Determining nucleosynthesis yields in supernovae with spectral modelling

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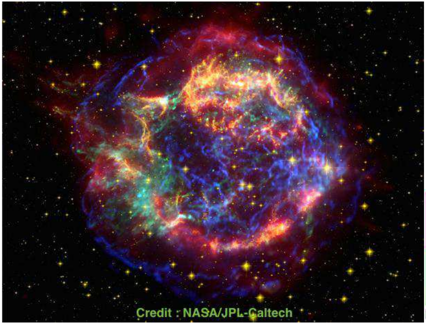


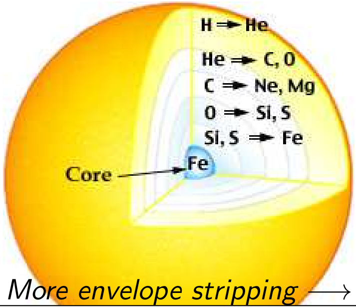
Outline

1. Introduction to SNe and their nucleosynthesis
2. Spectral synthesis modelling and the SUMO code
3. Application 1: Hydrostatic burning yields : Oxygen in Type II SNe
4. Application 2: Explosive burning yields : Ni and Fe

Supernovae - the deaths of stars

Rate: About 1 per century per galaxy. Discovery rate: 1000/year

1 Core-collapse of a **massive star** ($M \gtrsim 8\ M_\odot$) as it runs out of fuel at the end of its life (75%)

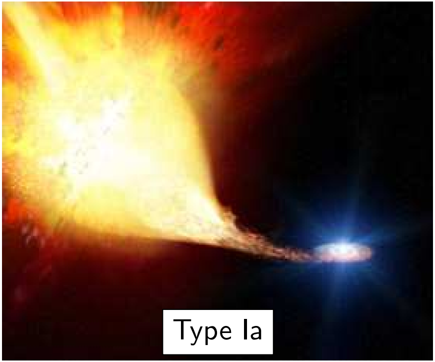


More envelope stripping ⟶

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

Credit: www.phys.olemiss.edu

2 Thermonuclear explosion of a **white dwarf** exceeding the Chandrasekhar limit (1.4 $M_\odot$) (25%)



Type Ia

Credit: hetdex.org

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

Mostly theory: Few quantitative results by direct source analysis

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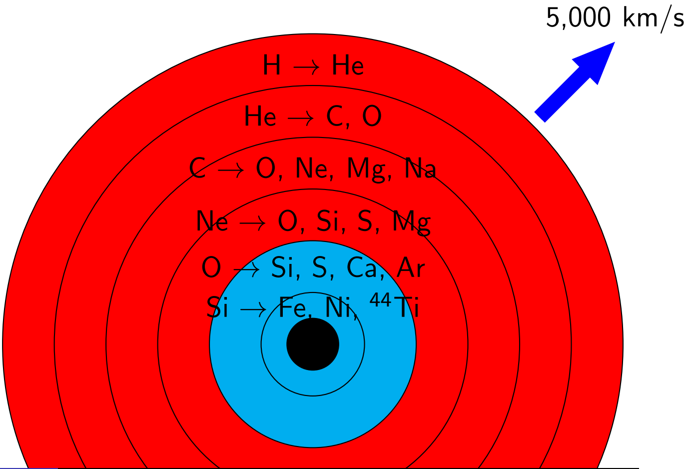
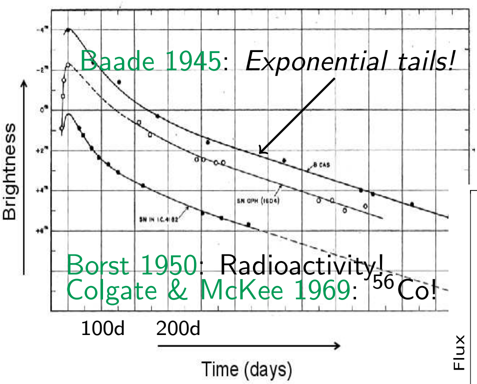
Elements with $Z > 30$ hard to see due to rapidly declining abundances

