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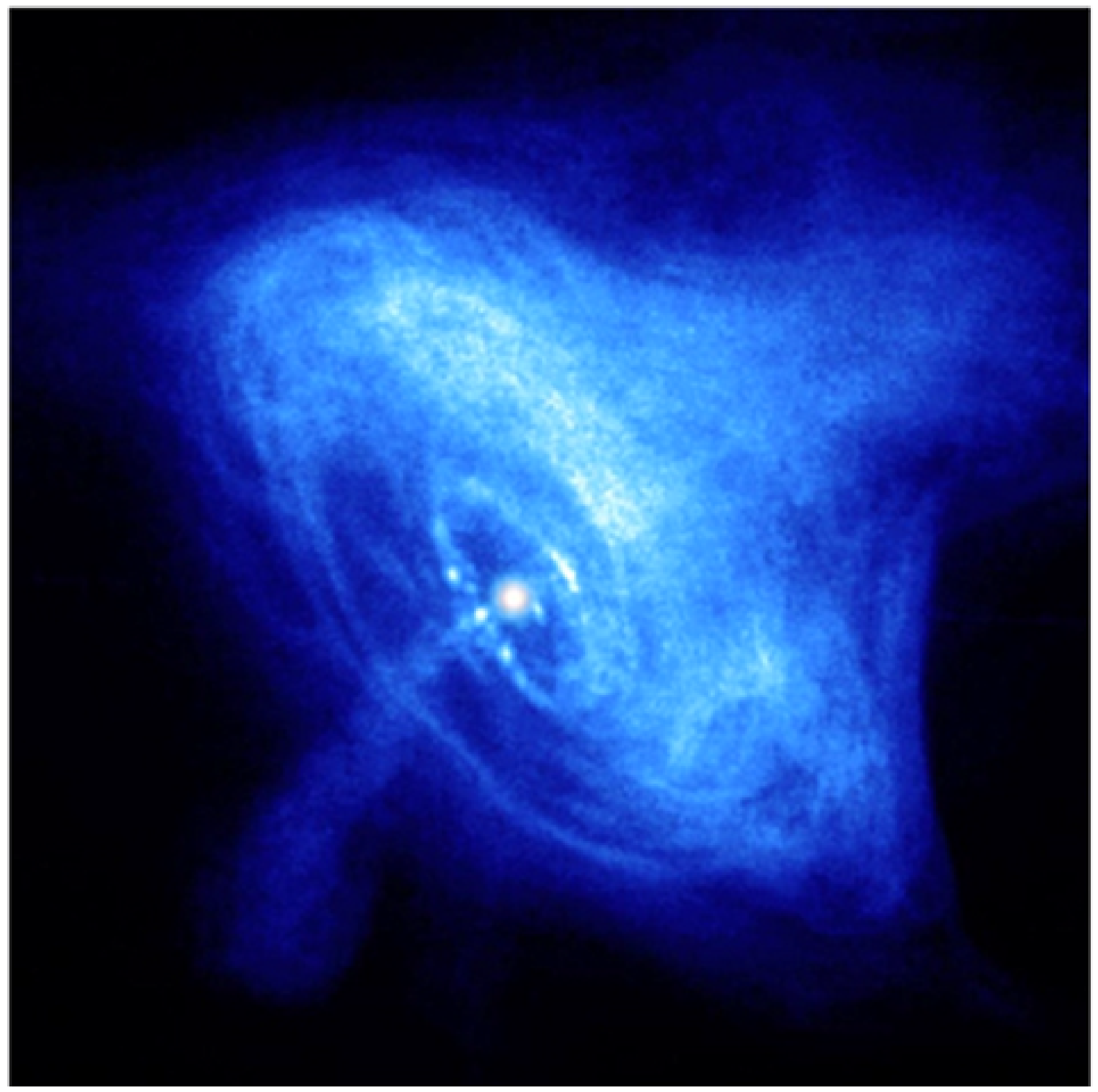
Double-torus pulsar wind nebulae as sources of high energy particles and radiation

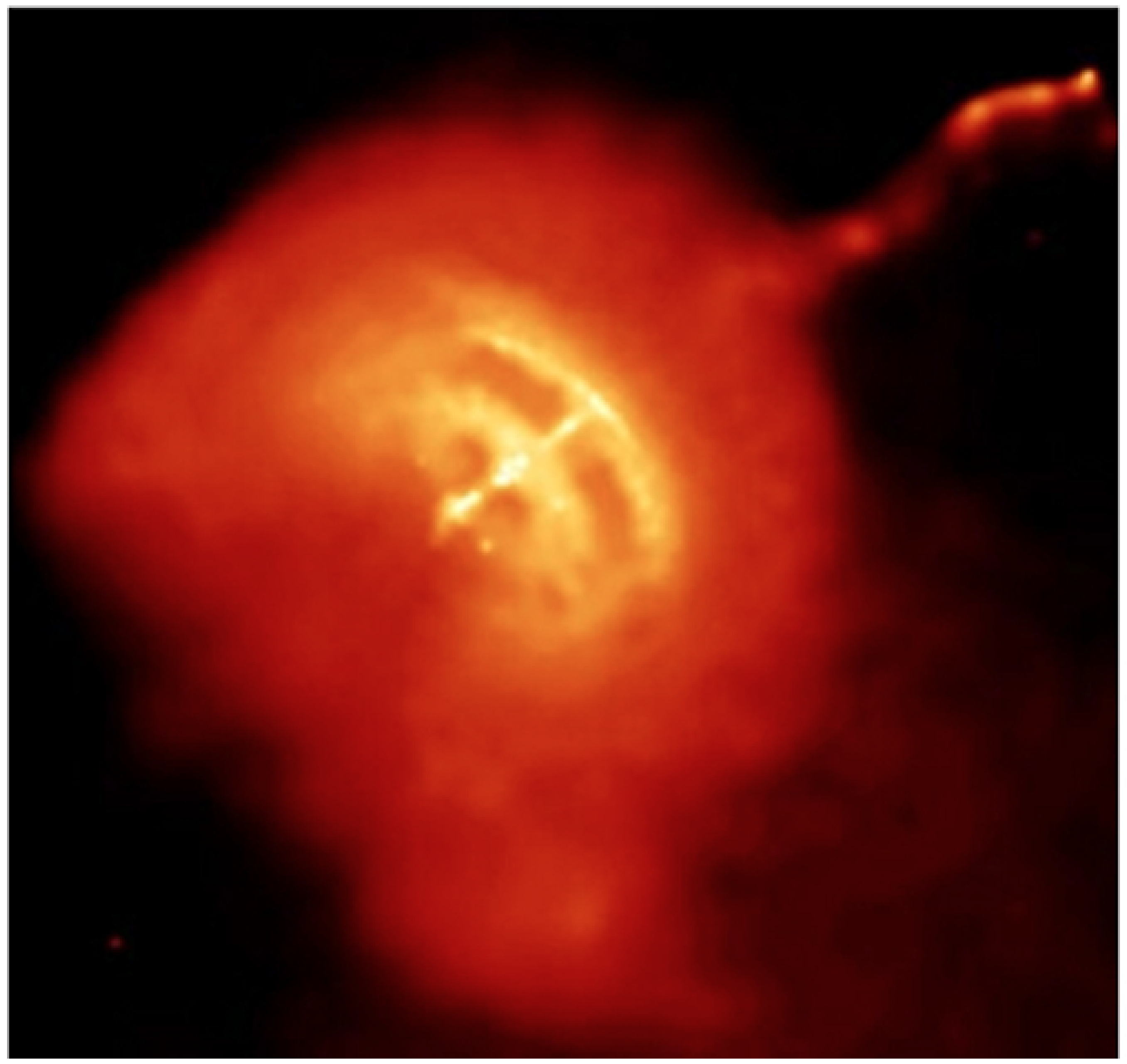
Yerevan, 19.06.2026

What is a pulsar wind nebula?

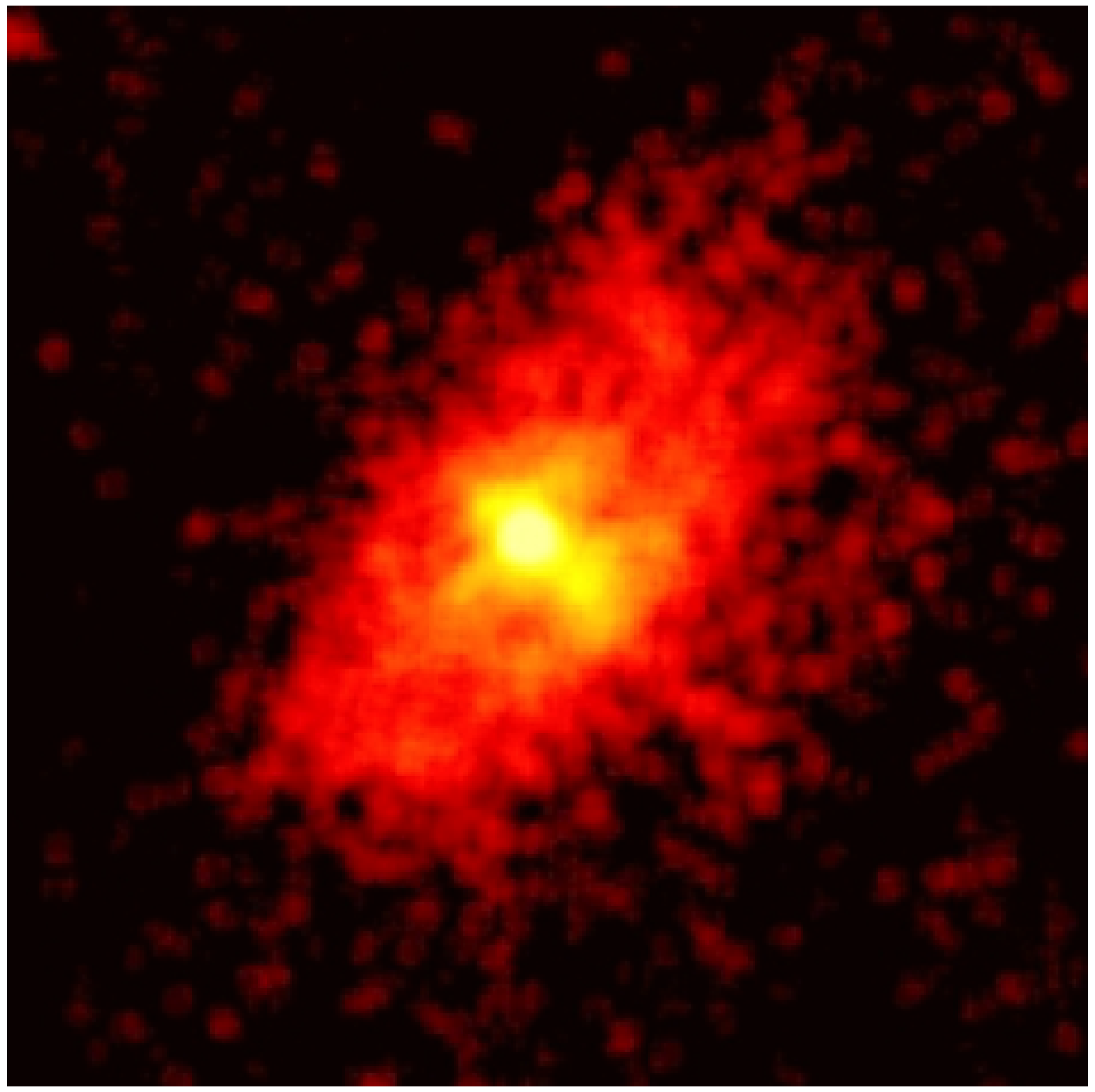
- A pulsar wind nebula (PWN) is a low-density bubble around a pulsar
- This bubble is filled with highly magnetized plasma of electrons and positrons supplied by the pulsar wind.
- A nebula forms through interaction of the wind with the surrounding matter and is powered at the expense of the pulsar's rotational energy



Crab nebula
Hester+2002



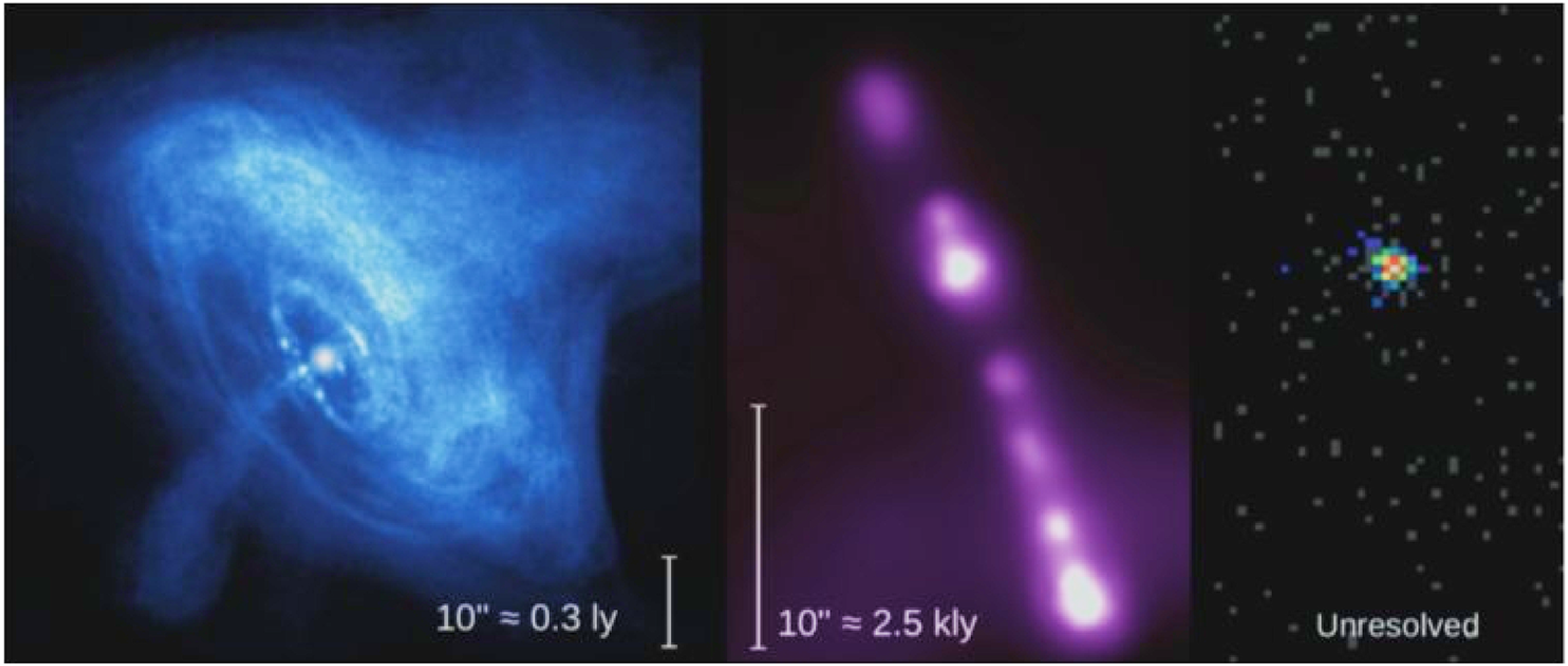
Vela nebula
Pavlov+2003



Dragonfly nebula
Van Etten+2008

Galactic PWNe as the most suitable sources for studying relativistic plasma

- can be spatially resolved in fine details
- emit across all energy ranges,
- highly dynamic and have a very complex pattern of MHD flow
- exhibit a wide variety of MHD structures
- can be subsonic and supersonic

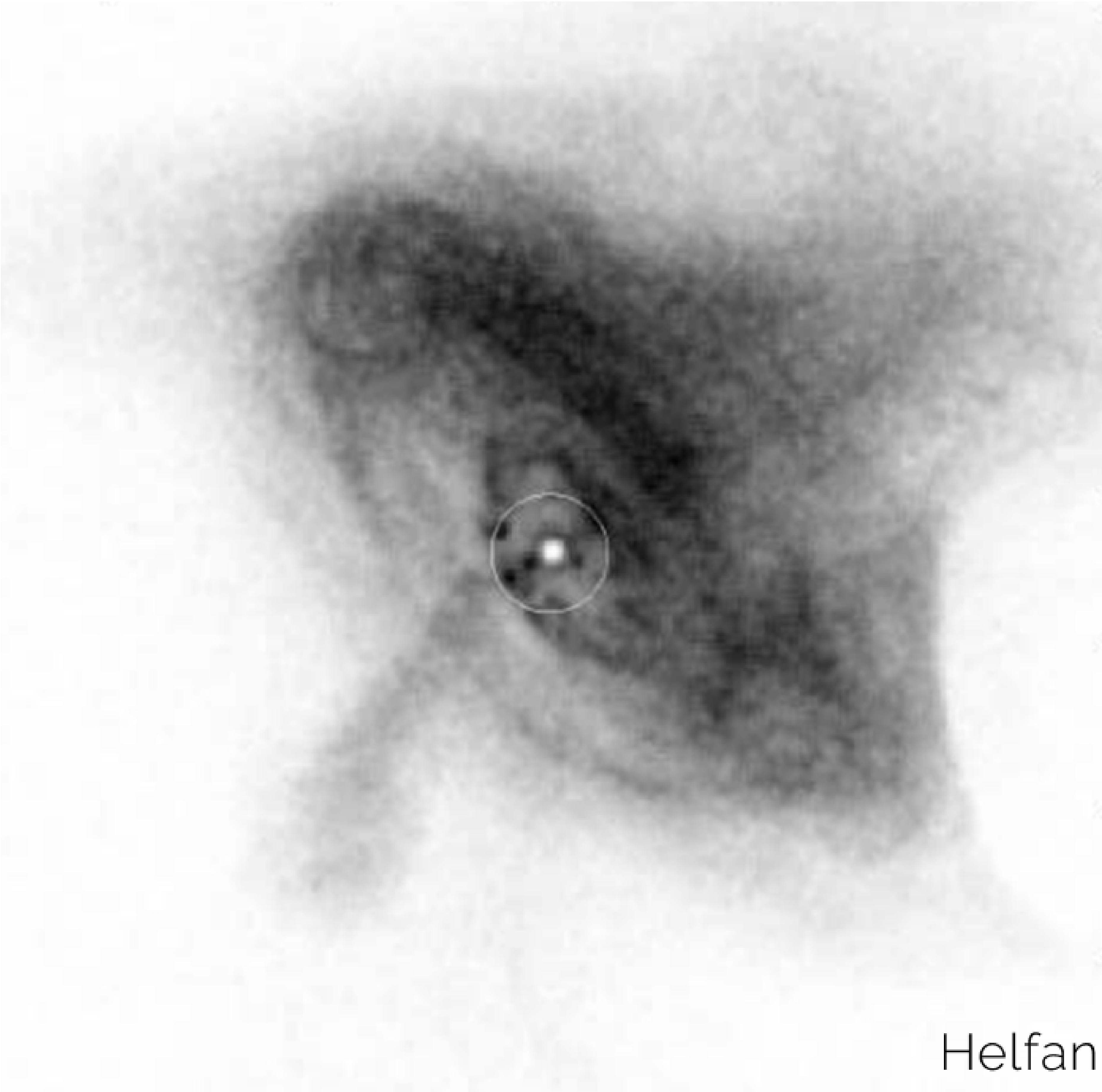


Left to right: Crab nebula, AGN M87, GRB 991216

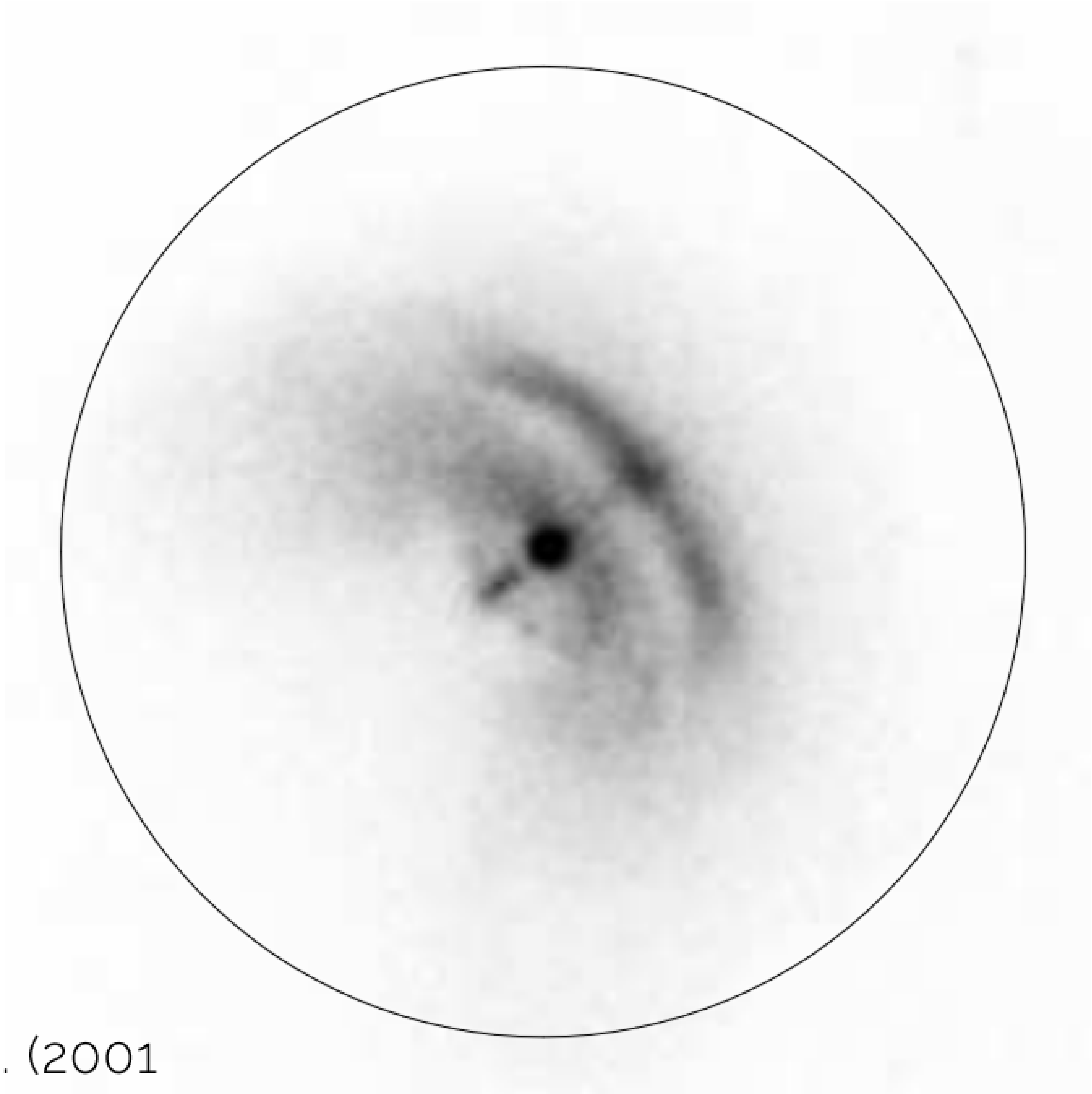
Fig. from Porth+2017
Images: NASA/CXC/ASU/J. Hester et al./E.Perlmanet al./L.Piro et al.

Most finely resolved nebulae: Crab and Vela

Crab



Vela



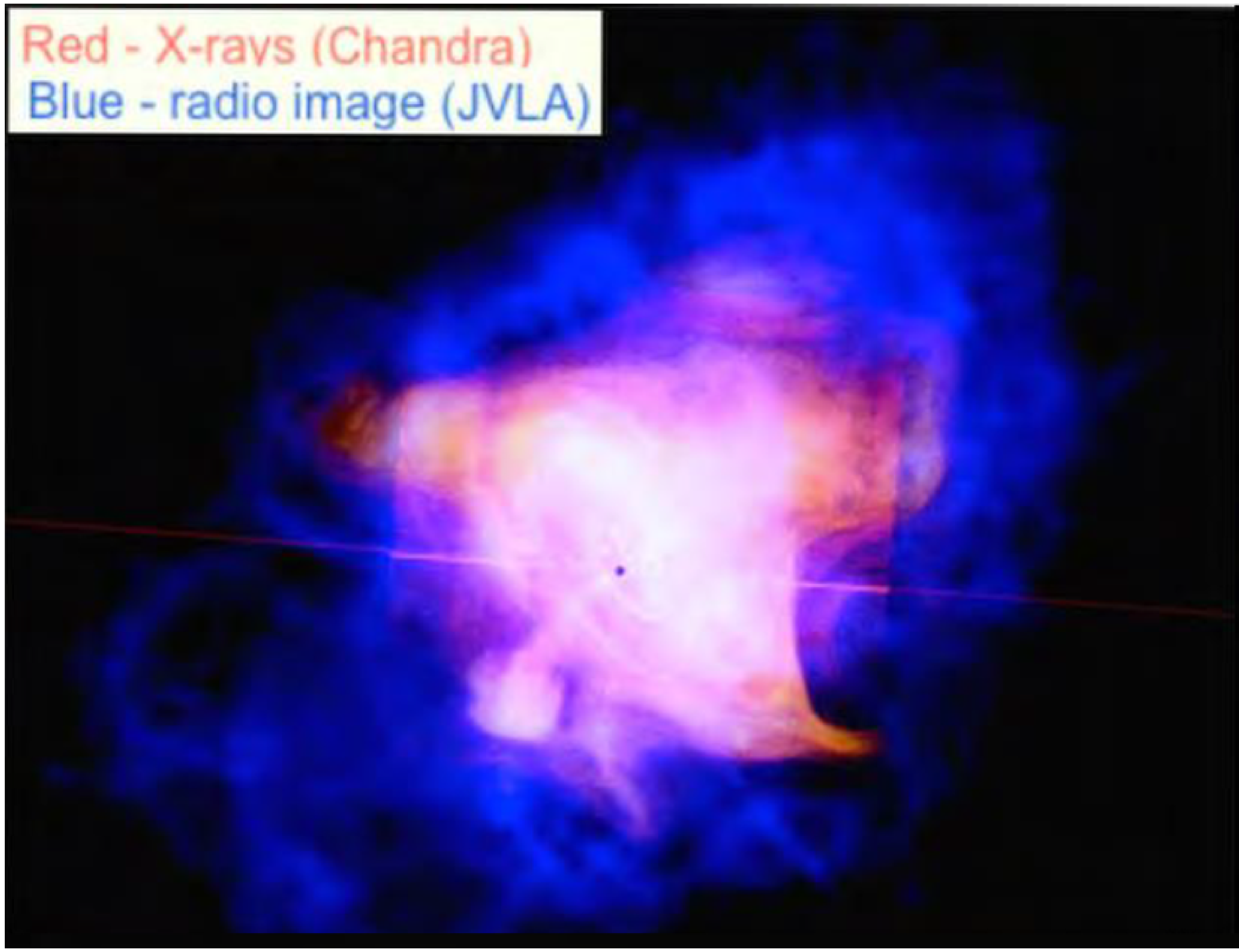
Helfand et al. (2001
Chandra HRC images (0.1 - 10 keV))

single torus

double torus

Large and compact nebulae

Crab



Vela

Kargaltsev et al. (2015)

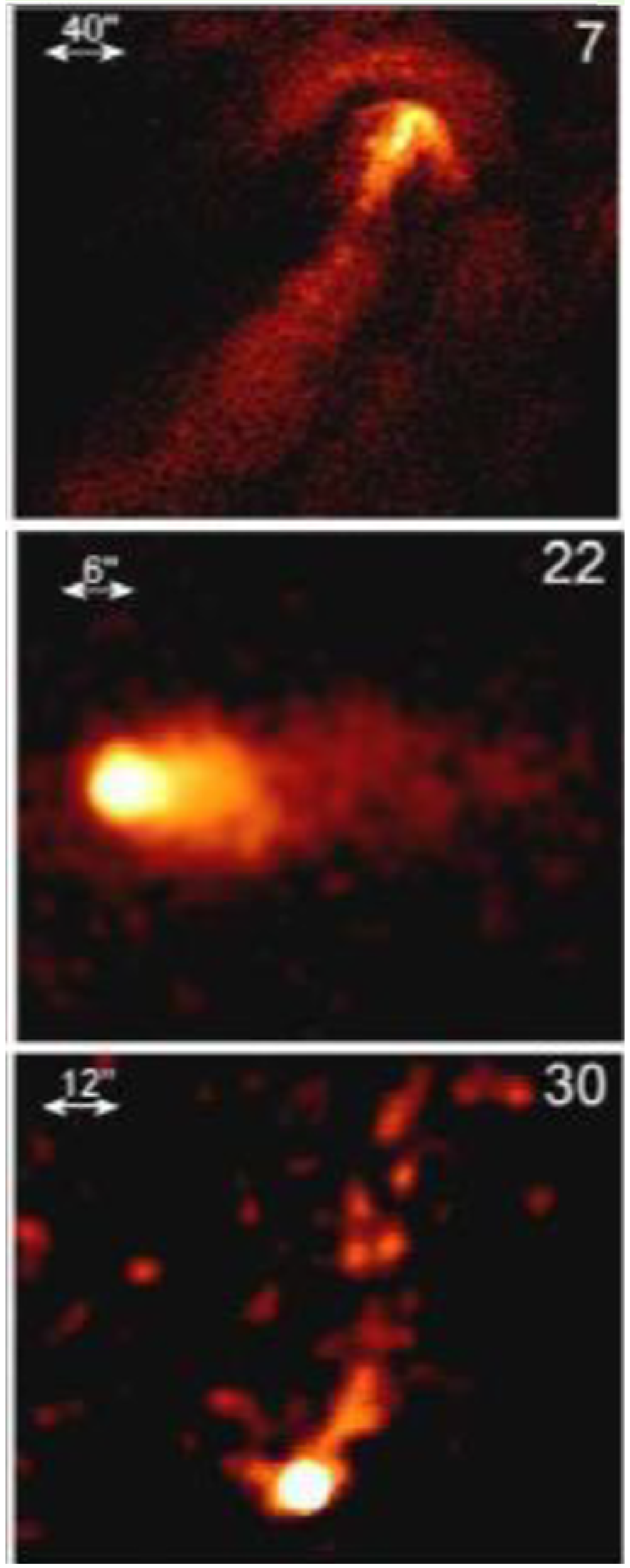
the inner **(compact)**, X-ray-bright nebulae
are the most efficient particle accelerators

compact -- in red

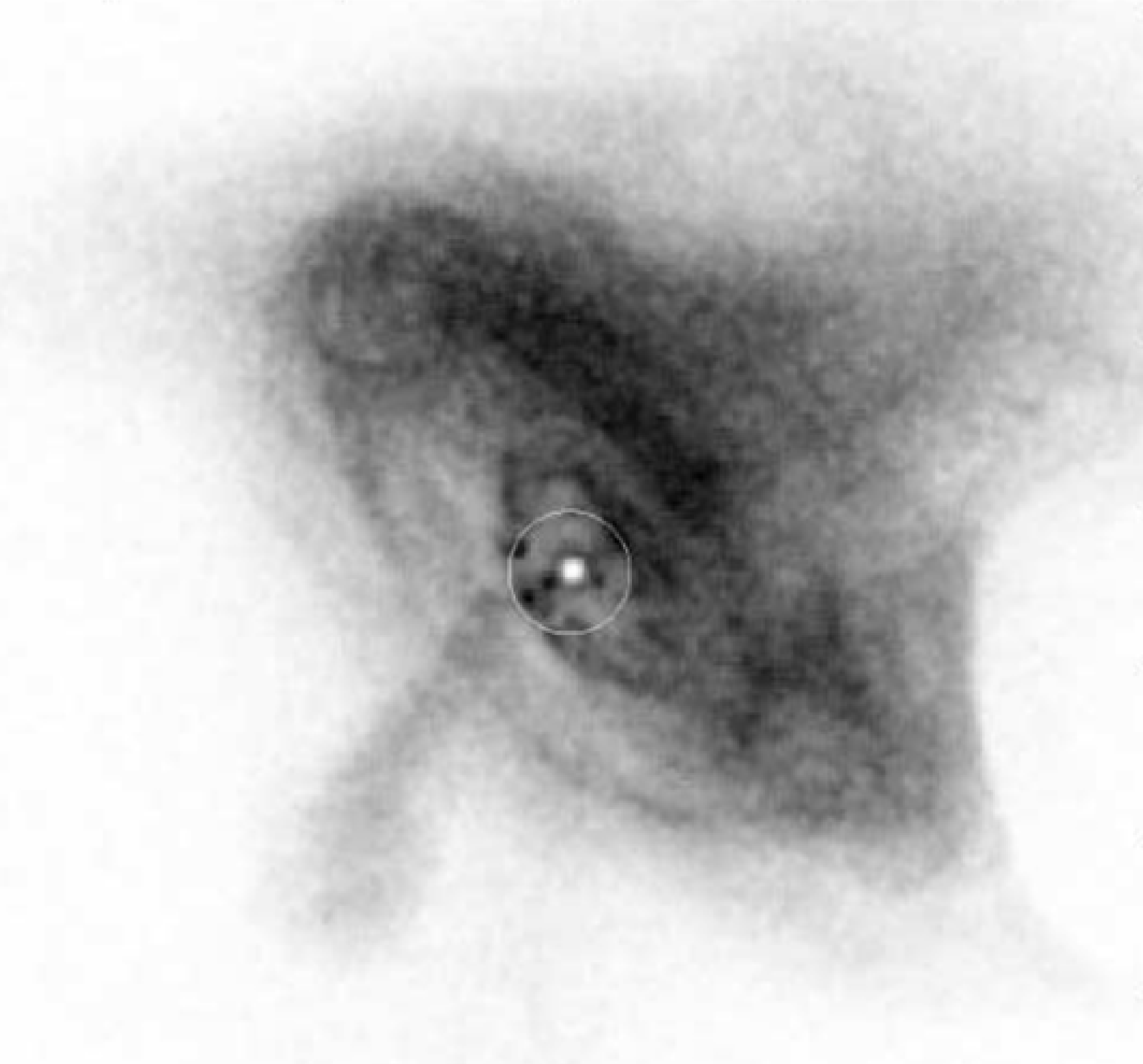
large -- in blue

Three general types of X-ray nebulae

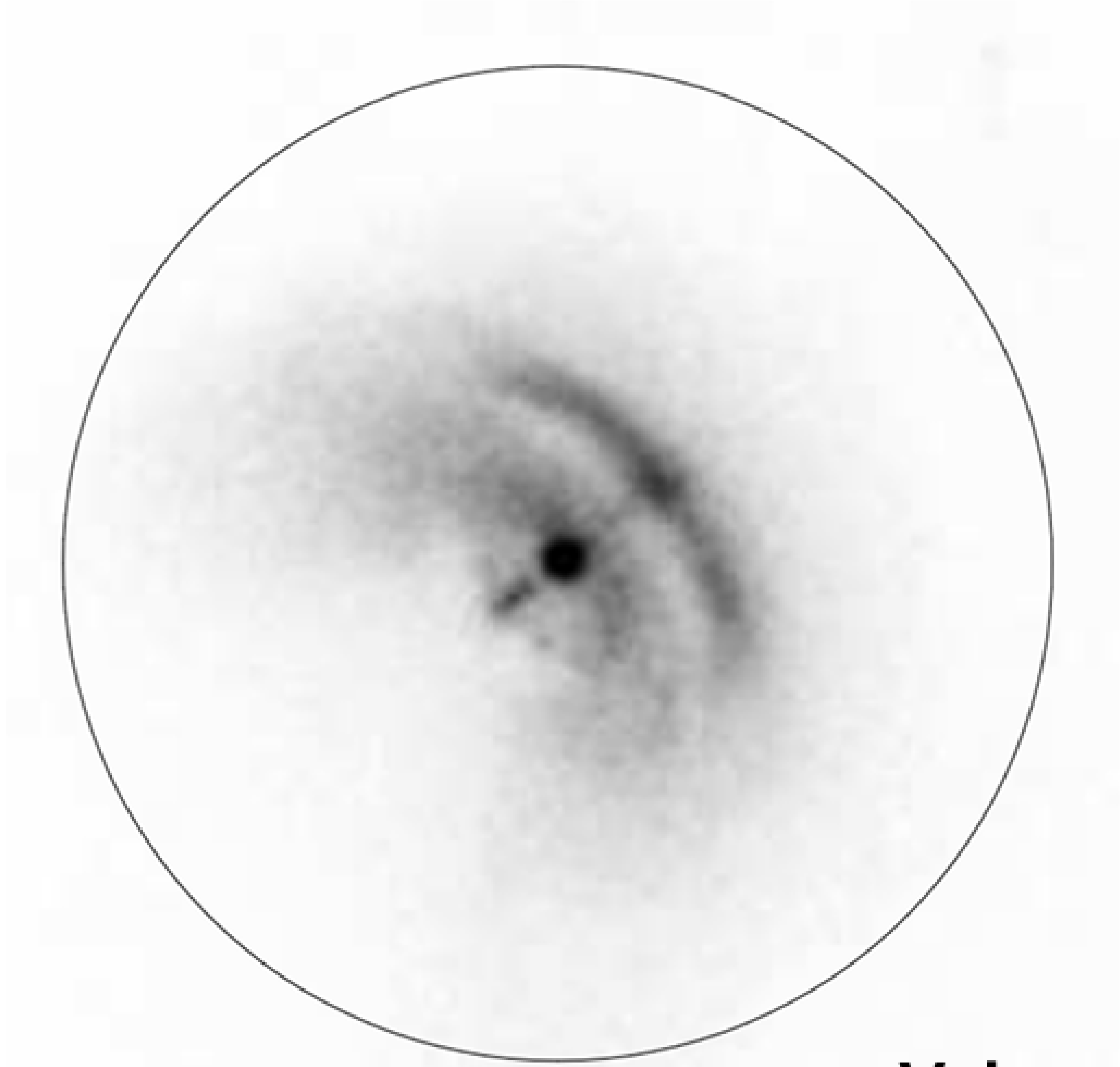
- **single-torus** - like Crab
- **double-torus** - like Vela
- **cometary** - like those around highly supersonic pulsars



