Study of middle-aged Pulsar Wind Nebulae showing large offsets between their pulsar and their VHE Gamma-ray Emission

Michelle Tsirou* – Zakaria Meliani** – Yves Gallant*

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* : LUPM, Montpellier - France
** : LUTh, Paris - France

Pulsar wind nebulae

"Magnetised clouds of

ultra-relativistic accelerated e^- and e^+,

powered by the rotational energy of

their central pulsar"

- Magneto-hydrodynamic driven outflow :
  - magnetisation $\sigma \sim 0.01$
  - Lorentz factor $\gamma \sim 10^4 - 10^7$
  - adiabatic index $\Gamma = 4/3$
- Prone to synchrotron radiation + Inverse Compton scattering on CMB, FIR and NIR radiation fields

- Pulsar with an energy loss rate $\dot{E}$ that will decrease due to braking over time
- Based on a "conventional" pulsar spin down

  + dipolar constant B-field assumption

  → τ_{ch} sets an upper limit on

  the age of the system

H.E.S.S. Galactic Plane Survey

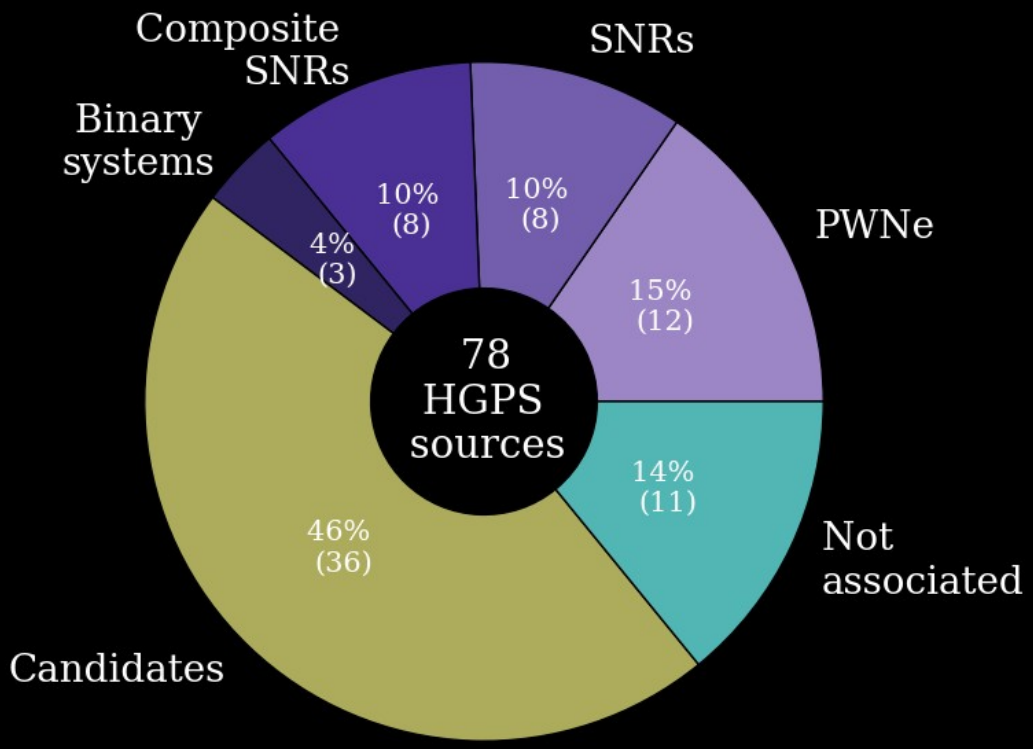
- 78 sources extracted from a homogeneous analysis

  in the Galactic plane region

- Population study of these TeV PWNe in companion paper

  (HESS Collaboration, 2018)

  → 14 **firmly identified** PWNe



Confirmed PWNe observed by H.E.S.S.

