UNDERSTANDING PULSAR WIND NEBULAE

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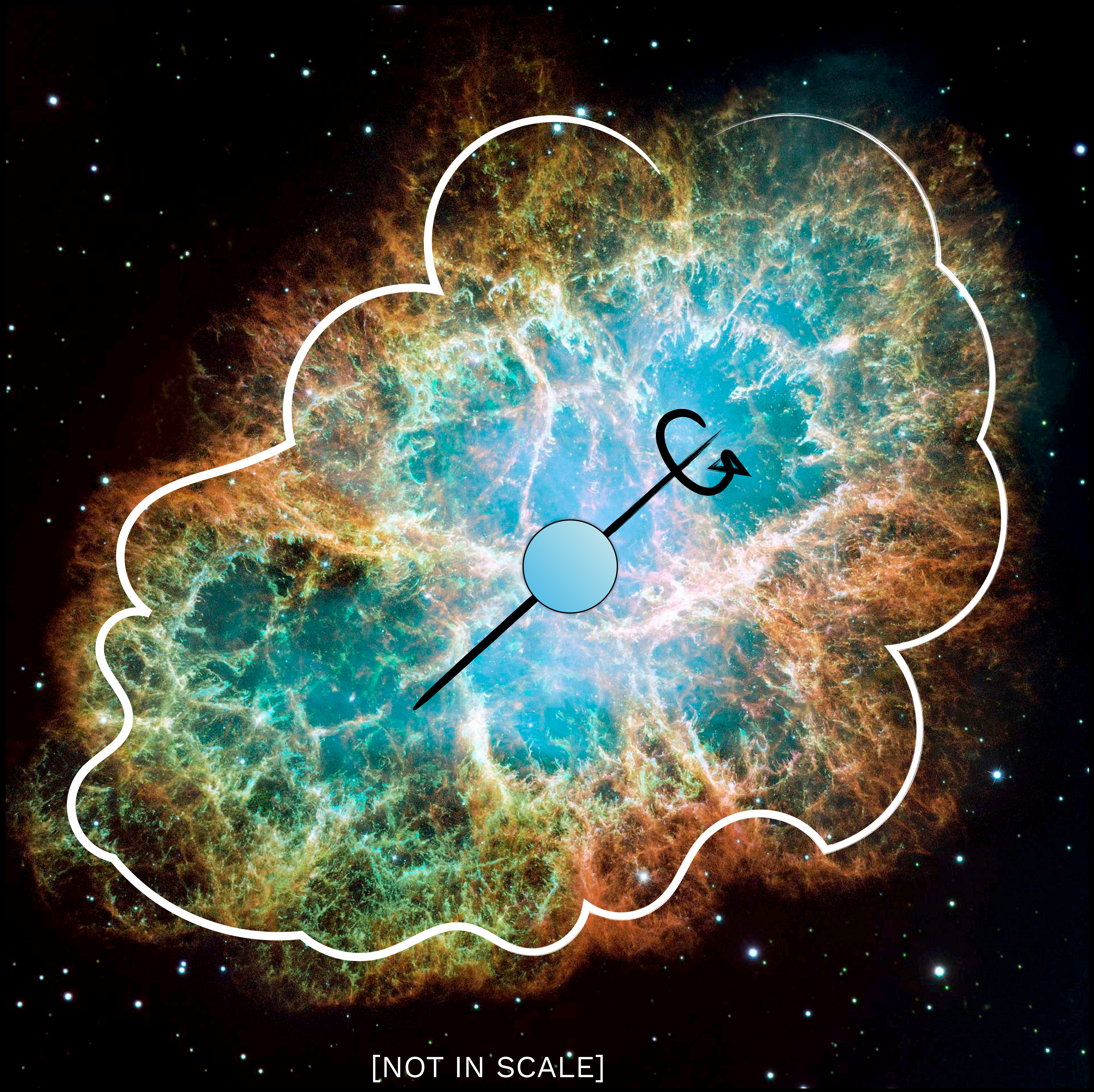
INTRO: WHAT IS A PWN?



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

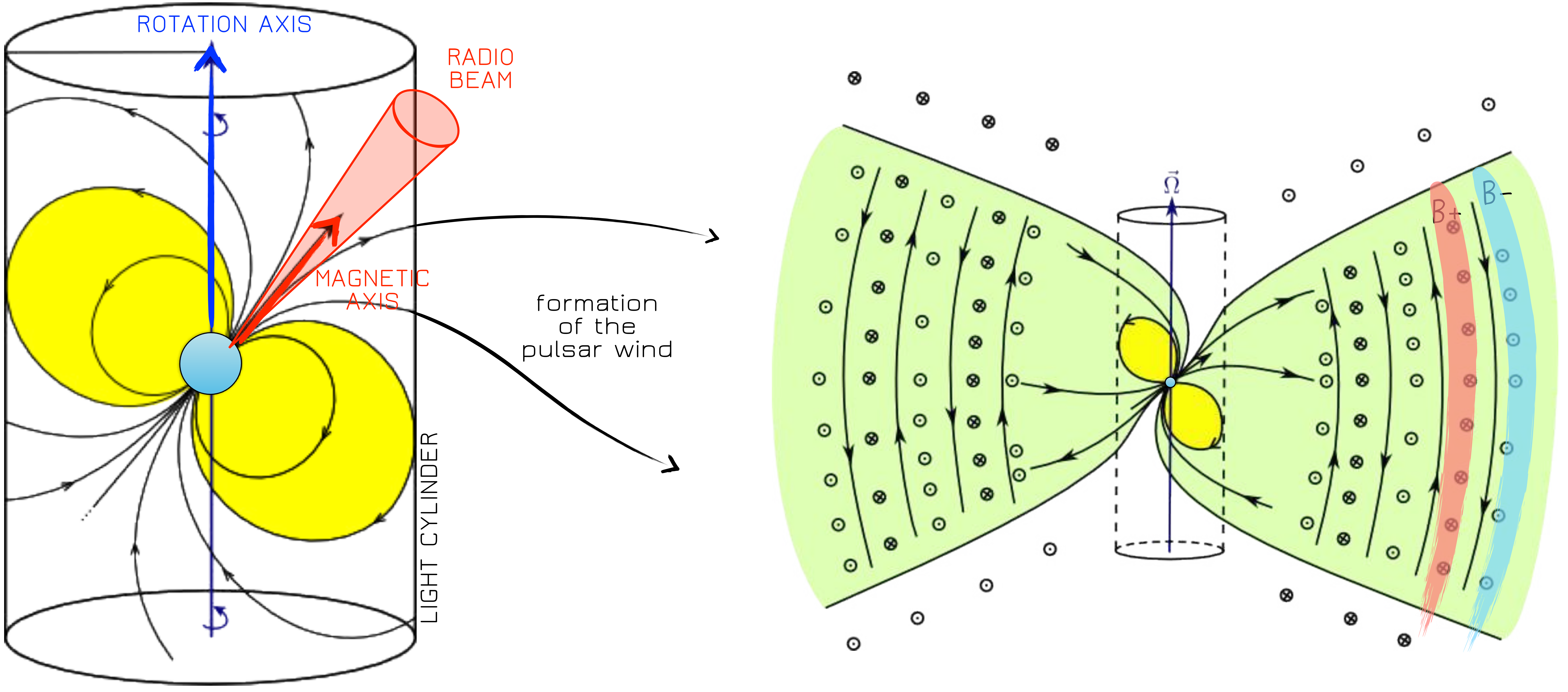
INGREDIENTS:

THE ROTATING NS = PULSAR

THE EJECTA OF THE SN EXPLOSION

THE ENGINE IS THE PULSAR

PULSAR = rotating magnet that slows down due to electromagnetic torque [Pacini 1969]



CLOSED MAGNETOSPHERE

OPEN MAGNETOSPHERE

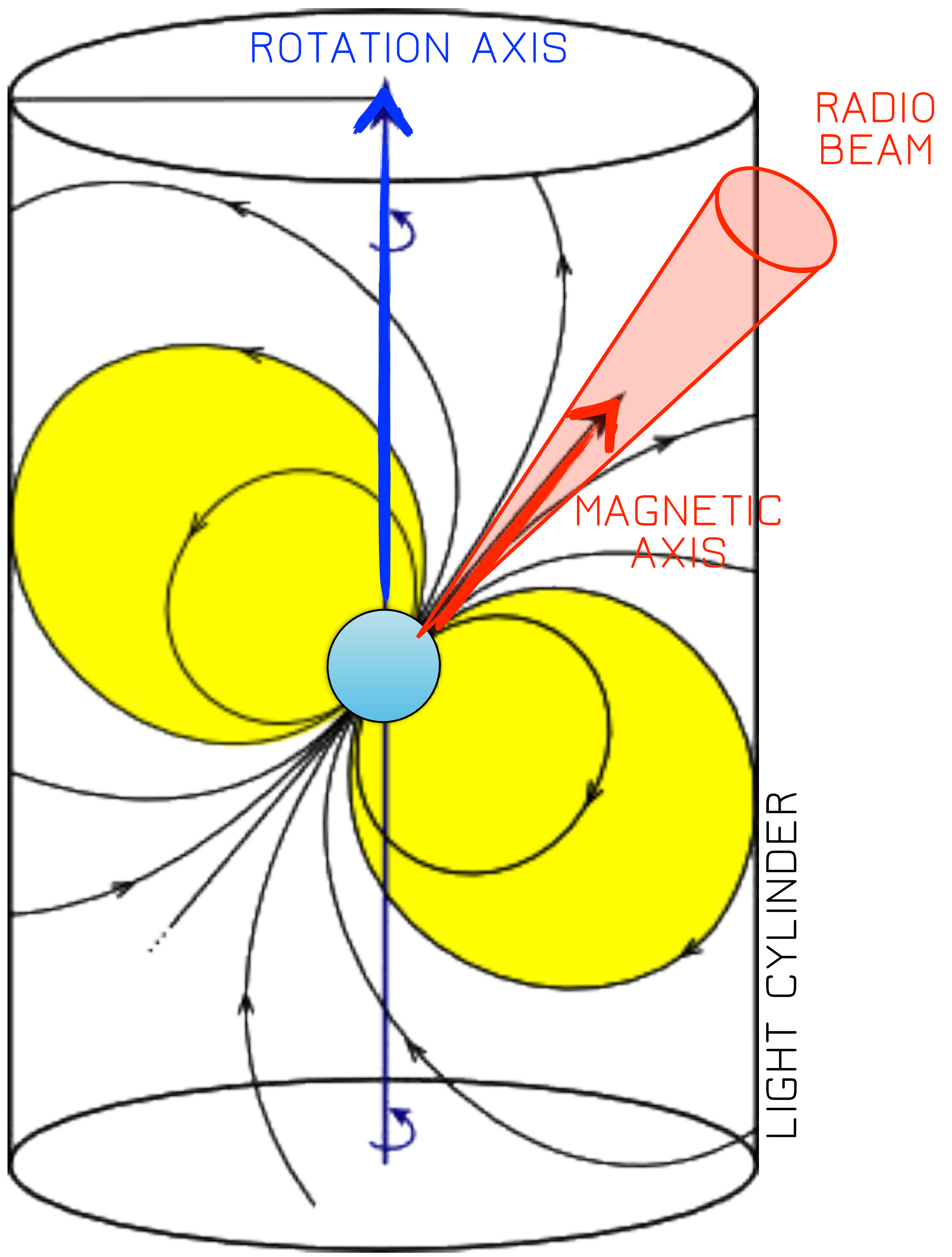
INJECTION FROM THE PULSAR:
RELATIVISTIC PARTICLES AND MAGNETIC FIELD

$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e}\right)(1+\sigma)$$

wind magnetization

$$\sigma = \frac{B^2}{4\pi\, n_\pm\, m_e\, c^2\, \Gamma^2}$$

COMPOSITION OF THE PULSAR WIND



CLOSED MAGNETOSPHERE

PRIMARY PARTICLES - extracted at the star surface [Goldreich & Julian rate]

$$\dot{N}_{GJ} = \dot{E}/e \sim 2.7 \times 10^{30} \left(\frac{B_{pc}}{10^{12}\, G} \right) \left(\frac{P}{1\, s} \right)^{-2} s^{-1}$$

can be both ions (m_i) or electrons (m_e)

SECONDARY PARTICLES - generated in e.m. cascades in the magnetosphere (leptons only)

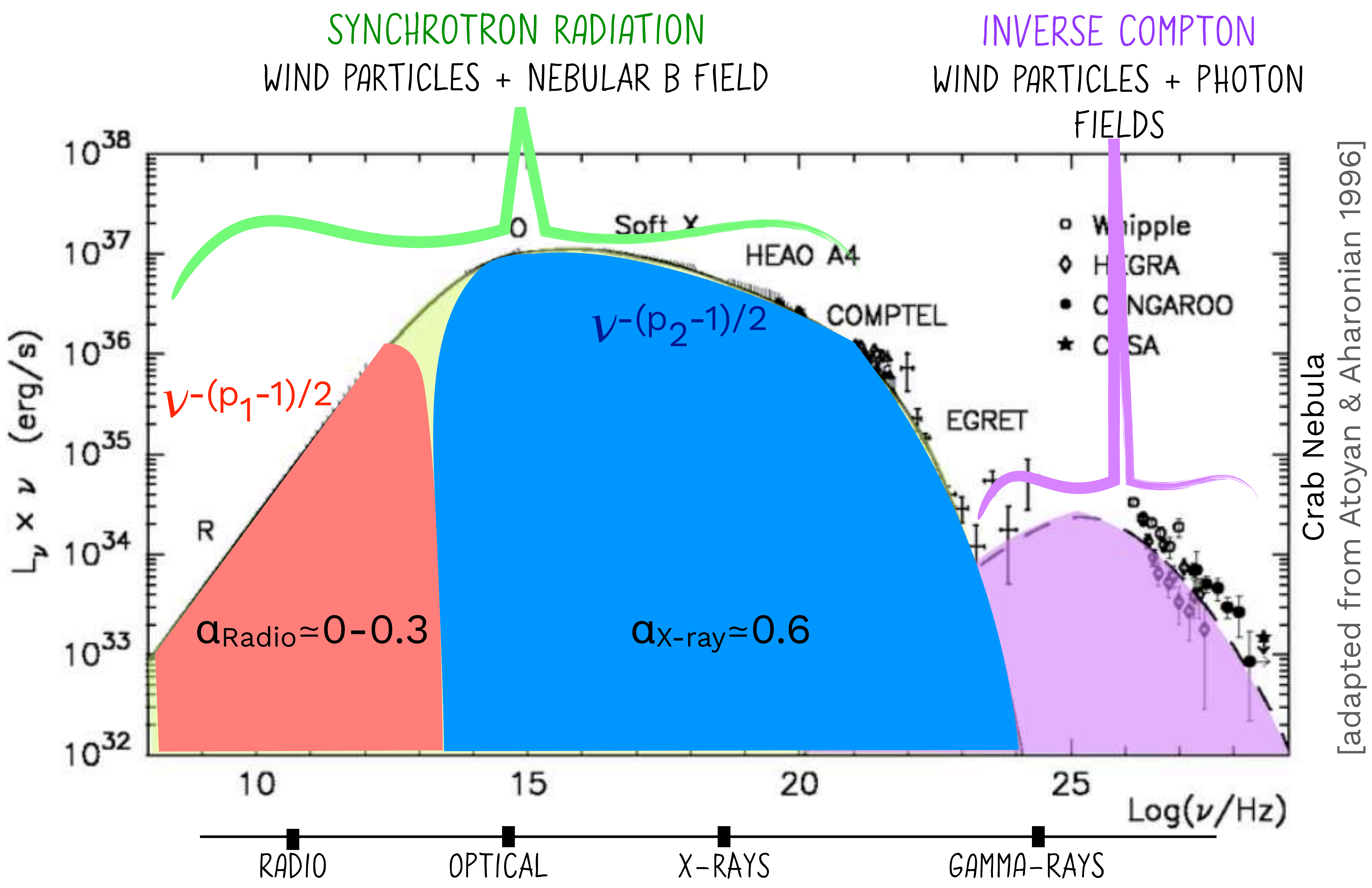
ions ~ 1/k electrons

k (pair multiplicity) = secondary/primary electrons ~10^4-10^7

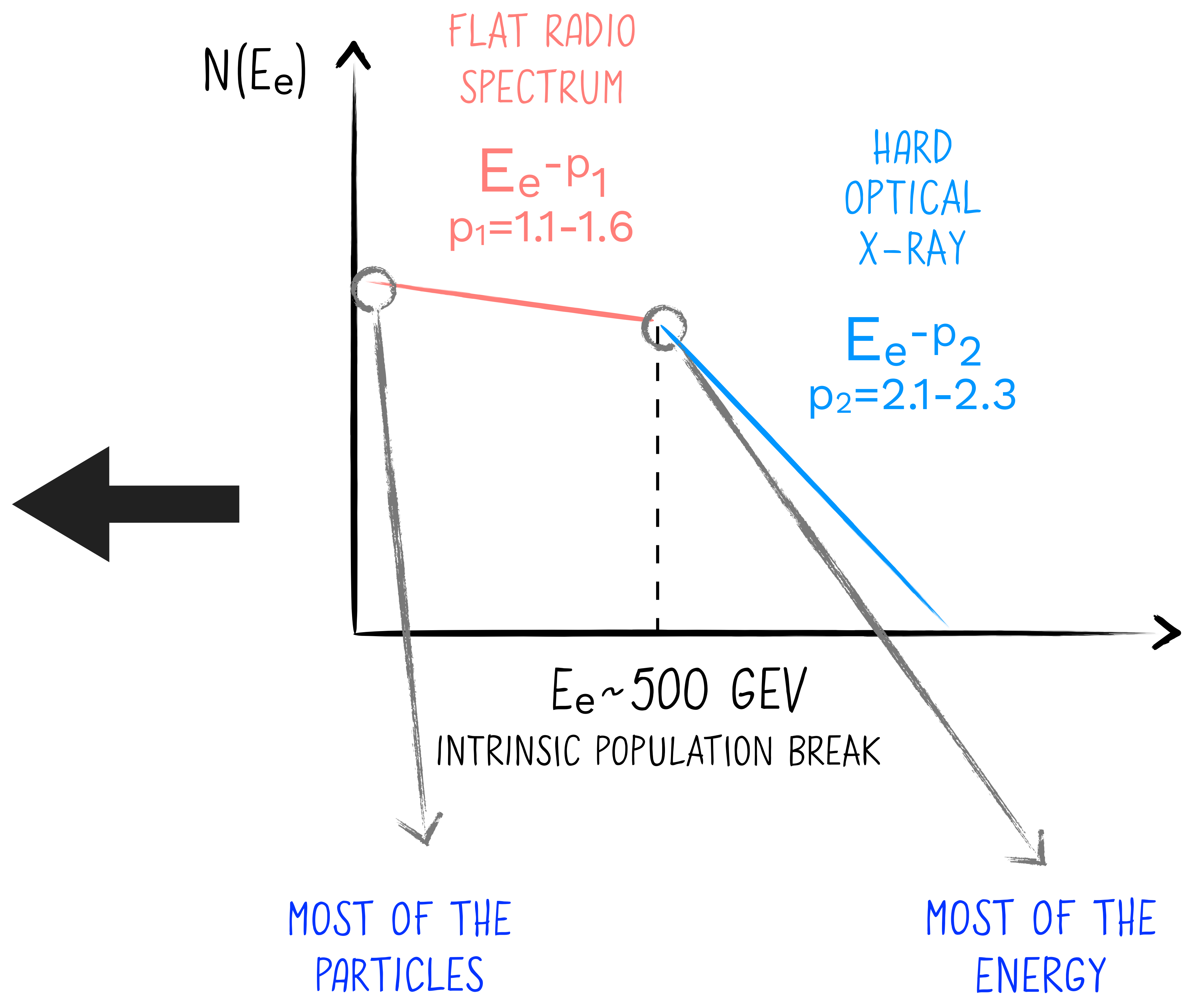
$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e} \right) (1 + \sigma)$$

PARTICLE SPECTRUM AND EMISSION

OBSERVED SPECTRAL ENERGY DISTRIBUTION FUNCTION



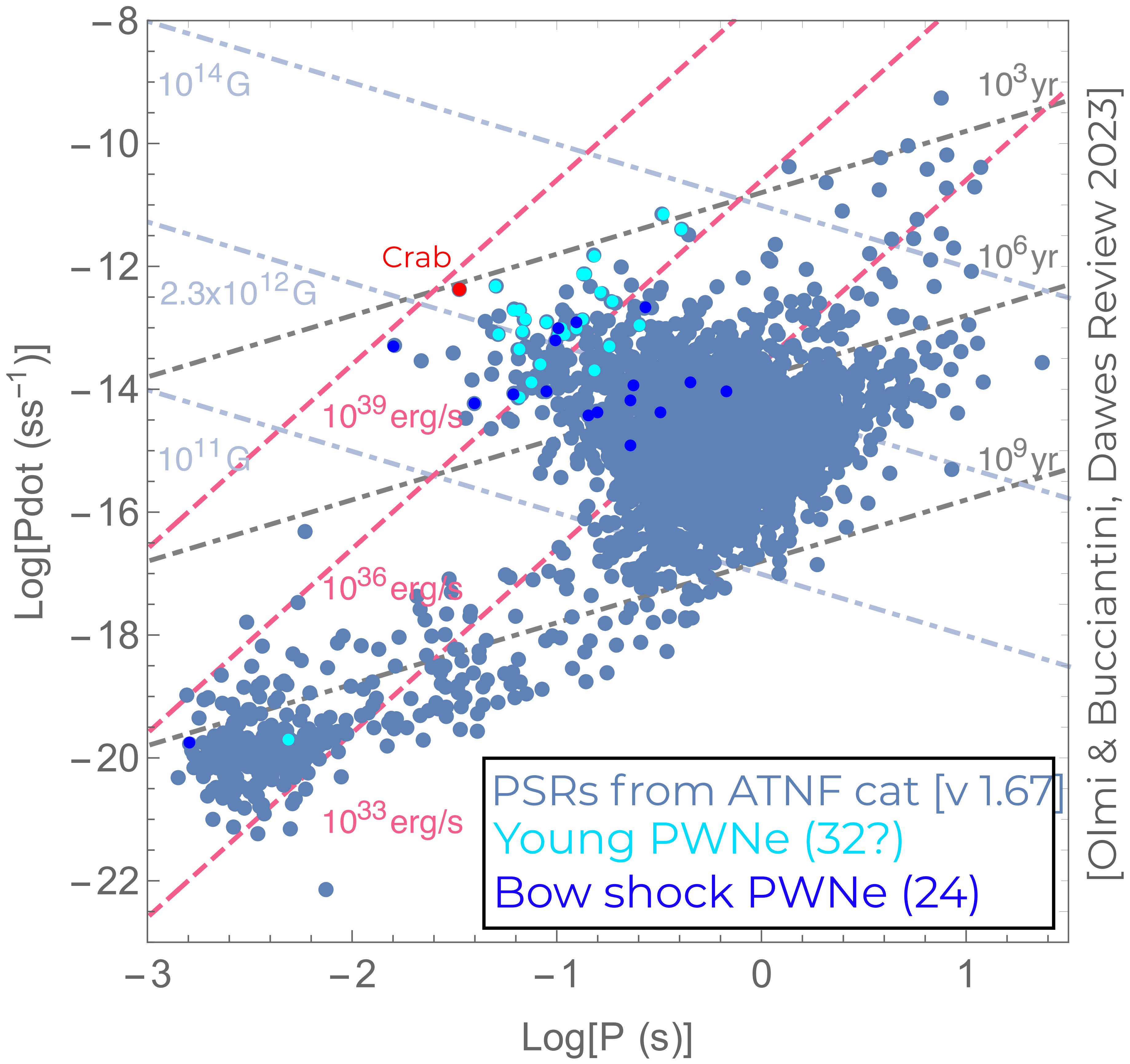
PARTICLES INJECTION SPECTRUM



PWNe ARE NUMEROUS IN THE GALAXY

KNOWN SYSTEMS (FIRMLY IDENTIFIED - MAINLY AT X-RAYS)

