Dust Grains Evolution by chemisputtering during protostar formation

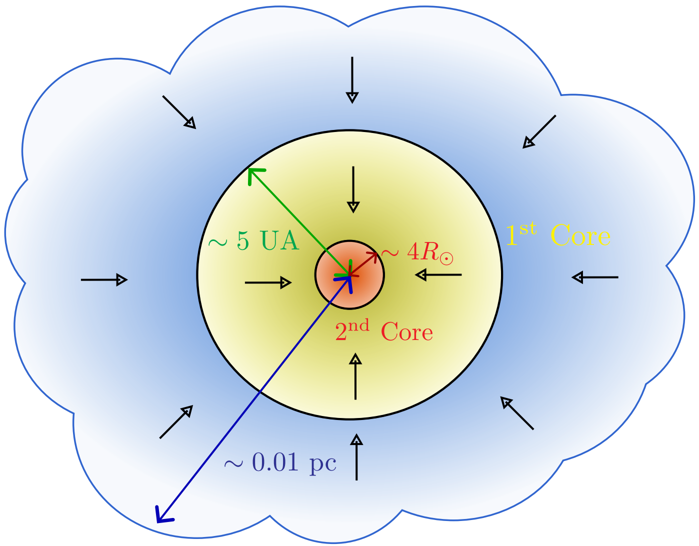
Antonin Borderies, Benoît Commerçon, and Bernard Bourdon

CRAL
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

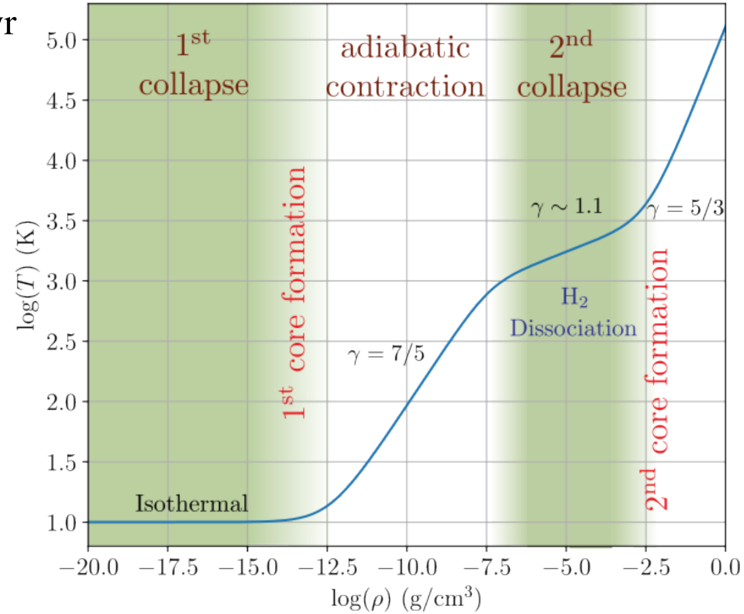
Context: The protostar formation by gravitational collapse

Pre-stellar Core	First Collapse	First Larson Core	Second Collapse	Second Larson Core
$T \sim 10$ K $\rho \sim 10^{-18}$ g/cm^3 $R \sim 2000$ AU	10^4 yr	$T \sim 100$ K $\rho \sim 10^{-13}$ g/cm^3 $R \sim 5$ AU	$< 10^2$ yr	$T \sim 10^5$ K $\rho \sim 10^{-2}$ g/cm^3 $R \sim 0.02$ AU

Larson (1969)



10^3 yr



Context: Dust handling in current collapse simulations

Dust grain sizes : **MRN Distribution** (Mathis, Rumpl & Nordsieck 1977)

$$dn = Ca^{-3.5}da$$

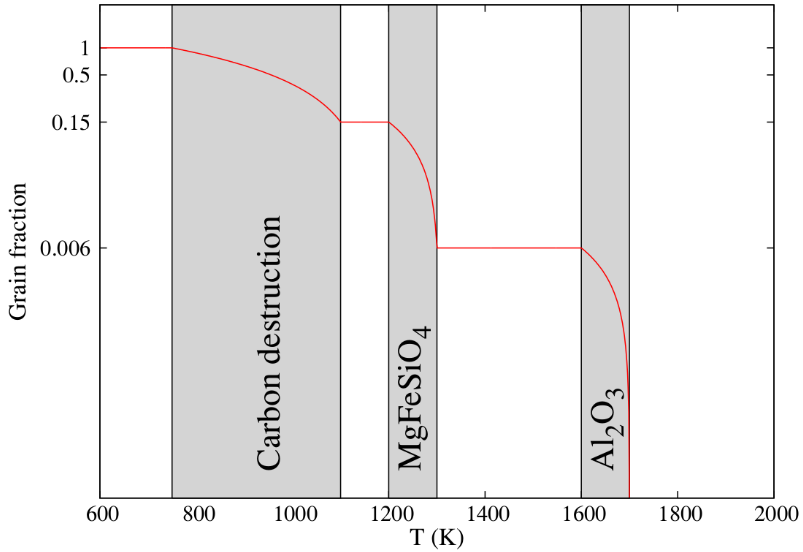
$$a_{\min} = 5 \times 10^{-7}\ \mathrm{cm}$$

$$a_{\max} = 2.5 \times 10^{-5}\ \mathrm{cm}$$

Grain evolution is tabulated :

-> So are its effects !

(Opacities, magnetic resistivities)



Marchand *et al.* (2016)

Dust has been assumed to be in equilibrium with the environment

Lenzuni *et al.* (1995) : In dense and warm region, interaction with the gas phase can limit this approach.

Evolutionary model: The dust grain

Goal: Given a time evolution in temperature and density, how the chemical interactions with the gas phase will make evolve a dust grain?

- Pure grains composed of *N* identical monomers (atoms or molecules)

