Nebular spectra of superluminous supernovae

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MPA

Outline

1. Observational overview
2. Parameterized O-zone models
3. Pair-instability models

Papers :

Jerkstrand, Smartt & Heger 2016 MNRAS

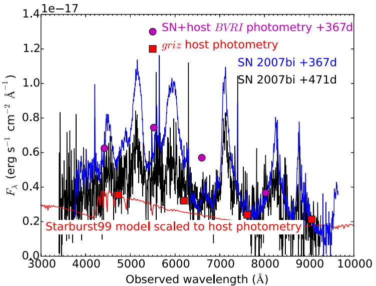
Jerkstrand, Smartt, Inserra, Nicholl, Chen, Kruhler, Sollerman, Taubenberger, Gal-Yam, Kankare, Maguire, Fraser, Valenti, Sullivan, Cartier, Young 2017 ApJ

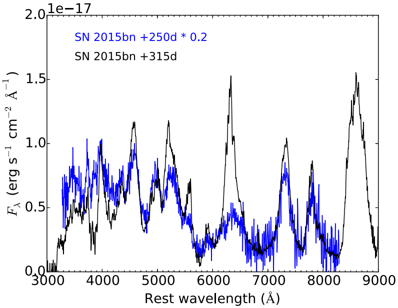
Observational overview, spectra >200d post-peak

SN	z	Epochs	Telescopes	Coverage (Å)	Comment
SN 2007bi	0.13	+367, +471	VLT, Keck	3300-8500	
PTF12dam	0.11	+509	GTC	4000-8000	[O I]
iPTF13ehe	0.34	+251	Keck	3000-10000	Hα
PS1-14bj	0.52	+202	Magellan	6000-10000	O III
LSQ14an	0.16	+205, 414, 478	VLT	3000-20000	O III
SN 2015bn	0.11	+200-390	Magellan, Gemini, VLT	3000-20000	07bi-clone
iPTF16bad	0.25	+242	Keck	4000-10000	Hα
Gaia16apd	0.10	+234	GTC	6000-9000	[O I]

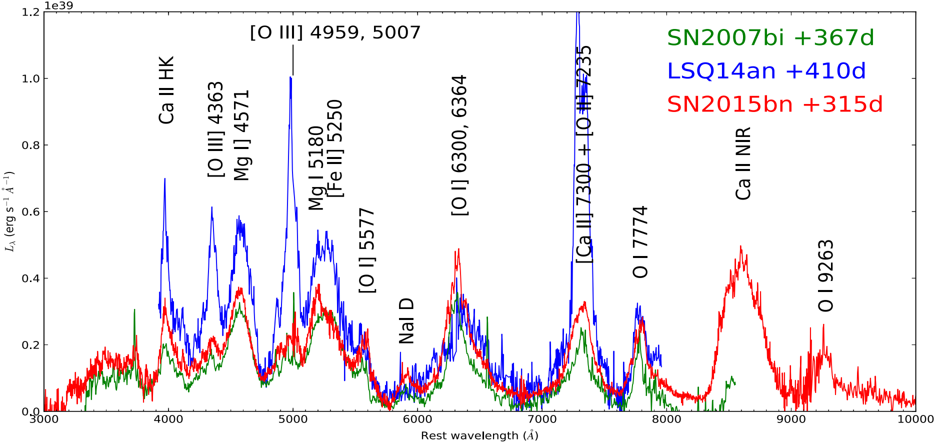
Papers: Gal-Yam+2009, Chen+2015, Yan+2015,2017, Lunnan+2016, Nicholl+2016, Jerkstrand+2017, Inserra+2017, Kangas+2017

- Quality varies a lot (redshift, decline rate, host brightness..)
- Often host galaxy contamination at late times