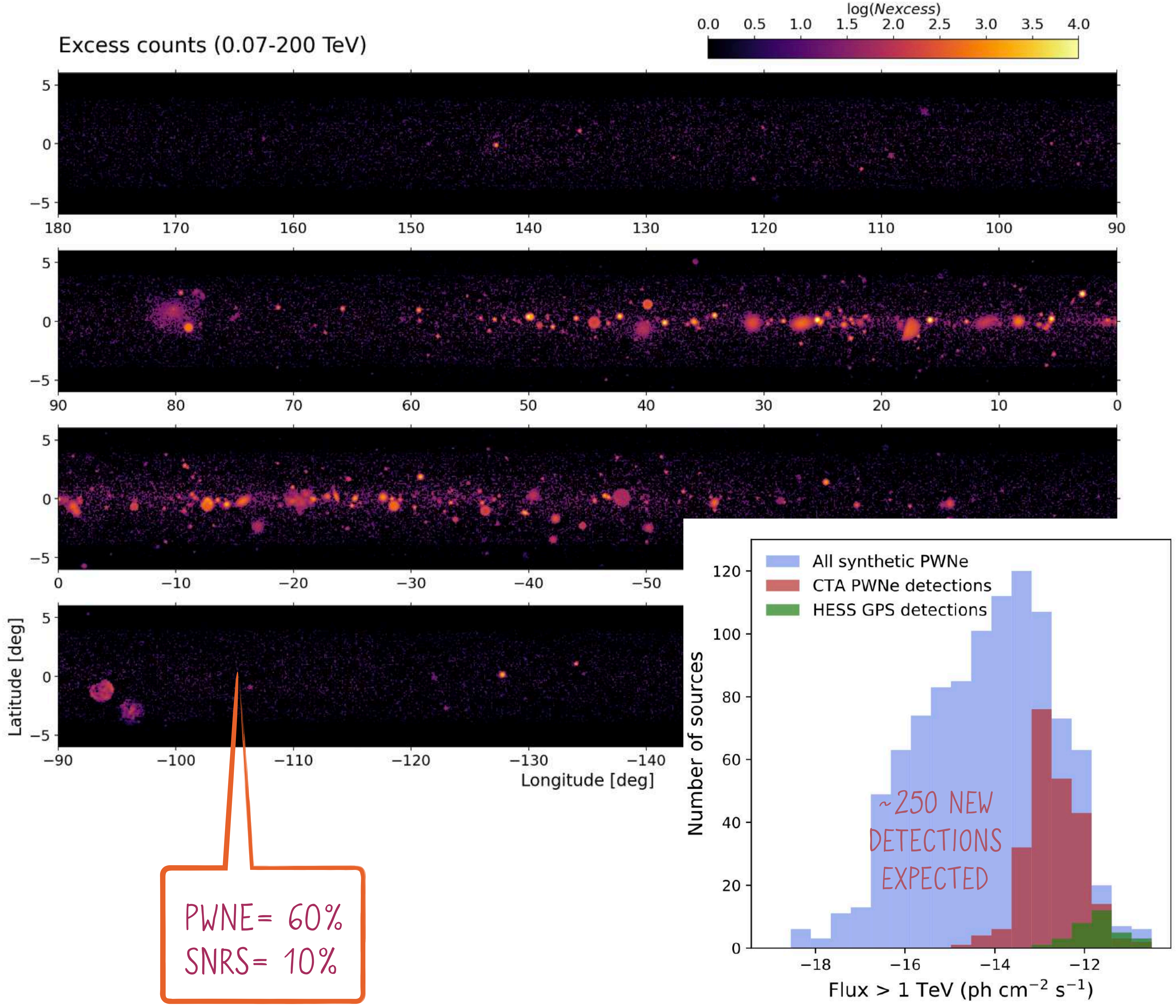
~50 PWNe



$$\tau_{\rm sync} \simeq 160 \left(\frac{B_{\mu \rm G}}{50}\right)^{-3/2} \left(\frac{E_{\rm ph,keV}}{1}\right)^{-1/2} \rm yr$$

τ_{sync}(radio) ~10^5 yr → radio and γ-ray lifetime much longer than at X-rays

THE FUTURE POPULATION

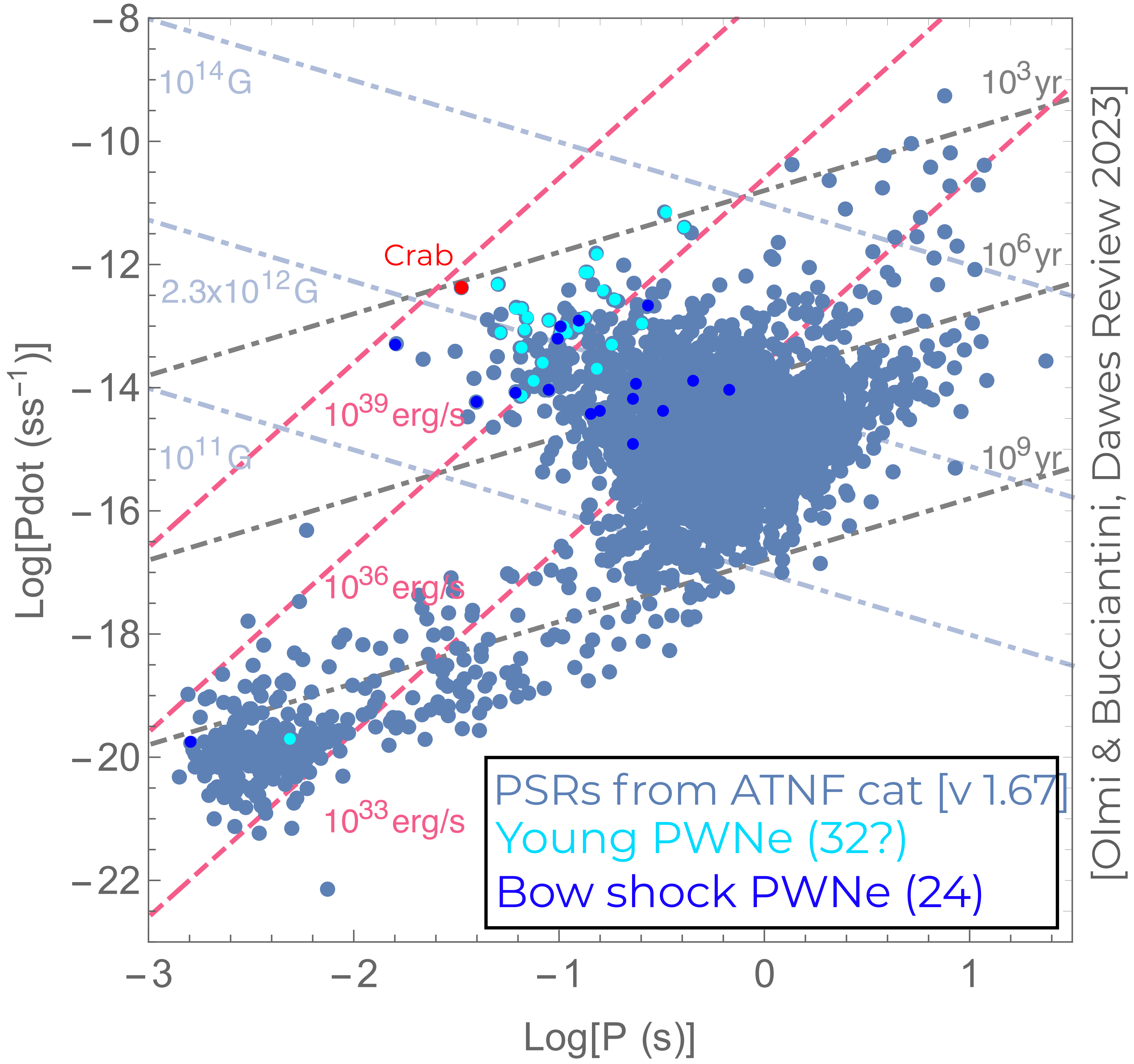


[Acero, Chernyakova, Olmi, Remy, Tibaldo + CTA coll- GPS paper, submitted]

WHY ARE PWNe INTERESTING?

KNOWN SYSTEMS (FIRMLY IDENTIFIED – MAINLY AT X-RAYS)

~50 PWNe



- GAMMA-RAY PHYSICS: MOST NUMEROUS EXPECTED POPULATION
- PULSAR PHYSICS: ENCLOSE MOST OF THE ENERGY LOST BY THE PULSAR

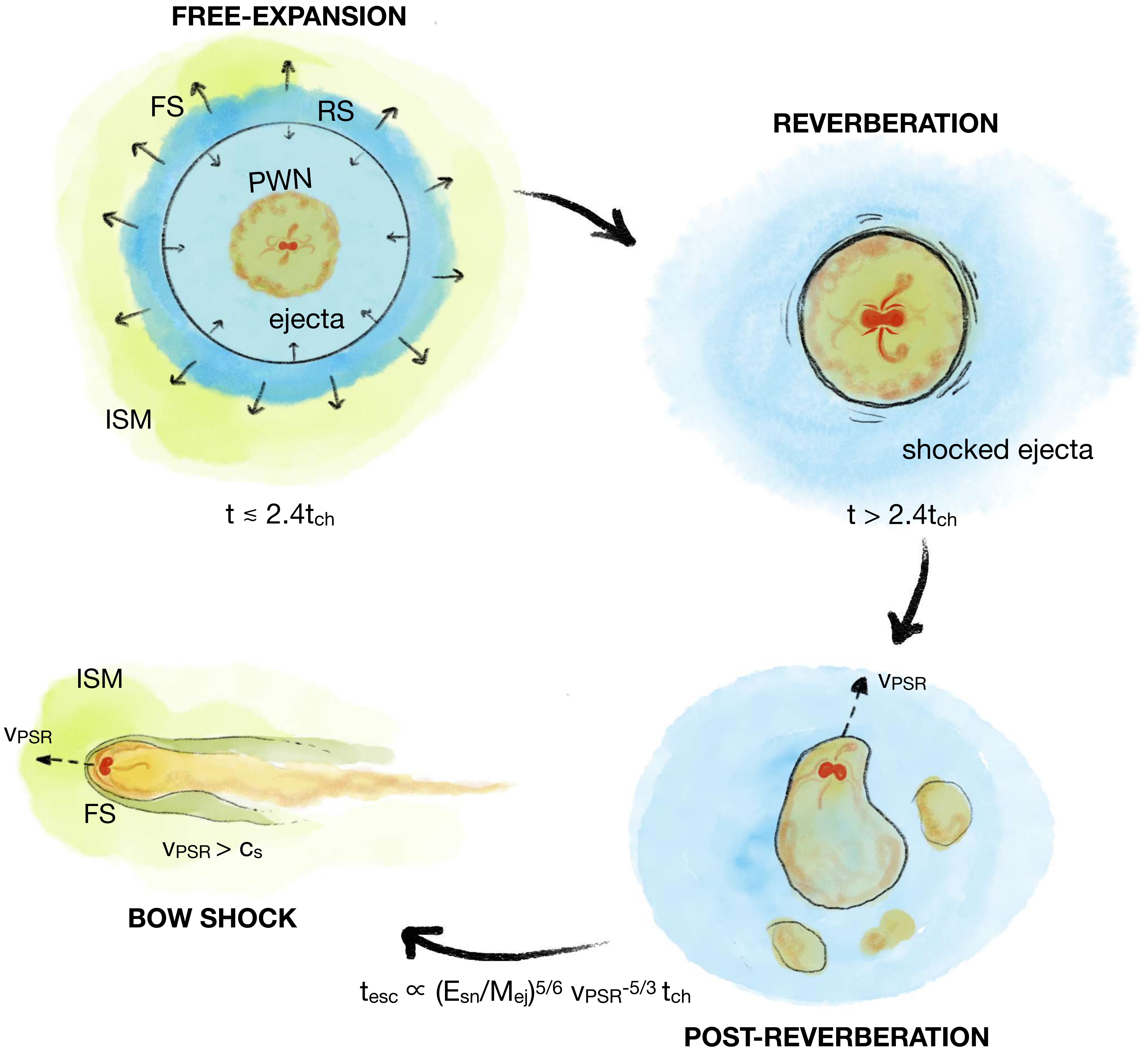
$L_{radio} \lesssim 10^{-10}\dot{E}_{psr}$

$L_{\gamma} \lesssim 0.01\dot{E}_{psr}$

WHILE $L_{PWN} > 0.1\dot{E}_{psr}$

- PLASMA PHYSICS: EXTREME CONDITIONS IN CLOSE AND BRIGHT SOURCES AND ACCELERATION IN HOSTILE ENVIRONMENT
- CR PHYSICS: UNIQUE IDENTIFIED PEVATRONS IN THE GALAXY + ANTIMATTER FACTORIES + PARTICLE LEAKAGE + POSSIBLY HADRONIC PEVATRONS

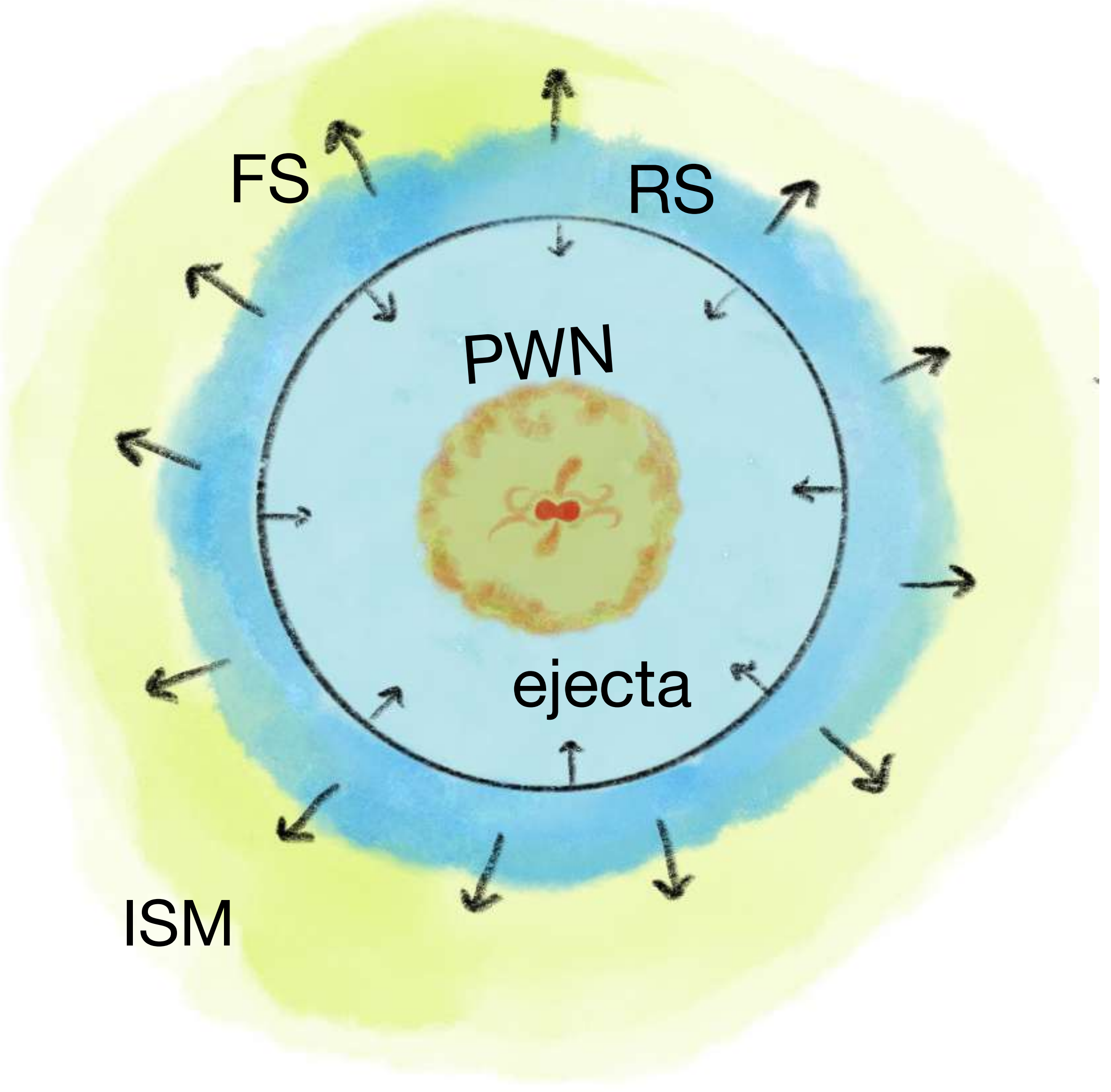
EVOLUTIONARY PHASES OF PWNe



[Olmi 2023]

EVOLUTIONARY PHASES OF PWNe

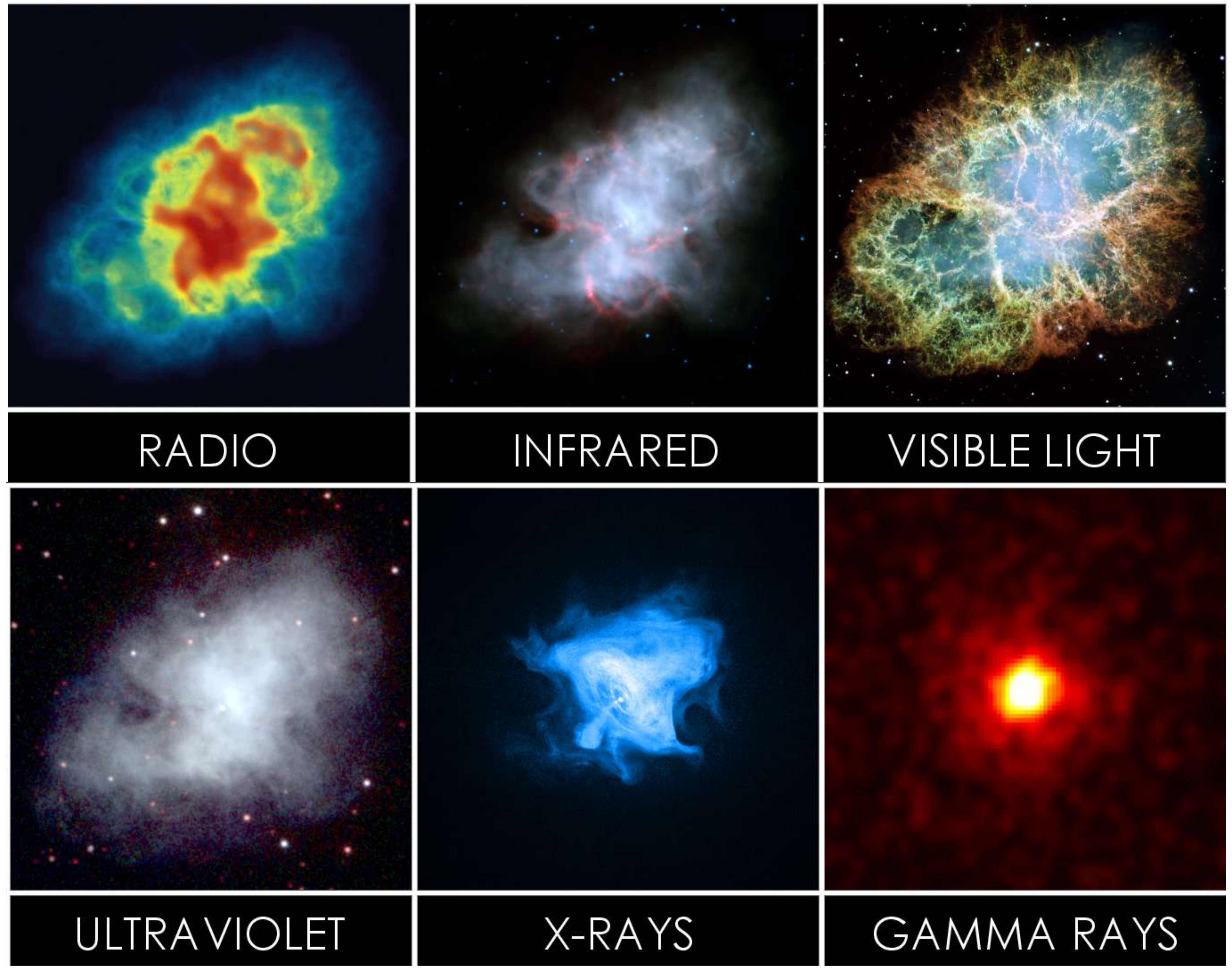
FREE-EXPANSION



$t \lesssim 2.4 t_{ch}$

YOUNG SYSTEMS
FILL CENTERED
MULTI-WAVELENGTHS EMISSION

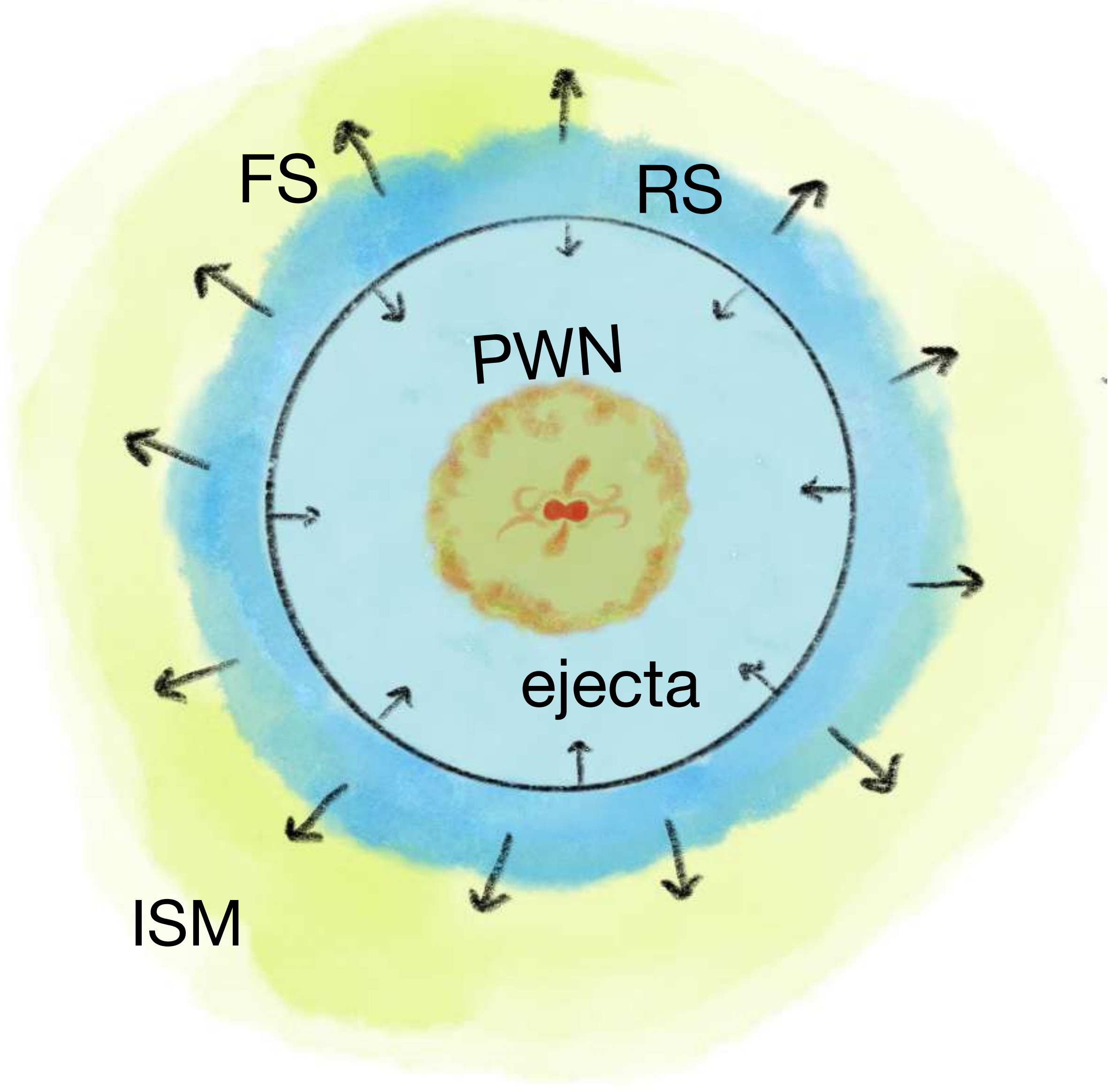
HIGH RESOLUTION IMAGES SHOWS COMPLEX MORPHOLOGY AT X-RAYS



[Olmi 2023]

