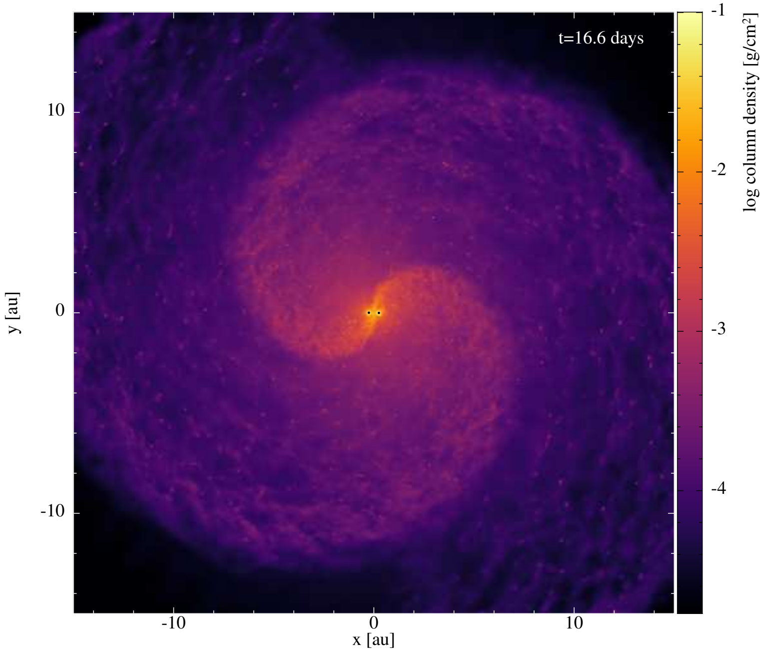
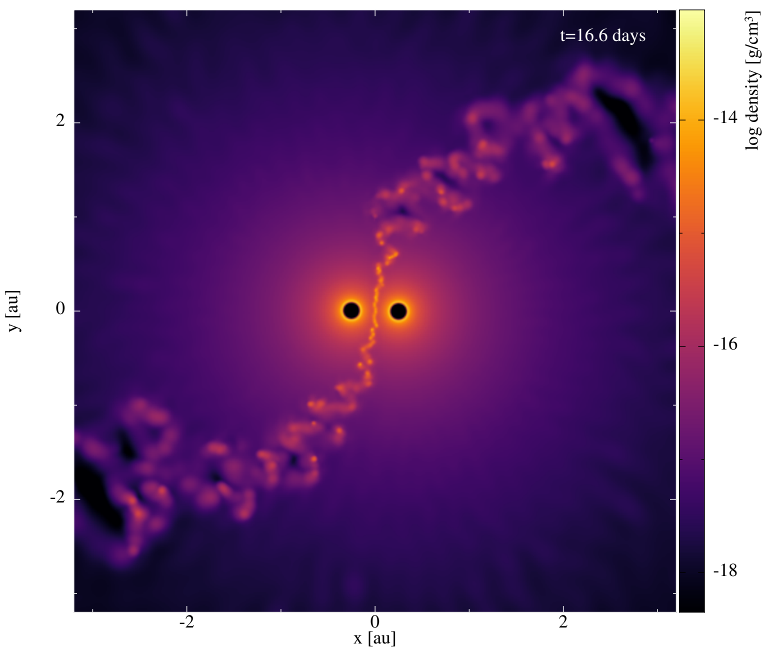
Interacting stellar winds



Lionel Siess

Institute of Astronomy and Astrophysics, ULB

D. Dionese, S. Deschaux (ULB),
Malfait J., Maes S., Esseldeurs M. (KUL)



Phantom users workshop

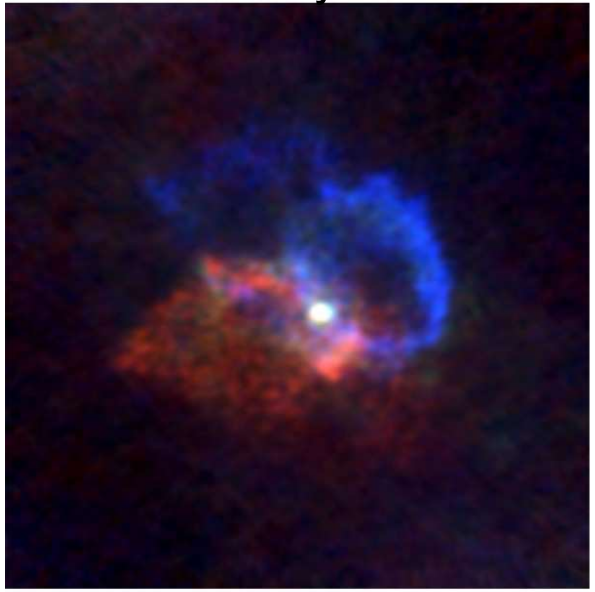
Grenoble University
Jun 2-6, 2025

AGB stars, dust and binaries

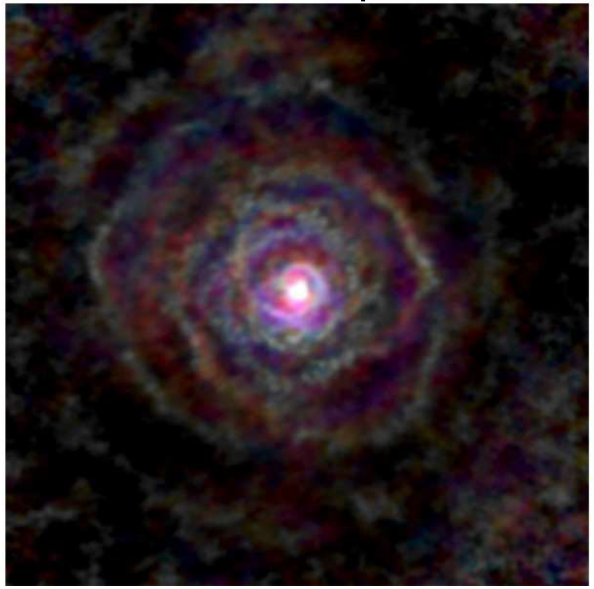
High-resolution observations reveal complex structures

- Spirals, disks, and shells
- Best explained by the interaction with a binary companion whicn can also impact mass loss rate determination → Owen’s talk

R Hya



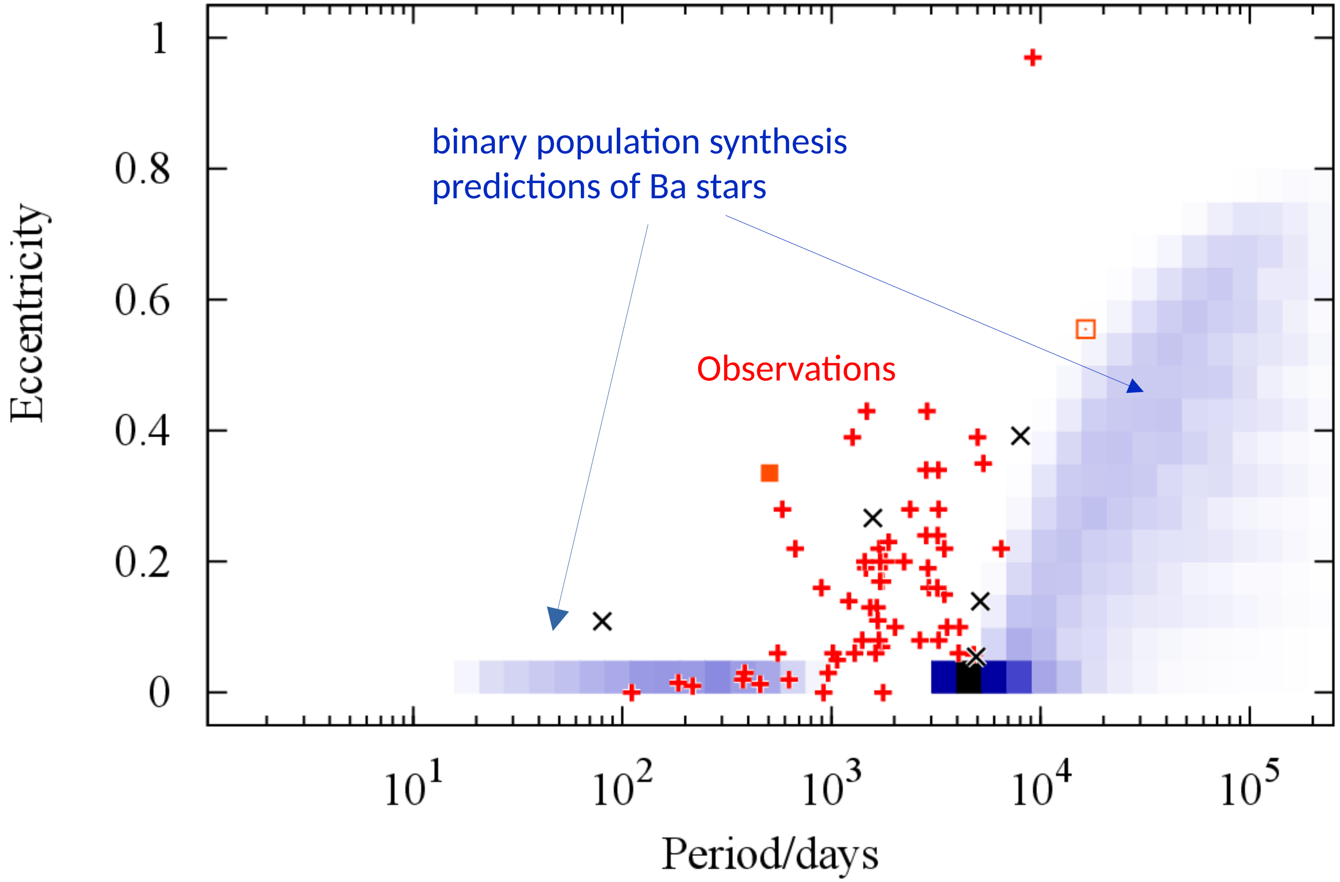
GY Aql



R sculptoris

AGB stars, dust and binaries

- The presence of a mass loosing AGB star in a binary can
  - induce mass exchange leading to
    - (*dusty*) common envelope evolution for short P system
    - Formation of chemically peculiar stars (Ba stars, CEMP, …) with **puzzling orbital parameters**



