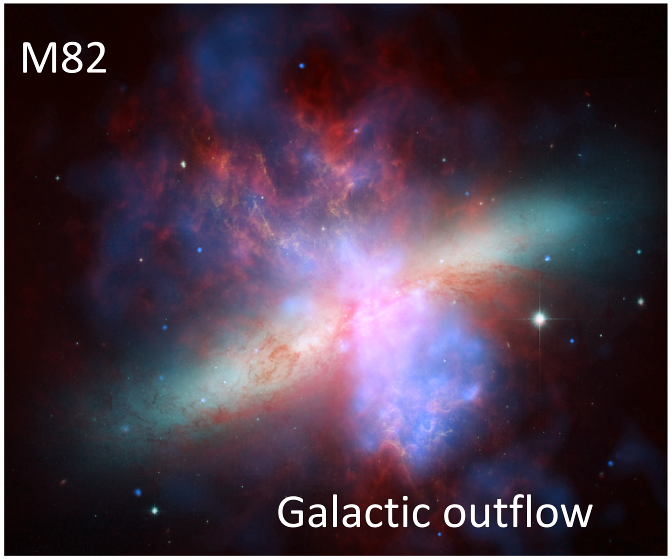
Can supernovae be important source of dust in the interstellar medium of galaxies?

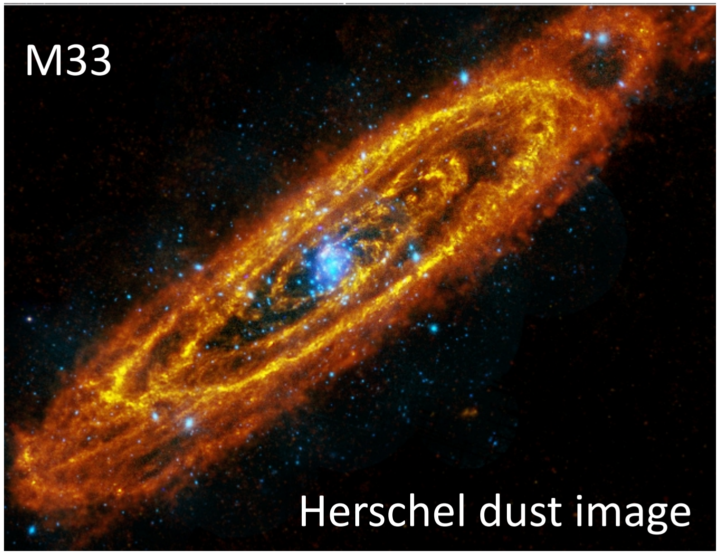
Mikako Matsuura

Cardiff University

20 February 2019

What is the role of SNe on evolution of interstellar medium of galaxies?





1. Providing kinetic energy
2. Source of elements and dust
3. Destroying existing ISM dust

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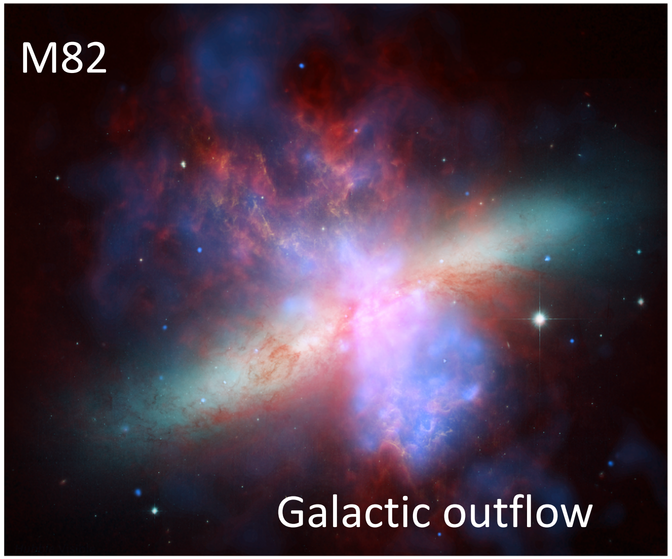
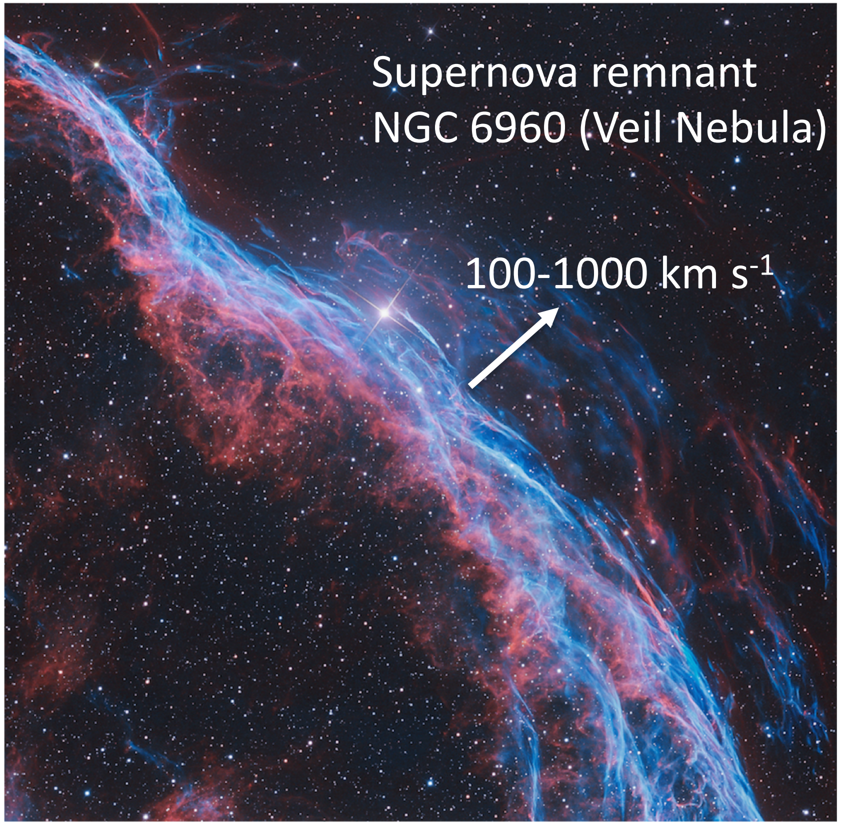
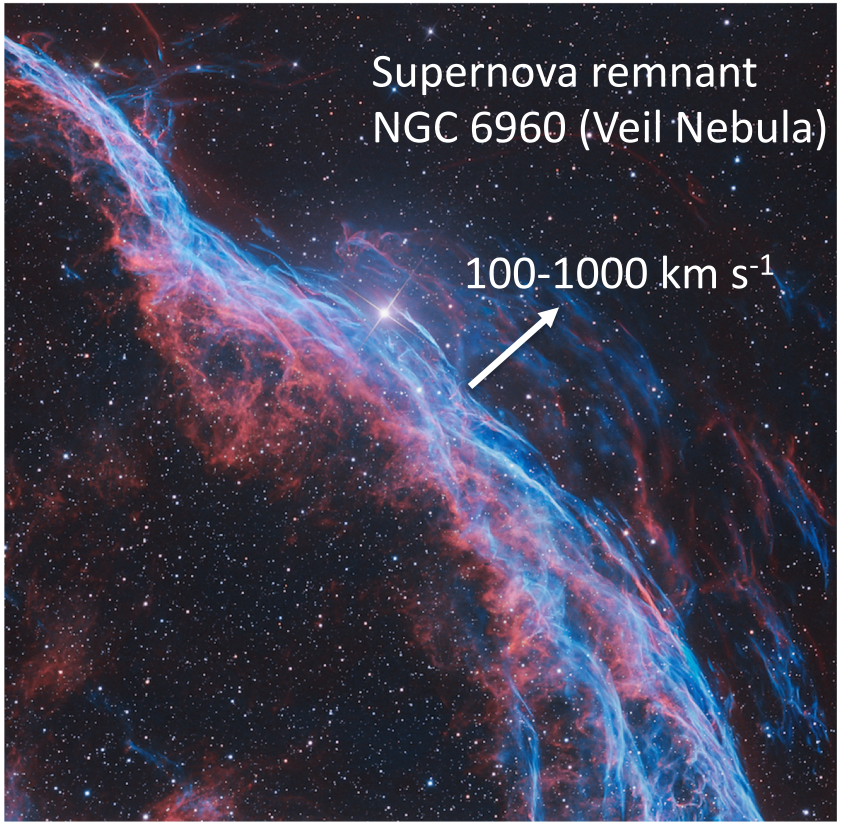


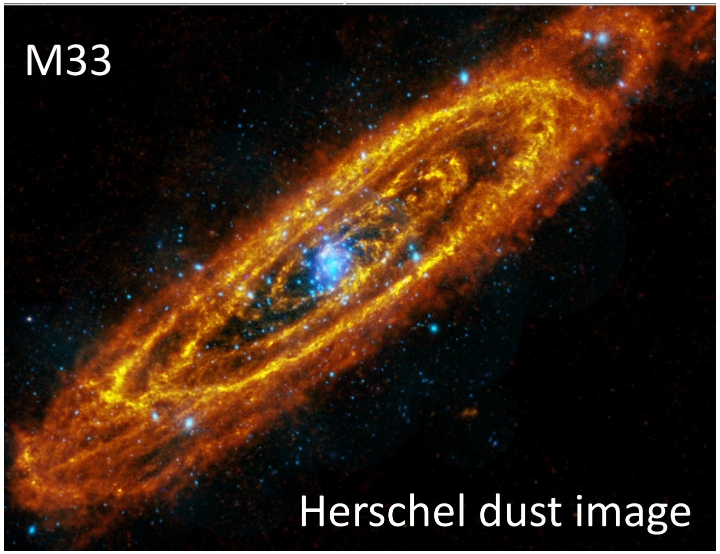


1. Providing kinetic energy

– SN explosion energy of 10^{51} ergs

What is the role of SNe on evolution of interstellar medium of galaxies?





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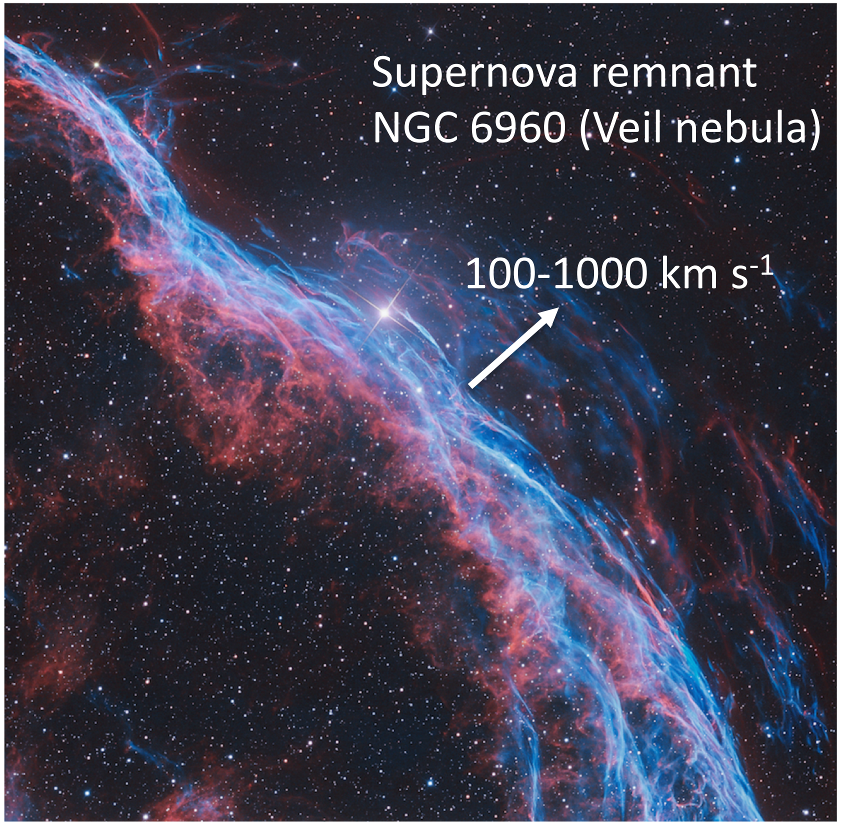
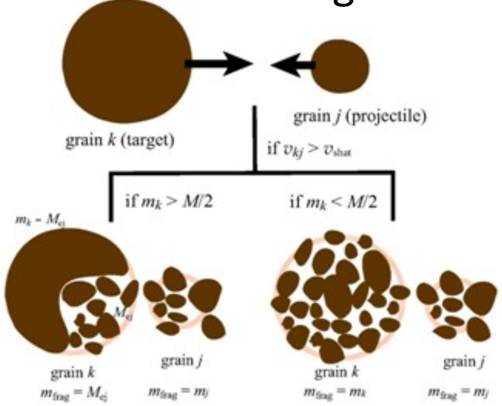


Supernova remnant
NGC 6960 (Veil nebula)

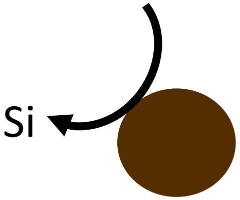
When SN shock waves meet with ISM dust -

Grain shuttering



Hirashita

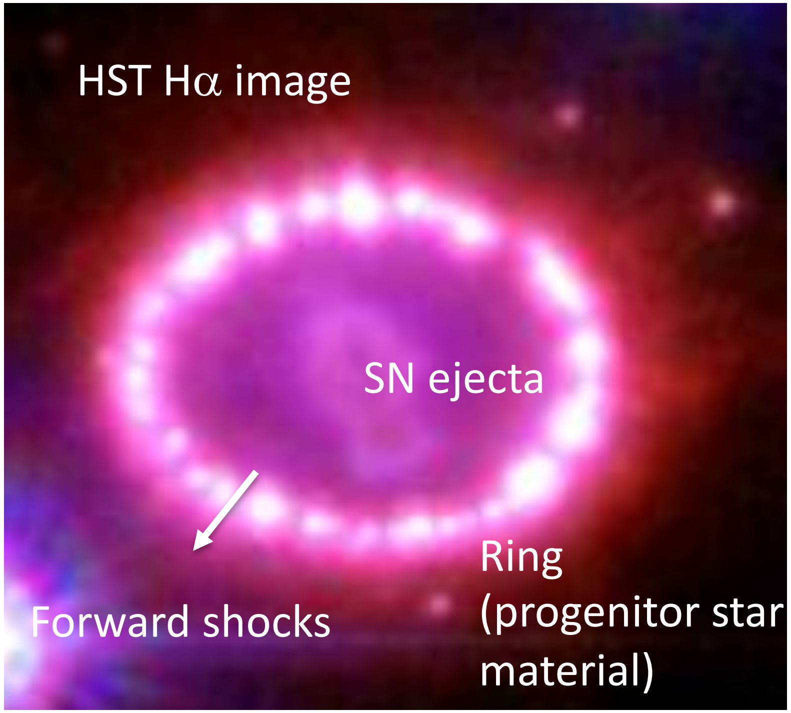
Grain spattering

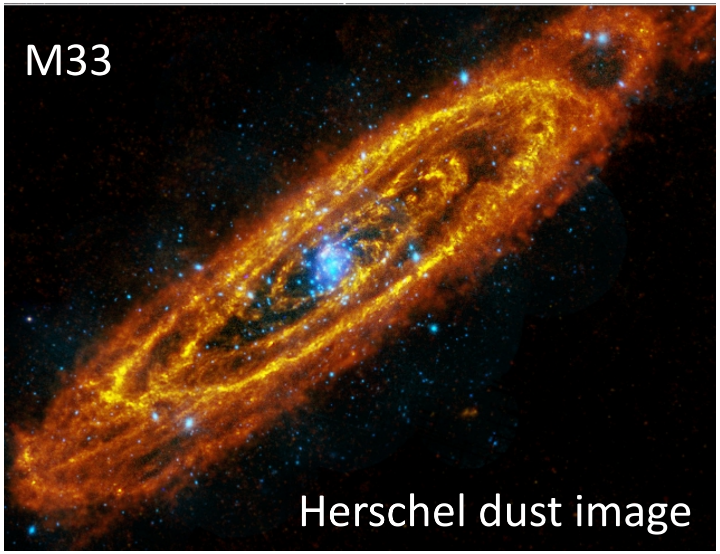


2. Source of elements and dust
3. Destroying existing ISM dust

What is the role of SNe on evolution of interstellar medium of galaxies?

