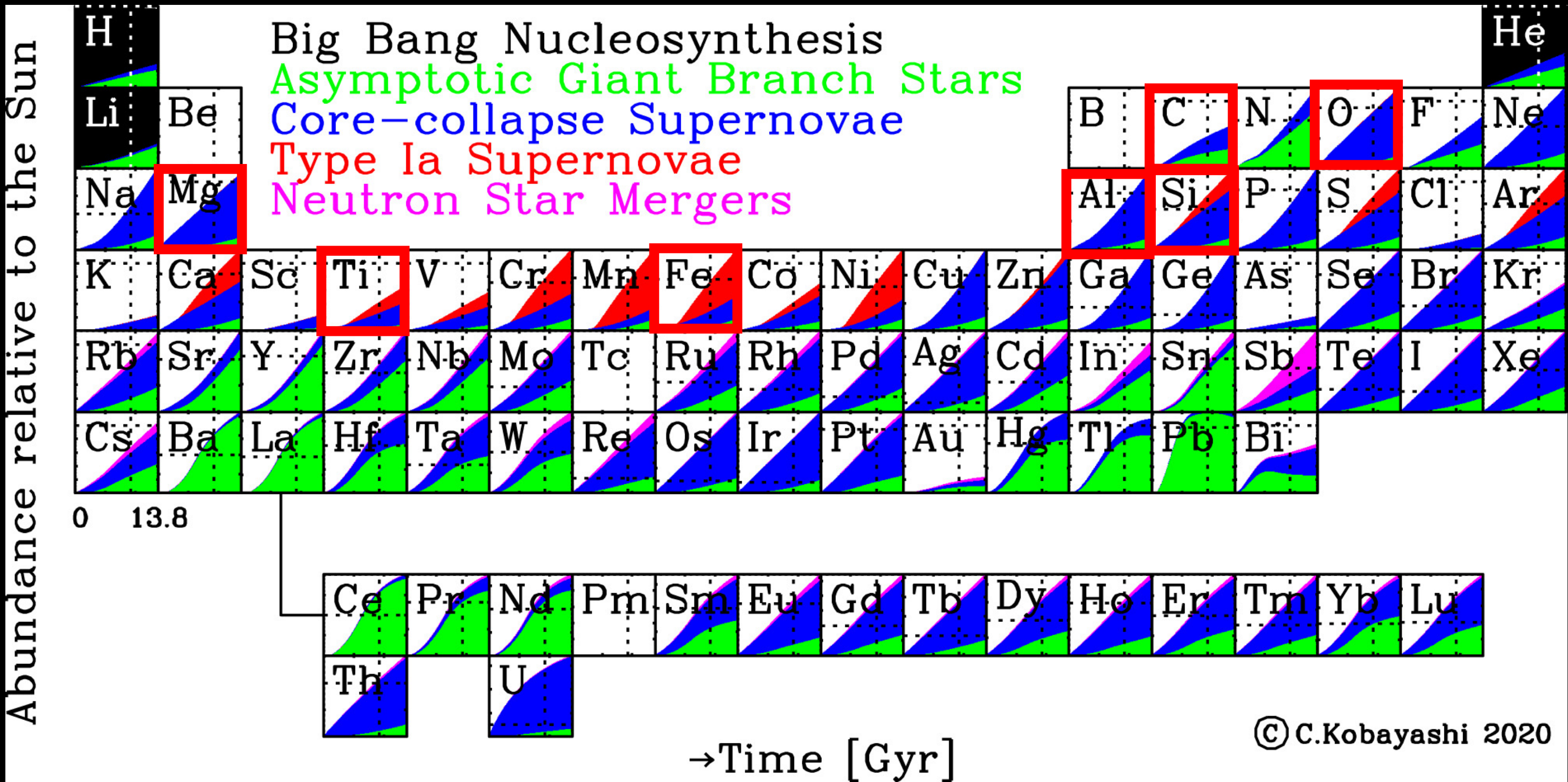
Lifecycle of dust
Supernovae: dust formation and destruction

Mikako Matsuura (Cardiff University)

Supernovae eject refractory elements

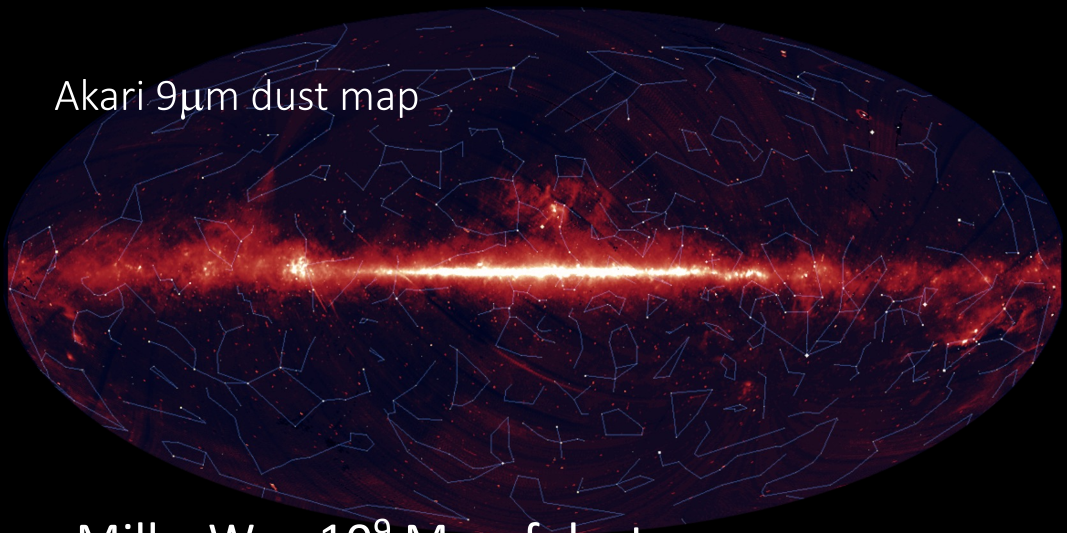
Known knowns



Known unknowns

- Stellar yields?
- Depletion rates?

Big problem: dust budget problem

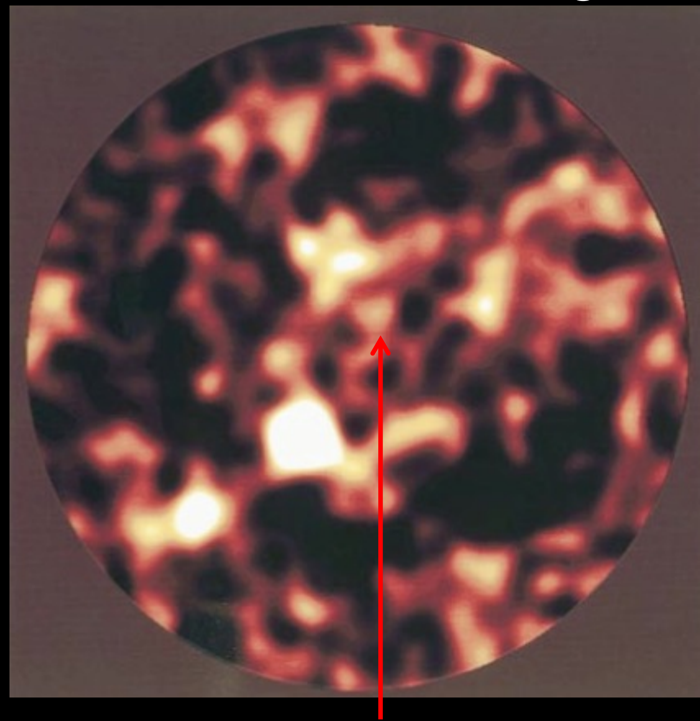


Milky Way:10^9 $M_{\odot}$ of dust

Known unknowns

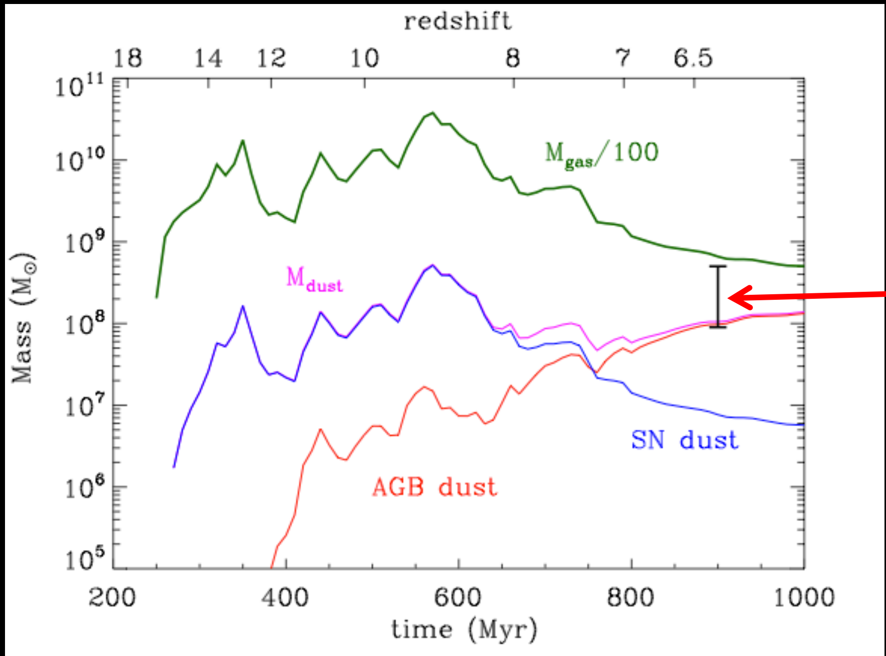
What is the origin of large quantities of dust?

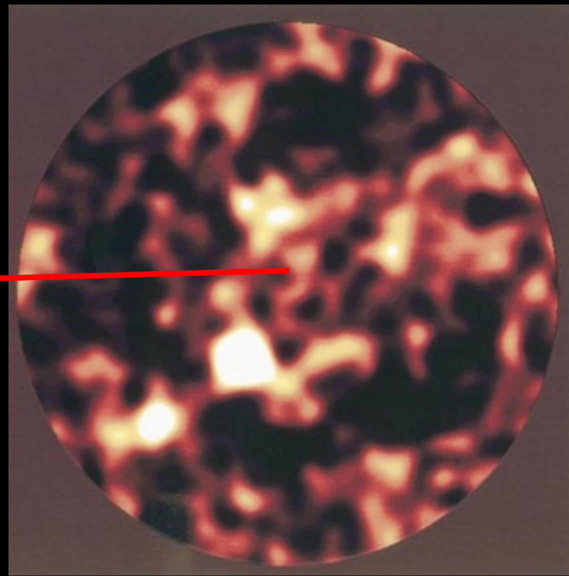
Submm galaxies



10^8 $M_{\odot}$ of dust at z~6.4; ~0.4 Gyrs old
(e.g. Bertoldi et al. 2003)

Big problem: dust budget problem





Dwek & Cherchneff (2011)

Known unknowns

What is the origin of large quantities of dust? – More acute problem at higher-z

- Timescales of AGB evolution and ISM grain growth are too slow for high-z galaxies
- Supernova dust? ~0.1 $M_\odot$ of dust per SN is required
- Dust destruction rate by SN?

