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Supernova-induced processing of interstellar dust in a turbulent, magnetized and high-density ISM.

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Presentation outline

Introduction

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The interstellar medium:

A brief overview

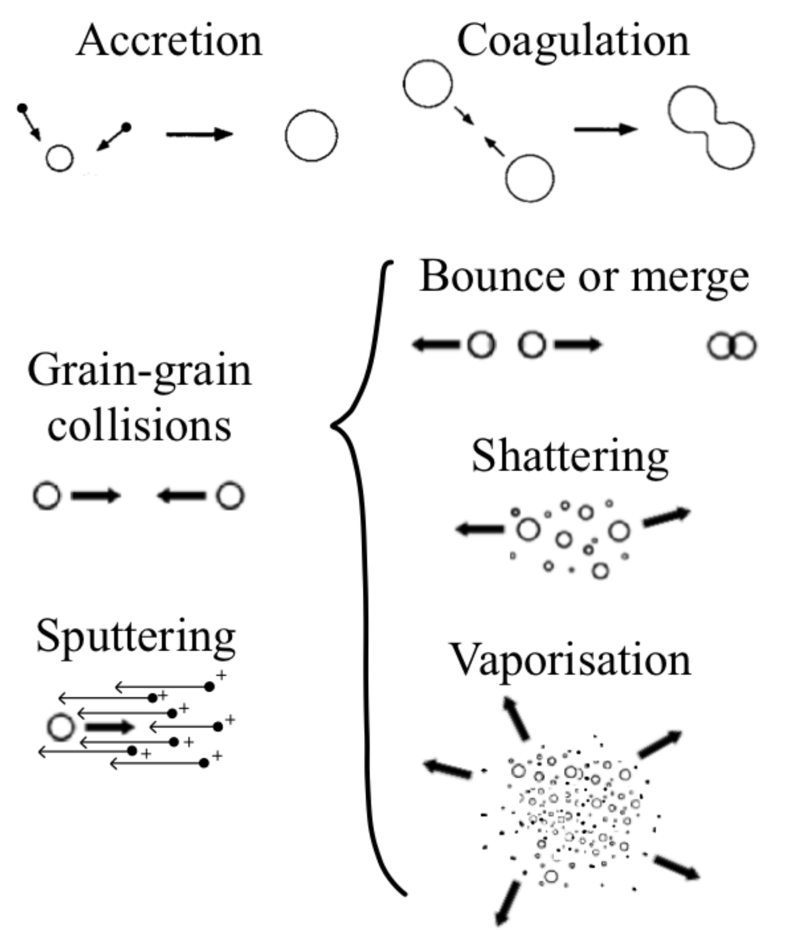
- Multi-phase structure affects the evolution and dynamics of astronomical objects.
- Magnetic fields: Large-scale and small-scale dynamos.
- Turbulence: amplification and maintenance of magnetic fields, driven by stellar outflows and gravitational instabilities.
- Dust injected in the ISM from Supernovae (Sne).

Taken from https://esahubble.org/videos/supernova_explosion_fd

Cosmic dust:

Properties and interactions

- The evidence of interstellar dust: extinction and reddening.
- Made mostly of silicates and carbonaceous material.
- Gas to dust mass ratio of 100 and grain size distribution MRN.
- Dust grains are important coolants, affecting the dynamical and thermal evolution of the gas in star formation.
- Dust processing in shocks.
- Ionised dust interacts with the magnetic field in the ISM.



Previous studies:

Beyond the observations

Dust formation versus destruction: a hot topic

Kirschlager, F. Mattsson, L. Gent, F.
Modelling supernova-induced processing of dust at gas density $n = 1\ \text{cm}^{-3}$ and $n = 0.1\ \text{cm}^{-3}$.

Sim B   Sim C

- 2021

In a uniform and modestly perturbed ISM: Gas and dust density at the site of injection affect the rates of dust processing.

- 2023

In a turbulent, magnetized multi-phase ISM: Magnetic field inhibits dust destruction.

