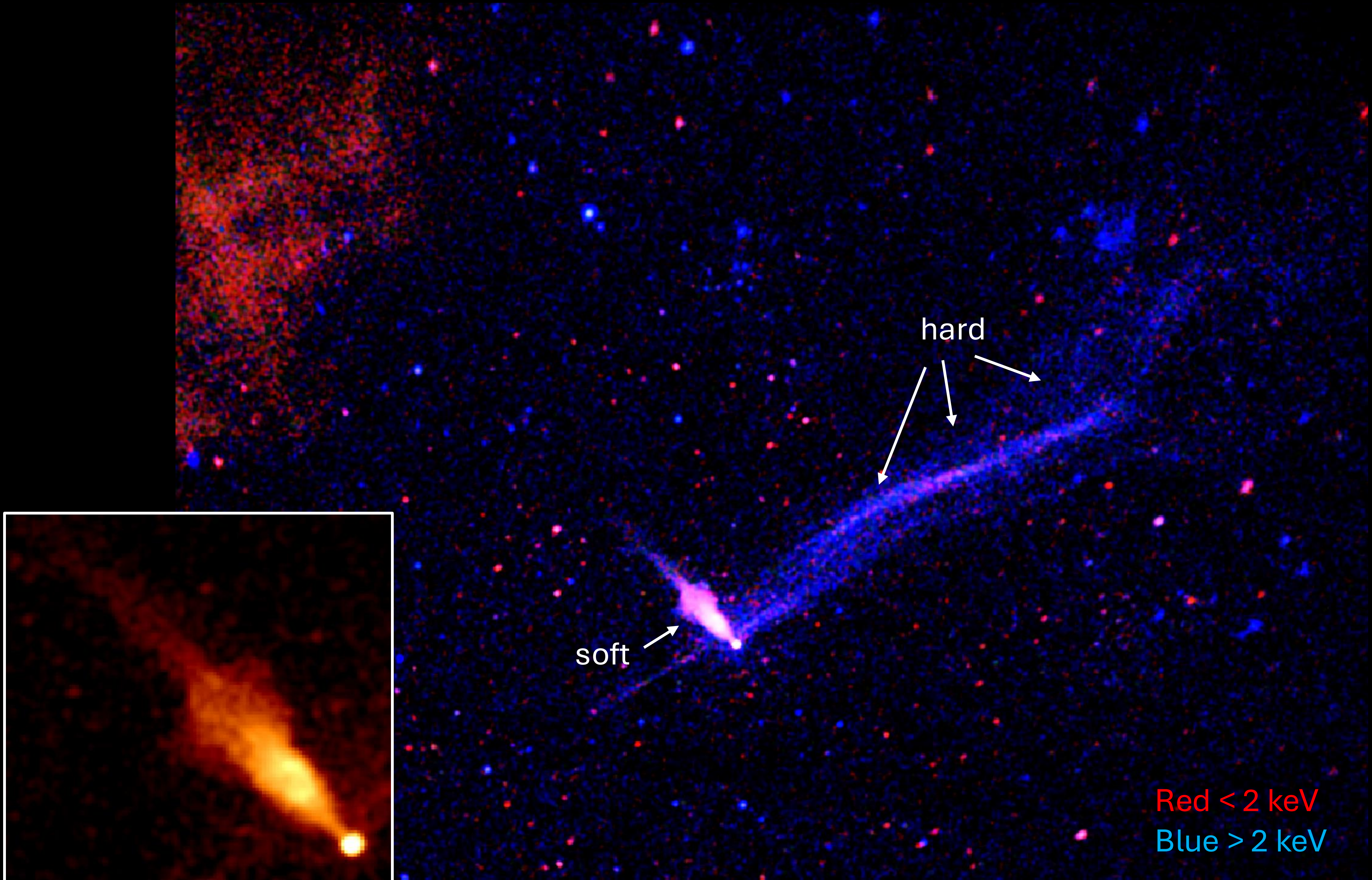




The deep radio image only shows the tail but not the misaligned outflow

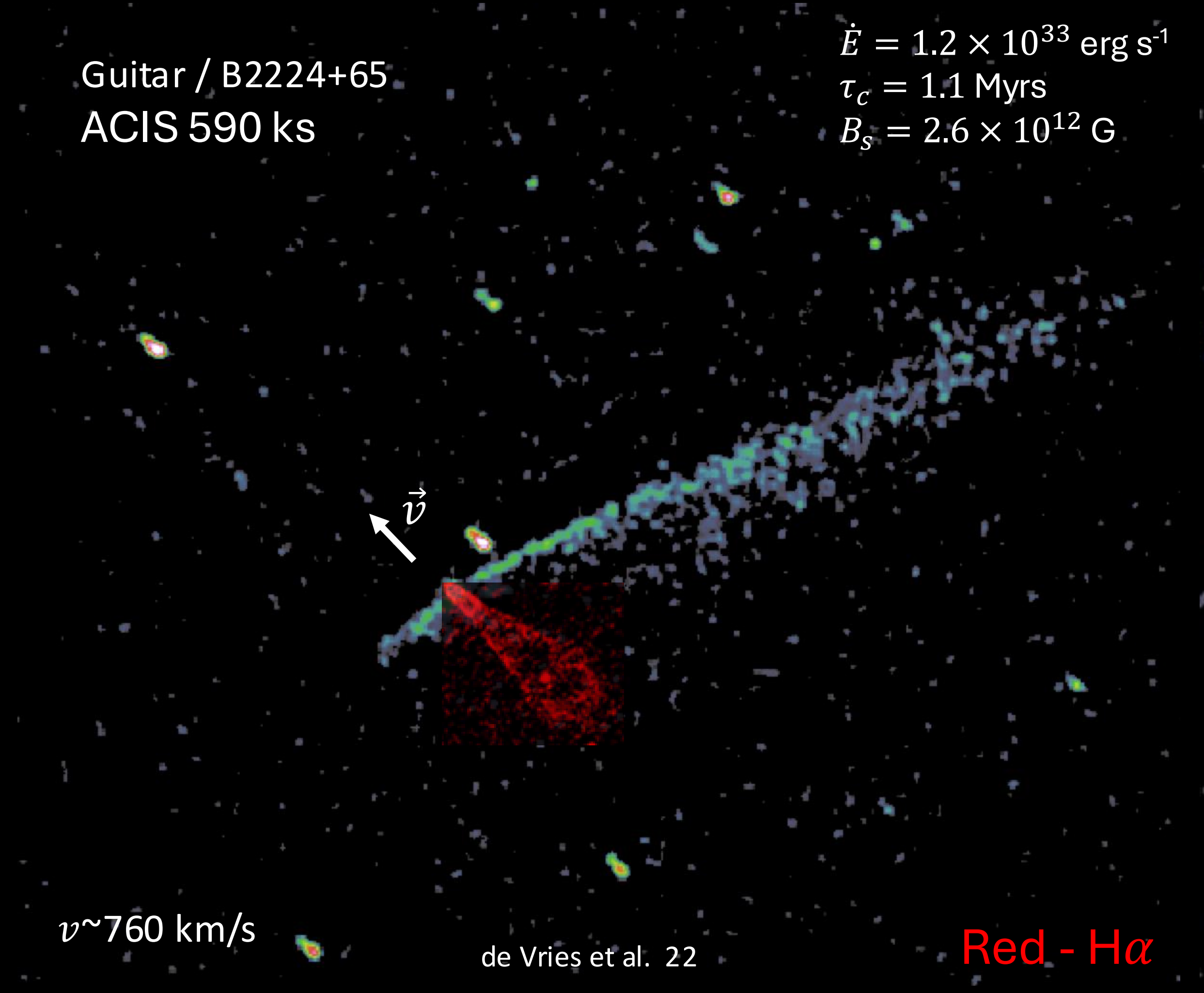


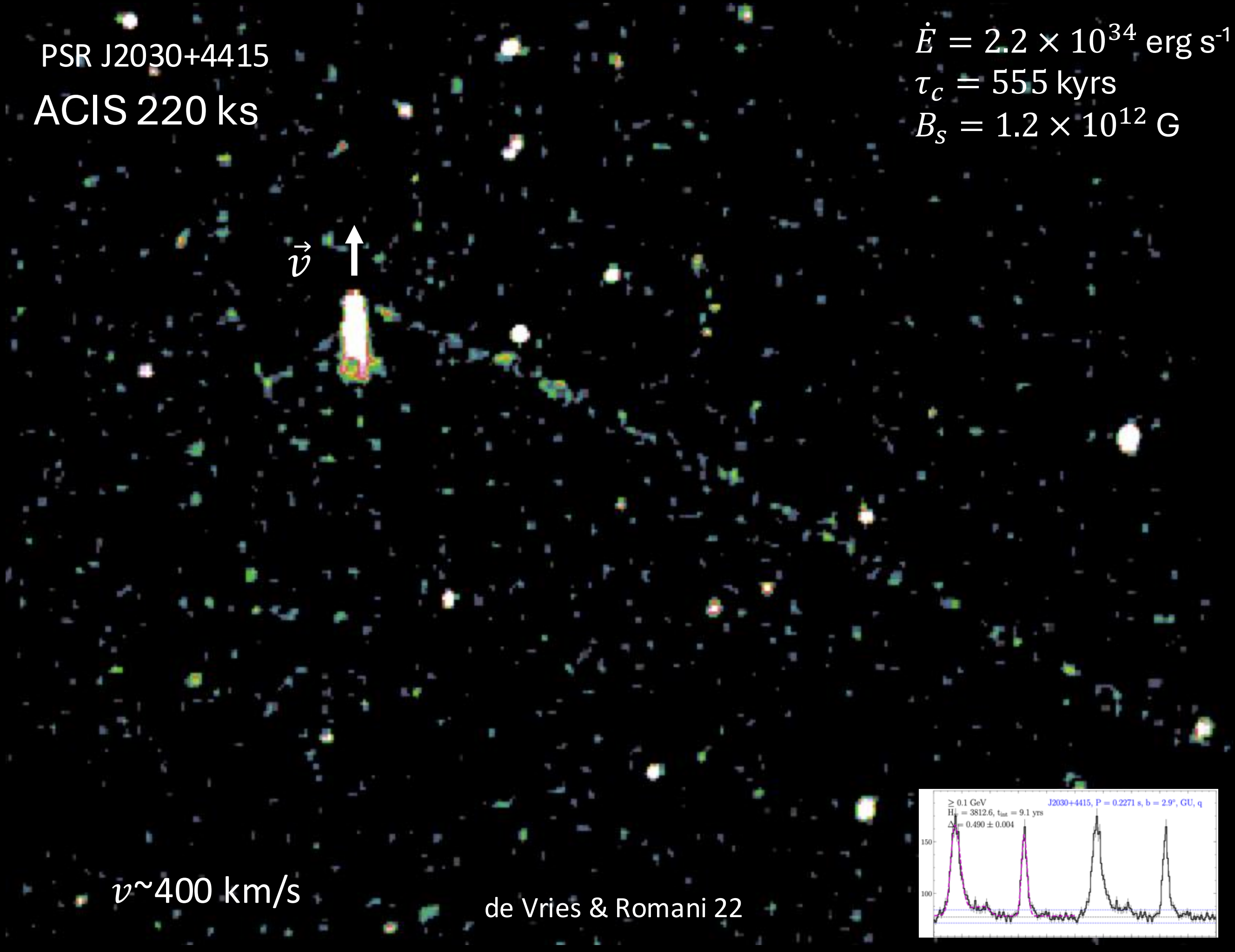
Hydrodynamically confined tail is soft, kinetically escaping particle beam is much longer, has hard spectrum.



More highly-supersonic PWNe with misaligned outflows

These faint and narrow structures would have been very difficult to study without Chandra!





Summary (I)

High-resolution view of compact PWN structures can…

- **establish morphological type of the compact PWN** (e.g., torus vs. jet-dominated; supersonic motion) and elucidate connection to pulsar's magnetic inclination angle (α);