Supernova dust formation and destruction

- Dust formation
  - Ejecta dust in core-collapse supernova (observations)
  - Ejecta dust in core-collapse supernova (models)
  - Type Ia SN (binary of white dwarfs)

- Dust destruction
  - Dust destruction by forward shocks (ISM and circumstellar dust)
  - Dust destruction by reverse shocks (SN ejecta dust)

Dust formation in Supernova

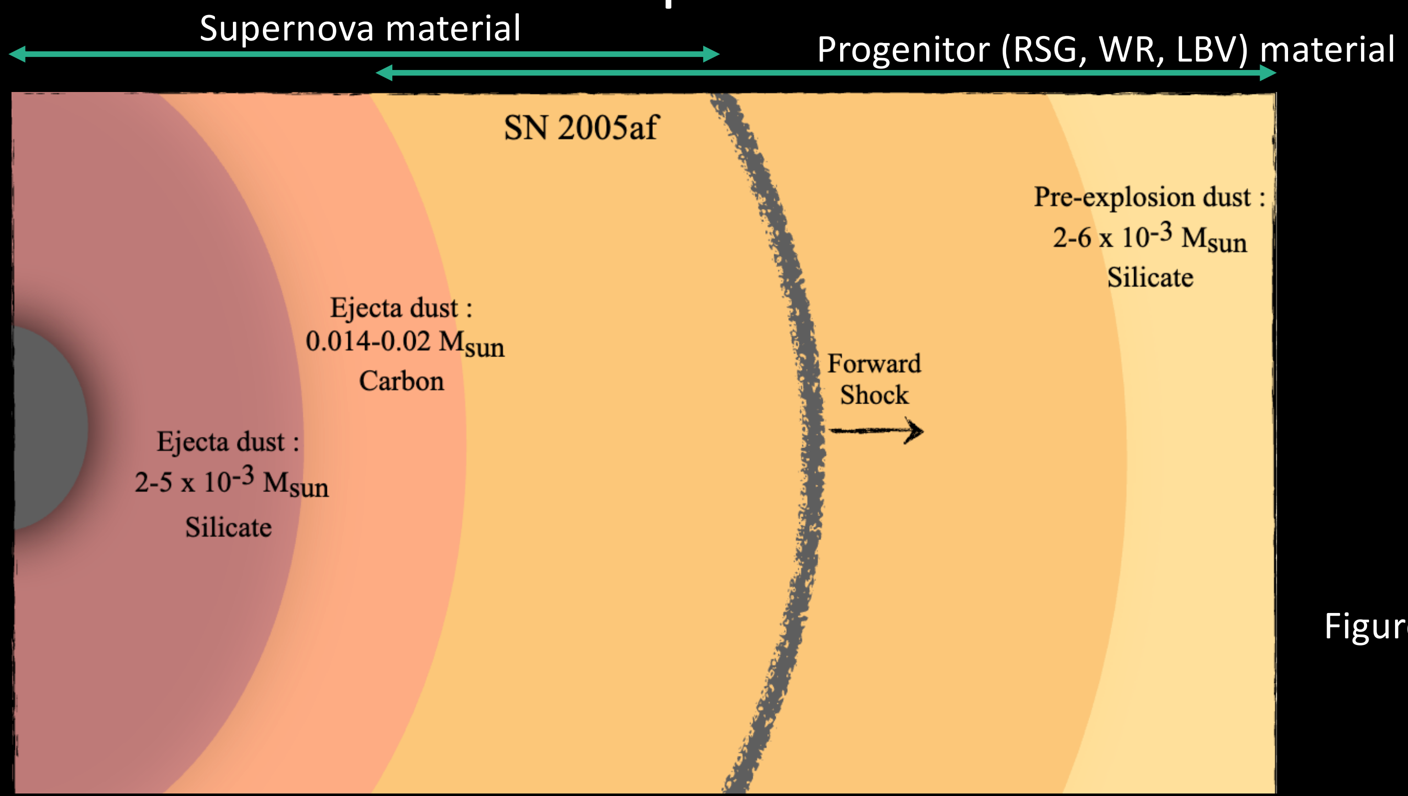


Figure: Sarangi et al. (2025)

Ejecta dust
Freshly formed SN dust from newly synthesised elements

Circumstellar dust
SN wind compresses circumstellar (progenitor) material, forming new dust

Progenitor dust
Present before SN explosion and survived UV flash from explosion

Ejecta dust in core-collapse supernovae

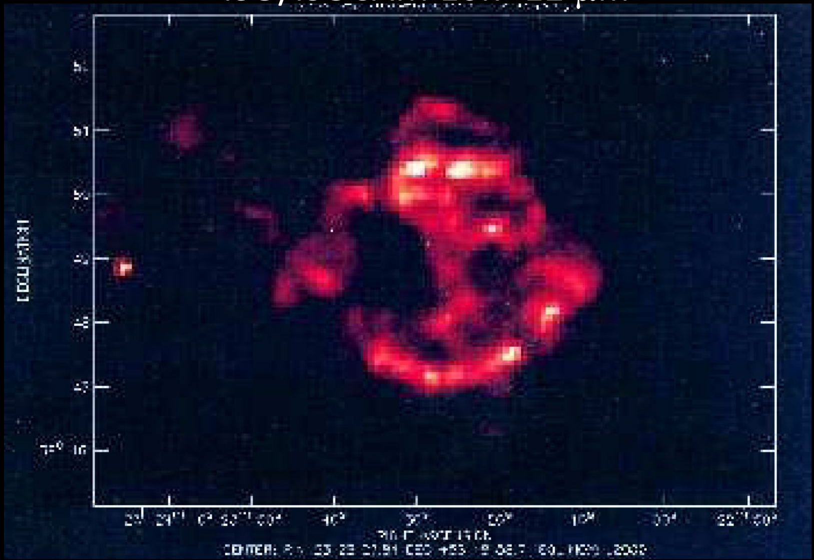
Cassiopea A: ejecta or circumstellar?

Cassiopea A

Remnant of Type IIb SN

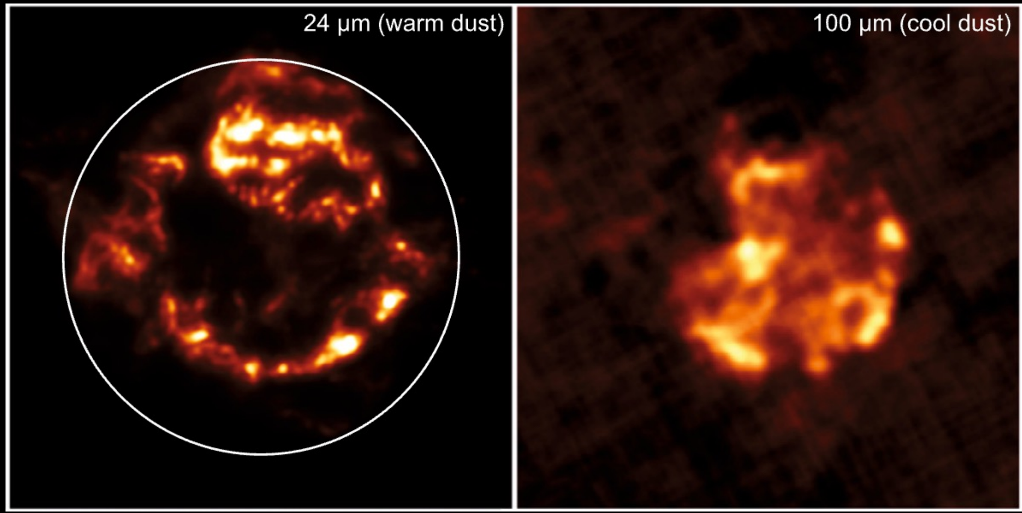
~20 $M_\odot$ progenitor

ISO/ISOCAM 10.7-12 μm



Lagage et al. (1996)

Spitzer MIPS + Herschel



Barlow et al. (2010)

~0.1 – 1 $M_\odot$ of dust

Ejecta dust in core-collapse supernovae

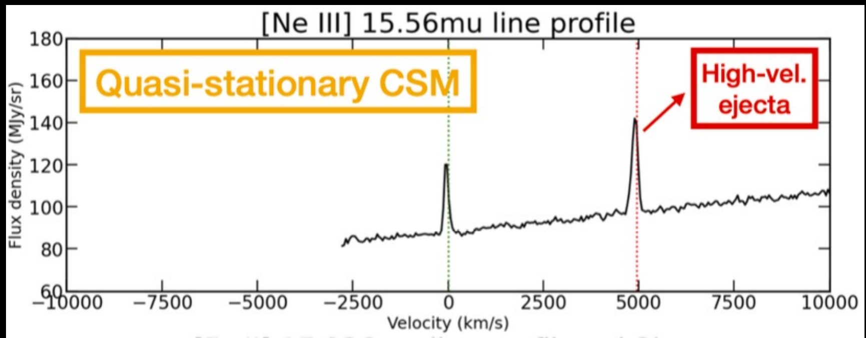
Cassiopea A: ejecta or circumstellar?

