EVOLVED PULSAR WIND NEBULAE

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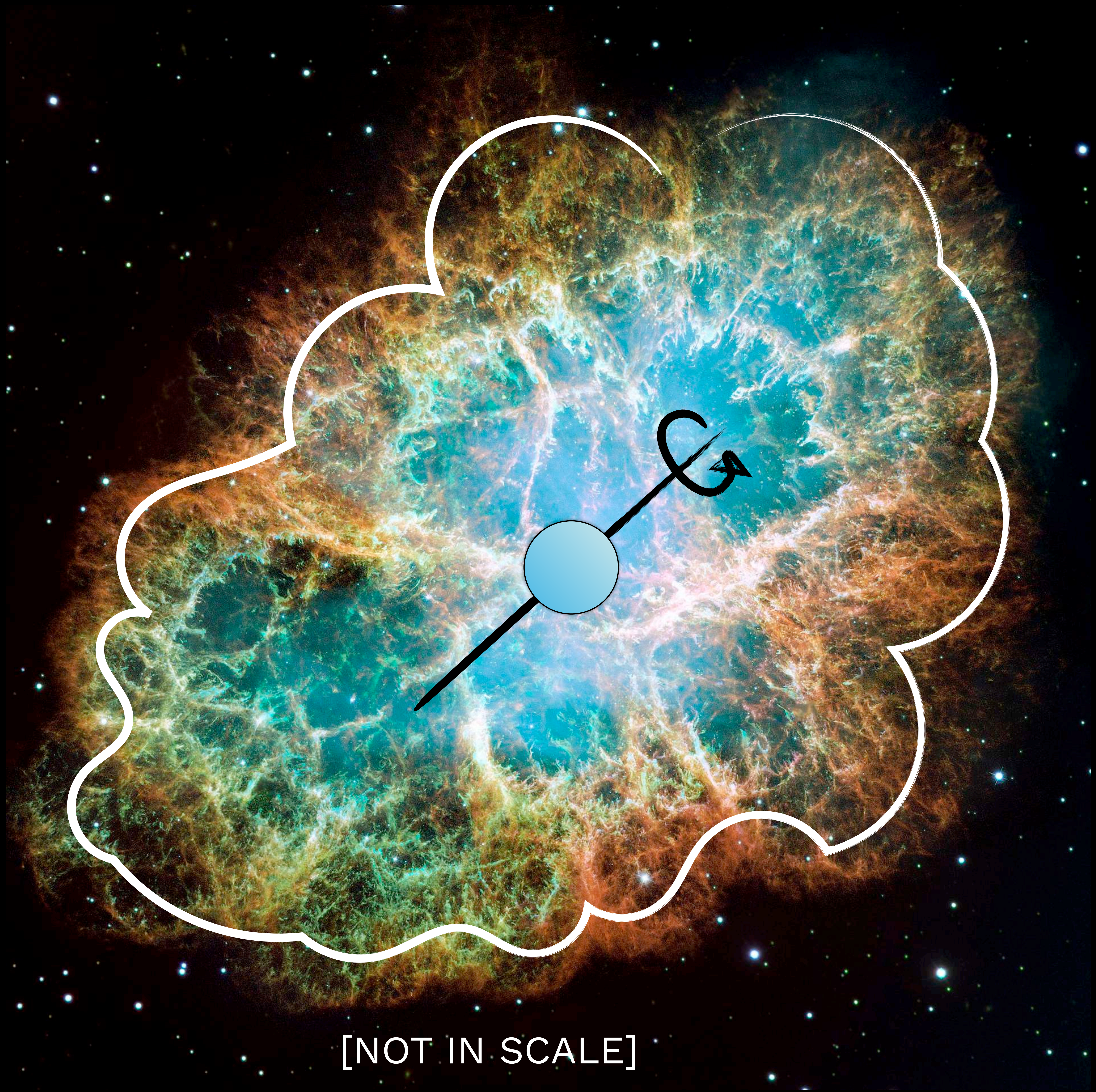
INTRO: WHAT IS A PWN?



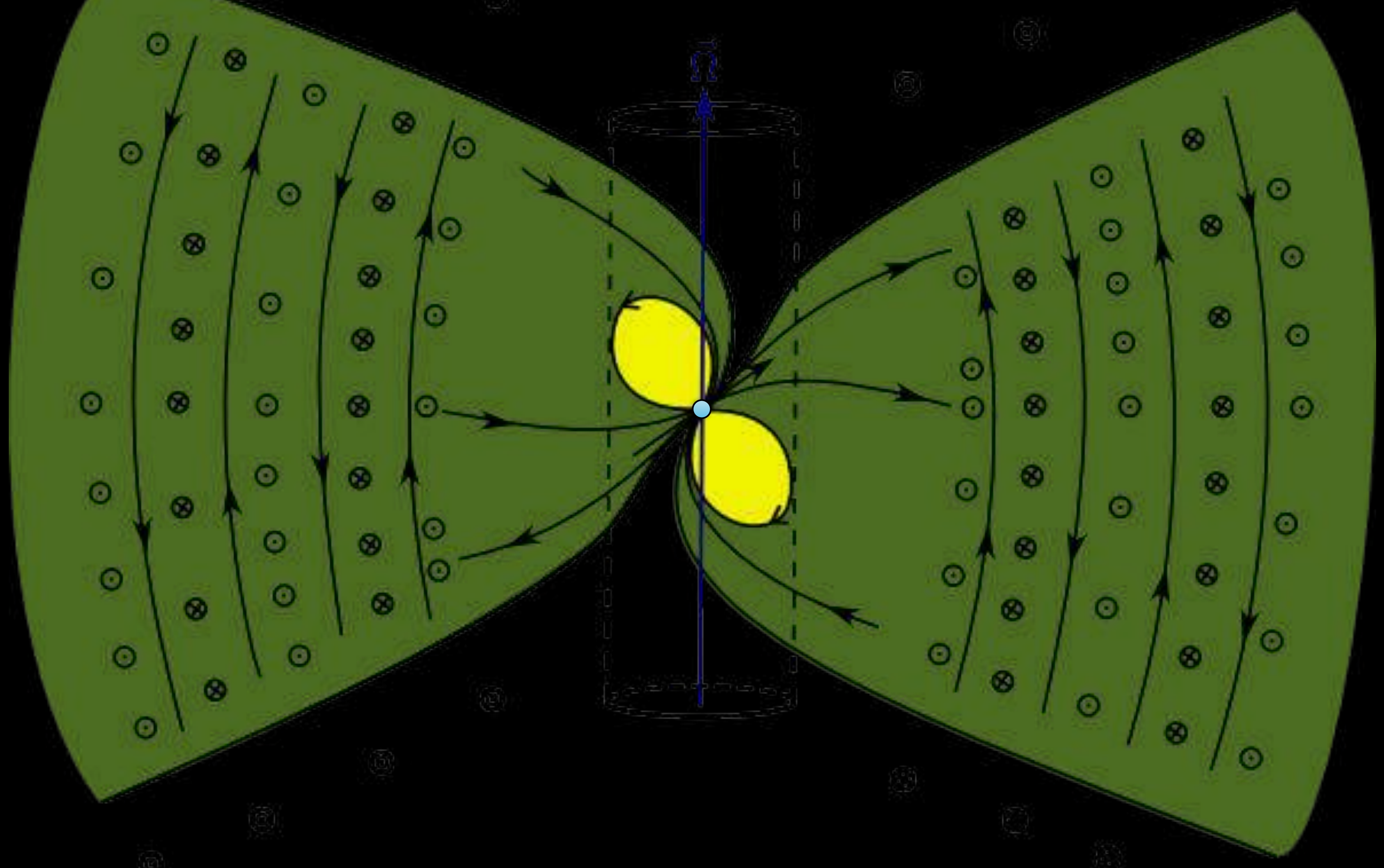
[NOT IN SCALE]

THE DEBRIS OF THE SUPERNOVA EXPLOSION OF A MASSIVE STAR ($M \gtrsim 8\ M_\odot$)

MAIN INGREDIENTS:

PULSAR

PULSAR WIND



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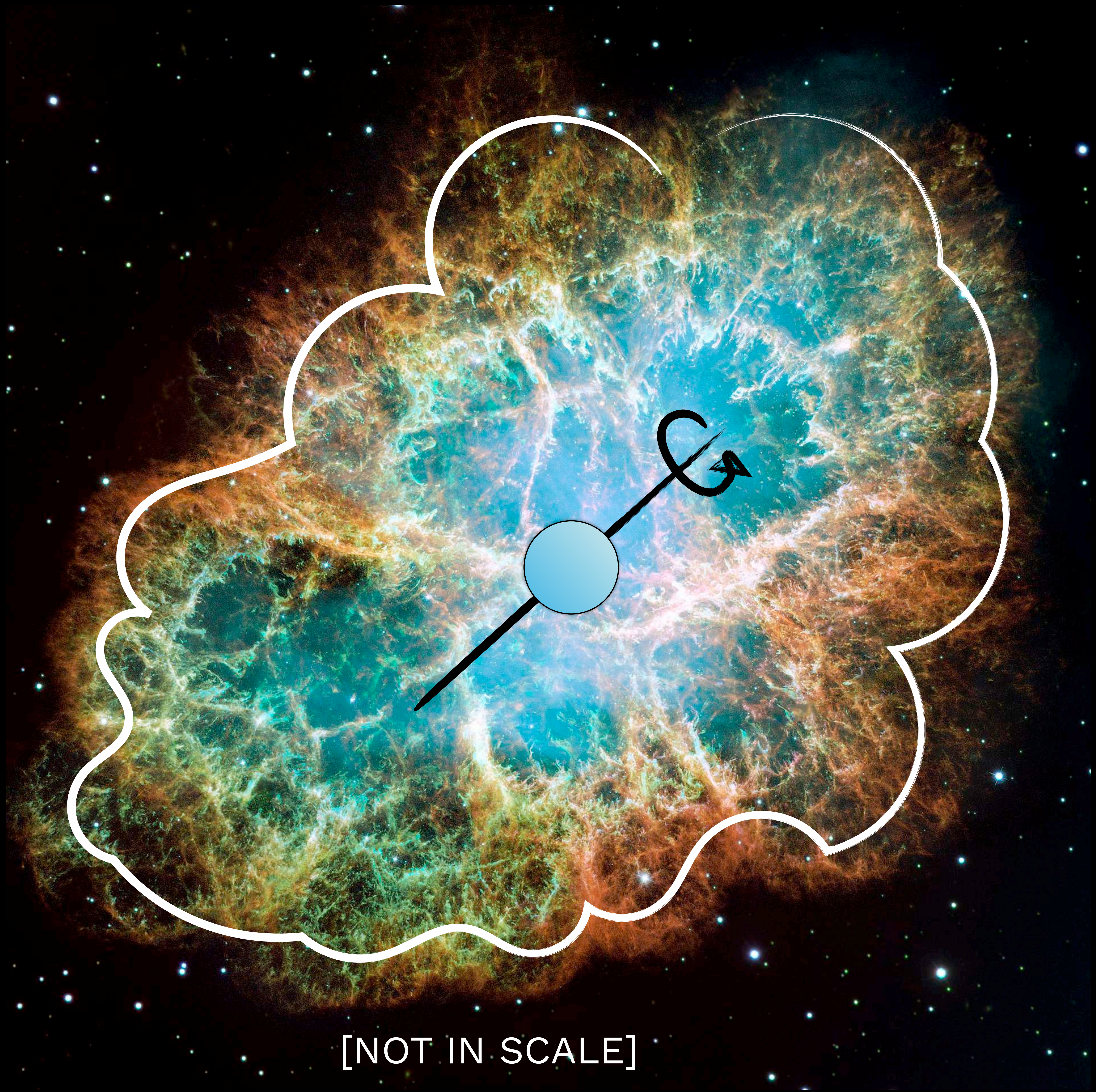
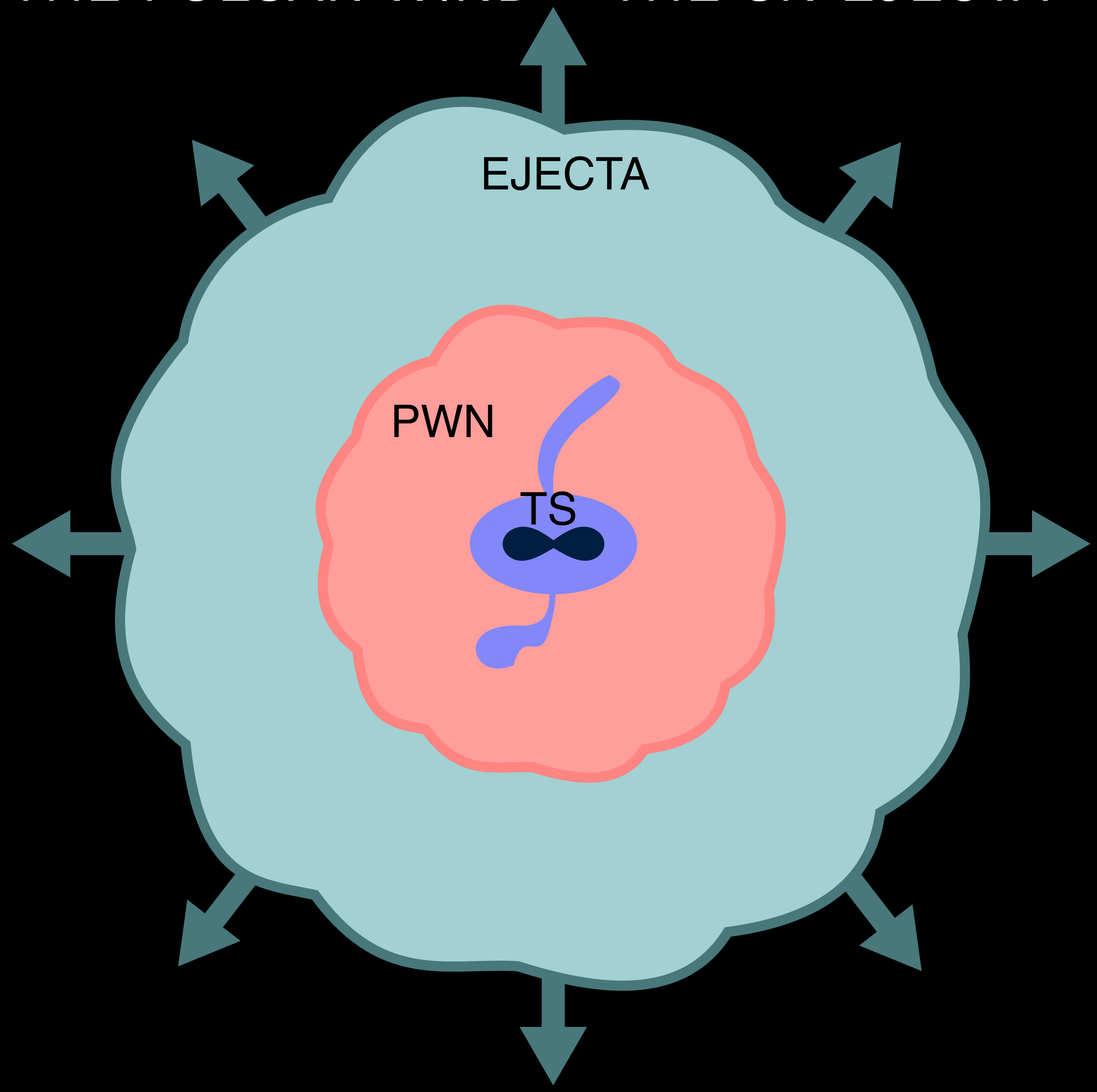


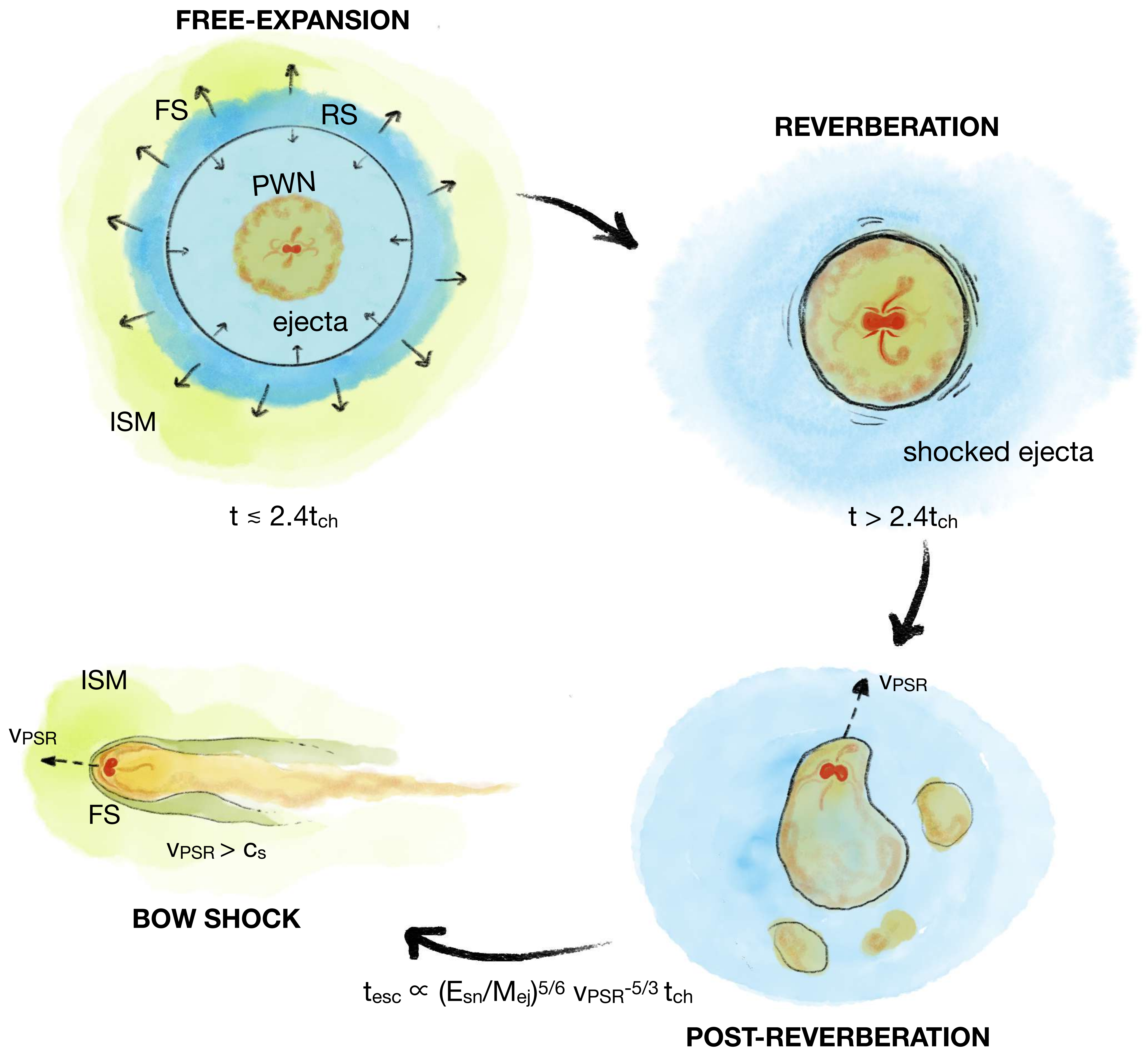
THE DEBRIS OF THE SUPERNOVA EXPLOSION OF A MASSIVE STAR ($M \gtrsim 8\ M_\odot$)