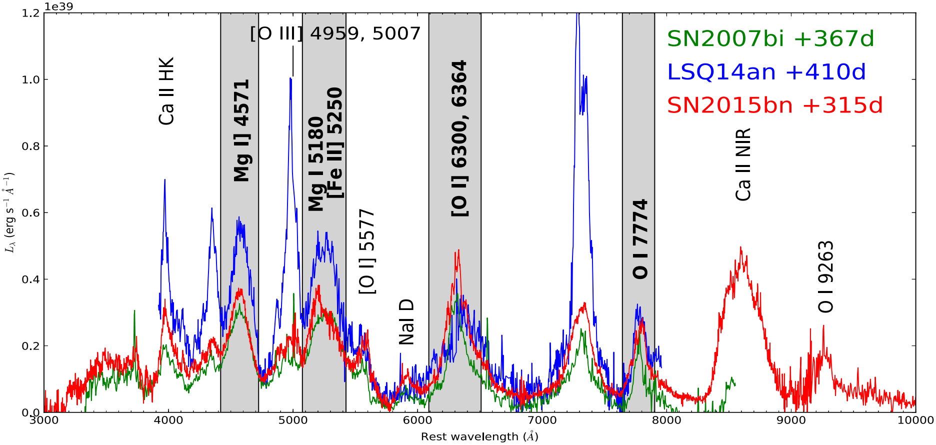


Long-duration SLSNe at nebular times



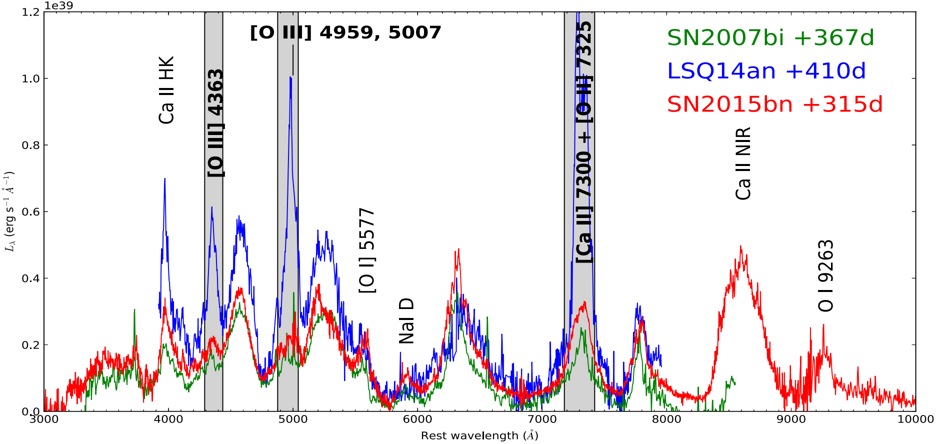
- O, Mg, Na, Ca identified. Probably also Fe.
- Expansion velocities 3000-10000 km/s.

Long-duration SLSNe at nebular times



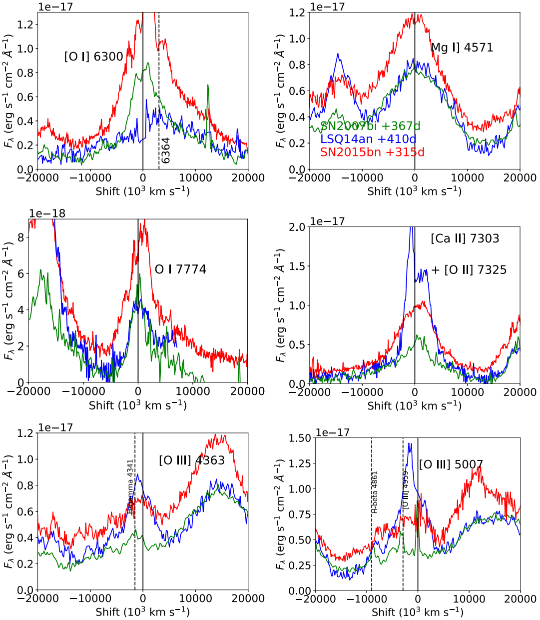
- Similarity of neutral lines

Long-duration SLSNe at nebular times

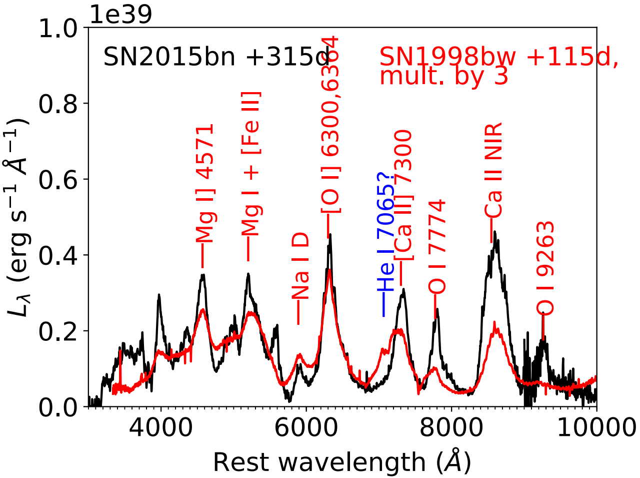


- Diversity for ionized lines (O II and O III)

Line profiles

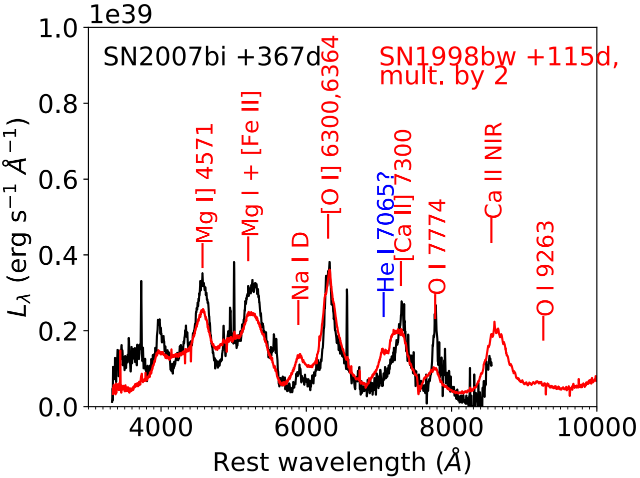


Strong similarity to GRB SNe such as SN 1998bw



- Unlikely to be some fundamentally different scenario like CSI (?)
- O I 7774 and O I 9263 stronger than in normal SNe
- Is 4000-5500 Å plateau evidence for 56Ni?

