Supernova spectral synthesis modelling: results on nucleosynthesis and exotic explosions

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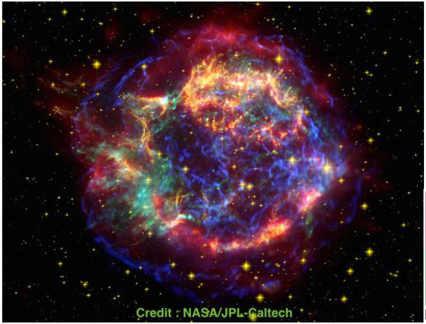


Max Planck Institute for Astrophysics

MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

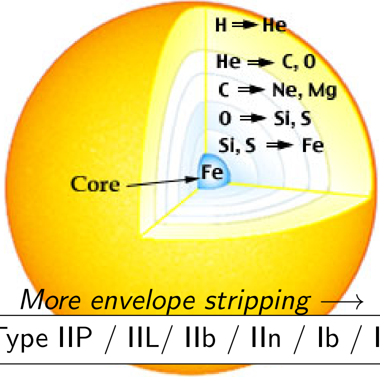
Outline

1. Introduction to SNe and their nucleosynthesis
2. Spectral synthesis modelling and the SUMO code
3. Application 1: Explosive burning yields of stable nickel in core-collapse SNe
4. Application 2: The origin and oxygen nucleosynthesis of superluminous SNe

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

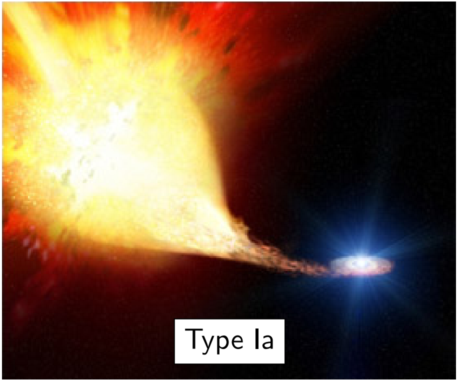
2 Thermonuclear explosion of a **white dwarf** exceeding the Chandrasekhar limit (1.4 $M_{\odot}$)



More envelope stripping ⟶

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

Credit: www.phys.olemiss.edu

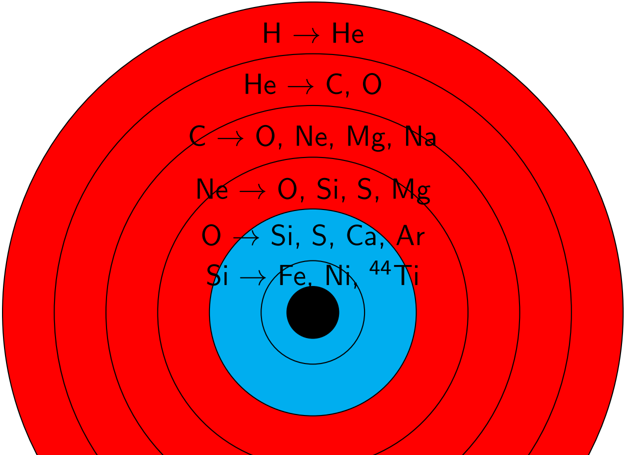


Type Ia

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



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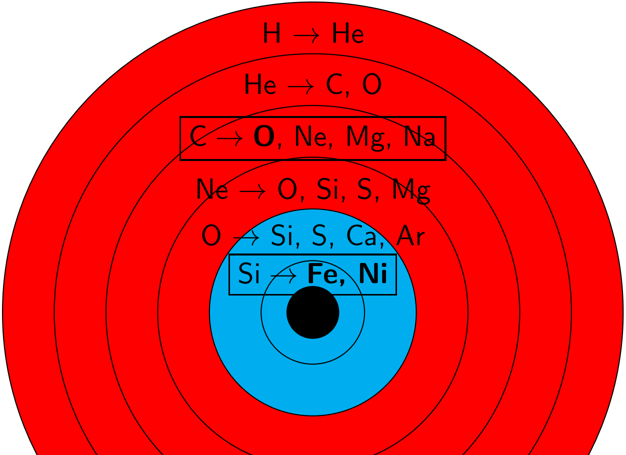


