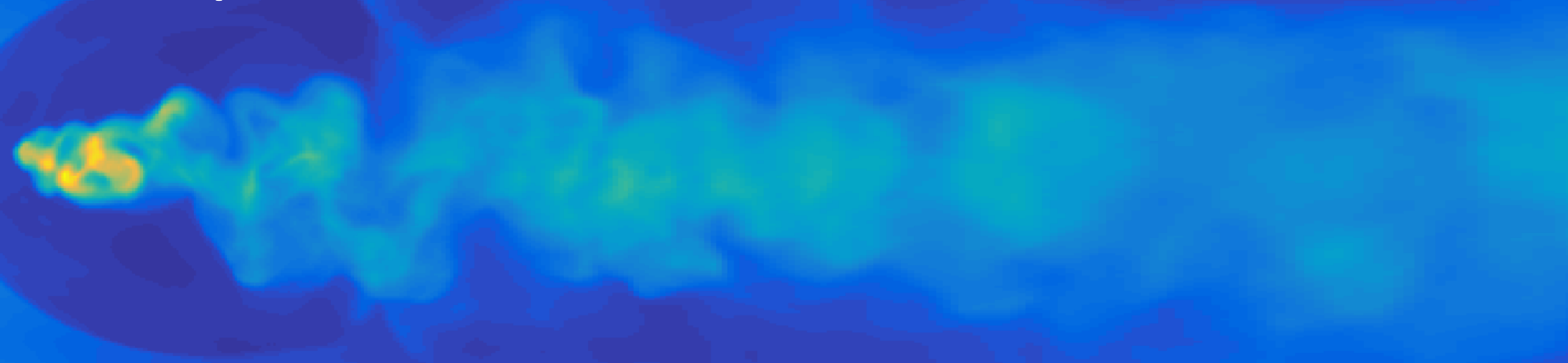
Relativistic 3D MHD simulations of pulsar bow-shock nebulae



Maxim Barkov

Purdue University, USA

RIKEN, Japan

In collaboration with

Maxim Lyutikov

Dmitry Khangulian

Noel Klingler

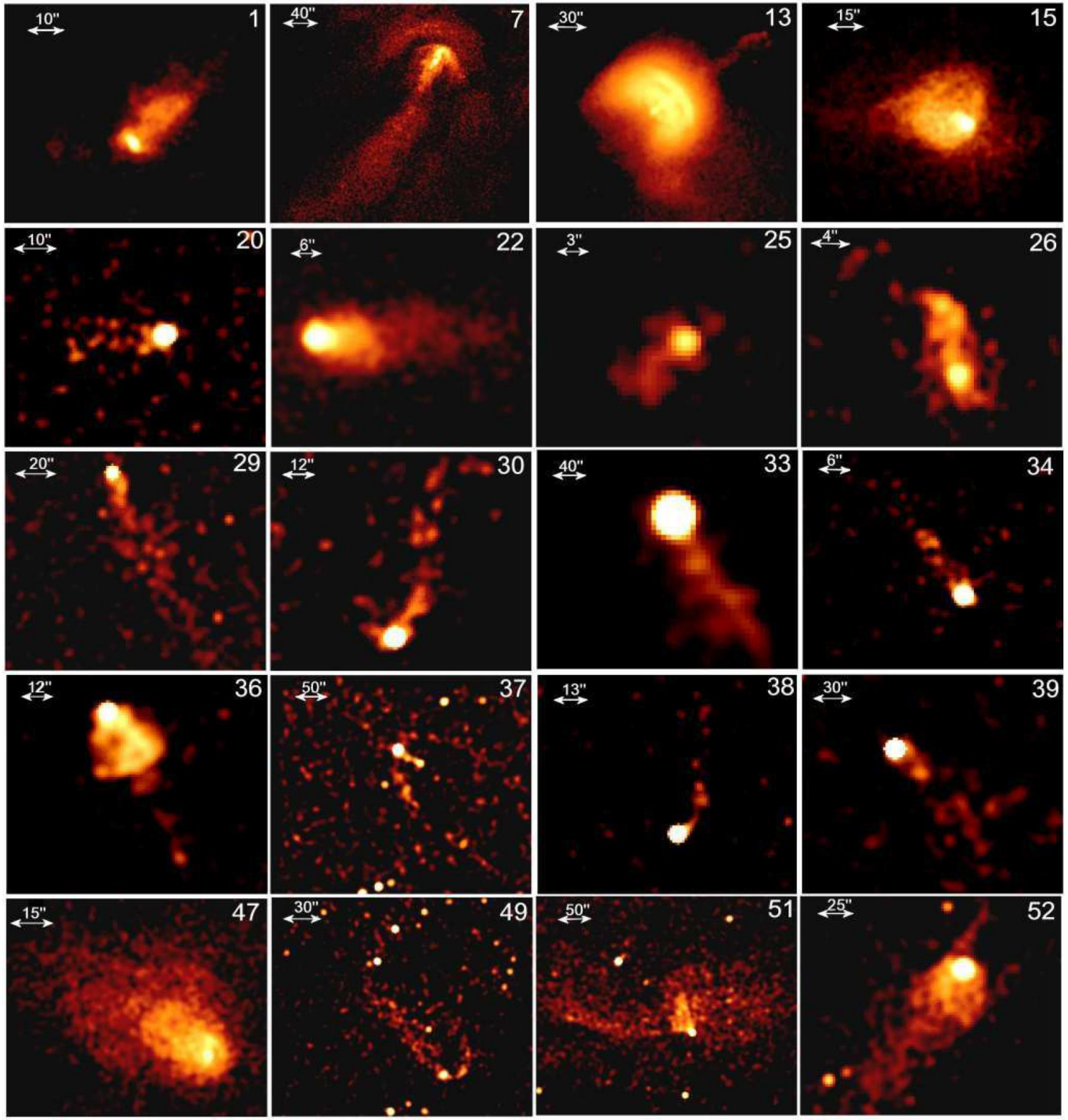
Pol Bordas

Theoretical slides

Numerical slides

Observational slides

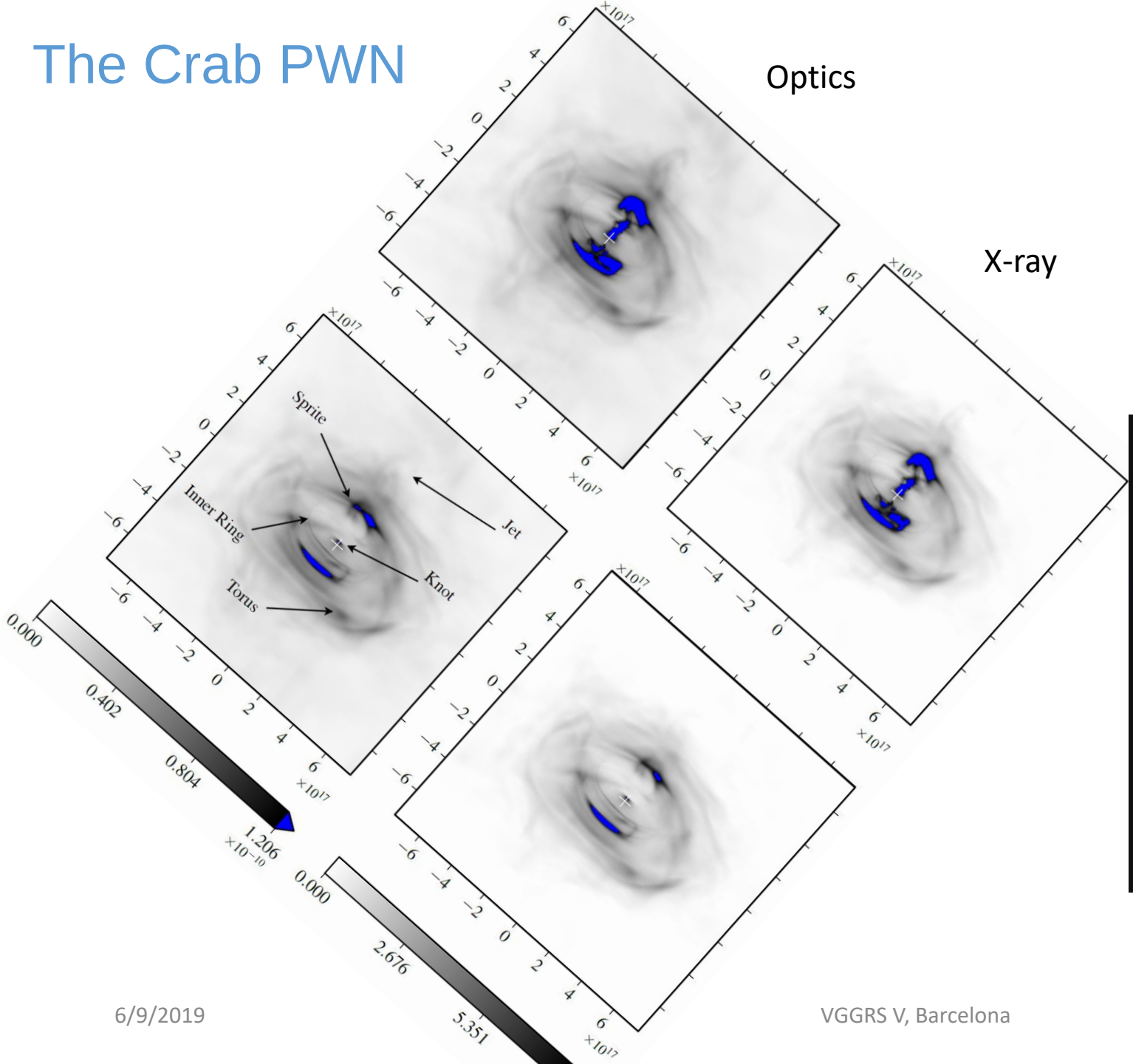
Chandra PWN ZOO



Kargaltsev & Pavlov 2008

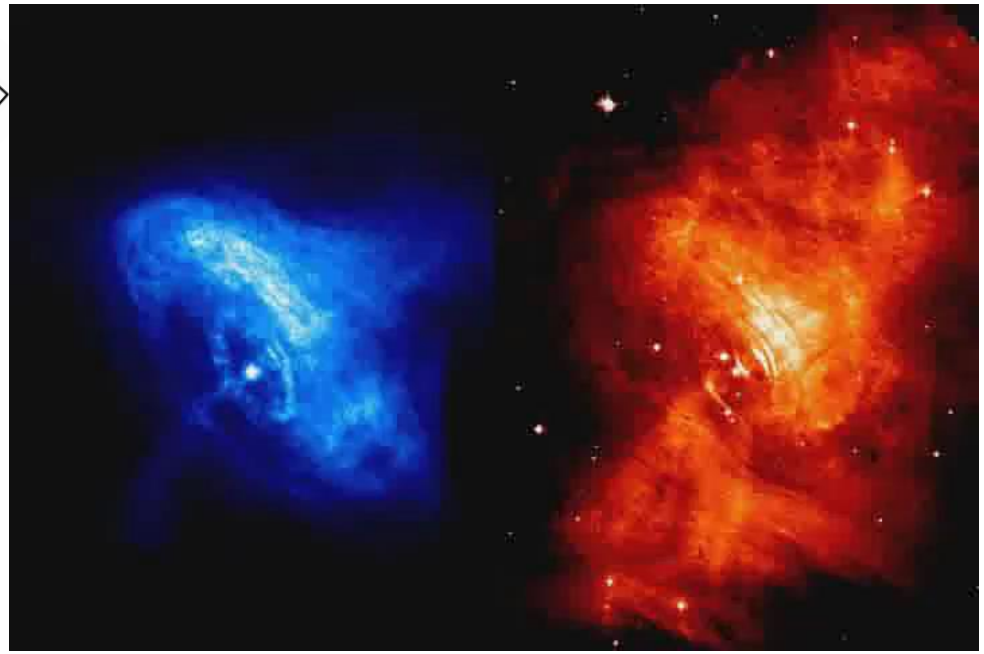
The Crab PWN

Porth et al. 2013



Optics

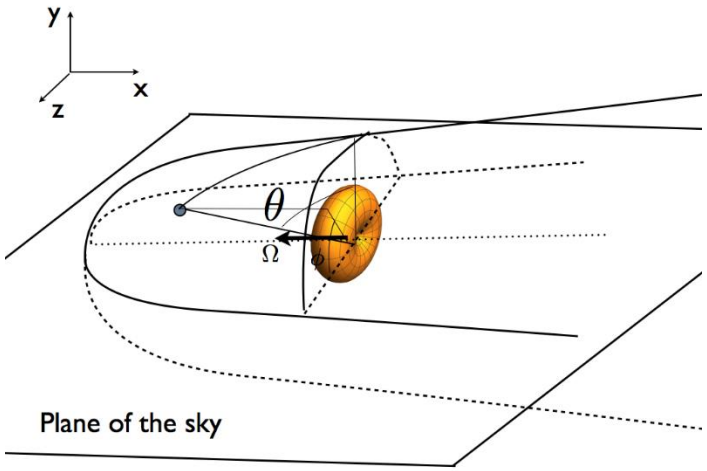
X-ray



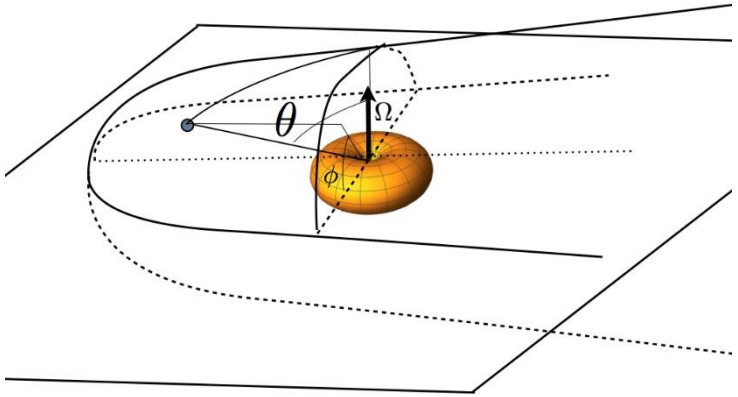
Pulsar and ISM interaction

Barkov, Lyutikov and Khangulian (2019a)

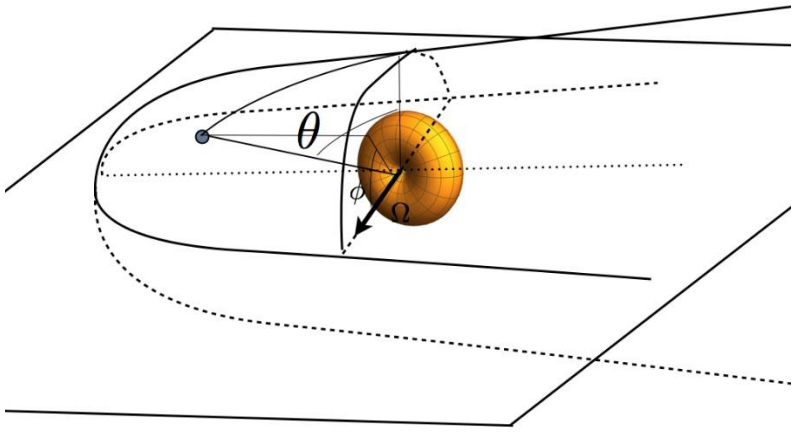
Rifle bullet



Frisbee



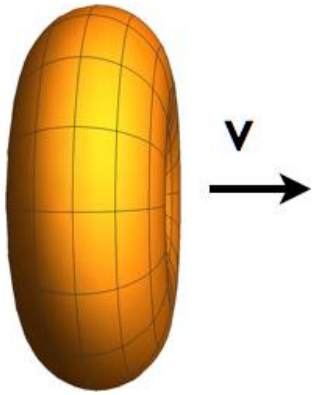
Cartwheel

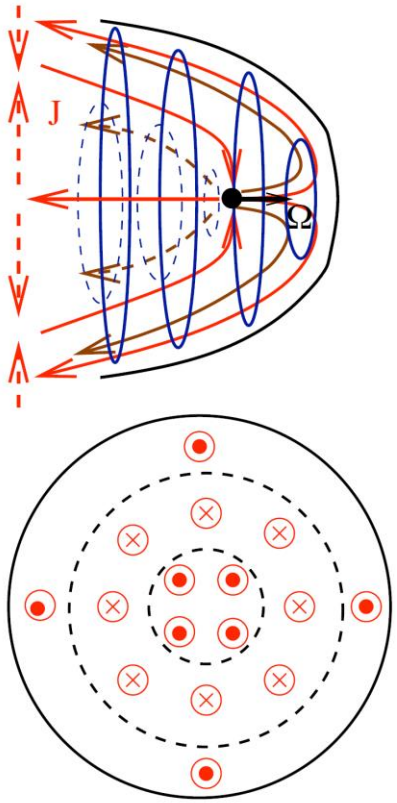


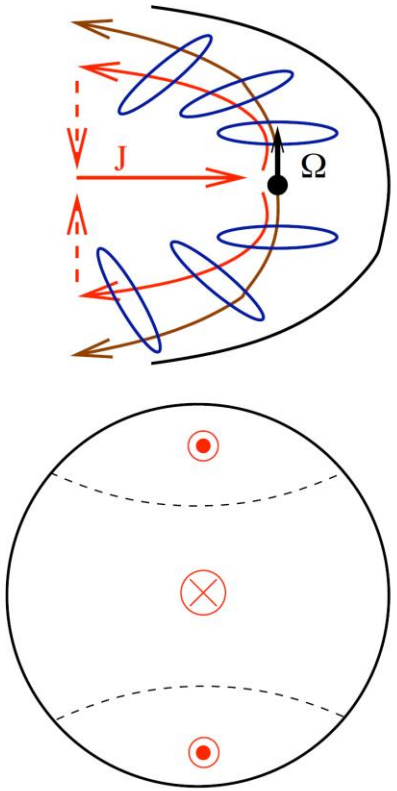
Barkov, Lyutikov and Khangulian (2019a)

