Supernova abundance analysis in the nebular phase

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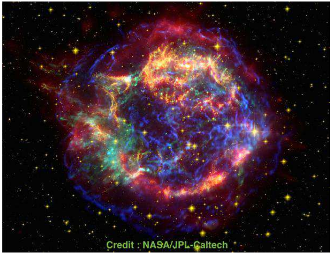
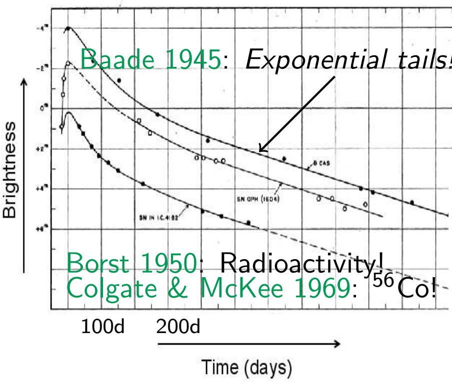


Outline

1. Introduction to supernova spectral modelling in the nebular phase
2. Diagnosing hydrostatic burning yields and progenitor masses
3. Diagnosing explosive burning yields and explosion mechanism
4. First 3D models : spectral tests of the neutrino explosion paradigm

The nebular phase: an opportunity to see what exploded stars are made of

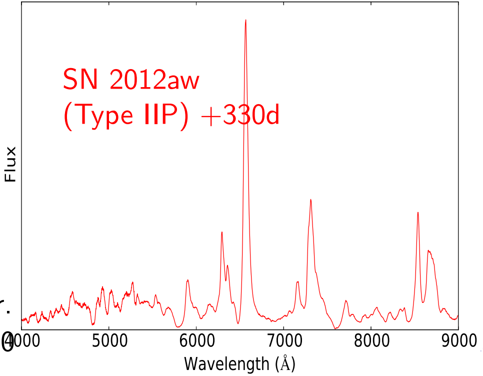


Baade 1945: *Exponential tails!*

Borst 1950: Radioactivity!

Colgate & McKee 1969: ^{56}Co!

From ∼100 to ∼1000 days post explosion



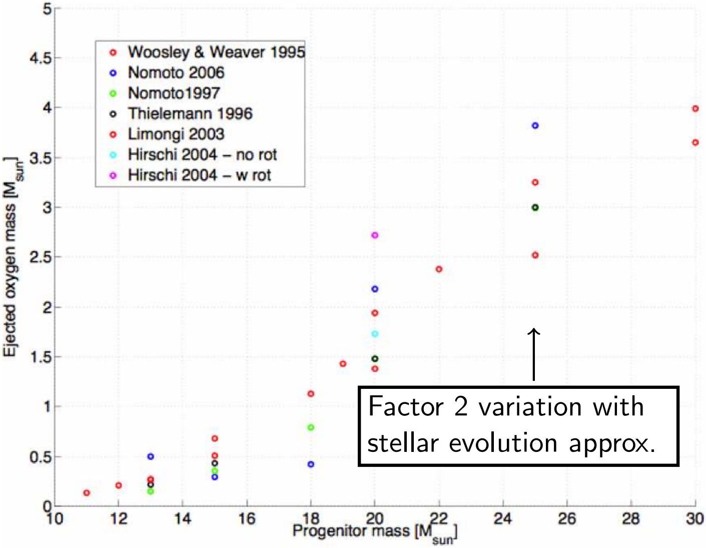
SN 2012aw (Type IIP) +330d

Data collection rate: a few per year.

Total number of objects today:∼100

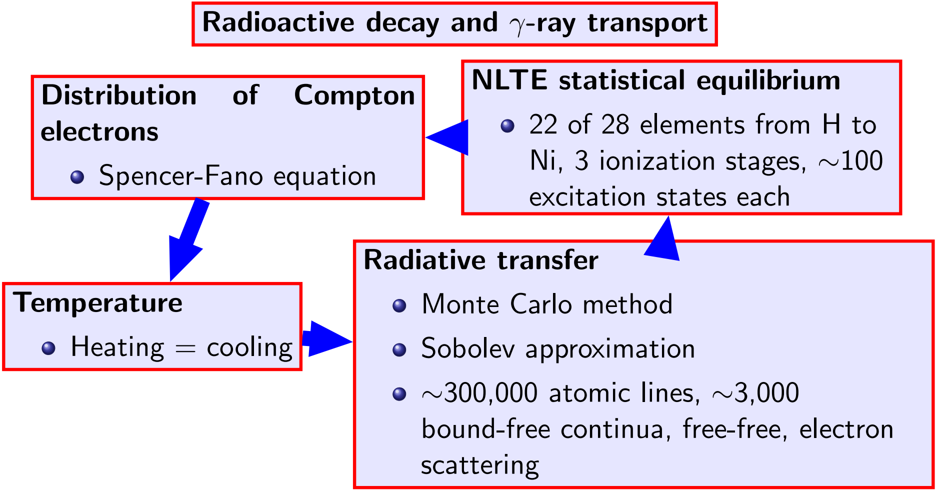
An opportunity to determine progenitor masses

Theoretical ejected oxygen masses vs M_{ZAMS}:



Factor 2 variation with stellar evolution approx.