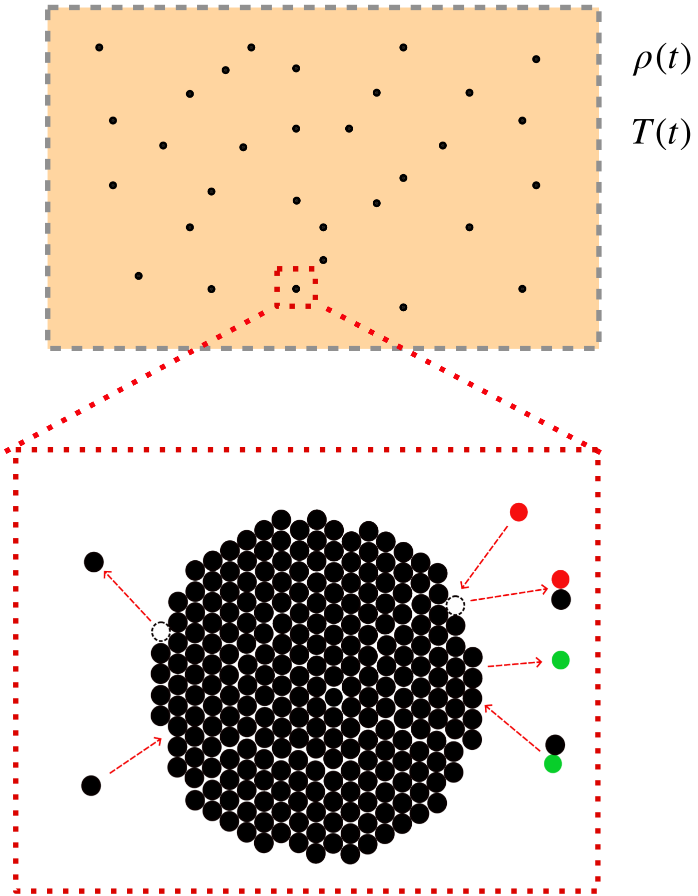
- Spherical grains

$$a \sim N^{1/3} \qquad A \sim N^{2/3}$$

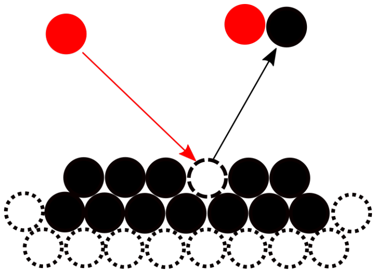
- Grain evolution equation

$$\frac{\mathrm{d}a}{\mathrm{d}t} = V_\mathrm{m}\left(J_\mathrm{abs} - J_\mathrm{des} + {\color{red}J_\mathrm{chem}}\right)$$

$$J_\mathrm{abs} = \frac{1}{4}\alpha v_\mathrm{rel}\frac{P_\mathrm{m}}{k_\mathrm{B}T} \qquad J_\mathrm{des} = \frac{1}{4}\alpha v_\mathrm{rel}\frac{P_\mathrm{m,sat}(T_\mathrm{g})}{k_\mathrm{B}T}$$



Evolutionary model: Chemical sputtering



$$\mathrm{M}_{N_{(s)}} + \sum_{k=1}^{N_{\mathrm{react}}} \nu_k \mathrm{X}_k \xrightleftharpoons[J_{\mathrm{vap}}]{J_{\mathrm{gr}}} \mathrm{M}_{N+1_{(s)}} + \sum_{k=1}^{N_{\mathrm{prod}}} \mu_k \mathrm{Z}_k$$

For a given reaction: $J_{\mathrm{chem}} = (J_{\mathrm{gr}} - J_{\mathrm{vap}})$

$$J_{\mathrm{gr}} = \frac{1}{4}\alpha\, v_{\mathrm{rel}} \frac{n_{\mathrm{react,key}}}{\nu_{\mathrm{key}}}$$

Detailed Balance Principle approach:

$$J_{\mathrm{vap}} = J_{\mathrm{gr,\ eq}} = \frac{1}{4}\alpha_j v_{\mathrm{rel},i} \frac{n_{\mathrm{react,key,\ eq}}}{\nu_{\mathrm{key}}}$$

With $n_{\mathrm{key,\ eq}}$ computed with law of mass action.

Kinetic approach:

$$J_{\mathrm{vap}} = \frac{1}{4} Y v_{\mathrm{rel}} \frac{n_{\mathrm{prod,key}}}{\mu_{\mathrm{key}}}$$

More accurate, but need data…

Application to collapse: The Initial Dust setup

➡ **Three types of grains:**

- **graphite** (carbon), monomer = C, $M_{\rm d}/M_{\rm g} = 2.35 \times 10^{-3}$

  chemical sputtering by H_2O, H_2, and H .

$$J_H = -\frac{1}{4} v_{\rm rel} n_H Y_H$$

Lenzuni *et al.* (1995)

$$J_{H_2O} = -\frac{1}{4} v_{\rm rel} n_{H_2O} Y_{H_2O}$$

Lenzuni *et al.* (1995)

$$J_{H_2} = -\frac{1}{4} v_{\rm rel} n_{H_2} Y_{H_2}$$

Krakowski (1970)

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- **silicates**, monomer = Mg_2SiO_4, $M_{\rm d}/M_{\rm g} = 2.19\times10^{-3}$

$$Mg_2SiO_{4\,\rm (s)} + 3H_2 \leftrightarrows 2Mg + SiO + 3H_2$$

$$Mg_2SiO_{4\,\rm (s)} \leftrightarrows 2Mg + SiO + \frac{3}{2}O_2$$

- **aluminium oxides**, monomer = Al_2O_3, $M_{\rm d}/M_{\rm g} = 1.05\times10^{-4}$

$$Al_2O_{3\,\rm (s)} + 3H_2 \leftrightarrows 2Al + 3H_2O$$

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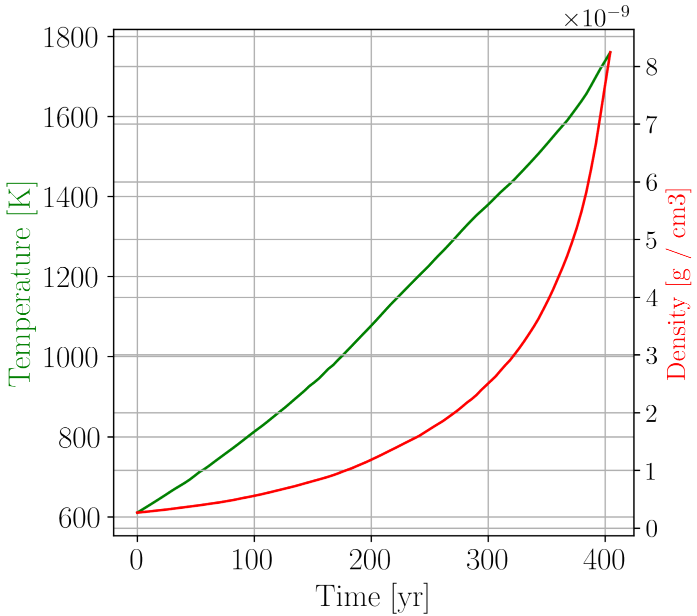
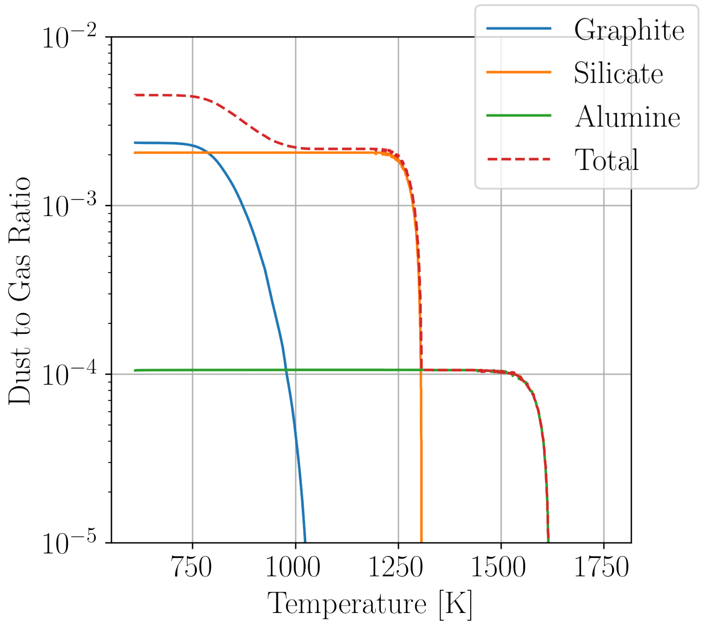
➡ **MRN distribution** at the beginning: $a_{\mathrm{min}} = 0.005\ \mu m$, $a_{\mathrm{max}} = 0.25\ \mu m$.

