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Fluid instabilities in wind-wind interactions at gamma-ray binaries

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Introduction

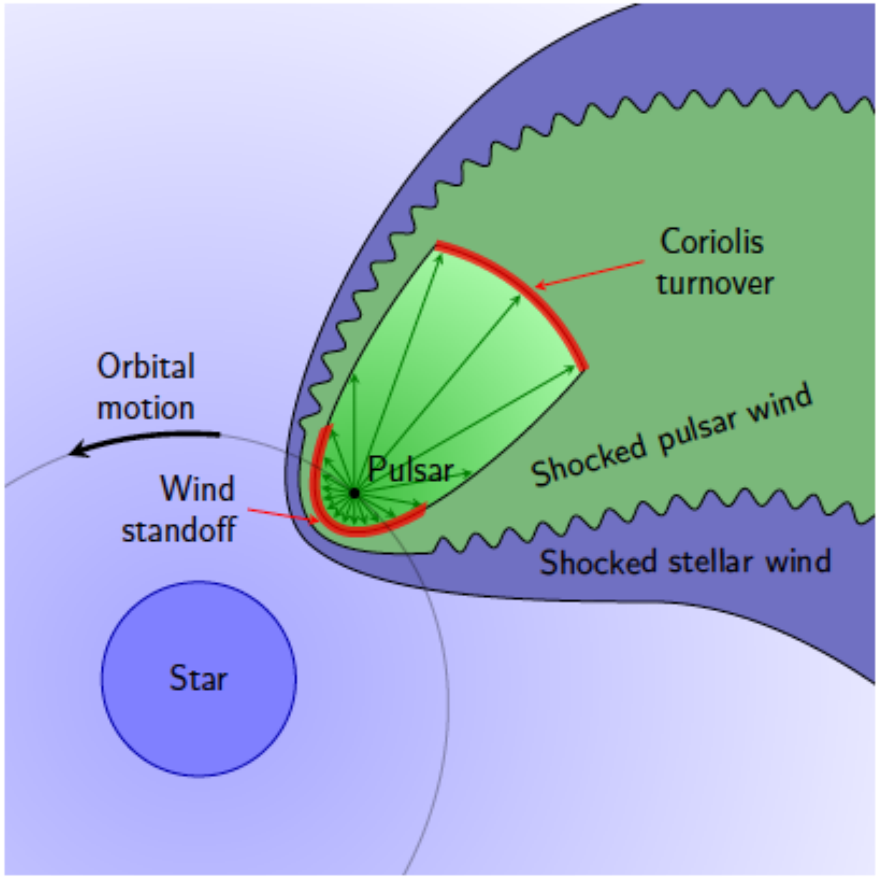


Figure 4 : Sketch of the scenario for the gamma-ray binary LS 5039. The red regions indicate the two proposed **high-energy gamma-ray emitter** locations. From Zabalza et al. 2013.

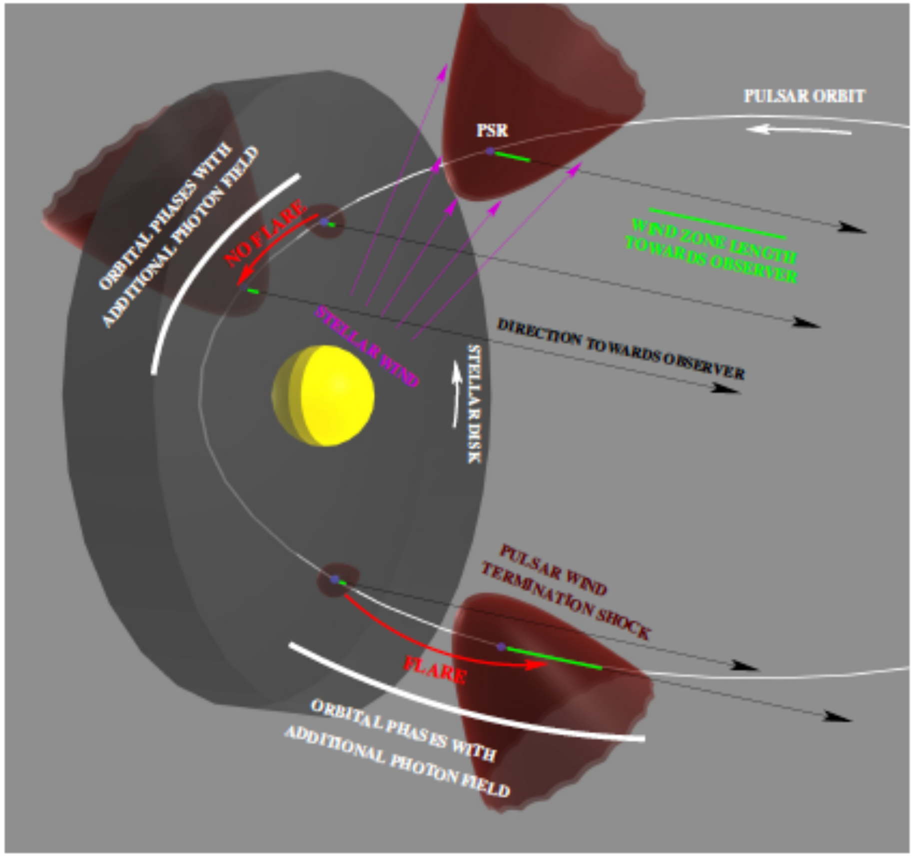
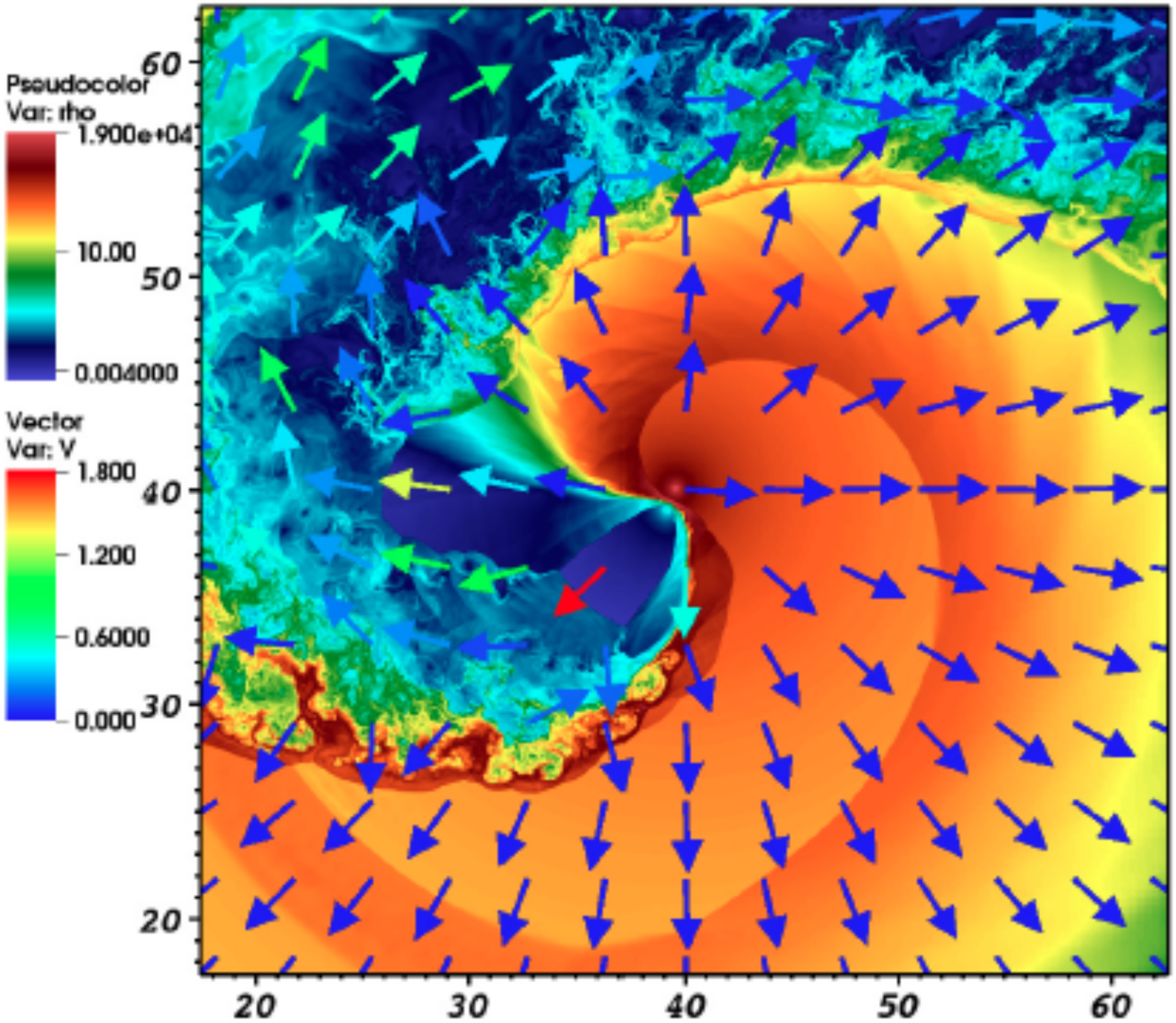


