Shattering and Coagulation of Dust Grains in Interstellar Turbulence

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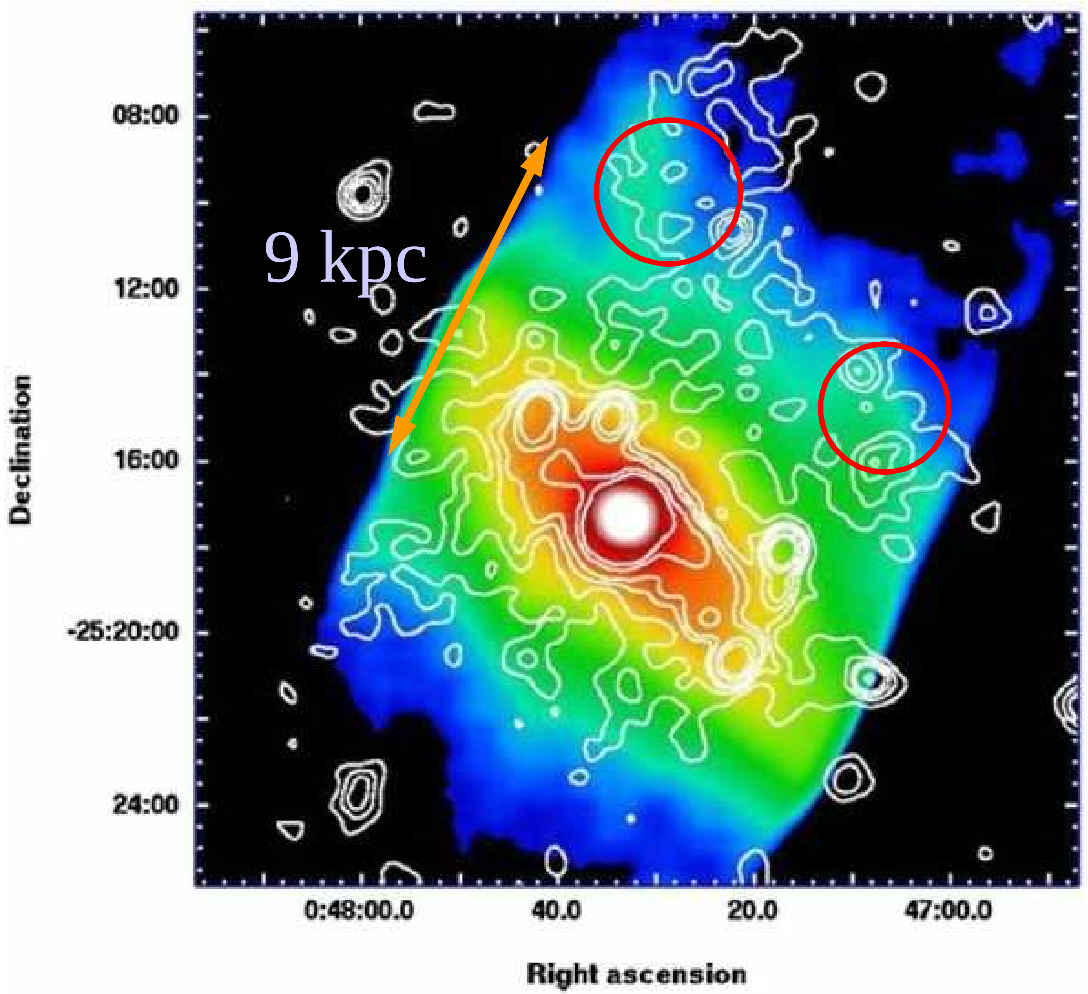
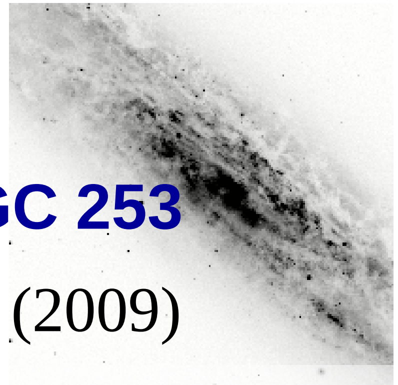
Outline

1. Dynamical Grain-Gas Coupling
2. Interstellar Turbulence
3. Formulation of Shattering and Coagulation
4. In a Cosmological Context

+ Analysis of M81 FIR image

1. Dynamical Grain-Gas Coupling





Kaneda et al. (2009)

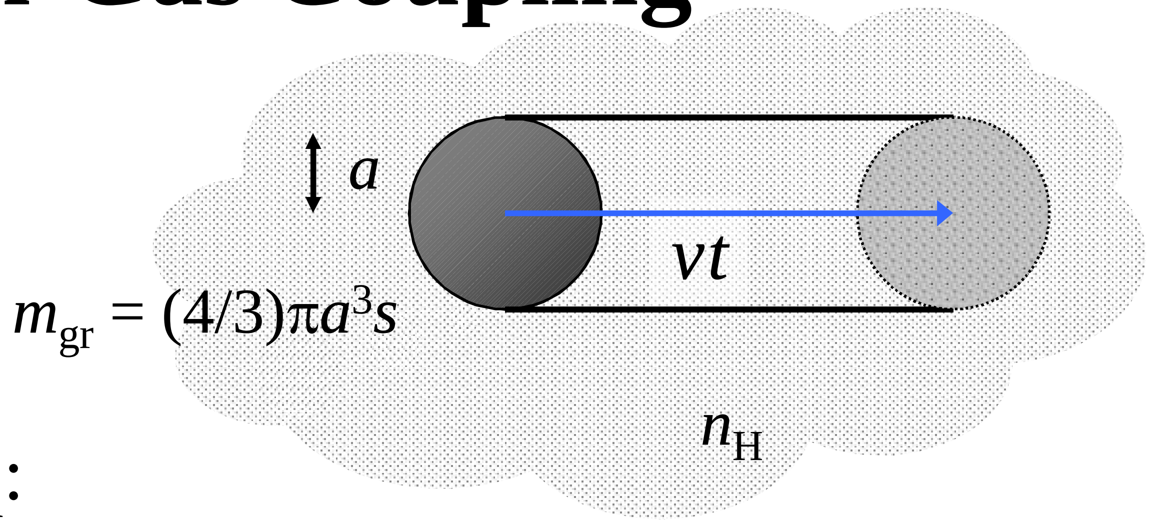
color: *AKARI* 90 μm
contour: *ROSAT* X-ray

The FIR extension coincides with the X-ray structure.

Dust is transported by gas ejection induced by stellar activity.

V_{escape} = 280 km/s (~ 10^7 K)
9 kpc / 280 km/s = 30 Myr

Grain-Gas Coupling



Gas drag timescale t_d:

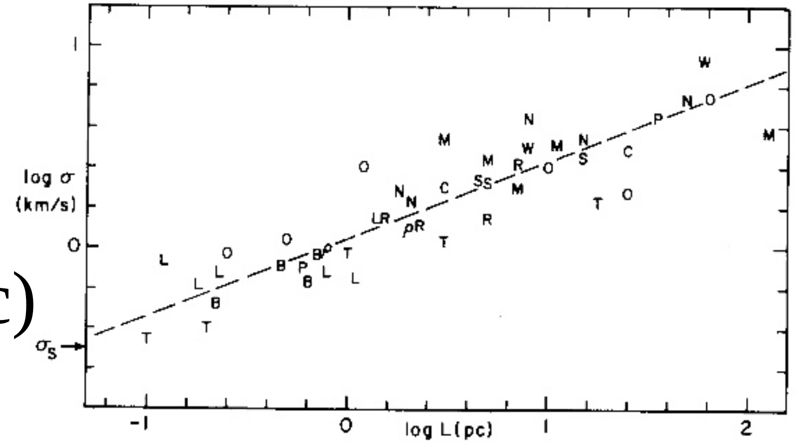
$(m_H v)(\pi a^2 v n_H) t_d \sim m_{gr} v.$

Grain motion is coupled with the gas motion on a scale ℓ large enough:

$\ell \sim v t_d = (4/3) a s/(m_H n_H) \sim (10/n_H)(a/0.1\ \mu\mathrm{m})$ pc

Large grains tend to be coupled with larger motions.

