3D Hydrodynamical models of AGB winds:

The Impact of a Companion on Dynamics and Dust Formation

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Astronomy Day 2025

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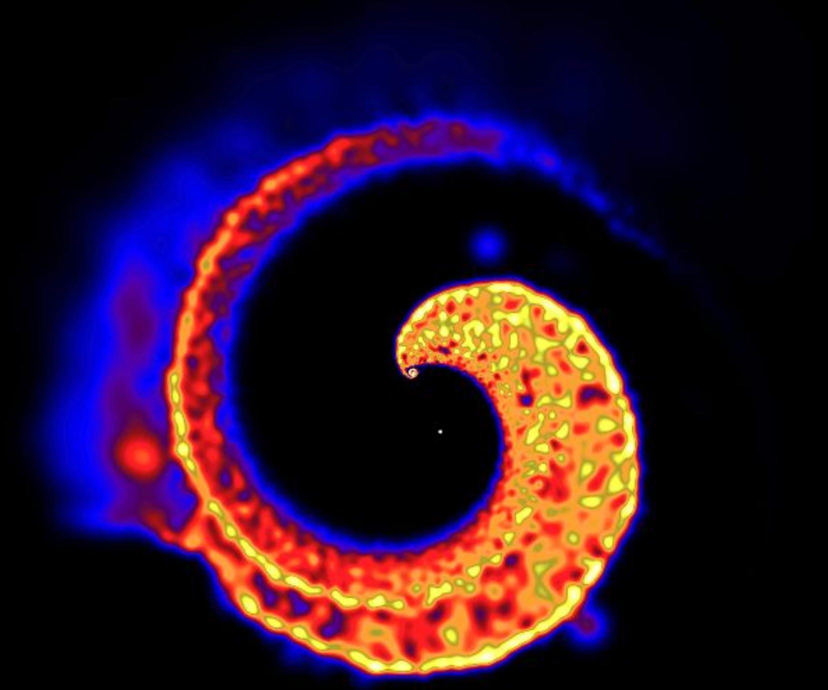

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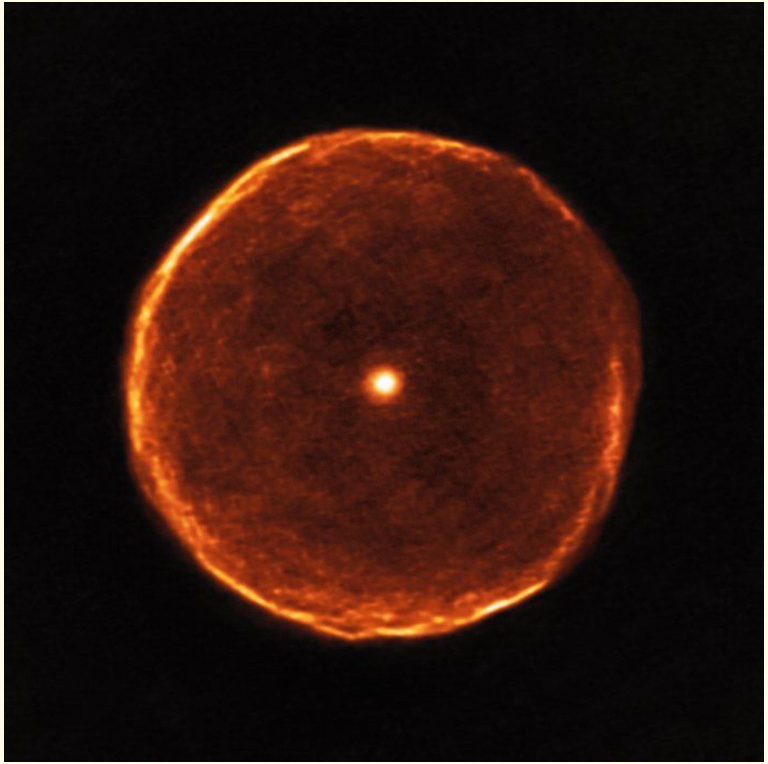
Evolved stars (RGB and AGB)

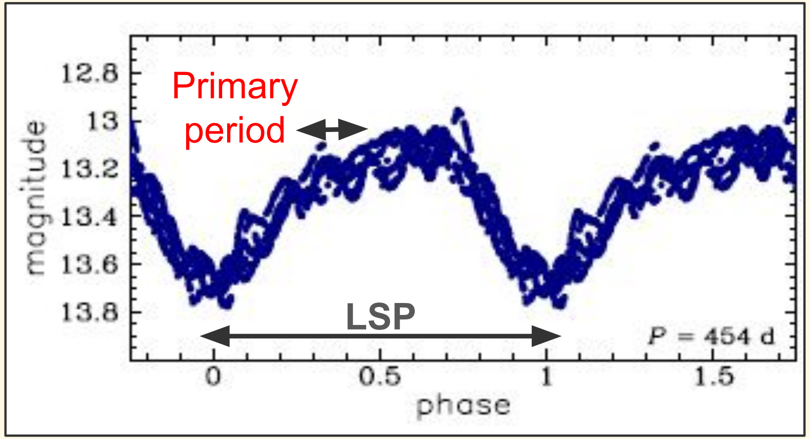
- Radii up to several AU
- Masses 0.8 - 8 M_sun
- $\dot{M} \sim 10^{-6}$ Msun/yr
- **Dust-driven** winds
- **Dusty** circumstellar envelope
- Pulsations