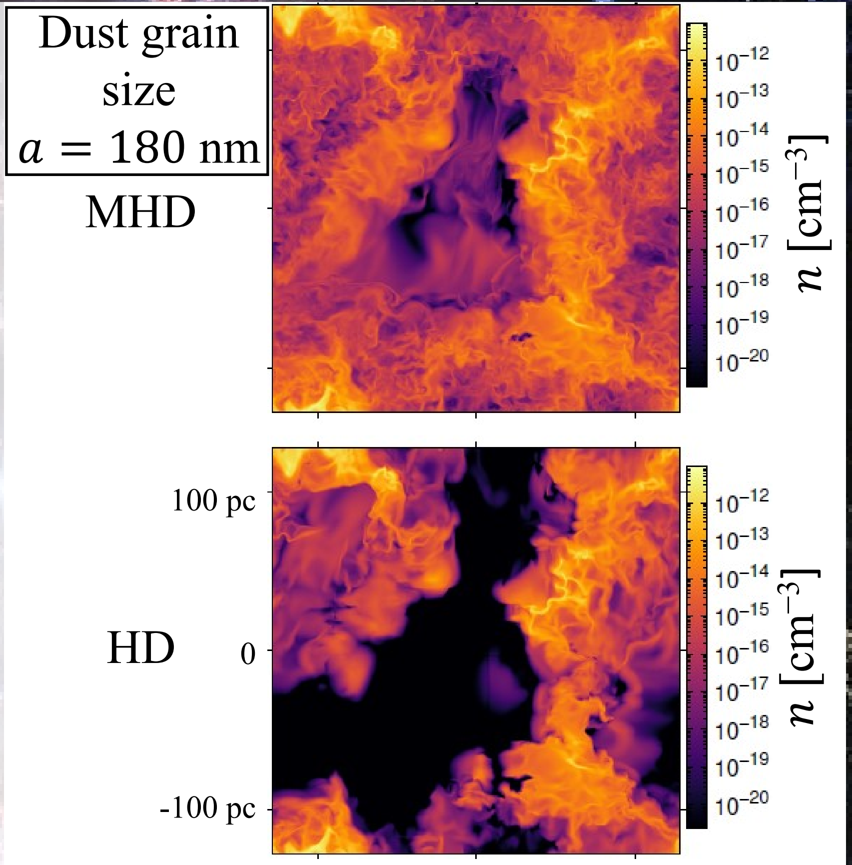


Figure 2 from Kirschlager, F. et al. 2023

Our study:

Motivation and aims

- 3D simulation of a blast wave propagating through an inhomogeneous, turbulent and magnetized ISM onto a high-density region.

- Dust processing models are applied in a medium of average gas density of 20 cm^{-3} reaching a peak density of 400 cm^{-3}.

- The magneto-hydrodynamic simulations are run with initial conditions emulating a realistic ISM and post-processing calculations include dust processing due to ion sputtering, accretion, and grain–grain collisions.

- The purpose of this investigation is to quantify the impact of ambient gas and dust density on the cleansing effect of a SN on surrounding dust particles.

Methods:

Softwares

The Pencil Code

- Grid-based, high-order finite-difference code.
- Solves the system of nonideal, compressible, nonadiabatic, MHD equations.
- Applied to a wide range of astrophysical fluid dynamics problems.

Brandenburg, A. et al. 2001

PAPERBOATS

- Developed to investigate dust advection and dust destruction, as well as potential dust growth in a gas.
- Utilizes the time - and spatially resolved density, velocity, and temperature to calculate the spatial distribution of the dust particles.

