2014/02/24

Our recent achievements and ongoing works

Takaya Nozawa

Kavli IPMU, Univeristy of Tokyo

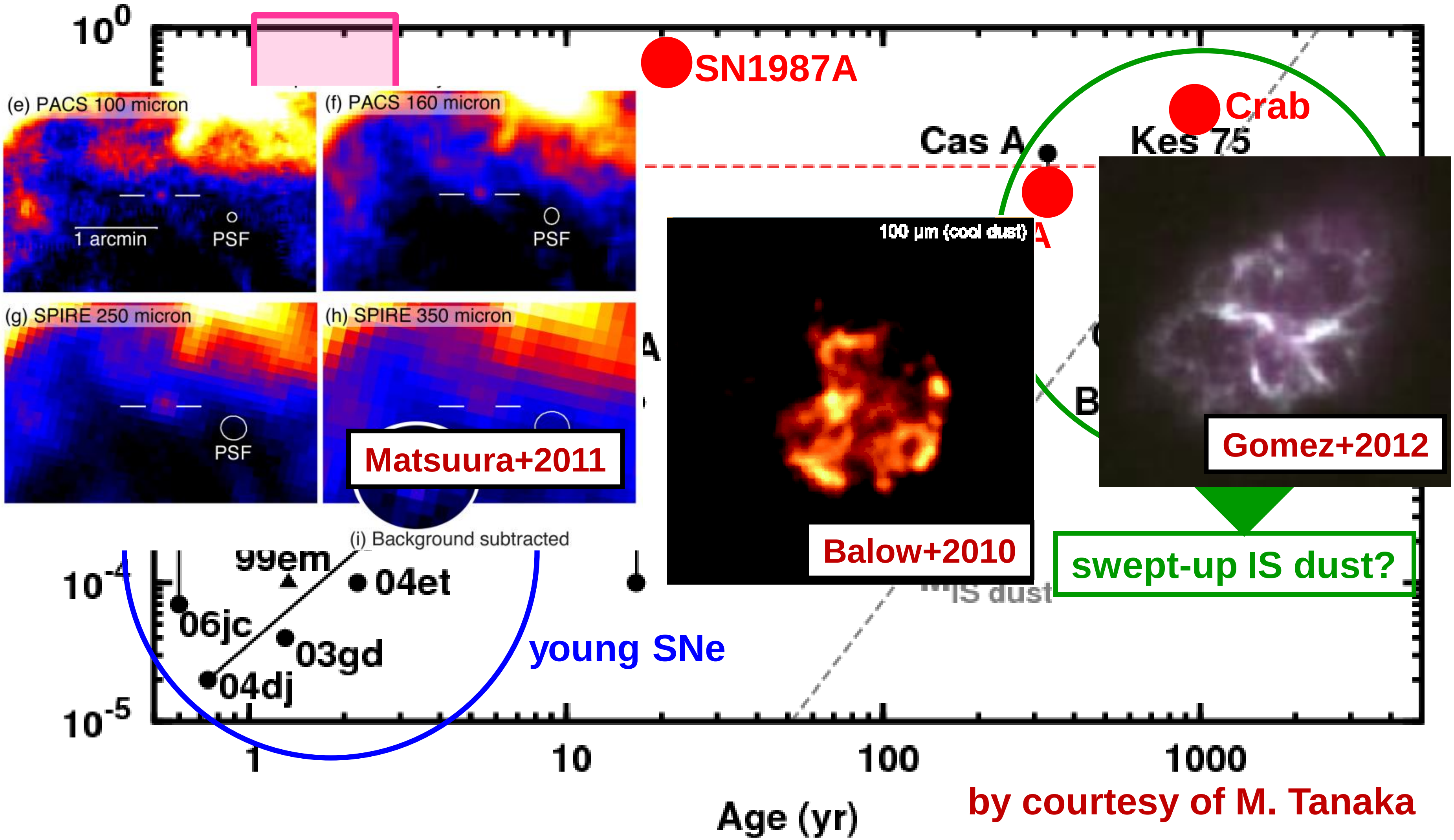
(➔ moving to the theory group of NAOJ from this April)

Contents

- Dust formation in supernovae (and RSG winds)
- Grain growth and formation of HMP stars
- Evolution of grain size distribution in the ISM

東京大学 THE UNIVERSITY OF TOKYO
TODIAS 東京大学国際高等研究所 TODAI INSTITUTES FOR ADVANCED STUDY
wpi World Premier International Research Center Initiative
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

1-1. Summary of observed dust mass in CCSNe

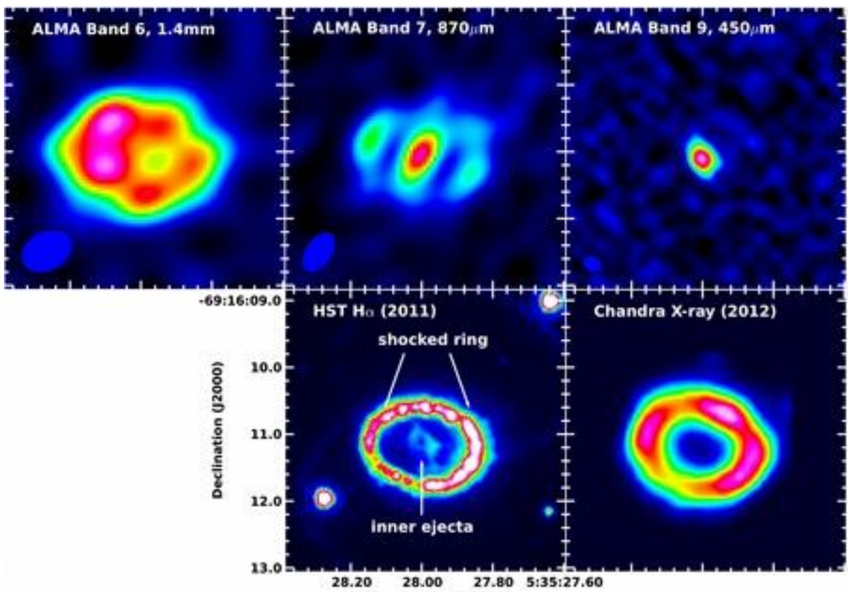


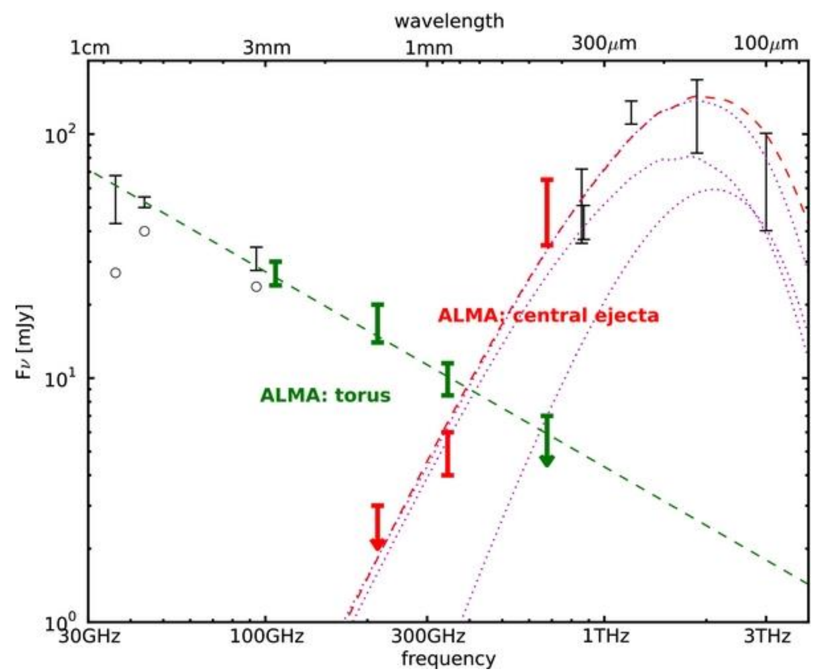
Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe

1-2. ALMA reveals dust and CO in SN 1987A

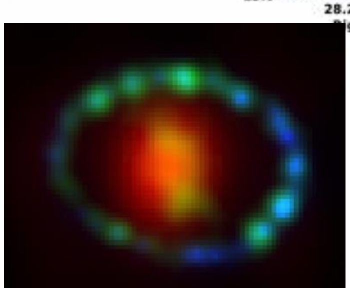
Herschel spatial resolution
: >10 arcsec

