# Modeling PWNe and their magnetic fields

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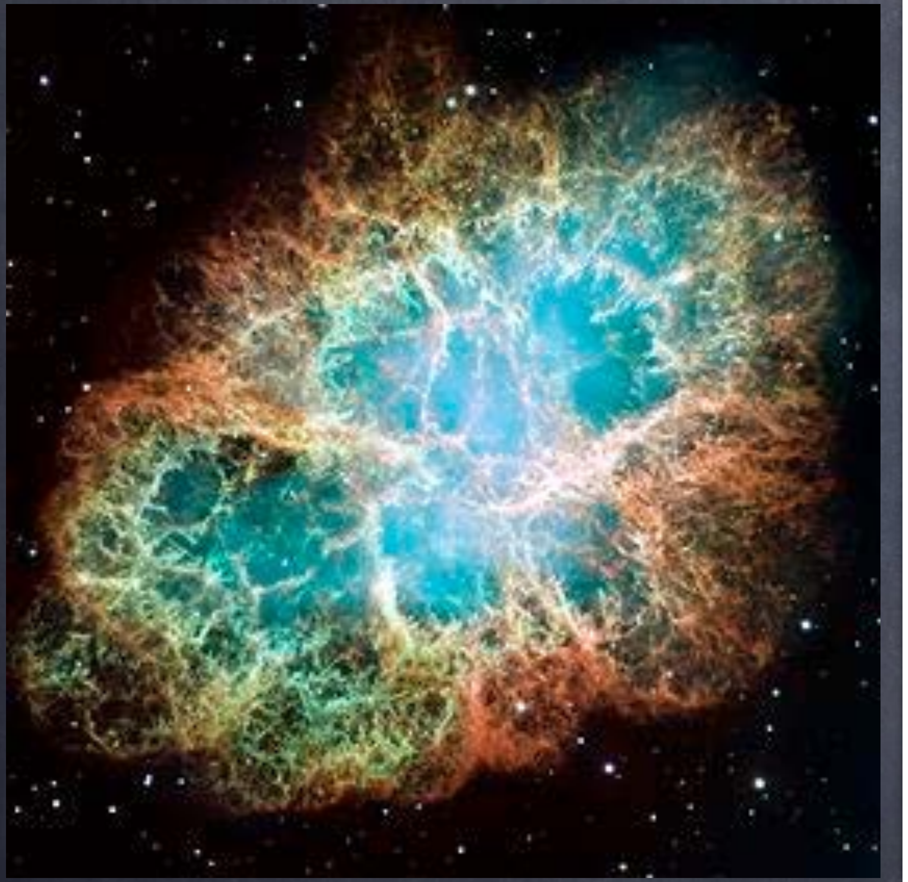
SUPERNOVA REMNANTS II
AN ODYSSEY IN SPACE AFTER STELLAR DEATH
3-8 June 2019, Chania, Crete, Greece

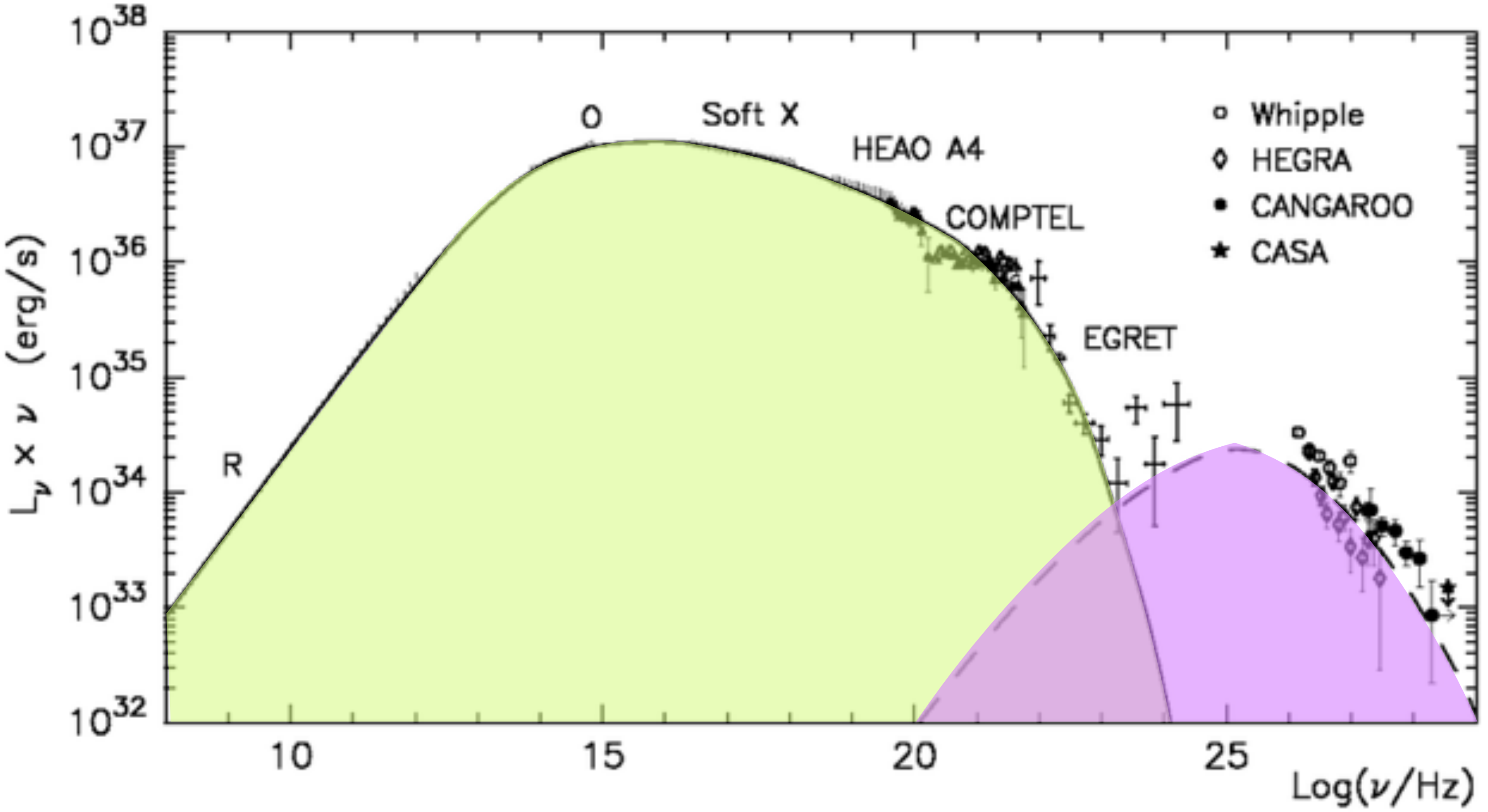
# Pulsar Wind Nebulae

Broad band non-thermal spectrum

Fill-centered morphology



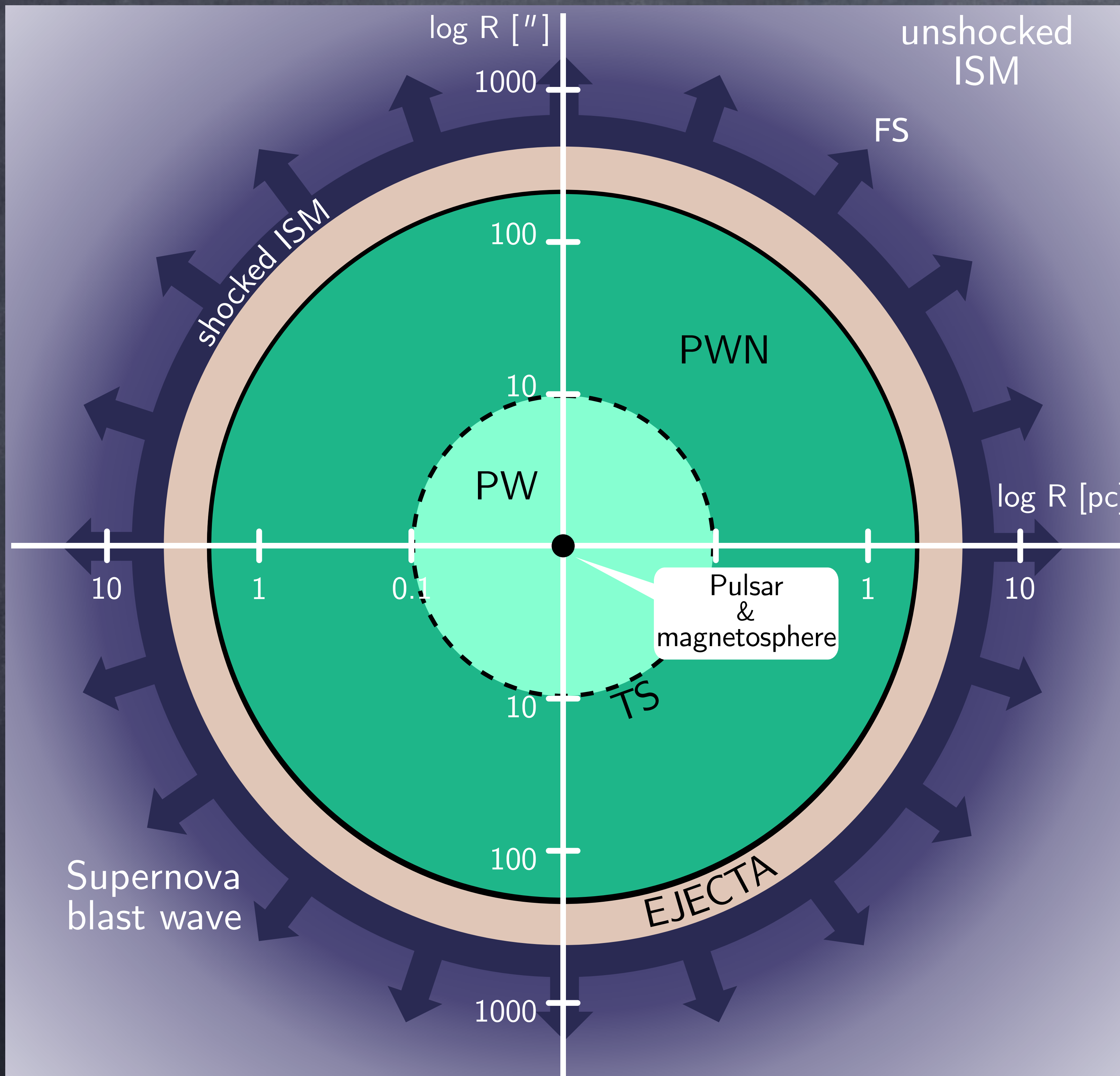
CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]




Primary mechanism: synchrotron radiation by relativistic particles in the nebular magnetic field

Gamma-rays: Inverse Compton scattering with local photon field

# Basic picture for young systems




Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

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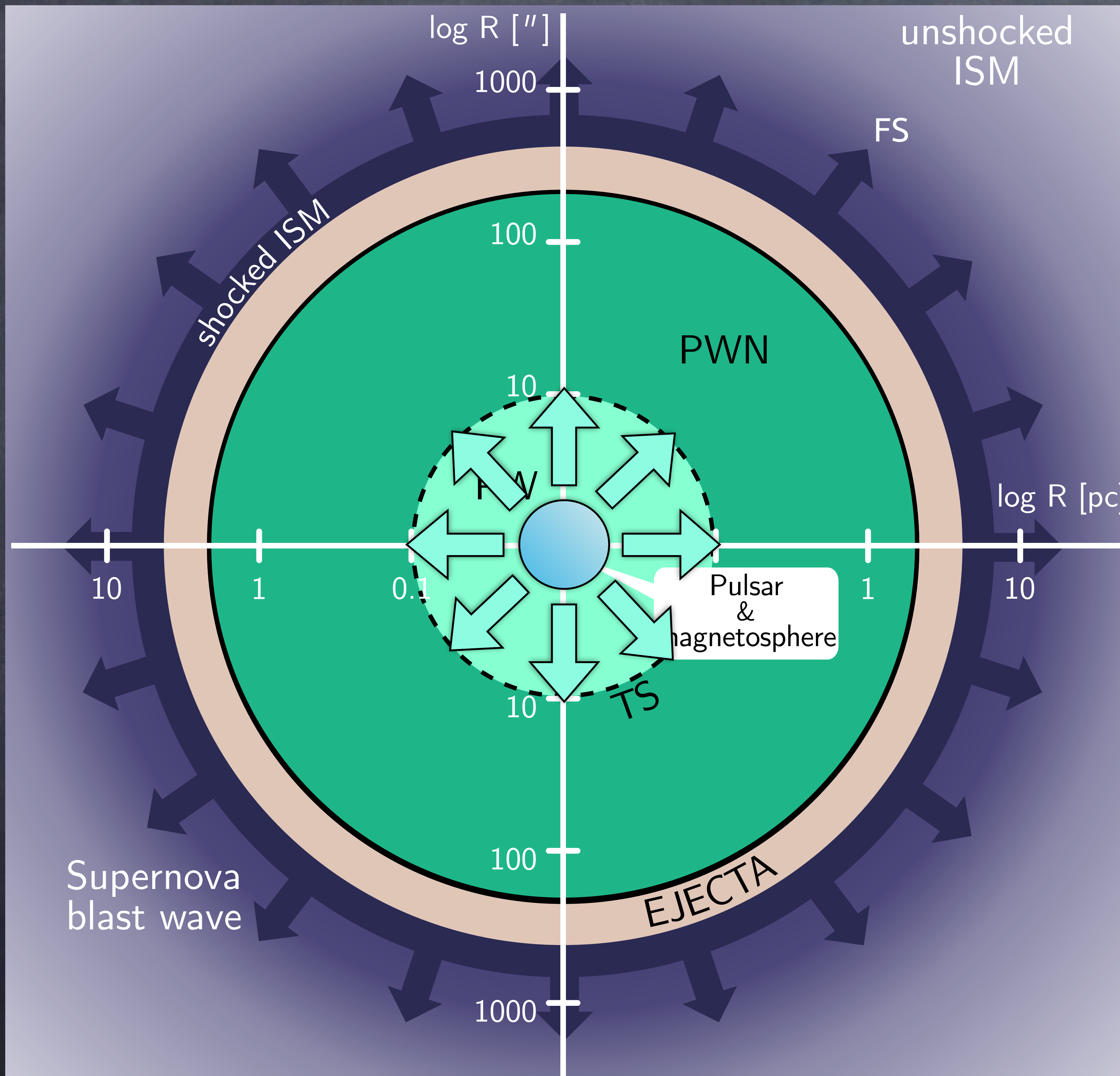
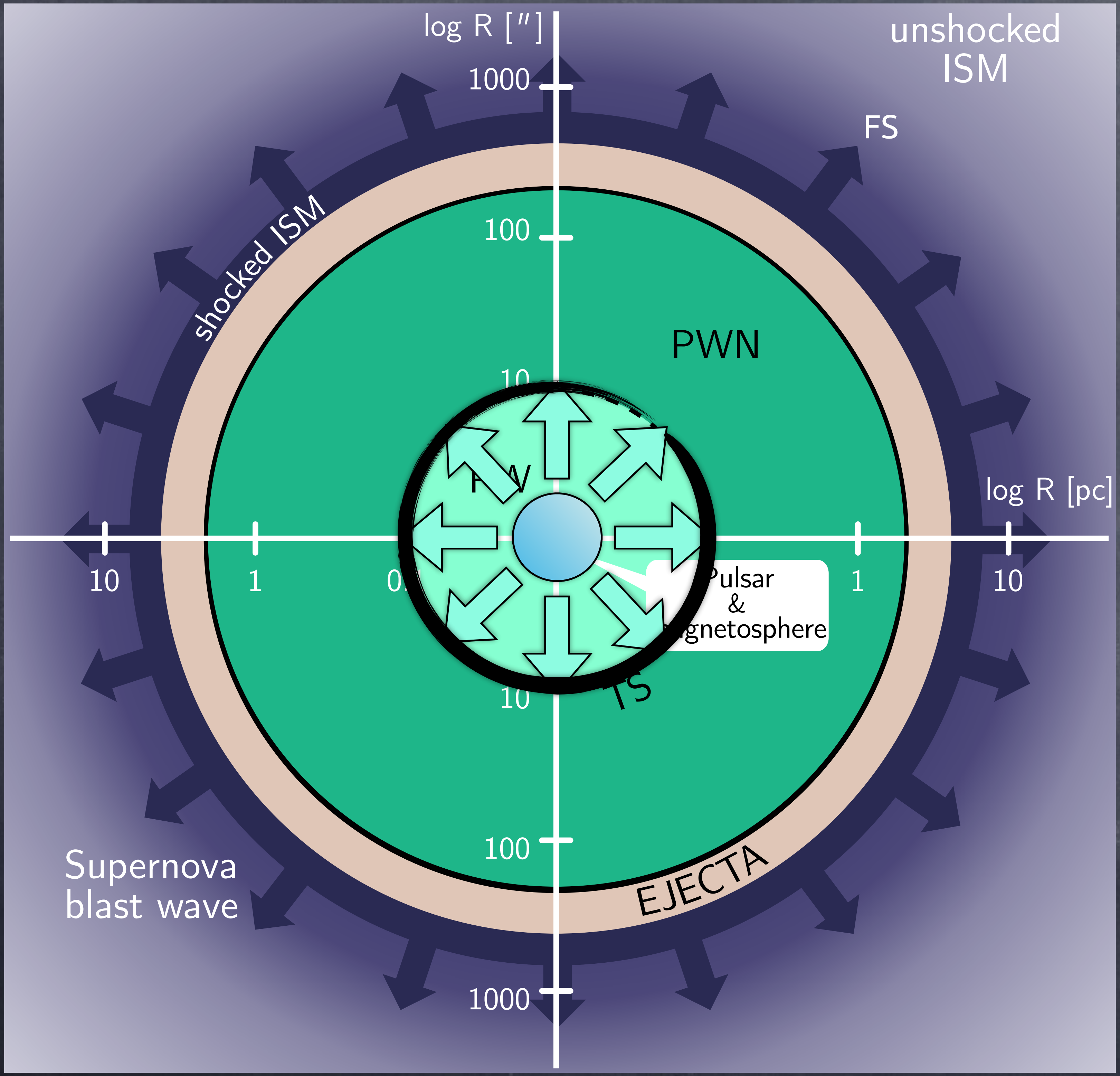



The central pulsar is both source of magnetic field and particles: it fills the remnant with a magnetized, relativistic and cold wind (mainly leptonic)

Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

# Basic picture for young systems

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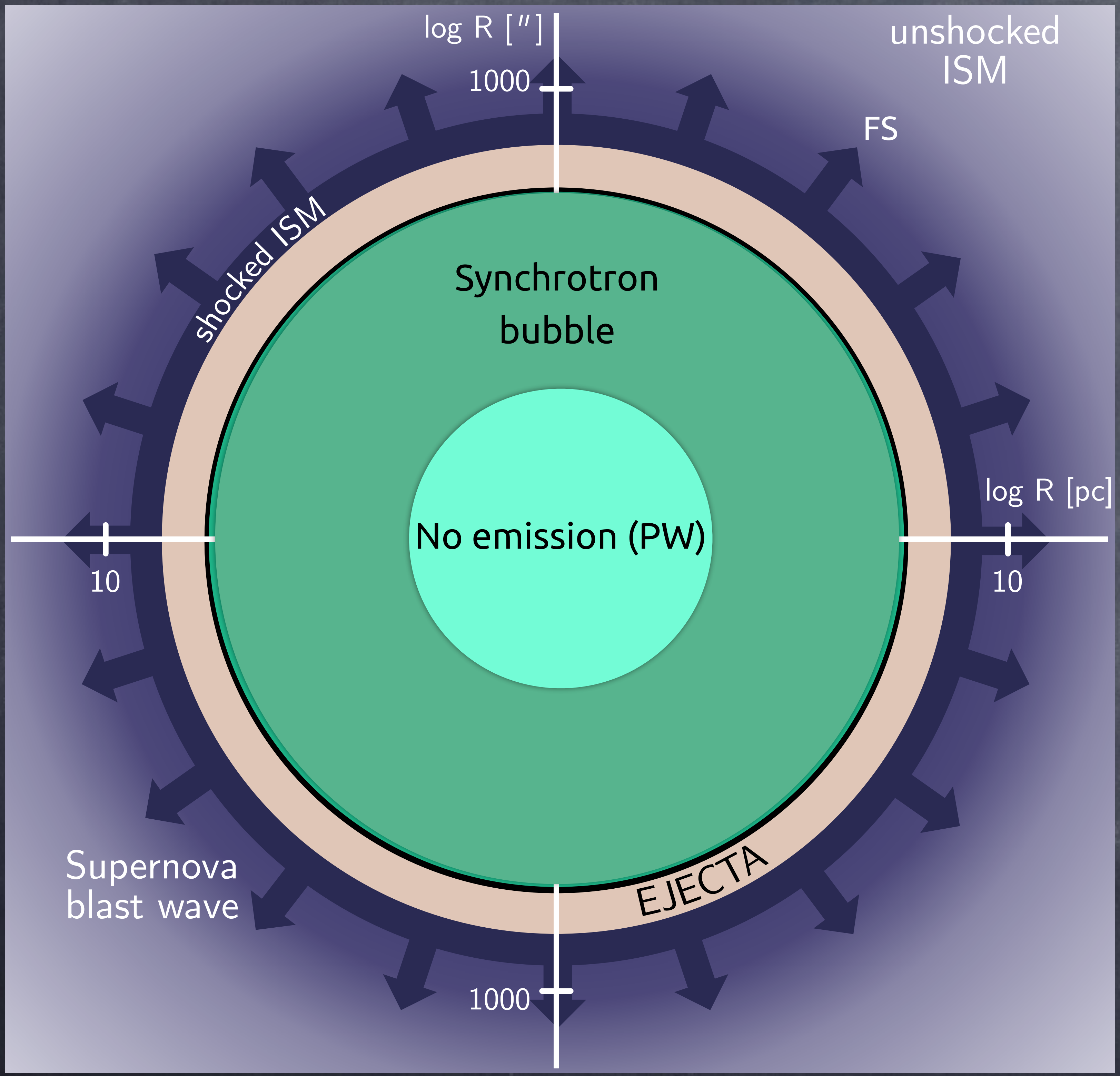
[Del Zanna & Olmi 2017]

Interaction of the pulsar wind with the SNR induces the formation of a Termination shock

# Basic picture for young systems

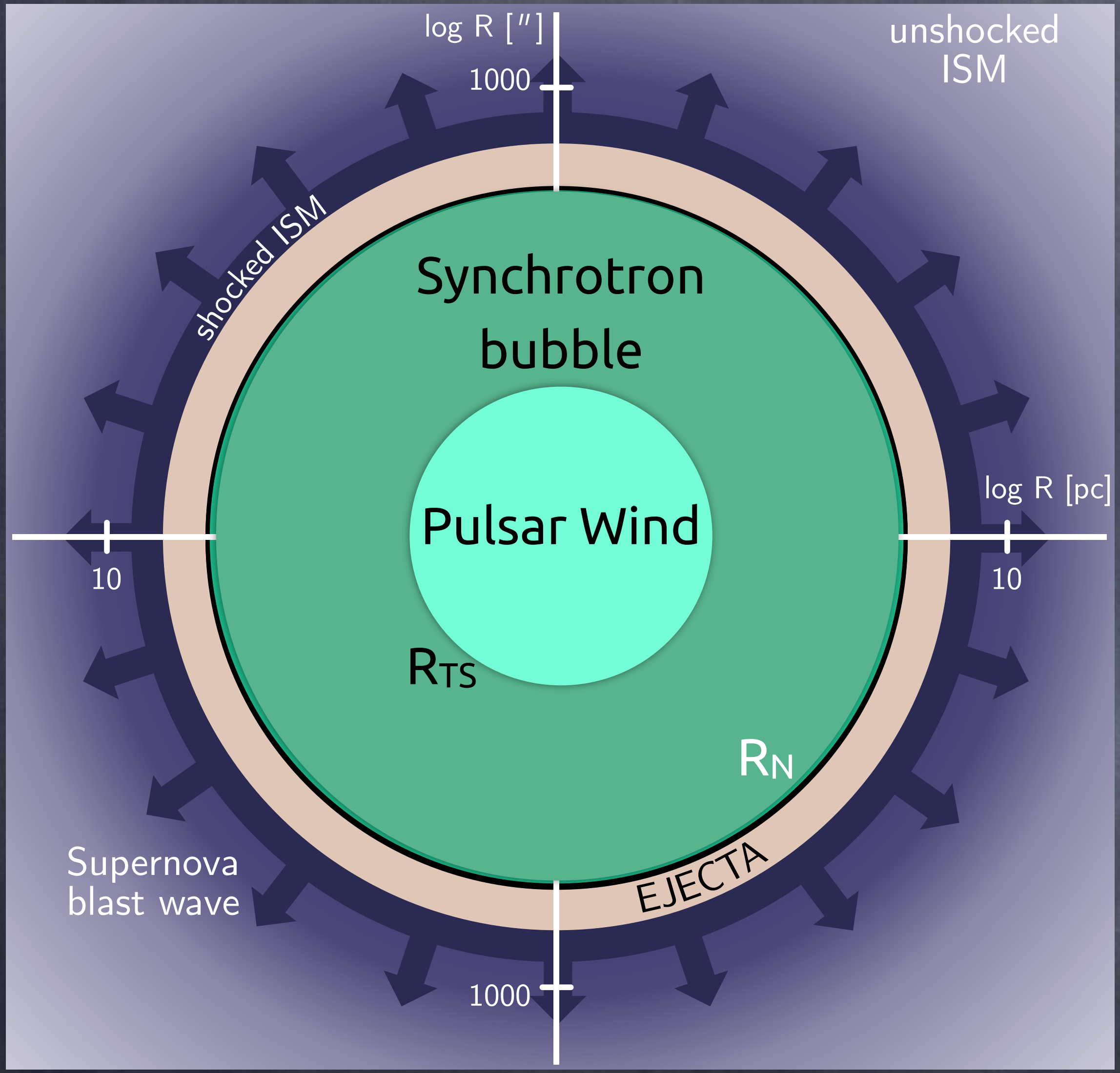



Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

The visible nebula corresponds to the shocked wind beyond the TS.
The PWN bubble is formed by a hot plasma and intense magnetic field (50-200 μG)

# 1D/2D static models of PWNe

[Rees & Gunn 1974, Kennel & Coroniti 1984, Emmering & Chevalier 1987, Begelman & Li 1992]




Assumptions:

- the cold isotropic relativistic PW terminates in a strong perpendicular shock
- the flow in the nebula is subsonic
- particle acceleration at the shock
- synchrotron losses beyond the shock

Main Free parameters:

- particle spectral indices
- wind Lorentz factor → $\Gamma$
- wind magnetization → $\sigma = B^2/(4\pi n m_e c^2 \Gamma^2)$

Predictions:

- positon of TS → $R_{TS} \sim R_N(V_N/c)^{1/2} \sim 0.1$ pc
- Optical / X-ray spectrum [de Jager & Harding 1992, Atoyan & Aharonian 1996]
- size shrinkage with increasing energy