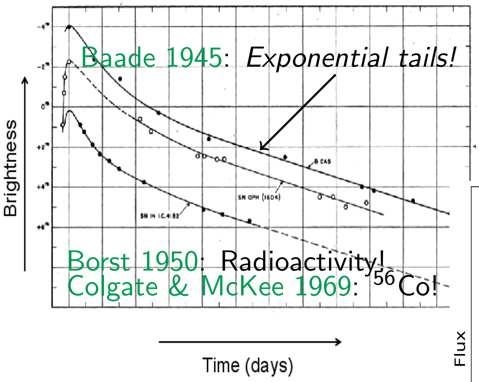
The origin of the elements

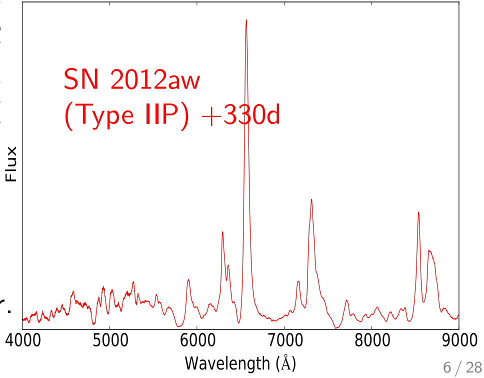
Ab.	El.	Main source	Nebular lines seen in SNe
1	H	Big Bang	Many
2	He	Big Bang	He I 5016, 7065, 1.08 μm, 2.06 μm
3	O	CCSN	[O I] 5577, **[O I] 6300, 6364**, O I 7774, O I 9263 + ..
4	C	AGB stars+CCSN	[C I] 8727, 9824/9850, 1.44 μm, CO lines
5	Fe	CCSN+TNSN	[Fe II] 7155, 1.26 μm, 1.64 μm, 18 μm, 26 μm
6	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

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: ~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 ↓ ↑ Identify physical regimes

2. **Forward modelling**: 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 (Kozma & Fransson 1992)

NLTE statistical equilibrium

- 21 of 28 elements from H to Ni, 3 ion. stages, ∼300 exc. states each
- Large charge transfer network

