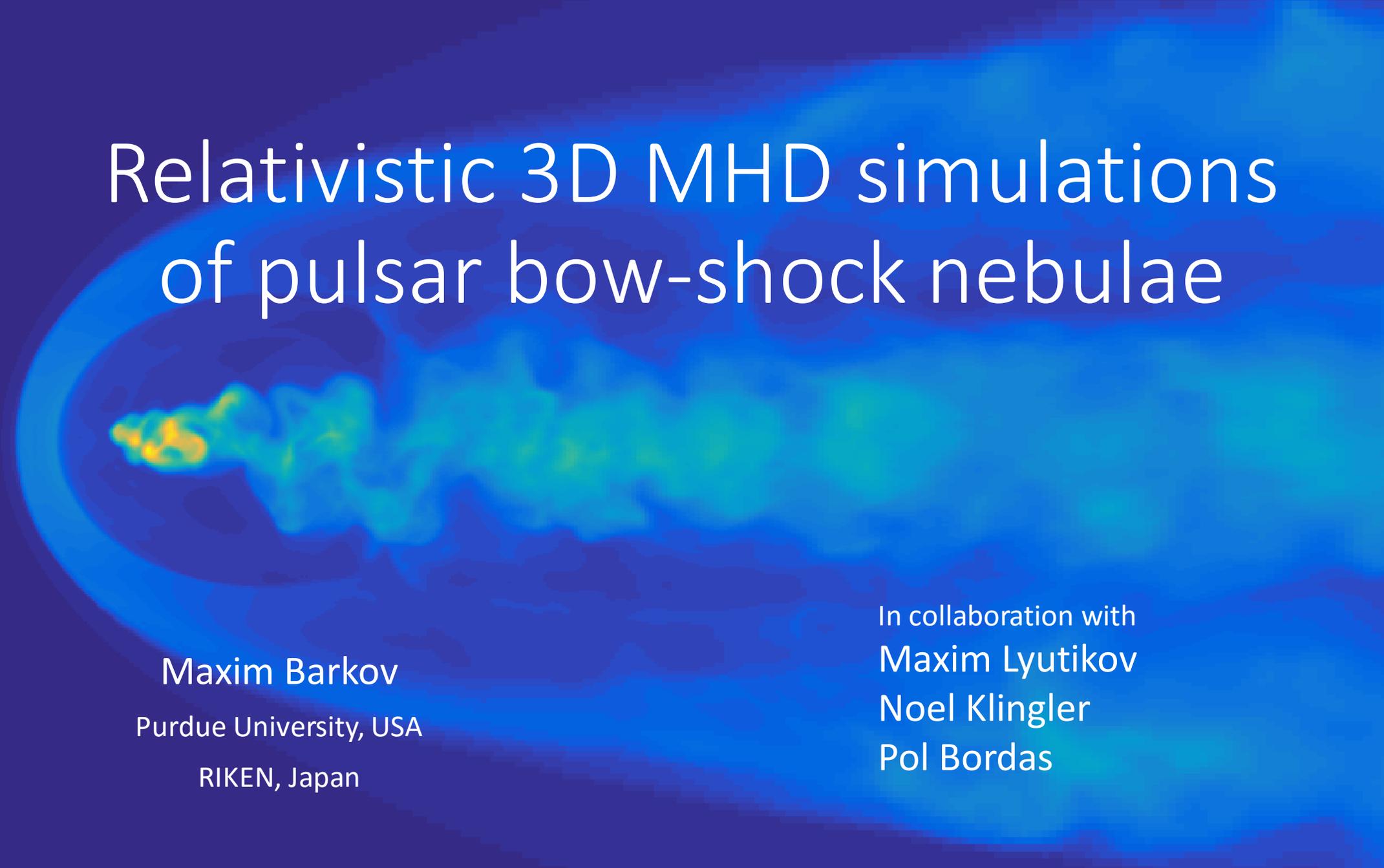


# Relativistic 3D MHD simulations of pulsar bow-shock nebulae



Maxim Barkov

Purdue University, USA

RIKEN, Japan

In collaboration with

Maxim Lyutikov

Noel Klingler

Pol Bordas

**Theoretical slides**

**Numerical slides**

**Observational slides**

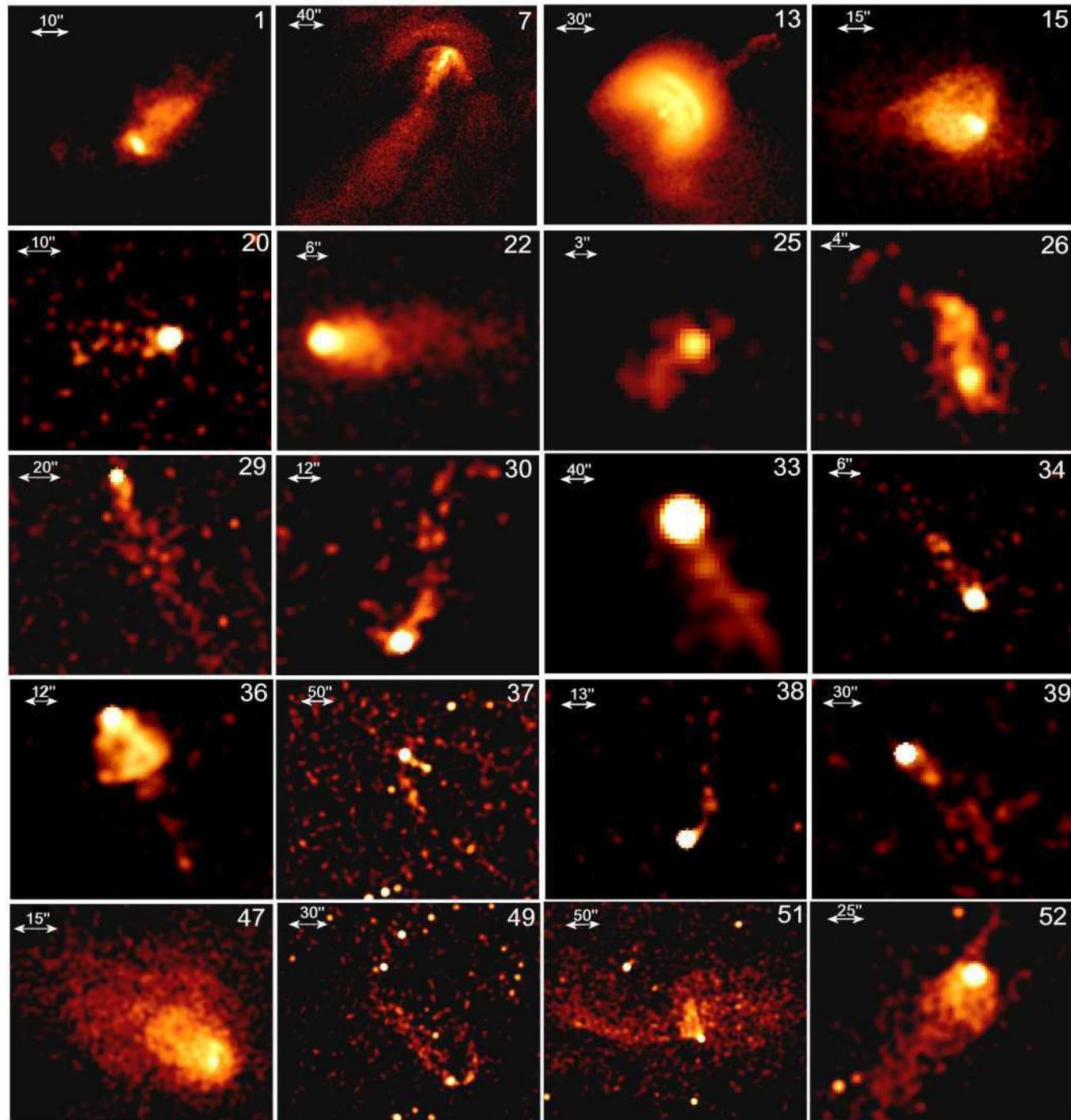
# What connects alien and snail eyes?



?



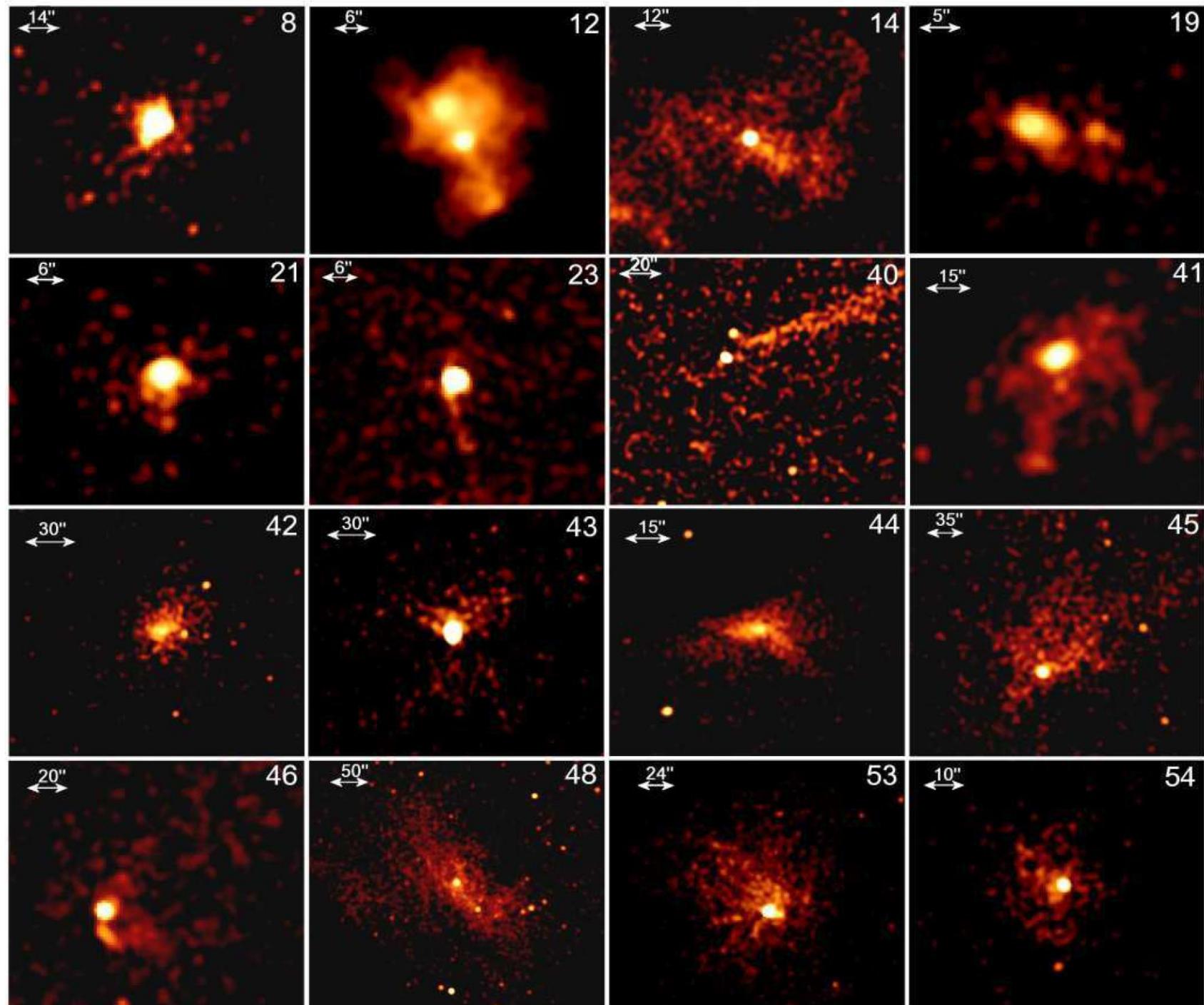
# Chandra PWN ZOO



Kargaltsev & Pavlov 2008

5/8/2018

# Chandra PWN ZOO again



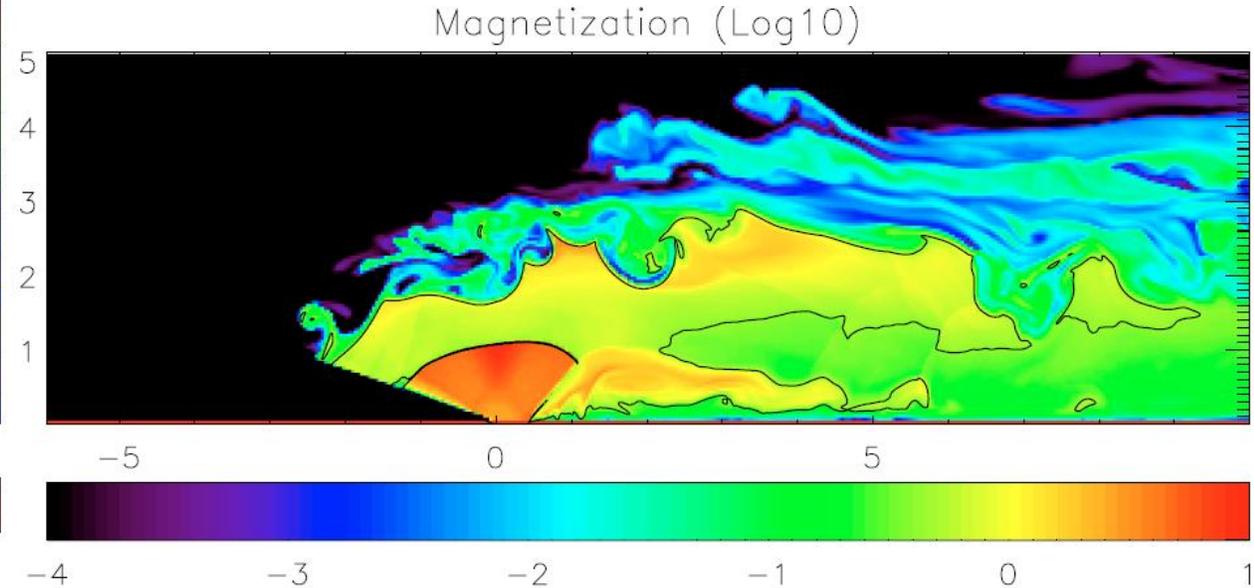
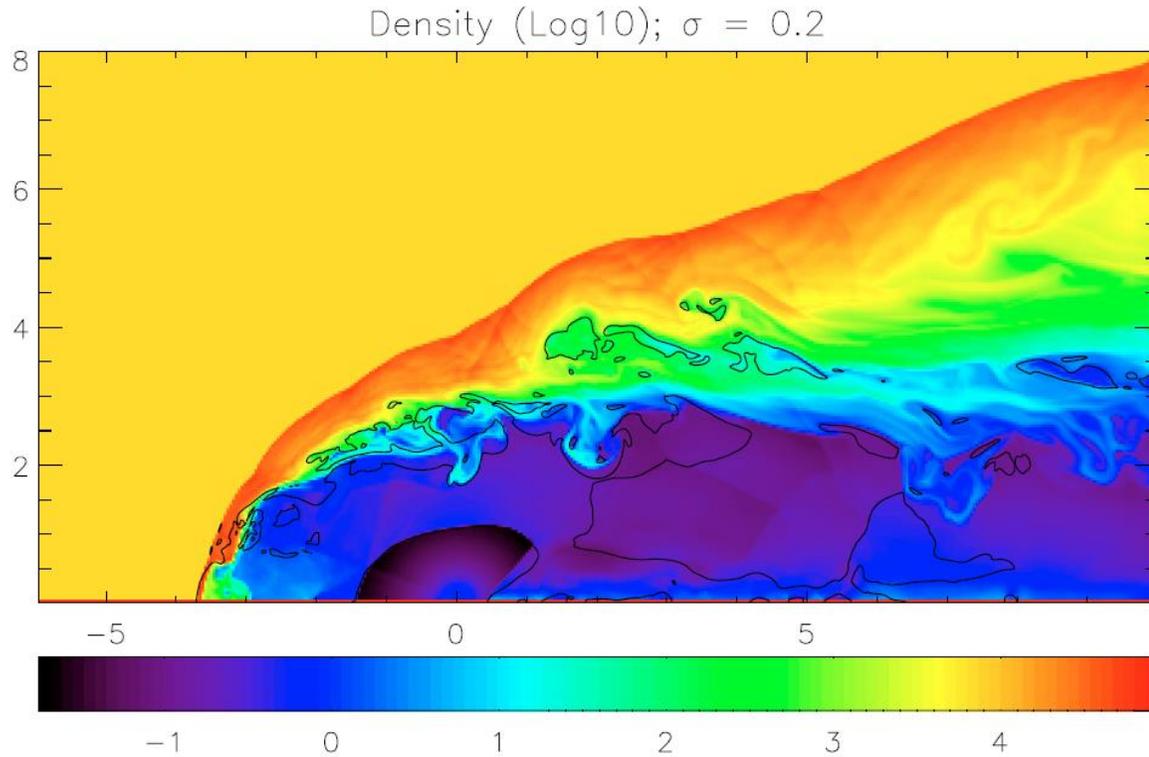
Kargaltsev & Pavlov 2008

