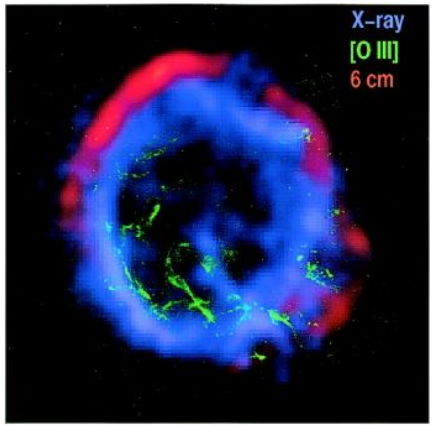
2019/08/28

Probing the formation and destruction processes of dust with large MIR telescopes

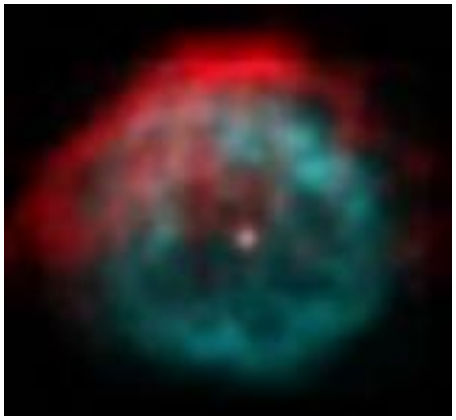
Takaya Nozawa

(National Astronomical Observatory of Japan)



SNR 1E0102-72.3

SN 1987A



LBV AFGL2298

1-1. Paradox in interstellar dust mass

○ Injection rate of dust from CCSNe/AGB stars

$$\frac{dM_{\rm dust}}{dt} \simeq 0.01 \left(\frac{\phi_{\rm sf}}{4\ M_\odot\ {\rm yr}^{-1}}\right) \left(\frac{f_{\rm AGB-SN}}{0.3}\right) \left(\frac{f_{\rm gas,ejected}}{0.75}\right) \left(\frac{f_{\rm dust,form}}{0.01}\right) \quad M_\odot\ {\rm yr}^{-1}$$

- SFR
- Fraction of stars evolving to SNe/AGB
- Mass fraction of gas ejected from SNe/AGB
- Condensation efficiency of dust

○ Destruction rate of interstellar dust by SN shocks

$$\frac{dM_{\rm dust}}{dt} \simeq -0.06 \left(\frac{R_{\rm SN}}{0.01\ {\rm yr}^{-1}}\right) \left(\frac{M_{\rm gas,swept}}{2000\ M_\odot}\right) \left(\frac{D_{\rm ISM}}{0.01}\right) \left(\frac{f_{\rm dust,dest}}{0.3}\right) \quad M_\odot\ {\rm yr}^{-1}$$

- SN rate
- Gas mass swept by a SN shock
- Dust-to-gas mass ratio
- Destruction efficiency of dust

Formation rate of dust in stellar sources is lower than destruction rate of dust

➜ Interstellar dust must decrease with time

1-2. What is wrong?

○ Underestimate condensation efficiency of dust?

- CCSNe eject ~10 M_{sun} gas and ~0.1 M_{sun} dust

↓ ~90% of dust destroyed by reverse shocks

$f_{dust,form}$ = 1 % would be the optimistic estimate

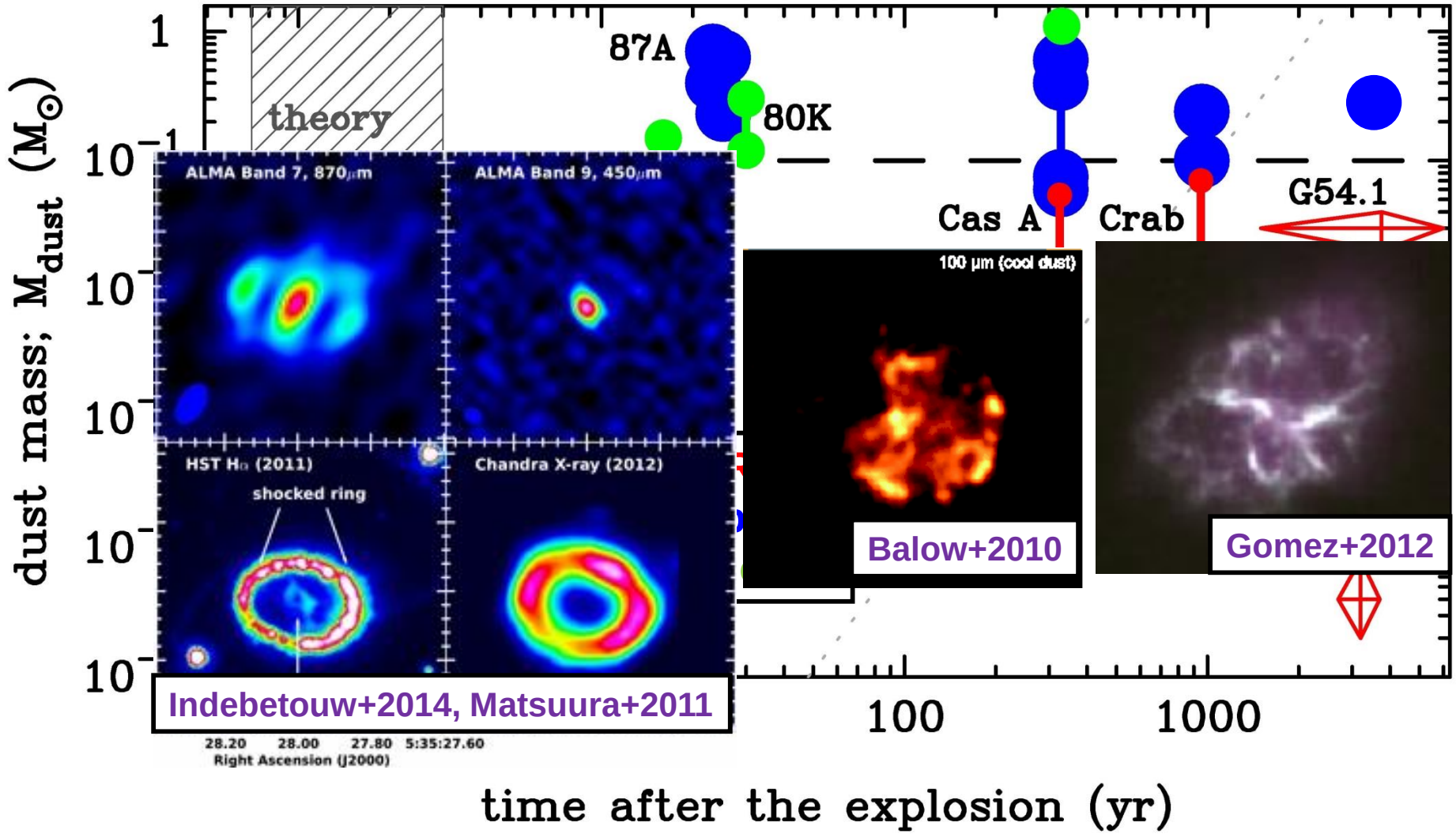
○ Overestimate destruction efficiency of dust?

- There is uncertainties in destruction efficiency
- Dust is destroyed by sputtering in shocked gas

○ Other sources of interstellar dust?

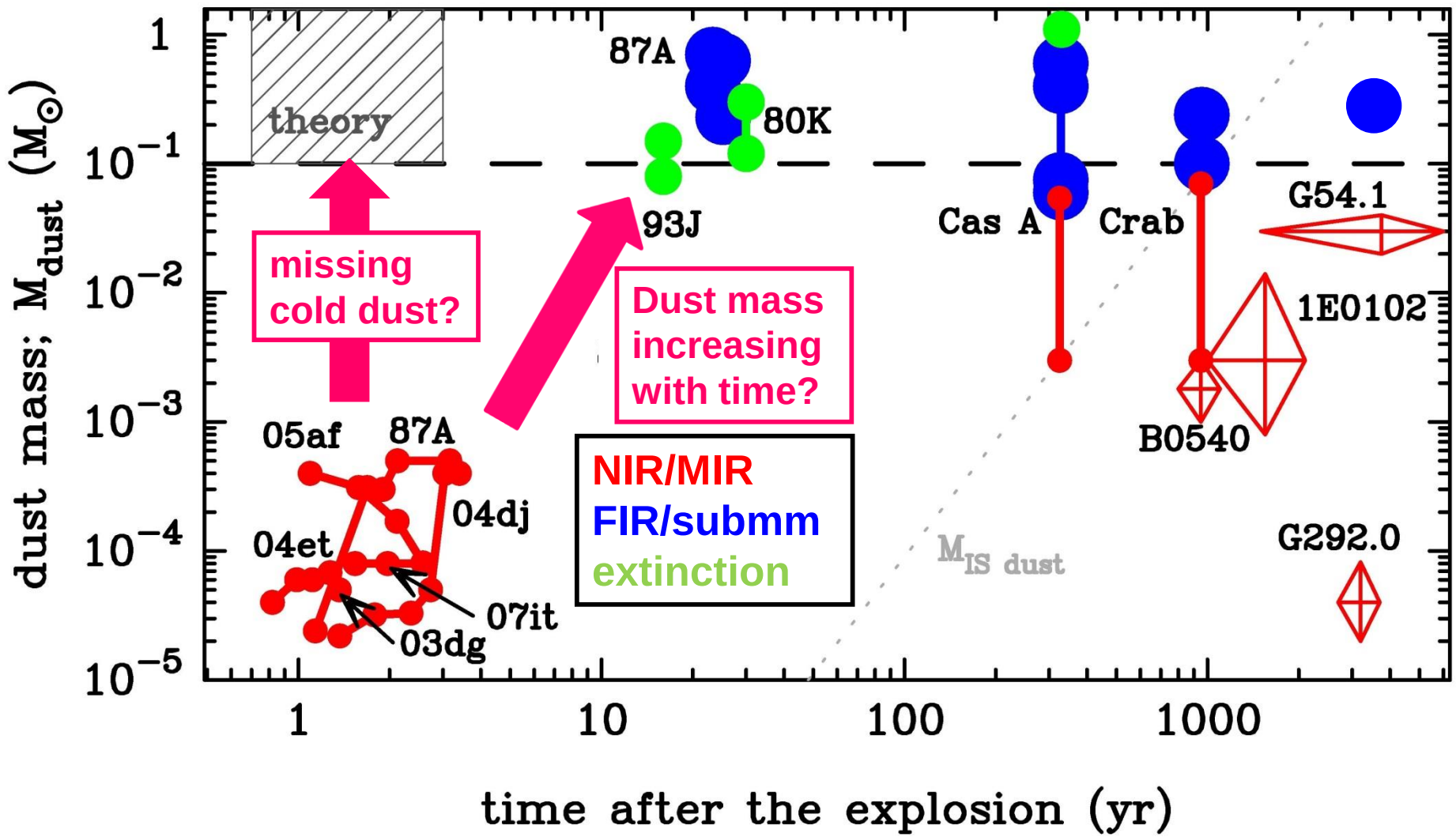
- RGs, RSGs, sAGB stars, LBVs, WR stars, Novae, …
- Grain growth in molecular clouds

