# Nebular-phase spectral models of explosive transients - recent progress in 1D and 3D

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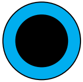
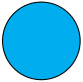
# Explosive transient evolution

| **Photospheric phase** | **Nebular phase** |
|---|---|
| Long escape time for radiation → diffusion light curve. | Short escape time for radiation → light curve follows radioactive decay. |

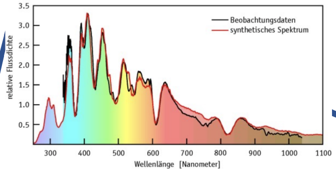
*Spectra probe* *surface layers*



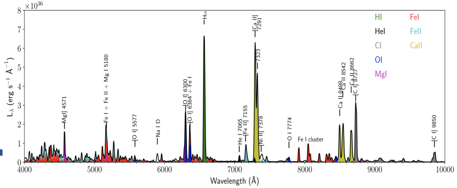
*Spectra probe* *all ejecta*



Many lines excited and significant optical depth → **scattering spectra**




Few lines excited and reduced optical depth → **emission line spectra**




*Time* →

Simple microphysics (LTE) | Complex michrophysics (NLTE)

Reviews: Sim 2017, Handbook of SNe | Jerkstrand 2017, Handbook of SNe

# SUMO(1D) and 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 Barmentloo+2024 Banerjee+,in pr

pulsar input molecules kilonovae Full 3D light elements r-process






# Nebular-phase Ia models

- W7
  - Fransson & Jerkstrand 2015 (optical/NIR)
  - Johansson+2017 (MIR)
  - Jerkstrand, Maeda & Kawabata 2020 (Ia-CSM config.)
- Delayed detonations (DDC10 and DDC25, simplified): Blondin+2022

# StandaRT : large RT code comparison project

A&A 668, A163 (2022)
https://doi.org/10.1051/0004-6361/202244134


Astronomy & Astrophysics

## StaNdaRT: a repository of standardised test models and outputs for supernova radiative transfer

Stéphane Blondin[1,2,27], Sergei Blinnikov[3,4,5,31], Fionntan P. Callan[6,26], Christine E. Collins[6,7,26], Luc Dessart[8,27], Wesley Even[9,10,33], Andreas Flörs[7,34], Andrew G. Fullard[11,34], D. John Hillier[12,27], Anders Jerkstrand[13,32], Daniel Kasen[14,30], Boaz Katz[15,35], Wolfgang Kerzendorf[11,16,34], Alexandra Kozyreva[17,31], Jack O'Brien[11,34], Ezequiel A. Pássaro[18,34], Nathaniel Roth[30], Ken J. Shen[19,30], Luke Shingles[6,7,26], Stuart A. Sim[6,26], Jaladh Singhal[34], Isaac G. Smith[11,34], Elena Sorokina[3,4,31], Victor P. Utrobin[3,20,28], Christian Vogl[17,33], Marc Williamson[21,34], Ryan Wollaeger[22,23,33], Stan E. Woosley[24,29], and Nahliel Wygoda[25,35]

