Emission line models for the lowest-mass core collapse supernovae. I: Case study of a 9 $M_\odot$ one-dimensional neutrino-driven explosion.

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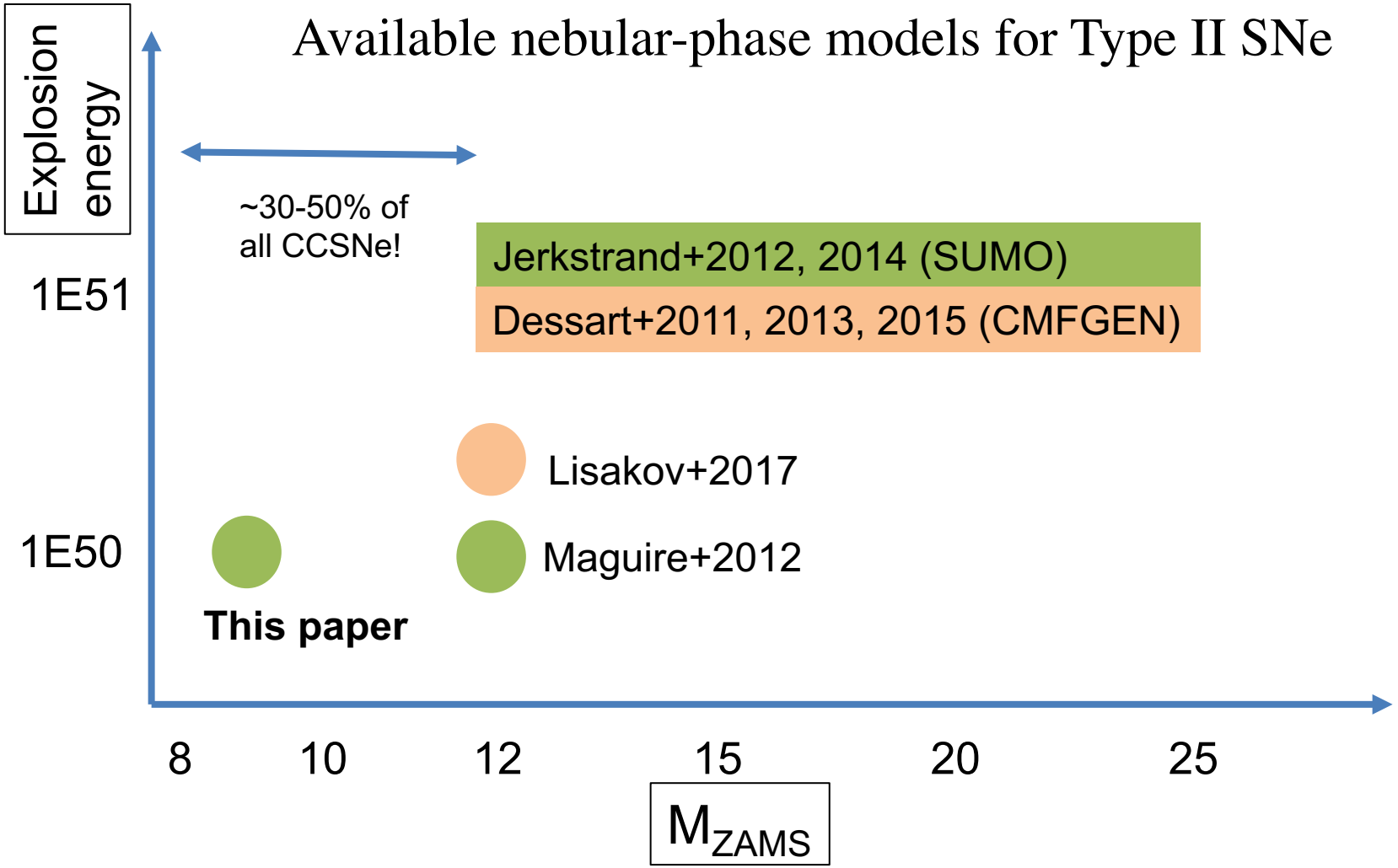
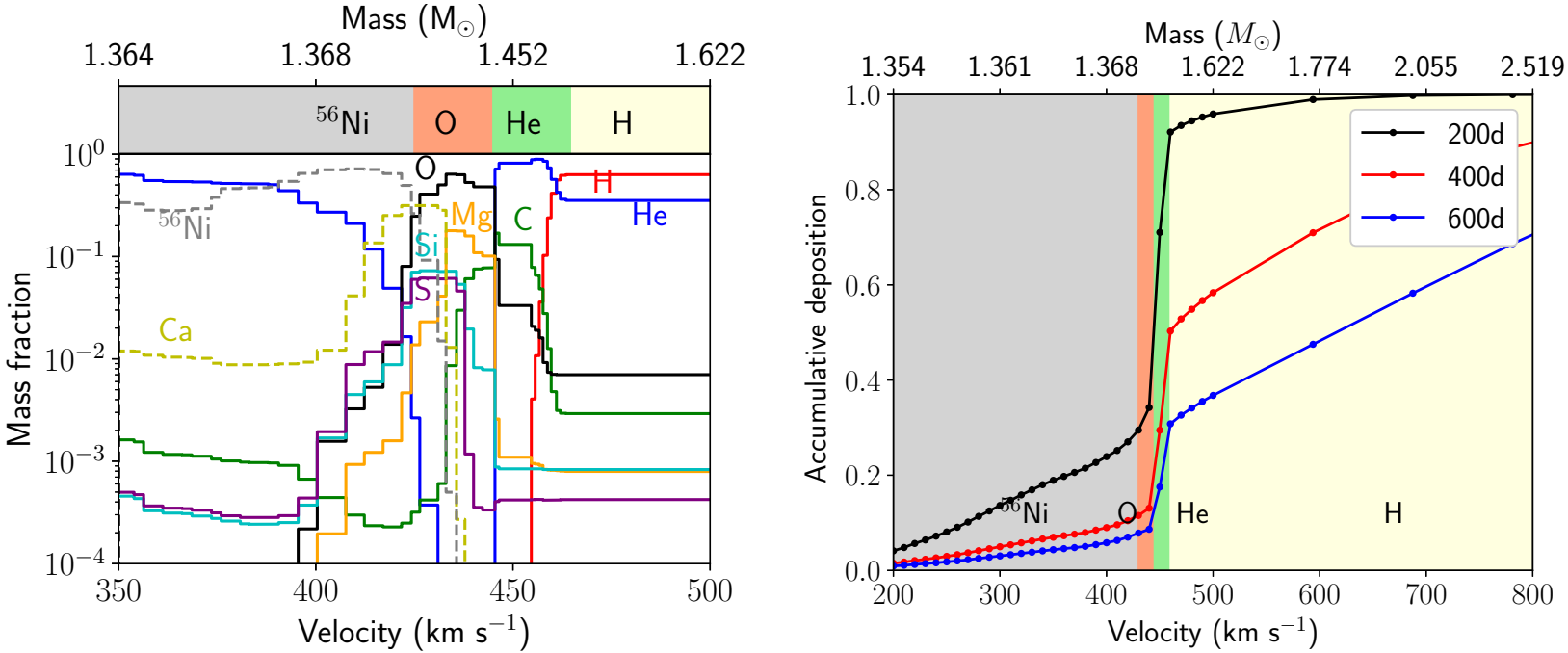
Available nebular-phase models for Type II SNe