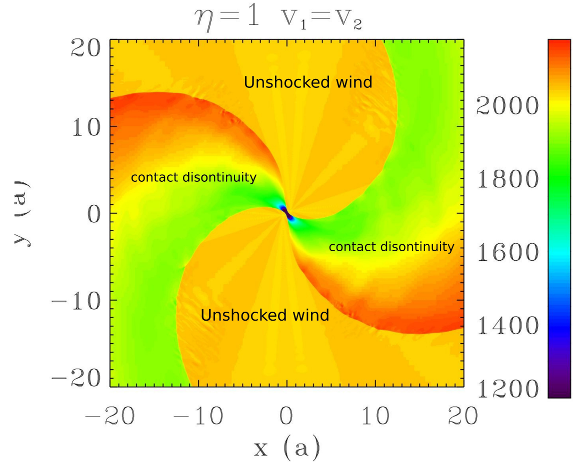
Figure 5 : Sketch of the scenario of the gamma-ray binary PSR B1259−63. From Khangulyan et al. (2012).

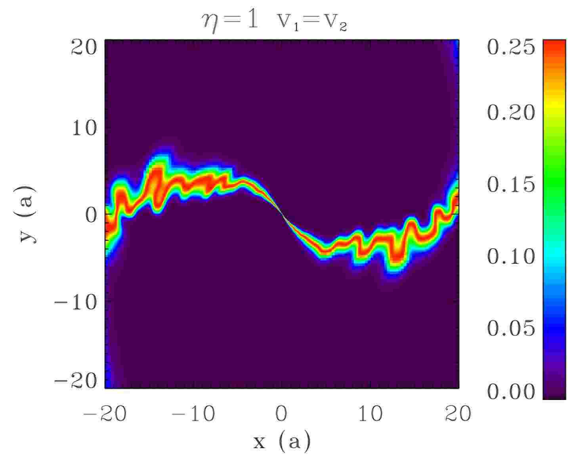
Slide: Xavier Paredes-Fortuny

Pulsar wind / Stellar wind interactions



Bosch-Ramon, Barkov, Khangulyan, MP 2012



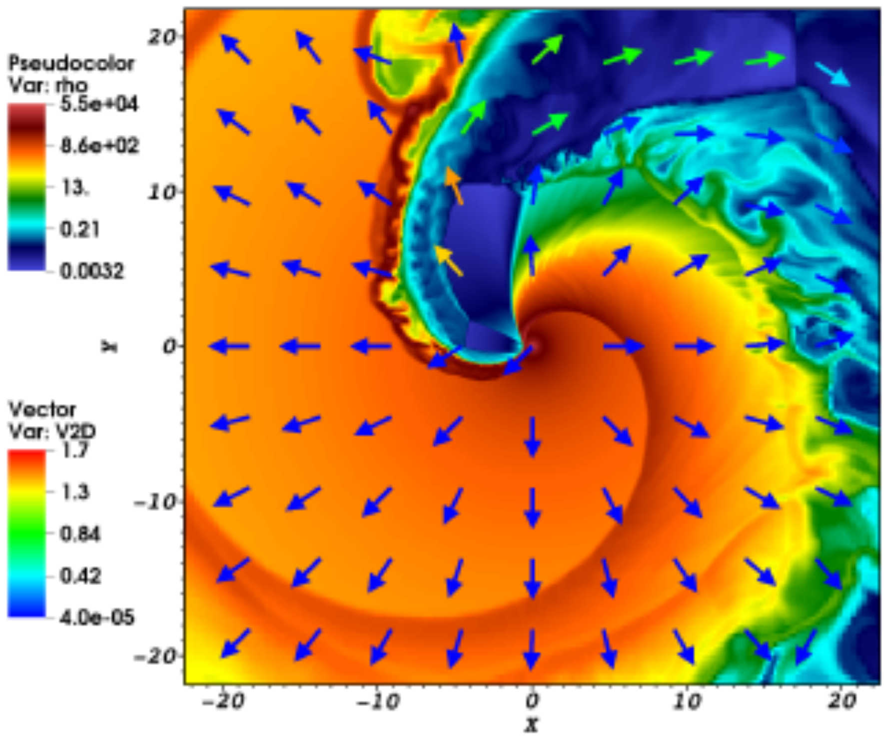


Lamberts et al. 2012
(non-relativistic flow)

See also:
Romero et al. 2007, Okazaki et al. 2011 (SPH, Newtonian)
Takata et al. 2012

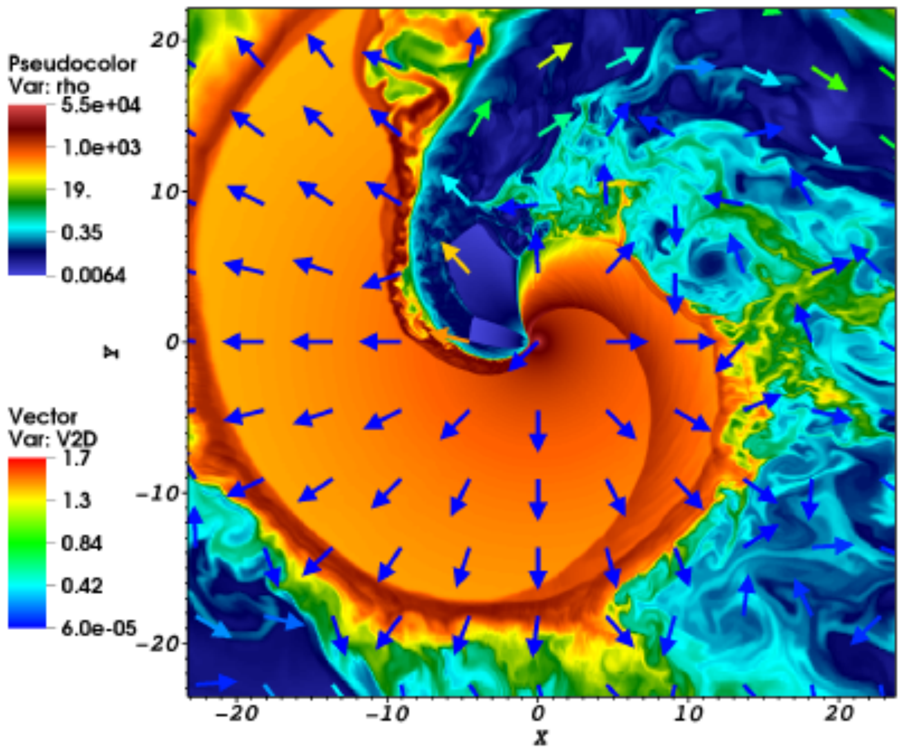
Introduction

2D with doubled resolution



Bosch-Ramon, Barkov, MP (2015)

