Nebular-phase models of CCSNe - recent progress in 1D and 3D

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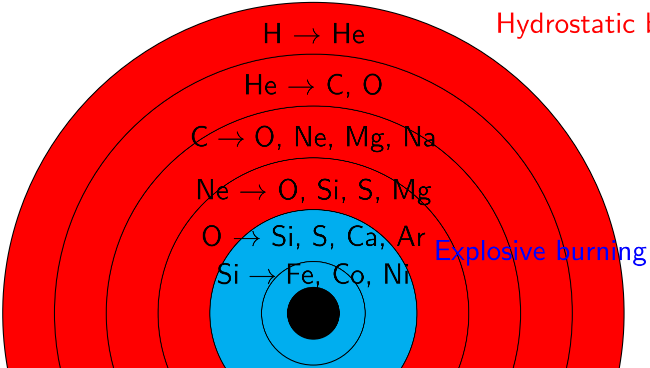
The nebular phase : a window on SN nucleosynthesis

- The **nebular phase** is when ejecta become (semi)-transparent ($\gtrsim$ few months). It offers a good opportunity to diagnose the composition and structure of the SN because we can see all of it.



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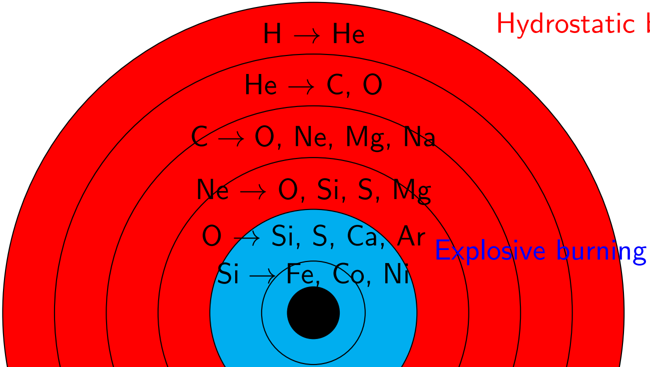
➤ Determination of **element masses** give information on progenitor and stellar evolution.



The nebular phase : a window on SN nucleosynthesis

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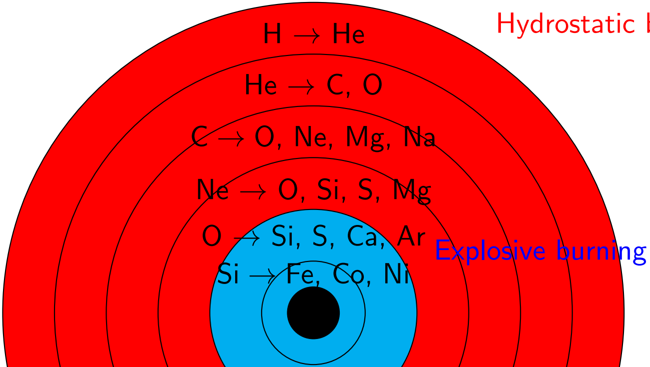
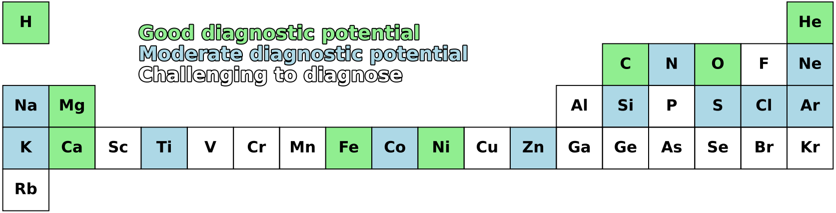
➤ Determination of **element masses** give information on progenitor and stellar evolution.

➤ Determination of **morphology and physical conditions** constrain explosion mechanism.



