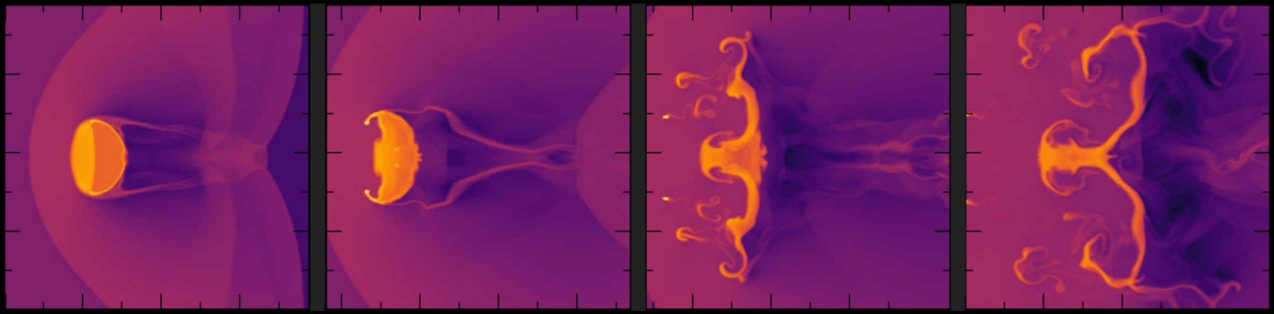
Dust destruction by the reverse shock in clumpy supernova remnants

Florian Kirchschlager

Ilse De Looze, Mike Barlow,
Nina Sartorio, Felix Priestley,
Franziska Schmidt, Tassilo Scheffler

SNRIII 2024

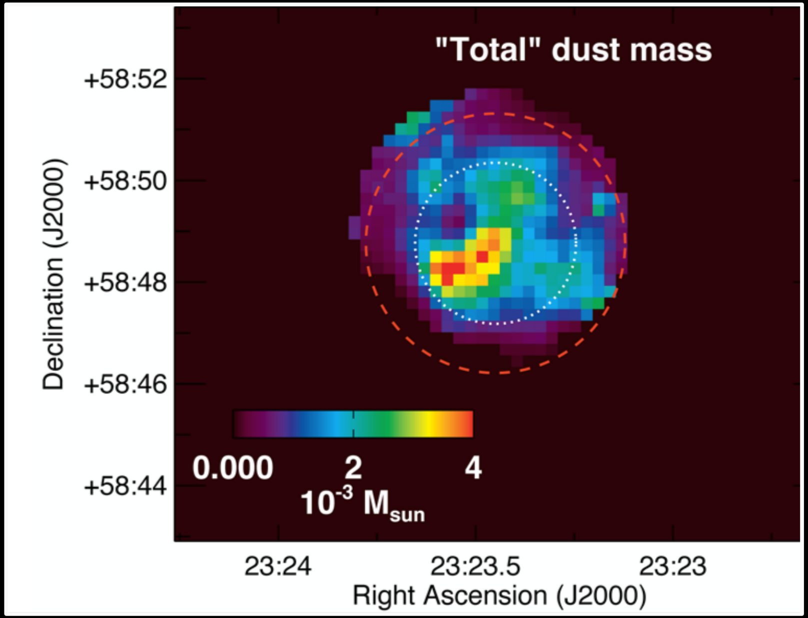


Do we 'see' dust destruction in observations?

- Yes, but is not easy to observe!

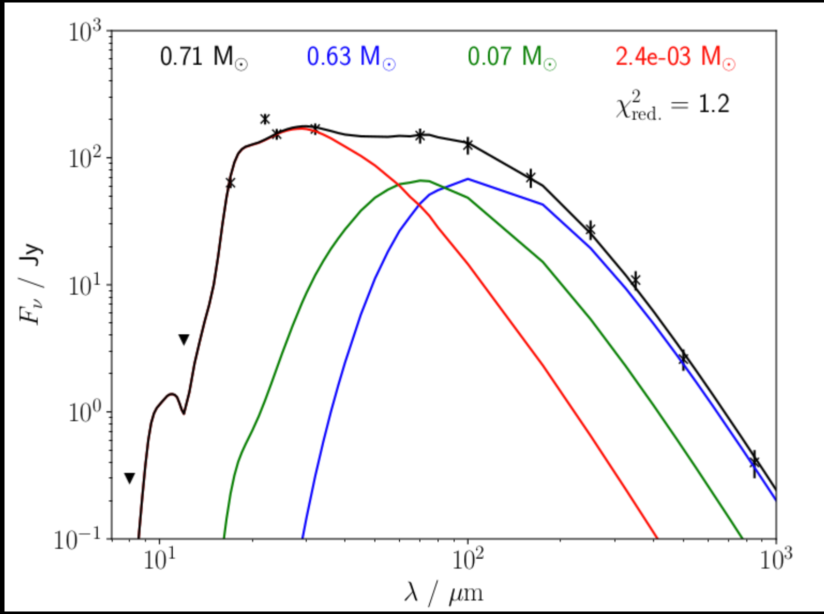
Cas A

De Looze+ (2017)



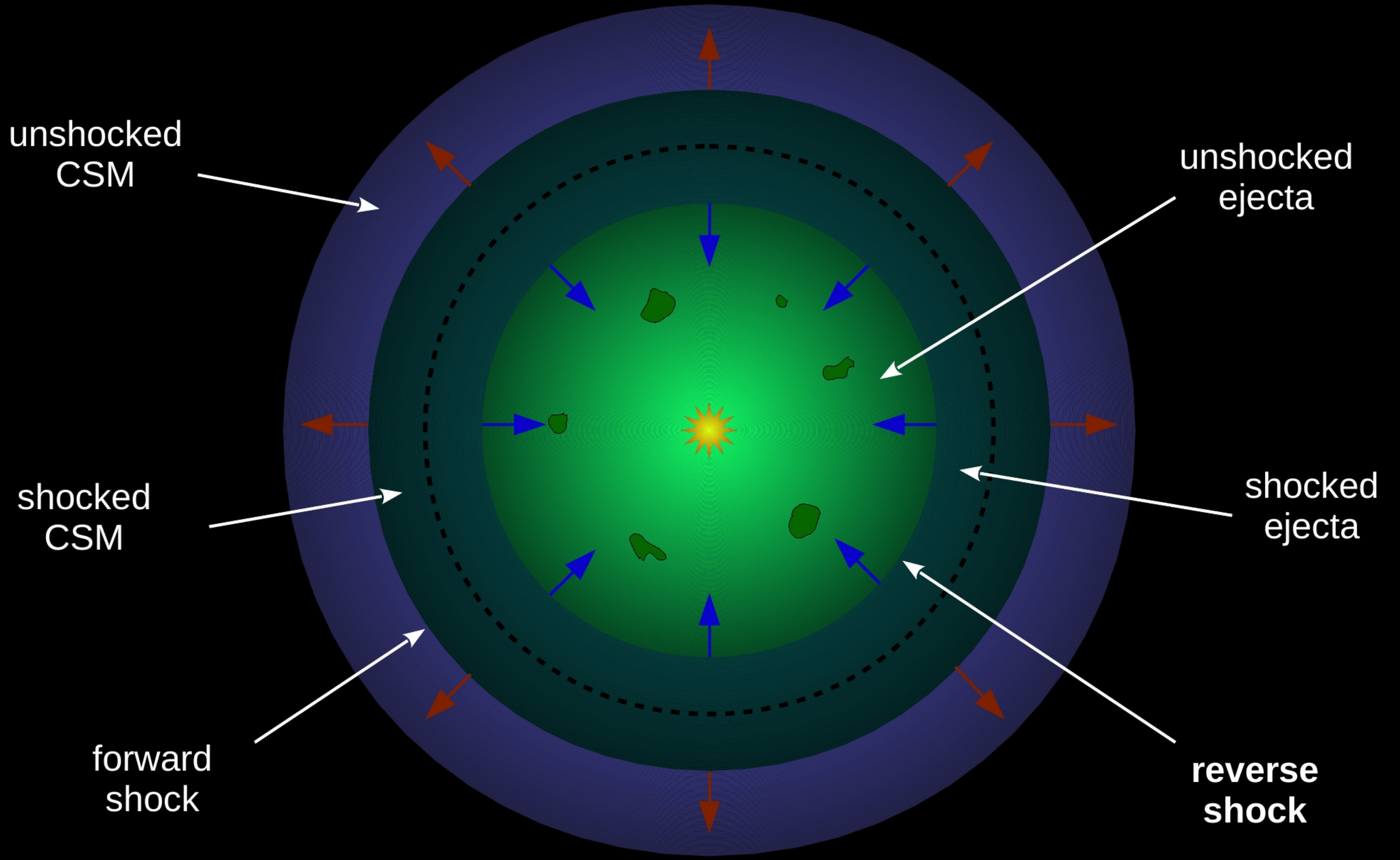
Herschel **FIR maps** show different emisson (and dust mass) inside and outside the reverse shock position
~70 % dust destruction

Priestley+ (2022)

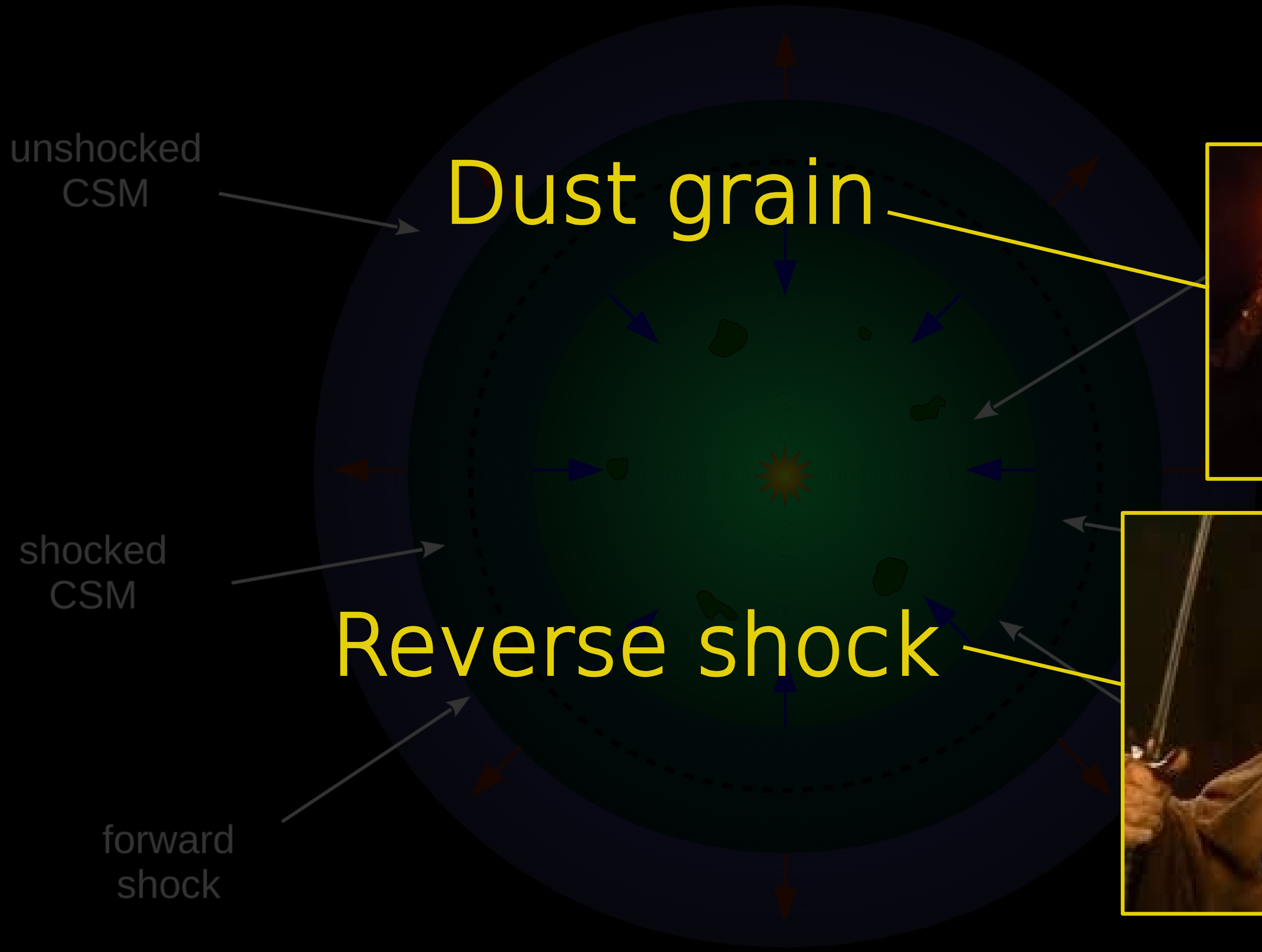


SED modelling indicates different temperature components, with different dust masses (shocked and unshocked regions)
~70 - 94 % dust destruction

Shocks and dust in SNRs



Shocks and dust in SNRs



Modelling of the whole SNR

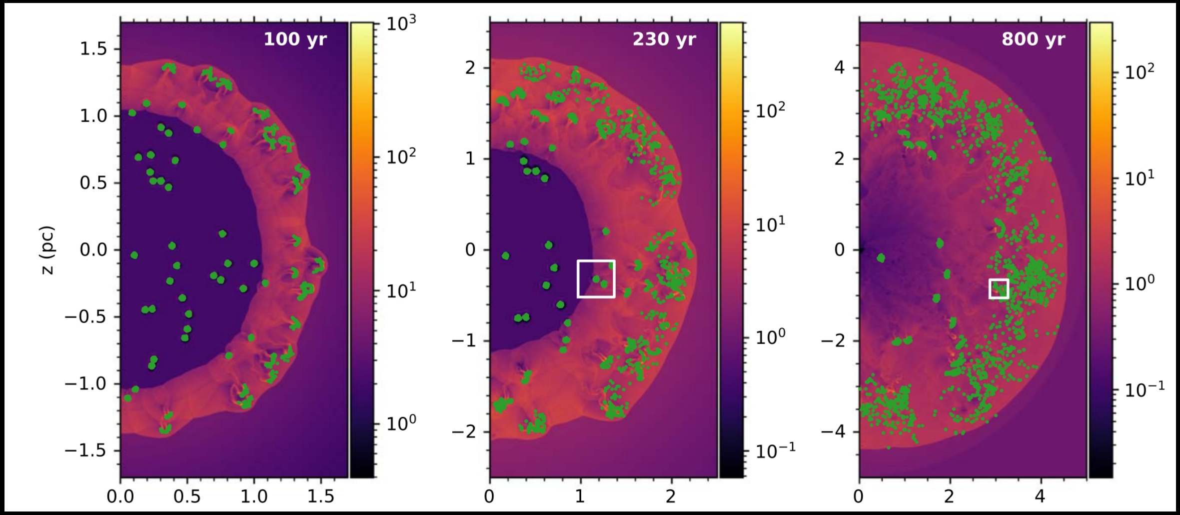
E.g. Bocchio+ (2016); Micelotta+ (2016); Slavin+ (2020); Vasiliev & Shchekinov (2024)