Nucleosynthesis in massive stars

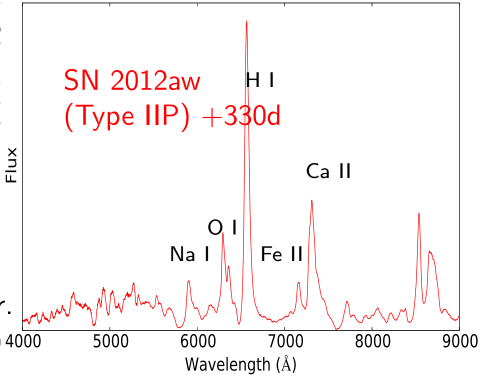
- Hydrostatic (pre-SN) burning: main source of C, O, F, Ne, Na, Mg, Al, P in Universe
- Explosive SN burning: main source of Si, S, Ar, Ca, Fe, Ni in the Universe



The nebular phase: an opportunity to see what supernovae 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

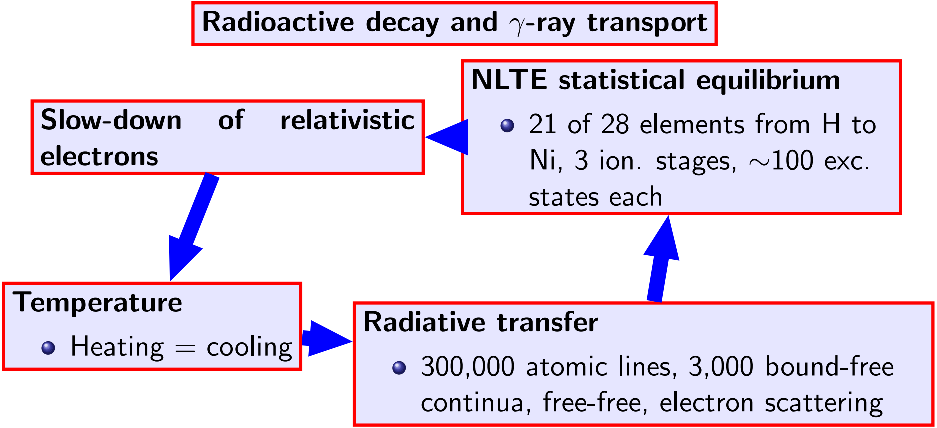
How can we determine element masses in SN ejecta from their nebular spectra?

1. **Inverse modelling**: Measure line luminosities + assume uniform conditions and analytic forms valid in certain limits (e.g. LTE, optically thin)
   - Accuracy varies a lot depending on line/epoch

Identify interesting explosion models to test ↓ ↑ Identify physical regimes

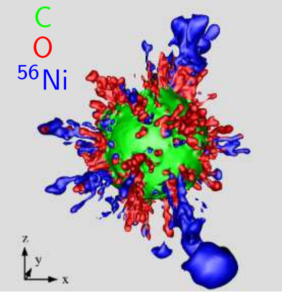
2. **Forward modelling**: Radiative transfer modelling of multi-zone explosion models with self-consistent nucleosynthesis
   - Time-consuming
   - If a line doesnt fit, is abundance wrong or something else in model?

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

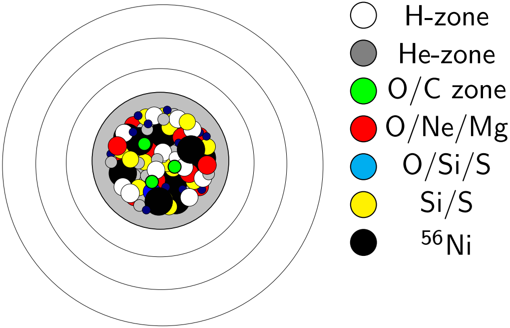


- Code is 1D but allows for mixing by 'virtual grid' option

- Stellar evolution/explosion models from KEPLER (Woosley & Heger 2007) → all nucleosynthesis self-consistent
- Consider **macroscopic mixing** effects of core from 2D/3D models