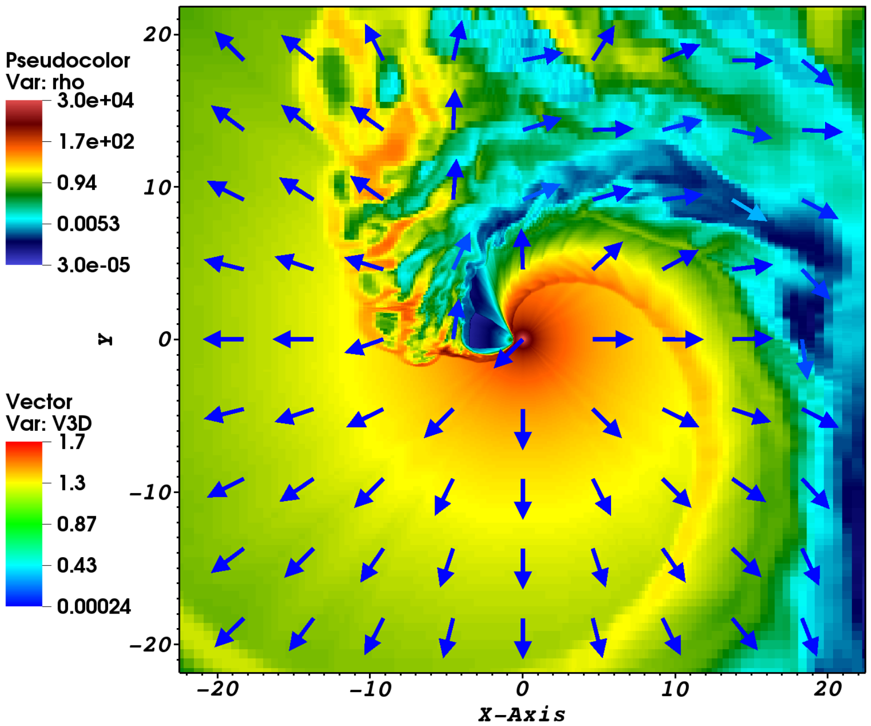
2D with doubled resolution

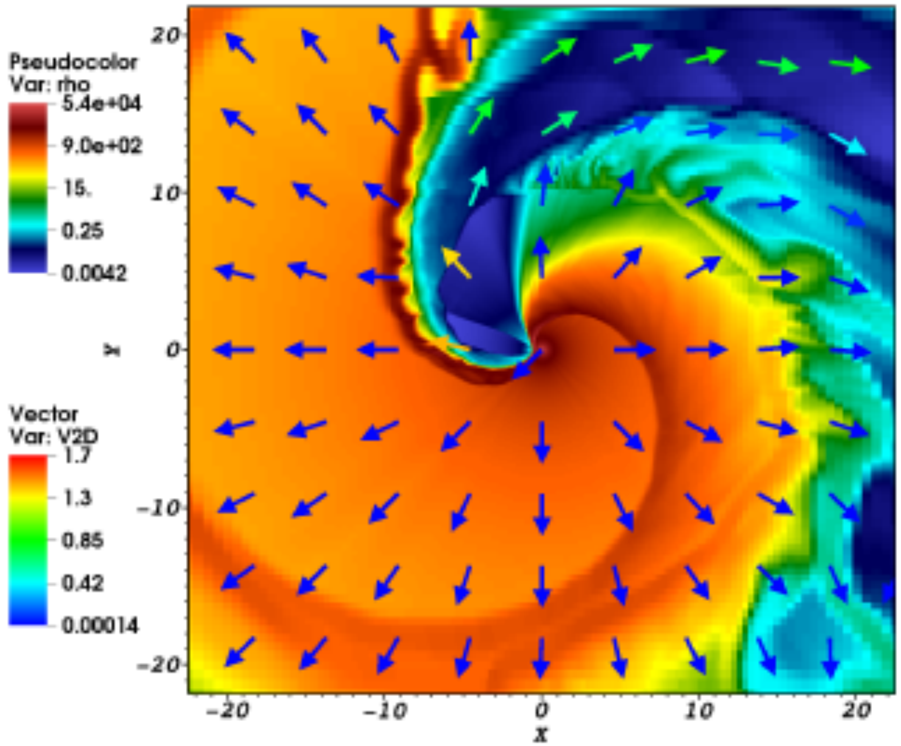


...and extended box

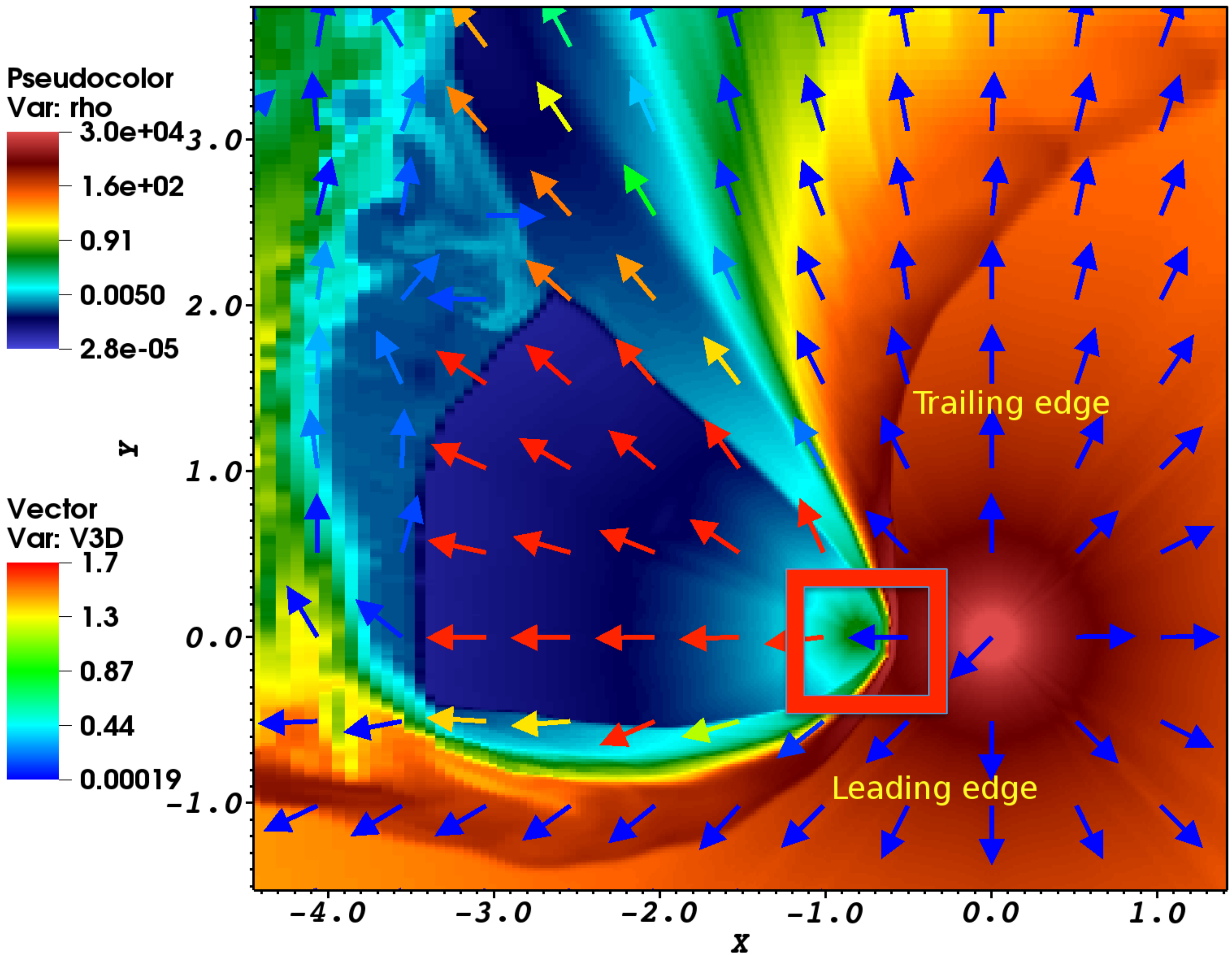
Introduction

3D and 2D with the same resolution





Bosch-Ramon, Barkov, MP (2015)



Bosch-Ramon, Barkov, MP (2015)

- Our aim is to characterize in detail the wind-wind interaction at scales of 1.e12-1.e13 cm.

