Modelling and interpreting supernova nebular spectra

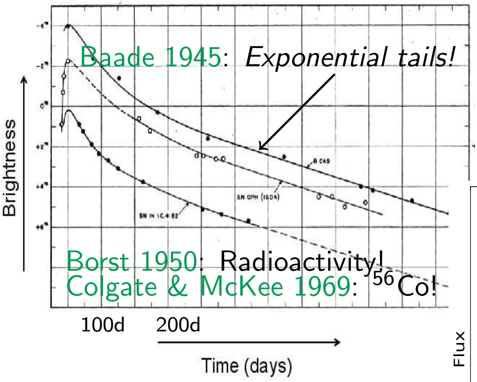
Anders Jerkstrand

Max Planck Institute for Astrophysics

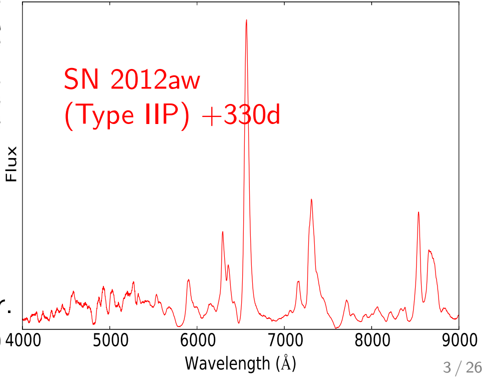
Outline

1. Spectral synthesis modelling and the SUMO code
2. Application 1: Explosive burning yields : stable nickel
3. Application 2: The upper extreme: Superluminous and pair-instability SNe
4. Application 3: The lower extreme : 8-10 $M_{\odot}$ stars

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 today: ~50

Spectral 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
- Energy loss by coll. ionization, excitation, and Coulomb cooling

NLTE statistical equilibrium

- 22 of first 28 elements in periodic table, 3 ion. stages, ~100 exc. states each

Temperature

- Heating (non-thermal, photoion., charge transfer) = cooling (line cooling, rec., free-free)

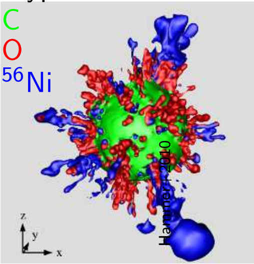
Radiative transfer

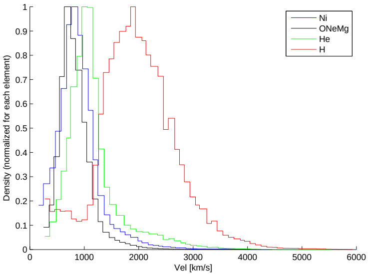
- Monte Carlo driver
- Sobolev approximation (modified for continuum destruction)
- 300,000 atomic lines, 3,000 bound-free continua, free-free, electron scattering

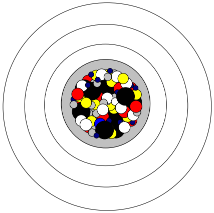
- Code is 1D but allows for mixing by 'virtual grid' option

Ways to consider multiD effects

Type II simulation







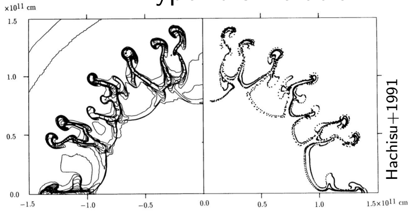
Approximate representation in virtual Monte Carlo grid

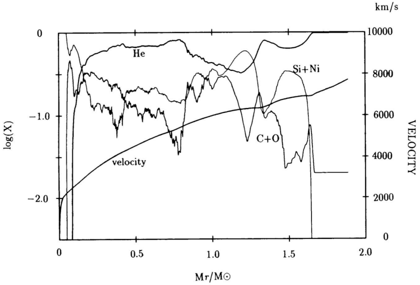
$$p_i = \frac{R_i^2}{\sum R^2}$$

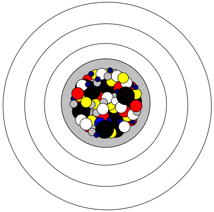
$$R_i = \left(\frac{3Vf_i}{4\pi N_i}\right)^{1/3}$$

