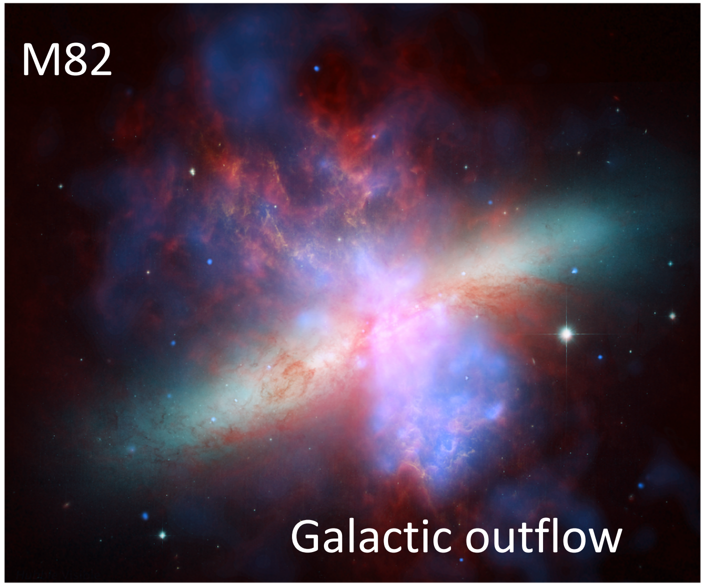
Core collapse

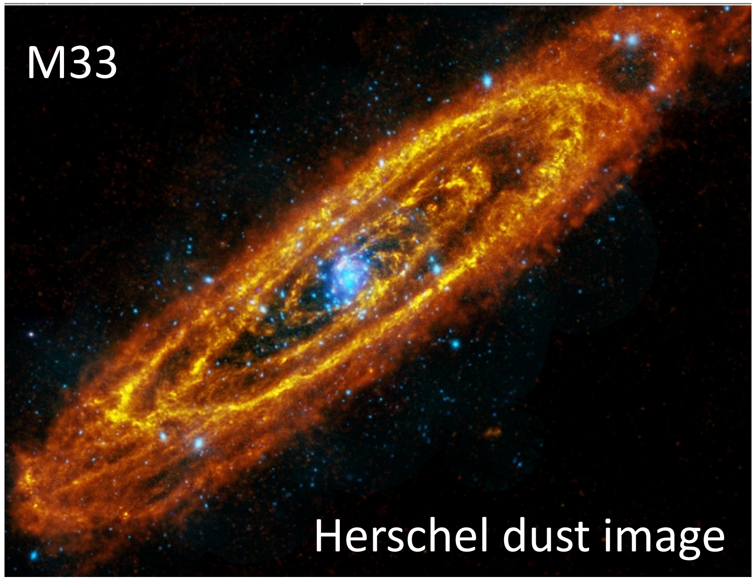
Supernovae and their impacts on surrounding environments

Mikako Matsuura

Cardiff University

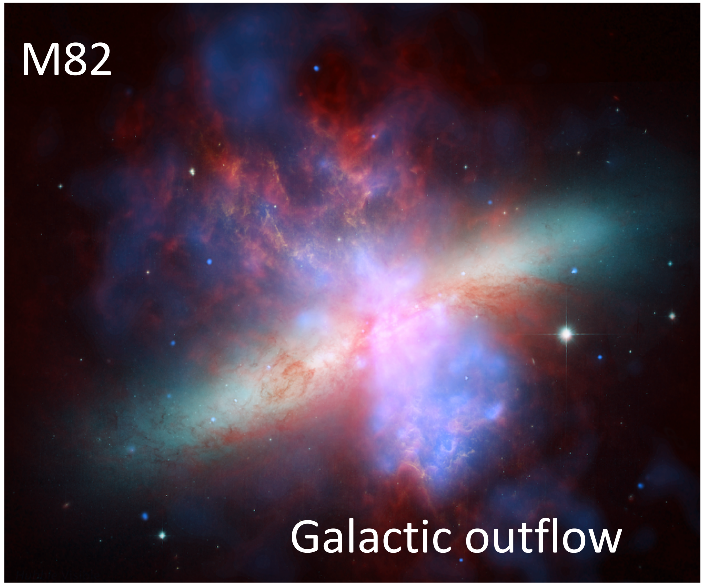
What is the role of supernovae on surrounding environments ?

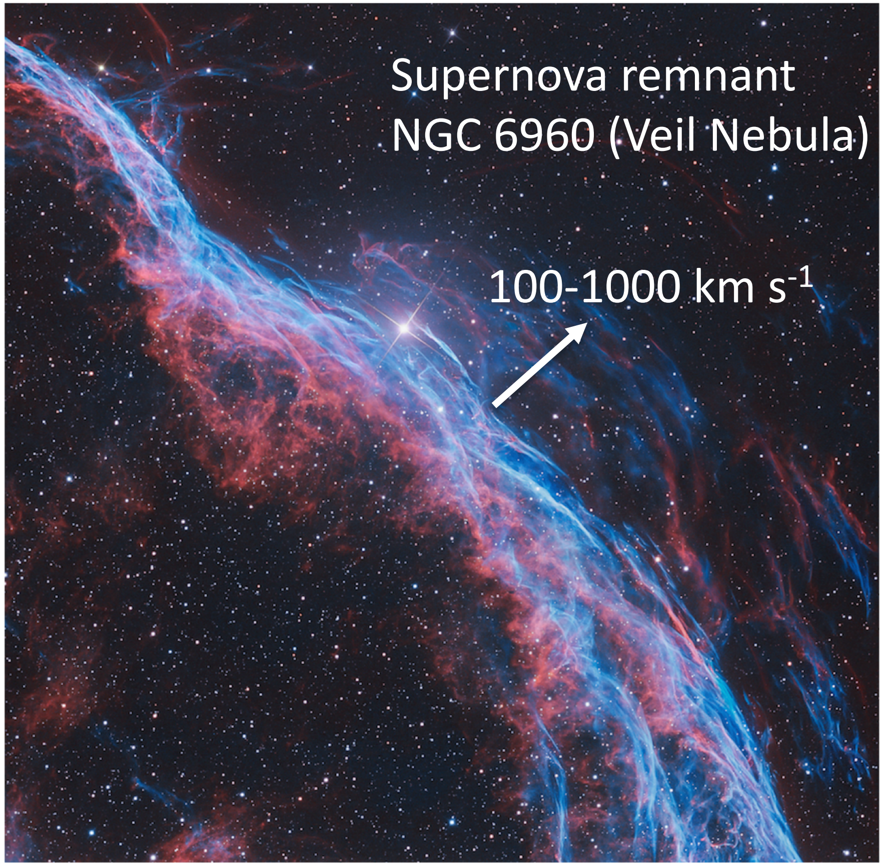




1. Providing kinetic energy
2. Destroying existing ISM dust
3. Source of elements and dust
4. Cosmic ray acceleration

What is the role of supernovae on surrounding environments ?



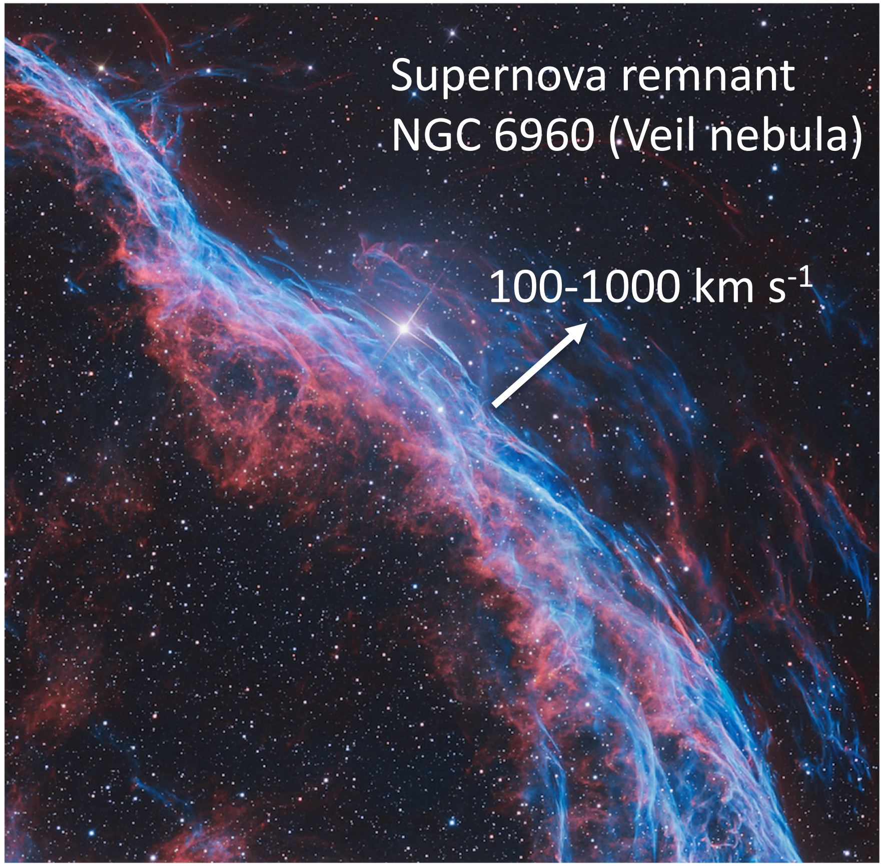


1. Providing kinetic energy

Core collapse SNe

- Explosion energy of 10^{51} ergs
- Majority of energy is carried away by neutrinos
- A few % of energy might turn into kinetic energy

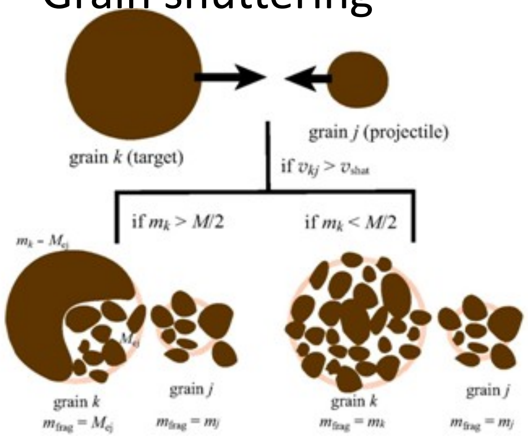
What is the role of supernovae on surrounding environments ?