SED of 25-years old SN 1987A





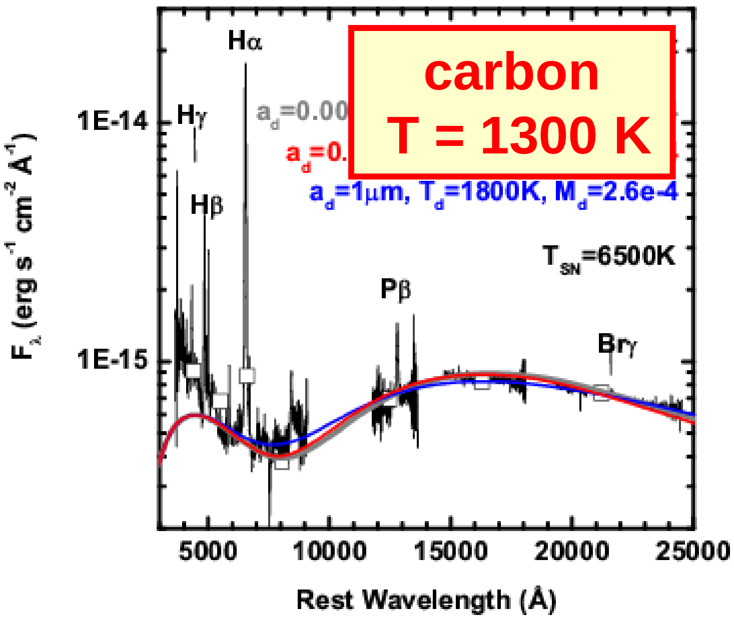
Indebetouw+2014

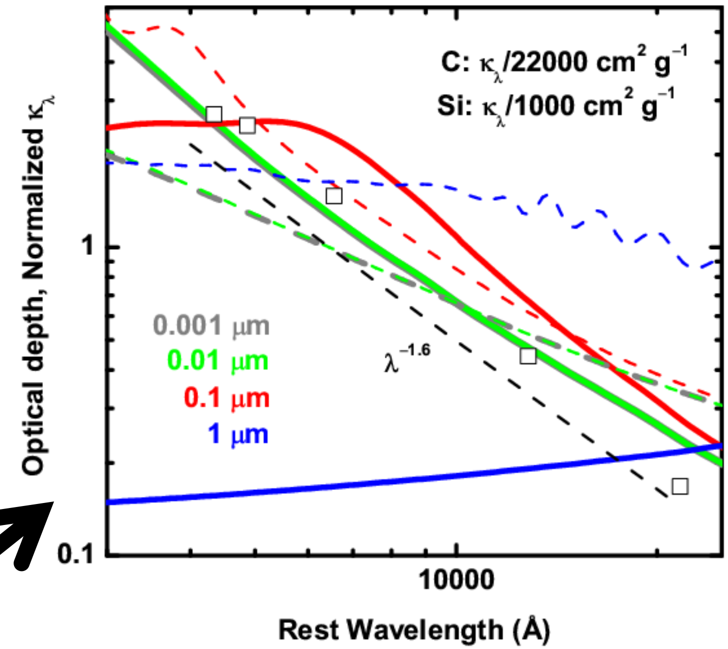


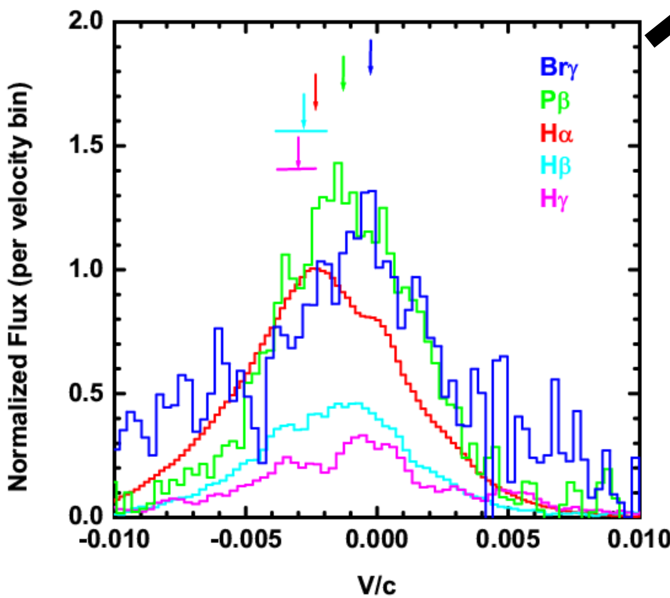
detection of CO in the ejecta
M_{CO} : >0.01 M_{sun}

ALMA resolves cold (~20 K) dust of ~0.5 M_{sun} (C dust ~ 0.2 M_{sun}) formed in the ejecta of SN 1987A
➔ SNe could be production factories of dust grains

1-3. Dust formation in Type IIn SN 2010jl





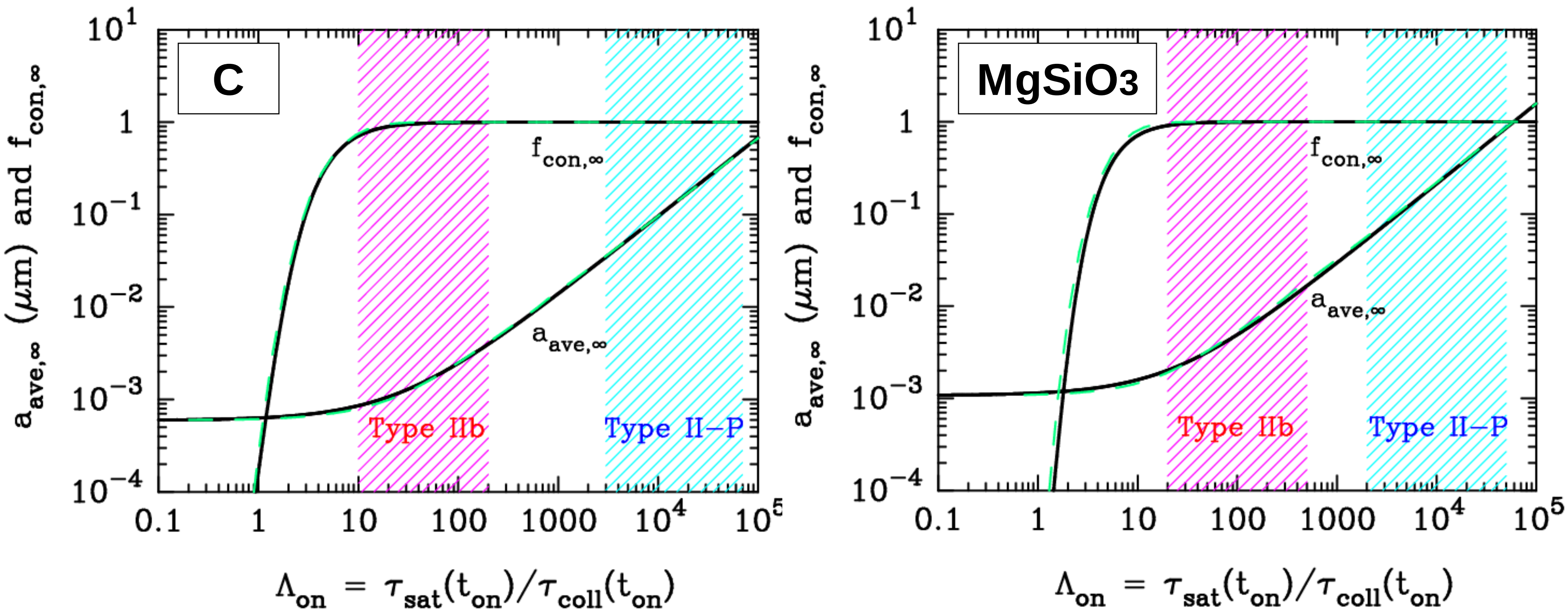


Dust in SN 2010jl

- dust species: carbon grains
- grain radius: <0.1μm
  (possibly <0.01 μm)
- dust mass: ~10^{-3} Msun

Maeda, TN, Sahu+2013

1-4. Scaling relation of average grain radius



TN & Kozasa 2013

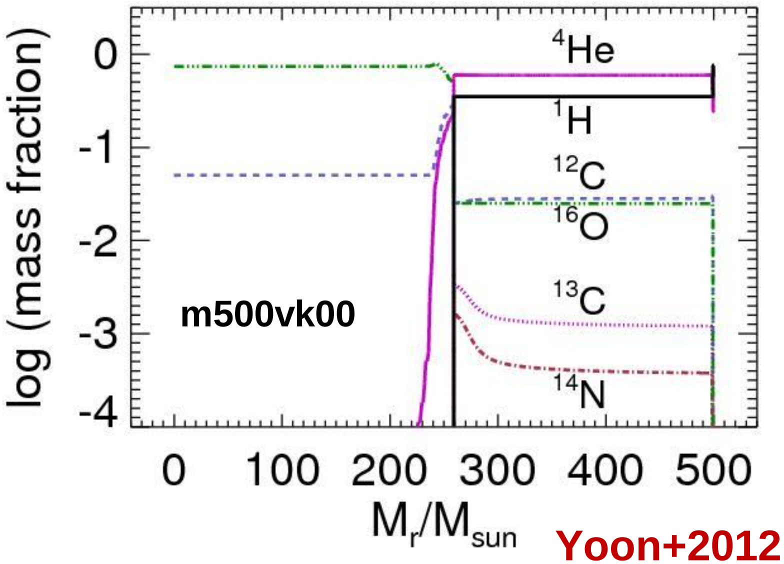
$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: ratio of supersaturation timescale to gas collision timescale at the onset time (t_{on}) of dust formation

