2013/10/22

Probing Dust Formation Process in SN 1987A with ALMA

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and

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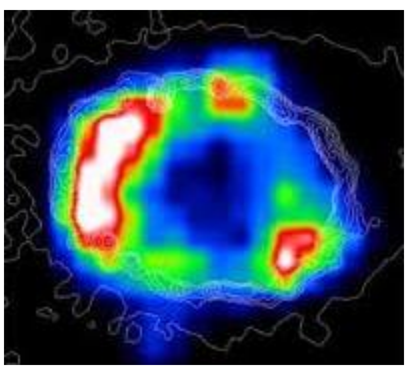
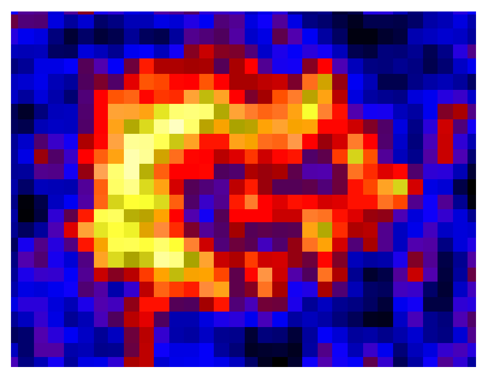
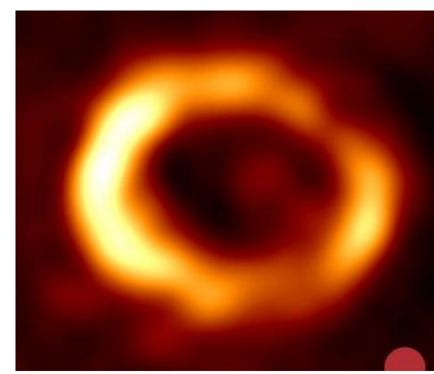


1-1. Introduction

SNe are important sources of interstellar dust?

– huge amounts of dust grains (>10^8 M_{sun}) are detected in host galaxies of quasars at redshift z > 5
➔ 0.1 M_{sun} of dust per SN is needed to be ejected to explain such massive dust at high-z (Dwek et al. 2007)

– contribution of dust mass from AGB stars and SNe

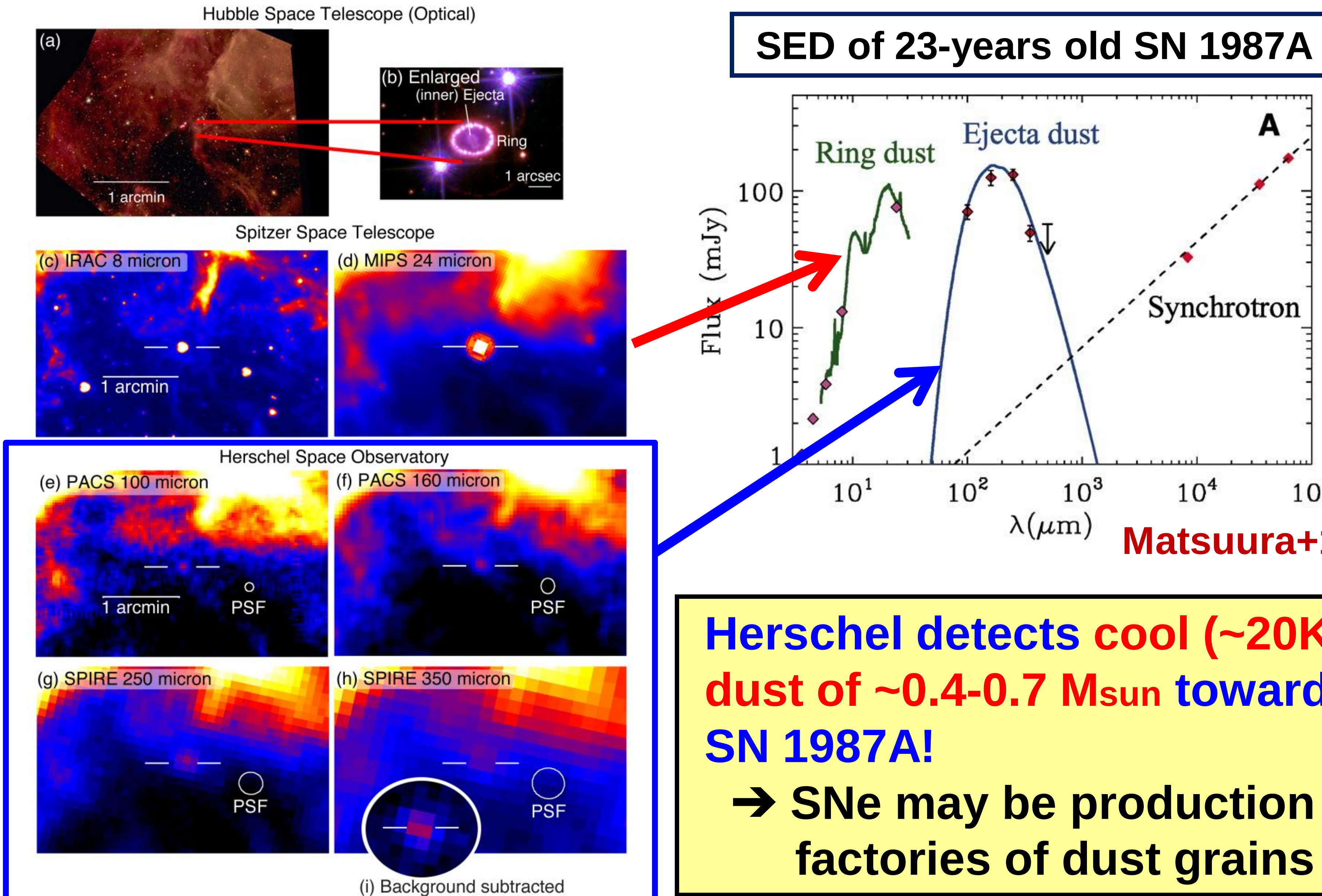
n(AGB stars) / n(SNe) ~ 10-20

M_{dust} = 0.01-0.05 M_{sun} per AGB (Zhukovska & Gail 2008)
M_{dust} = 0.1-1.0 M_{sun} per SN (Nozawa et al. 2003; 2007)

What composition, size, and mass of dust can be formed in SNe?

