

# Scientists Explain a Jet Pointing the Wrong Way

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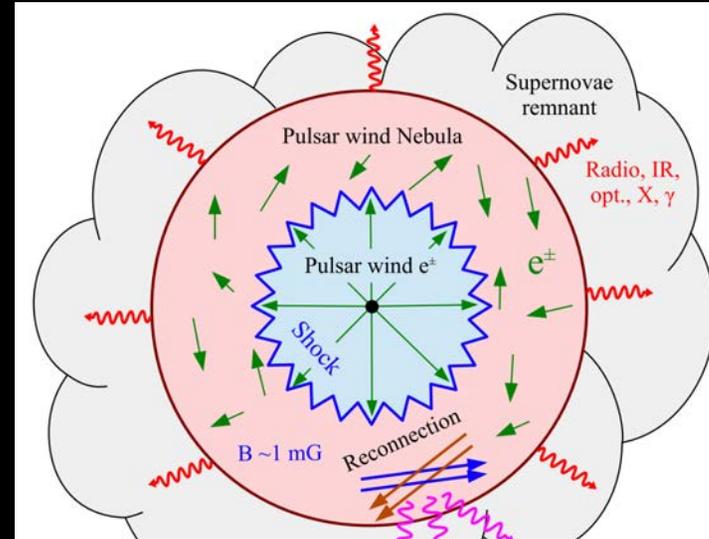
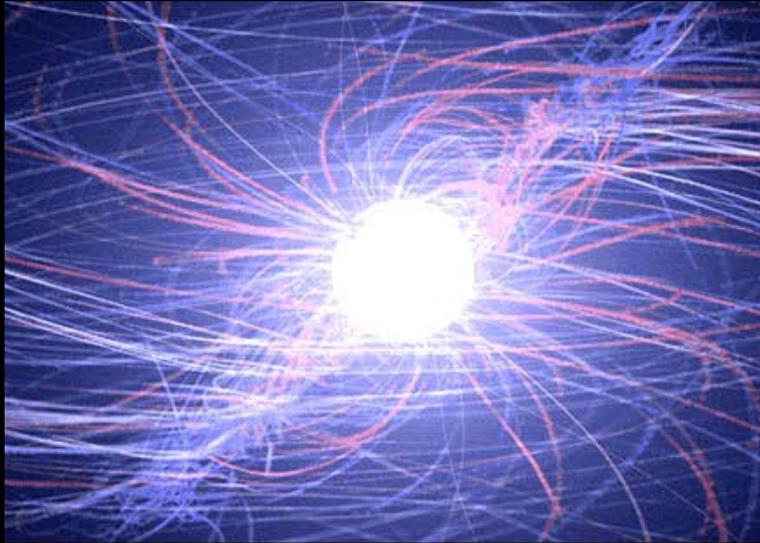
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Also see the article in the Research Notes of the AAS (<https://doi.org/10.3847/2515-5172/abd854>)

# Pulsar PSR B2224+65

- Period  $P = 0.68 \text{ s}$
- Spindown energy rate  $\dot{E}_s = 1.2 \times 10^{33} \text{ erg s}^{-1}$
- Spindown age  $t_s \sim 1.1 \text{ Myr}$
- Distance  $D \sim 1 \text{ kpc}$