Pulsar and ISM interaction

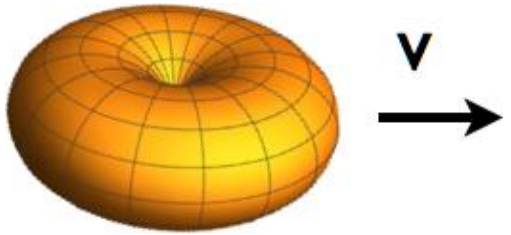
Bullet geometry



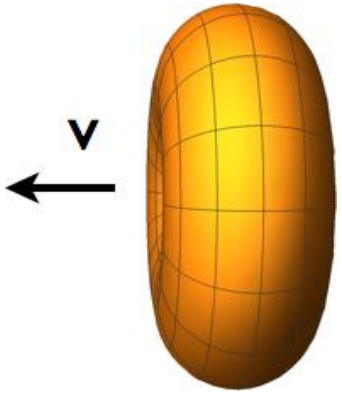


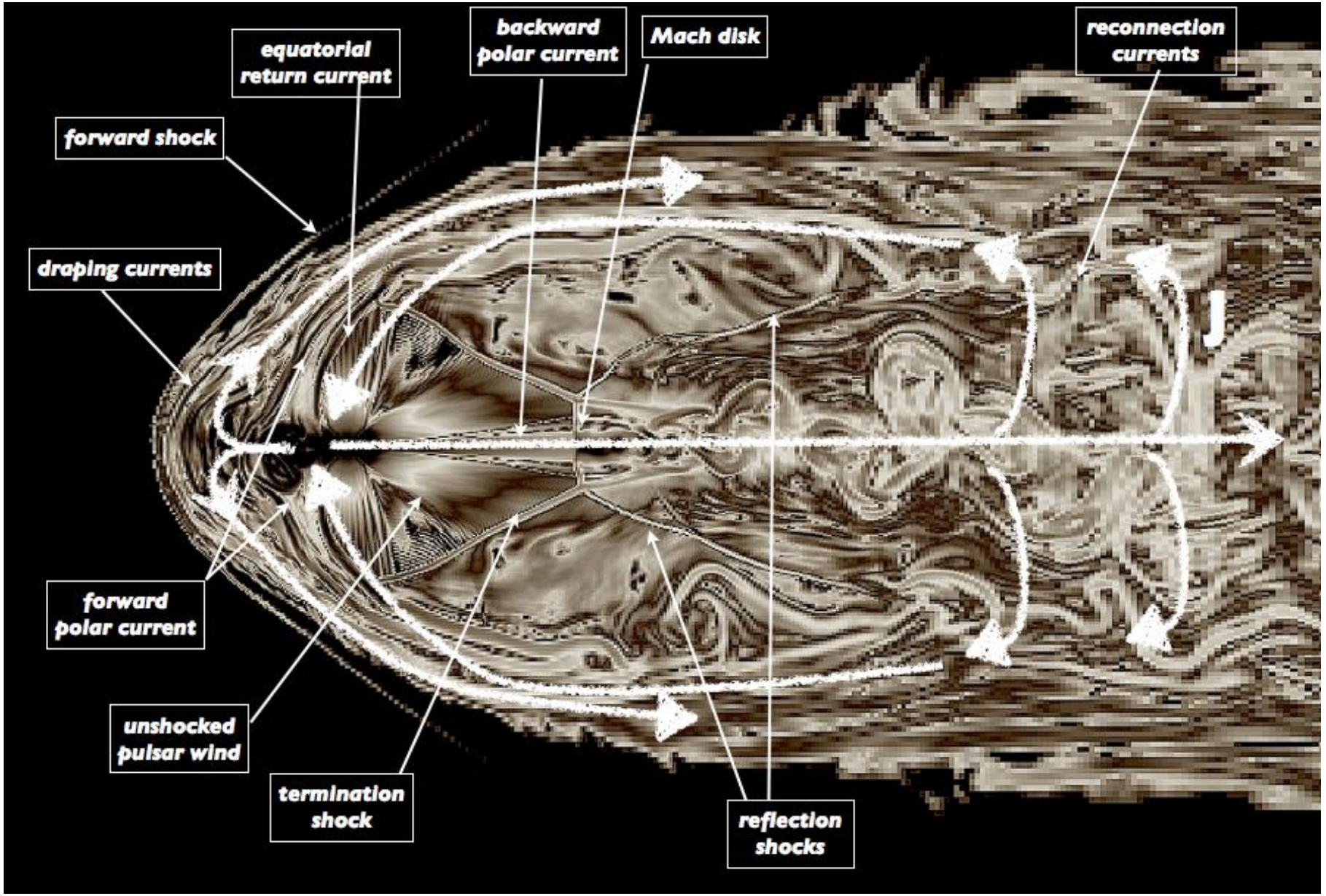


Frisbee geometry



Current


v


equatorial return current
backward polar current
Mach disk
reconnection currents
forward shock
draping currents
forward polar current
unshocked pulsar wind
termination shock
reflection shocks

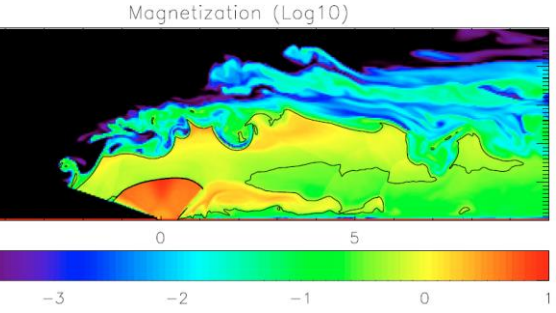
Pulsar and ISM interaction

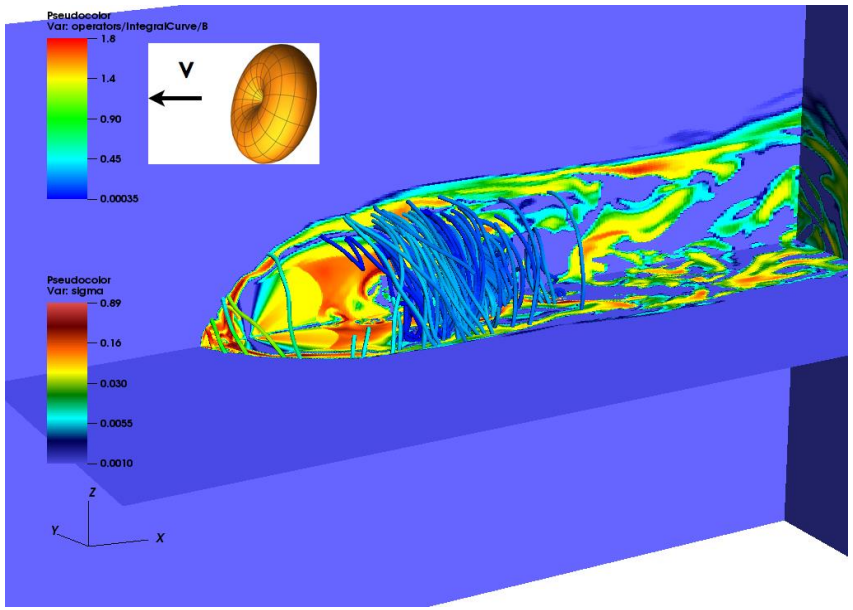
Barkov, Lyutikov and Khangulian (2019a)

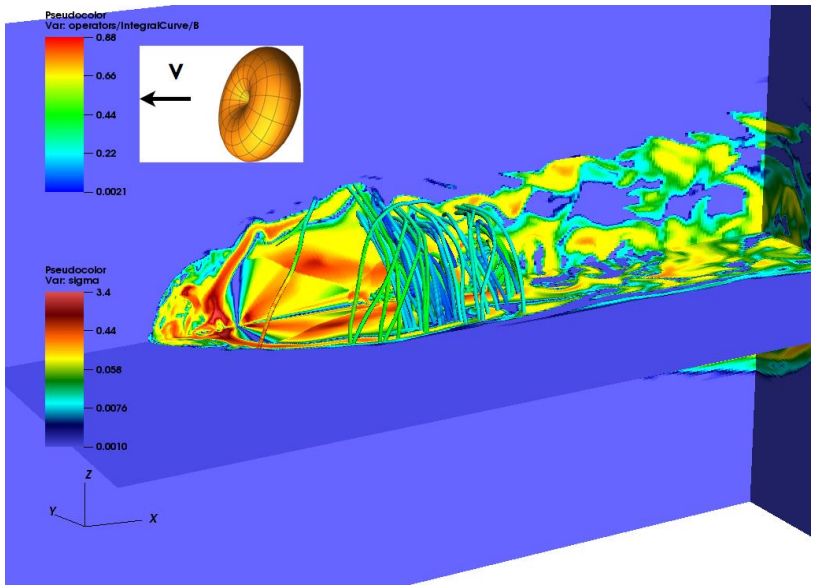
3D RMHD

Magnetization & Magnetic field

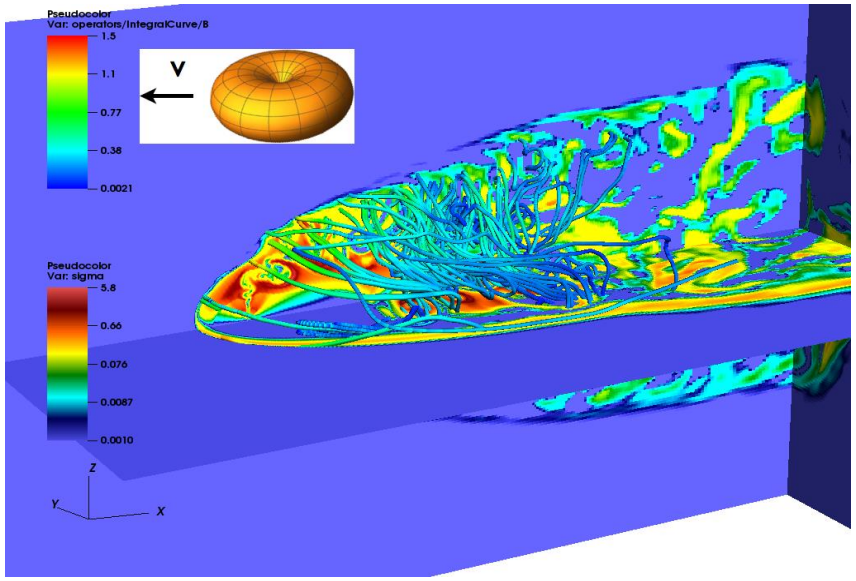
Bullet geometry

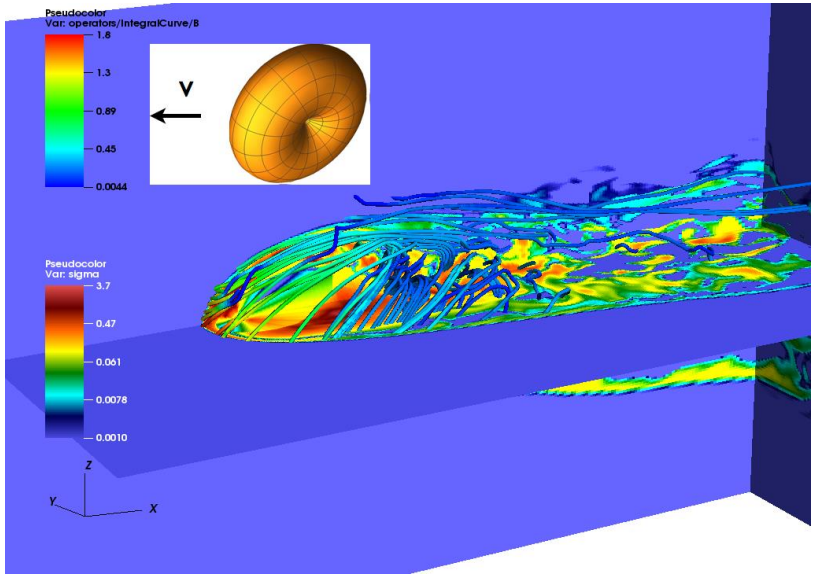






Frisbee geometry



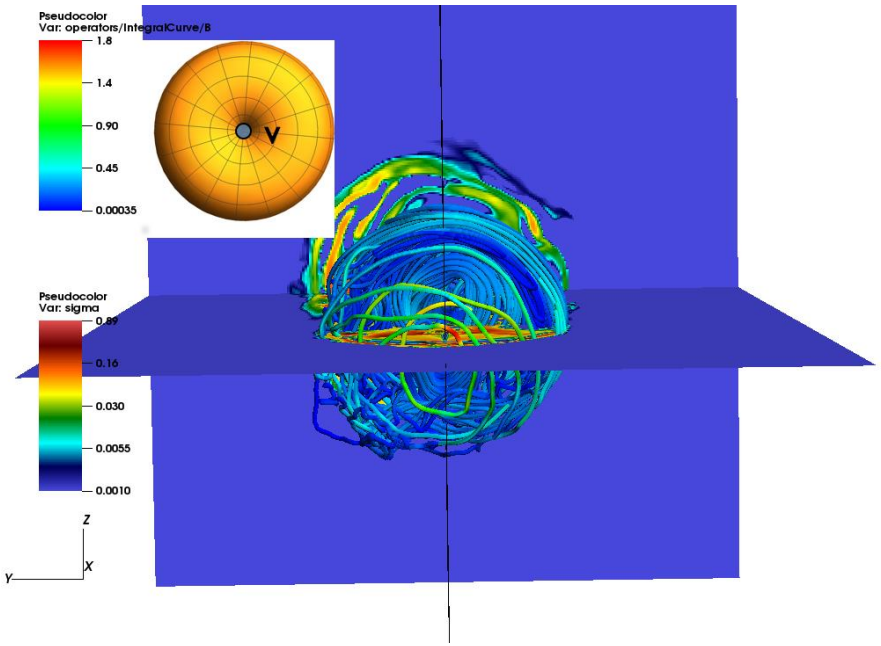


Pulsar and ISM

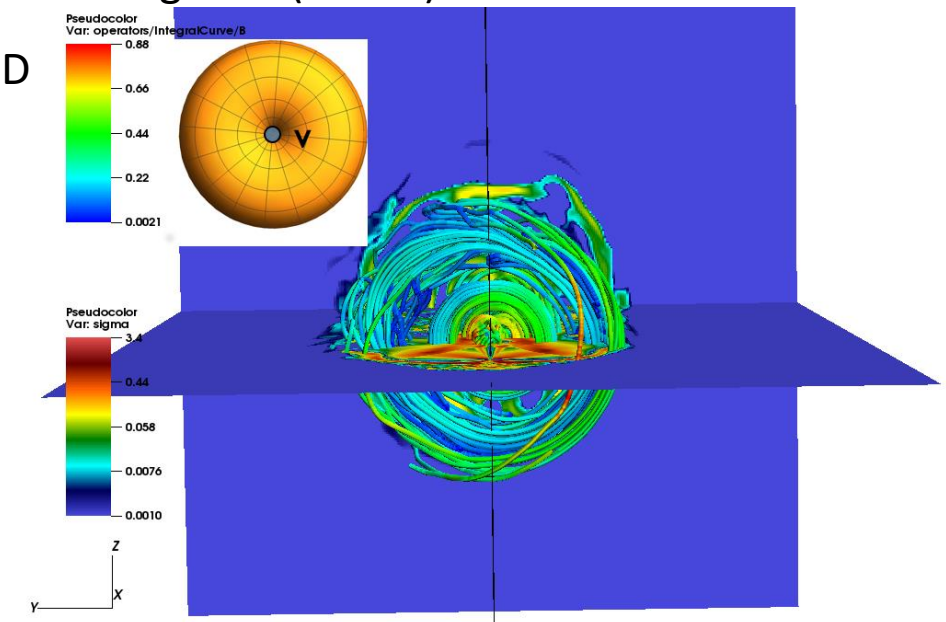
Barkov, Lyutikov and Khangulian (2019a)