5/8/2018

# Pulsar and ISM interaction

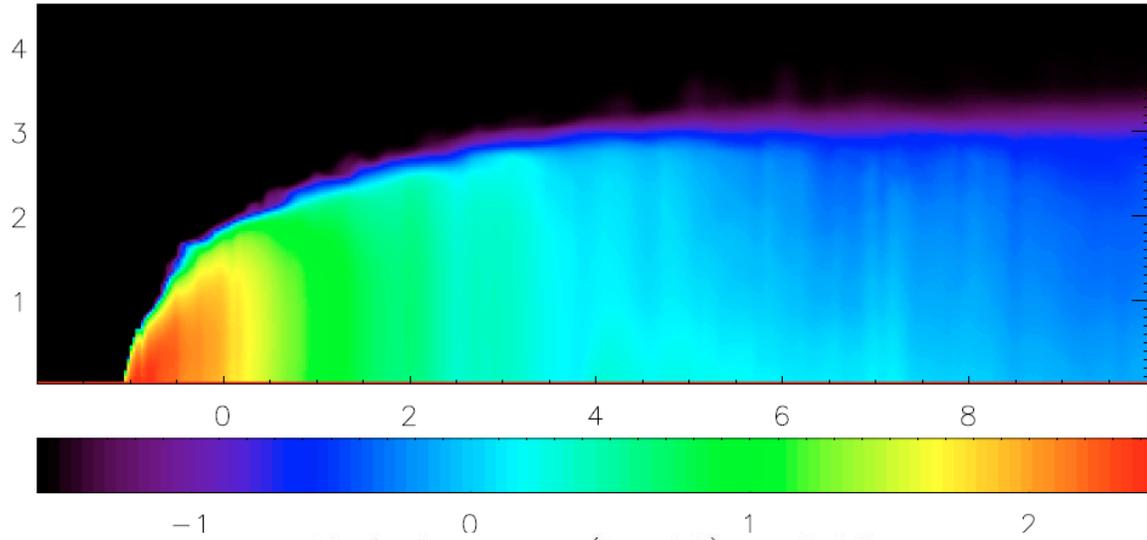
2D RMHD

Bucciantini et al. 2005

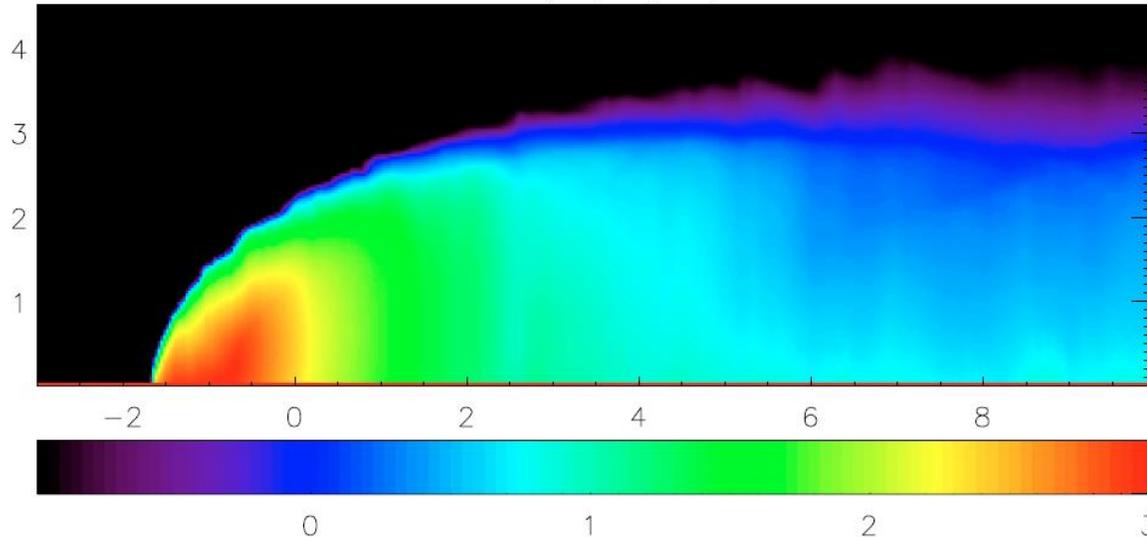


# Pulsar and ISM interaction

Emission map (Log10)  $\sigma=0.002$



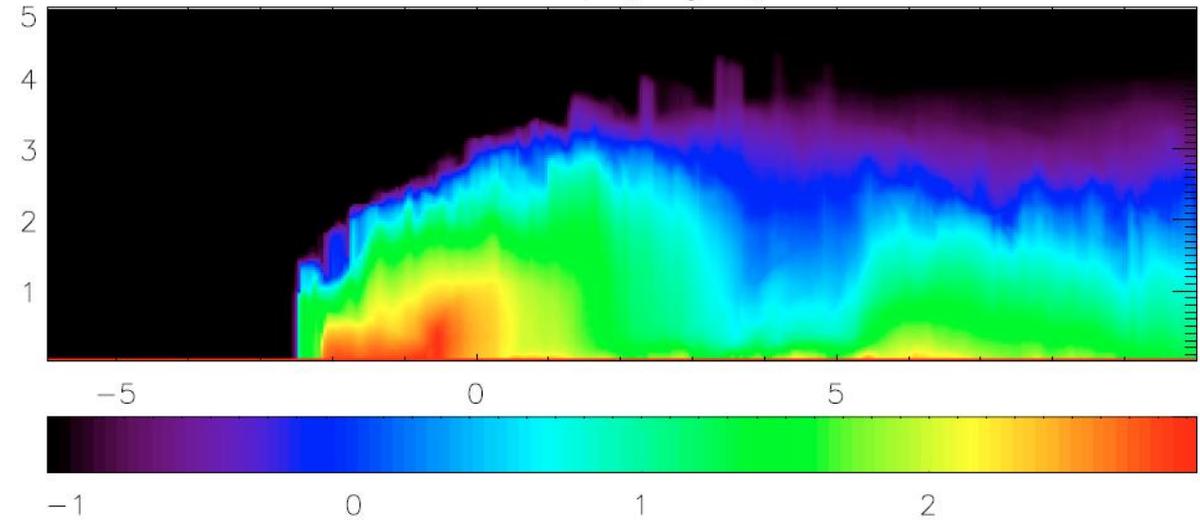
Emission map (Log10)  $\sigma=0.02$



2D RMHD

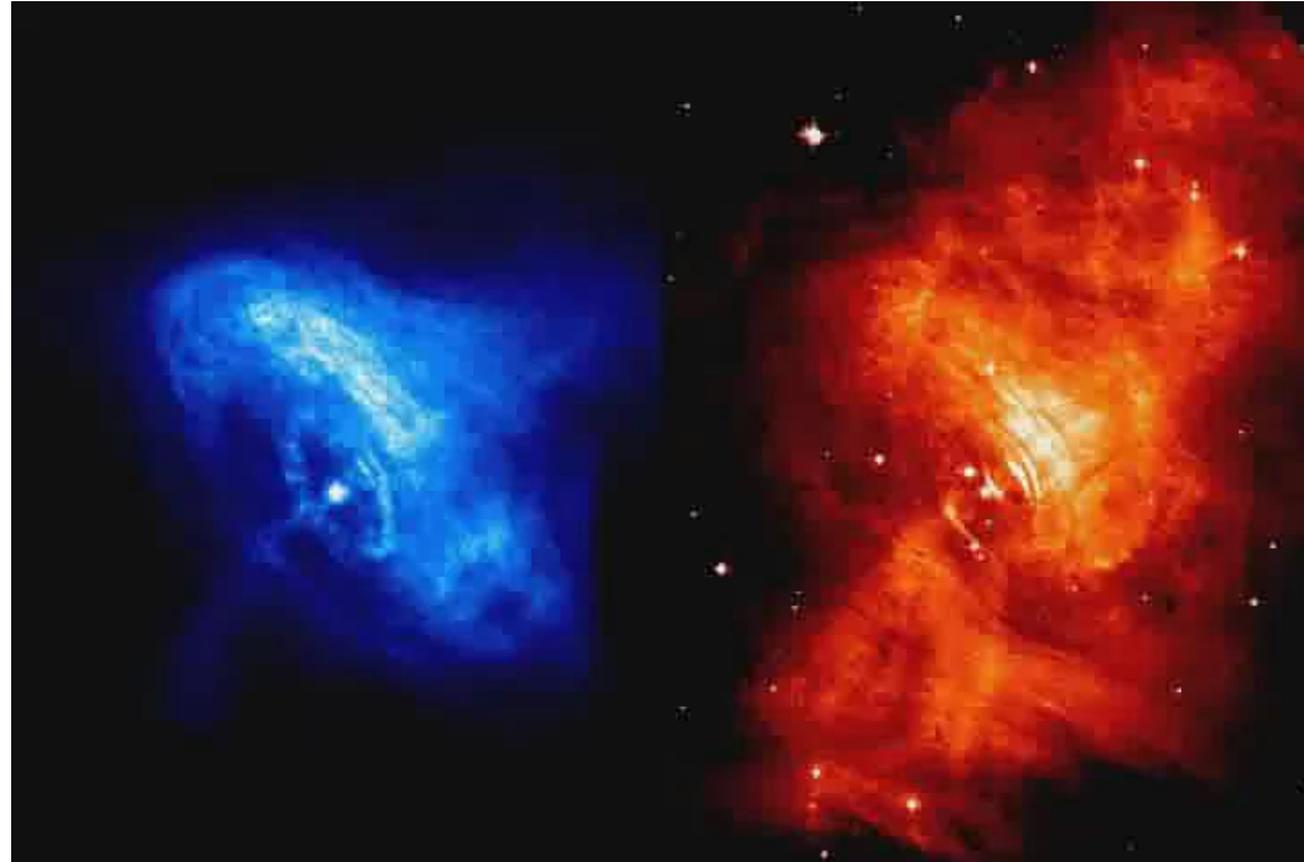
Bucciantini et al. 2005

Emission map (Log10)  $\sigma=0.2$



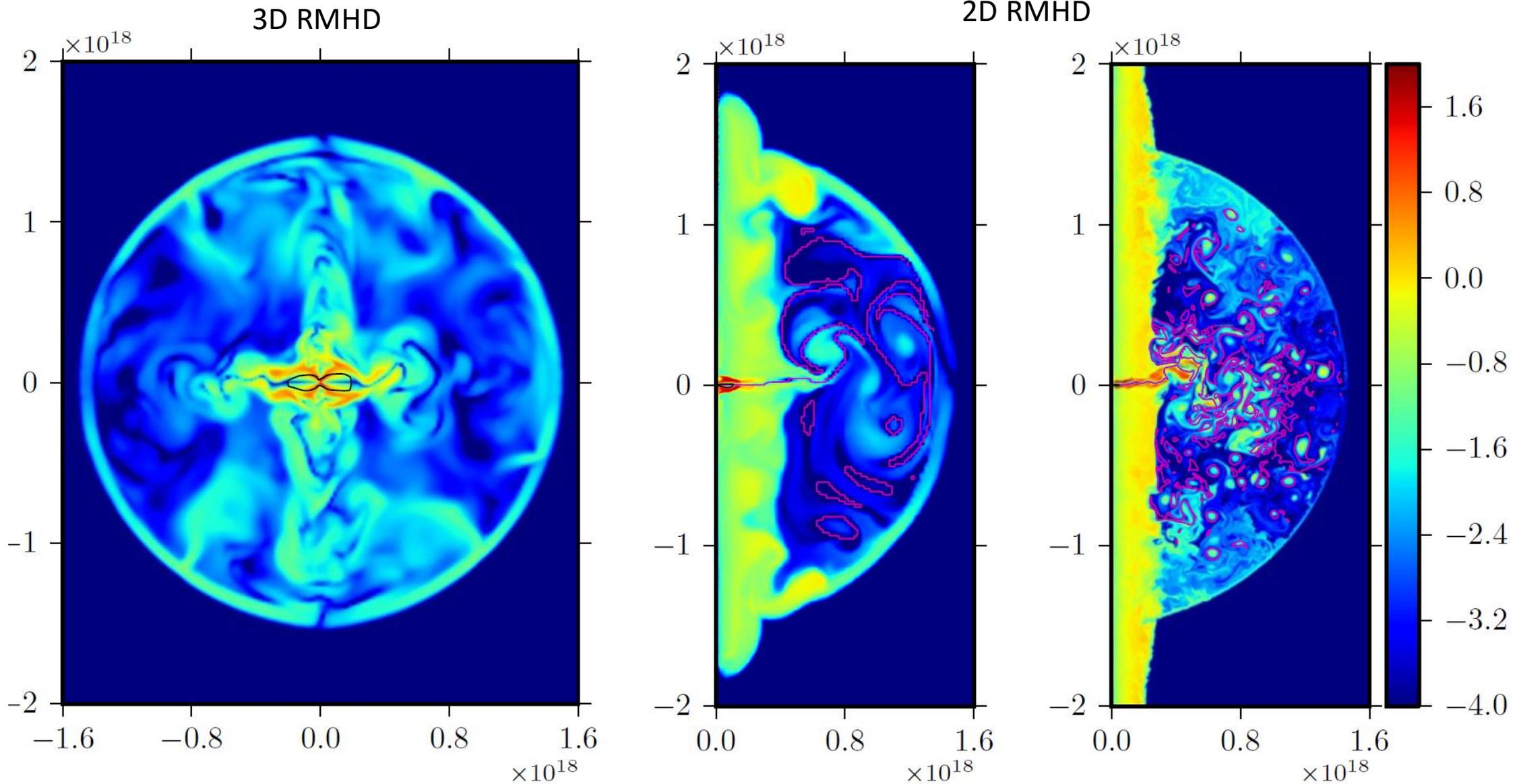
# The Crab PWN

NASA



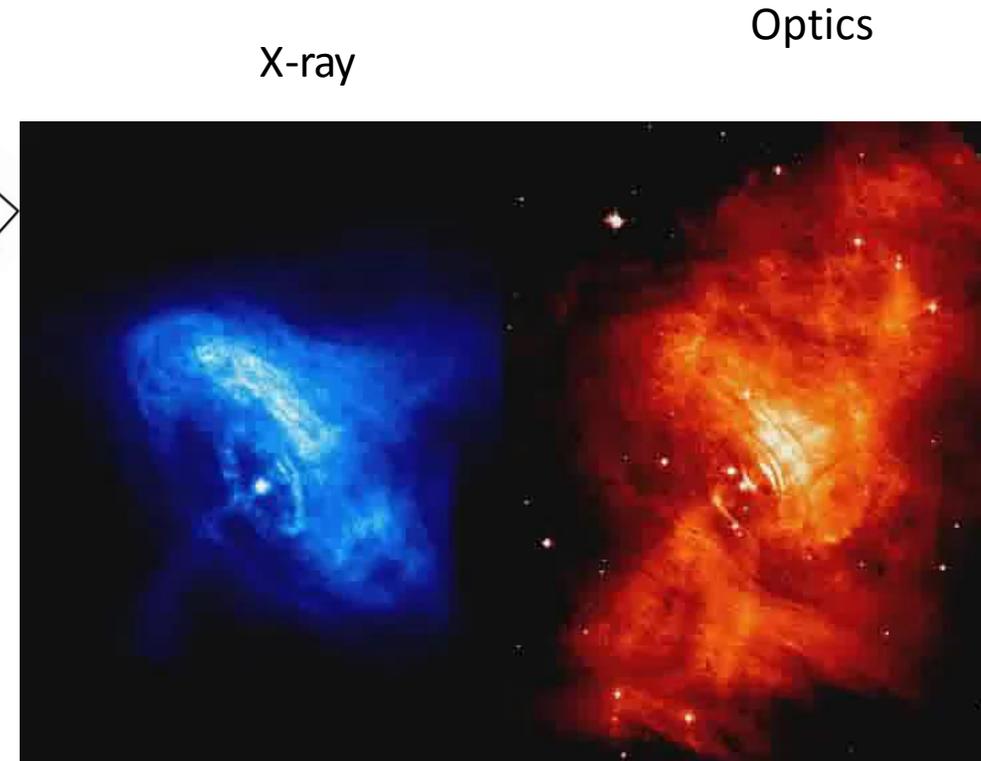
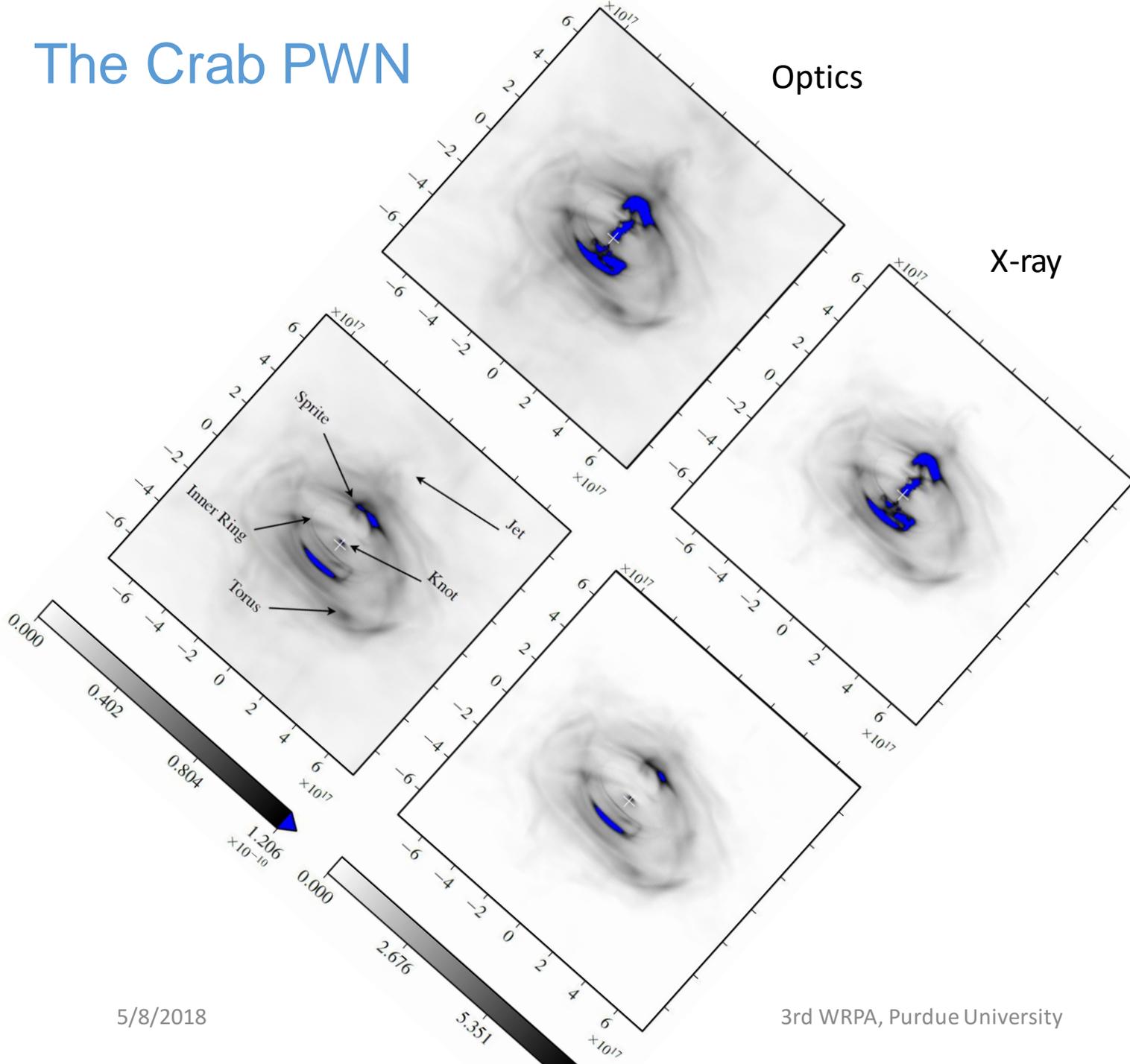