Implementation of mass loss

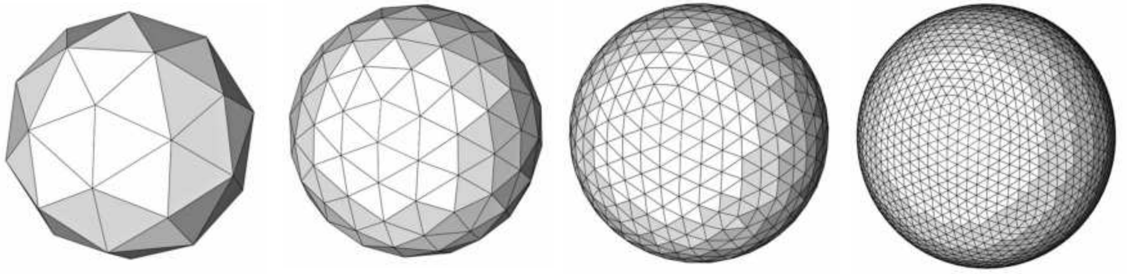
1. Shells of particles are ejected at specific times depending on the mass loss rate and number of particles on the sphere (N_p)
$$\delta t_{\rm inj} = \frac{N_p m}{\dot{M}}$$
2. the radial spacing between 2 consecutive shells depends on the injection velocity
$$\delta r \approx v_{\rm inj} \times \delta t_{\rm inj}$$
3. On the sphere, the distance of a particle to its neighbour $d_\perp$ is fixed and we impose $\delta_r = w_{ss} d_\perp$
4. Combining these equations the setup parameters fix the particle mass : $m = \frac{\dot{M} w_{ss} d_\perp}{N_p v_{\rm inj}}$

The only free parameters are the number of particles N_p and the wind shell spacing parameter w_{ss}

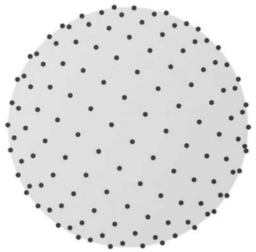
Distribution of particles on the sphere

1. Original method : particles are distributed on an isocahedron surface
   - All particles have equidistant neighbors
   - BUT the number of particles is discrete

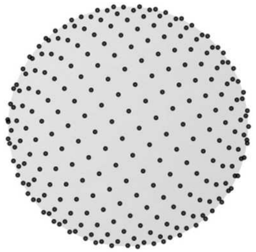
$$N_{\rm part} = 10(2q-1)^2 + 1 = 12,\ 92,\ 252,\ 492,\ 812,\ \ldots$$



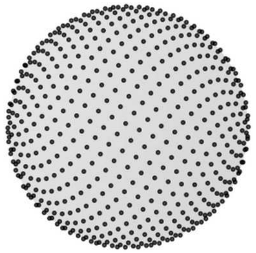
2. We implemented a new method based on the Fibonacci lattice which allows to place any integer number of particles on a sphere



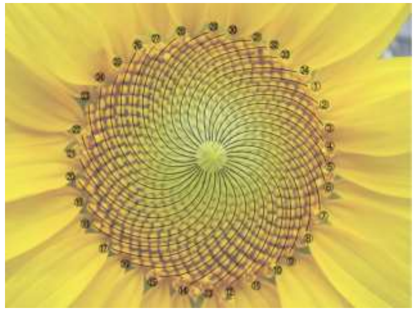
N=256

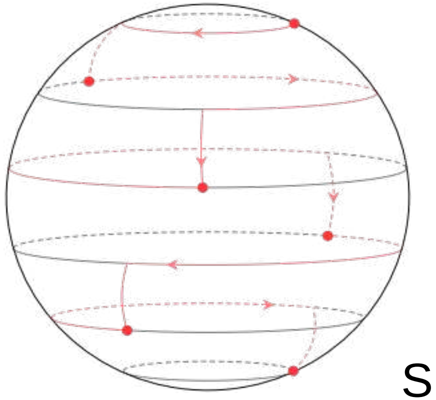


N=512



N=1024





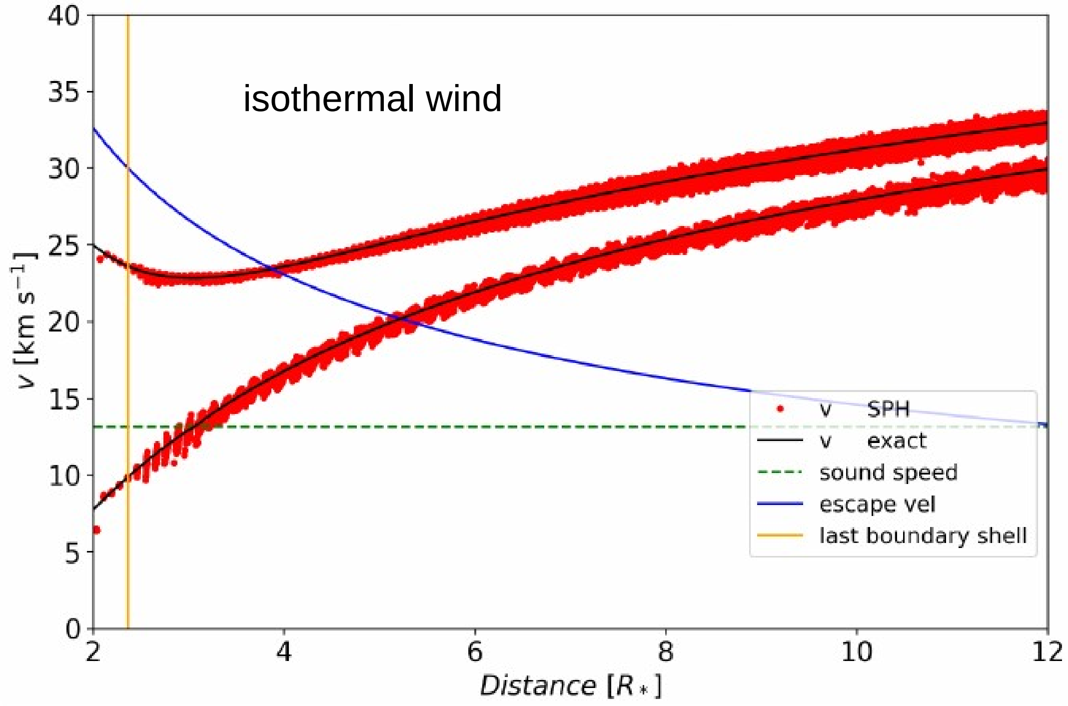
S. deschaux

Setting the initial particles properties

1. Given an injection radius (typically the stellar radius), wind temperature and mass loss rate we calculate the *steady 1D wind profile (Parker solution)*

$$\frac{\mathrm{d}v}{\mathrm{d}r} = \frac{2c_\mathrm{s}^2/r - GM_*(1-\Gamma)/r^2 - (\gamma-1)\Lambda/v}{v(1-c_\mathrm{s}^2/v^2)}$$

$$\frac{\mathrm{d}T_\mathrm{g}}{\mathrm{d}r} = (1-\gamma)T_\mathrm{g}\left(\frac{2}{r} + \frac{1}{v}\frac{\mathrm{d}v}{\mathrm{d}r}\right) + \frac{(\gamma-1)\,\mu m_\mathrm{u}}{k}\frac{\Lambda}{v}$$



2 important parameters :

Γ : the parameter that reduces the effective gravity and allows wind launching : radiative acceleration on dust or lines

Λ : the cooling rate → Davide's talk

2. When particles are released, they are assigned the properties of the 1D wind solution (v, u)
   - Spheres are rotated between injections to remove artifacts

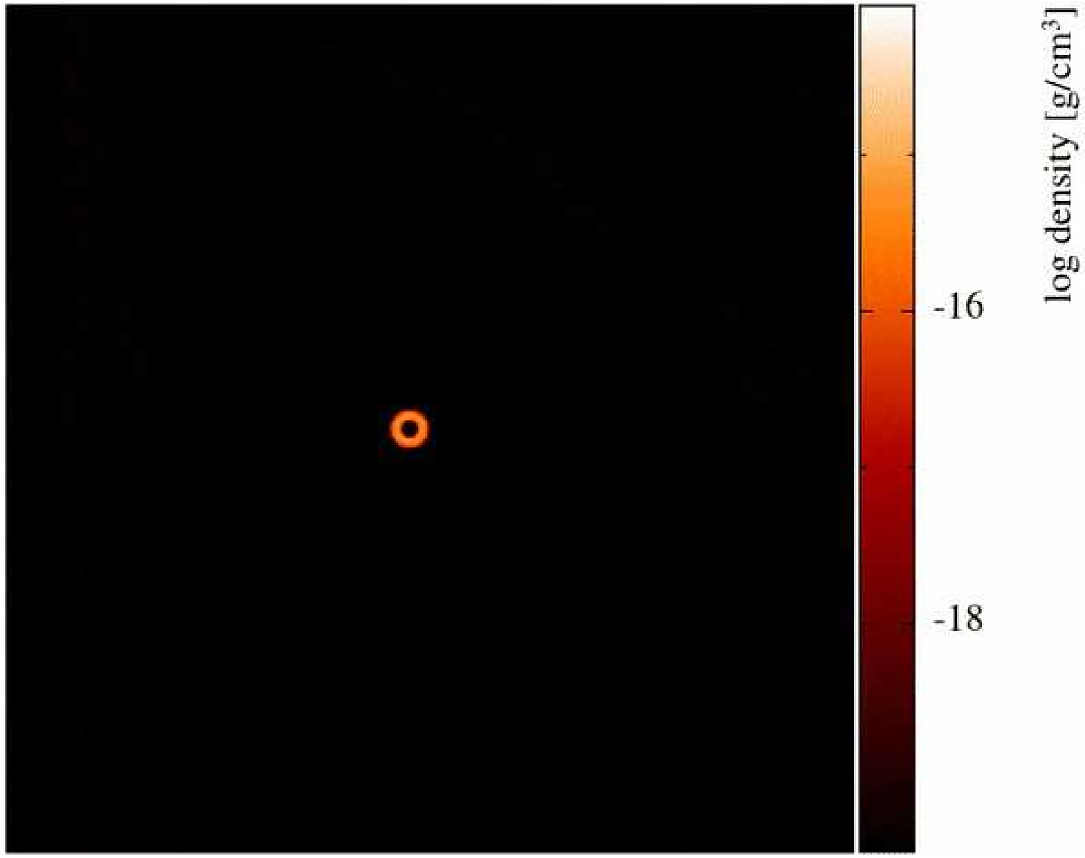
AGB wind-companion interaction

exploration of the parameter space (*e, a, M*)

using the free wind approximation ($\Gamma = 1$)