Supernova 1987A





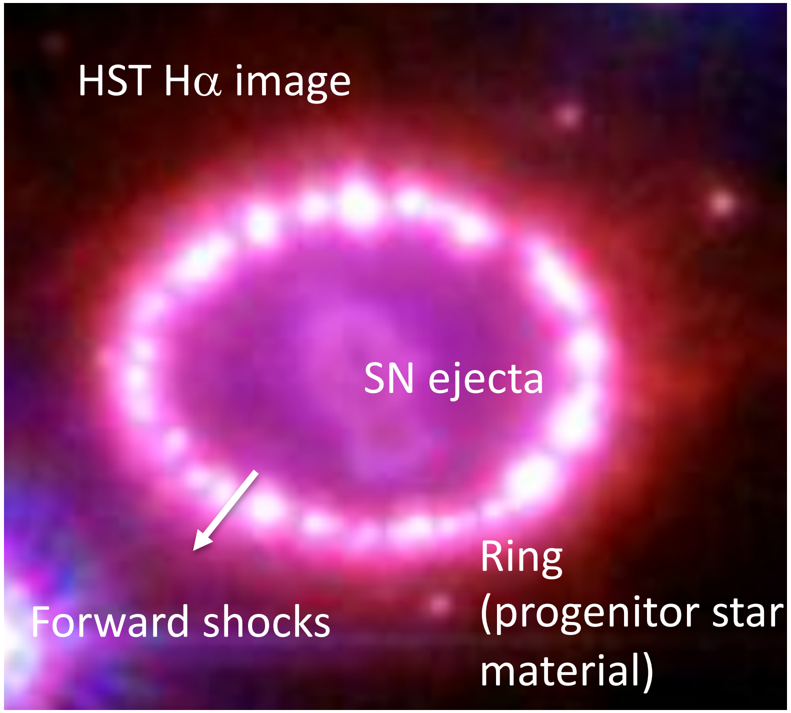
2. Source of elements and dust
3. Destroying existing ISM dust

SN ejecta – filled with heavy elements (C, Si, O, Mg, Fe)

These refractory elements eventually form dust grains

What is the role of SNe on evolution of interstellar medium of galaxies?

Supernova 1987A

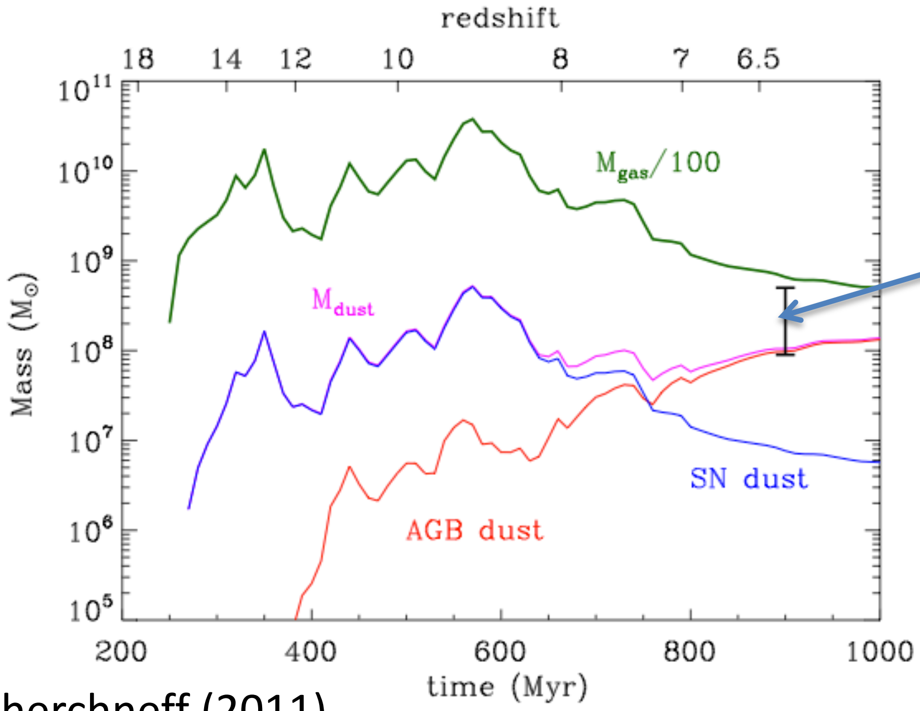


1. Providing kinetic energy
2. Source of elements and dust
3. Destroying existing ISM dust

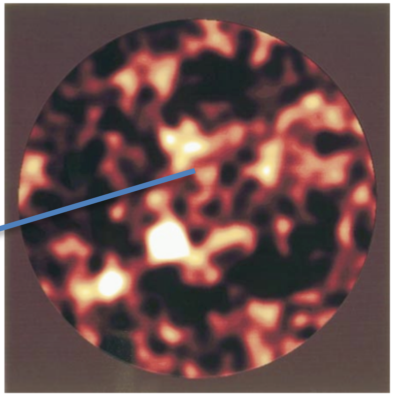
Context of my talk
Observational studies of
1. Dust formation in SNe
2. Destroying dust
3. Constrains on elements synthesized in SNe
4. SN explosion mechanism

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

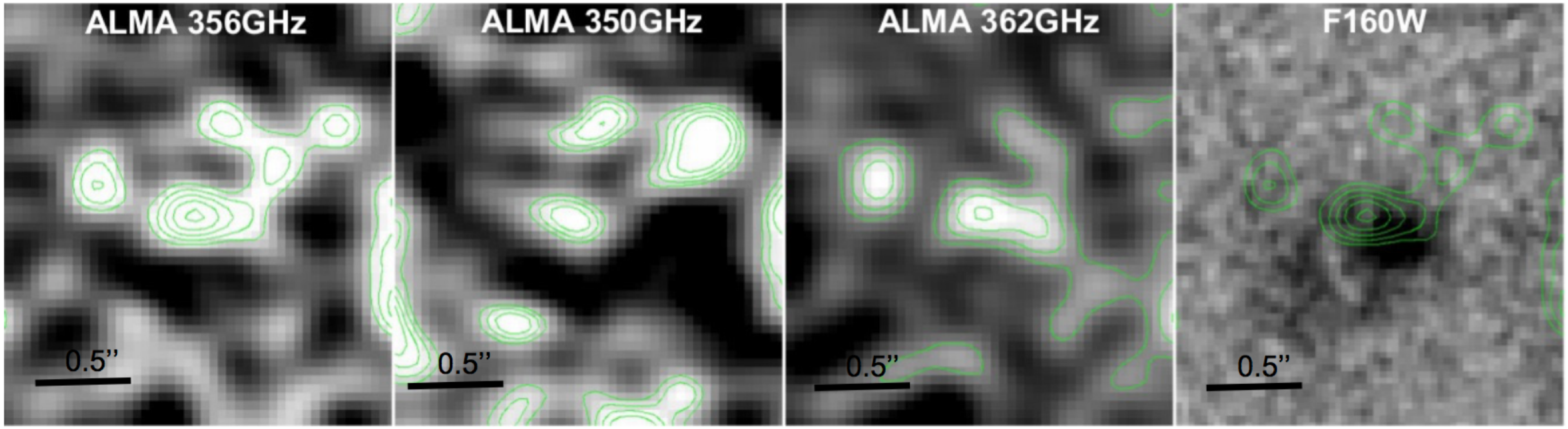


Dwek & Cherchneff (2011)



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

Dust history back to z=8.38



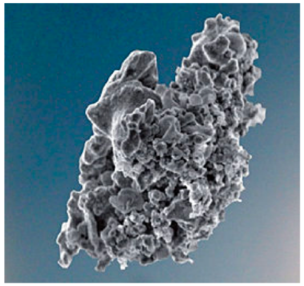
1.8-10.4x10^6 $M_\odot$ of dust

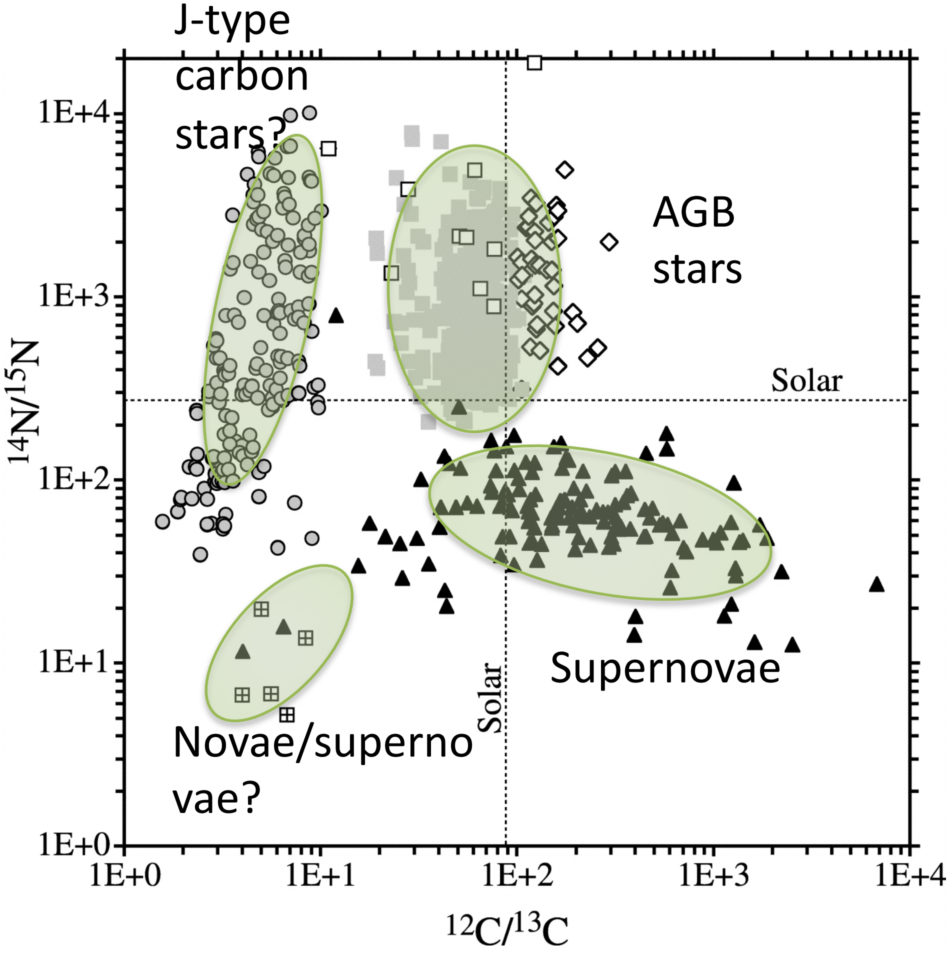
Lensed galaxy, A2744 YD4 (z=8.38)
~200 Myrs old

Laporte et al. (2017)

Evidence of dust formation in stars

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





J-type carbon stars?

AGB stars

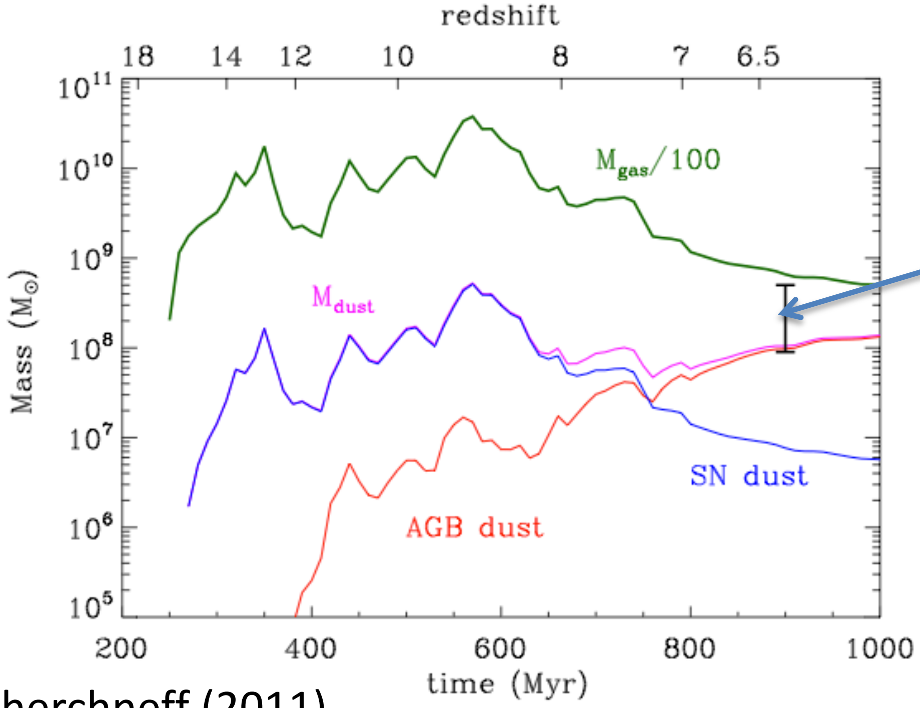
Supernovae

Novae/supernovae?

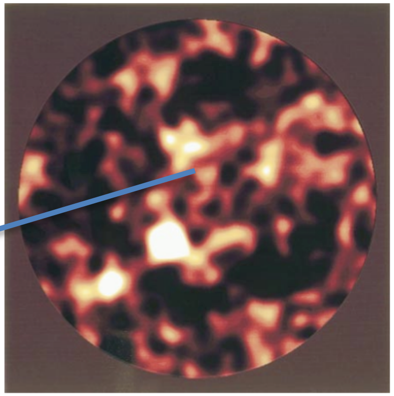
(Zinner et al. 2006)

What are the major sources of dust in galaxies?

- Stellar origin (SNe + AGB stars)
  - 0.1-1 $M_\odot$ of dust per SN needed
  - Spitzer observations: $10^{-6} – 10^{-4}$ $M_\odot$ of dust per SN
- ISM grain growth

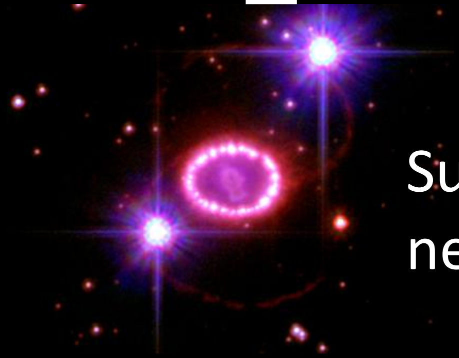


Dwek & Cherchneff (2011)



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

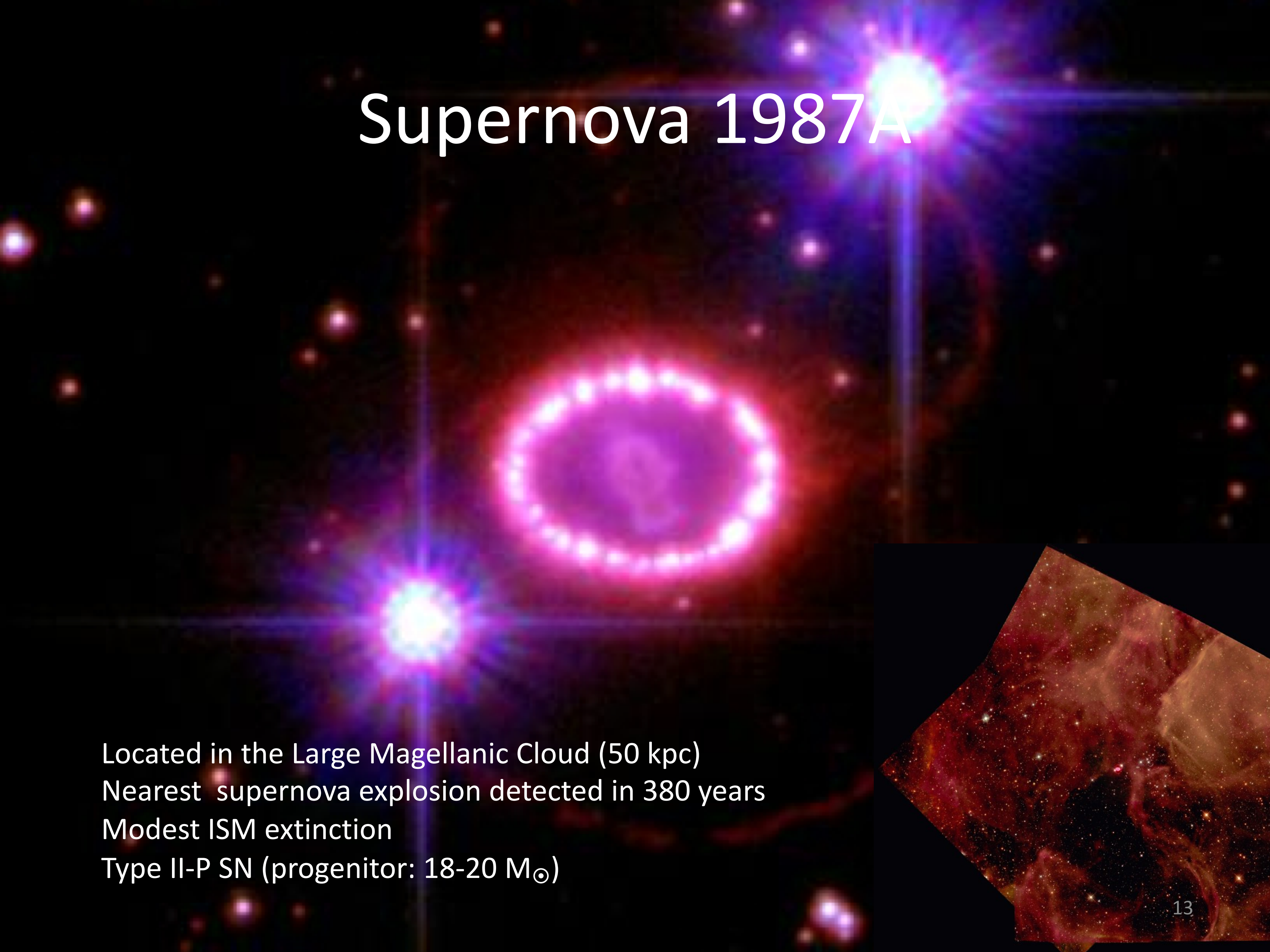
Role of SNe on galaxy evolution



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?



