Supernova abundance analysis with NLTE spectral models

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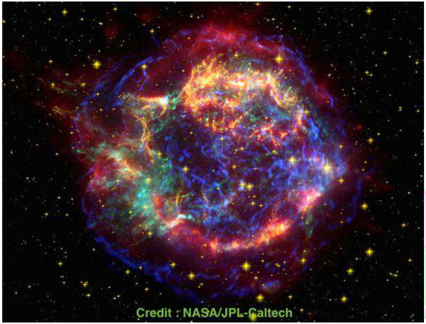

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Outline

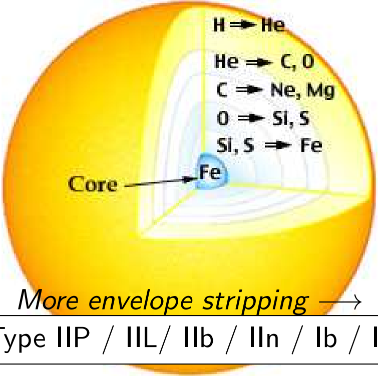
1. Introduction to SNe and their nucleosynthesis
2. Spectral synthesis modelling and the SUMO code
3. Application 1: Type II SNe and the origin of oxygen
4. Application 2: Explosive burning yields of stable nickel
5. Application 3: Superluminous and pair-instability SNe

Supernovae - the deaths of stars

About 1 per century per galaxy

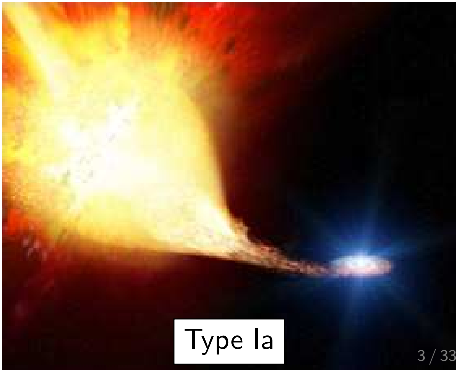
1 Core-collapse of a **massive star** ($M \gtrsim 8\ M_{\odot}$) as it runs out of fuel at the end of its life (80%)

2 Thermonuclear explosion of a **white dwarf** exceeding the Chandrasekhar limit (1.4 $M_{\odot}$) (20%)



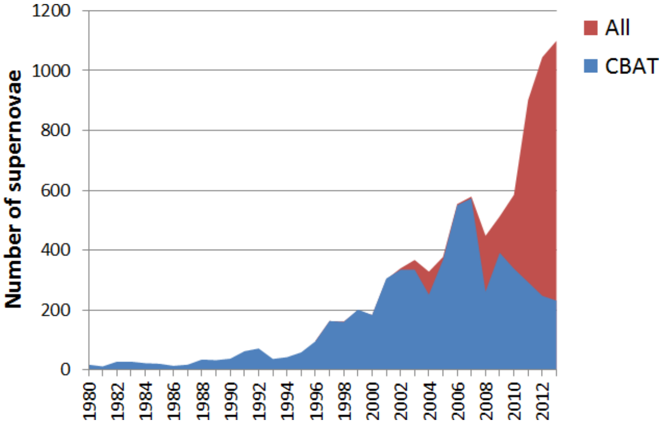
More envelope stripping ⟶

Type IIP / IIL/ IIb / IIn / Ib / Ic



Type Ia

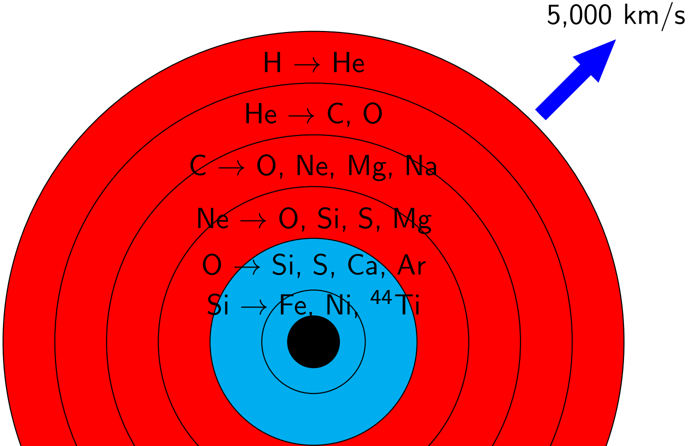
Discovery rates



http://proftimobrien.com/2014/02/supernova-2014j-in-m82/

Nucleosynthesis in massive stars

- Hydrostatic (pre-SN) burning: main source of C, O, F, Ne, Na, Mg, Al, P in Universe
- Explosive SN burning: main source of Si, S, Ar, Ca, Fe, Ni in the Universe