MAIN INGREDIENTS:

THE PULSAR WIND + THE SN EJECTA



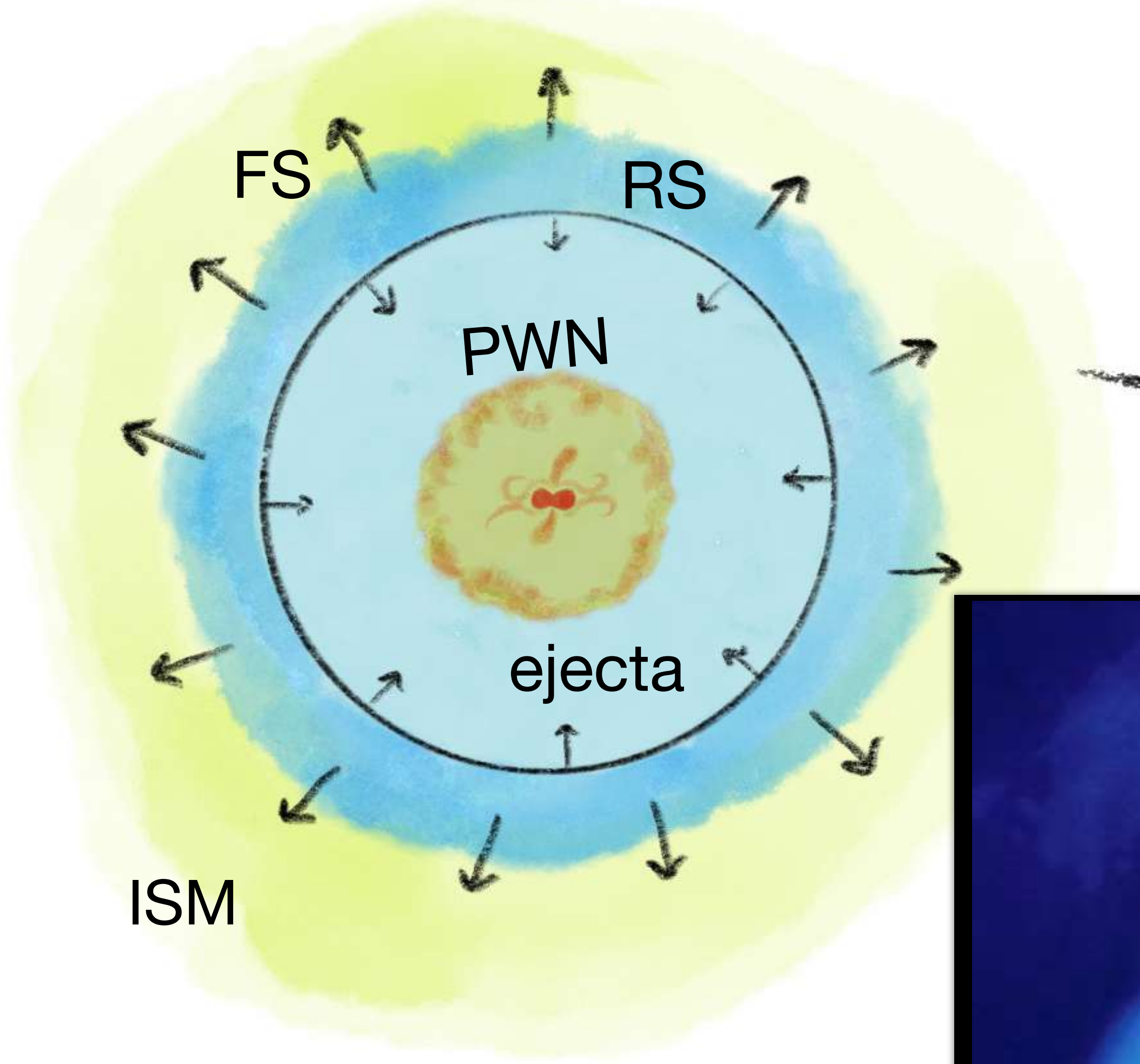
EVOLUTIONARY PHASES OF PWNe



[Olmi 2023]

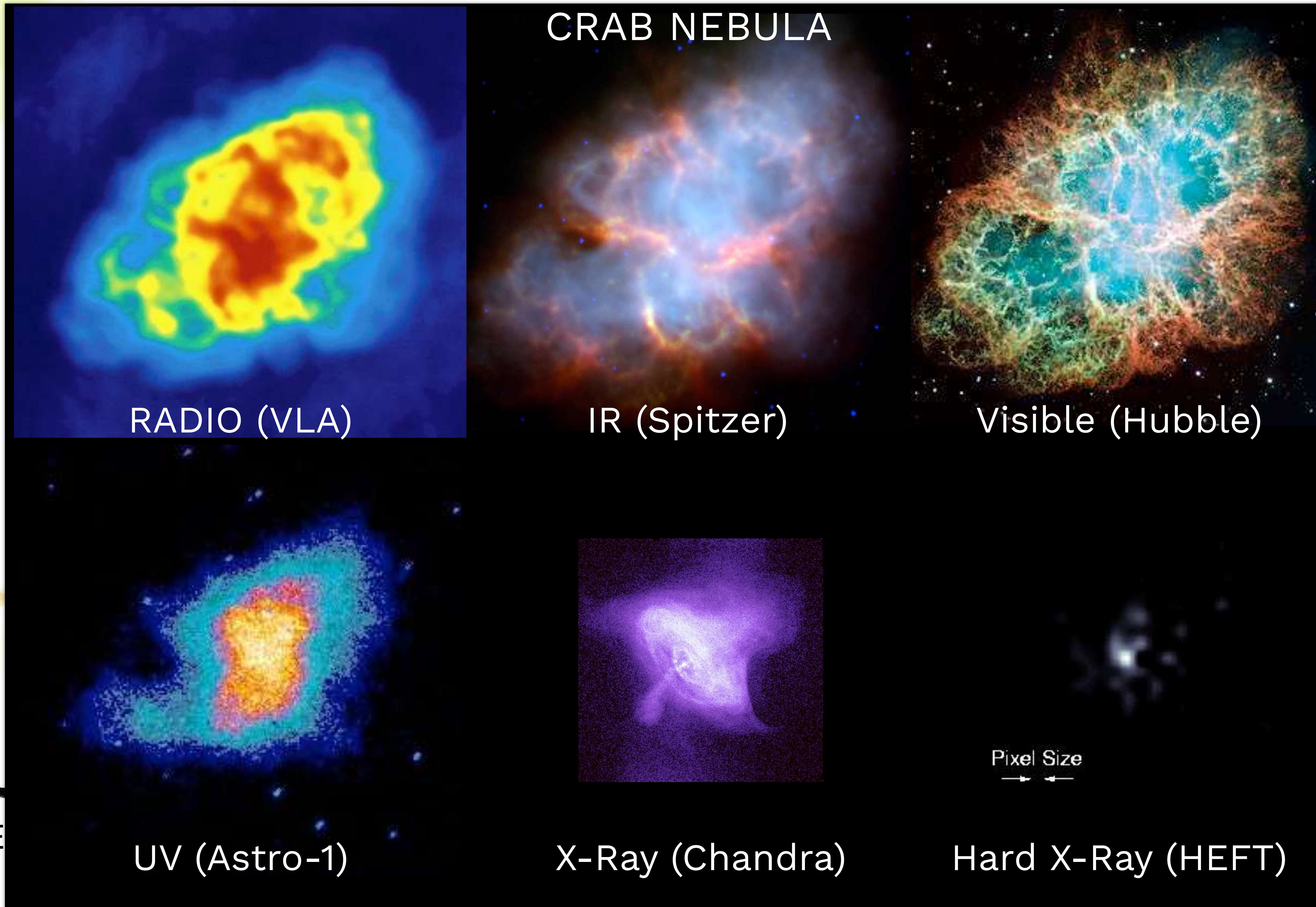
EVOLUTIONARY PHASES OF PWNe

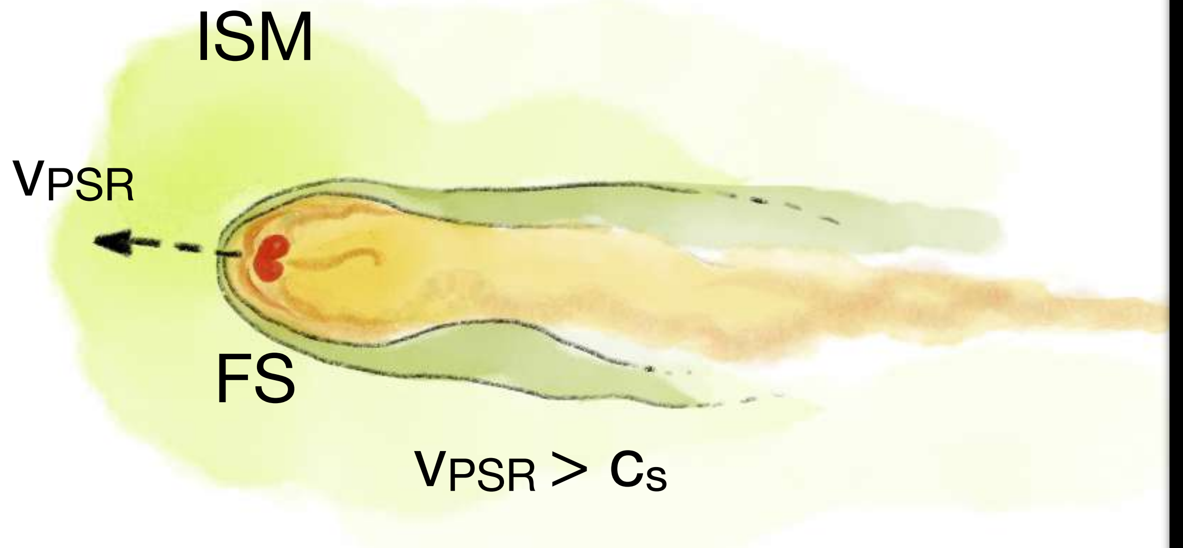
FREE-EXPANSION



$t \lesssim 2.4 t_{ch}$

YOUNG SYSTEMS
FILL CENTERED (NON-THERMAL) EMISSION
ACROSS THE EM SPECTRUM



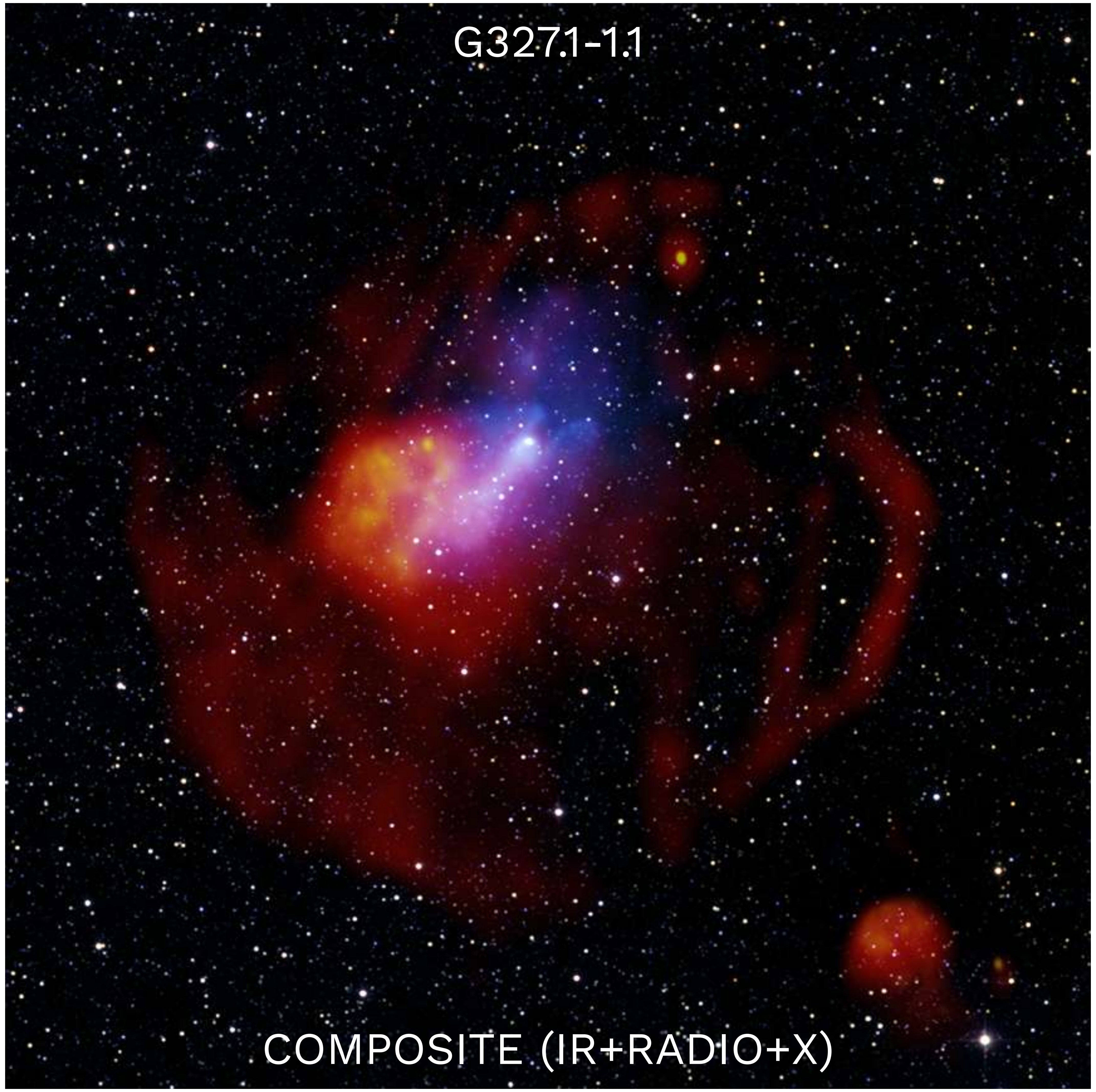


BOW SHOCK

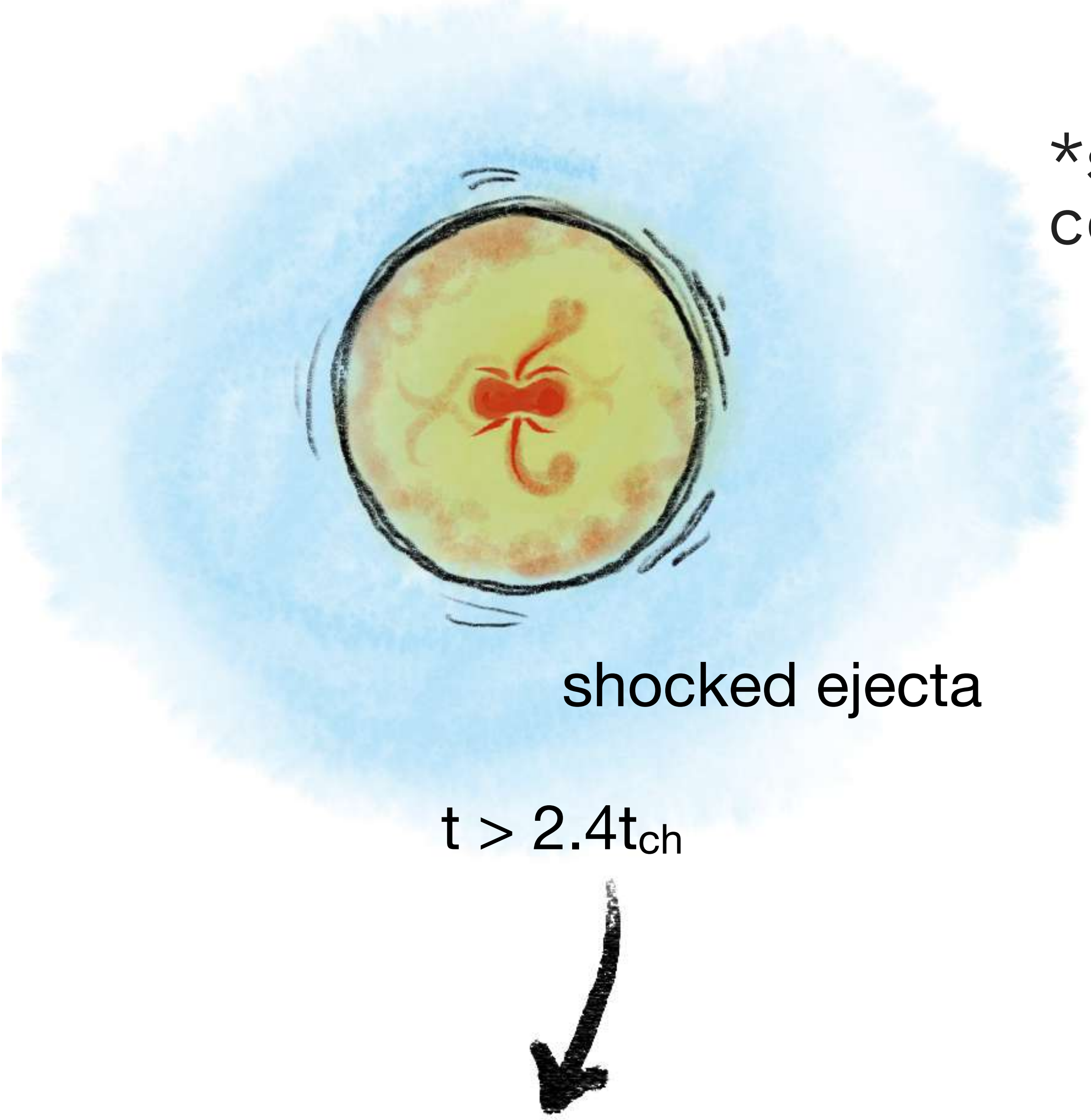
$t_{esc} \propto$ (E

[Olmi 2023]

