The origin of the elements: direct determination of nucleosynthesis in supernovae

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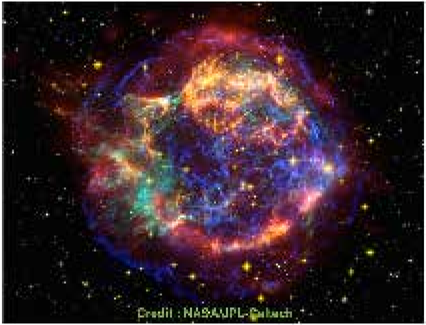
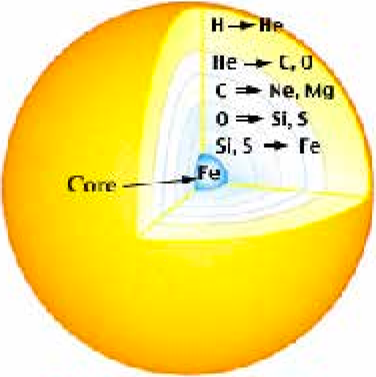


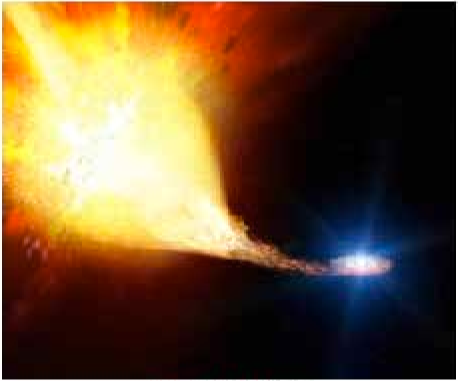
Supernovae - the deaths of stars

[1] Core-collapse of a **massive star** ($M \gtrsim 8M_{\odot}$) as it runs out of fuel at the end of its life



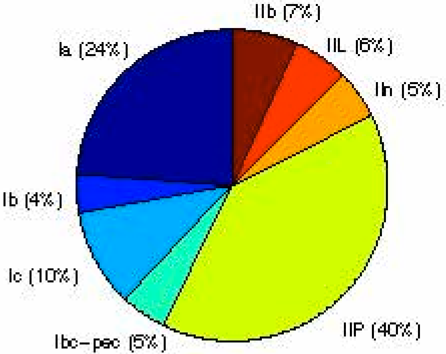
Credit: www.phys.olemiss.edu

[2] Thermonuclear explosion of a **white dwarf** exceeding the Chandrasekhar limit (1.4 $M_{\odot}$)

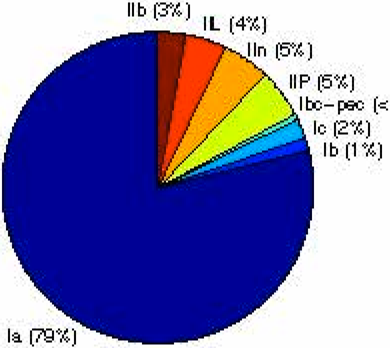


Credit: hetdex.org

Supernova types and their relative frequencies



Volume-limited

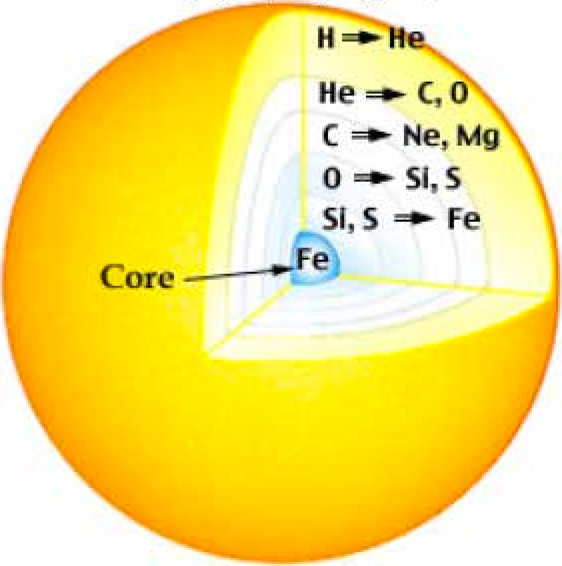


Magnitude-limited

Data from Li+2011

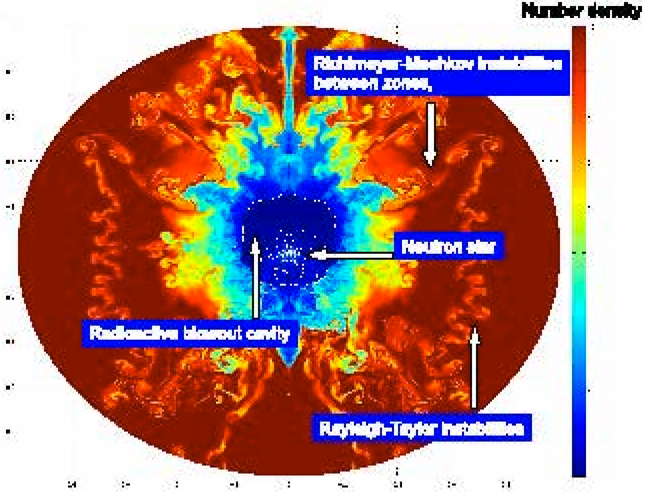
Hydrostatic burning in massive stars

Main source of O, F, Ne, Na, Mg, Al, P in Universe



Credit: www.phys.olemiss.edu

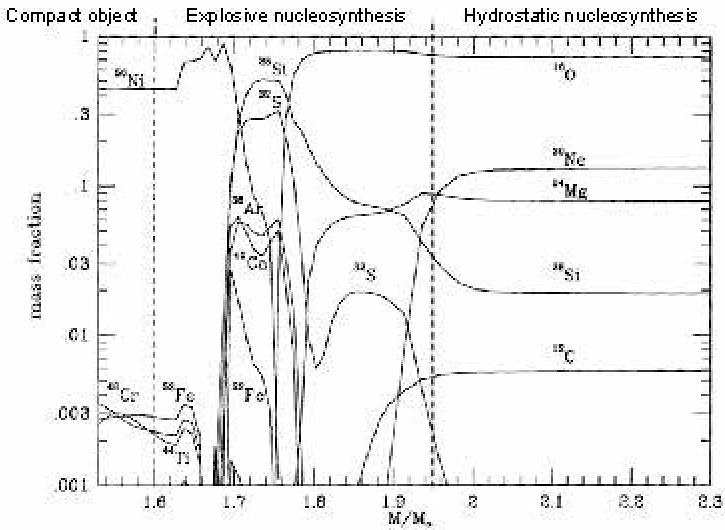
Core-collapse and explosion



Kifonidis+2006

Explosive burning

CC + TN → Main source of Si, S, Ar, Ca, Fe, Ni in the Universe



Thielemann+1990

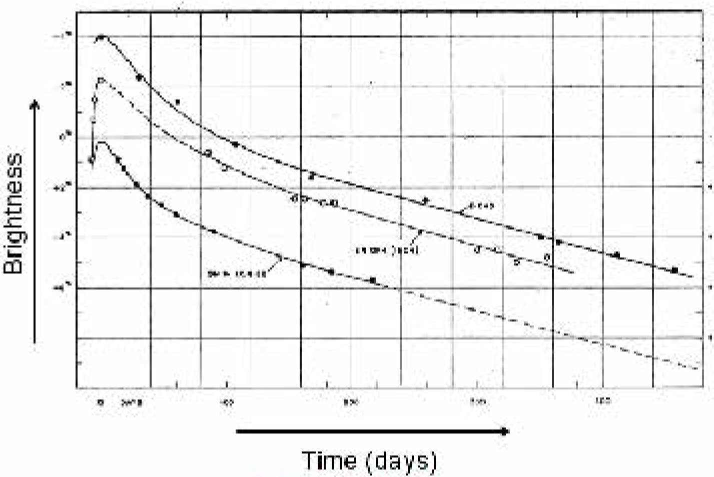
Core-collapse SNe : Questions we want to answer

- What are the progenitors of different SN types (M_{ZAMS}, Z, Ω, B, binarity)?
- How does the explosion occur, and what is left behind?
- What nucleosynthesis do SNe produce, and how well do we understand the cosmic abundances?