Ways to consider multiD effects

Type Ib simulation







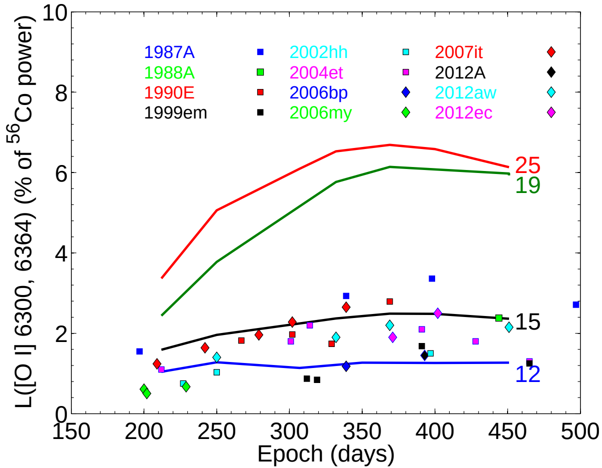
Approximate representation in virtual Monte Carlo grid

$$p_i = \frac{R_i^2}{\sum R^2}$$

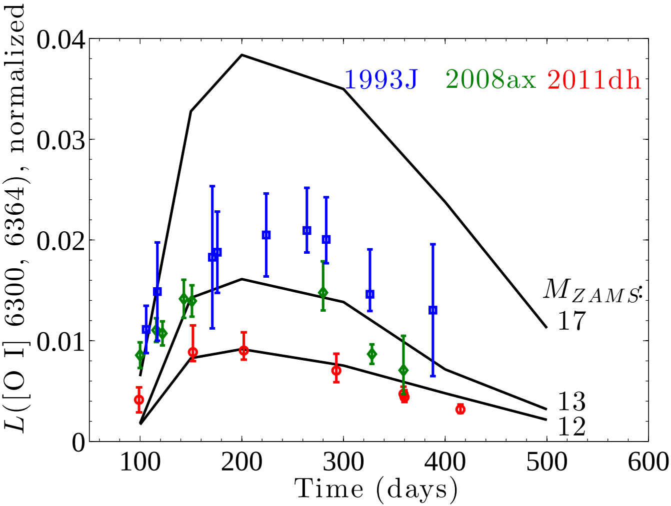
$$R_i = \left(\frac{3Vf_i}{4\pi N_i}\right)^{1/3}$$

Type IIP model grid using KEPLER ejecta with artificial mixing guided by 3D simulation *AJ+2014, AJ+2015 (MNRAS)*

No stars with $M_{ZAMS} \gtrsim 17\ M_{\odot}$ (or more robustly $M_{He-core} \gtrsim 5\ M_{\odot}$)



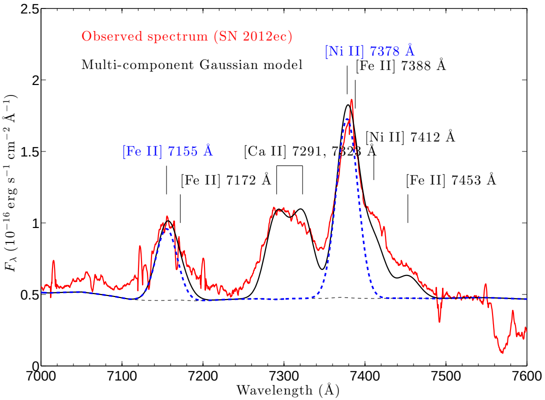
Type IIb SNe: Similar picture (but less data)



AJ+2015 (A&A)

Explosive nucleosynthesis yields: Stable nickel

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

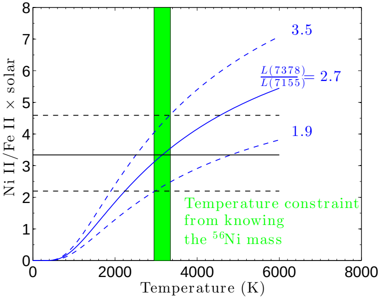


- Use forward model to identify lines present between 7000-7600 Å(7)
- 4-component fit (atomic data constraints remove 4 DOF)
- Determine L_{7378}, L_{7155}, L_{7300}, ΔV

AJ+2015 (MNRAS)

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 and L_{7378}/L_{7155} ratio gives Ni II/ Fe II ratio

