MODELING YOUNG PULSAR WIND NEBULAE

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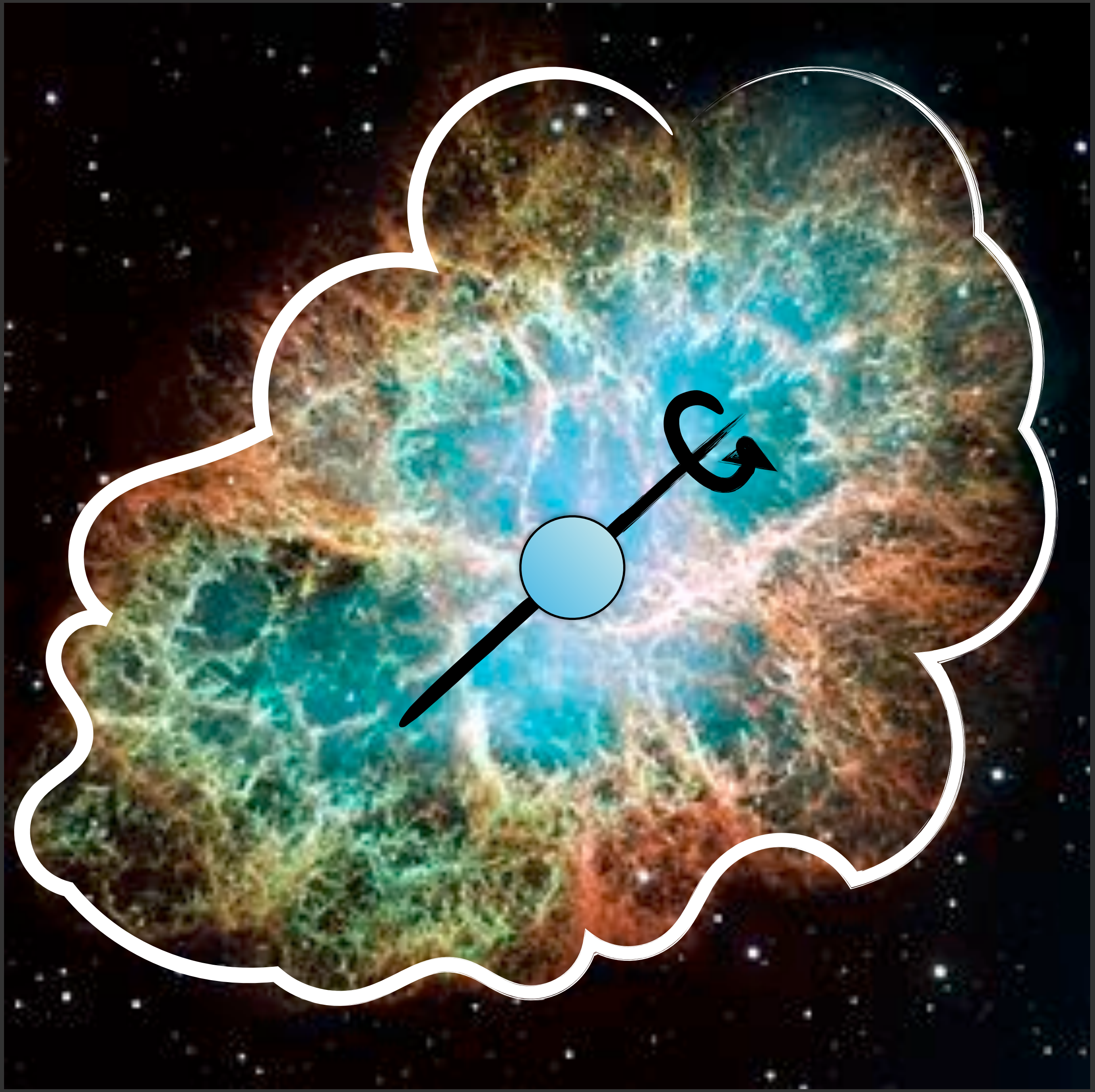
WHAT IS A PWN?

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



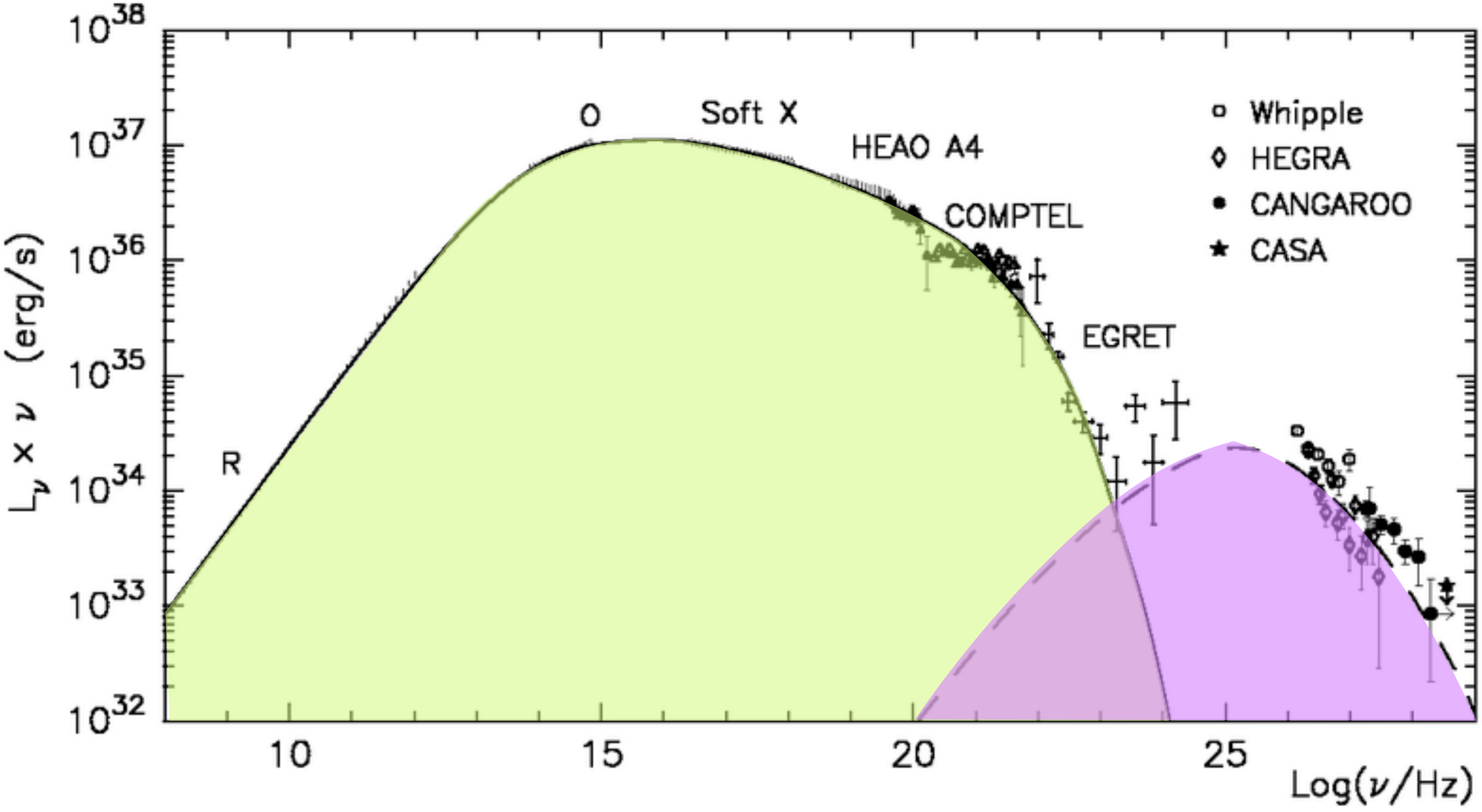
[NOT IN SCALE!!]

MAIN INGREDIENTS

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

HOW DO THEY LOOK? BROAD BAND NON-THERMAL SPECTRUM

CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]



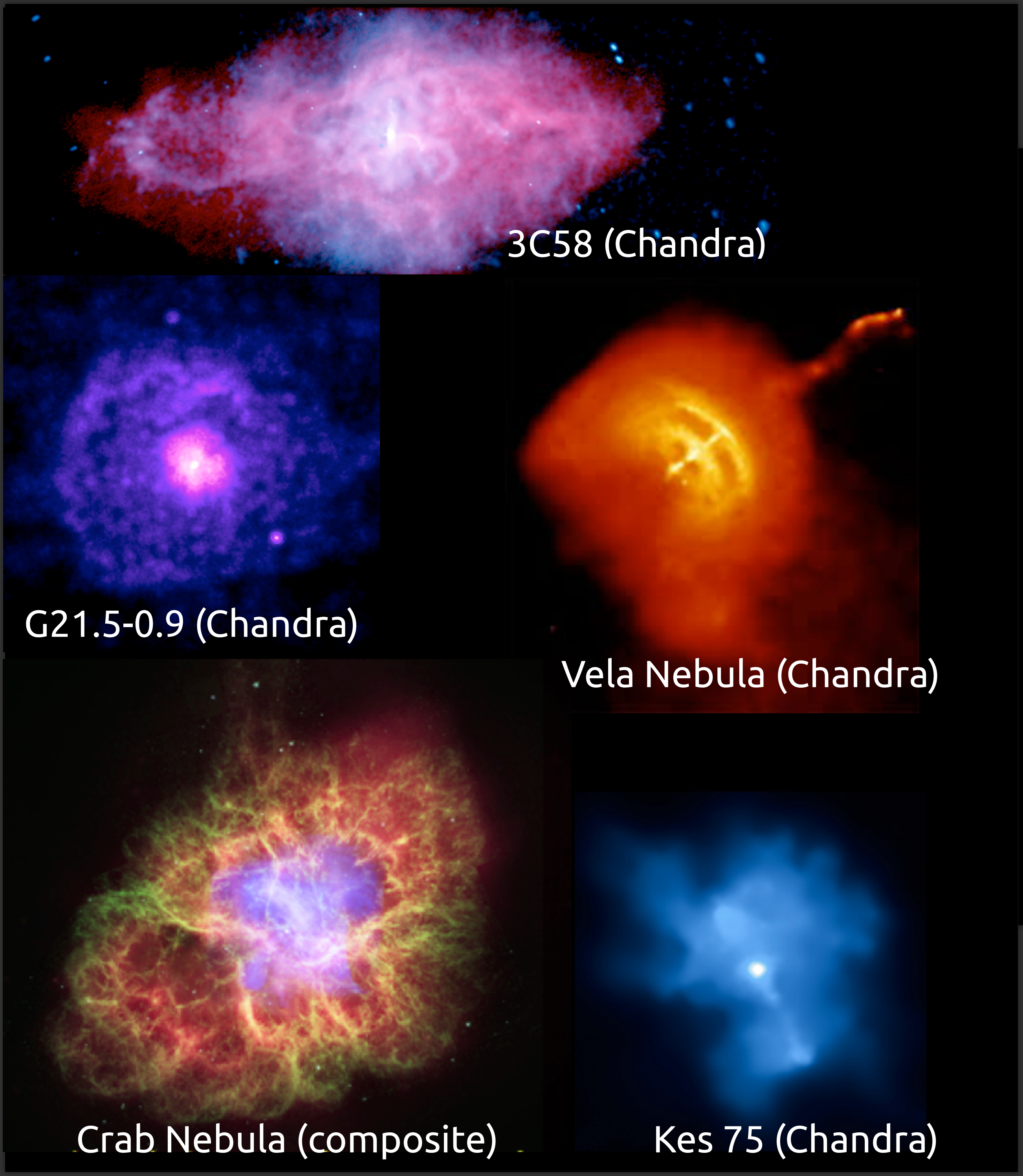
Primary mechanism: synchrotron radiation by relativistic particles in the nebular magnetic field

Gamma-rays: Inverse Compton scattering with local photon field

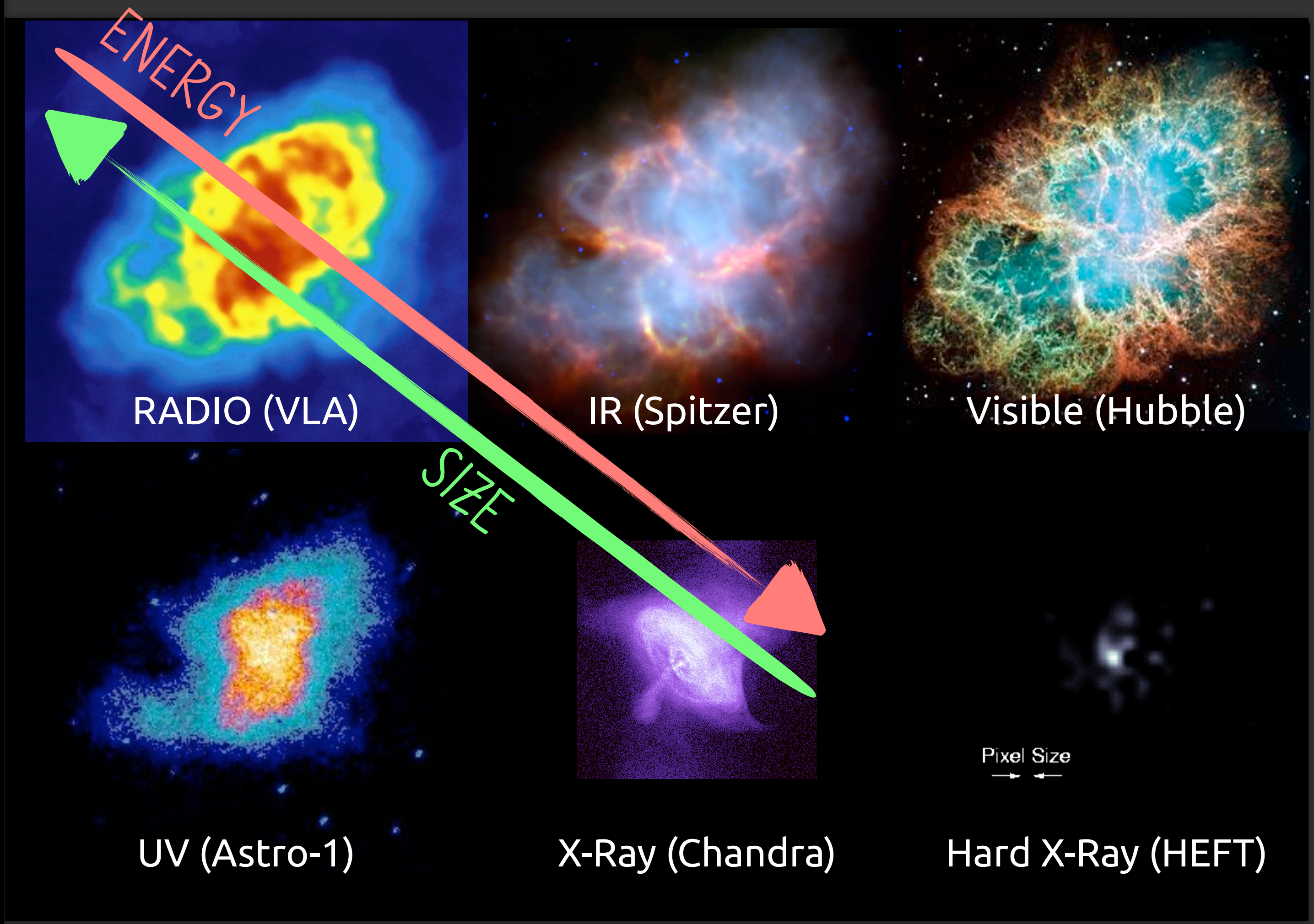
HOW THEY LOOK?

