



# Radio Observations of Pulsar Wind Nebulae

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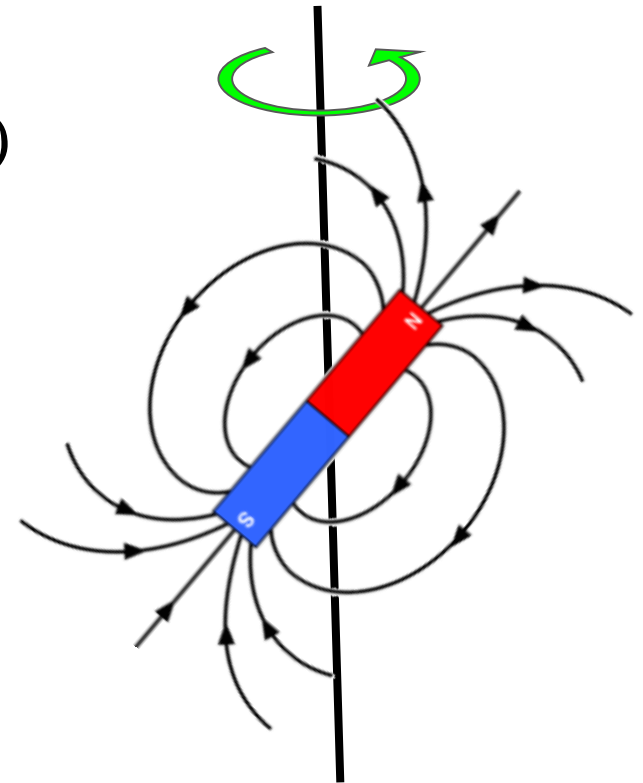
# Pulsar Wind

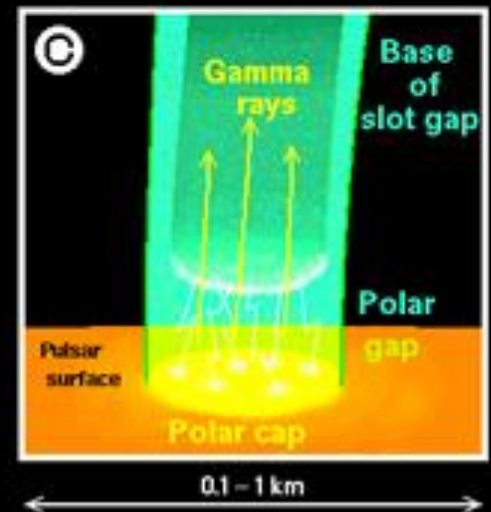
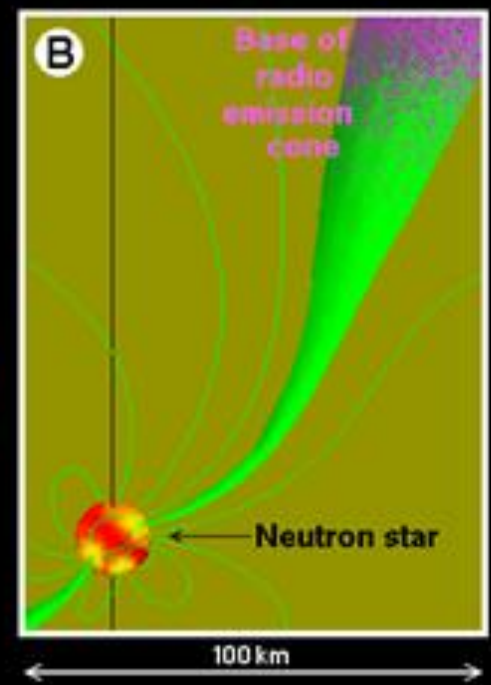
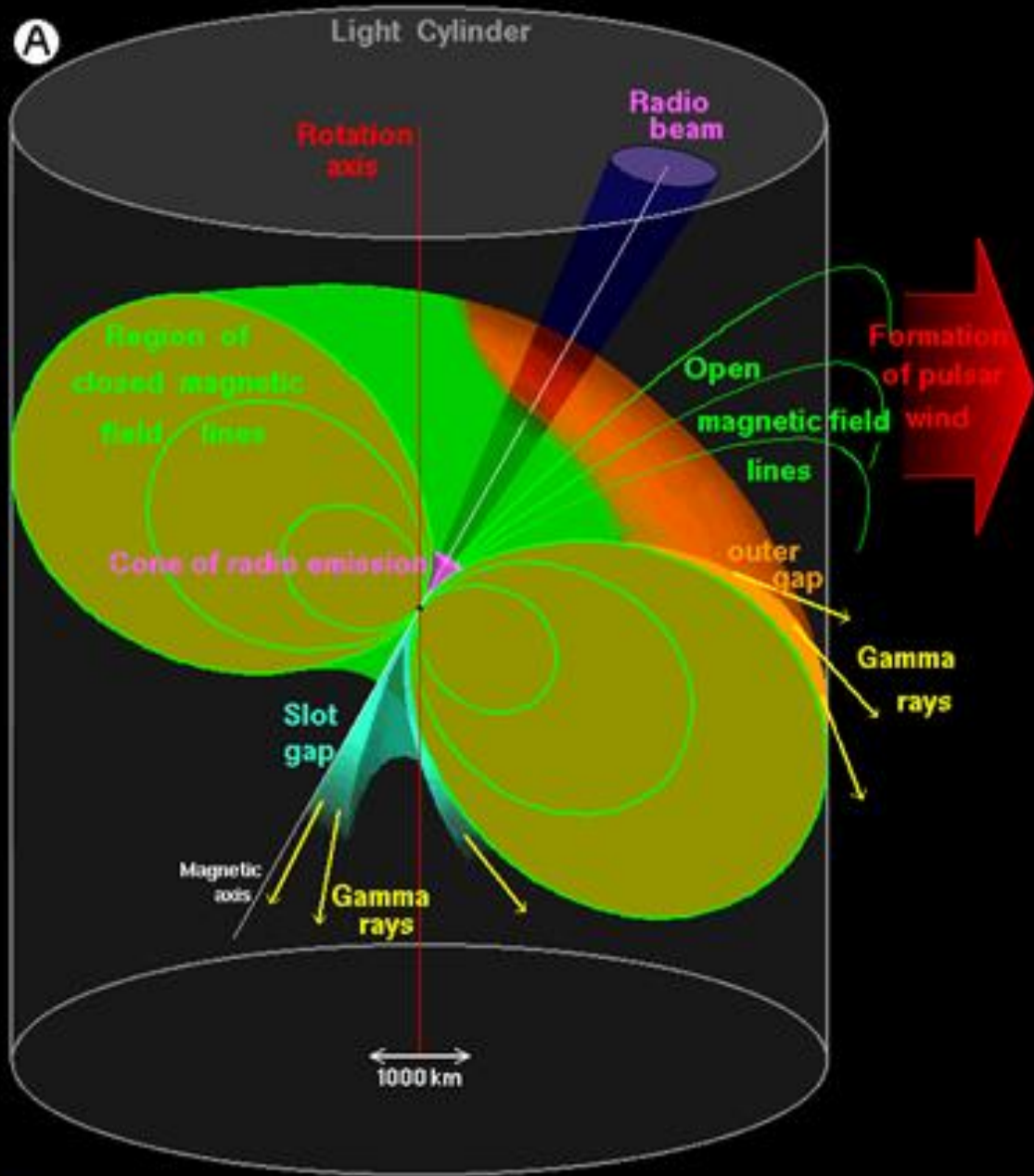
Where does the pulsar rotational energy go?

$$\dot{E} \equiv I\Omega\dot{\Omega} > 10^{35} \text{ erg/s}$$

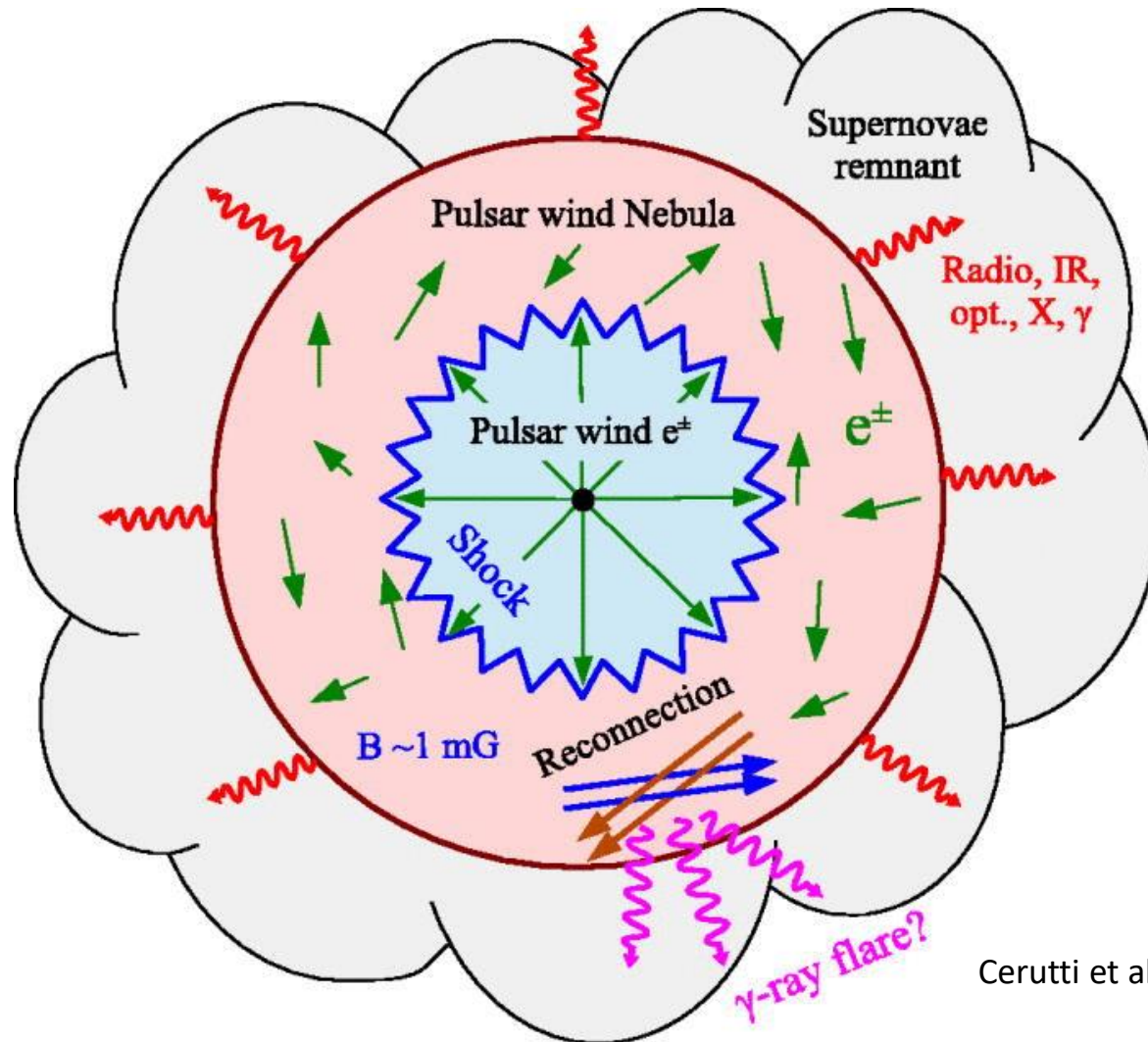
< 10% in radiation (mostly  $\gamma$ -rays)

> 90% in pulsar winds



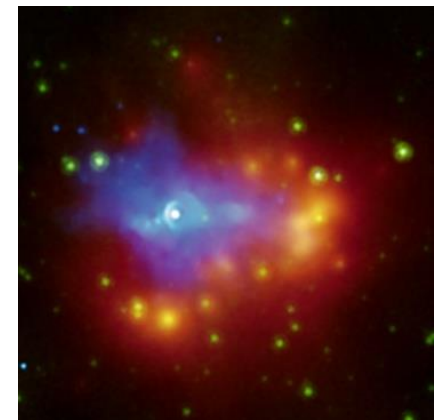
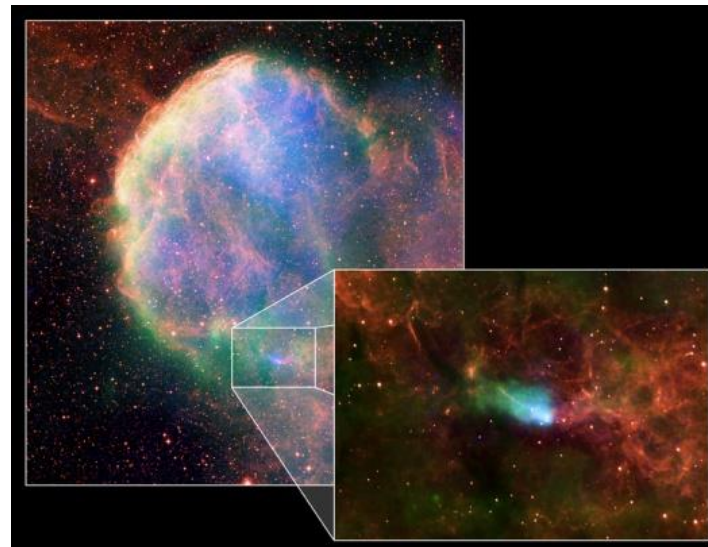
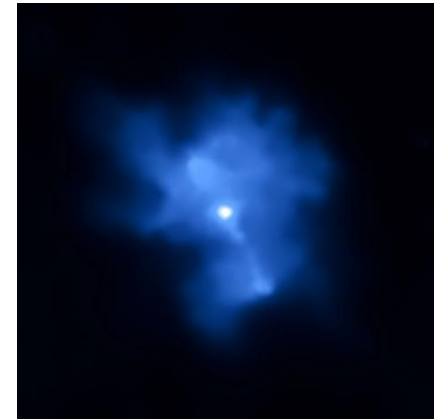
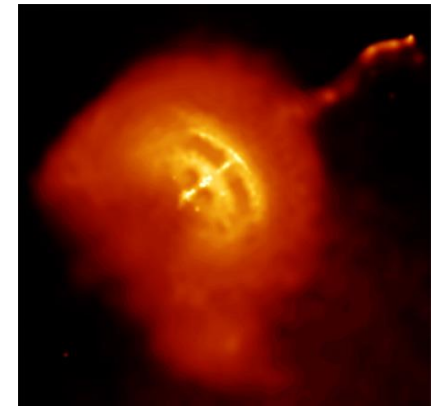
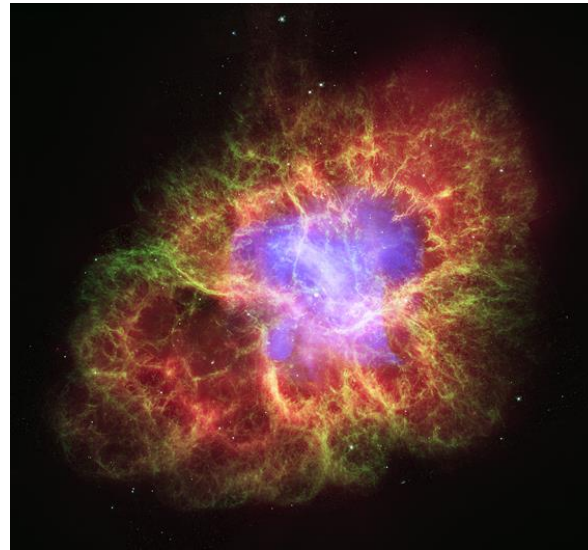
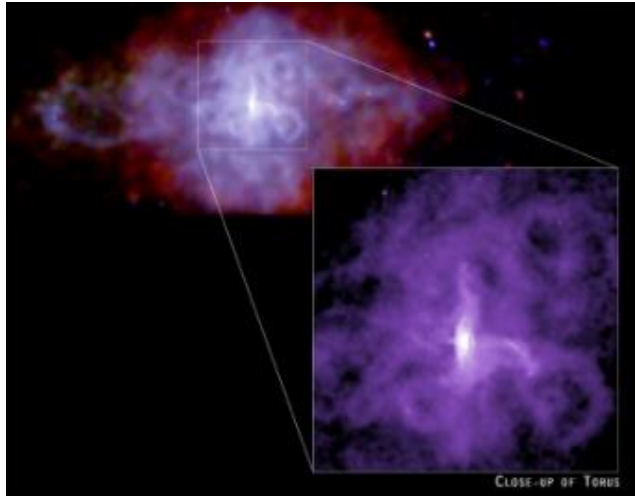