2. Destroying existing ISM dust

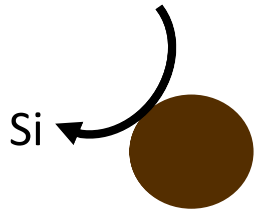
When SN shock waves meet with ISM dust -

Grain shuttering



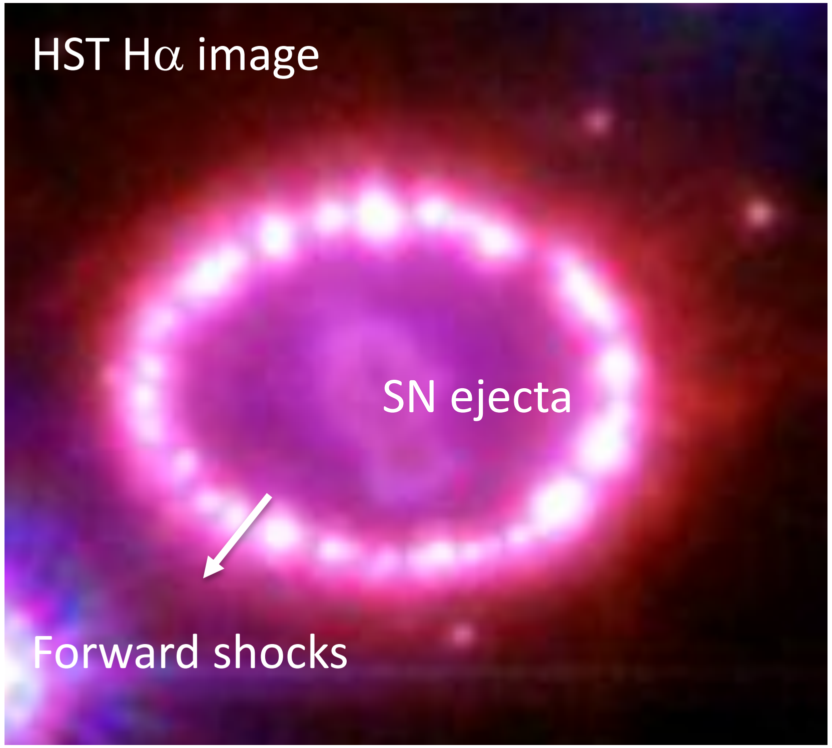
Hirashita

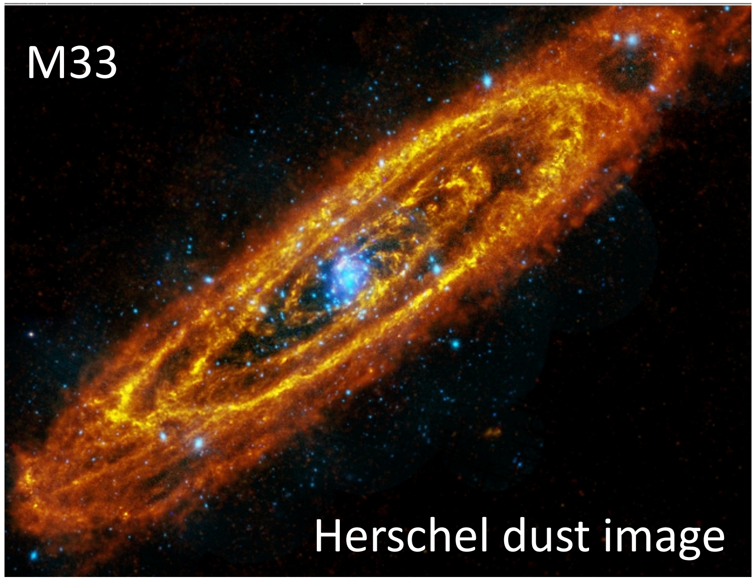
Grain spattering



What is the role of supernovae on surrounding environments ?

Supernova 1987A





3. Source of elements and dust

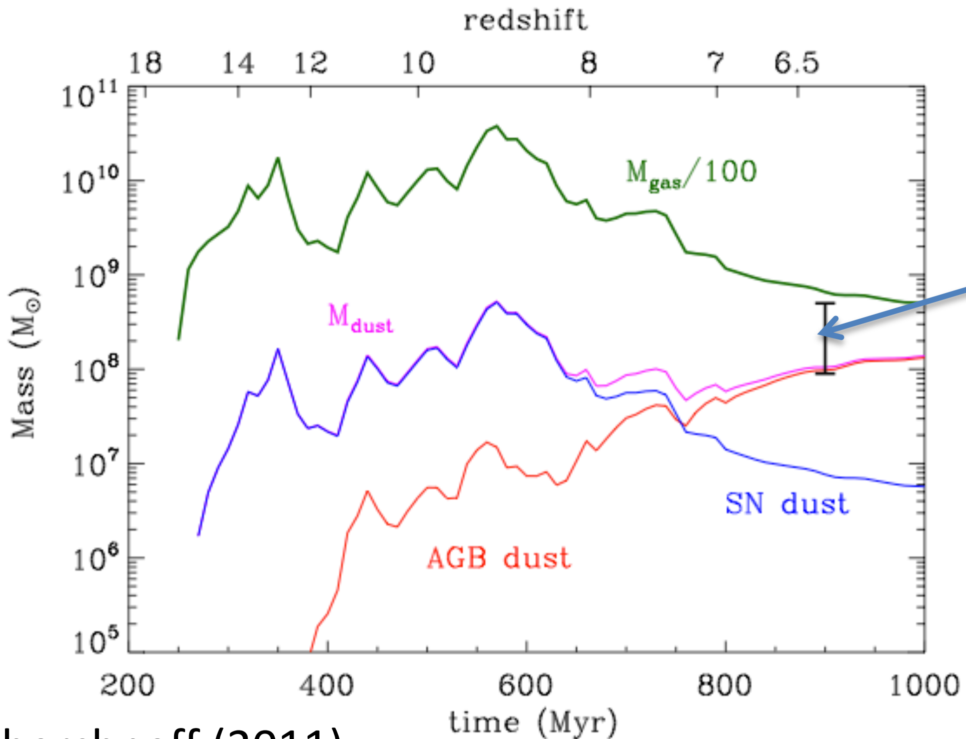
SN ejecta – filled with heavy elements (C, Si, O, Mg, Fe)
Some of these refractory elements eventually form dust grains

Contents

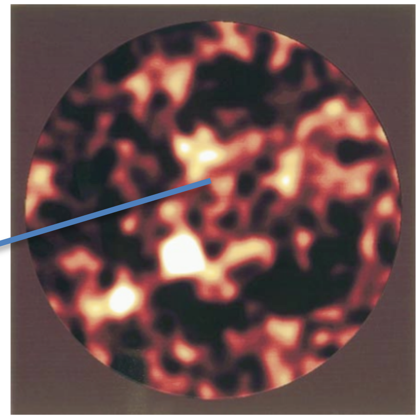
1. Dust formation in SNe
2. Destroying dust?
3. Constrains on elements synthesized in SNe
4. Explosion of core collapse SNe

What are the major sources of dust in galaxies?

- Stellar origin (SNe + AGB stars)
  - 0.1-1 $M_\odot$ of dust per SN needed
- ISM grain growth



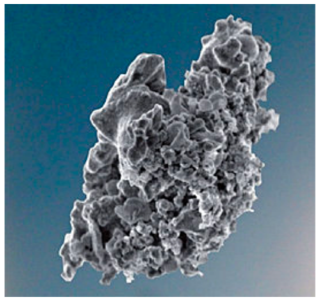
Dwek & Cherchneff (2011)

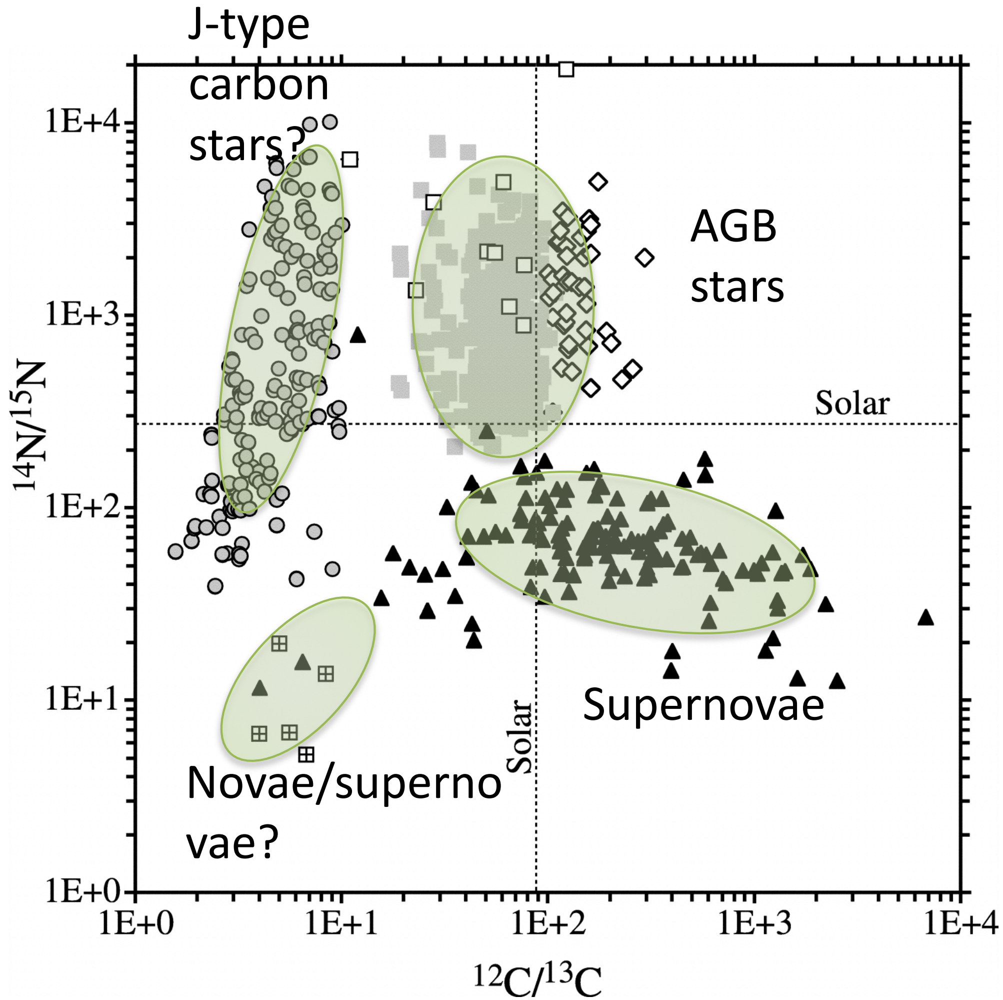


Submm galaxy
At z~6.4; ~0.4 Giga years
(e.g. Bertoldi et al. 2003)

Evidence of dust formation in SNe

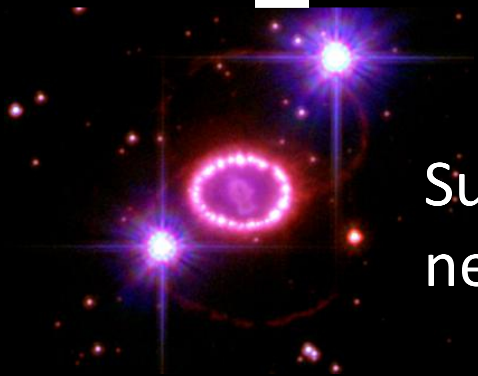
Laboratory measurements of isotope-ratios in SiC pre-solar grains