2-1. Observed dust mass in CCSNe/SNRs



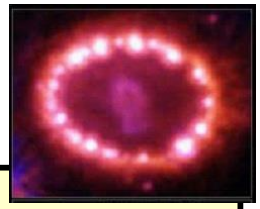
Dust mass formed in the ejecta is dominated by cold dust

2-1. Observed dust mass in CCSNe/SNRs

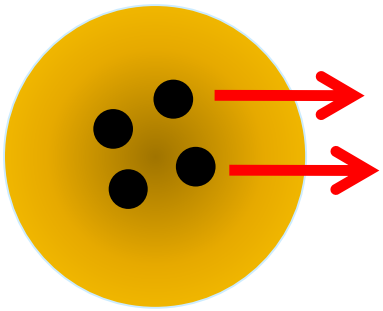


Dust mass formed in the ejecta is dominated by cold dust

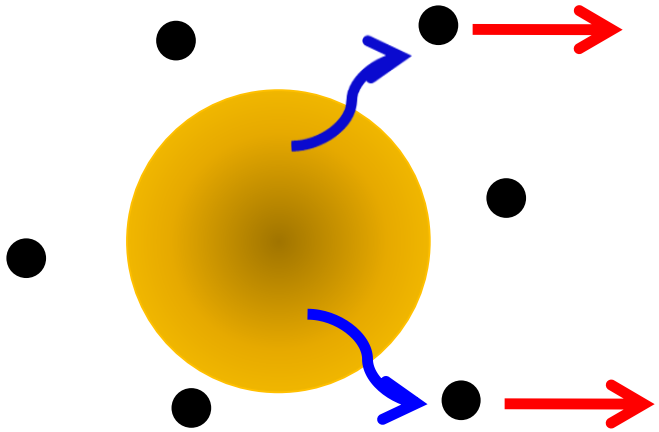
2-2. Origin of IR emission from CCSNe



Dust formation in the ejecta



IR echo by CS dust

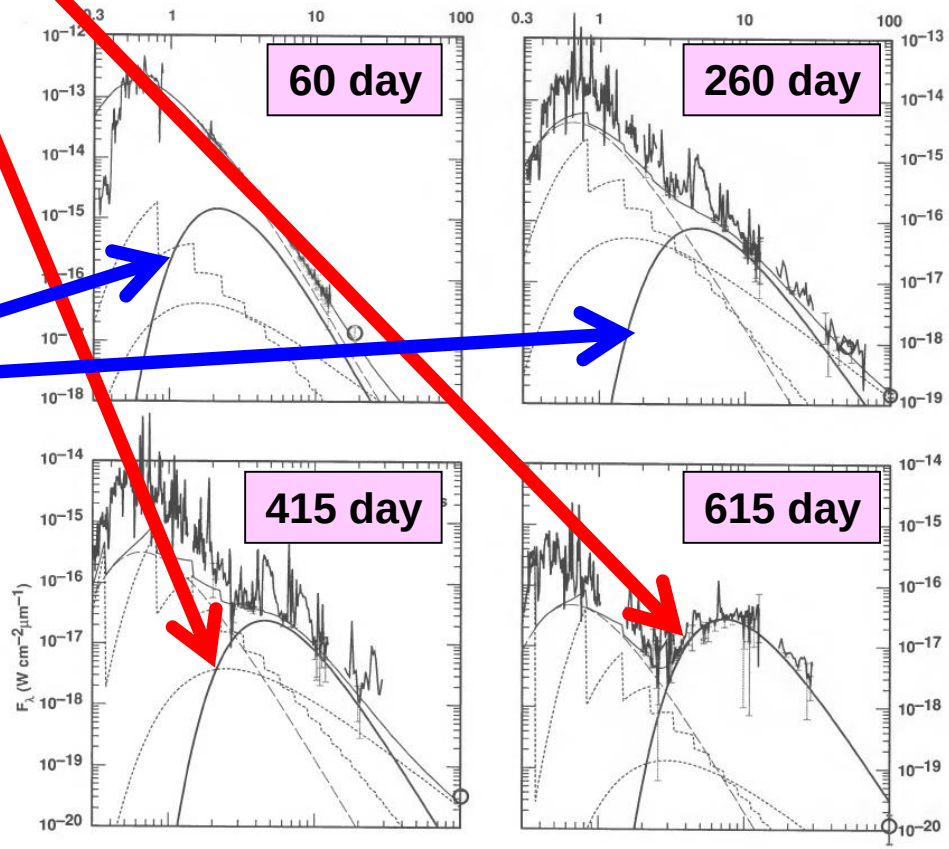


○ SN 1987A

with Kuiper Airborne Observatory

- dust mass : > ~10^{-4} Msun

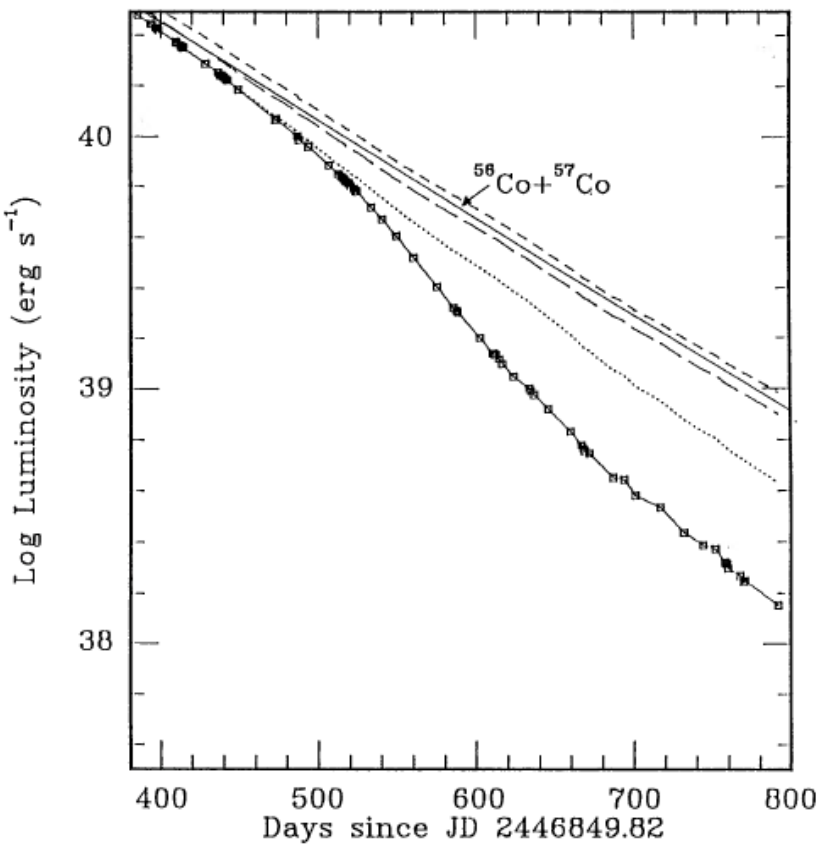
(optically thin assumed)



Wooden+93

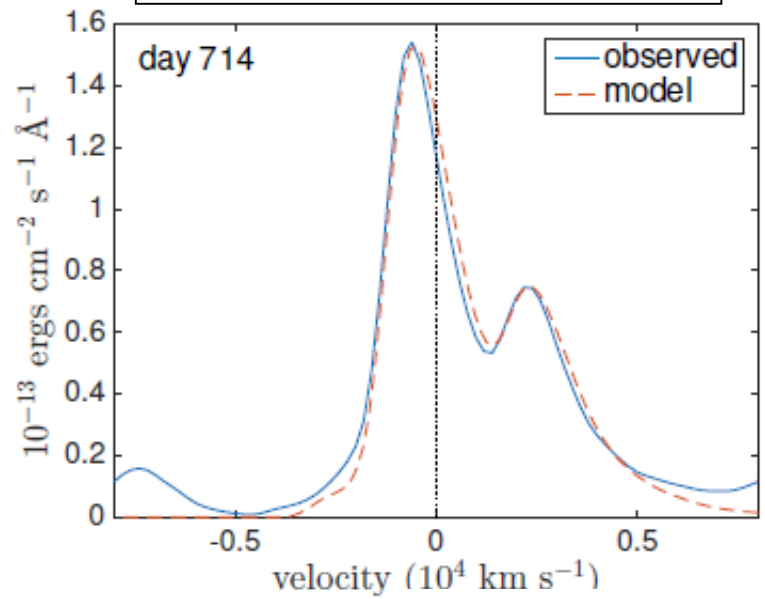
2-3. Rapid decline of light curve in SN 1987A

