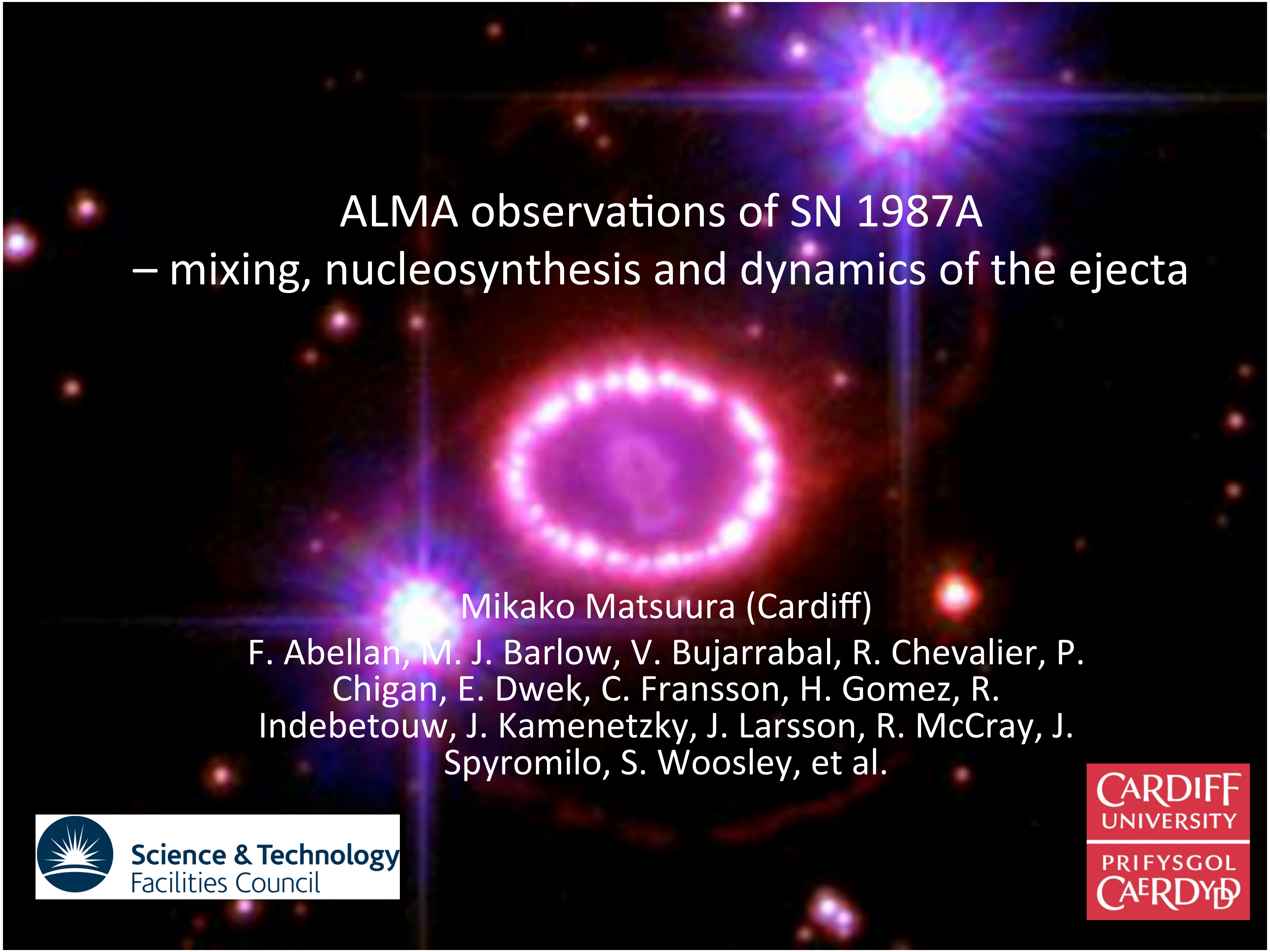


ALMA observations of SN 1987A – mixing, nucleosynthesis and dynamics of the ejecta

Mikako Matsuura (Cardiff)

F. Abellan, M. J. Barlow, V. Bujarrabal, R. Chevalier, P. Chigan, E. Dwek, C. Fransson, H. Gomez, R. Indebetouw, J. Kamenetzky, J. Larsson, R. McCray, J. Spyromilo, S. Woosley, et al.

Science & Technology Facilities Council

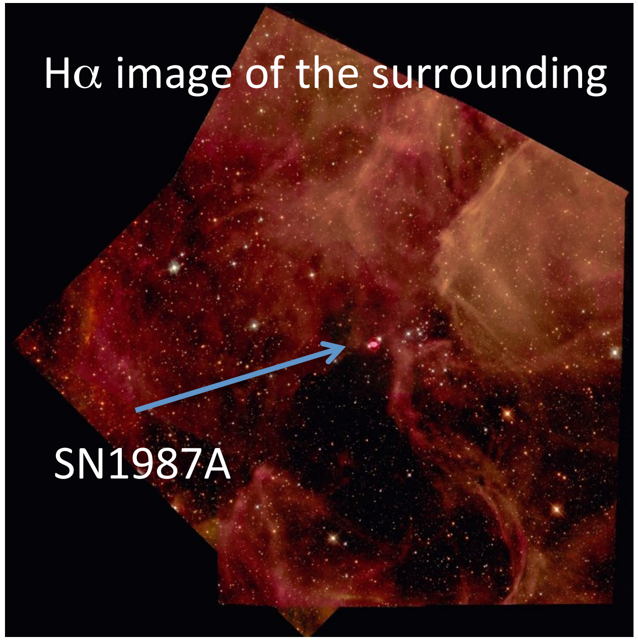
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

