Numerical simulations of circumstellar shells

Allard Jan van Marle

Rony Keppens, Zakaria Meliani, Leen Decin

Circumstellar shells

- High density features in the circumstellar medium
- Formed by wind interactions
  - colliding binary winds,
  - subsequent evolutionary phases
  - wind-ISM collisions
  - etc.
- (In-)directly visible as circumstellar nebulae
- Can be reproduced numerically with hydrodynamcs code (MPI-AMVAC)

Hydrodynamics + radiative cooling

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot \rho \vec{v} \vec{v} = -\nabla P$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e + P) \vec{v} = -\frac{\rho^2}{m_h^2} \Lambda(T)$$

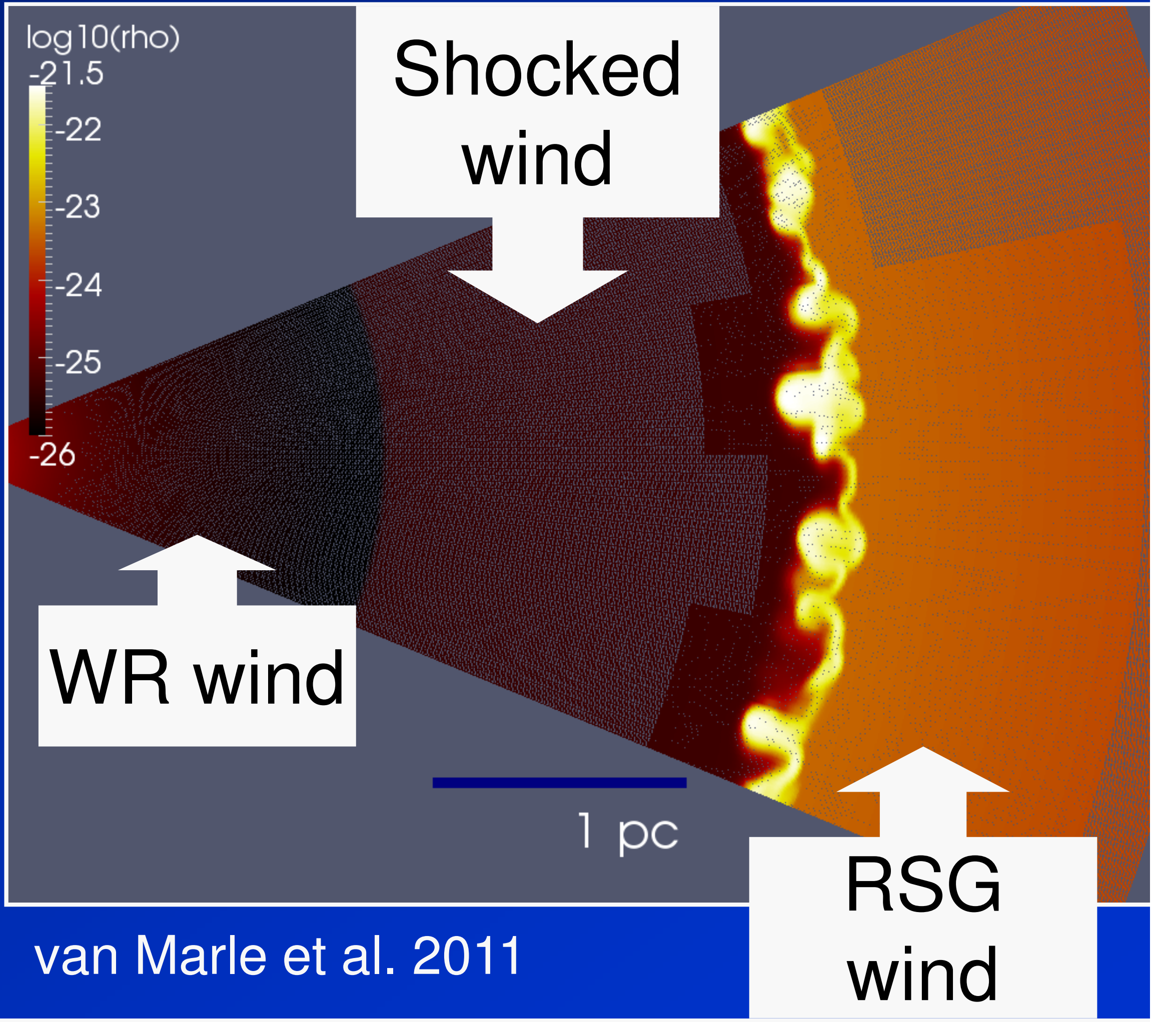
To form a nebula around a single star

- There has to be a rapid change in wind parameters (velocity, massloss rate)
- Typical examples:

