The Physics of Dust Evolution

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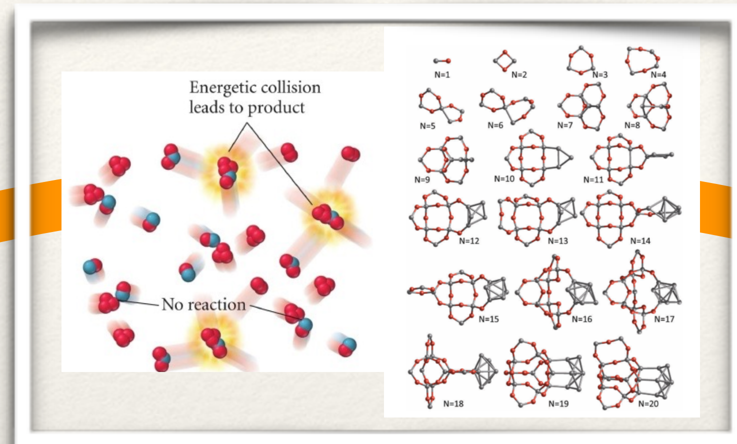
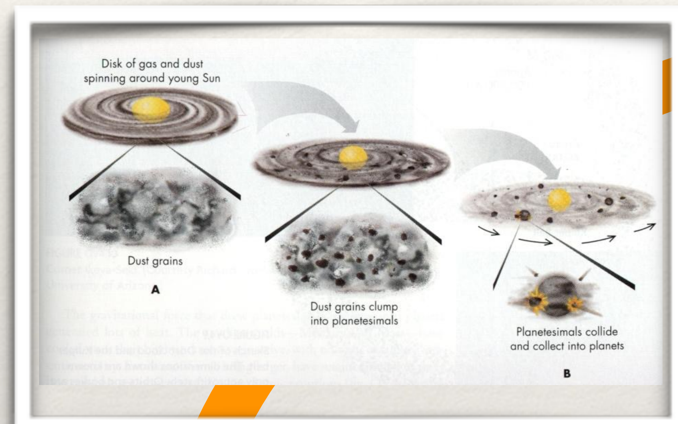
The Evolution of Dust: Physical Processes

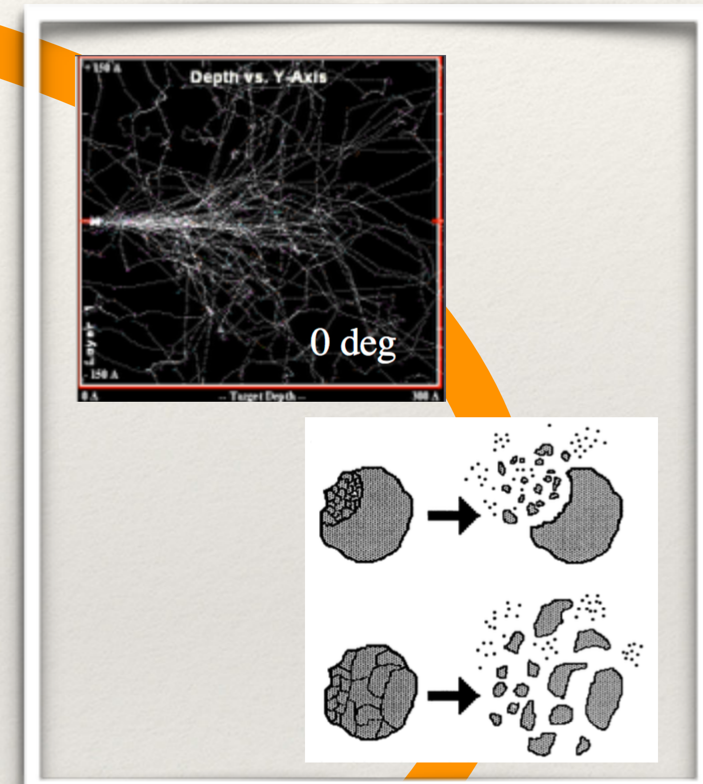
Formation:
Chemical kinetics
Stellar winds and SN ejecta



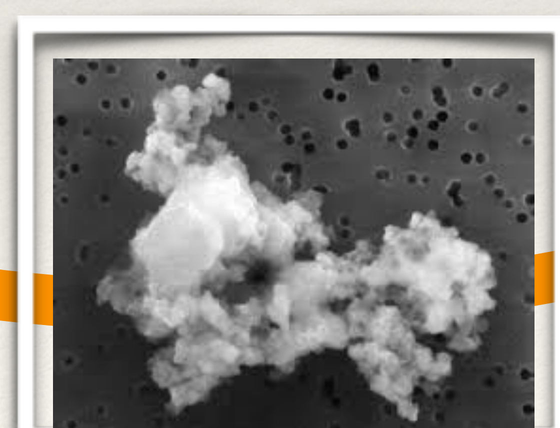
Buildup:
Asteroids, planetesimals
Debris disks