Temperature

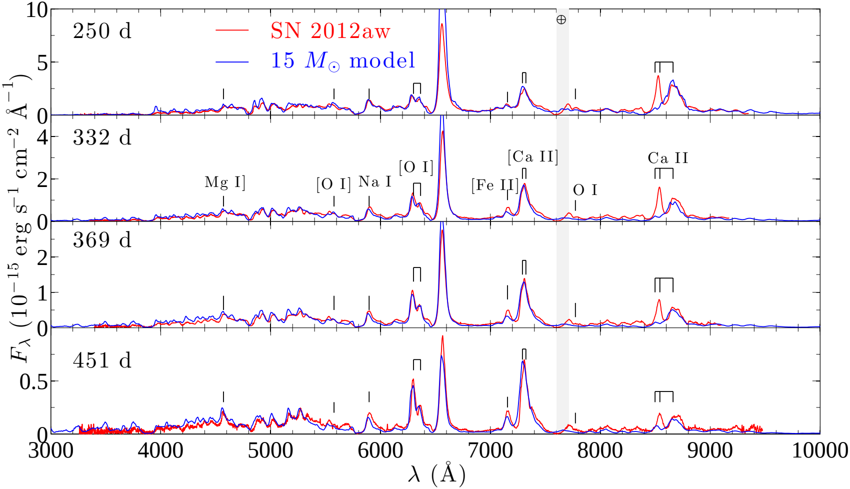
- Heating = cooling

Radiative transfer

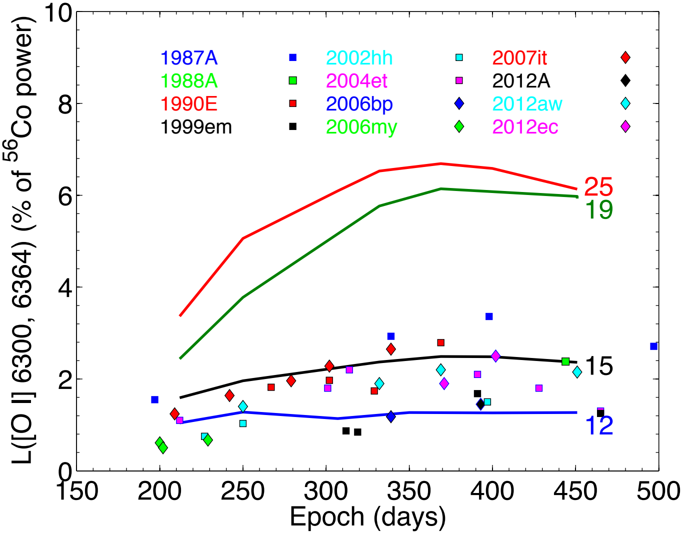
- Monte Carlo driver
- 300,000 atomic lines, 3,000 bound-free continua, free-free, electron scattering

- MPI code typically run of 100 cores

Type II SN models AJ+2014

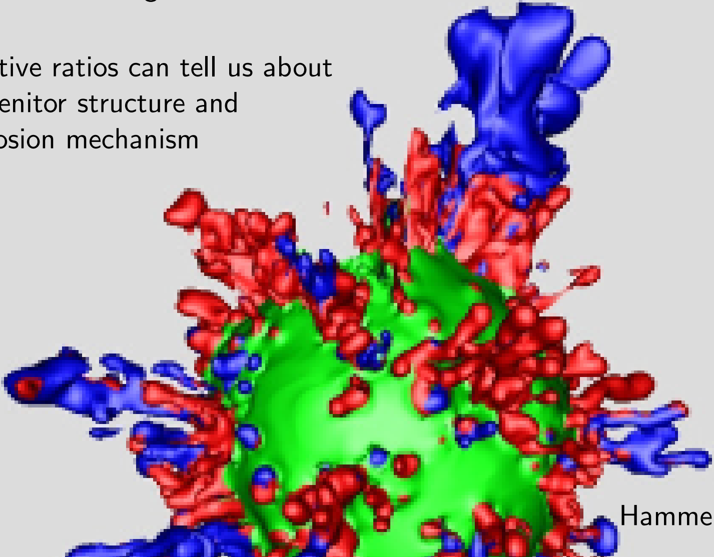


Type II SN models *AJ+2014*



Application 1: Stable nickel (^{58}Ni)

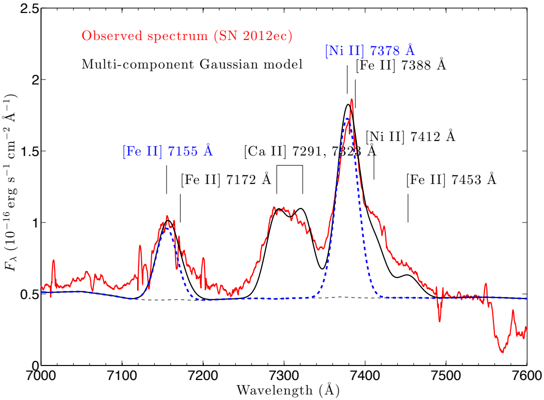
- Explosive burning → ^{56}Ni, ^{57}Ni, ^{58}Ni
- Relative ratios can tell us about progenitor structure and explosion mechanism



Hammer+2010

Stable nickel

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

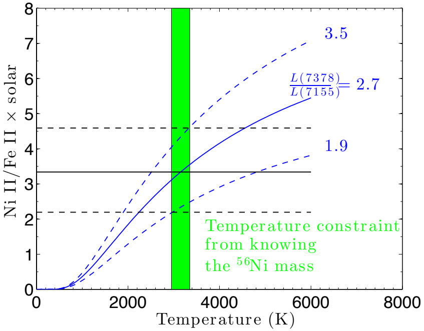


AJ+2015 (MNRAS)