RSG → WR, LBV→ WR, RSG→ BSG, AGB → post-AGB

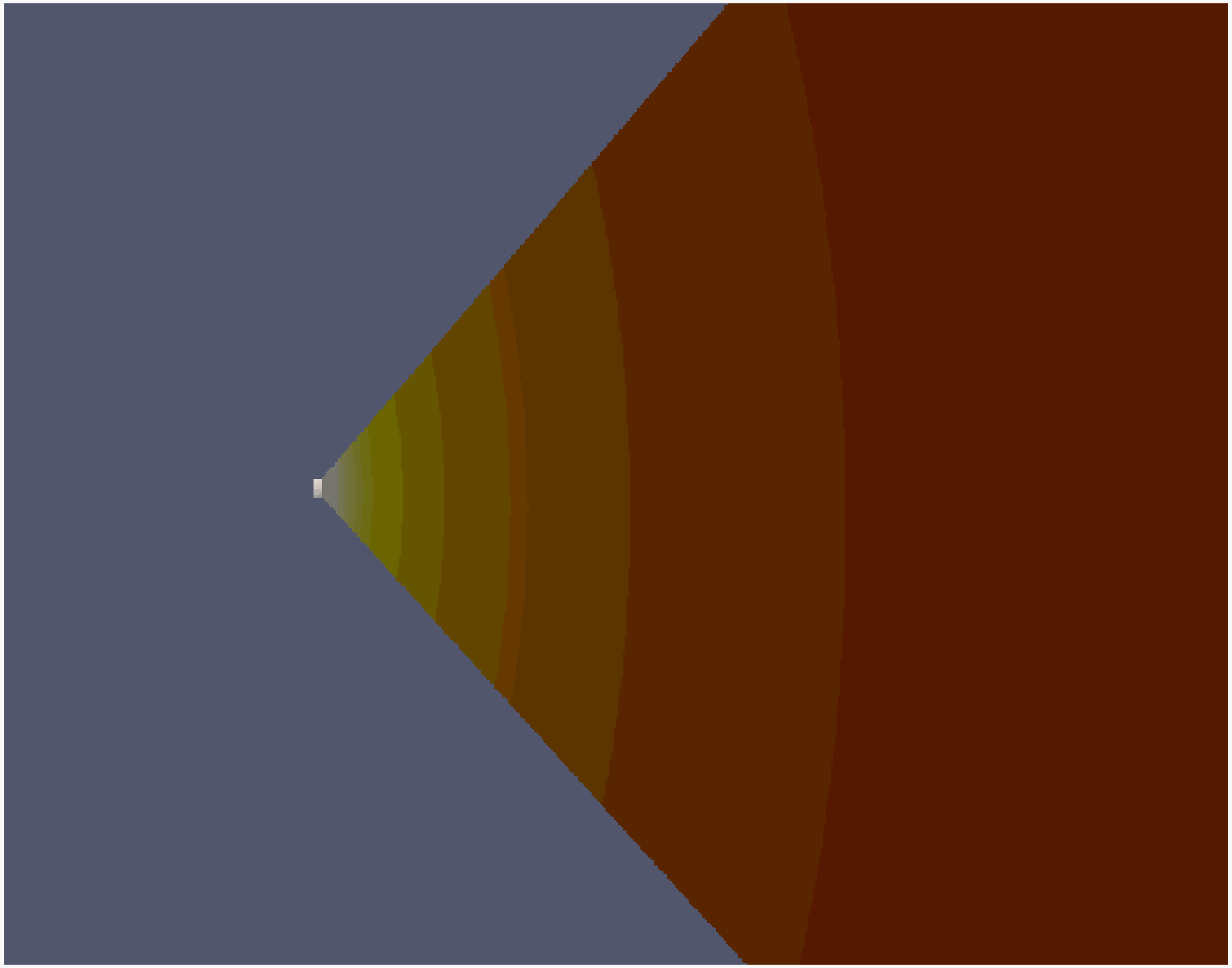
Cross section

- RSG: 10 km/s, 10^{-4} $M_\odot$/yr
- WR: 2000 km/s, 10^{-5} $M_\odot$/yr
- Runtime: 40,000 yr
- Radiative cooling
- 800x128x128



van Marle et al. 2011

Formation of WR nebula



How would it appear?