2. Interstellar Turbulence



Larson (1981)

ISM is turbulent (often supersonic) (e.g., McKee & Ostriker 2007).

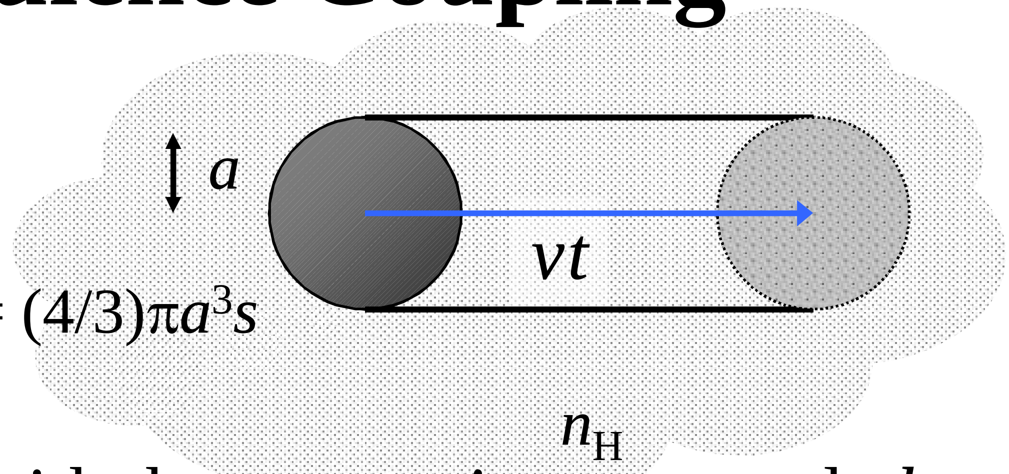
Implication for shattering (disruption):

c_s ~ 10 km/s in warm (~ 8000 K) medium
→ above the shattering threshold (~ a few km/s).

Implication for coagulation (sticking):

v_{turb} >> grain thermal speed. → If grain motion is coupled with turbulence, grain-grain collision occurs frequently (e.g., Ossenkopf 1993).

Grain-Turbulence Coupling



$m_{gr} = (4/3)\pi a^3 s$

Grain motion is coupled with the gas motion on a scale l large enough:

$l \sim vt_d = (4/3)as/(m_H n_H) \sim (10/n_H)(a/0.1\ \mu\mathrm{m})$ pc

Large grains tend to be coupled with larger motions.

Kolmogorov turbulence: $v_{turb} \propto l^{1/3}$

Large grains tend to acquire larger velocities.

In Reality, Complicated....

Magnetic fields ($B^2/8\pi \sim nkT$)
→ MHD turbulence
Velocity ~ Sound speed
→ Compressional
Grain charge (electron attachment, photo-electric eff.)
→ Coupling with magnetic fields, Coulomb interaction with plasma

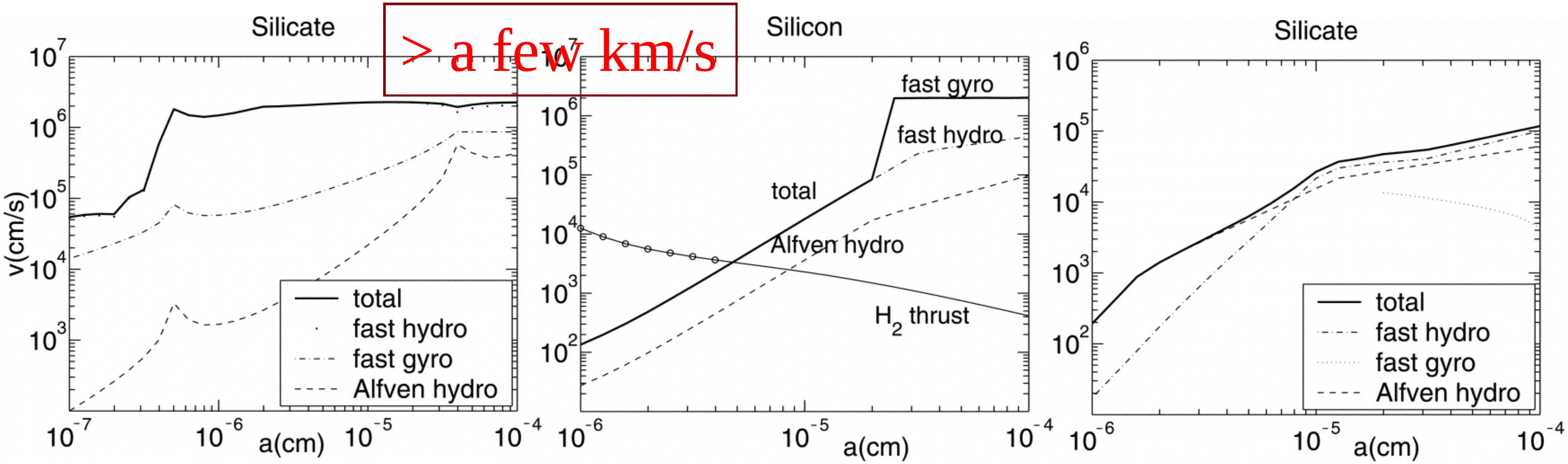
Grain Velocities

MHD turbulence model

hydro-drag, gyro-resonance

Yan, Lazarian, & Draine (2004)

> a few km/s



Warm ionized medium
$T = 8000$ K
$n_H = 0.1$ cm^{-3}
$B = 3.4$ μG

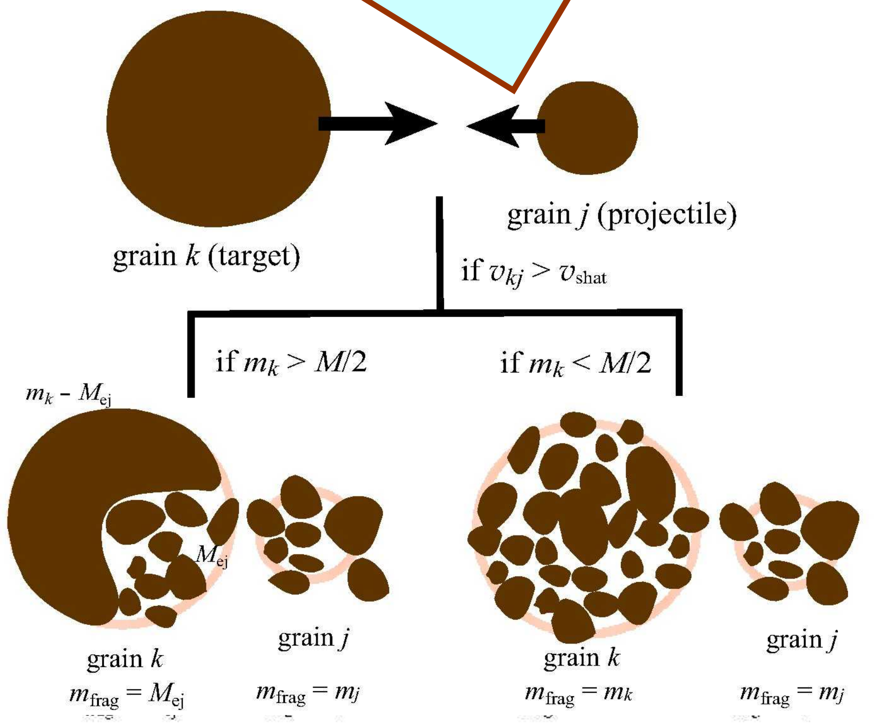
Warm neutral medium
$T = 6000$ K
$n_H = 0.3$ cm^{-3}
$B = 5.8$ μG