Ab. by number	El	Main source	Burning
1	H	Big Bang	-
2	He	Big Bang	H burn
3	O	CCSN	C burn
4	C	AGB stars	He burn
5	Ne	CCSN	C burn
6	N	AGB stars	He burn
7	Mg	CCSN	C burn
8	Si	CCSN + TNSN	O burn
9	Fe	TNSN	Si burn
10	S	CCSN	O burn

The nebular phase : the opportunity to see what massive stars are made of!

1940s: Slow exponential tails discovered. Decay time scale of ∼ 100 days.
Borst 1950 : Radioactivity! Colgate & McKee 1969 : ^{56}Ni → ^{56}Co → ^{56}Fe!



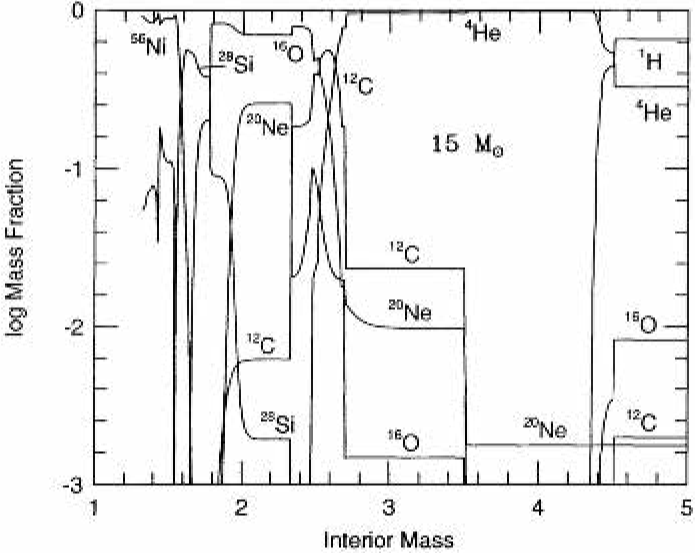
From Baade 1945

How can we determine element masses in SN ejecta from their nebular spectra?

Modelling methods:

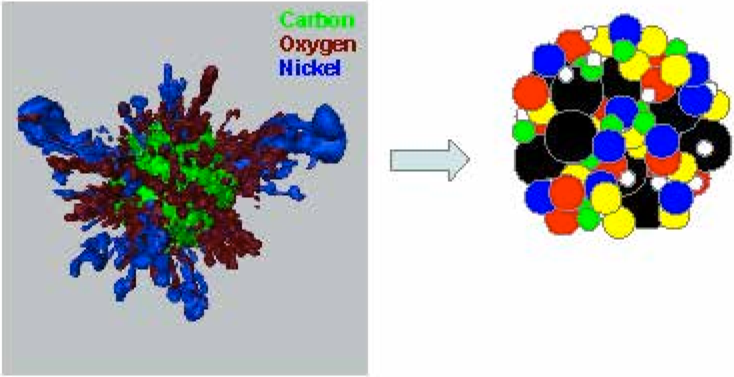
1. Measure line luminosities + assume uniform conditions and analytic forms valid in certain limits *Important but can only give rough ideas*
2. Fit full spectra by varying composition in single-zone model *Widely used but issues with microscopic mixing*
3. Forward modelling of multi-zone explosion models *Recent progress (Dessart & Hillier 2011, AJ 2011 (PhD thesis), Maurer 2011 (PhD thesis), AJ+2012, 2014, 2015a,b,c*

Zoning



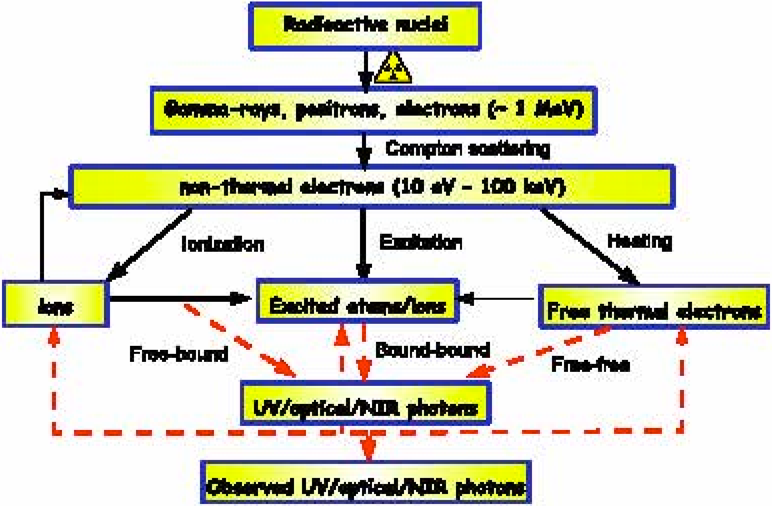
Composition of a SN ejects, from Woosley & Weaver 1995

Bringing mixing into a 1D Monte Carlo model



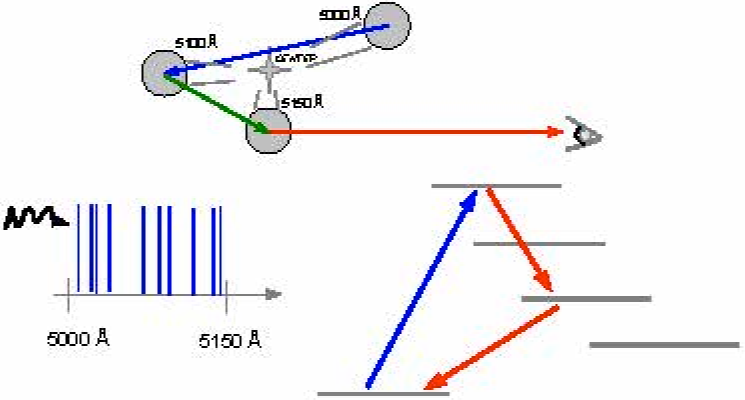
Left: 3D simulation by Hammer+2010. Right : Representation in our 1D Monte Carlo method.

Spectral modelling *Jerkstrand 2011, PhD thesis*



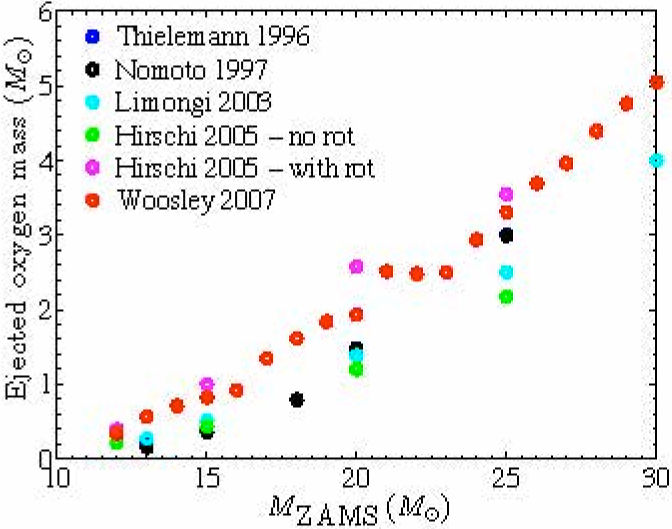
Radiative transfer

The SN nebula is in a **Hubble flow** : all points recede from all others. A photon is continuously redshifting with respect to the local, co-moving frame and has to traverse all lines with wavelengths withing $\lambda_0 \Delta V / c$. The collective opacity is called **line blocking**.