(Zinner et al. 2006)

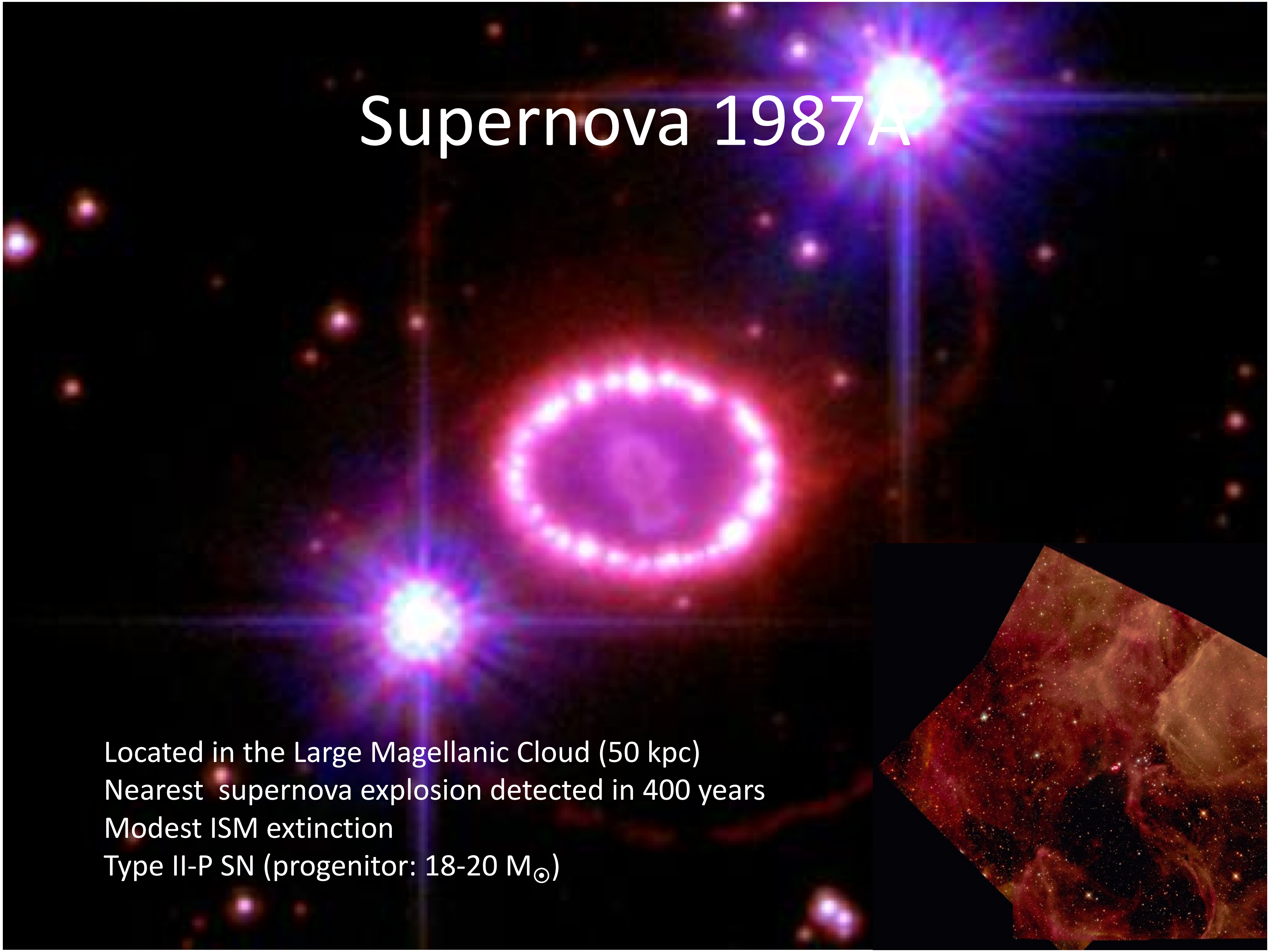
Role of SNe on galaxy evolution



Supernovae enrich the ISM of galaxies with newly synthesised elements and dust

Questions

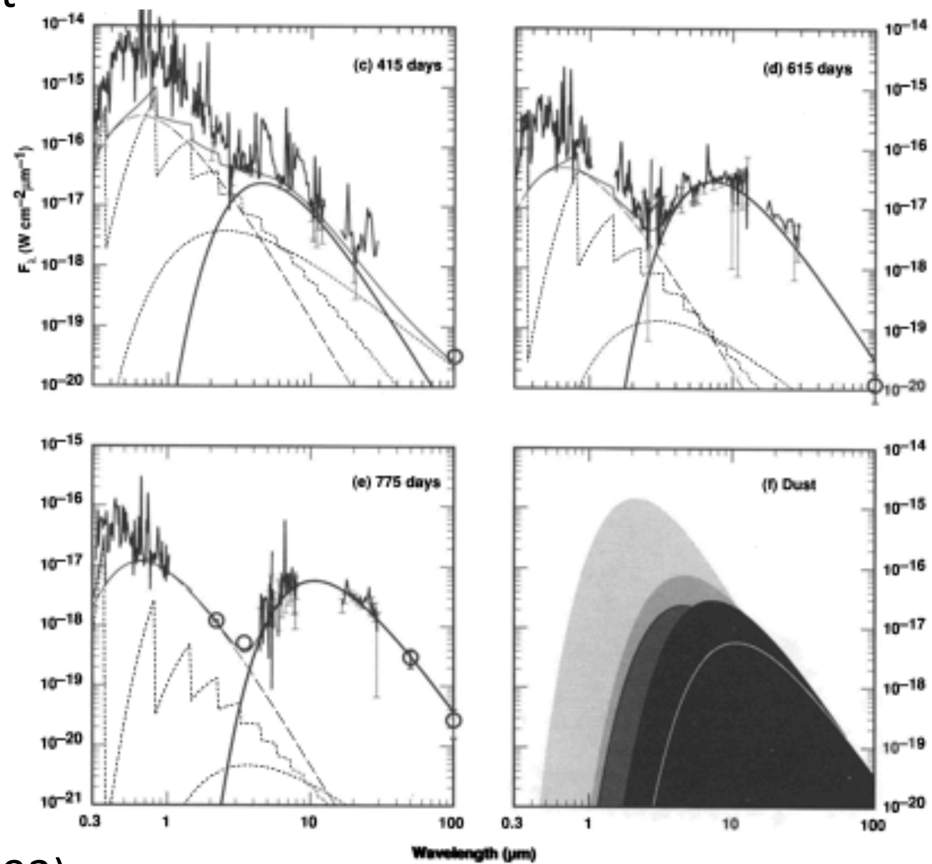
- How much elements ejected from SNe?
- How much dust is formed in SNe?
  - How to form dust?


Supernova 1987A
Located in the Large Magellanic Cloud (50 kpc)
Nearest supernova explosion detected in 400 years
Modest ISM extinction
Type II-P SN (progenitor: 18-20 $M_{\odot}$)

Detection of dust in SN 1987A

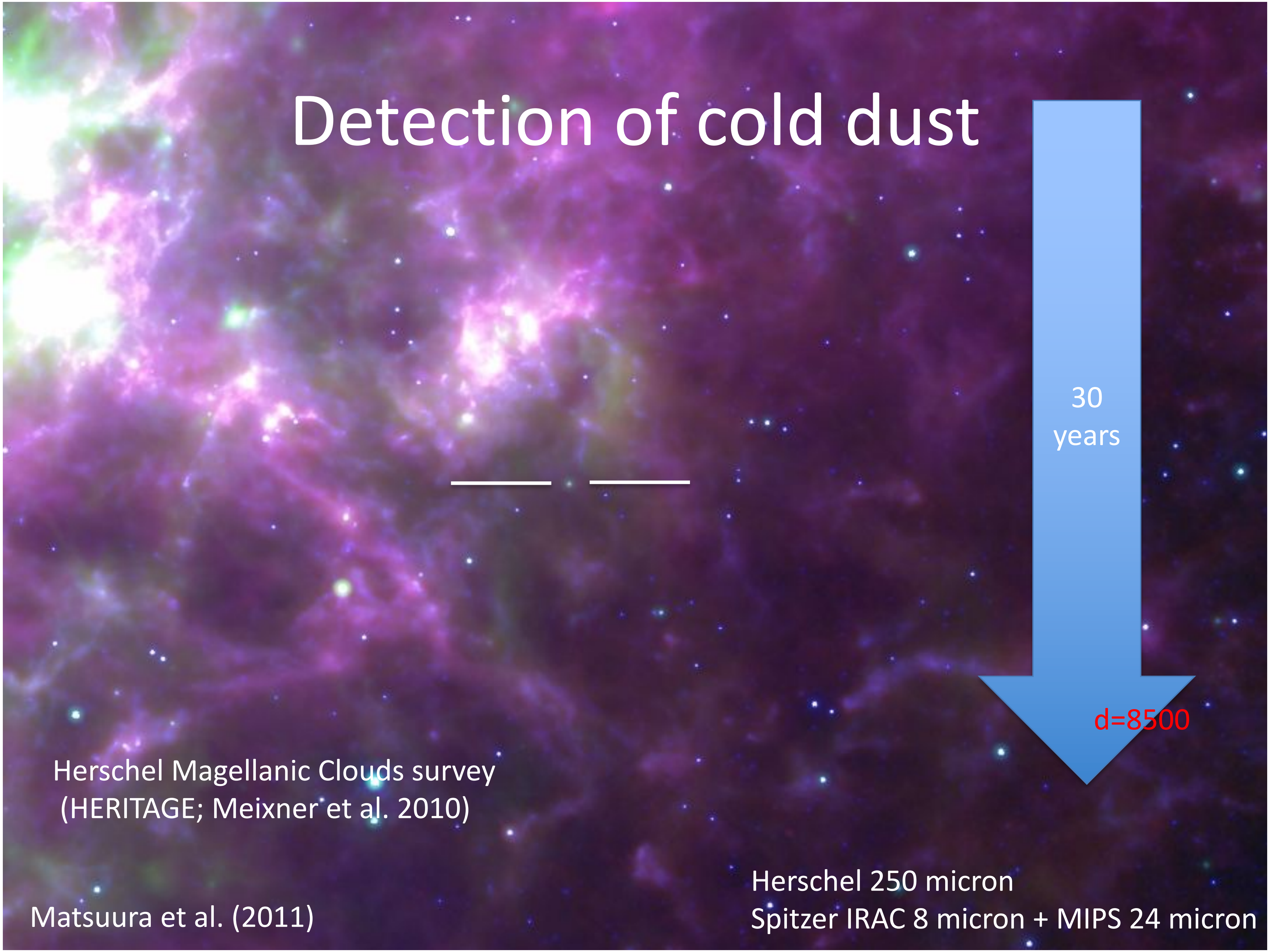
First detection of dust in SNe

- Kuiper air borne observatory
- 450-777 days
- 10^{-4} $M_{\odot}$ of dust



Wooden et al. (1993)