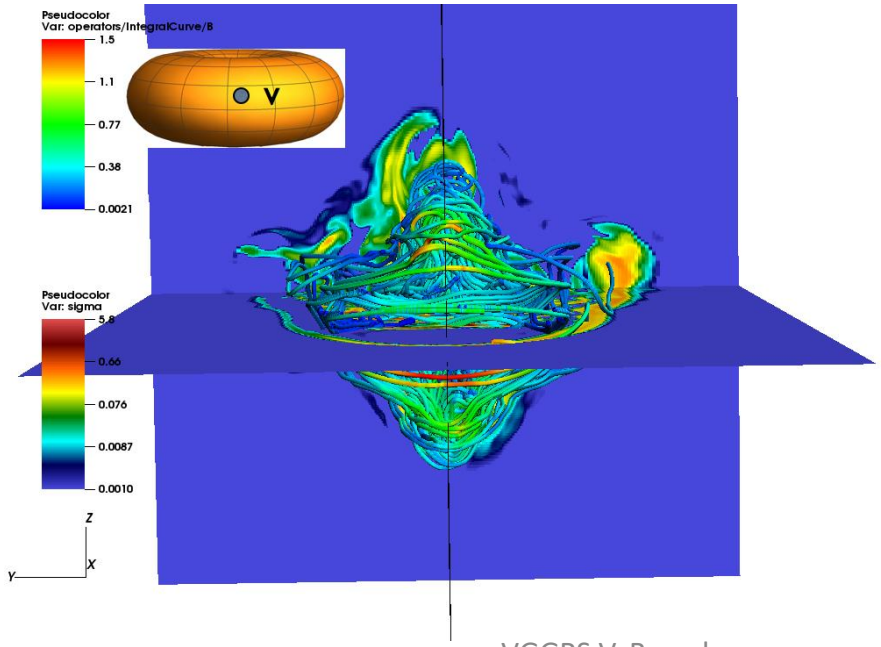
Bullet geometry

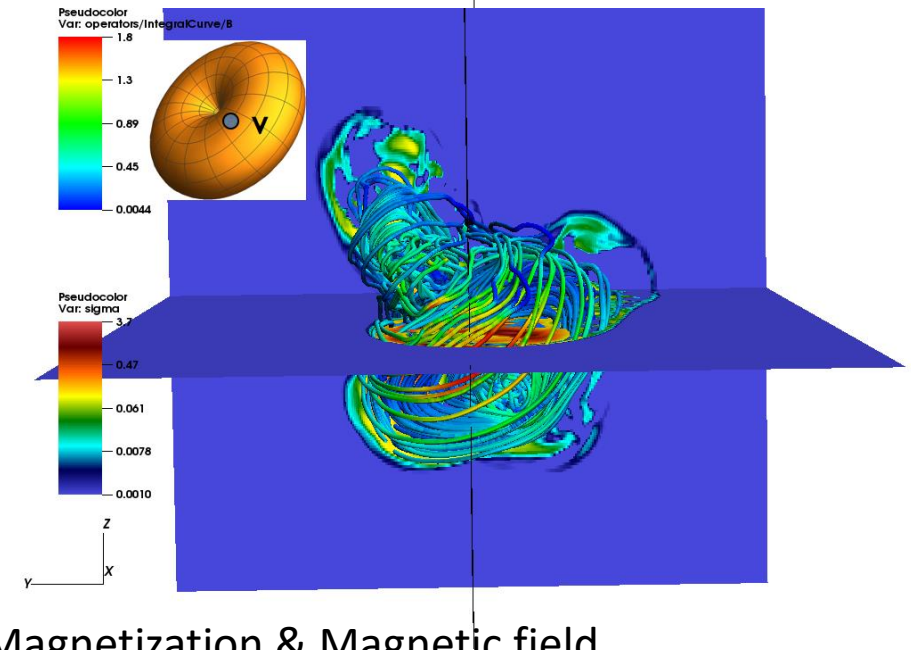
Frisbee geometry



HD



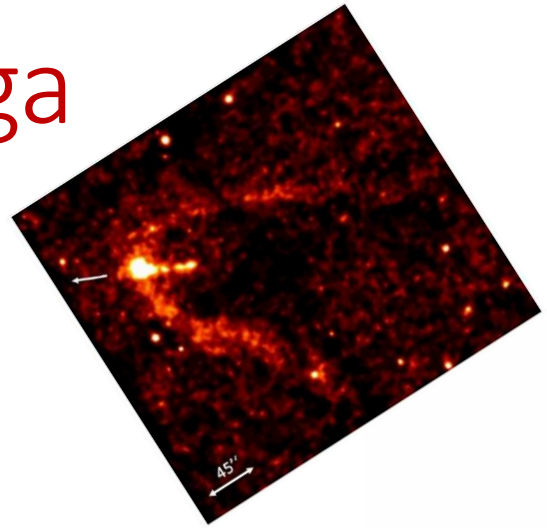




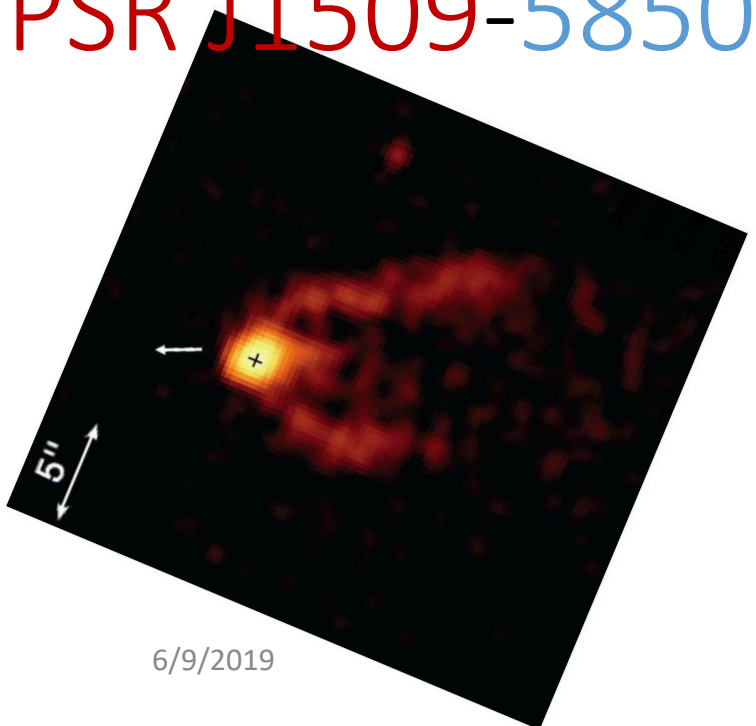
Magnetization & Magnetic field

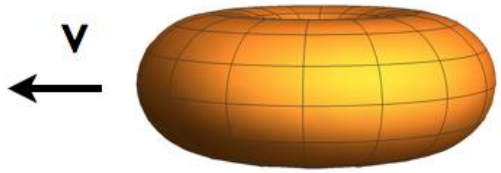
Barkov, Lyutikov and Khangulian (2019a)

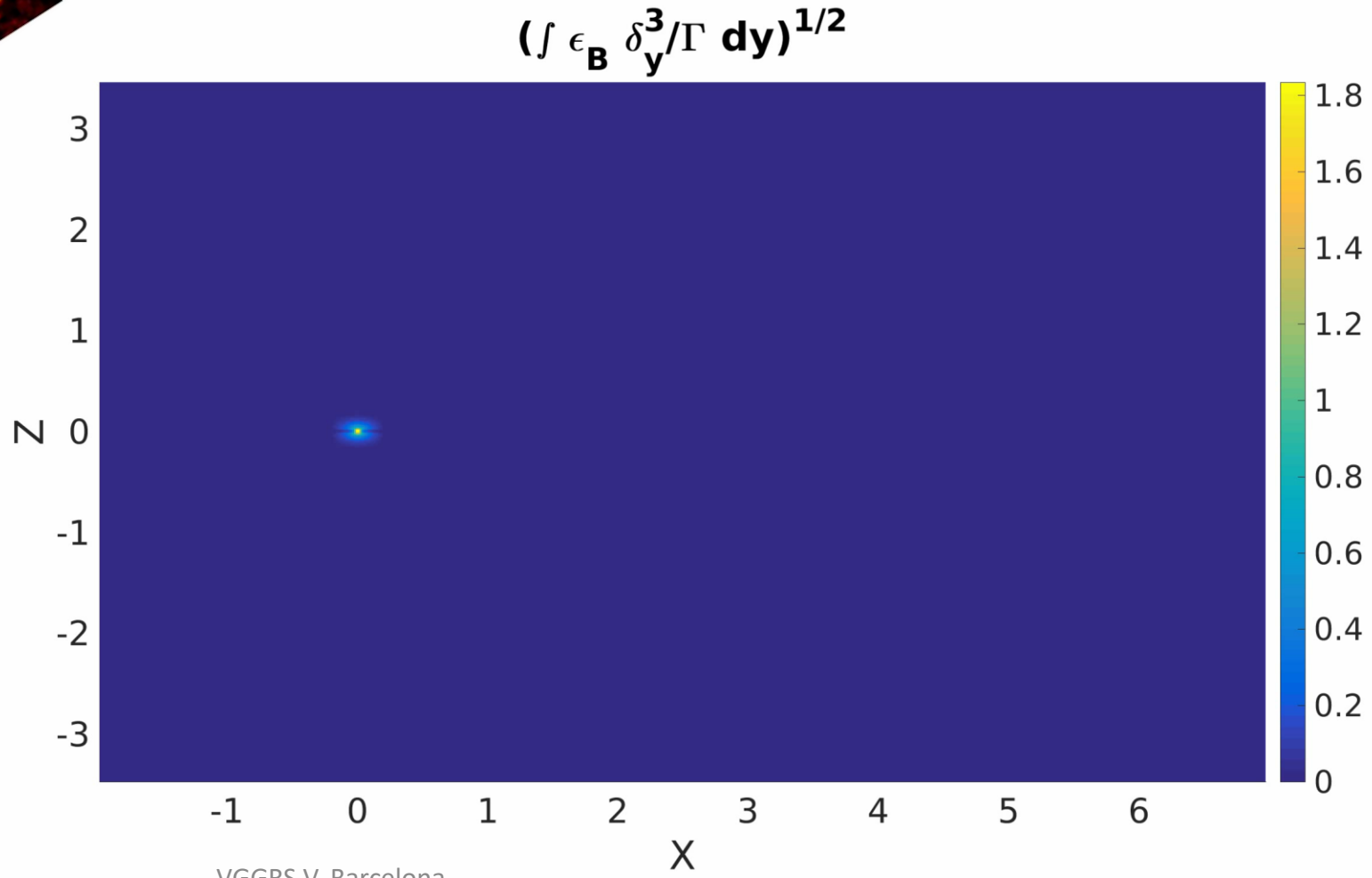
Geminga



PSR J1509-5850

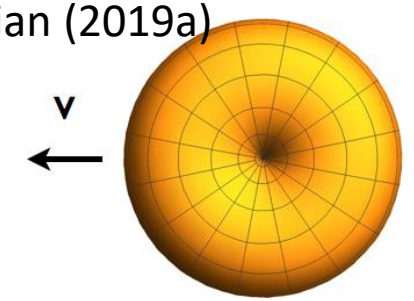


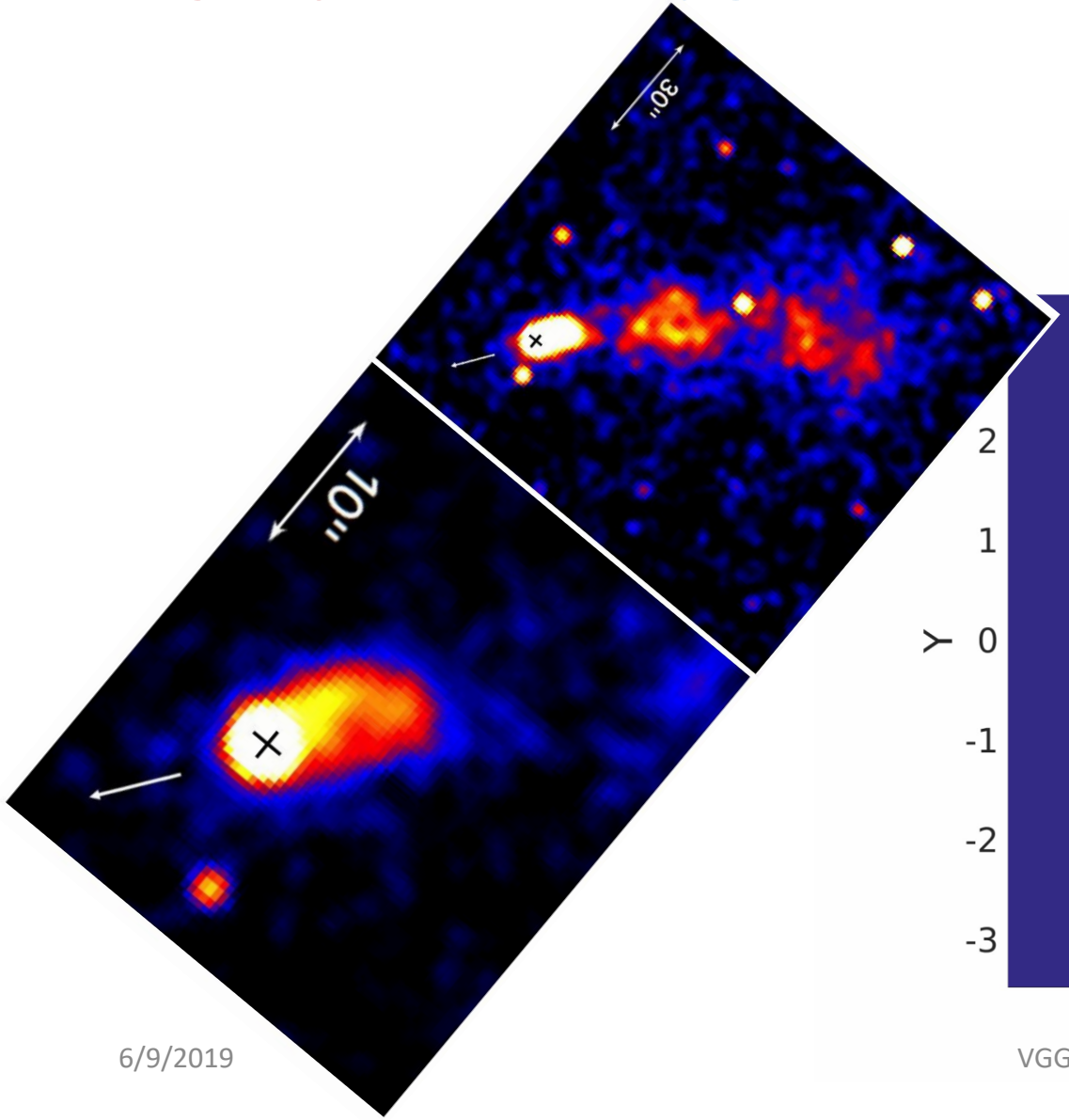


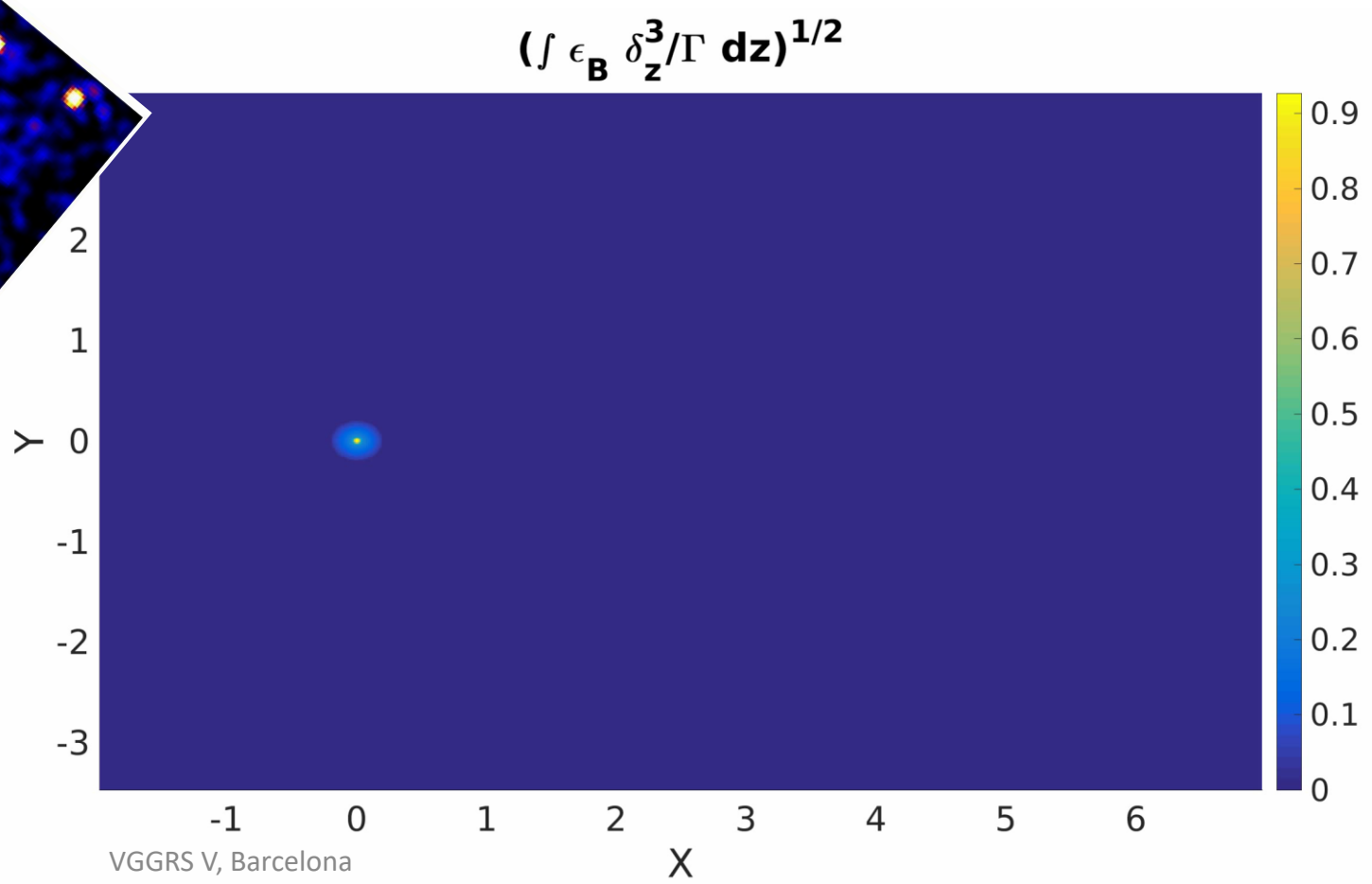


PSR J1741-2054

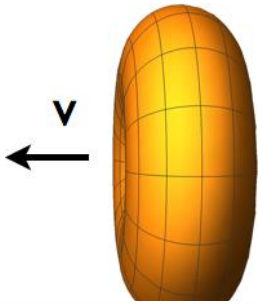
Barkov, Lyutikov and Khangulian (2019a)

