SIMULATING RELATIVISTIC PLASMAS IN HIGH ENERGY ASTROPHYSICS: THE CASE OF PULSAR WIND NEBULAE

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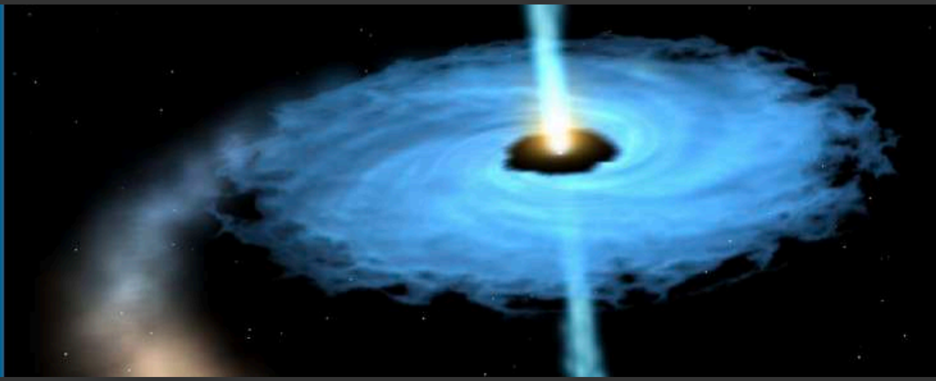
INAF

PLUS Collaboration

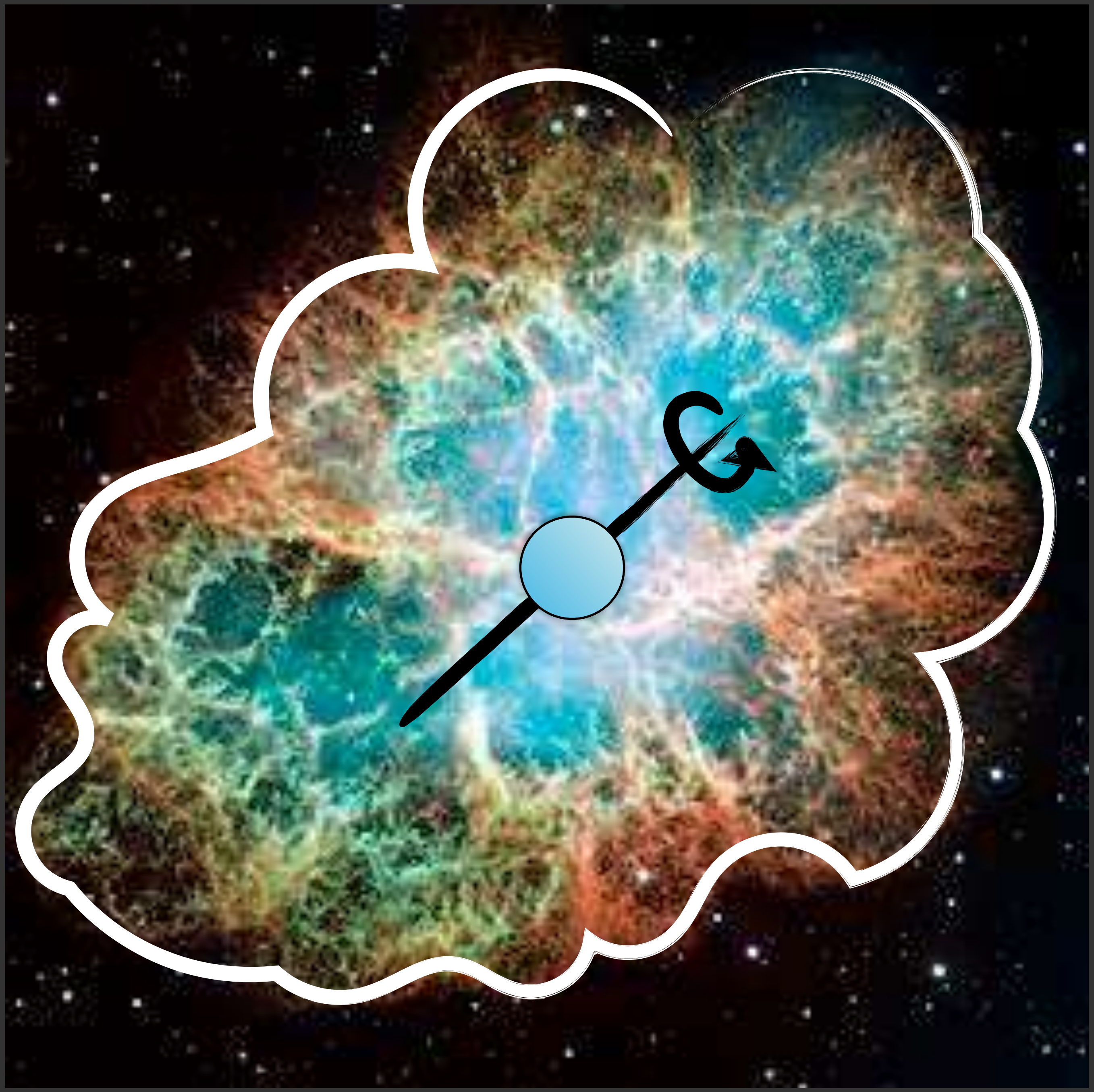
Plasma in Laboratory and Universe Systems



Webinar
Dec. 17 2021

WHAT IS A PWN?

The debris of the supernova explosion of a massive star $\gtrsim 8\,M_\odot$



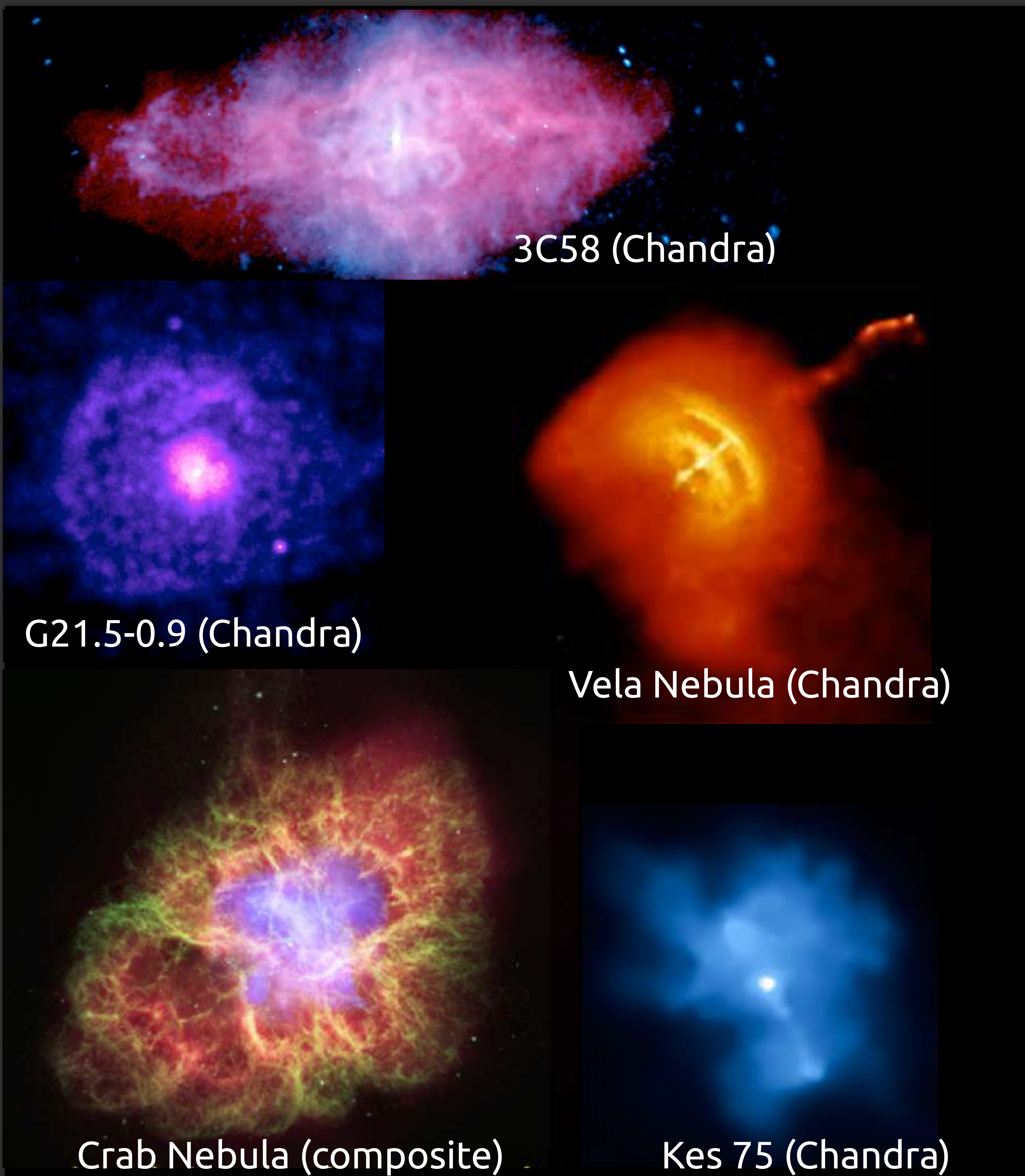
[NOT IN SCALE!!]

MAIN INGREDIENTS

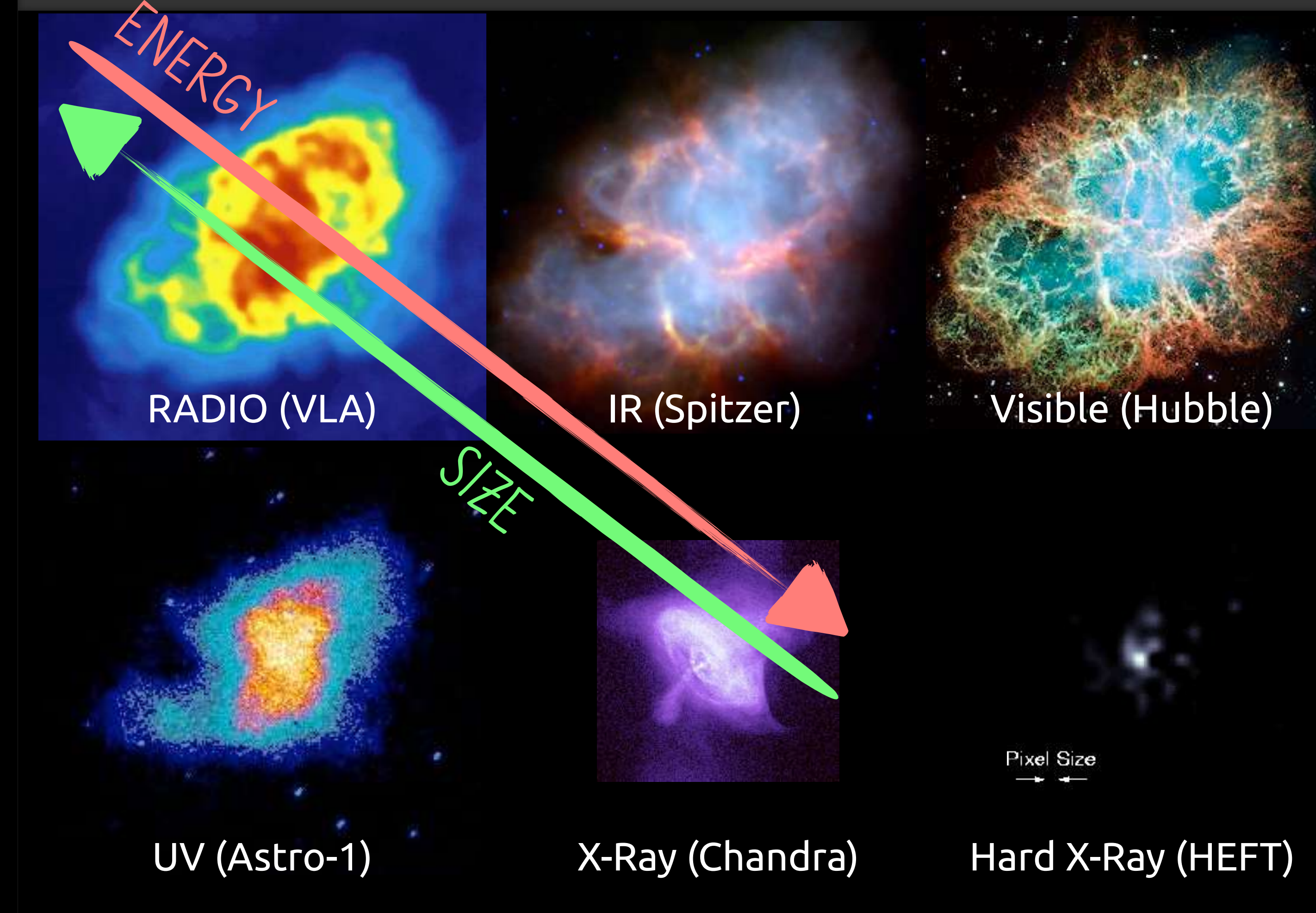
- a rapidly rotating neutron star (PULSAR)
- ejecta of the stellar explosion

HOW THEY LOOK?
EMISSION MORPHOLOGY AT MULTI-WAVELENGTHS

Fill-centered morphology

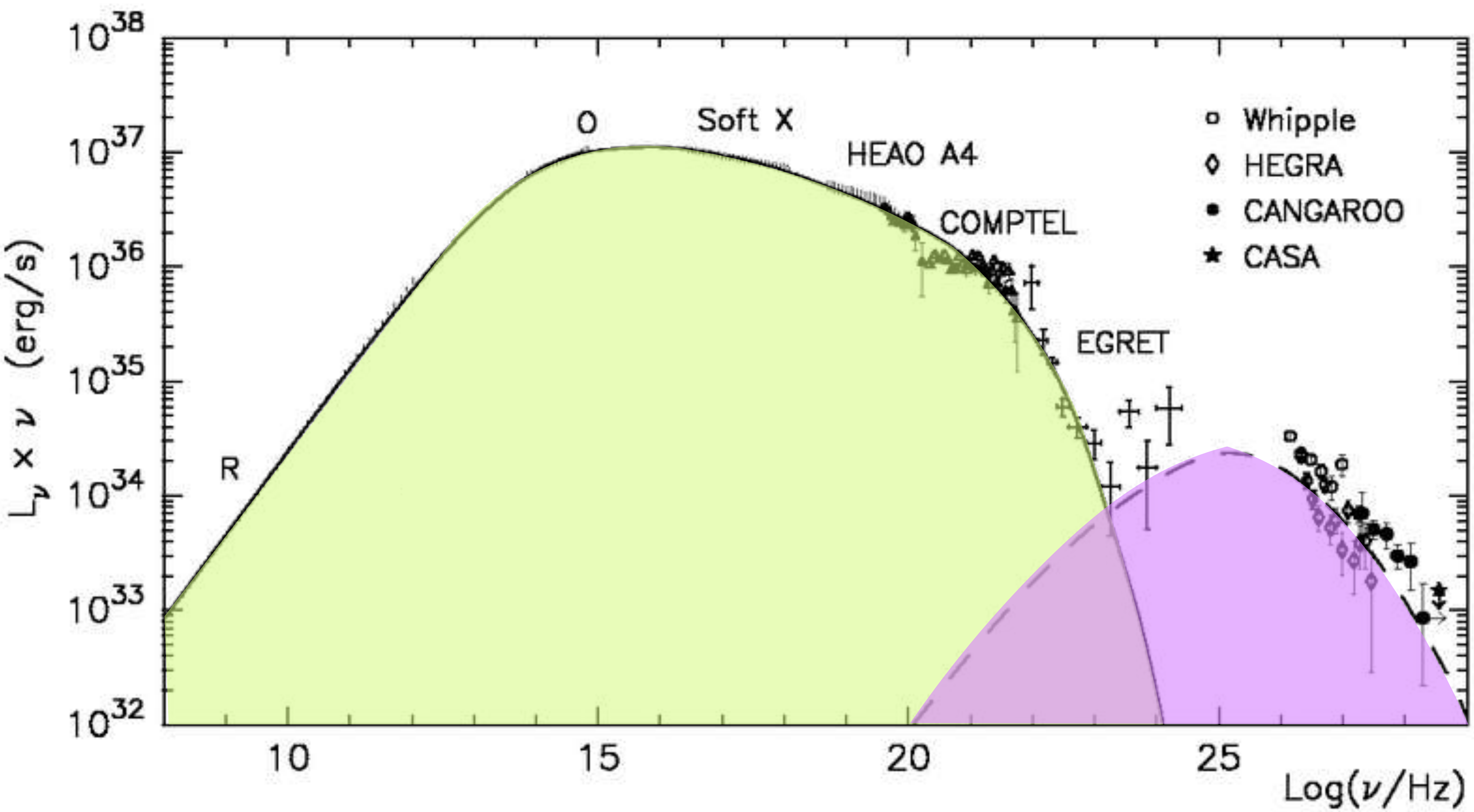


Decreasing size with energy



BROAD BAND NON-THERMAL SPECTRUM

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

WHY THEY ARE INTERESTING?

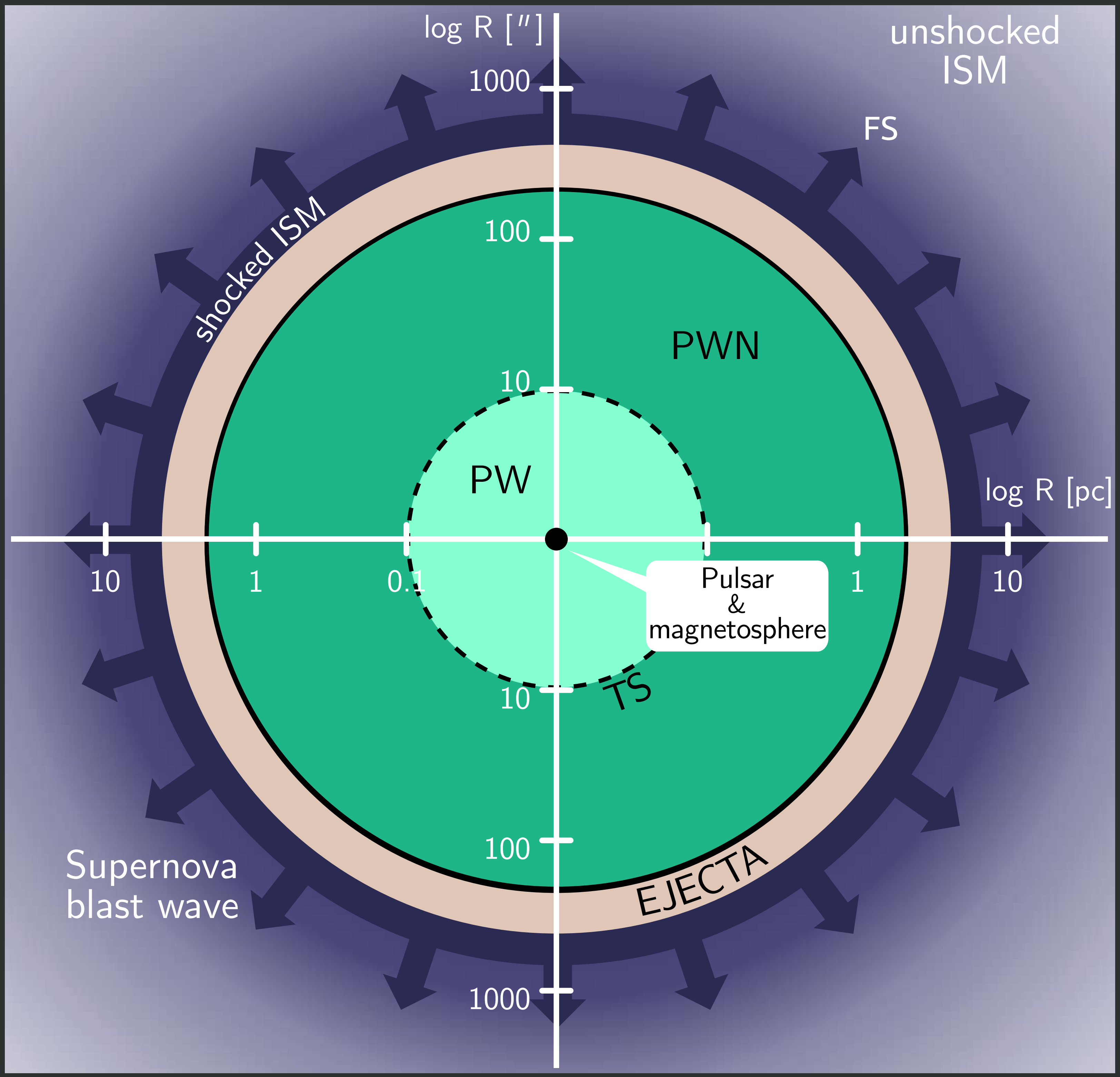
They enclose most of the energy lost by the pulsar ➡ PULSAR PHYSICS

Extreme conditions of the plasma in close and bright sources ➡ PLASMA PHYSICS

Evidence of particle acceleration up to PeV ➡ PARTICLE ACCELERATION IN EXTREME ENVIRONMENTS

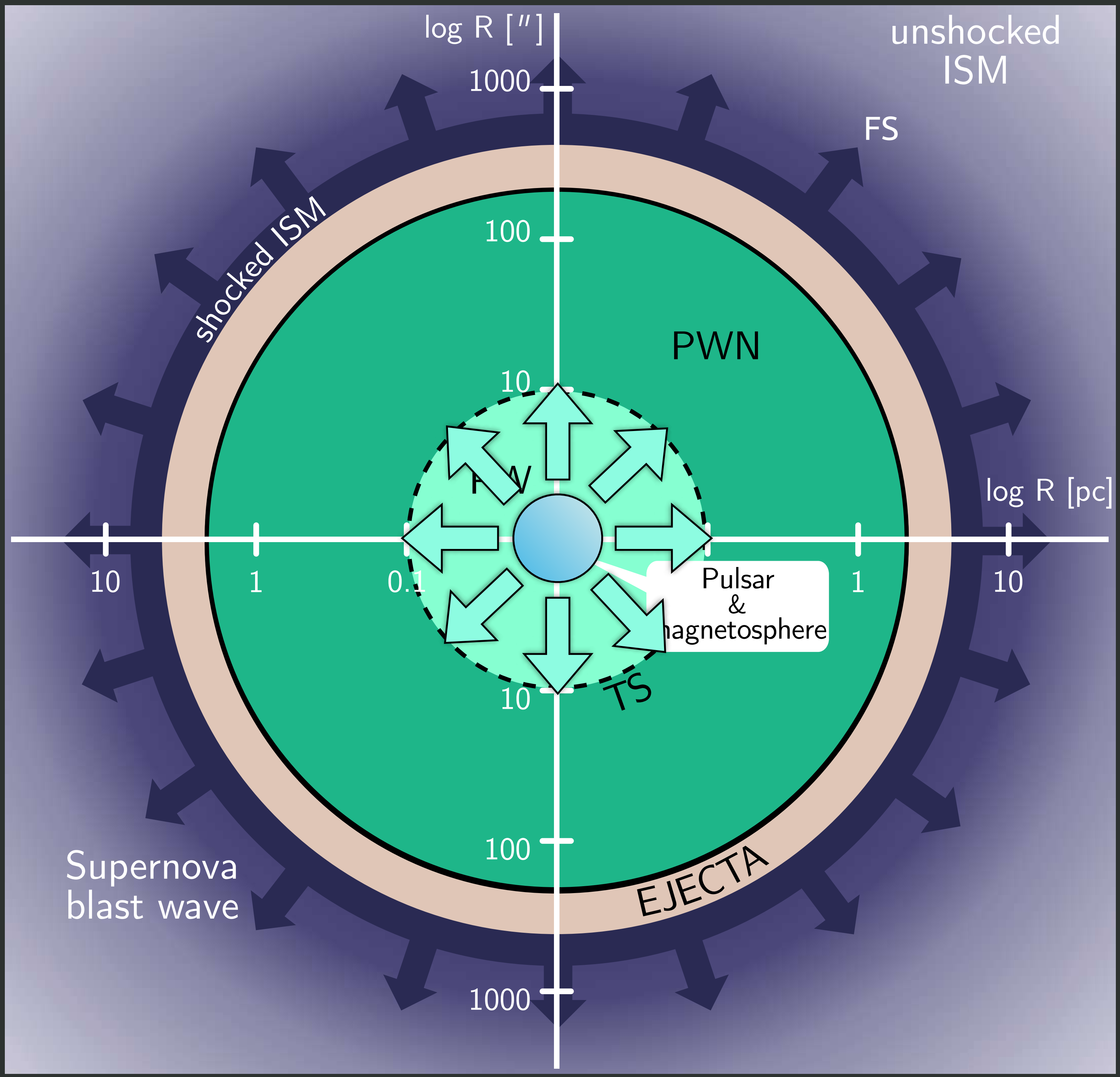
Escape of particles ➡ ROLE OF PULSARS AS GALACTIC ANTIMATTER FACTORIES (SOURCE OF CR POSITRON EXCESS?)