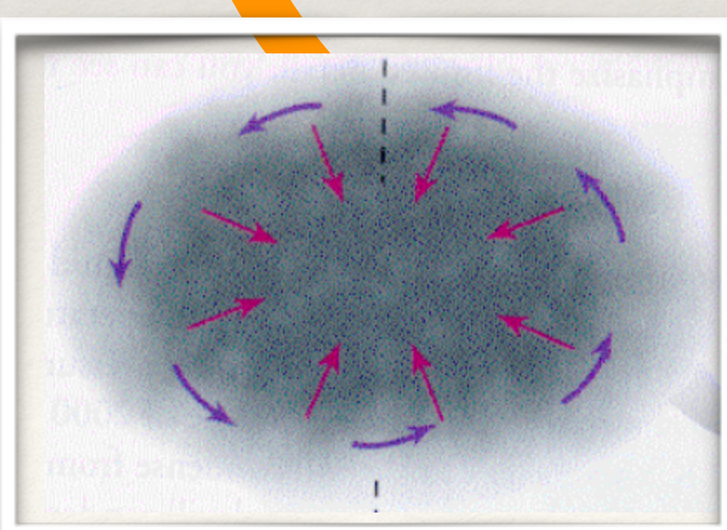
Destruction:
Sputtering, g-g collisions
Diffuse ISM