Strong similarity to GRB SNe such as SN 1998bw



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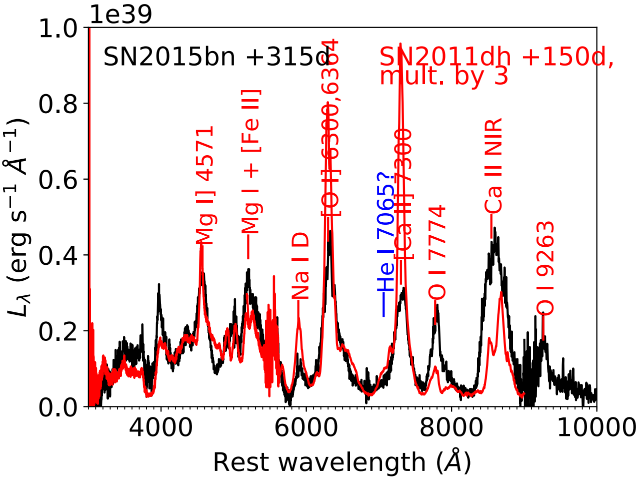
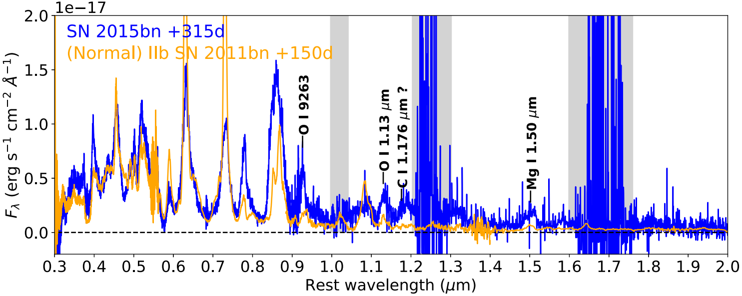
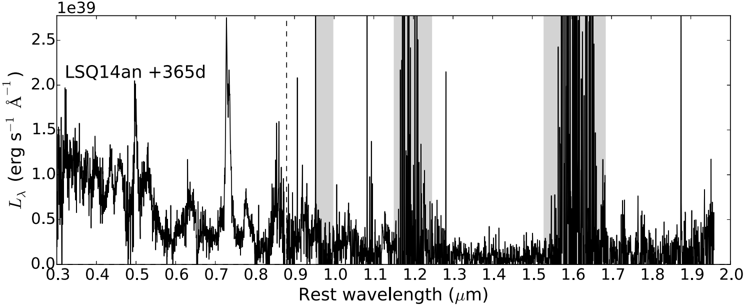


- But note that broad-lined Ic SNe are not that different to normal IIb/Ib/Ic SNe at nebular times

SLSNe in NIR



1e−17
SN 2015bn +315d
(Normal) IIb SN 2011bn +150d
O I 9263
O I 1.13 μm
C I 1.176 μm ?
Mg I 1.50 μm
F_λ (erg s^{-1} cm^{-2} Å^{-1})
Rest wavelength (μm)



1e39
LSQ14an +365d
L_λ (erg s^{-1} Å^{-1})
Rest wavelength (μm)

Late-time spectral modelling with SUMO *Jerkstrand 2011*

Mixing treatment

Macroscopic vs microsc. mixing
Clumping

Temperature

First law of thermodynamics.

Radioactive deposition

Compton scattering —>
High-energy electrons

NLTE ionization and excitation

~100 zones, ~50 ions, ~300 levels

High-energy electron degradation

Spencer-Fano equation.
Heating - ionisation - excitation

Radiative transfer

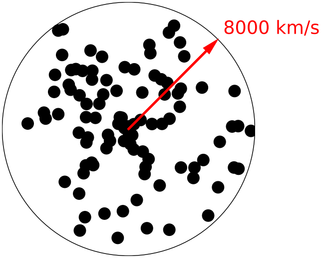
Scattering/fluorescence
in 0.1-1 million lines

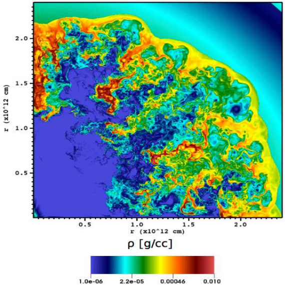
Modelling the O-zone emission *Jerkstrand+2017*

Motivation : 1) Decouple ejecta properties from (unknown) power source.
2) Extensive parameter space investigation.

Fix $V = 8000$ km s^{-1}, $N = 100$ clumps, t=400d. Then vary:

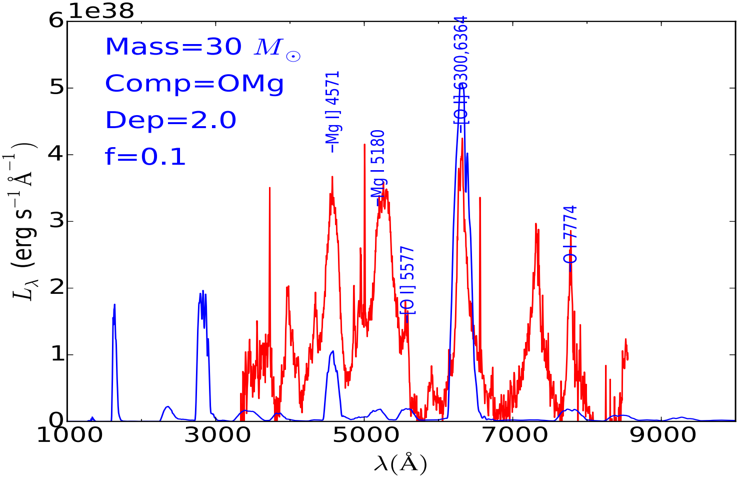
- Zone mass: $M = 3, 10, 30$ $M_\odot$
- Energy deposition: $d = 2.5, 5, 10, 20 \times 10^{41}$ erg/s.
- Filling factor: $f = 0.001, 0.01, 0.1$
- Composition: Pure O, OMg, C-burn