BASIC PICTURE FOR YOUNG SYSTEMS



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

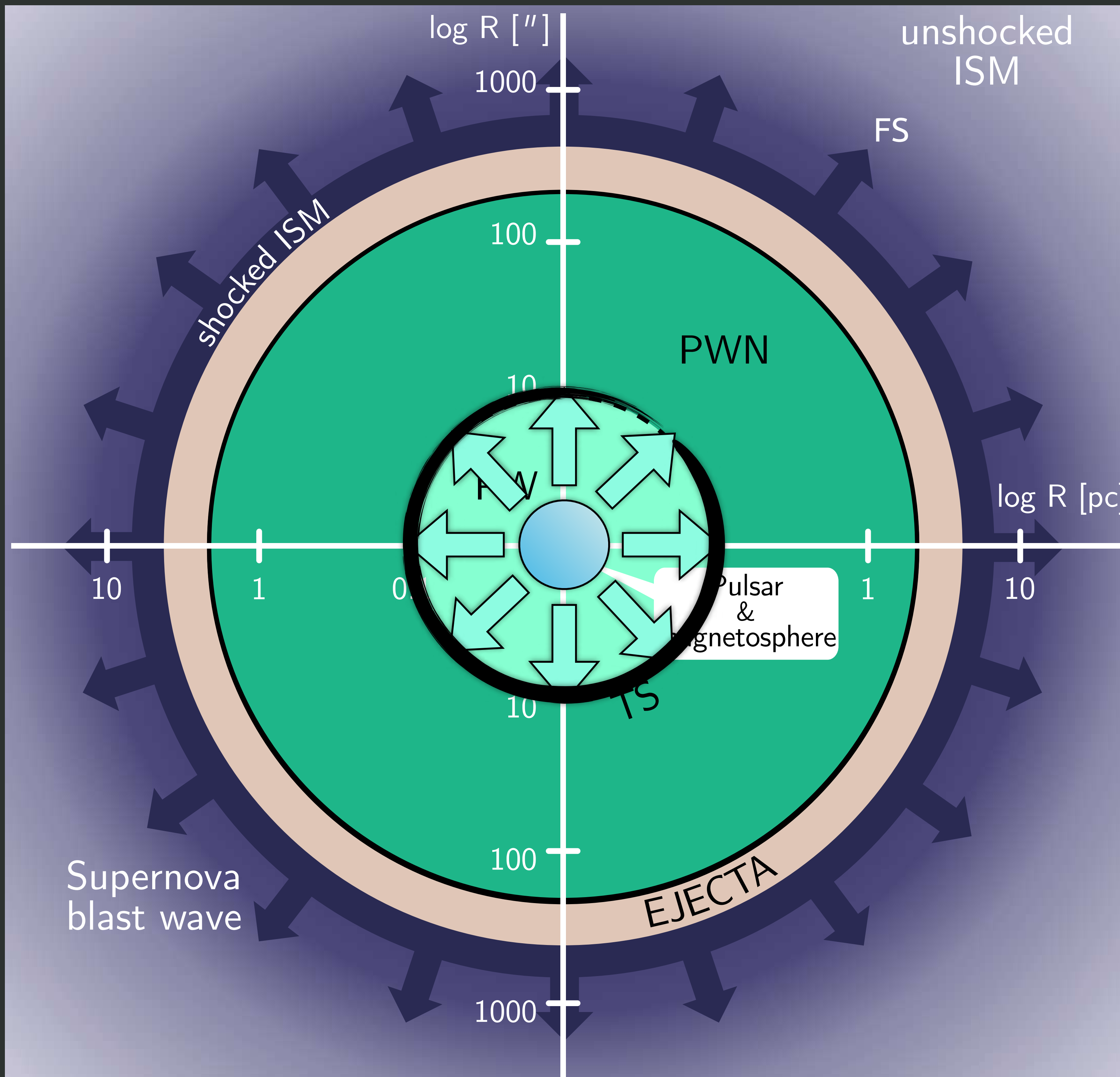
BASIC PICTURE FOR YOUNG SYSTEMS



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

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

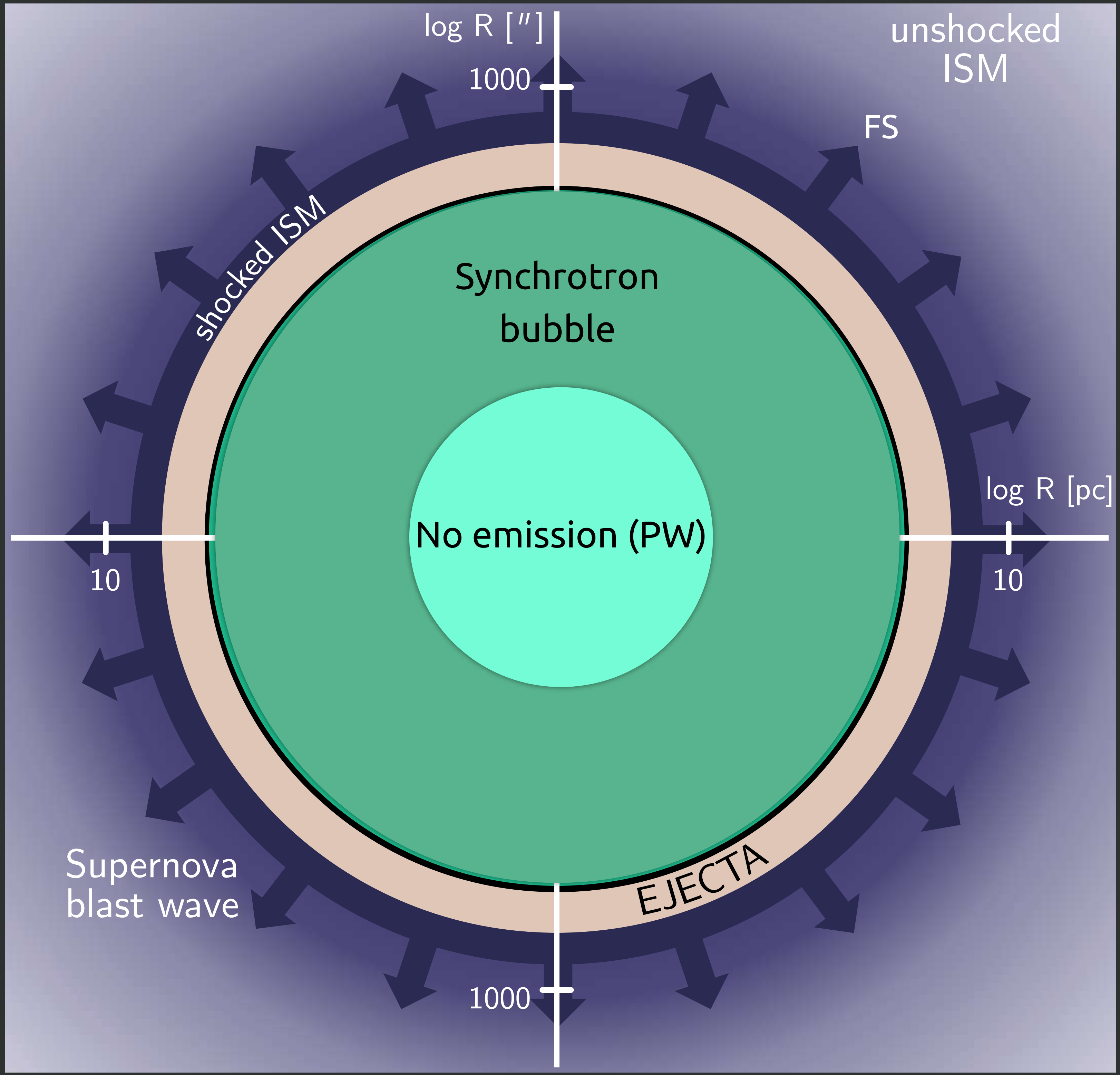
BASIC PICTURE FOR YOUNG SYSTEMS



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

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

BASIC PICTURE FOR YOUNG SYSTEMS

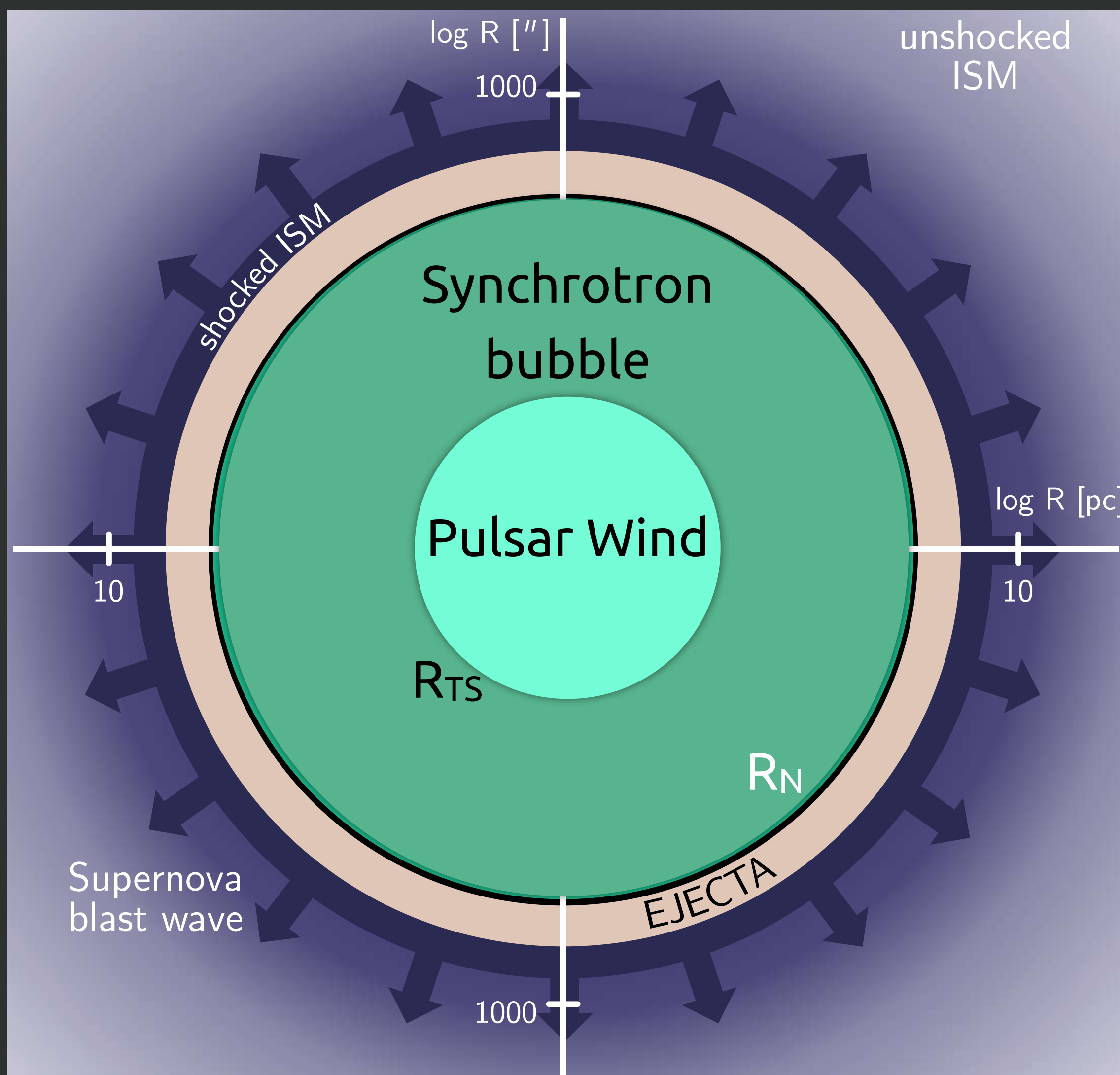


Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

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 → Γ
- wind magnetization → $\sigma = B^2/(4\pi n m_e c^2 \Gamma^2)$

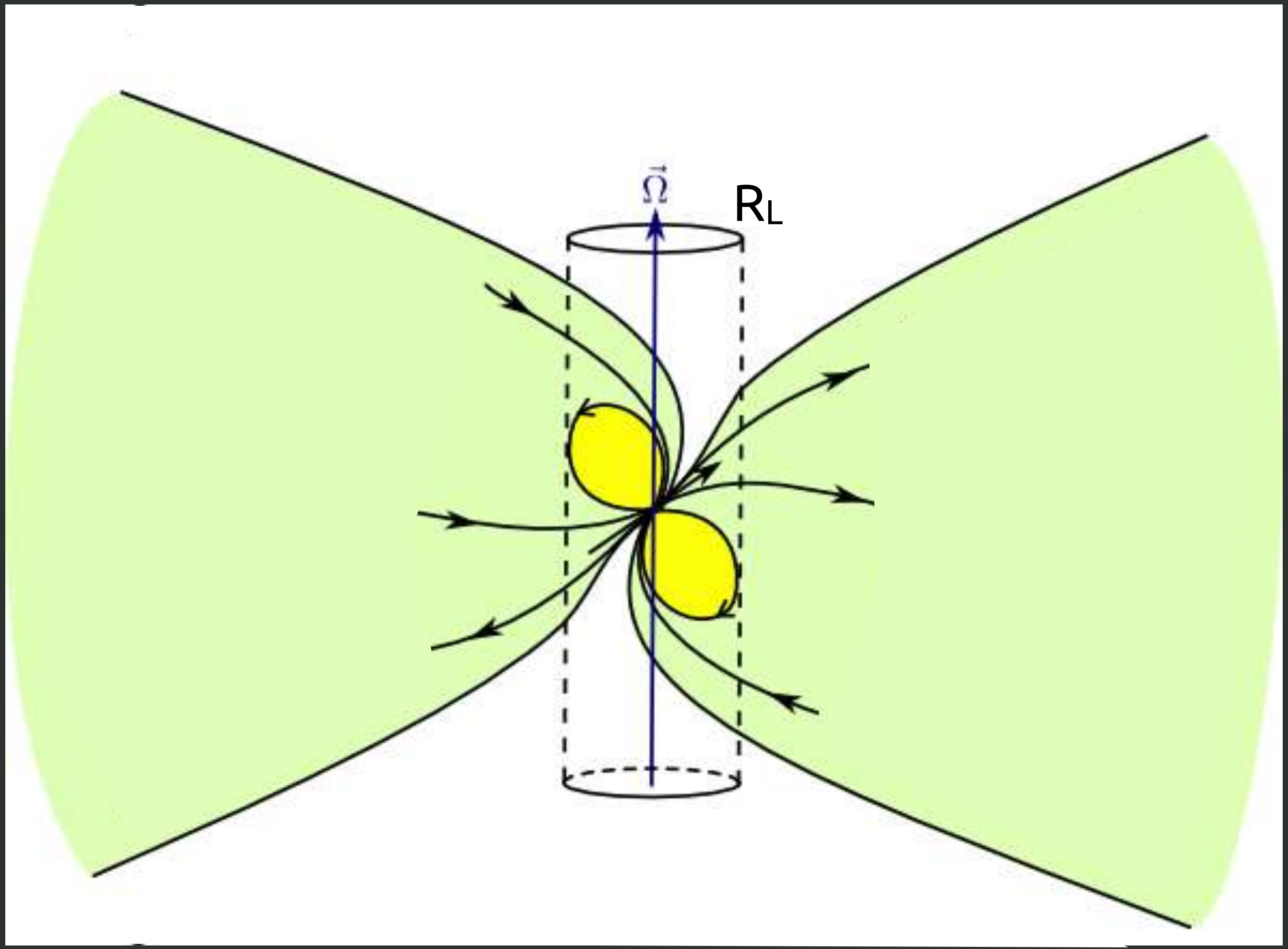
PREDICTIONS:

- 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

$$\Gamma \simeq 10^6$$
$$\sigma \simeq V_N/c \simeq 10^{-3}$$

THE SIGMA PARADOX

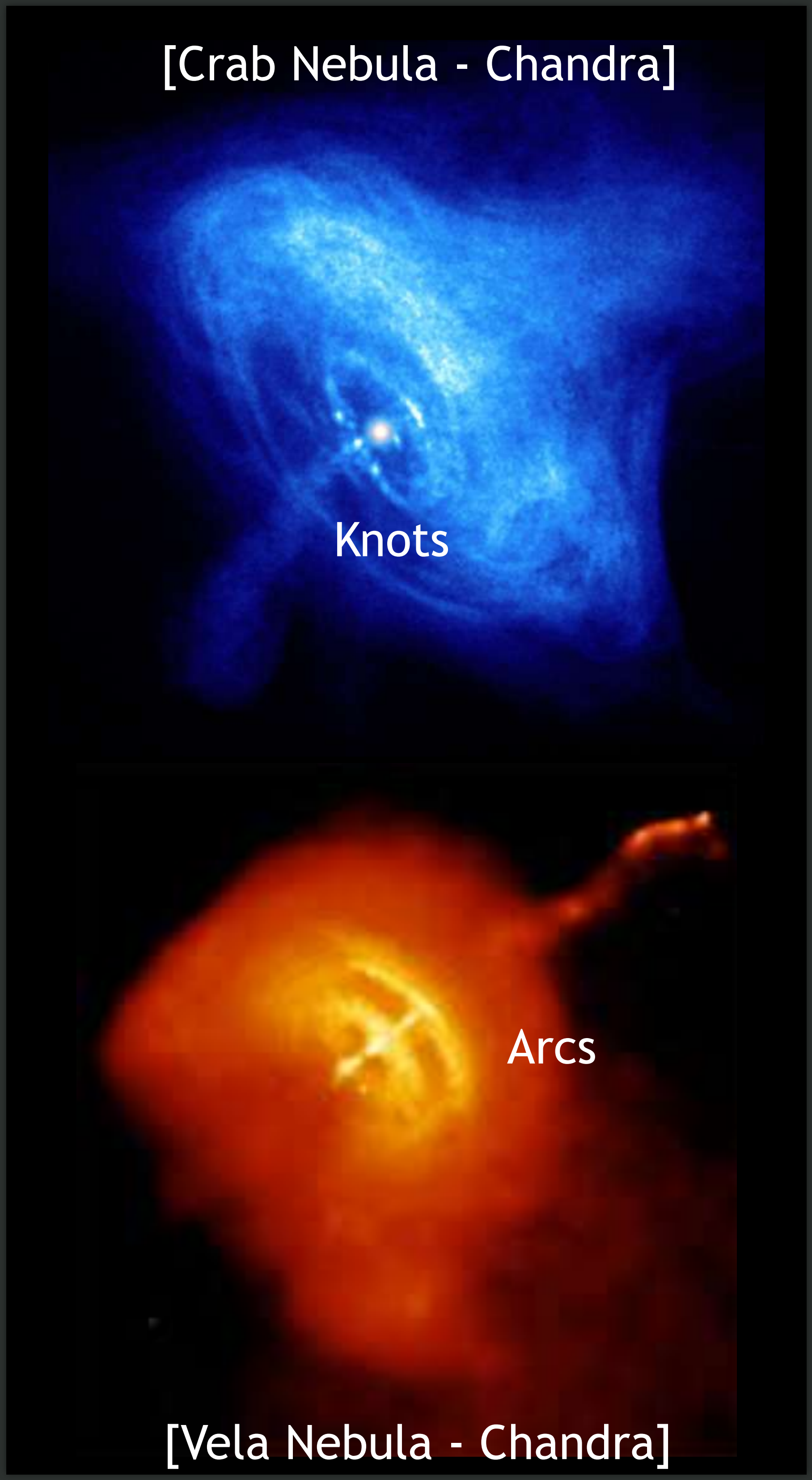
From pulsar theories → $\sigma \sim 10^4$ @ R_L

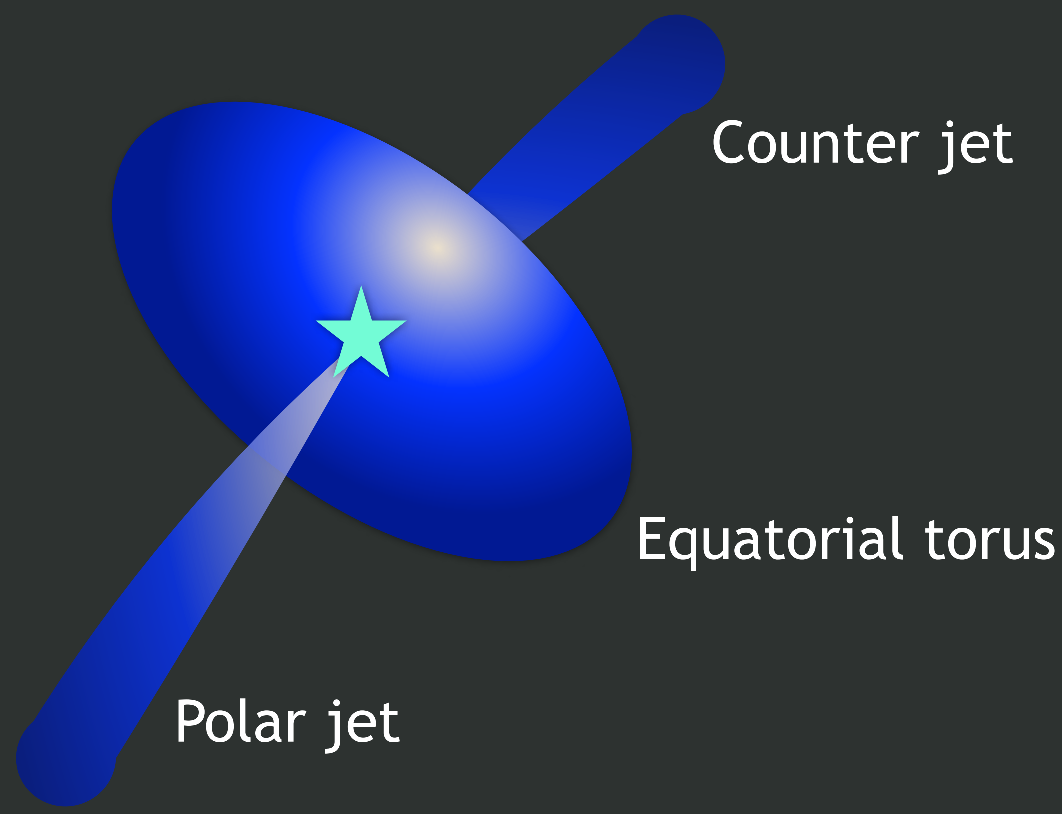


From 1D PWNe models → $\sigma \sim 10^{-3}$ @ R_{TS}

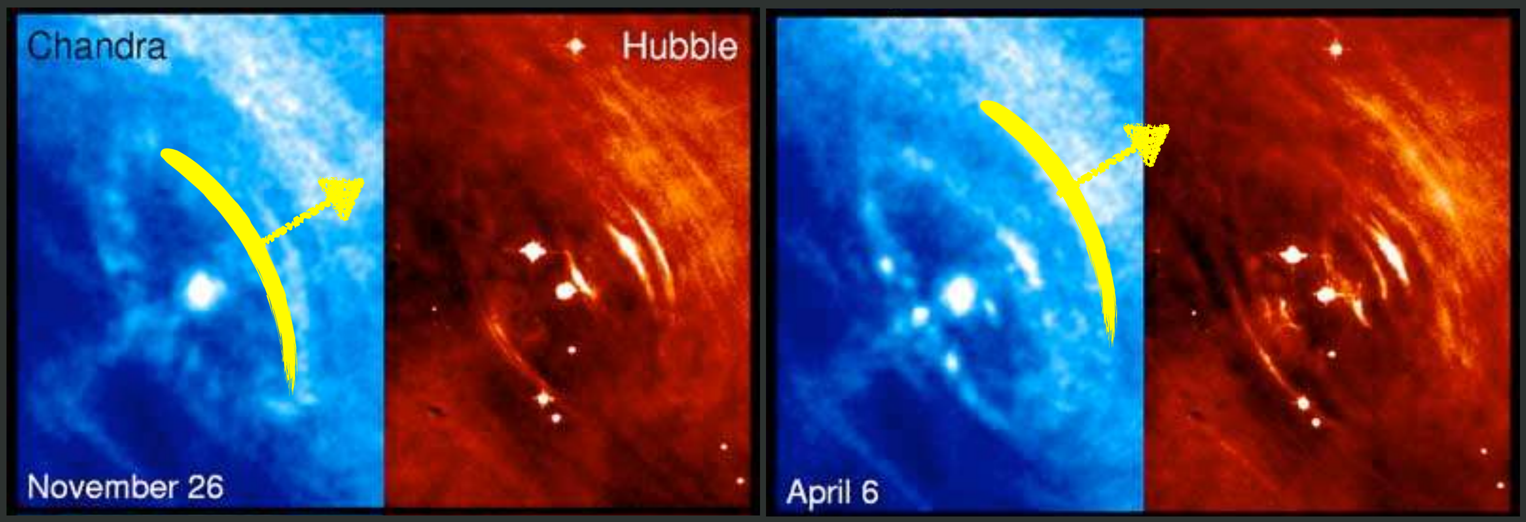
Even if $R_{TS} \sim 10^9 R_L$ dissipation is not sufficient to explain this discrepancy!

A DEEPER VIEW:
THE INNER NEBULA HAS A JET-TORUS SHAPE



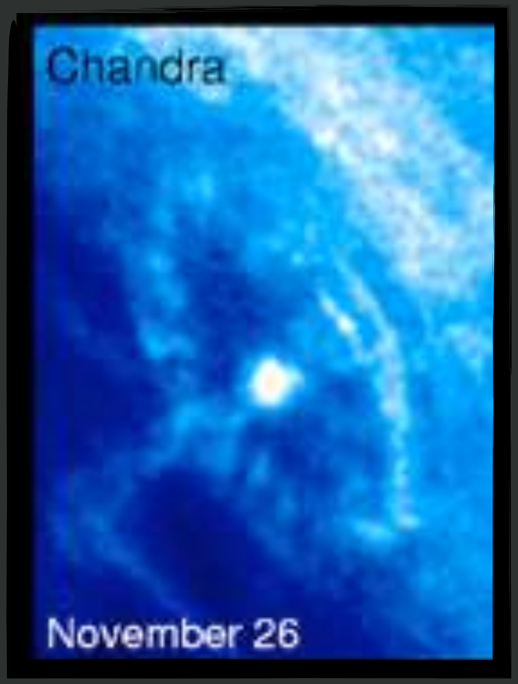


AND SHOWS HIGH VARIABILITY

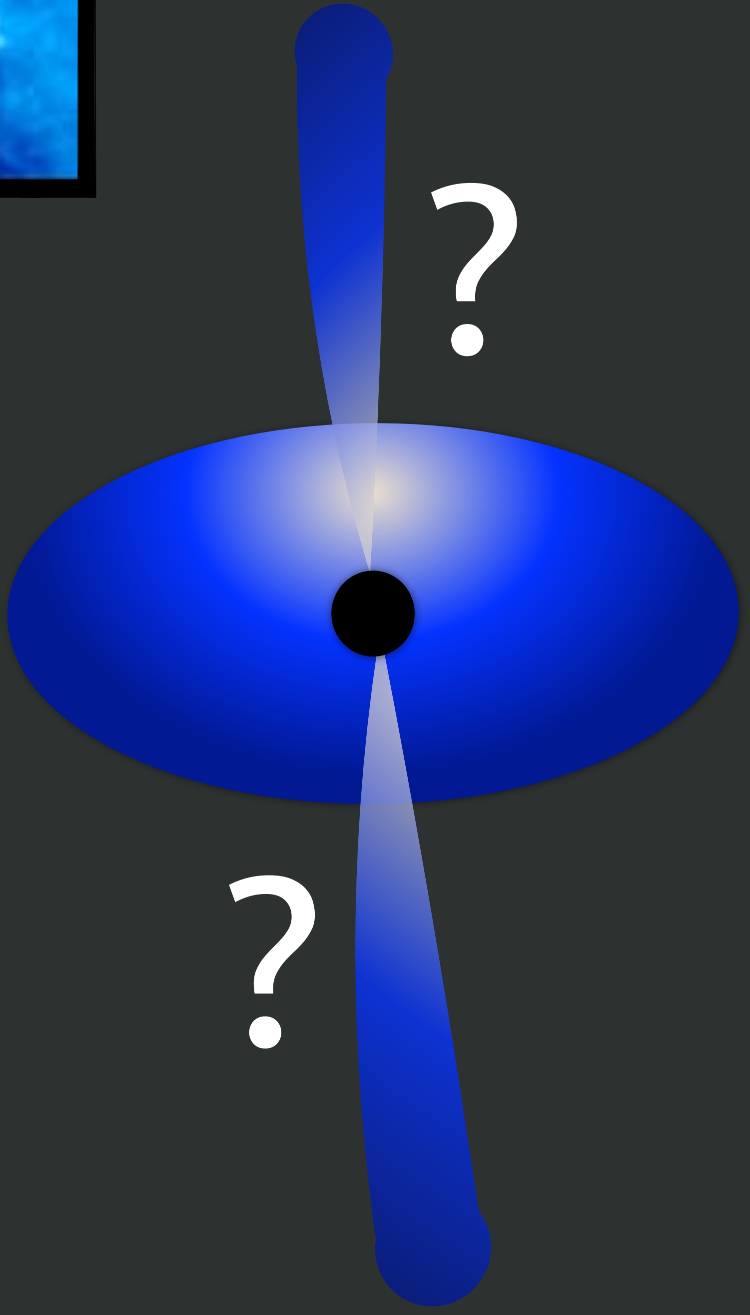


Outward moving wisps

HOW POLAR JETS FORMS?