# Pulsar Wind Nebula

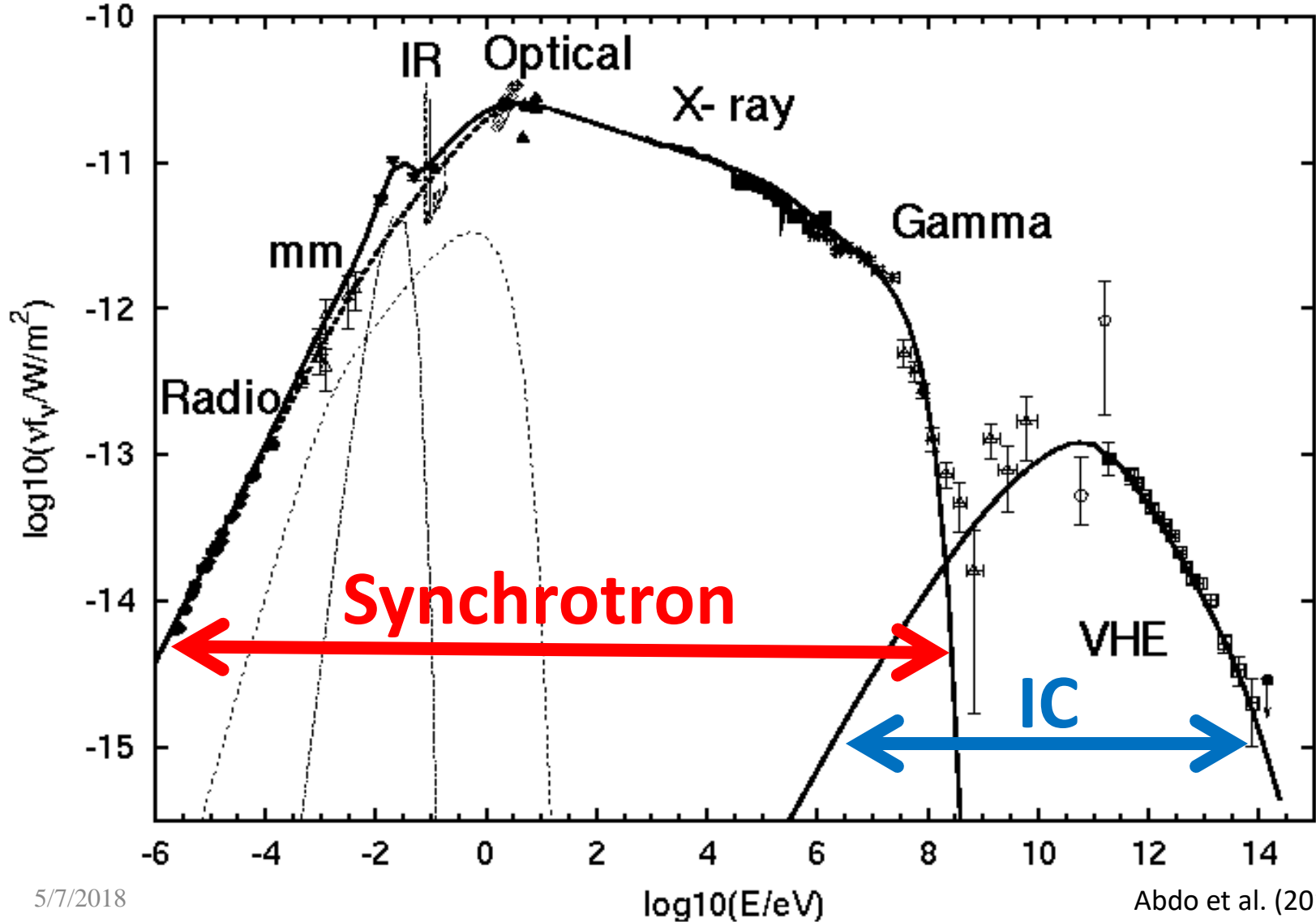


Cerutti et al. (2014)

# Pulsar Wind Nebula

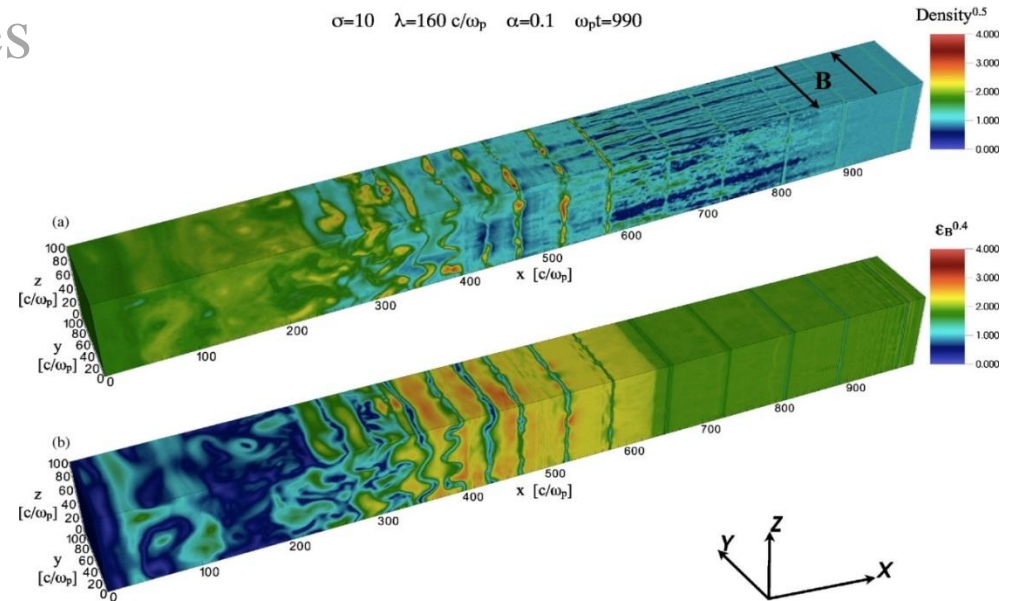


# Crab Nebula



# Why Study PWNe?

- Relativistic shock physics
- Cosmic ray acceleration
- Important TeV sources

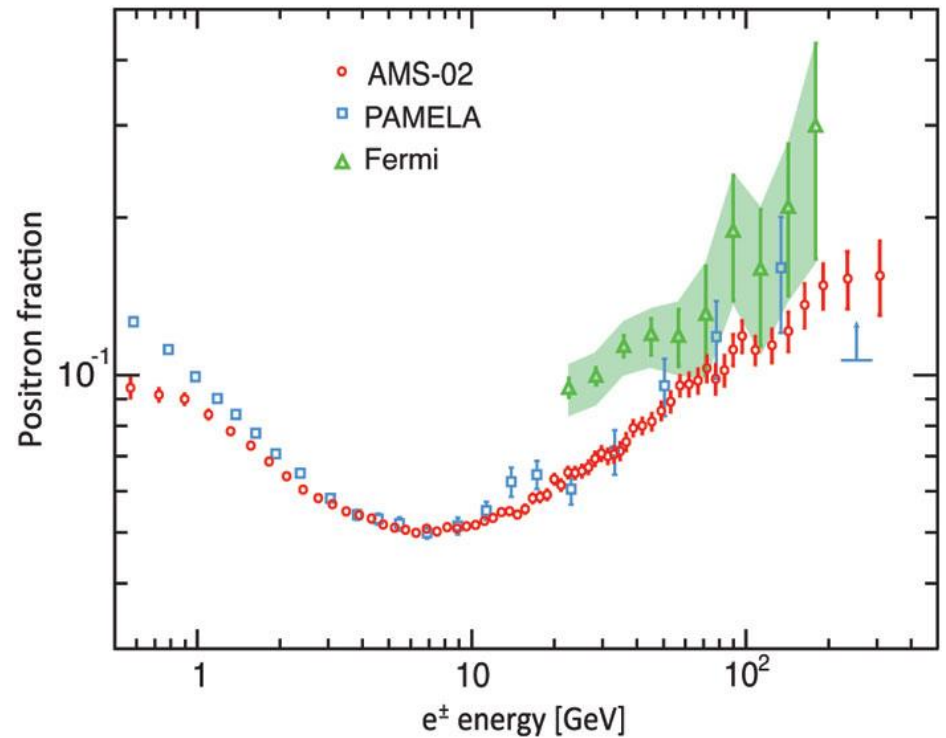


Sironi & Spitkovsky (2011)

# Why Study PWNe?

- Relativistic shock physics
- Cosmic ray acceleration
- Important TeV sources

**$e^+$  excess: dark matter? PWNe?**

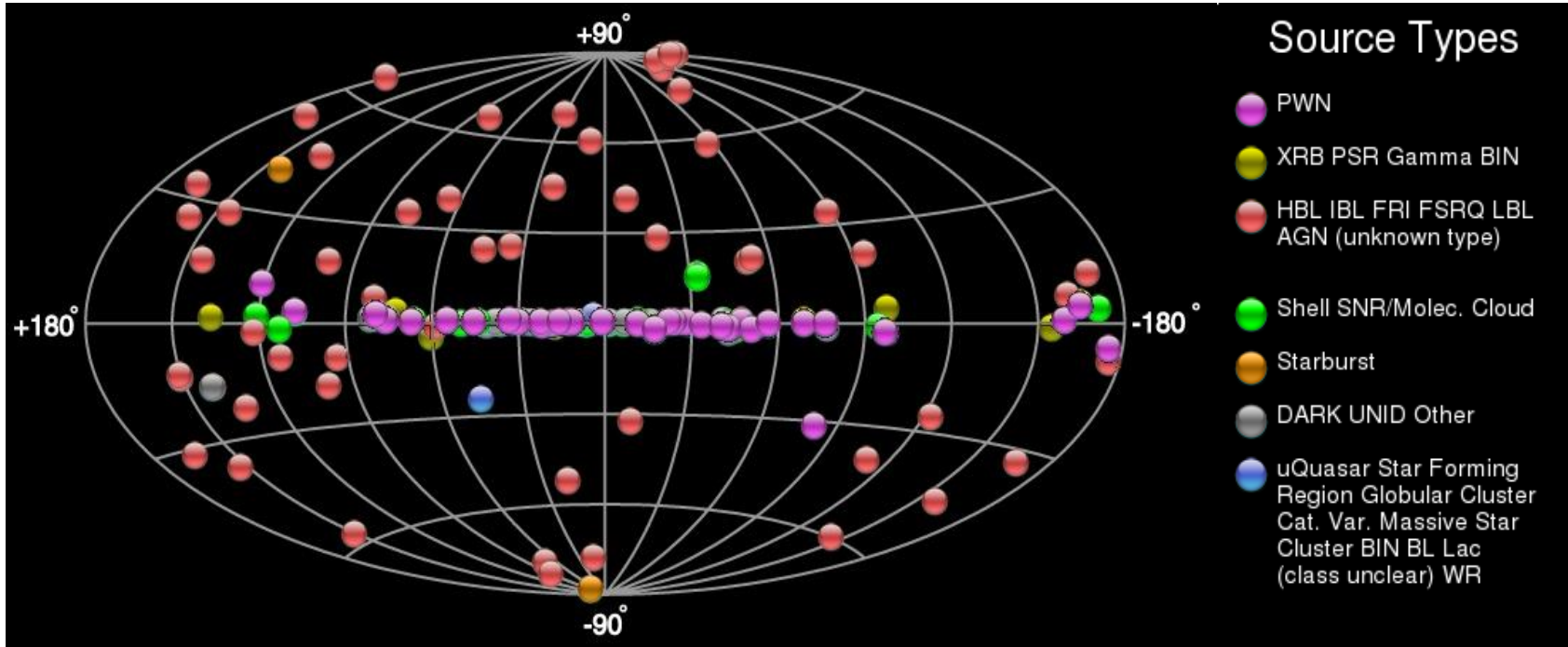




# Why Study PWNe

- Relativistic shock physics
- Cosmic ray acceleration
- Important TeV sources

**~1/4 TeV sources**



# X-ray Emission

- Synchrotron cooling time:

- $t_{cool} \approx 1.2 \times 10^3 \left( \frac{B}{10\mu\text{G}} \right)^{-\frac{3}{2}} \left( \frac{E}{1\text{keV}} \right)^{-\frac{1}{2}} \text{yr}$