SN 1987A

- Distance: 50 kpc (Large Magellanic Cloud)
- The nearest SN explosion detected in 400 years

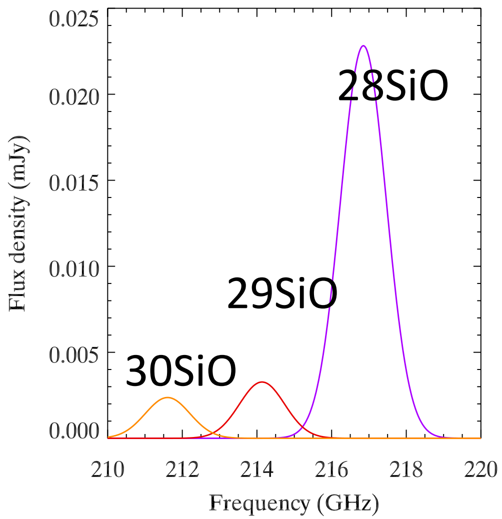
- A lot of talks and posters about SN 1987A
- Larsson, McCray, Dwek, Burrows, Fransson

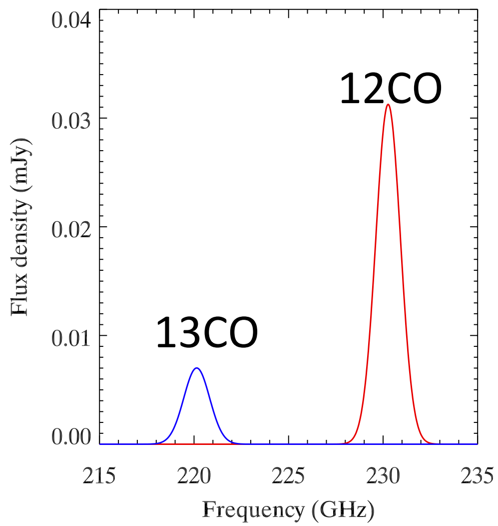
- This talk – molecules
  - Molecular Chemistry
  - Evidence of macroscopic mixing
  - Isotope ratios - SN nuclear synthesis
- Dust - Cigan et al. Poster S9.1



Using millimetre molecular lines to probe

- How does supernova remnant evolve?
- How efficient was the mixing in early days?
- What are isotope ratios?
- What was the condition to form molecules in supernova (remnant)?

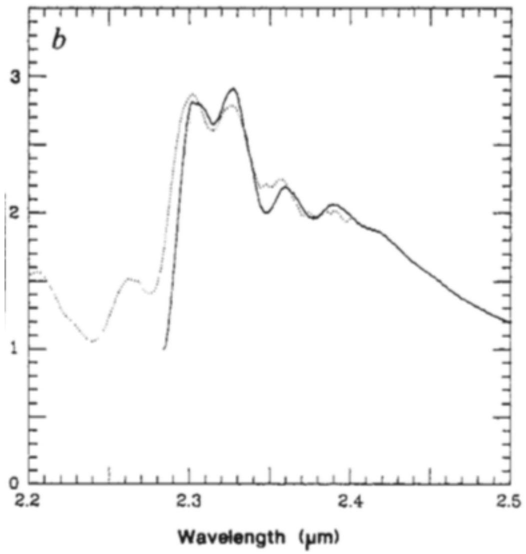




Historical detections of molecules

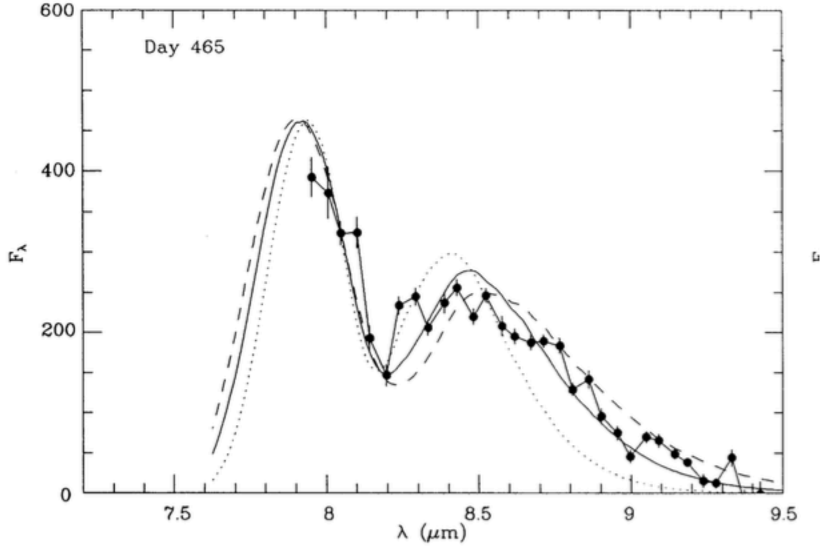
- SN 1987A: fist detections of molecules in SNe
- CO & SiO at infrared (up to day 500)

CO



Spyromilio et al. (1988)

SiO



Roche et al. (1991)