- Emission nebula
- High density dominates ($L \sim n^2$)
- Filamentary structure

NGC 6888 (Hα LRGB)

et al. Optical: SDSU/MLO/Y. Chu et al

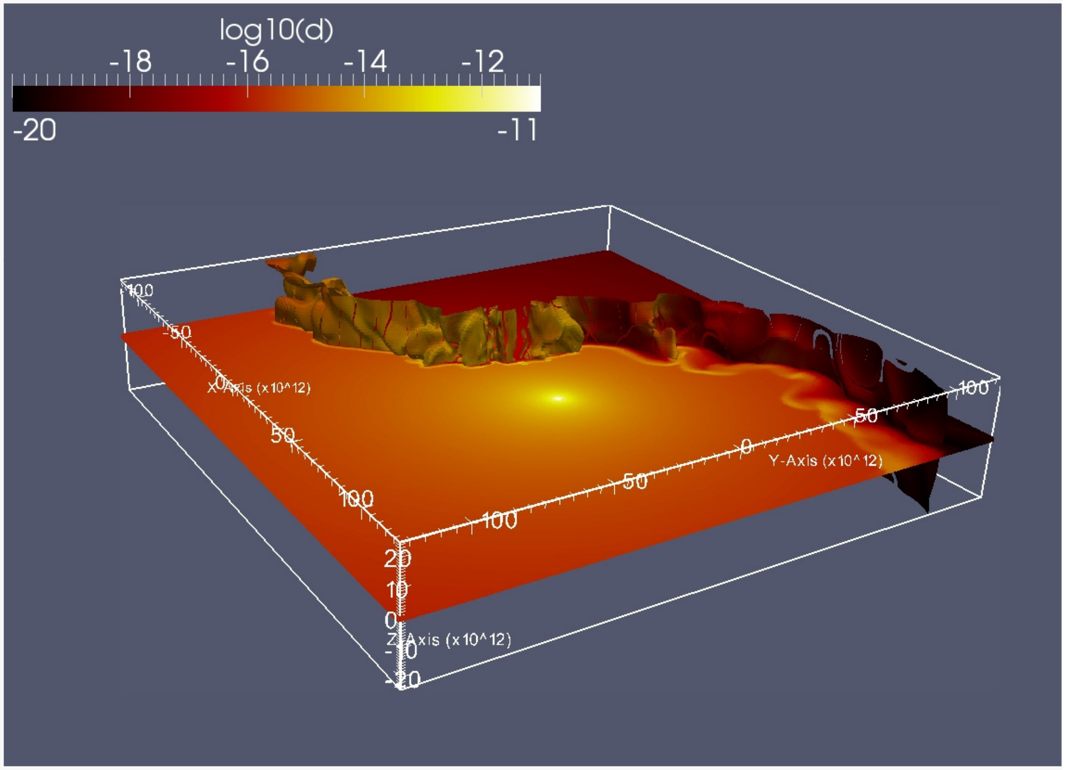
Massive stars often live in binaries

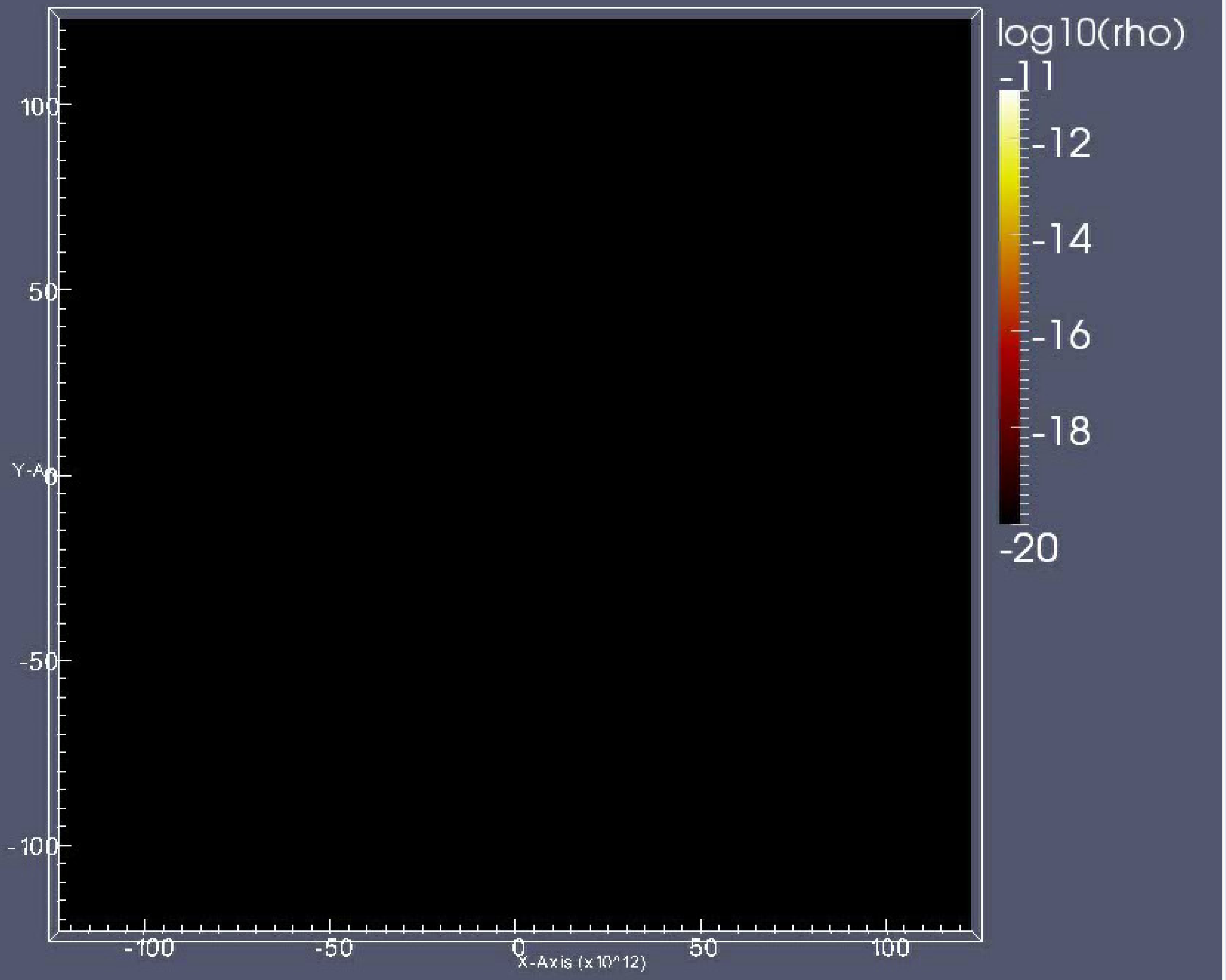
- Orbital motion destroys symmetry
- 3-D is no longer a luxury. It's a necessity
- Two stars in a 3-D cartesian grid.
- Both wind expansion and orbital motion
- Example: LBV+O binary with 1 yr period

(van Marle et al. A&A 2011)