- Fast cooling time
- Most recent condition

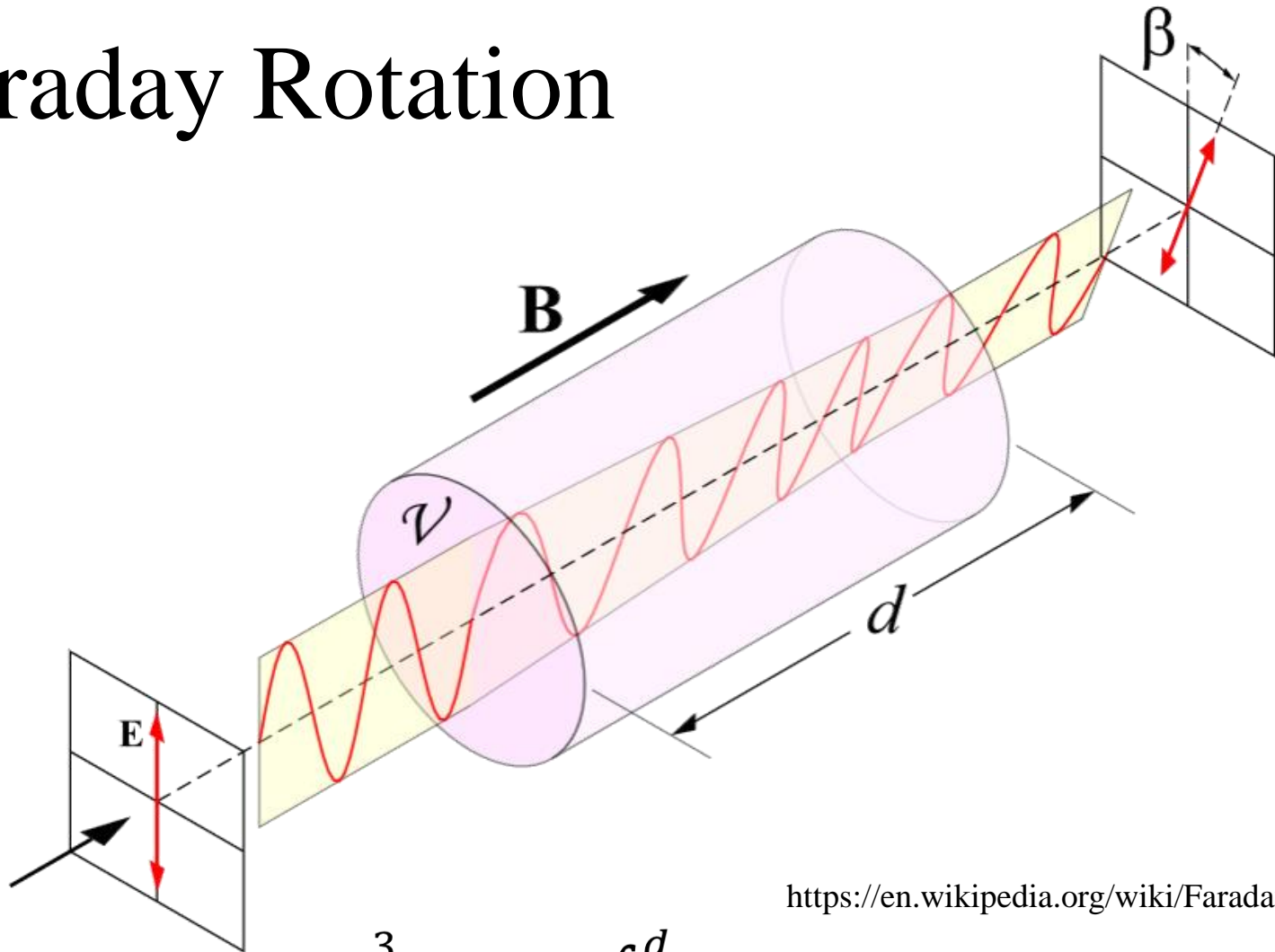
# Radio Emission

- Synchrotron cooling time:

- $t_{cool} \approx 2 \times 10^7 \left( \frac{B}{10\mu\text{G}} \right)^{-\frac{3}{2}} \left( \frac{\nu}{1\text{GHz}} \right)^{-\frac{1}{2}} \text{yr}$

- Preserve injection spectrum
  - Direct calorimeter
  - Trace pulsar motion to reveal birth site
- Polarization observations  $\Rightarrow$   $B$ -field structure

# Faraday Rotation



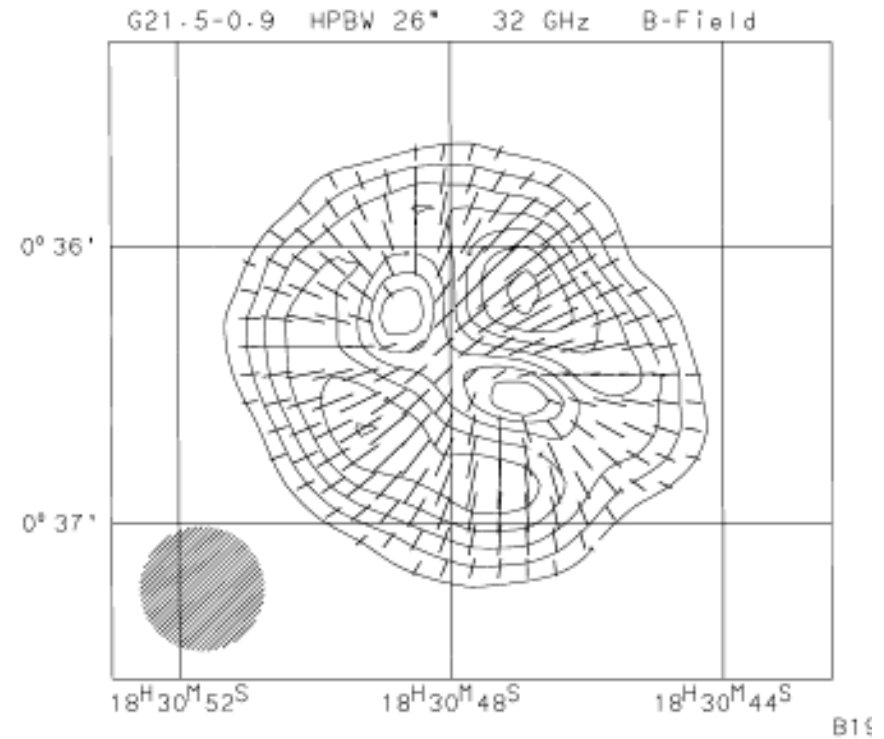
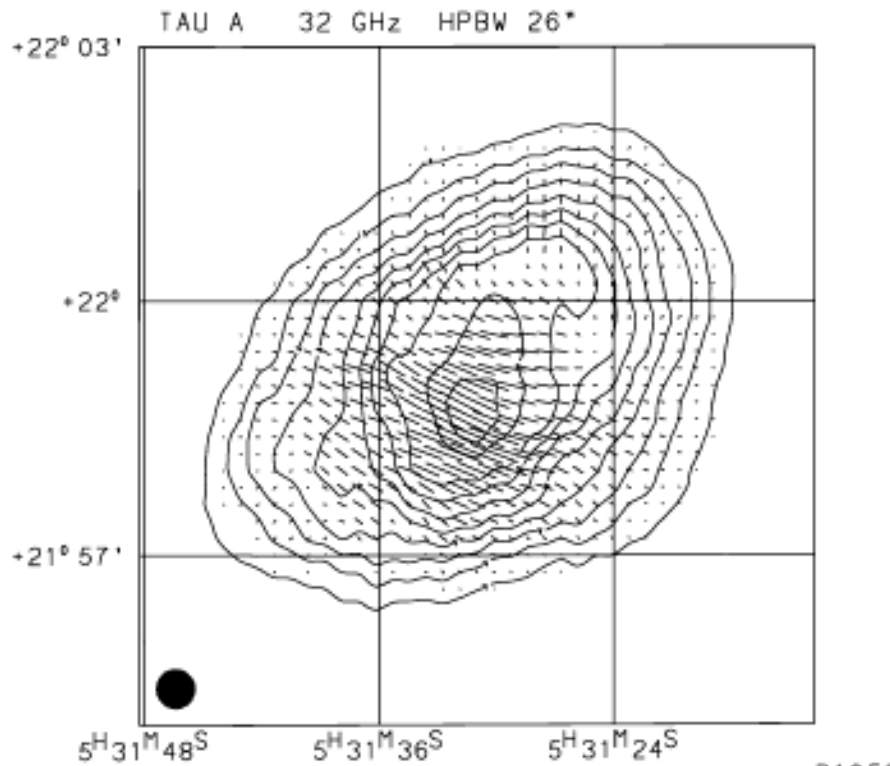
[https://en.wikipedia.org/wiki/Faraday\\_effect](https://en.wikipedia.org/wiki/Faraday_effect)

$$\Delta\chi = \frac{e^3}{8\pi^2\epsilon_0 m_e^2 c^3} \lambda^2 \int_0^d n_e(s) B_{\parallel} ds \equiv RM\lambda^2$$

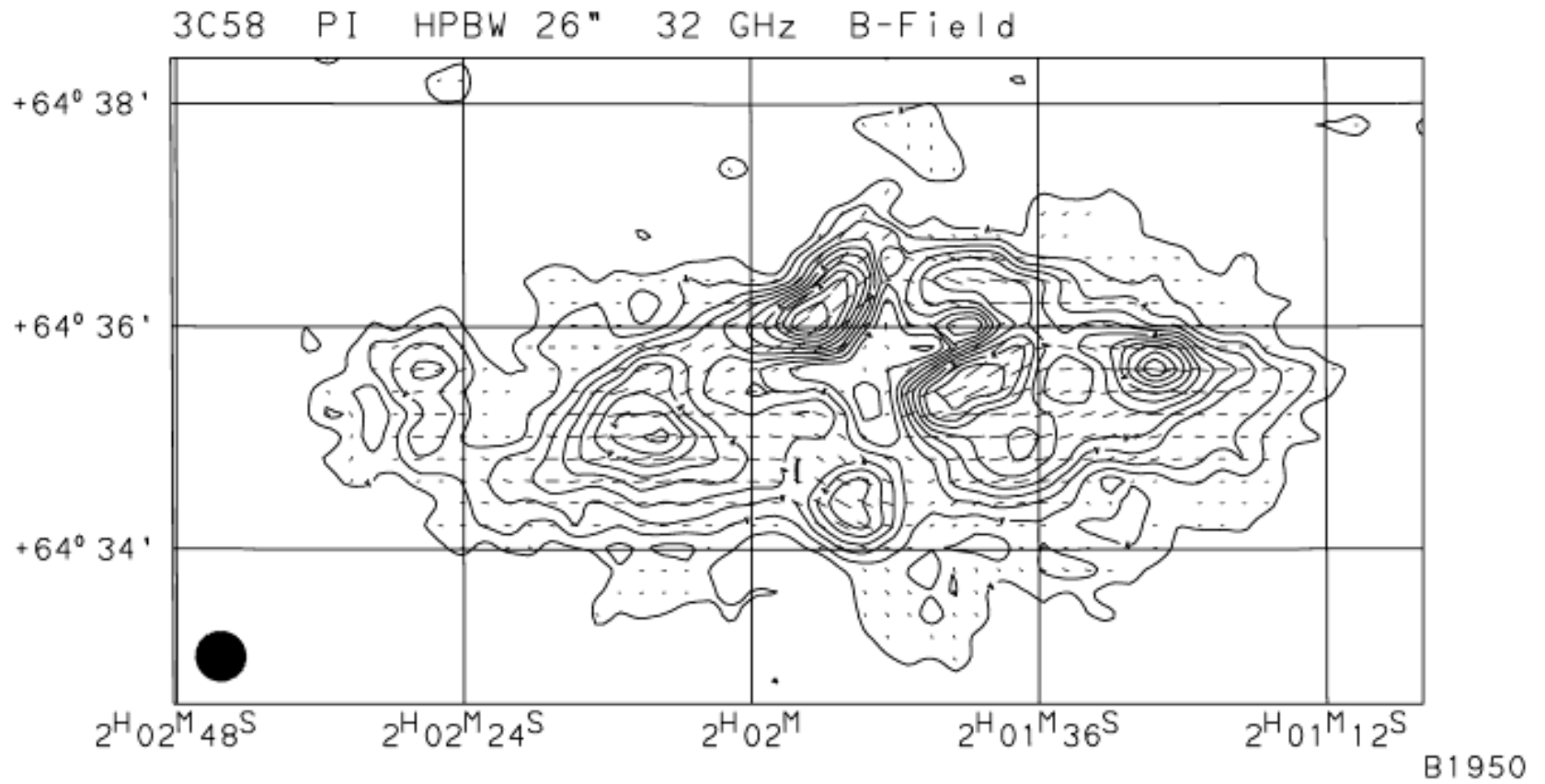
# Radio PWNe

- Flat radio spectrum ( $\alpha \sim -0.3$  to  $0$ ;  $S_\nu \propto \nu^\alpha$ )
- Highly linearly polarized ( $>10\%$ )

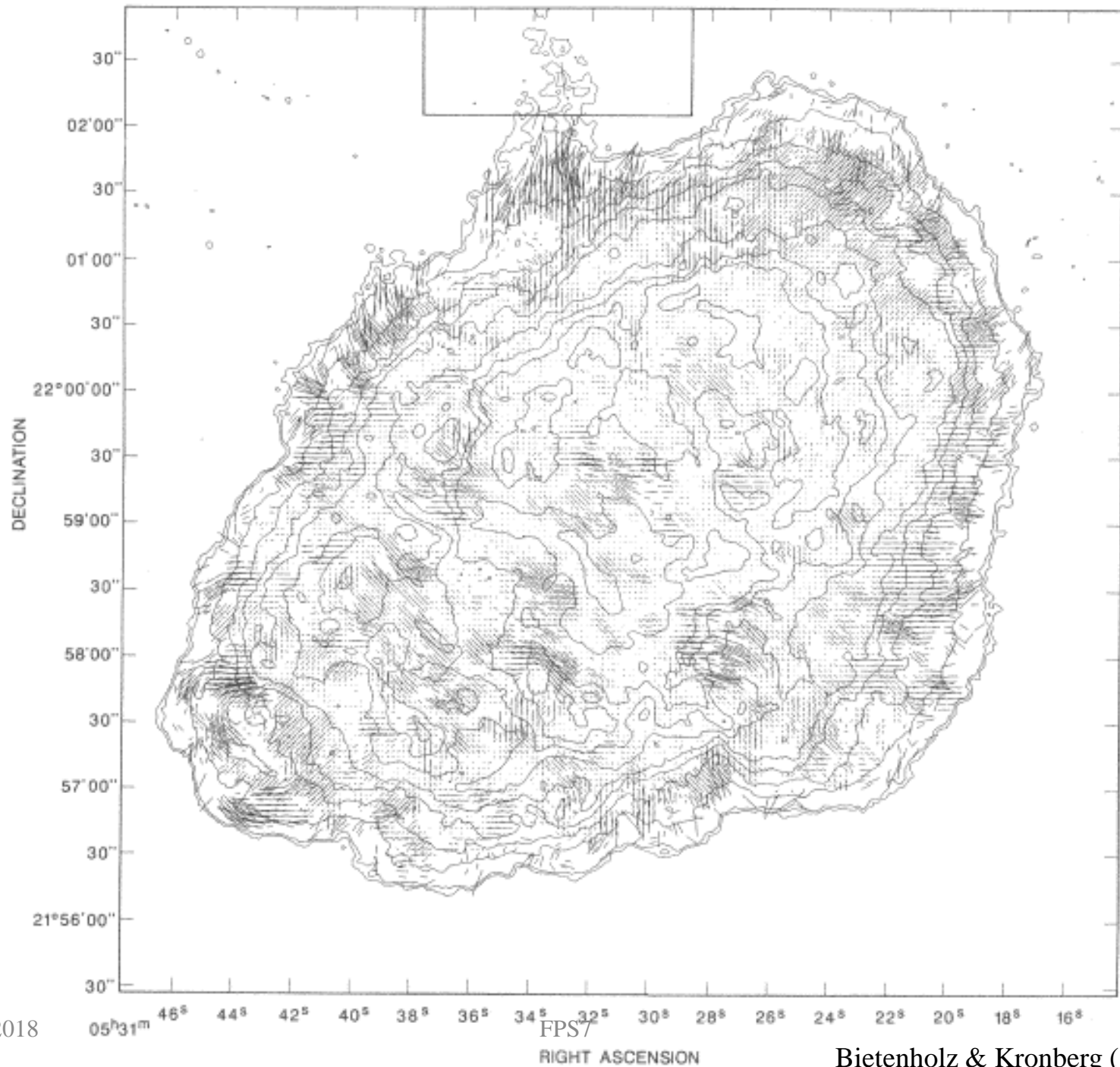
# Previous Studies



Reich (2002)



Reich (2002)