Processing:
Accretion, coagulation
Dense ISM

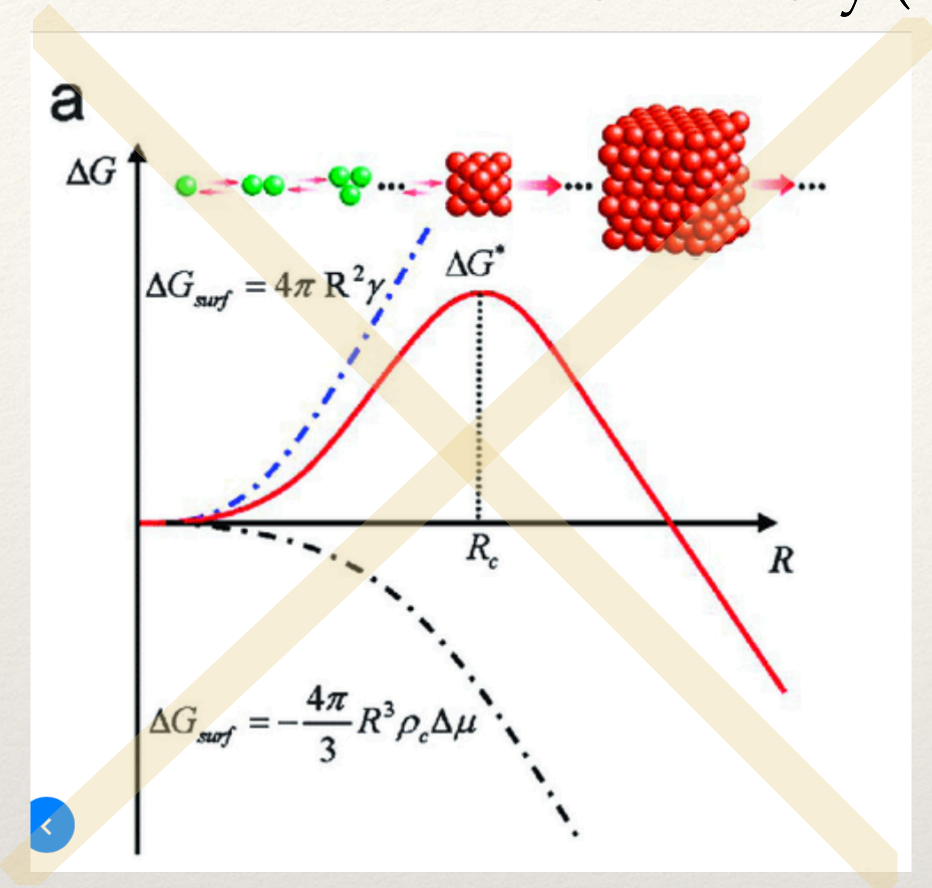


Evaporation:
Star formation
Dense ISM

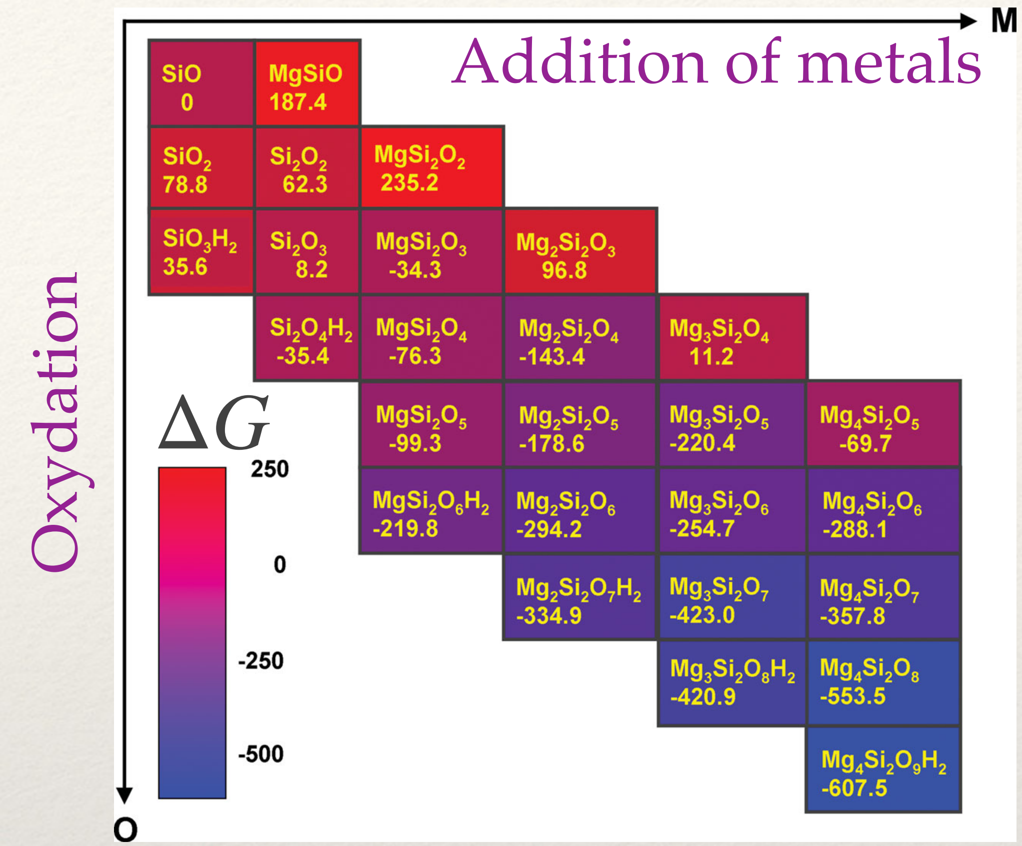


Dust Formation in CCSN Ejecta

Classical Nucleation Theory (CNT)



Molecular Kinetics



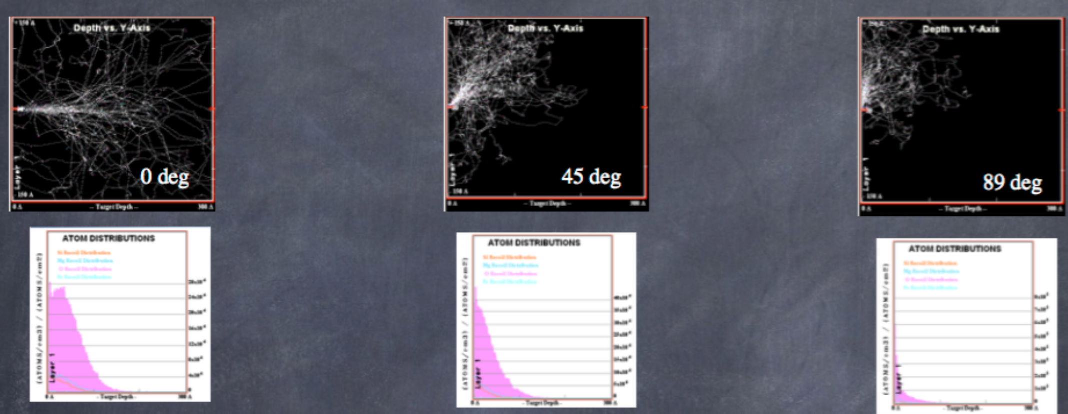
- Presence of radioactive ^{56}Ni
  - Hard radiation, fast electrons, ions He+, Ne+, Ar+ that break down stable molecules, SiO, CO
- Clumpy, stratified composition
- Mixing between layers
- Reverse shocks
- Uncertain composition and final yields

Sputtering

TRIM/SRIM Monte-Carlo simulations of particle stopping power and sputtering yields in solids