Oxygen yields : the key to determining the progenitor mass

Oxygen production from models:



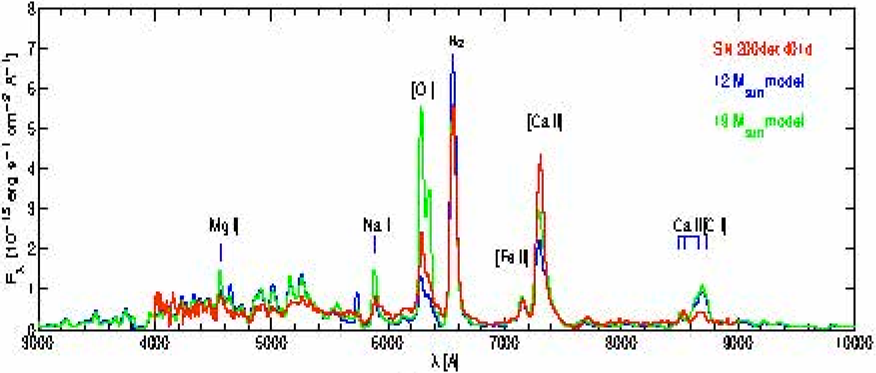
The important O/Ne/Mg zone (carbon burning ashes)

Prog. Mass → **Zone mass ↓**	**12 $M_\odot$**	**19 $M_\odot$**	**25 $M_\odot$**
Fe/He	~0.05	~0.05	~0.05
Si/S	0.061	0.14	0.21
O/Si/S	0.13	0.16	0.80
O/Ne/Mg	0.14	1.9	2.5
O/C	0.16	0.58	1.4
He	1.1	1.3	1.3
H	7.7	9.5	7.6
Total	*9.3*	*13.6*	*13.8*

Basic idea : compute models for different M_{ZAMS}, see which ones fit oberved [O I] 6300, 6364 and other O/Ne/Mg zone lines

AJ+2012, AJ+2014, AJ+2015a,b,c

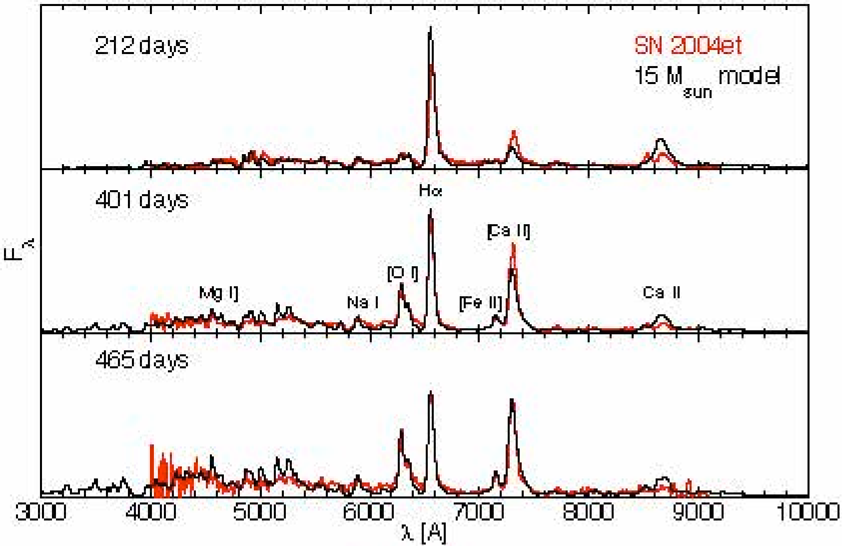
First test case : SN 2004et. $M_{ZAMS} = 12\ M_{\odot}$ too dim, $M_{ZAMS} = 19\ M_{\odot}$ too bright



AJ+2012

First test case : SN 2004et. $M_{ZAMS} = 15\ M_{\odot}$ just right

$M_{oxygen} \approx 0.8 M_{\odot}$

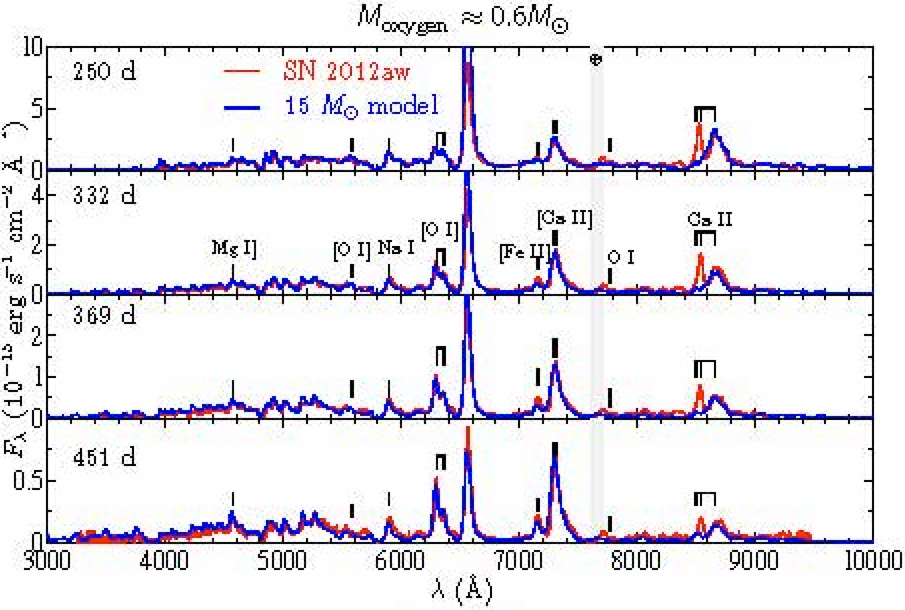


AJ+2012

SN 2004et : Some disagreement between methods

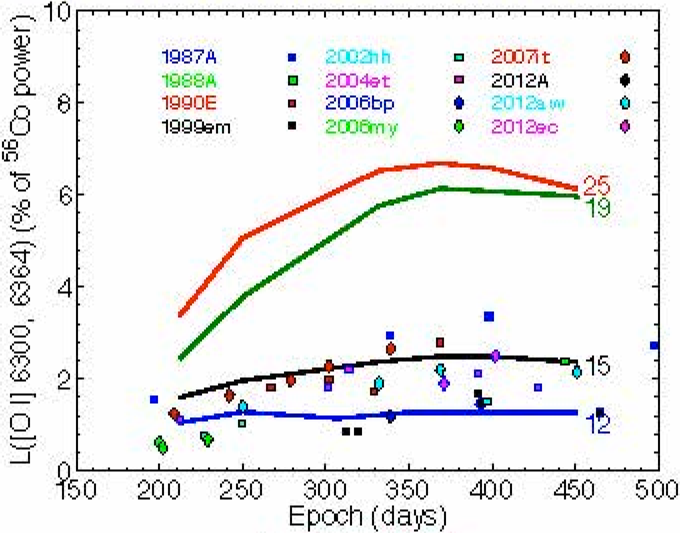
- Nebular modelling (AJ+2012) : $M_{ZAMS} \sim 15 M_\odot$
- Hydrodynamical modelling (Utrobin & Chugai 2009) : $M_{ZAMS} \gtrsim 30 M_\odot$
- Progenitor detection : $M_{ZAMS} \sim 12 M_\odot$ (Fraser+ in prep.)