EVOLUTIONARY PHASES OF PWNe



REVERBERATION



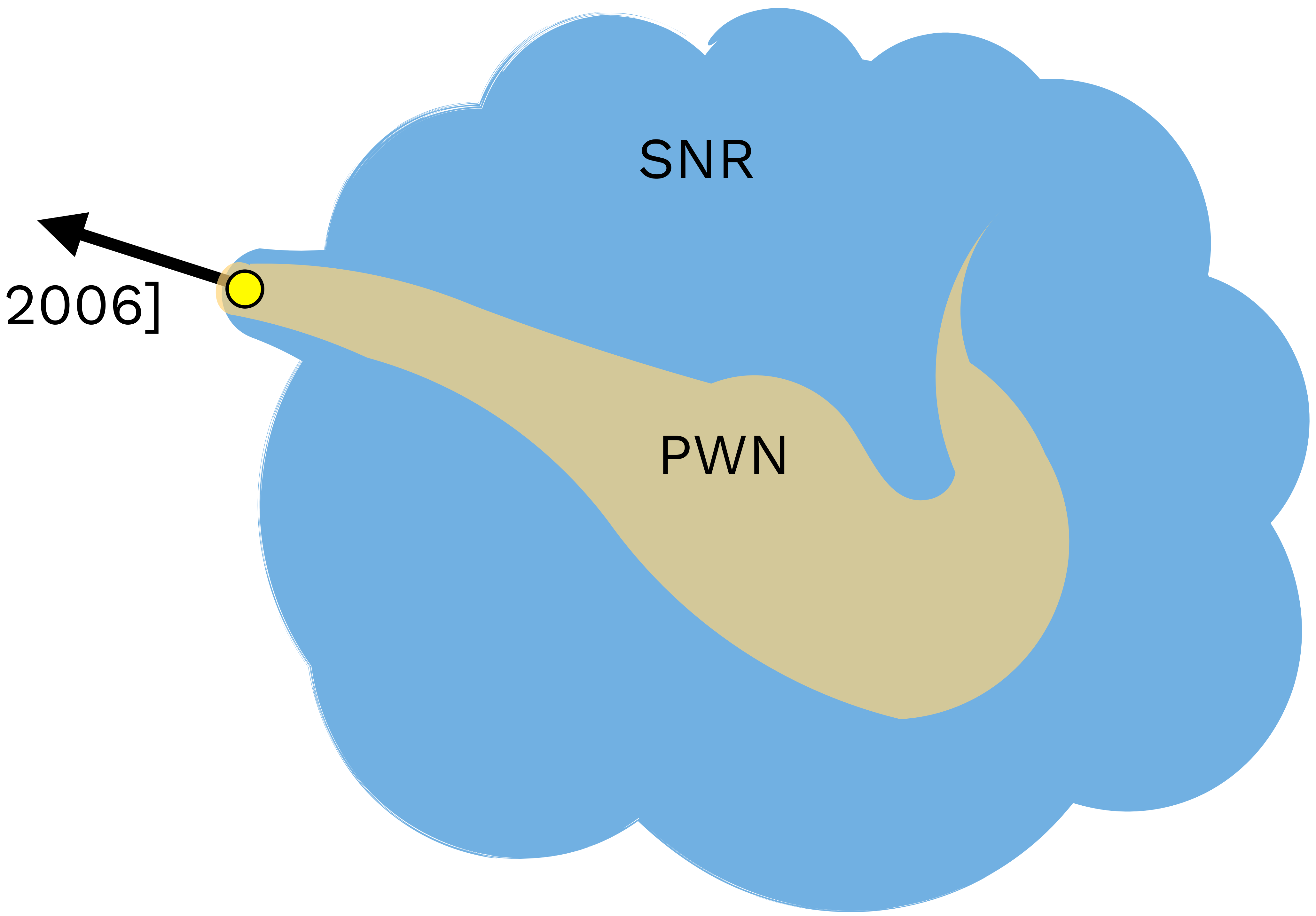
*see D.F. Torres contribution

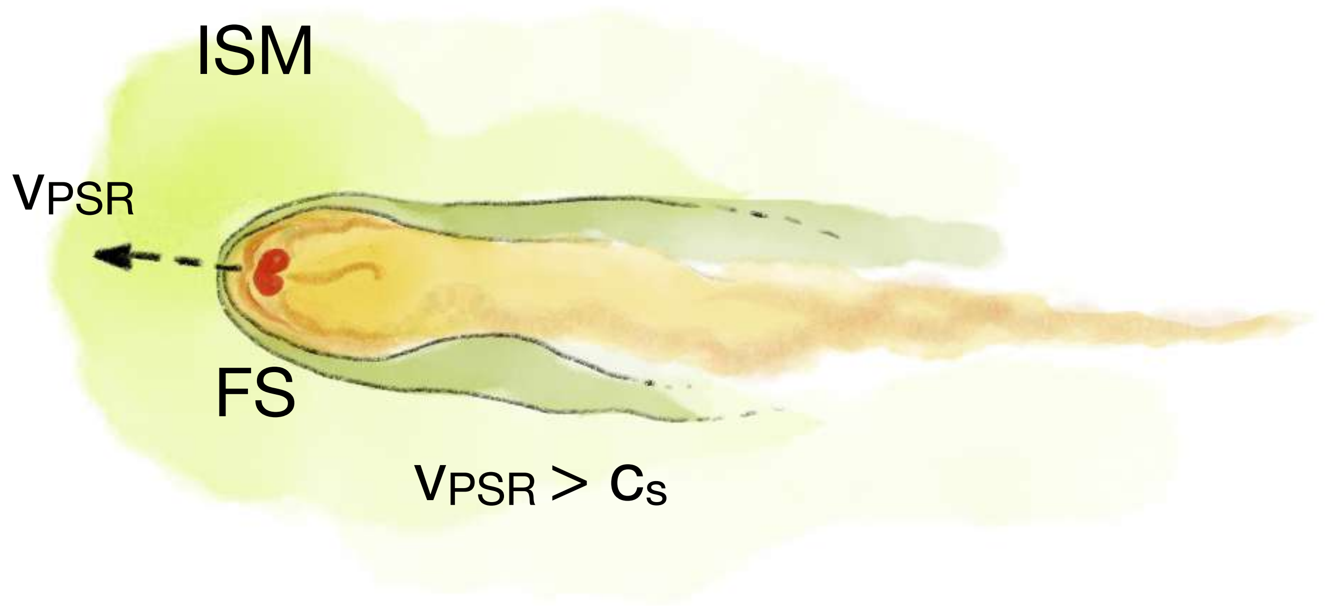
MIDDLE AGED - REVERBERATING SYSTEMS
ONLY A FEW IDENTIFIED
COMPLEX MORPHOLOGY DUE TO INTERACTION WITH SNR

[Olmi 2023]

EVOLUTIONARY PHASES OF PWNe

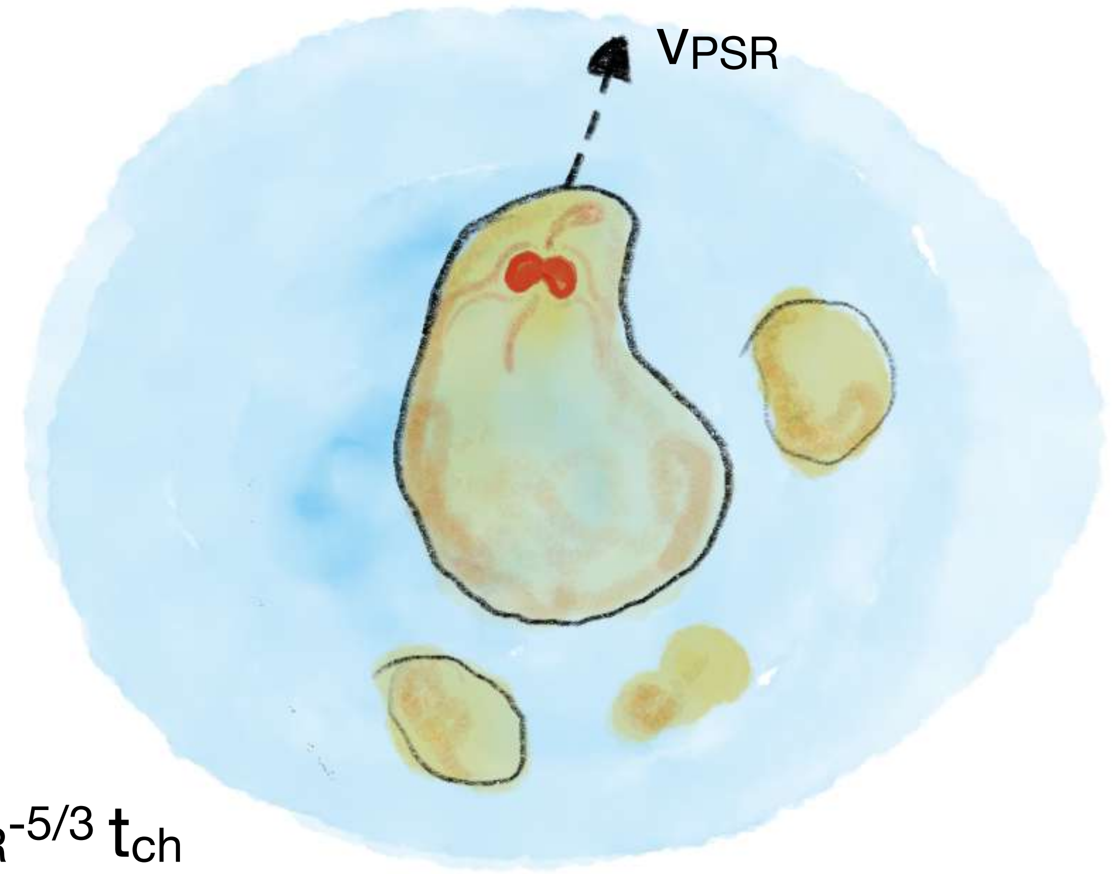
v_{PSR}~100-500 km/s
[Faucher-Giguere & Kaspi 2006]





BOW SHOCK

$t_{esc} \propto (E_{sn}/M_{ej})^{5/6}\, v_{PSR}^{-5/3}\, t_{ch}$



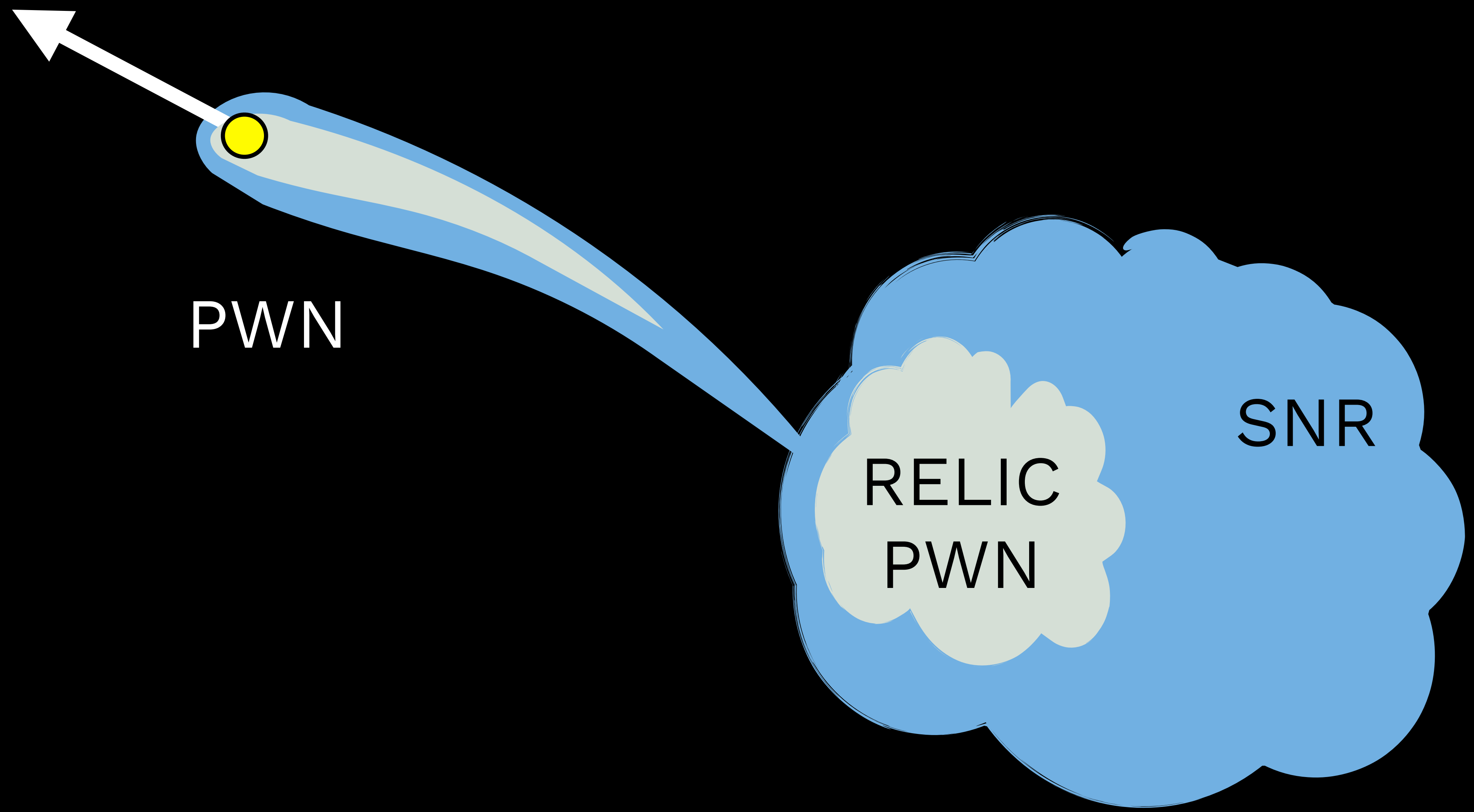
POST-REVERBERATION

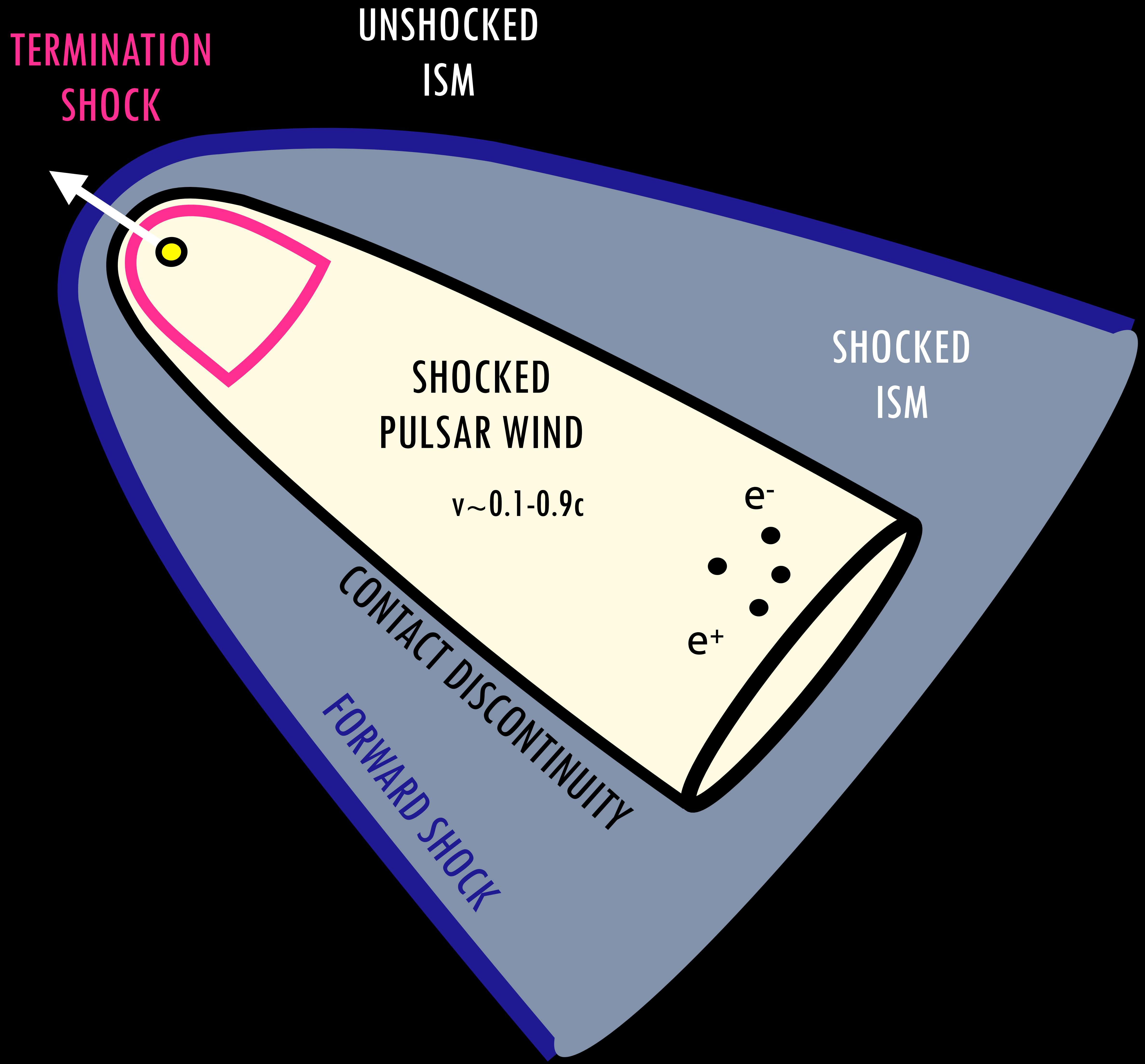
[Olmi 2023]