Sputtering: Forsterite $MgSiFeO_4$

H+ 0.3 keV X=300 Å



Mg	0.002450
Si	0.001500
Fe	0.001288
O	0.008163
total	0.0134

O/Fe ≈ 6.3 Mg/Si ≈ 1.6

Mg	0.003530
Si	0.001760
Fe	0.001550
O	0.011200
total	0.0180

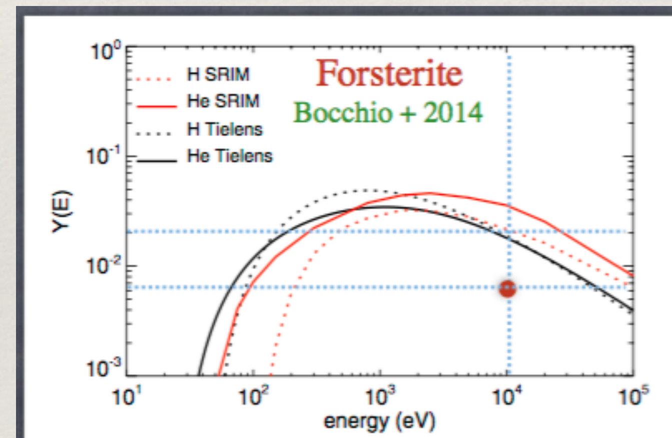
O/Fe ≈ 7.7 Mg/Si ≈ 2.0

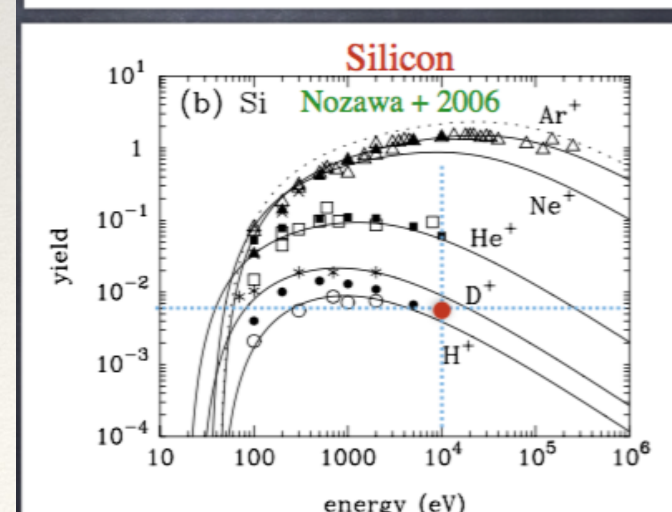
Mg	0.002950
Si	0.001290
Fe	0.001020
O	0.009870
total	0.0151

O/Fe ≈ 9.7 Mg/Si ≈ 2.3

- Dependence on incident angle of projectiles
- Finite grain size
- Non-stochiometric sputtering
- Step-size in the Monte-Carlo simulations