SN 2012aw : also here $M_{ZAMS} \approx 15\ M_\odot$ best fit



AJ+2014

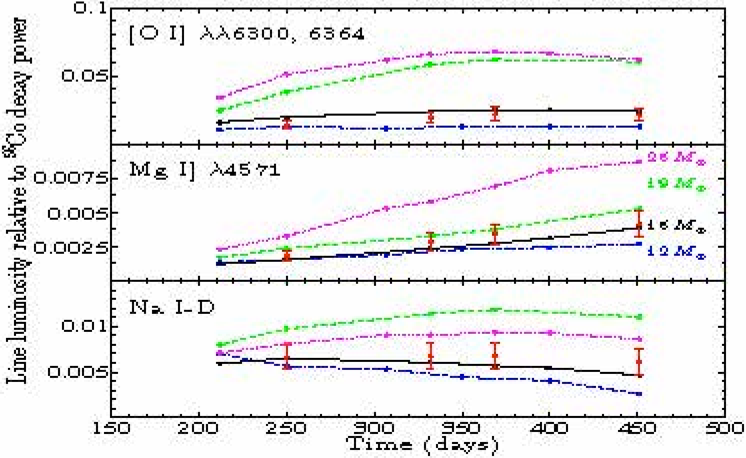
Oxygen luminosities in 12 Type IIP SNe : $M_{ZAMS} = 10 - 16\ M_\odot$ ($M_O = 0.1 - 1\ M_\odot$)



AJ+2015 (MNRAS)

SN 2012aw : consistent picture for Mg and Na

[Mg/O] ∼ 0 and [Na/O] ∼ 0 : First direct evidence for solar production of O, Mg, Na in individual SNe

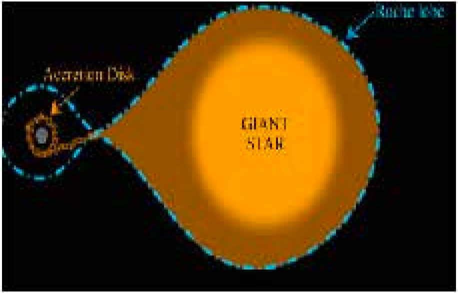


AJ+2014

Type IIb SNe

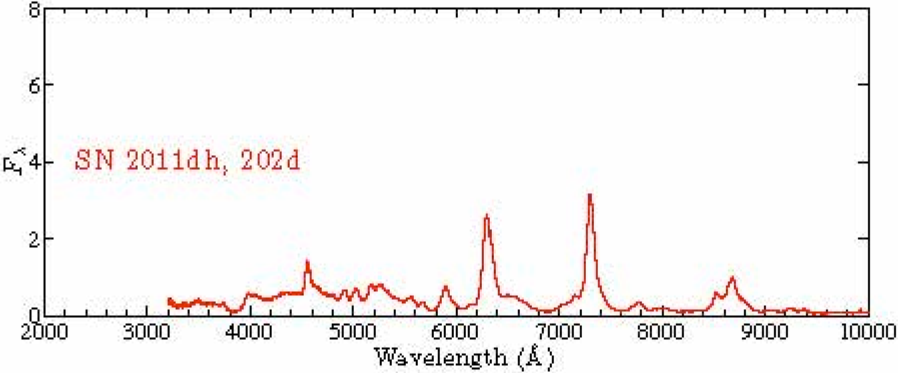
- Type II (H-rich) at early times, Type Ib (H-free) at late times : progenitor has been stripped but all but $\sim 0.1\ M_{\odot}$ of its H envelope. Recent surveys → 10-15% of all CCSNe.
- Two main candidate mechanisms for H envelope stripping:

Binary systems
(gravitational stripping)
Any M_{ZAMS}.



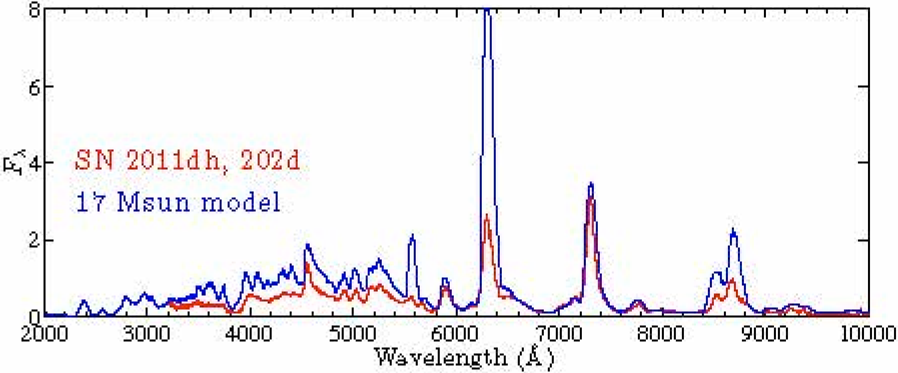
Single massive stars
(wind stripping)
$M_{ZAMS} \gtrsim 25\ M_{\odot}$

Type IIb case study : SN 2011dh - best-observed stripped-envelope SN since 1993J



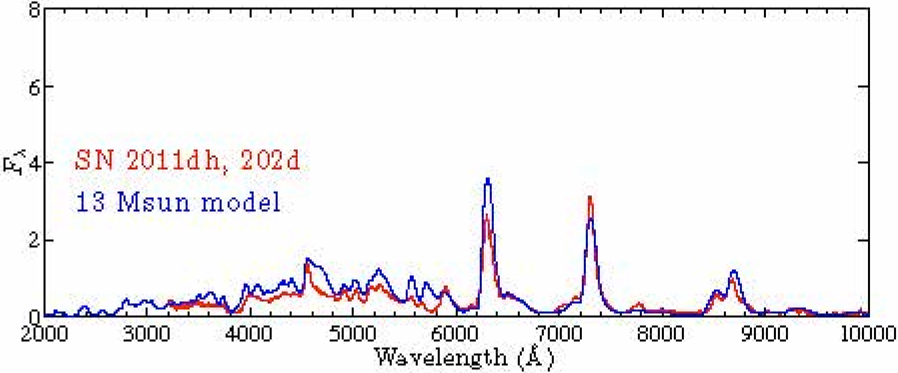
AJ+2015(A&A)

A $M_{ZAMS} = 17\ M_\odot$ model for SN 2011dh



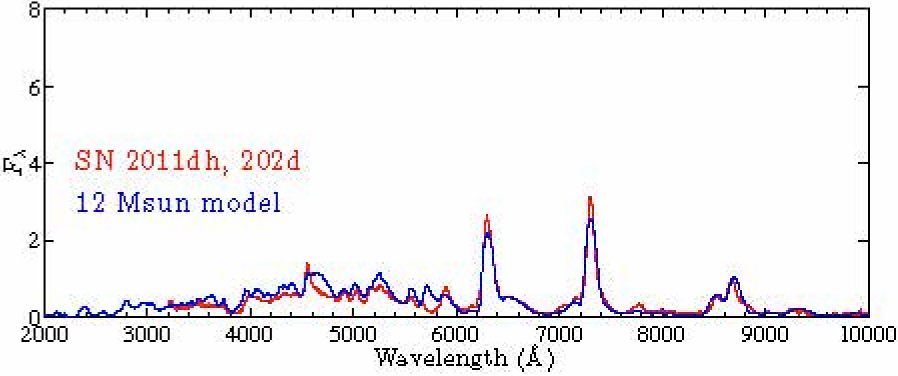
AJ+2015(A&A)

