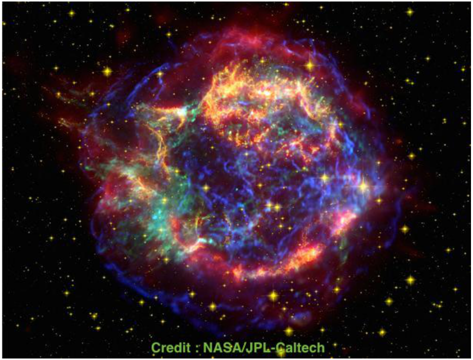
The origin of oxygen: results from supernova spectral synthesis modelling

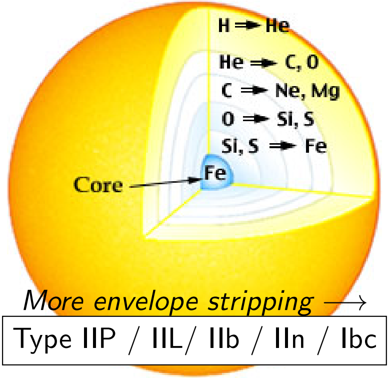
Anders Jerkstrand



Credit : NASA/JPL-Caltech

Supernovae - the deaths of stars

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

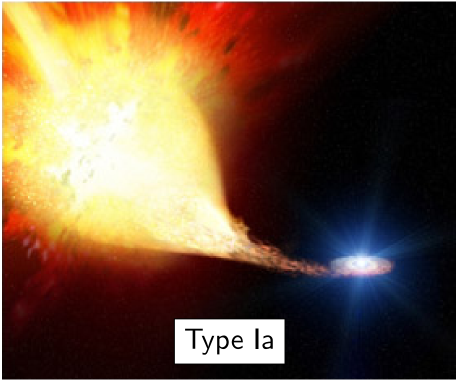


More envelope stripping ⟶

Type IIP / IIL/ IIb / IIn / Ibc

Credit: www.phys.olemiss.edu

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

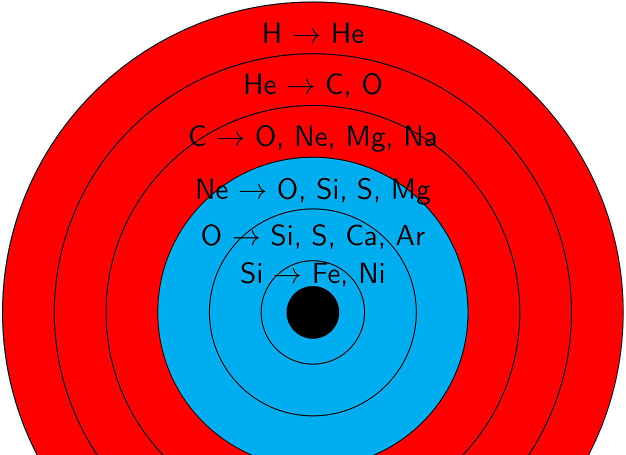


Type Ia

Credit: hetdex.org

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



H → He

He → C, O

C → O, Ne, Mg, Na

Ne → O, Si, S, Mg

O → Si, S, Ca, Ar

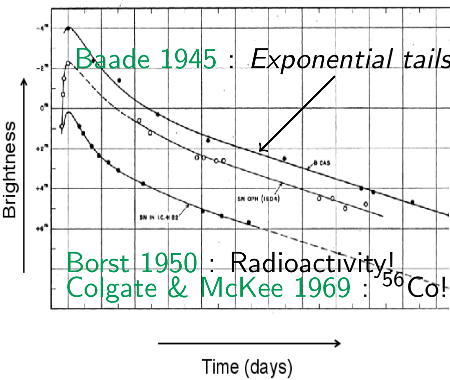
Si → Fe, Ni

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, 6300, 7774, 9263, 1.13 μm, 1.31 μm
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

Virtually no empirical confirmation by direct source analysis

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

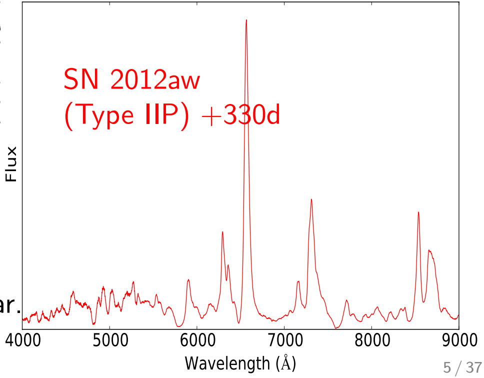


Baade 1945 : *Exponential tails!*

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.