- Setup for the simulations:
  - Γ= 1.4444 (cold protons and relativistic electrons)

  - $\rho_{pw,0}$= 1.067e-23 g/cm^3
  - $T_{pw,0}$= 1.85e12 K
  - $v_{pw,0}$= 0.996661754 c

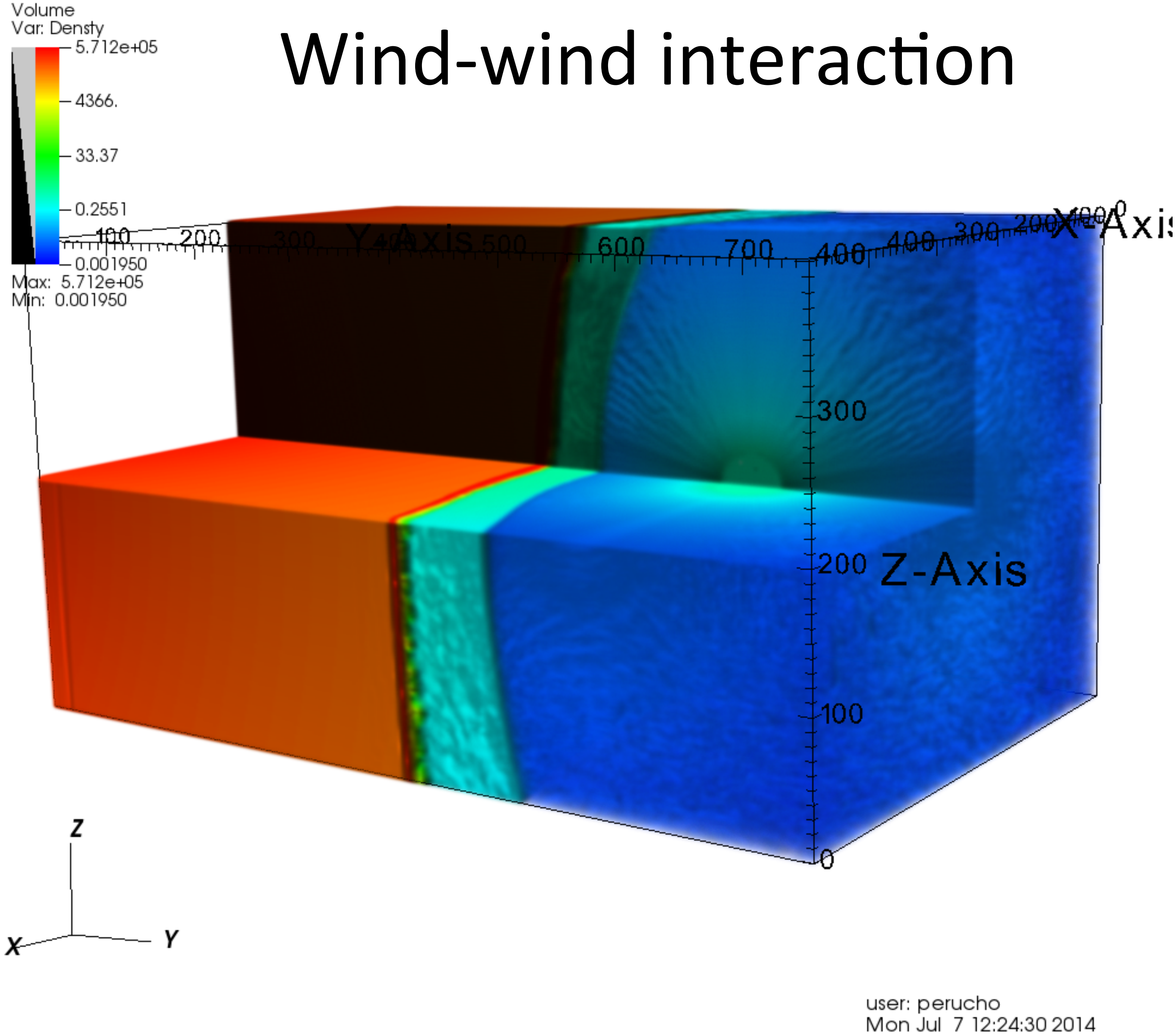
  - $\rho_{sw,0}$= 3.1e-15 g/cm^3
  - $v_{sw,0}$= 4.3333e-3 c
  - $T_{sw,0}$= 1.09e6 K

  - R_{char}= 4e11 cm
  - R_{orb} = 3e13 cm
  - R_{inj} = 1e12 cm

$\eta \approx 0.07$

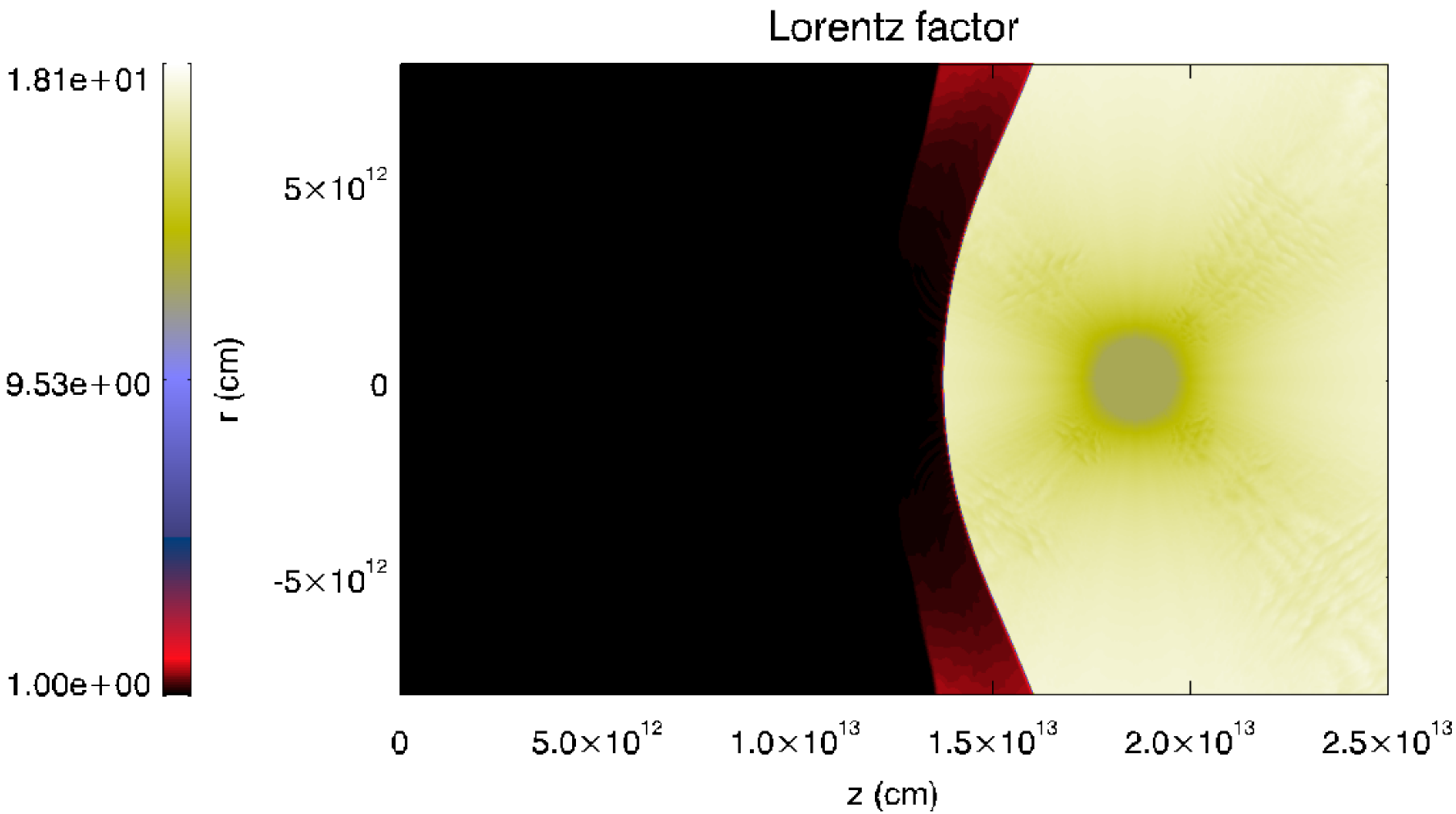
Ratpenat (3D RHD code)