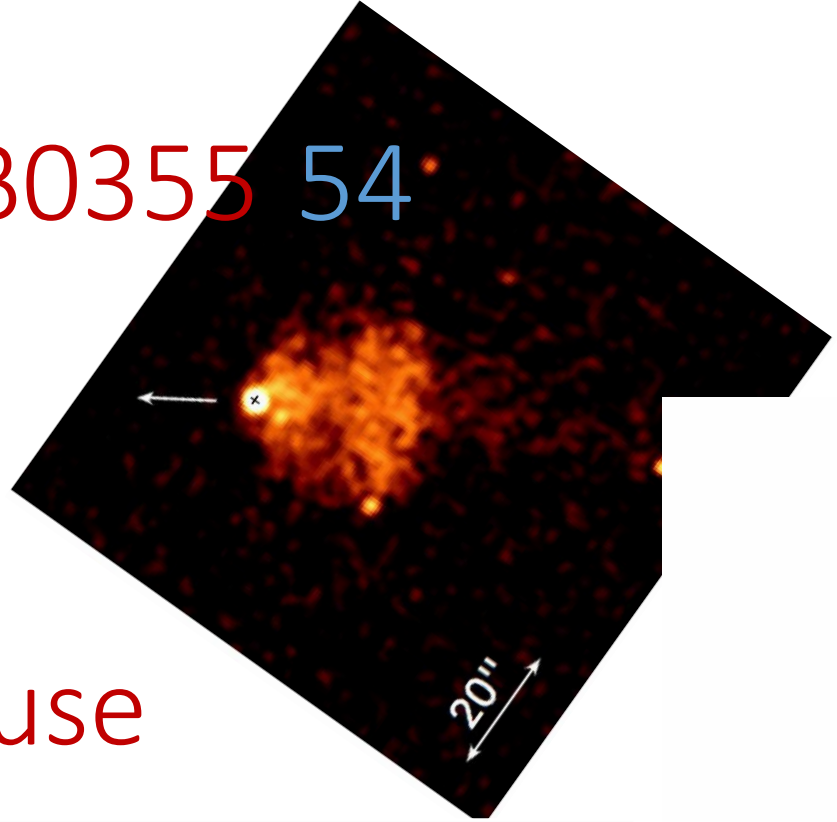




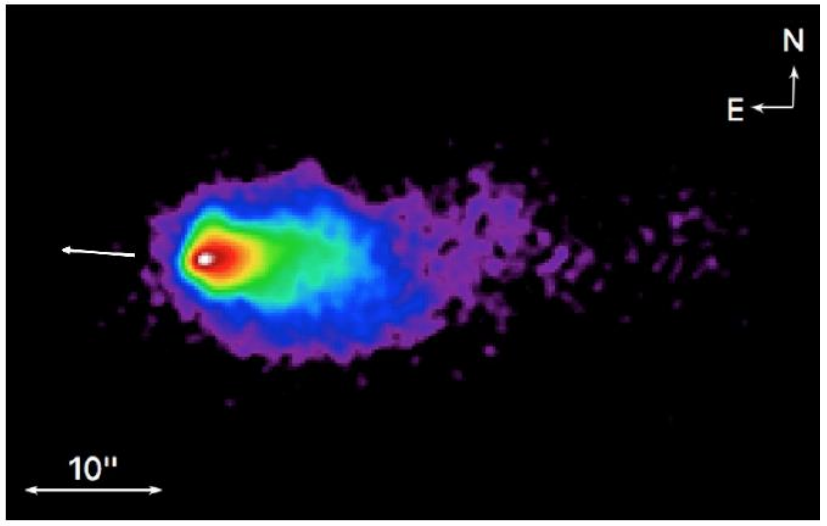


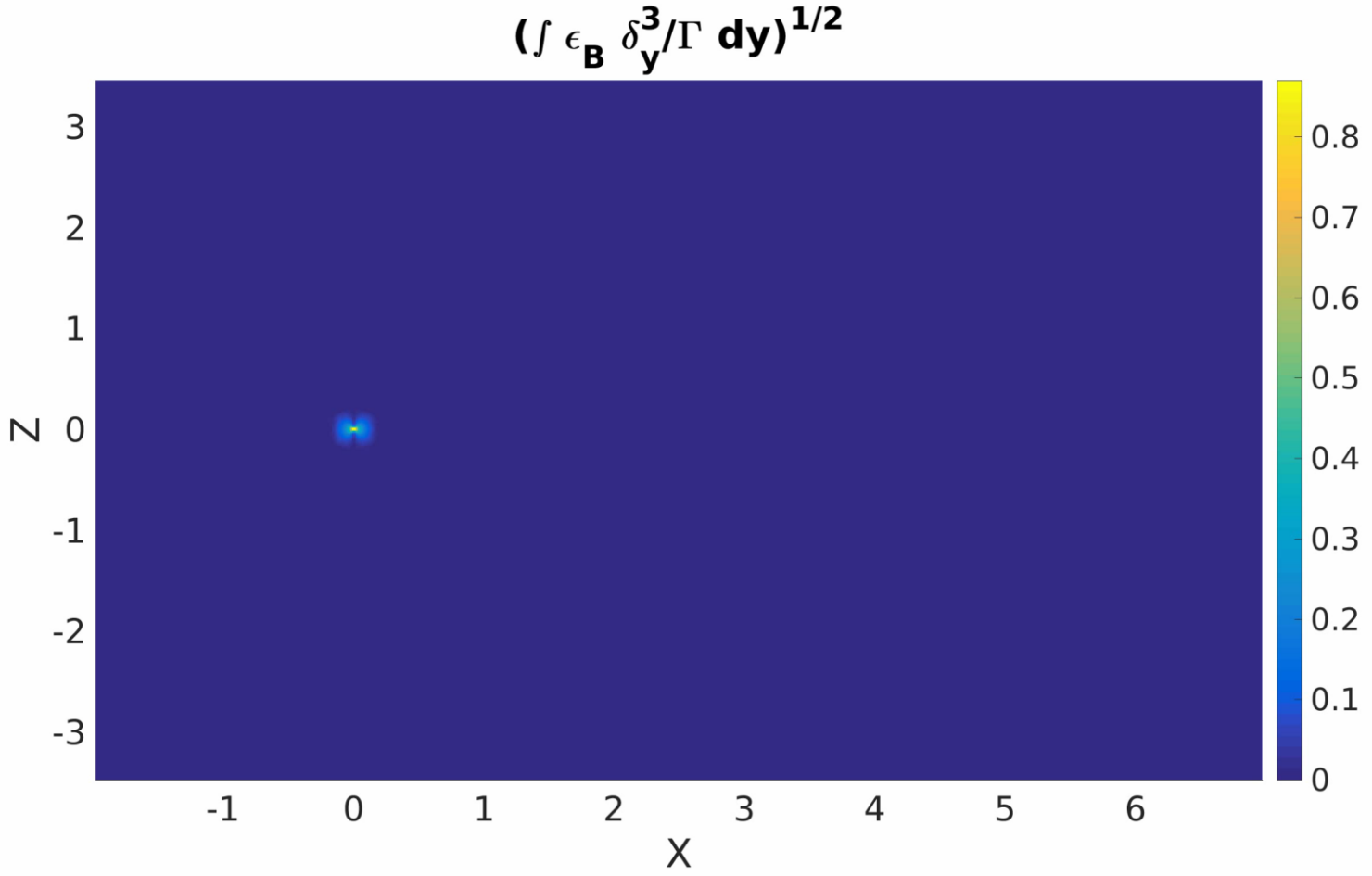
Barkov, Lyutikov and Khangulian (2019a)





Mouse

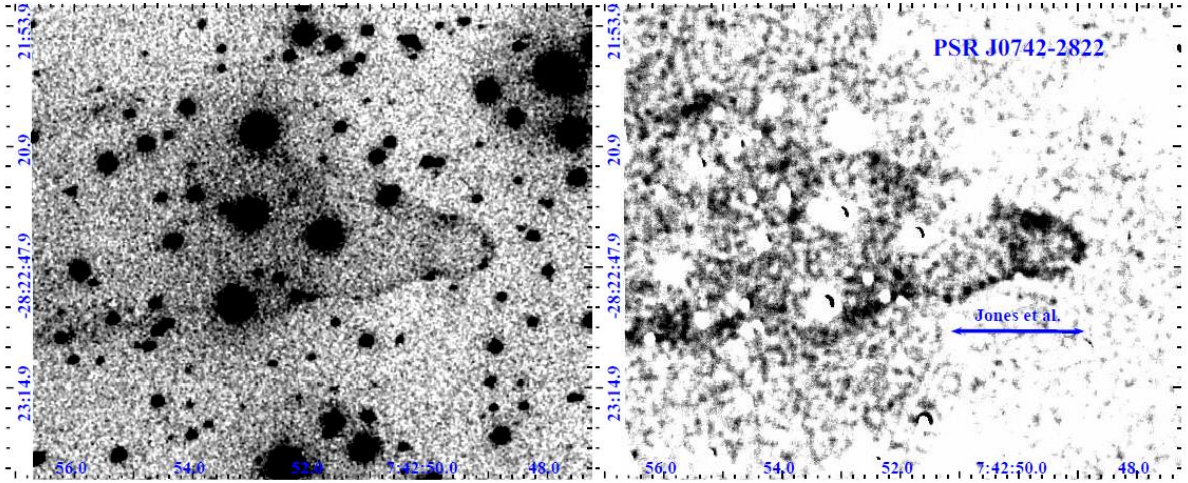


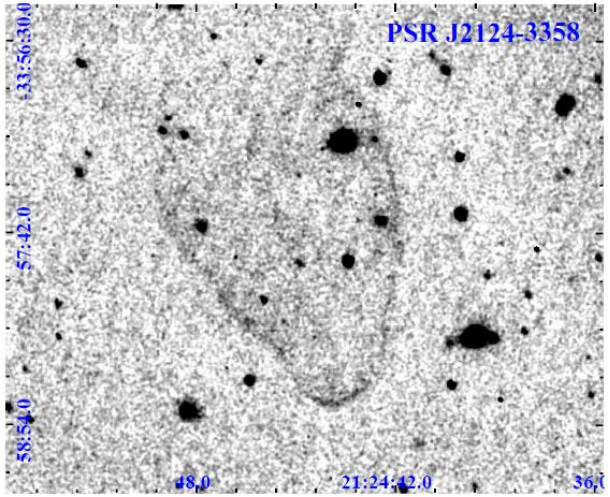


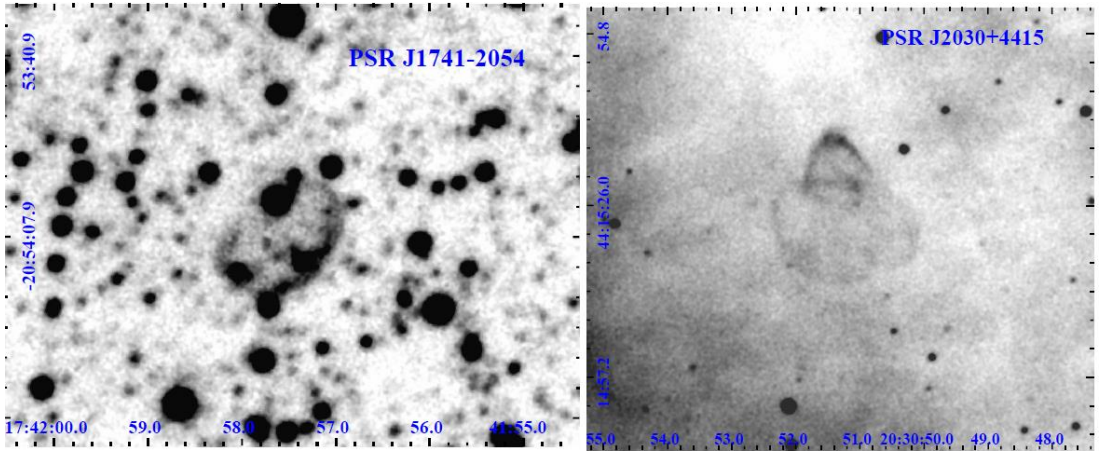
And one more thing…

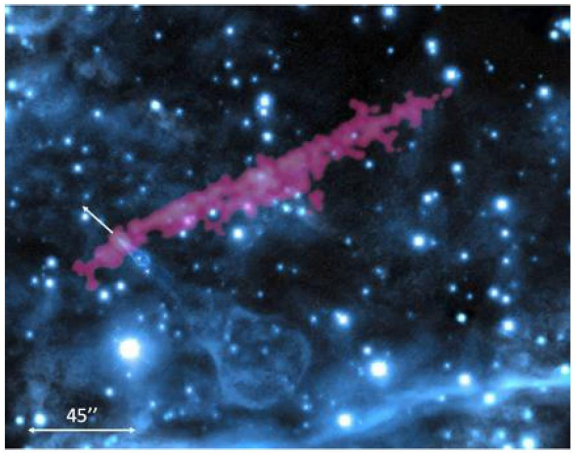
H_α emission

Brownsberger and Romani (2014)



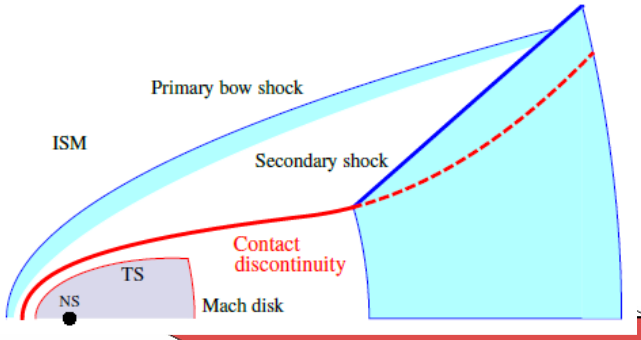




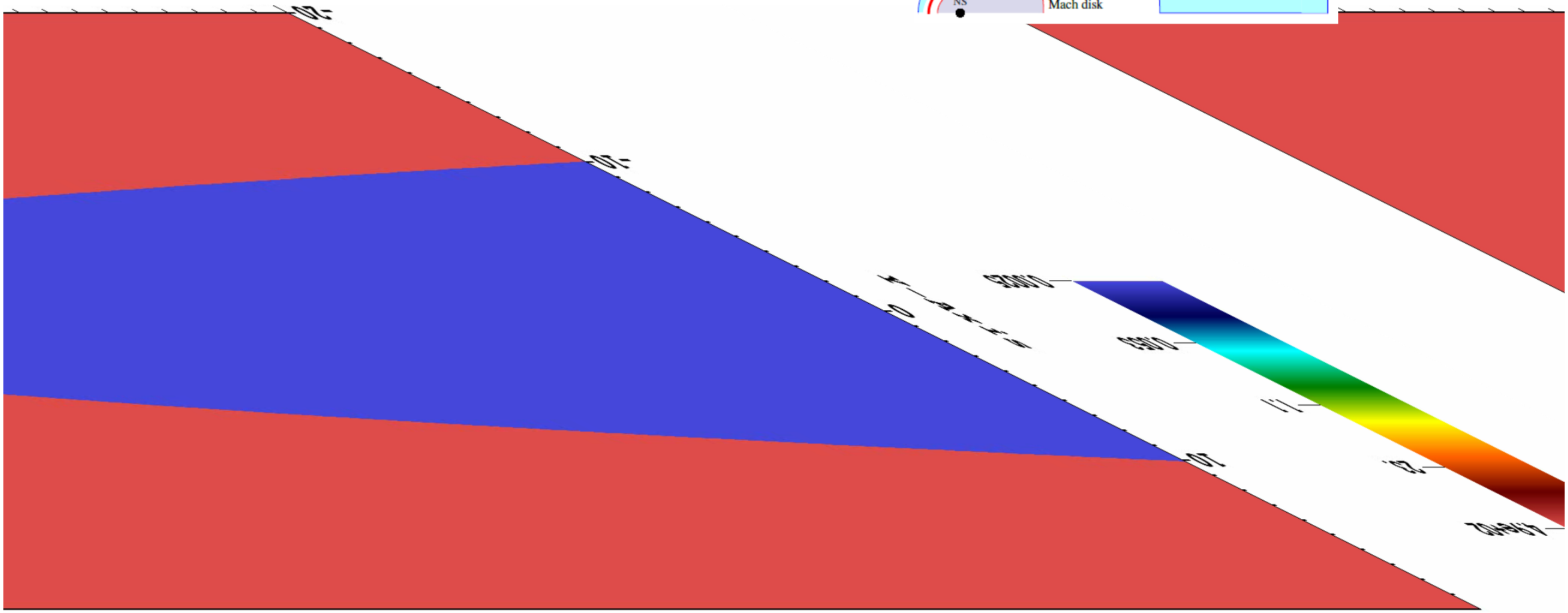


Reynolds et al. 2017

“Obstacles” in the tail?

