Supernovae from 8-10 $M_\odot$ stars: the first spectral models in the emission line phase

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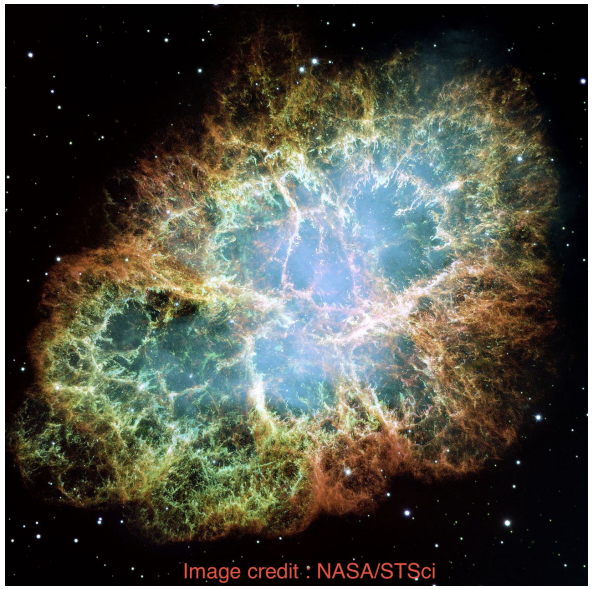

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Supernovae from 8-10 $M_\odot$ stars : motivation

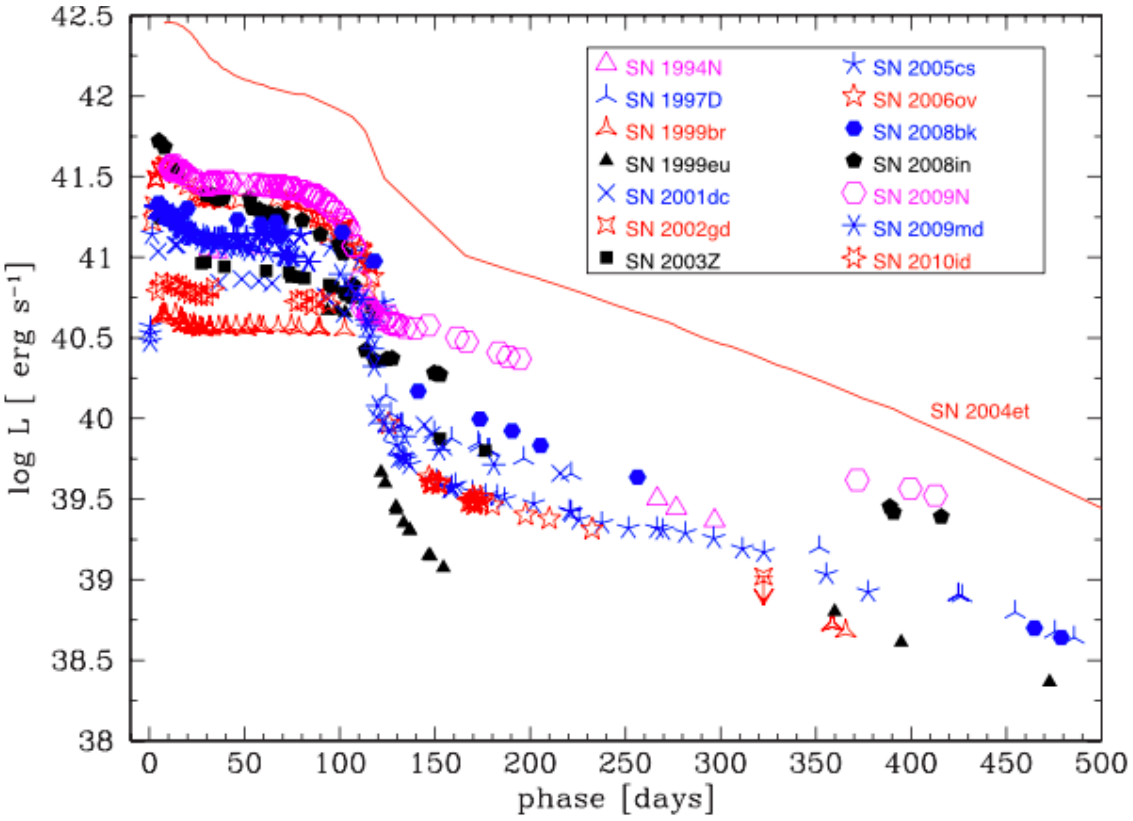
Significance:

- With standard Salpeter IMF, responsible for **30%** of all core-collapse SNe
- Only CCSNe for which standard **neutrino-driven explosion mechanism robustly works**. $E \sim 10^{50}$ erg and $M(^{56}\mathrm{Ni}) \sim 10^{-3}\ M_\odot$.

