Monte Carlo Simulations of Proton Acceleration in Colliding Wind Binaries

Astroparticle School

Obertrubach-Bärnfels, 9th October 2015

Overview

- Motivations
- Introduction
- Simulations
- Summary

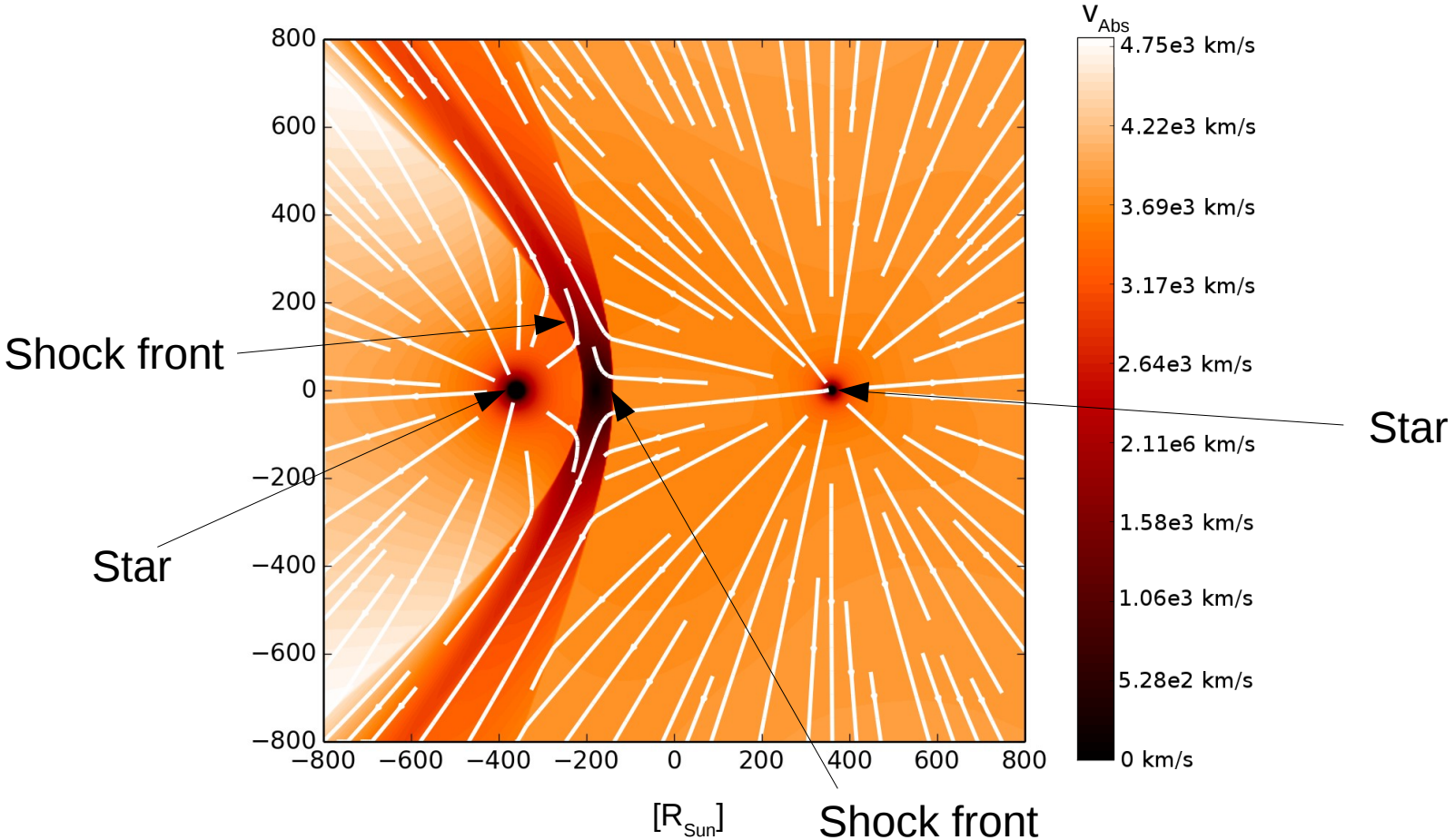
Motivations

- Theoretical models predict detectable gamma-ray emission from Colliding Wind Binaries (injection efficiency not considered)
- Only detection of gamma-rays from CWBs associated with Eta Carinae
- No detection of gamma-rays from WR140, nor WR147
- Simulations of particle acceleration can treat injection efficiency