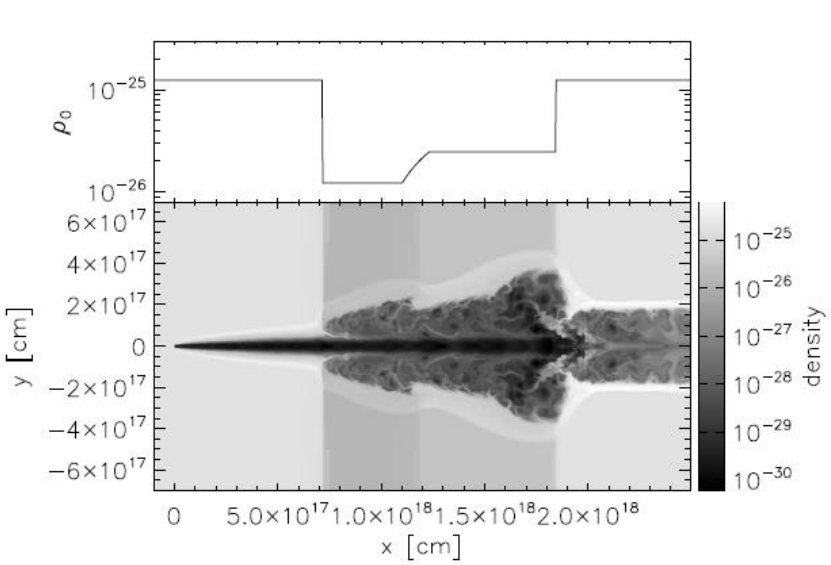


Morlino et al. 2015; Olmi et al. 2018

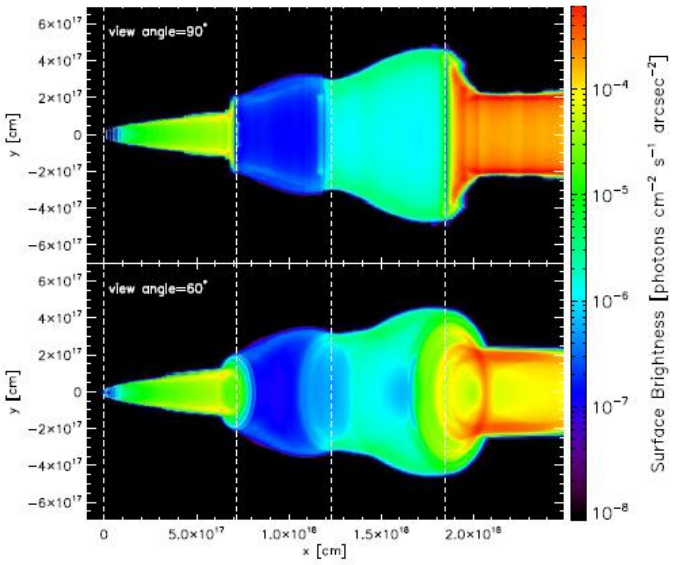


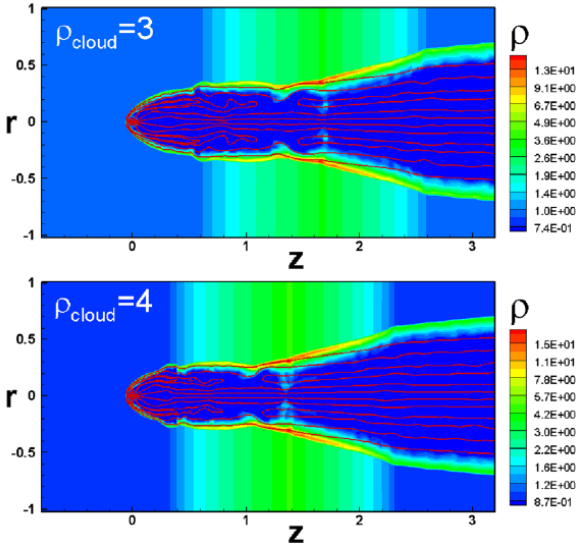
ISM variable density

Non relativistic (M)HD



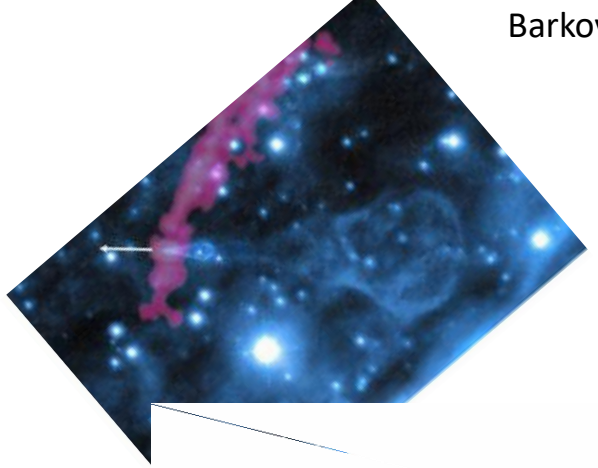
Yoon&Heinz 2017



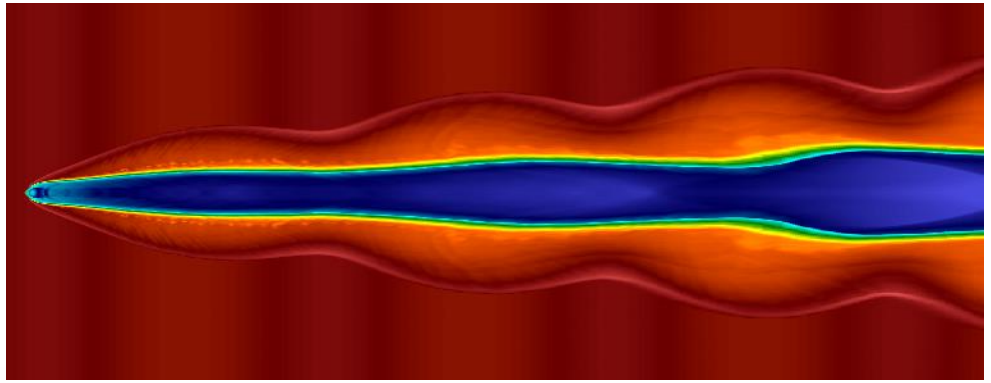


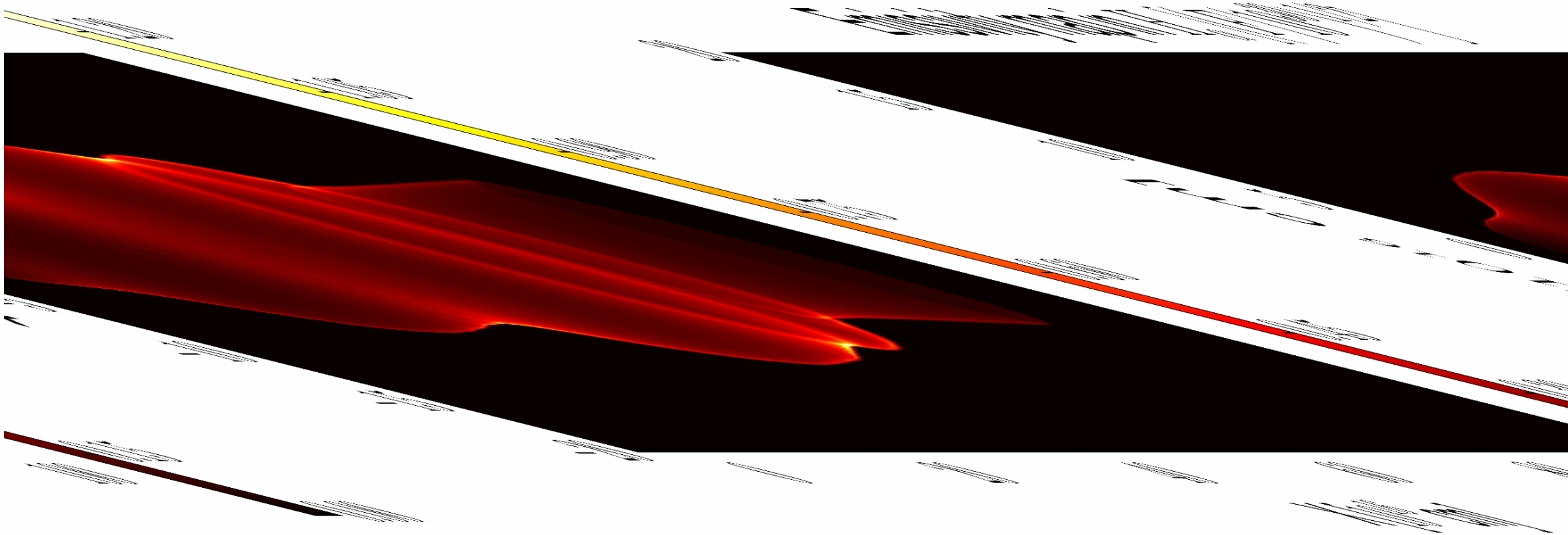
Toropina et al. 2019

Barkov, Lyutikov and Khangulian (in preparation)



H_α emission





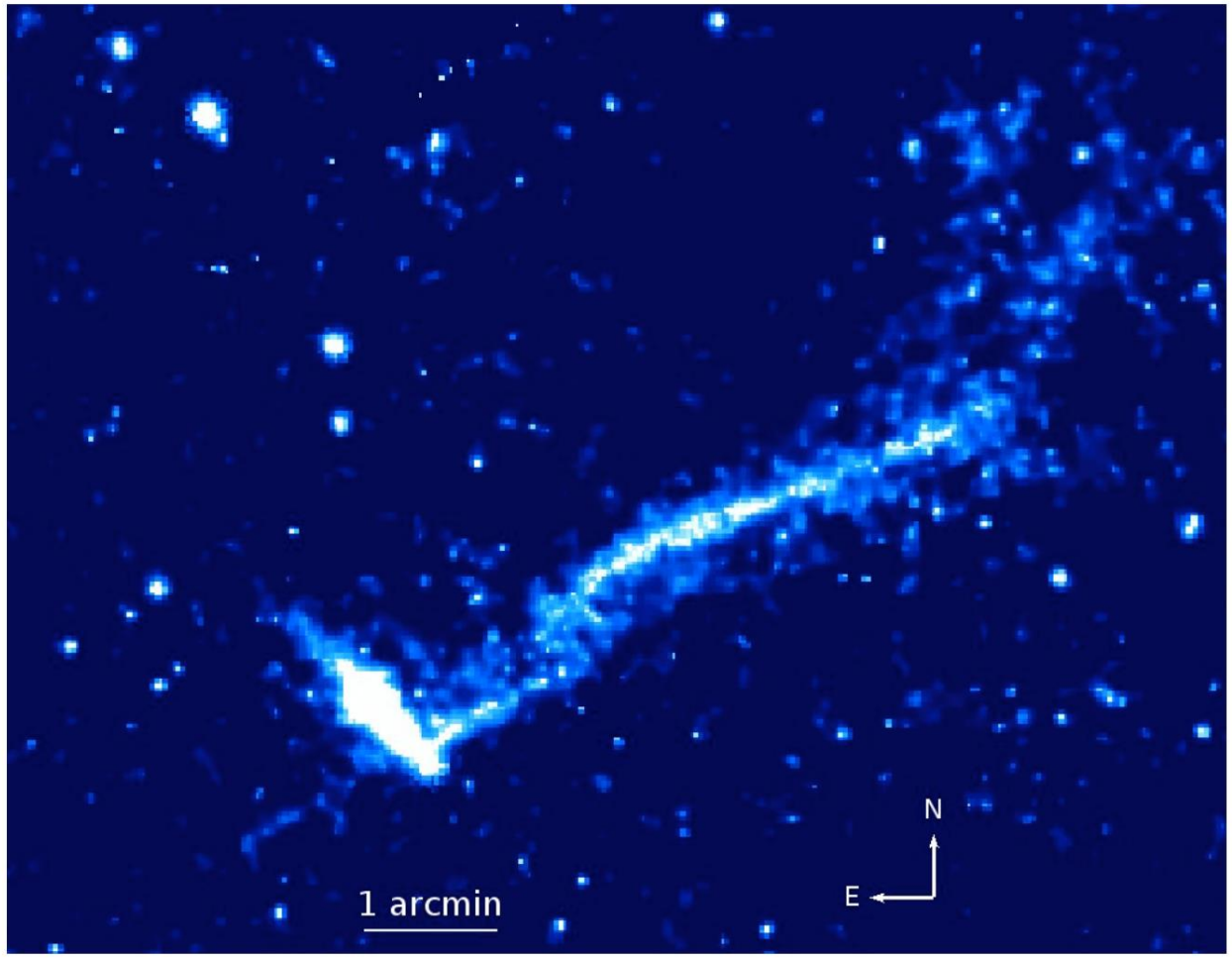
Kinetic meeting again…

Pulsar's "Jet"

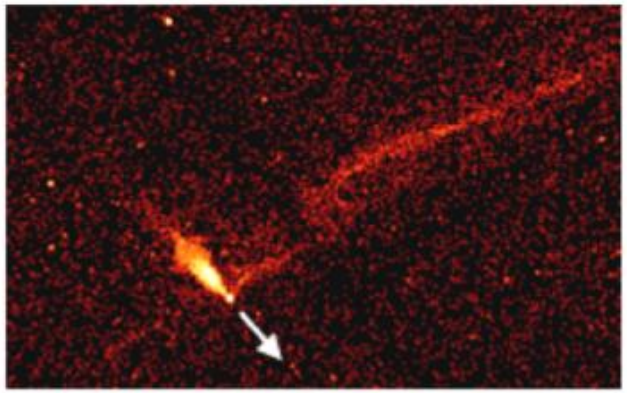
IGR J11014-6103 jets

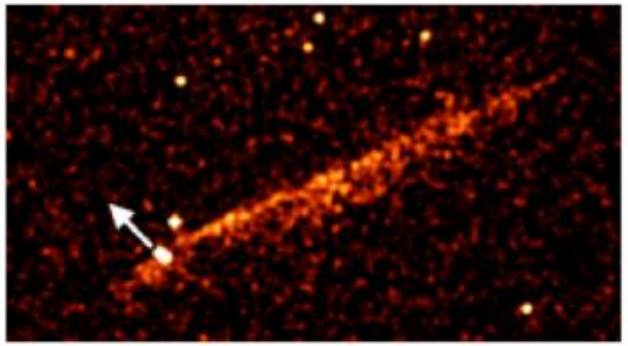
Pavan et al. 2014

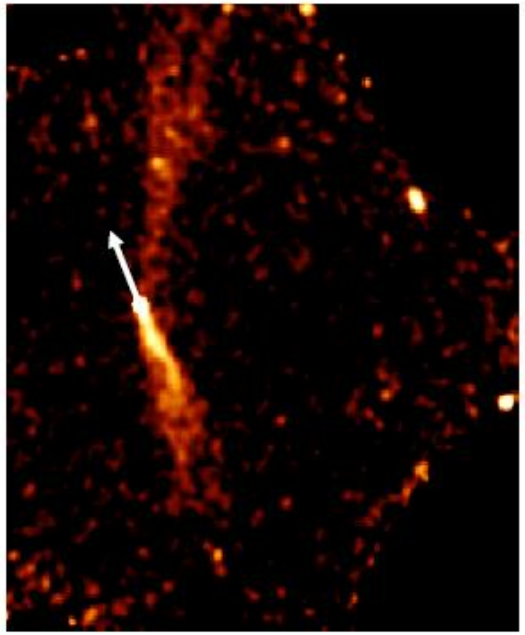
- @ 7 kpc, $l_{jet} \geq 11.5$ pc
  (longest jet in the Galaxy)
- precession-like pattern
- faint counter-jet (Doppler)
- chance prob. ~ negligible
  - alignement jet/counter-jet
  - flux change @ "PSR" position
- main jet ~ 1/3 of total flux
- no signatures of bending
  (diffuse emission @ jet tip?)

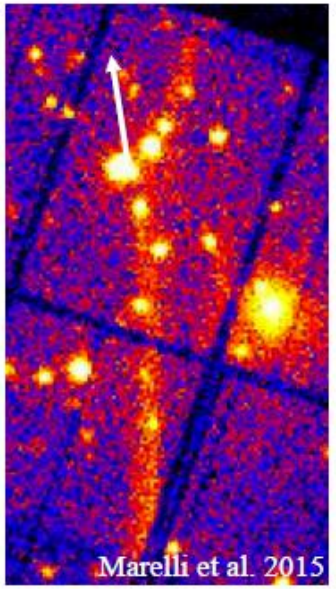


Pulsar's "Jet"



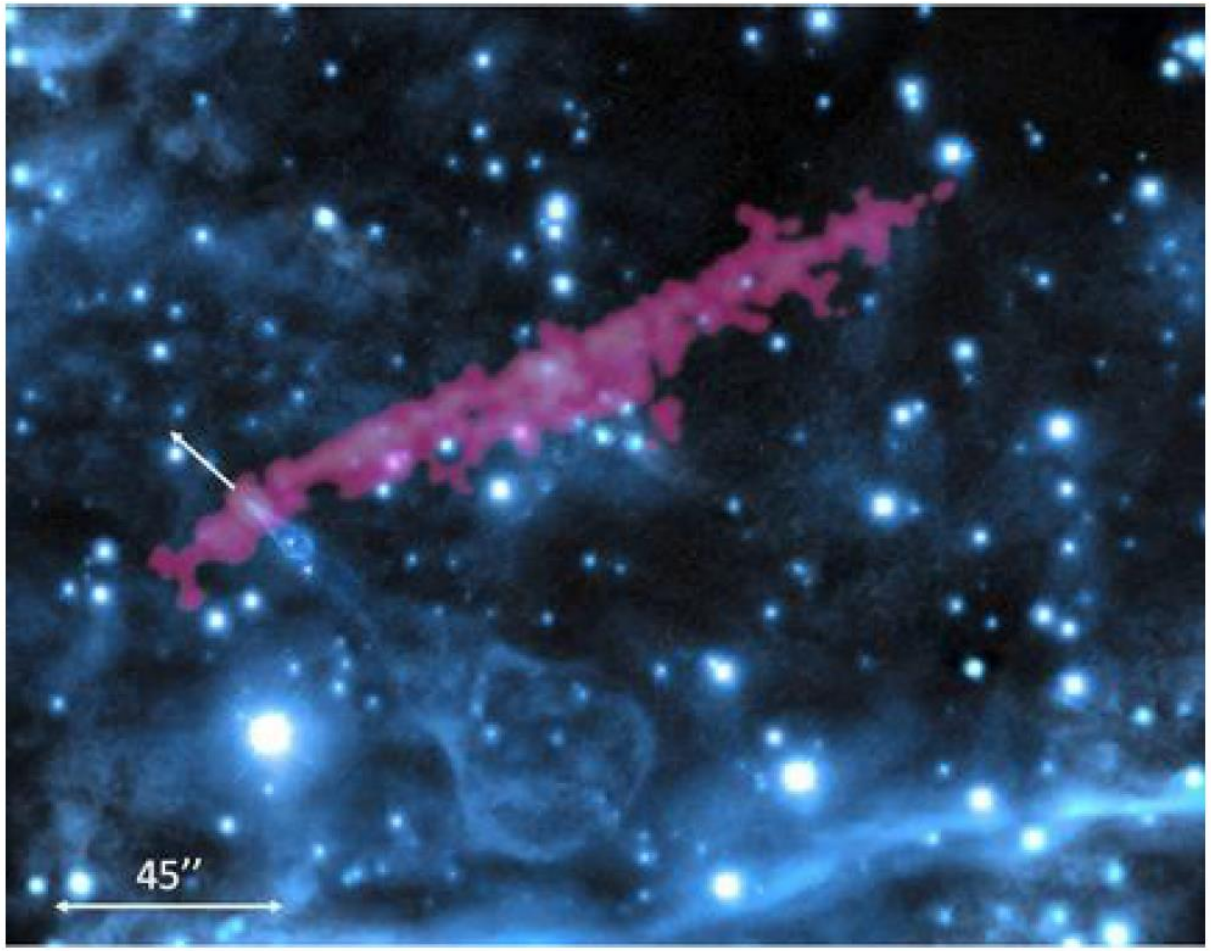






Marelli et al 2015
Klingler et al 2016

Guitar – X-ray and Hα

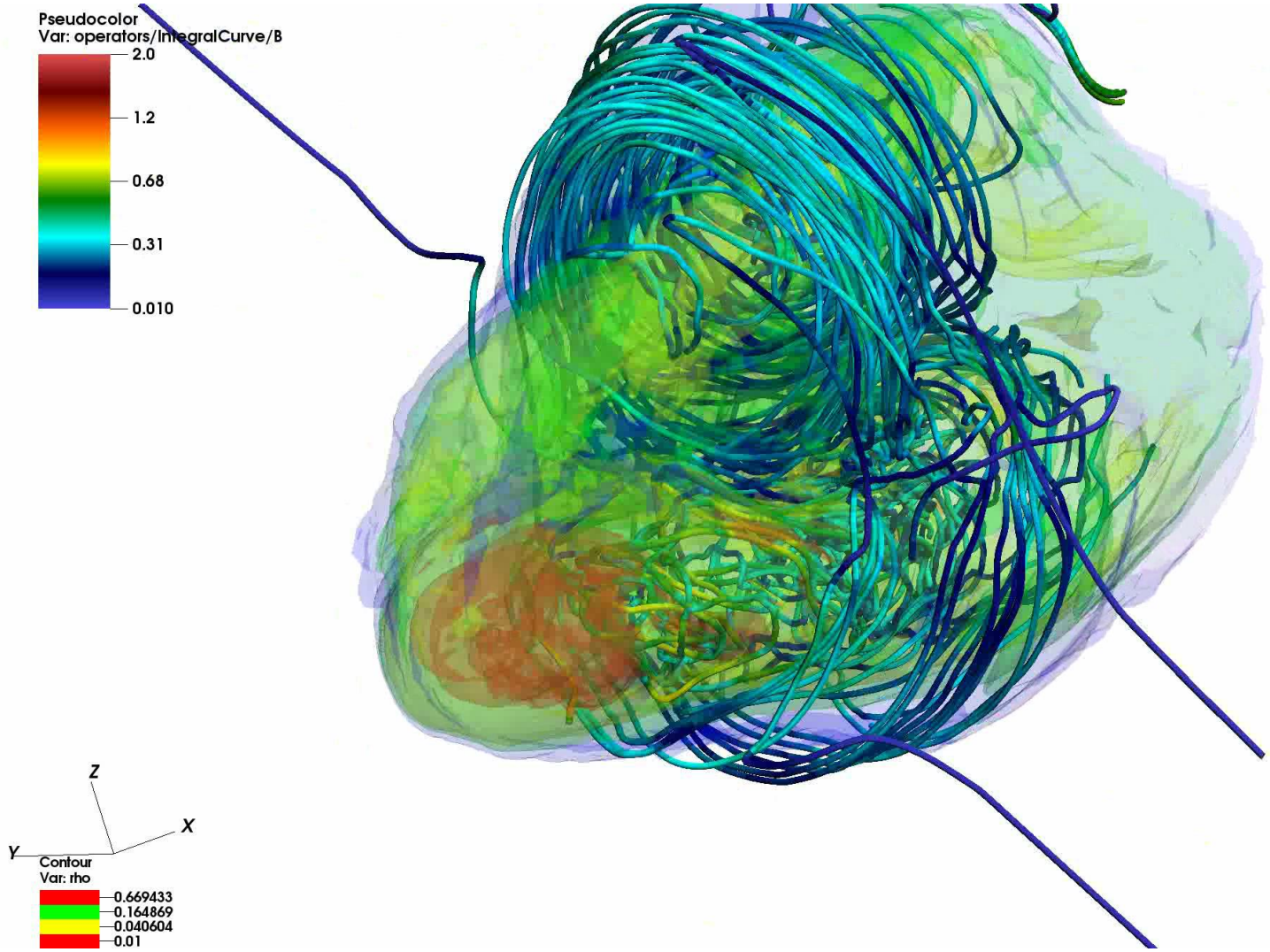


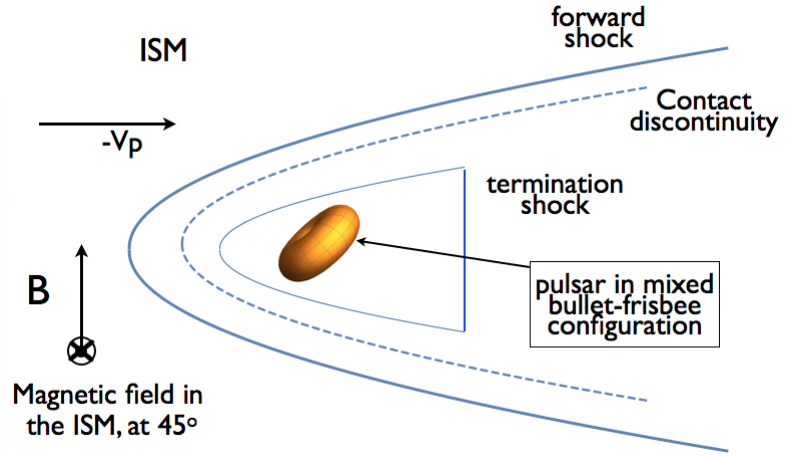
Reynolds et al. 2017

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

Barkov, Lyutikov, Klingler and Bordas (2019b)

