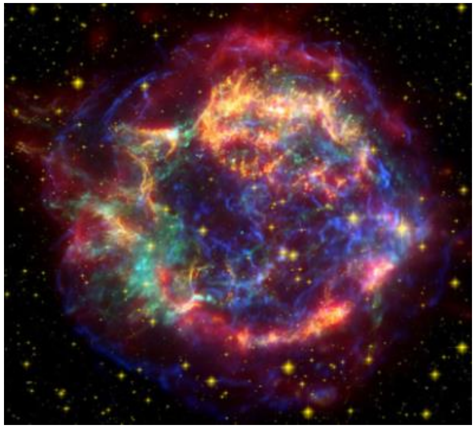
2019/02/06

Formation of dust and molecules in supernovae

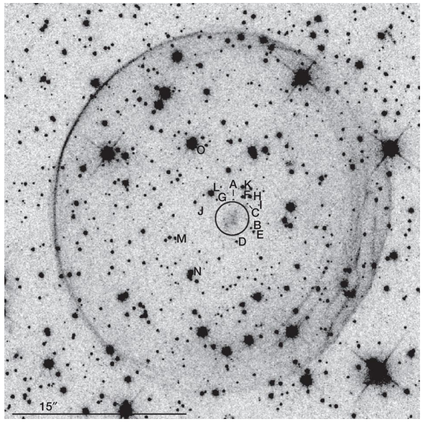
Takaya Nozawa

(National Astronomical Observatory of Japan)

SN 1987A



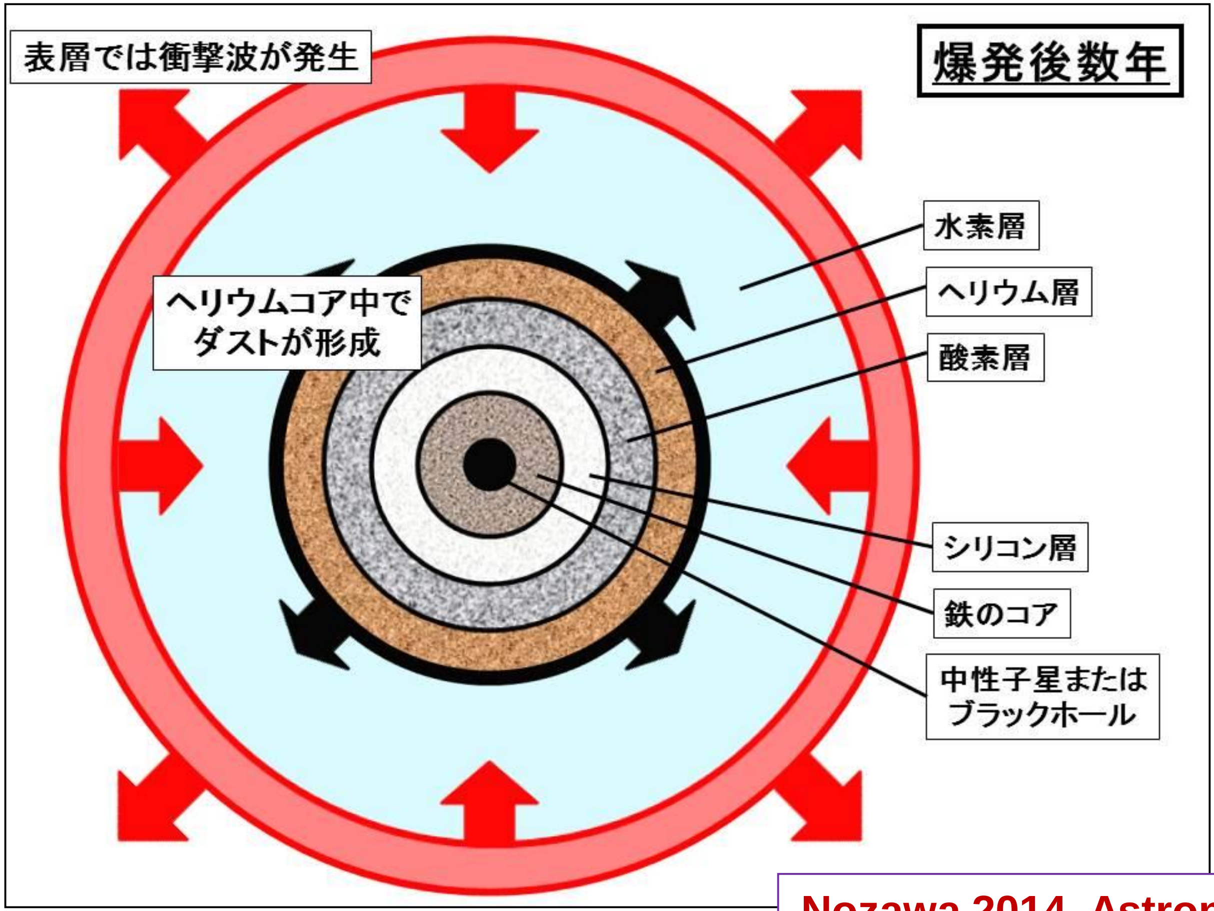
Cassiopeia A



SNR 0509-67.5

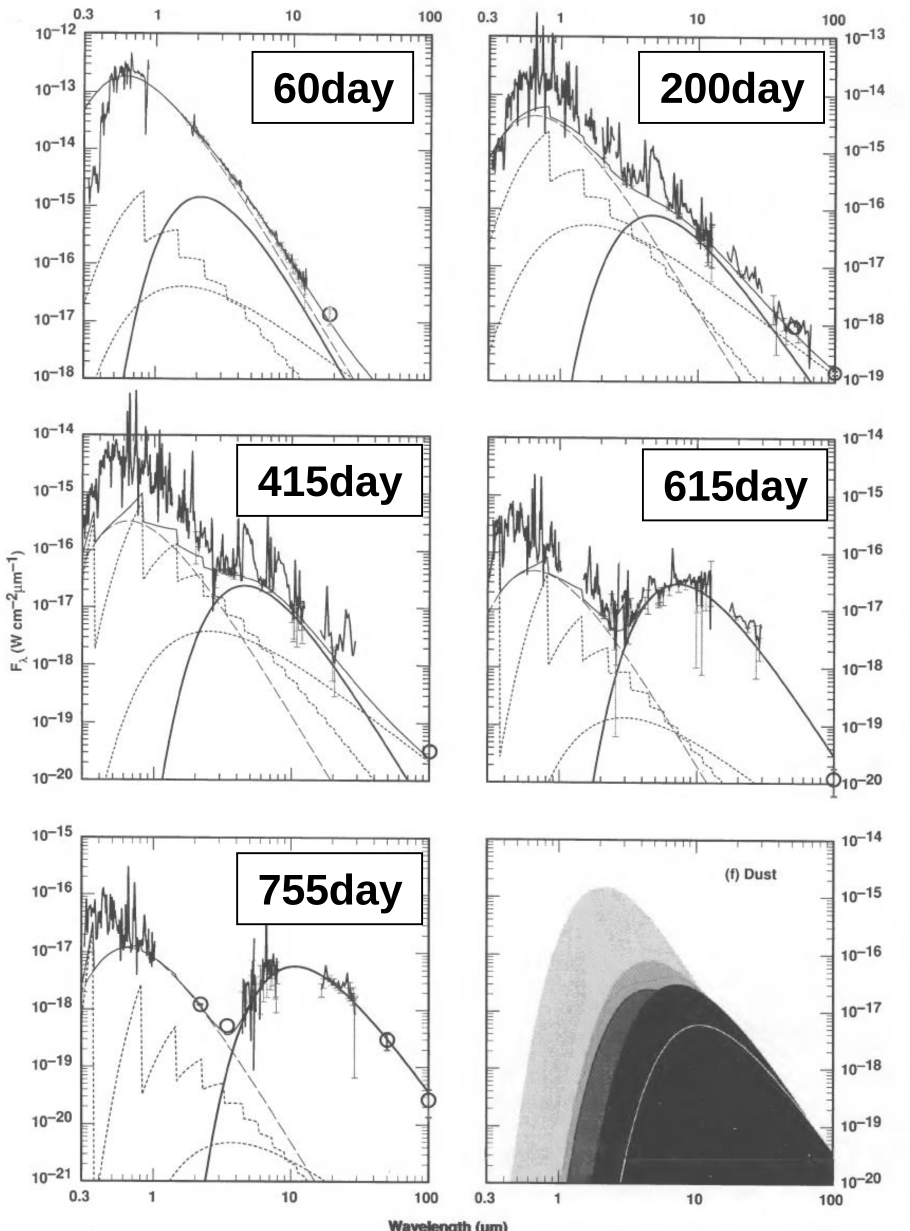
1-1. Introduction

Question : Can supernovae (SNe) produce molecules and dust grains?



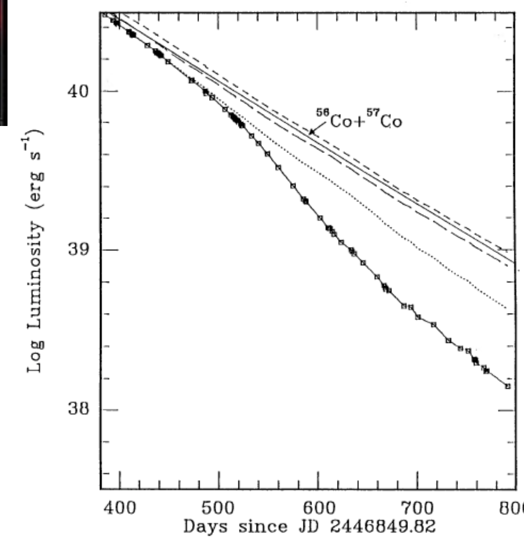
Nozawa 2014, Astronomical Herald

2-1. Thermal emission from dust in SN 1987A



Wooden+93

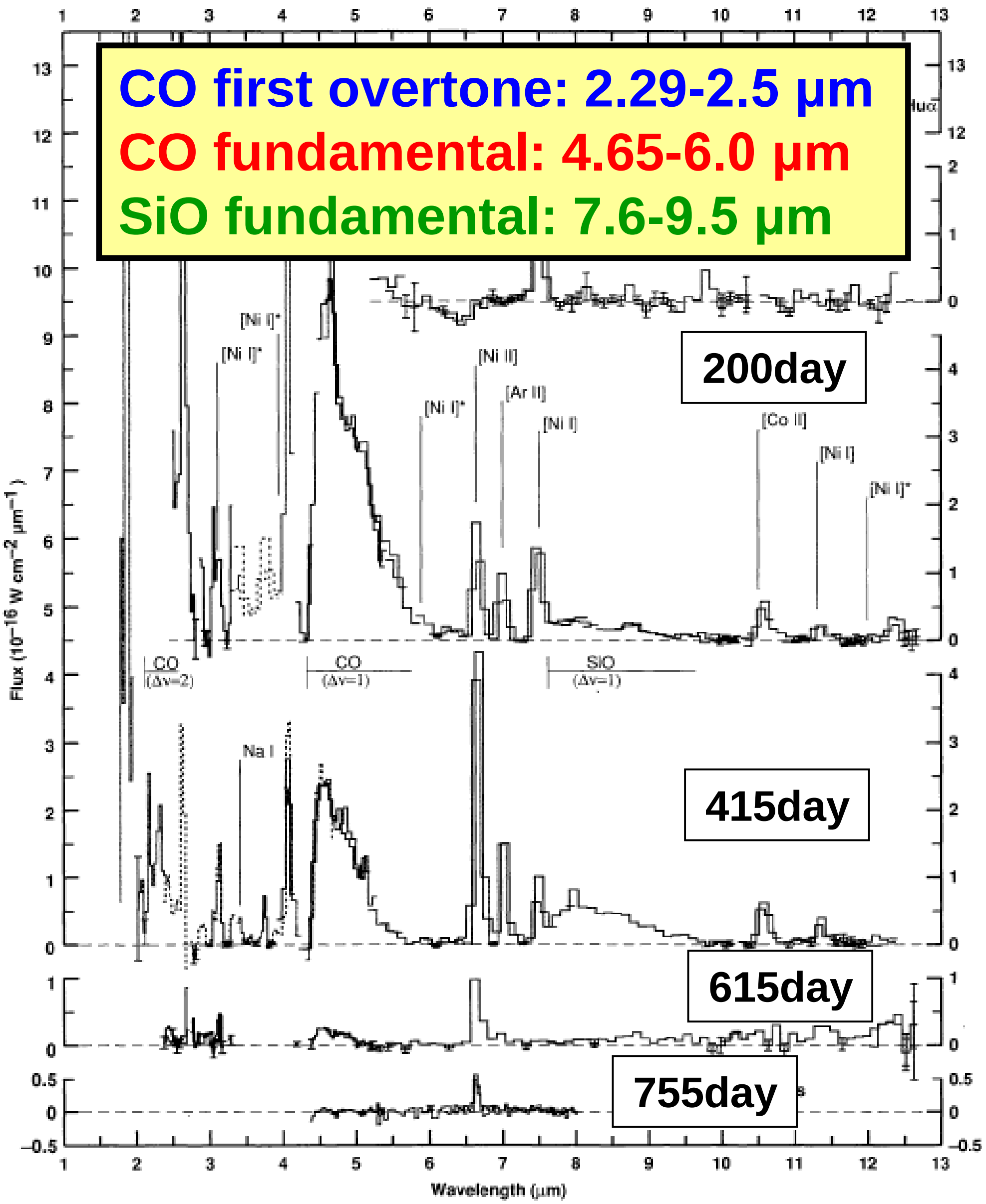
light curve
(optical luminosity)



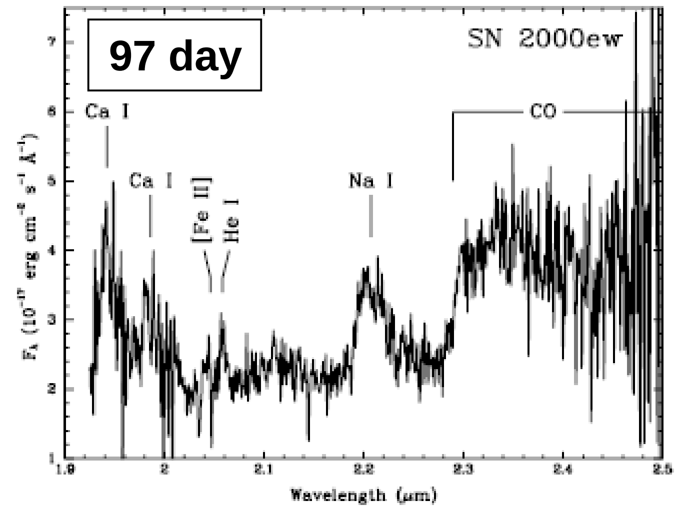
Whitelock+89

- dust starts to form in the ejecta at ~400 days
- dust mass ay 775 day: > ~10^{-4} Msun (optically thin assumed)