Spectral synthesis modelling with the SUMO code *Jerkstrand 2011, PhD thesis, Jerkstrand, Fransson & Kozma 2011, Jerkstrand+2012, later updates.*



Radioactive decay and γ-ray transport

NLTE statistical equilibrium

- 22 of 28 elements from H to Ni, 3 ionization stages, ~100 excitation states each

Distribution of Compton electrons

- Spencer-Fano equation

Temperature

- Heating = cooling

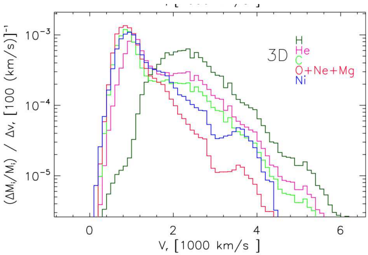
Radiative transfer

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

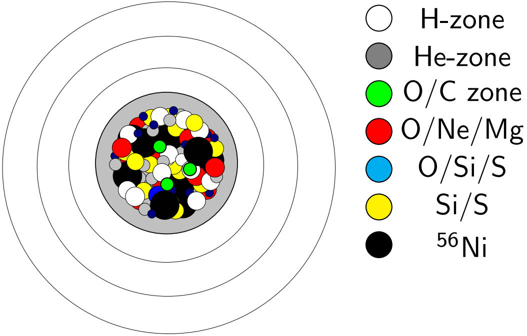
- Code is 1D but allows for mixing by 'virtual grid' option

Modelling Type IIP SNe *Jerkstrand+2012,2014,2015*

- Stellar evolution/explosion/nucleosynthesis models from KEPLER (Woosley & Heger 2007)
- Consider macroscopic mixing effects of core from multi-D models
- Describe composition regions statistically: only possible in Monte Carlo radiative transfer.

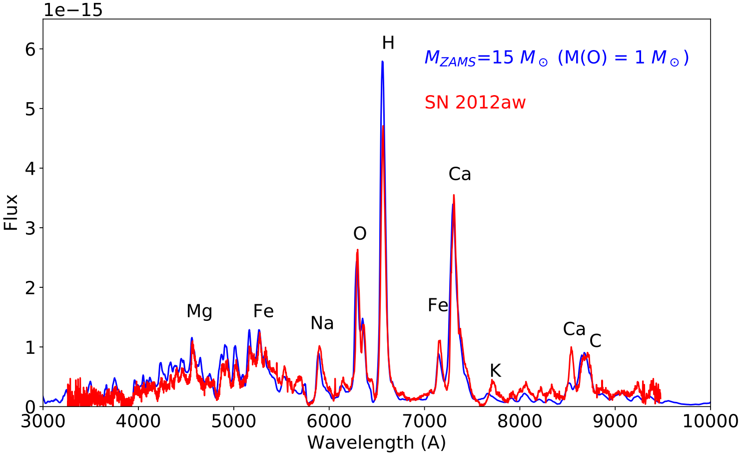


Hammer+2010, 3D model



Ejecta setup in SUMO

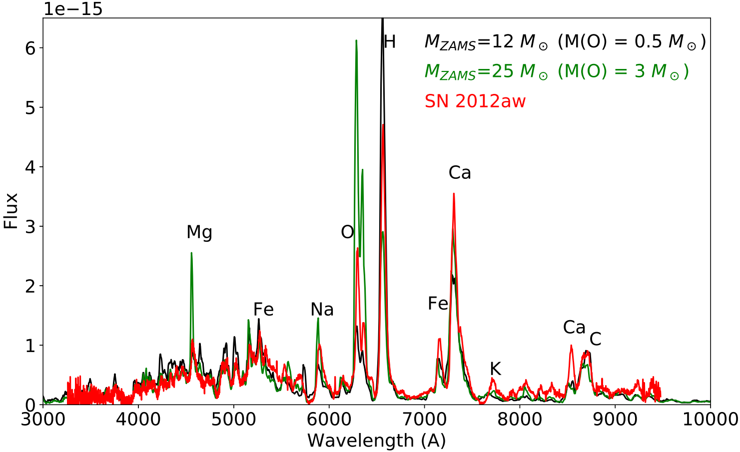
Type IIP spectral models: examples



Jerkstrand+2014

- Only last 5-10 years have spectral models in reasonable agreement with observed spectra emerged.