EMISSION MORPHOLOGY AT MULTI-WAVELENGTHS

Fill-centered morphology



Decreasing size with energy



WHY ARE THEY INTERESTING?

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

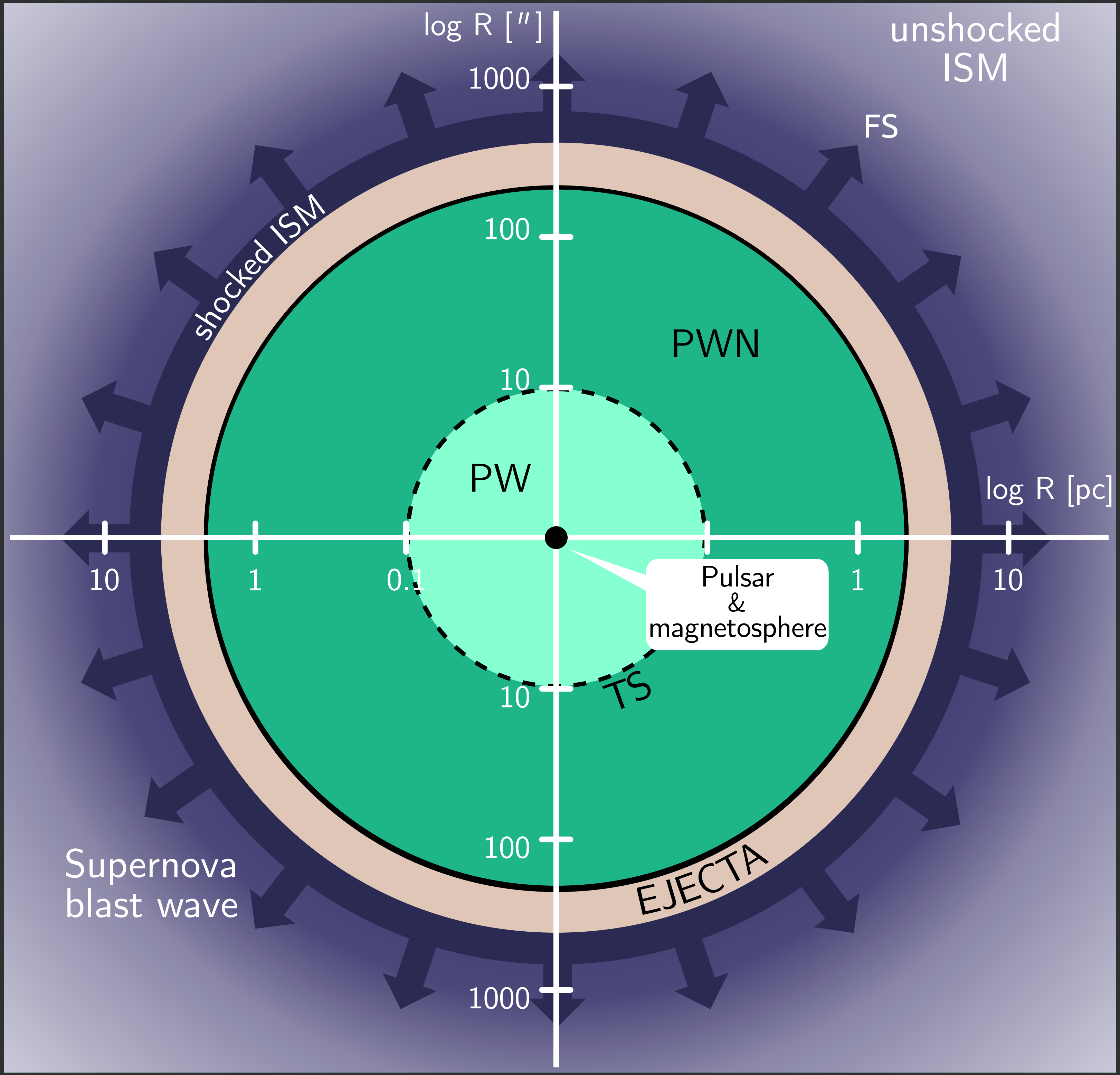
Extreme conditions of the plasma in close and bright sources → PLASMA PHYSICS

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?)

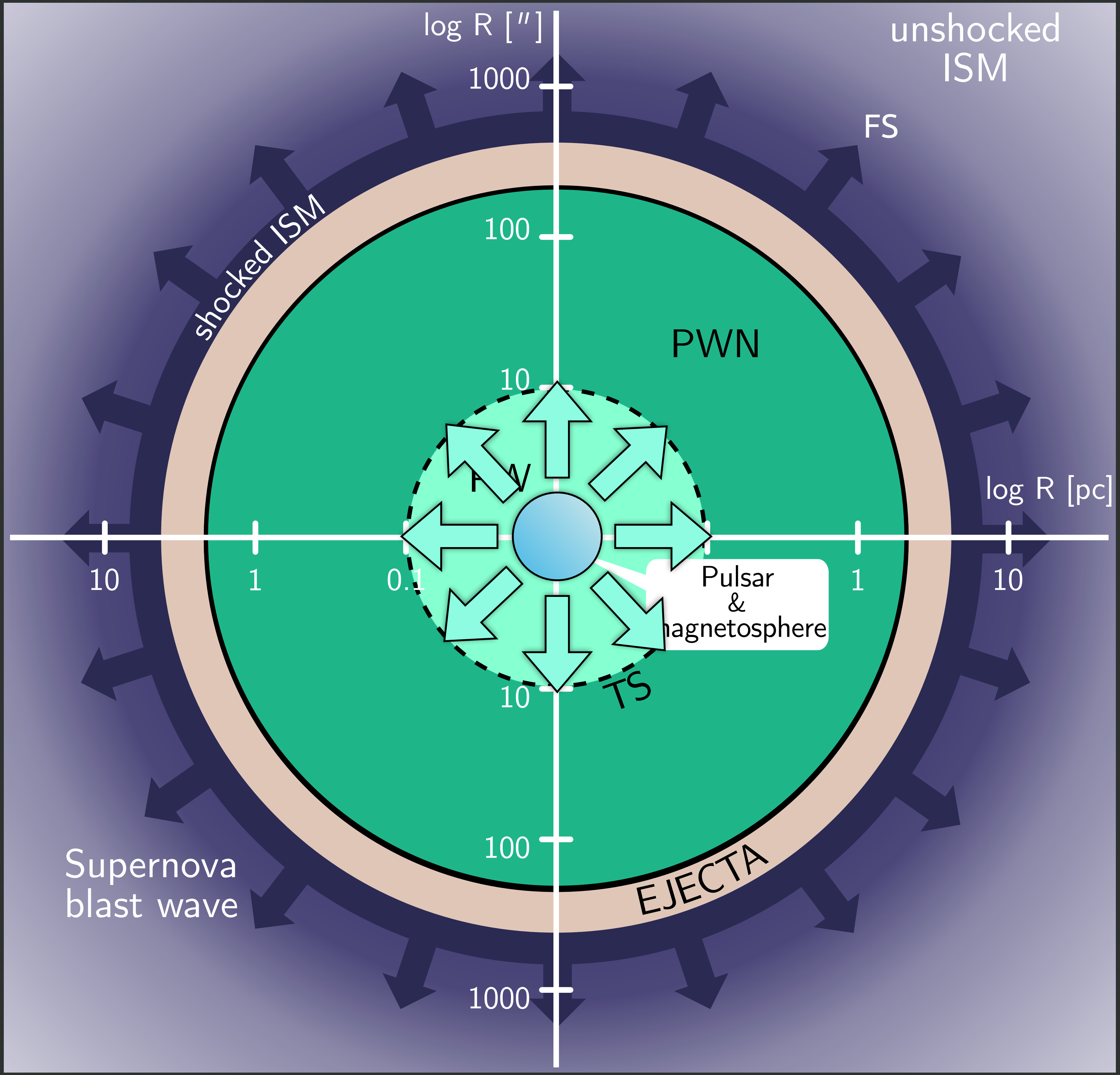
Gamma-rays → LARGEST GALACTIC POPULATION

A VERY BASIC PICTURE OF YOUNG PWN



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

A VERY BASIC PICTURE OF YOUNG PWN



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)

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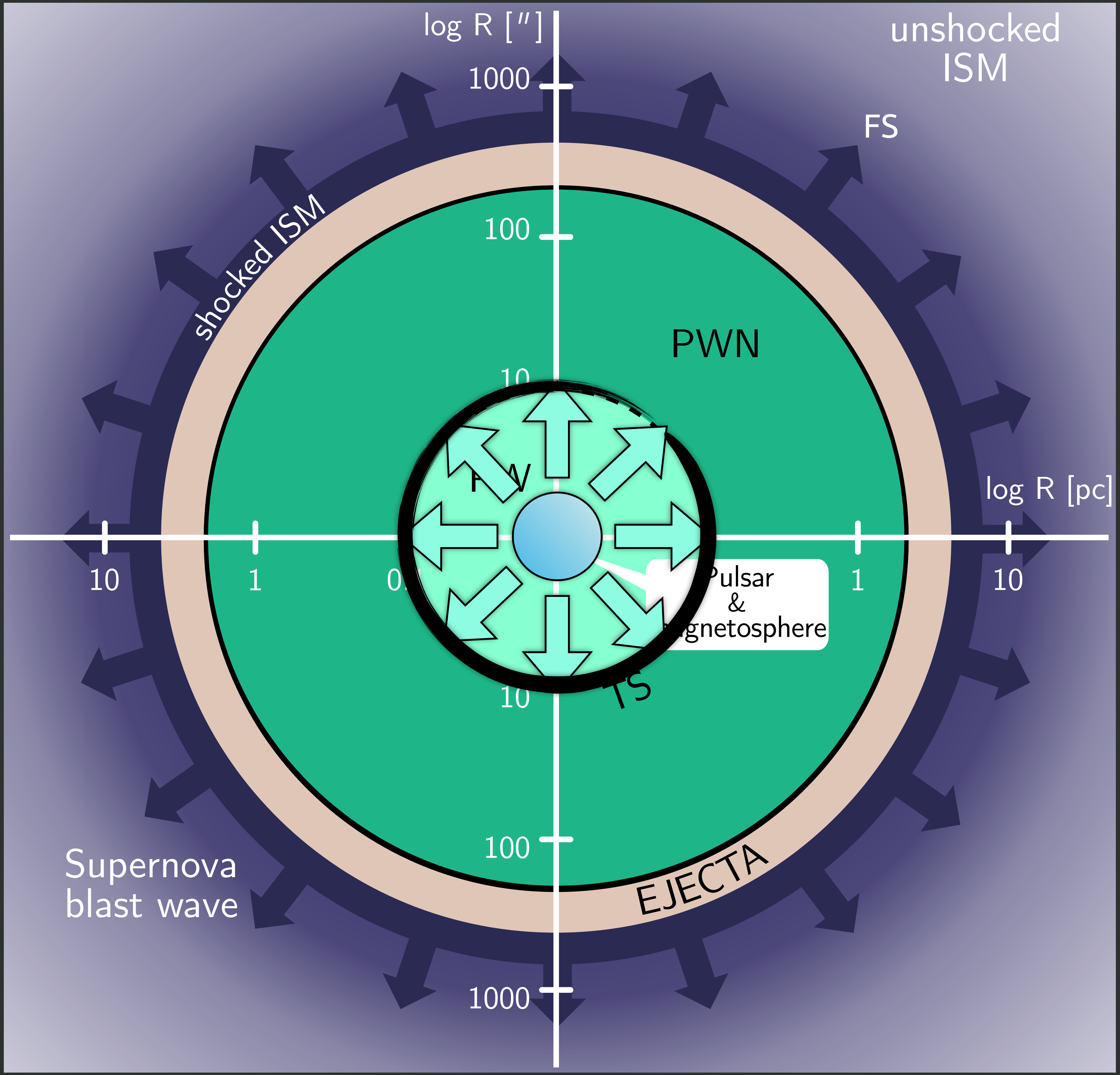
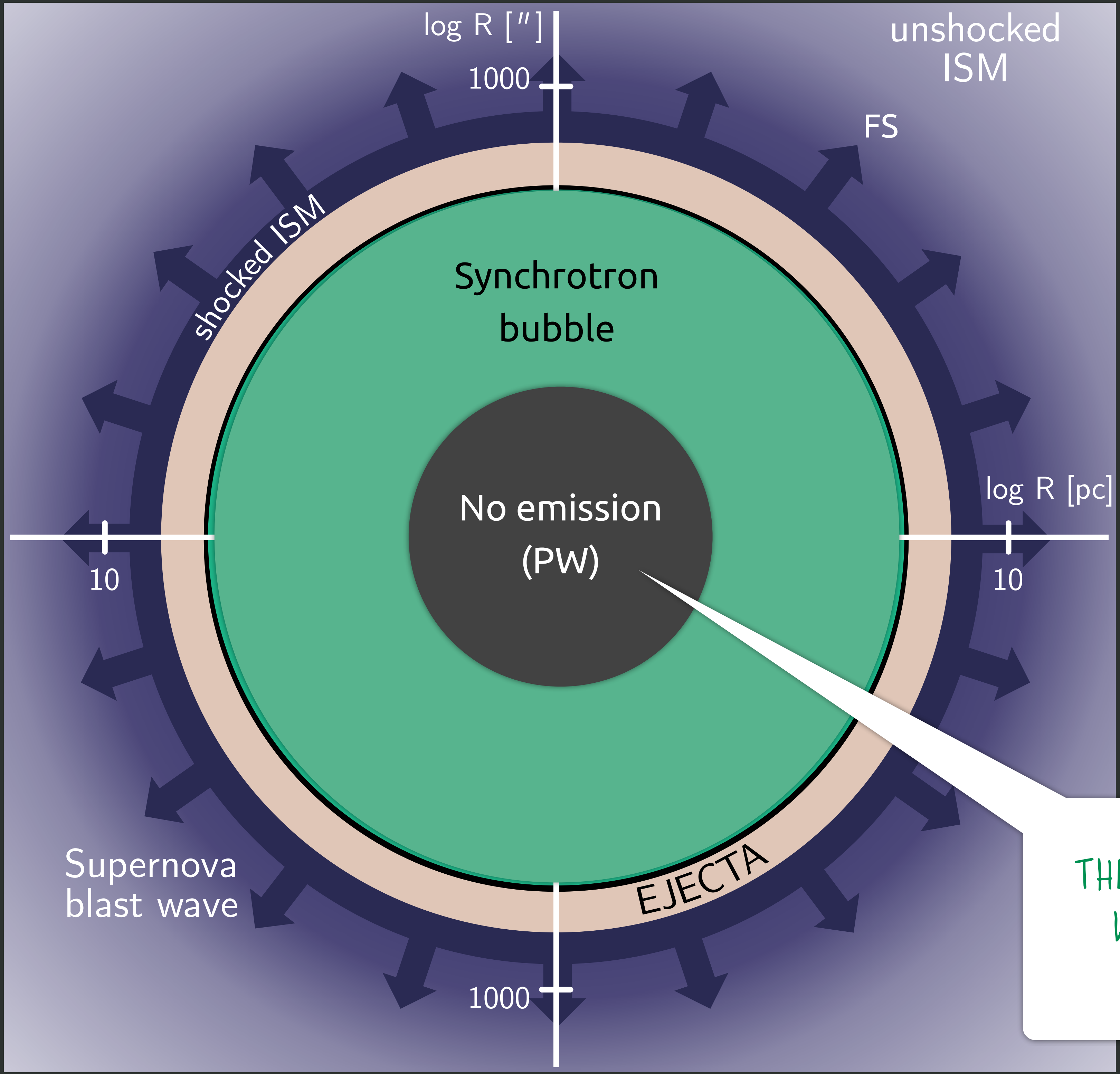


Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

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

A VERY BASIC PICTURE OF YOUNG PWN



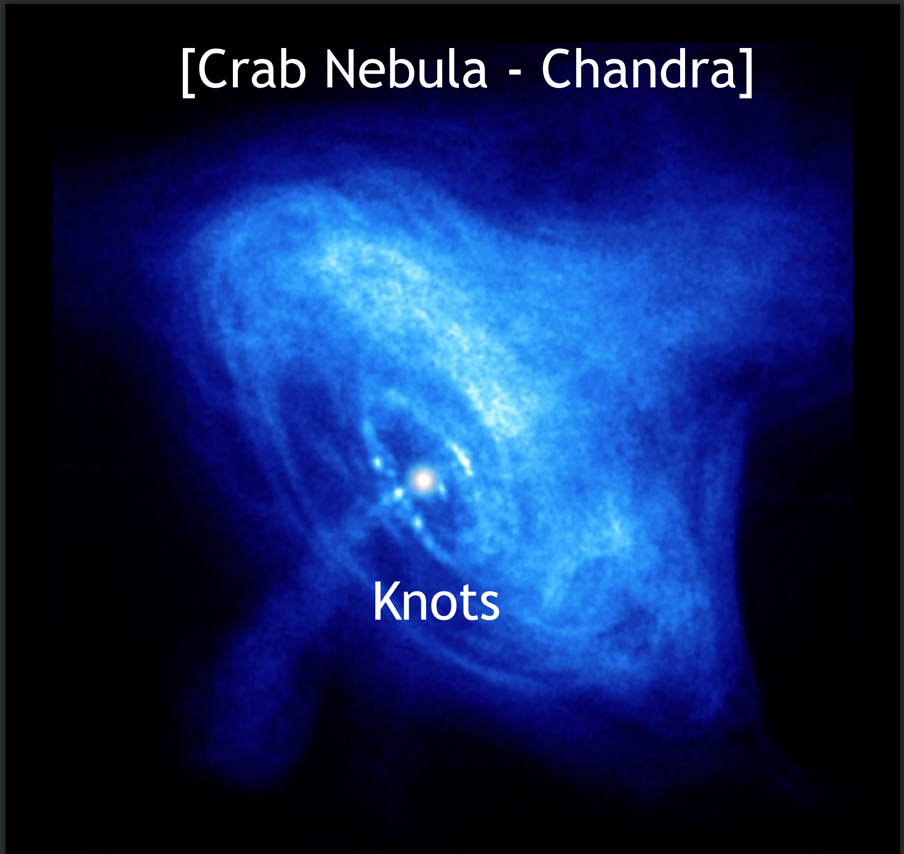
Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

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)

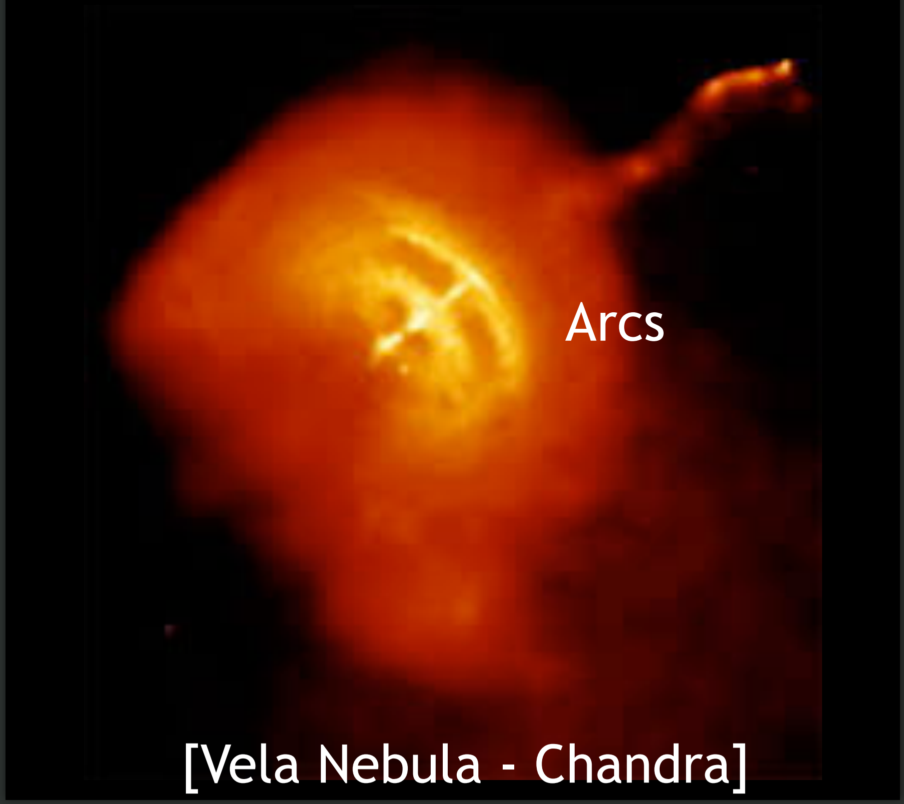
THE UNACCESSIBLE WIND REGION IS WHERE MOST OF THE PHYSICAL PROCESSES HAPPEN

THE COMPLEX STRUCTURE OF THE INNER NEBULA

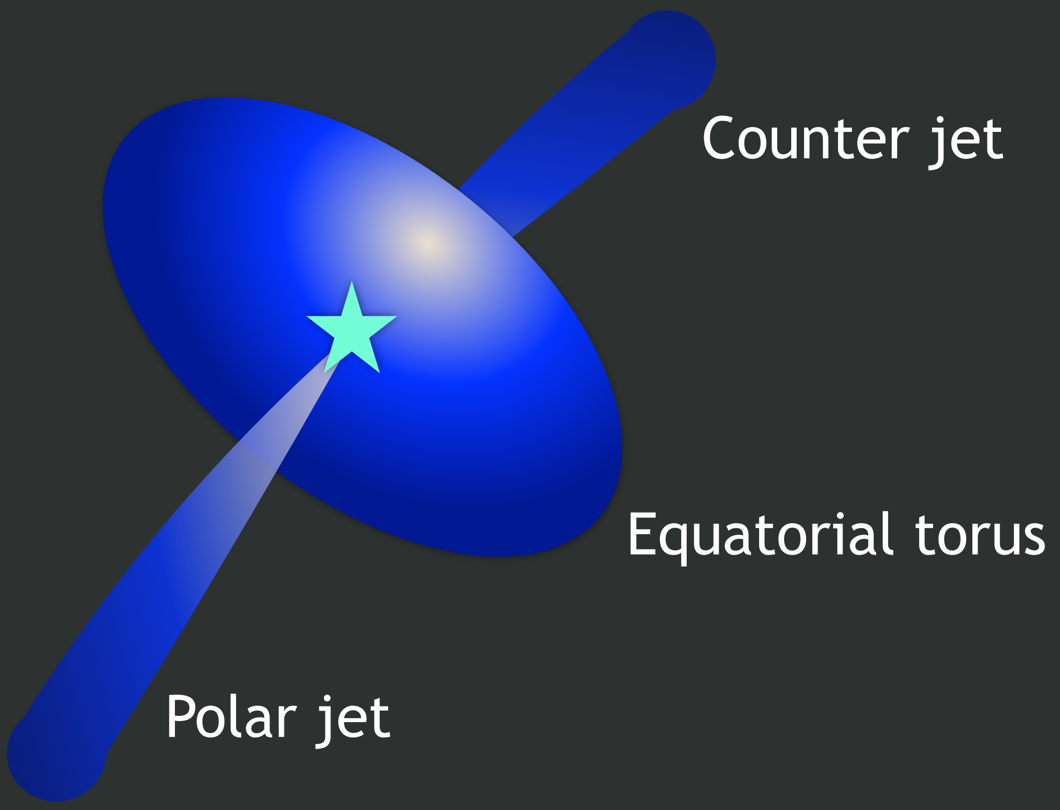
THE JET-TORUS



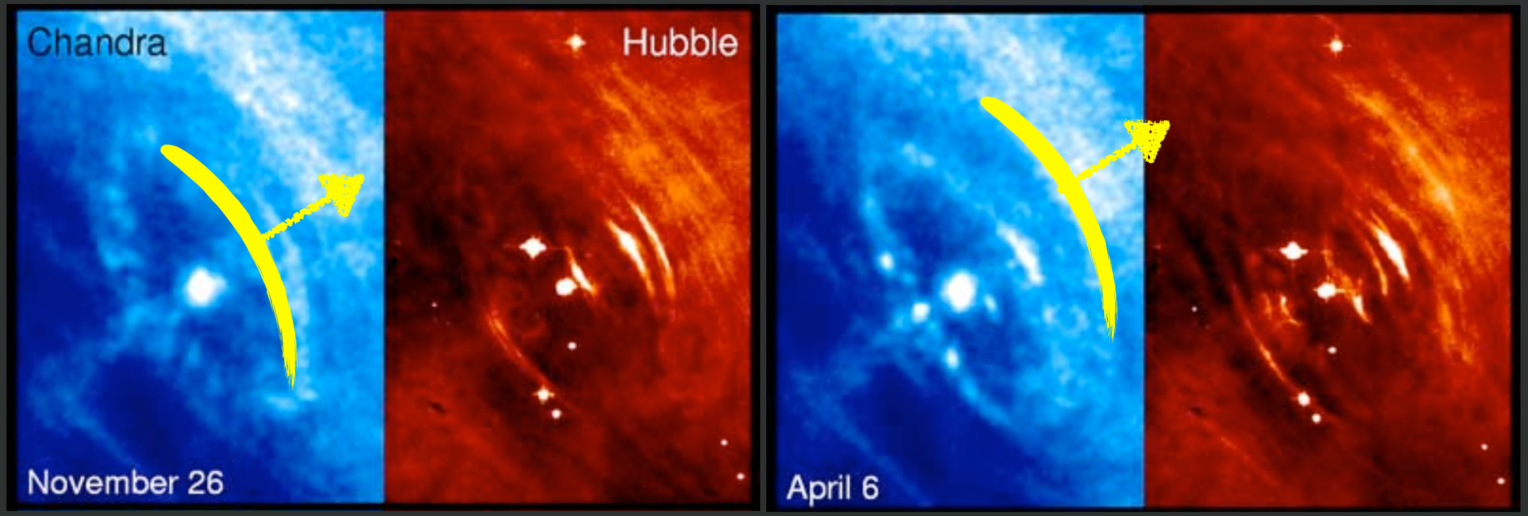
[Crab Nebula - Chandra]



[Vela Nebula - Chandra]

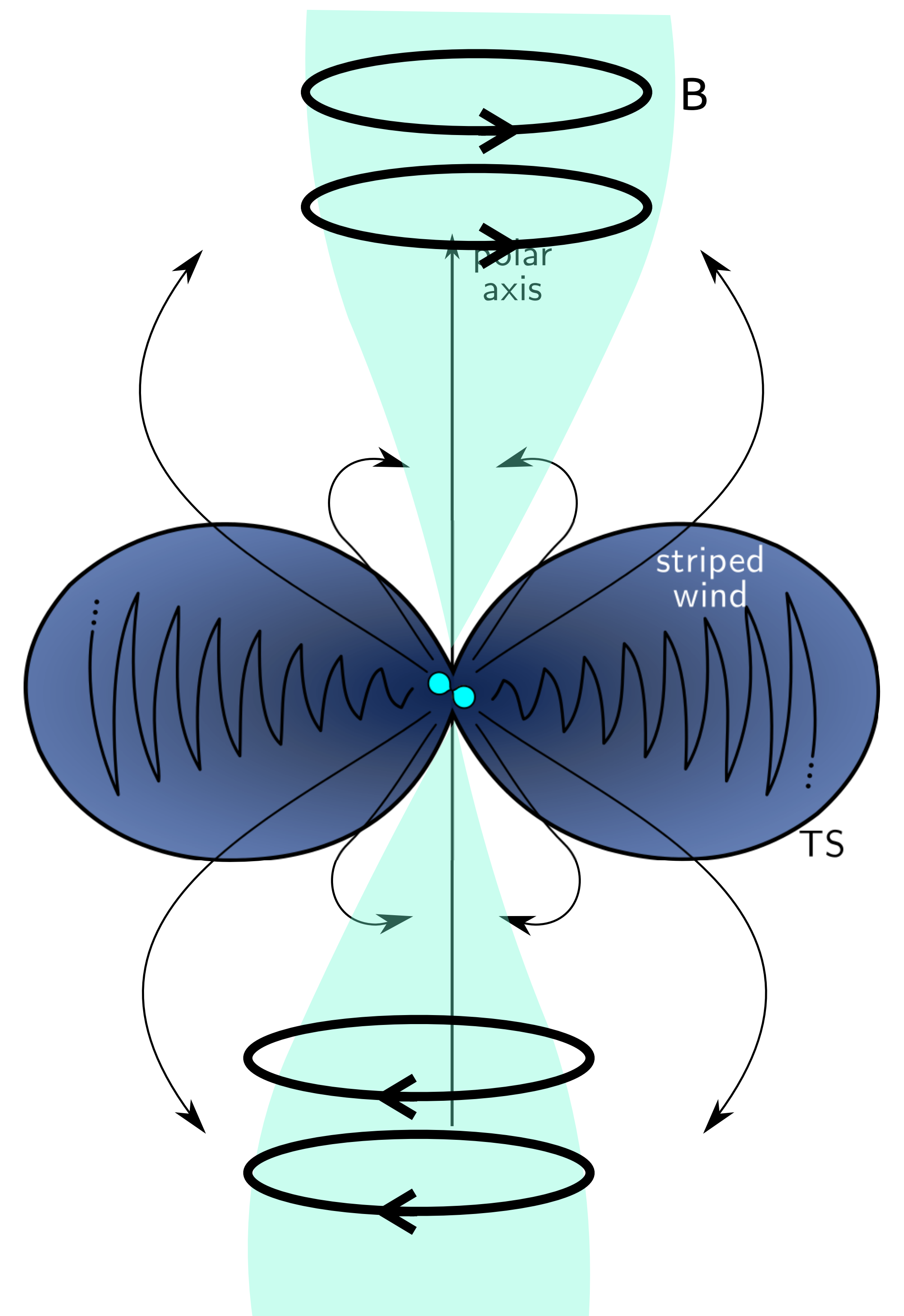


HIGH VARIABILITY (SPATIAL-BRIGHTNESS)



Outward moving wisps

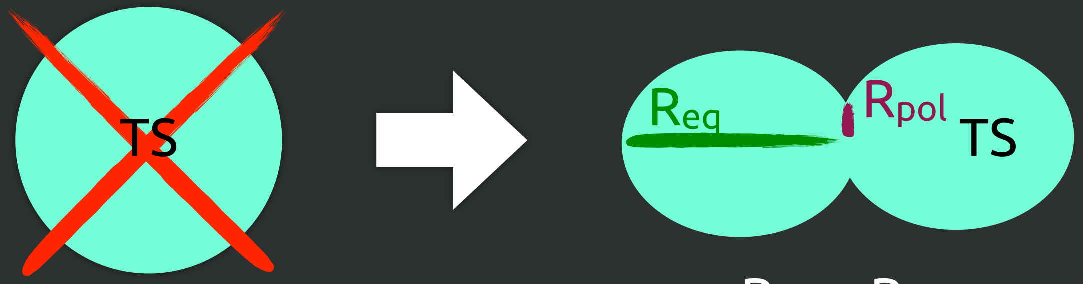
FORMATION OF THE POLAR JETS: THE ANISOTROPIC WIND



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!