$$\Lambda_{on} = \tau_{sat}/\tau_{coll} \propto \tau_{cool}\, n_{gas}$$

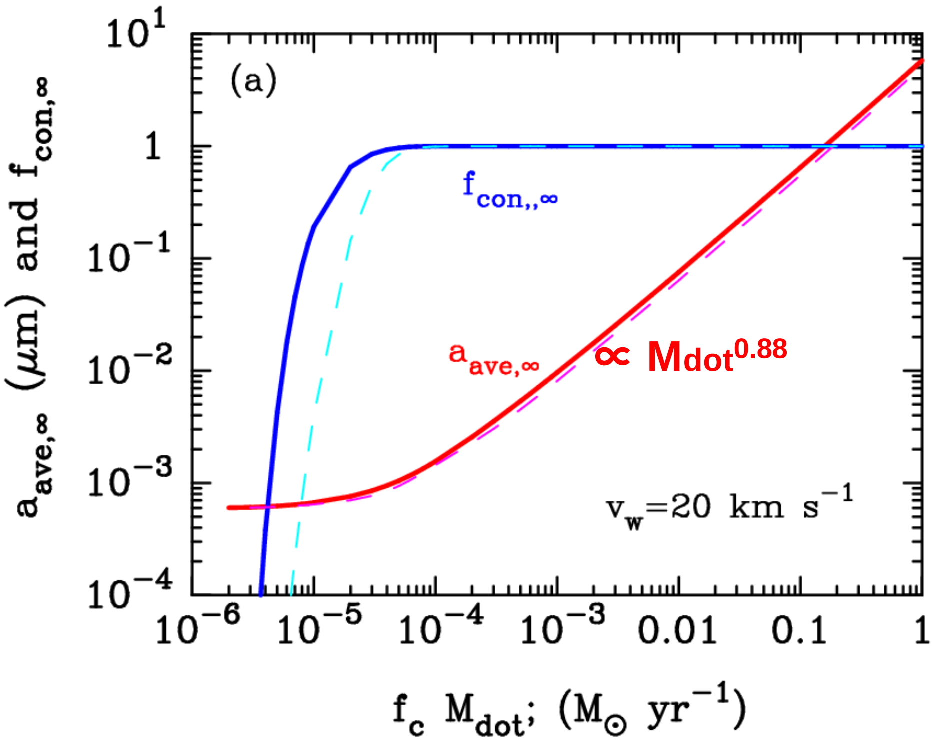
- $f_{con,\infty}$ and $a_{ave,\infty}$ are uniquely determined by Λ_{on}
- steady-state nucleation rate is applicable for $\Lambda_{on} > 30$

1-5. Dust formation in very massive Pop III star

non-rotating stars with >250 Msun undergo convective dredge-up of C and O during the RSG phase



Yoon+2012

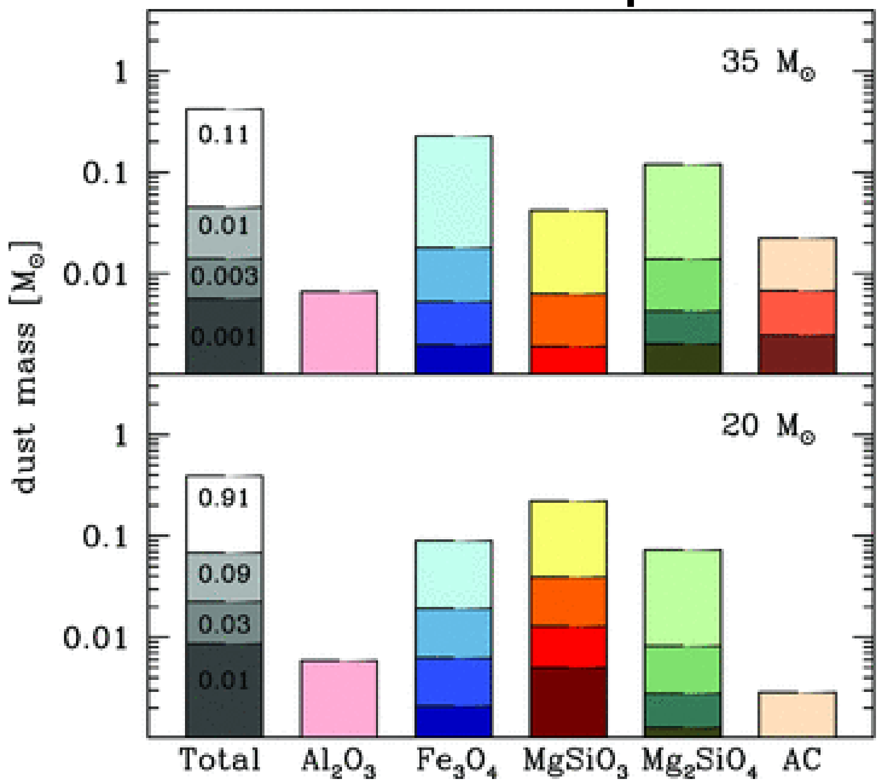


TN, Yoon, Maeda, submitted

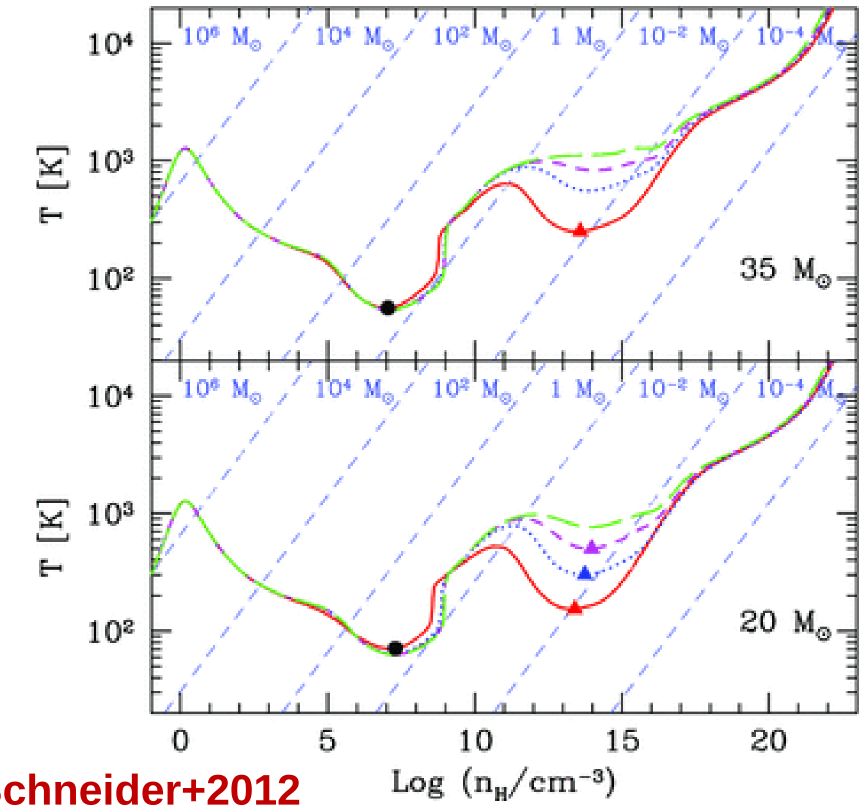
- 1.7 Msun of C grains is produced over the lifetime of the RSG
  ➔ Dust grains formed in the winds are unlikely to be destroyed by the SN shocks because the central star collapses into the BH
- Very massive Pop III RSGs could be sources of carbon grains
  ➔ carbon grains enable the formation of low-mass HMP stars whose chemical compositions are highly enriched with CNO