Questions:

- Where are these SNe?
- What stellar evolution and explosion physics for super-AGB stars can we constrain from SN properties?
- Do electron capture SNe exist (predicted fraction 0-20% of all CCSNe)?

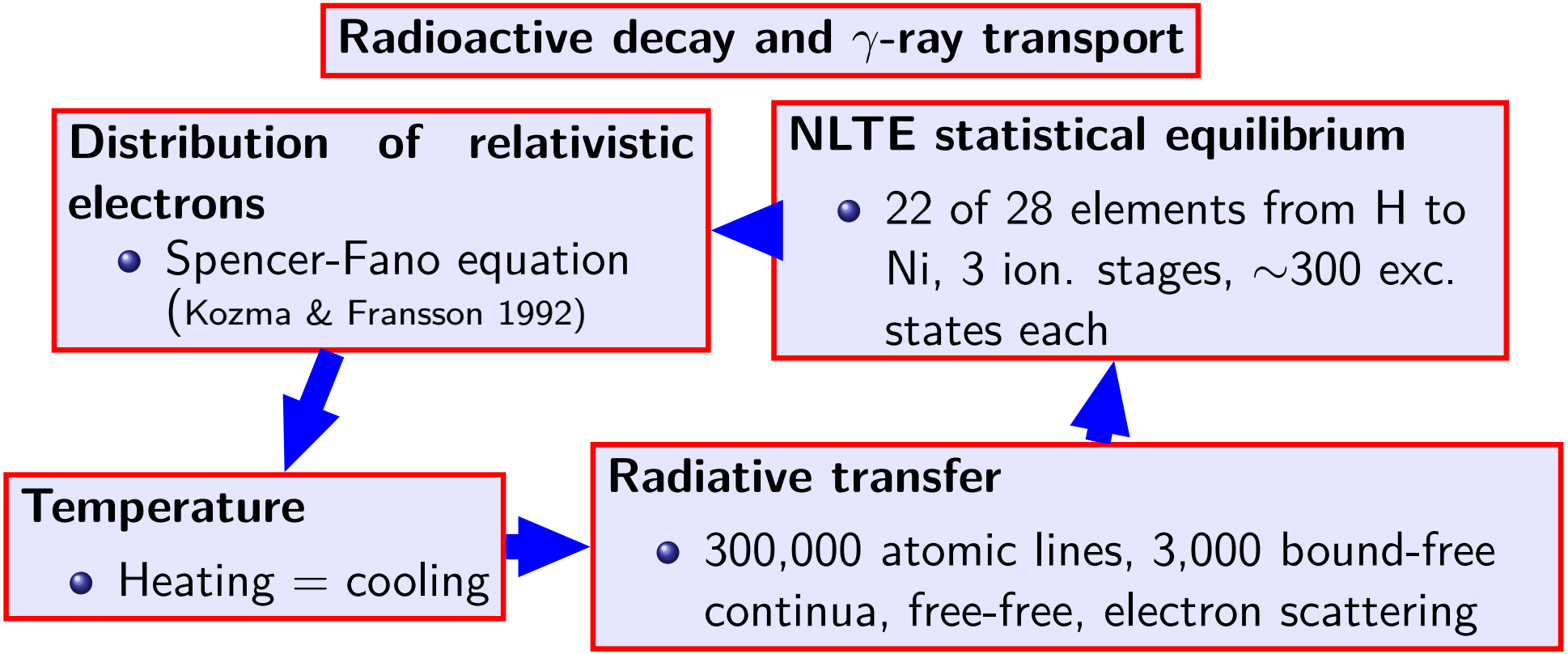
Prime suspects: Subluminous Type IIP SNe



Spiro+2014

- Class discovered with **SN 1997D**, today ∼15 known objects (see also talk on 2008S by Boticella)
- SNe from the lowest mass progenitors, or weak explosions of massive stars? *Current analysis points towards first scenario, but some tension*.