# The Crab PWN

Porth et al. 2013



# The Crab PWN

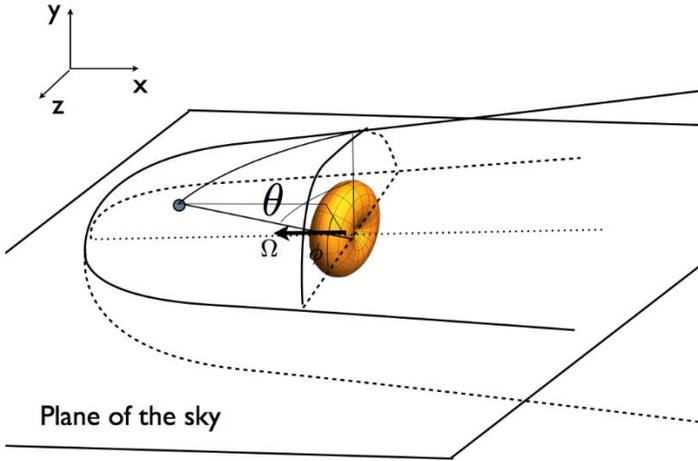
Porth et al. 2013



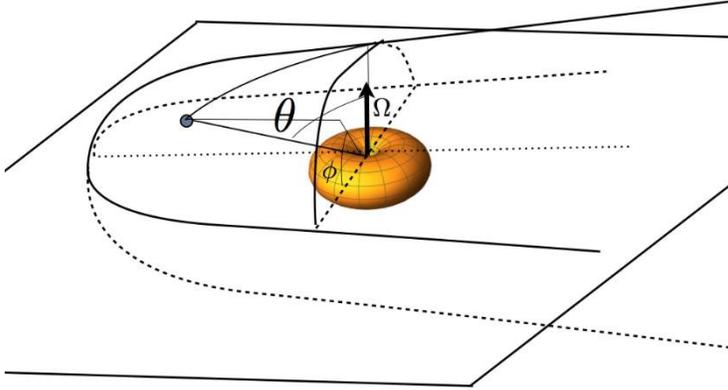
# Pulsar and ISM interaction

BMV and Lyutikov (2018)

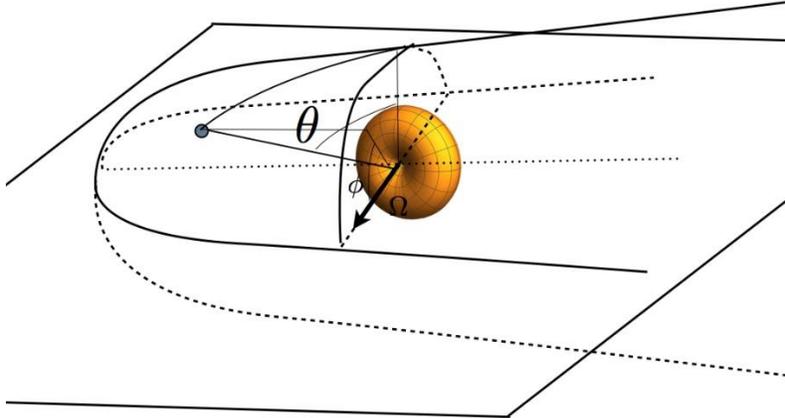
Rifle bullet



Frisbee



Cartwheel

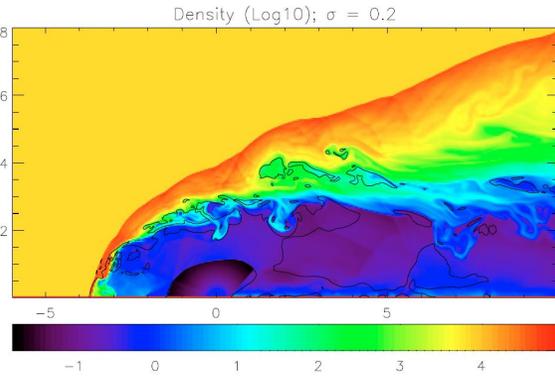
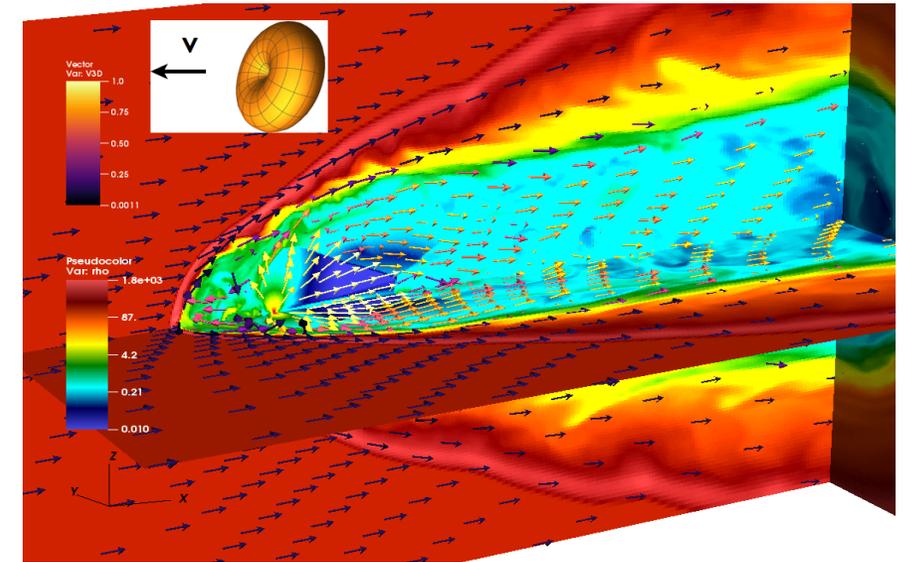
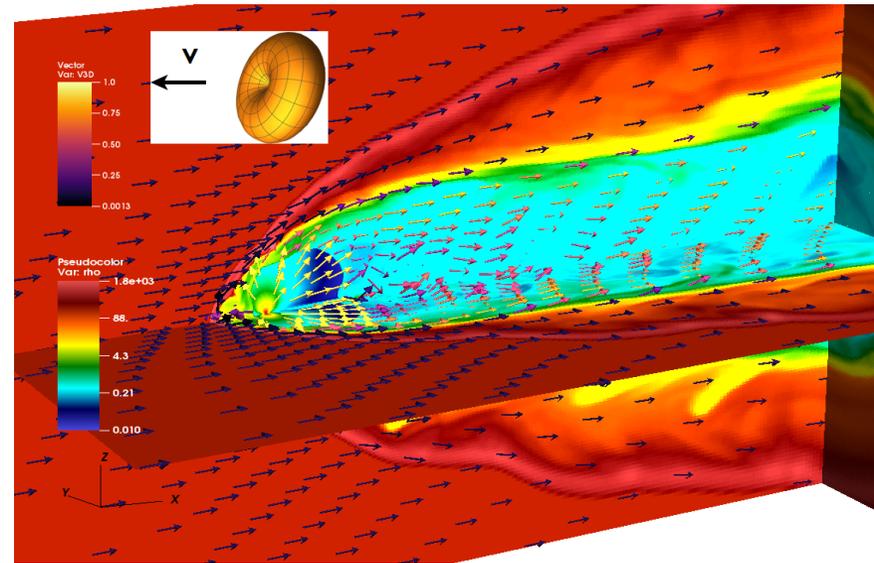


# Pulsar and ISM interaction

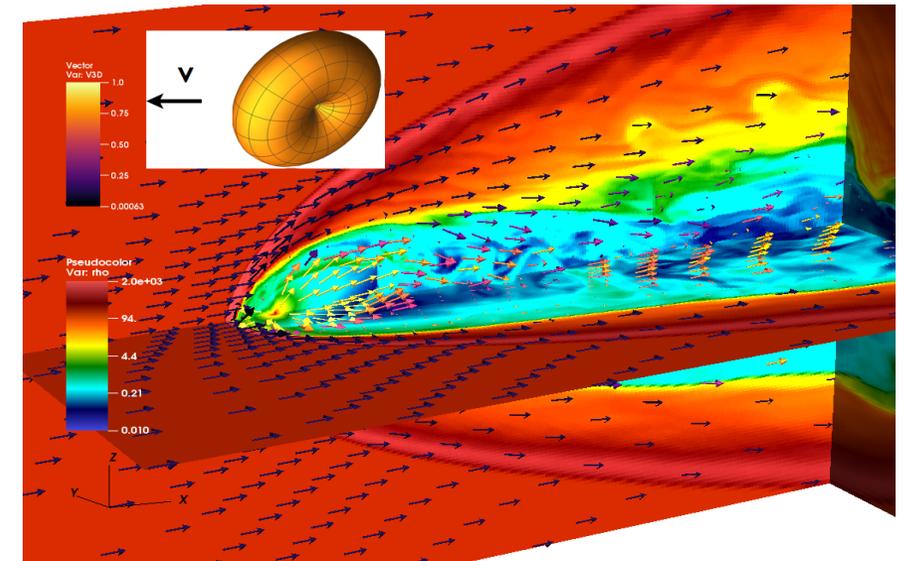
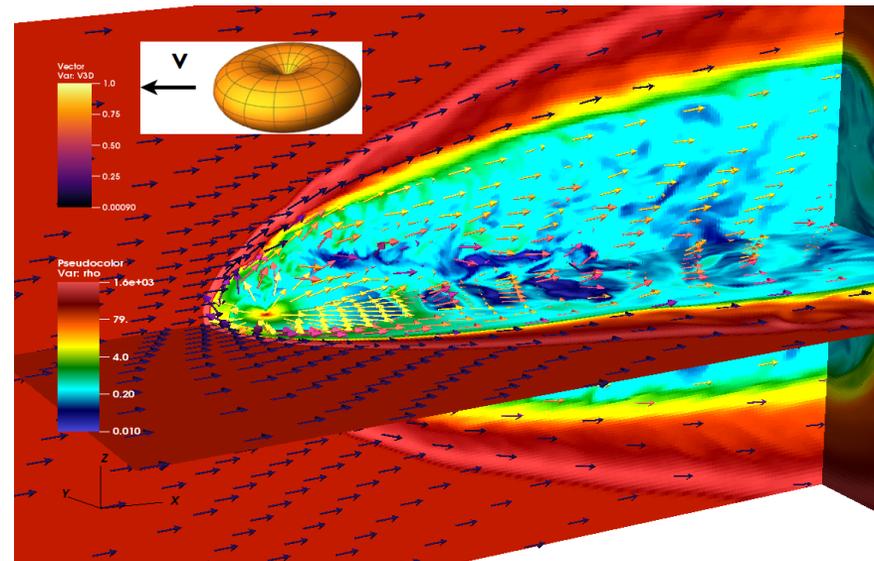
3D RMHD