2-1. Formation conditions of Caffau star

dust mass and composition



thermal evolution of clouds

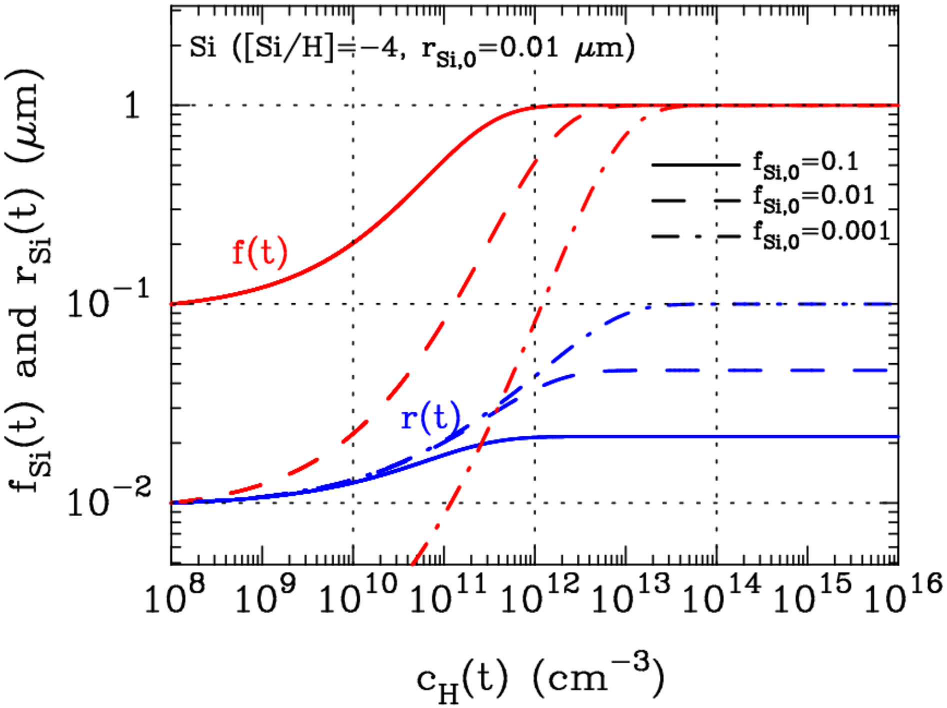


Schneider+2012

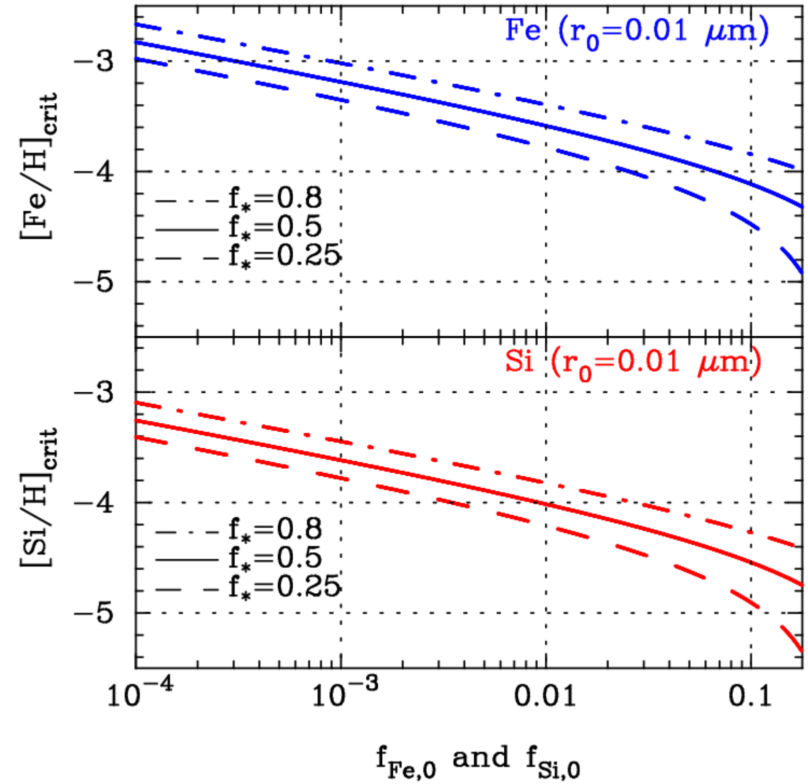
- **fragmentation occurs at $n_H = 10^{12}$-10^{14} cm^{-3} if $f_{dep} > 0.01$**
  - **➔ if dust formation in SNe is less efficient or strong dust destruction occur, only M > 8 M_{sun} fragments can form**
- **elemental composition, dust formation, fragmentation**

2-2. Grain growth in metal-poor gas clouds

growth of Si grains



critical metal abundances

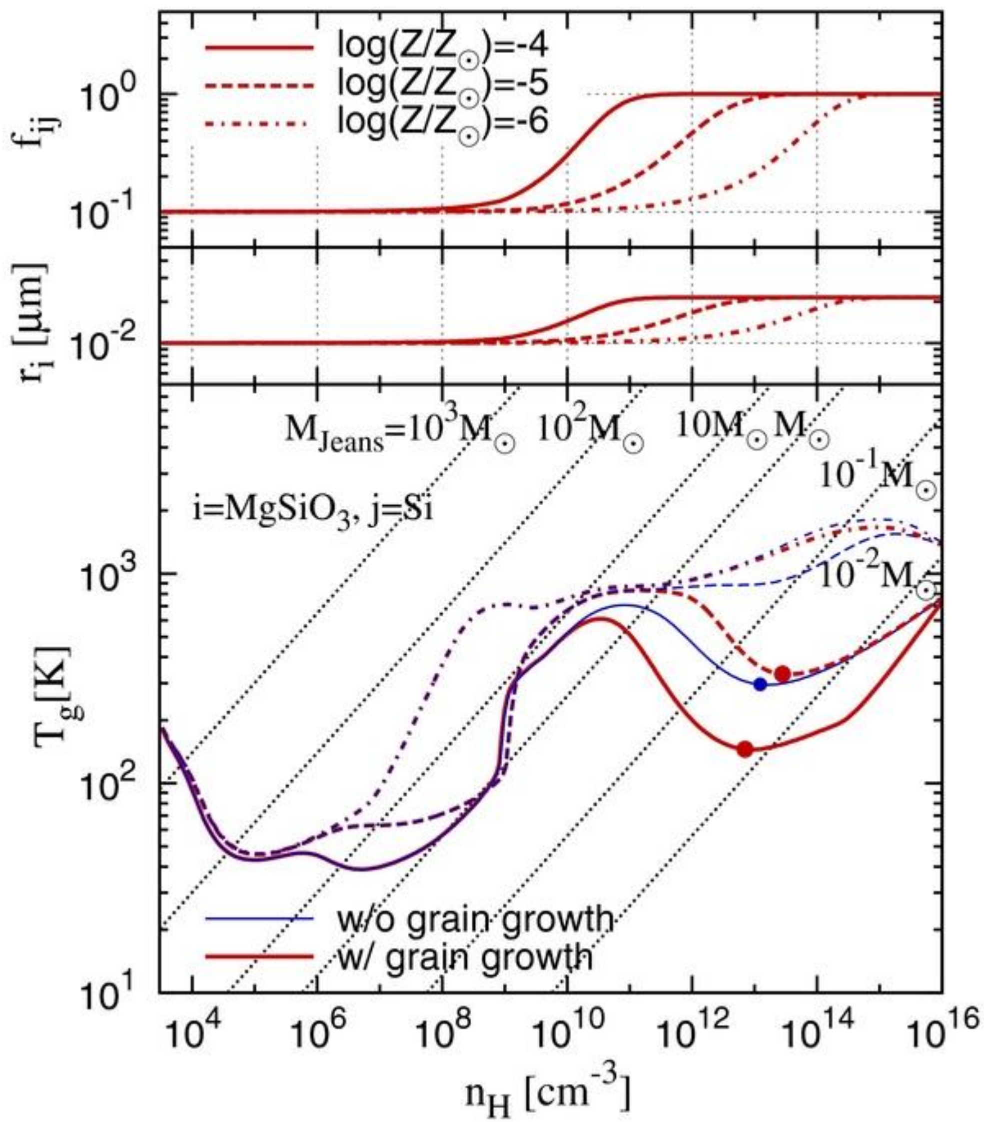


TN, Kozasa, Nomoto 2012

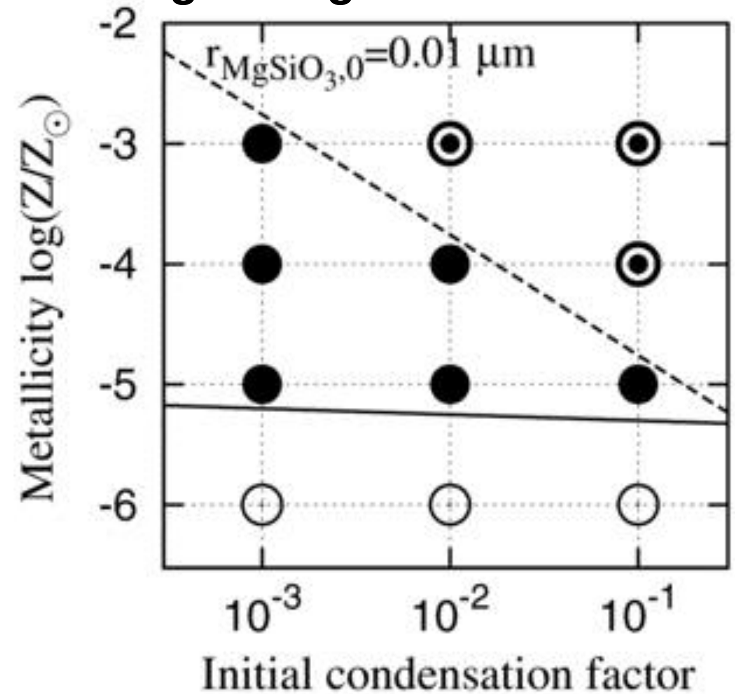
- **grain growth enhances *SD* in the clouds and enable the gas fragmentation into sub-solar mass clumps**
- **for $f_{i,*}$ = 0.5 and 0.001 < $f_{i,0}$ < 0.1,**
  -4.12 < [Fe/H] < -3.2, -4.6 < [Si/H] < -3.3
  ref. [Si/H] = -4.27 for SDSS J102915+2729

