2014/06/17

ダストの形成･破壊素過程の観測から探る星の進化

野沢 貴也（Takaya Nozawa）

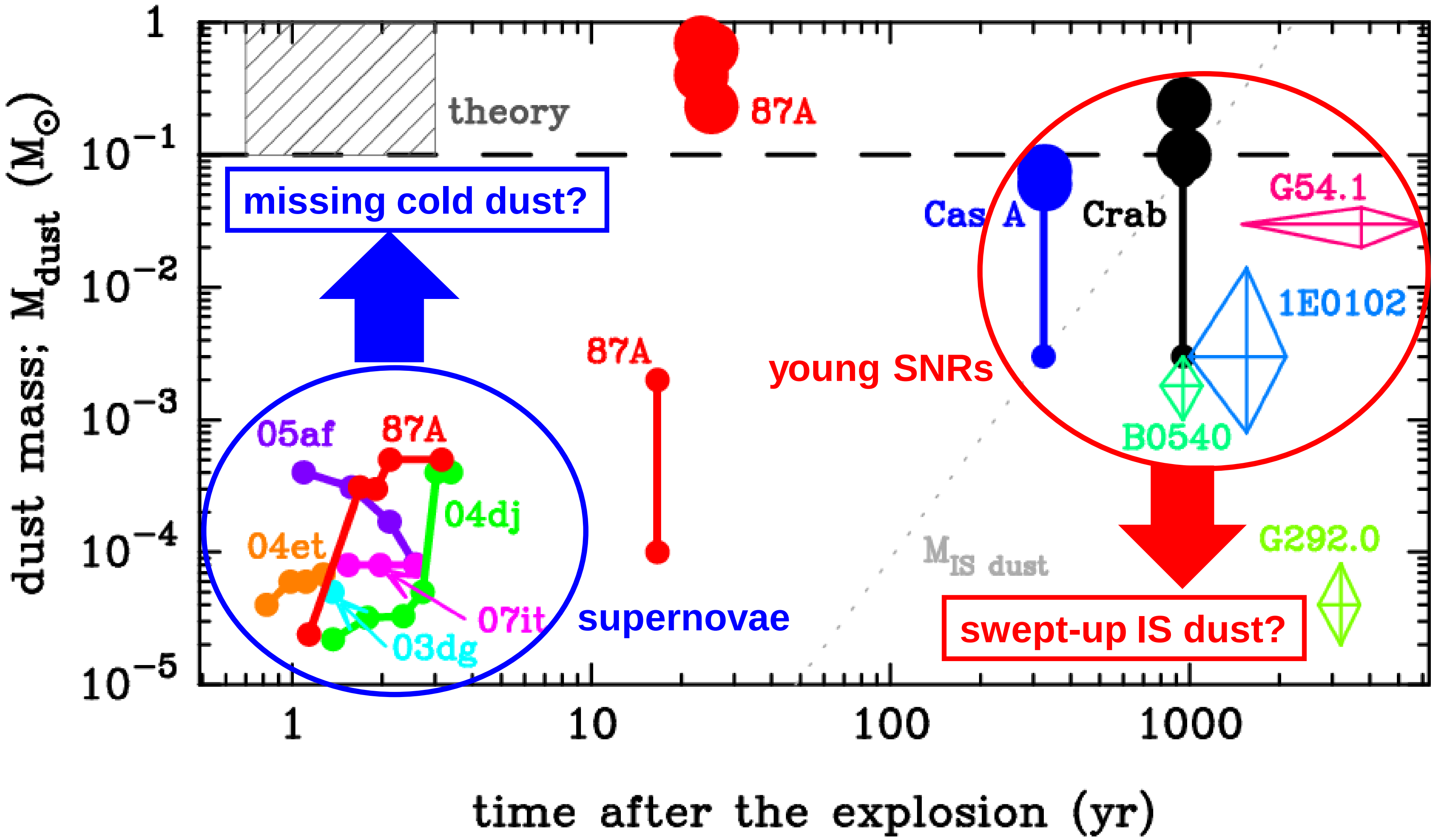
(National Astronomical Observatory of Japan)

1. Formation of dust in the ejecta of supernovae

2. Destruction of circumstellar dust by shock waves

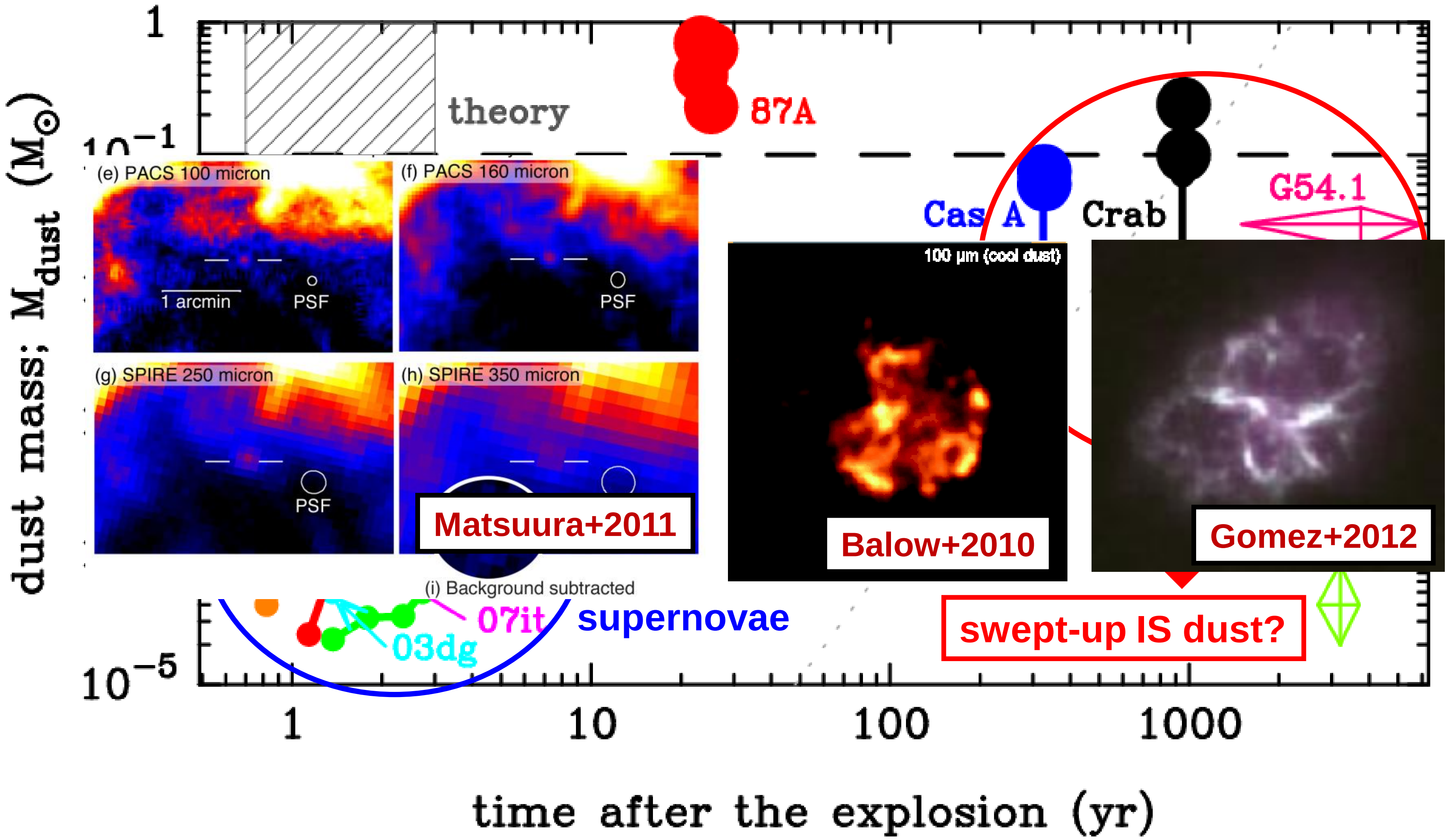
3. Formation of dust in mass-loss winds of RSGs

1-1. Summary of observed dust mass in CCSNe



Far-IR to sub-mm observations revealed that ~0.1 Msun of dust grains can be produced in the ejecta of SNe