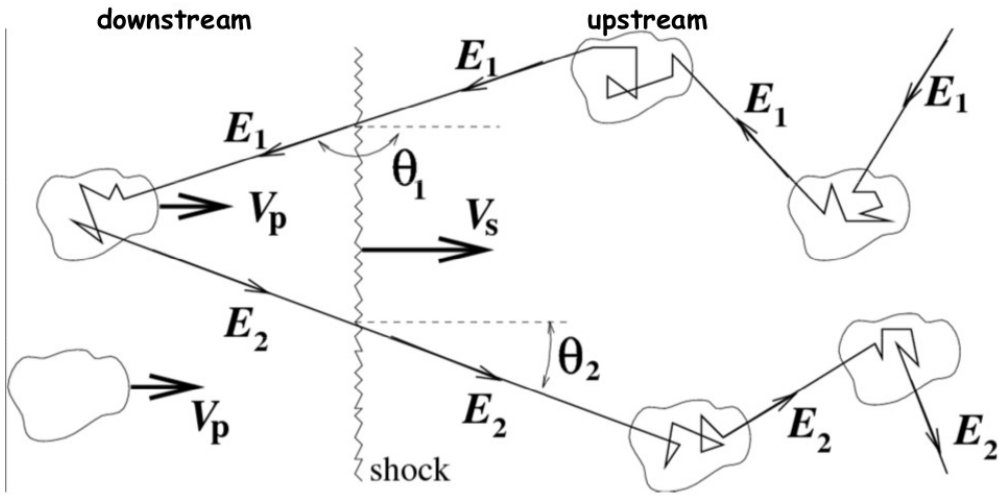
Introduction: Colliding Wind Binaries

- Why Colliding Wind Binaries?

  → Strong stellar winds collide and form shock fronts



Introduction: Diffusive Shock Acceleration (DSA)



Lecture slides Astroparticle physics

- First order Fermi process
- Magnetic turbulences responsible for scattering (scattering centers)
- In the frame of the scattering centers:
  → elastic scattering
  → pitch angle isotropization

Simulations - Different types

- Particle in cell (PIC)
- Hybrid simulations
- Monte Carlo simulations

Simulations - Different types

- Particle in cell (PIC): → particles followed in the simulation box

  → electromagnetic fields determined by particle distribution and Maxwell equations

  → computationally demanding

- Hybrid simulations

- Monte Carlo simulations

Simulations - Different types

- Particle in cell (PIC)

- Hybrid simulations:
  - → electrons treated as fluid
  - → protons followed in the simulation box
  - → electromagnetic fields determined by particle distribution and Maxwell equations
  - → computationally demanding (but less than PIC)

- Monte Carlo simulations

Simulations - Different types

- Particle in cell (PIC)
- Hybrid simulations
- Monte Carlo simulations (test particle):

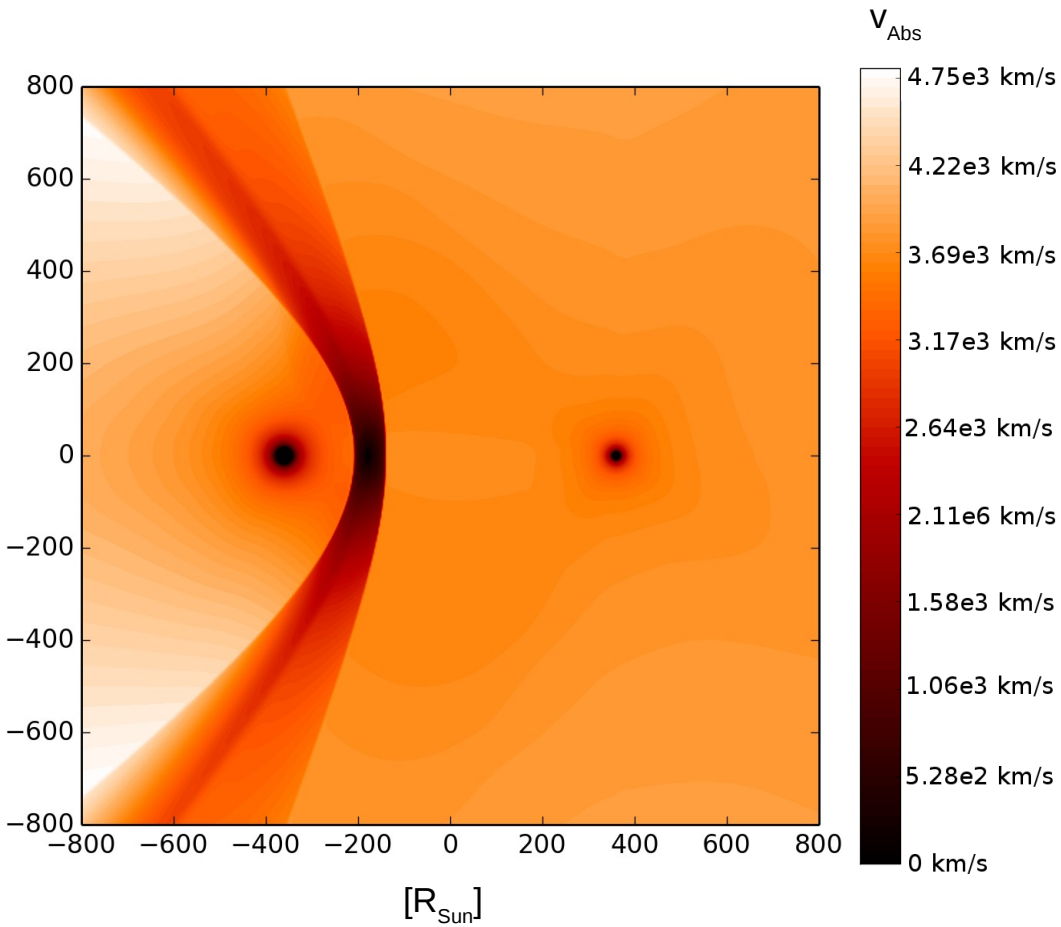
  → particles followed in simulation region