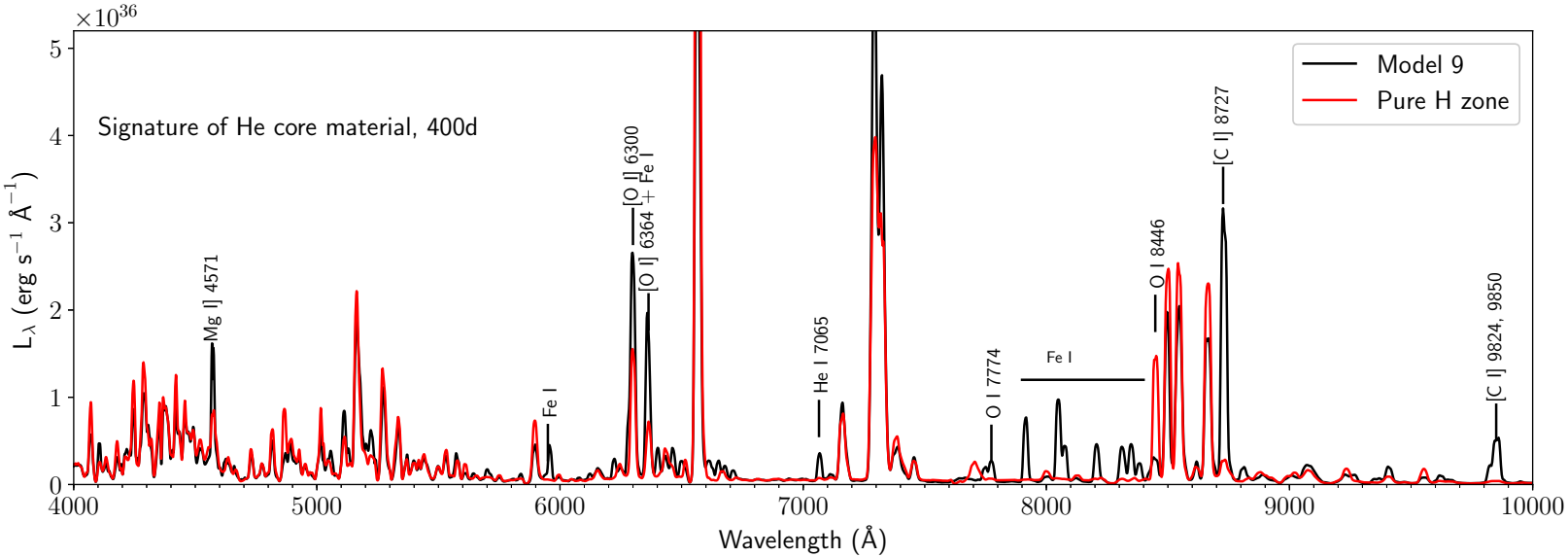


Spectral formation in a 9 $M_\odot$ model



- All hydrostatic nucleosynthesis in thin shell in 1D models.
- Despite low mass (0.2 $M_\odot$), this shell has $\boldsymbol{\tau_\gamma}$ ~1 and absorbs significant amount of gamma energy.