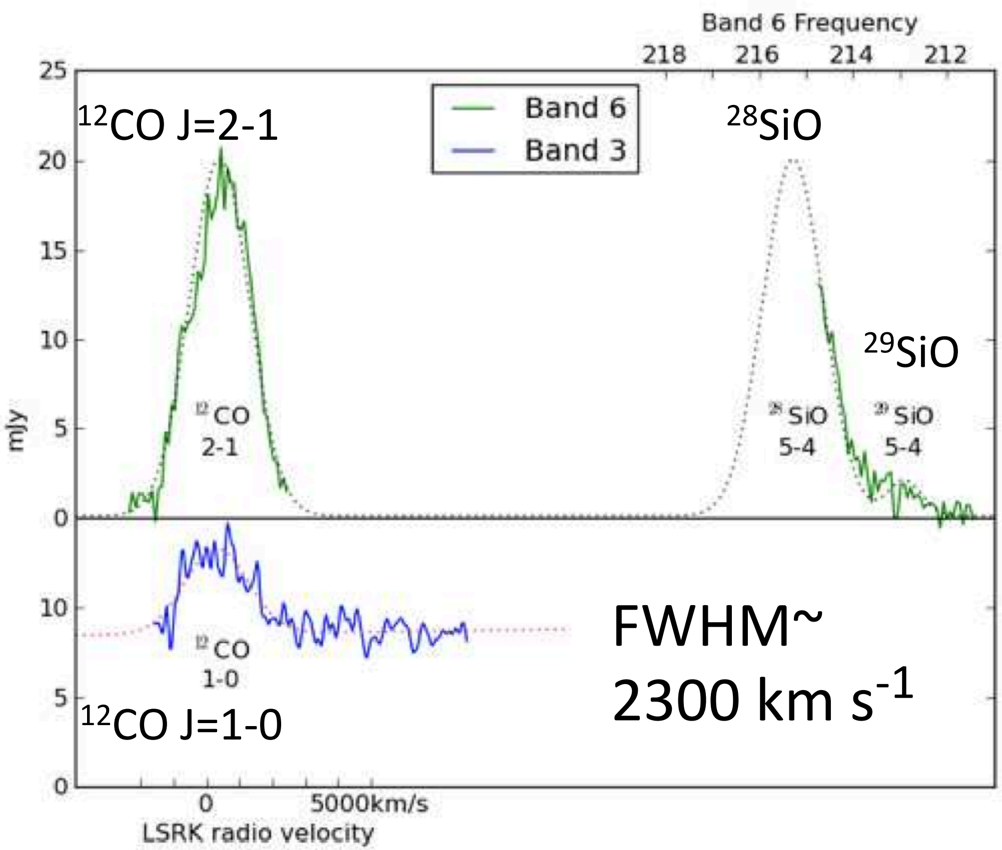
ALMA

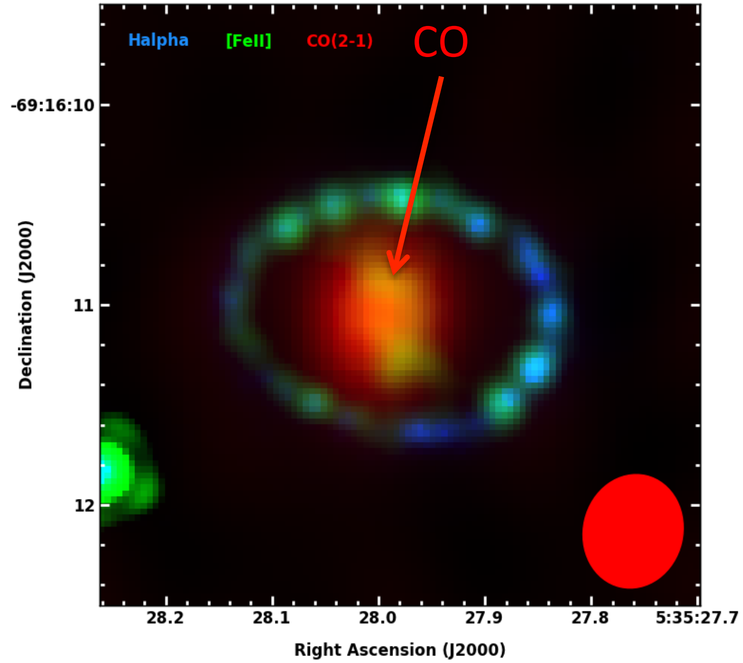
- Started operation in 2011
- High sensitivity & high angular resolution images/spectra at radio wavelengths

ALMA cycle-0 program

In 2012
(Day=9173-9300)