1-2. Herschel detects cool dust in SN 1987A

SED of 23-years old SN 1987A

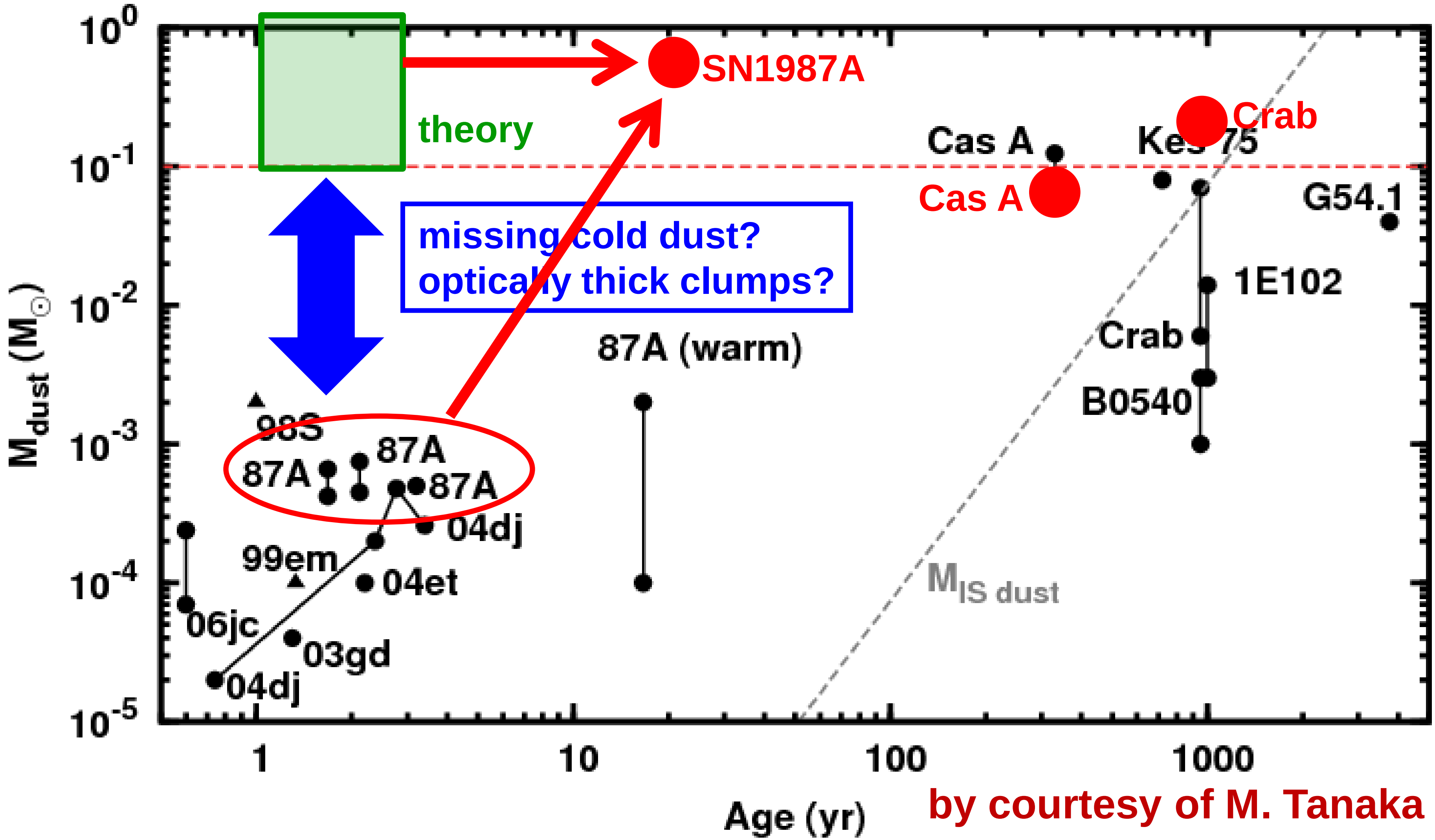


Matsuura+11

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

➔ SNe may be production factories of dust grains

1-3. Summary of observed dust mass in CCSNe



by courtesy of M. Tanaka

what is a cause of difference b/w warm/cool dust mass?
when and where are dust grains formed in SN 1987A?

1-4. Why SN 1987A with ALMA?

SN 1987A is the best target to detect cool dust

・ SN 1987A (➔ dust formation has been confirmed)

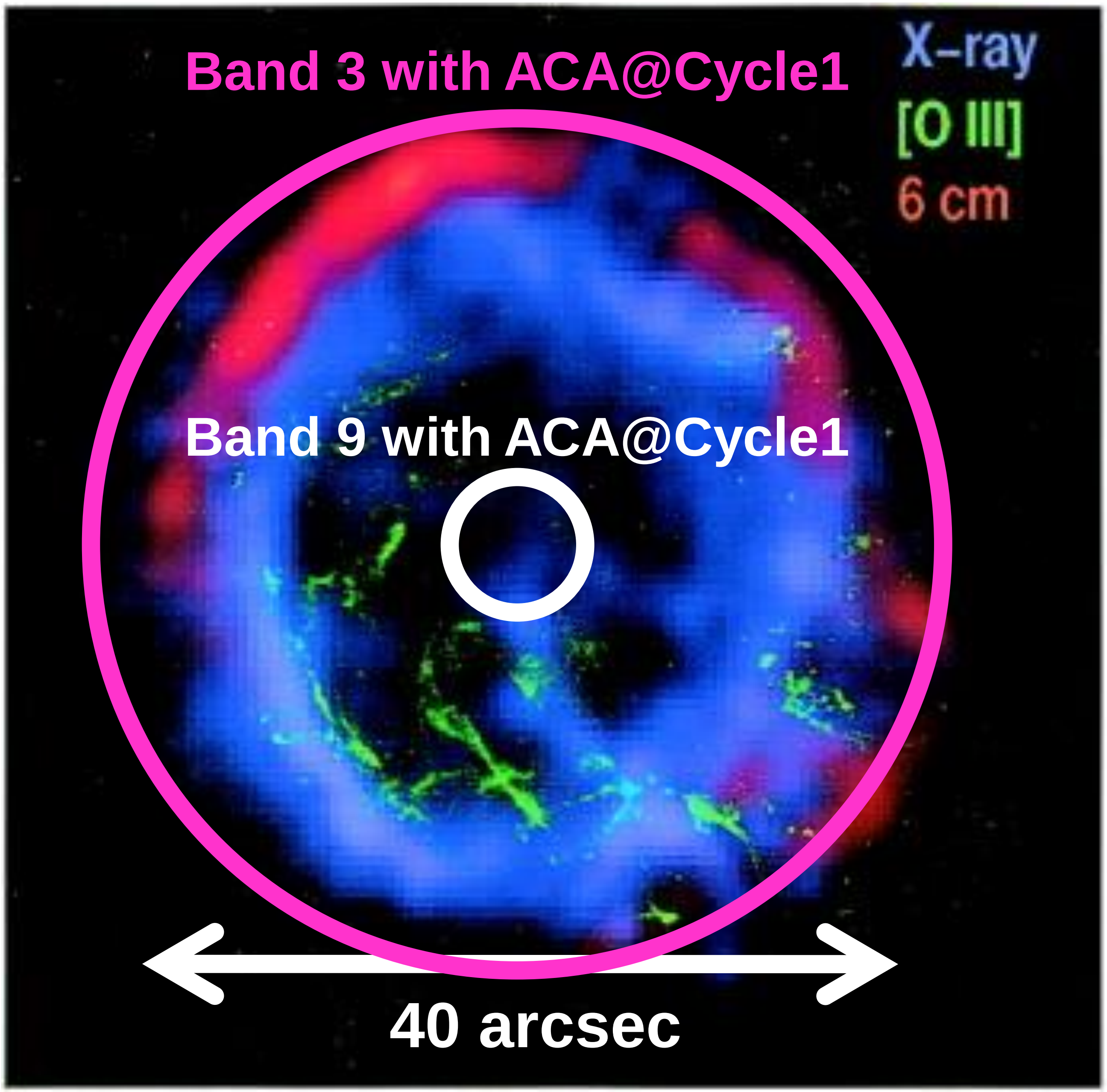
- **nearest SN ever observed (in LMC)**
- **young (~27 yr) and compact (~2” in diameter)**
- **well studied object at multi-wavelengths**

・ other candidates

- **extragalactic SNe ➔ too distant (too faint)**
- **Galactic SNRs ➔ too old (too extended)**

SN 1987A is the only target to detect cool dust

1-5. Young Type Ib SNR 1E0102-72.3 in SMC



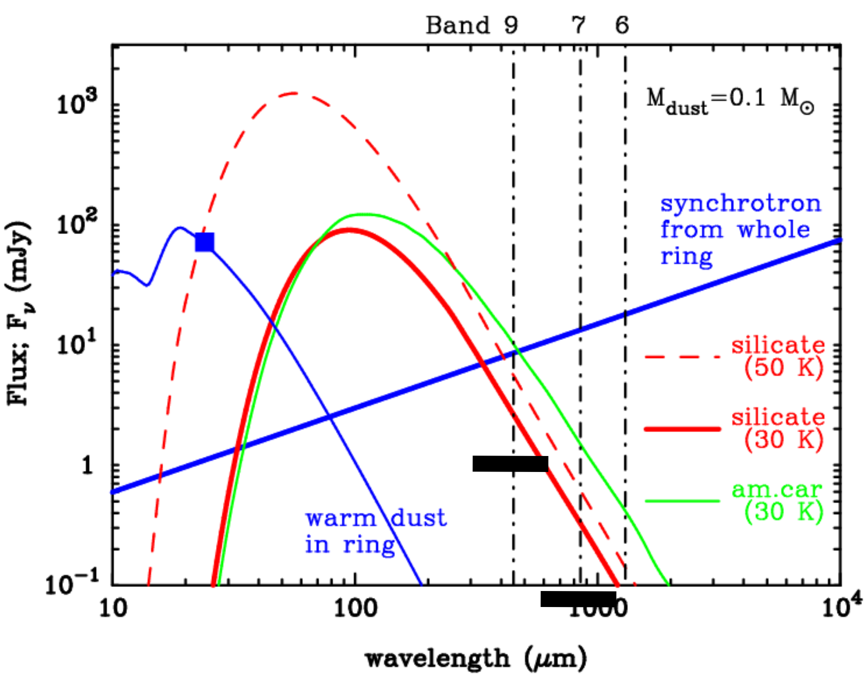
SNR 1E0102 in SMC
(age: ~1000 yr)