Wind-wind interaction

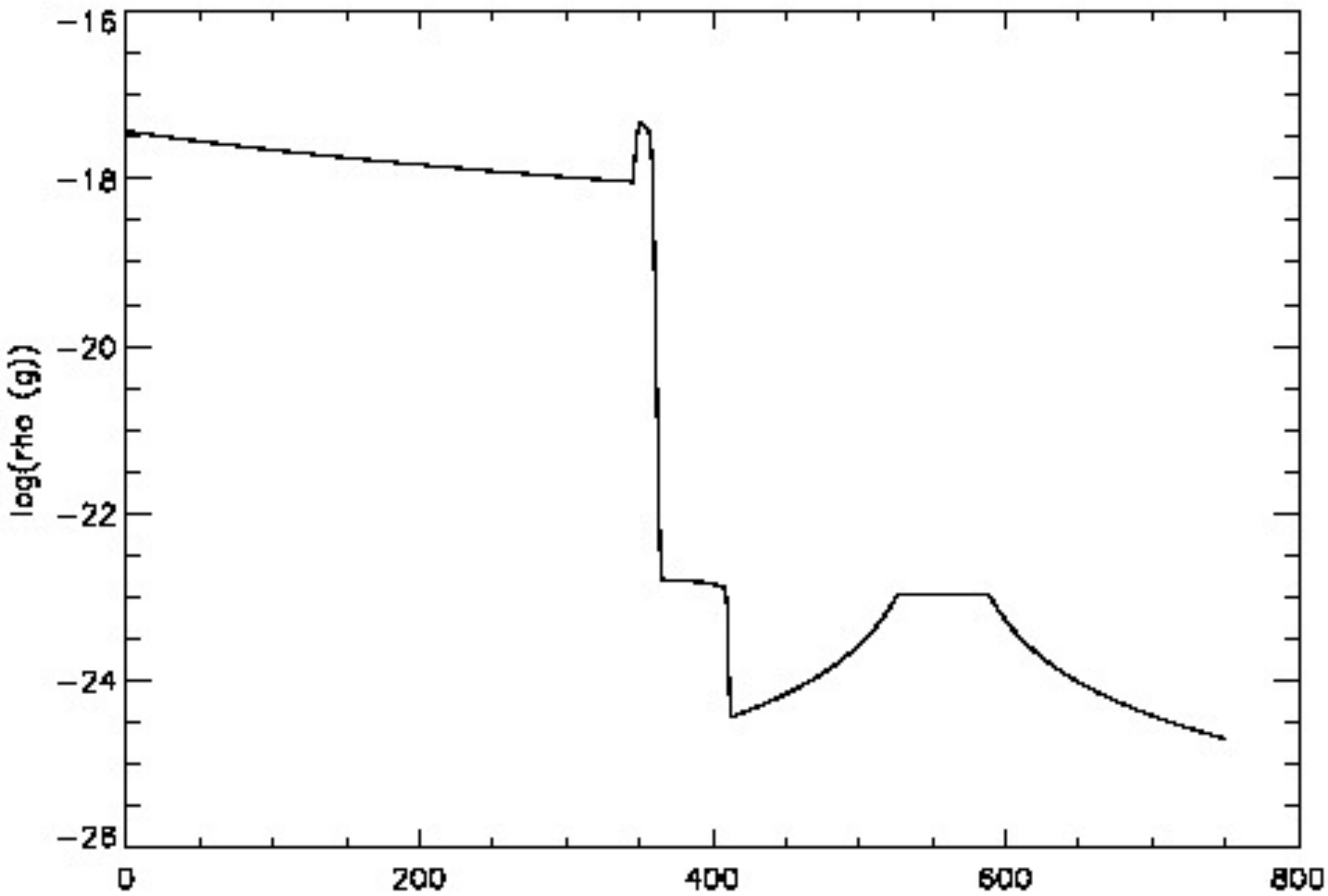


t = 7e3 s

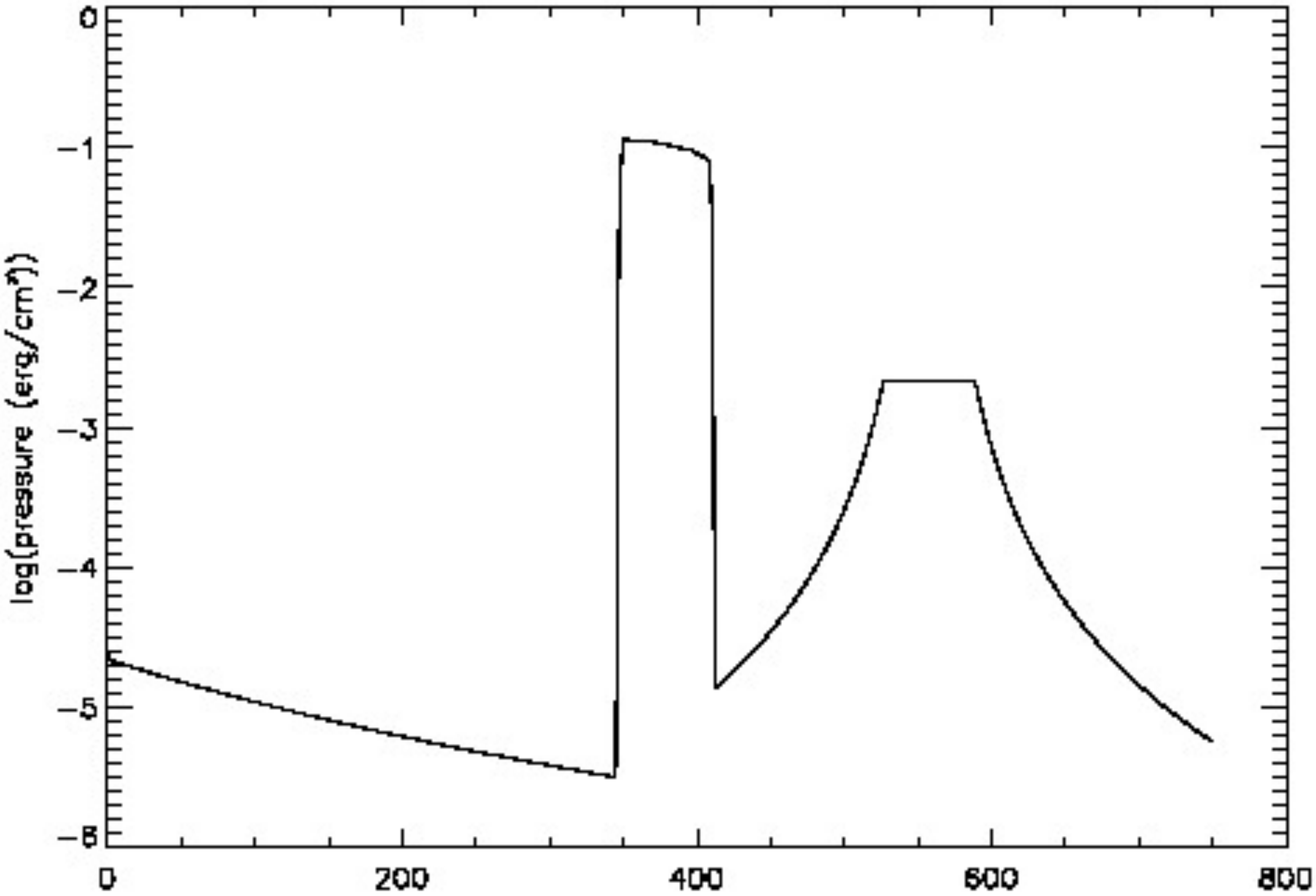
Wind-wind interaction



Density profile



Pressure profile



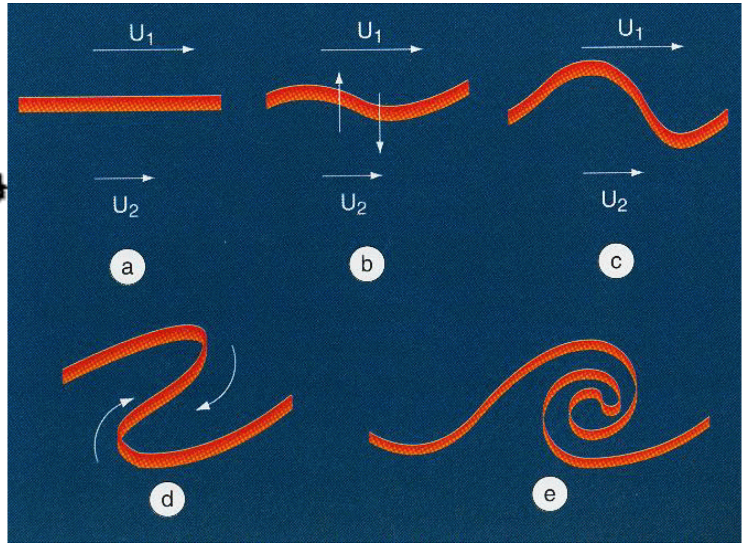
Kelvin-Helmholtz

$$A = A_0 \exp i(k_x x + k_y y + nt)$$

$$n = -k_x(\alpha_1 U_1 + \alpha_2 U_2) \pm [gk(\alpha_1 - \alpha_2) - k_x^2 \alpha_1 \alpha_2 (U_1 - U_2)^2]^{\frac{1}{2}}$$

$$\alpha_1 = \frac{\rho_1}{\rho_1 + \rho_2} \quad \text{and} \quad \alpha_2 = \frac{\rho_2}{\rho_1 + \rho_2}$$

$$k_x^2 \alpha_1 \alpha_2 (U_1 - U_2)^2 > gk(\alpha_1 - \alpha_2)$$



At the interaction region, $g \approx 0$, $\rho_2 \approx 10^6 \rho_1$ and:

$$n^2 \approx k_x^2 \alpha_1 \alpha_2 (U_1 - U_2)^2 \approx k_x^2 \rho_1/\rho_2 (U_1 - U_2)^2$$

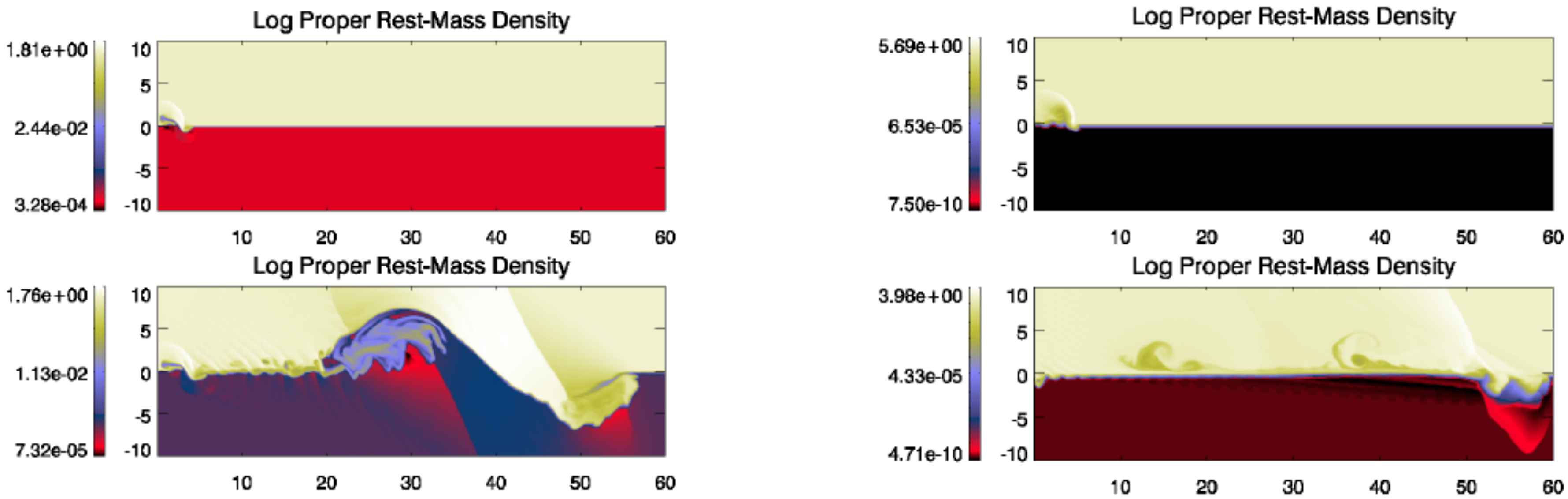
$Im(n) \approx 10^{-3} \mu k$ (growth rate), with $0 \le \mu \le 1.$

From Chandrasekhar, 1961

This means that the growth of KHI will be only relevant for wavelengths $\lambda \le 10^{-3} R_c$, with R_c the characteristic distance of the problem.

Kelvin-Helmholtz

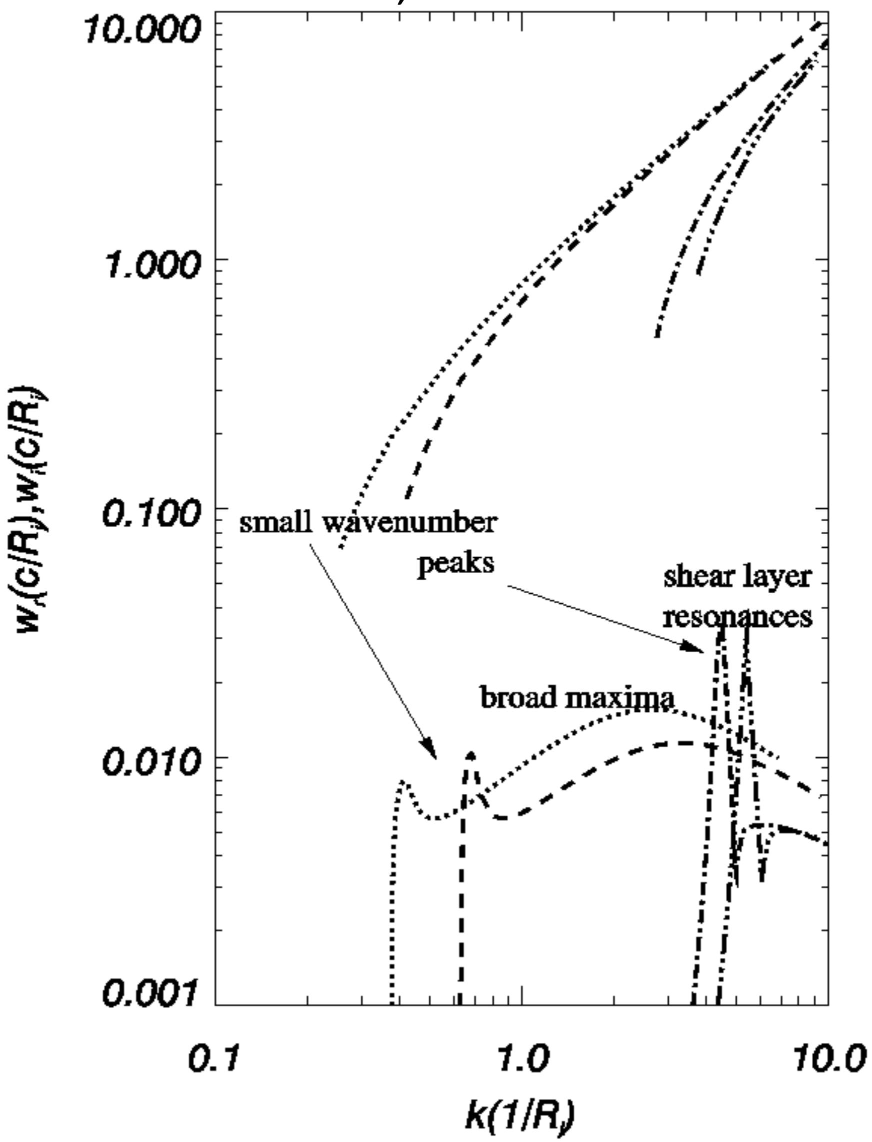
The reacceleration of the shocked pulsar wind to mildly relativistic velocities makes it more stable (Perucho et al. 2004, 2005, Bosch-Ramon et al. 2012).
Once the flow becomes supersonic, shocks would be responsible for mixing at any change of direction.