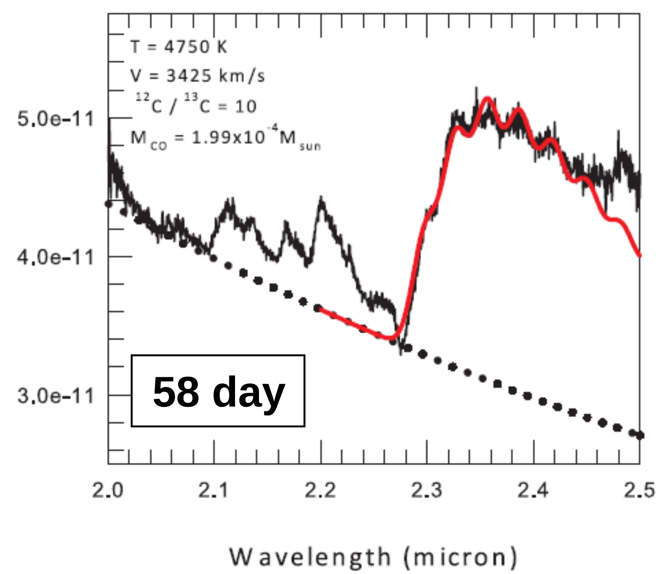
2-2. CO and SiO detection in SN 1987A



SN II-pec 1987A, Wooden+1993



SN Ic 2000ew, Gerardy+2002



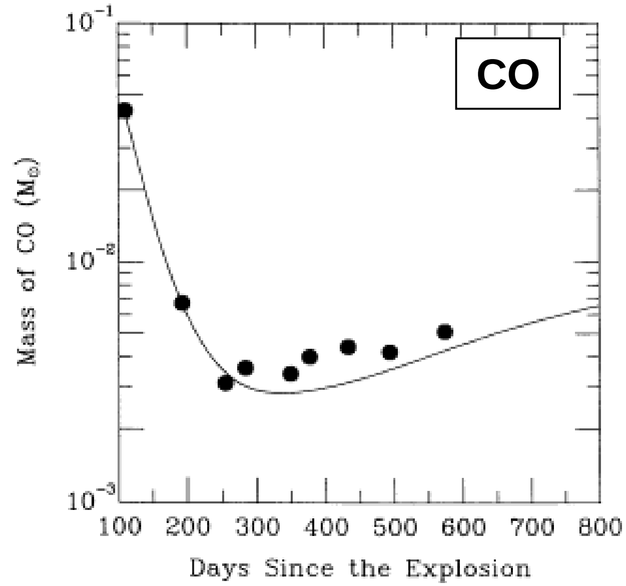
SN II-P 2016adj, Banerjee+2018

2-3. CO and SiO masses in SN 1987A

Table 1. CO detections in NIR spectra of SNe.

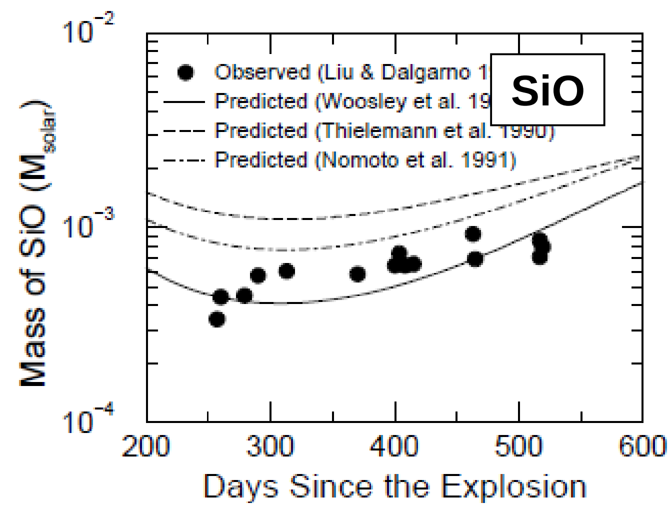
Event	SN type	Epoch of last CO non-detection	Epoch of first CO detection	References
CO detections				
SN 1987A	IIP Pec	112 d	192 d	1
SN 1995ad	IIP		105 d	2
SN 1998S	IIn	44 d	109 d	3
SN 1999dl	IIP		152 d	4
SN 1999em	IIP	118 d	178 d	4,5
SN 1999gi	IIP	74 d	126 d	5
SN 2000ew	Ic	39 d	97 d	6,7
Non-detections				
SN 1990W	Ic	90 d		8
SN 1995V	IIP	84 d		9
SN 2001B	Ib	60 d		7

Gerardy+2002, see also Banerjee+2018



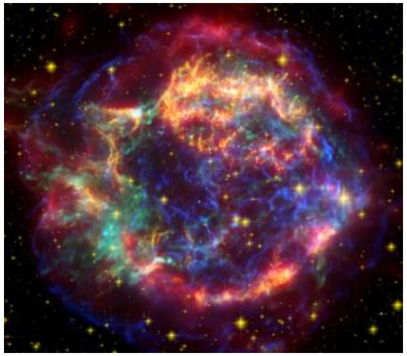
Liu+95

- CO emission is seen in various types of CCSNe from ~50 day
- CO/SiO masses in SN 1987A
  $M_{CO} > \sim 4\times10^{-3}$ Msun
  $M_{SiO} > \sim 7\times10^{-4}$ Msun



Liu & Dalgarno 1996

2-4. Dust mass in Cassiopeia A (Cas A) SNR



○ Estimated mass of dust in Cas A

- warm/hot dust (80-300K)

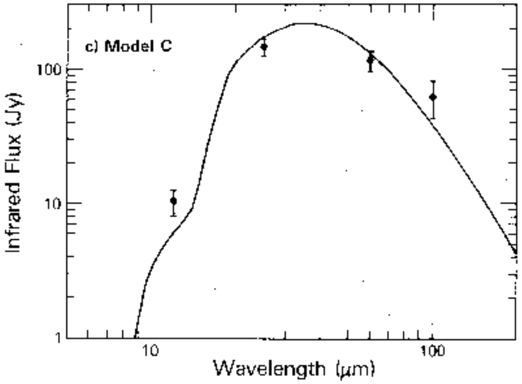
(3-7)x10^{-3} Msun (*IRAS,* Dwek et al. 1987)

~7.7x10^{-5} Msun (*ISO*, Arendt et al. 1999)

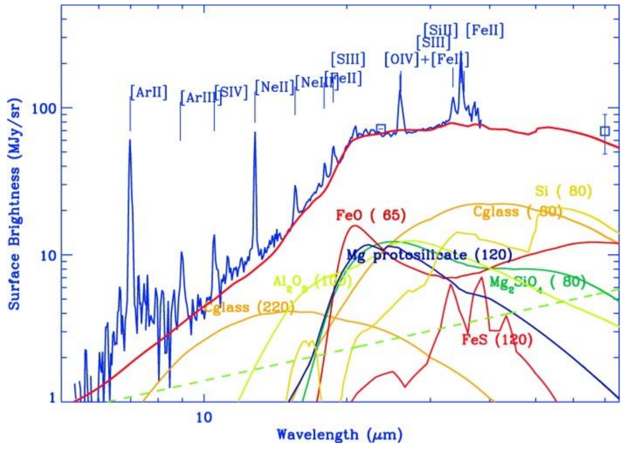
0.02-0.054 Msun (*Spitzer*, Rho+2008)

➜ Mdust = 10^{-4}-10^{-2} Msun

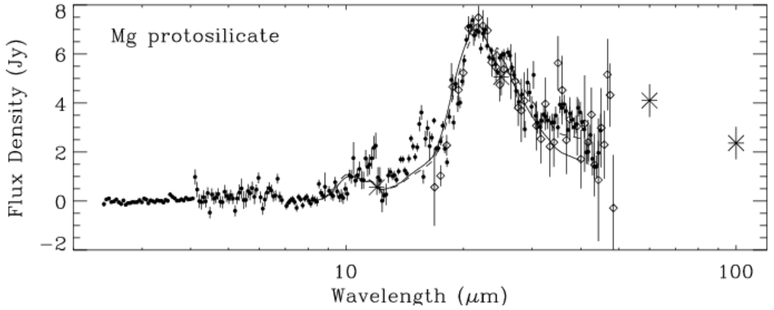
consistent with >10^{-4} Msun in SN 1987A



Dwek+1987, IRAS

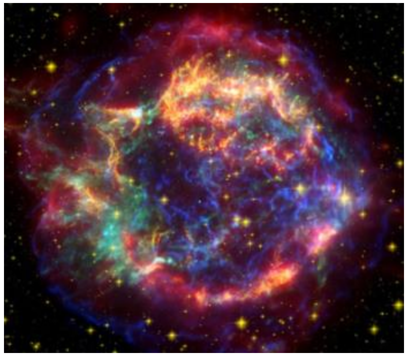


Rho+2008
Spitzer



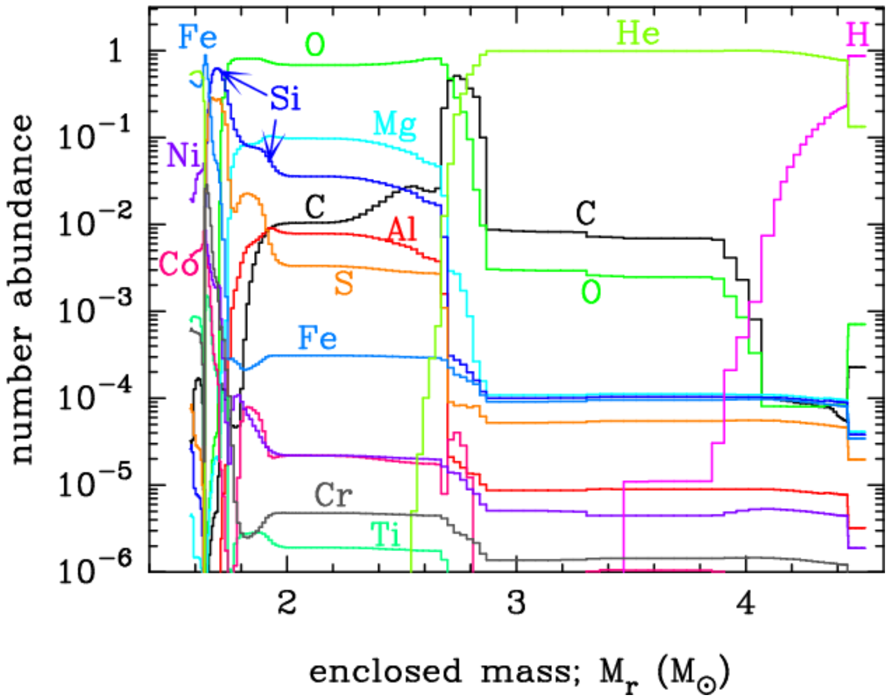
Arendt+1999, ISO

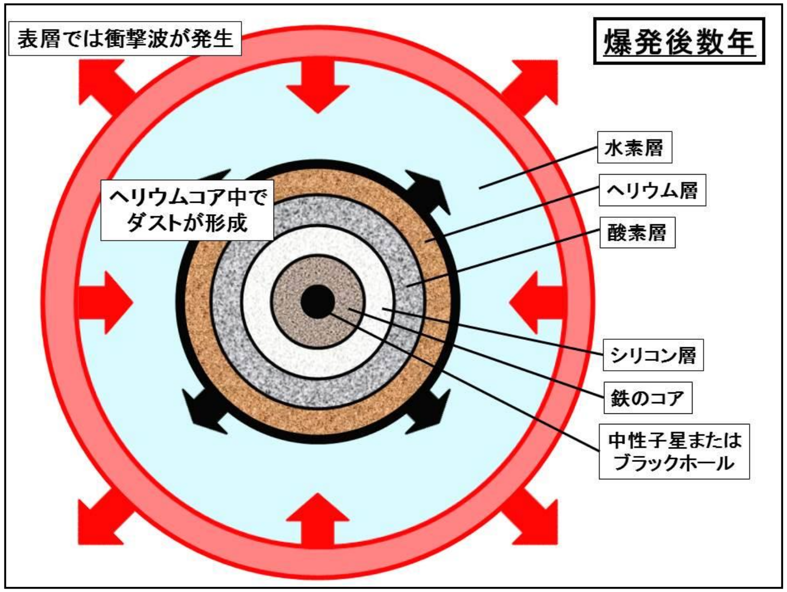
3-1. Dust formation in Type IIb SN



○ SN IIb model (SN1993J-like model)

- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1
- M(^{56}Ni) = 0.07 Msun



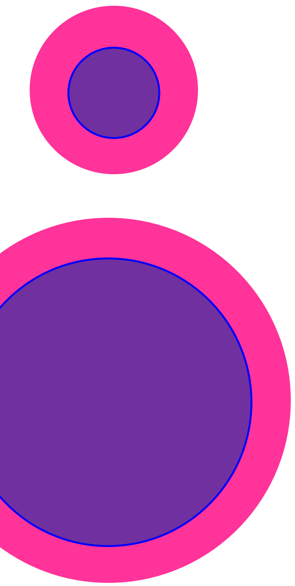


3-2. Equations for dust formation calculations

Formation rate of stable nuclei per volume

・ Nucleation rate

$$J_s(t) = \alpha_s \Omega \left(\frac{2\sigma}{\pi m_1} \right)^{\frac{1}{2}} \Pi c_1^2(t) \exp \left[-\frac{4}{27} \frac{\mu^3}{(\ln S)^2} \right]$$