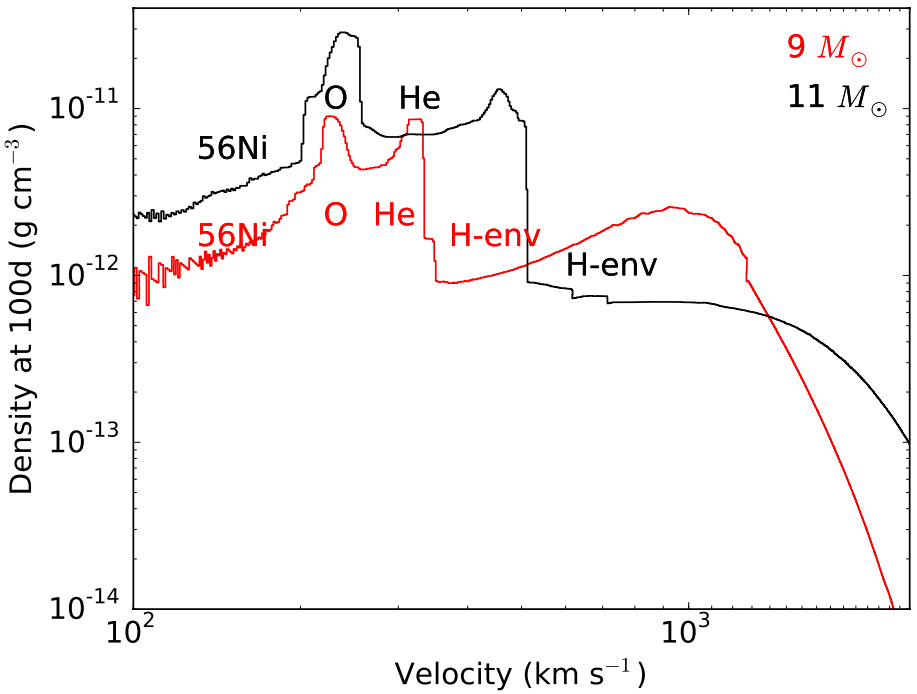
Spectral modelling with the SUMO code *Jerkstrand 2011, PhD thesis, Jerkstrand, Fransson & Kozma 2011, Jerkstrand+2012*