  → background of plasma and electromagnetic field (jump conditions)

  → spectrum over large energy range

  → scattering process modelled

Simulations – The chosen one: Monte Carlo



- Extremely large simulation region
- Hydrodynamic simulations can be used as background

  ⇓

  the particular geometry of the system can be taken into account
- Injection efficiency can be considered (under certain assumptions on the scattering process)

Simulations – Basic setup

- 2 Cells (upstream, downstream)
- Guiding center approximation
- Particles move in the cells until:

  (a) A scattering occurs after a mean free path (in the flow frame):

  $$\lambda_{mfp} = \eta r_g$$

  (b) The cell boundary is reached → the particle changes cell and moves there until (a), (b) or (c) occurs

  (c) The particle reaches the boundary of the simulation region → particle removed from the system

- Particle splitting

Simulations – Basic setup

- Scattering:

  → transformation of momentum from shock frame to plasma flow frame

  → new $\mu = \cos(\theta_{pitch})$ assigned with uniform distribution in [-1,1] (flow frame)

  → energy conserved (flow frame)

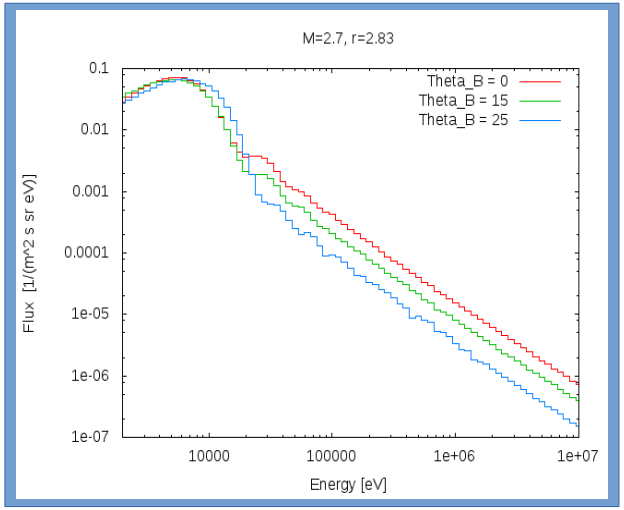
  → transformation from plasma flow frame to shock frame

Simulations – Basic setup

- Cross-field diffusion: guiding center moved in random direction by

$$d = 2 \cdot \varepsilon \cdot r_g \quad \text{with} \quad r_g = \frac{p \sin(\theta)}{qB} \quad \text{and} \quad \varepsilon \in [0,1]$$

- Record of spectrum: → when a particle crosses a certain surface, its statistical weight is added to the appropriate energy bin



Simulations with HD background

- Idea: use results of HD simulations of colliding wind binaries as background for Monte Carlo simulations (test particle approach)
- Considered binary system: Wolf-Rayet and B stars