# 1D/2D static models of PWNe

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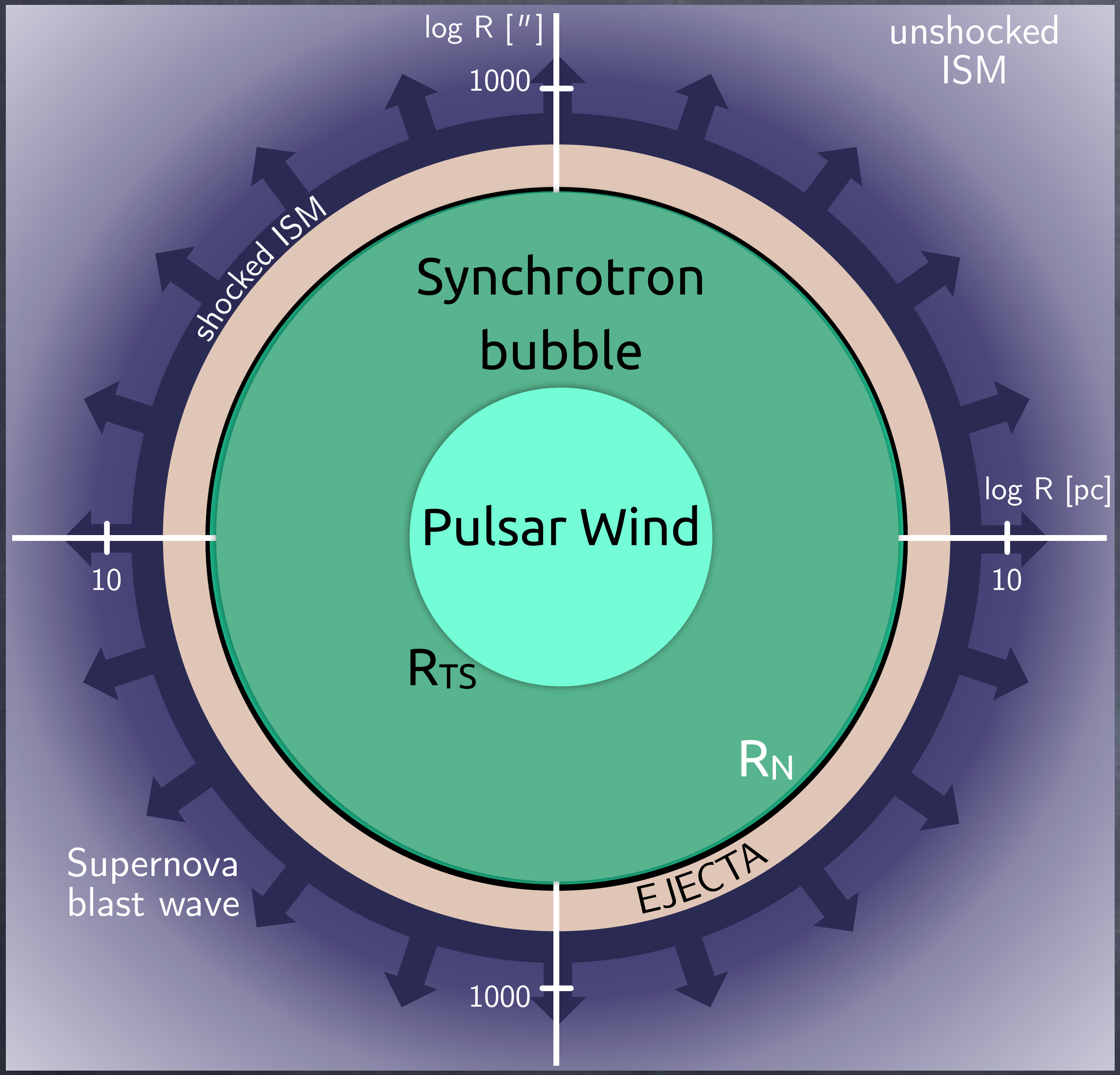


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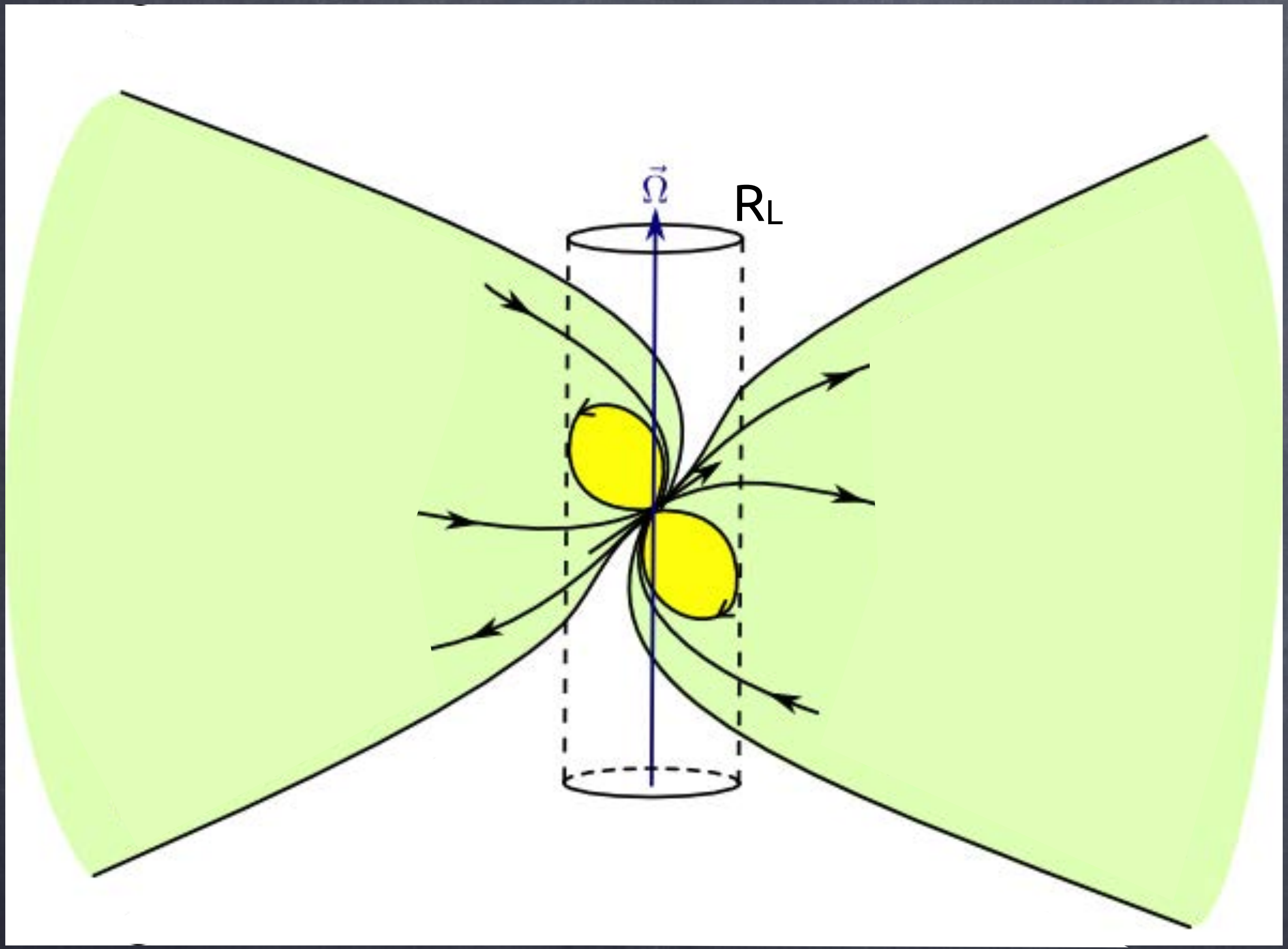
From basic dynamics or radiation properties:

$$\Gamma \simeq 10^6$$

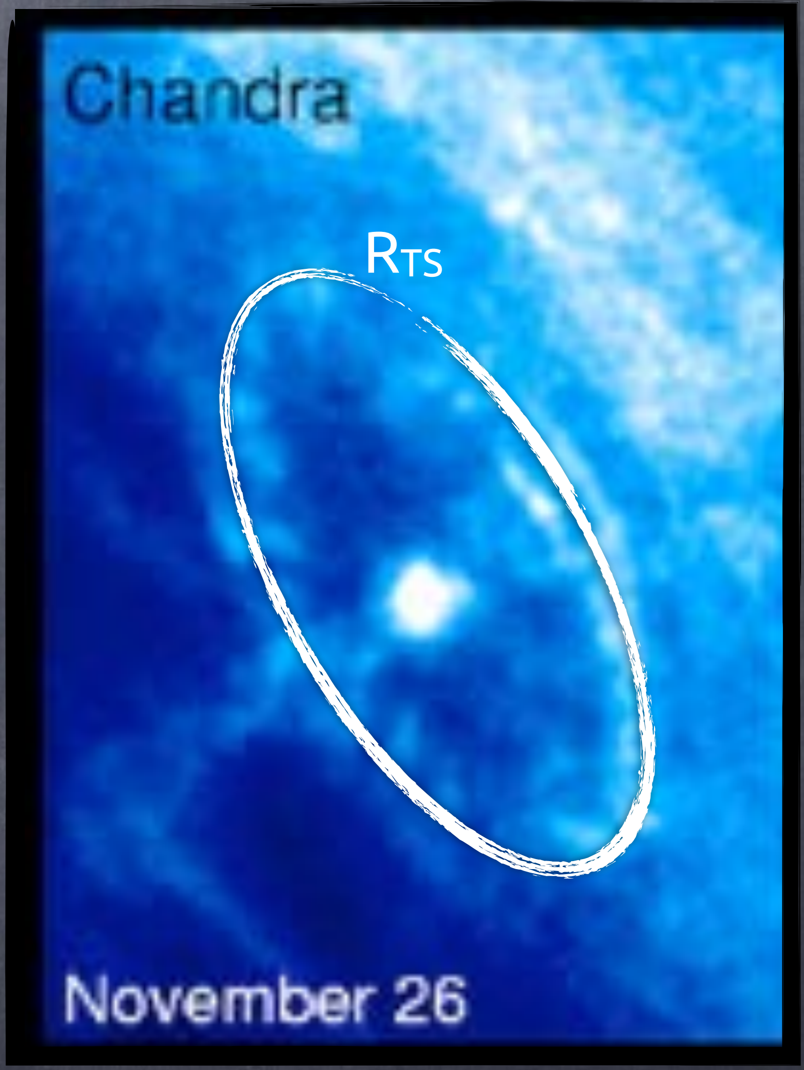
$$\sigma \simeq V_N/c \simeq 10^{-3}$$

# The sigma paradox

From pulsar theories → $\sigma \sim 10^4$ @ $R_L$

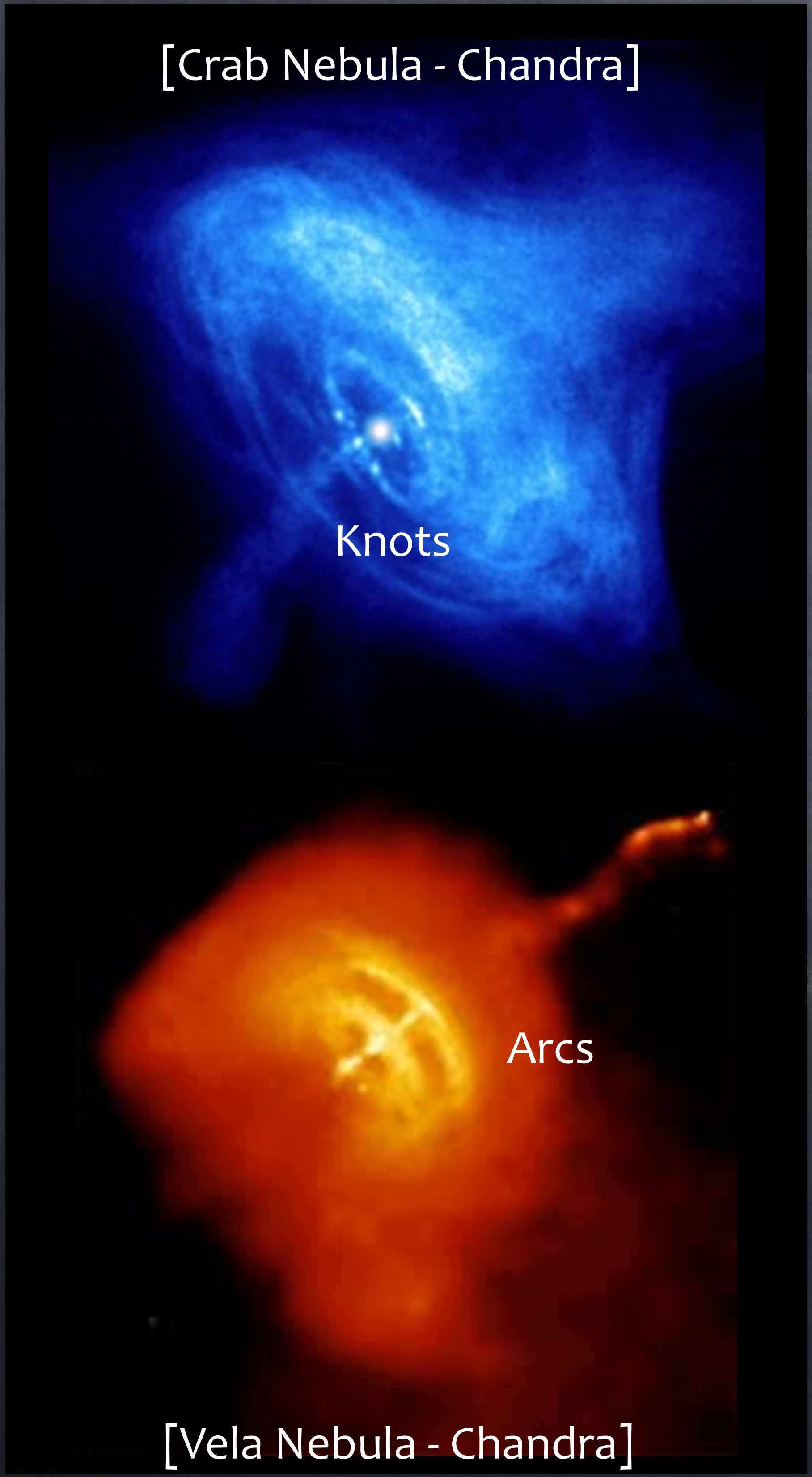



From 1D PWNe models → $\sigma \sim 10^{-3}$ @ $R_{TS}$

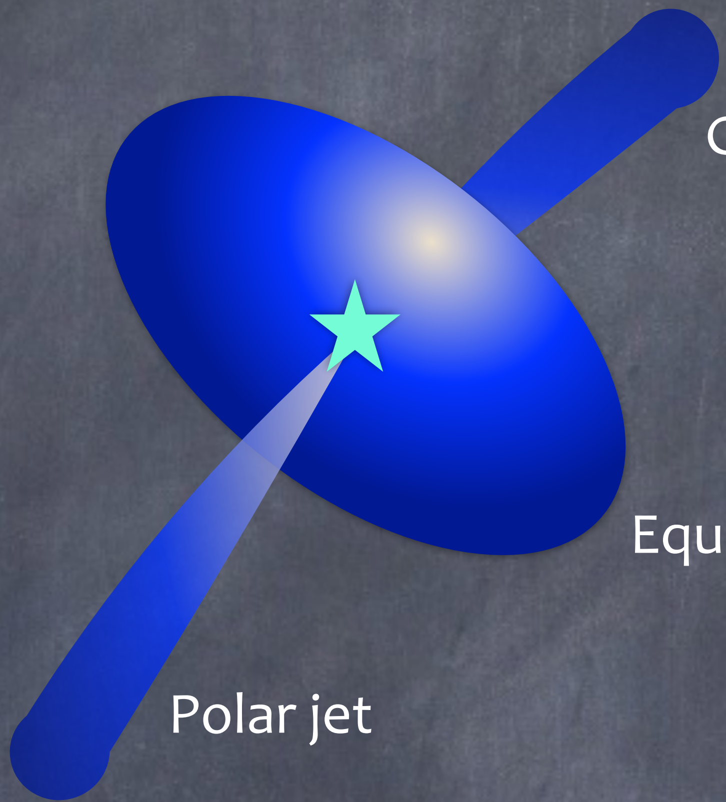



Even if $R_{TS} \sim 10^9 R_L$ dissipation is not sufficient to explain this discrepancy!

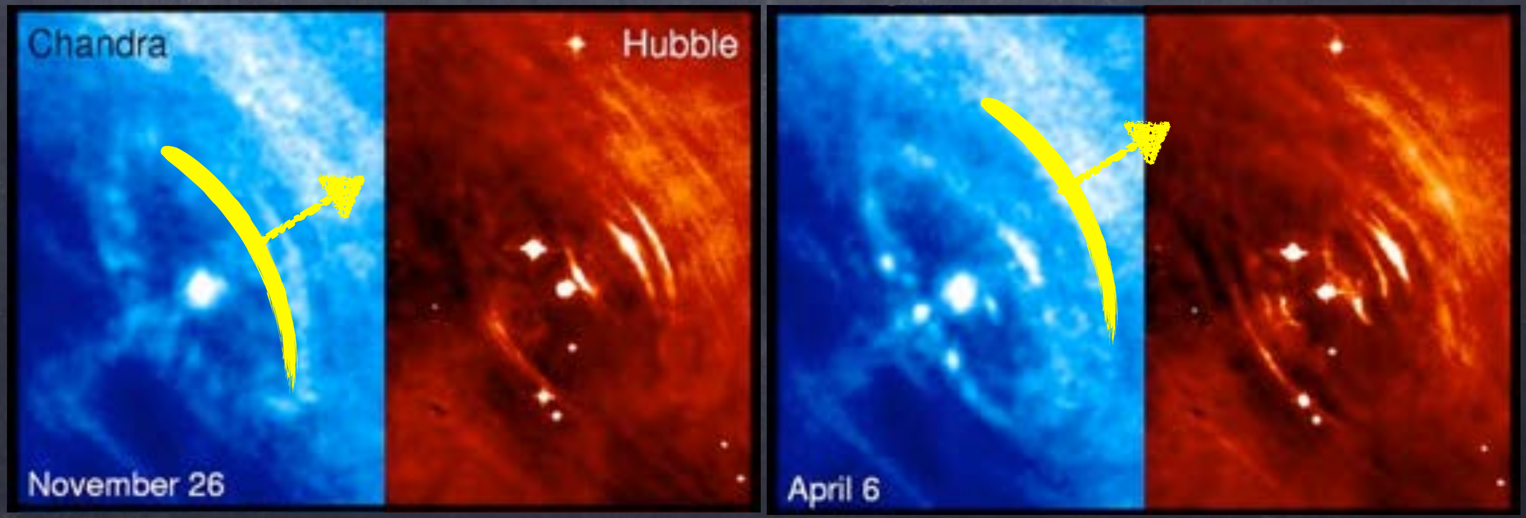
# A deeper view in PWNe



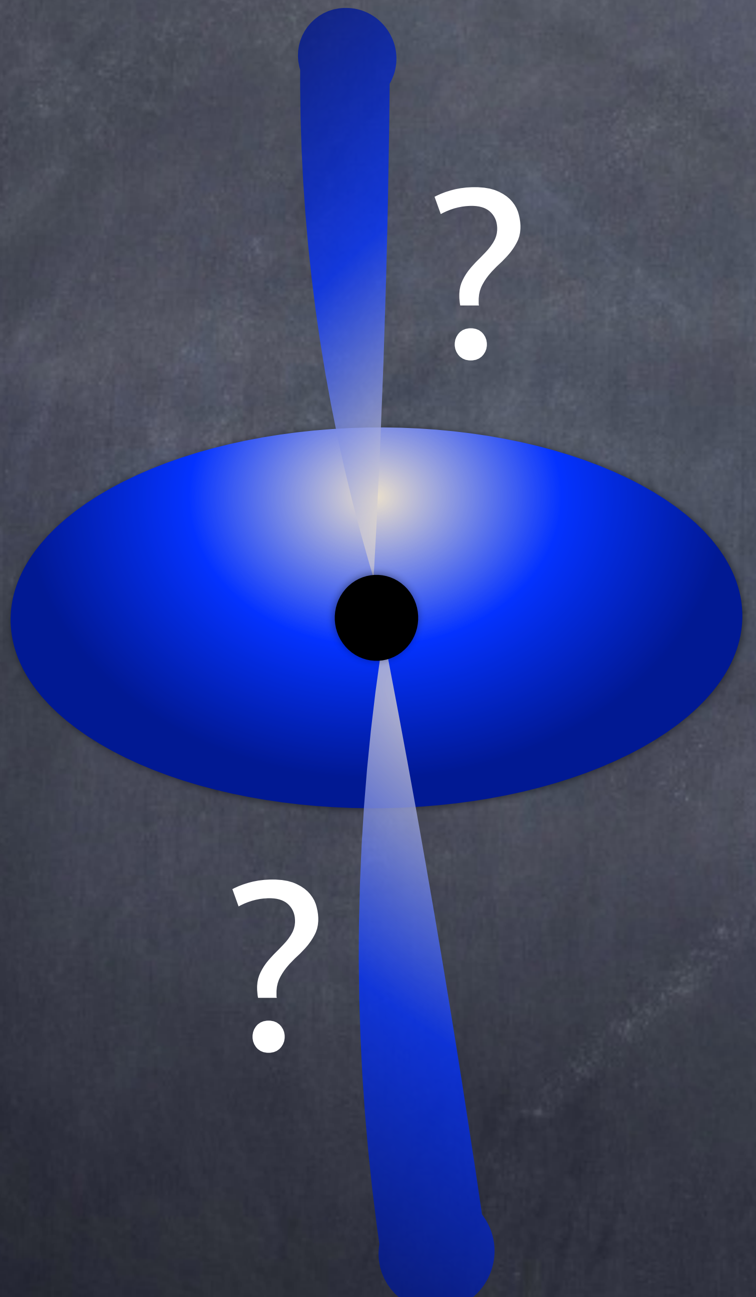

Jet-torus morphology of inner nebula




Outward moving wisps



# Formation of the polar jets




Magnetic collimation in the relativistic PW is not efficient [Lyubarsky & Eichler 2001]:

$$\Gamma \gg 1 \;\rightarrow\; \rho\vec{E} + \vec{J} \times \vec{B} \sim 0$$

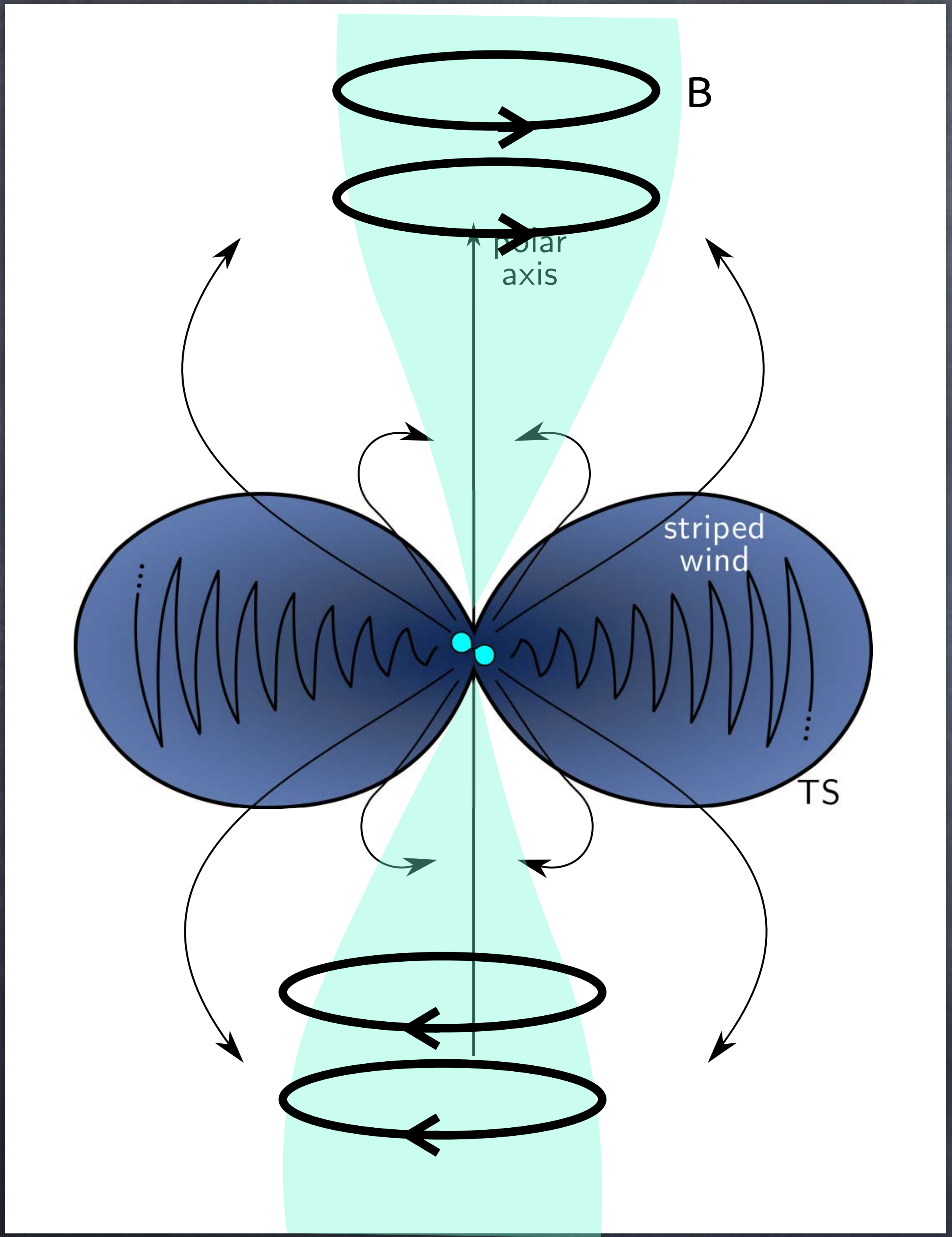
Collimation must occur inside the nebula via hoop stresses.

The energy flux is in the nebula is anisotropic!