1-1. Summary of observed dust mass in CCSNe



Matsuura+2011

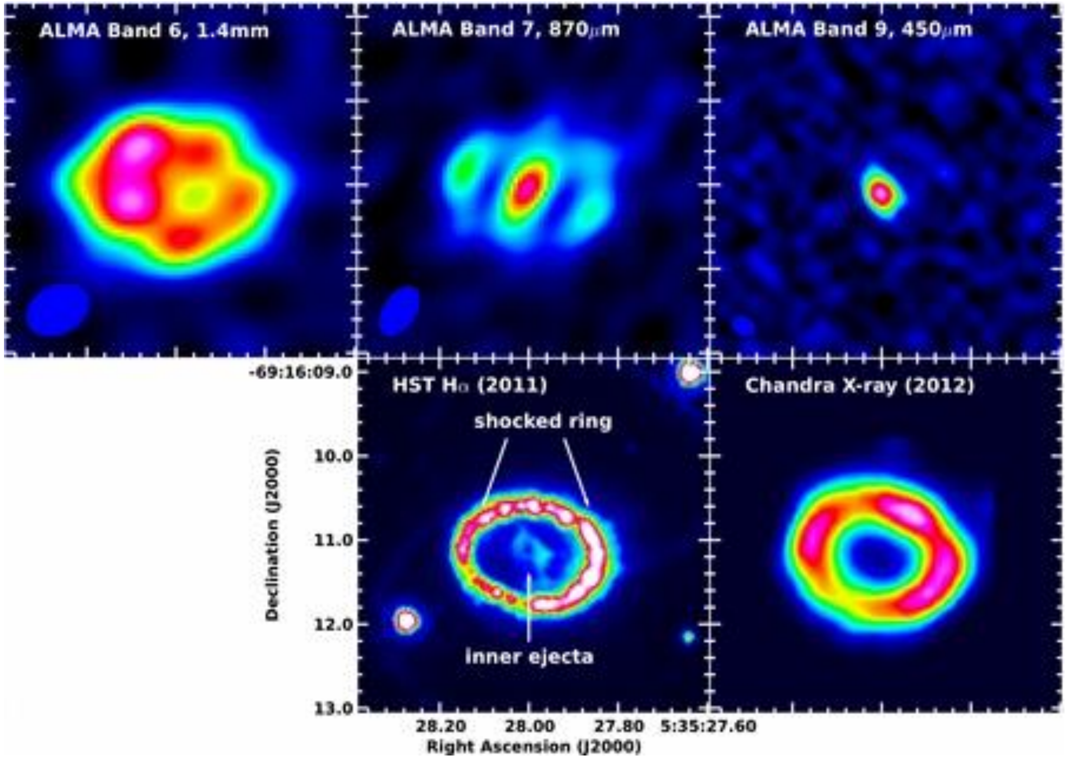
Balow+2010

Gomez+2012

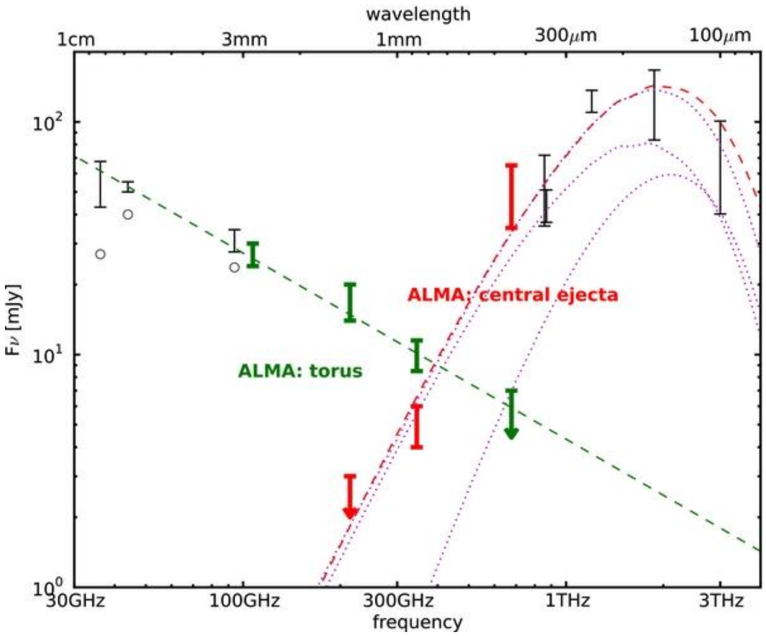
swept-up IS dust?

Far-IR to sub-mm observations revealed that ~0.1 Msun of dust grains can be produced in the ejecta of SNe

1-2. ALMA reveals dust formed in SN 1987A



SED of 25-years old SN 1987A



Indebetouw+2014

ALMA spatially resolves the thermal emission from cool (~20K) dust of ~0.5 Msun formed in the ejecta of SN 1987A

➔ core-collapse SNe could be production factories of dust grains

SN 1987A is the only target that can probe dust formation in
SNe with ALMA

1-3. Main problems on dust formation in SNe

- 形成されるダスト量はわかったが、形成されるダストの組成・サイズは？

（形成されたダストがリバースショックにどれだけ破壊されるかに重要）

➜ 可視近赤外線スペクトルの観測が必要（➜ JWST？）

- なぜ中間赤外線と遠赤外線でダスト量が違うのか？

（光学的厚さの問題？ダスト温度の違い？ダスト形成時期の違い？）

➜ 理論計算が必要（輻射輸送計算、密度の高いクランプ中のダスト形成）

例えば、中間赤外線ではまさに形成されたばかりの高温ダストを見ている？
(10^−4 Msun/day) x (1000 day) = 0.1 Msun？？

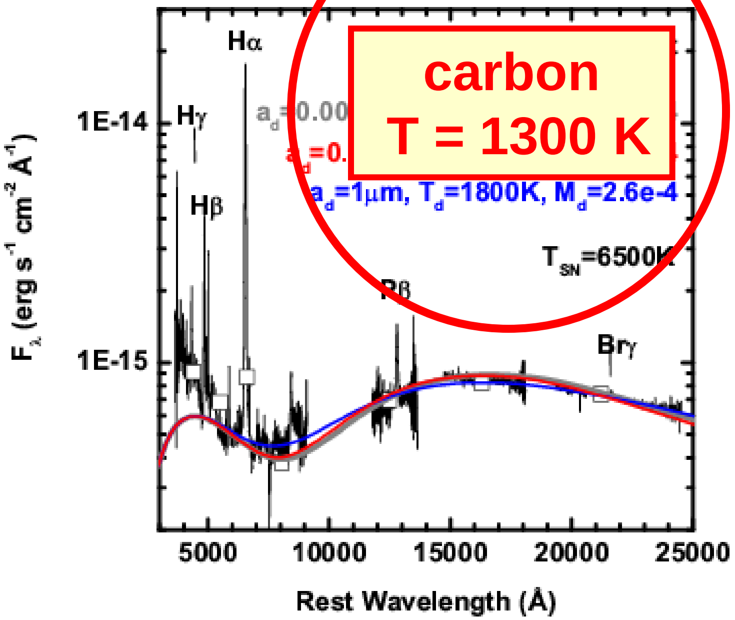
- ダストを形成する超新星の割合は？どんなタイプの超新星がダストを作る？

➜ JWSTなどによりサンプル数は増加するはず（が劇的に増えない？）

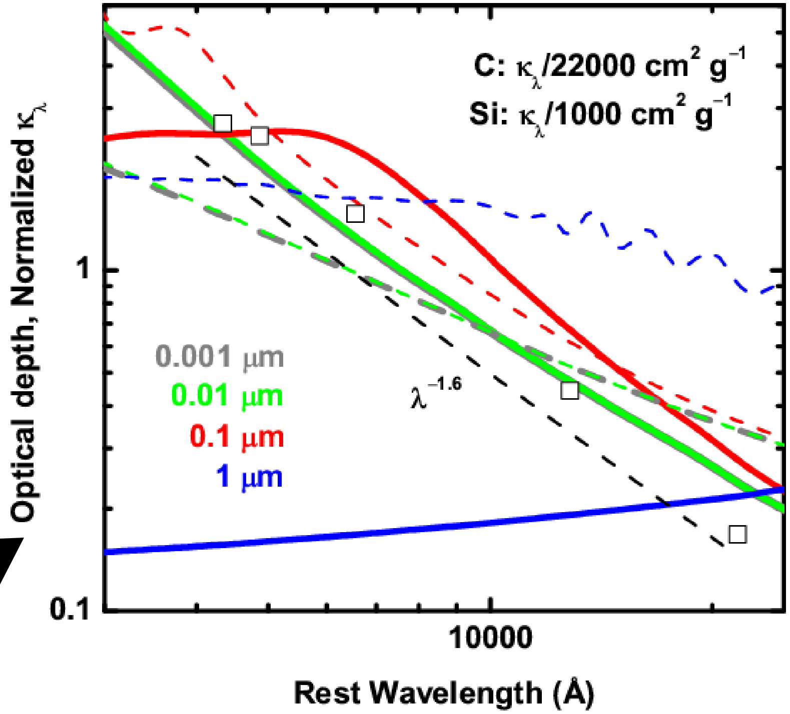
観測される基本物理量は変わらない (λ ＜ 24 μm)
➜ ダスト形成過程の理解そのものには、大きな躍進はないかも？