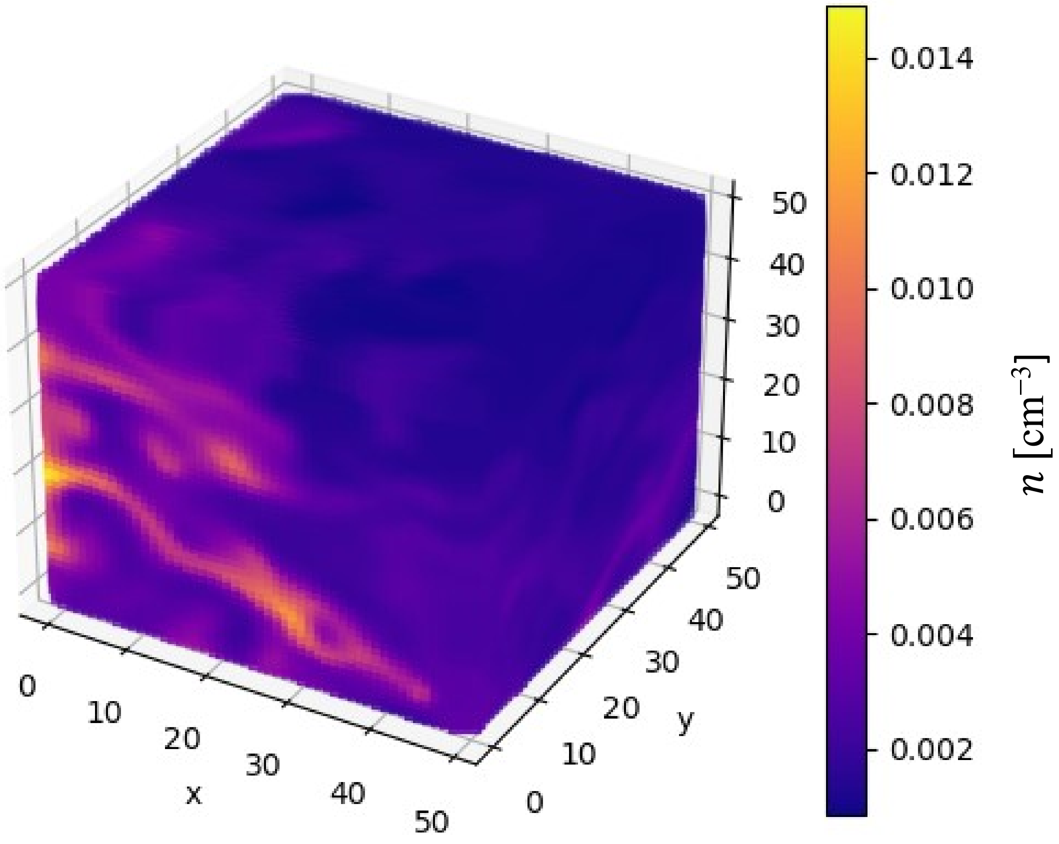
Kirschlager, F. et al. 2019

Starting simulation:

The inhomogeneous ISM

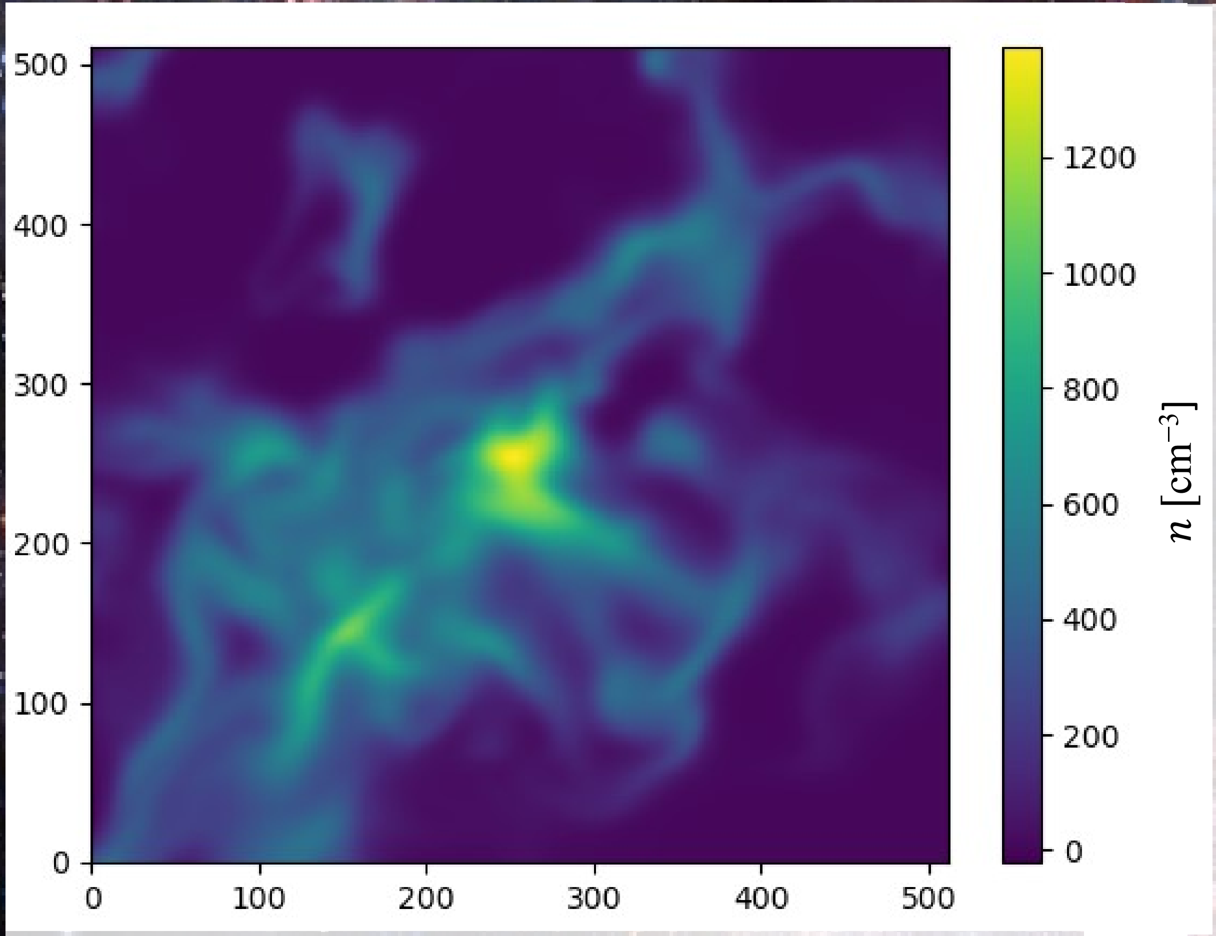
- Initial conditions:
  - Inhomogeneous ISM from a 3D MHD simulation of SN-driven turbulence.
  - A weak magnetic field is amplified by SNe explosions randomly located in an initially homogeneous ISM. Turbulence drives an SSD.
- Domain:

Periodic cartesian cube of length 256 pc with a grid resolution size of 0.5 pc (512 cells).