Optical light curve

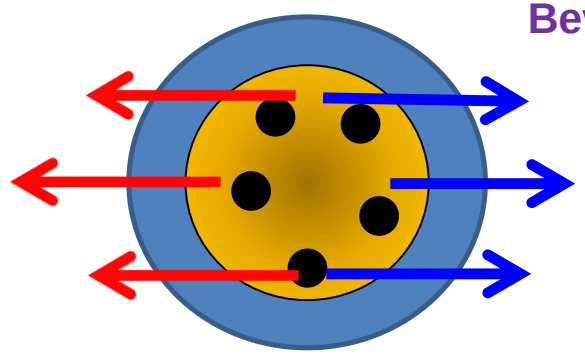


Whitelock+1989

OI 6300 emission line



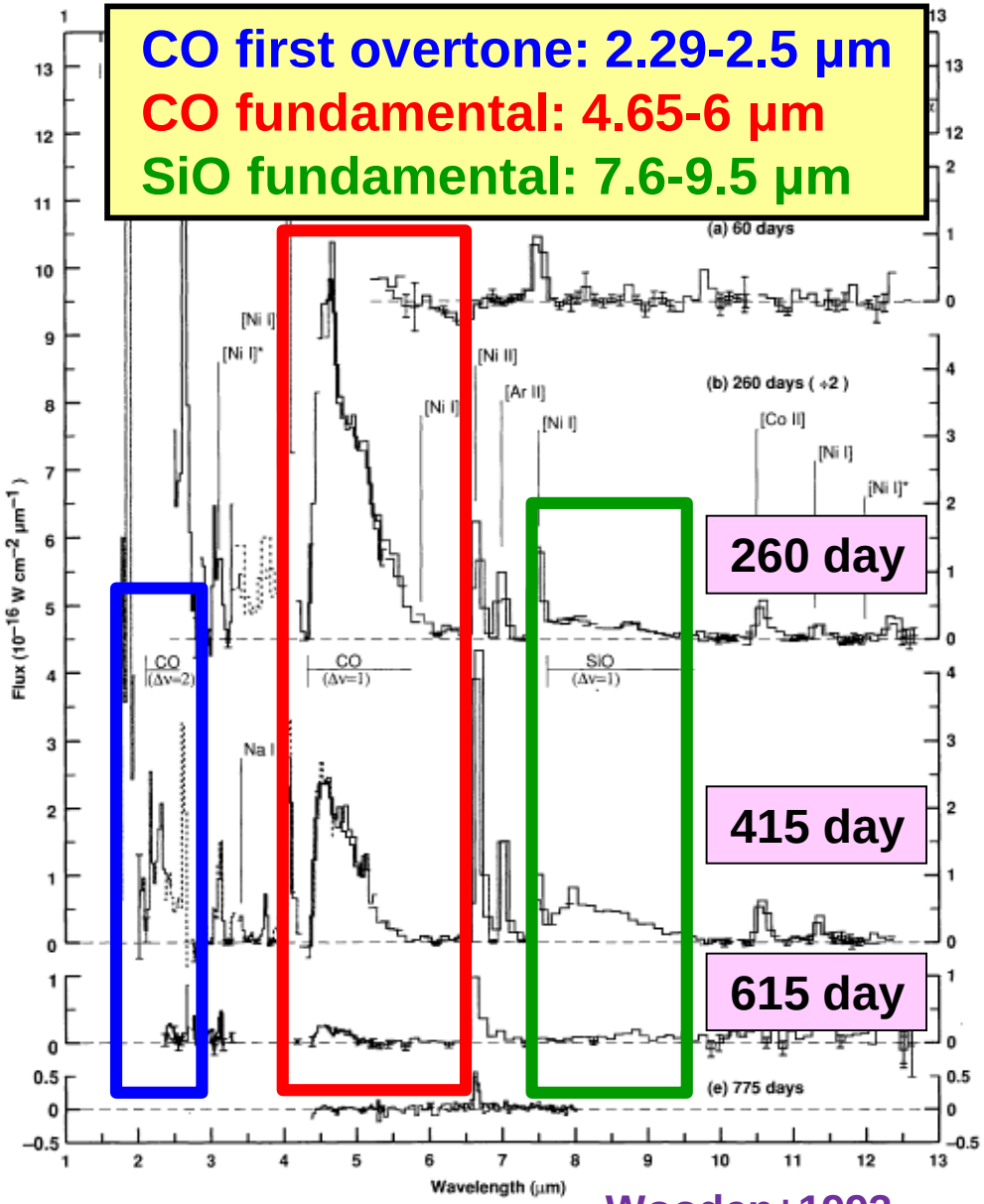
Bevan & Barlow 2016



Optical light curve starts to decline around 400 day
➜ dust starts to form at ~400 day in the ejecta

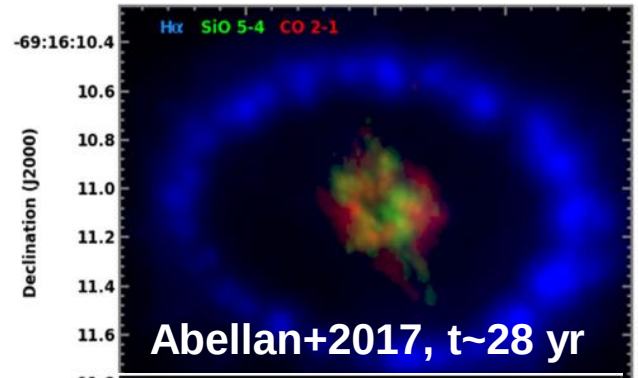
2-4. CO and SiO molecules in SN 1987A

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

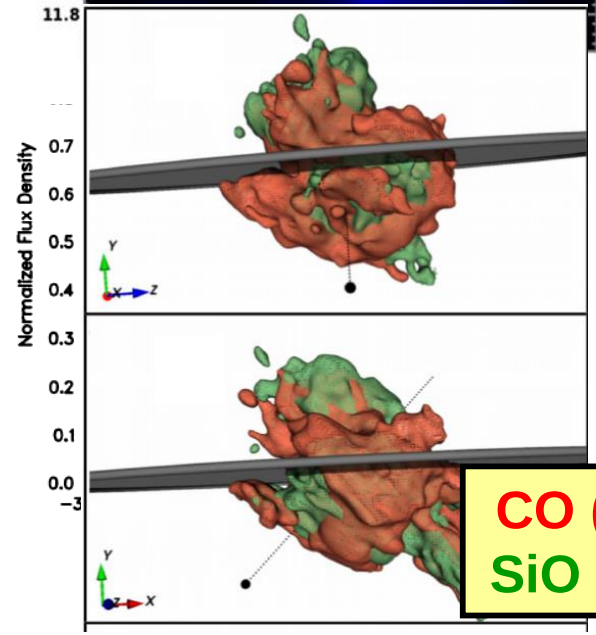


Wooden+1993

- M_{CO}~4x10^{-3} Msun (Liu+1995)
- M_{SiO}~7x10^{-4} Msun (Liu & Dalgarno 1996)



Abellan+2017, t~28 yr



CO (2-1)
SiO (5-4)

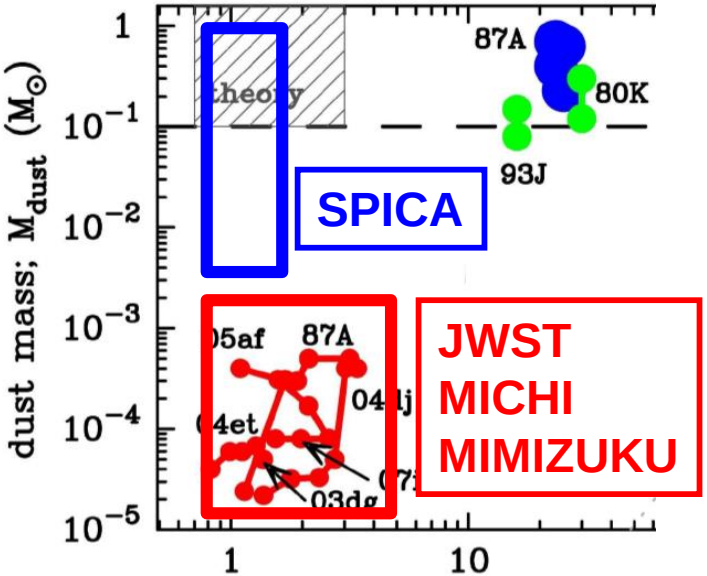
2-5. Observations of dust formation in SNe

○ Long-time monitoring of nearby CCSNe

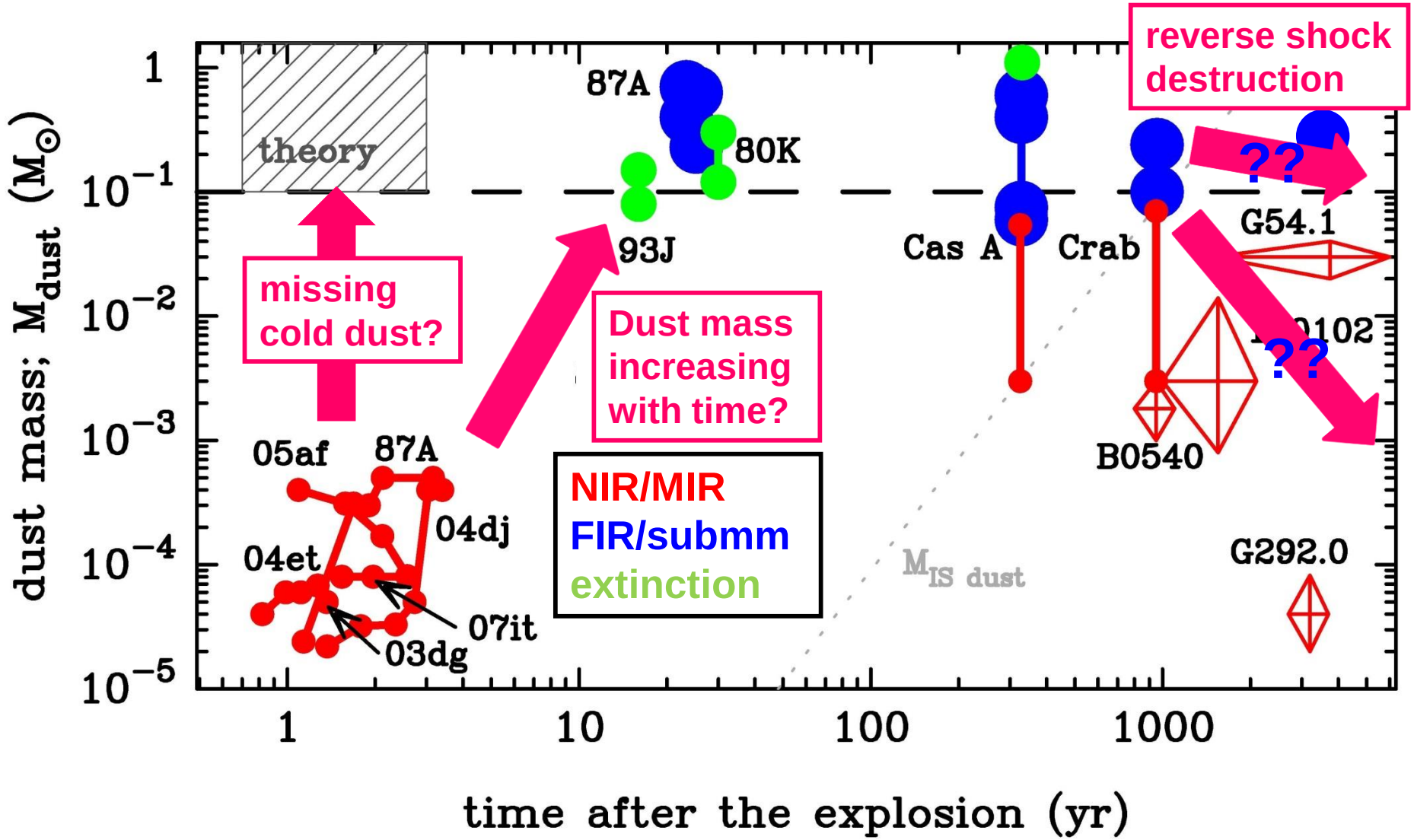
- emission lines of CO and SiO molecules in N/MIR
- thermal emission from newly formed dust in N/MIR
- Extinction of light curve in optical
- Blueshift of atomic emission lines in optical thru MIR