A $M_{\rm ZAMS} = 13\ M_\odot$ model for SN 2011dh



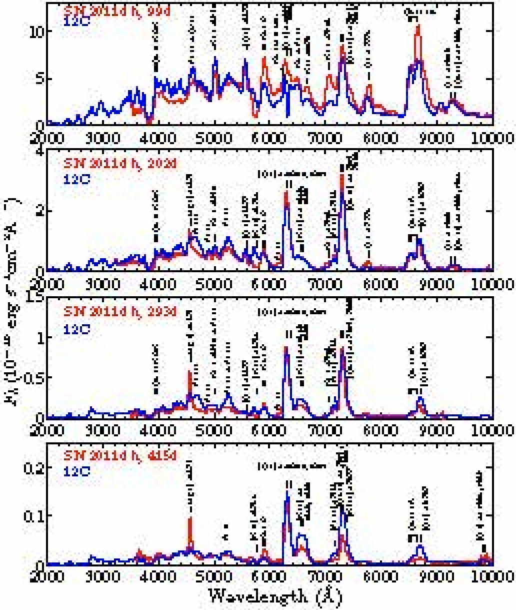
AJ+2015(A&A)

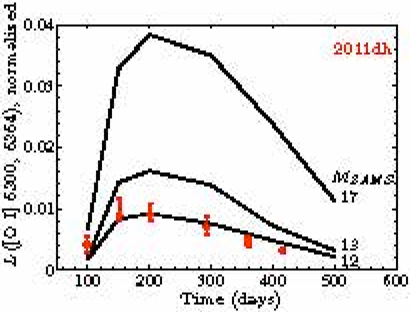
A $M_{\rm ZAMS} = 12\ M_{\odot}$ model for SN 2011dh



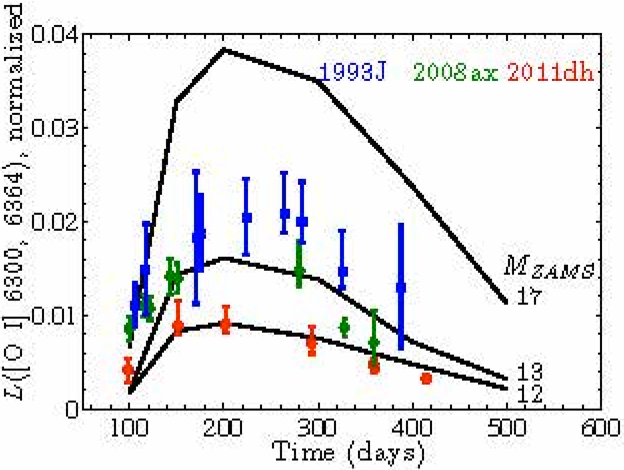
AJ+2015(A&A)

SN 2011dh : Time evolution AJ+2015(A&A)





[O I] $\lambda\lambda$6300, 6364 in SN 1993J, SN 2008ax and SN 2011dh $\rightarrow M_{ZAMS} = 12 - 15\ M_{\odot} (M_O = 0.3 - 0.8 M_{\odot}) \rightarrow$ *low-mass stars stripped by binary interaction*



AJ+2015(A&A)

Oxygen and magnesium recombination lines → synthesized Mg mass is $0.08^{+0.06}_{-0.06}$ $M_{\odot}$ in SN 2011dh ([Mg/O] = -0.5 - +0.4)

Oxygen : $n_{OII} \approx n_e$ →

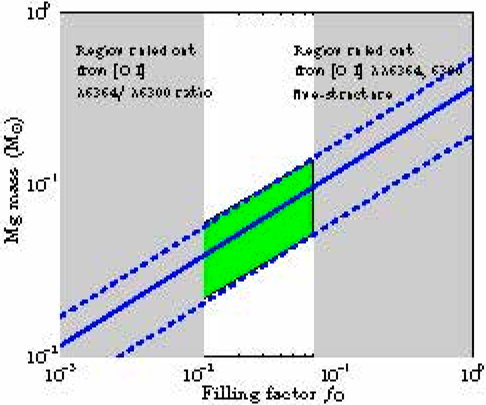
$$\boxed{L \propto f_O \times n_e^2}$$

Magnesium : $n_{MgII} \approx n_{Mg}$ → $\boxed{L \propto M_{Mg} \times n_e}$

Combine → determine

$$\boxed{M_{Mg} \times f_O^{-1/2}}$$

f_O constrained from [O I] 6300, 6364 line ratio and fine-structure.

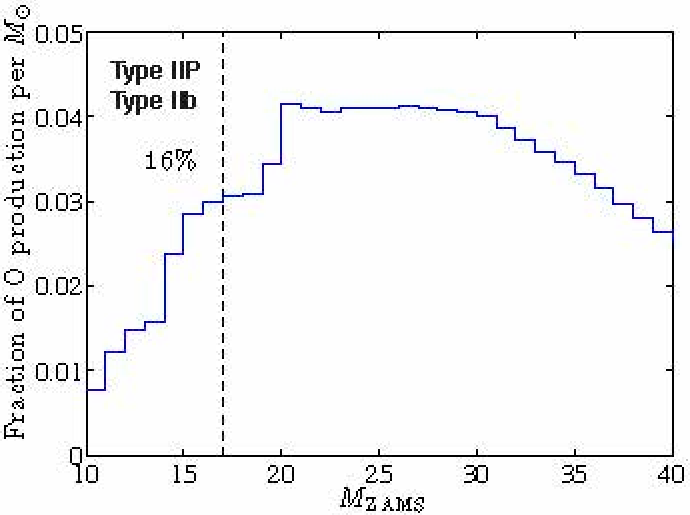


AJ+ 2015(A&A)

CCSNe: Results on oxygen production and M_{ZAMS} from nebular modelling

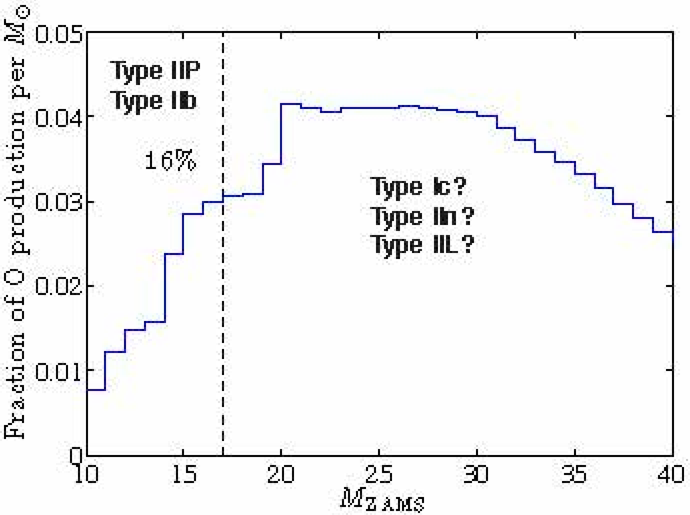
- Type IIP : $M_O = 0.1 - 1\ M_\odot$, $M_{ZAMS} = 10 - 17 M_\odot$ (AJ+2012, AJ+2014, AJ+2015 (MNRAS))
  Other work :
  - Dessart & Hillier 2010 : $M_O \sim 0.8$ in SN 1999em
- Type IIb : $M_O = 0.3 - 0.8\ M_\odot$, $M_{ZAMS} = 12 - 16 M_\odot$ AJ+2015(A&A)
  Other work :
  - Houch & Fransson 1996 : $M_O \sim 0.5\ M_\odot$ in SN 1993J
  - Shivvers, Mazzali+ 2013 : $M_O \sim 0.3\ M_\odot$ in SN 2011dh

Type IIP and IIb SNe make up 2/3 of all CCSNe but contribute $\lesssim$ 16% of total O production?



Based on Woosley & Weaver 1995 model

Type IIP and IIb SNe make up 2/3 of all CCSNe but contribute $\lesssim$ 16% of total O production?