Dense cloud
$T = 10$ K
$n_H = 10^4$ cm^{-3}
$B = 80$ μG

Sl… gulation

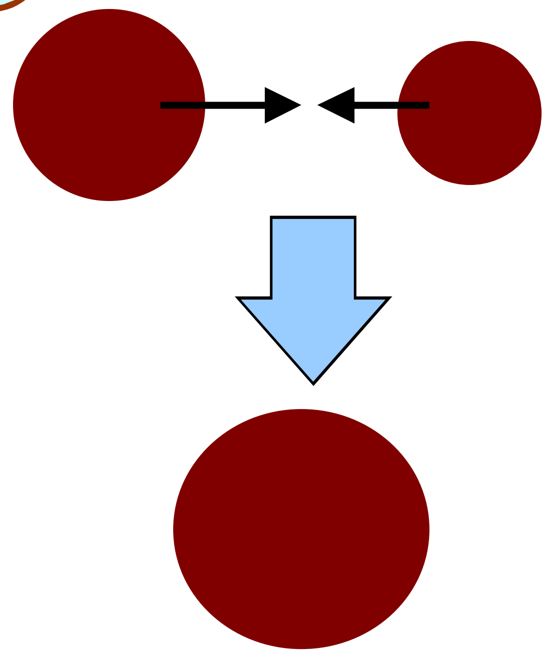
Relative velocities can be excited by interstellar turbulence.

Shattering



Shattering threshold:
2.7 km/s (silicate), 1.2 km/s (graphite)
(Jones et al. 1996)

…gulation



coagulation rate = grain-grain collision rate
Threshold: ~ 10^3 cm/s

Grain Size Distribution and Extinction

Extinction (absorption+scattering)

$$\tau_{\lambda,i} = \int_0^\infty \pi a^2 Q_\lambda(a) N_{\rm dust}(a)\, da$$

$$\tau_\lambda = \sum_i \tau_{\lambda,i}$$

a: grain radius (<~ 0.1 μm)

$Q_\lambda(a)$ ~ 1 for λ <~ a

$Q_\lambda(a)$ << 1 ∝ a for λ >> a

i: grain species (silicate, graphite)

Grain size distribution $N_{\rm dust}(a) \propto a^{-3.5}$

with 0.005 μm < a < 0.25 μm: MRN

What determines the grain size distribution?

- ☐ Source (supernova, AGB stars, etc.)
- ☐ **Shattering and coagulation?**

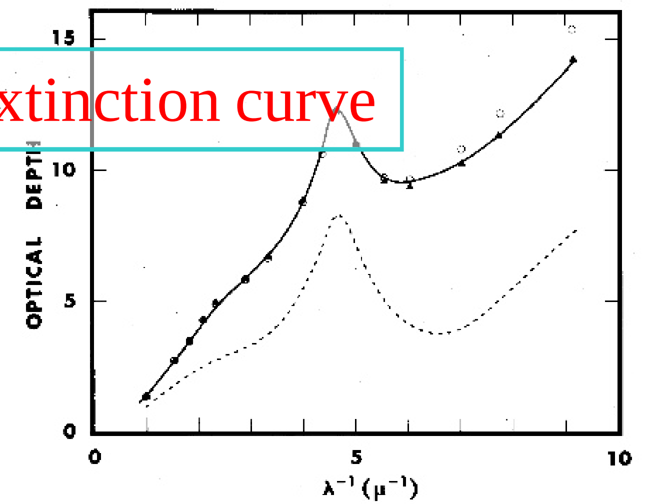


FIG. 4.—Optical depths, for column densities of 10^{22} H atoms cm^{-2}, versus inverse wavelength. *Solid line:* observed by OAO. *Triangles:* the extinction of (C + Ol) mixture of Fig. 2. *Dashed line:* the contribution of graphite to the extinction. *Dots:* a mixture of graphite and olivine, $n(a) \propto a^{-3.5}$, 0.005 μm < a < 0.25 μm, forced to fit at the maximum of the "bump" at 4.6 μm^{-1}.

Mathis, Rumpl, & Nordsieck (1977)

Specific Questions

A) Evolution of grain size distribution by shattering and coagulation under the grain motion induced by turbulence.
B) Do shattering and coagulation have a significant imprint in the extinction curve?

3. Formulation

Hirashita & Yan (2009)

Discrete size bins $a_0, \ldots, a_N$
The i-th bin contains grains of $\tilde{\rho}_i$ [g cm^{-3}].

Shattering

$$\left[\frac{\mathrm{d}\tilde{\rho}_i}{\mathrm{d}t}\right]_{\mathrm{shat}} = -m_i\tilde{\rho}_i\sum_{k=1}^{N}\alpha_{ki}\tilde{\rho}_k + \sum_{j=1}^{N}\sum_{k=1}^{N}\alpha_{kj}\tilde{\rho}_k\tilde{\rho}_j m_{\mathrm{shat}}^{kj}(i),$$

$$\alpha_{ki} = \begin{cases} \dfrac{\sigma_{ki}v_{ki}}{m_i m_k} & \text{if} \quad v_{ki} > v_{\mathrm{shat}}, \\ 0 & \text{otherwise}, \end{cases}$$

distribution of shattered fragments (power-law)

Coagulation

$$\left[\frac{\mathrm{d}\tilde{\rho}_i}{\mathrm{d}t}\right]_{\mathrm{coag}} = -m_i\tilde{\rho}_i\sum_{k=1}^{N}\alpha_{ki}\tilde{\rho}_k + \sum_{j=1}^{N}\sum_{k=1}^{N}\alpha_{kj}\tilde{\rho}_k\tilde{\rho}_j m_{\mathrm{coag}}^{kj}(i),$$

$$\alpha_{ki} = \begin{cases} \dfrac{\sigma_{ki}v_{ki}}{m_i m_k} & \text{if} \quad v_{ki} < v_{\mathrm{coag}}^{ki}, \\ 0 & \text{otherwise}. \end{cases}$$

$m_k + m_j$

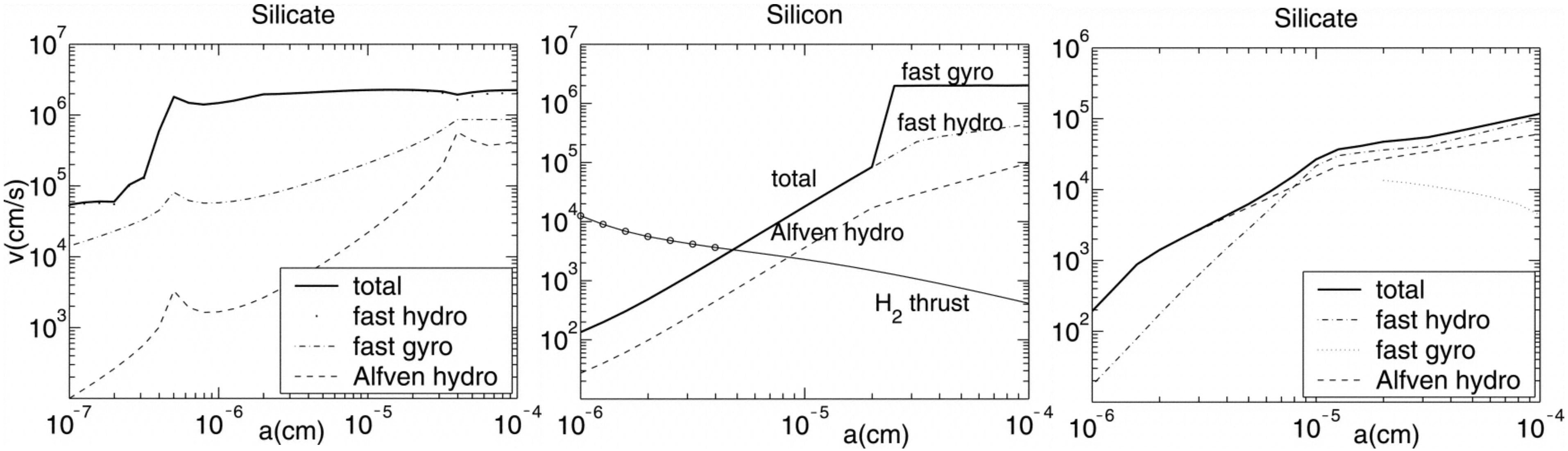
The grain velocities are adopted from Yan et al. (2004) (MHD turbulence).