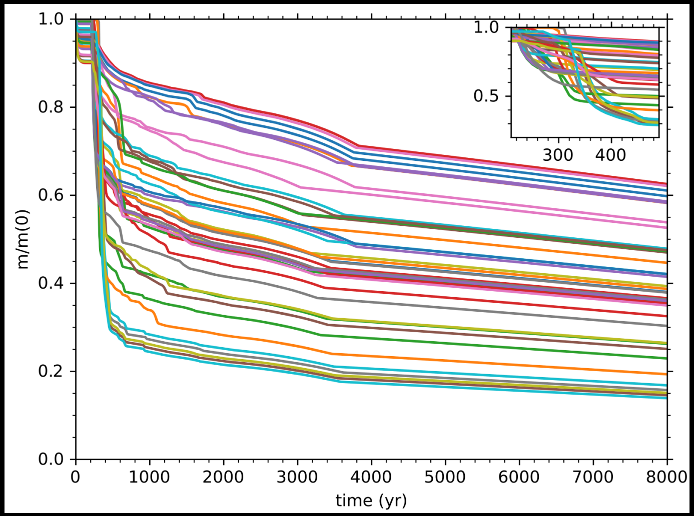
+ Allows to follow dust grain processing for the whole SNR expanison time
+ Maps of the whole remnant

- Low spatial resolution of structures (e.g. clumps)
- Influence on dust destruction efficiency

Remnant size at 1000 years : ~10 pc
Clump sizes ~0.001 pc

Clumps represented only by a few pixels, clump disruption is not modelled, or clumps are completely ignored





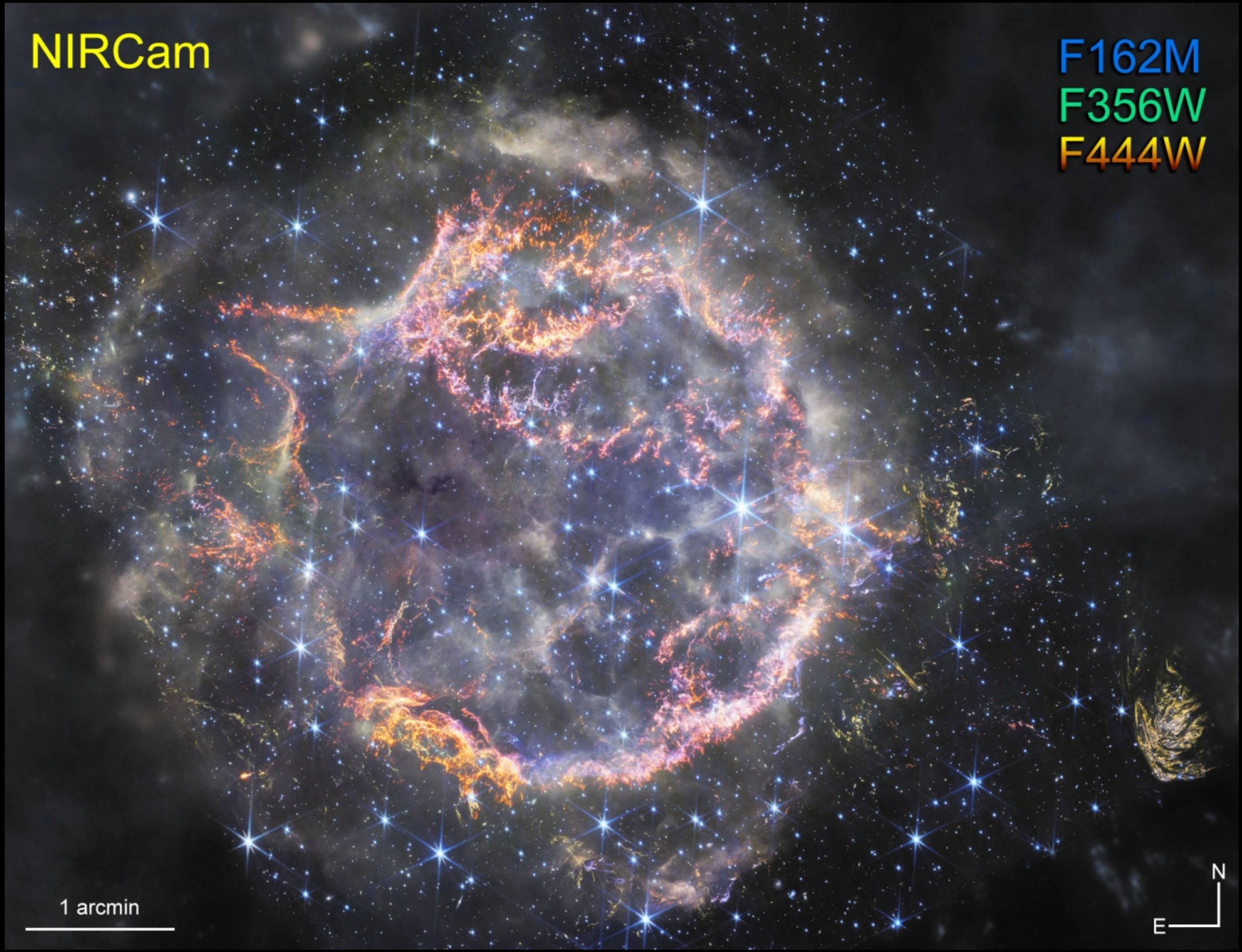
Slavin+ (2020)

SNRs are clumpy

Highly resolved observations reveal detailed structure of SNRs

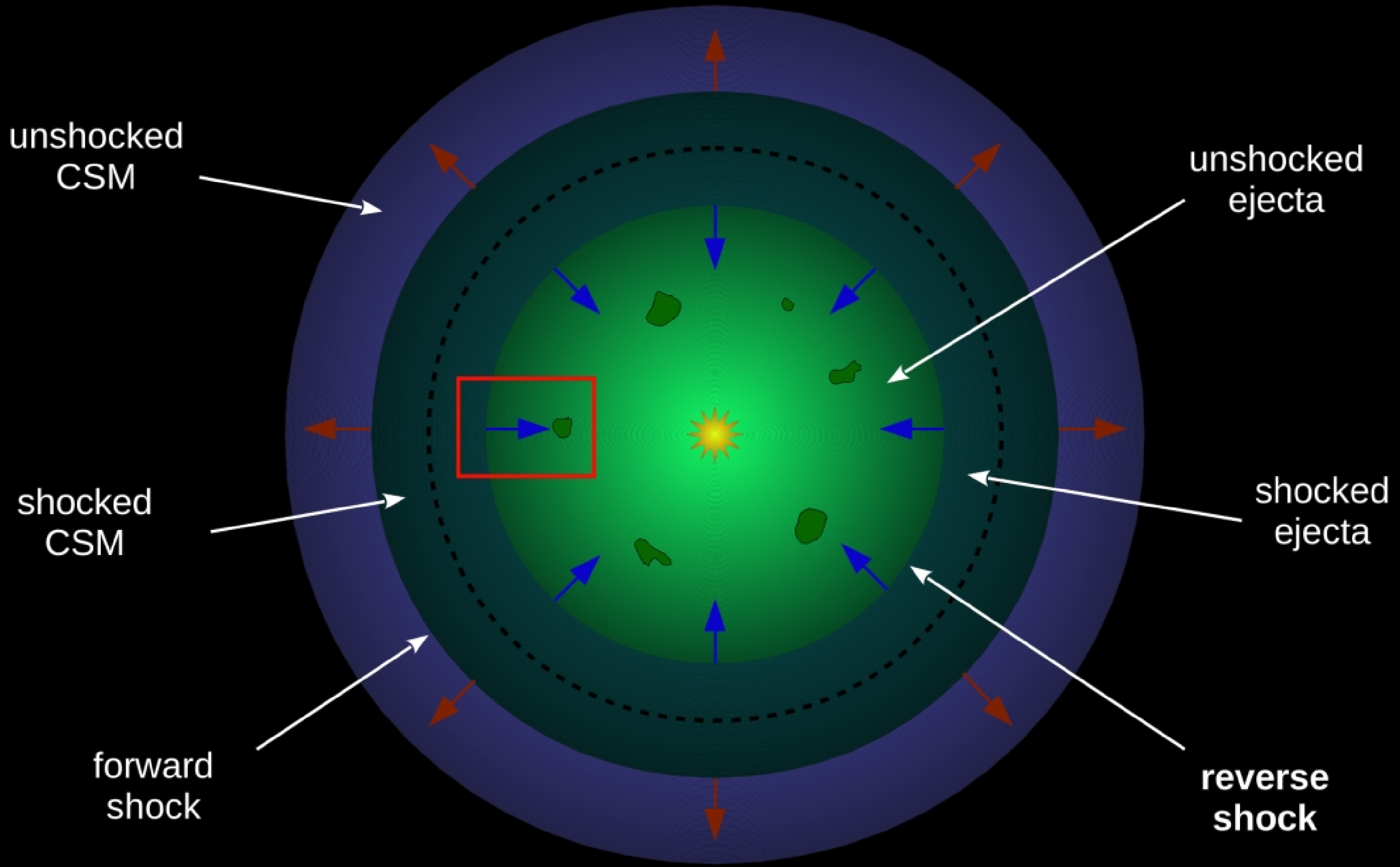
Full 3D models need high computational efforts

Solution: Model only a part of the remnant



Milisavljevic+ (2024)

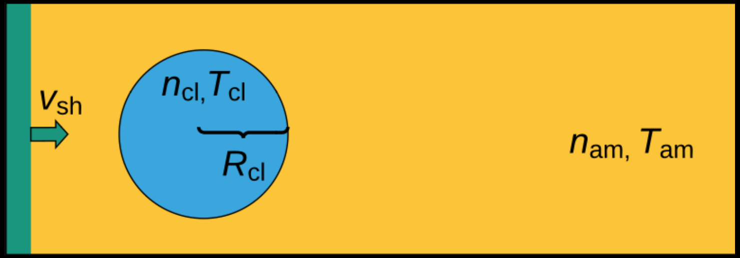
Zoom-in


unshocked
CSM
unshocked
ejecta
shocked
CSM
shocked
ejecta
forward
shock
reverse
shock

Cloud-crushing problem

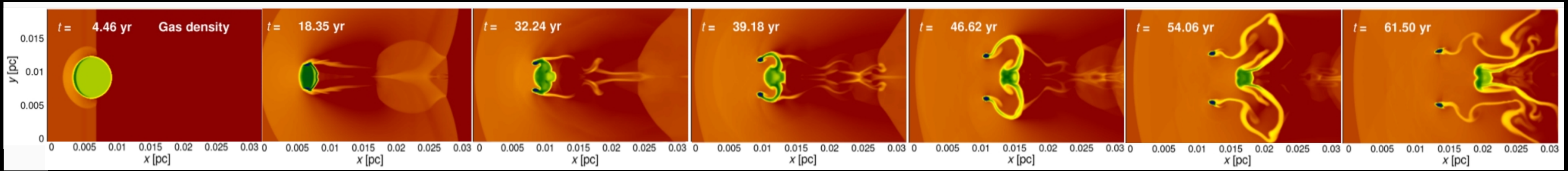
- Dense clump in an interclump medium
- Gas density contrast $\chi = n_{clump}/n_{interclump}$ (χ = 100 … 1000)
- MHD-simulation of a planar shock impacting the clump using AstroBEAR (Cunningham+ 2009)

- Silvia+ (2010, 2012) used it to simulate dust destruction in SNR clumps

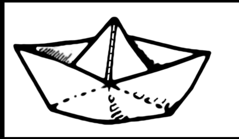


But this is only gas …

Impact ⇒ Compression ⇒ Reshaping ⇒ Disruption ⇒ Removal



Dust post-processing code Paperboats

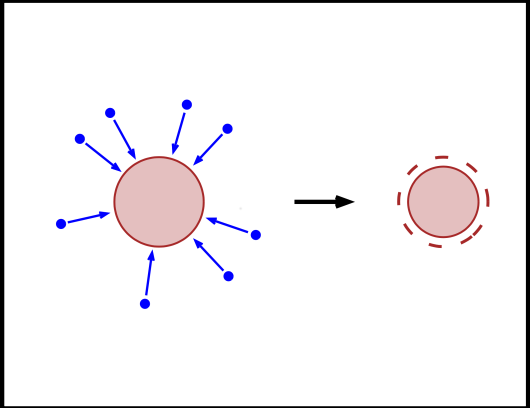


Uses: 2D or 3D output of an MHD code (Gas density, temperature,
velocity, magnetic field)

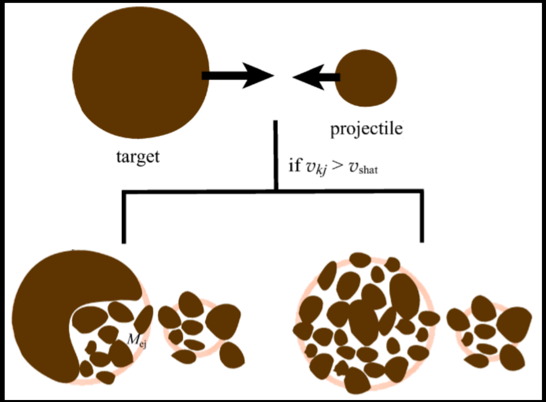
Calculates:

- Dust dynamics (gas & plasma drag, magn. field accelaration)
- Dust destruction (sputtering, fragmentation, vaporisation)
- Dust growth (gas accretion, ion trapping, coagulation)