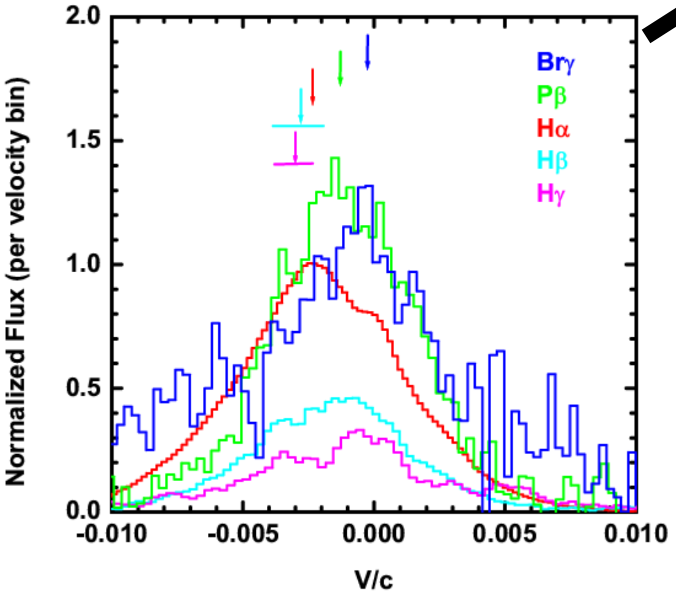
統計的な議論は可能になるだろう

1-4. Dust formation in Type IIn SN 2010jl



carbon
T = 1300 K





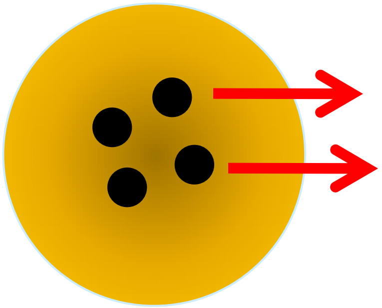
Newly formed dust in SN 2010jl

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

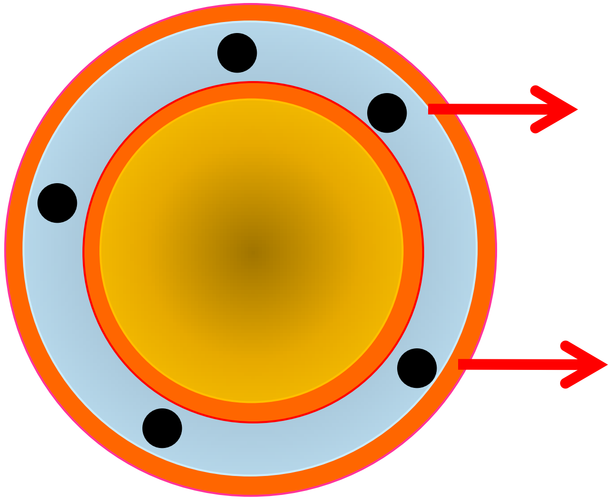
Maeda, TN, et al. (2013)

1-5. Origin of IR emission from SNe

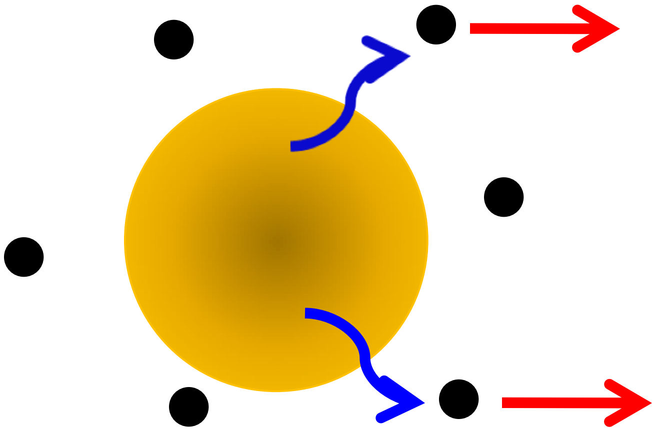
Dust formation in the ejecta



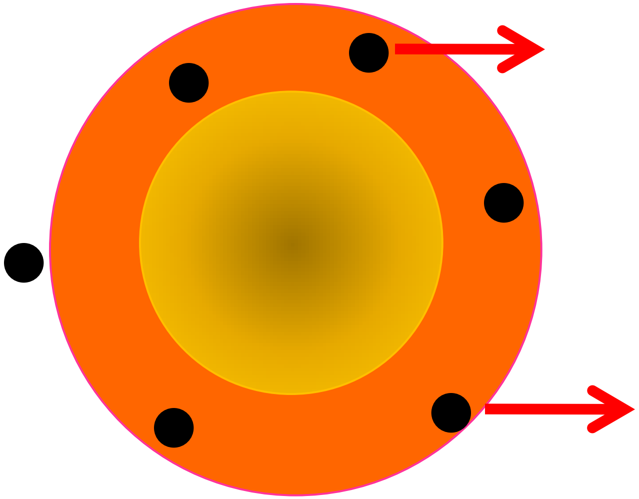
Dust formation in dense shell



IR light echo by CS dust



Shock heating of CS dust



1-6. Statistics of dust-forming SNe

- newly formed dust in the ejecta ➜ mainly Type II-P SNe

SN 1987A (II-pec), SN 2003gd (II-P), SN 2004dj (II-P), SN 2004et (II-P),
SN 2005ad (II-P), SN 2005af (II-P), SN 2006bc (II-L), SN 2006jc (Ib),
SN 2007it (II-P), SN 2007od (II-P) ➜ 10 SNe + several candidates

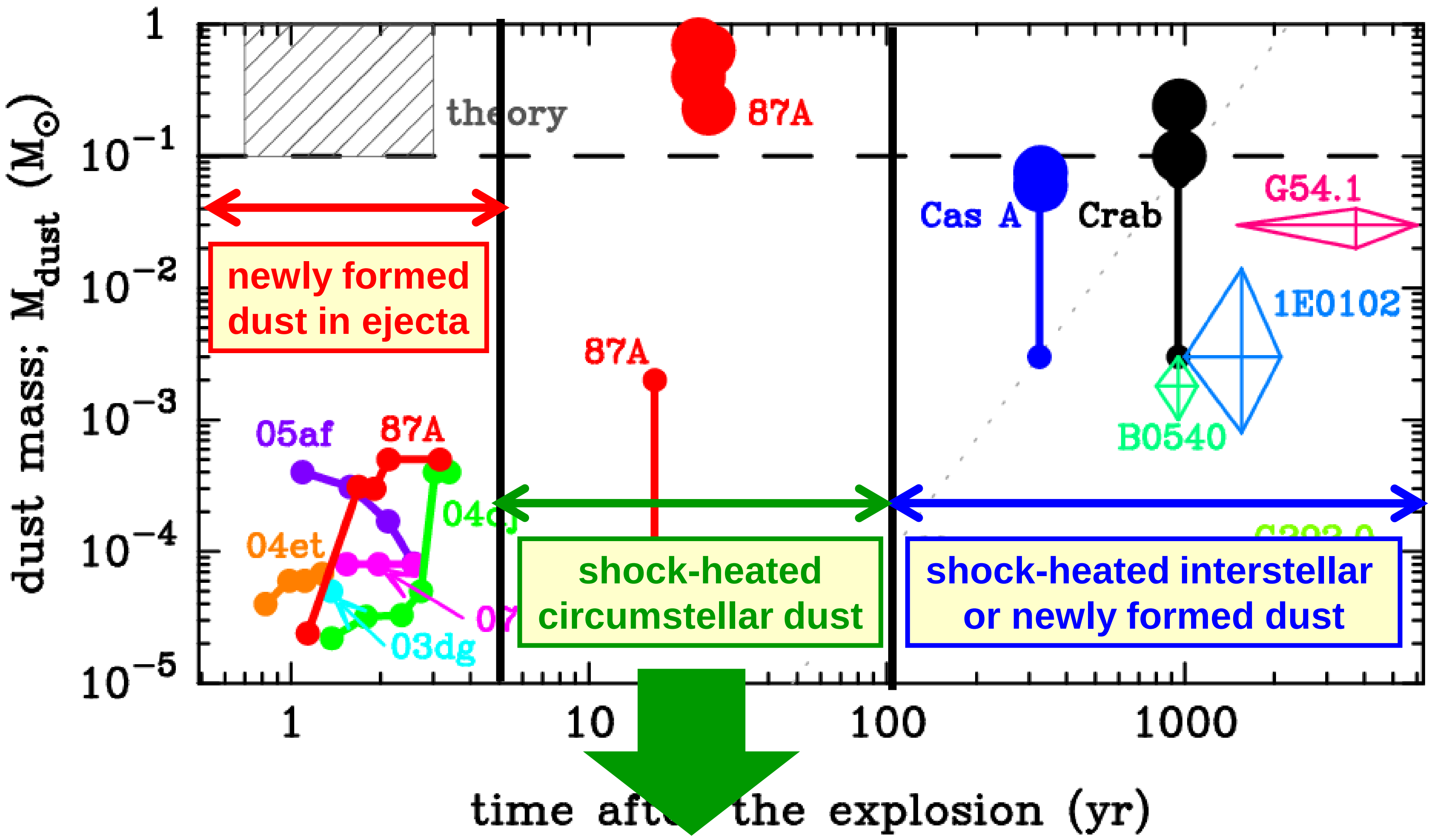
- newly formed dust in cool dense shell ➜ mainly Type IIn SNe