- key parameter determining the morphology

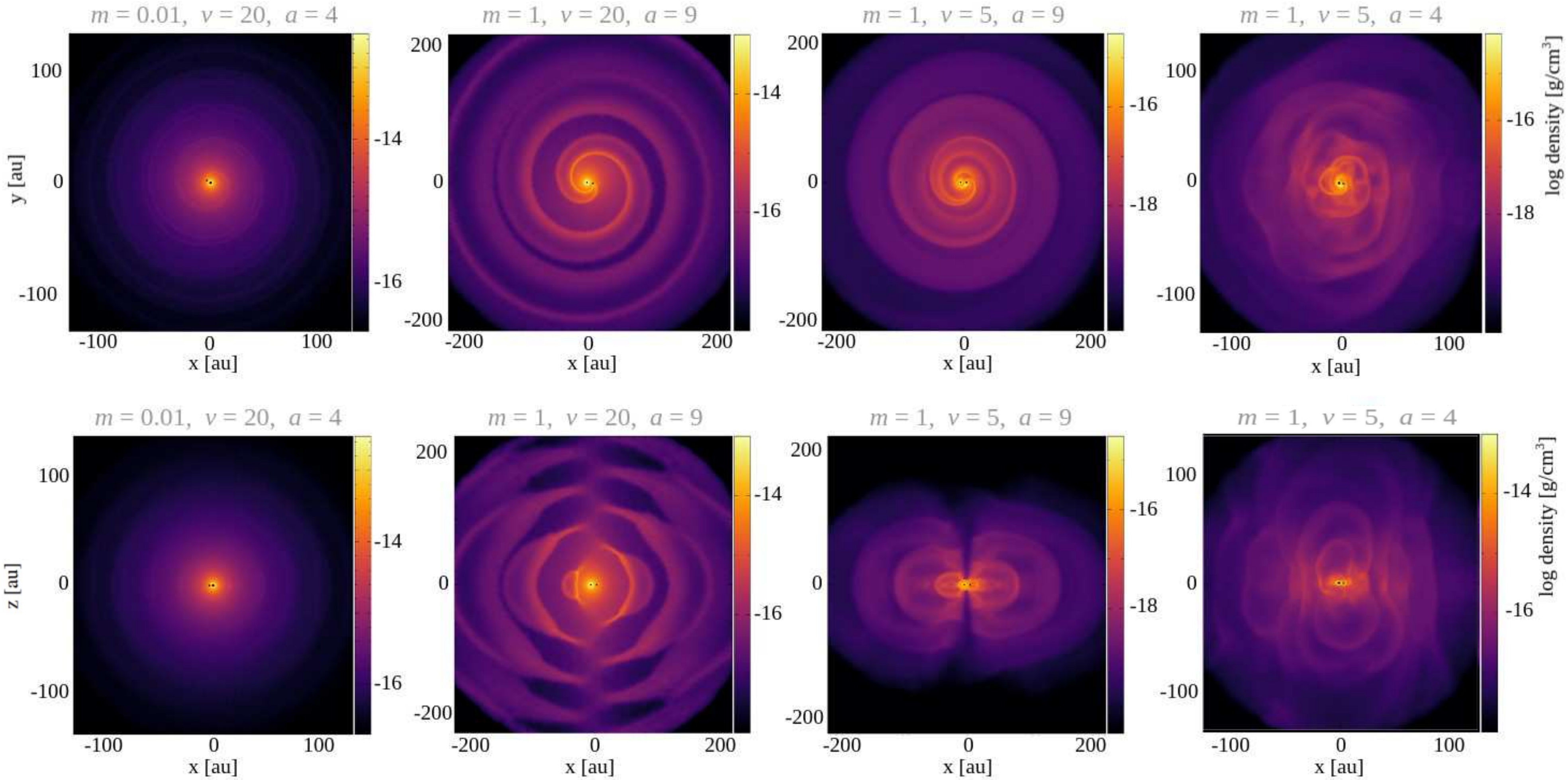
- v_{wind} / v_{orb}
- mass ration (M_1/M_2)
- eccentricity e