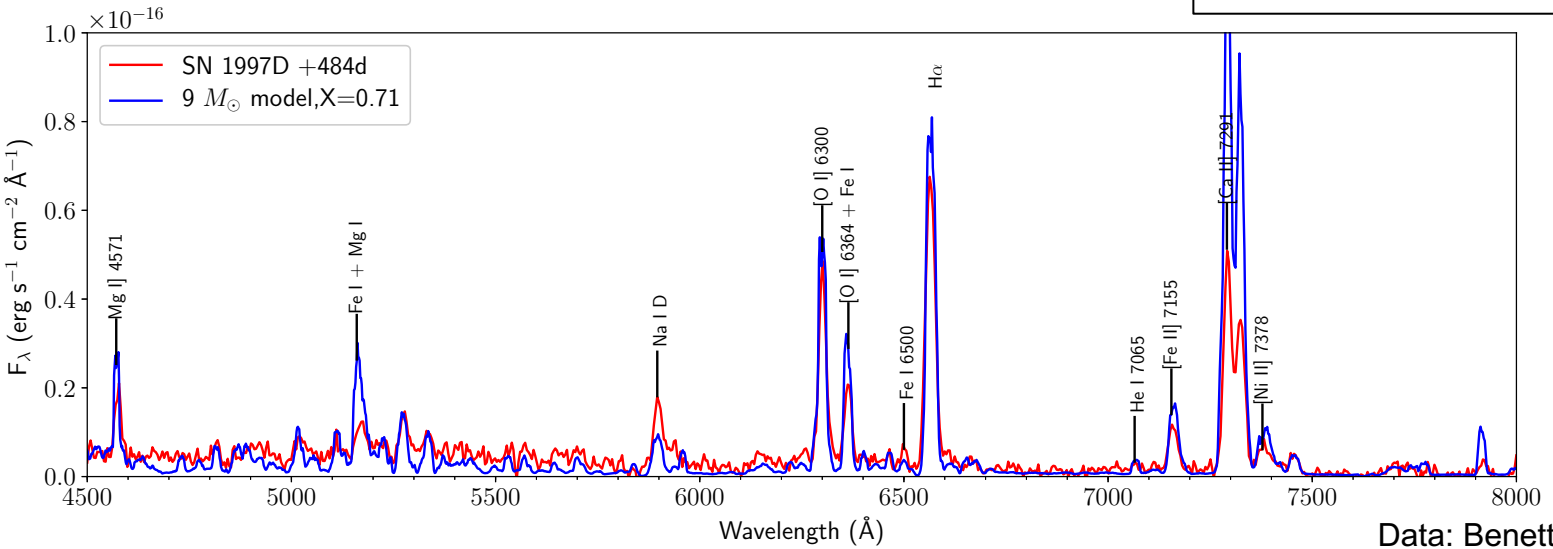
Nucleosynthesis signatures



- Mg I] 4571
- [O I] 6300, 6364 & 7774. Note 8446 *weakens* with more O.
- He I 7065
- [C I] 8727 & 9850
- Fe I lines

Comparison to **SN 1997D** (the prototype for the subluminous IIP class)

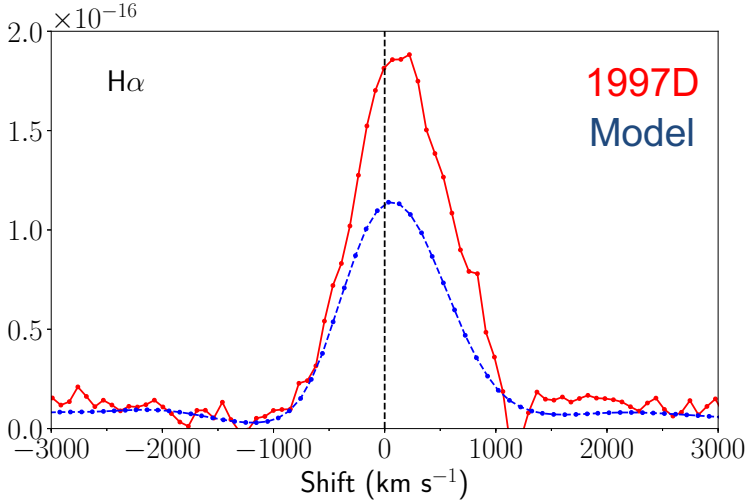
20 years of speculation: a low-mass progenitor or a high-mass star with fallback?

