Massive Stars and Supernovae as Drivers for Dust Evolution

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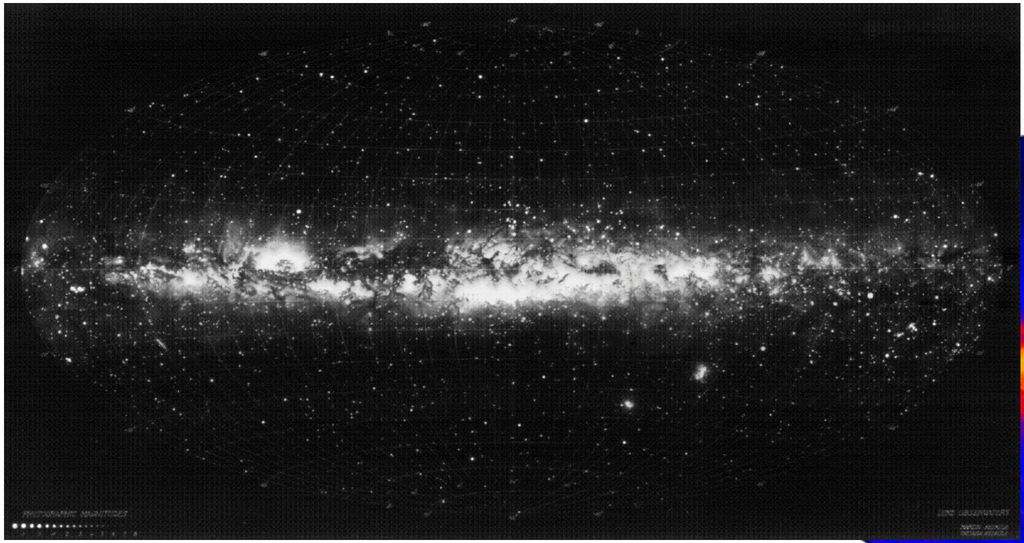
Outline

1. Introduction (for Cosmic Dust)
2. Important Roles of Massive Stars in Dust Evolution
3. Dust Formation in the Early Universe
4. Widely Distributed Dust
5. Summary

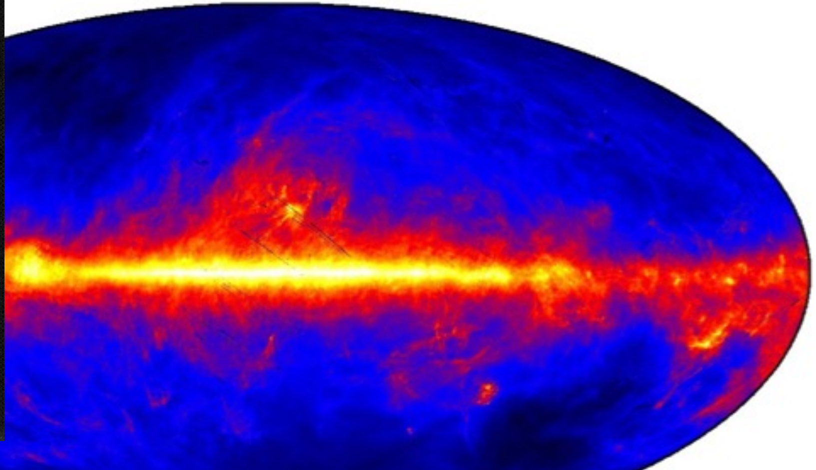
1. Introduction (for Cosmic Dust)

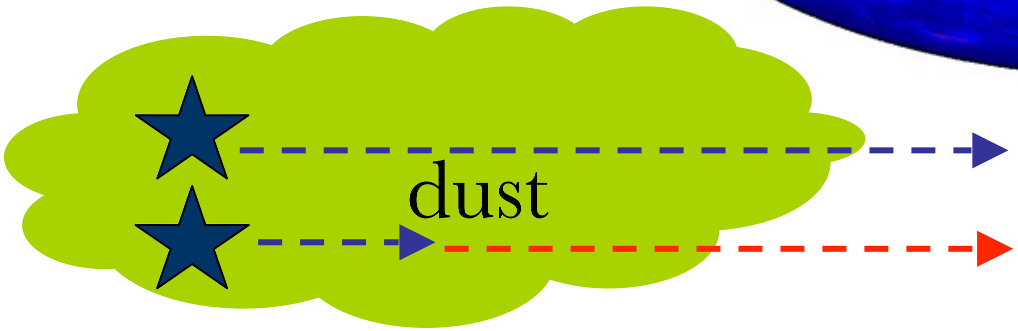
Dust Extinction and Emission

Milky Way in the optical



MW in *AKARI* 140 μm



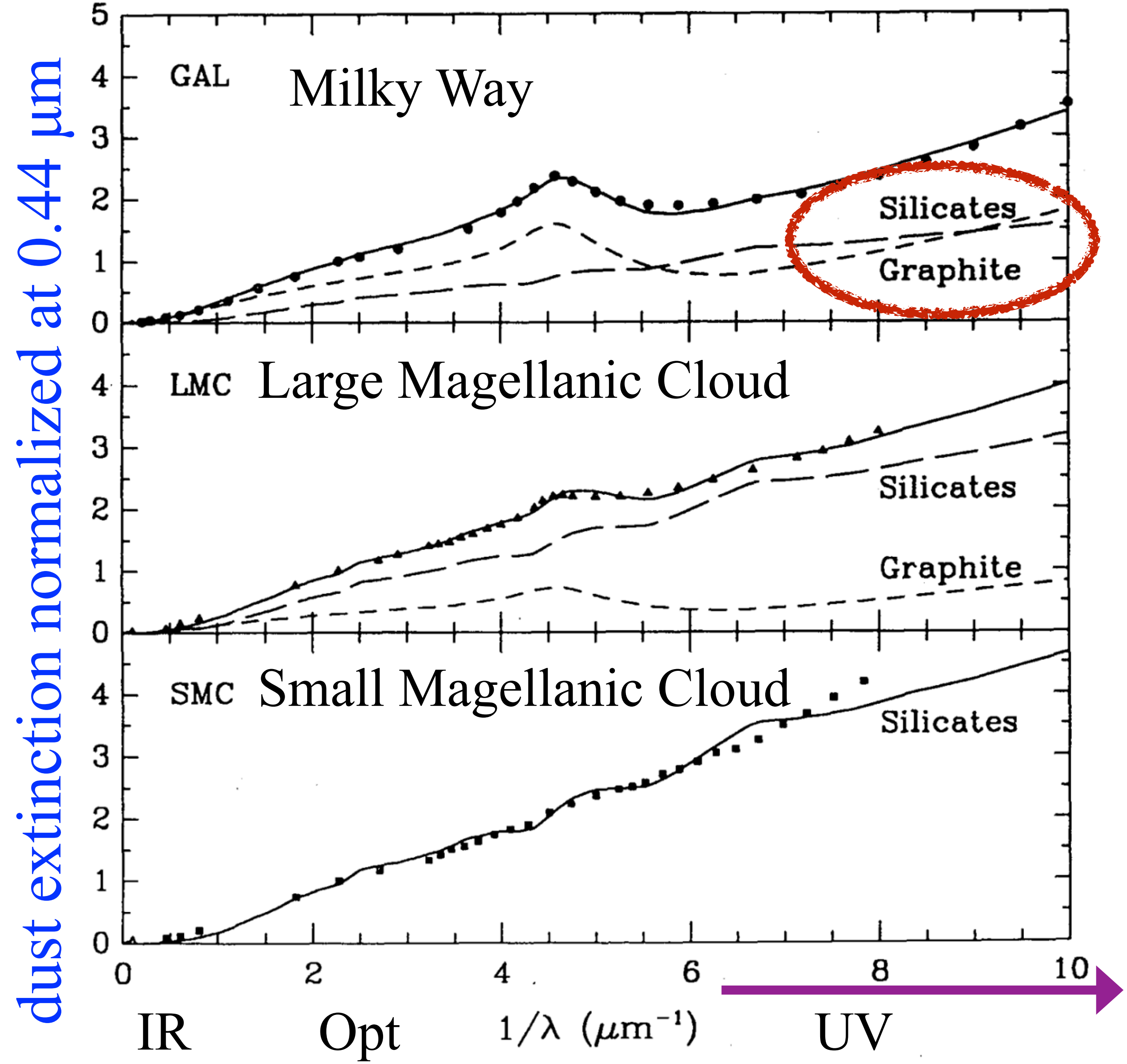


far infrared

Extinction = Absorption + Scattering (lost from the l.o.s)

Dust dominates the radiative processes in the optical/FIR.

What Is Dust?



Pei (1992)

Grain size distribution

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

$a_{\min} = 0.005\ \mu\text{m}$

$a_{\max} = 0.25\ \mu\text{m}$

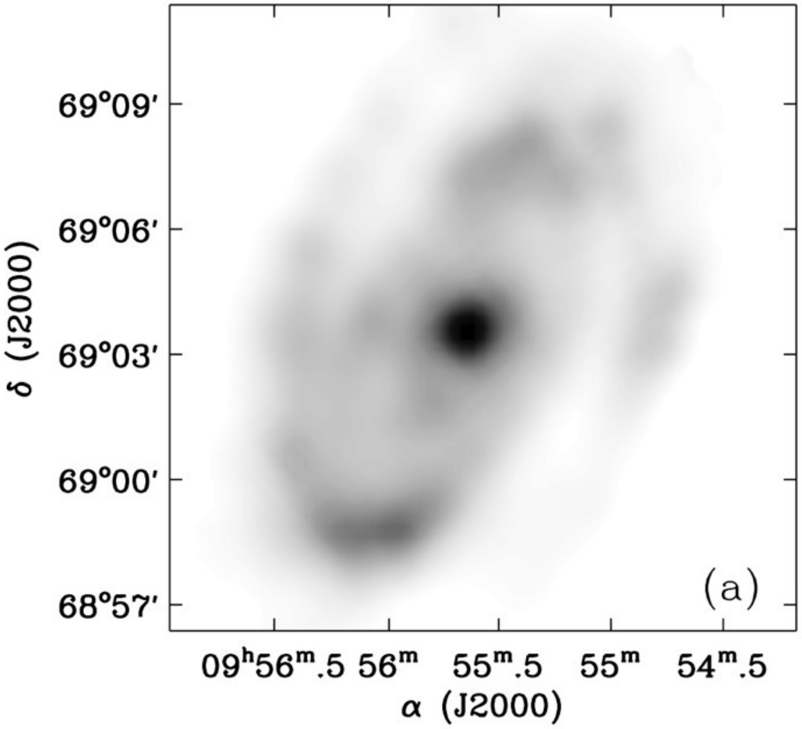
Dust causes reddening.