・ Grain growth

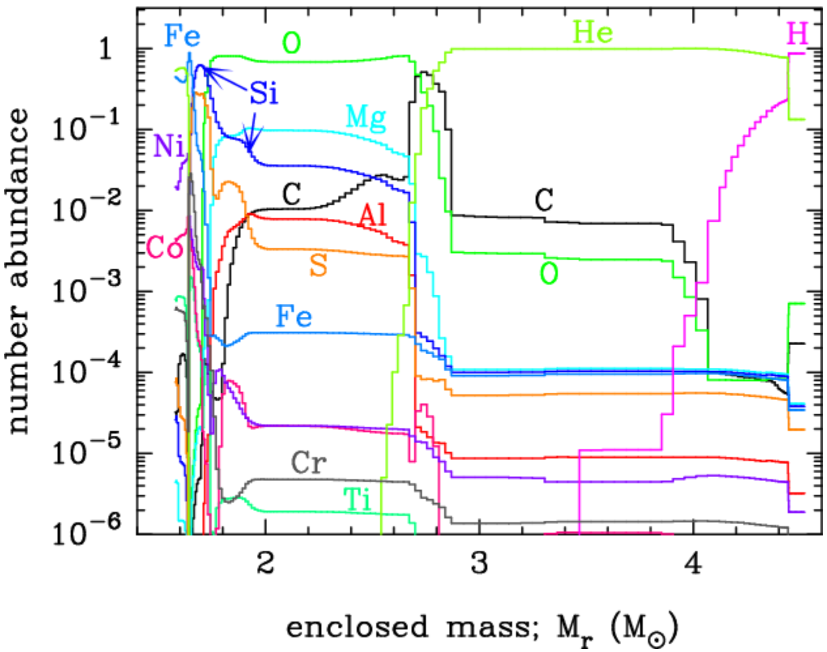
$$\frac{da}{dt} = s\Omega_0 \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S} \right),$$

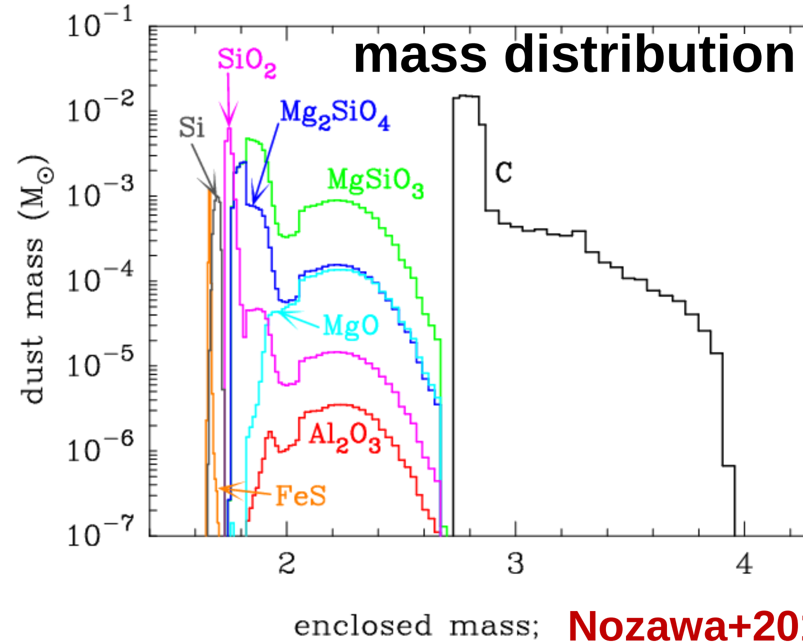
Growth rate of dust is independent of its size

・ Mass conservation

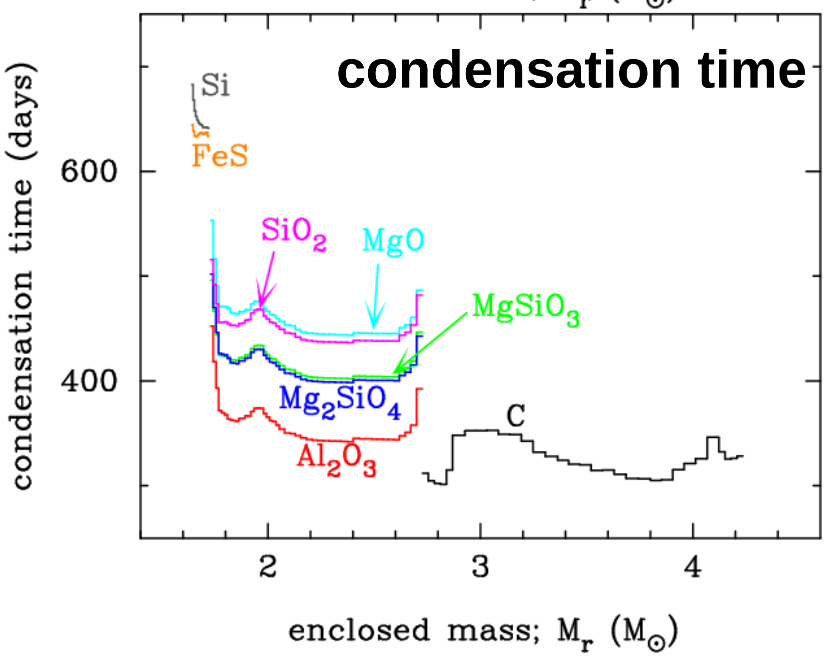
$$c_{10} - c_1 = \int_{t_0}^{t} J_{n_*}(t') \frac{a^3(t, t')}{a_0^3} dt',$$

3-3. Results of dust formation calculations





Nozawa+2010

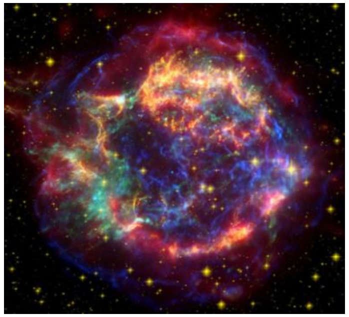


- condensation time of dust
  300-700 d after explosion
- total mass of dust formed
  - **Mdust = 0.167 Msun in SN IIb**
  - **Mdust = 0.1-1 Msun in SN II-P**

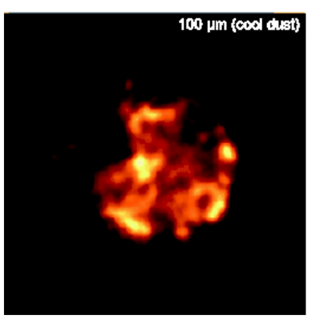
  ➜ **5-10% of metal mass**

3-4. Comparison with IR observations of Cas A

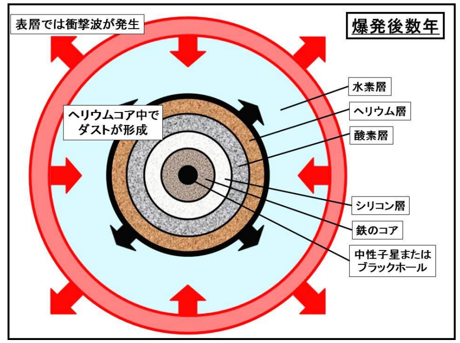
Cassiopeia A

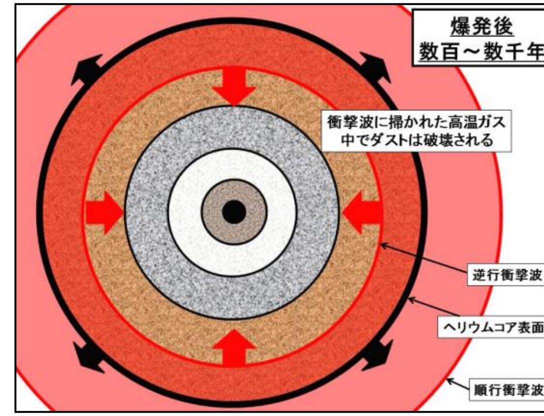


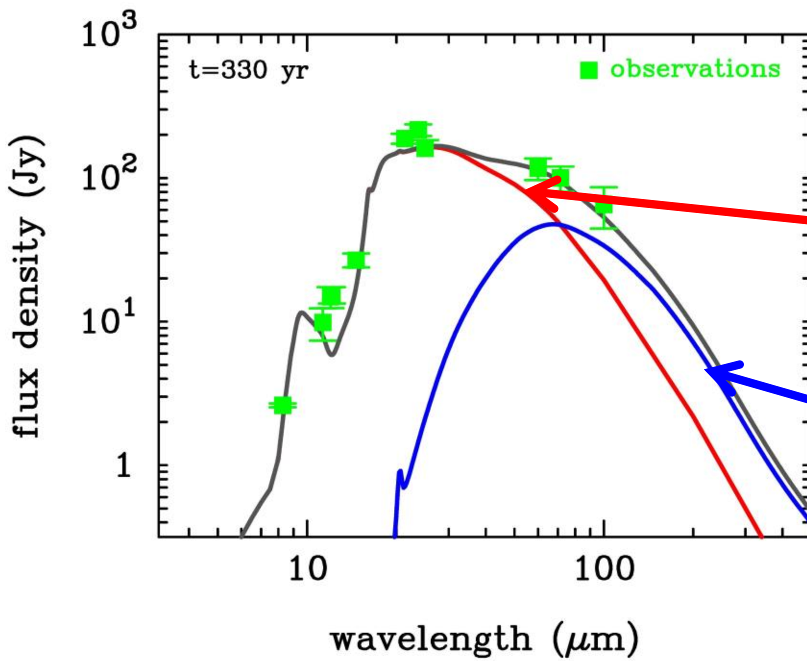
Herschel FIR observation



Barlow+2011







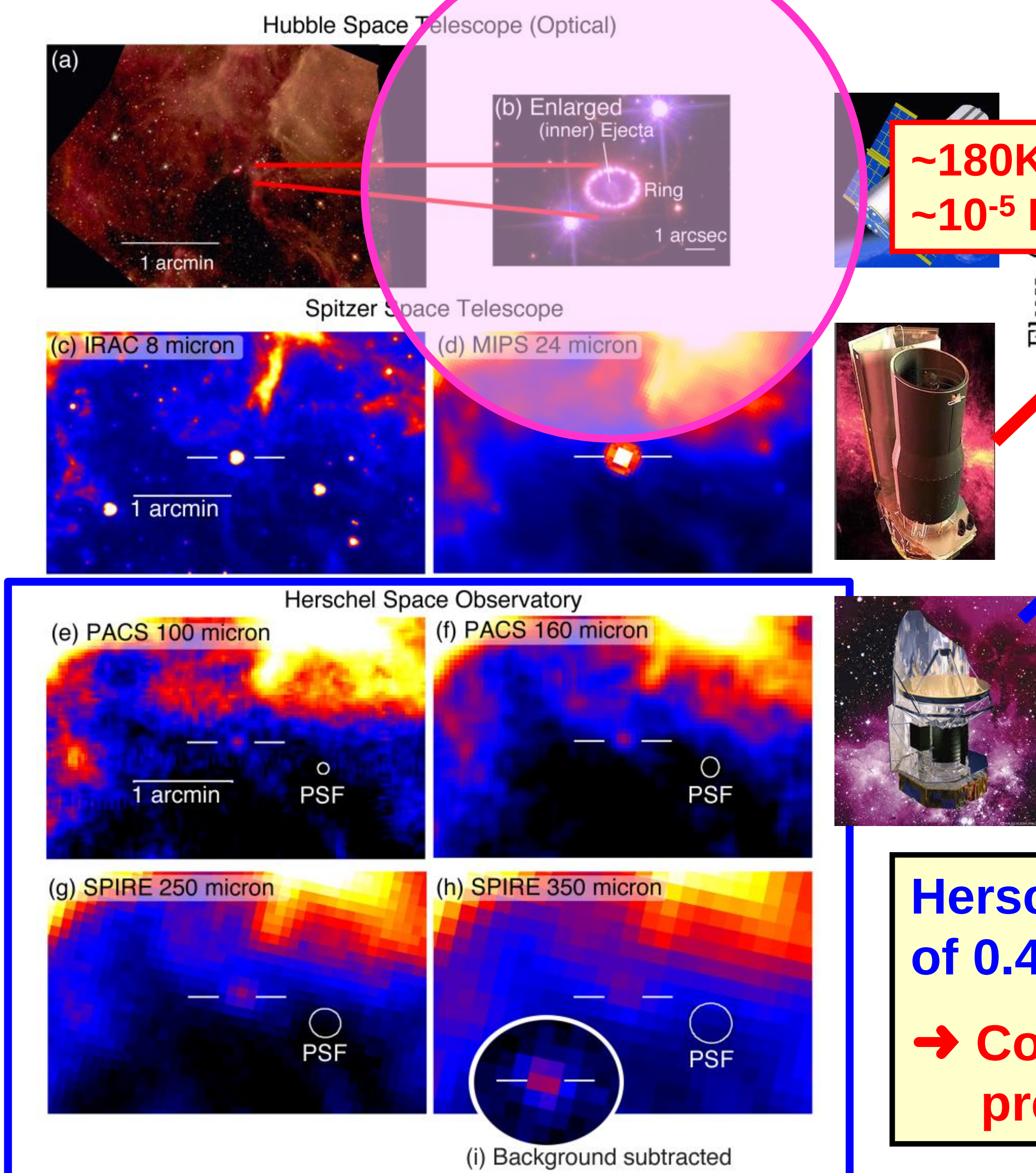
0.008Msun of shocked warm dust

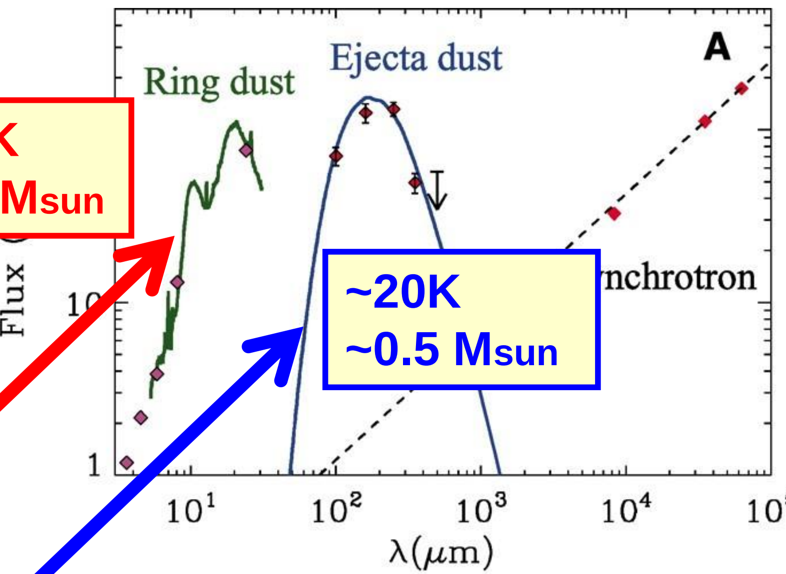
0.07Msun of unshocked cool dust

Nozawa+2010

FIR observations with Herschel revealed the presence of 0.06 Msun of cool dust inside Cas A