monitor : from 100 to 1000 days
nearby : <20 Mpc (~1 SN per yr)
➜ should focus on a few targets

※ suspect that JWST can monitor a SN every 6 month

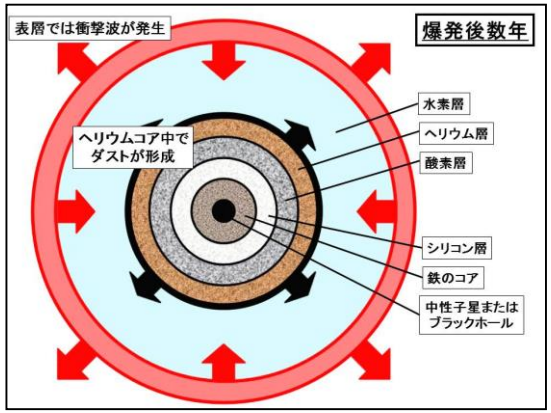


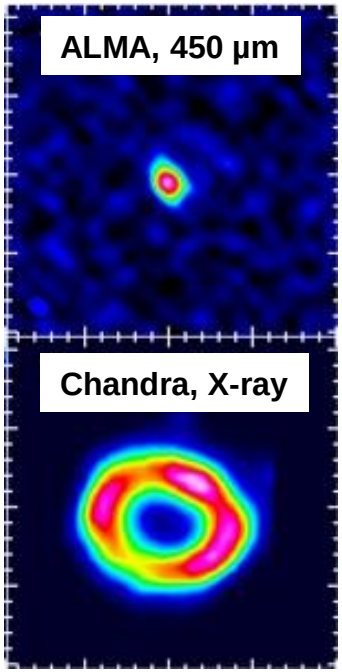
3-1. Observed dust mass in CCSNe/SNRs



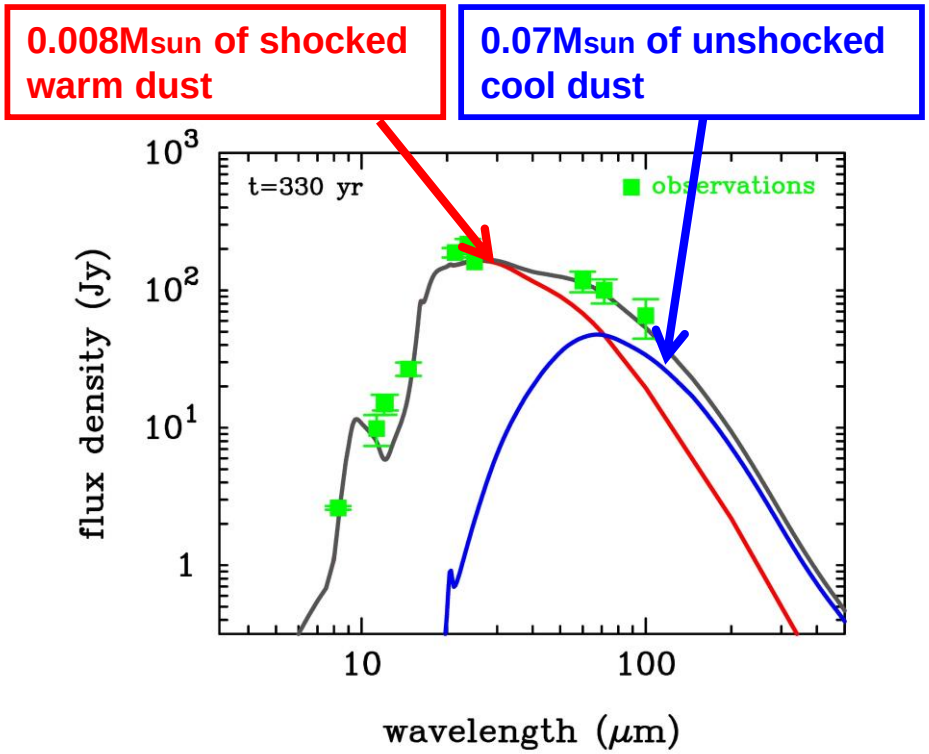
Dust mass formed in the ejecta is dominated by cold dust

