Simulations of stellar/pulsar-wind interaction along one full orbit

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The winds from a non-accreting pulsar and a massive star in a binary system collide forming a bow-shaped shock structure. The Coriolis force induced by orbital motion deflects the shocked flows, strongly affecting their dynamics. We study the evolution of the shocked stellar and pulsar winds on scales in which the orbital motion is important. Potential sites of non-thermal activity are investigated. Relativistic hydrodynamical simulations in 2D and in 3D, performed with the code PLUTO and using the adaptive mesh refinement technique, are used to model interacting stellar and pulsar winds on scales ~80 times the distance between the stars. The hydrodynamical results suggest the suitable locations of sites for particle acceleration and non-thermal emission. In addition to the shock formed towards the star, the shocked and unshocked components of the pulsar wind flowing away from the star terminate by means of additional strong shocks produced by the orbital motion. Strong instabilities lead to the development of turbulence and an effective two-wind mixing in both the leading and trailing sides of the interaction structure, which starts to merge with itself after one orbit. The adopted moderate pulsar-wind Lorentz factor already provides a good qualitative description of the phenomena involved in high-mass binaries with pulsars, and can capture important physical effects that would not appear in non-relativistic treatments. Simulations show that shocks, instabilities, and mass-loading yield efficient mass, momentum, and energy exchanges between the pulsar and the stellar winds. This renders a rapid increase in the entropy of the shocked structure, which will likely be disrupted on scales beyond the simulated ones. Several sites of particle acceleration and low- and high-energy emission can be identified. Doppler boosting will have significant and complex effects on radiation.

Subject :	:	oral
Topics	:	Astrophysics

Pulsar/Stellar wind collision in 3D

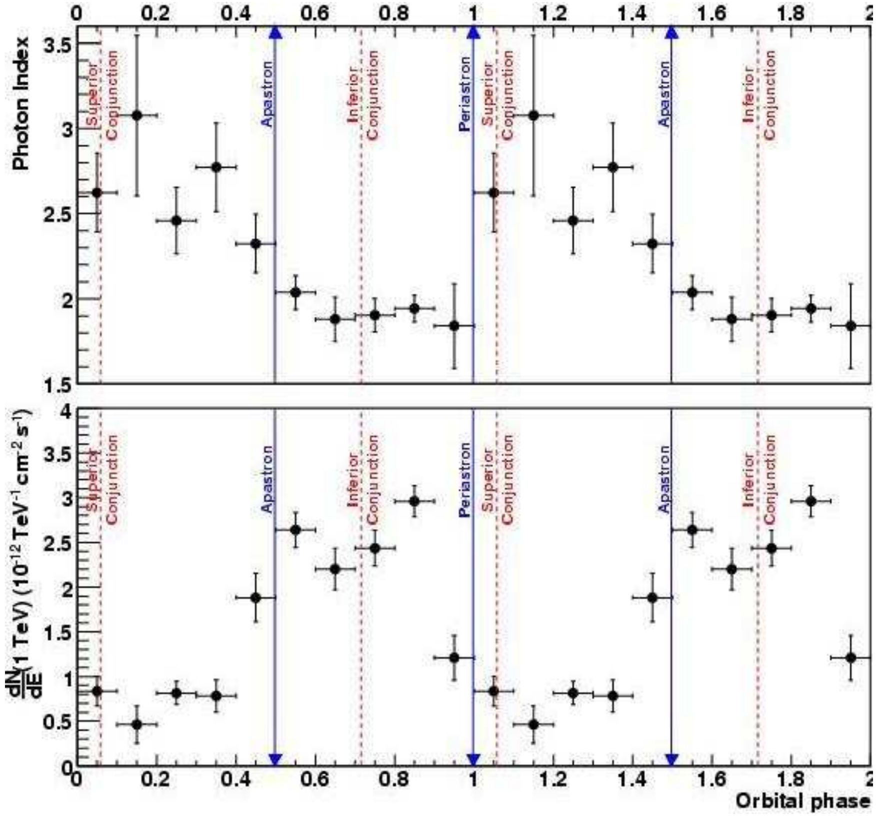
Barkov M.V.

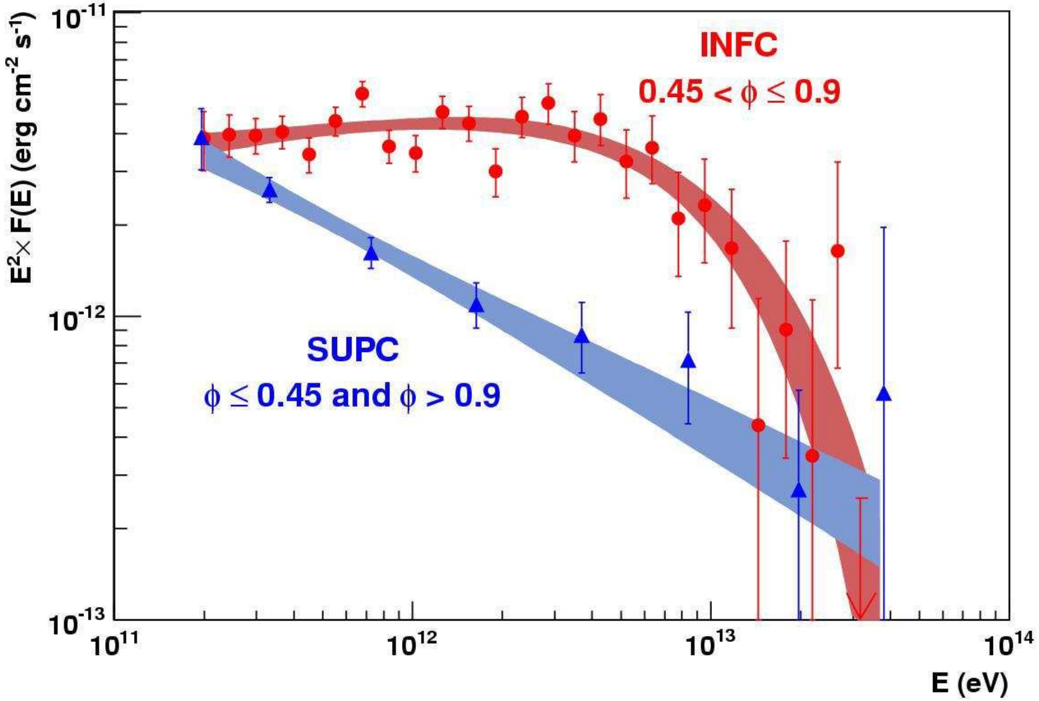
ABBL, RIKEN, JAPAN

Binary Systems in VHE Regime

Object	PSR B1259	LS 5039	J0632	J1086	LS I +61 303	Cyg X-1
Type	O8.5e+Pulsar	O6.5+?	Be+?	O6+?	Be+?	O9+BH
L_s, erg/s	3×10^{37}	7×10^{38}	10^{38}	7×10^{38}	10^{38}	1.3×10^{39}
Orbit Size, cm	$10^{13} - 10^{14}$	$10^{12} - 3 \times 10^{12}$	$10^{13} - 10^{14}$	$\sim 10^{13}$	$2 \times 10^{12} - 10^{13}$	3×10^{12}
Eccentricity	0.87	0.24	0.83	0.25?	0.72	0
Inclination	35	10-75	10?	???	~30	~30
HE Instrument	EGRET Fermi	EGRET Fermi	-	Fermi	EGRET Fermi	AGILE
GeV detection	LC+Spctr	LC+Spctr	-	LC+Spctr	LC+Spctr	Point
VHE Instrument	HESS	HESS	HESS, MAGIC VERITAS	HESS	MAGIC VERITAS	MAGIC
TeV detection	13σ	$\sim 100\sigma$	$\sim 10\sigma$	$\sim 10\sigma$	$\sim 10\sigma$	4σ
signal	periodic	Periodic, variable	periodic	periodic	Periodic, variable	flare

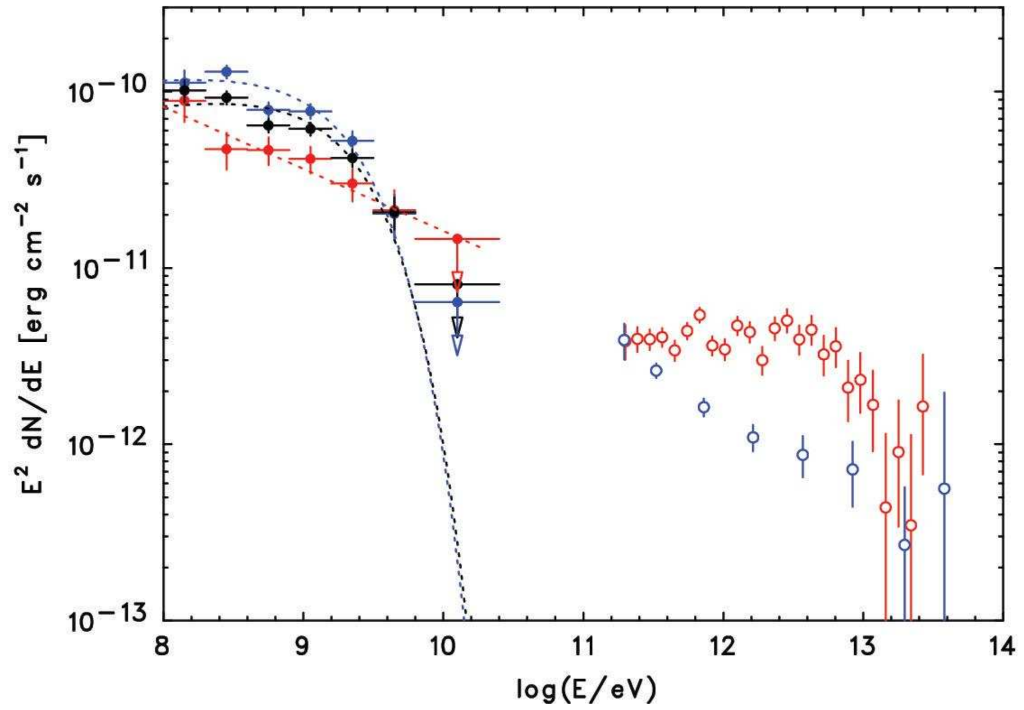
H.E.S.S.