Density & velocity

Bullet geometry



Frisbee geometry



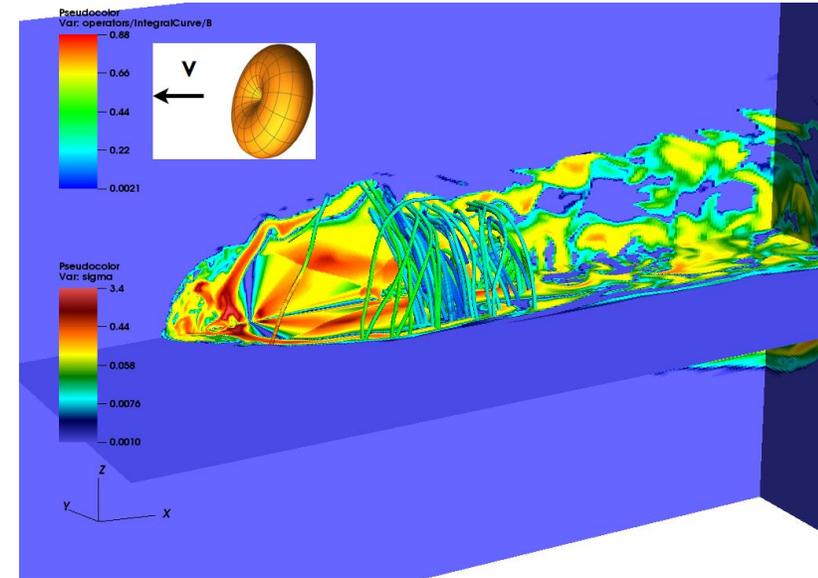
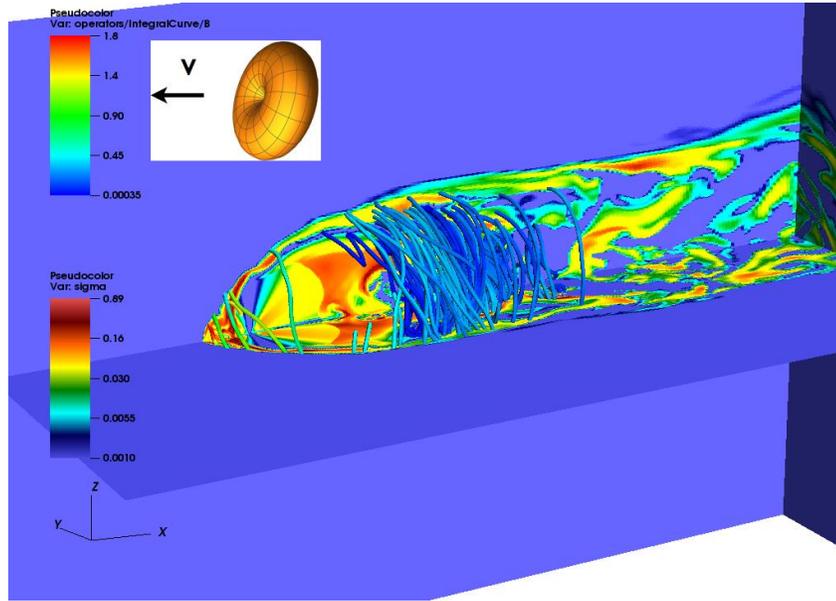
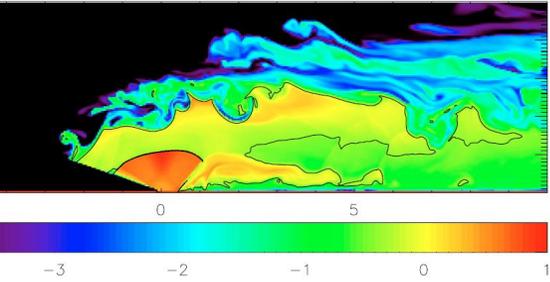
# Pulsar and ISM interaction

3D RMHD

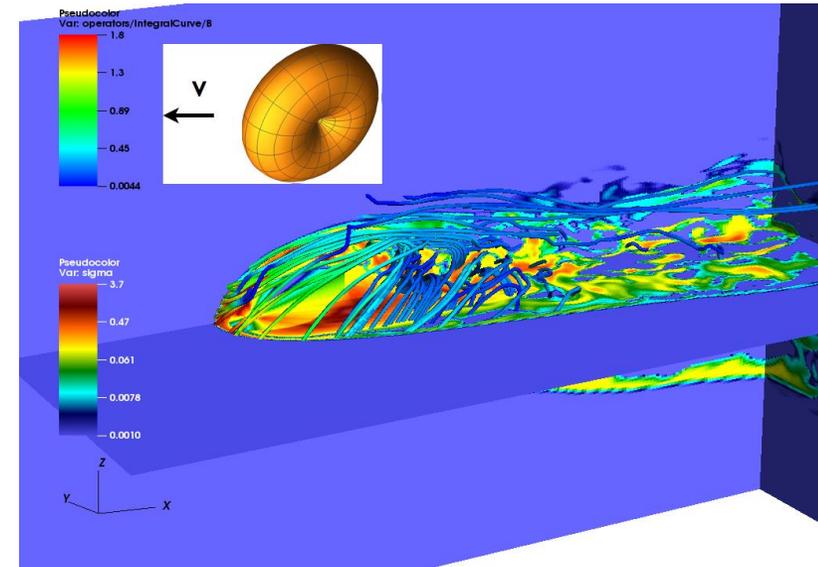
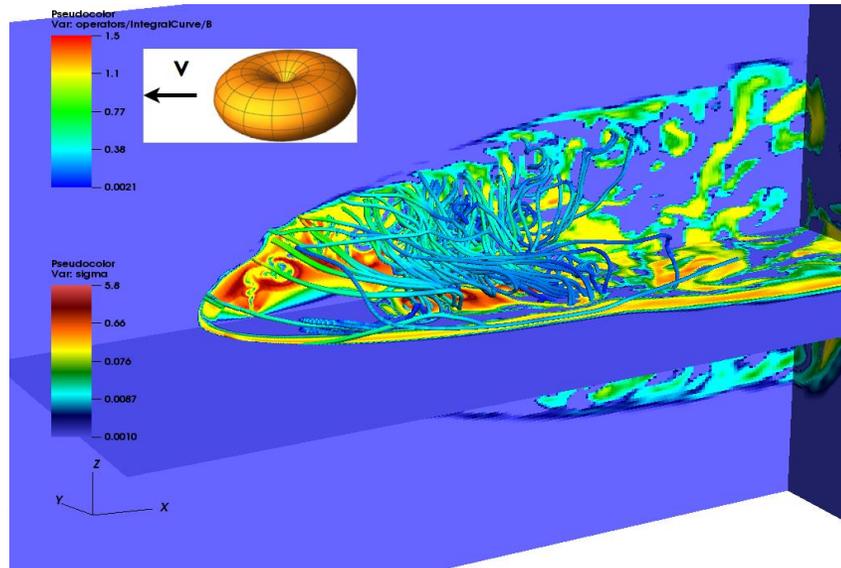
Magnetization & Magnetic field

Bullet geometry

Magnetization (Log10)

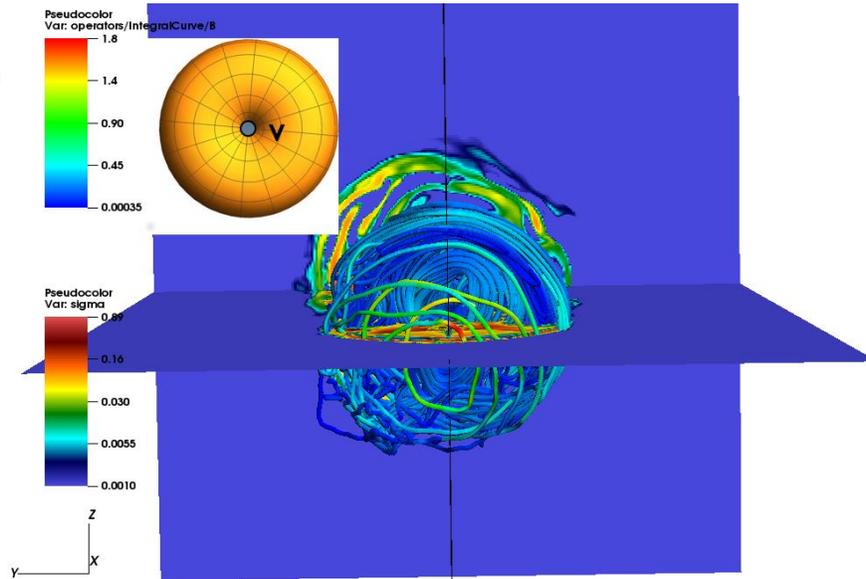


Frisbee geometry

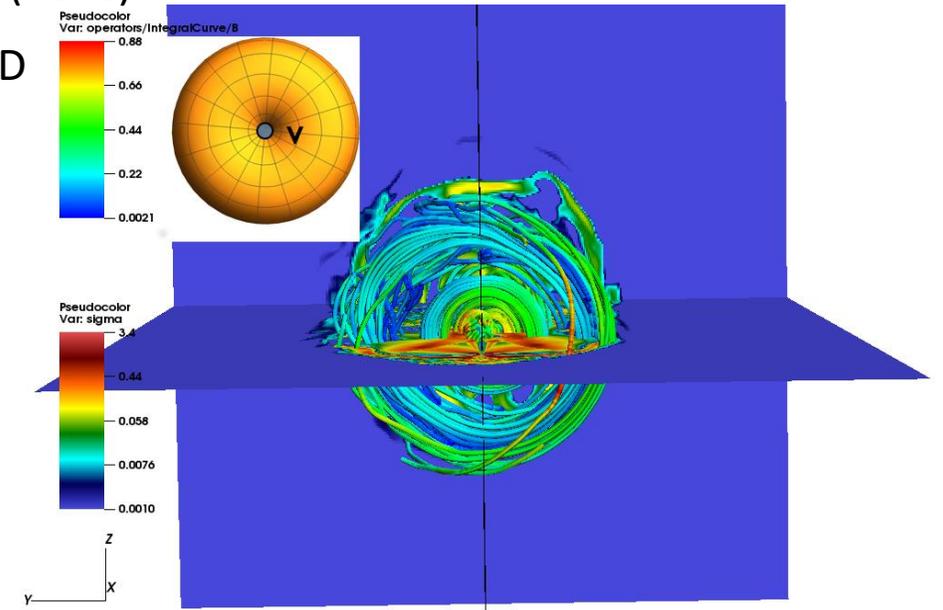


# Pulsar and ISM

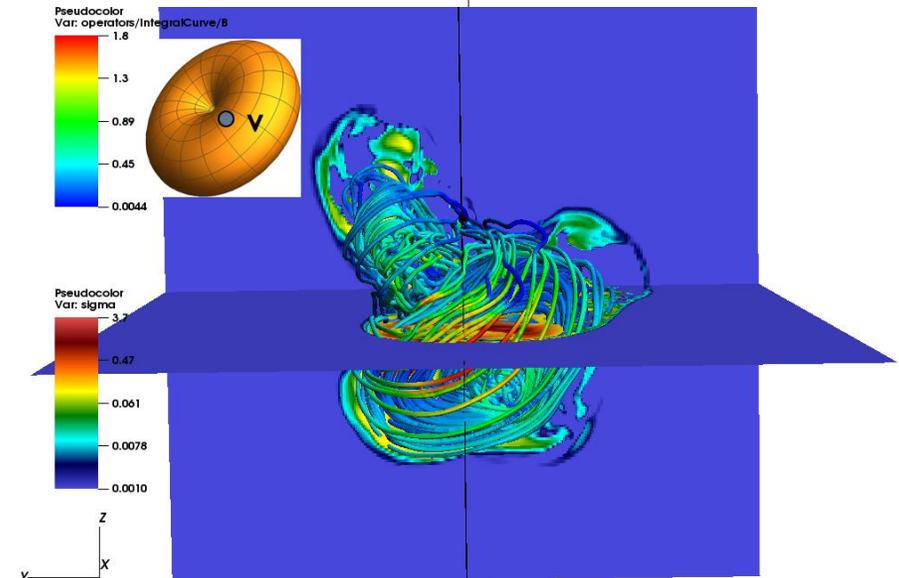
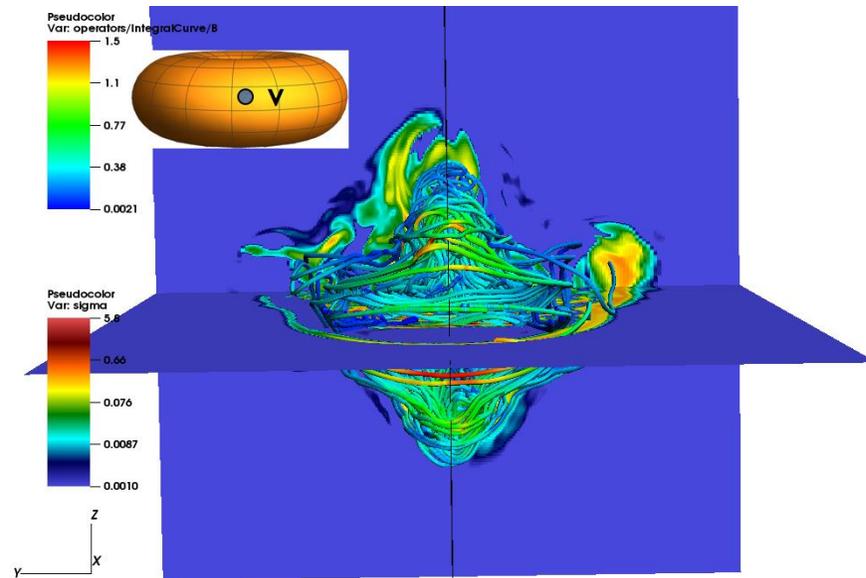
Bullet geometry



$\perp D$



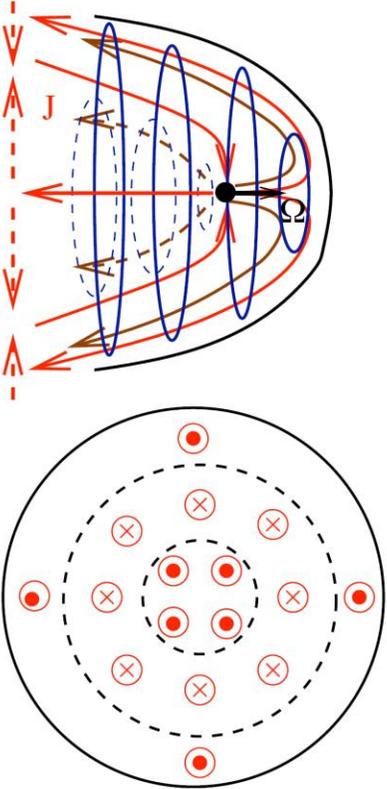
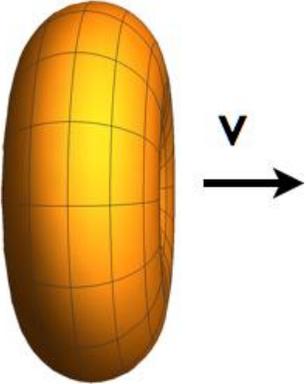
Frisbee geometry