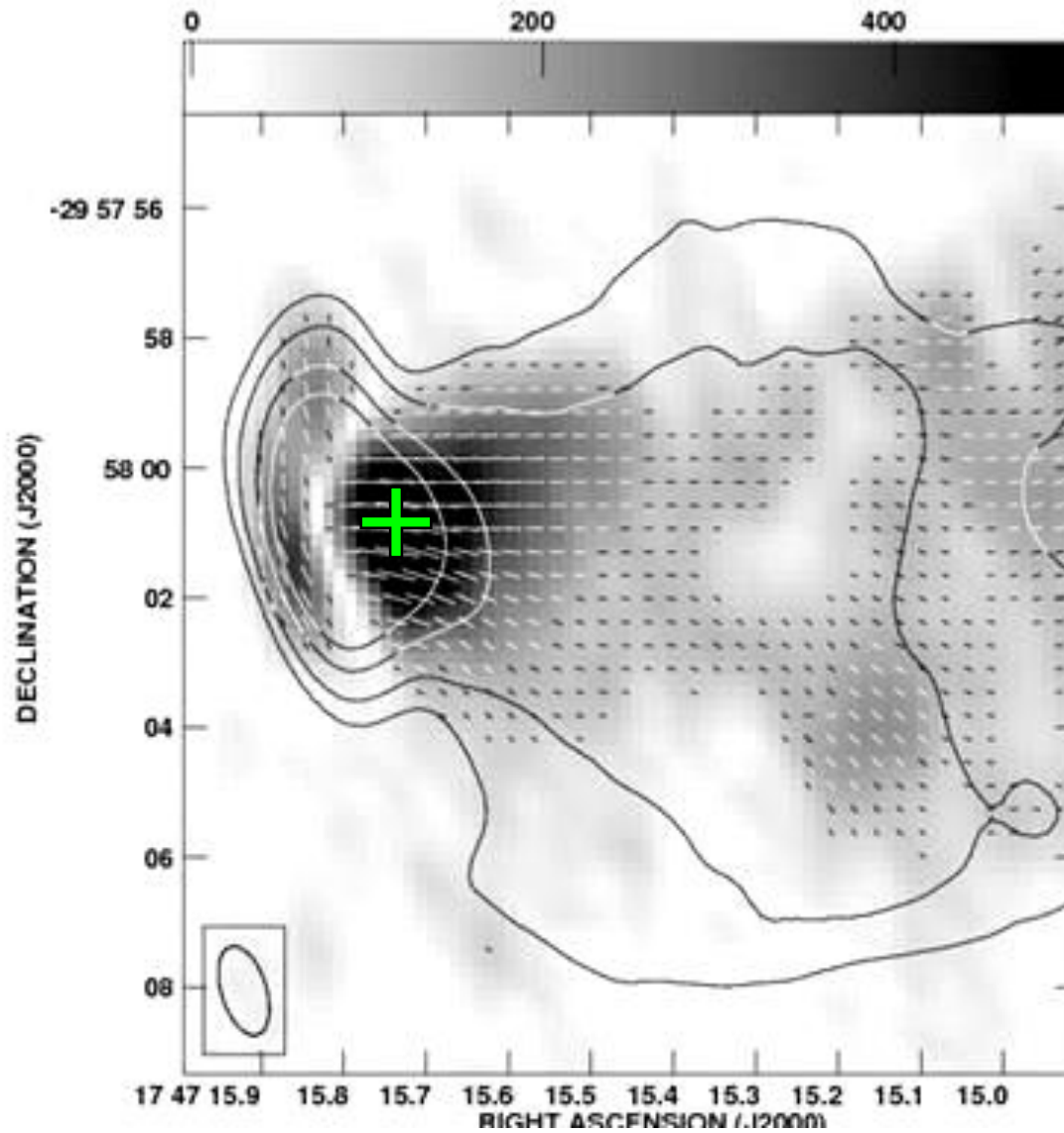
5/7/2018

FPS7

Bietenholz & Kronberg (1990)



# The Mouse / PSR J1747-2958



ATCA



ATNF/CSIRO



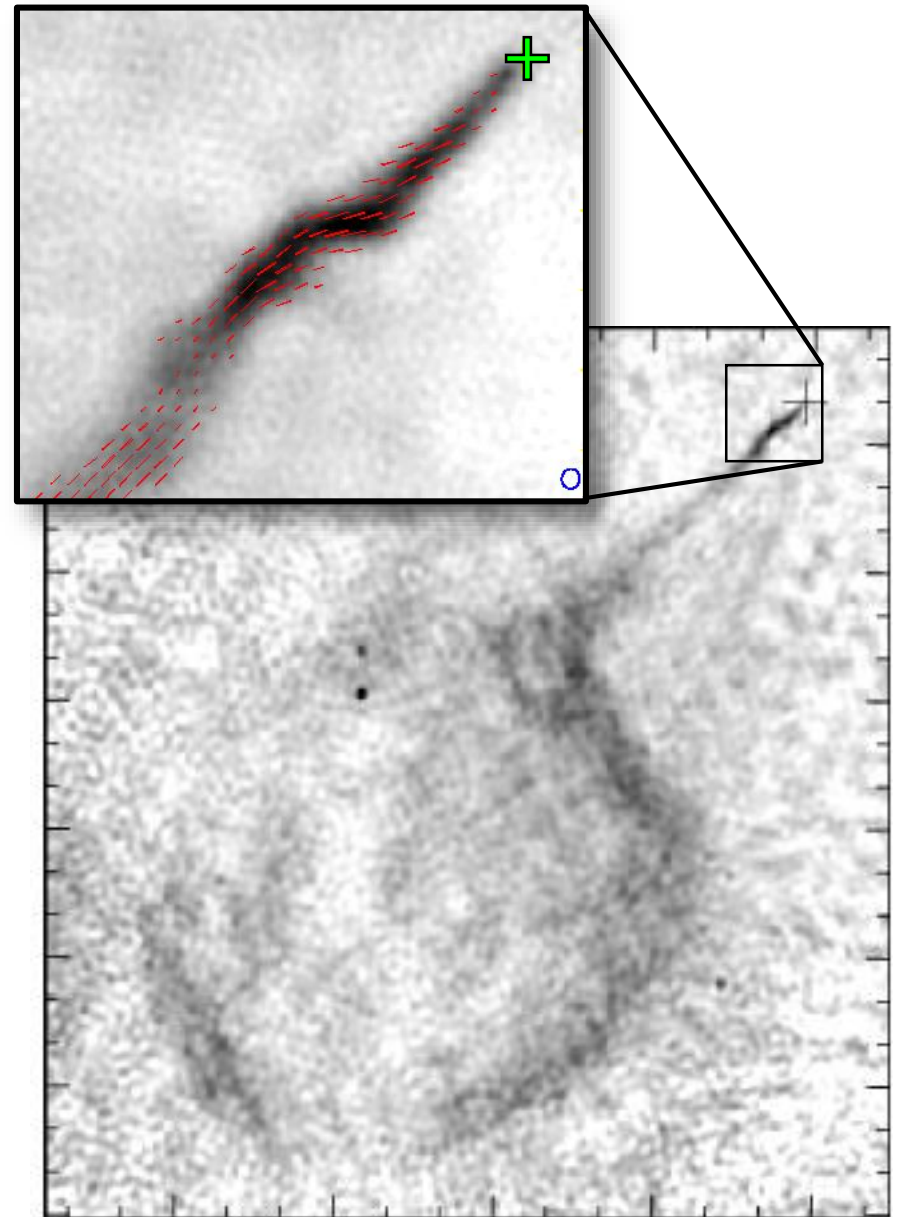
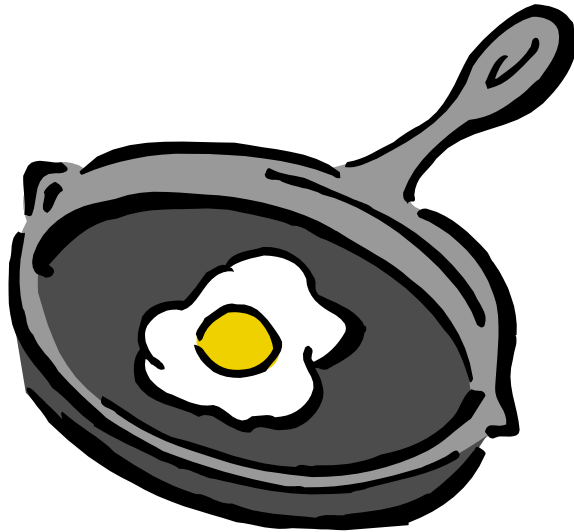
FPS7

W. Grammer, NRAO/AUI/NSF

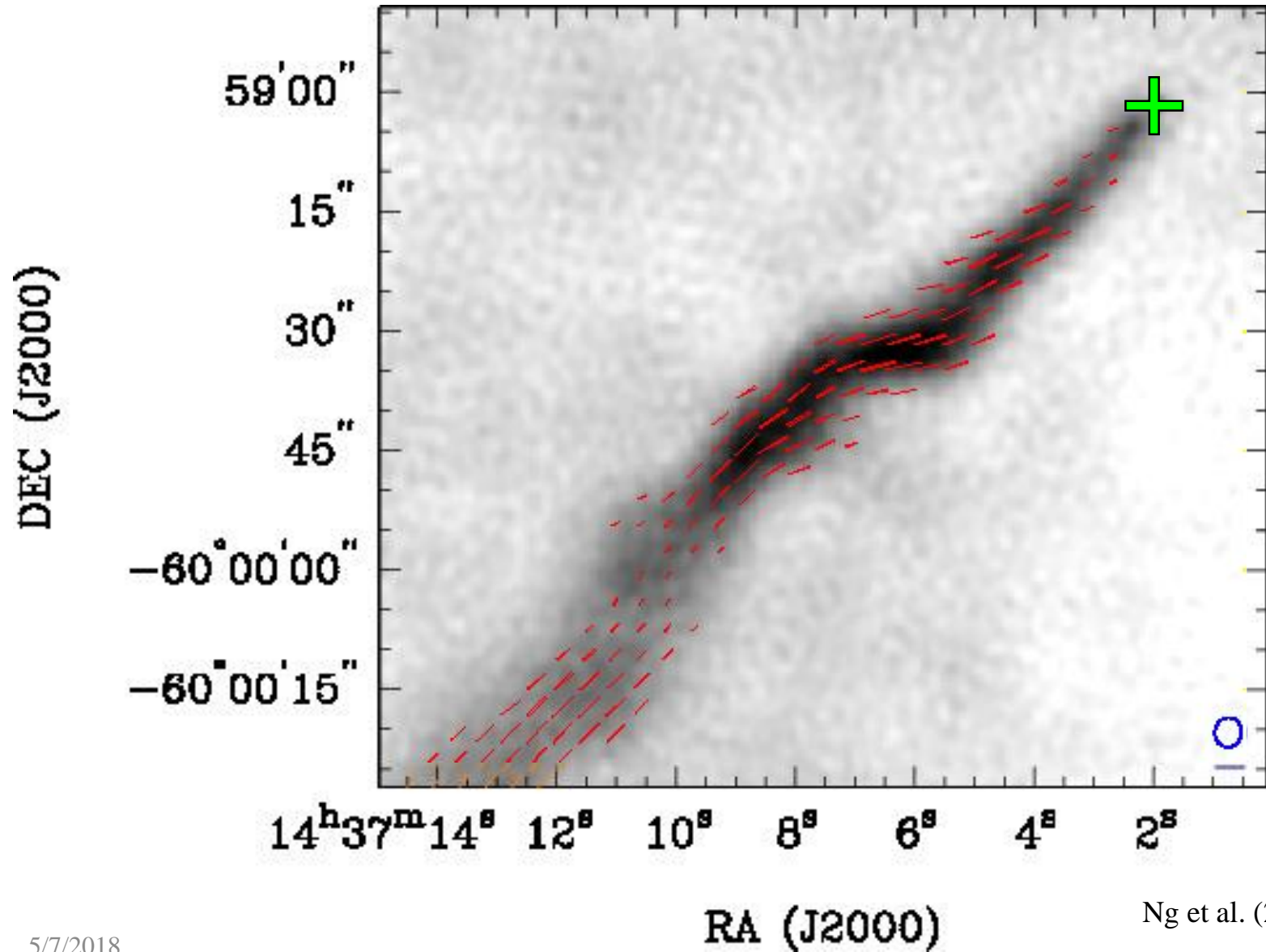
# The Frying Pan

## G315.9–0.0

- $\sim 2000$  km/s
- Longest pulsar tail  $> 20$  pc

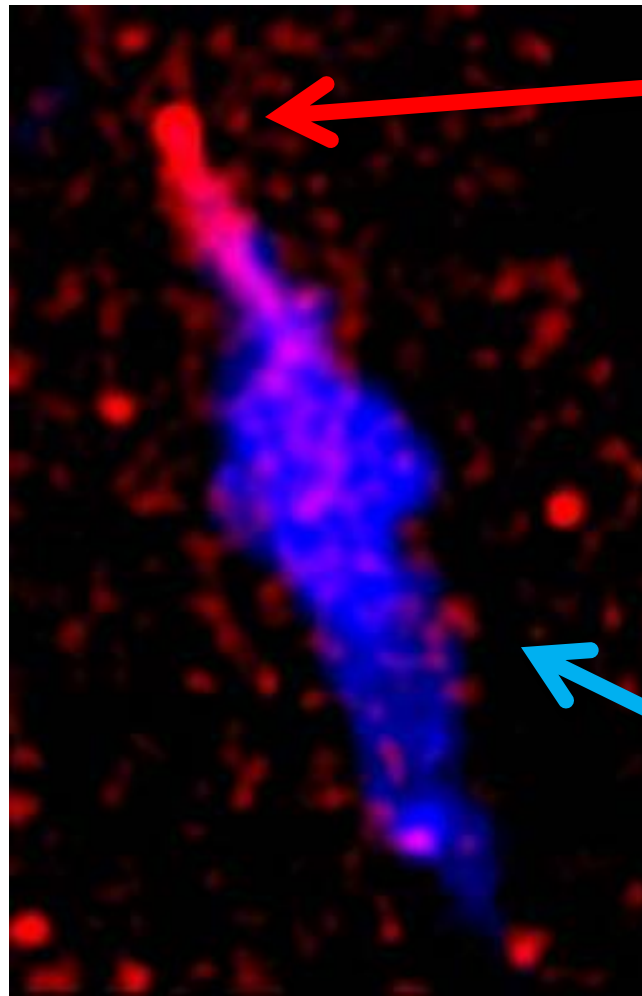


# ATCA 6cm



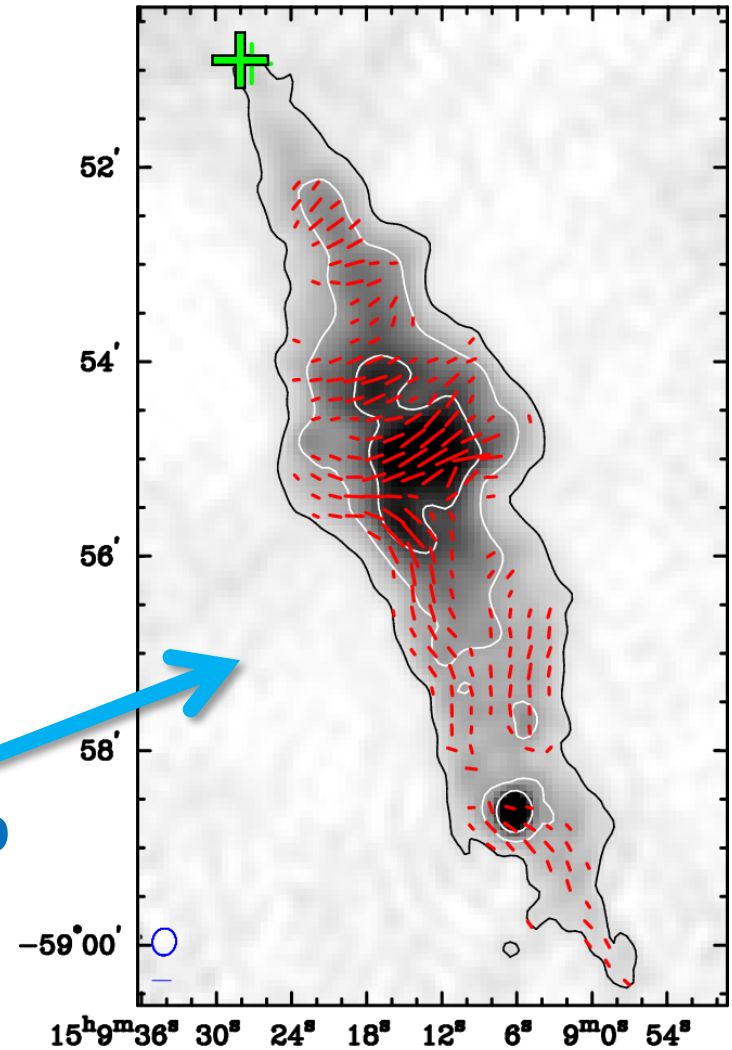
Ng et al. (2012)