$R_{eq} > R_{pol}$

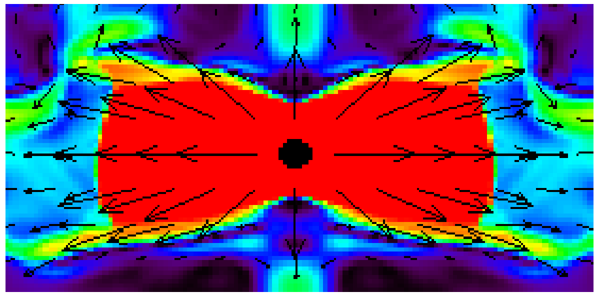
MODELING THE PULSAR WIND

Anisotropic distribution of the energy flux *F(r,θ)*:

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

anisotropy parameter

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

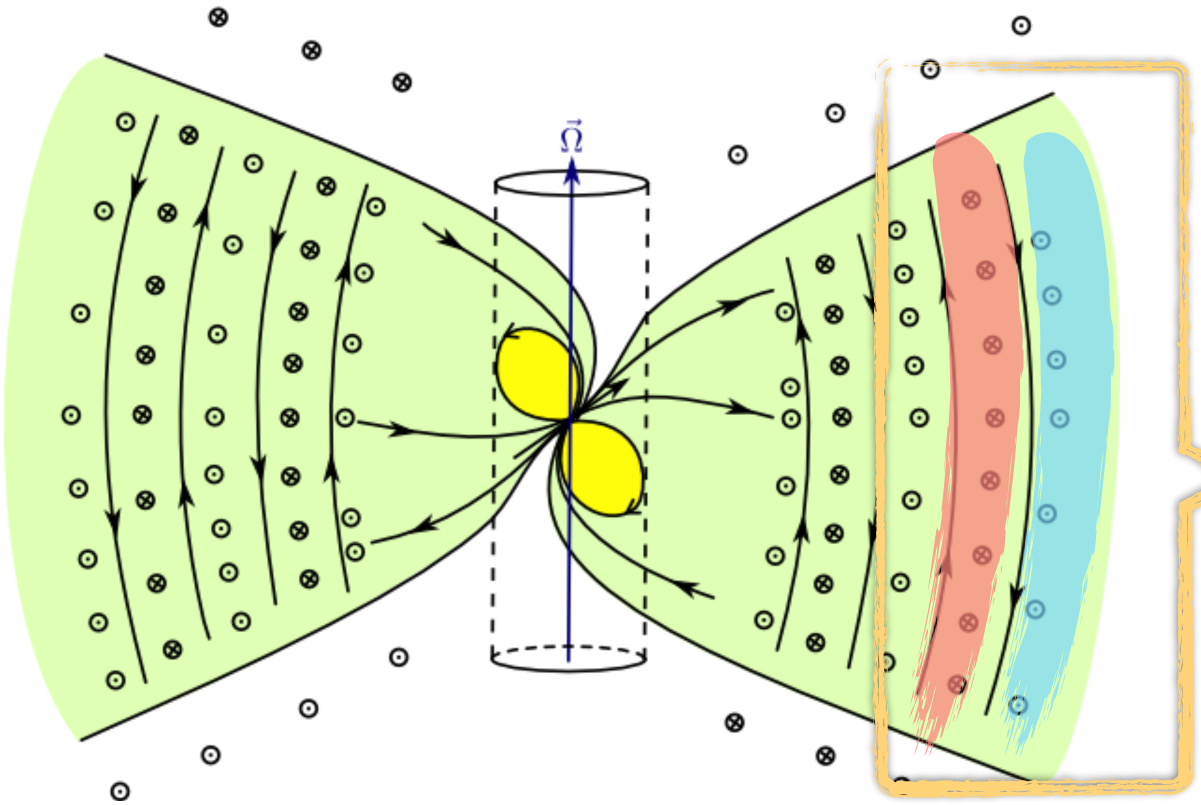


Striped morphology within an equatorial belt of extension ≃ 2×ζ

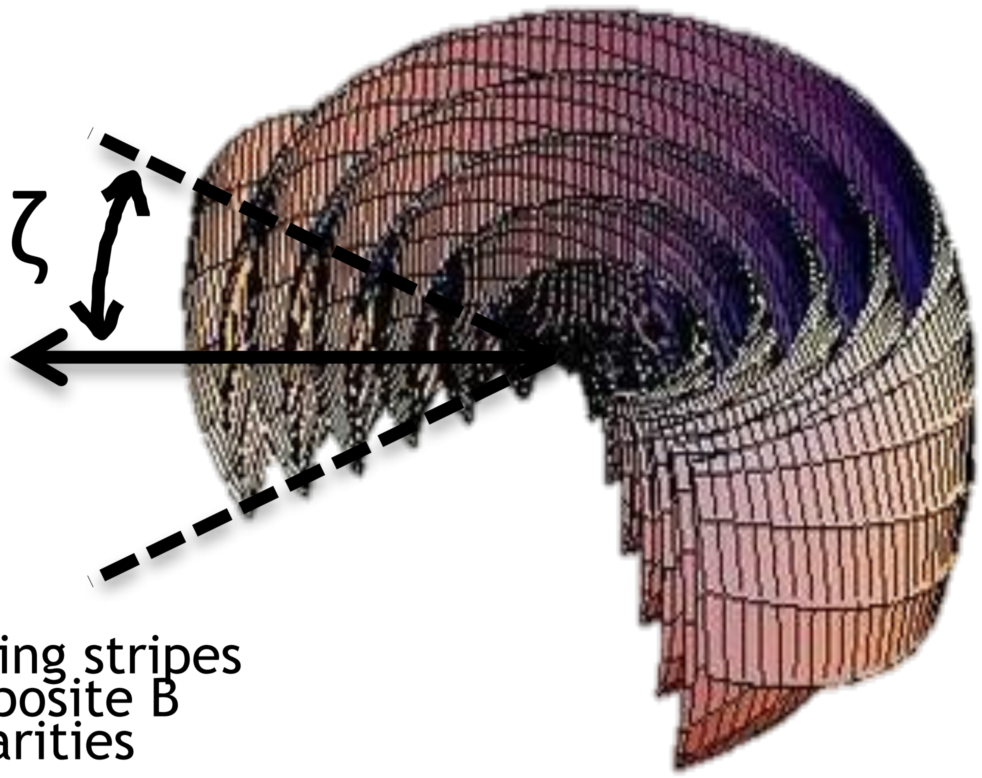
$$B(r,\theta) \propto \sqrt{\sigma}\,\mathcal{G}(\theta)\sin\theta$$

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]