ALMA detection of molecules



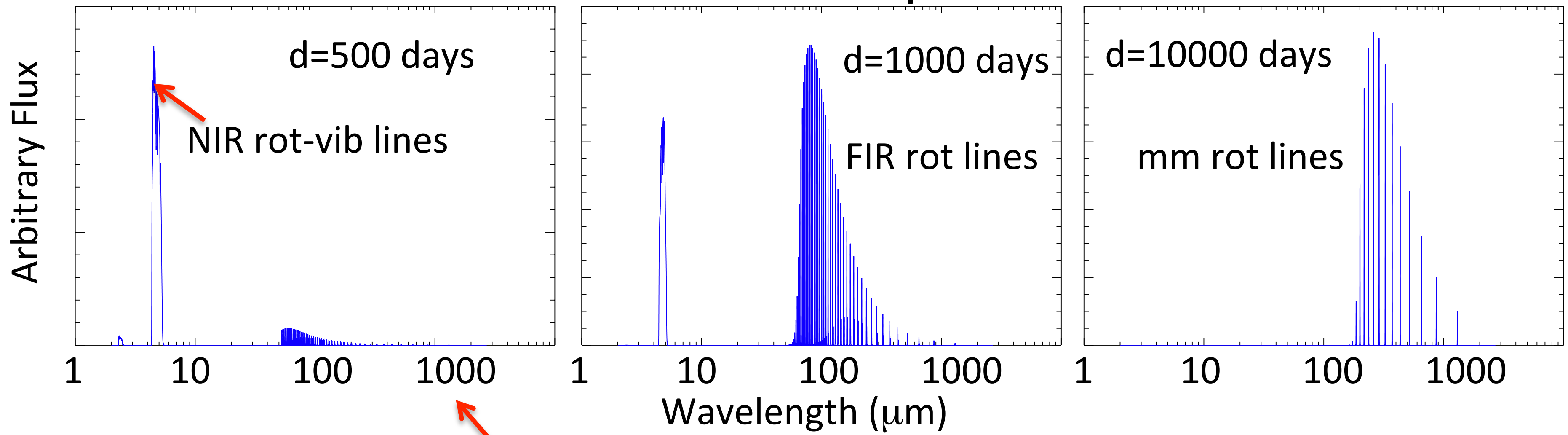


(Kamenetzky et al. 2013)

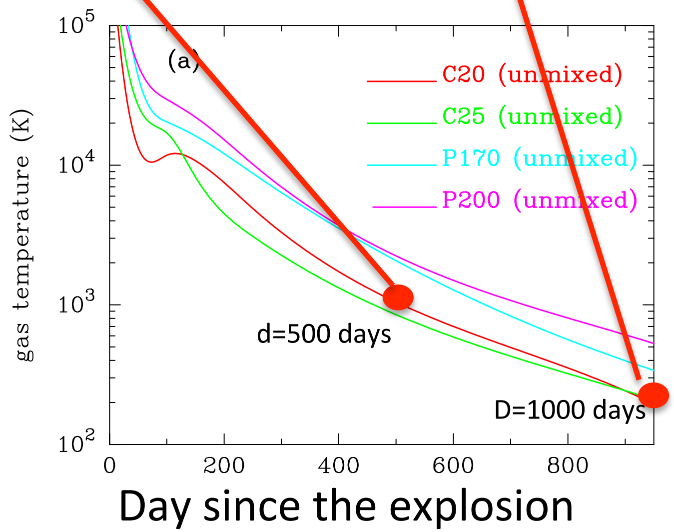
Cold (20-200 K) 'molecular gas' in the ejecta after 25 years

Time evolution of molecular spectra

CO model spectra



Model: declining gas temperature



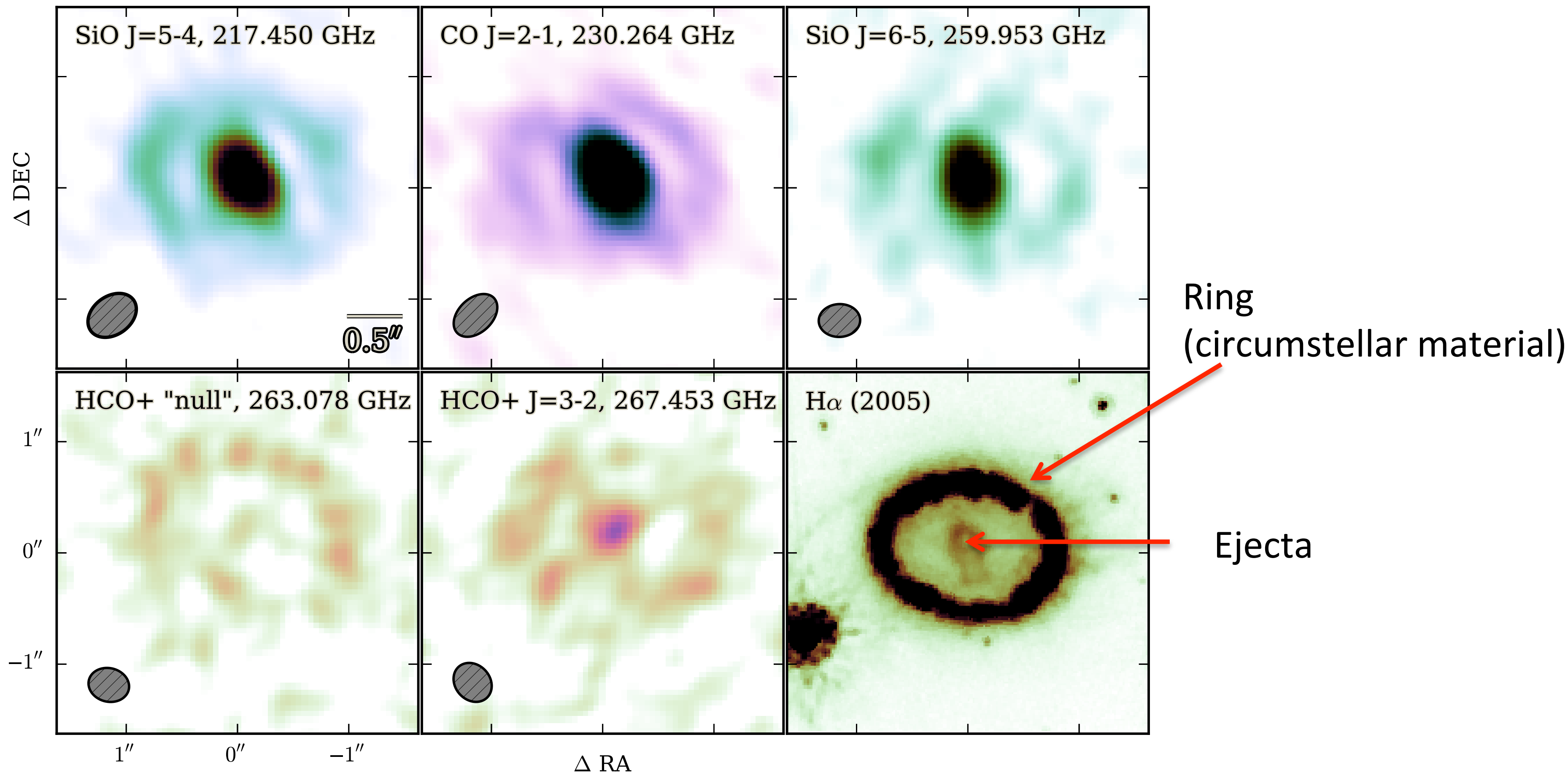
Nozawa et al. (2003 ApJ, 598, 785)