Elements we can currently diagnose from SN nebular phase spectra



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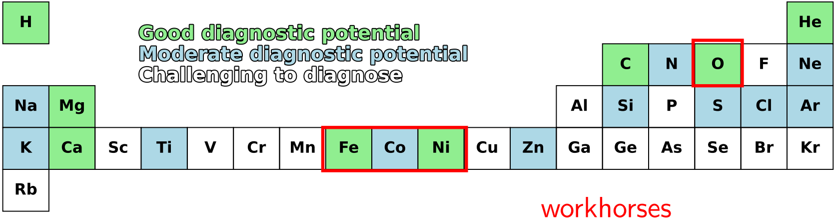
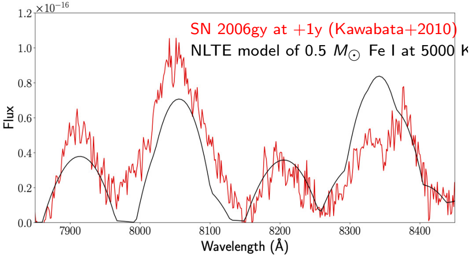
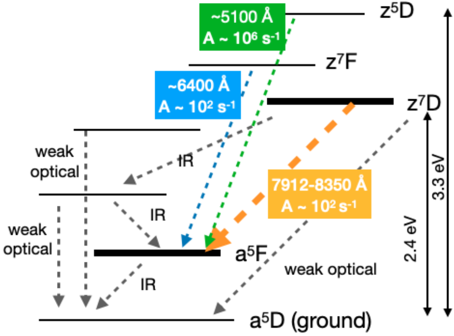


Identification of a large iron reservoir in SN 2006gy

Jerkstrand, Maeda & Kawabata 2020, Science

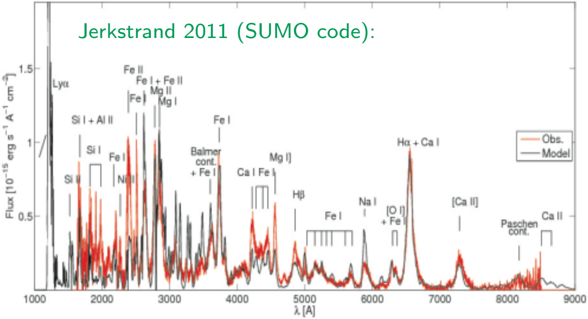
- Unique lines of **Fe I** at $\sim$ 1500 km/s.





- Modelling of the lines: $\boxed{0.3 < M_{Fe} < 2\ M_\odot}$.
- The brightness of the spectrum at +1y matches the decay of an initial ^{56}Ni mass of 0.5 $M_\odot$.
- We favour interpretation as a **Ia-CSM supernova** : the $\sim$ 1 $M_\odot$ ejecta slams into a $\sim$ 10 $M_\odot$ recently ejected common envelope.

NLTE spectral modelling



Quite complex physical situation:
Cold, radioactively powered gas,
at intermediate densities.

+Fransson, Mazzali, Maeda, Dessart, Höflich
Shingles, Blondin, Botyanszki, van Baal,+more

(see AJ+2017, Handbook of SN chapter, for a review)

SUMO(1D) and EXTRASS(3D)

	SUMO(1D)	EXTRASS(3D)
Dimensionality:	1D with artificial mixing	3D, spherical coordinates
Level populations:	NLTE	NLTE
Radiative transfer:	Sobolev local + global line-by-line	Sobolev local
Non-thermal physics:	Heating/ionization/excitation	Heating/ionization
Chemistry:	Molecules	None
Composition	H - U	H - Ni
Inner boundary inj.:	Yes	No