Jets appear to originate
very close to the pulsar

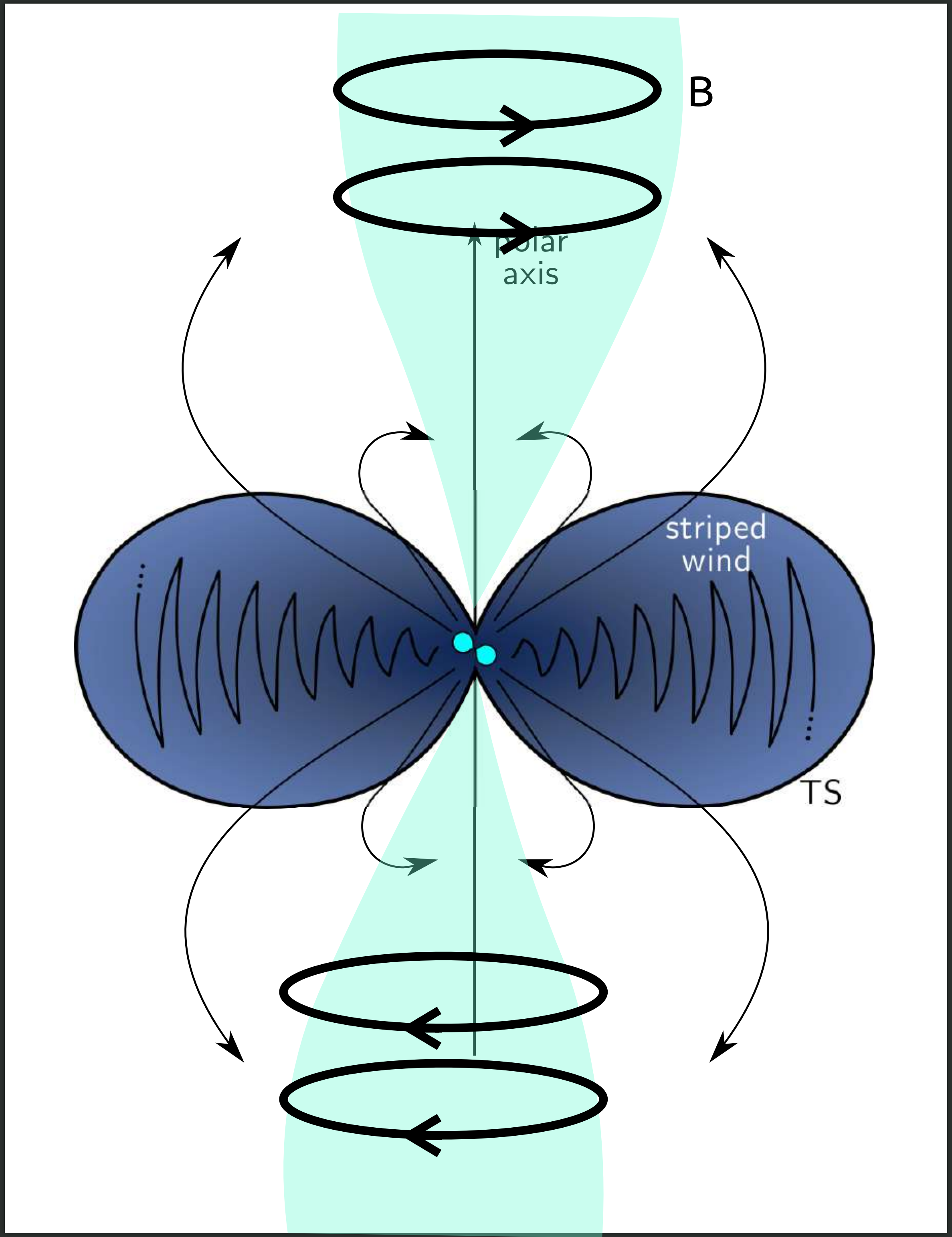


But magnetic collimation in the relativistic PW is not efficient [Lyubarsky & Eichler 2001]:

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

Collimation must occur in the shocked plasma (in the nebula, NOT in the wind)

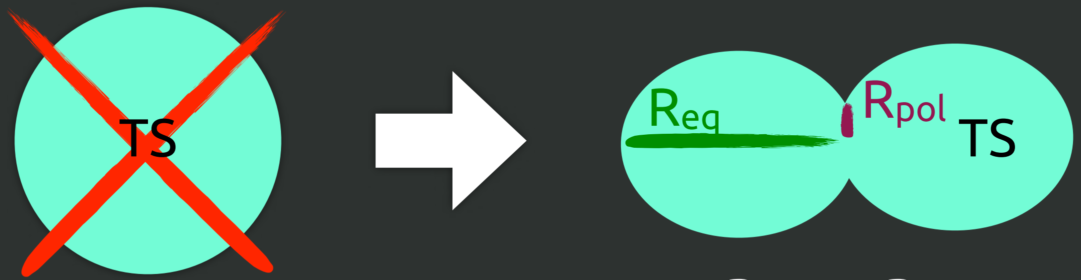
FORMATION OF THE POLAR JETS: THE ANISOTROPIC WIND



The energy flux is in the nebula is anisotropic!
[Bogovalov & Khangoulian 2002, Lyubarsky 2002]

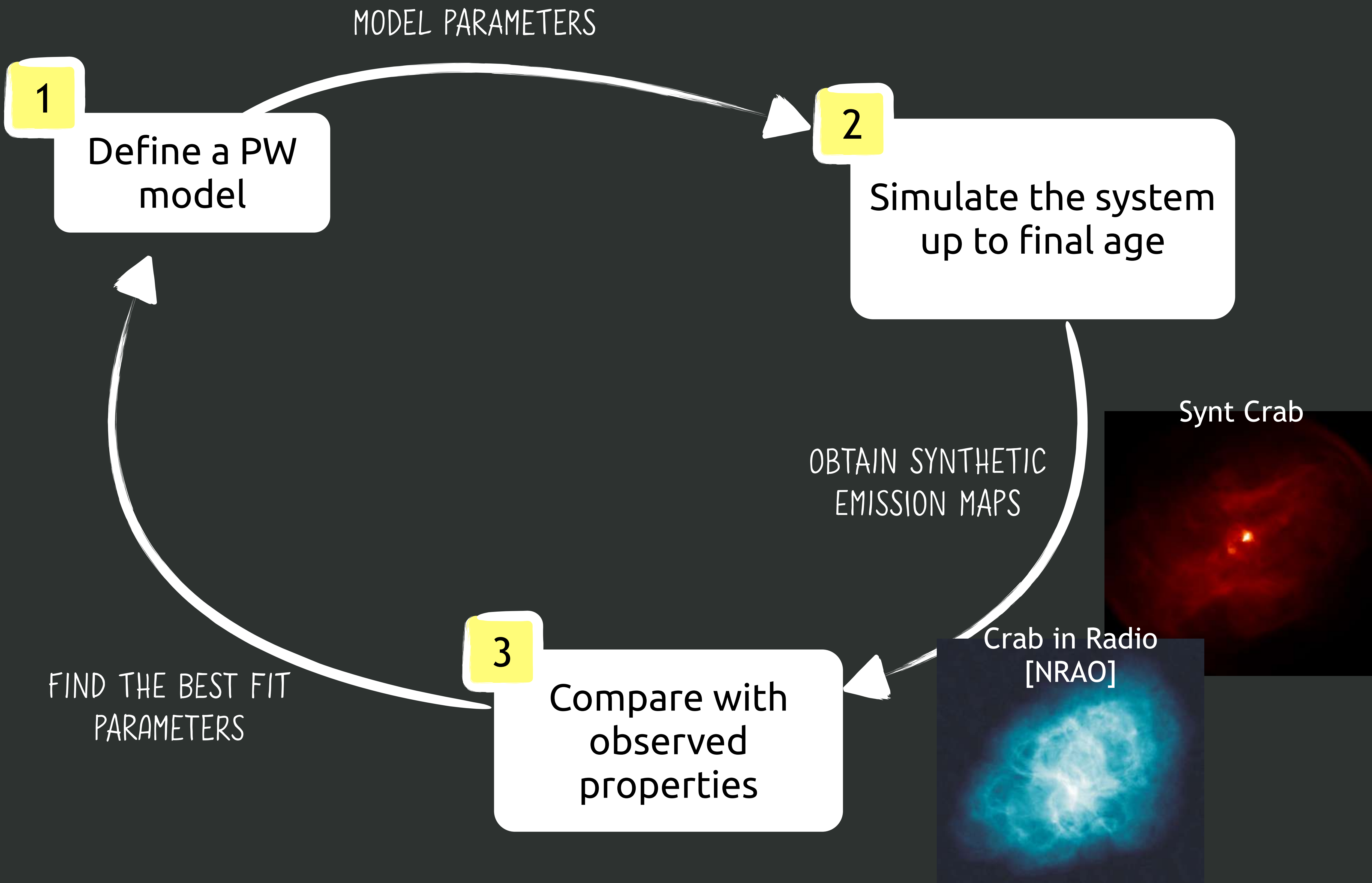
$$F \propto \sin^2(\theta)$$

This account for the apparent vicinity of the jets to the pulsar: the TS is oblate!



$R_{eq} >> R_{pol}$

SCHEME OF A PWNE NUMERICAL MODEL



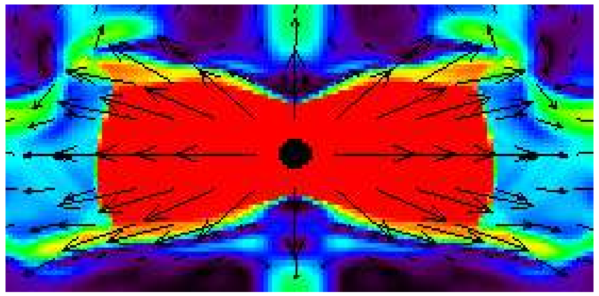
MODELING THE PULSAR WIND

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

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

anisotropy parameter

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

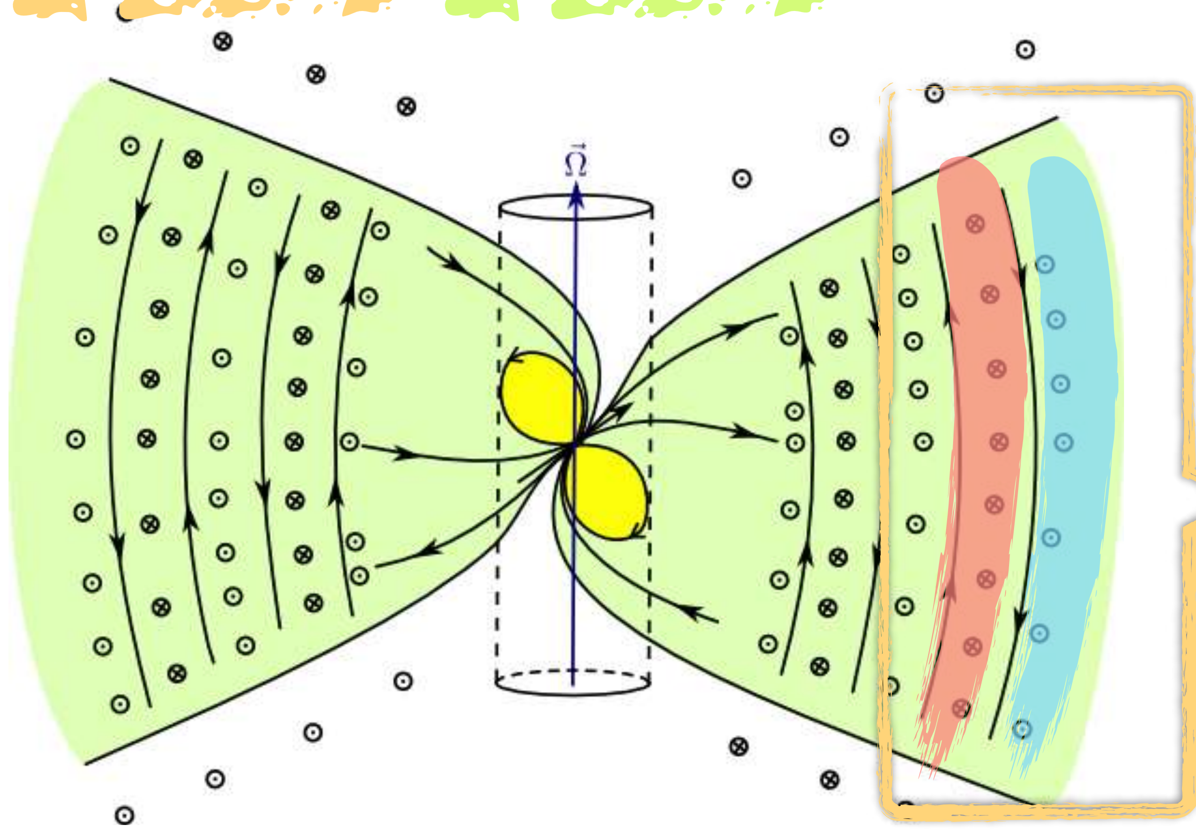


Striped morphology within an equatorial belt of extension ≃ 2×ζ

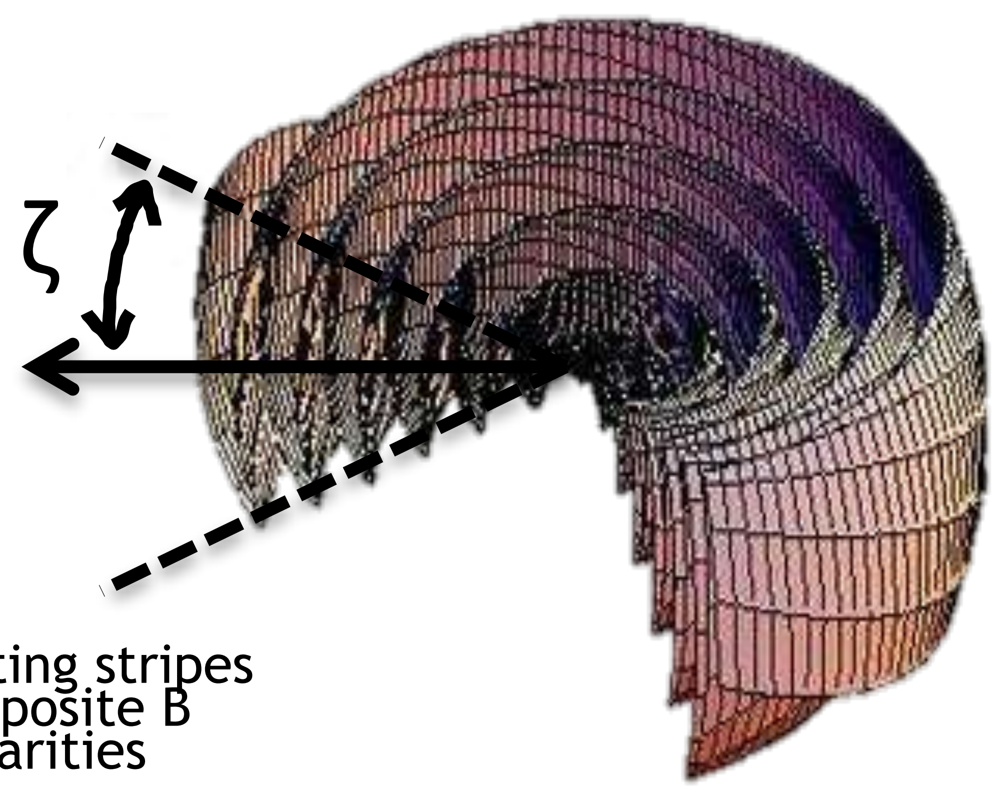
$$B(r,\theta) \propto \sqrt{\sigma}\,\mathcal{G}(\theta)\sin\theta$$

initial wind magnetization

striped wind



alternating stripes of opposite B polarities

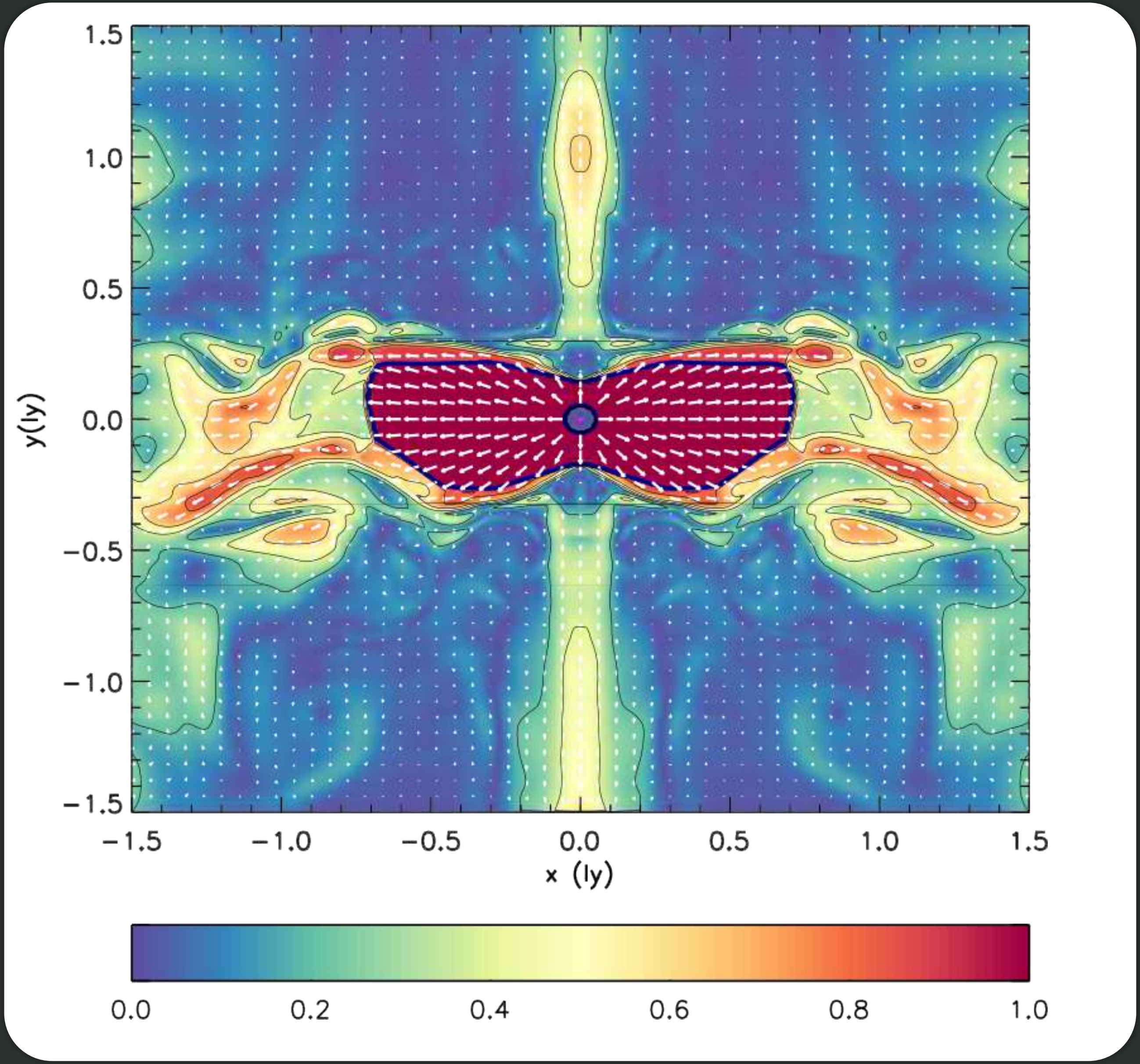


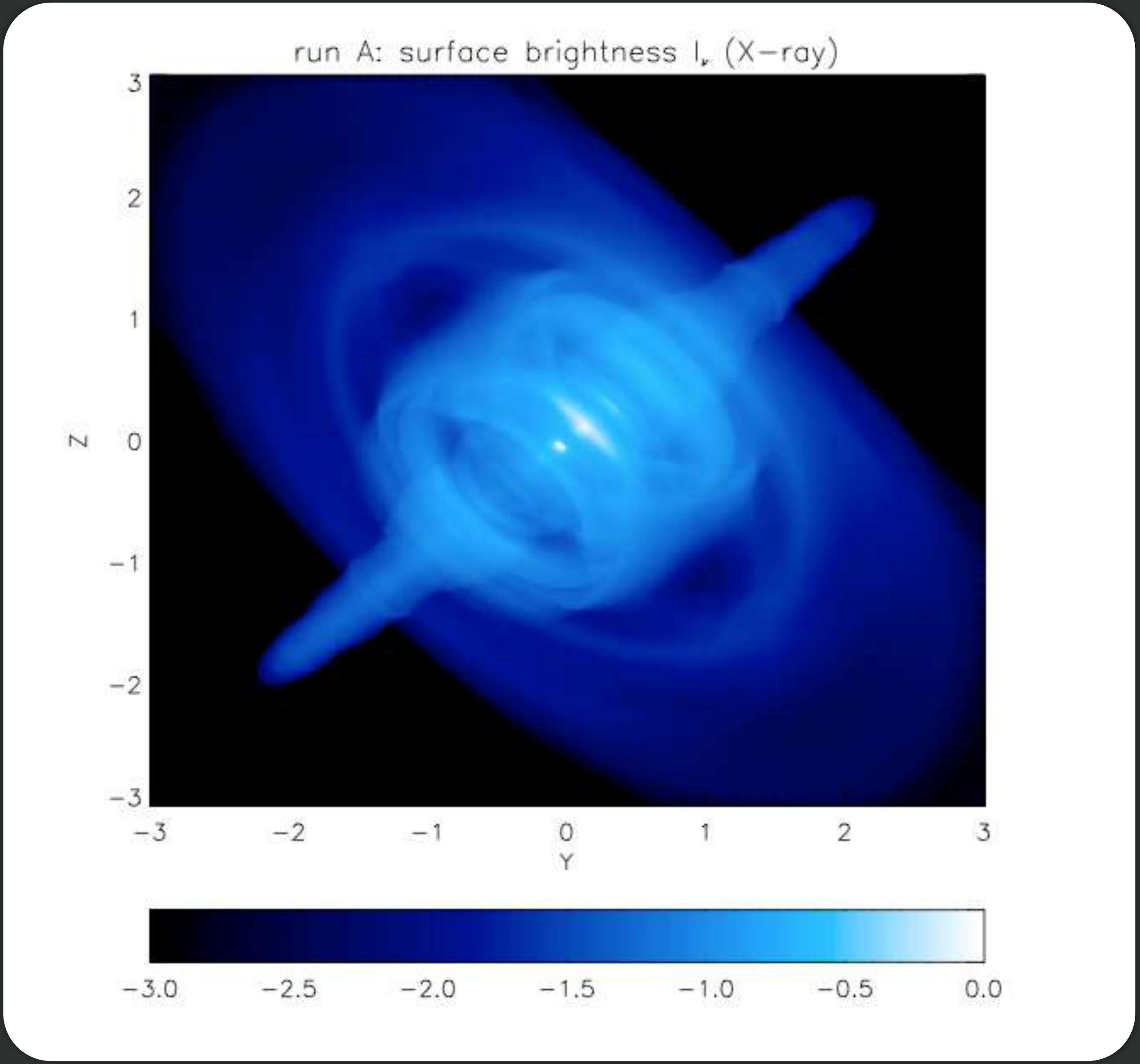
separated by a current sheet →place for dissipation

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

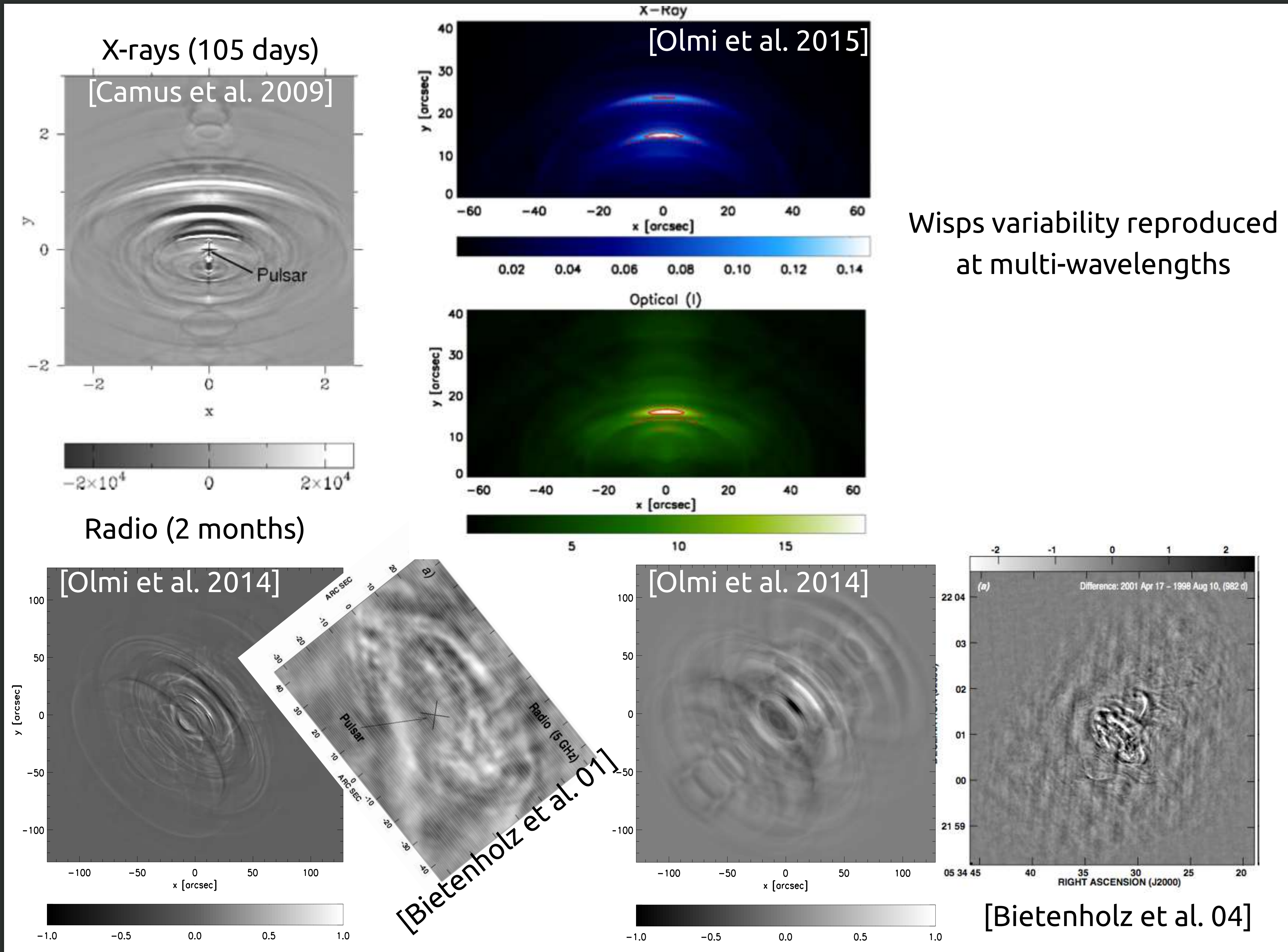
GOALS OF 2D MODELS: JET-TORUS

2D numerical models confirm the jet formation for values of magnetization $\sigma \gtrsim 0.01$
[Komissarov & Lyubarsky 2003-2004, Del Zanna et al. 2004]

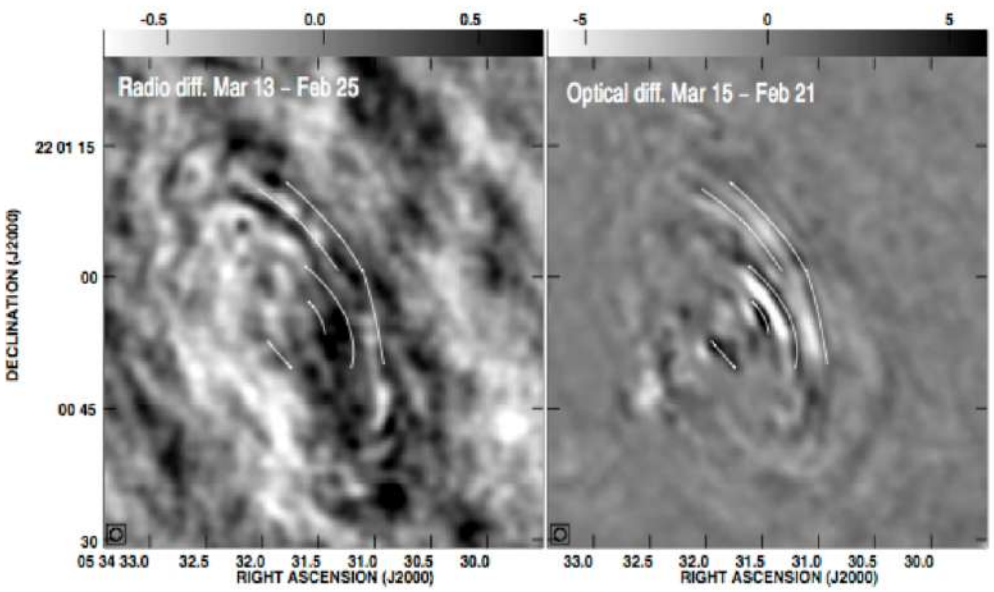




GOALS OF 2D MODELS: VARIABILITY OF THE INNER NEBULA

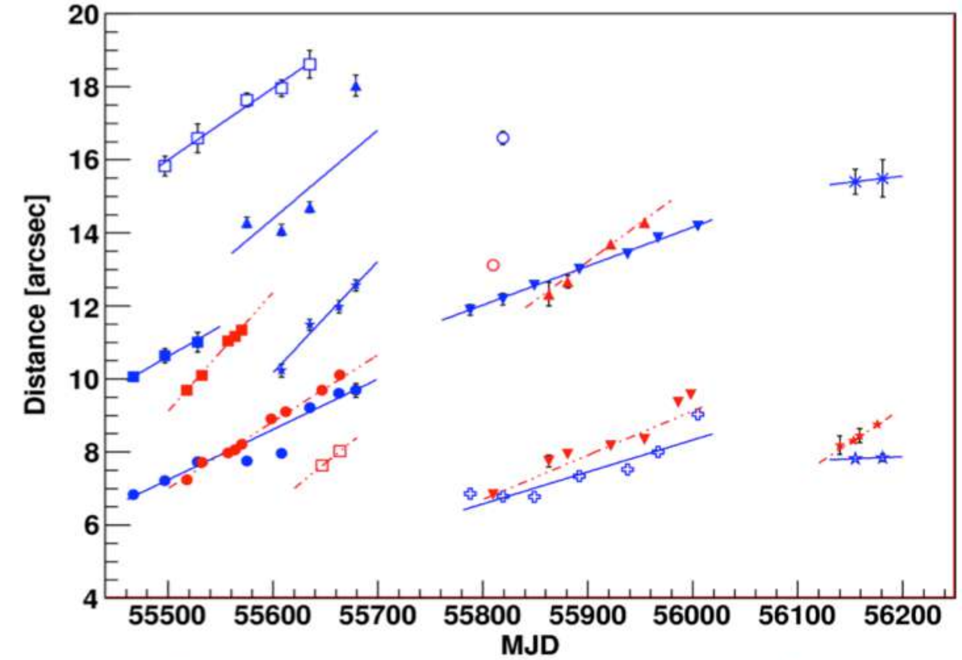


GOALS OF 2D MODELS: MULTI-WAVELENGTHS WISP PROPERTIES



[Bietenholtz et al. 2004]