Detection of cold dust

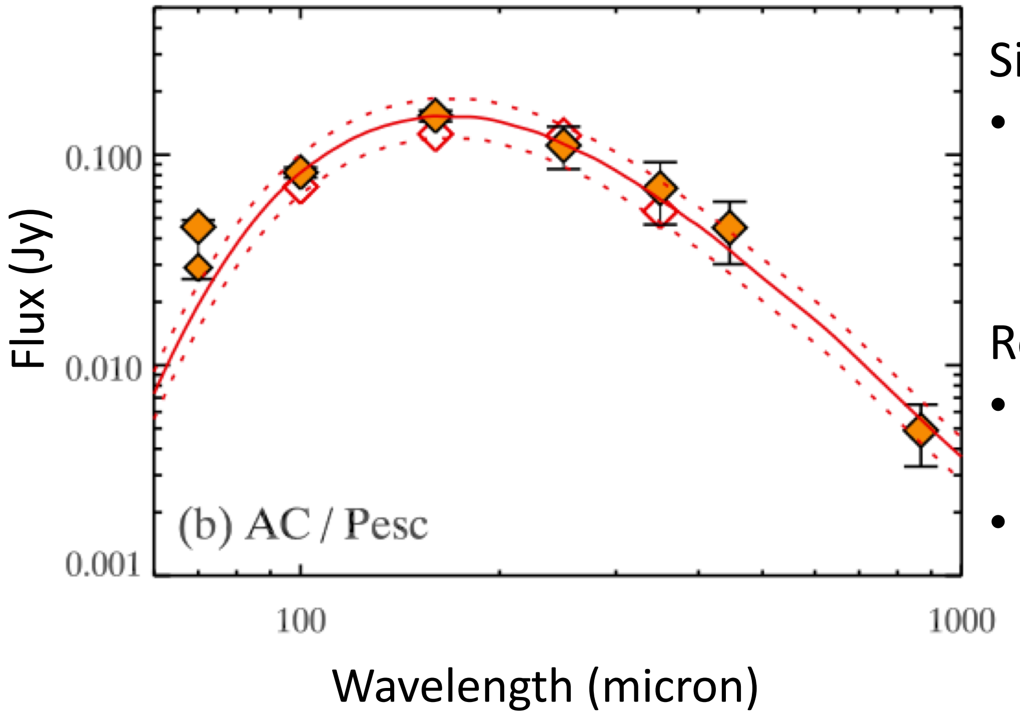


Herschel Magellanic Clouds survey
(HERITAGE; Meixner et al. 2010)

Matsuura et al. (2011)

Herschel 250 micron
Spitzer IRAC 8 micron + MIPS 24 micron

Herschel detection of SN 1987A



Significantly large mass of dust:

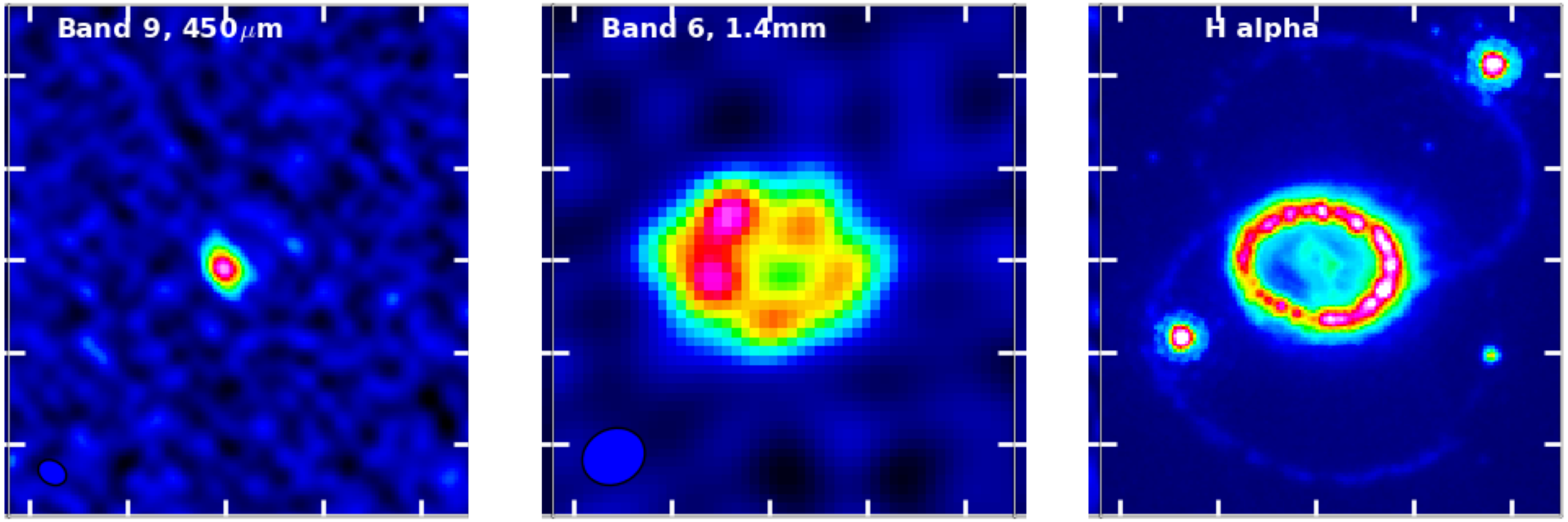
- 0.4-0.7 $M_\odot$ of dust
  - Must be in the ejecta

Response from supernova/dust communities

- Previously reported SN dust mass:
  - 10^{-6} -10^{-3} $M_\odot$
- Did dust grains really form in the ejecta?
  - Alternatives
    - Progenitor (red-supergiant) dust
    - ISM swept up dust

Matsuura et al. (2011;2015)

ALMA confined the location of cold dust

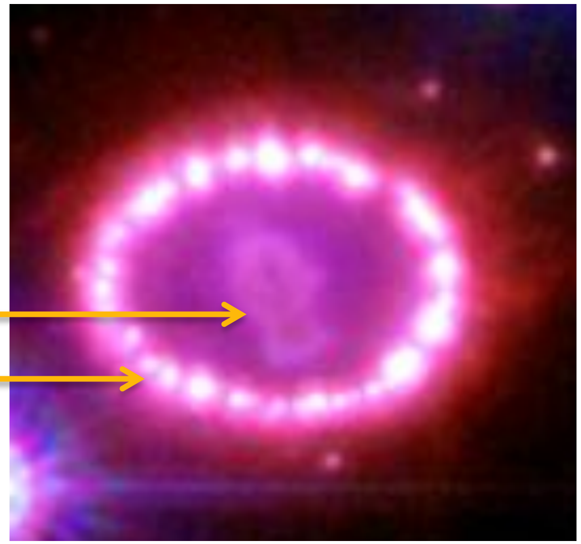


450 micron
Dust

1.4 mm
Synchrotron

H alpha

Cold dust in ejecta (~0.5 $M_{\odot}$)



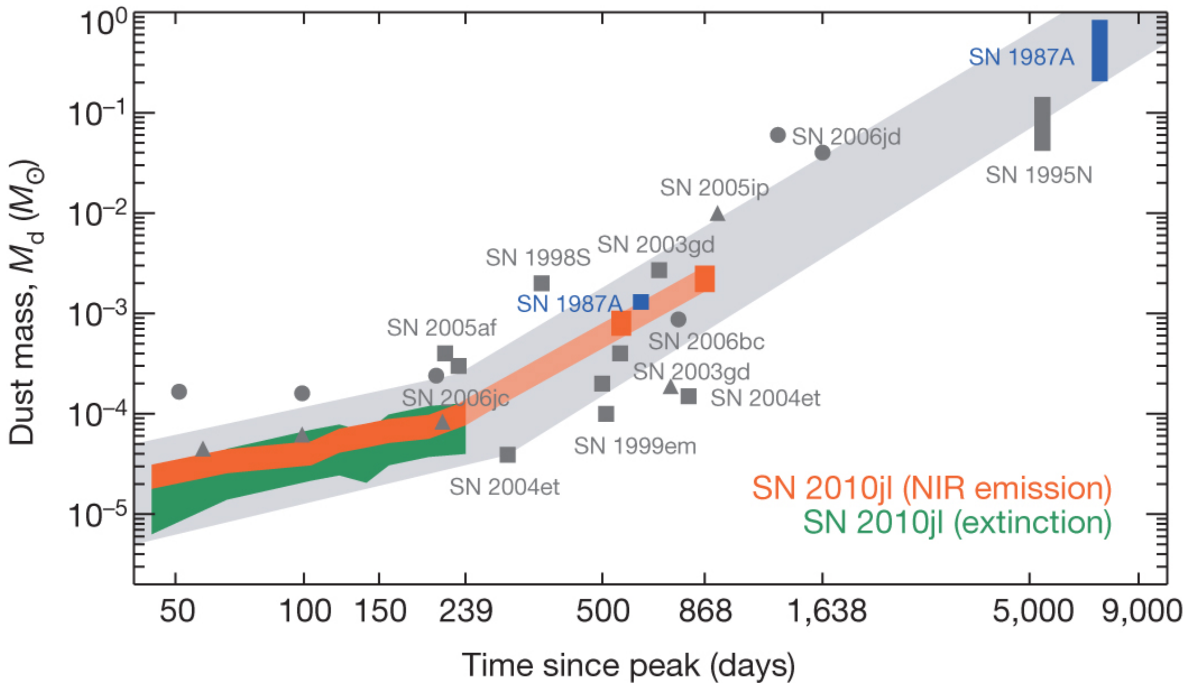
SN ejecta

Ring: progenitor

Indebetouw et al. (2014)

What is the true figure of dust mass? What is the time scale of dust formation?