Kargaltsev & Pavlov (2008)

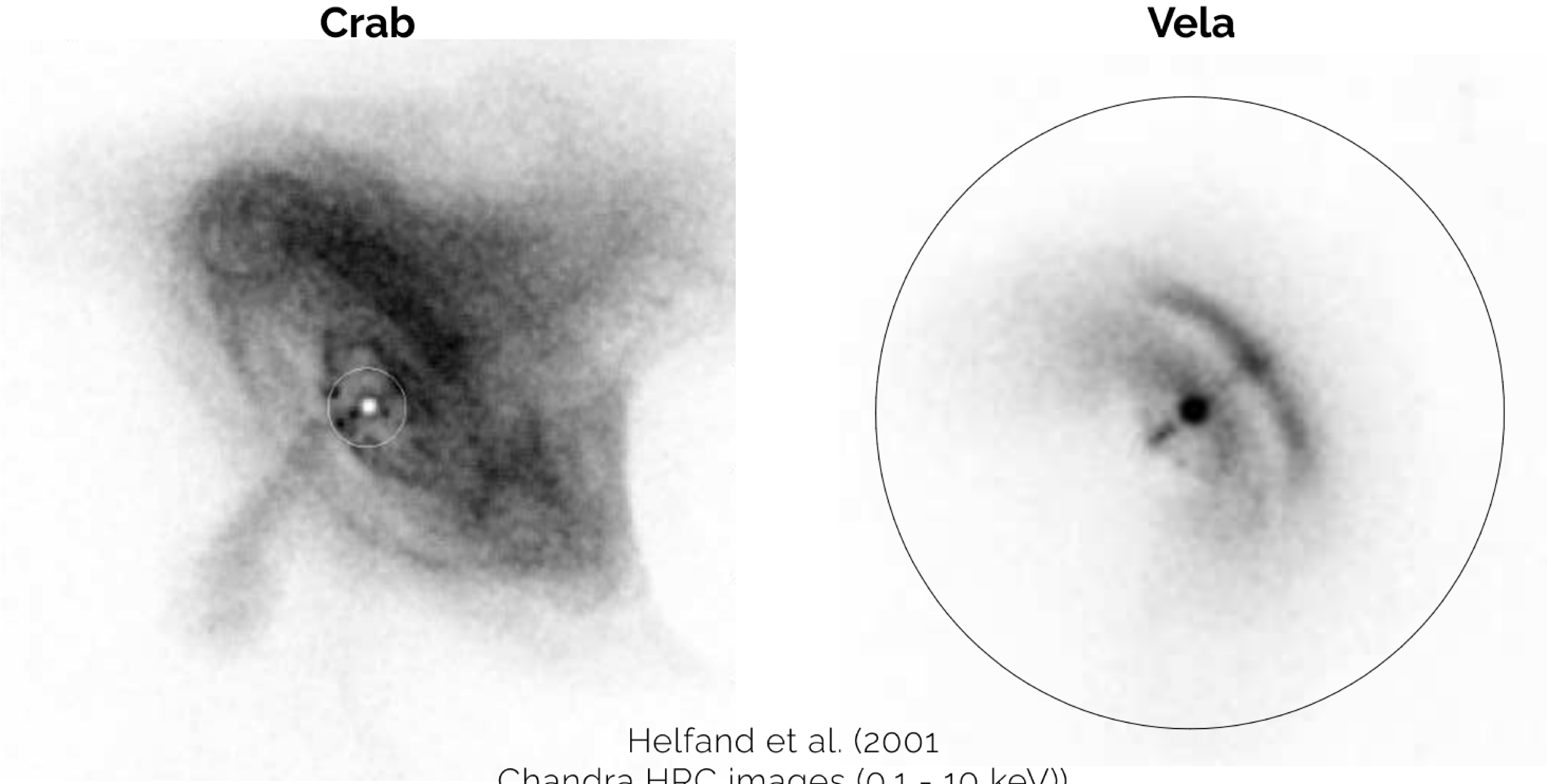


Helfand et al. (2001) **Crab**



Vela

Different X-ray morphologies: not a projection effect !

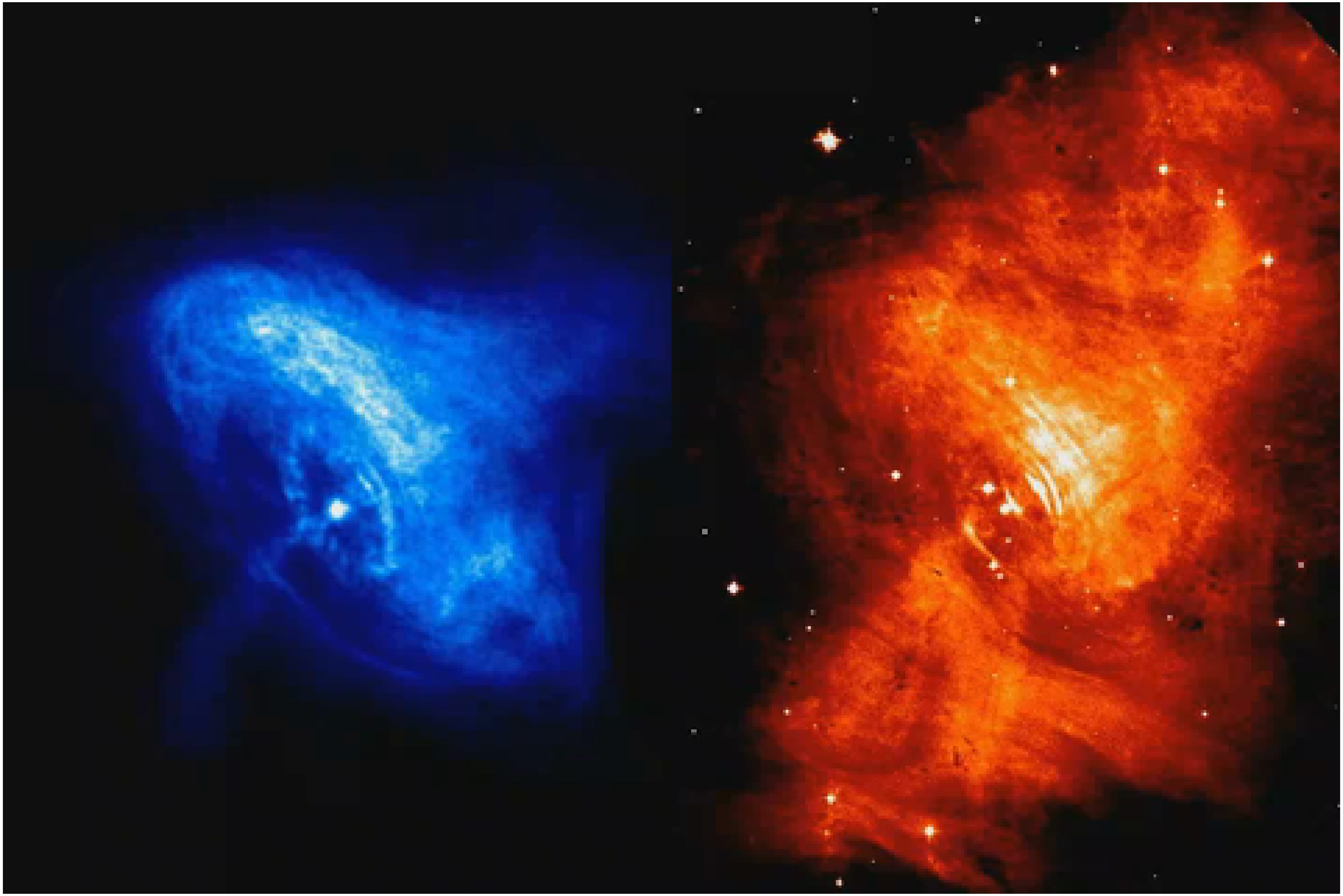


Helfand et al. (2001
Chandra HRC images (0.1 - 10 keV))

Crab and Vela:

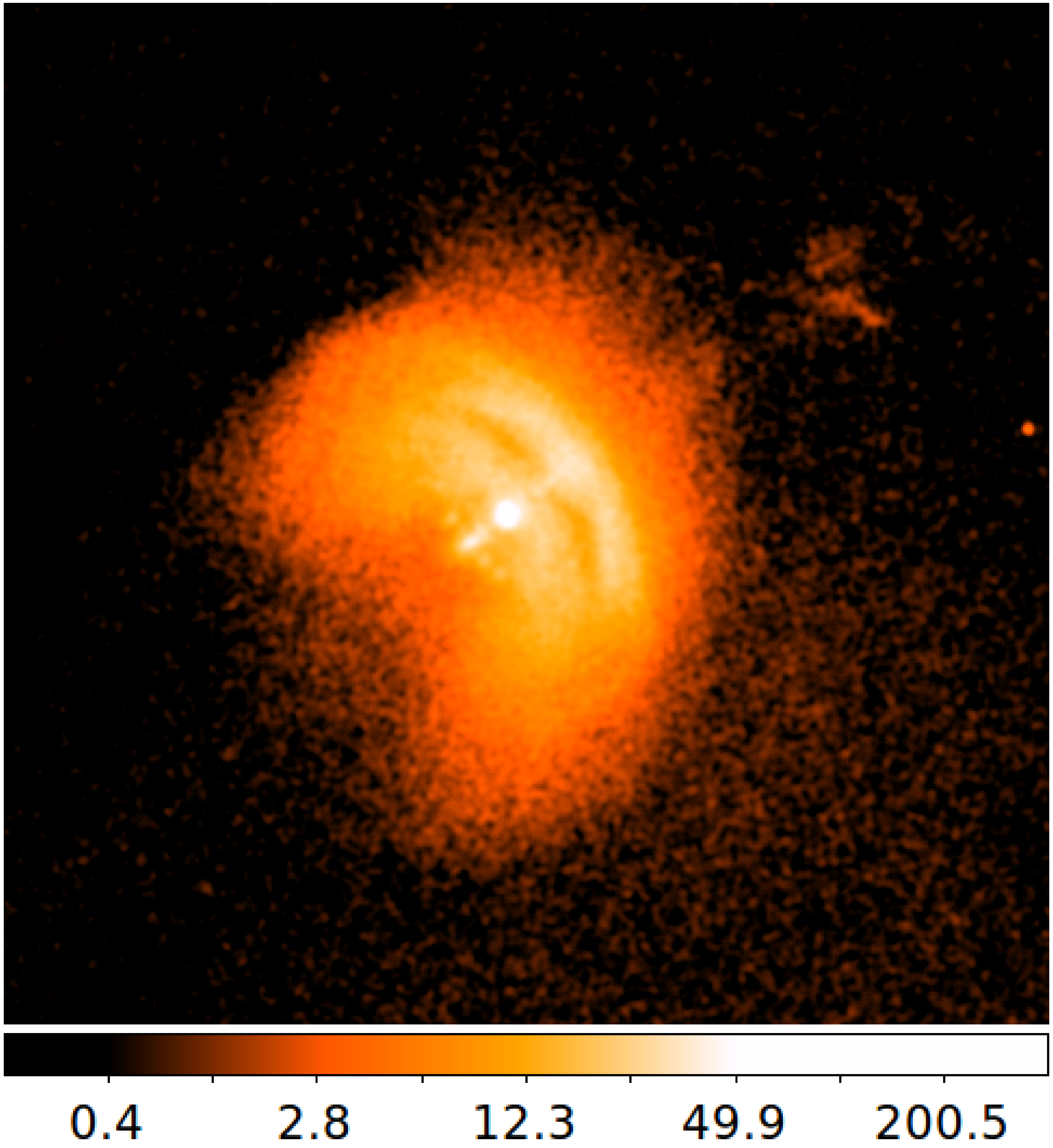
- seen in the same projection onto the celestial plane
- hence, their different X-ray appearances is not an effect of projection, but reflect **the different structure of their MHD flows**

Crab nebula dynamics

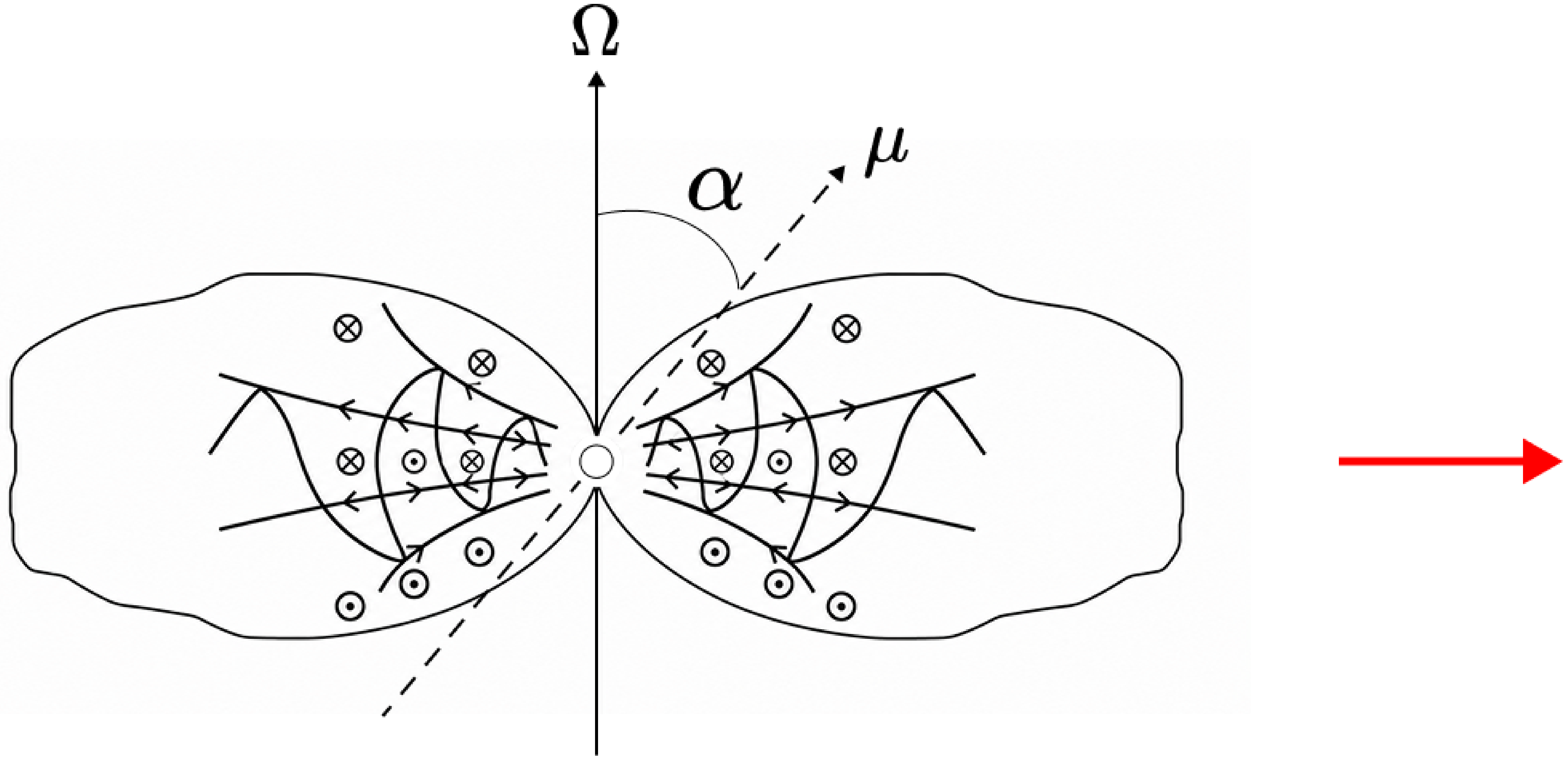


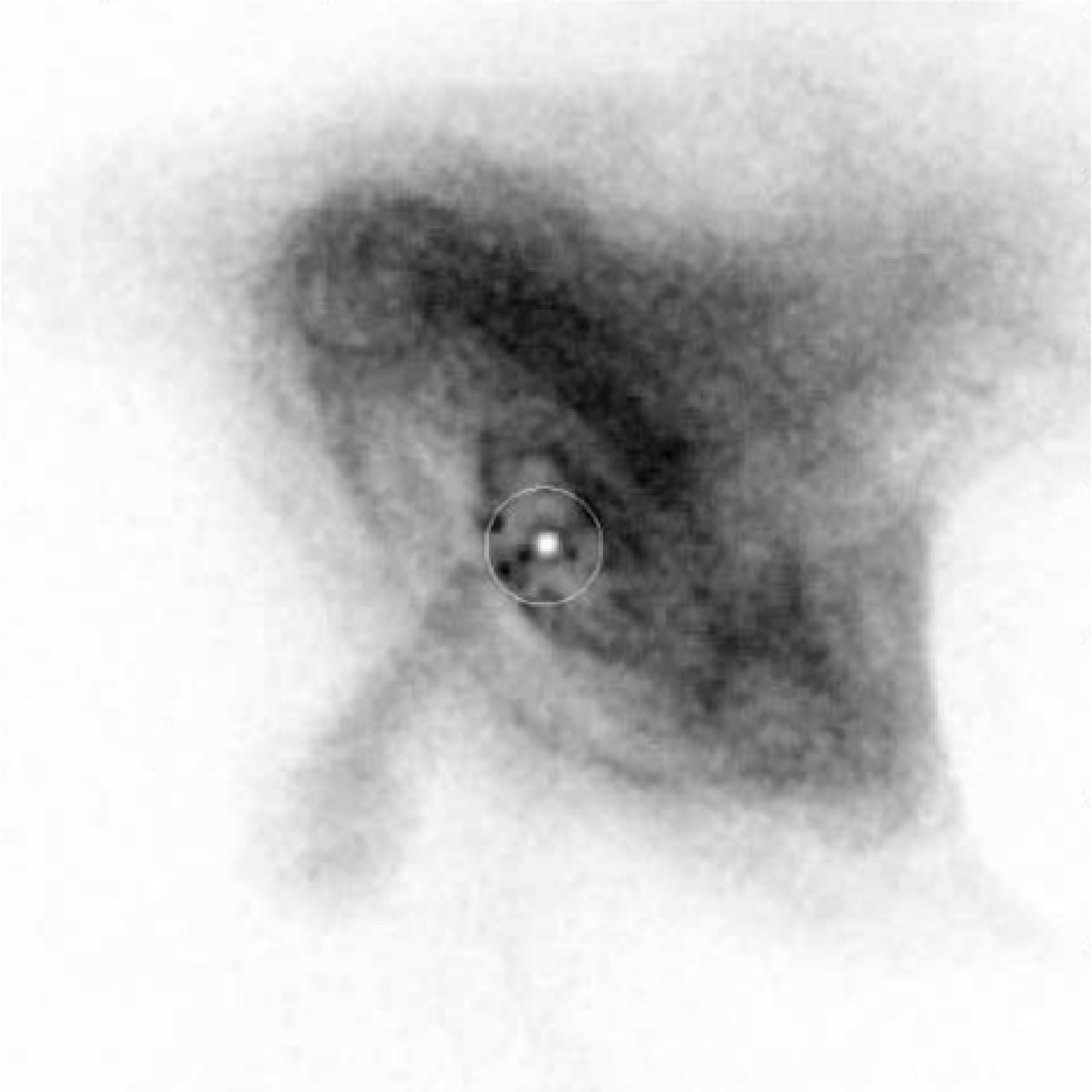
X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/HST/ASU/J.Hester et al.

Vela nebula dynamics

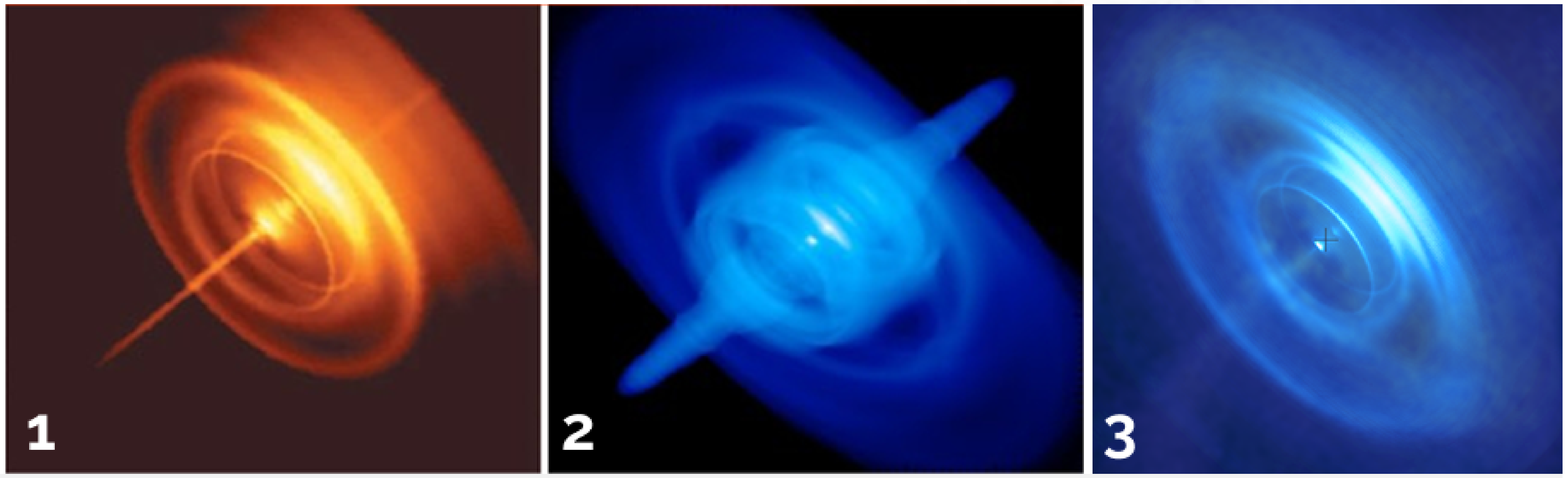


Canonical models of the Crab nebula



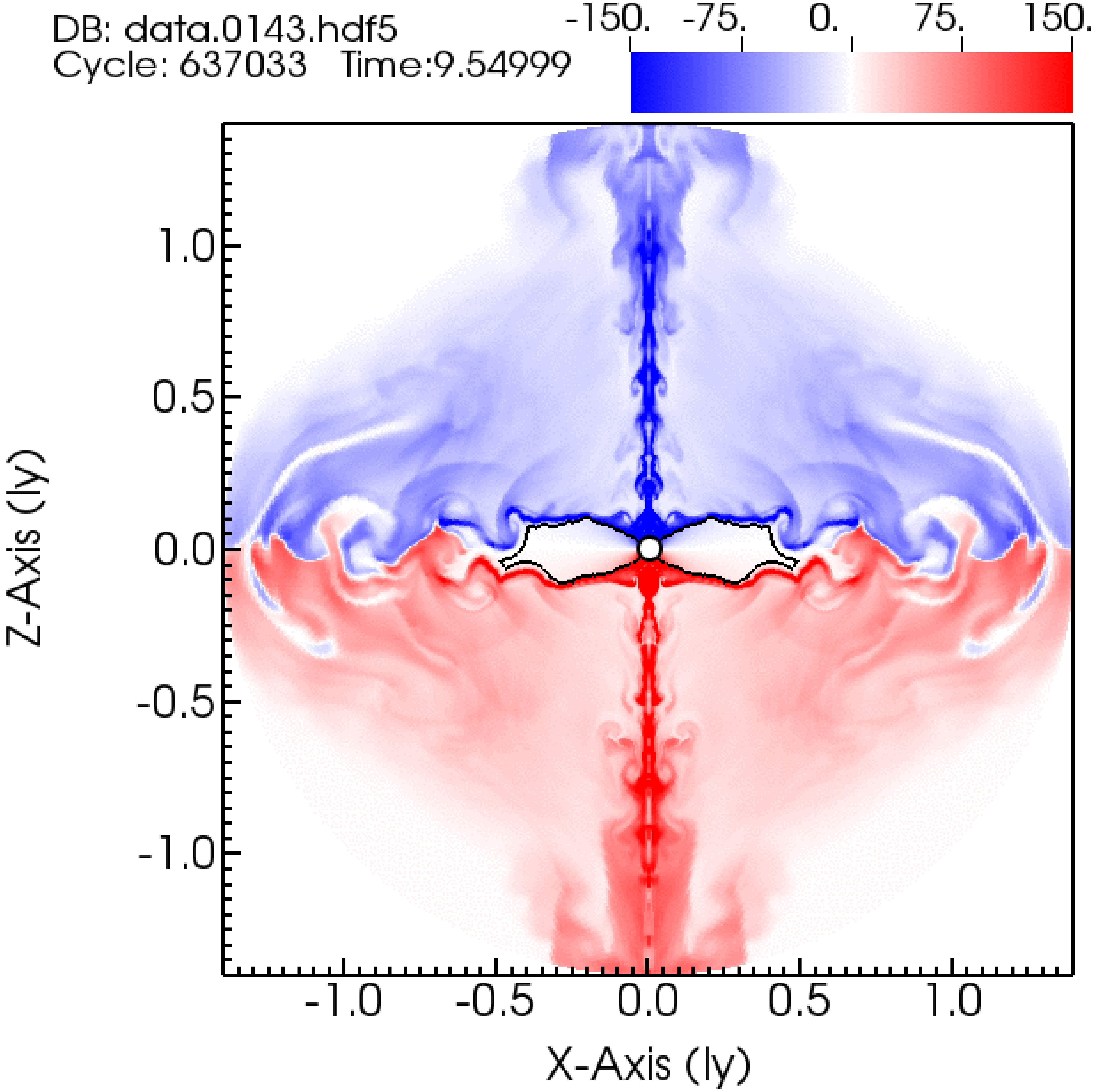


1. Komissarov & Lyubarsky, 2004
2. Del Zanna et al. 2006
3. Camus et al. 2009

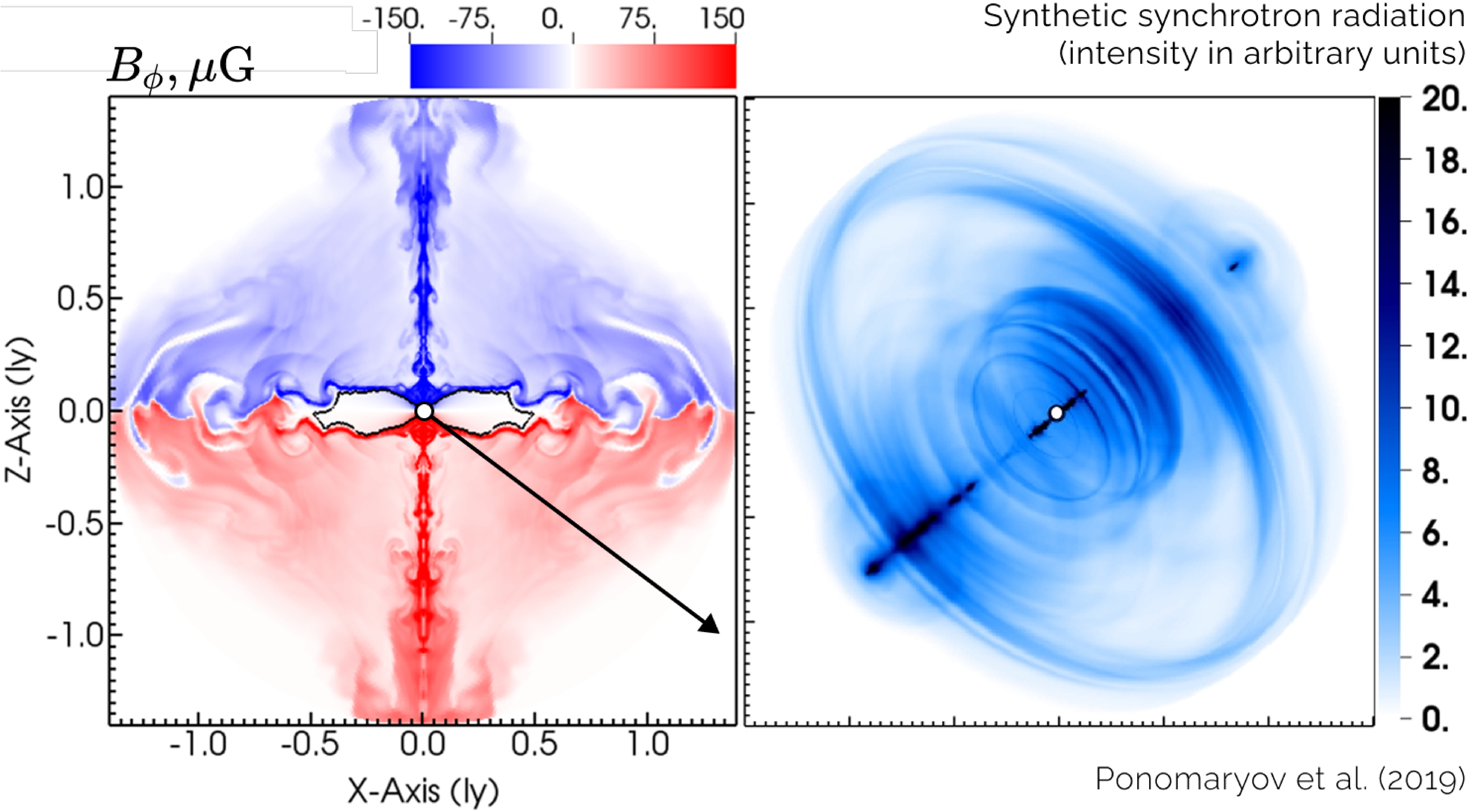


2002: Lyubarsky(2002), Bogovalov & Khangoulyan (2002a,b)
2004: del Zanna, Amato & Bucciantini (2004), Komissarov & Lyubarsky (2004)
2005 – 2006: Bogovalov+(2005), Bucciantini+(2005), del Zanna+(2006)
2008 – 2009: Volpi+(2008) Camus, Komissarov,+(2009)
2013 – 2016: Porth+('13,'14,'17), Olmi+('14,'15,'16), Mignone+(2013), Lyutikov+(2016), ...

Single torus model: dynamics



Single torus PWN model



Synthetic synchrotron radiation
(intensity in arbitrary units)

Ponomaryov et al. (2019)

$\alpha = 45^\circ,\ \sigma_0 = 3$

Numerical setup follows
Porth et al. (2014) and Bühler & Giomi (2016)

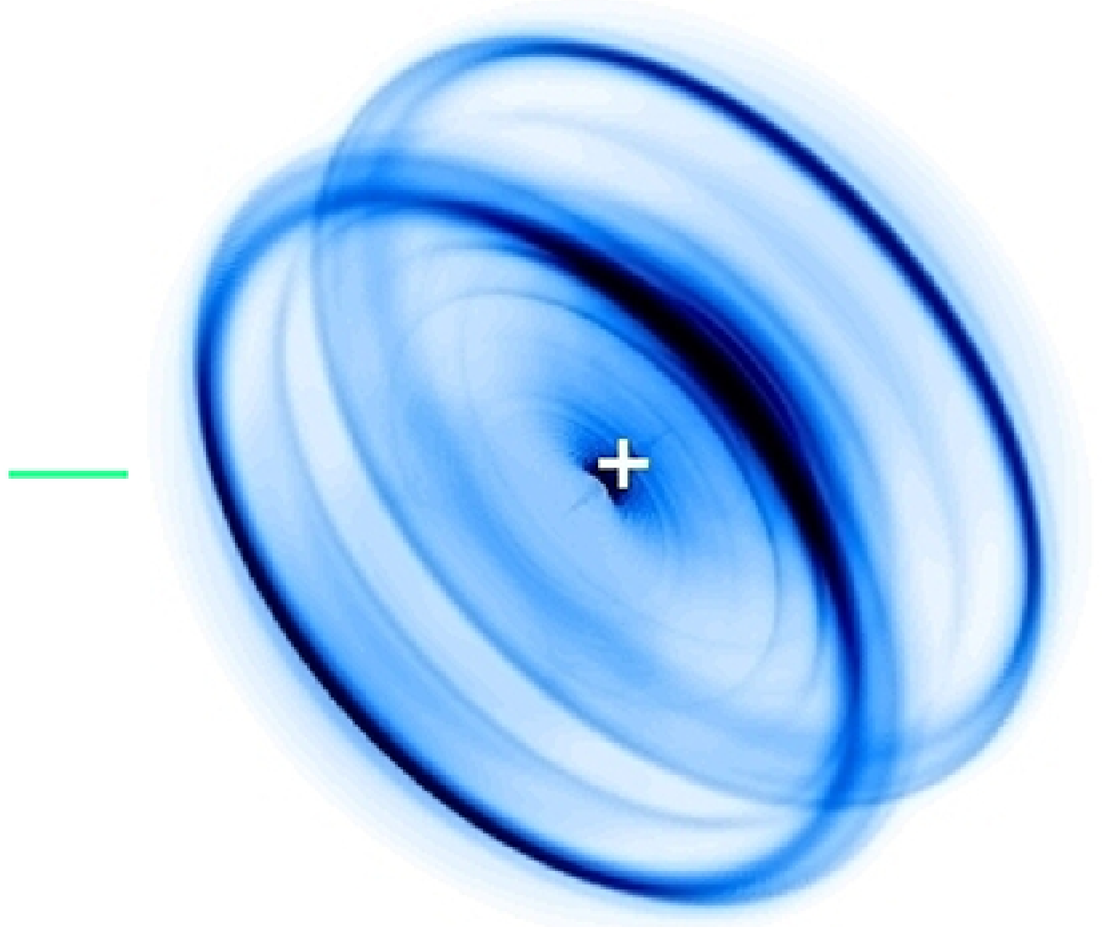
Double-torus PWNe: how to form?