1. Remeshing process:

Development and setup

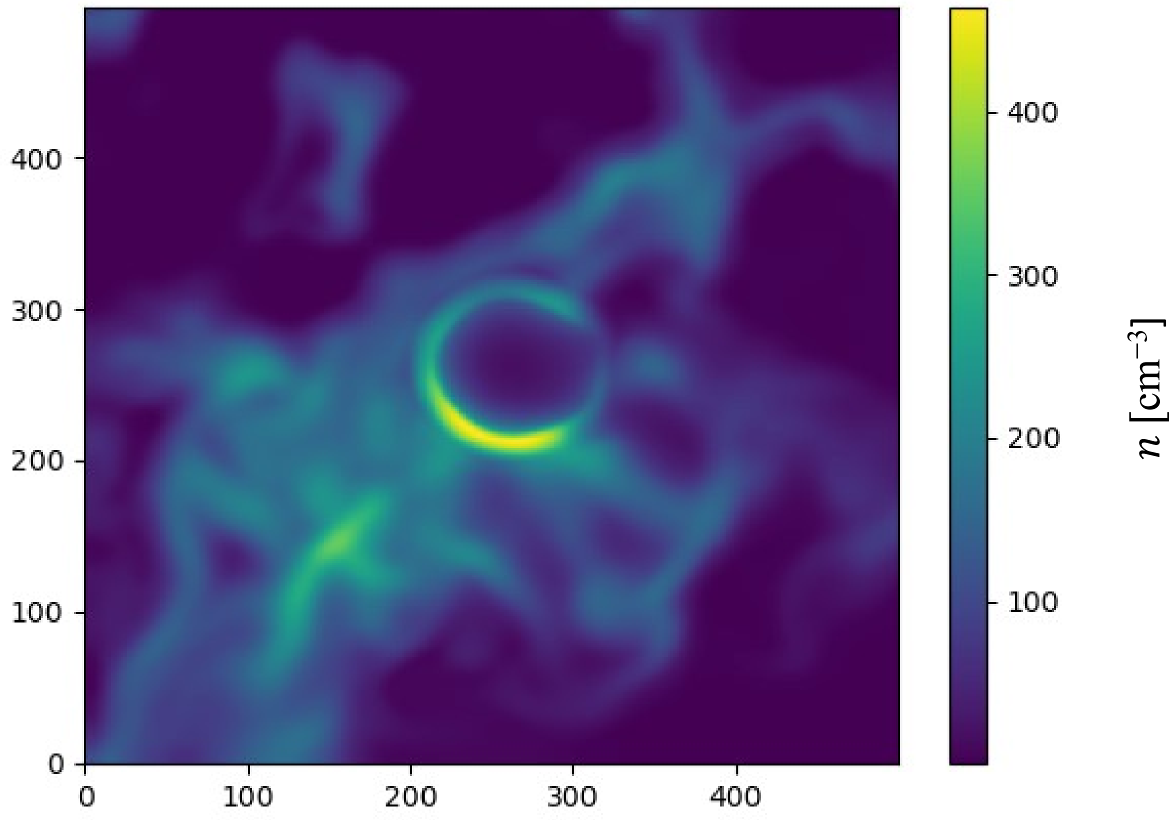


- High-density region of diameter 5 pc is chosen (n = 160 cm^{-3}).
- This process aims at obtaining a domain of 512^3 cells of size 0.125 pc compared to the initial 0.5 pc, with a resultant grid size equal to 64 pc.
- Increased the resolution of the simulation by using linear interpolation.
- Adapted boundary conditions and total mass.

2. Single SN injection:

Modelling and assumptions

- The single SN is modelled by injecting 10^{51} erg of thermal energy on a grid point located in the centre of the domain.
- The energy injection is applied in a single time step at $t = 100$ kyr.
- Any additional mass from the SN ejecta is negligible.



3. Dust processing:

Paperboats model

Method

- Input snapshots from Pencil Code simulation at intervals of 100 yr in the xy plane.

Mathis, Rumpl, and Nordsieck, 1977

$$n(a) \propto a^{-3.5}$$

Assumptions

- The dust grains are compact, homogeneous and spherical.
- Silicates, with MRN grain size distribution with $a_{min} = 5$ nm and $a_{max} = 250$ nm.
- Initial dust abundance proportional to the gas density, mass ratio of 100.
- The ratio is homogeneous throughout the domain everywhere at the start.

MHD evolution:

2D slice from the Pencil Code

- Density profile:

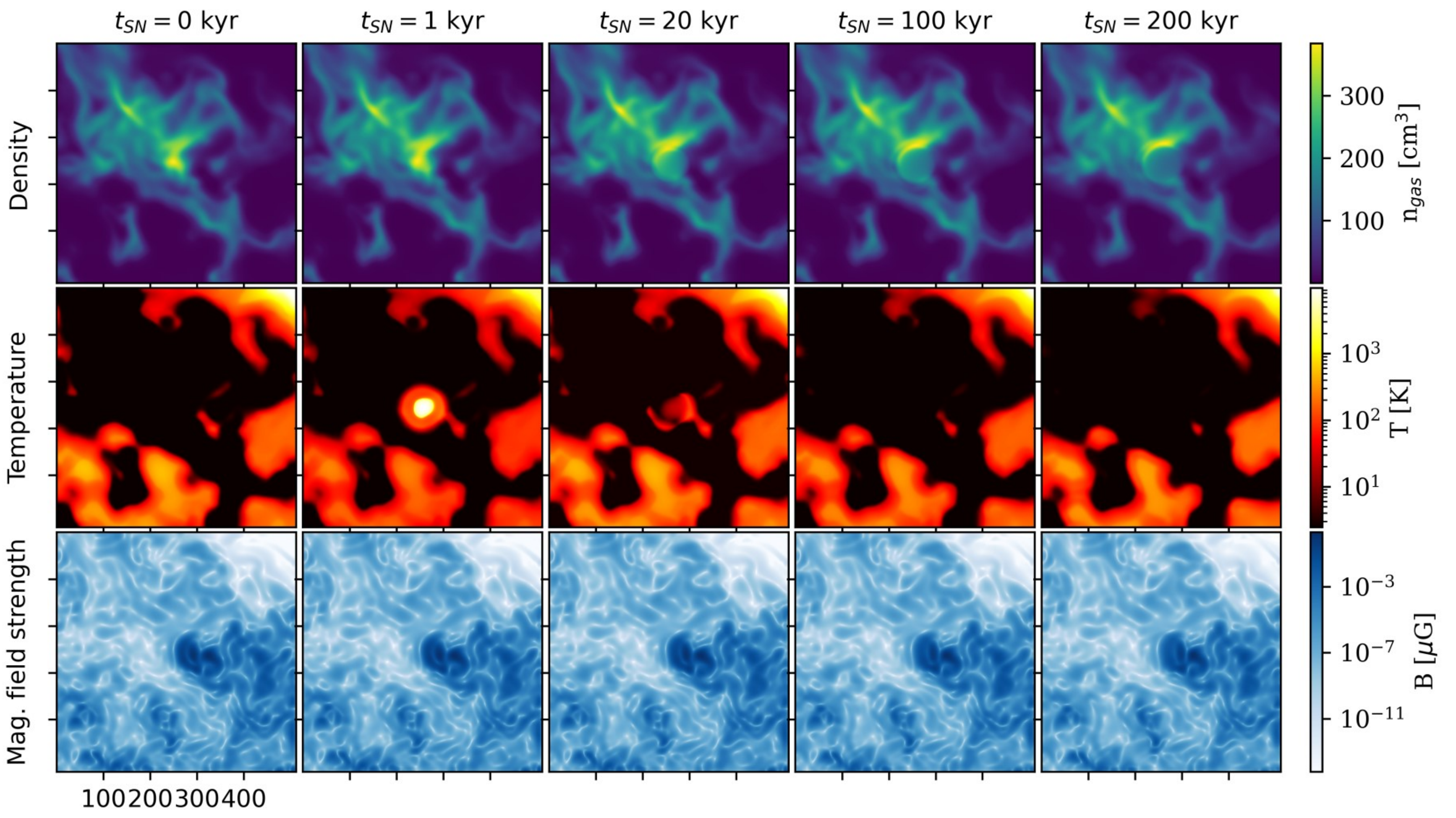
Shell size of about 10 pc across at $t_{SN} = 200$ kyr.