Based on Woosley & Weaver 1995 model

The Type Ic's (no H or He)

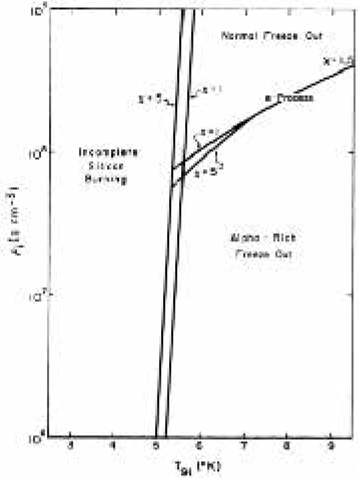
Essentially all work so far single-zone modelling (method 2)

SN	$M(O)$	Reference
1997ef	0.5	Mazzali+2004
1997dq	0.8	Mazzali+2004
1998bw	3-5	Mazzali+2001
2002ap	1.2	Mazzali+2007b
2006aj	1.5	Mazzali+2007a
2007gr	0.8	Mazzali+2010
2009bb	1.1	Pignata+2011
2012ap	0.5	Milisavljevic+2015
PTF10qts	0.7	Walker+2014

Except for SN 1998bw, low/moderate masses, $M_{ZAMS} \lesssim 20 M_{\odot}$

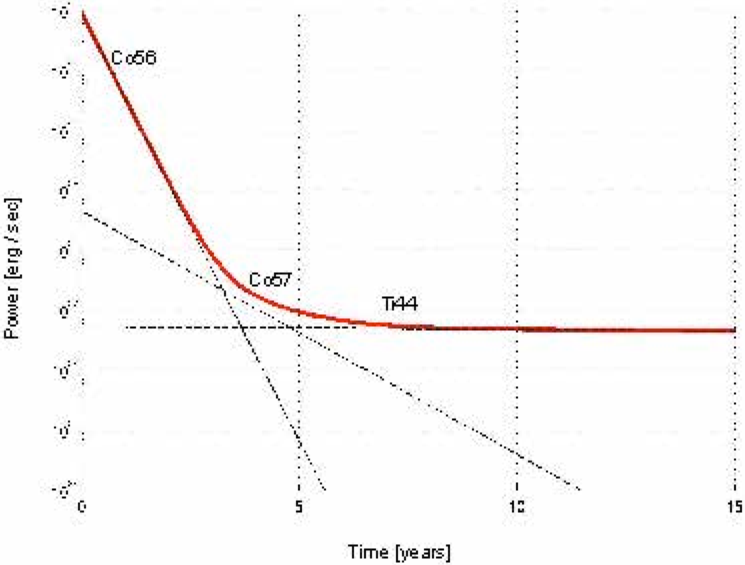
Explosive burning

^{56}Ni, ^{57}Ni, ^{58}Ni, ^{44}Ti, ^{4}He are smoking guns for how the explosion occurred



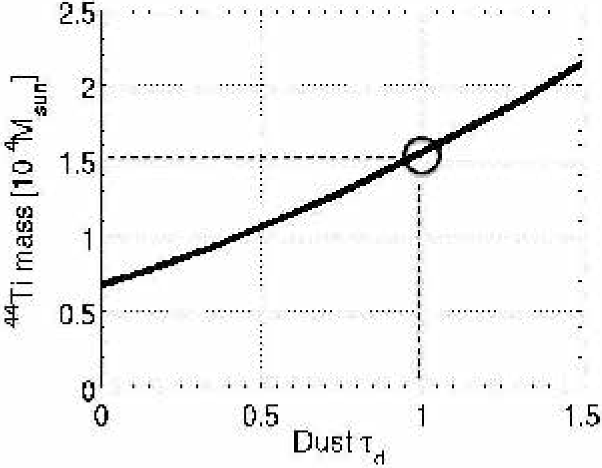
Woosley+1973

Radioactive isotopes : ^{44}Ti powers the SN after 5 years



SN 1987A : $M(^{44}\mathrm{Ti}) = \left(1.5^{+0.5}_{-0.5}\right) \times 10^{-4} M_\odot$ AJ+2011

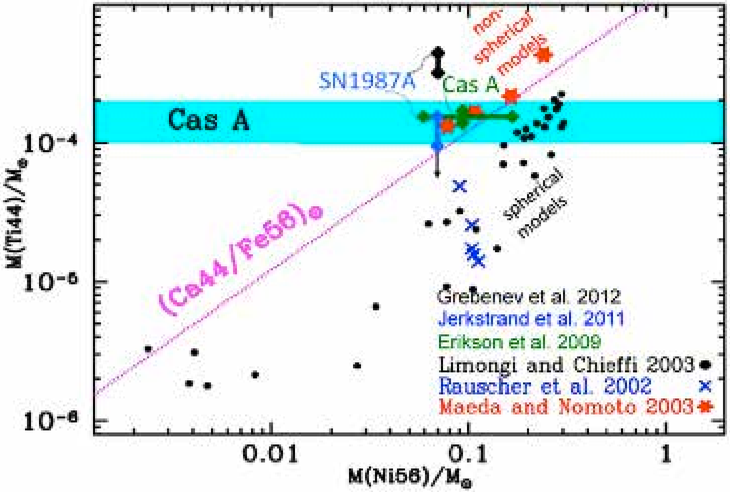
This is a high mass and direct evidence for α-rich freeze-out



Result directly confirmed by gamma-ray decay lines observed with NuSTAR this year (Boggs 2015, Science)

^{44}Ti production in SN 1987A and Cas A

High ^{44}Ti-masses in both → high entropy → need asymmetric explosions



Diehl+ 2014

^{44}Ti production in spherical and aspherical models

Model	Form of the Mass Cut	M_{NS}	$\langle ^{44}Ti/^{56}Ni\rangle$ [a]	$\langle ^{57}Ni/^{56}Ni\rangle$ [b]	$\langle ^{58}Ni/^{56}Ni\rangle$ [c]
		Case A: Value of Y_e for $M > 1.607\ M_\odot$ (=0.494) Artificially Changed to That of $M > 1.637\ M_\odot$ (=0.499)			
S1	S7	1.59	0.74	1.5	2.0
A1	S7	1.57	1.4	2.5	7.1
A2	S7	1.56	2.2	2.8	7.5
A3	S7	1.55	4.3	2.8	6.6
S1	A7	1.59	0.74	1.5	2.0
A1	A7	1.57	2.4	3.2	9.8
A2	A7	1.61	3.7	3.3	8.8
A3	A7	1.68	6.0	3.2	7.1
		Case B: Value of Y_e for $M > 1.5\ M_\odot$ (=0.494) Artificially Changed to That of $M > 1.637\ M_\odot$ (=0.499)			
S1	S7	1.59	0.76	1.5	1.5
A1	S7	1.59	1.4	1.7	1.9
A2	S7	1.58	1.9	1.7	1.8
A3	S7	1.57	4.0	1.8	1.6
S1	A7	1.59	0.76	1.5	1.5
A1	A7	1.60	2.2	1.8	1.5
A2	A7	1.75	2.5	1.8	1.3
A3	A7	1.50	6.0	1.8	0.97

NOTE.—"Mass of NS" means the baryon mass of the central compact object (neutron star).

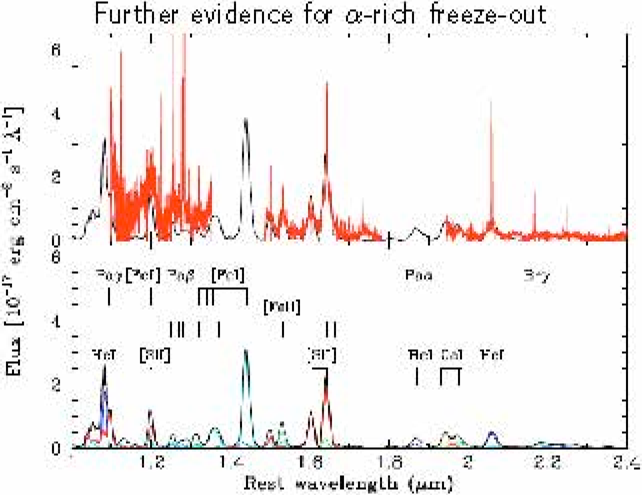
[a] $\langle ^{44}Ti/^{56}Ni\rangle = [X(^{44}Ti)/X(^{56}Ni)]/[X(^{44}Ca)/X(^{56}Fe)]_\odot$.