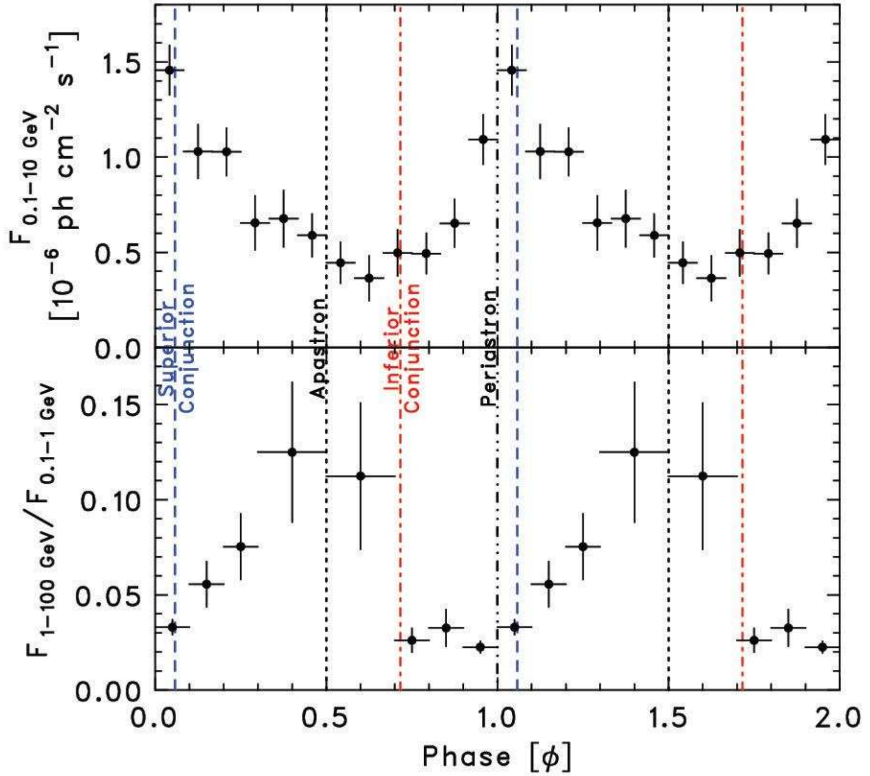
The best studied system in VHE: LS5039

Fermi Observations of LS 5039



Spectrum with a HE cutoff @ a few GeV

L_{GeV}=$2 \times 10^{35}\ erg/s$



Lightcurve in GeV has a maximum Close to the periastron

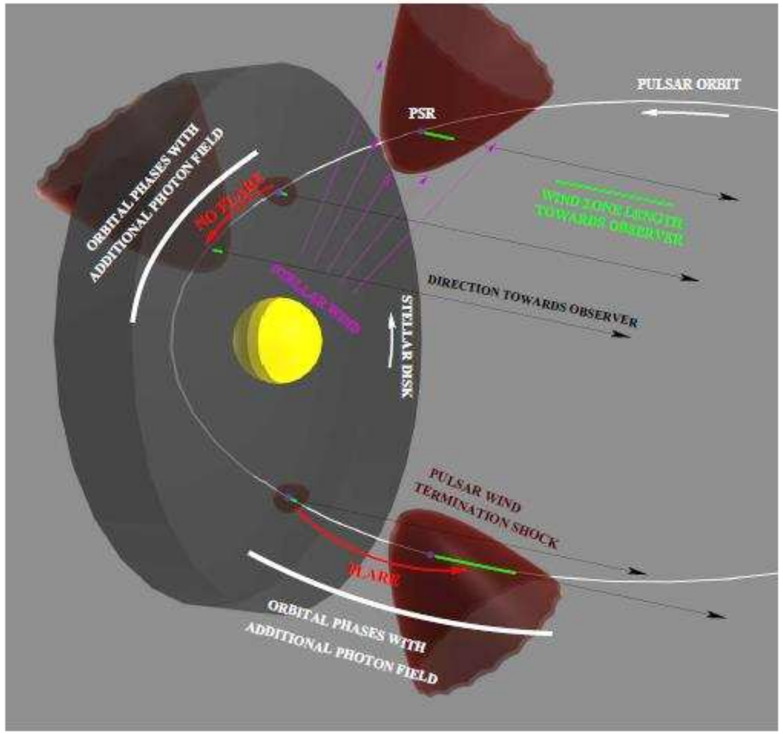
The parameters of the system LS5039

Table : Casares et al. 2005 and Sarty et al 2011

Description	Designation	Value
Mass of star	M_s	$26M_\odot$
Radius of star	R_s	$9.3R_\odot$
Temperature of the star	T_s	$39,000$ K
Stellar Wind termination velocity	V_∞	$2,400$ km/s
Stellar Wind loss rate	$\dot{M}_s$	$4 \times 10^{-7} \mathrm{M_\odot yr^{-1}}$
Orbital period	P_s	3.9 day
Eccentricity of the orbit	e	0.24
The mass of the BH	M_{BH}	$3M_\odot$
Semimajor axis	a_0	$3.5R_s$

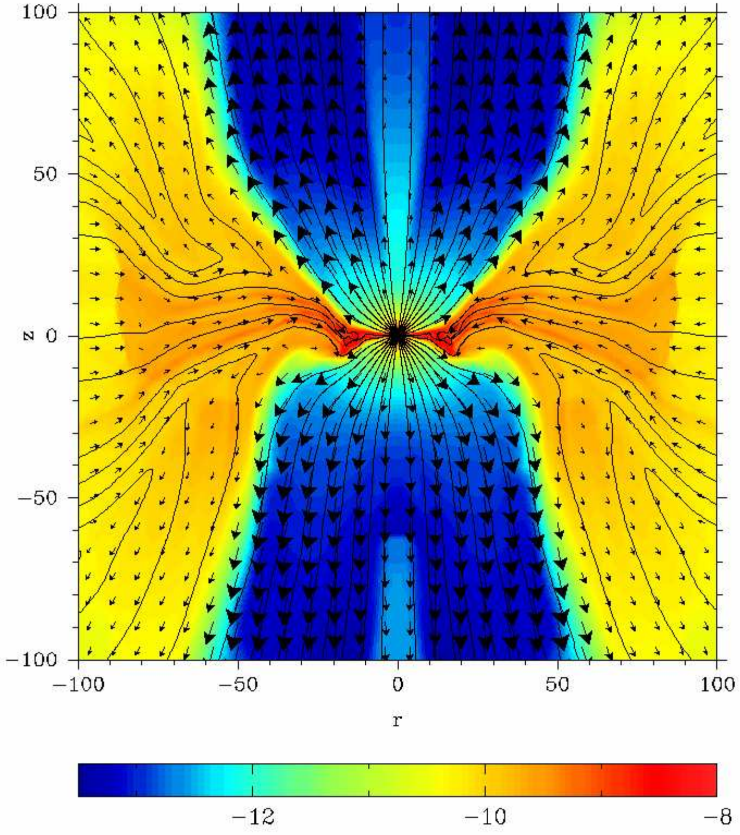
What are the Scenarios?

Binary Pulsar



(Khangulyan et al 2012)

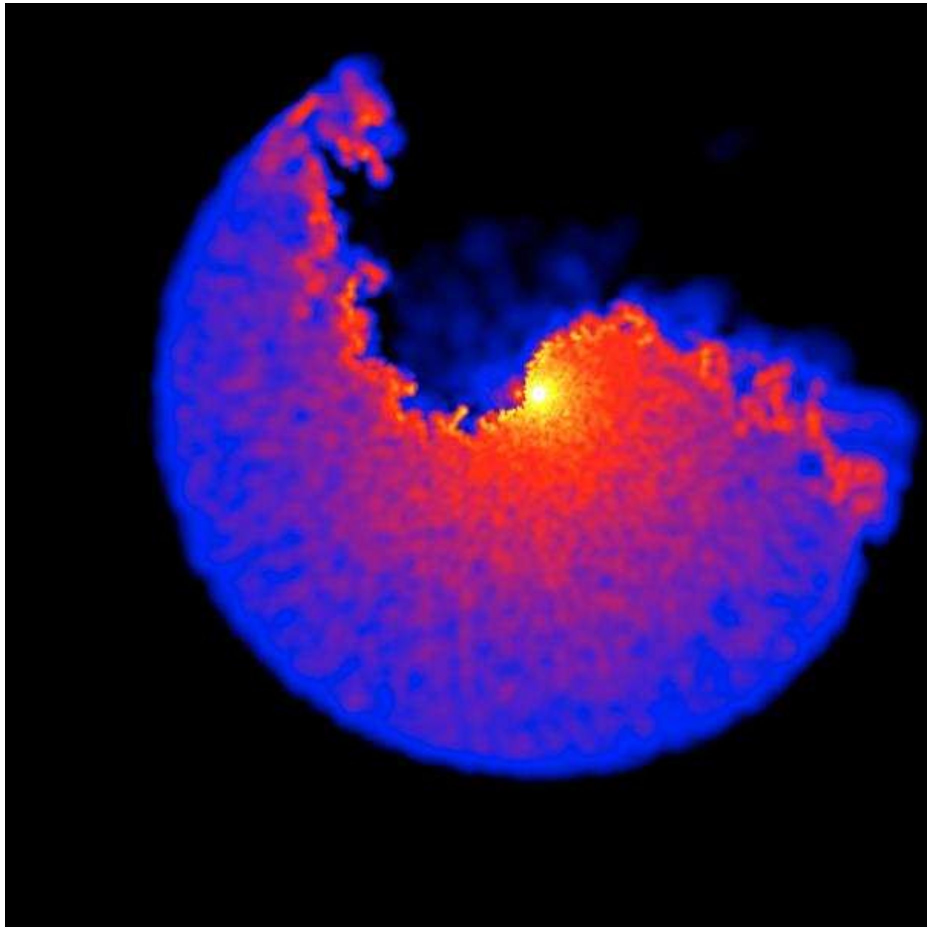
Jet from spherical accretion to BH



(MVB & Khangulyan 2012)