shorter wavelength

Dust in Nearby Universe

Optical: **stars**

FIR: **dust**

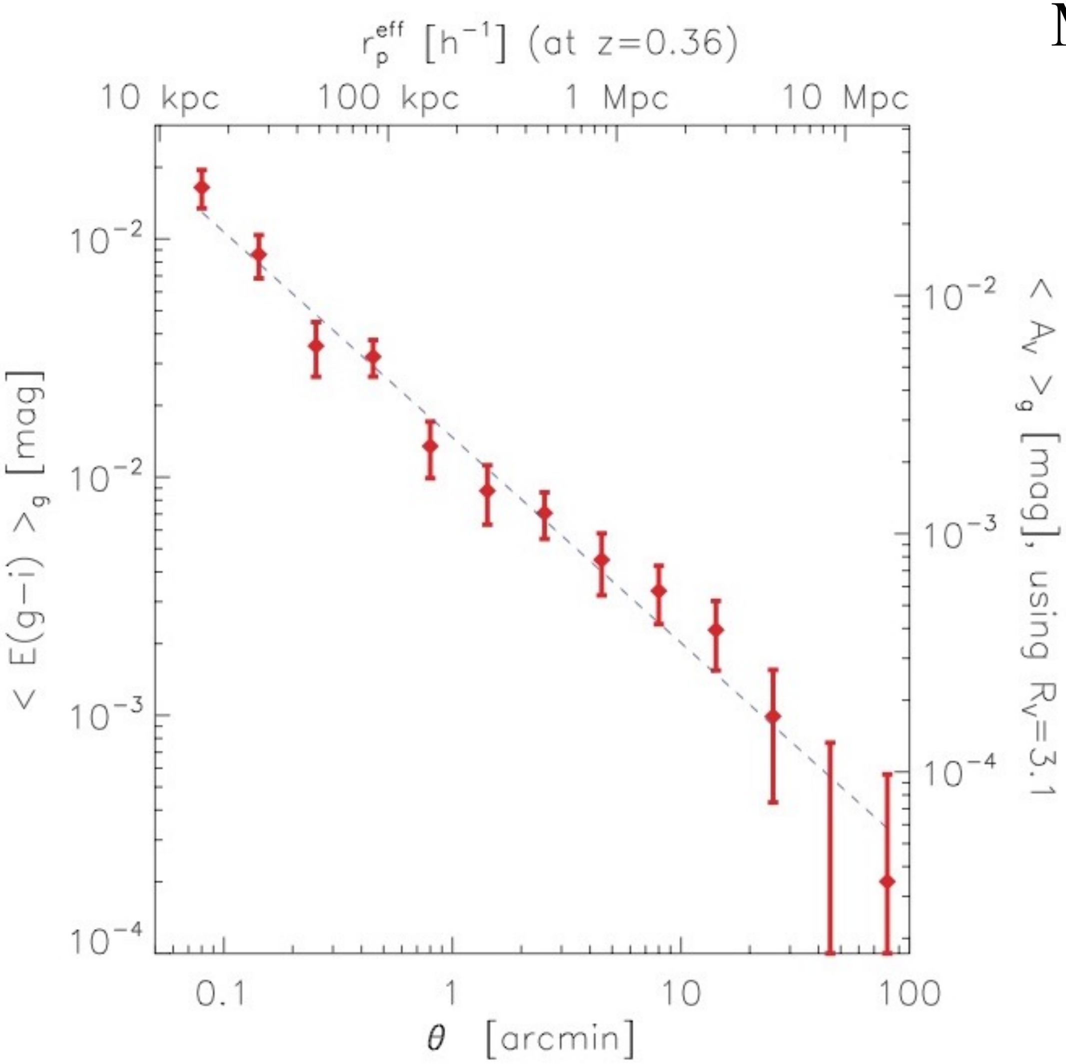


M81
Sun & Hirashita (2011)

Dust in Wide Areas

Ménard et al. (2010)

Reddening (indicator of dust)

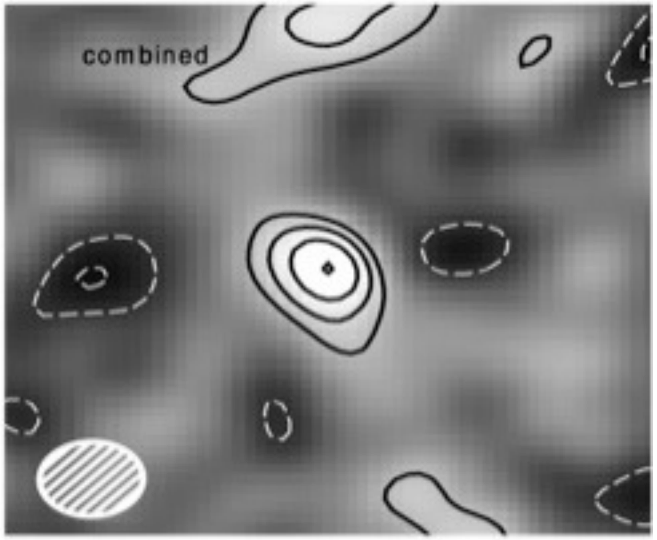


Distance from the galaxy center

Measured the correlation between galaxies and reddening of background quasars.

Dust in Distant Universe by ALMA

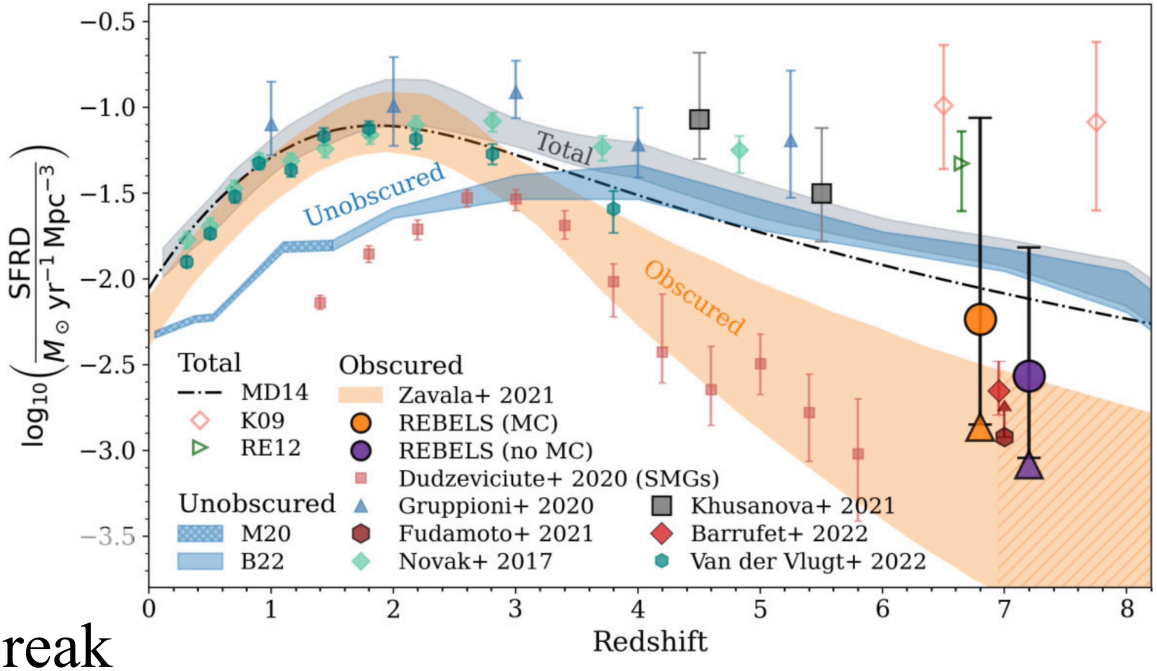
Direct detections



Watson et al. (2015)
at $z = 7.5$ (lensed Lyman break galaxies; Knudsen et al. 2017)
See also Laporte et al. (2017);
Tamura et al. (2019);
Hashimoto et al. (2019);
Schouws et al. (2021), …

Statistical studies

Dust obscured star formation

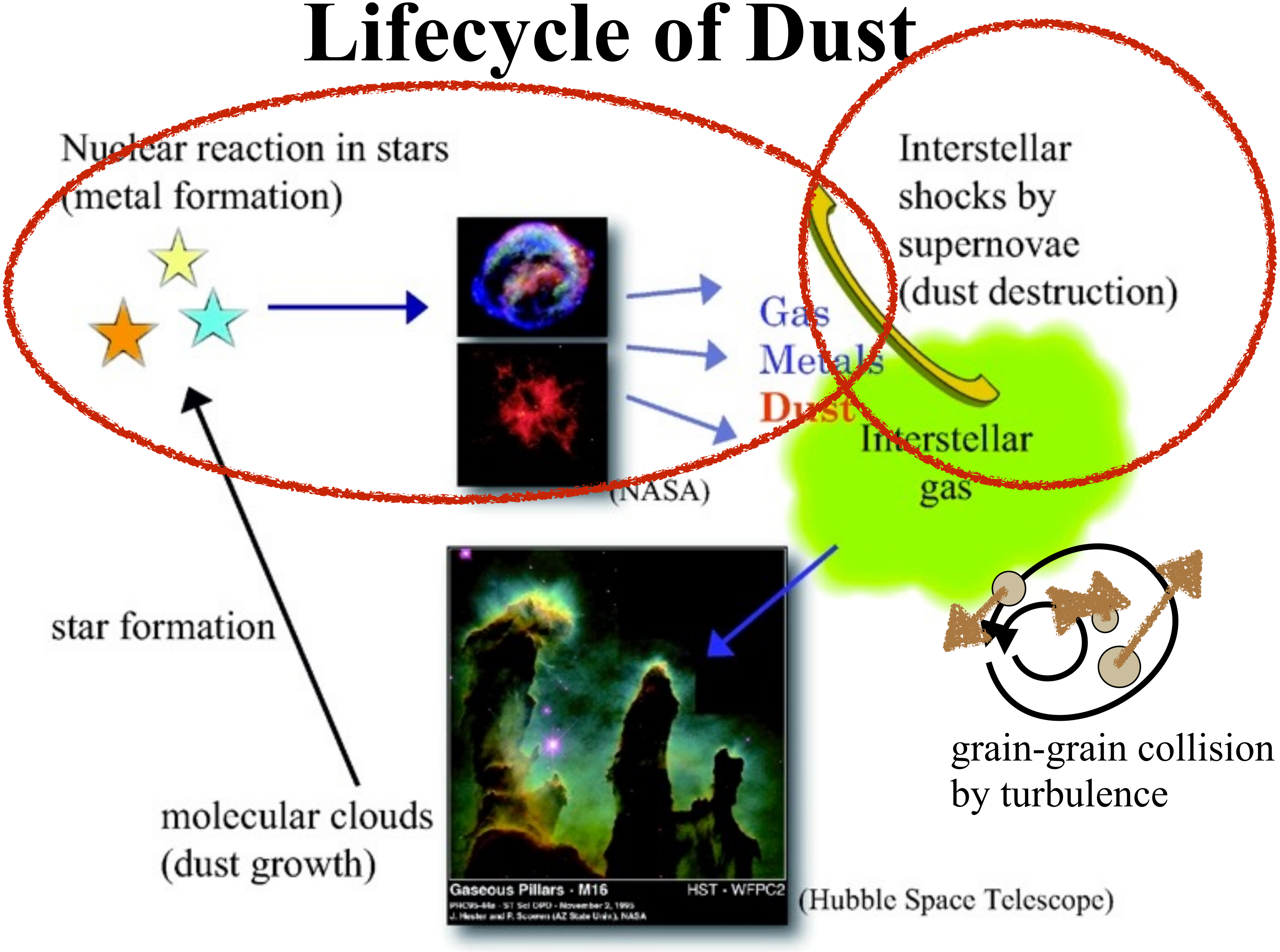


Algera et al. (2023)

(Some) galaxies are enriched with dust by at least $z \sim 7$.