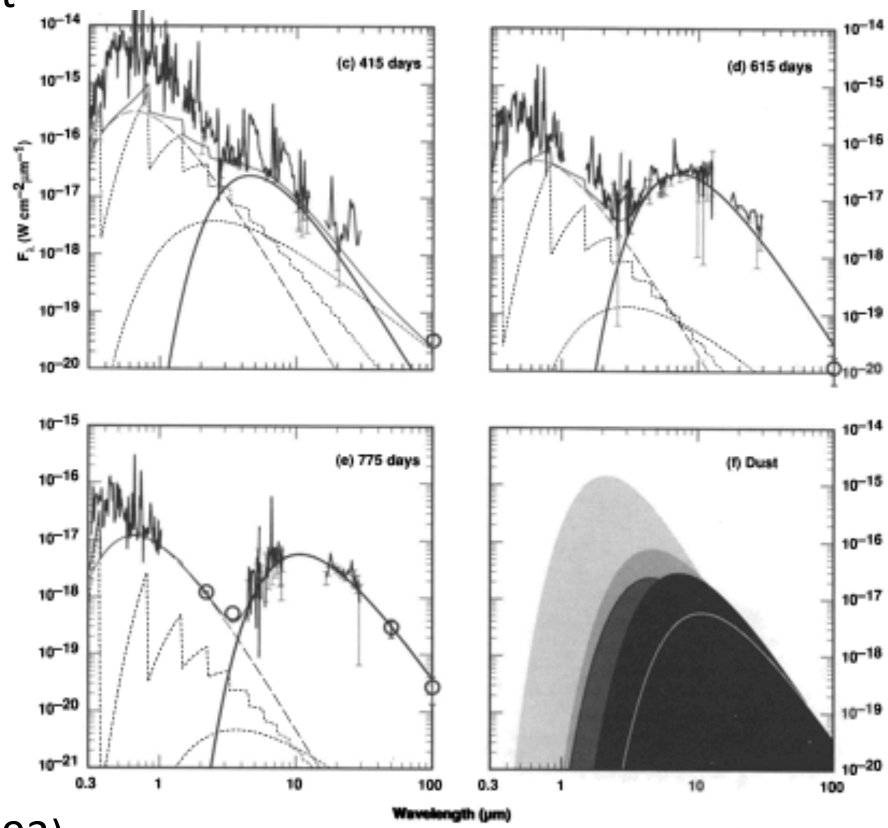
Supernova 1987A

Located in the Large Magellanic Cloud (50 kpc)
Nearest supernova explosion detected in 380 years
Modest ISM extinction
Type II-P SN (progenitor: 18-20 $M_\odot$)

Detection of dust in SN 1987A

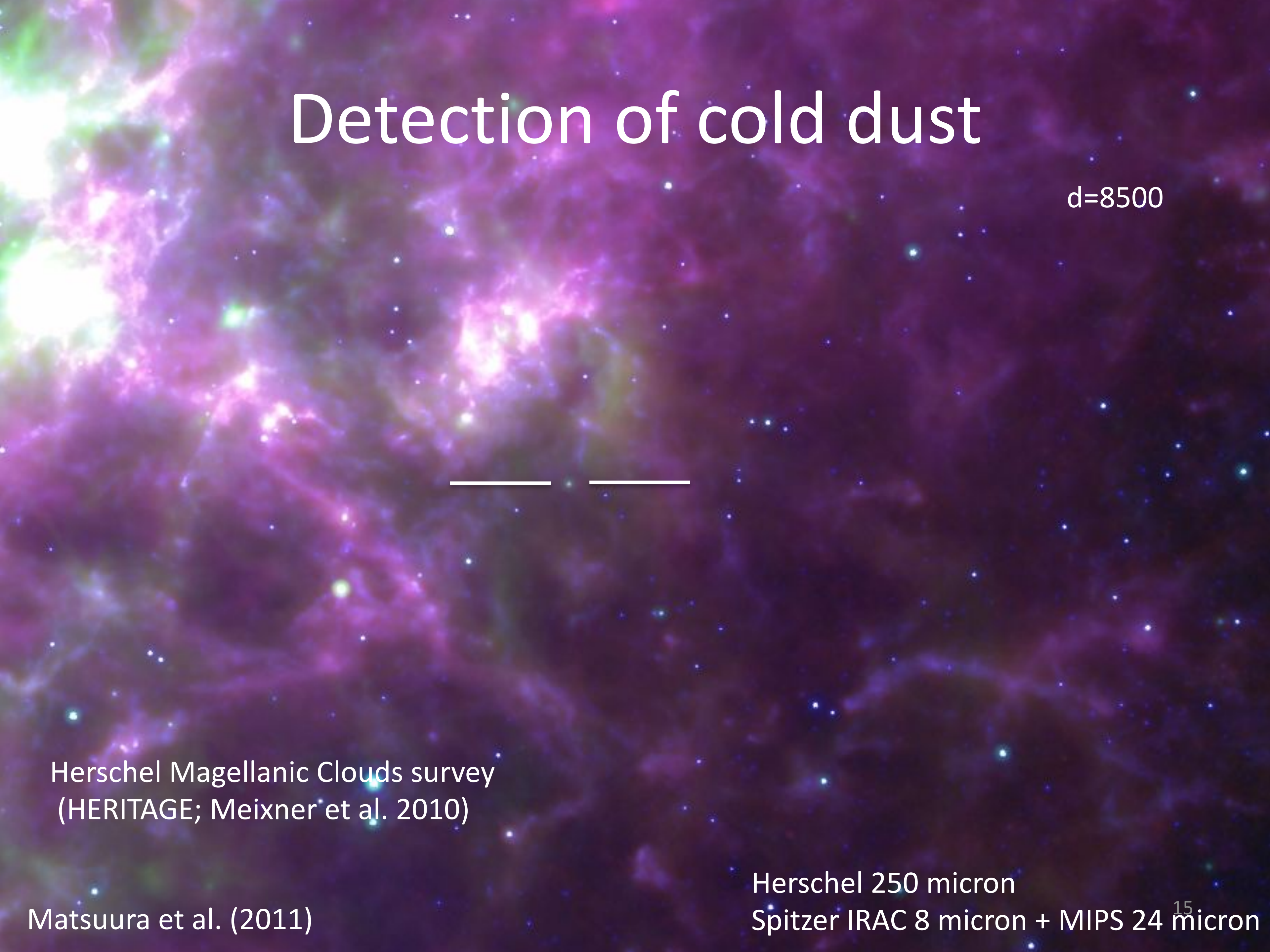
First detection of dust in SNe

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



Wooden et al. (1993)

Detection of cold dust

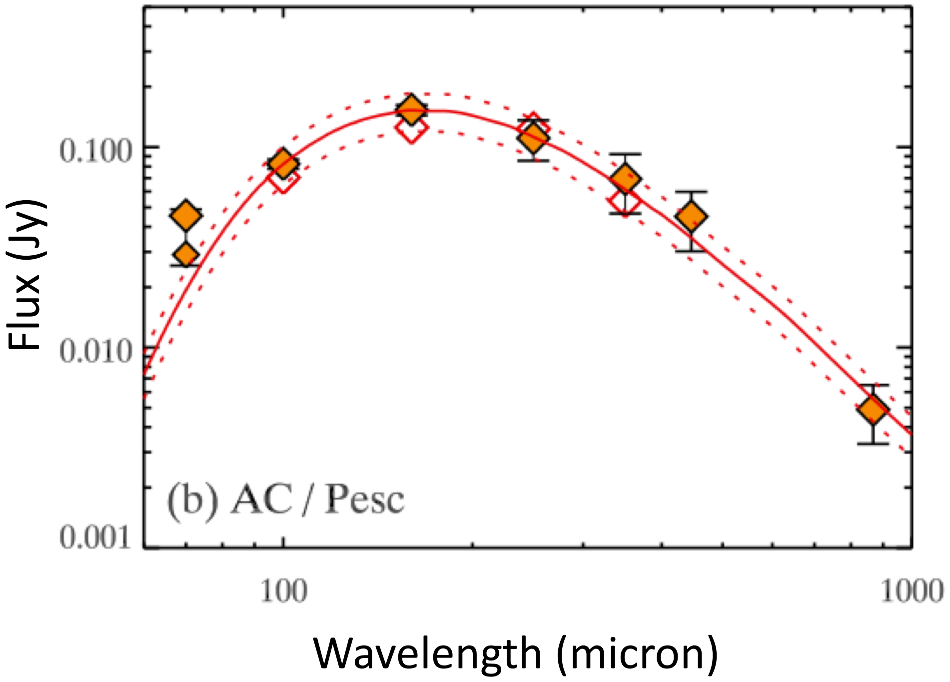


Herschel Magellanic Clouds survey
(HERITAGE; Meixner et al. 2010)

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
- C.f. previously reported mass: 10^{-6} -10^{-3} $M_\odot$

Matsuura et al. (2011;2015)

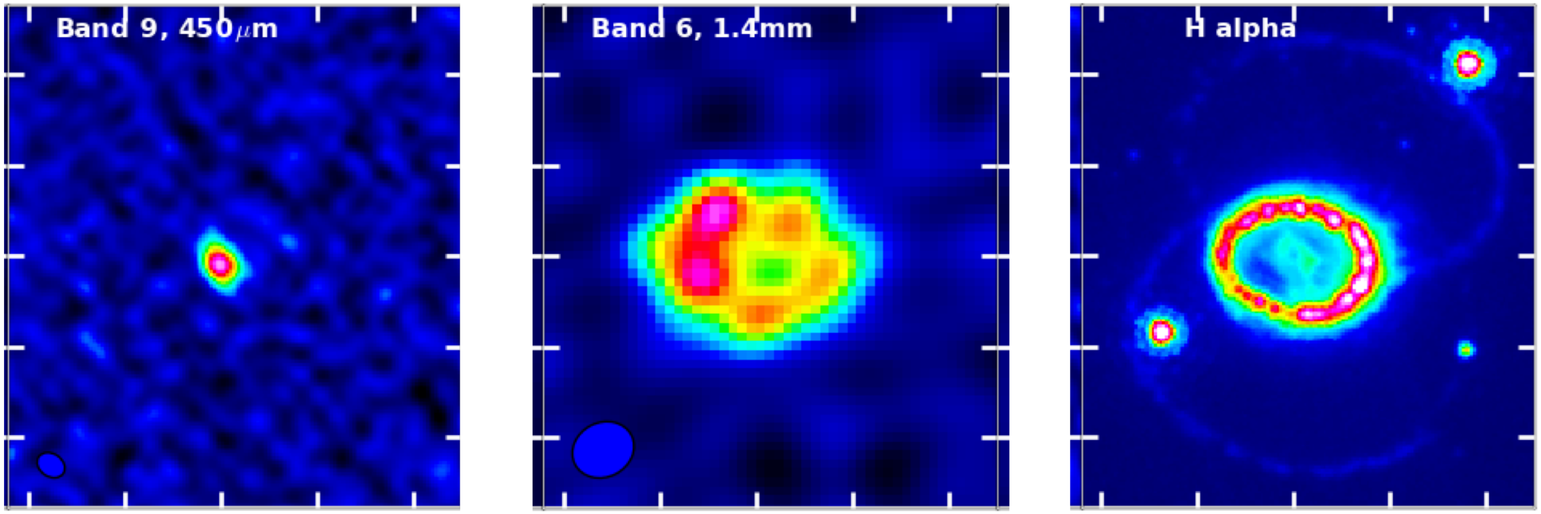
Our interpretation of large dust mass (0.4-0.7 $M_\odot$) in SN 1987A

- A large mass of dust must have formed in the SN ejecta where rich metals are available
  - 18-20 $M_\odot$ of the progenitor star
  - 2 $M_\odot$ of the metal mass

Questions raised by supernova/dust communities

- C.f. 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

ALMA confirmed dust formation in ejecta

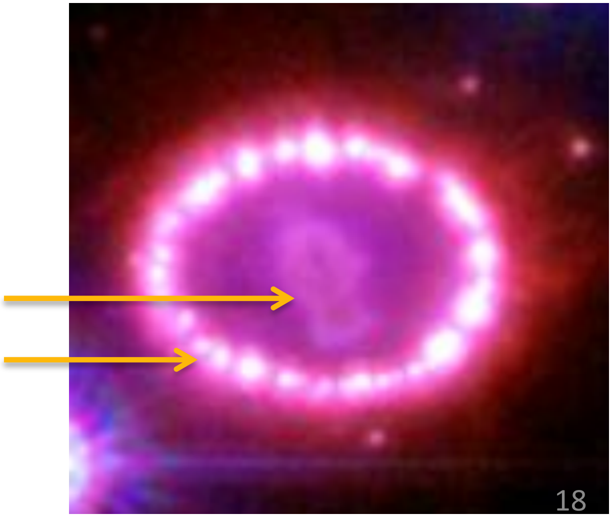


450 micron
Dust

1.4 mm
Synchrotron

H alpha

Cold dust in ejecta

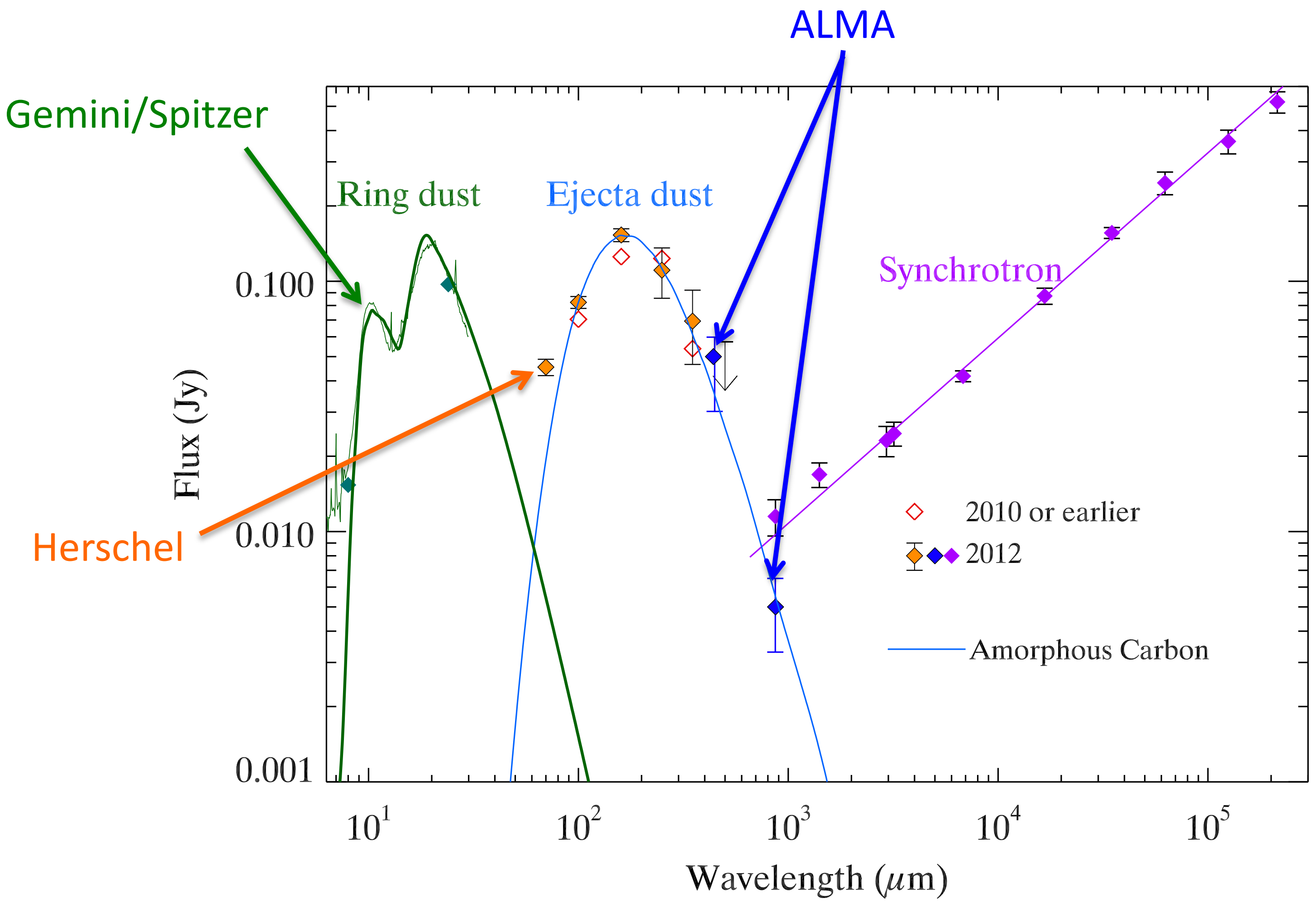


SN ejecta

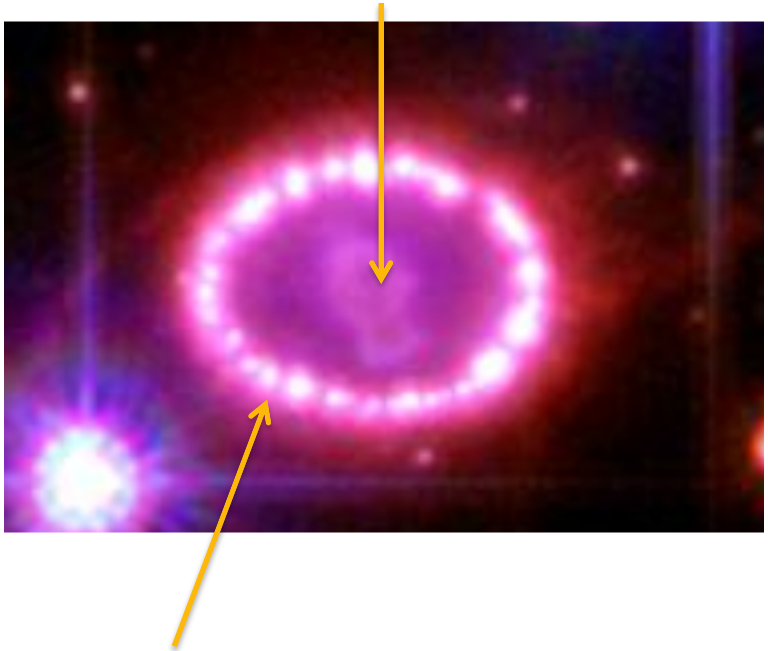
Ring: progenitor

Indebetouw et al. (2014)