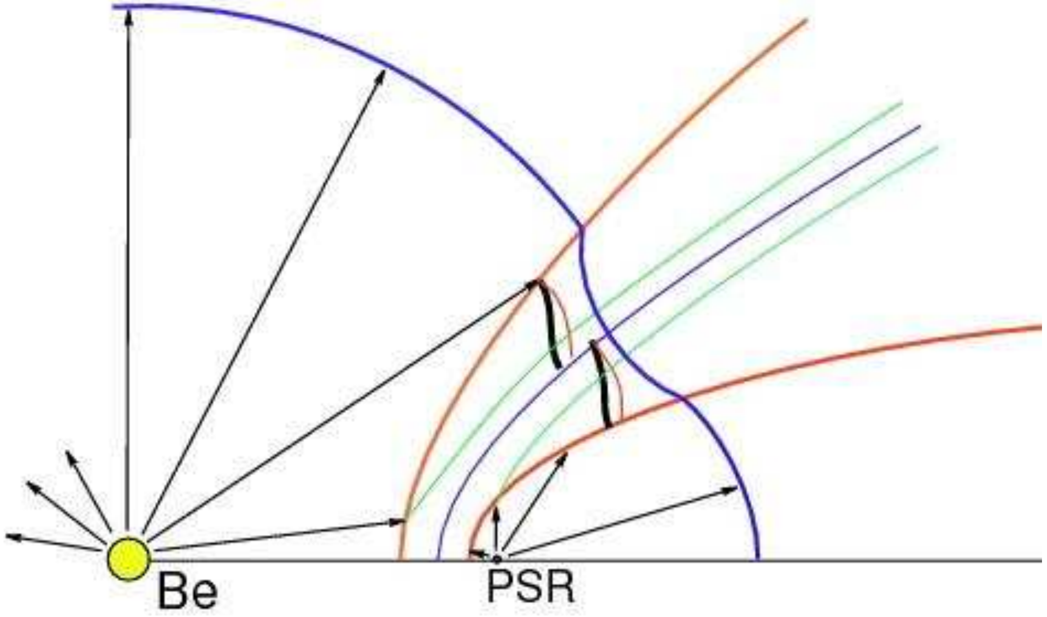
Stellar wind collision

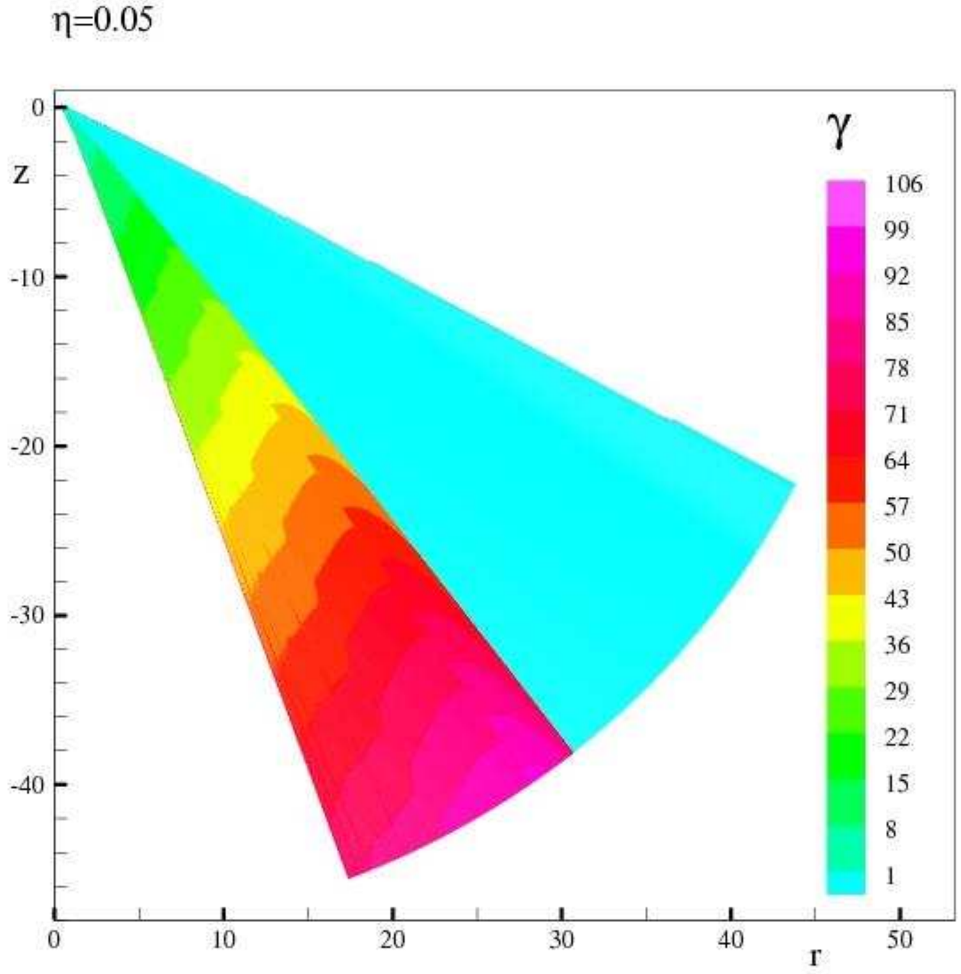
(Romero et al. 2007) SPH Newton



Stellar wind collision

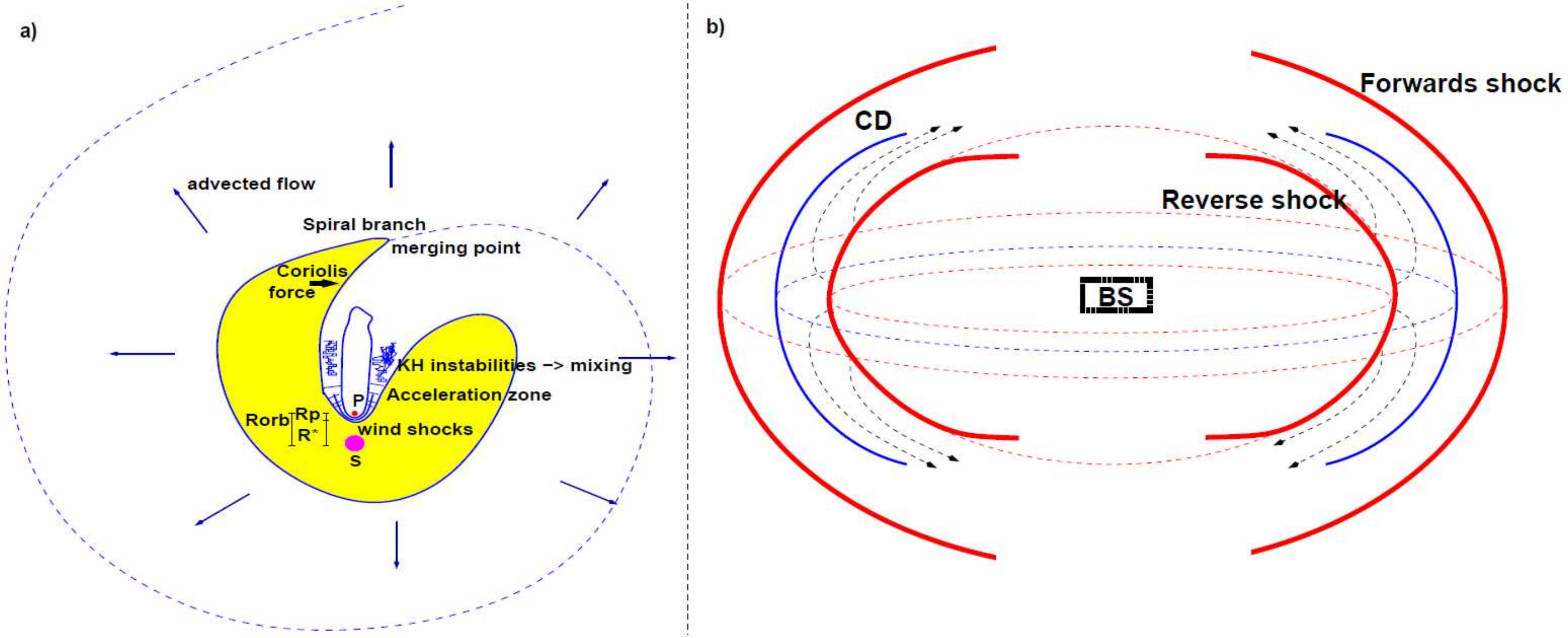
(Bogovalov et al. 2008,2012) RHD, RMHD





Stellar wind collision + orbital motion

(Bosch-Ramon & MVB 2011)