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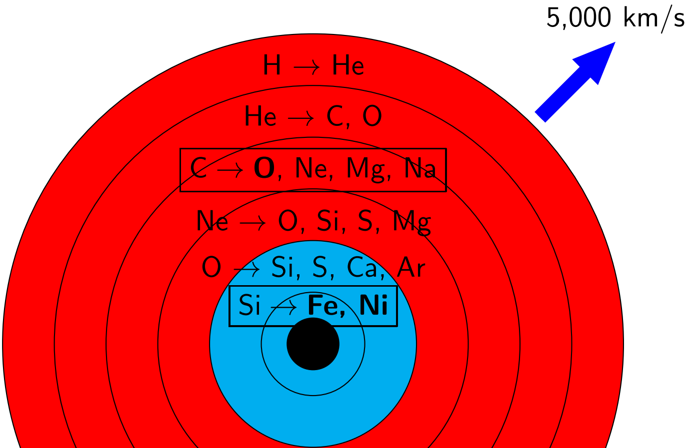
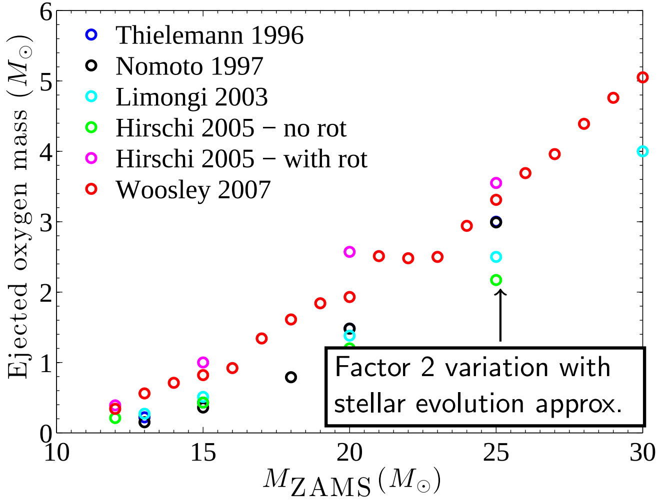


The origin of the elements

Ab.	El.	Main source	Nebular lines seen in SNe
1	H	Big Bang	Many
2	He	Big Bang	He I 5016, 7065, 1.08 μm, 2.06 μm
3	O	CCSN	[O I] 5577, **[O I] 6300, 6364**, O I 7774, O I 9263 + ..
4	C	AGB stars+CCSN	[C I] 8727, 9824/9850, 1.44 μm, CO lines
5	Fe	CCSN+TNSN	[Fe II] 7155, 1.26 μm, 1.64 μm, 18 μm, 26 μm
6	Ne	CCSN	[Ne II] 12.8 μm
7	Si	CCSN+TNSN	[Si I] 1.10 μm, 1.20 μm, 1.60/1.64 μm, SiO lines
8	N	AGB stars	[N II] 6548, 6583
9	Mg	CCSN	Mg I] 4571, 1.50 μm
10	S	CCSN	[S I] 1.082 μm, 1.13 μm
11	Ar	CCSN	[Ar II] 6.99 μm
12	Ni	CCSN+TNSN	**[Ni II] 7378**, 1.93 μm, 6.6 μm, 10.7 μm, [Ni I] 3.1 μm
13	Ca	CCSN	[Ca II] 7300, NIR triplet, Ca I 4200
14	Al	CCSN	-
15	Na	CCSN	Na I 5890, 5896, 1.14 μm

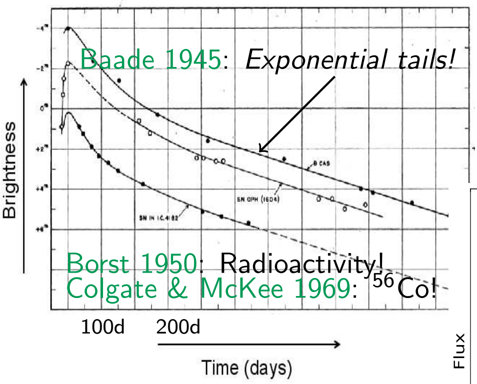
Few quantitative results by direct source analysis

Oxygen nucleosynthesis : theoretical $M(O)$ vs M_{ZAMS}

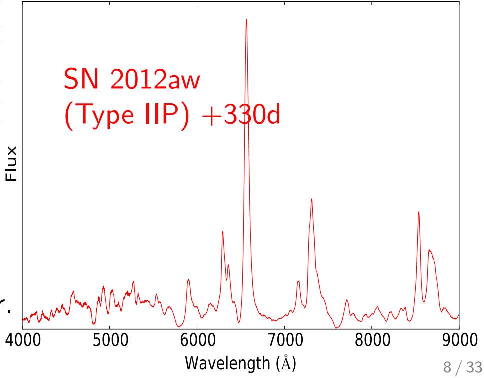


Factor 2 variation with stellar evolution approx.

The nebular phase: an opportunity to see what massive stars are made of and determine nucleosynthesis yields



From ~100 to ~1000 days post explosion



Data collection rate: a few per year.