Stronger impact for

(i) larger M_{comp} , (ii) smaller *a*, (iii) lower v_{wind} , (iv) higher *e*

Morphology types: binary systems



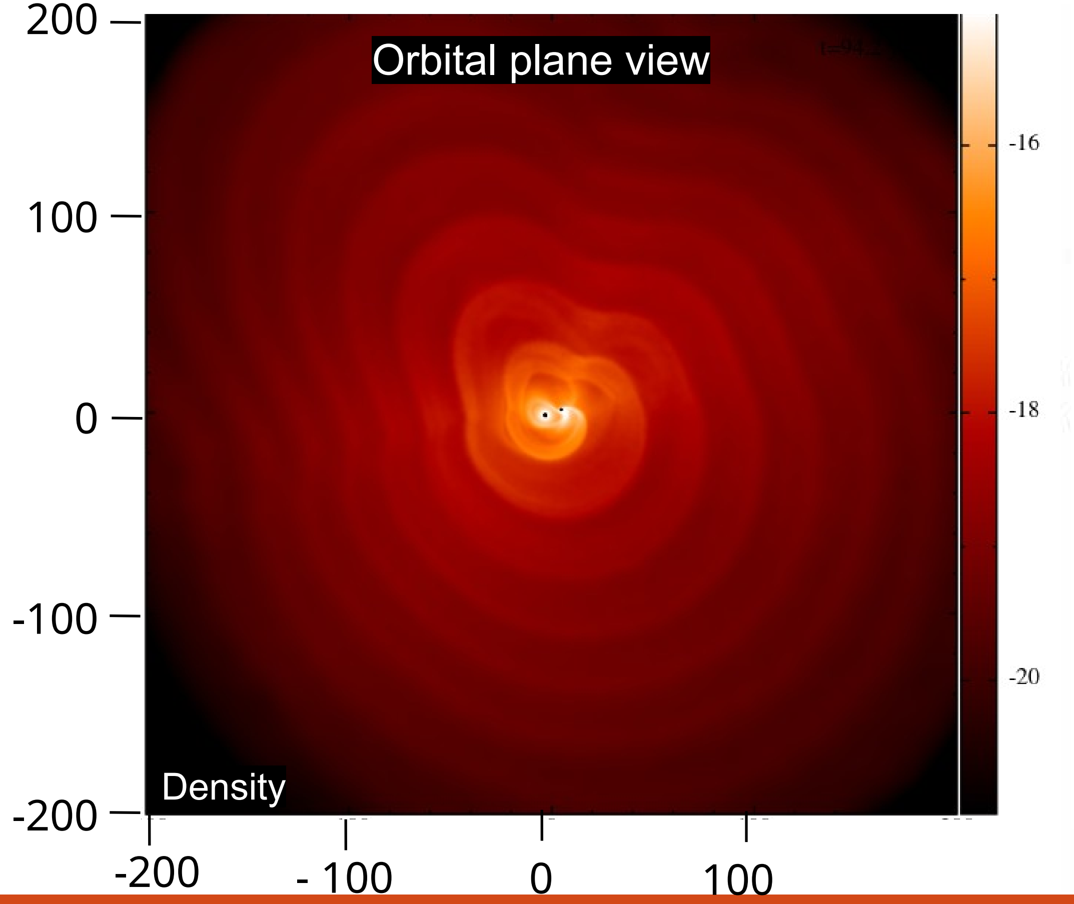
Maes+ 2021

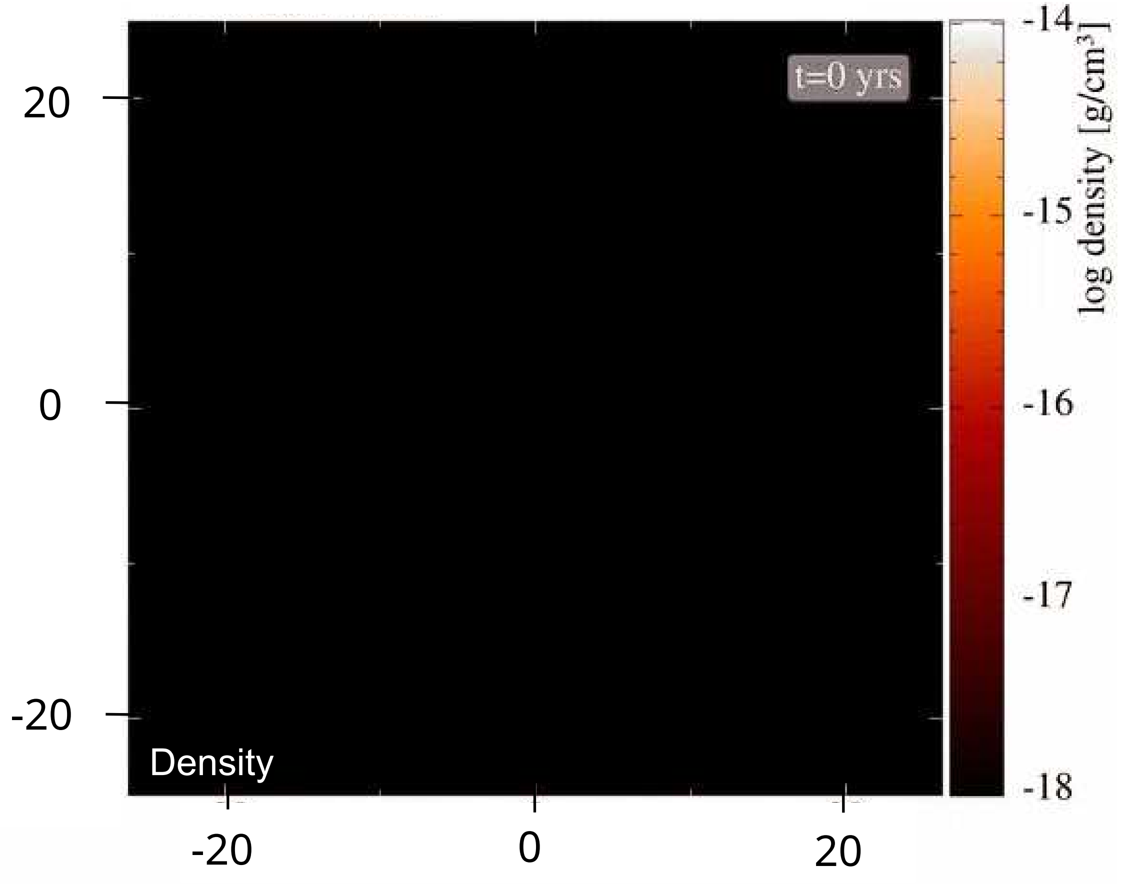
Eccentric binaries

a = 6 au
M_{AGB} = 1.5 M_{sun}
M_{comp} = 1 M_{sun}

e = 0.5, v_w = 5 km/s

Malfait+ 2021





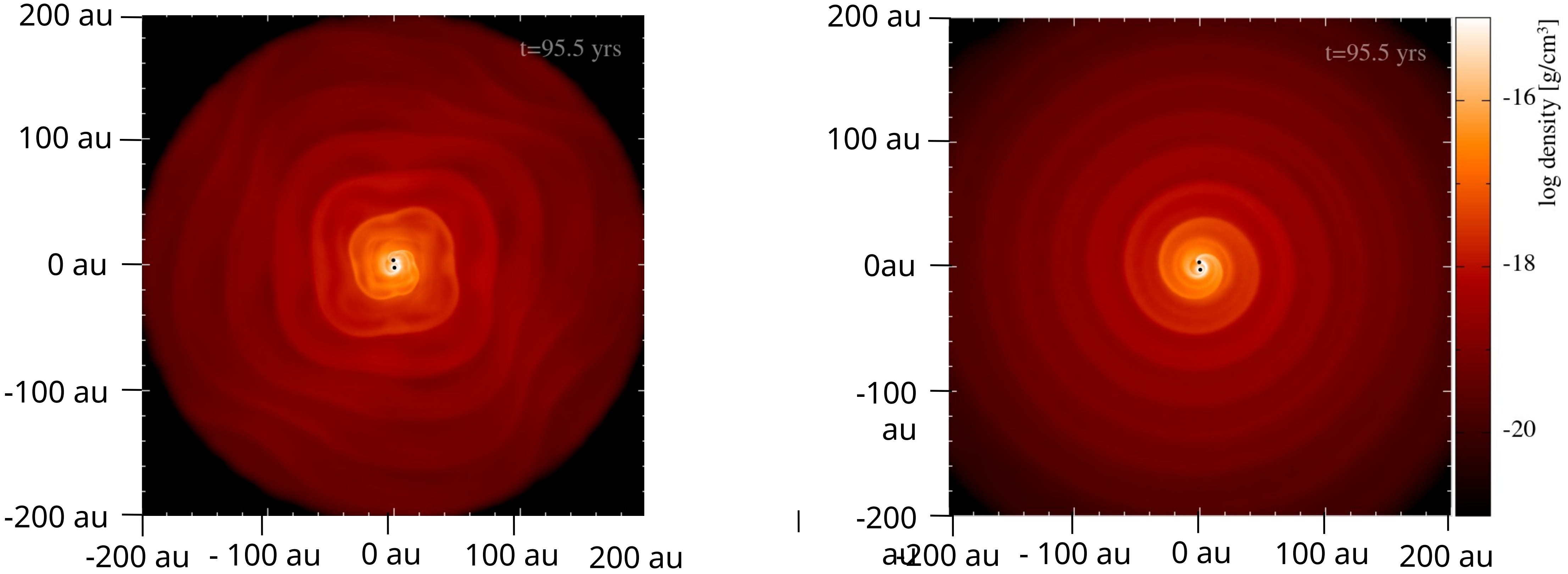
Impact HI cooling: *No periodic instabilities*

$e = 0, \boldsymbol{v = 5\ \mathrm{km/s}}$

Malfait+ 2024

no HI electron excitation cooling: Irregular

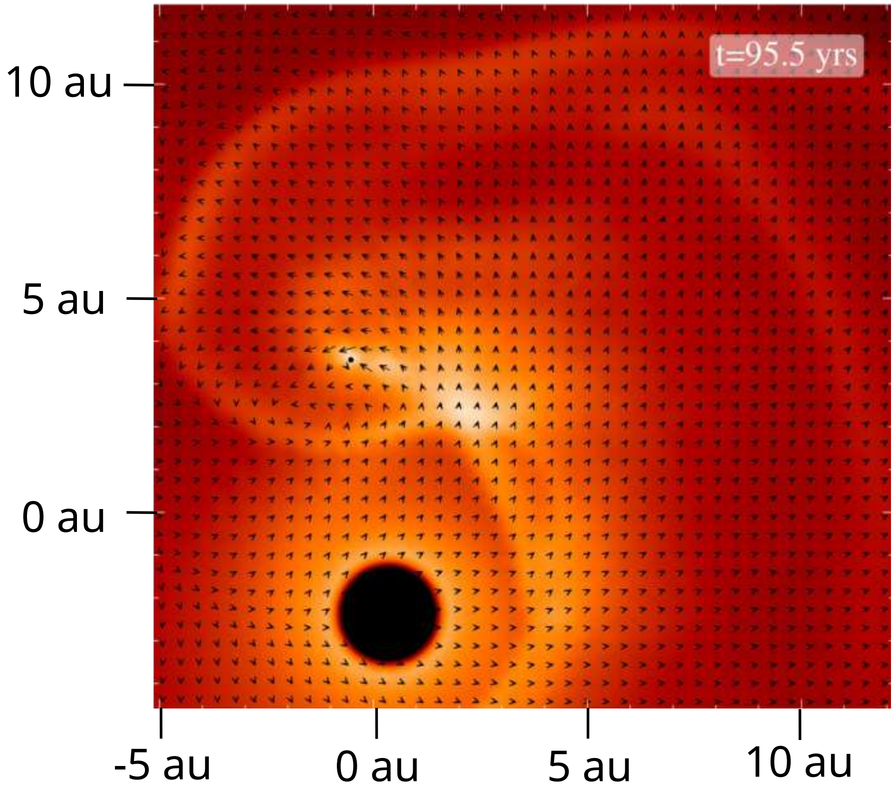
with HI electron excitation cooling: Archimedes spiral



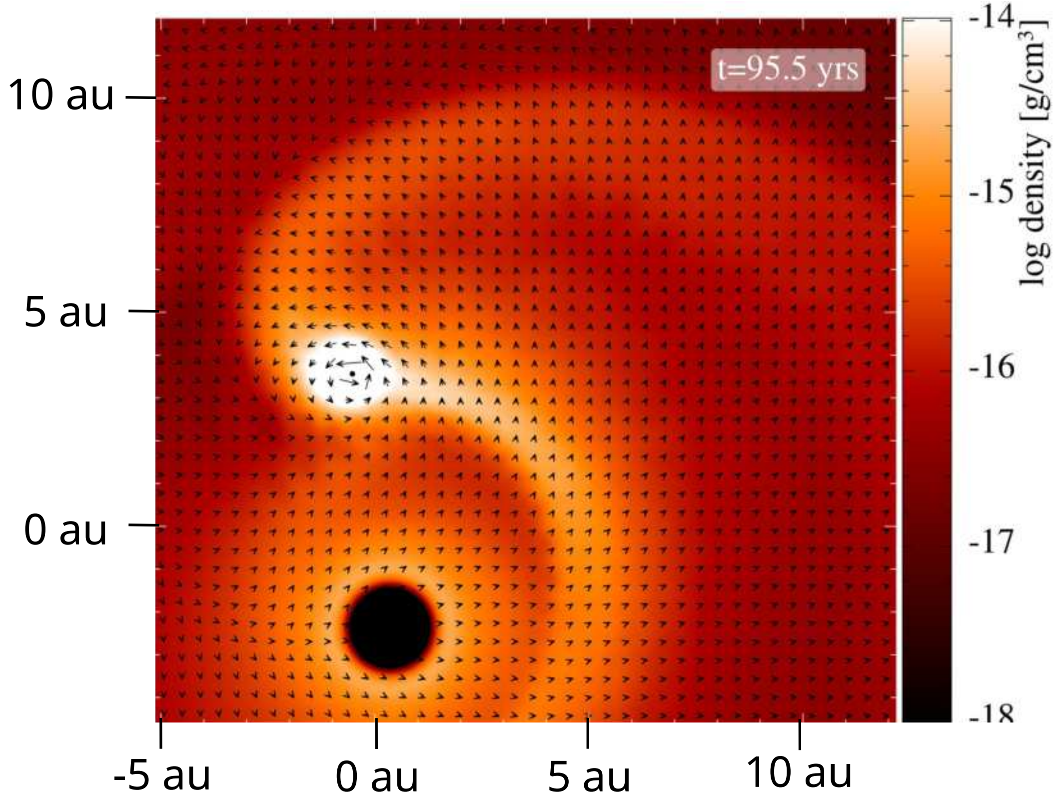
Impact HI cooling: formation of accretion disk

$e = 0$, $\boldsymbol{v = 5}$ **km/s**

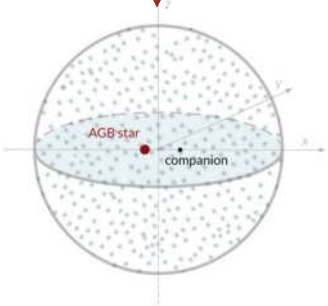
no HI electron excitation cooling:
Unstable bow shock