THE NUMERICAL MODEL

MODEL PARAMETERS

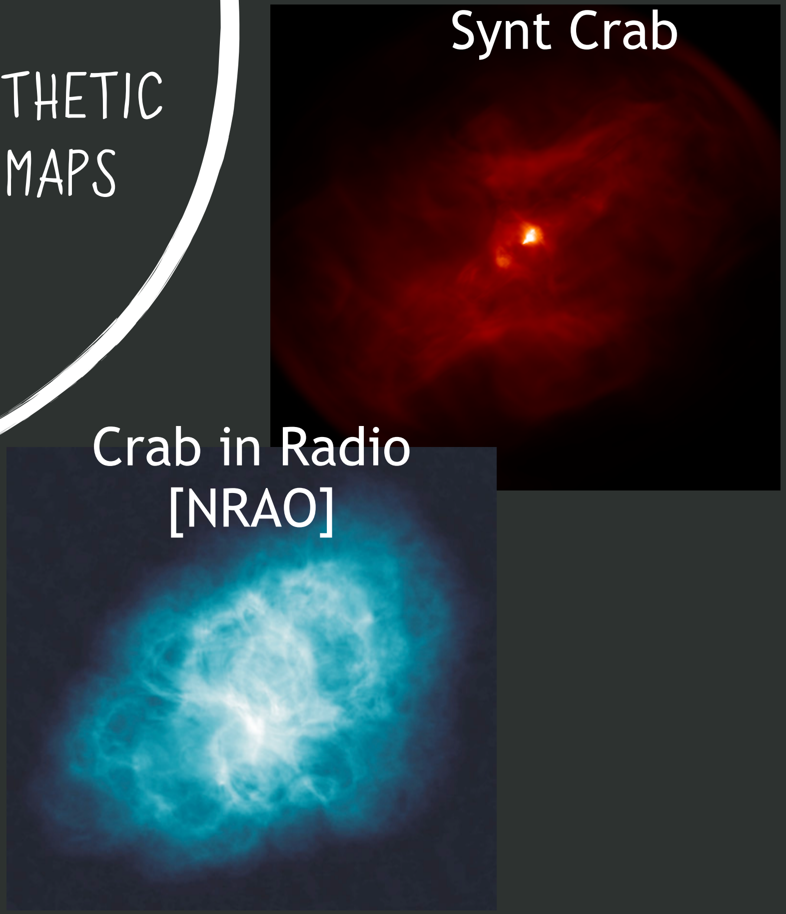
1 DEFINE A PW MODEL

2 SIMULATE THE SYSTEM UP TO FINAL AGE

OBTAIN SYNTHETIC EMISSION MAPS

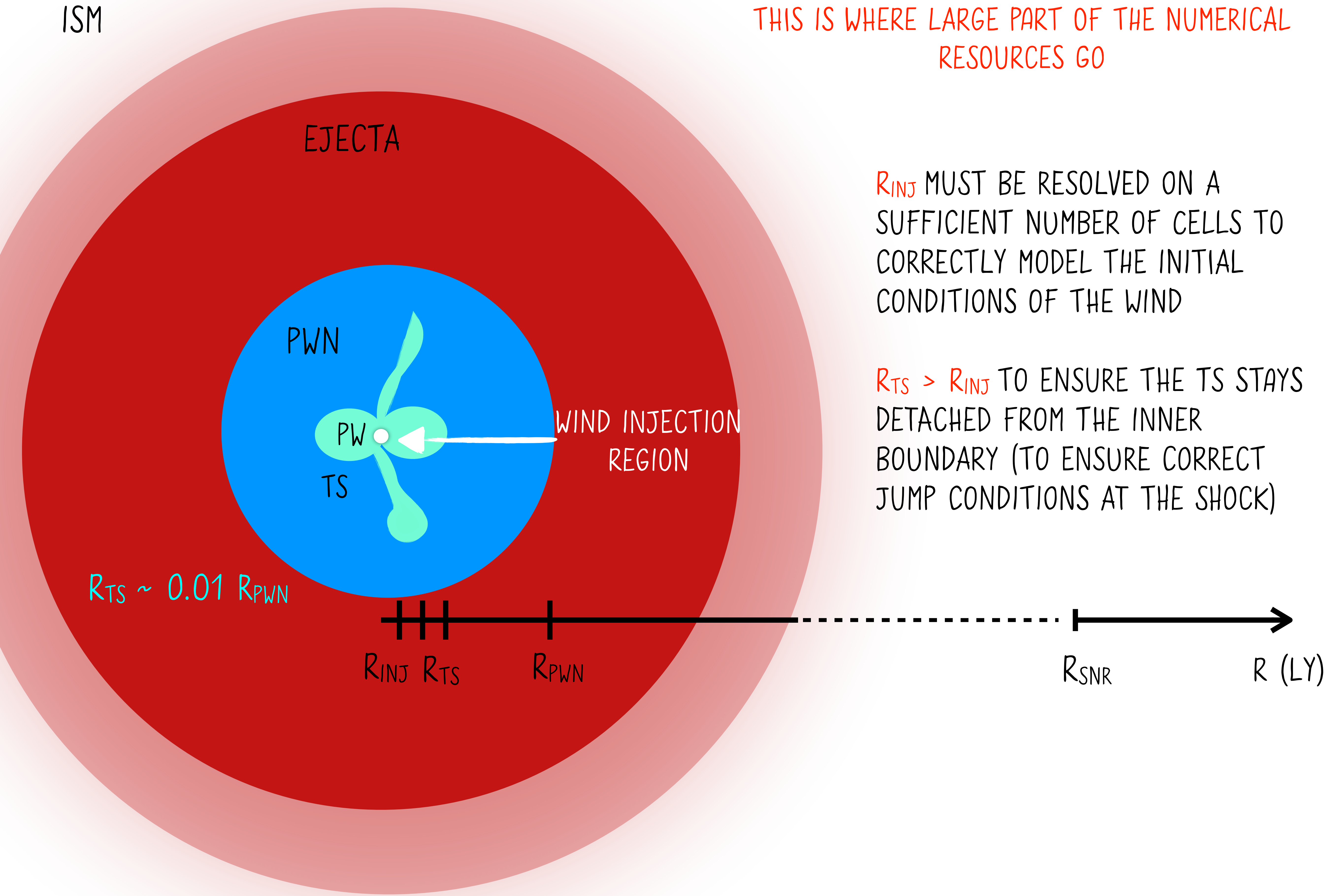
3 COMPARE WITH OBSERVED PROPERTIES

FIND THE BEST FIT PARAMETERS



SOLVE THE SCALES OF THE PROBLEM

THIS IS WHERE LARGE PART OF THE NUMERICAL RESOURCES GO

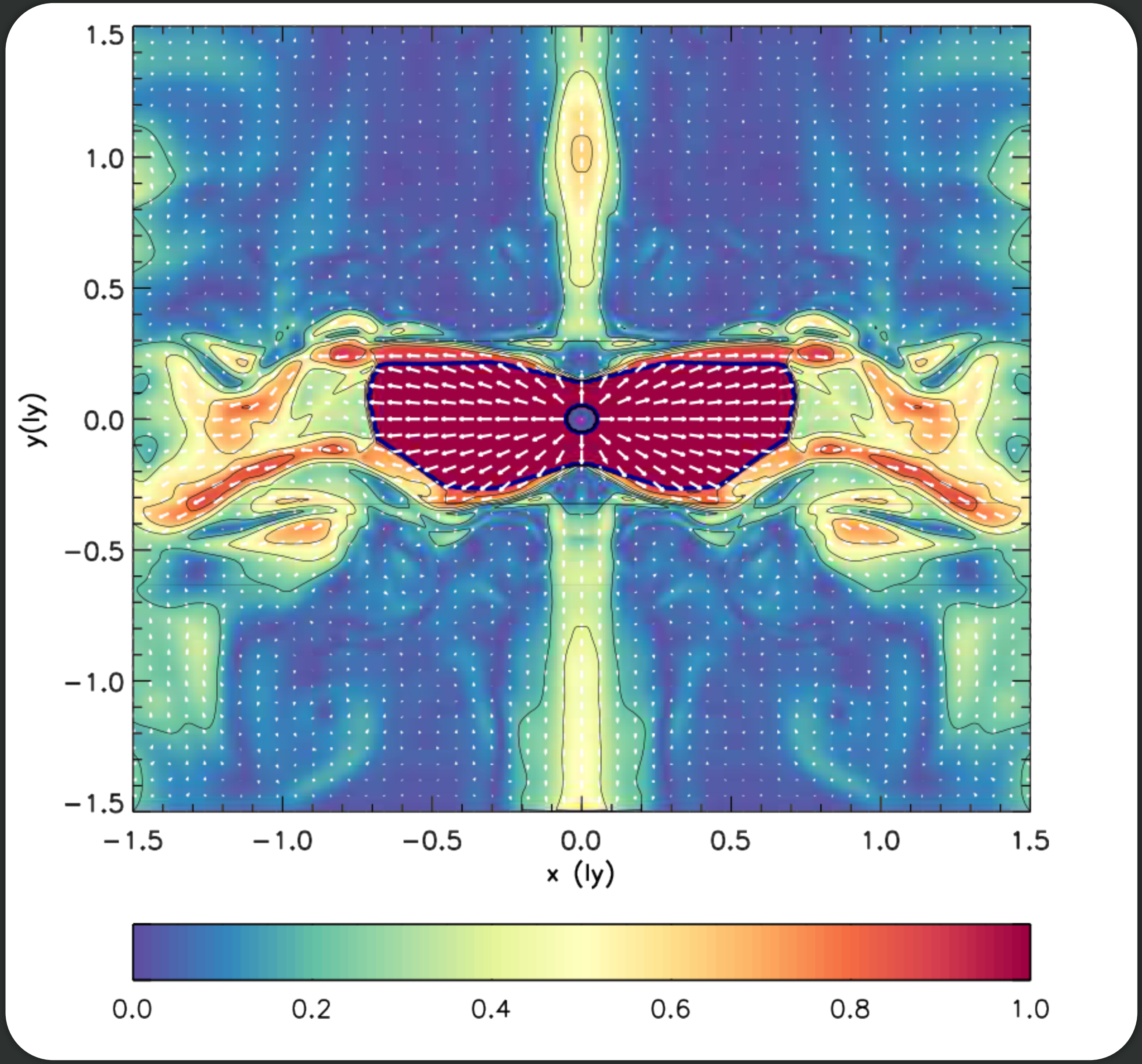


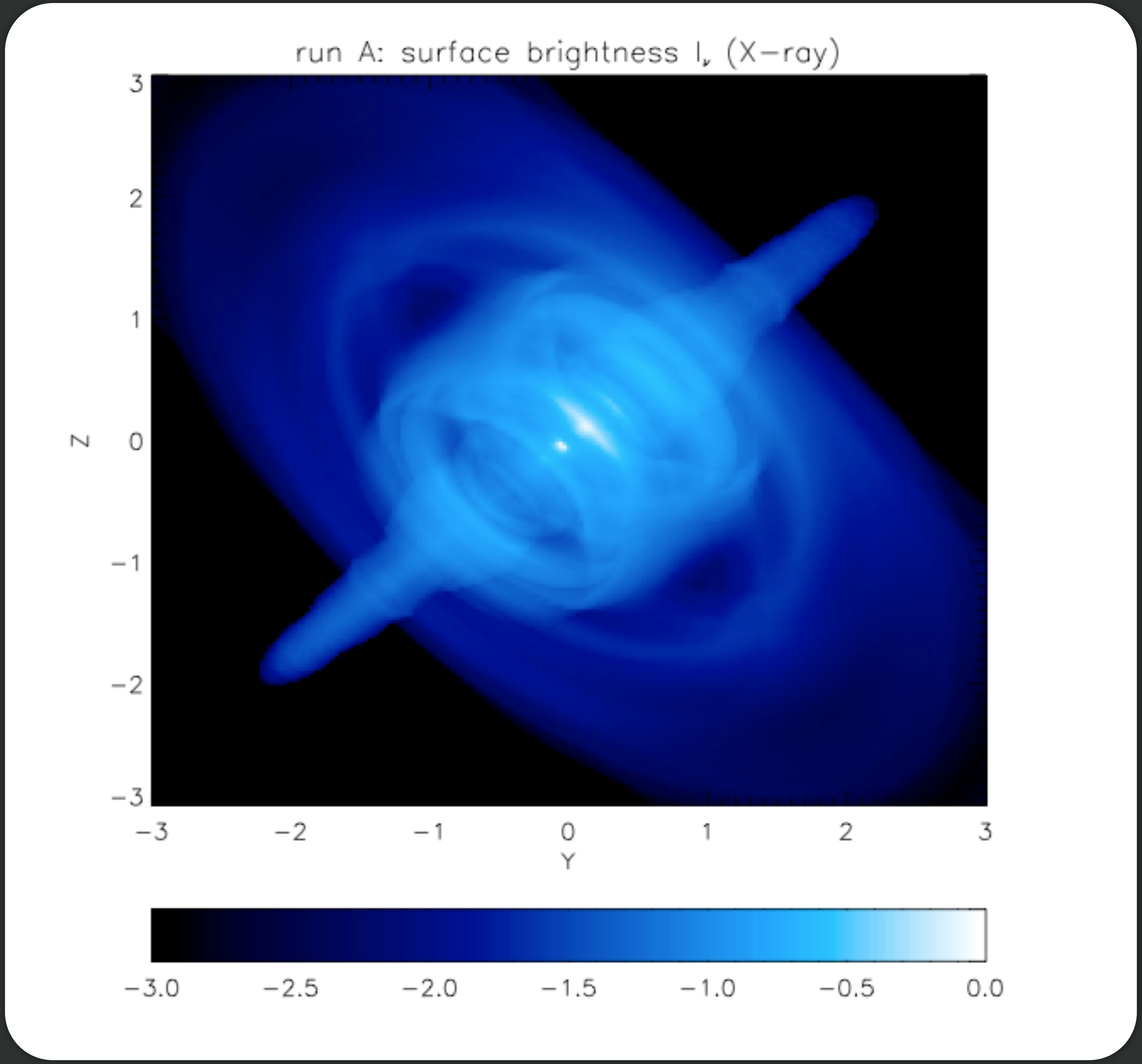
R_{INJ} MUST BE RESOLVED ON A SUFFICIENT NUMBER OF CELLS TO CORRECTLY MODEL THE INITIAL CONDITIONS OF THE WIND

$R_{TS} > R_{INJ}$ TO ENSURE THE TS STAYS DETACHED FROM THE INNER BOUNDARY (TO ENSURE CORRECT JUMP CONDITIONS AT THE SHOCK)

WHAT WE CAN REPRODUCE IN 2D: THE JET-TORUS

2D numerical models confirm the jet formation as consequence of the anisotropic wind magnetization must be above a threshold for the jets to collimate



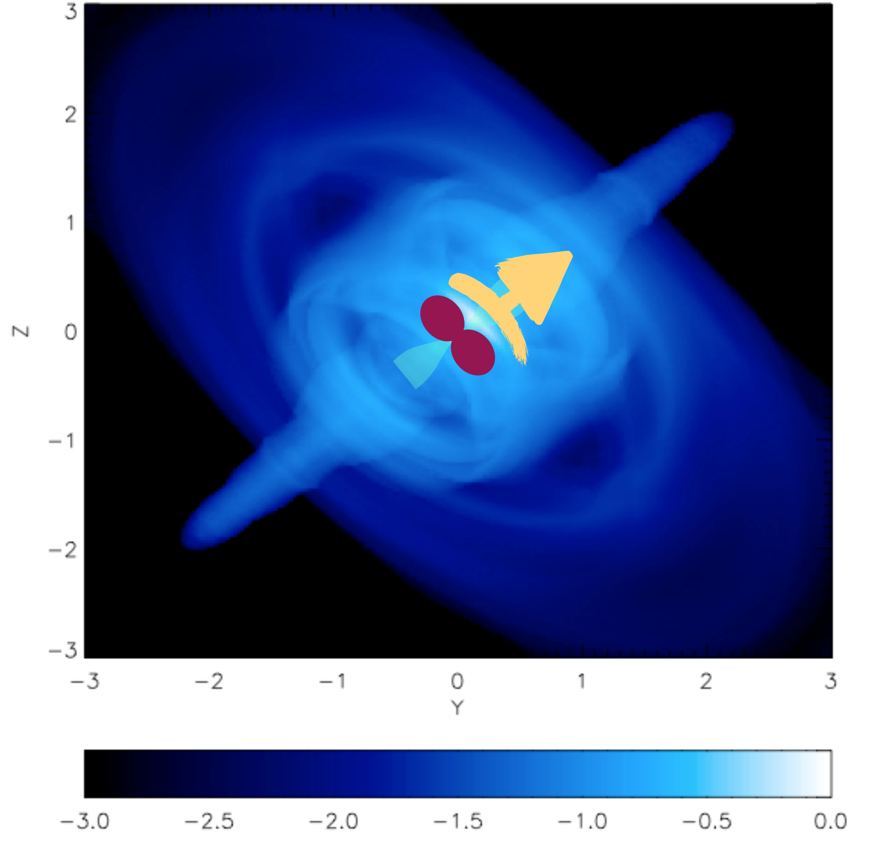


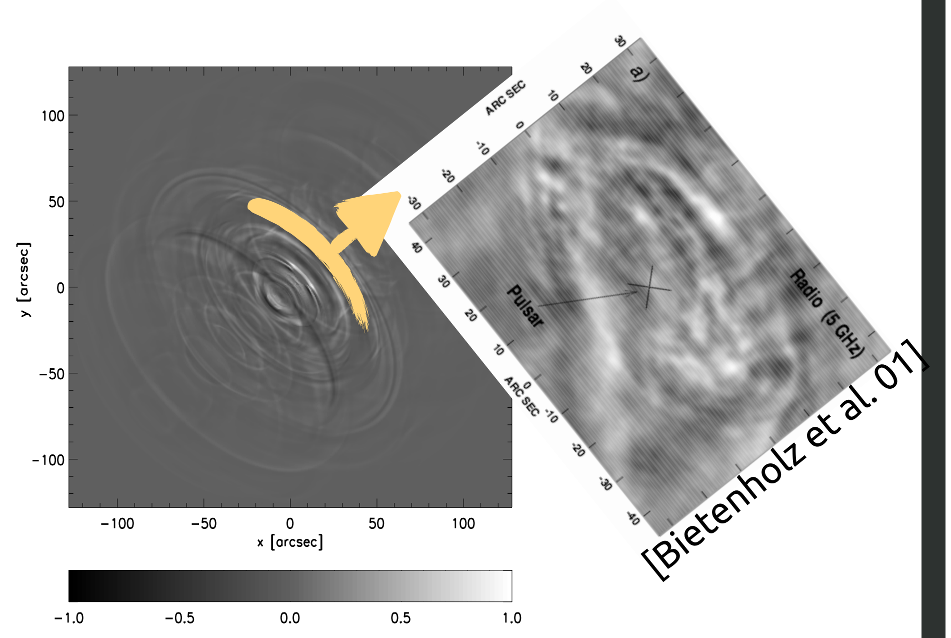
[Komissarov & Lyubarsky 2003-2004, Del Zanna et al. 2004]

WHAT WE CAN REPRODUCE IN 2D: THE JET-TORUS

CRAB INNER VARIABILITY

[Camus et al. 2009, Olmi et al. 2014]

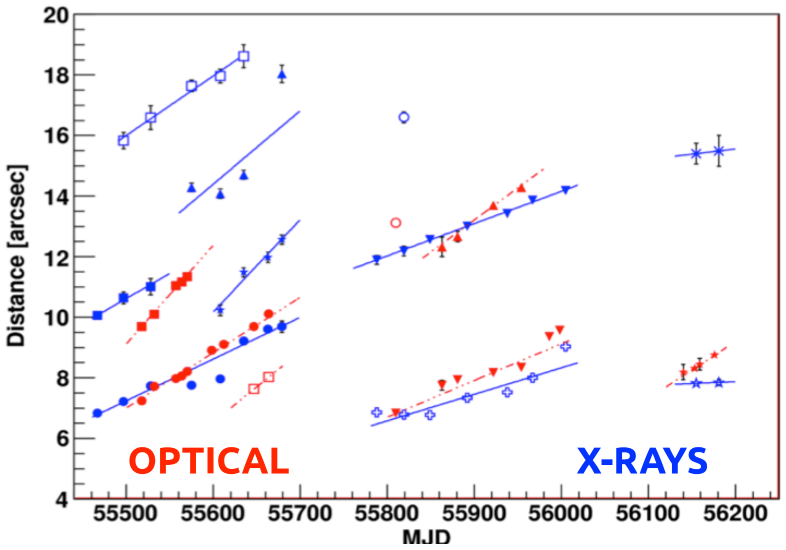




[Bietenholz et al. 01]

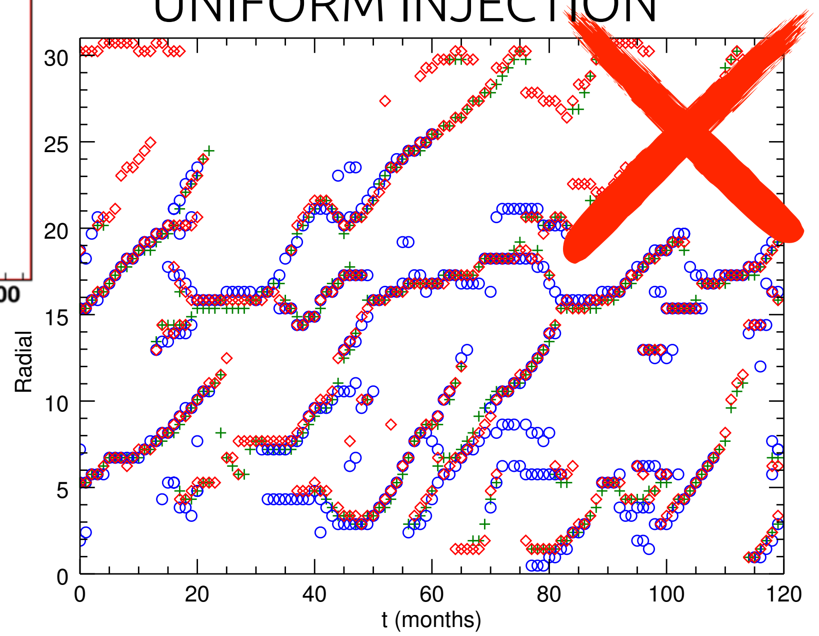
RADIO WISPs
[Olmi et al. 2014]

PROF OF INJECTION LOCATION/ACCELERATION MECHANISM

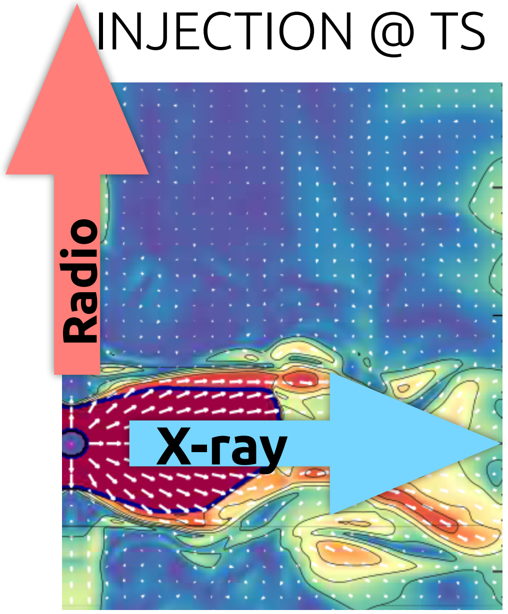


[Schweizer et al. 2013]