[Bogovalov & Khangoulian 2002, Lyubarsky 2002]

$$F \propto \sin^2(\theta)$$

# Formation of the polar jets

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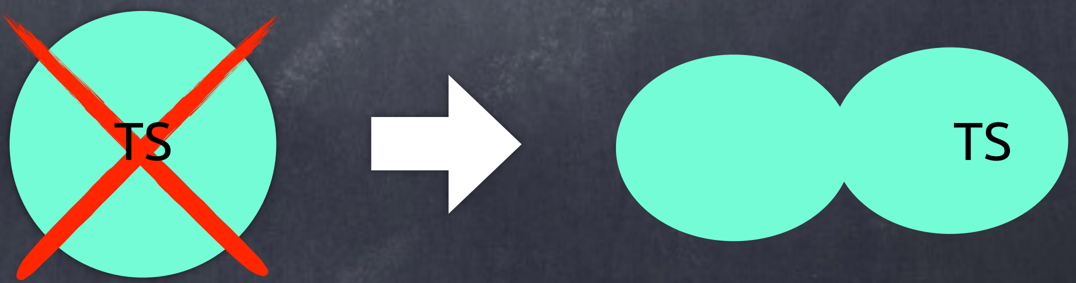



TS is now oblate, with $R_{eq} >> R_{pol}$

# 2D numerical models of PWNe

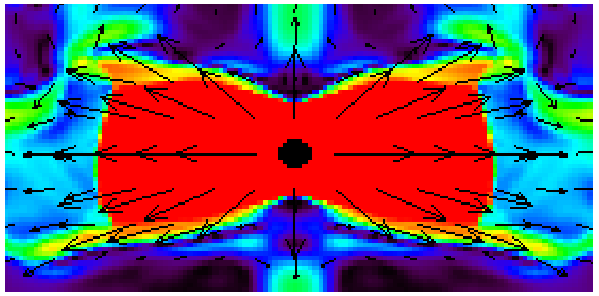
[Michel 1973, Bogovalov 1999, Contopoulos + 1999, Coroniti 1990, Gruzinov 2004, Bogovalov & Khangoulian 2002, Lyubarsky 2002]

- Anisotropic distribution of the energy flux $F(r,\vartheta)$:

$$F(r,\theta) \propto \frac{\alpha + (1-\alpha)\sin^2\theta}{(2+\alpha)r^2} \to F(r,\pi/2) \gg F(r,0) \to \alpha \ll 1$$

anisotropy parameter

Oblate TS, with $r_{eq} > r_{pol}$

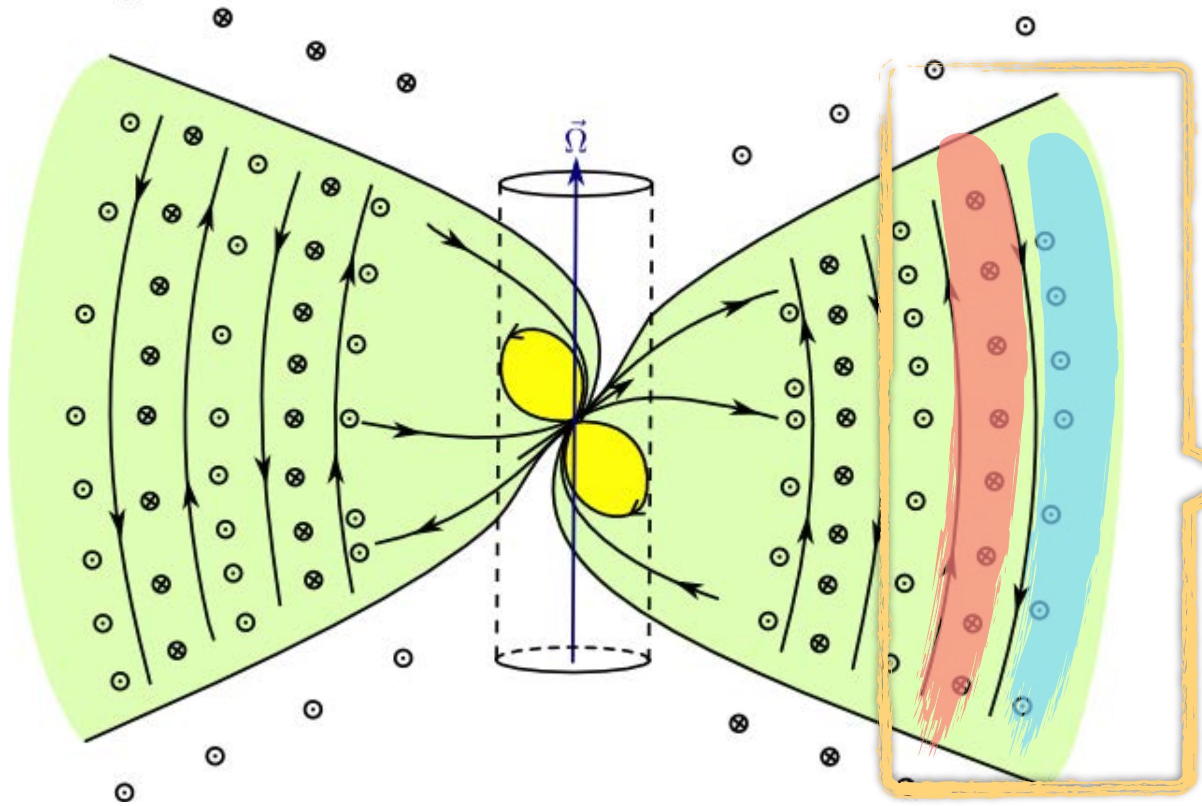


- Striped morphology within an equatorial belt of extension ≈ 2×ζ

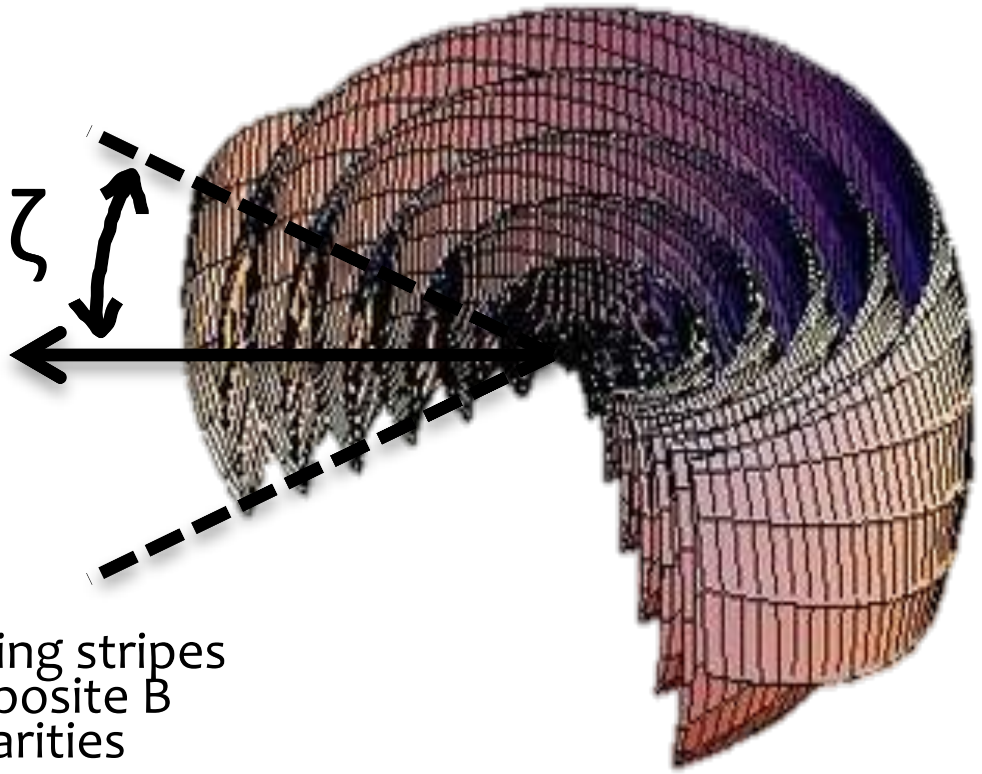
$$B(r,\theta) \propto \sqrt{\sigma}\,\mathcal{G}(\theta)\sin\theta$$

initial wind magnetization

striped wind




alternating stripes of opposite B polarities

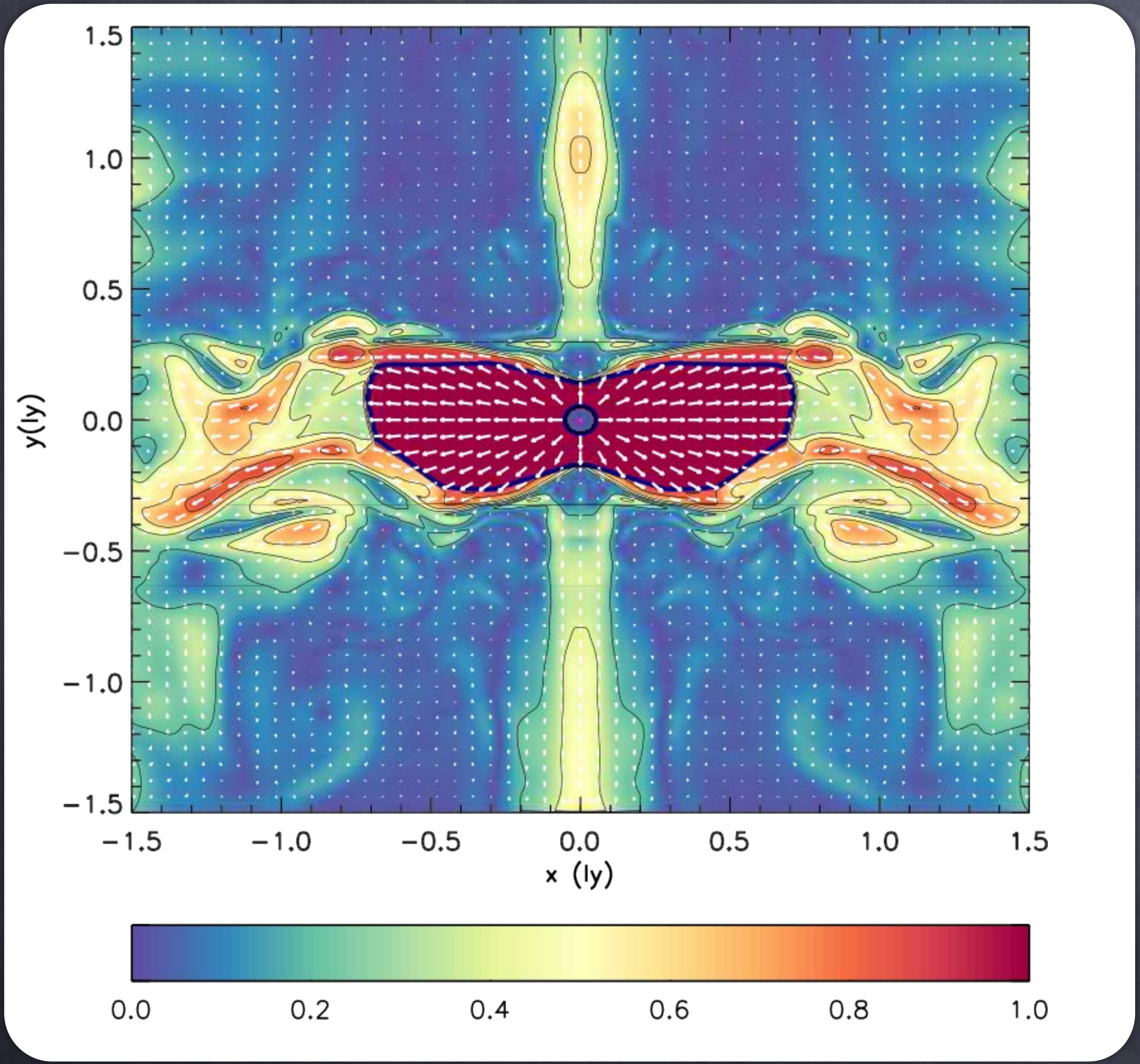


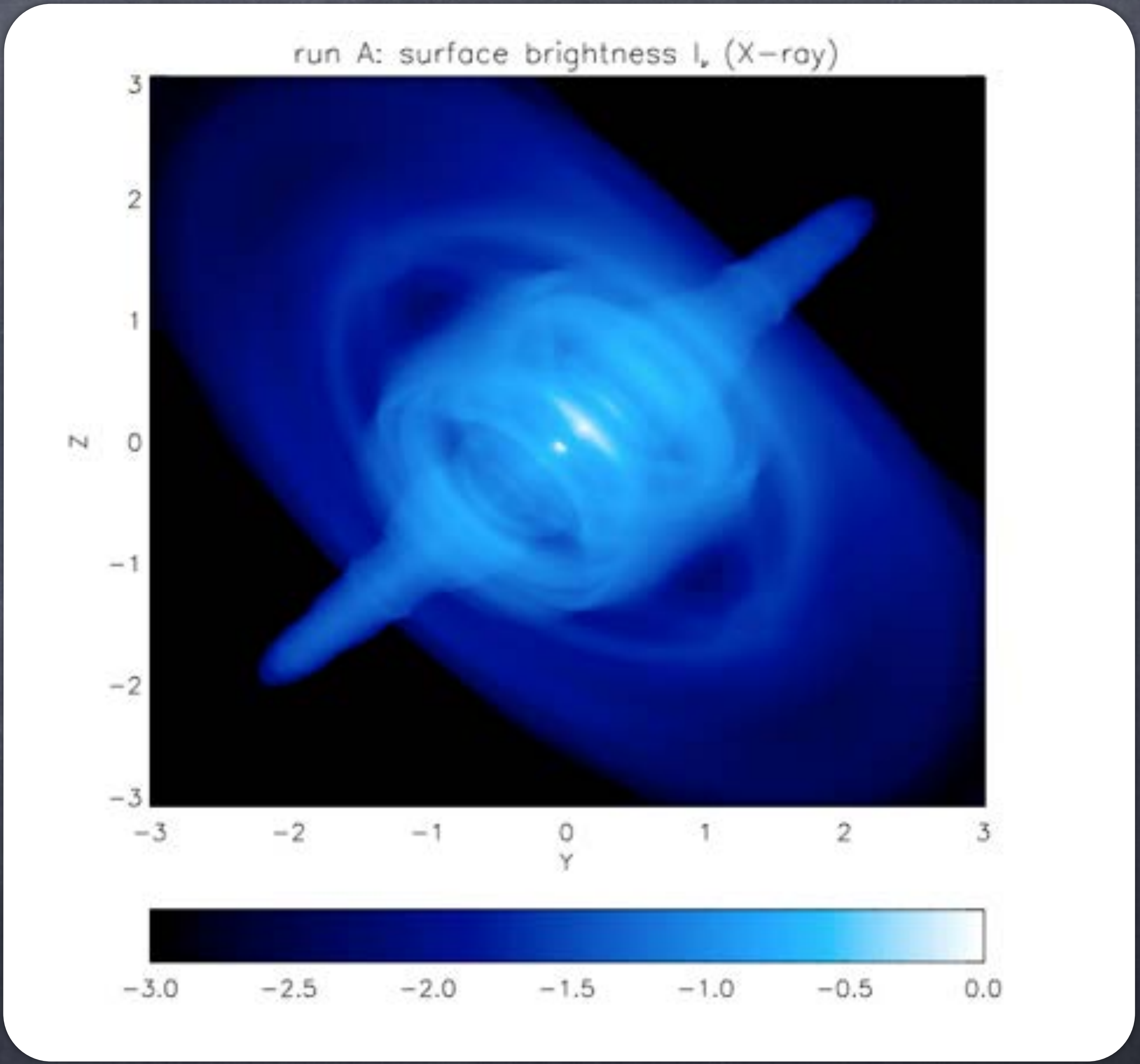

separated by a current sheet
→place for dissipation

# Goals of 2D models: jet-torus

2D numerical models confirm the jet formation for values of magnetization σ≳0.01

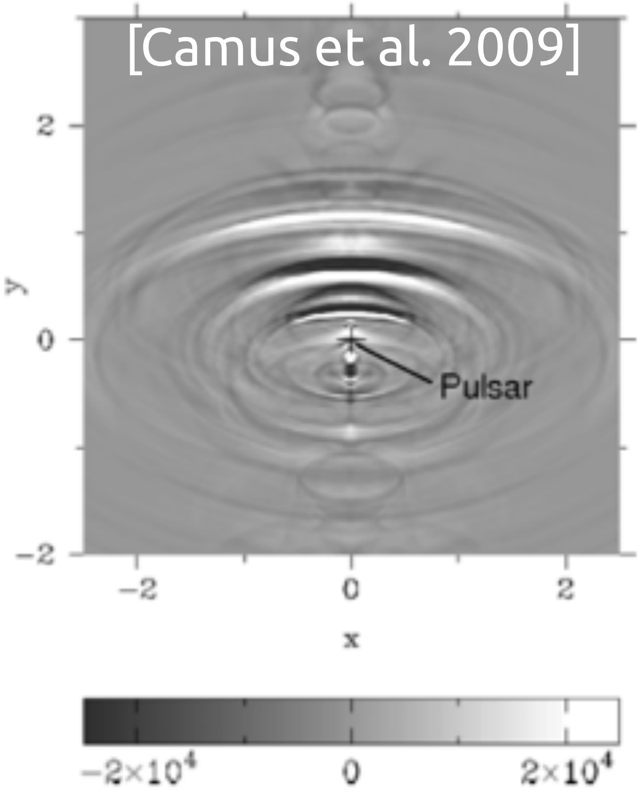
[Komissarov & Lyubarsky 2003-2004, Del Zanna et al. 2004]

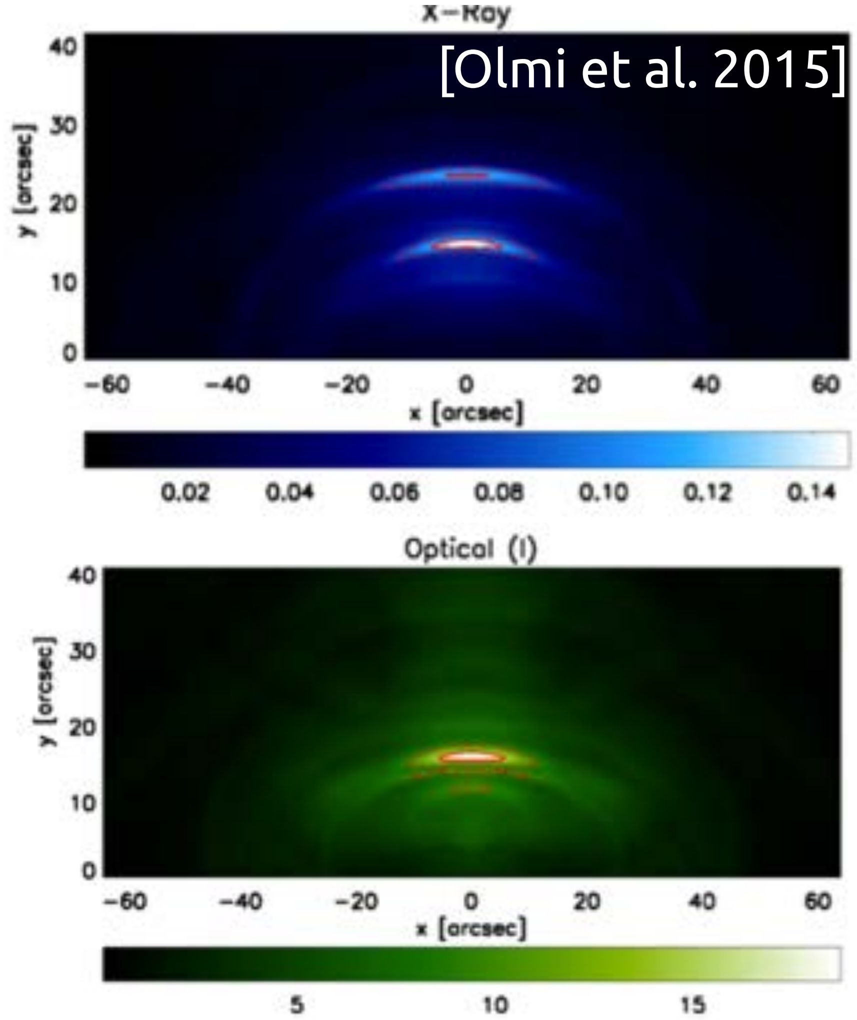


# Goals of 2D models: variability of the inner nebula

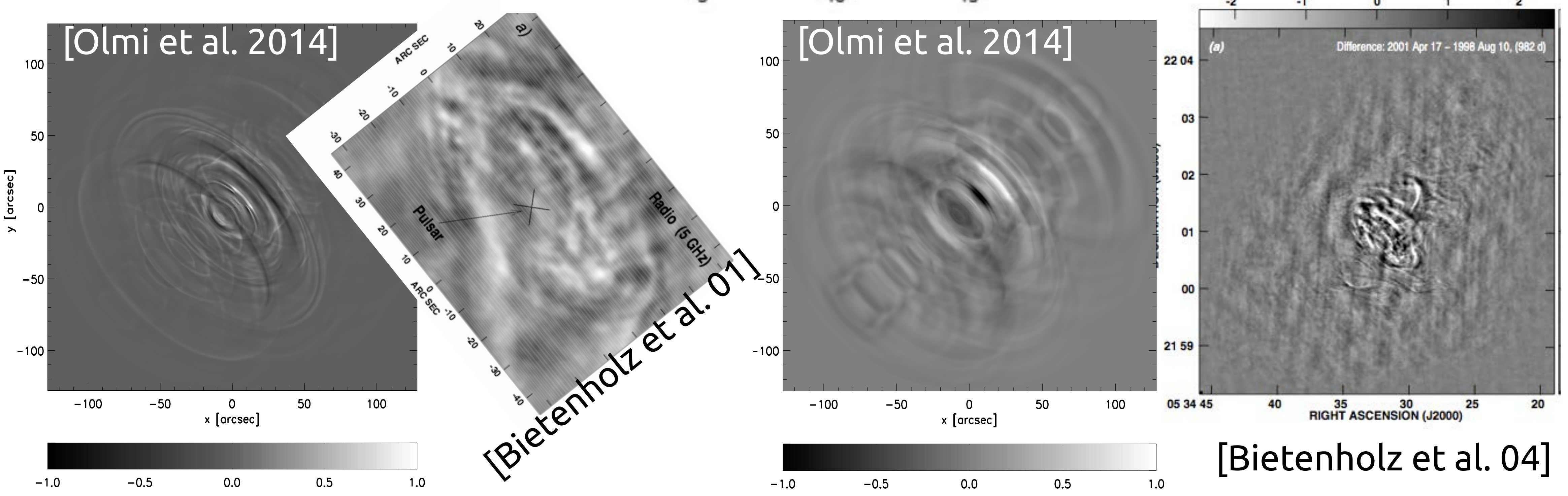
X-rays (105 days)



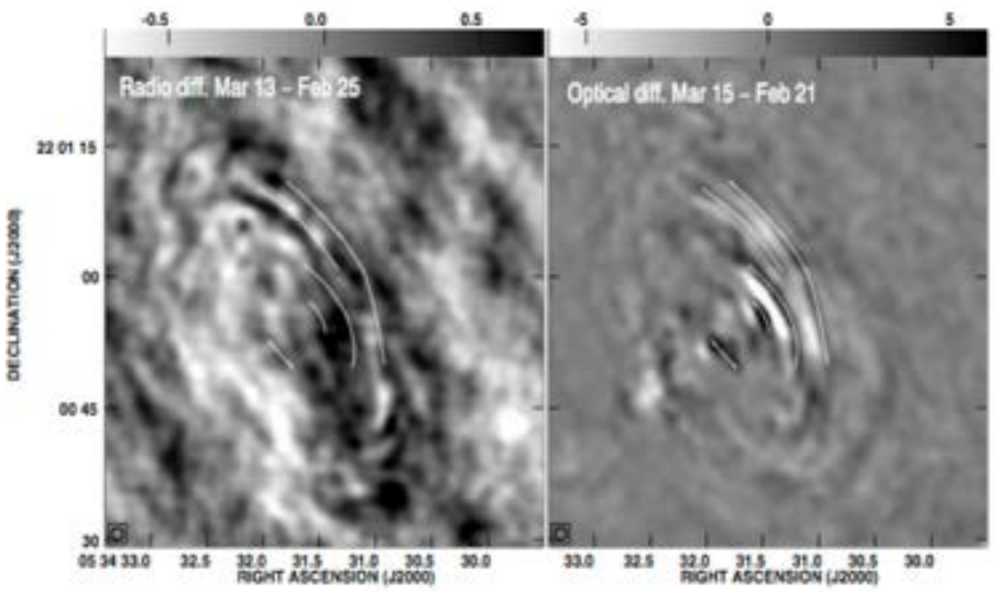

Wisps variability reproduced at multi-wavelengths

Radio (2 months)



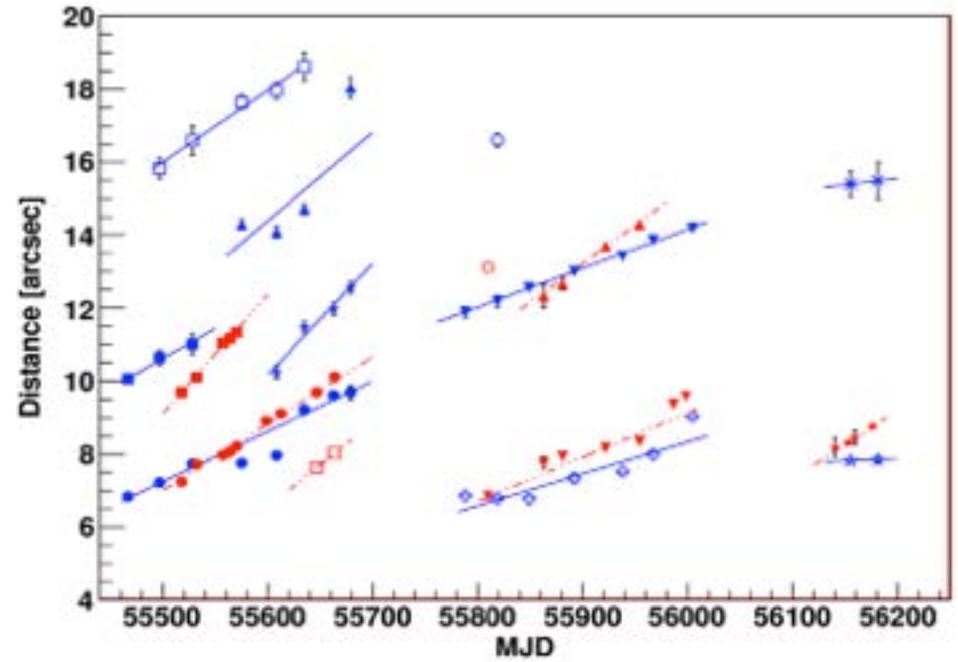

[Bietenholz et al. 04]

# Goals of 2D models: multi-λ wisps properties




[Bietenholtz et al. 2004]

Radio vs Optical wisps

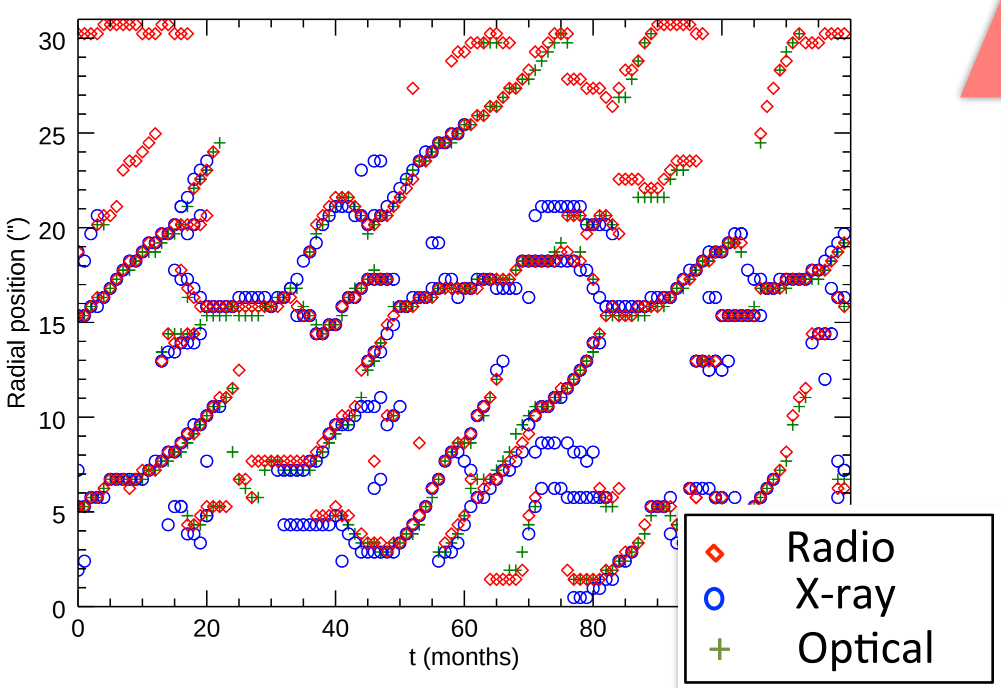


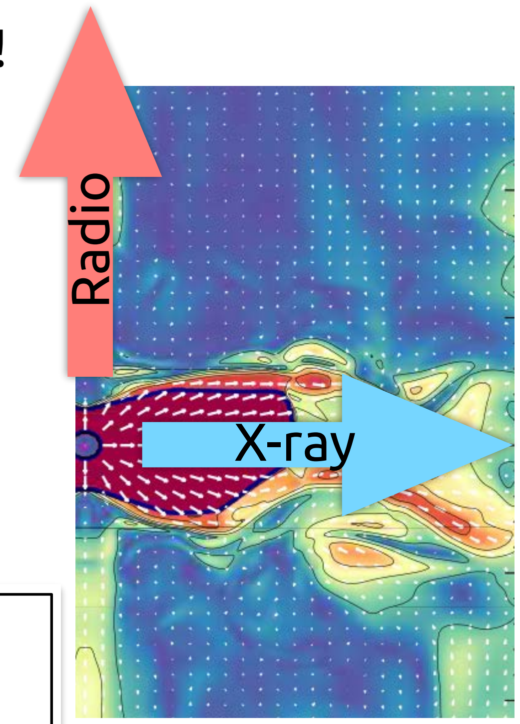

[Schweizer et al. 2013]

Optical vs X-ray wisps

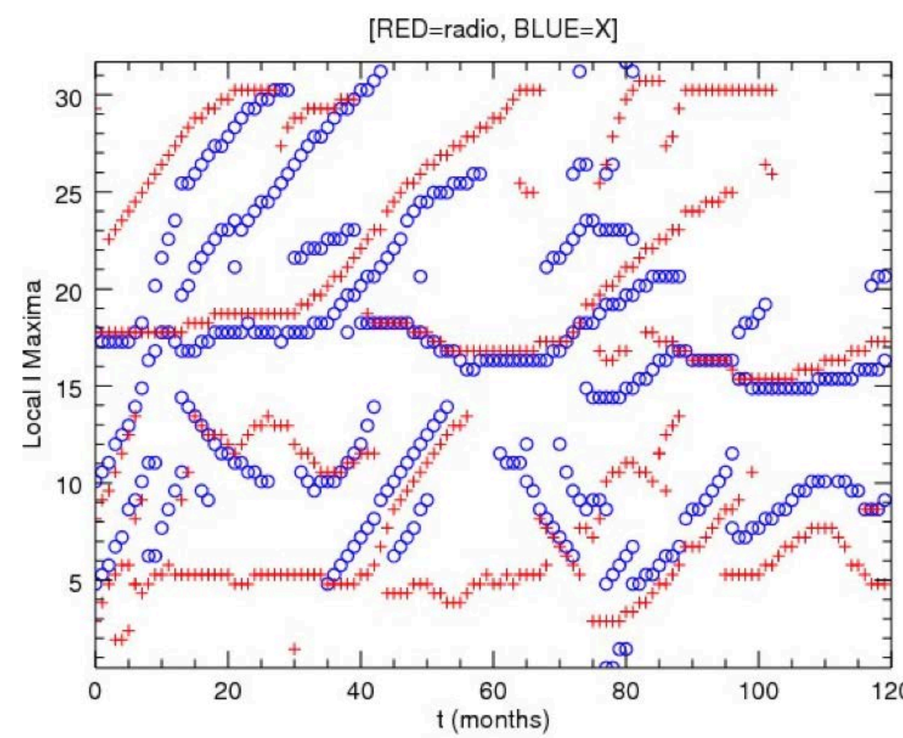
Non-coincident locations and different outward velocities at different wavelengths explained with non uniform injection of emitting particles:

If injection is uniform wisps are coincident!