➔ known as a cousin of CasA

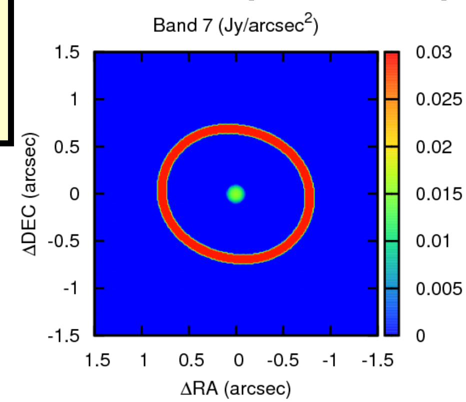
SN 1987A

2-1. Resolving cool dust in SN 87A with ALMA

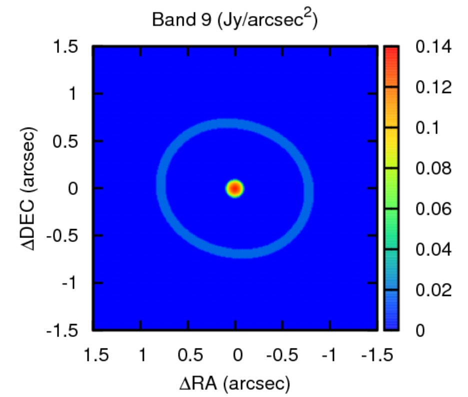
ALMA Cycle 0 Proposal
'Detecting cool dust in SN1987A'
(TN, Tanaka, et al.)



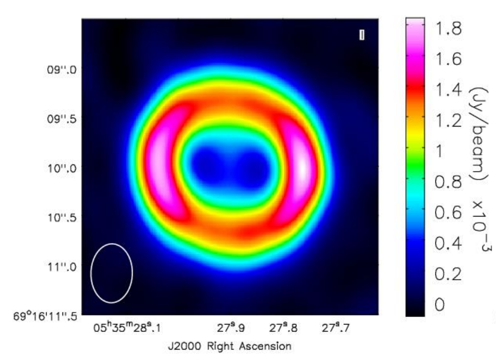
Band 7 (850 μm)

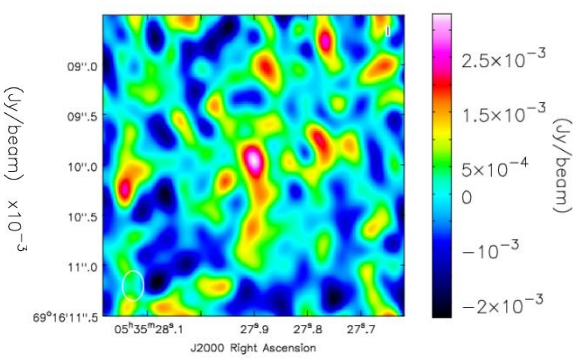


Band 9 (450 μm)



CASA simulation with extended config. (4 hrs)





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

2-2. Successful ALMA proposals for SN 1987A

2011.0.00221.S

PI	Exec	Country	Institute
Nozaw_, Takaya	EA	Japan	The University of Tokyo
COI			
Tanaka, Masa_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

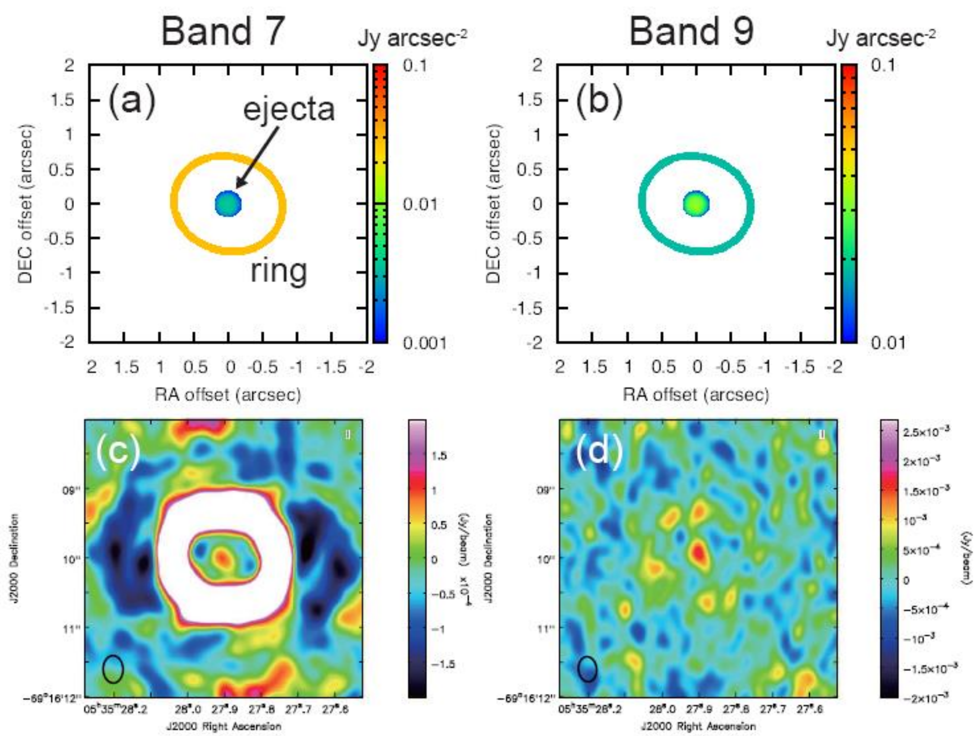
PI	Exec	Country	Institute
Indebetouw, Remy	NA	United States	Virginia, University of
COI			
McCray, Richard	NA	United States	Colorado at Boulder, Univ of
Matsuura, Mikako	EU	United Kingdom	London, University of
Andjelic, Milica	OTHER	Serbia	Belgrade, University of
Arbutina, Bojan	OTHER	Serbia	Belgrade, University of
Baes, Maarten	EU	Belgium	Ghent University
Urosevic, Dejan	OTHER	Serbia	Belgrade, University of
Vlahakis, Catherine	CL	Chile	Chile, University of
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

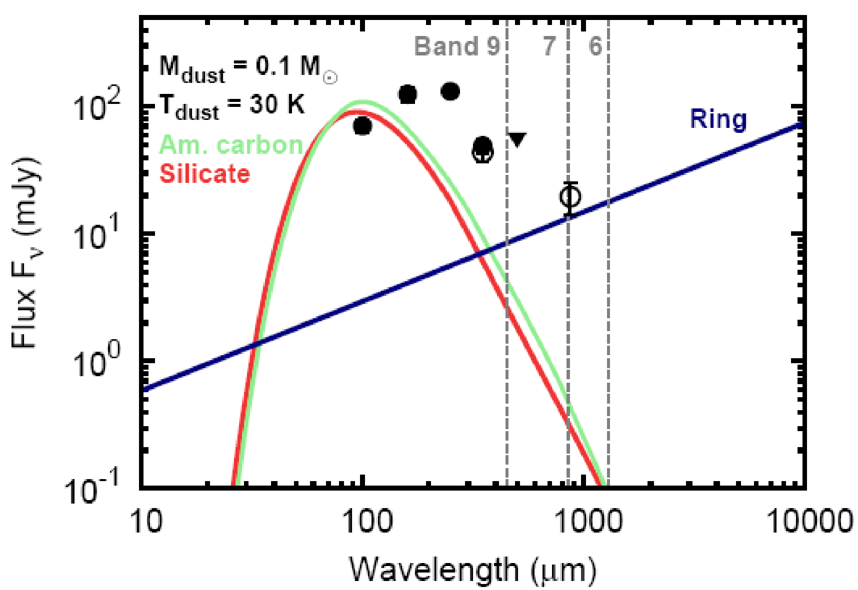
Band 3, 6, 7, 9 compact configuration

2-3. Our proposal for ALMA Cycle 1

ALMA Cycle 1 Proposal
'Detecting cool dust in SN1987A'
(Tanaka, TN, et al.)