AJ+2011,2012,2020

Omand+2023, Liljegren+2023, Pognan+2023, van Baal+2023

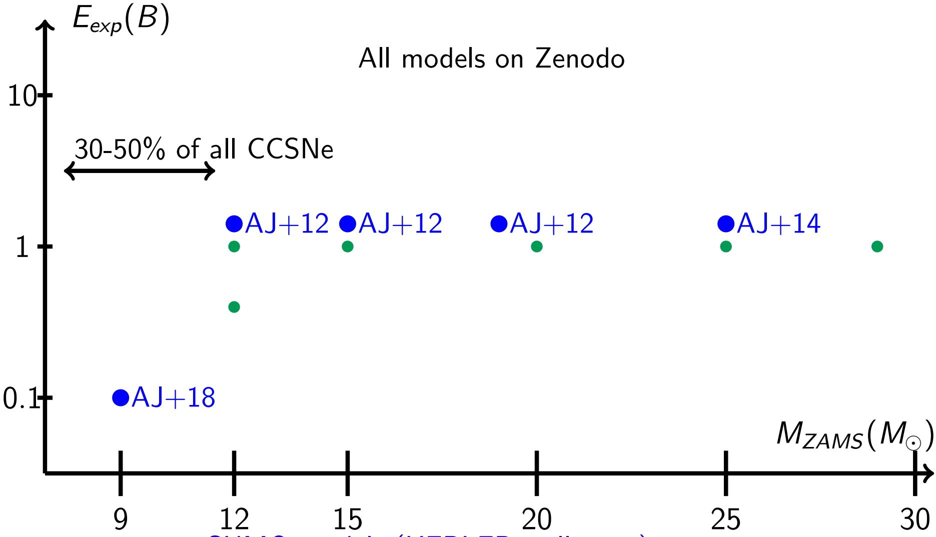
pulsar input

molecules

r-process

Full 3D

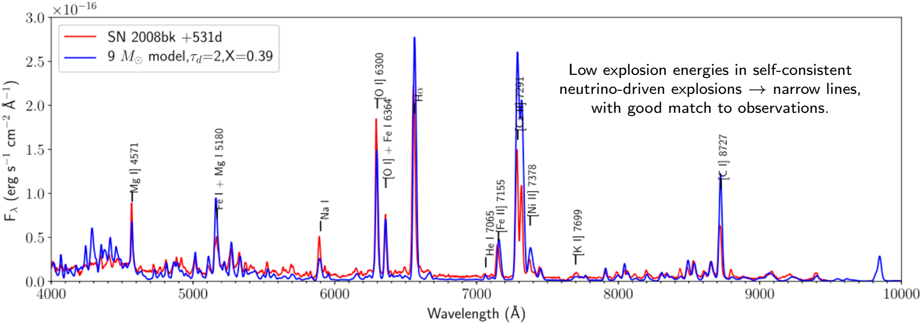
Available Type IIP nebular models



●SUMO models (KEPLER stellar ev.)

•CMFGEN models (Dessart+2013/2020/2021)

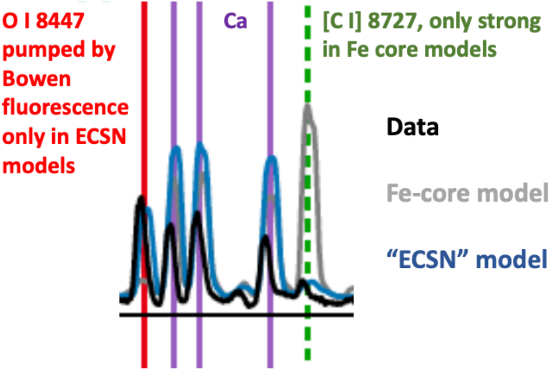
Subluminous IIP SNe - good match with low-mass ($M_{ZAMS} \sim 8-10\ M_{\odot}$) explosions AJ+2018



- Prototype is SN 1997D. Now known to constitute about 1/3 of all Type IIP SNe (e.g. Spiro+2014).
- Spectral models can distinguish **Fe CCSNe** to **ONeMg CCSNe (=Electron-capture SNe)** - most observed events fit first class better (see also Lisakov+17/18).