- Dust mass evolution vs optically thick
  - Dust mass starts with small number and increases in time
  - A large dust mass is present from early days, but hidden by optically thick dust clouds

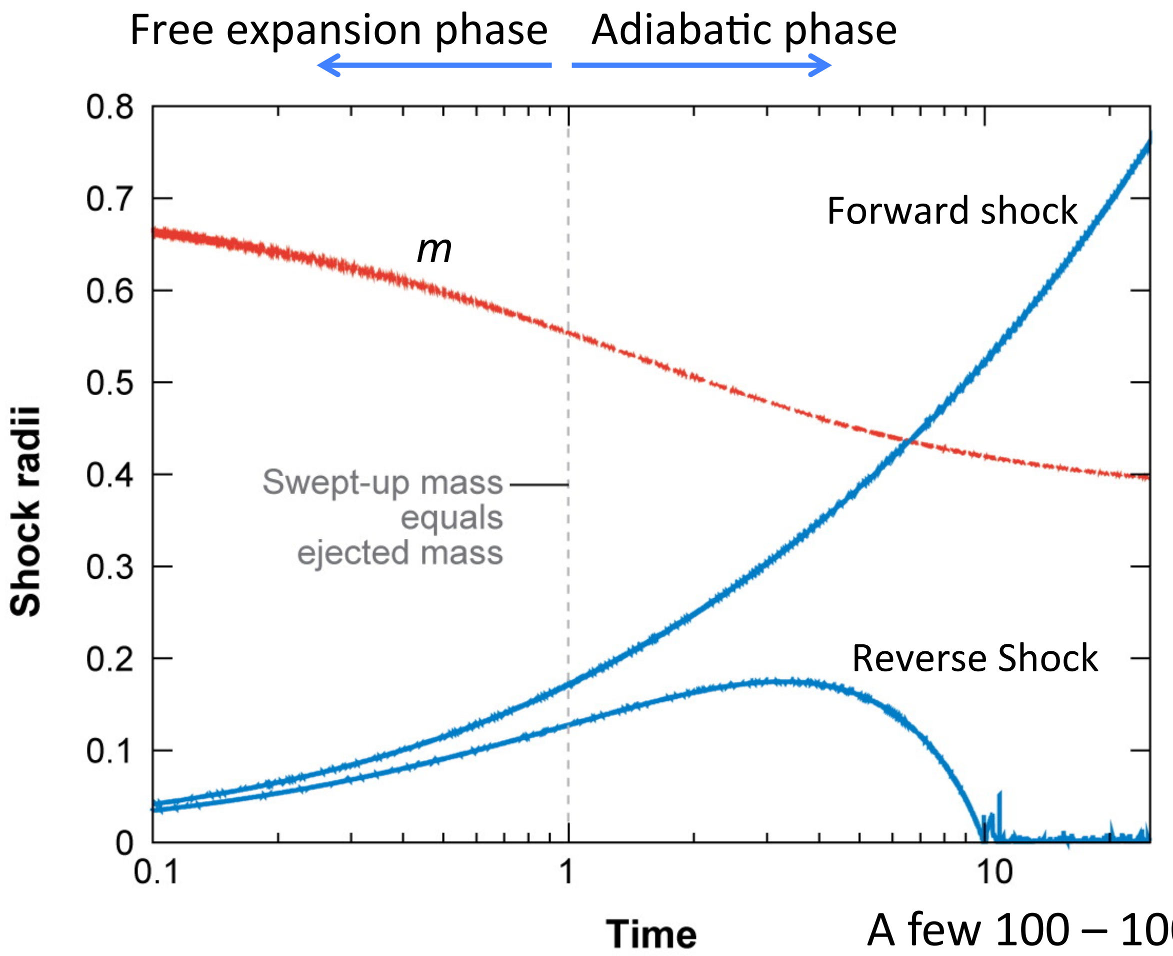


Gall et al. (2014, Nature 511, 326)

Context

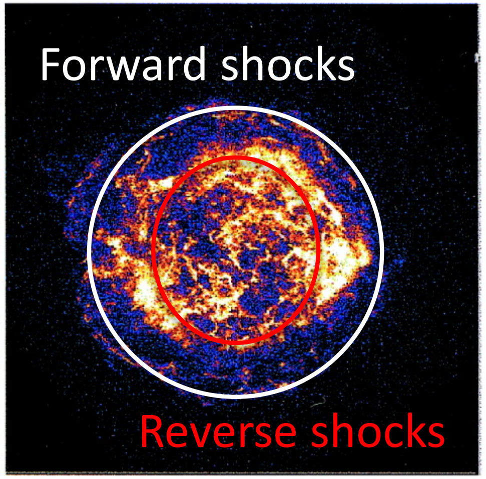
1. Dust formation in SNe
2. Destroying dust?
3. Constrains on elements synthesized in SNe
4. Explosion of core collapse SNe

How much dust is destroyed by SN forward shocks?



A few 100 – 1000 years

Cassiopeia A (AD 1681?)



Gotthelf et al. (2001)

A big problem in understanding of dust evolution of galaxies

- Theory predicts

Total dust input rate from AGB stars + SNe $\leqq$ Dust destruction rate by SNe

C.f. ISM grain growth

e.g. Jones & Nuth (2011)

Theoretical prediction of dust destruction by SNRs

	Destruction rate	
Forward shocks (Destroying existing ISM dust)		
Draine and Salpeter (1979)	10–30	Sputtered mass, v_s=100 km s^{-1}, a=0.1, graphite
	50–70	Silicate
McKee et al (1987)	25–38	Silicate, v_s=100 km s^{-1}
Jones et al (1994)	12	Graphite, v_s=100 km s^{-1}, n_H=0.25 cm^{-3}
	22	Silicate
Jones et al (1996)	8	Graphite, v_s=100 km s^{-1}
	16	Silicate
Bocchio et al (2014)	91	Hydrogenated amorphous carbon, v_s=100 km s^{-1}
	29	Silicate

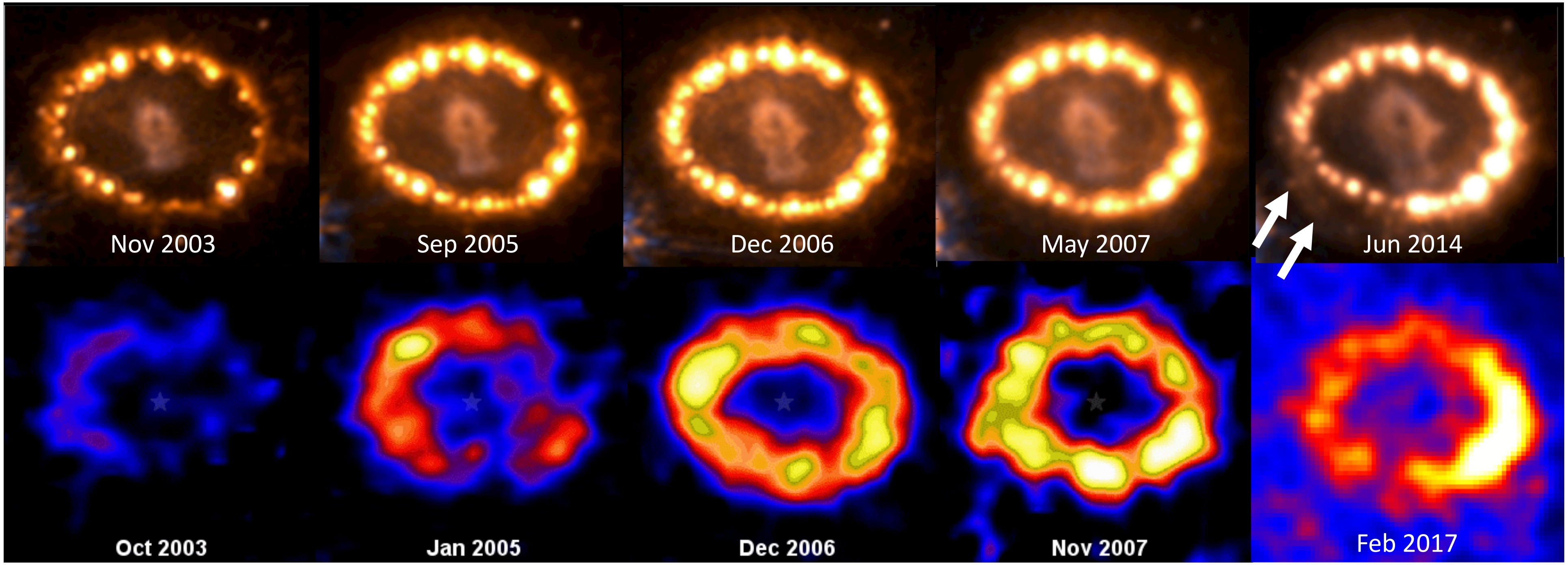
Reverse shocks (Destroying newly formed SN ejecta dust)		
Nozawa et al (2007)	100	$MgSiO_3$, M_p=20 $M_\odot$ n_H=1 cm^{-3}
	45	C, n_H=1 cm^{-3}
Bianchi and Schneider (2007)	97	M_p=20 $M_\odot$ n_H=10^{-24} g cm^{-3}
Nath et al (2008)	1	M_{ej}=2×10^{34} g, E_{ej}=10^{51} erg
Silvia et al (2012)	4–56	C
	5–93	SiO_2
Micelotta et al (2016)	20	Amorphous Carbon, v_s=100 km s^{-1}
	50	$MgSiO_3$