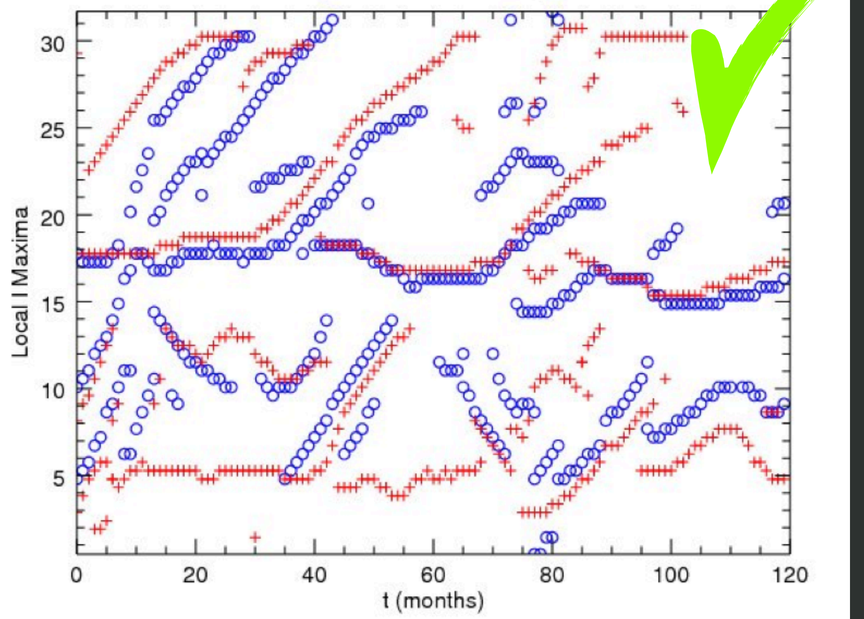
UNIFORM INJECTION



INJECTION @ TS



NON-UNIFORM INJECTION

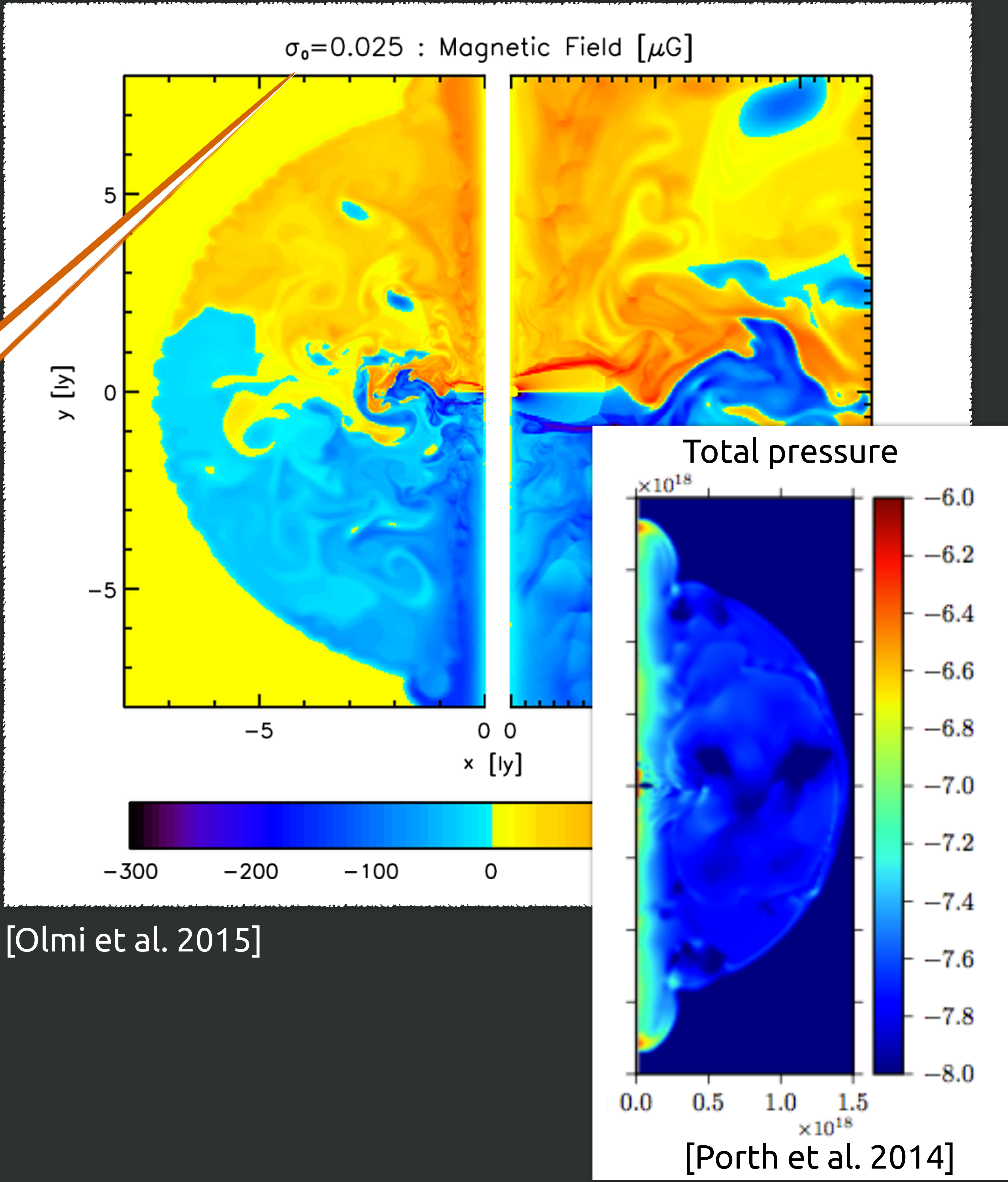


LIMITS OF THE 2D APPROACH

? 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

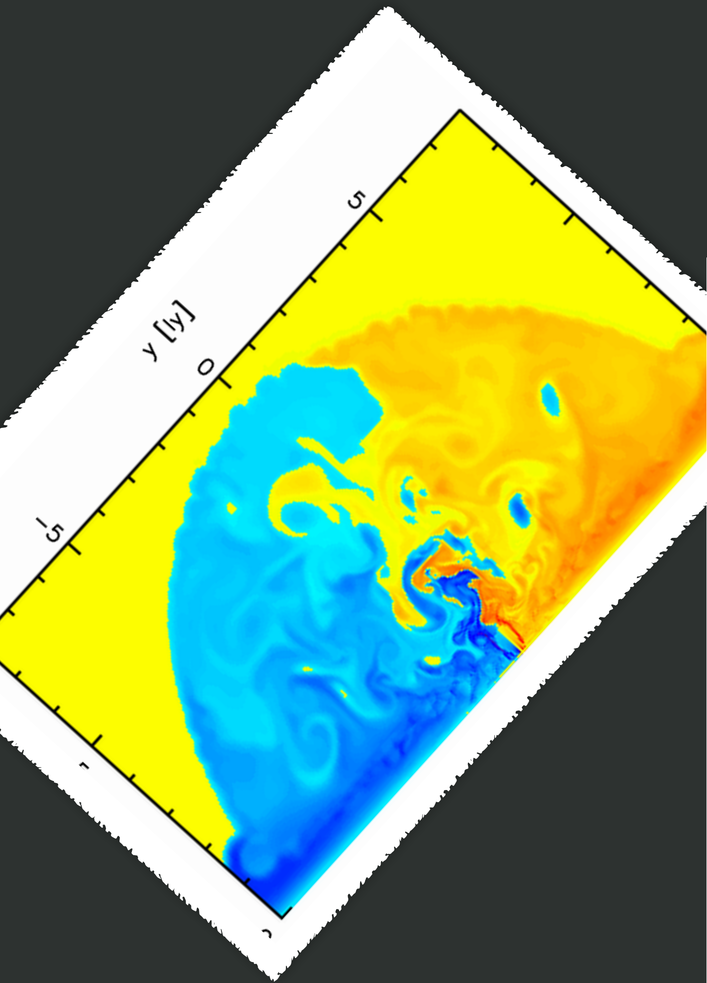


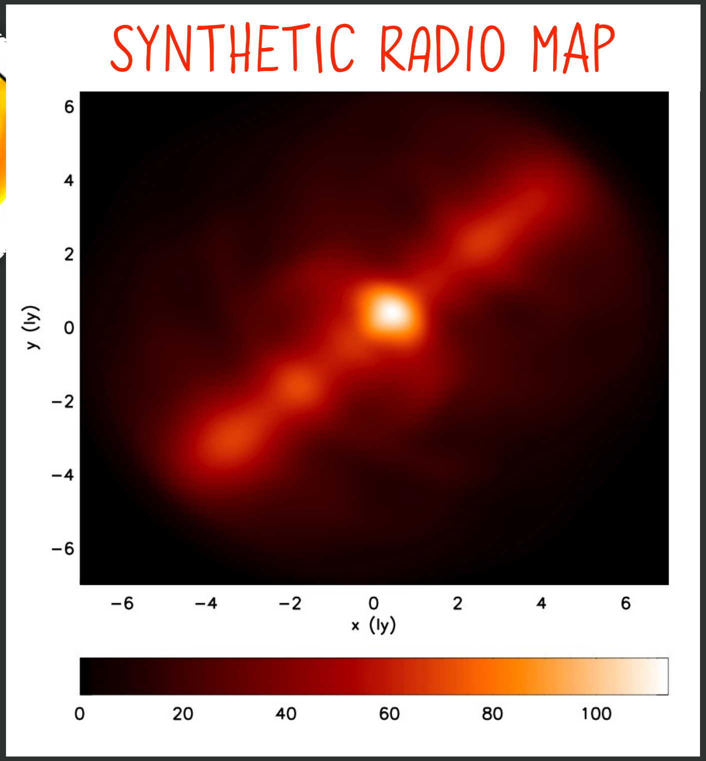
[Olmi et al. 2015]

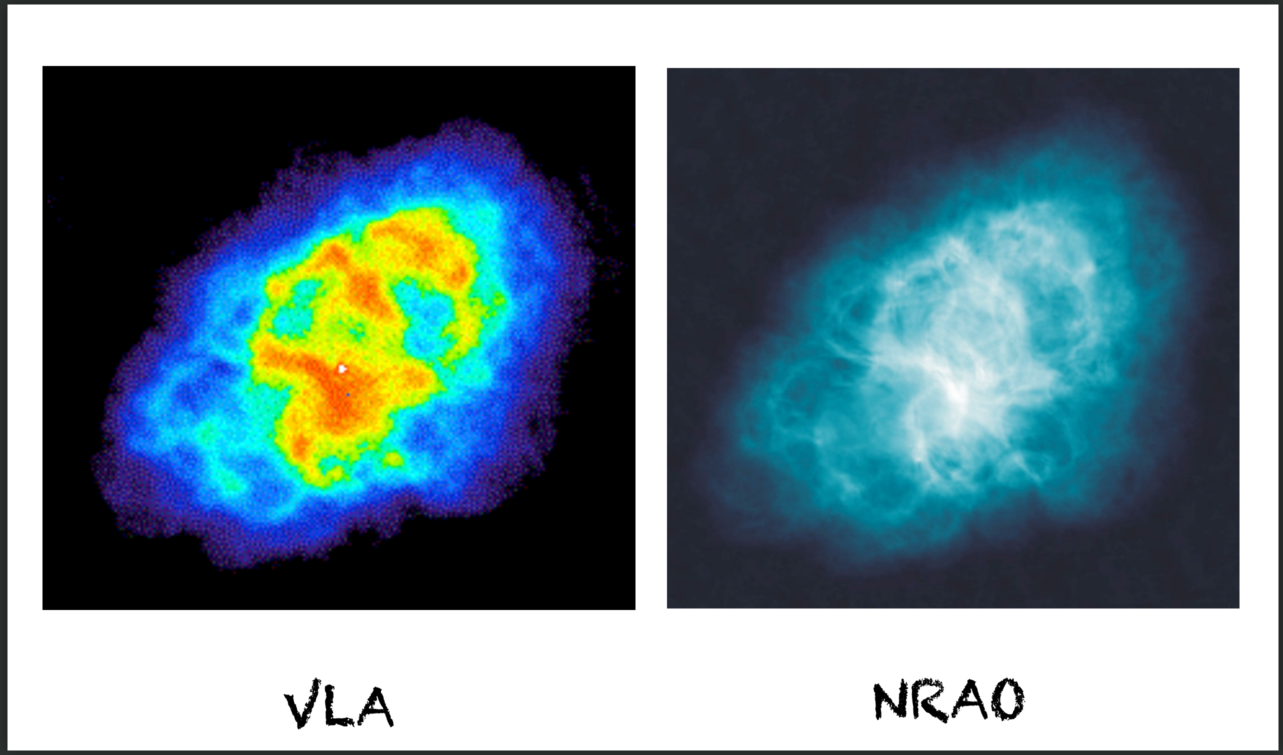
[Porth et al. 2014]