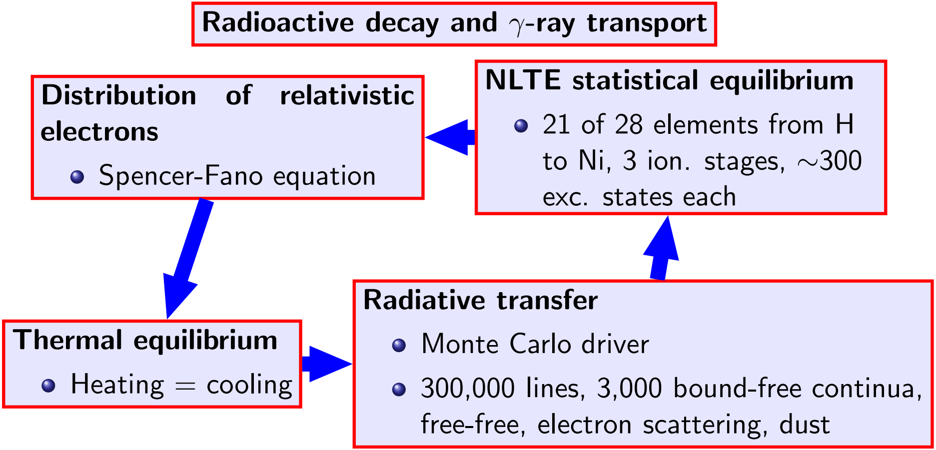
Total number of objects : ∼50

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

Methods:

1. Measure line luminosities + assume uniform conditions and analytic forms valid in certain limits (e.g. LTE, optically thin) *Important complement but not accurate enough on its own*
2. Forward modelling : free composition in single zone *Simple and fast, but many free parameters and to some extent unphysical*
3. Forward modelling : multi-zone explosion models with self-consistent nucleosynthesis *Recent progress (Dessart & Hillier 2011, AJ 2011 (PhD thesis), Maurer 2011 (PhD thesis), AJ+2012, 2014, 2015a, 2015b, 2016)*

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, ~300 exc. states each

Thermal equilibrium

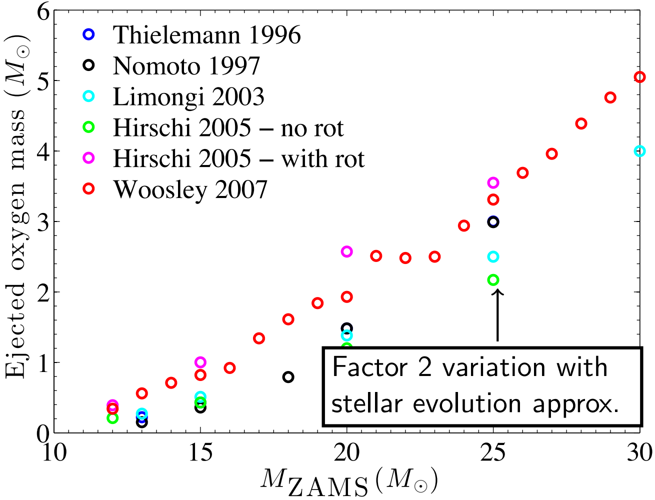
- Heating = cooling

Radiative transfer

- Monte Carlo driver
- 300,000 lines, 3,000 bound-free continua, free-free, electron scattering, dust

- MPI code typically run of 100 cores
- Code is 1D but allows for mixing

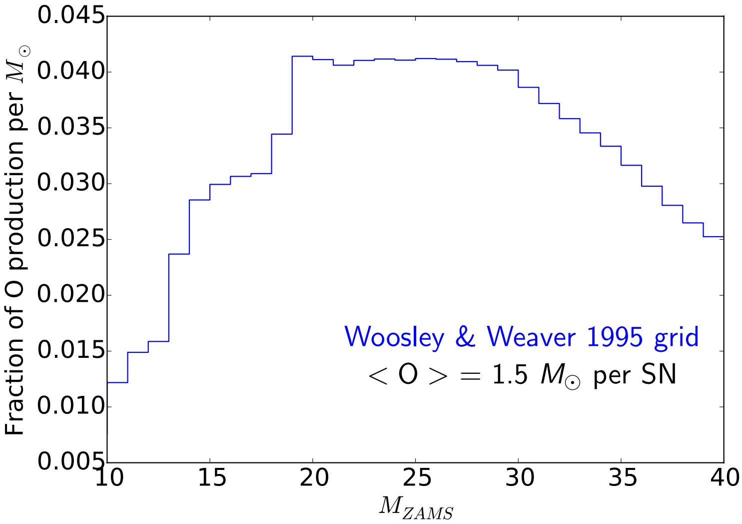
Oxygen nucleosynthesis : theoretical $M(O)$ vs M_{ZAMS}



Factor 2 variation with stellar evolution approx.

Oxygen nucleosynthesis

Convolve with a Salpeter ($SFR \propto M_{ZAMS}^{-2.35}$) Initial Mass Function (IMF):

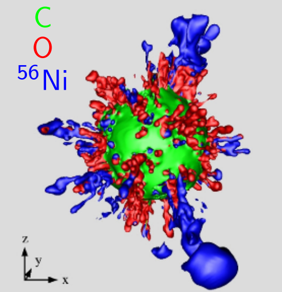


Candidate sources for O production

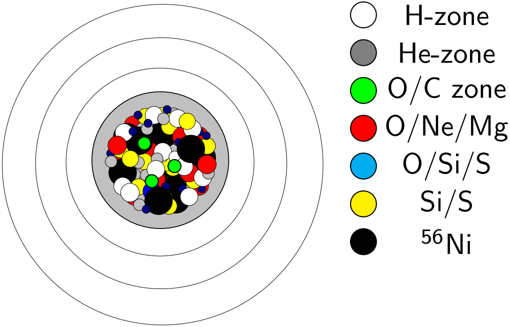
Source	M_{ZAMS}	Rate (yr^{-1})	$< O >$ ($M_\odot$)	O prod. rate ($M_\odot$ yr^{-1})
Supernovae				
Type II	8-40	0.02	1.5	0.03
Type Ib/c	40-130	0.007	3	0.02
Pair-instability	130-260	$< 5 \times 10^{-4}$	40	< 0.02
Type Ia	2-8	0.005	0.1	5×10^{-4}
Eruptions and winds				
Wolf-Rayet winds	>40	3×10^{-3}	5	2×10^{-3}
Pair-instability eruptions	100-130	$< 5 \times 10^{-3}$	1	$< 5 \times 10^{-3}$
Novae	2-8	30	1×10^{-5}	3×10^{-4}