ALMA photometric points trace cold dust



The ejecta of SN 1987A



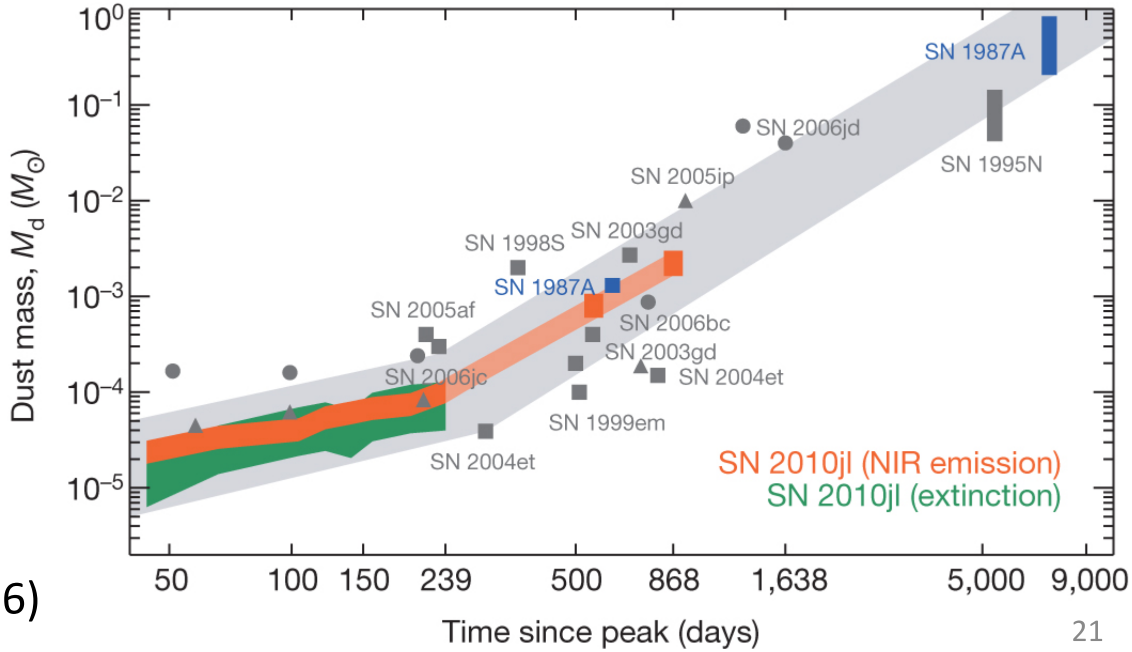
Supernova ejecta

Ring: progenitor star

- < 25 years after the explosion
- Cold and dense gas in the ejecta
  - ~20 K of dust
- Rich with dust and molecules
- Efficient cooling with adiabatic, lines and dust radiations

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

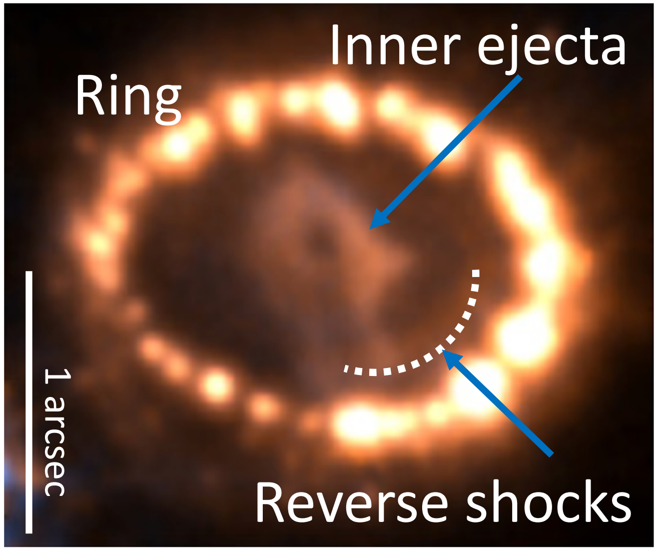
- Dust mass evolution vs optically thick
  - Dust mass starts with small number and increases in time
  - A large dust mass is present from early days, but hidden by optically thick dust clouds
- SPICA/Origin?



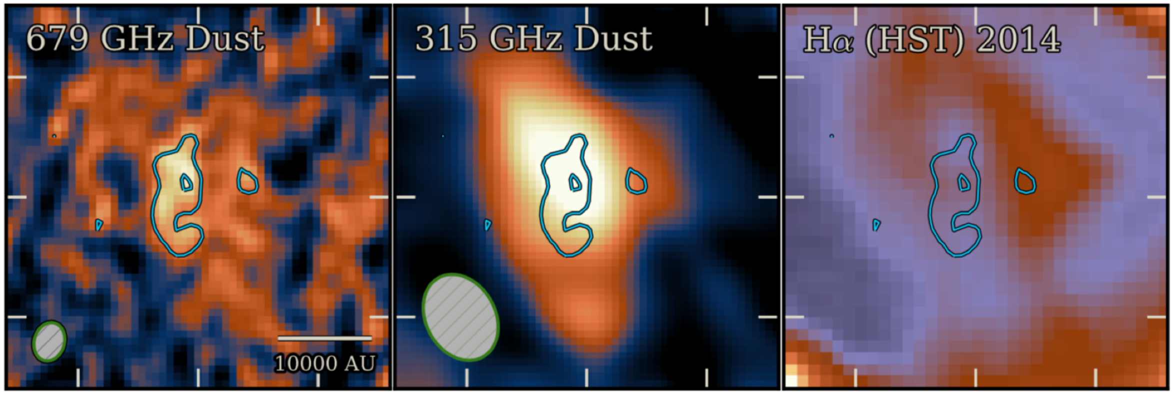
Gall et al. (2014, Nature 511, 326)

Dust chemistry

Hα



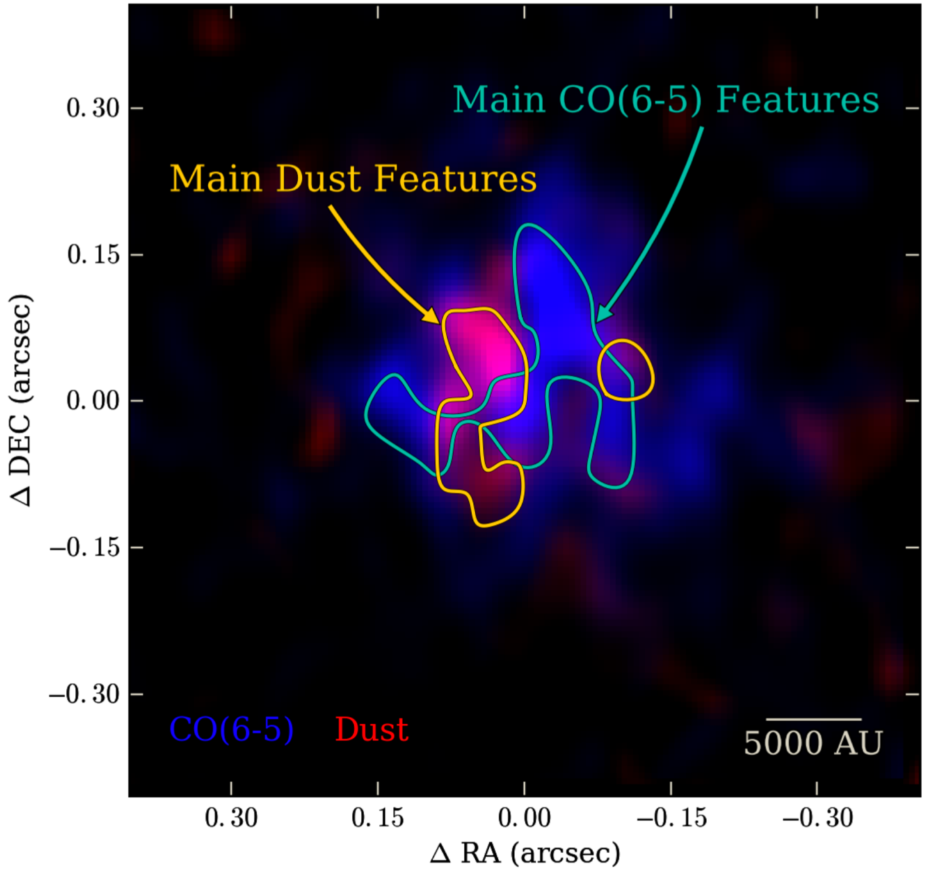
Higher angular ALMA resolution images



Cigan et al. (in preparation)

Dust chemistry

Higher angular ALMA resolution images



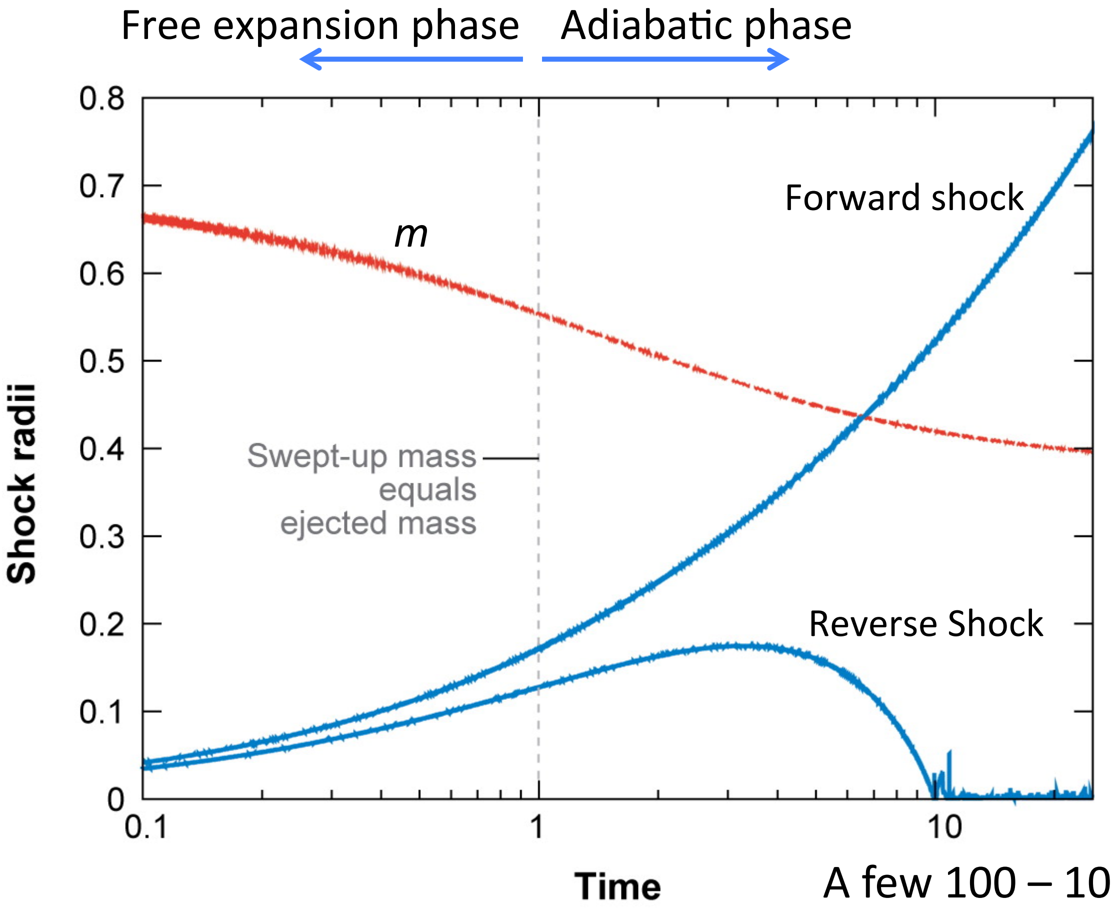
CO and dust emission are spatially anti-correlating
CO dissociation resulted in forming amorphous carbon dust from free C?

Cigan et al. (in preparation)

Context

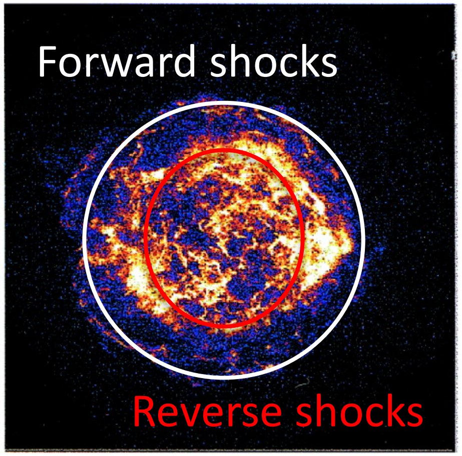
1. Dust formation in SNe
2. Destroying dust
3. Constrains on elements synthesized in SNe
4. SN explosion mechanism

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

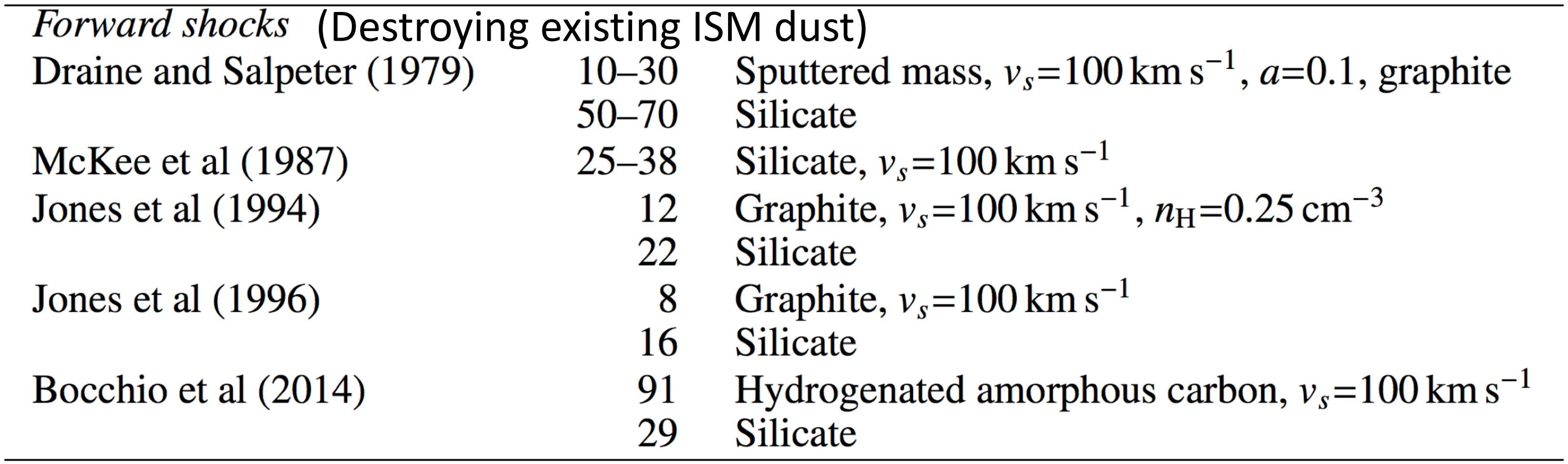
- Theory predicts

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

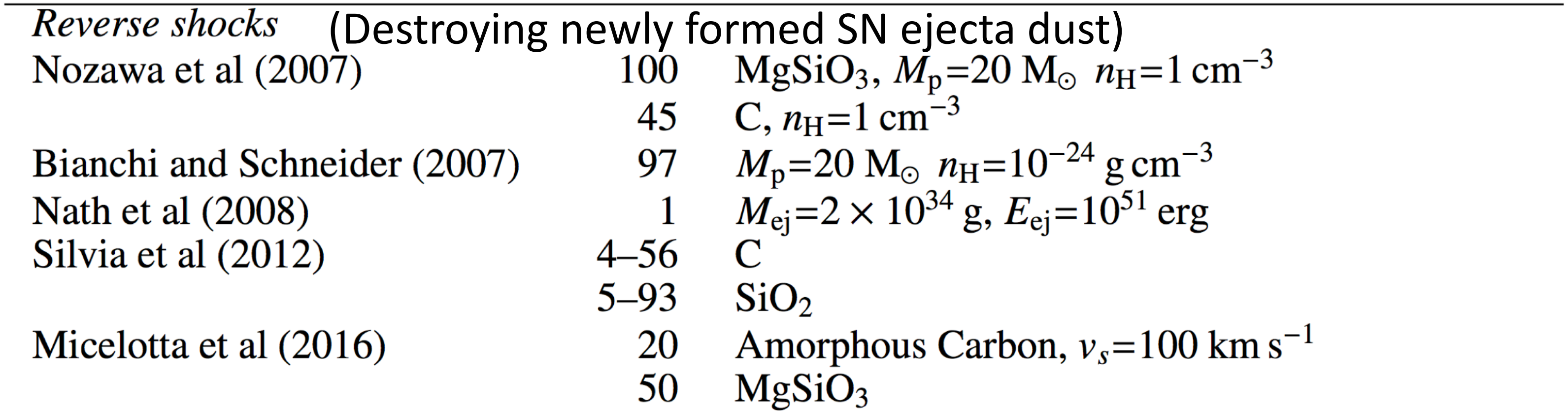
C.f. ISM grain growth

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

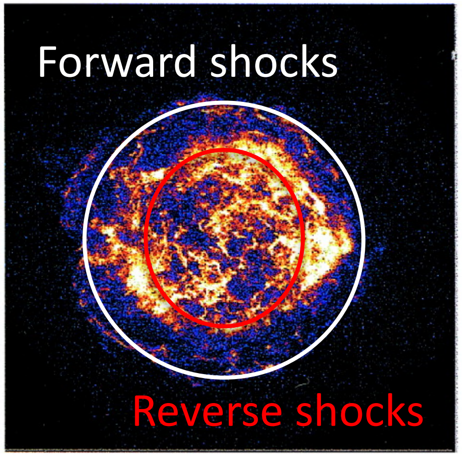


Reverse shocks (Destroying newly formed SN ejecta dust)		
Nozawa et al (2007)	100	$MgSiO_3$, M_{p}=20 M$_\odot$ n_{H}=1 cm^{-3}
	45	C, n_{H}=1 cm^{-3}
Bianchi and Schneider (2007)	97	M_{p}=20 M$_\odot$ n_{H}=10^{-24} g cm^{-3}
Nath et al (2008)	1	M_{ej}=2 × 10^{34} g, E_{ej}=10^{51} erg
Silvia et al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

Shock destructions in future?