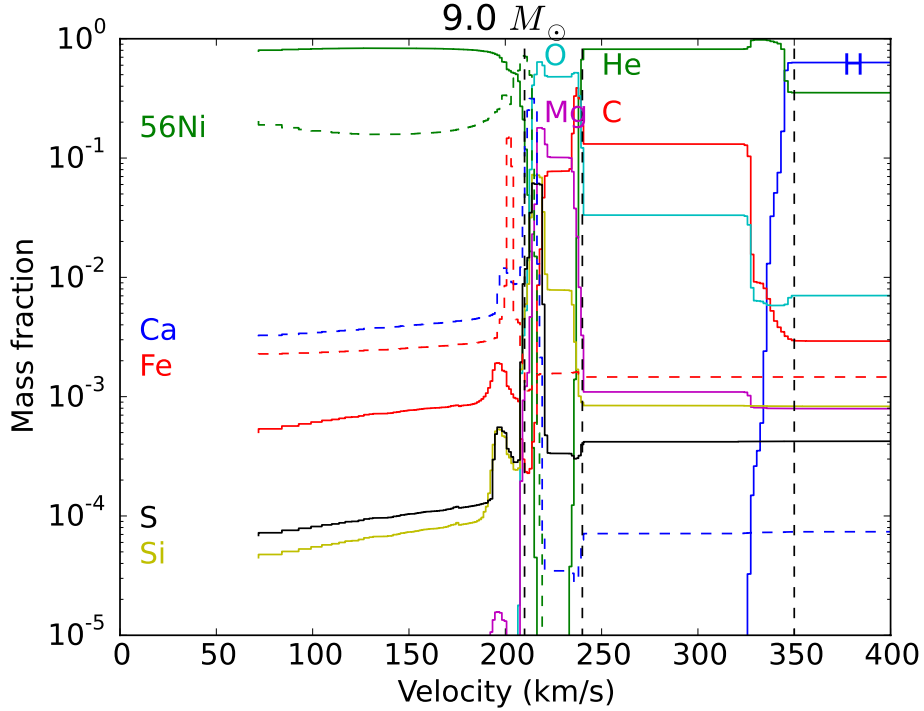


- Code is 1D but allows for mixing by 'virtual grid' option

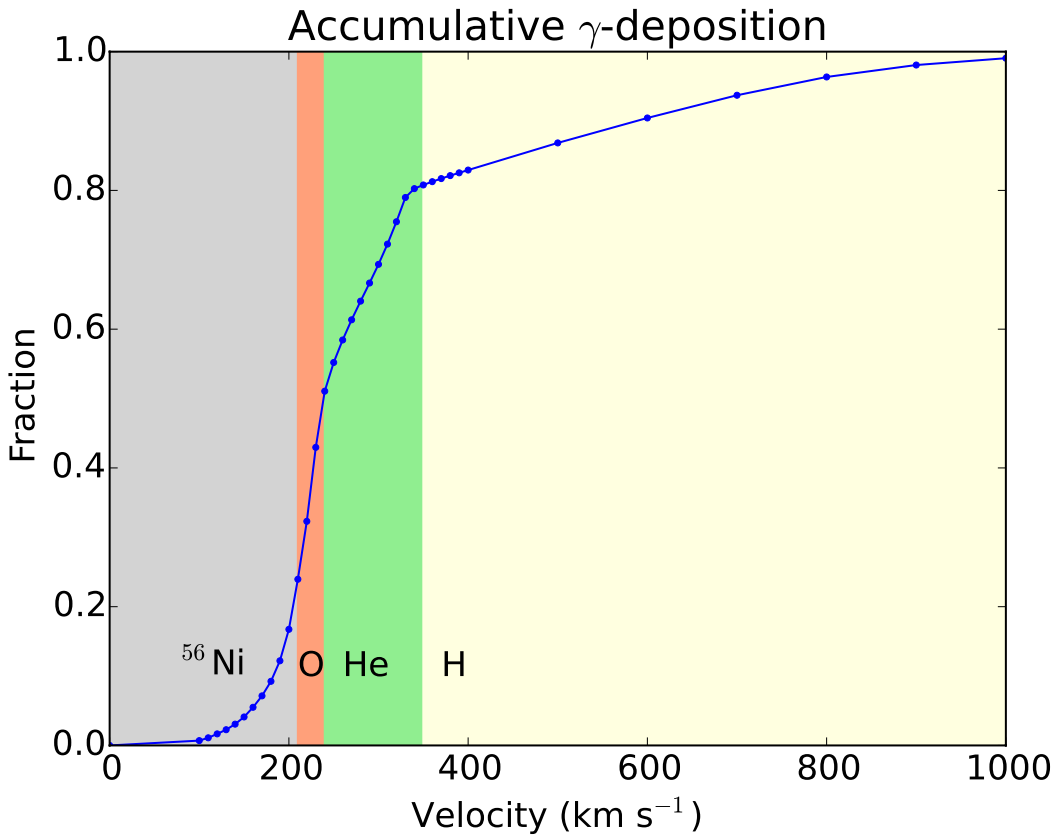
Explosion models

- 1D 9.0 and 11.0 $M_\odot$ Fe CCSNe from Sukhbold+2016
- Neutrino-driven dynamics giving $E \sim 10^{50}$ erg, $M(^{56}\mathrm{Ni}) \sim 0.01\ M_\odot$
- 14 α-element nuclear network