4-1. Herschel detects cool dust in SN 1987A





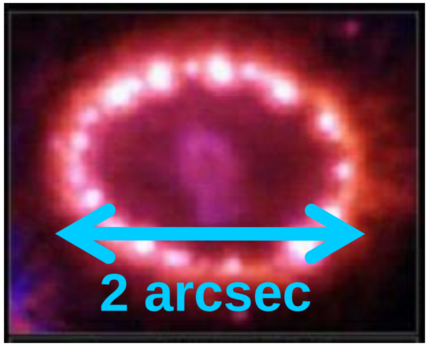
Matsuura+2011, Science

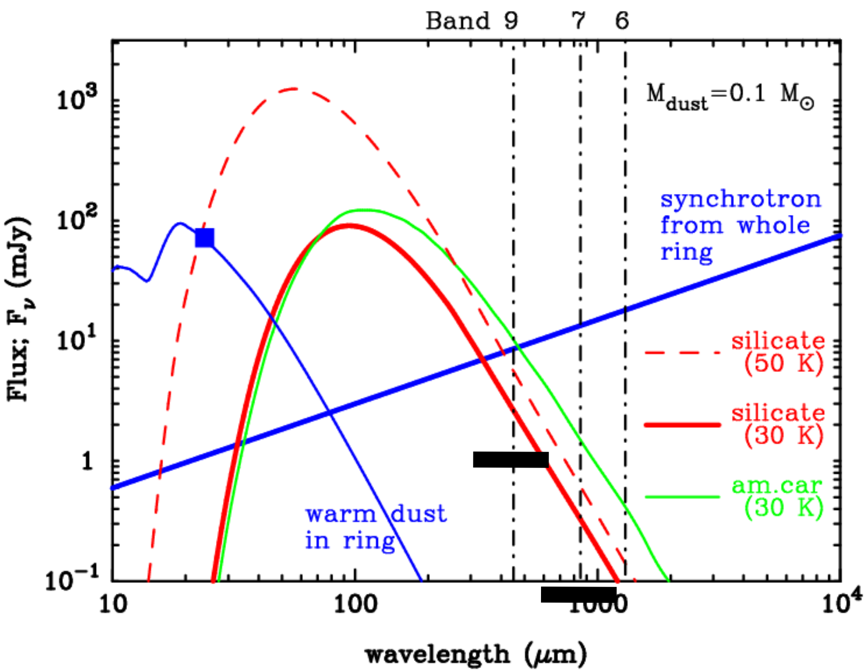
Herschel detected cool (20K) dust of 0.4-0.7 Msun toward SN 1987A!

➜ Consistent with theoretical prediction of Mdust =0.1-1 Msun

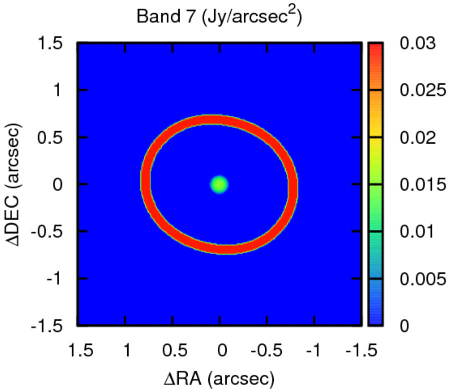
4-2. Resolving cool dust in SN 87A with ALMA

ALMA Cycle 0 Proposal
'Detecting cool dust in SN1987A'
(TN, Tanaka, et al.)

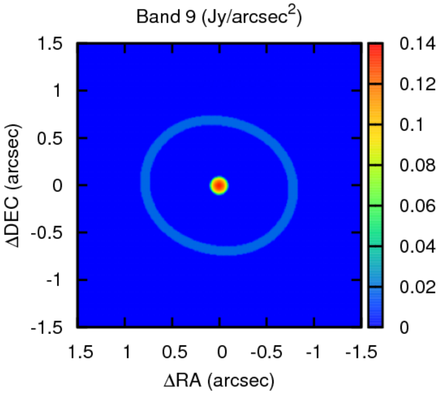




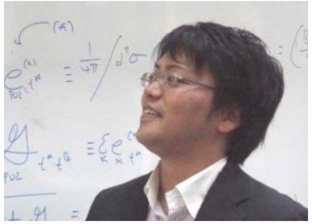
Band 7 (850 μm)

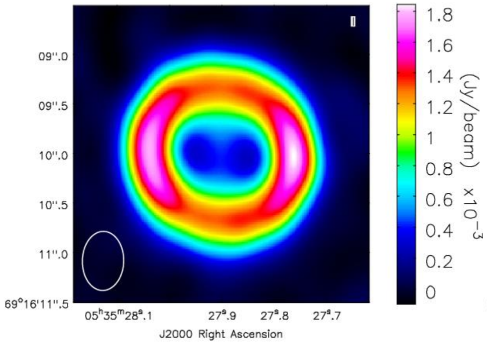


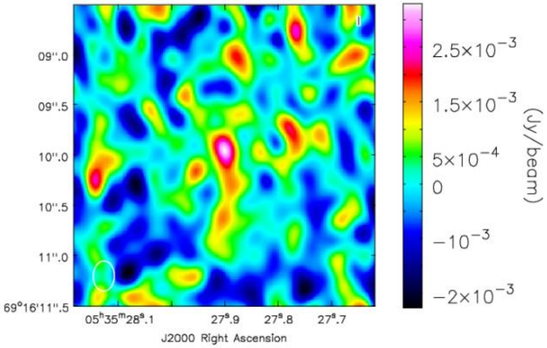
Band 9 (450 μm)



CASA simulation with extended config. (4 hrs)







0.1 Msun of silicate
➔ 5σ detection at Band 9 !!

4-3. Successful ALMA proposals for SN 1987A

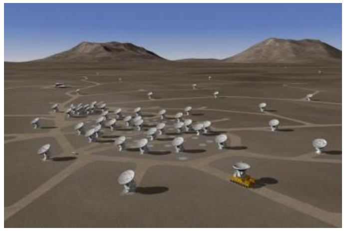
2011.0.00221.S

PI	Exec	Country	Institute
Nozawa, Takaya	EA	Japan	The University of Tokyo
COI			
Tanaka, Masa[illegible]i	EA	Japan	The University of Tokyo
Moriya, Takashi	EA	Japan	University of Tokyo
Minamidani, Tetsuhiro	EA	Japan	Hokkaido University
Kozasa, Takashi	EA	Japan	Hokkaido University

Our proposal was not executed

Band 9

extended configuration



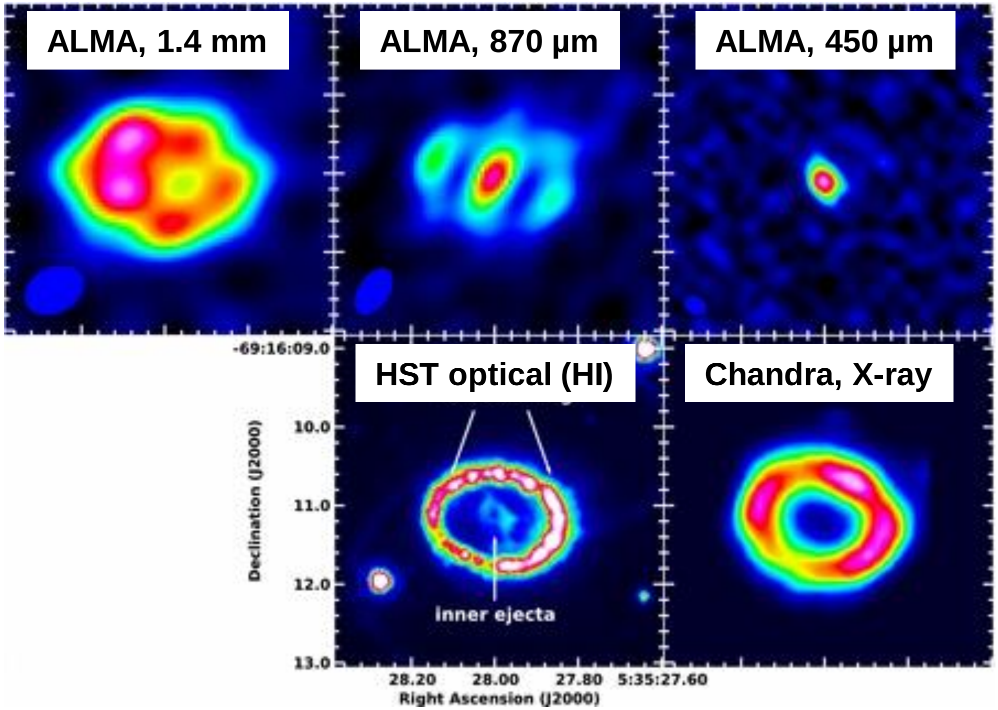
2011.0.00273.S

PI	Exec	Country	Institute
Indebetouw, Remy	NA	United States	Virginia, University of
COI			
McCray, Richard	NA	United States	Colorado at Boulder, Univ of
Matsuura, Mikako	EU	United Kingdom	London, University of
Andjelic, Milica	OTHER	Serbia	Belgrade, University of
Arbutina, Bojan	OTHER	Serbia	Belgrade, University of
Baes, Maarten	EU	Belgium	Ghent University
Urosevic, Dejan	OTHER	Serbia	Belgrade, University of
Vlahakis, Catherine	CL	Chile	Chile, University of
Ze			
Za			
Ng			
Pa			
Ba			
Cla			
Wesson, Roger	EU	United Kingdom	London, University of
Dwek, ELi	NA	United States	National Aeronautics and Space Administration
Bouchet, Patrice	EU	France	CEA Saclay
Lakicevic, Masa	EU	Germany	European Southern Observatory
Potter, Toby	OTHER	Australia	International Centre for Radio Astronomy Research

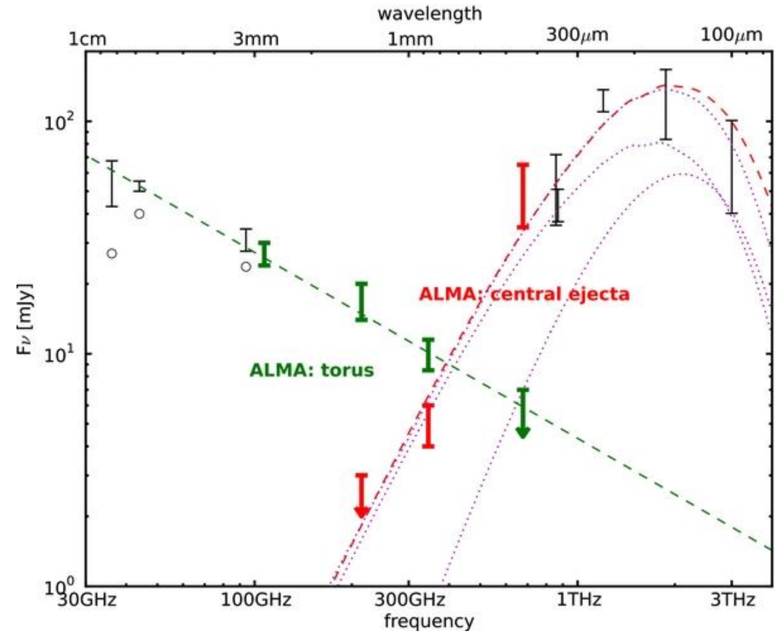
Band 3, 6, 7, 9

compact configuration

4-4. ALMA reveals dust formed in SN 1987A



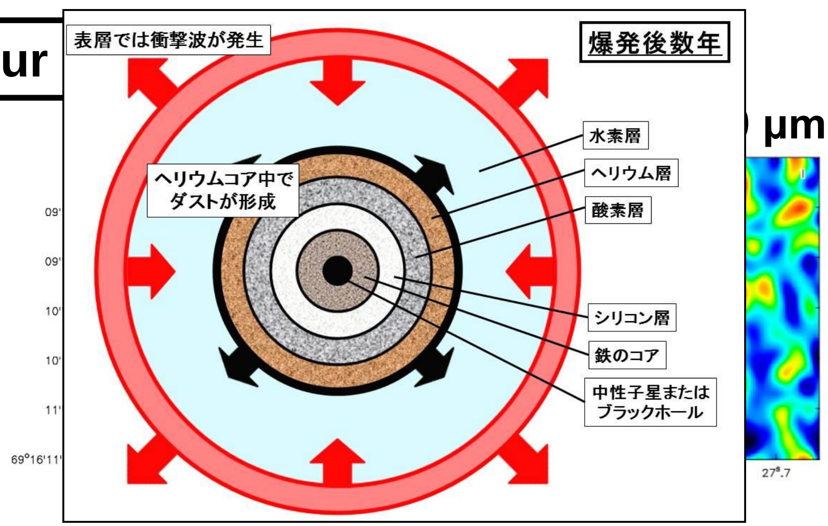
SED of 25-years old SN 1987A



Indebetouw+2014

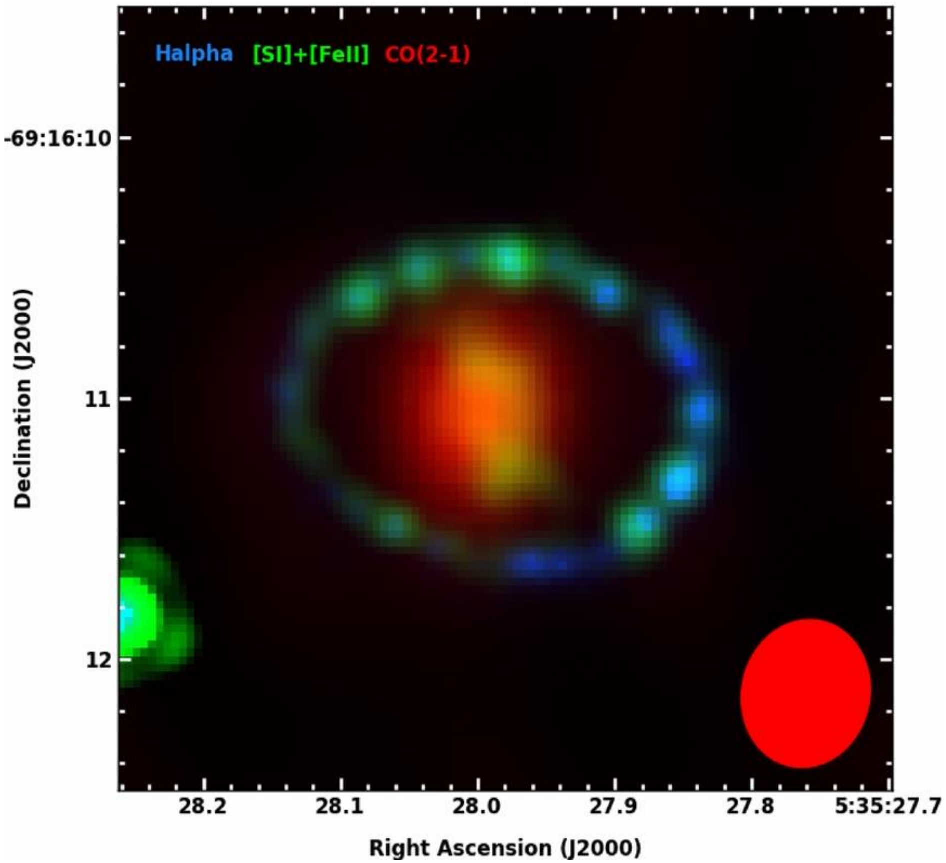
Our

μm)