VERY preliminary comparisons

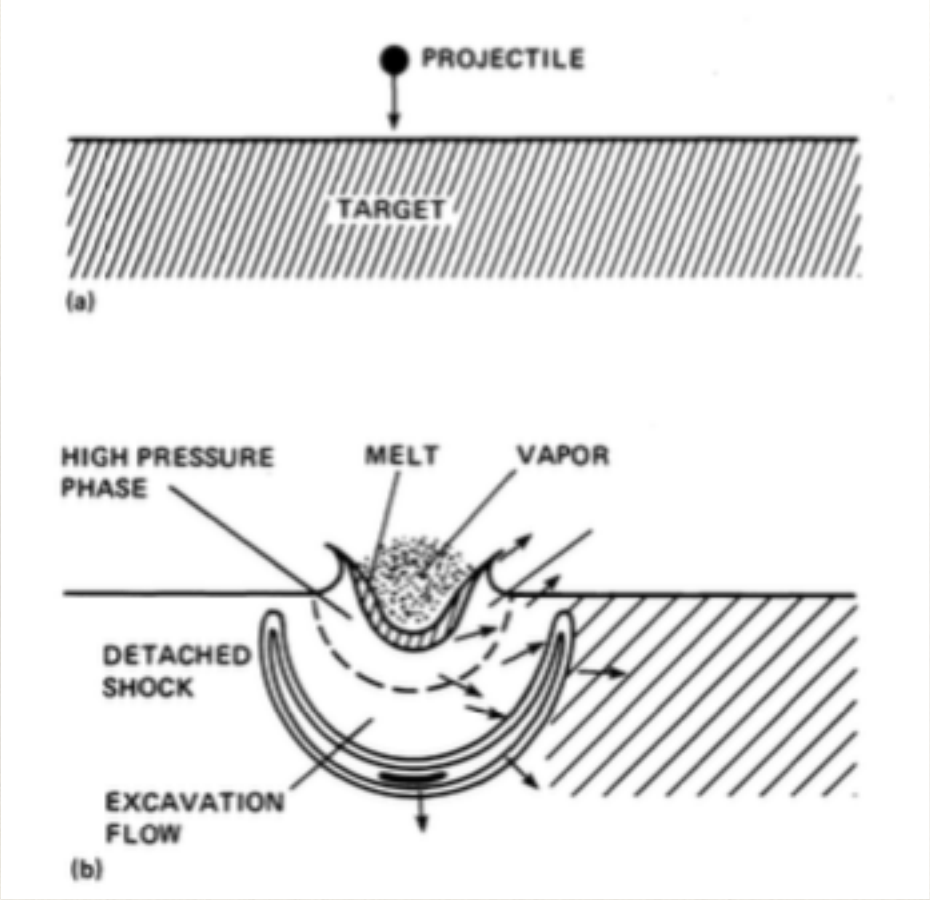




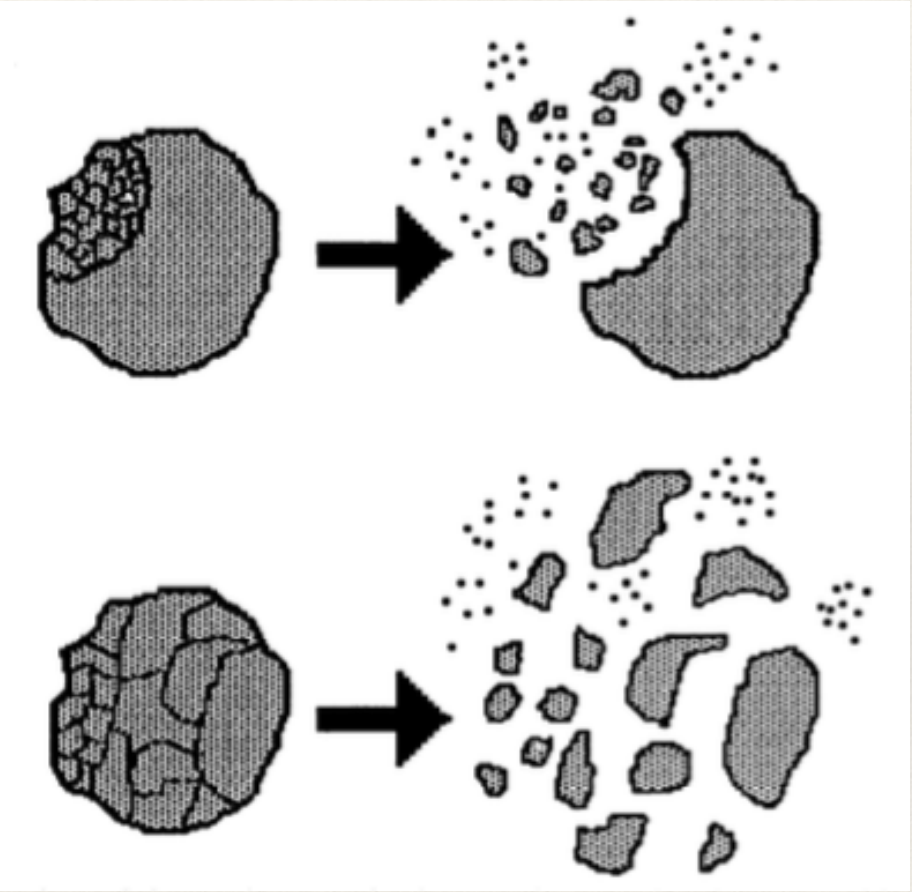
Grain-grain collisions

Theoretical approach
Shock wave in solids
(Tielens + 1994)

Semi-empirical approach
Theory+Lab data on cm-size solids
(Fujiwara+1989, Melosh+1992; Borkowski & Dwek 1994)



- impact velocity (shock strength)
- density, (porosity) size, composition
- eq. of state
- compressibility
- defects in solid
- tensile strength