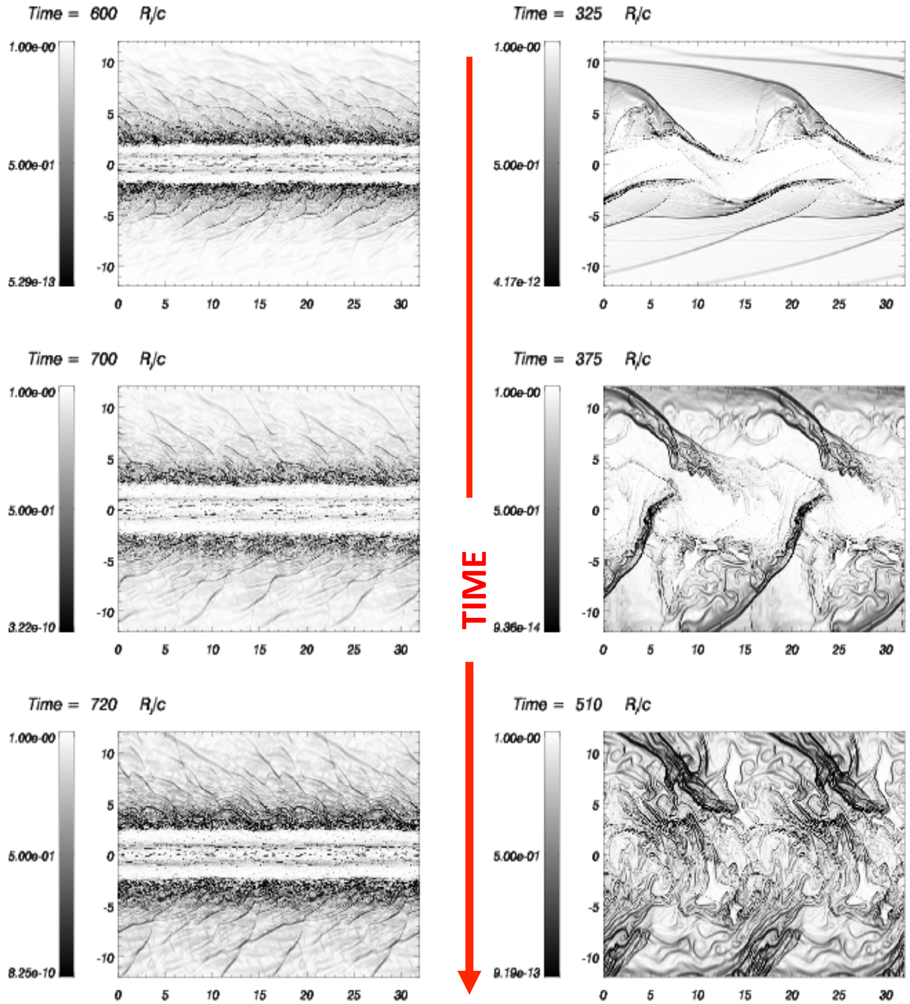


Bosch-Ramon et al. 2012

Kelvin-Helmholtz instability in relativistic flows

Perucho et al. 2005, 2007



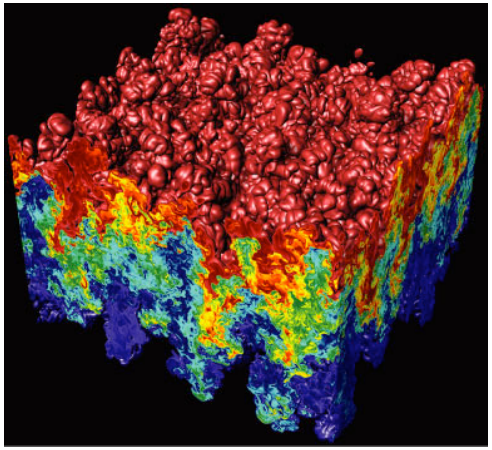


Sheared jet (d=0.2 Rj)
Lorentz factor 20

Sheared jet (d=0.2 Rj)
Lorentz factor 5

See also short λ saturation (Hardee 2011)

Rayleigh-Taylor



Cabot & Cook (2006)

$A = A_0 \exp(ik_x x + ik_y y + nt)$

$$n^2 = gk\left\{\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}\right\}$$

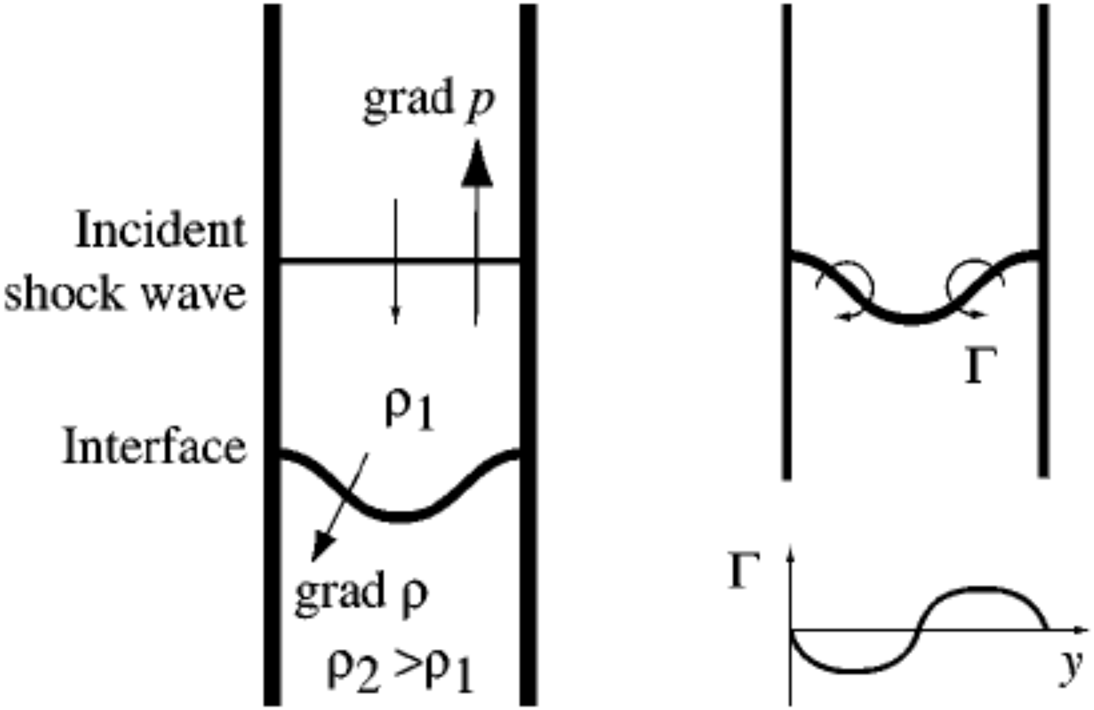
In this case, *n* must be real for the amplitude to grow.
In binaries, the acceleration (*g* in the equation) is given by the Coriolis force (v_{rot}^2/r). Taking $v_{rot} \approx 3 \cdot 10^8$ cm/s, at the scales of the system size, $r \approx 10^{12}$ cm, $a_{Cor} \approx 10^4$ cm/s^2.

If $\rho_2 >> \rho_1$:

$$n^2 \approx g\, k$$

Taking $g \approx 10^4$ cm/s^2, we obtain that values $k \geq 0.01$ ($\lambda \leq 600\ R_c$) will show high growth rates.
As ρ_1 approaches ρ_2, longer wavelengths reduce their growth-rates.