*(Affiliations can be found after the references)*

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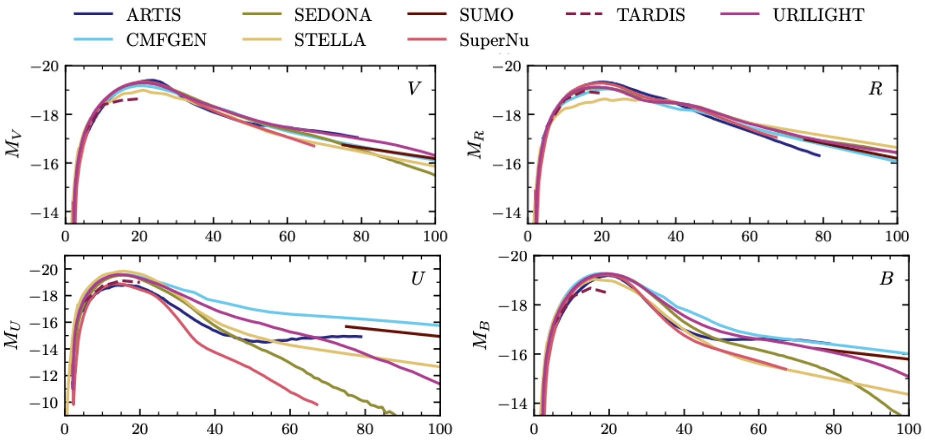
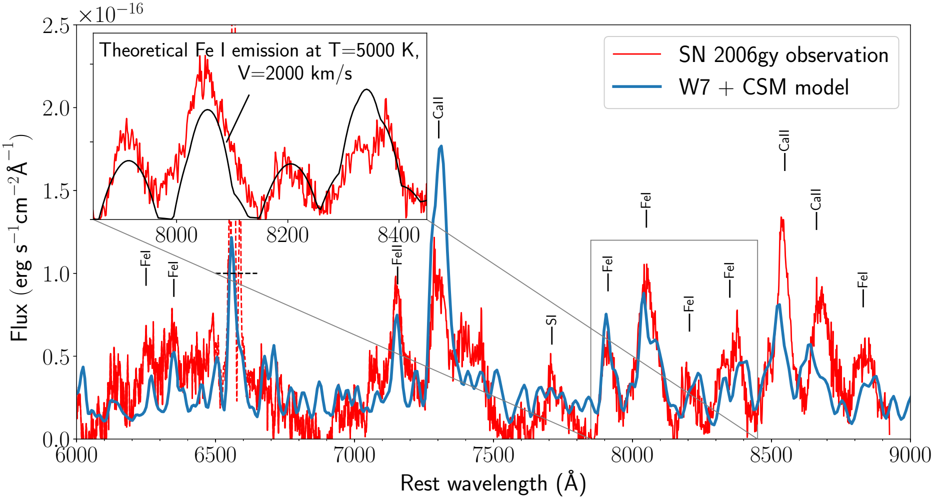
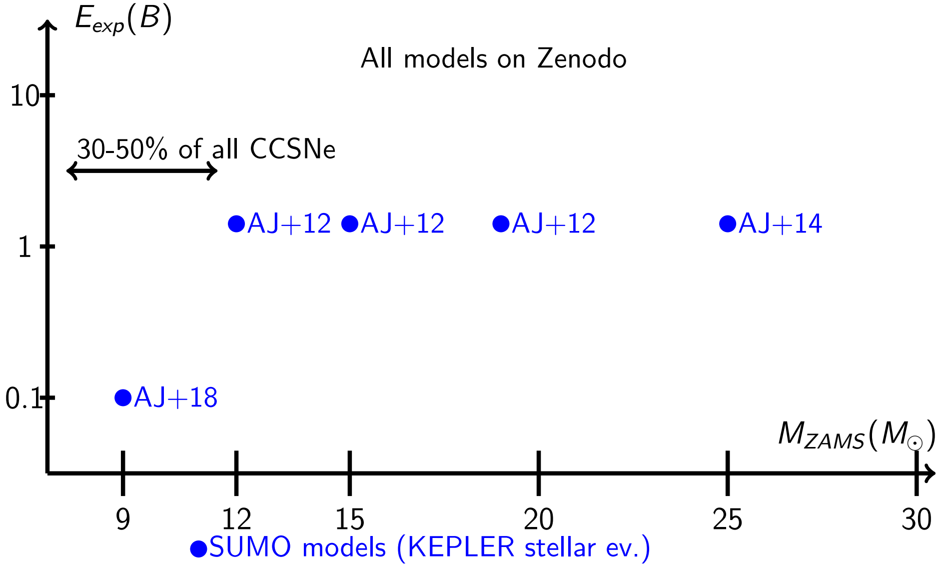
# Ia photometric light curve models, 0-100d.