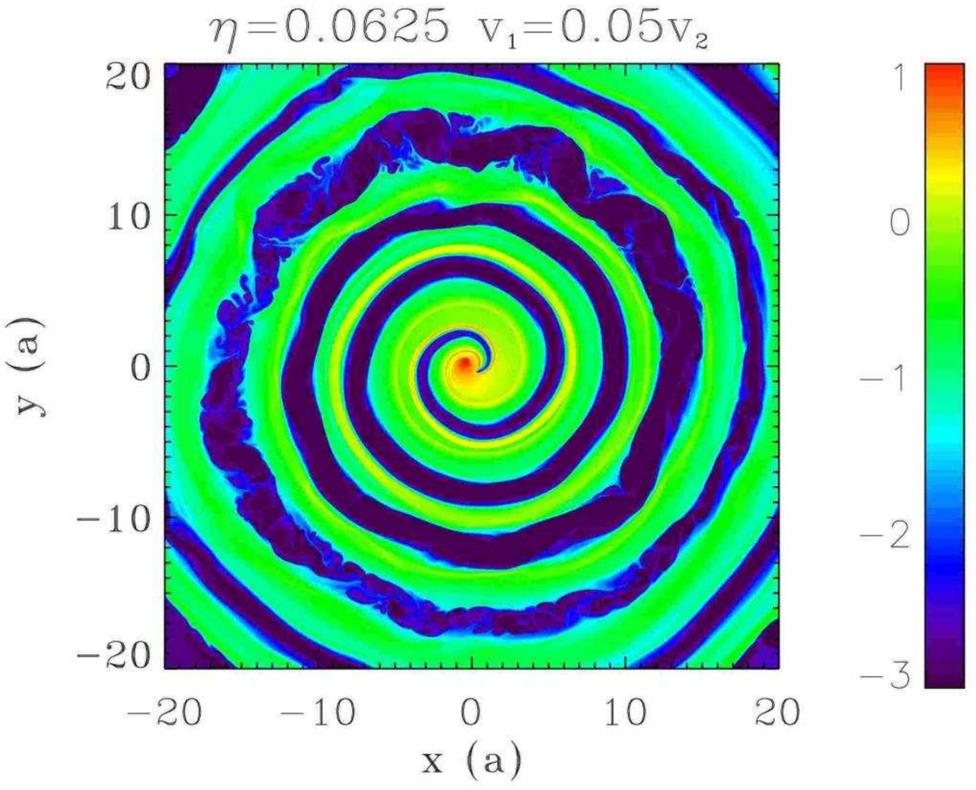


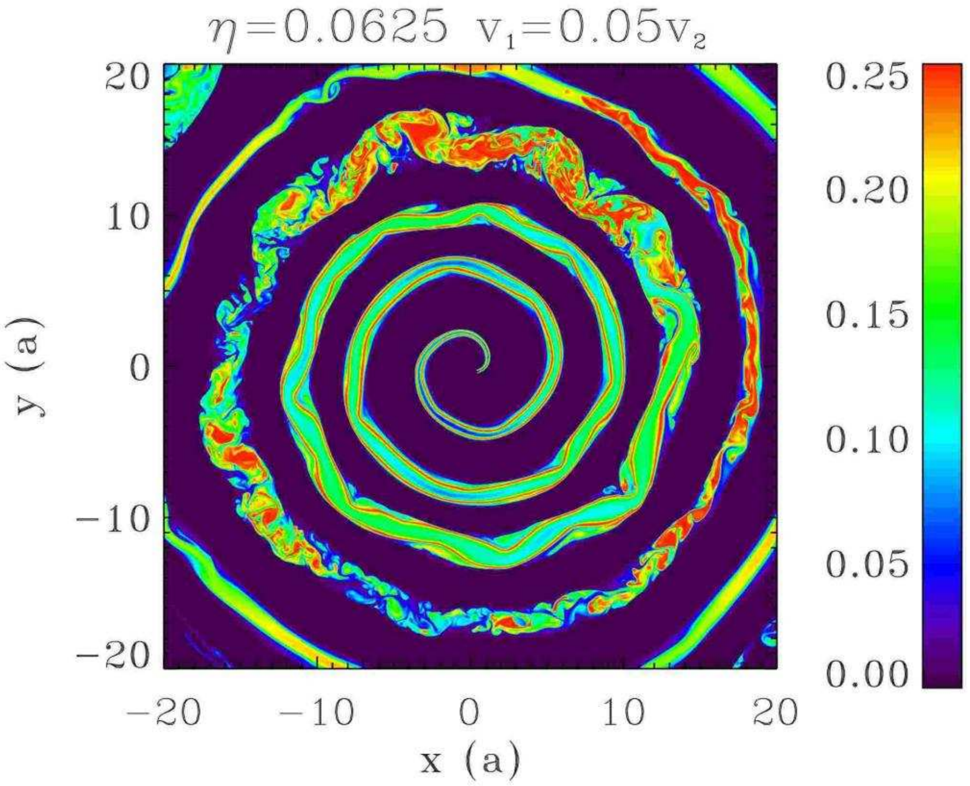
$$x_0 \sim 7 \times 10^{12} L_{sd37}^{1/2} v_{w8.5} T_6 \dot{M}_{-6.5}^{-1/2} cm$$

$$v_{exp} \sim 10^9 L_{sd37}^{1/2} \dot{M}_{-6.5}^{-1/2} cm/s$$

Density and tracer (Newton HD)

(Lamberts et al. 2012)
Outflow is stable.

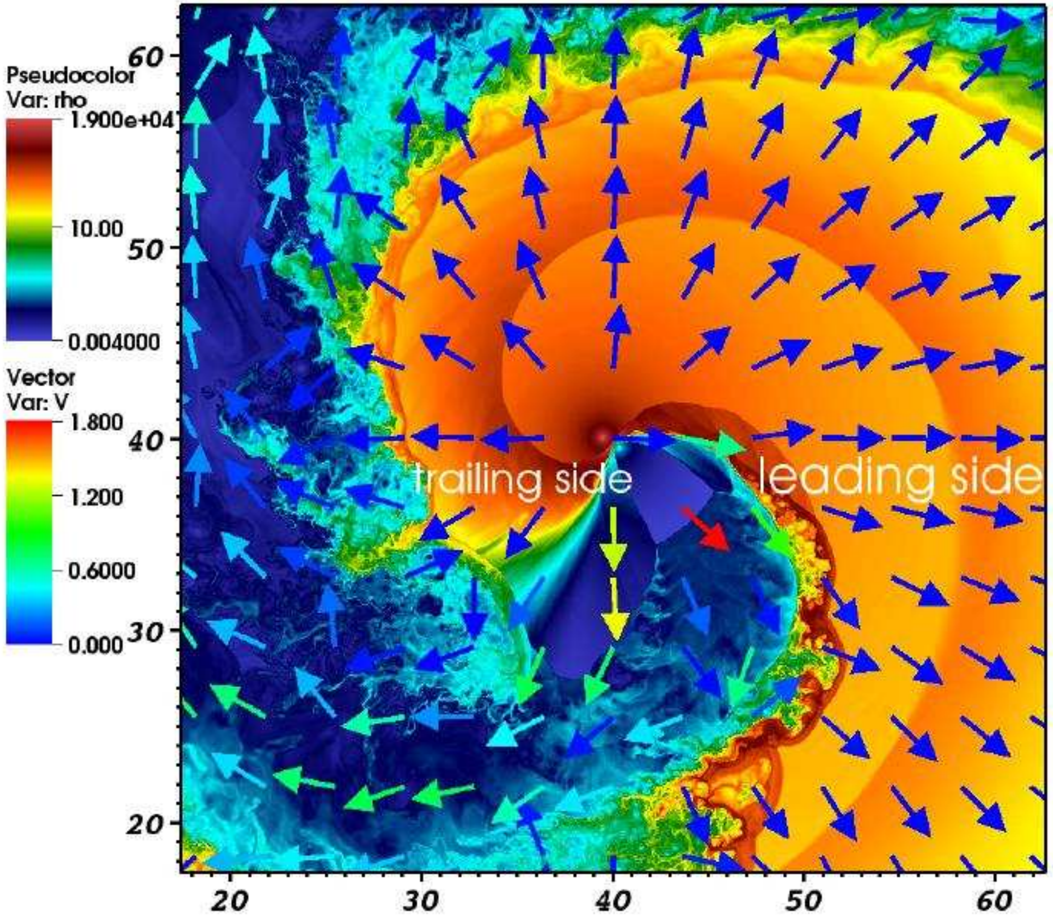




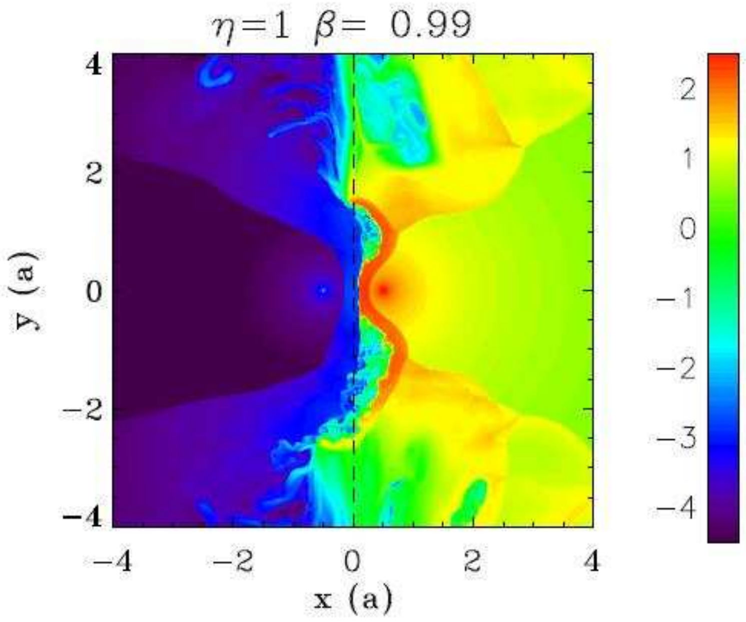
Density $\Gamma = 2$; $\eta = 0.6$

$$\eta = \frac{L_{sd}}{\dot{M} v_w c}$$

(Bosch-Ramon, MVB, Khangulyan and Perucho 2012)
2D RHD, PLUTO with AMR Chombo

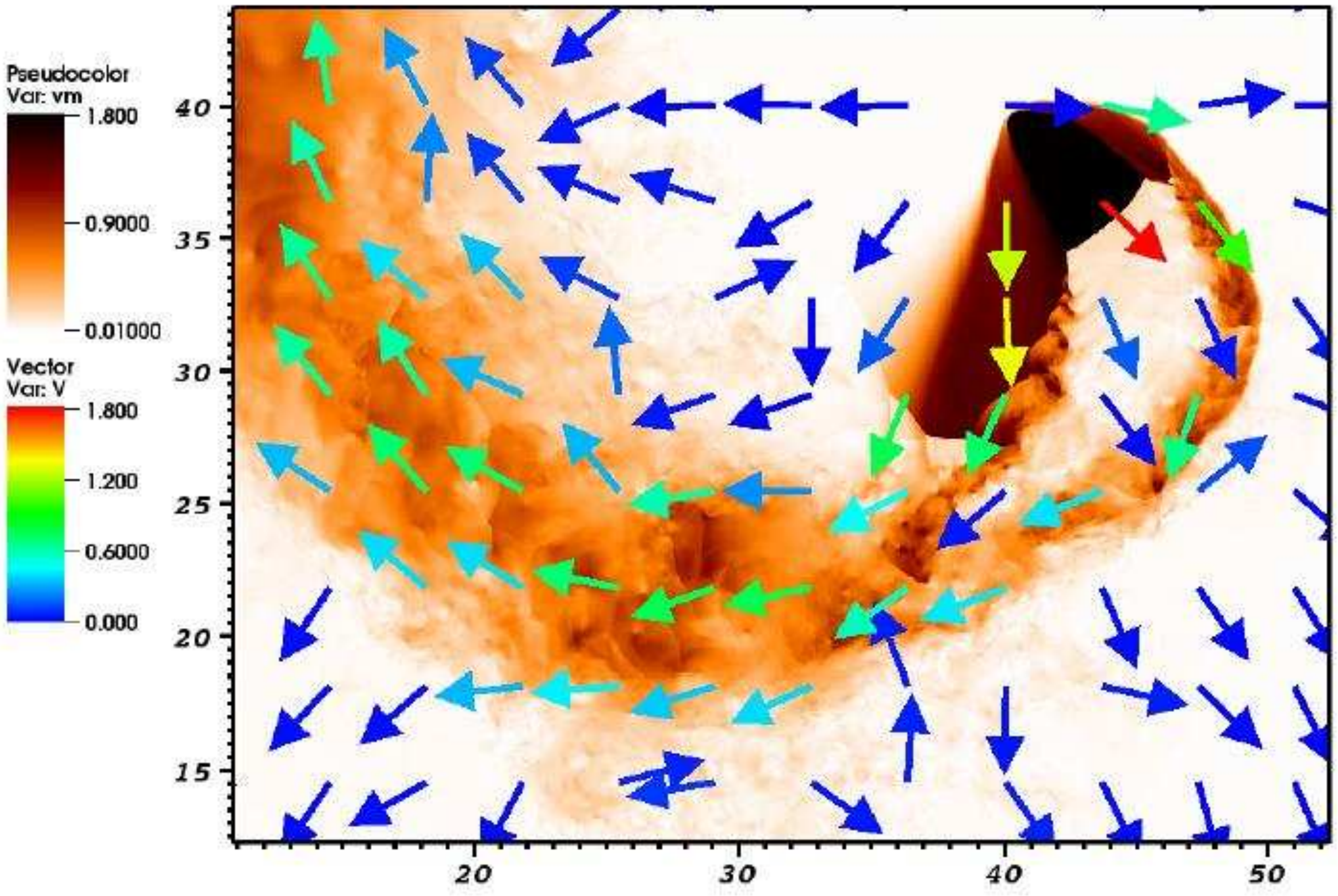


(Lamberts et al. 2013) RHD
Outflow is unstable.