Grain Destruction by SNR

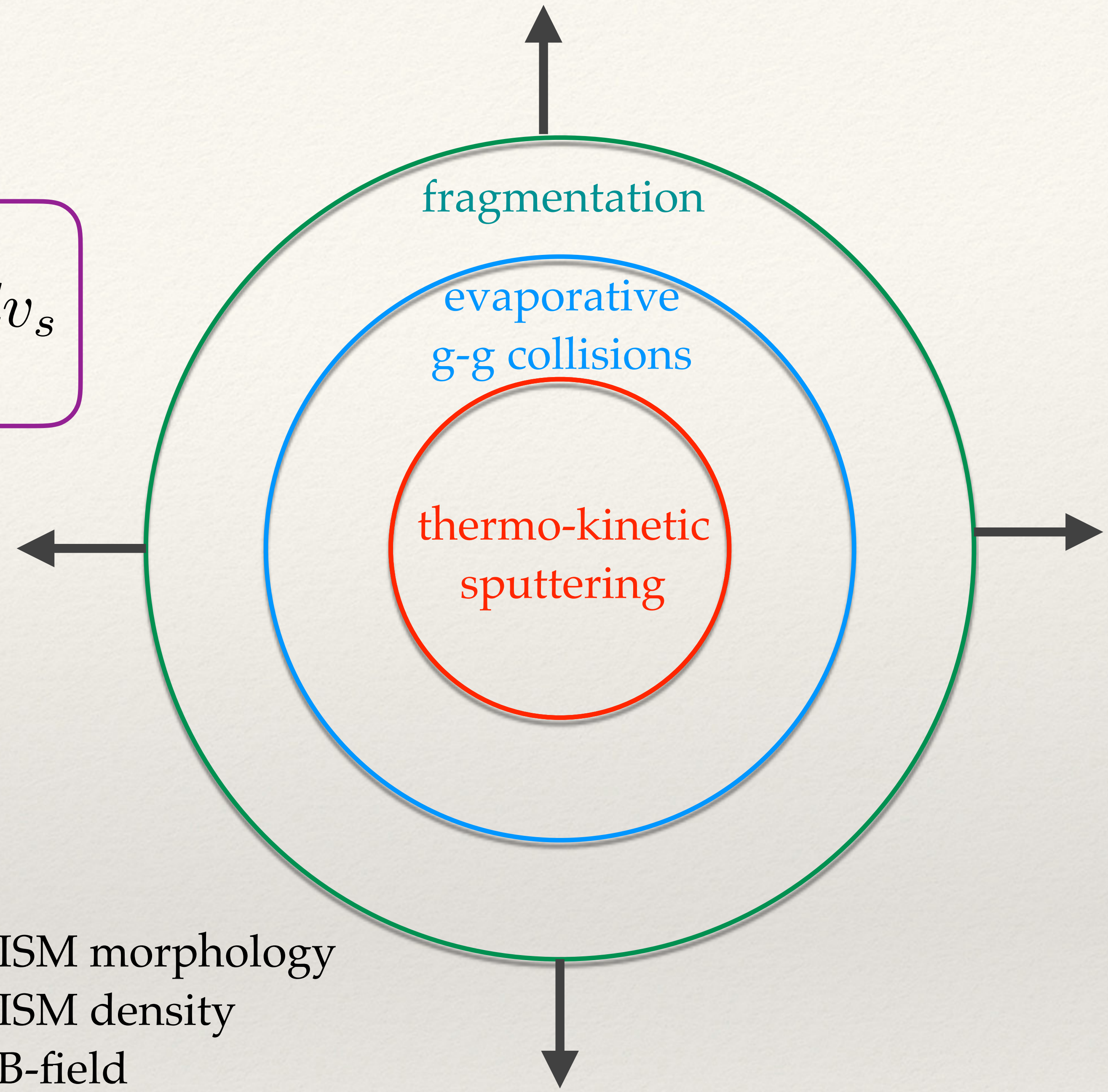
Mass of dust destroyed by single SNR

(e.g. Slavin +2015; Hu + 2019)

$$\boxed{m_d = Z_d \int_{v_0}^{v_f} f_d(v_s) \left[\frac{dM_{ISM}}{dv_s}\right] dv_s}$$

Dust lifetime (Dwek & Scalo 1980)

$$\boxed{\tau_d(t) \equiv \frac{M_d}{m_d\, R_{SN}}}$$



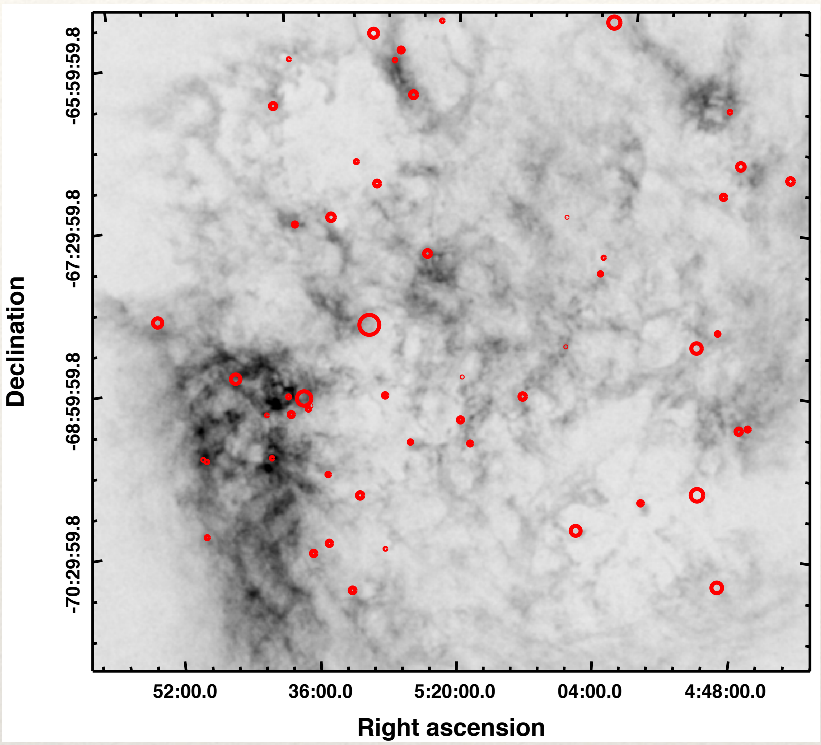
	$m_d[M_\odot]$	$\tau_d[Gyr]$
Slavin+ 2015 sput + g-g coll	~ 1.5	2-3
Hu+ 2019 sputtering	~ 1.4	0.4

- ISM morphology
- ISM density
- B-field
- Shock energy
- SN rate
- Correlated SNe
- Grain size distribution
- Total dust mass in ISM