BOW SHOCK PWNe

THE PWN IS RESHAPED BY THE SUPERSONIC MOTION IN THE ISM

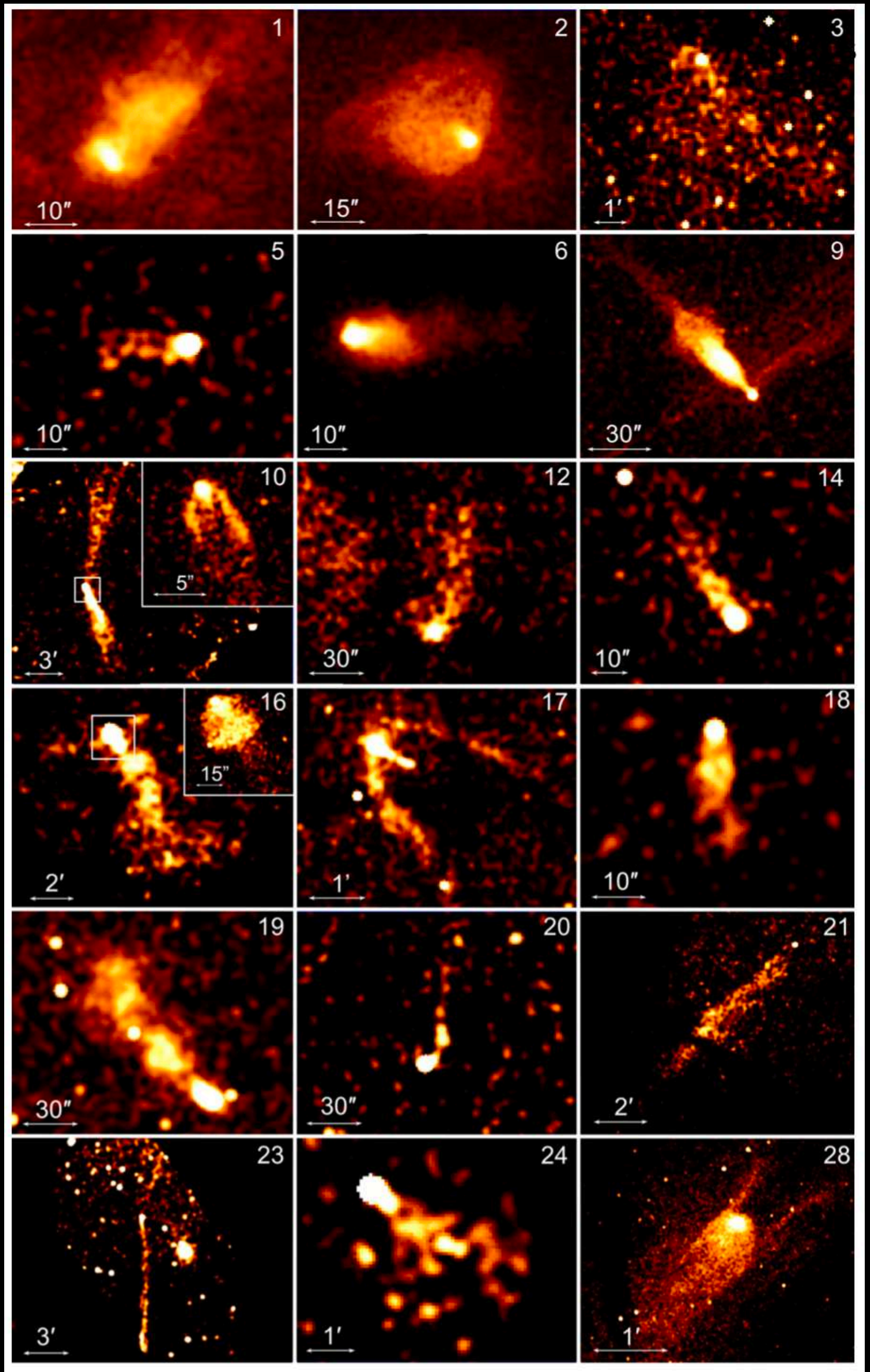
v_{PSR}~100-500 km/s > c_s





HOW DO THEY DO LOOK LIKE

X-rays

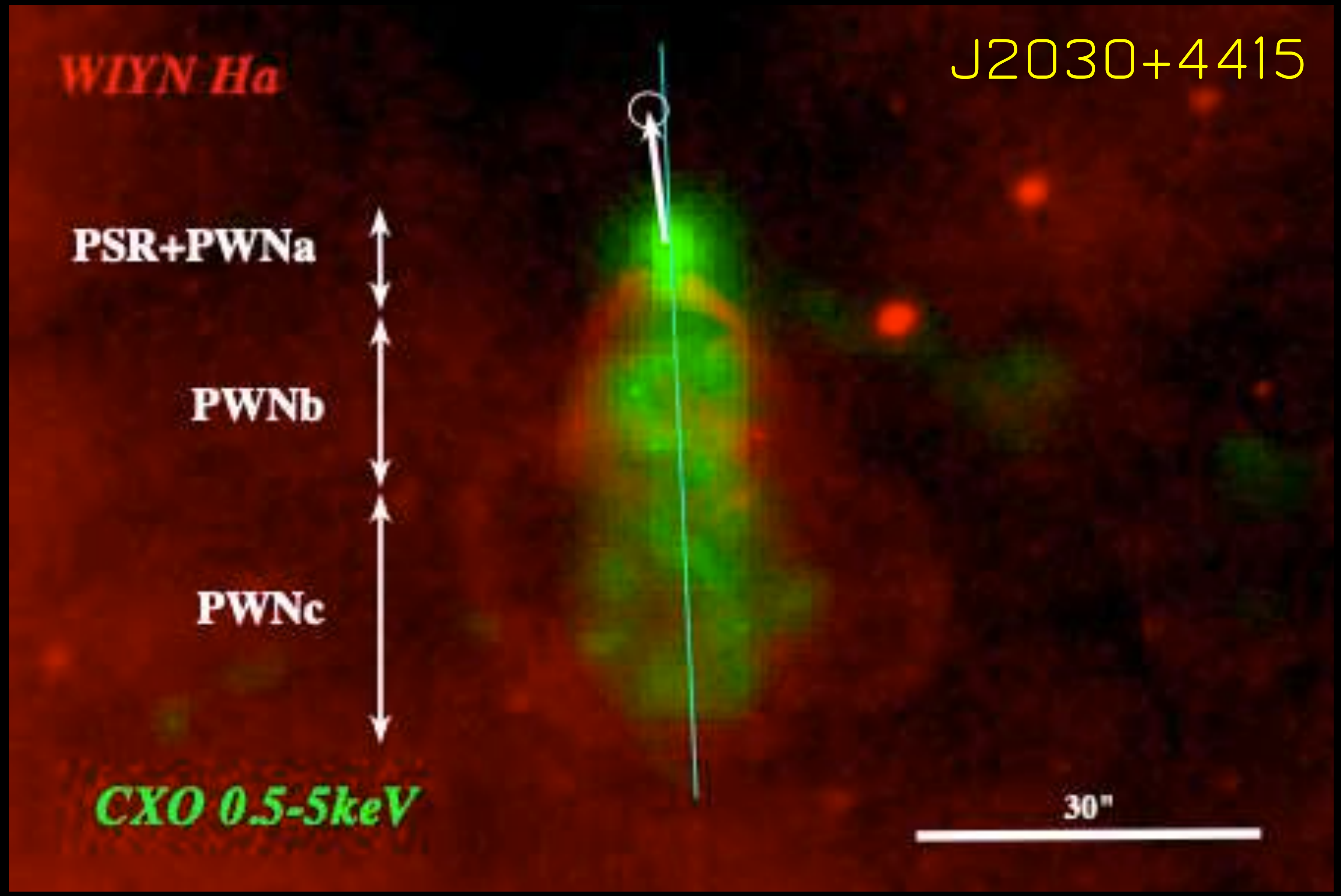


[Kargaltsev et al. 2017]

COMETARY SHAPED:

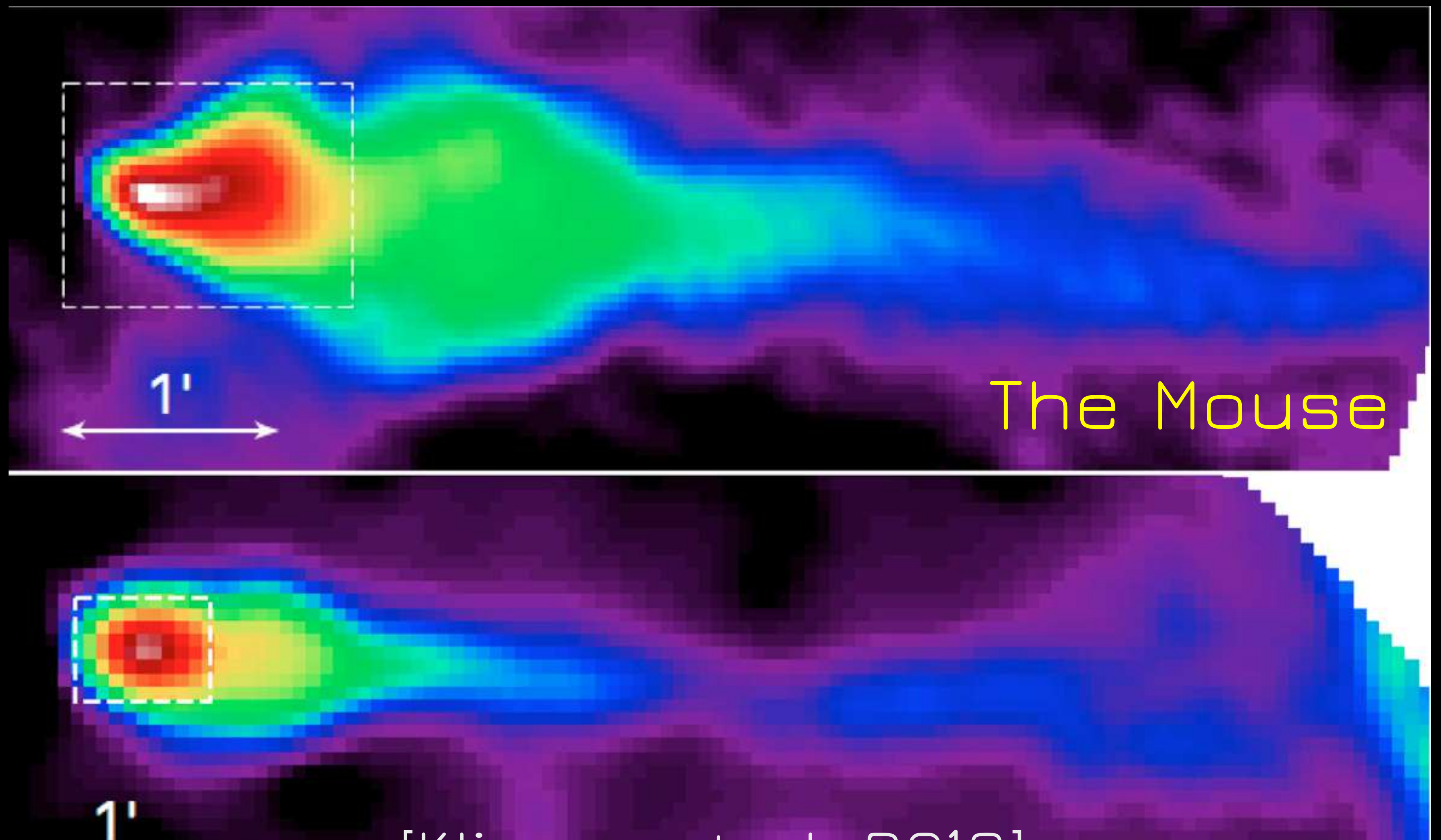
BRIGHT HEADS AND EXTENDED TAILS BEHIND THE PULSAR

Combined Hα + X-rays



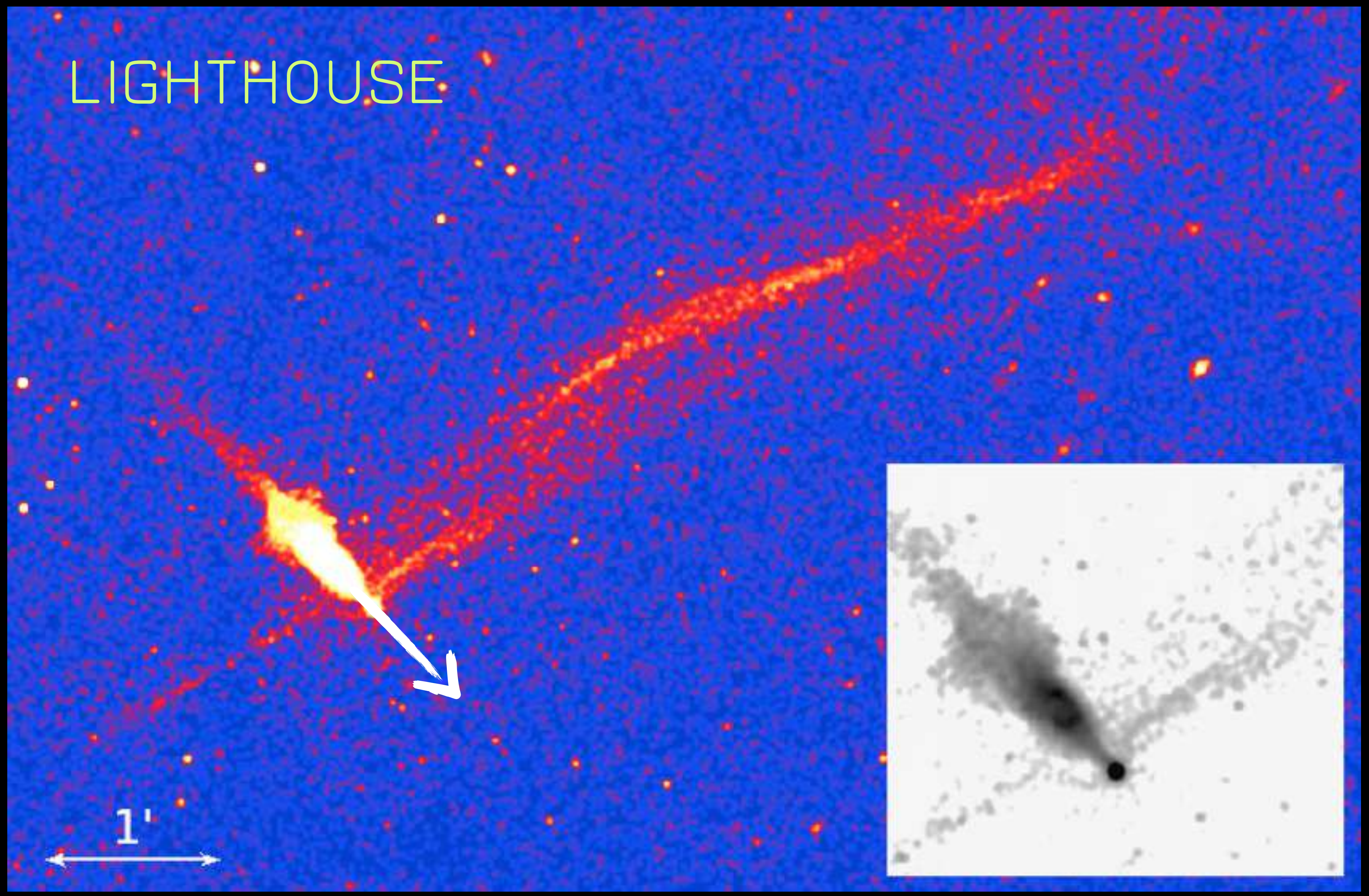
[De Vrie & Romani 2020]

Radio (VLA)

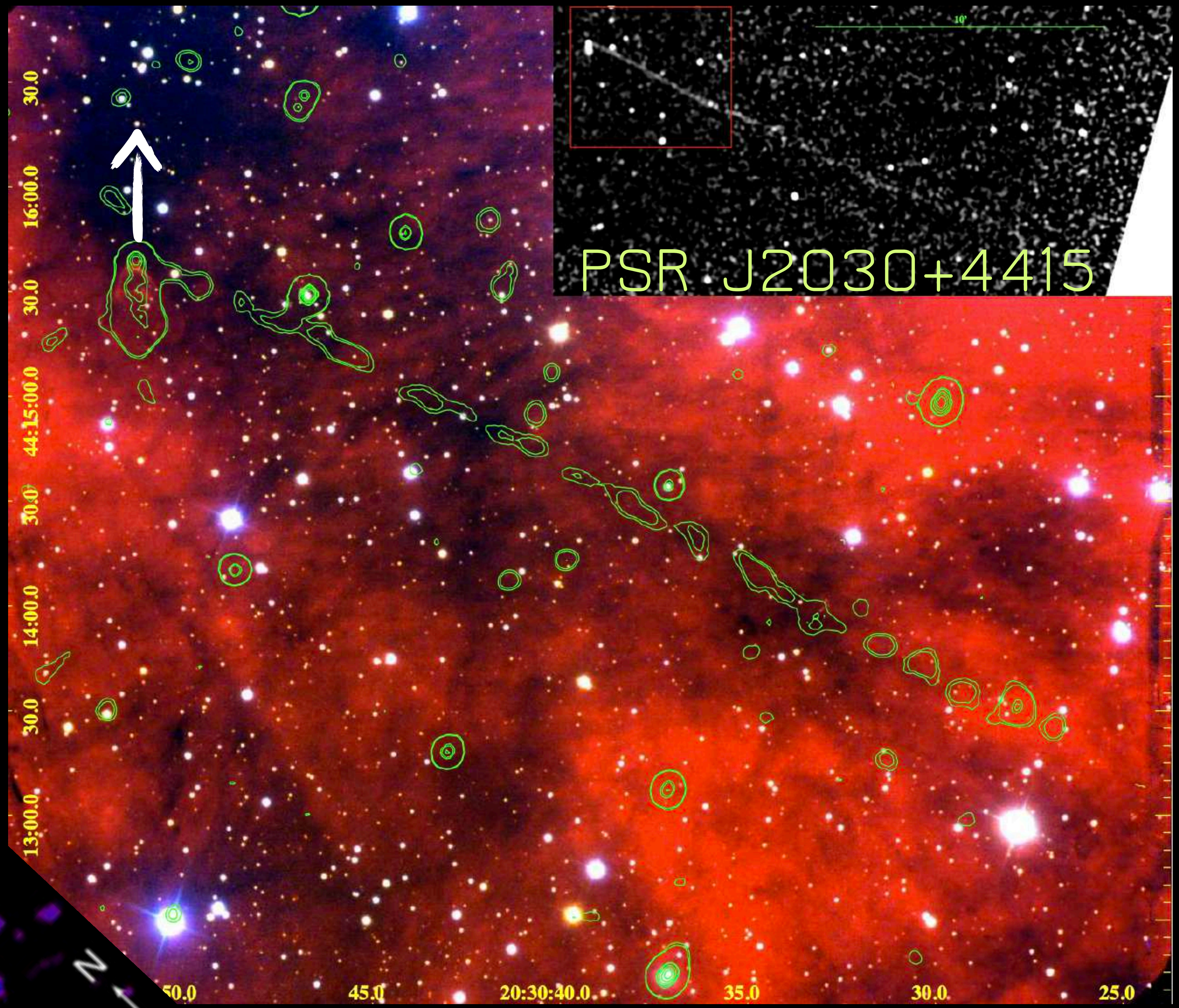


[Klinger et al. 2018]