Need a rare combination of conditions ! A pulsar should have:

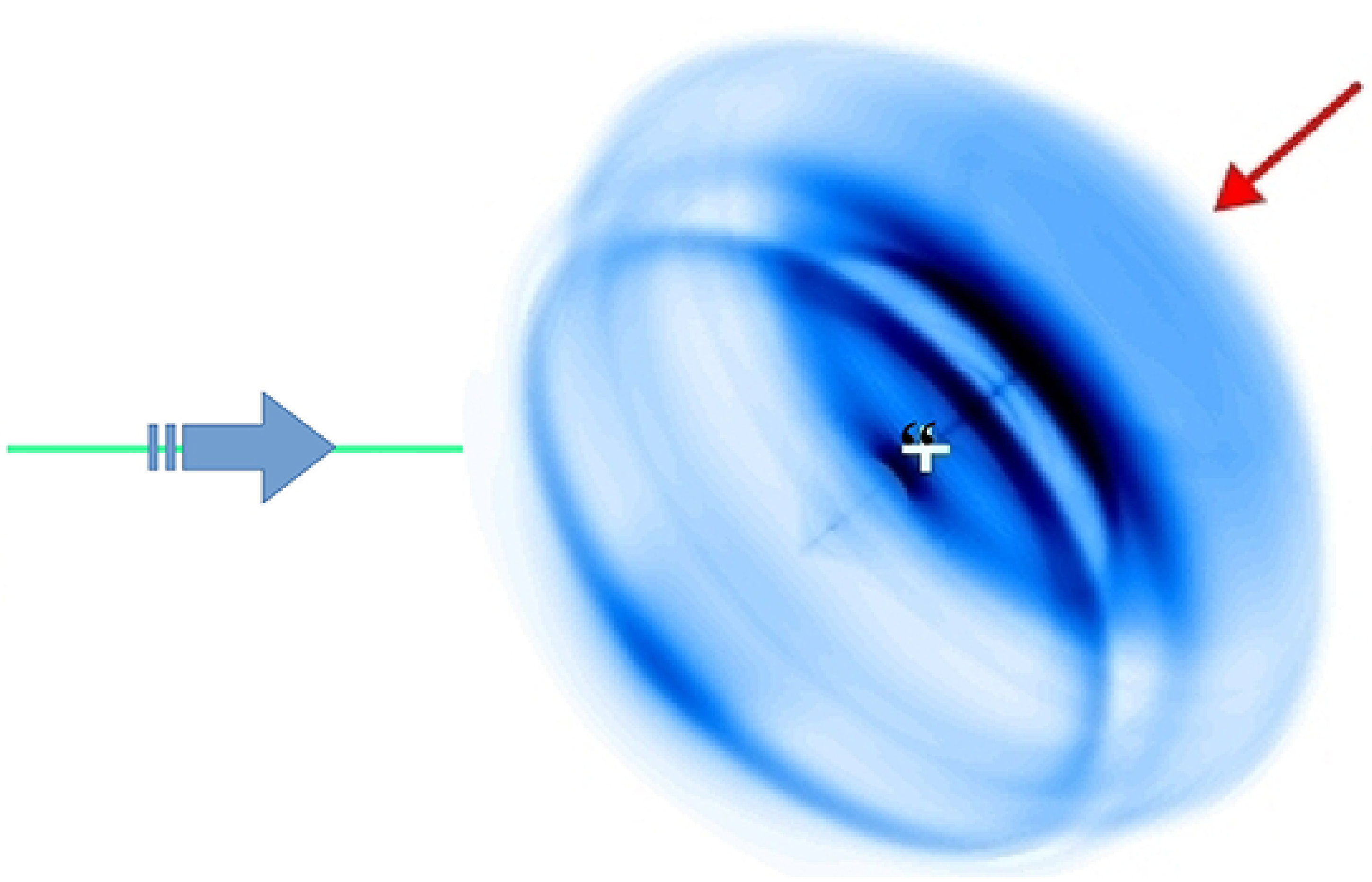
- a slightly supersonic speed,
- a weakly magnetized wind,
- a large magnetic inclination (an angle between the magnetic and rotational axes)

Each condition aims at maintaining **the steadiness of the wind termination shock!**

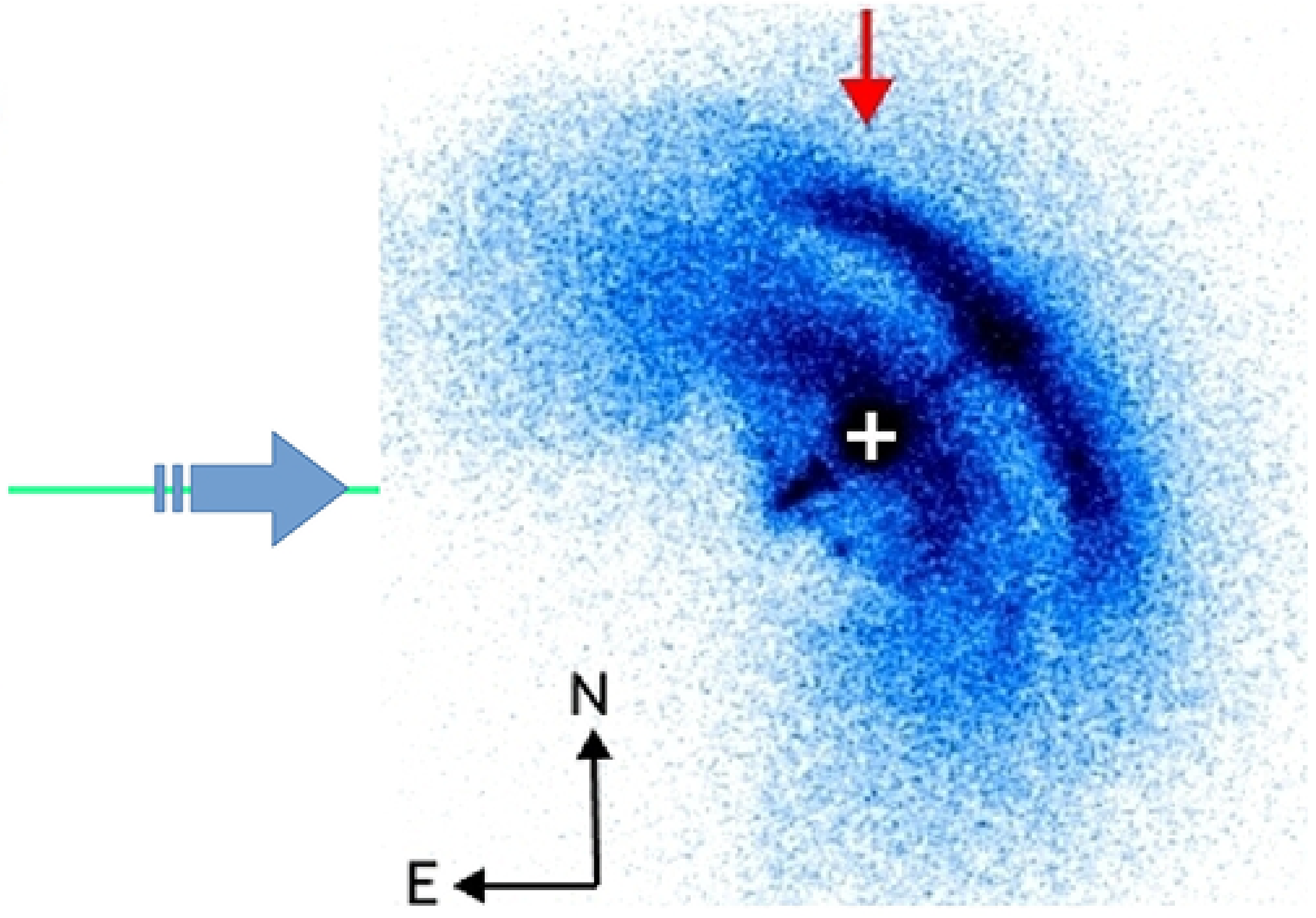
First condition also aims at constraining the compact nebula to ~2 TS radii



“Toy model” - pulsar is at rest relative to the surroundings, TS is stabilized artificially

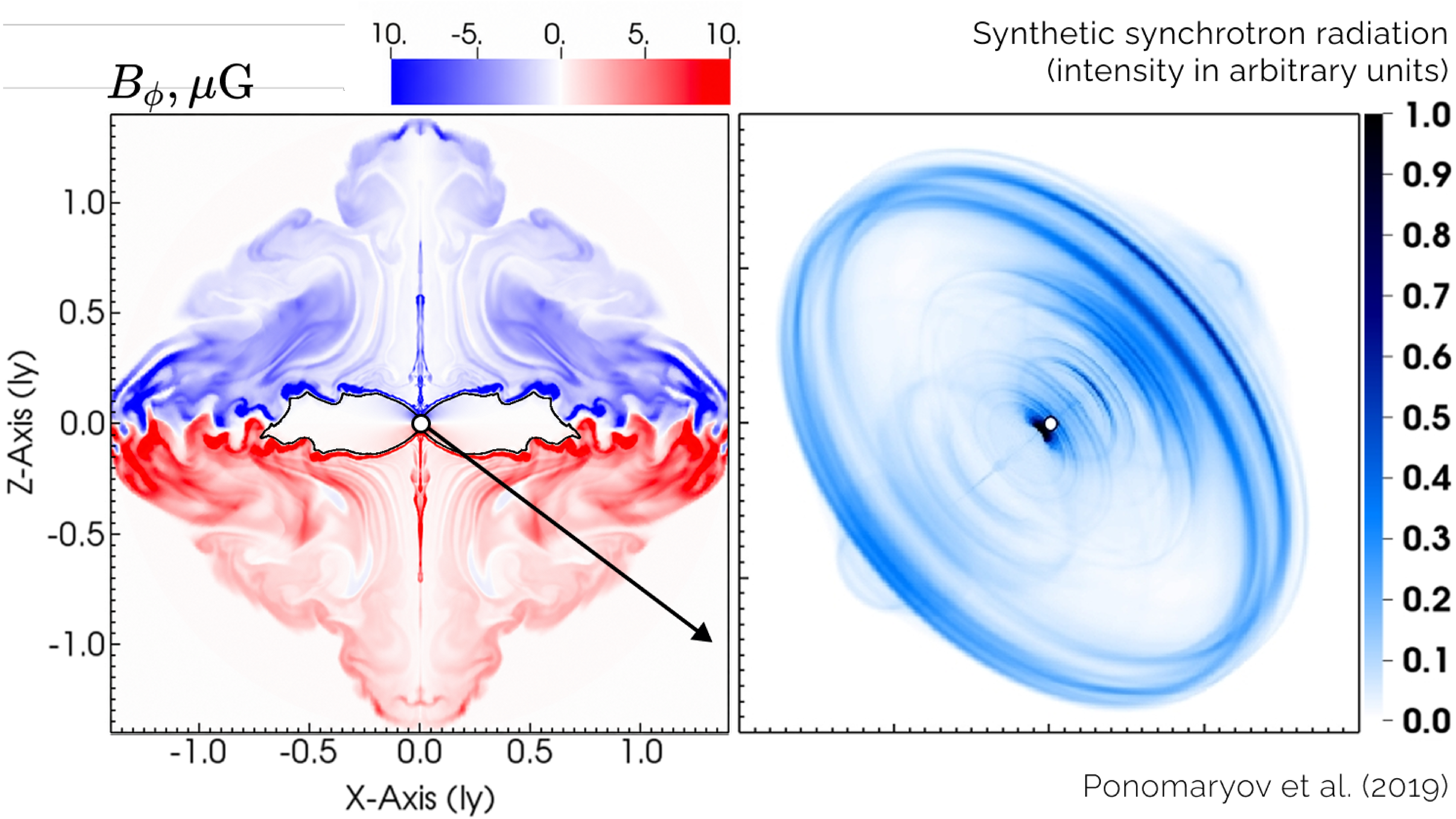


“Realistic model” - pulsar moves at $v \gtrsim c_s$ relative to the surroundings, TS is stabilized by an external flow



Vela PWN: X-ray map

A double torus can't form if the shock is unsteady

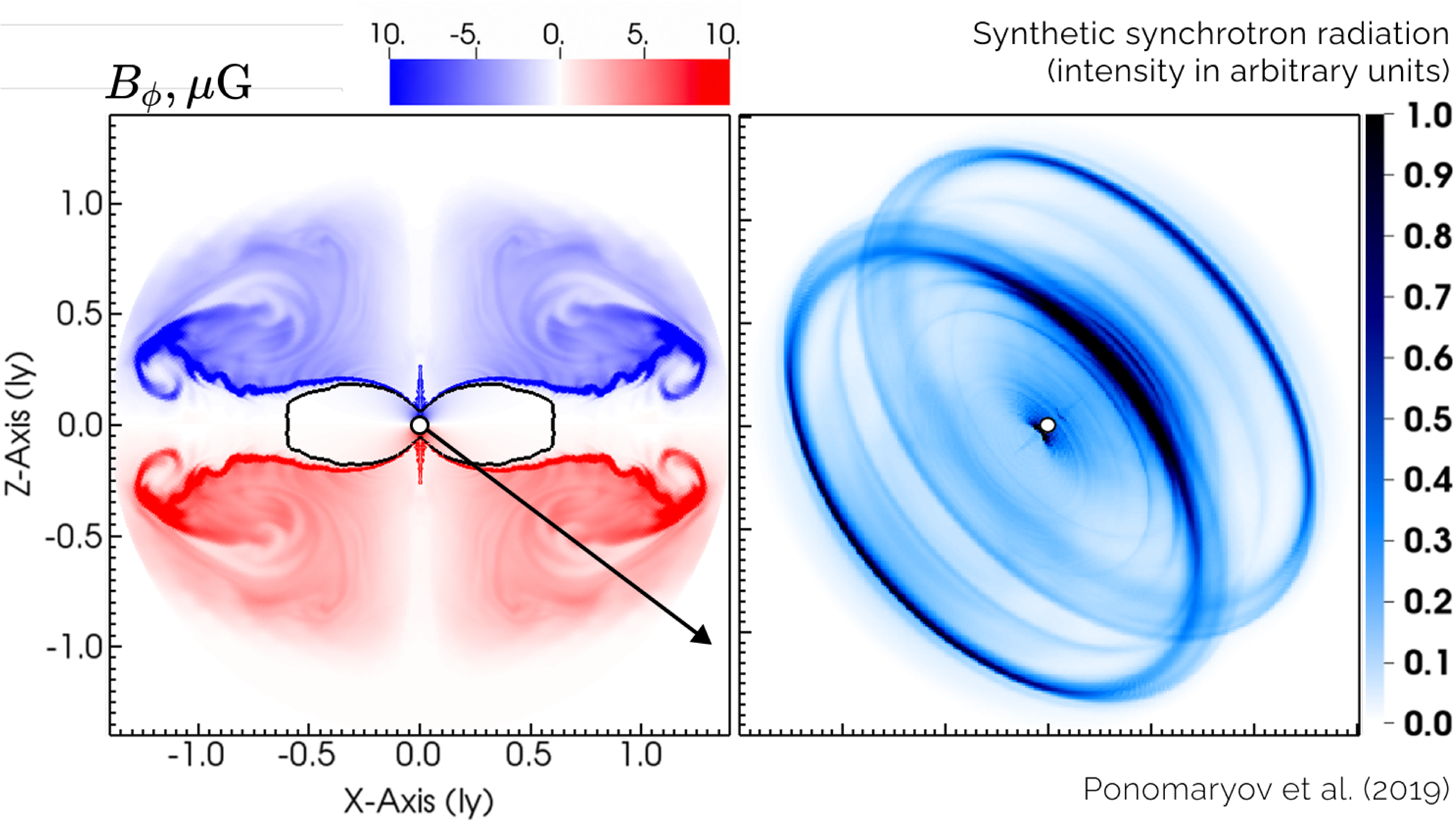


Ponomaryov et al. (2019)

$\alpha = 80^\circ,\ \sigma_0 = 0.03$

Numerical setup follows
Porth et al. (2014) and Bühler & Giomi (2016)

Double torus PWNe: Toy model (artificially stabilized TS)

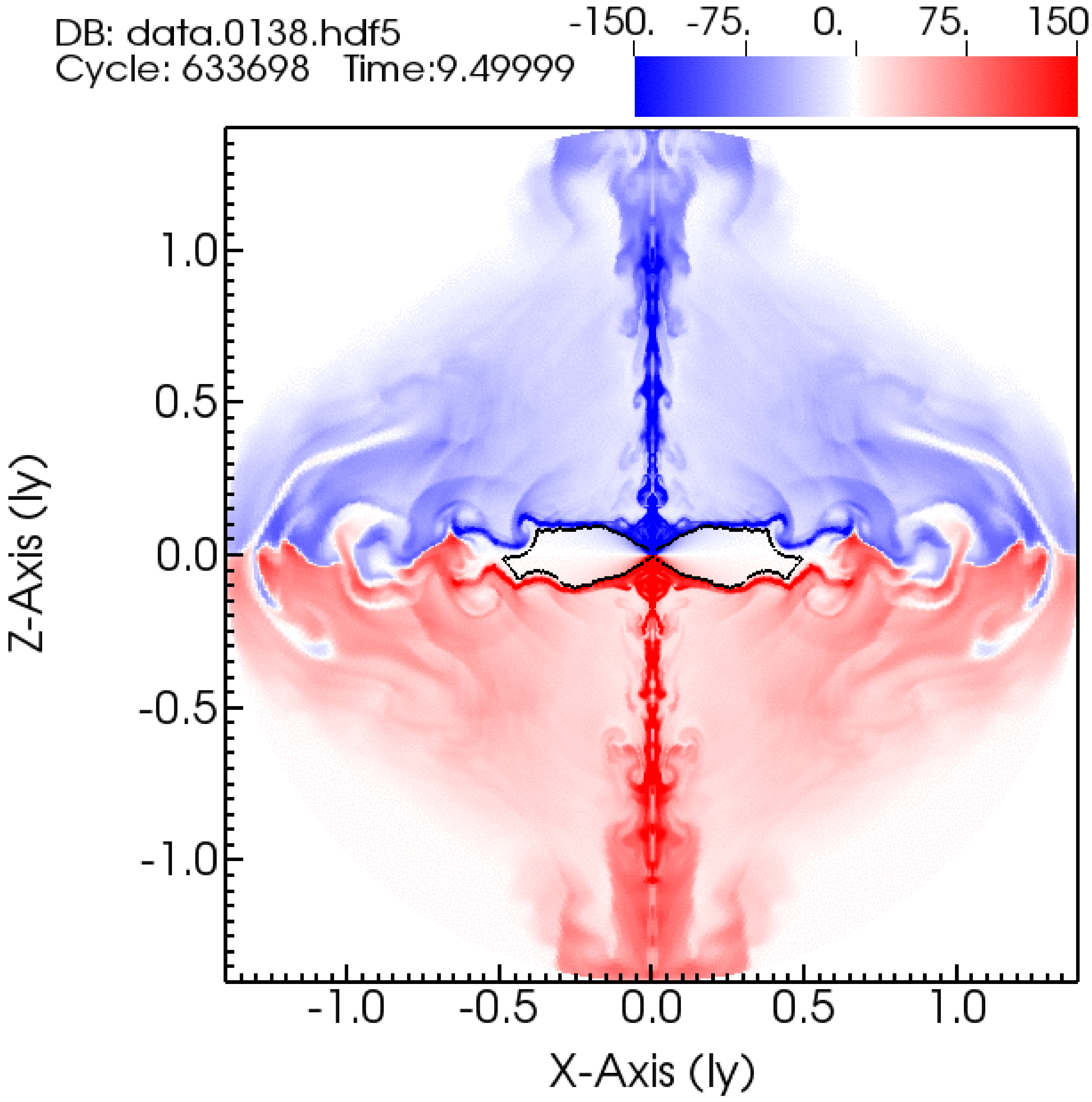


Ponomaryov et al. (2019)

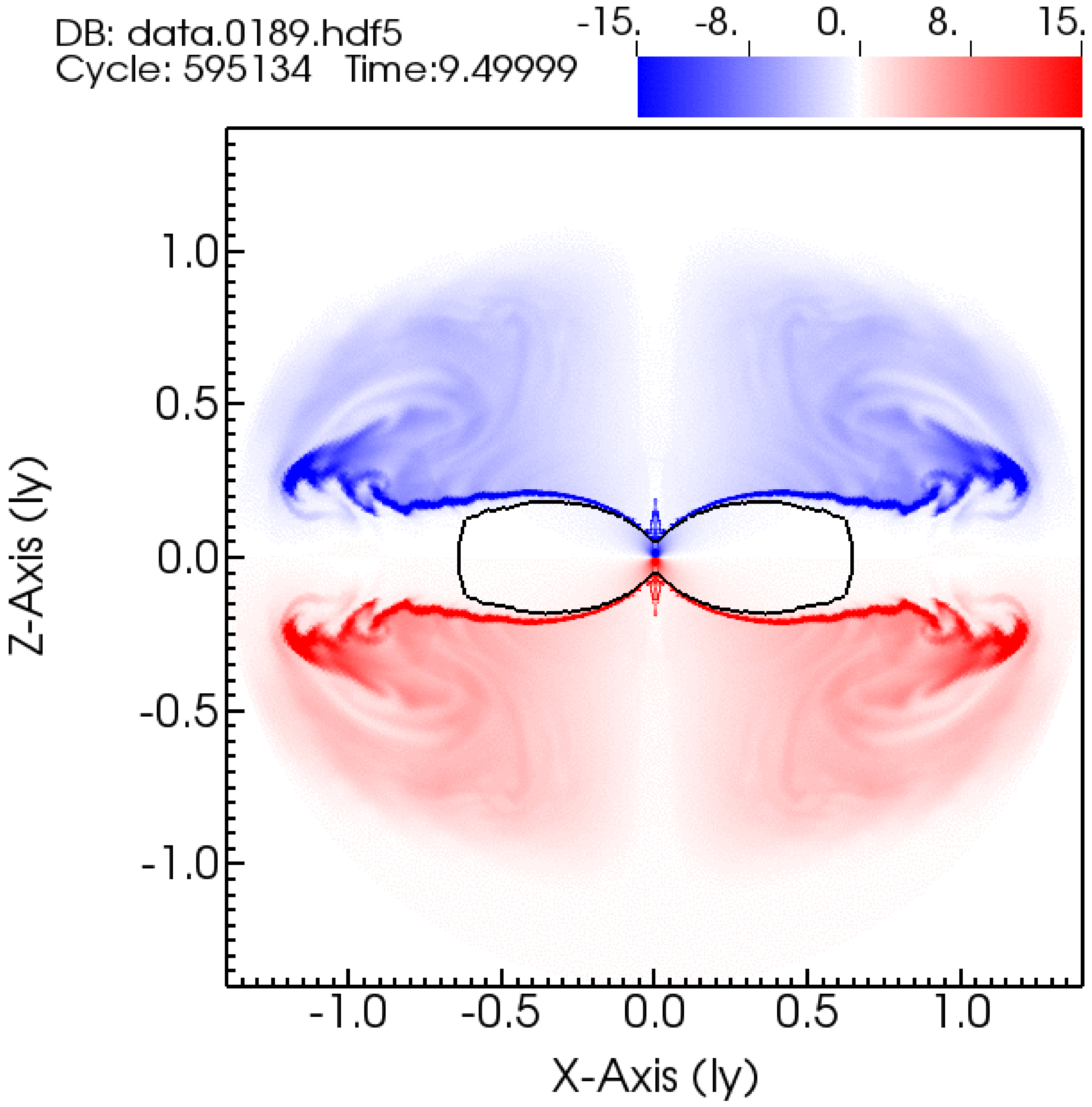
$\alpha = 80^\circ, \; \sigma_0 = 0.03$

Numerical setup follows
Porth et al. (2014) and Bühler & Giomi (2016)

Single vs Double torus: differences in flow patterns



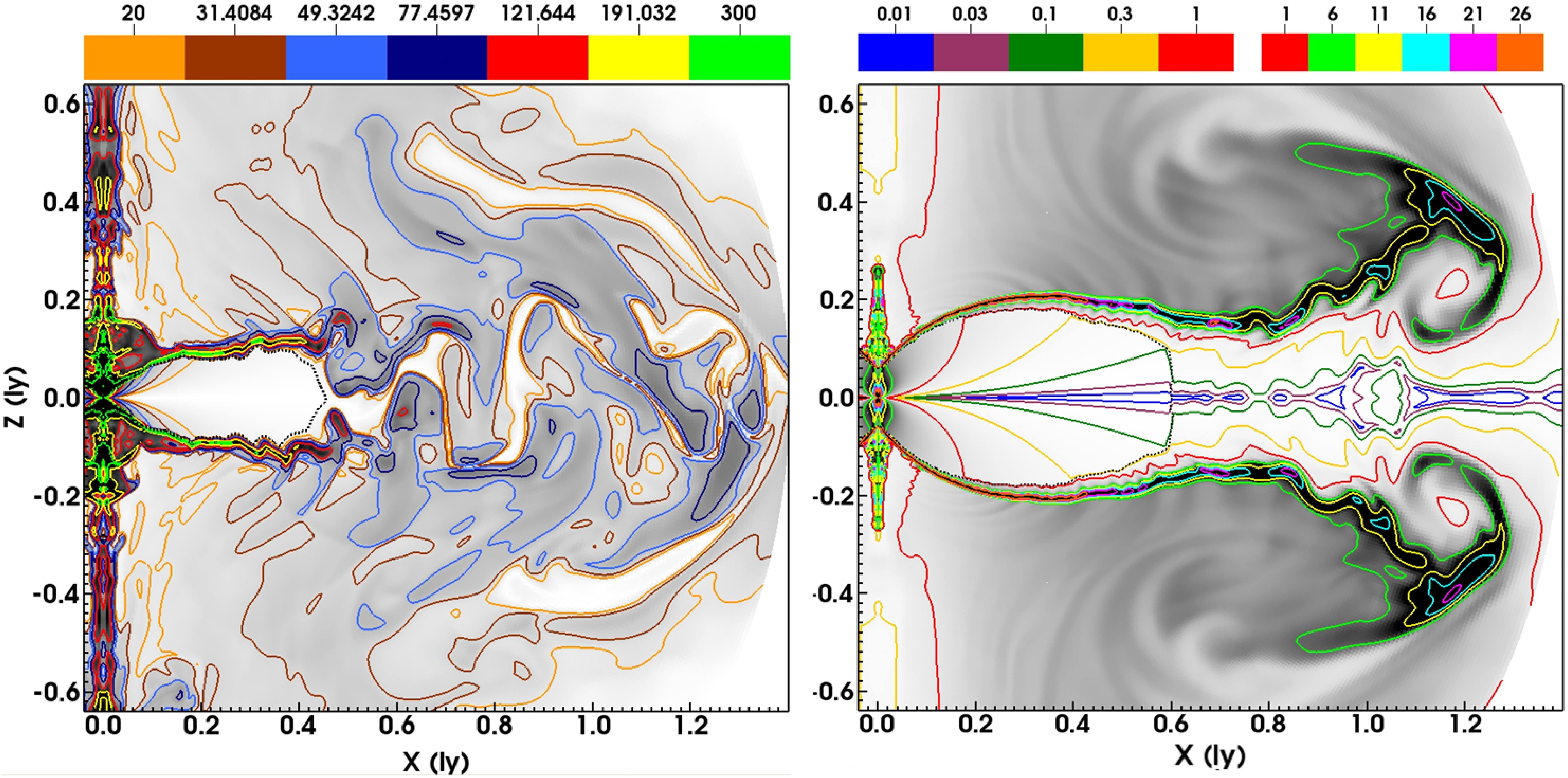
Один тор. $\alpha = 45^\circ,\ \sigma_0 = 3$



Два тора. $\alpha = 80^\circ,\ \sigma_0 = 0.03$

Single vs Double torus: differences in B-topology

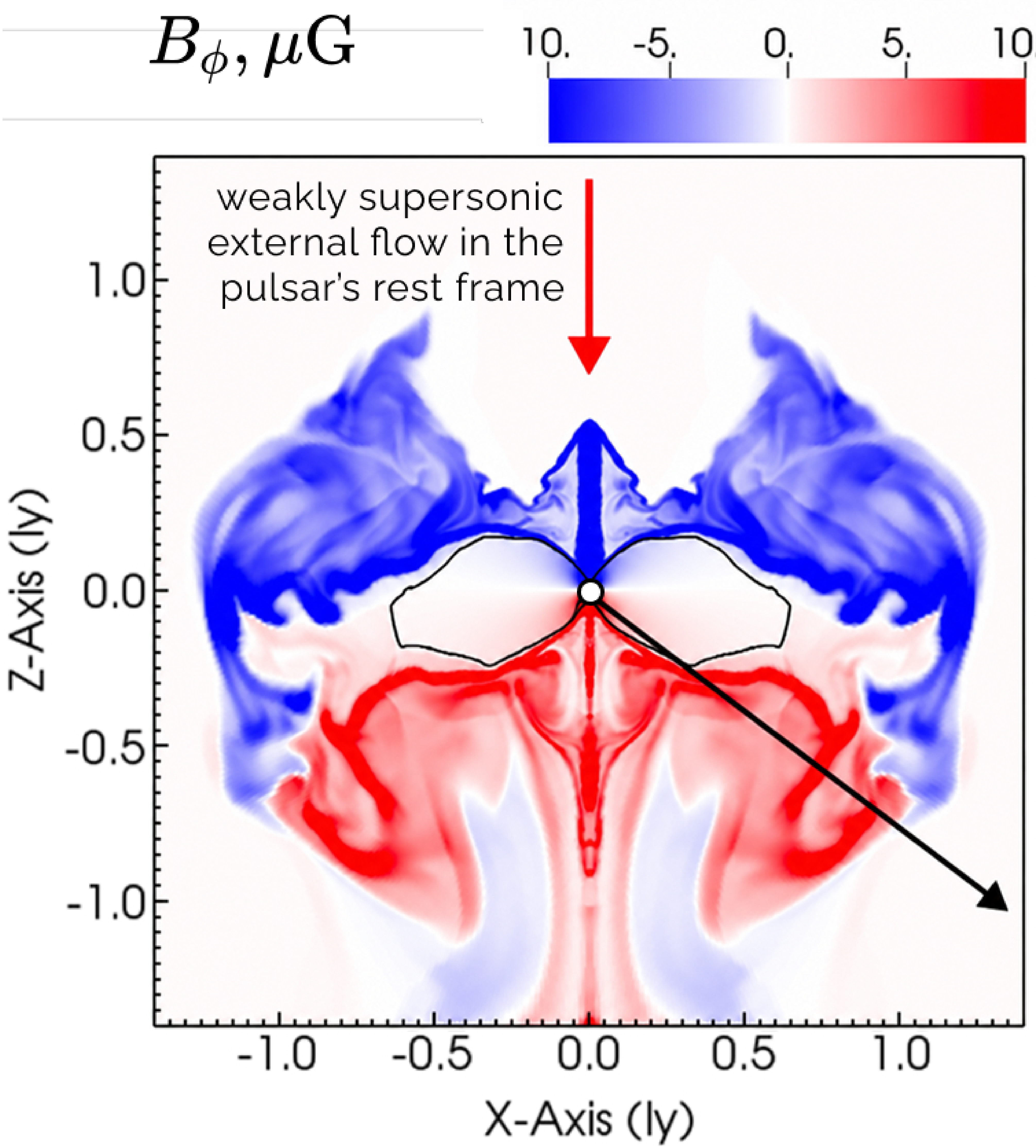
Azimuthal magnetic field (μG)



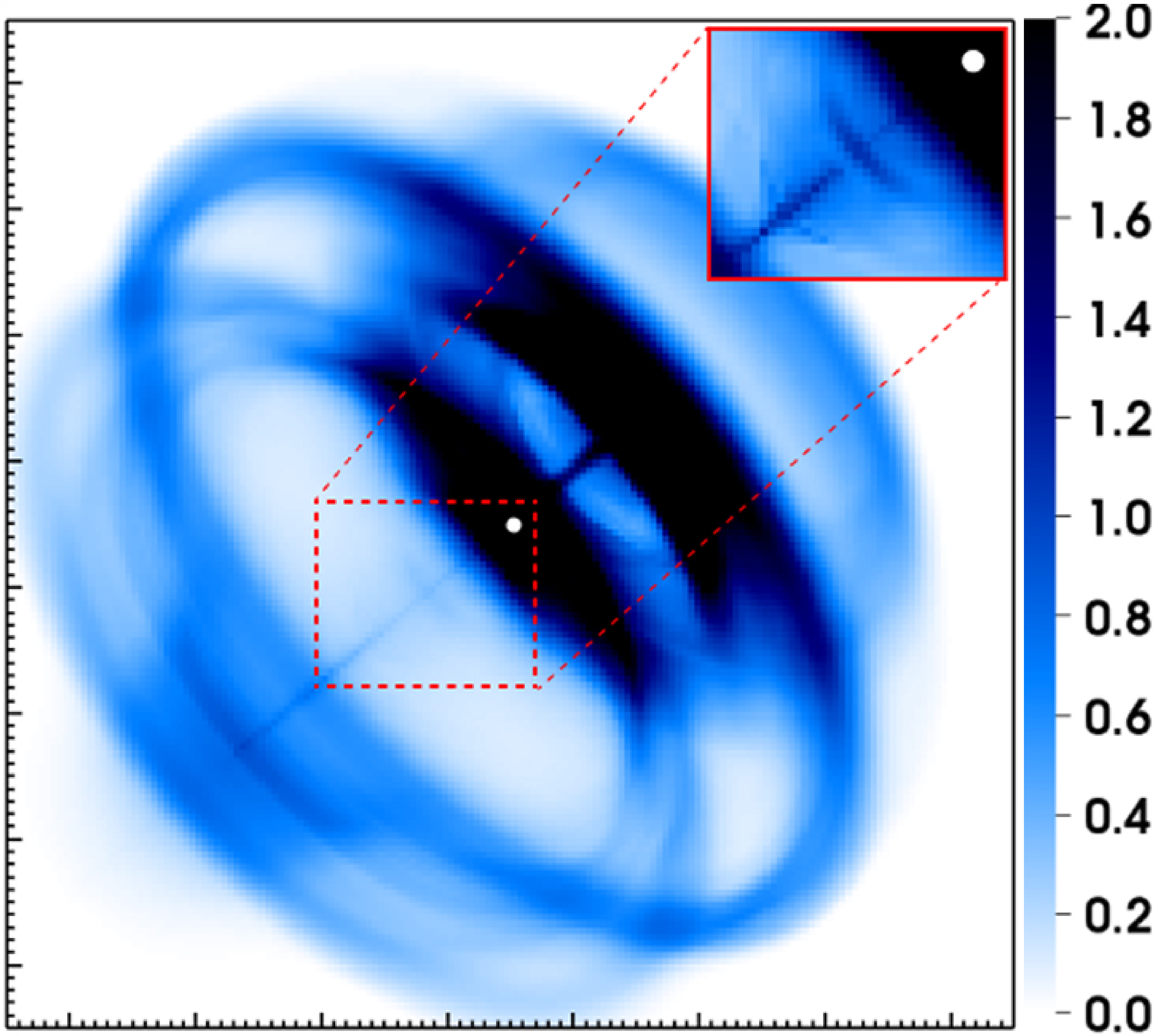
$\alpha = 45^\circ,\ \sigma_0 = 3$

$\alpha = 80^\circ,\ \sigma_0 = 0.03$

Double torus PWNe: Realistic model (TS is stabilized by a supersonic external flow)