➡ **Solar composition** for the elemental abundances in the gas-dust mixture.

Benchmark of the code: Comparison with Lenzuni *et al. 1995*





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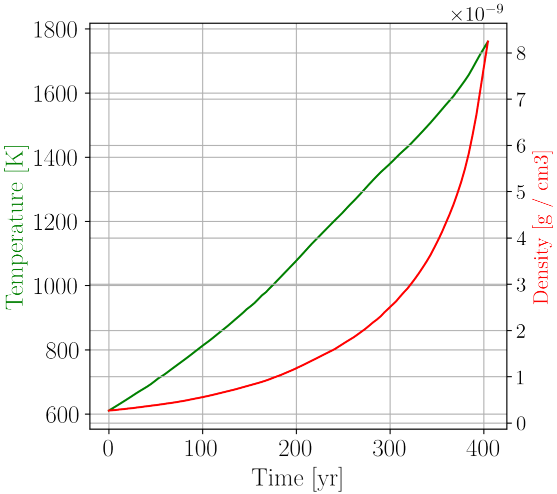
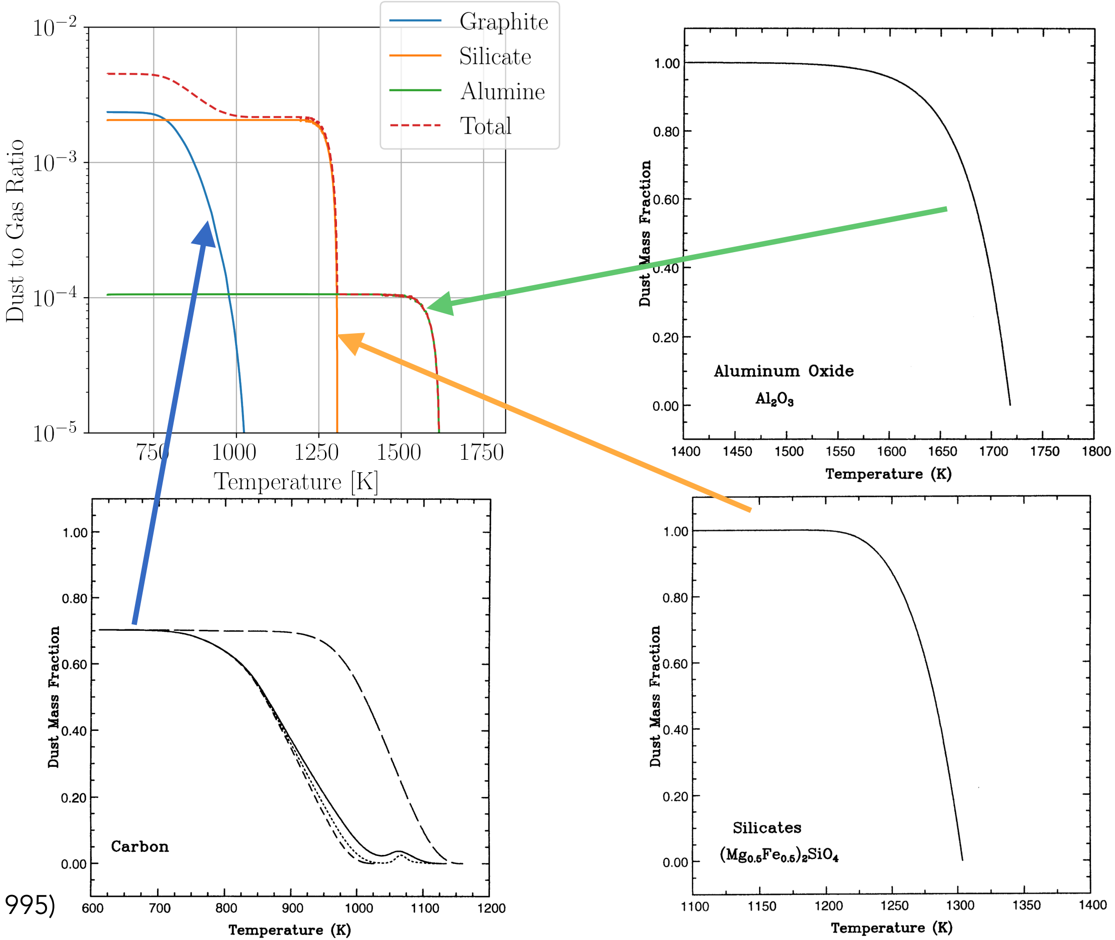
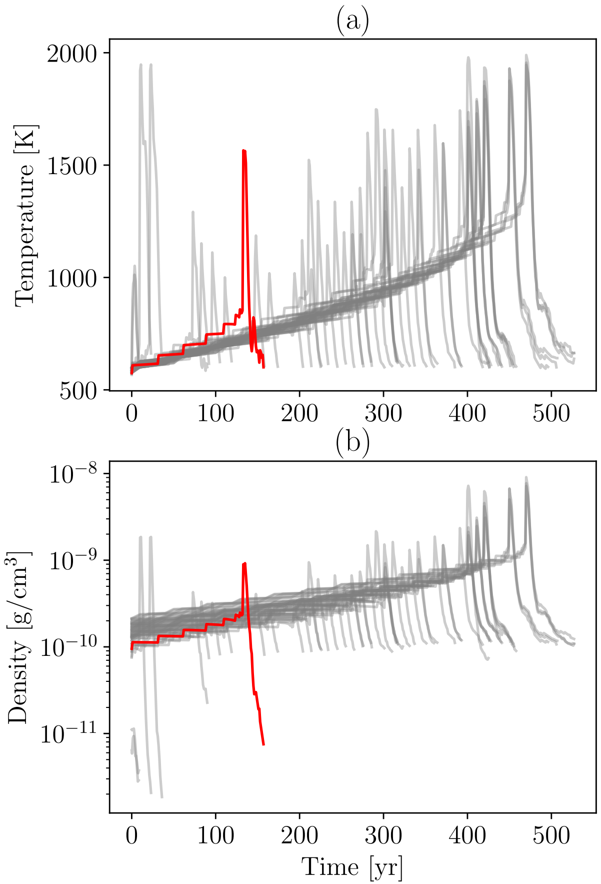