- **show orientation of the pulsar's spin axis (from torus ellipticity and Doppler boosting)** placing constraints on the viewing angle (ζ);
- can be used to **test predictions of pulsar magnetosphere models beyond pulse profiles**;
- separate pulsar and compact PWN emission, **measure PWN spectrum near the pulsar where it is minimally affected by radiative cooling** and explore the dependence of efficiency of the accelerating mechanism on α and ζ;
- **determine directions and magnitudes of SN kicks** and their connection to the host SNR and SN progenitor type.

Summary (II)

Deep imaging of faint large-scale structures can…

- **tell about ultra-relativistic particle transport and evolution of magnetic field** with distance from pulsars;

- for highly-supersonic PWNe, **separate part of ram-pressure-confined outflow** governed by fluid (MHD) dynamics laws (*pulsar tails*) **from beams of the highest energy particles escaping into ISM** (*misaligned outflows*);

- **probe the maximum energy attainable by the particle acceleration mechanism operating in pulsar winds;**

- whether **particles can be accelerated to a large fraction of a large fraction of $(\dot{E}/c)^{1/2}$ or the ambient (ISM) magnetic field is strongly amplified** by the particle beam within the misaligned outflow;

- require **revision of diffusion-type models used, e.g., to predict the positron flux at Earth orbit or to establish the connection between pulsars and offset from them extended VHE or UHE sources.**

Thank you!