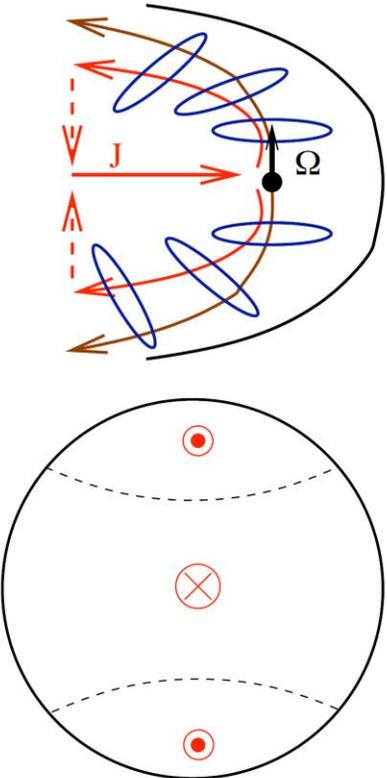
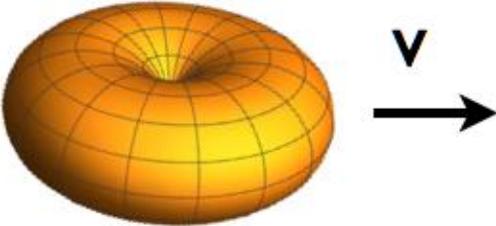
# Pulsar and ISM interaction

BMV and Lyutikov (2018)

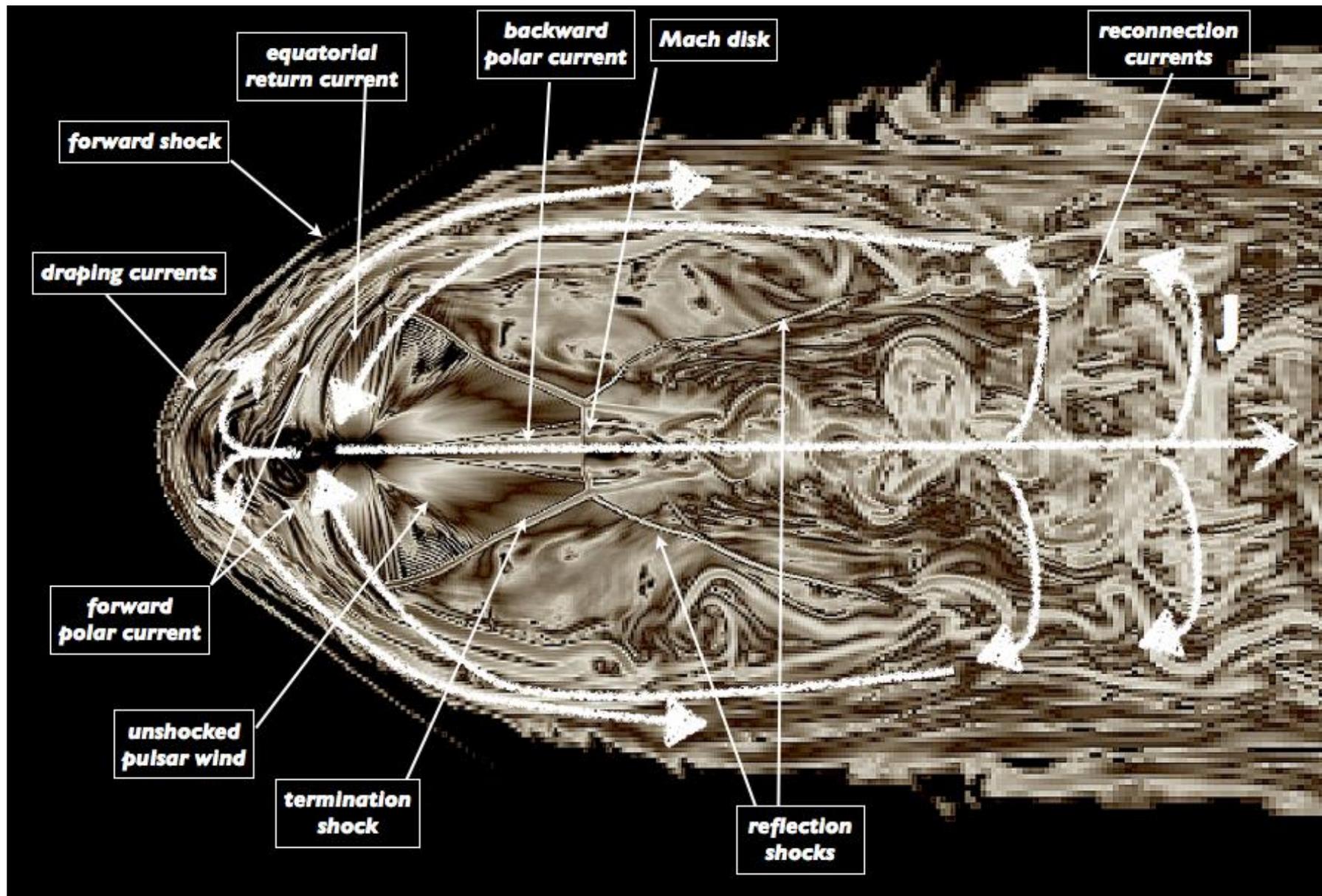
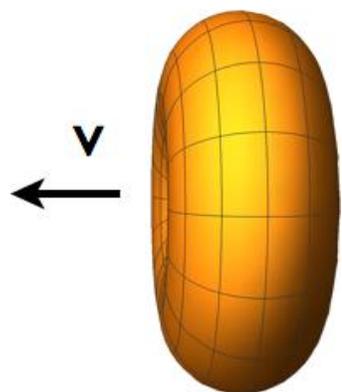
Bullet geometry



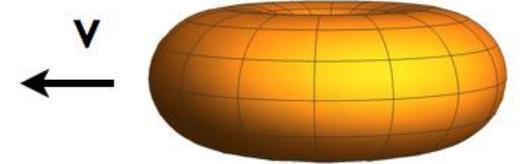
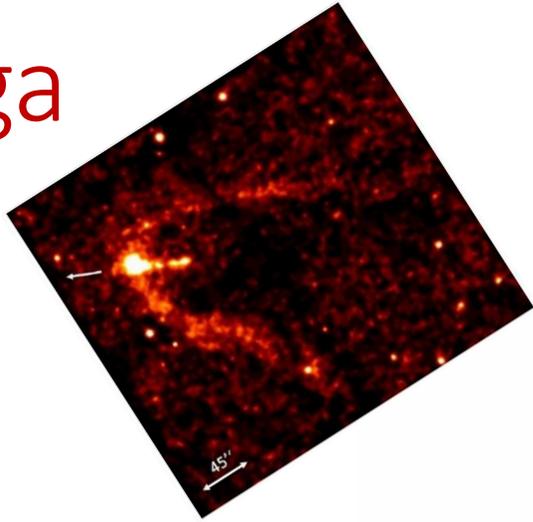
Frisbee geometry



# Current

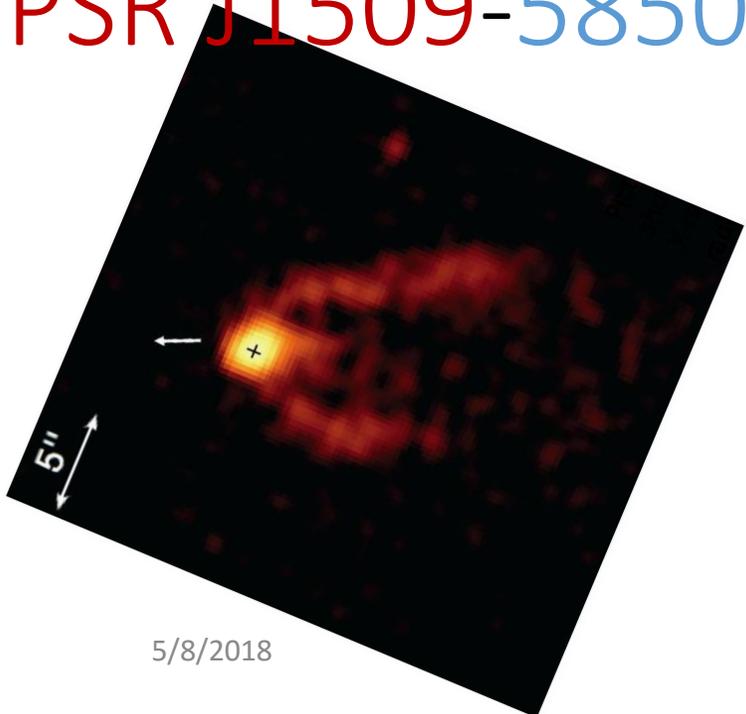


Geminga

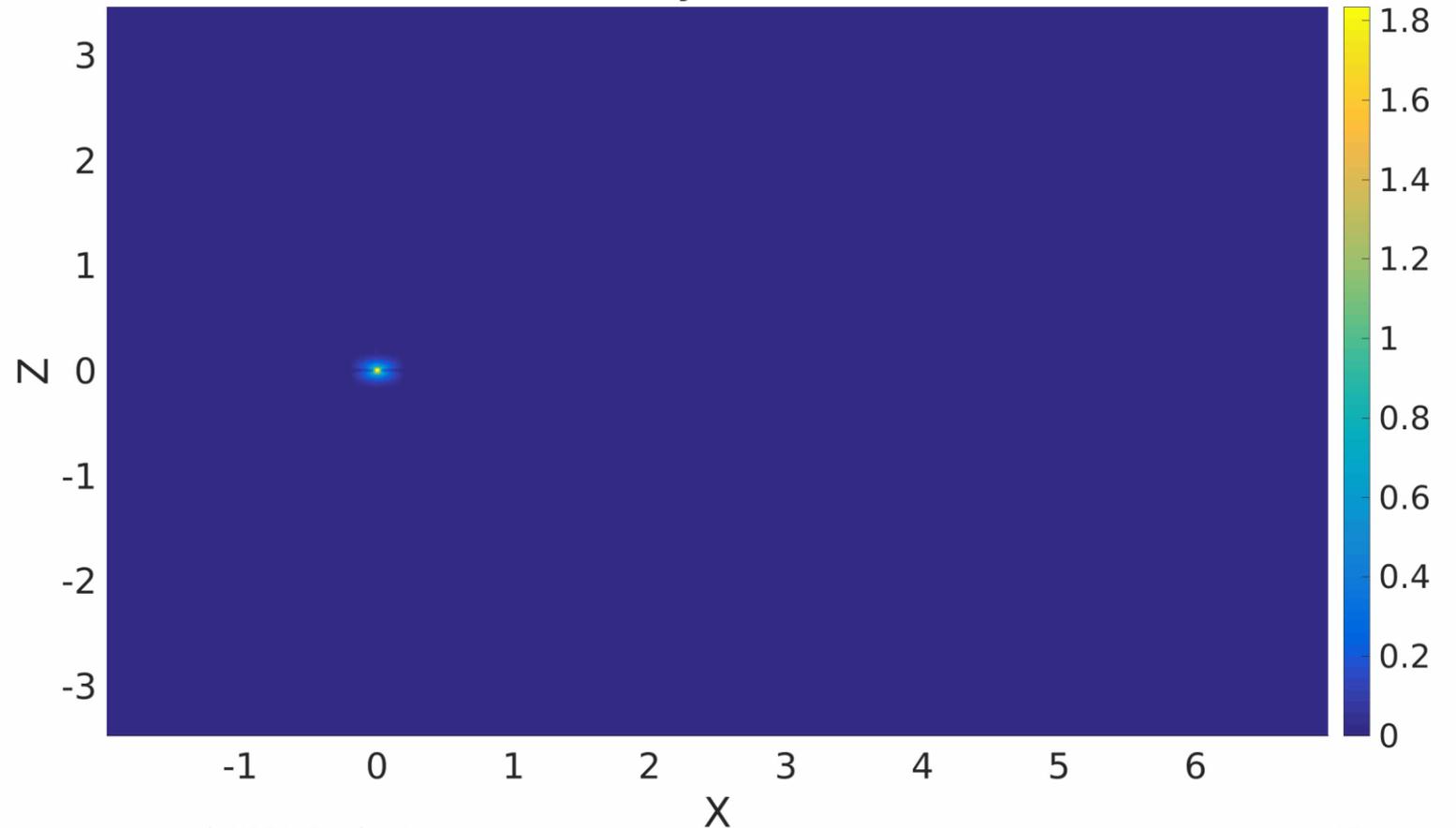


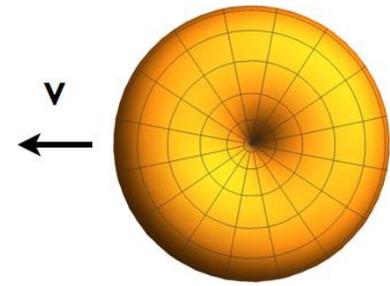
$$\left( \int \epsilon_{\mathbf{B}} \delta_{\mathbf{y}}^3 / \Gamma \, d\mathbf{y} \right)^{1/2}$$