Time evolution

SN 1987A forward shocks

HST Hα

Forward shocks are exiting the ring on the East

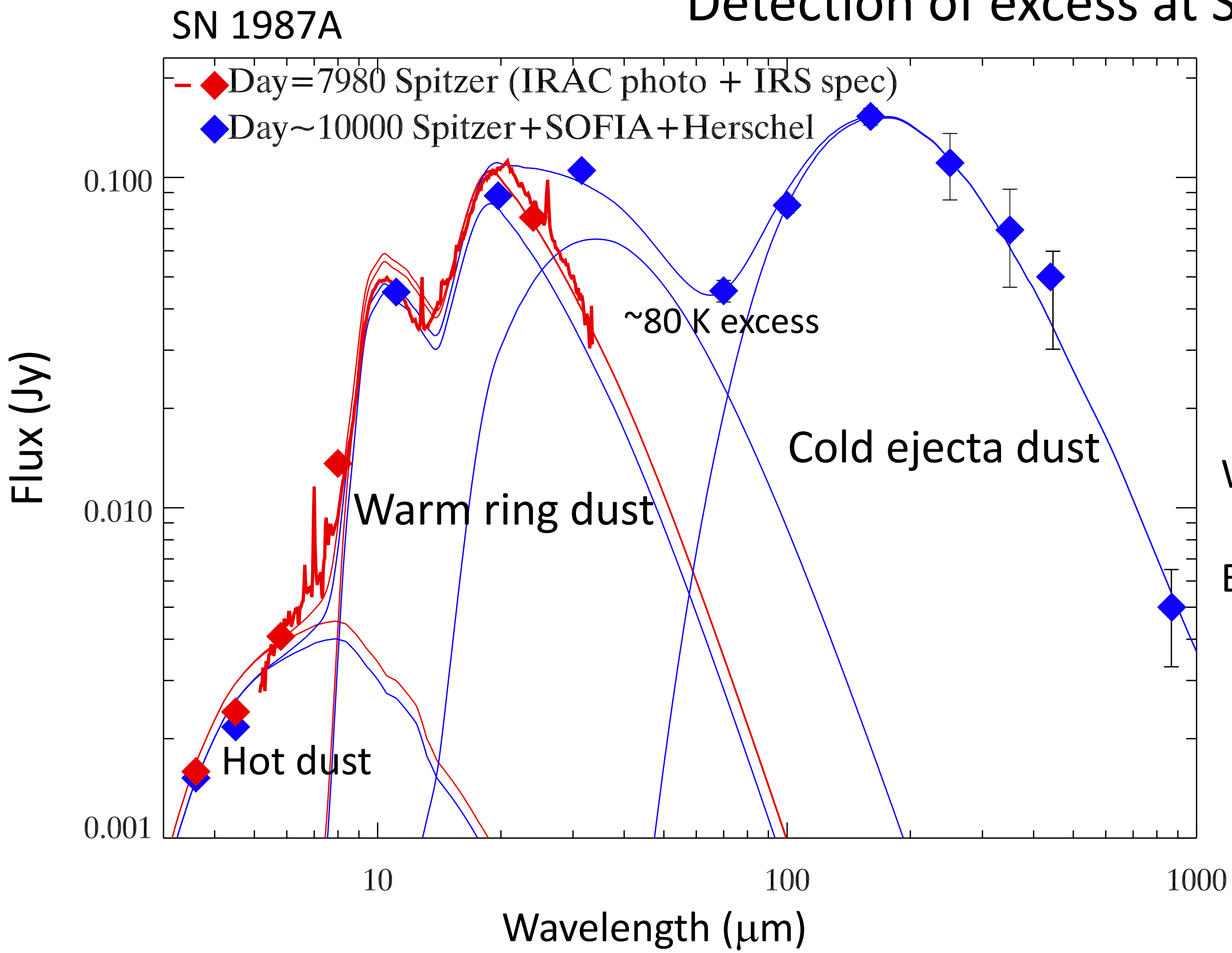


Mid infrared (dust) Gemini+VLT

Bouchet et al. (2006)
Fransson et al. (2015)
Matsuura et al. (2018)

Spectral energy distribution

Detection of excess at SOFIA 31 micron



Continuing to Herschel 70 micron

Warm dust

M_d=0.8x10^{-5} Msun T_d=191 K

Excess

M_d=3.5x10^{-4} Msun T_d=85K

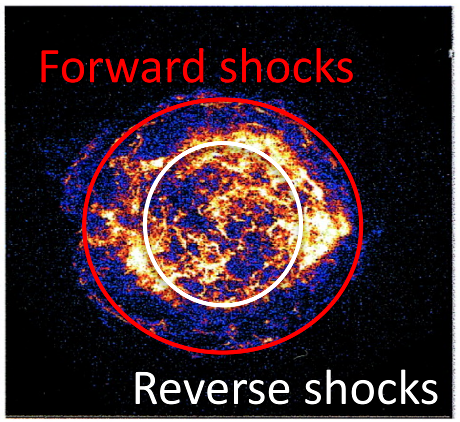
Dust reformed in the post shocked region?

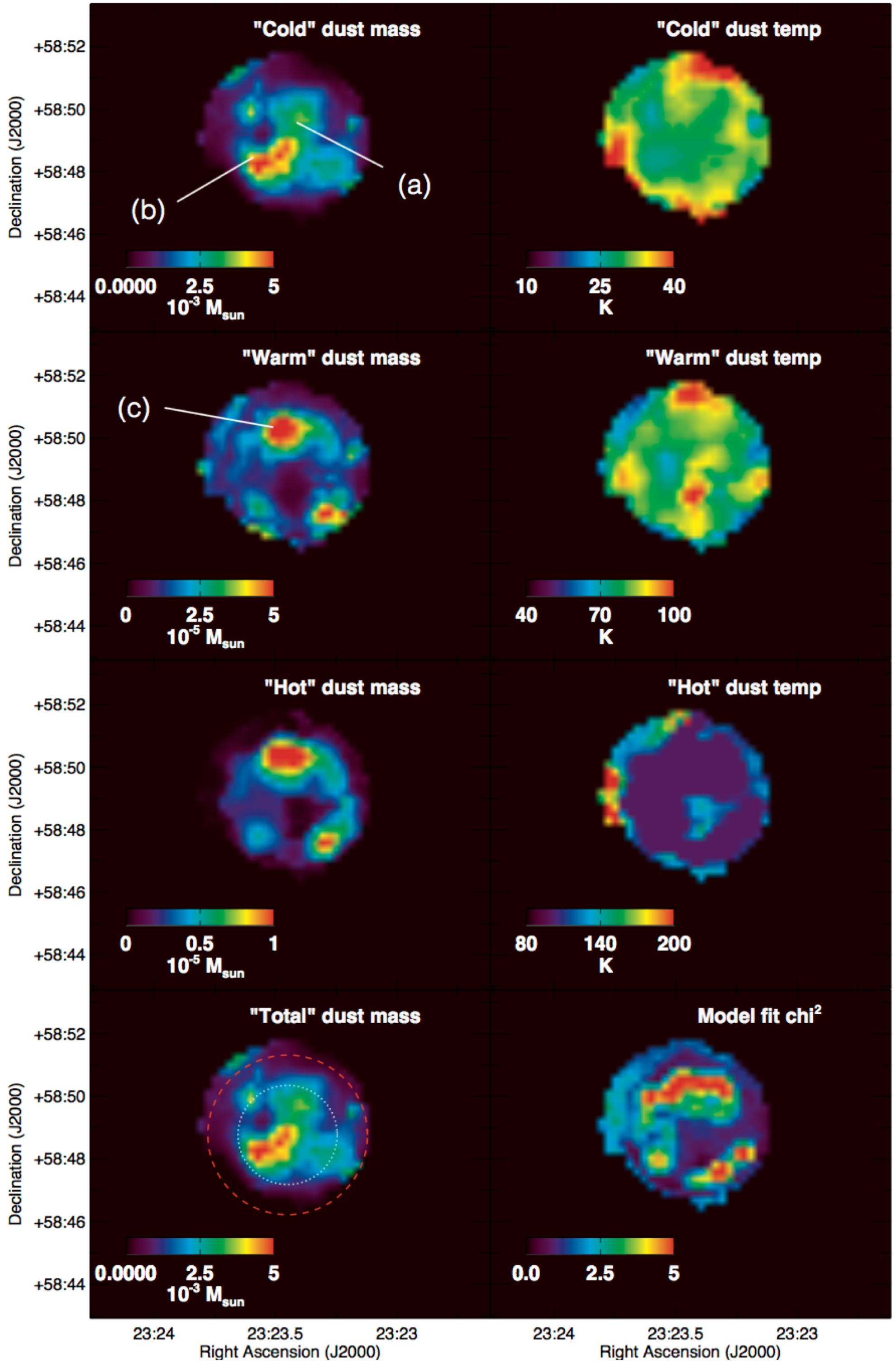
Cassiopeia A (AD 1681?)

Warm dust: 0.007 $M_\odot$
Cold dust: 0.4 $M_\odot$
(composition dependent)

Reverse shock destruction rate: ~70%

De Looze et al. (2017)

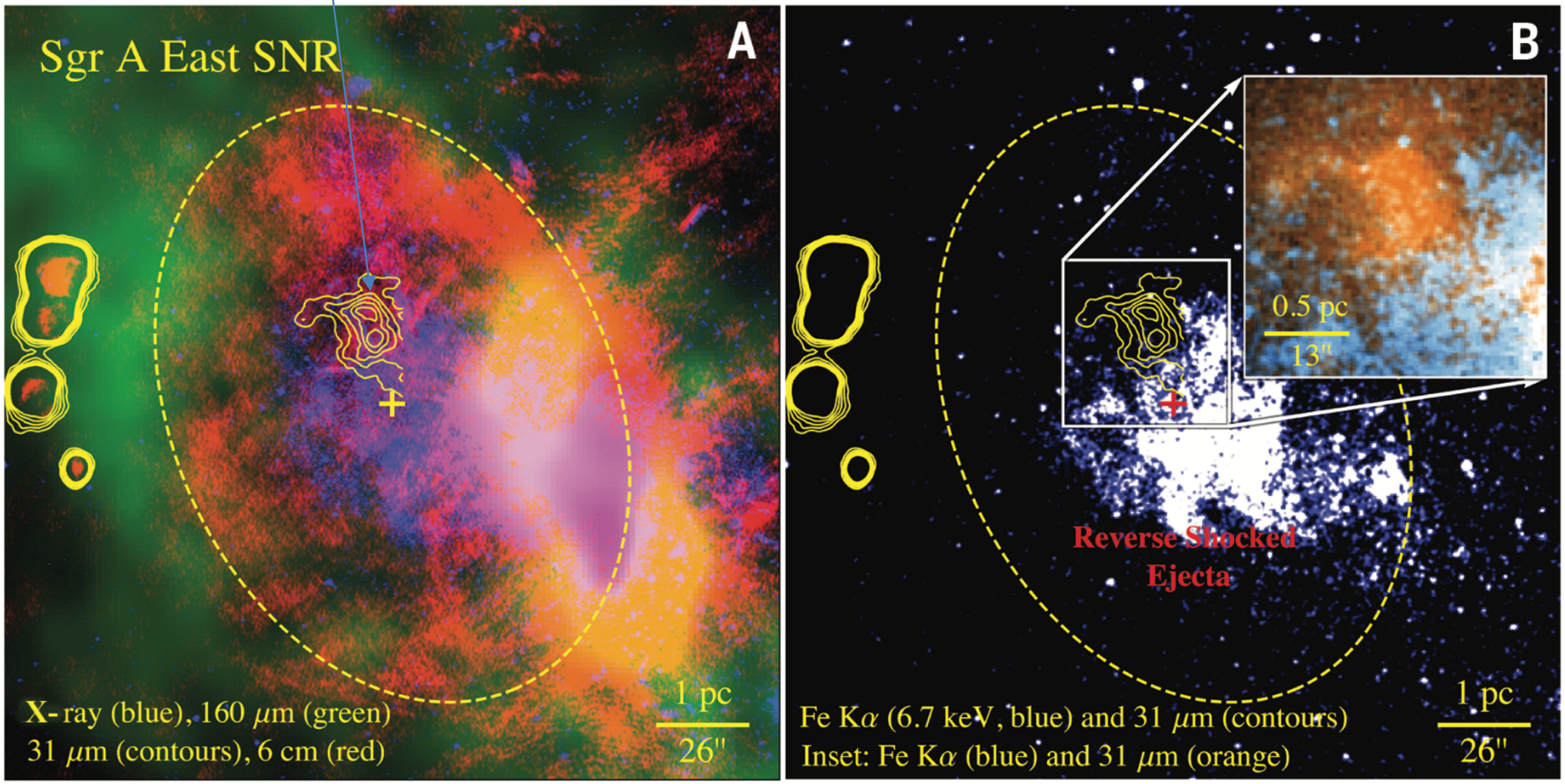




Reverse shocks: Srg A East

10^4 years old SNR

SOFIA detection of ejecta dust (survived after reverse shock passage): 0.02 $M_\odot$



Not so efficient dust destruction?