2-3. Grain growth and gas fragmentation

growth of MgSiO3 grains



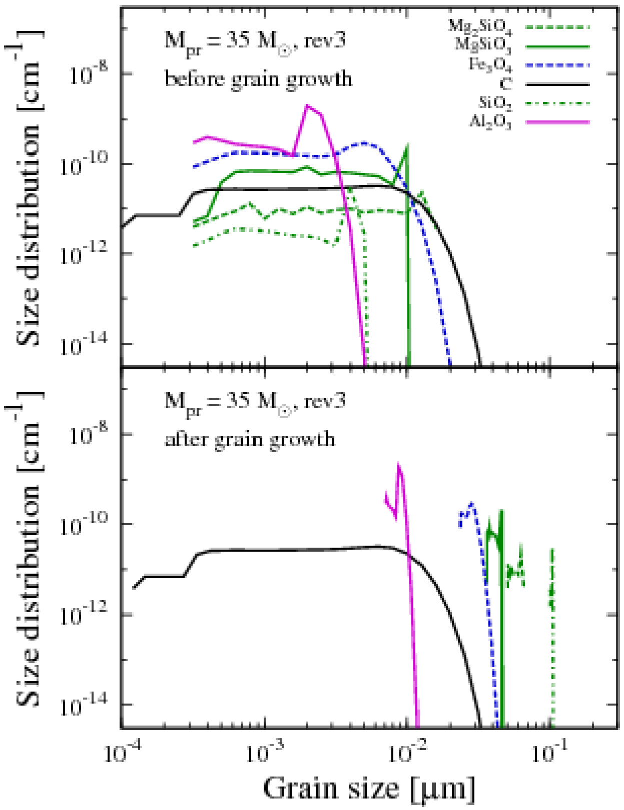
gas fragment condition

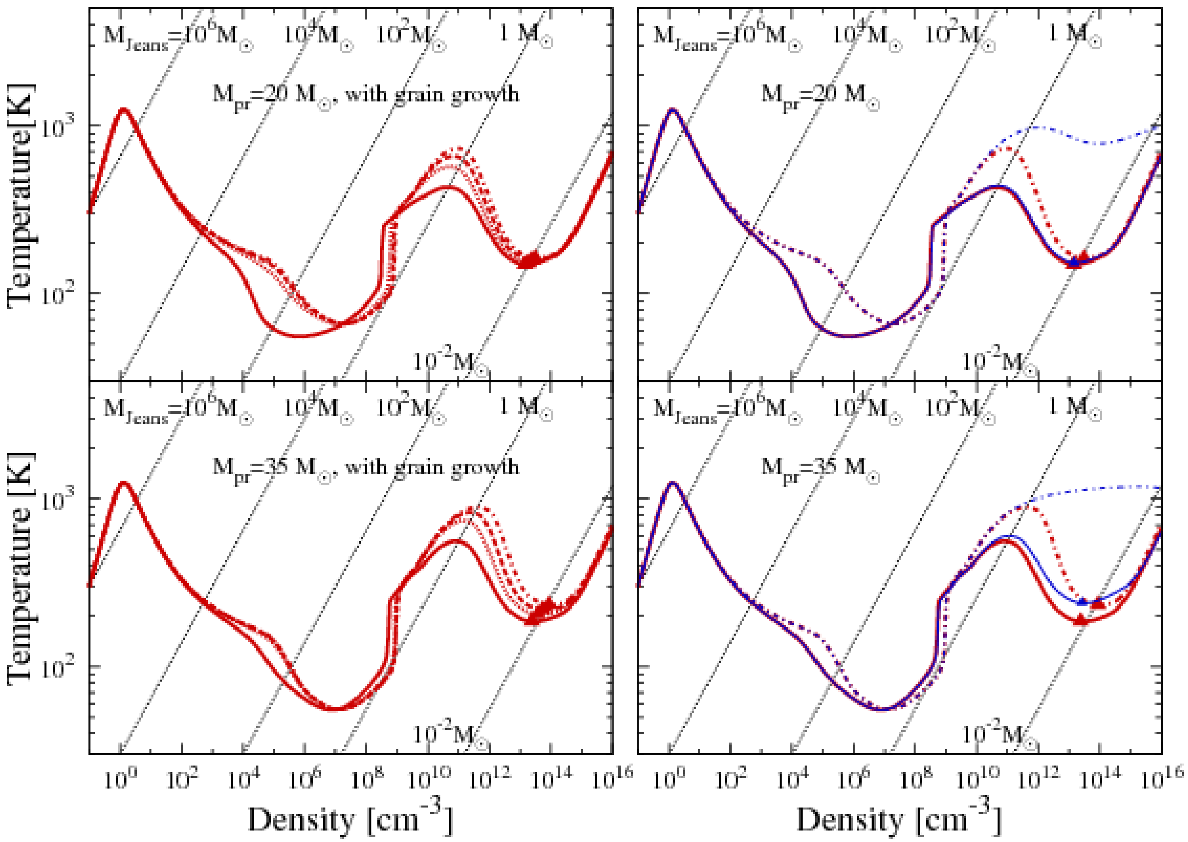


- the condition for efficient dust cooling is insensitive to the initial condensation factor
- critical metalicity Zcrit : ~$10^{-5.5}$ Zsun for r < 0.01 μm

Chiaki, TN, Yoshida 2013

2-4. Application to Caffau star

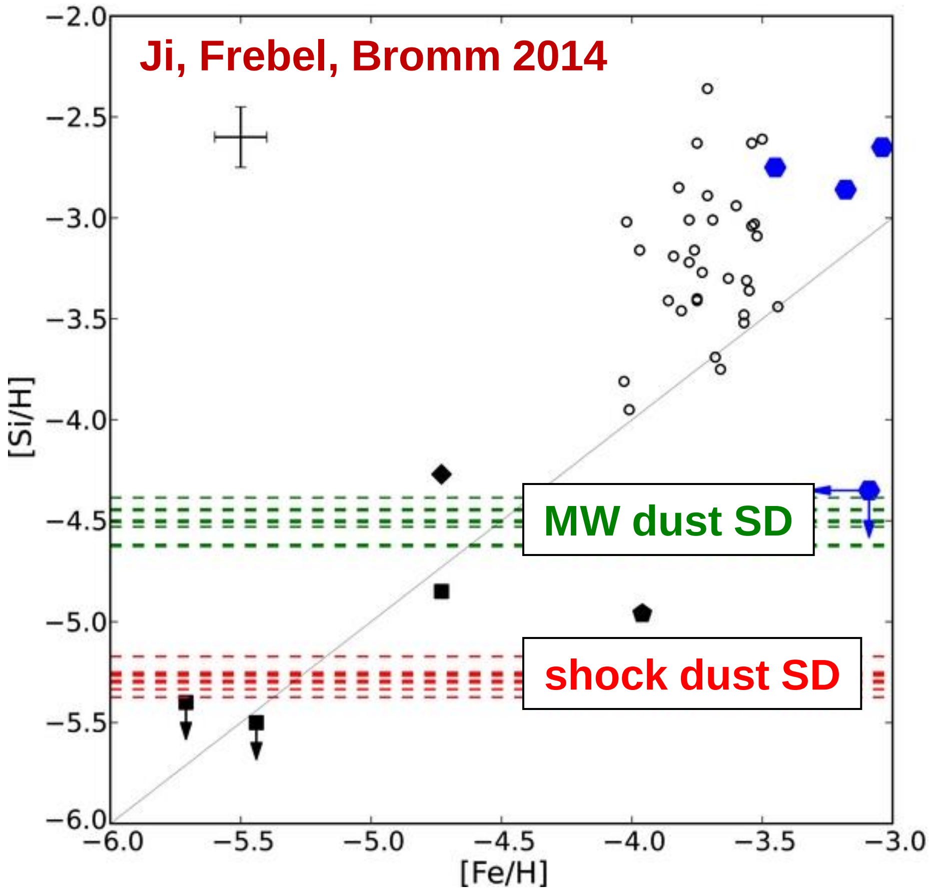




- **growth of multiple grain species with size distribution (SD)**
- **even if dust formation in the first SNe is inefficient or strong dust destruction occurs, grain growth during the collapse of parent gas cloud is sufficiently rapid to activate dust cooling**

Chiaki, Schneider, TN+2014, accepted

2-5. Towards C-rich HMP stars and Keller star



Si abundances in HE0107-5240 and HE1327-2326 are so low that silicate grains cannot cause the fragmentation of low-mass stars

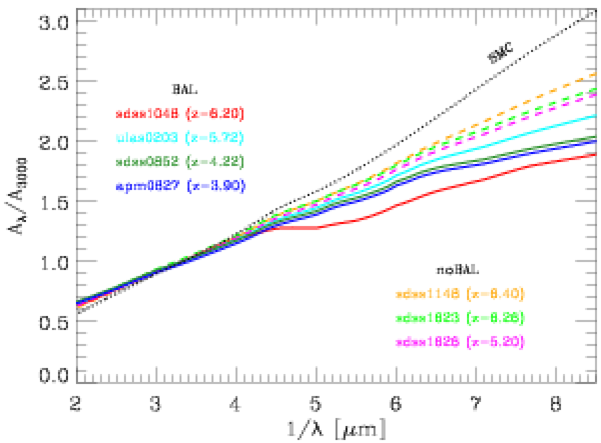
- Italy group (Schneider+)
- mixing-fallback SNe
- formation of C grains
  ➔ formation scenario of C-rich HMP stars

- Japanese group (Chiaki, TN+)
- more general picture
- Nozawa SN-dust model
  ➔ grain growth is not very important

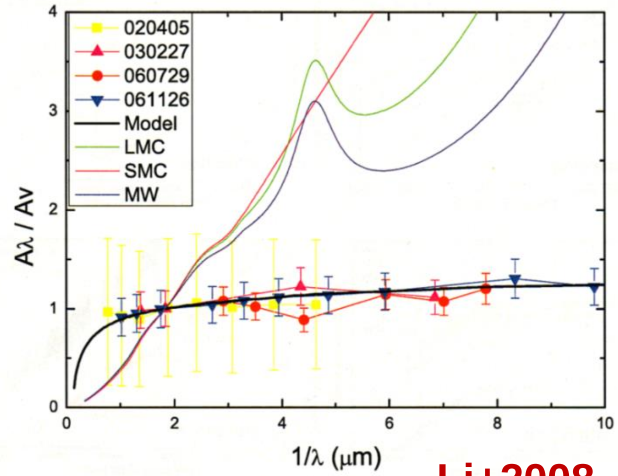
- Keller star with [Fe/H] < -7
- mixing-fallback SNe
- formation of C grains
- grain growth
- fragmentation