- 8 out of 14 PWNe show a **significant** pulsar-TeV emission offset

HGPS source name	d_{offset} (pc)	R_{PWN} (pc)	*ATNF* pulsar name	D (kpc)	τ_{ch} (kyr)	v_{PM} (km.s^{-1})	$\dot{E}_{\mathrm{sd}}$ (10^{36} erg.s^{-1})	B_{surf} (10^{12} G)	P (ms)
J1825-137	33.0 ± 6	32.0 ± 2.0	B1823-13	3.61	21.4	399	2.8	2.8	101.5
J1303-631	20.5 ± 1.8	20.6 ± 1.7	J1301-6305	10.72	11.0	-	1.7	7.1	184.5
J1837-069	17.0 ± 3	41.0 ± 4.0	J1838-0655	6.6	22.7	-	5.6	1.9	70.5
J1418-609	7.3 ± 1.5	9.4 ± 0.9	J1418-6058	1.89	10.3	-	4.9	4.4	110.6
J1356-645	5.5 ± 1.4	10.1 ± 0.9	J1357-6429	3.1	7.3	-	3.1	7.8	166.1
J1420-607	5.1 ± 1.2	7.9 ± 0.6	J1420-6048	5.63	13.0	-	10.4	2.4	68.2
J0835-455	2.37 ± 0.18	2.9 ± 0.3	B0833-45	0.28	11.3	77	6.9	3.4	89.3
J1514-591	< 4.0	11.1 ± 2.0	B1509-58	4.4	1.6	-	17.5	15.4	151.3

Physical drivers of PWN asymmetry

Deformation of the nebula

may be possibly caused by :

- Pulsar wind asymmetric outflow
- B-field topology

  (Reynolds et al. 2012)
- Asymmetric explosion → kick of the pulsar

  (Gaensler et al, 2006)
- Inhomogeneous ambient medium

  (*Blondin et al., 2001 ; Temim et al. 2015 ; Slane et al. 2018*)

Yield an asymmetric morphology of the pulsar wind nebula

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Offset of the TeV emission centroid