Sputtering



Grain-grain collisions

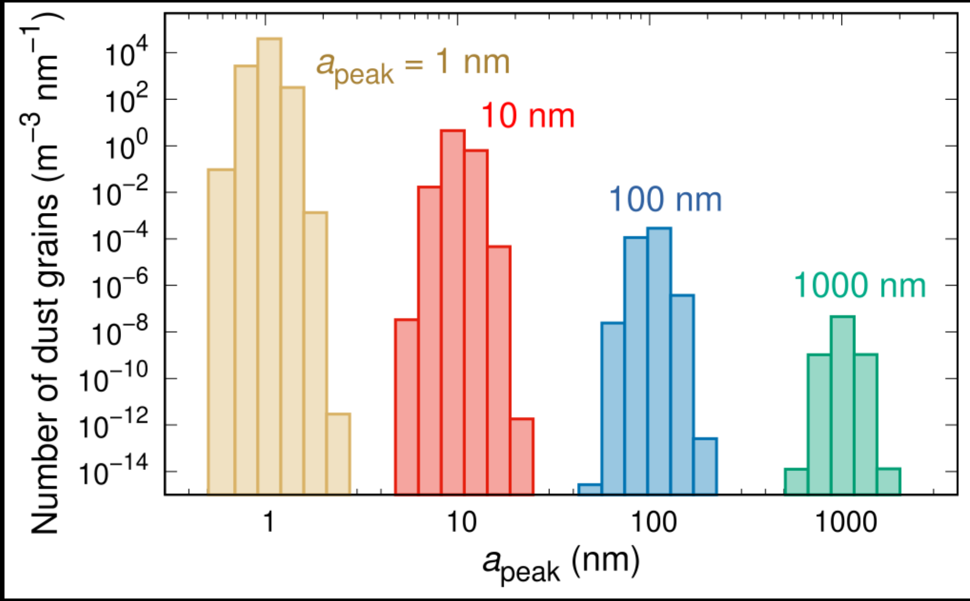


Hirashita & Yan (2009)

Kirchschlager + (2019);
Kirchschlager, Barlow, Schmidt (2020);
Kirchschlager, Mattsson, Gent (2022);
Kirchschlager+ (2023);
Kirchschlager, Mattsson, Gent (2024a);
Kirchschlager+(2024b)

In prep: Sartorio+; Scheffler+;
Reckelbus+; Capobianco+

Binned grain size distribution



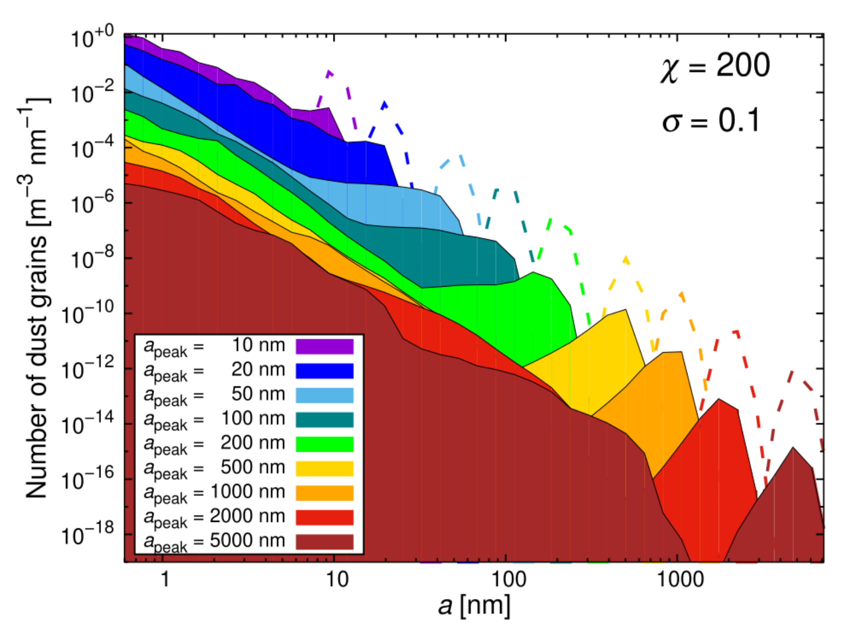
Kirchschlager+ (2024)

Initial grain size distributions

Focus today: silicate grains.

Final grain size distributions =

"Remnant" of initial grain sizes
+
Fragmentation distribution at lower sizes

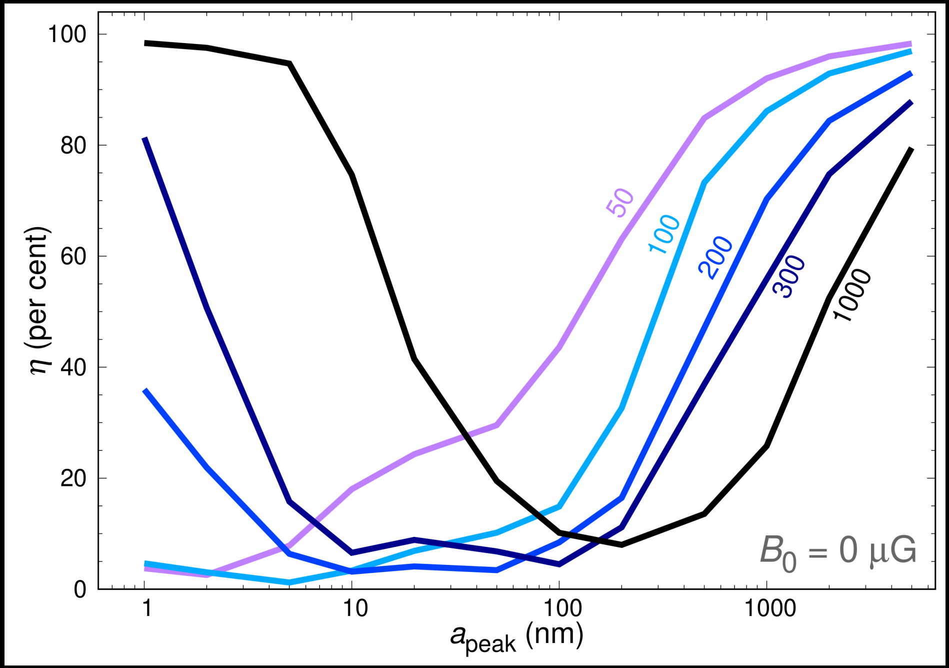


Kirchschlager+ (2019)

Survival for different clump densities and grain sizes

Low gas densities (χ~50-100):
Low survival rates for nm grains
High survival rates for µm grains

High gas densities (χ>100-1000):
Low survival rates at ~0.1 µm grains
High survival rates for nm & µm grains

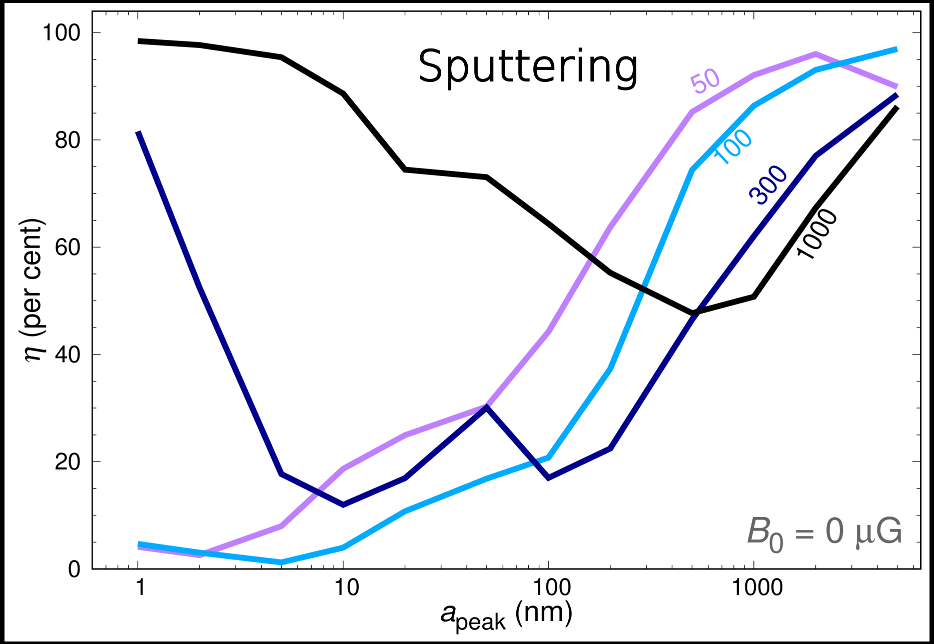


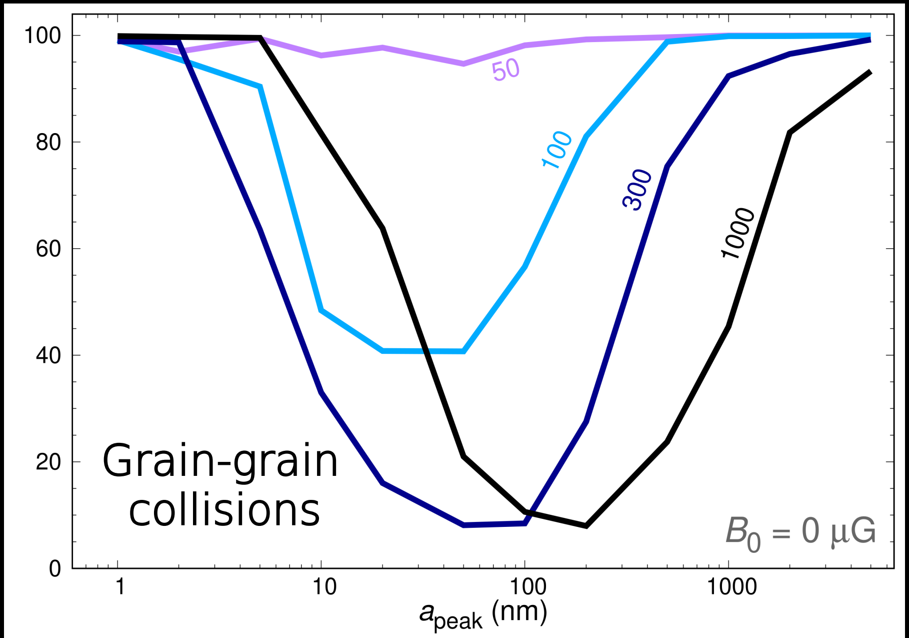
Sputtering vs. grain-grain collisions

Sputtering: Efficient at small grains (10 nm) if not too small
Large gas drag on nm-grains and at high gas densities reduces dust destruction

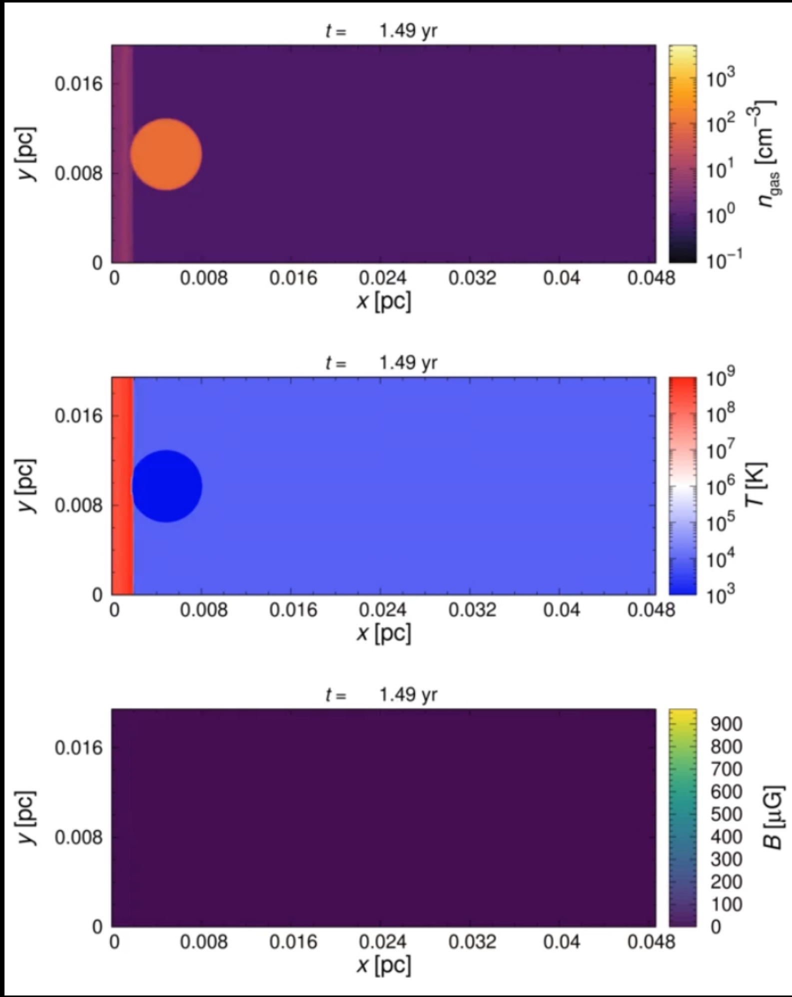
Grain-grain collisions: Efficient for ~100 nm grains at high gas densities