3-2. Destruction of dust in Cassiopeia A SNR

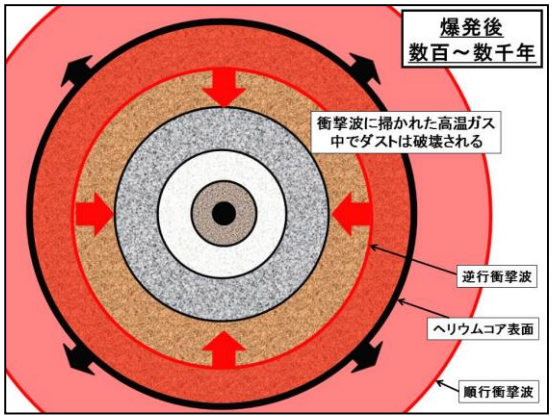




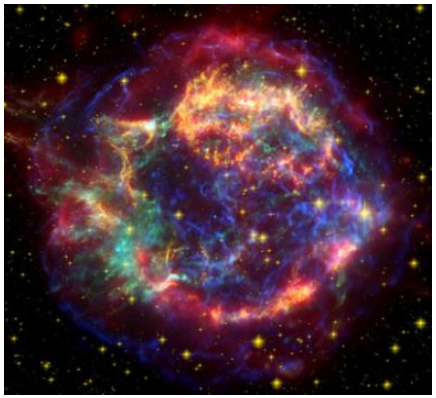
SN 1987A at 28 yr



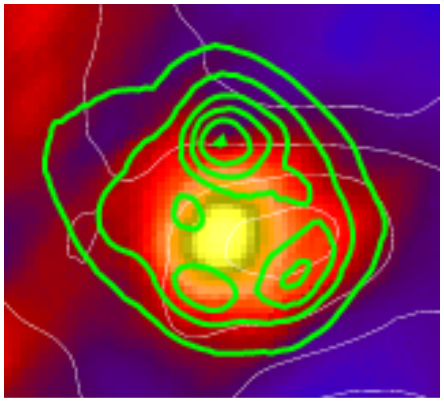
Nozawa+2010



Nozawa 2014



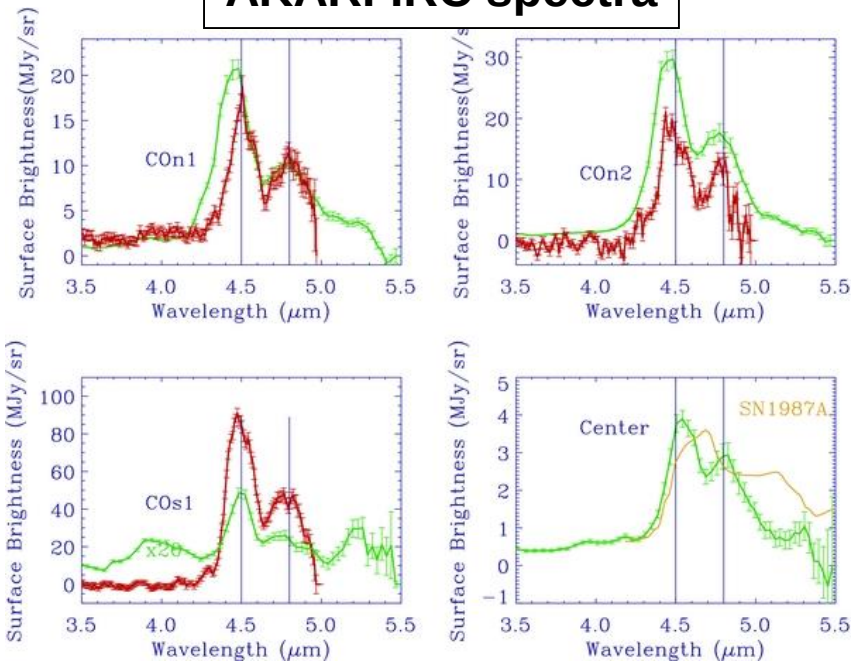
Cas A at 330 yr

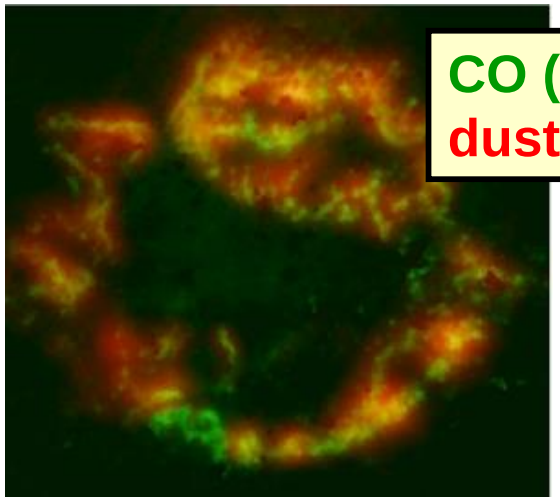


AKARI, Sibthorpe+2010

3-3. CO detection in Cassiopeia A SNR

AKARI IRC spectra

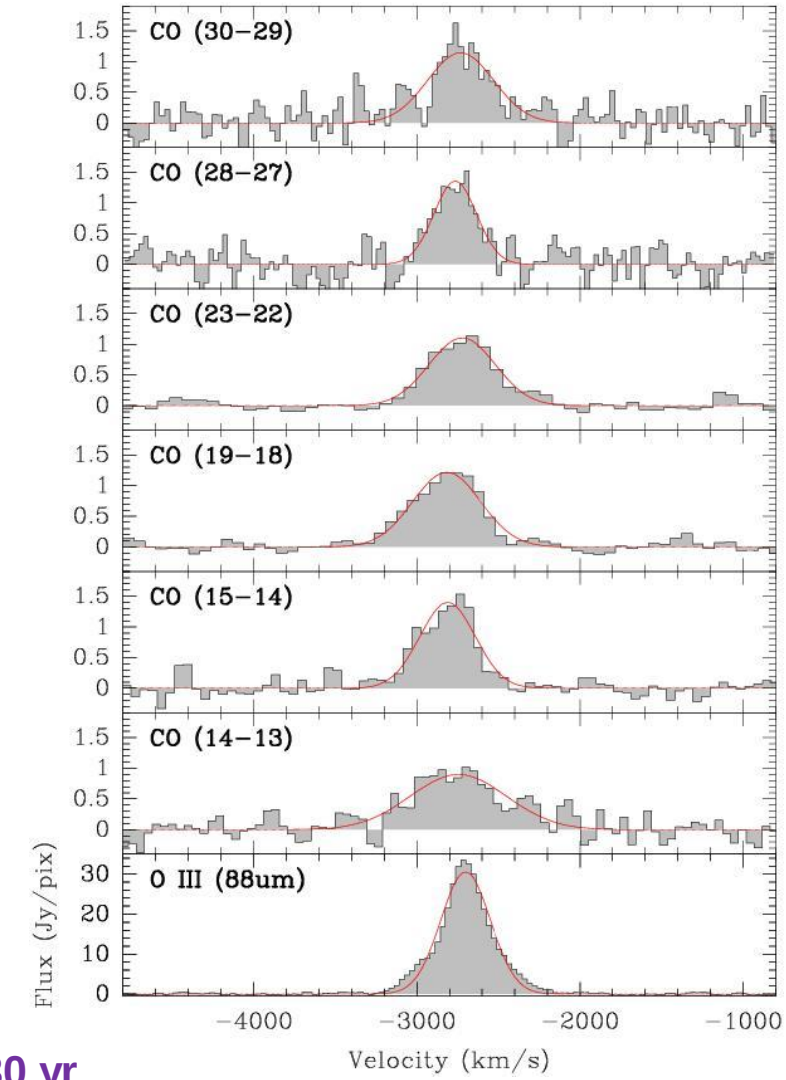




CO (4.5 μm)
dust (21 μm)

Rho+2012
Cas A at ~330 yr

Herschel PACS



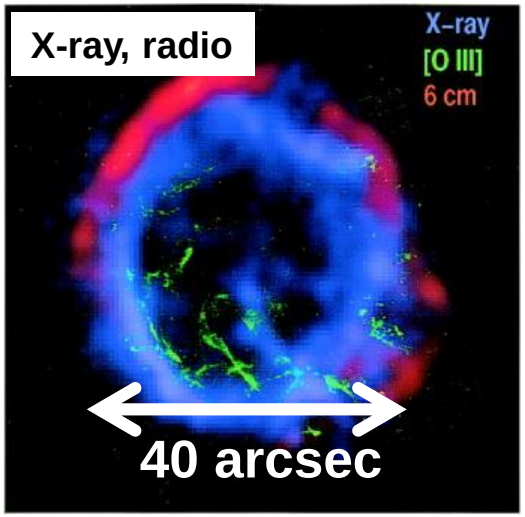
Wallstrom+2013

3-4. Possible target: SNR 1E0102-72.3 in SMC

○ SNR 1E0102-72.3 in SMC

- O-rich (similar to Cas A)
- age : ~1000 yr
- $M_{warm} \sim 10^{-3}\ M_{sun}$
- $M_{cool} \sim ???$

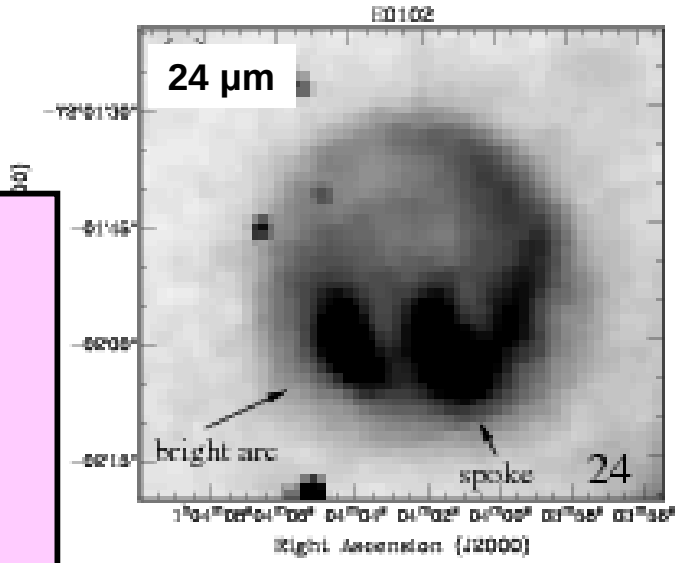
➜ spatial distributions of CO and dust with TAO/MIMIZUKU



Gaetz+2000

- what is the initial dust mass?
- how efficient is dust destruction?
- what fraction of dust can survive to be injected into the ISM?

※ SNR age : ~>10^5 yr

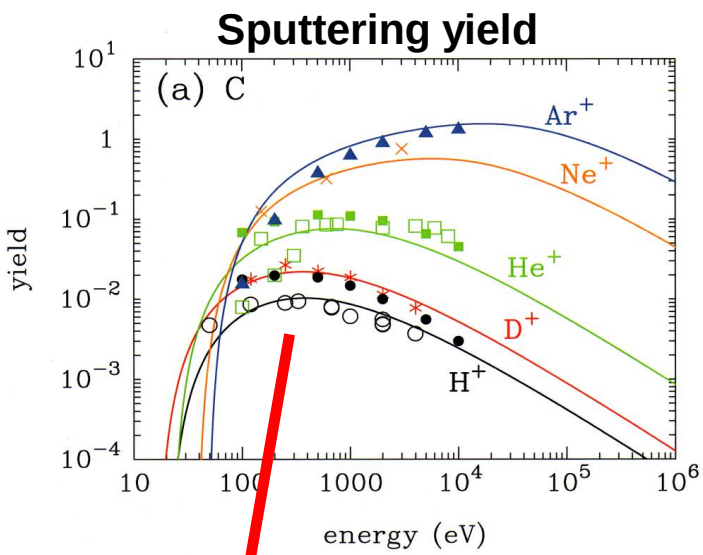


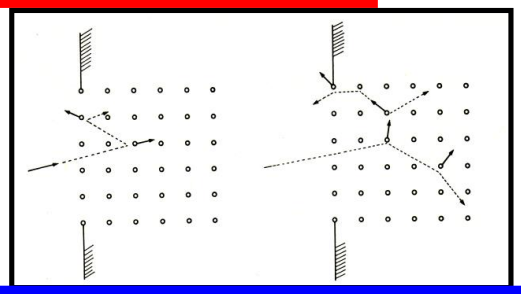
Stanimirovic+2005

3-5. Destruction rate of dust by sputtering

○ Erosion rate of dust by sputtering

$$\left|\frac{da}{dt}\right| = 10^{-6}\left(\frac{n_{\rm H}}{1\ {\rm cm}^{-3}}\right) \quad \mu{\rm m\ yr}^{-1}$$





$$4\pi a^2\left(\frac{da}{dt}\right) = -\Omega_0 \pi a^2 n_i \langle v_i Y_i\rangle$$

$$\frac{da}{dt} = -\frac{\Omega_0}{4} n_i \langle v_i Y_i\rangle$$

Targets of experimental data

bulk materials, crystal, no void, smooth surface, …

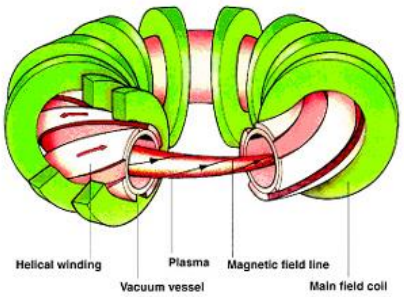
3-7. Destruction of dust by sputtering

○ Erosion rate of dust by sputtering

$$\left|\frac{da}{dt}\right| = 10^{-6}\left(\frac{n_{\rm H}}{1\ {\rm cm}^{-3}}\right) \quad \mu{\rm m\ yr}^{-1}$$