Synthetic synchrotron radiation (intensity in arbitrary units)

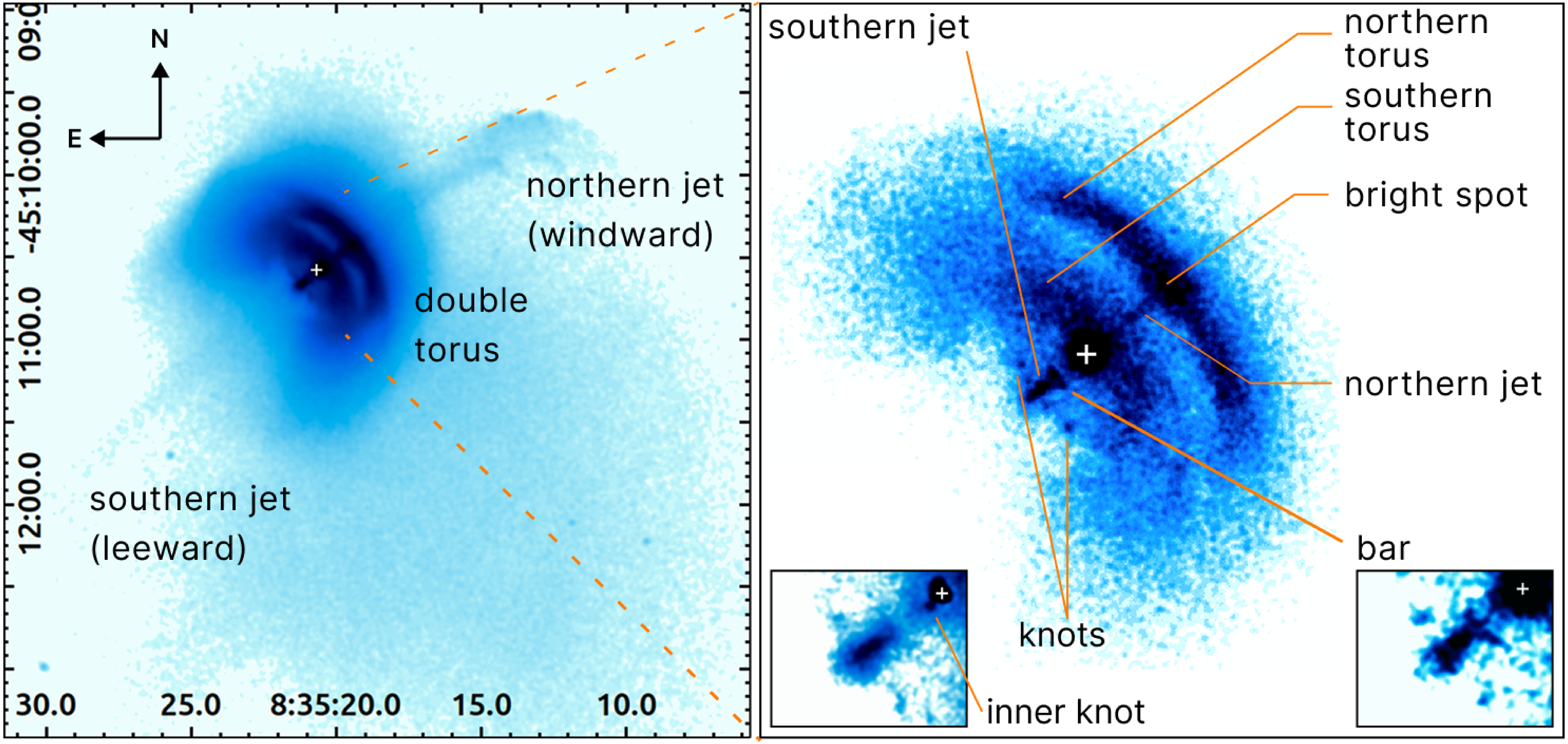


Ponomaryov et al. (2023), Levenfish et al. (2025)

$\alpha = 80^\circ,\ \sigma_0 = 0.1,\ M_s = 2.3$

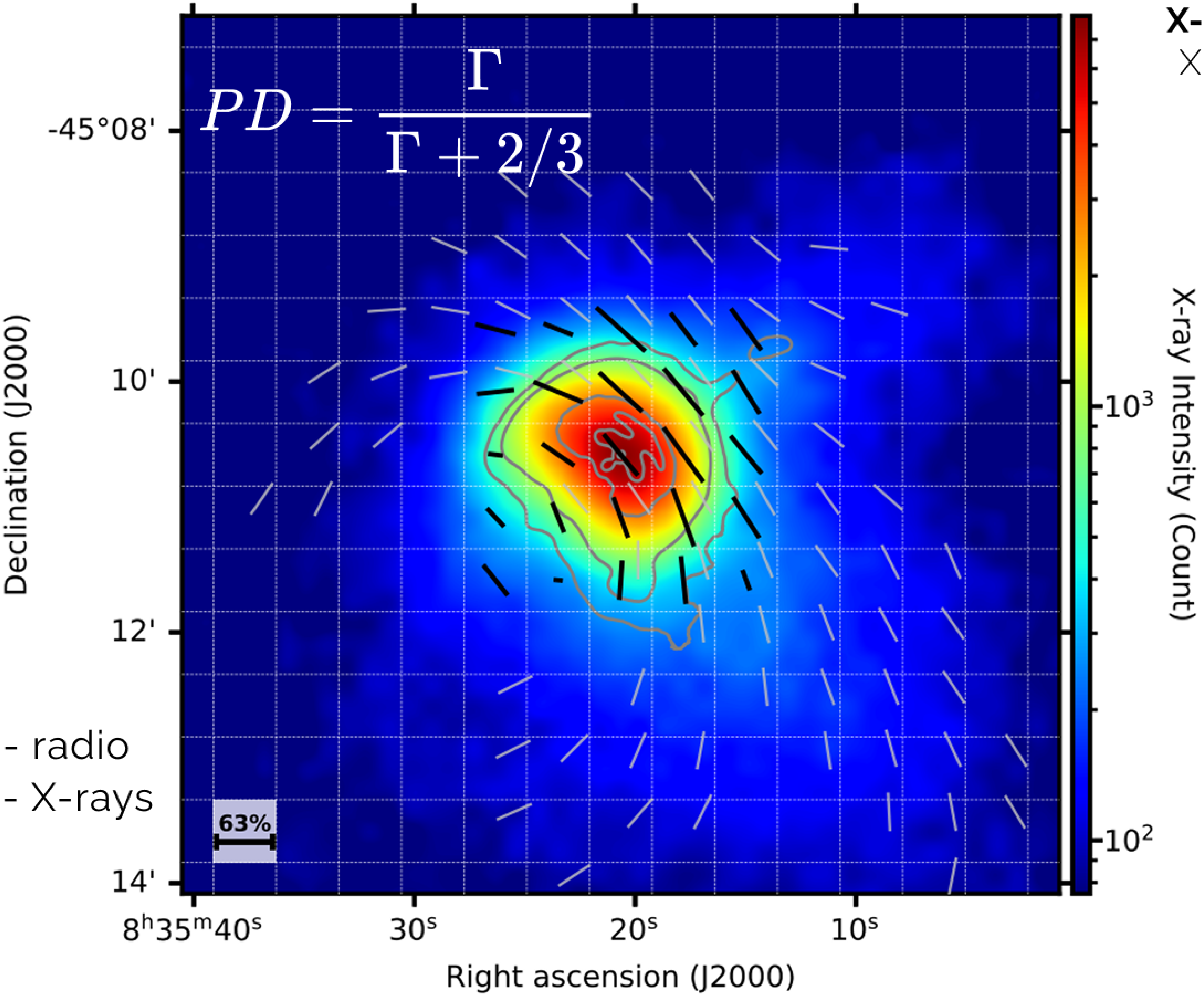
Numerical setup follows Porth et al. (2014) and Bühler & Giomi (2016)

Vela's X-ray features nomenclature



after Pavlov et al. (2001, 2003);
Kargaltsev et al. (2002, 2015)

IXPE observations of Vela: reconstructed B-field topology

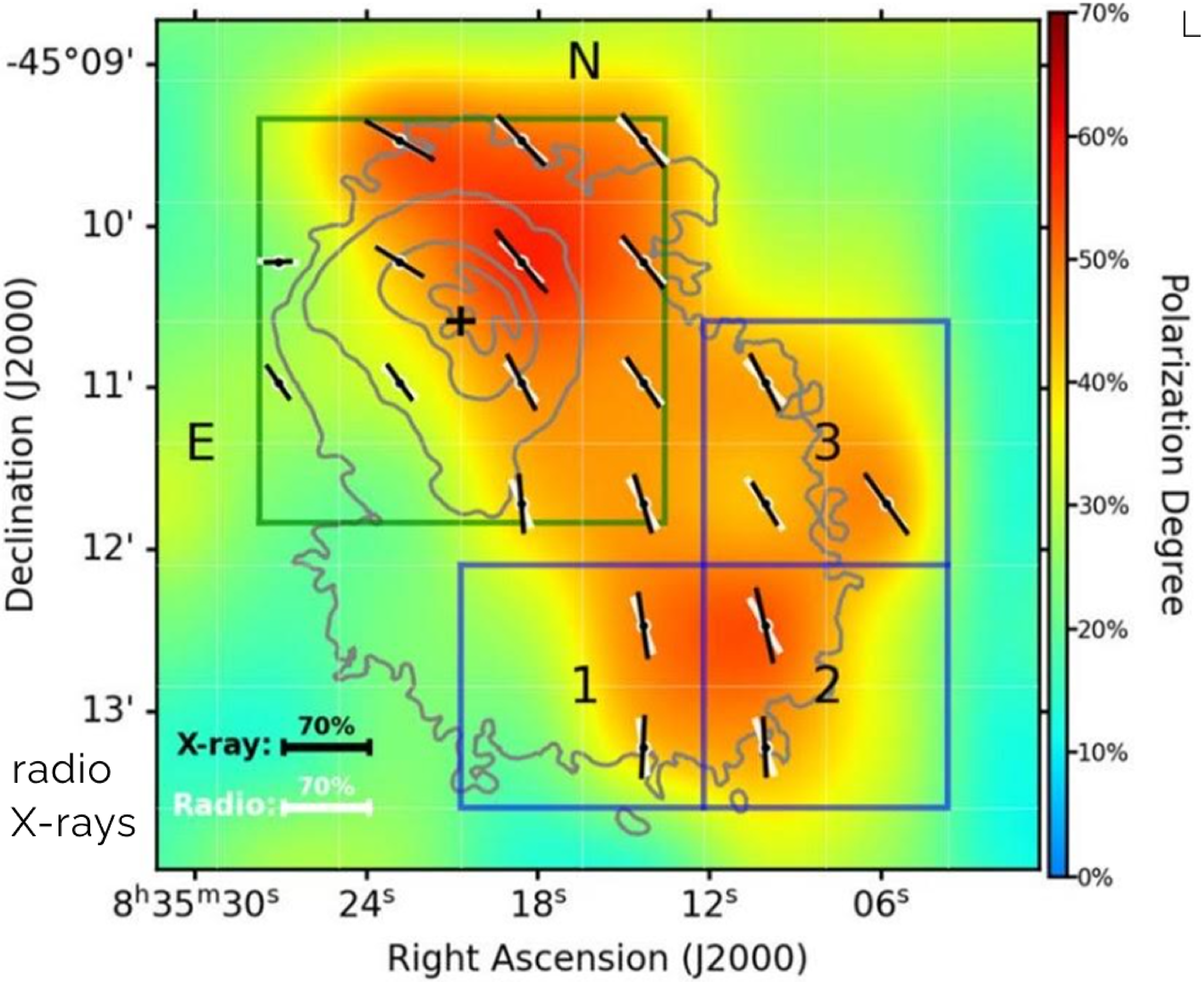


X-ray (2-8 keV)
Xie et al. 2023

white dashes - radio
black dashes - X-rays

Vela: PD = 65% <-- approach max. possible at synchrotron emission mechanism !
max. PD = 67% at photon index = 1.35 (Kargaltsev+03)

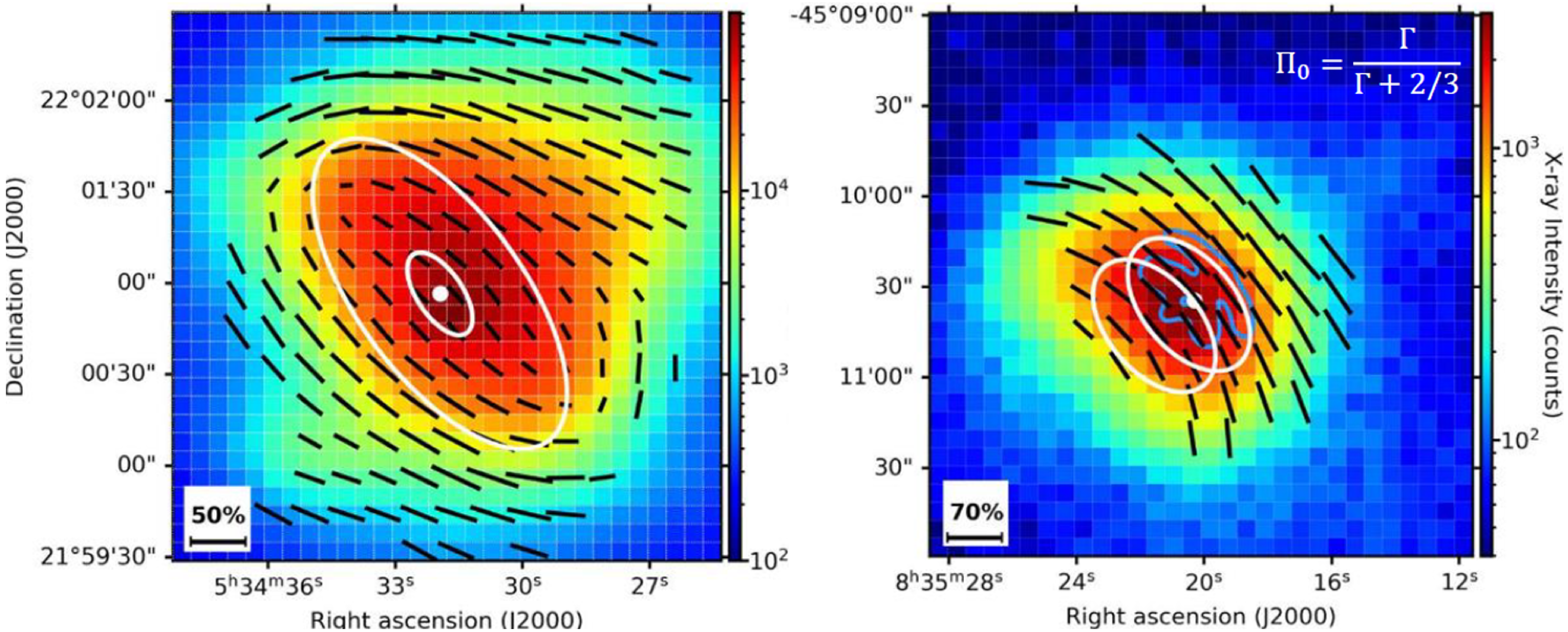
IXPE observations: highly ordered B in large Vela PWN



Liu et al. 2023

white dashes - radio
black dashes - X-rays

IXPE observations: Crab vs Vela



$$\Pi_0 = \frac{\Gamma}{\Gamma + 2/3}$$

Deng et al. (2024)

Measured polarization degrees:

- **Vela: PD = 65%** <-- approach max. possible at synchrotron emission mechanism !
  max. PD = 67% at photon index = 1.35 (Kargaltsev+03)

- **Crab: PD = 20%** <-- 3 times lower than in Vela !
  PD is larger along the periphery of the torus

The impact of an external flow on PD

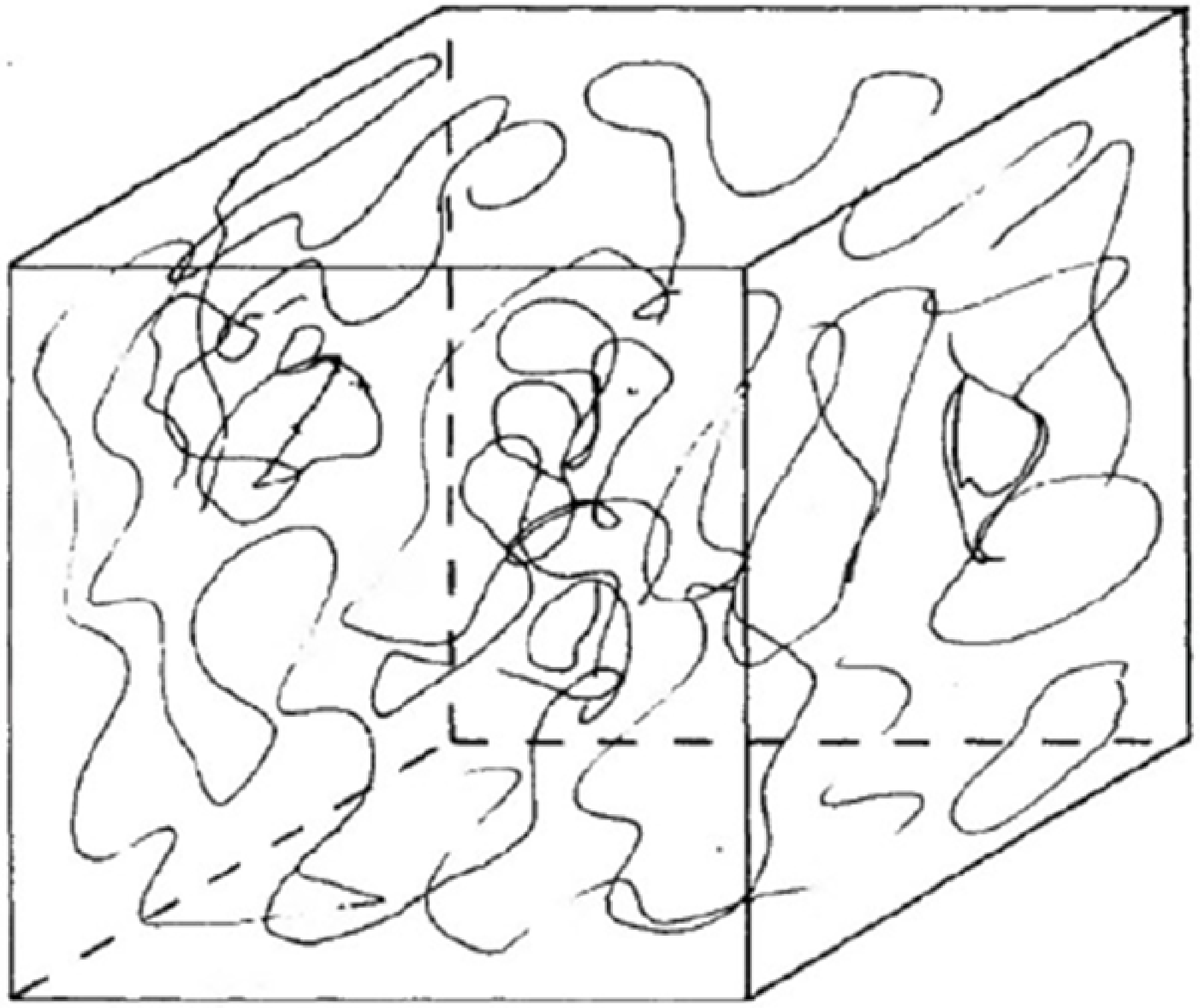
Our MHD model interpretation:

- the regularization of B along the perimeter of the torus is caused by a compression / stretching of the field in the outer layers of the torus

A partial regularization of initially random field happens at:

- a compression
- a stretching

of a region along a certain direction

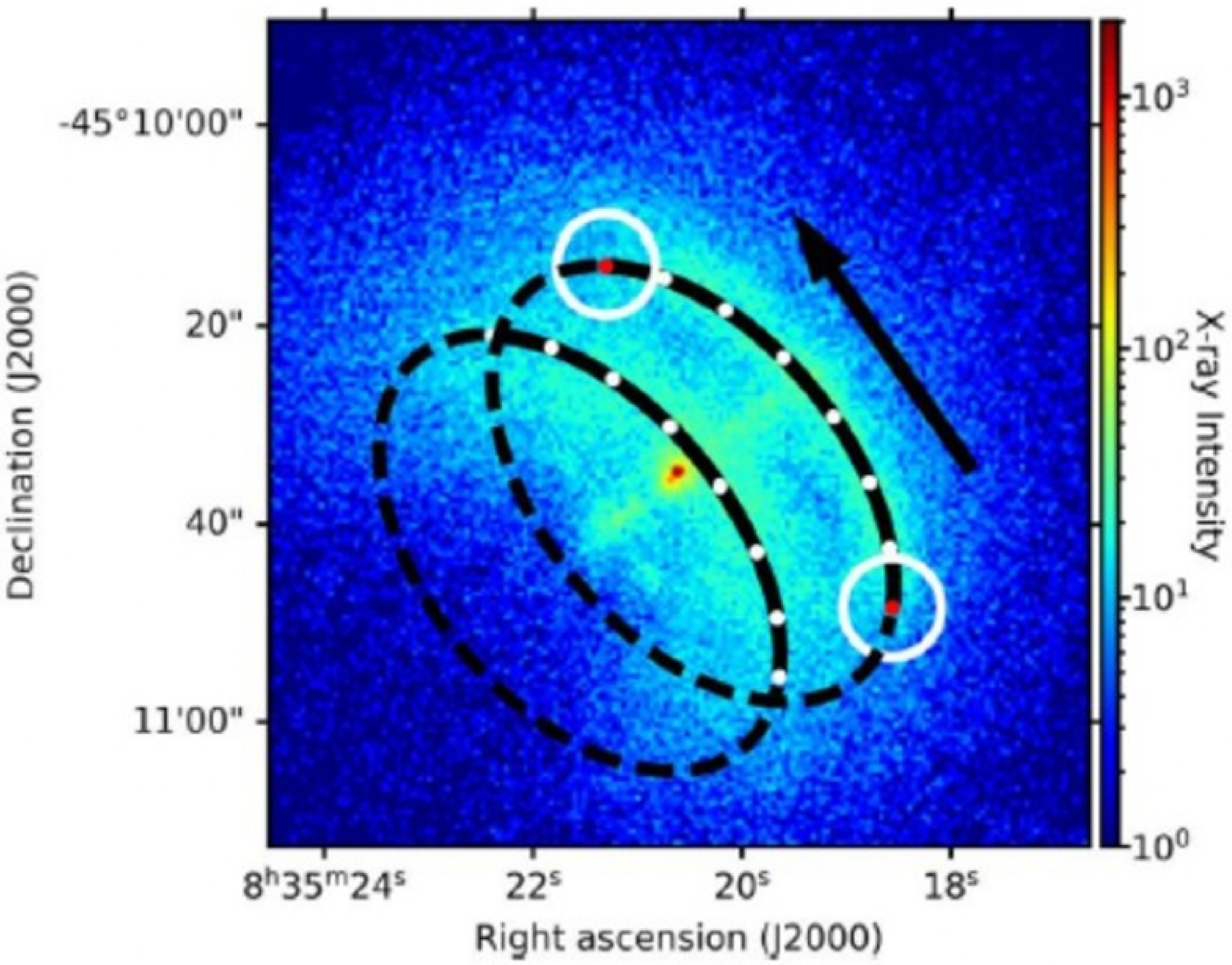


R.A.Laing (1980)

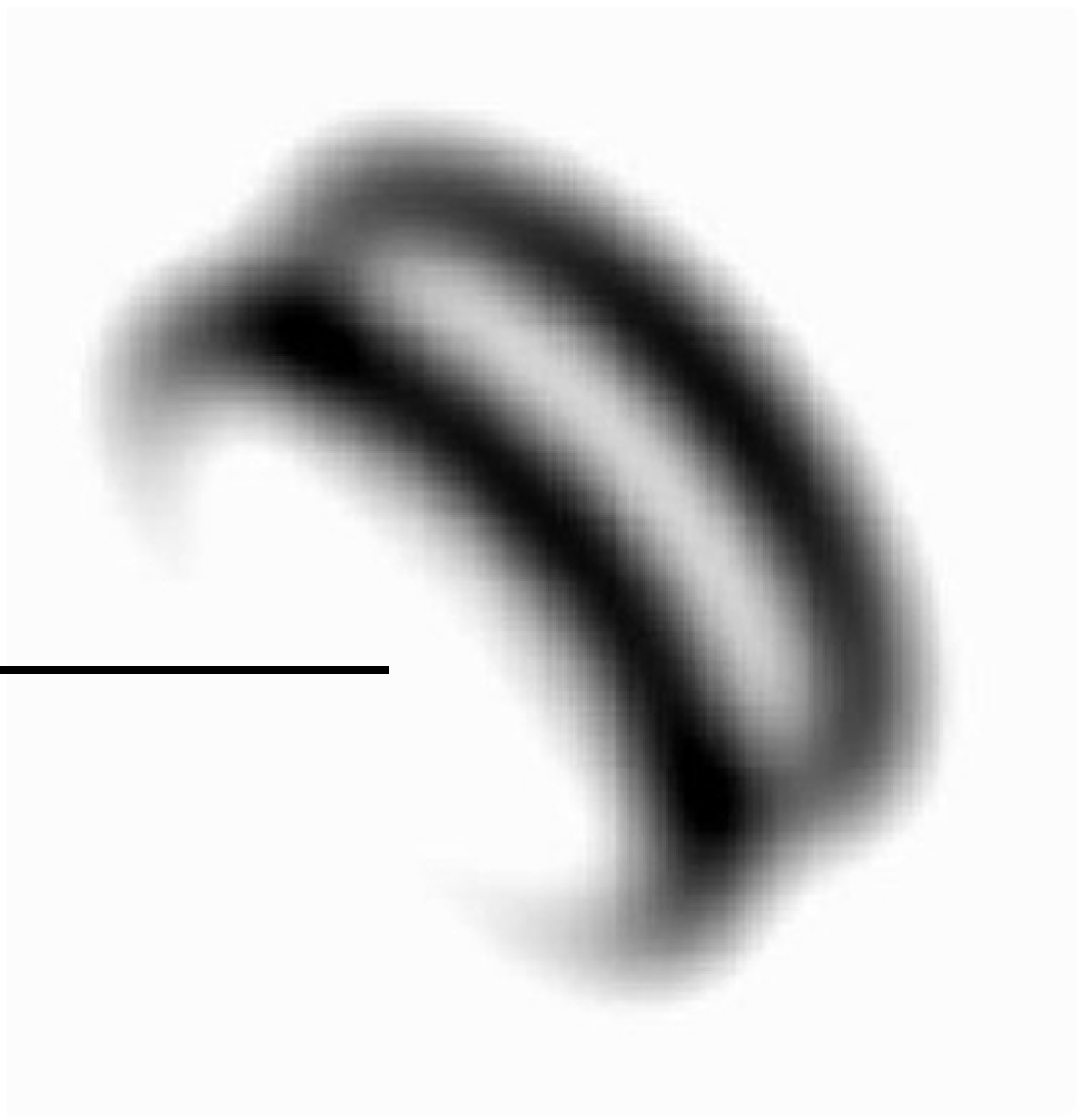
Before compression:
unpolarized synchrotron emission

After compression:
polarized synchrotron emission
(a preferred B-direction emerges)

Does the magnetic field follow the geometry of the tori?



Deng+2024



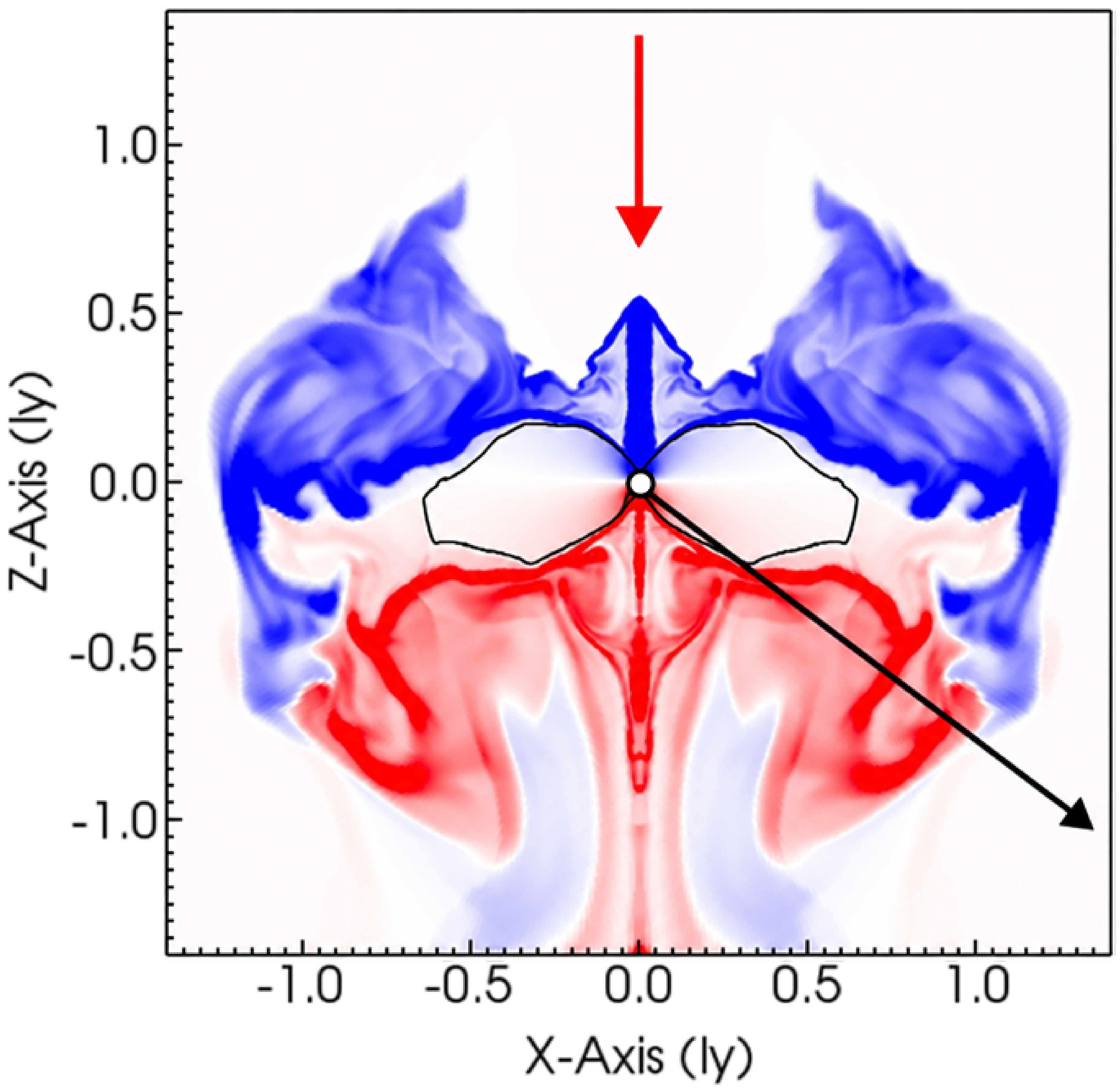
Ng & Romani (2004):
the fitting of the Chandra observations

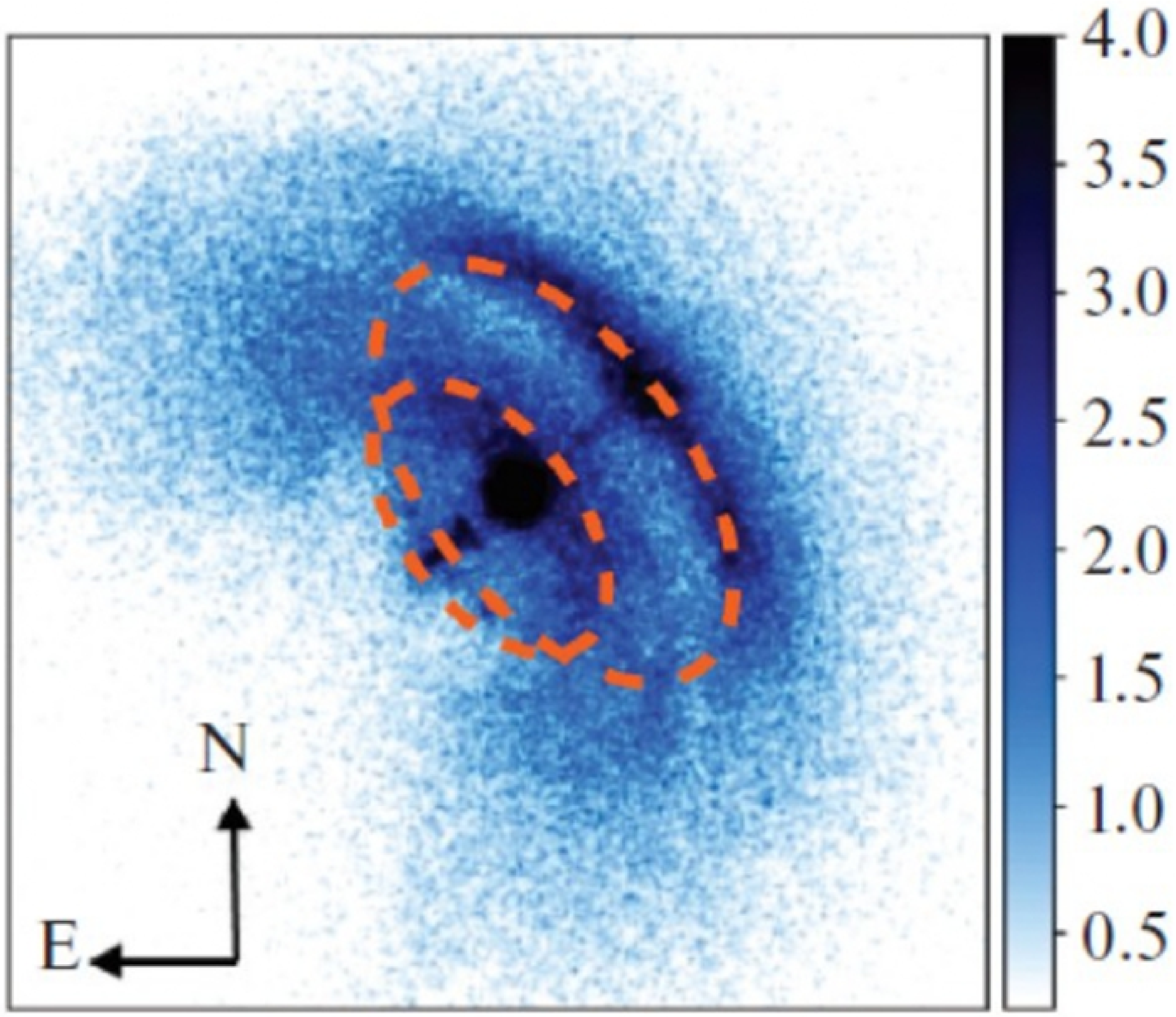
- pulsar in the center of the **windward (!)** torus
- two coaxial tori of the same size and orientation