Dust formation in falild (faint) SNe (Kochanek 2014)

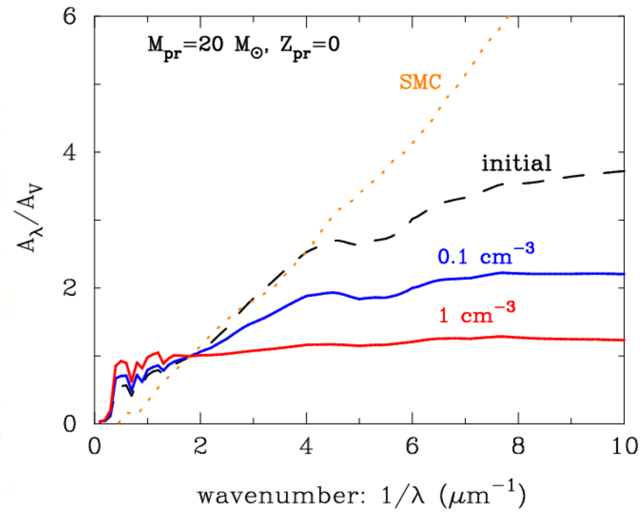
3-1. Flatter extinction curves at high-z



Gallerani+2010



Li+2008



Hirashita, TN+2008

- the extinction curves observed for high-z quasars and GRB afterglows tend to be flat

- extinction curve expected from SN dust is flat
  ## average radii of dust grains ejected from SNe are large (~0.1 μm) because small grains are destroyed by the reverse shocks

➔ these seem to support the idea that SNe II are the main dust sources in the early universe

3-2. Rapid grain growth at high-z objects?

○ A large amount of dust grains at high-z quasars

- in addition to SN dust (and AGB dust), grain growth is considered to be needed for explaining such an observed mass of dust

➔ how are extinction curves changed by grain growth?
➔ can grain growth take place efficiently in such an early epoch?

○ timescale of grain growth (gas accretion timescale onto dust)

$$\tau_{acc} = [\ (1/a)(da/dt)\ ]^{-1} = [\ (1/a)\ \alpha_s\ n_{metal}\ V_0 \langle v \rangle\ ]^{-1}$$

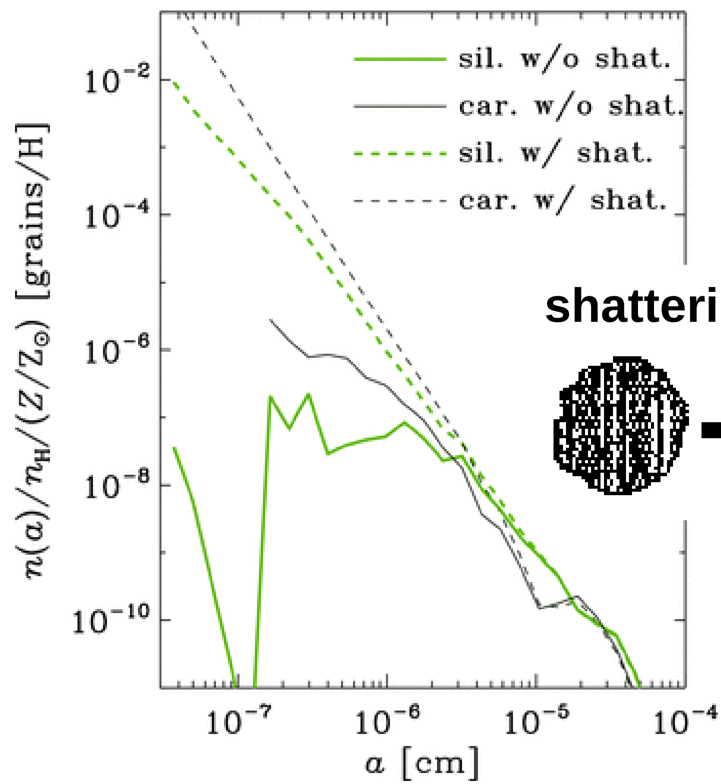
$$\sim 5\mathrm{x}10^7\ \mathrm{yr}\ (\alpha_s / 0.2)^{-1}\ (a / 0.01\mu\mathrm{m})\ (Z / 0.02)^{-1}\ (n_{gas} / 30\mathrm{cm}^{-3})^{-1}$$

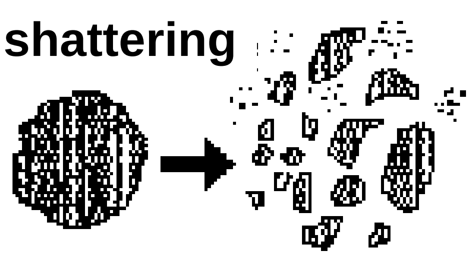
○ high-z quasars (age: ~0.5 Gyr)

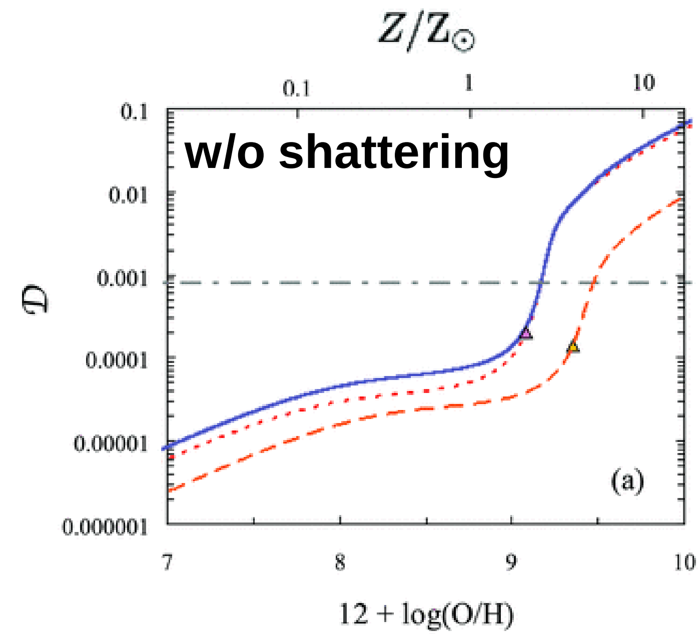
- metallicity ~ solar
- average radius of SN dust ~ 0.1 μm

$\tau_{acc} \sim 5\mathrm{x}10^8$ yr ➔ grain growth is not effective??

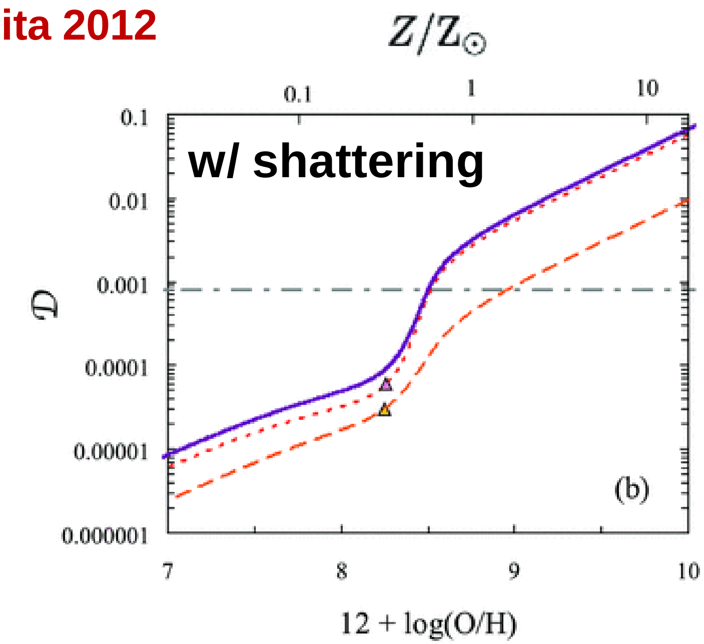
3-3. Effect of size distribution on grain growth