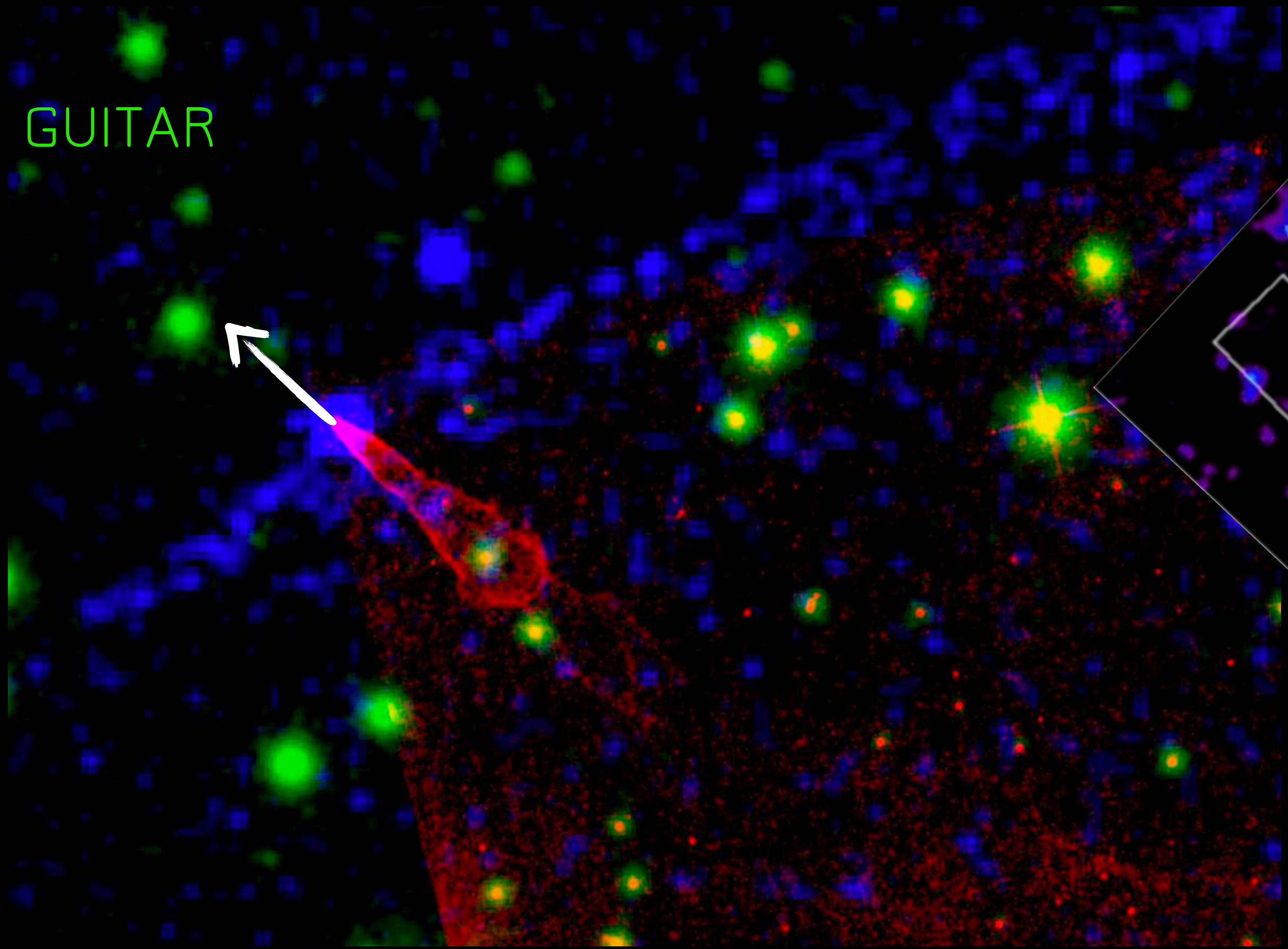
EVIDENCE OF PARTICLE ESCAPE: MISALIGNED X-RAY TAILS



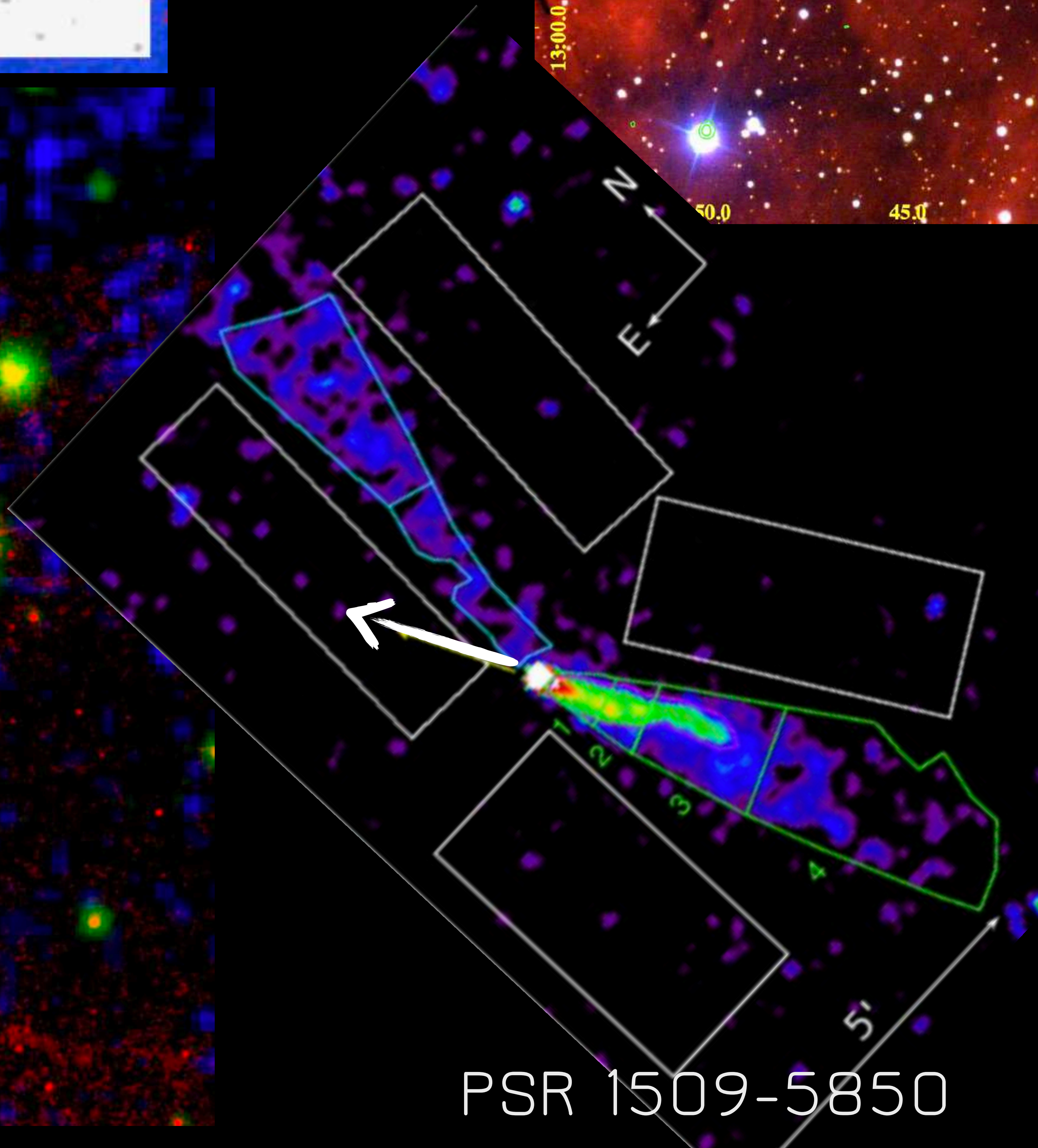
[Pavan et al. 2016]



[De Vrie & Romani 2020,2022]

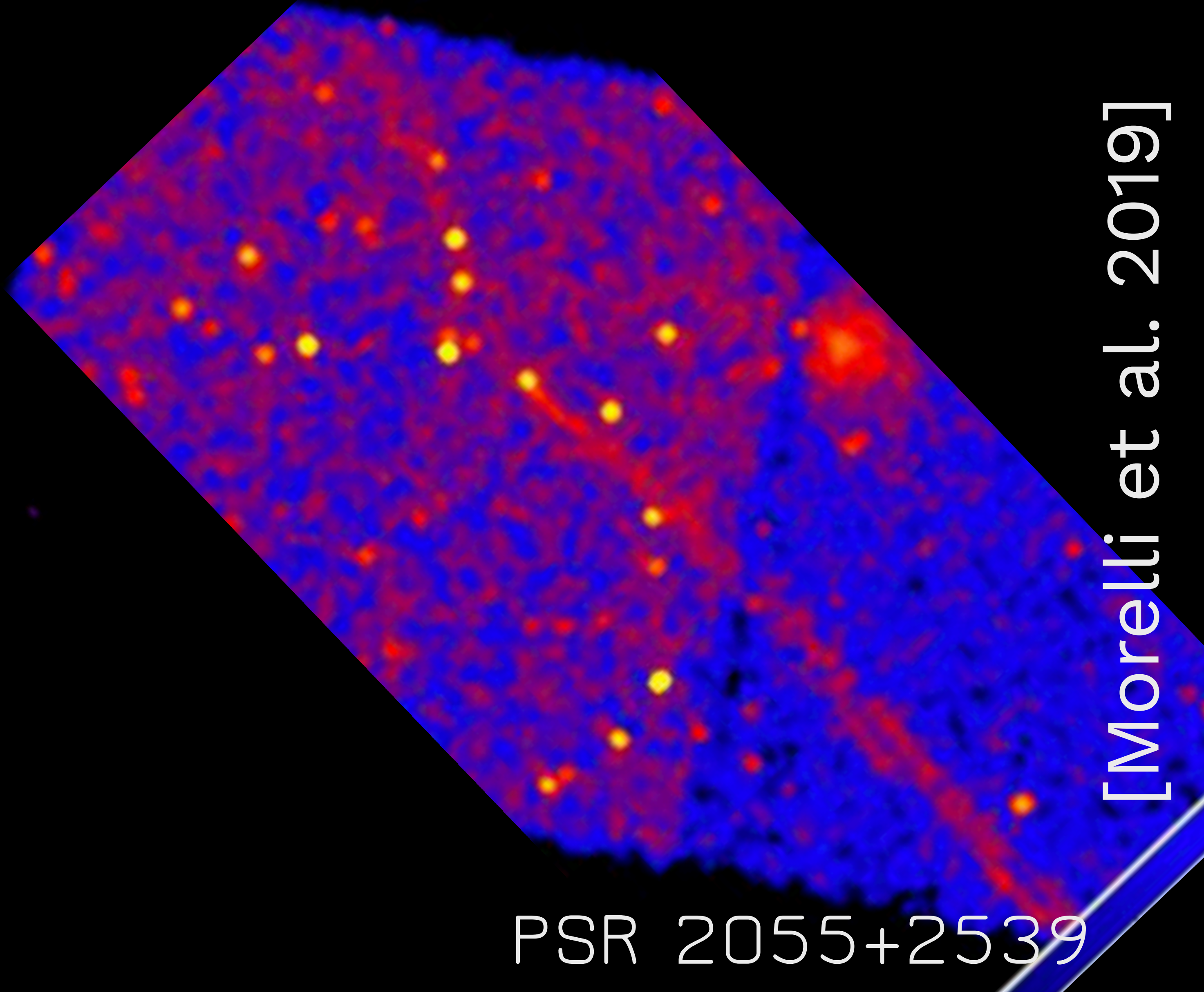


[Cordes et al. 1993, De Vries et al. 2022]



PSR 1509-5850

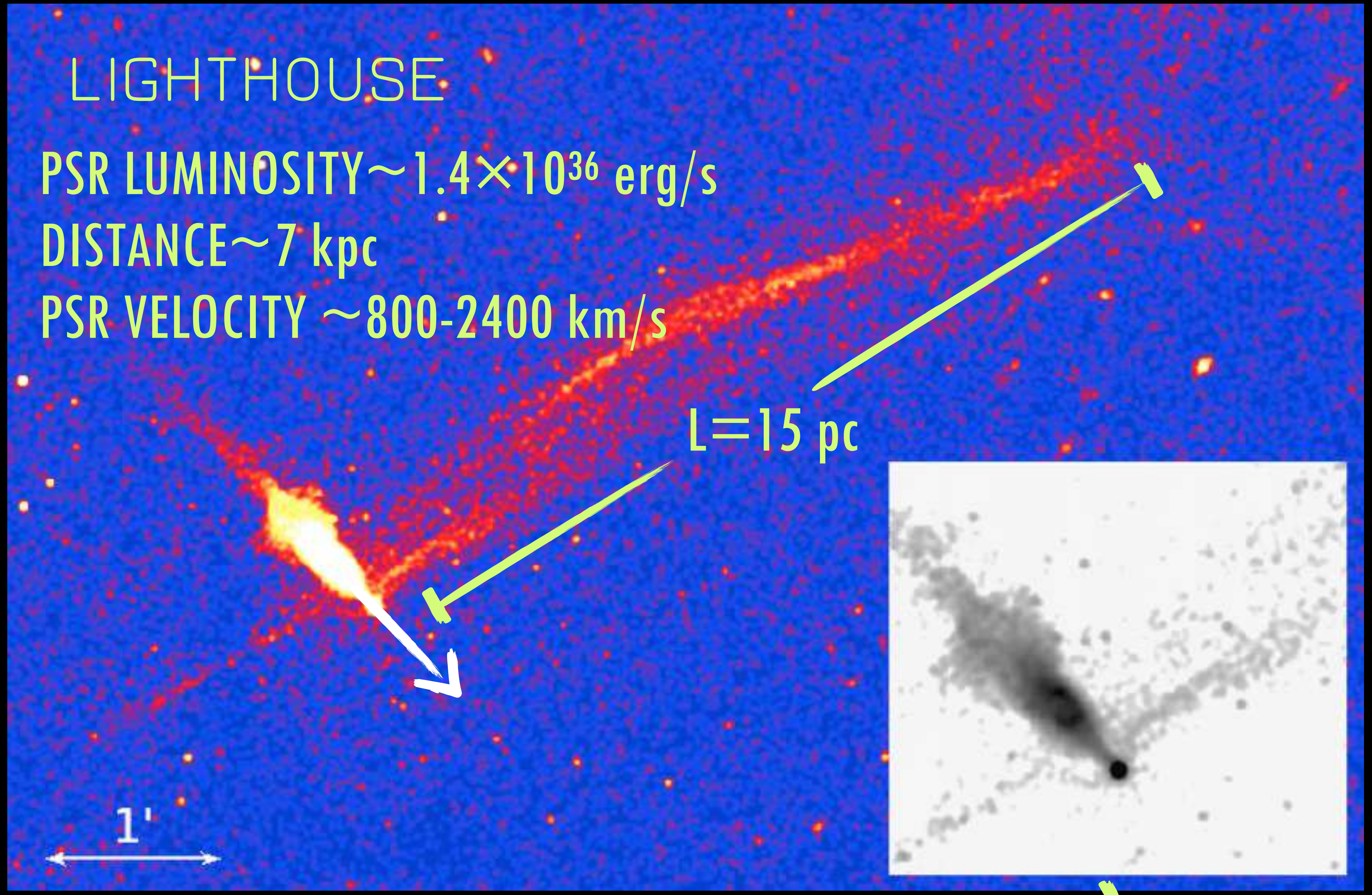
[Klingler et al. 2016]

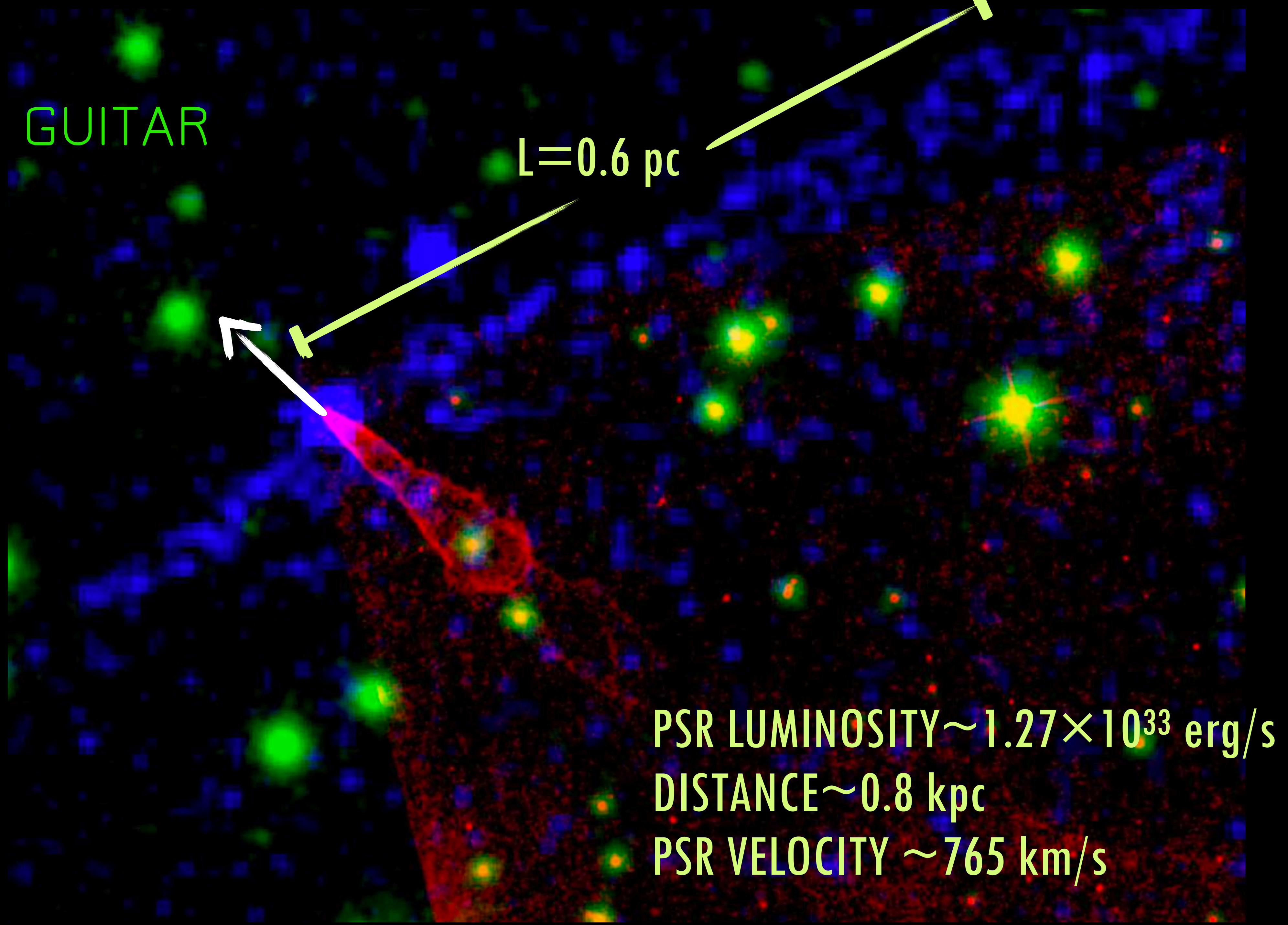


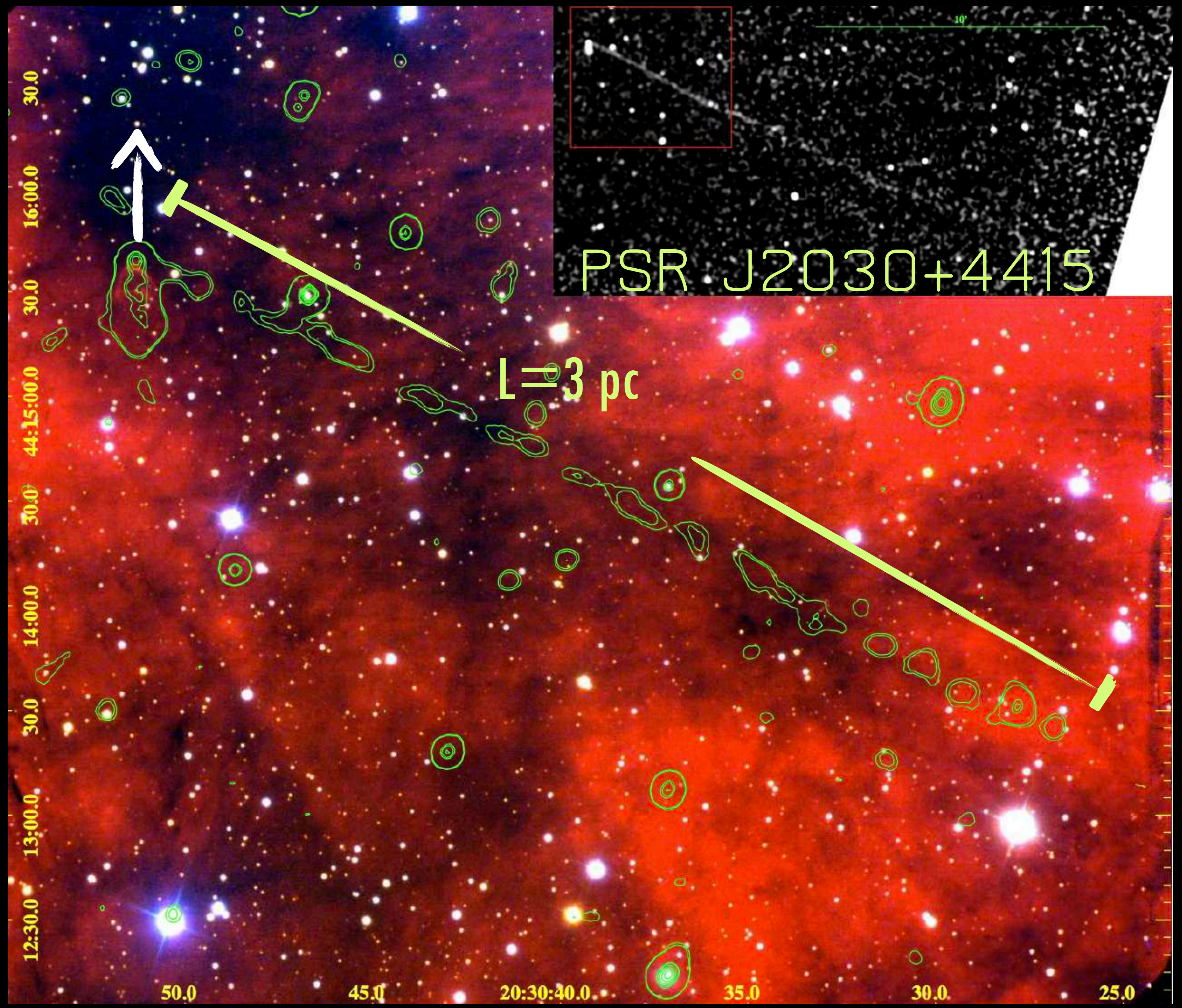
PSR 2055+2539

[Morelli et al. 2019]