# G319.9-0.7 / PSR J1509-5850

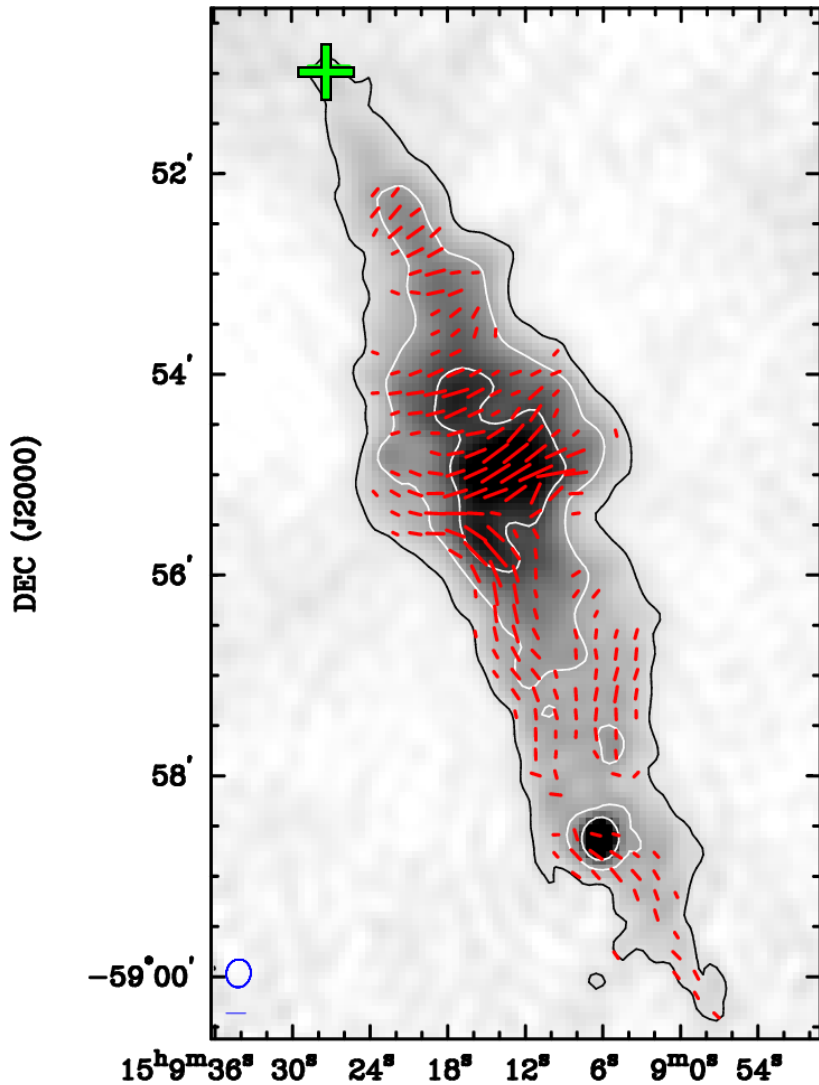


X-ray

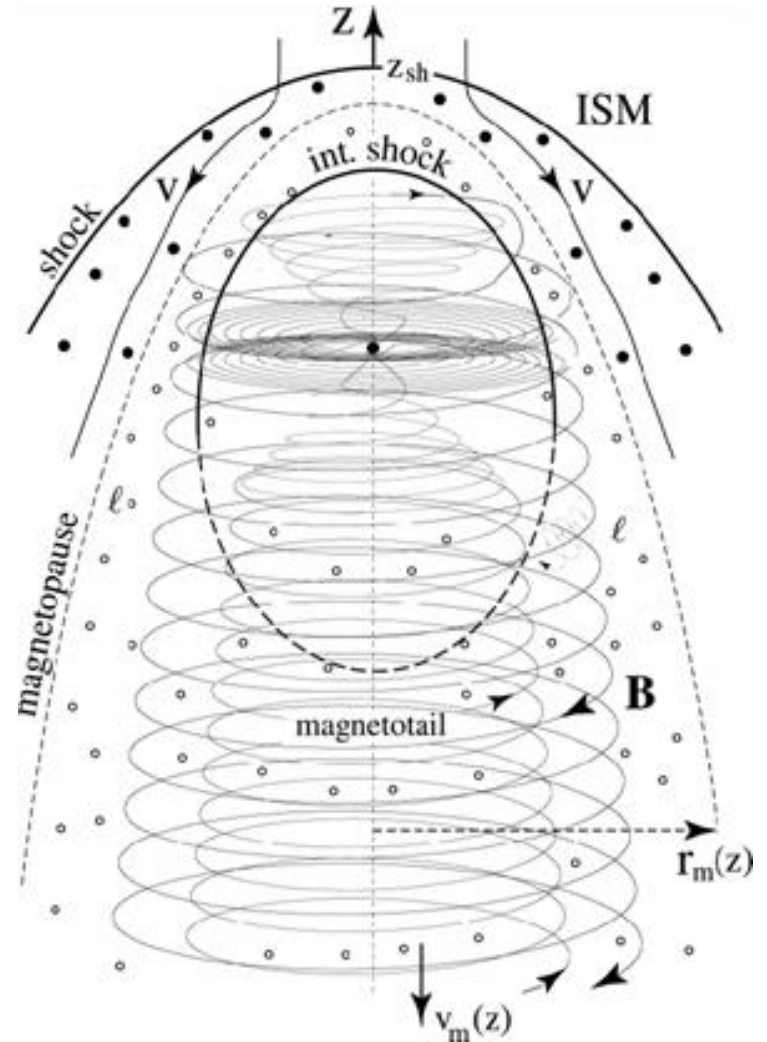
Radio



# G319.9-0.7 / PSR J1509-5850

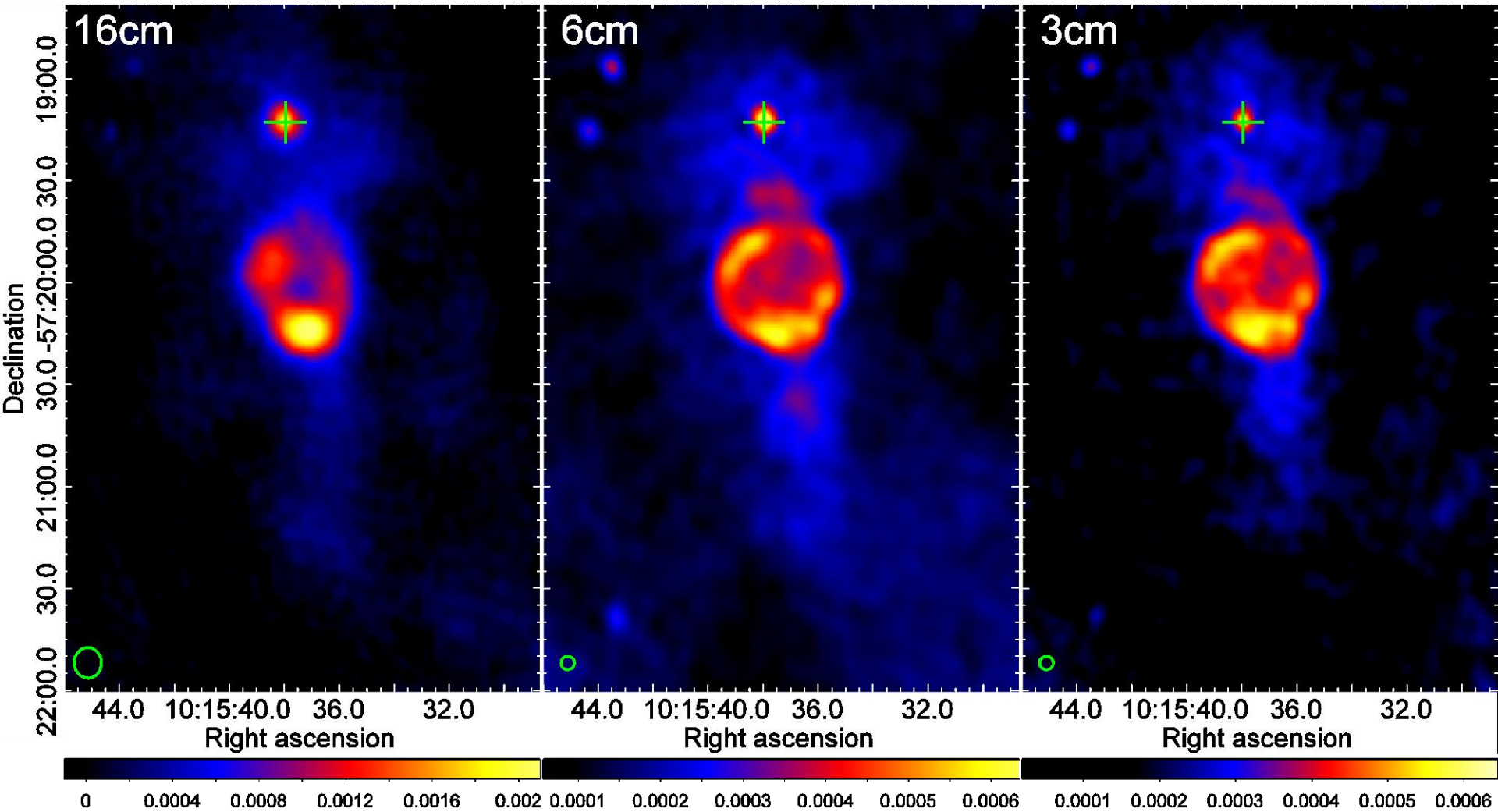


Ng et al. (2010)  
FPS7



Romanova et al. (2005)  
Stephen Ng

# PSR J1015-5719

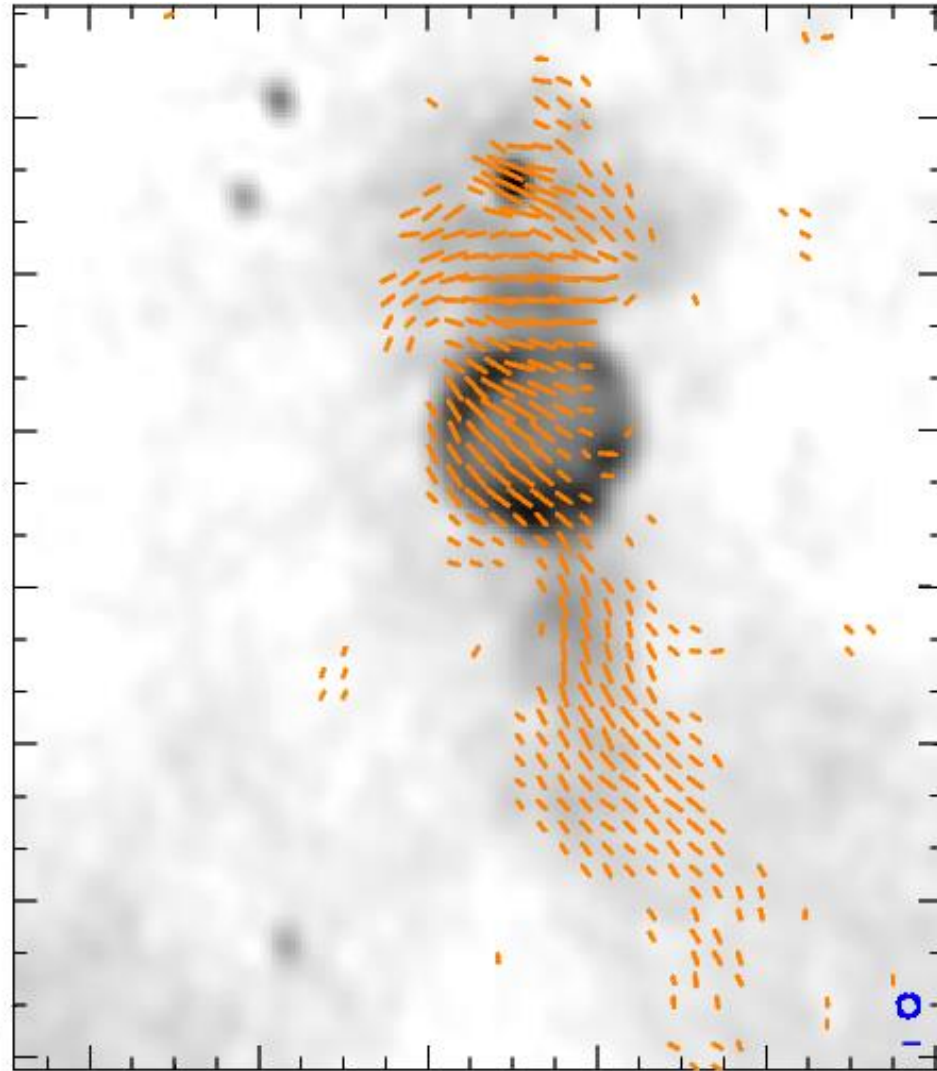


5/7/2018

FPS7

Ng et al. (2017)