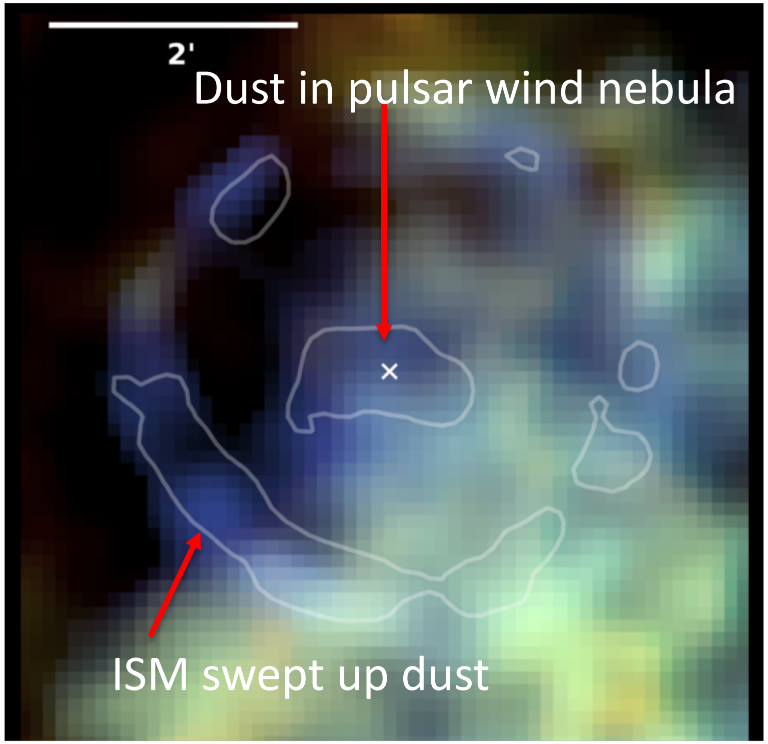
Lau et al. (2015)

What will happen in SNRs in long term?

Search for dust in 62 Galactic SNRs Detection of dust from 40% of SNRs

- Mostly associated with swept up ISM dust
- 3 are associated with pulsar wind nebula (ejecta dust)

G11.2-0.3
(1200-1400 years old)

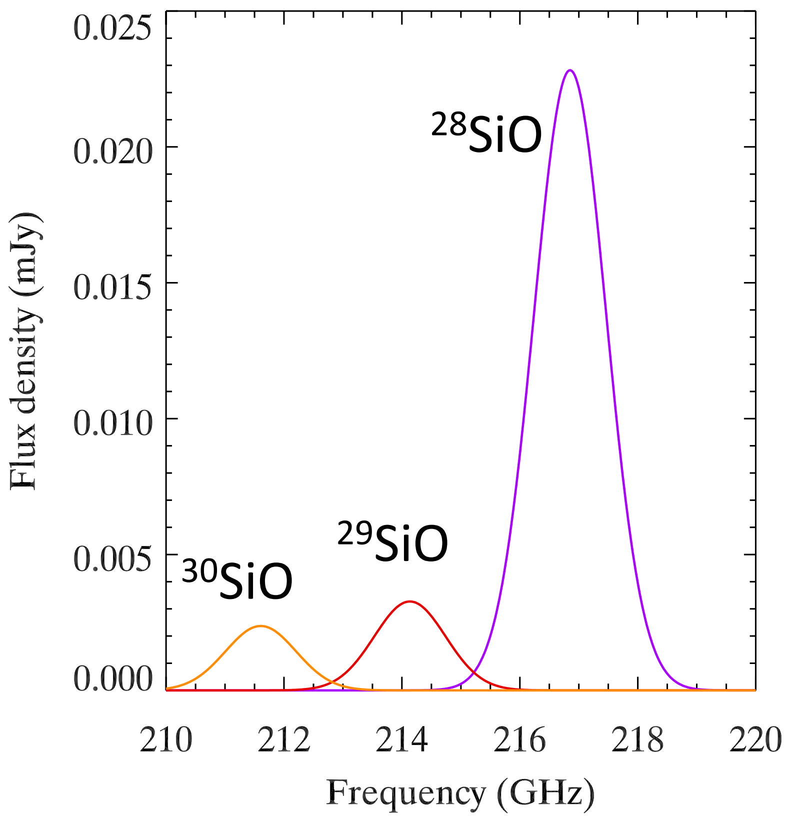


Chawner et al (submitted)

Context

1. Dust formation in SNe
2. Destroying dust?
3. Constrains on elements synthesized in SNe
4. Explosion of core collapse SNe

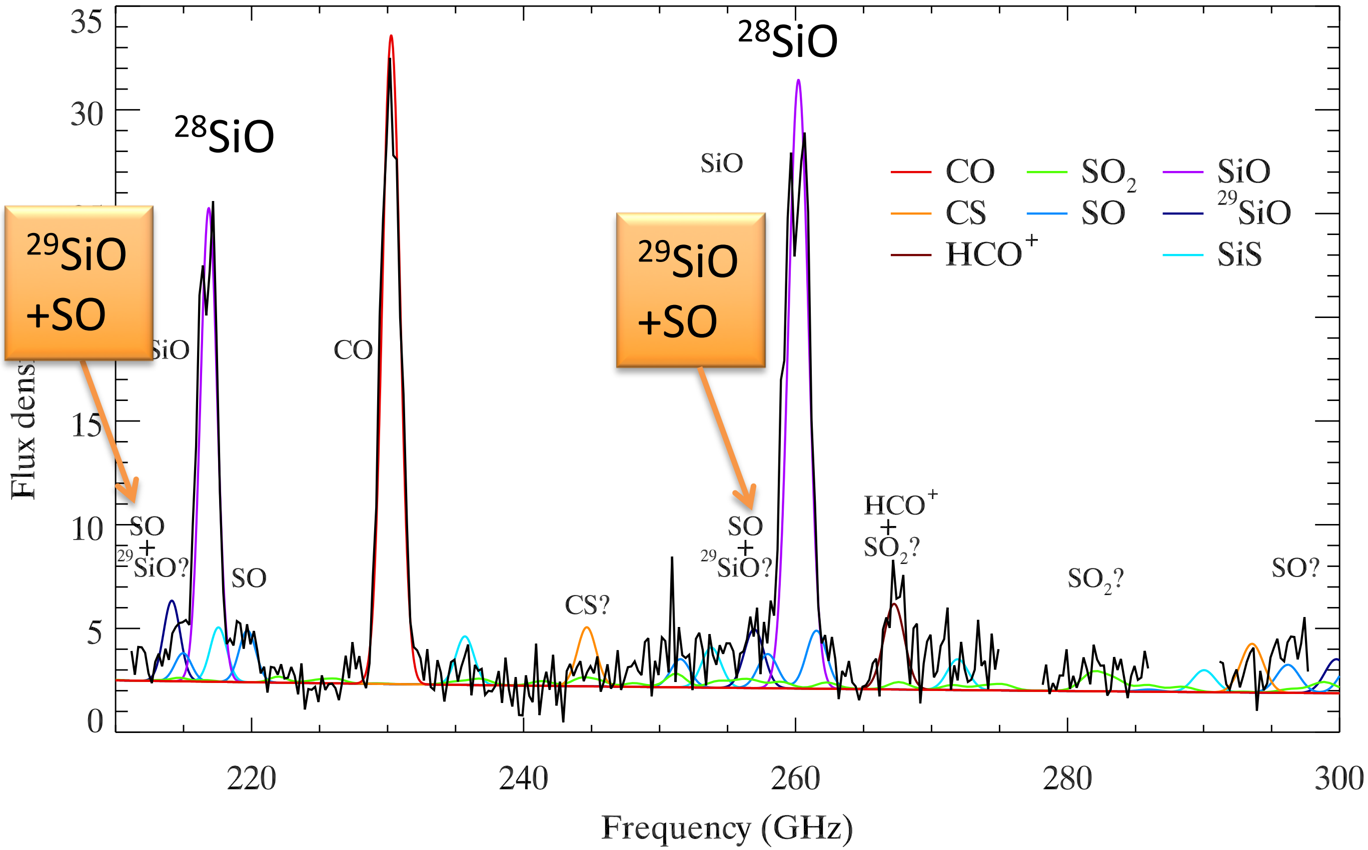
Isotopologues



At millimeter and submillimeter wavelengths, isotope shifts are larger than the SN expansion velocity (~2000 km s^{-1})