Grain Velocities

MHD turbulence model

hydro-drag, gyro-resonance

Yan, Lazarian, & Draine (2004)



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Dense cloud

$T = 10$ K

$n_H = 10^4\ \mathrm{cm}^{-3}$

$B = 80\ \mu$G

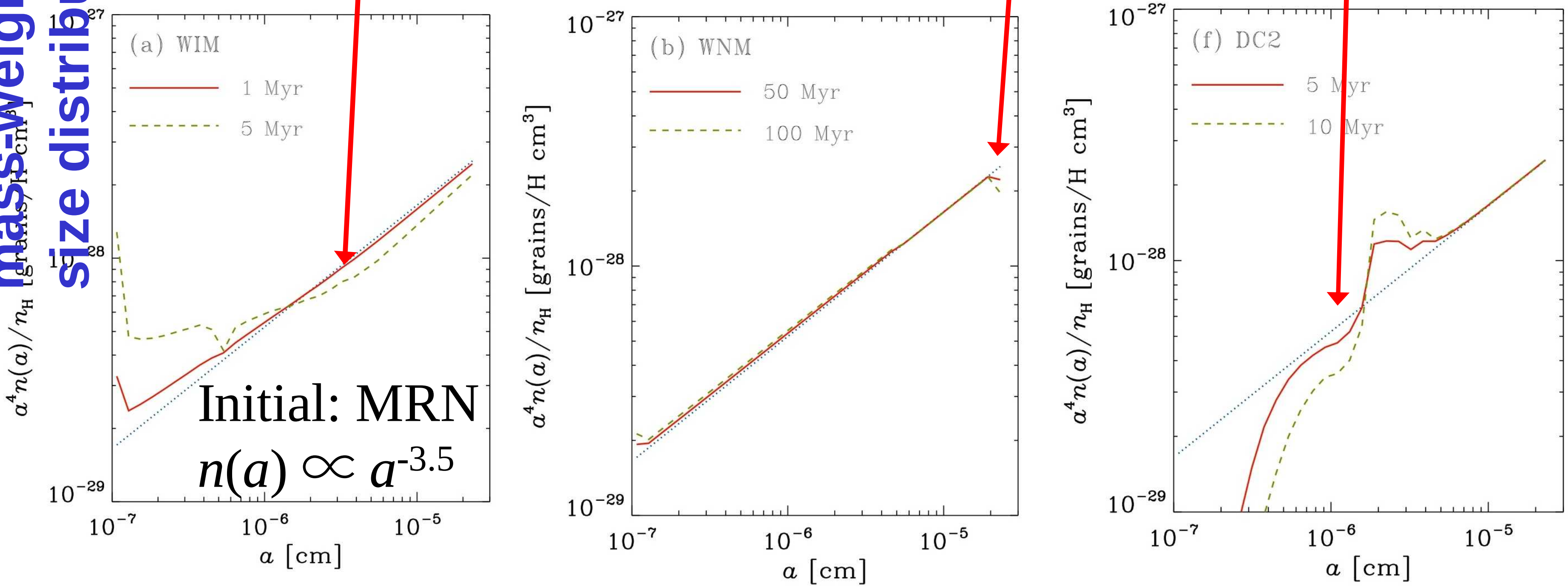
Results

Shattering of large grains on a short timescale

Upper limit?

Small grains are strongly depleted.

mass-weighted size distribution



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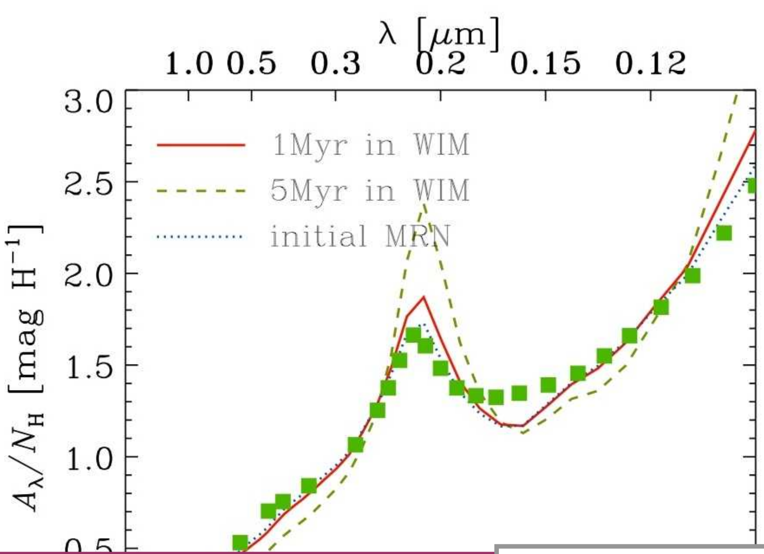
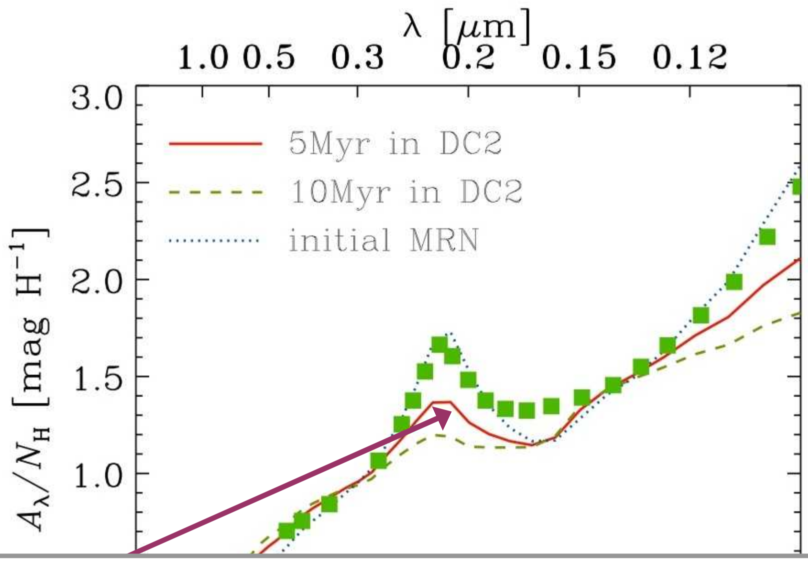
Effects on the Extinction Curves