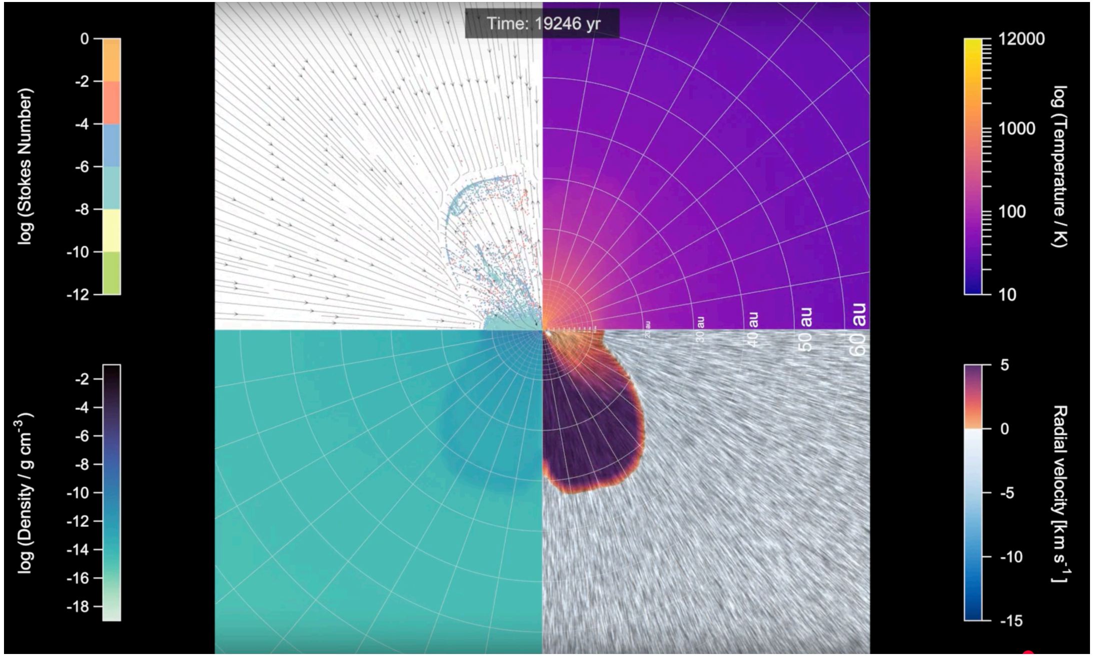


Lenzuni's results are reproduced

Lenzuni *et al.* (1995)

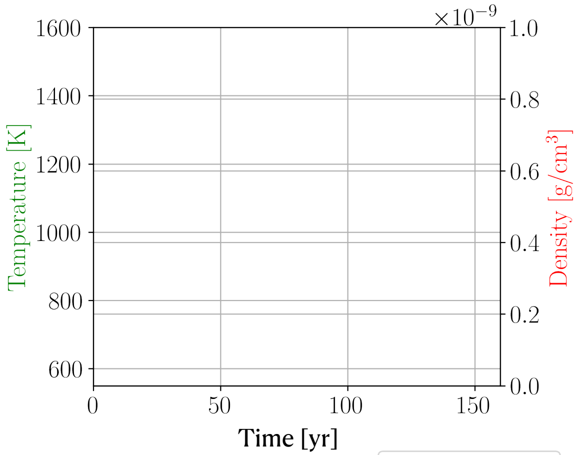
Application to collapse: Simulation Trajectories

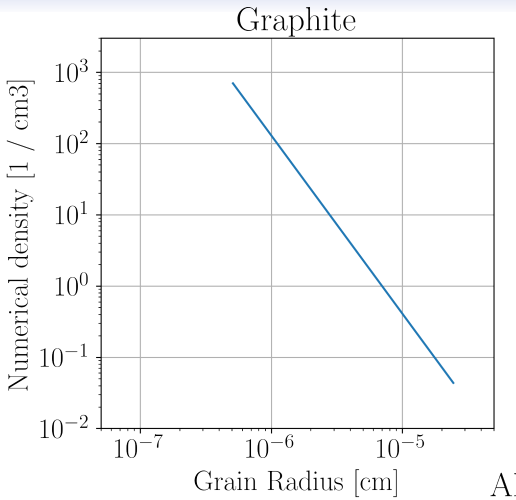


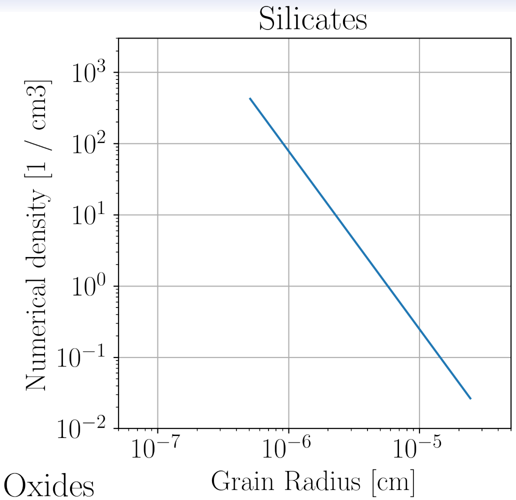


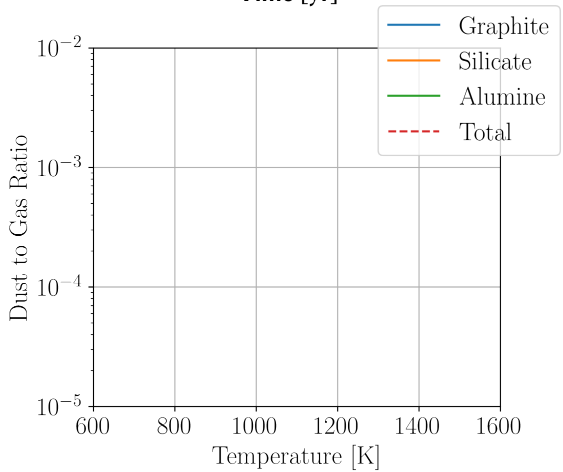
Bhandare *et al.* (2024)