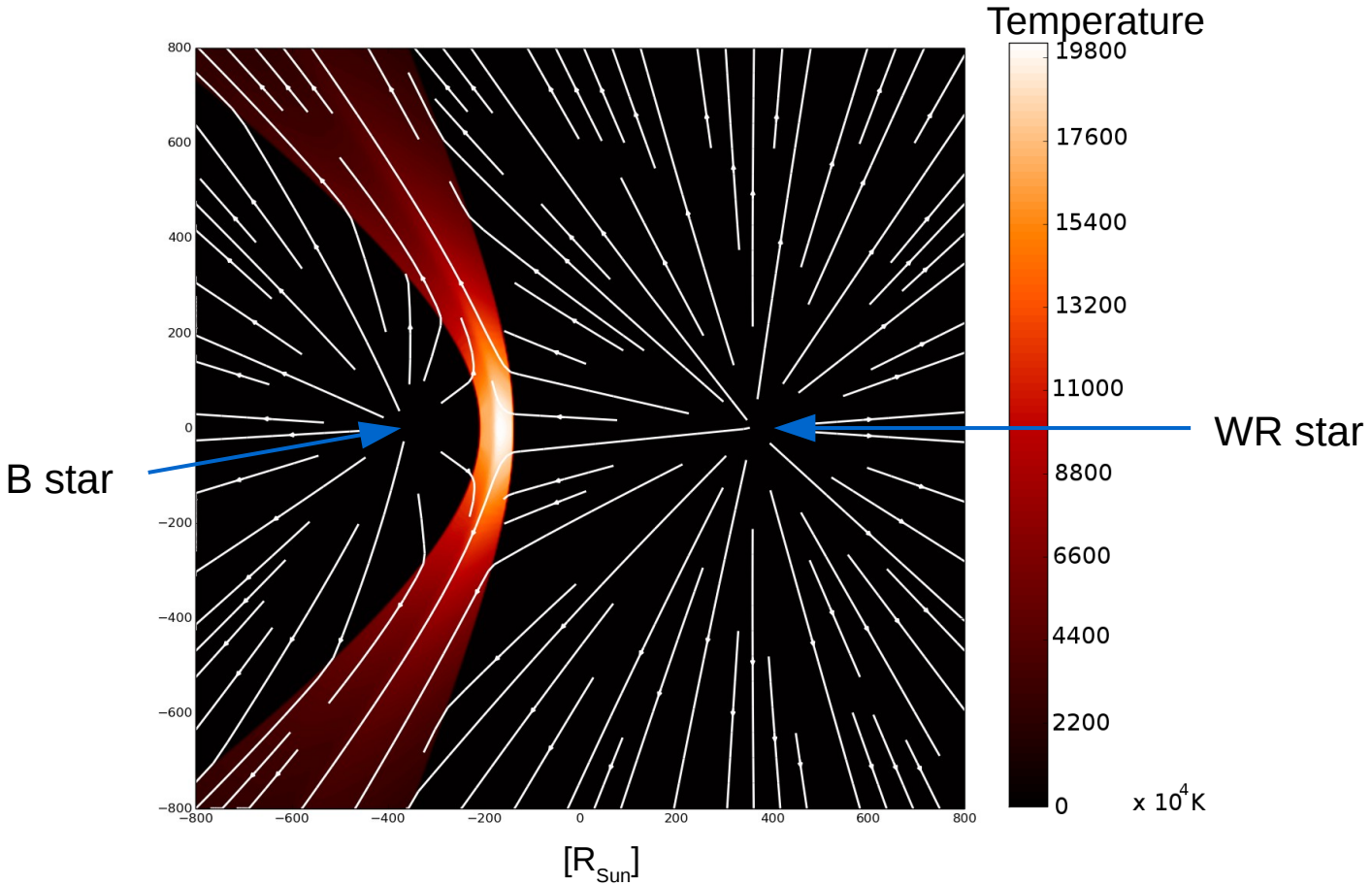
Star	M_* [$M_\odot$]	R_* [$R_\odot$]	T_* [K]	L_* [$L_\odot$]	$\dot{M}$ [$M_\odot$ yr^{-1}]	v_∞ [km s^{-1}]	B_* [G]
B	30	20	23000	10^5	10^{-6}	4000	100
WR	30	10	40000	2.3×10^5	10^{-5}	4000	100

- M_* stellar mass
- R_* stellar radius
- T_* effective temperature
- L_* luminosity
- $\dot{M}$ mass loss rate
- v_∞ terminal velocity of wind
- B_* surface magnetic field