Sputtering and grain-grain collisions are synergistic

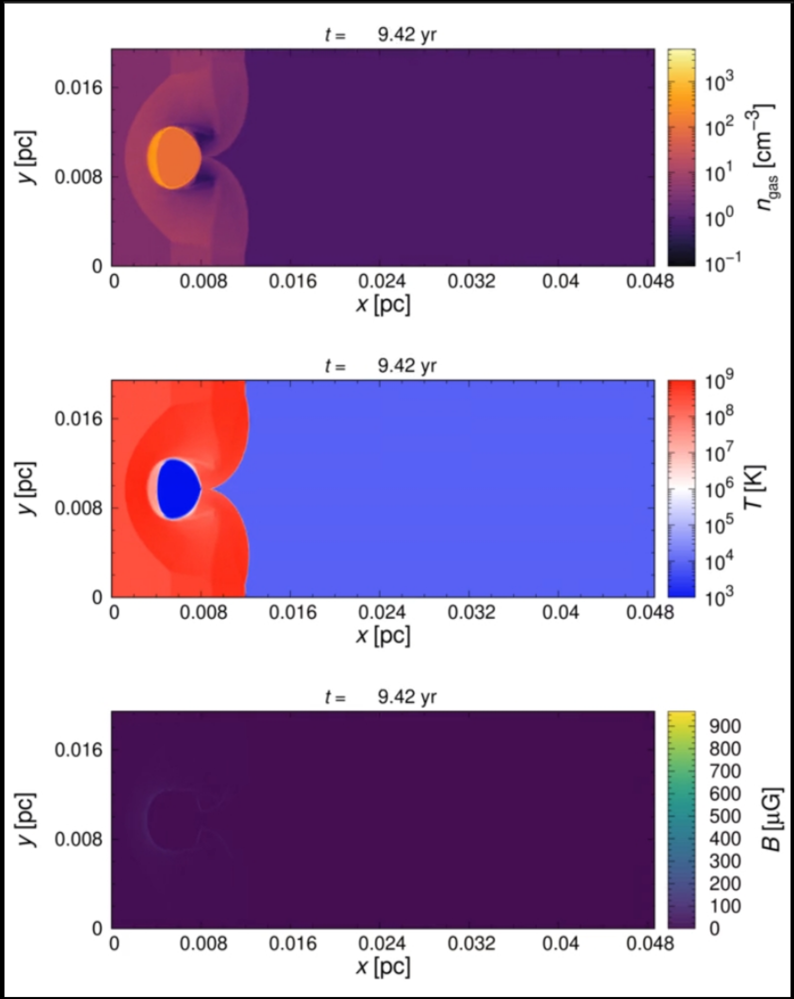




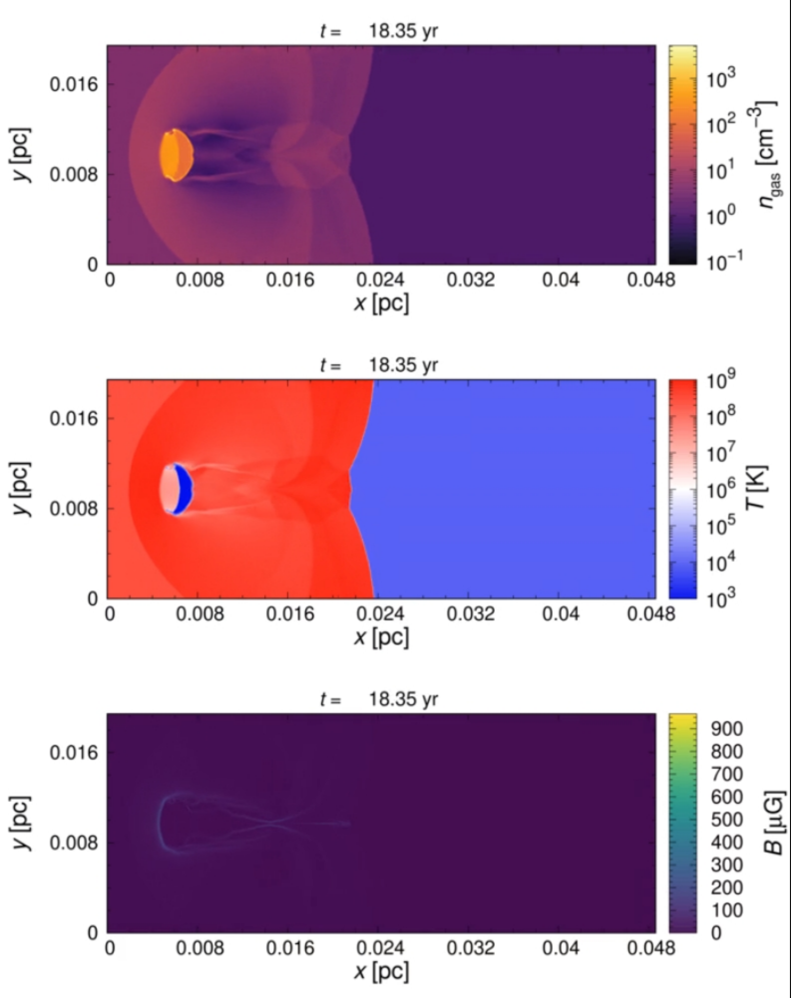
Magnetic fields in shocked clumps



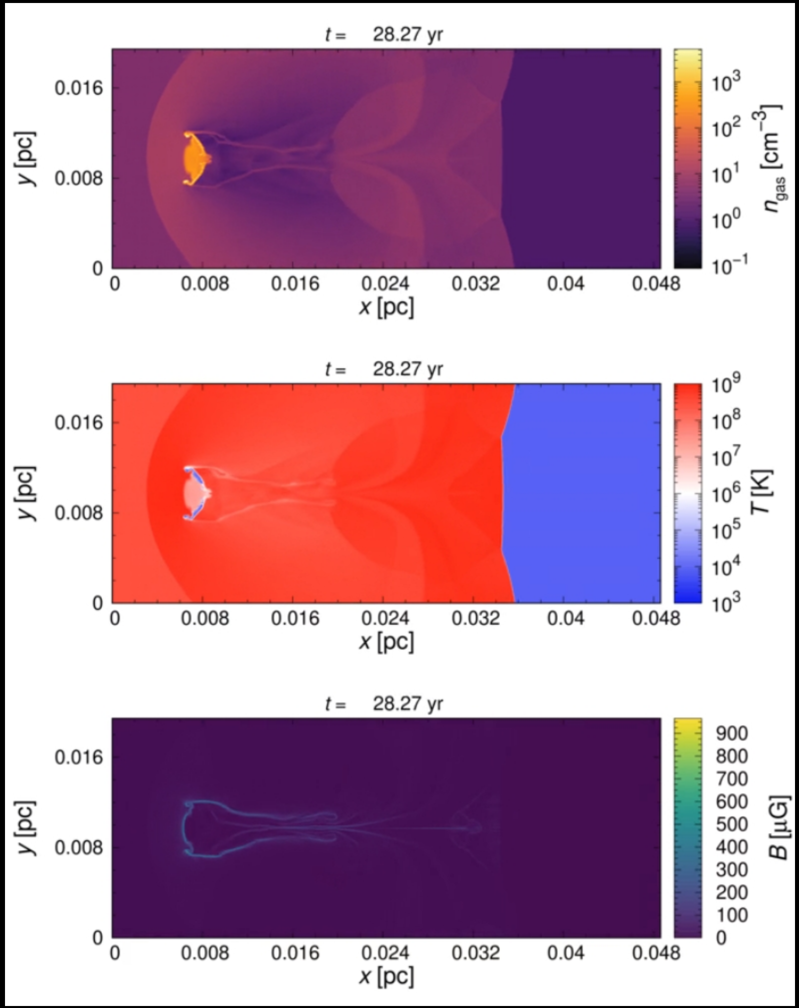
Magnetic fields in shocked clumps



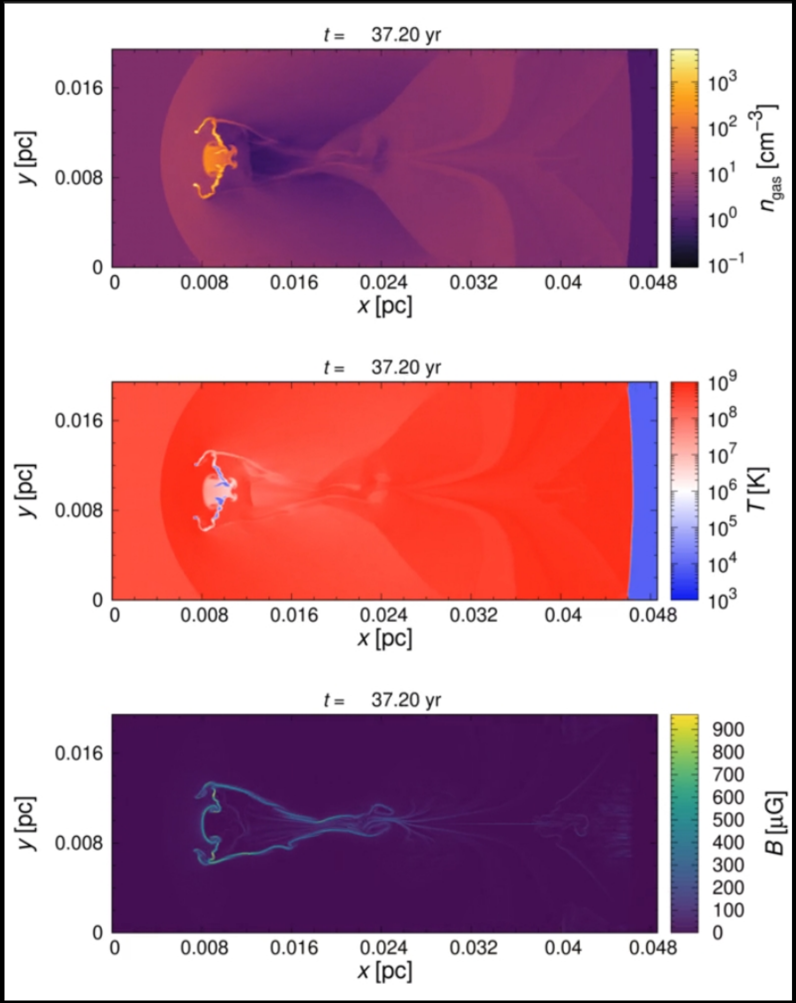
Magnetic fields in shocked clumps



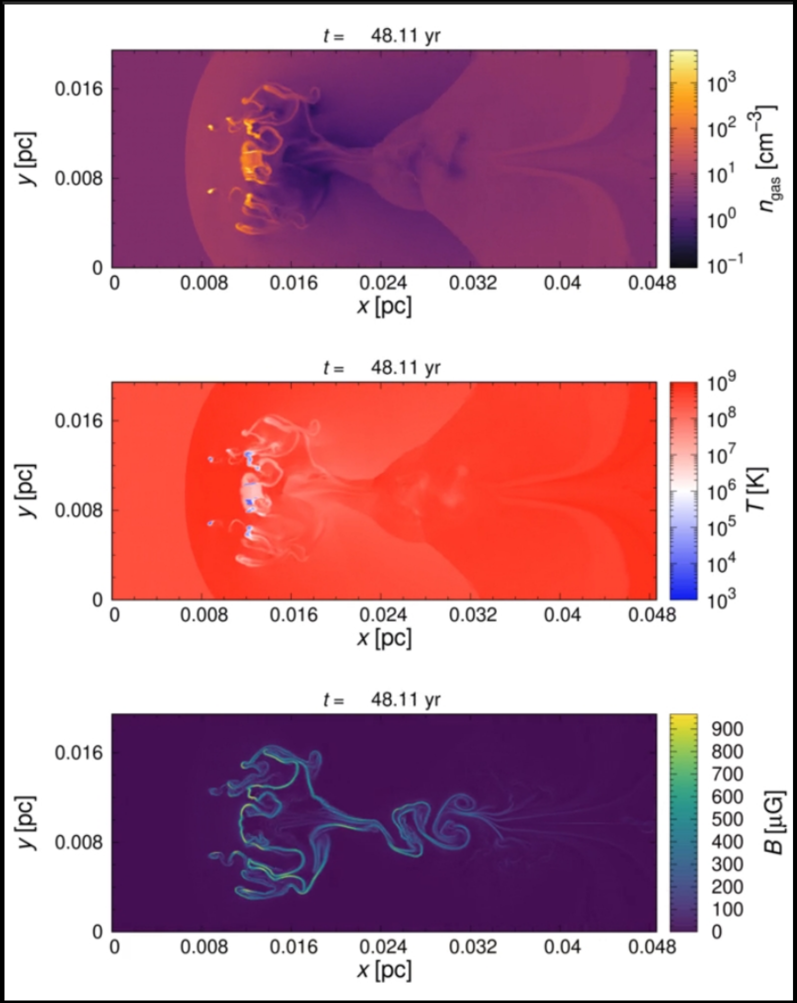
Magnetic fields in shocked clumps



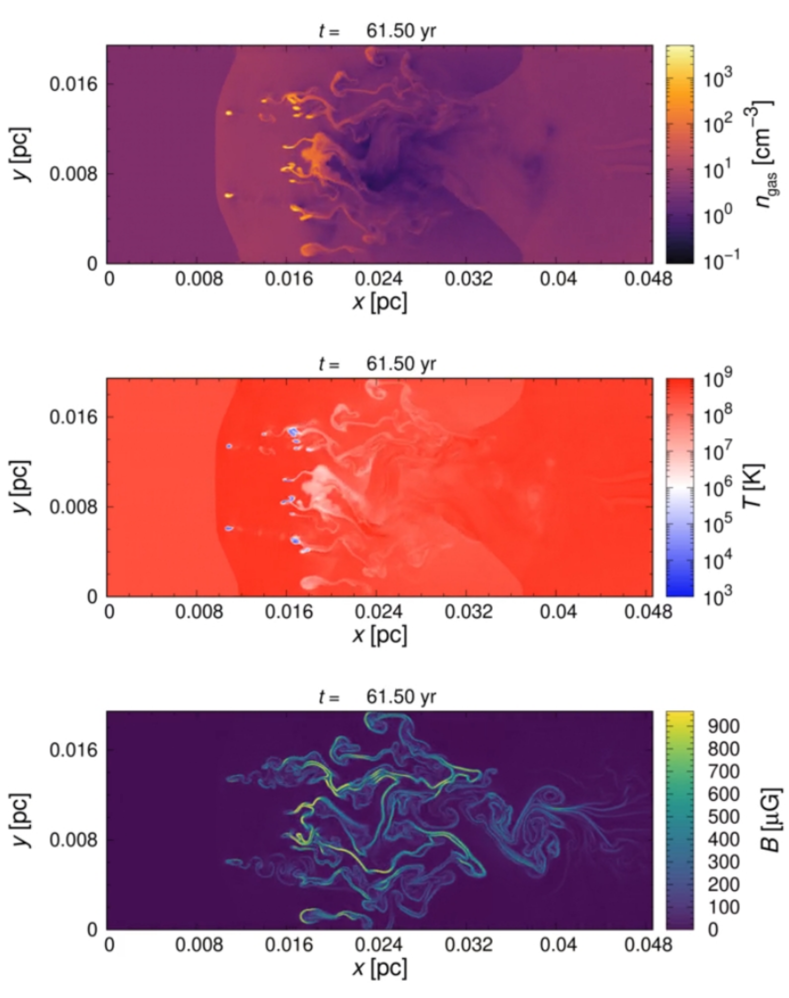
Magnetic fields in shocked clumps



Magnetic fields in shocked clumps



Magnetic fields in shocked clumps

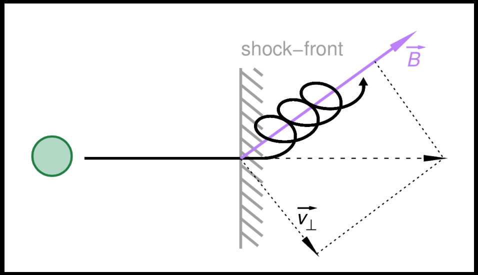


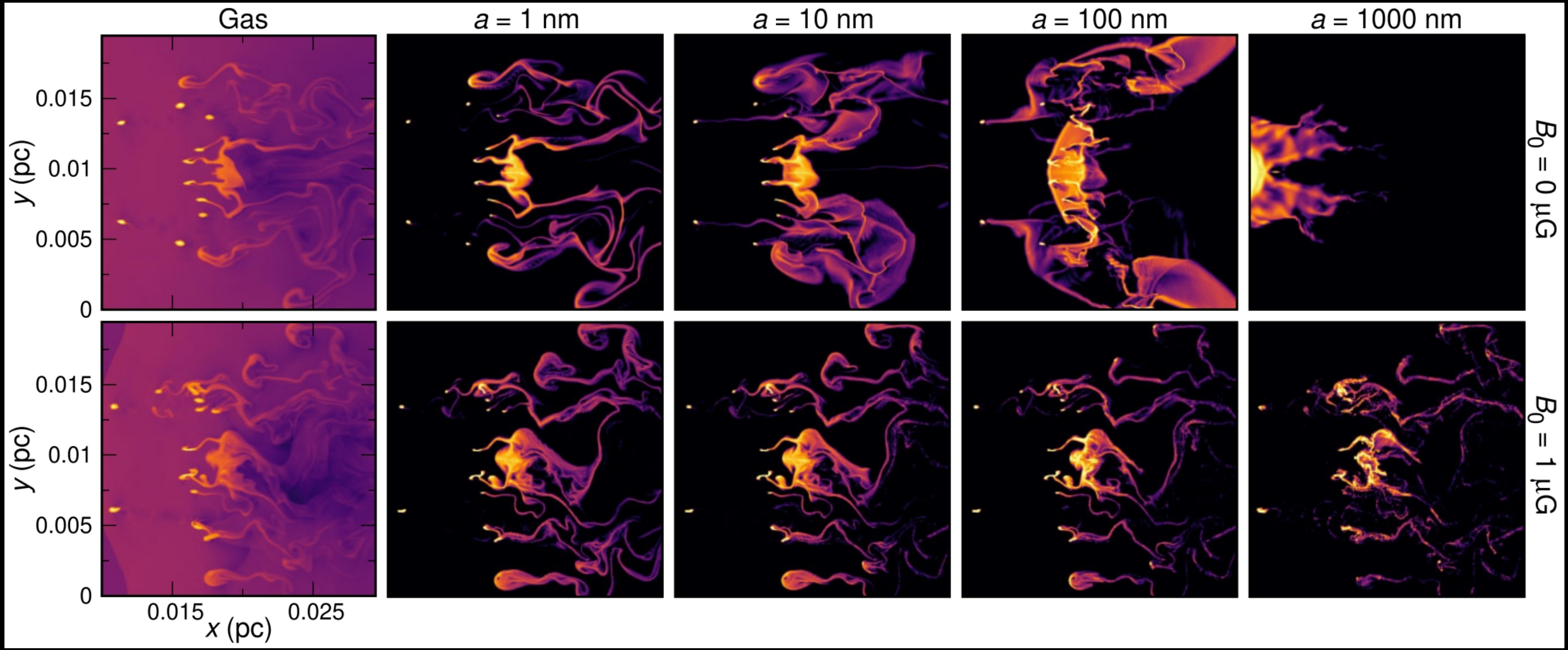
Coupling/Decoupling of grains in magnetic fields

Beta acceleration of charged grains in magnetic fields

Spiraling of grains around magnetic field lines