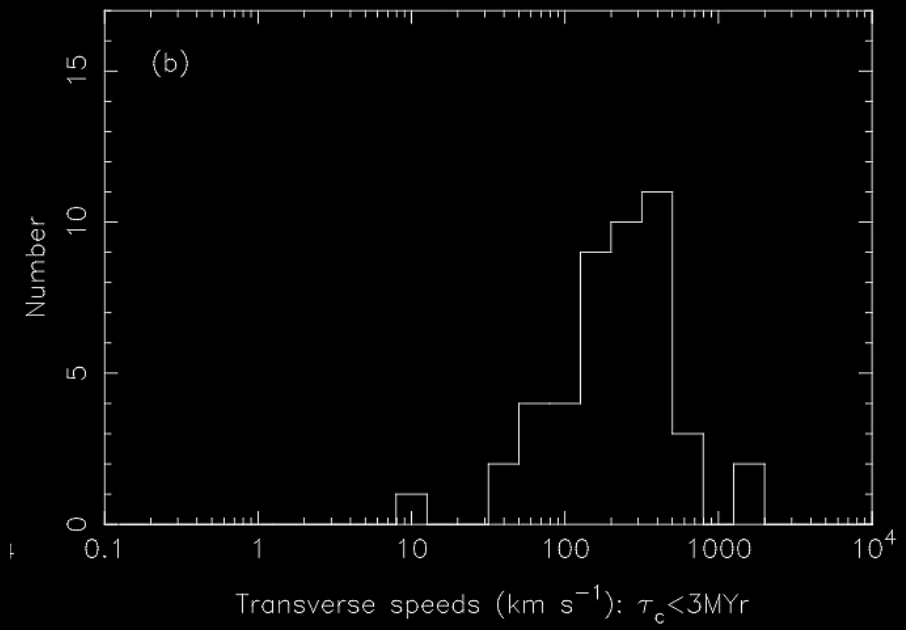
in respect to

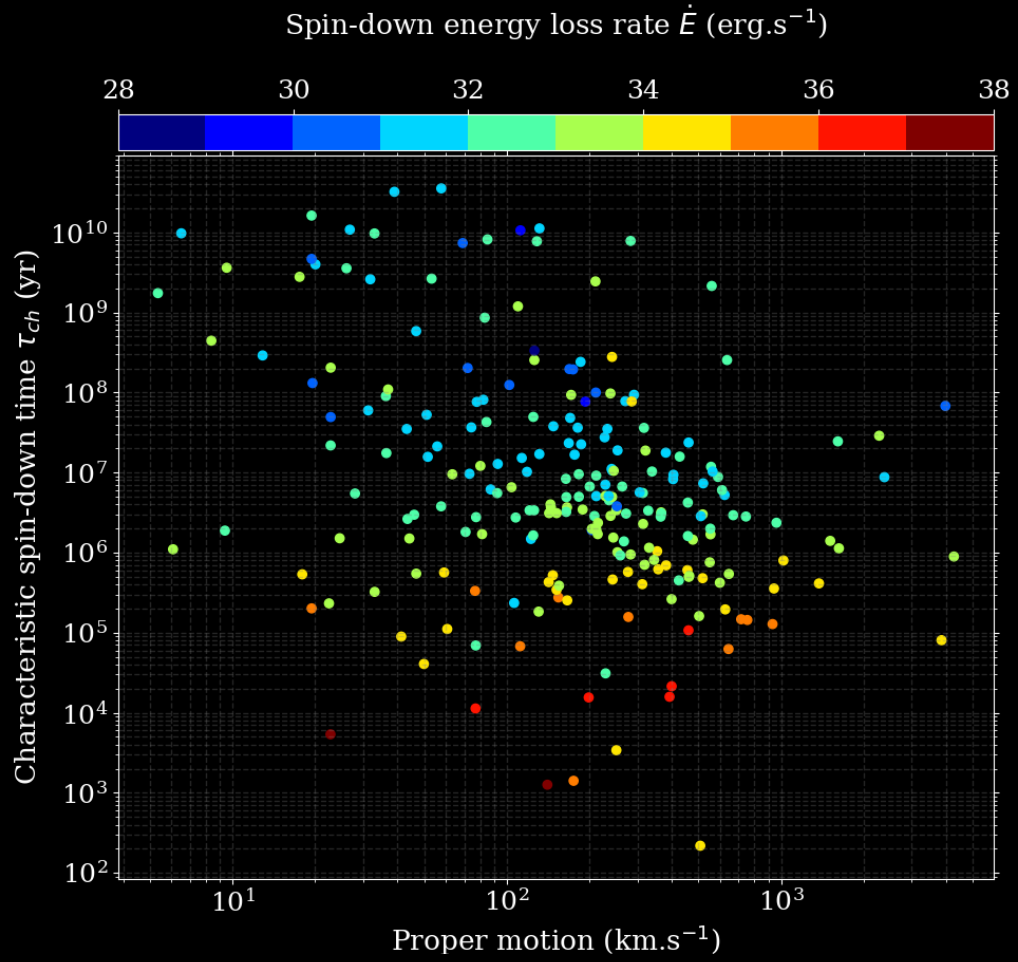
the pulsar position

Pulsar proper motion

- In Hobbs et al. (2005),

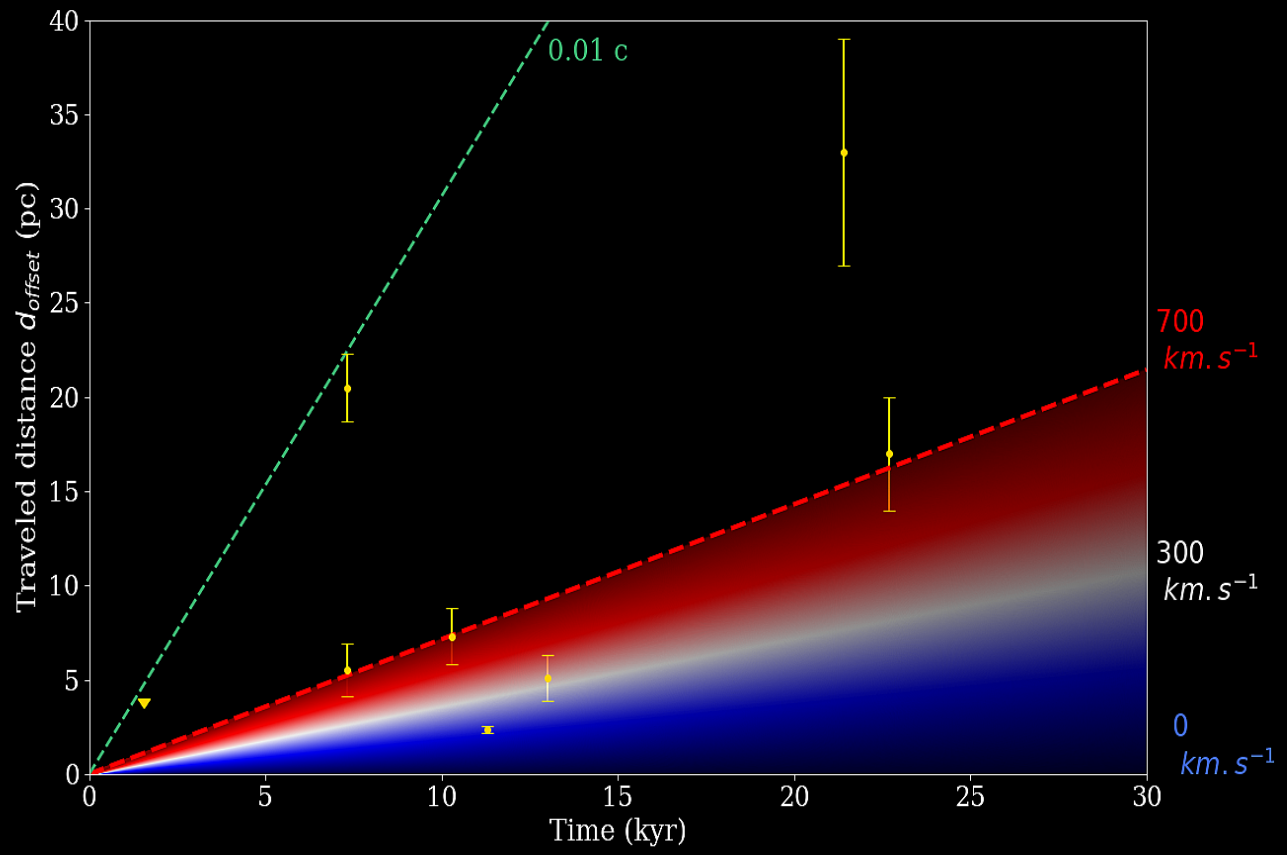
  2D $\langle v_{PM} \rangle$ 307 ± 47 km.s^{-1}