Radio vs Optical wisps

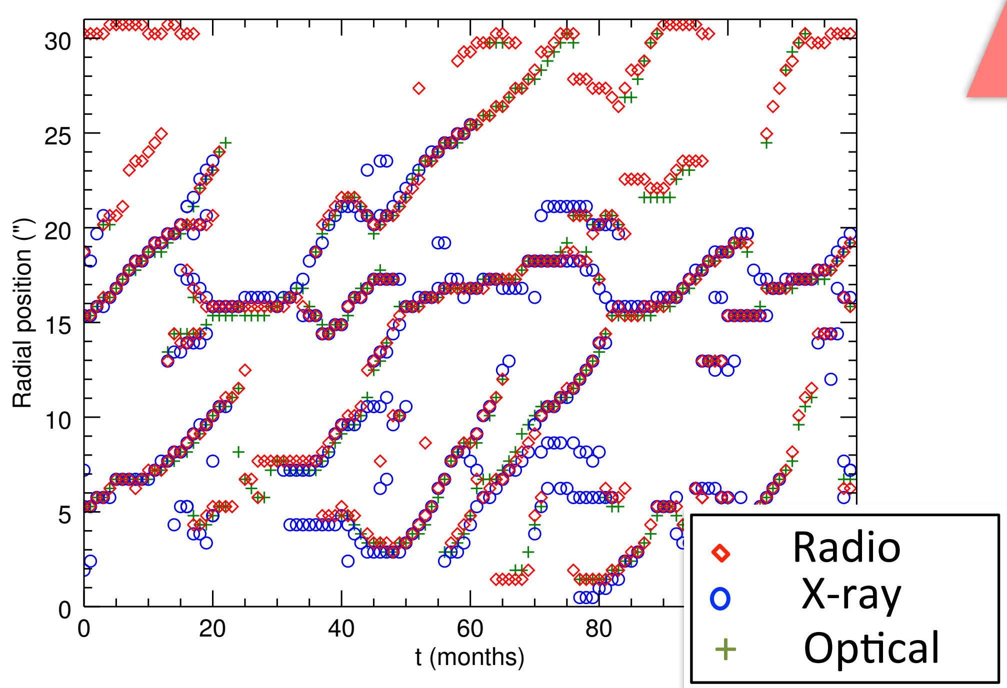


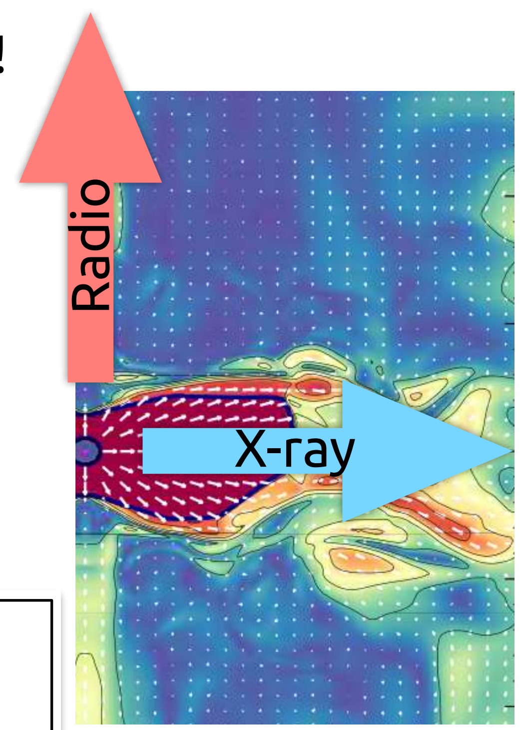
[Schweizer et al. 2013]

Optical vs X-ray wisps

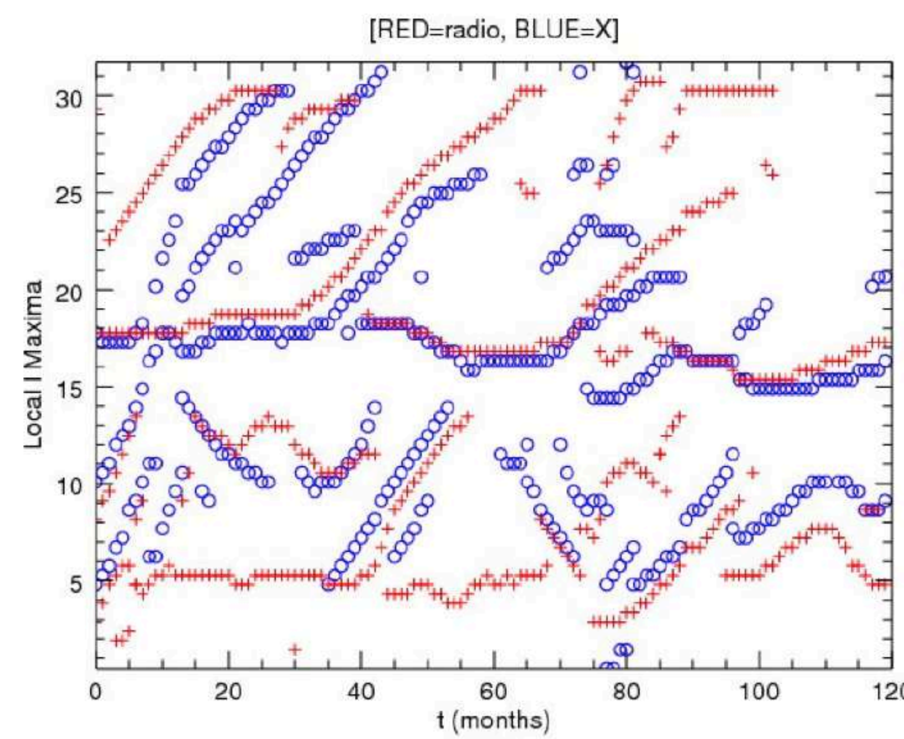
Non-coincident locations and different outward velocities at different wavelengths explained with non uniform injection of emitting particles:

If injection is uniform wisps are coincident!





[Olmi et al. 2015]

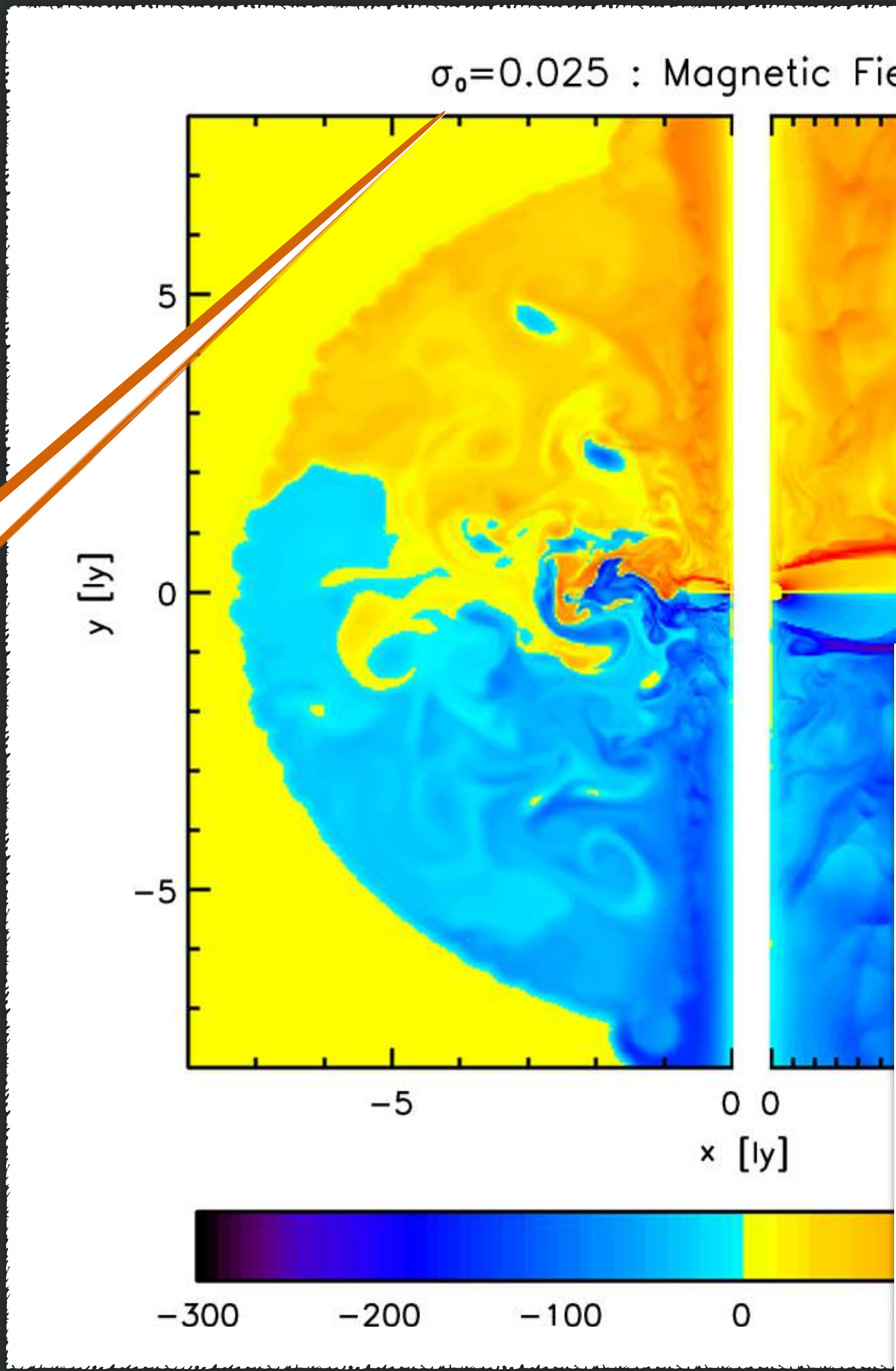


LIMITS OF 2D MODELS

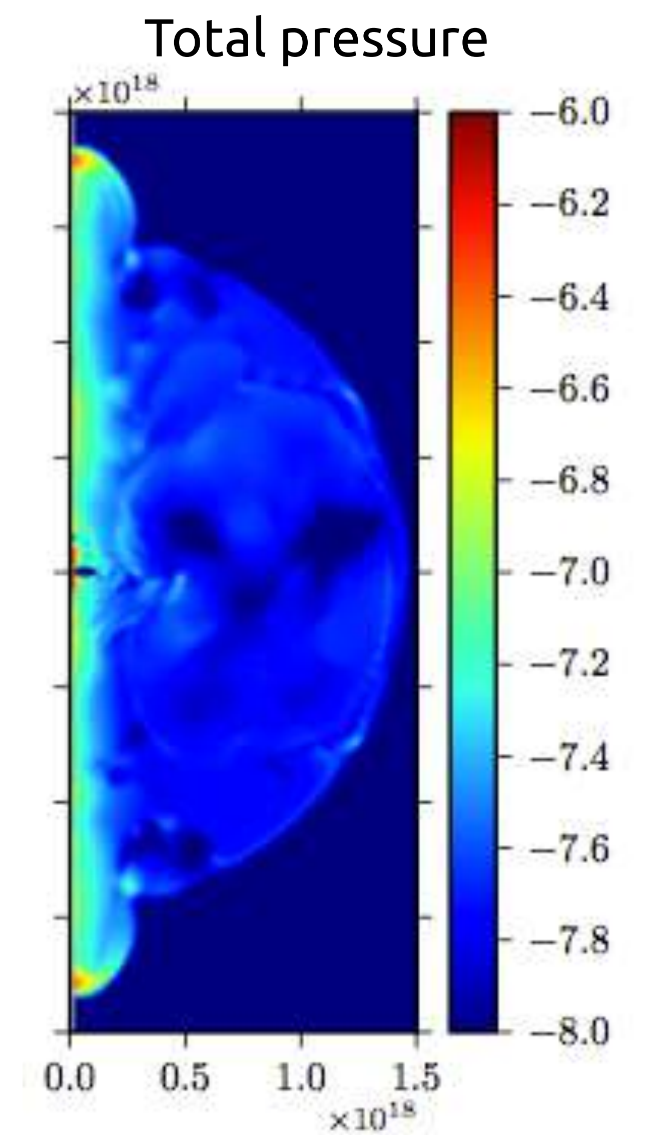
? MAGNETIC FIELD MORPHOLOGY
LEVEL OF MAGNETIZATION ?

2D simulations can only work with σ<1.

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

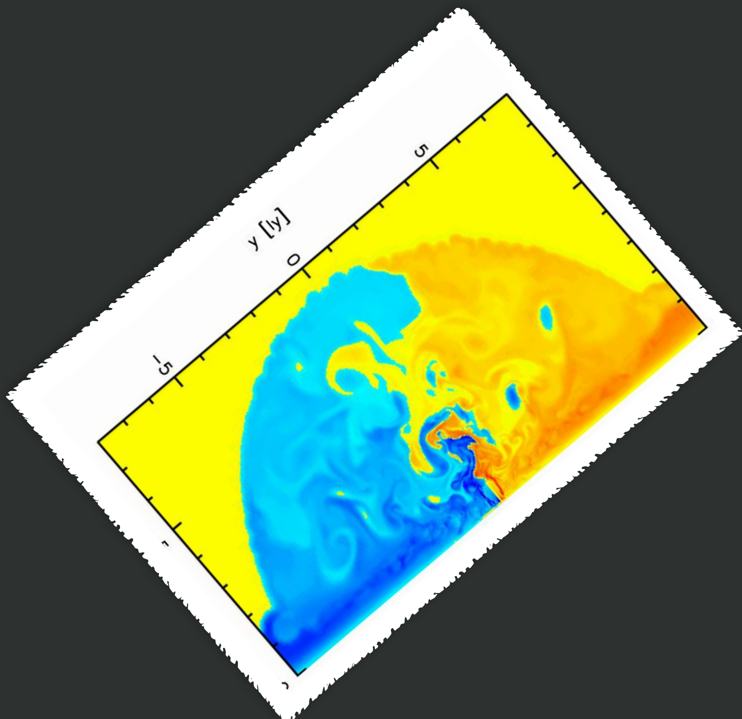


[Olmi et al. 2015]

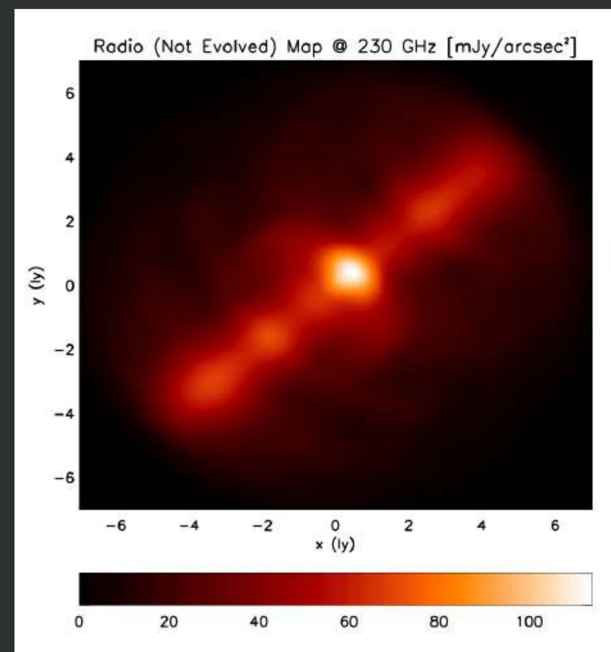


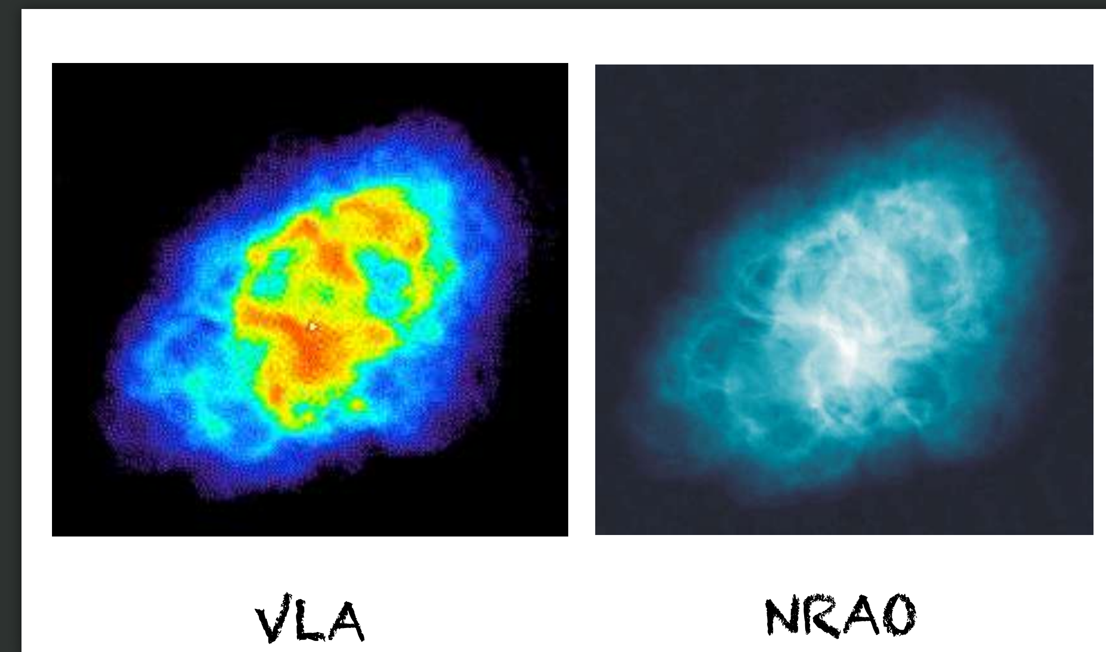
[Porth et al. 2014]

LIMITS OF 2D MODELS
THE MAGNETIC FIELD PROBLEMS AFFECT EMISSION

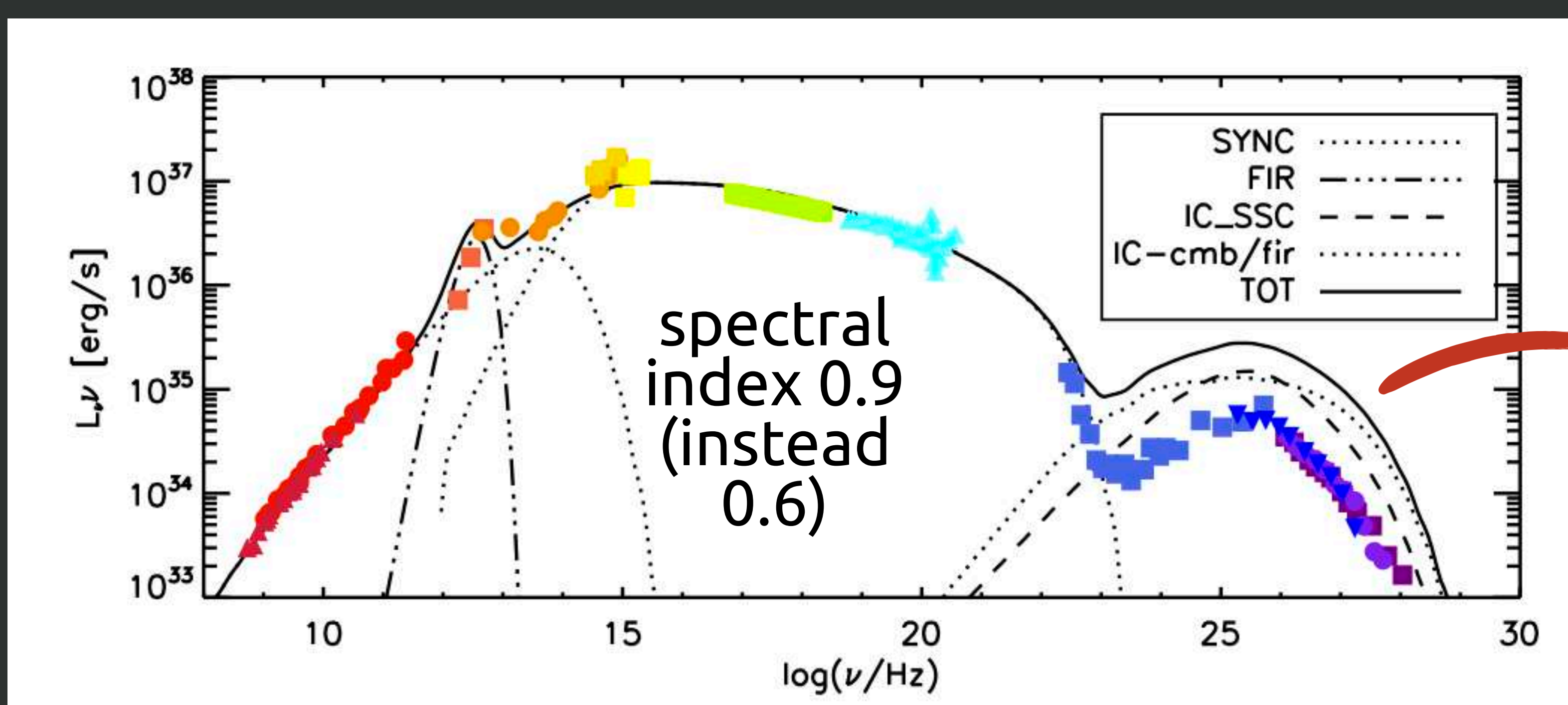


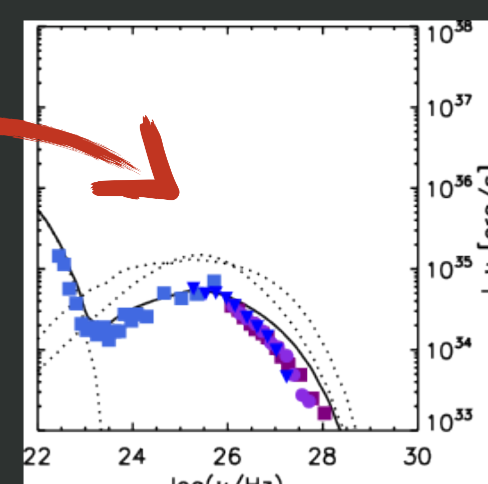
RADIO EMISSION IS NOT UNIFORM: TRACES THE FIELD COMPRESSION





HIGH-ENERGY SPECTRUM NEEDS ARTIFICIAL STEEPENING TO COMPENSATE LOWER ENERGY LOSSES
IC OVERESTIMATED



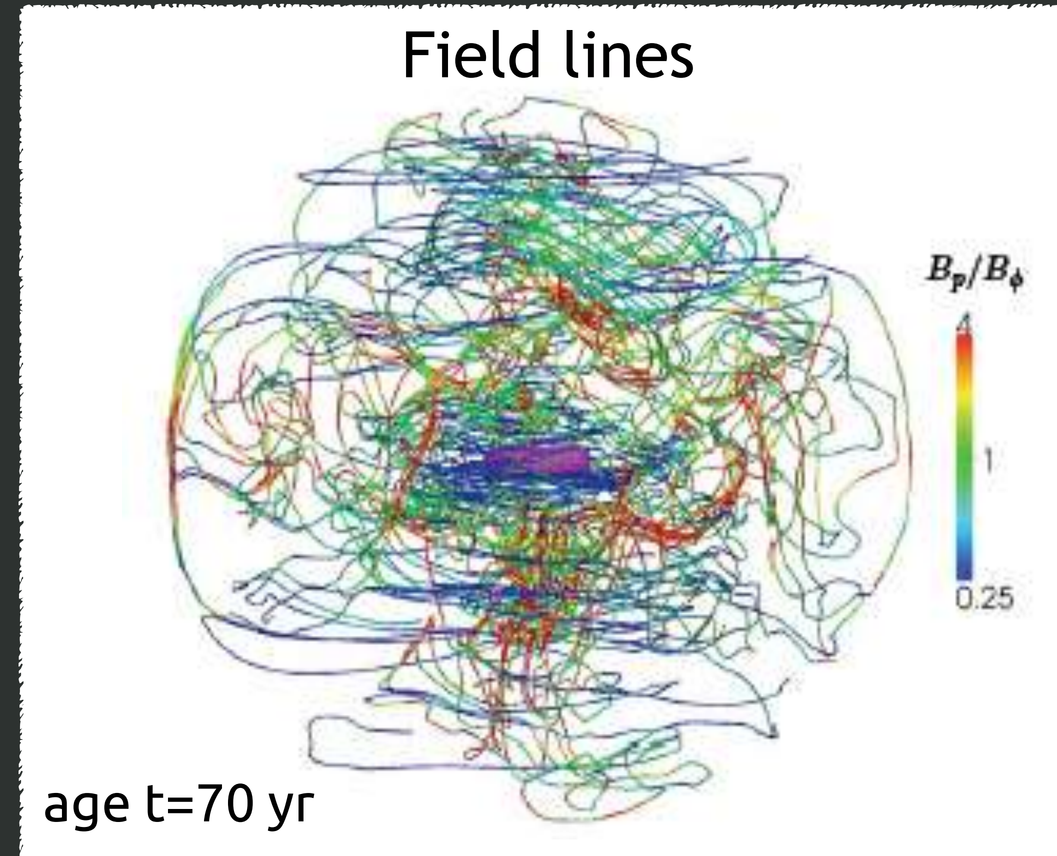


IC corrected to equipartition field

3D SIMULATIONS

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

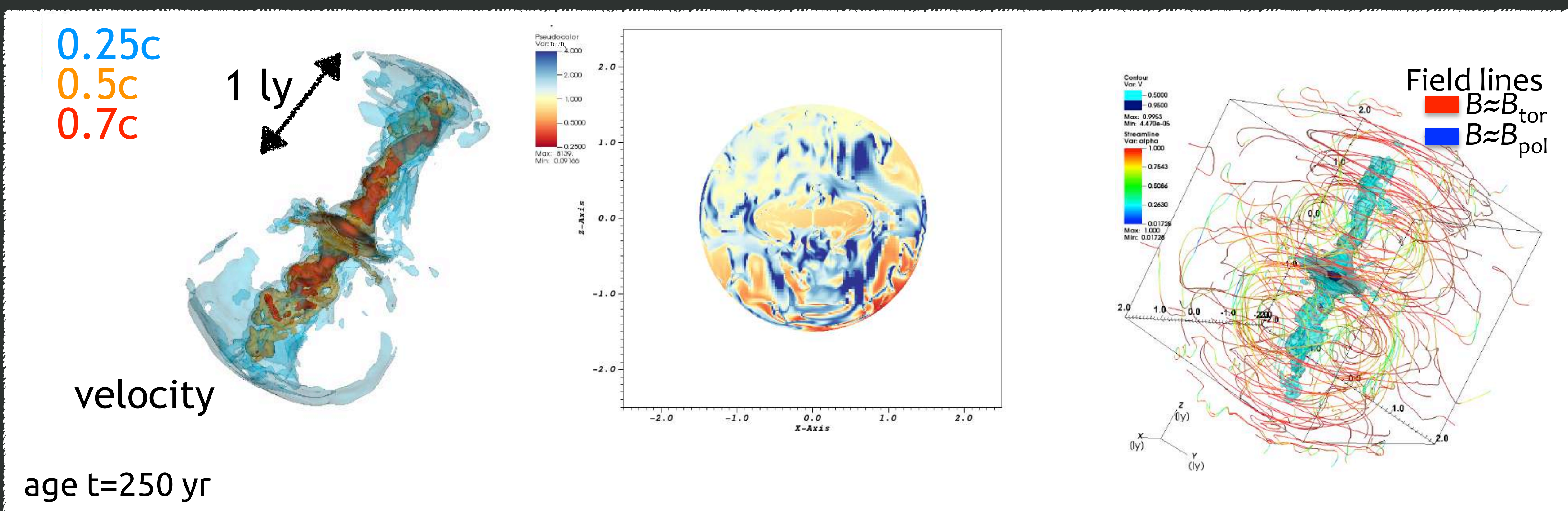
Possible solution to σ-paradox?