Additional transport process

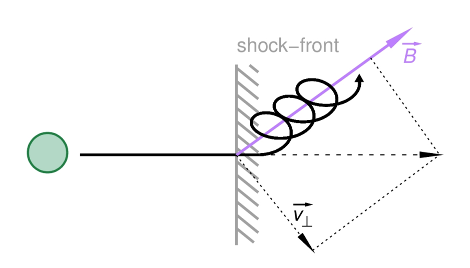


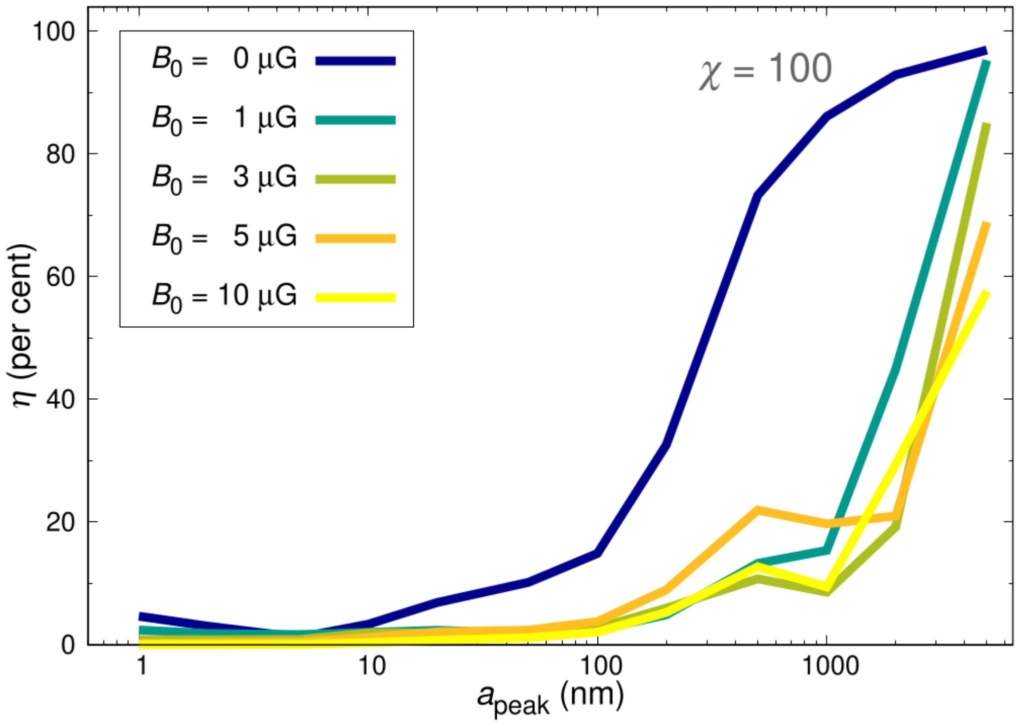


Coupling/Decoupling of grains in magnetic fields

Spiraling of grains around magnetic field lines

cause larger relative velocities of grains of different sizes

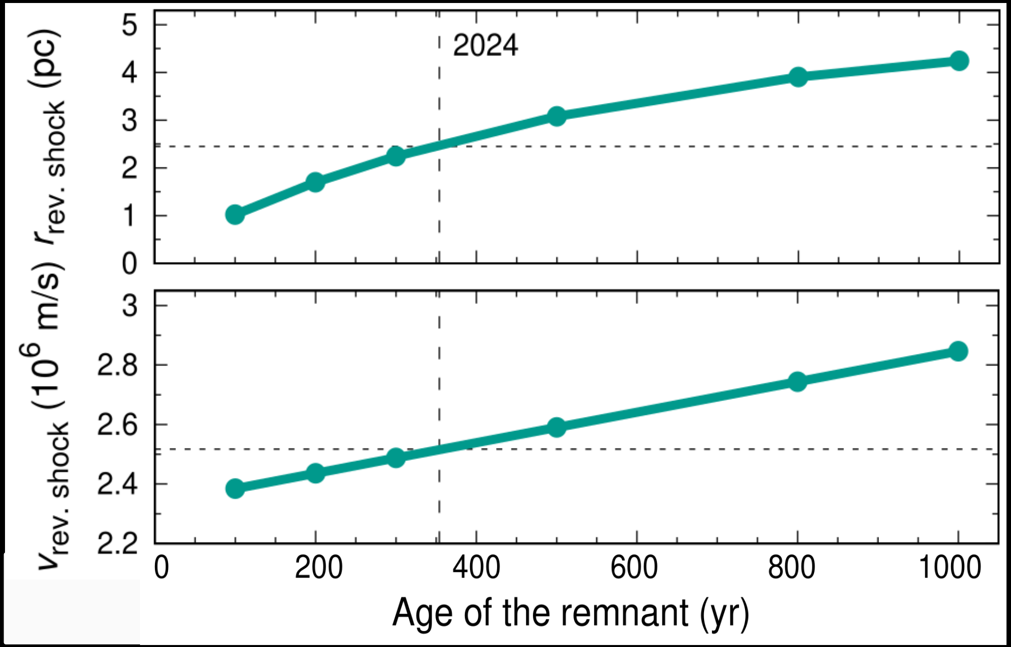


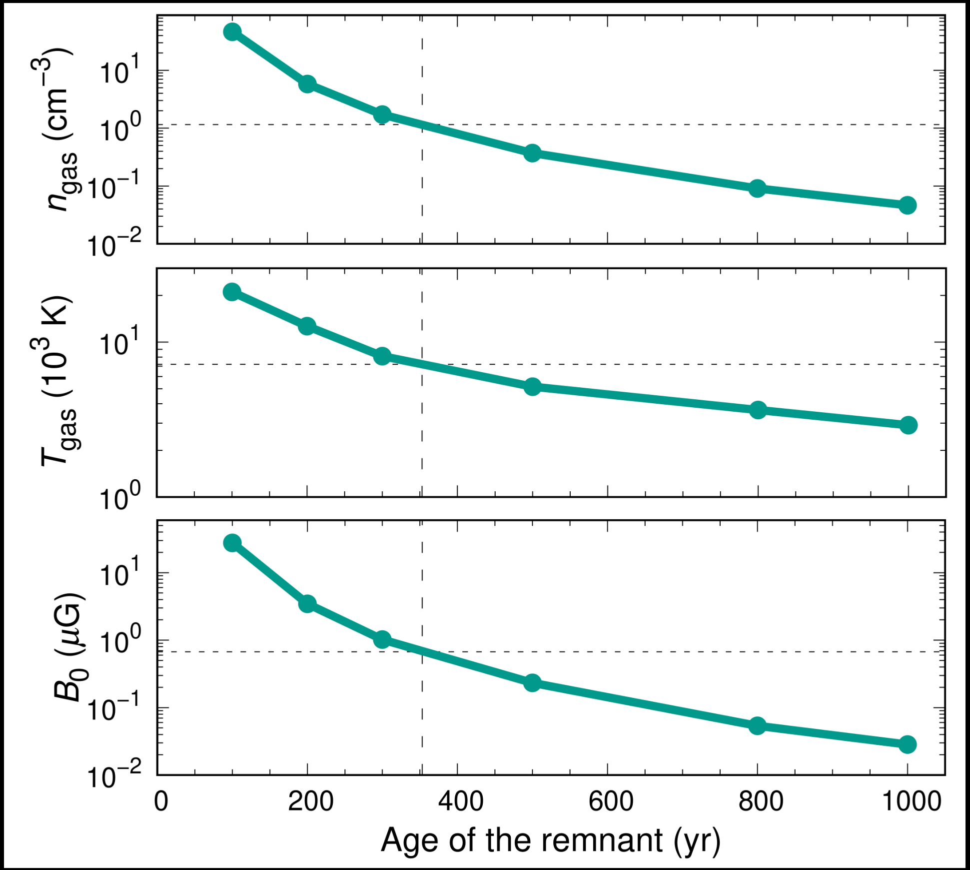


Larger dust destruction when magnetic fields are present

How does dust destruction change over time?

SNR expands: Gas conditions at the position of the reverse shock change.



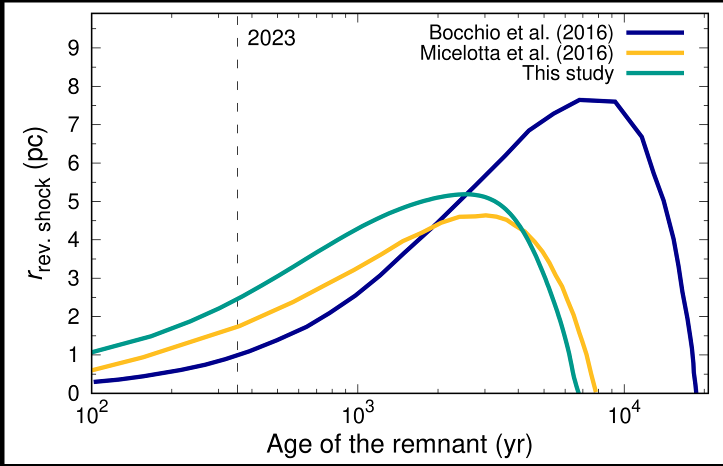


Shock and gas conditions for Cas A

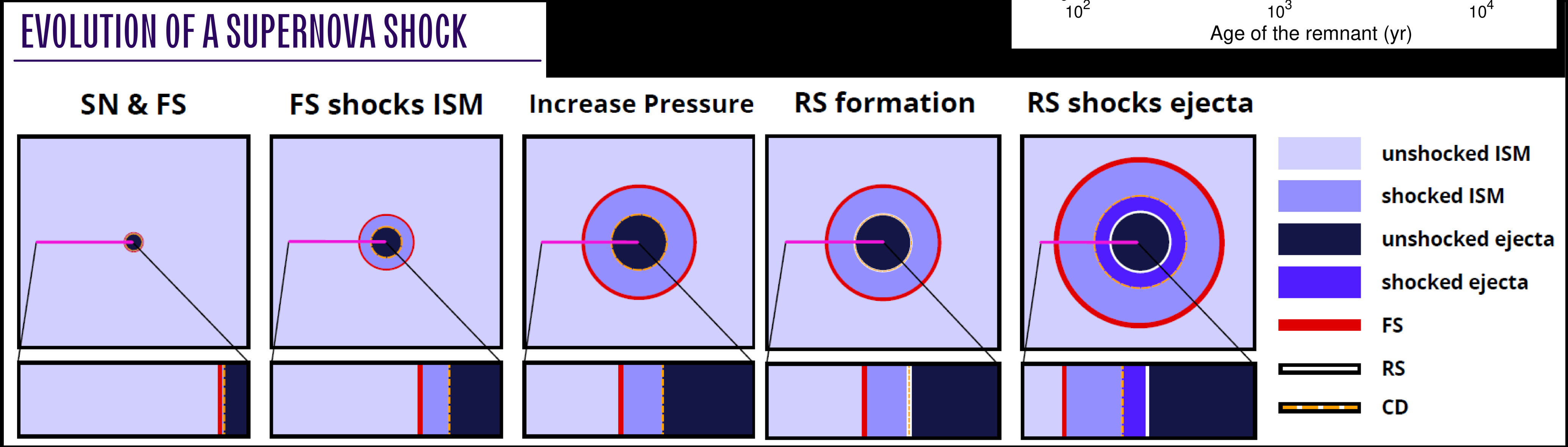
Analytical solution for formation of the reverse shock

Poster 4.23

Depends only on ISM conditions and properties of the SN explosion.