Pulsars from the ATNF catalogue with P > 10 ms

Expected proper velocities to explain offset



6 out of the 8 significantly offset PWN sub-sample

would require to have a pulsar proper motion

v_{PM} > 500 km.s^{-1}

→ can this PM effect

+ heterogeneous ISM

describe the observed offset scales?

Simulating composite systems

- Simulations done with MPI-AMRVAC 2.0 :

  MPI - Adaptive Mesh Refinement Versatile Advective Code

- Use of a relativistic MHD physics module applied in an adaptively refined/coarsened grid

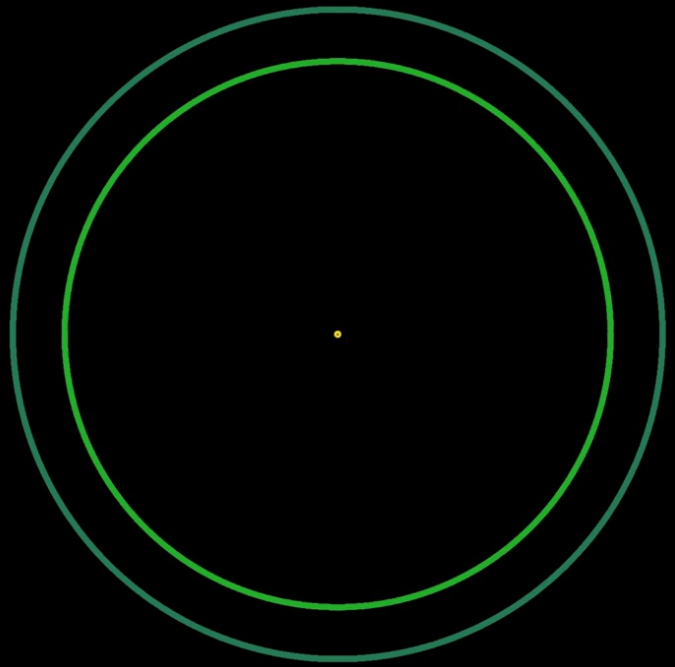
Why?

→ **multi-scale evolving system** of :

- The pulsar wind (PW)
  → size determined by its termination shock (TS)
- The pulsar wind nebula (PWN),
  → region defined by the TS up to the expansion region of the shocked outflow bubble
- The supernova remnant (SNR),
  → forward shock (FS) towards the ISM + reverse shock (RS) inwards the nebula

Simulating composite systems

Illustration of the system radii evolution with time in the rest frame of the SNR FS travelling in the ISM, up until the RS reaches the PWN
→ free expansion in an ejecta dominated phase



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Relativistic hydrodynamic simulations : 1D set-up

- Grid size = 6.10^{19} cm (~19.5 pc),

  96 grid cells → grid block resolution of 8 cells at level 1 of refinement (base grid) ,