[Olmi et al. 2015]

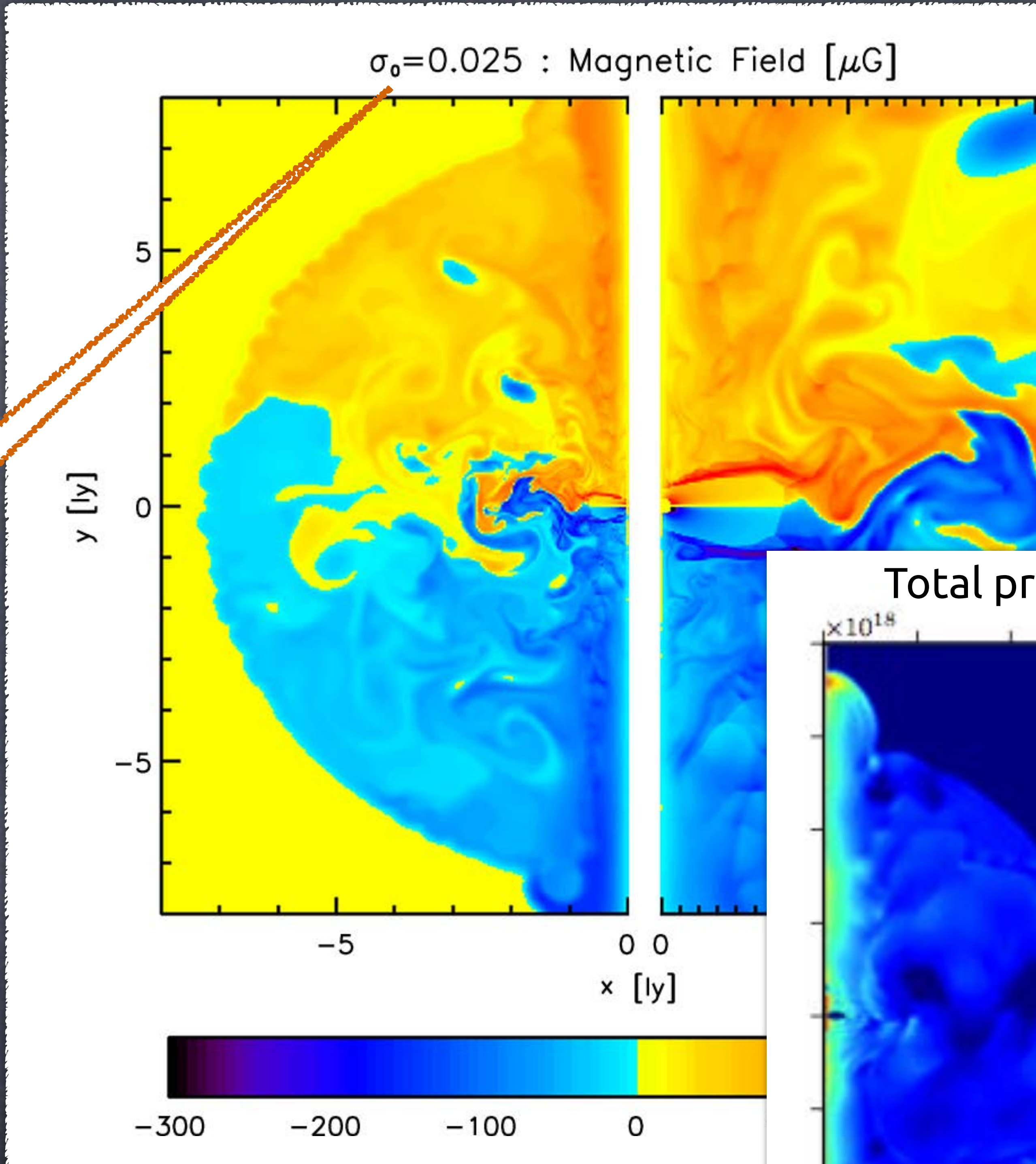


# Limits of 2D models

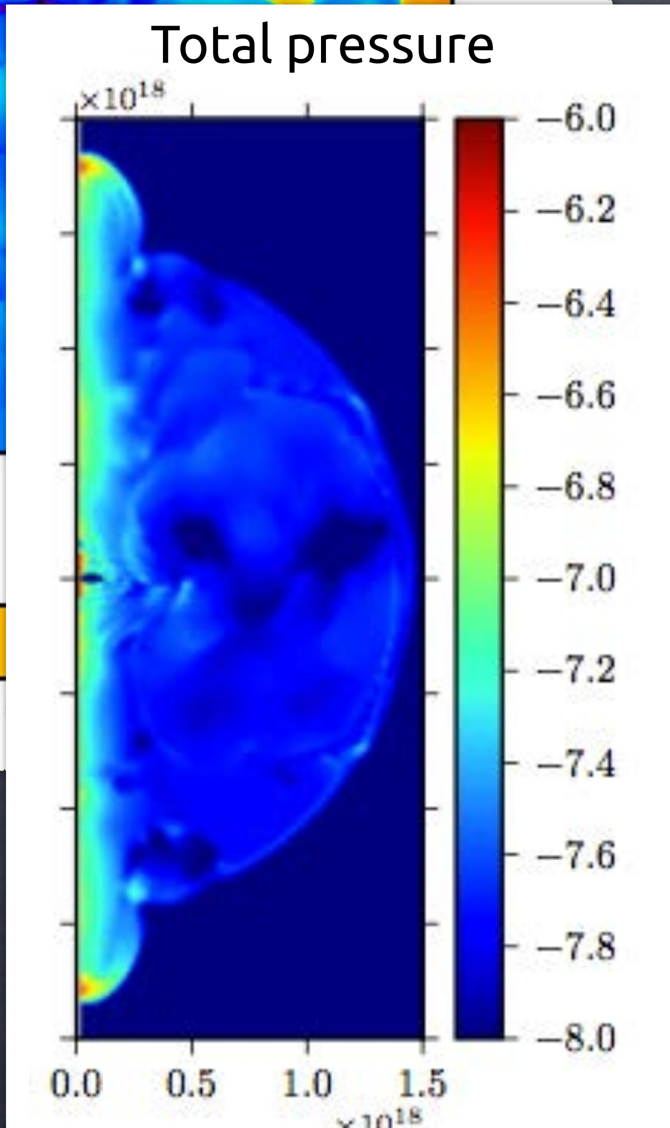
- ☐ Morphology of the magnetic field
- ☐ Level of magnetization

2D simulations can only work with $\sigma<1$.

Averaged field underestimated:
$\langle B \rangle_{SYM} \simeq 10^{-5}$ G
$\langle B \rangle_{OBS} \simeq 10^{-4}$ G




[Olmi et al. 2015]

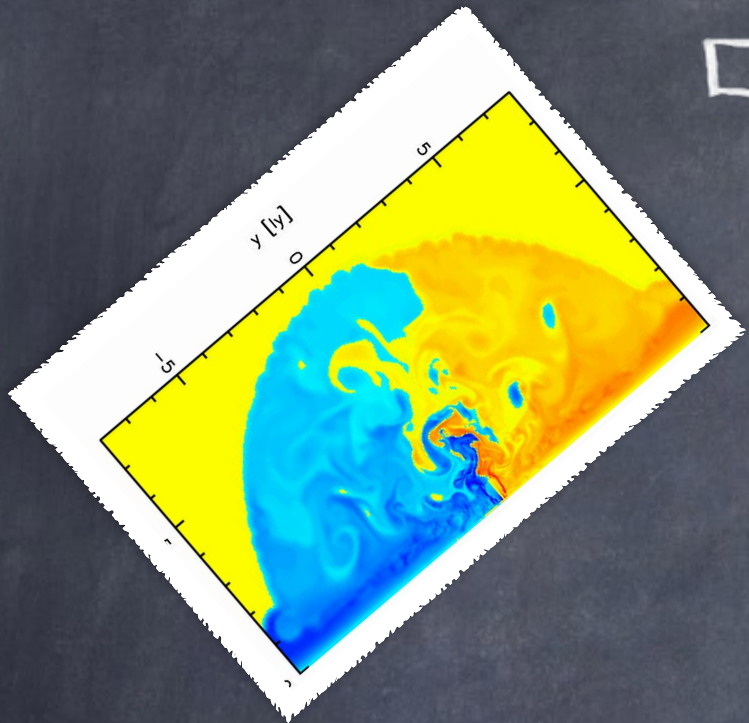


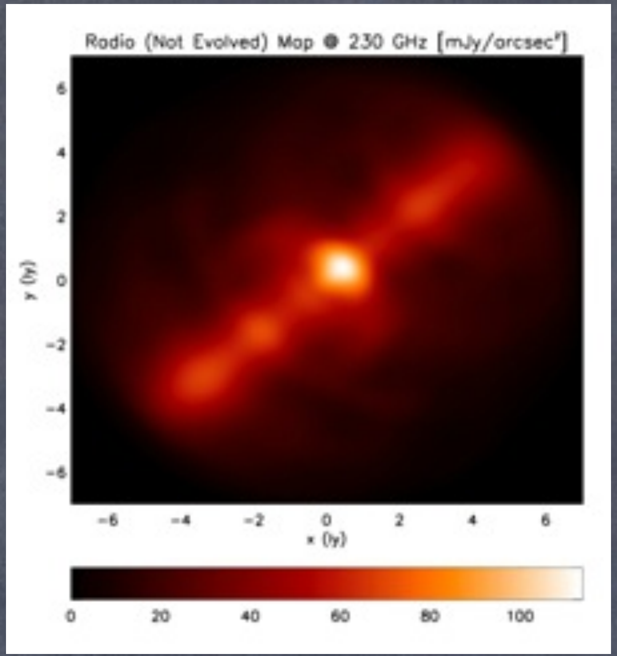

[Porth et al. 2014]

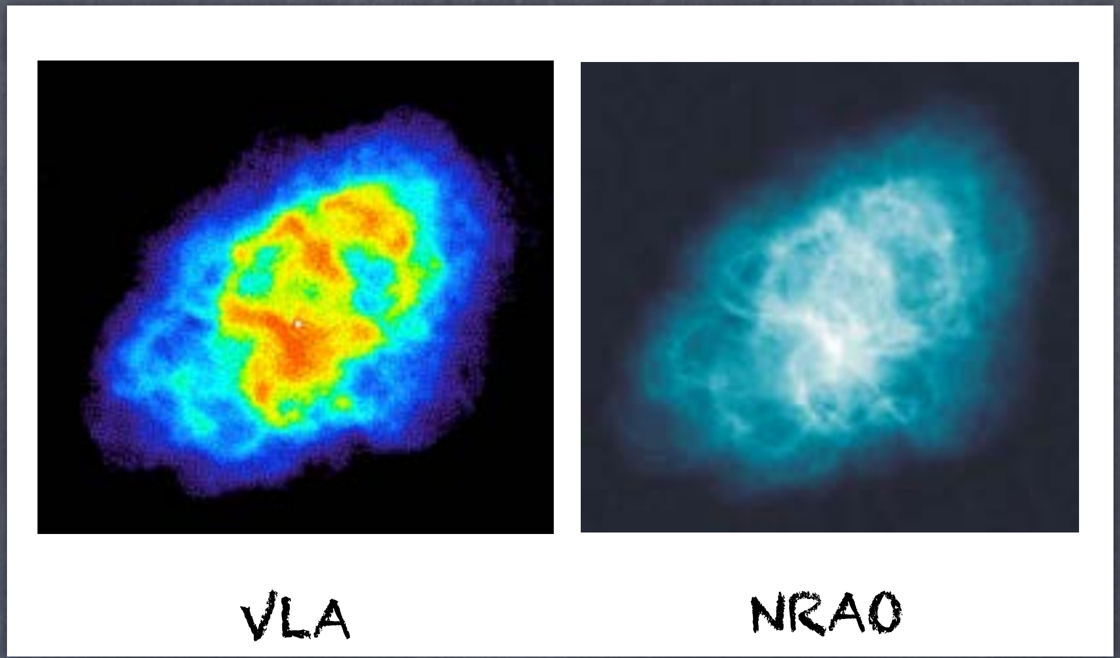
# Limits of 2D models

This strongly affects many of the emitting properties:

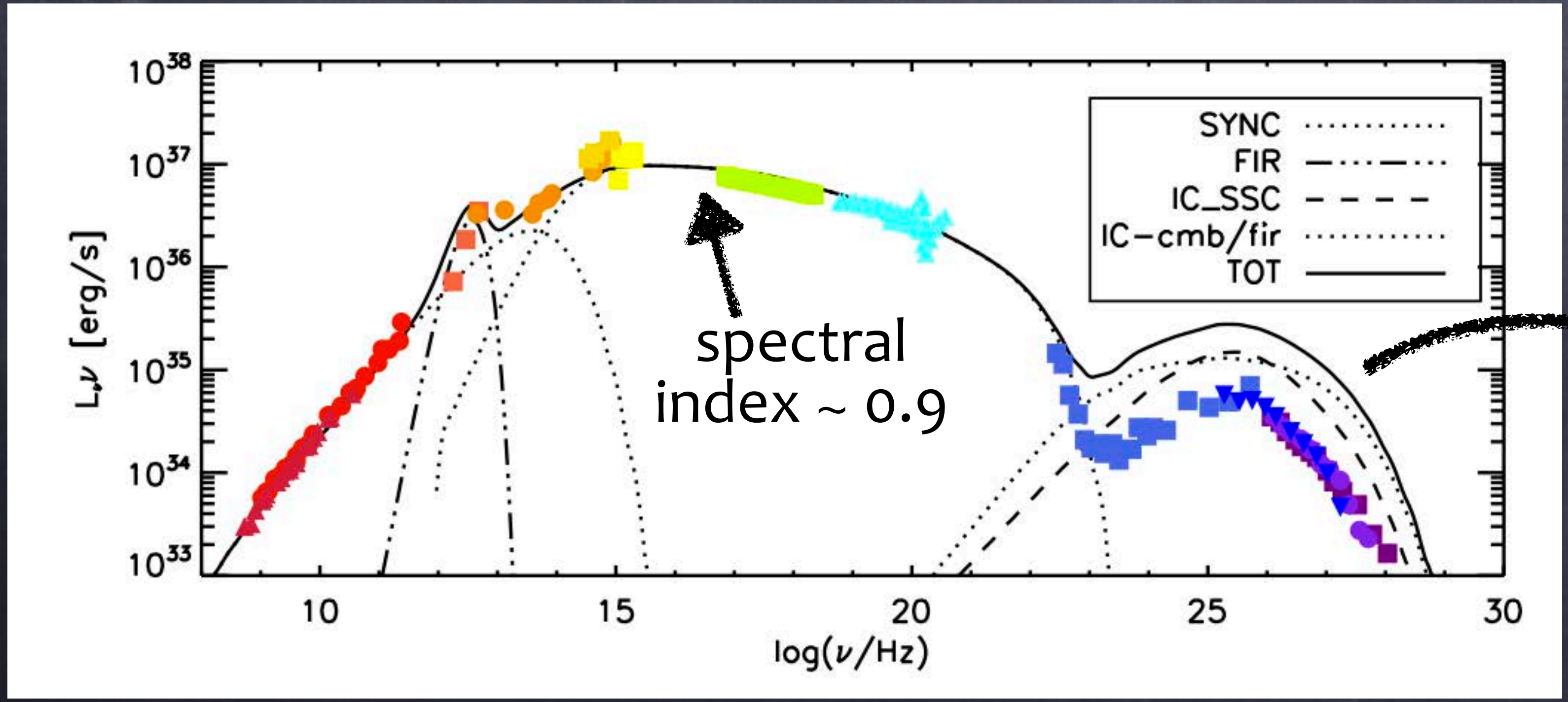
- Radio emission is not uniform: traces the field compression

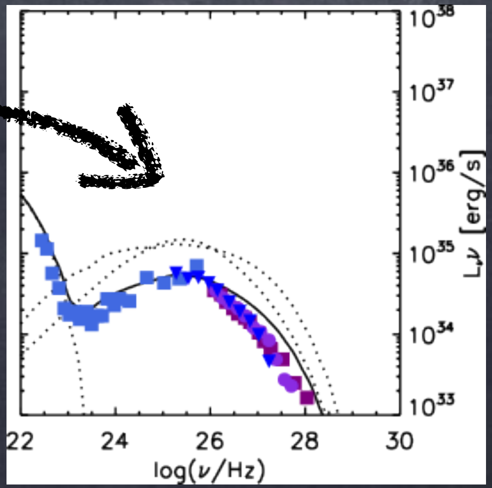





- Problems in reproducing high-energy spectrum: X-ray needs artificial steepening in order to compensate lower energy losses + IC overestimated



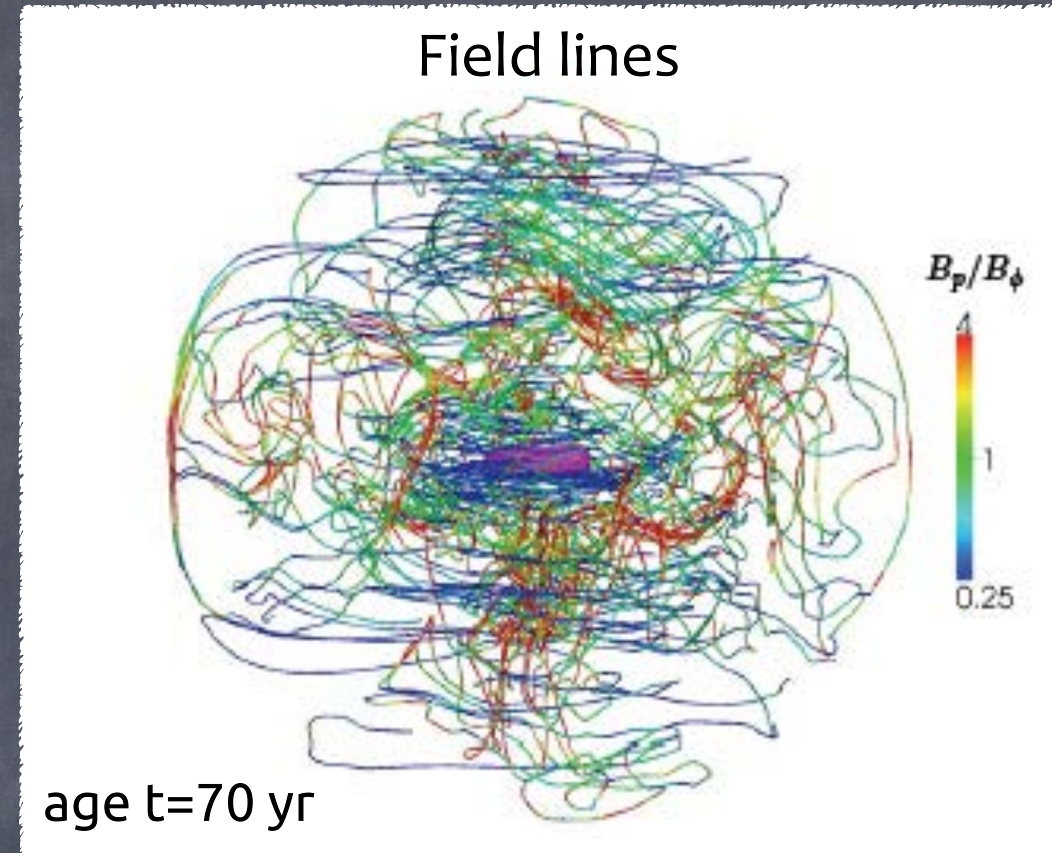




IC corrected to equipartition field

# Moving to 3D: Crab models

- 3D models allow for a more complex structure of the magnetic field
- In 3D the magnetic dissipation is stronger (Kink instability) and $\sigma \geq 1$ can be reached!

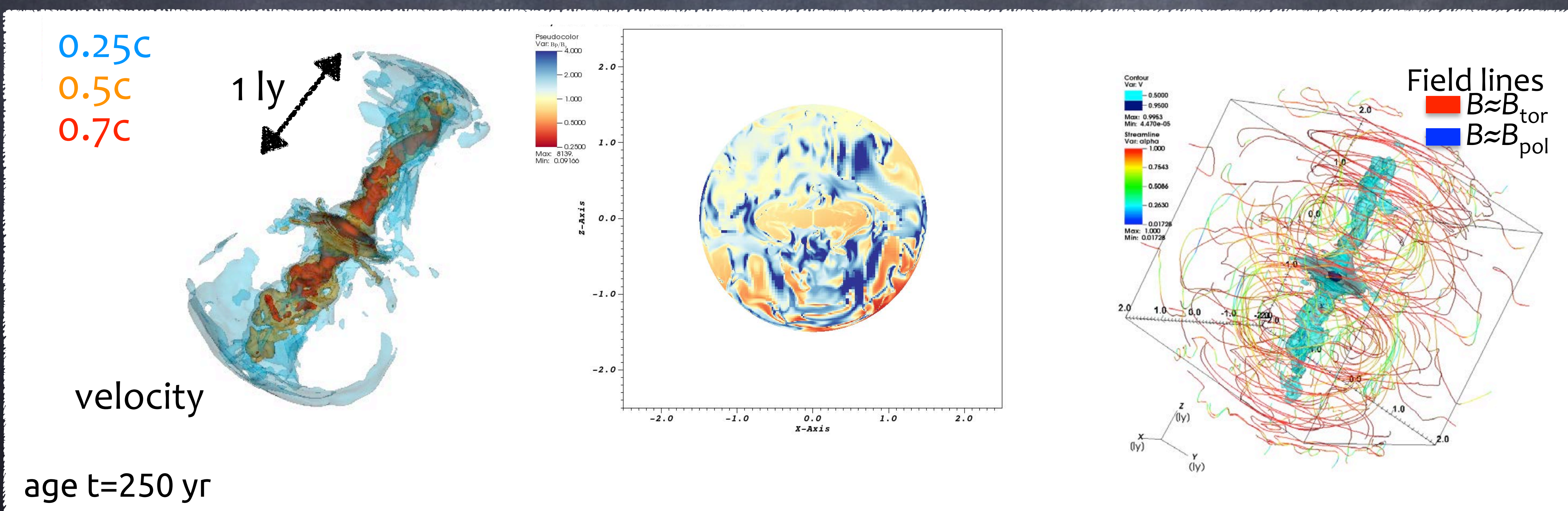
Possible solution to σ-paradox?




BUT 3D simulations are demanding in terms of resources and time, data are huge

> 1 Million CPU hours (ran @ CINECA with >2000 CPUs)

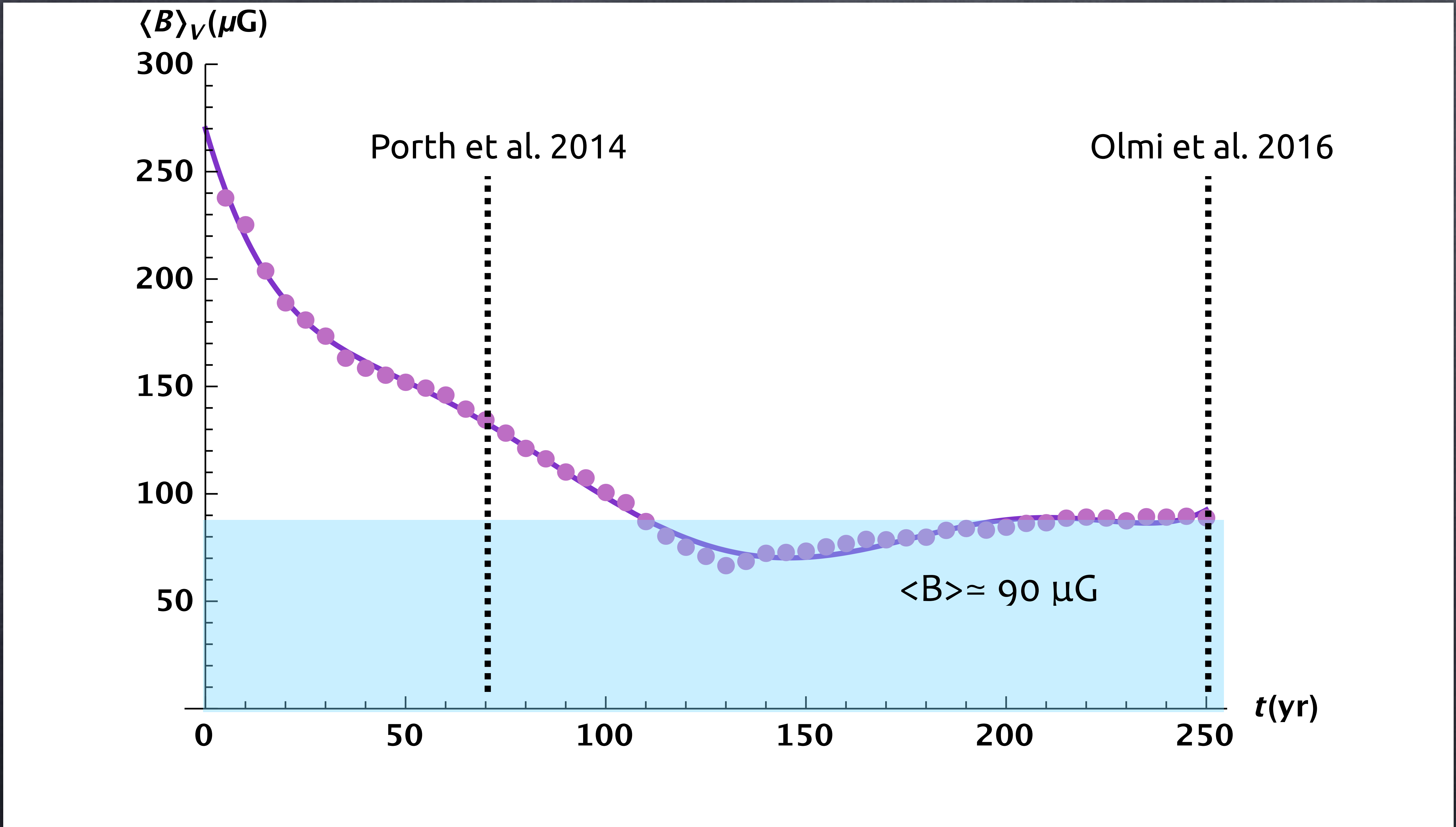
[Porth et al. 2013, 2014]




[Olmi et al. 2016]

# Not everything is solved...

The average field is again too low: σ=1 not sufficient?