Cassiopea A

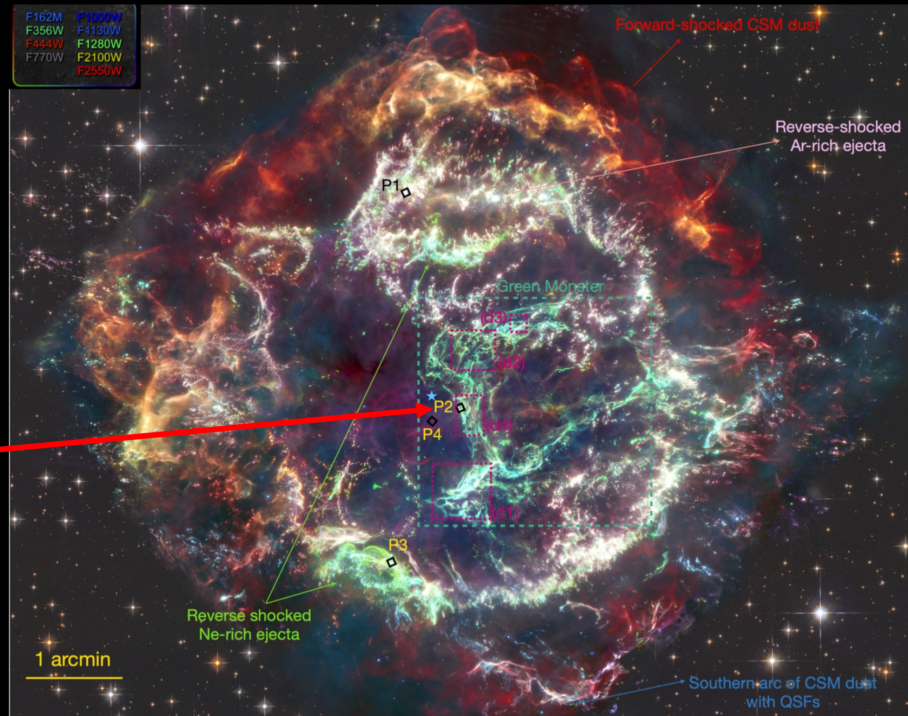
Remnant of Type IIb SN

~20 $M_{\odot}$ progenitor

JWST NIRCAM + MIRI images



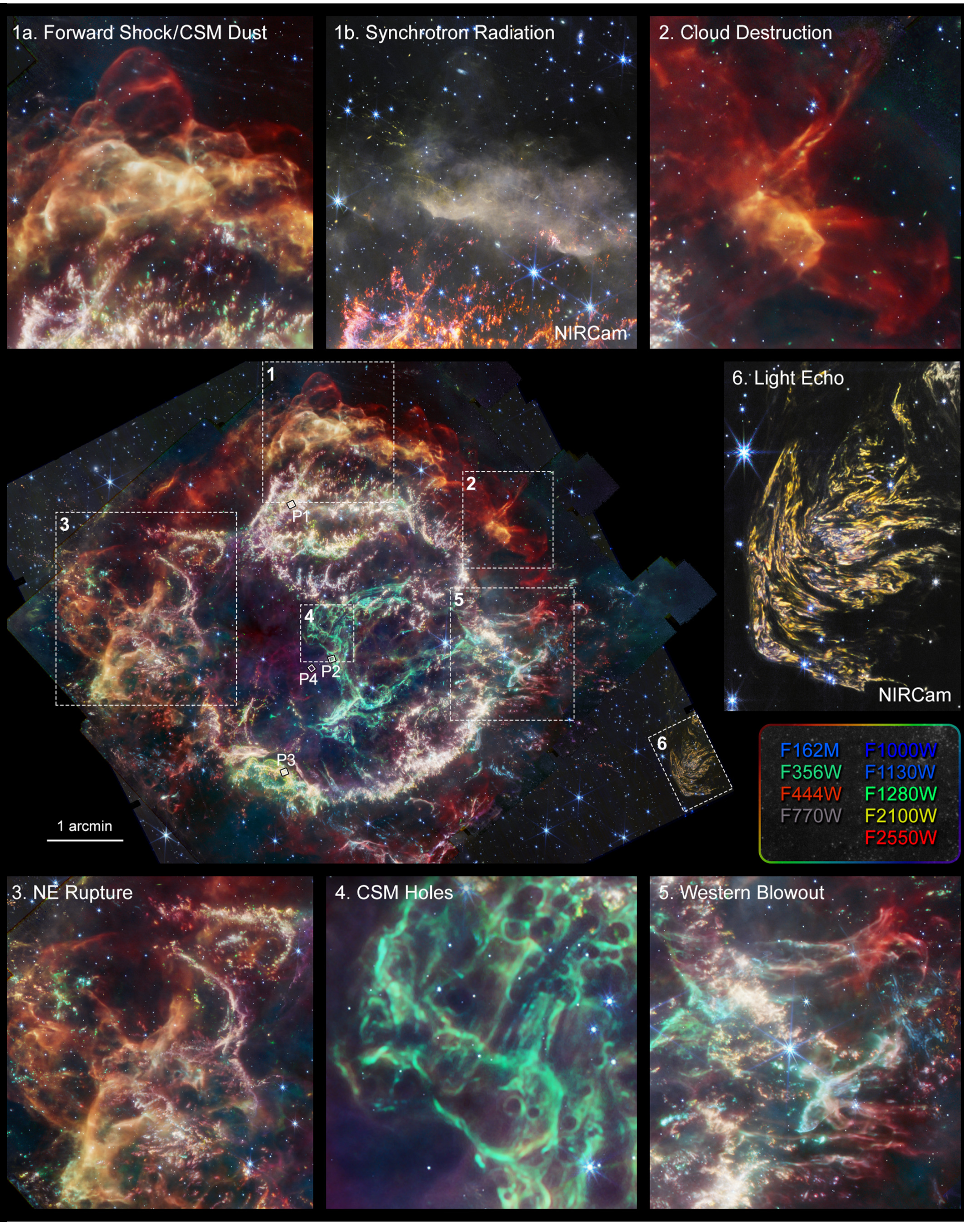
Circumstellar (progenitor star origin) dust

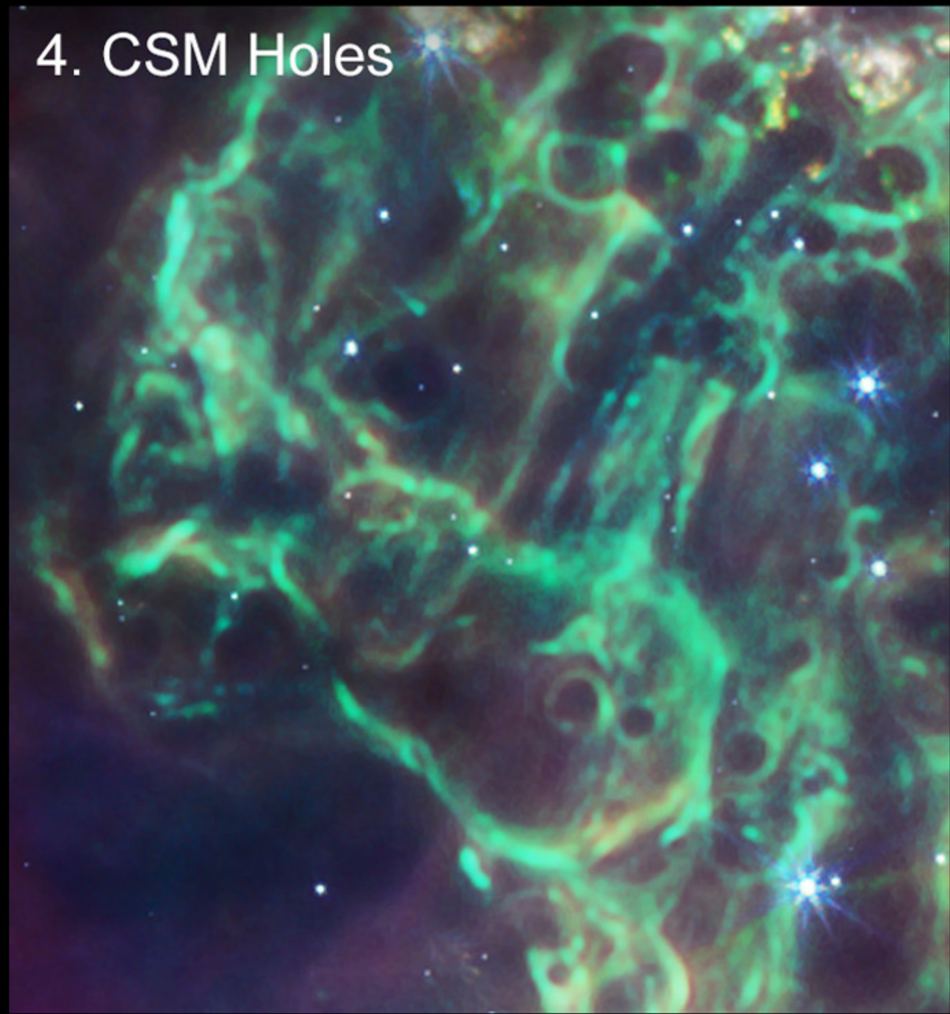


De Looze et al. (2024)

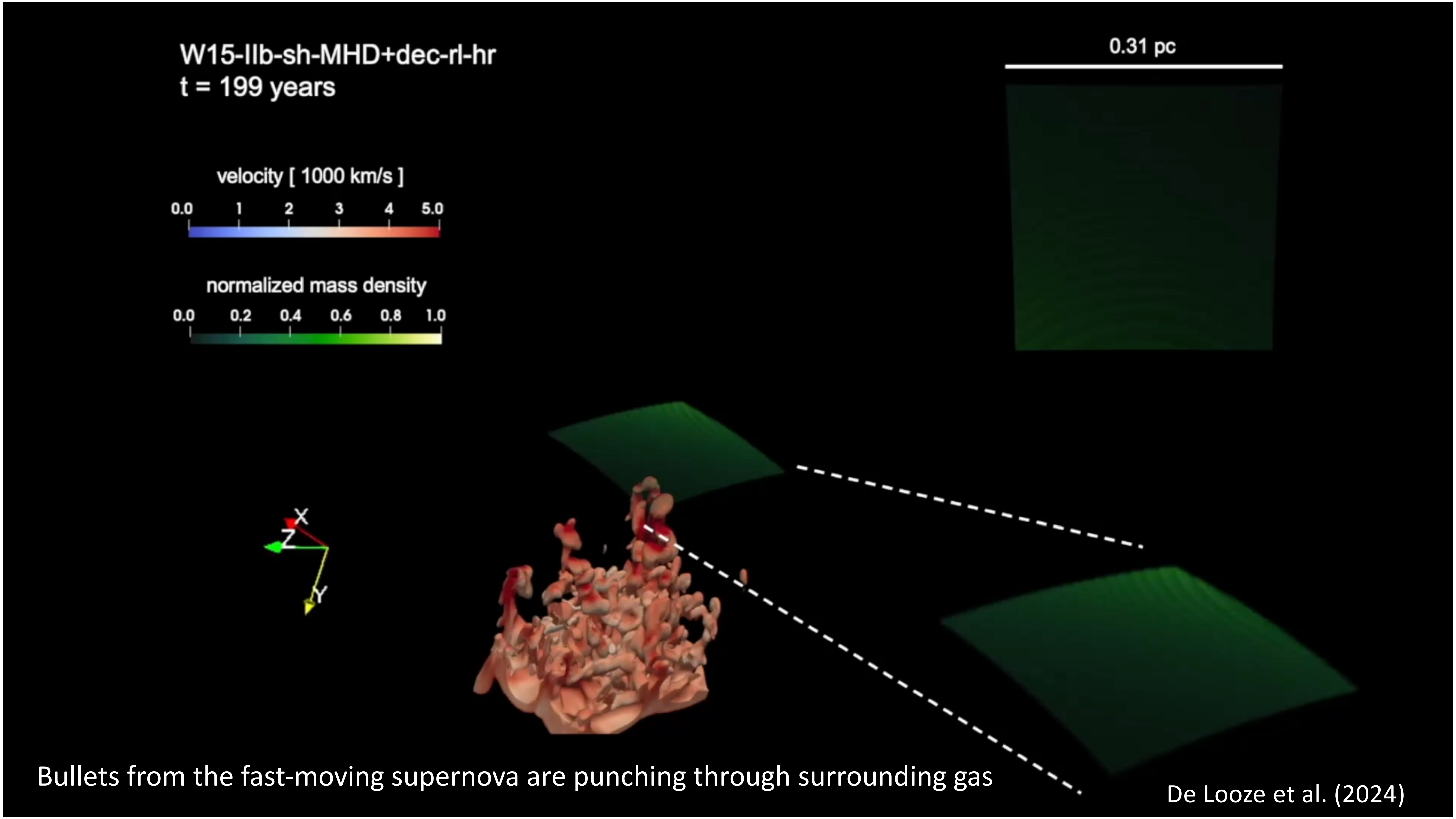
Known knowns → known unknowns

Herschel cold dust => This may contain circumstellar dust in front? (revision waiting)