What Is the Origin of Dust?

Lifecycle of Dust



Nuclear reaction in stars (metal formation)

Interstellar shocks by supernovae (dust destruction)

Gas
Metals
Dust

(NASA)

Interstellar gas

star formation

grain-grain collision by turbulence

molecular clouds (dust growth)

(Hubble Space Telescope)

2. Important Roles of Massive Stars in Dust Evolution (Review)

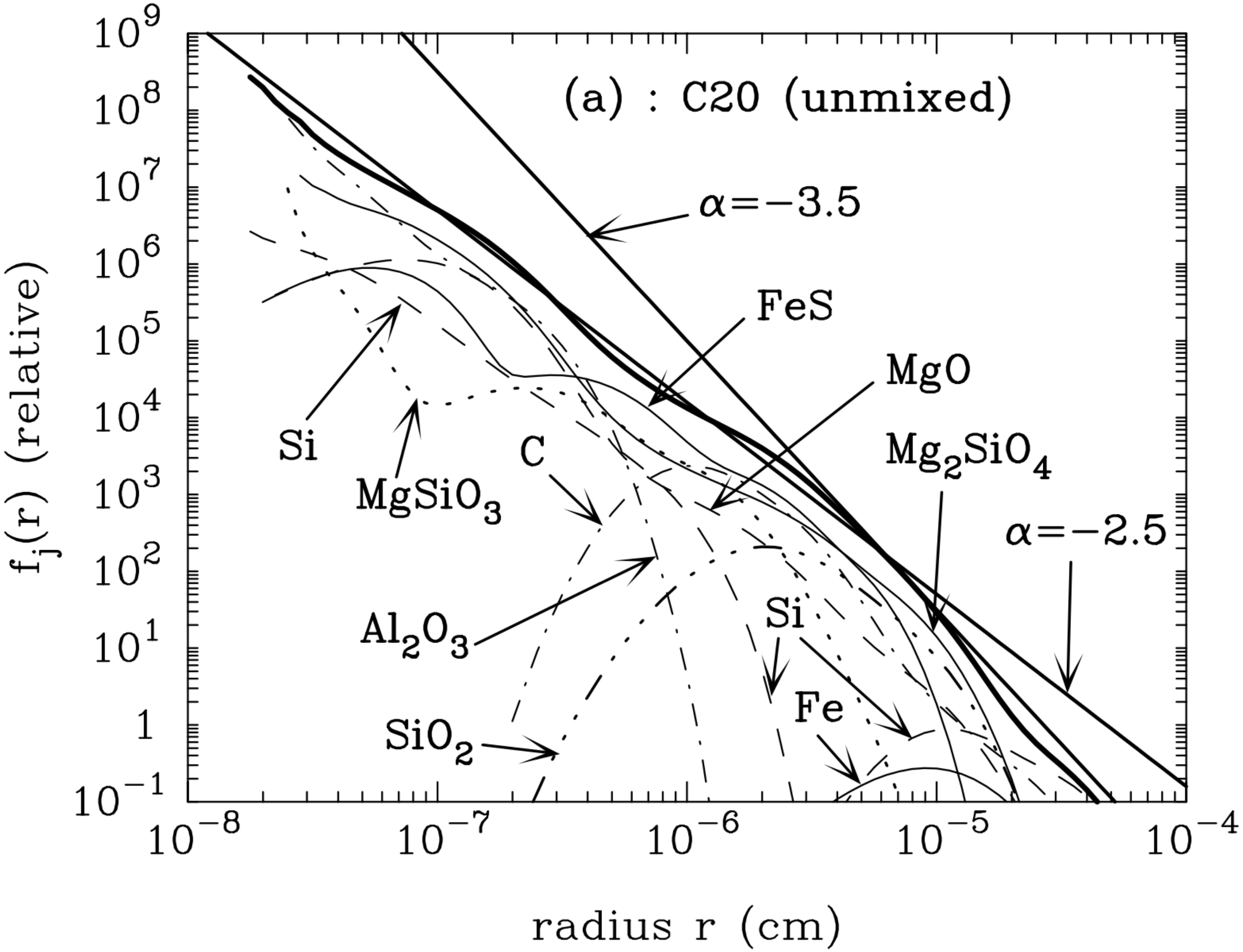
Dust Formation by Stars

Occurs at the end of stellar evolution
(AGB stars and supernovae)
only focus on **core-collapse SNe**

Dust Formation in Supernovae

Dust condensation calculations (Nozawa et al. 2003)

Grain size distribution of condensed dust



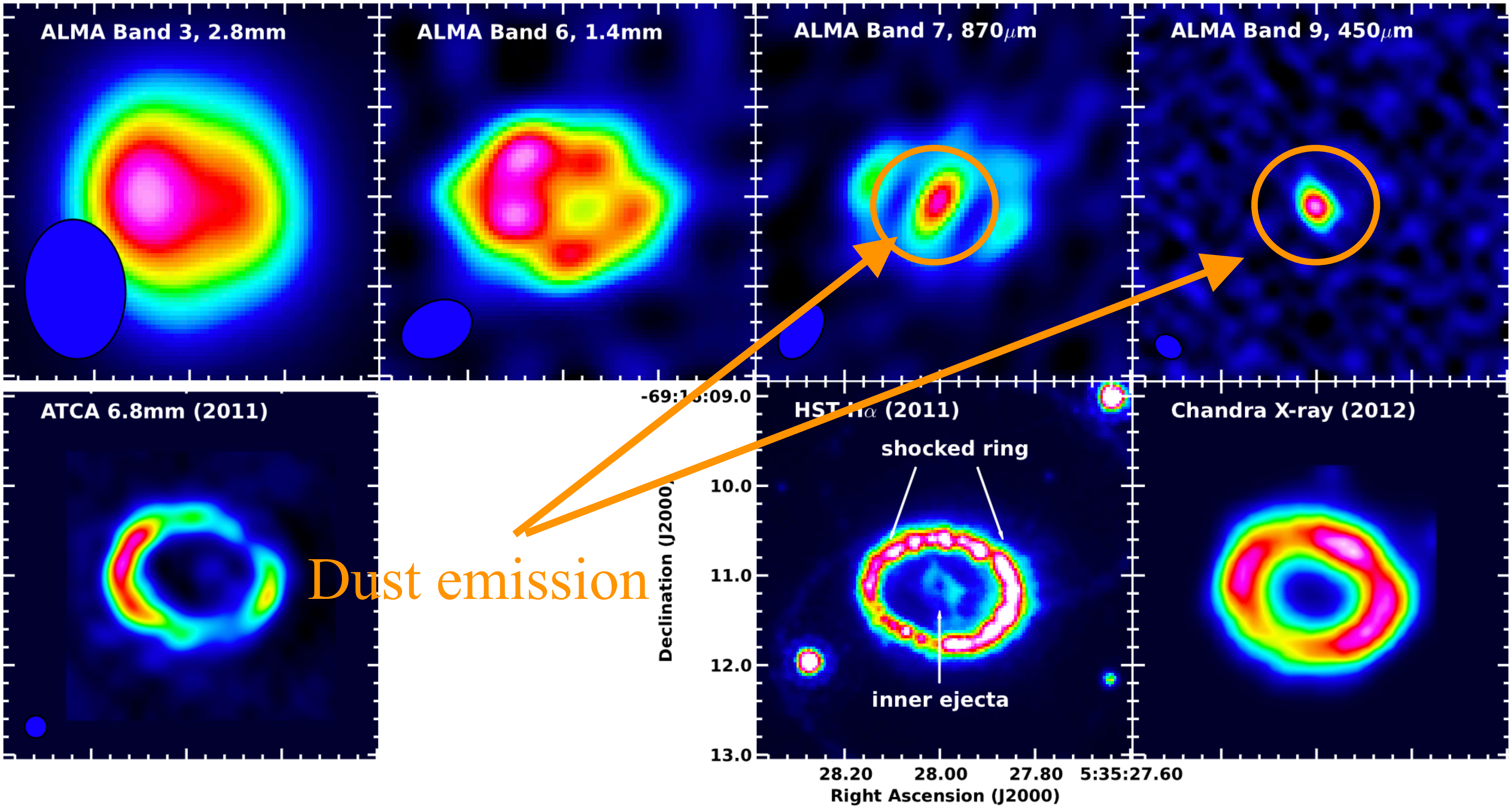
Dust mass/SN

~ 0.1 – 1 Msun

see also Kozasa et al. (1989); Todini & Ferrara (2001); …

Observational Evidence

Indebetouw et al. (2014); see also Matsuura et al. (2011)