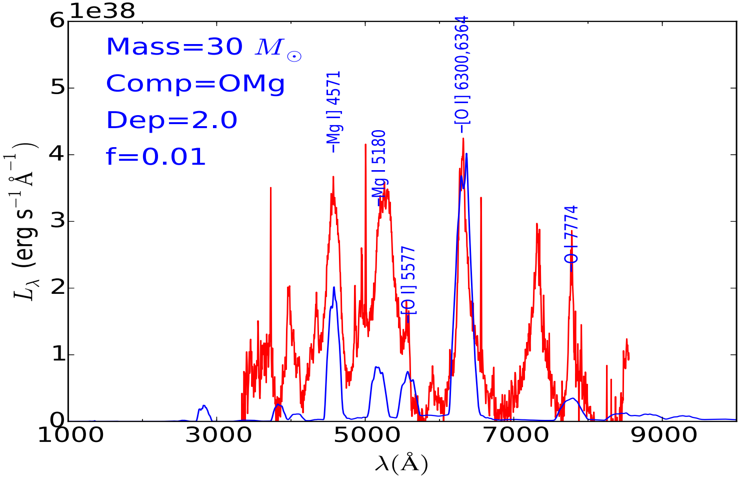
Chen+2016

Indication of clumping



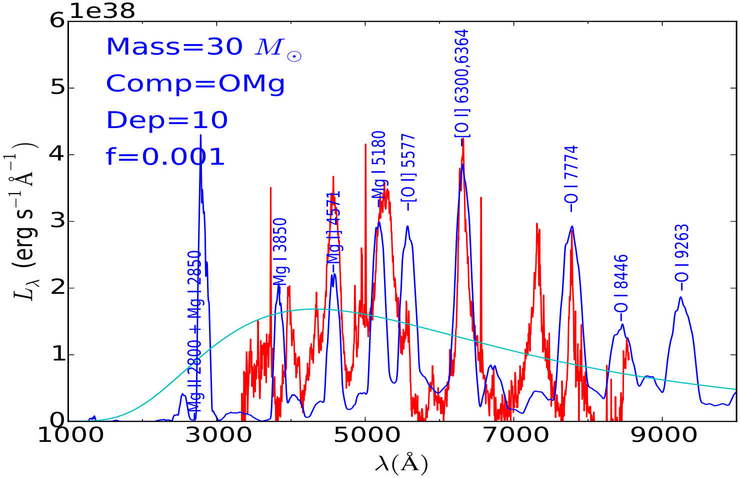
- High Mg I] 4571 luminosity requires cooling emission
- Large f : Mg fully ionized to Mg II $\rightarrow$ weak Mg I] 4571 cooling

Indication of clumping



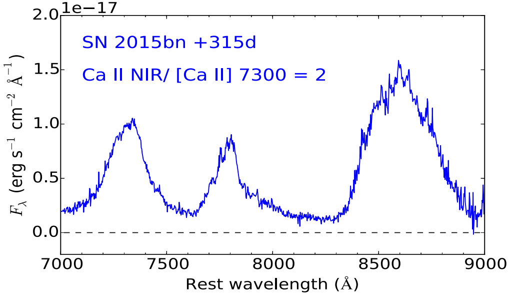
- Decrease f : Mg I fraction increases → Mg I] 4571 strengthens and Mg I 5180 emerges
- O I recombination lines strengthen, and can get also cooling contribution

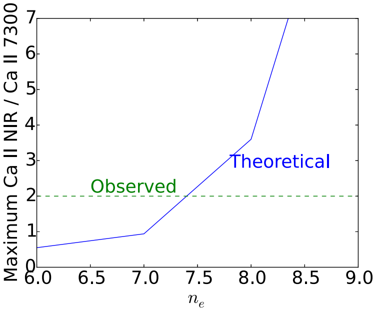
Indication of clumping



- At very low f, spectrum formed under LTE optically thick conditions → follow blackbody

The unusual Ca II ratio : further indication of clumping

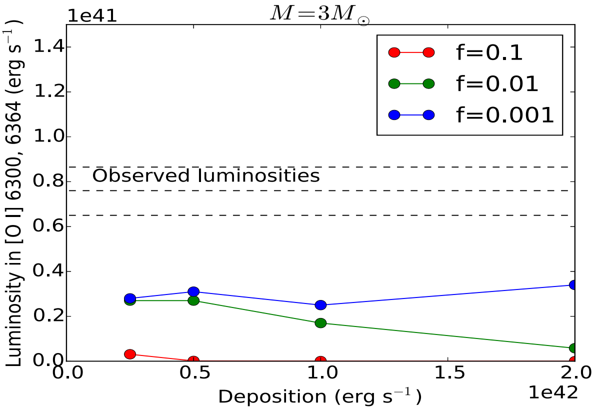




- Observed ratio requires high electron density, $n_e \gtrsim 10^8$ cm^{-3}.
- Similar result from O I recombination lines
- Need low filling factor to make reasonable masses