# PSR J1015-5719



6/12/2017

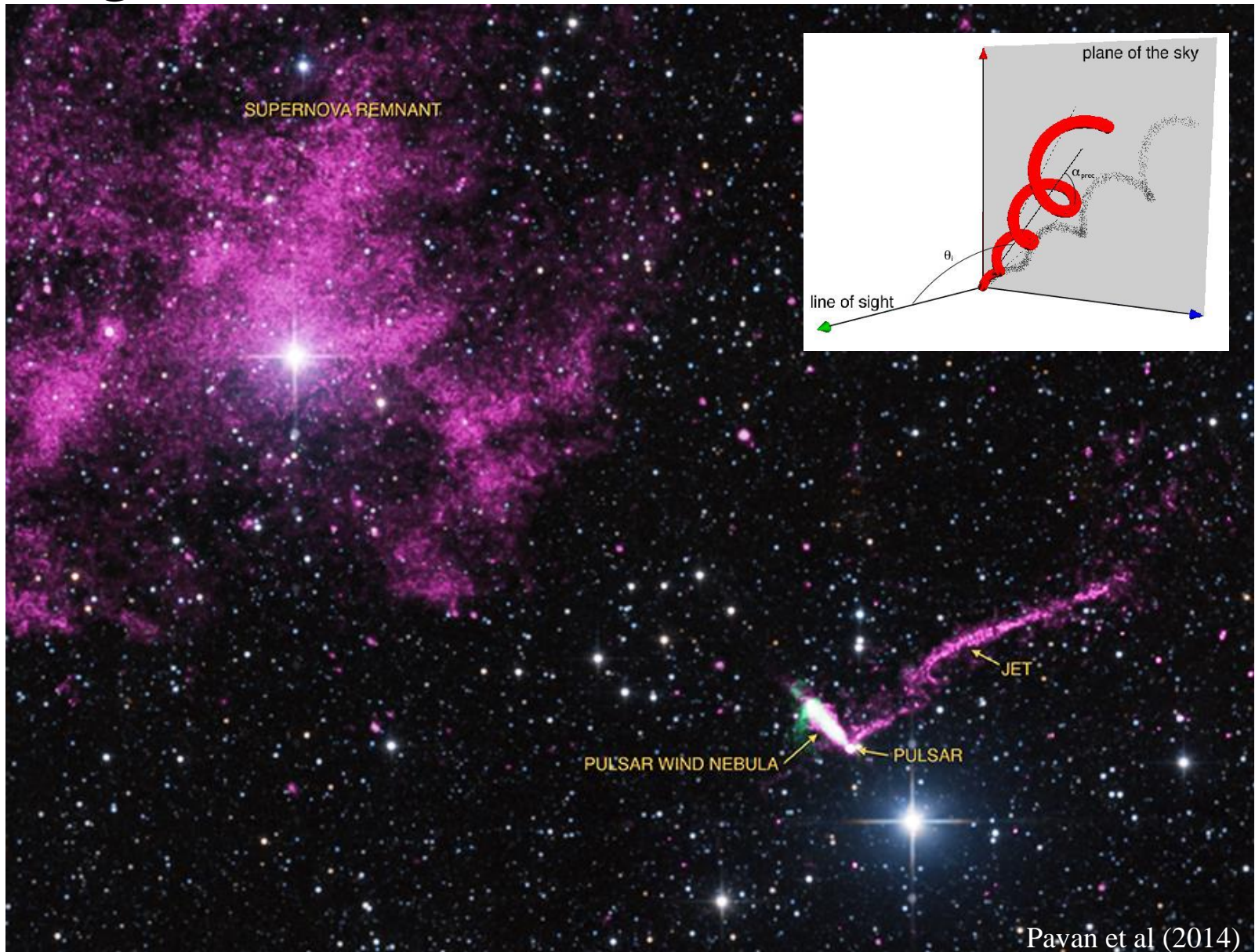
FPS7

Ng et al. (2017)