EVIDENCE OF PARTICLE ESCAPE: MISALIGNED X-RAY TAILS







PSR LUMINOSITY~2.2×10^{34} erg/s
DISTANCE~720 pc
PSR VELOCITY ~290 km/s

INTERPRETING THE X-RAY FEATURES

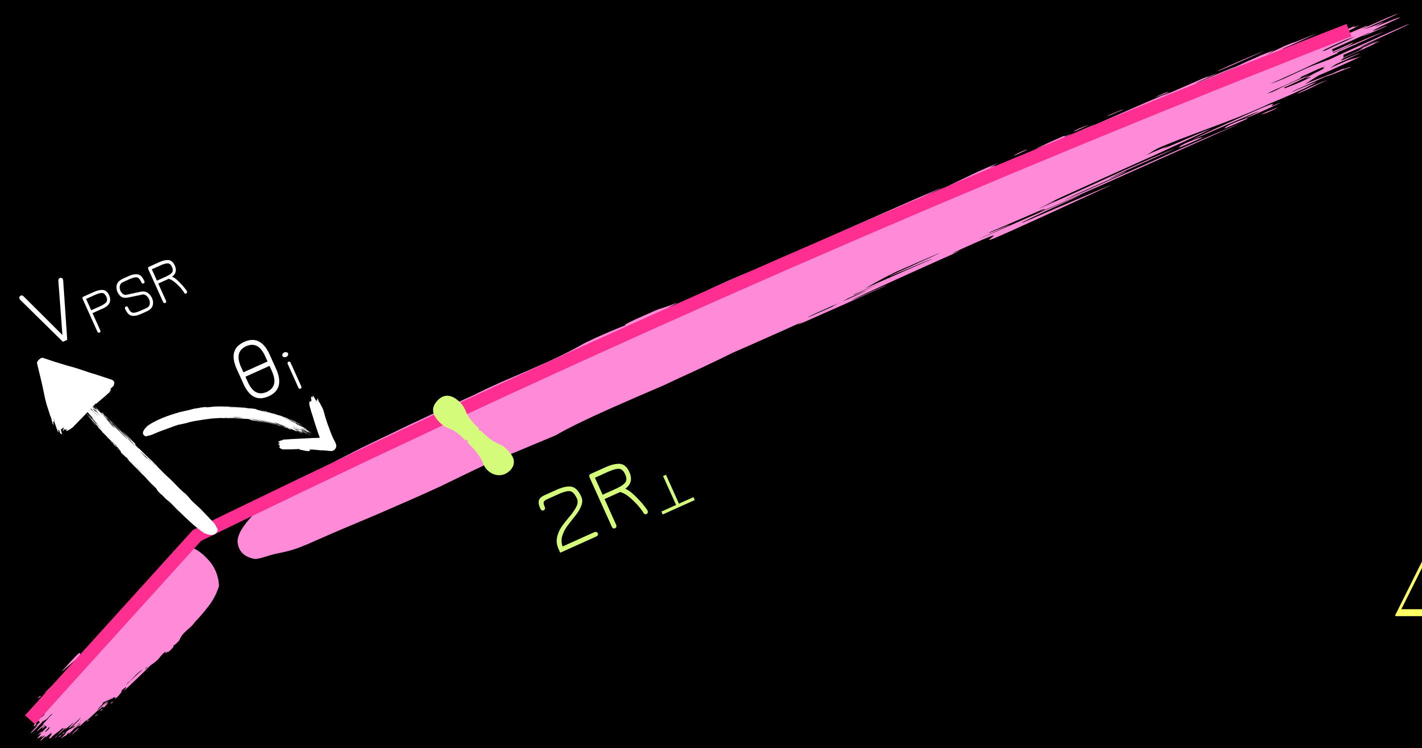
Can be explained as synchrotron radiation emitted by particles escaping the nebula, for which you need:

1. Massive particle escape

2. Particles of energy close to the maximum theoretically available one, connected with the pulsar potential drop:

$$\gamma_{\rm MPD} = \frac{e}{mc^2}\sqrt{\frac{\dot{E}}{c}} \simeq 3\times10^8 \left(\frac{\dot{E}}{10^{34}\,{\rm erg/s}}\right)$$

3. A mechanism to amplify the ambient magnetic field, estimated from the transverse size of the feature:



$2R_\perp/(V_{PSR}\sin\theta_i) \simeq \tau_{sync}$

$$\Delta B \simeq 40\left(\frac{E_{\rm ph}}{2\,{\rm keV}}\right)^{-1/3}\mu{\rm G}$$

[Bandiera 2008]

Guitar nebula [0.5-7 keV + Hα]

HOW TO AMPLIFY THE FIELD?

An efficient way is to excite the non-resonant Bell instability, for which you need:

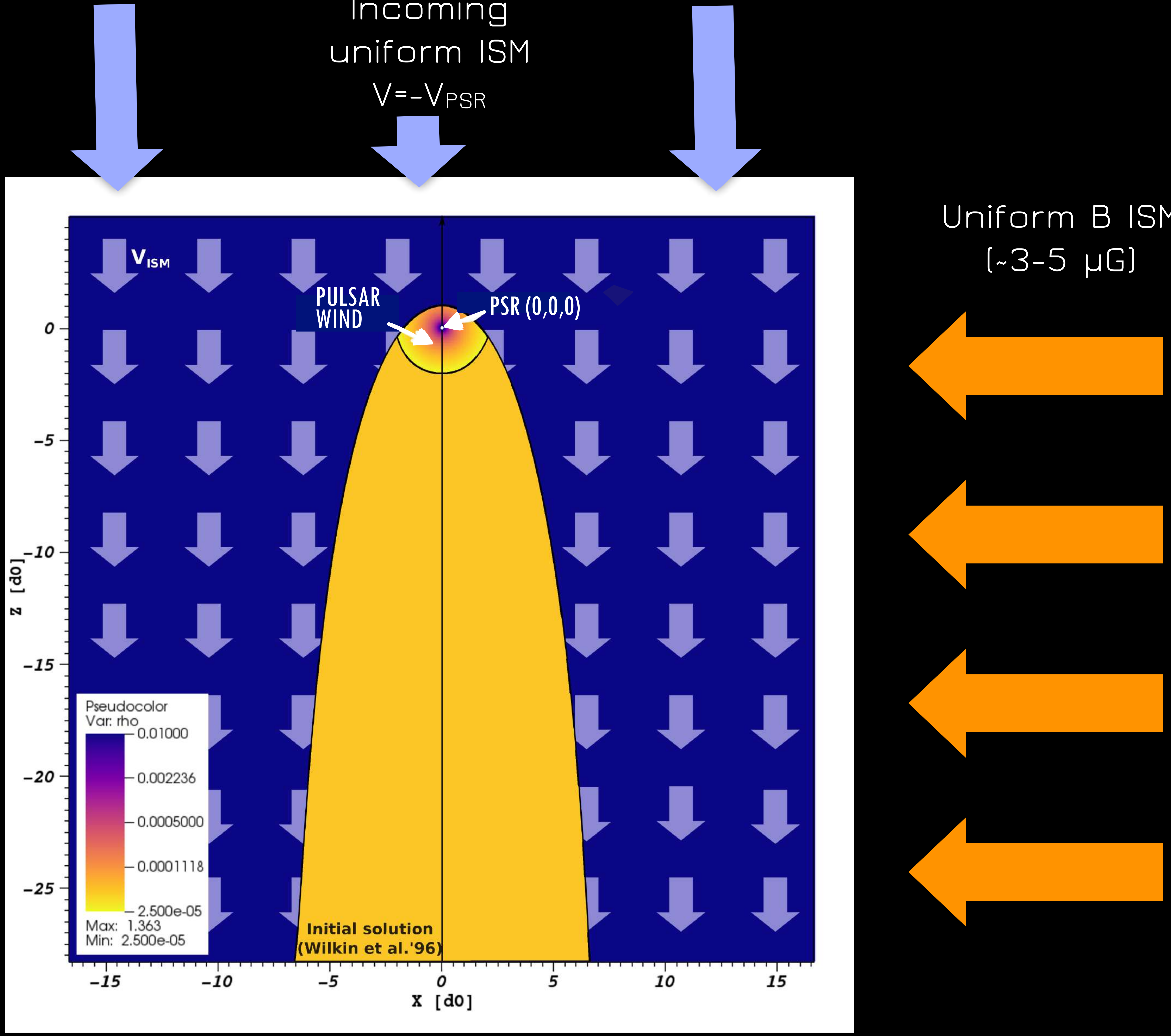
1. An electric current J

2. The escaping particles to carry an energy density larger than the magnetic energy density of the ambient medium:

$$n_{esc}\, mc^2\, (\gamma_{esc} - 1) \geq B_0^2/(8\pi)$$

HOW DO PARTICLES ESCAPE? INVESTIGATING THE PROCESS THROUGH NUMERICAL SIMULATIONS

Incoming
uniform ISM
V=-V_{PSR}



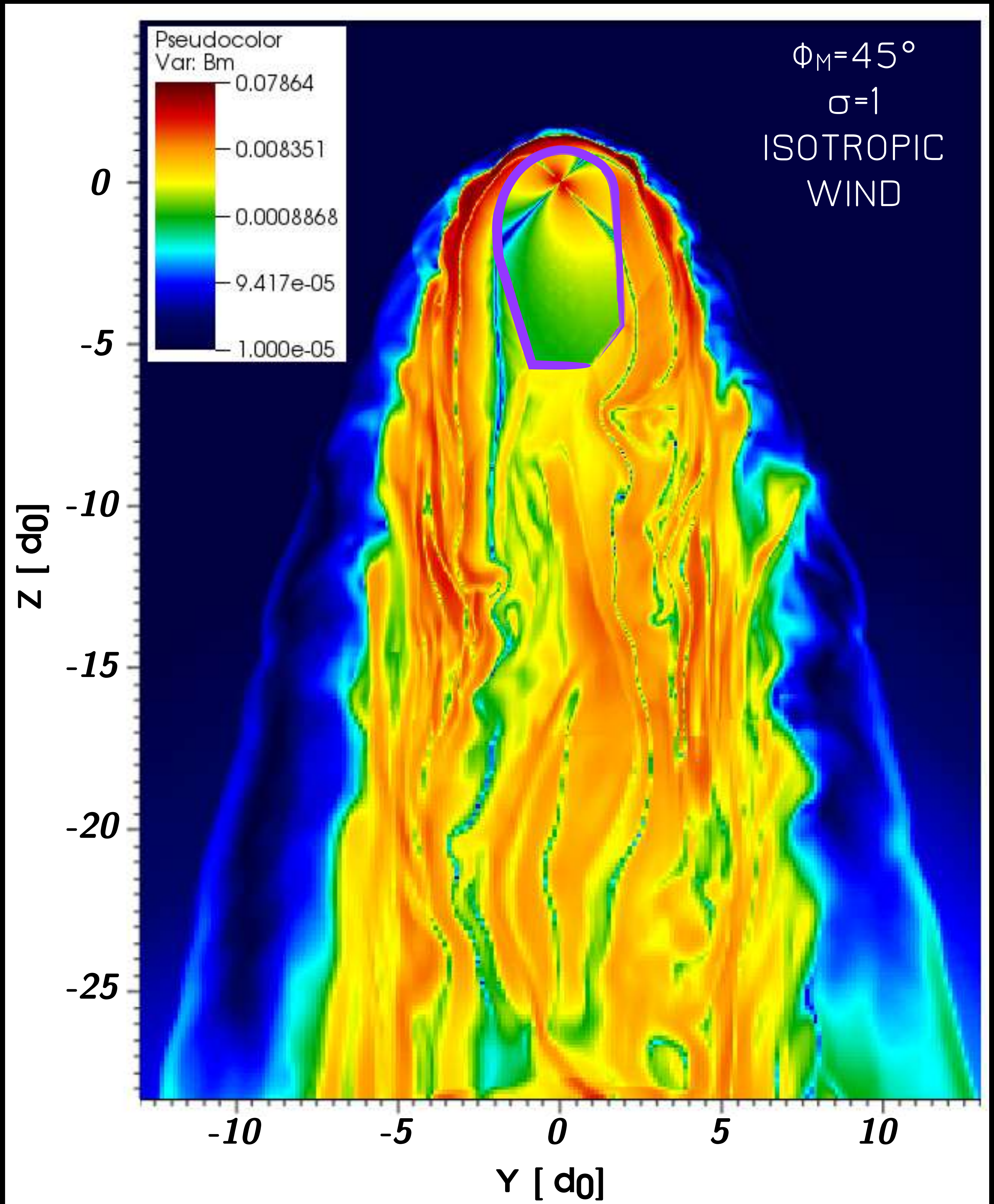
Uniform B ISM
(~3-5 μG)

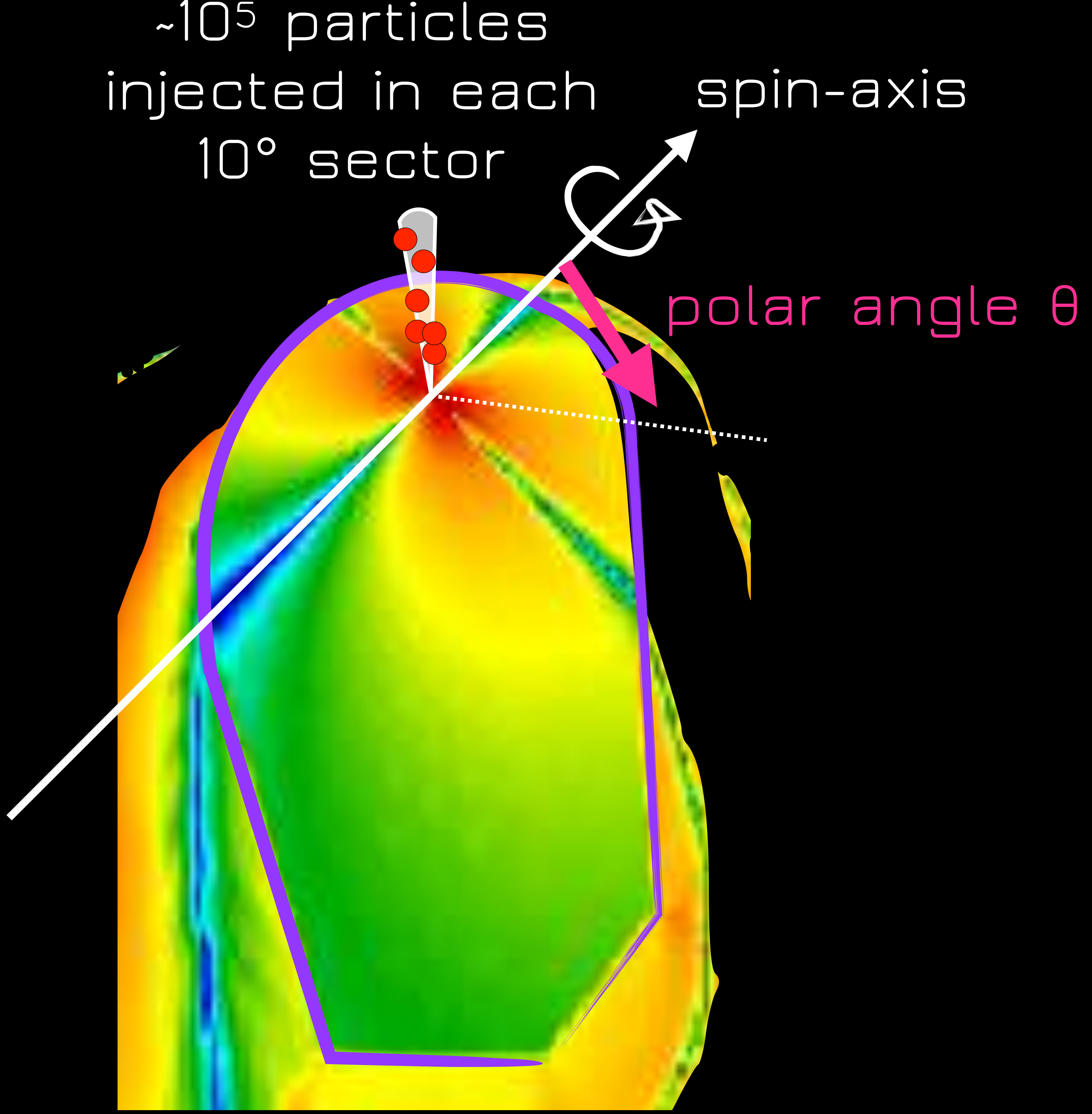
[Olmi & Bucciantini 2019-I/II]

Simulations with the PLUTO code [Mignone et al. 2007]

Class A project @

INJECTING PARTICLES IN THE PULSAR WIND





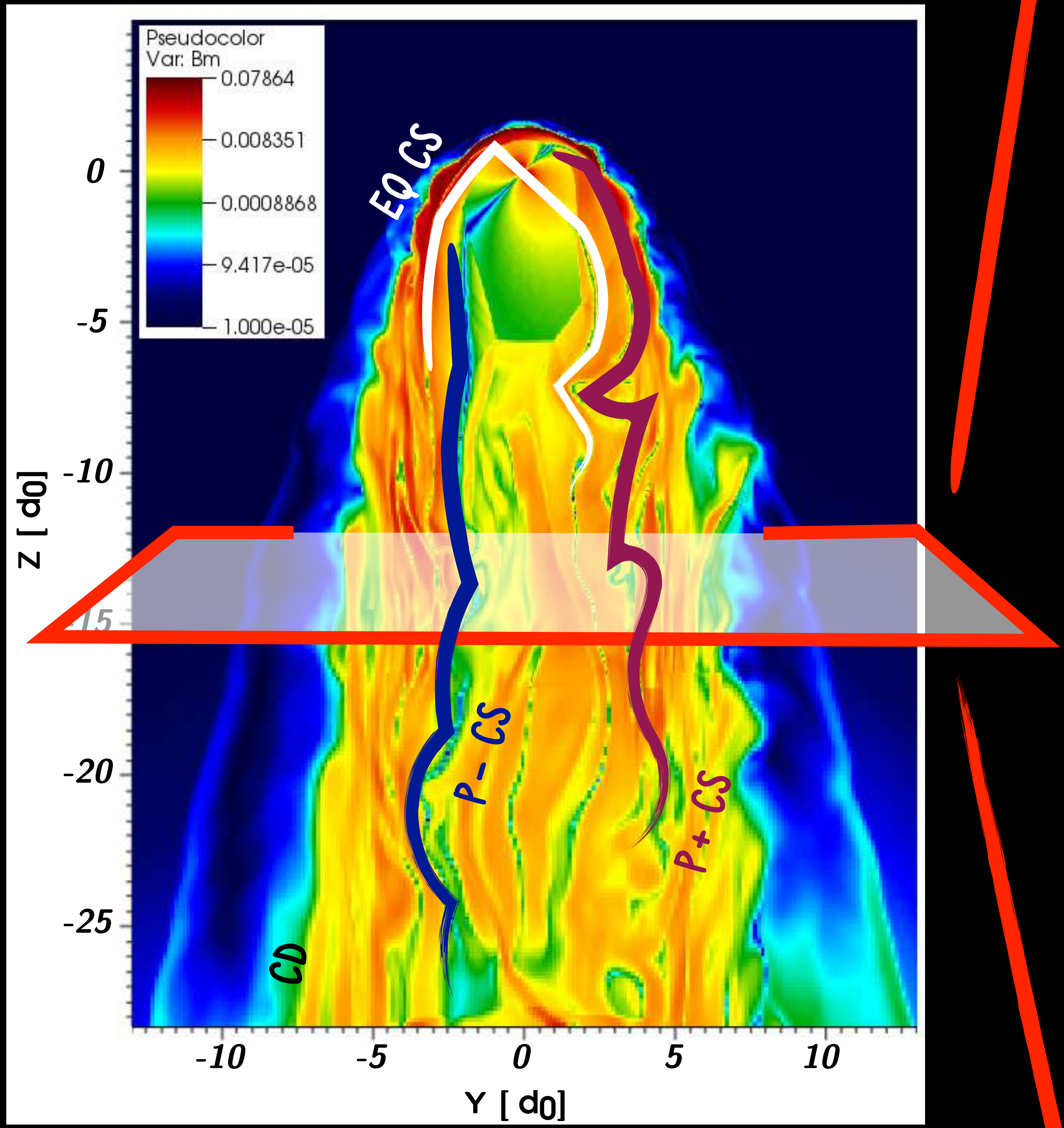
Electrons and positrons of different energies (1~50 TeV):