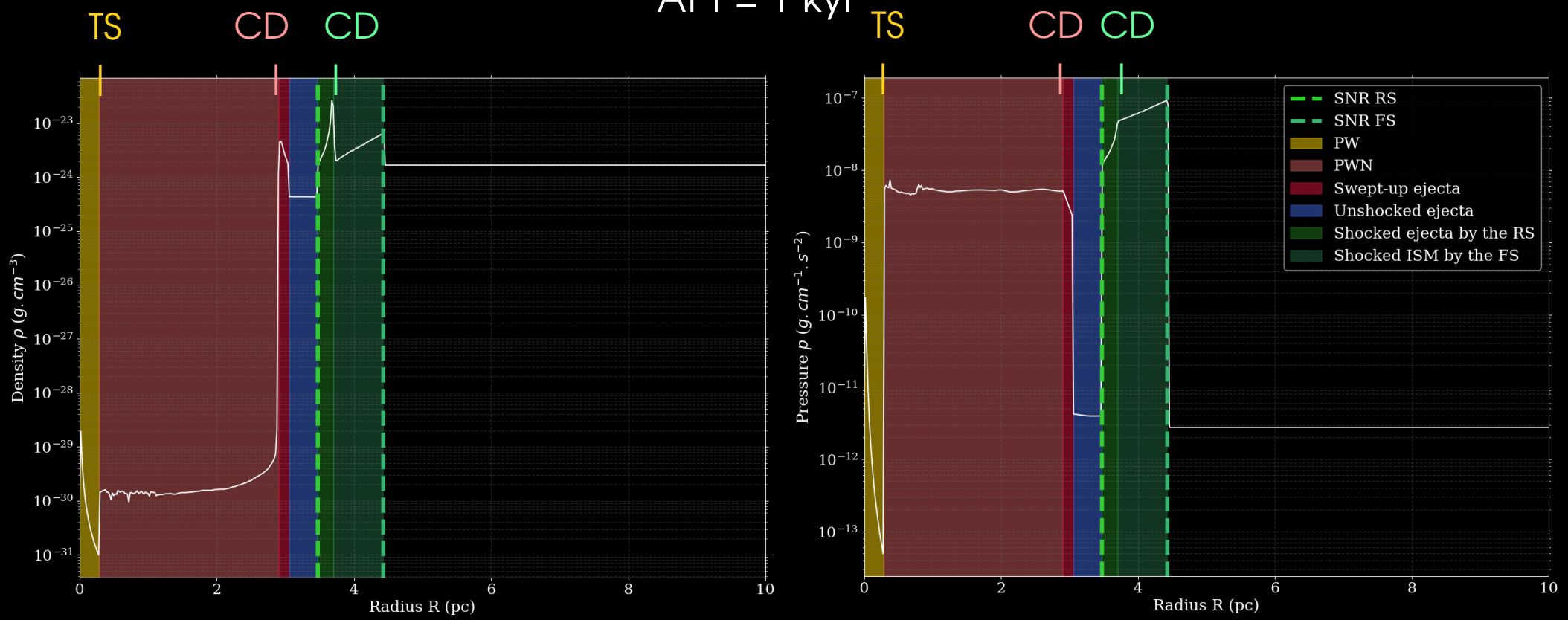
  total maximum number of grid levels set manually for each ROI

- ISM : n_0 = 1.0 cm^{-3}, T = 10^4 K
- SNR : $t_{start\ sim}$ = 80 yrs, E_{SN}= 3.10^{51} erg, M_{ej}= 5 $M_\odot$, $v_{ej,\ max}$ = 5 700 $km.s^{-1}$ (E_{kin} ~97 % E_{SN})
- PW : $\dot{E}$ = 5.10^{38} $erg.s^{-1}$, $t_{after\ start\ sim}$ = + 20 yrs, Lorentz γ = 10
- Pulsar : (R_{PSR} = 10 km, M_{PSR} = 1.5 $M_{\odot 0}$) , P_0 ~ 33 ms , braking index n=3