Milisavljevic et al. (2024); De Looze et al. (2024)


W15-IIb-sh-MHD+dec-rl-hr
t = 199 years
velocity [1000 km/s]
0.0 1 2 3 4 5.0
normalized mass density
0.0 0.2 0.4 0.6 0.8 1.0
0.31 pc
X
Z
Y
Bullets from the fast-moving supernova are punching through surrounding gas
De Looze et al. (2024)

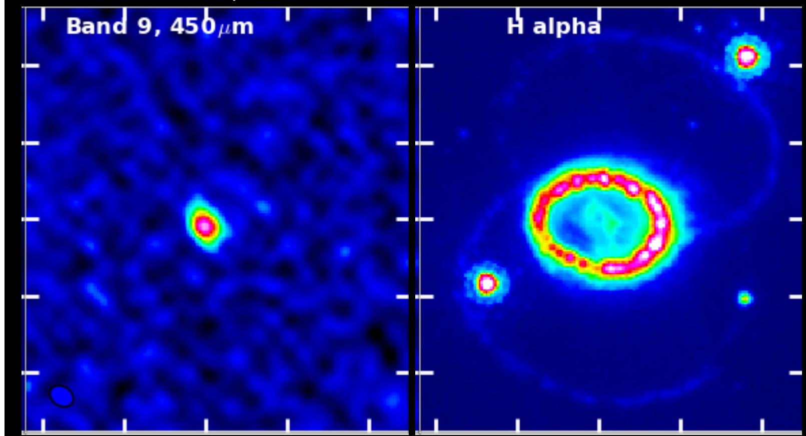
Ejecta dust in core-collapse supernovae

Supernova 1987A: yet the highest SN dust?

SN 1987A: Type II SN progenitor~18-20 $M_\odot$

Before

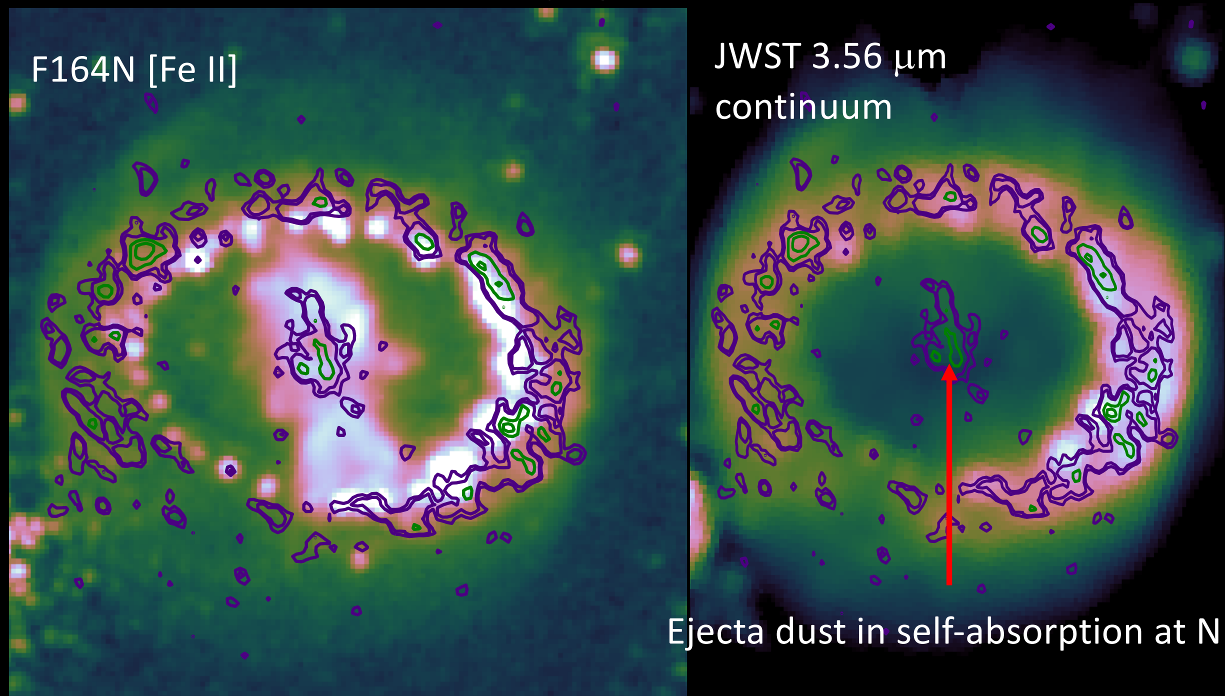
ALMA 450 μm dust HST Hα



~0.5 $M_\odot$ dust (Indebetow et al. 2014)

Now

JWST + ALMA



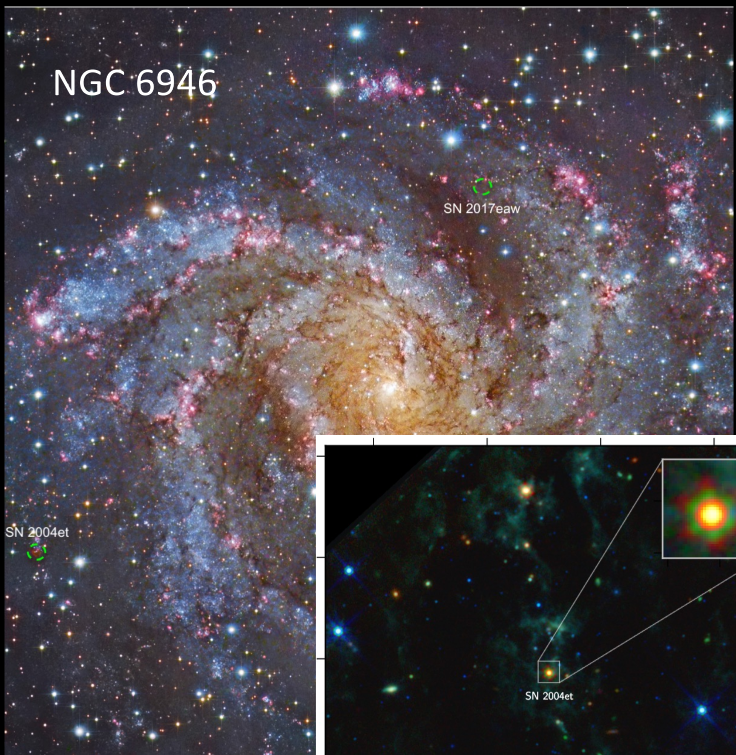
Line contour (ALMA 980 μm) shows dust @ejecta

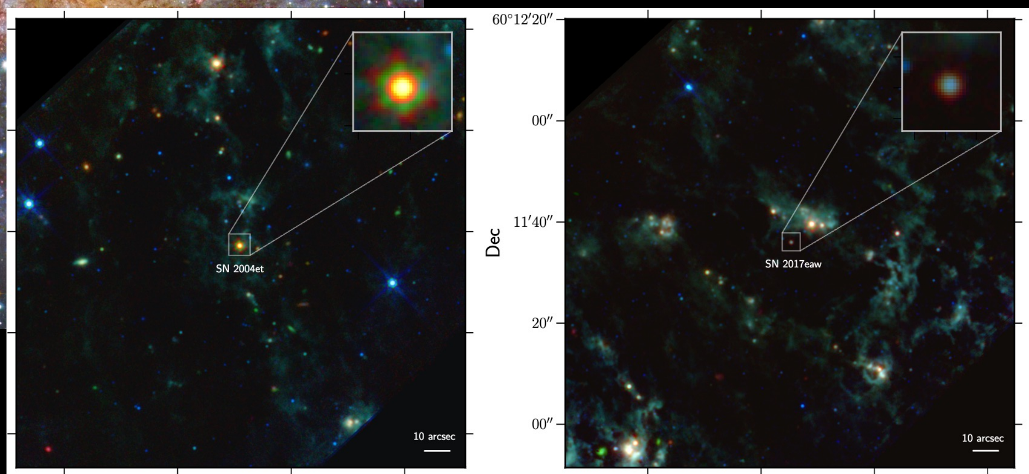
Known knowns ~0.5 $M_\odot$ dust still sustains

Matsuura et al. (2024)