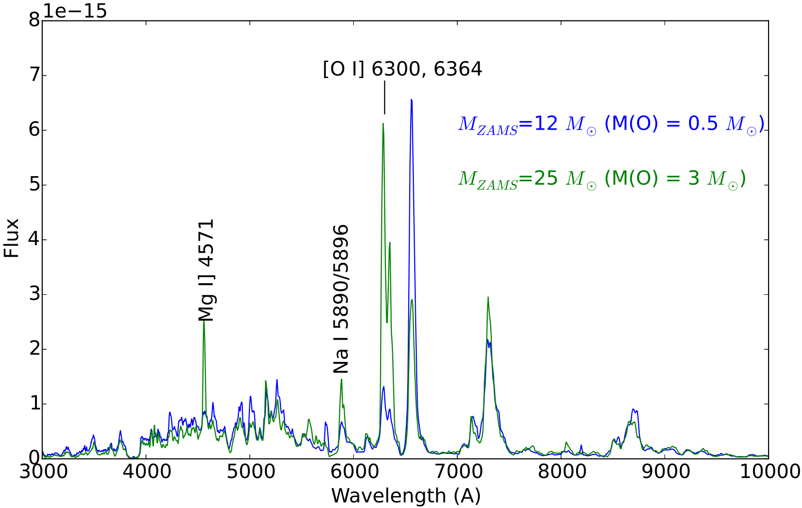


Hammer+2010, 3D model



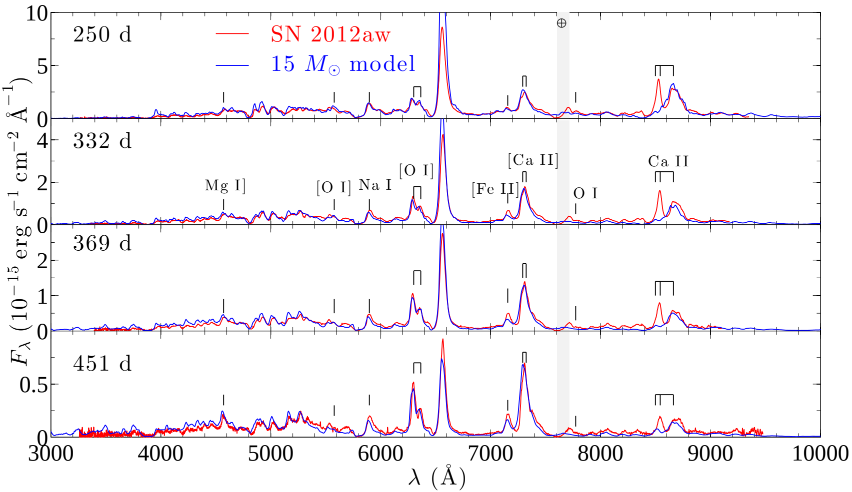
Ejecta setup in SUMO

Type IIP model spectra



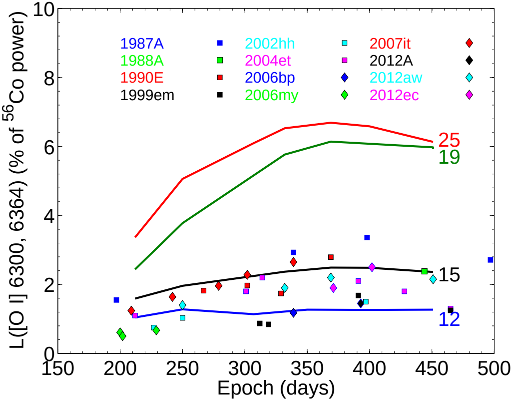
Jerkstrand+2012,2014

Type IIP model spectra *Jerkstrand+2014*



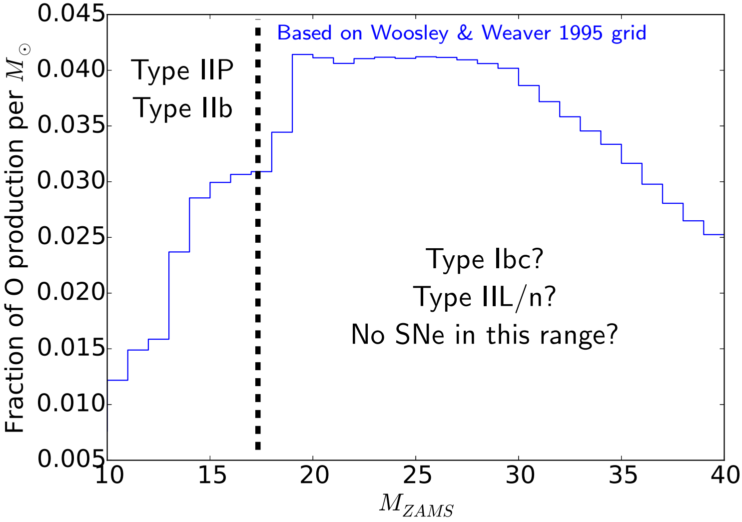
- First "well" matching SN models like these have only emerged in the last ∼5 years → modelling now at a point where we can start to infer abundances

- High mass stars ($M > 17\ M_{\odot}$) missing : are they collapsing directly to black holes or explode as other SN types?