Relativistic hydrodynamic simulations : evolution

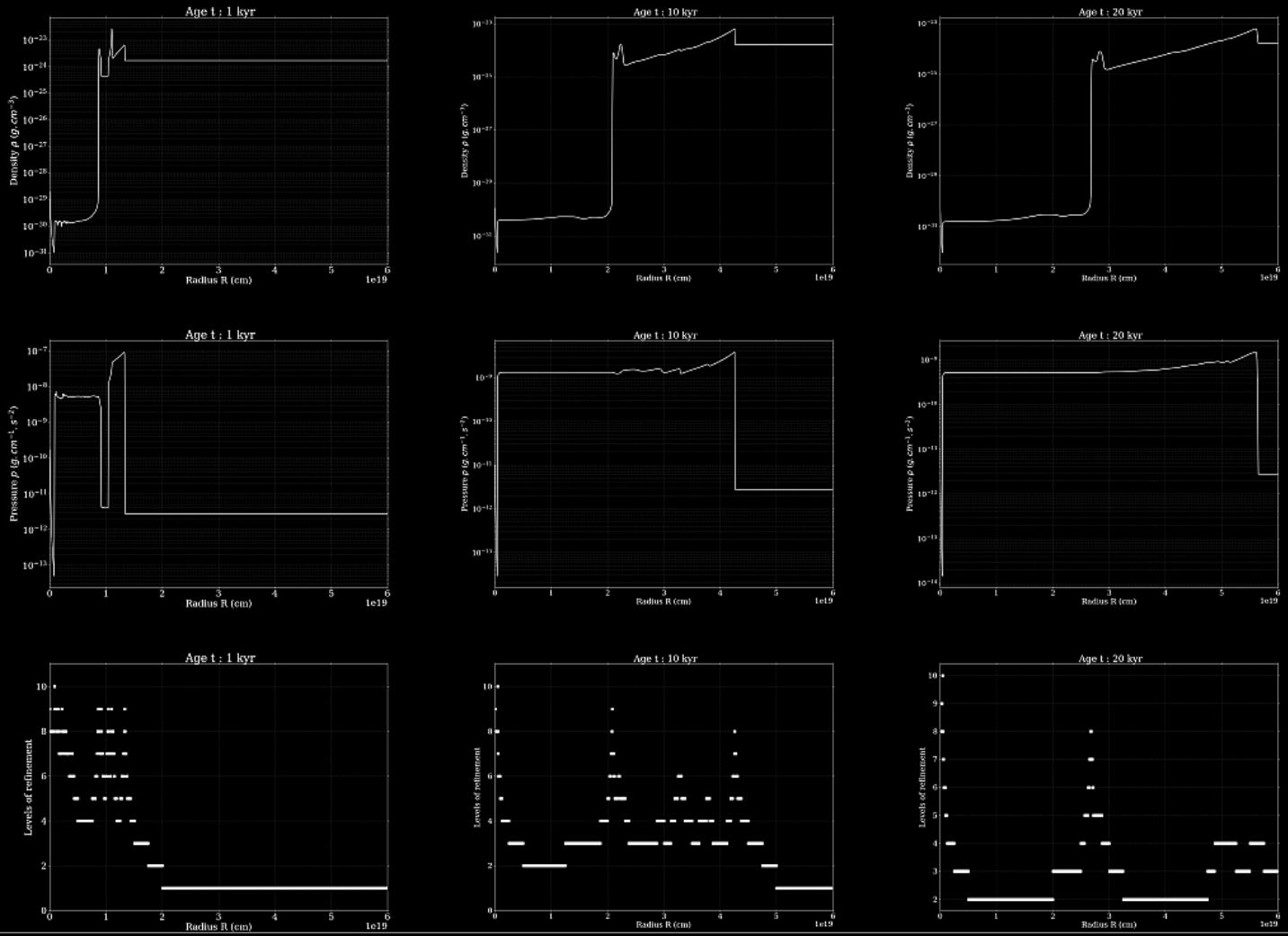
Relativistic hydrodynamic simulations : free expansion