- 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

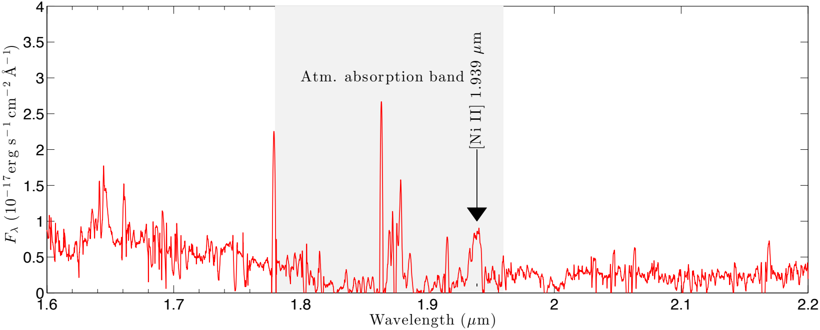


- Forward model: Ni II / Fe II ≈ Ni / Fe

SN 2012ec: Ni/Fe = 3.2 times solar

Stable nickel

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



Ni/Fe ratios in 7 CCSNe *AJ+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	$\sim$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 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?

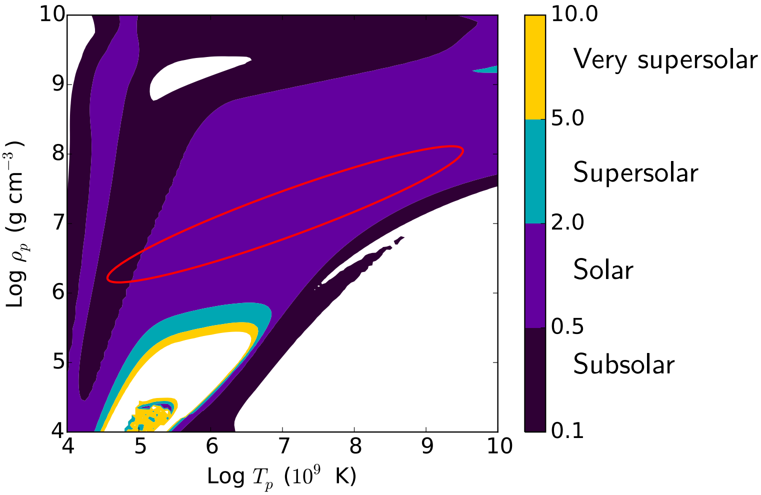
Jerkstrand, Timmes, Magkotsios+2015

- Nucleosynthesis simulations with *torch* code on parameterized thermodynamic trajectories
- Dependency on only three parameters: $\mathbf{T_p}$ (peak temperature), $\rho_\mathbf{p}$ (peak density), and $\mathbf{Y_e}$ (electron fraction).

$$\frac{dT}{dt} = \frac{-T}{3\tau}, \quad \frac{d\rho}{dt} - \frac{-\rho}{\tau}, \quad \tau = 446/\rho^{1/2} \tag{1}$$

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

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



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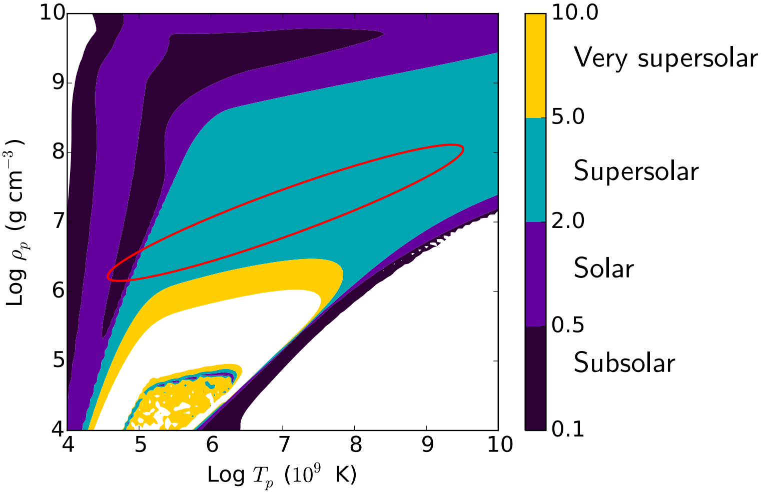
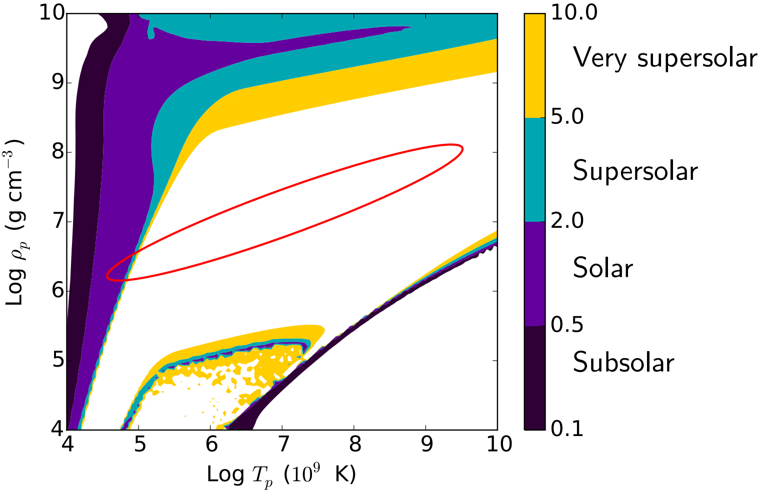
Follow-up analysis: what is Ni/Fe ratio diagnostic of?