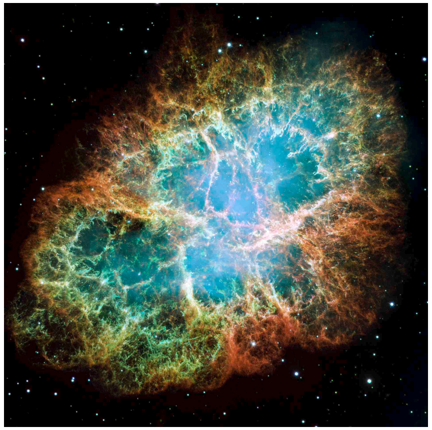
- Shocks: largely depending on the geometry of circumstellar matter and the presence of ambient ISM gas

Cassiopeia A (AD 1681?)



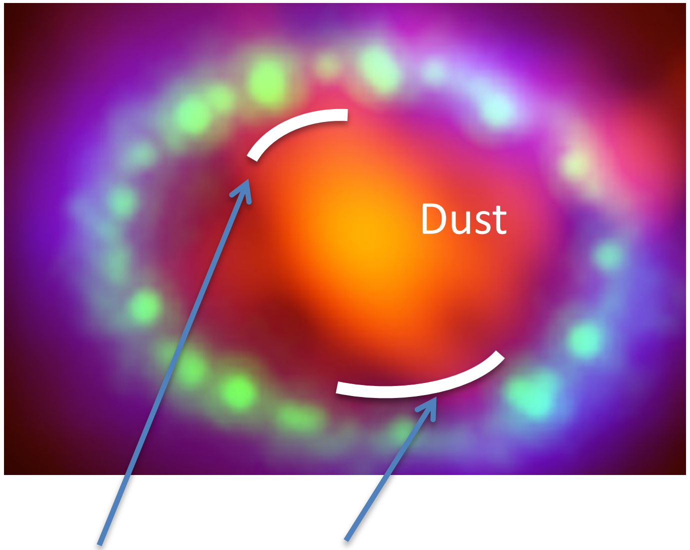
Gotthelf et al. (2001)

Crab Nebula (AD 1054)



No shock detected

Supernova 1987A



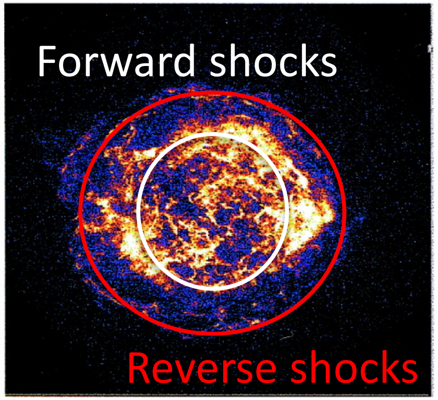
Reverse shocks in 2011

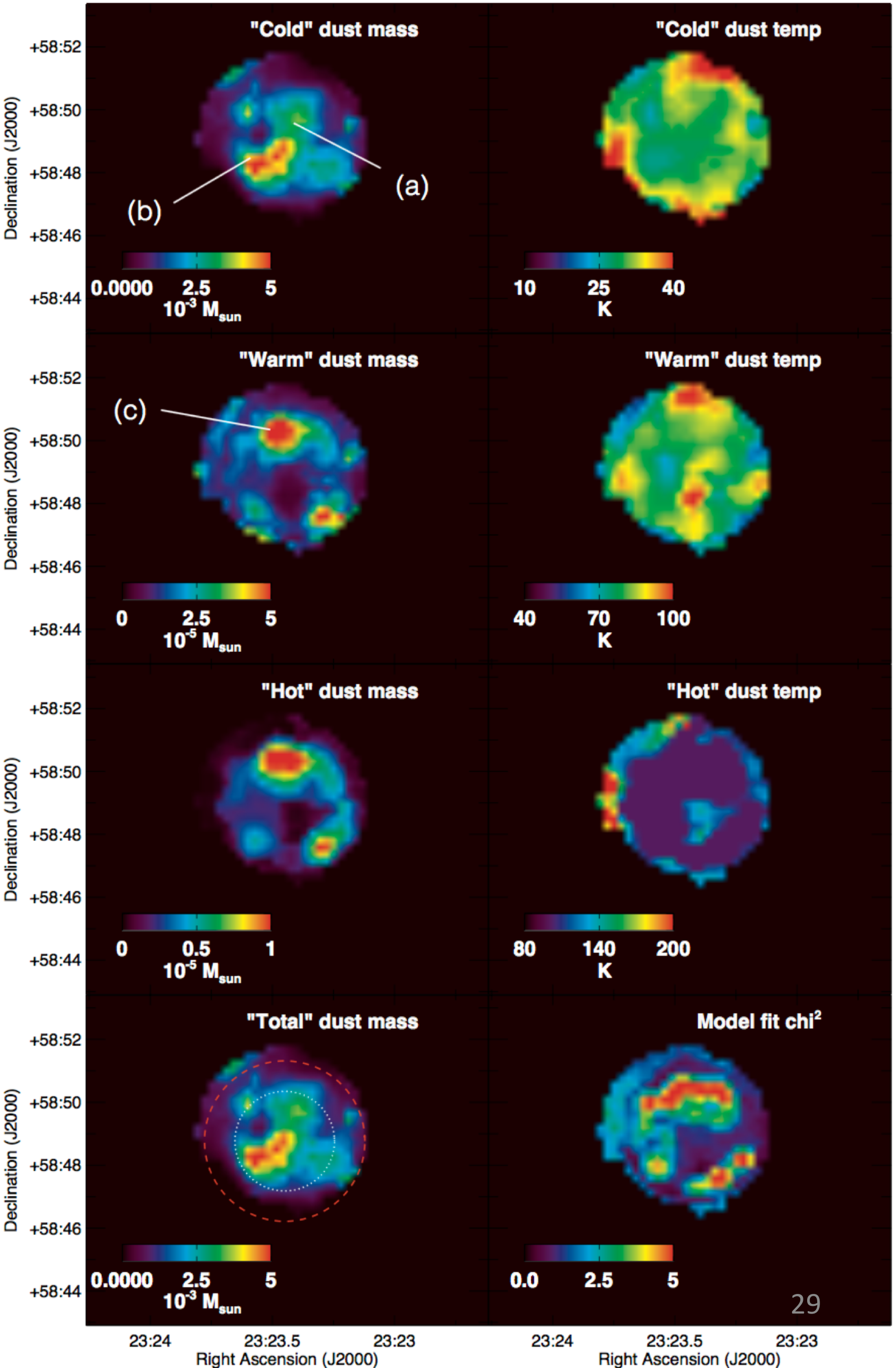
Cassiopeia A
(AD 1681?)

Warm dust: 0.7 $M_{\odot}$
Cold dust: 0.4 $M_{\odot}$
(composition dependent)

Reverse shock destruction rate: ~70%

De Looze et al. (2017)

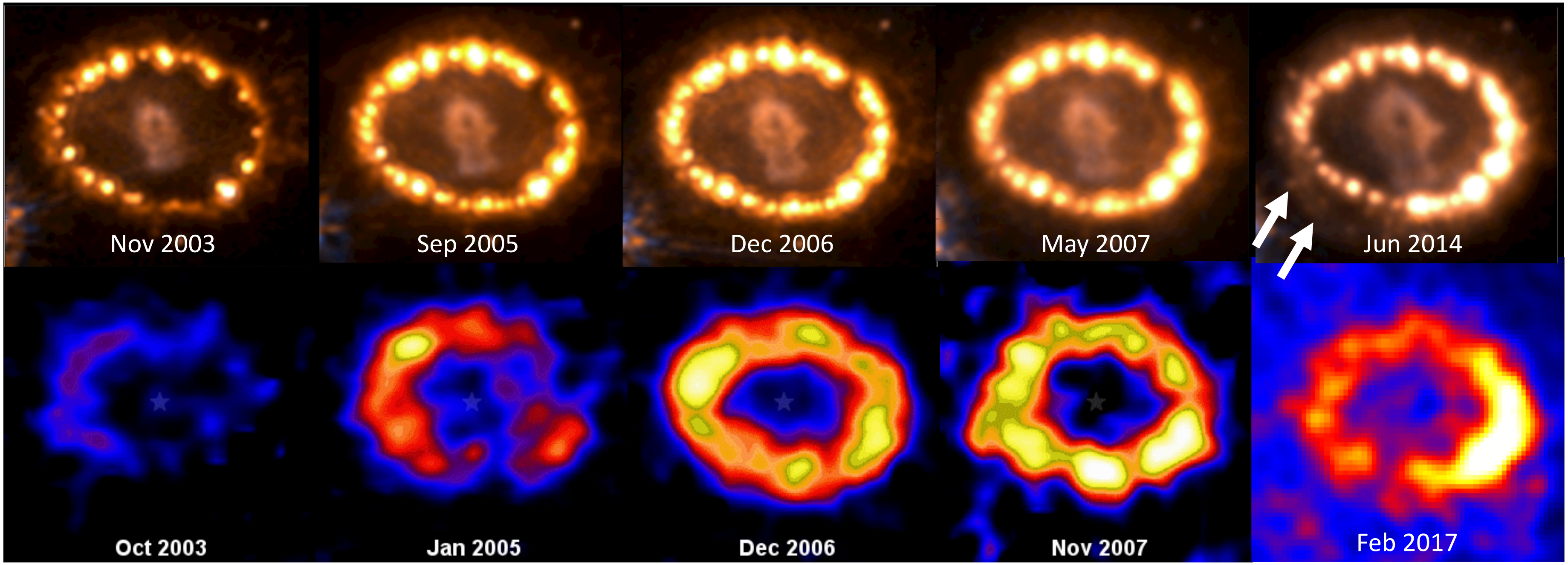




Time evolution of SN 1987A

HST Hα

Forward shocks exited the ring on the East side

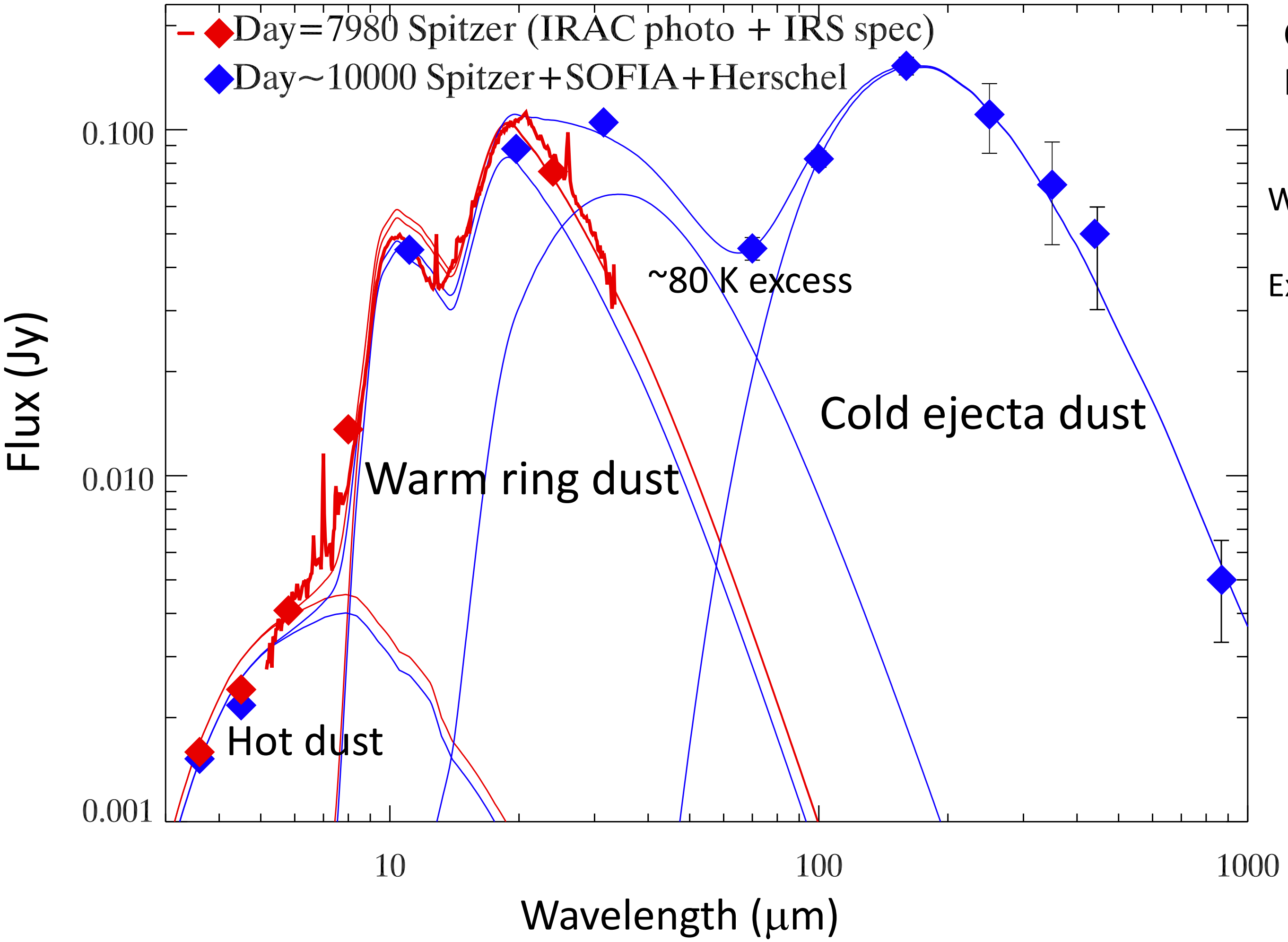


Mid infrared (dust)

Matsuura et al. (in preparation)

Spectral energy distribution

Detection of excess at 31 micron



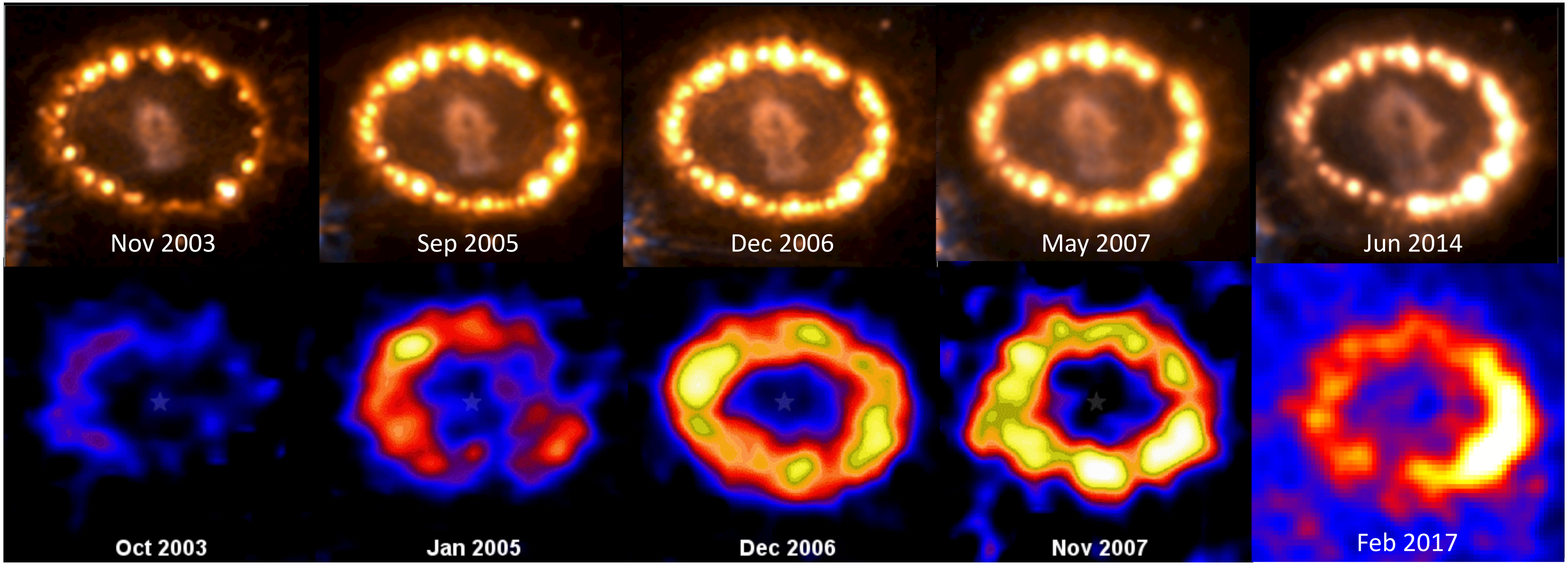
Continuing to
Herschel 70 micron

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

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

Matsuura et al. (2019)

Interpretation



Dust reformation in the post shocked region?