Conclusions:

- the magnetic field of Vela is not fully toroidal,
- it does not follow the geometry of the tori, the back parts of which are not visible

Does the magnetic field follow the geometry of the tori?





based on RMHD model (Levenfish+2025)

- two coaxial tori - have different sizes and slightly misaligned axes
- the back sides of the tori appear close in projection
- PSR is **projected** under the lower arc, since the PWN encounters a supersonic flow

Conclusions:

- **the magnetic field** lines are **purely azimuthal and closed,**
- the B-lines closely follow the tori morphology
- **the back parts of the tori are visible** and are traced by a chain of X-ray knots

Characteristic features of double-torus nebulae suggested by our MHD model - I

1. **magnetic field:**
   - very uniform,
   - purely azimuthal,
   - strongly dominated by a regular component

2. **double torus:**
   - formed by two regular large-scale circulation vortices at mid-latitudes
   - can reverberate and precess as a whole in a directed external flow
   - the lee torus is smaller than the windward one

3. **recirculation: regular large-scale toroidal vortex in the lee funnel of the TS**

4. **equatorial belt:**
   - barely magnetized
   - overpressured
   - equalizes its pressure through a series of oblique and normal shocks
   - oblique shocks generate folds in adjacent highly-magnetized flows

Characteristic features of double-torus nebulae suggested by our MHD model - II

5. highly magnetized flows:

- relativistic (v ~ 0.75–0.85 c),
- quasi-laminar
- do not meet until the boundary of the compact nebula,
- form regular, quasi-periodic folds
- split in two parts while approaching the nebula's boundary
- the parts splitting towards the equator produce magnetic plumes; plumes are highly dynamic and can sporadically penetrate to the hemisphere of the opposite magnetic polarity

6. the leeward jet:

- most of time is blocked within the lee circulation vortex
- can sporadically break through the lee circulation
- has 3 different sections: the two initial are a true jet, while the outer is not
- the outer section is a submerged flow, formed of plasma blobs
- the middle section is the brightest; its outer tip sways from side to side

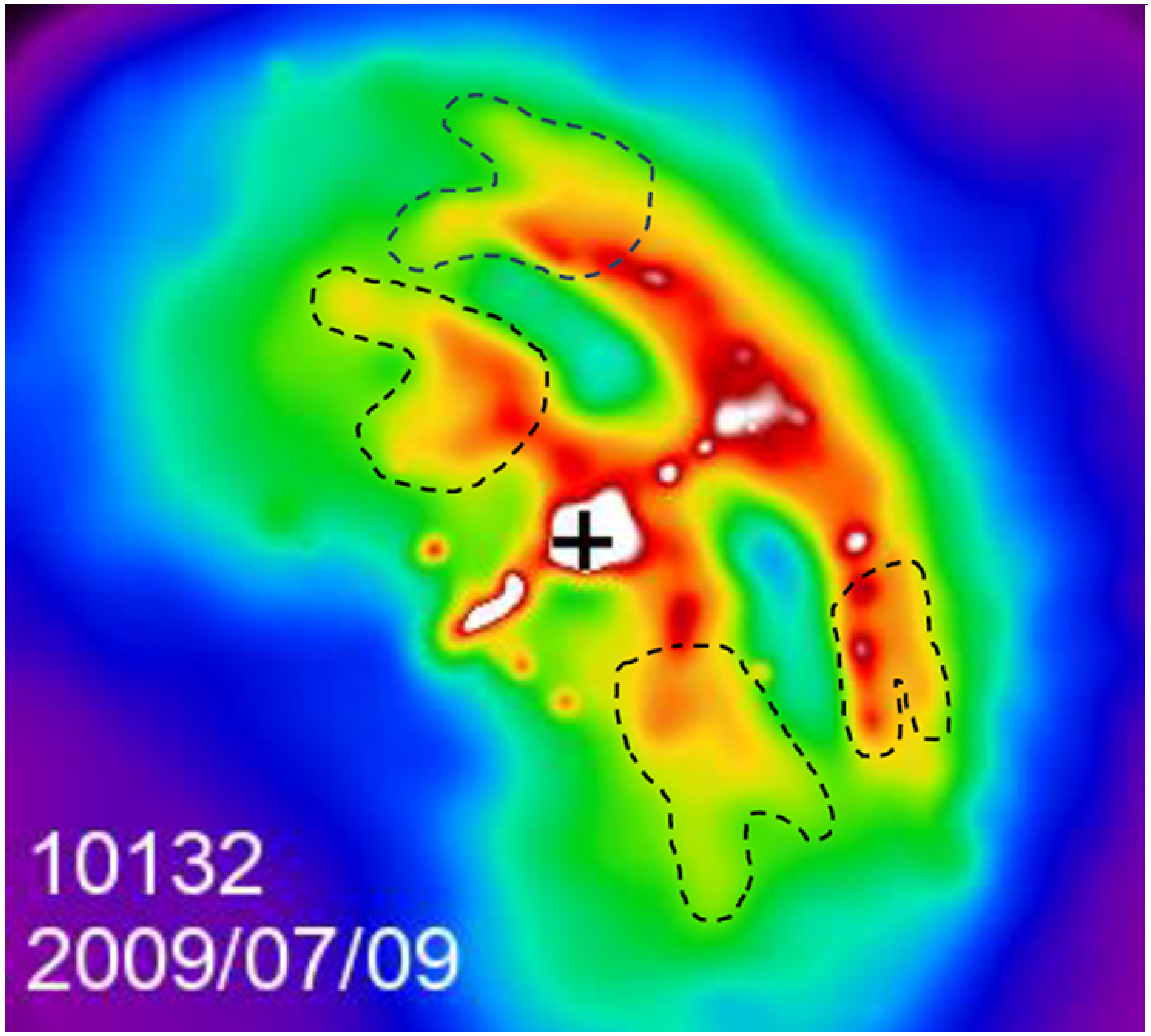
7. the windward jet:

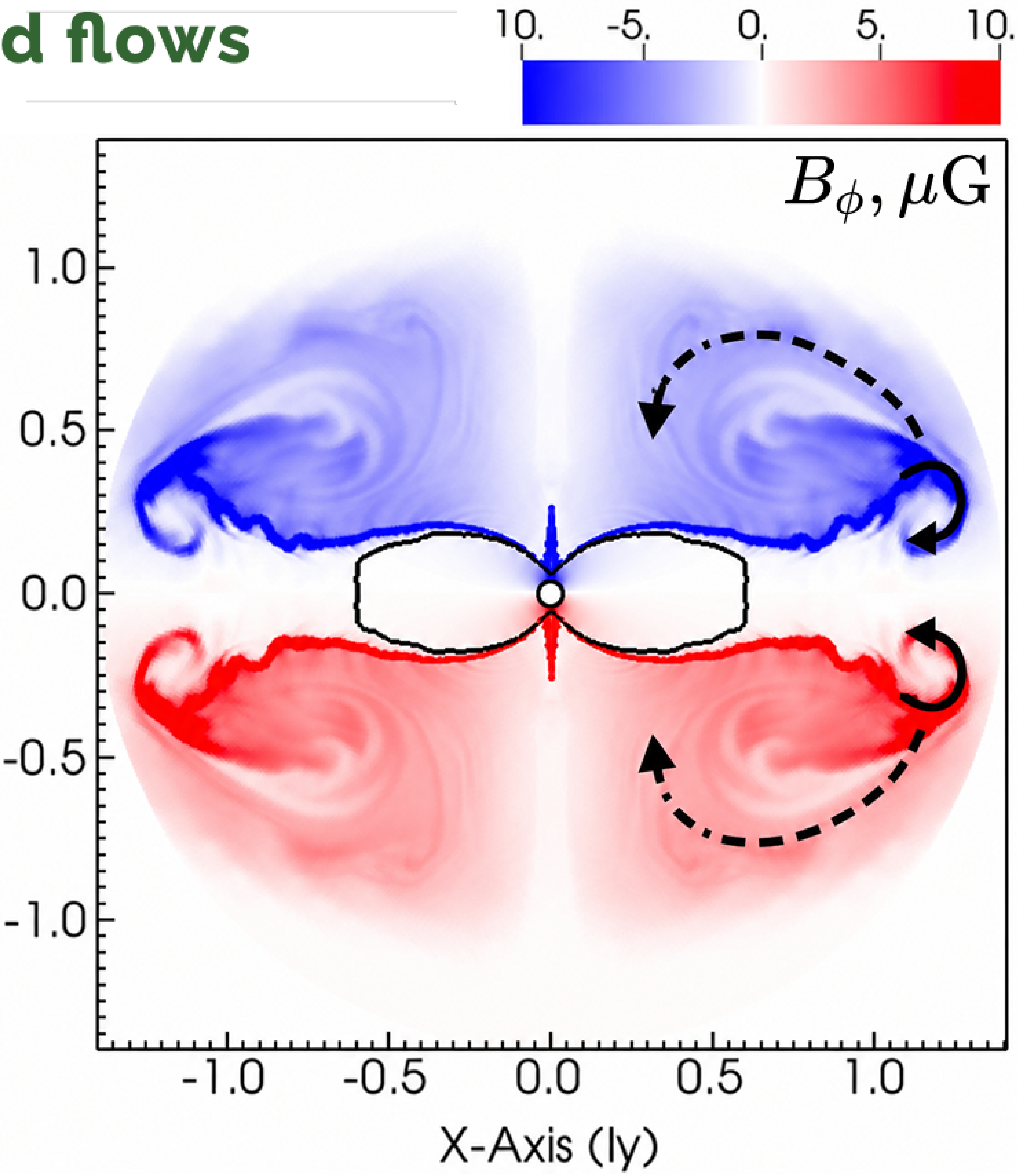
- has 2 different sections: thick, bright and steady + thin, dim and dynamic

Our publications

1. Ponomaryov G.A., Levenfish K.P., Petrov A.E. Two tori of the Vela pulsar wind nebula // J. Phys.: Conf. Ser. – 2019. – Vol. 1400, Issue 2. – id 022027
2. Ponomaryov G.A., Levenfish K.P., Petrov A.E., Kropotina Yu.A. On stability of toroidal structures in two-tori pulsar wind nebulae // J. Phys.: Conf. Ser. – 2020. – Vol. 1697. – id 012022
3. Levenfish K.P., Ponomaryov G.A., Petrov A.E., Bykov A.M., Krassilchtchikov A.M. Slow motion pulsar wind nebulae // J. Phys.: Conf. Ser. – 2021. – Vol. 2103. – id 012020
4. Ponomaryov G.A., Levenfish K.P., Petrov A.E. Jet and counter-jet in transonic pulsar wind nebulae // J. Phys.: Conf. Ser. – 2021. – Vol. 2103 – id 012021
5. Levenfish K., Ponomaryov G., Petrov A. X-ray morphology of pulsar wind nebulae: the effect of local medium motion // Astronomy at the Epoch of Multimessenger Studies, Proceedings of the VAK-2021 conference, held 23-28 August, 2021 in Moscow. – 2022. – P. 285-287
6. Fateeva S.S., Levenfish K.P., Ponomaryov G.A., Petrov A. E., Fursov A.N. // Astronomy Letters. – 2023. – Vol. 49, Issue 2. – P.56-64
7. Ponomaryov G.A., Fursov A.N., Fateeva S.S., Levenfish K.P., Petrov A.E., Krassilchtchikov A.M. On the Origin of Knots in the Vela Nebula // Astronomy Letters. – 2023. – Vol. 49, Issue 2. – P.65-79
8. Petrov A.E., Levenfish K.P., Ponomaryov G.A., Reverberation of the Vela Pulsar Wind Nebula // Astronomy Letters. – 2023. – Vol. 49, Issue 12. – P.777-786
9. Bykov A.M., Petrov A.E., Ponomaryov G.A., Levenfish, K.P., Falanga, M. PeV proton acceleration in gamma-ray binaries // Advances in Space Research. – 2024. – Vol. 74, Issue 9. – P. 4276-4289
10. Levenfish K.P., Ponomaryov G.A., Fursov A.N. On New X-ray features of the Vela Pulsar Wind Nebula // Astronomy Letters. – 2025. – Vol. 51, Issue 3, – P.151-176

Splitting of highly magnetized flows





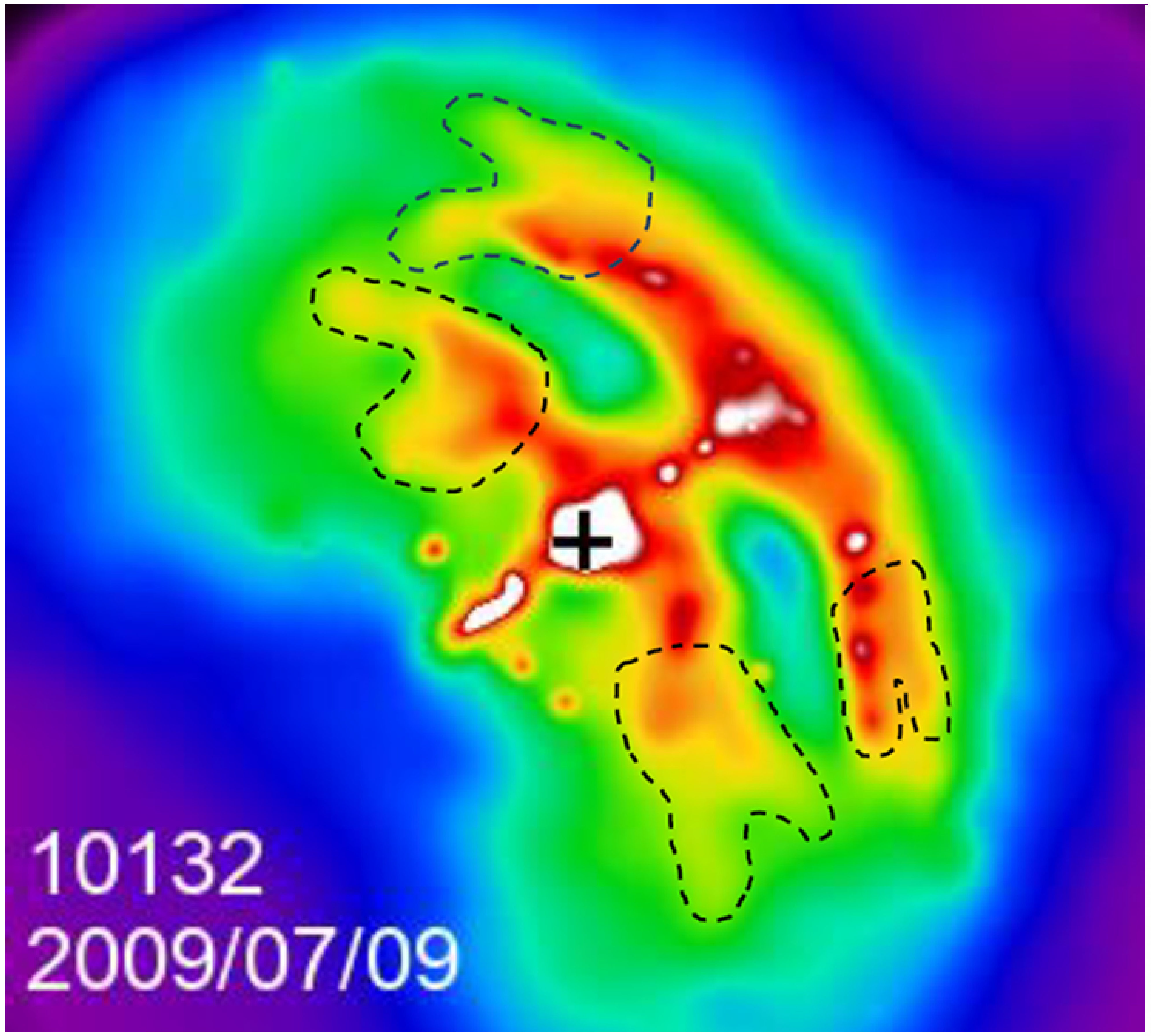
$\alpha = 80^\circ,\ \sigma_0 = 0.03$

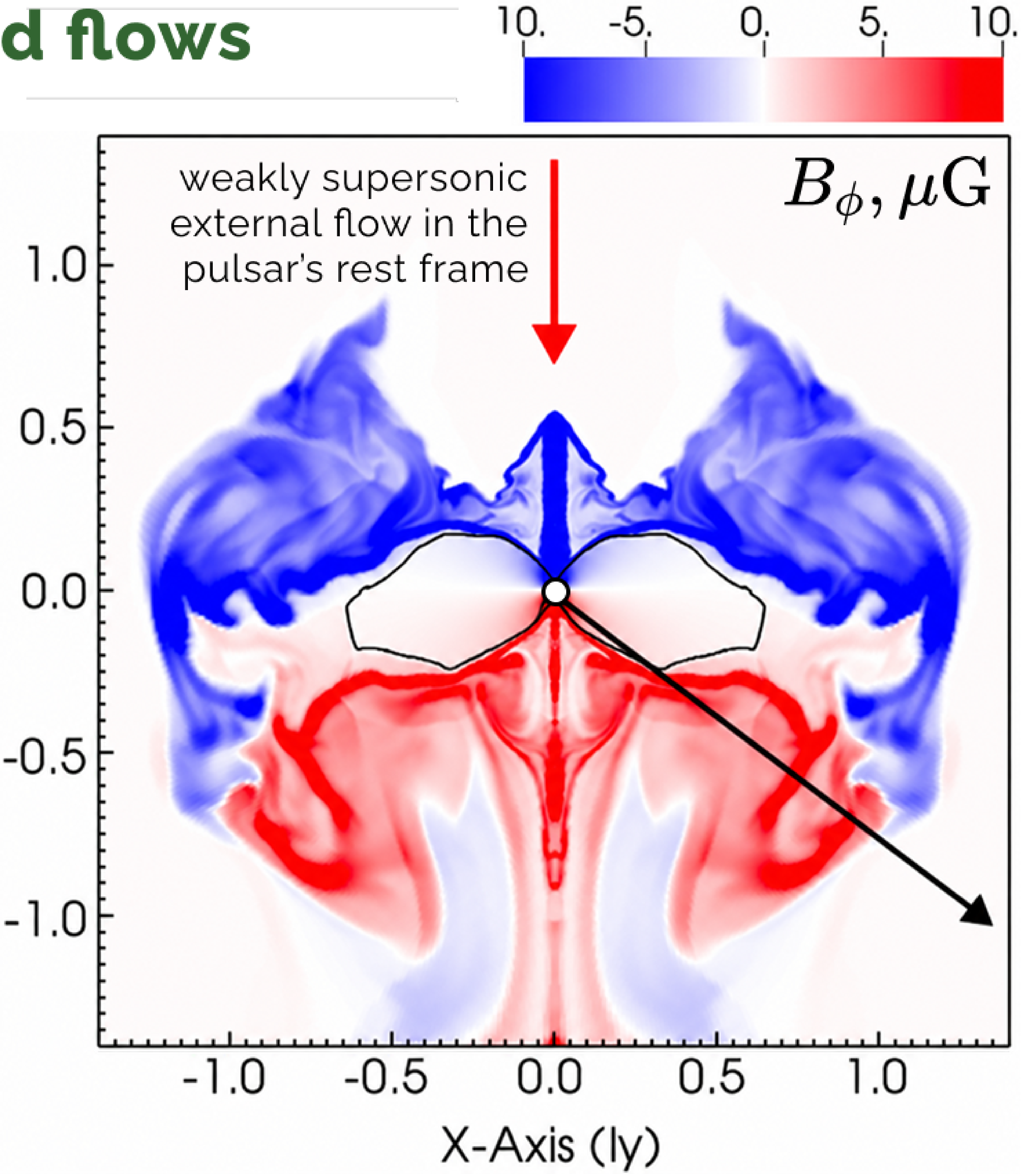
The highly magnetized flows:

- do not meet until the outer boundary of the compact nebula;
- split in two upon approaching this boundary

splitting is visible in all 11 Vela images taken by Chandra in 2009-2010

Splitting of highly magnetized flows



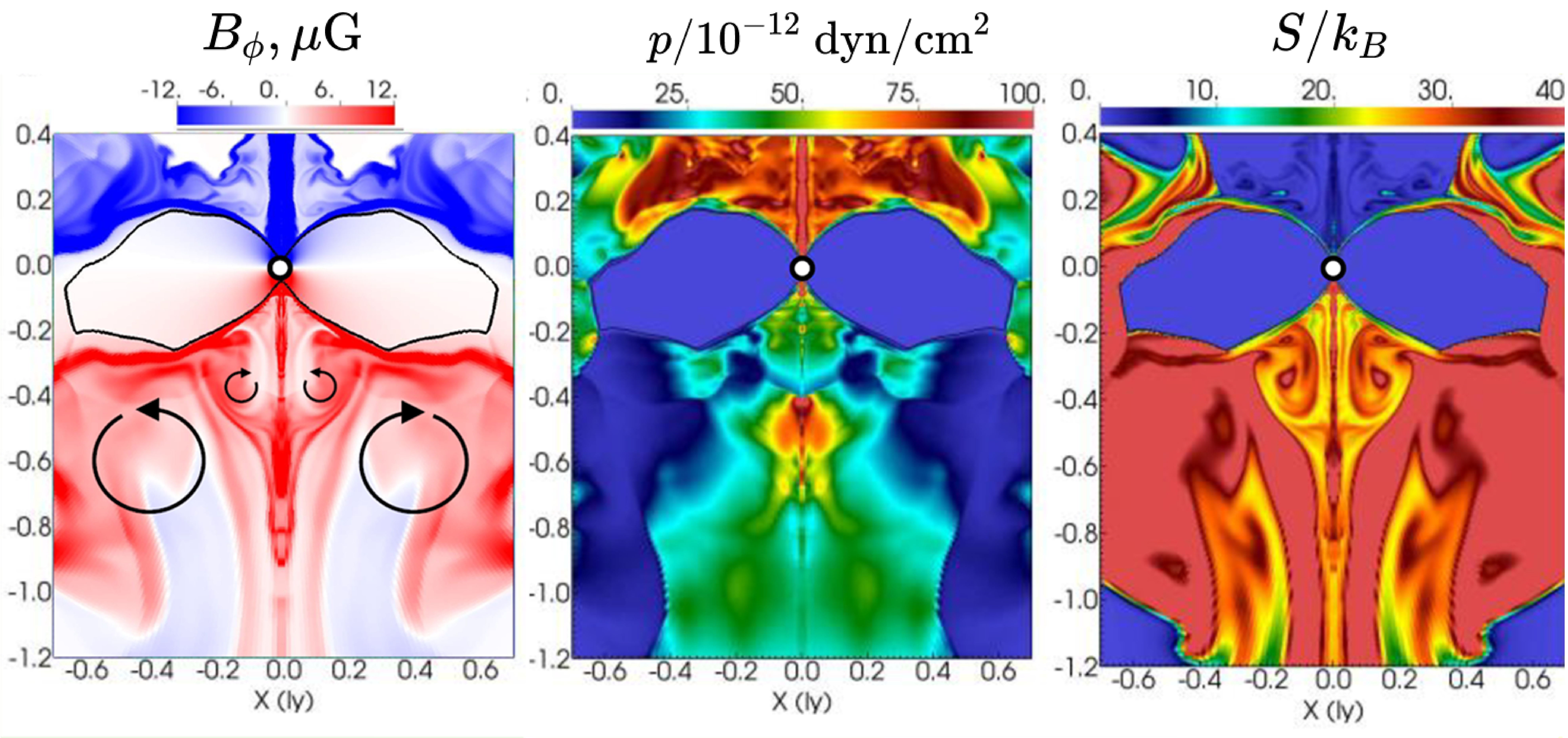


$$\alpha = 80^\circ,\ \sigma_0 = 0.1,\ M_s = 2.3$$

The highly magnetized flows:

- do not meet until the outer boundary of the compact nebula;
- split in two upon approaching this boundary
- the smaller vortices, that split off from each circulation toward the equator are stretched into magnetic plumes (sporadically penetrating into the opposite hemisphere) when a nebula is set to evolve in a directed external flow

Recirculation vortex: zoom in the lee funnel of the TS



magnetic field

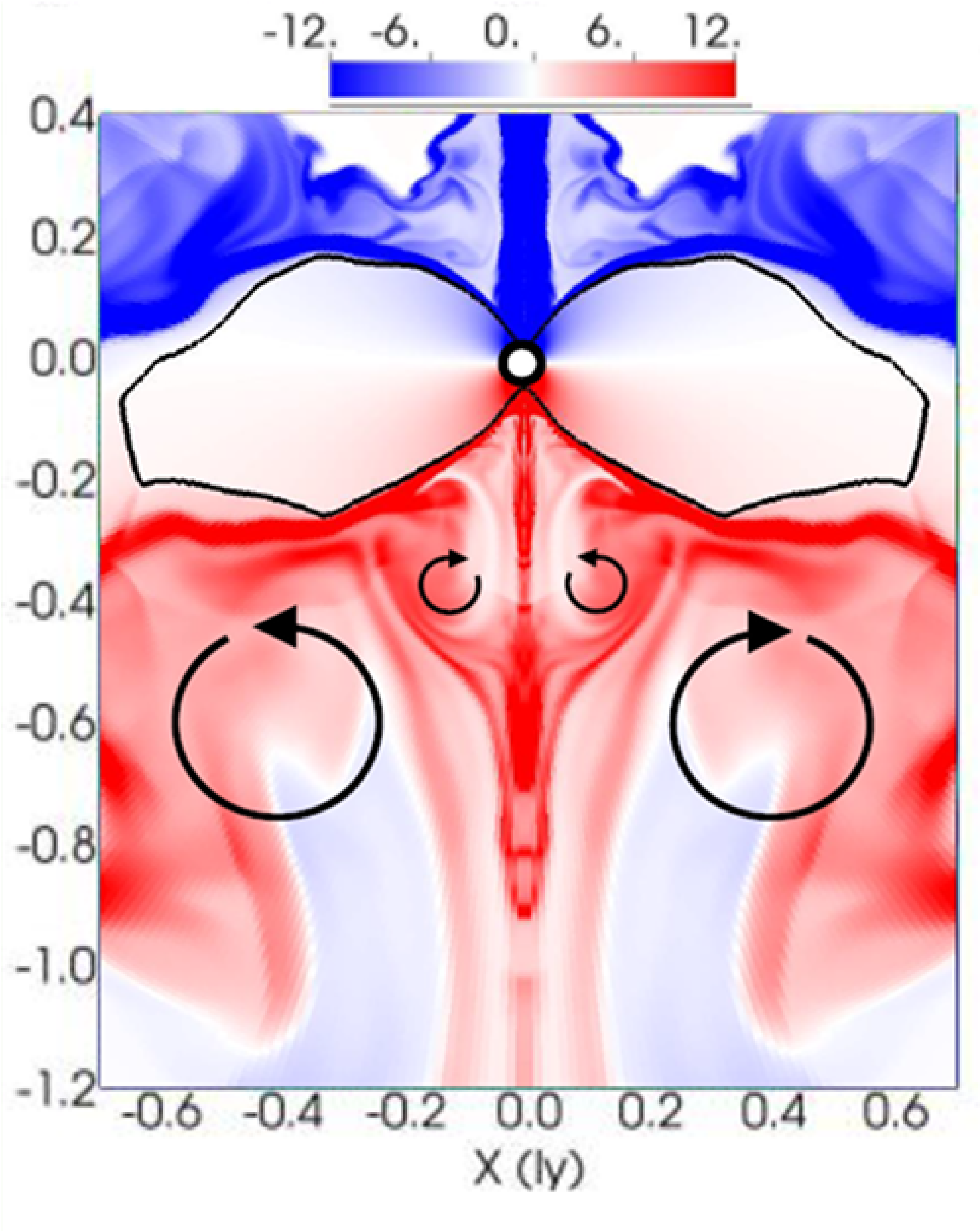
pressure

enthropy

Fateeva+2023

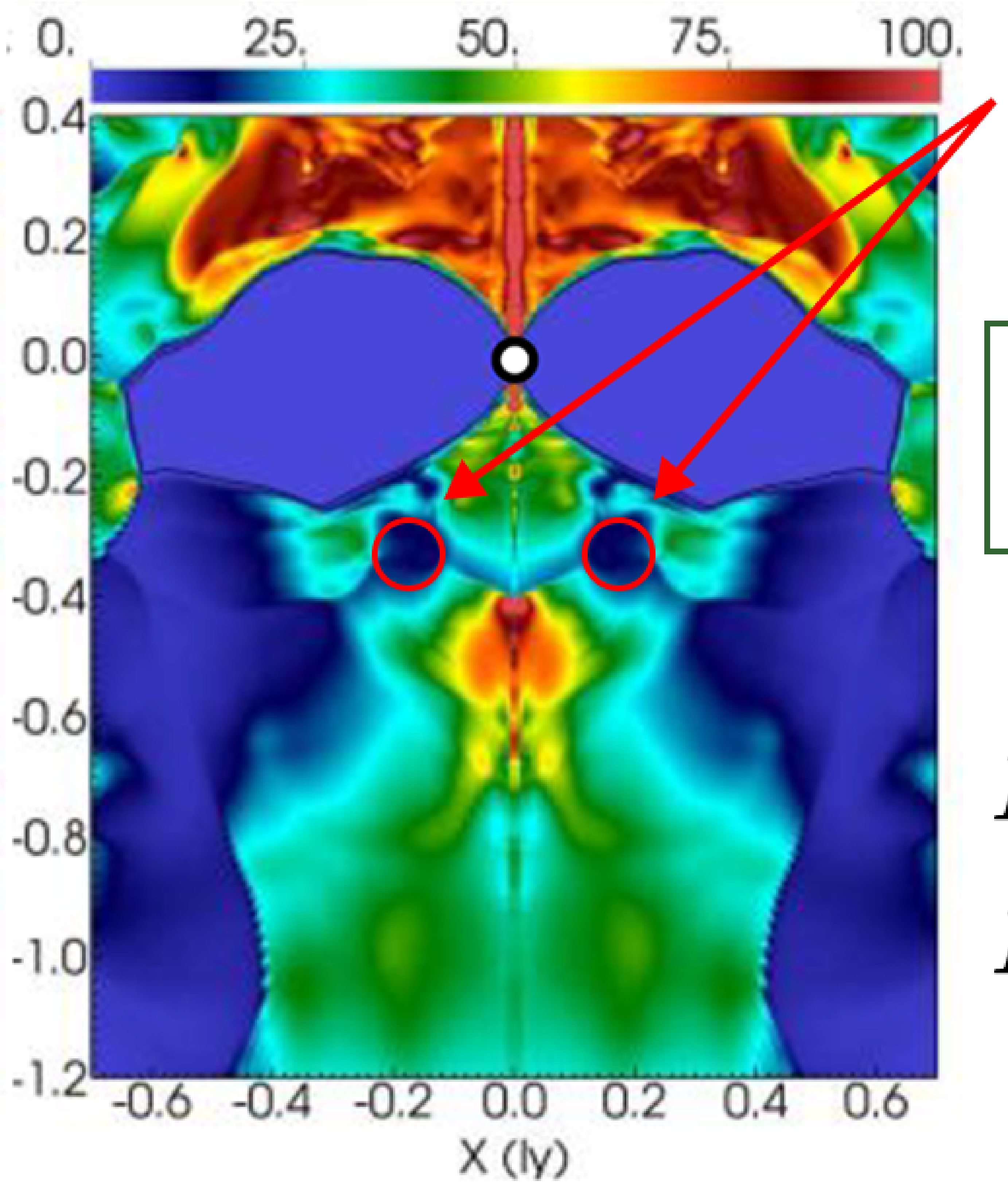
Recirculation vortex: zoom in the lee funnel of the TS

B_ϕ, μG



Fateeva+2023

$p/10^{-12}$ dyn/cm^2



regions of reduced P

$$\boxed{\epsilon \propto p B'^{\lambda+1}_{\perp} D^{\lambda+2} \nu^{-\lambda}}$$