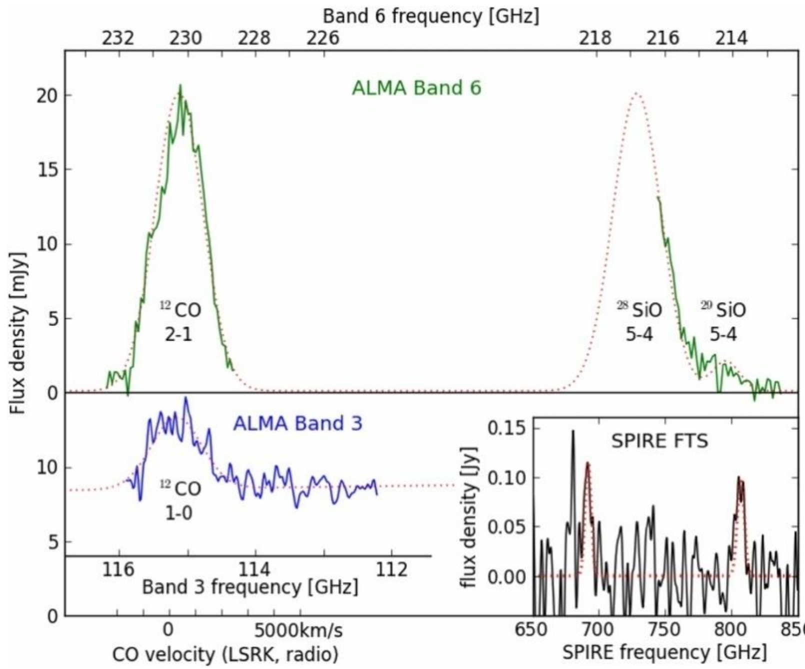


ALMA spatially resolves cool (~20K) dust of ~0.5 Msun formed in the ejecta of SN 1987A
➔ SNe could be production factories of dust grains

4-5. CO detection in SN 1987A with ALMA



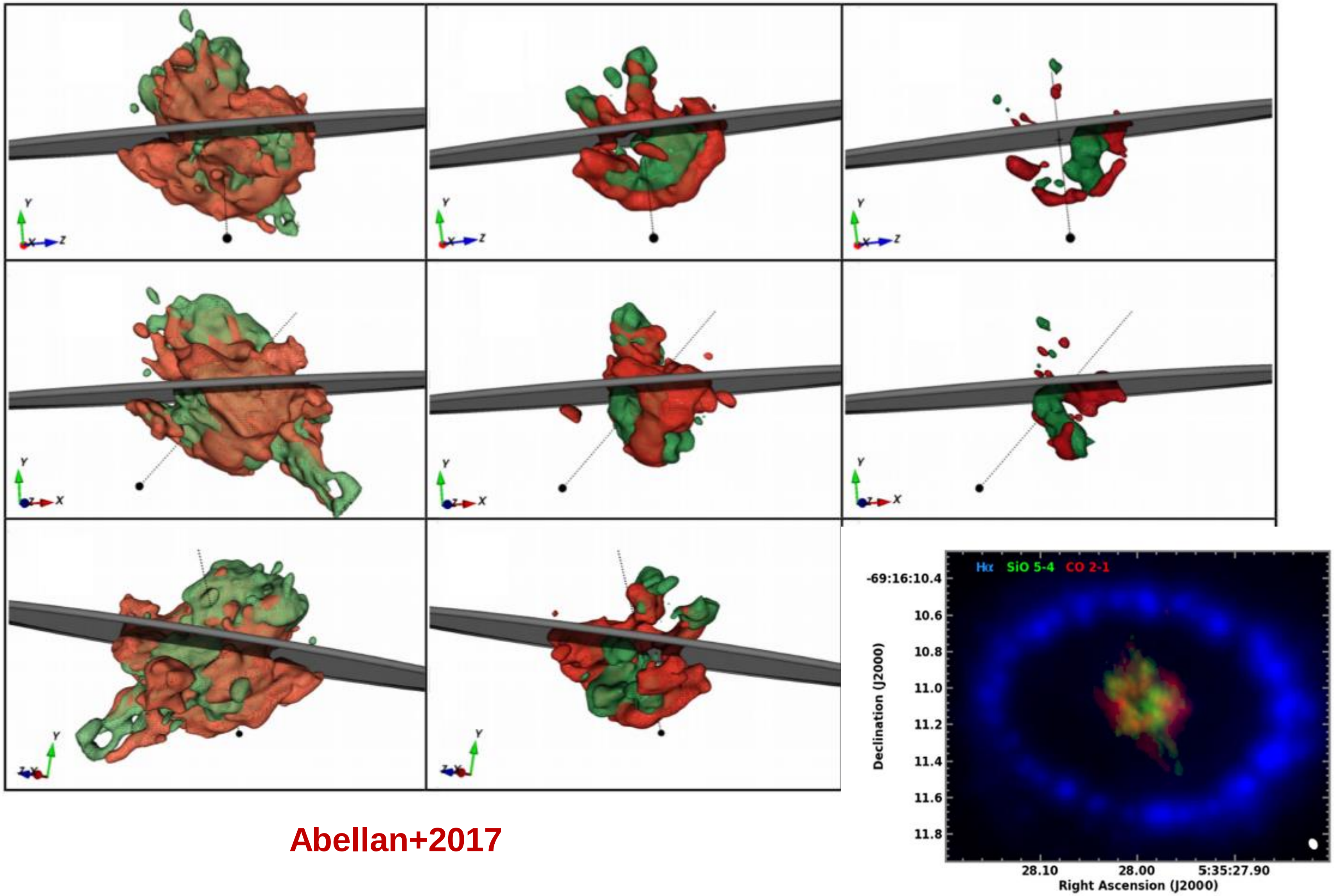
blue: Hα
green: [SiI]+[FeII] (1.64 μm)
red: CO(2-1)



Kamenetzky+13

- **CO properties**
  - Vco ~ 2200 km/s
  - Mco > 0.01 Msun
  - Tco > 14 K
- **For ALMA full operation, 3D maps of CO and SiO**

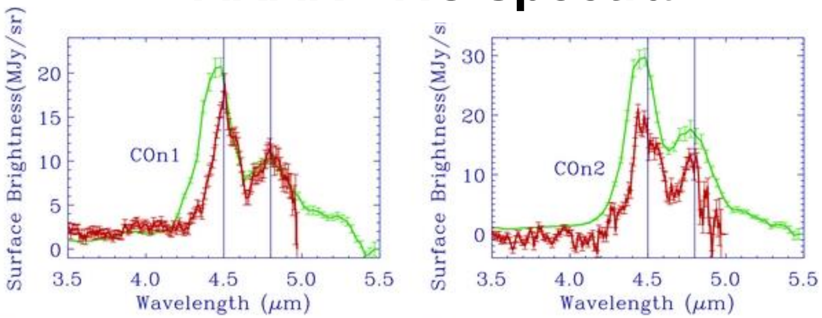
4-6. 3D-structure of CO and SiO emission