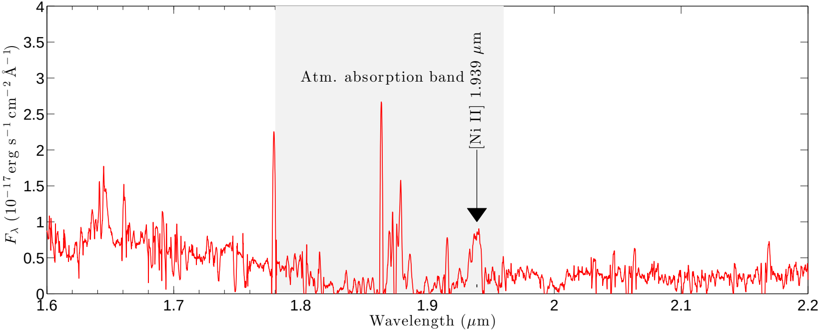


- Forward model: Ni II / Fe II $\approx$ Ni / Fe

SN 2012ec: Ni/Fe = 3.2 times solar

Stable nickel

- Strong [Ni II] 1.93 μm line gives very similar number → robustness of result



Ni/Fe ratios in 7 Type II CCSNe *AJ+2015 (MNRAS)*

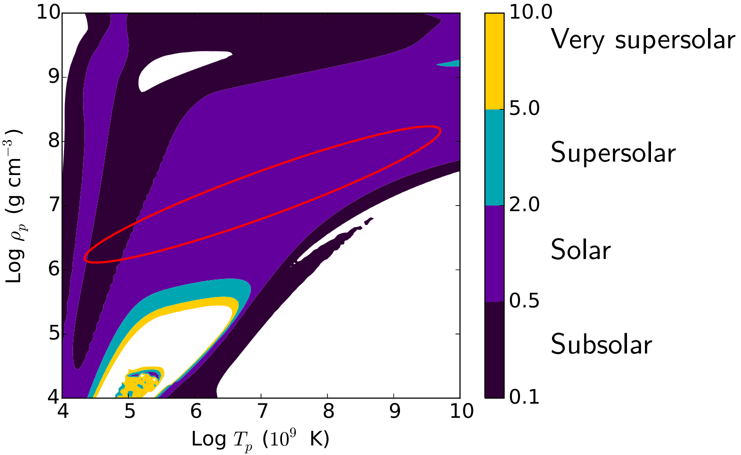
SN	Ni/Fe (times solar)	Reference
Crab	$60-75$	Macalpine 1989, Macalpine 2007
SN 1987A	$0.5-1.5$	Rank1988, Wooden1993, AJ+2015
SN 2004et	$\sim$1	AJ+2012
SN 2006aj	$2-5$	Maeda+2007, Mazzali+2007
SN 2012A	~ 0.5	AJ+2015
SN 2012aw	~ 1.5	AJ+2015
SN 2012ec	$2.2-4.6$	AJ+2015

- Average ratio $\geq$ solar
- If true in larger samle, Type Ia must make Ni/Fe $\leq$ solar $\rightarrow$ constraints on both CC and TN explosions models
- Sometimes much larger: what does it mean?

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

- Nucleosynthesis simulations with *torch* code on parameterized thermodynamic trajectories. *AJ+2015 (ApJ)*

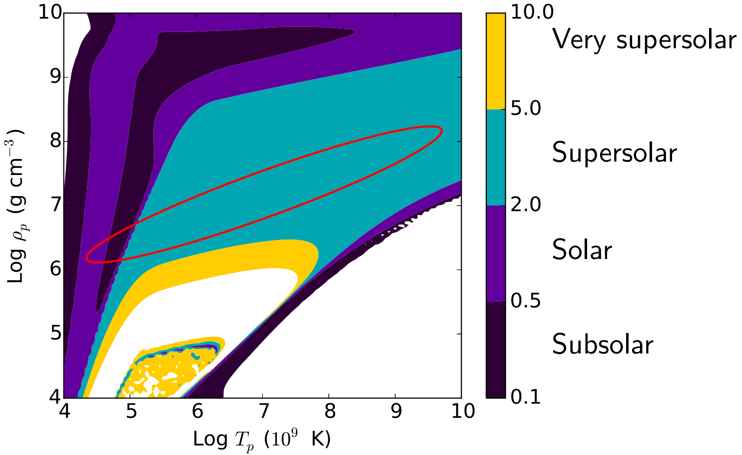
$\boxed{Y_e = 0.499}$: Prediction is Ni/Fe $\sim$ solar



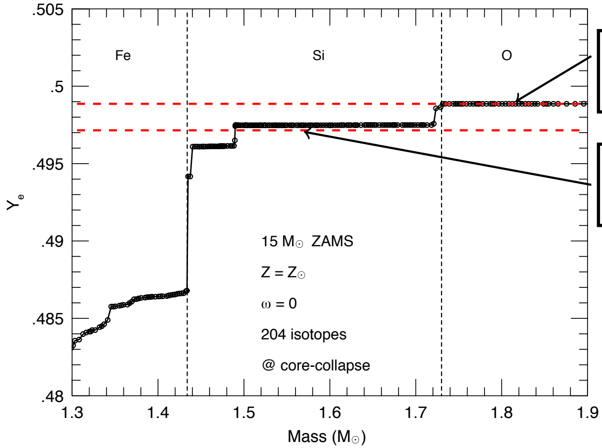
Follow-up analysis: what is Ni/Fe ratio diagnostic of?