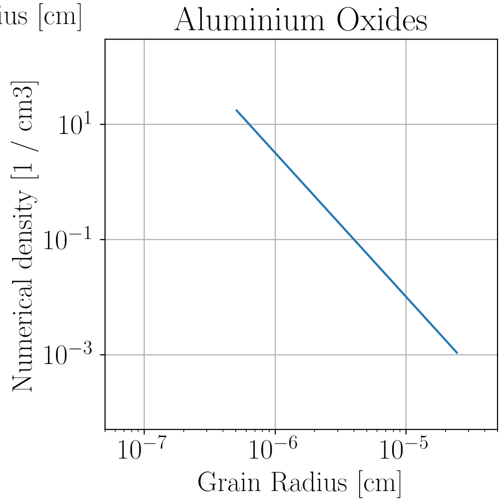
Application to collapse: Dust evolution











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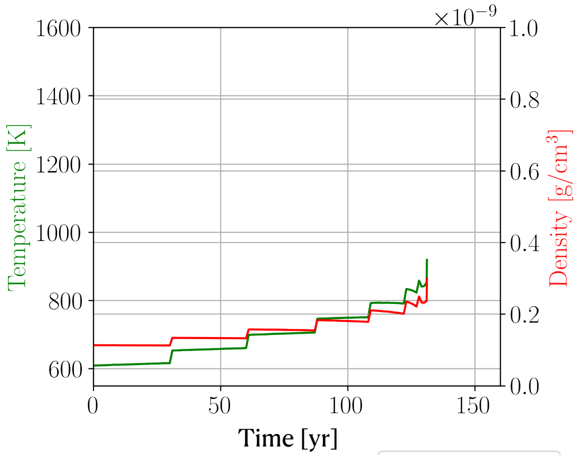

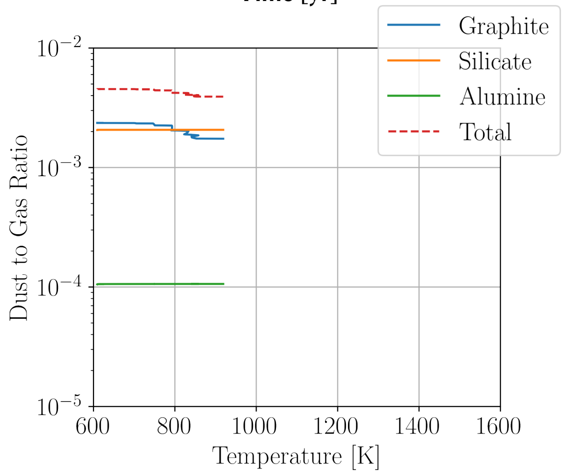

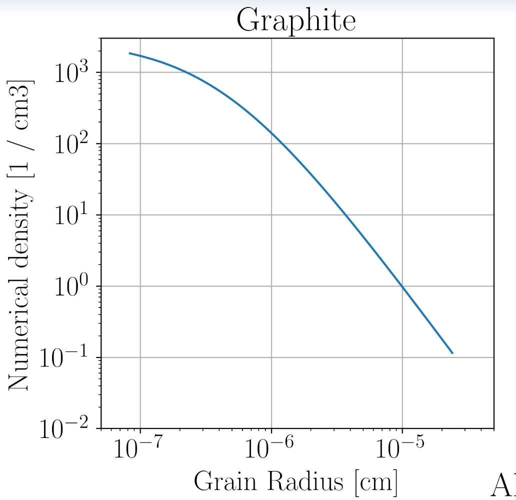

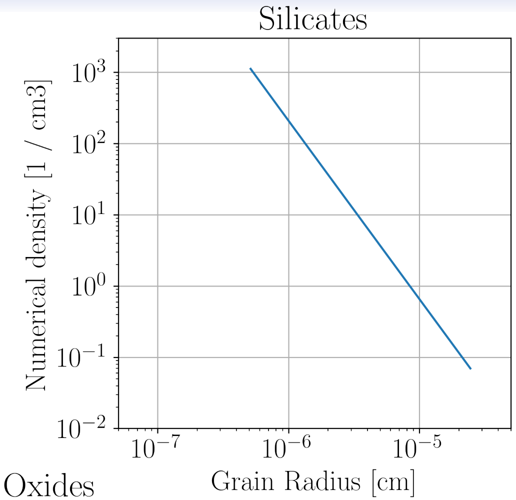

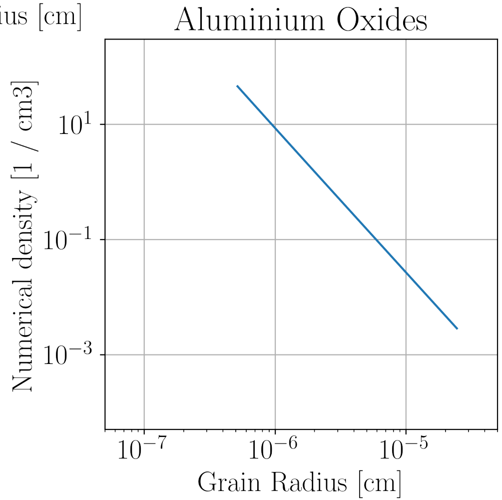

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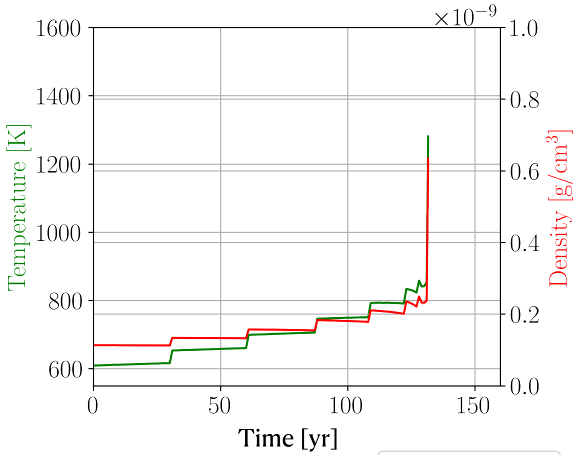