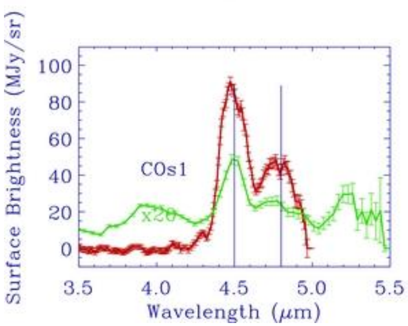


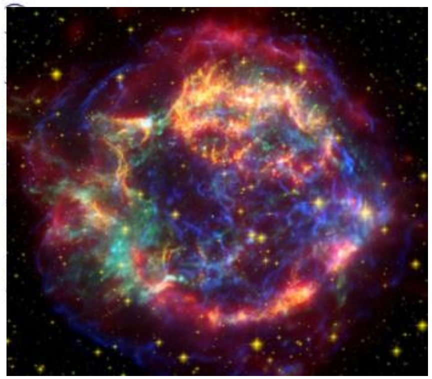
Abellan+2017

4-7. CO detection in Cassiopeia A SNR

AKARI IRC spectra

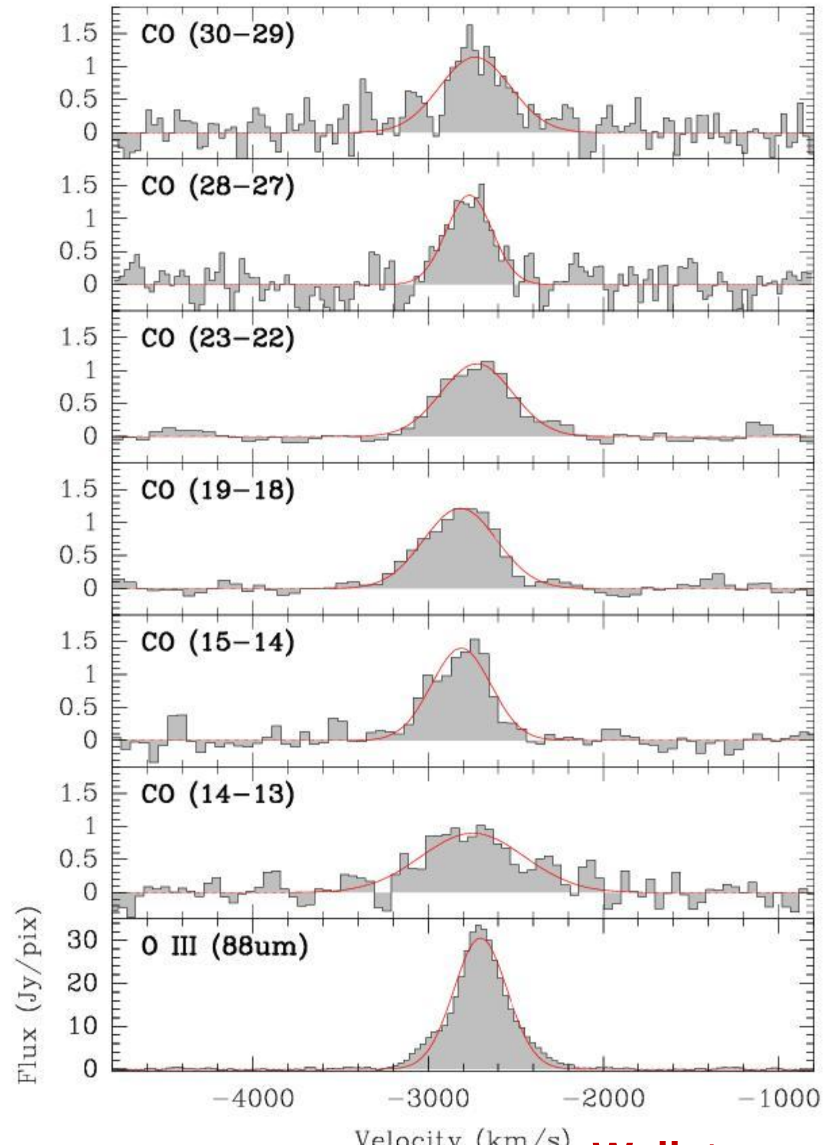






Rho+12

Herschel PACS

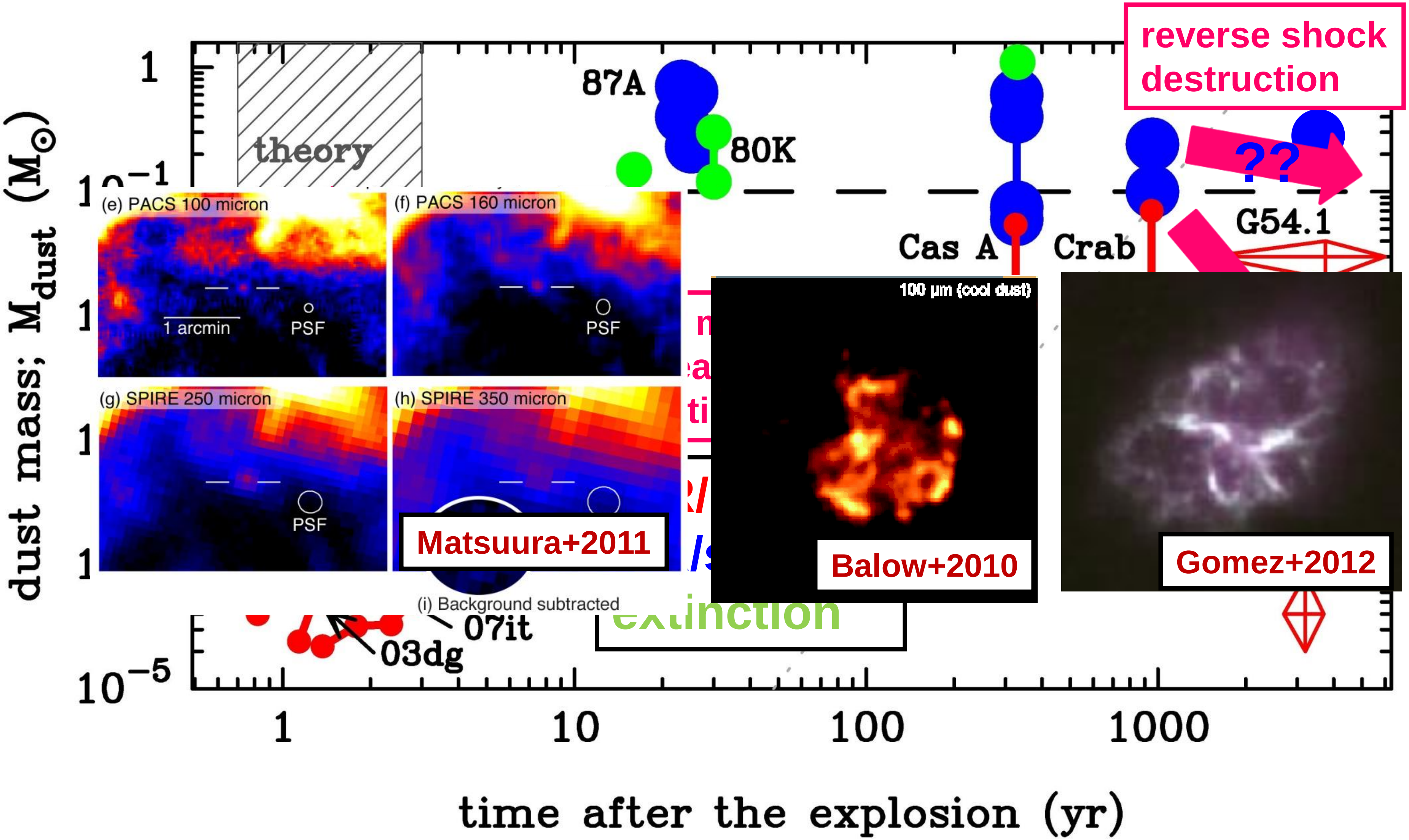


Wallstrom+13

- M_{CO} ~ 6×10^{-7} -$x10^{-6}$ M_{sun}
- T_{CO} = 400 K and 2400 K
- knot density: 10^{6-7} /cm^3

CO was not destroyed by the shock or was reformed recently

5-1. Observed dust mass in CC-SNe/SNRs



Dust mass formed in the ejecta is dominated by cold dust

5-2. Questions for dust formation in SNe

(1) What fraction of newly formed dust can survive the destruction by reverse shock?

- theory: ~5-50 % (M_{dust} ~ 0.01-0.1 M_{sun} per CCSN)
- obs.: very hard to detect dust from more extended SNRs

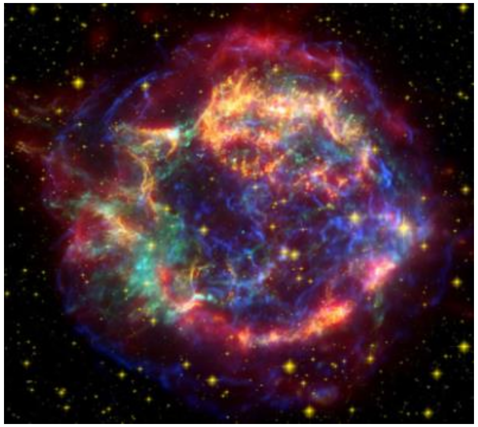
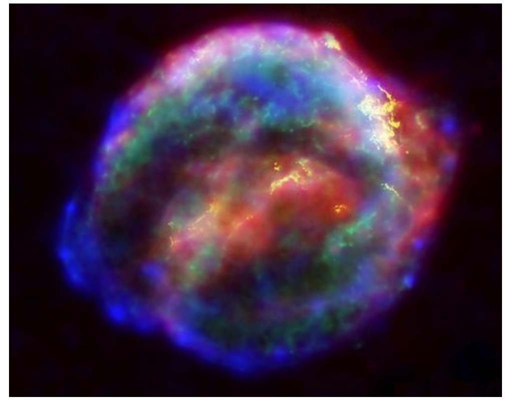
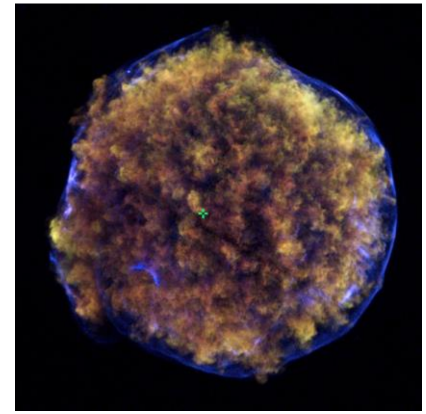
(2) When do the majority of grains form?

- theory (1-3 yr) vs obs (~10-20 yr)
- JWST will not be able to resolve this question
- ALMA can disclose it if CCSNe happen in MW and L/SMC

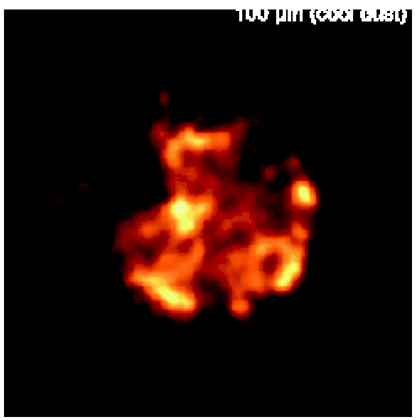
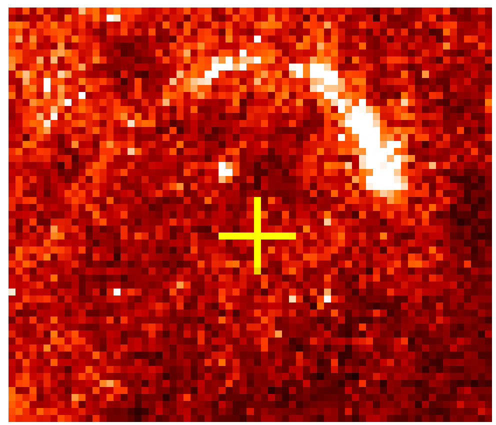
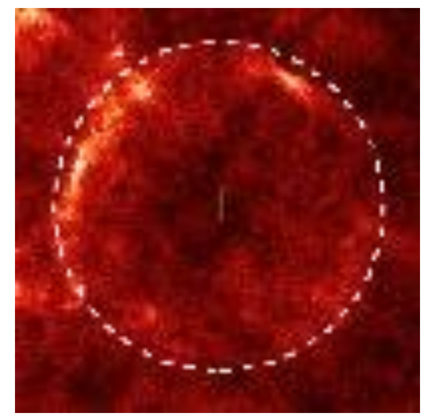
(3) Can dust (and molecules) form in SNe Ia?

6-1. No dust in the ejecta of Type Ia SNRs

Cas A (Type IIb) | Kepler (Type Ia) | Tycho (Type Ia)

Herschel 100 μm image

Barlow+2011

Gomez, Clark, TN, +2012

Herschel detected no cool dust in Galactic Type Ia SNRs, Kepler and Tycho (M_{dust} < ~10^{-3} M_{sun})

6-2. No evidence for dust formation in SNe Ia

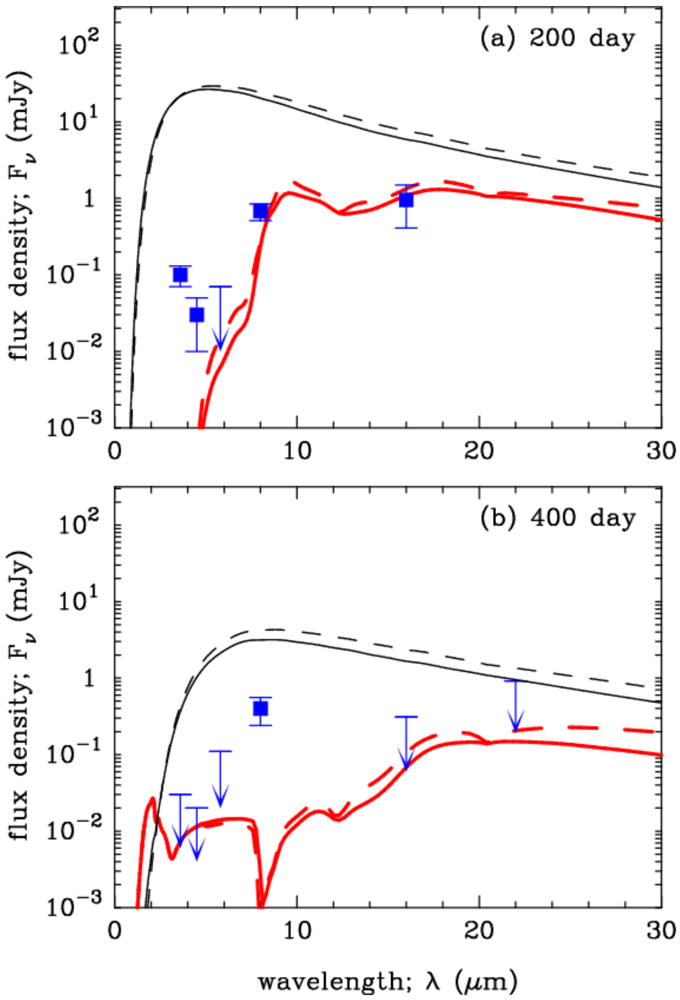
○ Hard to observe SNe Ia in IR

- SNe Ia fade more rapidly
  ➜ Luminosity is small at >100 day

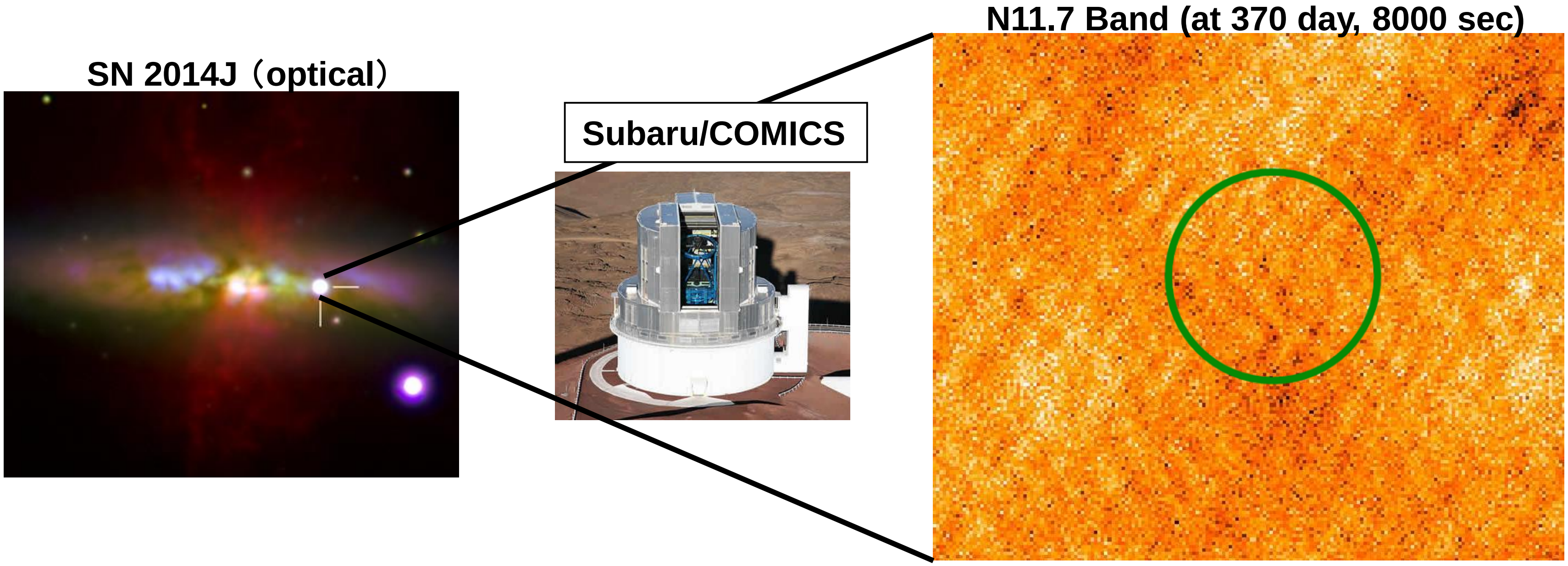
- SNe Ia hardly occur in nearby galaxies
  ➜ too far to be detected in MIR

- SN 2011fe and SN 2014J
  ➜ Spitzer stopped MIR obs in 2009

MIR obs of SN 2005bf at day 200 and 400
(Gerardy+2007)