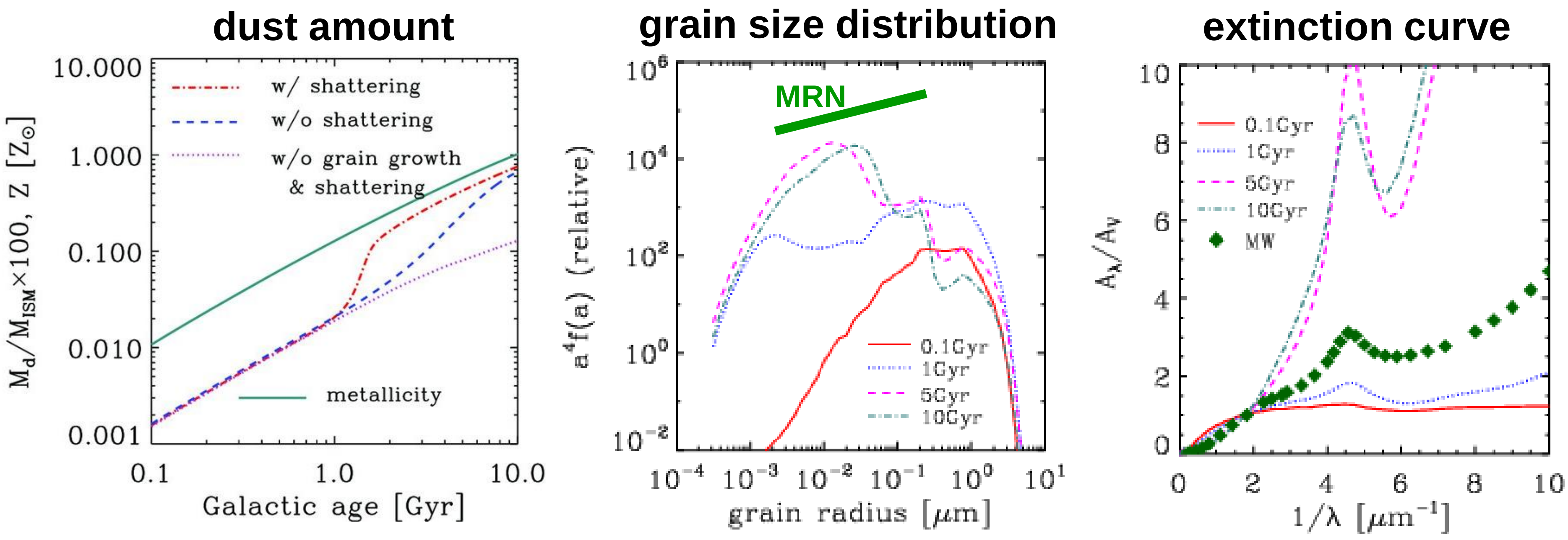
Kuo & Hirashita 2012



- **w/o shattering : grain growth becomes efficient at super-solar metallicity**
- **w/ shattering : grain growth becomes efficient at sub-solar metallicity**

➔ production of small grains due to shattering is needed for grain growth

3-4. Evolution of extinction curves in galaxies

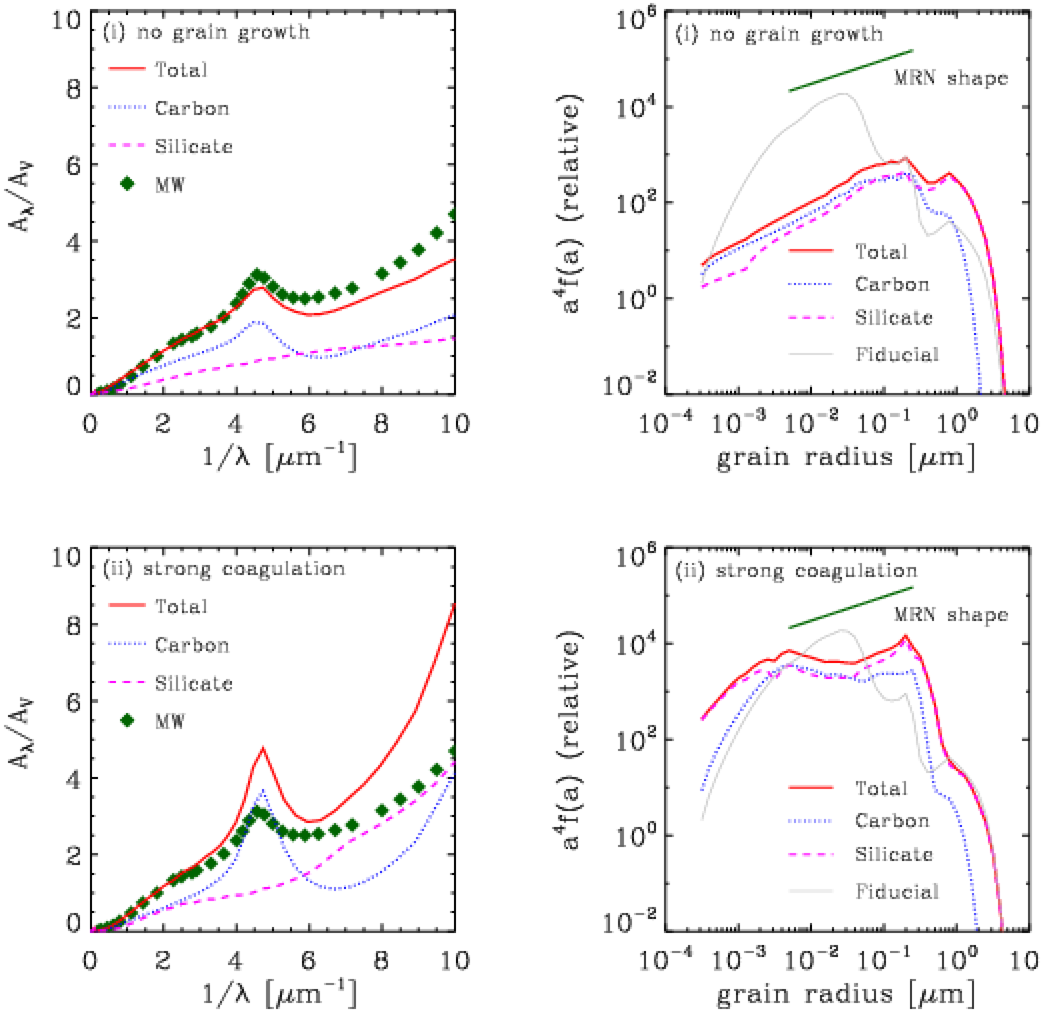


Asano, Takeuchi, Hirashita, TN+13, MNRAS, 432, 637
Asano, Takeuchi, Hirashita, TN+14, accepted for MNRAS, arXiv/1401.7121

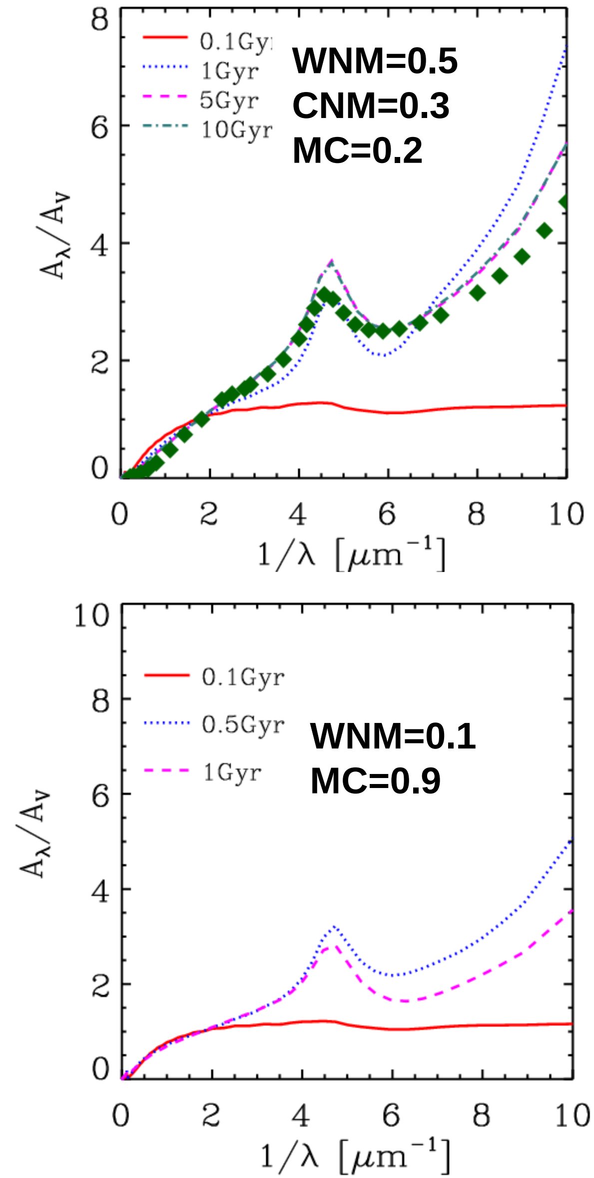
- **early phase** : formation of dust in SNe II and AGB stars
  ➔ large grains (~0.1 μm) are dominant ➔ flat extinction curve
- **middle phase** : shattering, grain growth due to accretion of gas metal
  ➔ small grains (< 0.03 μm) are produced ➔ steep extinction curve
- **late phase** : coagulation of small grains
  ➔ shift of peak of size distribution ➔ making extinction curve flatter

3-5. Reproducing the MW extinction curve

steep extinction curve is due to the presence of too much small grains



Asano, Takeuchi, Hirashita, TN+14



Asano, TN+2014, in prep

4. Ongoing and future works

・Dust formation in Supernovae (and RSG winds)

- Dust formation in RSG winds of very massive Pop III stars
- faint (falling-back) SNe, SN 1987A, CO formation …