SN 1998S (IIn), SN 2005ip (IIn), SN 2006jc (Ib), SN 2006jd (IIn),
SN 2007rt (IIn), SN 2010jl (IIn) ➜ 6 SNe

- Why no evidence for dust formation in Type Ic and Ia SNe?
  ➜ observational bias? Type Ic: rare, Type Ia: distant
  ➜ too low ejecta density to produce dust grains

- Why SNe IIn (~10% of all SNe) produce dust more efficiently?
  ➜ observational bias? Type IIn: relatively bright
  ➜ dust temperature high enough to be detected in NIR

2-1. Observing CS dust in aged dusty SNe



newly formed dust in ejecta

shock-heated circumstellar dust

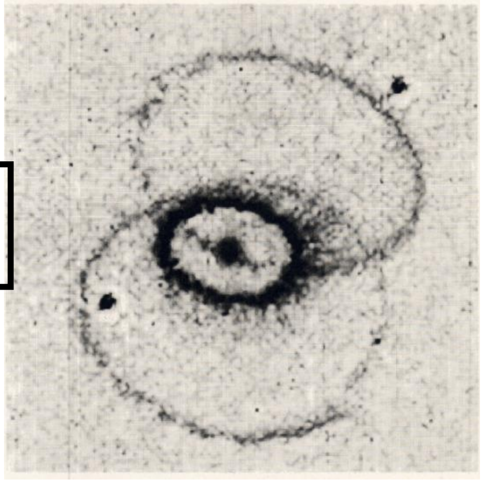
shock-heated interstellar or newly formed dust

Exploring the evolution of circumstellar dust by MIR observations of SNe 5-100 yr after explosions

2-2. MIR observations of SN 1987A

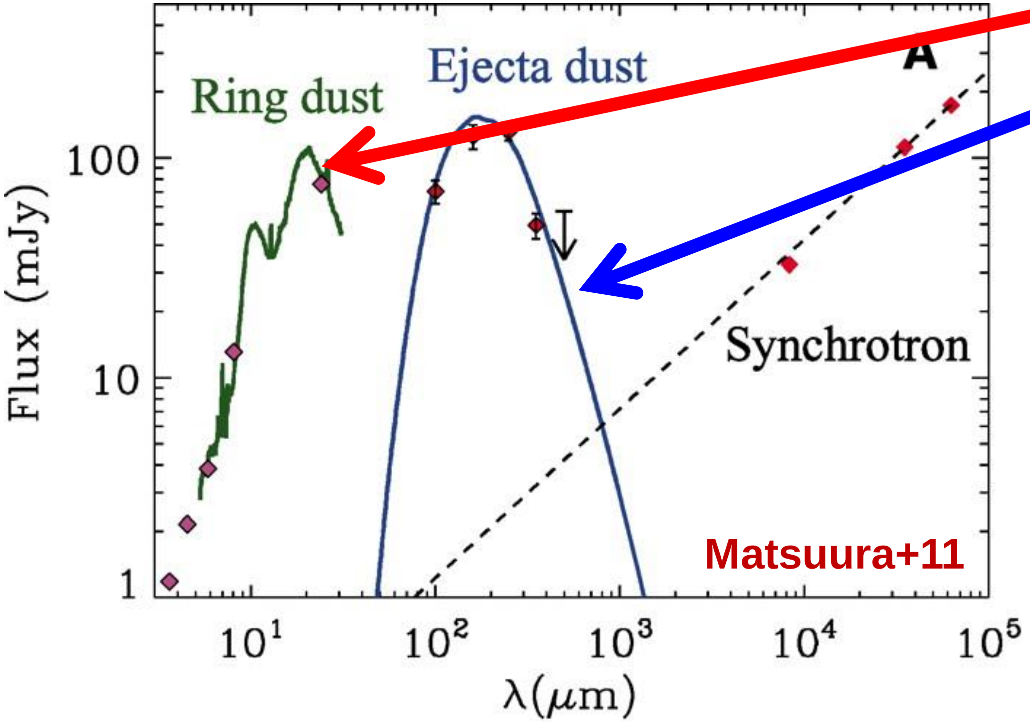
○ SN 1987A (Type II-pec)

- **host galaxy: LMC (d = 50 kpc)**
- **shocked equatorial ring**
- **ring diameter : 2” (=0.5 pc@50 kpc)**

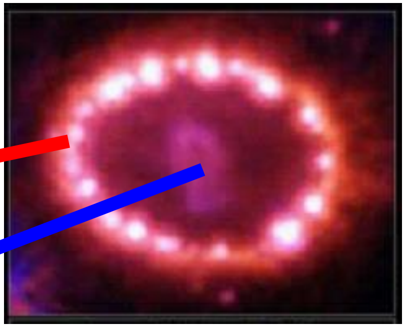


on 1994 Feb
(Burrow+95)

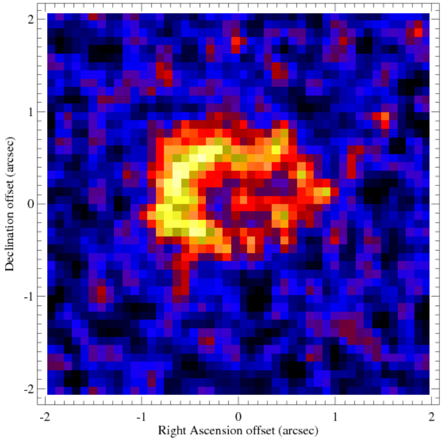
IR-mm SED of 23-years old SN 1987A



Matsuura+11



on 2009 Apr
(Larsson+11)

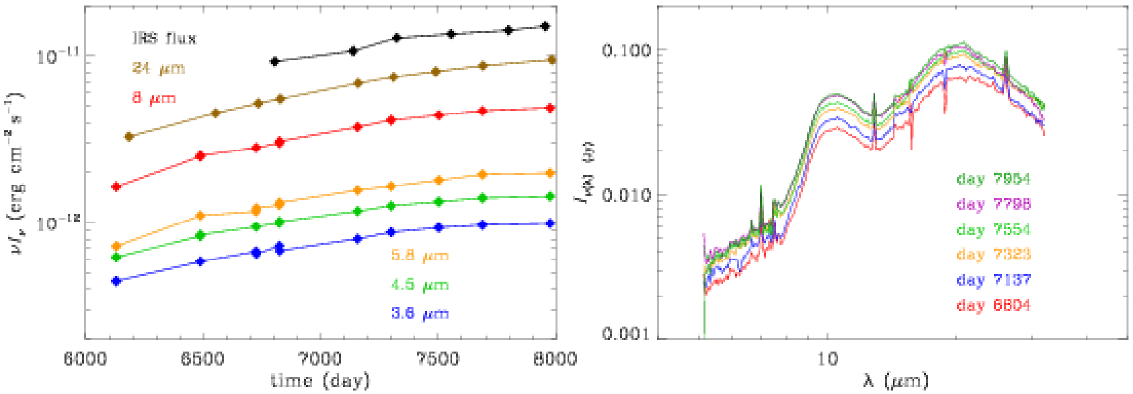


on 4 Oct 2003
Gemini T-ReCS
(λ = 10.36 μm)
2 pixels : 0.18”
(Bouchet+04)