6-3. MIR Observations of SN 2014J with Subaru



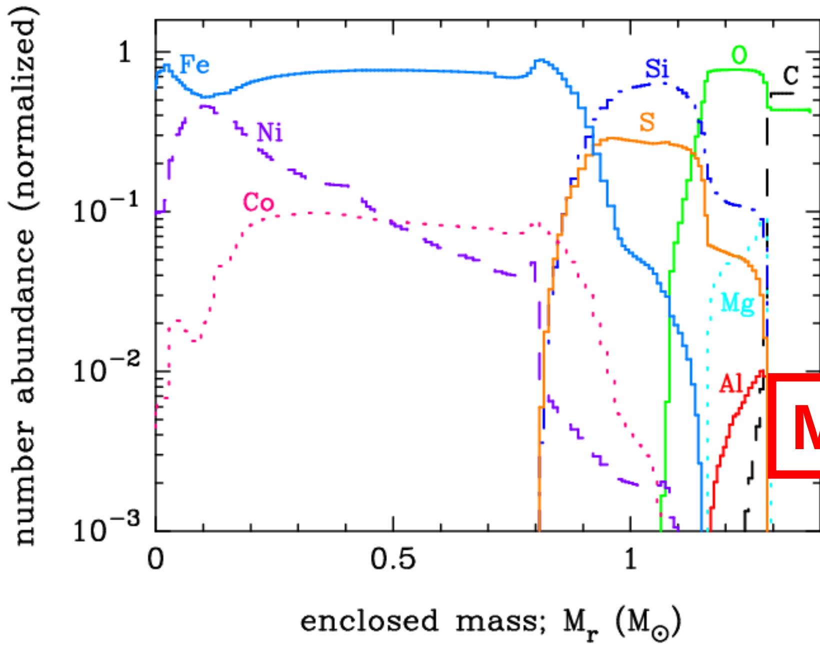
T. Nozawa et al. unpublished

○ No detection of SN 2014J with Subaru/COMICS

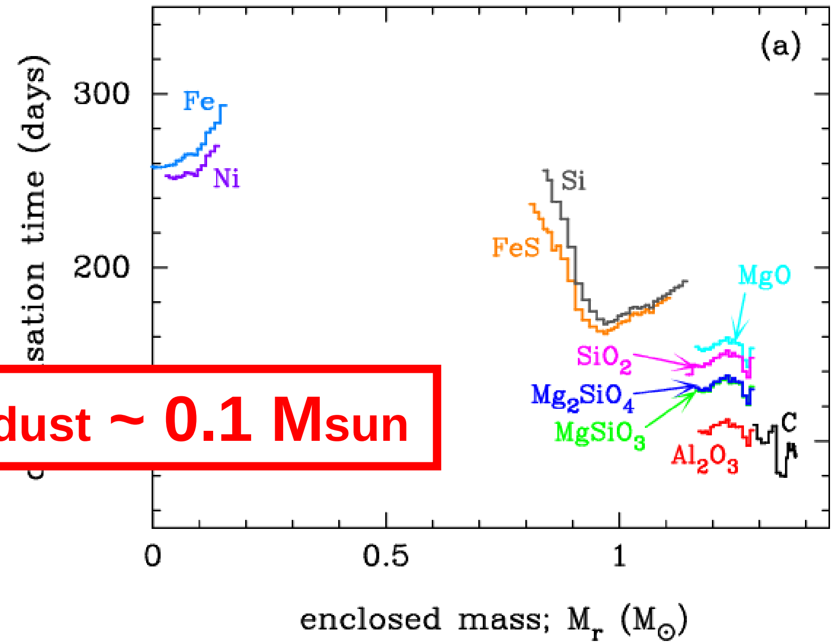
- No massive amounts of dust grains formed in the ejecta (M_{dust} < ~0.1 M_{sun})
- No massive circumstellar dust grains around SN 2014J

6-4. Suppressed formation of dust in SNe Ia?

W7 SN Ia model (C-deflagration)
(Nomoto+1984; Thielemann+1986)



Condensation time



Mdust ~ 0.1 Msun

Nozawa+2011

○ SNe Ia are harsher than CCSNe?

M(56Ni) ~ 0.6 Msun ➜ 10 times higher than that of CCSNe

dust and molecules can be destroyed by energetic photons and electrons prevailing in the ejecta

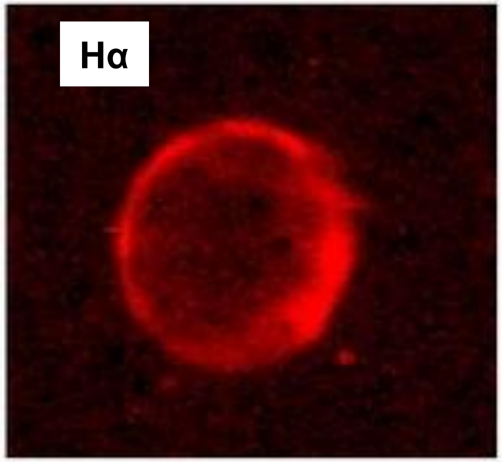
6-5. Can ALMA detect dust in SNe Ia?

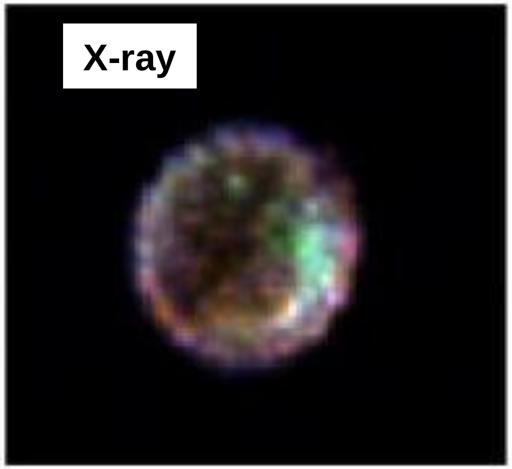
- extragalactic SNe are too far (D > 1 Mpc) to detect the thermal emission from cool dust in ejecta with ALMA
- young Galactic SNRs are too extended (θ > 1 arcmin) for good spatial resolution of ALMA (~0.1 arcsec)

young (compact) SNRs in LMC/SMC !

○ SNR 0509-67.5

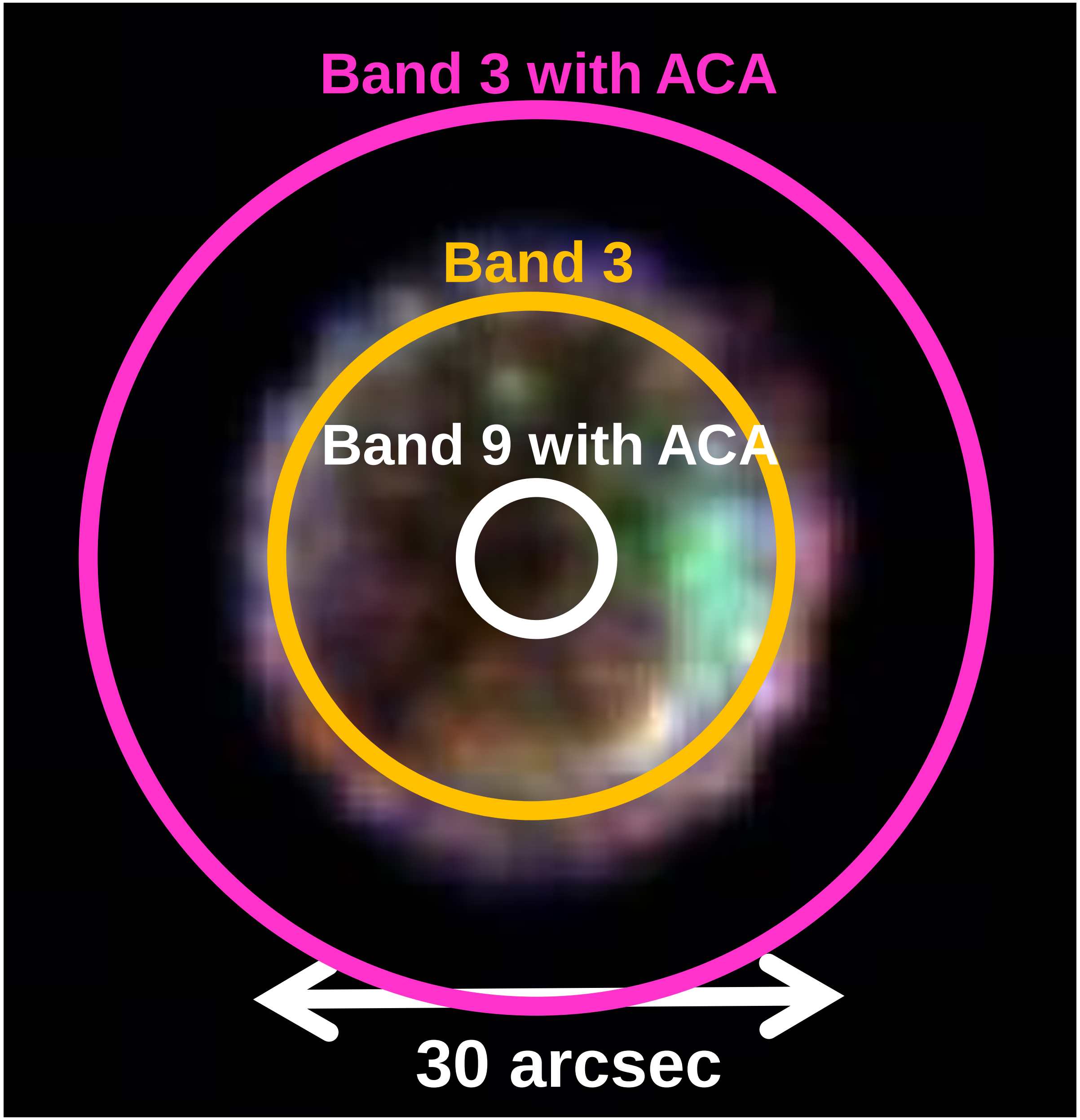
- Type Ia SNe
- age : ~400 yr
- in LMC (d=50 kpc)





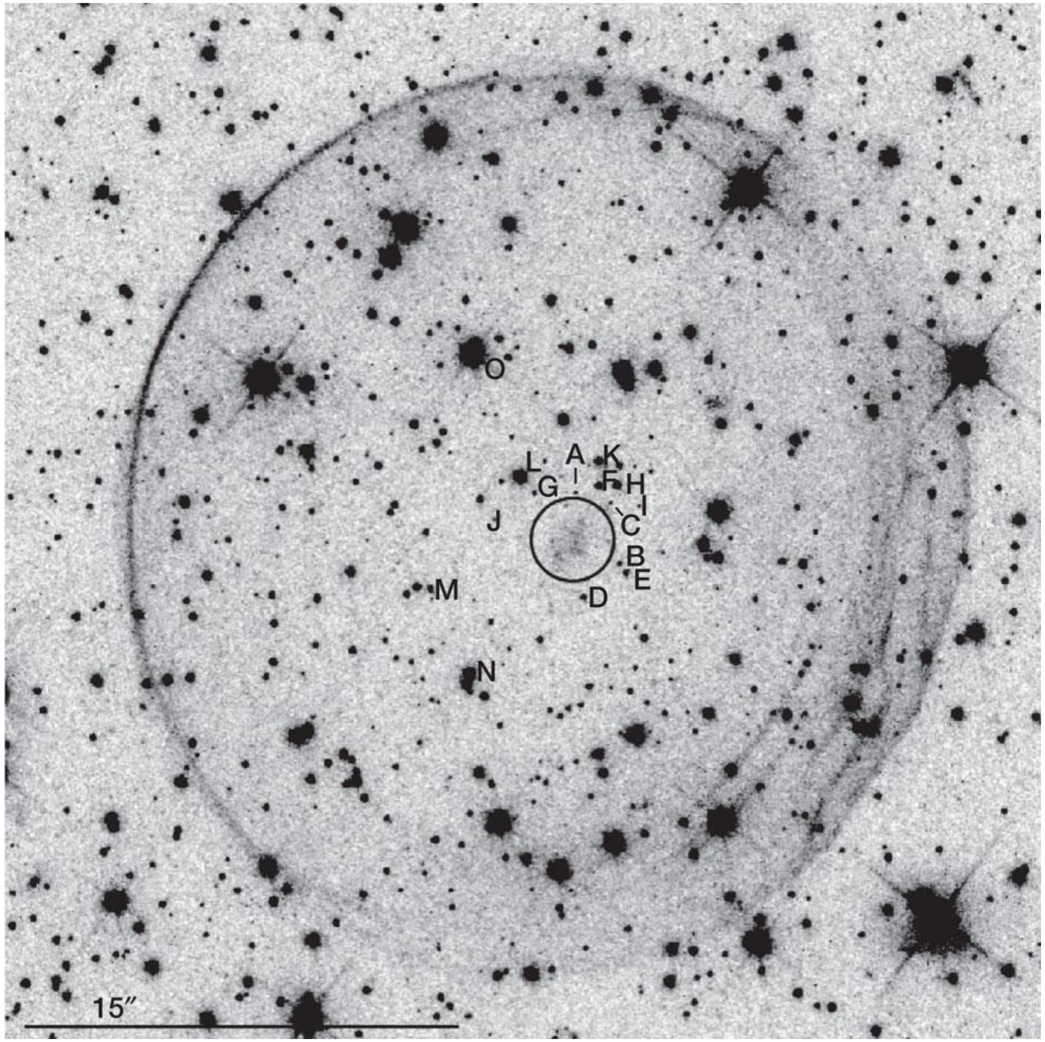
Borkowski+2006

6-6. SNR 0509-67.5 is too extended!



6-7. Fe grains formed in SNR 0509?

optical image of SNR 0509-67.5 in LMC



Schaefer & Pagnotta+2012

Radius of the central circle :
1.5" = 1.1×10^{18} cm @ 50 kpc

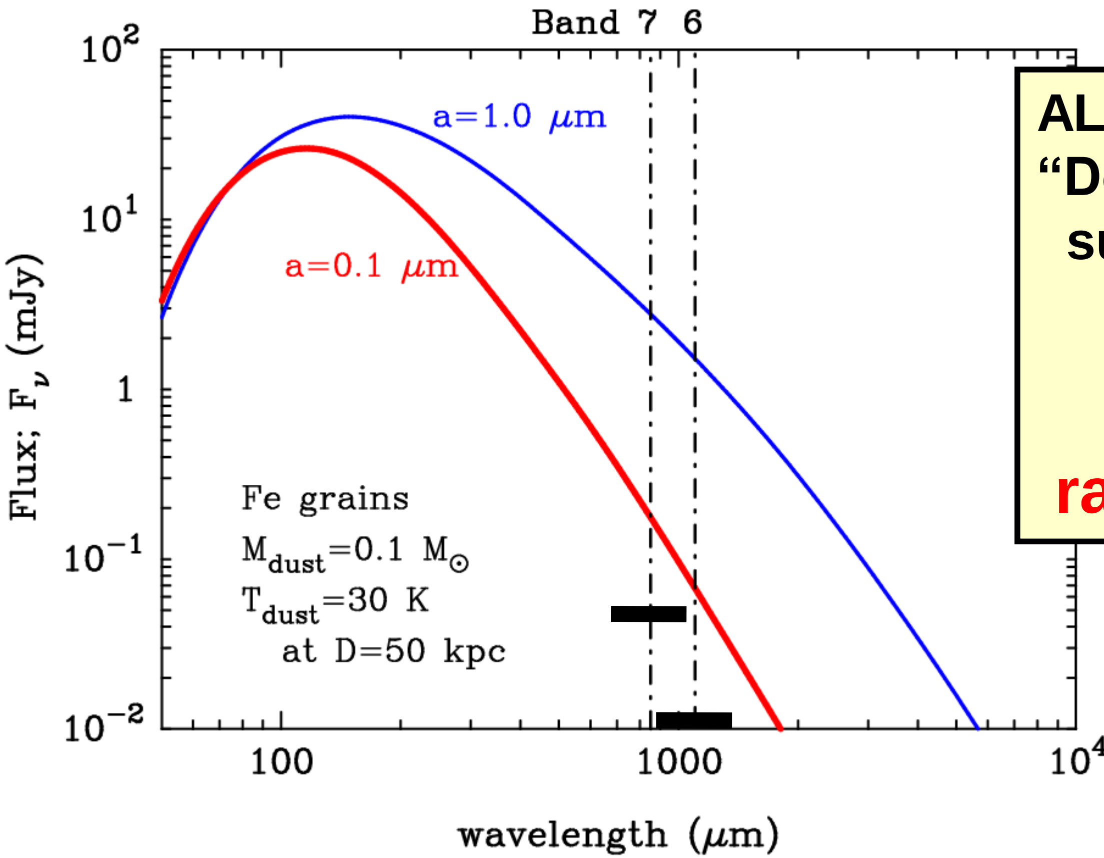
V_{exp} = 850 km/s @ 410 yr

corresponds to Fe core !