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

- Stellar evolution/explosion models from KEPLER (Woosley & Heger 2007) → 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

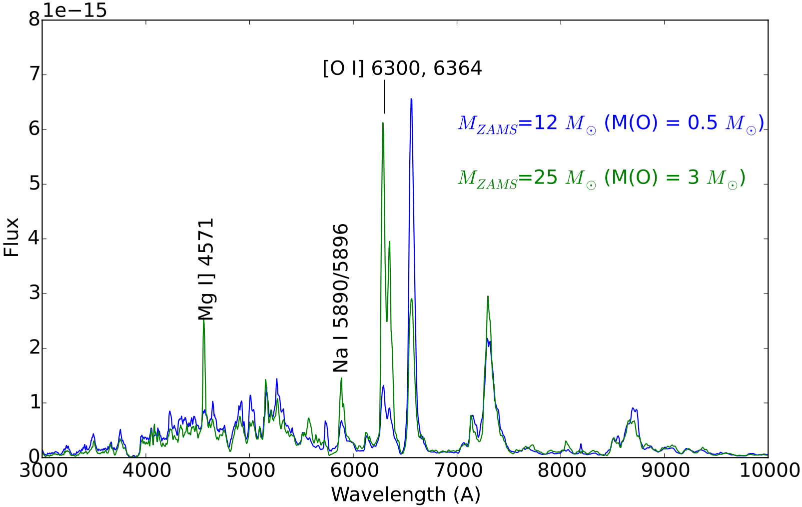


Hammer+2010, 3D model



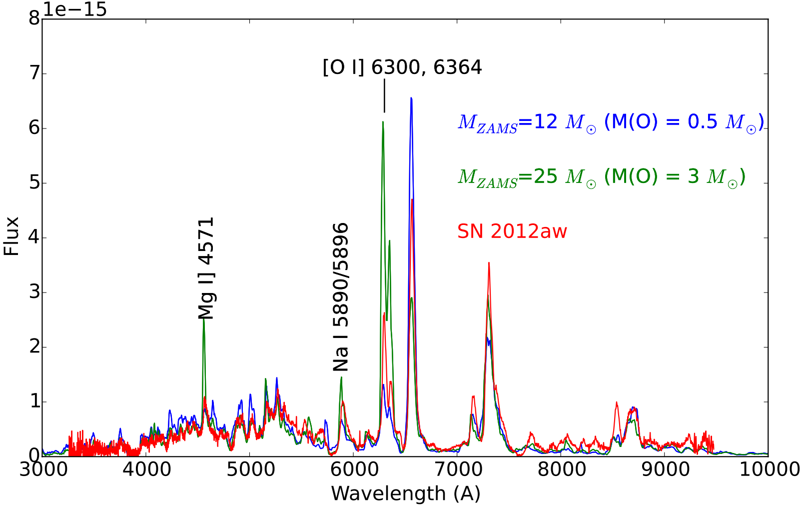
Ejecta setup in SUMO

Type IIP model spectra



AJ+2012,2014

Type IIP model spectra



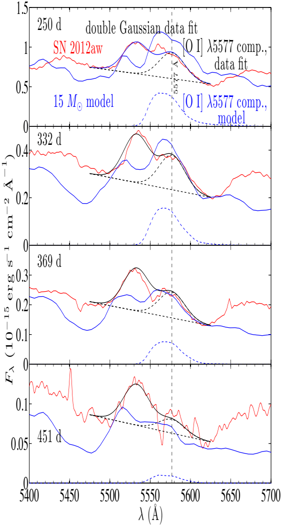
AJ+2012,2014

The power of [O I] 6300, 6364

- Most O is neutral → traces total O mass
- Forms by thermal collisional excitation
- Neglegible blending
- Minor radiative transfer effects
- This wavelength range always observed with high S/N

→ Probably the most robust diagnostic of any SN element

Robustness check 1 : [O I] 5577 AJ+2014



LTE formulae expected to be accurate:

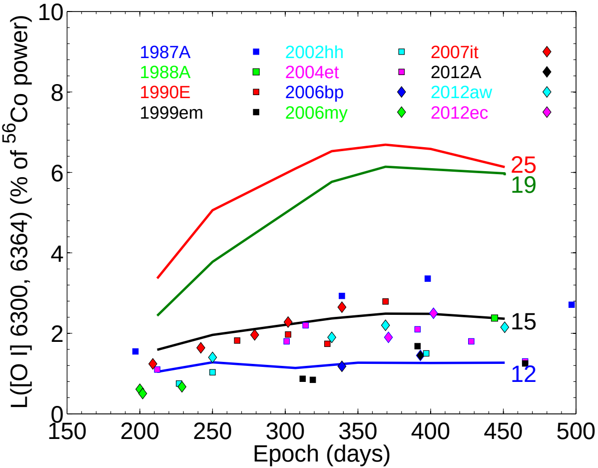
$$\frac{L_{5577}}{L_{6300,6364}} = 38 \exp\left(\frac{-25790}{T}\right) \quad (1)$$

$$L_{6300,6364} = 9.7 \times 10^{41} \exp\left(\frac{-22720}{T}\right) M_{OI} \text{ erg/s} \quad (2)$$