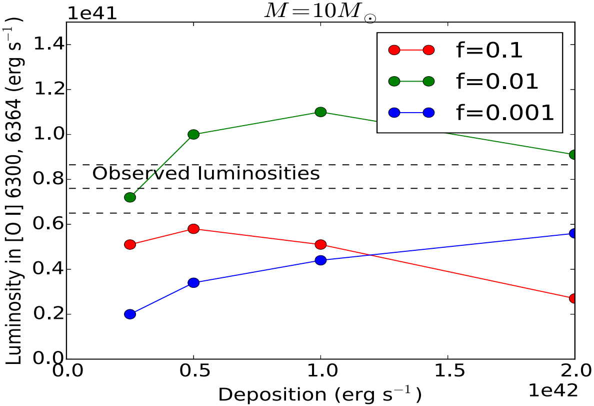
$$M = 3000\ M_\odot f \left(\frac{n_e}{10^8}\right)\left(\frac{\bar{A}}{40}\right)\left(\frac{x_e}{0.1}\right)$$

Constraints on the O mass



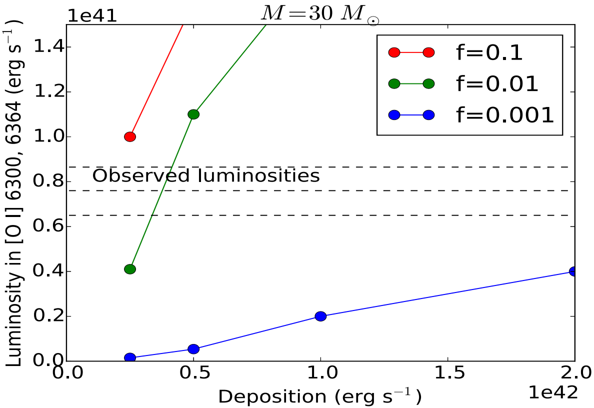
- Models with 3 $M_\odot$ are over 3 times too dim for ANY deposition and density
- Oxygen ionizes to O II for too high depositions
- Also Mg lines much too weak

Constraints on the O mass



- Models with 10 $M_\odot$ fare better
- Complex curves due to competing effects : ionization, optical depth, not only for O but other cooling lines

Constraints on the O mass

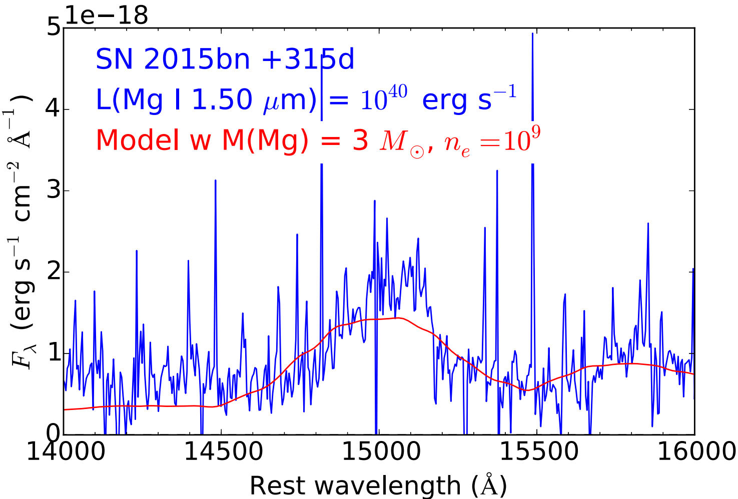


- Models with 30 $M_\odot$ also fare ok

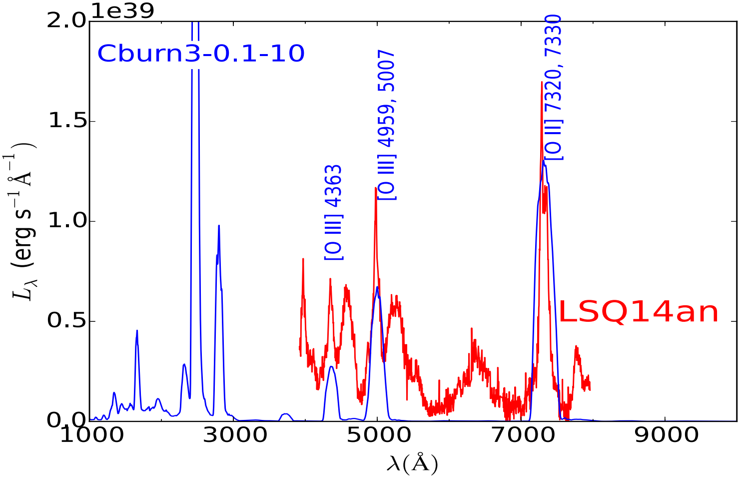
Constraints on the Mg mass

Mg I 1.50 μm expected to follow recombination luminosity

$$L = 1 \times 10^{40} \text{ erg s}^{-1} \times \left(\frac{M_{\rm Mg}}{15\ M_\odot}\right)\left(\frac{n_e}{10^8\ \text{cm}^{-3}}\right)\left(\frac{\alpha^{eff}(T)}{10^{-13}\ \text{cm}^3\text{s}^{-1}}\right) \quad (1)$$