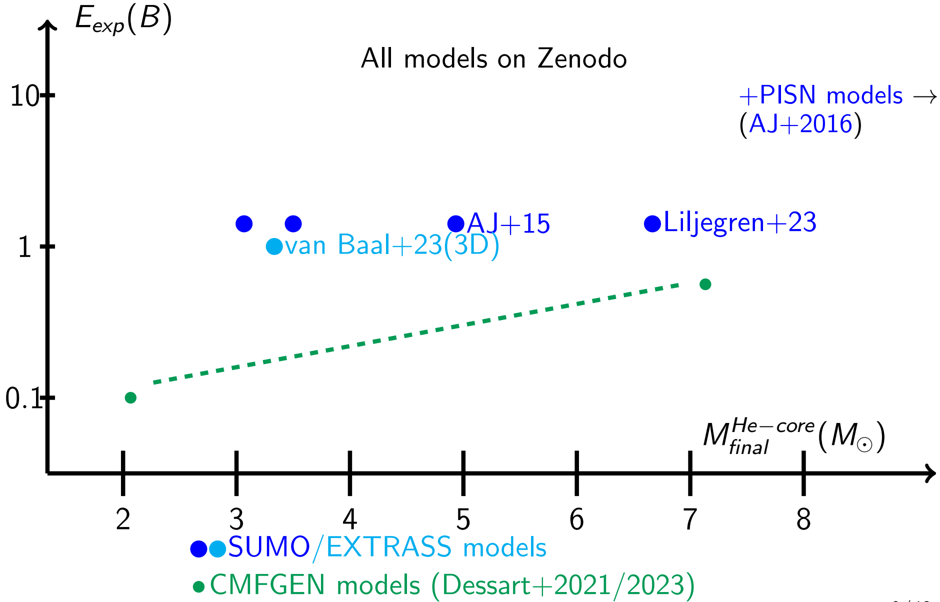
ECSN candidates

SN 2016bkv Hosseinzadeh+2018

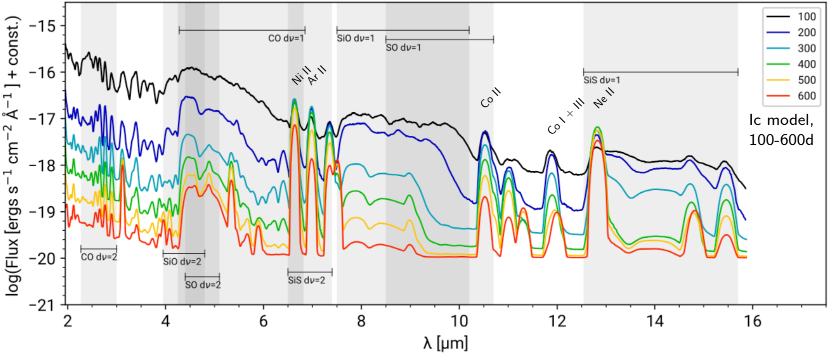


- However, estimated ejecta and ^{56}Ni masses not fully consistent with ECSN hypothesis.
- The determination of whether ECSNe exist or not (see also Hiramatsu+2021) is important for stellar evolution theory in the 8-10 $M_{\odot}$ range, and for GCE of light trans-iron elements.

Available stripped-envelope nebular models

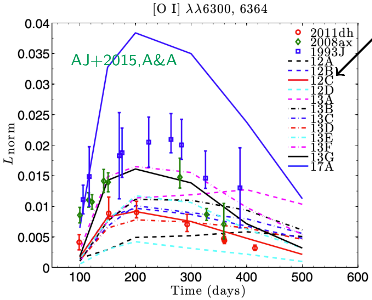


SESNe with molecules *Liljegren+2023*

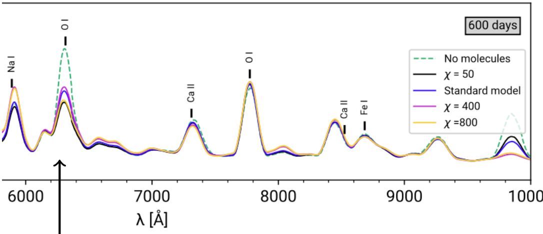


- Rich diagnostics for both molecular and atomic emission in IR - opportunities with JWST. Molecules trace three different nuclear burning layers:
  - He burning (CO)
  - Neon burning (SiO, SO, early SiS)
  - Explosive O burning (late SiS)

SESNe with molecules *Liljegren+2023*



For each M_{ZAMS} (12,13,17 $M_\odot$), different assumptions about molecules and other microphysics.