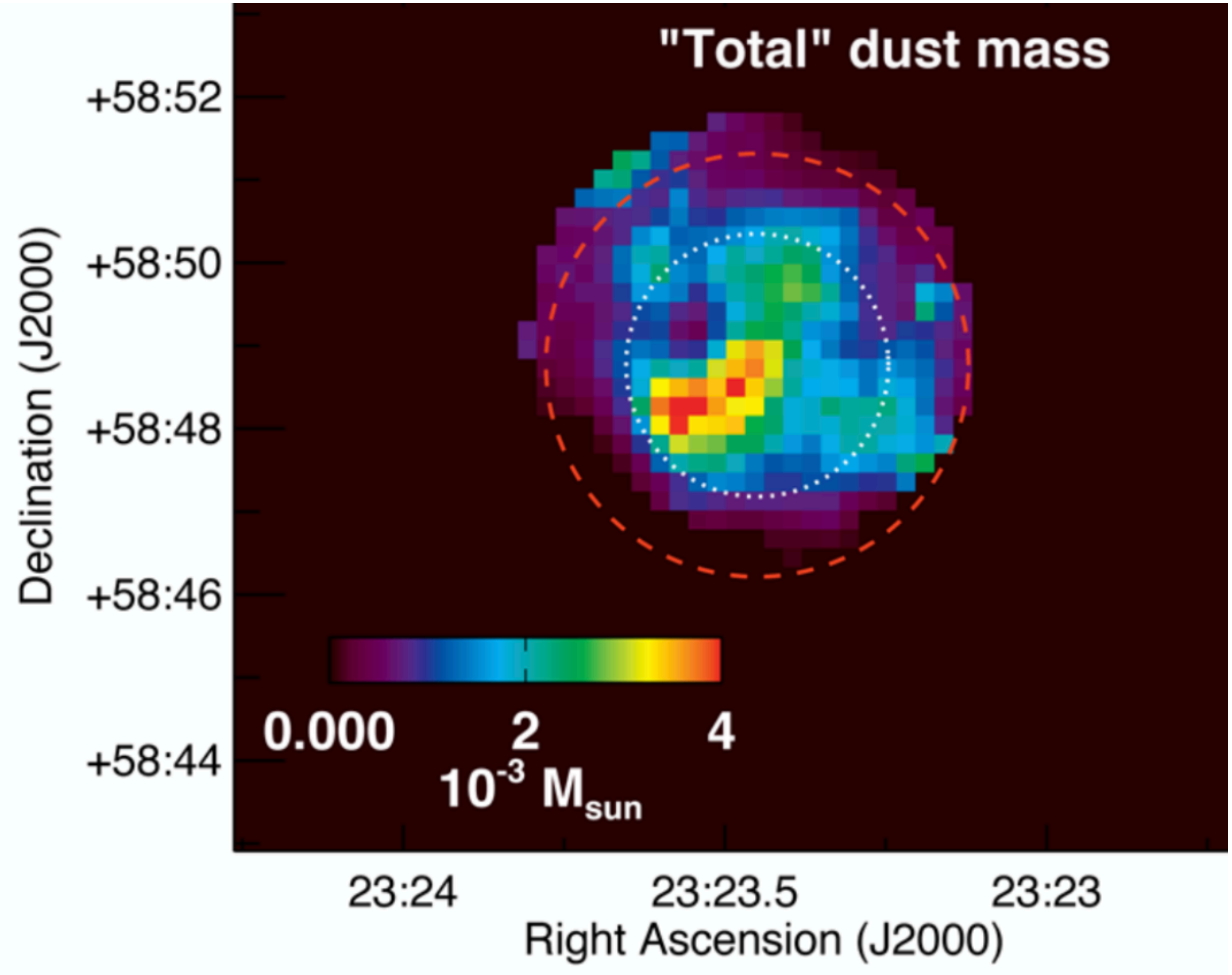


Dust emission

Dust formation in SN1987A with dust mass $\sim 0.2\ M_\odot$

Observational Evidence

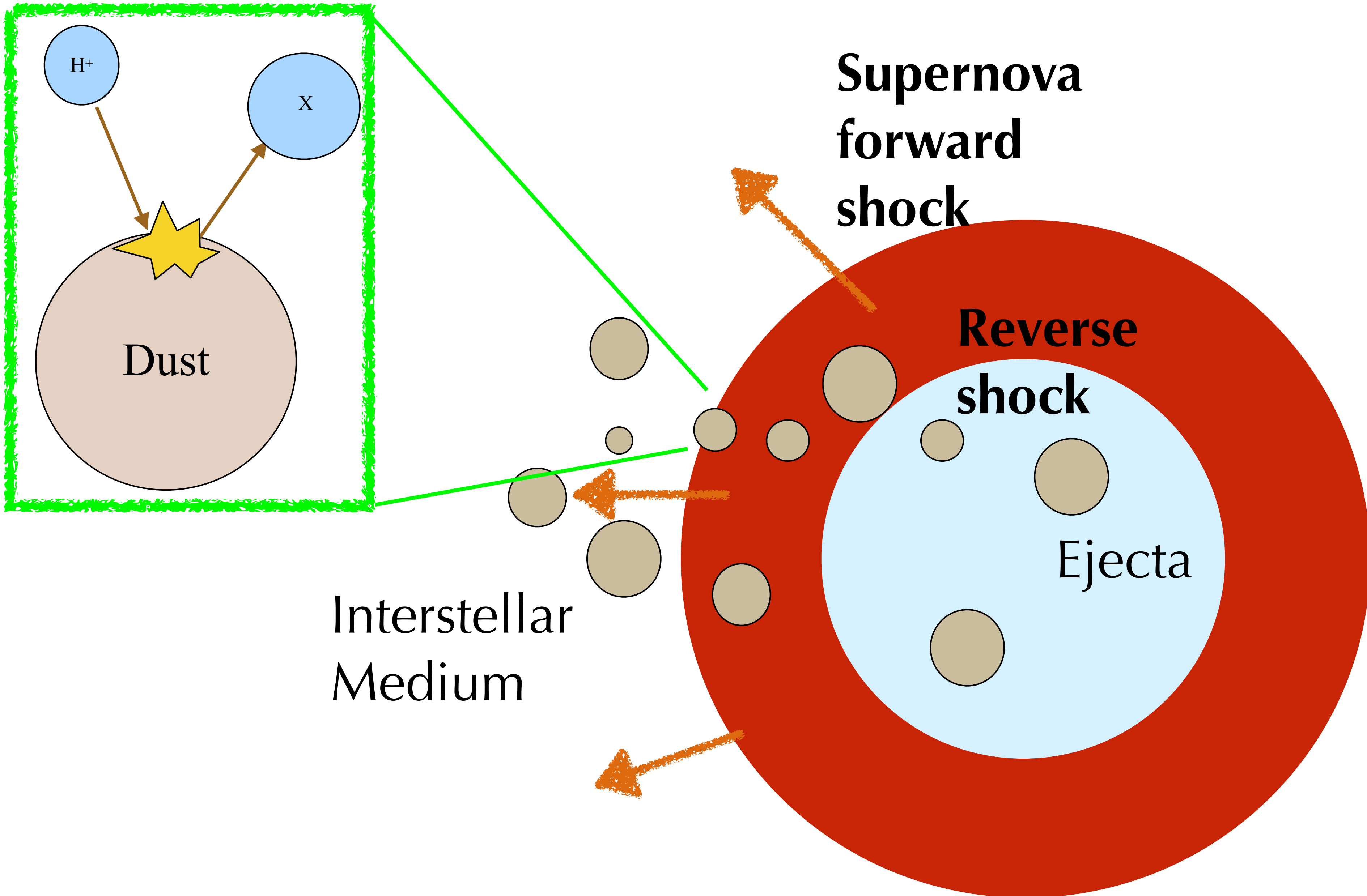
De Looze et al. (2017); see also Barlow et al. (2010); Arendt et al. (2014); Niculescu-Duvaz et al. (2021); Rho et al. (2023); …
Gall & Hjorth (2018) for compiled data.



Cas A ~ 0.5 $M_\odot$

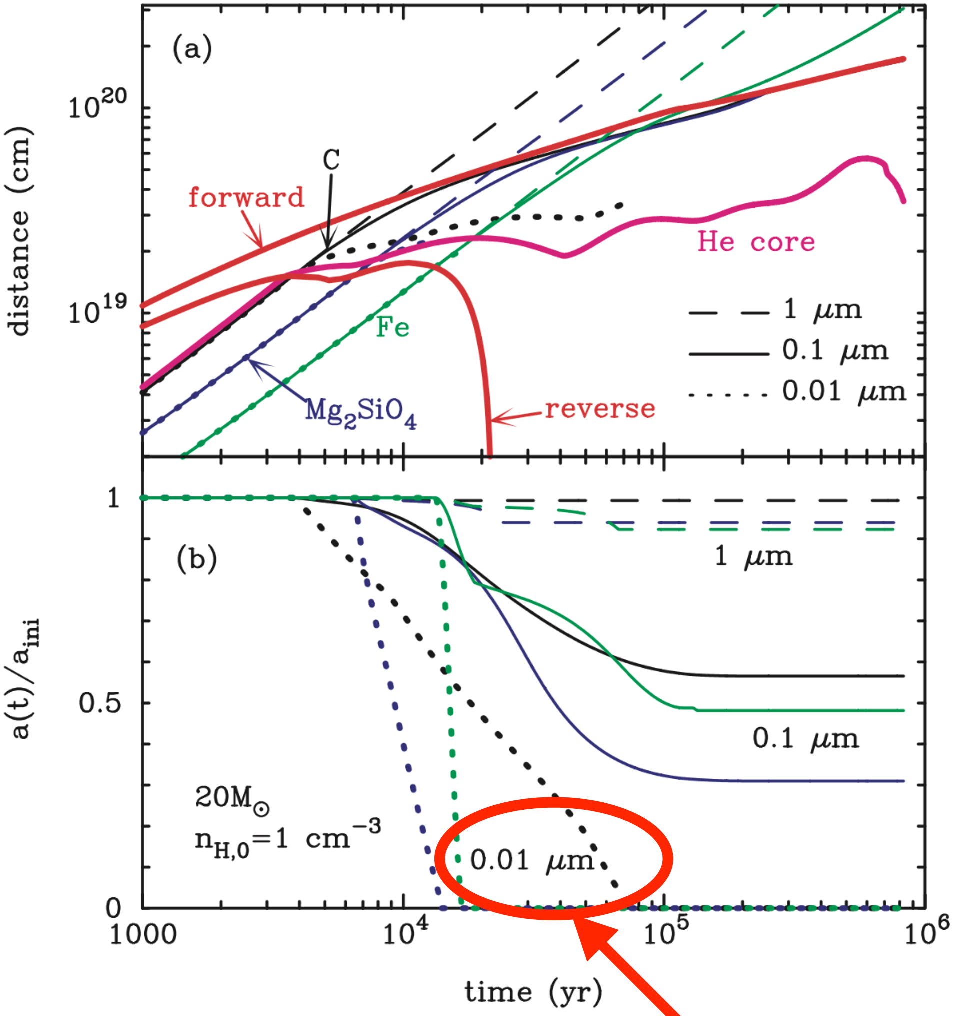
Not all the formed dust is ejected into the interstellar medium.