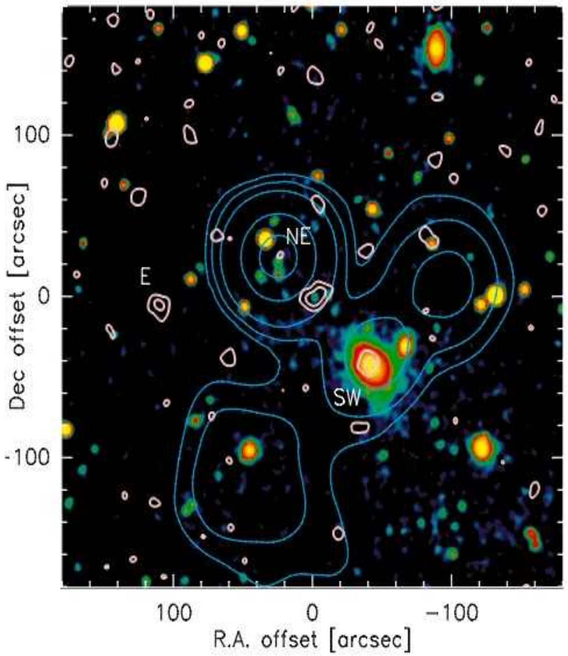


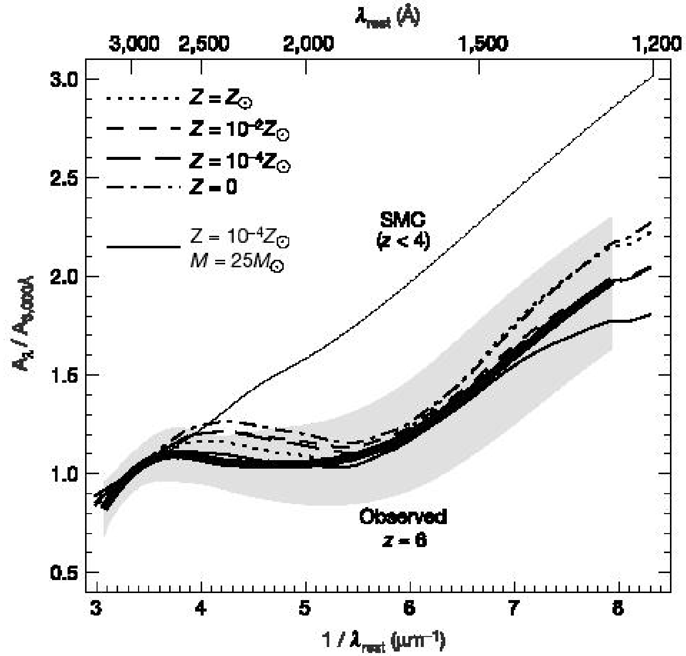


(1) The UV slope ...
the bump stren...
sense.
(2) The central pos...
carbon bump is...
(3) Small variation in IR
extinction curve.

Shattering and Coagulation in ISM can regulate the grain size distribution (and the extinction curve).

Dust in Cosmological Context





Dust already existed at
z ~ 6 (Bertoldi et al. 2003).

Extinction curve at *z* ~ 6
Maiolino et al. (2004)

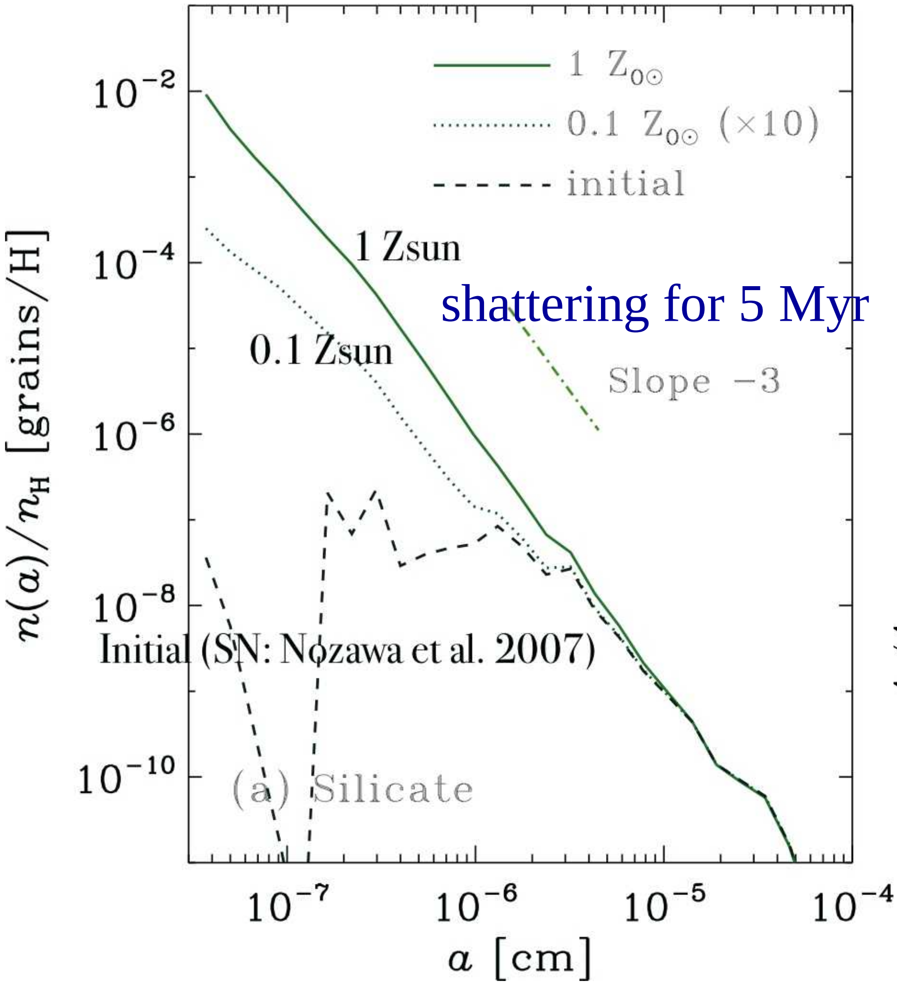
Beginning of Metal (dust) Production

Grasp of "primeval galaxies" in the Universe

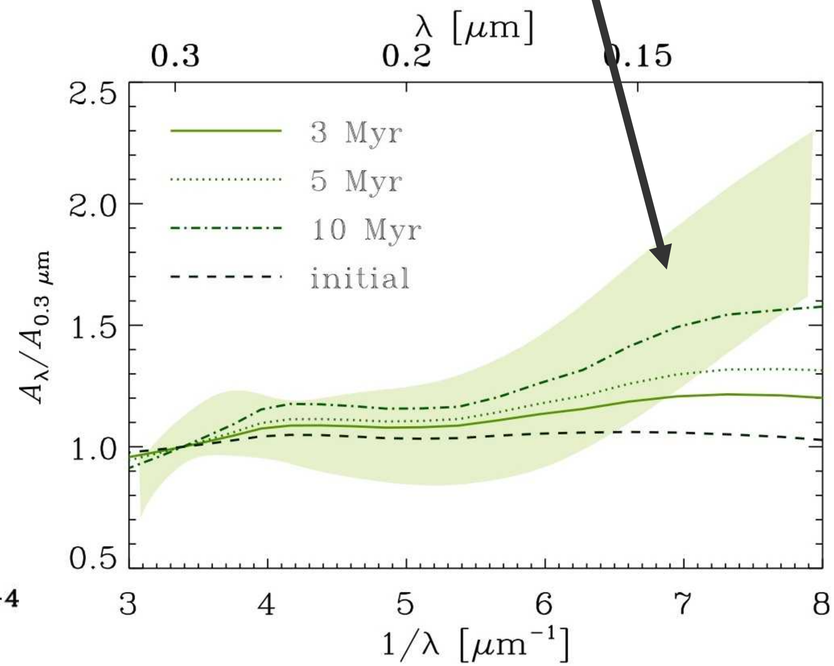
＝ Understanding of the initial metal/dust enrichment

Shattering of SN Dust in WIM

Hirashita et al. (2010)



extinction curve at z = 6.2
(Maiolino et al. 2004)



Small grain production by shattering contributes to the steepness of the UV extinction curve (in solar metallicity).