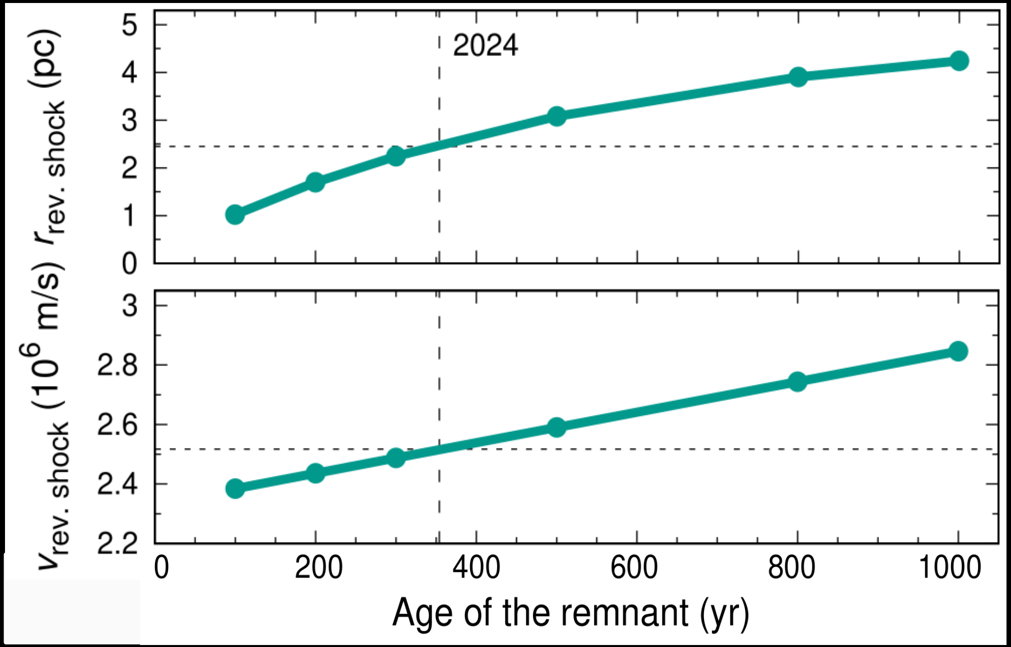


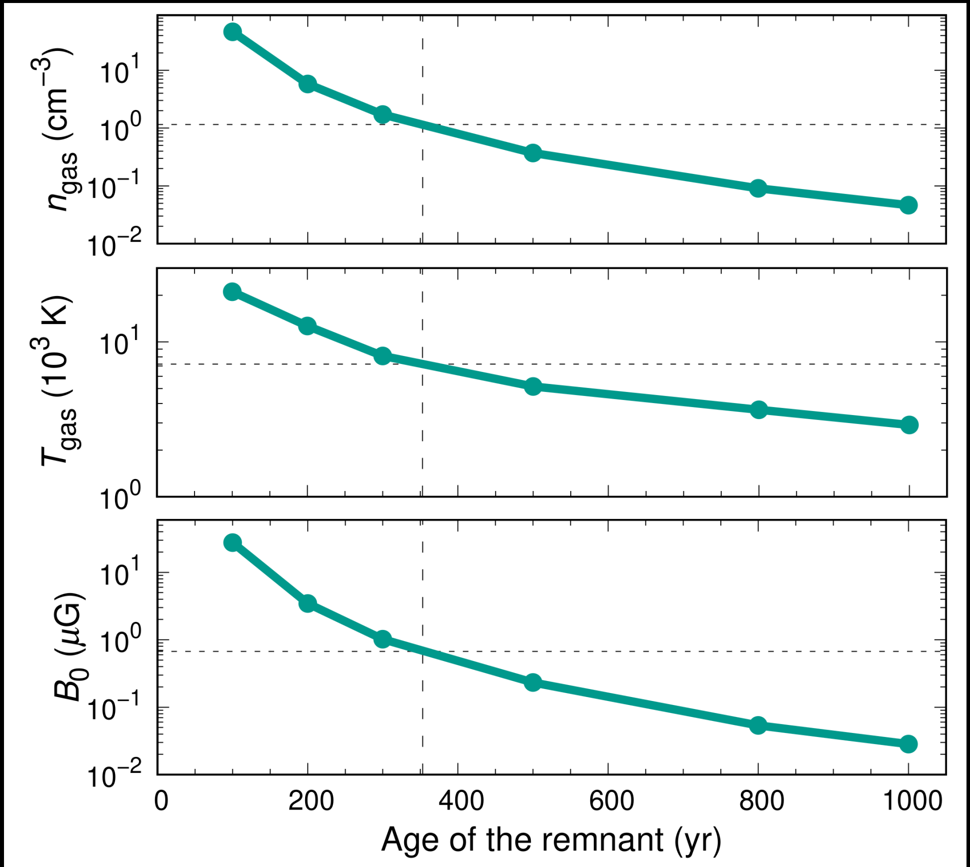
Bulckaen, Sartorio, Kirchschlager+



How does dust destruction change over time?

SNR expands: Gas conditions at the position of the reverse shock change.

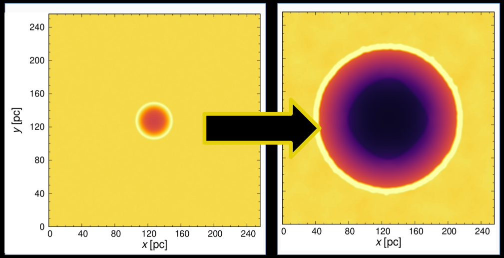




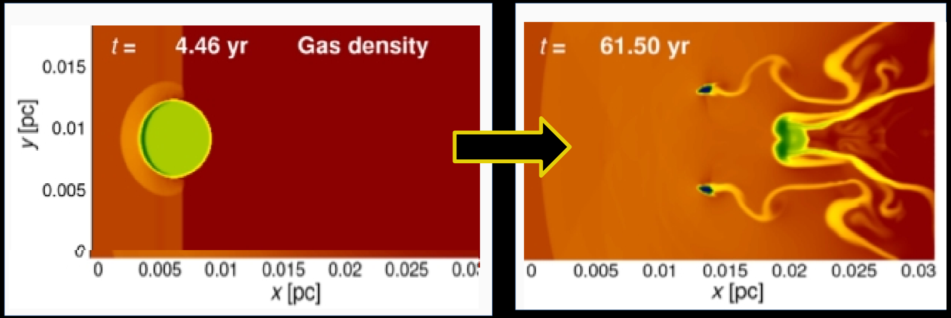
Shock and gas conditions for Cas A

3-step-approach

1) SN expansion



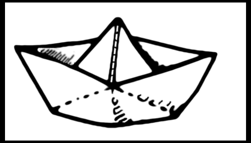
2) Clump – shock interaction



3) Dust

Dust dynamics

Dust processing

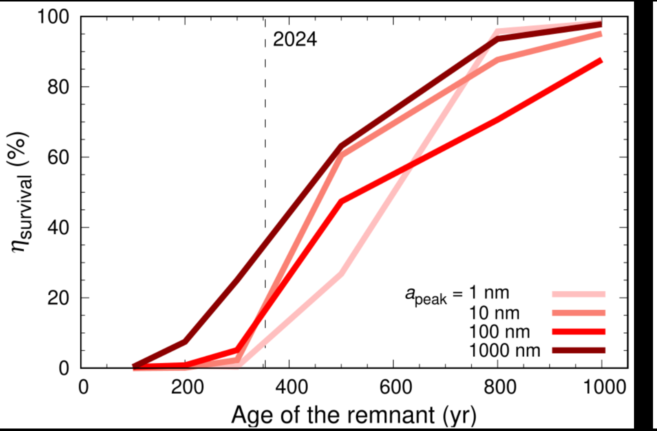


First step:

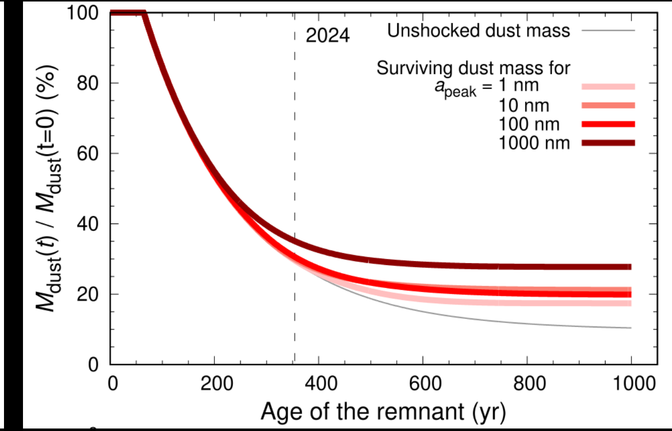
- 1D MHD simulation of a SN expanding into a homogeneous ISM using AREPO (Springel+ 2010)
- Parameter set to reproduce Cas A like SNR (Micelotta+ 2016):
  $n_0 = 2.08\ \mathrm{cm}^{-3}$; $E_{SN} = 2.2 \times 10^{51}$ ergs; $M_{ej} = 2.2\ \mathrm{M}_{sun}$; $n = 9$

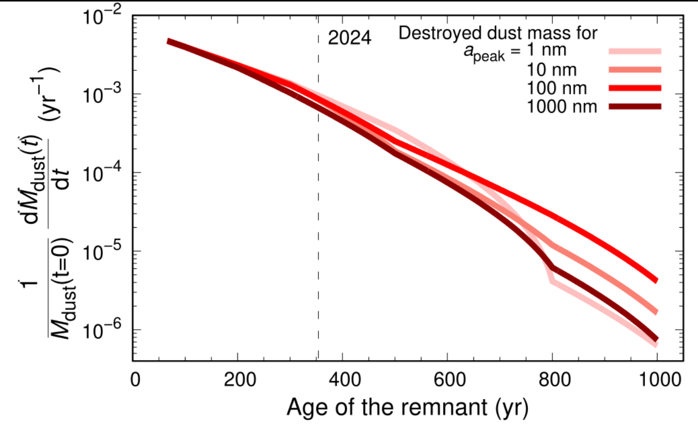
Dust destruction changes over time

Dust destruction per clump



Dust destruction in the whole SNR

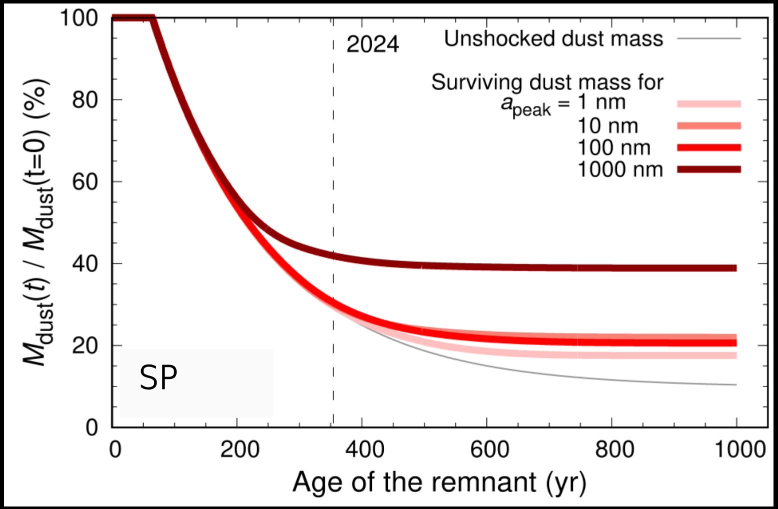


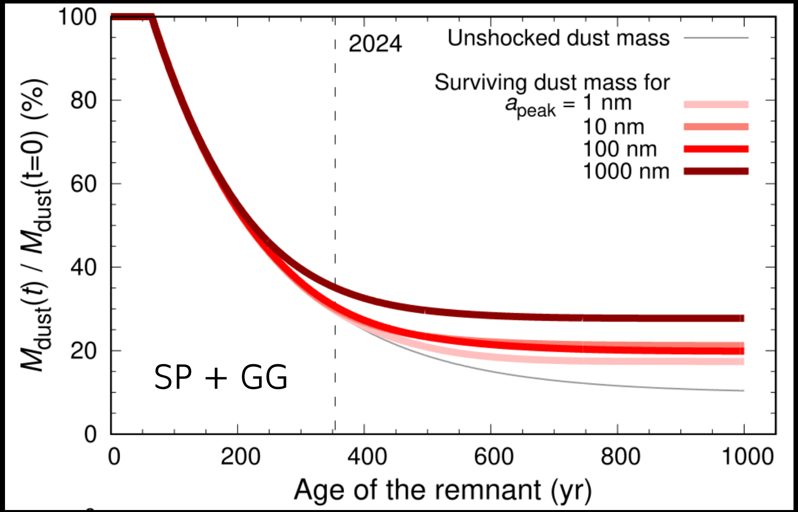


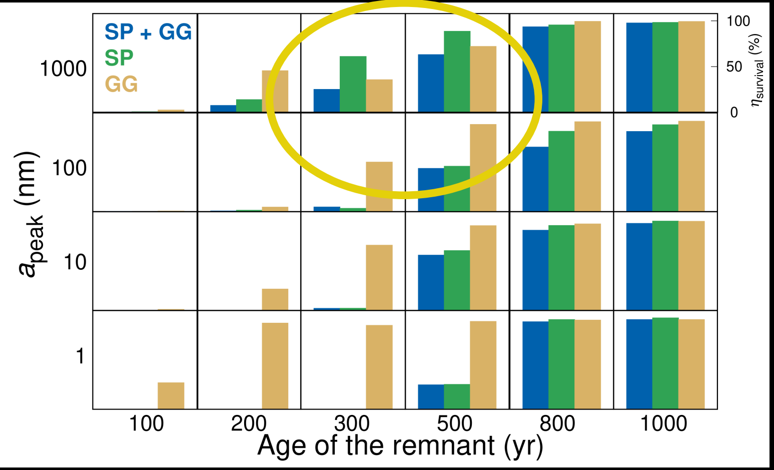
- Clumps colliding early with RS:
  Total dust destruction.
- Clumps colliding at ~1000 yr with RS:
  Total survial.
- 2024: 10-35 % dust survival (grain size-dependent).
- Rough trend: The smaller the grains, the faster the destruction.