Total number of objects today: ~50

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

1. **Inverse modelling**: Measure line luminosities + assume uniform conditions and analytic forms valid in certain limits (e.g. LTE, optically thin)

Identify interesting explosion models to test ↓

↑ Identify physical regimes

2. **Forward modelling**: Radiative transfer modelling of multi-zone explosion models with self-consistent nucleosynthesis

Forward modelling: the SUMO code *Jerkstrand 2011, PhD thesis, Jerkstrand, Fransson & Kozma 2011, Jerkstrand+2012*

Radioactive decay and γ-ray transport

Distribution of relativistic electrons

- Spencer-Fano equation

NLTE statistical equilibrium

- 21 of 28 elements from H to Ni, 3 ion. stages, ~100 exc. states each

Temperature

- Heating = cooling

Radiative transfer

- Monte Carlo driver
- Sobolev approximation
- 300,000 atomic lines, 3,000 bound-free continua, free-free, electron scattering

- Code is 1D but allows for mixing by 'virtual grid' option

NLTE solutions and atomic data set

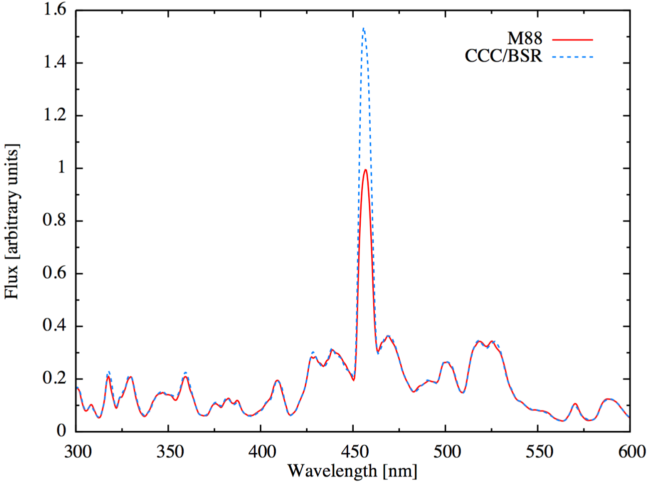
60 atoms/ions in NLTE, $\sim$ 100 levels each $\rightarrow$ 8500 level solutions in each zone and $\sim$300,000 transitions

- Energy levels : Good
- A-values : Good
- Thermal collision strengths : Medium, probably cover most important lines
- Non-thermal collision cross sections Weak, mostly Bethe approximation
- Photoionization cross sections Medium. GS ok, meta-stable some
- Recombination rates Medium
- Charge transfer rates : Weak. 150 rates, lack many important metal-metal

Current reference library maintained at https://star.pst.qub.ac.uk/wiki/doku.php/users/ajerkstrand/start

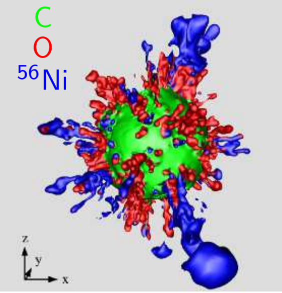
NLTE solutions and atomic data set

New thermal collision strengths from Barlem et al (submitted) in Type Ib SN model

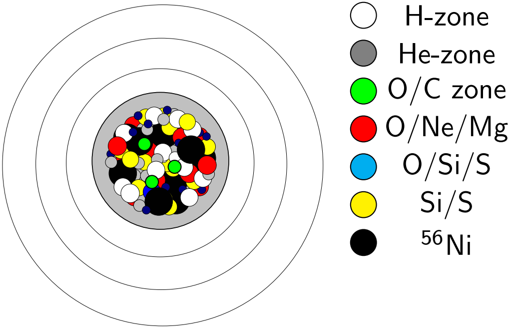


Modelling Type IIP SNe *AJ+2012, AJ+2014*

- Stellar evolution/explosion models from KEPLER (Woosley & Heger 2007) $\rightarrow$ all nucleosynthesis self-consistent
- Consider macroscopic mixing effects of core from 2D/3D models
- Parameterized molecular cooling of O/Si/S and O/C zones