EVOLUTIONARY PHASES OF PWNe

FREE-EXPANSION



$t \lesssim 2.4 t_{ch}$

ASSUMPTIONS:

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

PREDICTIONS

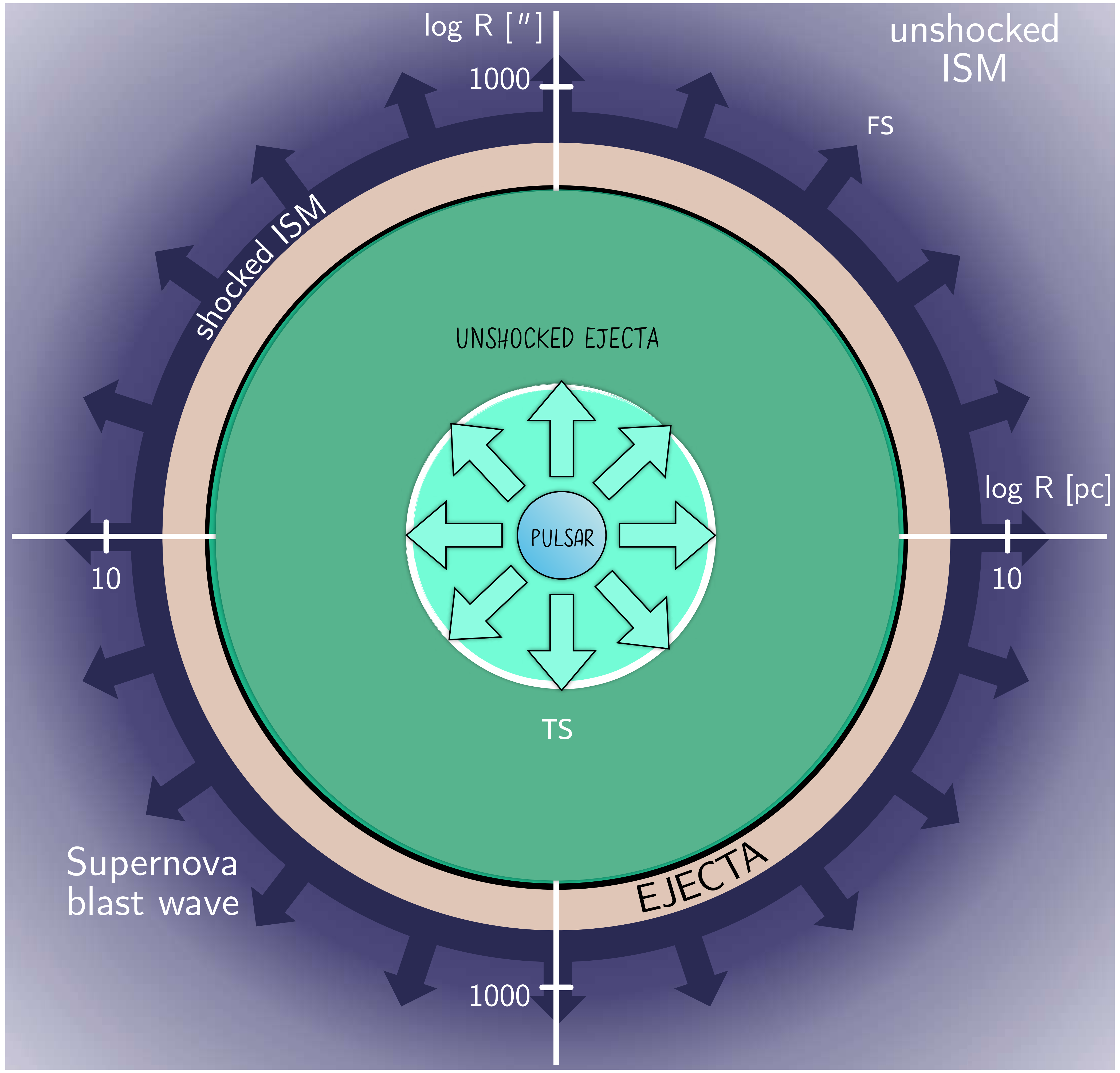
- positon of TS → $R_{TS} \sim R_N (V_N/c)^{1/2} \sim 0.1$ pc
- Optical / X-ray spectrum
- size shrinkage with increasing energy

[Rees & Gunn 74, Kennel & Coroniti 84, Emmering & Chevalier 87, Begelman & Li 92,de Jager & Harding 92, Atoyan & Aharonian 96]

YOUNG SYSTEMS

FILL CENTERED

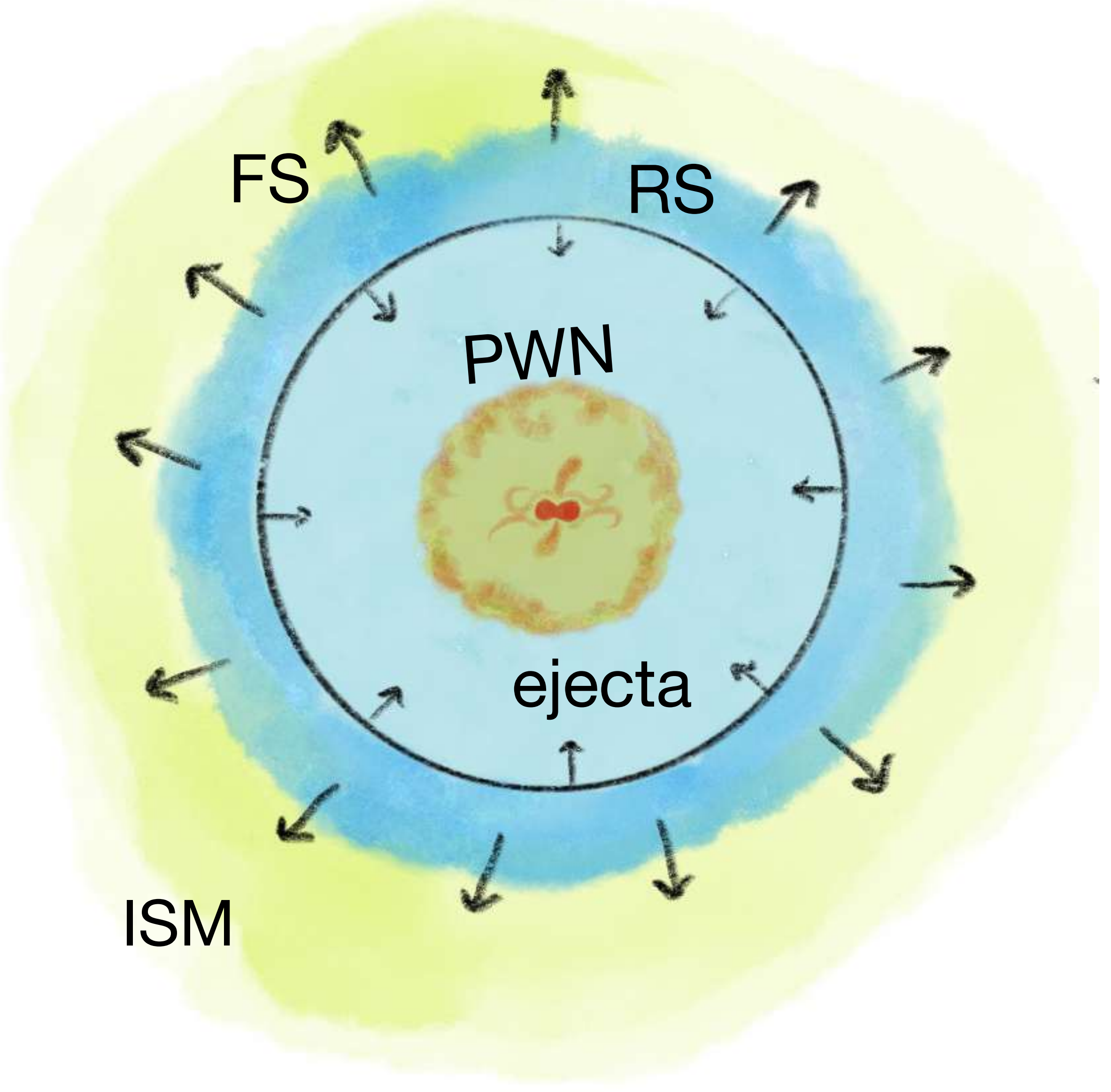
MULTI-WAVELENGTHS EMISSION



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

EVOLUTIONARY PHASES OF PWNe

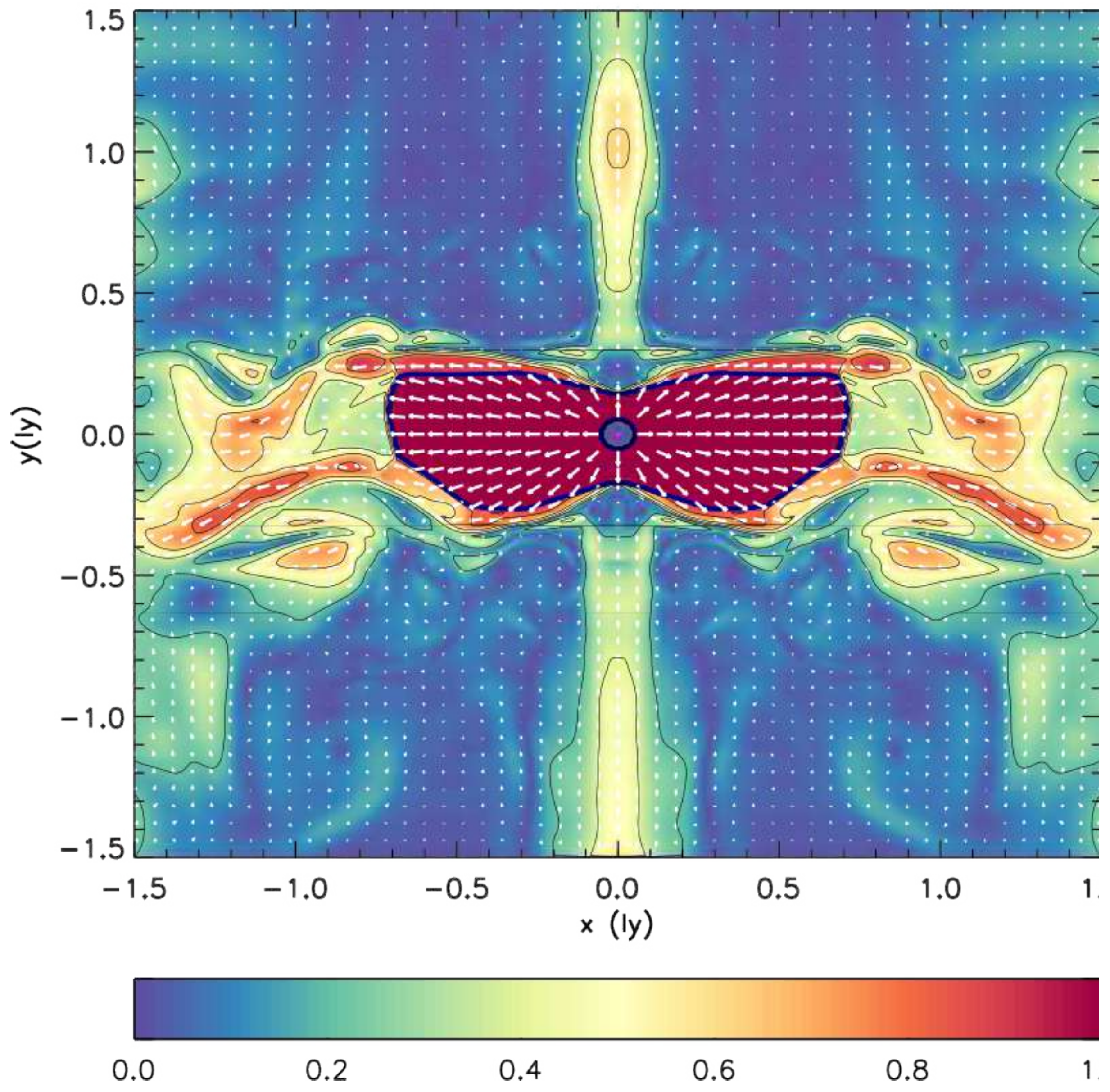
FREE-EXPANSION

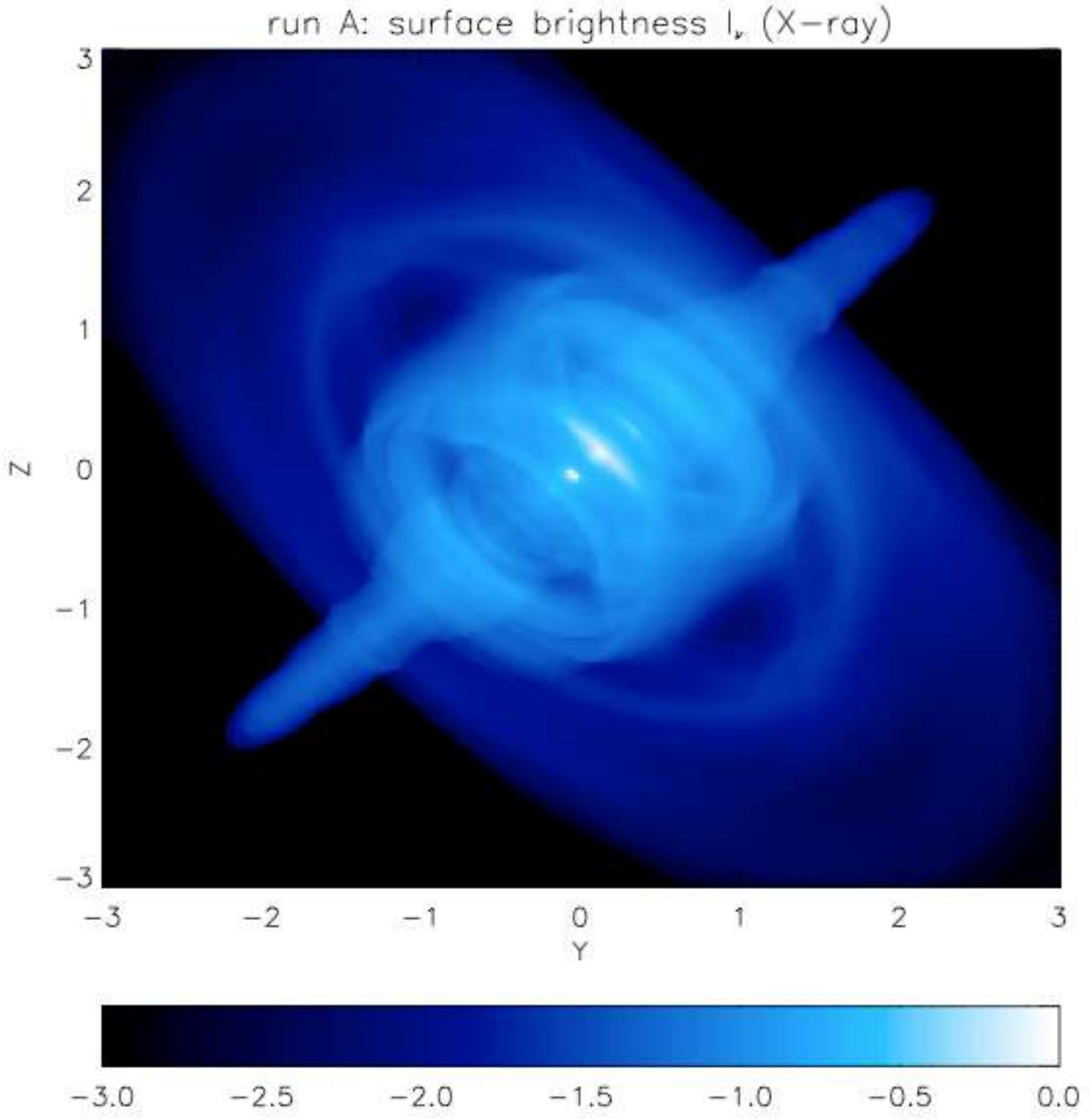


t ≲ $2.4t_{ch}$

YOUNG SYSTEMS

MORE REALISTIC DESCRIPTION

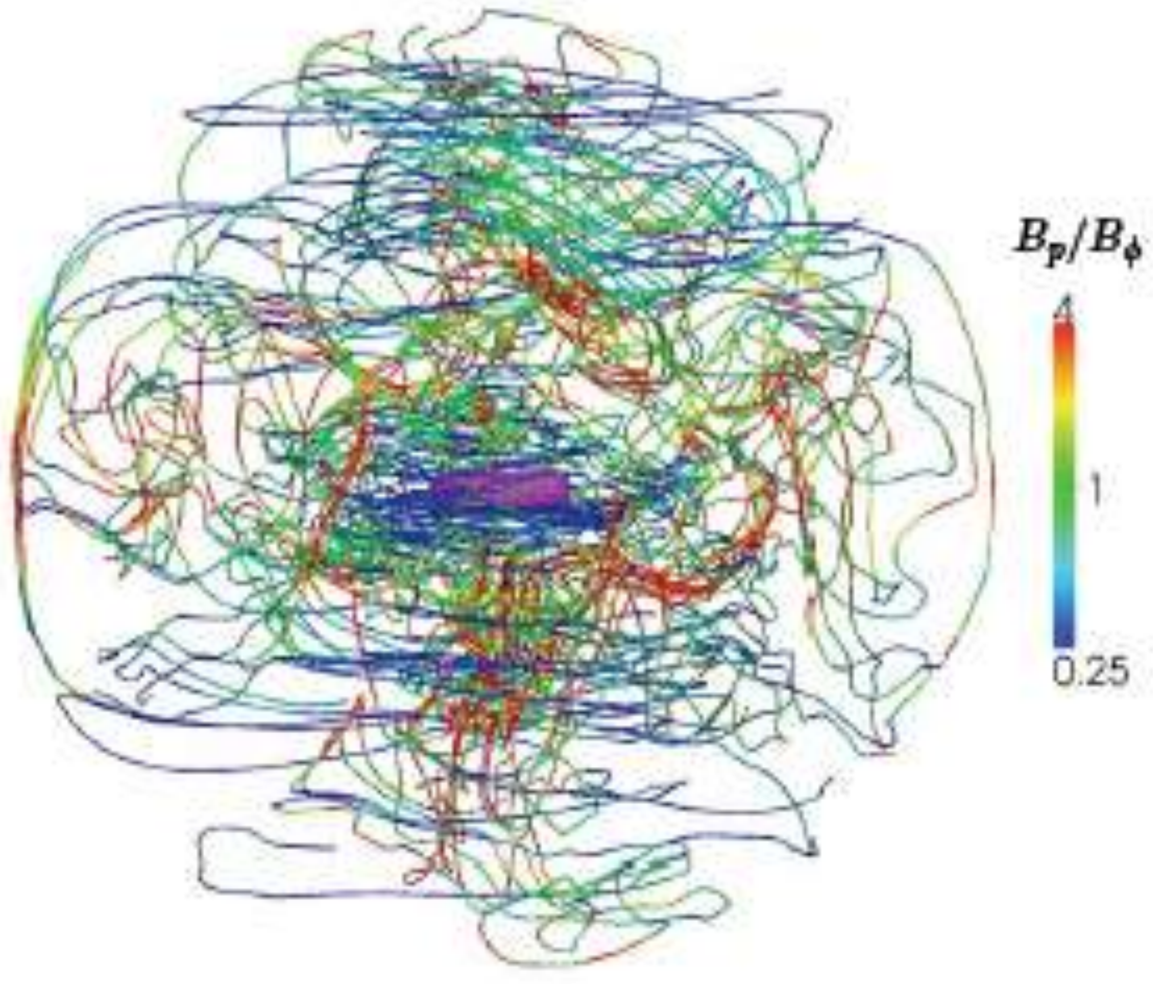


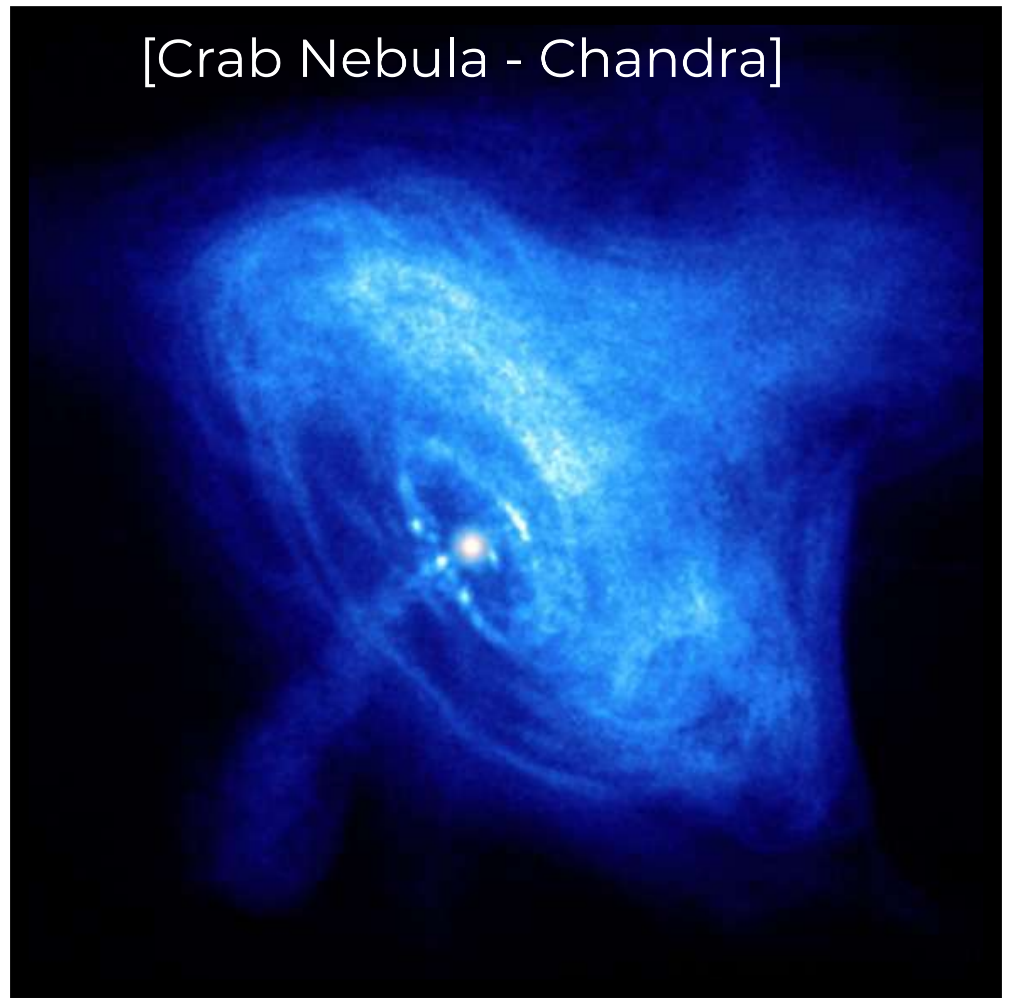


ANISOTROPIC DISTRIBUTION OF THE ENERGY FLUX IN THE PW MAKES THE TS OBLATE AND ALLOWS FOR THE FORMATION OF THE POLAR JETS SEEN IN THE INNER NEBULA