Dust destruction in the entire SNR:
- 2024: 70 % of the ejecta dust has already passed the reverse shock.
  65 – 70 % of the ejecta dust is destroyed.
- At 1000 yr: 17 % (1 nm) to 28 % (1 µm) survival.
- Rough trend: The larger the grains, the higher the survival.
- Destruction at >1000 years can be ignored.

Sputtering vs. grain-grain collisions

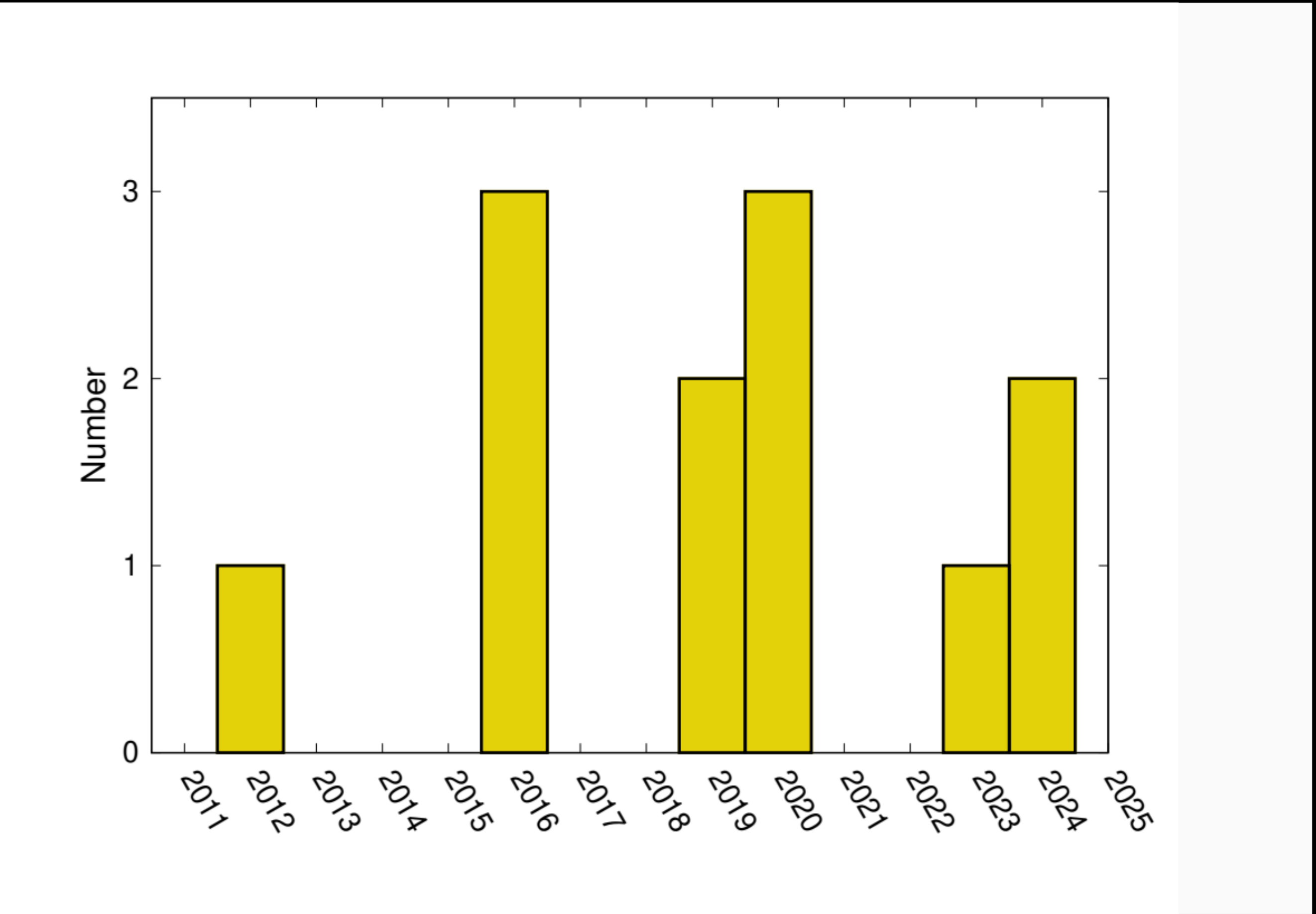




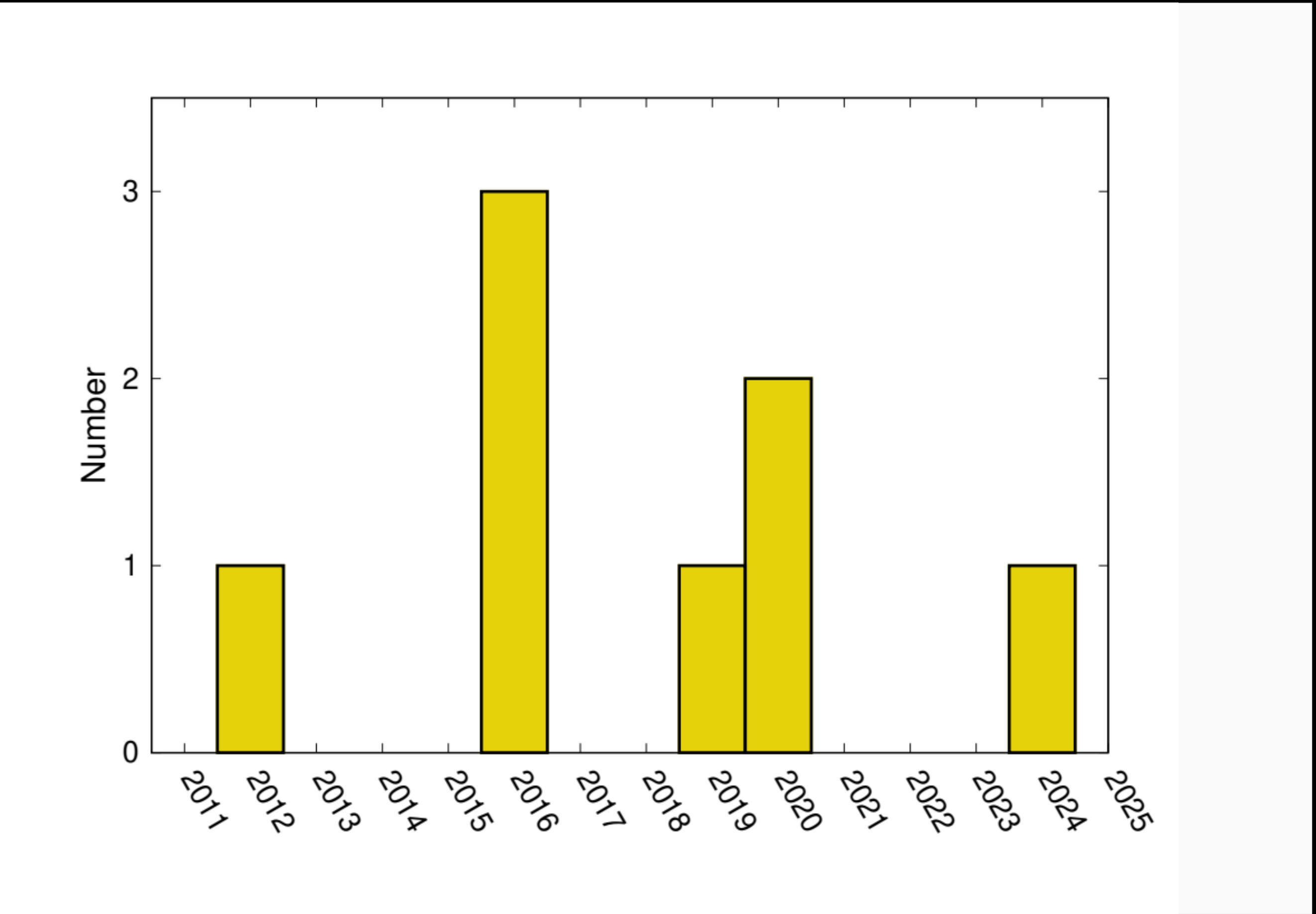


- Sputtering (SP) dominant factor for most grain sizes and remnant ages.
- GG collisions additionally reduce survival fraction (large grains).
- At 300 and 500 yr, GG collisions even dominate against sputtering.

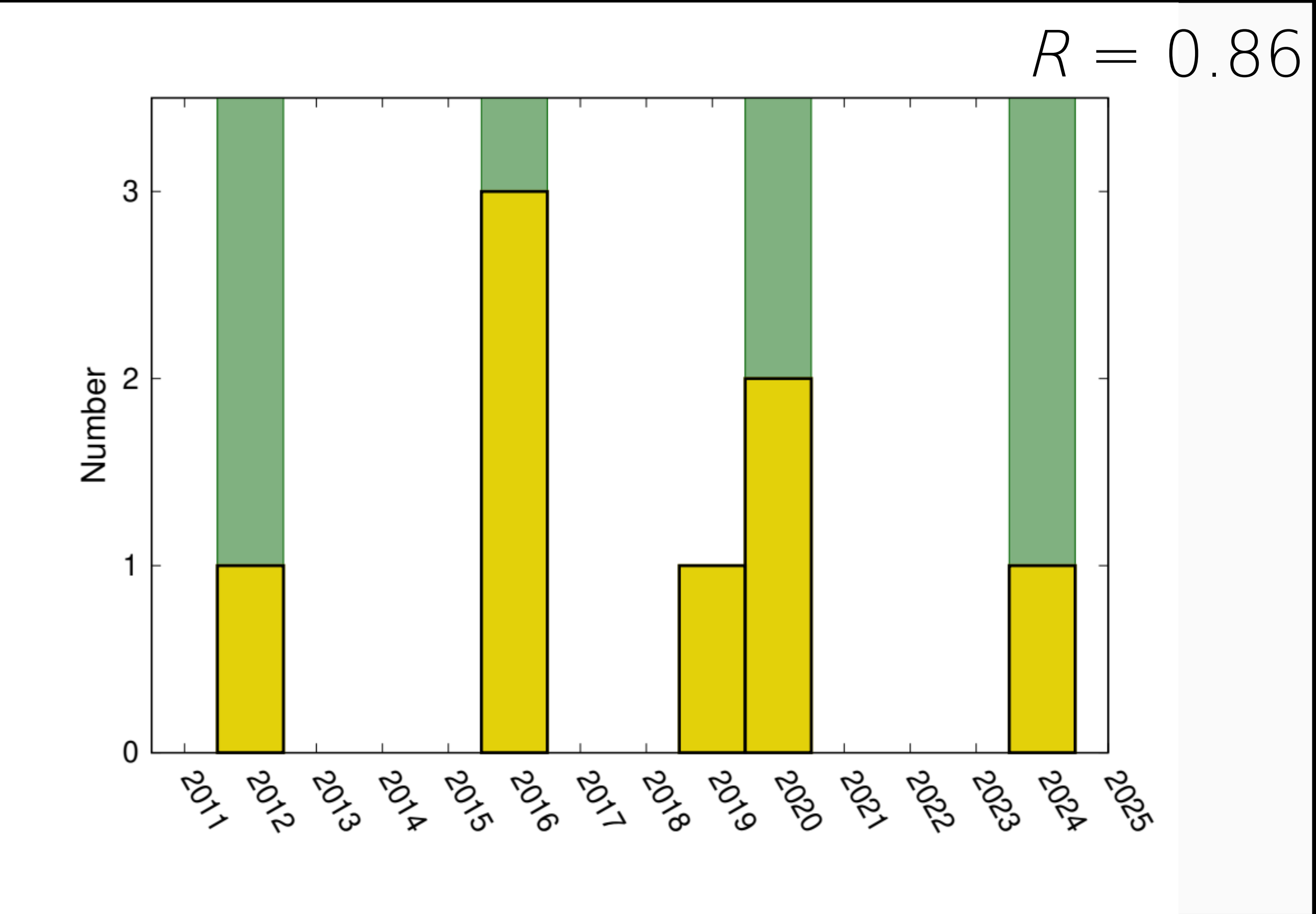
Publications about dust destruction simulations in SNRs