In 2014 + 2015
(Day=10,048 + 10,378)

ALMA cycle 2 spectral scan of SN 1987A

First detections of SO and HCO^+ from supernovae
HCO^+ : tracer of dense molecular clouds (at least 10^3 cm^{-3}; typically 10^5 cm^{-3})
SiO mass: $1 \times 10^{-3} - 2 \times 10^{-5}$ $M_\odot$ – only small fraction of SN Si (0.2 $M_\odot$) is in SiO (most Si in dust?)

ALMA images

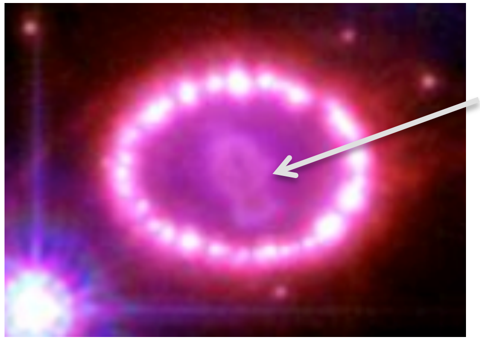


Molecular emissions are from the ejecta

CO + SiO mass/temperature

Current (day~10053)

- SiO
  - T=20 – 170 K
  - M=1×10^{-3} – 2×10^{-5} $M_{\odot}$
- CO
  - T=20 – 50 K
  - M= 0.5 – 9×10^{-3} $M_{\odot}$



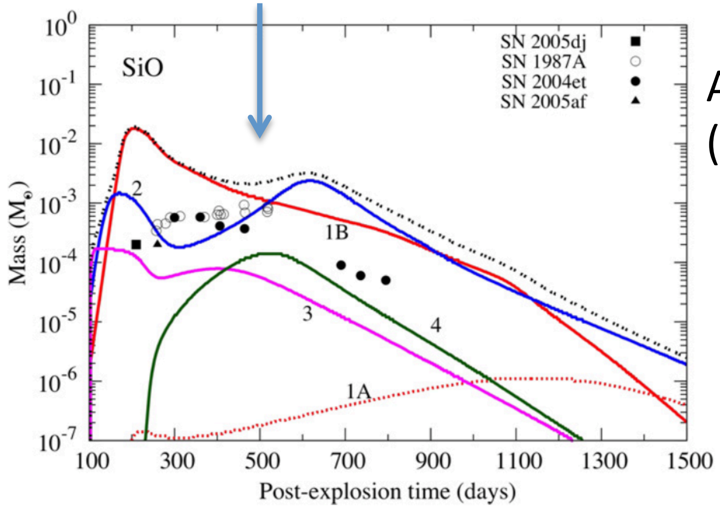
Cold ejecta

Early days

- SiO
  - T=1000 – 1500 K
  - M=4×10^{-6} $M_{\odot}$
  - day~500 (Roche et al. 1991)
  - Some increase in mass and temperature drop in 25 years
- CO
  - M=10^{-5} – 10^{-4} $M_{\odot}$ at day~200 (Spyromilio et al. 1988)
  - 0.45 $M_{\odot}$ at day~100 and decreased to 2-6×10^{-3} $M_{\odot}$ at day 200-600 (Liu & Dalgarno 1995)

Comparisons with chemical models

Silicate dust formation

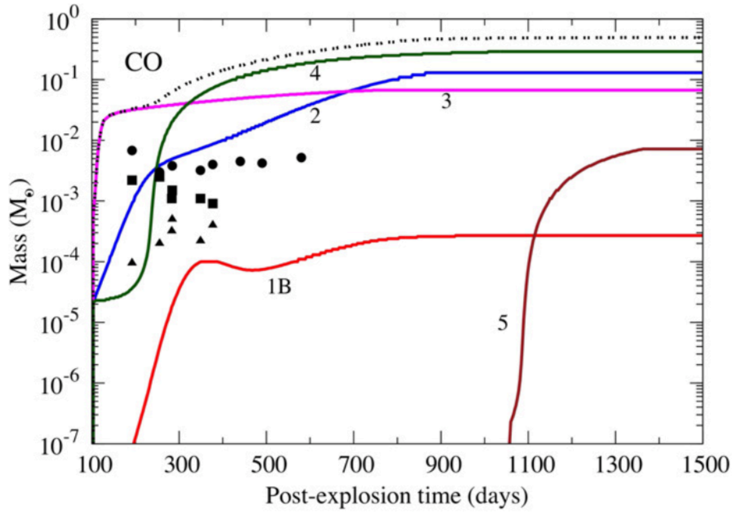


ALMA
(day~10000)