# PSR B2224+65 and Guitar Nebula

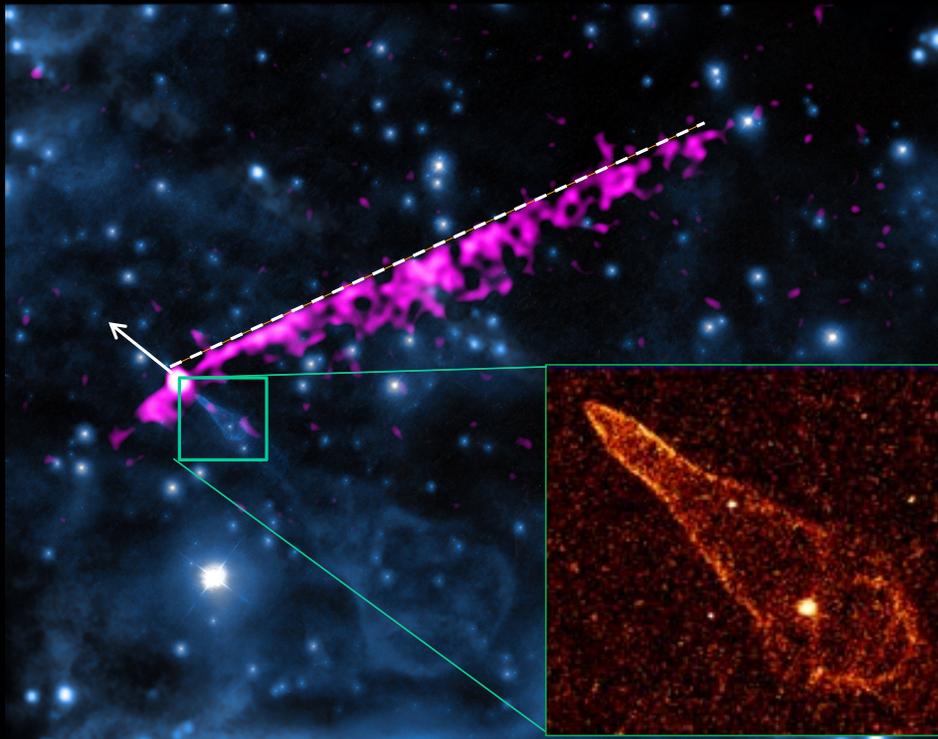