Time	$L_{5577}/L_{6300,6364}$	T	M(OI)
(d)	–	(K)	($M_\odot$)
250	0.12	4170	**0.6**
369	0.057	3740	**0.6**
451	0.025	3330	**0.6**

Good consistency with best-fit model for 6300, 6364 : M(O) = **0.8** $M_\odot$ (all ejecta), M(O) = **0.4** $M_\odot$ (ONeMg zone)

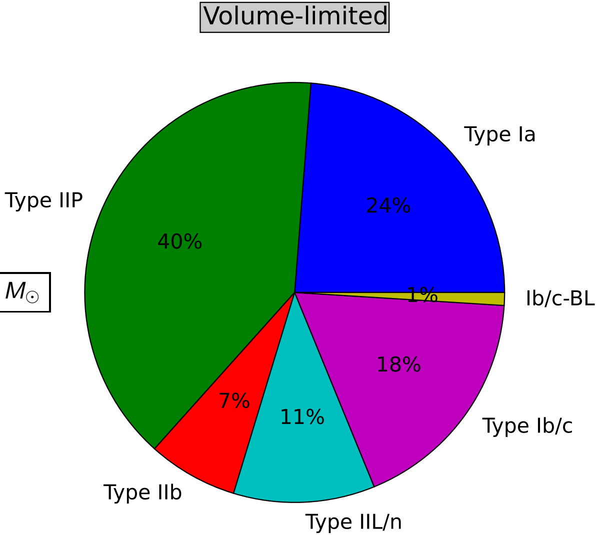
Oxygen luminosities in a sample of Type IIP SNe : $M_{ZAMS} \approx 10 - 17\ M_\odot, < O >= 0.4\ M\odot$



AJ+2015b

- Standard models predict Type IIP SNe also in the 17-30 range, and $< O >= 1.0\ M_\odot$.

Supernova types and their relative frequencies

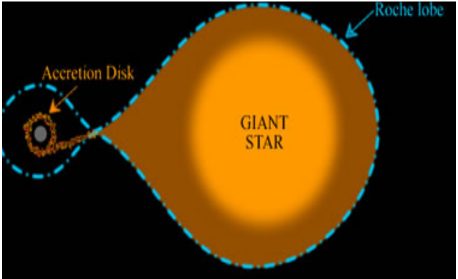


$< O > = 0.4\ M_\odot$

Type IIb SNe

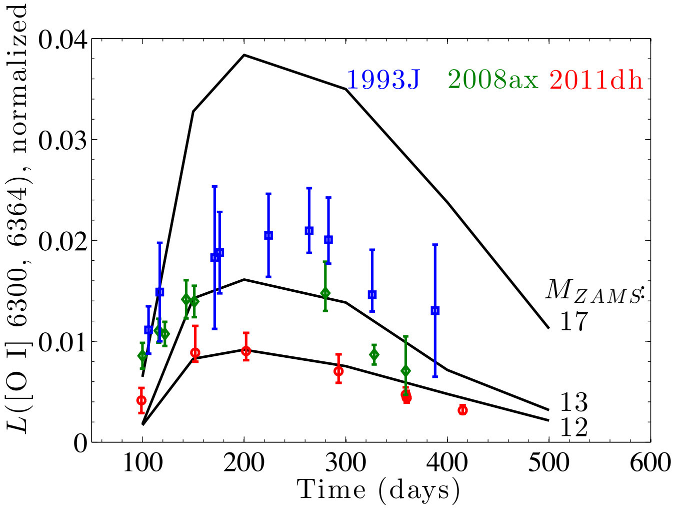
- Progenitor has been stripped but all but $\sim 0.1\ M_\odot$ of its H envelope.
- Class includes famous SNe such as Cas A and 1993J. Recent surveys → 10-15% of all CCSNe.
- Two main candidate mechanisms for H envelope stripping:

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



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

Type IIb SNe: $M_{ZAMS} = 12 - 15\ M_\odot (< O >= 0.4\ M\odot)$ $\rightarrow$ *low-mass stars stripped by binary interaction*