Supposition

Diffuse emission within the central circle may be optical lights scattered by Fe grains formed in the ejecta

6-8. Expected SEDs of Fe grain emission



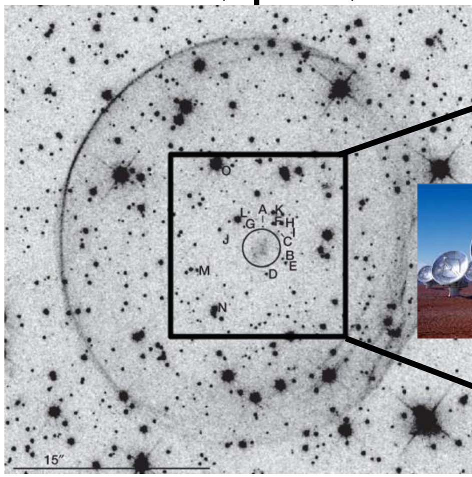
ALMA Cycle 2 Proposal
"Detecting cool dust in Type Ia supernova remnant 0509-67.5"

ranked as priority grade B

If the source is detected, this is the first detection of the formation of massive dust grains in SNe Ia !

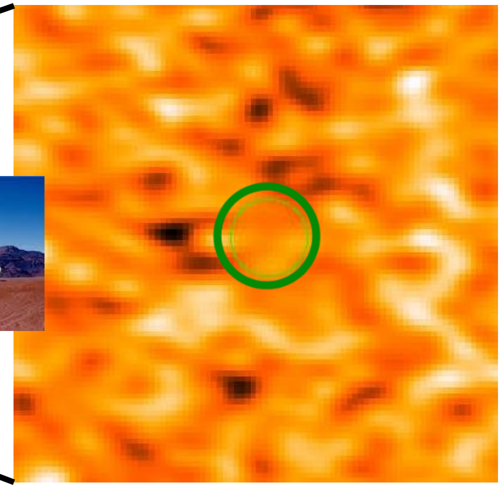
6-9. ALMA Observation of SNR 0509-67.5

HST（optical）



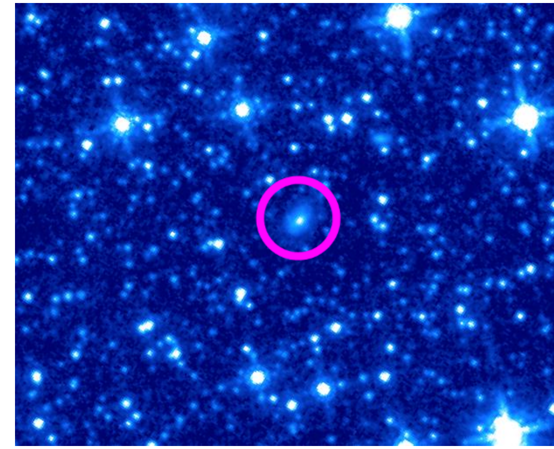
ALMA

ALMA（Band 6, 1.2 mm）

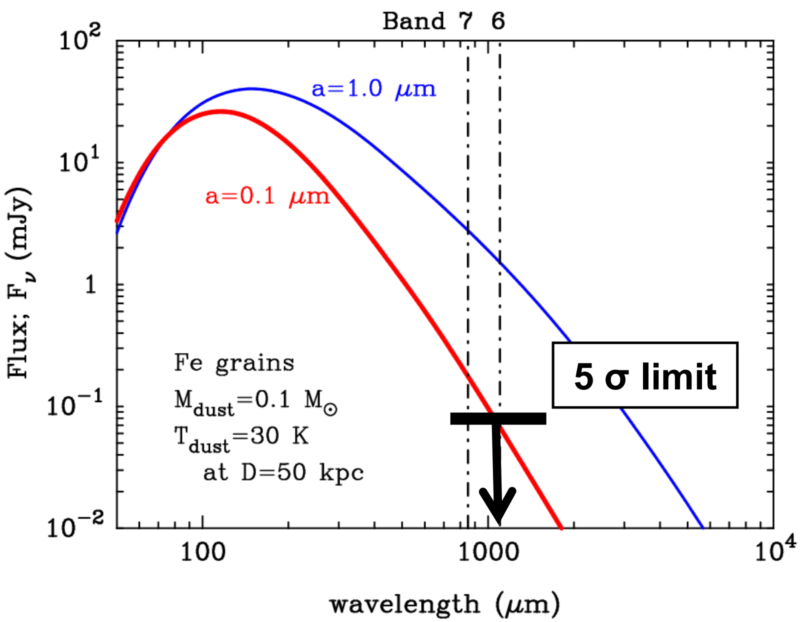


Nozawa et al., unpublished

HST（H band）



Pagnotta+2014

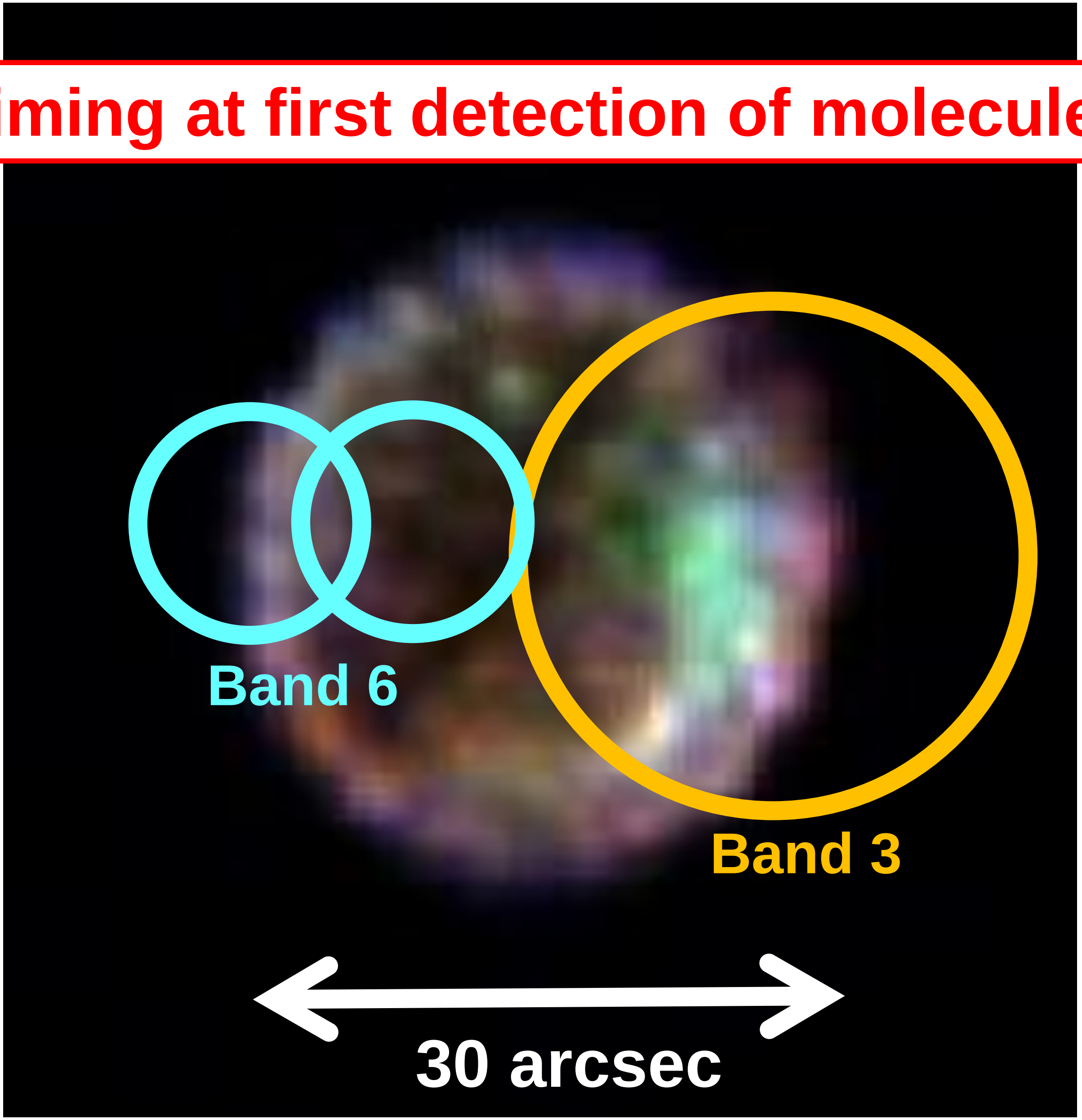


○ No detection in Band 6

- Massive Fe grains are not formed in Type Ia SNe (< ~0.1 Msun)
- Diffuse source is a background galaxy at z=0.031 (Pagnotta+2014)

7-1. Next challenge to SNe Ia?

Aiming at first detection of molecules in SNe Ia

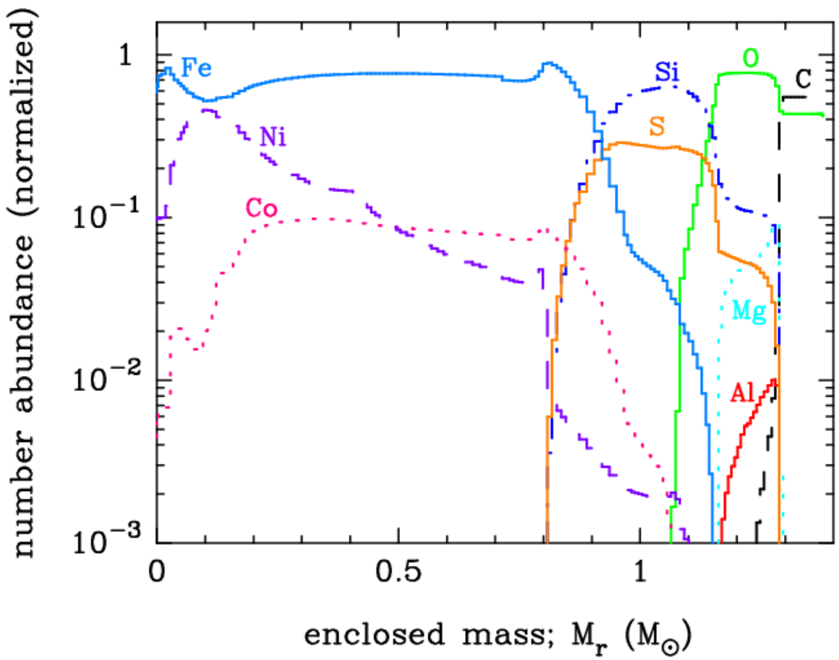


7-2. Explosion mechanism of SNe Ia

Detection of molecules can gives insight into

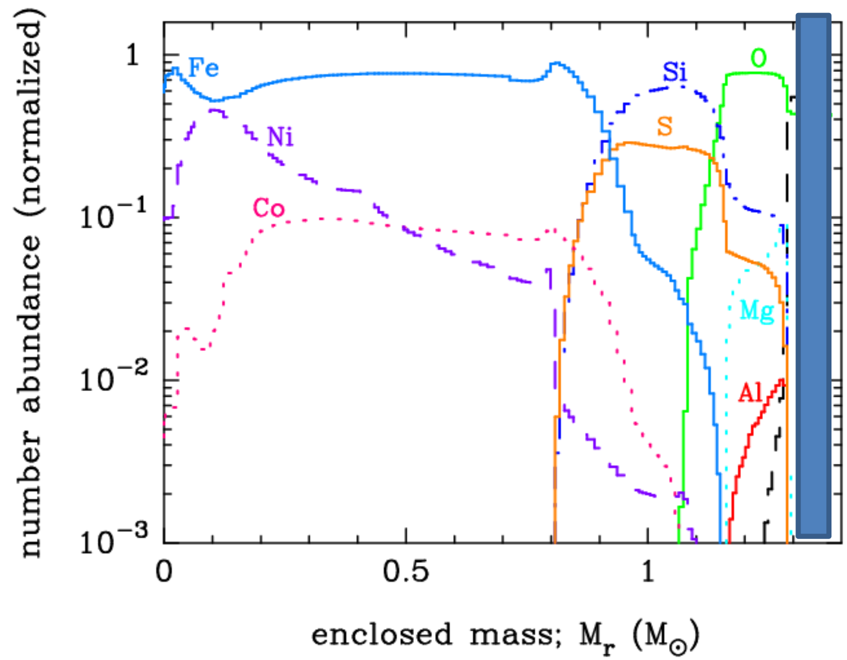
- explosion mechanism of SNe Ia
- physical condition of the expanding ejecta

Deflagration



unburned carbon : 0.05 Msun

Detonation



unburned carbon : <0.01 Msun

7-3. Summary of this talk

- CCSNe are production factories of dust and molecules
  - ➜ Theoretical calculations predicts 0.1-1 M_{sun} of dust formed
  - ➜ ALMA and Herschel confirmed the presence of a large amount of dust in the ejecta of CC-SNe/SNRs
  - ➜ Still unclear what fraction of dust grains can survive the destruction in reverse shocks and be injected into the ISM

- hard to detect thermal emission from cool dust in any SNe/SNRs other than SN 1987A with ALMA
  - ➜ even the youngest SNR in LMC/SMC are too extended
  - ➜ if SNe happen in MW or L/SMC, we see cool dust with ALMA

- There is no evidence for the formation of dust and molecules in SNe Ia