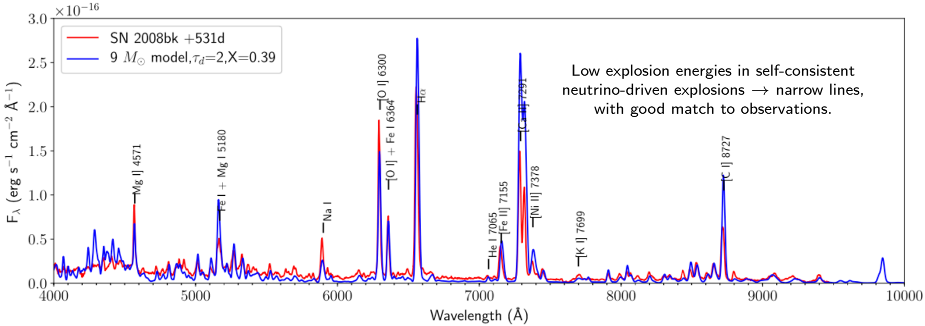
# SN 2006gy as a Ia-CSM SN *Jerkstrand, Maeda & Kawabata, Science 2020*



# Nebular-phase models for H-rich CCSNe

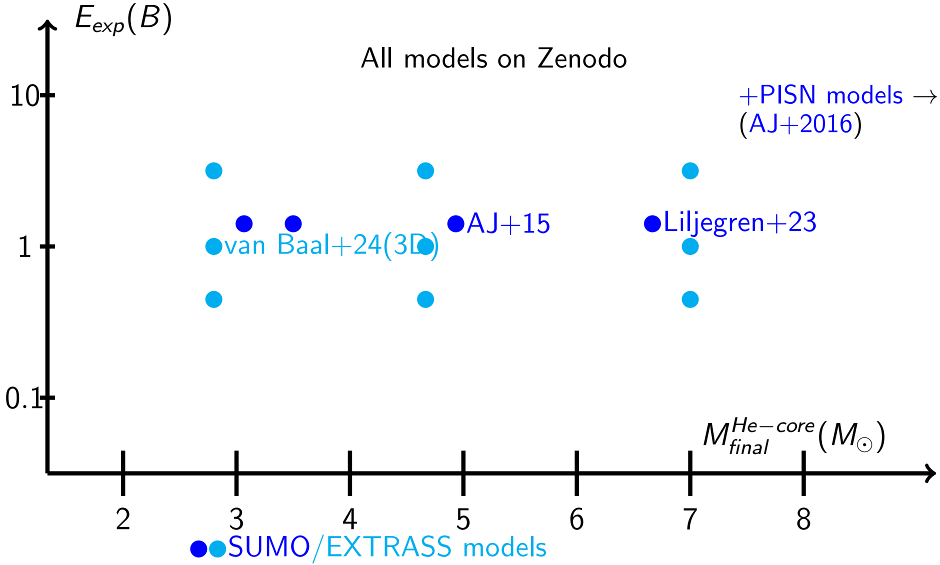


# Subluminous IIP SNe - good match with low-mass ($M_{ZAMS} \sim 8-10\ M_\odot$) explosions *AJ+2018*

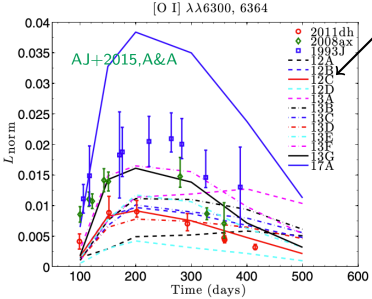



- Spectral models can distinguish **Fe CCSNe** to **ONeMg CCSNe (=Electron-capture SNe)** - most observed events fit first class better (see also Lisakov+17/18 ).