AJ+2015a

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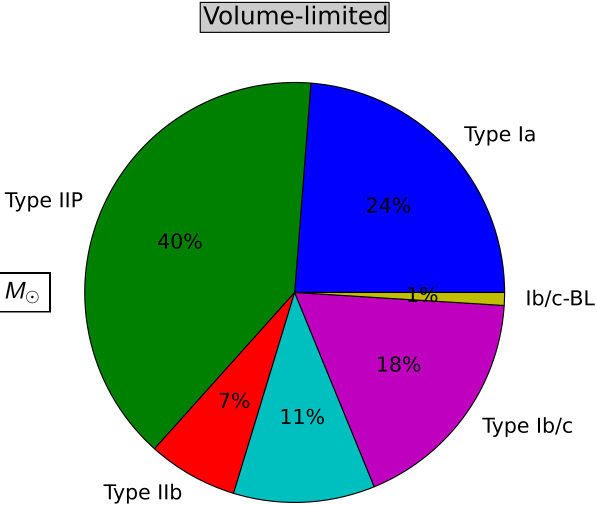
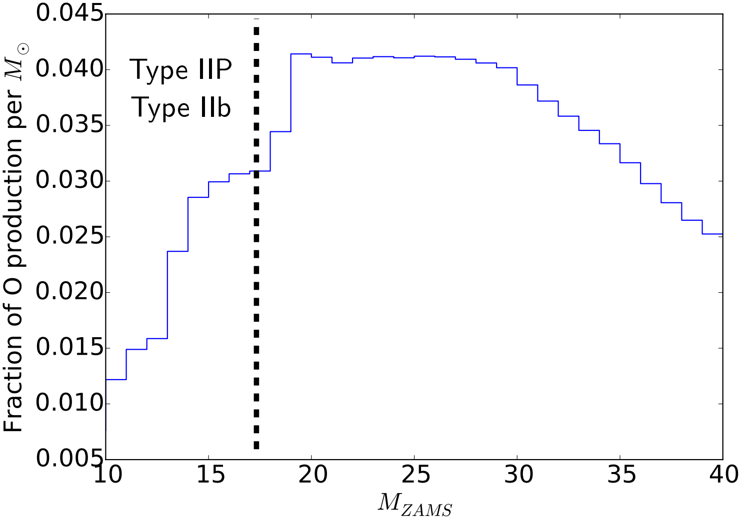


$< O >= 0.4\ M_\odot$

$< O >= 0.4\ M_\odot$

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



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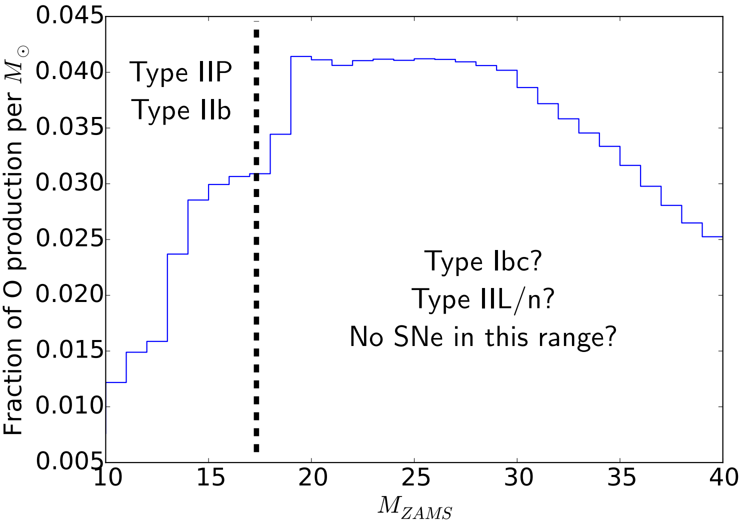
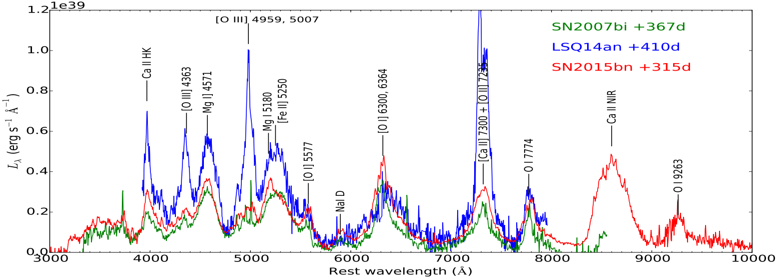
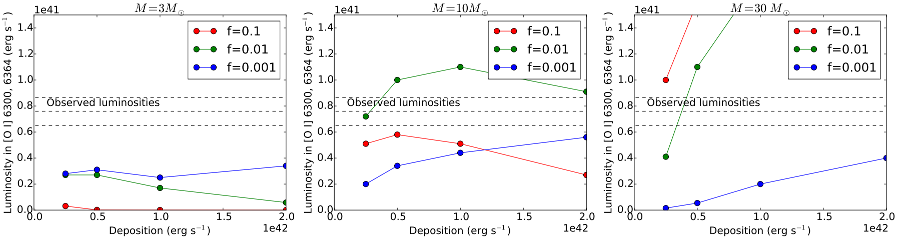


Type Ib/c-BL SNe : Highest O masses observed so far ($\sim 5\ M_\odot$) *AJ+2017*





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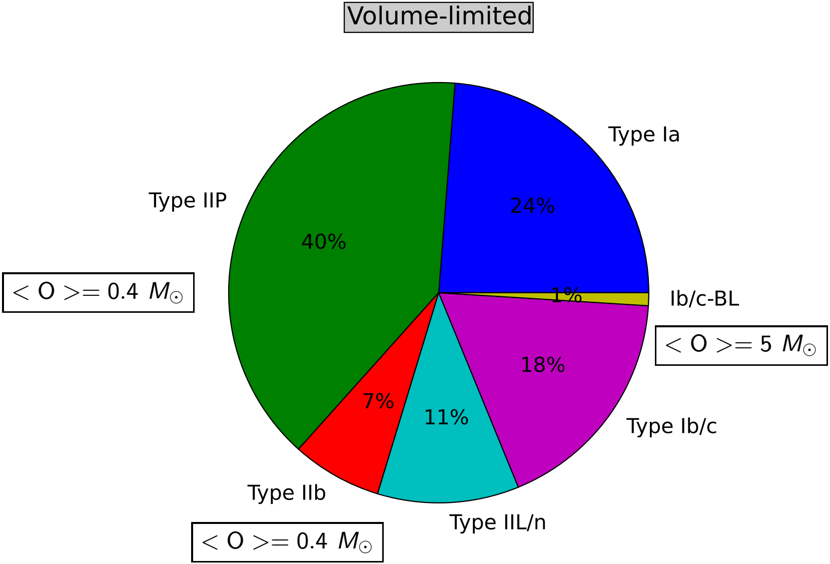