- Same results for Type IIb SNe Jerkstrand, Ergon, Smartt+2015 (A&A)

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

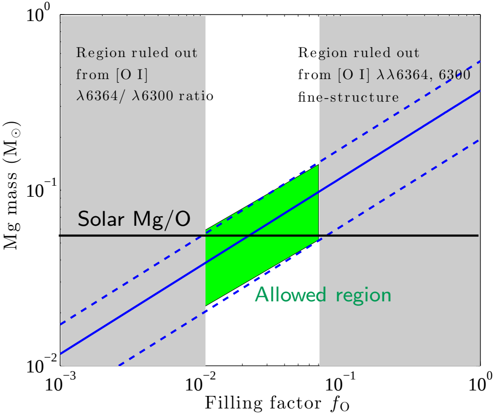


Relative abundances: example of magnesium

- Most stellar evolution models underpredict Mg/O compared to solar by factor ∼2...why?
- Main diagnostic line : Mg I 1.50 μm.

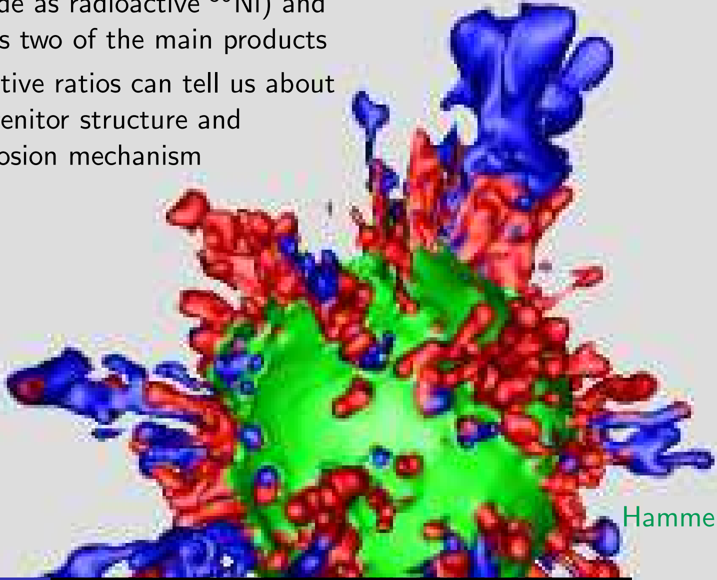
New method presented in Jerkstrand+2015 (A&A):

- Show Mg/O ≈ 0.5-2 times solar in SN 2011dh (IIb)
- Sample study under way



Application 2: Explosive yields of Ni and Fe

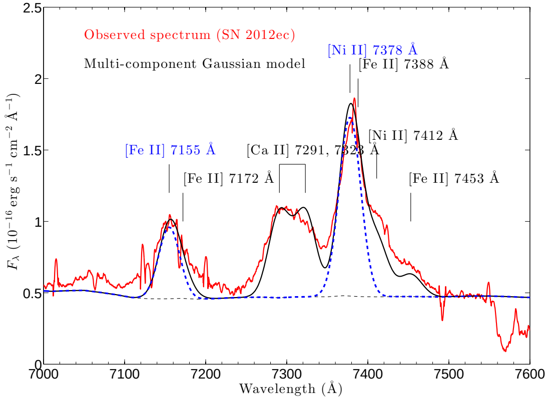
- Explosive silicon burning → Fe (made as radioactive ^{56}Ni) and Ni as two of the main products
- Relative ratios can tell us about progenitor structure and explosion mechanism



Hammer+2010

Stable nickel

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



- Determine L_{7378}, L_{7155}, ΔV
- Ratio depends weakly on temperature, and Fe and Ni have similar ionization $\rightarrow$ robust mass ratio

Jerkstrand, Smartt, Sollerman+2015 (MNRAS)