・Grain growth and formation of HMP stars

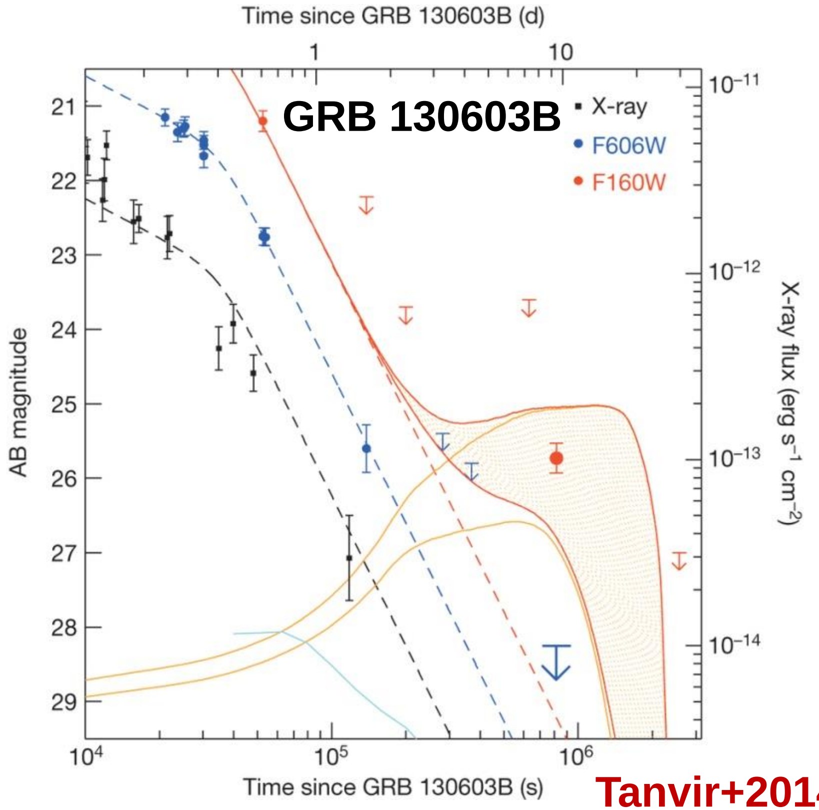
- fragmentation calculations in the Nozawa SN-dust model
- formation scenario of Keller star, 3D calculations

・Evolution of grain size distribution in the ISM

- Model that self-consistently explain the flat extinction curves and huge amounts of dust observed for high-z quasars
- Dust evolution in dwarf galaxies, relation of [CII] line at high-z

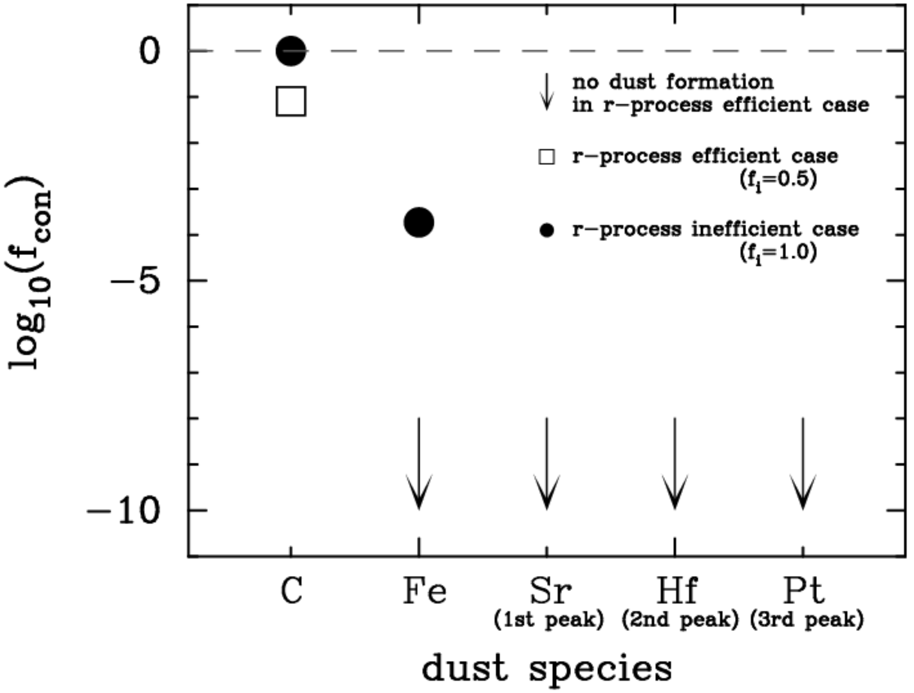
- Dust formation in NS-NS (NS-BH) mergers (macronovae)

5-1. Dust formation in Macronovae



Tanvir+2014

condensation efficiency



Takami, TN, Ioka 2014 in prep

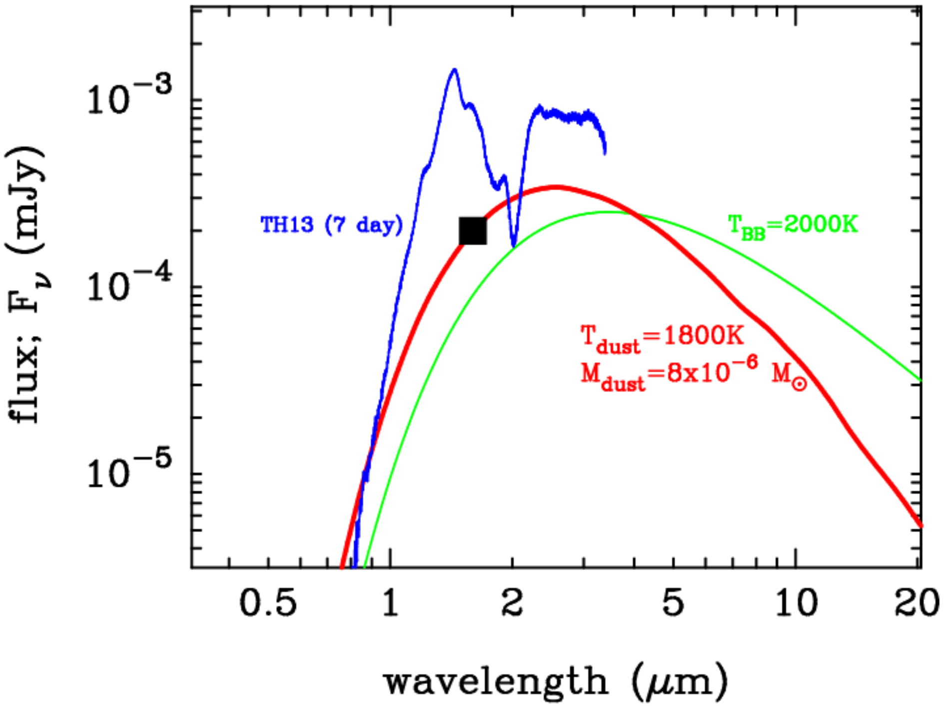
excess of NIR around 7 day

- processing of optical light by r-process elements
- NS-NS (NS-BH) merger is the formation sites of r-process elements

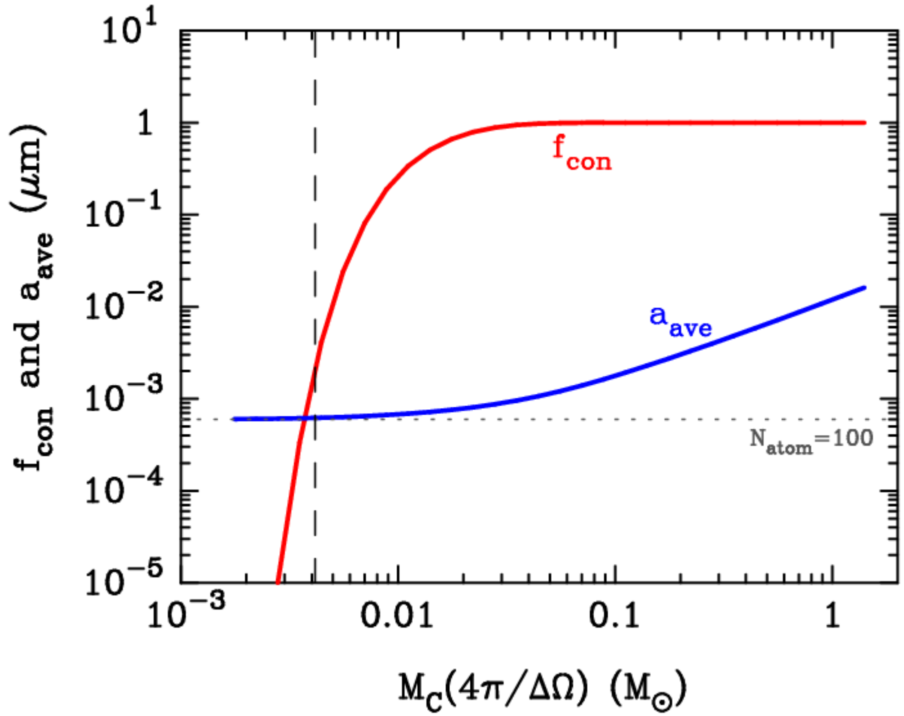
- r-process elements cannot condense into dust grains
- formation of C (and Fe) grains could be possible

5-2. Dust in Macronovae

thermal emission from C grains



condensation efficiency of C grains



- NIR detection of GRB 130603B around 7 day can be explained by thermal emission from hot (~1800 K) C grains with the mass of ~10^{-5} M_{sun}

Takami, TN, Ioka 2014 in prep

amount of C atom to achieve 10^{-5} M_{sun} of C grains

- NS-NS merger (ΔΩ/4π~1)
  ➔ $M_C = 4\times10^{-3}$ M_{sun}
- NS-BH merger (ΔΩ/4π~0.1)
  ➔ $M_C = 4\times10^{-4}$ M_{sun}