Measured molecular masses are
- Slightly larger SiO mass
- Consistent or smaller CO mass

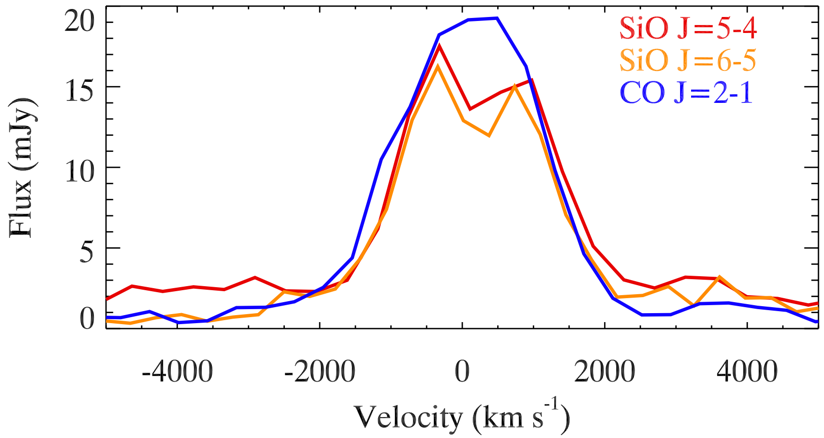
than theoretically predicted mass at day 1500

Sarangi & Cherchneff (2013)



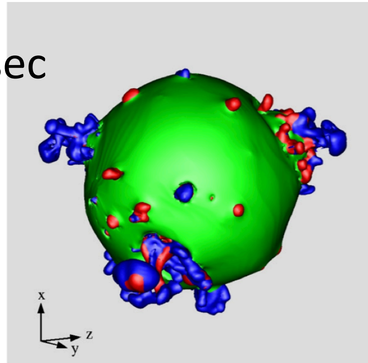
ALMA
(day~10000)

A dip in SiO line profiles

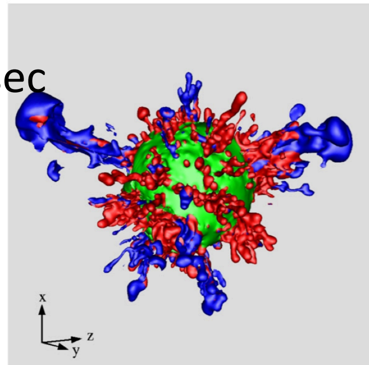


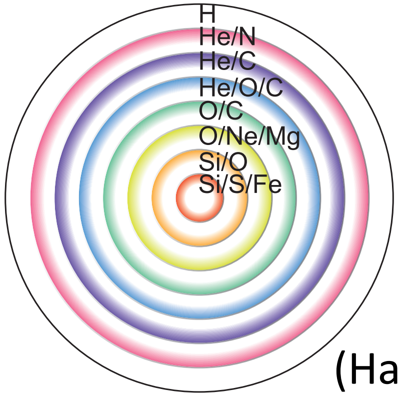
SiO: bipolar shape caused at the time of the explosion?
ALMA high resolution images are just delivered
– clumpy (McCray's talk)

t=350 sec



t=9000 sec





Prior to the explosion

3D simulation of instability in SN explosion
(Hammer et al. 2010; Wongwathanarat et al. 2015)
Carbon/Oxygen/Nickel

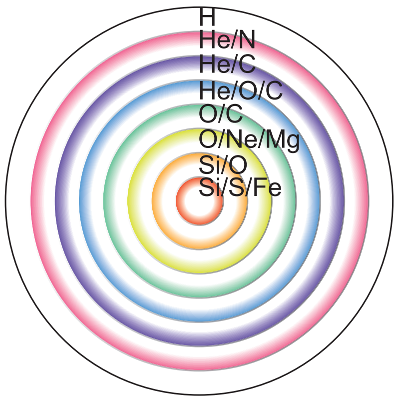
In 2014
(Day=10,048-10,053)