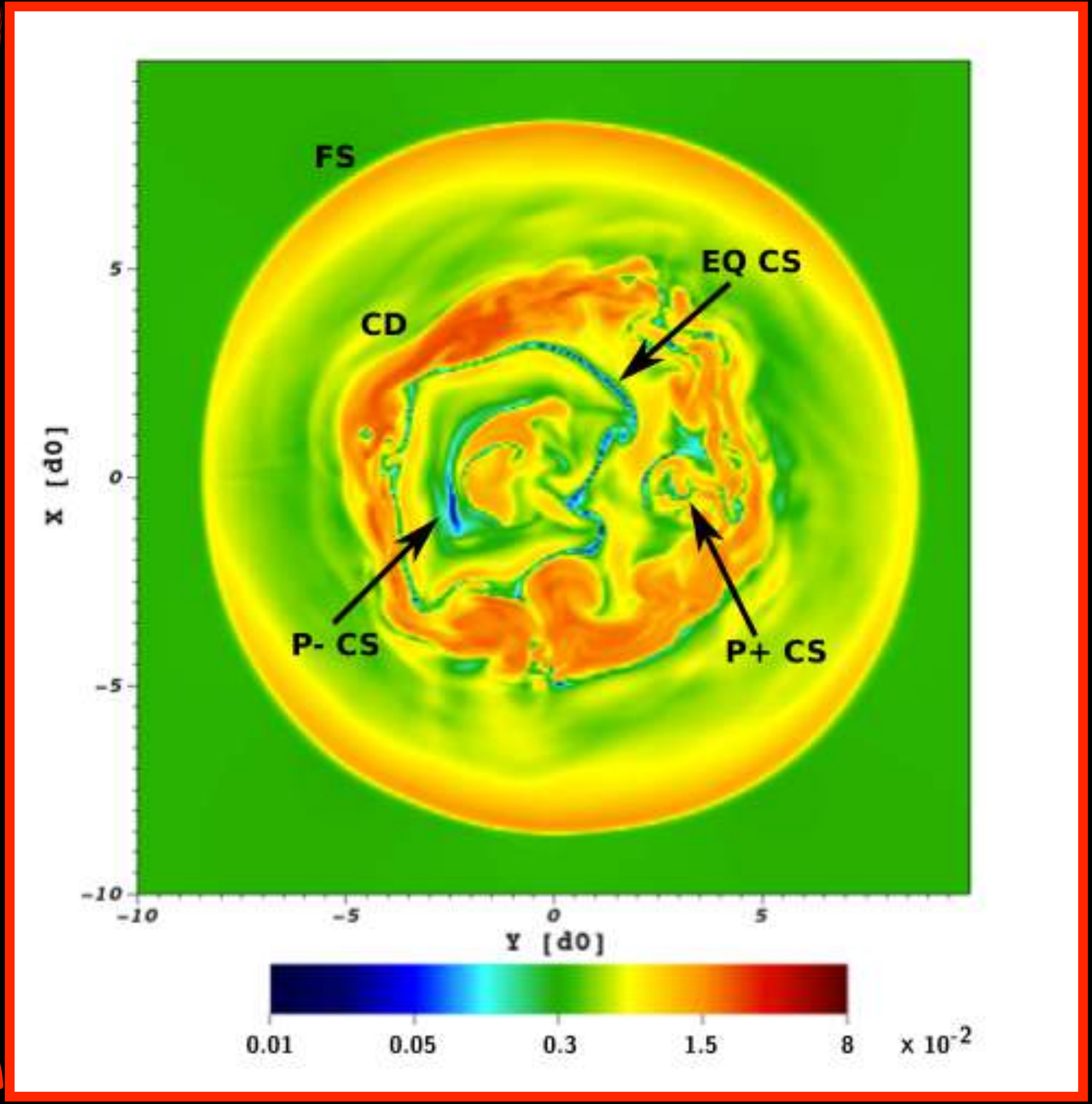
$\gamma = E/(m_e c^2) = [0.5, 1.0, 3.0, 10] \times 10^7$

[Olmi & Bucciantini 2019-III]

THE ROLE OF CURRENT SHEETS IN THE TAIL

Particles remain confined in current sheets from injection

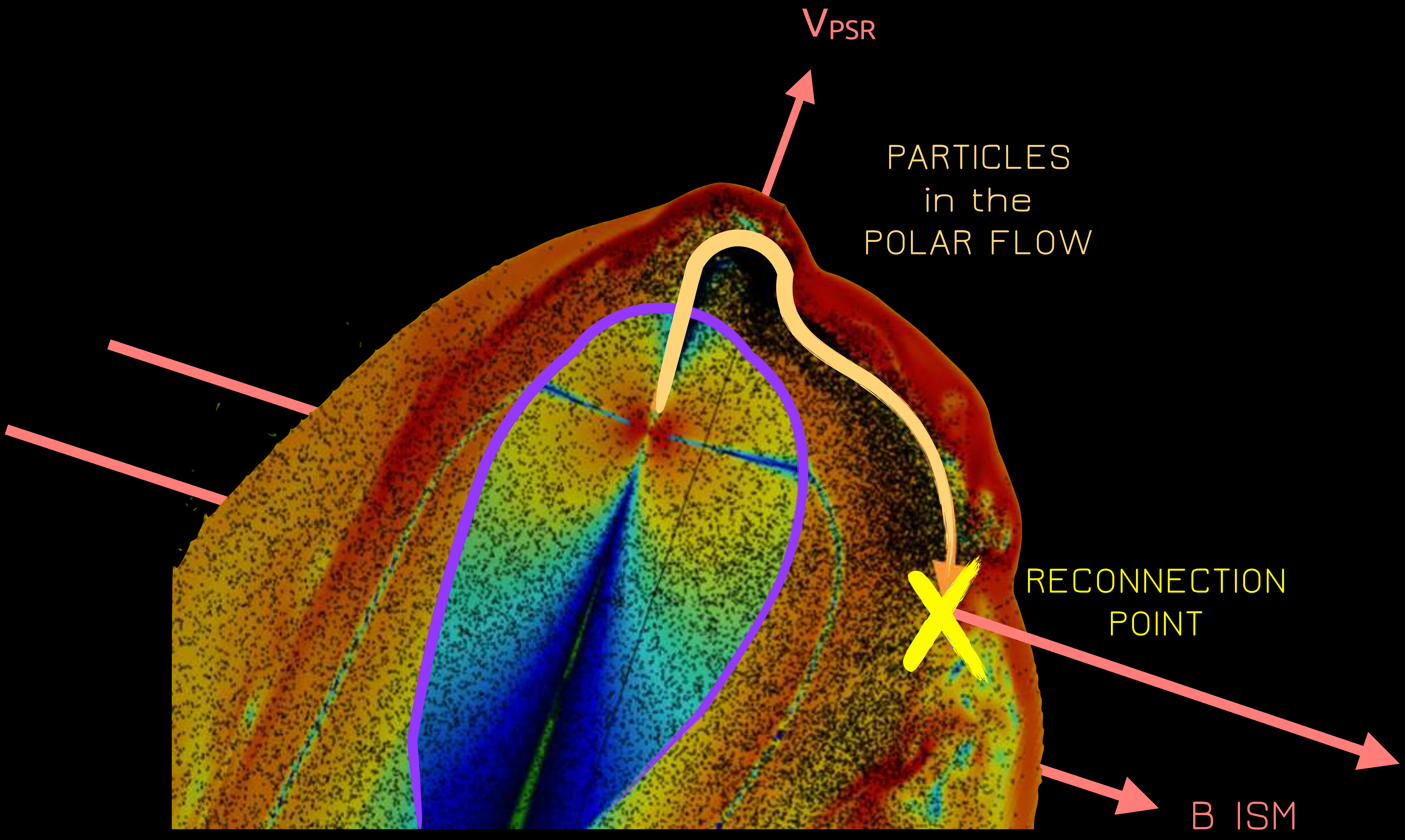




[Olmi & Bucciantini 2019-I/II]

ESCAPE OF PARTICLES: HOW AND FROM WHERE

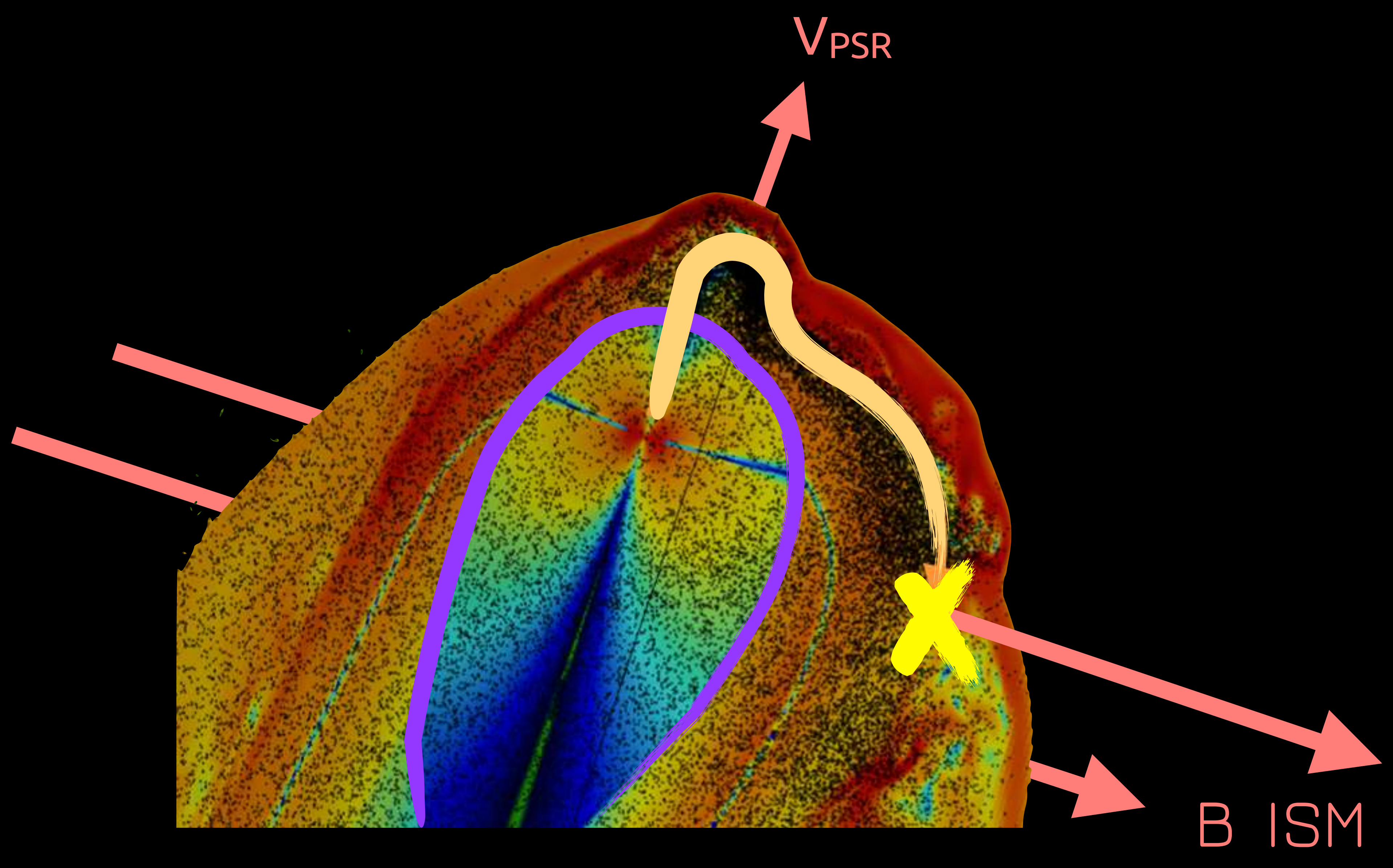
When the current sheet points towards the CD, particles can escape at reconnection points of the magnetopause



[Olmi & Bucciantini 2019-III]

ESCAPE OF PARTICLES: EFFICIENCY

How efficient the process is depends on the particle energy = its Larmor radius R_L



Low energy particles have small R_L, are closely attached to the streamlines and can only escape directly at reconnection points.

High energy particles have large R_L, and efficiently escape in the vicinity of reconnection points.

ENERGY of ESCAPING PARTICLES

$\gamma \sim 10^6$	$\gamma \sim 10^7$	$\gamma \sim 10^8$
1 TeV	10 TeV	10ns of TeV

← confinement

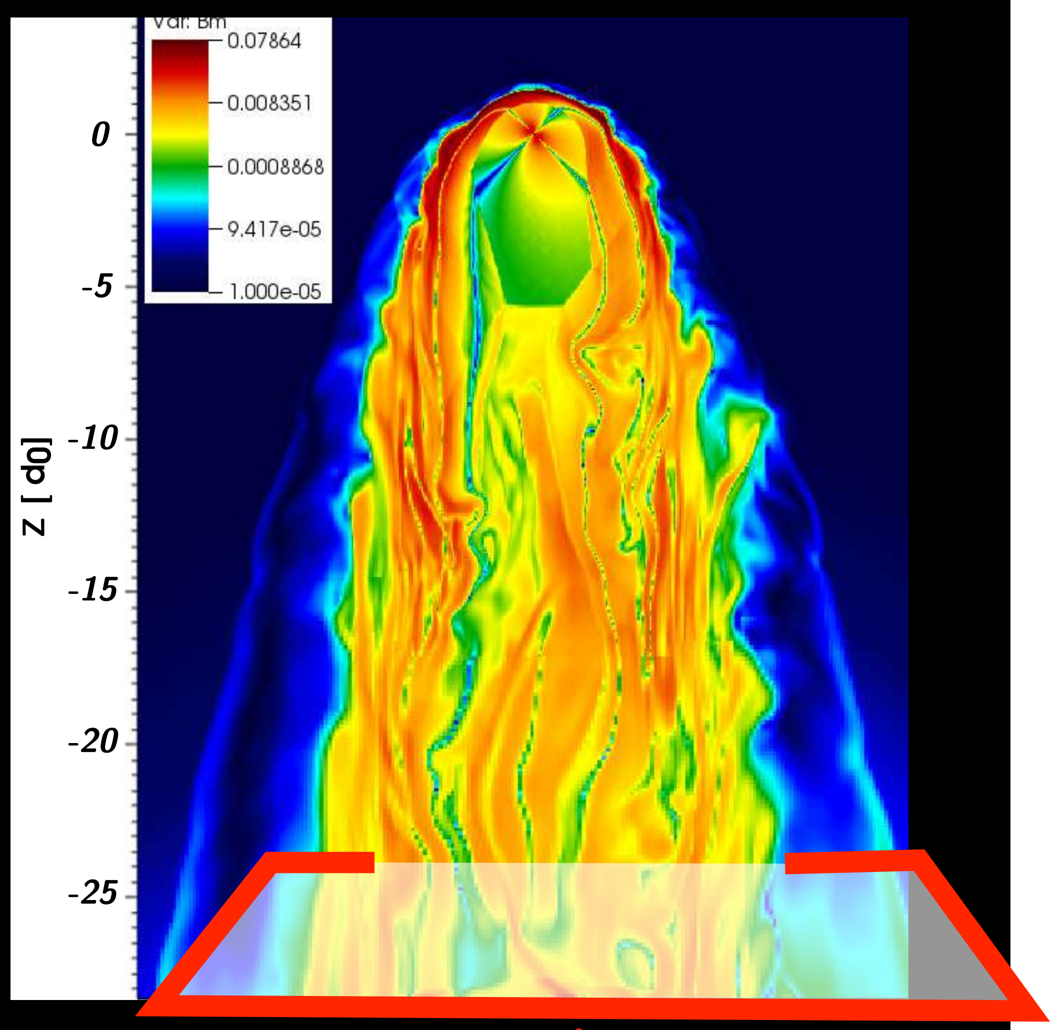
escape →

only particles carrying a large enough fraction of the maximum available energy escape efficiently:

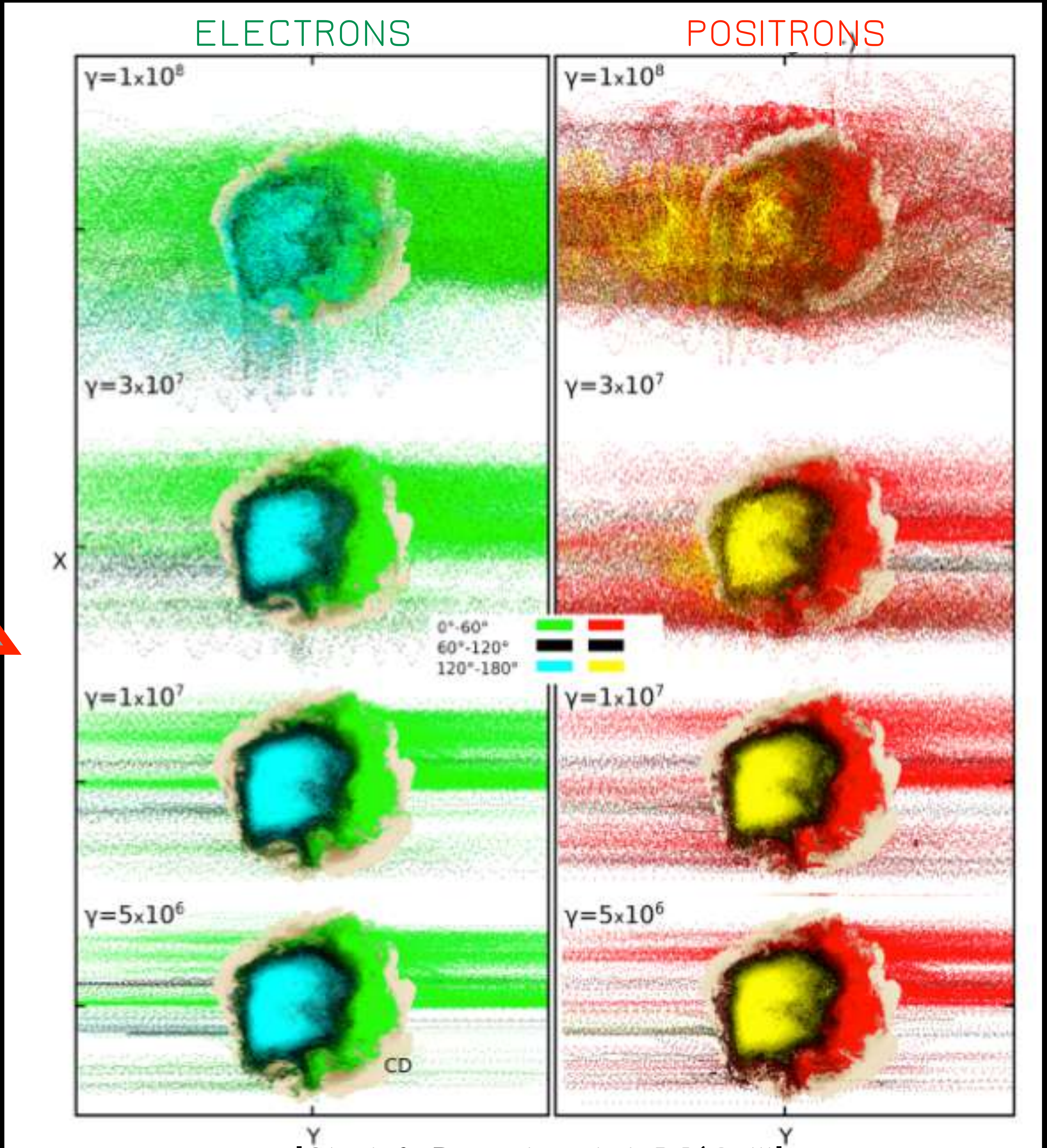
$\gamma_{esc} \gtrsim 10\text{-}50\% \ \gamma_{MPD}$

[Olmi & Bucciantini 2019-III]

ESCAPE OF PARTICLES: CHARGE DEPENDENCE AND ASYMMETRY



view from the back of the tail



[Olmi & Bucciantini 2019-III]

ENERGY

high escape - isotropic

low escape - asymmetric

charge separation

particles diffused

particles advected

HOW TO AMPLIFY THE FIELD?