Ejecta dust in core-collapse supernovae

Extra-galactic SNe: >20 years after explosions

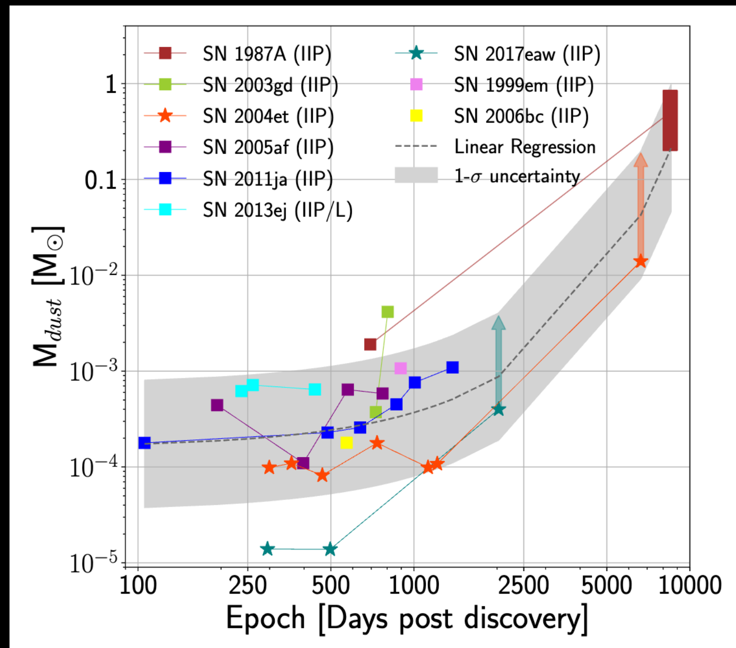




New knowns

Spitzer detected SN dust up to 3 years after the explosion

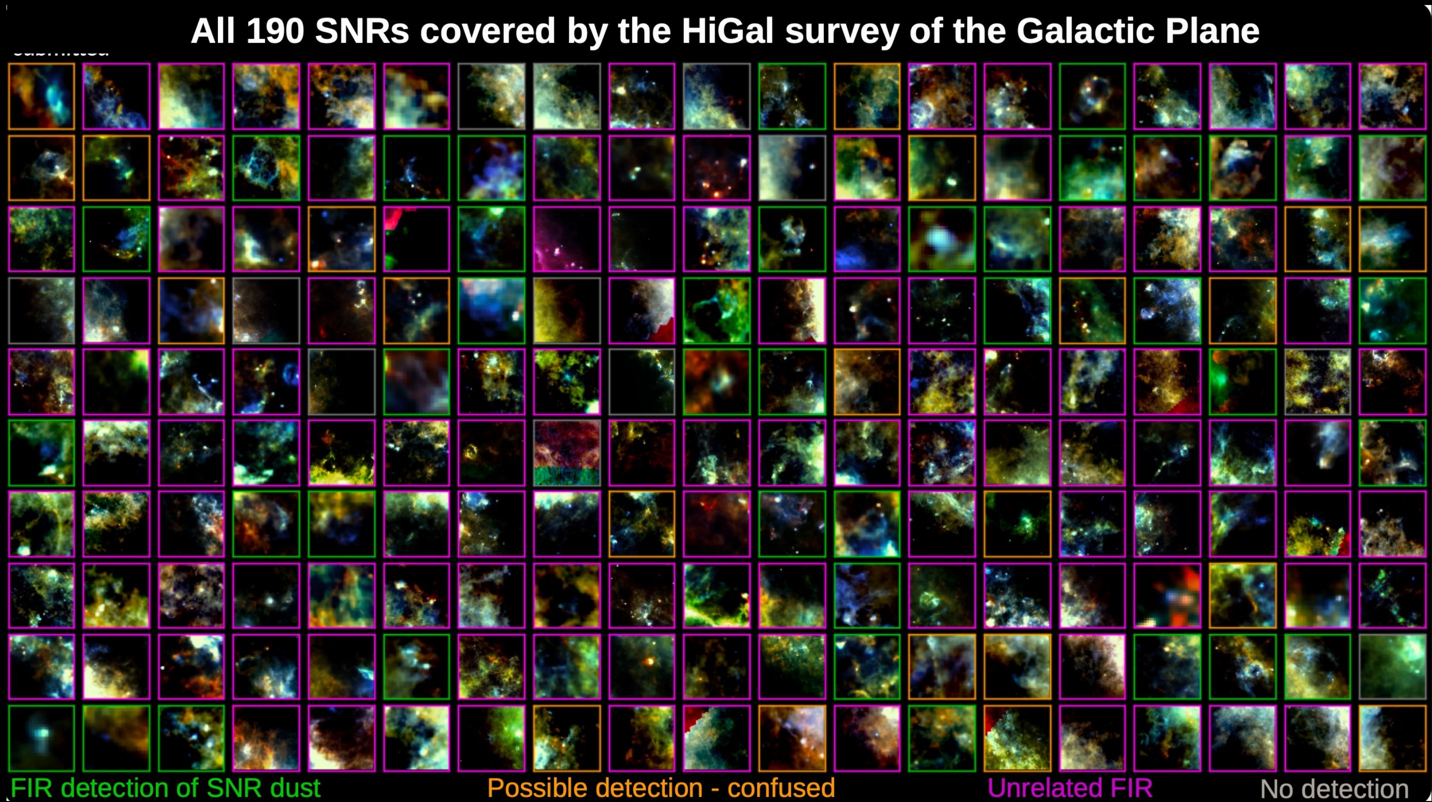
JWST can now detect SNe >20 years after the explosion



Shahbandeh et al. (2024)

Ejecta dust in core-collapse supernovae

Detections of the ejecta dust in late epoch



Chawner et al. (2019)

Ejecta dust in core-collapse supernovae

Detections of the ejecta dust in late epoch

- Decay of ^{44}Ti (half-life ~60 years) cannot supply enough energy to heat dust grains.
- An additional heating source is required to produce the observed dust emission from SN ejecta.

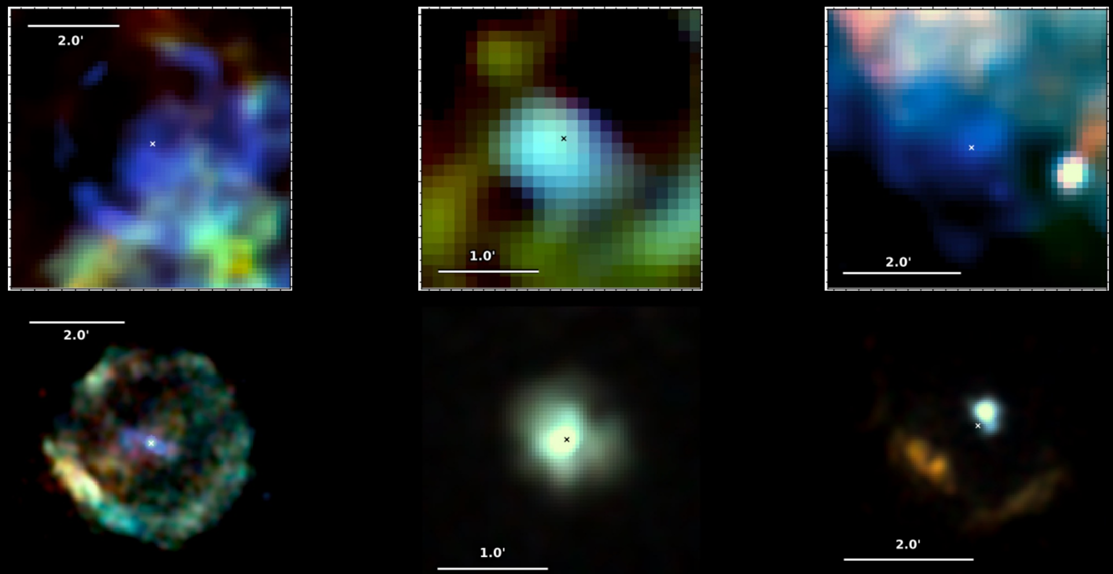
1000-2000 years old | 1000-4000 years old | 500-2000 years old

Far-Infrared

Herschel 70 - 250µm

X-Ray

Chandra



G11.2-0.3 | G21.5-0.9 | Kes 75

Known unknown

This limits ejecta dust detections in the late epoch to pulsar wind nebulae

SNR-ISM interaction: shock-heated dust

Chawner et al. (2019)

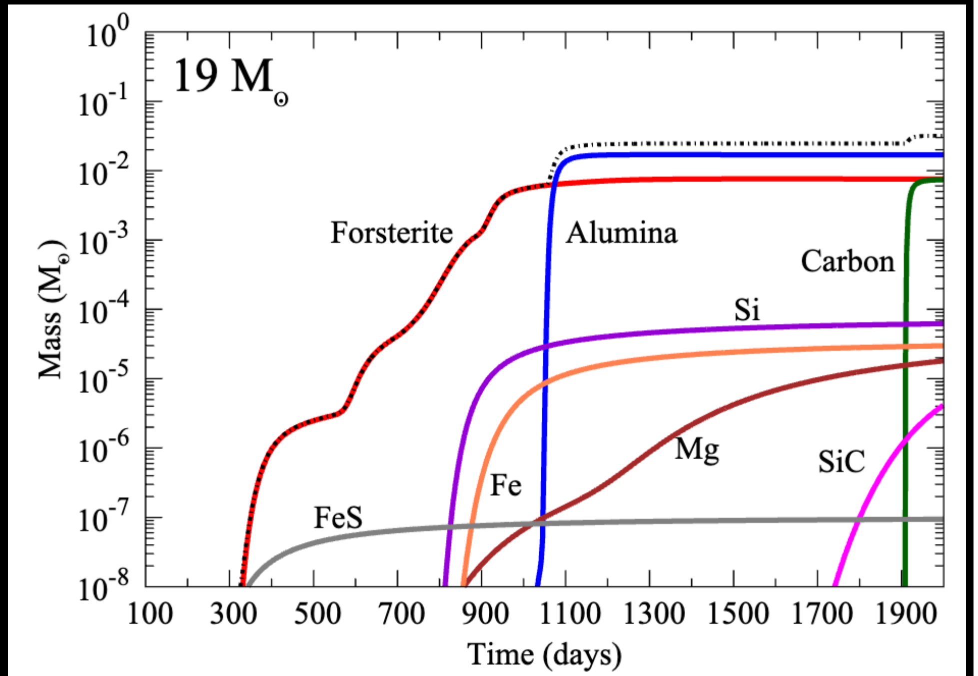
Ejecta dust in core-collapse supernovae

Chemical model predictions

Known knowns

Dust nucleation and growth:

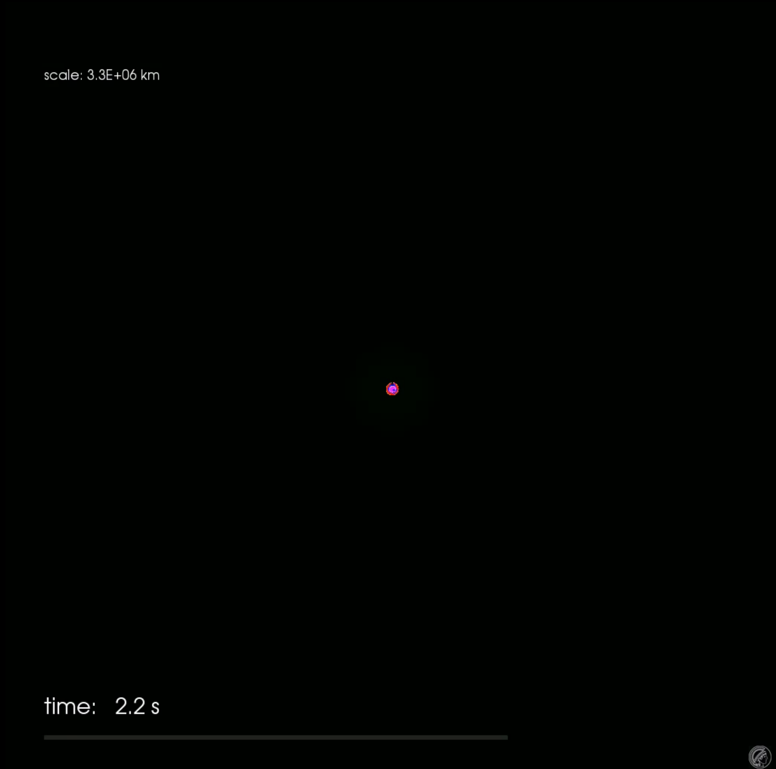
- Coagulation is less efficient at lower temperatures
- Dust grains form early and then stabilise