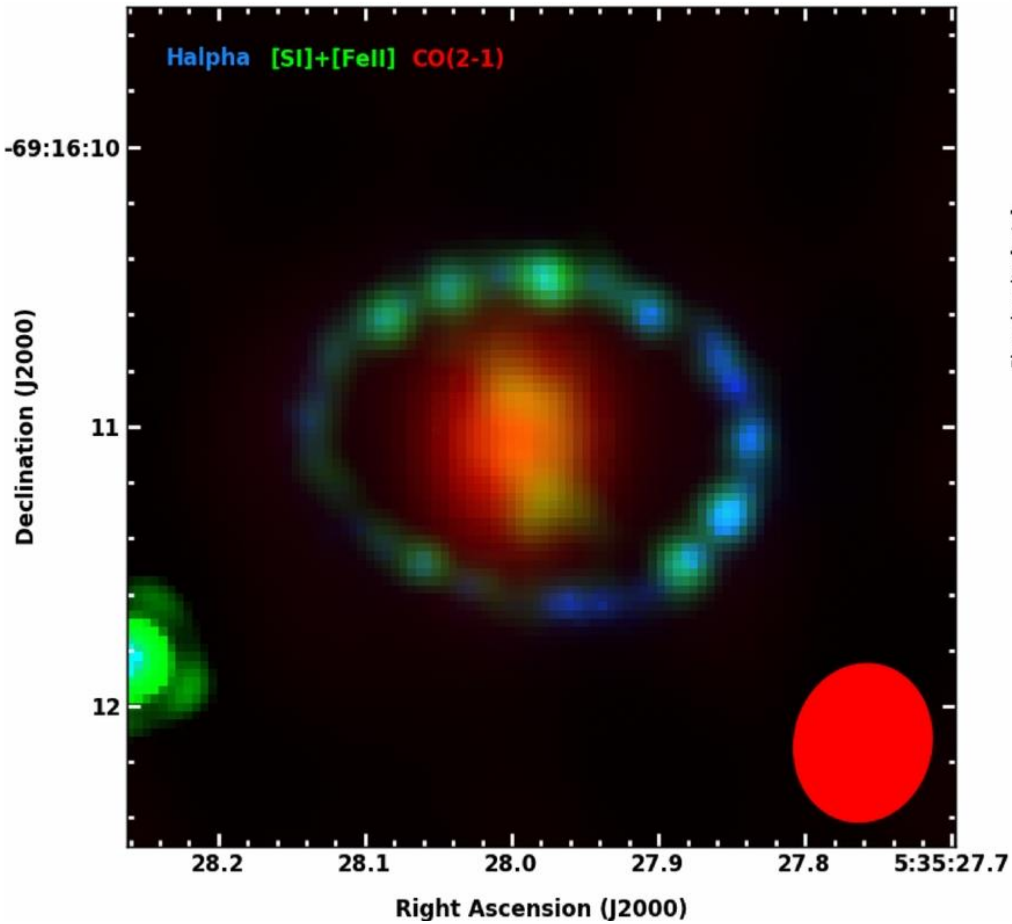
This proposal was not ranked as high priority

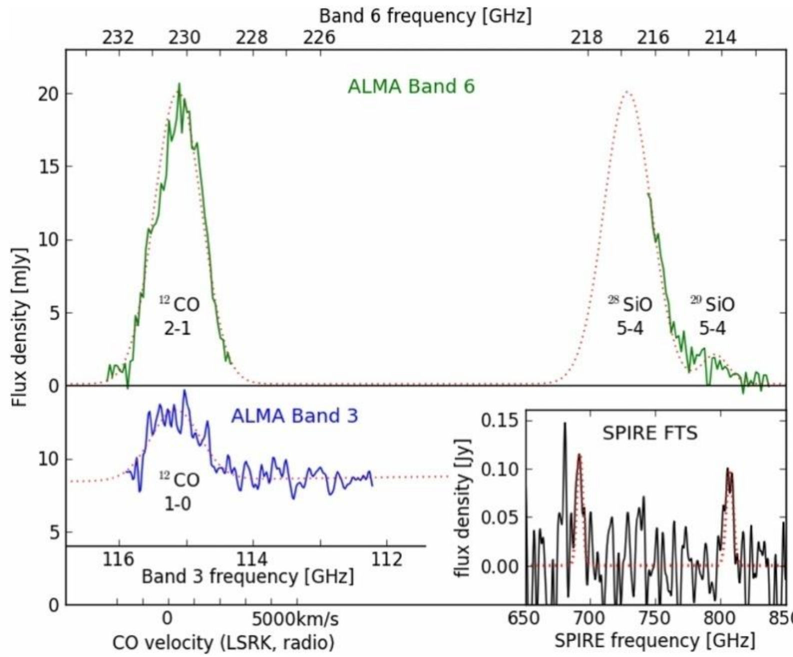




Observing with the resolution of 0.25" in Bands 7 and 9
➔ 10σ detection for silicate of 0.1 Msun and 30 K

2-4. CO detection in SN 1987A with ALMA





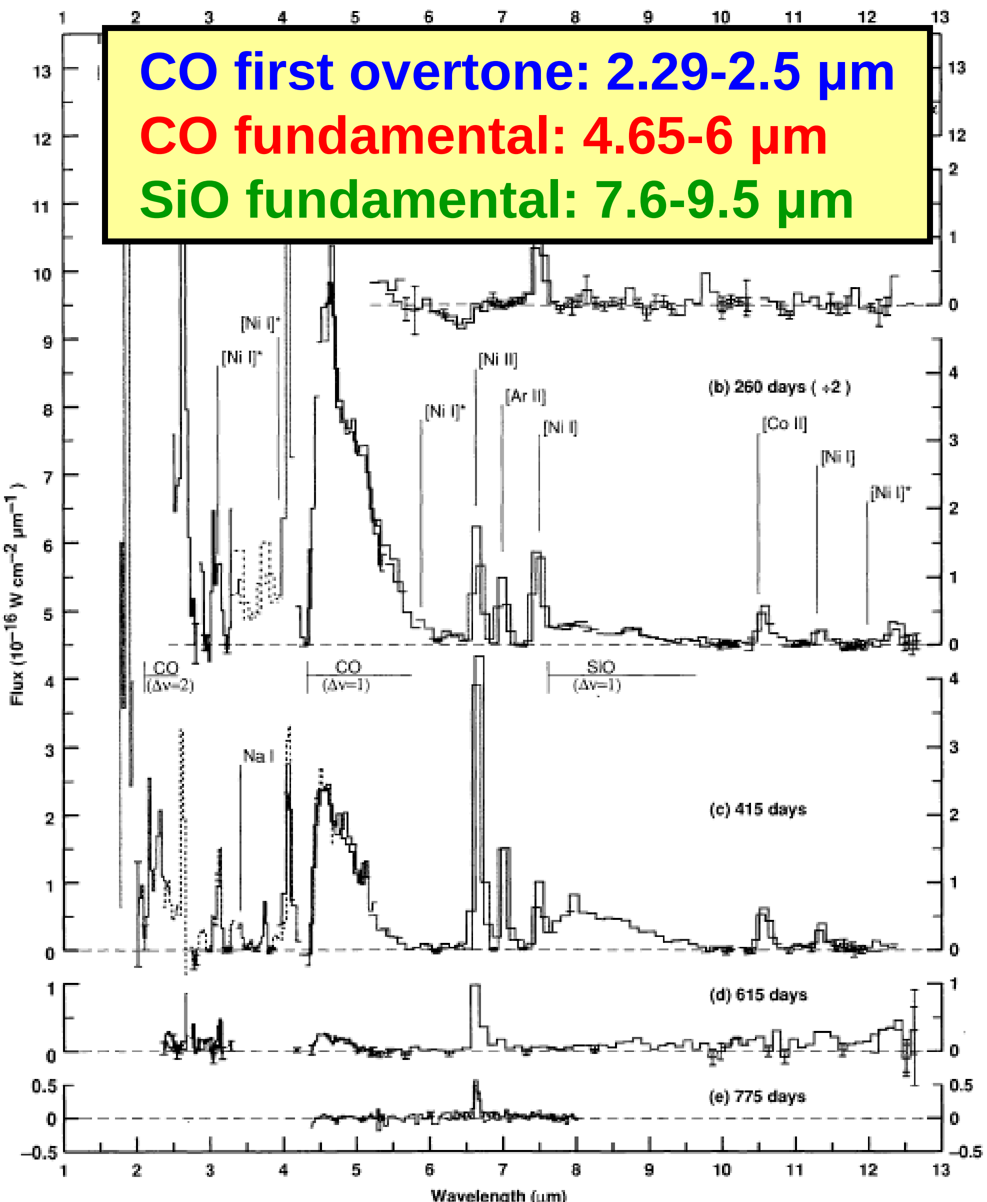
Kamenetzky+13

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

- **CO properties**
  - Vco ~ 2200 km/s
  - Mco > 0.01 Msun
  - Tco > 14 K
  - fco = 0.025-0.141
- **For ALMA full operation, 3D maps of CO and SiO**