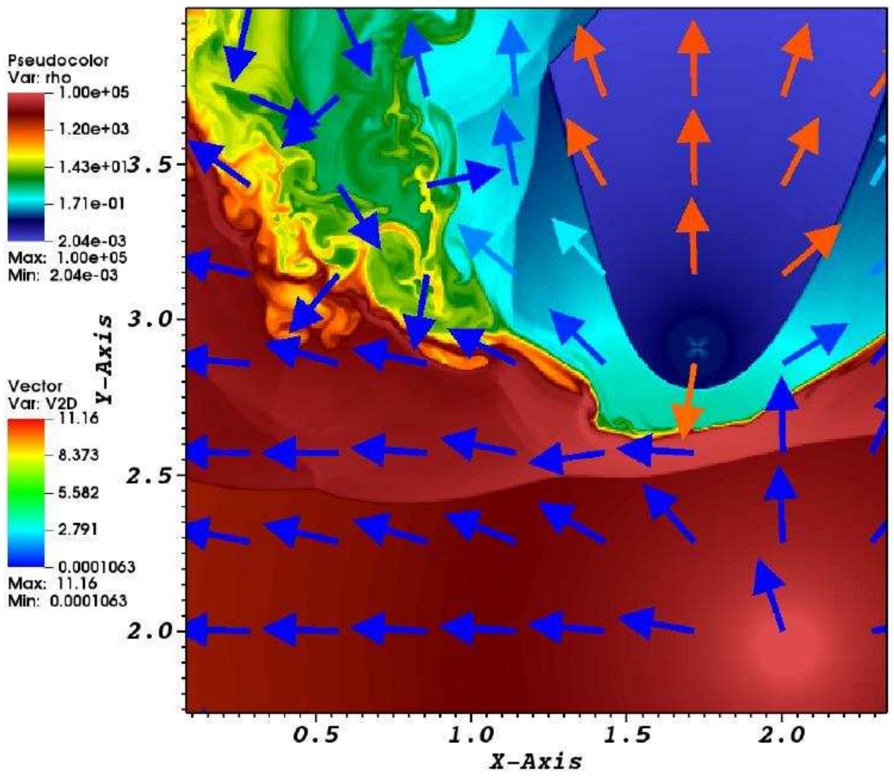
Density $\Gamma = 2; \eta = 0.6$

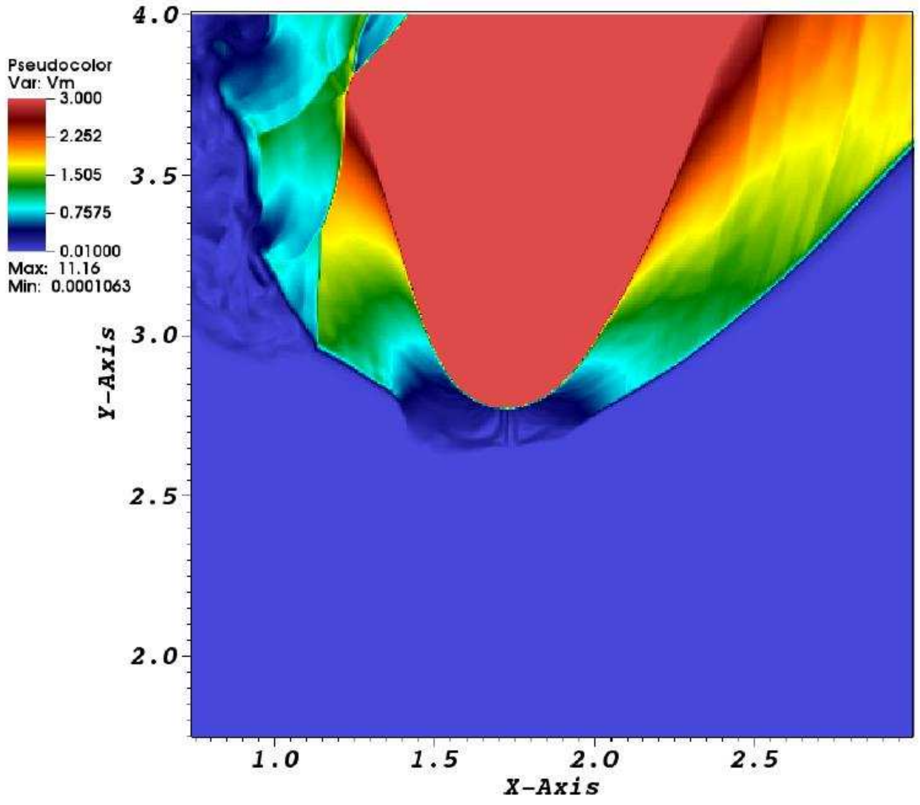
(Bosch-Ramon, MVB, Khangulyan and Perucho 2012) RHD



Density and velosity $\Gamma = 10; \eta = 0.3$

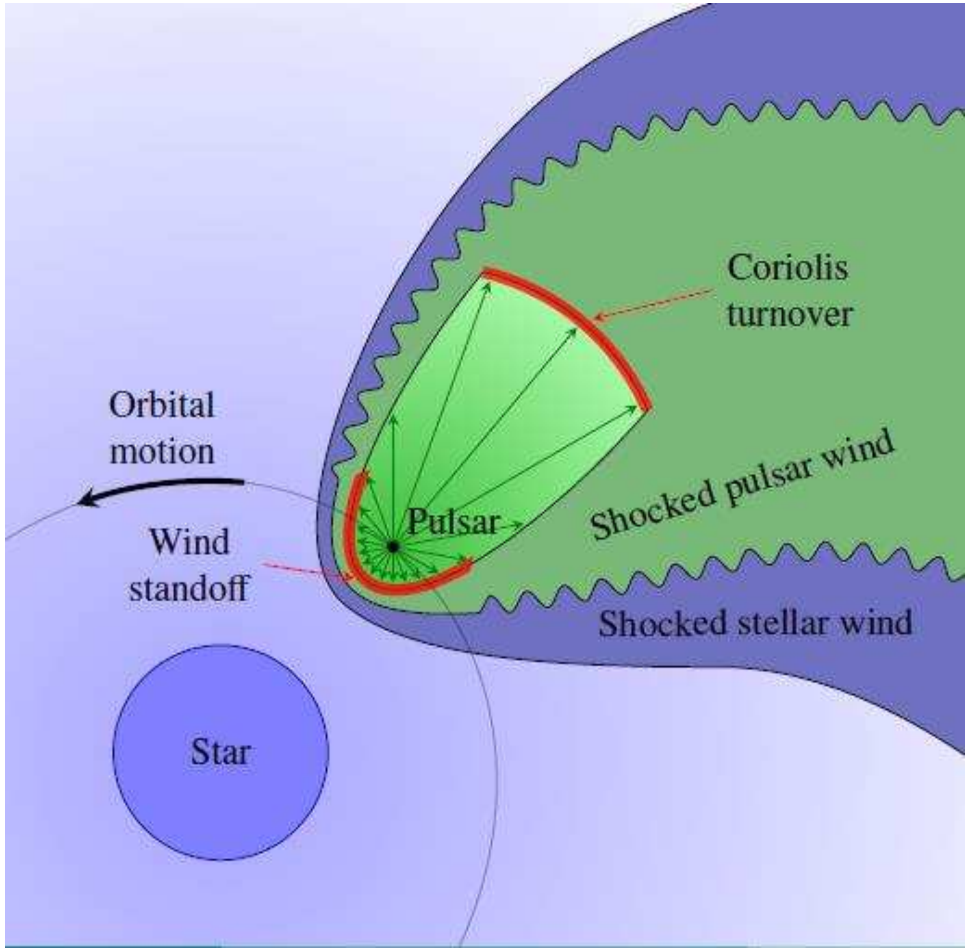
(Bosch-Ramon, MVB, Khangulyan and Perucho 2012) RHD

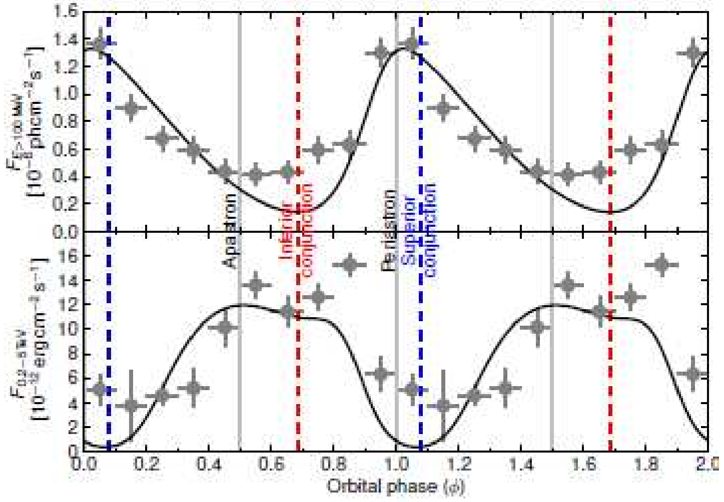


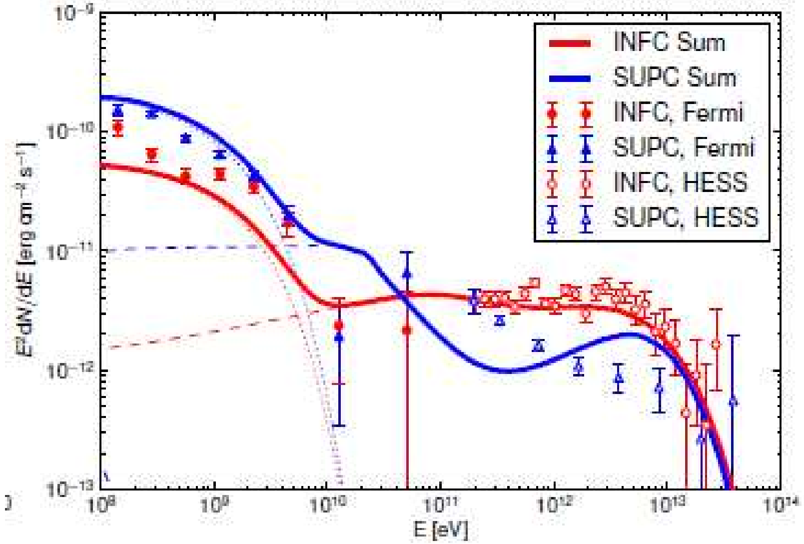


Light curve formation

(Zabalza et al 2013)