O II and O III lines

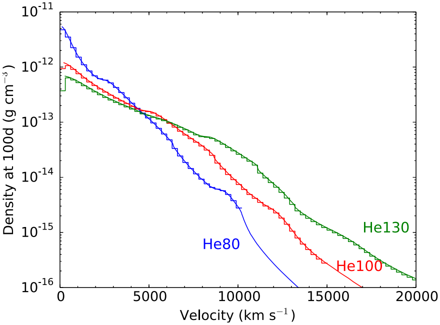


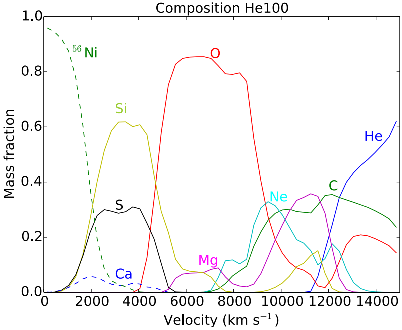
- Seen in PS1-14bj and LSQ14an only
- Need large energy per unit mass and low density
- Inner pulsar wind nebula? Circumstellar interaction component?

Pair-instability supernovae *Jerkstrand, Smartt & Heger 2016*

Compute spectra of 3 explosion models from Heger & Woosley 2002:

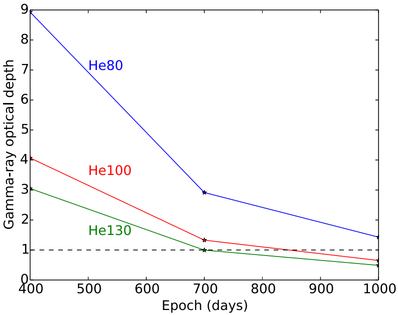
Model	V_{char} (km s^{-1})	O ($M_\odot$)	Si+S ($M_\odot$)	^{56}Ni ($M_\odot$)	Brightness
He80	5500	47	19	0.1	dim/normal
He100	7600	44	33	6	SLSN
He130	9700	33	35	40	SLSN

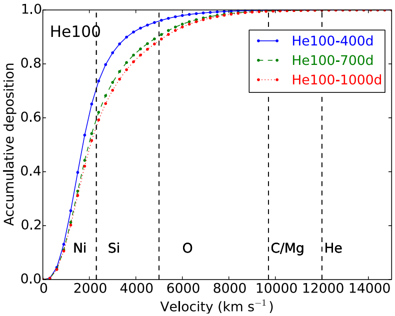




- 1D models expected to be accurate as mixing demonstrated to be weak (Joggerst & Whalen 2011, Chatzopoulos+2013, Chen+2014, Whalen+2015)

Gamma deposition

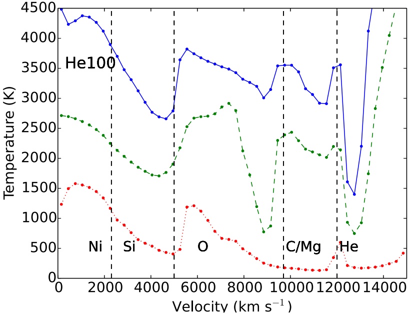


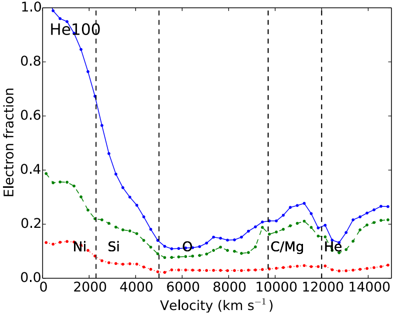


- Gamma rays are fully trapped for >2 years
- Almost all absorbed in ^{56}Ni and Si/S layers

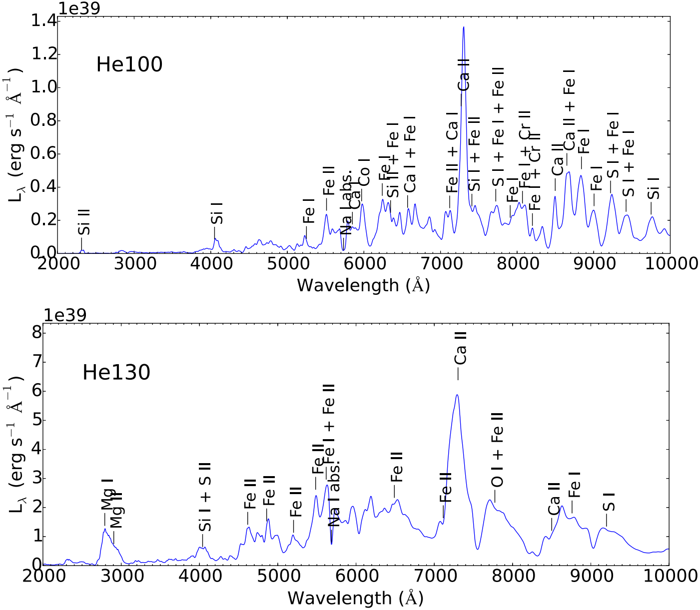
Physical conditions

- Ejecta are cold and neutral
- Expect lines of Fe I, Si I, S I, ...