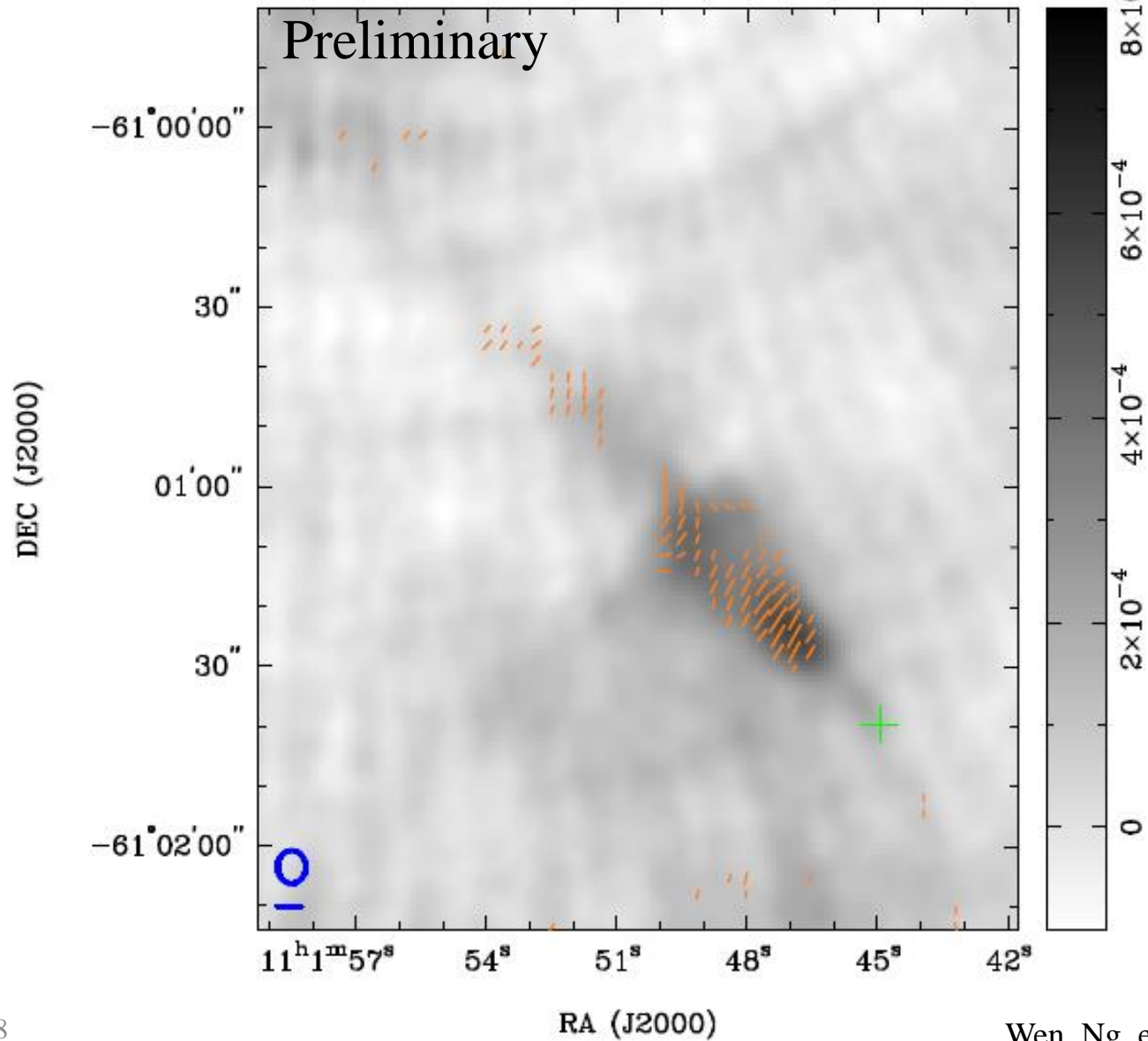
Stephen Ng



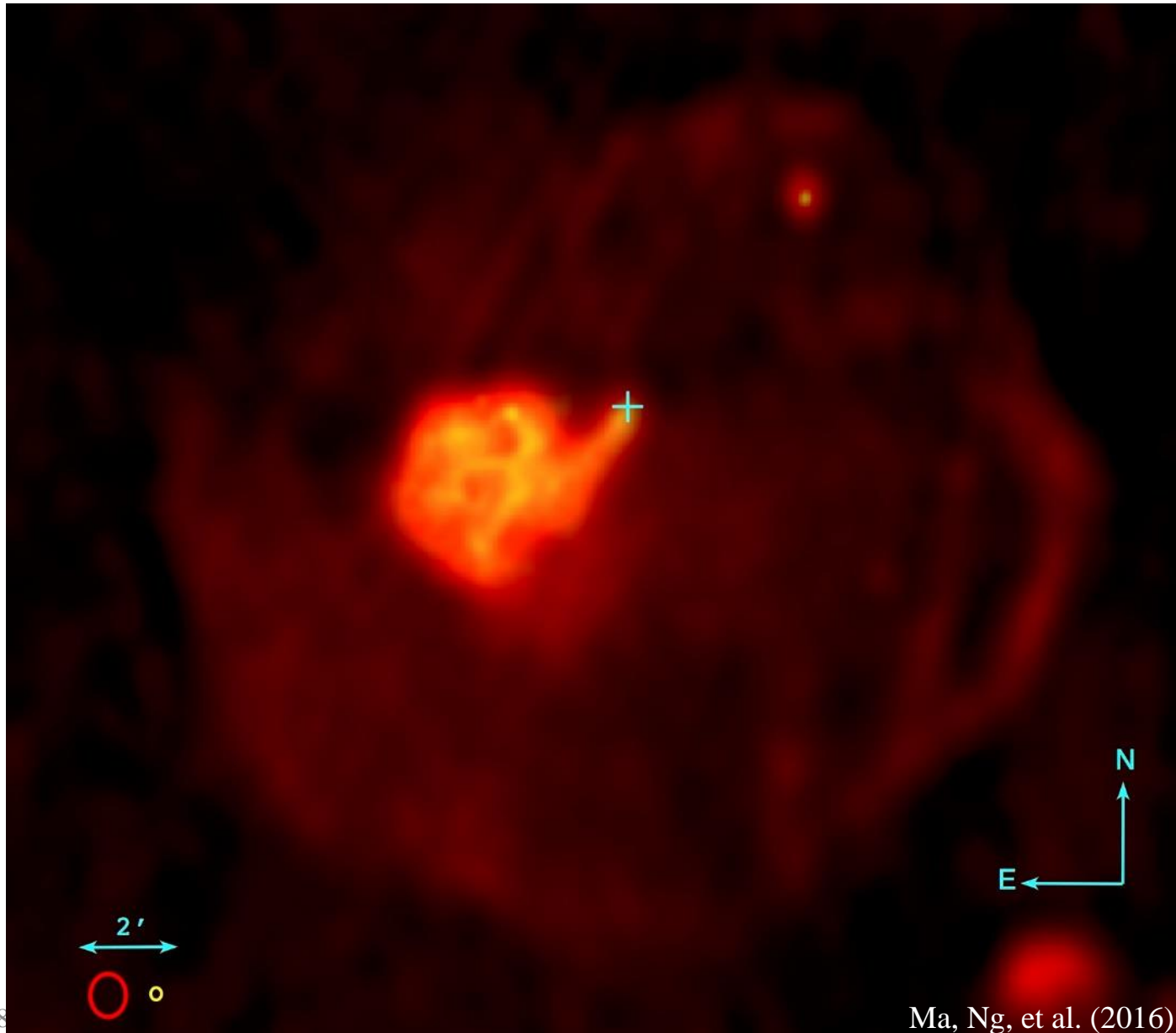
# Lighthouse Nebula/IGR J111014-6103



# Lighthouse Nebula



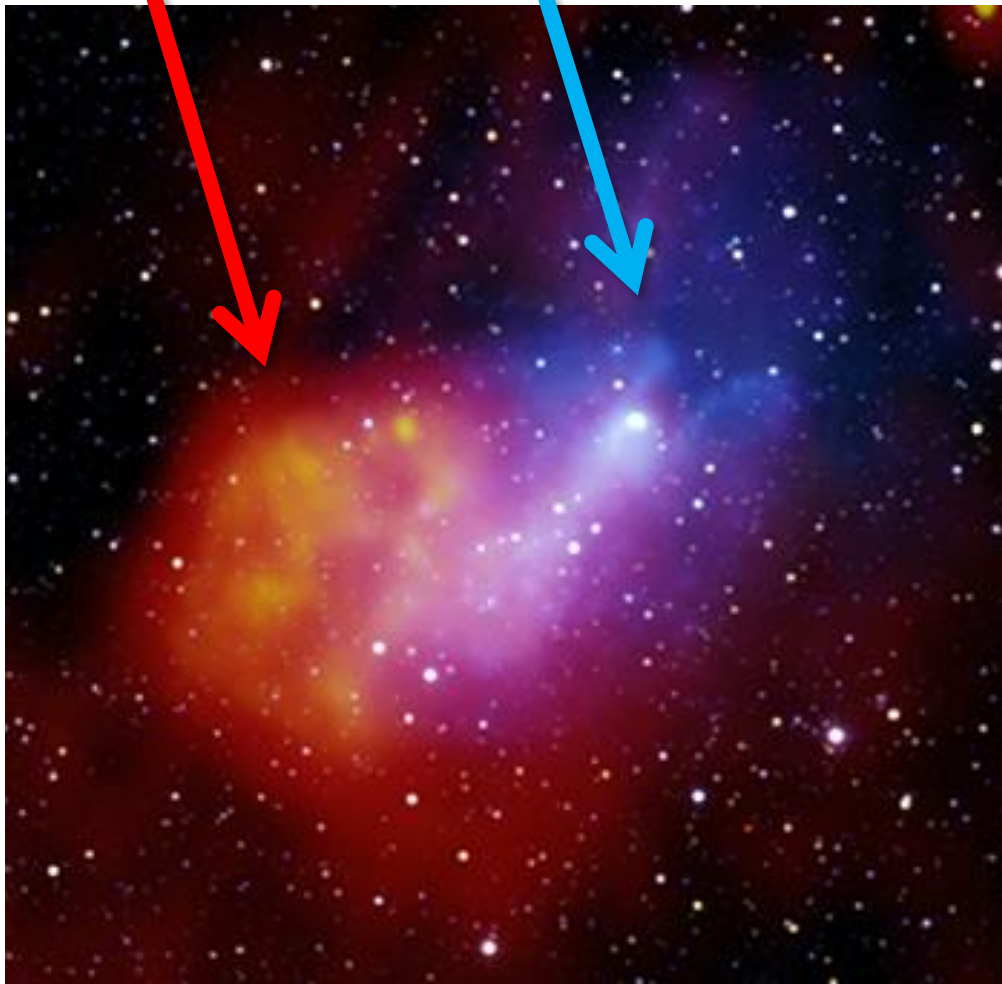
# The Snail G327.1-1.1

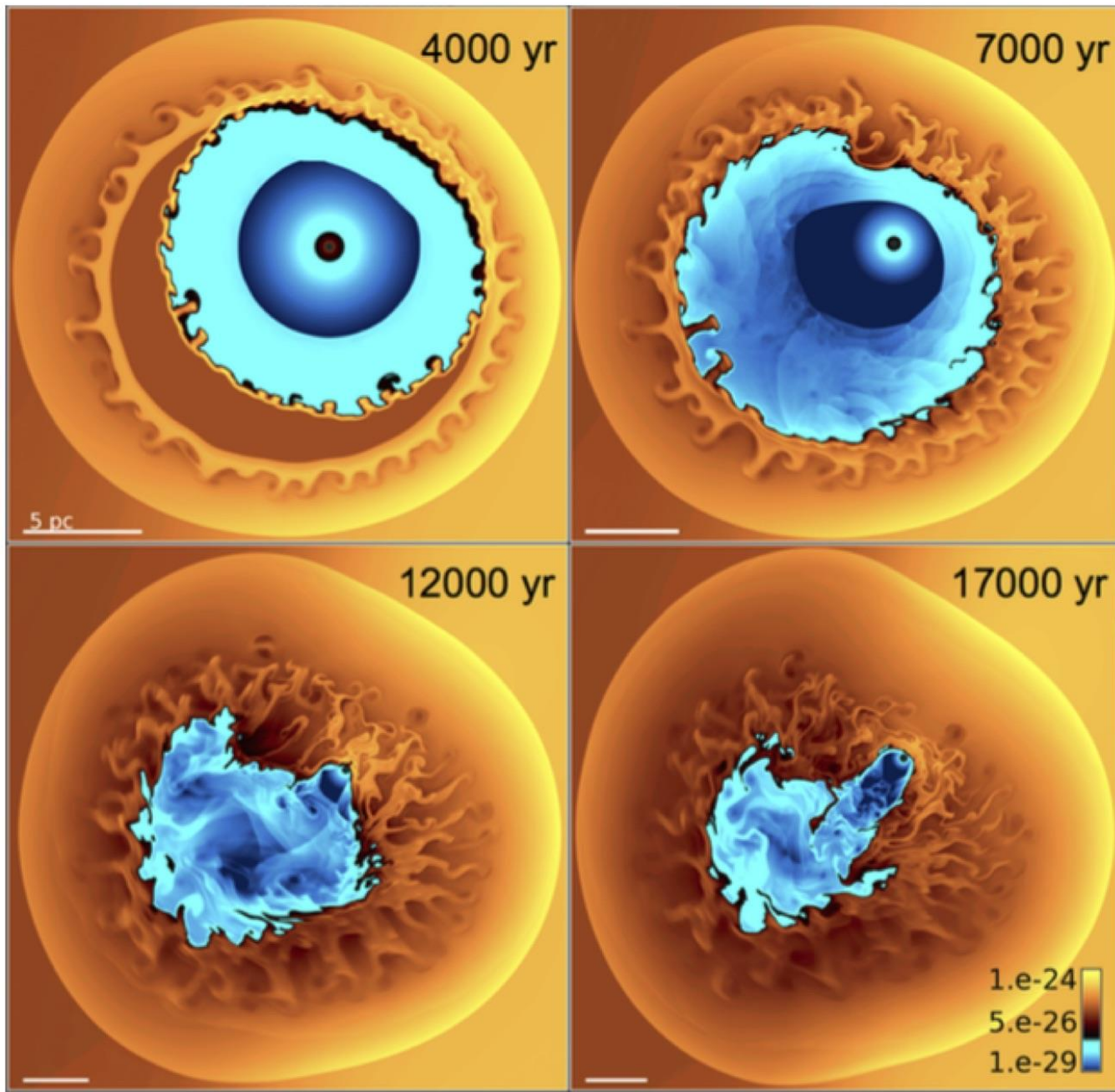


# The Snail G327.1-1.1

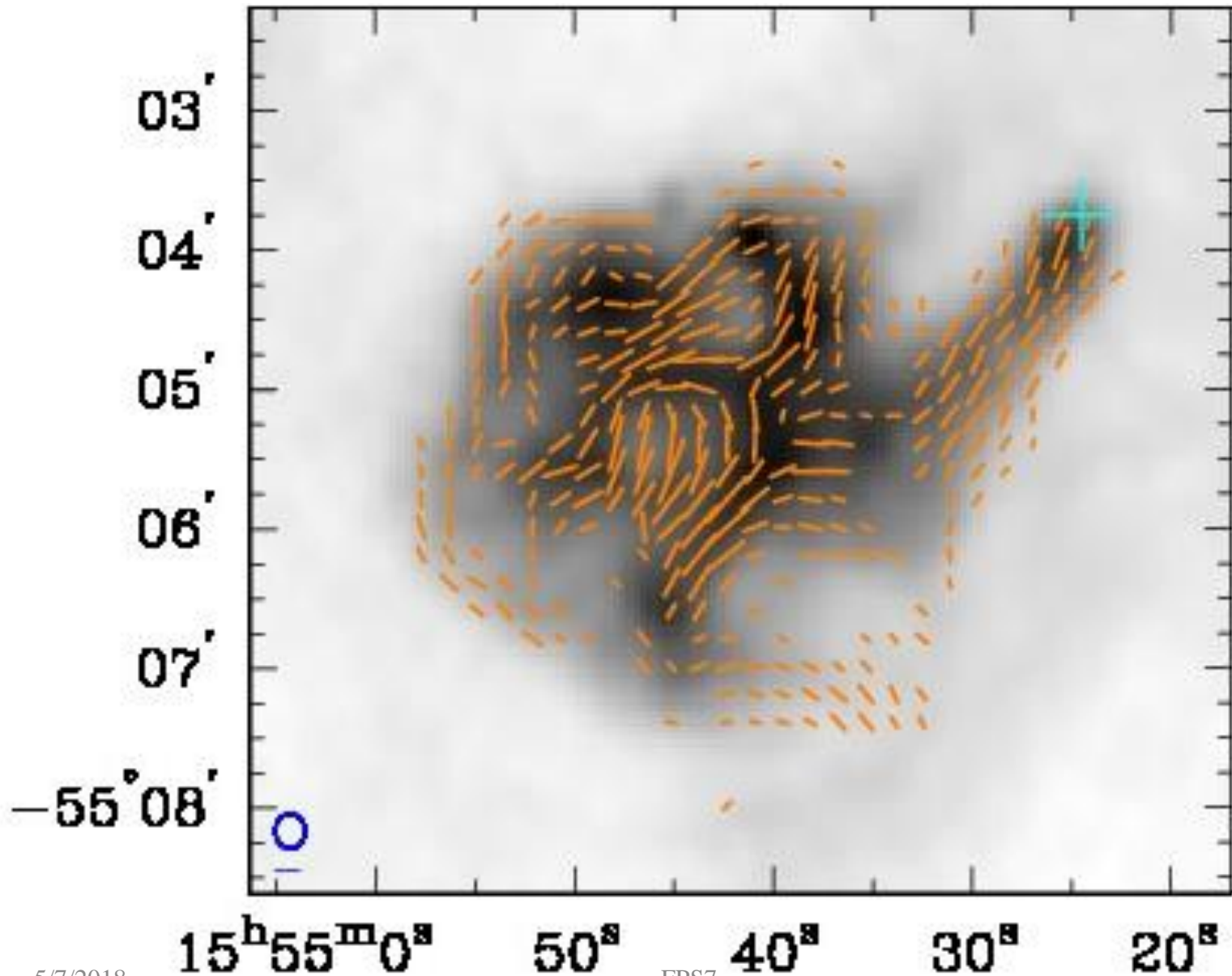
**Radio**

**X-ray**





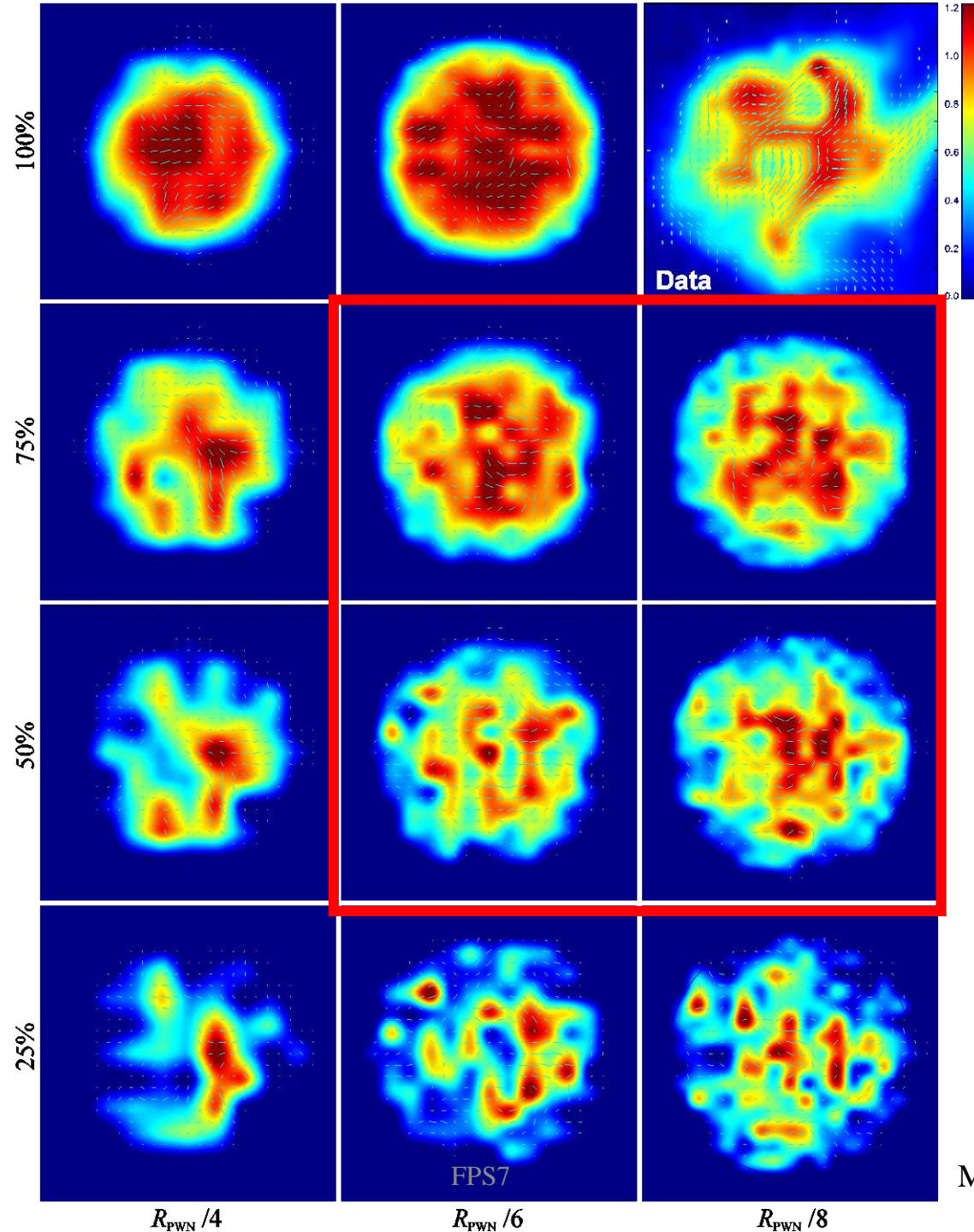
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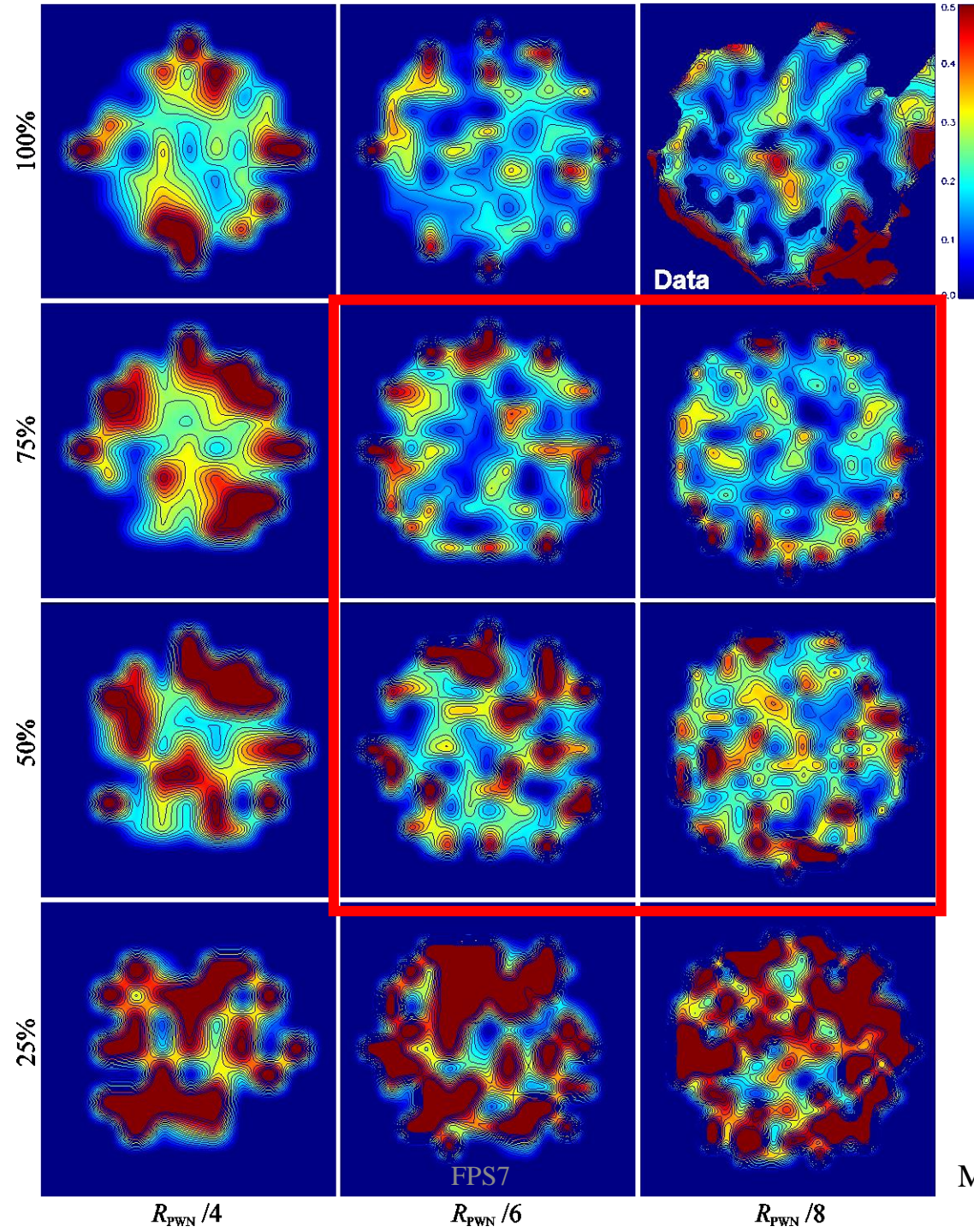
FPS7

Ma, Ng, et al. (2016)



5/7/2018

Ma, Ng, et al. (2016)



5/7/2018

Ma, Ng, et al. (2016)