U Antliae, observed with ALMA.
Credit: ALMA (ESO/NAOJ/NRAO)/F. Kerschbaum

Long Secondary Period (LSP)

- Observed in ⅓ of evolved solar-type stars
- Detected as periodic oscillations in luminosity
- ~10 times longer than primary period (from pulsations)
- Amplitudes up to ~1 mag
- Decline faster than rise



Light curves in I band

Eclipsing binary hypothesis

Evolved star
+
Sub-stellar companion hidden in dust

- Companion focuses the wind
  dusty shell and wake

- Originally a planet, accreted to the mass of brown dwarf

Main proof: Observed **secondary eclipse** in IR, when companion is behind the primary

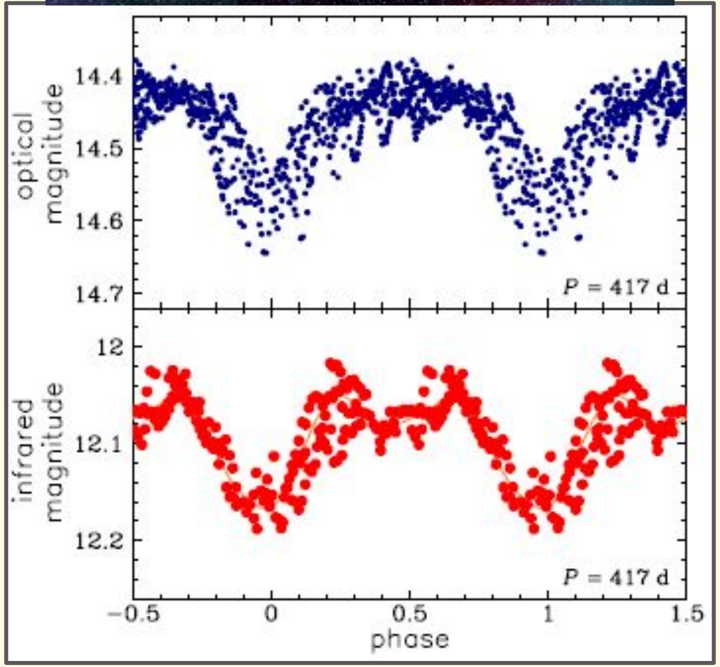


Image from OGLE Atlas of Variable Star Light Curves.
IR observations by NEOWISE.

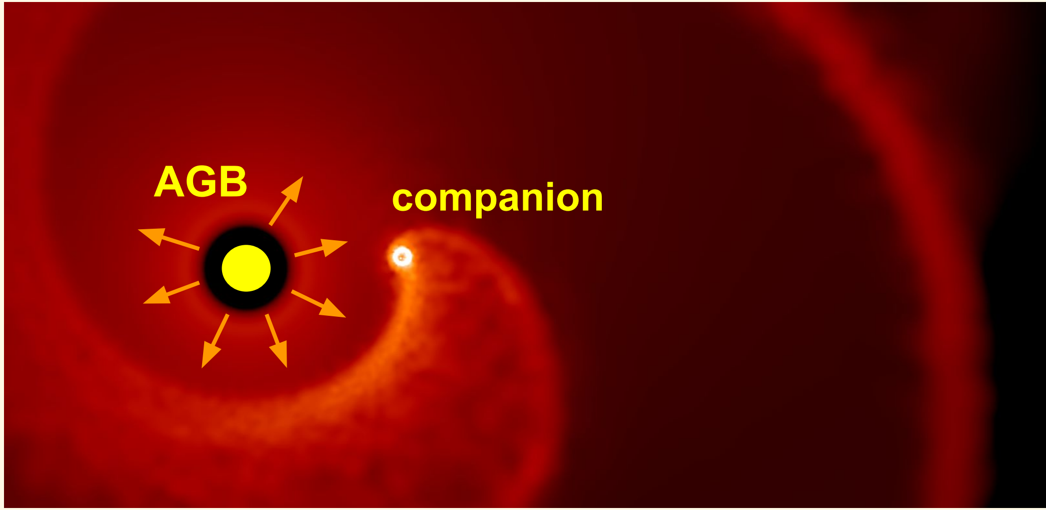
3D Hydrodynamical wind simulations with PHANTOM

Phantom: 3D Smoothed Particle Hydrodynamics (SPH) code

AGB + (sub)stellar companion

Main goals:

- Model wind-companion interaction
- Follow mass accretion on the companion
- Include dust to explain eclipses
- Assess companion's impact on AGB outflows at large scales



Gas cooling and dust formation

Major upgrades to Phantom code.
Gas cooling is fundamental in AGB outflows:

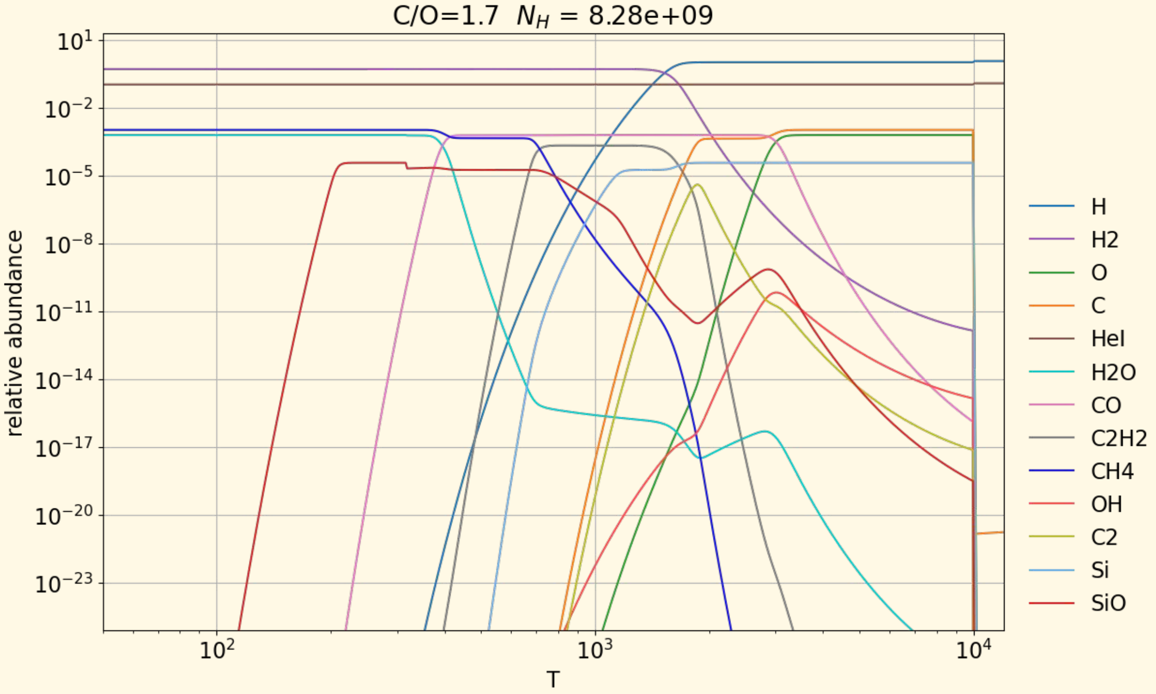
- Allows dust formation (C-rich dust condensation temperature ~ 1500 K)
  - ➢ Wind driving
  - ➢ LSPs (through eclipses due to high optical depth dust cloud)

- Allows larger densities around the companion (mass accretion)

<u>Equilibrium</u> chemistry for radiative cooling

7 elements: H, C, N, O, S, Si, Ti
26 molecules
26 chemical reactions to describe their formation

Network extended to lower temperatures



New cooling rates

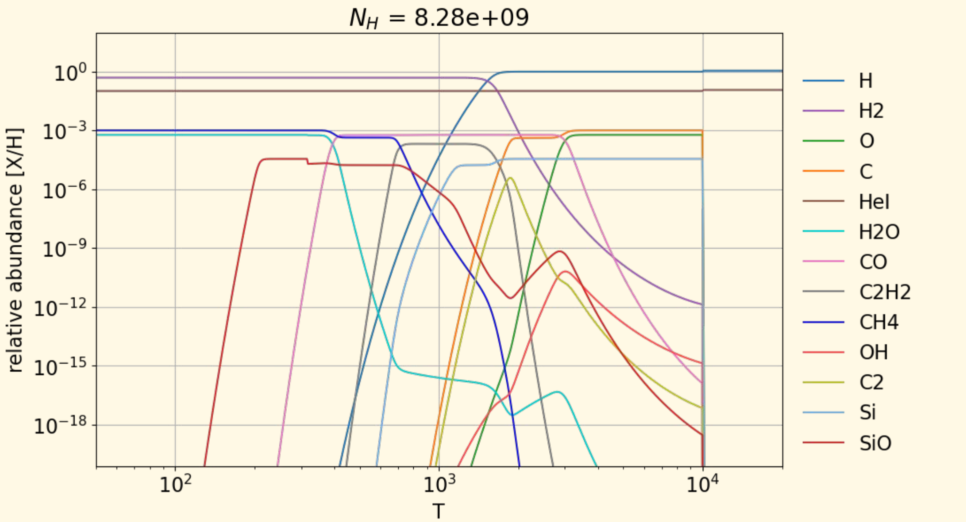
“AGB cooling”

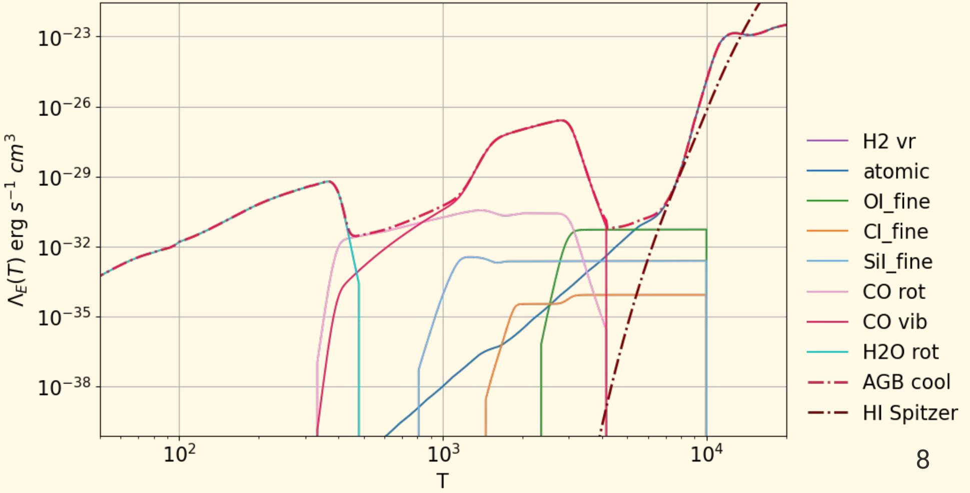
$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}(\nabla \cdot \boldsymbol{v}) + \Lambda_{\text{shock}} - \frac{\Lambda_{\text{cool}}}{\rho}$$