with HI electron excitation cooling:
Accretion disk + stable bow shock



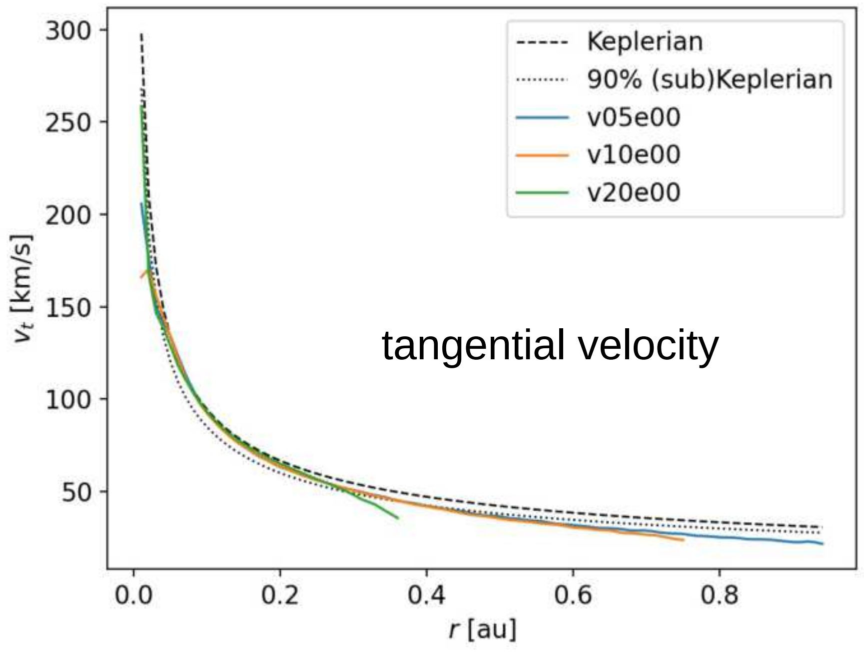
Orbital plane view

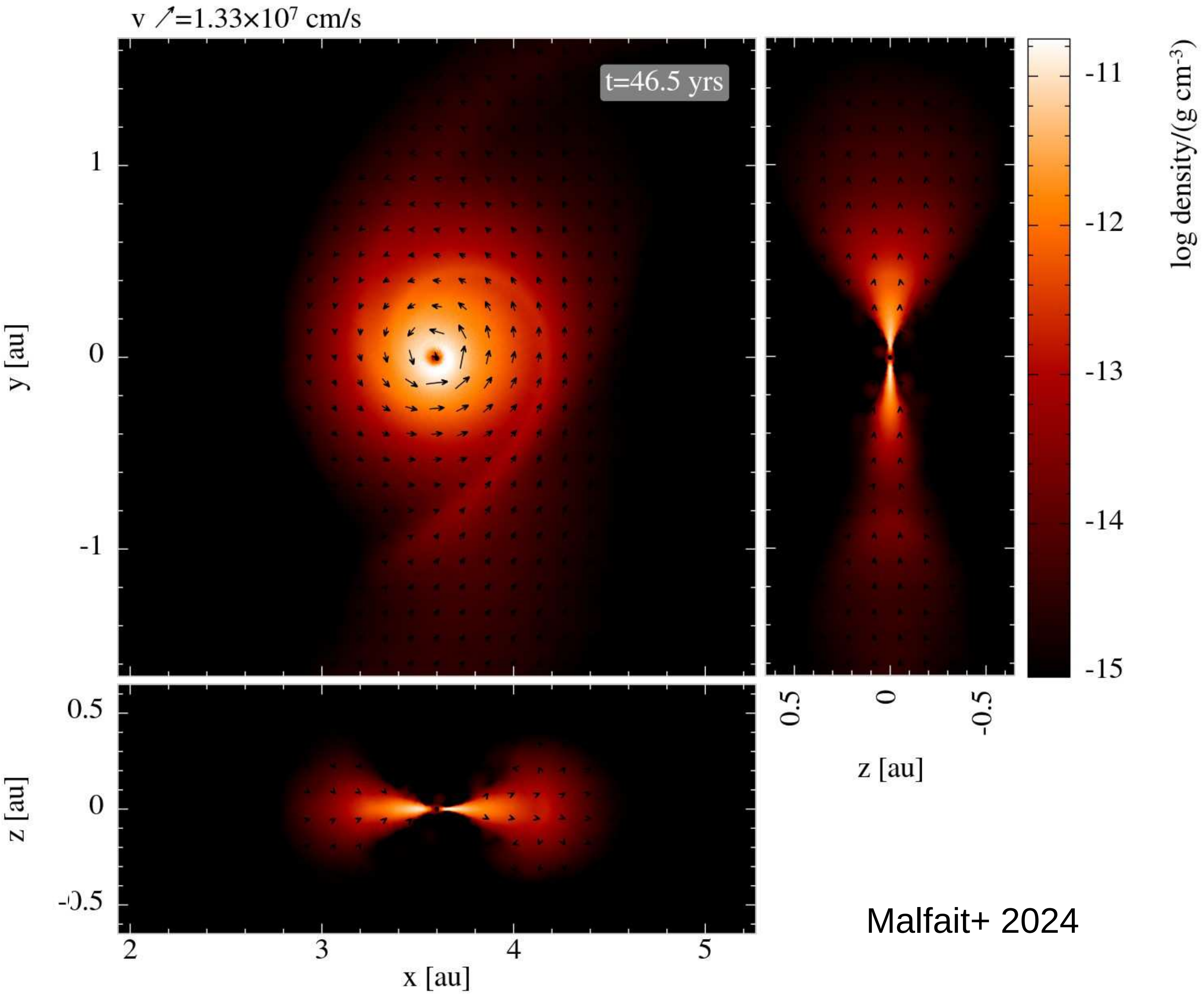


Malfait+ 2024

Disc structure

- Flared disc
- disc mass and scale height increase with wind mass loss rate
- keplerian disc

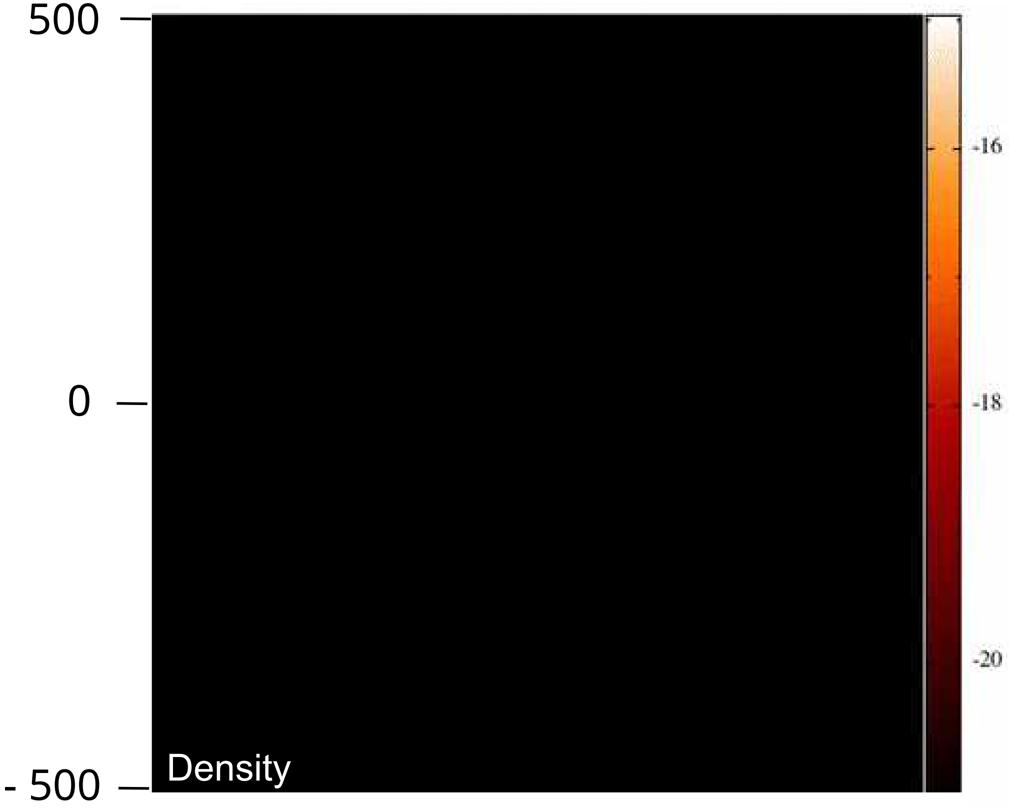




Malfait+ 2024

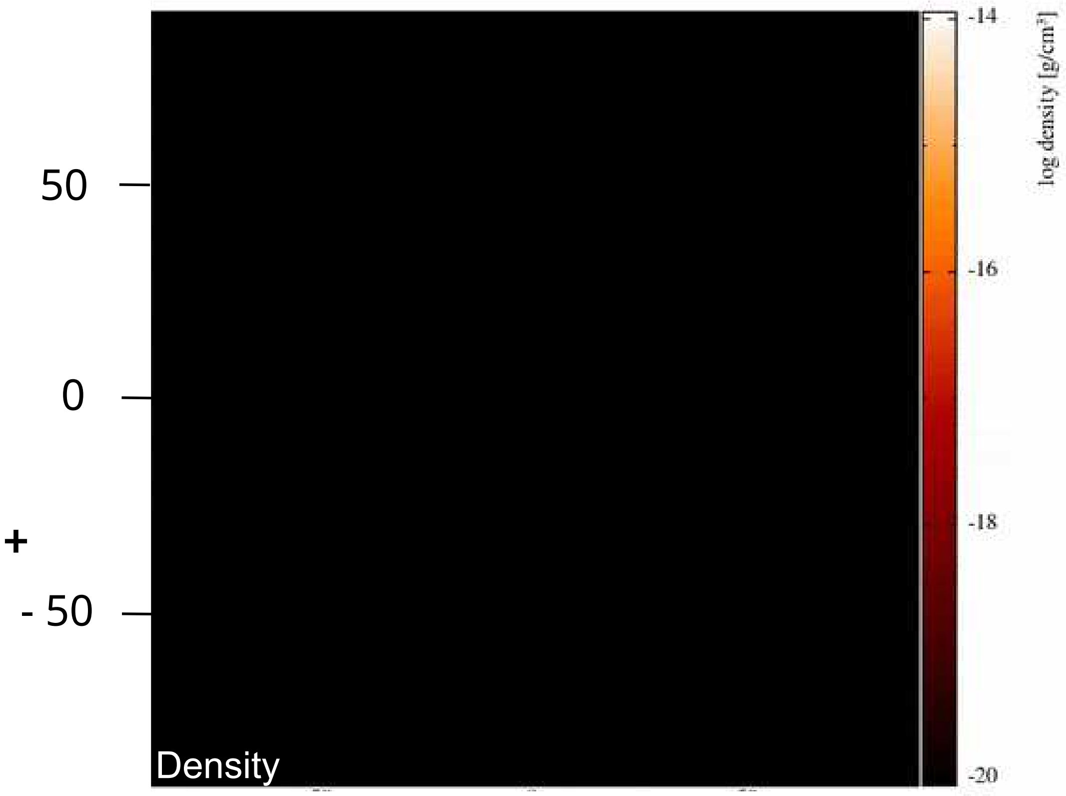
Hierarchical triple systems

Malfait+ 2024b



v_w = 15 km/s
e_2 = 0
m_2= 0.6 M_{sun}
a1 = 5 au
a2 = 35 au
M_{AGB}= 1.6 M_{sun}
m_1= 0.4 M_{sun}

Inner snail shell + outer spiral



Effect of dust on the hydro equations

Dust is opaque and can absorb radiation which translates into

- **radiation force**

$$\frac{d\mathbf{v}}{dt} = -\frac{\nabla P}{\rho} + \Pi_{\rm shock} + \mathbf{a}_{\rm sink-gas} + \mathbf{F}_{\rm rad}$$

$$a_{\rm sink-gas} + F_{\rm rad} = -\frac{GM_{\rm sink}}{r^2}(1-\Gamma) \qquad \Gamma = \frac{(\kappa_{\rm g} + \kappa_{\rm dust})L_*}{4\pi cGM} e^{-\tau}$$

radiation force

dust opacity

optical depth

- **extra heating/cooling** because $T_{dust} \neq T_{gas}$

$$\frac{du}{dt} = -\frac{P}{\rho}(\nabla \cdot \mathbf{v}) + \Lambda_{\rm shock} - \frac{\Lambda_{\rm cool}}{\rho} \qquad \Lambda_{\rm cool} = \frac{3R}{2\mu}\frac{(T_{\rm gas} - T_{\rm dust})}{C'} + \Lambda_{\rm HI} \qquad \tau = \int_{R_*}^{r} \kappa\rho\, dr$$

gas-dust heat exchange

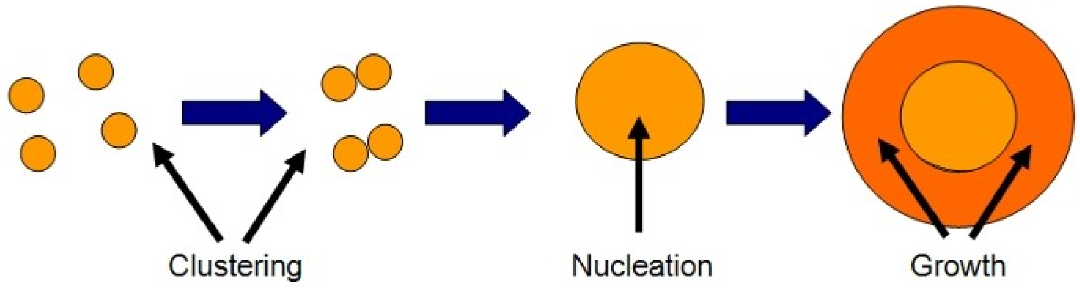
- **drift** terms

Determination of T_{dust}

- Approximate solutions require calculation of optical depth
- Exact solutions need coupling with RT codes e.g. MCFOST

$$T_{\rm dust}^4 = \frac{1}{2}\left(1 - \sqrt{1 - \left(\frac{R_*}{r}\right)^2}\right) T_*^4 e^{-\tau}$$

Dust formation



A two step process

1. Nucleus formation

- Process operates at the molecular scale
- seeds contain 100 to 1000 atoms
- To compute the nucleation rate, we need abundances of *monomers* (dust building blocks)

→ chemical network including 7 atoms : H, C, O, N, Si, S, Ti and 25 molecules (C_2, H_2, OH, H_2O, CO, CO_2, CH_4, C_2H, C_2H_2 , TiO, SiO ….)