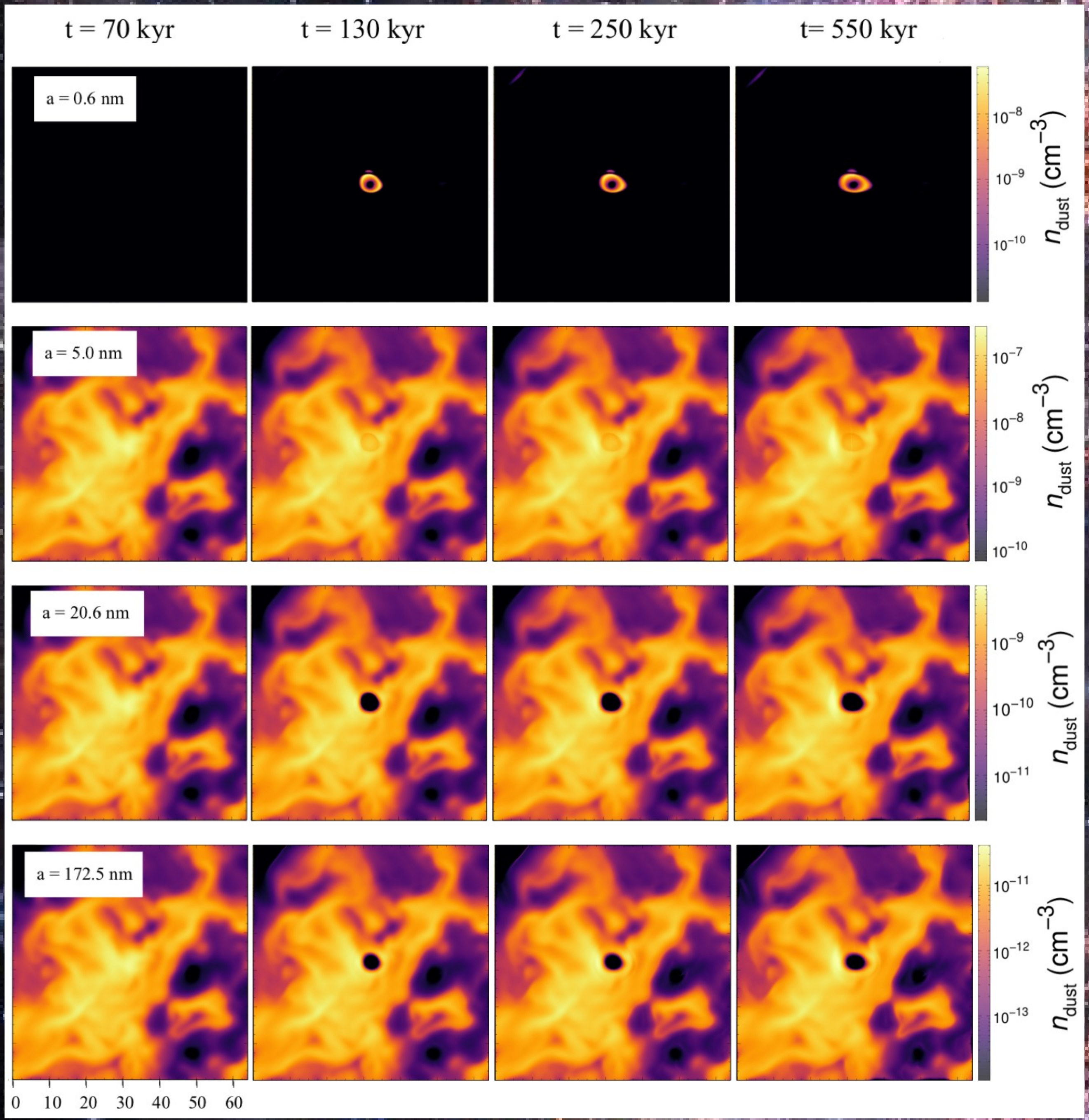
- Temperature profile:

Self-similar spherical origins until 20 kyr.
At $t_{SN} = 100$ kyr there is no SN signature.

- Magnetic field strength:

Almost unaffected, much weaker than expected





Results from the post-processing run showing the evolution of the dust component for different grain sizes

	n_{centre} (cm^{-3})	Accumulated dust losses ($M_\odot$)		
		5 kyr	25 kyr	50 kyr
Sim A	350	12	12	12
Sim B	0.7	1	12	14
Sim C	0.03	0	0.3	1

Research impact:

Conclusions and next steps

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Possible improvements and grounds for future research