Scenario

(1) The grain size distribution in the formation by supernovae (or AGB stars) is not processed by turbulence if the metallicity is << 1/10 $Z_{\odot}$.
(2) After the metallicity enrichment, grain processing in ISM should be considered.
(3) In considering the origin of the grain size distribution at the present cosmic age, **interstellar processing by turbulence should be important**.

AKARI Observation of M81

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AKARI Observation of M81

Sun & Hirashita (2010)

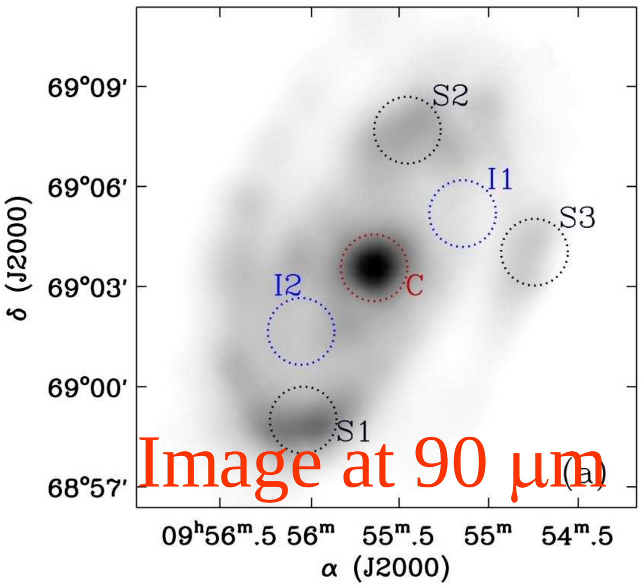
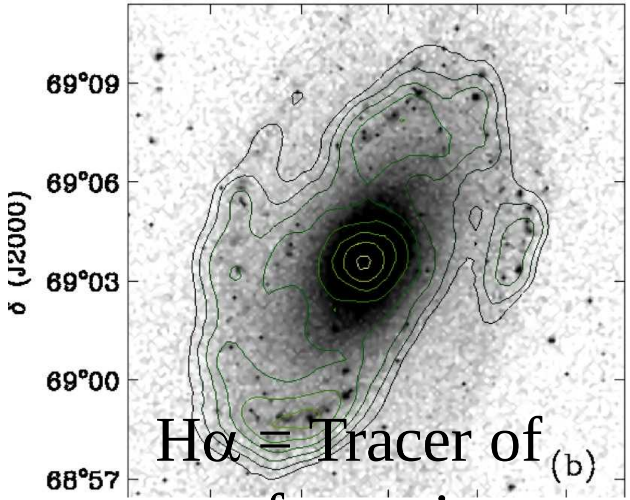
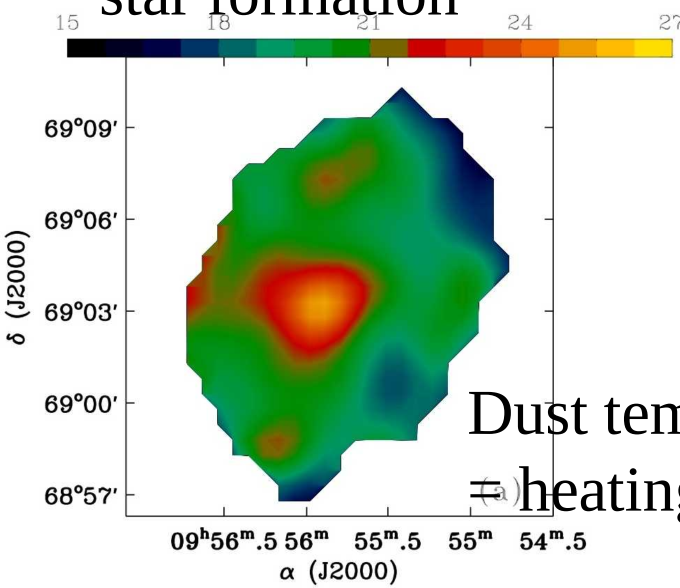


Image at 90 μm



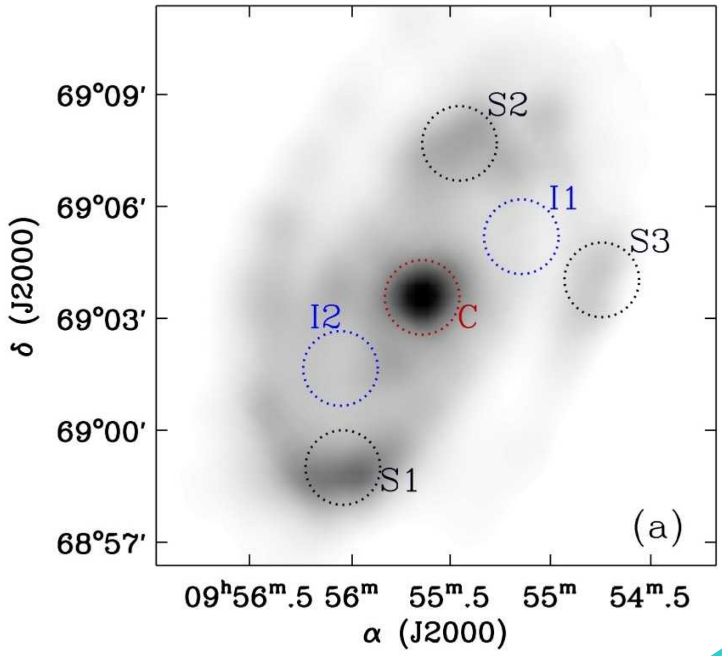
Hα = Tracer of star formation

65 μm
90 μm
140 μm

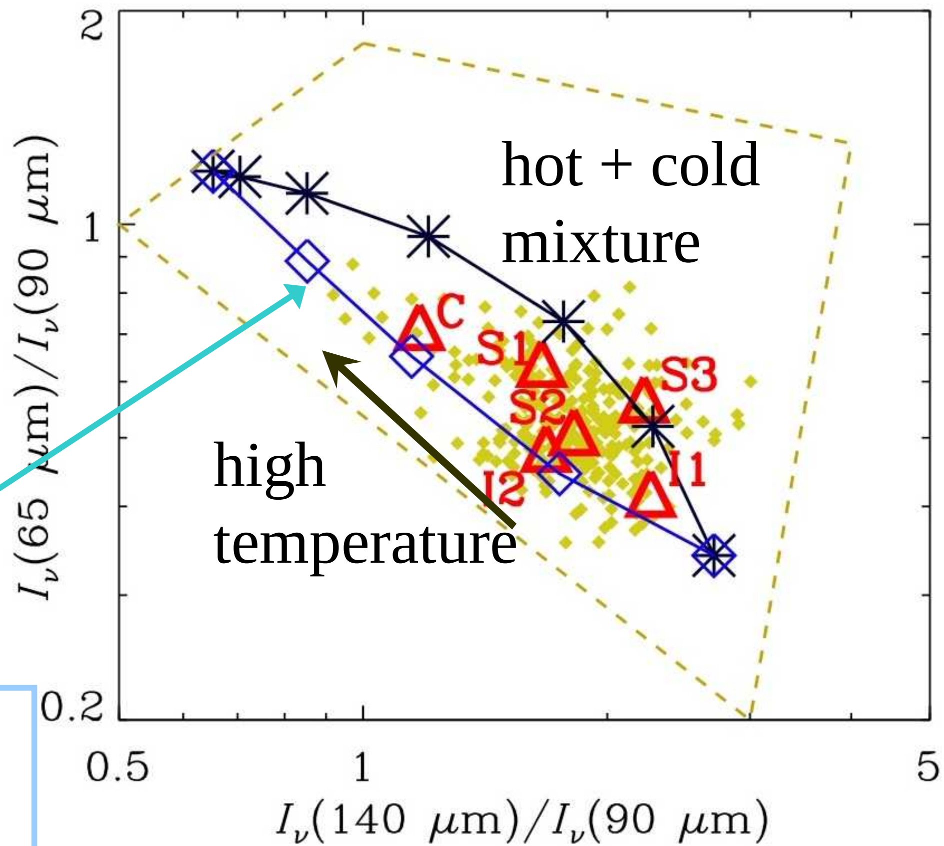


Dust temperature ∝ heating by stars

Theoretical Analysis



Sun & Hirashita (2010)



Theoretical prediction by using Li & Draine (2001)'s framework.