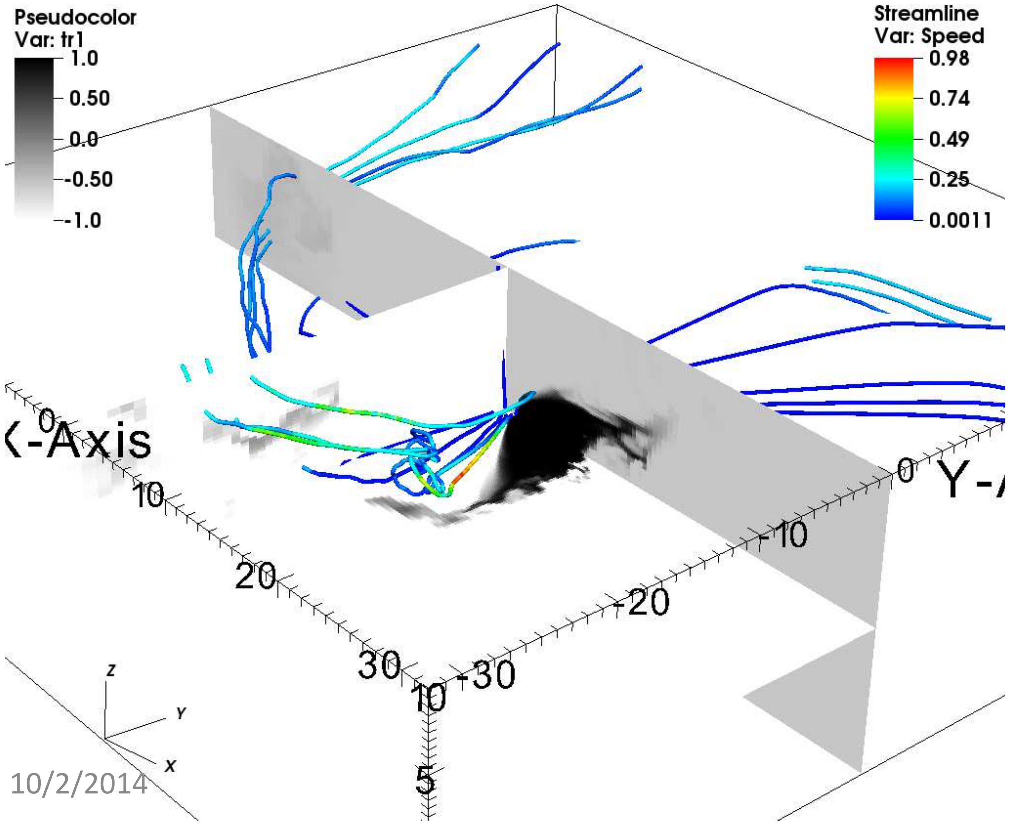


3D show time!...

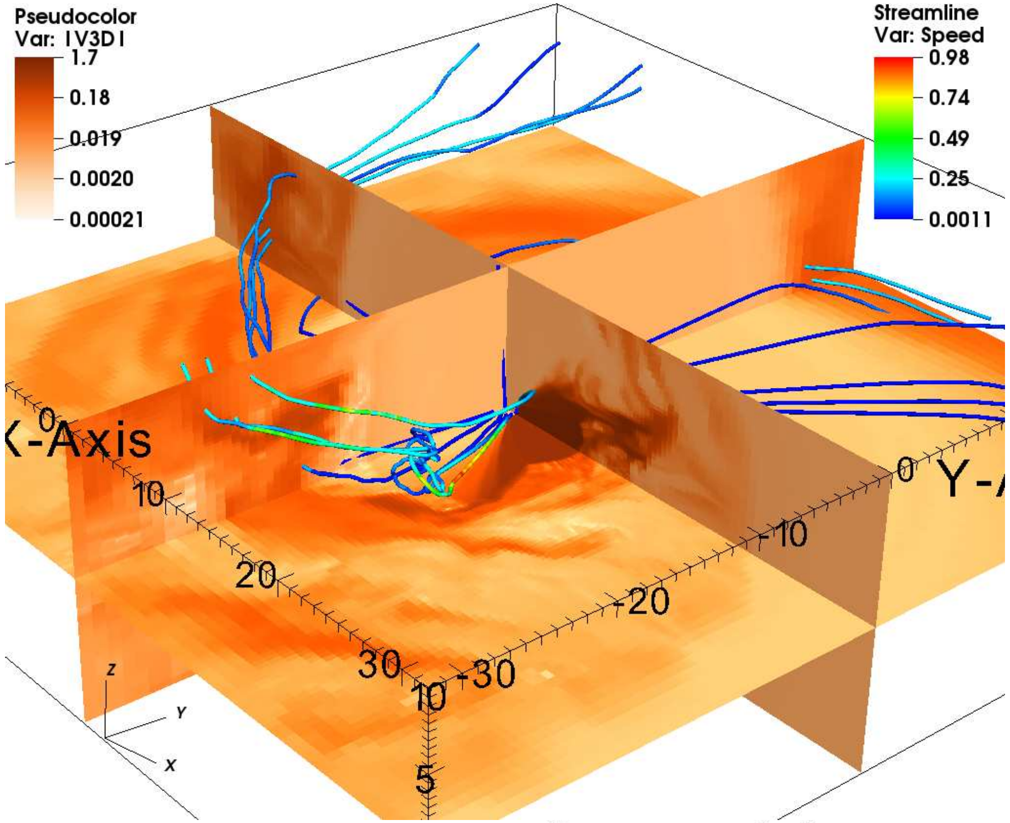
3D run with $\Gamma = 2$; $\eta = 0.1$

PLUTO non uniform grid

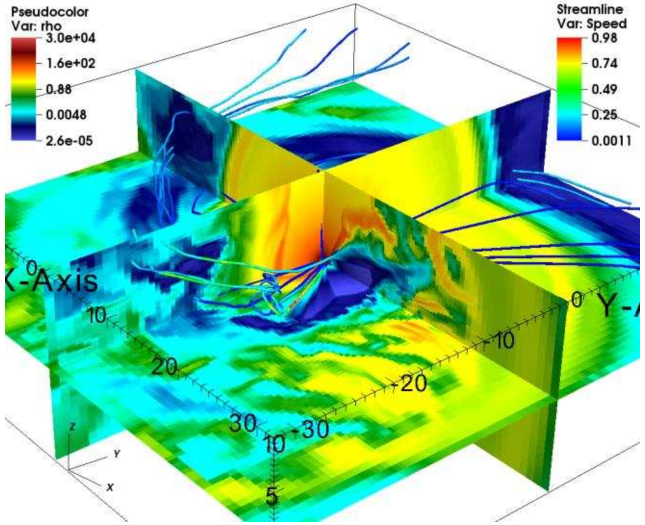
Tracer.



Four velocity.