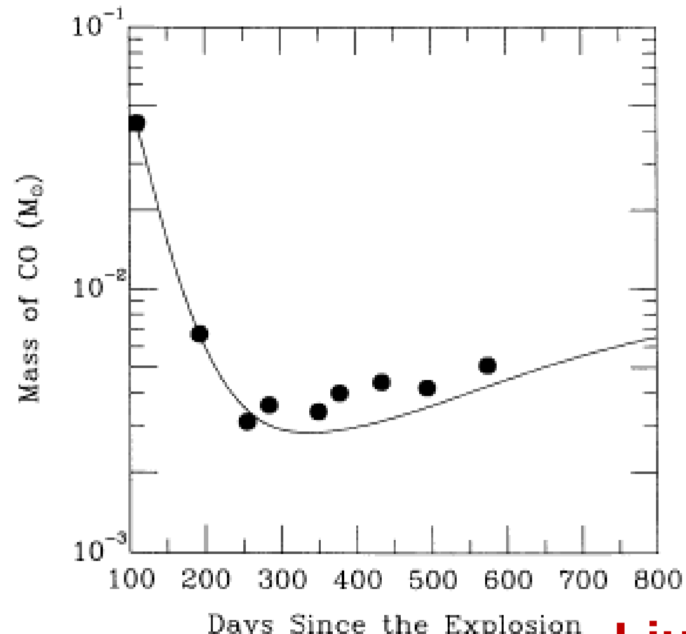
3-1. CO and SiO detection in SN 1987A

CO first overtone: 2.29-2.5 μm
CO fundamental: 4.65-6 μm
SiO fundamental: 7.6-9.5 μm



Wooden+93

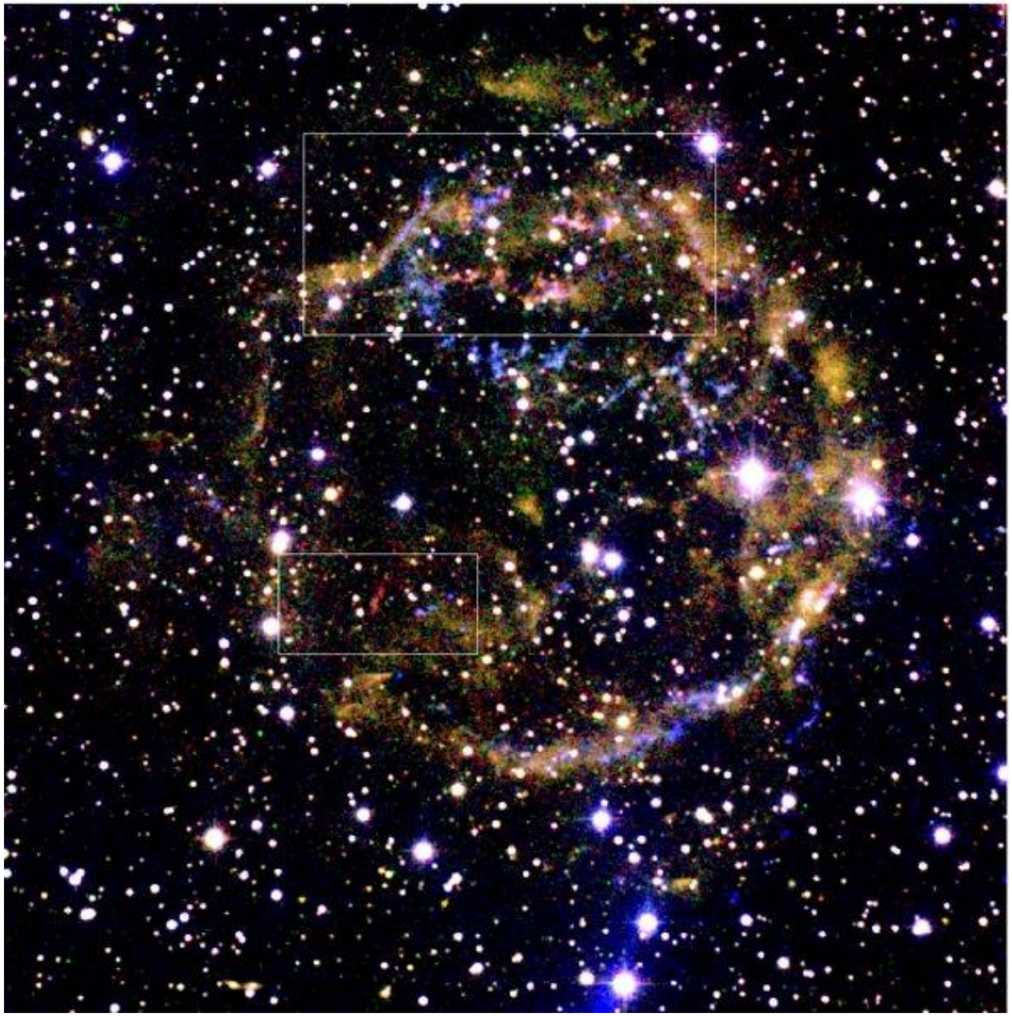
Evolution of CO mass



Liu+95

- CO emissions were observed during ~100-600day after explosion
- CO mass in SN 1987A: $M_{CO} \sim 4\times10^{-3}$ M_{sun}

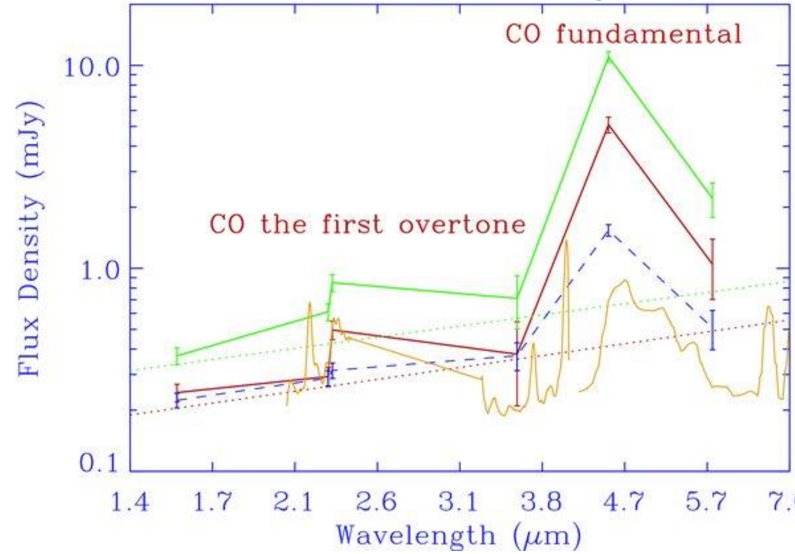
3-2. CO detection in Cassiopeia A SNR (1)



blue: Pβ
green: K band
red: CO(2-0)

Rho+09

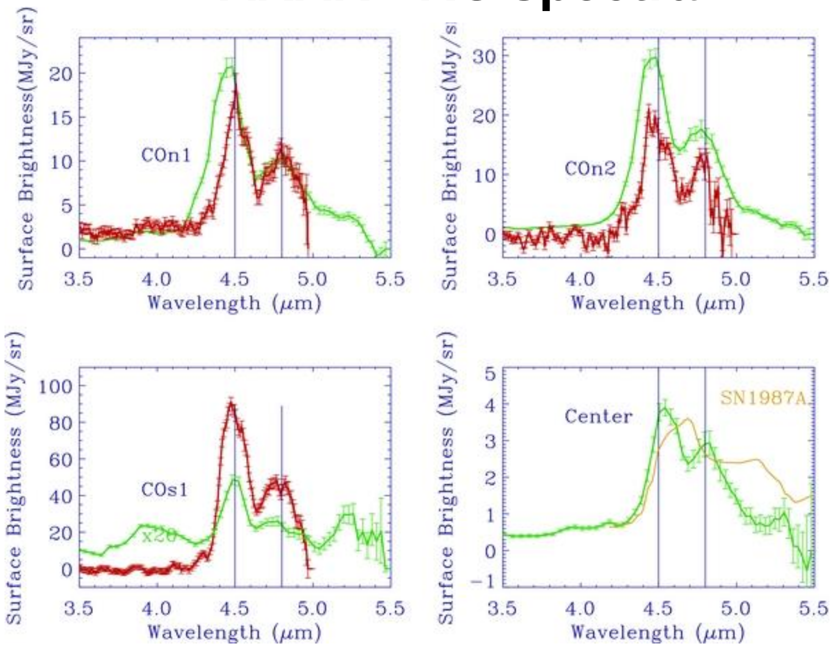
SED of CO emitting knots



- CO mass in Cas A:
  $M_{CO} \sim 10^{-6}$-10^{-5} M_{sun}
- CO knots are within the shocked ejecta
  ➔ continuing molecular formation over 300 yr?