- Nucleosynthesis simulations with *torch* code on parameterized thermodynamic trajectories. *AJ+2015 (ApJ)*

$\boxed{Y_e = 0.497}$: Prediction is 2-5 times supersolar



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



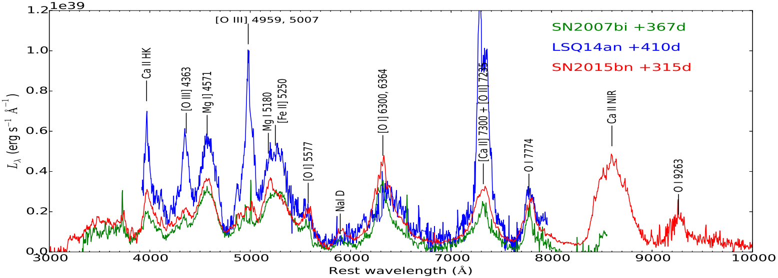
Ye = 0.499 (solar Ni/Fe): Oxygen layer

Ye = 0.497 (supersolar Ni/Fe): Silicon layer

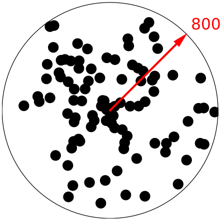
Important constraints on explosion mechanism

Type Ic SLSNe : Very high O masses inferred ($\gtrsim 10\ M_\odot$)

AJ+2017, ApJ

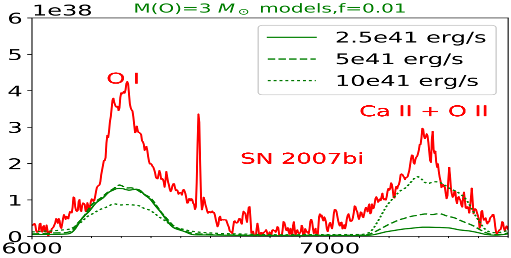


- Model with 100 O-rich clumps of mass M distributed in sphere with $V = 8000$ km s^{-1}, and parameterized energy deposition

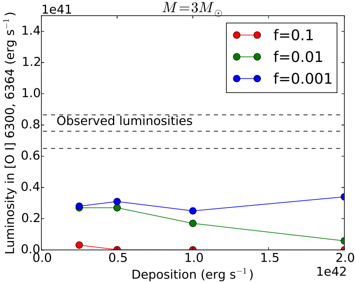


Type Ic SLSNe : Very high O masses inferred ($\gtrsim 10\ M_\odot$)

AJ+2017, ApJ

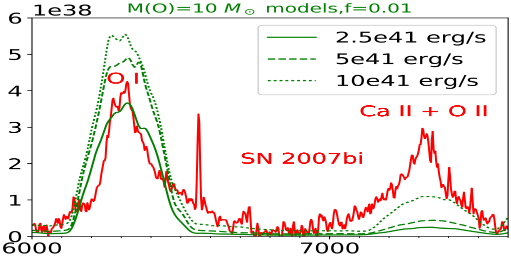


- At $M = 3\,M_\odot$, [O I] luminosities never reached as ionization to O II occurs before T gets high enough

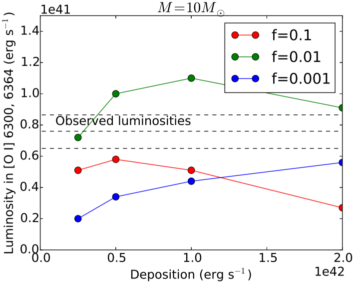


Type Ic SLSNe : Very high O masses inferred ($\gtrsim 10\ M_\odot$)