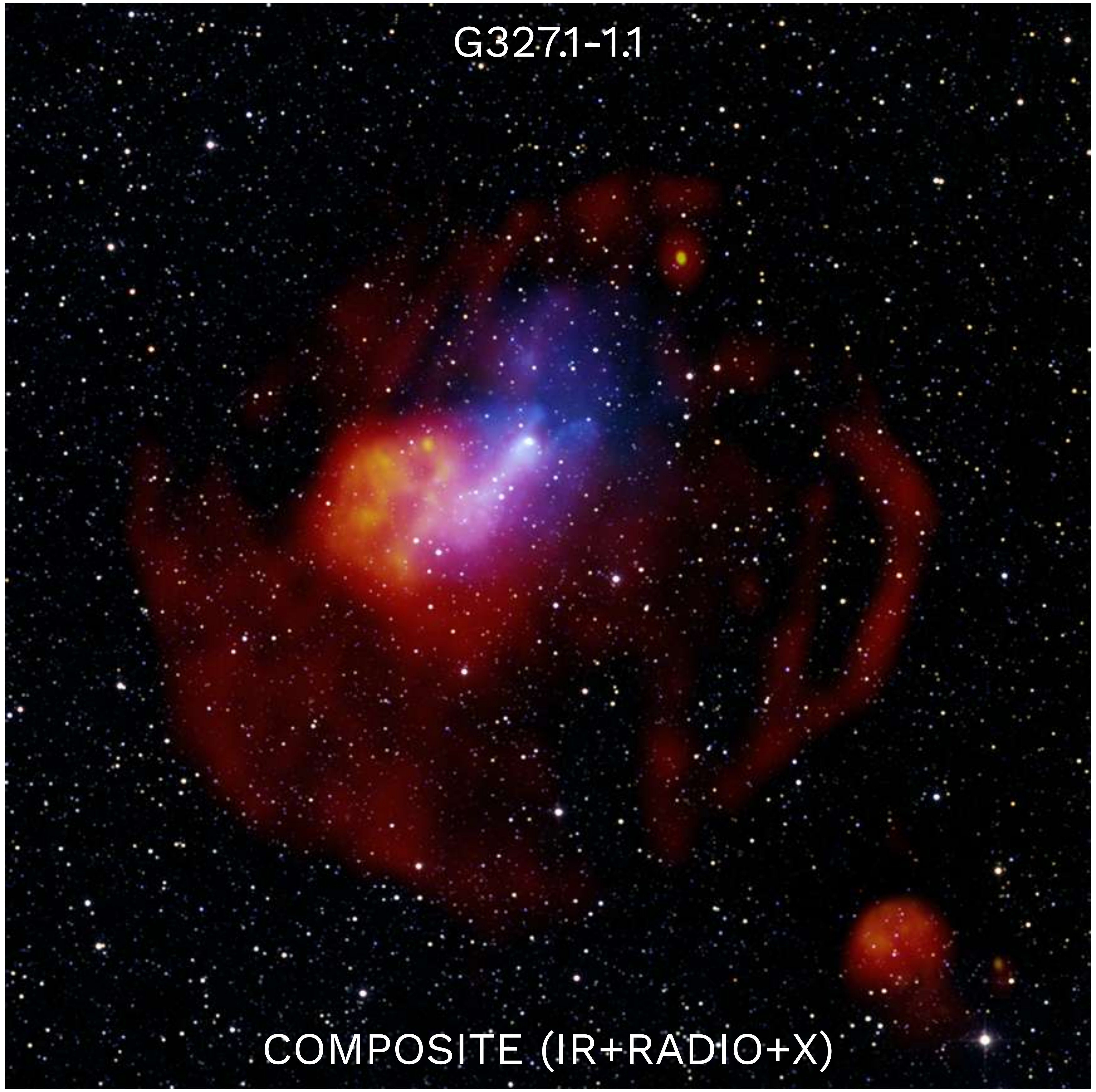
CORRECT REPRESENTATION OF THE MAGNETIC FIELD ONLY POSSIBLE IN 3D

[Komissarov & Lyubarsky 2003-4, Del Zanna et. al 2004-6, Olmi et al. 2014-15–16, Porth et al 2013-14]

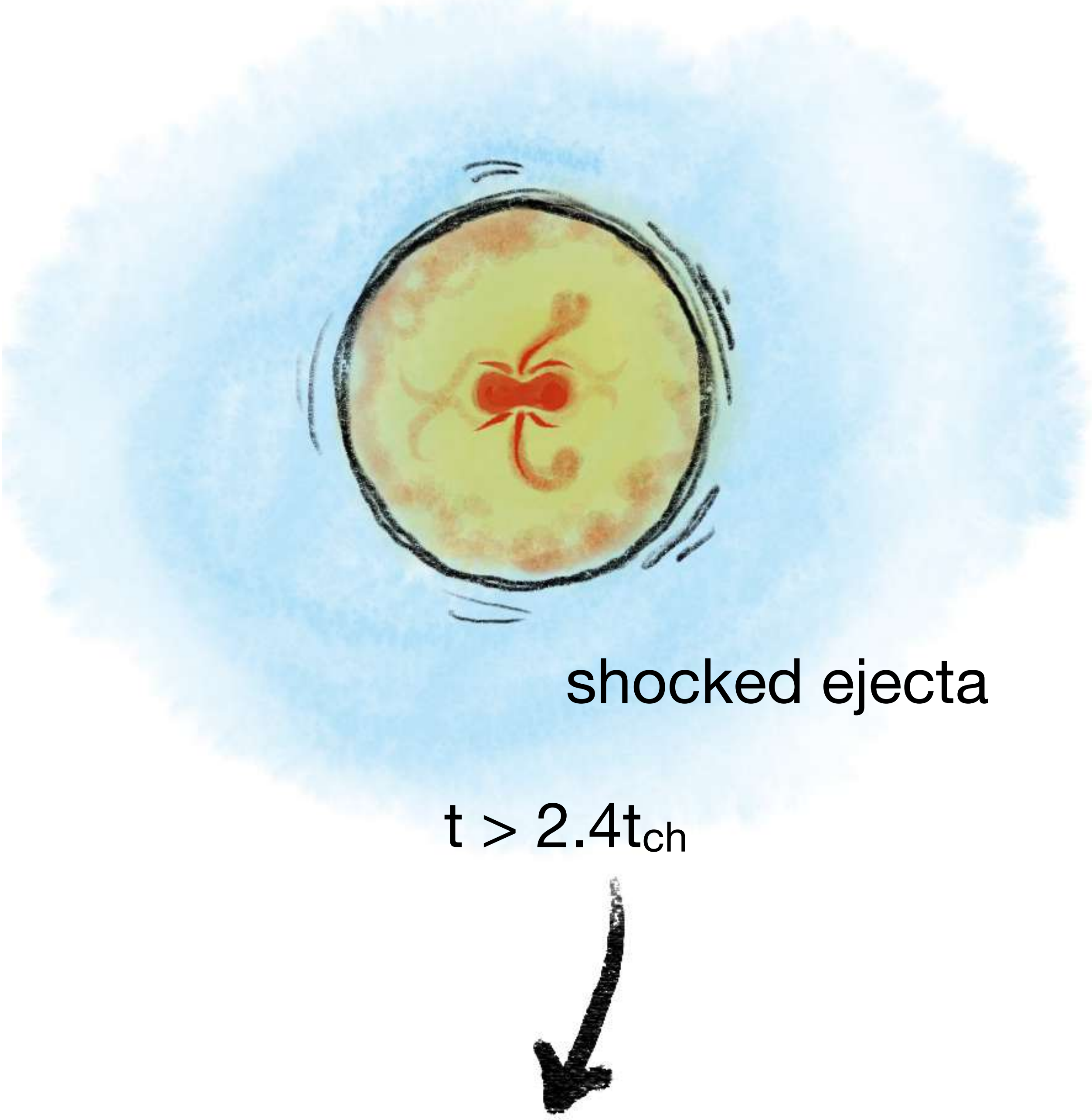




EVOLUTIONARY PHASES OF PWNe



REVERBERATION

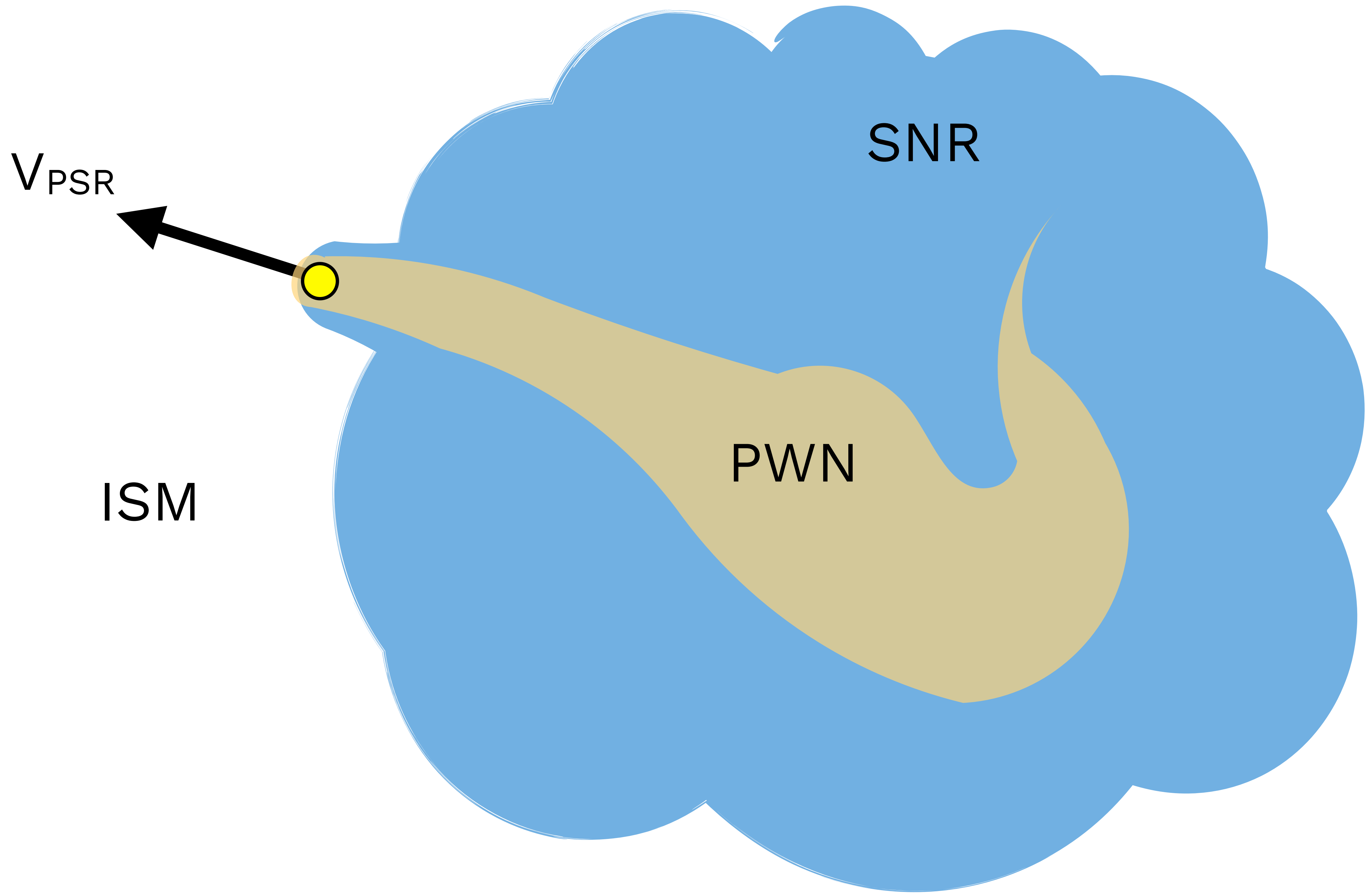


MIDDLE AGED – REVERBERATING SYSTEMS

ONLY A FEW IDENTIFIED
COMPLEX MORPHOLOGY DUE TO INTERACTION WITH SNR

[Olmi 2023]

EVOLUTIONARY PHASES OF PWNe



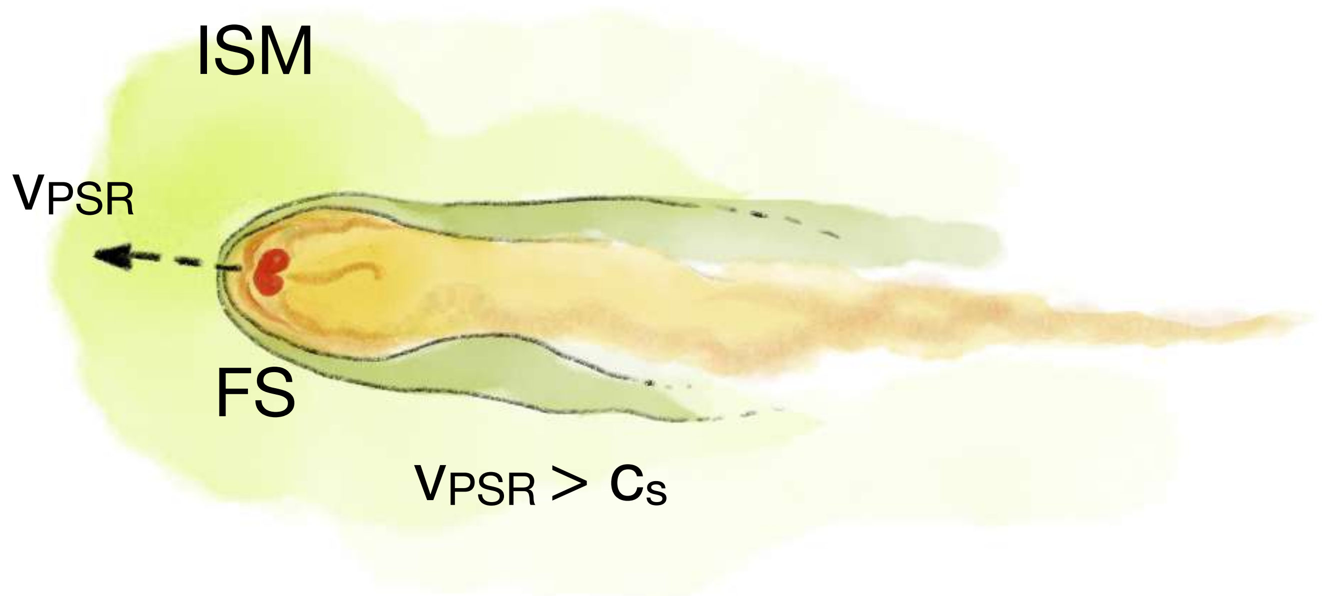
EVOLVED SYSTEMS

Large part of the PSRs have high kick of velocity:

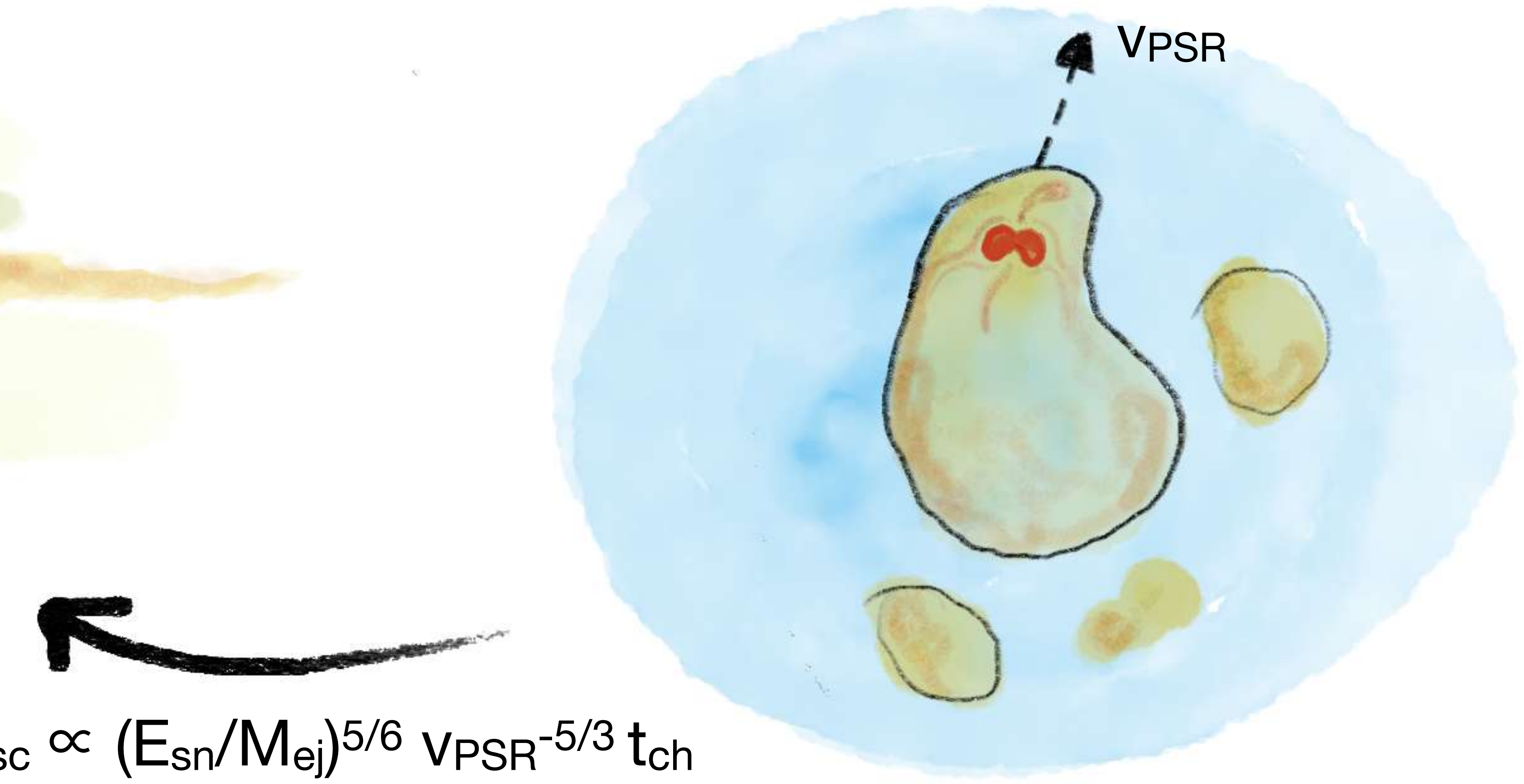
$\langle V_{PSR} \rangle \sim 300$ km/s

[Faucher-Giguere & Kaspi 2006]