$\boxed{Y_e = 0.497}$: Large allowed region opens up for supersolar

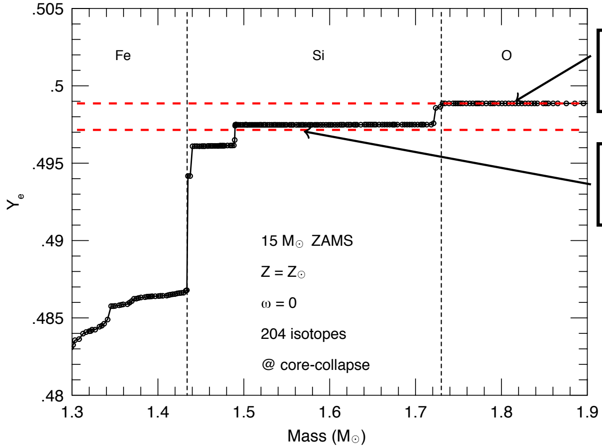


Follow-up analysis: what is Ni/Fe ratio diagnostic of?

$\boxed{Y_e = 0.490}$: Extreme densities required



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

How does ^{58}Ni, ^{57}Ni, ^{56}Ni relate to ^{44}Ti?

- SN 1987A: all 4 isotopes determined

Ratio	Ratio (times solar)	Reference
^{44}Ti/^{56}Ni	1.5	Jerkstrand, Fransson, Kozma 2011 Boggs 2016, Science
^{58}Ni/^{56}Ni	~ 1	AJ+2015
^{57}Ni/^{56}Ni	1-2	Kurfess 1992

- A high-entropy burning of O-shell fuel is needed: all spherically symmetric models fail

Application 2: 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. Candidates:

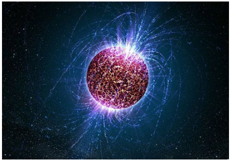
Radioactivity

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

Ex: Pair-instability SNe

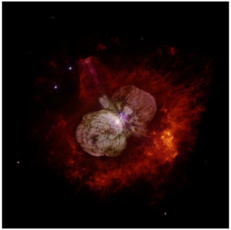
Neutron star rotation energy

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

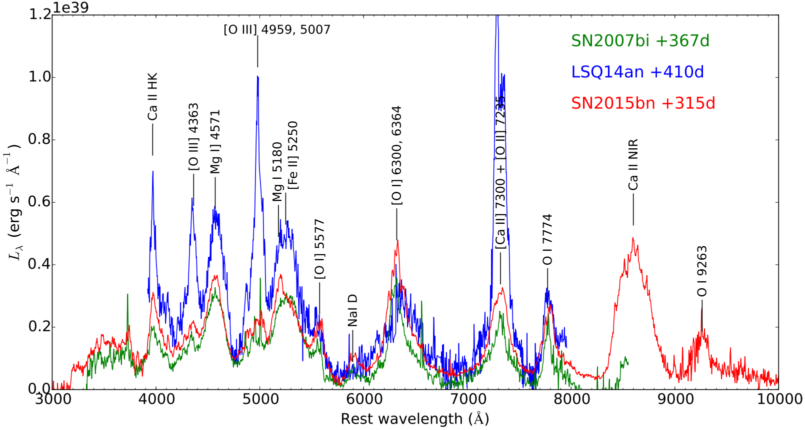


Ejecta kinetic energy

$E \approx 10^{51}$



Observed spectra at 400d *Jerkstrand+2017*

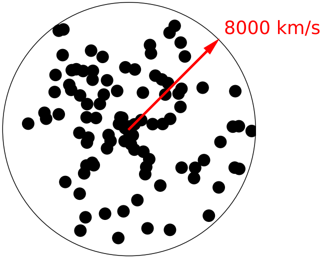


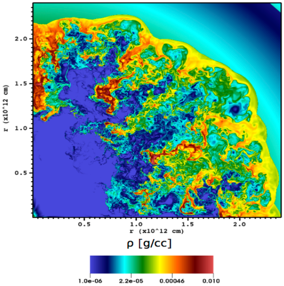
- Strong O, Mg lines
- Expansion velocities $\sim$8,000 km s^{-1}

Modelling 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 composition, mass, deposition, and filling factor (clumping).





Chen+2016

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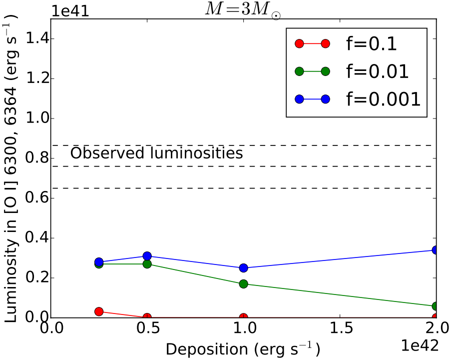

- At $M = 3\ M_\odot$, [O I] 6300, 6364 never reaches observed levels: more deposition ionizes O I to O II

Modelling O-zone emission *Jerkstrand+2017*

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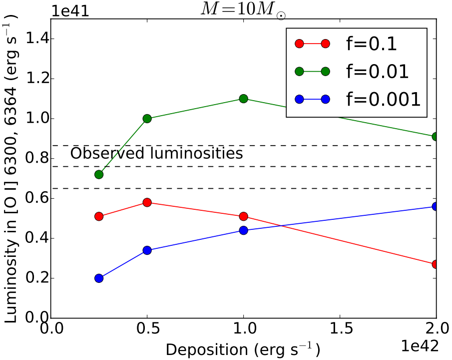
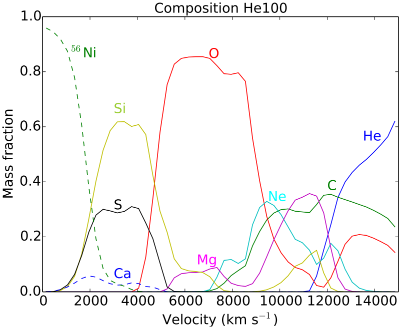


- At least $M = 10\ M_\odot$ is need for [O I] 6300, 6364 to reach observed levels $\rightarrow$ **highest O-masses inferred for any SNe**
- SLSNe must come from very massive stars, $M_{ZAMS} > 40\ M_\odot$

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

Explosion models (Heger & Woosley 2002)

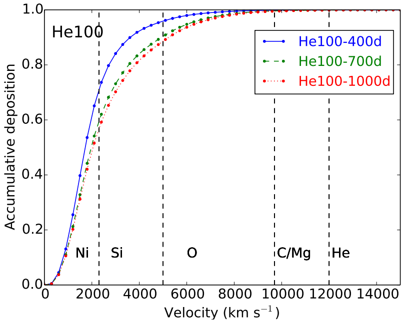
Model	M_{ZAMS} ($M_\odot$)	O ($M_\odot$)	Si ($M_\odot$)	S ($M_\odot$)	^{56}Ni ($M_\odot$)	SN Type
He80	~140	47	14	5	0.1	normal SN
He100	~200	44	23	10	6	superlum.
He130	~260	33	24	11	40	superlum.