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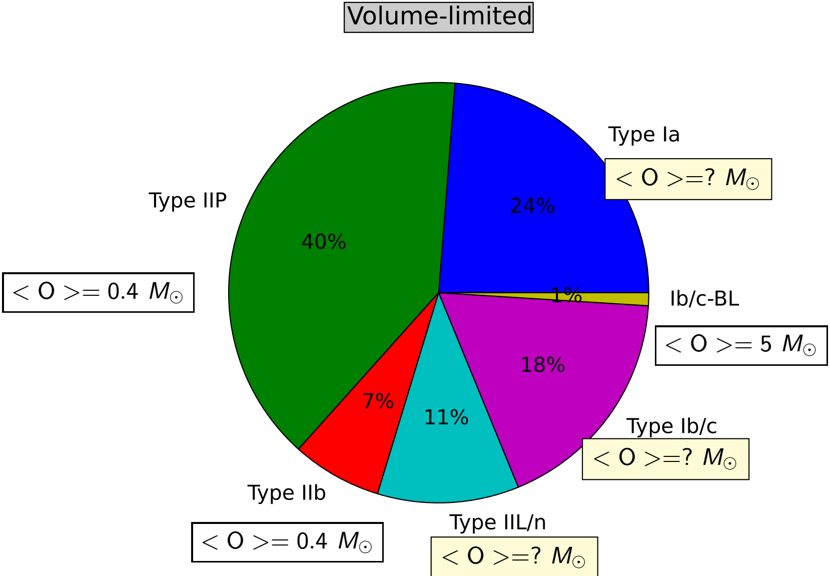
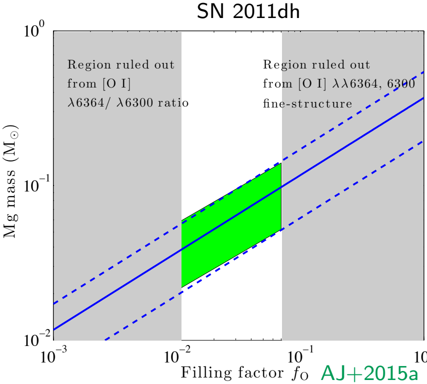


Magnesium

- Current stellar evolution models underpredict Mg/O by factor >2...why?
- Two main diagnostics : Mg I] 4571 and Mg I 1.50 μm.
- Mg I] 4571 : Relatively sensitive to model detail → large error bars
- Mg I 1.50 μm : Simpler formation, but less often observed

New method presented in AJ+2015a:

- Oxygen : $n_{OII} \approx n_e \rightarrow$ $\boxed{L_{O-rec} \propto f_O \times n_e^2}$
- Magnesium : $n_{MgII} \approx n_{Mg} \rightarrow$ $\boxed{L_{Mg-rec} \propto M_{Mg} \times n_e}$
- f_O constrained from [O I] 6300, 6364 properties



AJ+2015a

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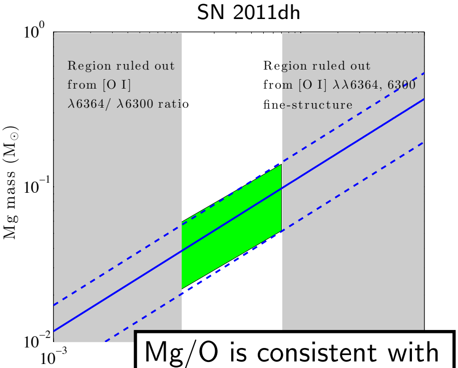
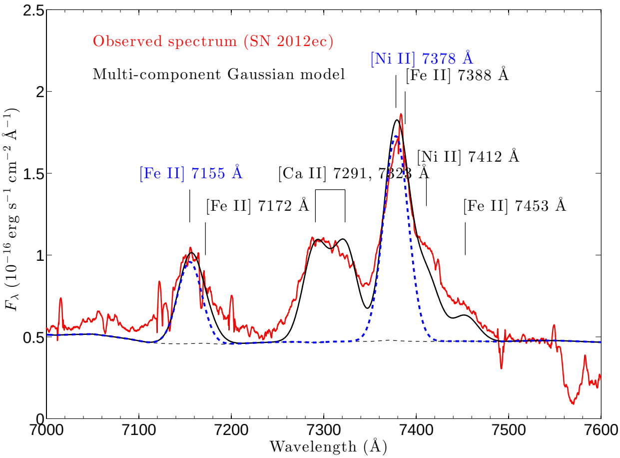


Mg/O is consistent with solar ratio in individual source (SN 2011dh)