→ we assume chemical equilibrium : no need to store individual abundances, only that of atomic carbon

2. Grain growth

- Gas molecules stick to the grain surface and make it grow
- The growth proceeds via addition of monomers

$$C_N + C \rightarrow C_{N+1}$$
$$C_N + C_2 \rightarrow C_{N+2}$$
$$C_N + C_2H_2 \rightarrow C_{N+2} + H_2$$
$$C_N + C_2H \rightarrow C_{N+2} + H$$

Dust evolution : Moment equations

This theory does not calculate the grain size distribution $f\,(N,\,t)$ but uses its moments $\mathcal{K}_i$ to describe the global dust properties:

- Average grain radius $<a> \propto \mathcal{K}_1/\mathcal{K}_0$
- Average grain surface $<S> \propto \mathcal{K}_2/\mathcal{K}_0$
- Number monomers condensed in grains $\mathcal{K}_3 \propto$ opacity

$$\mathcal{K}_i = \sum_{N=N_l}^{\infty} N^{i/3} f(N,t)$$

N is the number of monomers in the grain

The evolution of the moments is given by

$$\begin{aligned}
\frac{\mathrm{d}\widehat{J_*}}{\mathrm{d}t} &= \frac{\widehat{J^s_*} - \widehat{J_*}}{\tau_*} \\
\frac{\mathrm{d}\widehat{\mathcal{K}_0}}{\mathrm{d}t} &= \widehat{J_*} \\
\frac{\mathrm{d}\widehat{\mathcal{K}_i}}{\mathrm{d}t} &= \frac{i\,\widehat{\mathcal{K}_{i-1}}}{3\tau} + N_l^{i/3}\widehat{J_*},
\end{aligned}$$

J_* : nucleation rate $f(T,P_i)$

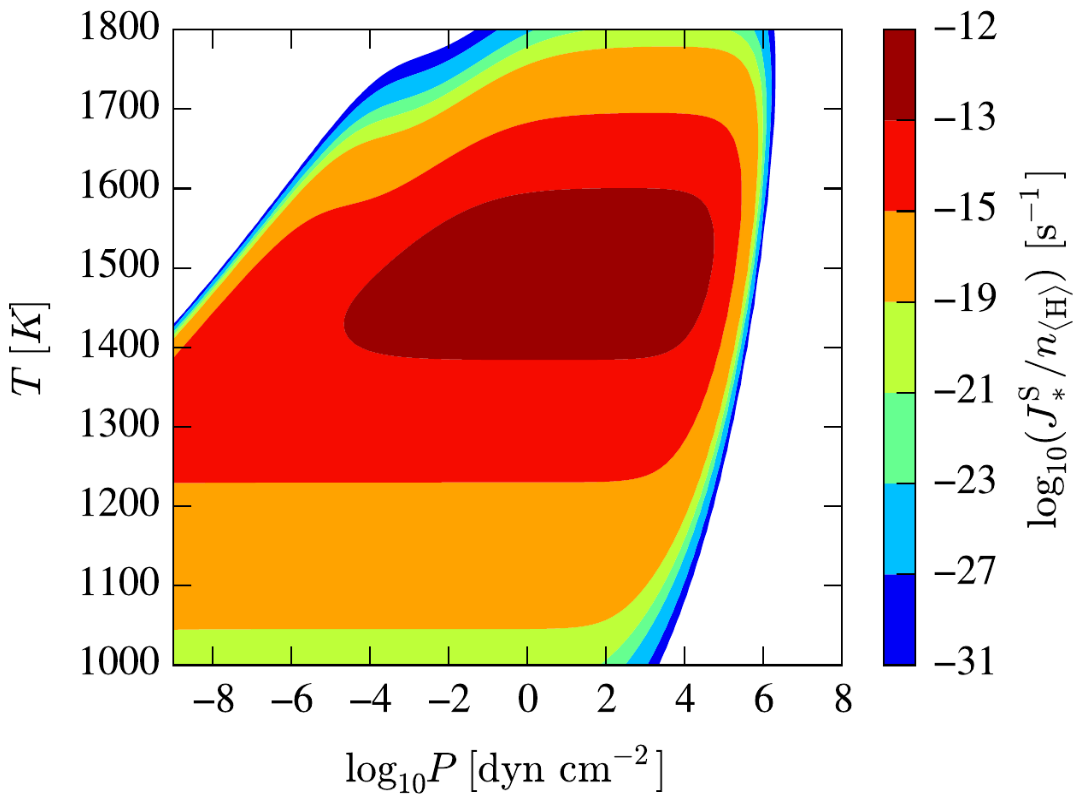
τ^{-1} : rate of growth/destruction of the grains

J_*^s : rate of formation of critical clusters

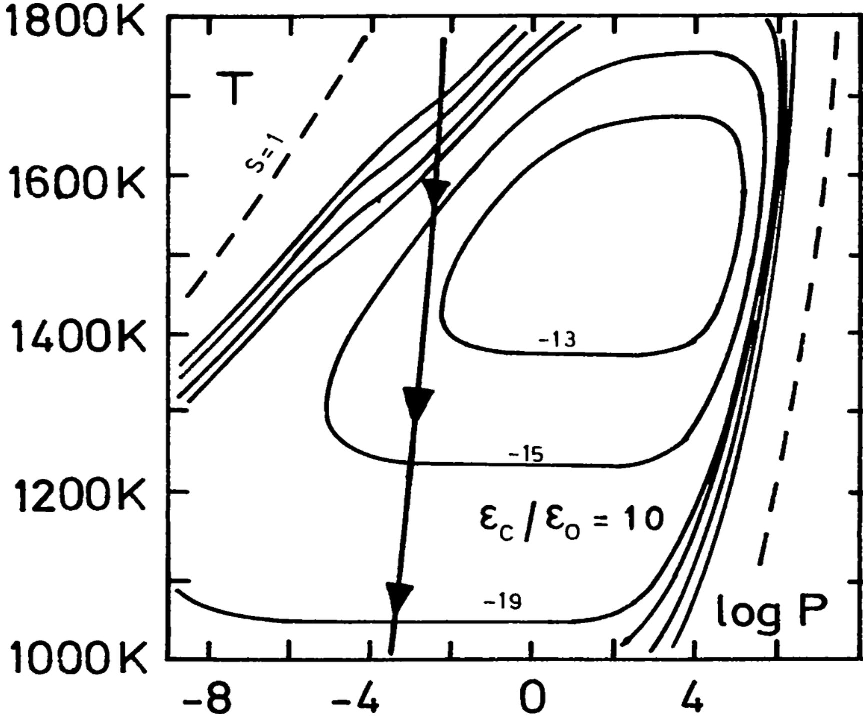
τ_* : relaxation time to equilibrium

Each SPH particle now carries the information about the moments $\mathcal{K}_i$ and J_*