and are then fated to escape their (decelerated) expanding SNR bubble



BOW SHOCK

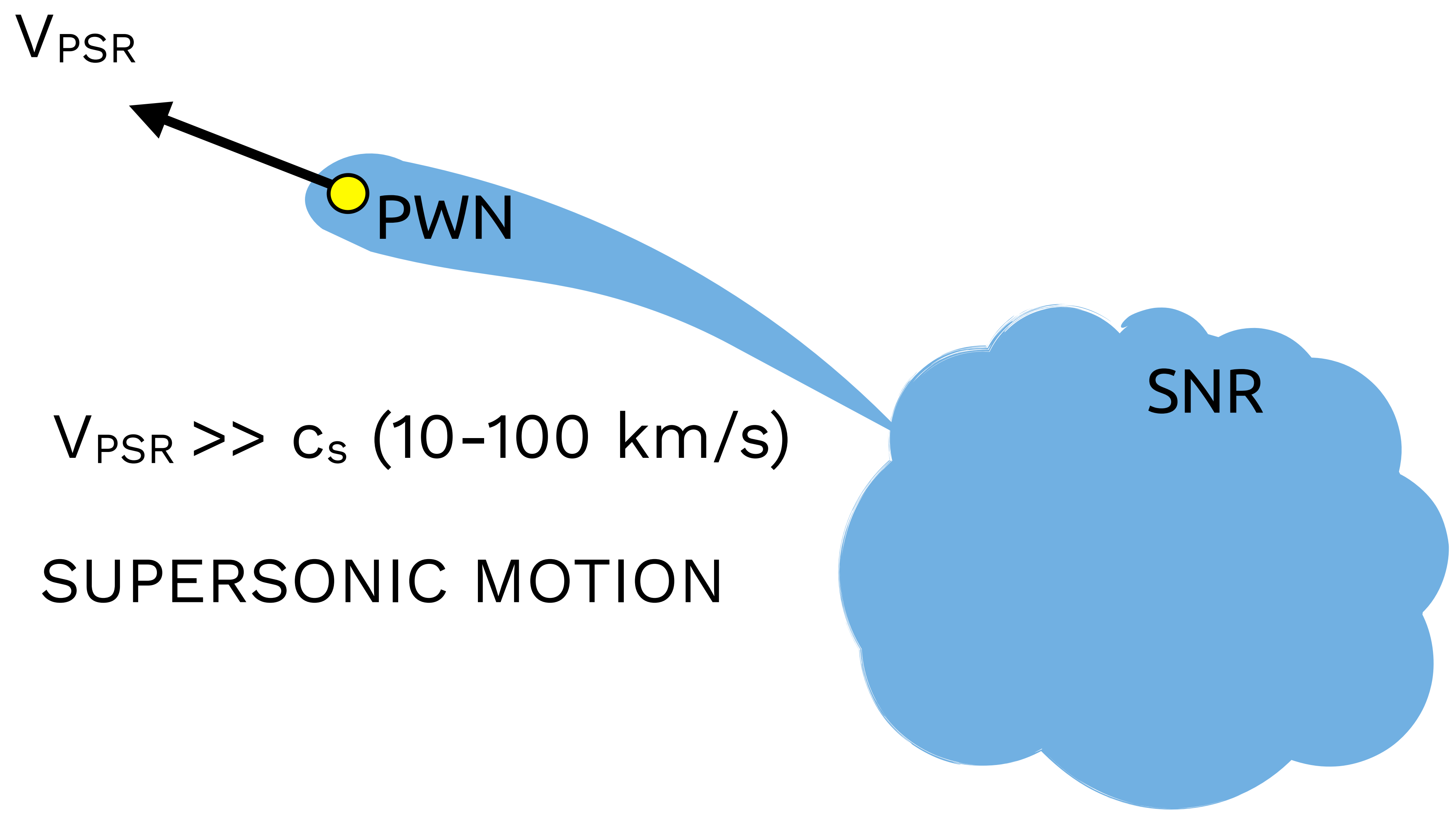


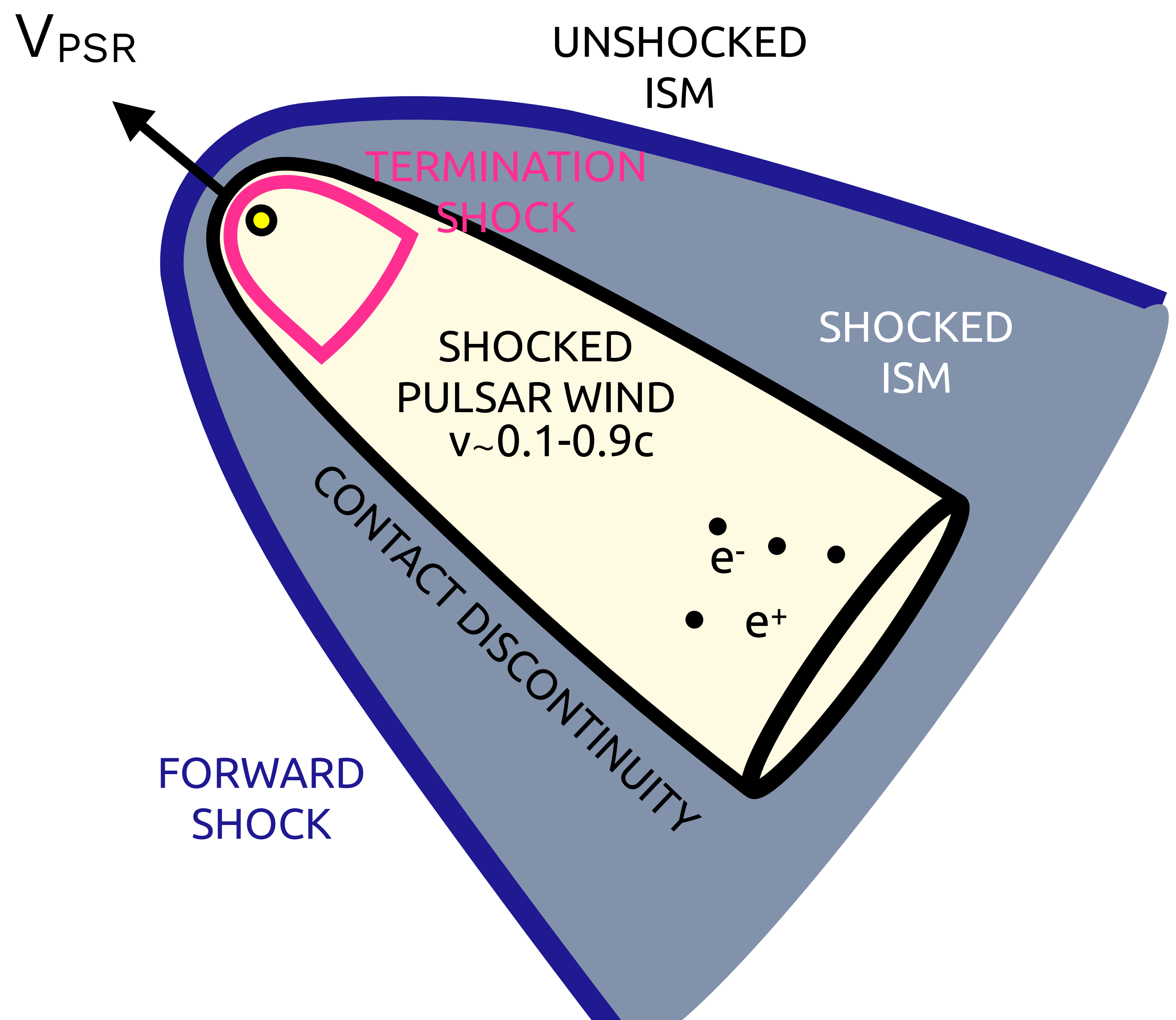
$t_{esc} \propto (E_{sn}/M_{ej})^{5/6}\, v_{PSR}^{-5/3}\, t_{ch}$

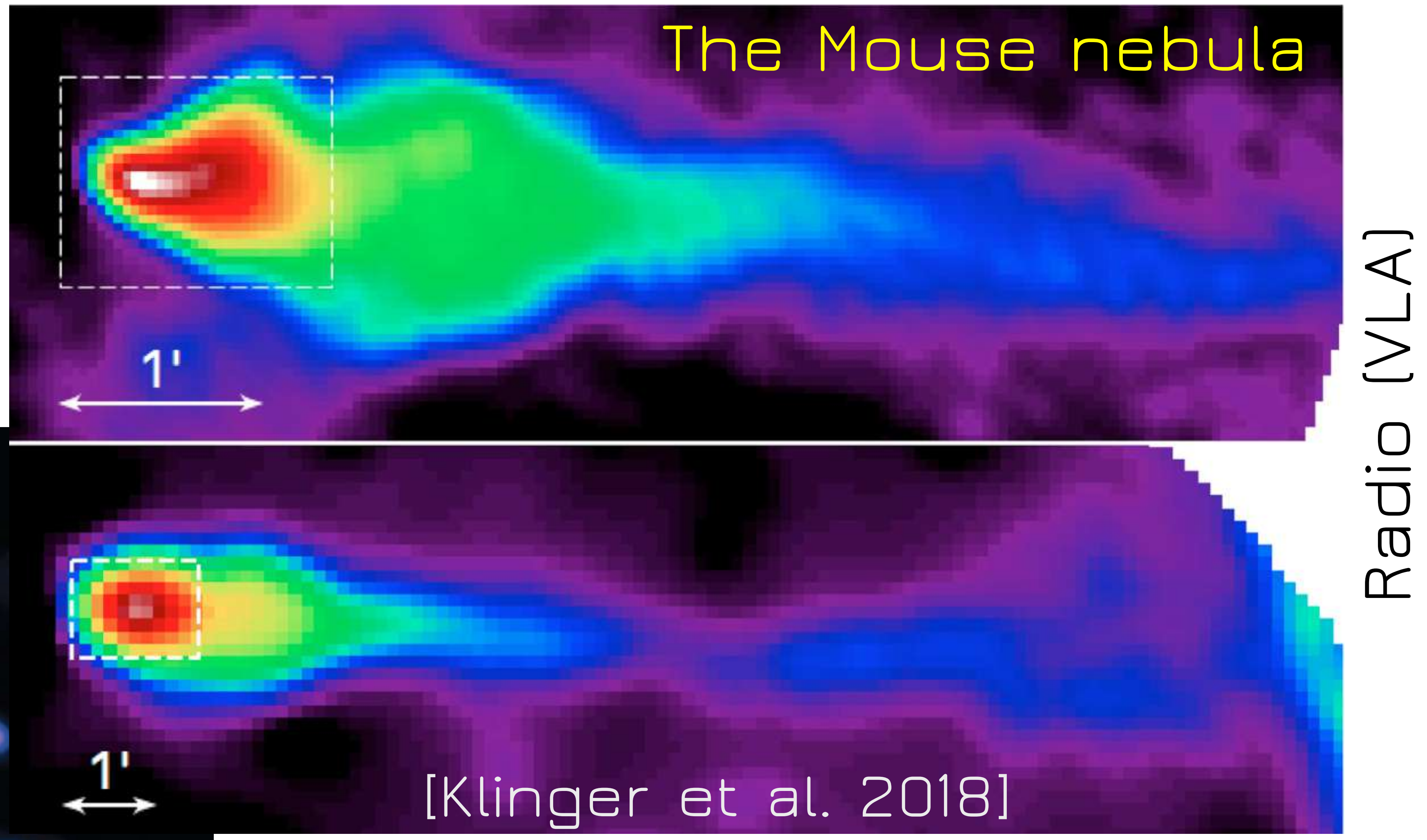
POST-REVERBERATION

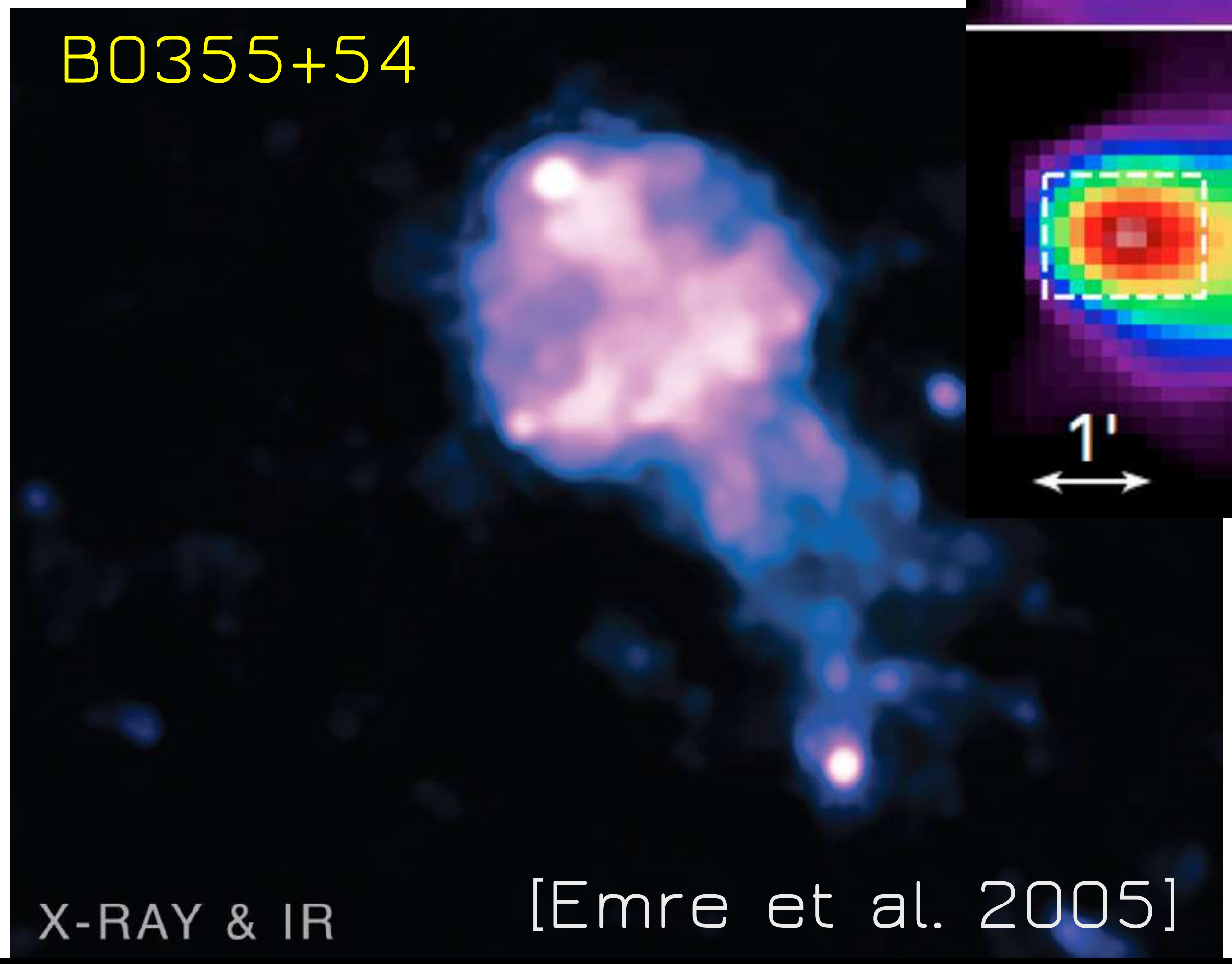
[Olmi 2023]