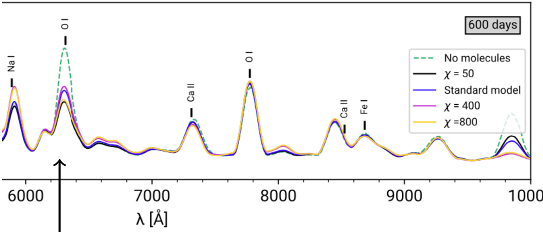
# Stripped-envelope spectral models



# Stripped-envelope SN models with molecules *Liljegren+2023*




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

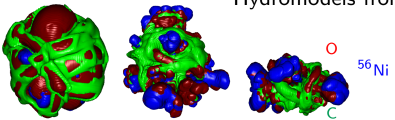



Can now calculate this self-consistently.

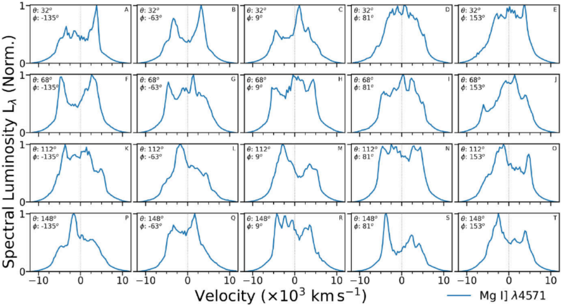
- Understanding the molecular chemistry is important to reach sufficient accuracy for the important [O I] 6300, 6364 line.

# Stripped-envelope SNe in 3D *van Baal+2023,2024*

Hydromodels from Garching group

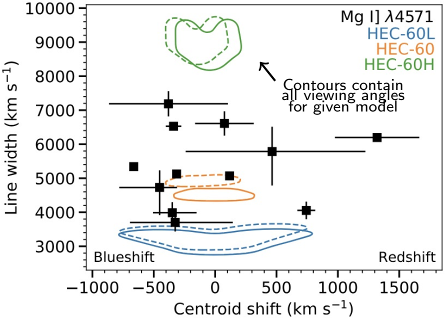


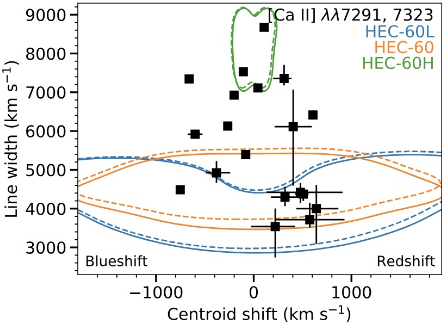

Mg I] 4571 line in a Type Ib model,different viewing angles




- Valuable inputs for interpreting statistical distributions of line profile properties (e.g Modjaz+08, Taubenberger+09, Fang+18/22/23).

# Stripped-envelope SNe in 3D *van Baal+2023,2024*




Qualitatively new type of use of spectral data.

# Semi-analytic methods

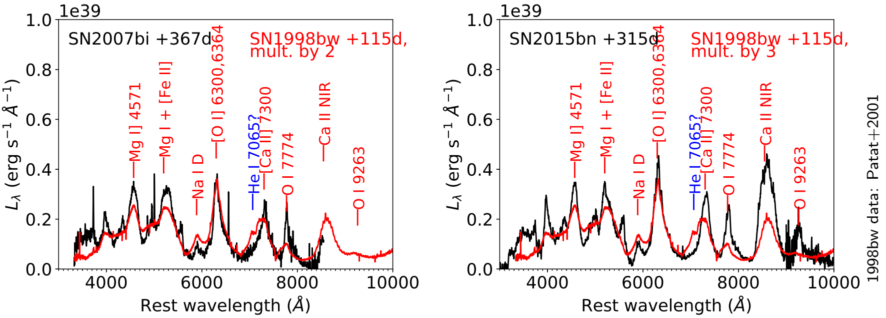
ttt.astro.su.se/~anje1871/semianalyticmethods/