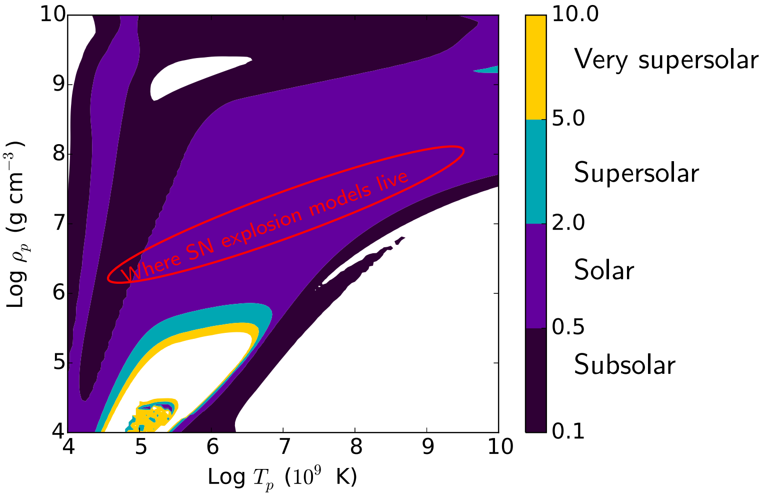
Ni/Fe ratios in 7 CCSNe *Jerkstrand,Smartt,Sollerman+2015 (MNRAS)*

SN	Ni/Fe (times solar)	Reference
Crab	60 – 75	Macalpine1989, Macalpine2007
SN 1987A	0.5 – 1.5	Rank1988, Wooden1993, AJ+2015
SN 2004et	∼1	AJ+2012
SN 2006aj	2 – 5	Maeda+2007, Mazzali+2007
SN 2012A	∼ 0.5	AJ+2015
SN 2012aw	∼ 1.5	AJ+2015
SN 2012ec	2.2 – 4.6	AJ+2015

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

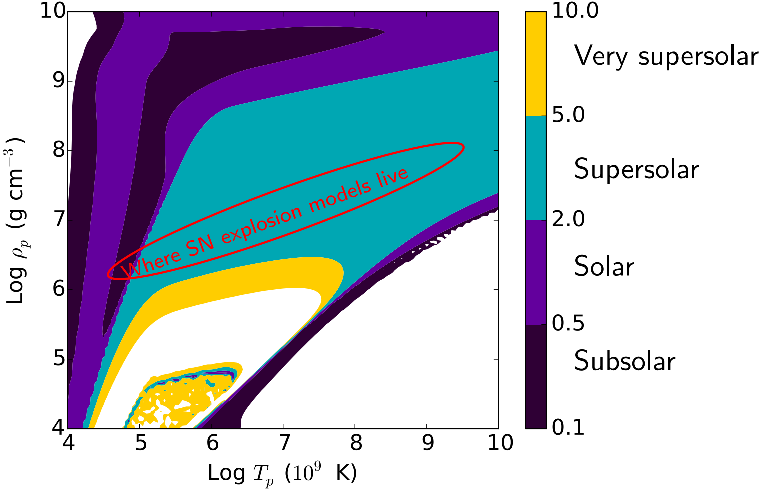
$$\boxed{Y_e(= \frac{N_p}{N_n + N_p}) = 0.499}$$

: Only good solutions for Ni/Fe $\sim$ **solar**



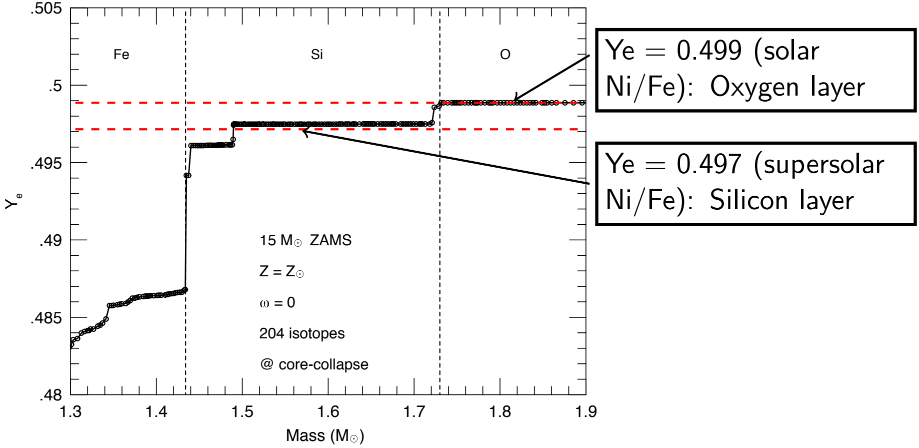
Follow-up analysis: what is Ni/Fe ratio diagnostic of?