(Thermal) Sputtering (in SN shocks)

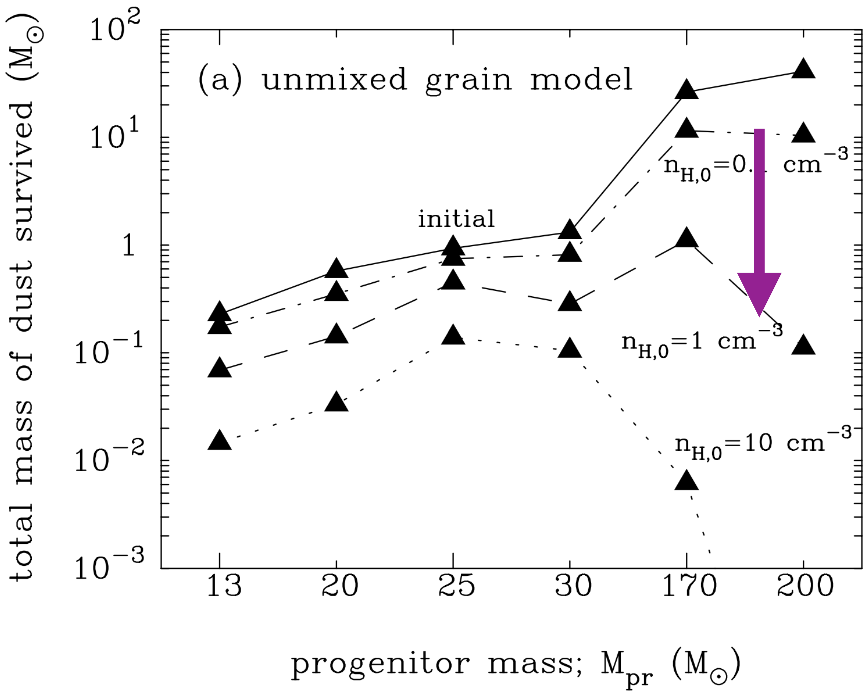


Reverse Shock Destruction

(Nozawa et al. 2007; Bianchi & Schneider 2007; Micelotta et al. 2018 for a review)

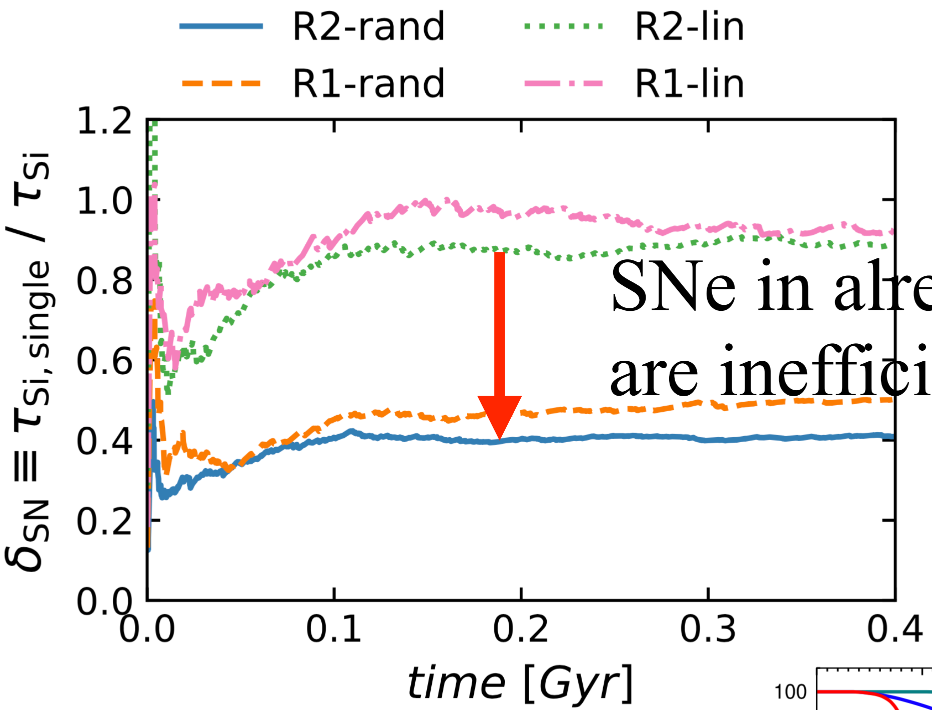


Efficiently trapped in the shocked region



Destruction depending on the ambient gas density

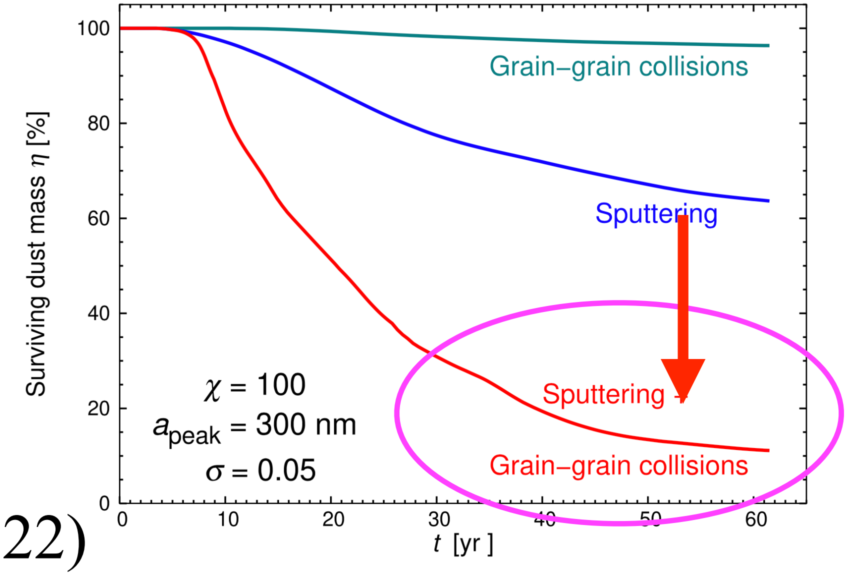
Complexity in SN destruction



Hu et al. (2019)

SNe in already diffused/swept regions are inefficient in destroying dust.

Shattering (grain disruption/ fragmentation) included



Kirchschlager et al. (2022)

Destruction of Pre-existing Dust

Dust destruction timescale in the entire ISM

~ M_{ISM} / [SNR × ε(Mass Swept by a SN)]

~ M_{ISM} / [SFR(SNR/SFR) × 0.1 (10^4 $M_\odot$)]

~ 5 × 10^9 $M_\odot$/ [3 $M_\odot$/yr (0.01/$M_\odot$) × 10^3 $M_\odot$]

~ 2 × 10^8 yr (McKee 1989; Jones et al. 1996; Nozawa et al. 2006; etc.)

SNR: supernova rate

SFR: star formation rate

Dust Budget

Dust supply timescale ~ Metal supply timescale

$\sim Z M_{\mathrm{gas}} / [Y \times (1 - R) \times \mathrm{SFR}]$

$\sim 0.02 \;\; 5 \times 10^9 \, \mathrm{M}_\odot / (0.01 \times 0.7 \times 3 \, \mathrm{M}_\odot/\mathrm{yr})$

~ 5 Gyr >> dust destruction timescale

(Z: metallicity, Y: yield, R: returned fraction of gas)

too slow to compensate the dust mass destroyed by SNe

There should be an extra grain production/growth mechanism (Dwek 1998; Hirashita 1999; Zhukovska et al. 2008; Draine 2009; Michalowski et al. 2011; Mattsson 2011; Valiante et al. 2011; Kuo & Hirashita 2012; …).

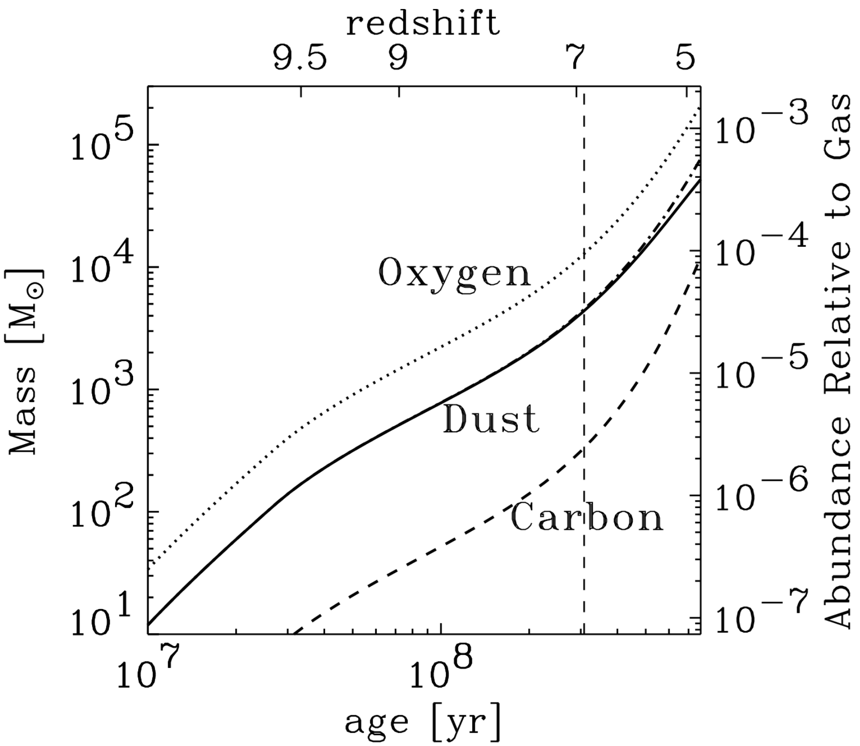
But we should be careful about the uncertainties

(Jones & Nuth 2011; Slavin et al. 2015).

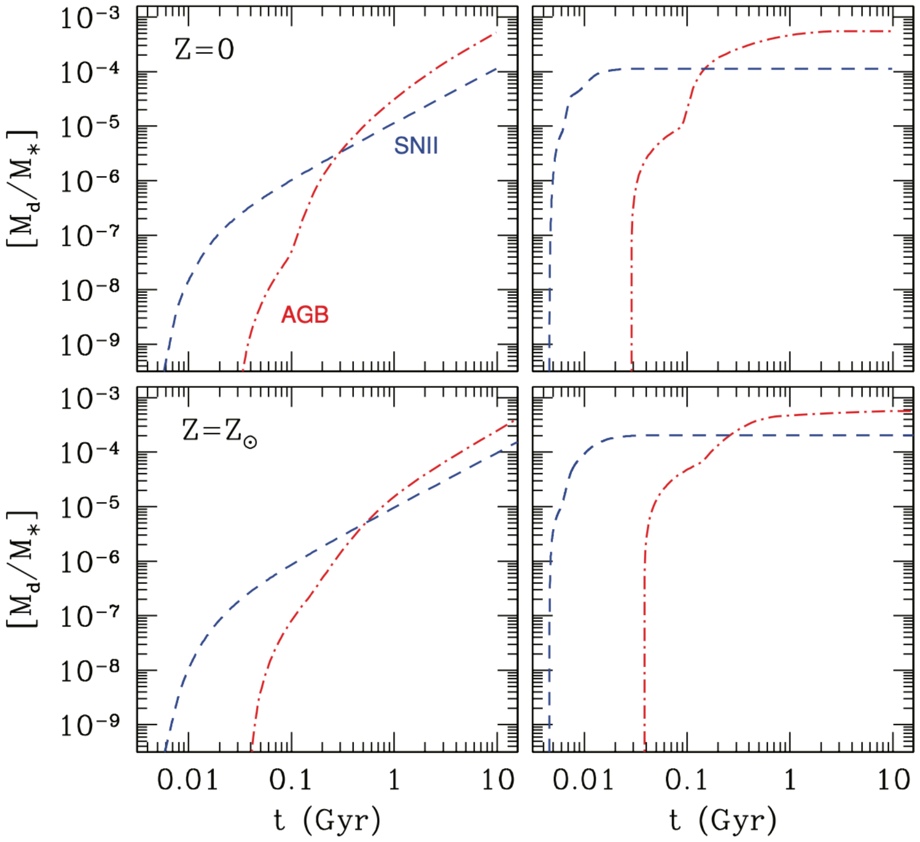
3. Dust Formation in the Early Universe

Massive Stars as the First Dust Sources

Hirashita & Ferrara (2002)