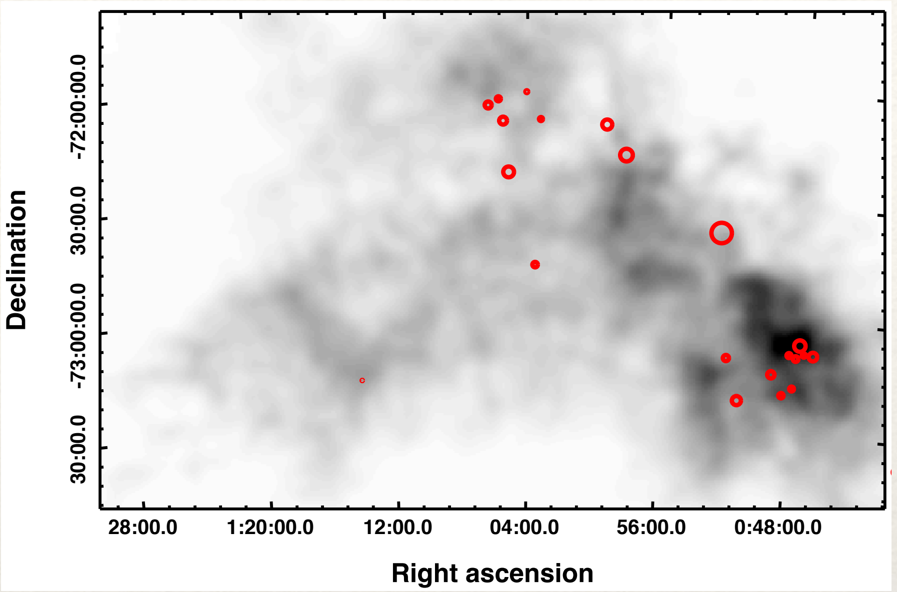
Dust Lifetime in LMC-SMC

(Temim + 2015)

LMC



SMC



- ✦ ISM morphology
- ✦ ISM density
- ✦ B-field
- ✦ Shock energy
- ✦ SN rate
- ✦ Correlated SNe
- ✦ Grain size distribution
- ✦ Total dust mass in ISM

	$m_d[M_\odot]$	$\tau_d[Myr]$
LMC	2 – 6	10 – 50
SMC	1 – 3	20 – 110

Dust destruction rate

$$\sim 2 \times 10^{-2}\ M_\odot\, yr^{-1}$$

Dust formation rate

$$\sim 1 \times 10^{-3}\ M_\odot\, yr^{-1}$$

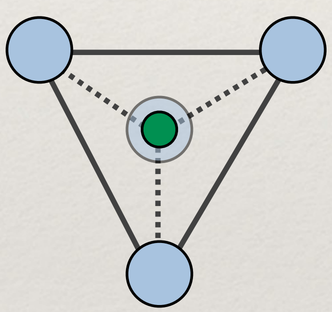
Accretion in Dense ISM

THE EVOLUTION OF REFRACTORY INTERSTELLAR GRAINS IN THE SOLAR NEIGHBORHOOD[1]

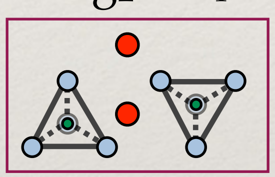
Dwek & Scalo 1980

parameters. We find that the maximum possible fraction of an element that can be locked up in thermally condensed cores is about 60% for the highly refractory elements like Ca, Al, and Ti, and about 30% for the more abundant refractory elements like Si, Mg, Mn, and Fe, independent of model parameters. Typically observed interstellar depletions (~ 10–10^3) and their elemental variations can therefore not be interpreted in terms of condensation efficiencies in the sources, and must instead be attributed to the selective growth of mantles in interstellar clouds. The strong