[Porth et al. 2013, 2014]

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

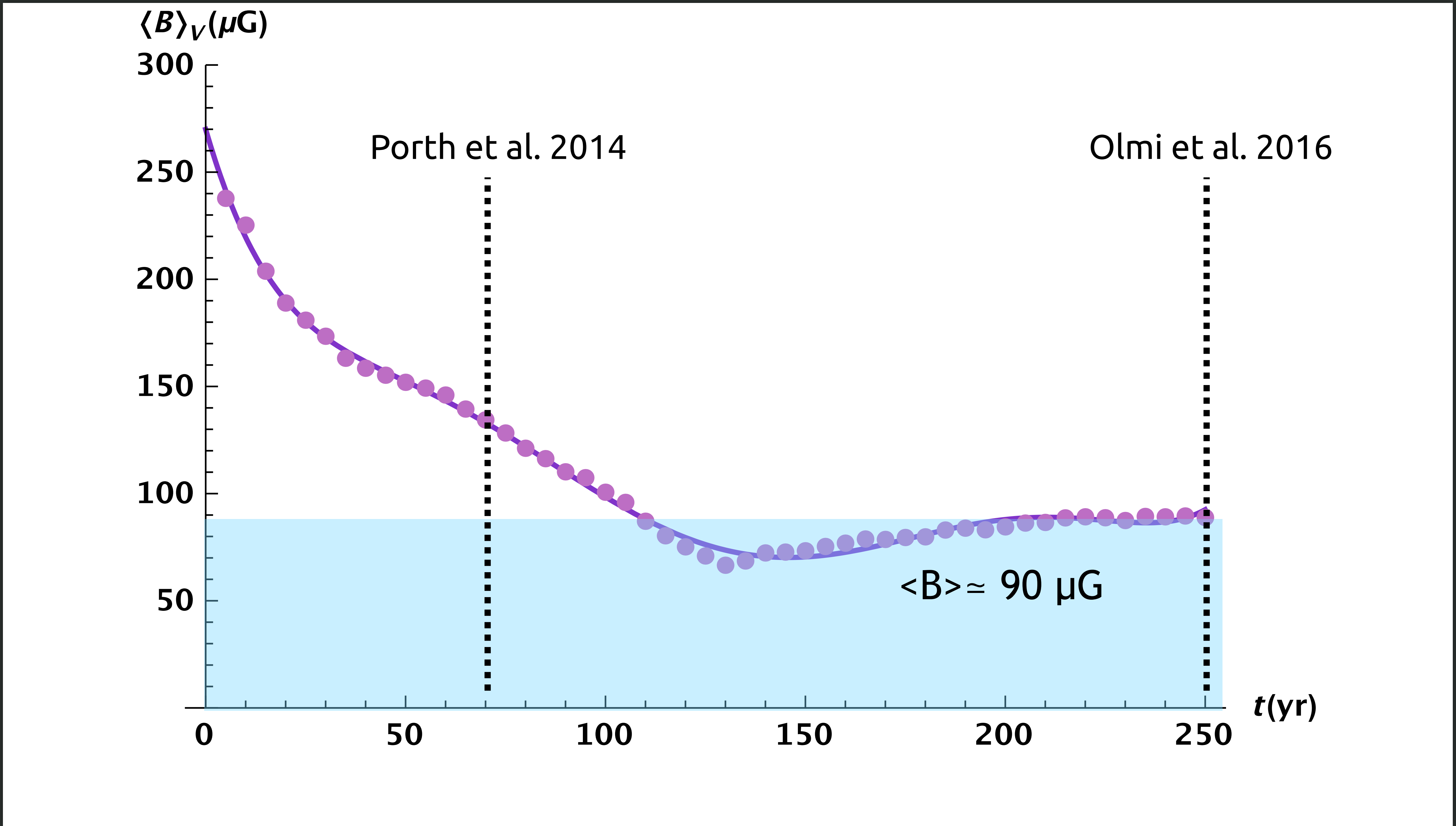
> 1 Million CPU hours (ran @ CINECA with >2000 CPUs)



[Olmi et al. 2016]

AND NOT ALL IS SOLVED...

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

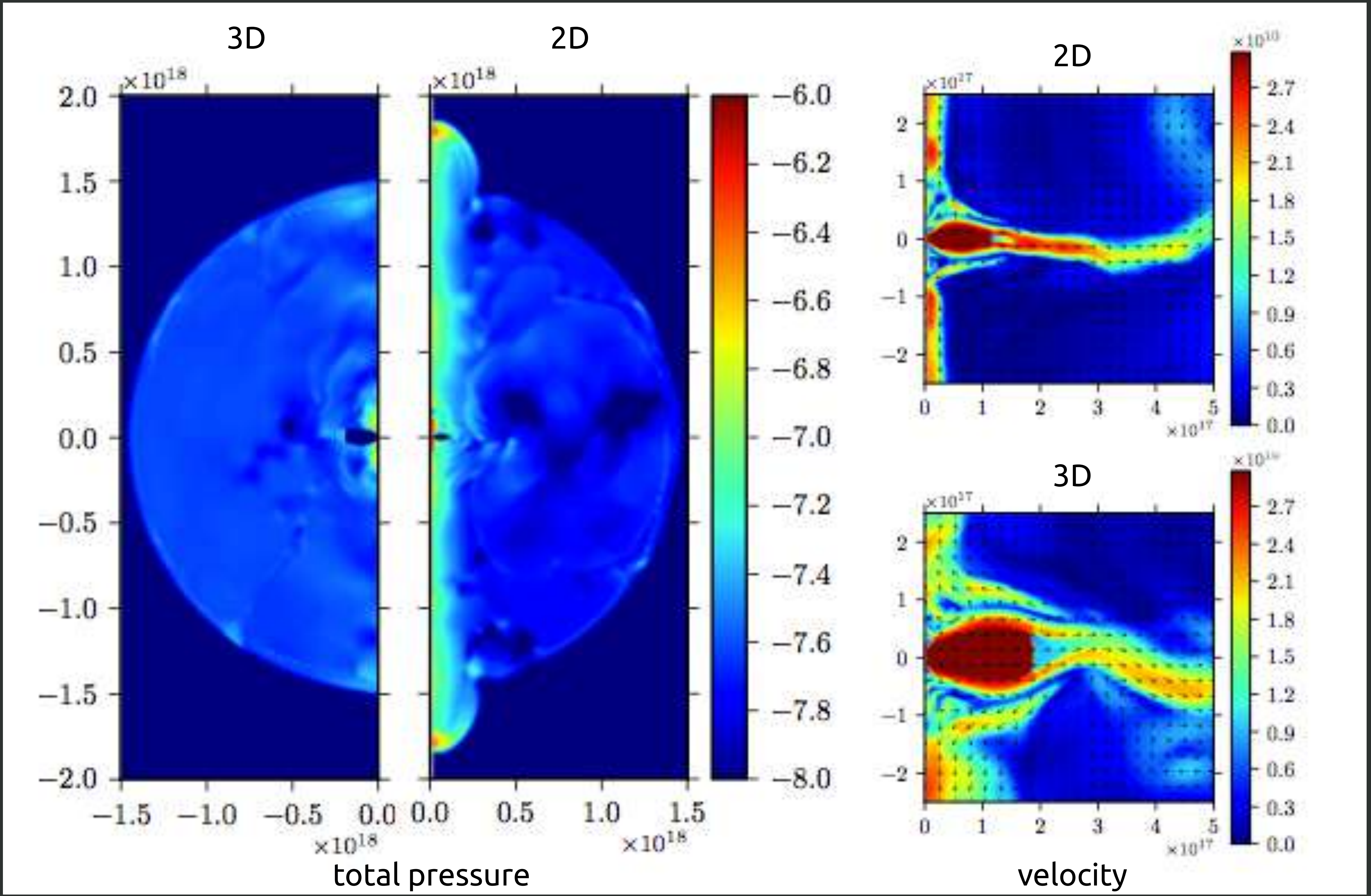


Same problems with the spectrum!

3D VS 2D

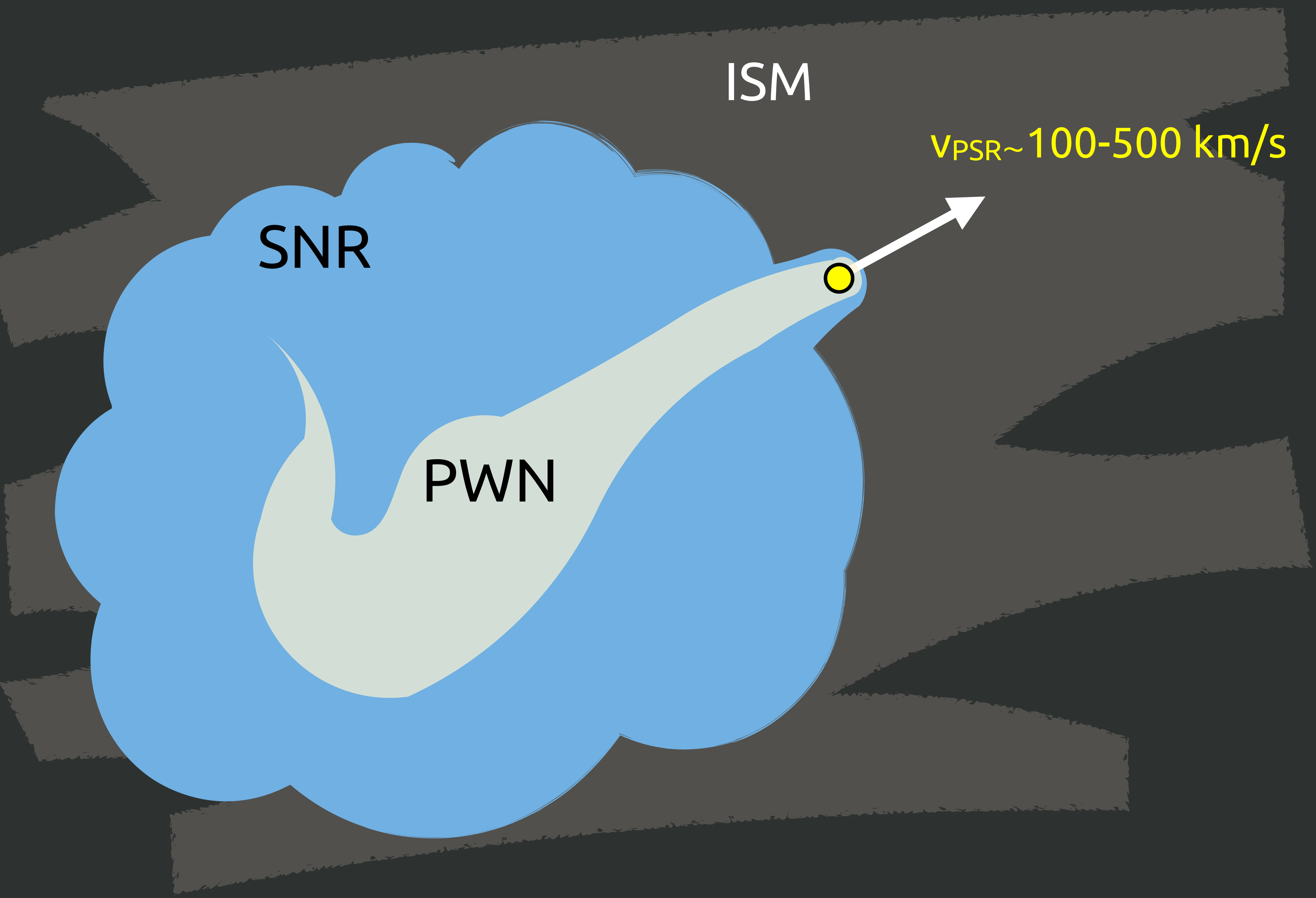
global dynamics completely different

inner dynamics comparable



[Porth et al. 2013, 2014]

A DIFFERENT PROBLEM: EVOLVED PWNE

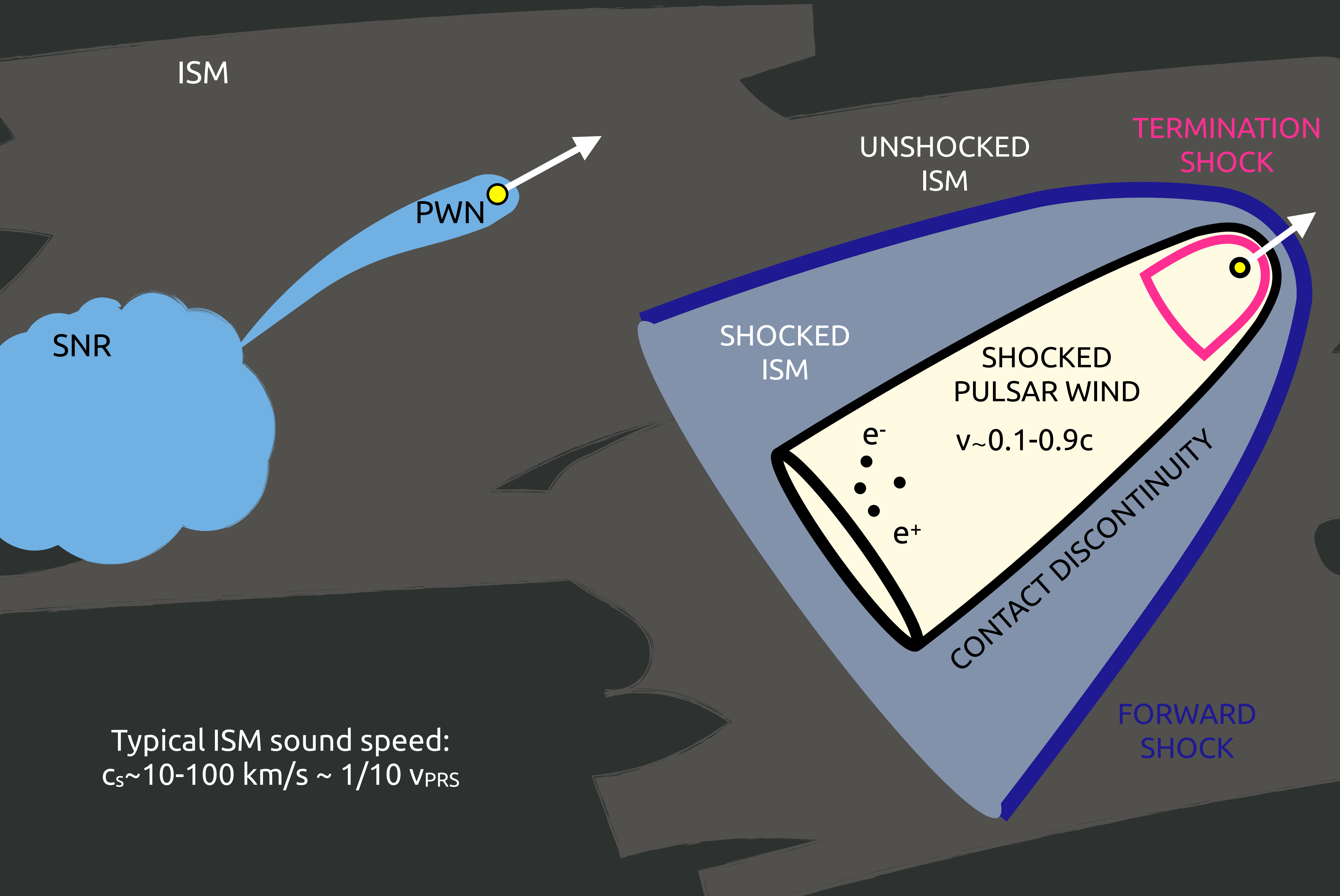


Large fraction of all the pulsars born with high kick velocity (10%-50%)

↓

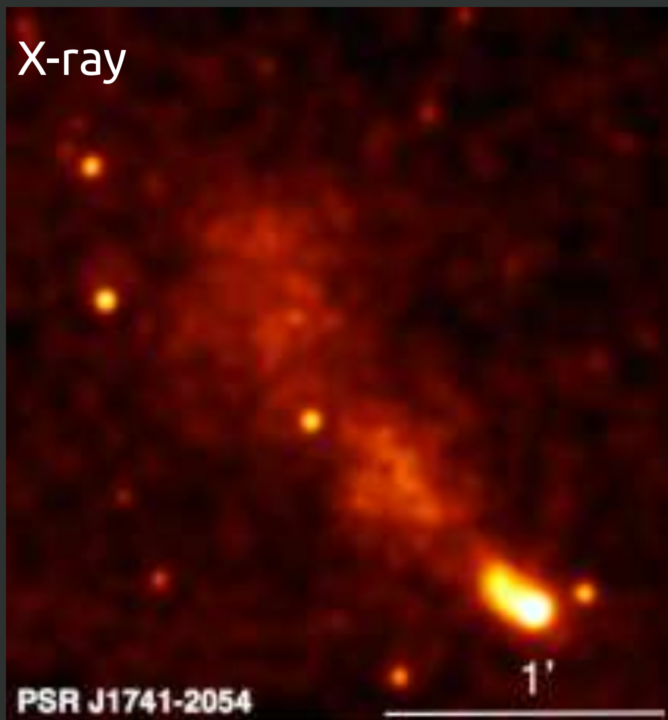
fated to escape the SNR on timescales << than typical pulsar ages (~10^6 yr)

BOW SHOCK PWNe

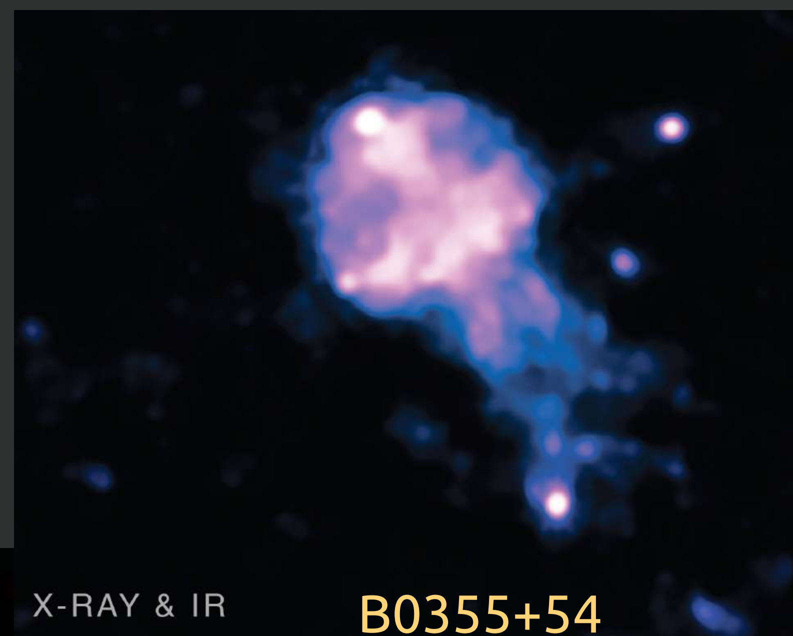


Typical ISM sound speed:
c_s~10-100 km/s ~ 1/10 v_{PRS}

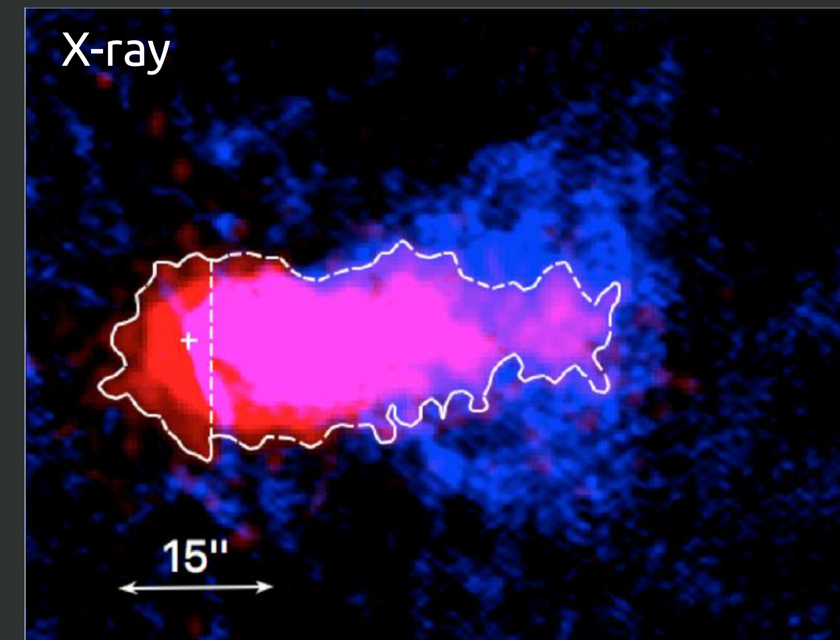
THE COMETARY SHAPE of BSPWNe



PSR J1741-2054
[Kargaltsev et al. 2016]

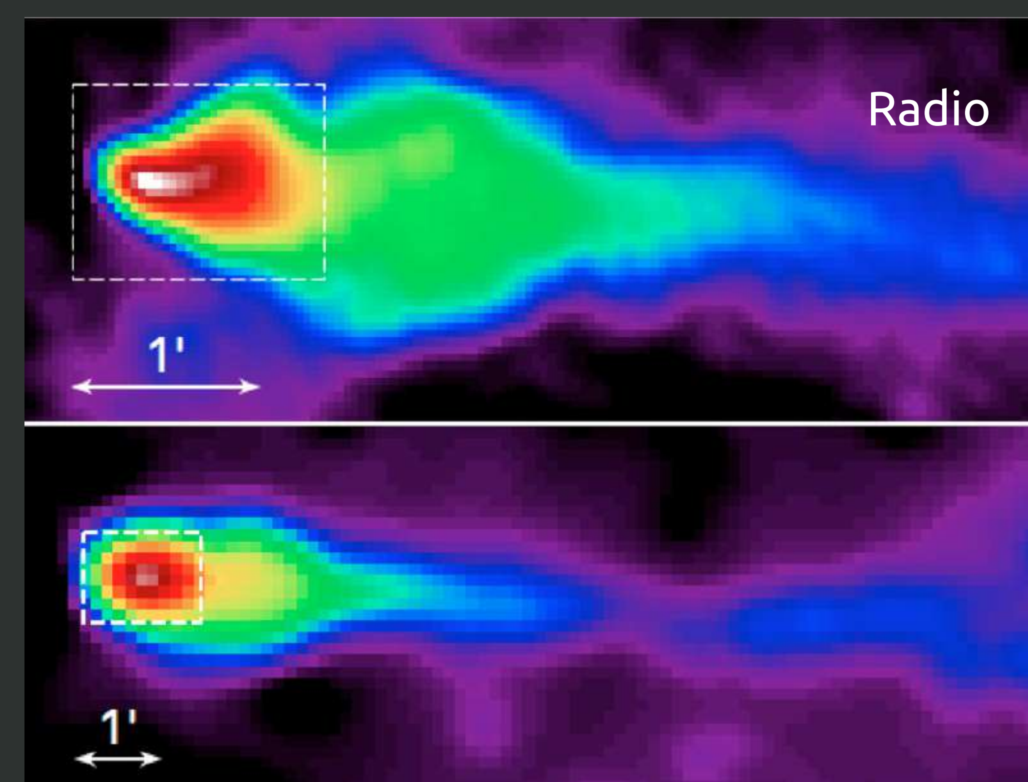


B0355+54
[Emre et al. 2005]



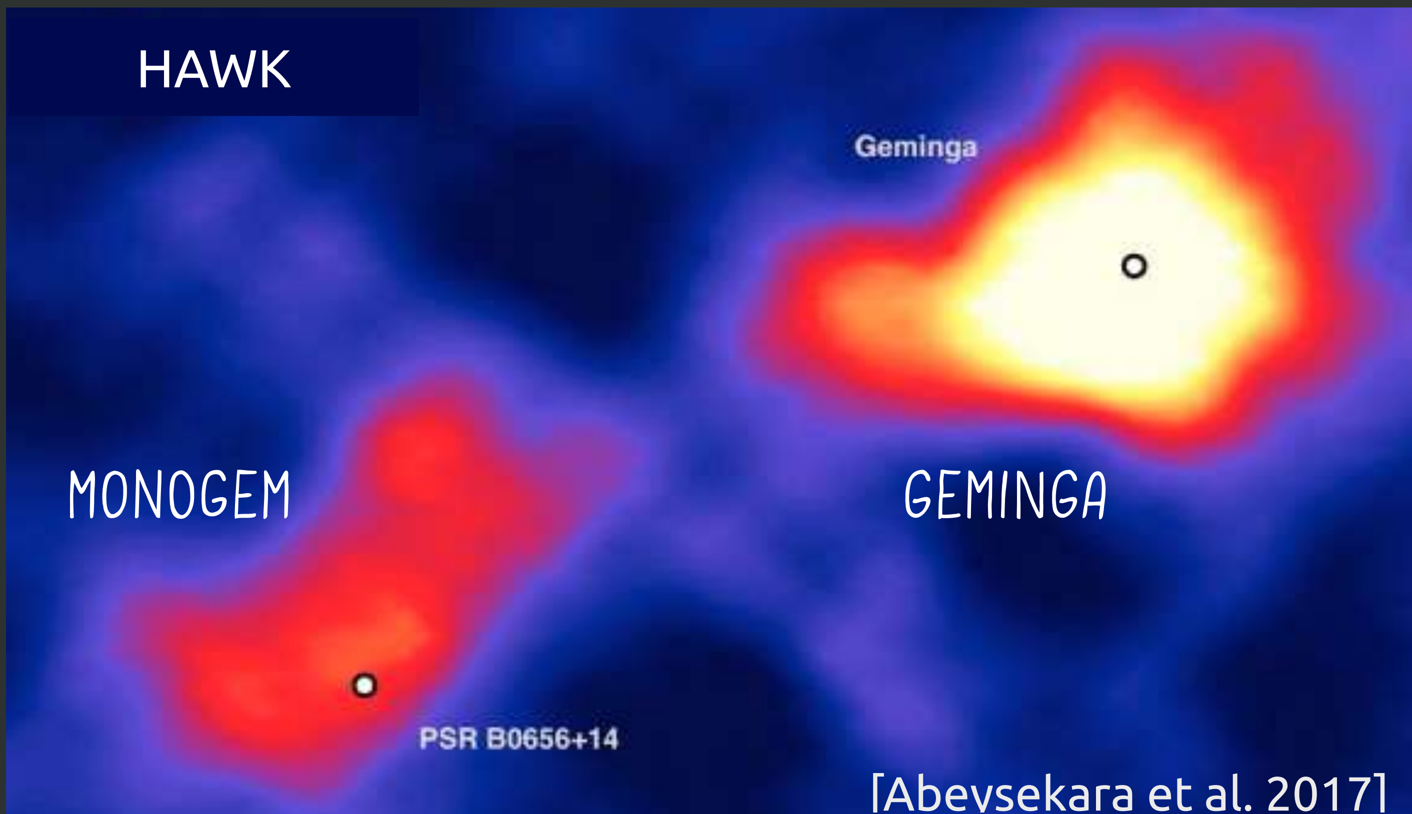
Mouse PWN
[Yusef-Zadeh & Bally 1987,
Yusef-Zadeh & Gaensler 2005,
Klinger et al. 2018]

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



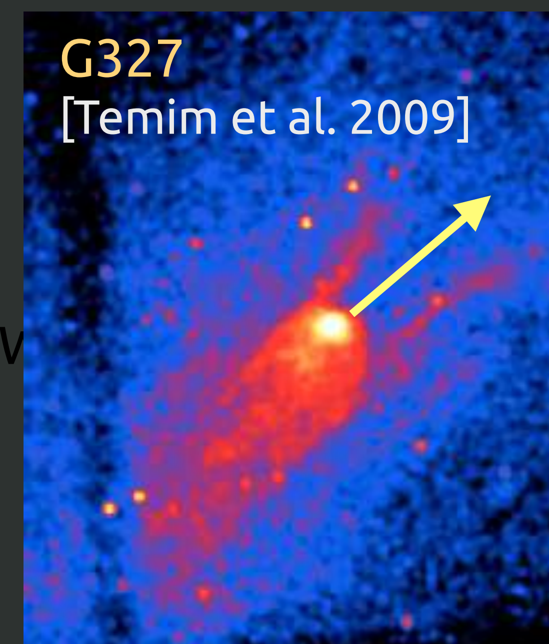
BSPWNe as SOURCEs of ENERGETIC PARTICLEs?