Del Zanna+2006

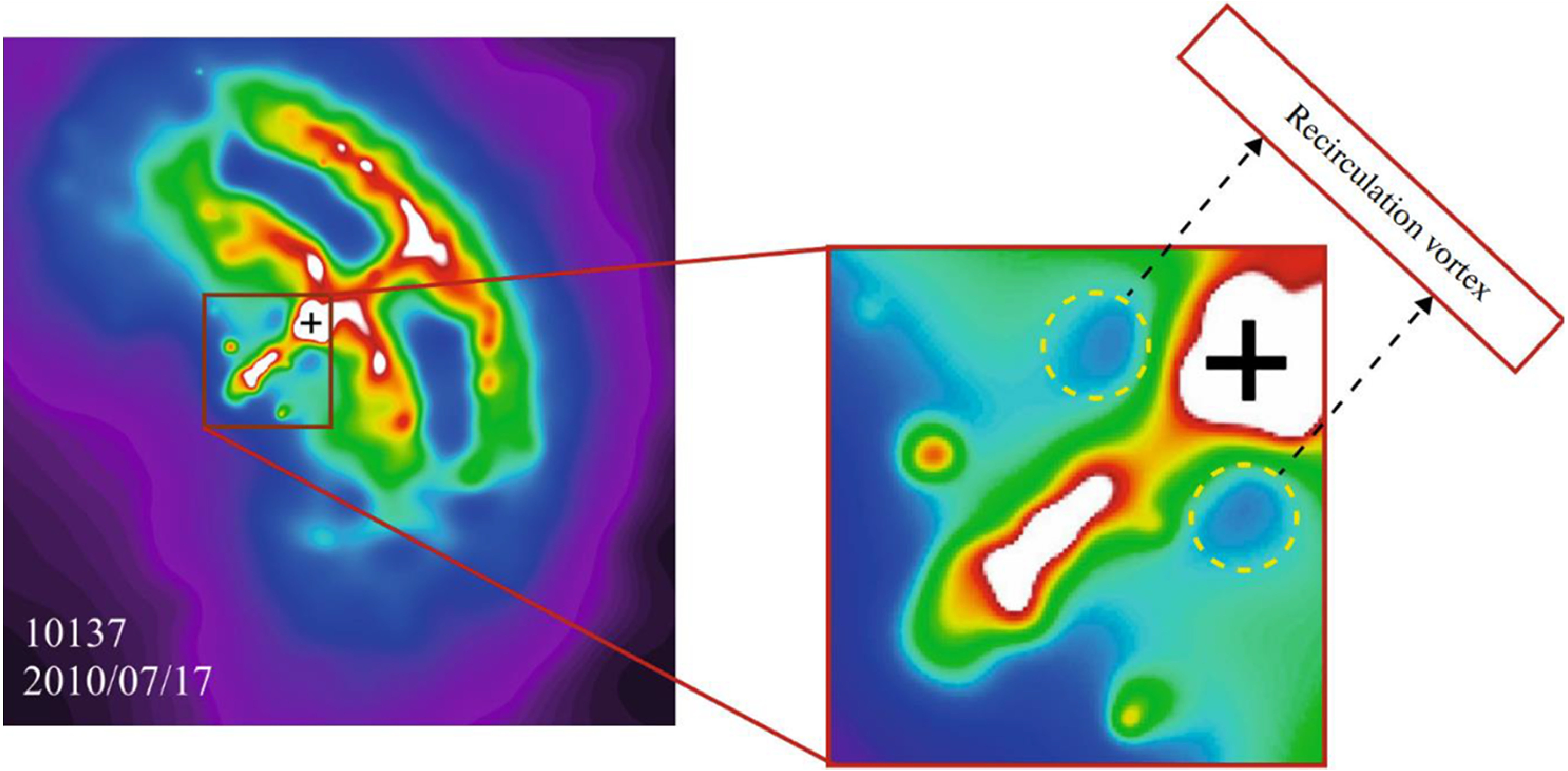
$$B'_\perp = |\mathbf{B}' \times \mathbf{n}'|$$

$$D = 1/[\gamma(1 - \mathbf{n} \cdot \mathbf{v}/c)]$$

- in the eye of the vortex the pressure is reduced

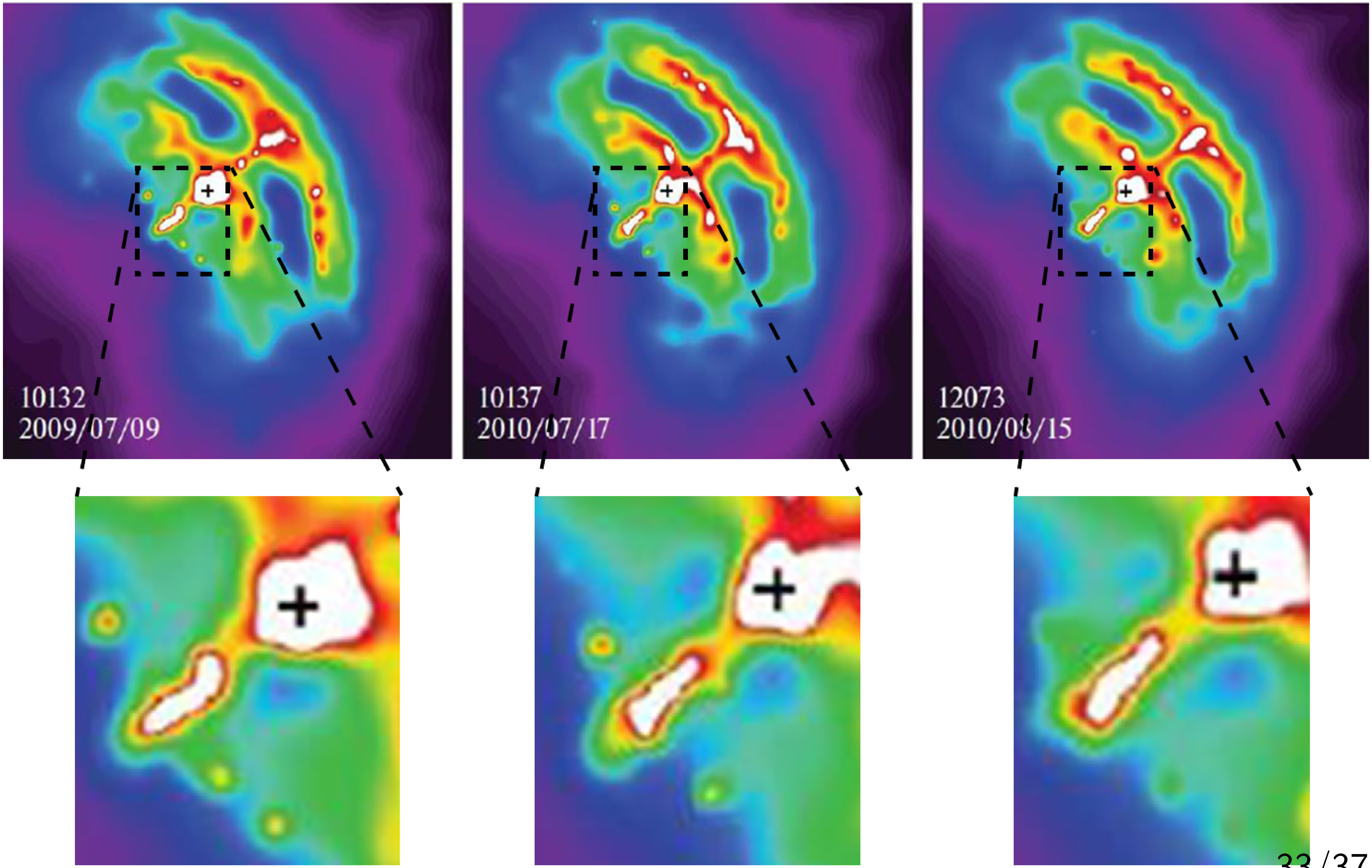
- lower pressure → lower synchrotron emissivity

Recirculation vortex in the lee funnel of the TS

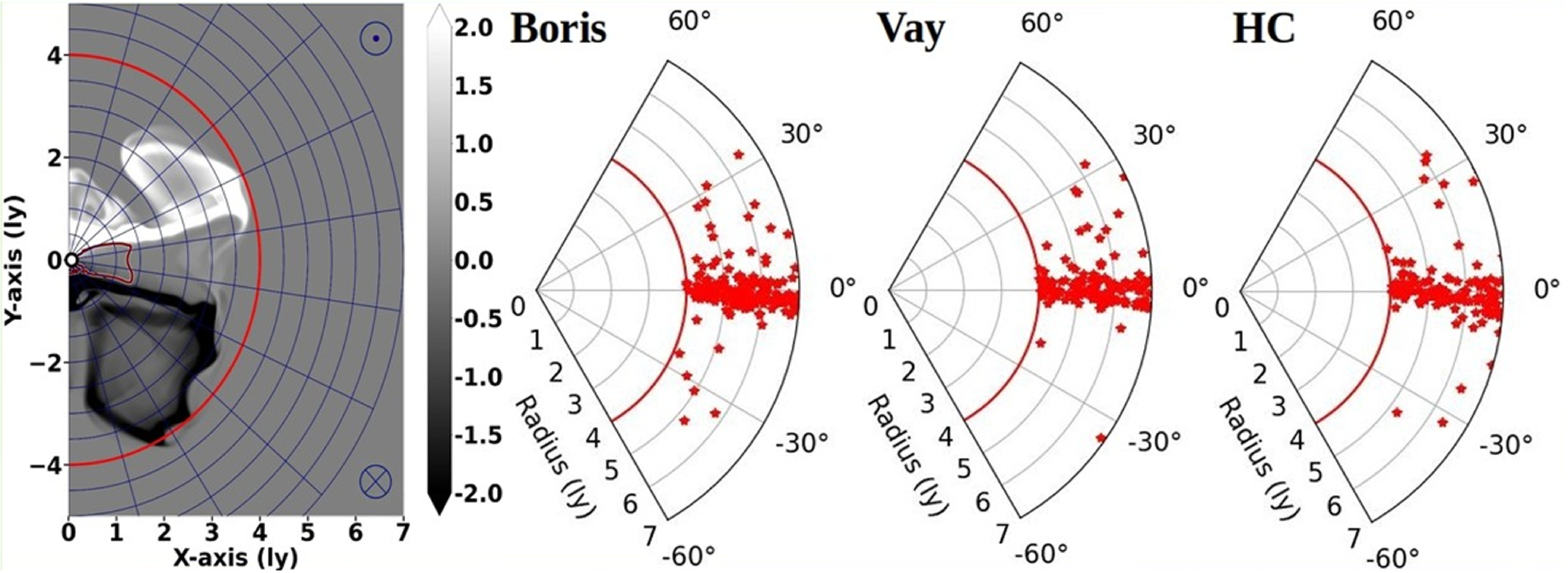


Recirculation vortex is quite dynamic

An oblique external flow can cause some asymmetry in Vela's MHD structures



Acceleration of electrons in double-torus nebulae

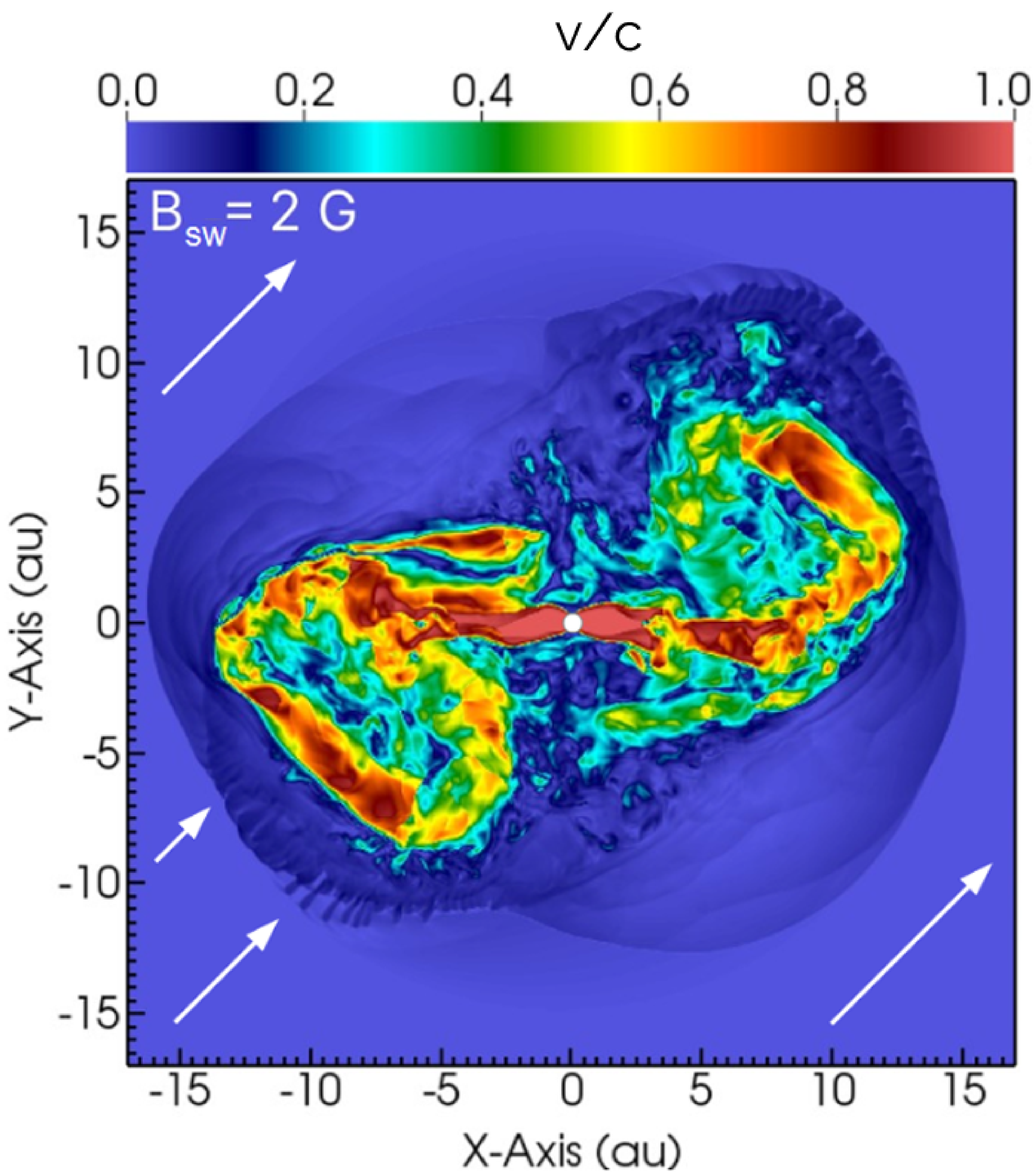


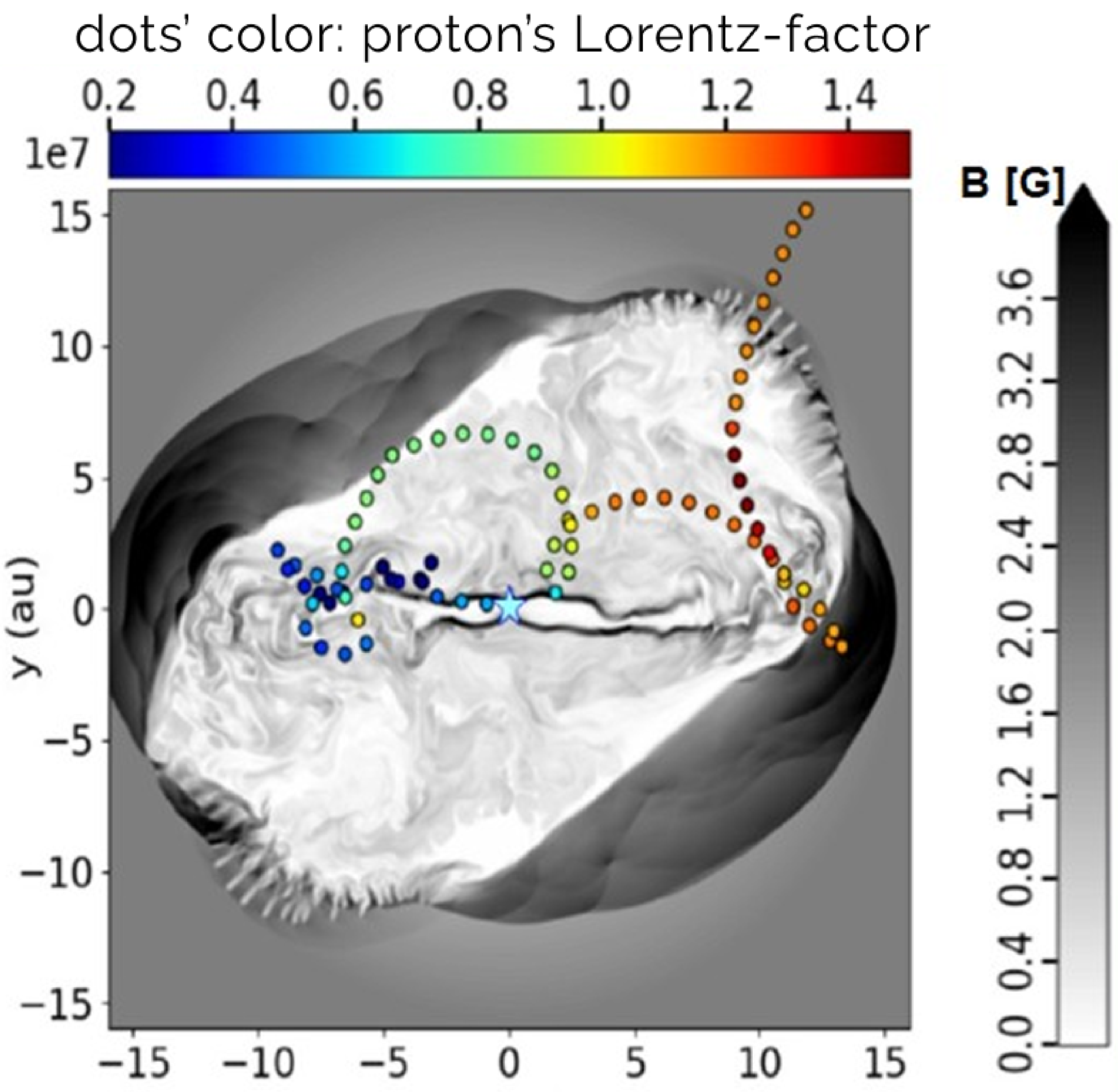
Levenfish et al. 2025

- The electrons were injected into the region, outlined in red uniformly and isotropically, with a Lorentz factor 10^7

- The figure shows the the angular distribution of **e** accelerated to Lorentz factors $\gtrsim 7 \cdot 10^8 \quad (E_e \gtrsim 350\ \mathrm{TeV})$

Proton acceleration to 14 PeV in gamma-ray binary





MHD inhomogeneities:

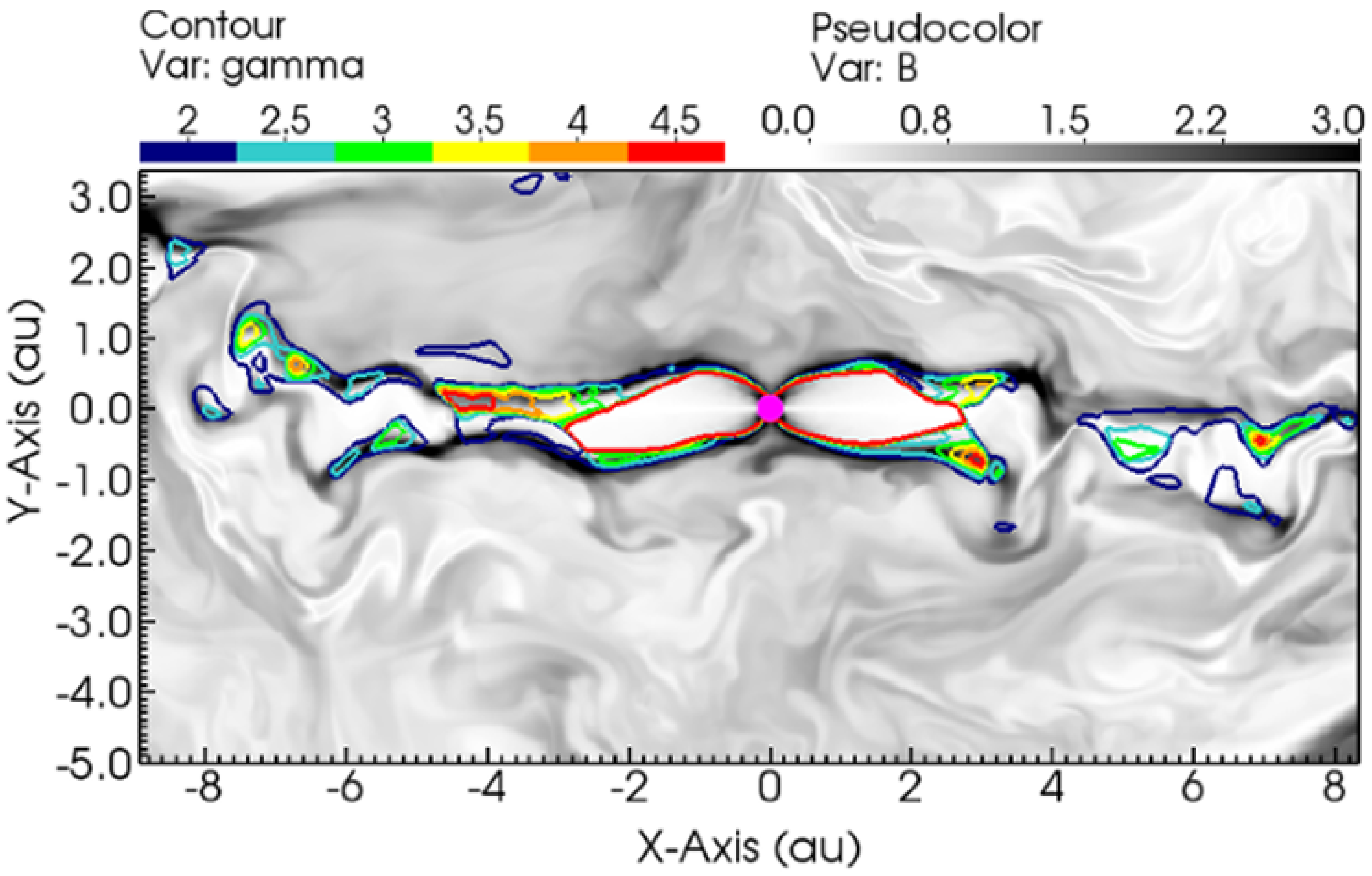
- Lorentz factors up to ~4.5
- scales ~ gyroradius of a PeV proton

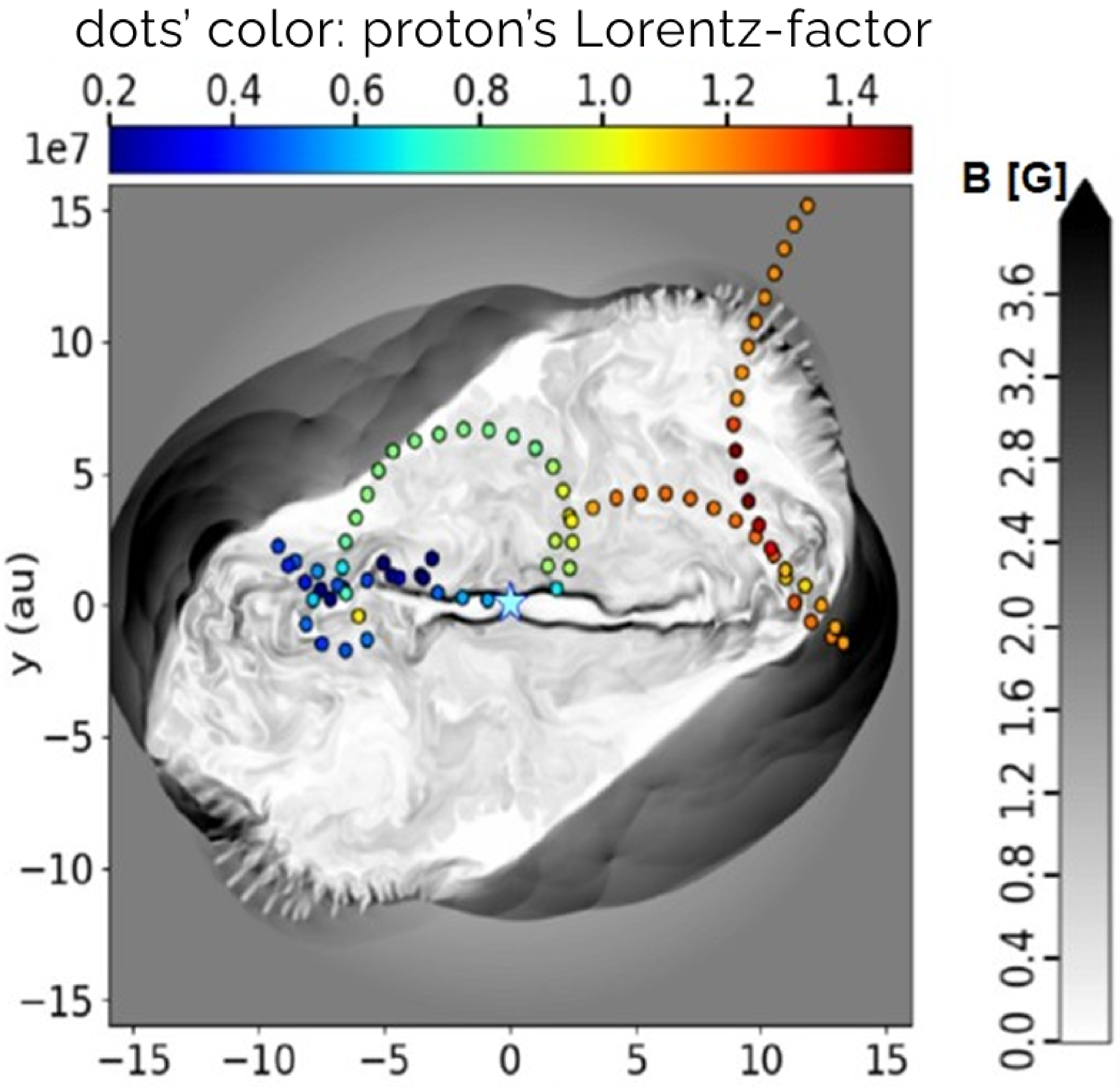
Sub-PeV proton:

- injected near the pulsar wind TS
- after few hours boosts its energy to 14 PeV and escapes the nebula

Bykov et al. 2024

Proton acceleration to 14 PeV in gamma-ray binary




dots' color: proton's Lorentz-factor

MHD inhomogeneities:

- Lorentz factors up to ~4.5
- scales ~ gyroradius of a PeV proton

Sub-PeV proton:

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- after few hours boosts its energy to 14 PeV and escapes the nebula

Bykov et al. 2024

Conclusions

- A numerical model of a double torus PWN is proposed and tested against the observations of the Vela PWN.

- The test showed that the model naturally reproduced virtually all structures of Vela including the double torus

- Based on the model predictions, several additional, previously unknown X-ray features of Vela were revealed in archived Chandra observations

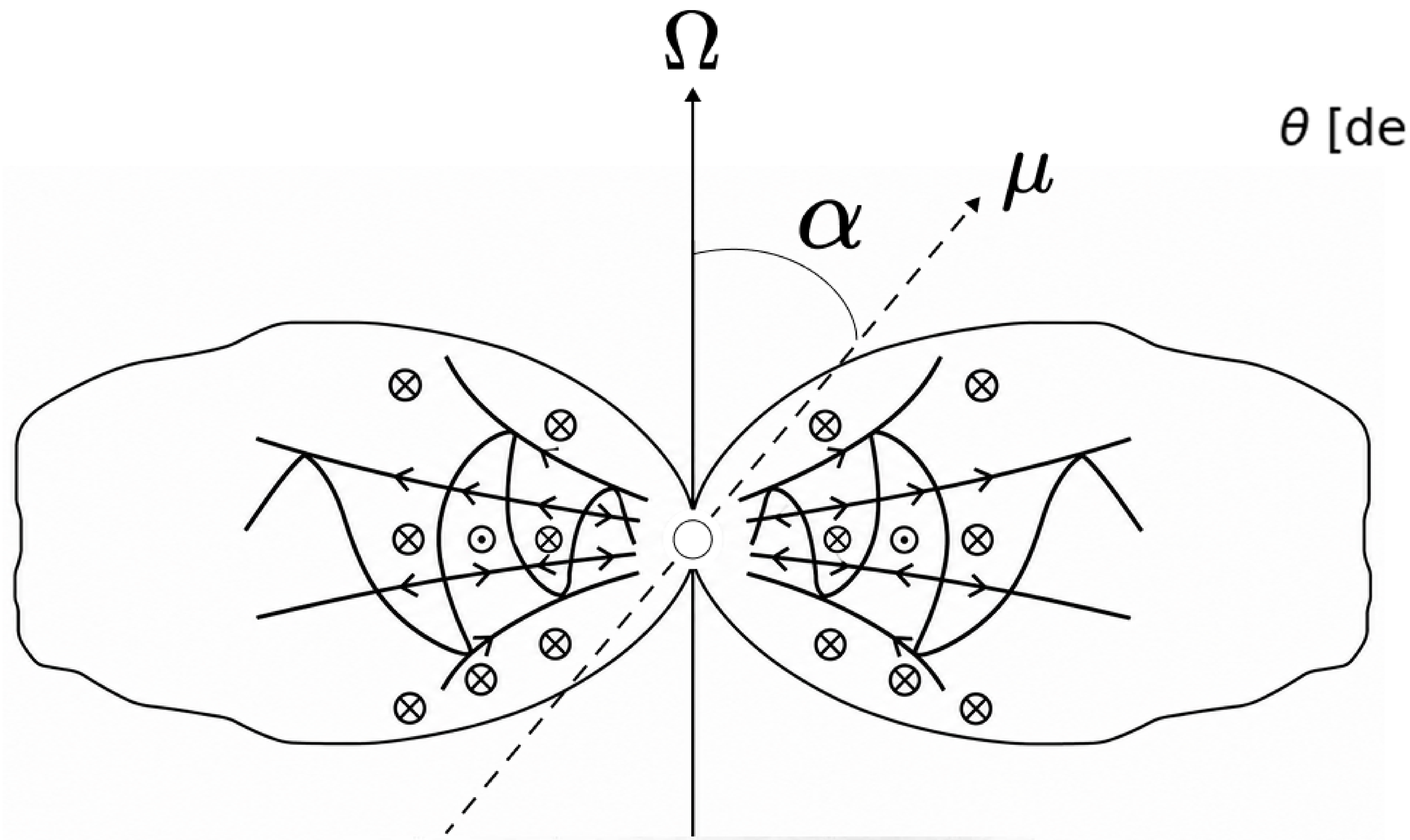
- The double torus nebulae are very unusual objects. Their large-scale magnetic fields are highly uniform and strongly dominated by a regular component

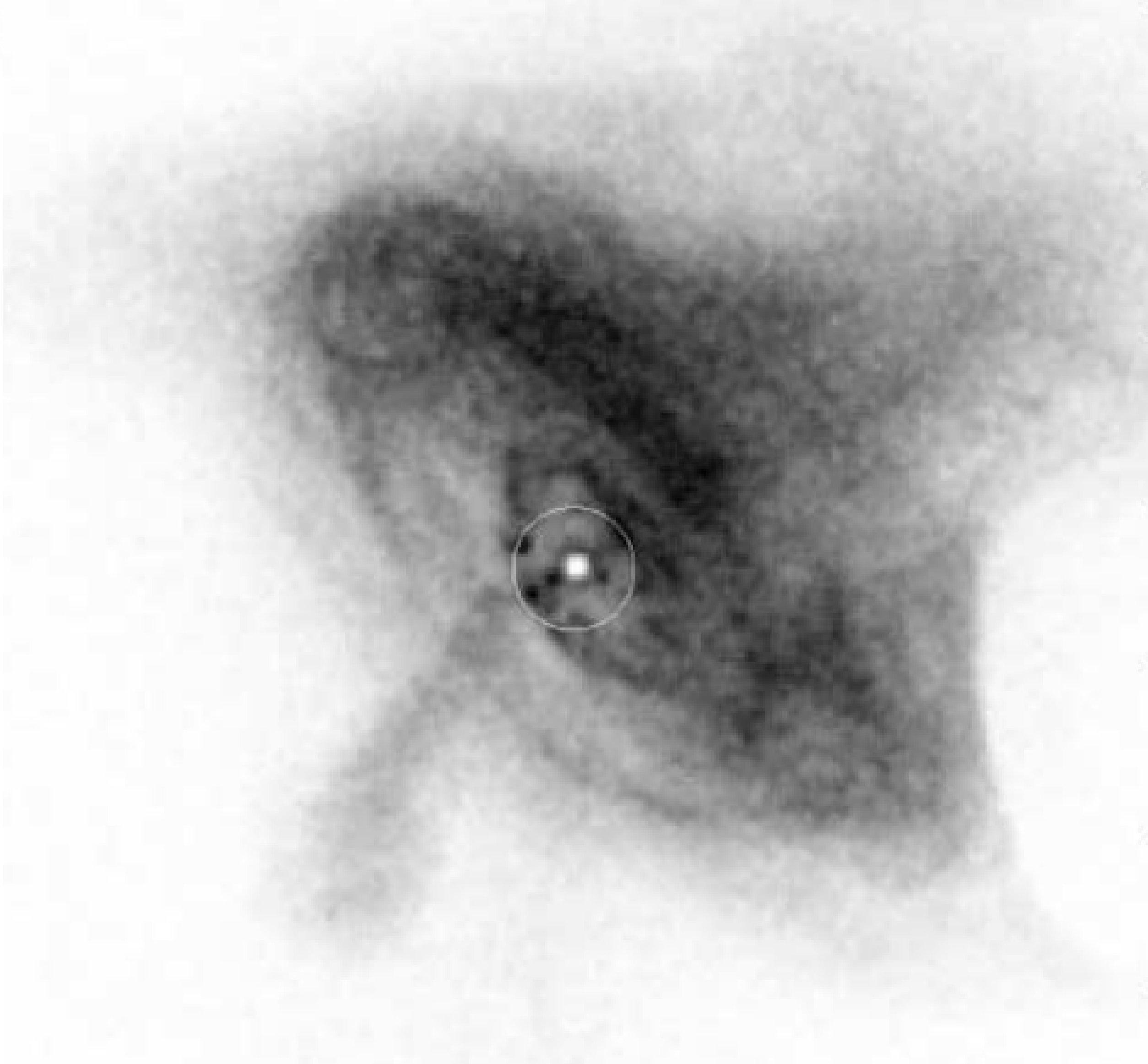
- By direct numerical modeling, we showed that high energy electrons can be accelerated <u>in the body</u> of double-torus nebulae to E ~ few hundred TeV

- We showed that PWNe in gamma-ray binaries can accelerate protons to the energies above the max. energy allowed by a pulsar's magnetospheric potential

- In gamma-ray binaries the protons can be accelerated to energies above 10 PeV. So the PWNe in gamma-ray binaries are good candidates to galactic Pevatrons!