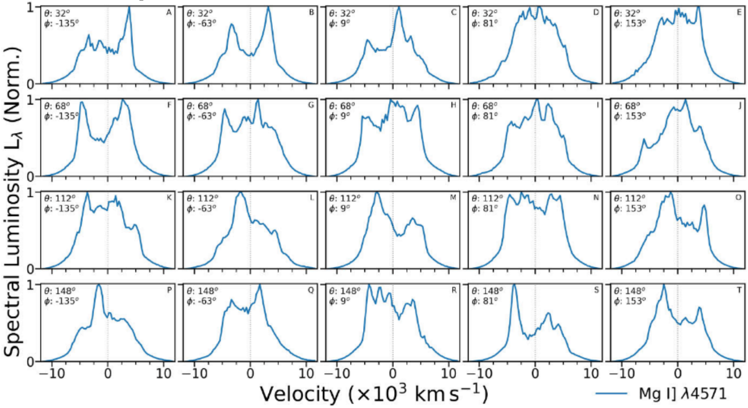


Can now calculate this self-consistently.

- Understanding the molecular chemistry is important to reach sufficient accuracy for the [O I] 6300, 6364 line.

SESNe in 3D *van Baal+2023,van Baal+,in prep.*

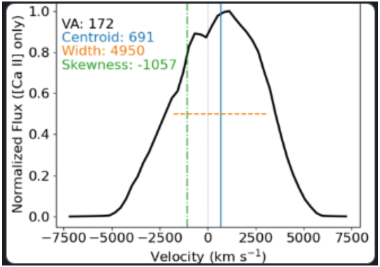
Mg I] 4571 line in a Type Ib model,different viewing angles



- Complex line profiles and large variation with viewing angle.
- Valuable inputs for interpreting statistical properties of line profiles (e.g Fang+18/22/23, Modjaz+08, Taubenberger+09).

SESNe in 3D *van Baal+2023,van Baal+,in prep.*

- New metrics for nebular lines beyond luminosities: **shift** (1st moment), **width** (2nd moment), and **skewness** (3d moment).



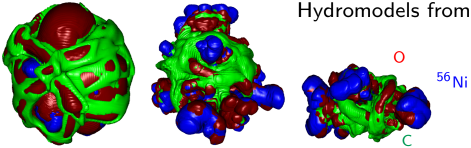
$$v_{\rm shift} = \frac{\int_{-v_{max}}^{v_{max}} L_\lambda v(\lambda) d\lambda}{\int_{-v_{max}}^{v_{max}} L_\lambda d\lambda},$$

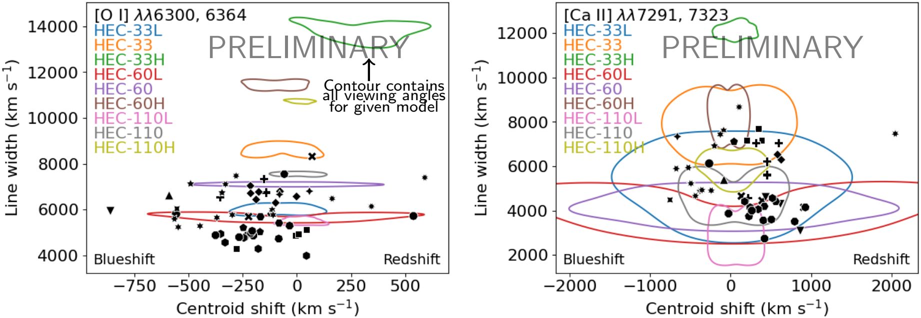
$$v_{\rm width} = 2.35 \times \left(\frac{\int_{-v_{max}}^{v_{max}} [v(\lambda) - v_{\rm shift}]^2 L_\lambda d\lambda}{\int_{-v_{max}}^{v_{max}} L_\lambda d\lambda} \right)^{1/2},$$

$$v_{\rm skew} = \left(\frac{\int_{-v_{max}}^{v_{max}} [v(\lambda) - v_{\rm shift}]^3 L_\lambda d\lambda}{\int_{-v_{max}}^{v_{max}} L_\lambda d\lambda} \right)^{1/3}.$$

SESNe in 3D *van Baal+2023,van Baal+,in prep.*

Hydromodels from Garching group





Qualitatively new type of test for explosion models.