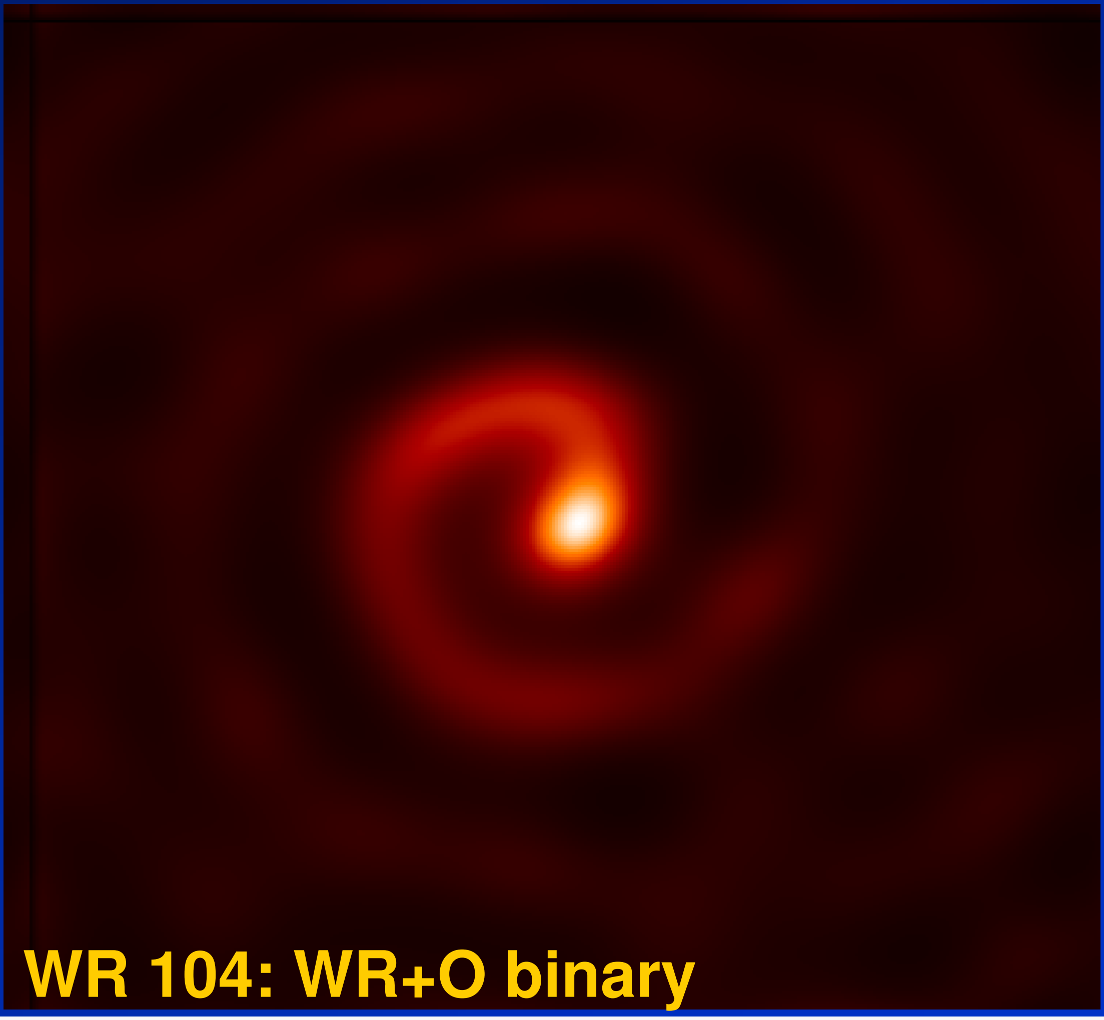
LBV+O binary

- Stellar masses:
  50 & 20 $M_\odot$
- Mass loss rates:
  10^{-4} & $5\text{x}10^{-7} M_\odot$/yr
- Wind velocities:
  200 & 2000 km/s
- Orbital period: 1 yr
- 4x4x0.4 orbital distance
- Grid: 480x480x40 gridpoints




log10(rho)
-11
-12
-14
-16
-18
-20
100
50
Y-A
0
-50
-100
-100
-50
0
50
100
X-Axis (x10^12)

Observation


WR 104: WR+O binary

Dust vs. gas

- Infrared observations often show dust, rather than gas
- Gas and dust motion are linked through drag-force
- Question: Is dust-density representative of gas morphology?

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Combining gas and dust:

Epstein:

$$f_{drag} \propto n_d \rho_g a_d^2 v_T (v_g - v_d) \qquad |v_g - v_d| < c_s$$

Stokes:

$$f_{drag} \propto n_d \rho_g a_d^2 (v_g - v_d)^2 \qquad |v_g - v_d| > c_s$$

Kwok (1975), Paardekooper & Mellema (2006), Woitke (2006) etc.

Hydrodynamics + radiative cooling + dust

$$\frac{\partial \rho_g}{\partial t} + \nabla \cdot \rho_g \vec{v}_g = 0$$

$$\frac{\partial \rho_g \vec{v}_g}{\partial t} + \nabla \cdot \rho_g \vec{v}_g \vec{v}_g = -\nabla P_g - f_{drag}$$

$$\frac{\partial e_g}{\partial t} + \nabla \cdot (e_g + P_g)\vec{v}_g = -\frac{\rho_g^2}{m_h^2}\Lambda(T_g) - f_{drag} v_g$$