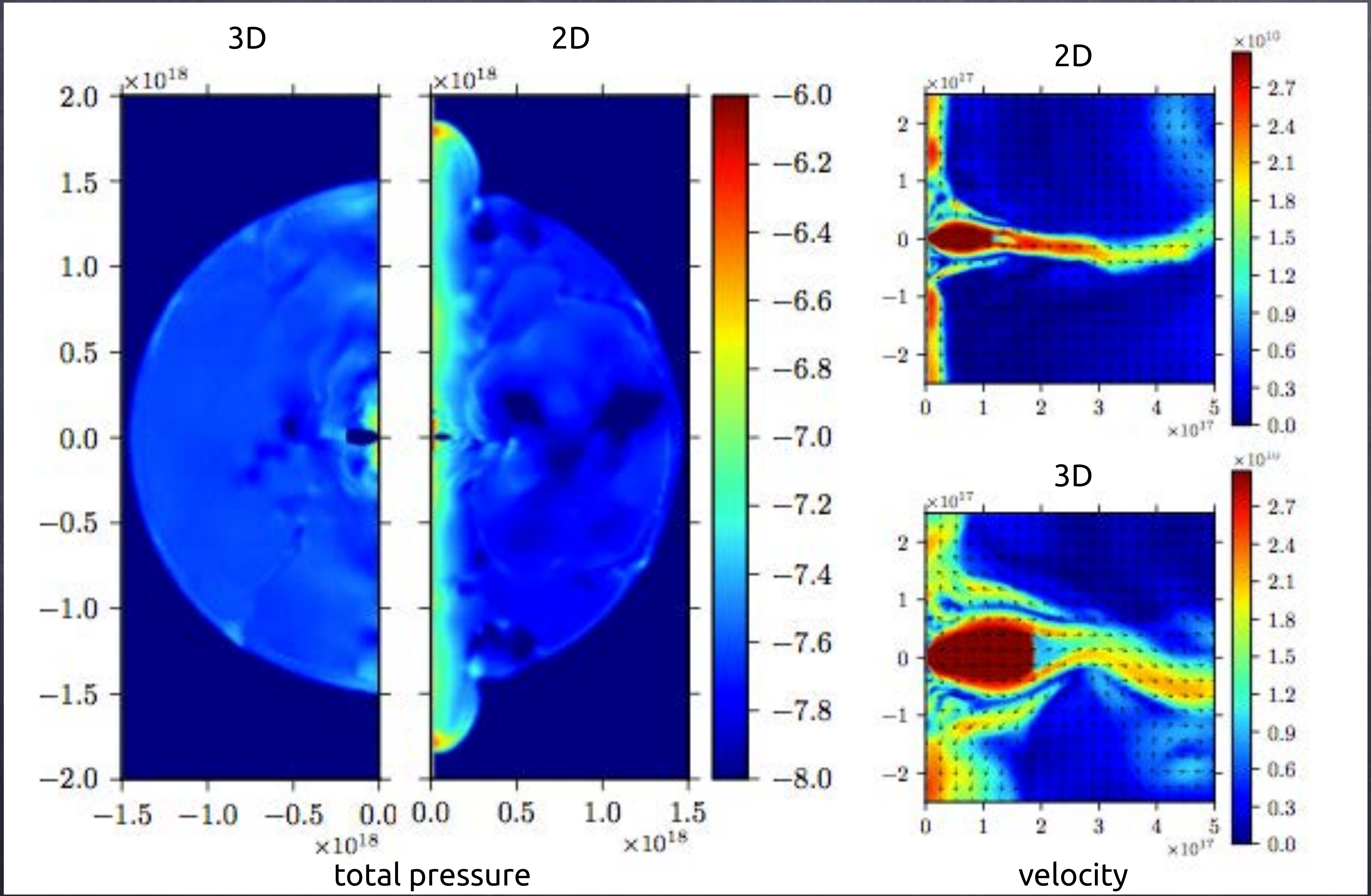



Same problems with the spectrum!

# 3D vs 2D

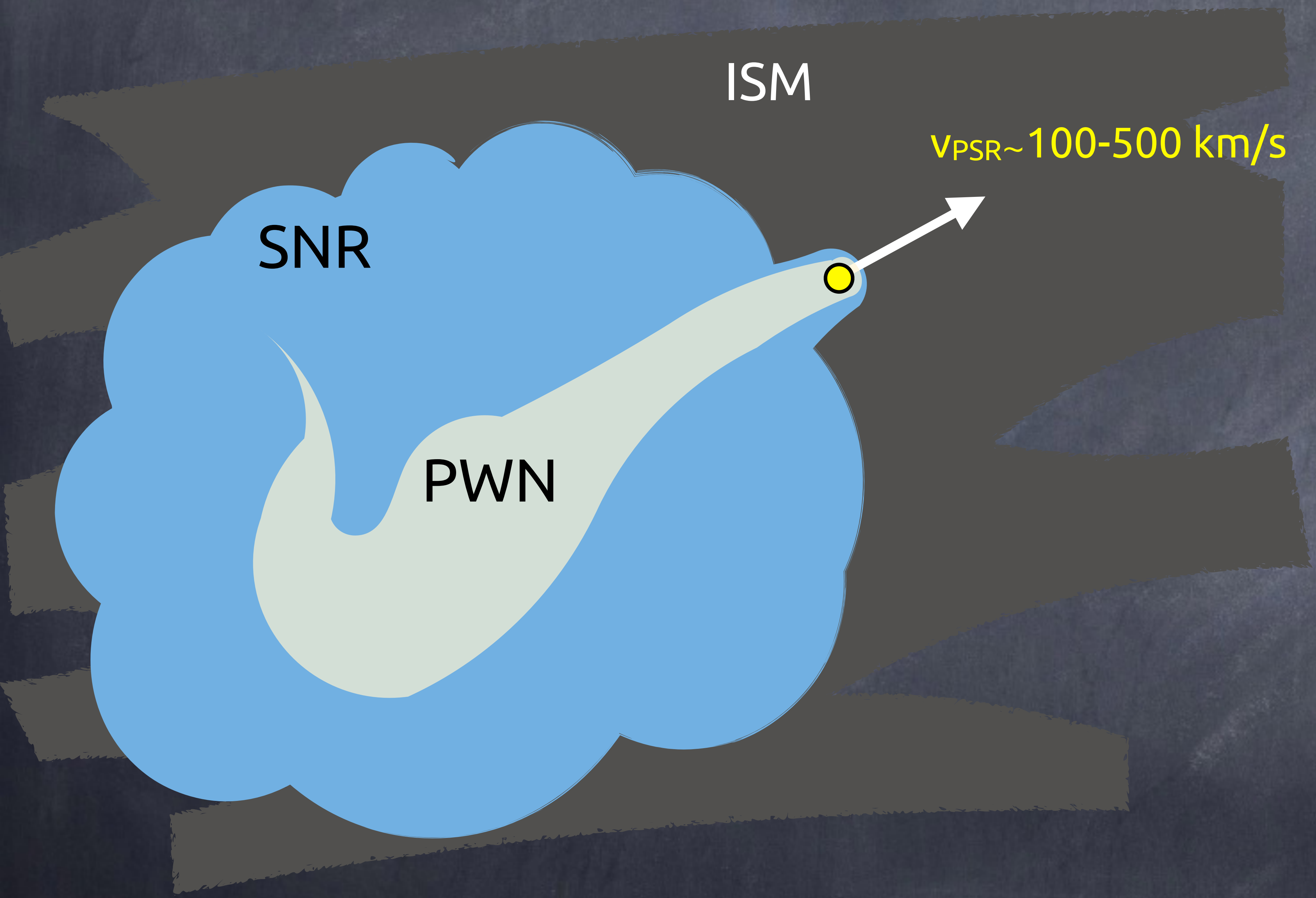
global dynamics completely different

inner dynamics comparable




[Porth et al. 2013, 2014]

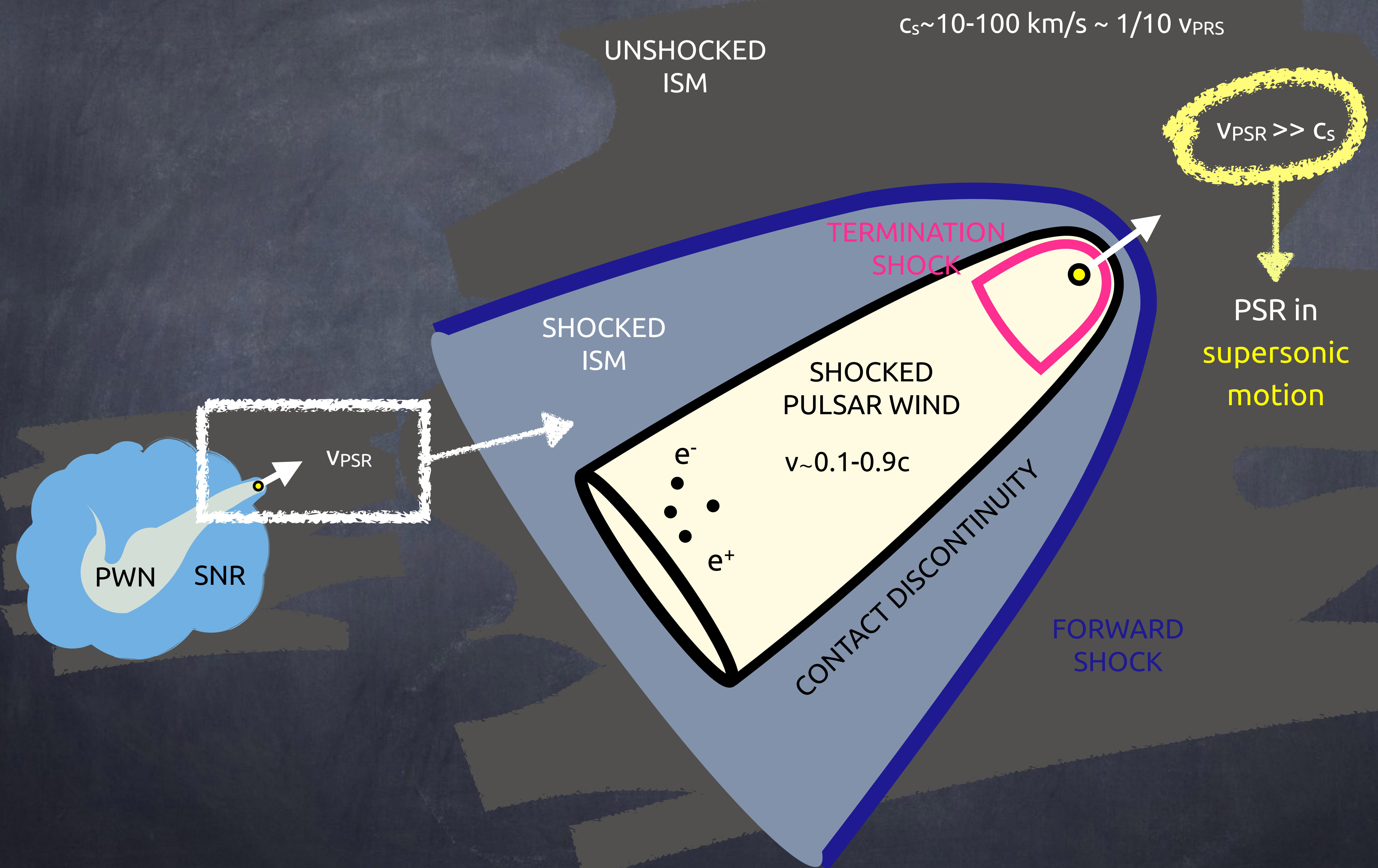
# Evolved PWNe



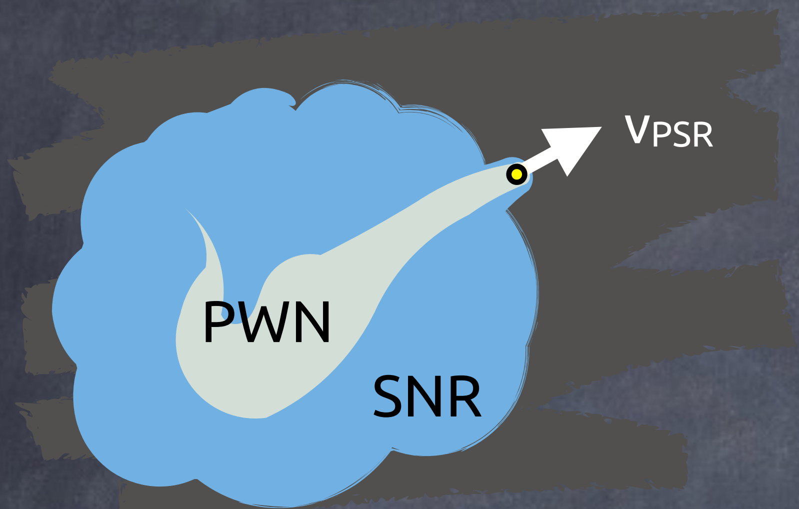

Large fraction of all the pulsars born with high kick velocity (10%-50%)

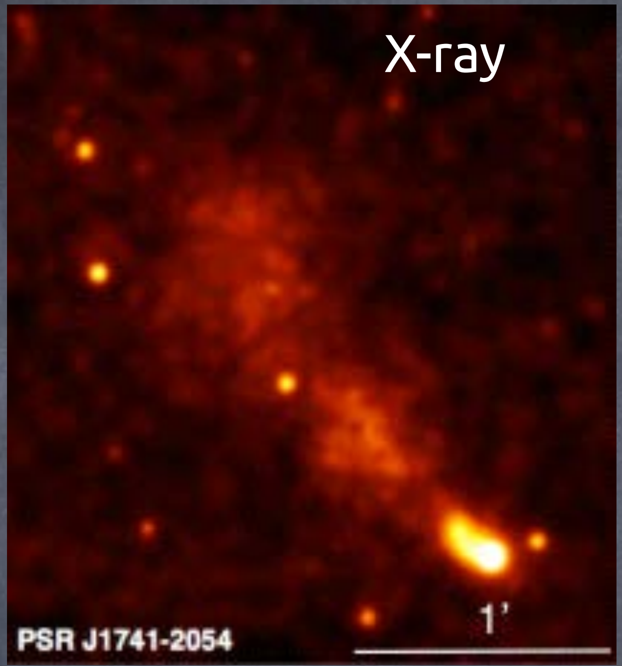
fated to escape the SNR on timescales << than typical pulsar ages (~$10^6$ yr)

# Bow shock nebulae

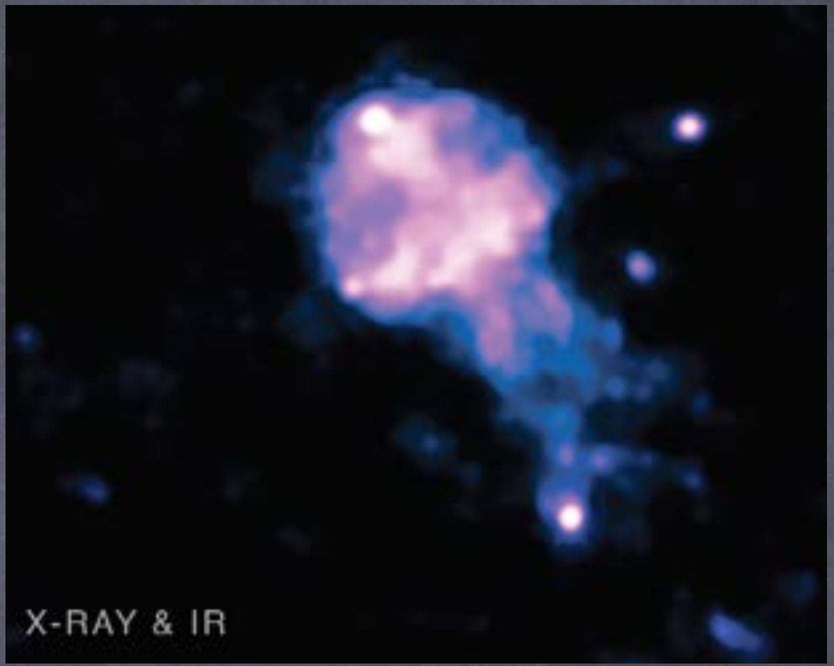


# Bow shock nebulae: cometary shape

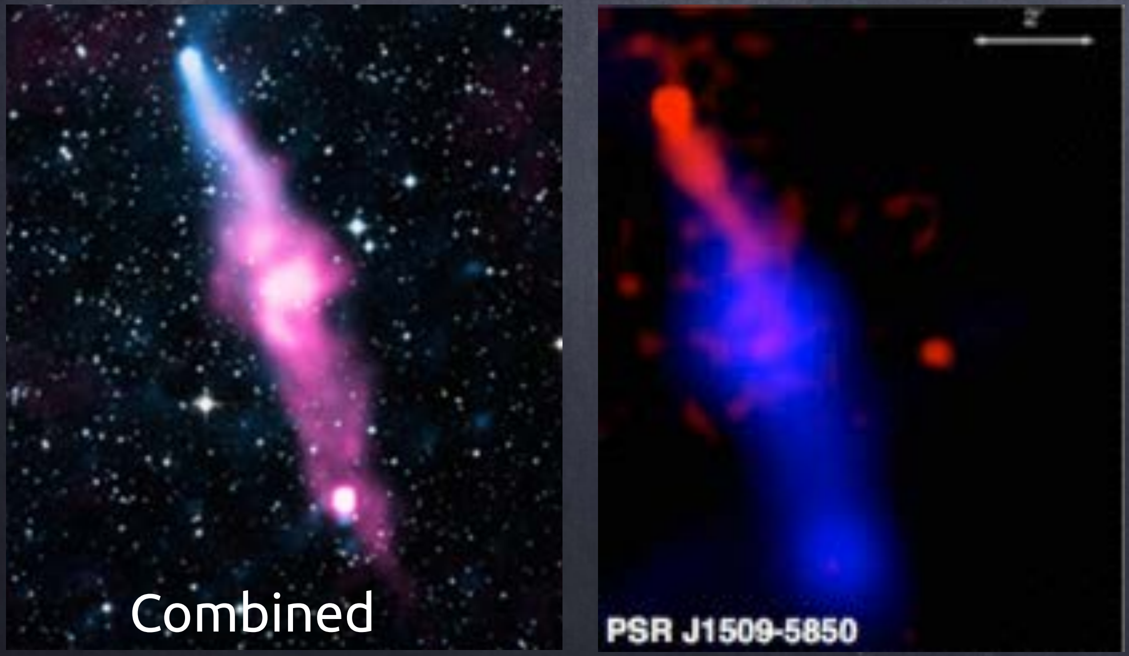


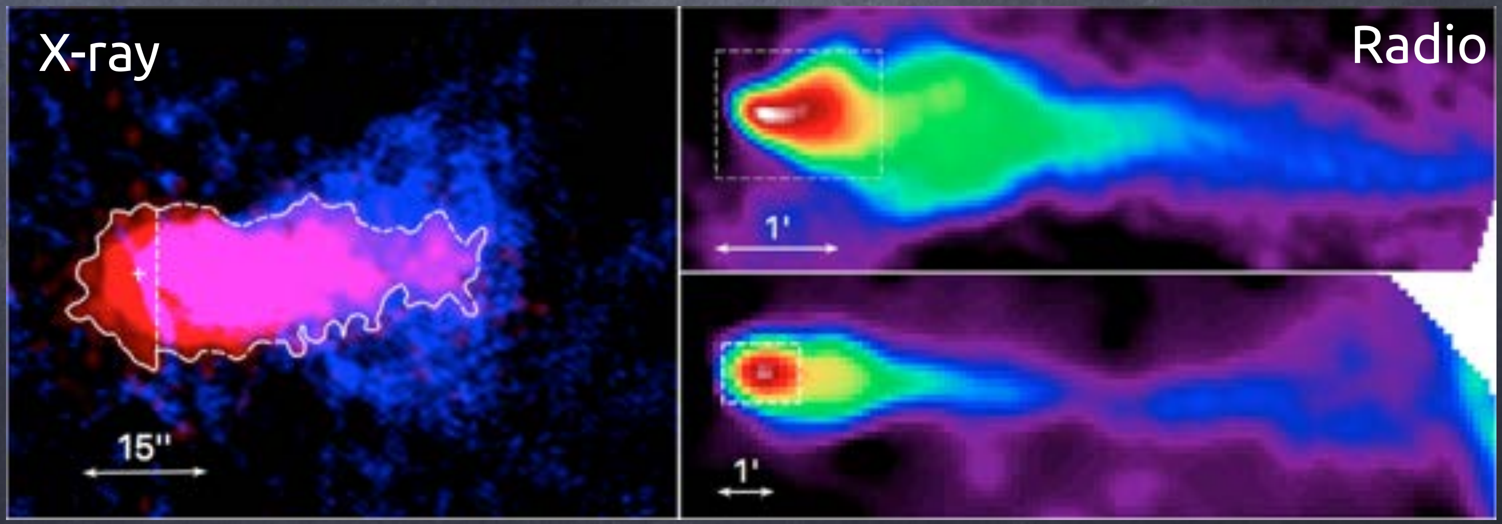

PSR J1741-2054
[Kargaltsev et al. 2016]




B0355+54
[Emre et al. 2005]

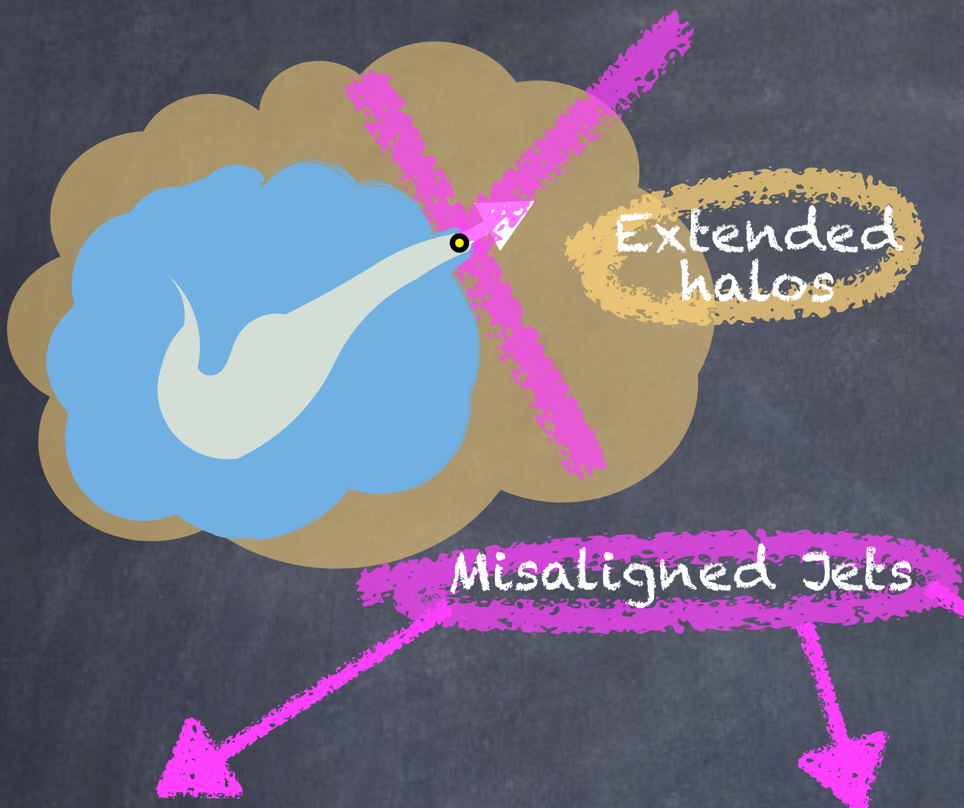


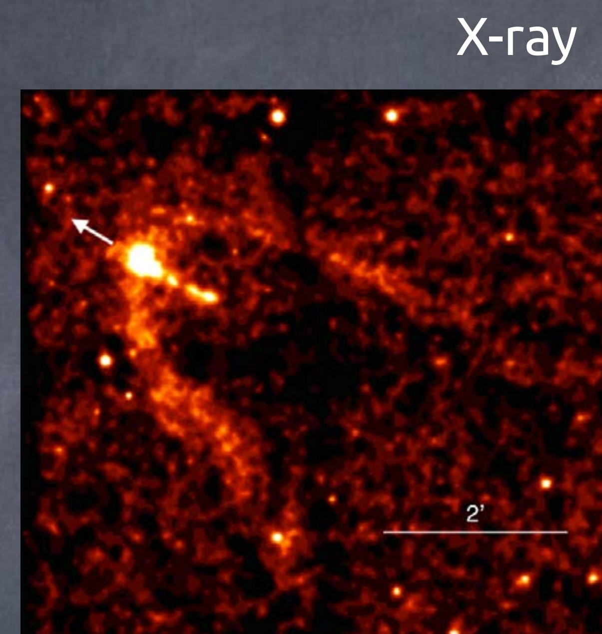

PSR J1509-5850
[Hui & Becker 2007, Klinger et al. 2016]



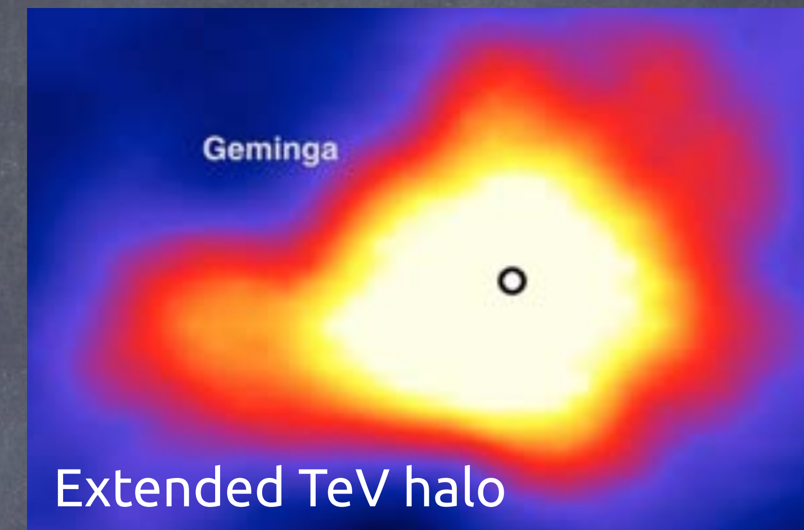

Mouse PWN
[Yusef-Zadeh & Bally 1987, Yusef-Zadeh & Gaensler 2005, Klinger et al. 2018]