Constraints on SN nucleosynthesis: isotope ratio

ALMA spectra of SN 1987A

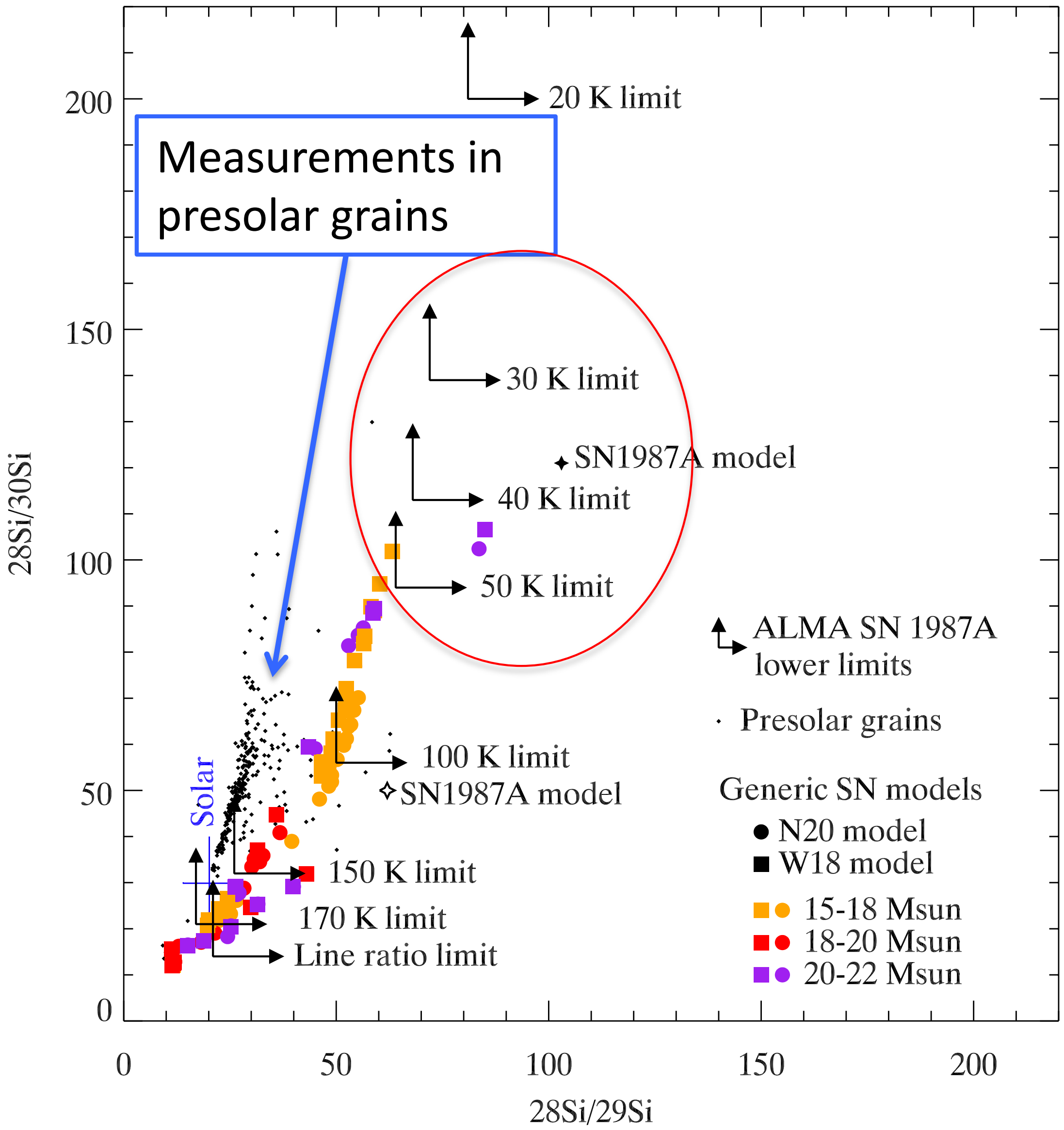


ALMA

^{28}SiO / ^{29}SiO >13

Matsuura et al. (2017)

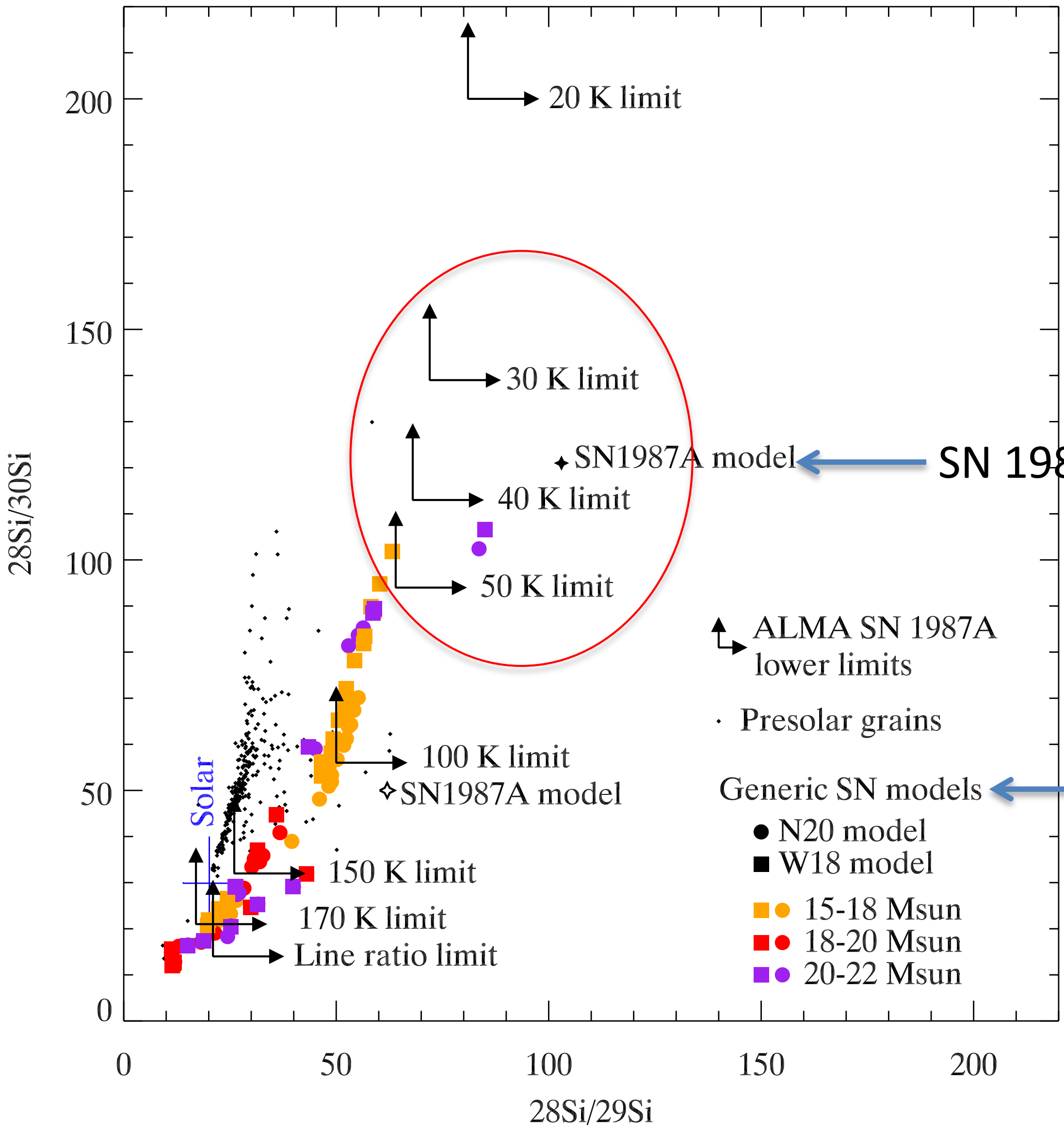
SiO isotopologue ratios



- SN 1987A could be slightly offset from presolar grains sequence
- Low metallicity effects
  - Neutron-rich isotopes are poor at low metallicity

Matsuura et al. (2017)

SiO isotopologue ratios



SN 1987A (~30% of solar $Z_{\odot}$; Woosley)

Solar metallicity models

Models require to increase ^{29}Si and ^{30}Si slightly

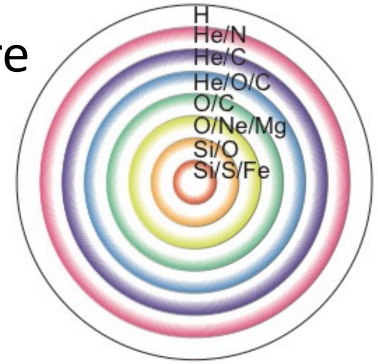
Matsuura et al. (2017)

Context

1. Dust formation in SNe
2. Destroying dust?
3. Constrains on elements synthesized in SNe
4. Explosion of core collapse SNe

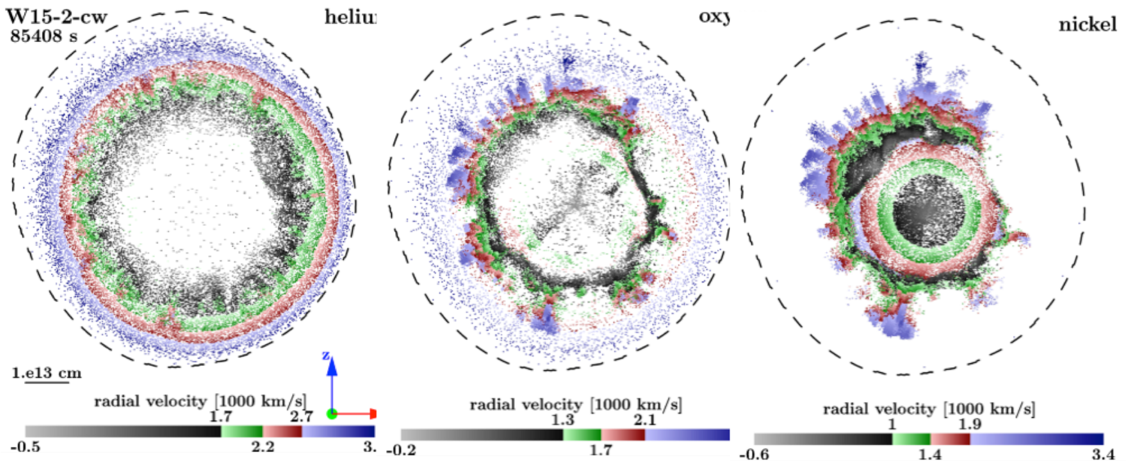
Supernova explosion is not symmetric

Historical picture

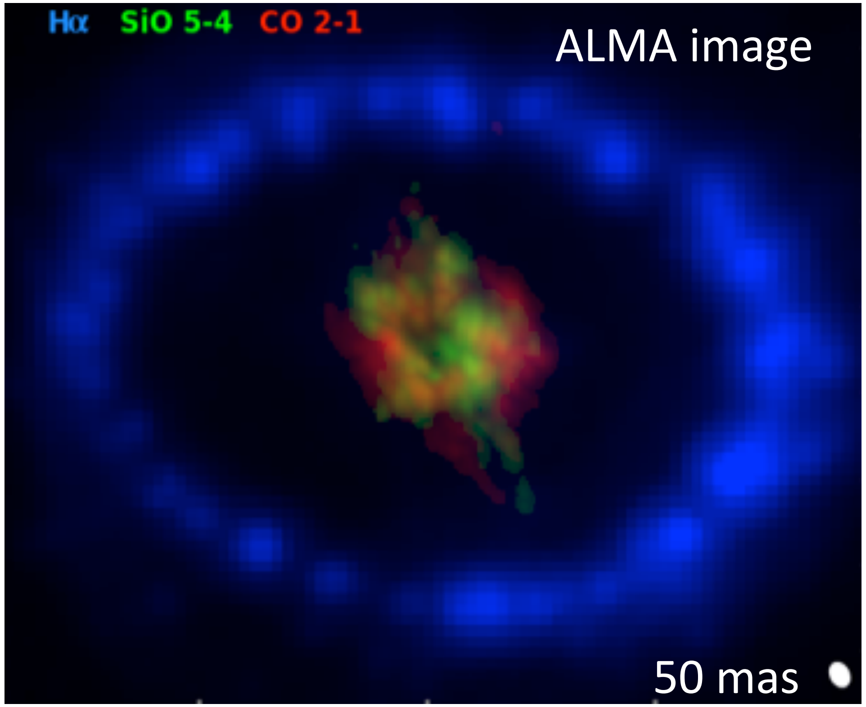


Hydrodynamic simulation of the explosion of core collapse SN

Map of elements immediately after the explosion



Wongwathanarat et al. (2015)



Fossils of clumps formed by shocks at the time of SN explosion

Abellan et al. (2017)

Summary

- Dust formation in SNe
  - Core collapse SNe form dust
  - No evidence of dust formation in type Ia SNe
- Destroying dust?
  - Theory – yes
  - Observations – challenging to measure the destruction efficiency
- Constrains on elements synthesized in SNe
  - ALMA constraints isotope ratios
- SN explosion
  - Rayleigh-Taylor instabilities cause clumps