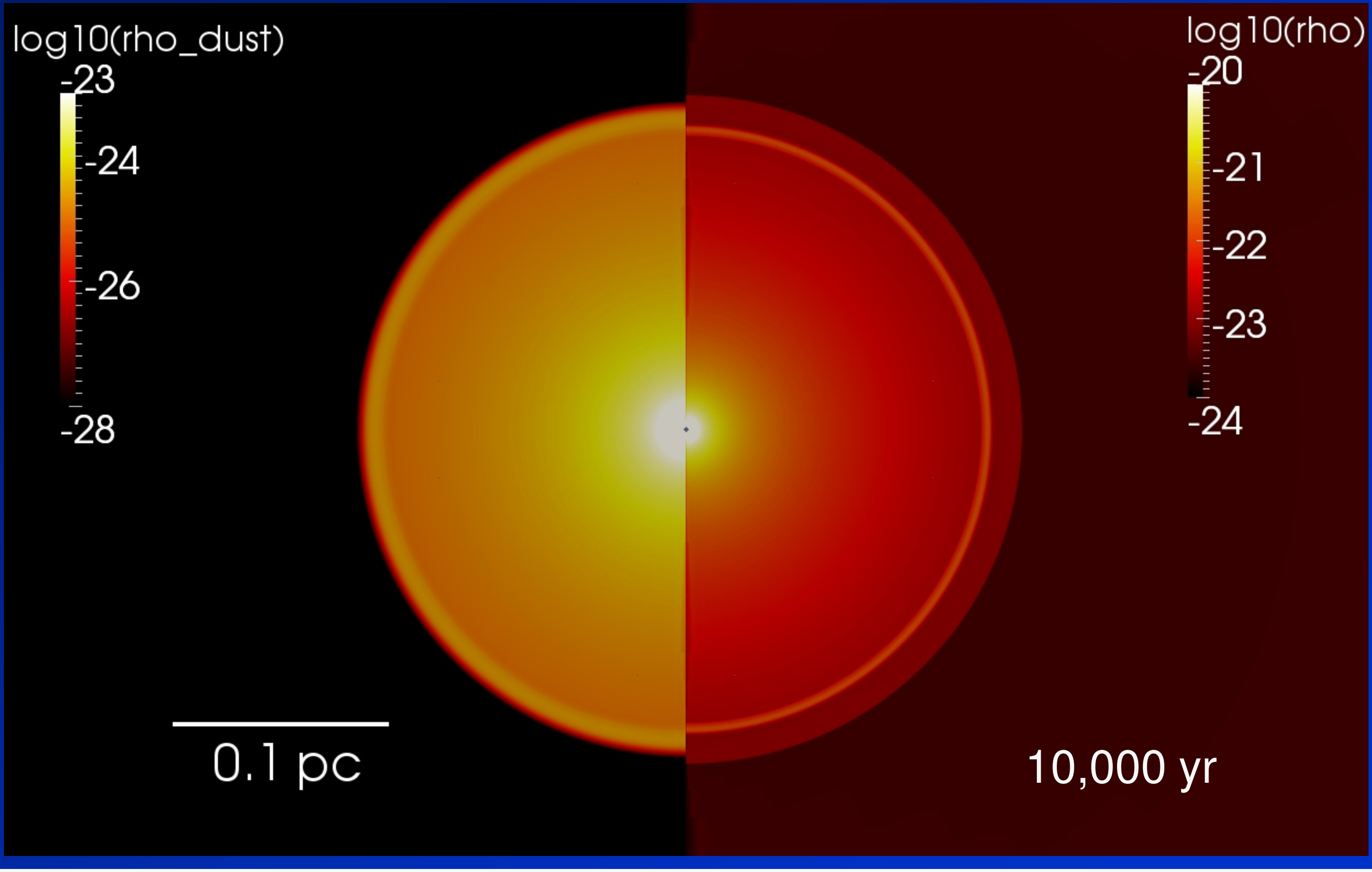
$$\frac{\partial \rho_d}{\partial t} + \nabla \cdot \rho_d \vec{v}_d = 0$$

$$\frac{\partial \rho_d \vec{v}_d}{\partial t} + \nabla \cdot \rho_d \vec{v}_d \vec{v}_d = f_{drag}$$