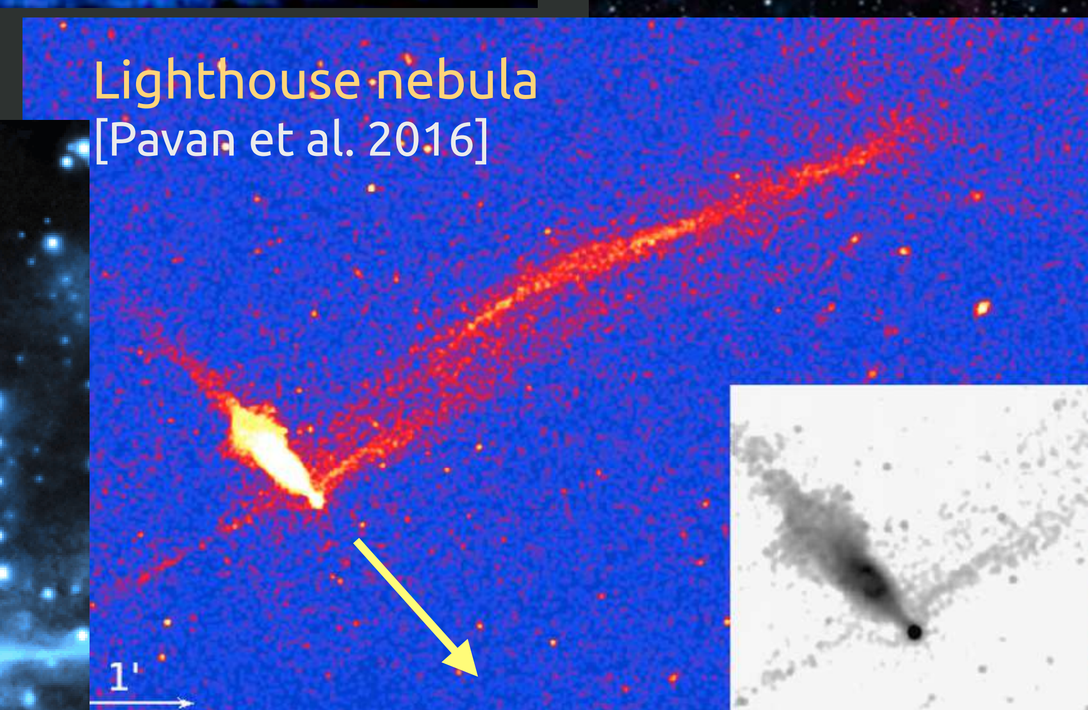
Extended TeV halos surrounding evolved pulsars

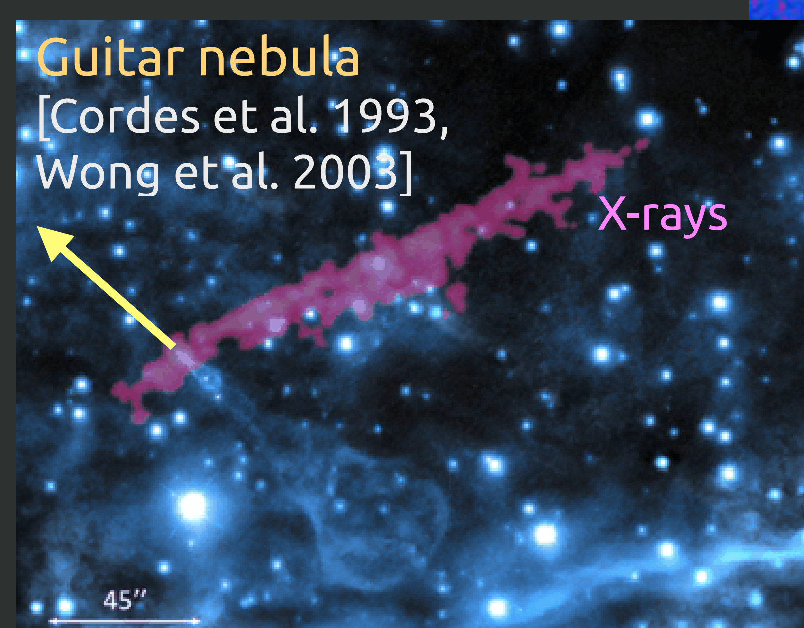


Asymmetric X-ray jets

HAV







Other recent observations in:
J1809-1917 [Klinger et al. 2020]
J2030+4415 [de Vries & Romani 2020]
B1929+10 [Kim et al. 2020]

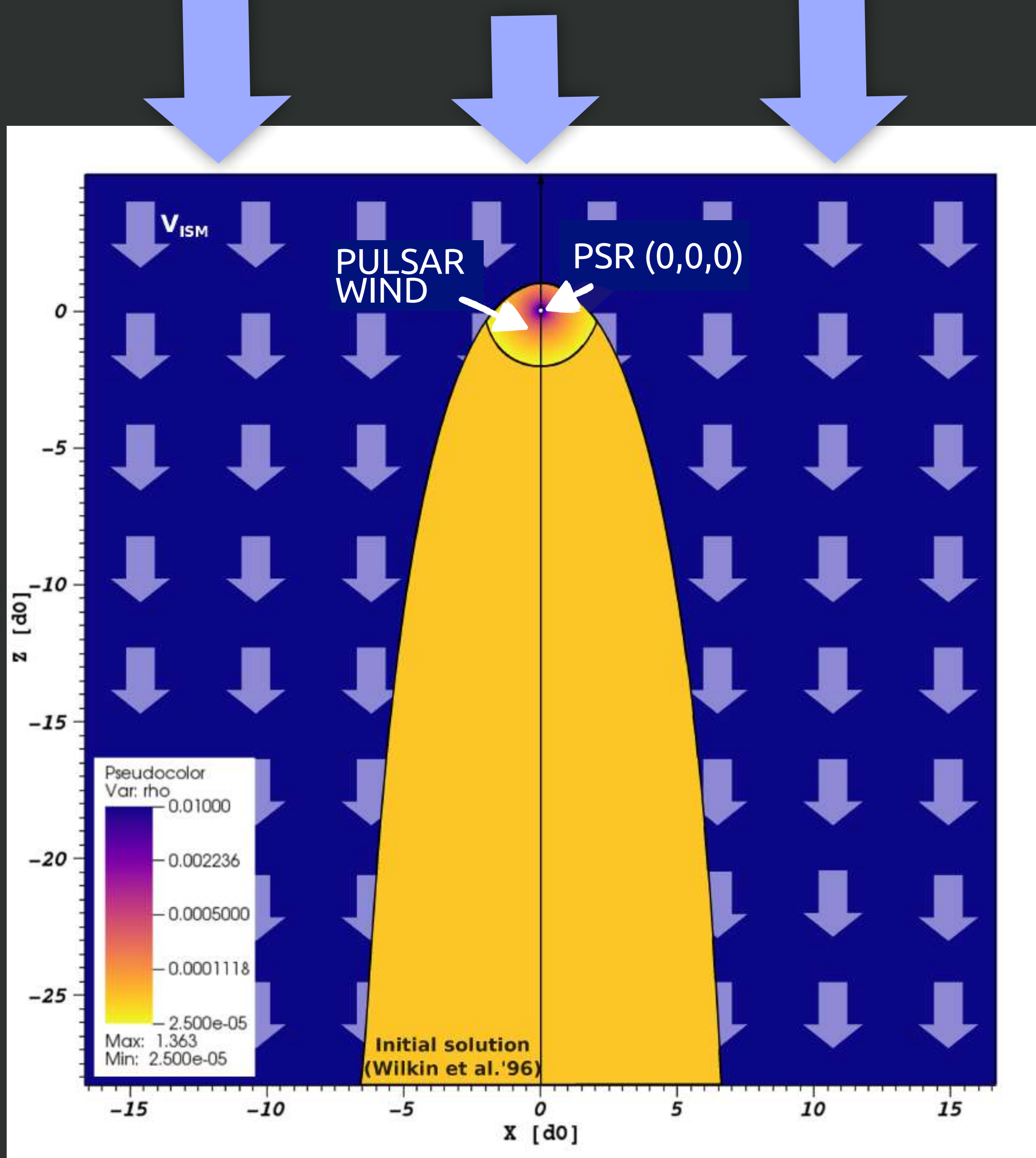
3D MHD SIMULATIONs of BSPWNe

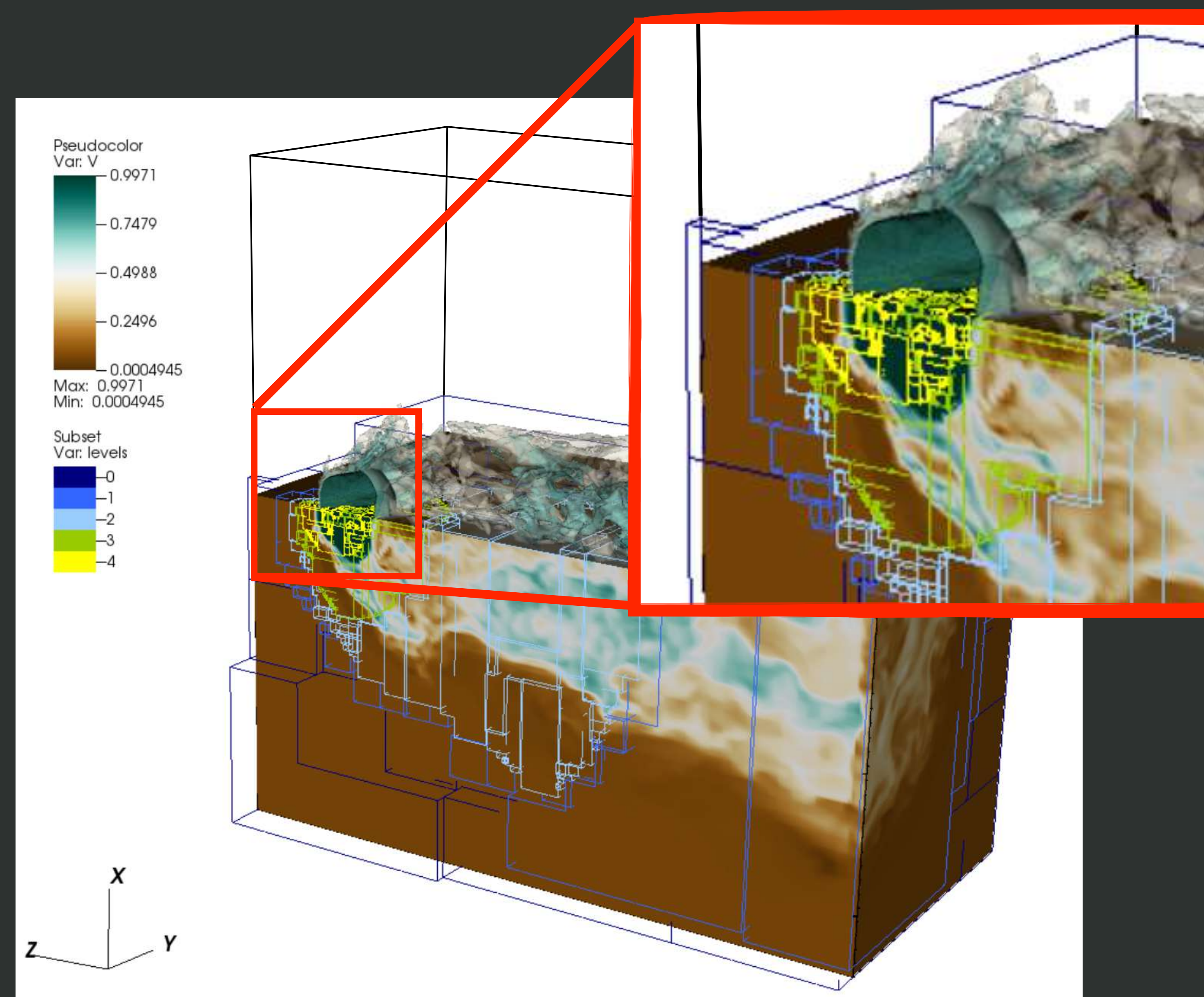
Uniform unmagnetized

ISM V=-V_{PSR}

High resolution required to resolve the PW injection region and allow the TS to correctly detach from the inner boundary (use of Adaptive Mesh Refinement - AMR)

[Olmi & Bucciantini 2019a]





The numerical tool is the **PLUTO code** [Mignone et al. 2007]

Simulations supported by
MoU INAF-CINECA
class A projects

MODELING THE PULSAR WIND AND GEOMETRY

DISTRIBUTION OF ENERGY

Energy flux as function of the colatitute from the spin axis:

$$F(\psi) \propto 1 + \alpha \sin^2 \psi$$

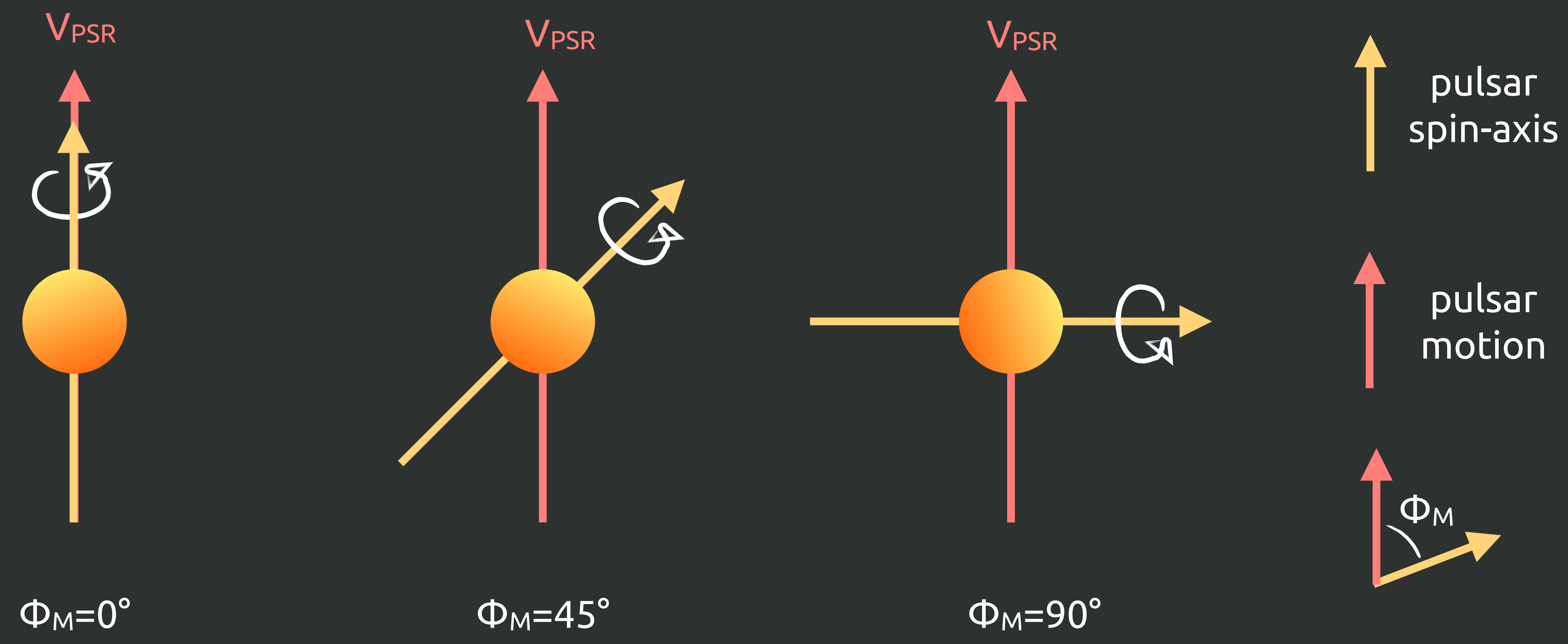
$\alpha = 0 \Longrightarrow$ ISOTROPIC

$\alpha \neq 0 \Longrightarrow$ ANISOTROPIC

WIND MAGNETIZATION

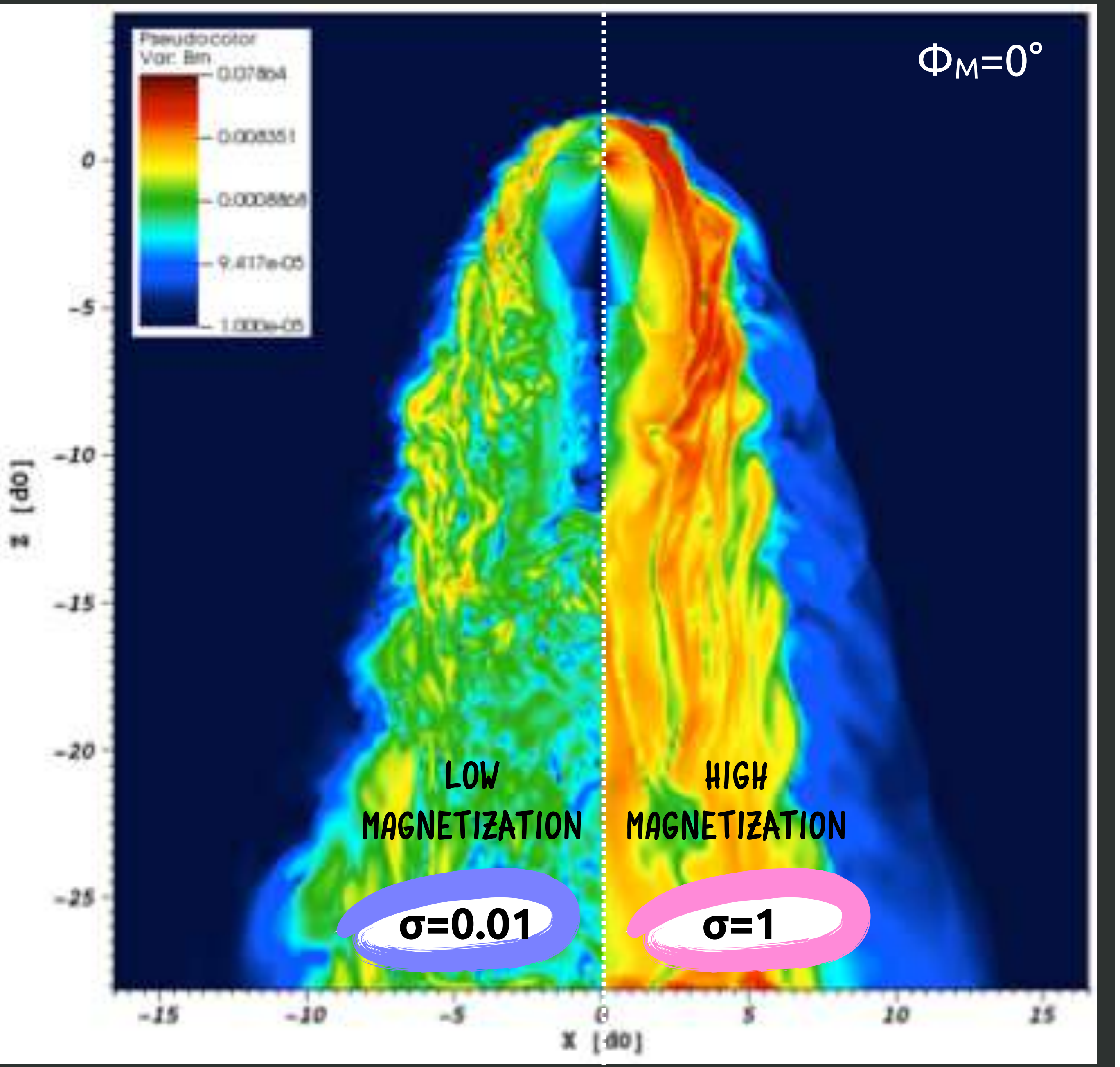
σ= magnetic flux/kinetic flux=0.0, 0.01, 0.1, 1