At t = 1 kyr



CD : contact discontinuity

Relativistic hydrodynamic simulations : evolution



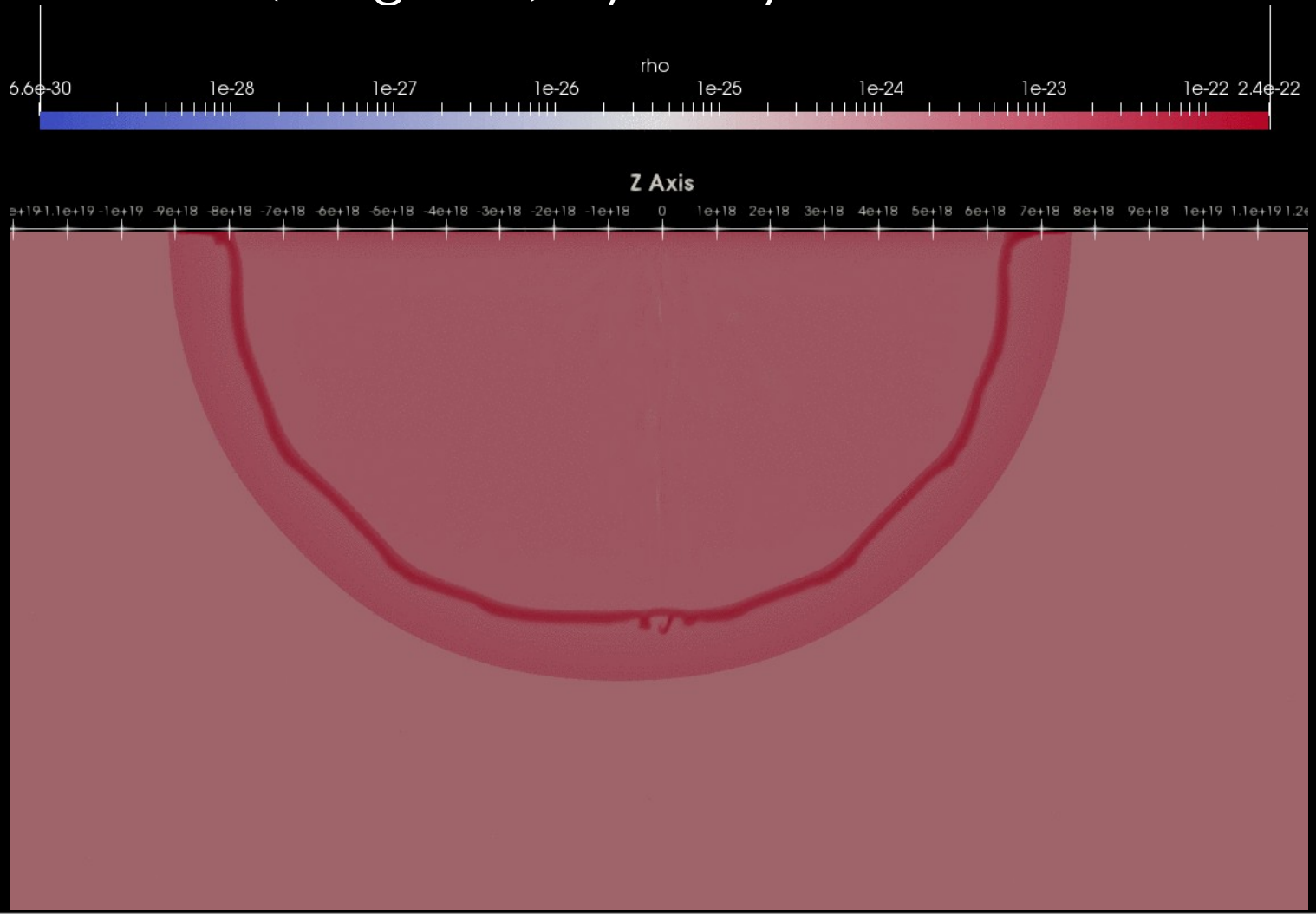
Towards a relativistic (magneto)-hydrodynamic 2D framework

- Ongoing tests on 2D HD simulations with :
  - Grid size = $1.2 \cdot 10^{20}$ cm (~40 pc),
  - 96 x 192 grid cells → grid block resolution of 8 cells at level 1 of refinement (base grid) ,
  - total maximum number of grid levels set manually for each ROI → computationally expensive

  - ISM : n_0 = 1,0 cm^{-3}, T = 10^4 K
  - SNR : $t_{start\ sim}$ = 500 yrs, E_{SN}= 3.10^{51} erg, M_{ej}= 5 $M_\odot$, $v_{ej,\ max}$ = 5 700 $km.s^{-1}$ (E_{kin} ~97 % E_{SN})
  - PW : E = 5.10^{38} $erg.s^{-1}$, Lorentz γ = 10
  - Pulsar : (R_{PSR} = 10 km, M_{PSR} = 1.5 $M_\odot$), P_0 ~ 33 ms , braking index n=3 , **v_{PM} = 500 $km.s^{-1}$**

Towards a (magneto)-hydrodynamic 2D framework

Still early evolution : from 500 to 543 yr



ejecta dominated phase

Goals, questions and future work

- We simulate in a **relativistic** (M)HD framework the dynamical evolution of composite {pulsar wind - pulsar wind nebula – supernova remnant} systems.