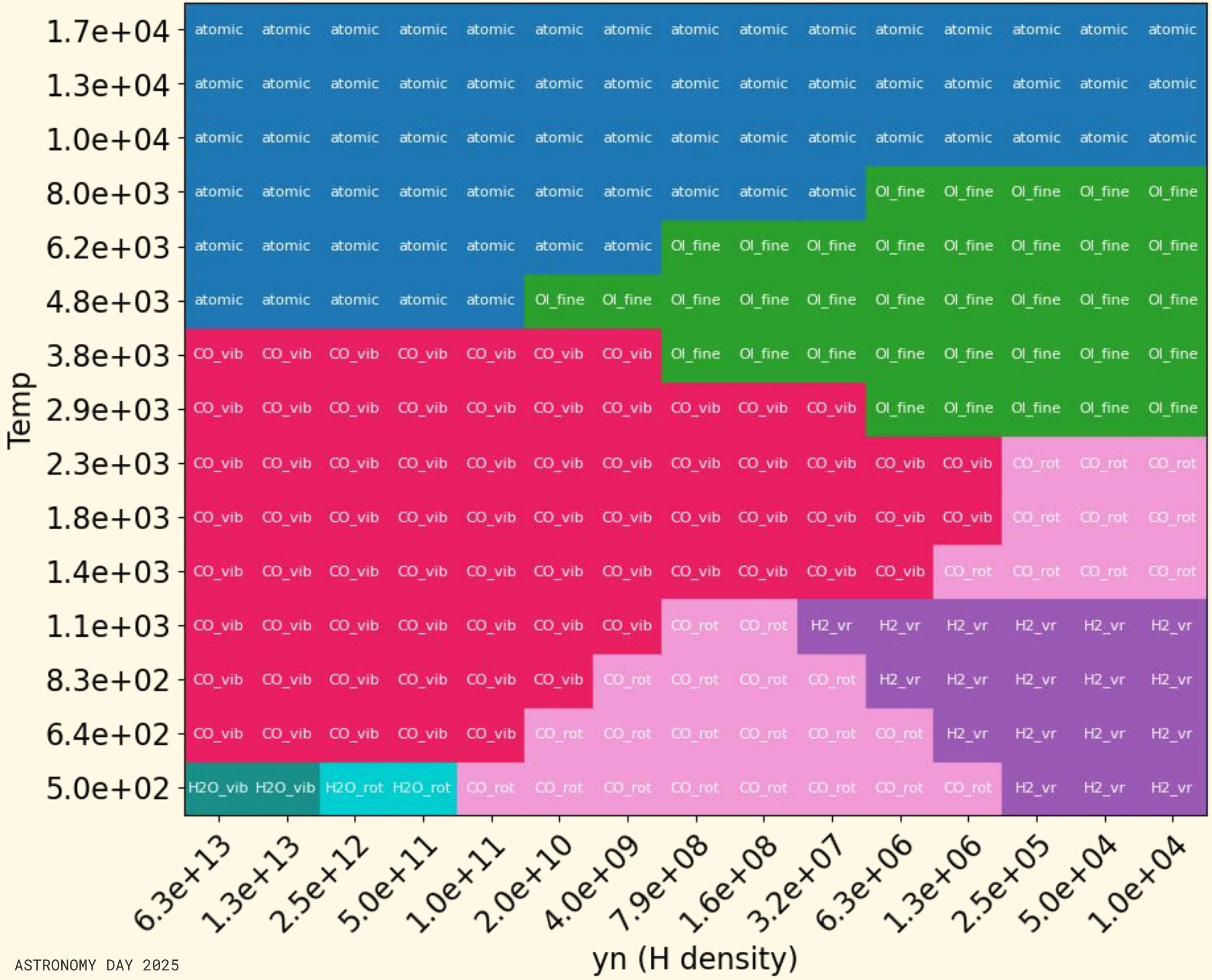
Radiative cooling processes
Adapted from Glover et al. 2012

H2 rot / vib	OH	H2 CIE
Atomic (HI)	H2O (H2O18) rot / vib	CO (C13O, CO18) rot/vib
CI	OI	SiI