Type IIP spectral models: examples

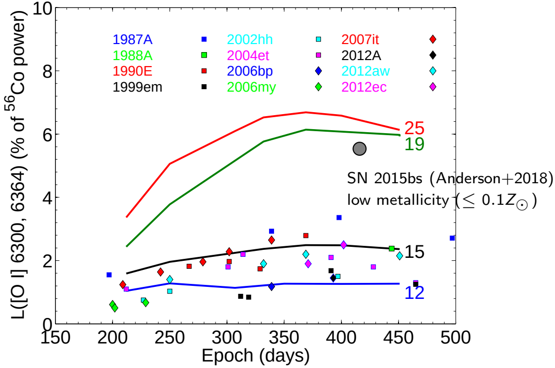


Jerkstrand+2014

- Only last 5-10 years have spectral models in reasonable agreement with observed spectra emerged.

Type IIP progenitors from their oxygen yields Jerkstrand+2015 ,MNRAS

- 18-30 $M_\odot$ RSGs do not seem to explode as IIP SNe. Black hole formation? Type IIL/IIn/Ib SNe? *Stay tuned for tonights debate.*

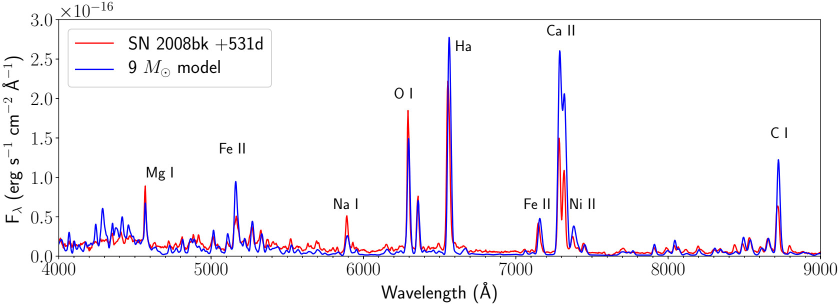


SN 2015bs (Anderson+2018)
low metallicity ($\lesssim 0.1 Z_\odot$)

- Same picture for Type IIb SNe Jerkstrand,Ergon,Smartt+2015, A&A.
- Problem for standard GCE models where 20-30 $M_\odot$ stars make most O.

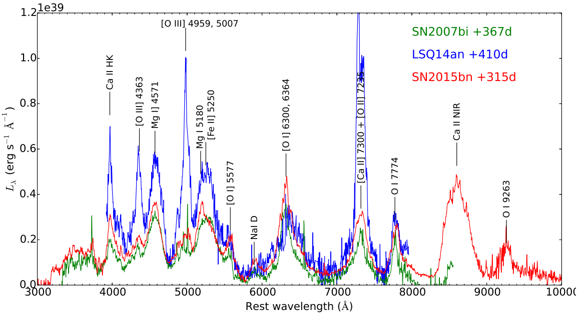
The low-mass RSG end: A population of low-mass iron core ($M_{ZAMS} \sim 9-12$) explosions with $E \sim 10^{50}$ erg is now convincingly established

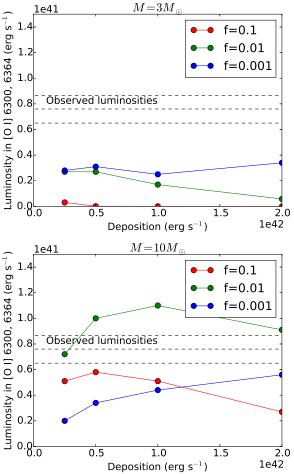
Good matches with un-tuned neutrino-driven explosion models (Jerkstrand, Ertl, Janka+2018):



- No evidence yet for electron capture SNe : all observed objects have He, C, O, Mg lines that would be absent/weak in ECSNe but consistent with Fe CC models.