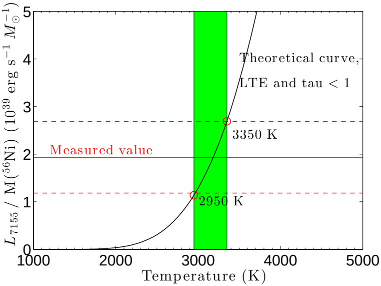
Stable nickel

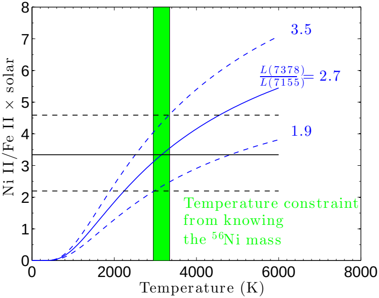
- Use forward model to identify lines present (7)
- 3-component fit (atomic data constraints remove 4 DOF)

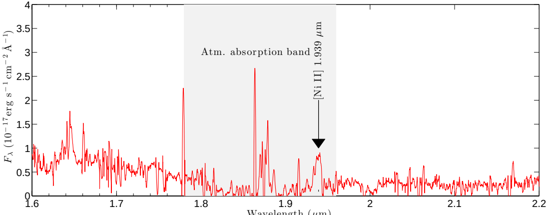


Stable nickel

- Determine T range, and from this determine mass range





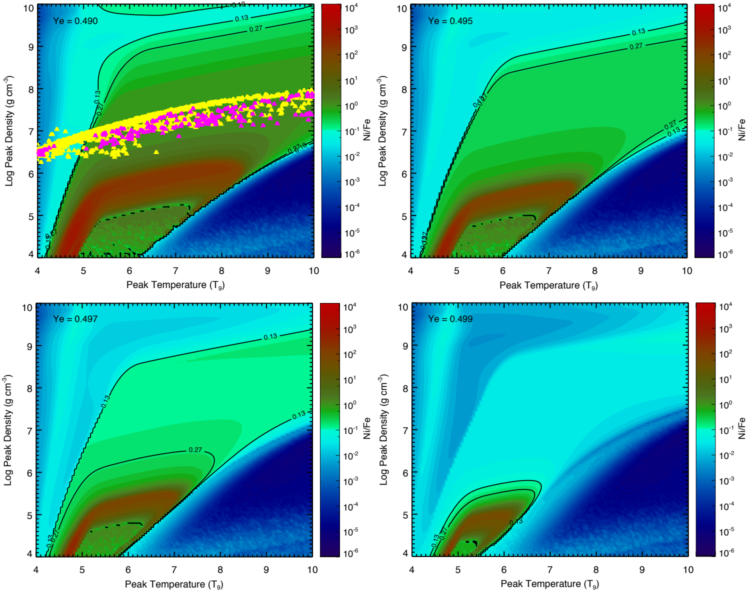


Ni/Fe ratios in 7 CCSNe

SN	Ni/Fe (times solar)	Reference
Crab	60 – 75	Macalpine1989, Macalpine2007
SN 1987A	0.5 – 1.5	Rank1988, Wooden1993, AJ+2015b
SN 2004et	∼1	Jerkstrand2012
SN 2006aj	2 – 5	Maeda2007, Mazzali2007
SN 2012A	∼ 0.5	AJ+2015b
SN 2012aw	∼ 1.5	AJ+2015b
SN 2012ec	2.2 – 4.6	AJ+2015b

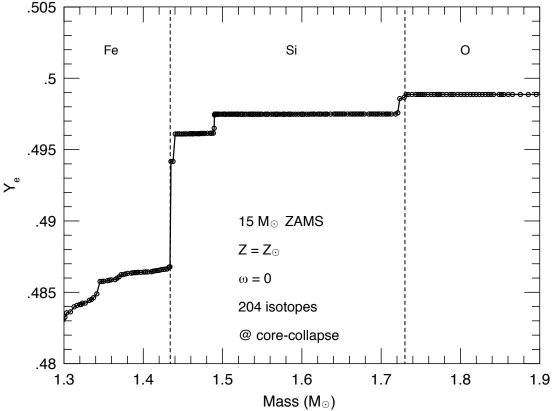
- Average ratio close to solar
- If true in largee samle, Type Ia much make Ni/Fe < 1 → constraints on explosions models
- Sometimes much larger : what does it mean?
- The Crab is extreme : only viable model is electron capture SN

Need $Y_e \sim 0.497$



AJ+2015 (ApJ)

Ne/Fe is a tracer of which progenitor layer was explosively burnt



SLSNe

- A new class of extremely bright SNe discovered about 10 years ago
- Emit 100 times more energy than normal SNe
- Type IIn or Type Ic
- Power source is unknown. Candidates:

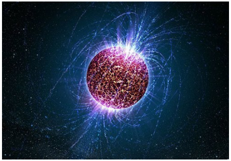
Radioactivity

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

Gamma-ray thermalization.

Neutron star rotation energy

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



Magnetic spin-down + thermalization of pulsar wind

Ejecta kinetic energy

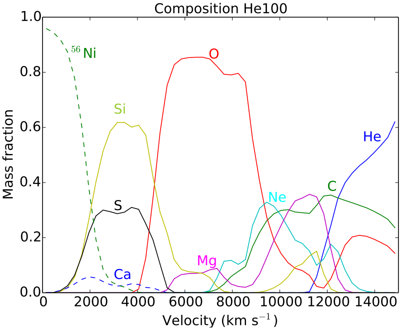
$E \approx 10^{51}$

Circumstellar interaction + X-ray thermalization.