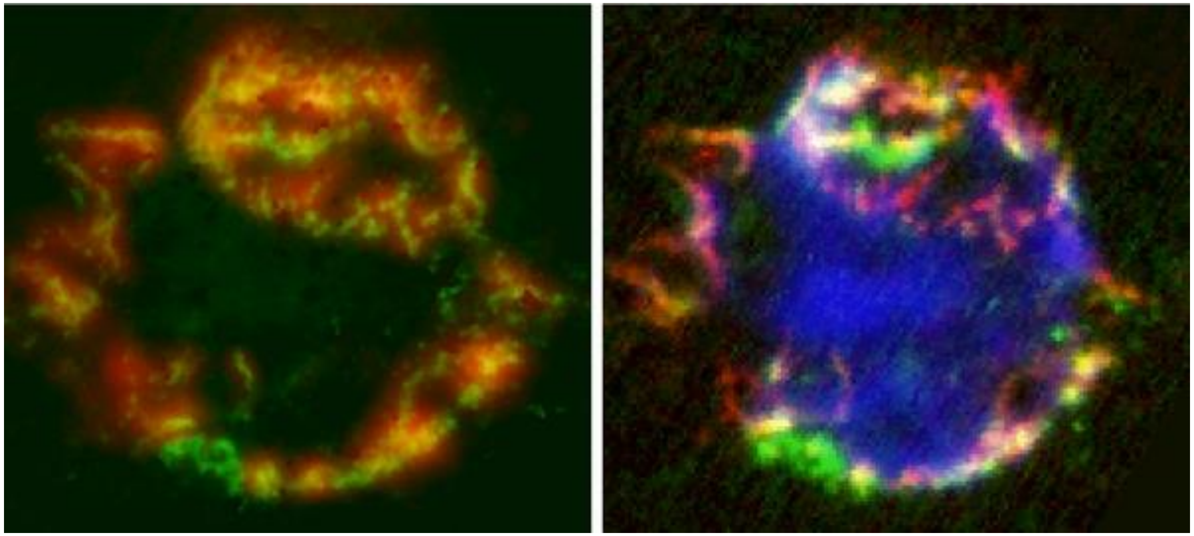
3-3. CO detection in Cassiopeia A SNR (2)

AKARI IRC spectra



- **CO mass and temperature**
  Mco ~ 6x10^{-7} Msun
  Tco = 900-2400 K
- **significant amounts of carbon may have been locked up in CO**
- **CO is correlated to Ne ejecta and has not been destroyed efficiently**

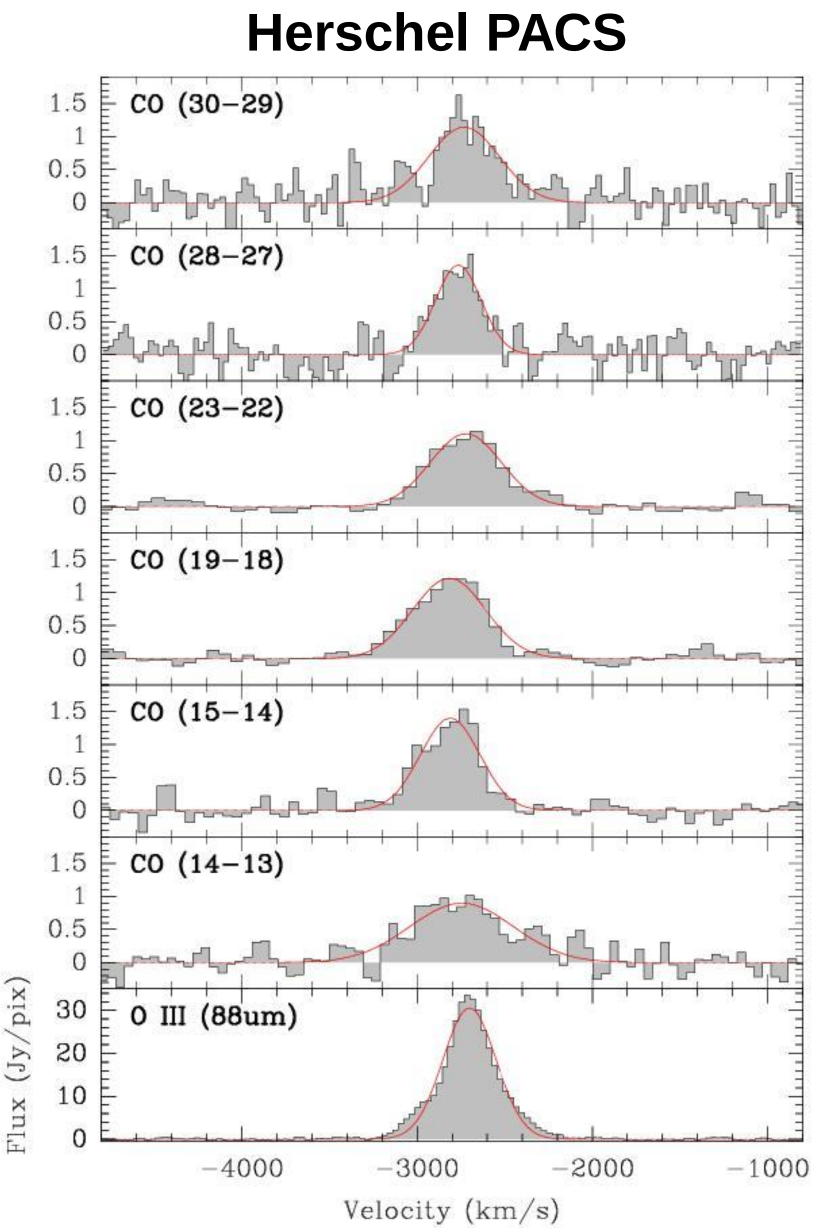
Rho+12

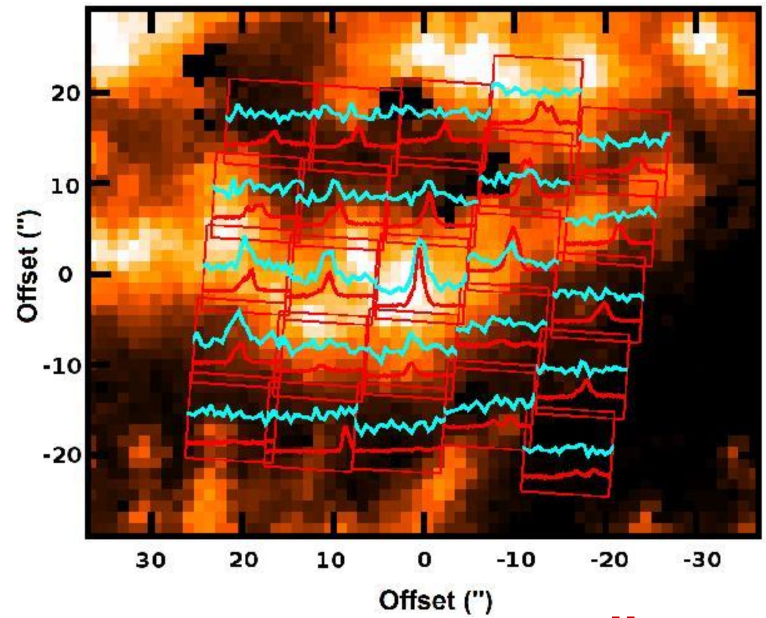


Left panel
green: CO (4.5 μm)
red: dust (21 μm)

Right panel
green: Ne
red: Ar
blue: Si

3-4. CO detection in Cassiopeia A SNR (3)





Wallstrom+13

- **CO properties**
  - **$V_{CO,ave}$ ~ -2740 km/s**
  - **M_{CO} ~ 5×10^{-6} M_{sun}**
  - **T_{CO} = 400 K and 2000 K**
  - **knot density: 10^{6-7} /cm^3**
- **CO was dissociated by the shock, but has reformed recently**

4-1. Probing CO molecules in SNRs

・ CO (and SiO) are confirmed in many Type II SNe/SNRs

➔ CO (and SiO) molecules are considered to be obstacles (precusors) for dust formation