# Bow shock nebulae: puzzling outflows and halos



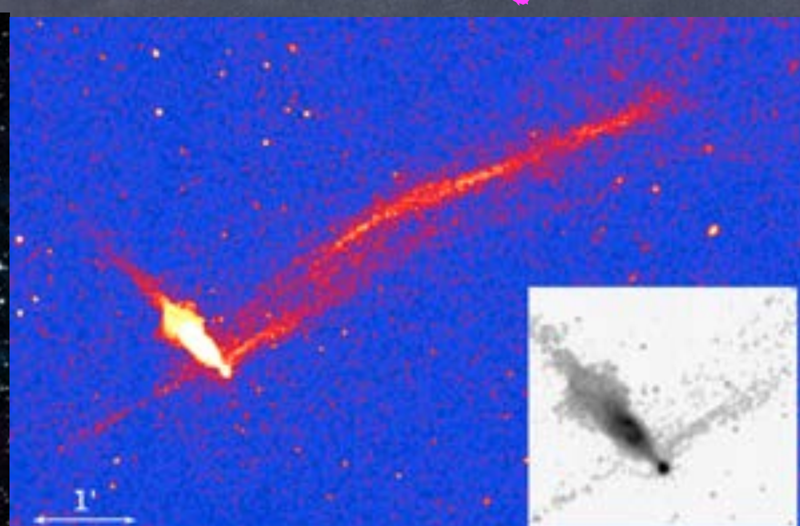




Geminga
[Posselt et al. 2017]

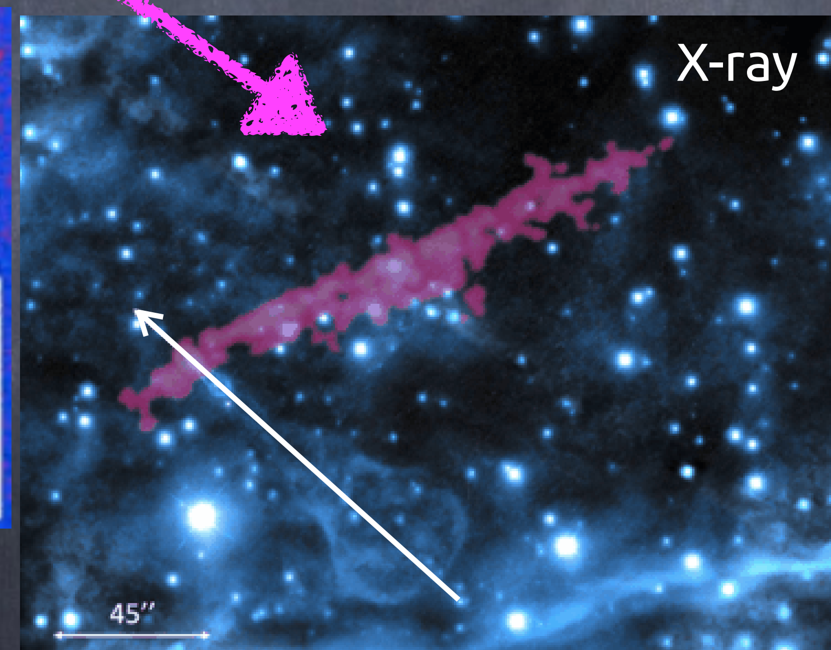



[Abeysekara et al. 2017]

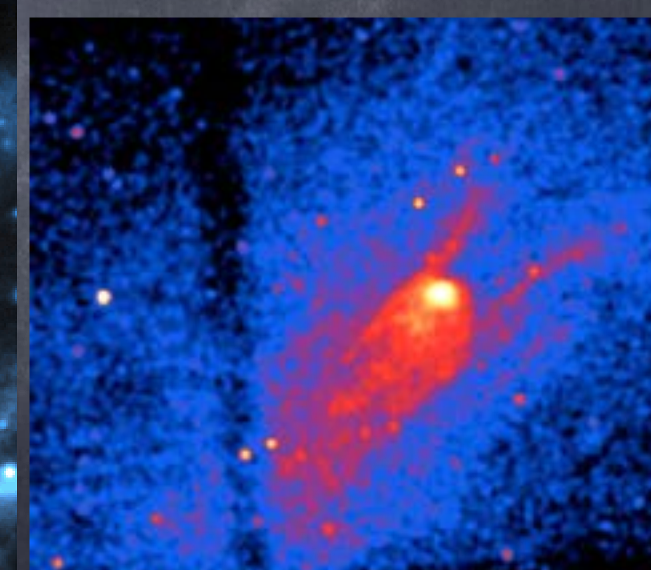
PSR J1509-5850
[Klinger et al. 2016]




Lighthouse nebula
[Pavan et al. 2016]



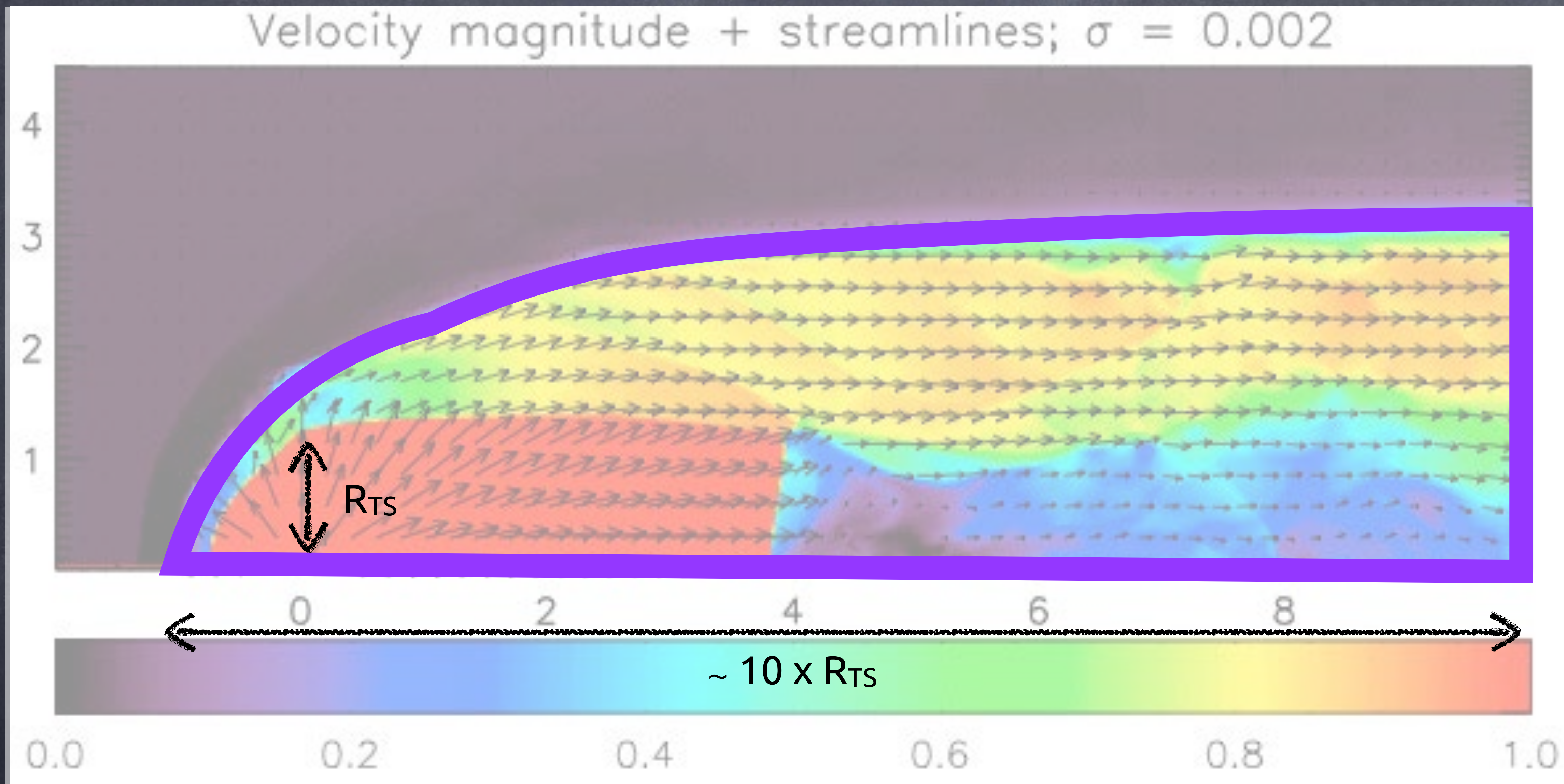

Guitar nebula
[Cordes et al. 1993, Wong et al. 2003]



G327
[Temim et al. 2009]

# 2D MHD Models of BSPWNe

Relativistic MHD axisymmetric simulations [Bucciantini et al. 2005] were able to account for the formation of the bow shock, TS deformation, generation of the tail.

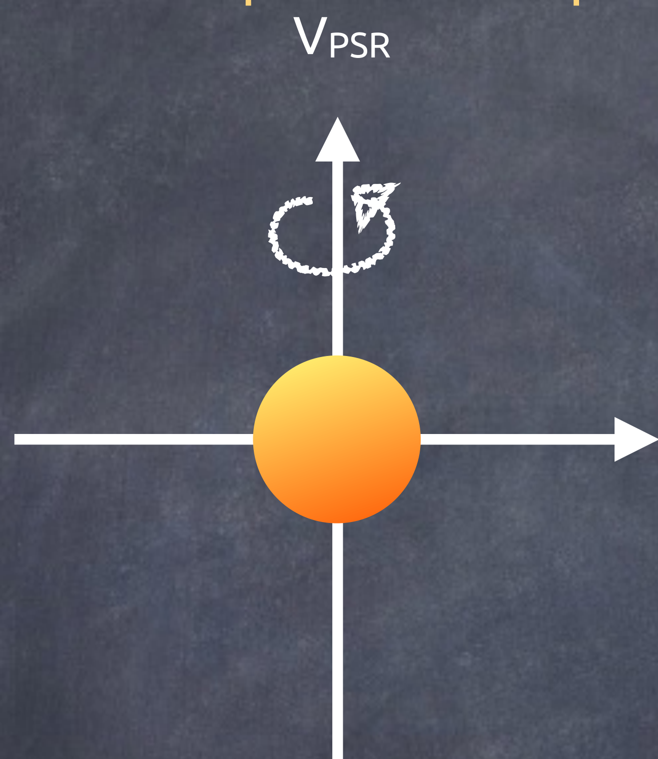



Tail with cylindric shape with constant area.

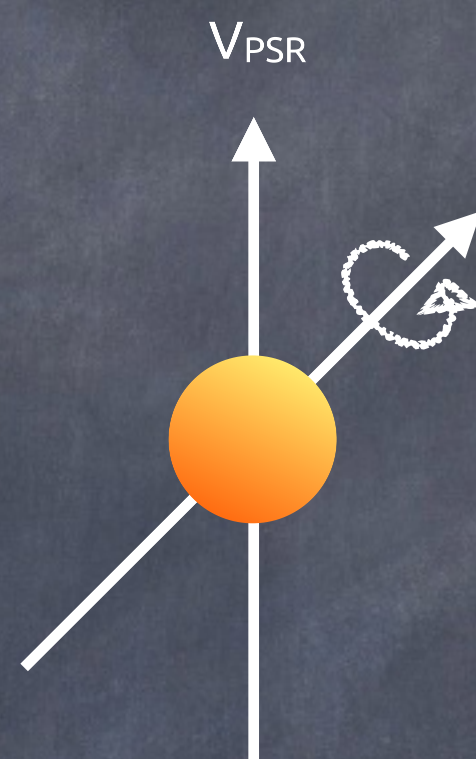
# 3D MHD Models of BSPWNe

How to model the pulsar wind:

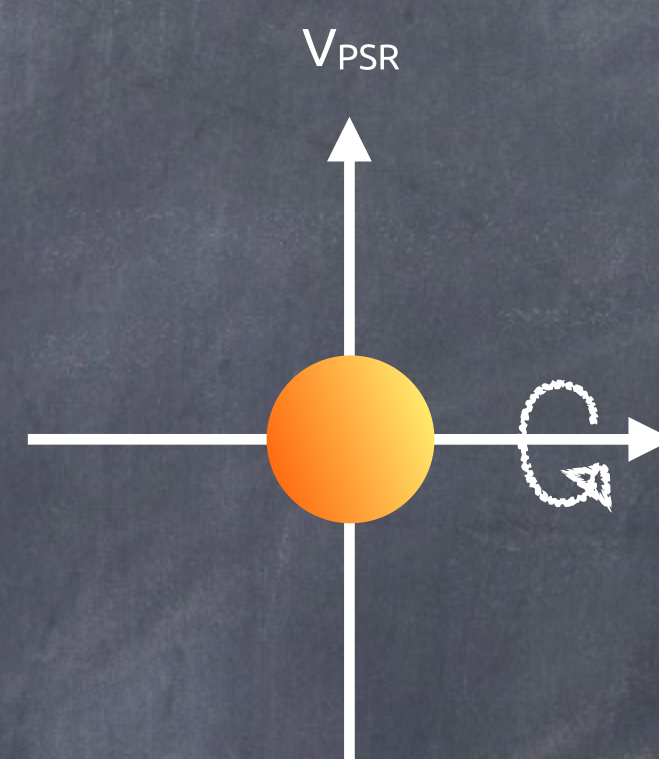
Inclination of the spin-axis and pulsar speed:




Spin-axis aligned with pulsar motion $\Phi_M$=0°




$\Phi_M$=45°




$\Phi_M$=90°

Anisotropy in the energy flux: $F(\psi) \propto 1 + \alpha \sin^2 \psi$

$\psi$ colatitude from the spin-axis

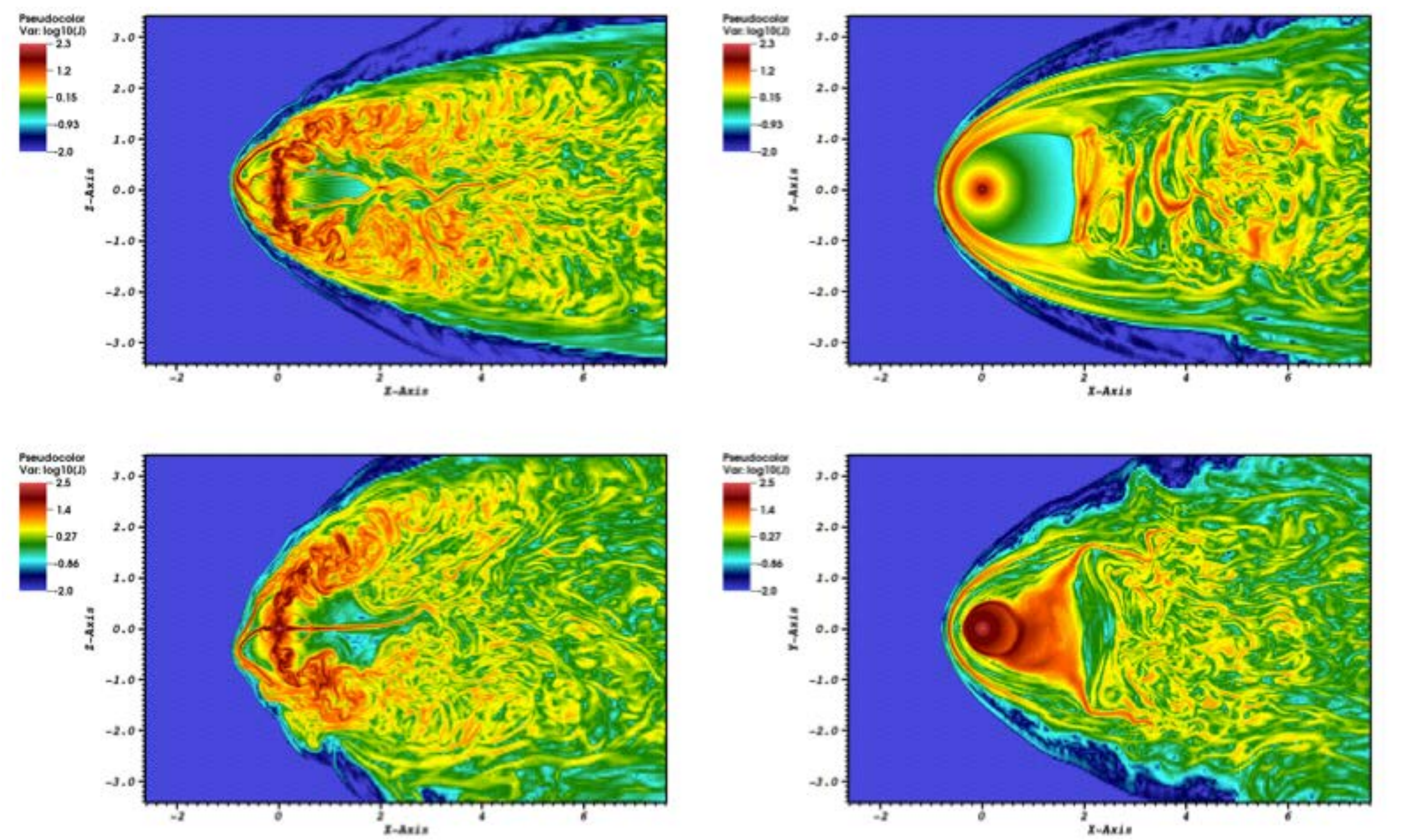

ISOTROPIC case ($\alpha$=0)


ANISOTROPIC case ($\alpha \neq 0$)

Wind magnetization: $0.01 \lesssim \sigma \lesssim 1$

# Effects of magnetic field geometries on the BS

[Barkov & Lyutikov 2018]



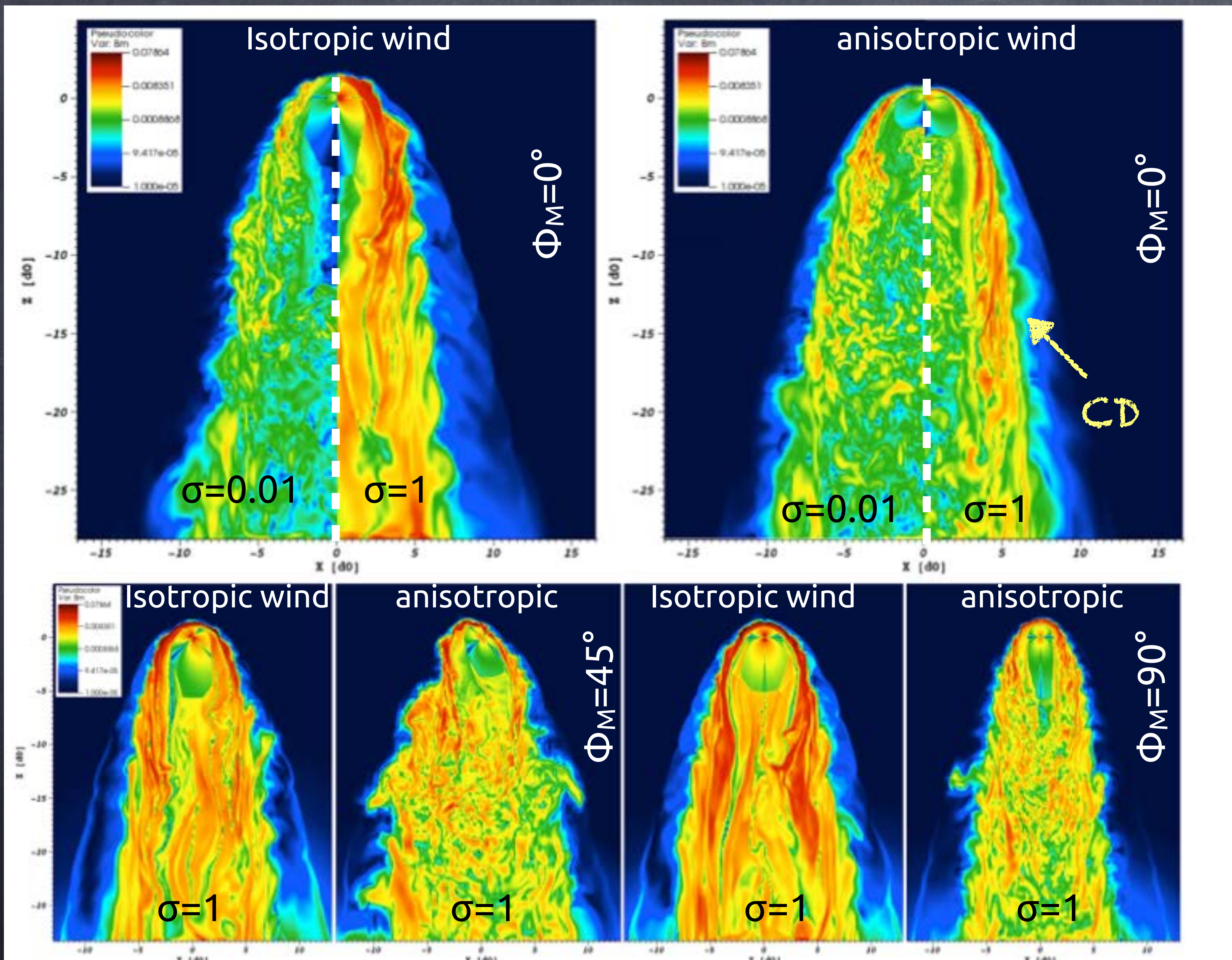

Maps of the current density [Barkov & Lyutikov 2018]

Anisotropy of ISM density only slightly affect the FS morphology
[Toropina 2018, Barkov & Lyutikov 2018]

Simulations supported by MoU INAF-CINECA class A projects

# Dynamics of the tail

[Olmi & Bucciantini 2019]




Maps of the magnetic field for different geometries and magnetizations

Different field geometries (inclinations)

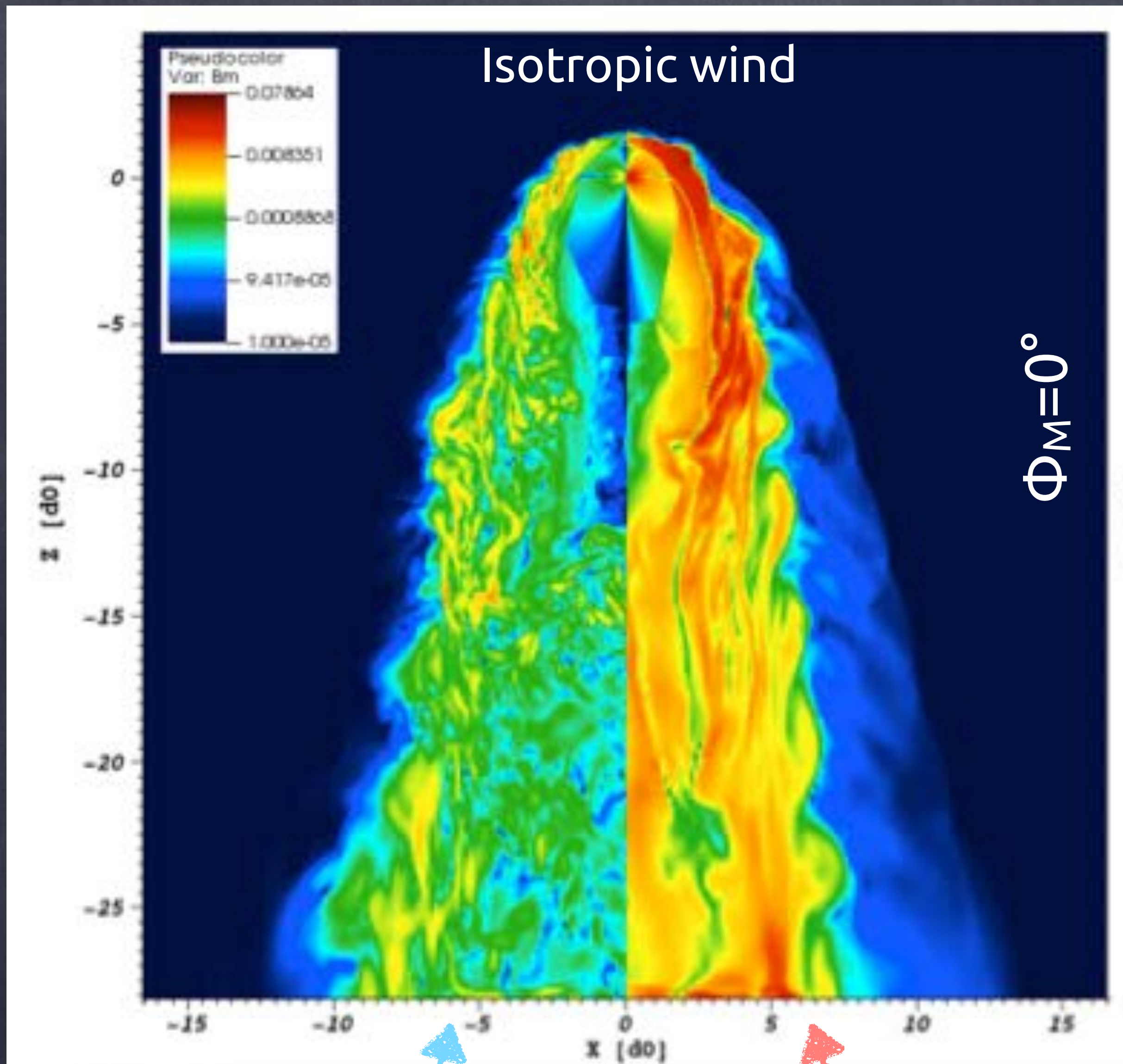
Shape of the contact discontinuity

Magnetization + isotropy/anisotropy

Dynamics in the tail

# Development of turbulence

[Olmi & Bucciantini 2019]