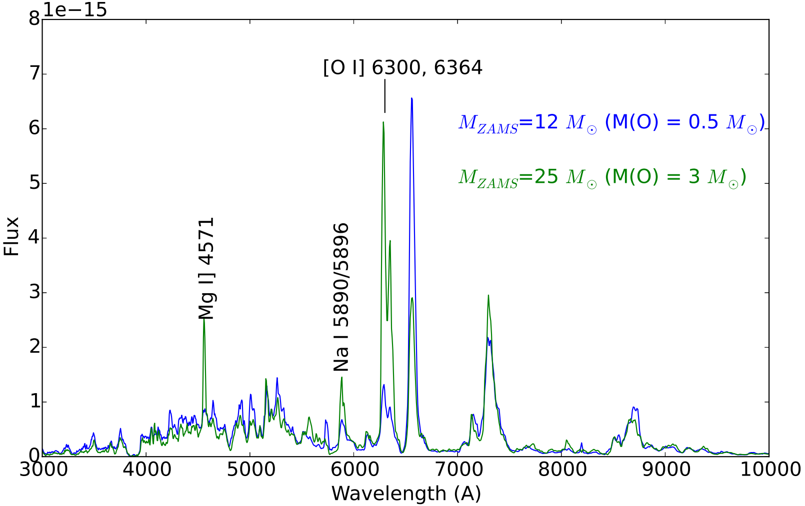


Hammer+2010, 3D model



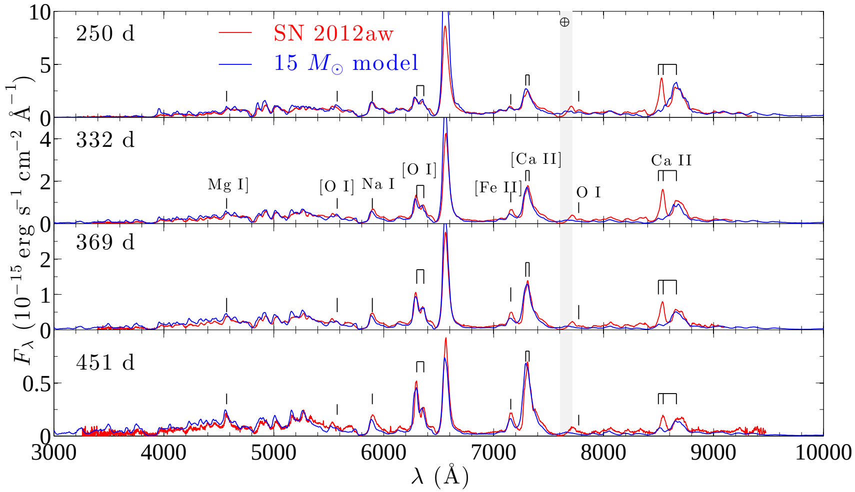
Ejecta setup in SUMO

Type IIP model spectra



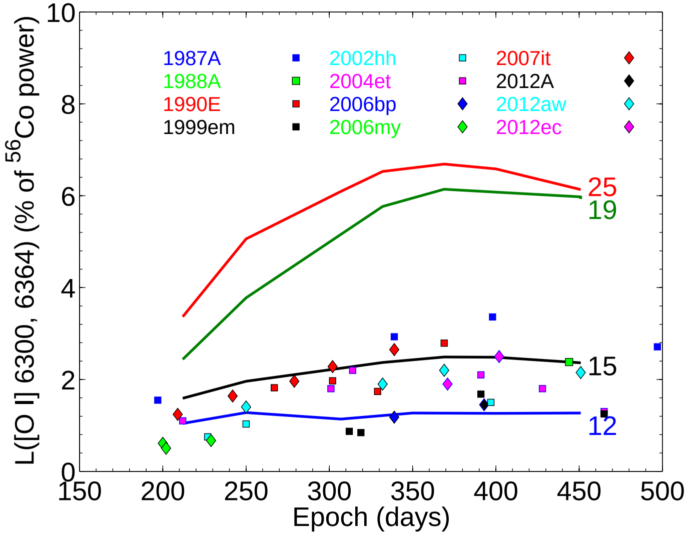
AJ+2012,2014

Type IIP model spectra *AJ+2014*

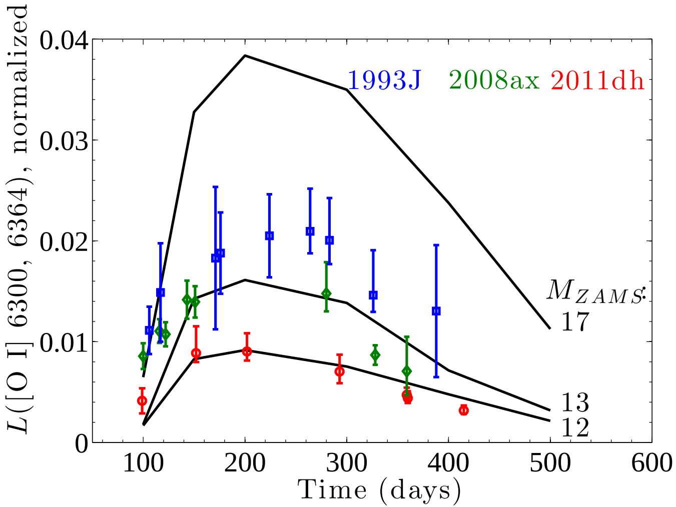


Type IIP model spectra *AJ+2015b (MNRAS)*

Highest mass stars missing : are they collapsing directly to black holes?

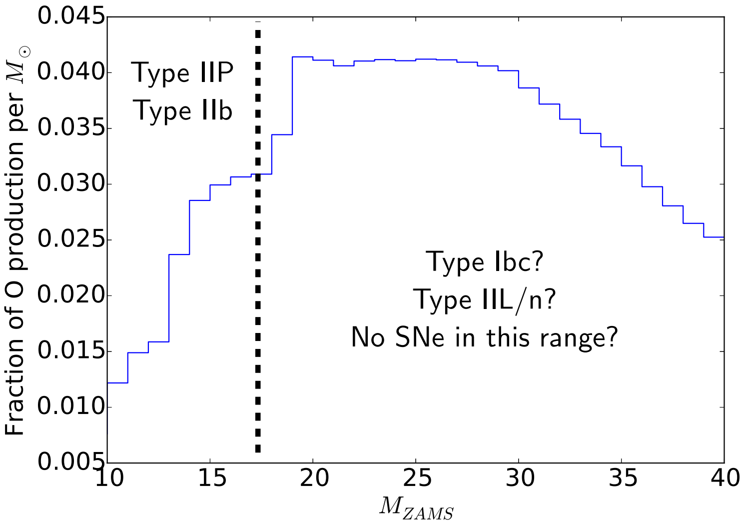


Type IIb SNe: Stars that have lost almost all their H envelope



AJ+2015a (A&A)