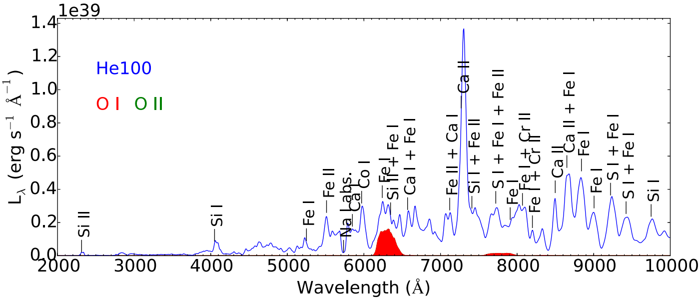


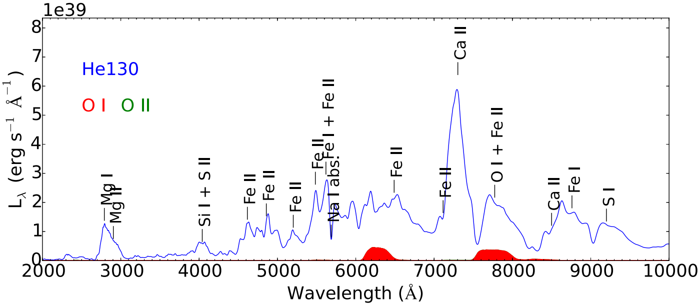


Spectra at 400d post-explosion

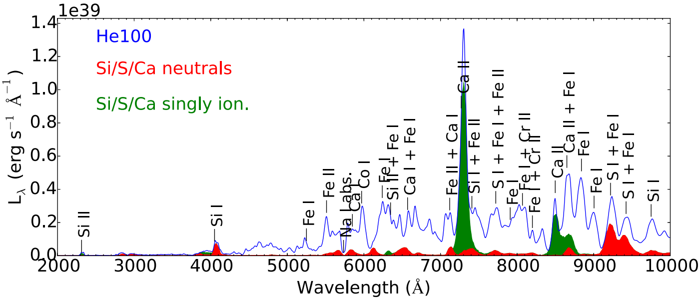


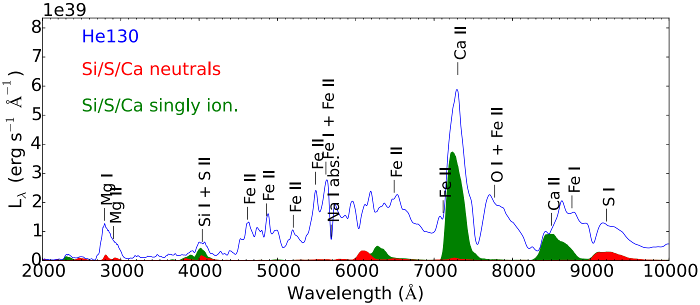
Weak contribution by O



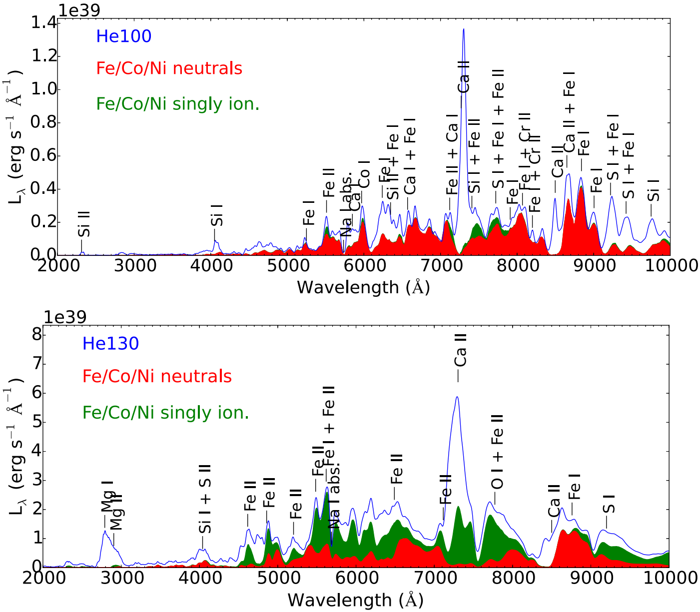


Intermediate contribution by Si/S/Ca

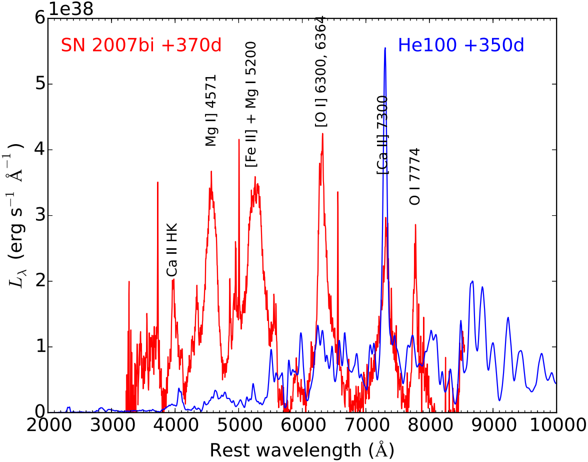




Strong contribution by Fe/Co/Ni

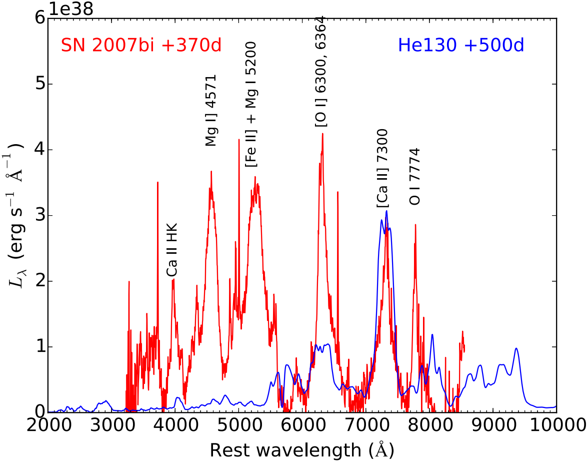


Comparison with PISN candidates



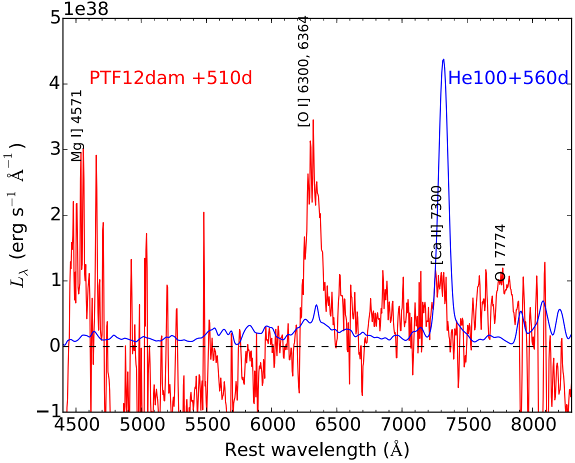
- Models too dim in blue region ($\lesssim 6500$ Å)
- He100 has too low velocities

Comparison with PISN candidates



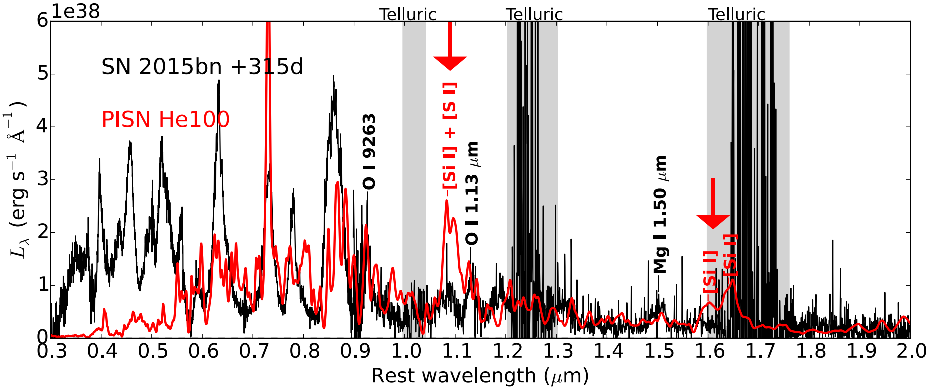
- He130 no significant improvement

Comparison with PISN candidates



- For PTF12dam, which probes later epochs, similar problems

NIR



- No sign of strong Si/S lines at 1.08 μm predicted by PISN models
- Similar picture for LSQ14an

SLSNe : overview of model classes and links to nebular spectra

Radioactivity

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

* Similarity to SN 1998bw and other broad-lined Ic.
* Blue plateau and 5200 line by Fe?
* PISNe too red. Can we make massive CCSNe explode?
* Gamma-ray deposition at small f? Especially O II/OIII hard.