2-3. Properties of CS dust around SN 1987A

IR light curve

MIR SEDs

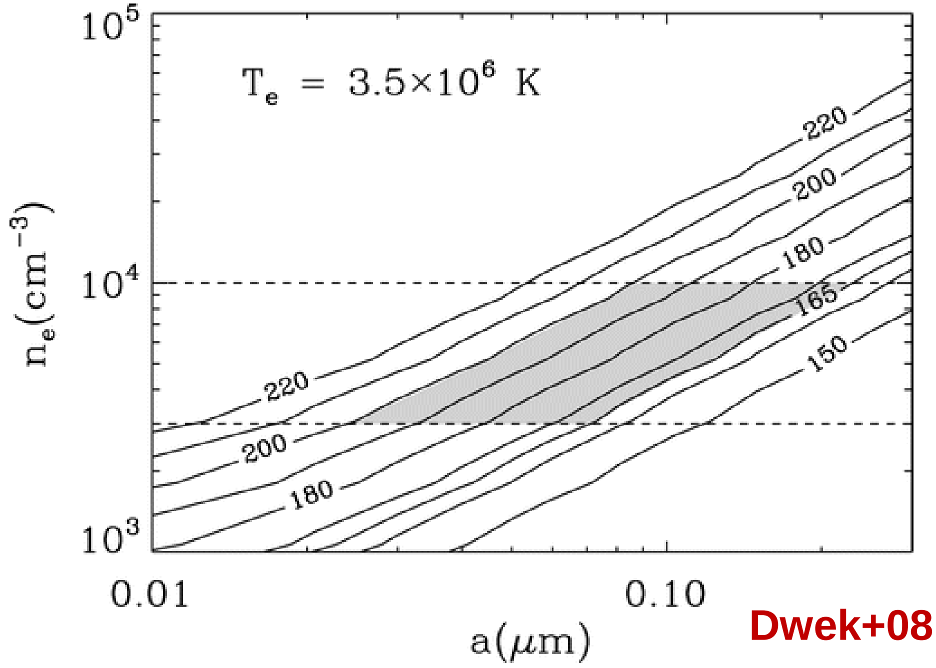


Spitzer observation, Dwek+10

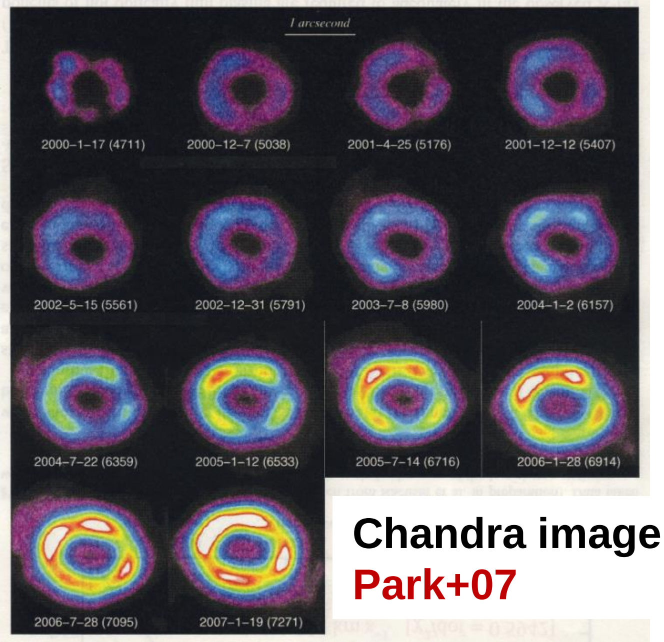
- **properties of CS dust**
  - **silicate**
  - **T_{dust} = 180 K**
  - **M_{dust} = 10^{-6}-10^{-5} M_{sun}**
  - **L_{IR} = 10^{36}-10^{37} erg/s**

(Seok+08, Dwek+08)

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



Dwek+08



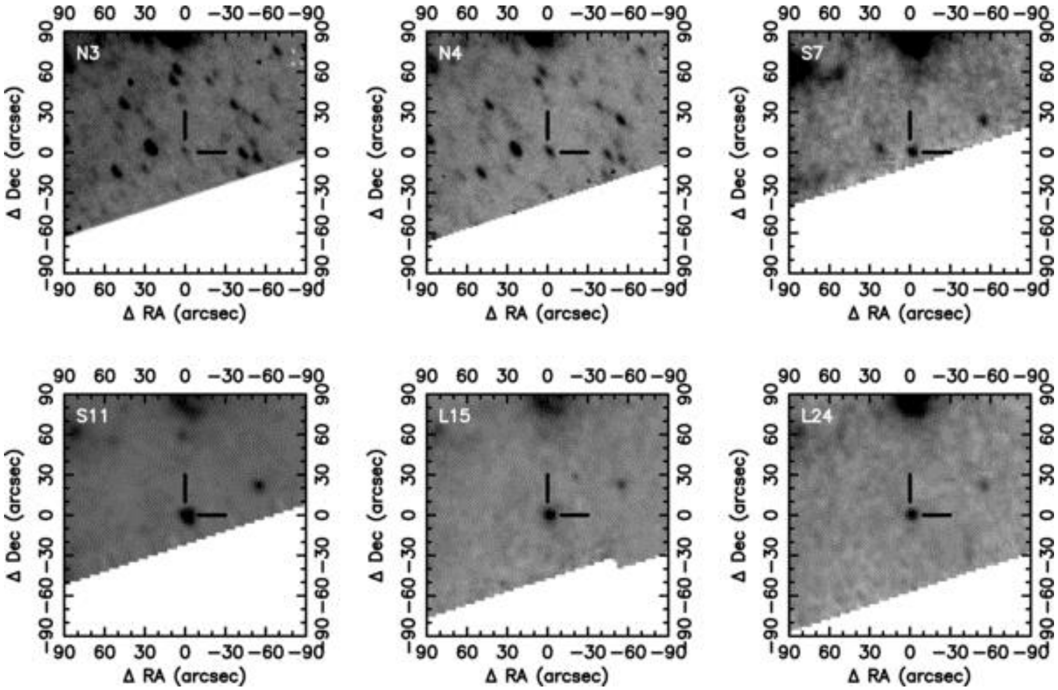
Chandra image
Park+07

2-4. MIR observations of SN 1978K with AKARI

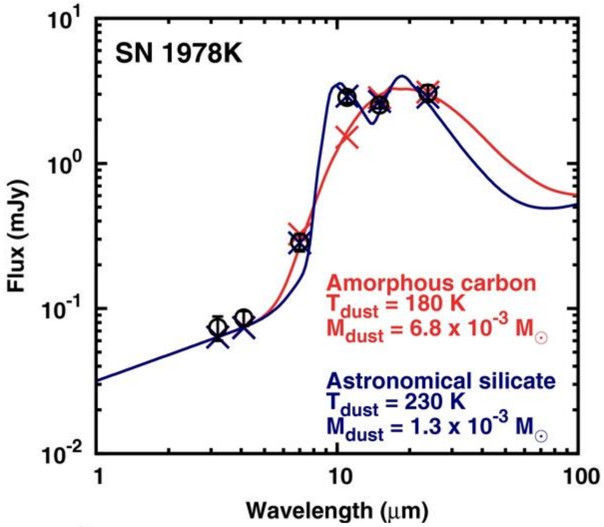
○ SN 1978K (Type IIn)

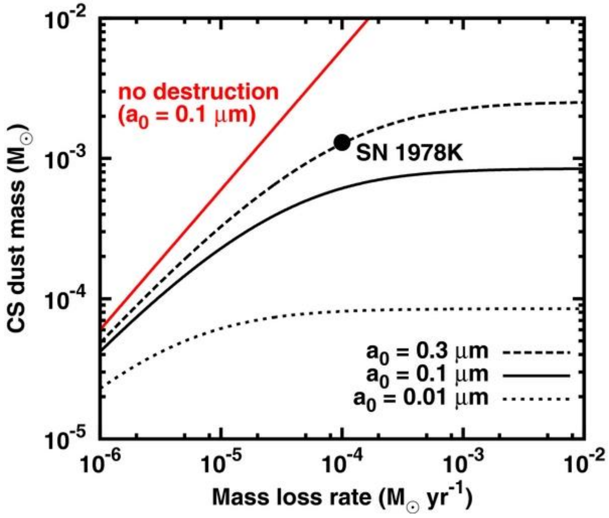
- host galaxy: NGC 1313 (d = 4.1 Mpc)
- X-ray luminous ➔ massive CSM
- IR luminous: L$_{IR}$ = 1.5×10^{39} erg/s

AKARI images at 28 yr post explosion



Tanaka, TN, et al. (2012)





- silicate
- T$_{dust}$ = 230 K
- M$_{dust}$ ~10^{-3}M$_{sun}$

2-5. MIR observations of aged dusty SNe

- 超新星爆発10−100年後の中間赤外（マルチエポック）観測

➜ 衝撃波に掃かれた星周ダストの温度、質量、組成の時間進化
（衝撃波によるダスト加熱・破壊、輻射輸送の理論計算）
➜ 星周ガスの密度 ➜ 質量放出史 （X線の観測があればより良い）