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



Relative abundances: example of magnesium

- Most stellar evolution models underpredict Mg/O compared to solar...why?
- Two main diagnostics : Mg I] 4571 and Mg I 1.50 μm.
- Mg I] 4571 : Relatively sensitive to model detail $\rightarrow$ large error bars
- Mg I 1.50 μm : Simpler formation, but less often observed

New method presented in AJ+2015a (A&A):

- Oxygen : $n_{OII} \approx n_e \rightarrow$

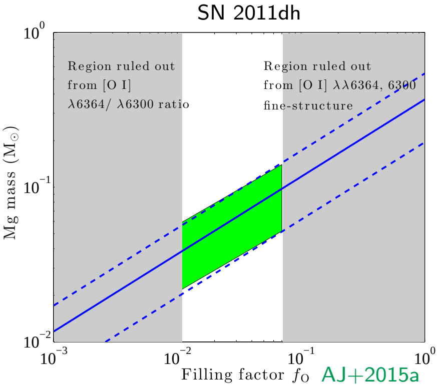
$$L_{O-rec} \propto f_O \times n_e^2$$

- Magnesium :

$n_{MgII} \approx n_{Mg} \rightarrow$

$$L_{Mg-rec} \propto M_{Mg} \times n_e$$

- f_O constrained from [O I] 6300, 6364 properties



AJ+2015a

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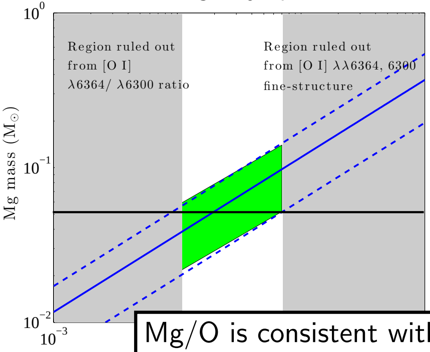
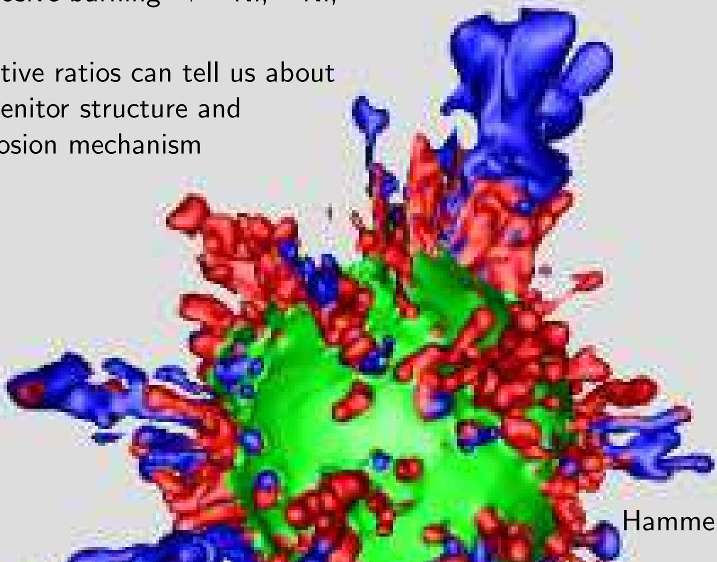
SN 2011dh



Mg/O is consistent with solar ratio in individual

Application 2: Stable nickel (^{58}Ni)

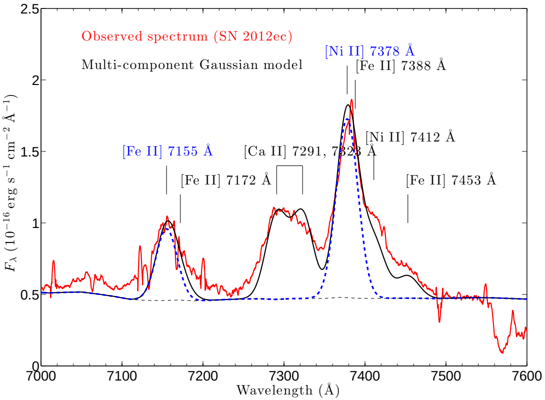
- Explosive burning → ^{56}Ni, ^{57}Ni, ^{58}Ni
- Relative ratios can tell us about progenitor structure and explosion mechanism