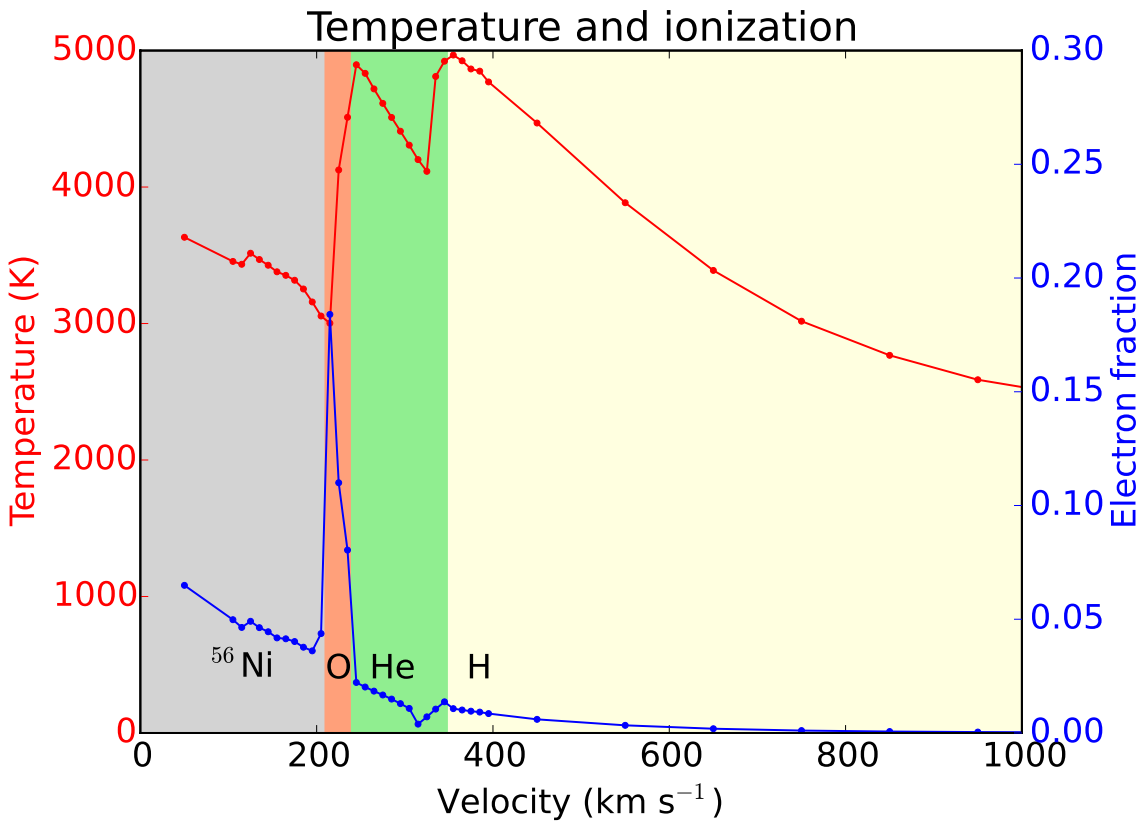


Physical conditions : 9 $M_\odot$ model at 400d



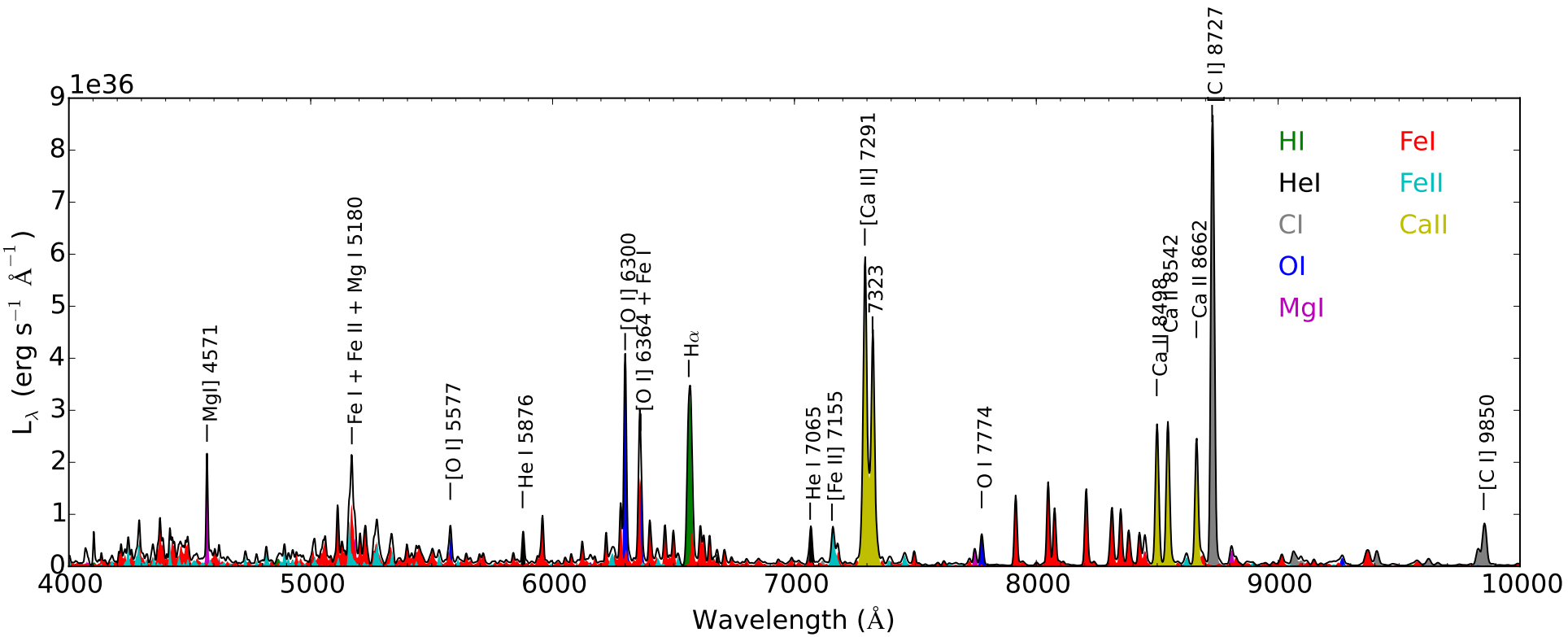
- Most γ-rays trapped in inner regions $\rightarrow$ **200-500 km s^{-1} broad line profiles**
- Roughly equal powering of all 4 major zones $\rightarrow$ **signatures of all layers expected**.