The high-mass end: SLSNE Ic shows the highest O masses inferred so far in any SN ($\gtrsim 5\ M_\odot$). This means *some* massive stars do explode *AJ+2017*



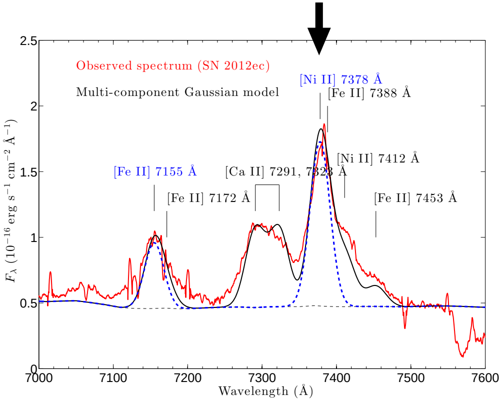


- Whats new here is that low O masses shown to be excluded by **fundamental conflicts between powering levels and ionization states**, for all plausible densities and compositions.

f=volume filling factor

Diagnosing iron-group production: example of stable nickel

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



- Confirm with [Ni II] 1.94 μm when available.

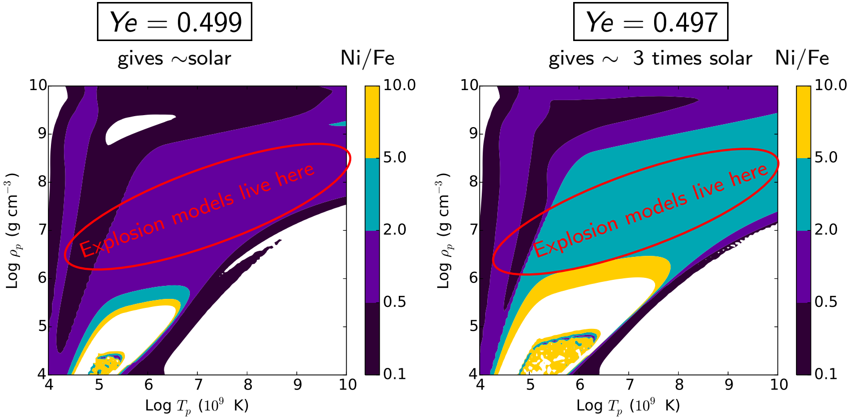
- Use forward model to identify which lines present in spectral region (result: 7) and in which regime they form (similar departure coefficients, and close to 1 (LTE))
- Make 4-component fit (atomic data constraints remove 4 DOF) for $L_{\mathrm{Ni\ II\ 7378}}$, $L_{\mathrm{Fe\ II\ 7155}}$, $L_{\mathrm{Ca\ II\ 7300}}$, ΔV
- Obtain Ni/Fe ratio analytically, and know method is robust because atomic physics suggests $Fe_{II}/Fe \approx Ni_{II}/Ni$, and models confirm, lines have similar excitation energy and therefore weak T-sensitivity, etc..

Ni/Fe ratios in 7 CCSNe *Jerkstrand+2015, MNRAS*

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

- Average ratio $\geq$ solar.
- If true in larger sample, Type Ia must make Ni/Fe $\leq$ solar $\rightarrow$ constraints on both CCSN and TNSN nucleosynthesis.

Parameterized burning trajectories reveal which Y_e needed for which Ni/Fe ratio



$\boxed{Ye = 0.499}$ gives ~solar

$\boxed{Ye = 0.497}$ gives ~ 3 times solar

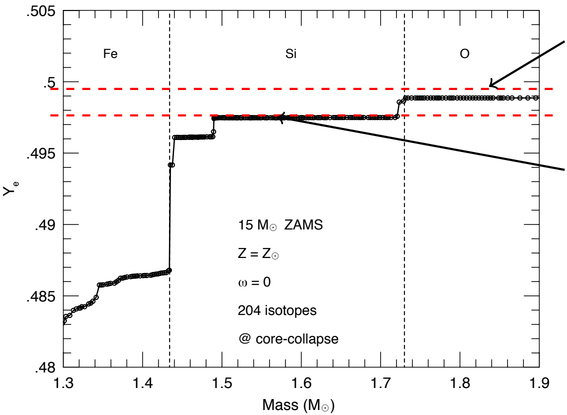
Explosion models live here

Explosion models live here

Jerkstrand, Timmes, Magkotsios+2015

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

Standard MESA pre-SN structure of a 15 $M_\odot$ star:



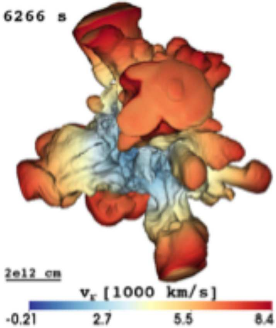
Oxygen layer: Ye ∼ 0.499. Gives Ni/Fe ∼ solar

Silicon layer: Ye ∼ 0.497. Gives Ni/Fe ∼3 times solar

- It all works out nicely with 1D picture..will it hold in 3D and with neutrino modifications of Ye?
- Ni/Fe in Crab requires ν-modified Ye happening i EC(-like) SNe.