Hammer+2010

Stable nickel

- Main diagnostic line: **[Ni II] 7378**

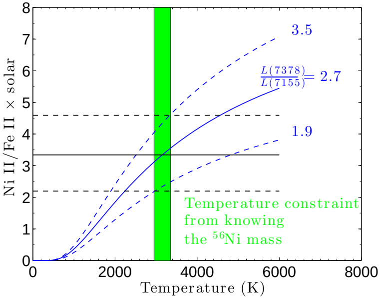


AJ+2015b (MNRAS)

- Use forward model to identify lines present between 7000-7600 Å(7)
- 4-component fit (atomic data constraints remove 4 DOF)
- Determine L_{7378}, L_{7155}, L_{7300}, ΔV

Stable nickel: inverse modelling with guidance from forward model

- Forward model: LTE, optically thin conditions. Then
  - L_{7155} and $M(^{56}\mathrm{Ni})$ determines T
  - T, L_{7378}, L_{7155} gives Ni II/ Fe II ratio

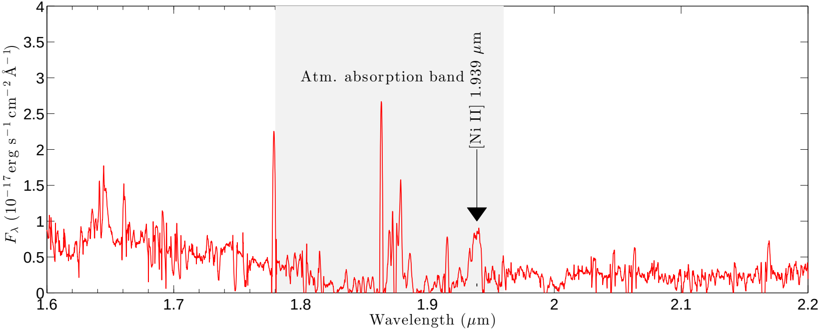


- Forward model: Ni II / Fe II ≈ Ni / Fe

SN 2012ec: Ni/Fe = 3.2 times solar

Stable nickel

- Analysis of [Ni II] 1.93 μm line gives very similar numbers $\rightarrow$ robustness of result



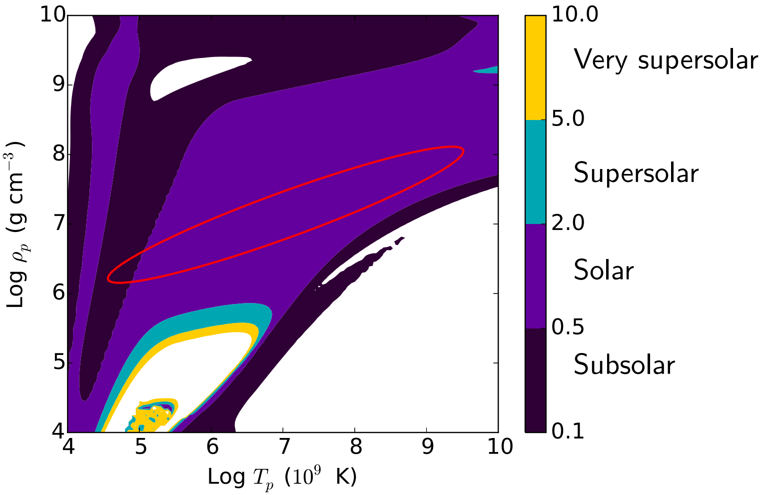
Ni/Fe ratios in 7 CCSNe *AJ+2015b (MNRAS)*

SN	Ni/Fe (times solar)	Reference
Crab	$60 - 75$	Macalpine1989, Macalpine2007
SN 1987A	$0.5 - 1.5$	Rank1988, Wooden1993, AJ+2015
SN 2004et	$\sim$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

- Average ratio $\geq$ solar
- If true in larger samle, Type Ia must make Ni/Fe $\leq$ solar $\rightarrow$ constraints on explosions models
- Sometimes much larger: what does it mean?

Follow-up analysis: what is Ni/Fe ratio diagnostic of?

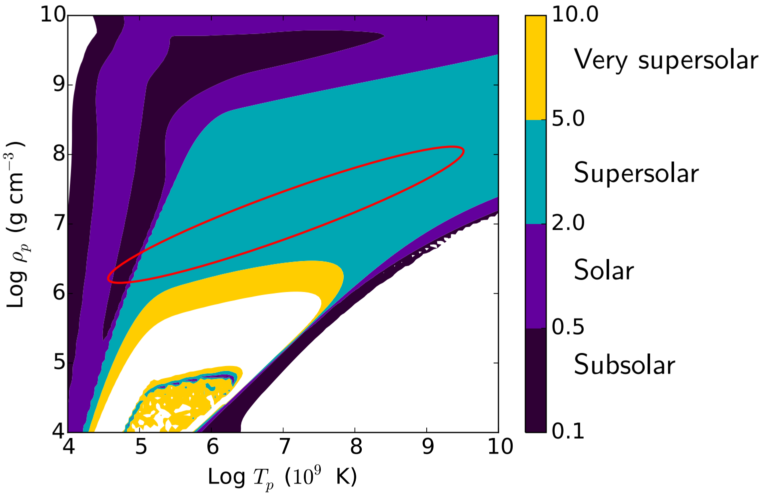
$\boxed{Y_e = 0.499}$: Only good solutions for Ni/Fe $\sim$ solar