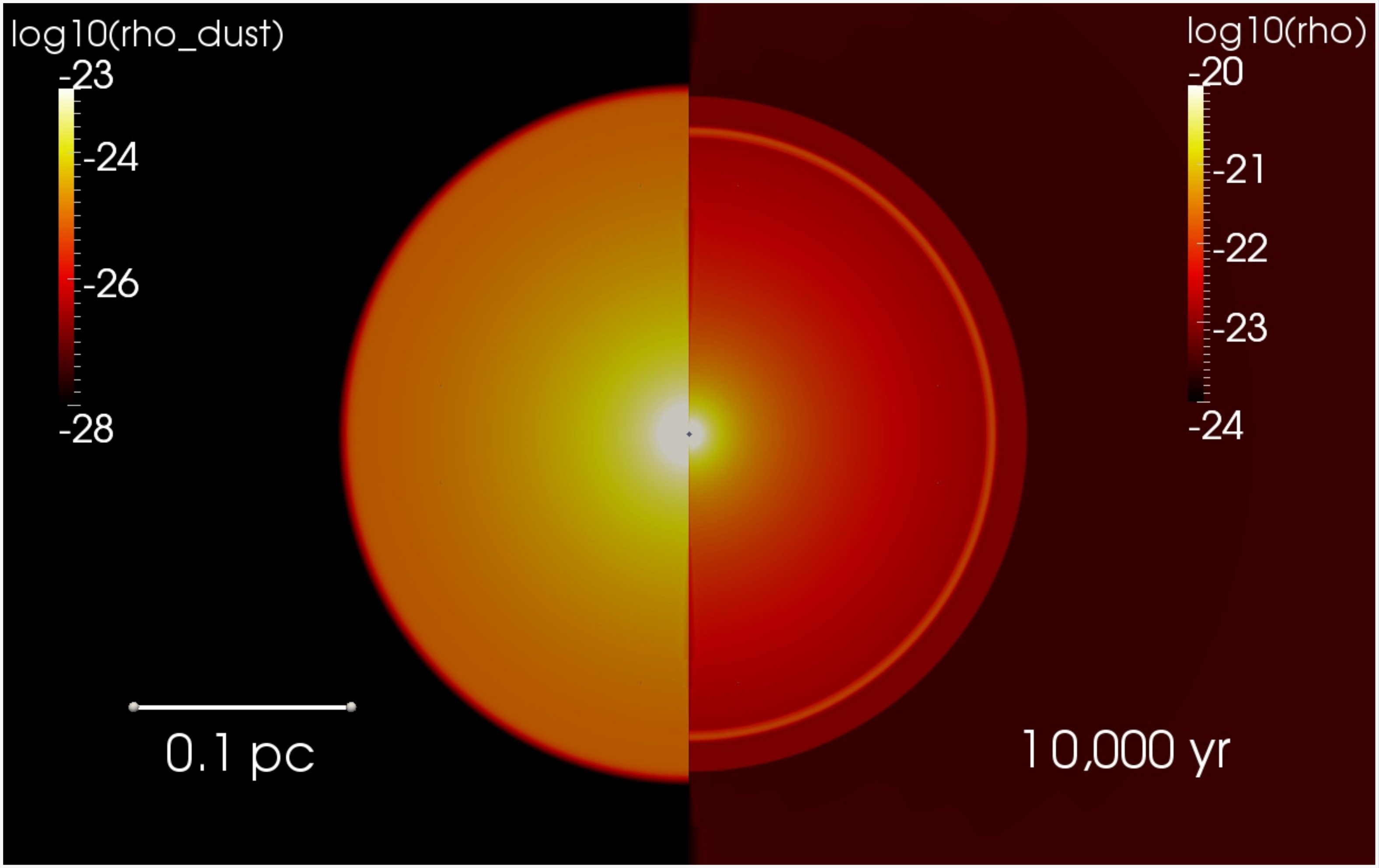
AGB wind expansion

- Model: AGB star in constant density ISM
- Wind parameters: $10^{-6}\ M_\odot$/yr, 15 km/s
  $\dot{M}_{dust} = 0.5\%\ \dot{M}_{gas}$, $v_{dust} = v_{gas}$
- ISM gas: $2\#/cm^3$, no dust
- Test for different dust grain sizes

Result for a = 0.005µm



Result for a = 0.05μm



Conclusions:

- Wind interactions can form thin circumstellar shells in several ways
  - Through wind-wind collision
  - Through evolutionary changes in the wind
  - By sweeping up the ISM
- These shells are subject to multiple instabilities, depending on wind parameters and (for binaries) orbital motion
- Dust distribution may deviate from gas morphology depending on grain-size

Legal stuff

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