Neutron star rotation energy

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

* Pulsar wind could explain inferred compression
* O II and O III lines may be from inner pulsar wind
* Predictive test failed for PTF12dam : ad-hoc escape needed
* Line profiles?

Ejecta kinetic energy

$E \approx 10^{51}$

* Shock regiom could explain small f and O II/O III
* Why no narrow He,C,O lines from unshocked CSM? (compare IIn SNe)
* Large inferred O masses problematic, at least for PPISNe

Summary

- We now have nebular-phase ($t > 200d$) observations of 7 SLSNe, z=0.11-0.52
- O II and O III lines, and sometimes Hα, latest observational clues
- The Type Ic class shows significant degree of homogeneity, and strong similarity with GRB-powered SNe such as SN 1998bw.
- Parameterized single-zone models show that the [O I] 6300, 6364 luminosity is only reproduced in models with M(O-zone) $\gtrsim$ 10 $M_\odot$. Mg I] 1.50 mu gives Mg mass of several $M_\odot$, supporting high mass.
- A high degree of clumping is indicated, $f_O \lesssim 0.01$, and calcium lines show $n_e \gtrsim 10^8$ cm^{-3}.
- Nebular models of PISNe show cold and neutral ejecta, with Fe I dominating the spectrum. Agreement with observed spectra of long-duration SLSNe is poor.