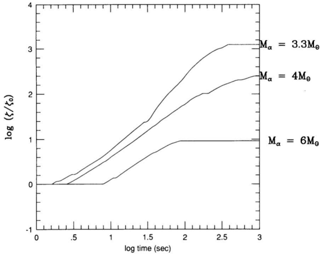
3D models : motivation

Type II SNe: Low-mode asymmetries: not captured by virtual grid method.



Wongwathanarat+2015

Type Ib SNe: Amount of reverse shock mixing depends on He core mass Shigeyama 1990, Hachisu 1991, 1994, Iwamoto 1997, Wongwathanarat 2017

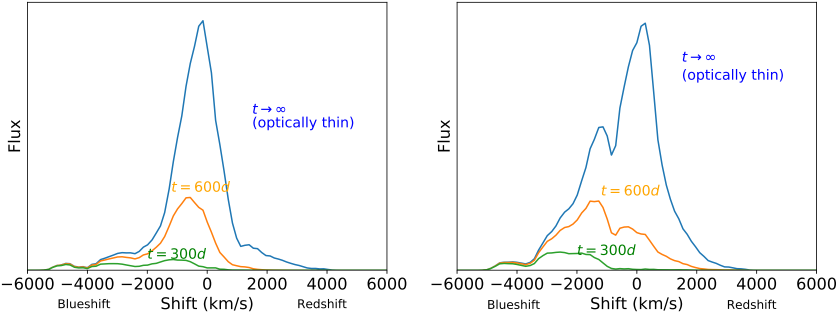


Shigeyama+1990

Type Ic SNe: Only explosion asymmetry itself imprinted. *Most direct test of the explosion mechanism*.

First simple application: Gamma-ray decay lines

Model L15-1 (Wongwathanarat+2017, Limongi & Chieffi progenitor). Two different viewing angles:

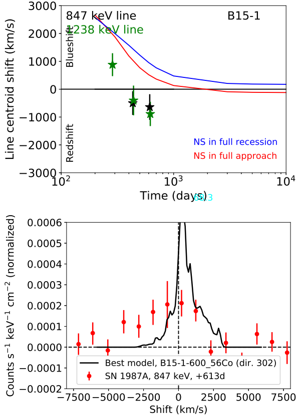


- Some viewing angles Gaussian-like line profiles, others asymmetric with structure.
- Compton scattering attenuates → **at early times line gets skewed towards blue** compared to optically thin limit.

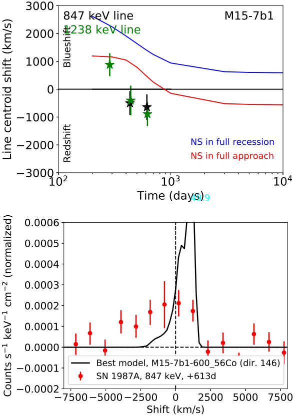
SN 1987A ^{56}Co decay lines *Preliminary*

- Model needs 1) Right distribution of ^{56}Ni (enough asymmetry) 2) Right amount of ejecta (right amount of attenuation)

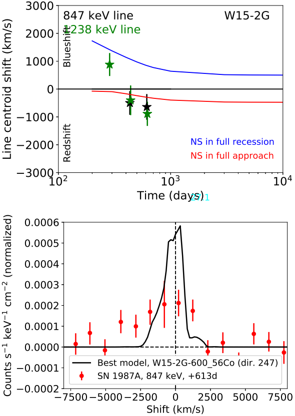
$\boxed{B15}$:V=**100** km/s, Mej=**13**.
Too low ^{56}Ni asymmetry.



$\boxed{M15}$:V=**600** km/s, Mej=**20**.
Too high ejecta mass.



$\boxed{W15}$: V=**600** km/s, Mej=**13**.
Fits observations ok.



Summary

- The nucleosynthesis in supernovae can be diagnosed in the nebular phase using NLTE spectral synthesis models.
- Diagnostic results for hydrostatic burning includes O, C, Mg, Na, Ne. Type IIP and IIb SNe seem to come from stars $<$20 Msun.
- The low-mass end of RSG progenitors is now well identified from their late-time spectra.
- For superluminous Ic SNe, modelling shows the highest O masses (> 5 $M_\odot$) found in any SN so far. Must originate from very massive stars.
- Diagnostic results for explosive burning (^{58}Ni) suggest CCSNe make supersolar Ni/Fe. The value in any SN determines which layer outside the iron core was burned and ejected.
- 3D models in preparation. First application of gamma decay lines in SN 1987A constrains the bulk asymmetry of ^{56}Ni and the ejecta mass.

THANK YOU FOR LISTENING