Timing – forward shocks are about to pass the ring in the east

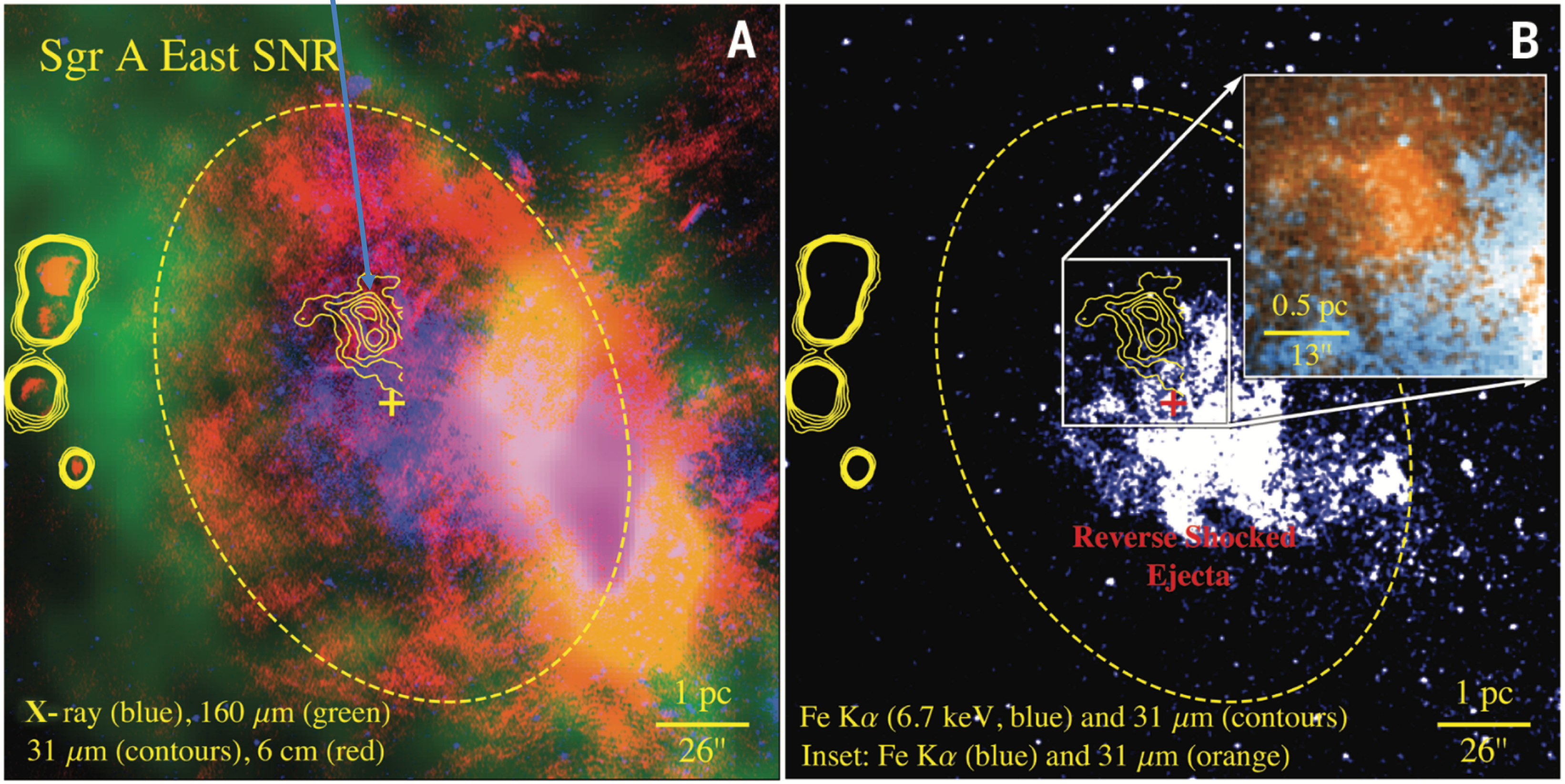
Problem: how to overcome available mass of refractory elements, if dust condensation rate was already 100 % at red supergiant phase?

Test the hypothesis with JWST MIRI observations

Reverse shocks: Srg A East

10^4 years old SNR

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



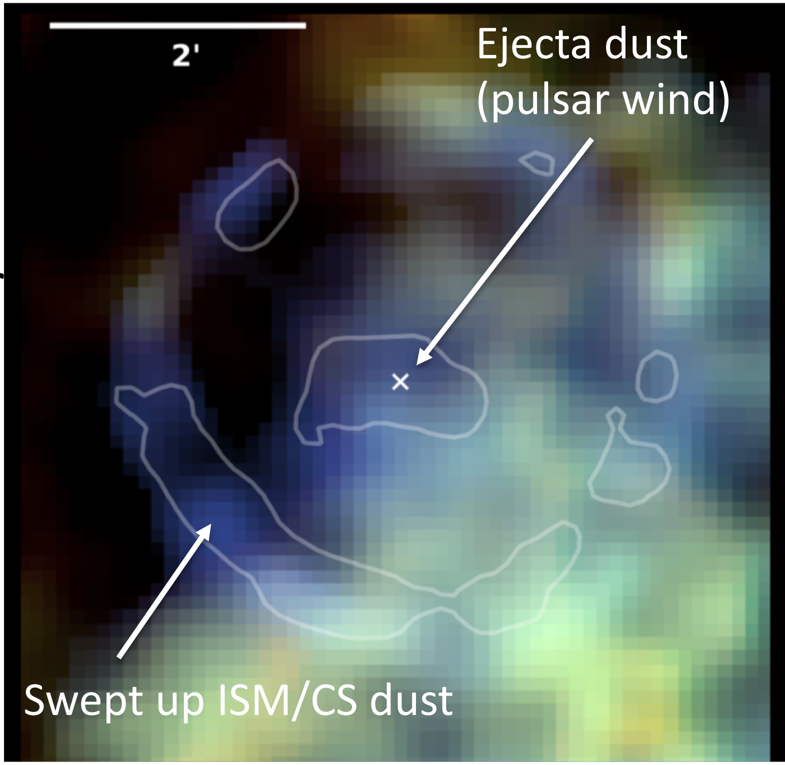
Not so efficient dust destruction?

Lau et al. (2015)

What will happen to dust in SNRs in long term?

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

Majority of SNRs: swept up interstellar or circumstellar dust
5 SNRs: ejecta dust in pulsar wind nebula



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

Contour: radio (synchrotron)
Color: Herschel dust

Chawner et al (2019)

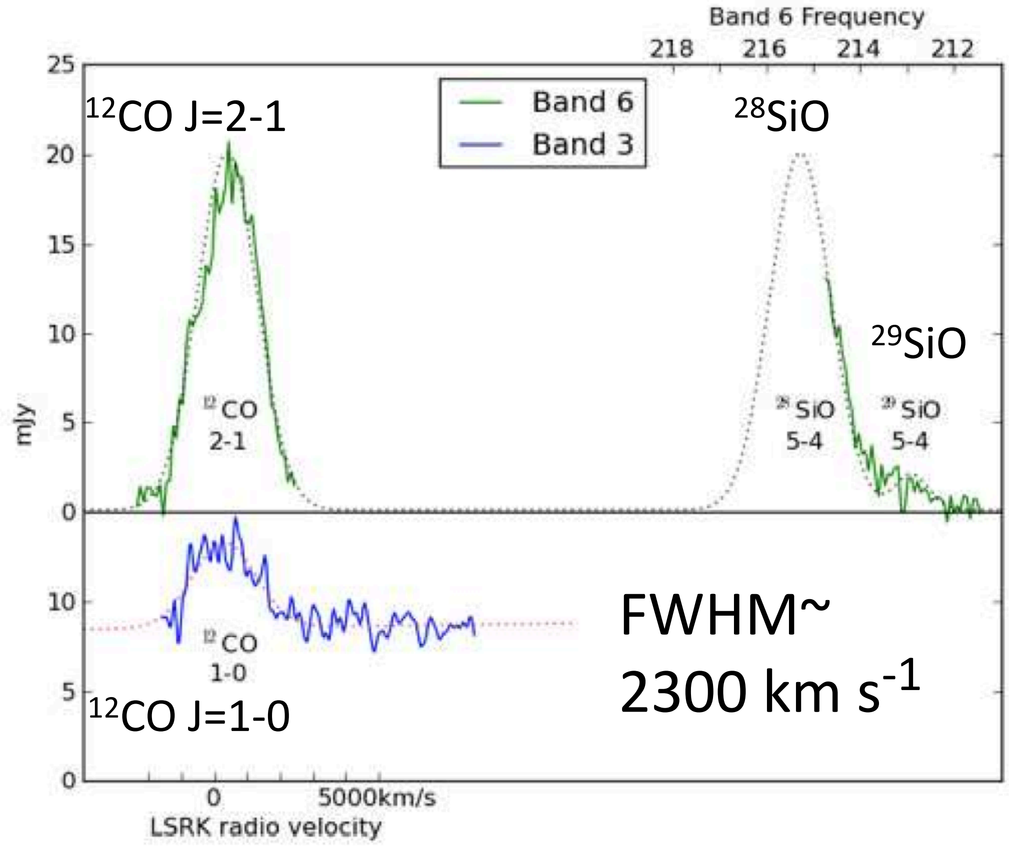
Context

1. Dust formation in SNe
2. Destroying dust?
3. Constrains on elements synthesized in SNe
4. SN explosion mechanism

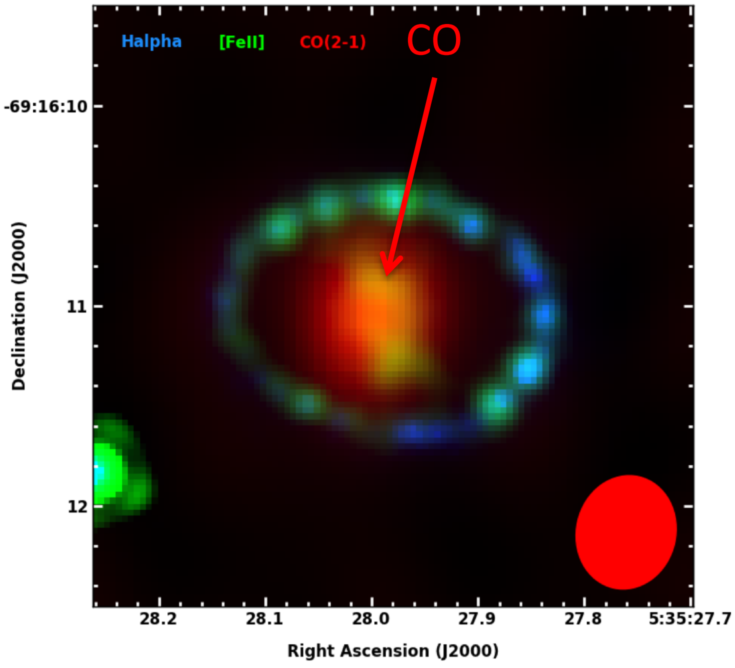
ALMA cycle-0 program

In 2012
(Day=9173-9300)

ALMA detection of molecules



FWHM~
2300 km s^{-1}



(Kamenetzky et al. 2013)

Cold (20-200 K) 'molecular gas' in the ejecta after 25 years

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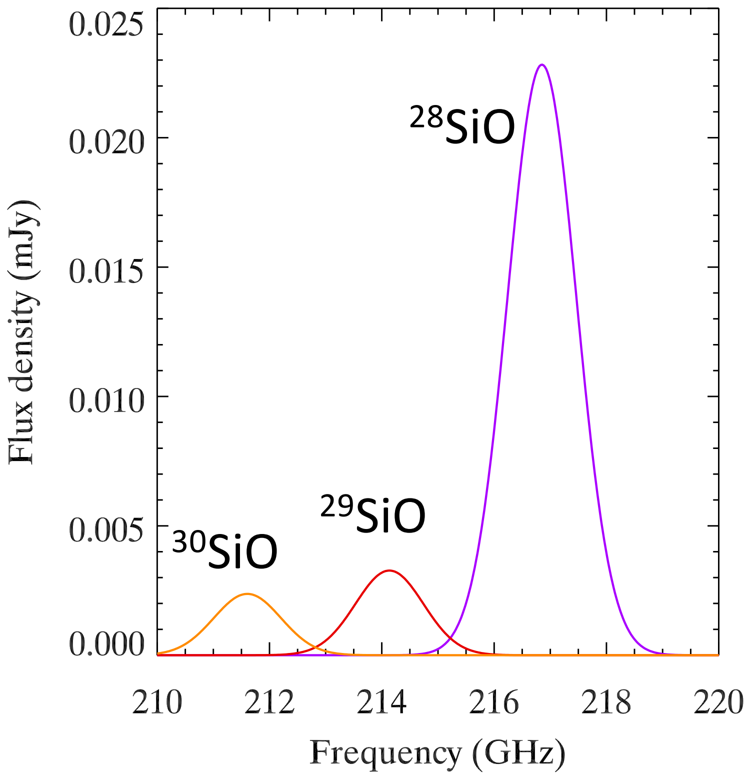
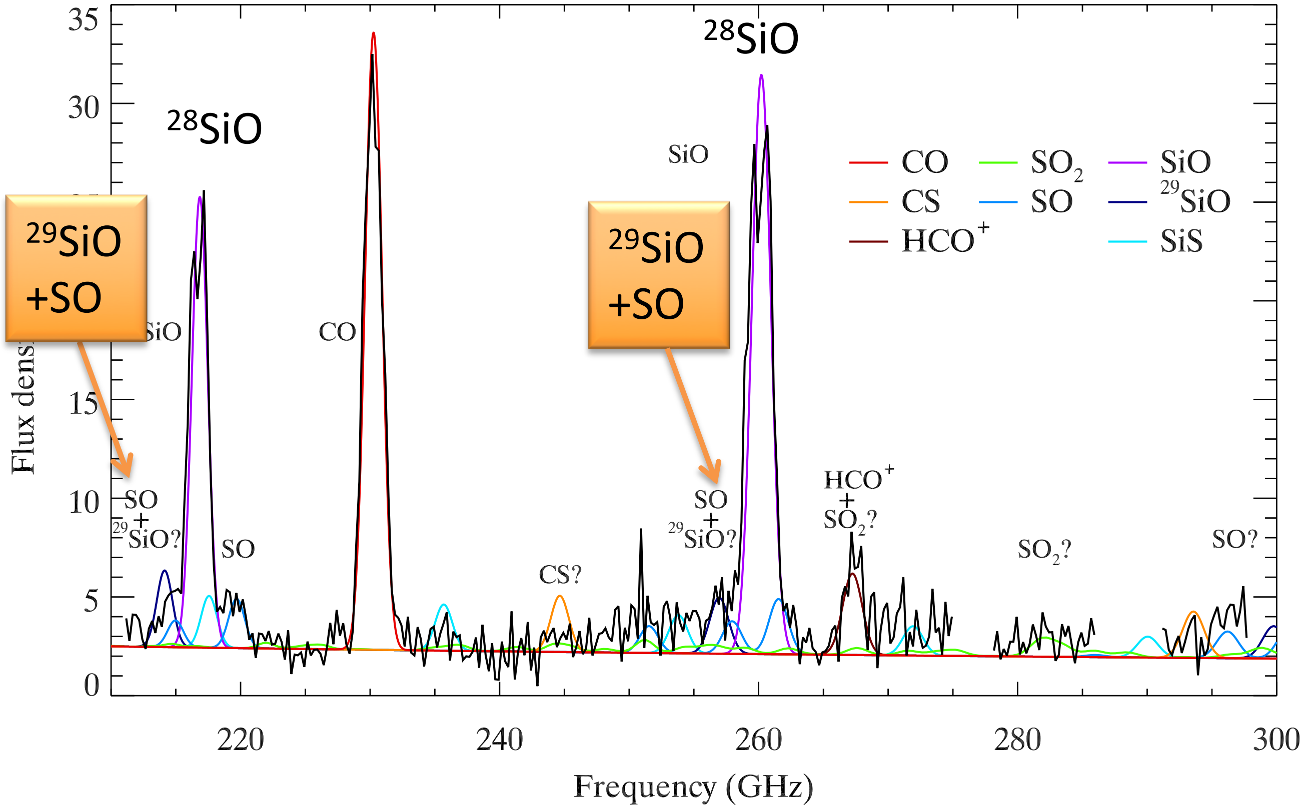
4. SN explosion mechanism