AJ+2017, ApJ

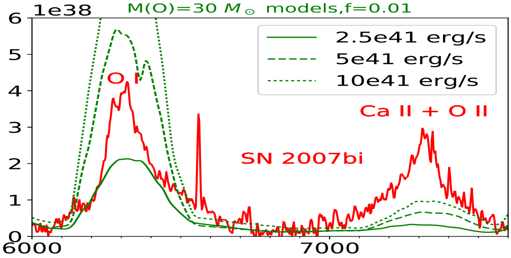


- At $M \gtrsim 10\ M_\odot$, [O I] luminosities are possible to reach

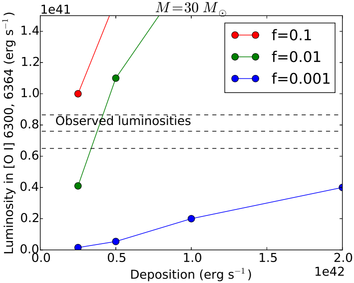


Type Ic SLSNe : Very high O masses inferred ($\gtrsim 10\ M_\odot$)

AJ+2017, ApJ



- At $M \gtrsim 10\ M_\odot$, [O I] luminosities are possible to reach



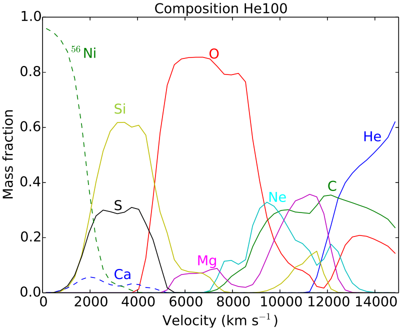
Significance

- These SNe occur in regions with $Z \gtrsim 0.5 Z_\odot \rightarrow$ CO cores of at least 10 $M_\odot$ survive to core collapse at high metallicities
- At least some very massive CO cores explode
- The explosiom energy is at least 3E51 erg

Are these massive CO core explosions pair-instability supernovae? *Jerkstrand, Smartt & Heger 2016*

Explosion models (Heger & Woosley 2002)

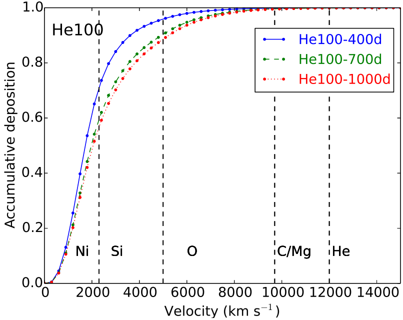
Model	M_{ZAMS} ($M_\odot$)	O ($M_\odot$)	Si ($M_\odot$)	S ($M_\odot$)	^{56}Ni ($M_\odot$)	SN Type
He80	~140	47	14	5	0.1	normal SN
He100	~200	44	23	10	6	superlum.
He130	~260	33	24	11	40	superlum.

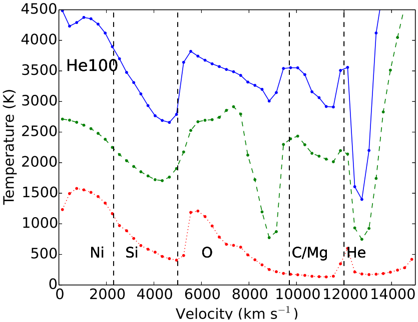


- Macroscopic mixing small (e.g. Joggerst & Whalen 2011, Chatzopoulus+2013) → can use 1D ejecta models to good accuracy.

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

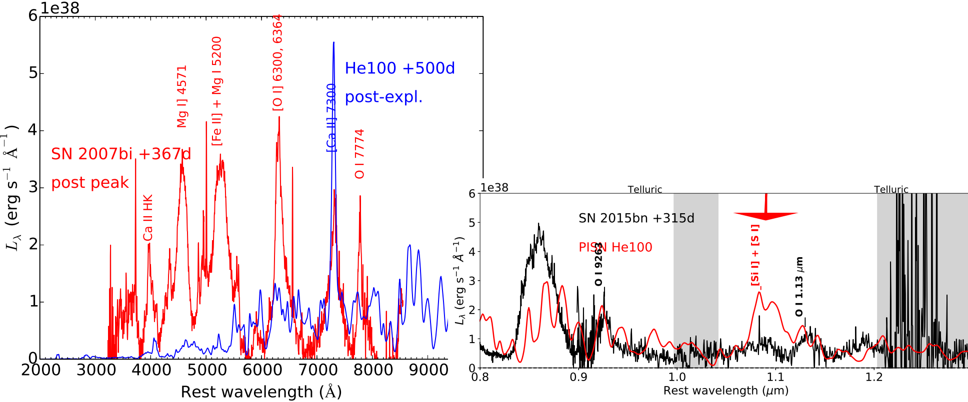
- Gamma rays are trapped in deep-lying ^{56}Ni, Si, S, Ca layers
- Gas is cold ($T < 4000$ K) and neutral ($x_e < 1$)





→ Expect lines of Fe I, Si I, S I, Ca I, Ca II,...