Sarangi & Cherchneff (2015)

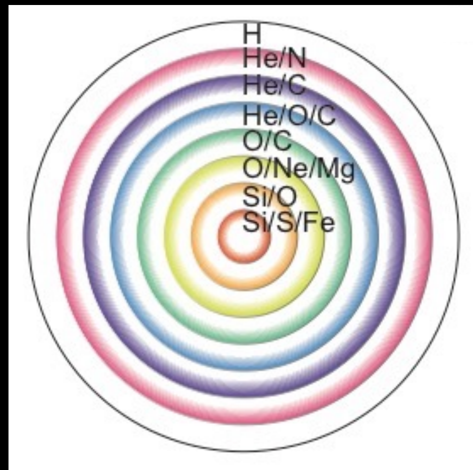
Ejecta dust in core-collapse supernovae

Hydrodynamic models predict asymmetric explosion

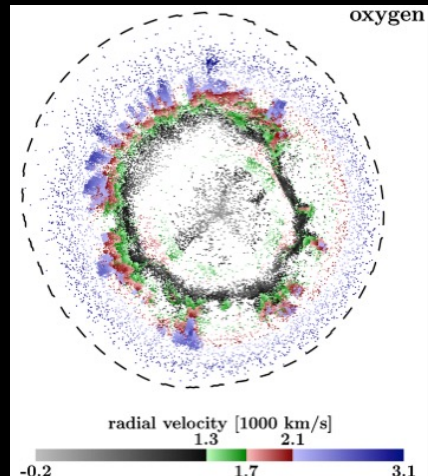


Wongwathanarat et al. (2015)

Map of elements disturbed by SN explosion



(old textbook description)



Clumps!

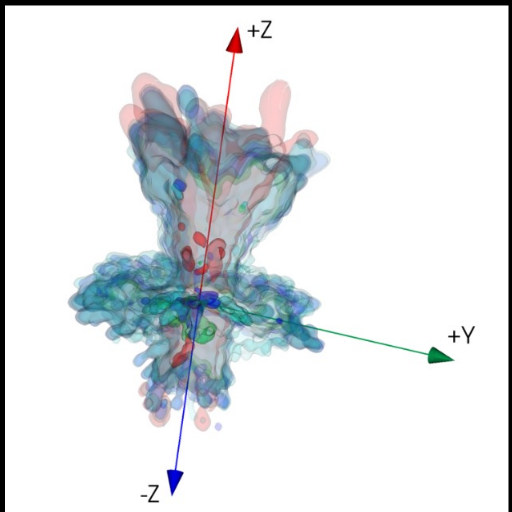
Rayleigh-Taylor instabilities

Ejecta dust in core-collapse supernovae

Chemical model predictions

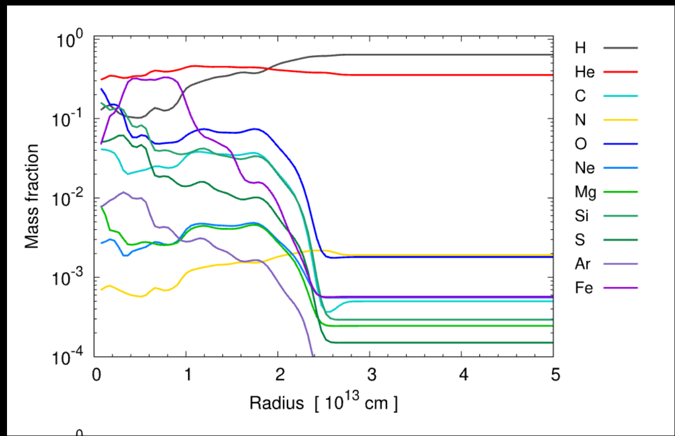
On the way to knowns

3D-SN explosion models produce highly asymmetric ejecta structure

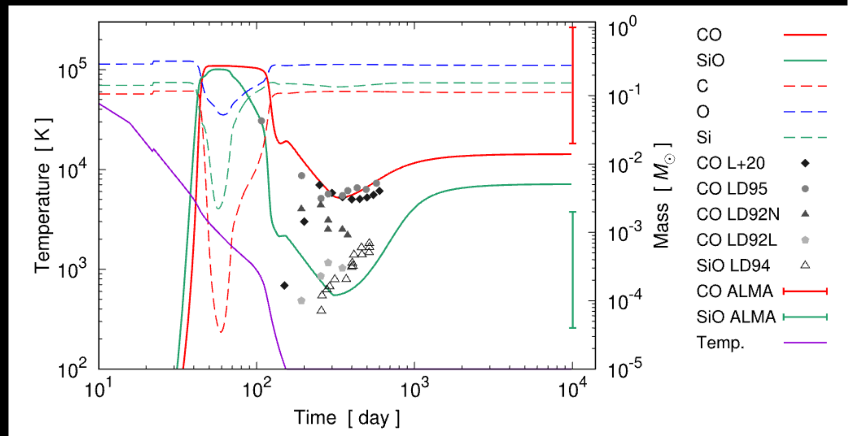


Mass distribution of elements
Si (green), O (blue) & C(cyan)

Translate clumps into 1-D structure



Model prediction of molecules (not yet dust)



Ono et al. (2024)

Type Ia SNe

Ejecta speed is x10 times faster (~10,00 km s^{-1}) than that of CC SNe
Ejecta density drops quickly