# Hand of God



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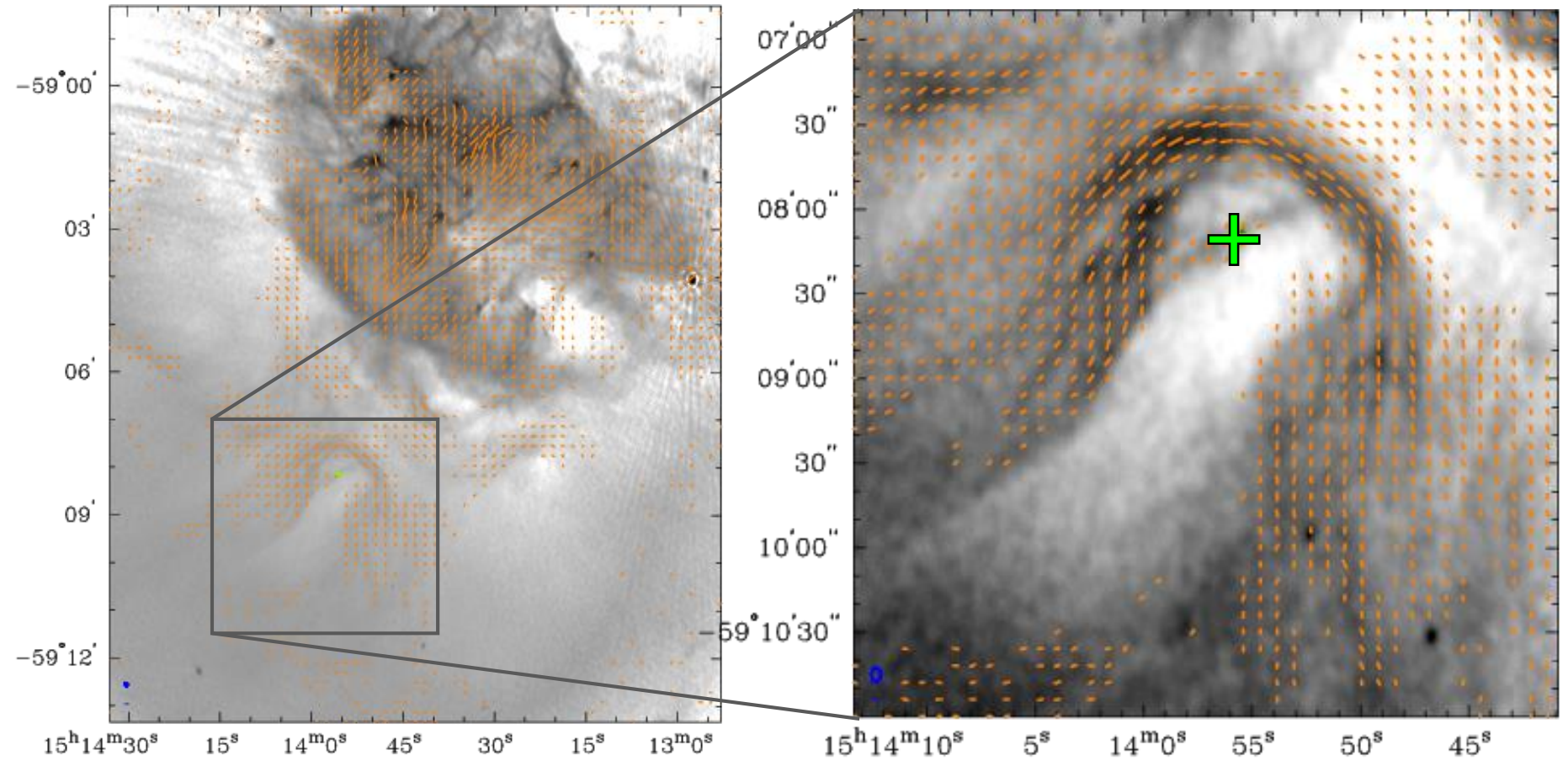
# Hand of God



5/7/2018

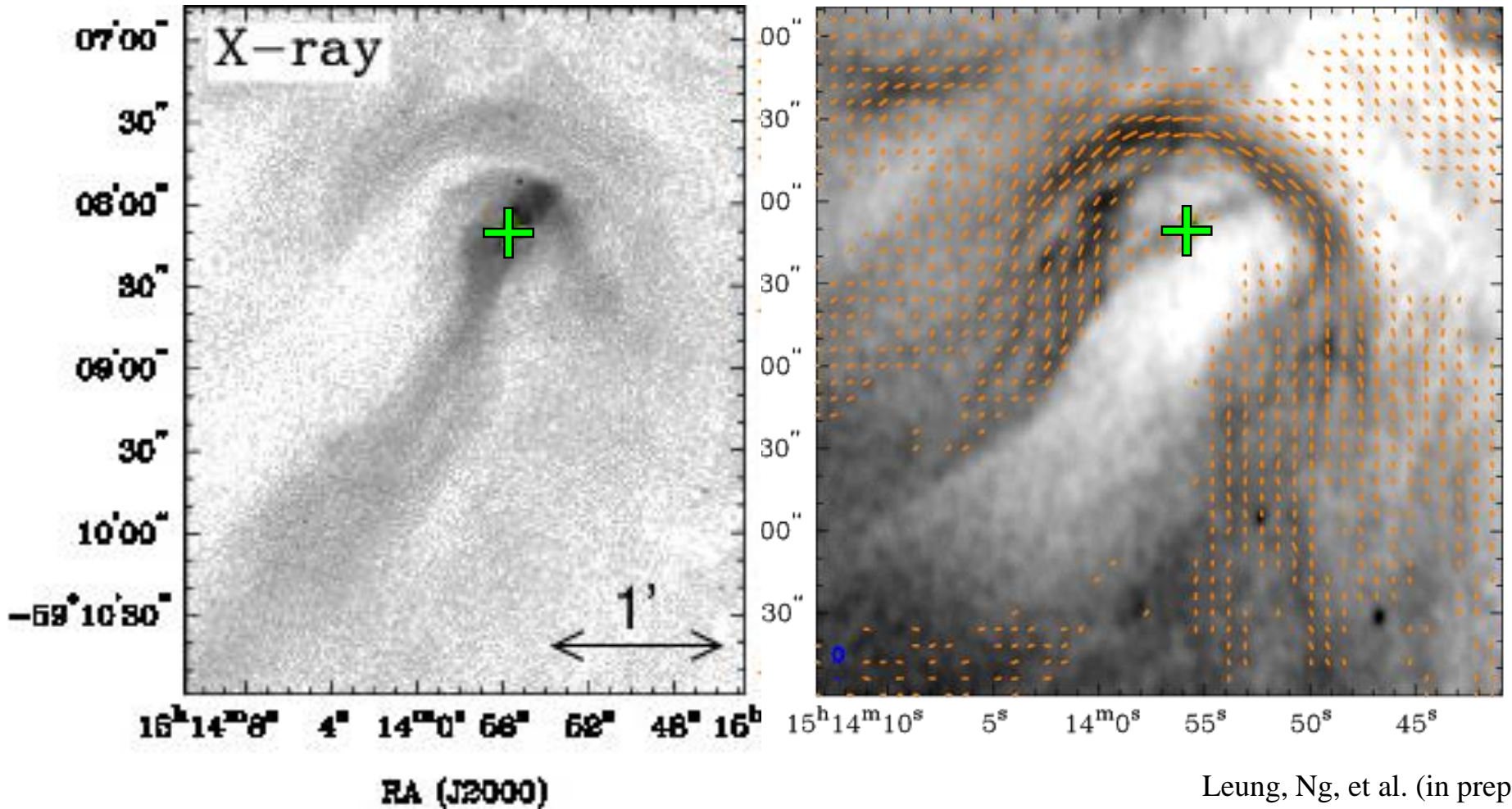
Leung, Ng, et al. (in prep.)

# MSH 15-52 / PSR B1509-58



Leung, Ng, et al. (in prep.)

# MSH 15-52 / PSR B1509-58



Leung, Ng, et al. (in prep.)

# Future Works

- FAST survey (with W.W. Zhu)
- X-ray polarimeters, e.g. IXPE, eXTP

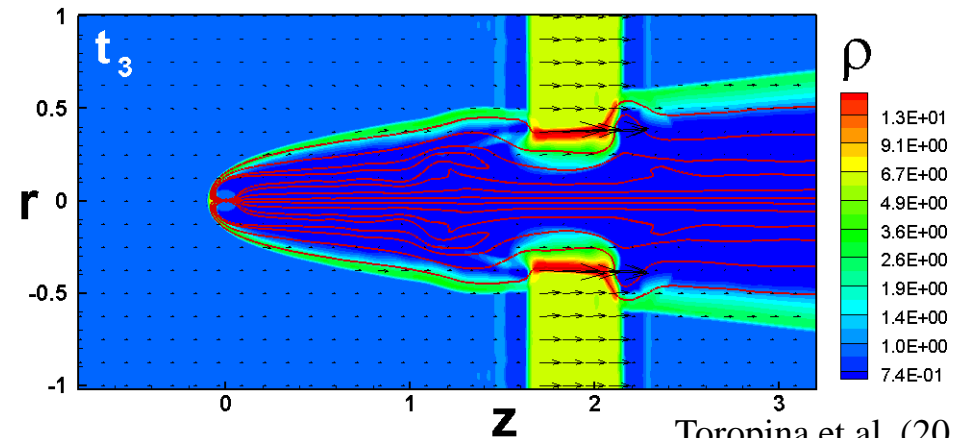
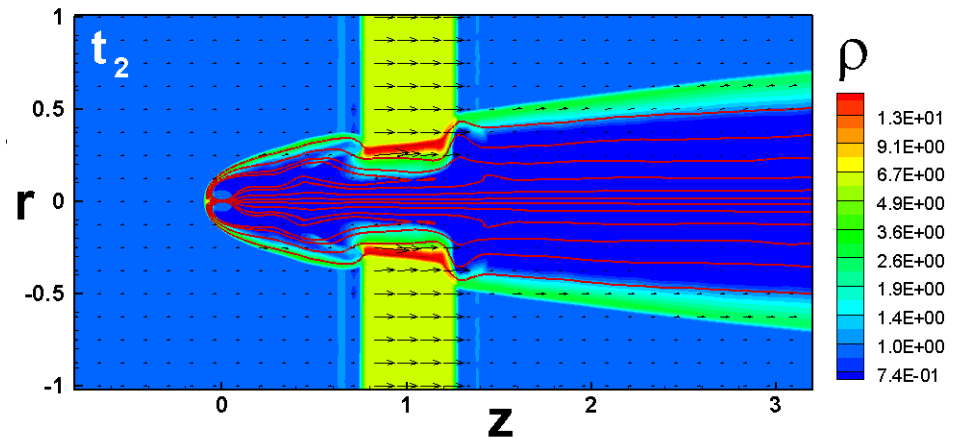
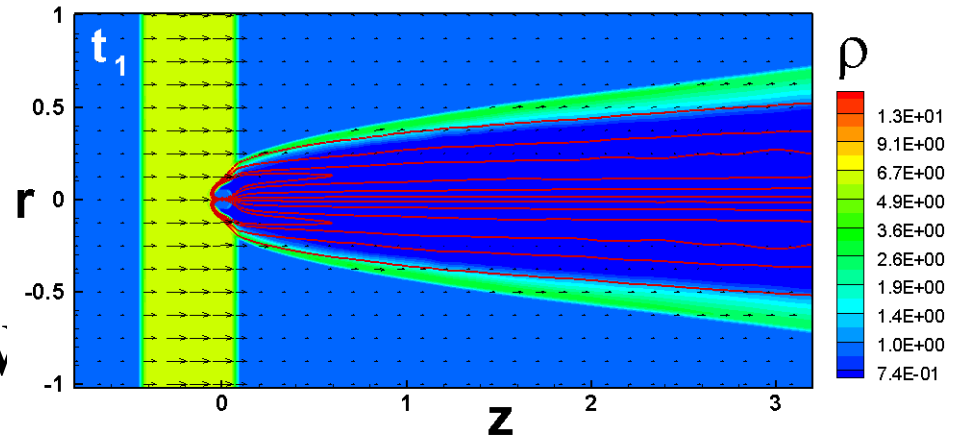


# Future Works

- FAST survey (with W.W. Zhu)
- X-ray polarimeters, e.g. IXPE, eXTP
- Testing theories

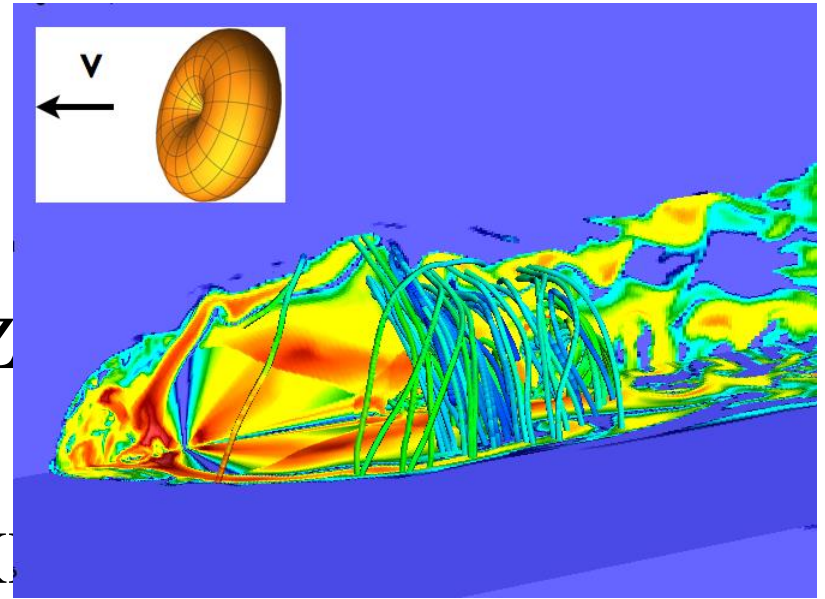
# Future Works

- FAST survey (with W.V)
- X-ray polarimeters, e.g.
- Testing theories

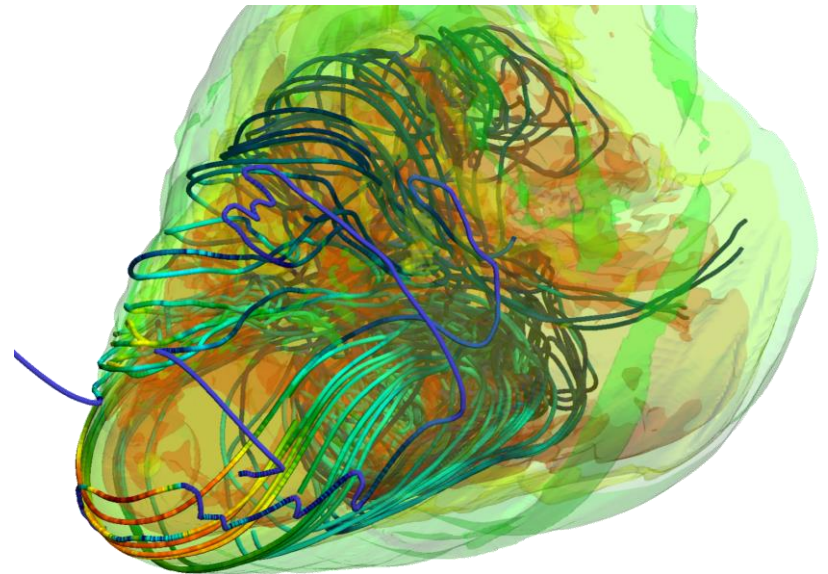


# Future Projects

- FAST survey (with W.W. Z
- X-ray polarimeters, e.g. IX
- Testing theories



Barkov et al. (2018)



Barkov & Lyutikov (2018)



# Summary

- Radio observations of PWNe provide a powerful probe of the  $B$ -field structure
- Large diversity in field geometry:
  - Parallel / perpendicular  $B$ -field in bow-shocks
  - Highly ordered field in crushed PWNe
  - Filamentary structure in young objects
- Theoretical modeling and simulations:
  - Connection with other physical parameters, e.g. Mach number, pulsar spin orientation.
  - Particle acceleration and transport