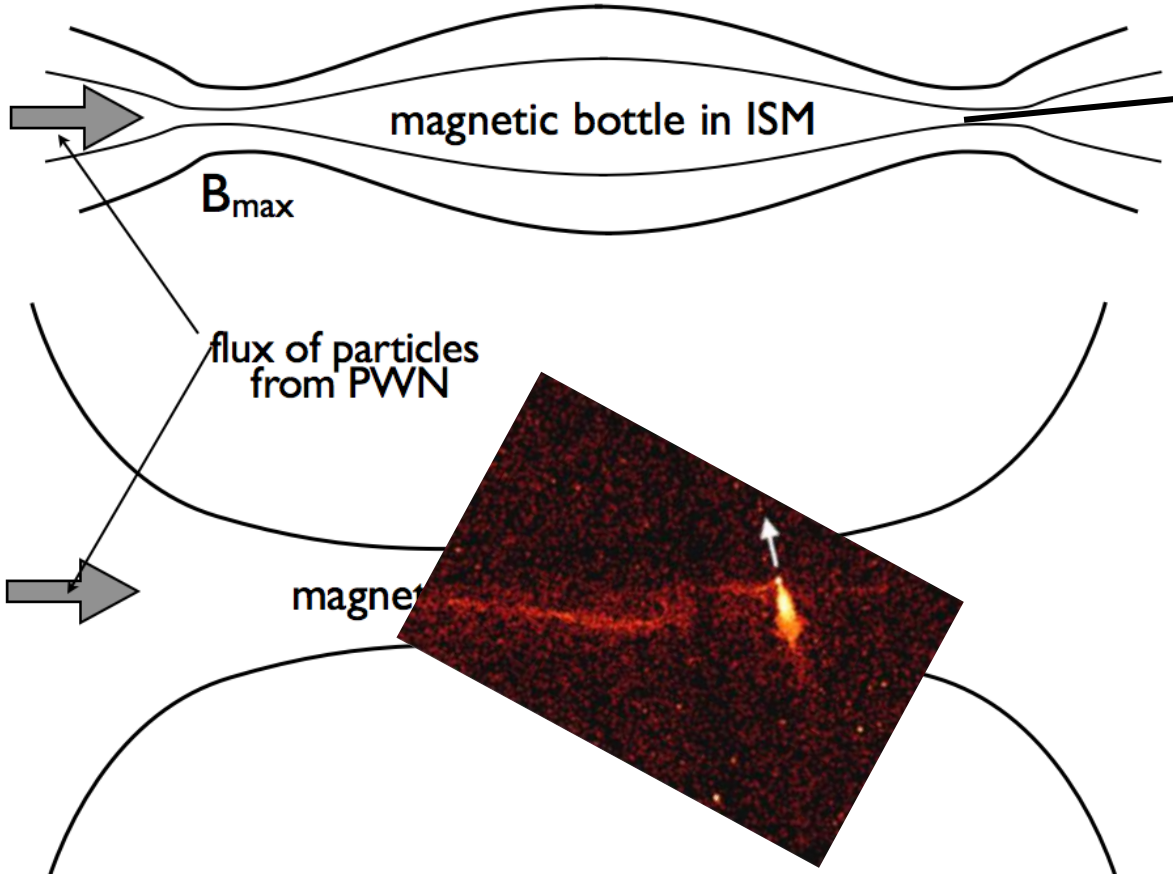
Pulsar and ISM interaction

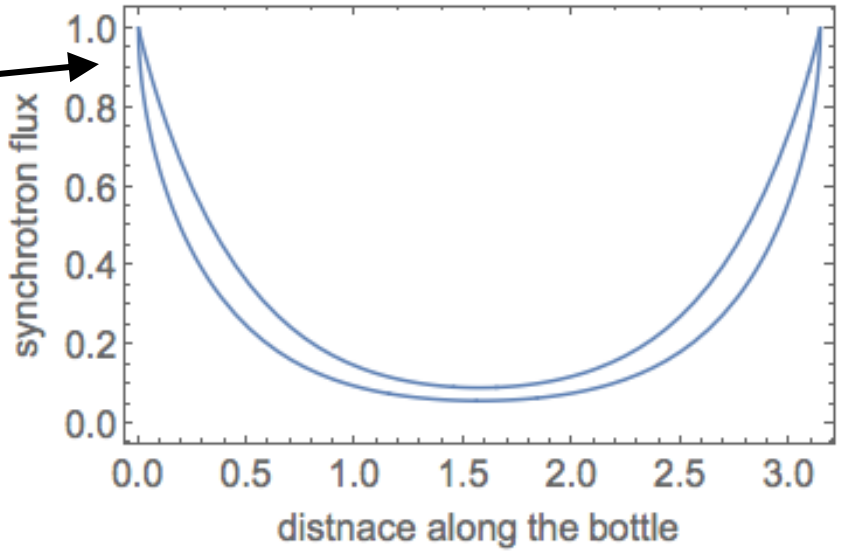




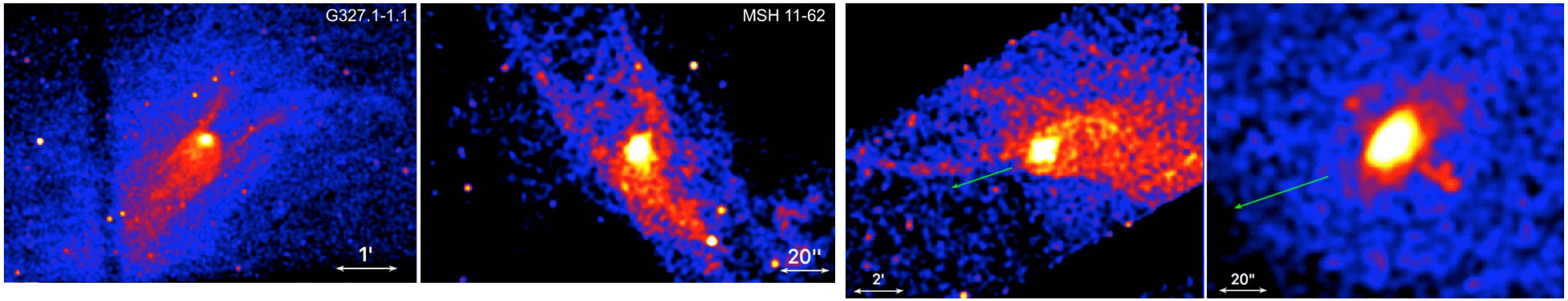
Barkov, Lyutikov, Klingler and Bordas (2019b)

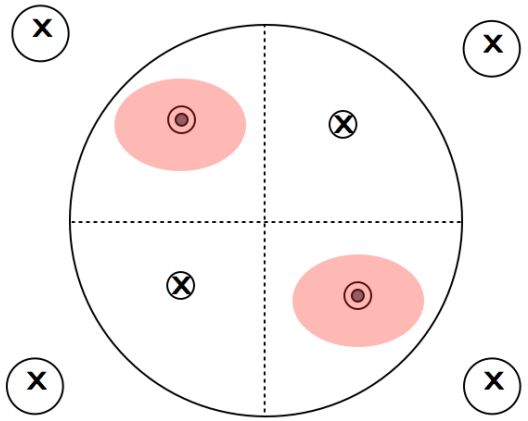
Magnetic anti-bottle?

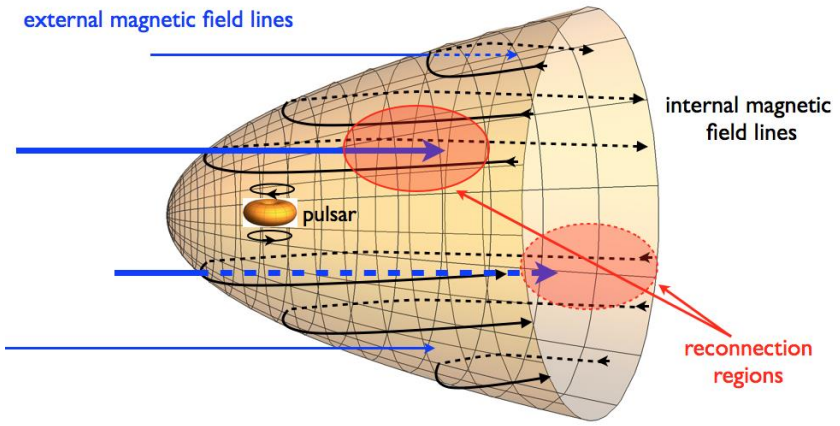


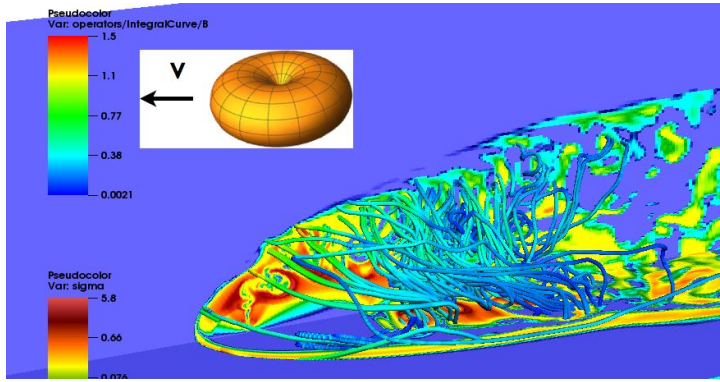


Snail eyes.





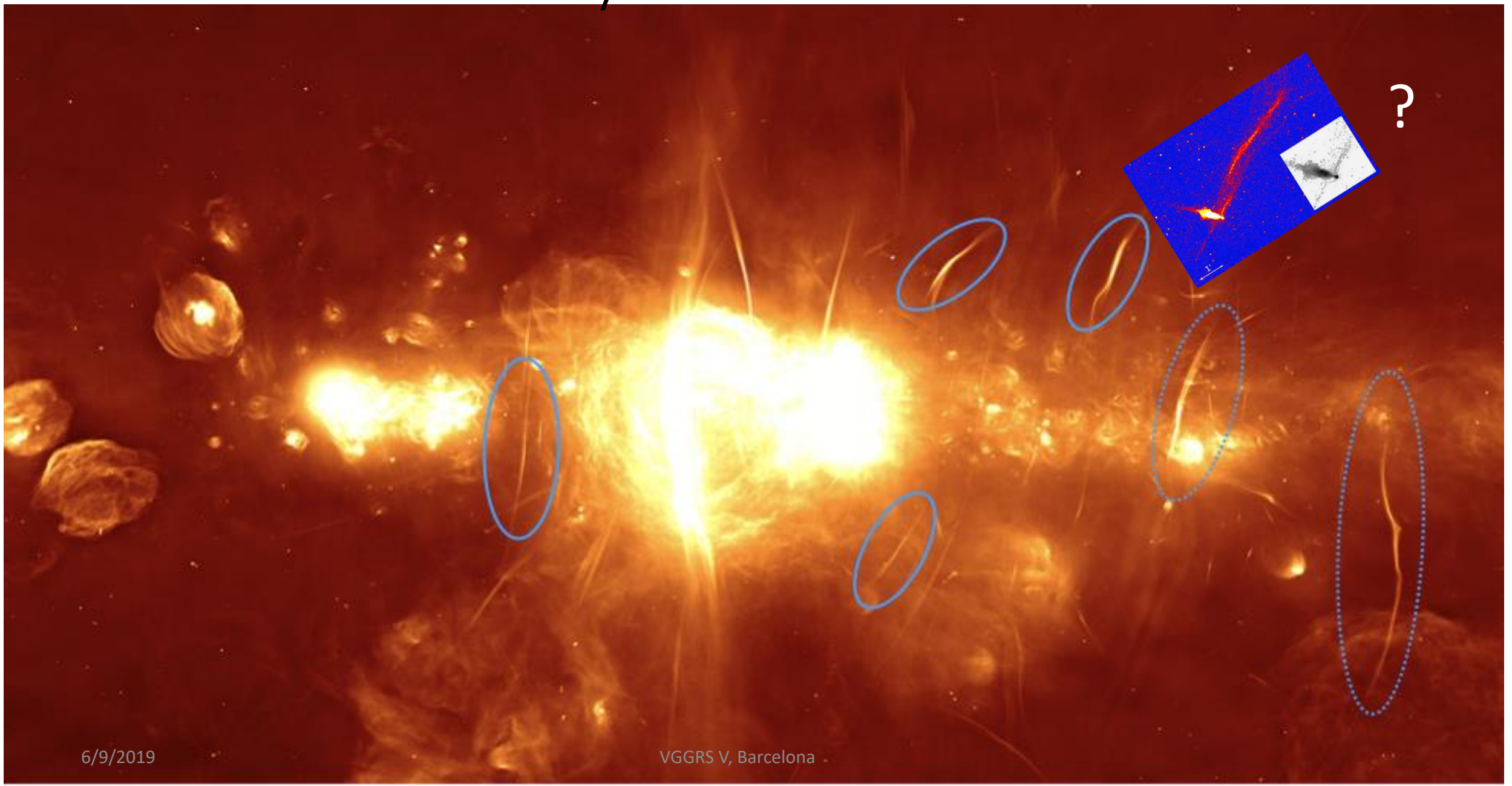




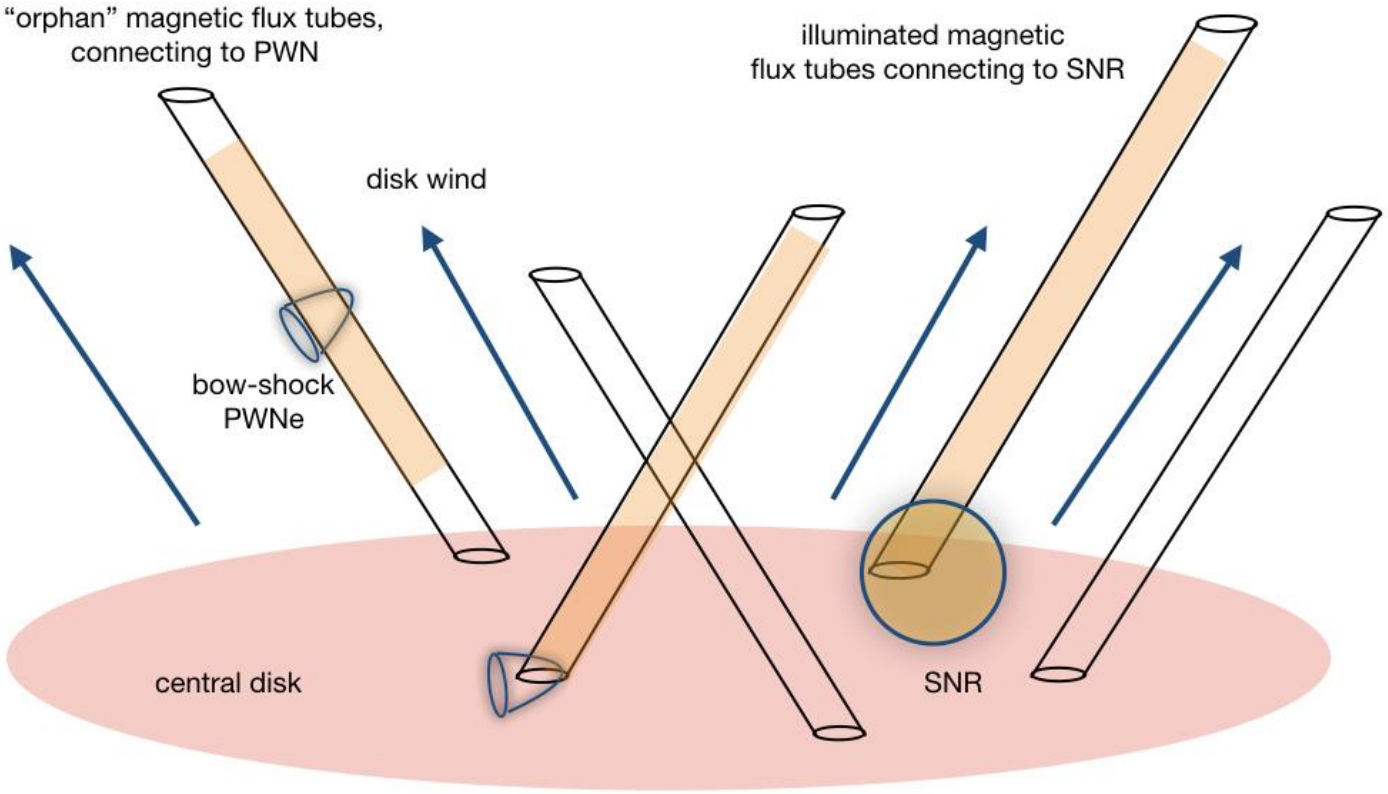
Barkov, Lyutikov, Klingler and Bordas (2019b)