C/O = 1.7
Solar abundances





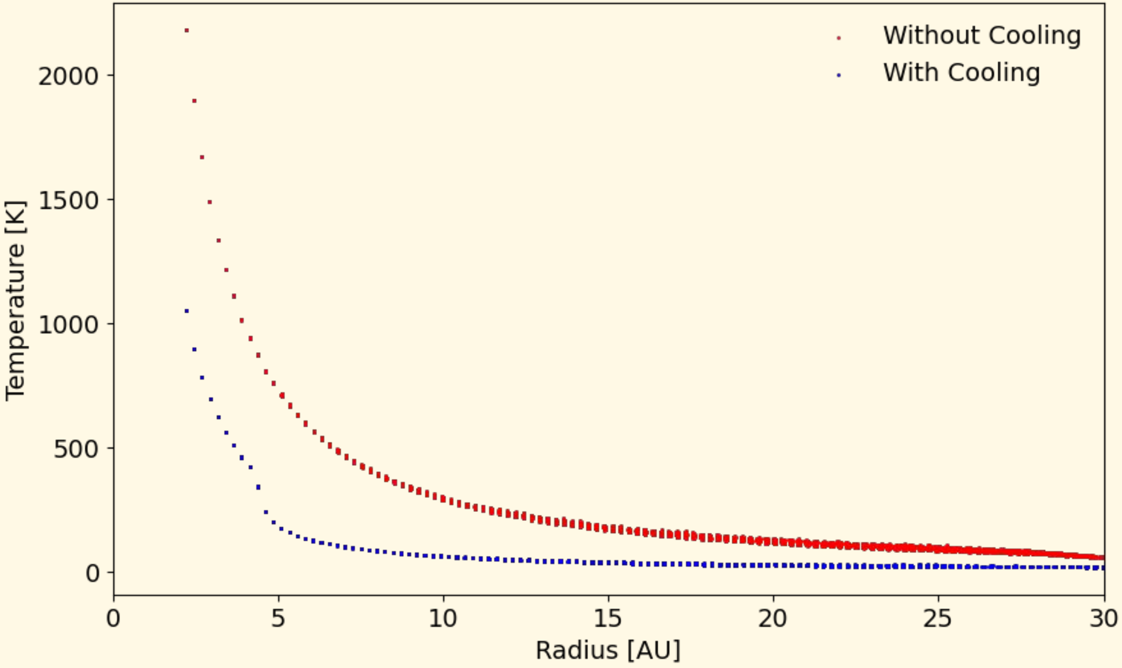


Most relevant cooling species

C/O = 1.7
Solar abundances

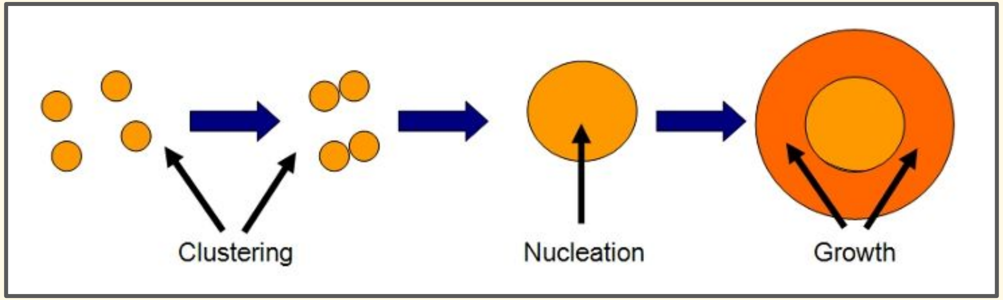
Effects of new cooling rates on spherically symmetric single star AGB wind

Mass	1.2 M_sun
Radius	1 AU
T_eff	3000 K
Wind inj. radius	2 AU
Wind inj. temp.	2500 K
Wind inj. vel.	20 km/s
M_dot	10^5 M_sun/year



Dust formation

2-step process



1. Nucleus formation

- Process operates on a molecular scale
- Seeds contain 100 to 1000 atoms
- Nucleation rate computed from abundance of monomers (dust building blocks)

2. Grain growth

- Gas molecules stick to grain surface and make it grow
- Growth proceeds via:

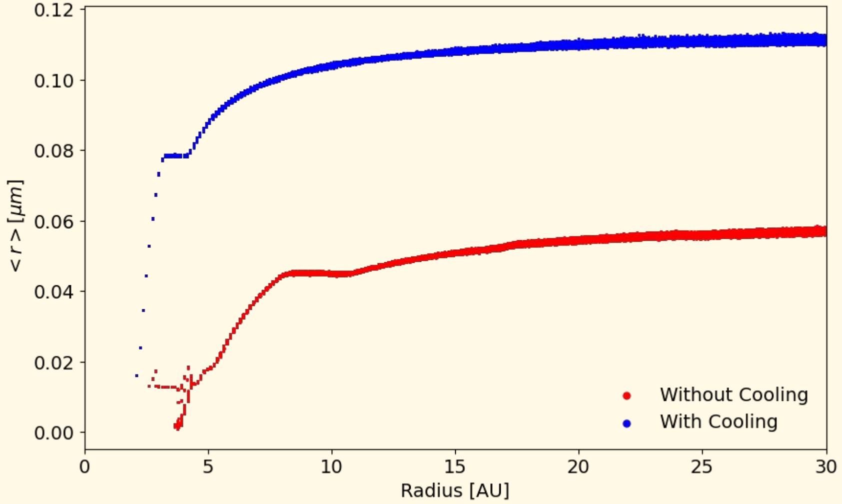
$$C_N + \boxed{C} \longrightarrow C_{N+1}$$
$$C_N + \boxed{C_2} \longrightarrow C_{N+2}$$
$$C_N + \boxed{C_2H_2} \longrightarrow C_{N+2} + H_2$$
$$C_N + \boxed{C_2H} \longrightarrow C_{N+2} + H$$