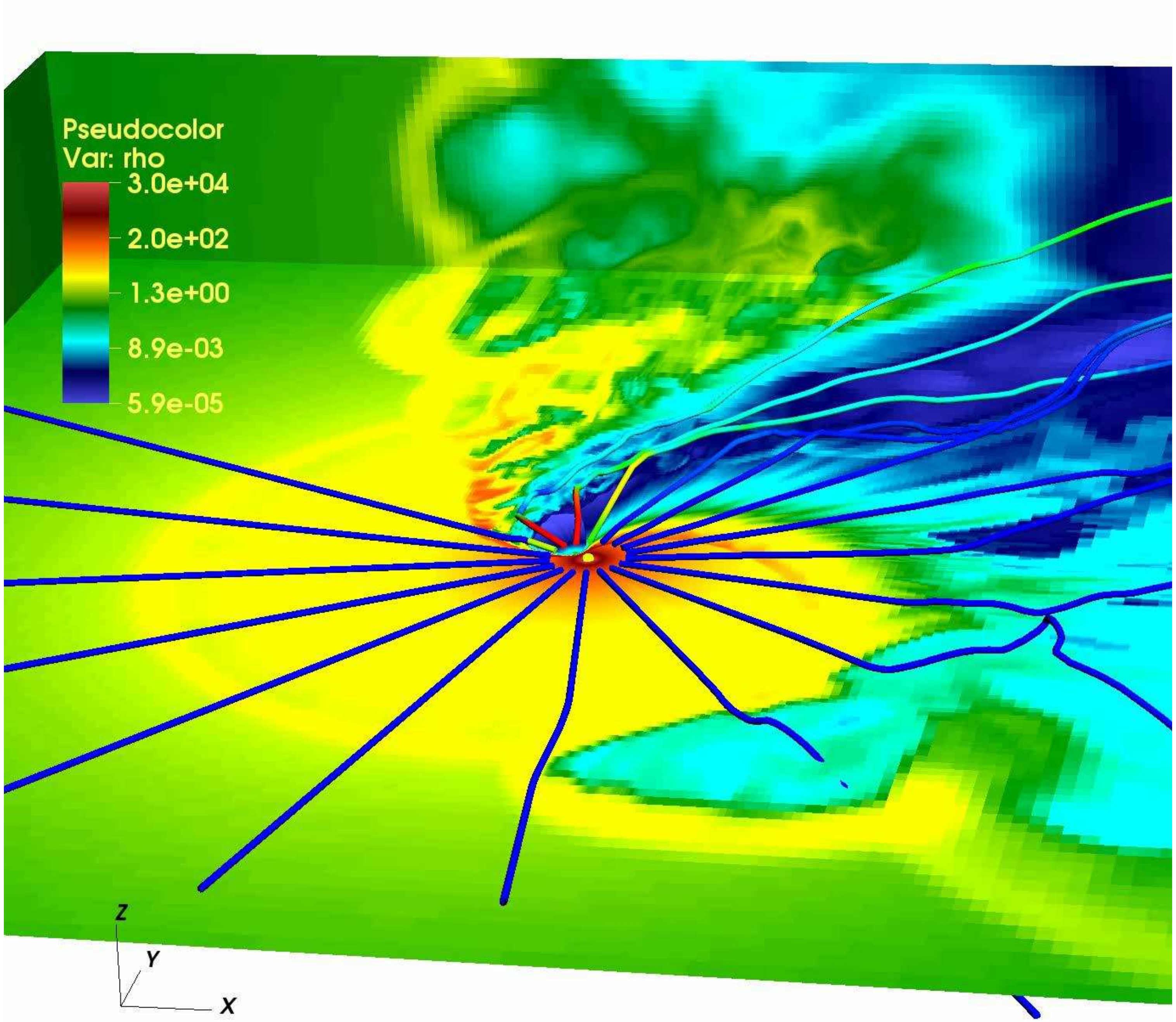


Density



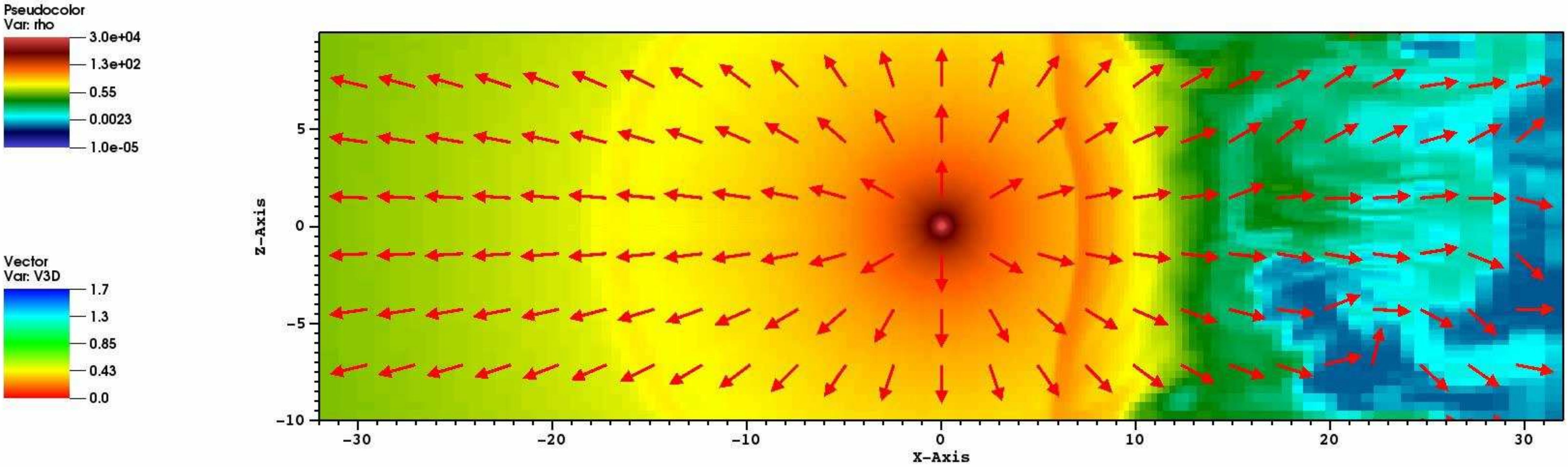
3D run $\Gamma = 2$; $\eta = 0.1$

density and stream lines.



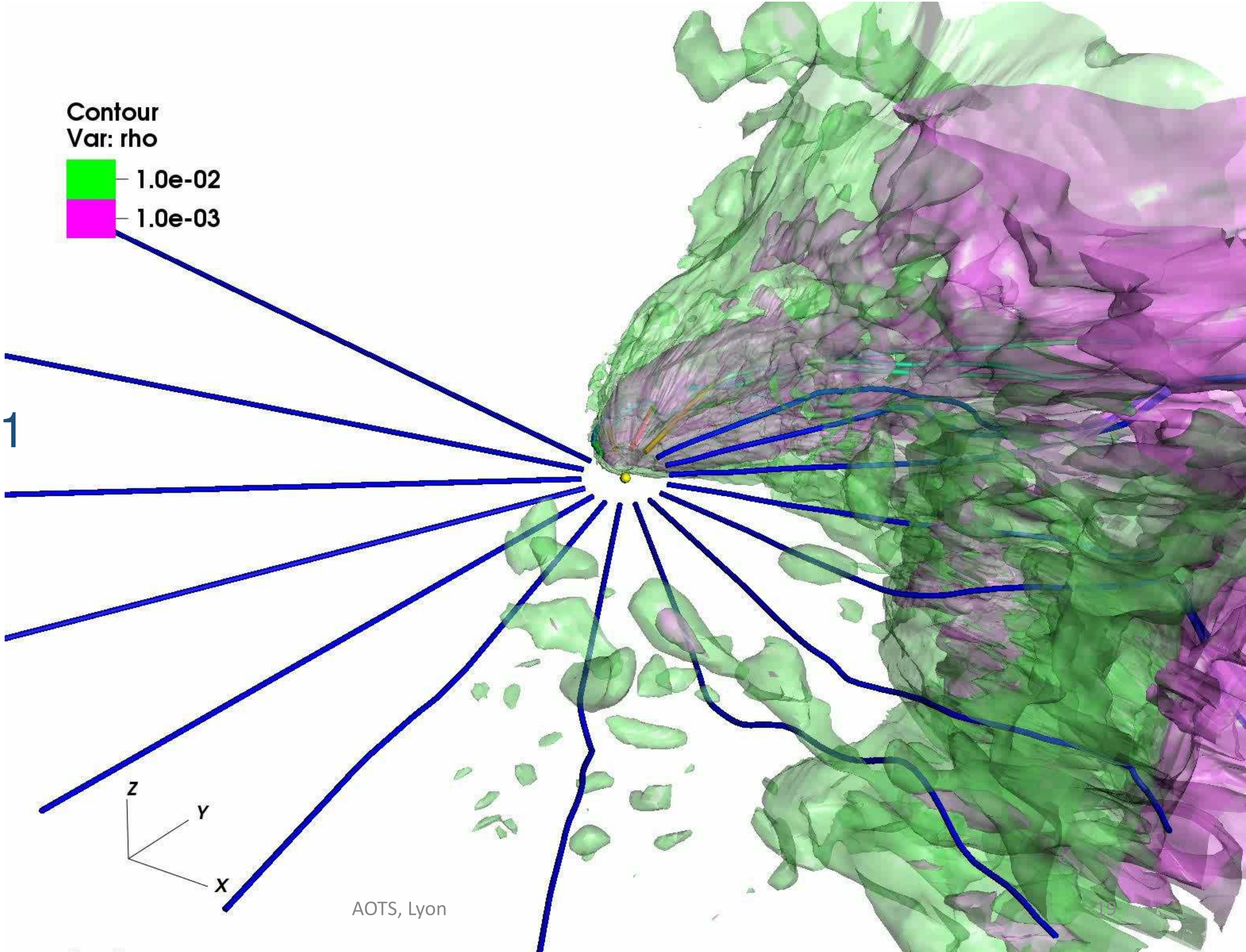
3D run $\Gamma = 2$; $\eta = 0.1$

Density and four velocity in XZ plane



3D run $\Gamma = 2$; $\eta = 0.1$

density contours and stream lines.

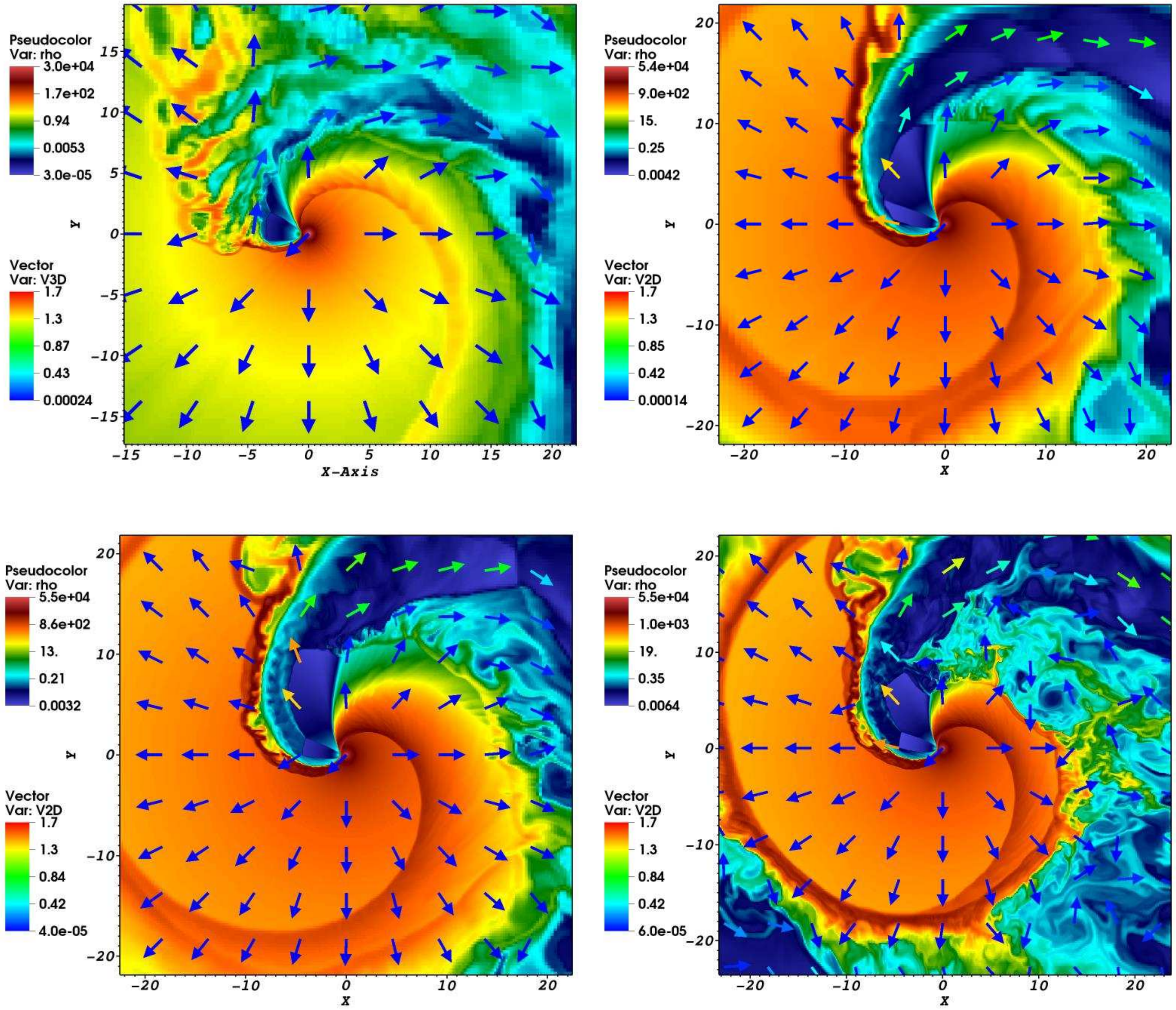


Comparison of the 3D case and 2D cases with different resolution.