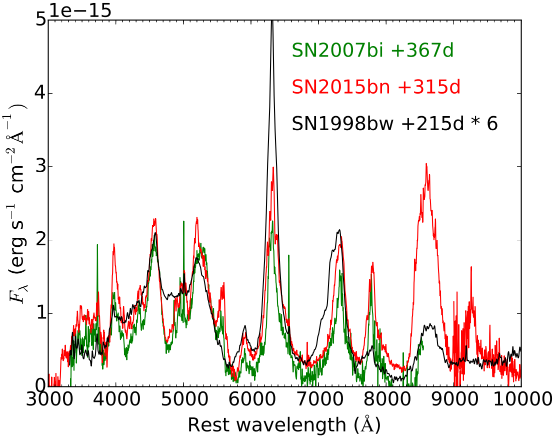
Pair-instability SNe: fit to candidates is poor



Jerkstrand, Smartt, & Heger+2016 (MNRAS)

- No good fit to current PISN candidates (SN2007bi, PTF12dam, LSQ14an, SN2015bn). *Qualitative* problems: No sign of massive (30 $M_\odot$) Si/S reservoirs either by emission or blocking of O-zone.

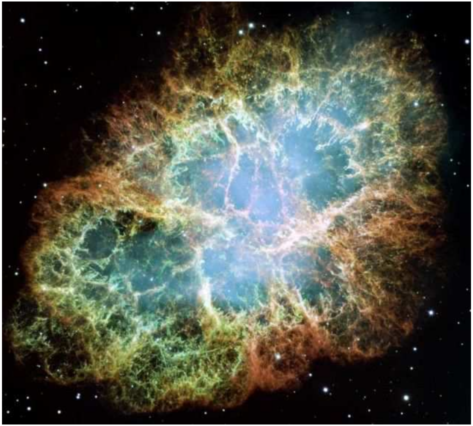
Superluminous SNe: New observations and recalibration of old rather reveal strong similarity to GRB SNe Jerkstrand+2017



- Same lines with similar velocities
- Both classes appear to be mainly O-rich nebulae

The lowest mass SNe : $M_{ZAMS} = 8 - 10\ M_{\odot}$ range

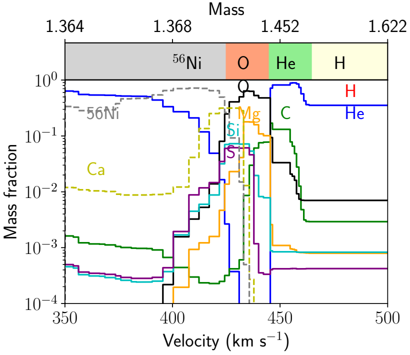
- Expect 30-50% of all CCSNe from this range
- Low compactness → confidence and success of neutrino mechanism
- Observational class of Subluminous IIP prime candidates. But complexity in stellar evolution → few LC and spectral models.

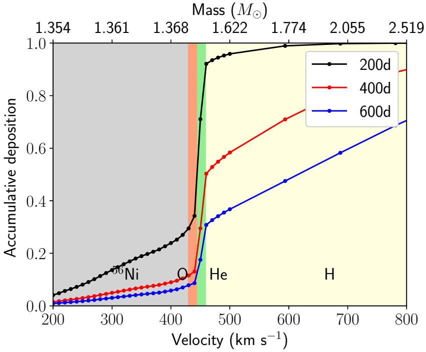


ECSN!

The lowest mass SNe : $M_{ZAMS} = 8 - 10\ M_{\odot}$ range

- Explore spectral formation in a 9.0 $M_{\odot}$ Fe core progenitor (Woosley & Heger 2015), exploded in 1D with neutrinos (Prometheus-HOTB), with ^{56}Ni expansion dynamics.