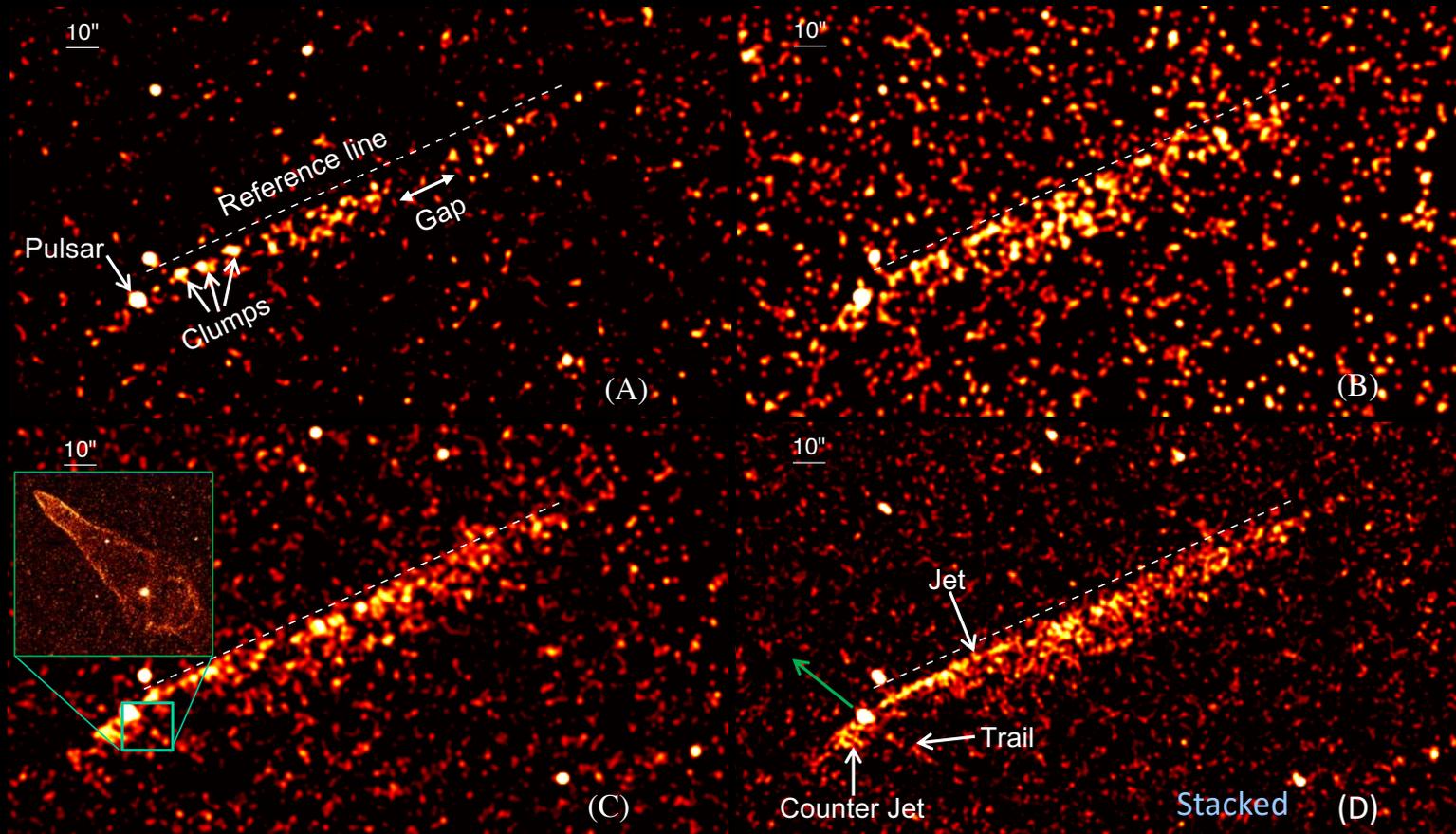