PSR J1509-5850

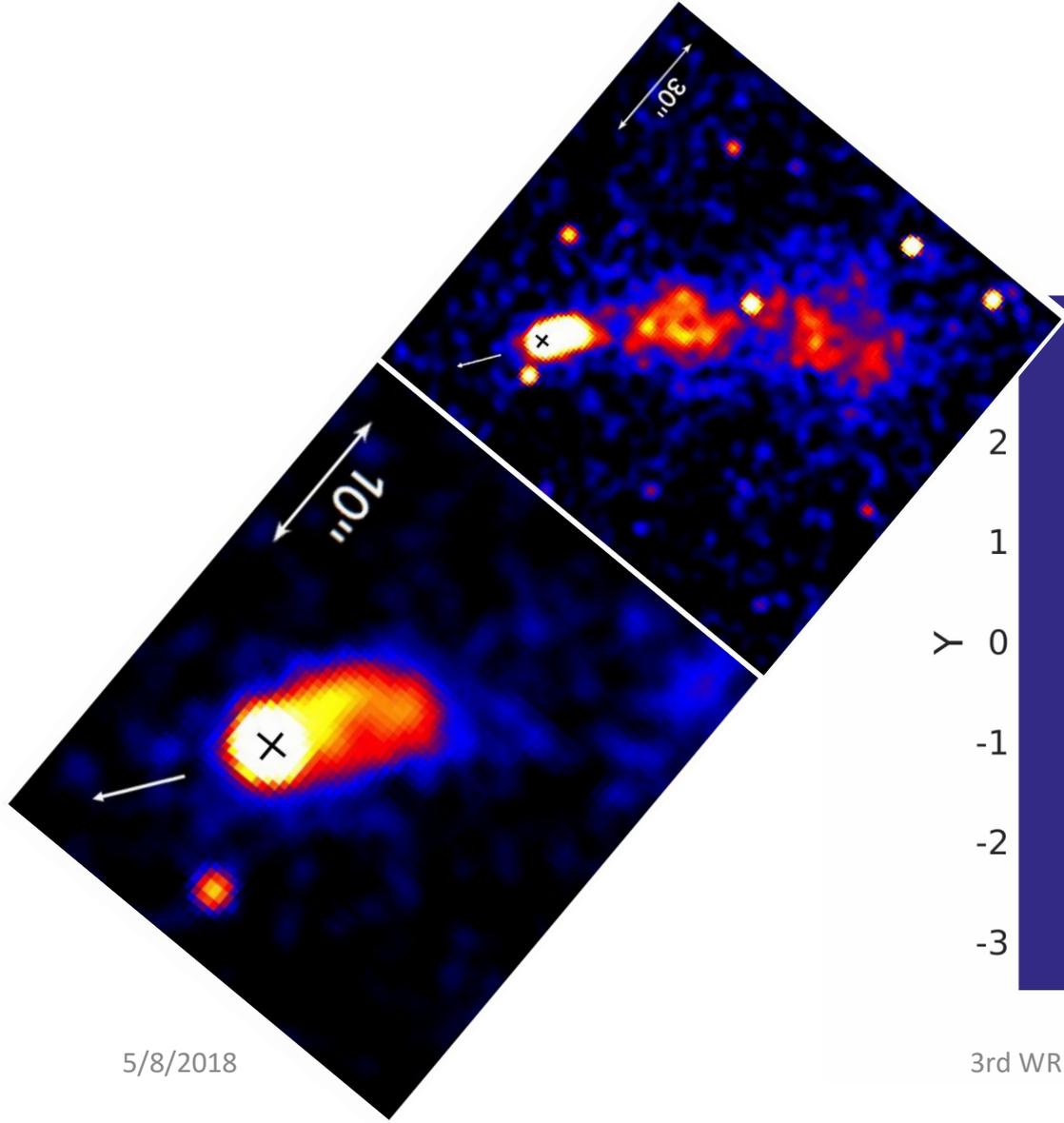


5/8/2018

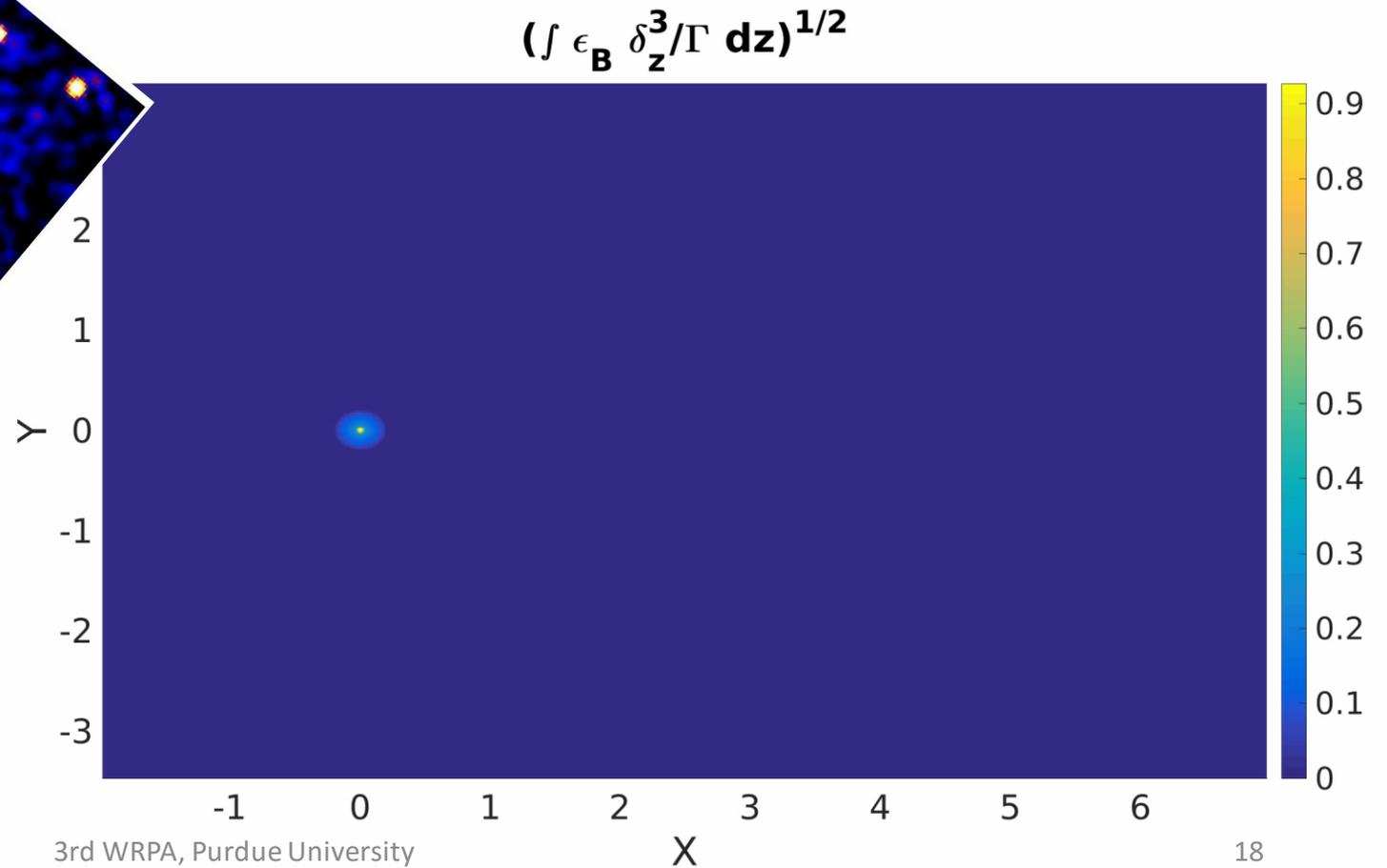




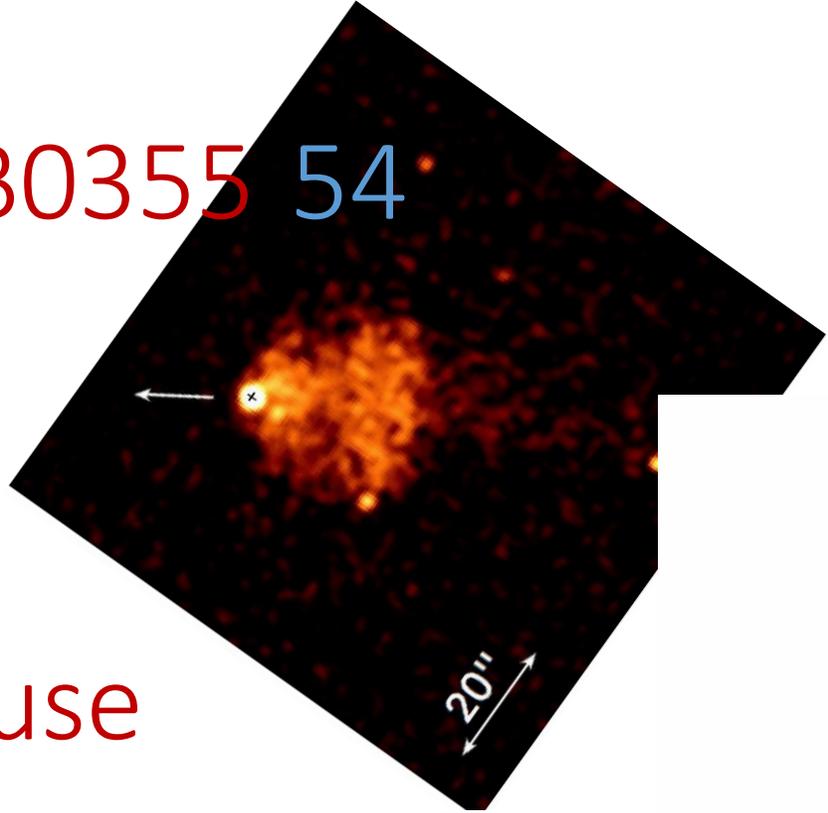
# PSR J1741-2054



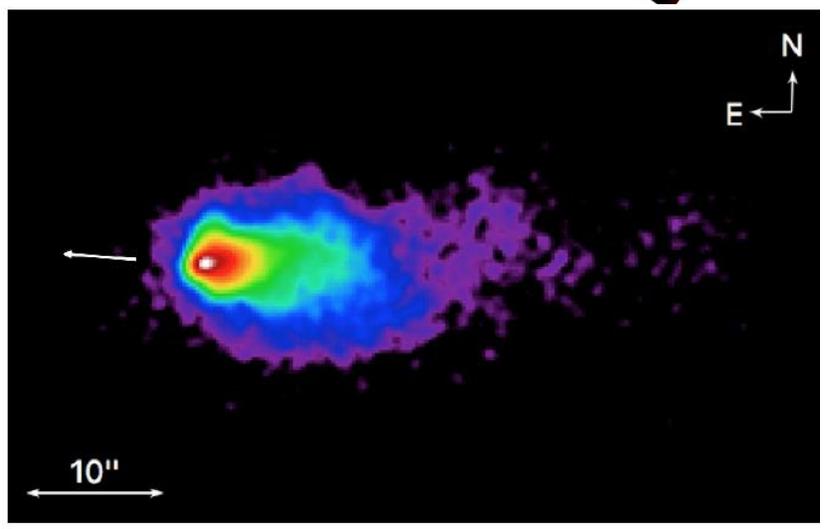
5/8/2018



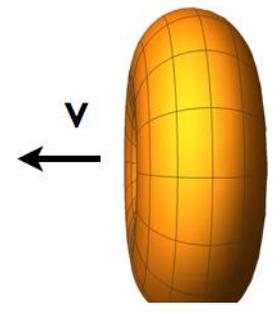
B0355 54



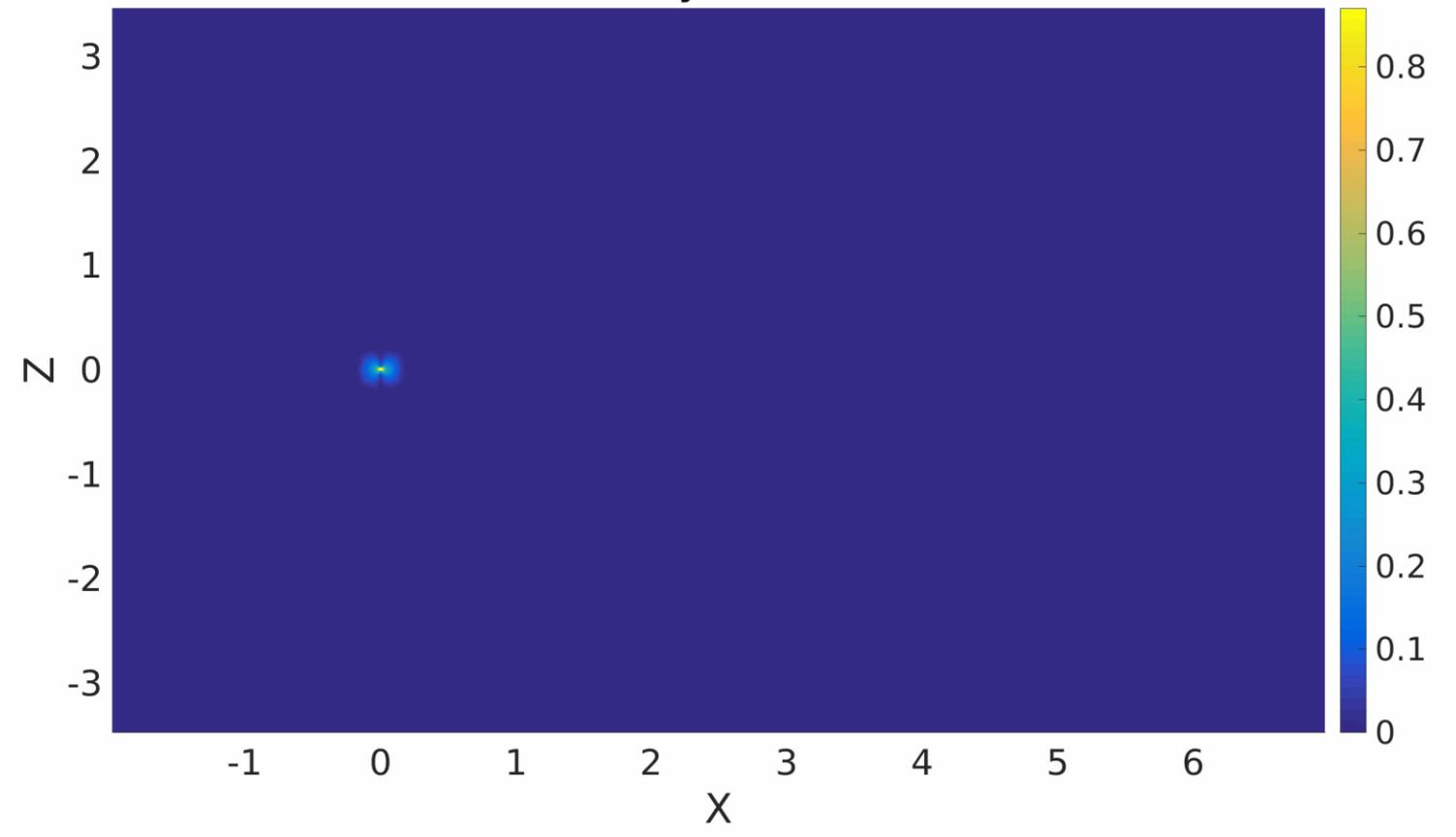
Mouse



5/8/2018

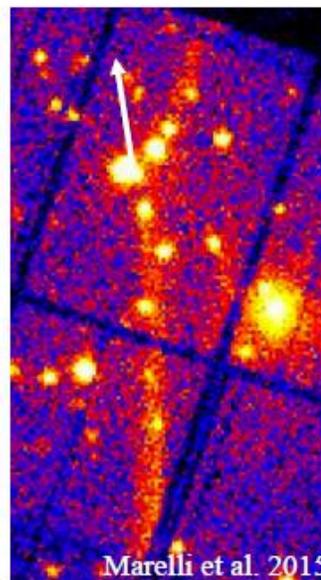
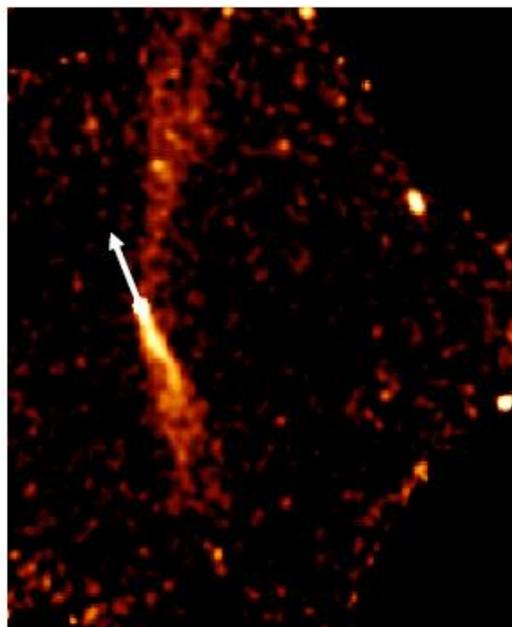
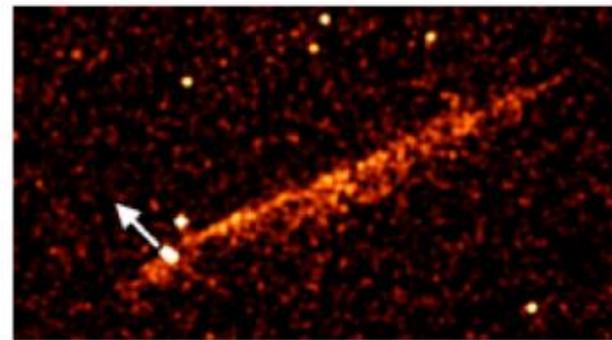
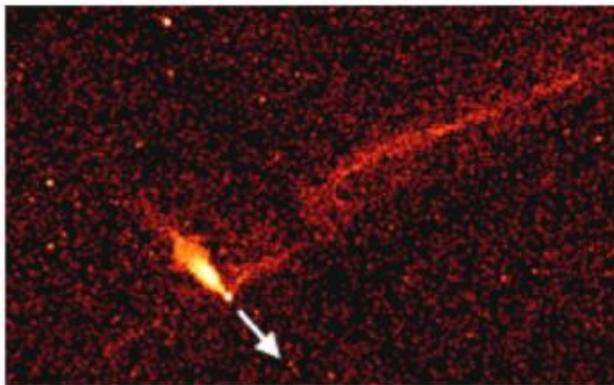


$$\left( \int \epsilon_{\mathbf{B}} \delta_{\mathbf{y}}^3 / \Gamma \, d\mathbf{y} \right)^{1/2}$$