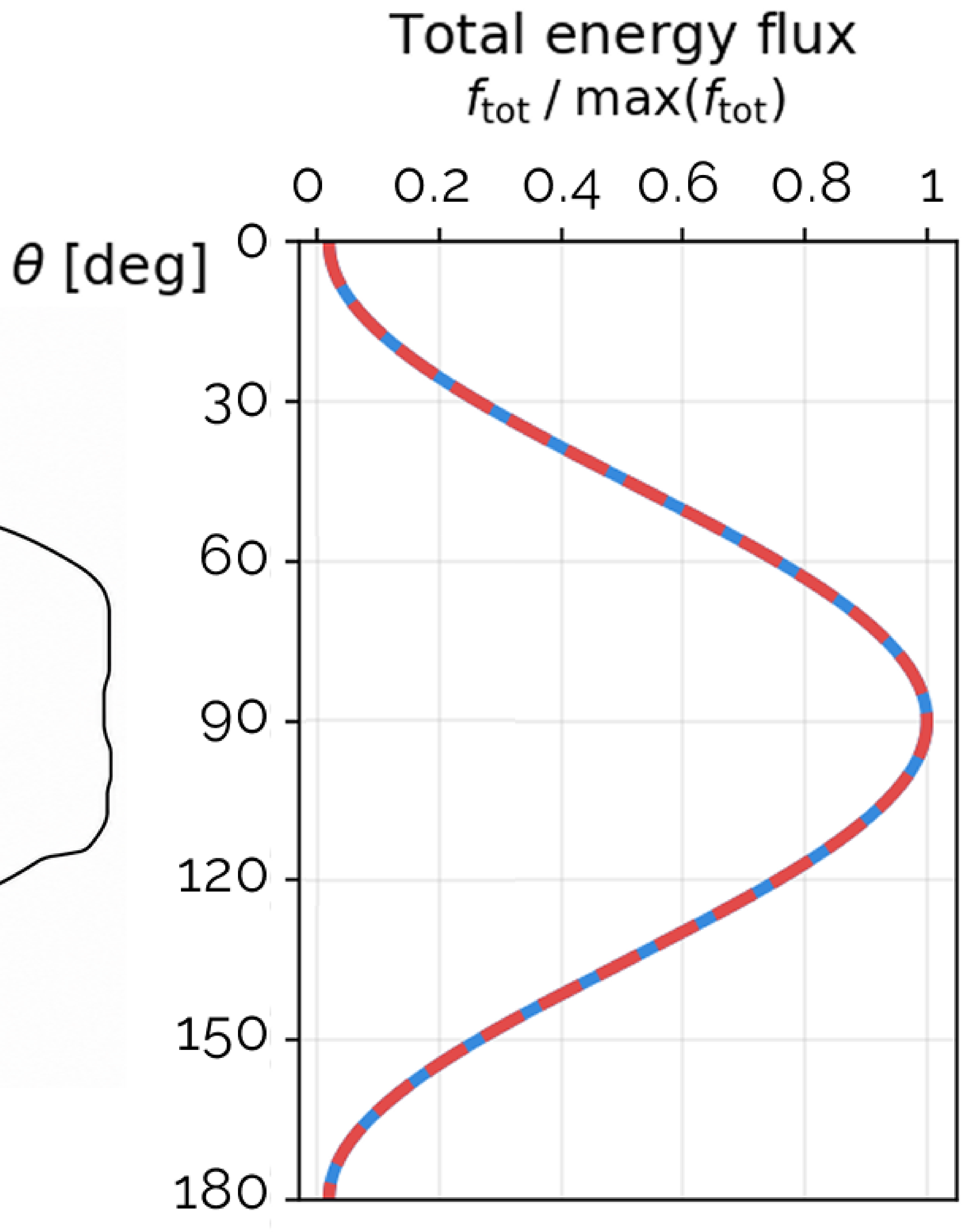
Backup slides





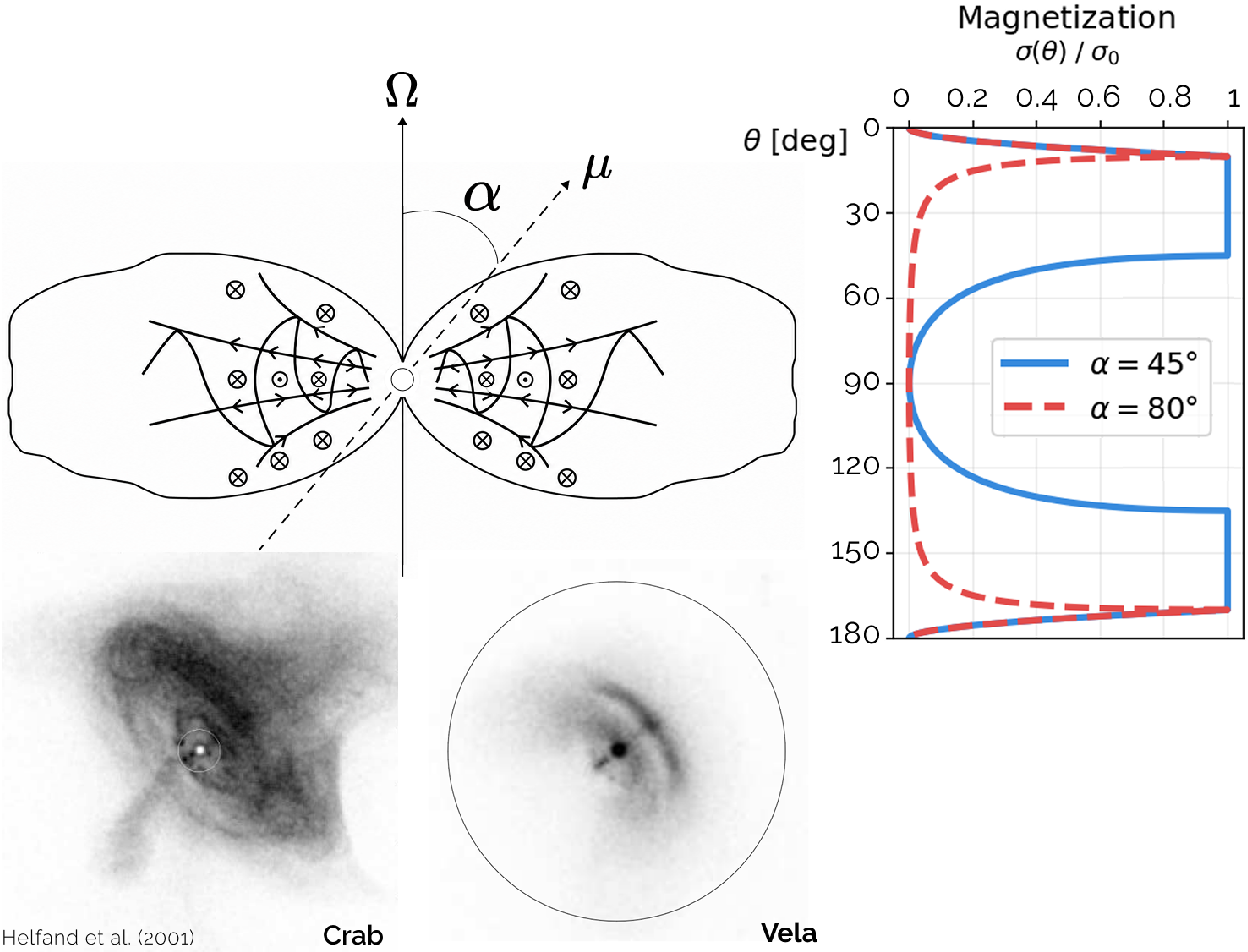
Helfand et al. (2001)

Crab PWN



$$f_{\rm tot}(r,\theta)=\frac{L}{L'}\left(\frac{1}{r^2}\right)(\sin^2\theta+b)$$

see e.g. Porth et al. 2014

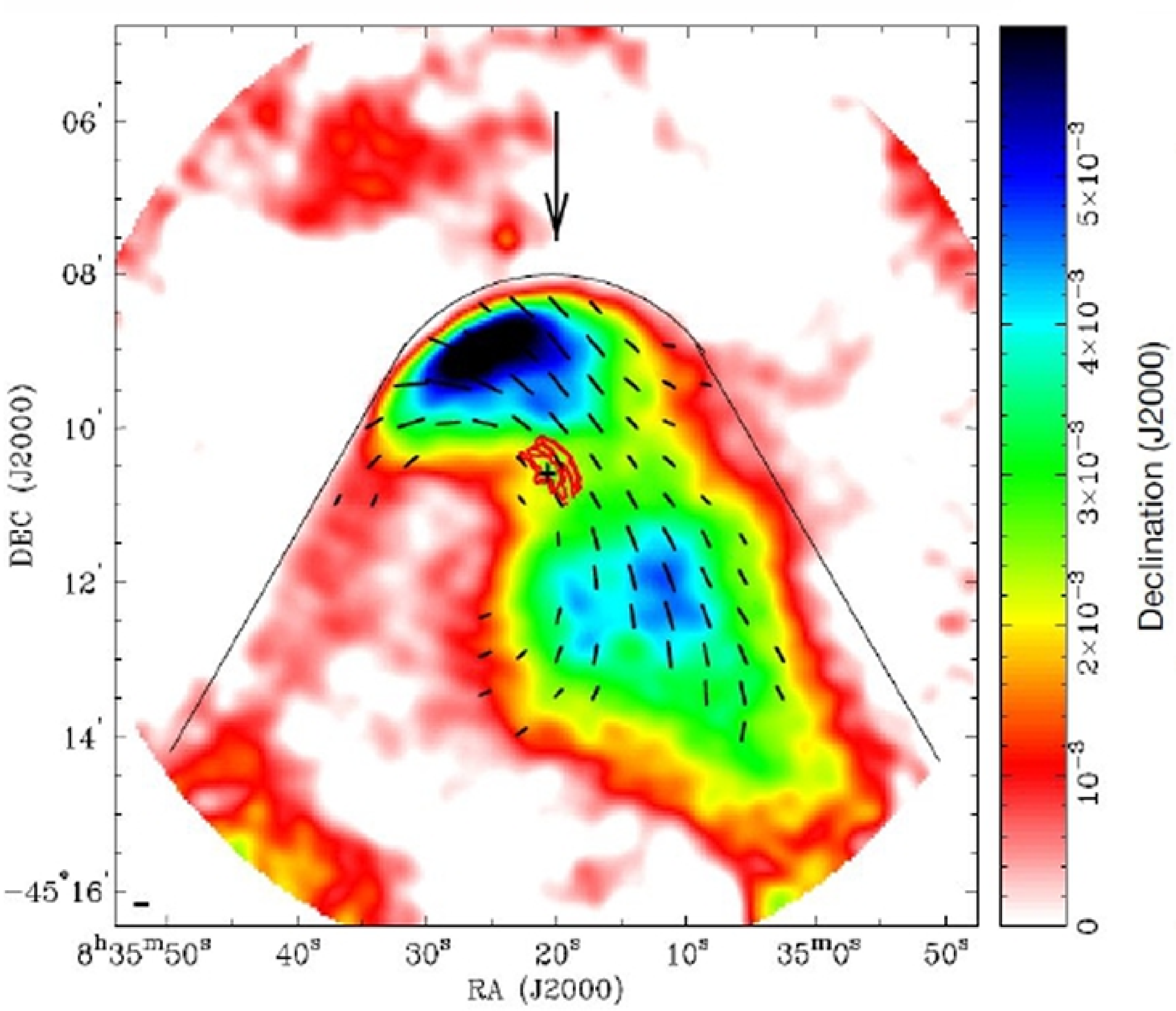


Helfand et al. (2001)

Polarization of the Vela PWN: Radio vs X-ray

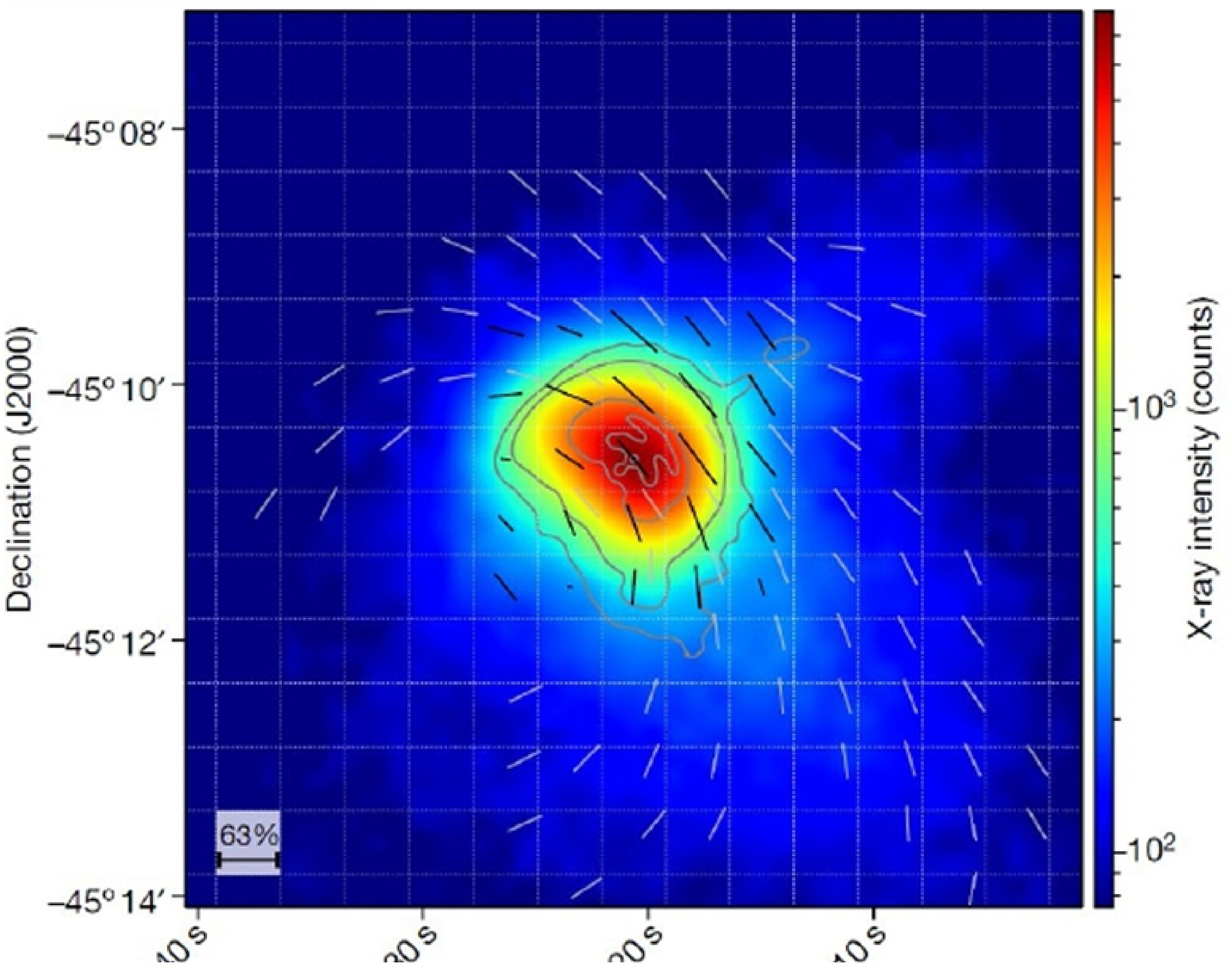
Radio (5 GHz)

Dodson+2003; Chevalier & Reynolds (2011)



X-ray (2-8 keV)

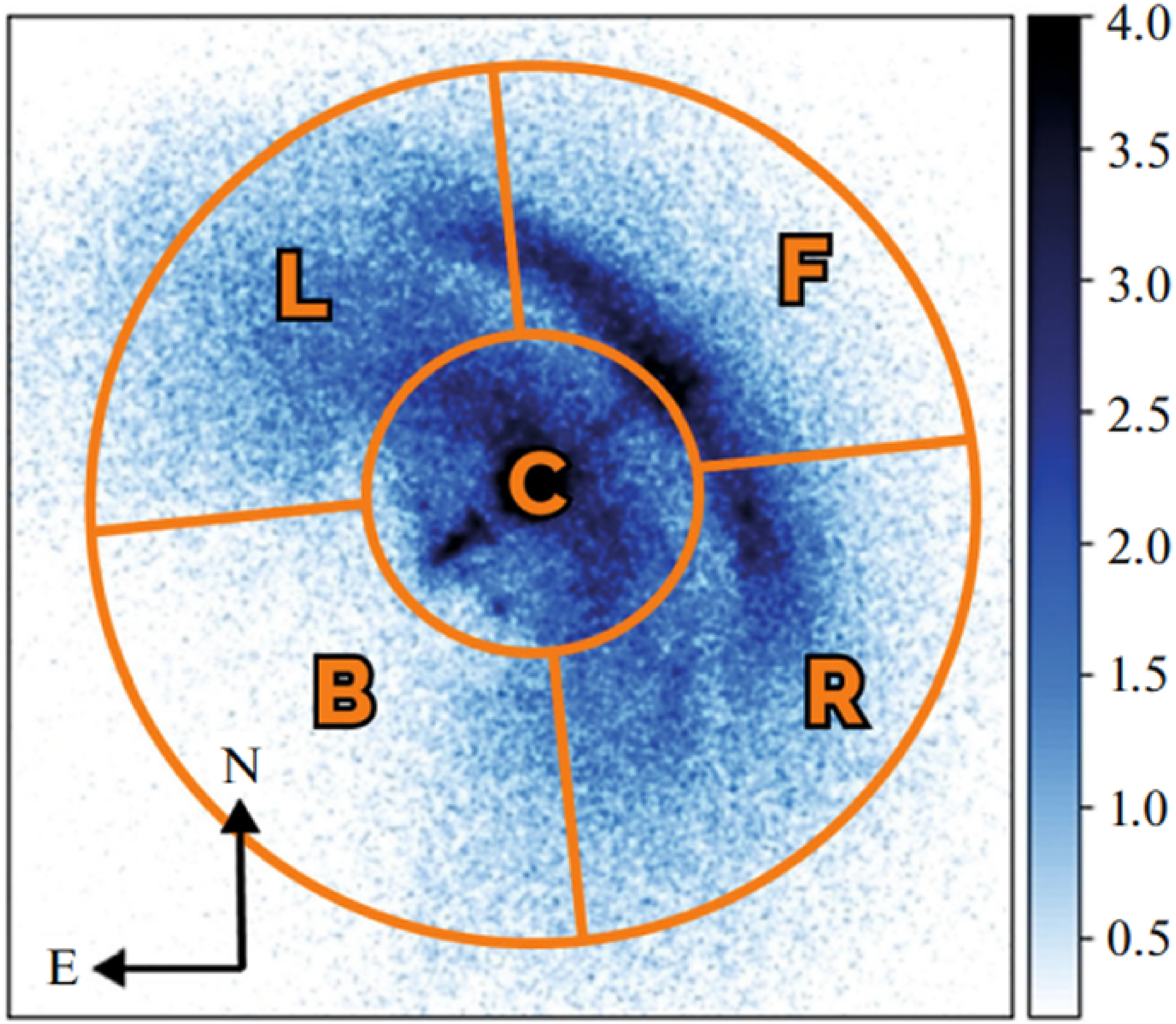
Xie et al. 2023



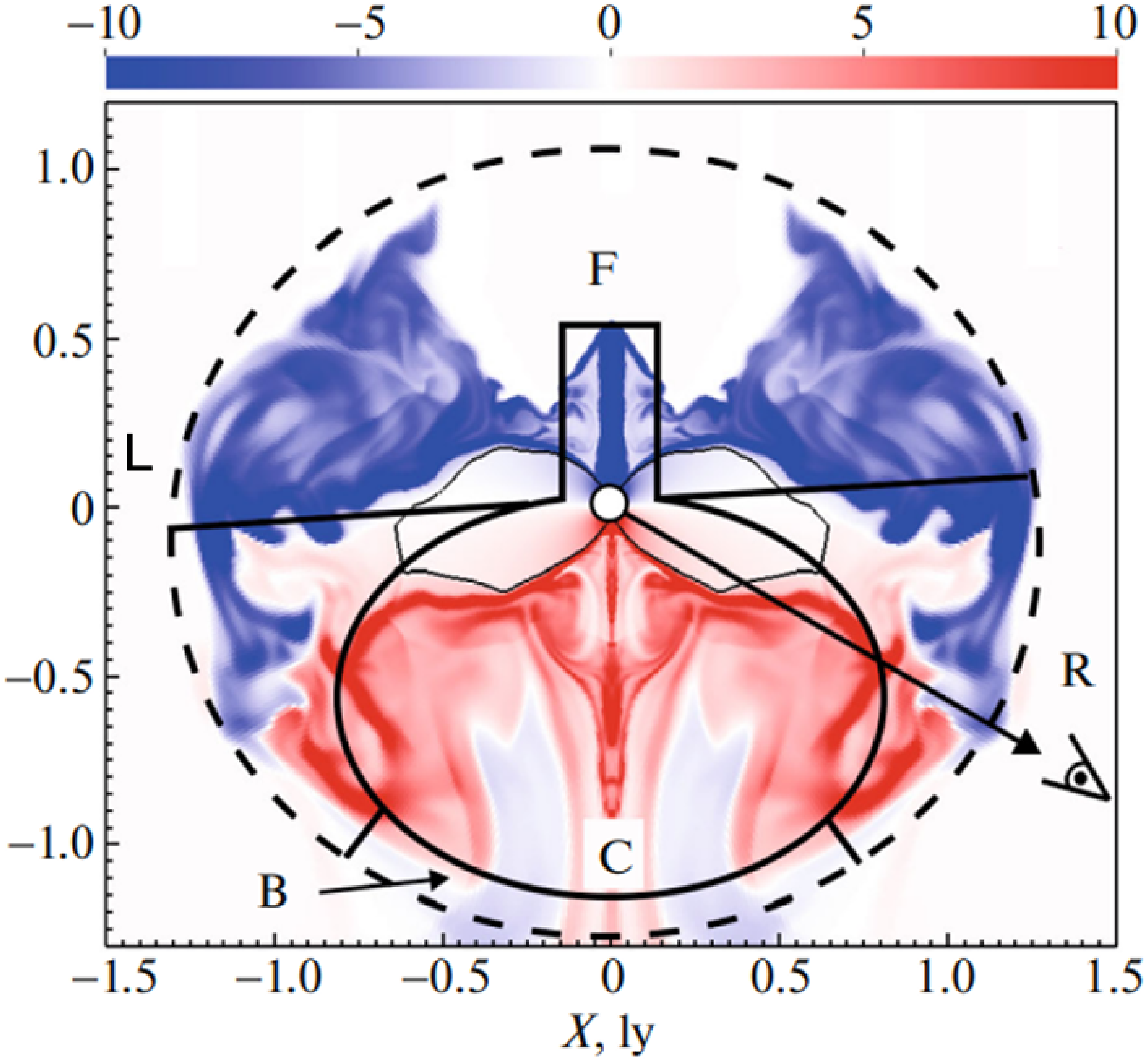
In both radio and X-rays the polarization vectors are symmetric relative to the PWN axis, which indicates that:

- the toroidal field is highly regular in the whole nebula's volume
- the level of the large-scale turbulence is extremely low

Polarization of different regions of the compact Vela



reproduced after Xie et al. (2022)

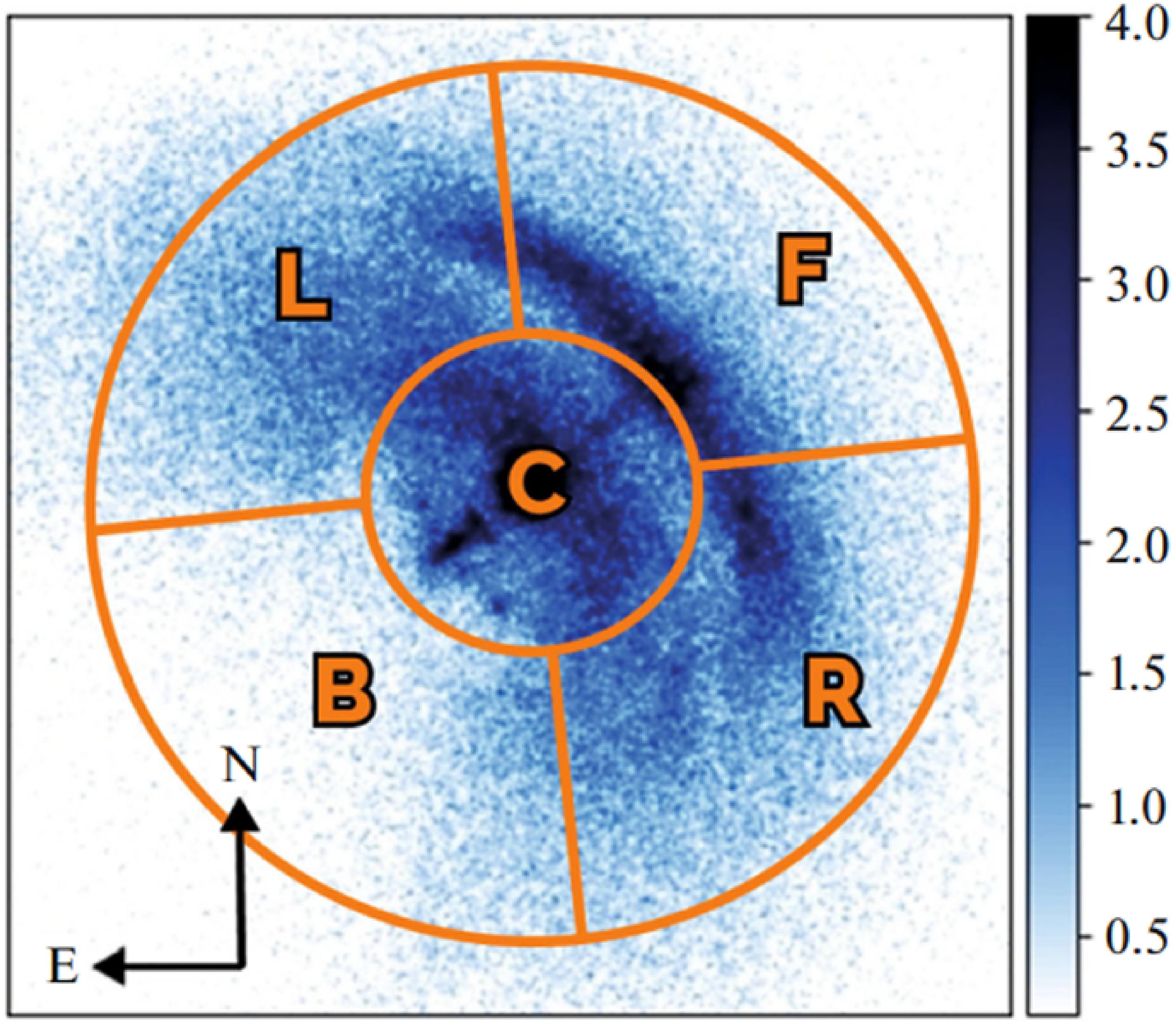


	PD (%)
F	70.0 +/- 3.6
R	56.0 +/- 3.1
L	42.0 +/- 3.0
C	49.6 +/- 2.5
B	33.3 +/- 3.6

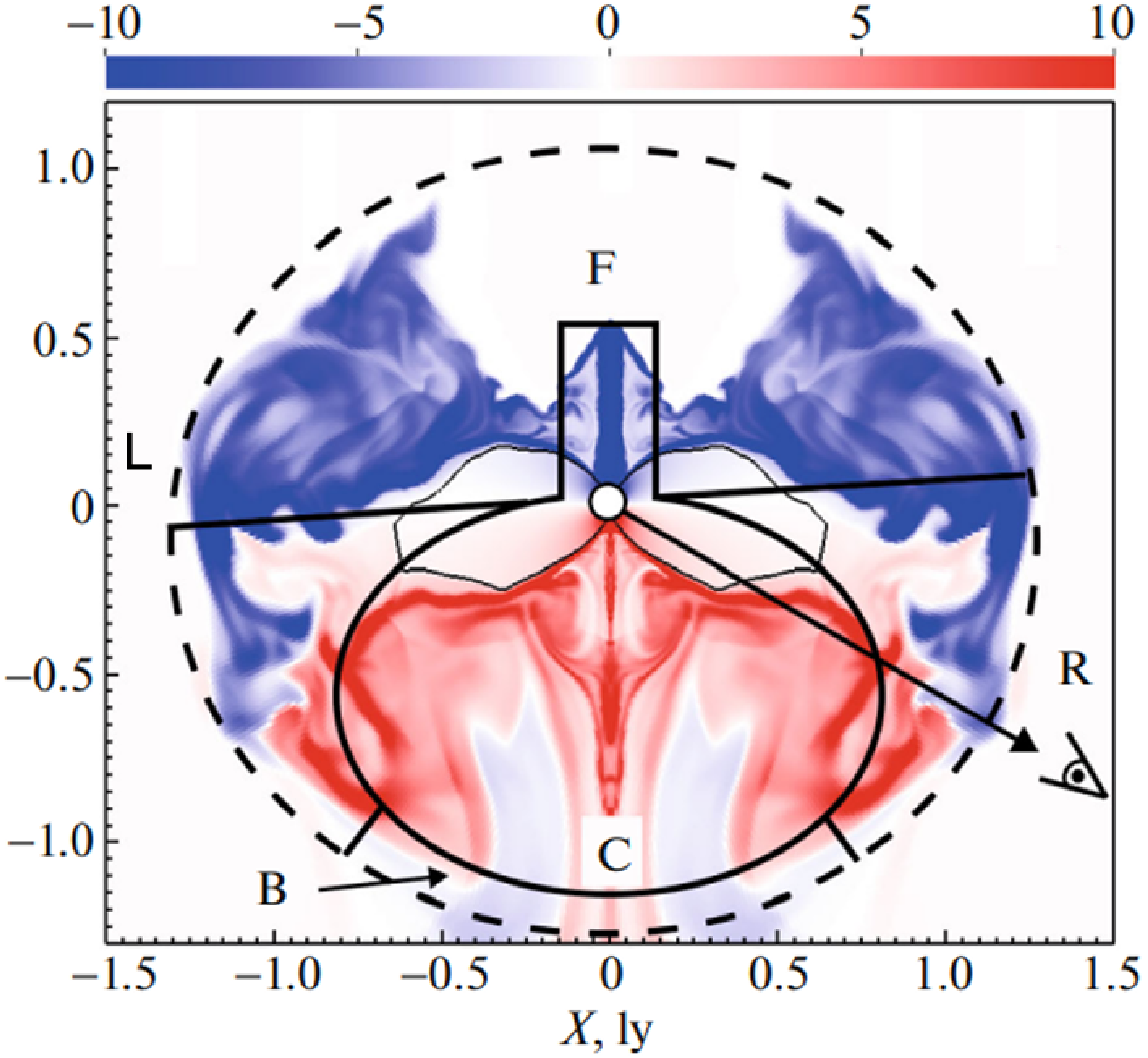
Causes of depolarization:

- several (overlapping) MHD structures with different B-field orientations in a region
- a strong projected curvature of MHD structures
- relativistic aberration → E-field vector rotates faster than the curvature changes.
- a significant turbulent B-component in a region

Polarization of different regions of the compact Vela



reproduced after Xie et al. (2022)



PD (%)	
F	70.0 +/- 3.6
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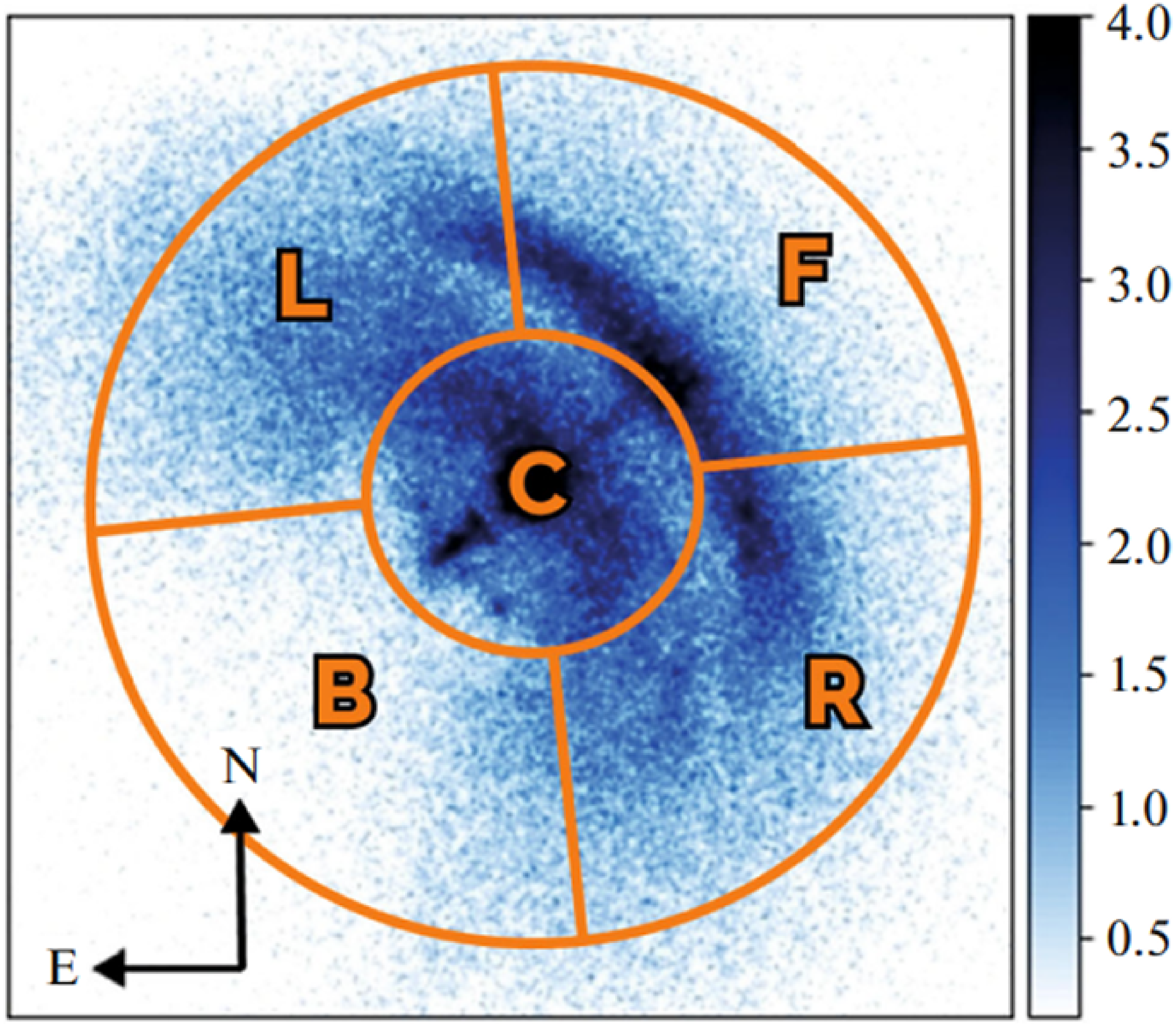
C	**49.6 +/- 2.5**
B	33.3 +/- 3.6

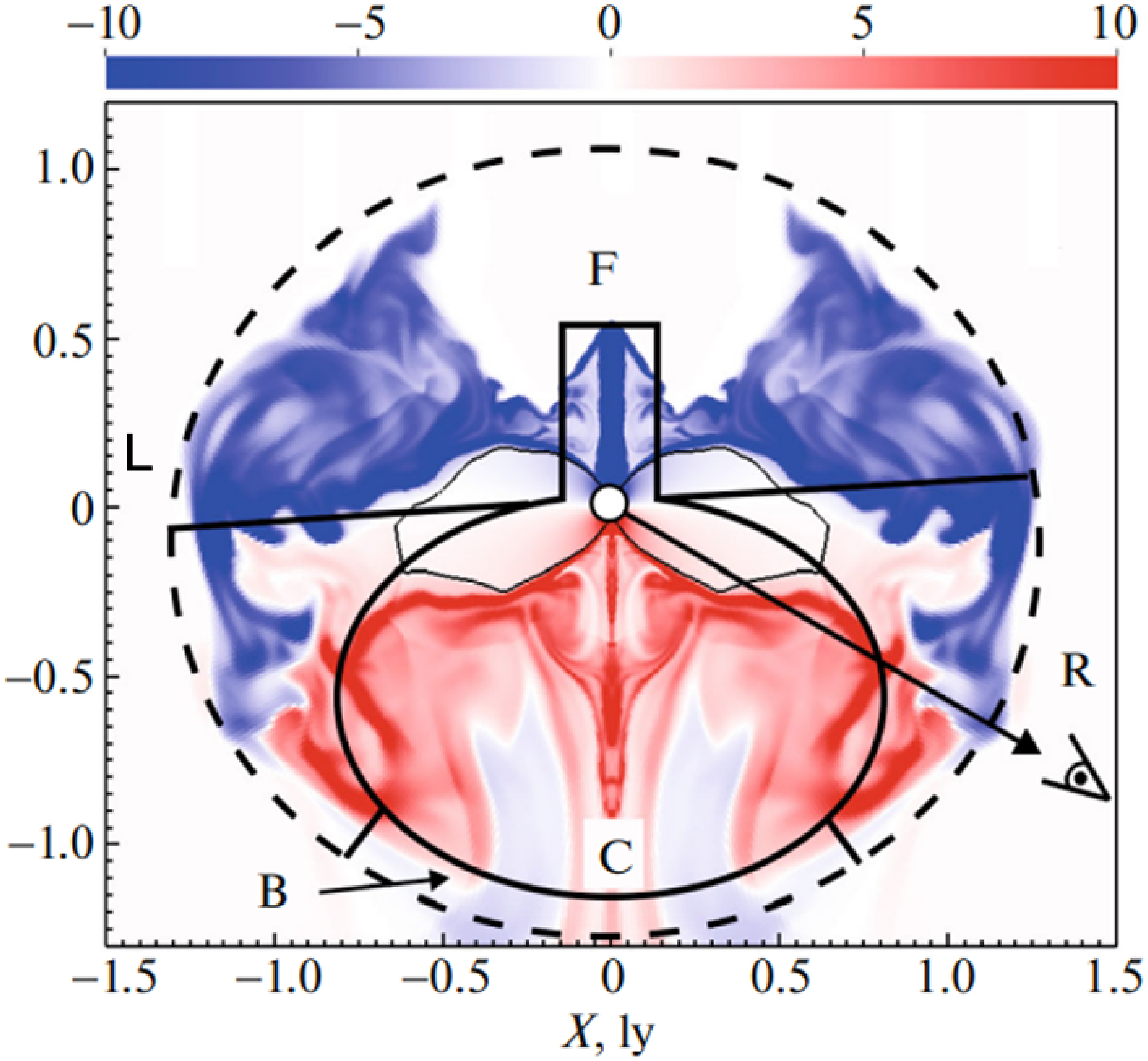
features in the region C

- pulsar
- lee torus
- back part of the windward torus
- recirculation vortex
- bright lee jet's part
- bright transverse bar
- chain of knots

Polarization of different regions of the compact Vela



reproduced after Xie et al. (2022)