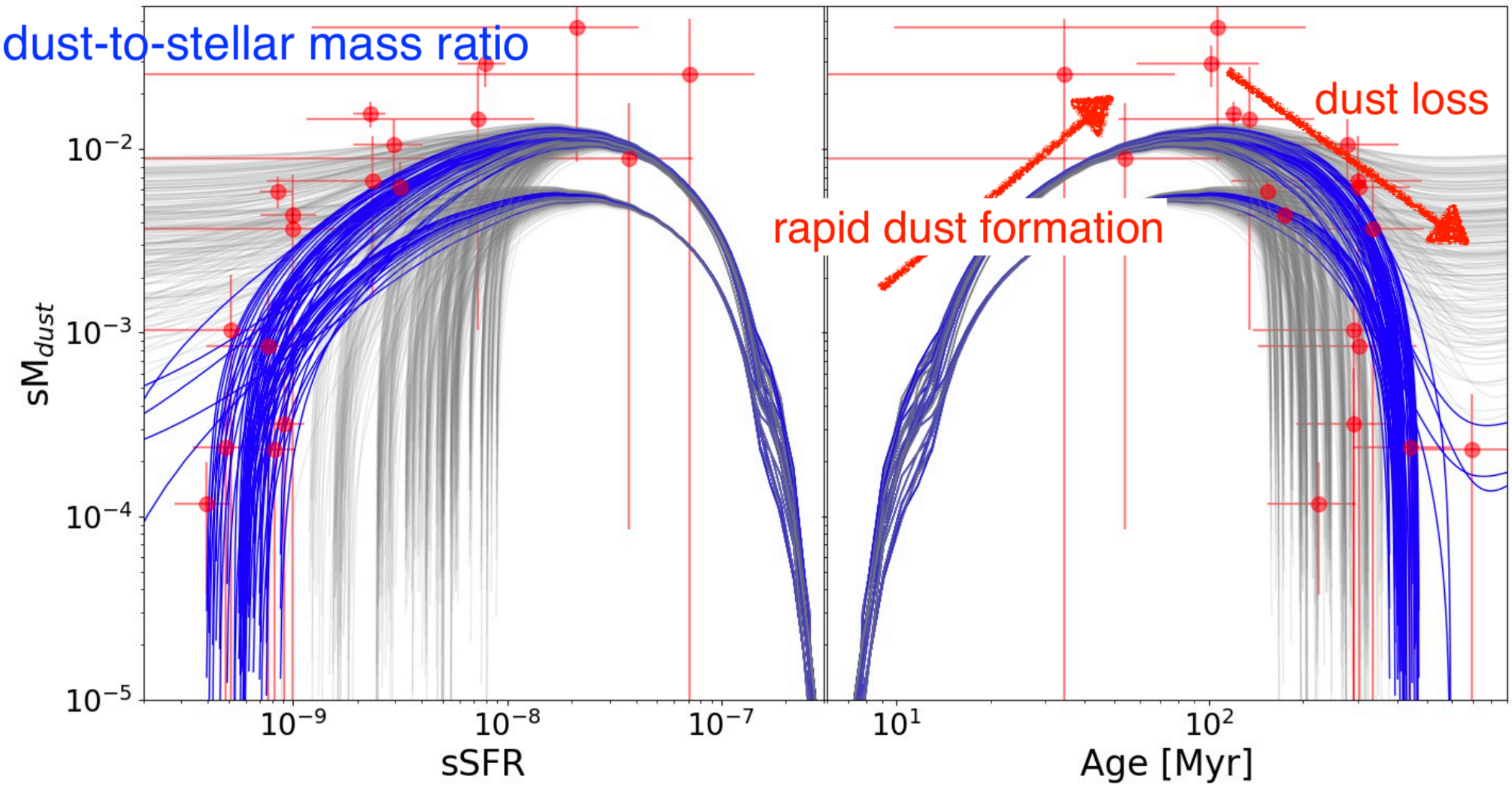
Valiante et al. (2009)



Supernovae can significantly enrich the enrich galaxies with dust up to ~ 10% of the current dust abundance at *z* ~ 5.

Efficient Production Is Required

Burgarella, …, Hirashita, et al. (2020); Nanni, …, Hirashita, et al. (2020)

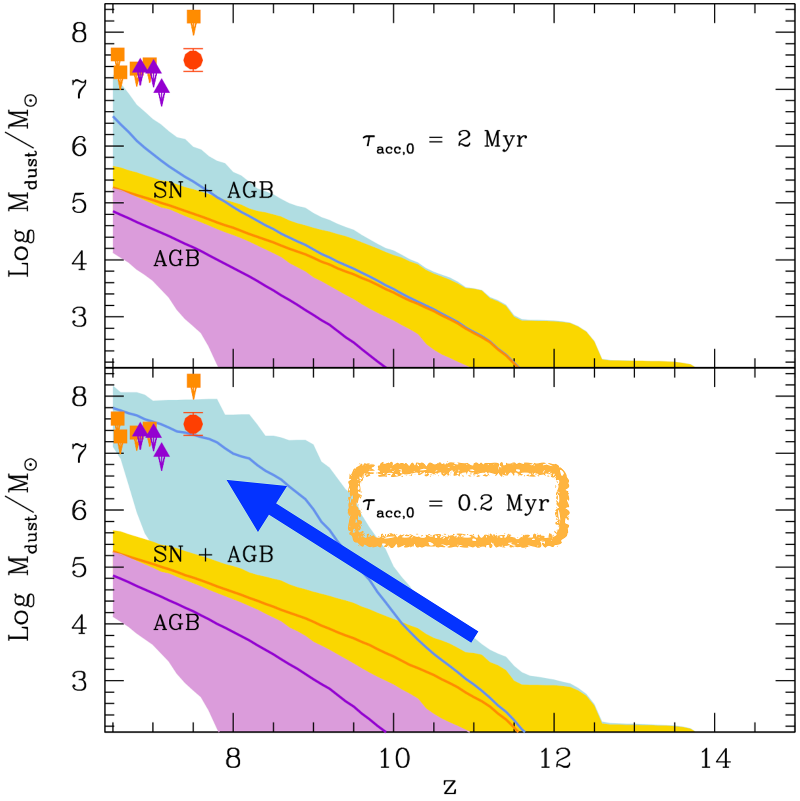


High condensation efficiency of metals in SNe (> 0.5) reproduce the observed dust mass for $z > 5$ LBGs.

See also Leśniewska & Michałowski (2019).

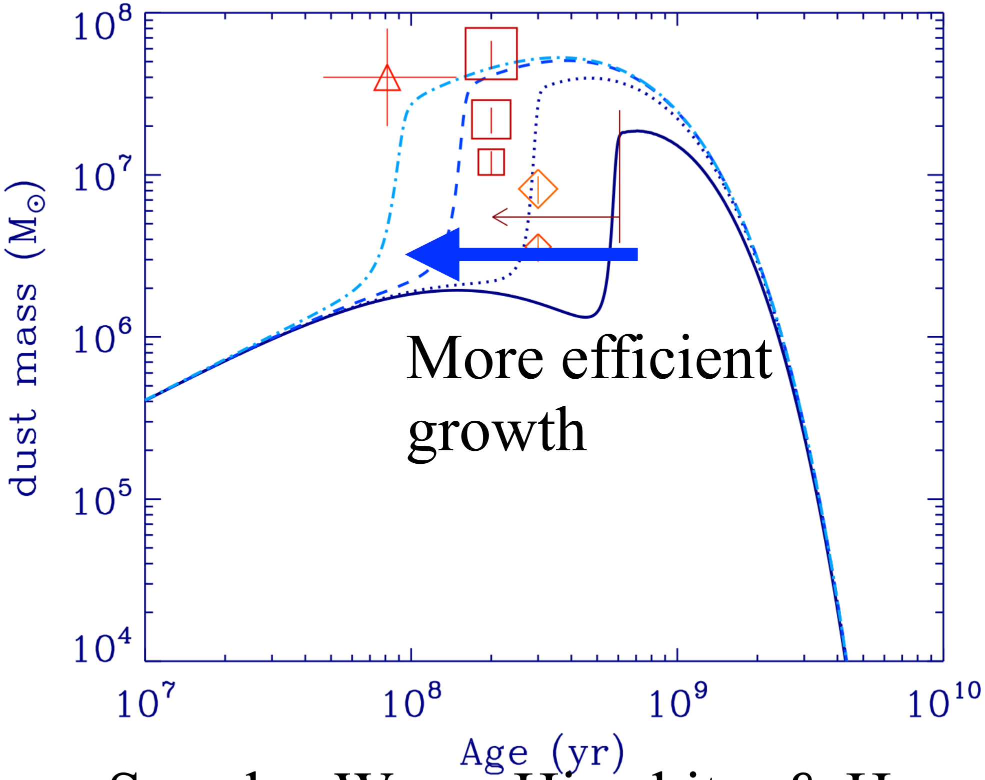
Dust Growth in the Interstellar Medium

Mancini et al. (2016)



See also Popping et al. (2017)

Liu & Hirashita (2019)



More efficient growth

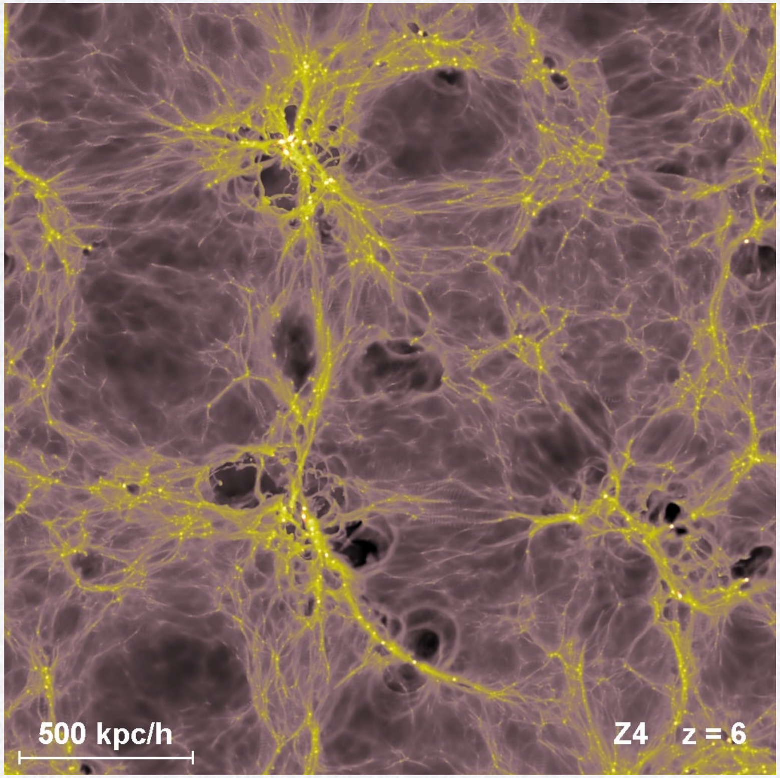
See also Wang, Hirashita, & Hou (2017)