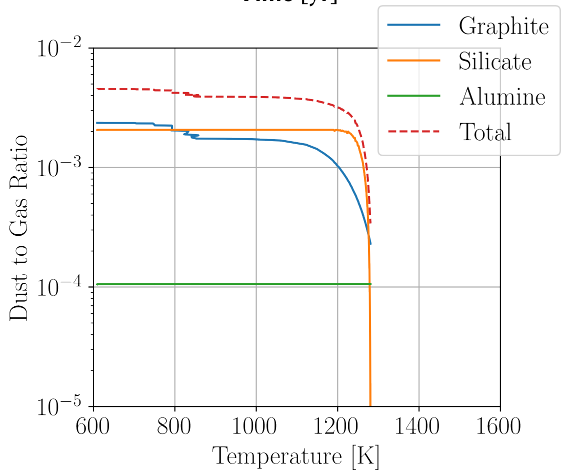

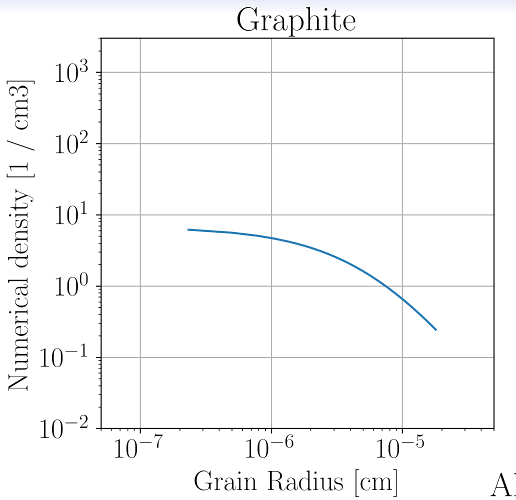

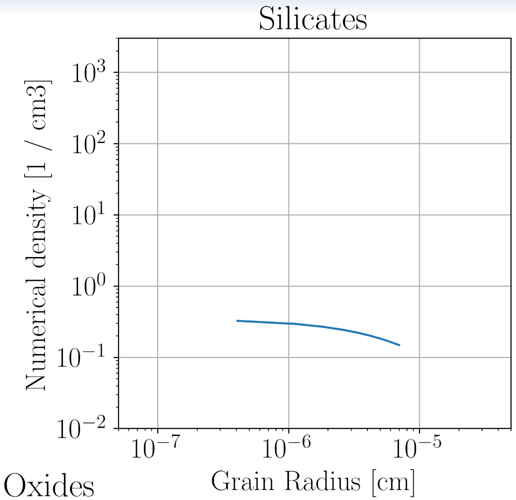

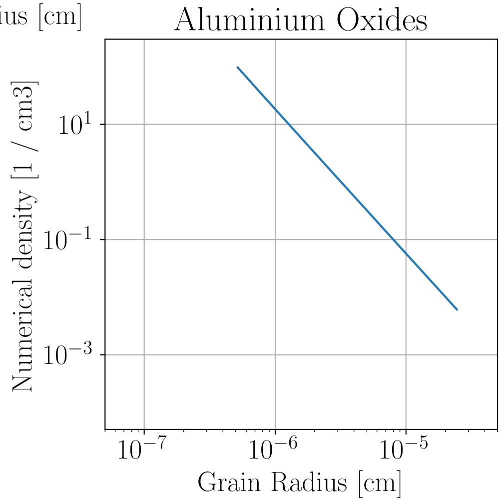

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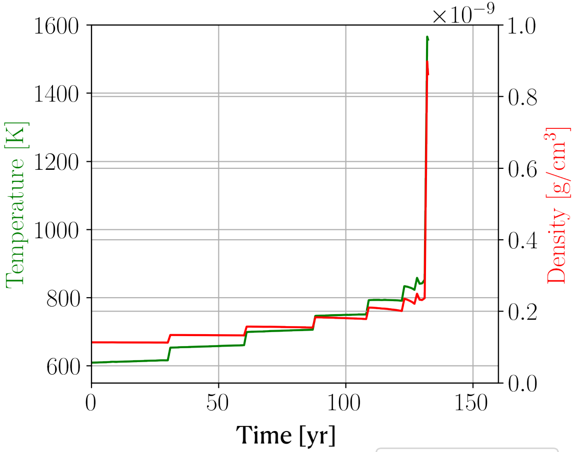
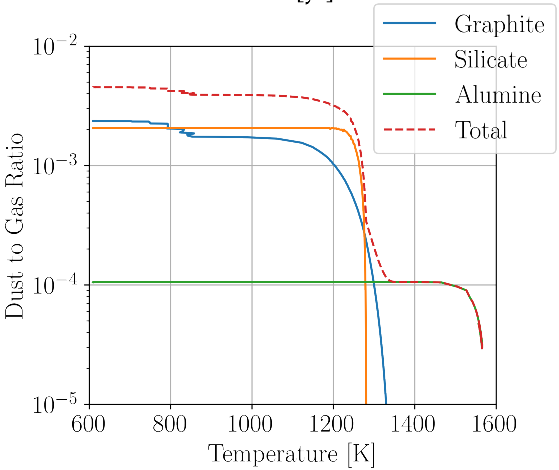
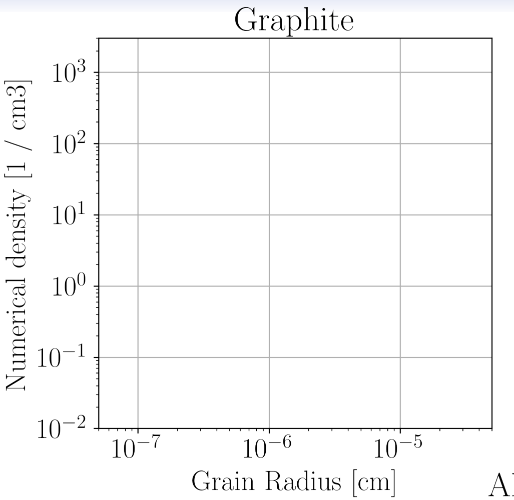
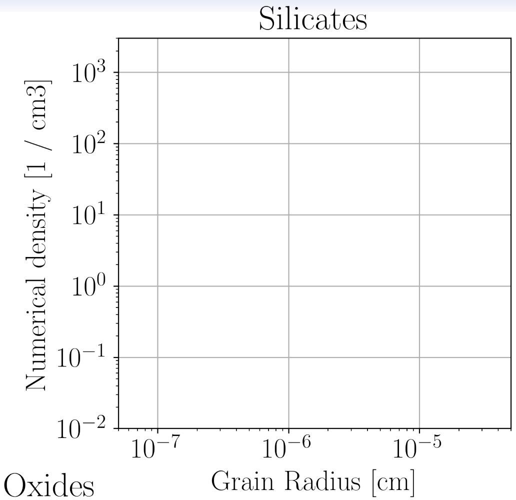
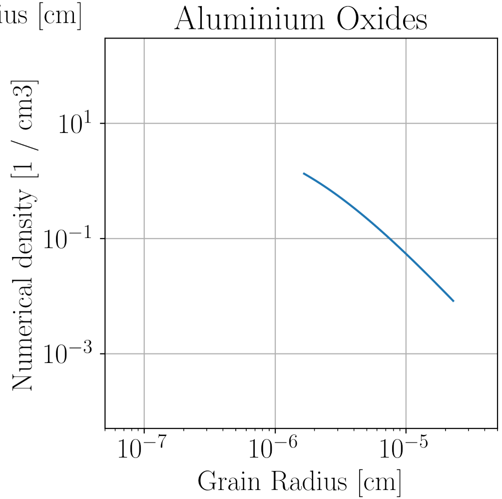