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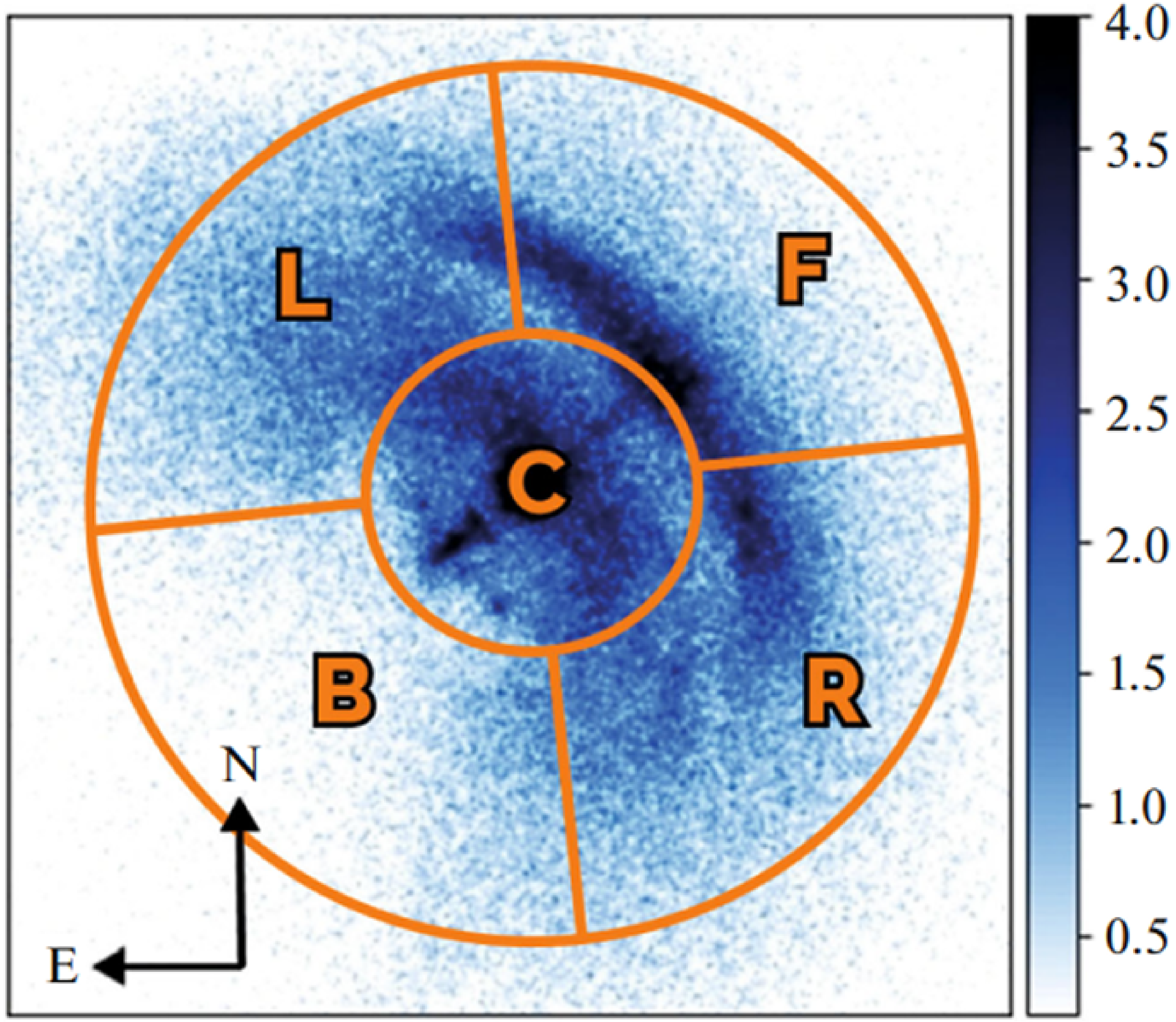
features the in region F

- the bright, near-axis part of the windward arc, which is less curved in projection
- the outer part of the windward jet

Polarization of different regions of the compact Vela



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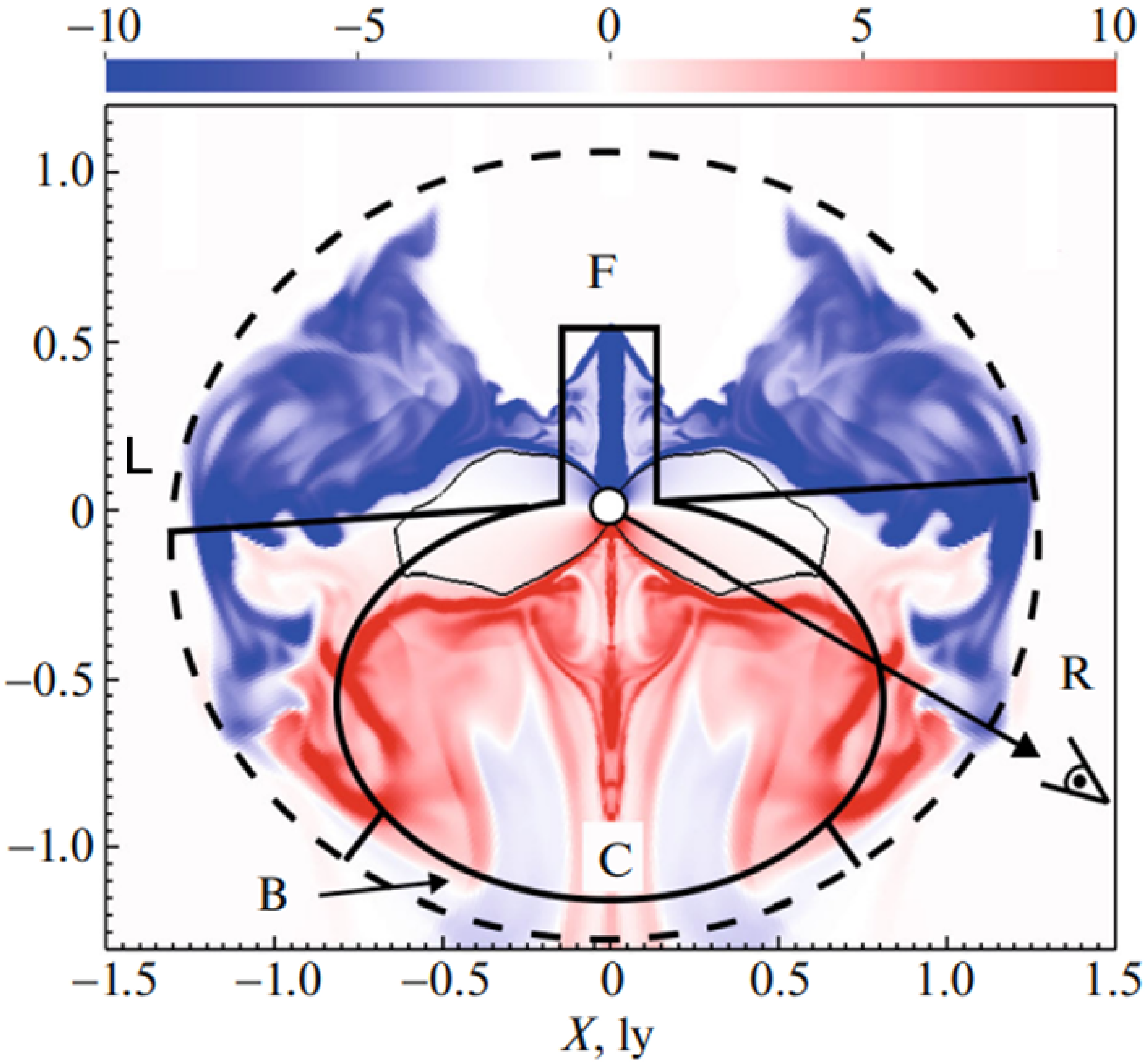

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features in the regions L, R

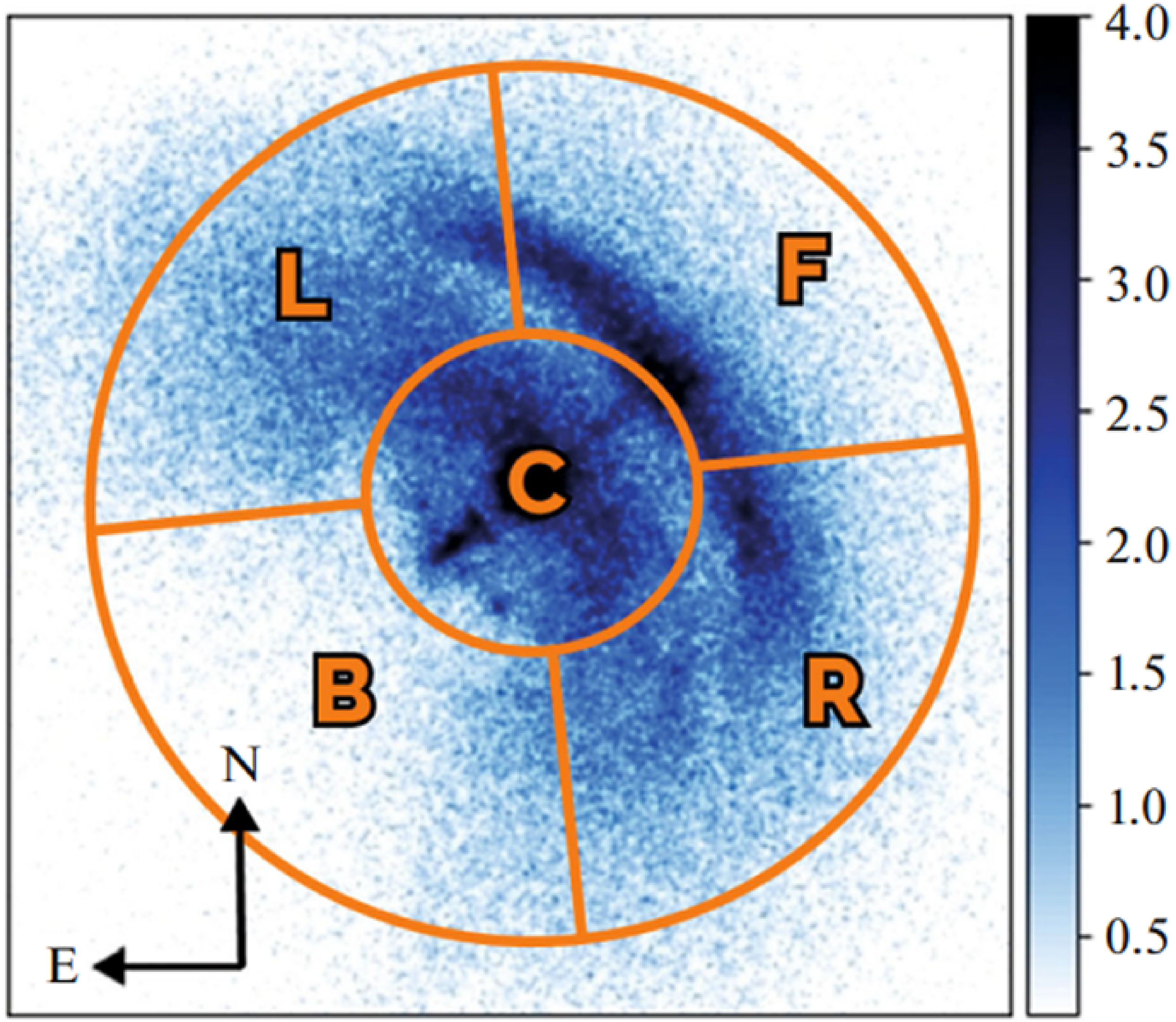
L - NE region

- NE wings of two splitted arcs,
- overlapped side parts of two tori

R - SW region

- SW wings of two splitted arcs,
- overlapped side parts of two tori
- a segment of the paraxial part of the NW arc

Polarization of different regions of the compact Vela



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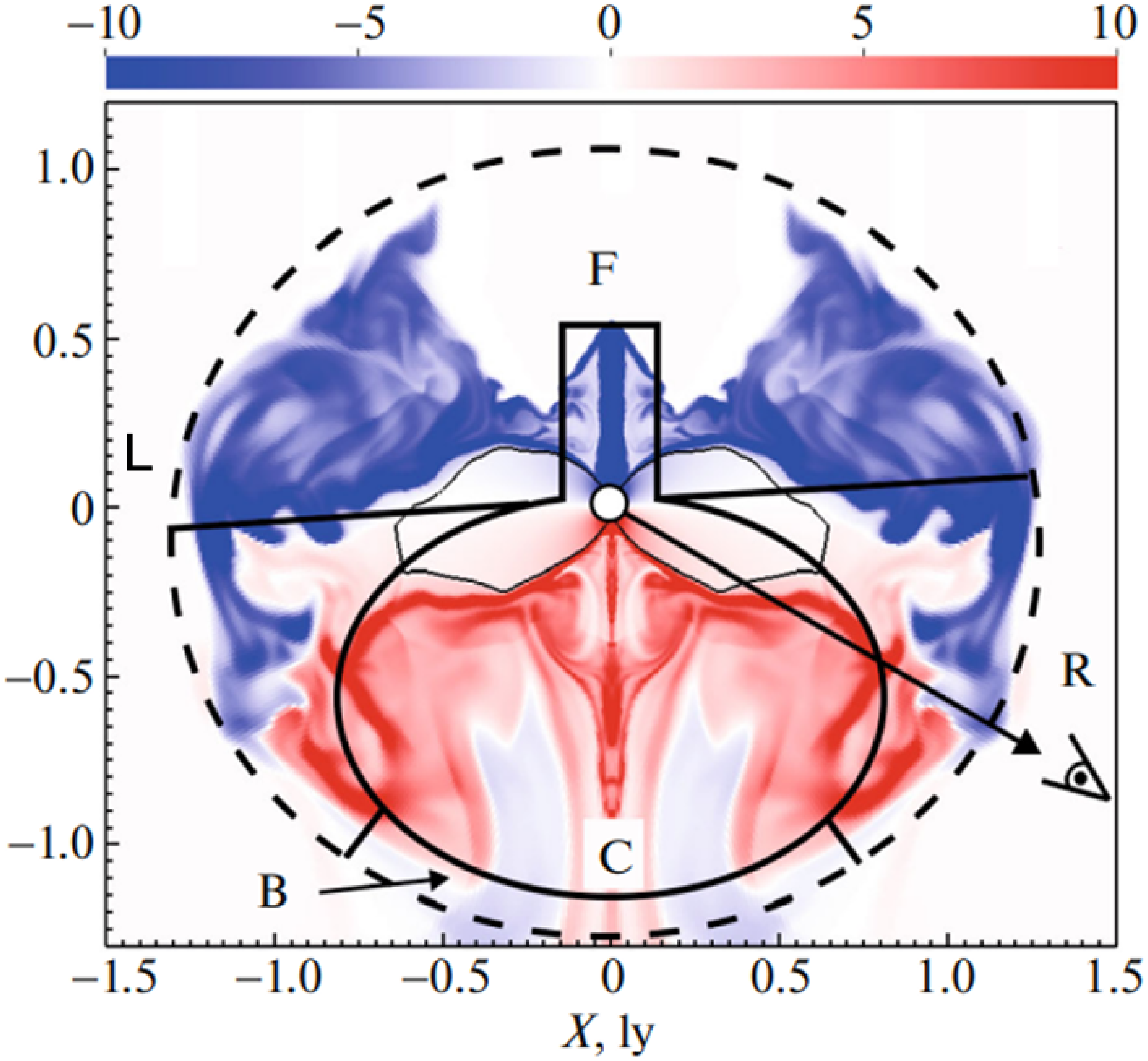

	PD (%)
F	70.0 +/- 3.6
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C	49.6 +/- 2.5
B	**33.3 +/- 3.6**

B - back part: already behind (!) the compact nebula

Features:

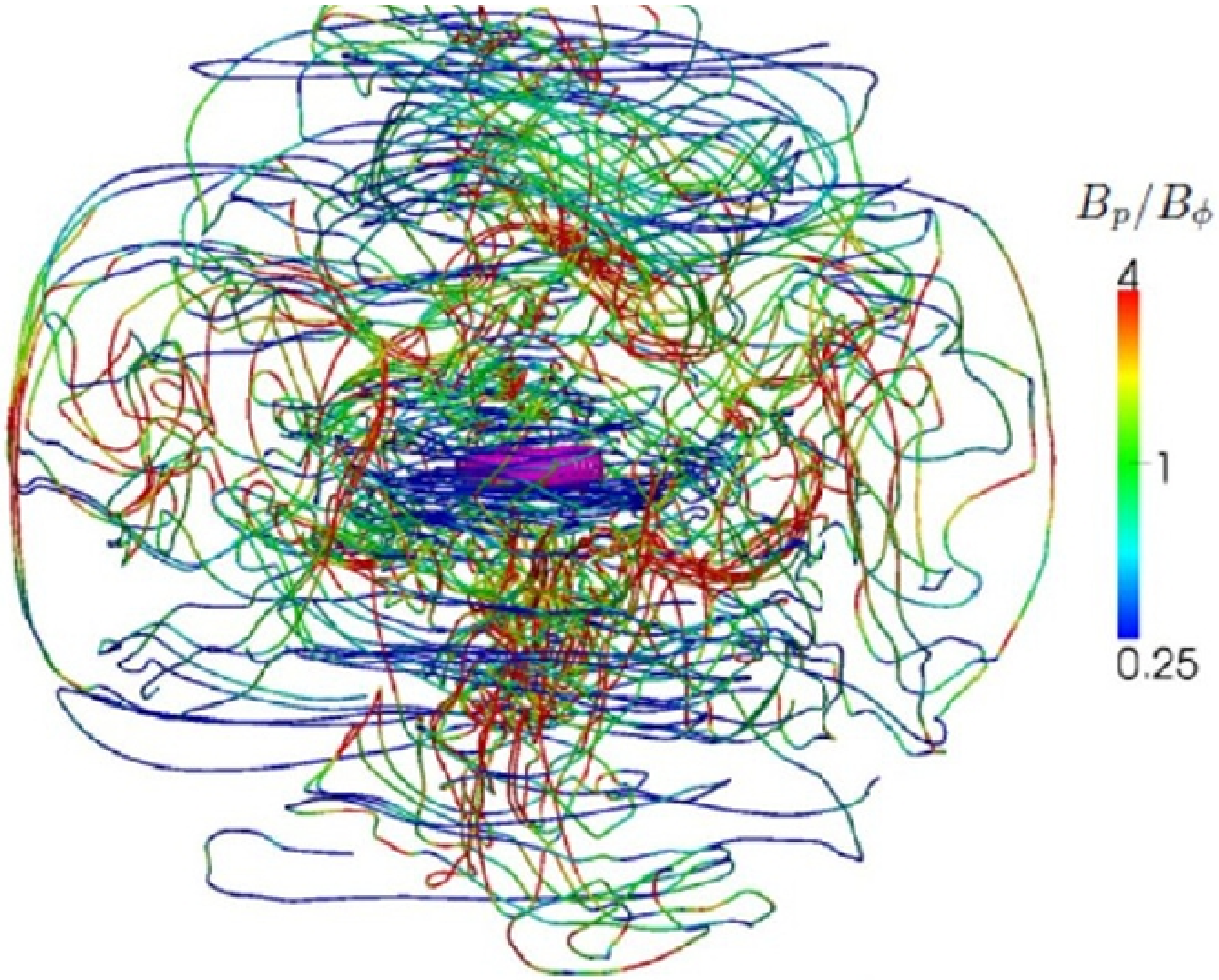
- the tail (trail) of the compact nebula
- dim and diffuse outer extension of the lee jet, submerged in the tail

Canonical MHD models of single-torus PWNe:

- the magnetic field becomes more turbulent with the distance from the wind TS
- PD must be higher near the TS

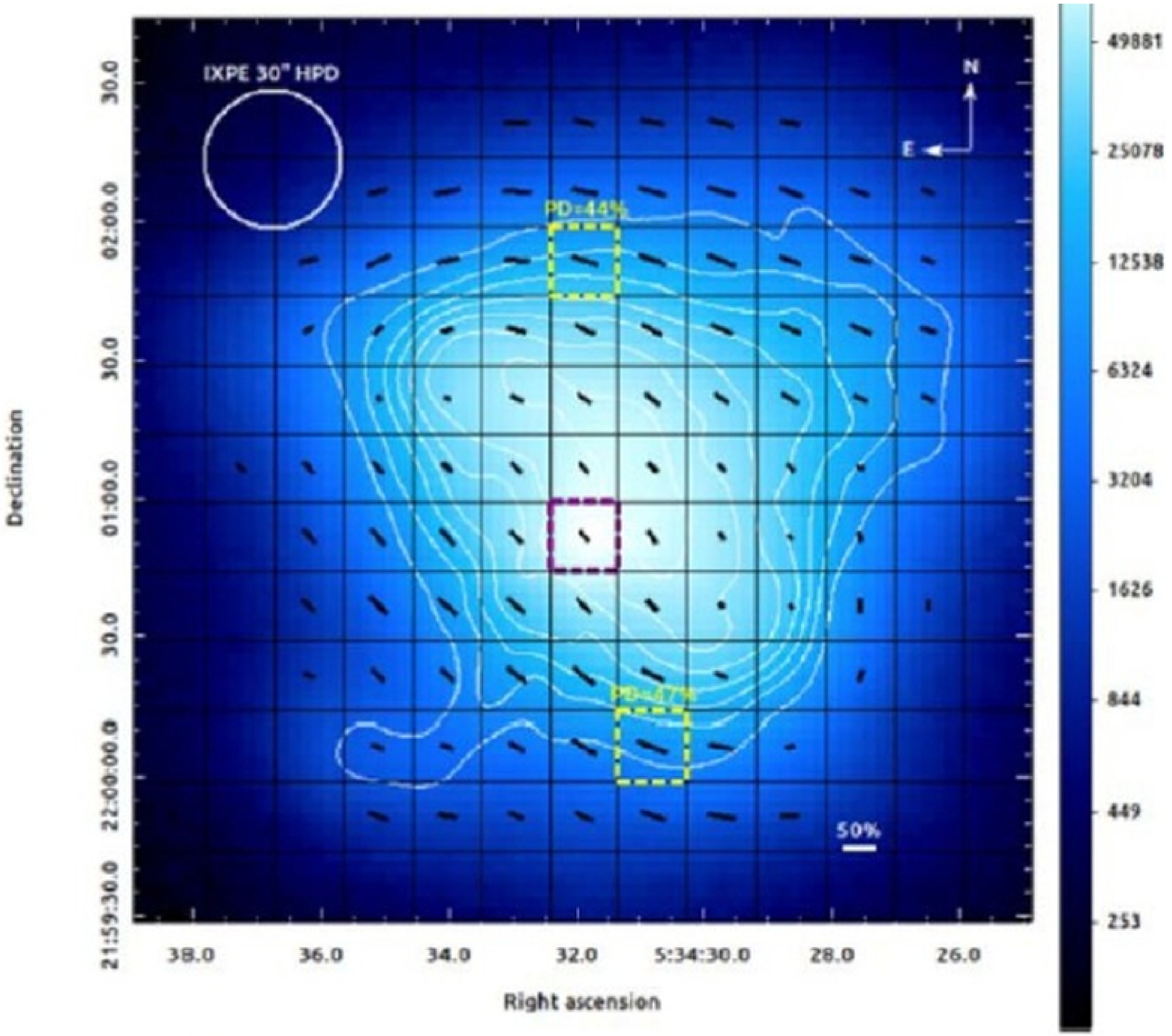
Wong et al. (2024) - IXPE: the most highly polarized regions in the Crab nebula

- are not in the torus body, **but along its perimeter**
- max PD regions are shown in yellow boxes



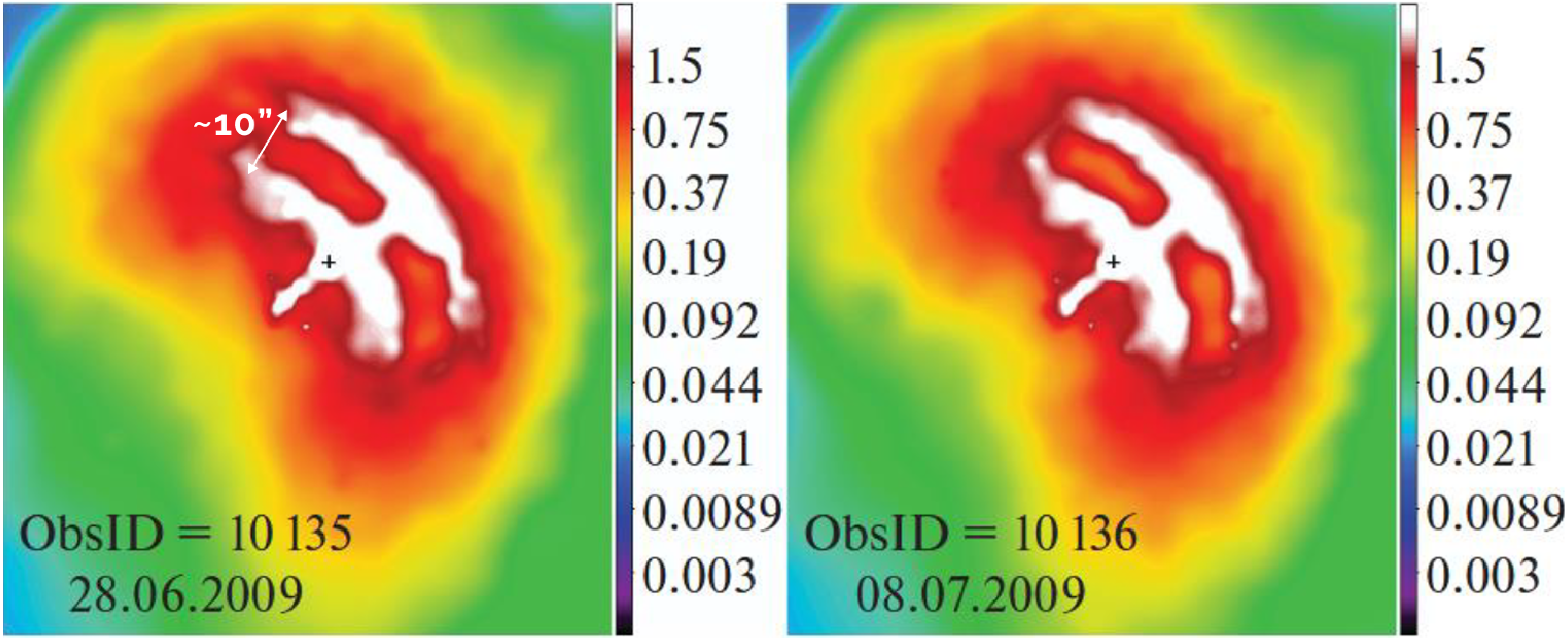
Porth+2014 : 3D MHD model

Contours: the ratio of **poloidal** and **toroidal** components of B



Wong+2024 : IXPE

Magnetic plumes and speed of highly magnetized flows

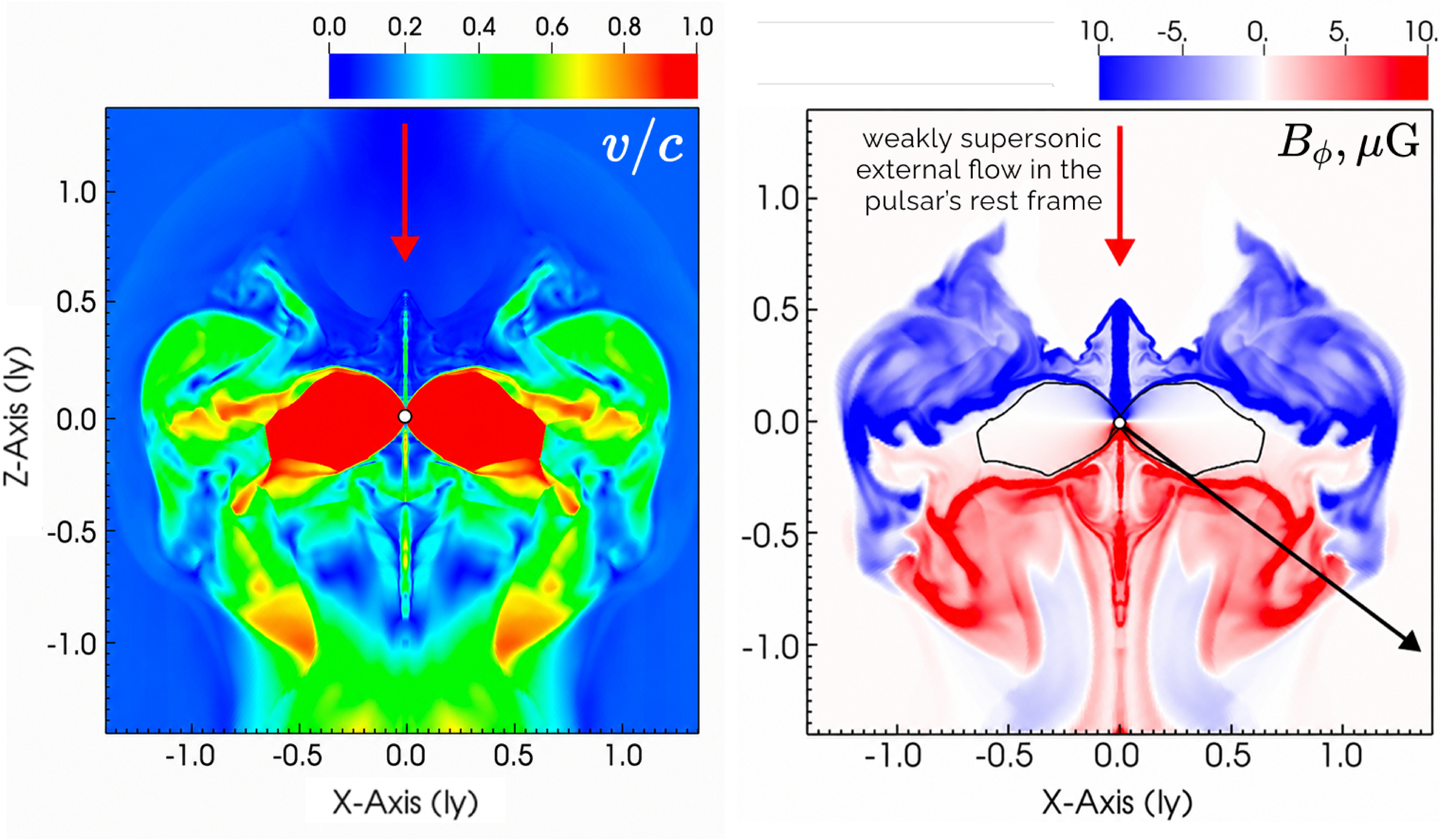


11 days

Equatorial belt width: $l = d \times 10'' \sim 0.047\,\mathrm{ly}$

Plumes' speed: $v \simeq (l/2) \times (11/365) \simeq 0.78c$

Highly magnetized flows are relativistic



weakly supersonic external flow in the pulsar's rest frame

Ponomaryov+23, Levenfish+25

$\alpha = 80^\circ, \ \sigma_0 = 0.1, \ M_s = 2.3$

Plumes' speed in Vela: $v \simeq (l/2) \times (11/365) \simeq 0.78c$

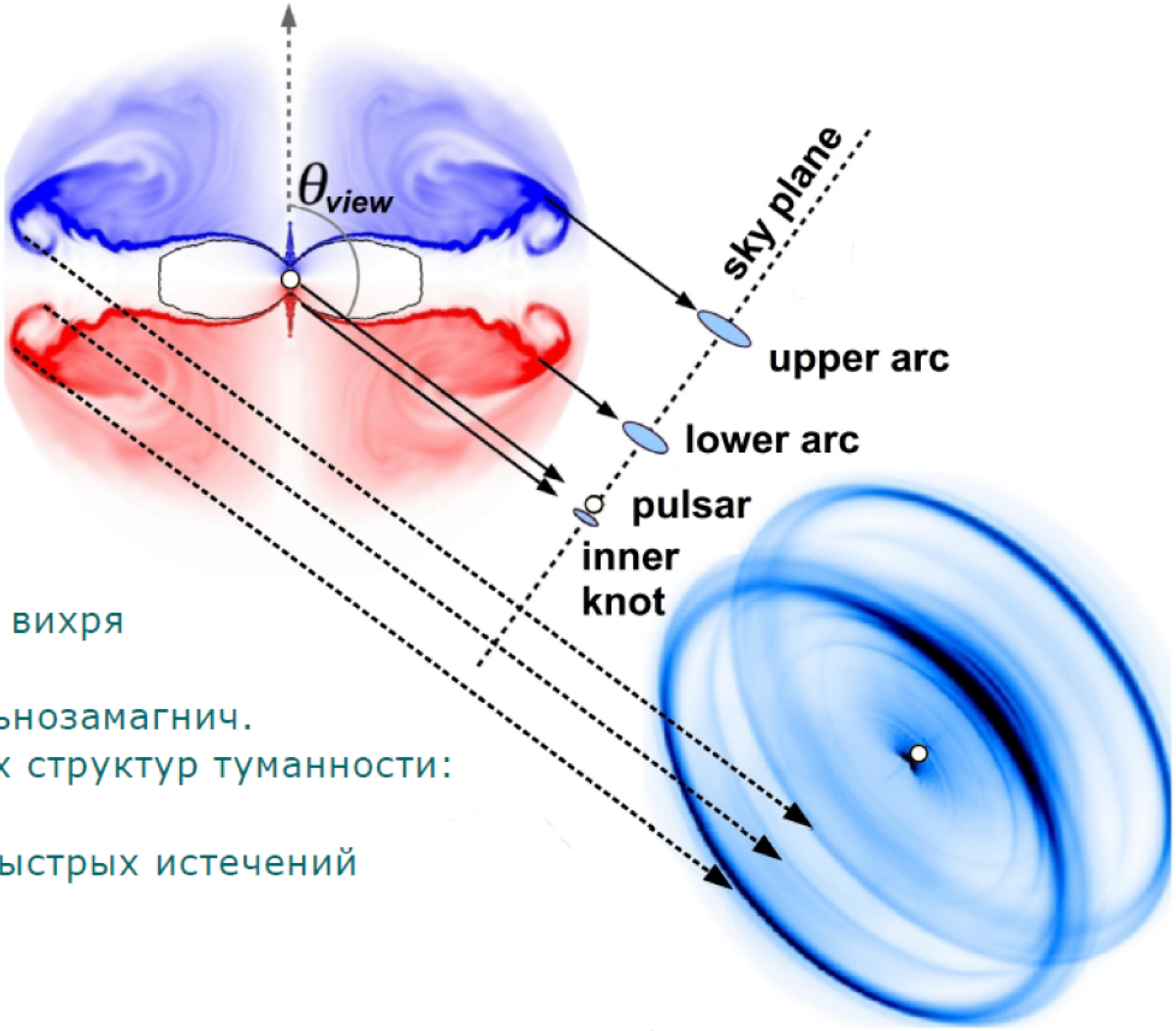
The origin of bright structures on the X-ray maps

TOY RMHD MODEL : MAGNETIC vs SYNCHROTRON FEATURES

$$\epsilon \propto B_{\perp}'^{\,\alpha+1} D^{\alpha+2} \nu^{-\alpha} P \left[\frac{\mathrm{erg}}{\mathrm{s}\cdot\mathrm{cm}^3}\right]$$

$$D = 1/(\Gamma(1-(\mathbf{v}\cdot\mathbf{n})/c))$$

Ponomaryov+21
Fateeva+23



2 рентгененовких тора =
4 регулярных тороидальных вихря

Яркие синхр. детали – от сильнозамагнич. и/или доплеровски уярченных структур туманности:

- от быстрых истечений
- от области расщепления быстрых истечений
- от циркуляцинных вихрей
- от пограничных вихрей

За каждую половинку каждого X-тора – разные (!) структуры