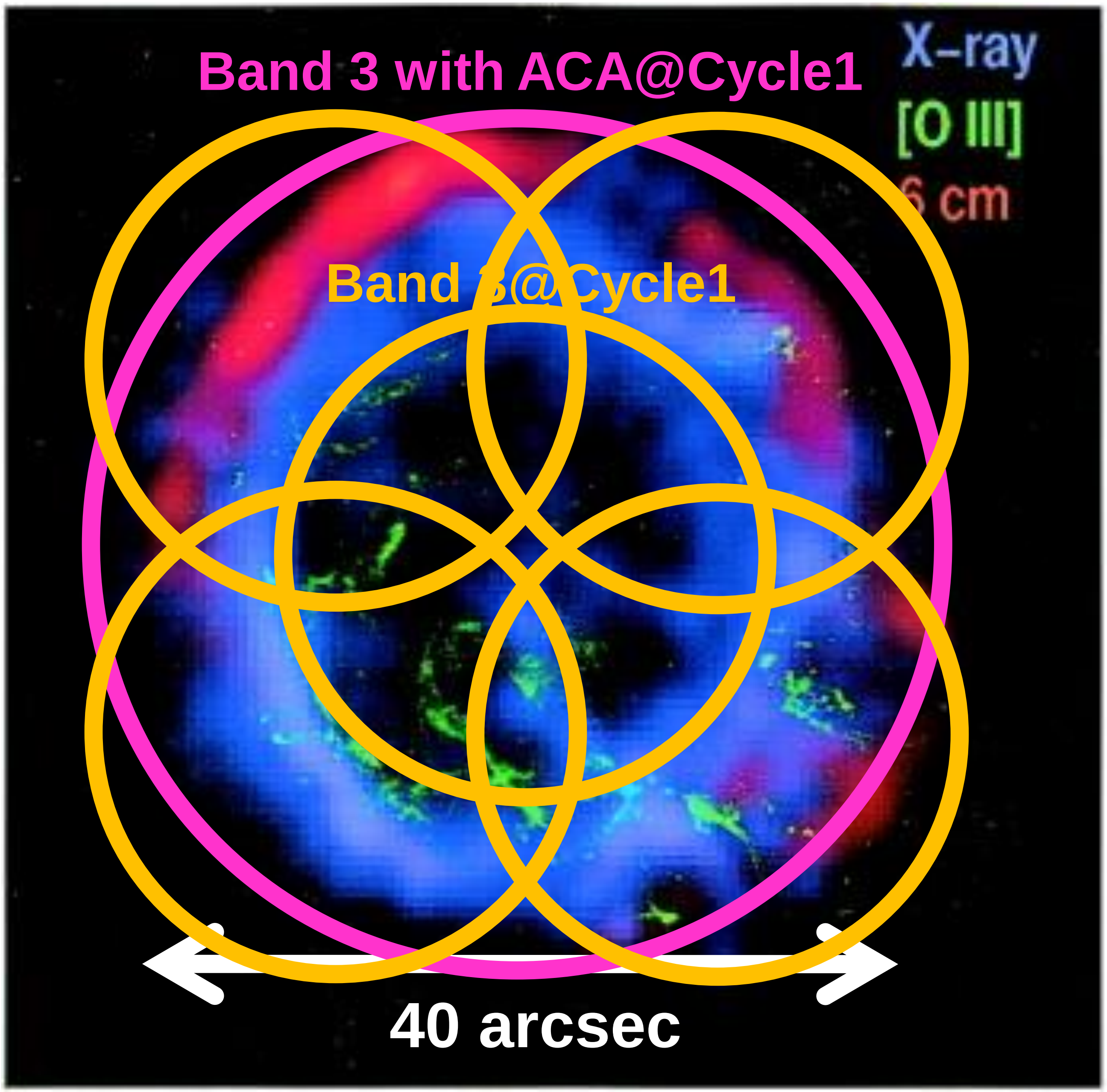
・ CO (and SiO) line observations of SNRs with ALMA

- expansion velocity of the ejecta
  ➔ elemental distribution and mixing in the ejecta

- temperature and density (column density) of CO
  ➔ clues about clumpiness and clumpy factor

- estimated mass of CO
  ➔ chemistry and environments in the ejecta
  ➔ its effect on dust formation process

4-2. Searching for CO emission in SNR 1E0102?

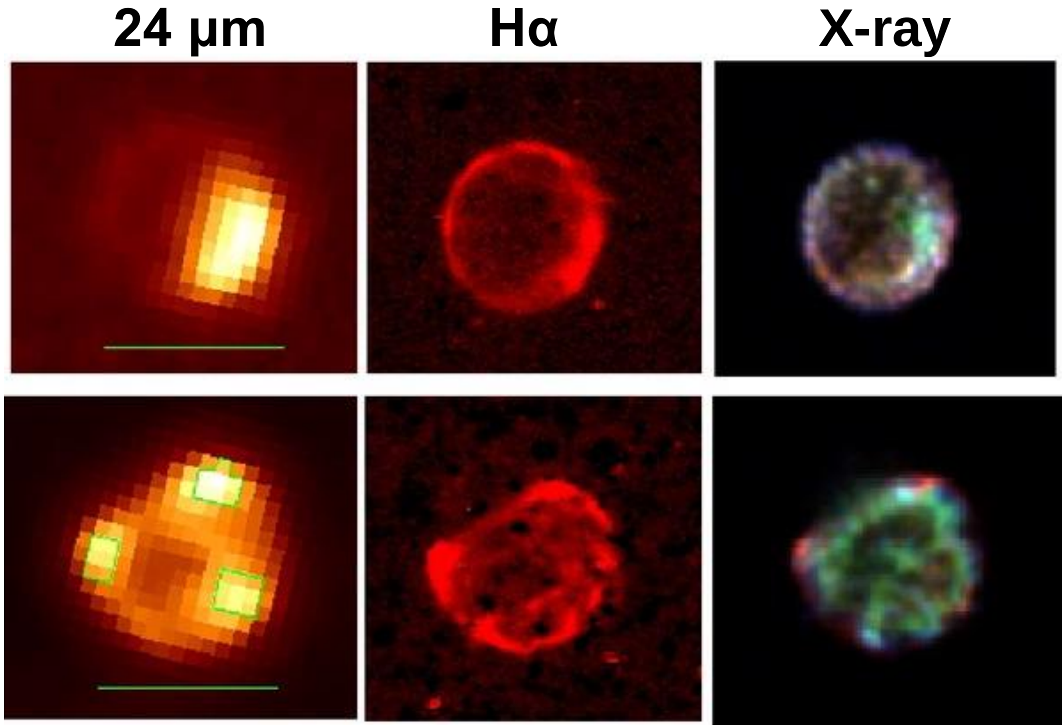


SNR 1E0102 in SMC
(age: ~1000 yr)

➔ known as a cousin of CasA

SN 1987A

4-3. Possible targets: young Ia SNRs in LMC



0509-67.5
(400 yr)

0519-69.0
(600 yr)

Borkowski+06

- Type Ia SNe
- age: ~500 yr
- radius: ~15”