Impact of AGB cooling on dust formation

Single AGB star outflows

Additional cooling has a major effect on dust production

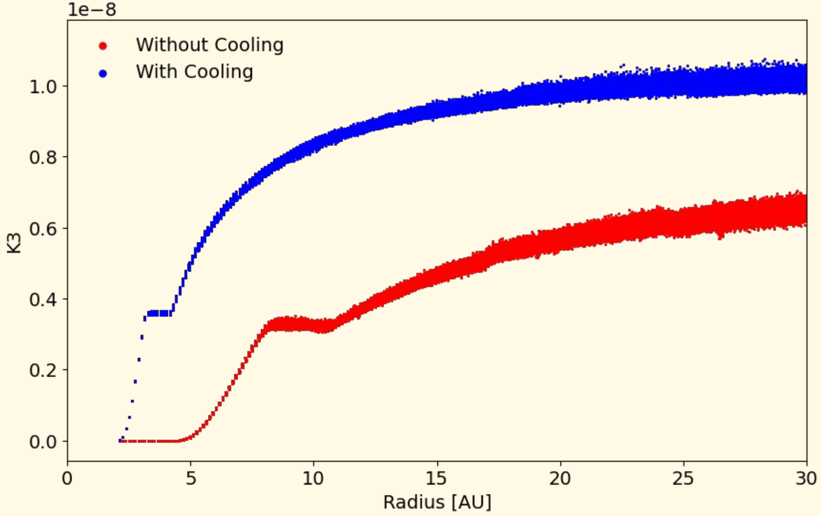
Average grain size



3rd moment:
~ number density of available monomers trapped into dust

↓

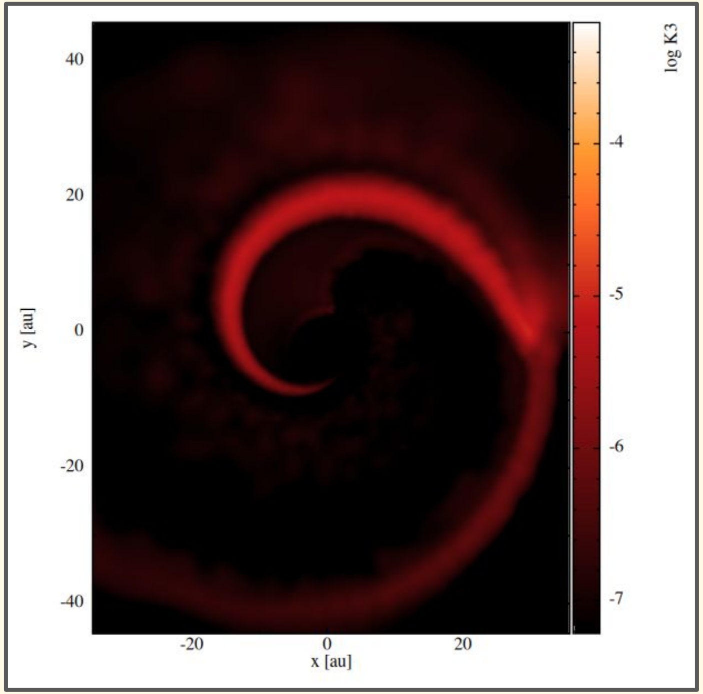
Proxy for dust density

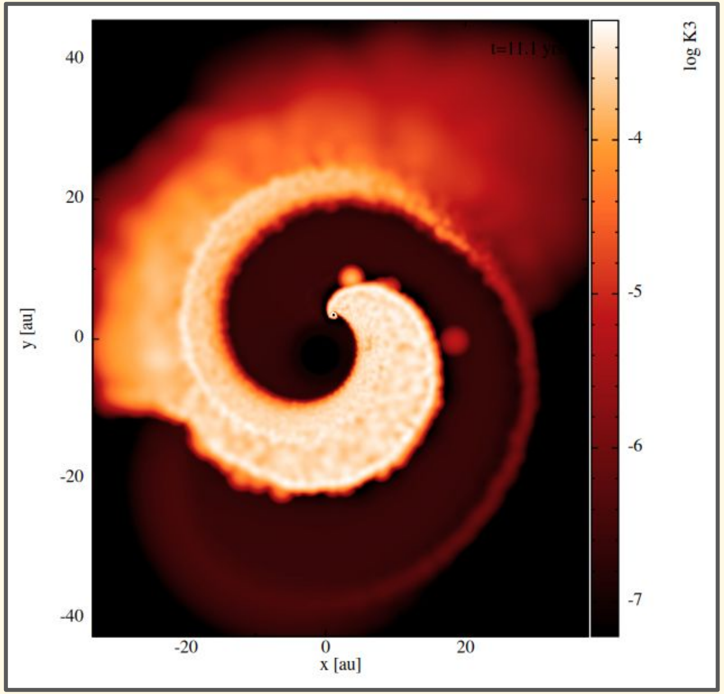


Impact of AGB cooling on dust formation

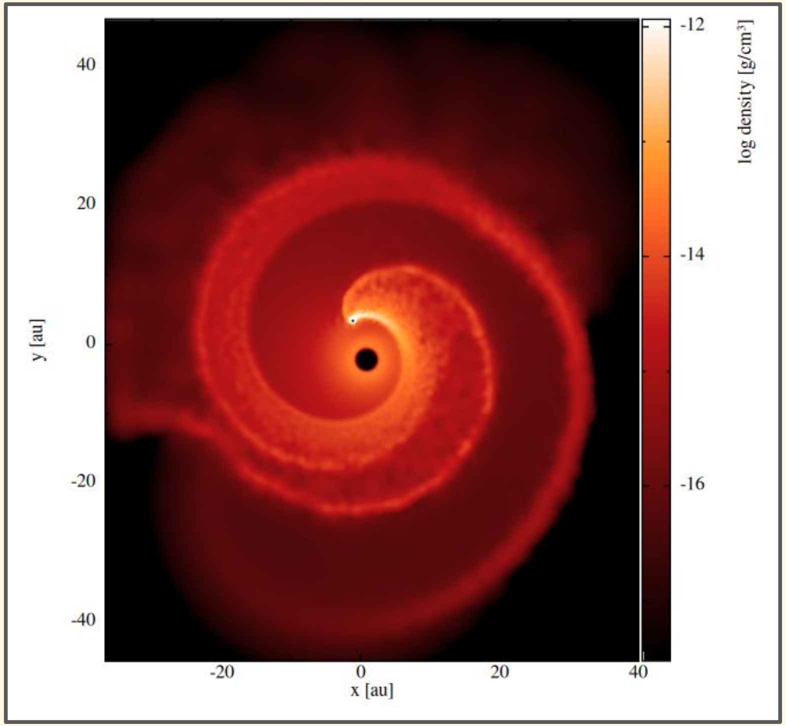
Mass Primary	1.5 M_sun
Mass secondary	1 M_sun
Separation	6 AU