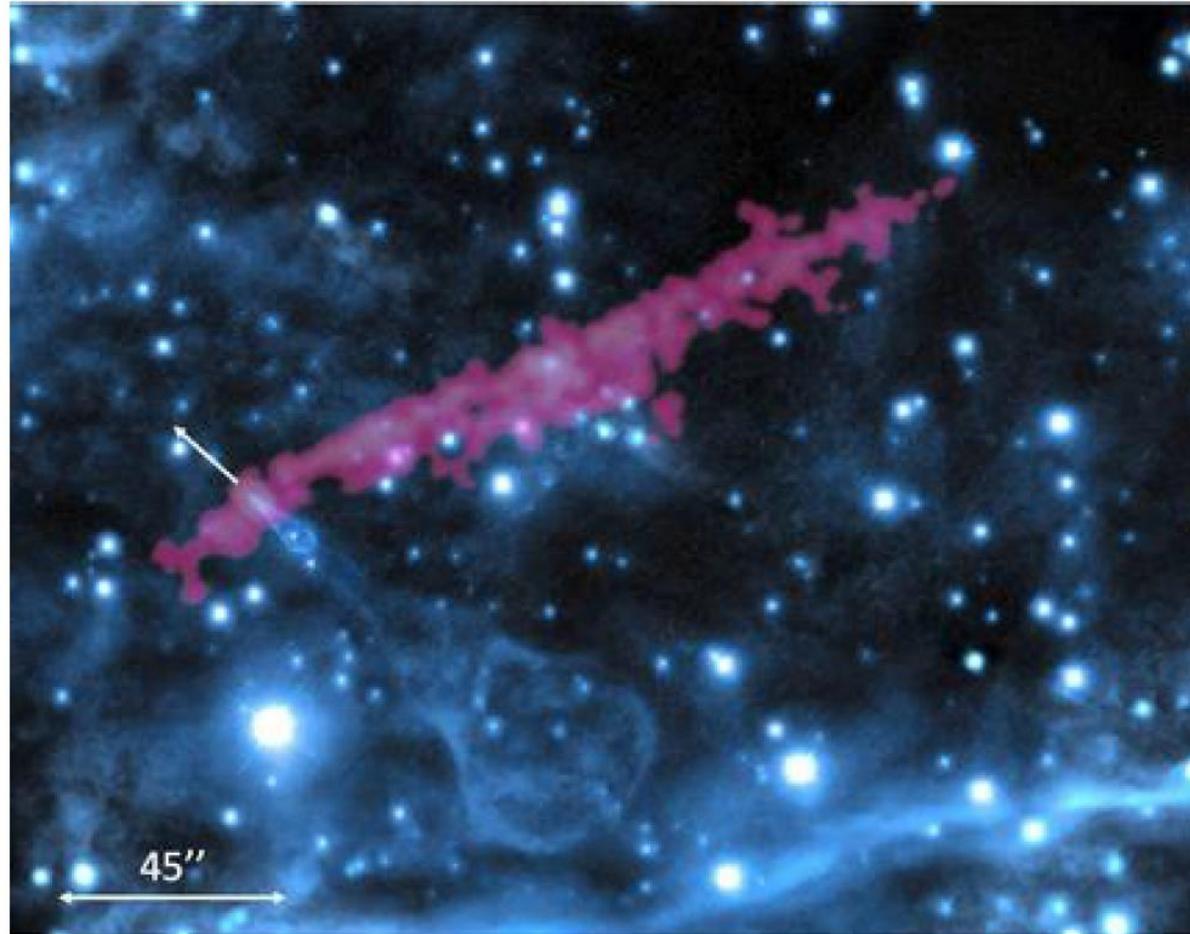
Kinetics  
Kinetics

# Pulsar's "Jet"



Marelli et al 2015  
Klingler et al 2016

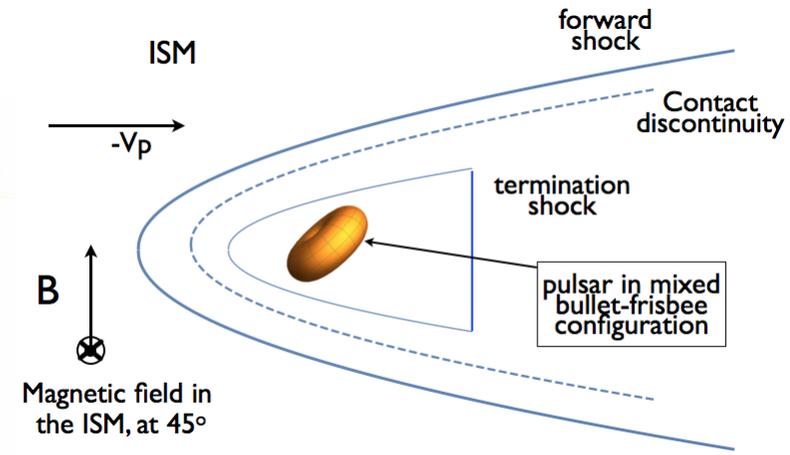
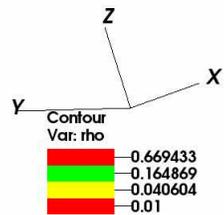
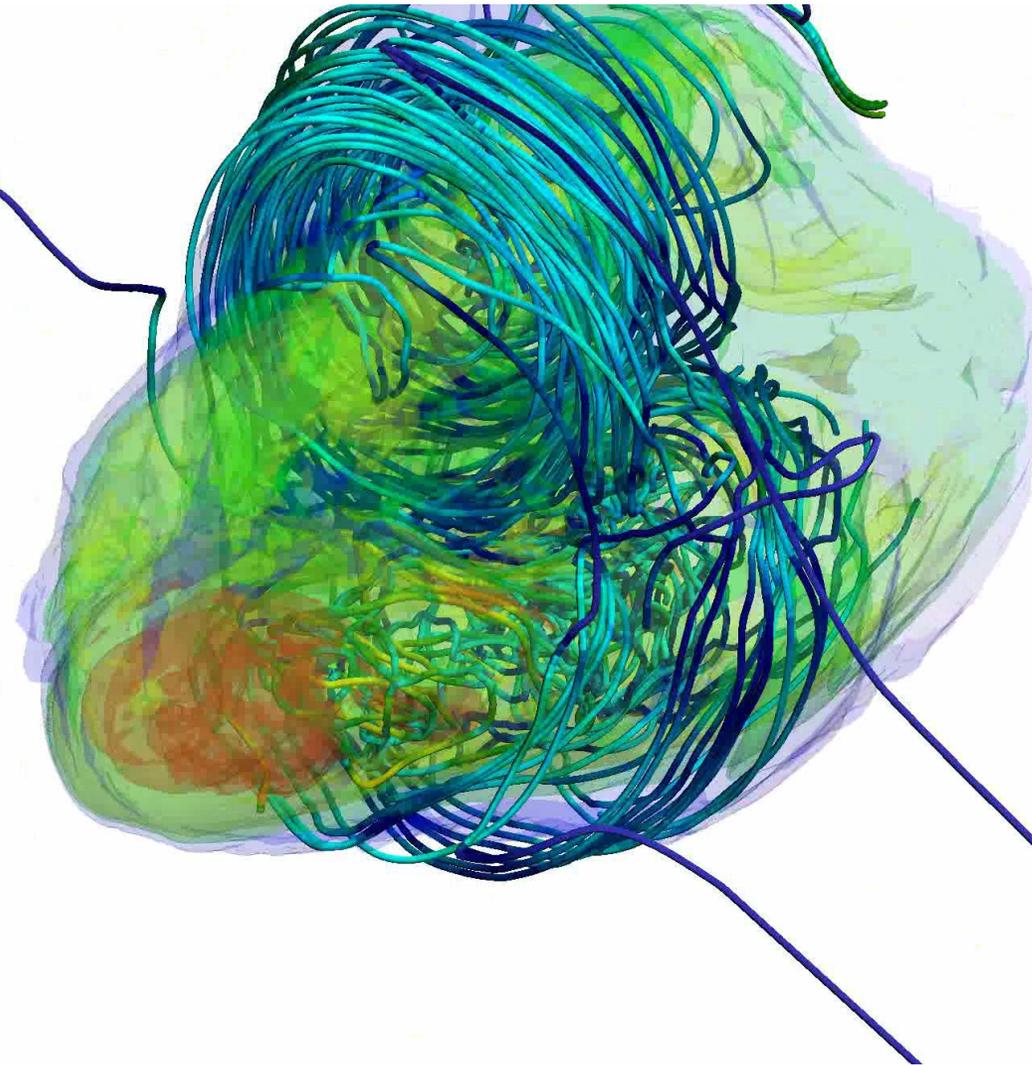
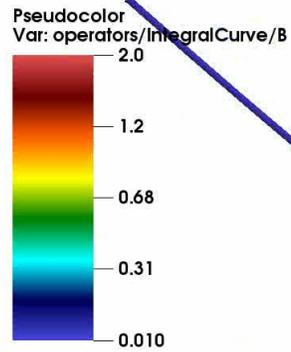
# Guitar – X-ray and H $\alpha$



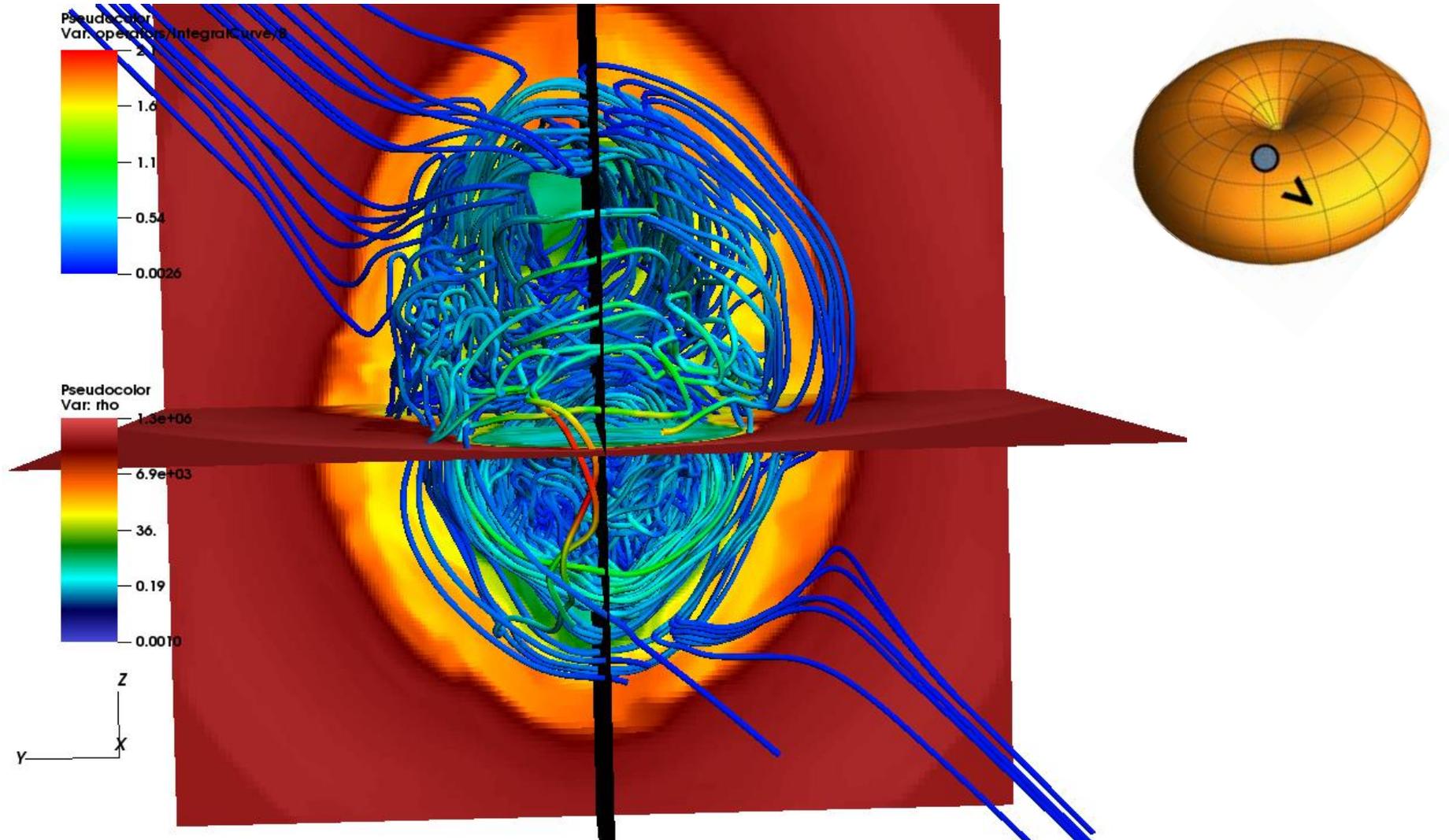
Reynolds et al. 2017

NT particle leakage idea  
for explanation of kinetic  
Jets was proposed by  
Bandiera (2008)