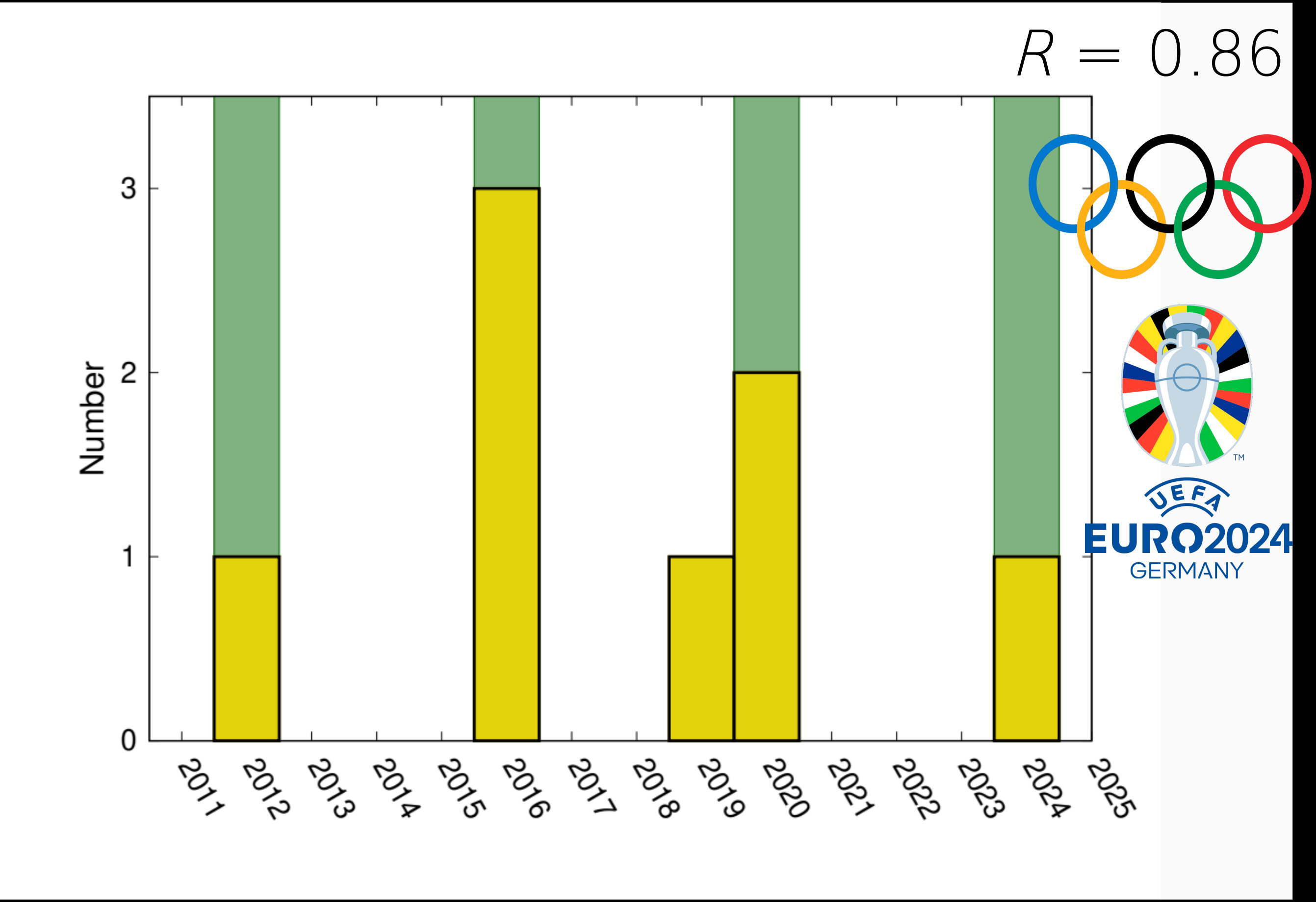
Publications about dust destruction simulations in SNRs



Publications about dust destruction simulations in SNRs

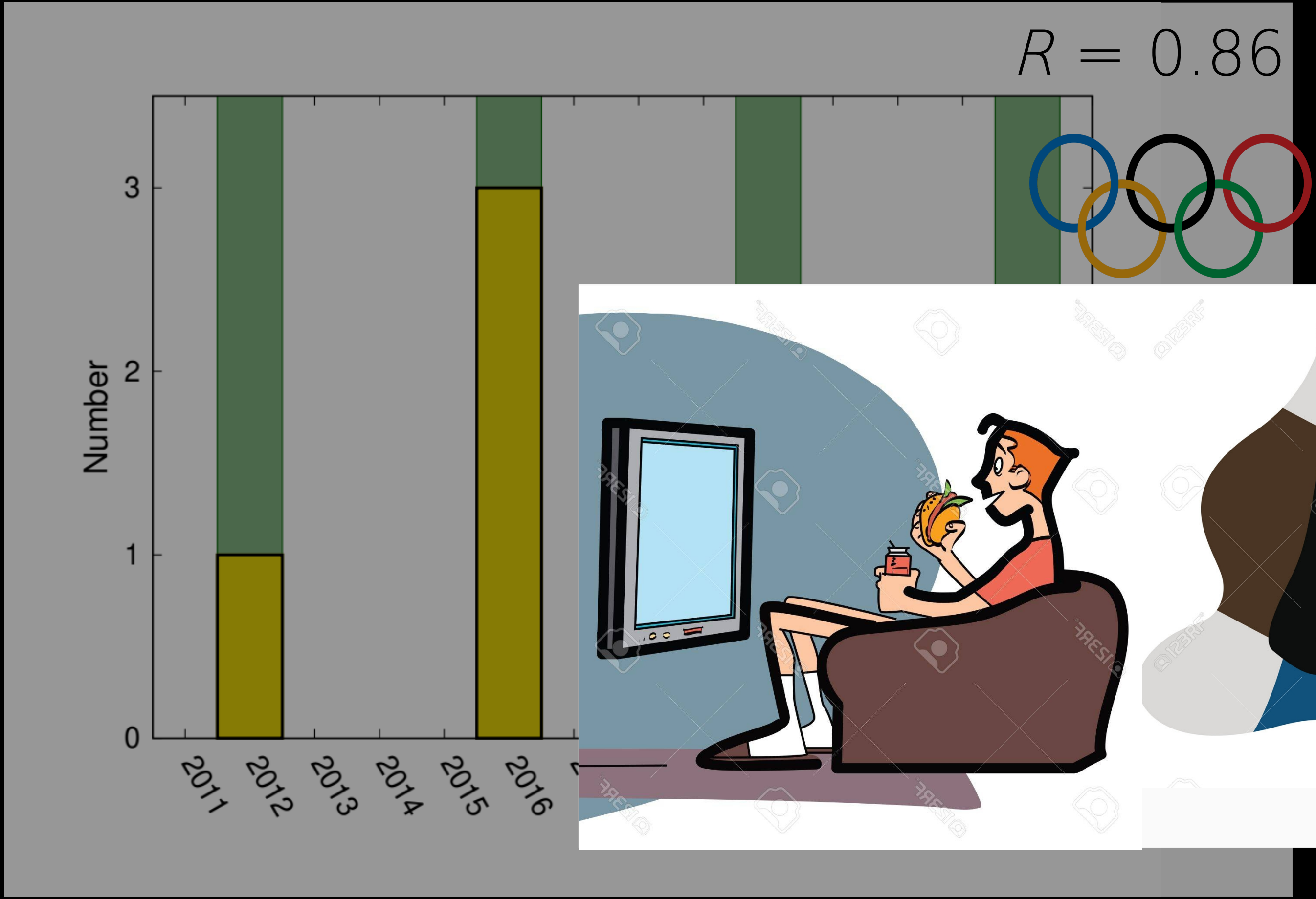


Publications about dust destruction simulations in SNRs



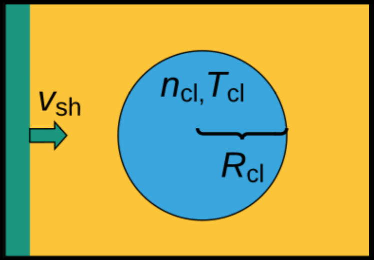
4-year period of the Summer Olympic Games and European Football Championships

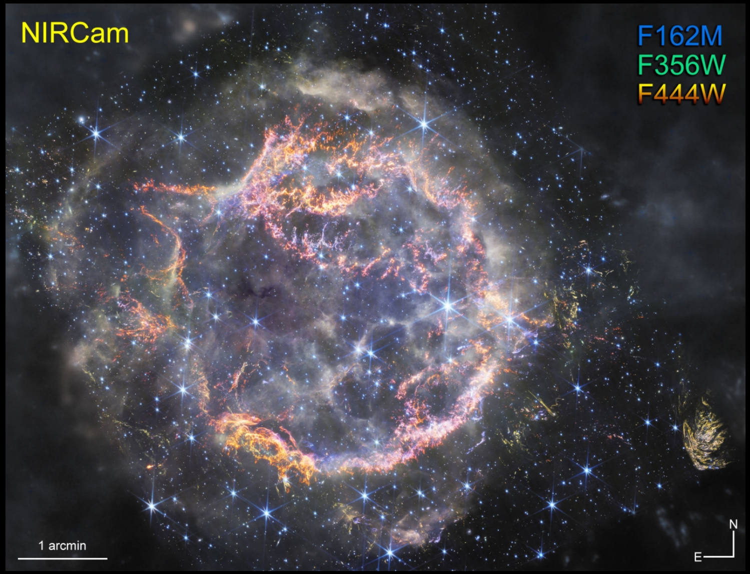
Publications about dust destruction simulations in SNRs



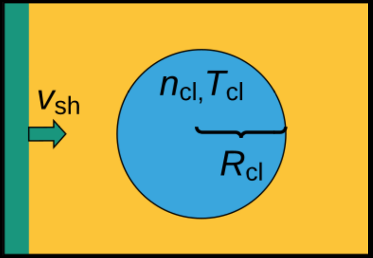
4-year period of the Summer Olympic Games and European Football Championships

Outlook

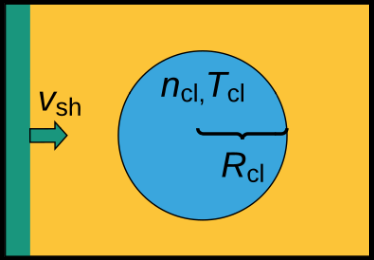




Outlook

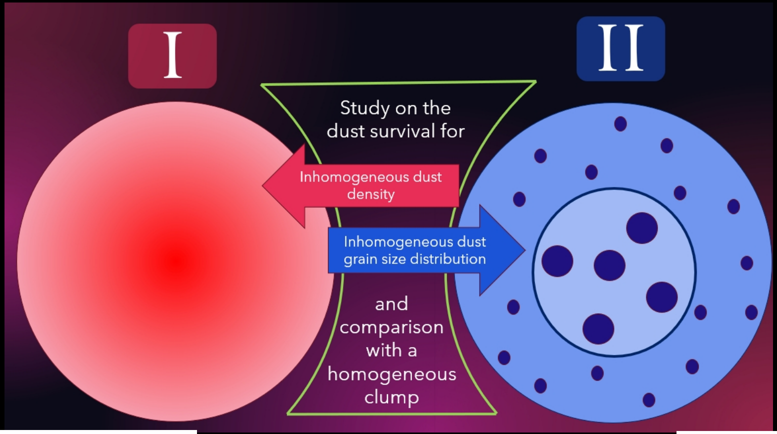


Outlook



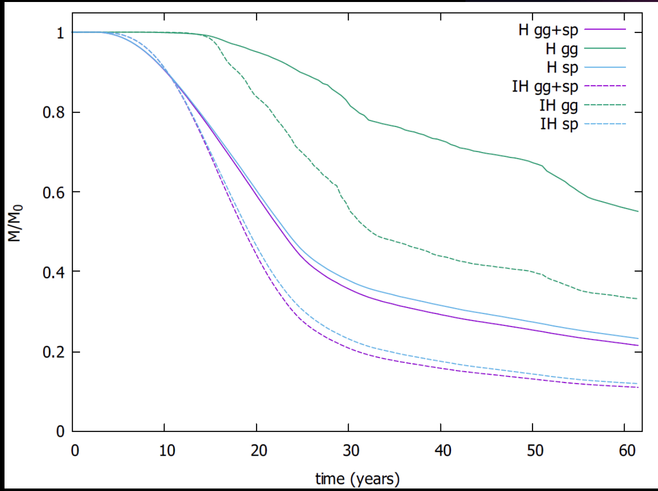
We need to study more realistic structures
- observed filaments, knots, and clumps.

Inhomogeneous clumps

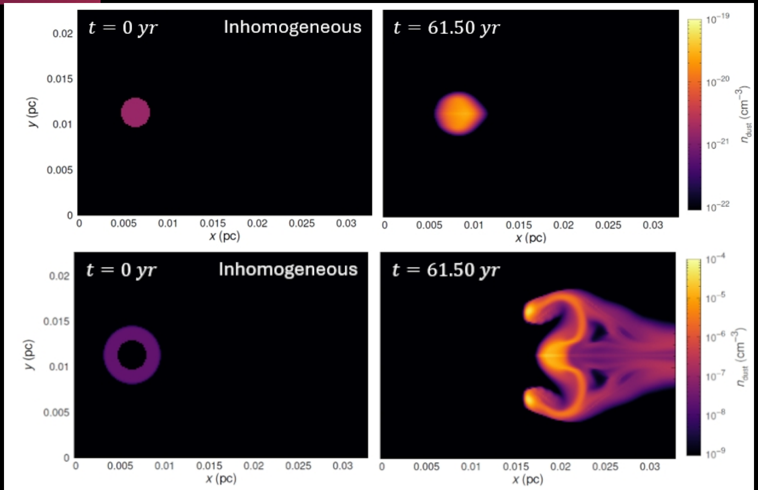


Poster 6.2

Dust density profiles



Heterogeneous grain sizes



Reckelbus, Kirchschlager +, in prep.

Not enough dust yet?

Then come to the AG 2024 in Cologne, Germany, 12. + 13.9.2024 !

2024

Astronomische Gesellschaft
German Astronomical Society

Splinter Meeting DustEvol

Dust evolution in galaxies - focus on supernovae, AGB stars and the ISM

Time: Thursday September 12, 14:00-15:45 and 16:15-18:00 and Friday September 13, 14:00-16:30 CEST (UTC+2)

Room: S12

Convenor(s): Florian Kirchschlager, Ilse De Looze, Nina Sartorio, Tassilo Scheffler, Fabian Walter, Kathryn Kreckel
Ghent University, MPIA Heidelberg, Heidelberg University

Summary

Dust destruction in and around SNRs (strongly) depends on
- Grain sizes
- Clump/Gas densities
- Magnetic fields
- Remnant evolution

For Cassiopeia A: 17 % - 28 % dust mass survival.

General: We need to study more complex structures and environments to understand past, current and future dust destruction in SNRs.