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

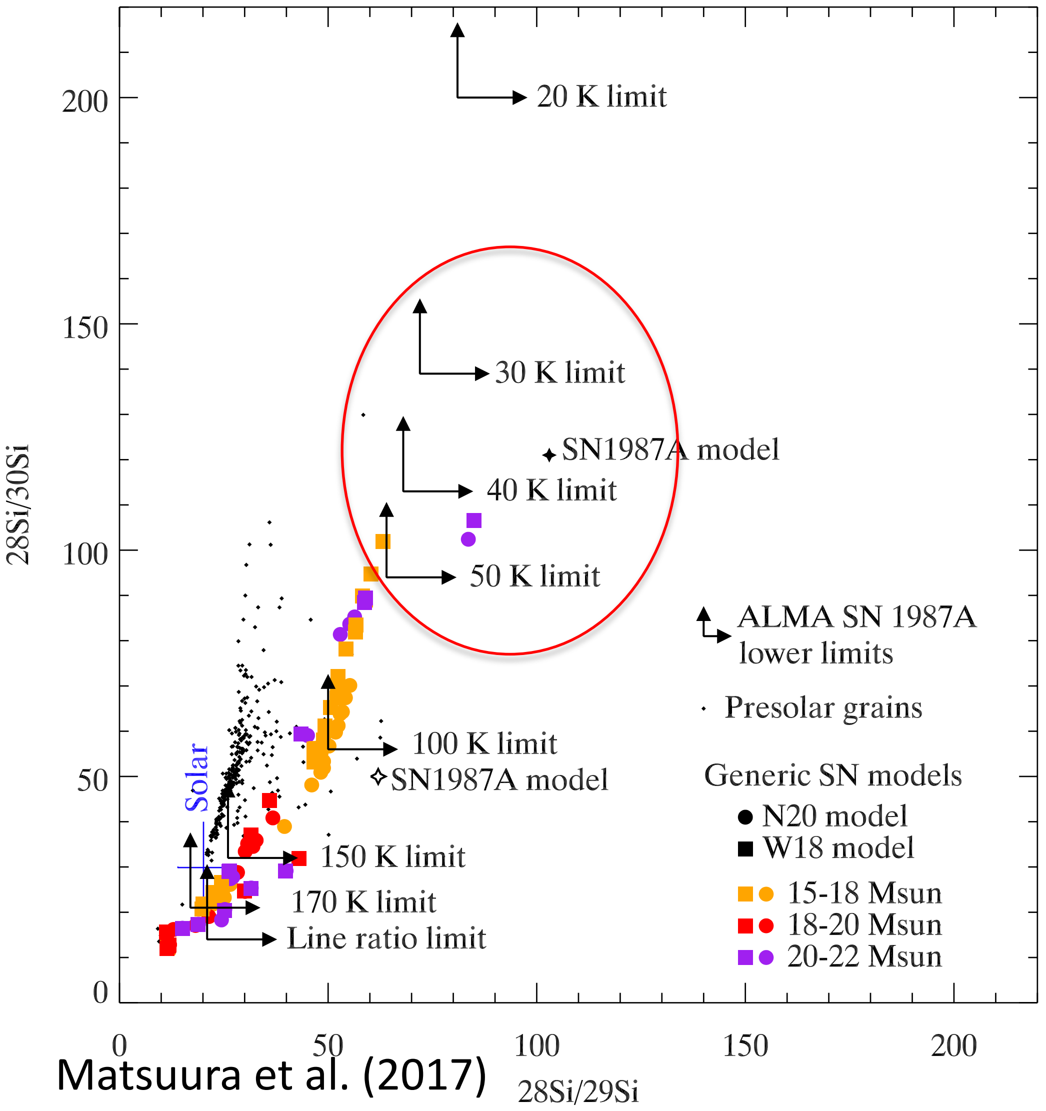


ALMA

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

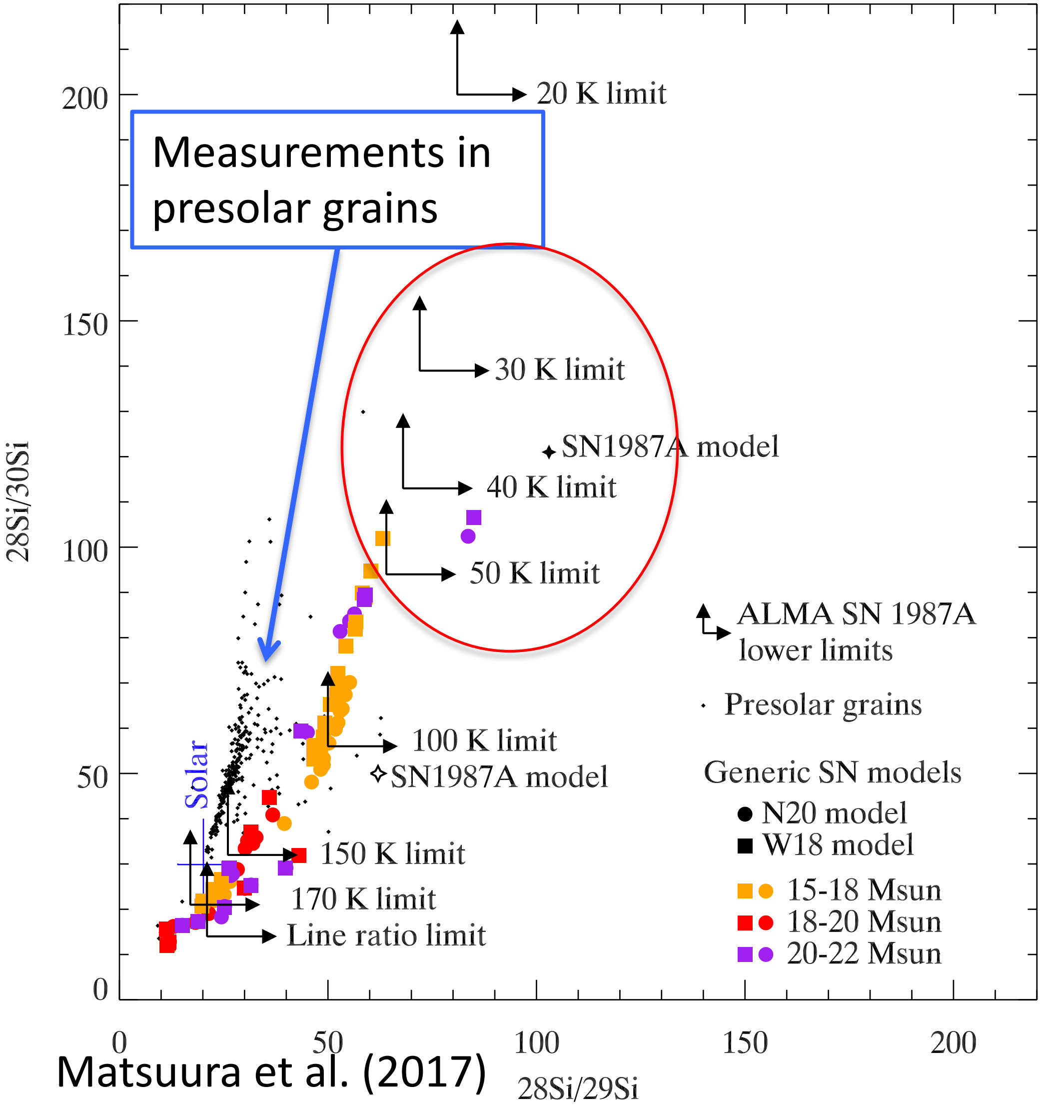
Matsuura et al. (2017)

SiO isotopologue ratios



Matsuura et al. (2017)

SiO isotopologue ratios

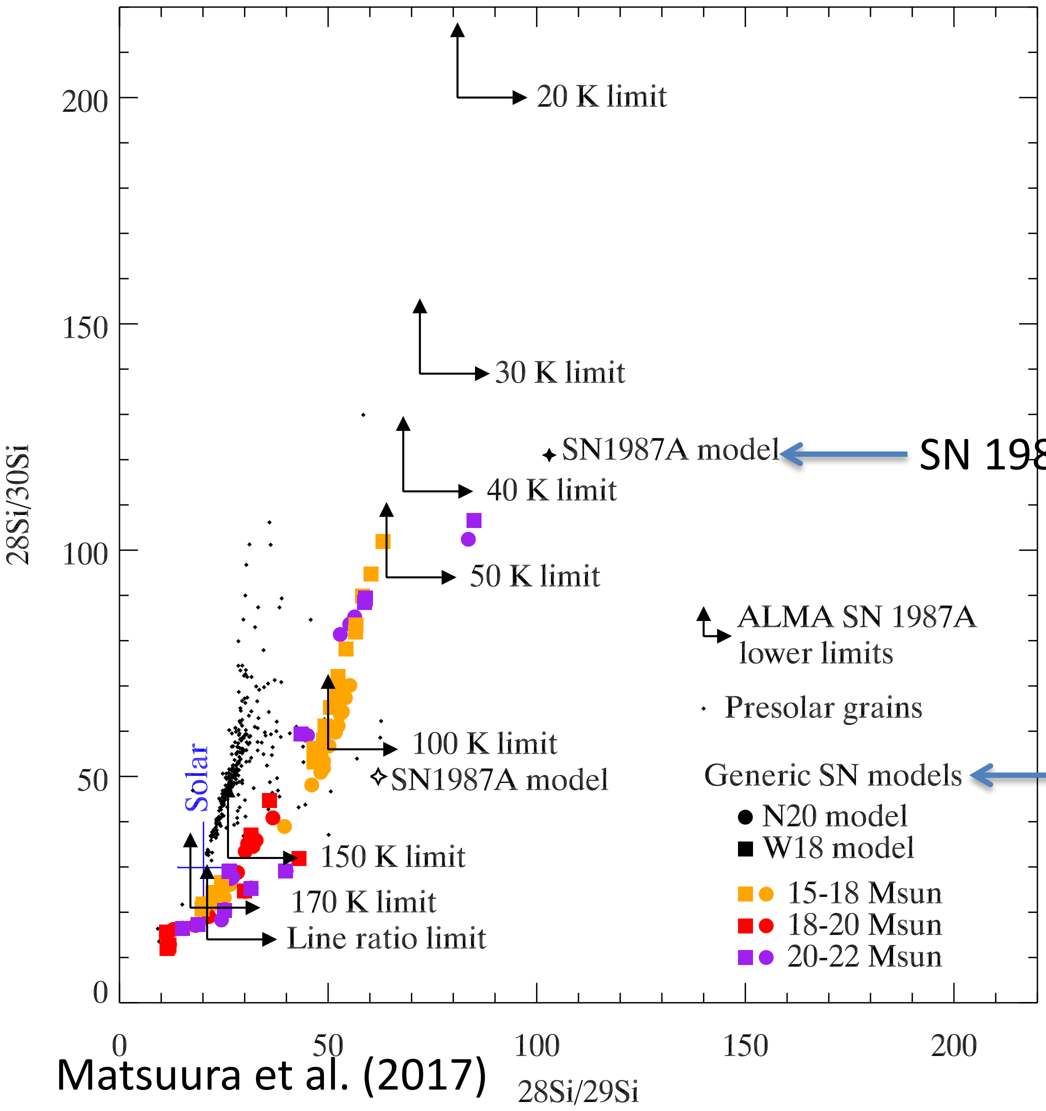


Measurements in presolar grains

Matsuura et al. (2017)

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

SiO isotopologue ratios



SN 1987A (~30% of solar Z⊙ ; Woosley)

Solar metallicity models

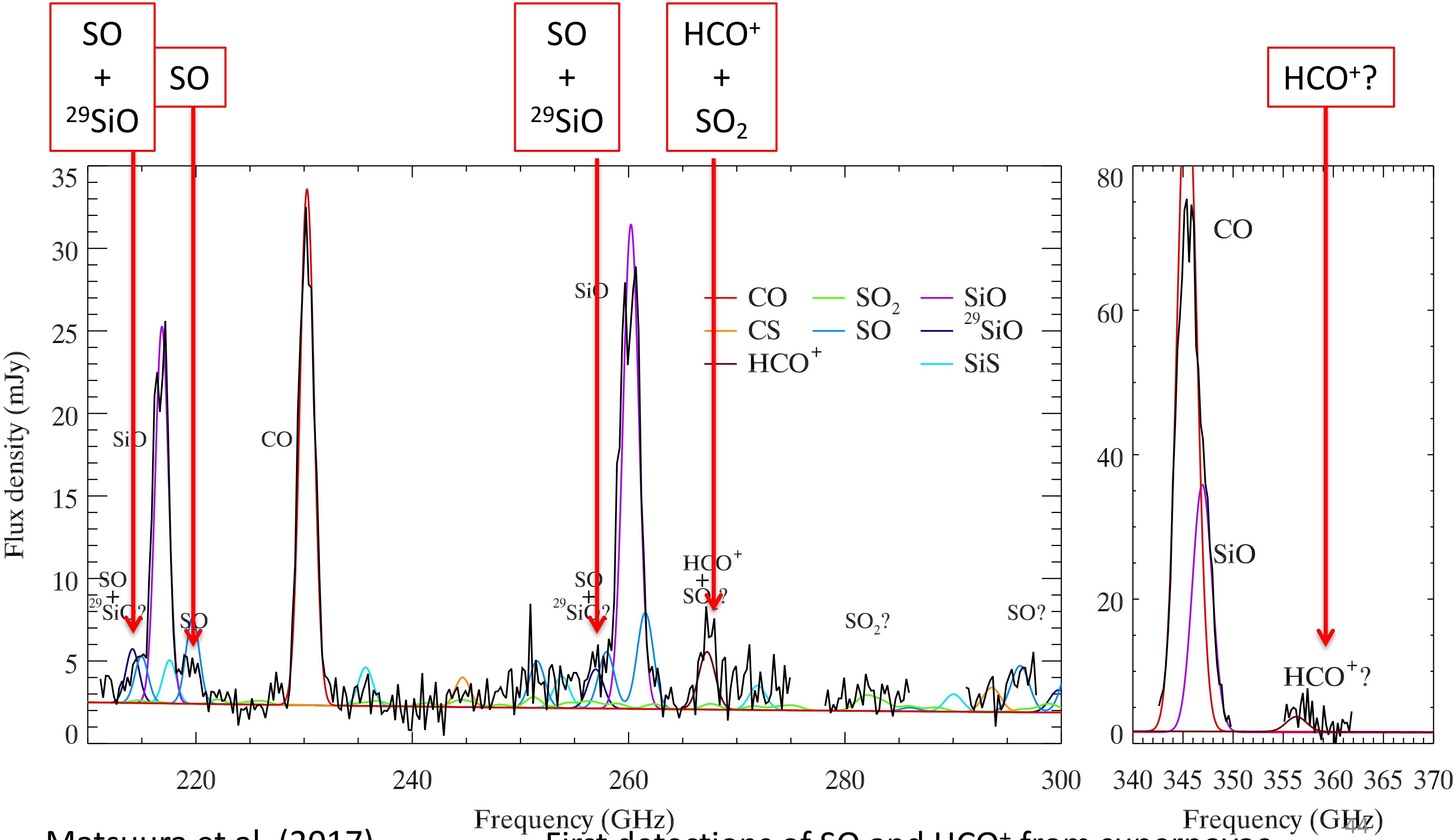
Models require to increase ^{29}Si and ^{30}Si slightly

Matsuura et al. (2017)