Thank you.

3. Effects of Coagulation on SF

Hirashita & Omukai (2009)

(1) How about the denser regime?

(2) Importance of dust grains in star formation:

A) H_2 formation (H_2 is an efficient coolant for $Z < 0.01$ $Z_\odot$) ⇒ The grain surface S is important.

B) Dust cooling ⇒ The grain opacity κ_P is important.

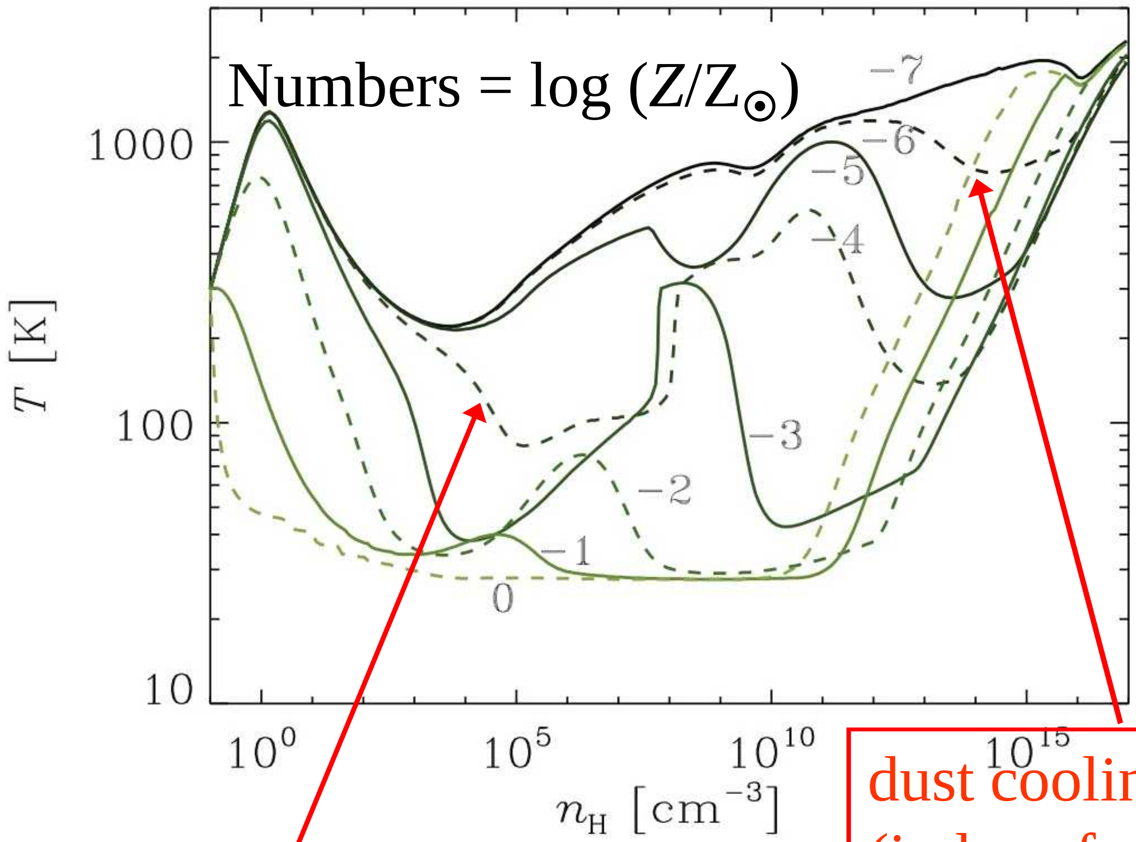
↓

We calculate the variation of S and κ_P in star-forming (collapsing) clouds.

Grain motion is assumed to be thermal.

Gas Evolution in Collapsing Clouds

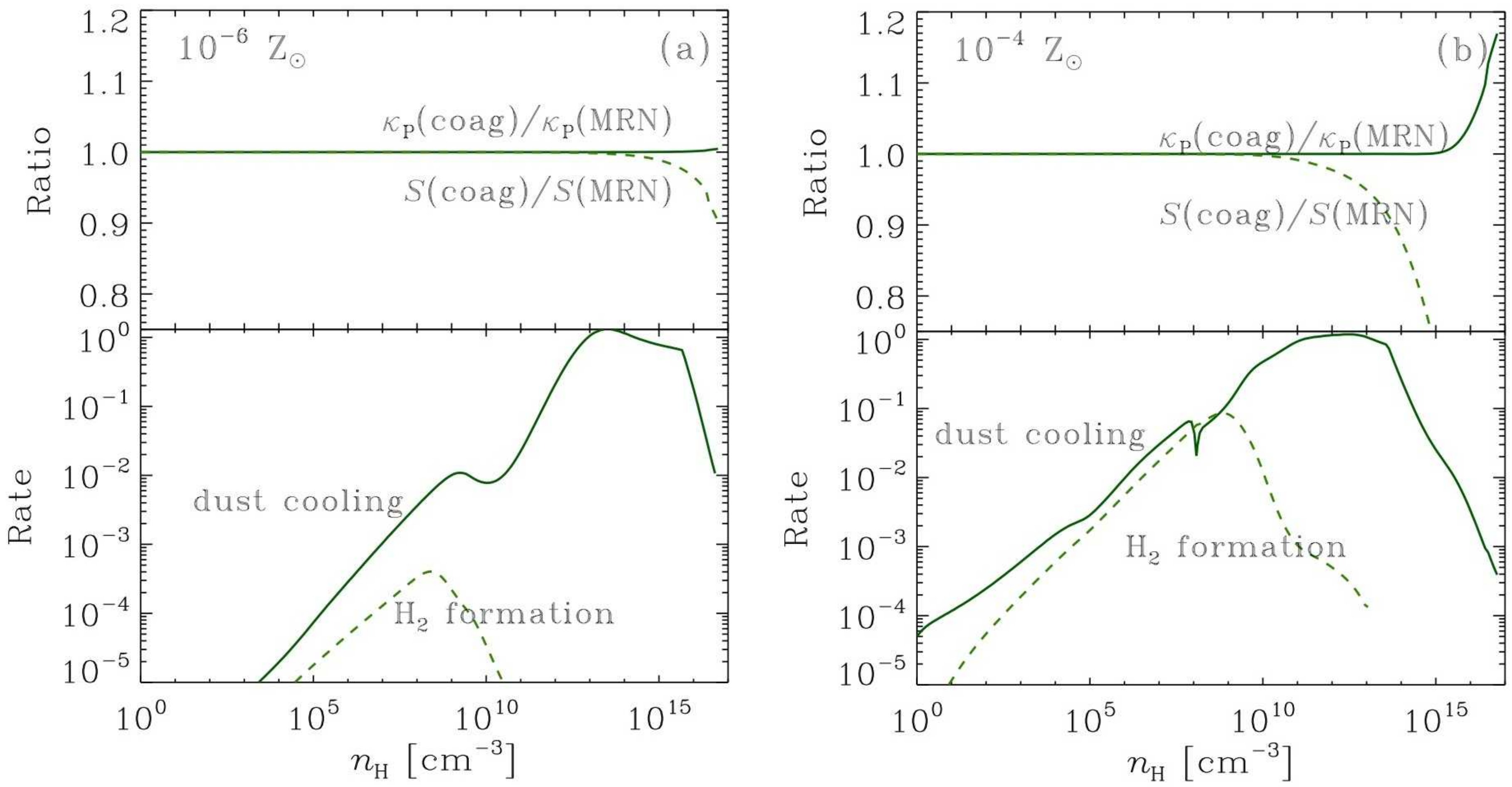
Omukai et al. (2005)