Richtmeyer-Meshkov



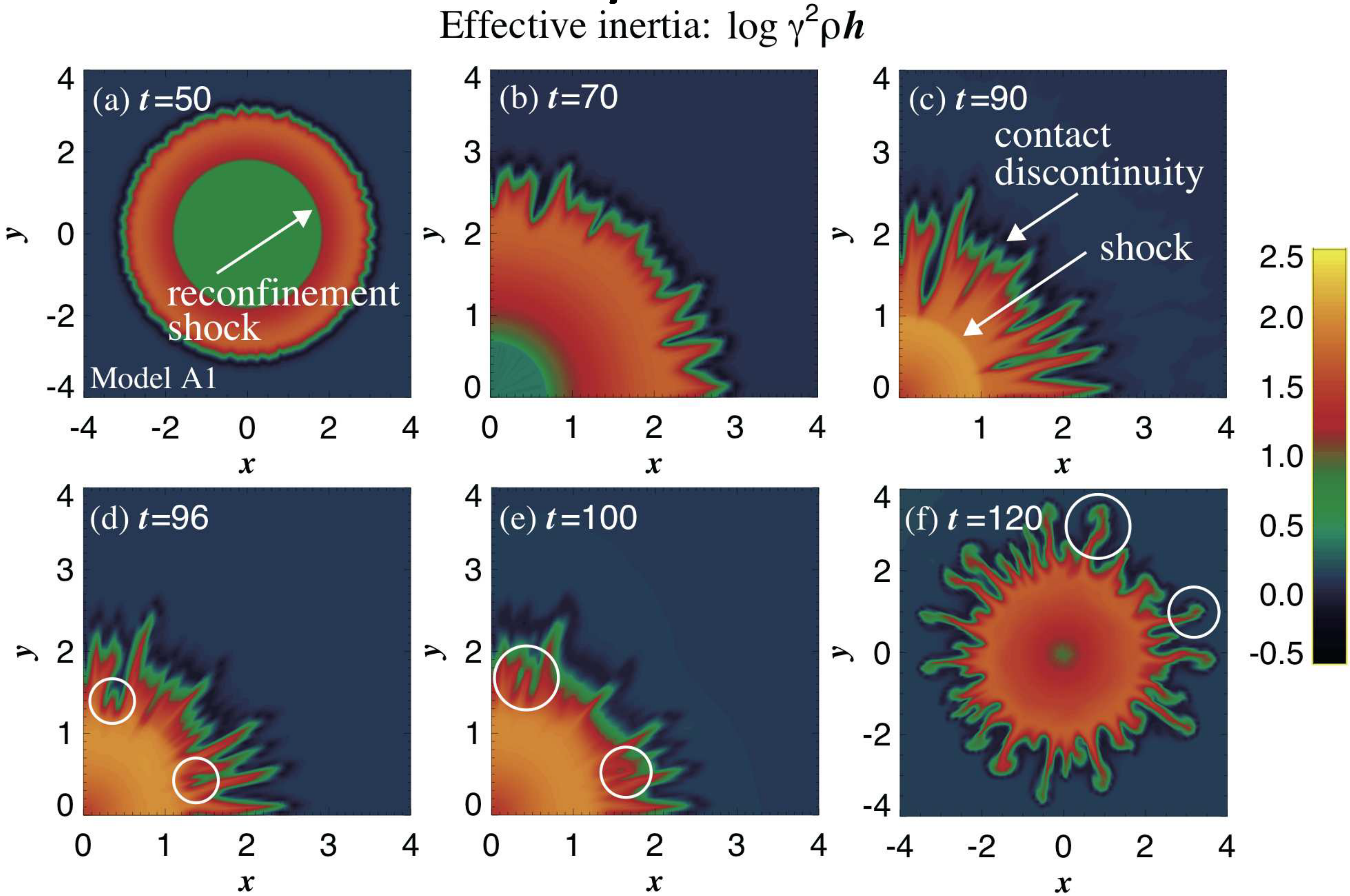
Brouillette (2002)
Holmes et al. (1995)

$\dot{\eta}_{imp} = k[u]A\eta_0$ $\quad A \equiv (\rho_2 - \rho_1)/(\rho_1 + \rho_2)$ Richtmeyer (1960)

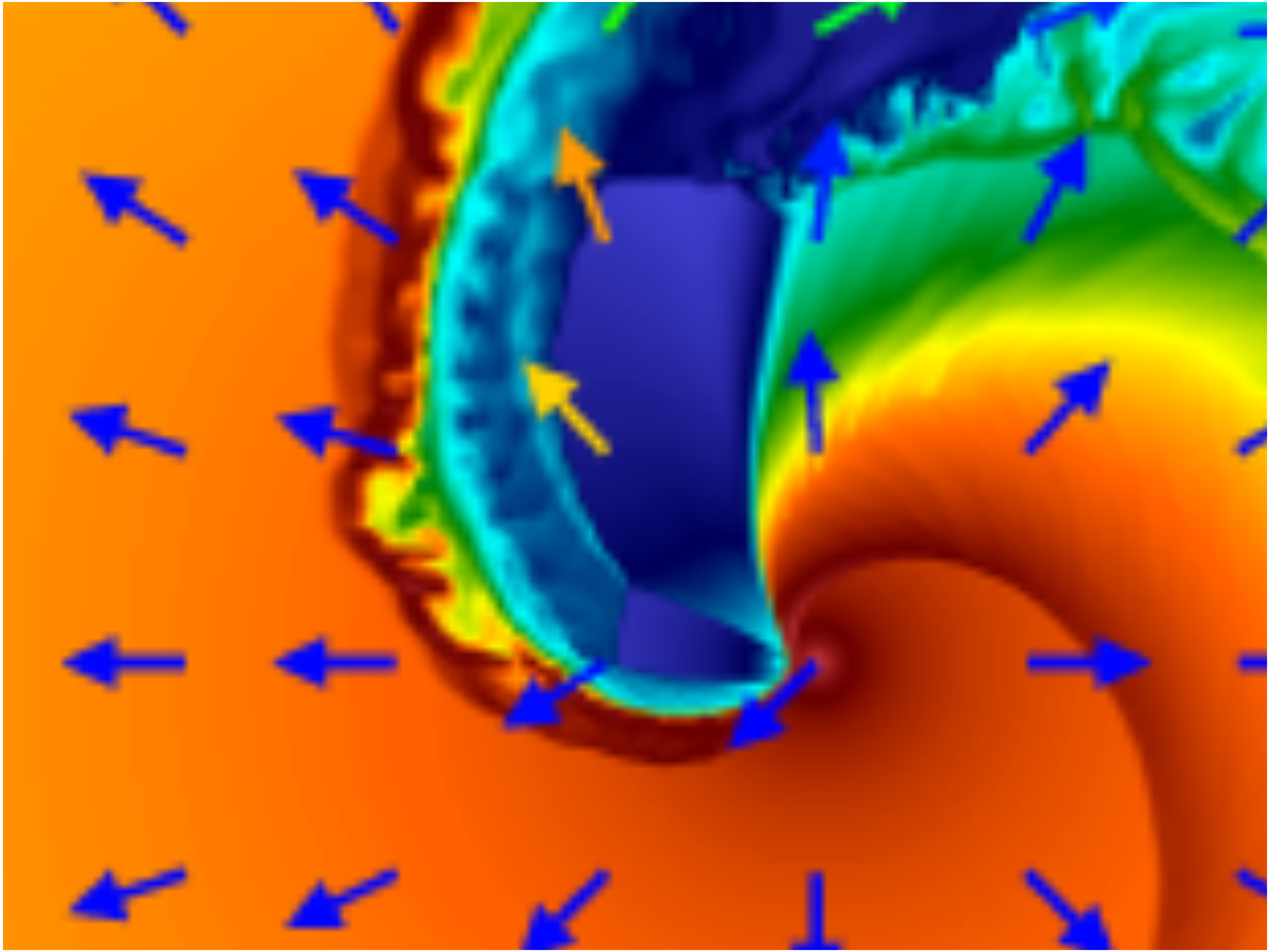
η is the amplitude

$[u]$ is the change in the interface velocity induced by the refraction of the shock wave.

Richtmeyer-Meshkov



Matsumoto & Masada (2013). Reconfinement shocks in jets.



Conclusions

- KHI will produce small scale mixing regions and may grow fast before the shocked pulsar wind is accelerated.

- RTI grows faster at different wavelengths and its growth can be accelerated by the RMI.