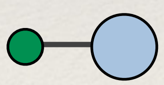
SiO_4 tetrahedra



Mg_2SiO_4

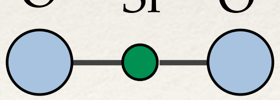


Si O



stretch: 9.7 μm

O Si O



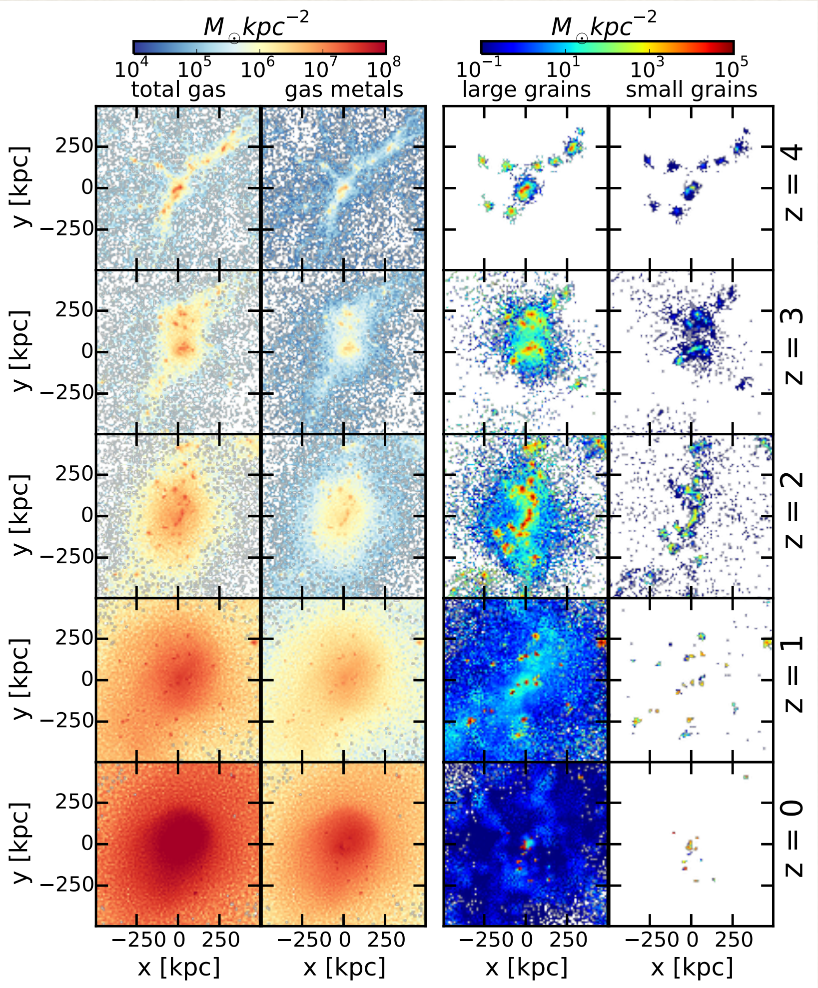
bend: 18 μm

Problems that need to be resolved in accretion models

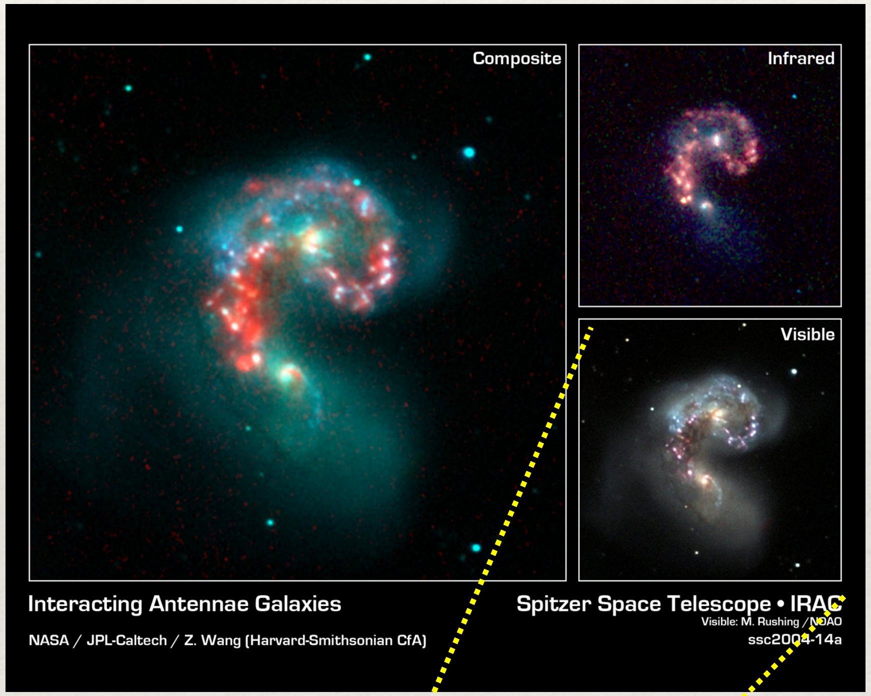
- Nature of impinging molecules and accretion sites
  - Compositions (MgO, SiO_2, refractory organics), sticking probabilities
- The origin if the interstellar depletion pattern
- The properties of the regrown dust are not the same as regular interstellar dust
  - In particular, cold accretion will not form the SiO_4 tetrahedral structure needed to give rise to the 9.7 and 18 μm silicate emission features
- Amount of needed accretion still uncertain
  - Uncertain rates of dust production and destruction
- Iron is SOFAR the only element that needs to be grown in the ISM independent on grain destruction rates

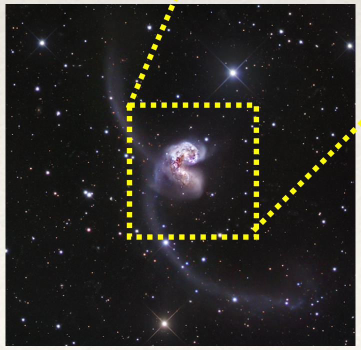
Large-scale dust evolution

In galaxy cluster simulations
(Gjergo + 2018)



In galaxy mergers





Fundamental issues

- Fate of dust in galaxy merger / assembly process
- Grain destruction efficiency (too high)
- Grain growth in the dense ISM (dust properties do not match the general ISM)
  - How does the grain size evolve (two size approx)

Takeaway

- The very presence of dust in the universe highlights the many physical processes that lead to the formation, survival, destruction, and reformation of dust in the various sources and the general ISM
- Understanding these processes is a major challenge in astrophysics


END