Nucleation rate



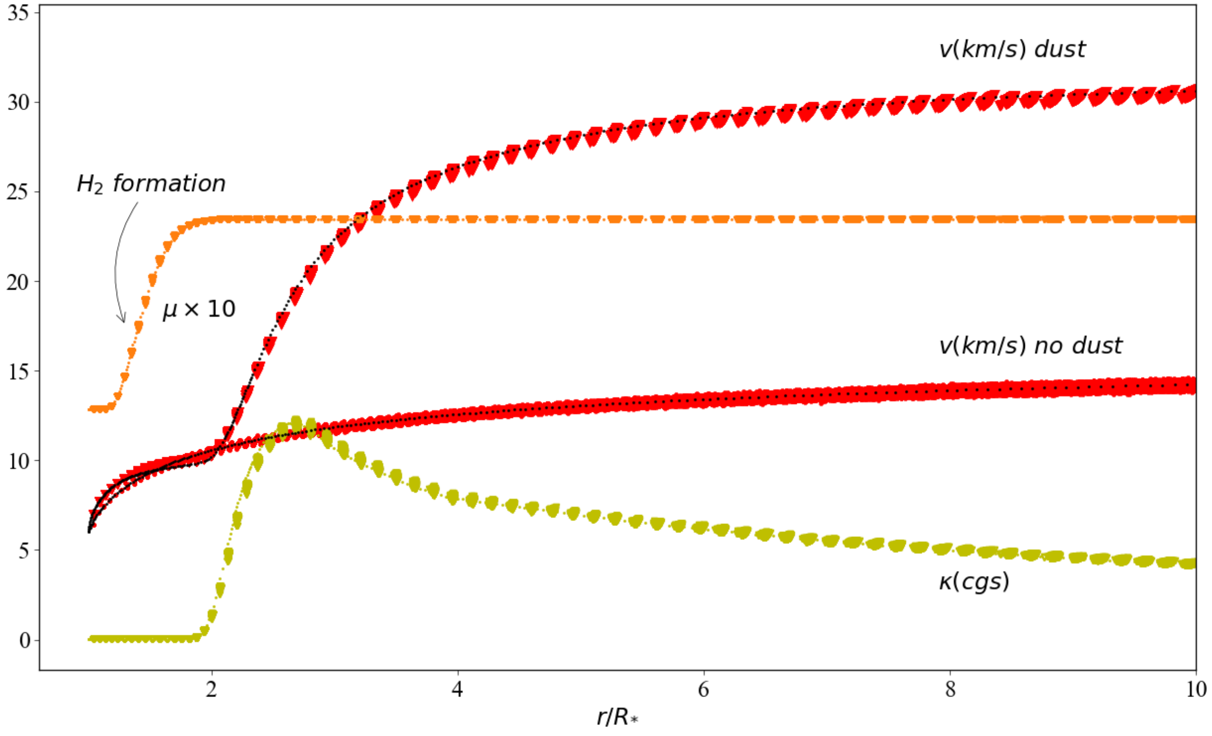
Siess+ (2022) for C/O = 10



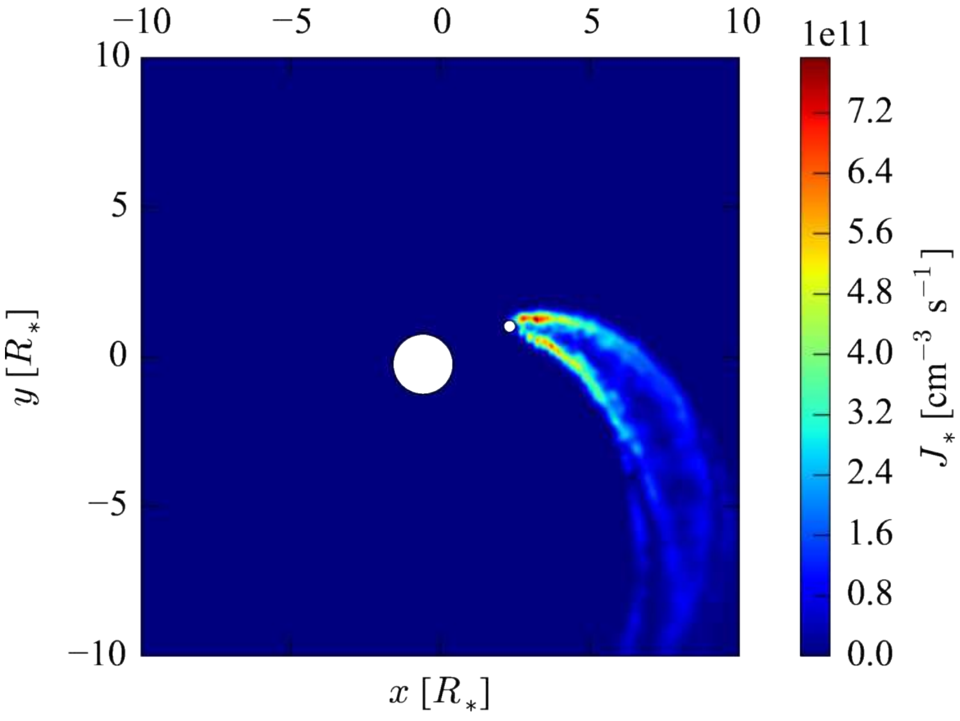
Gail & Sedlmayr (1984)

Dust in the wind

Dust can provide a strong wind acceleration



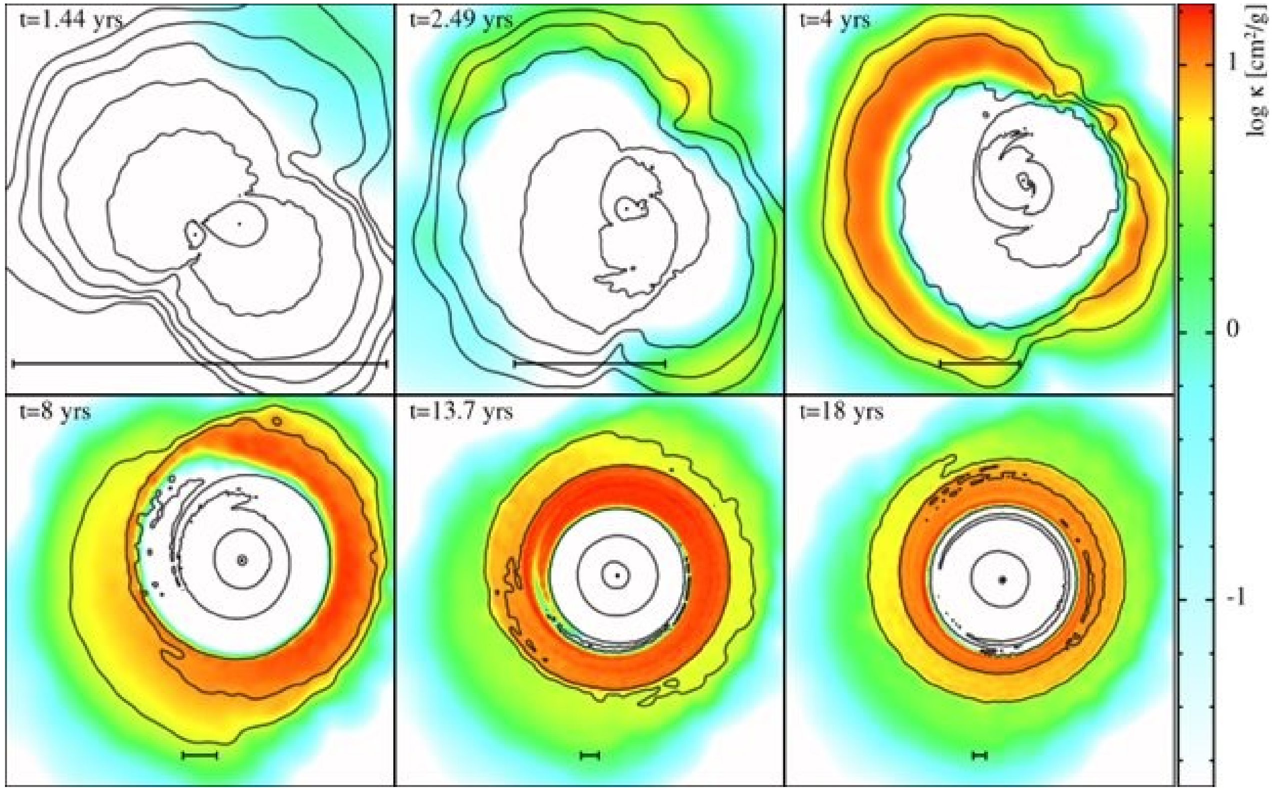
Siess+ (2022)



Nucleation rate high in the wake of the binary companion where density is higher

Dust in common envelopes

- Dust forms in the unbound material and does not help unbinding more mass
- Dust forms early in the simulation (~ 1 yr after start of simulation)
- Dust formation is very efficient (~ 10^{-3} – 10^{-2} $M_\odot$)
- Dust dramatically impacts the optical appearance of the object



Bermudez+ (2023)

Colliding winds

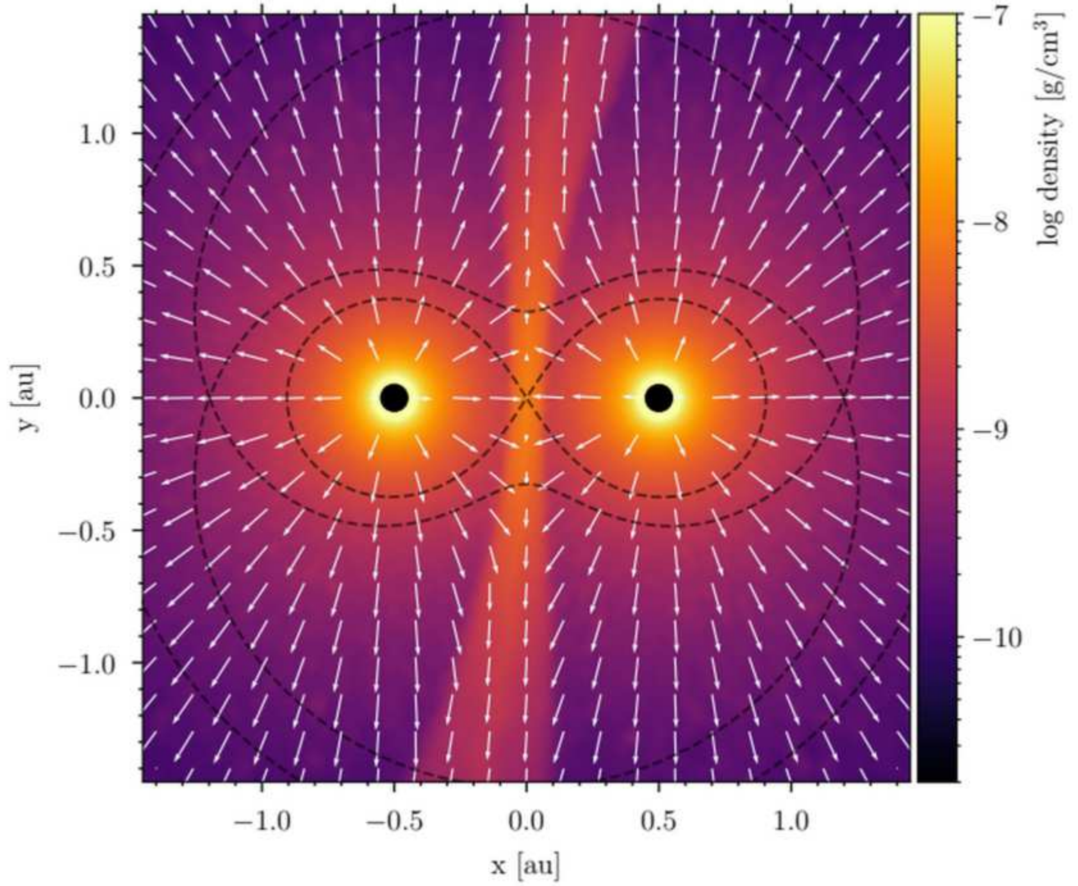
New sink properties

- mass loss rate
- wind velocity
- wind temperature
- resolution N_p

Line driven wind (CAK theory) : absorption and scattering of photons provides the momentum and acceleration of the gas.