Low magnetization

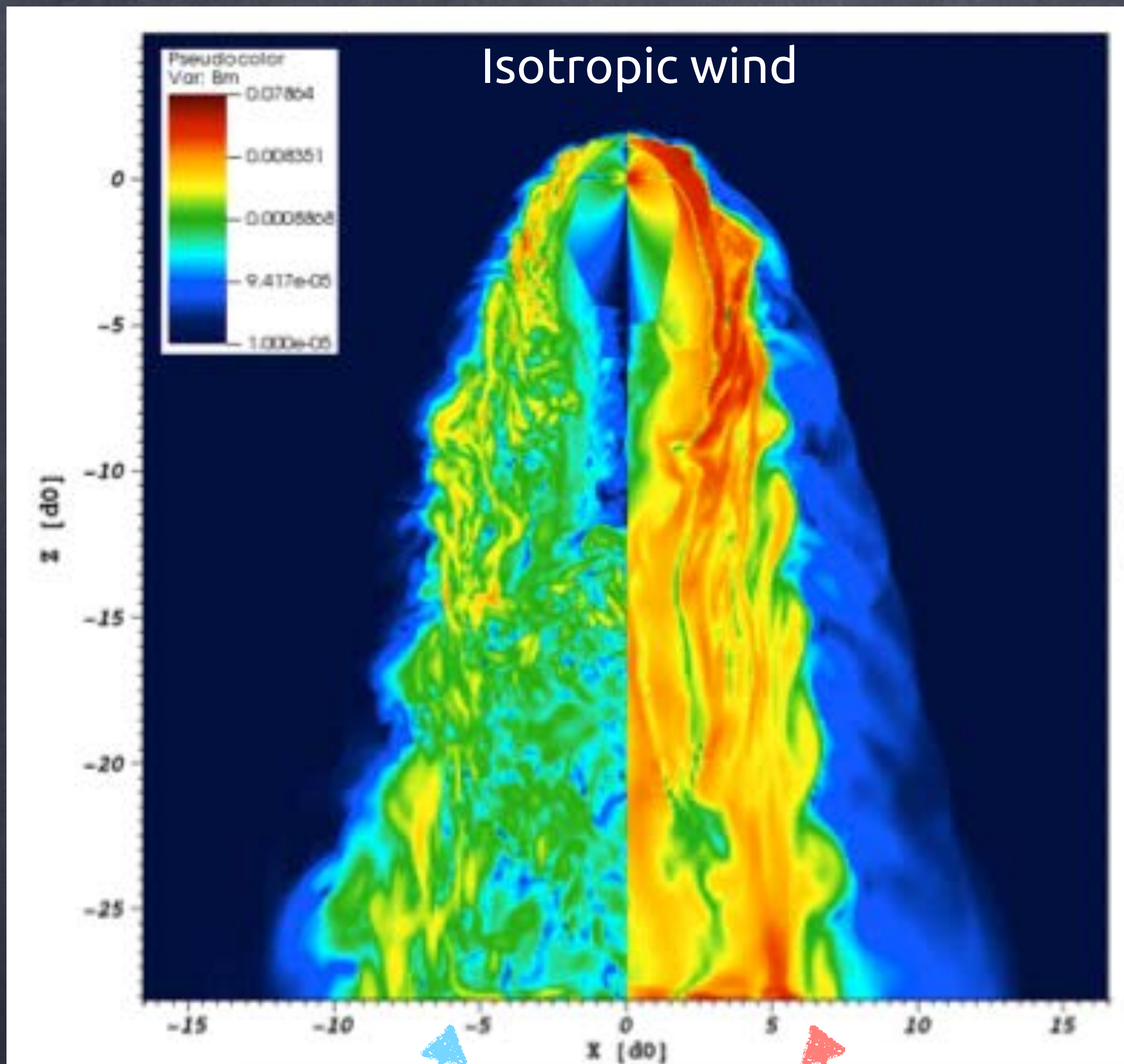
high level of turbulence, chaotic flow

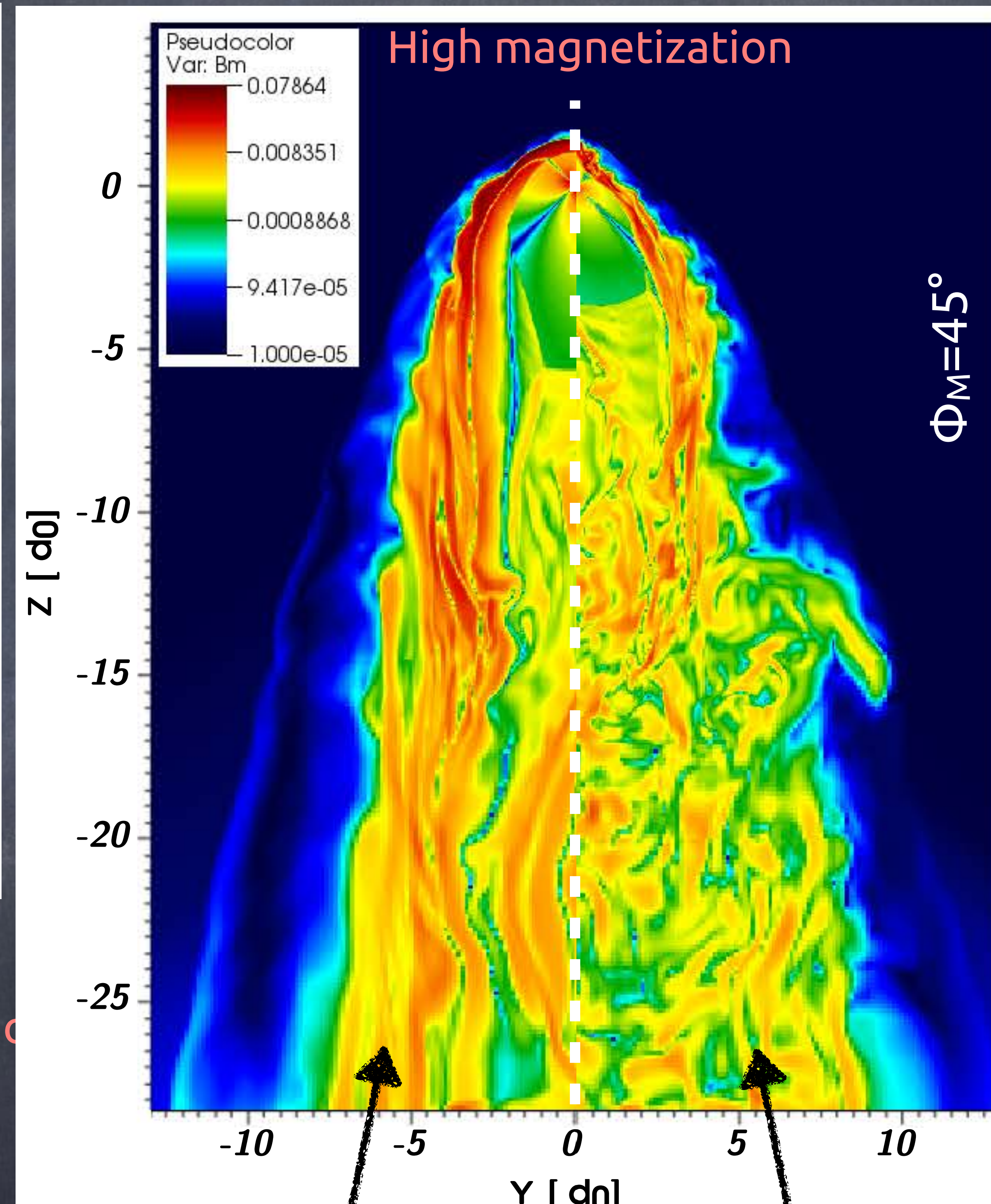
High magnetization

low level of turbulence, flow almost laminar

# Development of turbulence

[Olmi & Bucciantini 2019]




Low magnetization

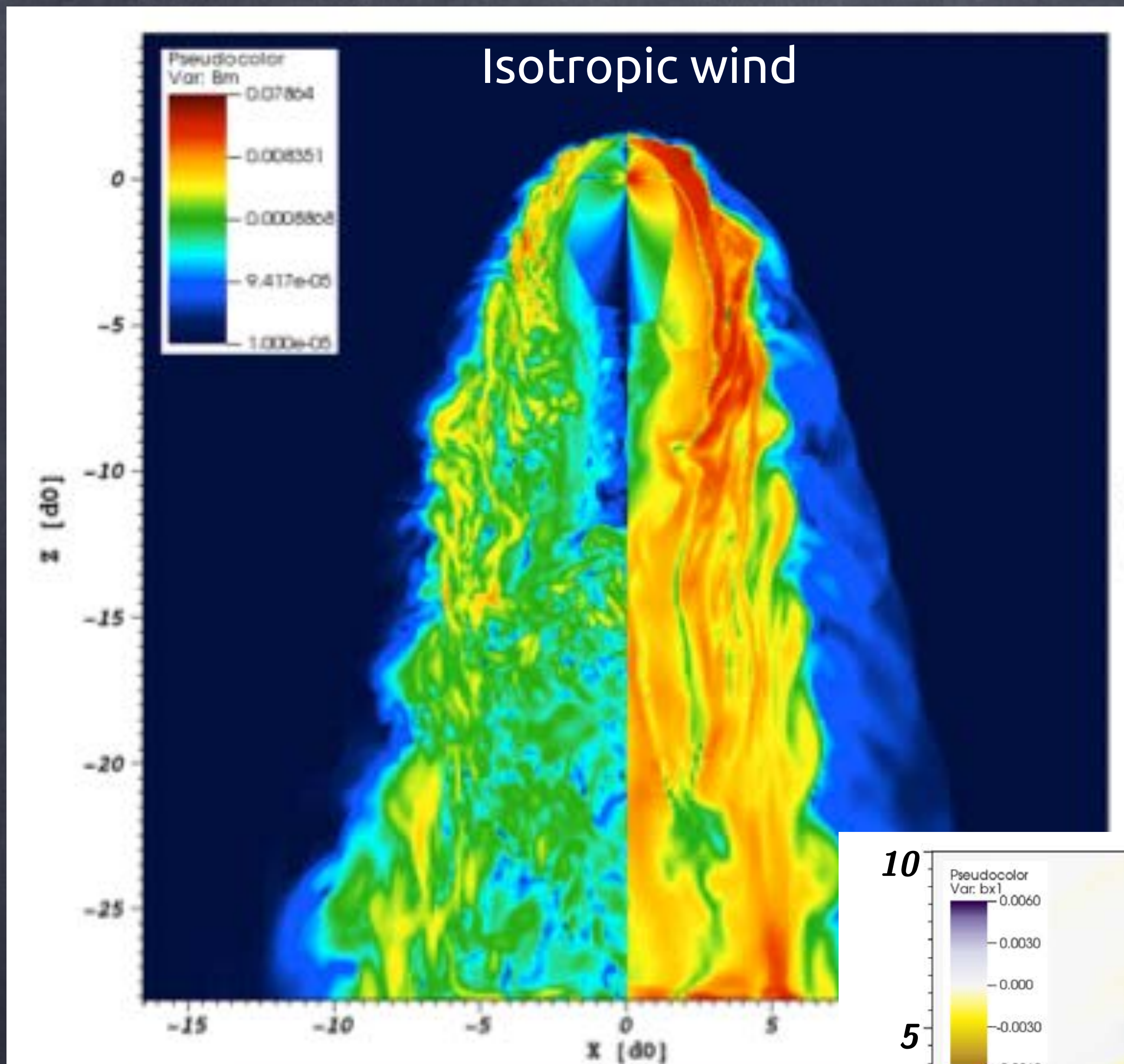
High magnetizatio

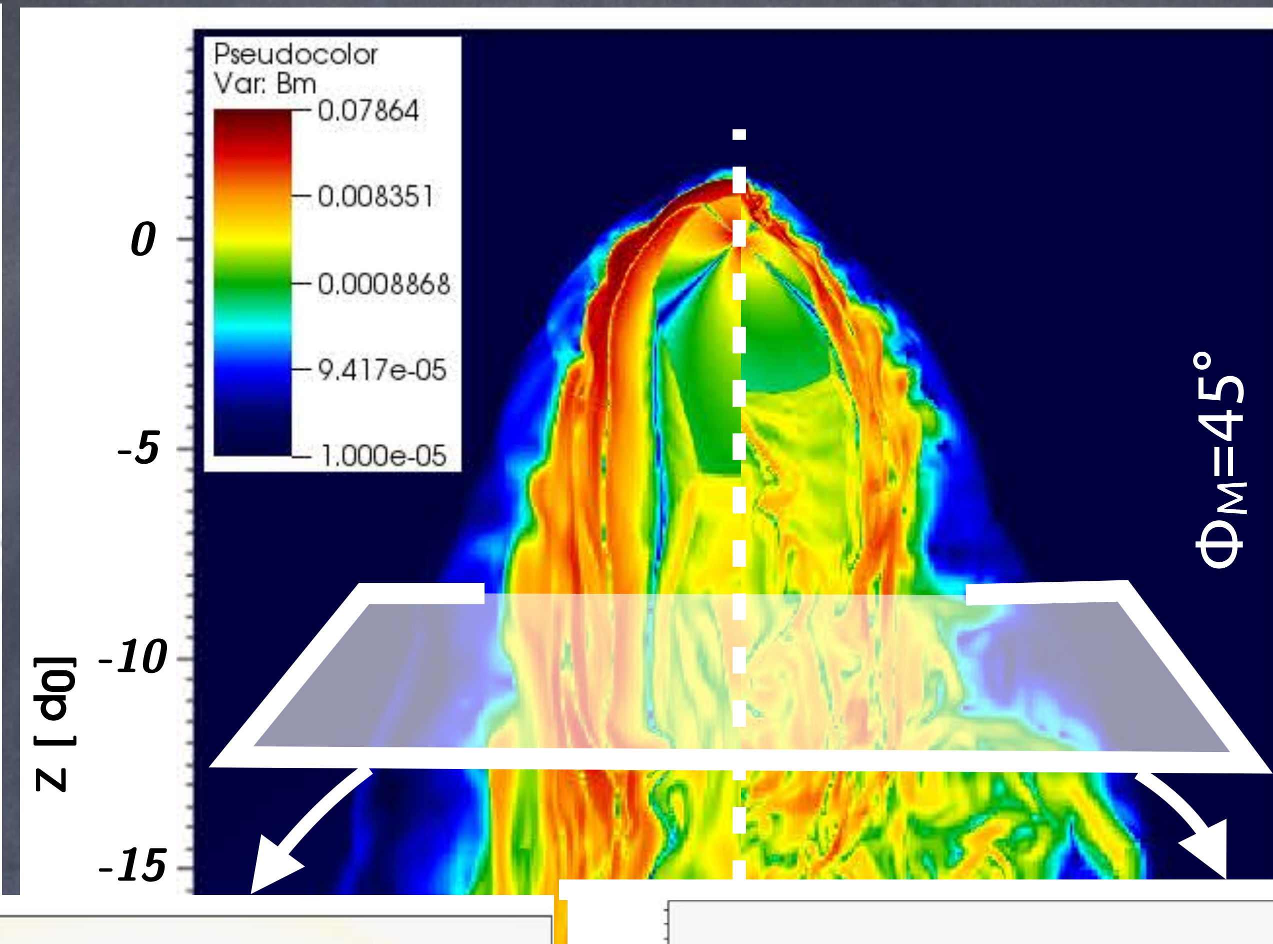
Isotropic wind

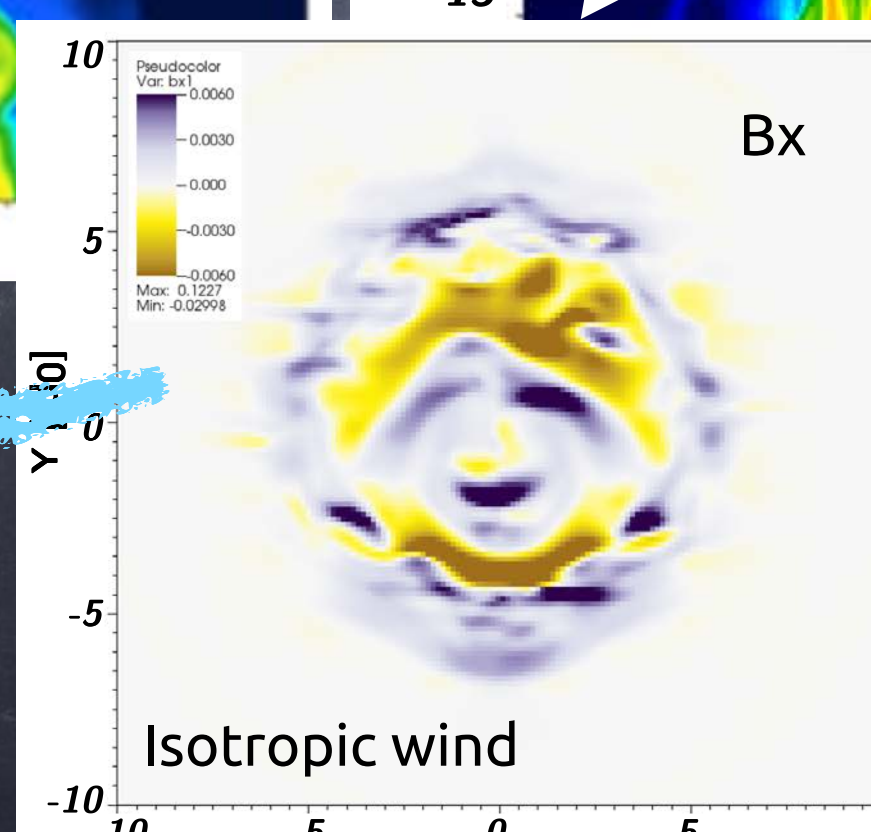
Anisotropic wind

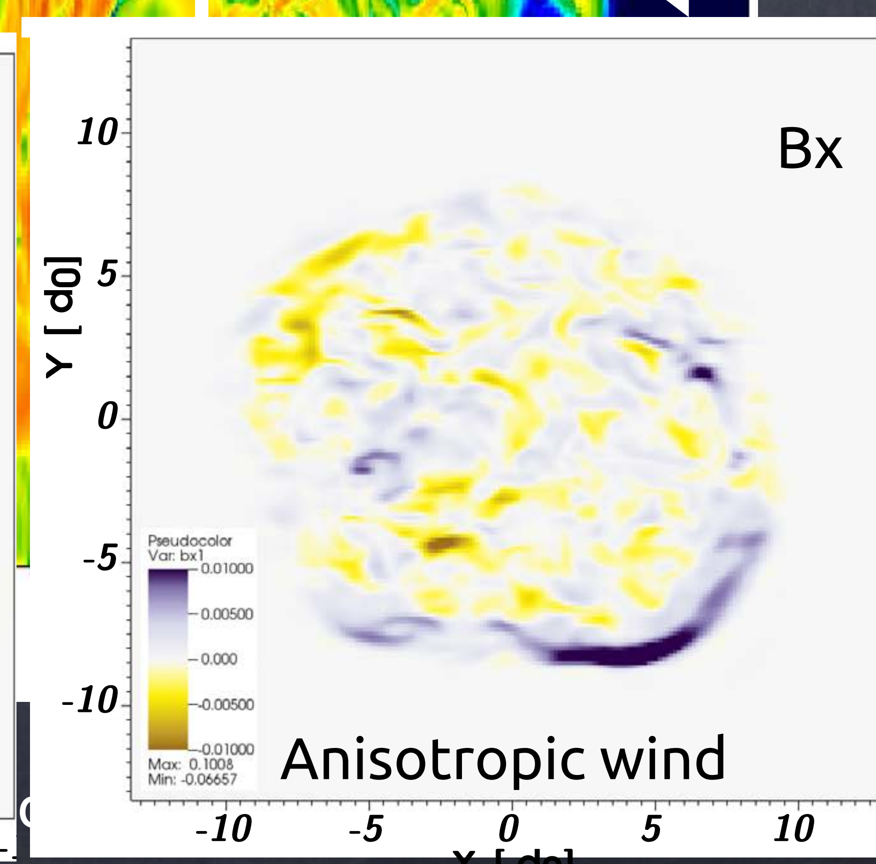
# Development of turbulence

[Olmi & Bucciantini 2019]



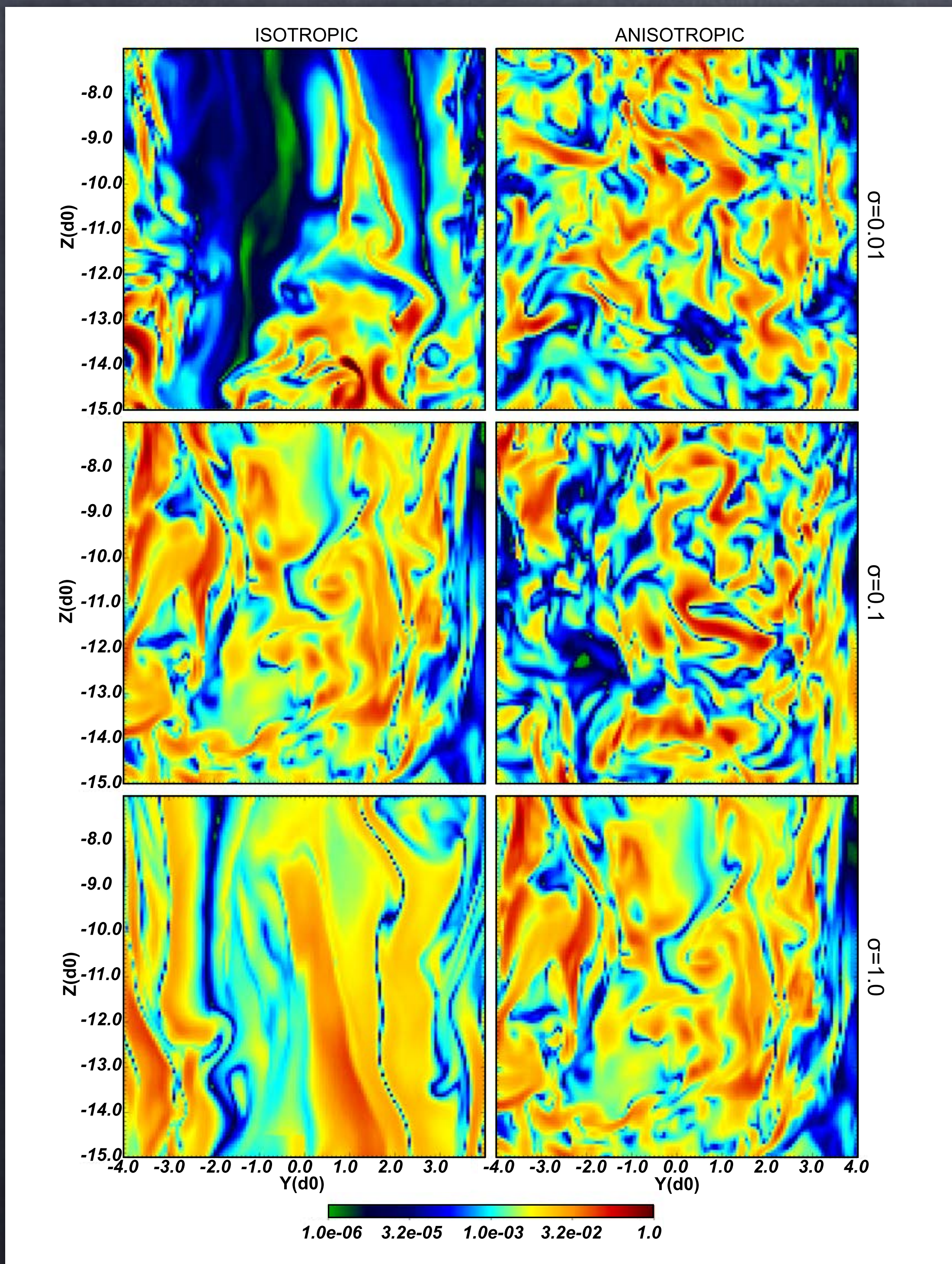



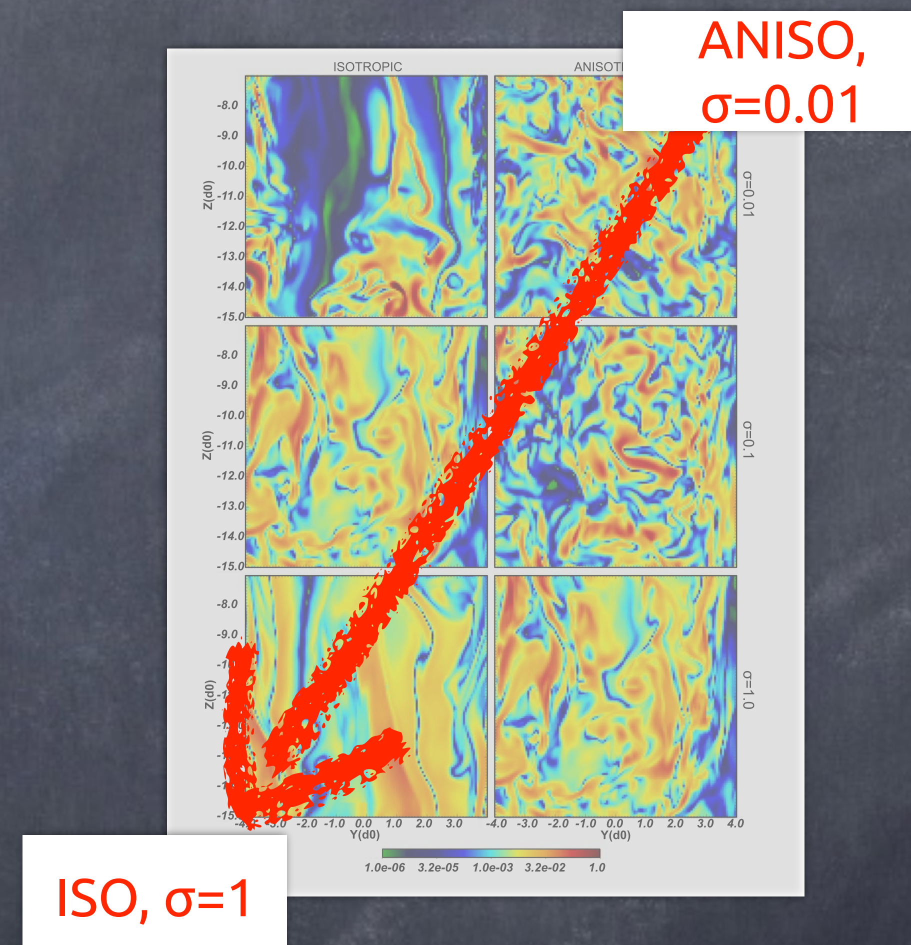

injection properties only maintained for isotropic models

# Development of turbulence




Maps of the magnetization

HIGH TURBULENCE with complete loss of injection information

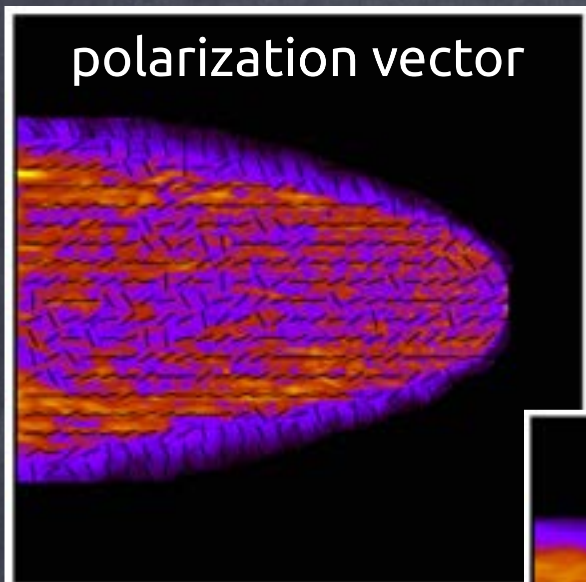



LOW TURBULENCE with injection information maintained and laminar flow

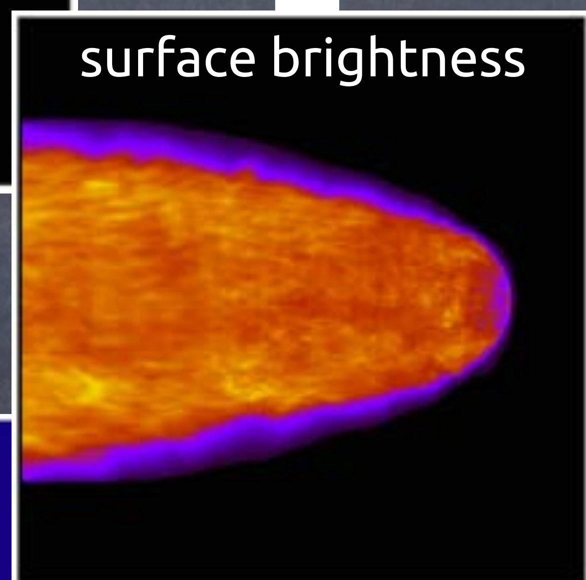
[Olmi & Bucciantini 2019]