Semianalytic methods

ttt.astro.su.se/~anje1871/semianalytictmethods/

Index of /~anje1871/semianalyticmethods

Name	Last modified	Size	Description
Parent Directory		-	
56Ni-bubble_diagnostic_from_[Ni_II]_6.63	2022-04-01 17:12	1.5K	
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mu,_[Co_II]_10.52_mu,_[Fe_II]_26_mu_lines	2022-04-01 17:12	0	

- A major use of the forward models is to **inform and validate semi-analytic methods**.

Summary

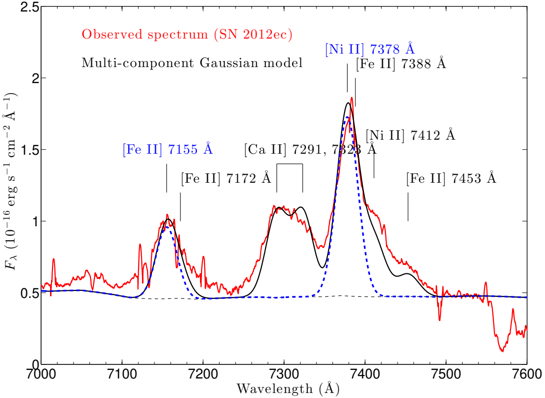
- Nebular-phase spectral model grids (1D with artificial mixing) are available from SUMO and other codes.
- The models also spawn a suite of semi-analytic methods.
- The first 3D models and grids are now becoming available.
- Recent results include
  - ^{56}Ni masses from Fe/Co lines useful to distinguish models.
  - Better understanding of molecular effects on optical lines, and diagnostic potential in MIR.
  - Strong linkage of subluminous IIP class to low-mass Fe CCSNe.

If you are interested to use SUMO or EXTRASS models, or would like to request models to be computed for specific SN ejecta, please contact us.

Thank you for listening!

Stable nickel

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

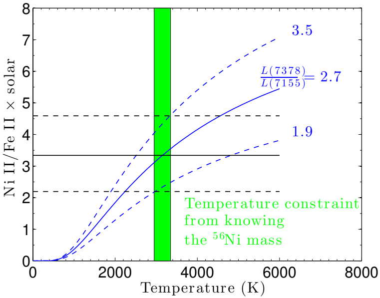


AJ+2015b (MNRAS)

- 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

- Forward model: LTE, optically thin conditions. Then
  - L_{7155} and $M(^{56}\text{Ni})$ determines T
  - T, L_{7378}, L_{7155} gives Ni II/ Fe II ratio

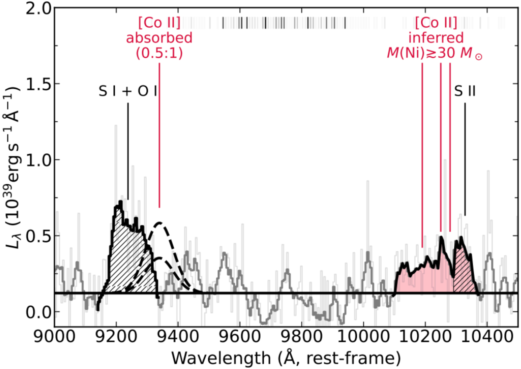


- Forward model: Ni II / Fe II ≈ Ni / Fe

SN 2012ec: Ni/Fe = 3.2 times solar

Possible identification of a large cobalt reservoir SN 2018ibb

Schulze+, in press. arXiv:2305.05796



- **[Co II] 1.025 μm** is the strongest predicted Co line in SNe at nebular times (e.g. AJ+2015), closely followed by **[Co II] 9340**.
- If the emission at 1.02 μm in 2018ibb is interpreted as Co II, the initial ^{56}Ni mass is $\gtrsim$ 30 $M_\odot$.
- However, [Co II] 9340 is not seen, which requires postulation of absorption of this line.