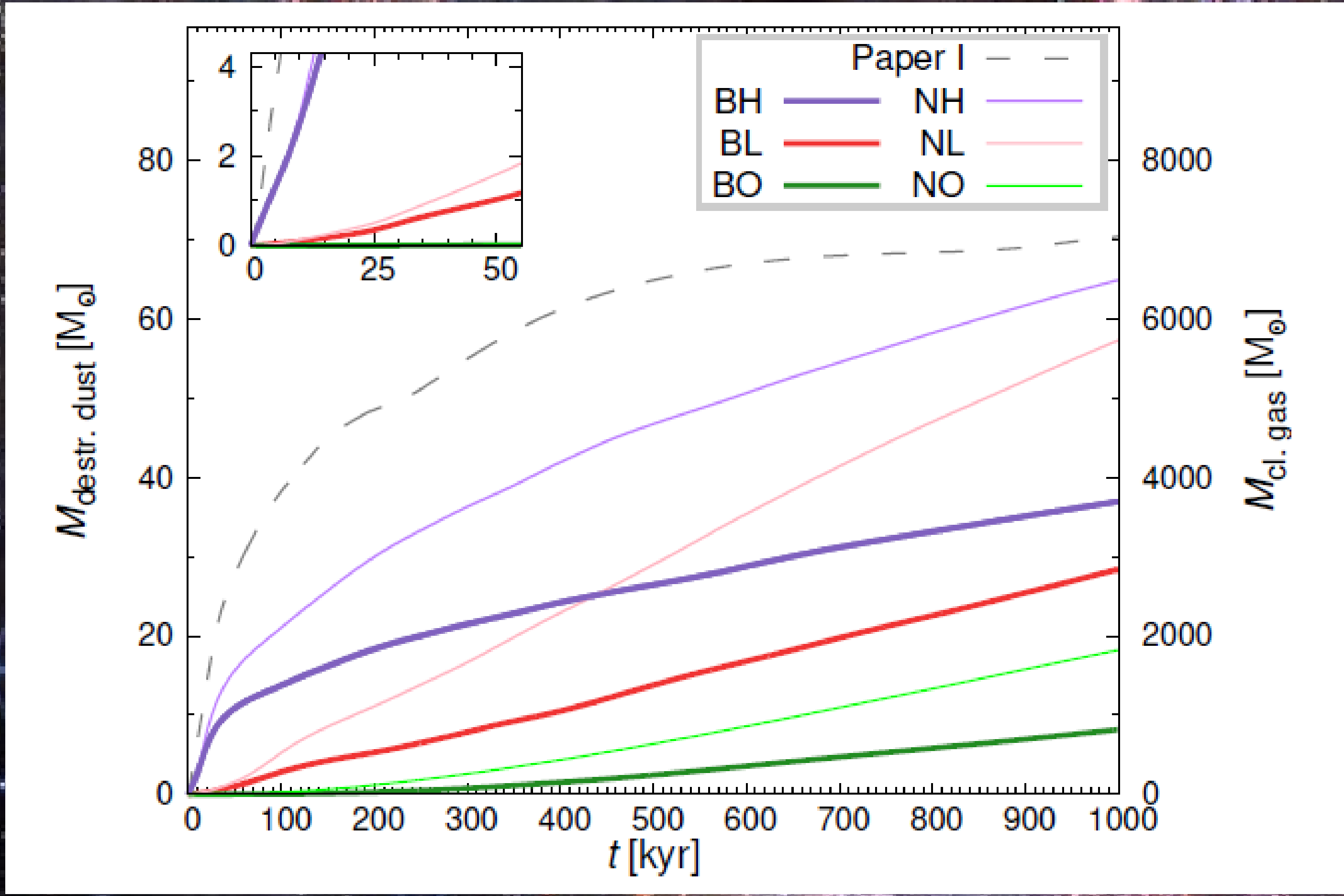
- Use a smaller domain with increased resolution.
- Consider a smaller SN injection radius.
- Perform background processing.
- Consider a mixture of Silicate and Carbon.
- Allow for inflows in PAPERBOATS.

Conclusions

Due to the slow and inhibited SN blast wave expansion, the dust processing results are limited. It was found that the SN had swept dust grains rapidly and that the dust mass being destroyed increased with the amount of dust initially present in the ISM.
Further investigation is required to understand the impacts of shocks in a magnetized high-density medium and possibly solve the dust-budget crisis.

Previous studies:

Magnetic field effects



Total dust mass and cleared gas mass as a function of time.

B → magnetic field included
N → no magnetic field
H → $n = 1\ \mathrm{cm}^{-3}$
L → $n = 0.1\ \mathrm{cm}^{-3}$

Figure 4 from Kirschlager, F. Gent, F., Mattsson, L. 2023