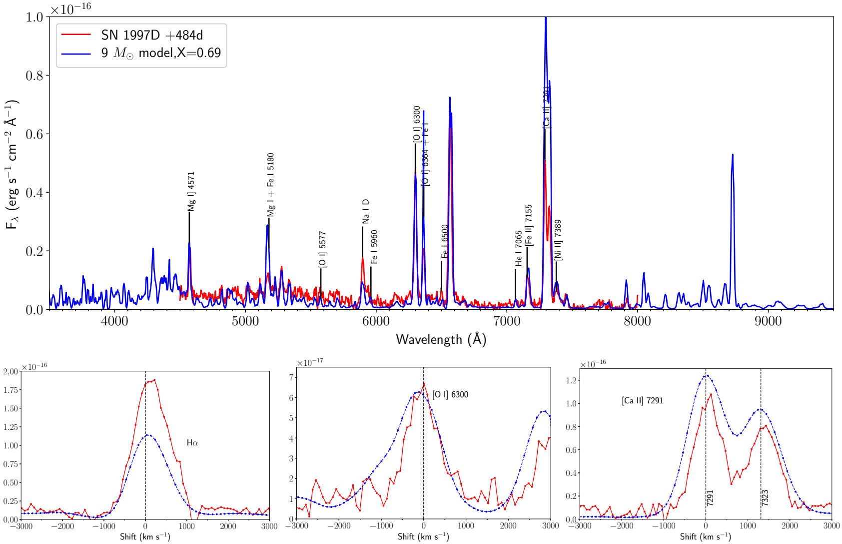




Jerkstrand, Ertl, Janka+ 2017, submitted

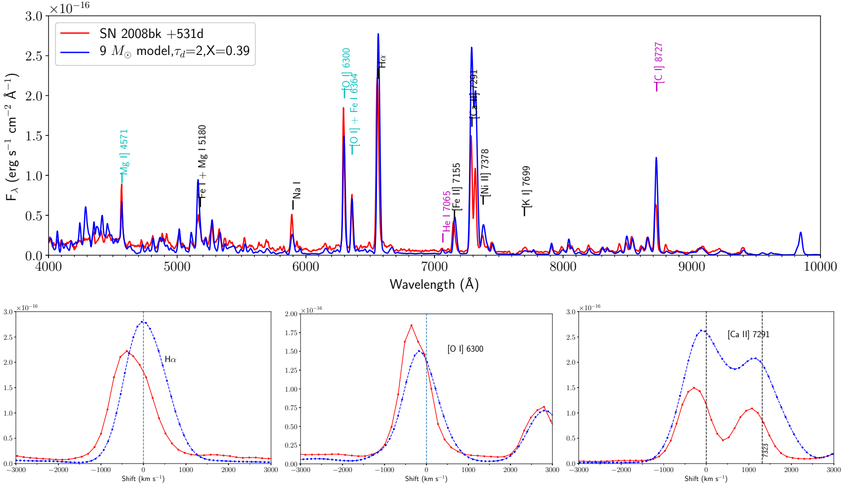
The lowest mass SNe : 8-10 $M_\odot$ range

- Three Subluminous IIP SNe have nebular spectra. SN 1997D fits well..



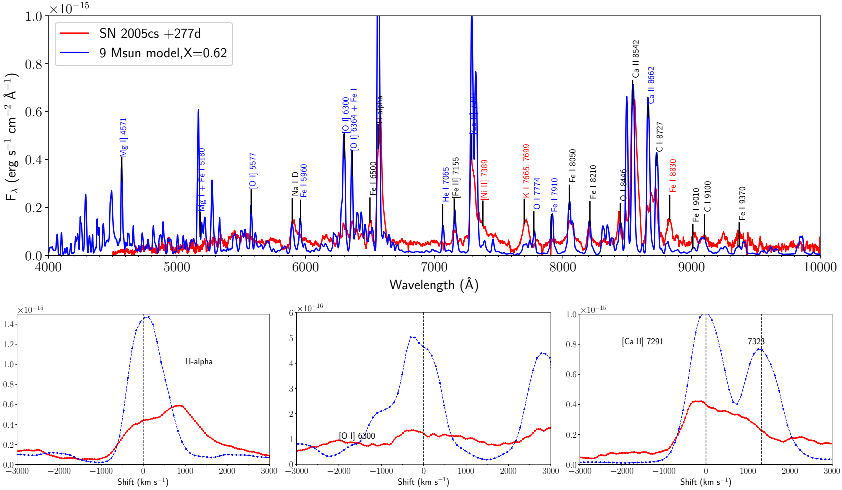
The lowest mass SNe : 8-10 $M_\odot$ range

- Also SN 2008bk (but dust formation complicates)...



The lowest mass SNe : 8-10 $M_\odot$ range

- But SN 2005cs less well...