Simulations with HD background

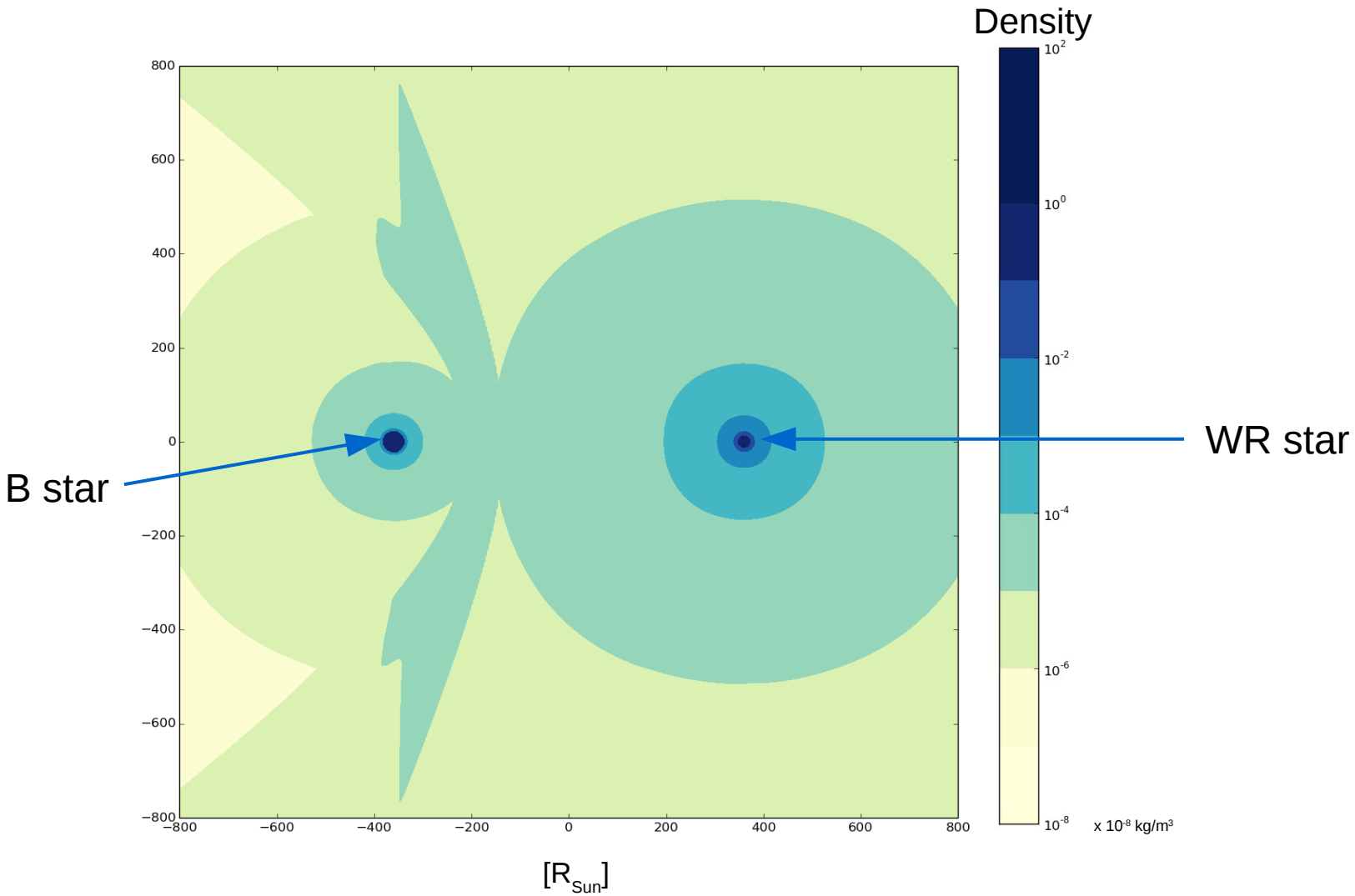
- Idea: use results of HD simulations of colliding wind binaries as background for Monte Carlo simulations (test particle approach)