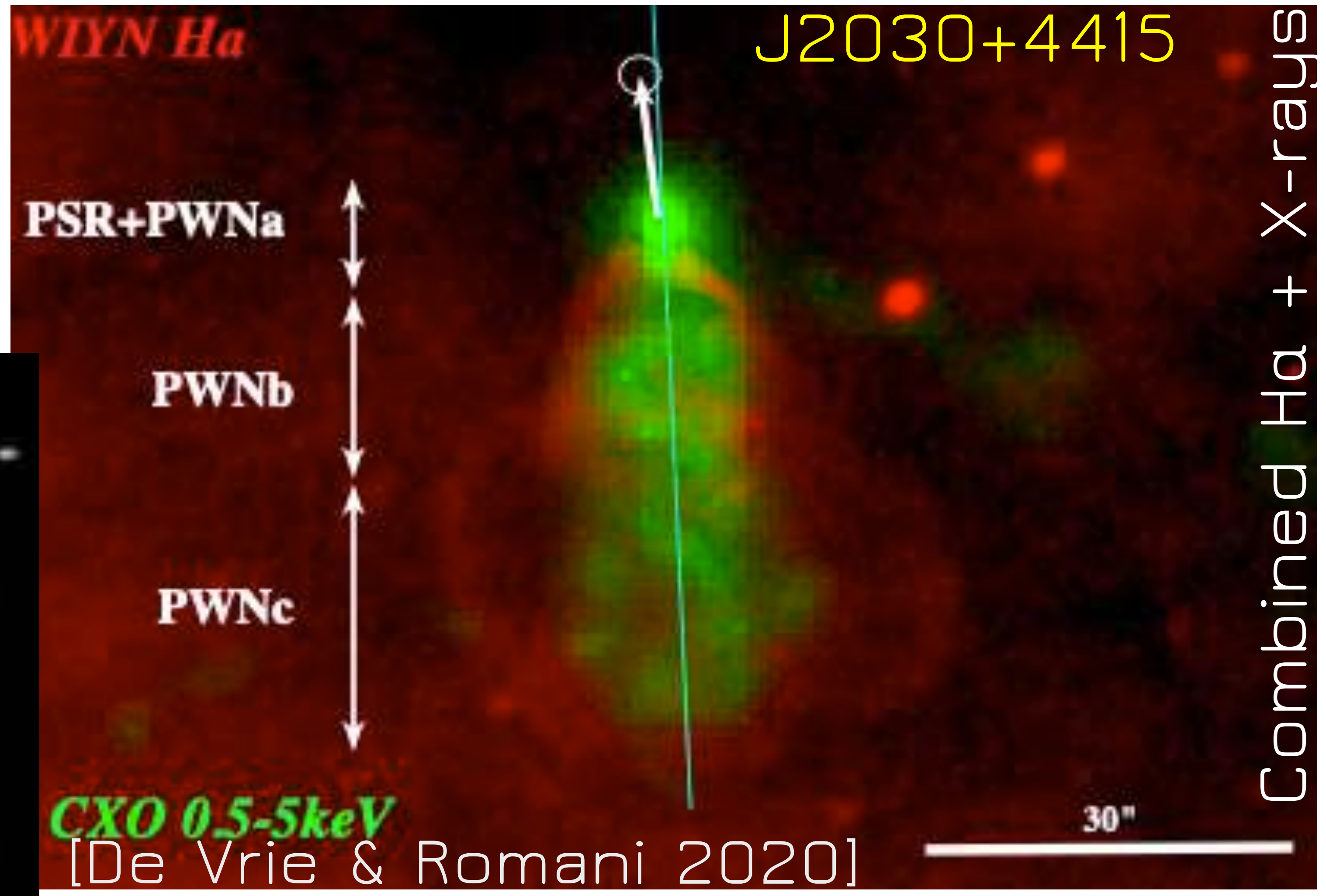
BOW SHOCK PWNe



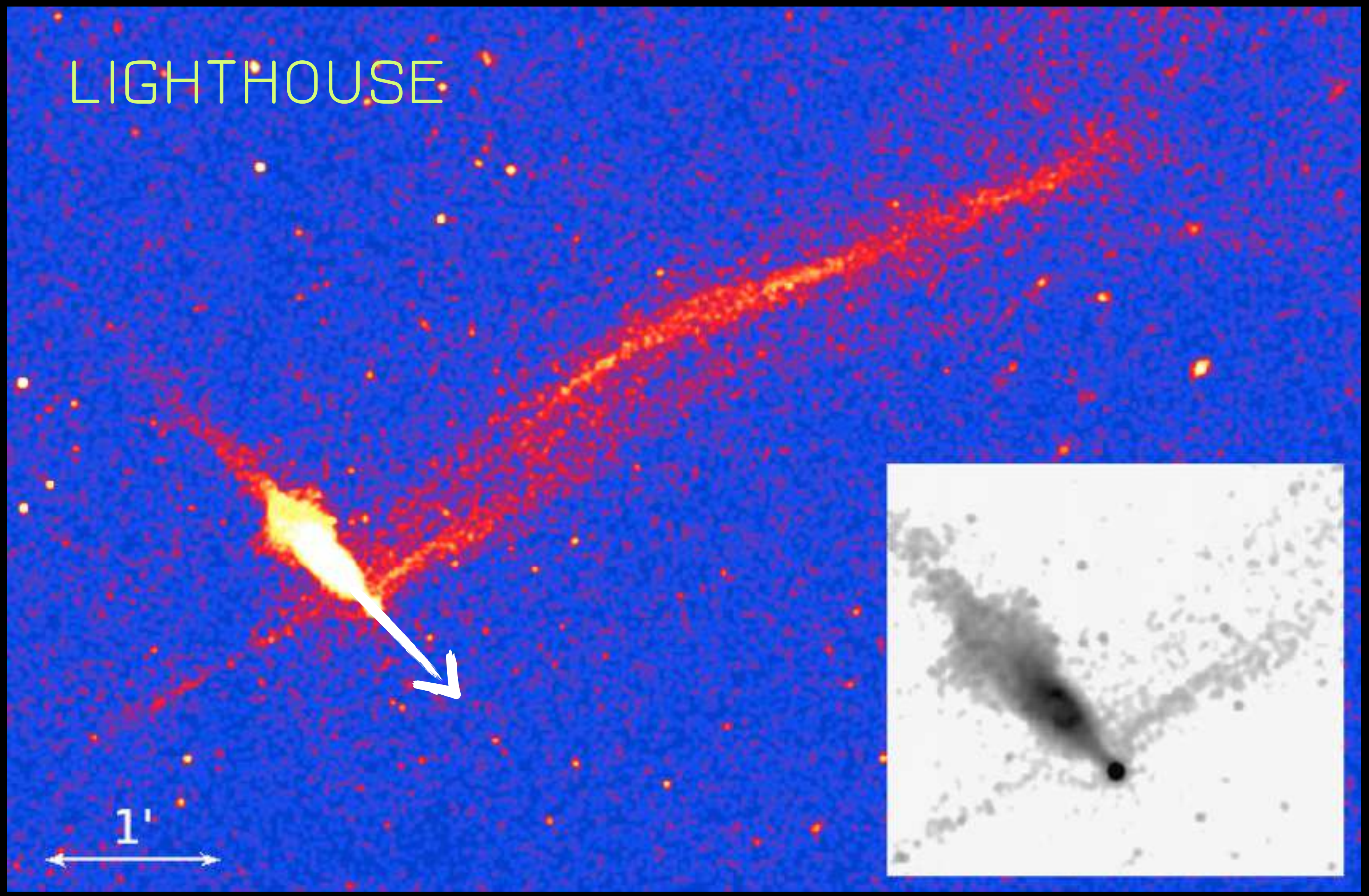




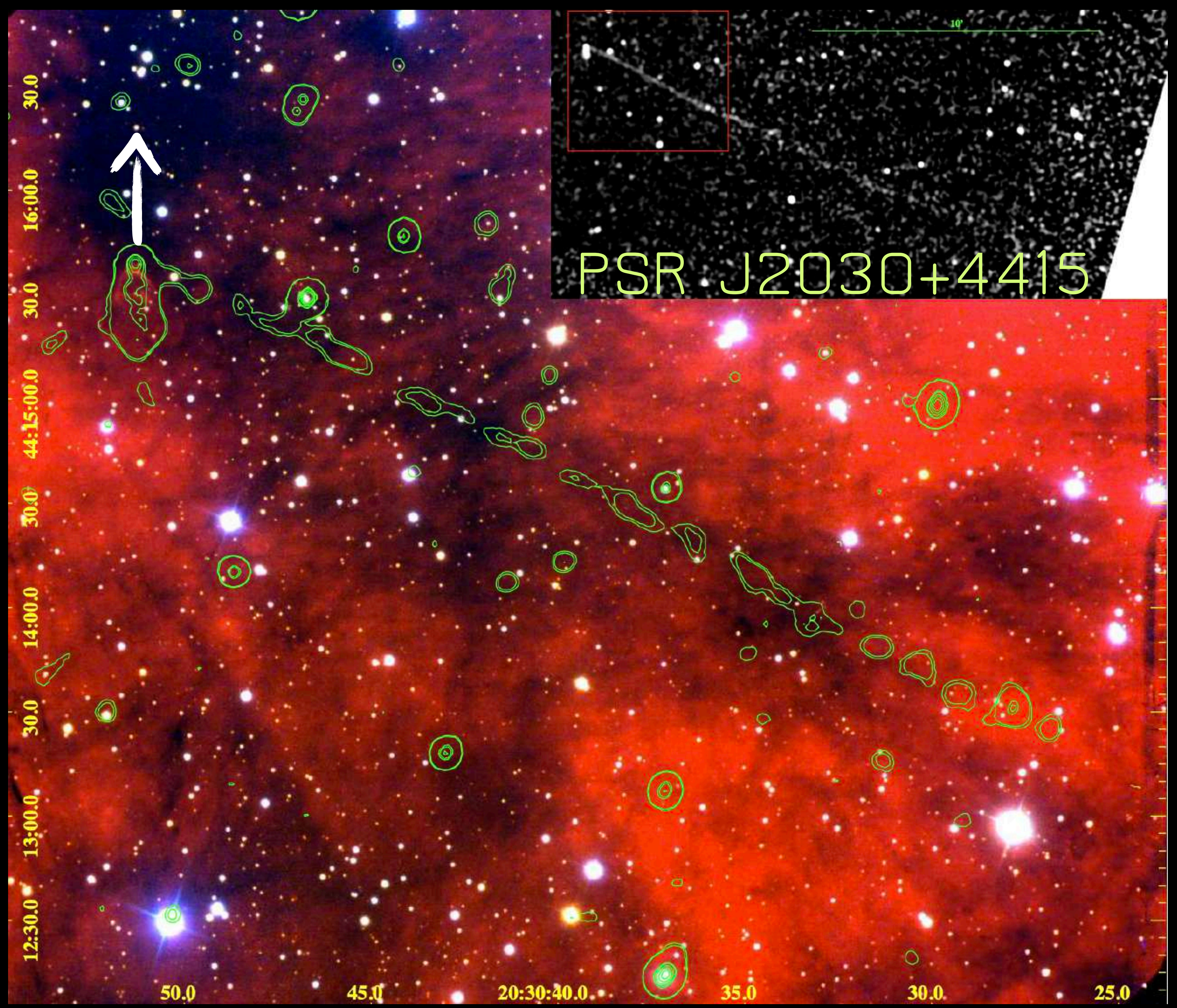




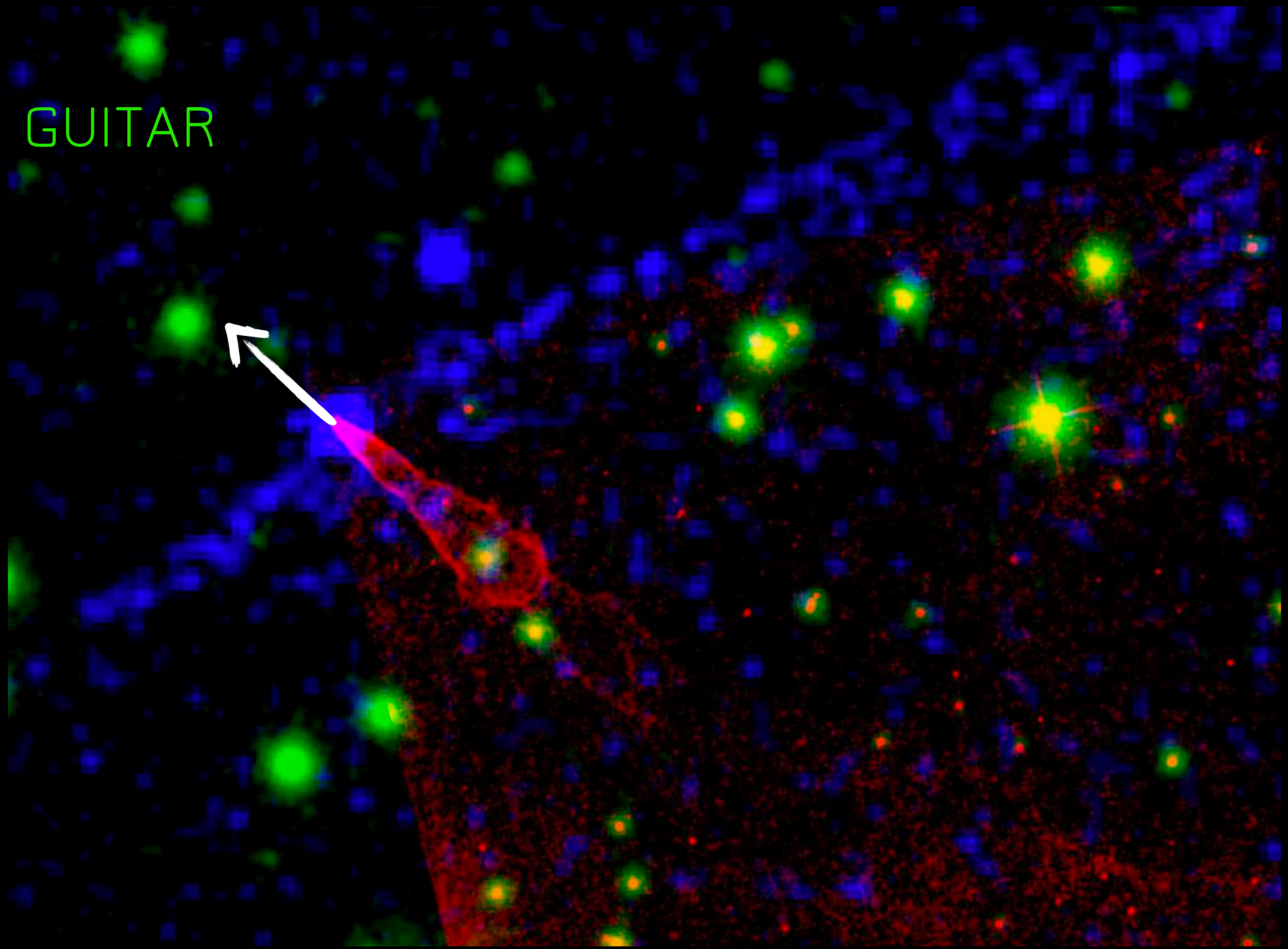
PARTICLES ESCAPING FROM BSPWNe



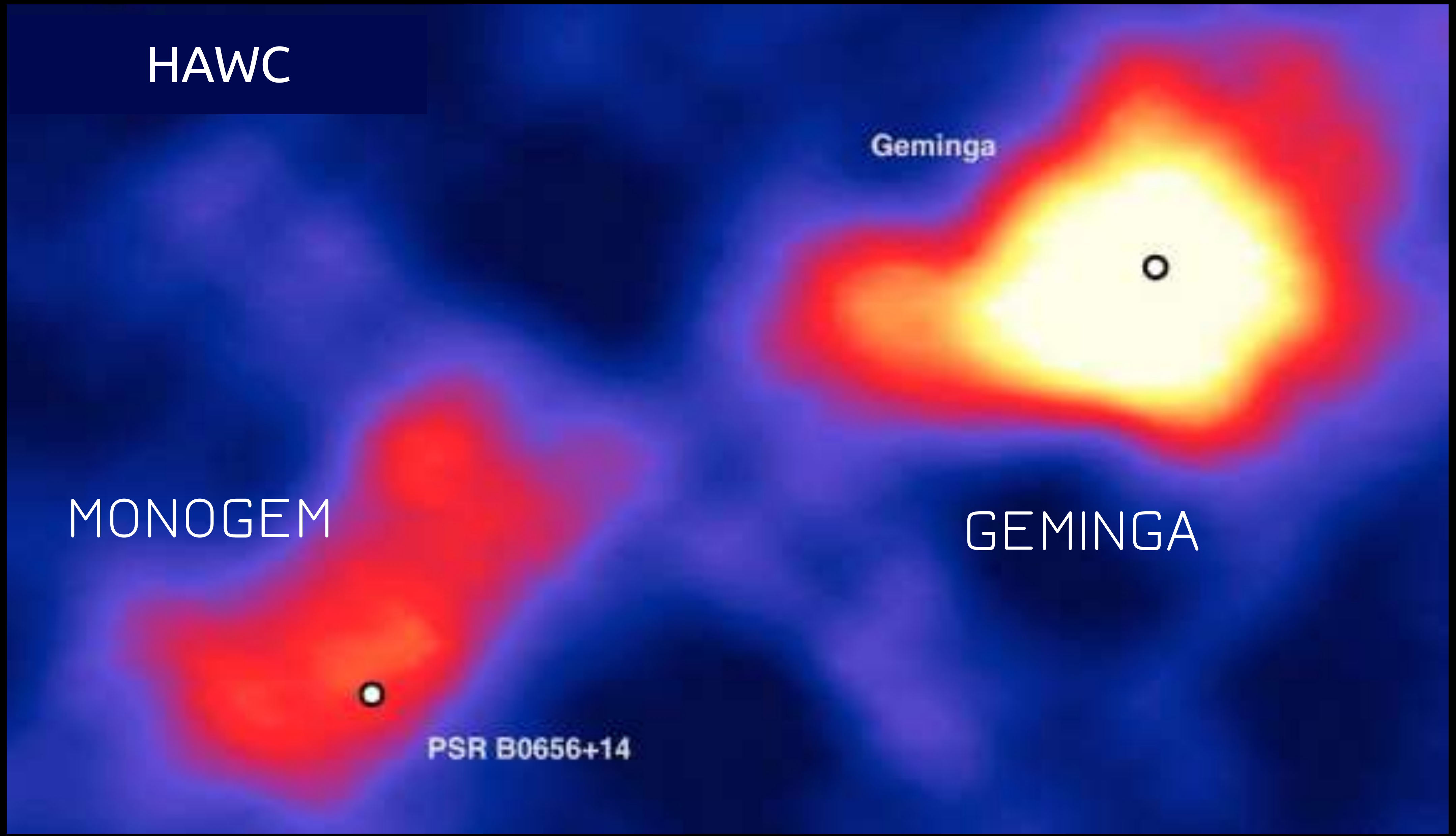
[Pavan et al. 2016]



[De Vrie & Romani 2020,2022]

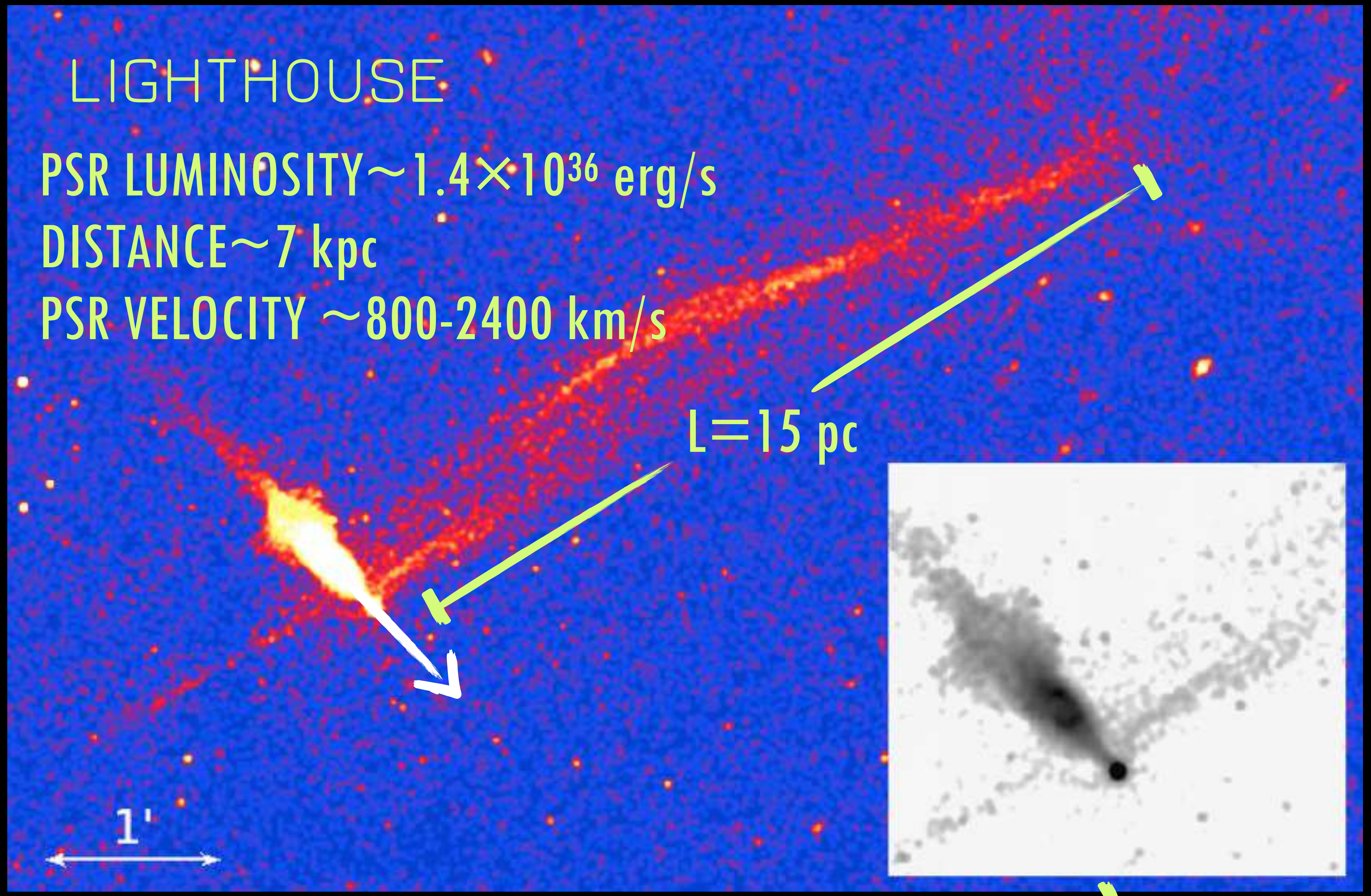


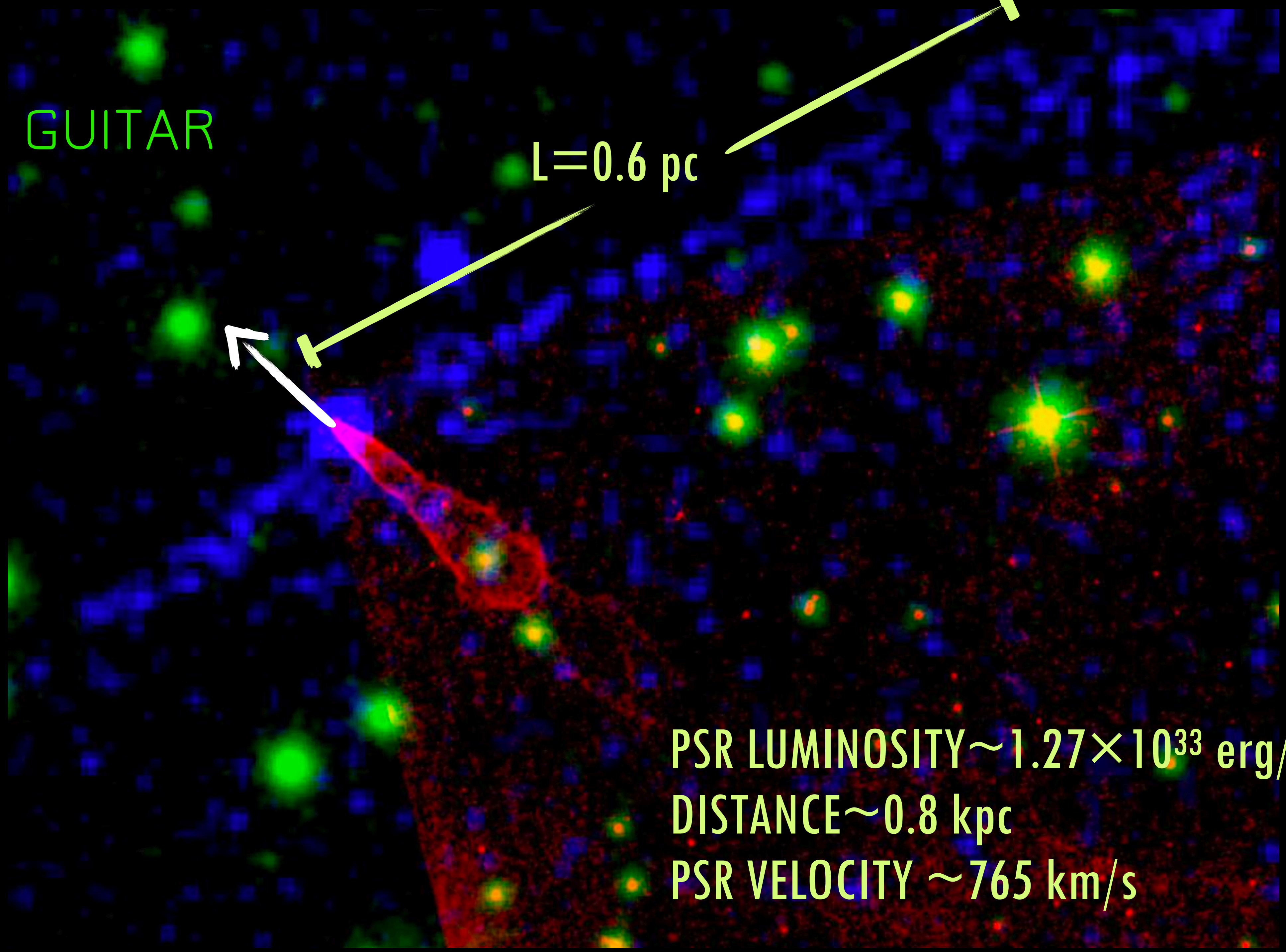
[Cordes et al. 1993, De Vries et al. 2022]

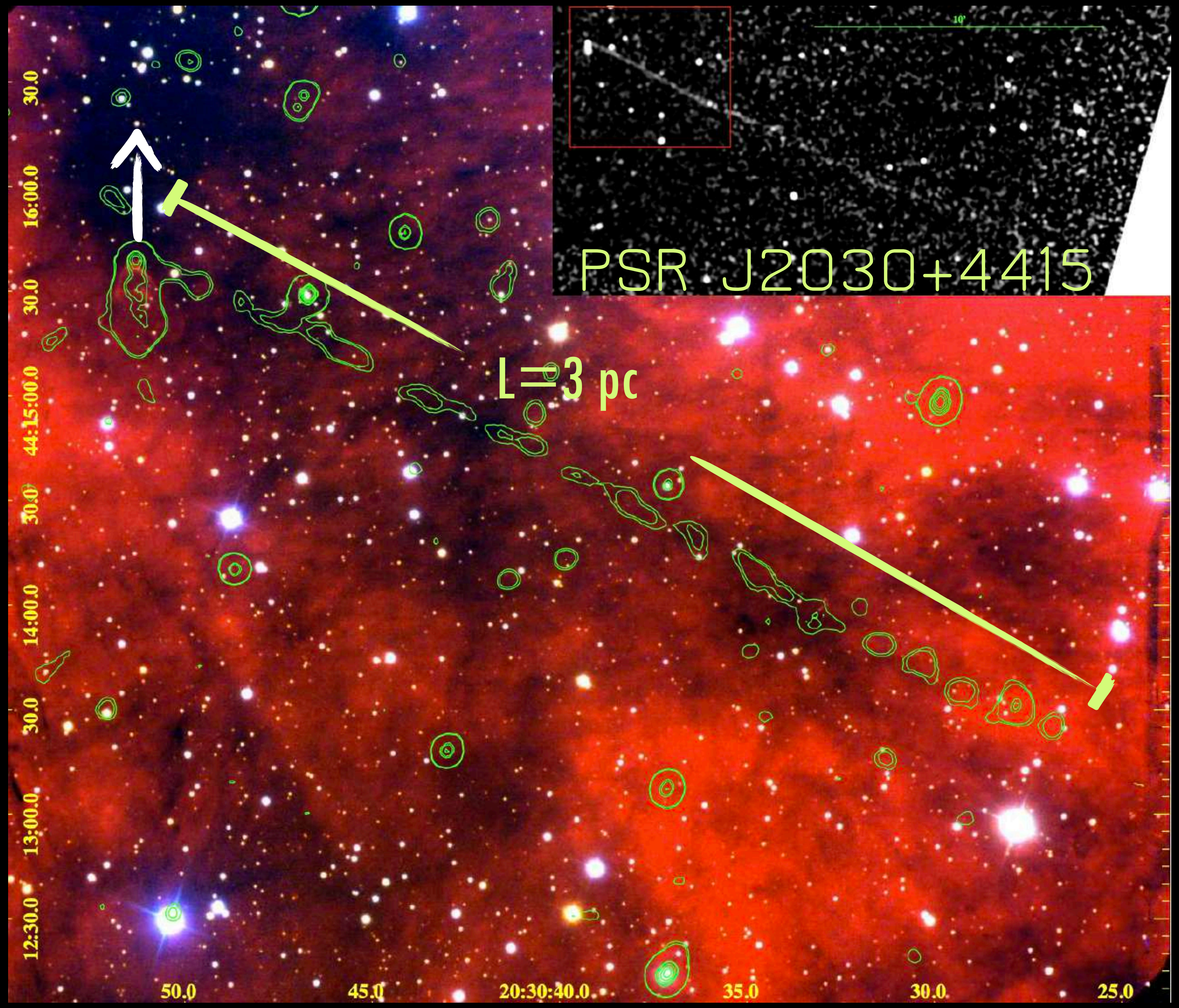


[Abeysekara et al. 2017]

A DEEPER LOOK TO 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

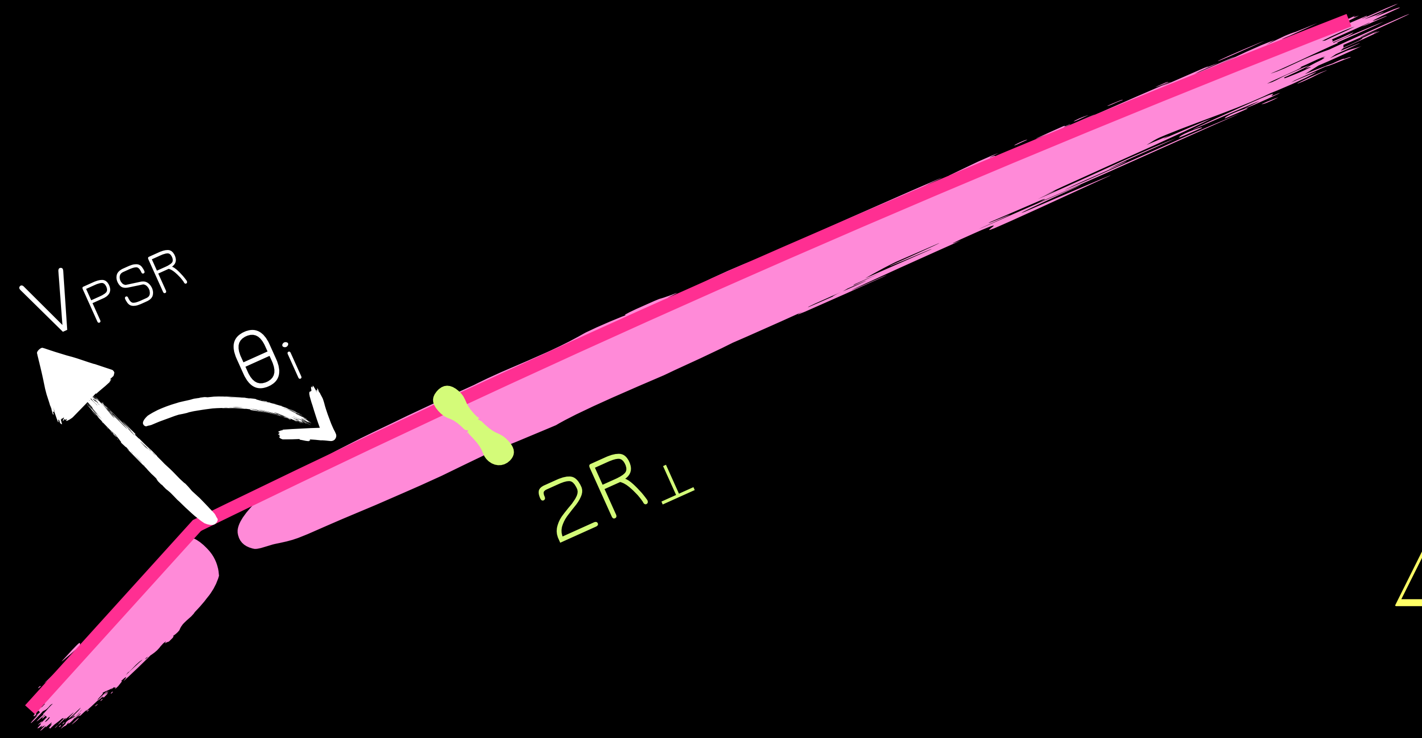
Can be explained as synchrotron radiation emitted by particles escaping the nebula, for which you need:

1. Massive particle escape

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

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

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:

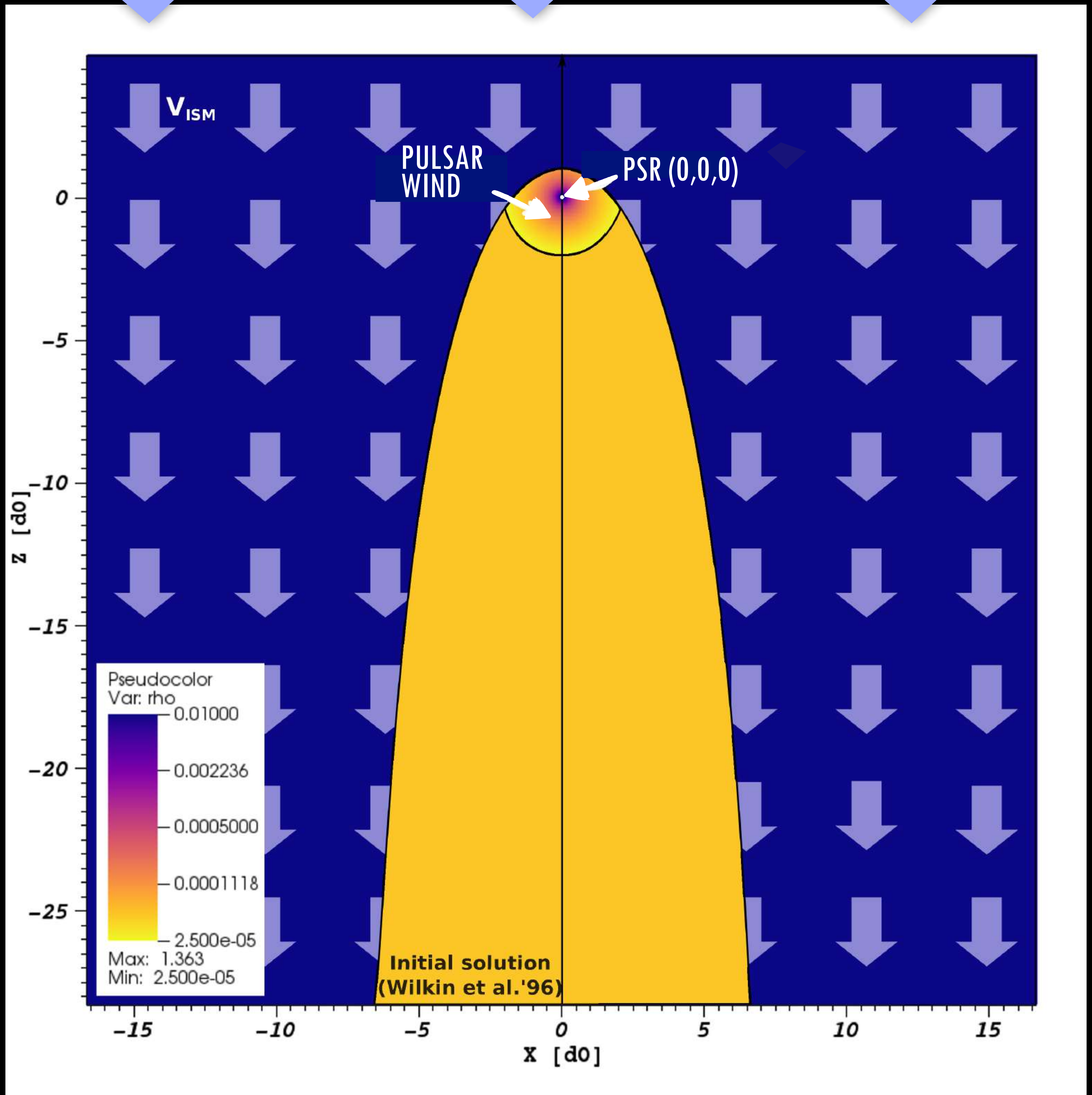
1. An electric current J

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
$V = -V_{PSR}$



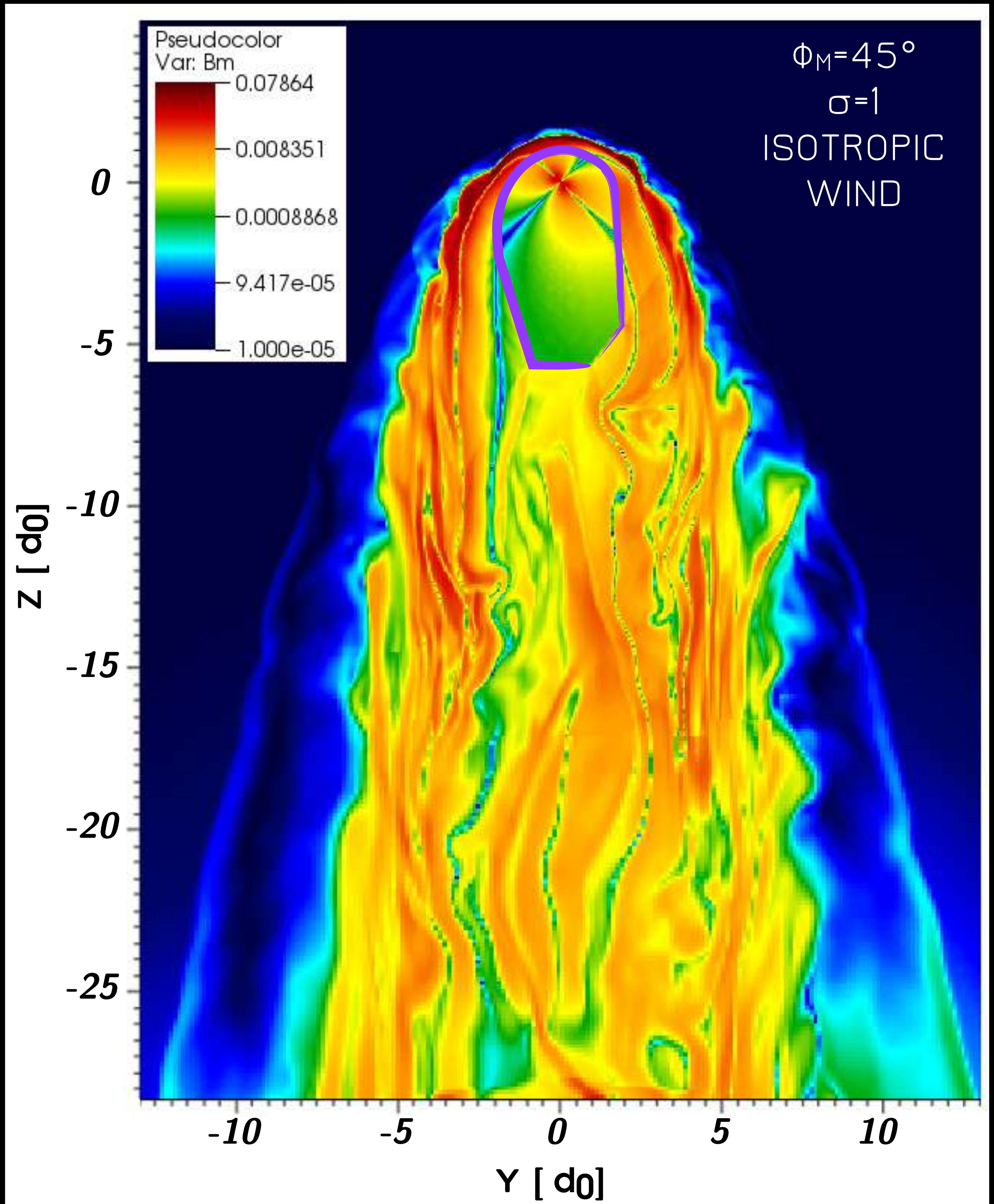
Uniform B ISM
(~3-5 μG)

[Olmi & Bucciantini 2019-I/II]

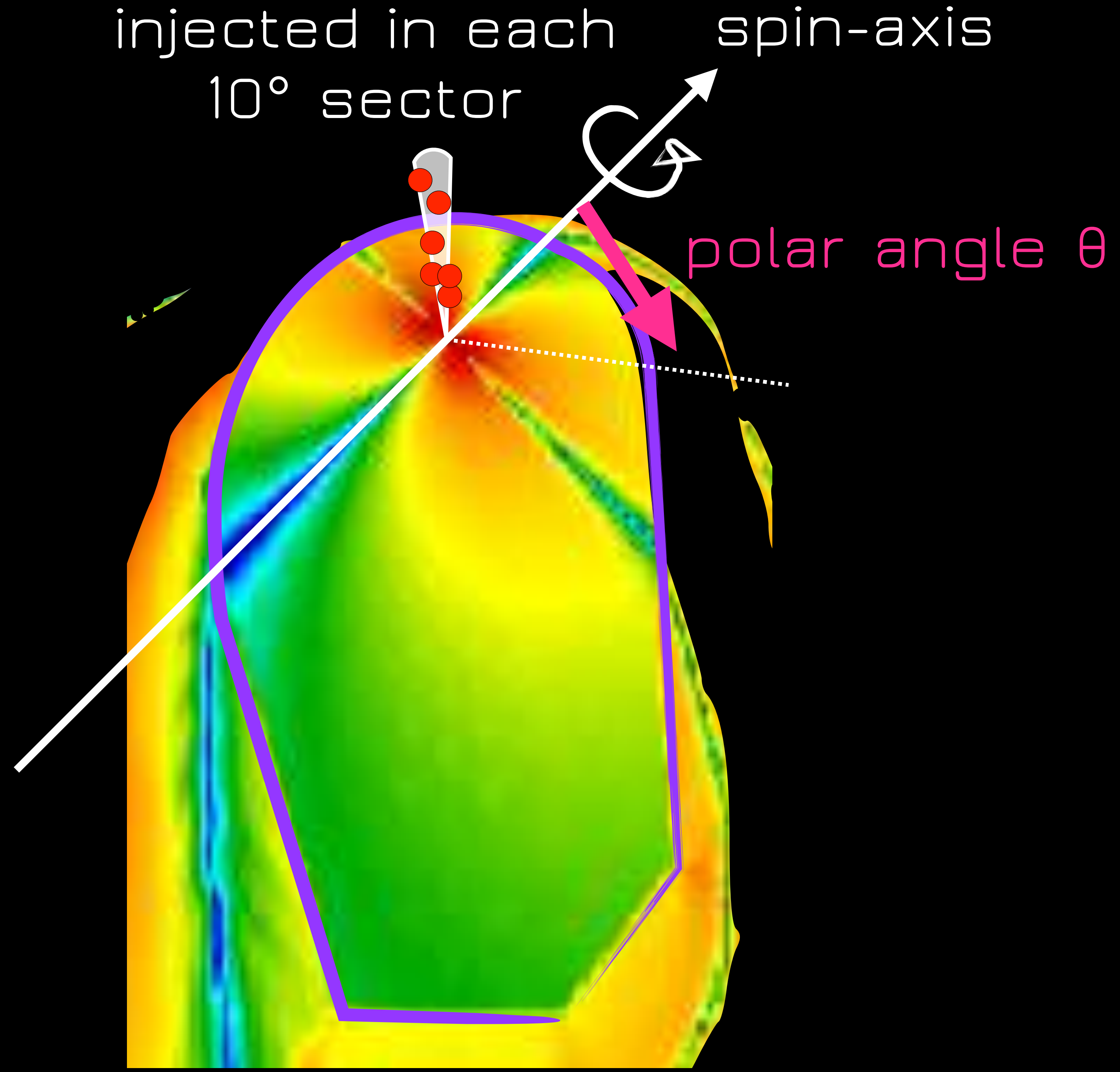
Simulations with the PLUTO code [Mignone et al. 2007]

Class A project @

INJECTING PARTICLES IN THE PULSAR WIND



~10^5 particles injected in each 10° sector



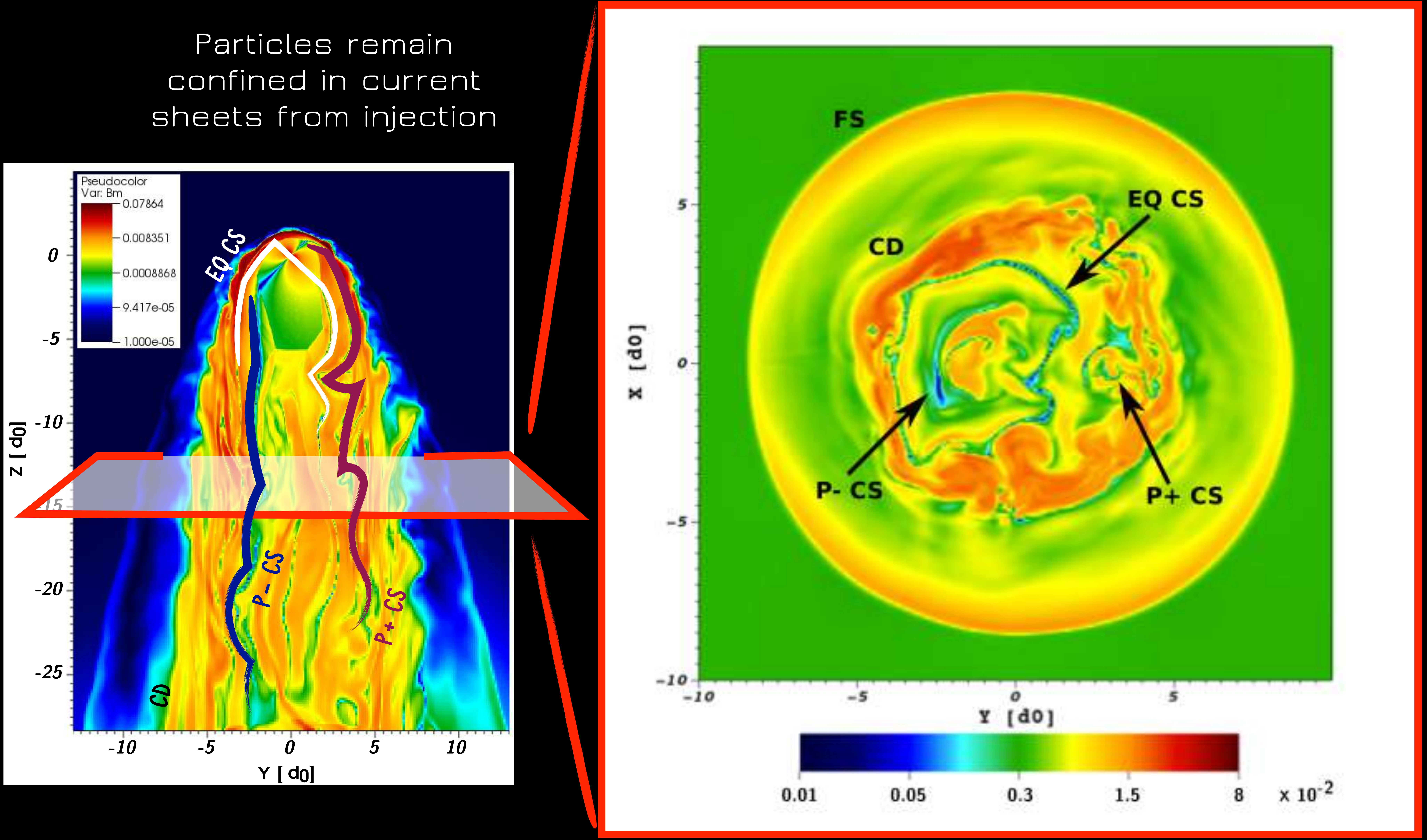
Electrons and positrons of different energies (1-50 TeV):

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

[Olmi & Bucciantini 2019-III]

THE ROLE OF CURRENT SHEETS IN THE TAIL

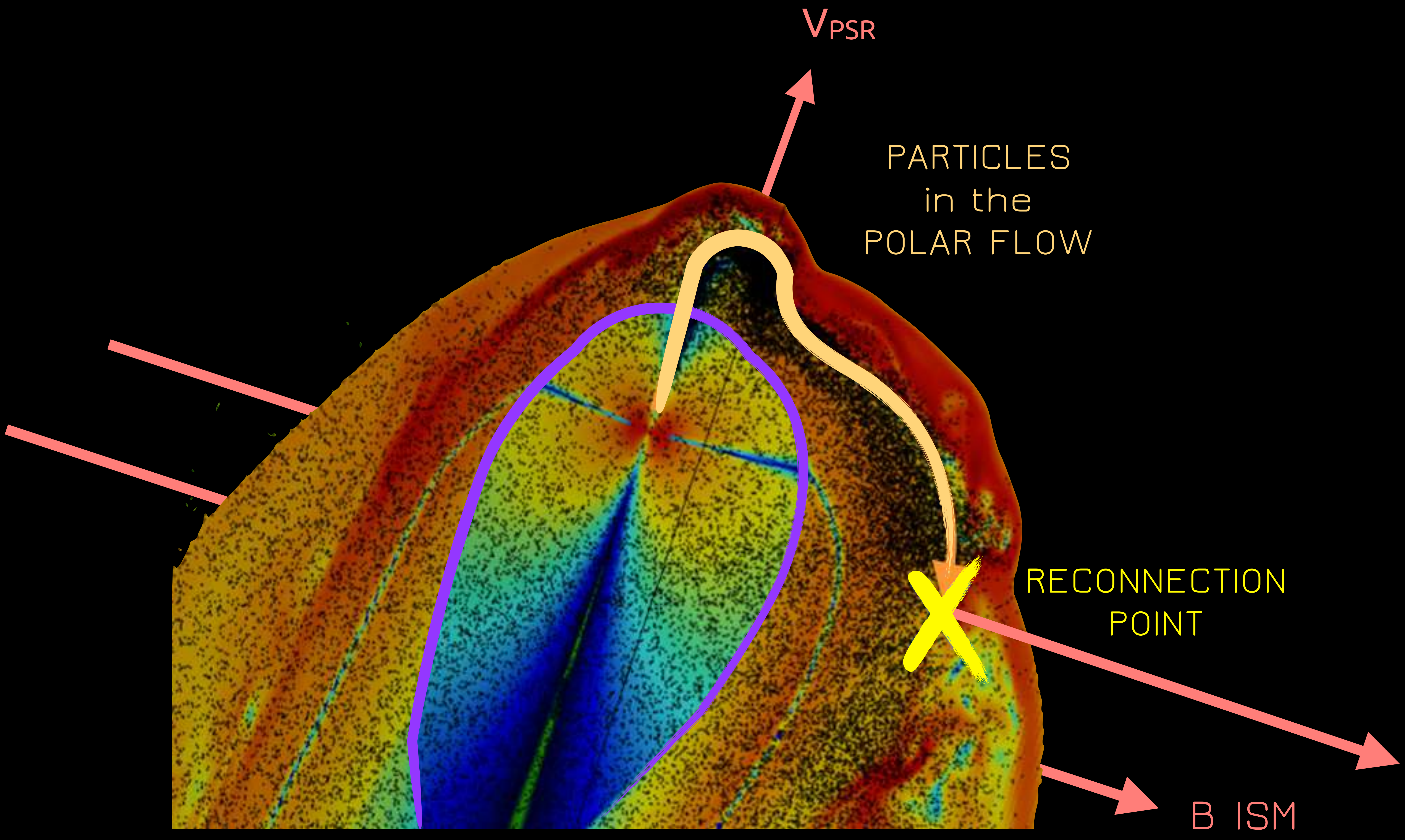
Particles remain confined in current sheets from injection



[Olmi & Bucciantini 2019-I/II]

ESCAPE OF PARTICLES: HOW AND FROM WHERE

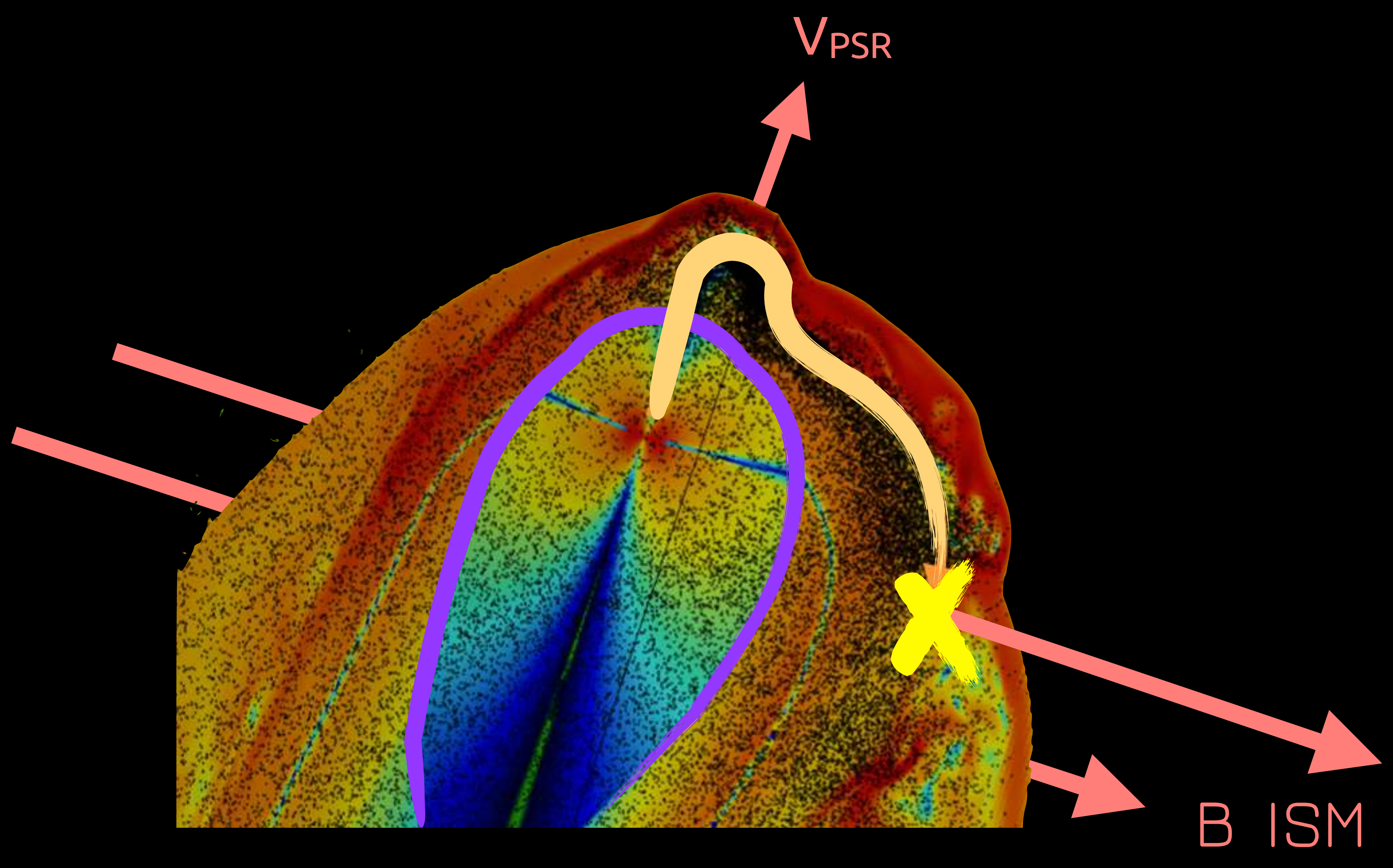
When the current sheet points towards the CD, particles can escape at reconnection points of the magnetopause