AJ+2015c (ApJ)

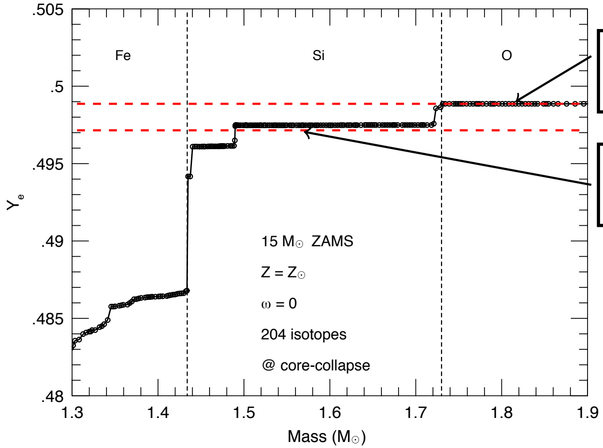
Follow-up analysis: what is Ni/Fe ratio diagnostic of?

$Y_e = 0.497$: Large allowed region opens up for supersolar



AJ+2015c (ApJ)

Ne/Fe is a tracer of which progenitor layer was explosively burnt *Jerkstrand, Timmes, Magkotsios+2015*



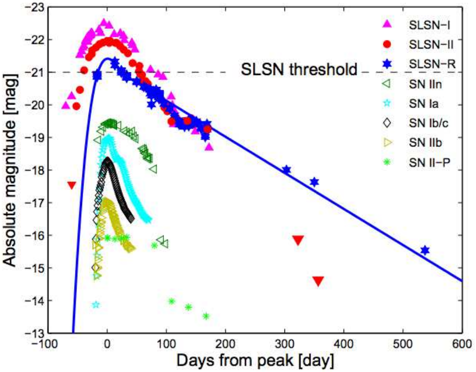
Ye = 0.499 (solar Ni/Fe): Oxygen layer

Ye = 0.497 (supersolar Ni/Fe): Silicon layer

Important constraints on explosion mechanism

Application 3: Superluminous SNe

- A new class of extremely bright SNe discovered about 10 years ago
- Emit $E = 10^{51}$ erg, 100 times more energy than normal SNe
- Power source is unknown.



Gal-Yam 2012

Application 3: Superluminous SNe

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- Power source is unknown.

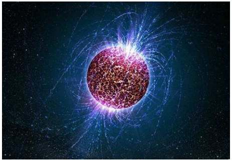
Radioactivity

$E \approx 10^{51} \left(\frac{M(^{56}\mathrm{Ni})}{5 M_\odot}\right)$

Ex: Pair-instability SNe

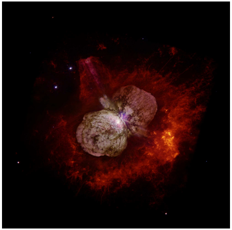
Neutron star rotation energy

$E \approx 10^{51} \left(\frac{P}{5\ \mathrm{ms}}\right)^{-2}$

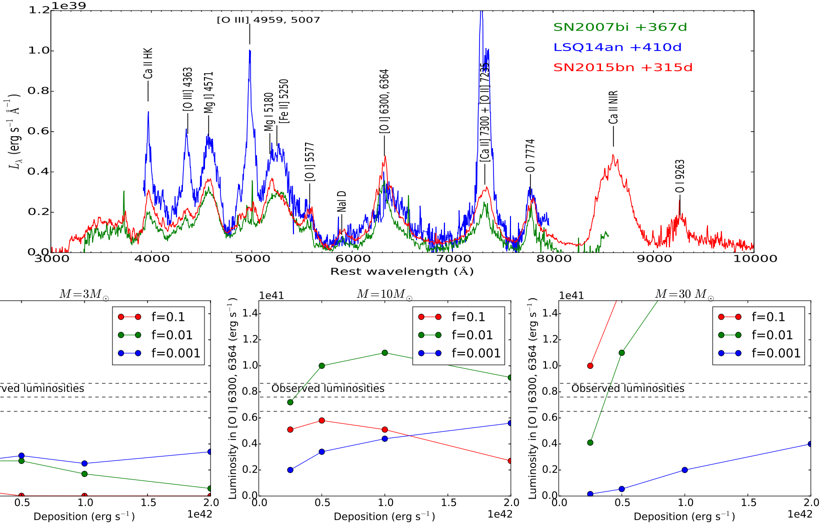


Ejecta kinetic energy

$E \approx 10^{51}$



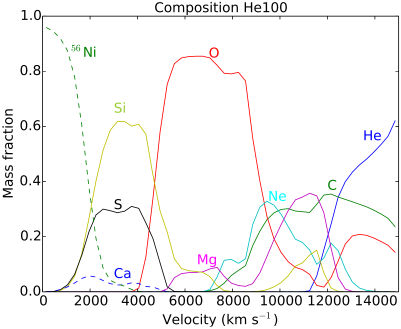
Type Ib/c-BL SNe : Highest O masses observed so far ($\sim 5\ M_\odot$) AJ+2017