- Considered binary system: Wolf-Rayet and B stars

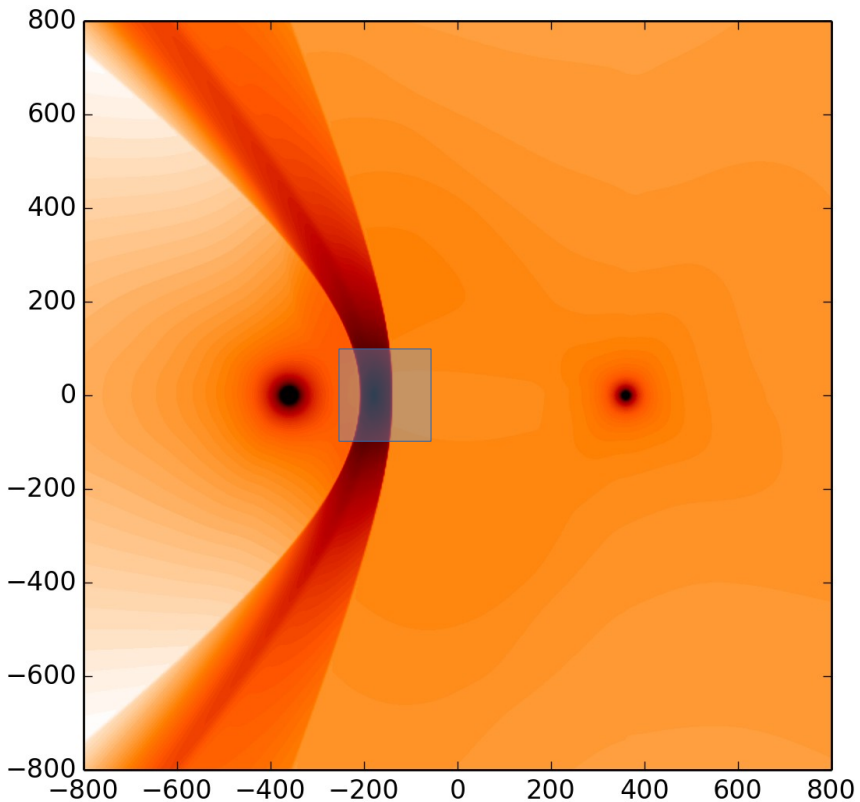


Simulations with HD background

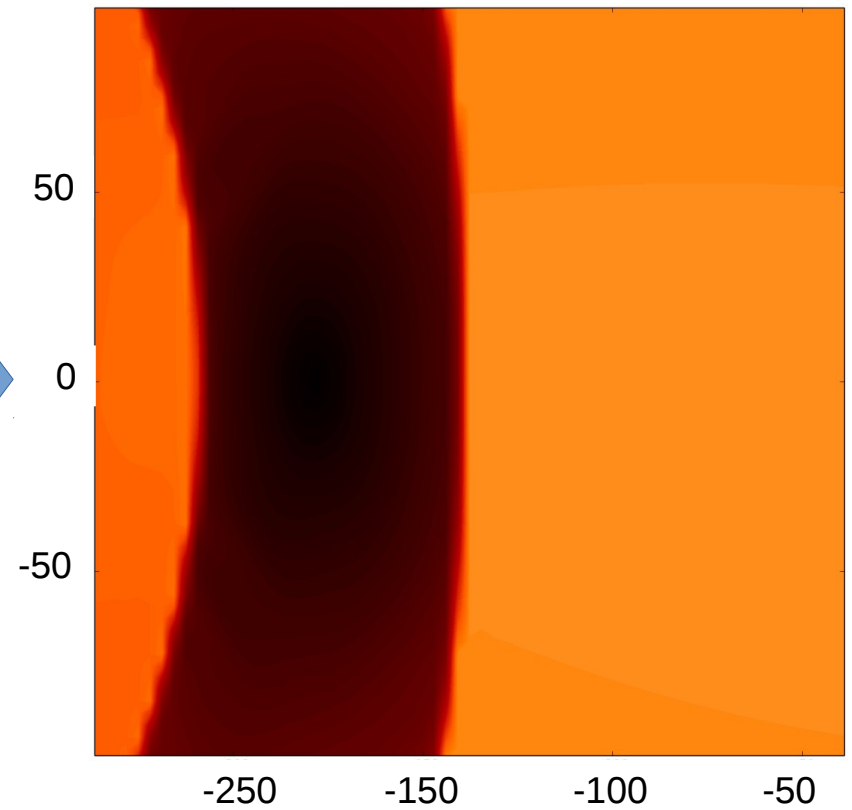
- Compression ratio r >≈ 4 along shocks