ALMA cycle 2 spectral scan of SN 1987A

First detections of SO and HCO^+ from supernovae/supernova remnants

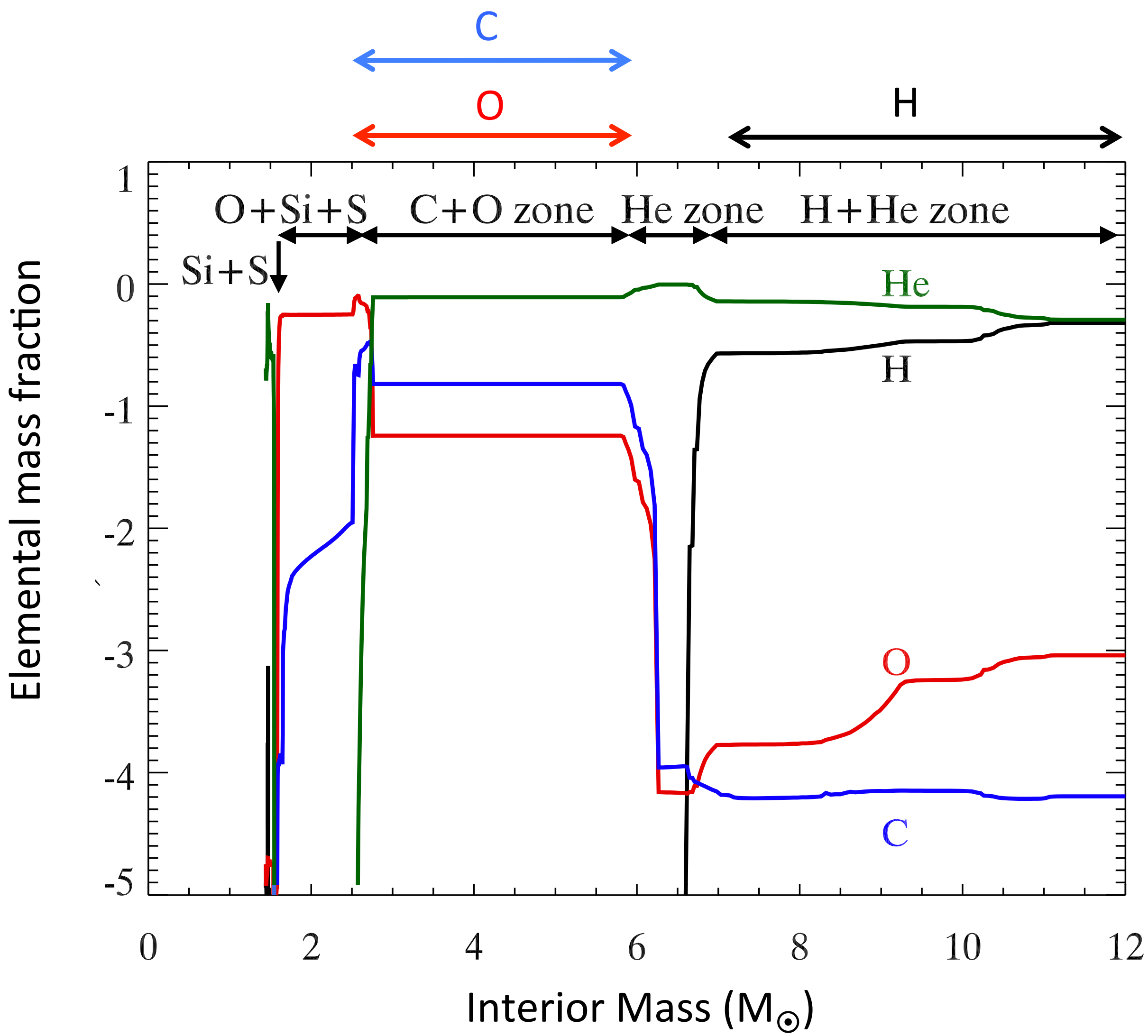
HCO^+ : tracer of dense molecular clouds (at least 10^3 cm^{-3}; typically 10^5 cm^{-3})

SiO mass: 9×10^{-5}-6×10^{-3} $M_\odot$ – only small fraction of SN Si (0.2 $M_\odot$) is in SiO (most Si in dust?)



HCO$^+$ formation (~3x10^{-5} $M_\odot$)

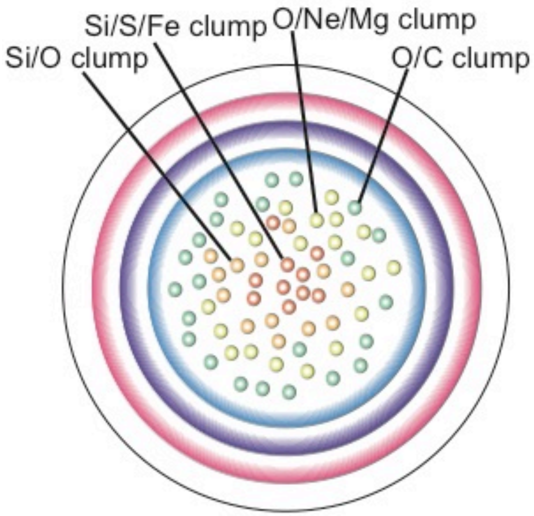
Explosive nucleosynthesis without mixing