[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

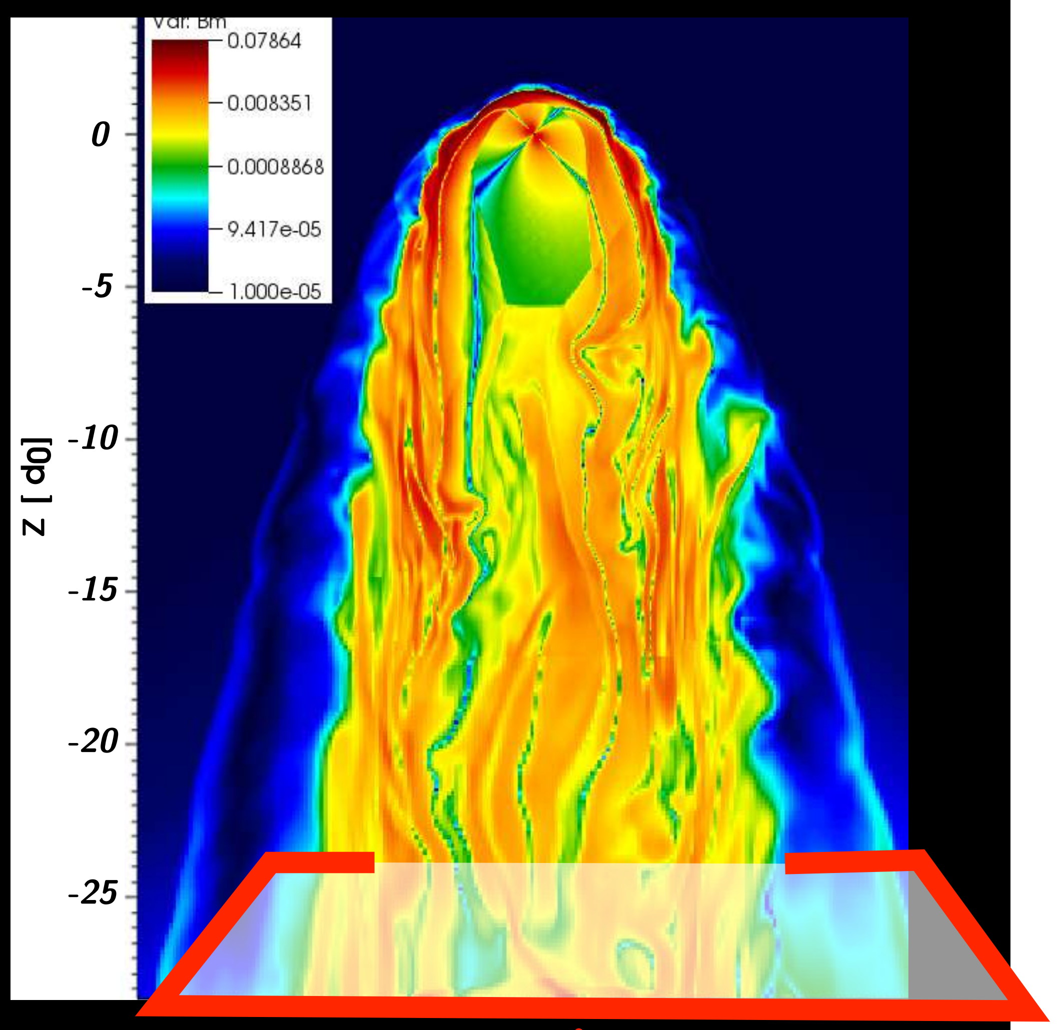
escape →

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

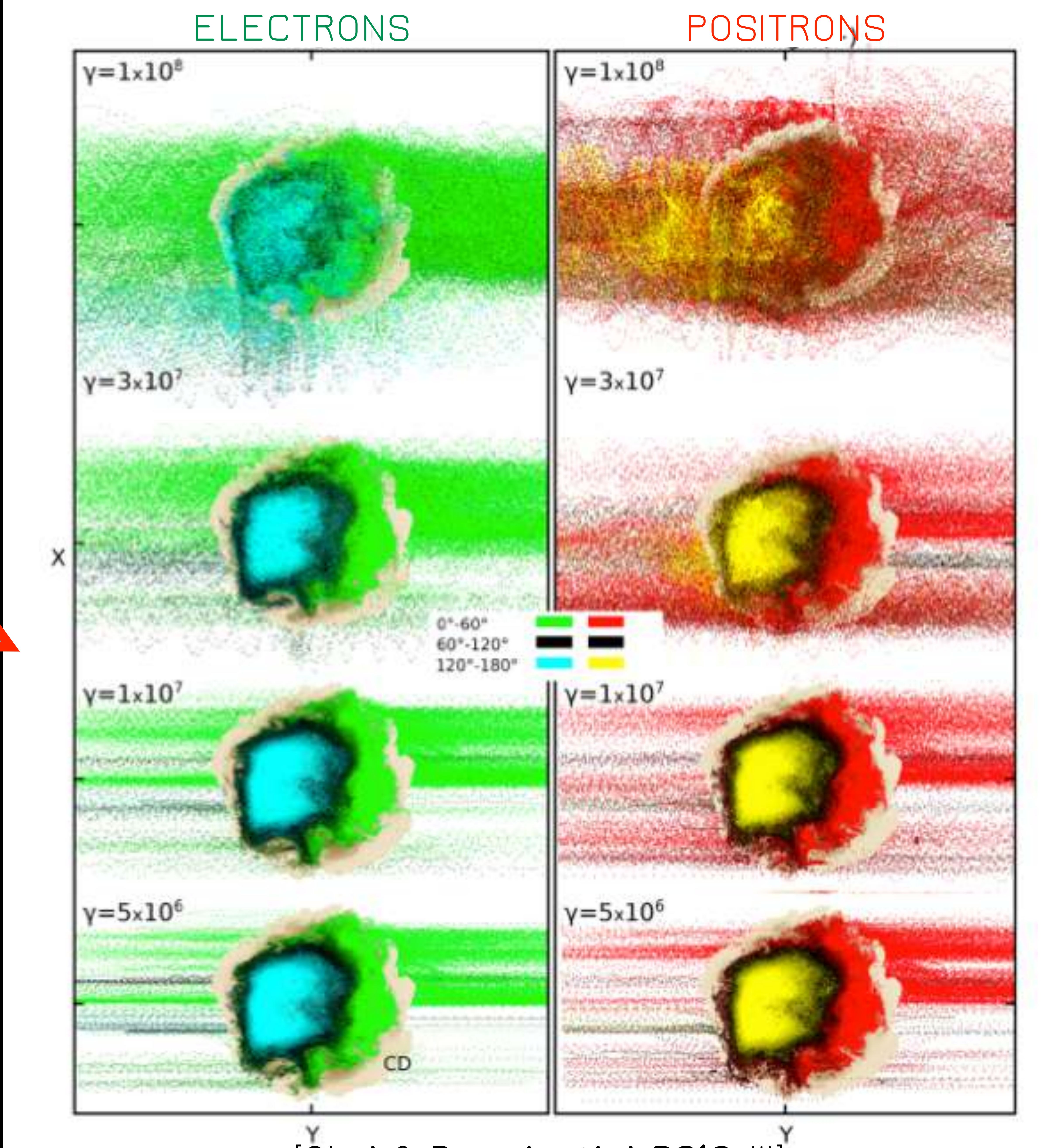
$\gamma_{esc} \sim 10\text{-}50\% \ \gamma_{MPD}$

[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:

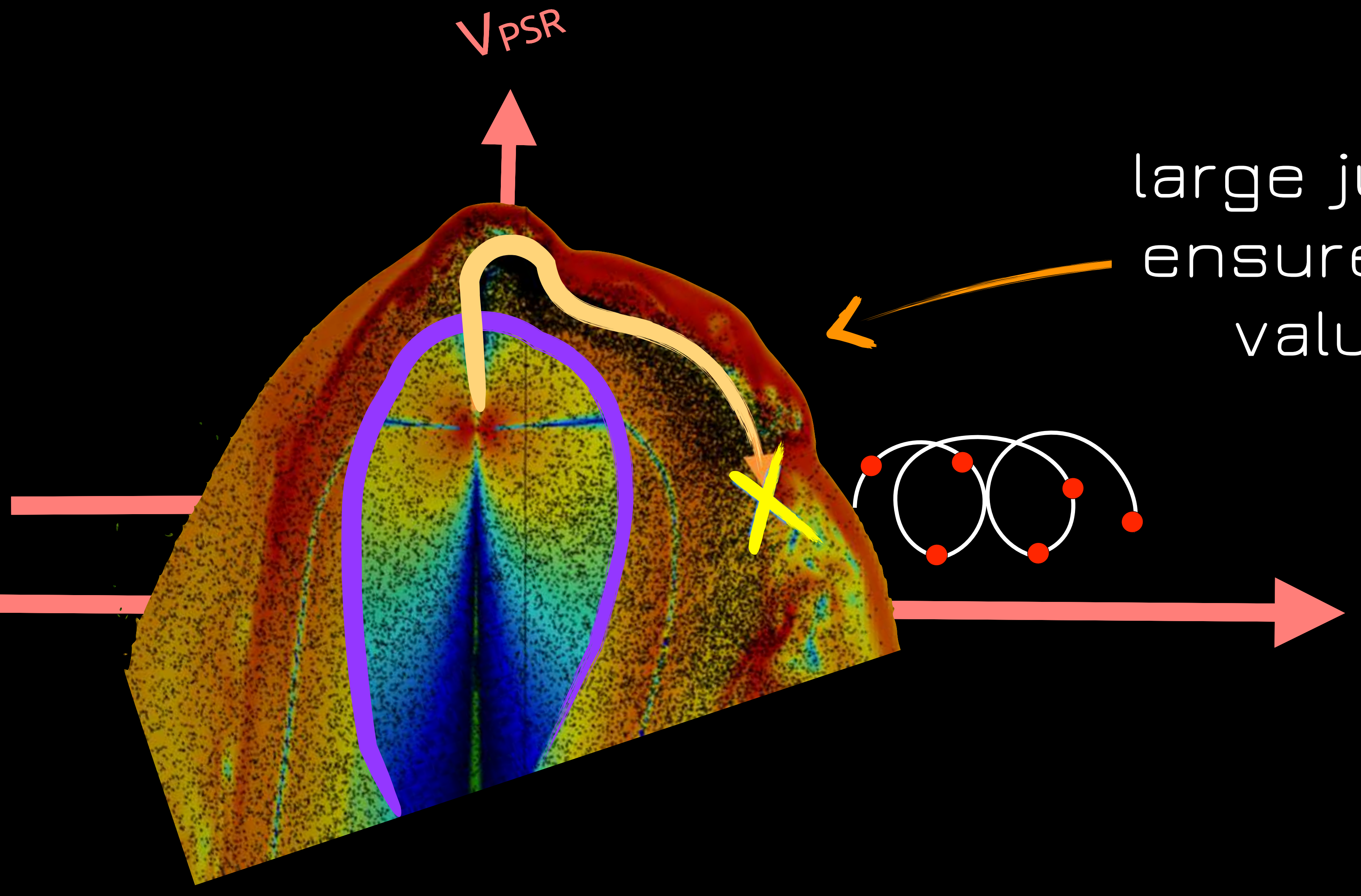
saturation scale $\Delta x \simeq R_{gyro,\perp}(\gamma_{esc})$

$$\left(\frac{\Delta B}{B_{\rm ISM}}\right)_{\rm sat} = \frac{2\sqrt{\epsilon}}{\sin\alpha}\left(\frac{\gamma_{\rm MPD}}{\gamma_{\rm esc}}\right) \sim 5\text{-}10$$

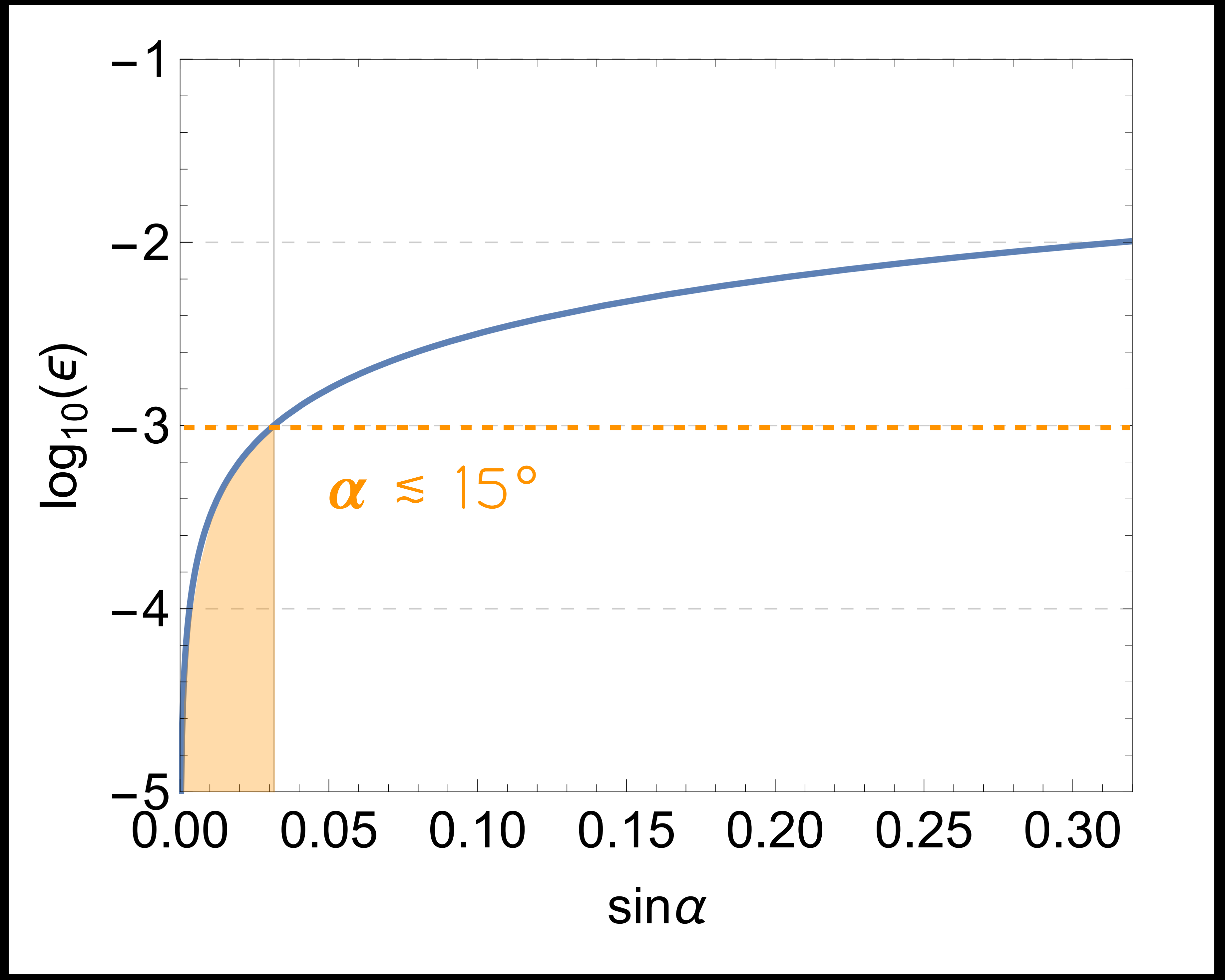
$\boldsymbol{\alpha}$ → particle pitch angle

ϵ → fraction of PSR luminosity going in the feature

Possible for small sin$\boldsymbol{\alpha}$



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



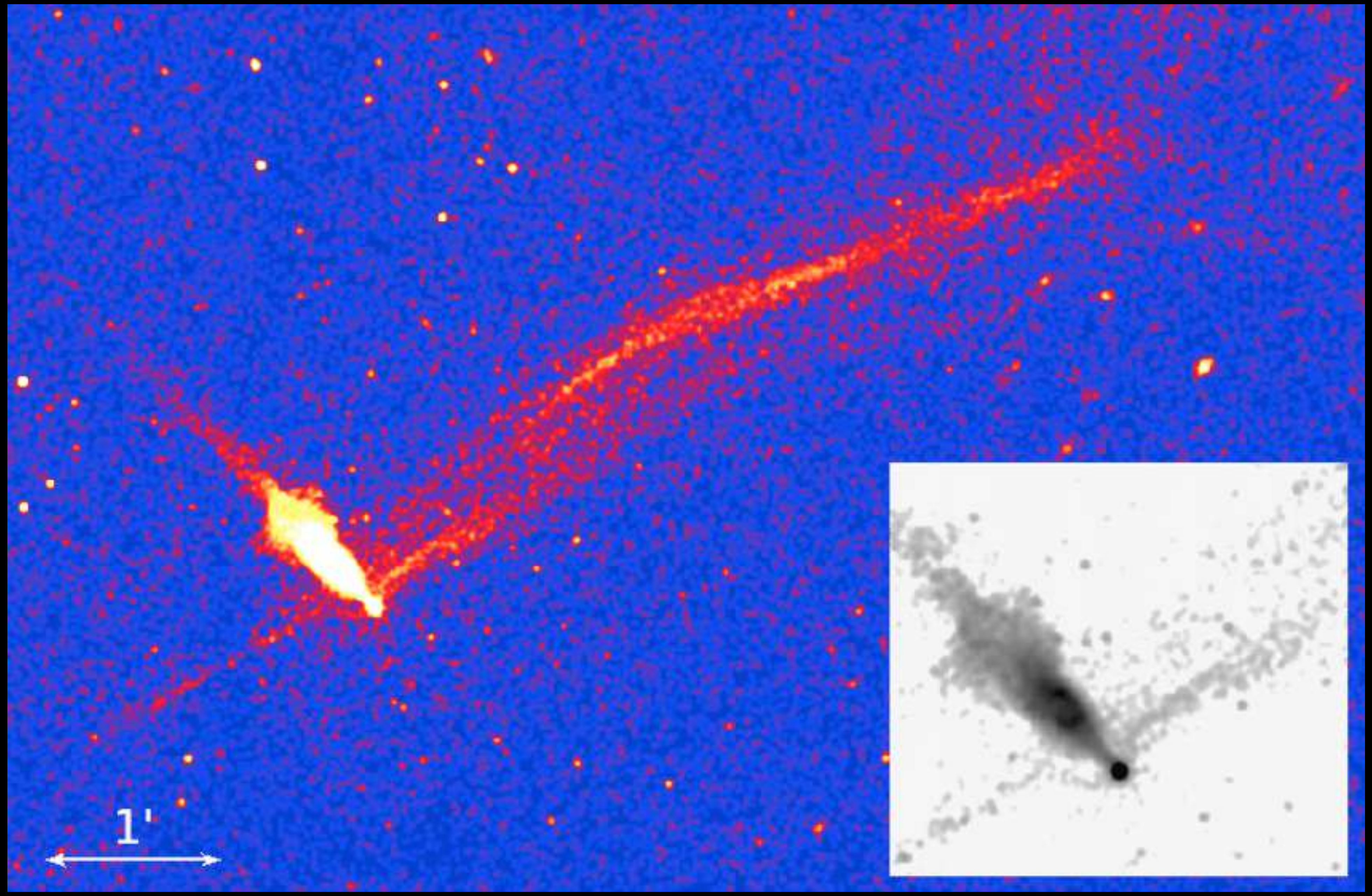
[Bandiera, Olmi, Blasi, Amato, in preparation]

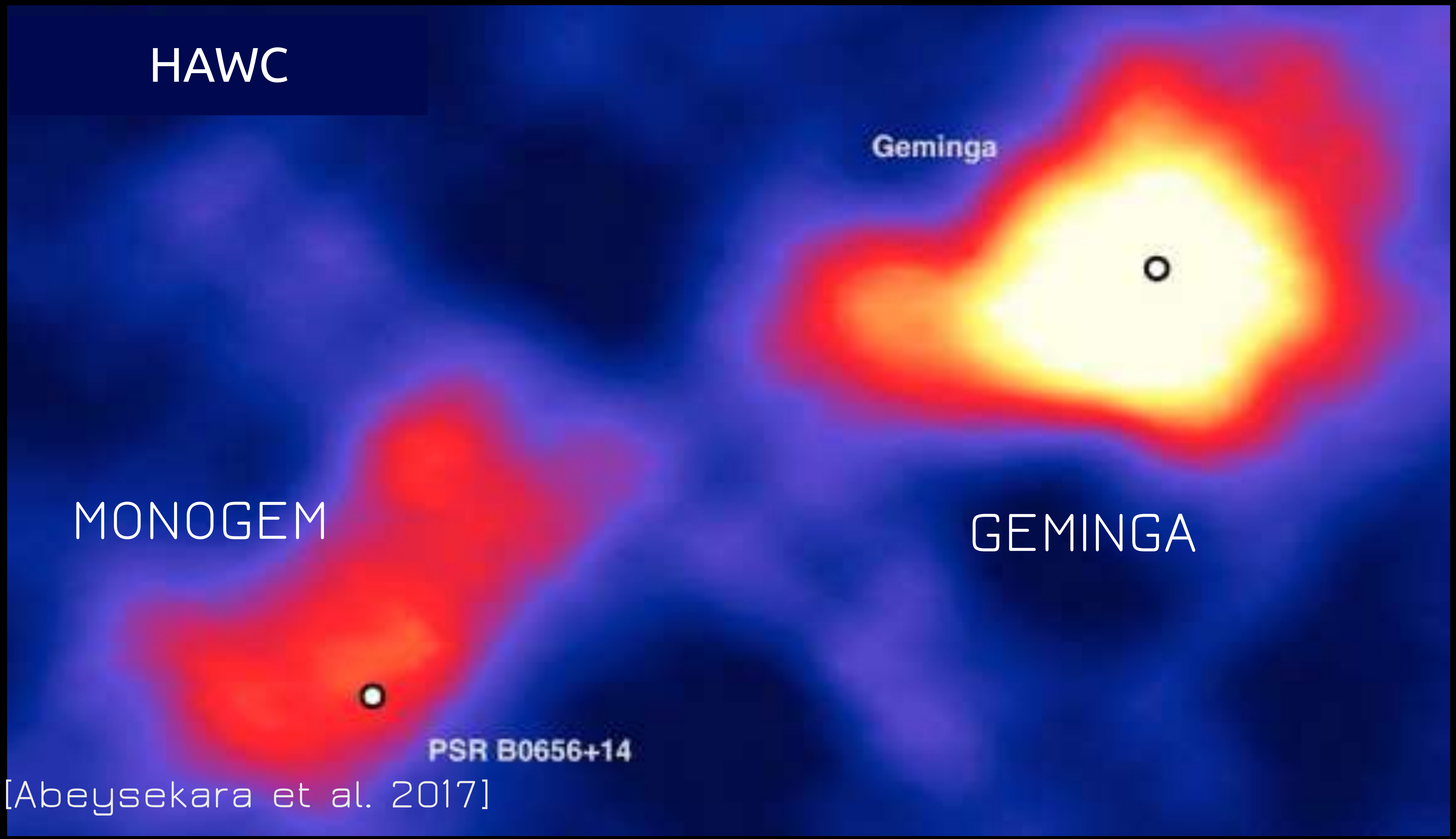
CONCLUSIONS

PWNe (or their halos) will dominate the Galactic gamma-ray sky.

Evolved PWNe do show evident leakage of particles in the ambient medium -> formation of features (X-rays / gamma-rays) outside the PWN due to the interaction of the escaping particles with the ambient medium.

In X-rays we see the details of the escaping flow -> understanding their nature may shed light also on the formation of halos. These could be manifestations of the same process, happening in an ambient with different physical conditions!





[Abeysekara et al. 2017]