Simulations with HD background - First runs

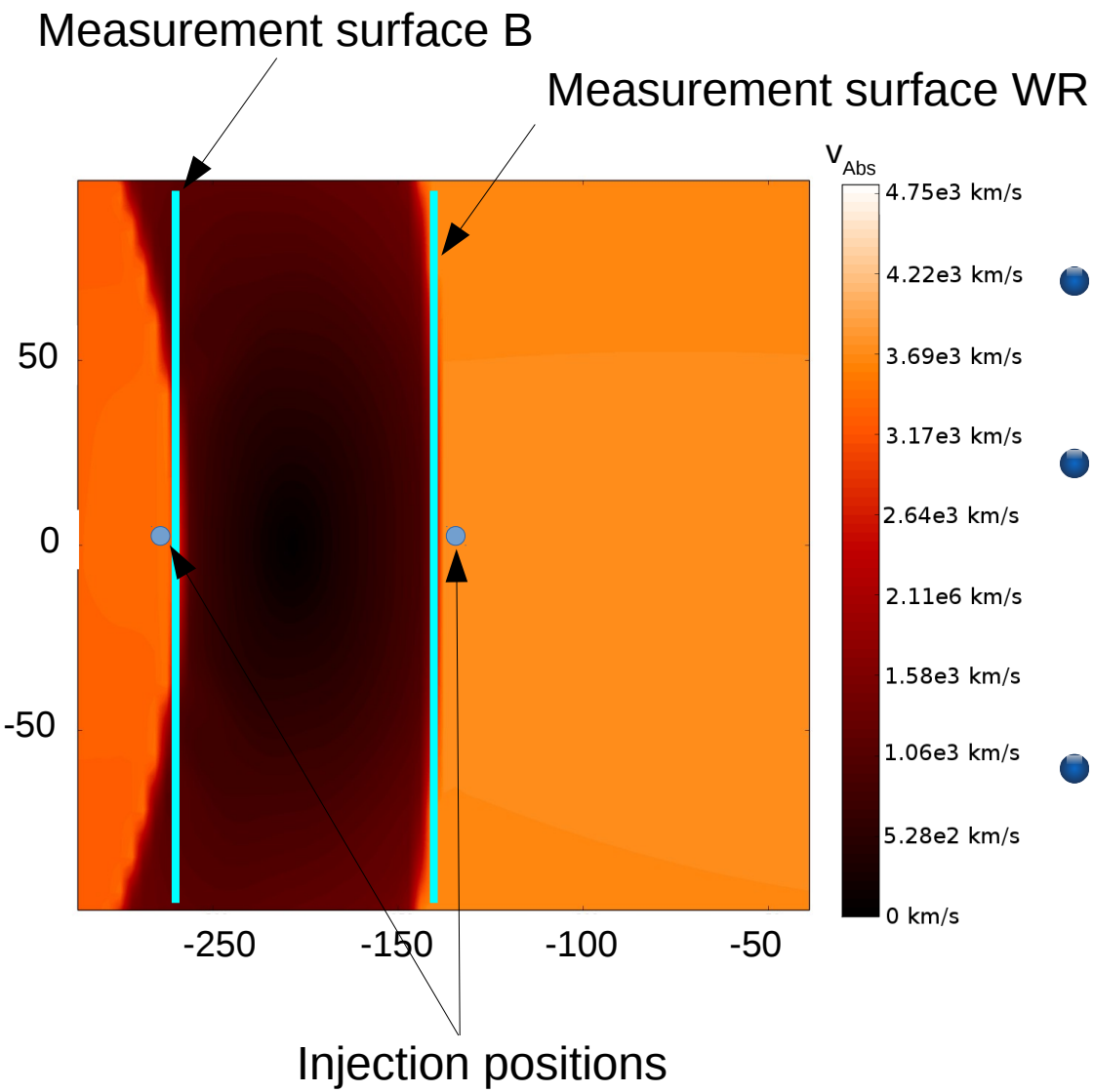


HD simulation region



Selection:
60x60x60 cells

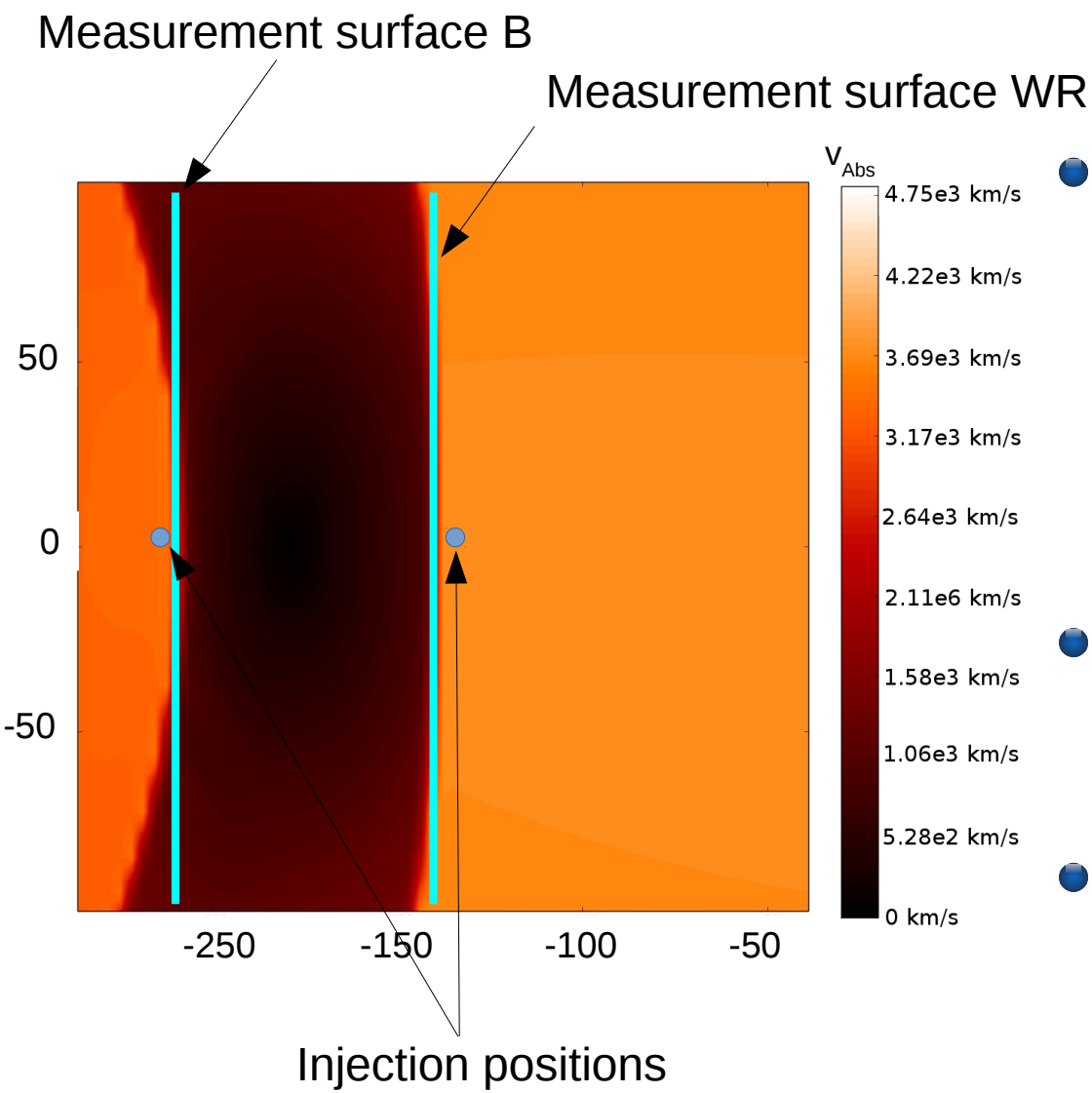
Simulations with HD background - First runs