Physical conditions : 9 $M_\odot$ model at 400d



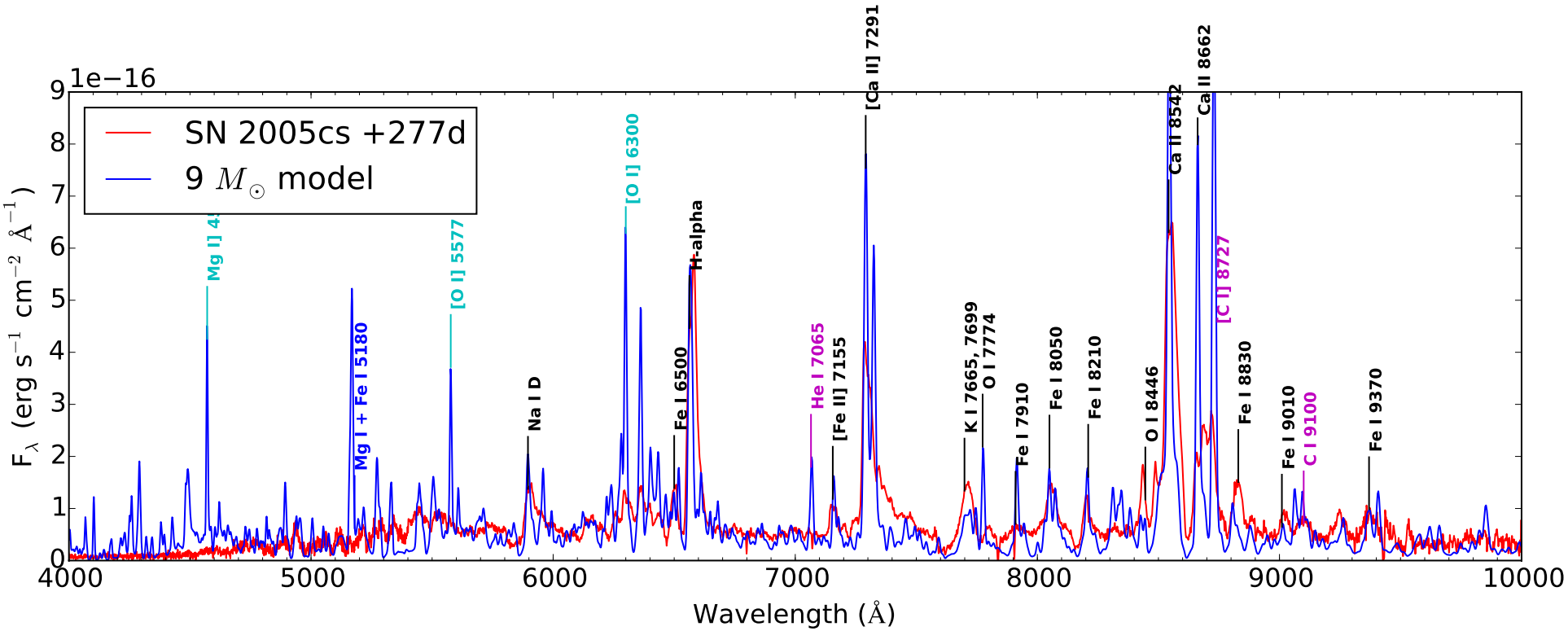
- Gas is a **few thousand degrees** and **neutral** $\rightarrow$ optically dominated emission by Fe I, Si I, O I, Mg I, He I, C I, H I to be expected