  → In the process of producing (and understanding!) 2D simulations to study the asymmetry

What are the offset distances expected if :

- A pulsar has a high proper velocity ?
- Ambient medium has a strong density gradient?
- Both of the above?

- Implications on the modelling of PWNe from future high resolution VHE gamma-ray observations

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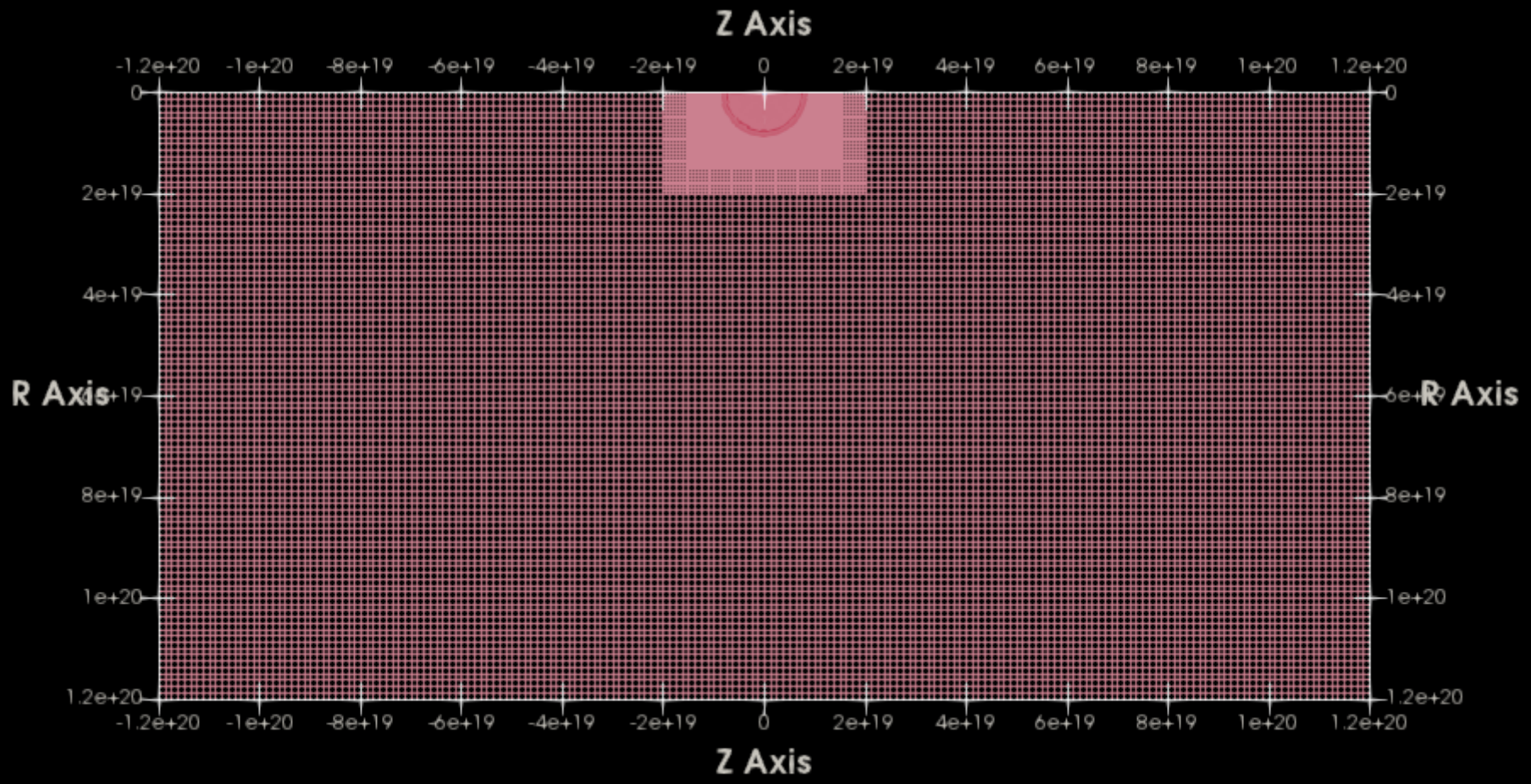
Thank you for your attention!

Back-up

Grid at $t_{sim} = 0$, $t_{age} = 500$ yr



Rel 2D HD with no PM

Still early evolution : from 500 to 528 yr