[b] $\langle ^{57}Ni/^{56}Ni\rangle = [X(^{57}Ni)/X(^{56}Ni)]/[X(^{57}Fe)/X(^{56}Fe)]_\odot$.

[c] $\langle ^{58}Ni/^{56}Ni\rangle = [X(^{58}Ni)/X(^{56}Ni)]/[X(^{58}Ni)/X(^{56}Fe)]_\odot$.

Nagataki+1997

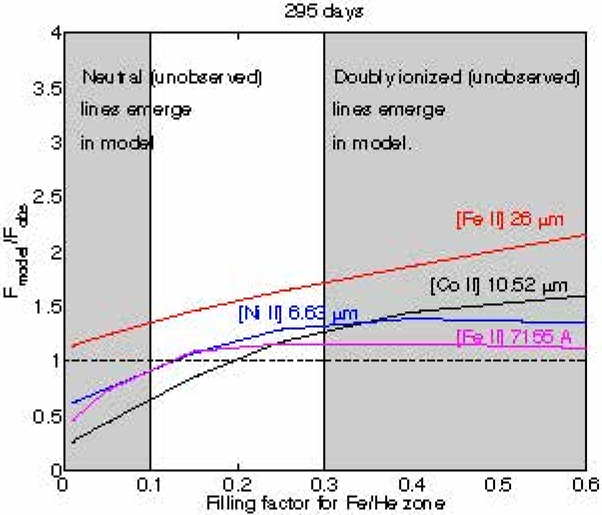
SN 1987A : He I 2.058 μm from core region visible at 20 years



Kjaer+2010

The "^{56}Ni bubble" has a filling factor of ~ 0.2 (SN 2004et)

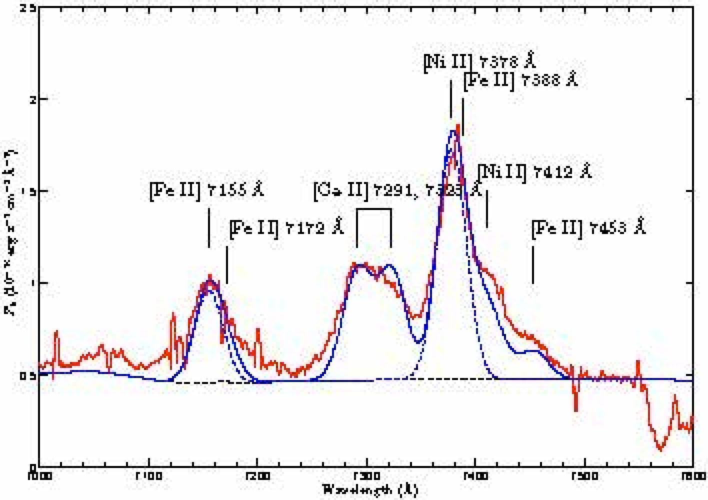
Contains only 1% of the core mass, but expands to 20% of the core volume due to the radioactive heating



AJ+2012

Diagnosis of stable nickel (mainly ^{58}Ni)

$\frac{L([\text{Ni II}]\ 7378)}{L([\text{Fe II}]\ 7155)} \approx 3$ in SN 2012ec. Model in blue.

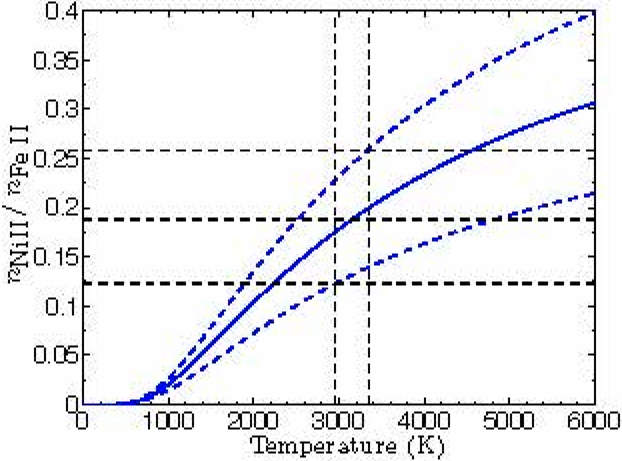


AJ+2015 (MNRAS)

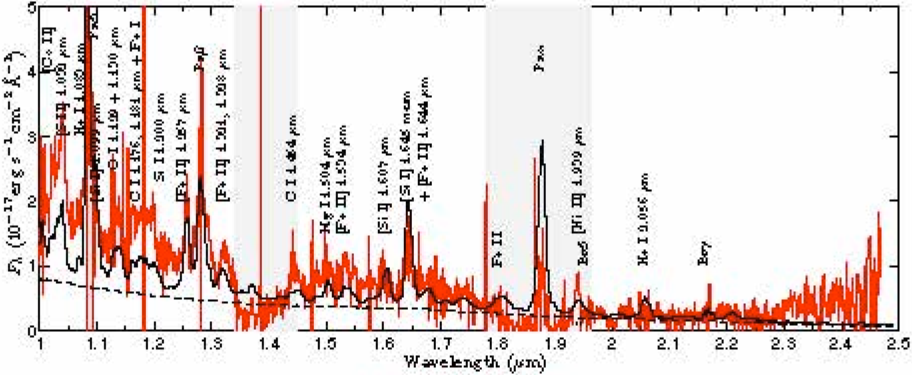
Diagnosis of stable nickel (mainly ^{58}Ni)

Temperature constraint (3000-3300 K) from Fe line strengths and known ^{56}Ni mass →

$$\frac{M(\mathrm{Ni})}{M(\mathrm{Fe})} = 0.2 \pm 0.07 \text{ (3-4 times solar)}$$



Stable nickel in SN 2012ec : [Ni II] 1.939 μm line gives same result $\rightarrow$ robustness



AJ+2015 (MNRAS)

Ni/Fe production ratios in CCSNe

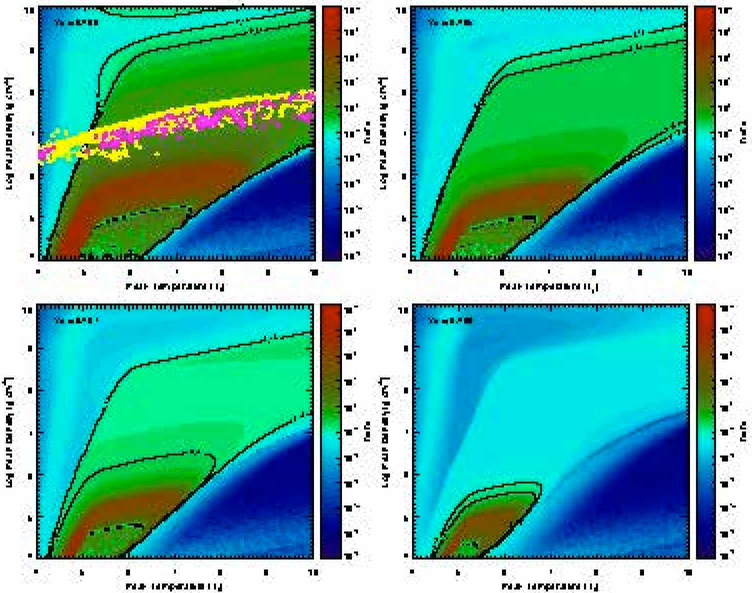
Indication of $\gtrsim 1\times$ solar on average. This has direct implications for burning conditions in thermonuclear SNe to make $\lesssim 1\times$ solar.