And the rotor filaments again…

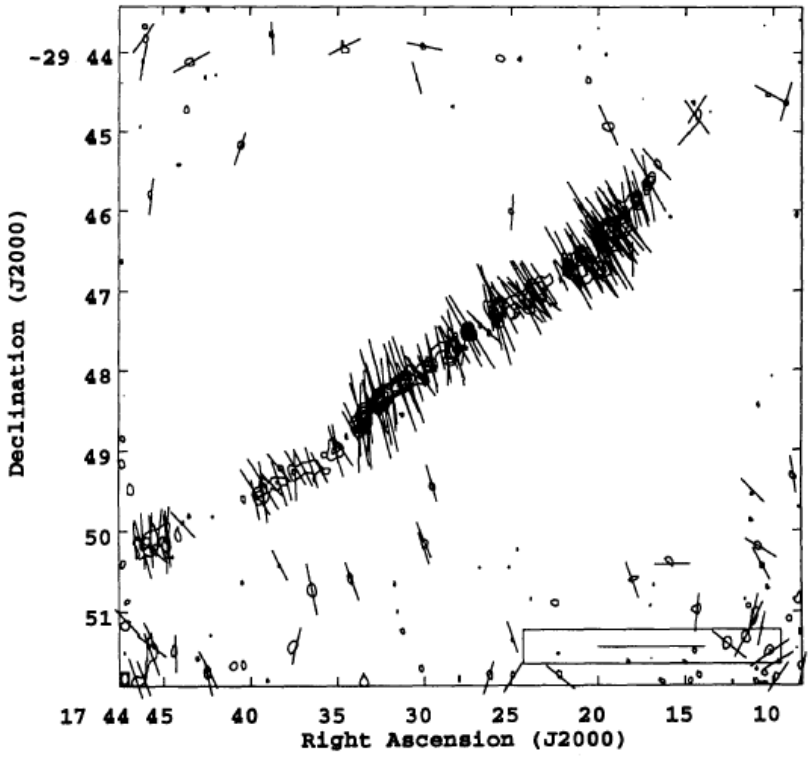
Galactic center by MeerKAT



Our idea



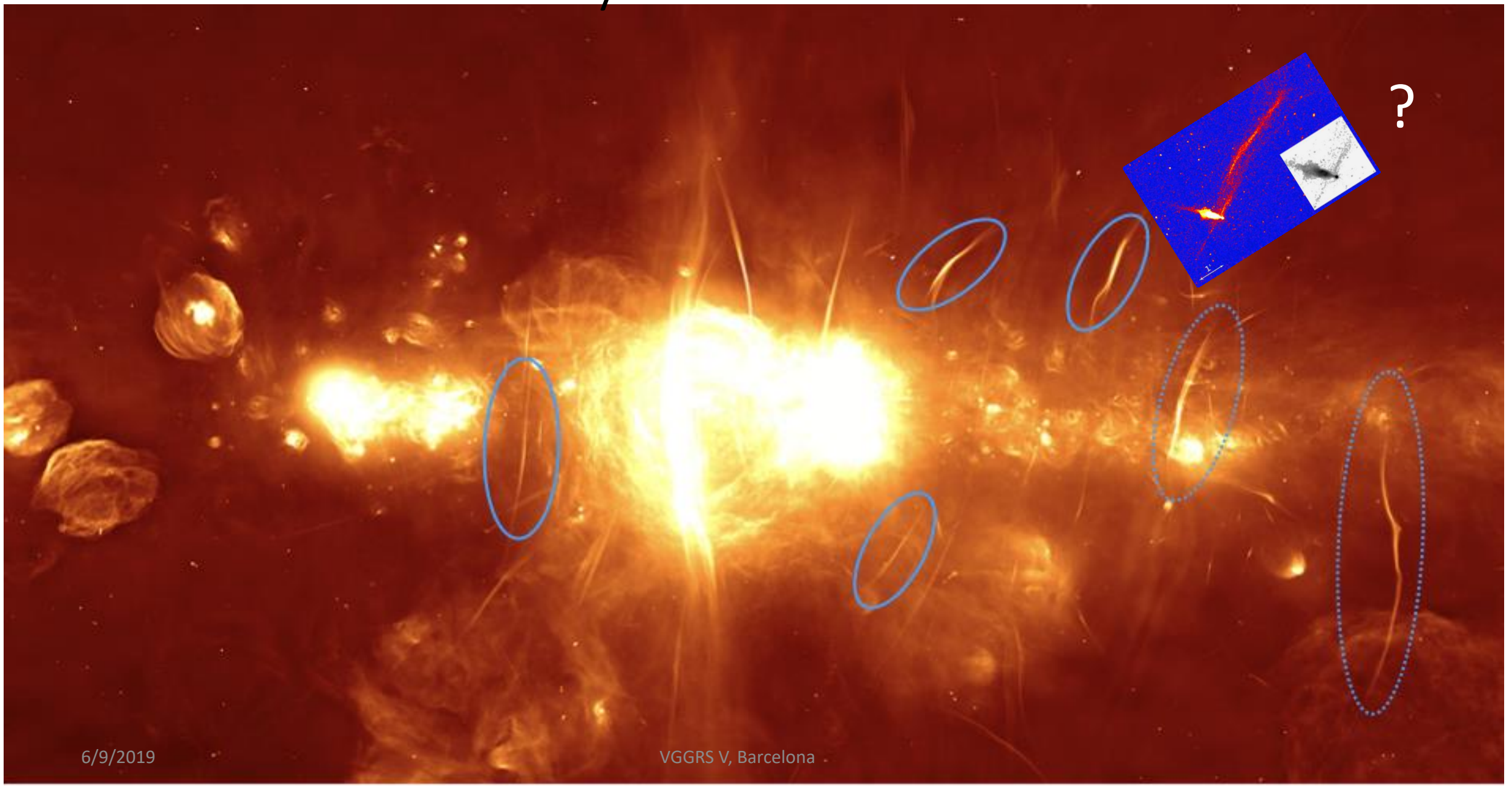
Barkov & Lyutikov 2019c



Gray et al. 1995

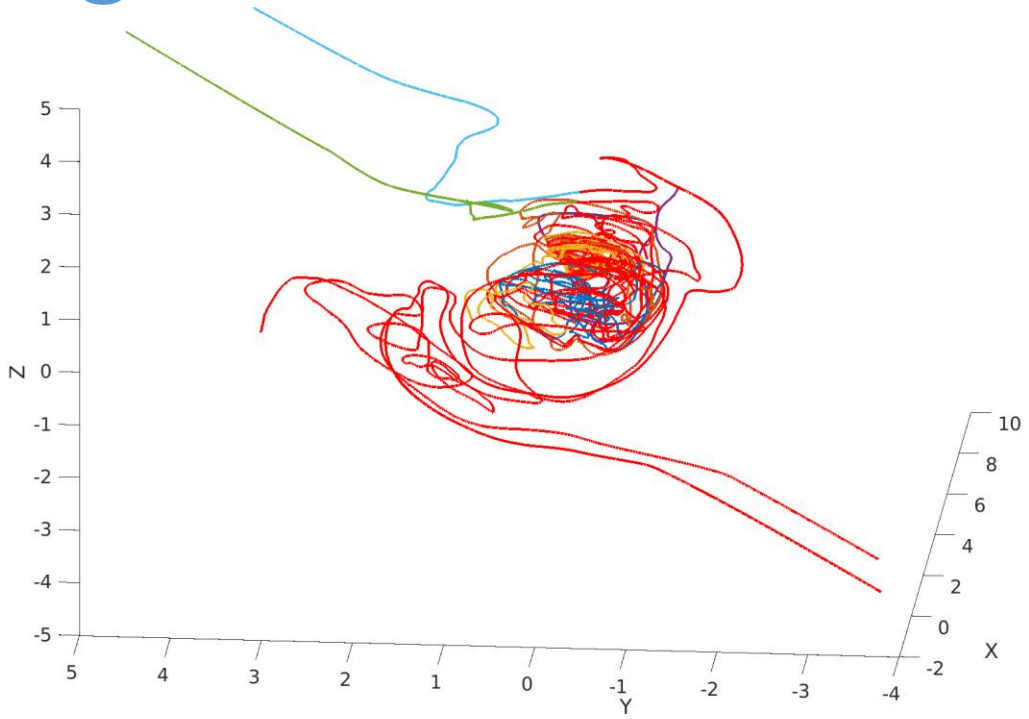
Thank you!

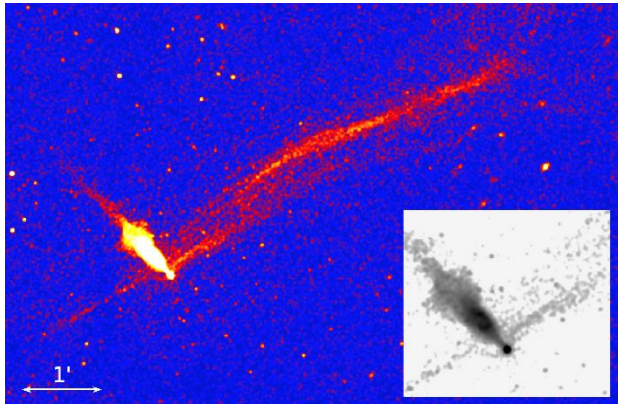
Galactic center by MeerKAT

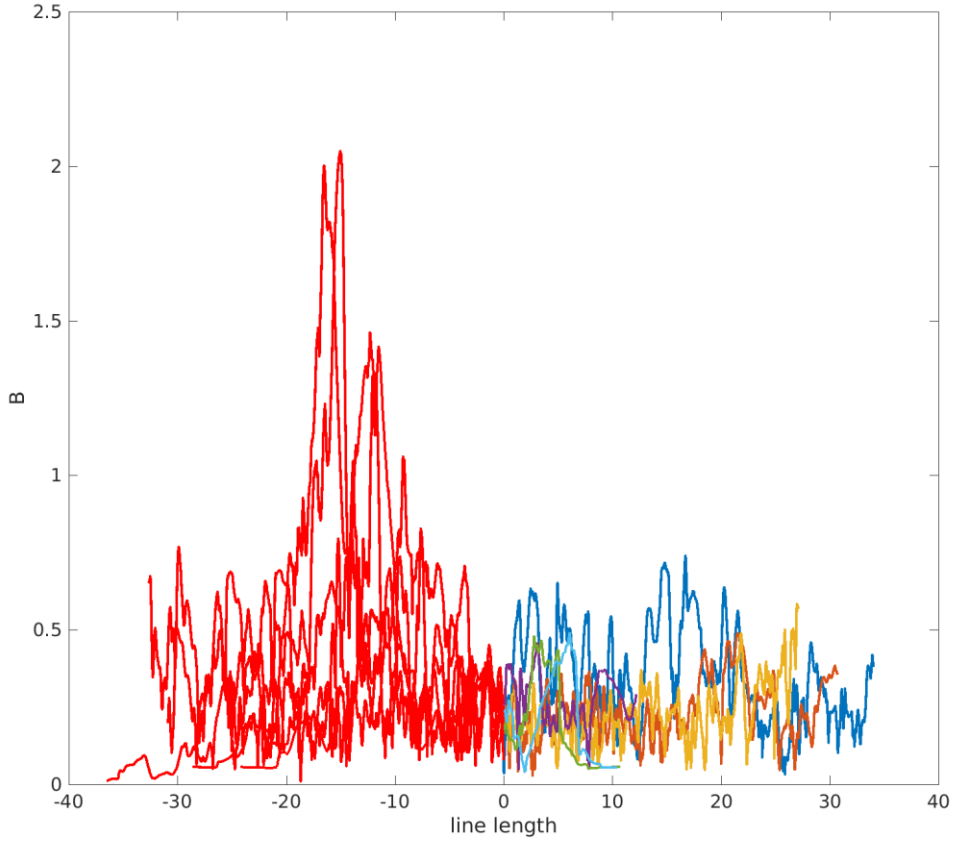


BMV, Lyutikov, Klingler and Bordas (2019b)

Magnetic bottle?

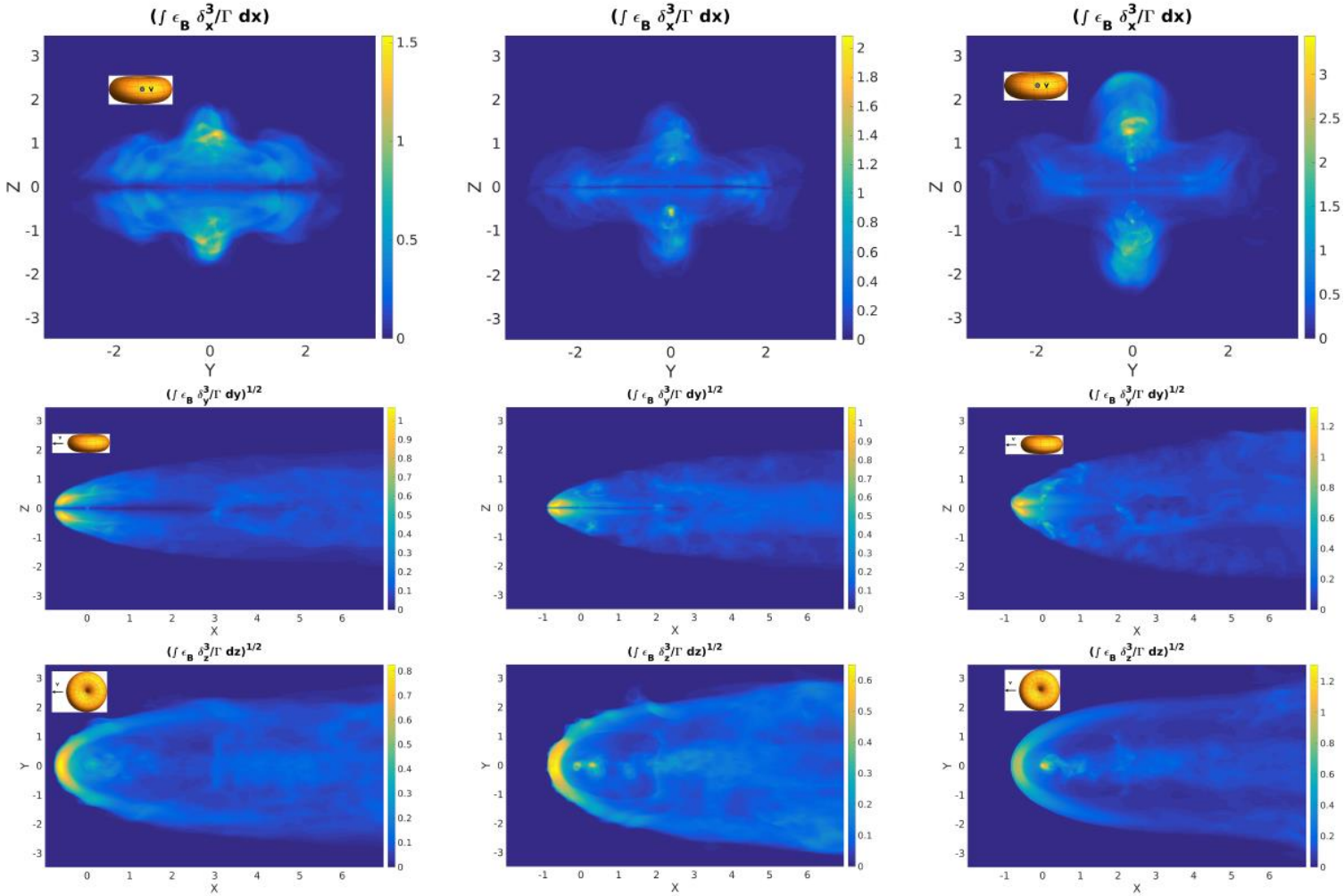


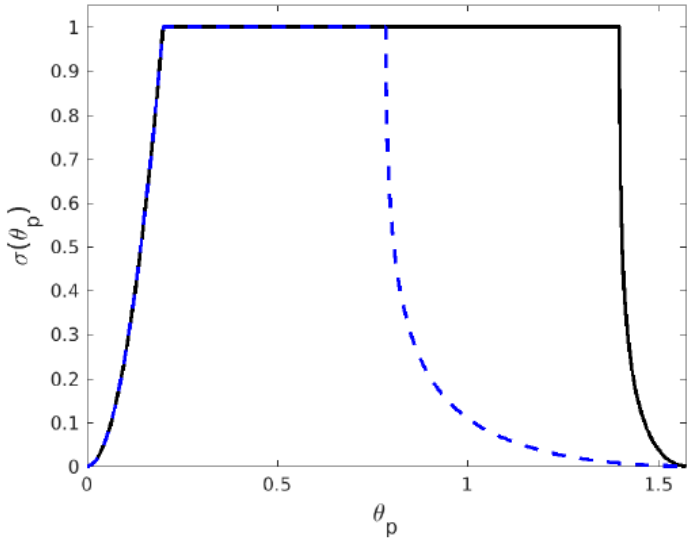


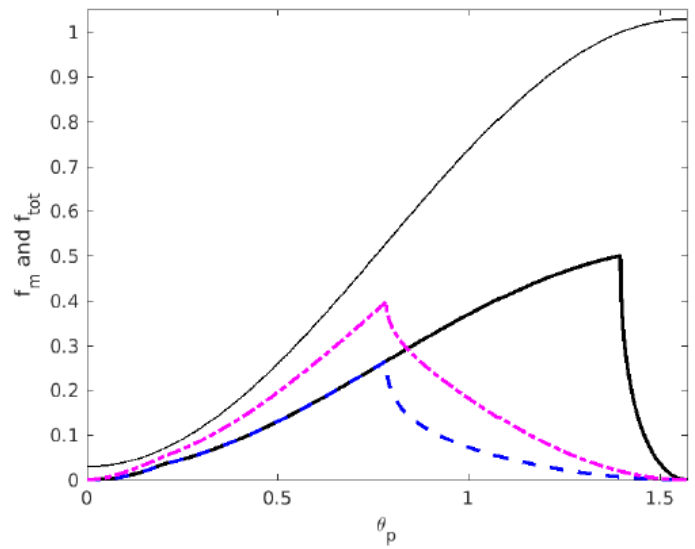


$$p_{esc} = 1 - \sqrt{1 - \frac{1}{R}} \approx \frac{1}{2R}$$

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


$(\int \epsilon_B \delta_x^3/\Gamma\, dx)$
$(\int \epsilon_B \delta_y^3/\Gamma\, dy)^{1/2}$
$(\int \epsilon_B \delta_z^3/\Gamma\, dz)^{1/2}$
Z
Y
X