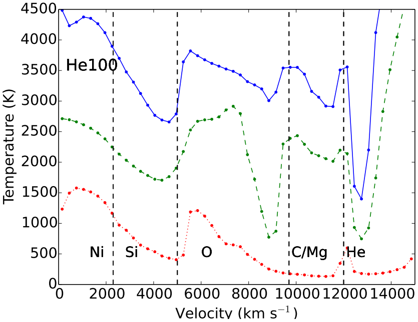
- Macroscopic mixing small (e.g. Joggerst & Whalen 2011, Chatzopoulus+2013) → can use 1D ejecta models to good accuracy.

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

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

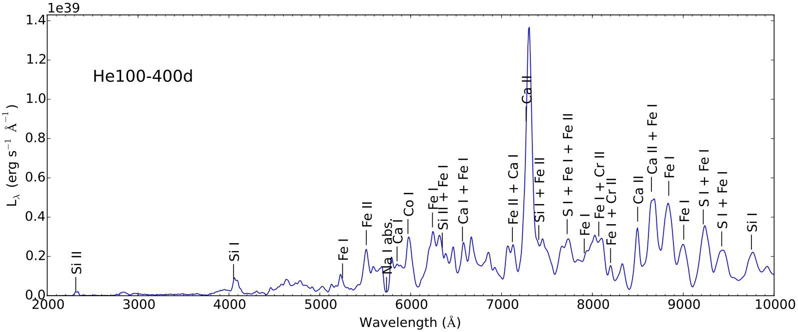


- Gas is cold ($T < 4000$ K) and neutral ($x_e < 1$)



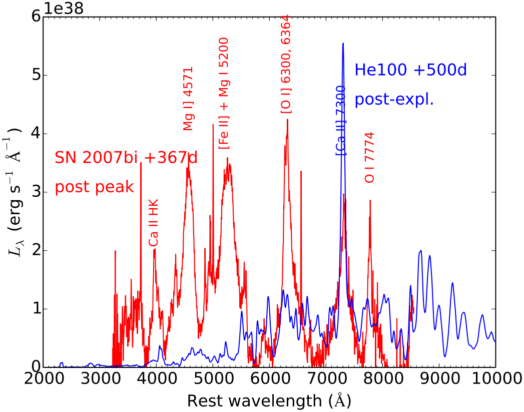
$\rightarrow$ Expect lines of Fe I, Si I, S I, Ca I, Ca II,...

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 data

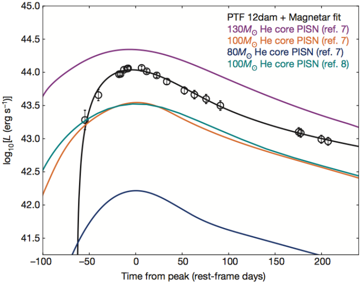


Jerkstrand, Smartt, & Heger+2016 (MNRAS)

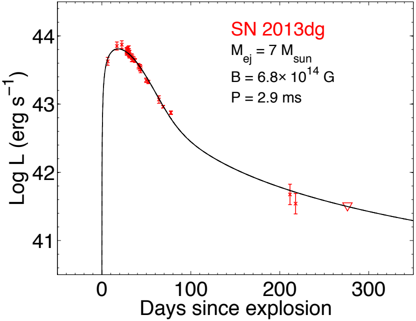
- No good fit to current PISN candidates (SN2007bi, PTF12dam, LSQ14an, 2015bn)

Superluminous SNe: Light curve modelling

- New method developed where semi-analytic methods were
  1. Generalized from ^{56}Ni to arbitrary power source
  2. Calibrated to grid of radiation hydrodynamic solutions
- Application to both long-duration and short-duration events showed viability of **magnetar scenario**



Nicholl, Smartt, Jerkstrand+, 2013, Nature



Inserra, Smartt, Jerkstrand+, 2013, ApJ

Code available on https://star.pst.qub.ac.uk/webdav/public/ajerkstrand/Codes/Genericarnett/

Summary

- Supernovae are important sources of nucleosynthesis, but so far we have few quantitative results on production in individual sources and classes
- **SUMO** is a state-of-the-art spectral synthesis code used for analysing nebular spectra of SNe
- 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.
- New light curve models have shown viability of **magnetar models** to explain the new class of superluminous SNe
- Single-zone spectral grid shows **highest O masses** ($> 10\ M_\odot$) **found in any SN so far**
- **Pair-instability models** fail in spectroscopic modelling test