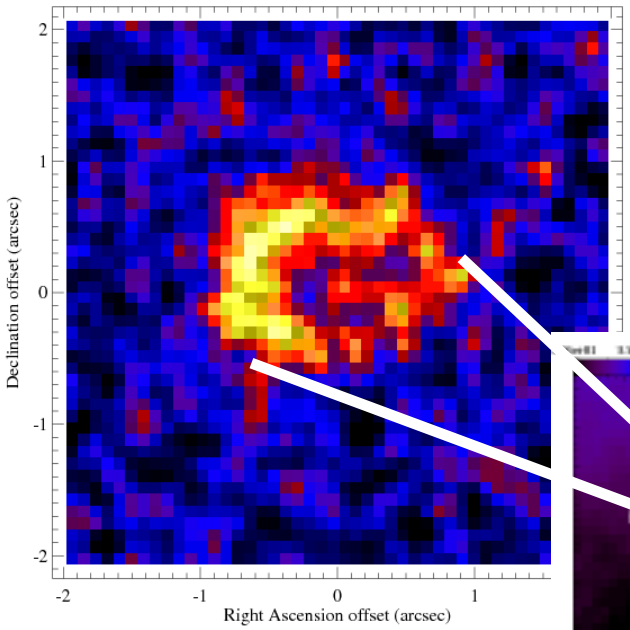
○ Erosion rate of inner wall of nuclear fusion

$$\begin{aligned}\left|\frac{da}{dt}\right| &= 10^{8}\left(\frac{n_{\rm H}}{10^{14}\ {\rm cm}^{-3}}\right) \quad \mu{\rm m\ yr}^{-1}\ {\rm cm}^{-3} \\ &= 10^{4}\left(\frac{n_{\rm H}}{10^{14}\ {\rm cm}^{-3}}\right) \quad {\rm cm\ yr}^{-1}\ {\rm cm}^{-3} \\ &\simeq 30\left(\frac{n_{\rm H}}{10^{14}\ {\rm cm}^{-3}}\right) \quad {\rm cm\ day}^{-1}\ {\rm cm}^{-3}\end{aligned}$$

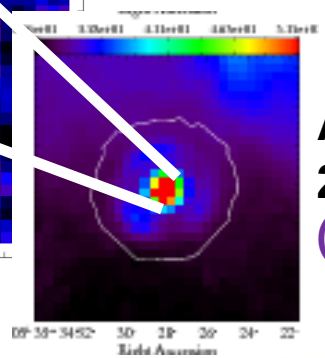


Is this erosion rate correct？

4-1. Expected IR images of SN 1987A



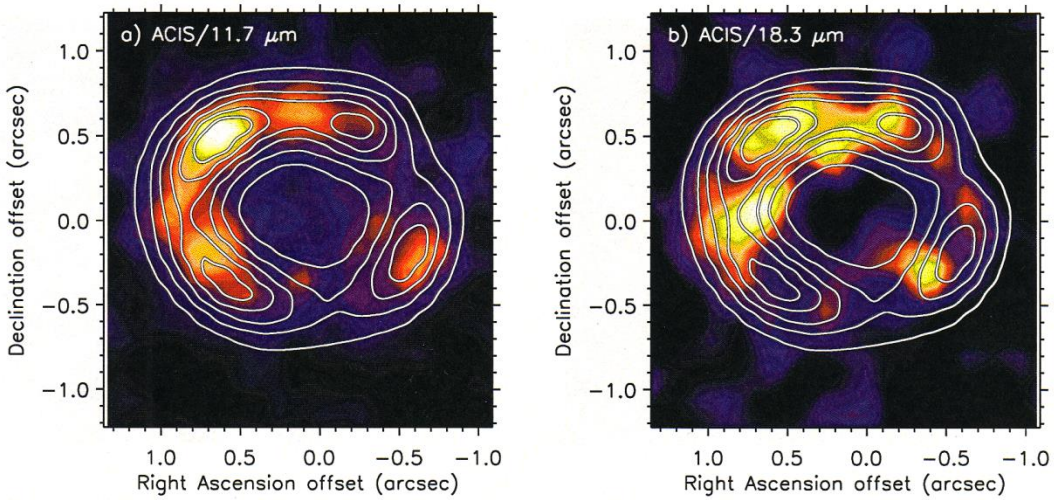
on 4 Oct 2003
Gemini T-ReCS
(λ = 10.36 μm)
2 pixels : 0.18”
(Bouchet+2004)



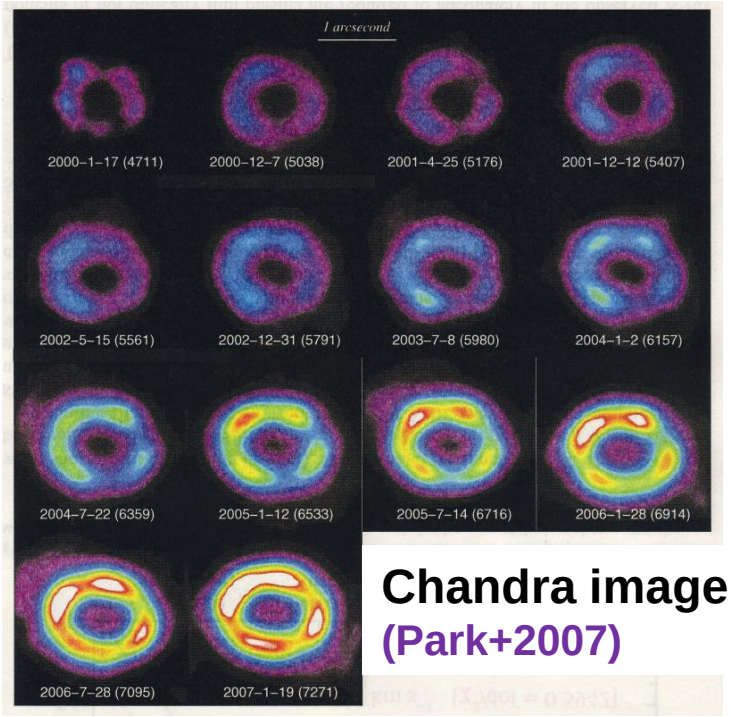
AKARI
24 μm
(Seok+2008)

SN 87A with MIMIZUKU

- spatially resolving equatorial ring
- multi-epoch (monitoring)
  ➜ evolution of CS dust
- MIR flux: 10-100 mJy



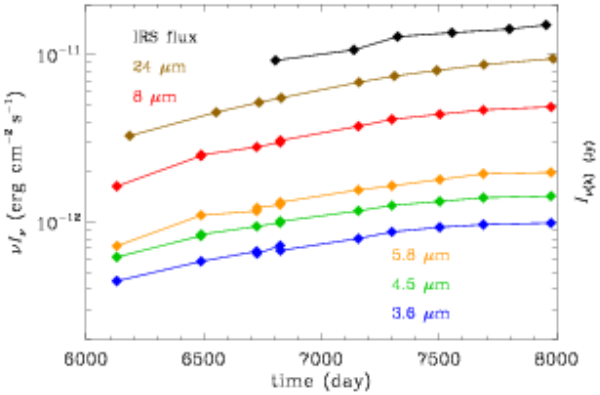
On 6 Jan and 1 Feb 2005 (Bouchet+2006)



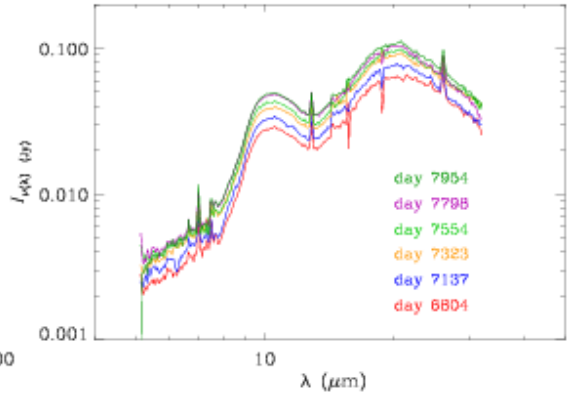
Chandra image
(Park+2007)

4-2. Properties of CS dust around SN 1987A

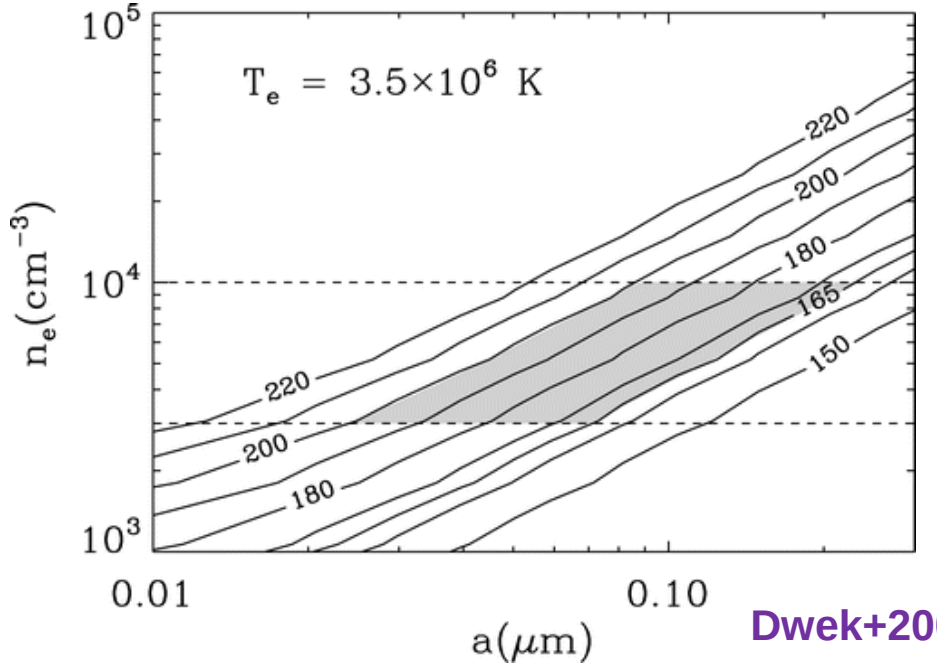
IR light curve



MIR SEDs



Spitzer observation (Dwek+2010)



Dwek+2008

- **IR fluxes increase in all bands by a factor of ~3 between 17 yr and 22 yr**

- **properties of CS dust in ER**

silicate
T_{dust} = 180 K
M_{dust} = ~10^{-5} M_{sun}
L_{IR} = 10^{36}-10^{37} erg/s

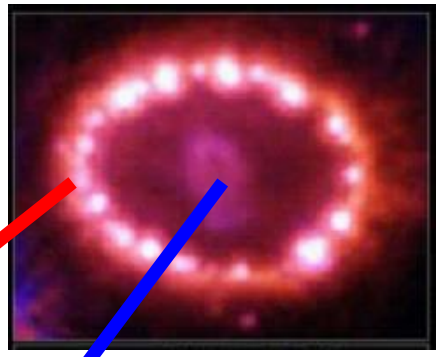
(Seok+2008, Dwek+2008)