大質量星の爆発前数百年間の質量放出史を、数年の観測でフォロー

大質量星風中でのダスト形成環境の復元

- ダスト破壊効率に決定打を与えるかも？

（銀河のダストの破壊のタイムスケールは、供給のタイムスケールよりも短い）

スパッタリングによるダスト半径の減少率
da/dt ˜ 10^−6 (n / 1.0 cm^{-3}) μm yr^{-1} （experimental data for bulk materials）

➜ スパッタリングによるダスト破壊効率は過大評価されているかも？

- aged dusty SNeの候補天体はそれなりにある （＋超新星の情報もある）

➜ JWST・SPICAなどによりサンプル数は増加するはず

2-6. Expected targets of aged dusty SNe

nearby SNe, for which IR echo emissions were observed a few years after the explosions

- SNe that have been done already

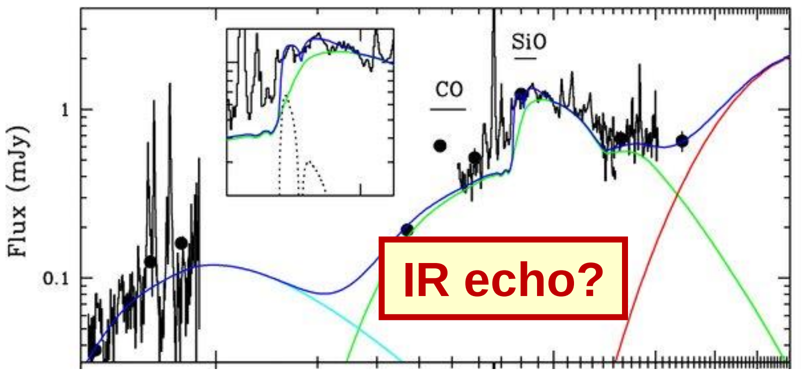
SN 1987A (II-pec, 50 kpc) (Dwek+08, 10)
SN 1978K (IIn, 4.1 Mpc) (Tanaka+12)
SN 1980K (II-L, 5.6 Mpc) (Sugerman+12)
SN 1995N (IIn, 24 Mpc) (van Dyk+12)

- nearby Type IIn Sne

SN 1998S (IIn, 17 Mpc) (Pozzo+04)
SN 2005ip (IIn, 30 Mpc) (Fox+11, 12)

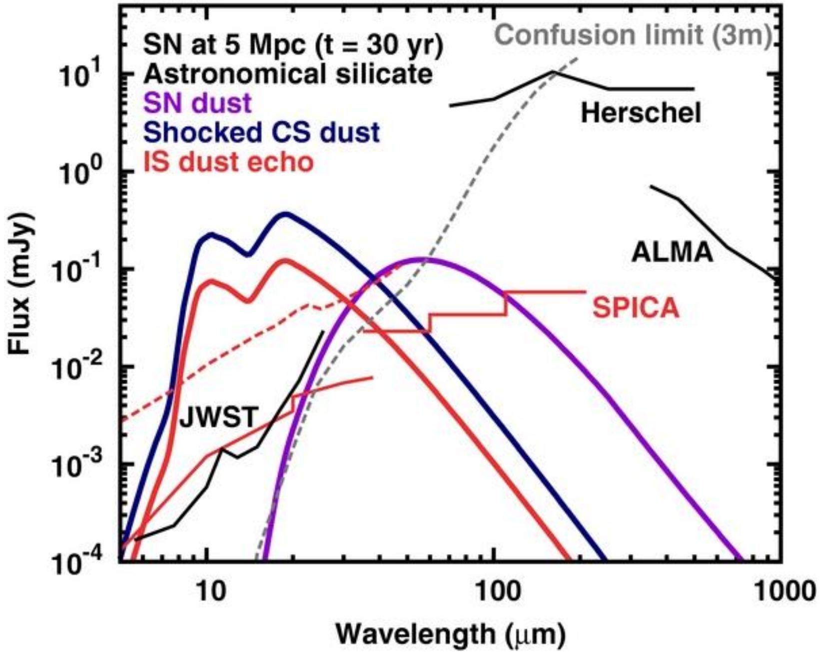
- very nearby Type II-P SNe

SN 1993J (IIb, 3.6 Mpc)
SN 2002hh (II-P, 5.6 Mpc) (Barlow+05)
SN 2004et (II-P, 5.6 Mpc) (Kotak+09)
SN 2004dj (II-P, 3.5 Mpc) (Meikle+11)



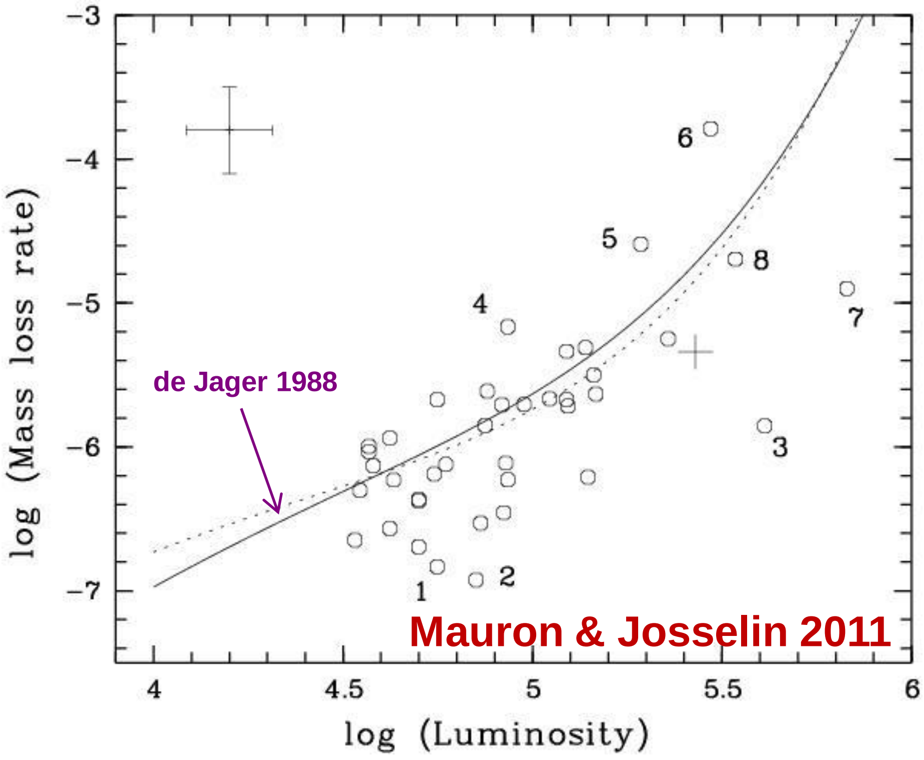
IR echo?

SN 2004et (Kotak+09)



Tanaka, TN, et al. (2012)