GEOMETRY



DEVELOPMENT OF TURBULENCE IN TAILS

ISOTROPIC WIND



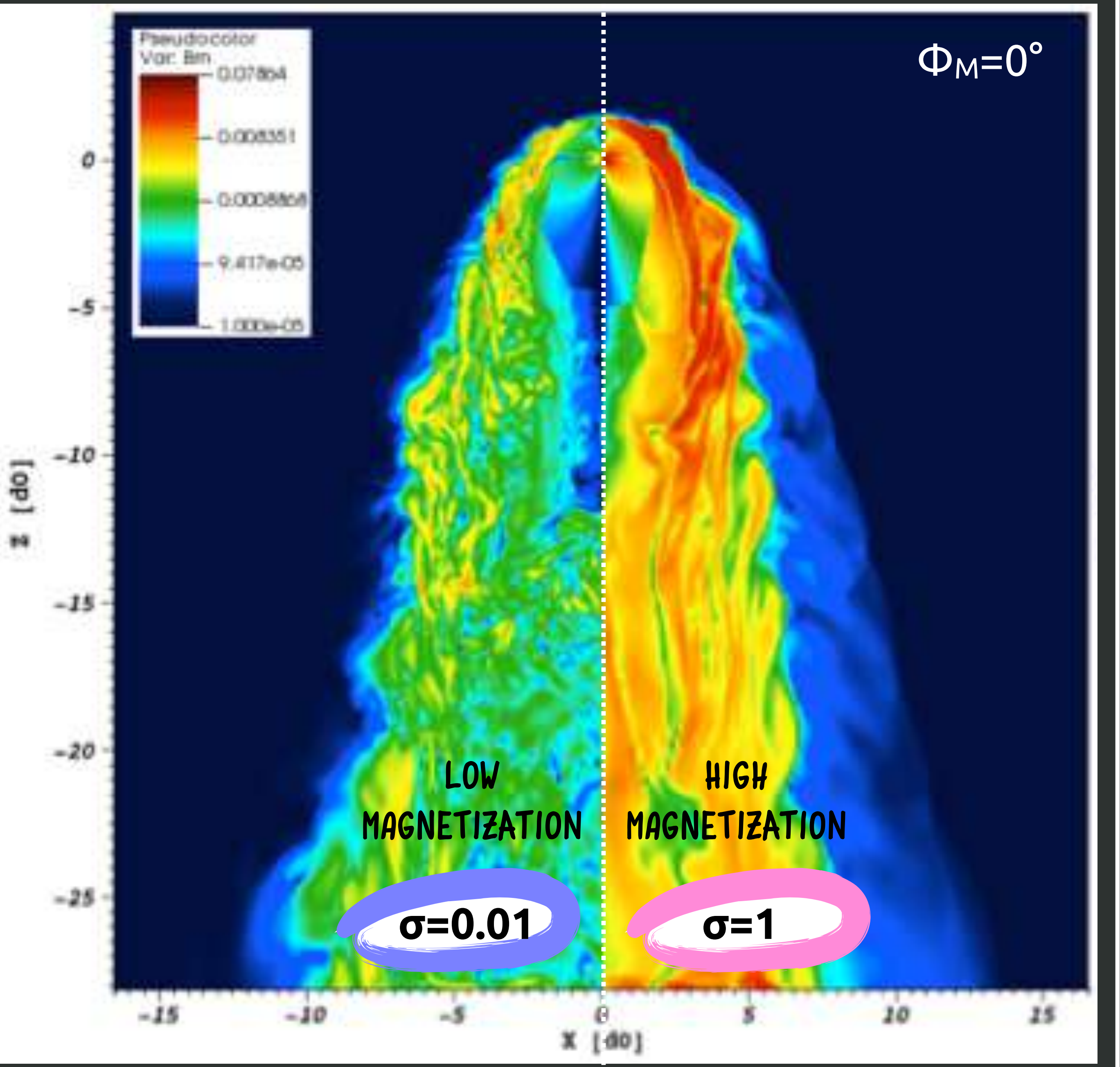
HIGH LEVEL OF TURBULENCE
CHAOTIC FLOW

LOW LEVEL OF TURBULENCE
LAMINAR FLOW

Olmi & Bucciantini 2019a

DEVELOPMENT OF TURBULENCE IN TAILS

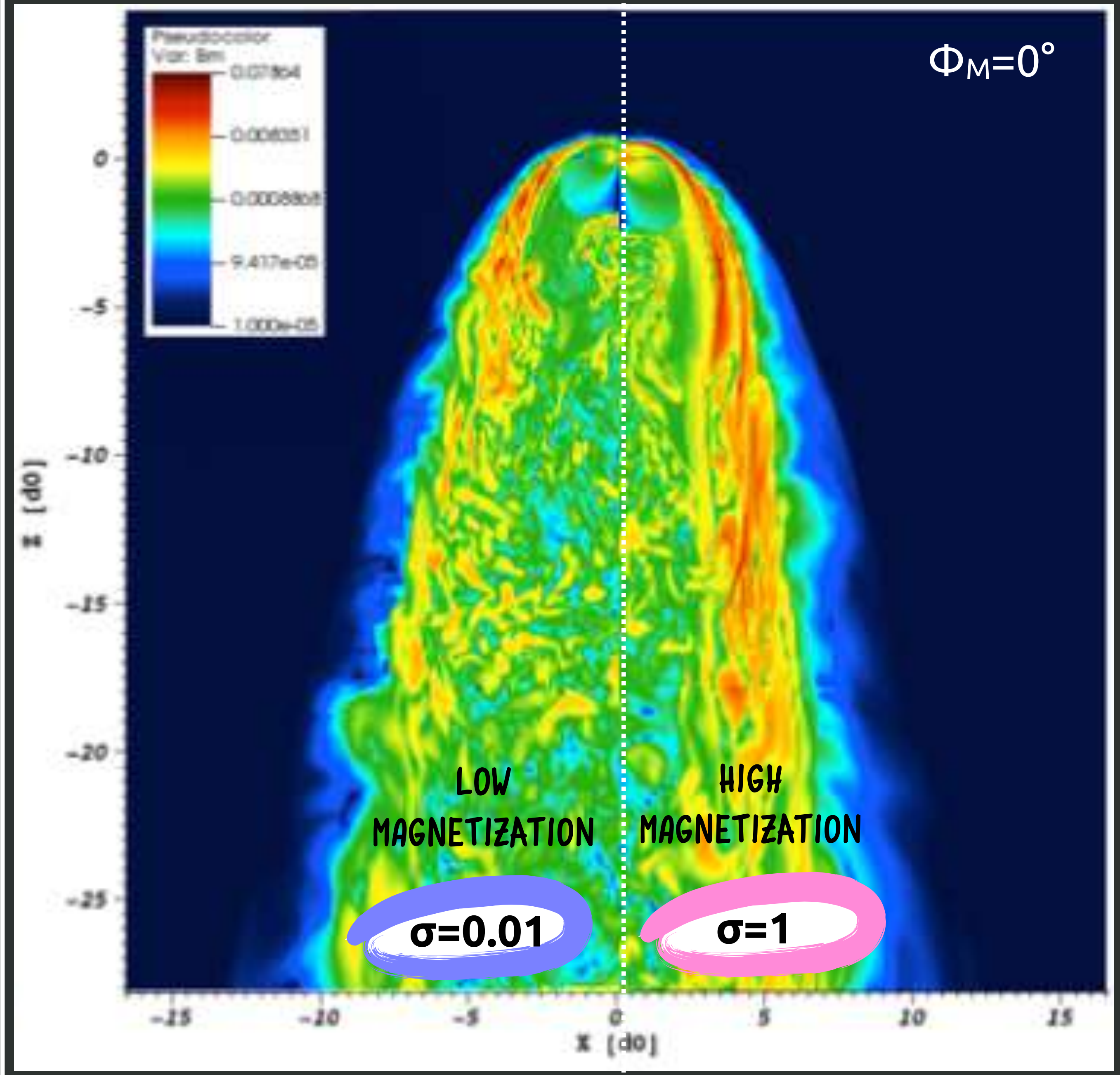
ISOTROPIC WIND



HIGH LEVEL OF TURBULENCE
CHAOTIC FLOW

LOW LEVEL OF TURBULENCE
LAMINAR FLOW

ANISOTROPIC WIND

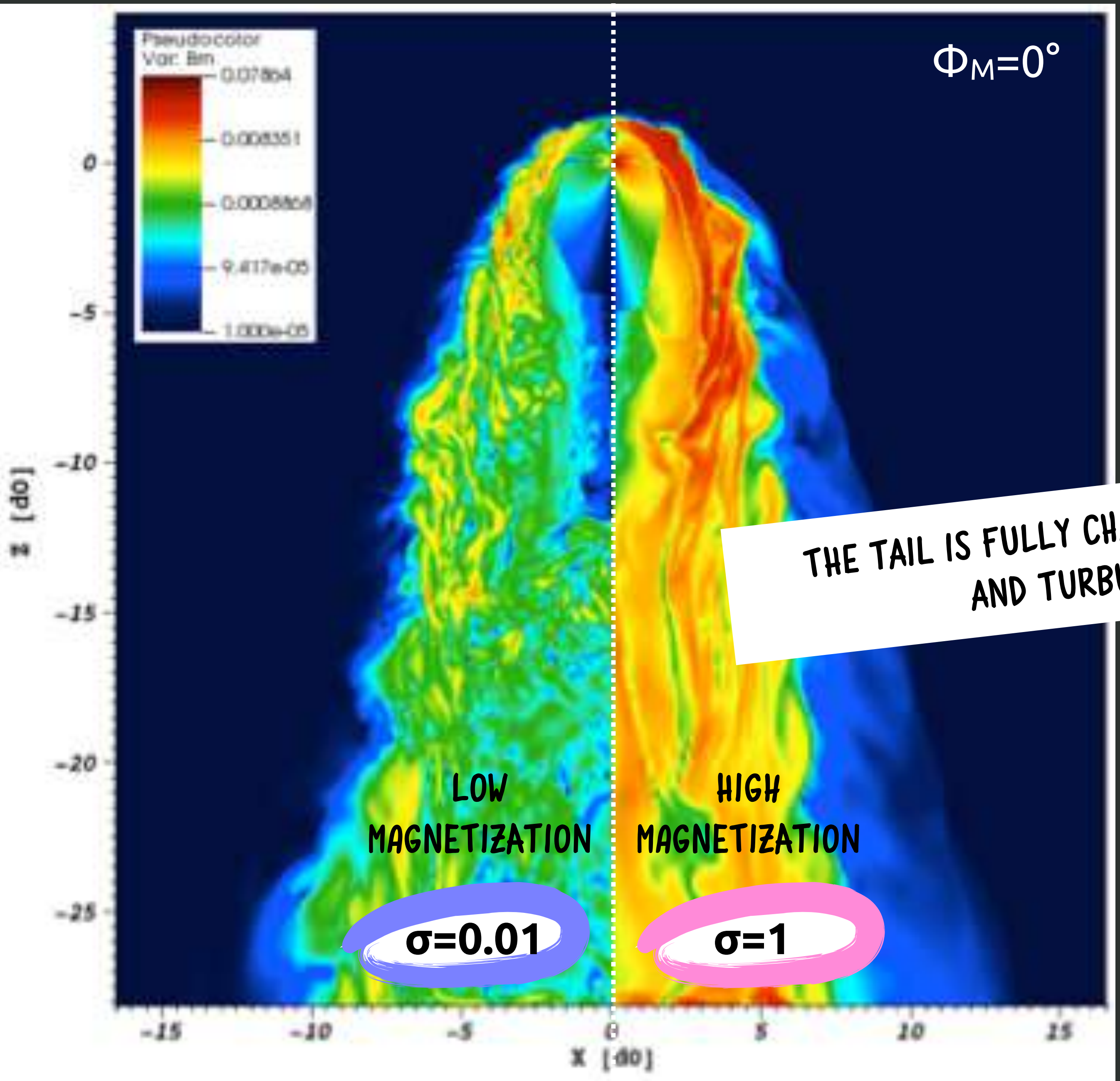


LESS MARKED DIFFERENCE IN ANISOTROPIC WINDS

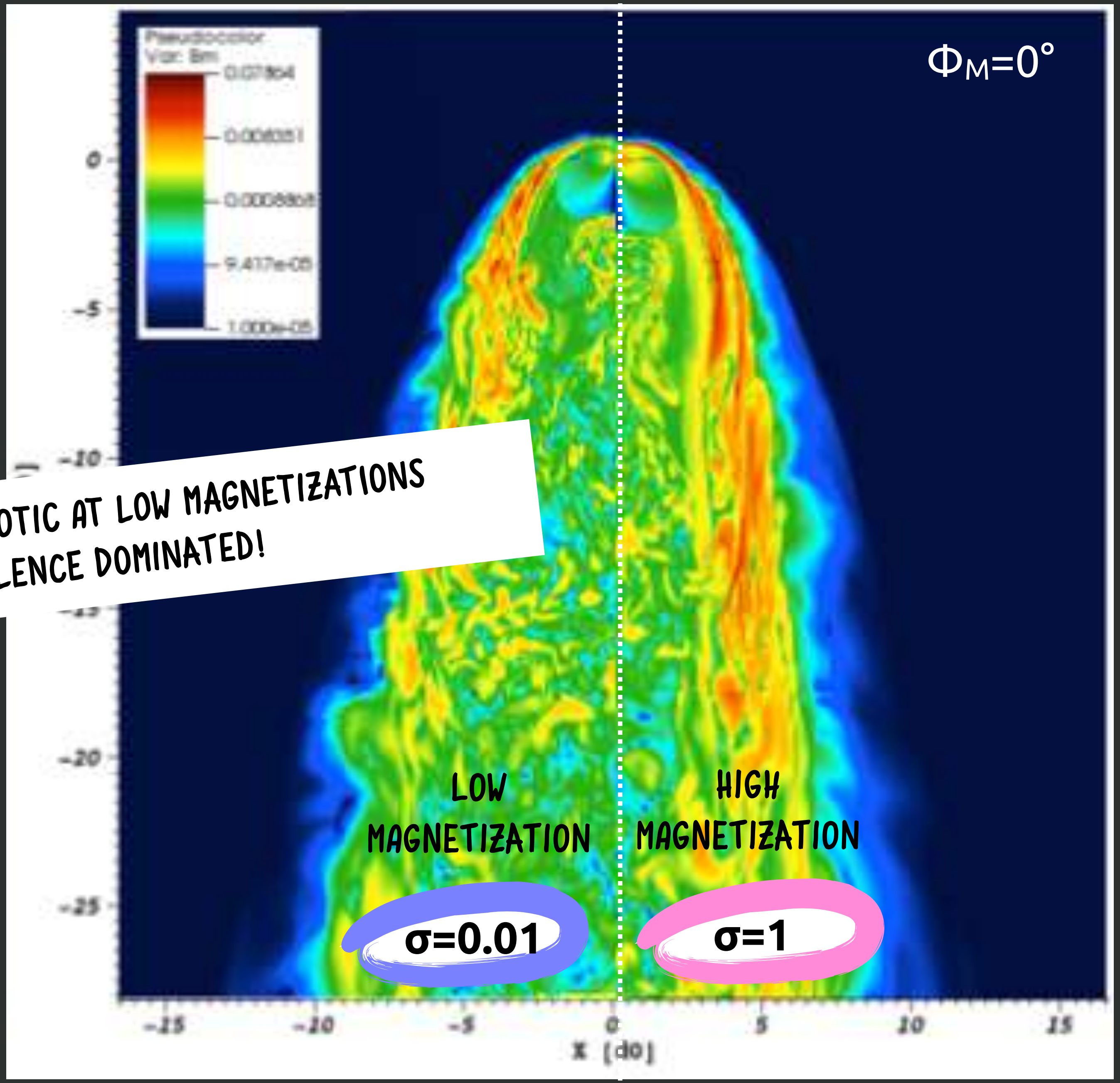
Olmi & Bucciantini 2019a

DEVELOPMENT OF TURBULENCE IN TAILS

ISOTROPIC WIND



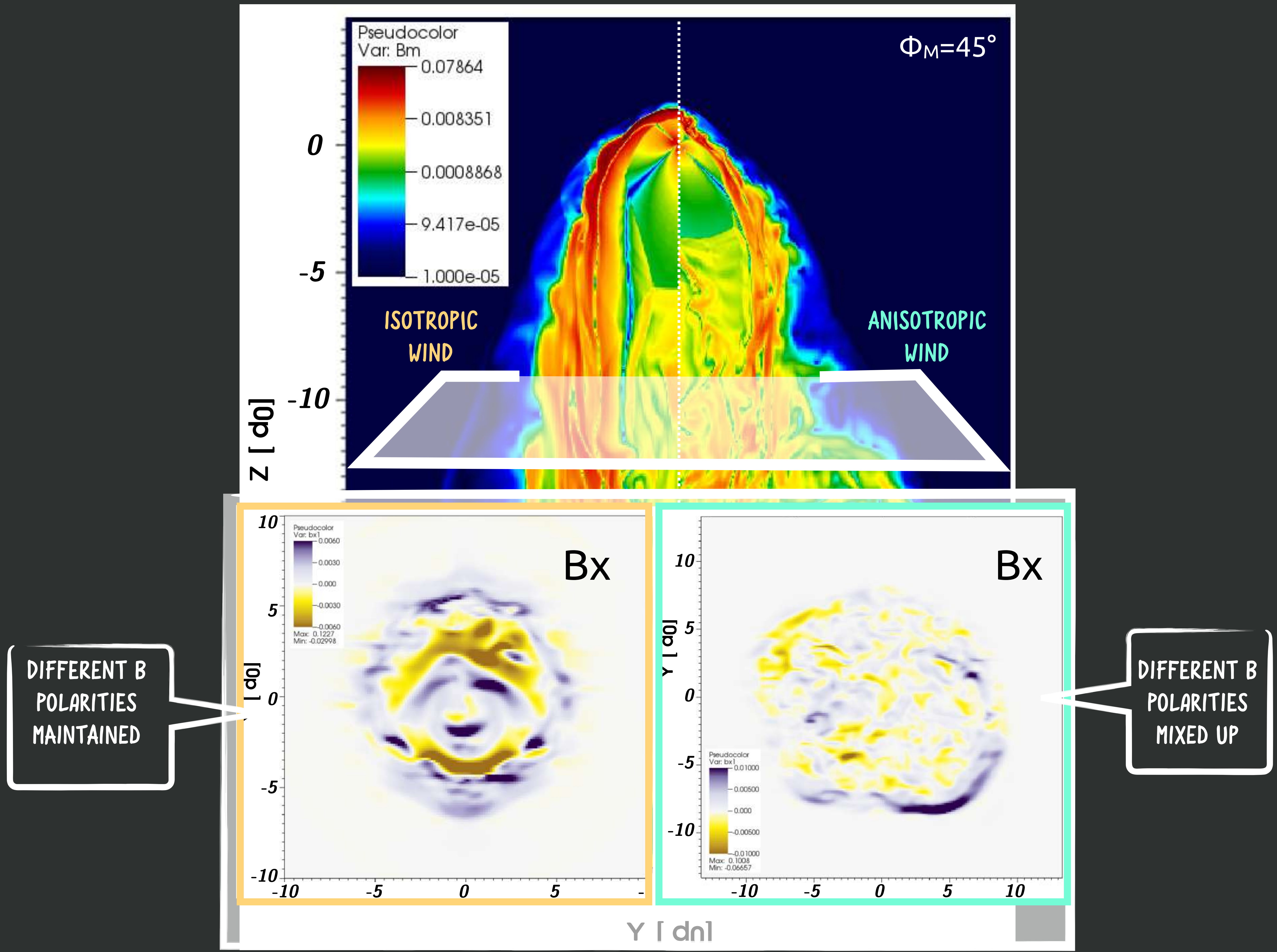
ANISOTROPIC WIND



THE TAIL IS FULLY CHAOTIC AT LOW MAGNETIZATIONS AND TURBULENCE DOMINATED!

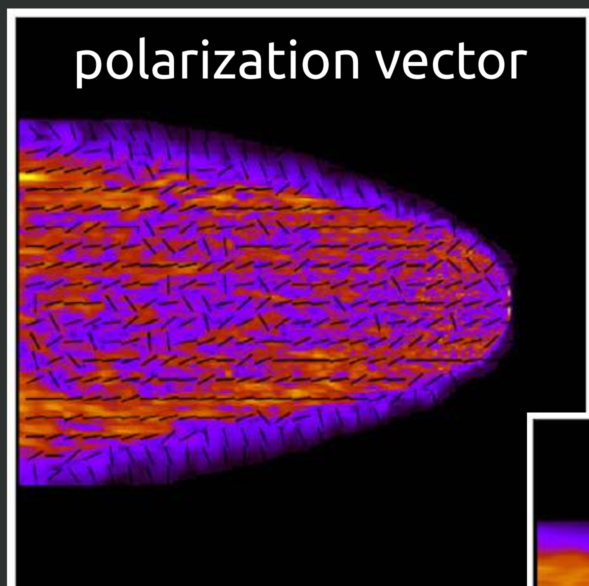
Olmi & Bucciantini 2019a

TAIL DYNAMICS FOR HIGH MAGNETIZATION (σ=1)

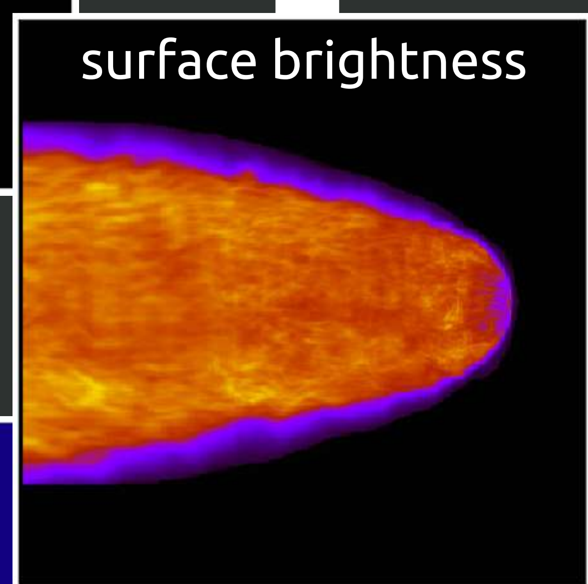


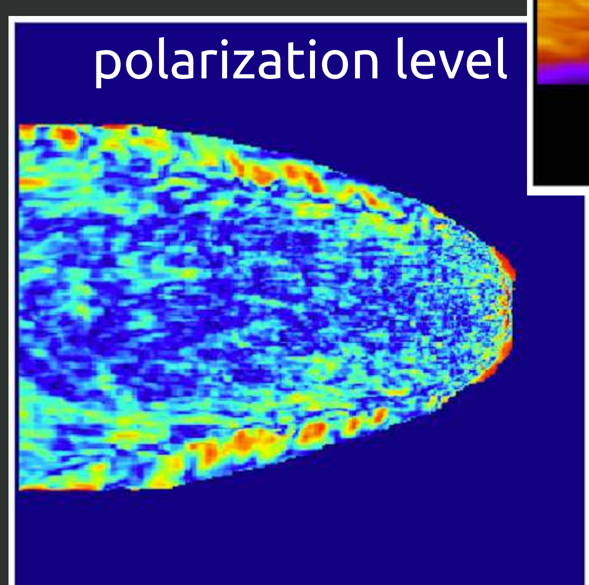
CONSEQUENCES FOR EMISSION

ANISOTROPIC σ=0.01



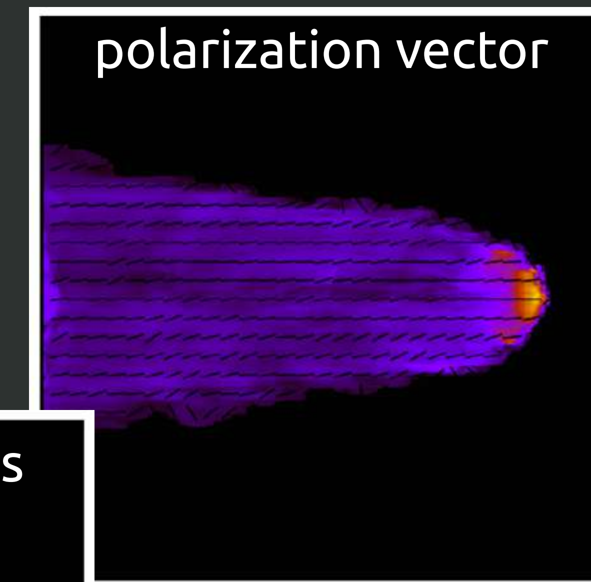
High level of turbulence



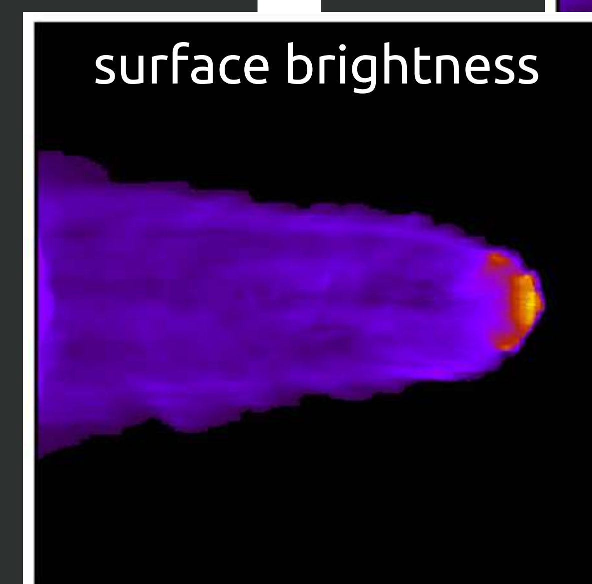


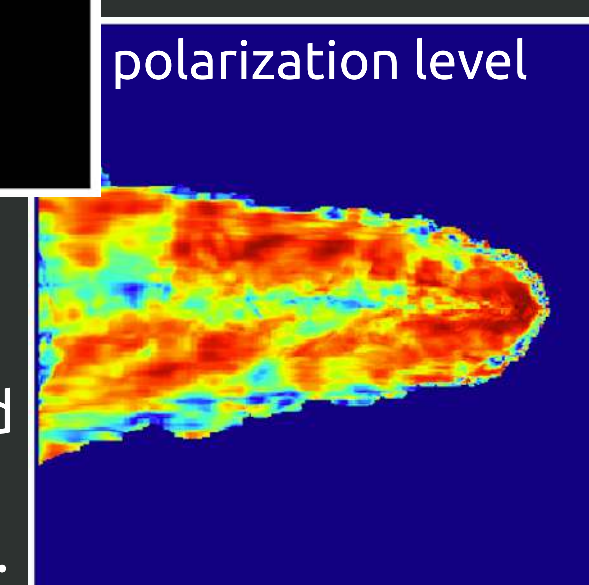
Uniform emissivity.
Unpolarized

ISOTROPIC σ=1



Low level of turbulence

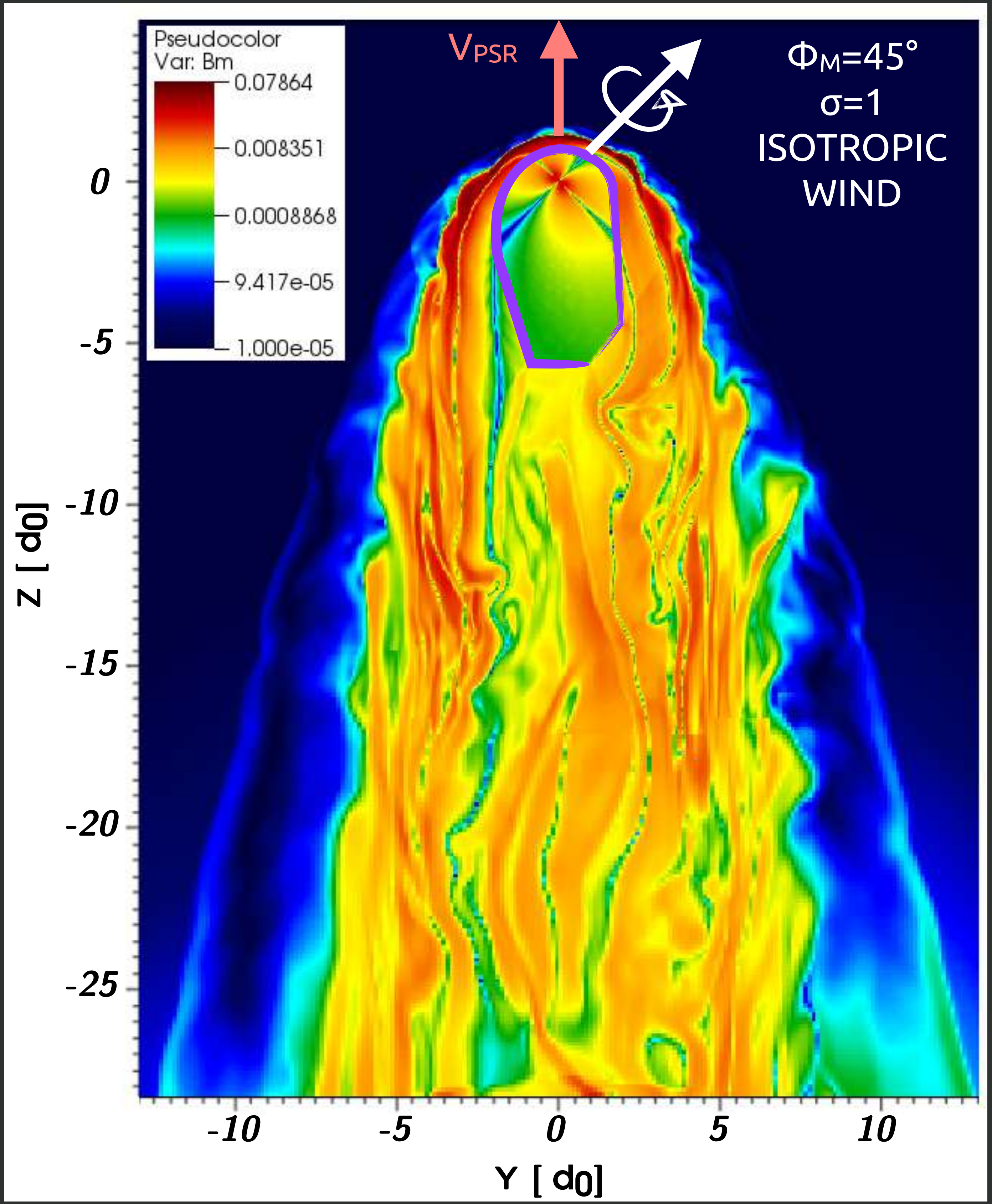


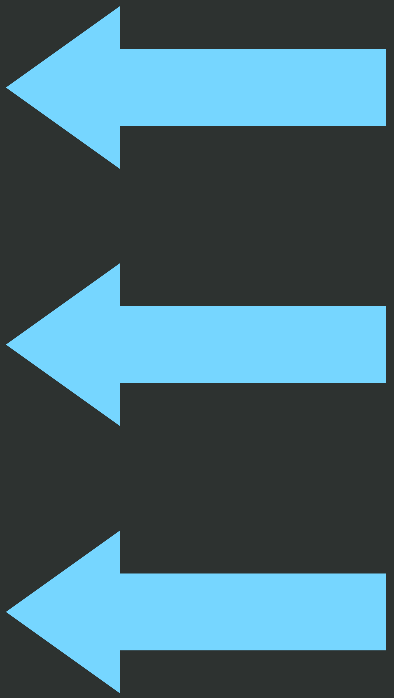


Emission dominated by the head.
Strong polarization.