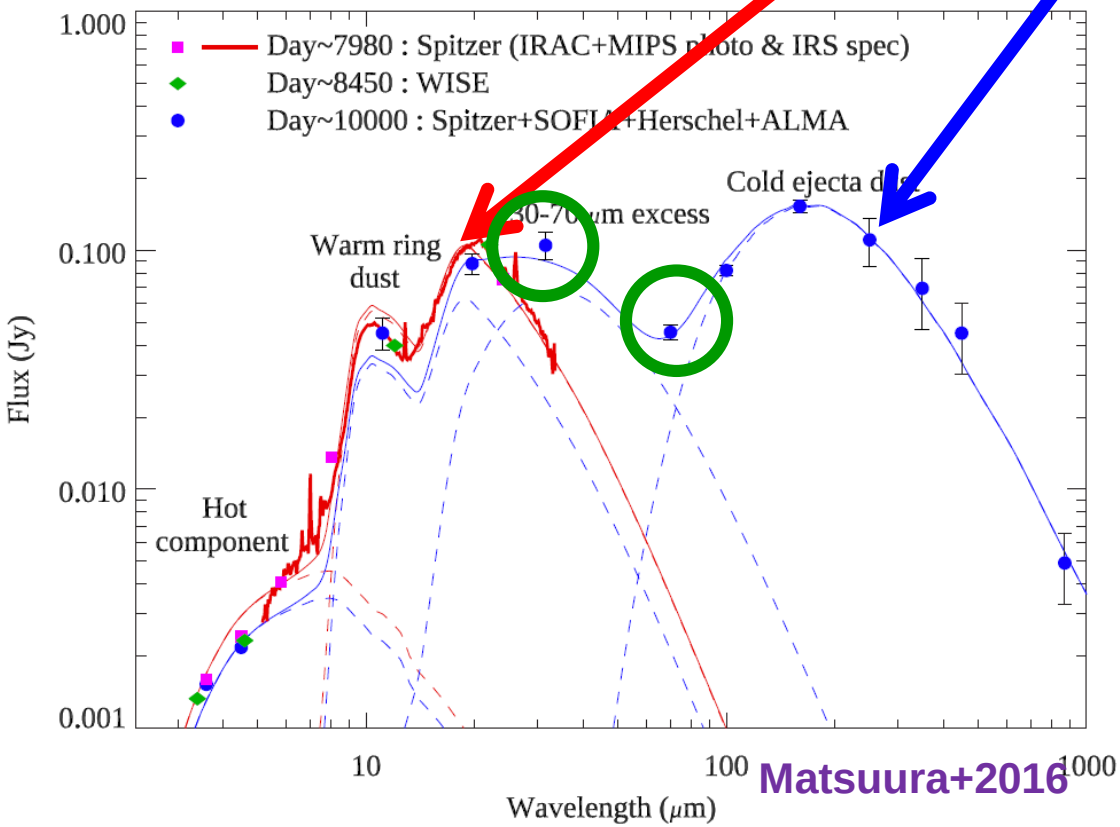
- **grain radius:**
  a = 0.02-0.2 μm
  ➔ relatively large

4-3. Re-formation of dust in equatorial ring?

○ SOFIA observations of SN 1987A

- 30-70 μm excess appeared at 10000 day
  - cool dust = ~4x10^{-4} Msun
    - ➜ re-formation of dust in the ring??
  - hot dust = ~10^{-5} Msun





Matsuura+2016

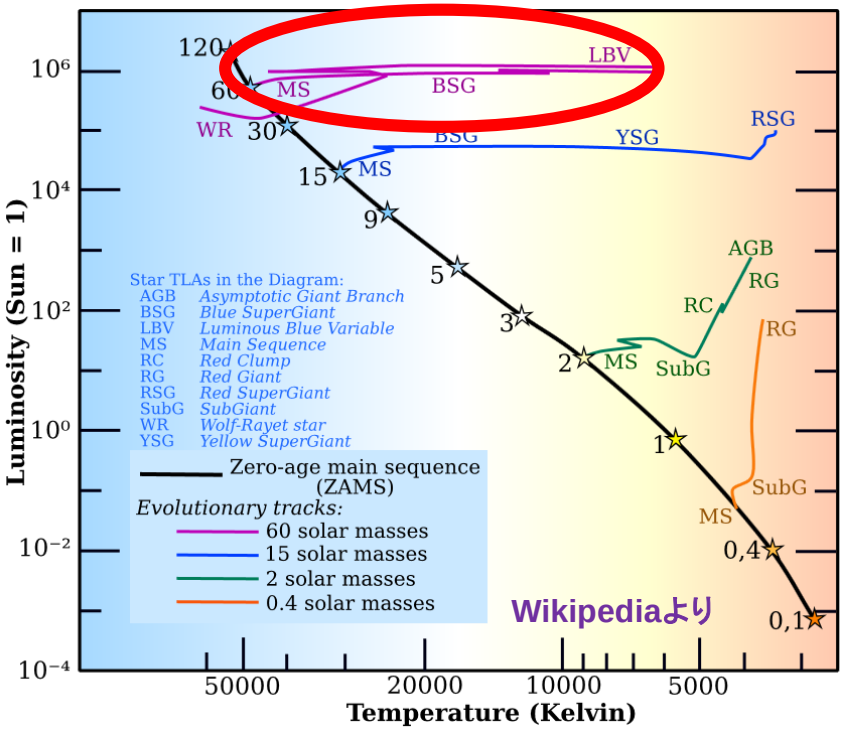
5-1. What is LBVs?

○ LBVs (luminous blue variables)

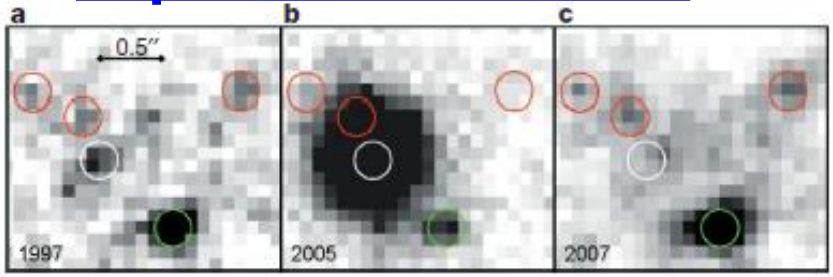
- $\log_{10}(L / L_{sun}) = 5.5\text{-}6.5$
- $\log_{10}(T_{eff} / K) = 3.8\text{-}4.6$

➜ $M_{star} = 40\text{-}150\ M_{sun}$

17 LBVs in our Galaxy (at Mar 2016)



○ Is Type IIn SN 2005gl explosion of a LBV?

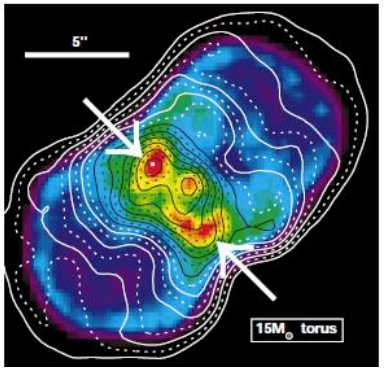


Gal-Yam & Leonard 2007, 2009

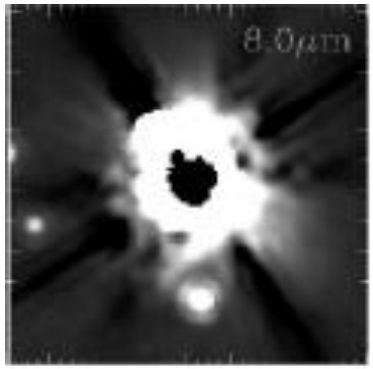
➜ **Challenge to the stellar evolution theory**

5-2. Dusty envelopes around LBVs

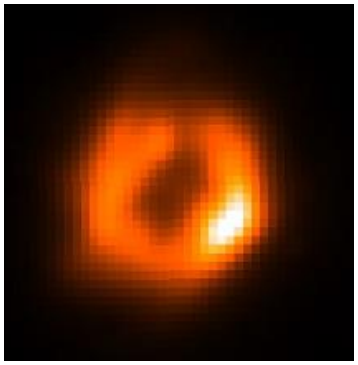
Eta Carina
TIMMI 17 μm
Morris+1999



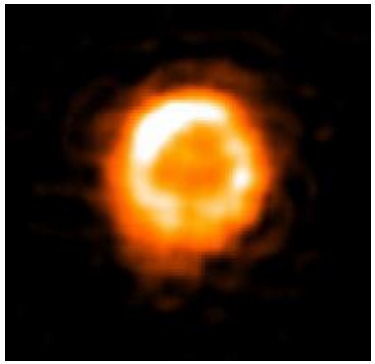
HR Car
Spitzer 8 μm
Umana+2009



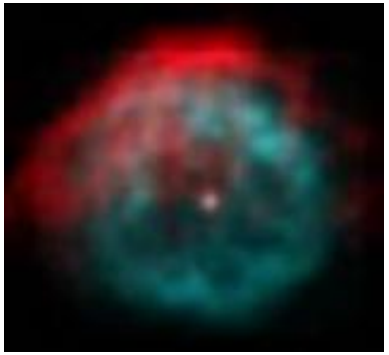
AG Car
Herschel 70 μm
Vamvatira-Nakou+2015