An efficient way is to excite the non-resonant Bell instability, for which you need:

1. An electric current J

→ Charge separation in the escaping flow makes it possible!

2. The escaping particles to carry an energy density larger than the magnetic energy density of the ambient medium:

$n_{esc}\, mc^2\, (\gamma_{esc} - 1) \geq B_0^2/(8\pi)$

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2. The escaping particles to carry an energy density larger than the magnetic energy density of the ambient medium:

$n_{esc}\, mc^2\, (\gamma_{esc} - 1) \geq B_0^2/(8\pi)$ → This condition is satisfied if a high enough fraction of the pulsar luminosity (ϵ) goes into escaping particles:

$$\epsilon \gtrsim 10^{-6} \dot{E}$$

[Bandiera, Olmi, Blasi, Amato, in preparation]

CAN WE REACH THE REQUIRED AMPLIFICATION?

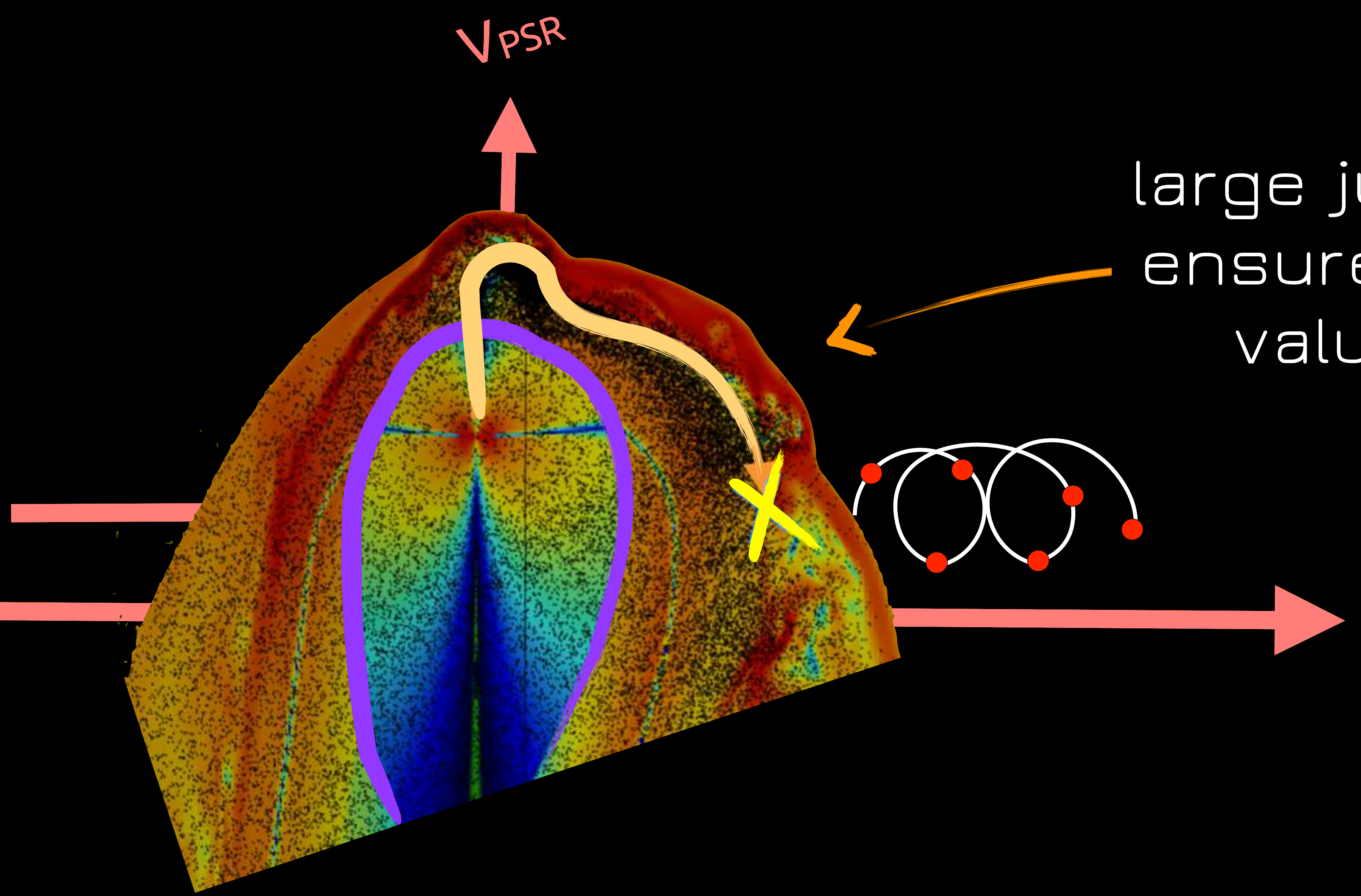
The observed synchrotron emission in the feature required a factor ~x5-10 of amplification of the ambient field, that must be reached when the instability saturates:

saturation scale $\Delta x \simeq R_{gyro,\perp}(\gamma_{esc})$

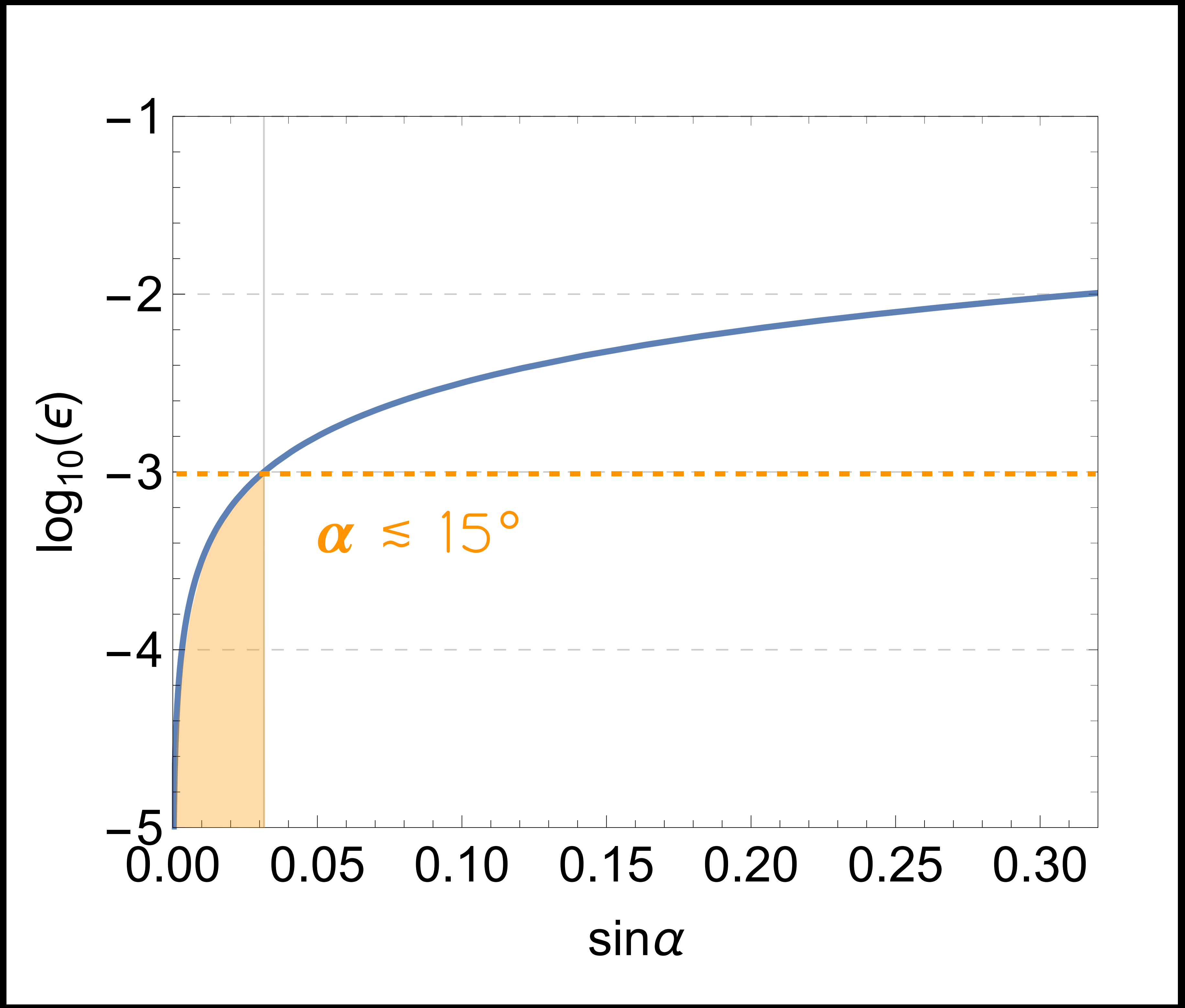
$$\left(\frac{\Delta B}{B_{\rm ISM}}\right)_{\rm sat} = \frac{2\sqrt{\epsilon}}{\sin\alpha}\left(\frac{\gamma_{\rm MPD}}{\gamma_{\rm esc}}\right)$$

$\boldsymbol{\alpha}$ → particle pitch angle

ϵ → fraction of PSR luminosity going in the feature



large jump in B field (70→3 μG) ensures anisotropy and small values of escaping pitch angles



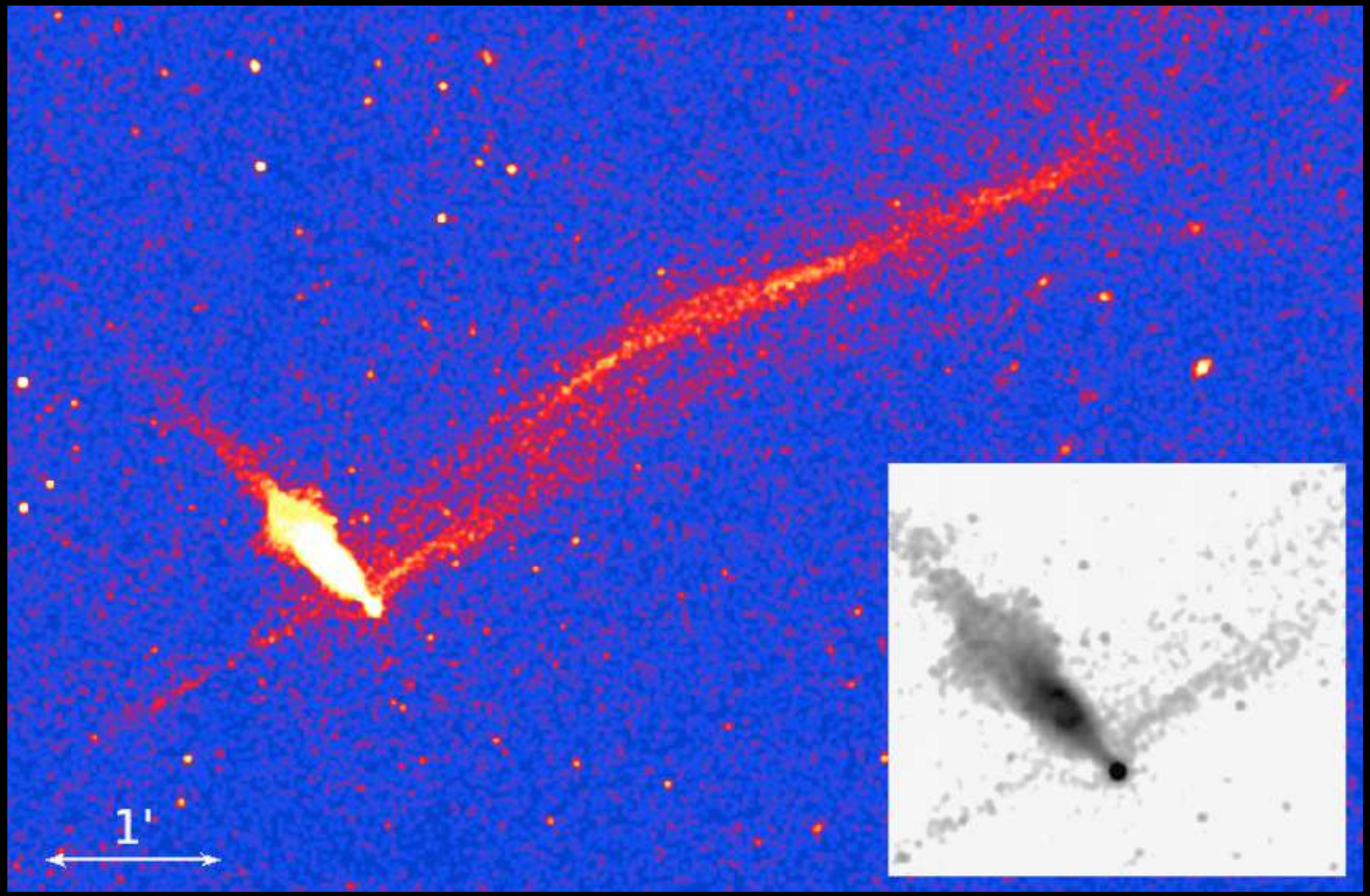
[Bandiera, Olmi, Blasi, Amato, in preparation]

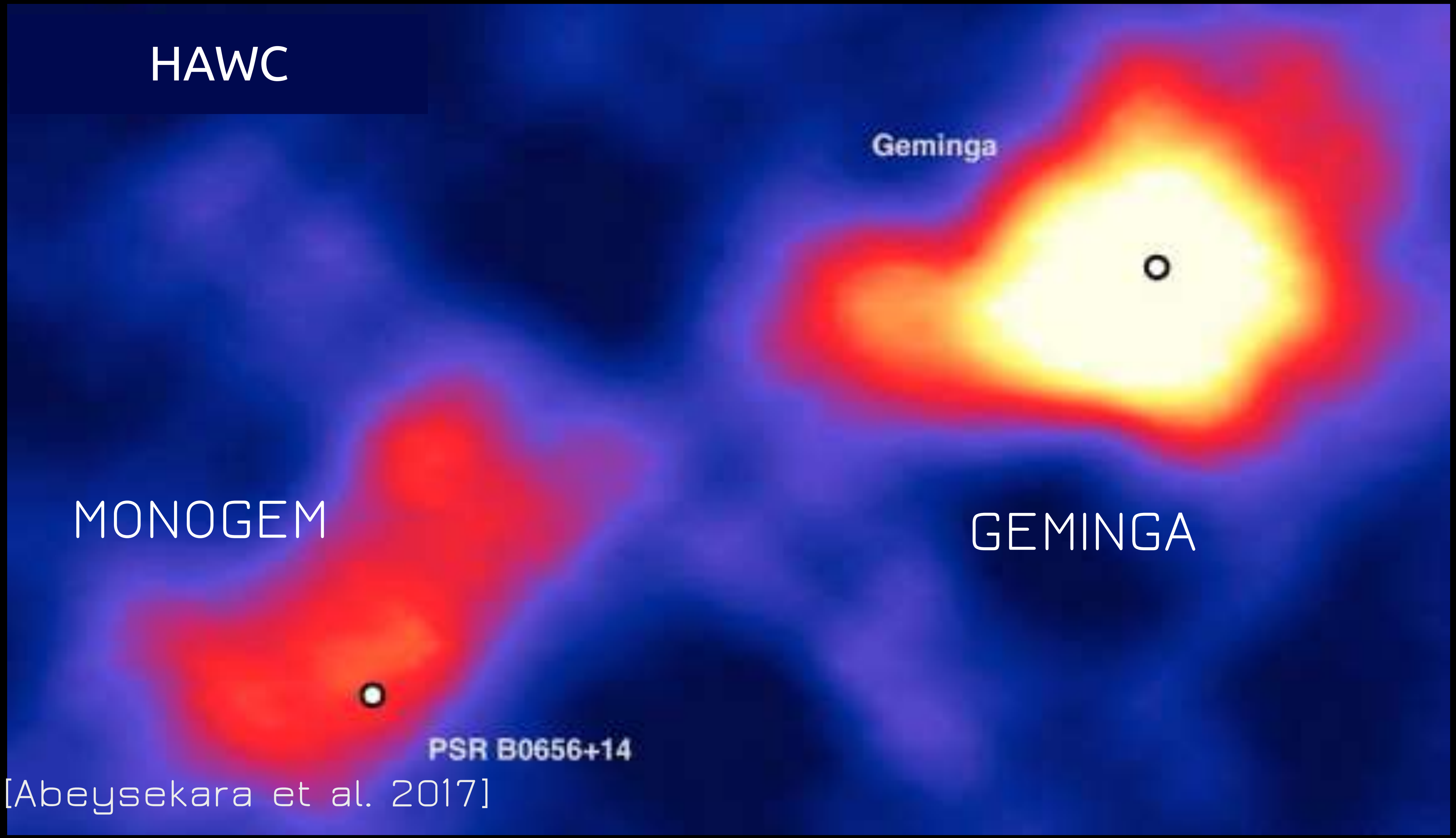
CONCLUSIONS

Evolved PWNe do show evident leakage of particles in the ambient medium.

In the last ~10 yrs the number of misaligned X-ray features detected increased → are them a universal feature of bow shock nebulae?

Understanding the nature of these features is fundamental to understand how PWNe load the Galaxy with particles (energy, number, charge, etc) and have important consequences on many open problems (CR physics, nature of TeV halos, PeVatrons)





[Abeysekara et al. 2017]