Model spectra : 9 $M_\odot$ model at 400d



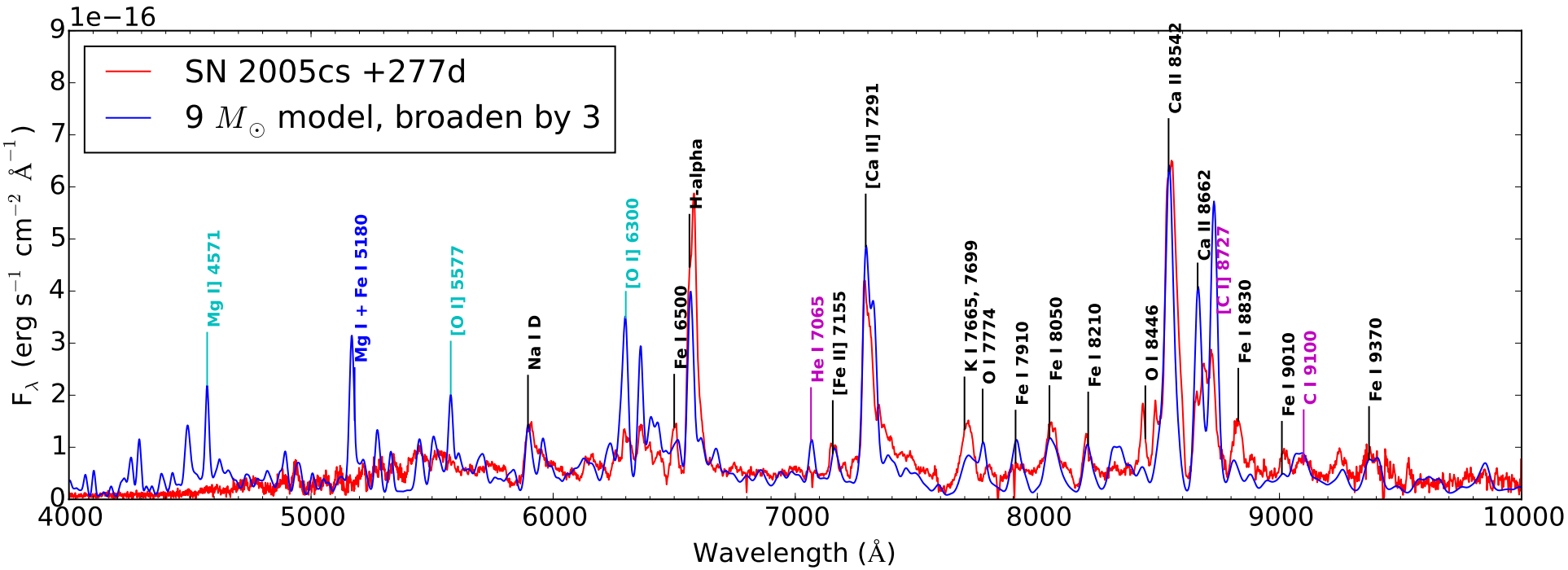
- Clear signatures of **O shell** (Mg I 4571, [O I] 5577, [O I] 6300, 6364)
- Clear signatures of **He shell** (He I 5876, He I 7065, [C I] 8727)