New Knowns

Newly formed circumstellar dust

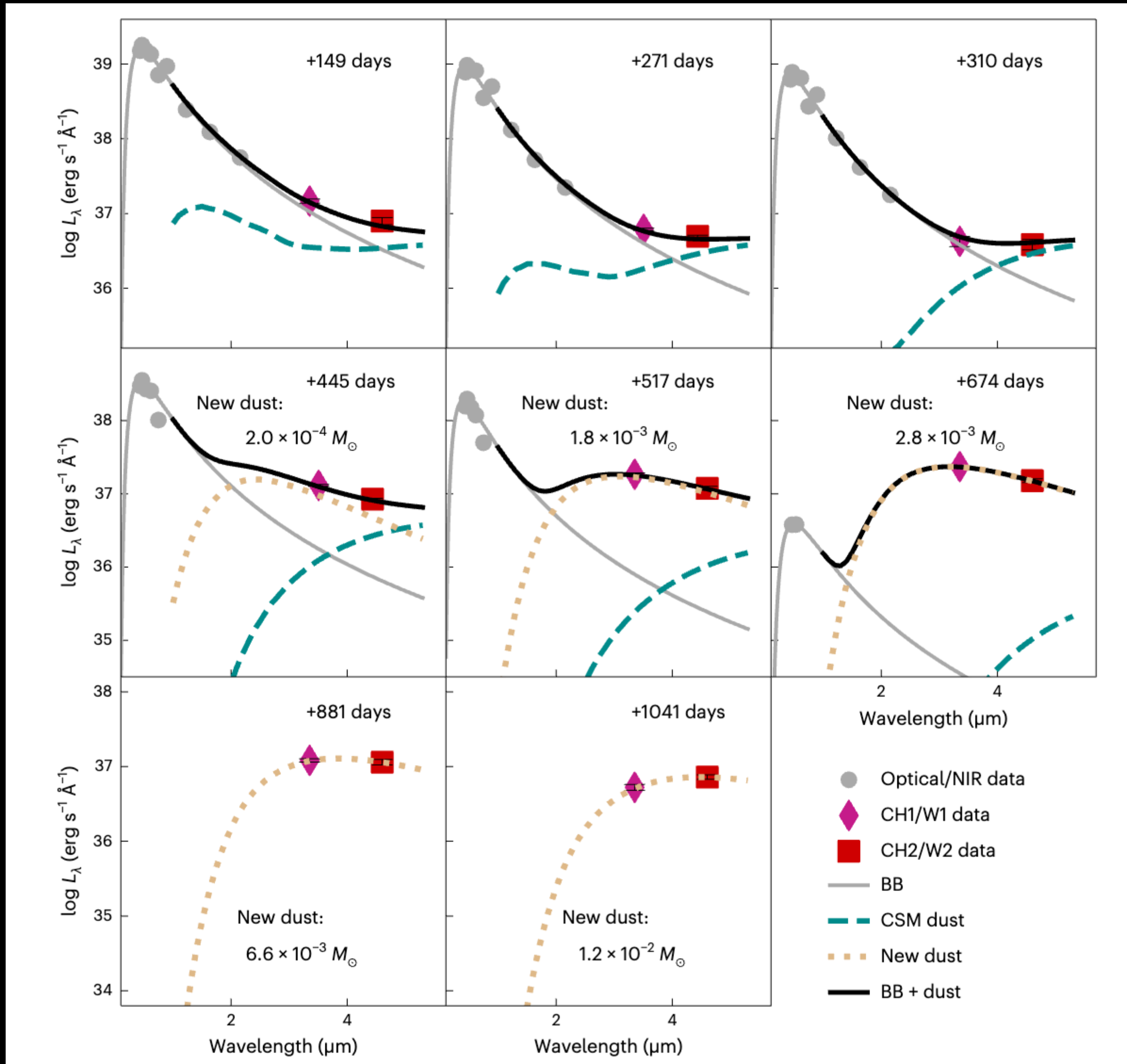
SN2018evt

~0.01 $M_\odot$ of dust

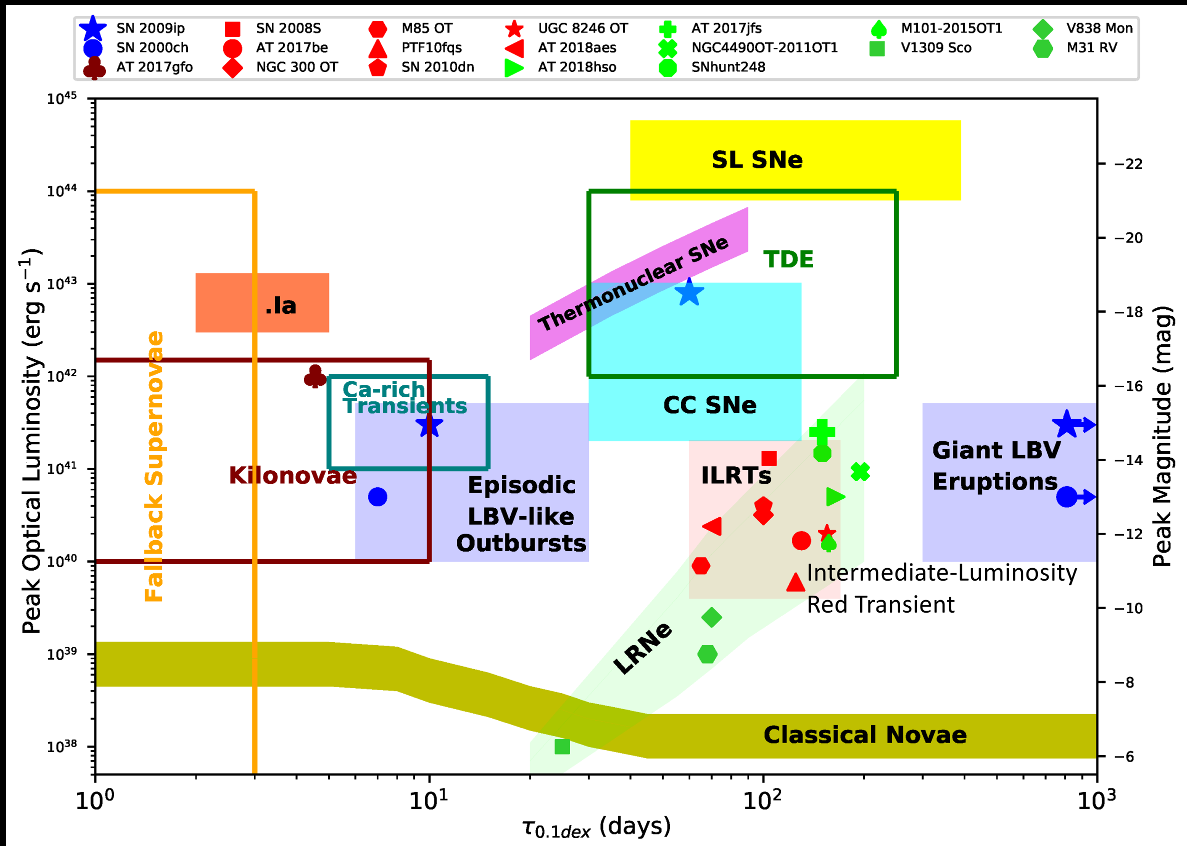
Unkowns

What happened to Fe? Dust or gas?

Wang et al. (2024)



The Transient Universe Is Rapidly Expanding



Superluminous SNe (SLSNe)
Ejecta (?) Dust in SN 2018bsz

Luminous blue variables (LBV)
Dust in η Car

Luminous Red Novae (LRNe)
Circumstellar dust in V838 Mon

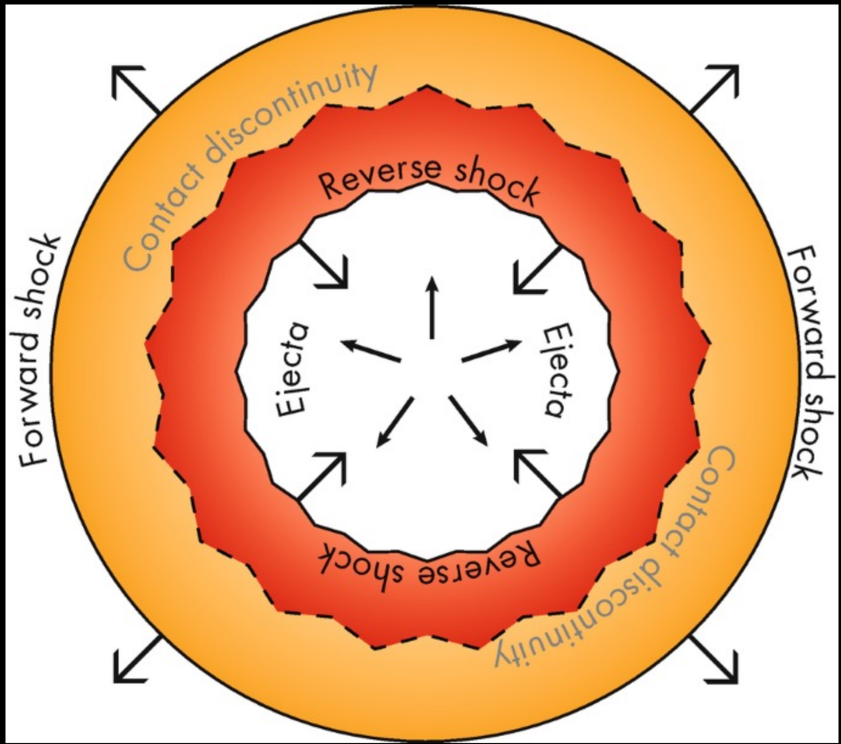
Kasliwal et al. (2009)

Dust from SN impostor "SN" 2008S (ILRTs?)

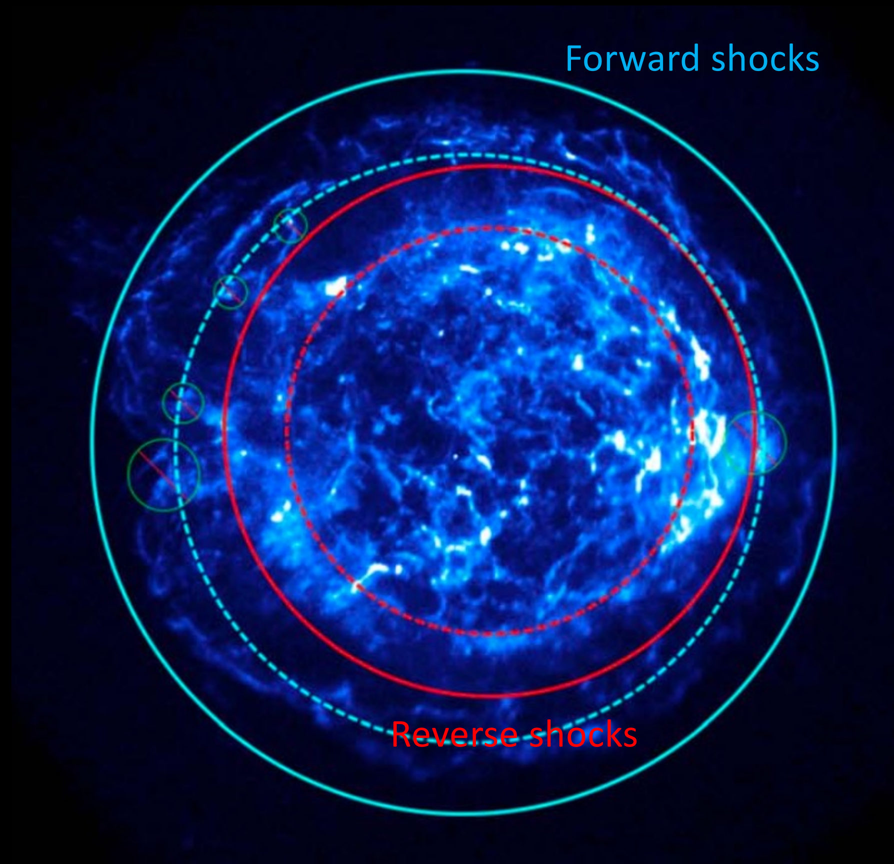
Dust destruction by shocks

Supernova shocks

ISM or CSM



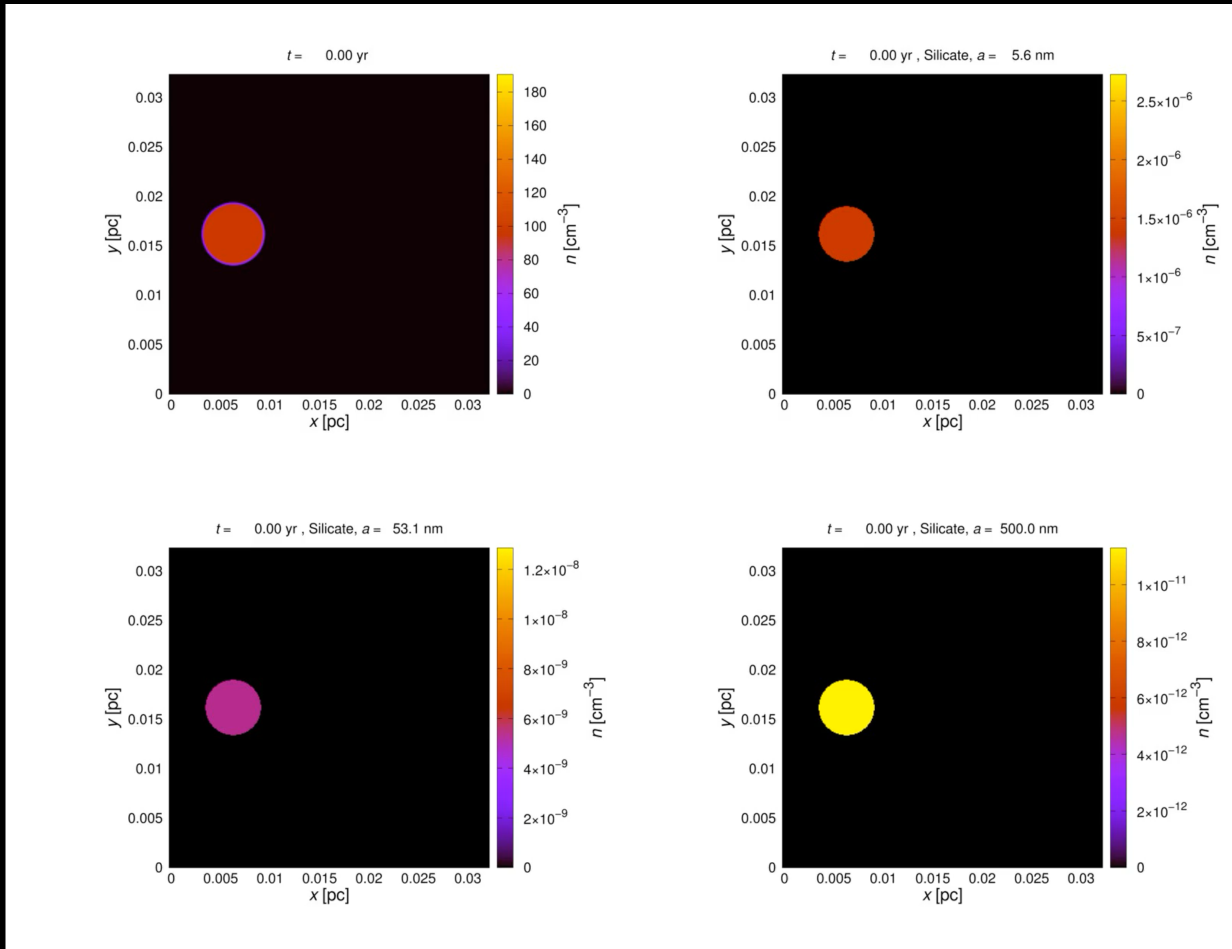
Cas A (X-ray)



Vink (2020)