$$\Gamma_{\rm line} = g_0 \left(1 - \frac{R_{\rm inj}}{r}\right)^{2\beta-1}$$

Muijres+ 2012



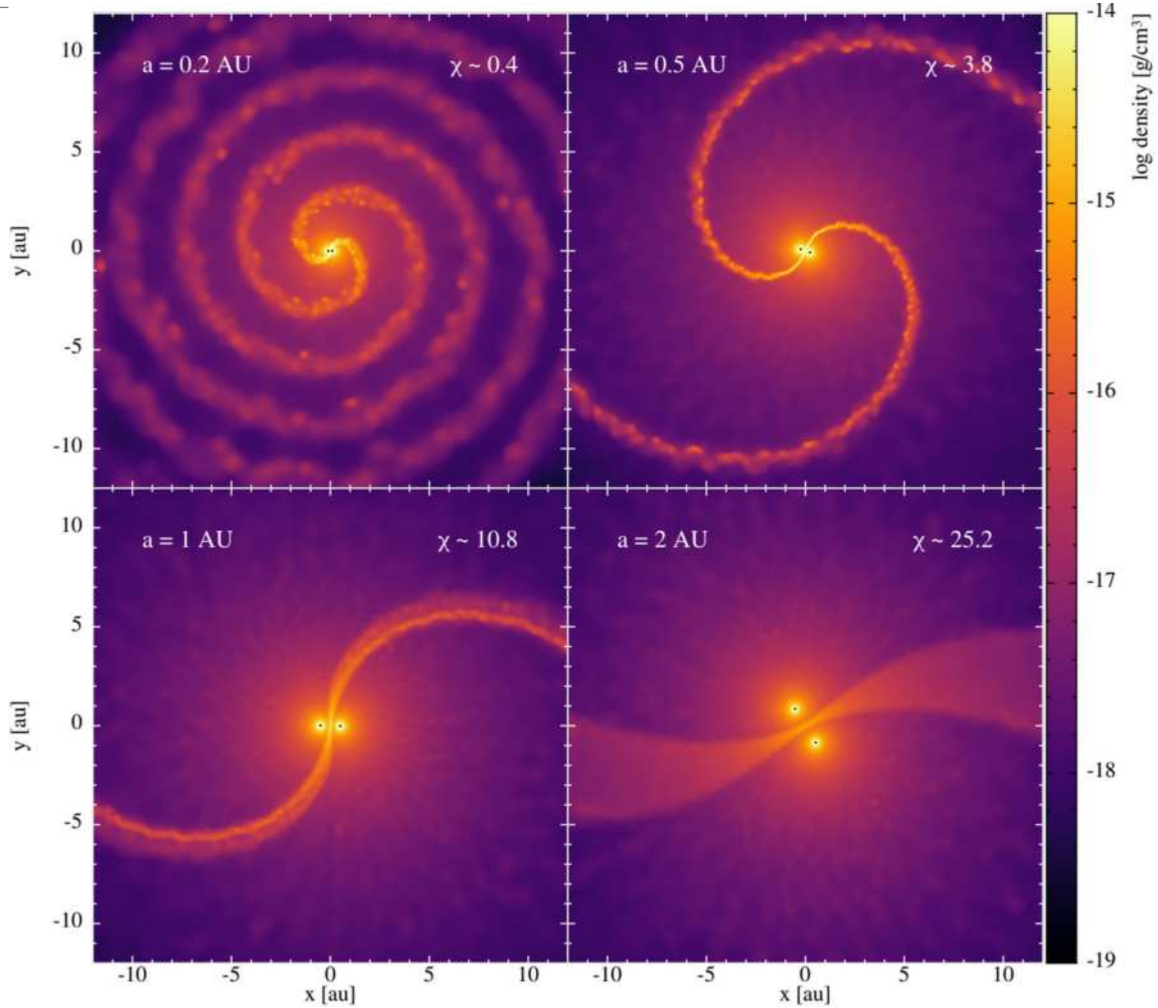
Colliding winds

An important quantity to describe colliding winds is the cooling parameter

$$\chi = \frac{t_{\rm cool}}{t_{\rm esc}} \approx \frac{v_8^4 d_{12}}{\dot{M}_{-7}}$$

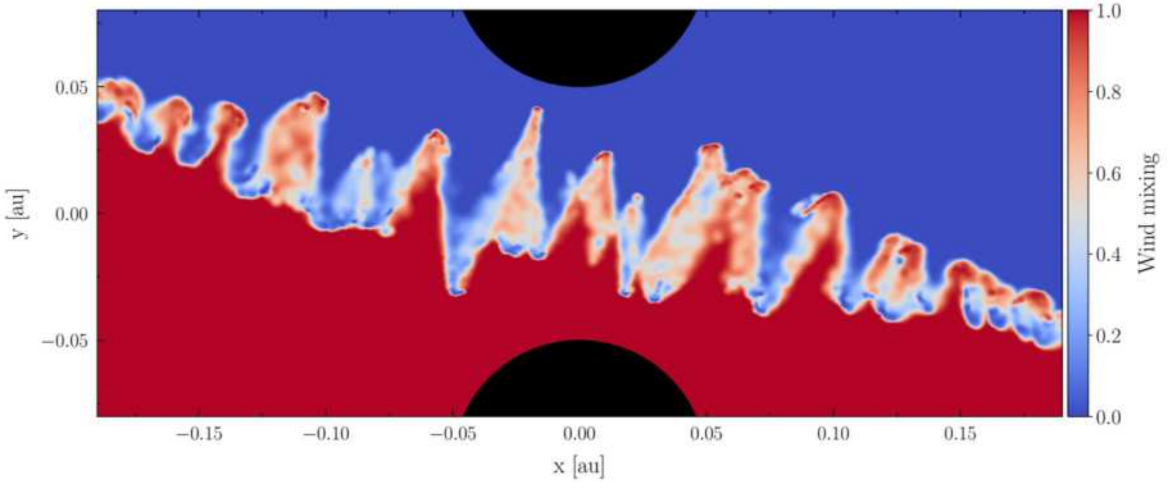
- if χ < 1 the shock is radiative, temperature drops rapidly → loss of pressure, wind collision region dense and thin, subject to thin-shell instability
- if χ > 1 the shock is adiabatic, pressure high, shock front stable

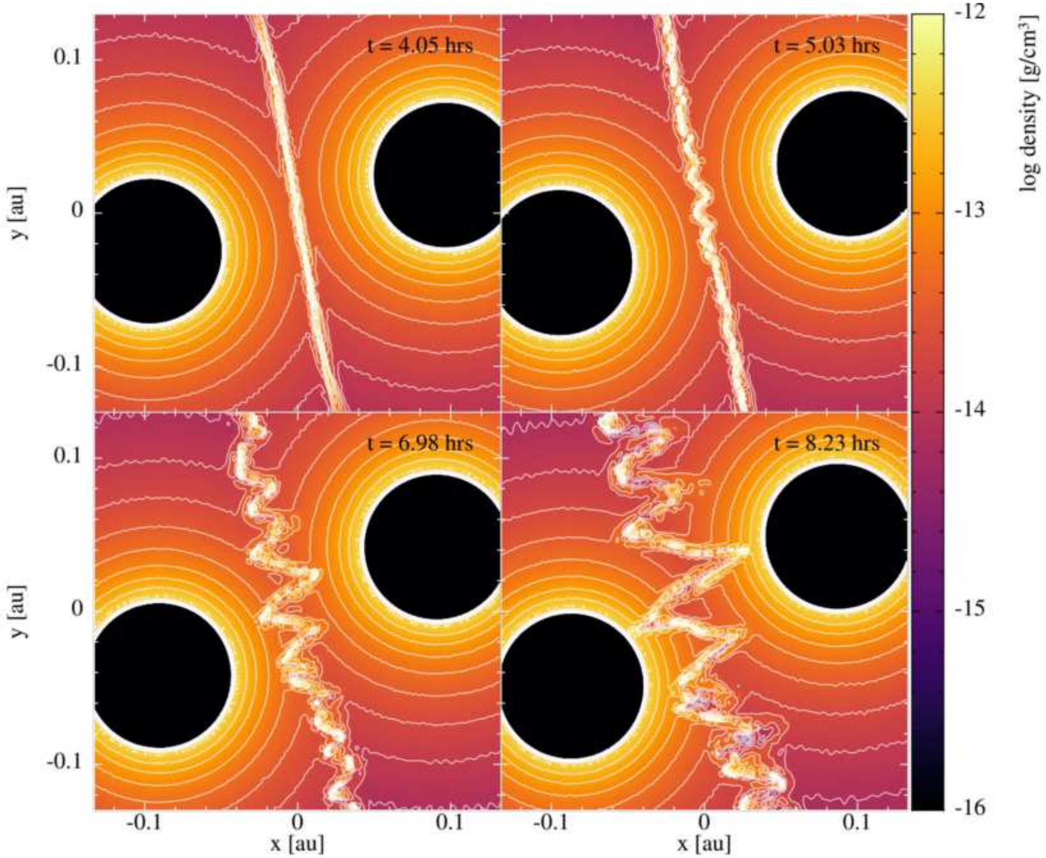
S. Deschaux



Thin shell instability

- deformation of the shock front
- mixing of material across the shock
- in agreement with other simulations

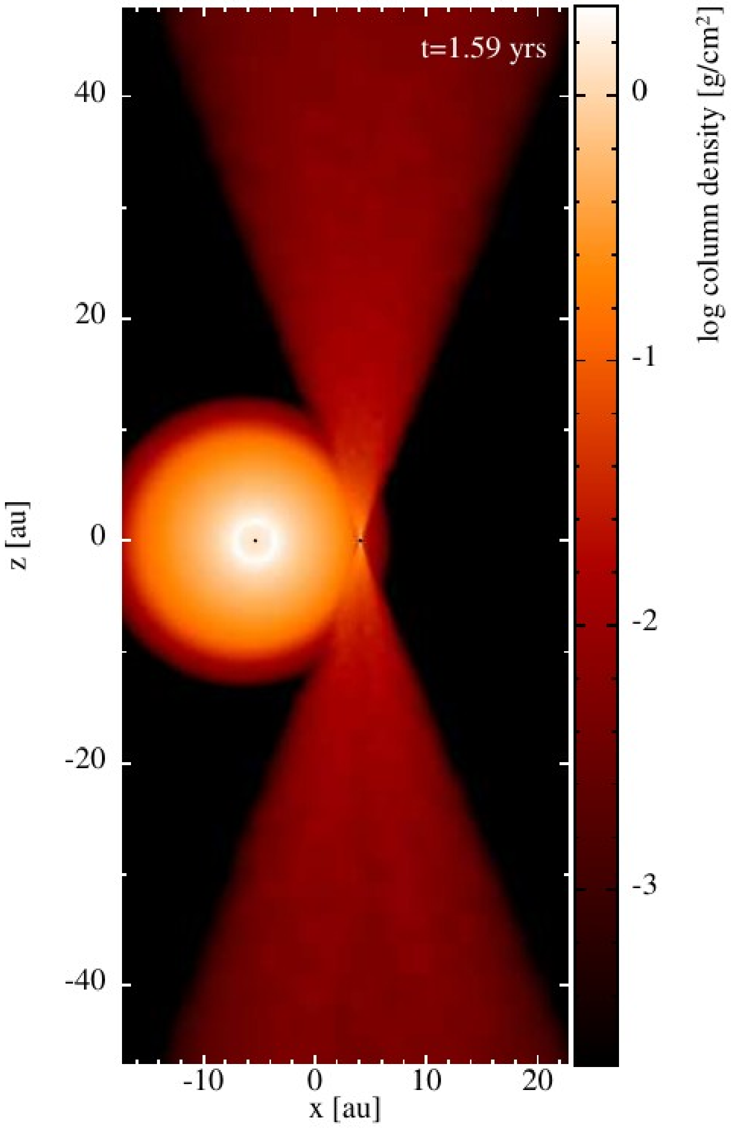




S. Deschaux

Future prospects

- **Radiative transfer** - coupling with MCFOST to estimate T_{dust} , optical depth (τ), radiation force (Γ)
- **Chemistry : O-rich dust** (C/O<1)
- **Pulsations** - improve wind launching mechanism. May need to solve the energy transport in the STAR
- explore new wind geometries (collimated winds, jets)
- **Dust-gas coupling**



S. Deschaux