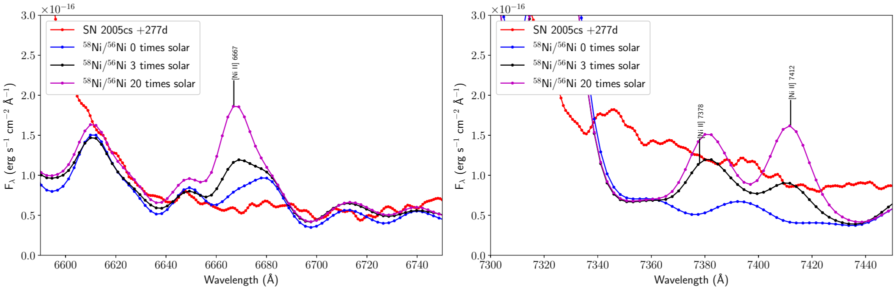
Context : the 3 subluminous IIP with nebular spectra

SN	Method	M_{ZAMS} *estimate* ($M_\odot$)	Ref
1997D	Progenitor	N/A	
	Hydro-1	$\sim$8	Chugai & Utrobin 2000
	Hydro-2	> 20	Zampieri 2003
	Nucleo	$\sim$10	Chugai & Utrobin 2000
	Nucleo	$\sim$9	Jerkstrand+, in prep.
2005cs	Progenitor	10 ± 3	Maund+2005
	Hydro-1	> 17	Utrobin & Chugai 2008
	Hydro-2	$\sim$12	Pastorello 2009
	Nucleo	$<$10 (No sign of He core material)	Jerkstrand+, in prep.
2008bk	Progenitor	13 ± 2	Maund+2014
	Hydro	12 ± 1	Pumo+2017,Lisakov+2017
	Nucleo	$\sim$9	Jerkstrand+, in prep.

2008bk is best case today for an iron CCSN from the low-mass end.

If we accept the low-mass hypothesis, are these ECSNe or CCSNe?

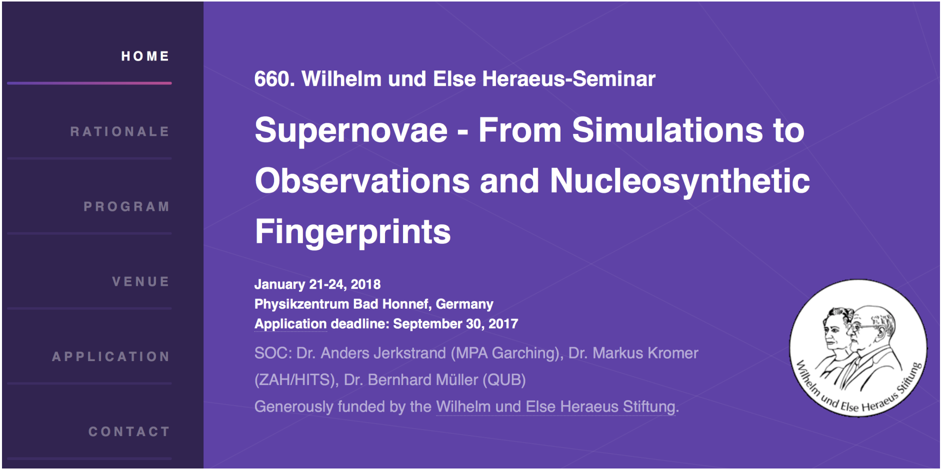
- Clear detection of He core material (C, O, Mg)
- Strong Ni lines predicted for ECSNe. Not clearly seen, but lack of mixing may also explain.



Summary

- Spectral modelling of Type II SNe with SUMO indicate low/moderate amounts of **oxygen**, and origin in low-mass stars ($M_{ZAMS} \sim 8 - 18$). Some results on **abundance ratios** are becoming available, e.g. Mg/O
- 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 3-5 times higher. Nucleosynthesis simulations show high values requires **high neutron excess** of the fuel, only found in the **silicon shell** of the progenitor. This puts constraints on explosion models.
- For superluminous SNe, spectral grid shows **very high O masses** (> 10 $M_{\odot}$). Origin must be very high mass stars, so indication is that at least some of these explode.
- **Pair-instability SN models** fail in spectroscopic modelling tests : not confirmed to exist in local Universe
- Models of neutrino driven explosions for the **8-10 range** match the class of subluminous IIP SNe to these.

Upcoming workshop in Bad Honnef, Germany, January 2018.



http://weh660.h-its.org