Image: Credit: X-ray: NASA/CXC/UMass/Q. Daniel Wang, Optical: NASA/STScI & Palomar Observatory 5-m Hale Telescope

- Pulsar proper motion  $\sim 900$  km/s
- Bow shock nebula in H $\alpha$  emission (Cordes et al. 1993).
- Linear X-ray feature apparently stemming from pulsar, but  $\sim 62^\circ$  misaligned with the nebula.
- This linear feature (main jet) showing a consistent proper motion (Johnson & Wang 2010).

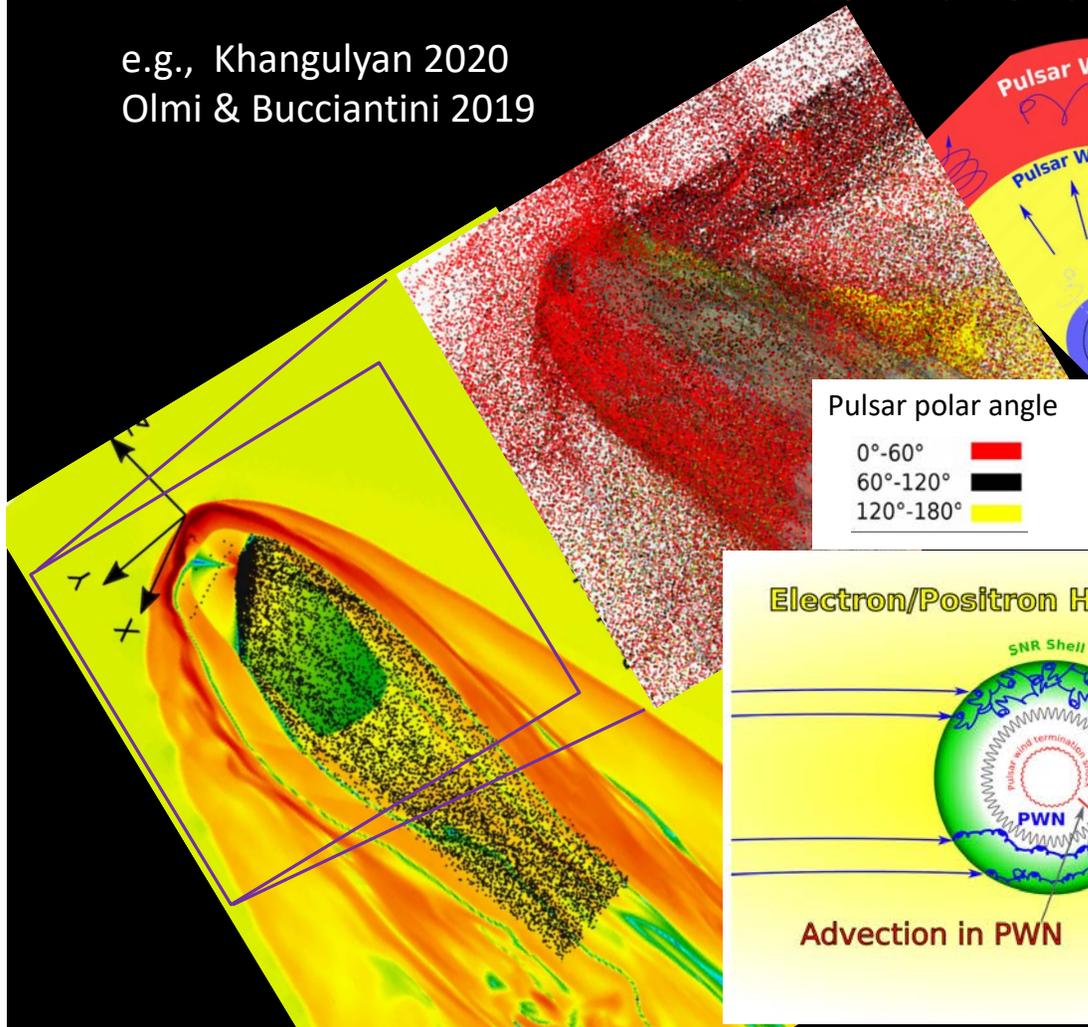
# Chandra/ACIS X-ray features in 3 epochs



A few more such misaligned X-ray filaments have been discovered around similar pulsars.

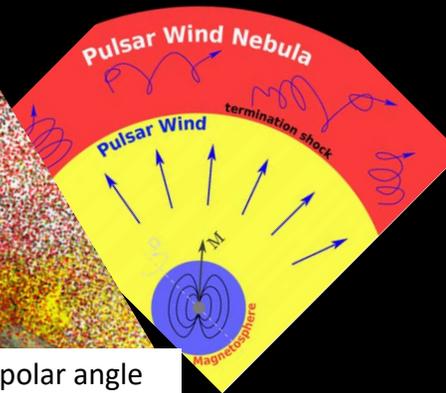
# Theoretical Picture

e.g., Khangulyan 2020  
Olmi & Bucciantini 2019



Pulsar polar angle

0°-60° █  
60°-120° █  
120°-180° █



- This picture qualitatively explains the main characteristics of the features associated with PSR B2224+65.
- Such energetic particle streams from nearby pulsars may explain the local cosmic-ray positron excess.

## Electron/Positron Halo



✓ HE particles can freely cross CD and shock fronts

# Summary

- Jet-like X-ray features are detected from the fast-moving pulsar PSR B2224+65. They have the same proper motion!
- The main jet,  $62^\circ$  misaligned from the Guitar nebula, is  $\sim 2.4'$  (or 2.1 ly) long and shows substructure variation with time.
- A "counter-jet", as well as a faint X-ray trail along with the nebula, are also detected.
- Magnetic field plays a central role in the formation of the features, which represent the synchrotron radiation of energetic ( $\sim 100$  TeV) particles leaked out from the bow shock nebula and streaming along interstellar magnetic field lines.
- PSR B2224+65 thus provides a lab for studying extremely energetic particles and their dynamic interplay with magnetic fields of the pulsar wind and interstellar medium.

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