H_2 formation on grain surface: important coolant for log $(Z/Z_\odot) < -2$

dust cooling
(induce fragmentation)
Omukai et al. (2005)
Schneider et al. (2004)

Change of Grain Surface and Opacity by Coagulation



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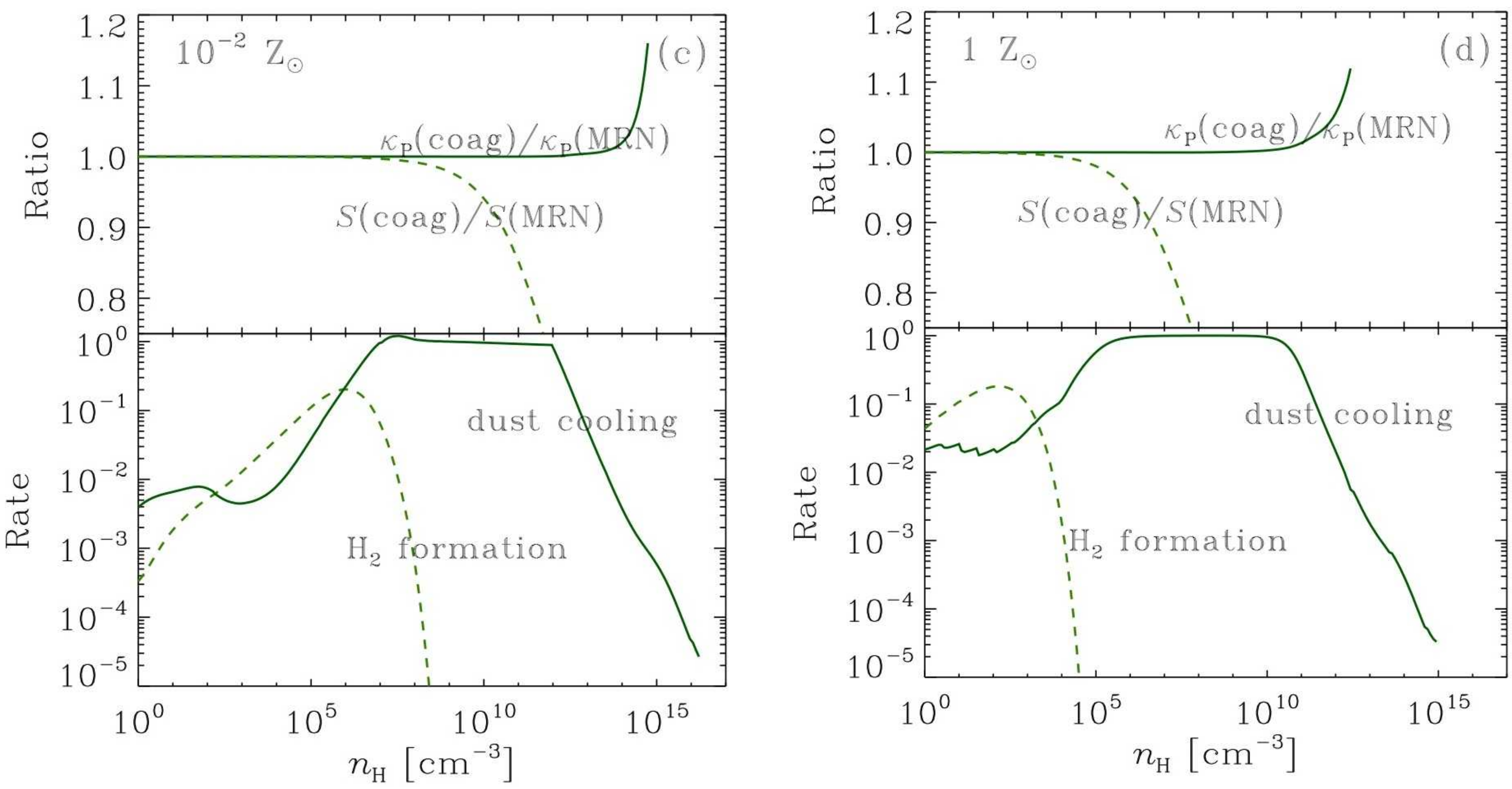


Physical Considerations

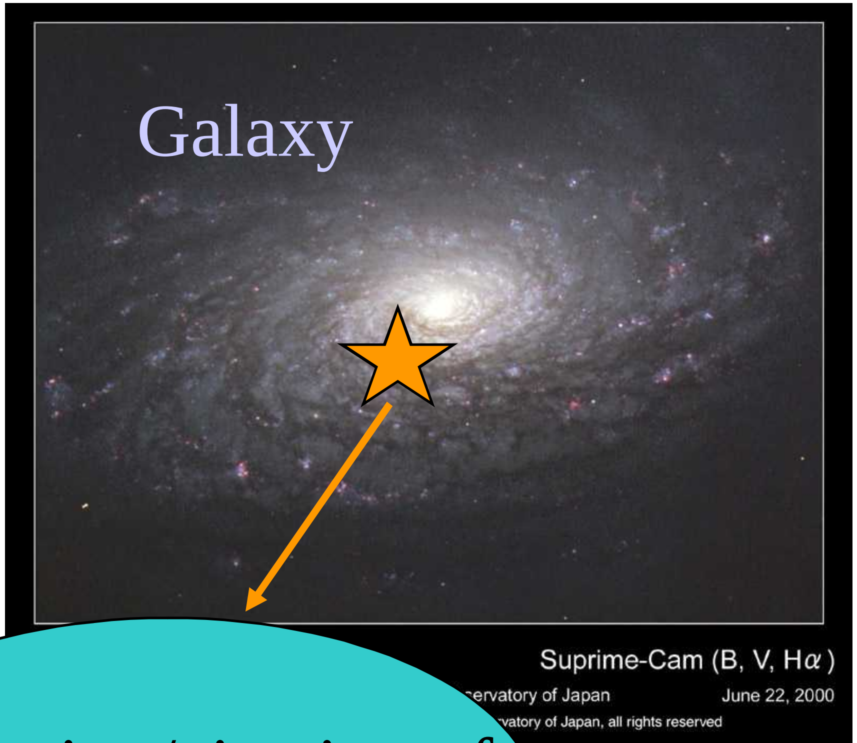
☆ Grain surface is dominated by small grains. → Once the smallest grains are affected by coagulation, S begins to decrease (however, H_2 formation occurs faster).

- $t_{ff} > t_{coag} \Leftrightarrow n_H > 10^7 (Z/Z_\odot)^{-2} (T/30\ K)^{-1}\ cm^{-3}$

☆ Opacity ($\kappa_P \propto \pi a^2 Q_\lambda \propto a^3$) is only a function of mass as long as $a << \lambda$. ⇒ κ_P does not change even if coagulation proceeds.

Coagulation has no effect on the thermal evolution in protostellar collapse.

1. Dust Grains in Galaxies



gas, plasma
(heating by supernovae, stellar radiation, etc.; radiative cooling)

turbulence
magnetic fields

Formation/ejection of heavy elements (≧ C)

Condensation of
dust grains