LIMITS OF THE 2D APPROACH

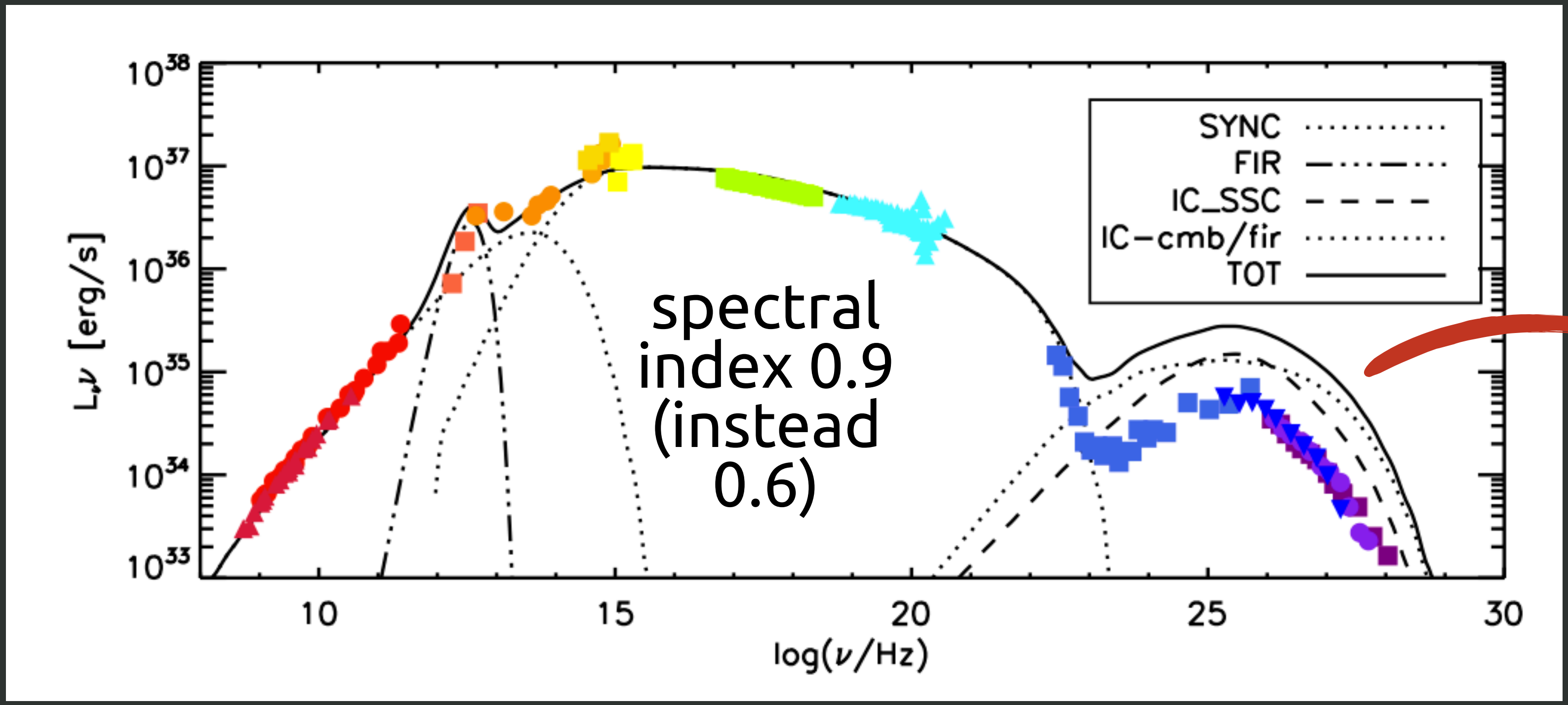
RADIO EMISSION IS NOT UNIFORM: TRACES THE FIELD COMPRESSION



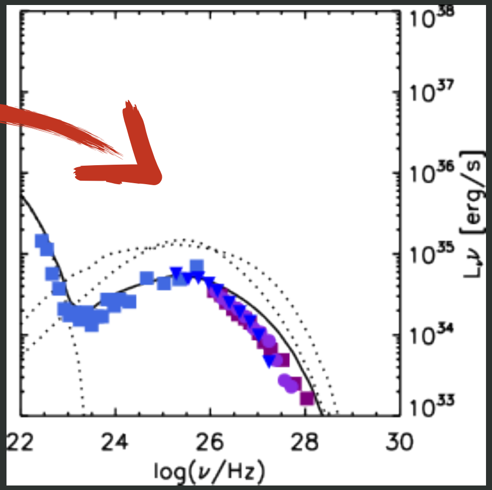

SYNTHETIC RADIO MAP



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

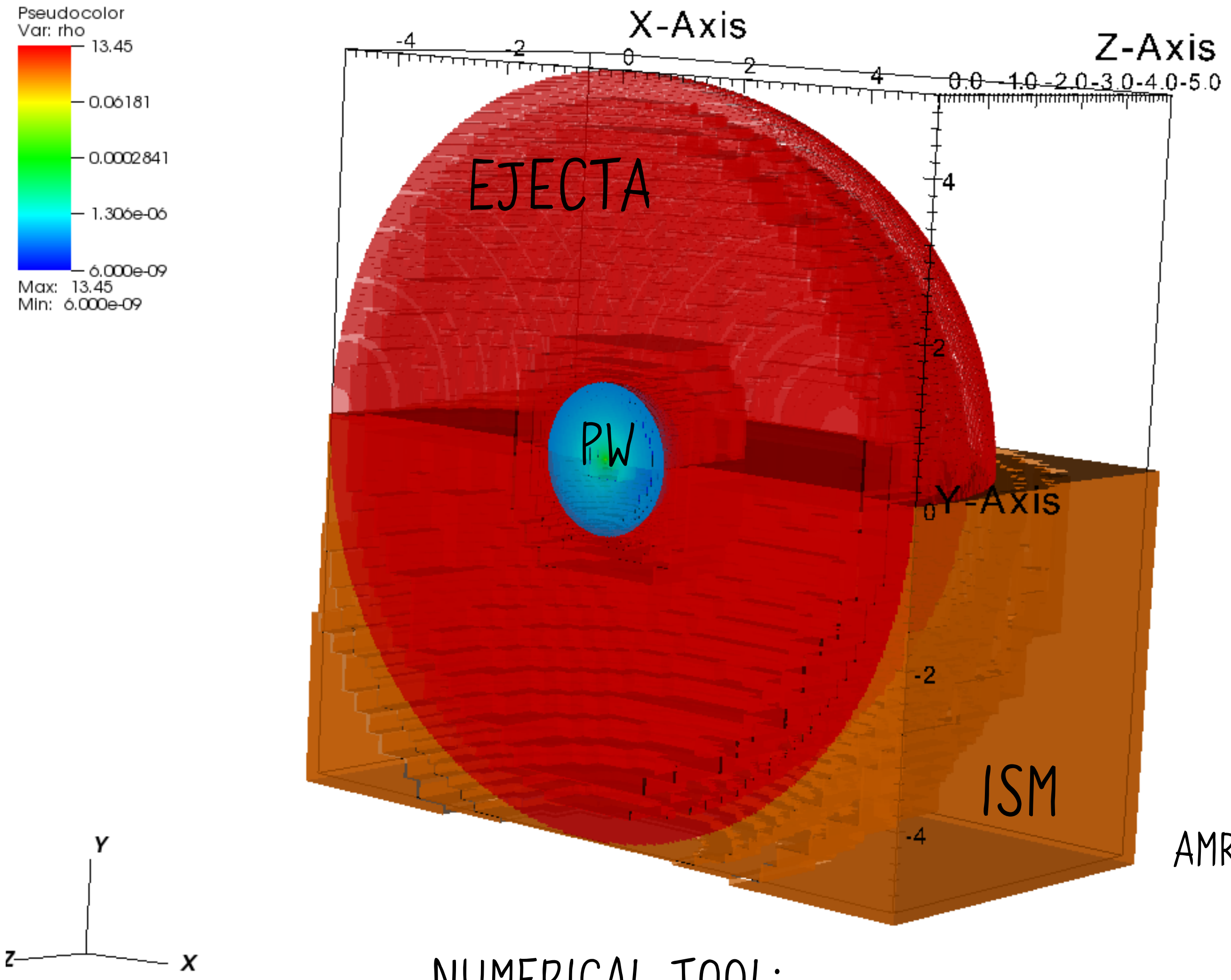


spectral index 0.9 (instead 0.6)



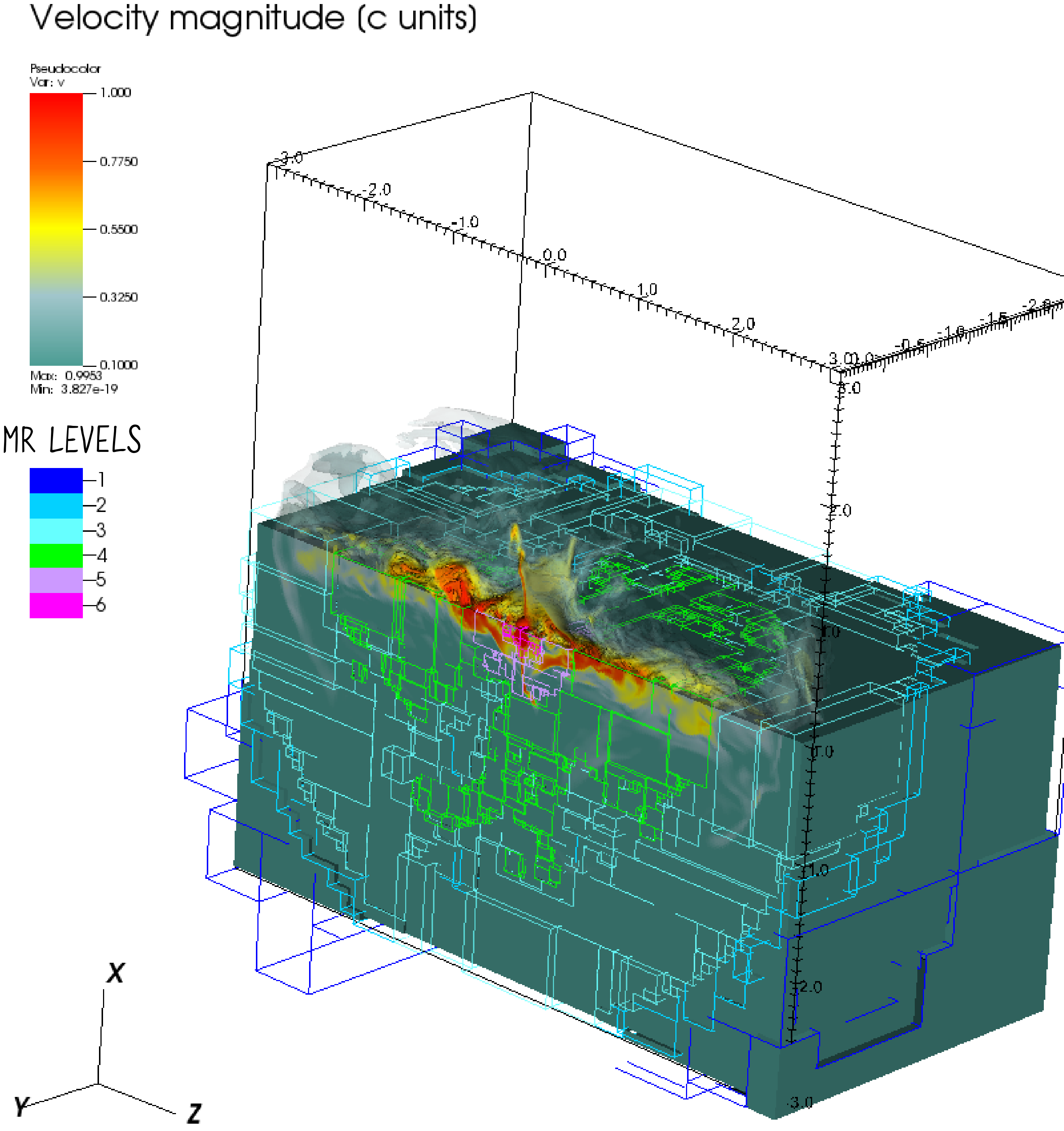
IC corrected to equipartition field

GOING 3D



NUMERICAL TOOL:
THE **PLUTO** CODE [MIGNONE ET AL.
2007-2012]

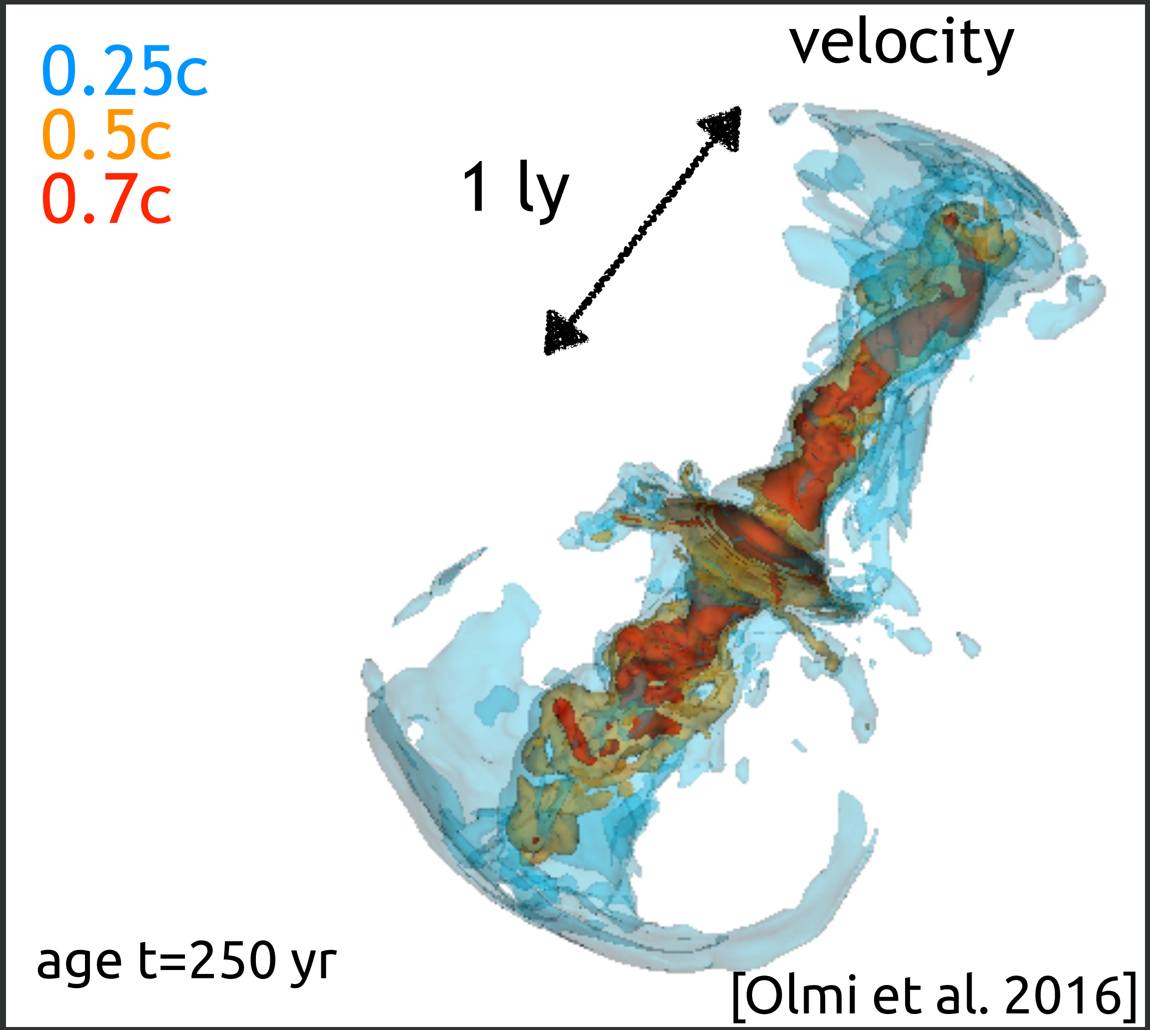
RESOLUTION REQUIREMENTS MAKE NECESSARY
TO USE AMR + MASSIVE HPC



BASE GRID: $[128]^3$
6 AMR LEVELS → EQUIVALENT GRID: $[8192]^3$

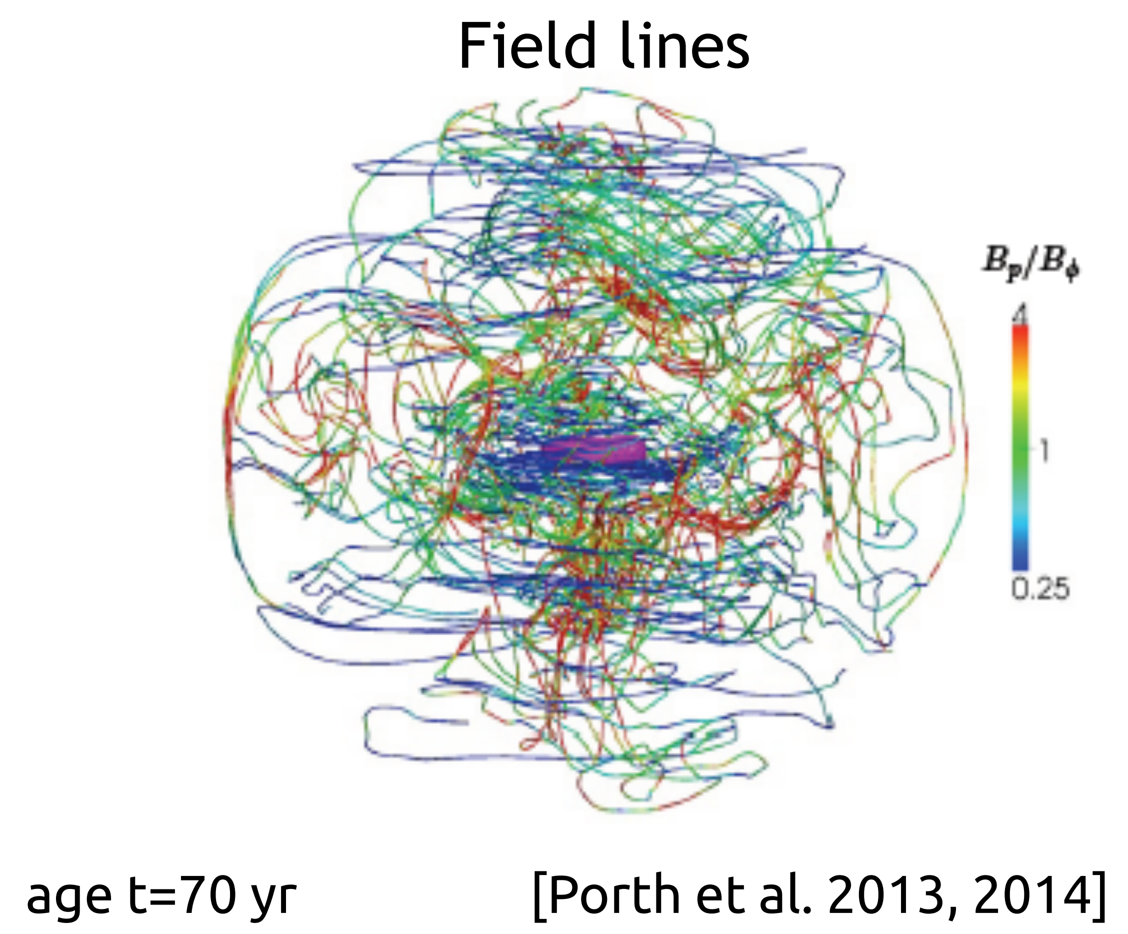
3D MHD MODELS

- ✓ 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!