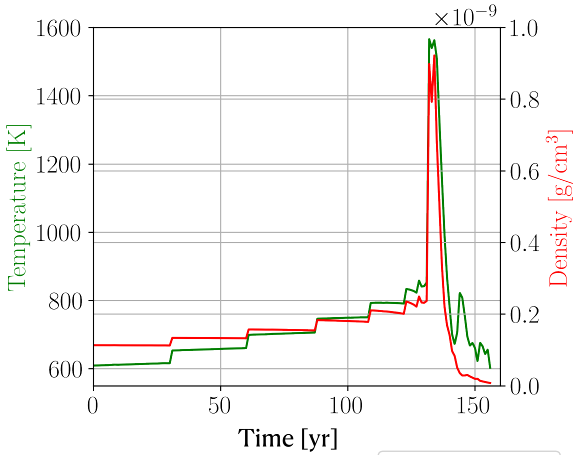


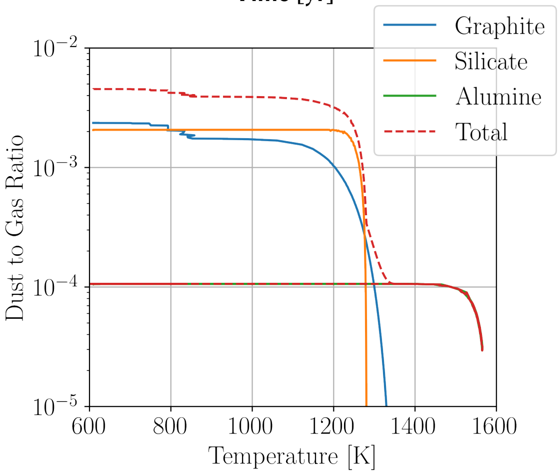


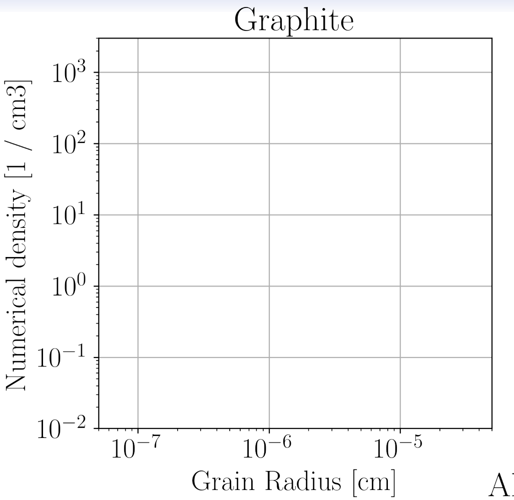


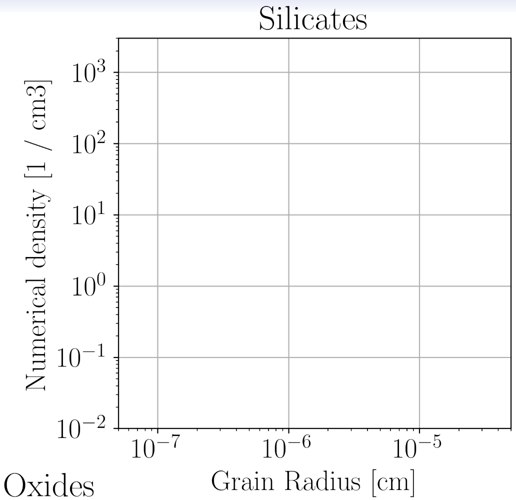


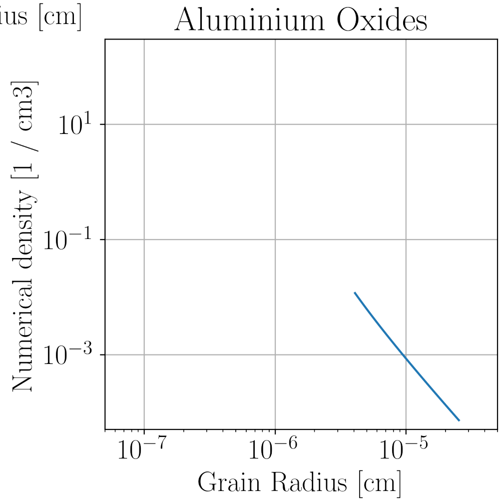
Application to collapse: Dust evolution



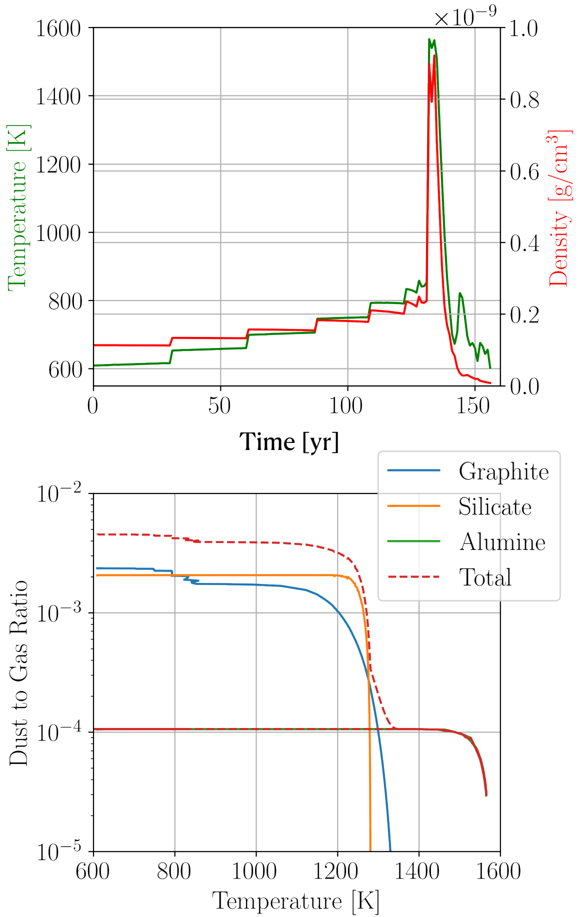


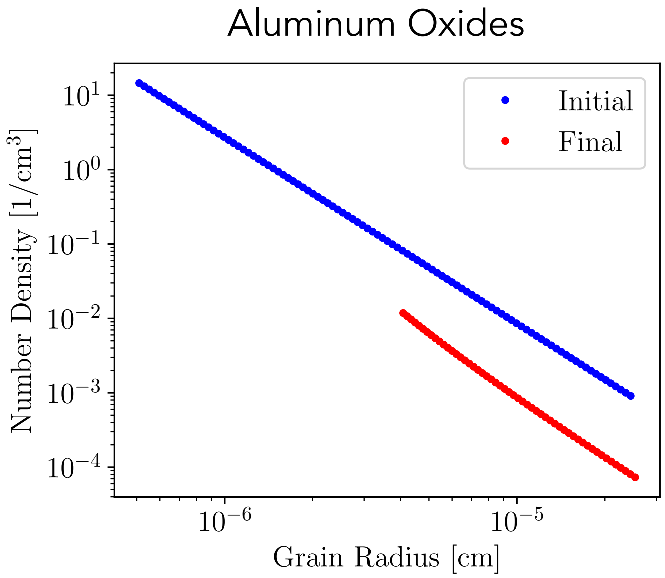






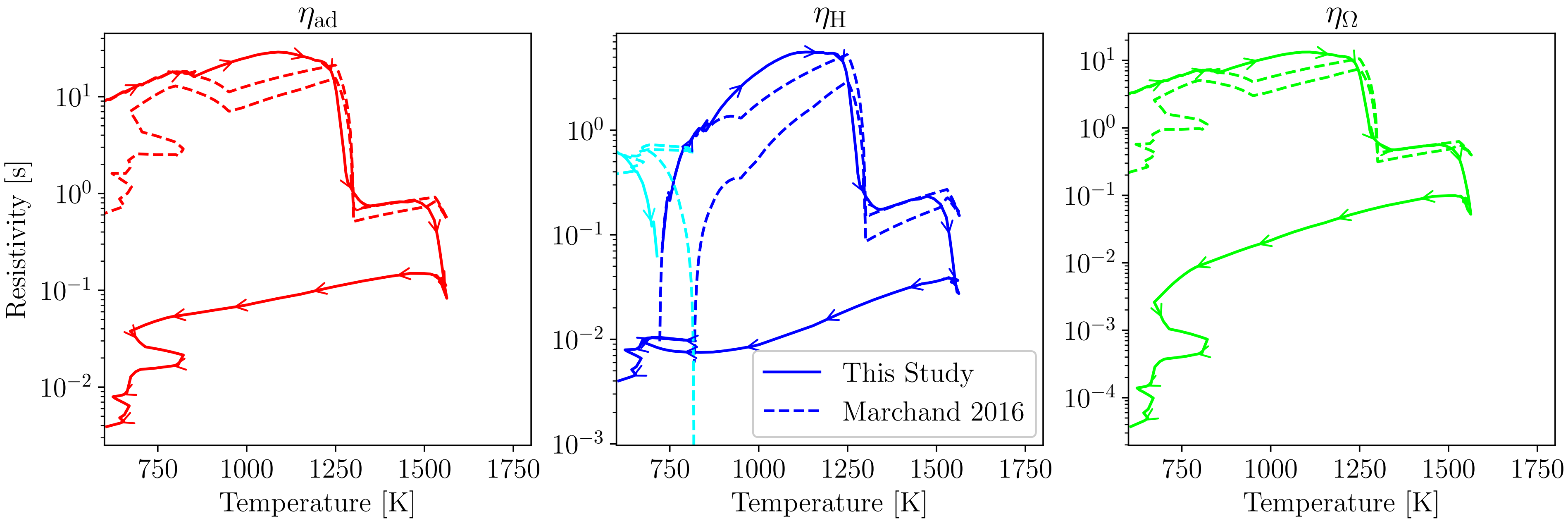
Application to collapse: Dust evolution





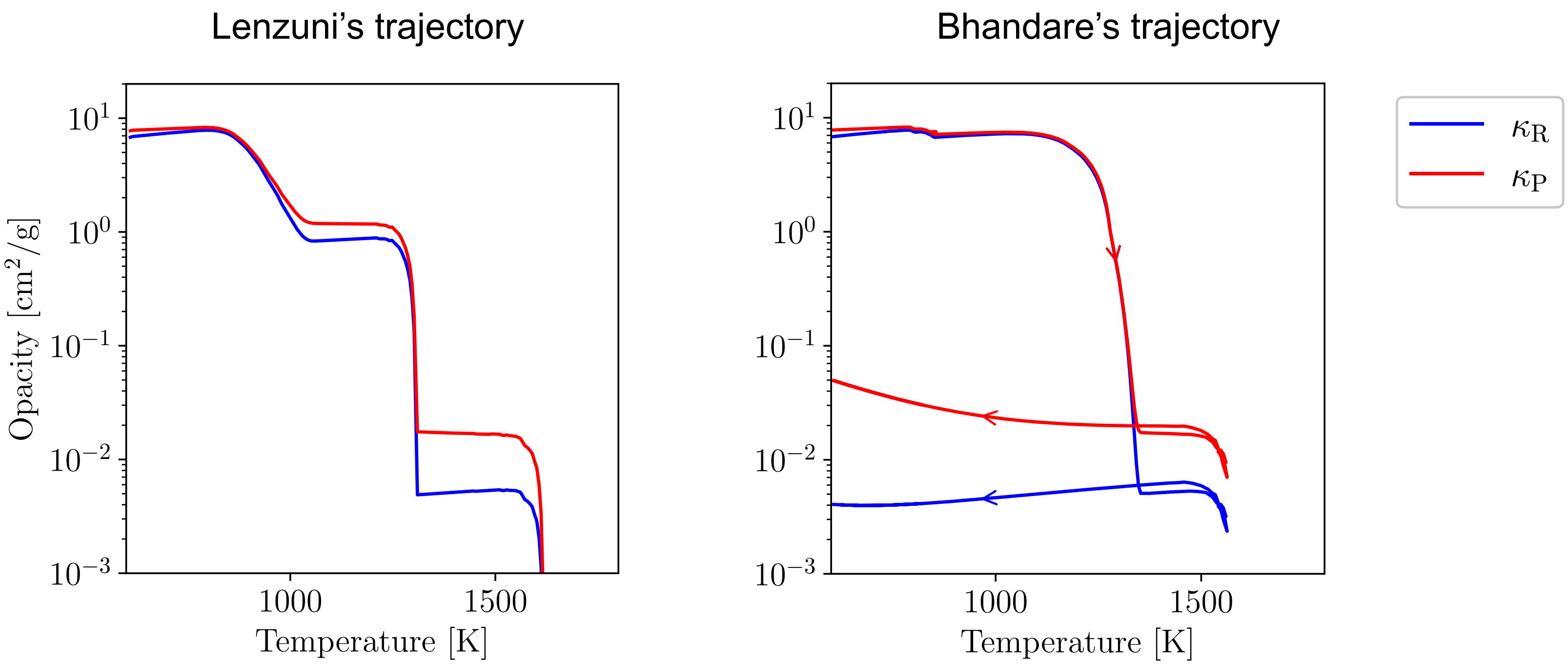
Application to collapse: Non-Ideal MHD resistivities

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left(-\mathbf{u} \times \mathbf{B} - \frac{4\pi}{c}\eta_{\rm ad}\mathbf{J} \times \mathbf{e_B} \times \mathbf{e_B} + \frac{4\pi}{c}\eta_{\rm H}\mathbf{J} \times \mathbf{e_B} + \frac{4\pi}{c}\eta_{\Omega}\mathbf{J} \right)$$



Strong difference when the temperature goes down

Application to collapse: Opacities



Conclusion

Outcomes:

- The initial MRN distribution **is not conserved** through the evaporation process.

- Dust quantity cannot be determine only by the temperature and density, it depends **on the history of the dust grains**. Also the case for the resistivities and opacities.

Possible following:

- Add dust evaporation in MHD code (RAMSES or Idefix).