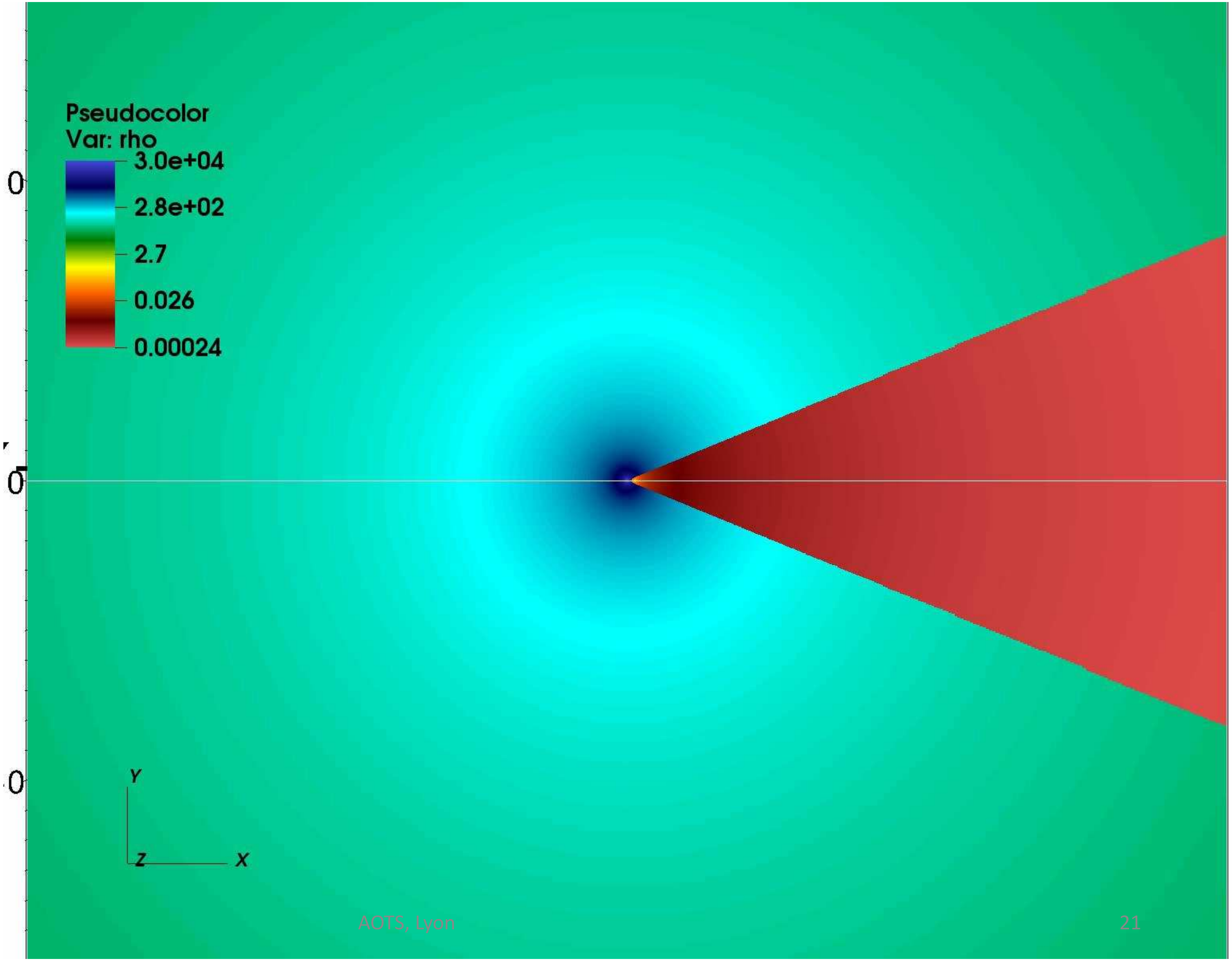
3D $\Gamma = 2$; $\eta = 0.1$
2D $\Gamma = 2$; $\eta = 0.3$

Density presented in the XY plane.

$$\eta = \frac{L_{sd}}{\dot{M} v_w c}$$



2D Γ= 2; η = 0.3 with high resolution in big domain, density in XY plane.



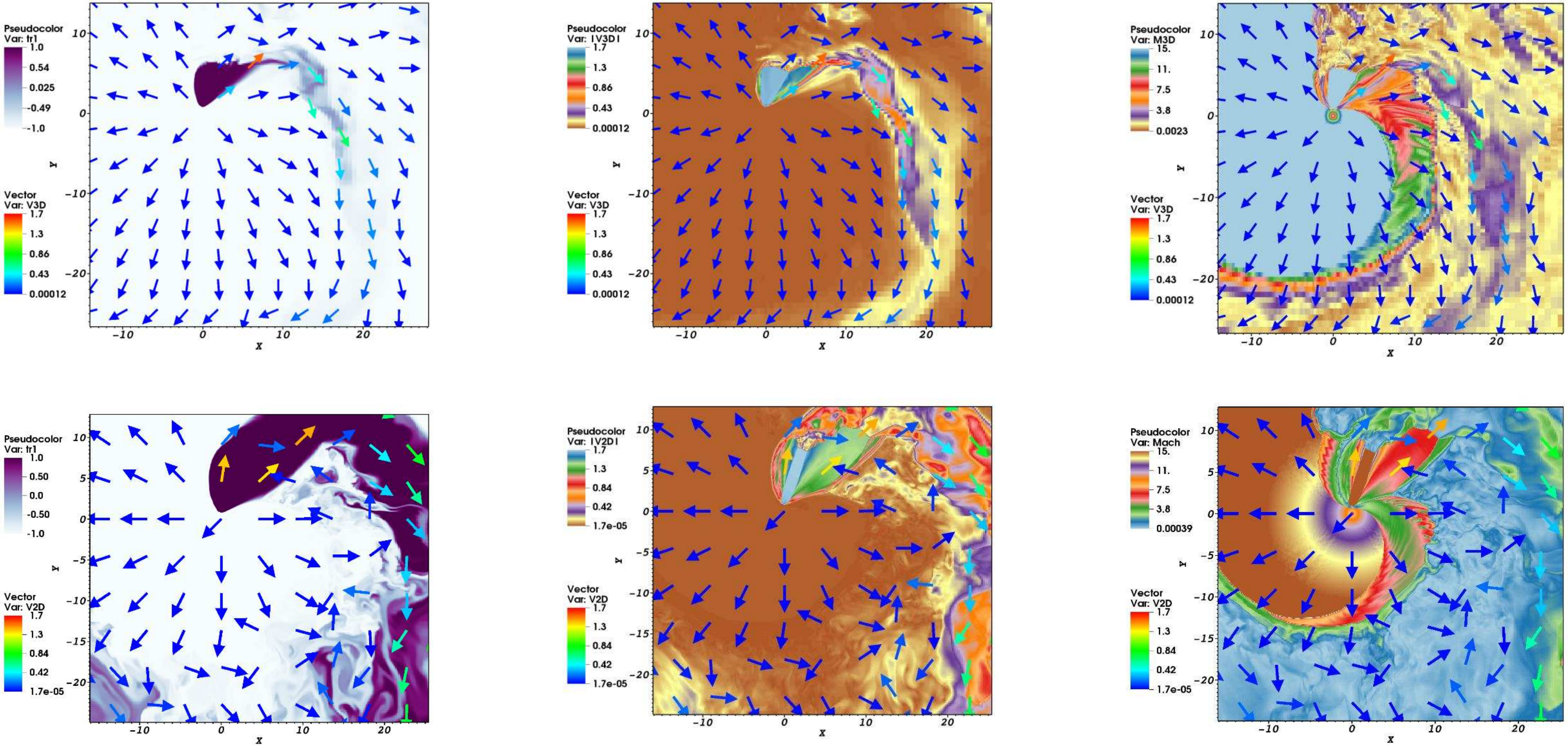
Comparison of 3D and 2D

Tracer | Four velocity | Mach

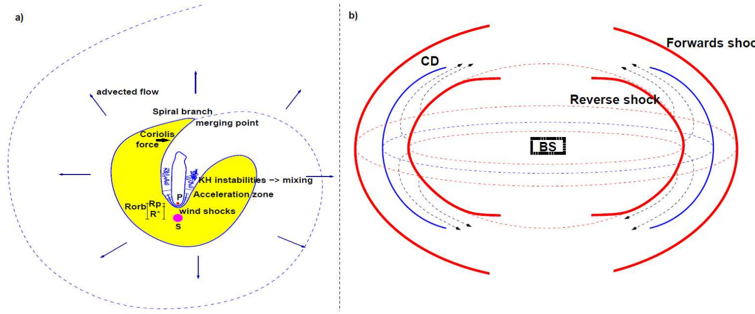
3D

vs

2D



Conclusions:



- First 3D RHD simulations of stellar and pulsar wind collision confirm that the interaction of stellar and pulsar winds yields structures that evolve non-linearly and get strongly entangled.
- In the 3D case turbulence grows quicker and mixing of the winds has place faster compared to 2D simulations.
- Large scale simulations show that spiral arms loose their integrity on scales about 100a.
- Orbital eccentricity leads to variation of the Coriolis turnover tail size.
- The evolution is accompanied by strong kinetic energy dissipation, rapid changes in flow orientation and speed, and turbulent motion; all this should affect the non-thermal emission originated under those conditions.