## 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 | |
| Constraints_on_T,_ne,_n_CaII_from_[Ca_II]_7291,7323_and_Ca_Ii_triplet | 2022-04-01 17:12 | 828 | |
| NiFe_ratio_from_[Ni_II]_7378_and_[Fe_II]_7155 | 2022-04-01 17:12 | 2.7K | |
| O_mass_from_[O_I]_6300,_6364_and_[O_]_5577_in_Type_II_SNe | 2022-04-01 17:12 | 1.6K | |
| O_mass_from_[O_I]_6300,_6364_and_[O_]_5577_in_stripped-envelope_SNe | 2022-04-01 17:12 | 859 | |
| The_Fe_mass_from_[Fe_II]_7155_and_[Fe_II]_1.26_mu_in_stripped-envelope_SNe | 2022-04-01 17:12 | 575 | |
| The_Mg_mass_from_Mg_I_1.50_mu_and_O_I_7774,_9263,_1.13_mu,_1.31_mu_lines | 2022-04-01 17:12 | 1.1K | |
| 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**.

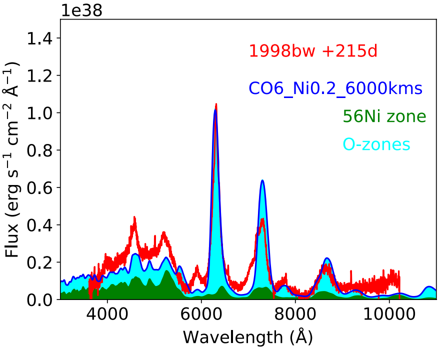
# Most massive CCSNe Jerkstrand+2017,AJ+ in prep.

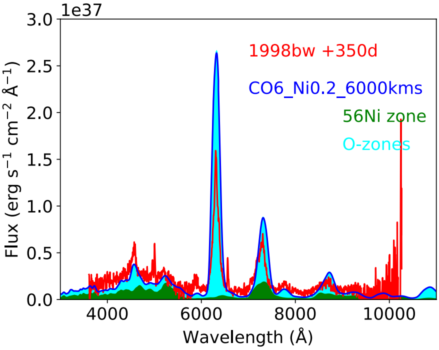



- Strong similarity between nebular spectra of luminous Ic SNe →unlikely to involve fundamentally different scenarios (?).
- Is 4000-5500 Å plateau due to large amounts of Fe and therefore evidence for $^{56}$Ni?
- Signatures of r-process elements? (e.g. Anand+2023 )

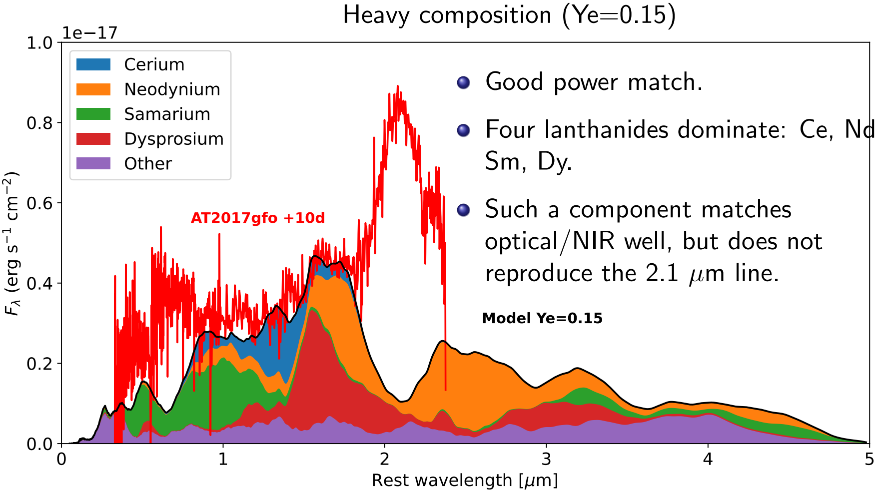
# Understanding Ic-BL spectra *Jerkstrand+, in prep.*

- Standard $^{56}$Ni-powered models powering 6-10 $M_{\odot}$ CO cores fit quite well.
- $\lambda$ <5500 Å region formed by complex radiative transfer effects. Fe presence improves fits.