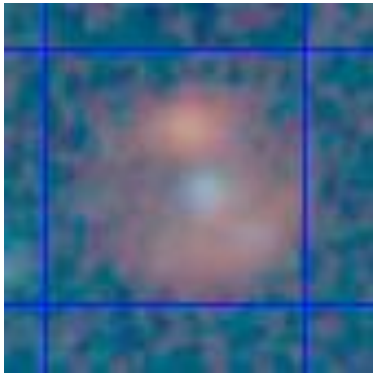


Wray15-751
Herschel 70 μm
Vamvatira-Nakou+2013

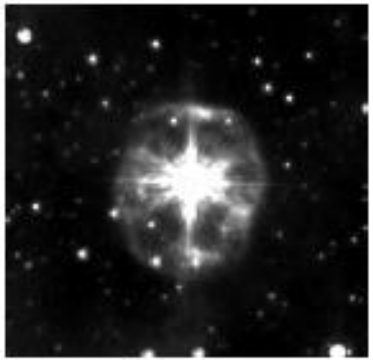


AFGL2298
VISIR 17.65 μm
Buemi+2010

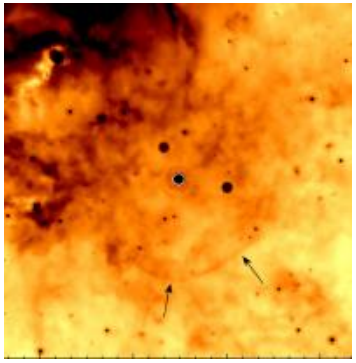




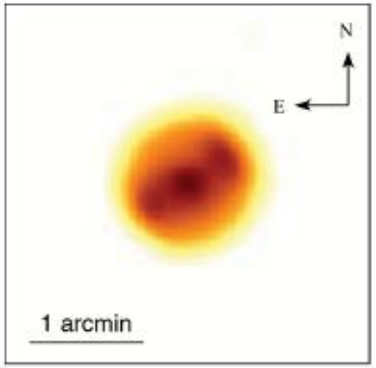
G24.73
MSX 7-25 μm
Clark+2003



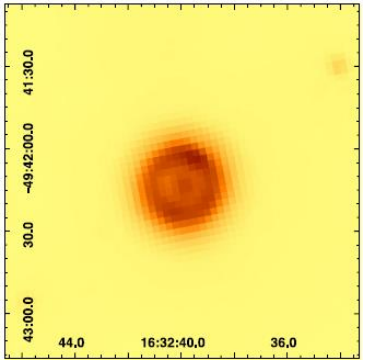
MWC 930
WISE 22 μm
Cerrigone+2014



Wray16-137
Spitzer 24 μm
Gvaramadze+2014



WS1
WISE 22 μm
Gvaramadze+2012



MN44
Spitzer 24 μm
Gvaramadze+2015

70% of LBVs have thick circum-dust envelopes
➜ dust formation in mass-loss winds

5-3. Dust formation in mass-loss winds of LBVs

○ Two difficulties of dust formation in LBVs

- fast wind velocity (~100-300 km/s) ➜ low gas density

$$\rho_{gas} = M_{dot} / (4 \pi r^2 v_{wind})$$

cf. v_{wind} = 10-30 km/s for AGB stars

- high BB temperature ➜ dissociation of dust by UV radiation

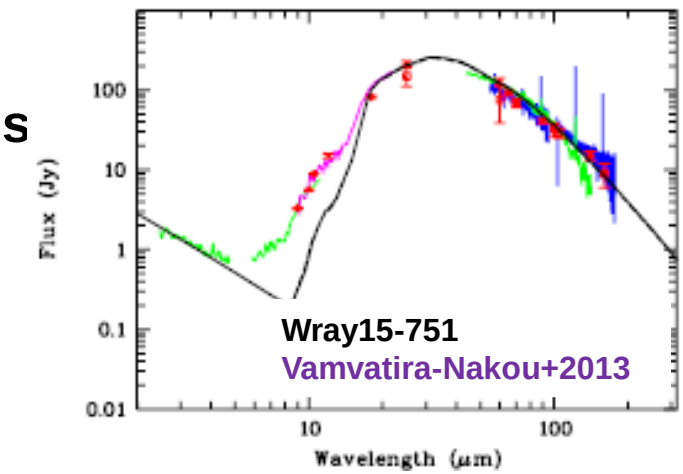
Studies of dust formation in LBVs are challenging !!

○ Dust formation in dense clumps?

- high gas density, shielding of UV photons

Spatial distribution of CS dust

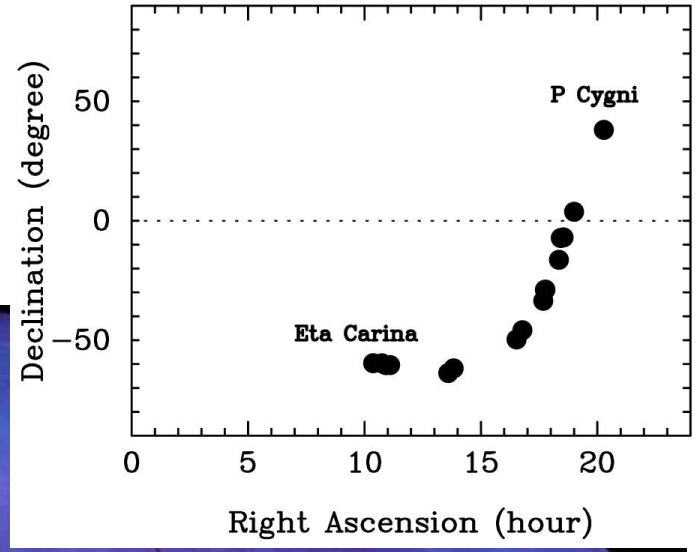
➜ N/MIR high spatial-resolution mapping of LBVs

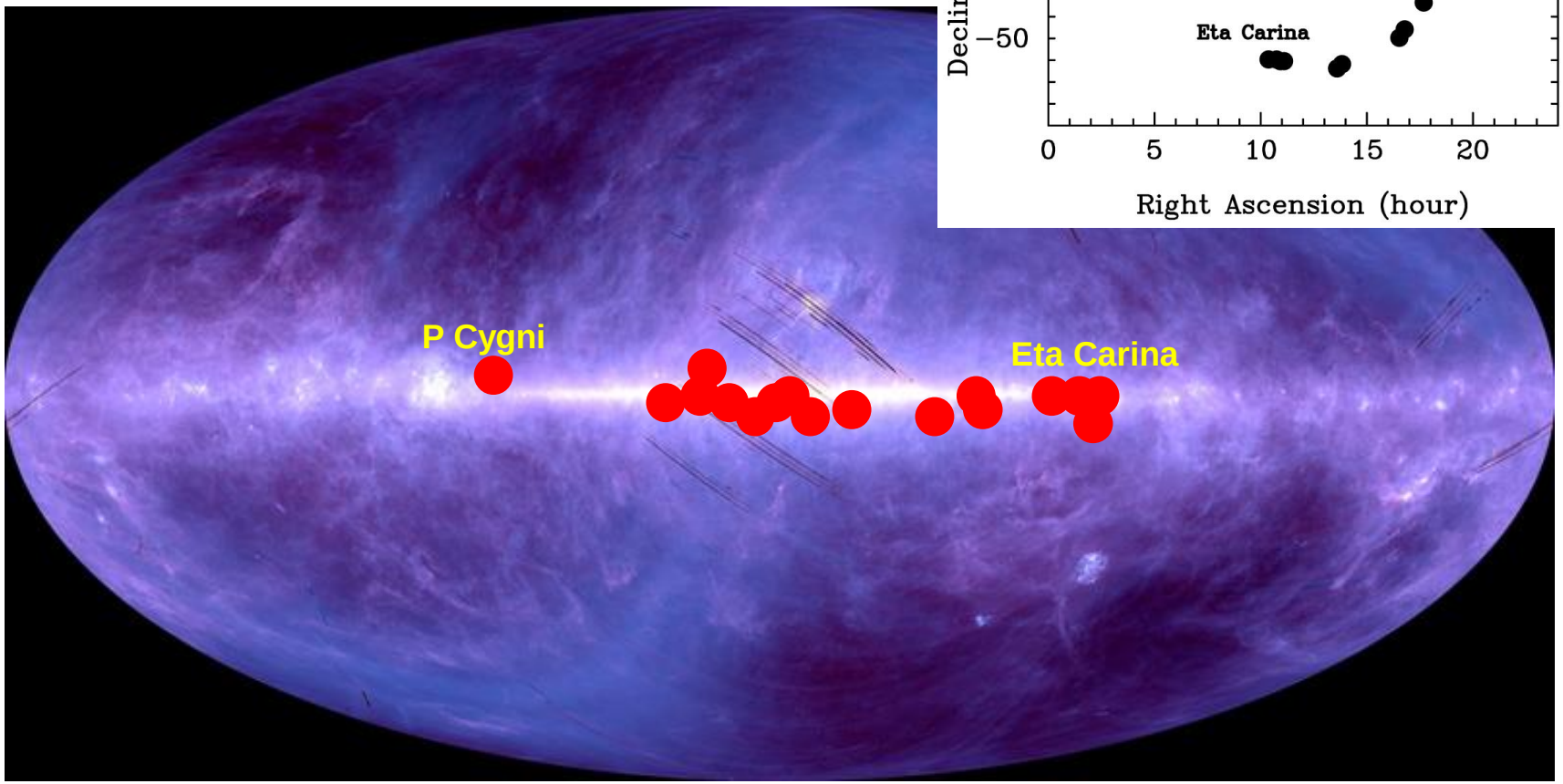


5-4. Most LBVs only from southern hemisphere

○ 16 of 17 LBVs in southern sky

➜ ideal targets to be observed by TAO/MIMIZUKU





AKARI FIR images, Credit: JAXA/ISAS

5-5. Significance of studying LBVs

○ Important topics related to LBVs

- Dust formation processes in extreme environments
  - ➜ laboratories that probe dust condensation in space
- Mechanisms of (explosive) mass loss
  - ➜ mass-loss rate, asymmetry of ejected gas
- Relationship with Type IIn SNe
  - ➜ Are LBVs progenitor stars of Type IIn SNe?
- Understanding of massive star binaries
  - ➜ many of LBVs are binaries

Observations of LBVs ➜ Dust formation theory
Stellar evolution theory

Obs targets w.r.t. dust formation/destruction

(1) long-term monitoring of nearby CCSNe with TMT

- ➜ line emissions of CO/SiO and Fe group elements
- ➜ IR emission and optical extinction of dust grains

(2) young SNRs in LMC/SMC

- ➜ spatial distribution of CO and dust grains
- ➜ dust destruction of dust by reverse shocks

(3) MIR monitoring of SN 1987A with TAO/MIMIZUKU

- ➜ evolution of dust in the equatorial ring
- ➜ derivation of dust destruction efficiency

(4) IR mapping observations of Galactic LBVs

- ➜ most of LBVs are seen only from southern sky