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



Jerkstrand, Timmes, Magkotsios+2015 (ApJ)

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



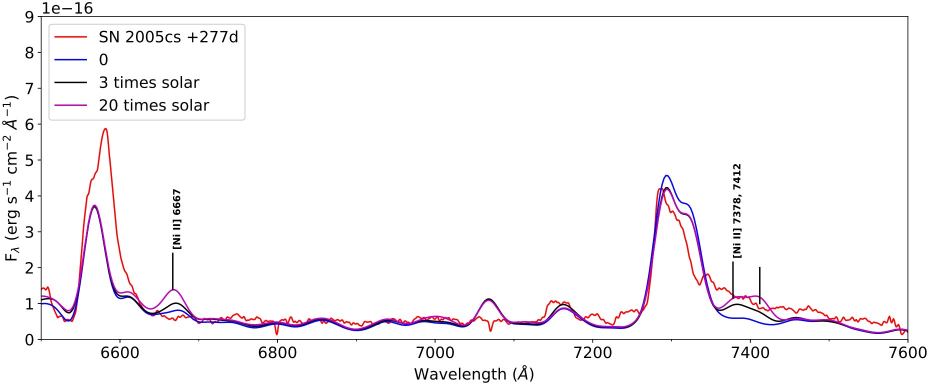
- Important constraints on explosion mechanism, as well as consequences for yield grids used in galactochemical evolution models

Electron capture supernovae

- Hypothesized explosion mechanism for $\sim$8-9 $M_\odot$ stars
- Despite small mass range, steep IMF $\rightarrow$ $\sim$10% of all core-collapse SNe
- May dominate production of a few heavy elements Z=30-40 (Zn,Ge,As,Se,Br,Kr,Rb,Sr,Y,Z) Wanajo2011

Electron capture supernovae

- Spectral models suggest **no known SN matches expections from ECSN nucleosynthesis** (e.g. >20 times solar Ni/Fe) → remain to be discovered and may not exist Jerkstrand, Ertl, Janka, Mueller in prep.
- Crab SN remnant not included in analysis



The two radioisotopes ^{57}Ni and ^{44}Ti

- SN 1987A: only SN with 4 explosive burning isotopes (^{56}Ni, ^{57}Ni, ^{58}Ni, ^{44}Ti) determined

Ratio	Ratio (times solar)	Reference
^{44}Ti/^{56}Ni	1.6 ± 0.5	Jerkstrand, Fransson, Kozma 2011 Boggs 2016, Science
^{58}Ni/^{56}Ni	~ 1	Jerkstrand+2015 (MNRAS)
^{57}Ni/^{56}Ni	1-2	Kurfess 1992

- A high-entropy burning of O-shell fuel is needed
  - Strong asymmetry Nagataki 1998,2000
  - Neutrino wind Wongwathanarat+2017
- Cas A : Similar mass of ^{44}Ti ($1.5 \times 10^{-4} M_\odot$), but ^{56}Ni mass unknown. Renaud+2006

Summary

- Nucleosynthesis yields in SNe an be analyzed in the nebular phase. Clear signals from newly produced He, C, N, O, F, Ne, Na, Mg, Si, S, Cl, Ar, Ca, Fe, Co, Ni have been identified
- Radiative transfer models have in the last $\sim$5 years advanced to the point that model spectra resemble observed spectra
- Type II SNe appear to come from low-mass stars ($8 < M_{ZAMS} < 17 M_\odot$) with $< O >= 0.4 M_\odot$. The large O masses of 1.5 $M_\odot$ per SN used in standard chemical evolution models is not confirmed by observations.
- Mg/O and Na/O ratios generally close to solar
- As with progenitor analysis, nucleosynthesis analysis indicates that many stars with $MZAMS > 18 M_\odot$ may collapse directly to black holes
- However, some massive stars definately explode (hypernovae)
- Ni/Fe ratios in core-collapse SNe are mostly around solar, but sometimes significantly higher.
- Solar values means burning of O-shell fuel, supersolar burning of Si-shell fuel.
- No evidence for electron-capture SNe from nebular spectra