Ejecta dust destruction by reverse shocks

Hydrodynamic model simulations



Different grain size

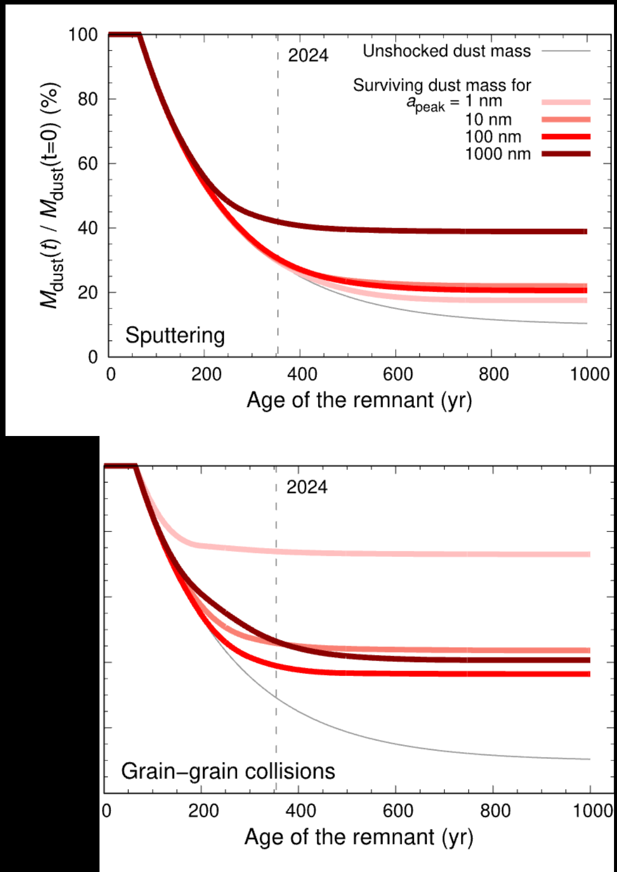
Poster #18

Kirchschlager et al. (2019; 2023)

Ejecta dust destruction by reverse shocks

Hydrodynamic model simulations

Surviving dust mass



Large dust grains have a better chance of surviving sputtering

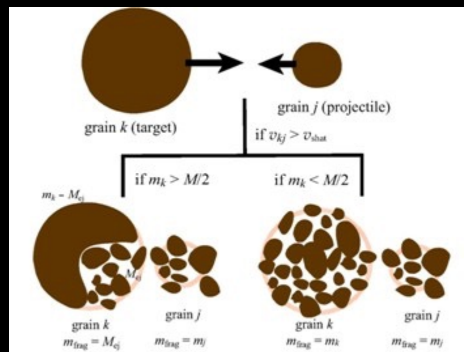
Large dust grains are destroyed by shattering

Kirchschlager et al. (2019; 2024)

New knowns

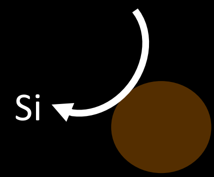
Grain-grain collisions increase in high-density regions, increasing the destruction rate of large grains by shattering

Grain shattering



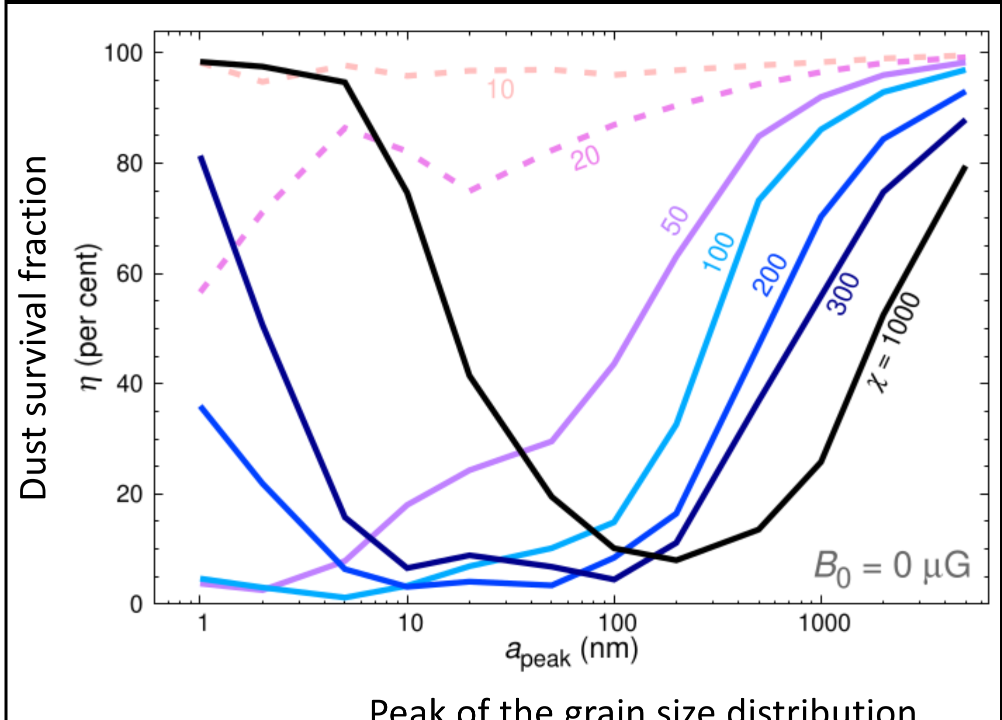
Hirashita

Grain sputtering



Ejecta dust destruction by reverse shocks

Hydrodynamic model simulations

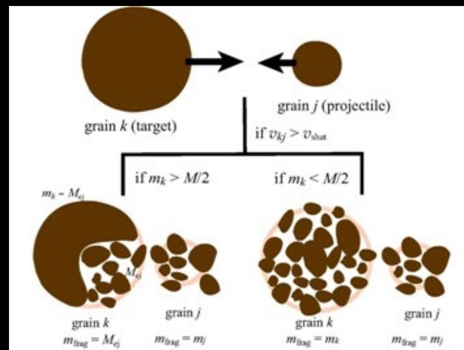


χ: the ratio of gas in clump and ambient medium (the lower the value, the more gas in clumps)

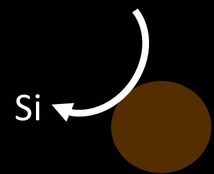
New knowns

Grain-grain collisions increase in high-density regions, increasing the destruction rate of large grains by shattering

Grain shattering



Grain sputtering

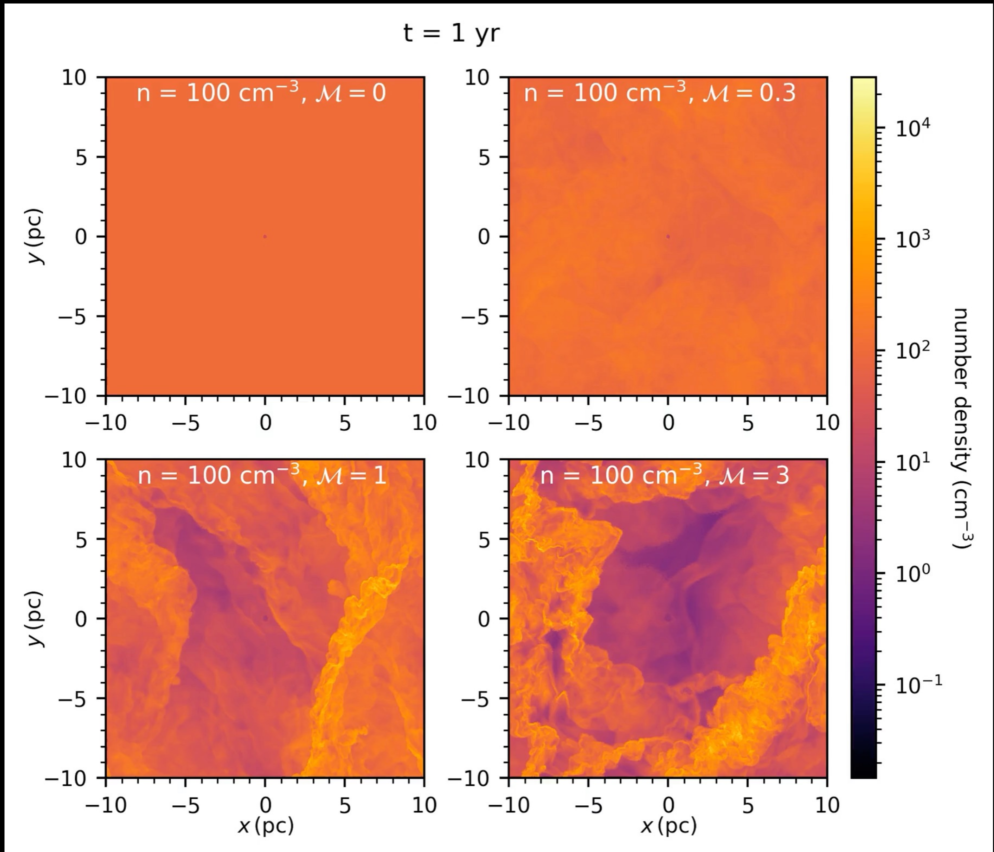


Hirashita

Kirchschlager et al. (2019; 2024)

Dust destruction by forward shocks

Hydrodynamic model simulations



Dust destruction rate: high density makes more dust destroyed

ρ=1 cm^{-3}: 25-57%

ρ= 10 cm^{-3}: 46-92%

ρ= 100 cm^{-3}: 73-87%

New knowns

Inhomogeneous ISM makes dust destruction rate lower

Scheffler et al. (submitted)

Kirchschlager et al. (2022)

Inhomogeneous ISM

Dust evolution of ISM galaxies

- Still relies on historical descriptions for both SN dust formation and destruction
- Next step: incorporating hydrodynamic simulations of dust destruction

Dust evolution model by Choban et al. (2022)

2.4.1 Dust creation by SNe

The exact dust yields from SNe are not well known and so both of our implementations follow the same simplified prescriptions from Dwek (1998) which assumes a set fraction of the metal yields from SNe condense into dust.

2.6.1 Thermal sputtering

Dust grains residing in hot gas in the galactic halo can undergo thermal sputtering, which causes erosion of dust grains by energetic atoms and can limit the depletion of gas-phase metals on to grains. Protons and helium ions are the main sputtering agents, and predictions of thermal sputtering rates indicate that sputtering overwhelms dust growth via accretion for $T \gtrsim 10^5$ K (Draine & Salpeter 1979).

Conclusions

- Supernovae form dust
- Unresolved issues
  - Uncertainties in ejecta dust masses and dust compositions
  - Grain size is undetermined
  - Difficulties in measuring dust destruction (rate)
- The next FIR mission (PRIMA) can measure cold ejecta dust masses

- Hydrodynamics models are developing fast
  - Inhomogeneous gas distributions affect the dust destruction rate and grain formation.
- Supernova remnants are complex
  - JWST observations and simulations provide a pathway to understanding this complexity.