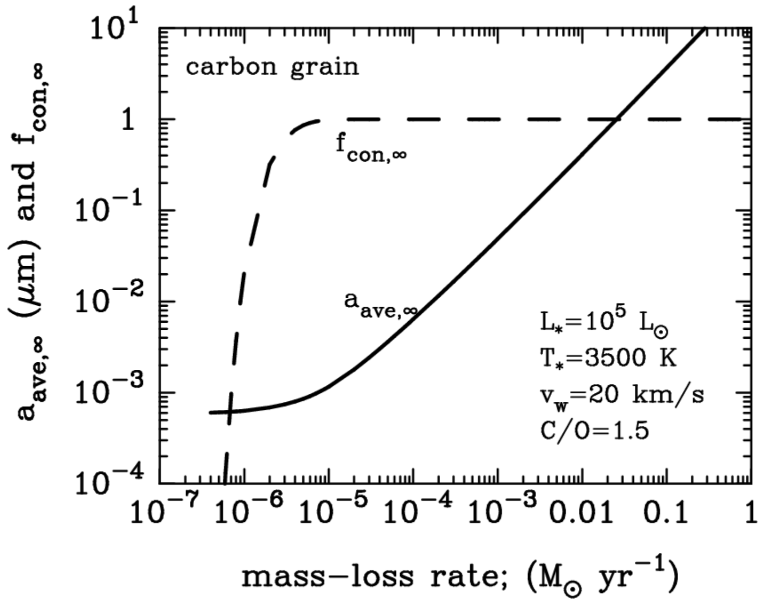
3-1. Mass-loss rates of RSGs

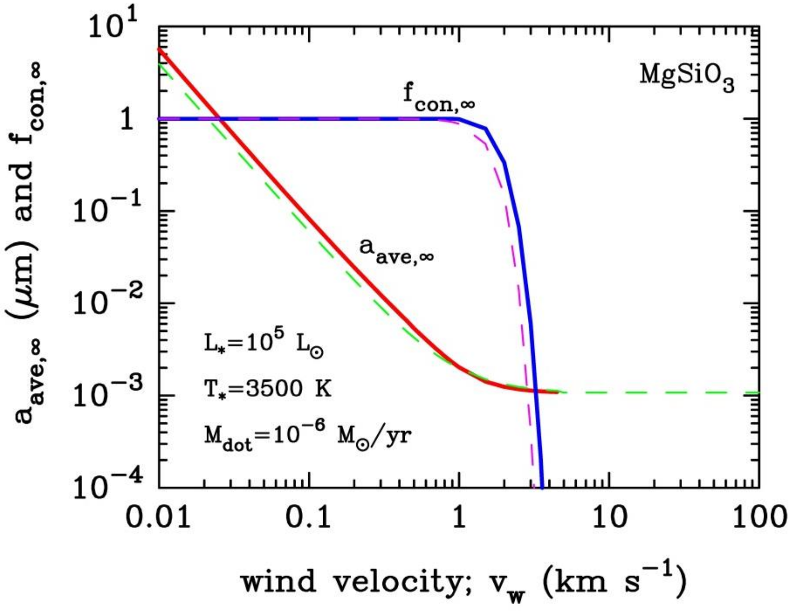


x-axis: 60 μm-flux based
dust-to-gas mass ratio = 200

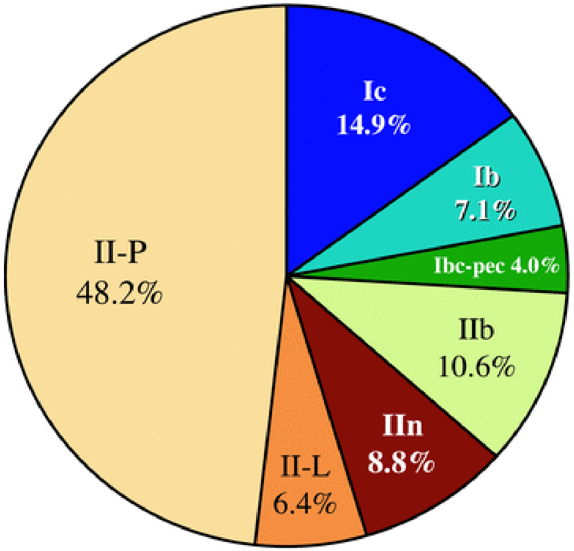
dust grains form for high mass-loss rate and/or low expansion velocity

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\rm w}} = \rho_* \left(\frac{r}{R_*}\right)^{-2}$$

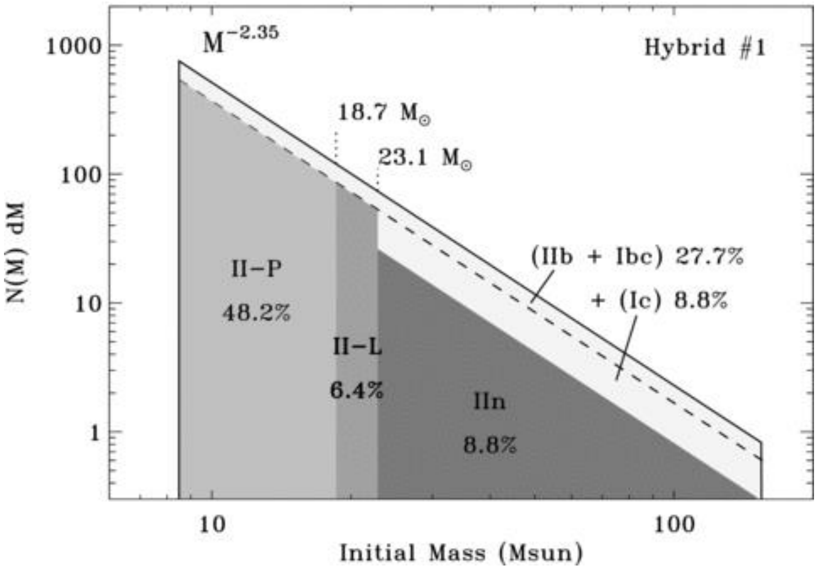




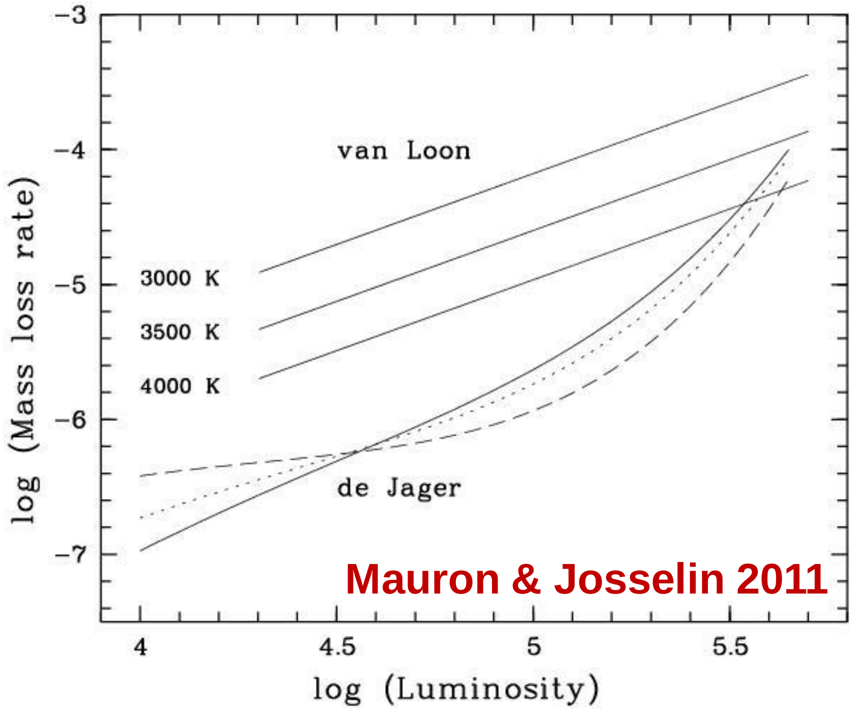
3-2. Observed fraction of supernova types



Core-Collapse SN Fractions



Smith+2011



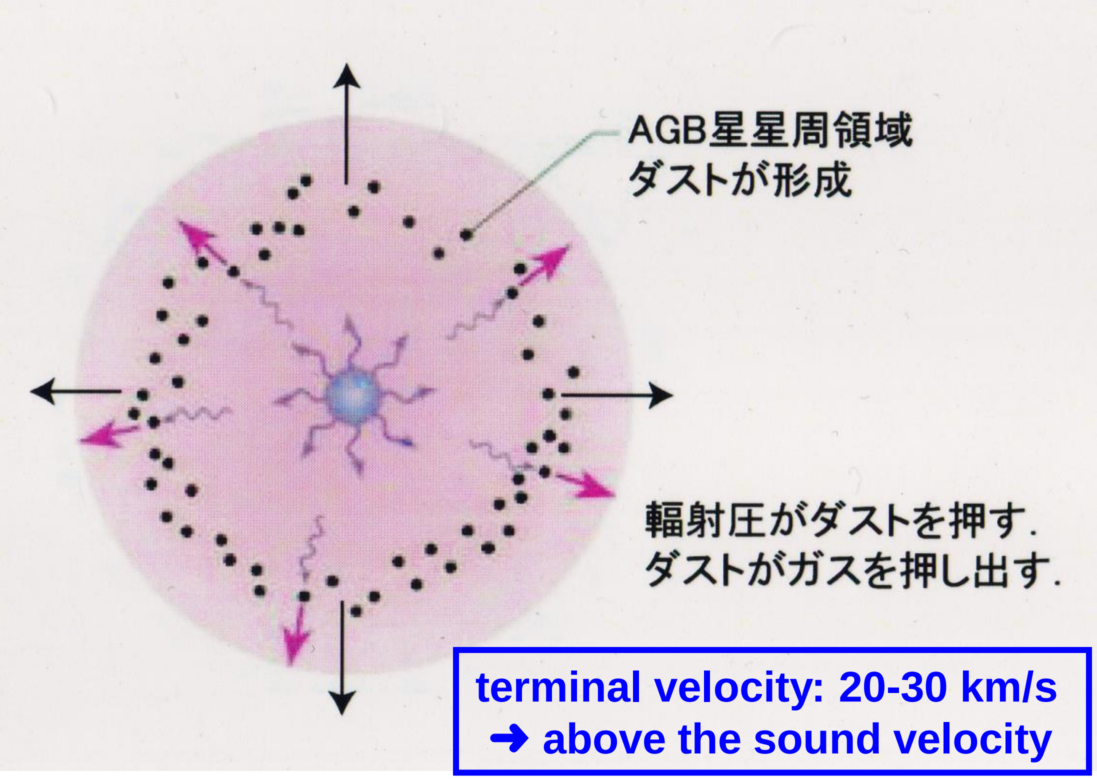
Mauron & Josselin 2011

- massive stars above ~20 Msun may undergo strong mass loss

➜ Stellar evolution models must rely on a high mass-loss rate driven by dust formation