Multi-zone modelling: Pair-instability supernovae *Jerkstrand, Smartt & Heger 2016*

Explosion models (Heger & Woosley 2002)

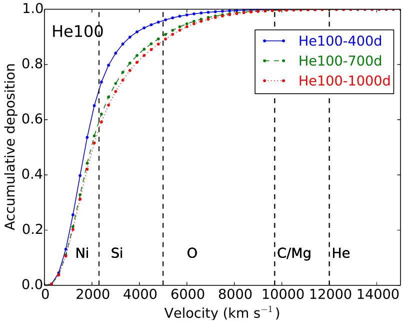
Model	M_{ZAMS} ($M_\odot$)	O ($M_\odot$)	Si ($M_\odot$)	S ($M_\odot$)	^{56}Ni ($M_\odot$)	SN Type
He80	$\sim$140	47	14	5	0.1	normal SN
He100	$\sim$200	44	23	10	6	superlum.
He130	$\sim$260	33	24	11	40	superlum.



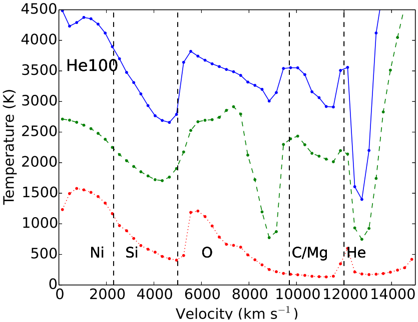
- Macroscopic mixing small (e.g. Joggerst & Whalen 2011, Chatzopoulus+2013) $\rightarrow$ can use 1D ejecta models to good accuracy.

Pair-instability SNe: Physical conditions *Jerkstrand, Smartt & Heger 2016*

- Gamma rays are trapped in deep-lying ^{56}Ni, Si, S, Ca layers

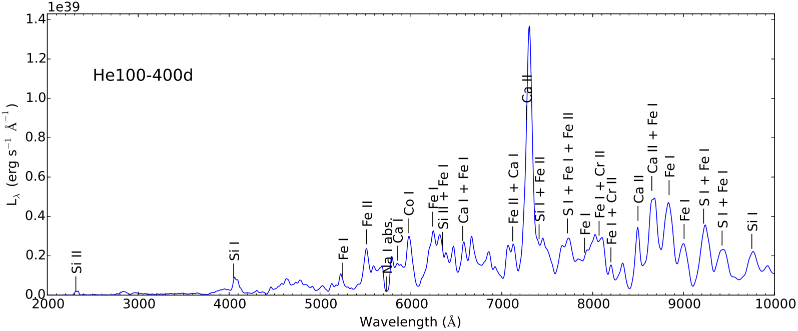


- Gas is cold ($T < 4000$ K) and neutral ($x_e < 1$)



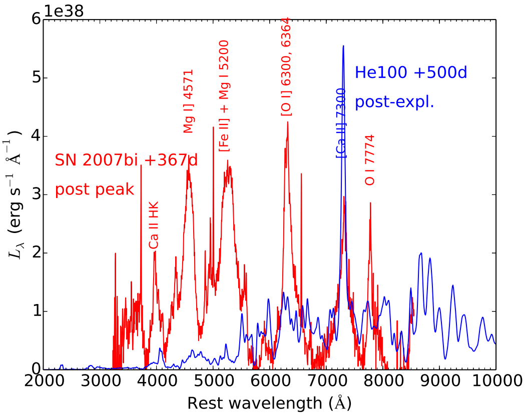
$\rightarrow$ Expect lines of Fe I, Si I, S I, Ca I, Ca II,...

Pair-instability SNe: model spectra at +400d



- Forest of Fe I, Ca I, Ca II, S I, Si I lines.
- Cold gas + strong line blocking → **dim below 6000 Å**

Pair-instability SNe: fit to candidates is poor



Jerkstrand, Smartt, & Heger+2016 (MNRAS)

- No good fit to current PISN candidates (SN2007bi, PTF12dam, LSQ14an, 2015bn) → PISNe probably remain to be discovered

Summary

- Supernovae are important sources of nucleosynthesis, but so far we have few quantitative results on production in individual sources and classes
- Spectral modelling of Type II SNe with SUMO indicate low/moderate amounts of **oxygen**, and origin in low-mass stars ($M_{ZAMS} \sim 8 - 18$). Some results on **abundance ratios** are becoming available, e.g. Mg/O
- The [Ni II] 7378 line can be used to determine the **amount of ^{58}Ni** produced in the explosion. A sample of CCSNe show Ni/Fe $\sim$ solar, but in a few cases much higher. Follow-up analysis with nucleosynthesis simulations show high values requires **high neutron excess** of the fuel, only found in the **silicon shell** of the progenitor. This puts constraints on explosion models.
- For superluminous SNe, spectral grid shows **highest O masses** (> 10 $M_\odot$) **found in any SN so far**. Origin must be very high mass stars.
- **Pair-instability SN models** fail in spectroscopic modelling tests : not confirmed to exist