Comparison to observational candidates : SN 2005cs



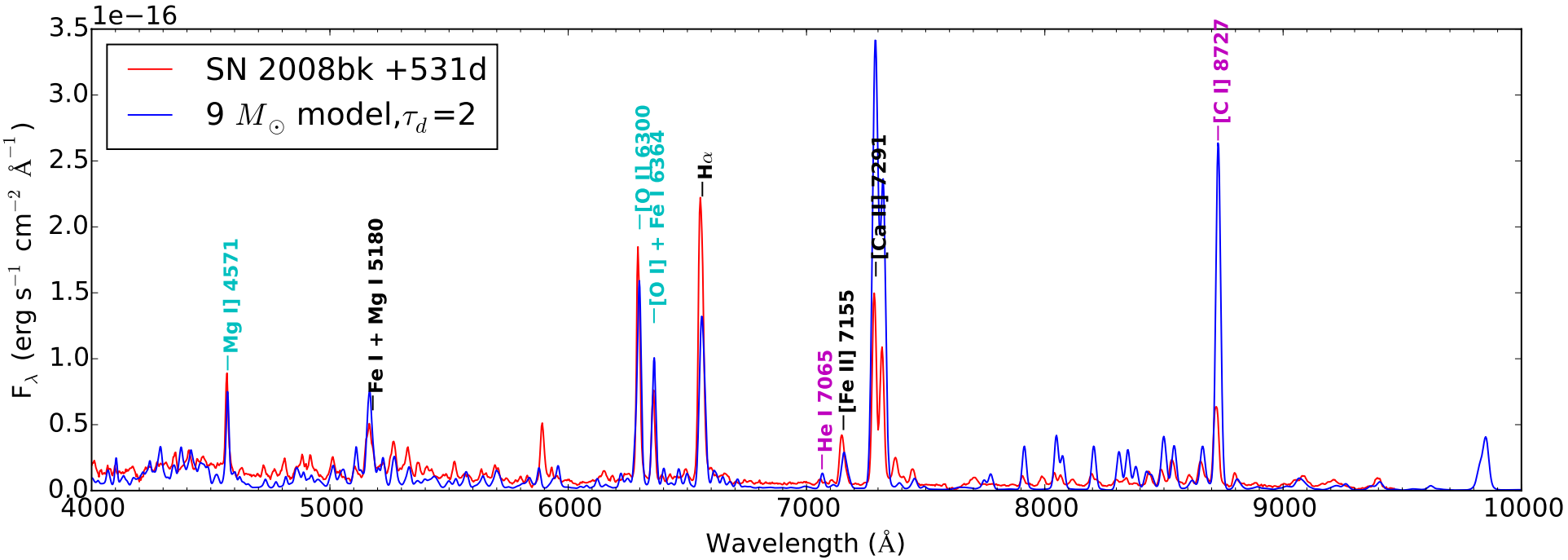
1. Model lines (250-500 km s^{-1}) too narrow compared to observed ones ($\sim$ 1000 km s^{-1})
2. No observed lines from O shell or He shell.

Comparison to observational candidates : SN 2005cs



1. Artificially broadened spectrum shows improved agreement
   - Higher explosion energy? *Hard to reconcile with low ^{56}Ni mass*
   - Strong Rayleigh Taylor mixing? *Hard to avoid overproduction of H-zone lines*

Comparison to observational candidates : SN 2008bk



1. Strong dust formation has occurred with $\tau_{dust} \sim 2$.
2. Lines narrower than in SN 2005cs $\rightarrow$ better match with model.
3. Lines from O shell observed. Lines from He shell still overproduced.
4. High O mass can be ruled out from [O I] 6300/6364 ratio

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
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$10	Jerkstrand+, in prep.

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

Outlook

Desired models with more advanced physics:

- **Nucleosynthesis** : Effect of larger network?
- **Multidimensionality** : What are the 2D/3D effects?
  - Macroscopic level
  - Microscopic level
- **Molecule and dust formation**

Summary

- Properties of stars from the 8-10 $M_\odot$ range can be studied from their SN spectra. We have data for 3-4 candidate events.
- The first set of spectral models in the emission line phase is now being completed, using 1D neutrino-driven explosion models.
- The models produce narrow emission lines from a wide range of elements
- At least one candidate event from this range (SN 2008bk) shows consistent nucleosyntheis with a low-mass Fe CCSN
- Another candidate (SN 2005cs) shows no O/He lines and expand much faster.

Discussion points:

- Stellar evolution front : what are we looking for that can constrain stellar evolution of sAGB stars?
- Is the "massive star with fall-back" scenario tenable?

Thank you!