SN	Ni/Fe (times solar)	Reference
Crab	60 – 75	Macalpine+1989, Macalpine+2007
SN 1987A	0.5 – 1.5	Rank+1988, Wooden+1993, AJ+2015b
SN 2004et	∼1	AJ+2012
SN 2006aj	2 – 5	Maeda+2007, Mazzali+2007
SN 2012A	∼ 0.5	AJ+2015b
SN 2012aw	∼ 1.5	AJ+2015b
SN 2012ec	2.2 – 4.6	AJ+2015b

AJ+2015 (MNRAS)

What kind of burning can make 3 times solar Ni/Fe?

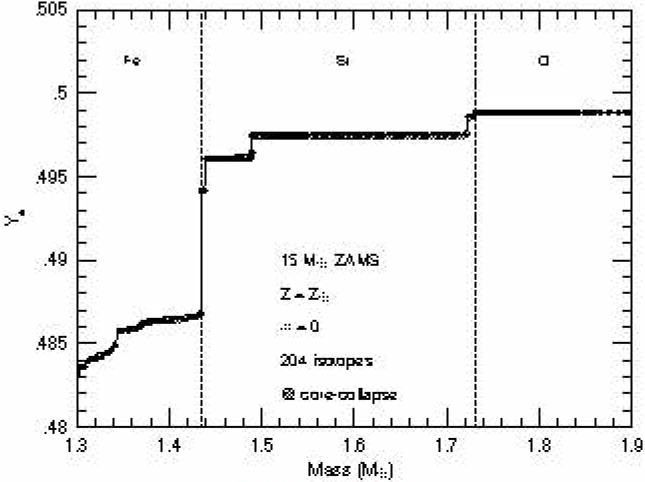
Need $Y_e \sim 0.497$



AJ+2015 (ApJ)

What kind of burning can make 3 times solar Ni/Fe?

Such a Y_e is found in the deep-lying **silicon layer** of the star → mass cut inside the Si/O interface



AJ+2015 (ApJ)

Core-collapse SNe : Summary of nucleosynthesis yields

Hydrostatic burning:

- O : $\mathbf{0.1 - 1} M_{\odot}$ (12 Type IIP and 3 IIb).
- Na : $(\mathbf{1 - 3}) \times \mathbf{10^{-3}} M_{\odot}$ (3 IIPs)
- Mg: $\mathbf{0.02 - 0.14}\ M_{\odot}$ in 2011dh, $\sim \mathbf{0.05}\ M_{\odot}$ (3 IIPs)

Explosive burning:

- Si : $\sim \mathbf{0.05}\ M_{\odot}$ (4 IIP)
- Ca : $\sim \mathbf{5} \times \mathbf{10^{-3}} M_{\odot}$ (3 IIbs)
- ^{44}Ti/^{44}Ca : $(\mathbf{1 - 2}) \times \mathbf{10^{-4}} M_{\odot}$ (SN 1987A)
- Fe (via ^{56}Ni) : $\mathbf{0.01 - 0.1} M_{\odot}$ (12 IIP, 3 IIb)
- Ni : $(\mathbf{3 - 6}) \times \mathbf{10^{-3} M_{\odot}}$ (3 IIPs)

Note:

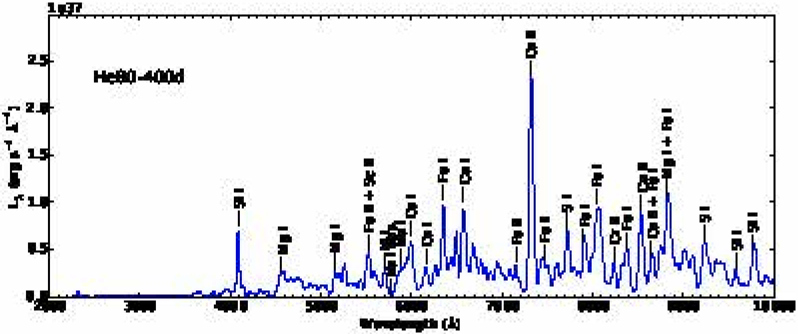
- Helium/carbon burning ashes (O,Na,Mg) consistent with solar production ratios (within factor 2)
- The Ni/Fe ratio from CCSNe is somewhat higher than solar $\rightarrow$ mass cuts in oxygen layer and sometimes in silicon layer
- We have not identified the main source of oxygen in Universe. Except for one or two cases nucleosynthesis yields point to $M_{ZAMS} \lesssim 20$ Msun.

Summary

- Analysis of supernova nucleosynthesis can be made by nebular-phase modelling of e.g. [O I] $\lambda\lambda$6300, 6364, Na I 5890, 5896, Mg I] λ4571, [Ni II] λ7378.
- 2/3 of all CCSNe have hydrogen (Type IIP and IIb). Modelling of these shows production of $0.1 - 1\ M_\odot$ of oxygen, with Mg/O and Na/O produced in roughly solar ratios.
- No evidence yet for massive ($M_{ZAMS} > 17\ M_\odot$) progenitors for these. **Type IIP and IIb SNe are not the main source of oxygen in the Universe. Type Ib/Ic/IIn/IIL SNe?**
- Analysis of explosively synthesized isotopes (^{44}Ti, ^{56}Ni, ^{58}Ni) constrains the explosion mechanism. We find that it must involve strong asymmetries and sometimes eject neutron-rich layers giving high Ni/Fe ratios. The 56Ni bubbles have been demonstrated to expand by factor ~20 during early evolution.

Pair-instability supernovae

What would spectra of exploding 100 Msun stars look like?



AJ+2016 (MNRAS)

Pair-instability supernovae

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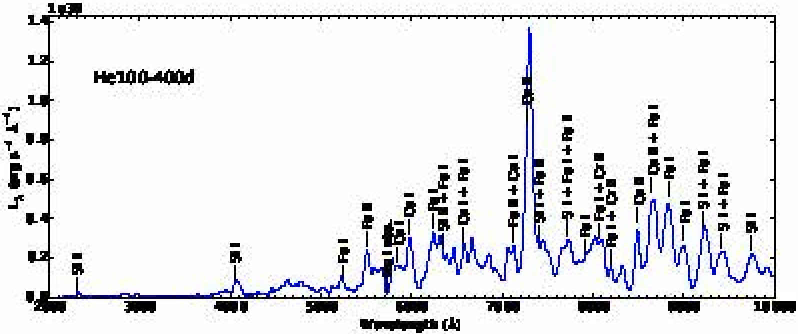

AJ+2016 (MNRAS)

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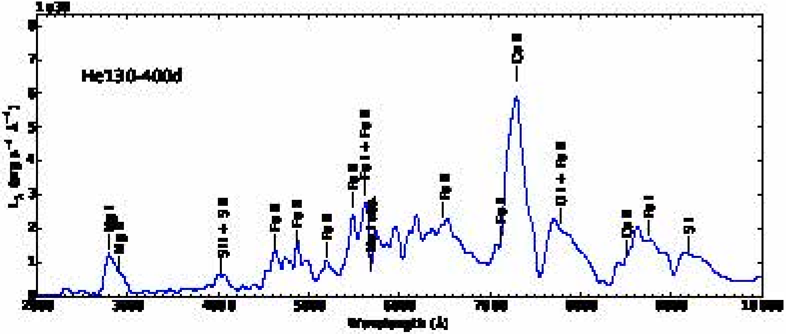

AJ+2016 (MNRAS)

Pair-instability supernovae

No good fit to current PISN candidates (SN2007bi and PTF12dam)