$\sigma(\theta_p)$
θ_p


f_m and f_{tot}
θ_p

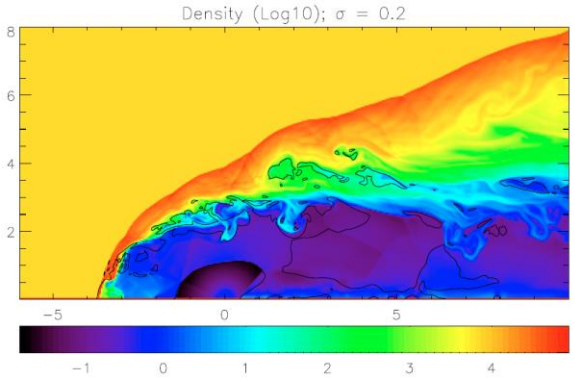
Pulsar and ISM interaction

Barkov, Lyutikov and Khangulian (2019a)

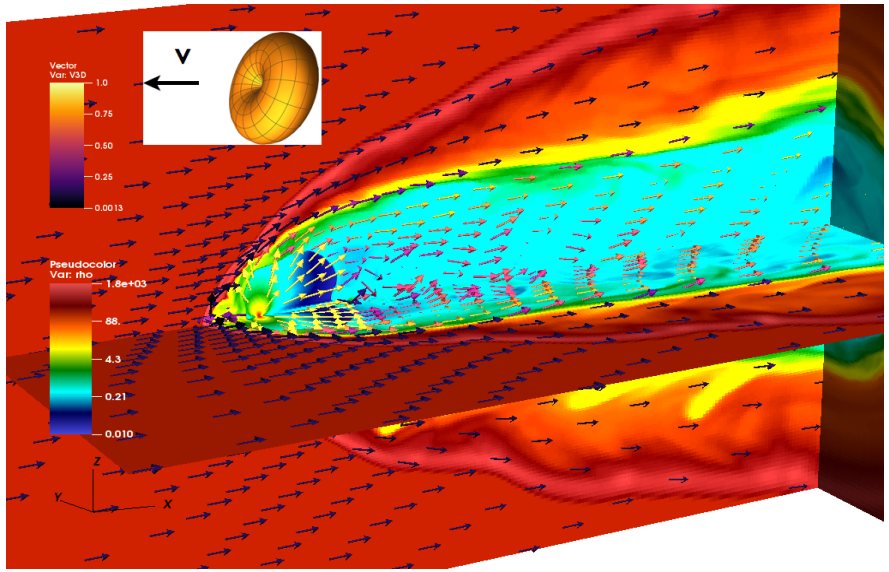
3D RMHD

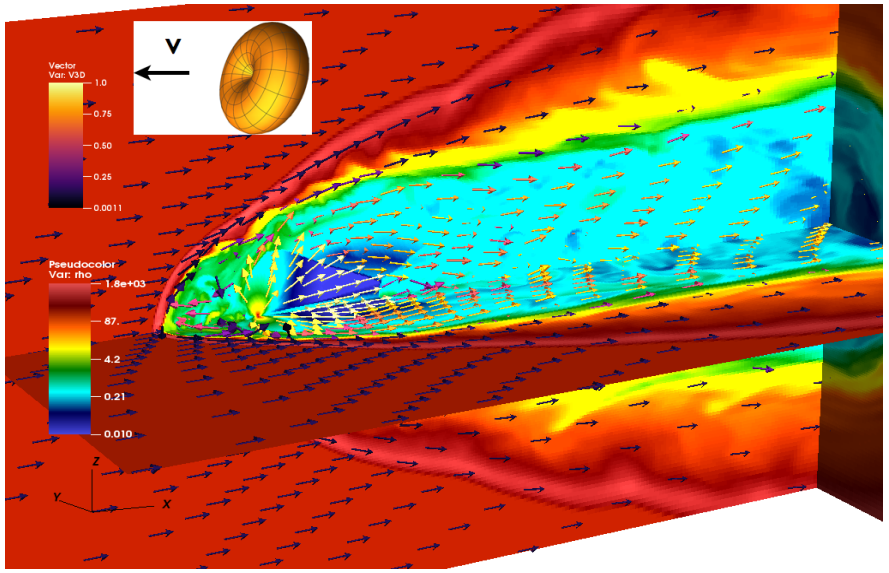
Density & velocity

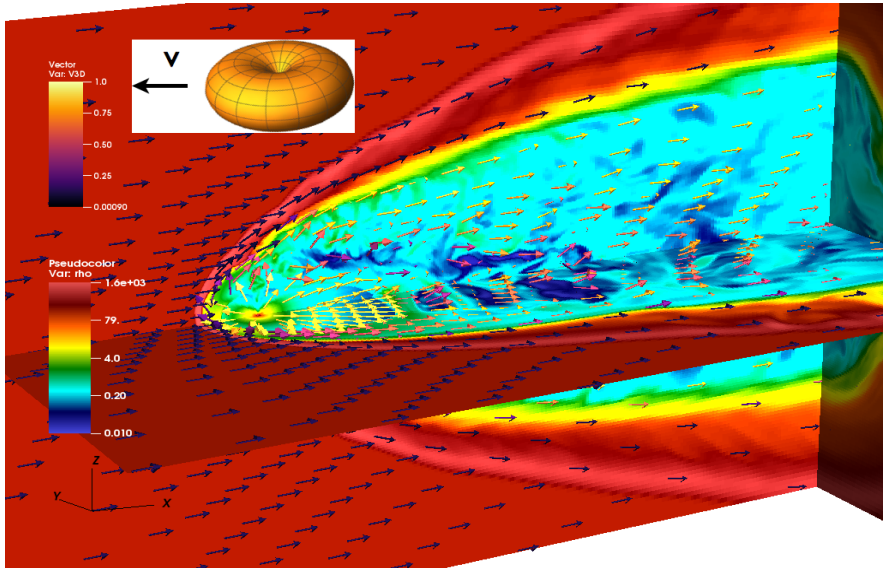
Bullet geometry

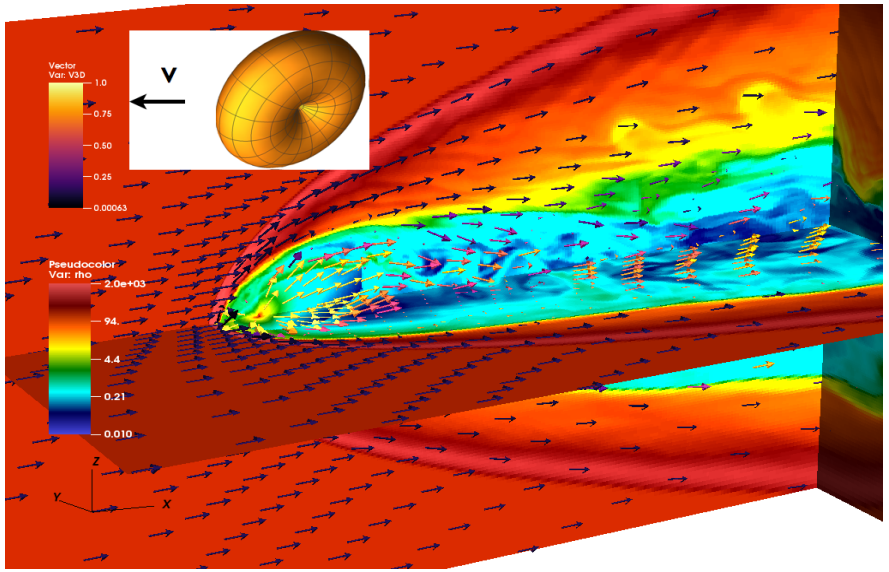


Frisbee geometry



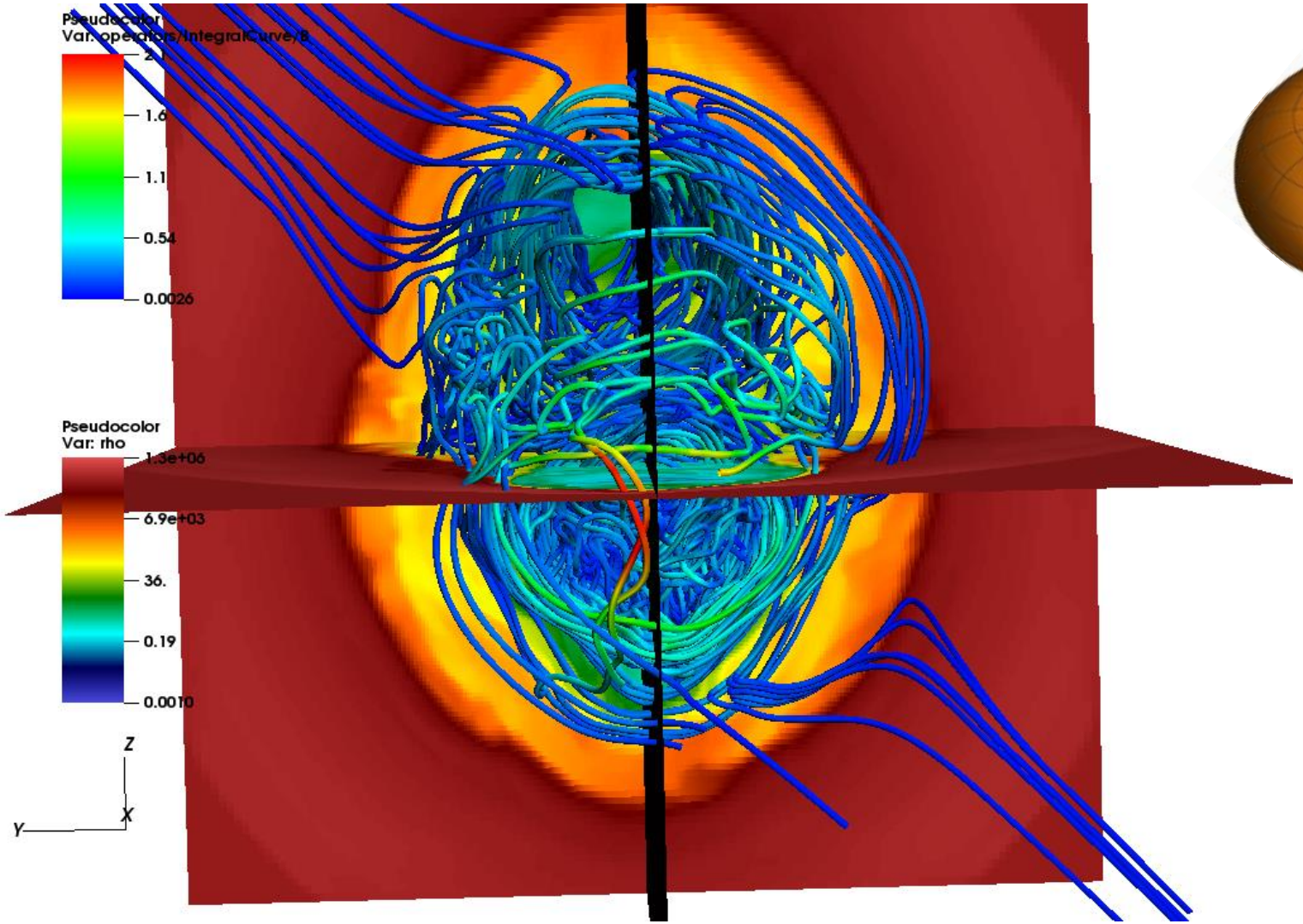


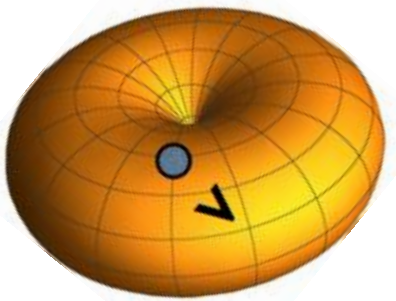




BMV, Lyutikov, Klingler and Bordas (2018)

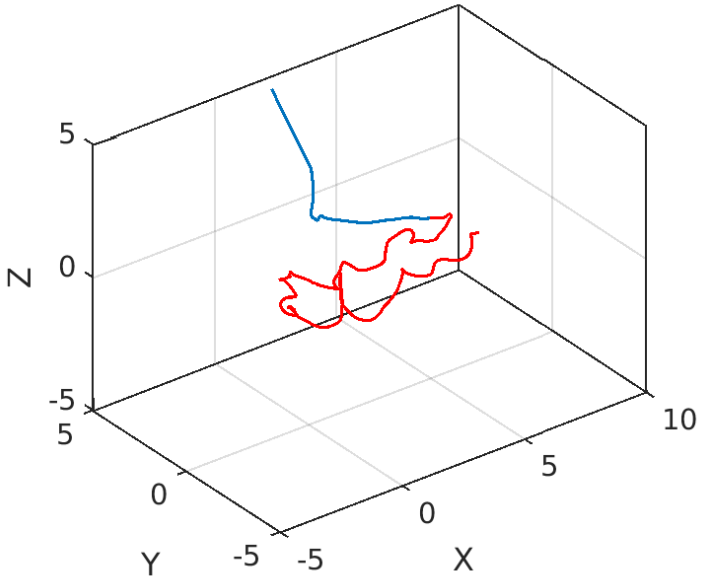
Magnetic field lines

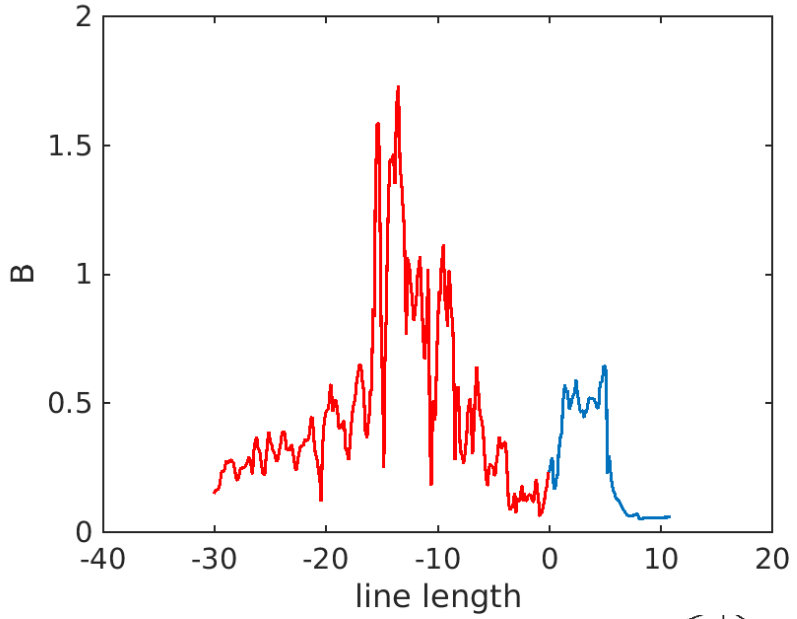


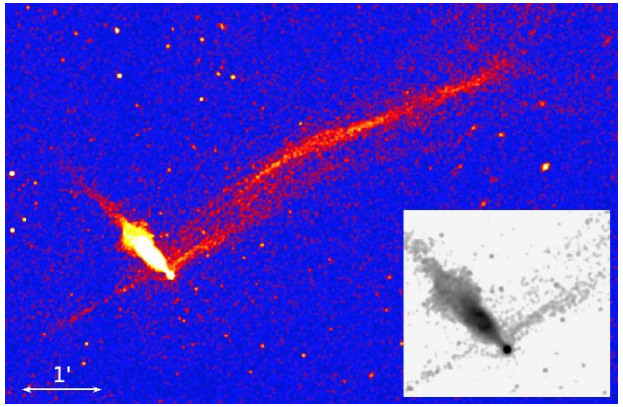


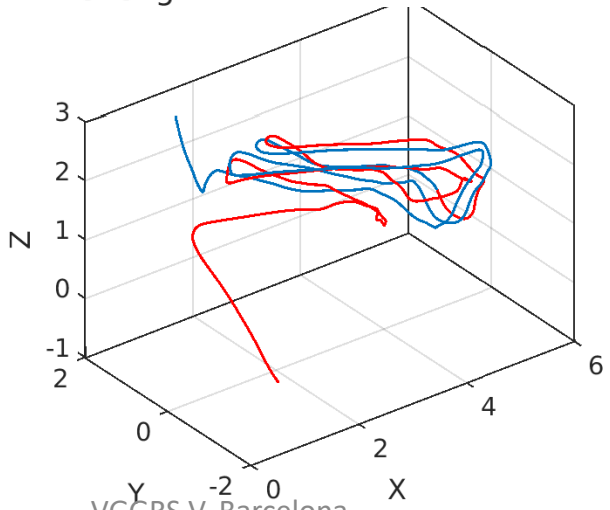
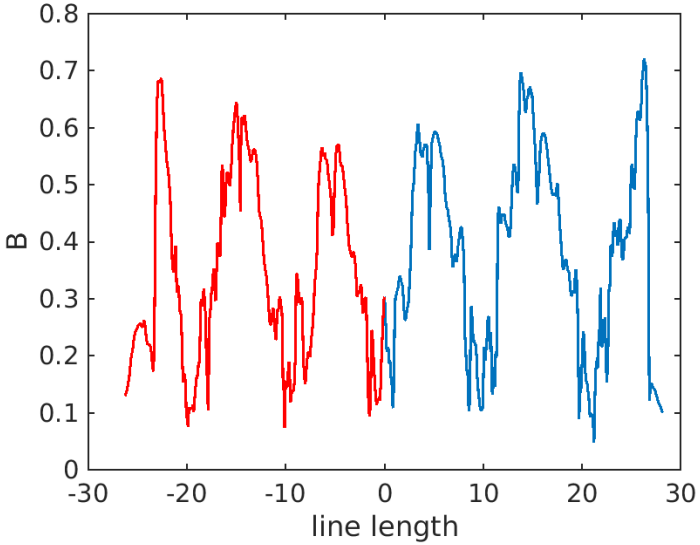
Barkov, Lyutikov, Klingler and Bordas (2019b)

Magnetic bottle?







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

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