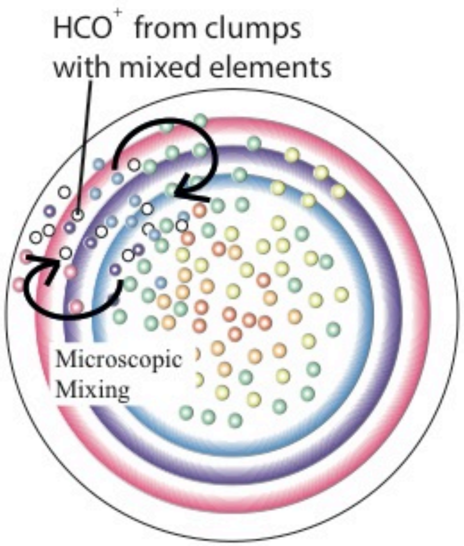


No mixing
= very little HCO$^+$

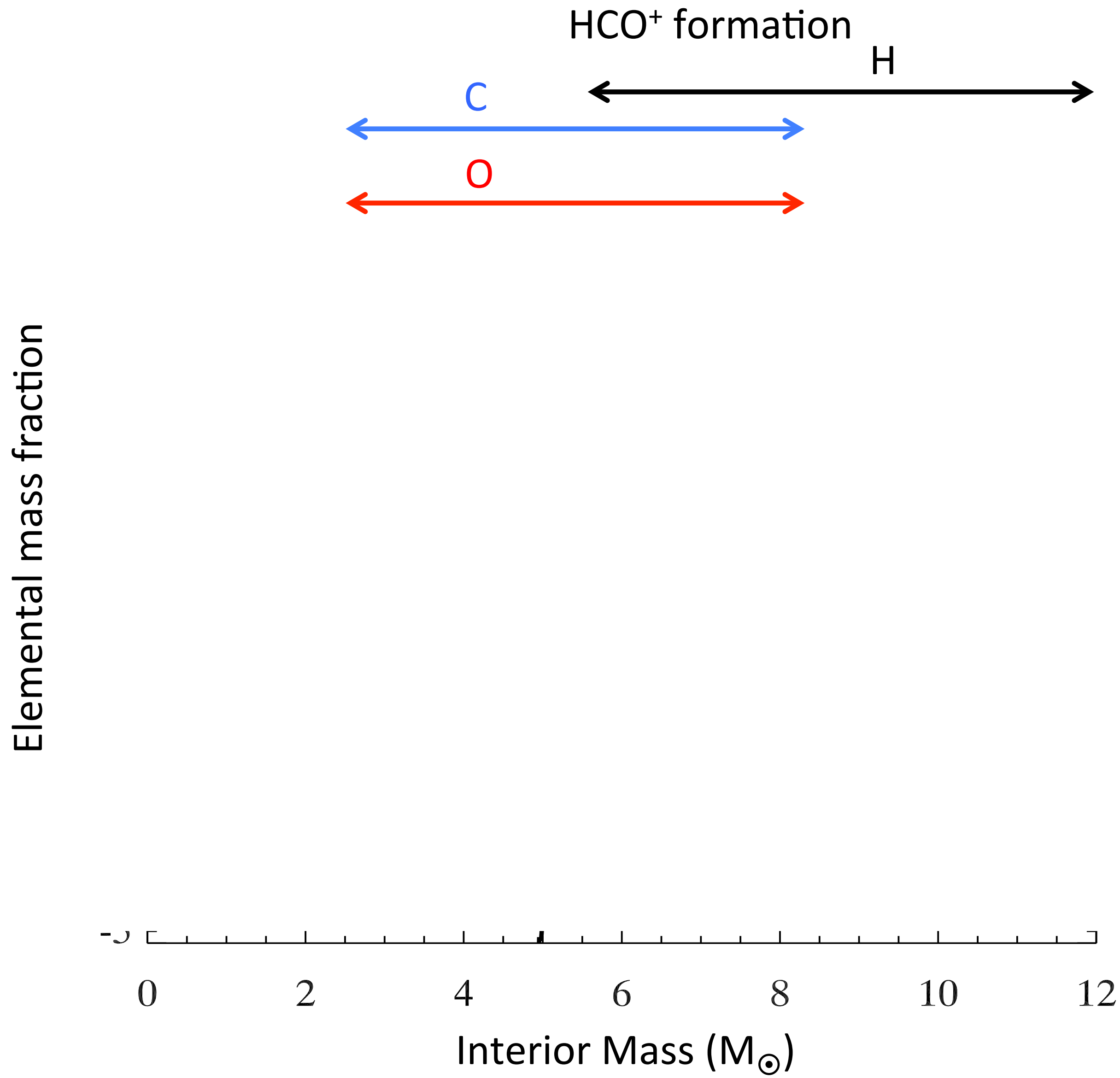
Explosive nucleosynthesis for SN 1987A (Sukhbold et al. 2015)

Explosive nucleosynthesis with macroscopic mixing between zones





(With macroscopic mixing)



Explosive nucleosynthesis for SN 1987A (Sukhbold et al. 2015)

Constraints on SN nucleosynthesis: isotope ratio

^{28}SiO

^{28}SiO

^{29}SiO
+SO

ALMA
^{28}SiO / ^{29}SiO >20

Theoretically predicted $^{28}Si/^{29}Si$
65 (Woosley & Weaver 1995)
8 (Thielemann et al. 1996)

Isotope ratio – model vs observations

- Measurements
  - SN 1987A (ALMA)
  - Presolar grains
  - Solar: $^{28}Si/^{29}Si=20$, $^{28}Si/^{30}Si=30$
- Explosive nucleosynthesis models
  - Solar abundance
    - Woosley
    - Nomoto
  - SN 1987A (~30% of solar $Z_{\odot}$; Woosley)

- Theory predicts: at lower metallicity, fewer neutron-rich atoms
  - ALMA suggests a lower metallicity origin of SN 1987A progenitor

Pre-solar grains

Solar abundance model

From molecules to dust

- SiO -> amorphous silicates ($Mg_{2x}Fe_{2-2x}SiO_4$ etc)
- C -> amorphous carbon

Continuum

Hα

Cigan et al. Poster P9.1

Dust in old supernova remnant – fate of dust in supernova

- Cas A – Barlow, de Looze (tomorrow’s talks)
- W44 (SNR with pulsar) – Tsiakaliari (poster S9.6)

W44: Herschel 70 micron image

Summary

- Molecules and dust are now formed in the cold ejecta
  - CO, SiO, HCO+
  - Non-spherical shape (Tomorrow's McCray's talk)
- Supernova elemental abundance
  - Isotope ratios are constrained
  - Progenitor of SN 1987A might have had lower metallicity than LMC average (<half solar)