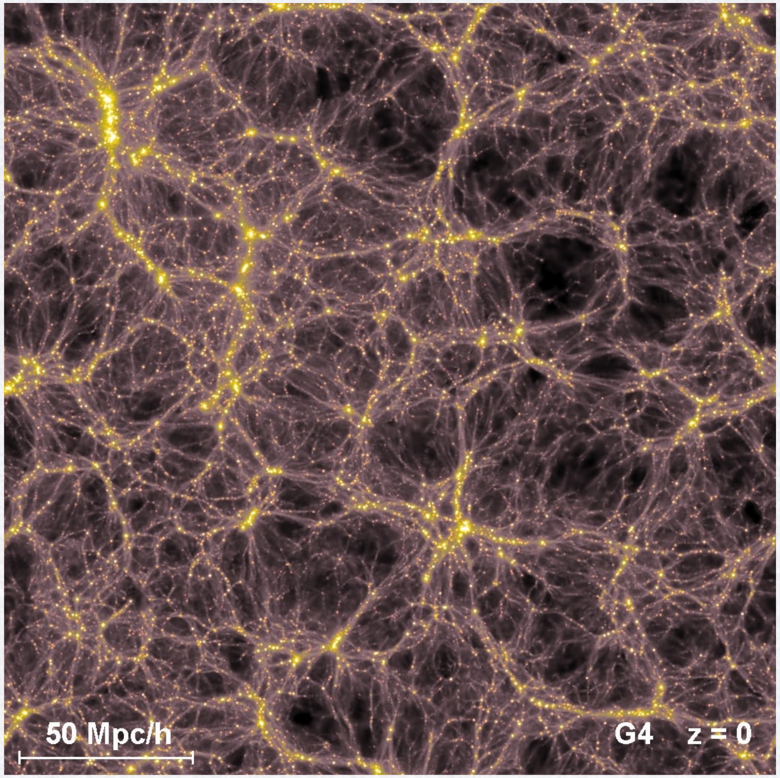
Dust growth by the accretion of gas-phase metals may be needed to explain the dust abundance in high-redshift galaxies detected by ALMA.

4. Widely Distributed Dust

Cosmological Hydrodynamical Simulation

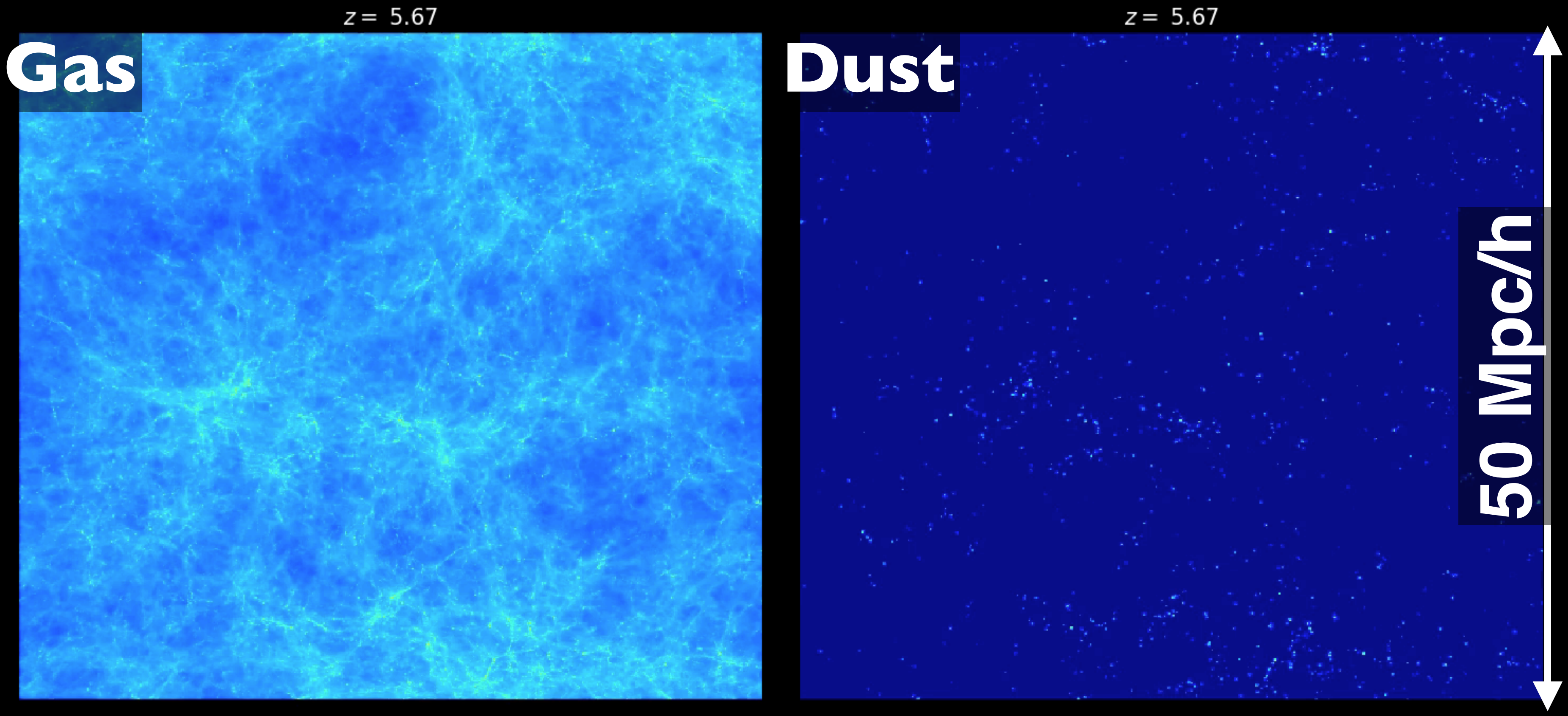
- **SPH** (smoothed particle hydrodynamic) simulation using modified **GADGET** (Springel 2005) (GADGET3(4)-Osaka) (Aoyama+17; Shimizu+17)