- Particles injected upstream of shock
- Maxwell-Boltzmann distribution,

  $T \approx 10^4$ K
- Particles leave the system by crossing boundary of simulation region

Simulations with HD background - First runs



- Magnetic field and plasma flow aligned

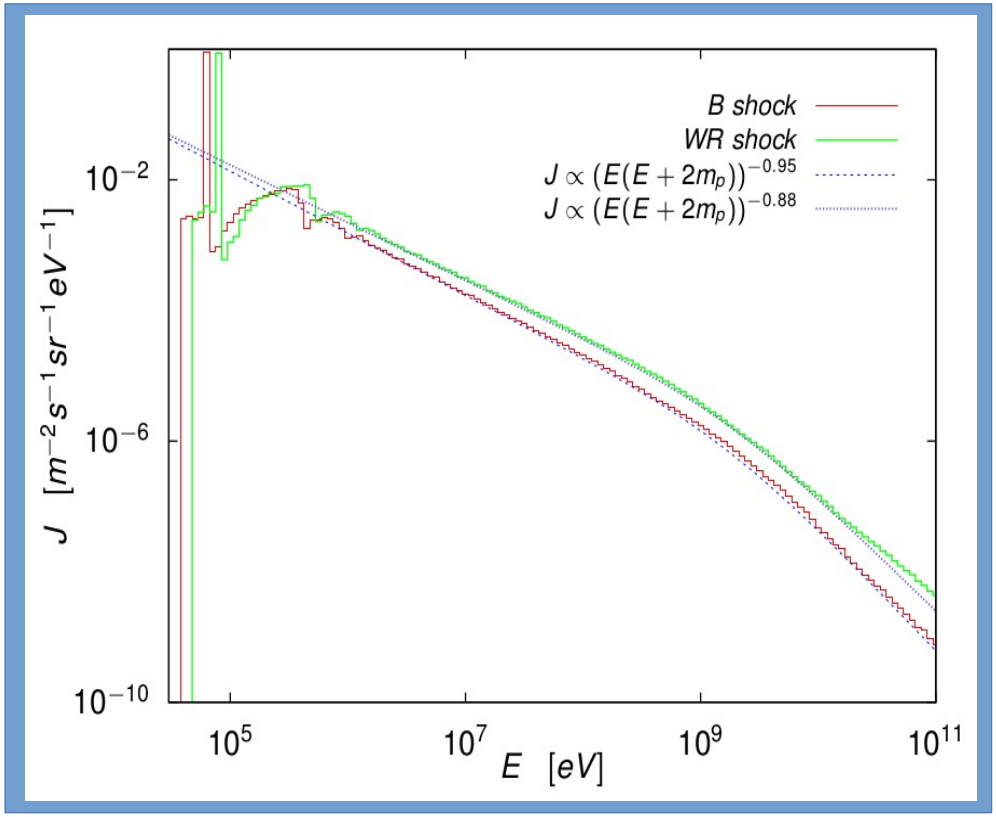
  $B_{surface} = 100$ G

  $B \approx 10^{-4}$ T at injection position (B shock)
  $B \approx 10^{-5}$ T at injection position (WR shock)

- B field directly downstream determined by shock-jump conditions

- B field inside collision region scales with thermal pressure

Simulations with HD background - First runs



First simulations with HD background

- Results:

Star	Spectral index σ	Injection efficiency ε
B	1.90 ± 0.02	$\approx 11\%$
WR	1.76 ± 0.02	$\approx 14\%$

- Slightly different spectral indices and injection efficiencies on the two sides of wind collision region

Summary

- Eta Carinae only CWB system with gamma-ray emission detected
- Simulations needed for considering injection efficiency
- Monte Carlo simulations: can extend over large energy range
- Test-particle approach with background determined by HD simulations
- Future: → background from MHD simulations
  → computation of gamma-ray fluxes

References

- M. G. Baring, D. C. Ellison and F. C. Jones, *Monte Carlo simulations of particle acceleration at oblique shocks*, Astrophysical Journal Supplement Series **90** (1994) 547-552

- M. G. Baring, D. C. Ellison and F. C. Jones, *Monte Carlo simulations of particle acceleration at oblique shocks: Including cross-field diffusion*, Advances in Space Research **15** (1995) 397-400

- A. Reimer, M. Pohl and O. Reimer, *Nonthermal high-energy emission from colliding winds of massive stars*, The Astrophysical Journal **644** (2006) 1118

- K. Reitberger et al., *High-energy Particle Transport in Three-dimensional Hydrodynamic Models of Colliding-wind Binaries*, The Astrophysical Journal **782** (2014) 96

- M. Werner, O. Reimer, A. Reimer and K. Egberts, *Fermi-LAT upper limits on gamma-ray emission from colliding wind binaries*, Astronomy & Astrophysics **555** (2013) A102