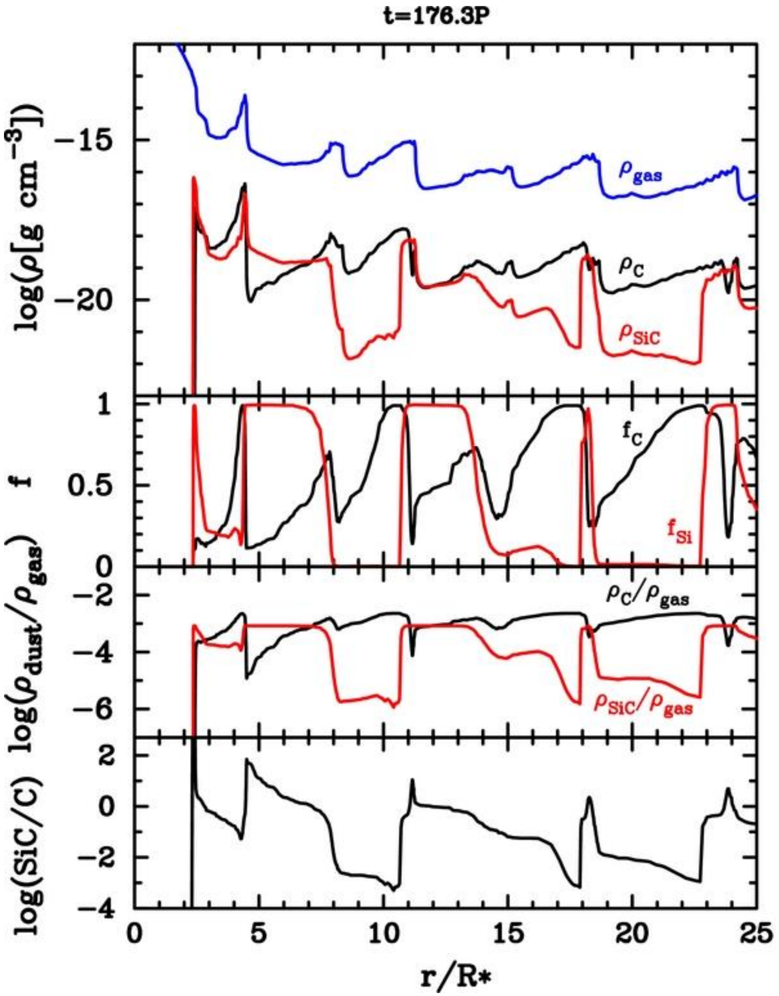
(Chieffi & Limongi 2012)

3-3. Models of dust-driven winds



terminal velocity: 20-30 km/s
➜ above the sound velocity

- **dust-driven wind model**
  - **dynamical (pulsation)**
  - **dust (and molecular) formation**
  - **dust acceleration and gas drag**
  - **radiative transfer (molecular lines)**
  - **two-fluid model**



Yasuda & Kozasa 2011

3-4. Effects of Dust-driven winds

· RSG model: m500vk00 (Yoon+2012)

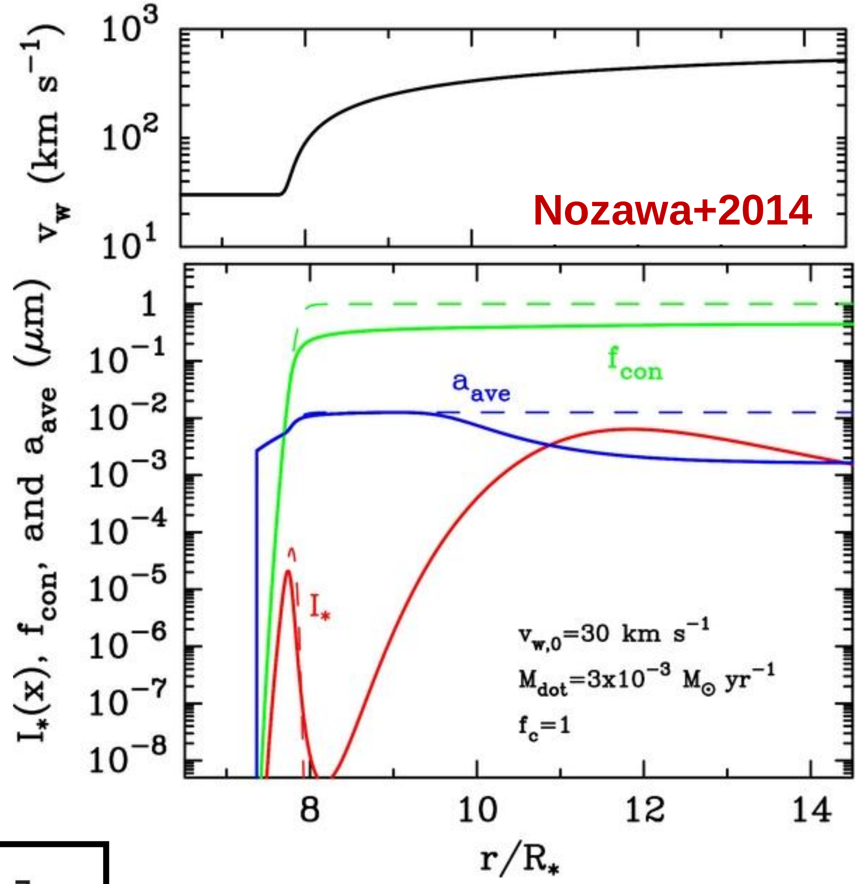
- $M_{\rm ZAMS}$ = 500 $M_{\rm sun}$ (no rotation)
- L = $10^{7.2}$ $L_{\rm sun}$
- $T_{\rm star}$ = 4440 K ($R_{\rm star}$ = 6750 $R_{\rm sun}$)
- $A_{\rm C} = 3.11\text{x}10^{-3}$, $A_{\rm O} = 1.75\text{x}10^{-3}$

➔ C/O = 1.78, Z = 0.034

$$\boxed{\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\rm w}} = \rho_* \left(\frac{r}{R_*}\right)^{-2}}$$

$$\boxed{T(r) = T_* \left(\frac{r}{R_*}\right)^{-\frac{1}{2}}}$$

$$\boxed{v_{\rm w}\frac{dv_{\rm w}}{dr} = -\frac{GM_*}{r^2}\left[1 - \frac{L_*\langle\kappa_{\rm ext}(T)\rangle}{4\pi c G M_*}D\right],}$$



Nozawa+2014

position coupling
(momentum coupling)

The acceleration of the wind by radiation pressure onto newly formed dust reduces the gas density, suppressing grain growth

3-5. Topics on dust formation in stellar winds

- 星周ダストの素過程を明らかにしたい

dust−driven windsは本当に働くのか？
どれくらいの量のダストが形成されるのか？

➜ もし働くならダストは細長く成長するかも？➜ polarization?
➜ ダスト形成・運動の理論モデルの確立 ➜ 観測との比較・検討

- PAH（poly−aromatic hydrocarbon）の起源

RSG, AGB starではPAHは検出されていない？（PNeでは検出されている）

➜ PAHの形成 ➜ top−down? or bottom−up?

- ダストが形成されるものと形成されていないものの違い

MW, LMC, SMCのサンプルから統計的な議論

➜ 星の光度、有効温度の関数としての質量放出率
➜ RSGsだけでなく、WR starsやLBVsではどうか？

4. Summary

○ Formation of dust in the ejecta of supernovae

- aim: clarifying the composition, size, and amount of dust
- observational: seems no new physics, statistic study
- theoretical: dust formation in clumpy, radiaive transfer

○ Destruction of circumstellar dust by shock waves

- aim: probing mass-loss history of massive stars from MIR
- observational: aged dusty SNe with JWST and SPICA
- theoretical: destruction and heating of dust by shock waves

○ Formation of dust in mass-loss winds of RSGs

- aim: connecting between mass loss and dust formation
- observational: well-observed objects, statistic study
- theoretical: formation and dynamics of dust, dust emission