Pair-instability supernovae : explosion models

Heger & Woosley 2002

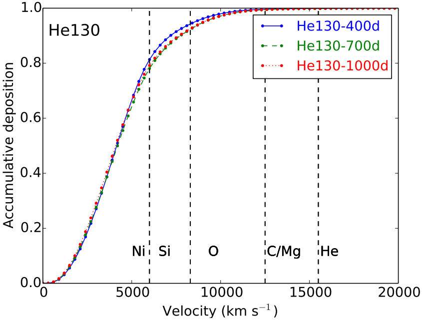
Model	M_{ZAMS} ($M_\odot$)	E_{kin} (10^{52} erg)	He ($M_\odot$)	O ($M_\odot$)	Si ($M_\odot$)	S ($M_\odot$)	^{56}Ni ($M_\odot$)	SN Type
He80	~140	1.6	0.7	47	14	5	0.1	normal SN
He100	~200	3.8	0.9	44	23	10	6	superlum.
He130	~260	8.1	2	33	24	11	40	superlum.



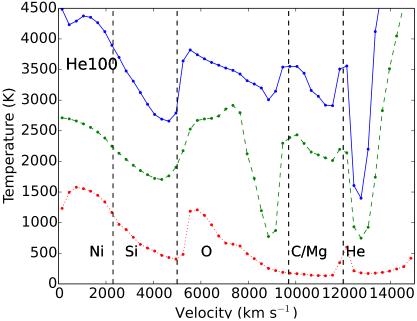
- Macroscopic mixing small (Joggerst & Whalen 2011, Chatzopoulus+2013, Chen+2014, Whalen+2014)? can use 1D ejecta models to good accuracy.

Physical conditions

- Gamma rays are trapped in deep-lying Fe, Si, S, Ca layers

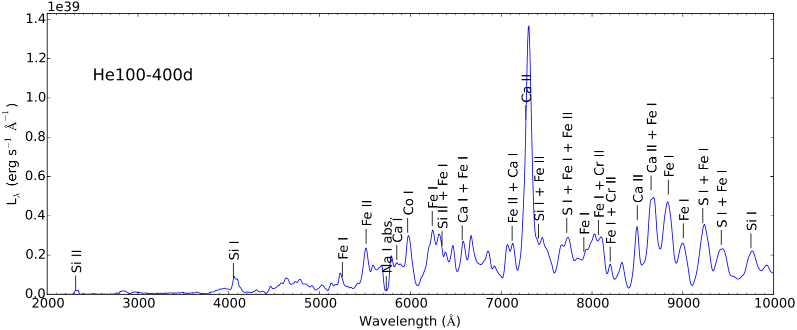


- Gas is cold and neutral



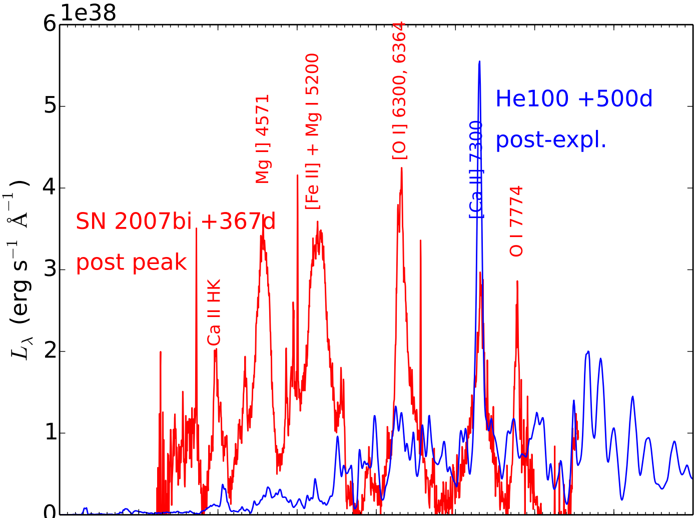
Expect lines of Fe I, Si I, S I,...

Spectra at +400d



Pair-instability supernovae

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



Outlook

- A subclass of low-velocity Type IIP SNe : match with electron capture SNe or low-mass iron core SNe? Compute spectra of 1D explosion models produced in-house
- The key to more accurate modelling is to use full 3D explosion models Development of 3D spectral code underway, application to in-house 3D models
- Build up statistically significant samples for each SN class
- Type Ib/c SNe High mass stars and the main source of O, or gravitationally stripped low-mass stars? What explosion models to use?

Questions adressed in this talk

- What nucleosynthesis products do we observe in SNe?
  - Clear signals from newly produced He, C, N, O, Ne, Na, Mg, Si, S, Ca, Fe, Co, Ni have been identified
- How do inferred yields of O and related products compare with assumptions in standard chemical evolution models?
  - Type II SNe appear to come from low-mass stars ($M_{ZAMS} \lesssim 18$) with small amounts of nucleosynthesis, $< \mathrm{O} >= 0.4\ M_\odot$
  - The large O masses of 1.5 $M_\odot$ per SN used in standard chemical evolution models is not confirmed by observations, and the main source of O is unclear
  - Mg/O and Na/O ratios general close to solar
- What do the yields tell us about stellar nucleosynthesis and SN physics?
  - As with progenitor analysis, nucleosynthesis analysis indicates that many stars with $M_{ZAMS} > 18 M_\odot$ may collapse directly to black holes
  - However, *some* massive stars definately explode
  - SN ejecta are not microscopically mixed → constraints on convection
  - Current stellar evolution models fail to reproduce high enough Mg/O ratio