age t=250 yr

[Olmi et al. 2016]



Field lines

age t=70 yr

[Porth et al. 2013, 2014]

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

⚠

3D SIMULATIONS ARE DEMANDING (RESOURCES, TIME, DATA STORAGE)

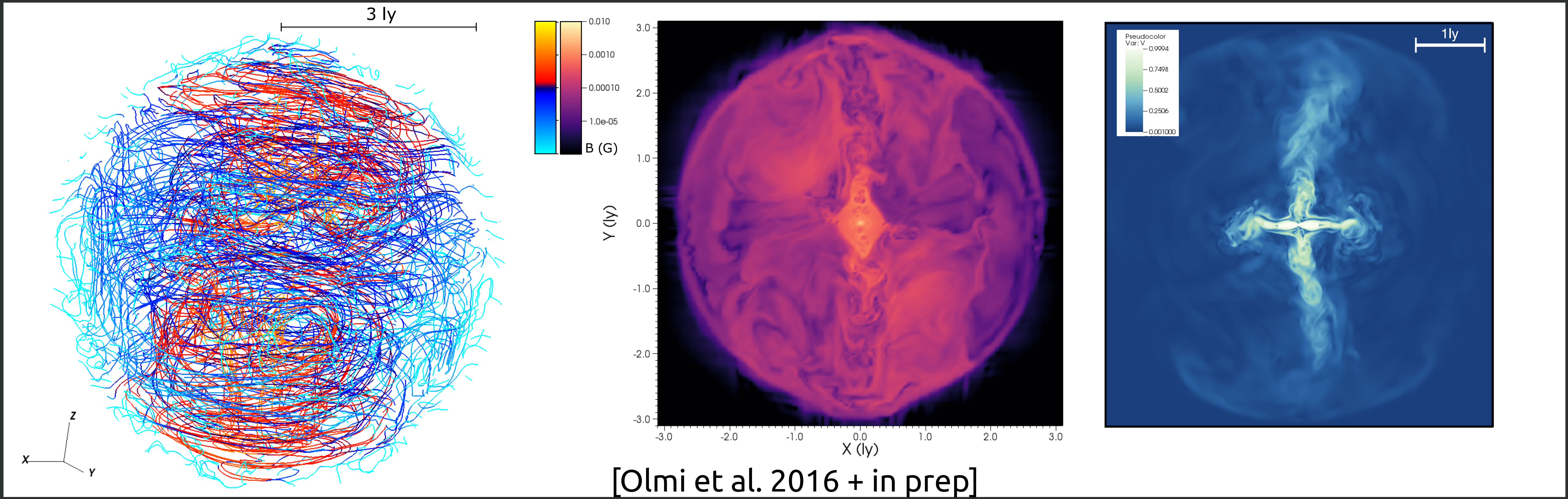
ONLY RUN FOR SELECTED OBJECTS + LIMITED EVOLUTION

NUMERICAL RESOURCES USED

ROUGH TOTAL OF 5 MILLIONS CPU HOURS

SEVERAL APPROVED NUMERICAL PROJECTS:

- 2 CLASS B PROJECTS IN THE MOU INAF-CINECA AGREEMENT [2019-2020]
- 1 ISCA B DEDICATED PROJECT [2016-2017]
- PARTIAL RESOURCES FROM A NON FULLY-DEDICATED ISCRA B [2015-2016]



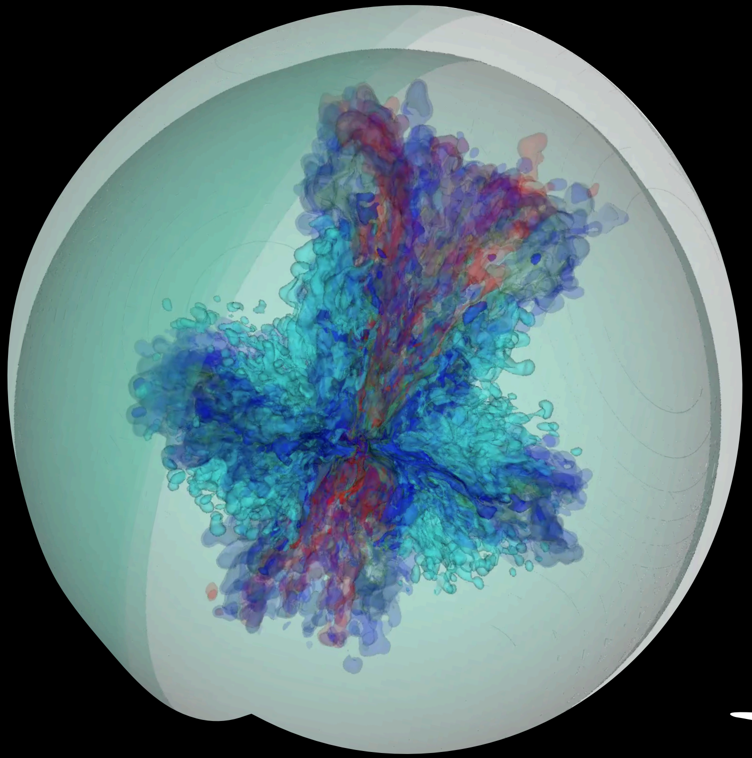
[Olmi et al. 2016 + in prep]

ONGOING RESEARCH

FIRST MODEL OF A PWN EVOLVING IN A REALISTIC / STRUCTURED SUPERNOVA REMANT

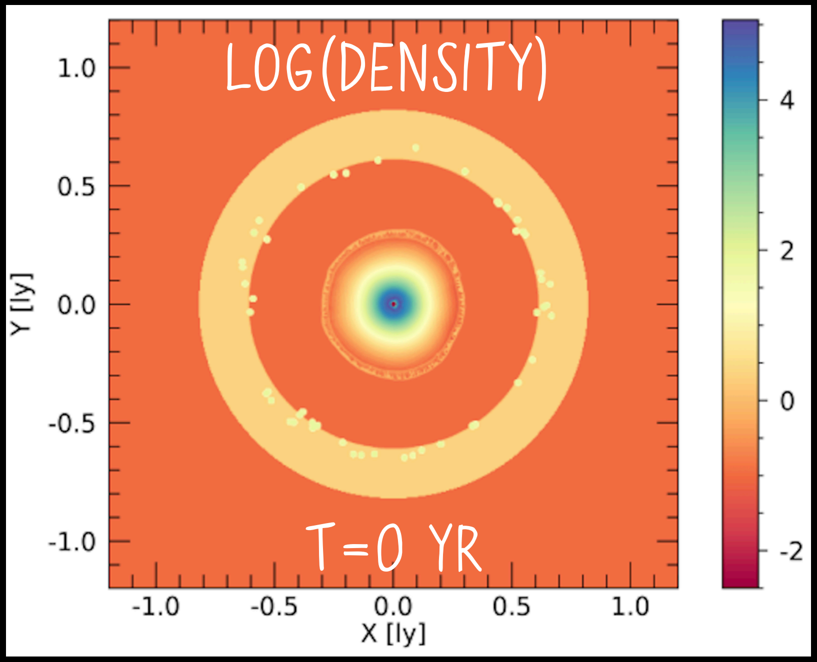
THE PROJECTS BRINGS TOGETHER STATE-OF-THE-ART MODELS DEVELOPED BY INAF RESEARCHER (OLMI -> PWN; ORLANDO -> SNR)

SIMULATIONS RUNNING AT THE OAPA HPC FACILITY MEUSA

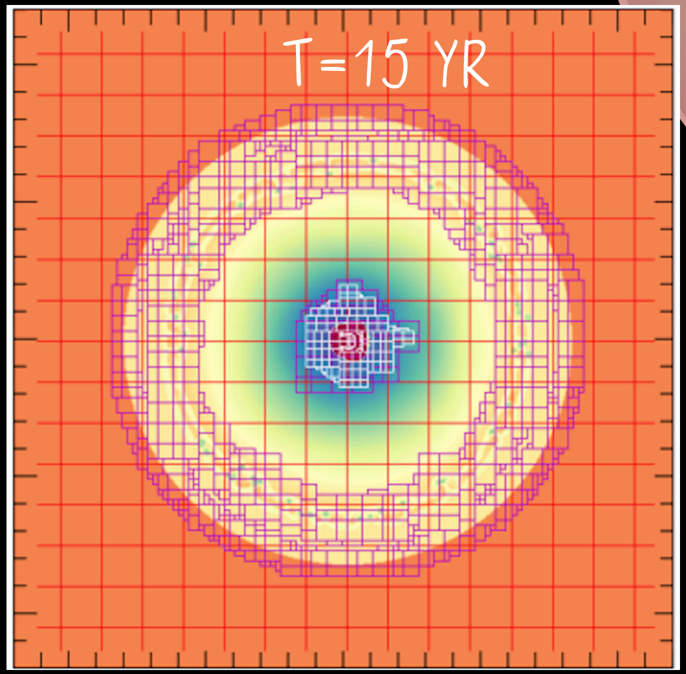


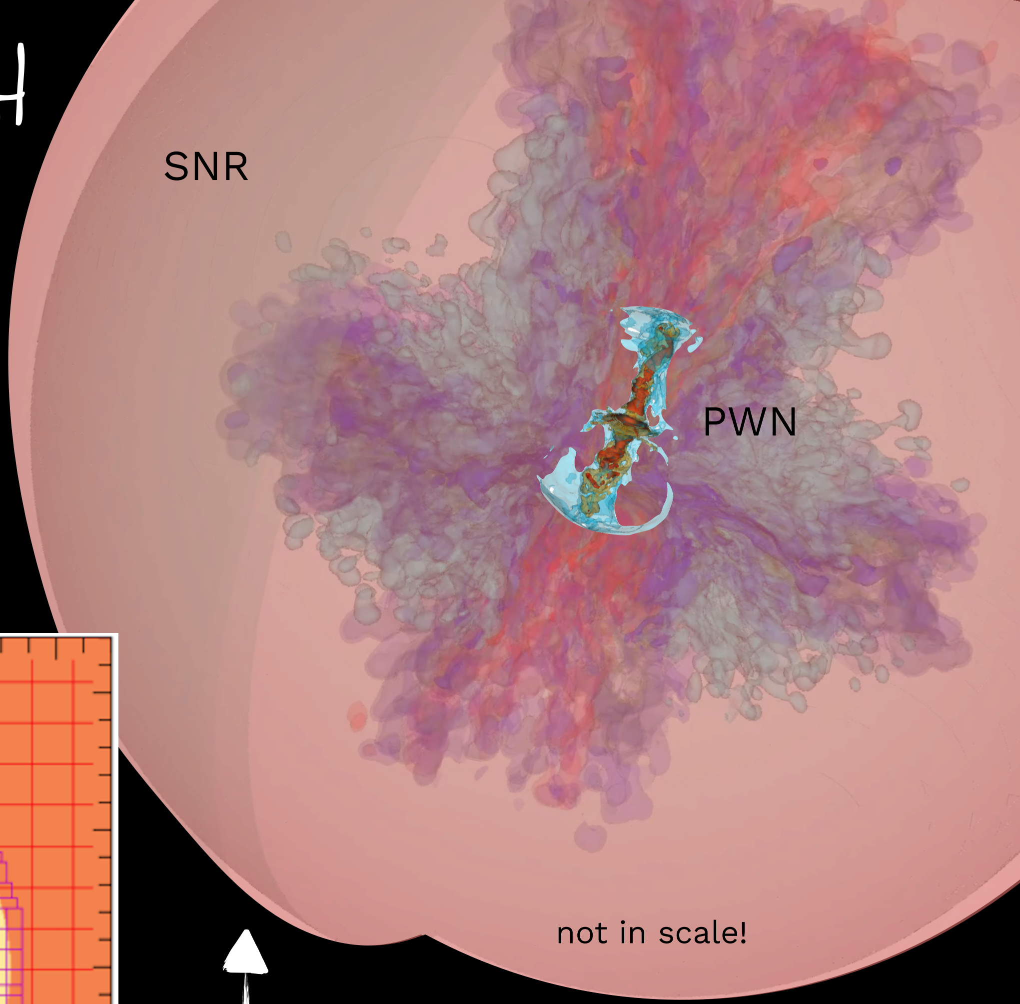
SNR 3D MHD SIMULATION

EXTRACT PROFILES OF PHYSICAL QUANTITIES



REGRID (AMR) AND EVOLVE





not in scale!

CONCLUSIONS

PWN ARE INTRINSICALLY 3D SYSTEMS: CORRECT MODELING OF THEIR ALL-SCALES PROPERTIES REQUIRE THE USE OF 3D RELATIVISTIC MHD NUMERICAL SIMULATION

HPC IS THE ONLY POSSIBILITY

RESOLVING THE VARIETY OF SCALES IN THE PROBLEM WITH PRESENT TOOLS MAKES MANDATORY THE USE OF ADAPTIVE MESH REFINEMENT TECHNIQUES

WITH PRESENT FACILITIES (AND NUMERICAL TOOLS) MASSIVE HPC IS THE UNIQUE WAY

WHAT'S NEXT?

- GPLUTO-> FAR FROM BEING USED FOR THIS SIMULATIONS
- GENERAL RELATIVISTIC PLUTO MAY OPEN NEW POSSIBILITIES THAT PERMIT A BETTER TREATMENT OF THE INVOLVED SCALES
- PLUTO PARTICLES + AMR?