Context

1. Dust formation in SNe
2. Destroying dust?
3. Constrains on elements synthesized in SNe
4. SN explosion mechanism

Further detections of molecules



SO + ^{29}SiO

SO

SO + ^{29}SiO

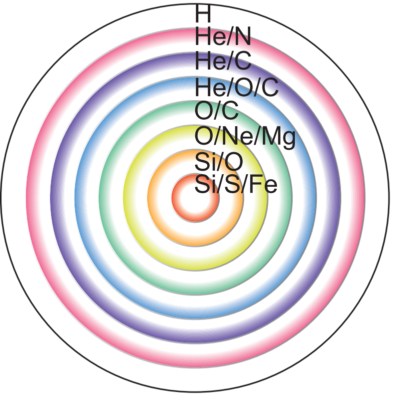
HCO$^+$ + SO$_2$

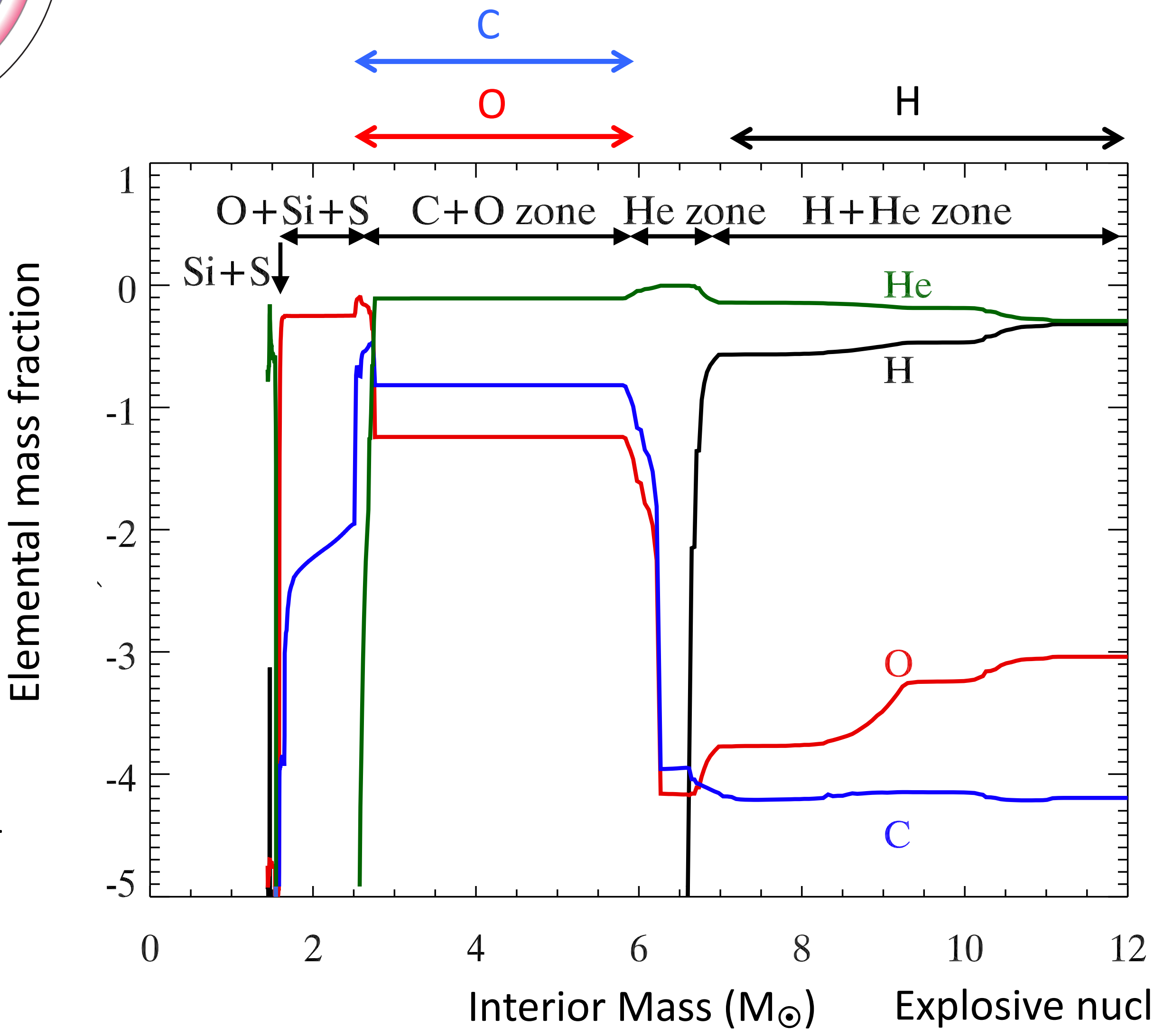
HCO$^+$?

Matsuura et al. (2017)

First detections of SO and HCO$^+$ from supernovae

How to form HCO^+? Explosive nucleosynthesis without mixing



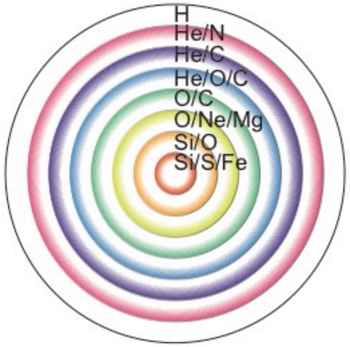


Explosive nucleosynthesis for SN 1987A (Woosley)

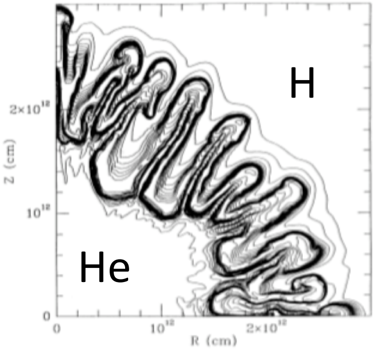
No mixing
= no HCO^+

How does mixing happen?

Historical picture



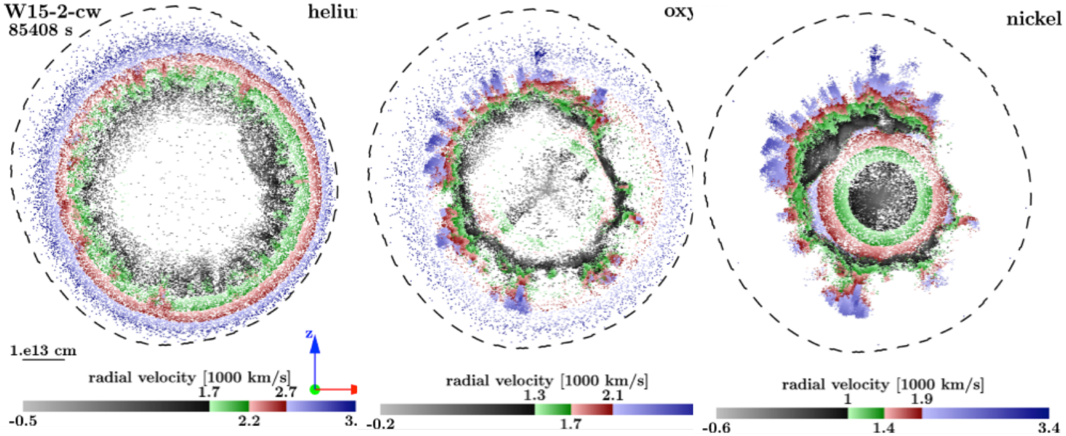
SN Explosion causes shocks inside the star core



Rayleigh-Taylor instabilities

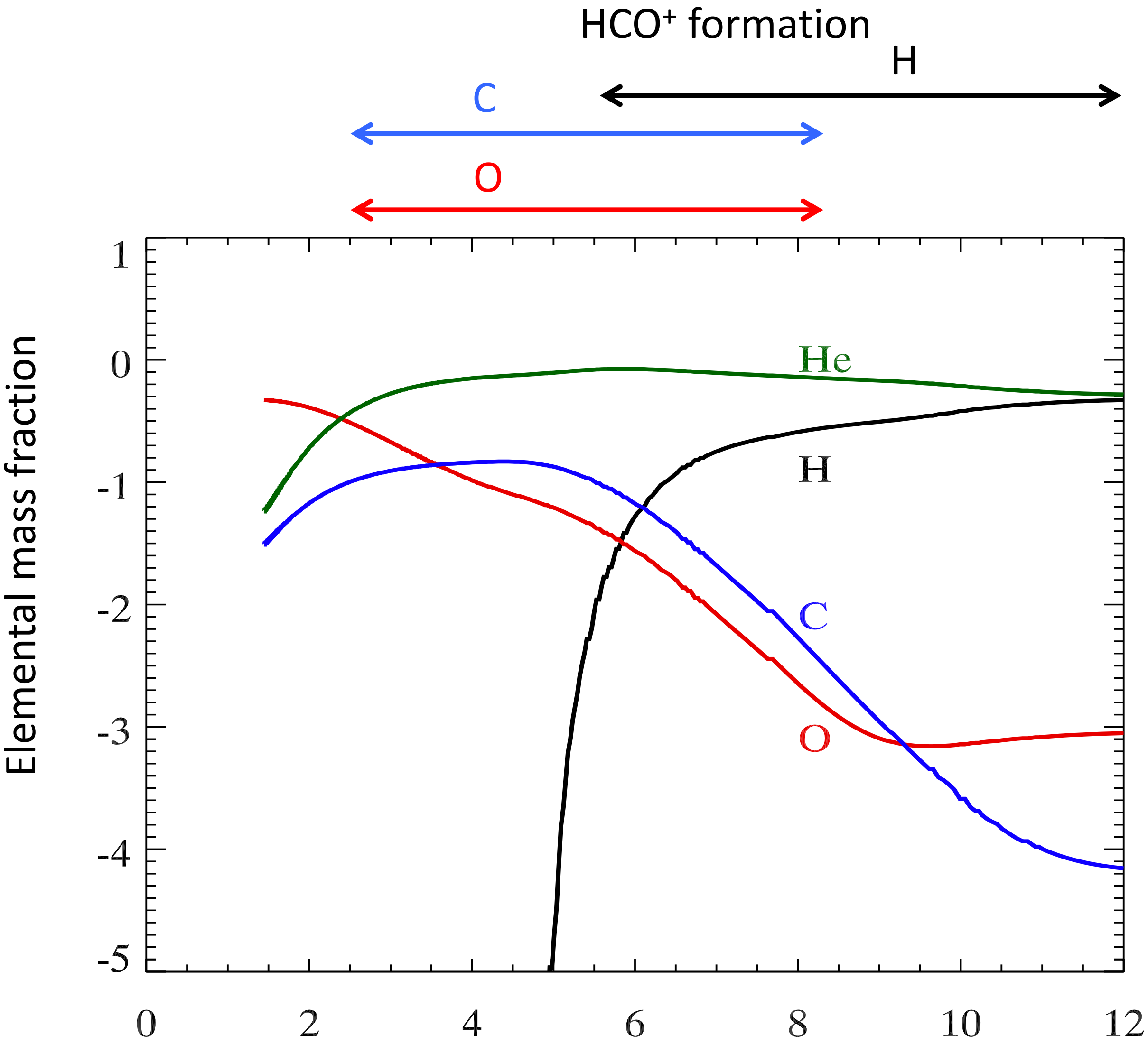
Fryxell et al. (1991)

Map of elements immediately after the explosion



Wongwathanarat et al. (2015)

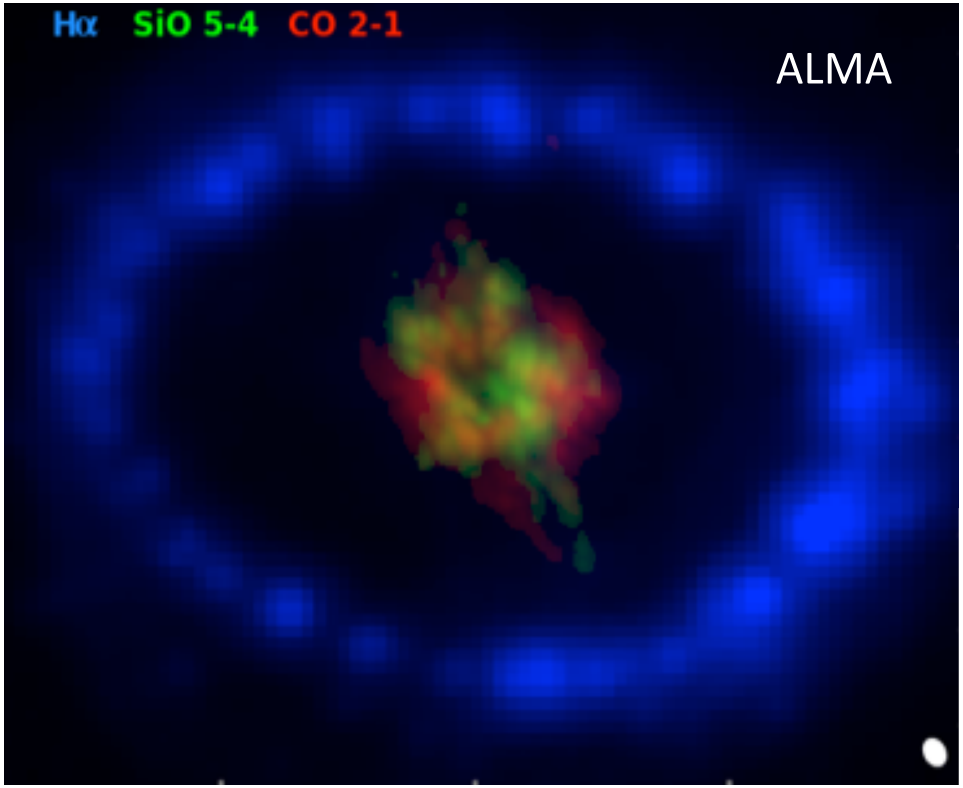
Explosive nucleosynthesis with mixing between zones



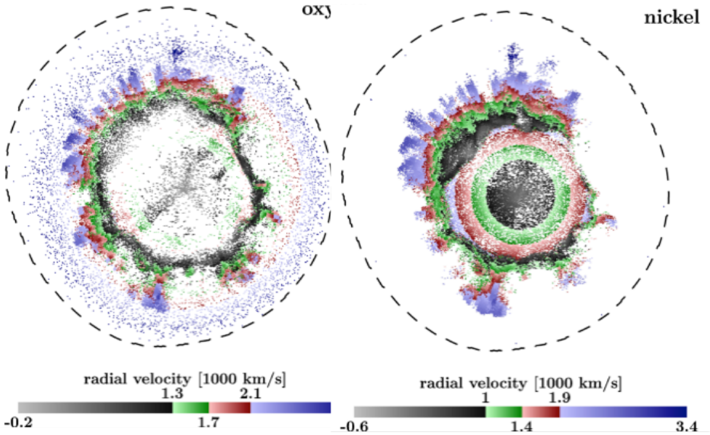
HCO$^+$ formation

Explosive nucleosynthesis for SN 1987A (Woosley)

Clumpy structure found in ejecta



Hydrodynamic simulation



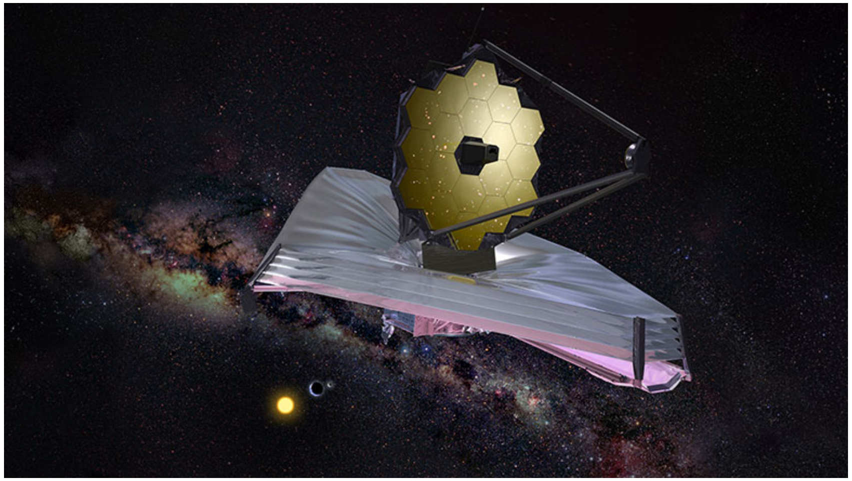
Wongwathanarat et al. (2015)

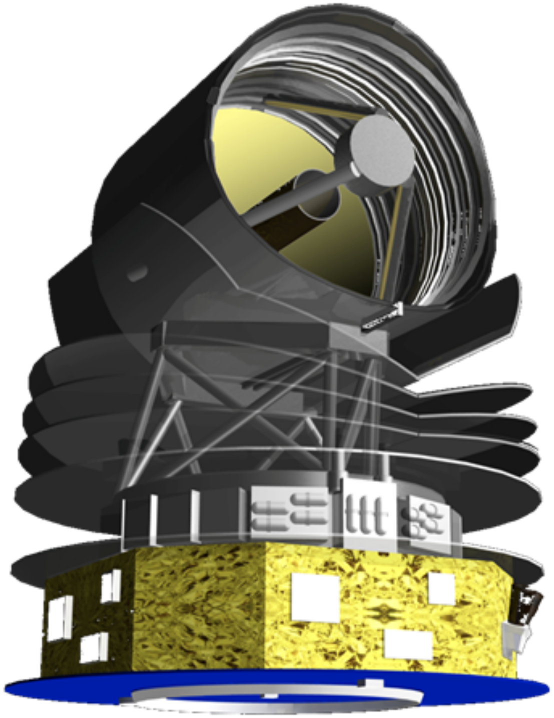
Fossils of clumps formed by shocks at the time of SN explosion

Abellan et al. (2017)

Future

- The number of sample will increase with future space missions – JWST, SPICA & Origin





Summary

- Herschel and ALMA has provided excellent opportunity to understand physic and chemistry of supernovae
- Dust
  - SNe can form significant mass of dust
  - Unresolved problems
    - Dust destruction
    - Dust formation in SNe is common place?
    - Can SN dust be important source of ISM dust?
- Molecules
  - Isotope ratios constraints to explosive nucleosynthesis
  - Clumps traces dynamical motion of gas at the time of the explosion