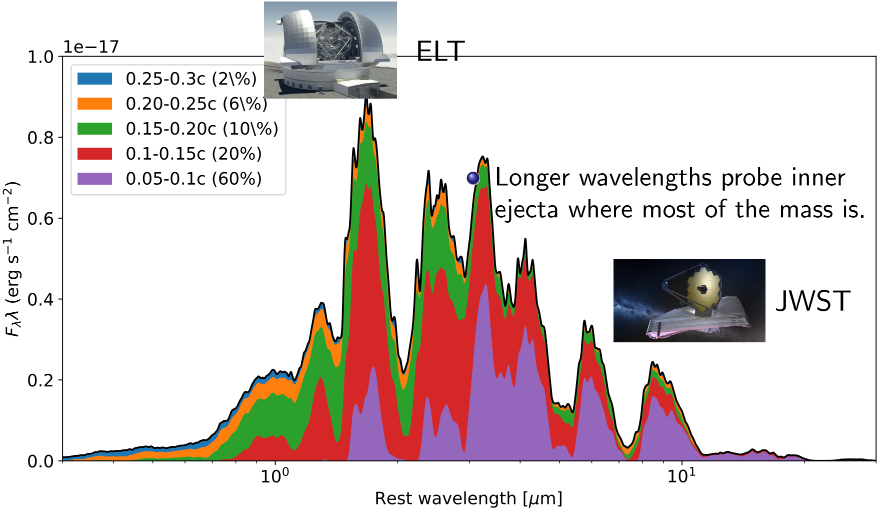
# First NLTE KN spectra Pognan+2022ab,2023




- Good power match.
- Four lanthanides dominate: Ce, Nd, Sm, Dy.
- Such a component matches optical/NIR well, but does not reproduce the 2.1 $\mu$m line.

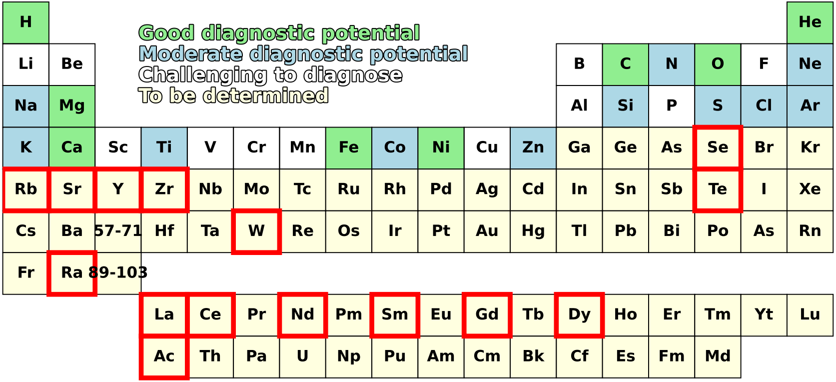
Pognan+2023(optical),Jerkstrand+in prep(IR).

# First NLTE KN spectra Pognan+2022ab,2023




Pognan+2023(optical),Jerkstrand+in prep(IR).

# Elements we can currently diagnose from SN and KN nebular-phase spectra




Claimed (possible) detection in AT2017gfo, or potential for detection

Watson+2019,Domoto+2021,2022,Hotokezaka+2022,2023
Sneppen+2023,Pognan+2023,Gillanders+2024

# Summary

- Nebular-phase spectral model grids are available for TNSNe (1D), CCSNe (1D and 3D), and KNe (1D).
- The models can be used both to design ZTF follow-up strategies and for analysing data.

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 me.

Thank you for listening!