Olmi & Bucciantini 2019b

EFFECTS OF OUTER MAGNETIC FIELD



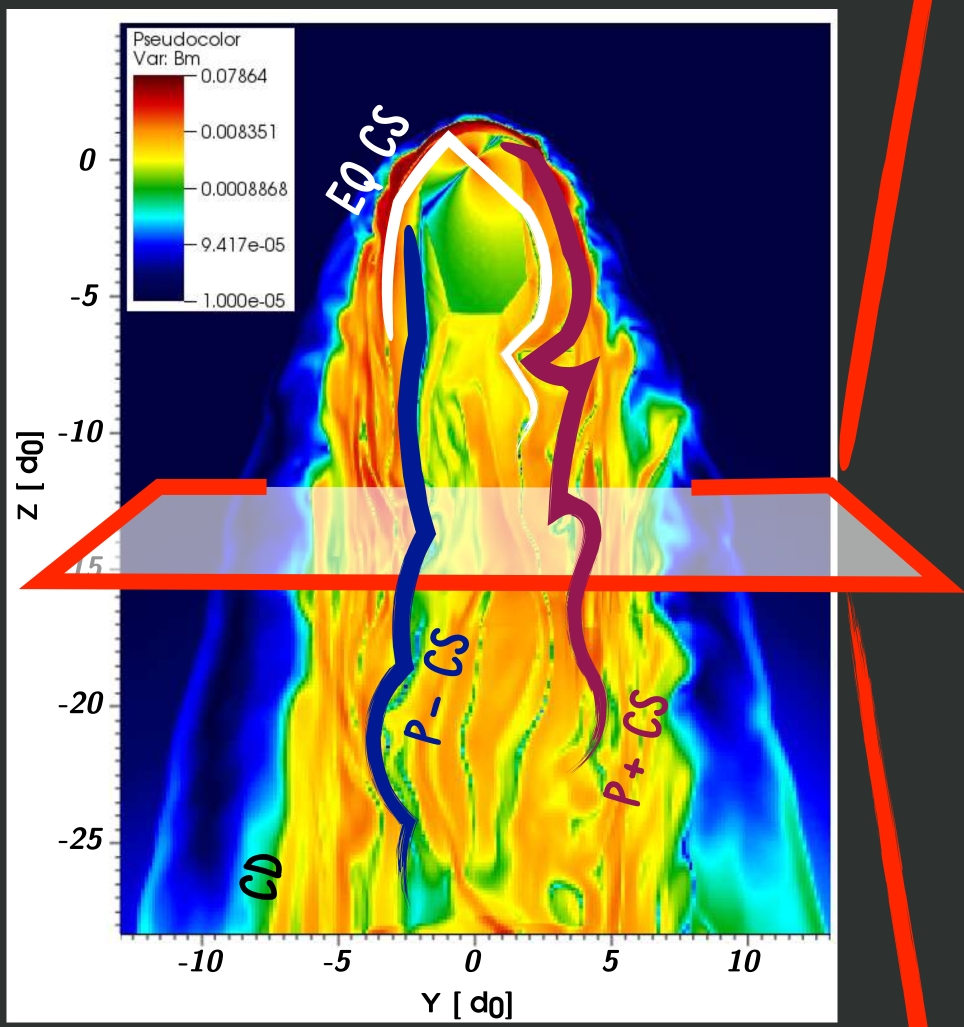


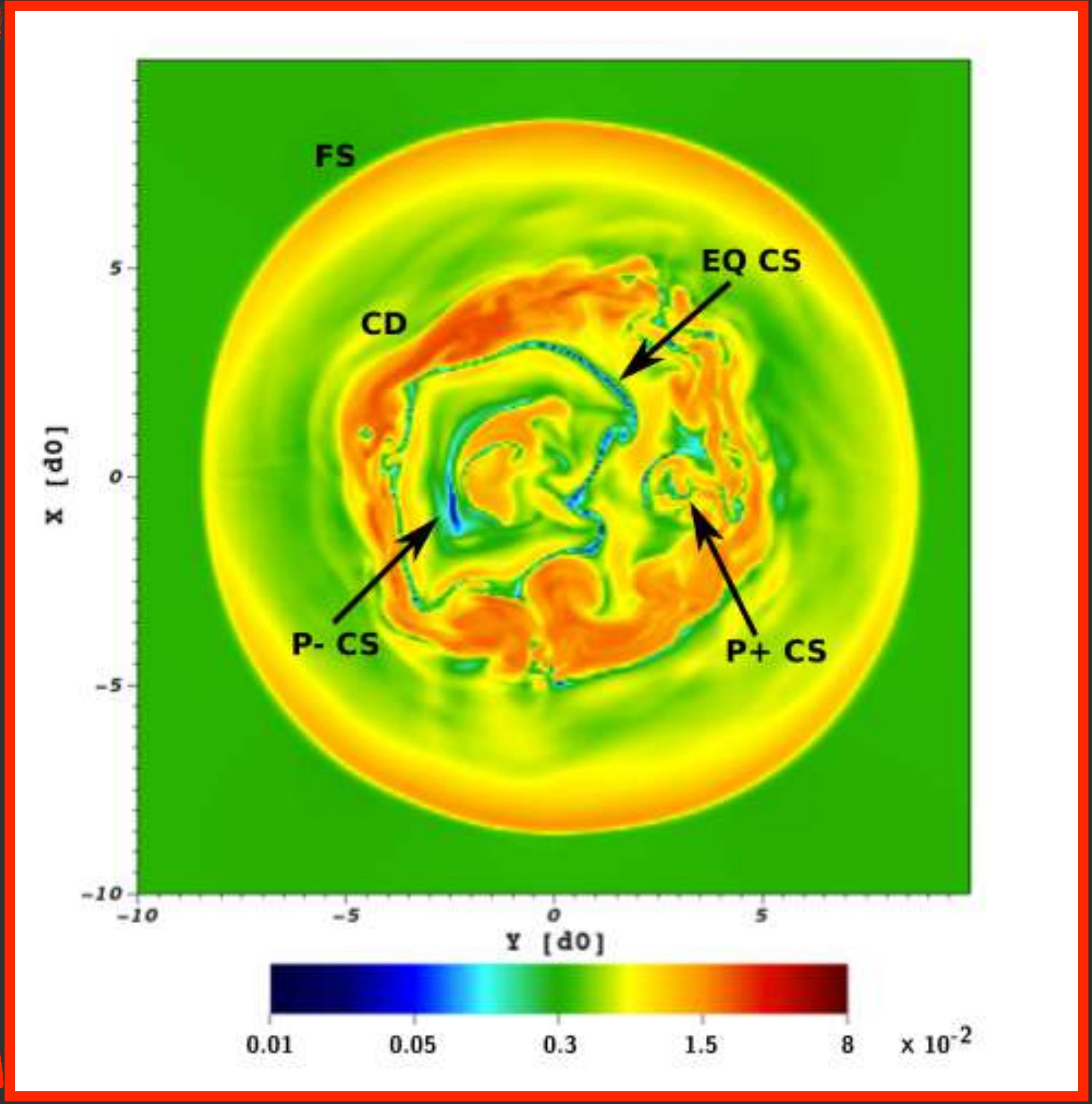
B ISM

$|B|=0.01\rho_{ISM}v_{PSR}\sim$ 3-5 μG

Olmi & Bucciantini 2019c

SURVIVAL OF CURRENT SHEETS IN THE TAIL

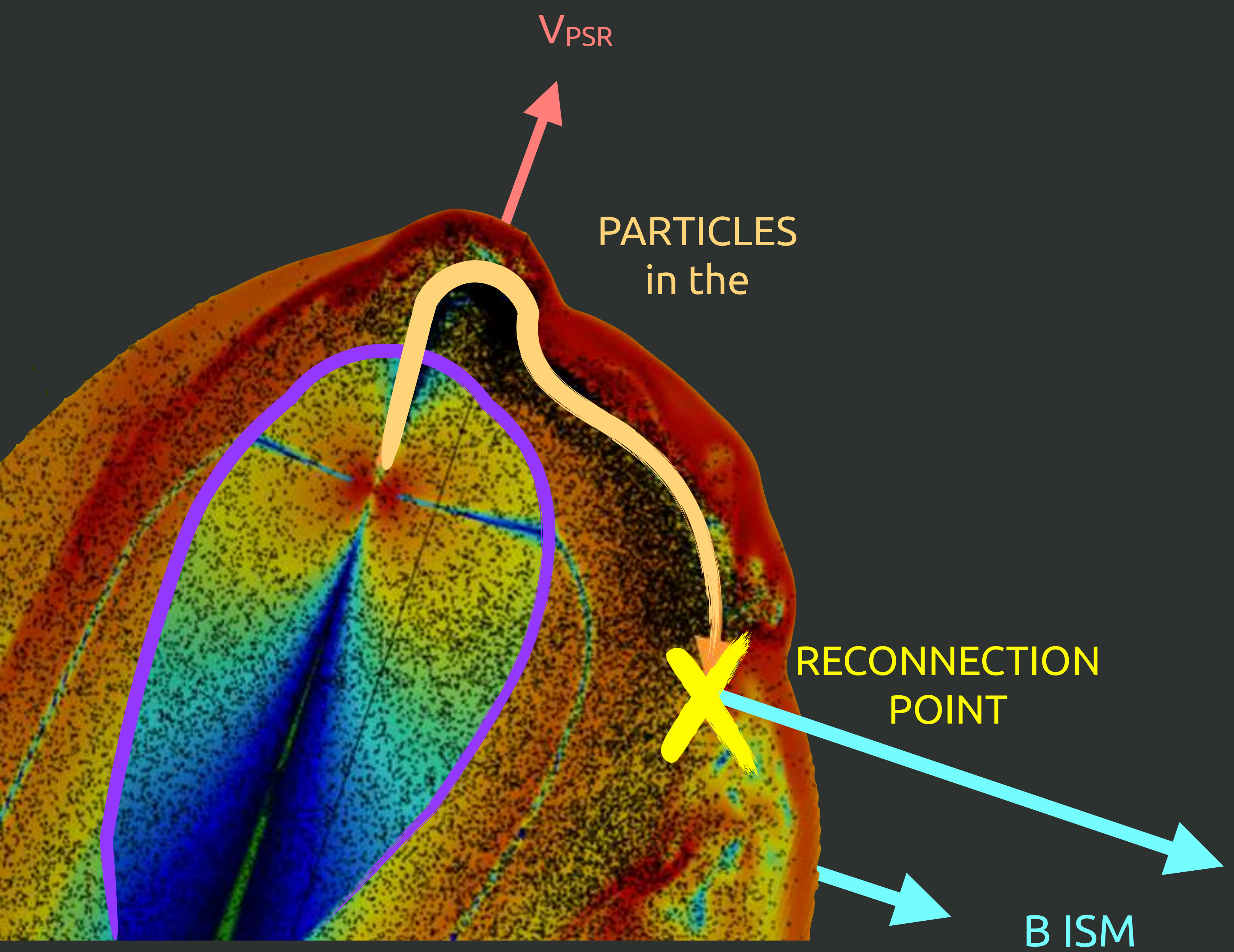




Olmi & Bucciantini 2019c

PARTICLES LEACKAGE

Particles remain confined in current sheets: those injected in the polar flow can escape at reconnecting points at the magnetopause, efficiently jumping on external field lines.



[Barkov et al. 2019, Bucciantini 2018, Olmi & Bucciantini 2019c]

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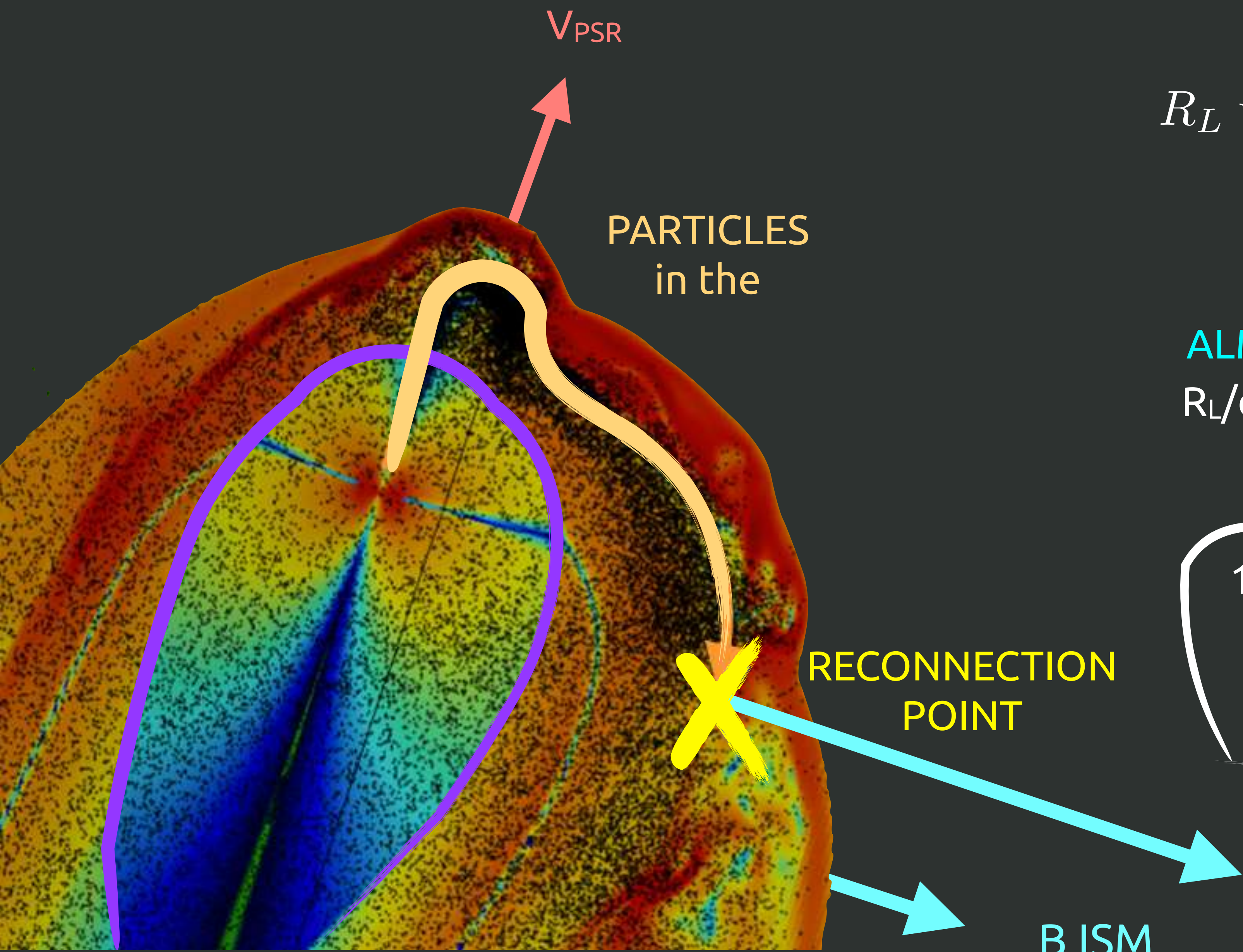


ESCAPE EFFICIENCY

$$R_L \text{ vs } \mathrm{d_0} = \sqrt{\dot{\mathrm{E}}/(4\pi \mathrm{c} \rho_{\mathrm{ISM}} \mathrm{v}^2_{\mathrm{PSR}})} \sim 10^{16}\,\mathrm{cm}$$

ALMOST 0

$R_L/d_0 \lesssim 0.1$

HIGH

$R_L/d_0 > 0.1$

ENERGY of ESCAPING PARTICLES

1 TeV — 10 TeV — 10ns of TeV

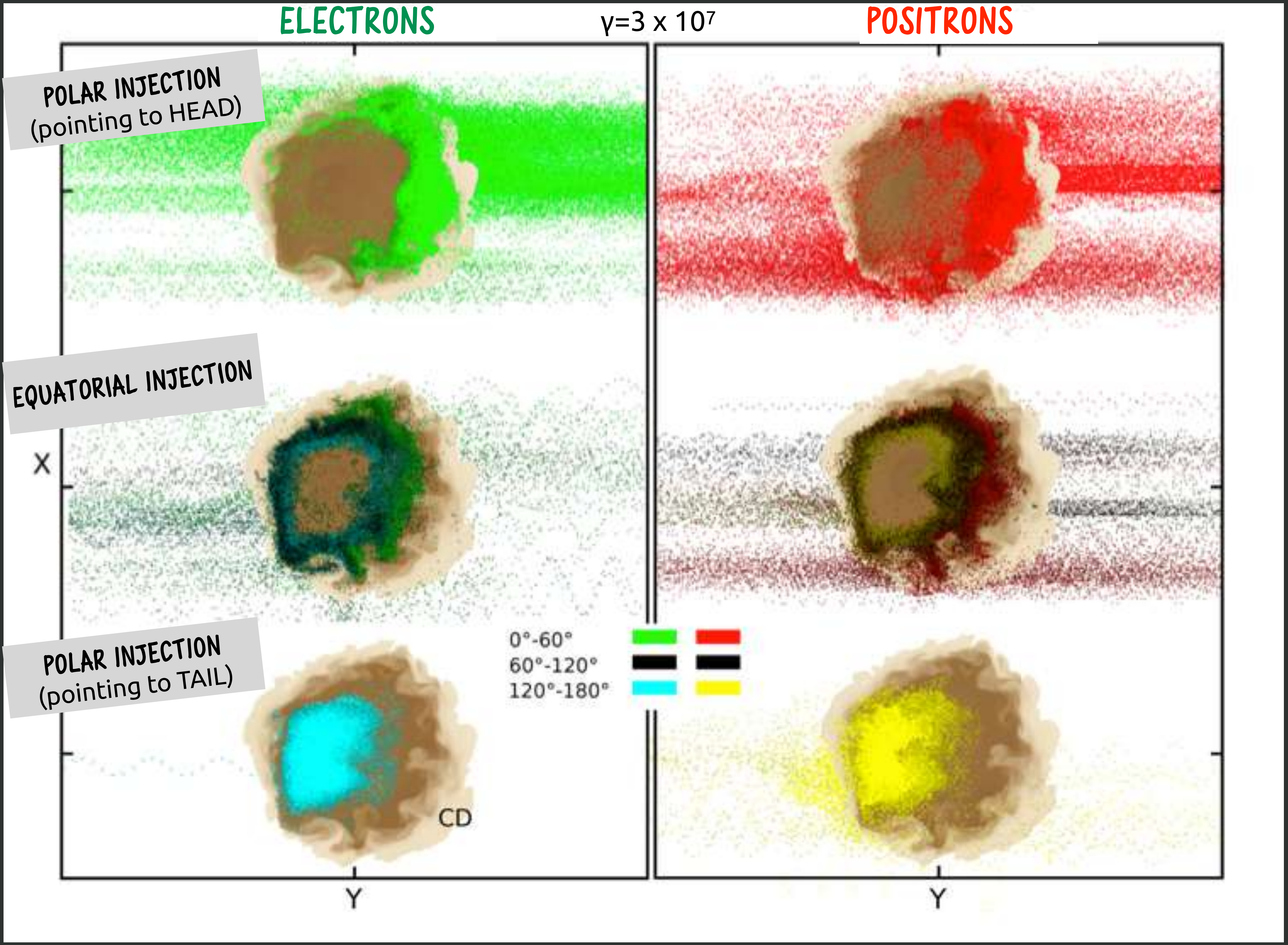
← confinement

escape →

[Barkov et al. 2019, Bucciantini 2018, Olmi & Bucciantini 2019c]

PARTICLES LEAKAGE IS CHARGE DEPENDENT AND ASYMMETRIC

Particles escape as seen from tail:



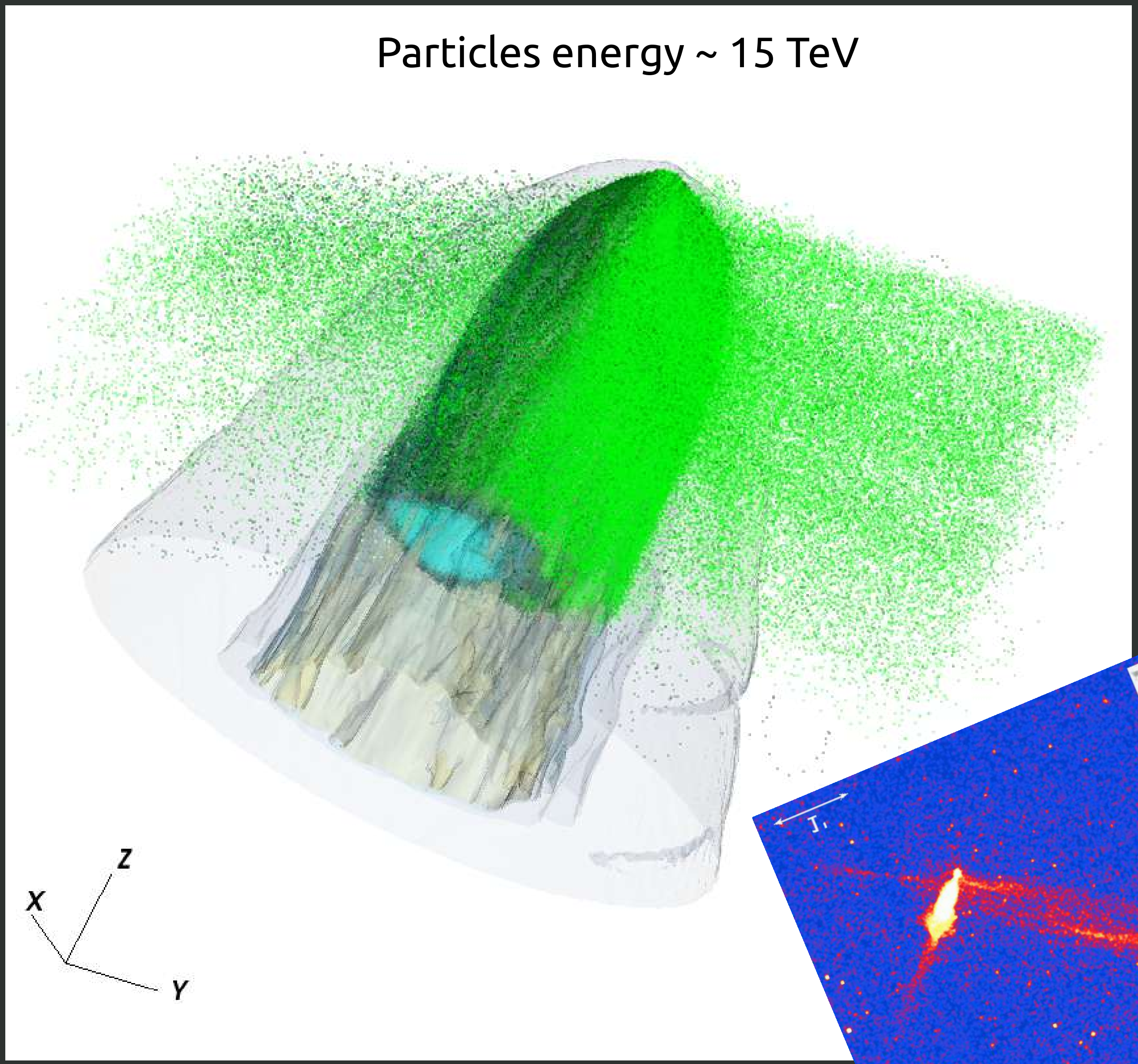
ESCAPE IN LARGE FRACTIONS

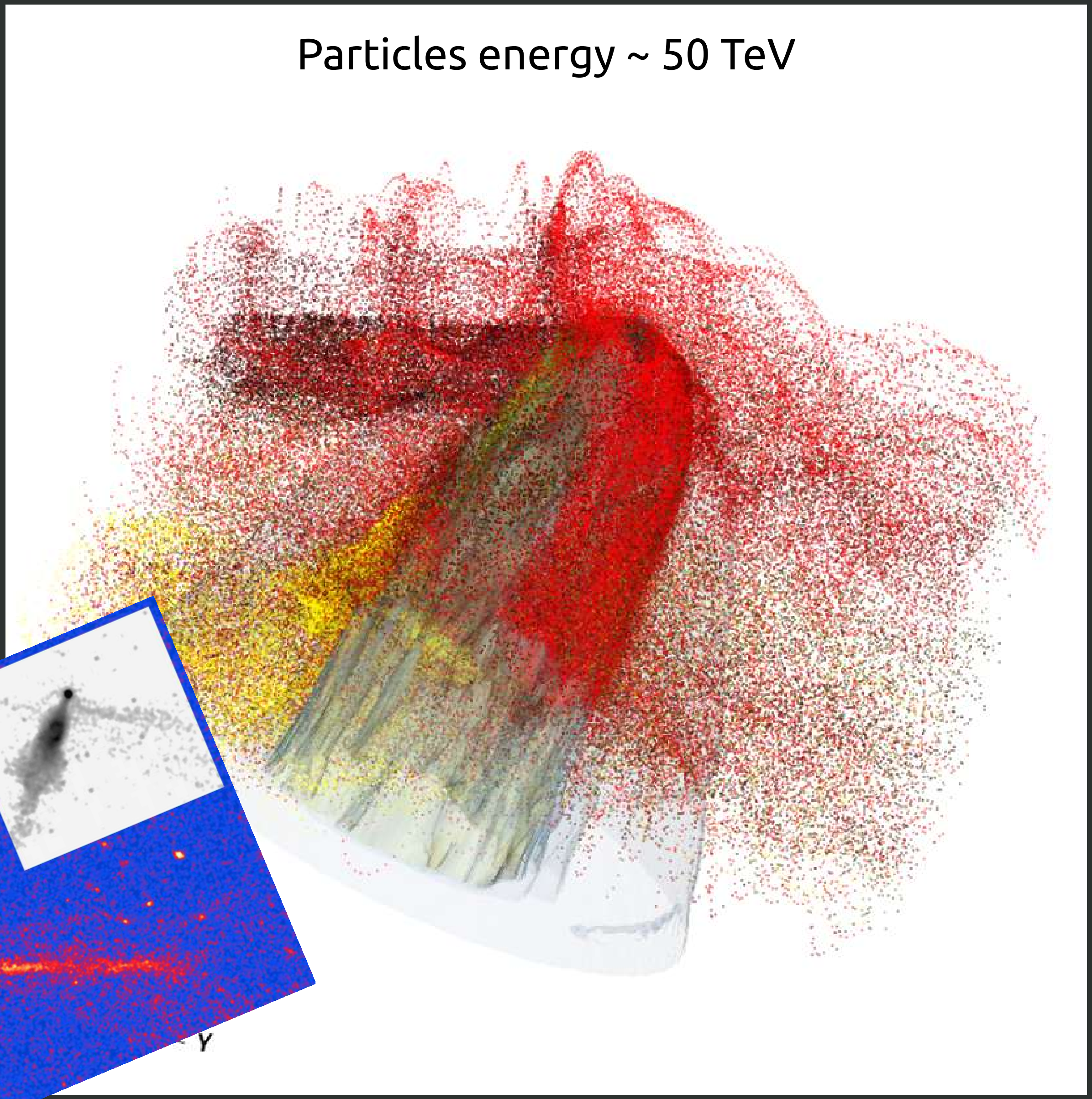
PARTLY CONFINED

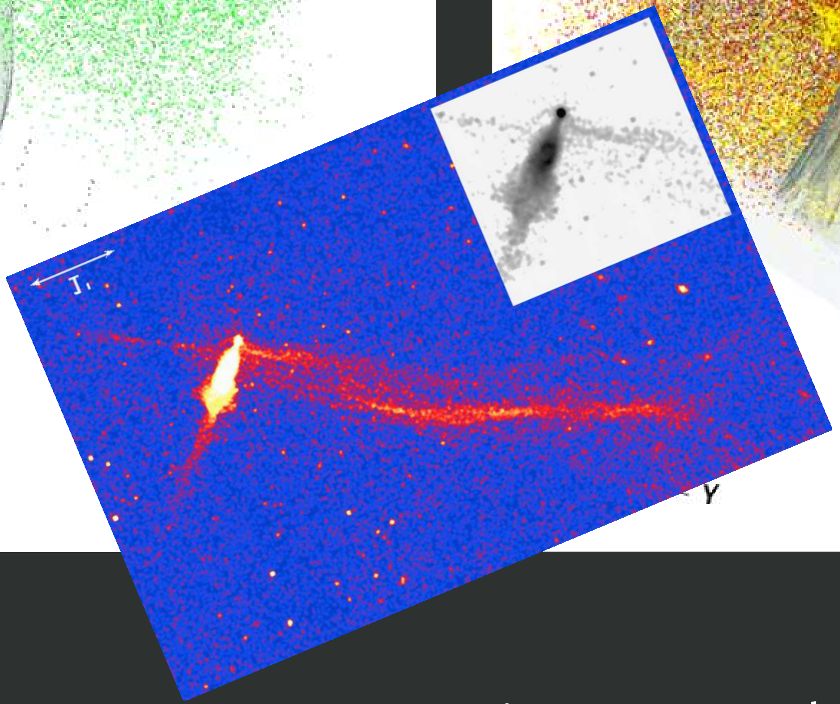
HIGHLY CONFINED

Olmi & Bucciantini 2019c

FORMATION OF JETS OR HALOS







[Olmi & Bucciantini 2019c]

Particles can efficiently escape from BSPWNe + escape is energy and charge dependent:

- sporadic escape of LOW ENERGY particles through reconnection points between PWN and ISM B field. Escape strongly asymmetric (depeding on the system geometry). The charge asymmetry is small (~10%).

- HIGH ENERGY particles enter a diffusive regime when r_L ~ thickness of the current sheet. Now the escape flow is less asymmetric but strongly charge separated.

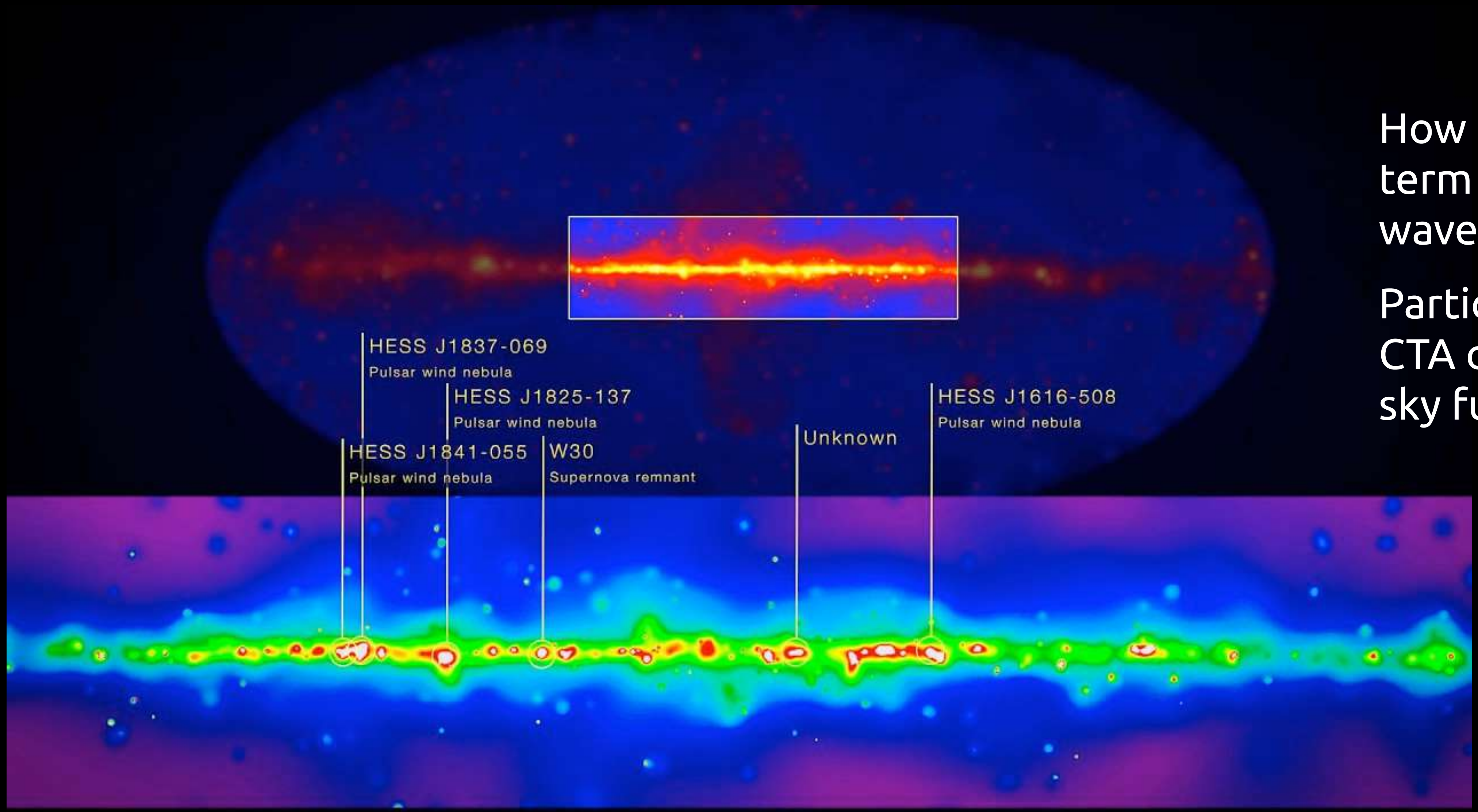
CONCLUSIONS

MULTI-D MHD simulations have shown to be successful at accounting of many properties of PWNe, but:

Magnetic field can be realistically modeled ONLY in 3D → Huge computational efforts

2D MHD simulations are less demanding → Can realistically describe ONLY the inner nebula, but down to fine details

The very missed part: evolution of particles spectra together with dynamics



How could we model long term evolution + multi-wavelengths emission?

Particularly relevant with CTA coming -> Gamma ray sky full of PWNe!