3rd moment:
~ number density of carbon monomers trapped into dust

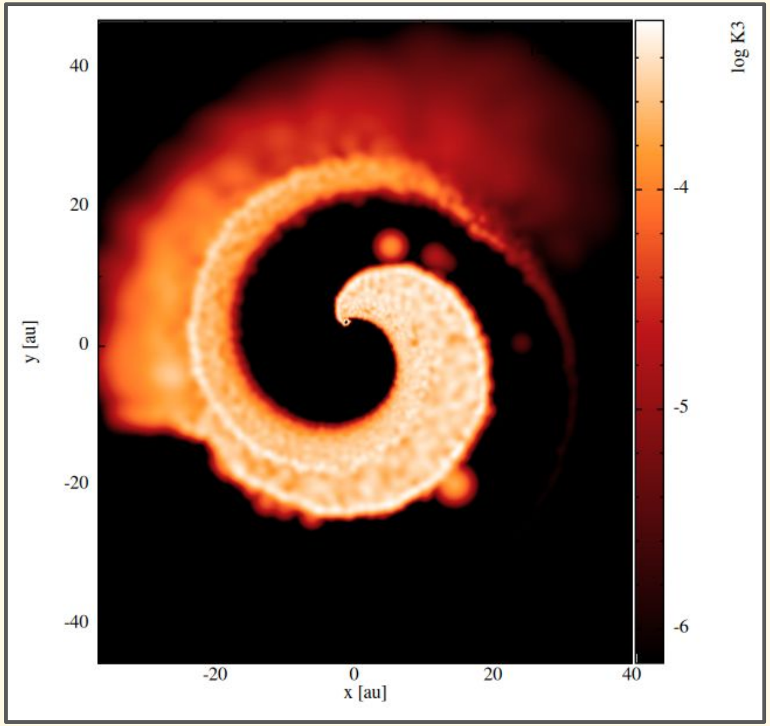




Dust formation in the companion's wake

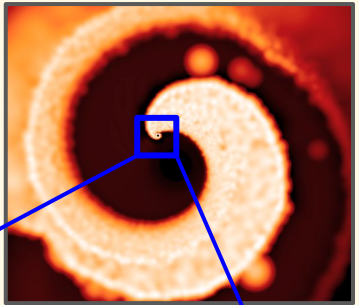


Gas density

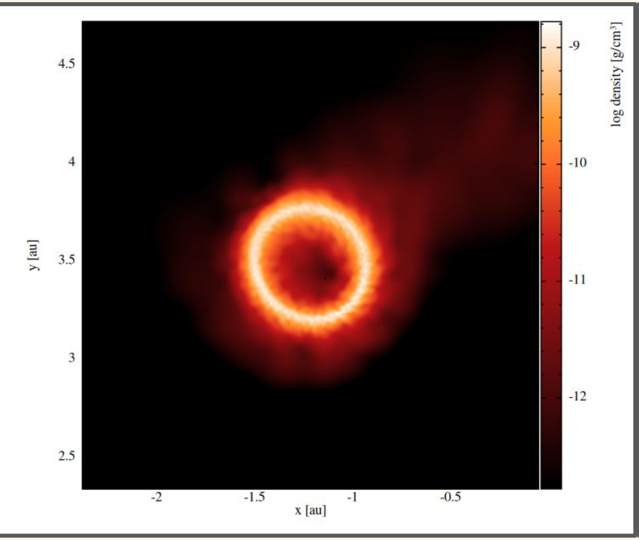


K3 (~ dust density)