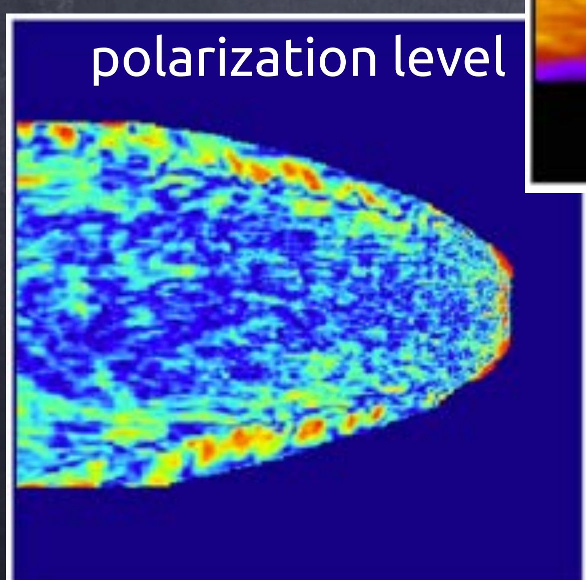
# Consequences for emission

ANISOTROPIC σ=0.01



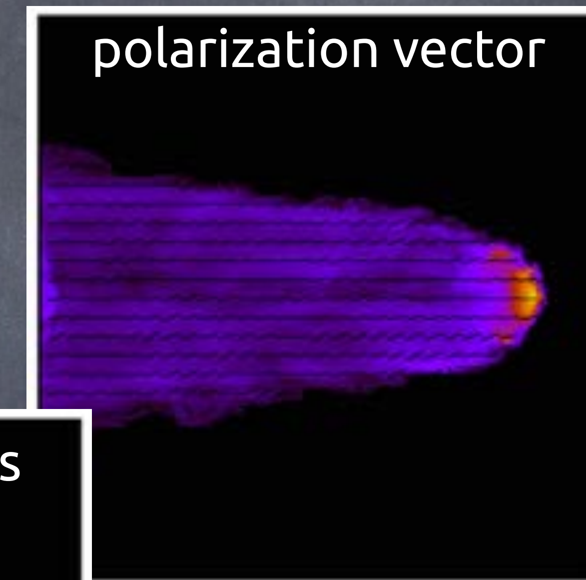

High level of turbulence



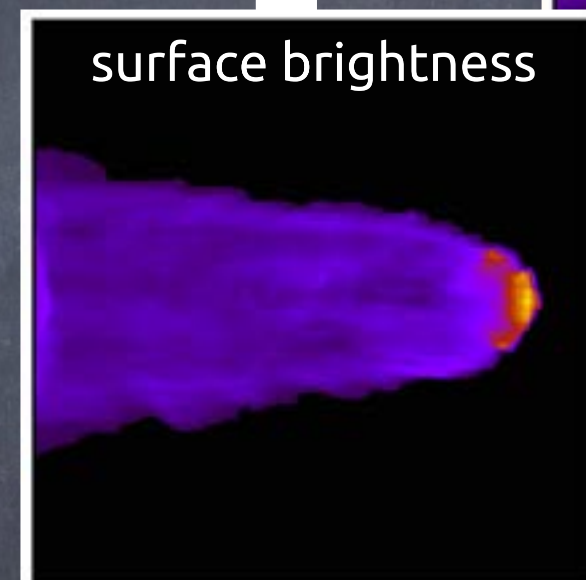



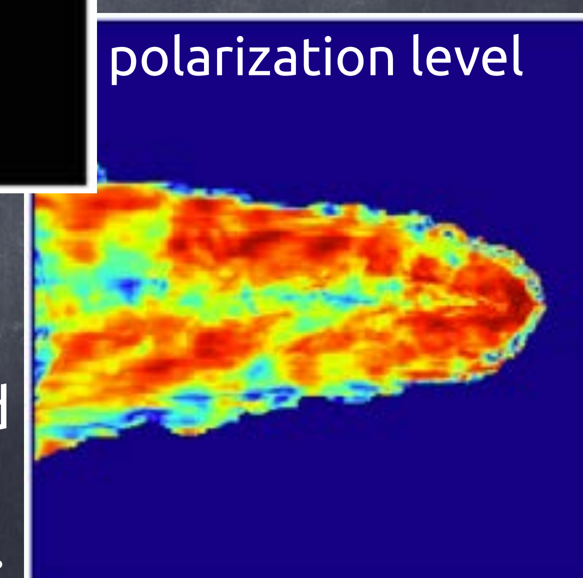

Uniform emissivity.
Unpolarized

ISOTROPIC σ=1




Low level of turbulence

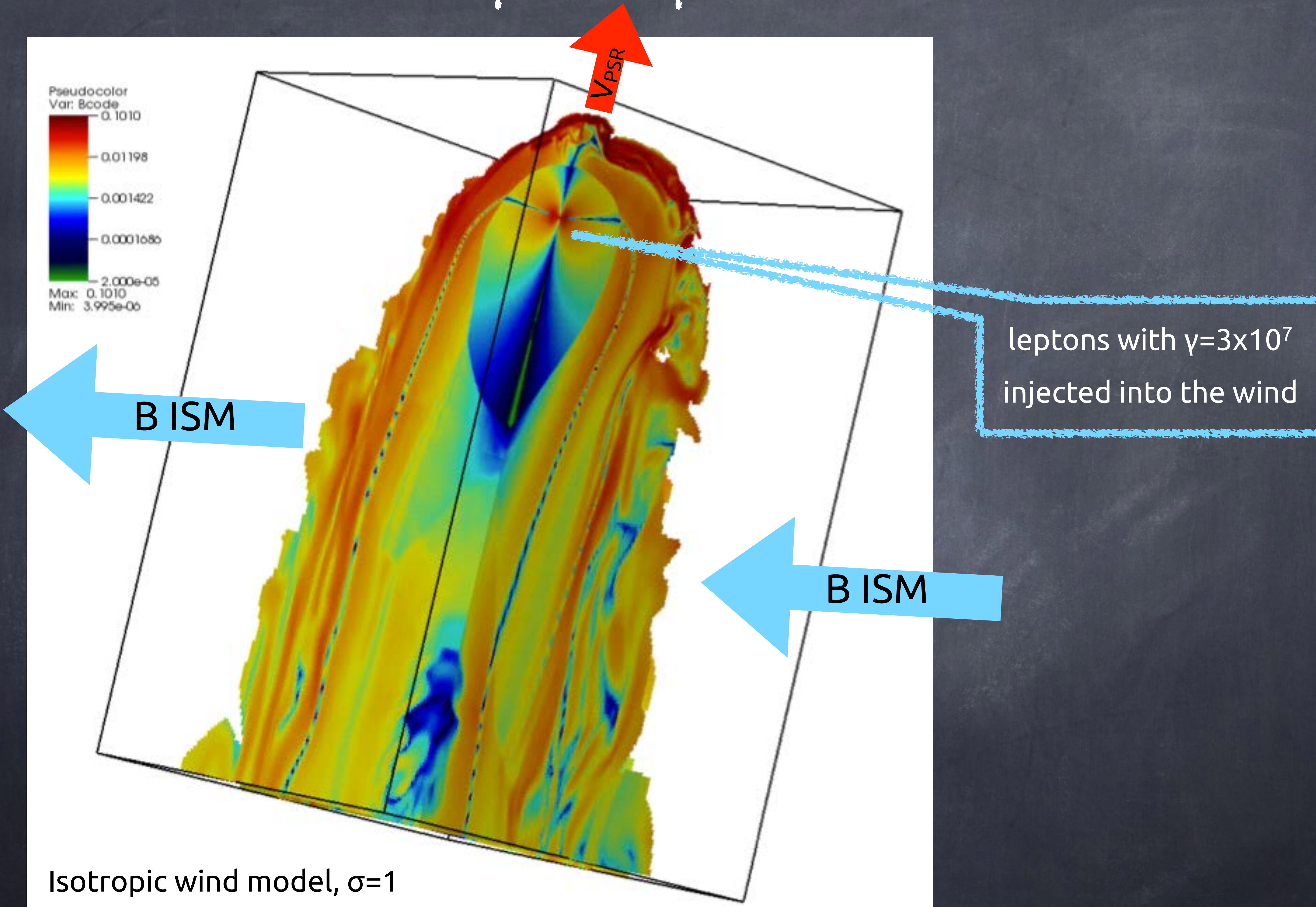



Emission dominated by the head.
Strong polarization.

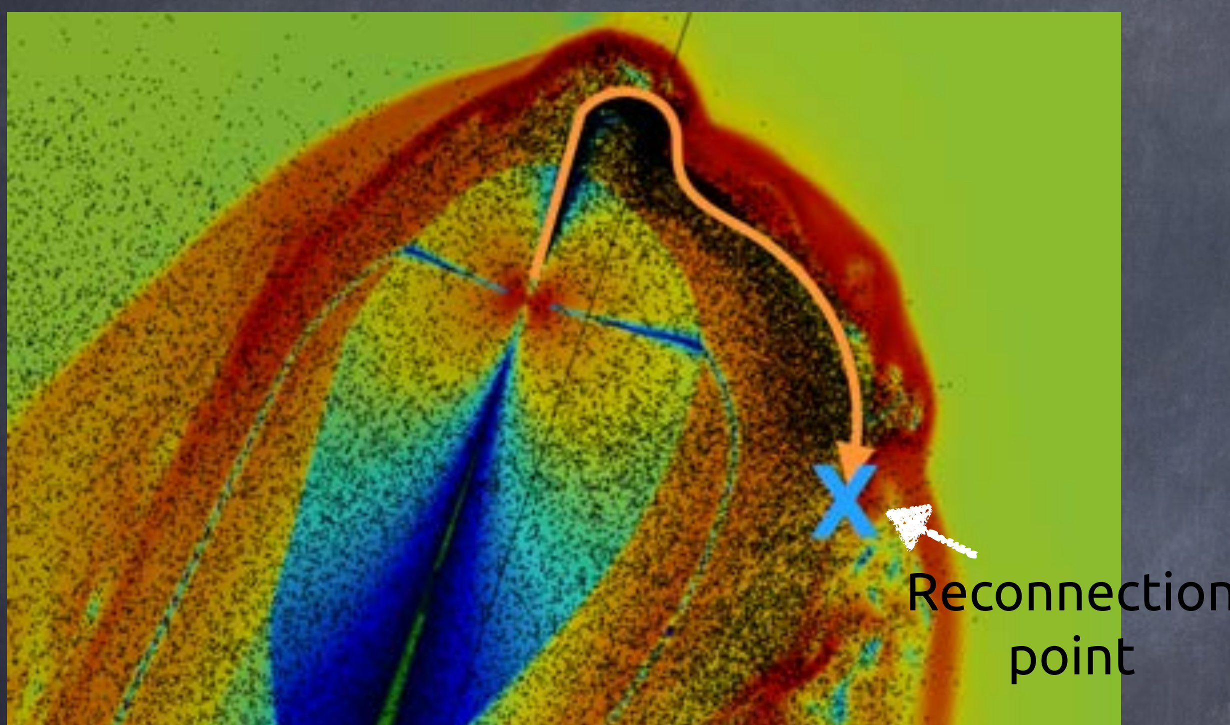
Preliminary from Olmi & Bucciantini 2, in prep.

# Escape of particles

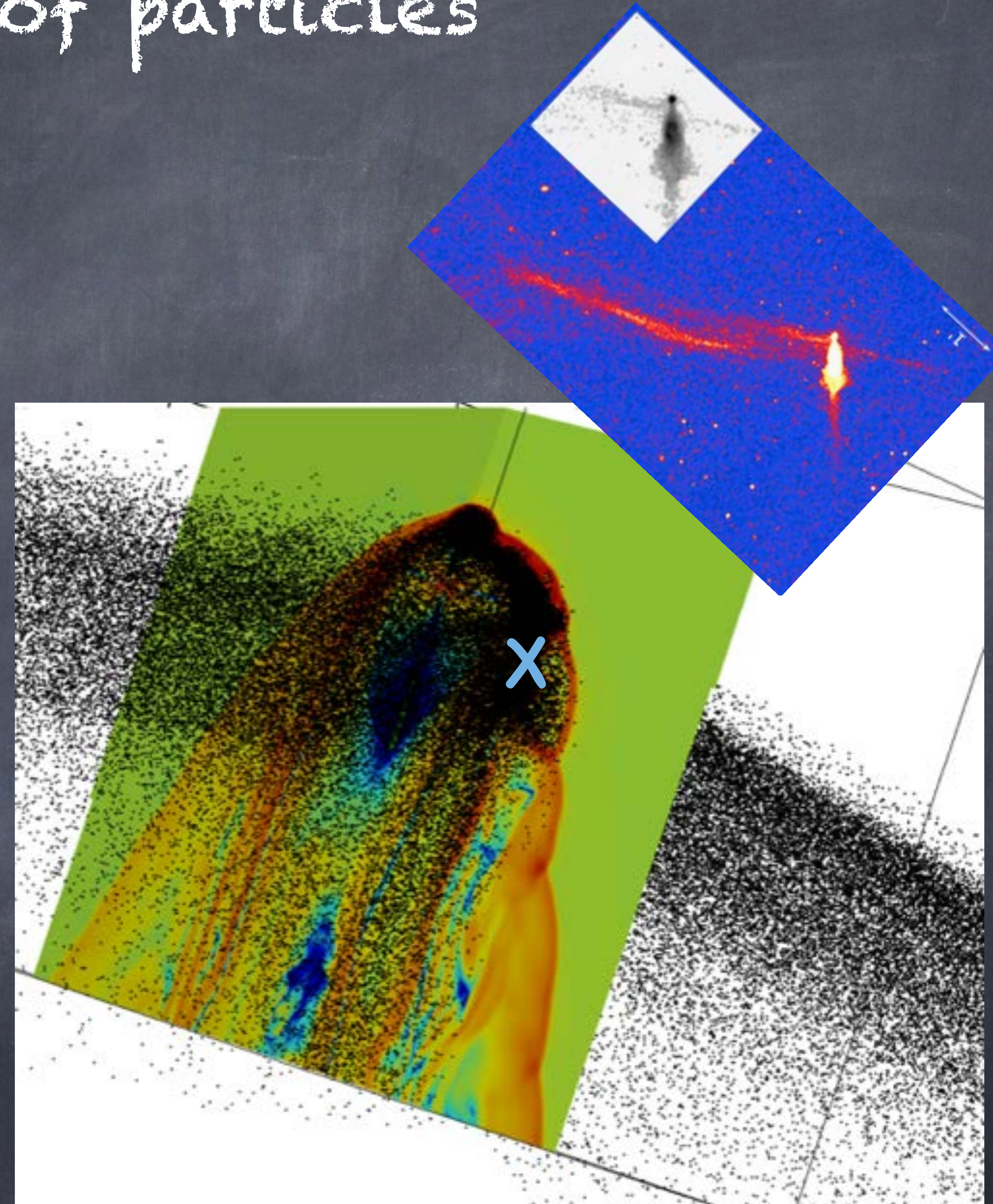


# Escape of particles

Particles in the polar flow are confined by the currents in the magnetopause layer.




From the reconnection point particles stream out along the ISM magnetic field, forming jets (here symmetric since the wind is symmetric).




Preliminary from Olmi & Bucciantini 3, in prep.

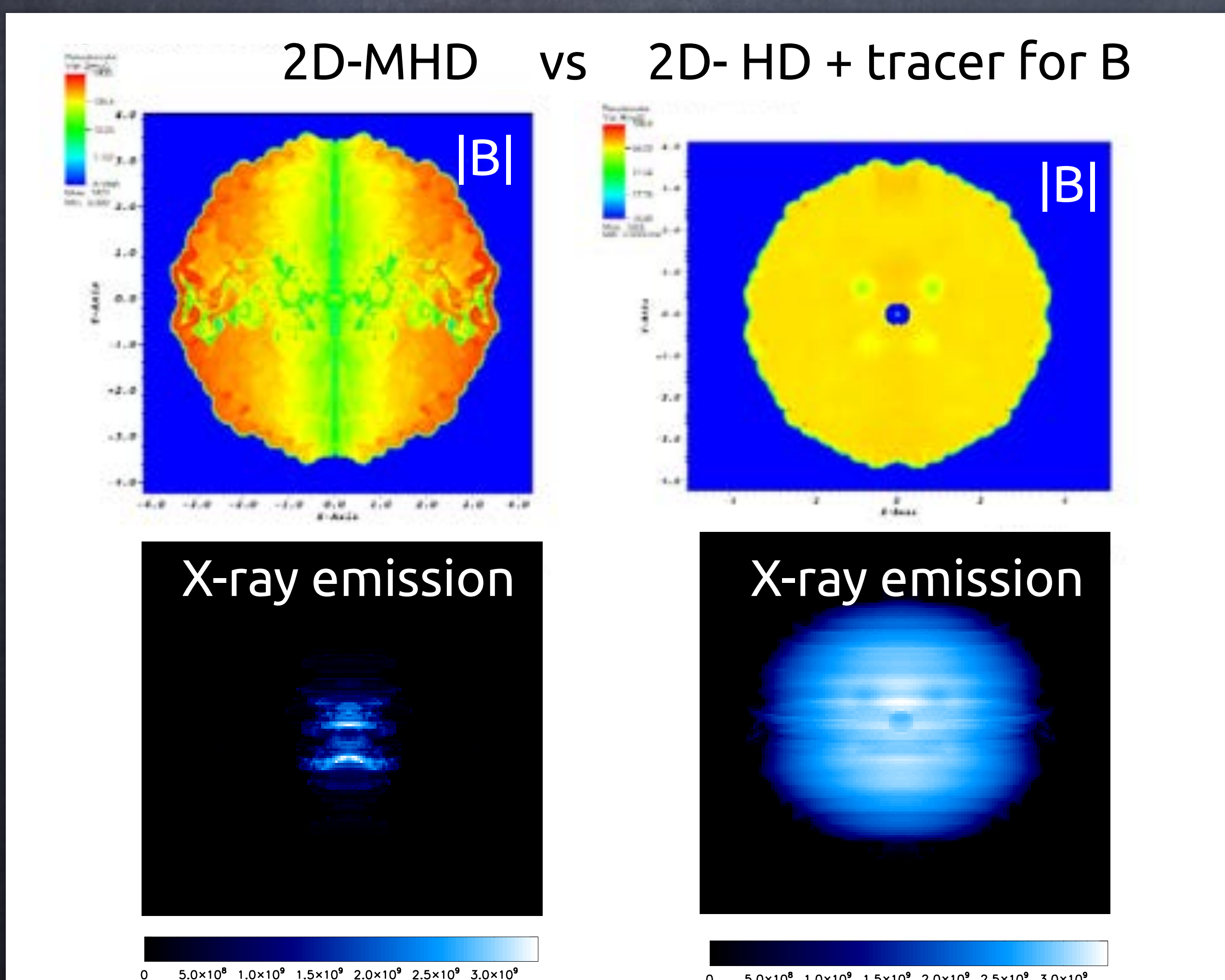
# Conclusions

## Take home message

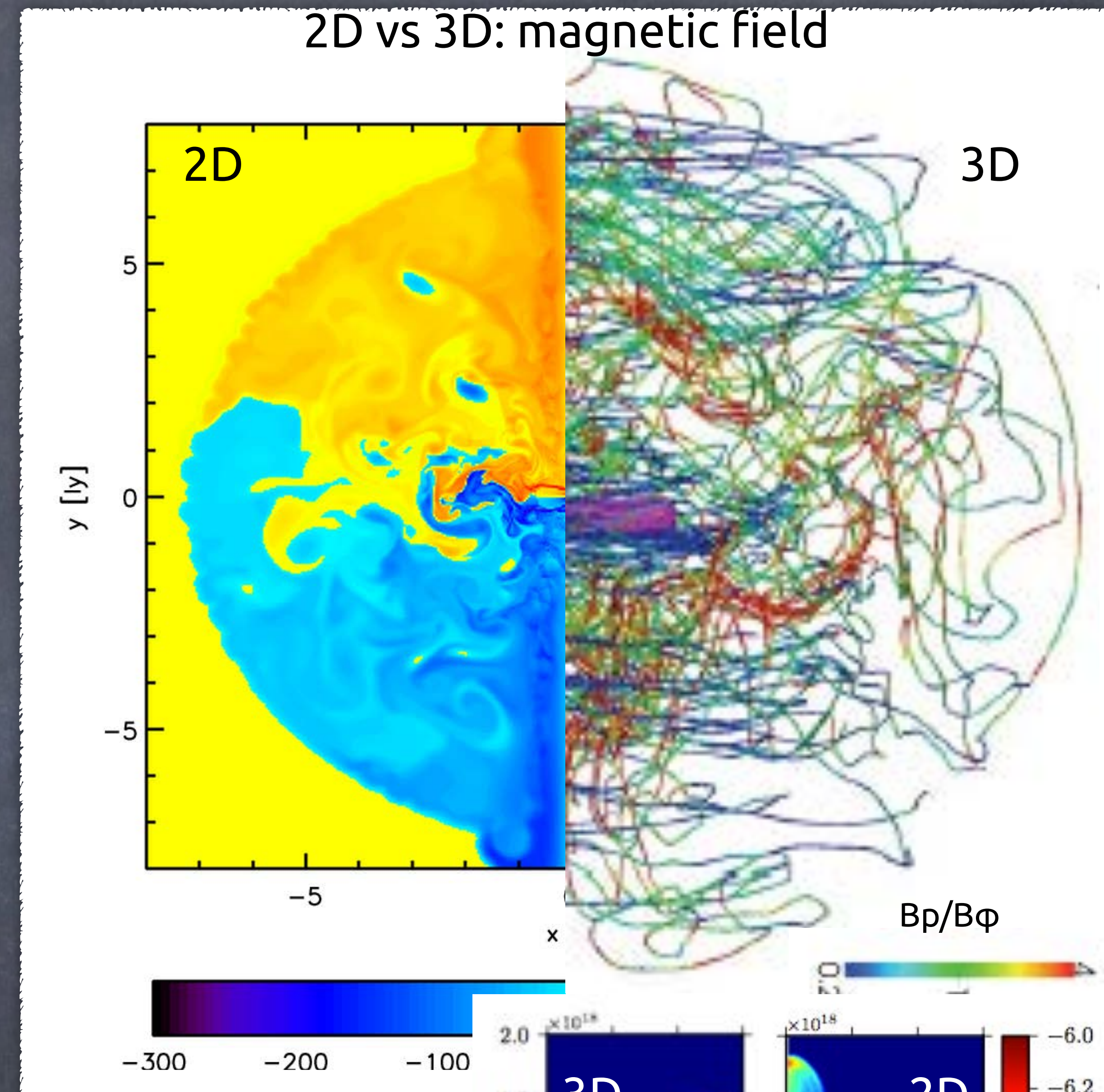
Magnetic field can be realistically modeled ONLY in 3D

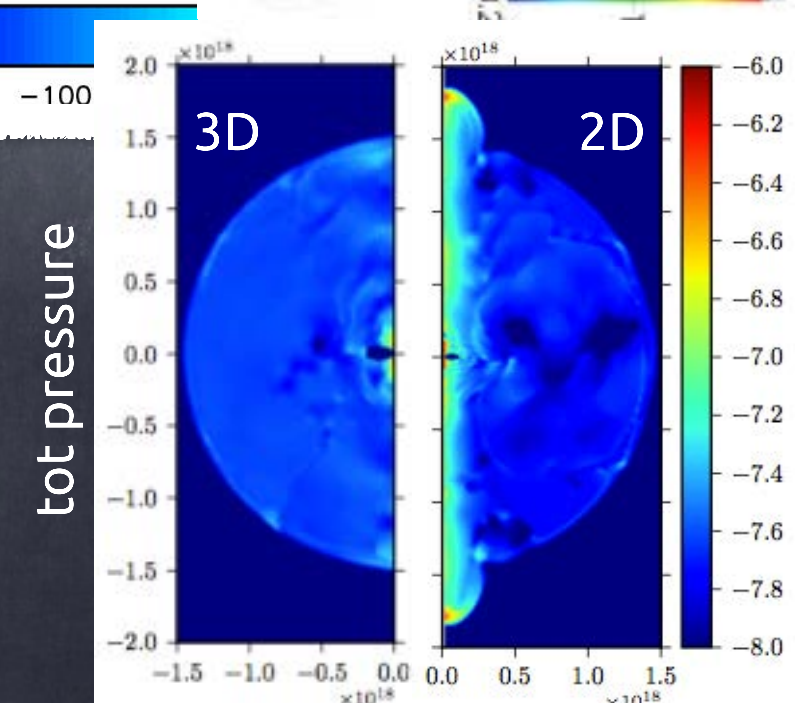
2D MHD simulations can only reproduce the inner nebula properties, where deviations from 3D are small.

A realistic morphology matching with the overall emission properties based on 2D model is more safe with HD simulations:




G21.5-0.9 simulations, Olmi & Torres in prep.



# Conclusions

## Take home message

Magnetic field can be realistically modeled ONLY in 3D

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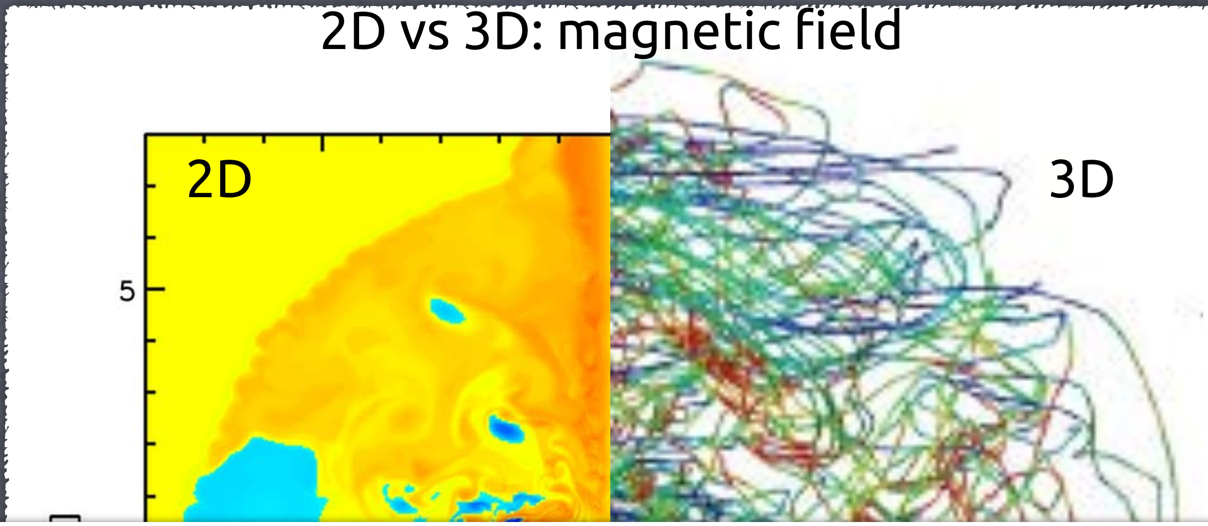
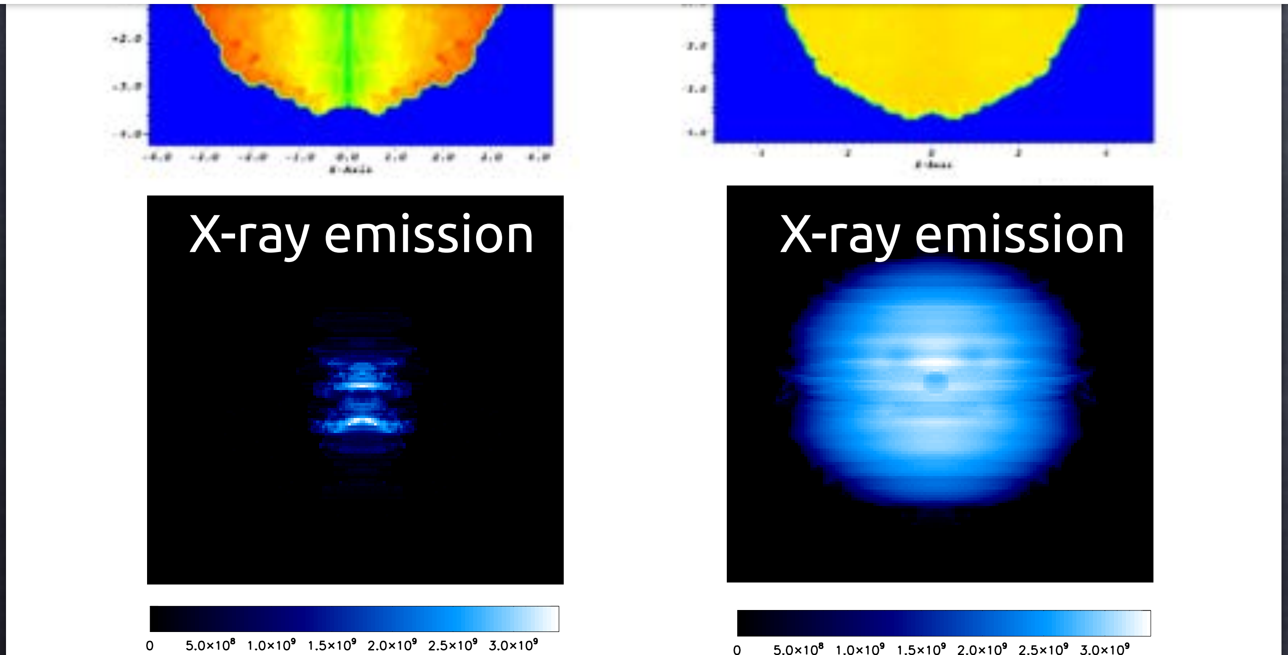



# Thank you!!!




G21.5-0.9 simulations, Olmi & Torres in prep.