↓

$M_{dust} < 3\mathrm{x}10^{-3}\ M_{sun}$

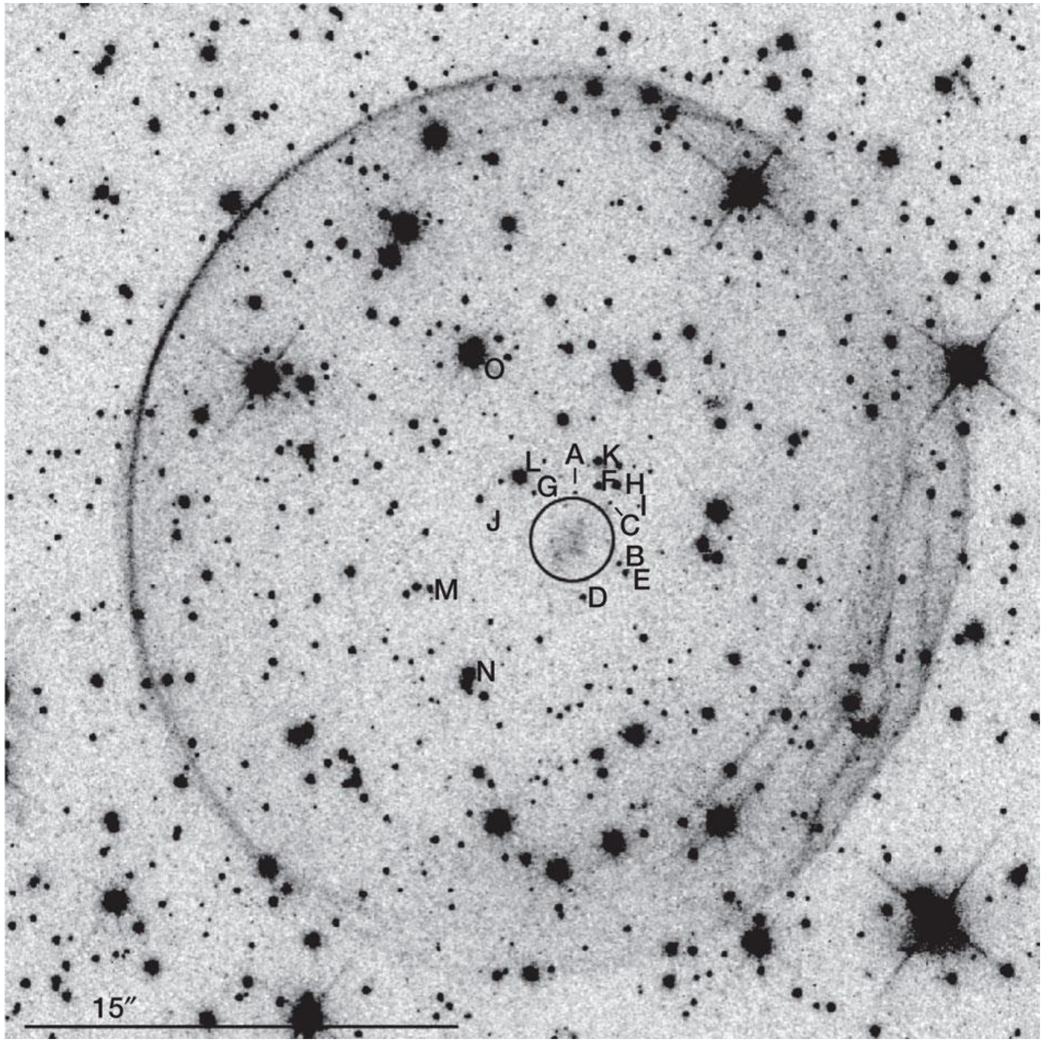
・ shock-heated interstellar dust
➔ dust destruction by SNe

- deflagration:
  leaving unburned carbon
- detonation:
  burning most carbon

CO detection in SNe Ia
➔ some hints about explosion mechanism

4-4. Where is the companion star of SNR 0509?

SNR 0509-67.5 in LMC



Schaefer & Pagnotta+12

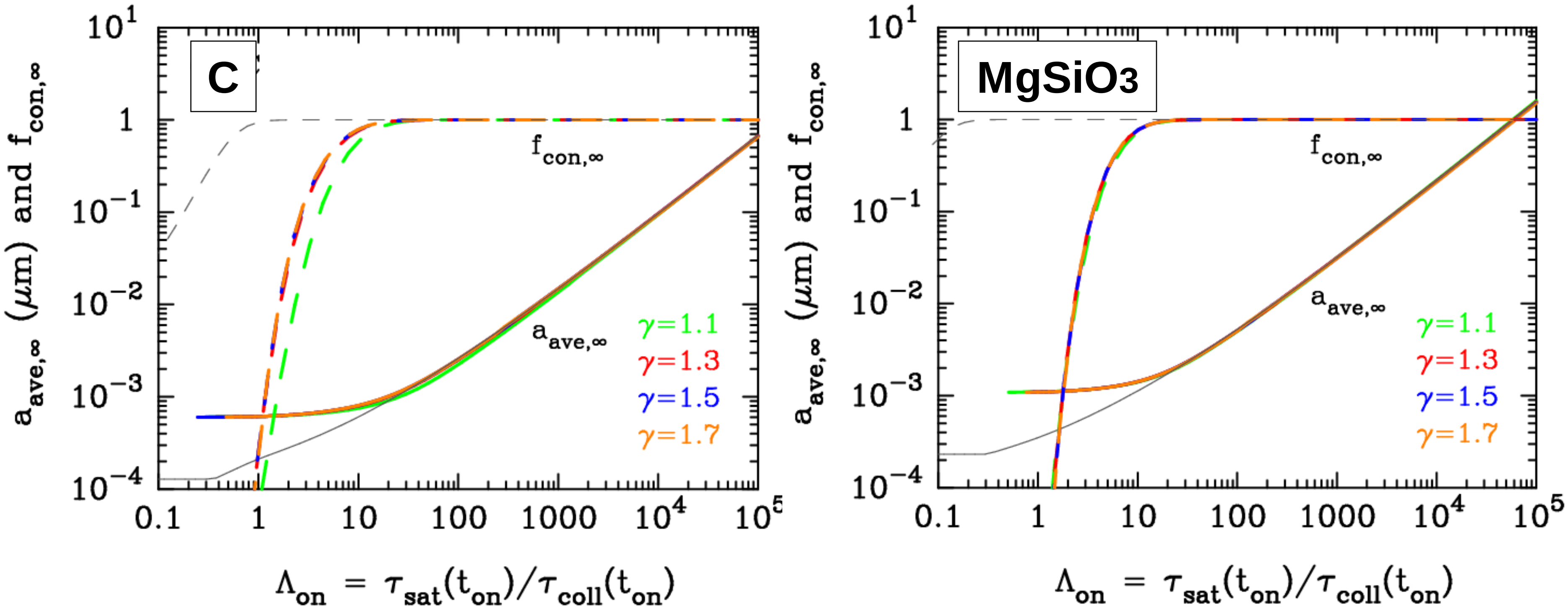
There is left no possible companion star in SNR 0509-67.5

➔ This SN exploded as double degenerate?

- **central region with the radius of 2”**
  ➔ V_{exp} = 1200 km/s
- **formation of Fe grains (10^{-3} M_{sun}) is expected**
  (e.g., Nozawa+11)

Is the companion star hidden by Fe grains formed in the ejecta?

4-5. Scaling relation of average grain radius



Λ_{on}: ratio of supersaturation timescale to gas collision timescale at the onset time of dust formation

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

where $\tau_{cool} = t_{on} / 3 (\gamma - 1)$

Nozawa & Kozasa (2013)

5. Summary: possible science for ALMA Cycle2

・Detecting dust and molecules in SN 1987A

- 3D maps of dust emission in Band 7 and 9
- something using molecular lines?

➔ not much impressive in rivalry with EU/US group

we are seeking any other ideas and strategy!

・Detecting CO in young SNRs in LMC and SMC

- searching for CO emission in Band 6, 7, and 9

➔ it seems new and interesting even if not detected

we are seeking the collaborators who can tell us about observations of CO emission!

A-1. How dense is cool dust in 1E0102?

・ 1E0102.2-7219

R = 15 arcsec ➔ 1.3×10^{19} cm = 4.4 pc @ 60 kpc

what is the mass of dust if ISM dust is included in the sphere with this radius?

$$M_{dust} \sim (4\pi R^3 / 3)\ D\ (n_H\ m_H)$$

$$= 0.077\ M_{sun}\ (D / 0.01)\ (n_H / 1\ cm^{-3})$$

・ Cassiopeia A

R = 100 arcsec ➔ 4.8×10^{18} cm = 1.6 pc @ 3.4 kpc

A-2. Importance of molecular lines in SN 1987A

- CO and SiO molecules were detected around 300 days after explosion in SN 1987A
  (CO and SiO were confirmed in many dust-forming SNe)

- Measuring the expansion velocity of the ejecta

- CO molecule has been detected in Cas A SNR

- All condensible metals have to be tied up in dust grains to explain 0.4-0.7 M_{sun} of dust in SN 1987A
  ➔ CO and SiO molecules can survive??

- How much CO and SiO line fluxes can contribute the continuum flux?
  ➔ expected mass of CO and SiO: ~10^{-3} M_{sun}

A-3. Summary of molecular lines

Band 3: 84-115 GHz
Band 6: 211-274 GHz
Band 7: 275-373 GHz
Band 9: 607-720 GHz

・CO molecule

v=0, 1-0: 115.271 GHz (B3)
v=0, 2-1: 230.538 GHz (B6)
v=0, 3-2: 345.796 GHz (B7)
v=0, 4-3: 461.041 GHz
v=0, 5-4: 576.268 GHz
v=0, 6-5: 691.473 GHz (B9)

・SiO molecule

v=0, 2-1: 86.847 GHz (B3)
v=0, 3-2: 130.269 GHz
v=0, 4-3: 173.688 GHz
v=0, 5-4: 217.105 GHz (B6)
v=0, 6-5: 260.518 GHz (B6)
v=0, 7-6: 303.927 GHz (B7)
v=0, 8-7: 347.331 GHz (B7)

v=0, 15-14: 650.958 GHz (B9)
v=0, 16-15: 694.296 GHz (B9)