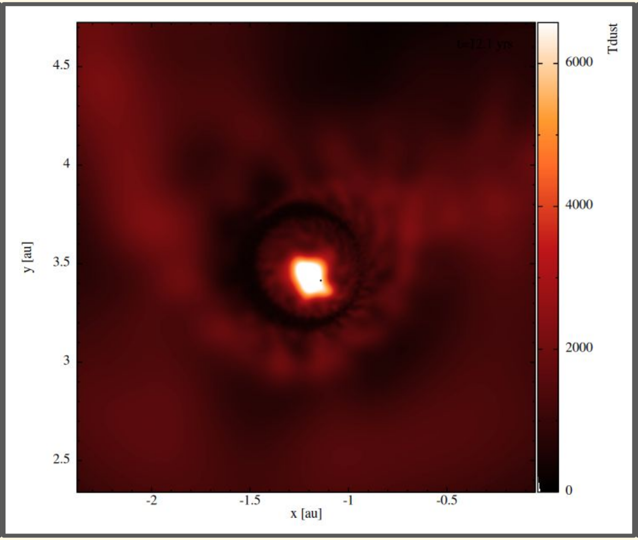
Dust destruction



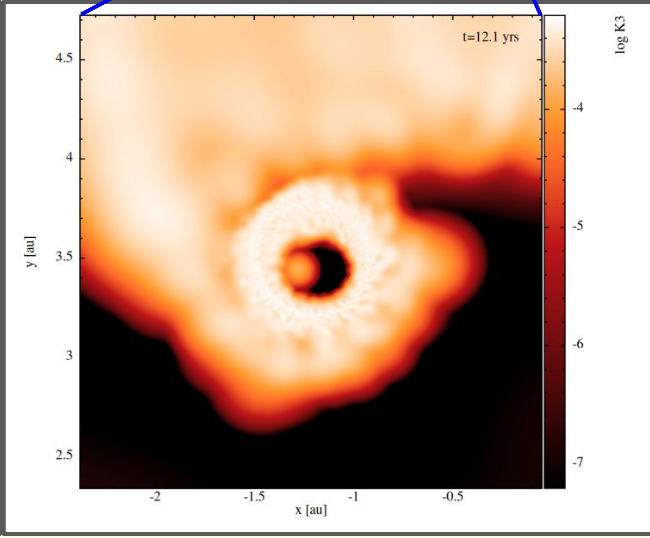
Dust is destroyed when temperature rises above evaporation temperature,
For instance around the companion



Gas density



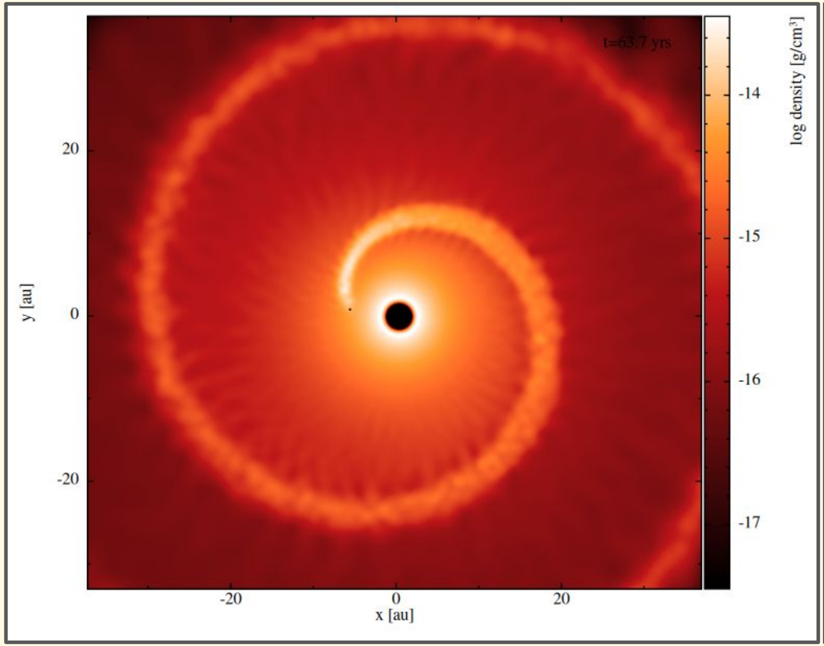
Temperature



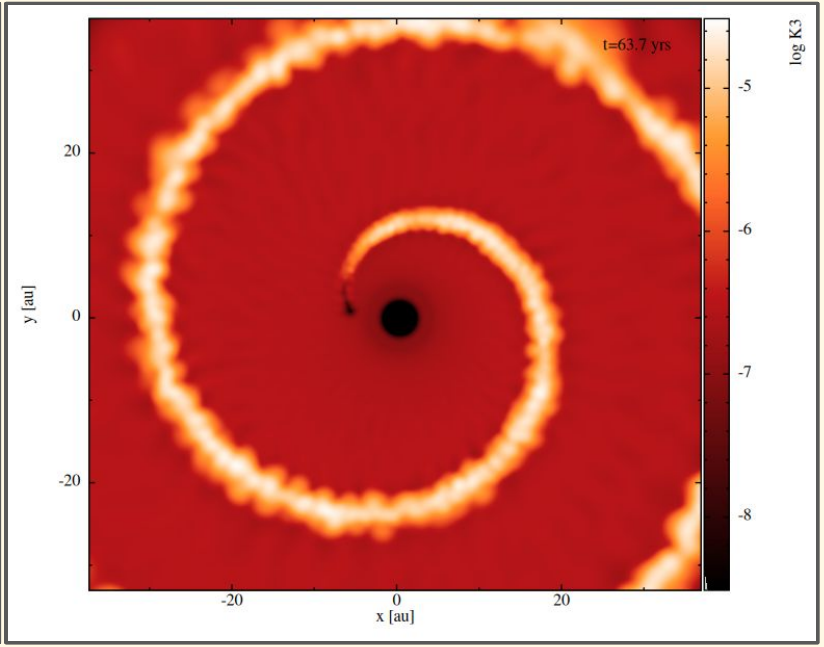
K3 (~ dust density)

Brown dwarf companion

Mass Primary	1.5 M_sun	Wind inj. radius	2 AU
Mass Secondary	0.1 M_sun	Wind inj. temp.	2500 K
Separation	6 AU	Wind inj. vel.	10 km/s
T_eff	3000 K	M_dot	10^5 M_sun/year



Gas density



K3 (~ dust density)

Conclusions

- Inclusion of additional cooling rates within Phantom simulations

→ Allowed to reach gas temperature favorable to dust formation

- First Phantom simulations featuring new cooling with both dust formation and evaporation
- Dust forms in the wake of the companion

The main desired physical process are now included in the simulations;
We can derive observables and test the binary hypothesis of LSPs.