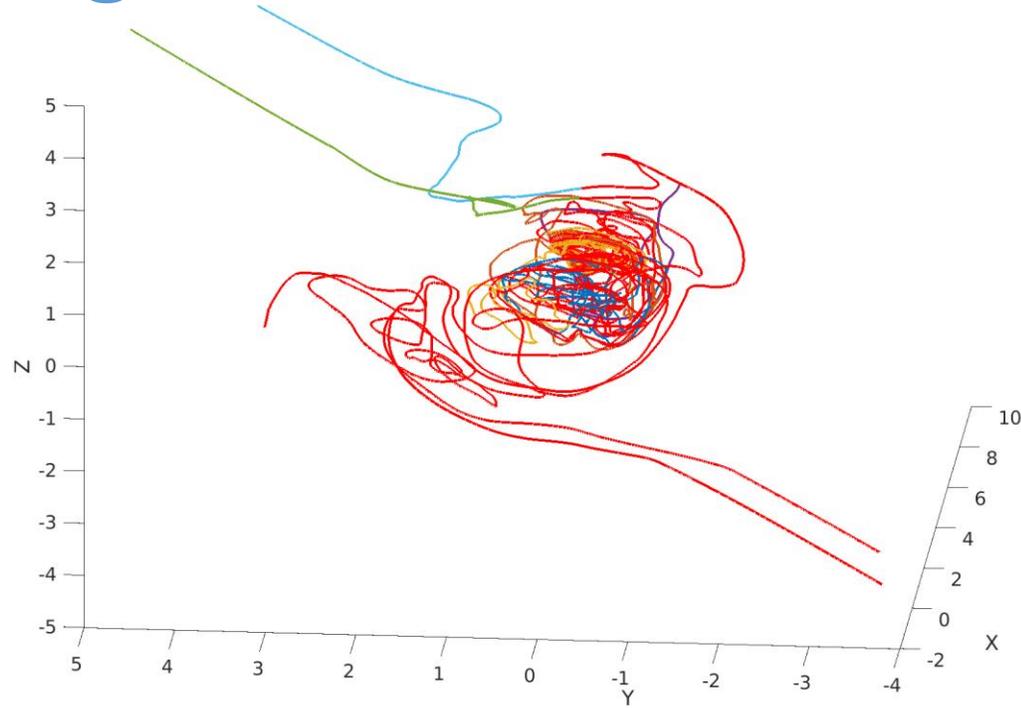
# Pulsar and ISM interaction



# Magnetic field lines

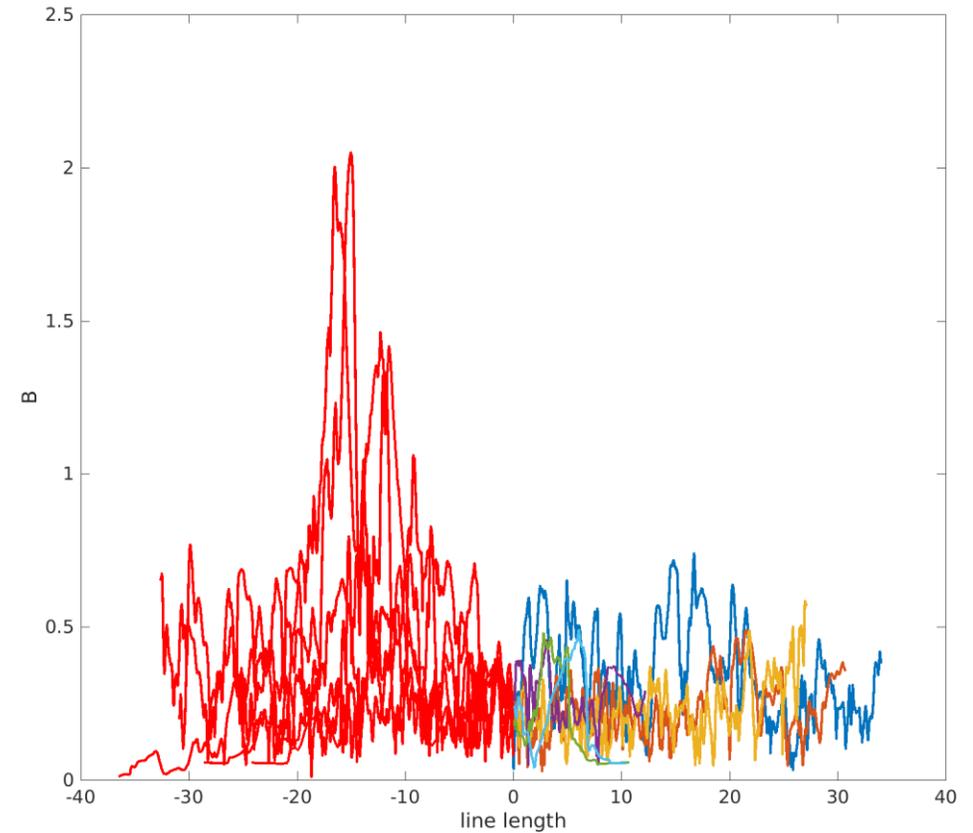
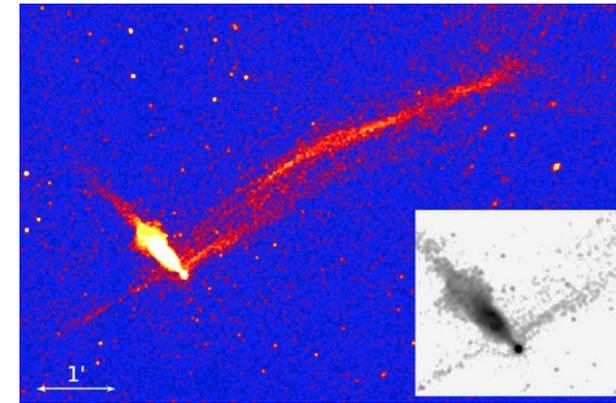


# Magnetic bottle?

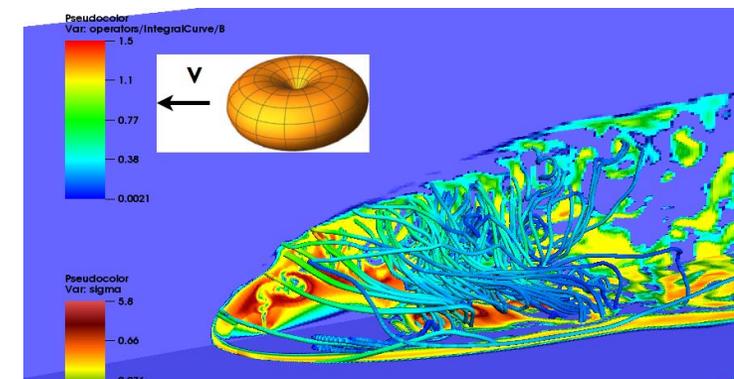
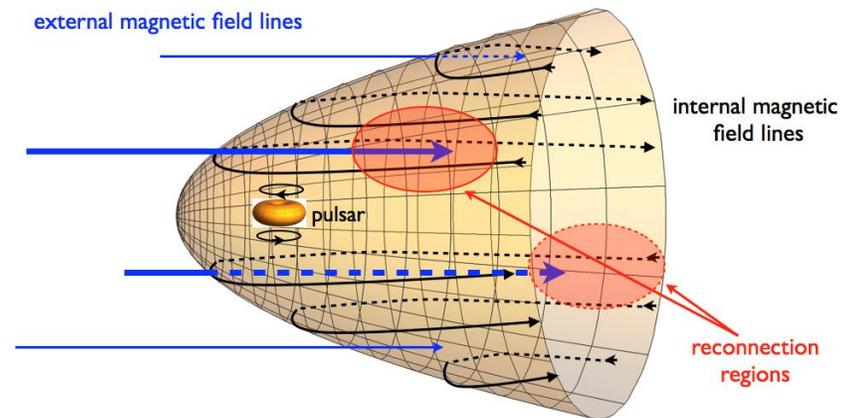
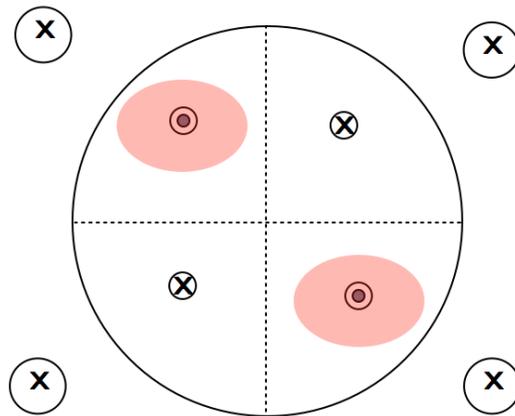
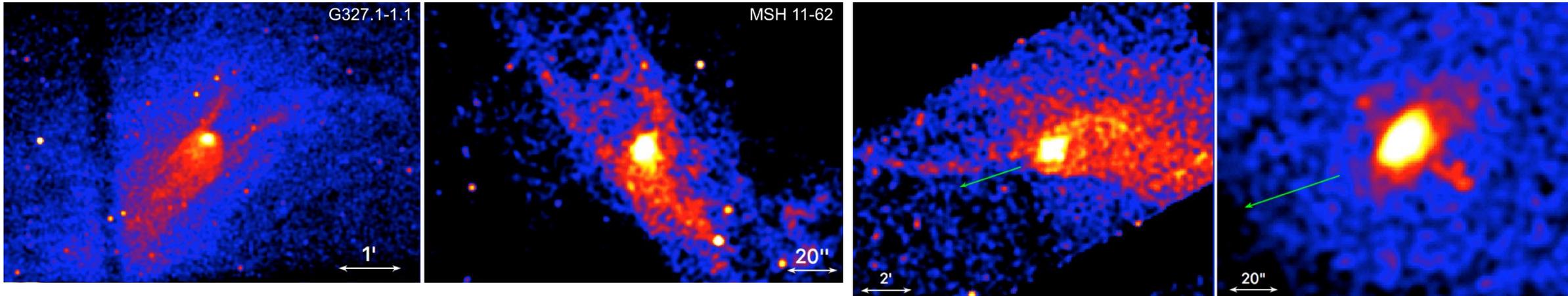


$$p_{esc} = 1 - \sqrt{1 - \frac{1}{R}} \approx \frac{1}{2R}$$

$$R \equiv B/B_0 \geq 1$$



# Snail eyes.



BMV, Lyutikov, Klingler and Bordas (2018)

Thank you!

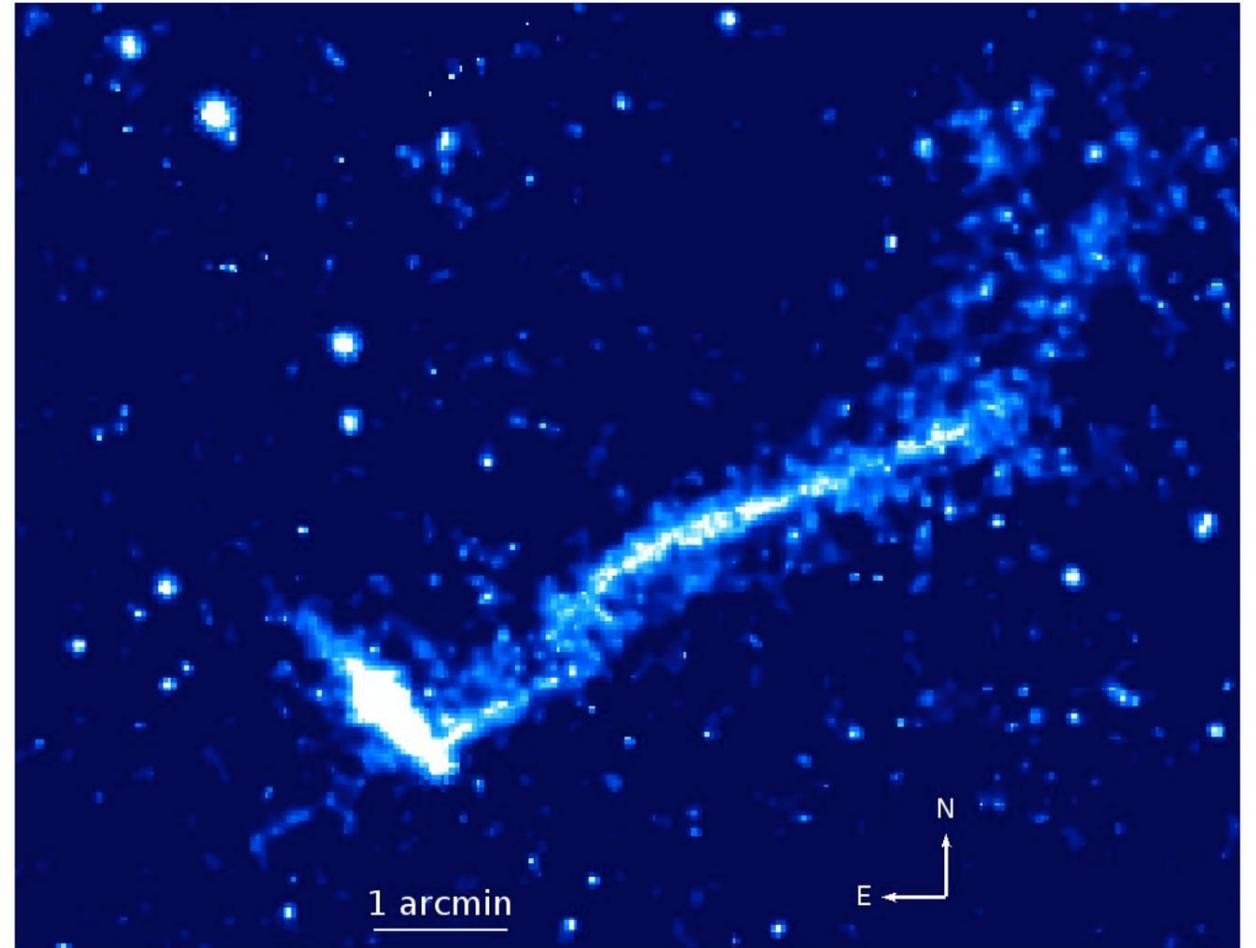


# Pulsar's "Jet"

## IGR J11014-6103 jets

Pavan et al. 2014

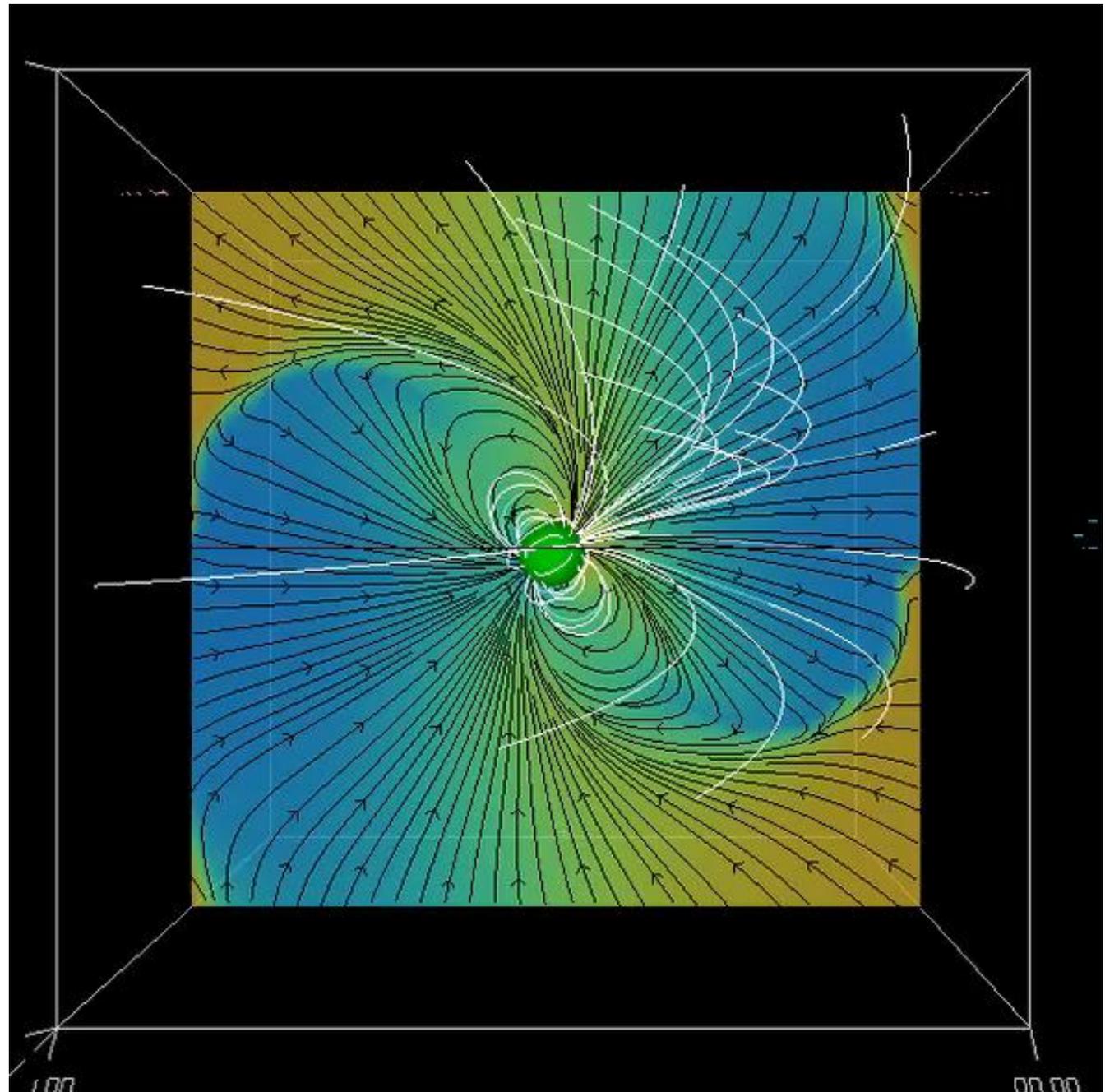
- @ 7 kpc,  $l_{\text{jet}} \geq 11.5$  pc  
(longest jet in the Galaxy)
- precession-like pattern
- faint counter-jet (Doppler)
- chance prob.  $\sim$  negligible
  - alignment jet/counter-jet
  - flux change @ "PSR" position
- main jet  $\sim$  1/3 of total flux
- no signatures of bending  
(diffuse emission @ jet tip?)



# Pulsar magnetosphere

Oblique Rotator

Spitkovsky 2006



# Structure of the Heliotail