GADGET web page

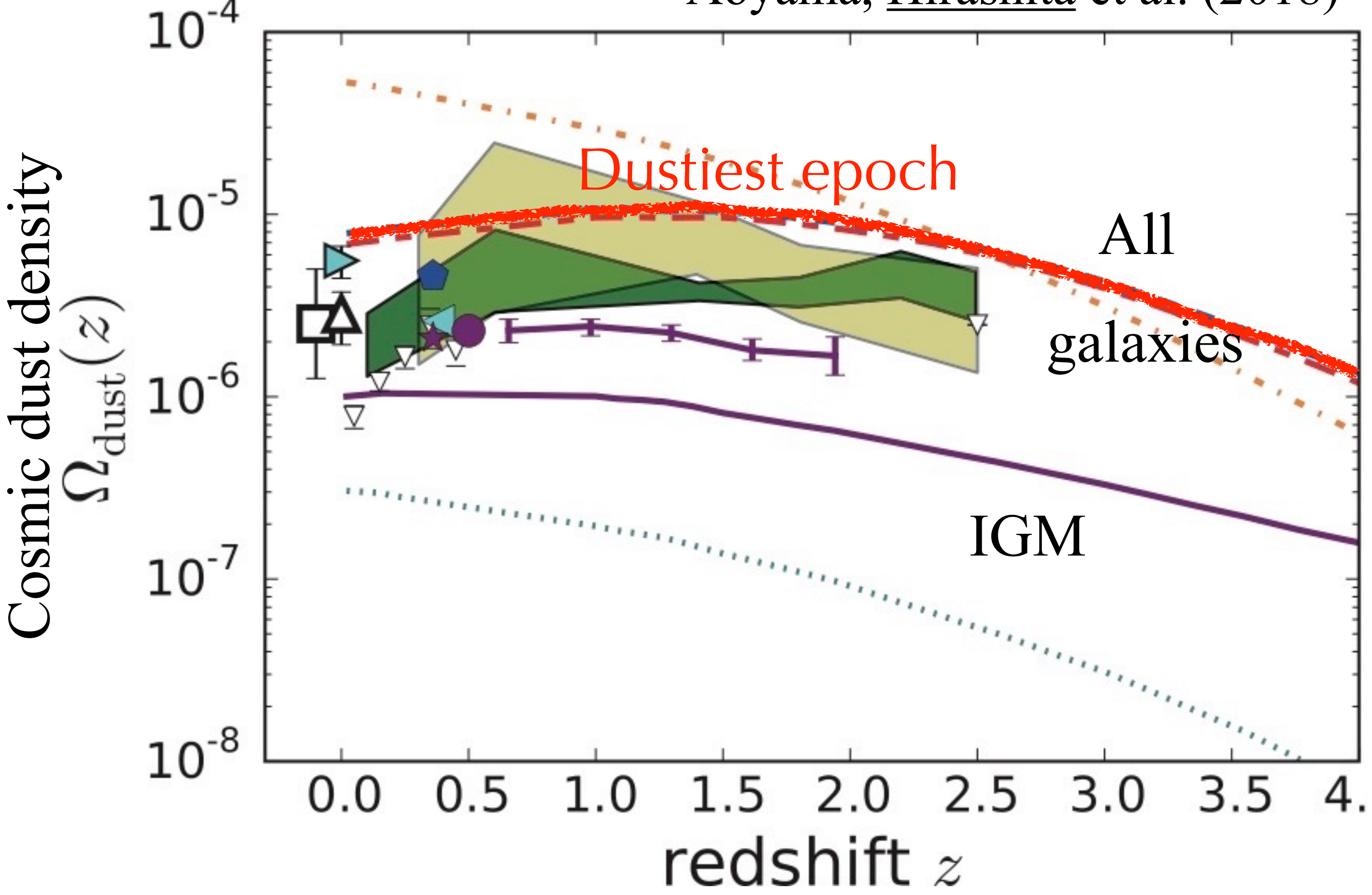
Gas and Dust distribution



Kuan-Chou Hou

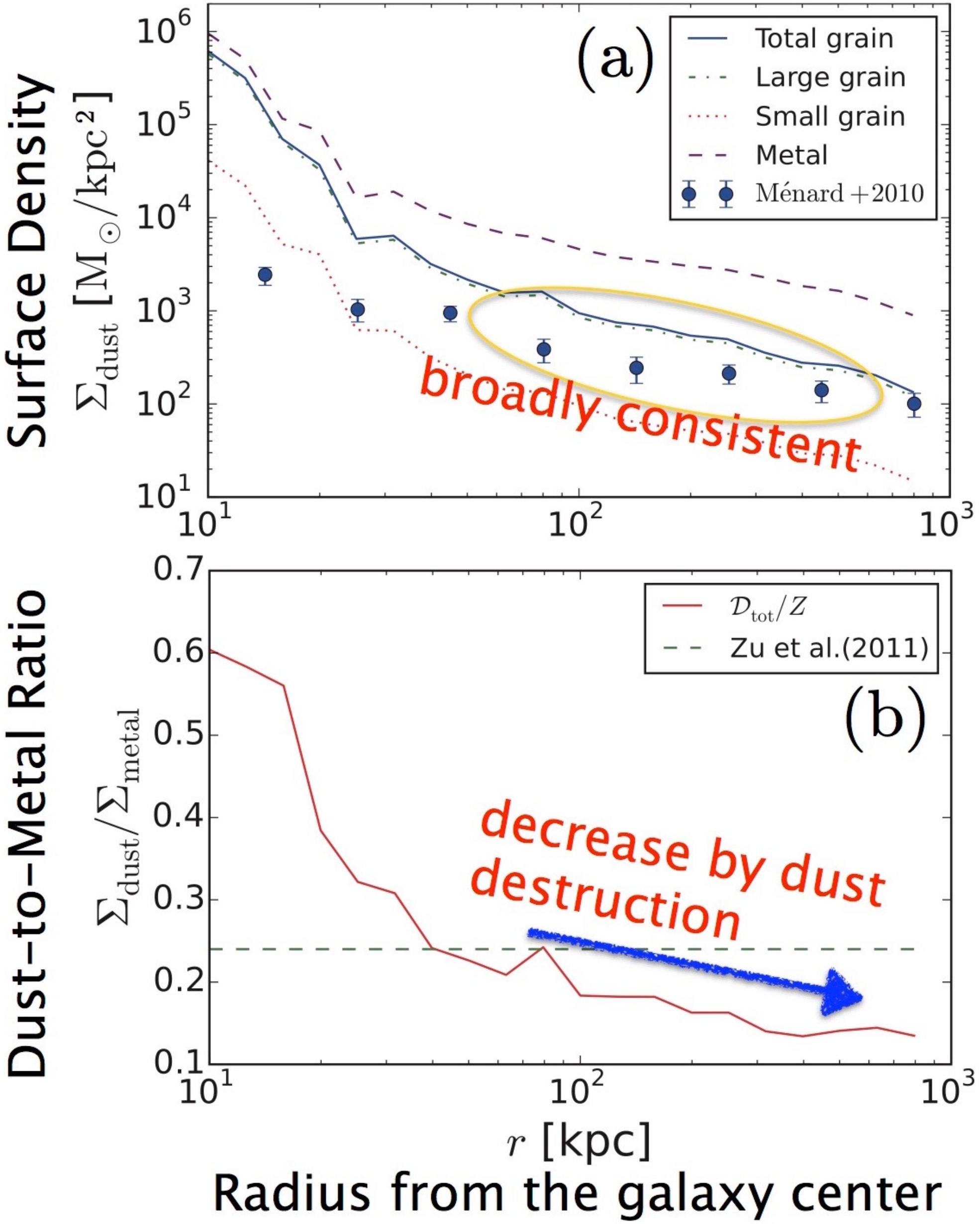
Evolution of Dust Abundance

Aoyama, Hirashita et al. (2018)



Dust Distribution from ISM to IGM

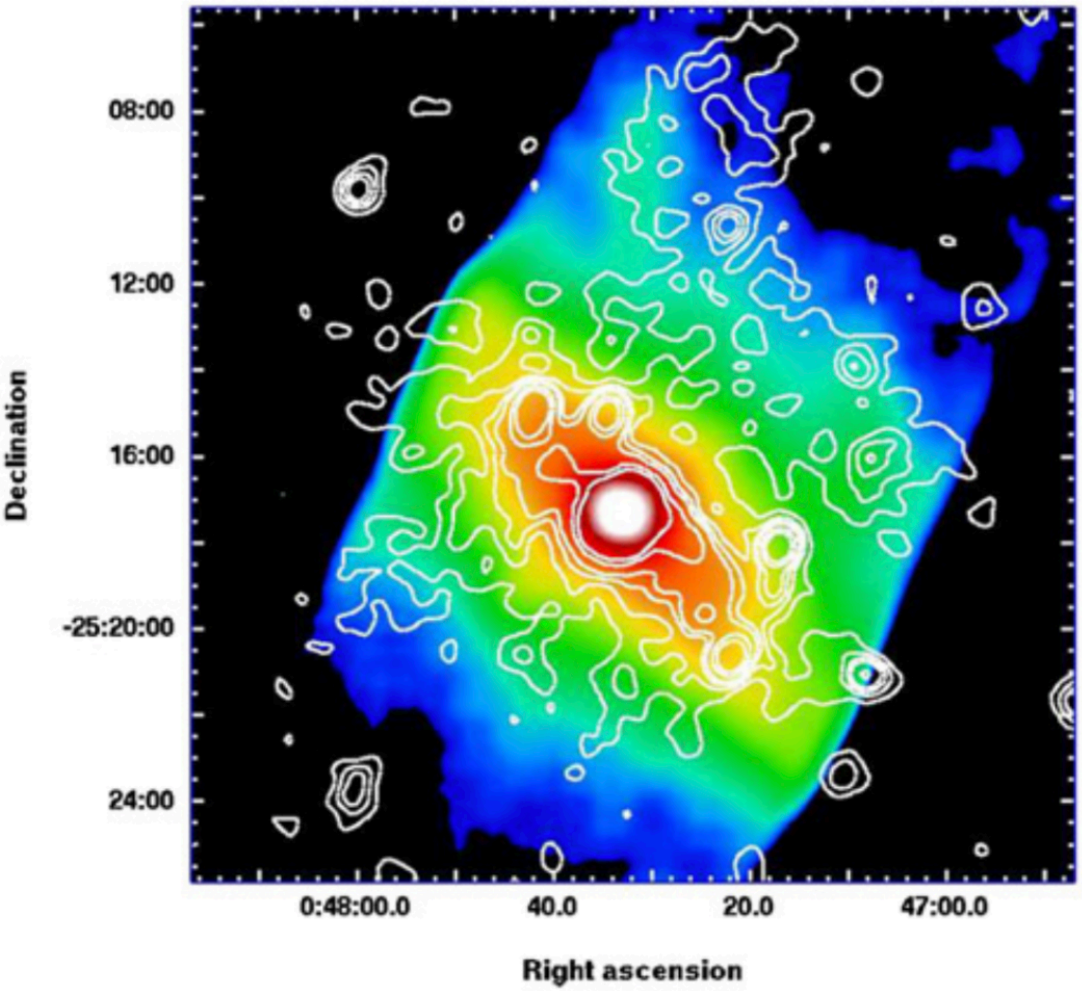
Aoyama et al. (2018)



Dust is transported into outer-galaxies through the stellar feedback.

Successful in explaining the dust distribution from tens kpc (galaxy scale) to Mpc (IGM scale).

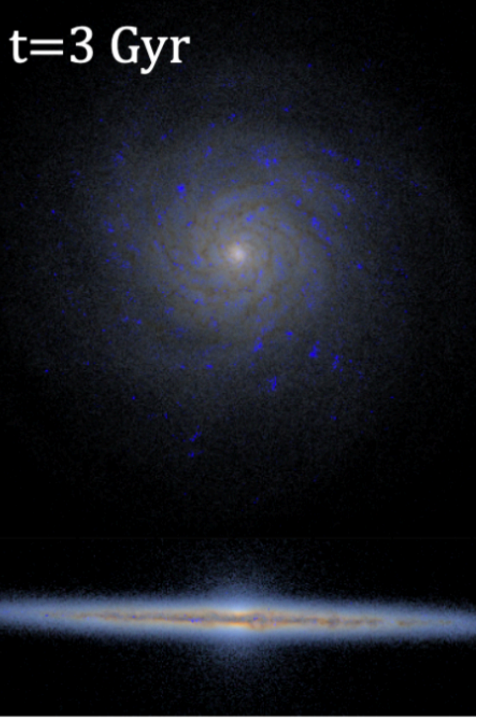
Extended Dust Emission

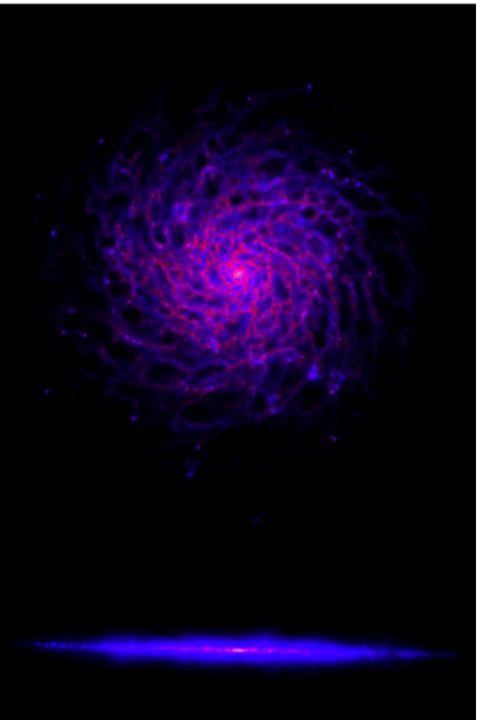


Kaneda et al. (2009)

NGC 253
AKARI 90 μm
(Contour X-ray)

Extended dust emission above the galactic disk.





Galaxy Simulations

Romano, Nagamine, & Hirashita (2022);
Matsumoto, Nagamine, Hirashita, et al. (in prep.)

Isolated galaxy simulation (using GADGET4-Osaka)
+ Post-processed by radiative transfer calculations by SKIRT (Baes et al. 2011; Camps & Baes 2020).

Detailed comparison with nearby galaxies including the CGM.

Effects yet to be included:
radiative torques (Hoang et al. 2019; Le Ngoc Tram's talk),
radiative pressure (Ferrara et al. 1991; Bianchi & Ferrara 2005; Hirashita & Inoue 2019).

5. Summary

(1) Supernovae produce dust, and they play an important role in dust enrichment in the early phases of galaxy evolution.

(2) Uncertainties: reverse shock destruction, shock destruction of pre-existing dust.

(3) To better explain the dust content in dust-rich galaxies, dust growth in the interstellar medium is a viable source of dust.

(4) Galactic outflows triggered by energy input from supernovae enrich the circum/inter-galactic medium with dust.

(5) Hydrodynamic simulations provide a viable platform in which we investigate the galaxy-wide dust evolution.

Thank you.