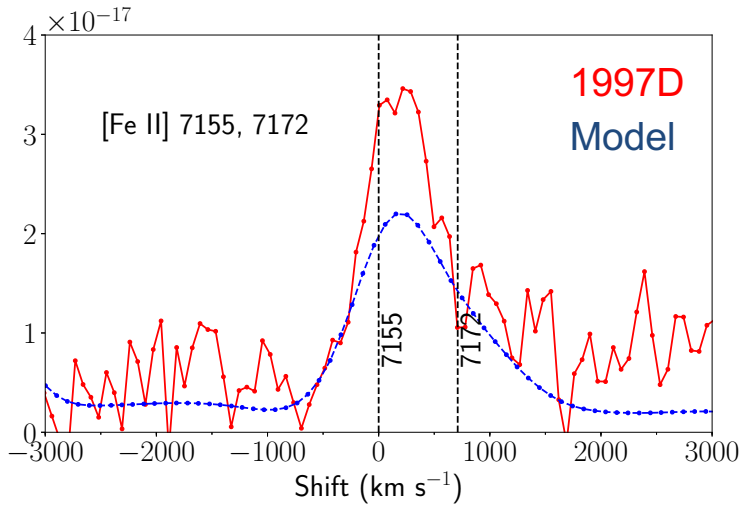


Data: Benetti+2001

- Mg and O lines in good agreement
- He I 7065 is seen → He shell is present
- No data beyond 8000 A → cannot test C predictions
- 1997D convincingly linked to low-mass progenitor (no tuning)

Testing explosion models through line profiles



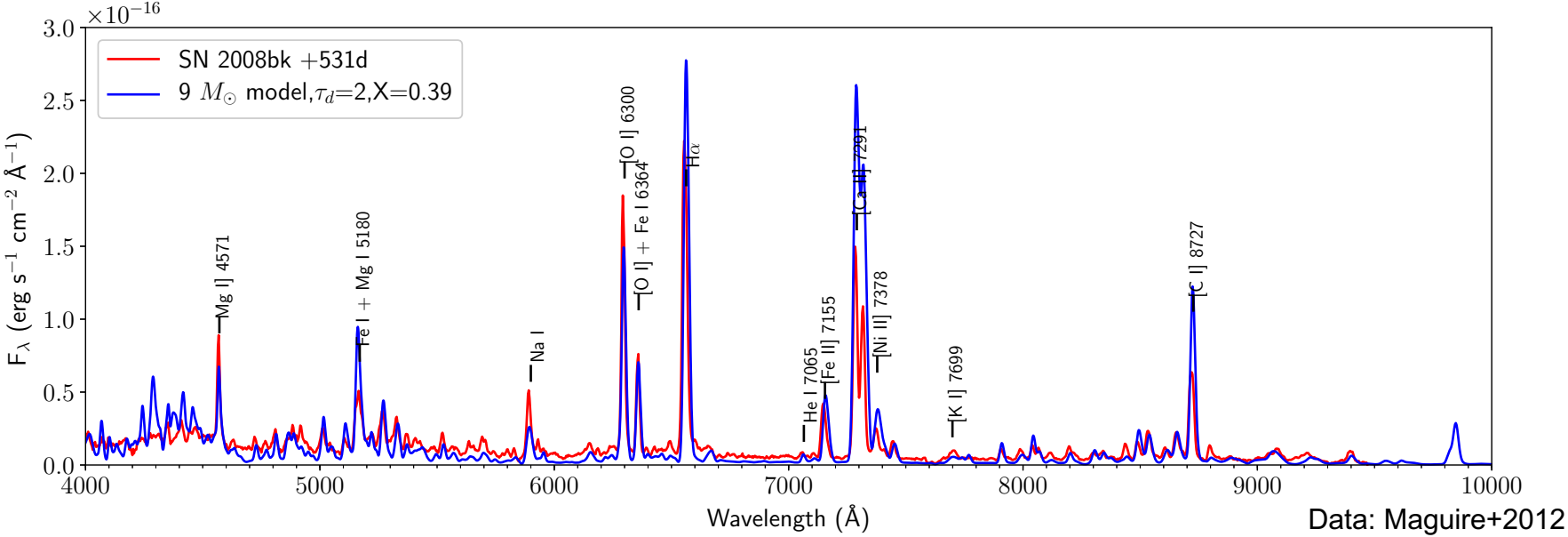


Line	FWHM (km s^{-1})	FWHM$_{dec.}$ (km s^{-1})	Model (km s^{-1})
Hα	1020	820	1100
He 7065	950	740	900
O I 6300,6360	940	720	900
Ca II 7291	820	560	900
Fe II 7155	730	420	800

Table 3. Observed line profile widths in SN 1997D, at +350d, compared to the model (unconvolved) values.

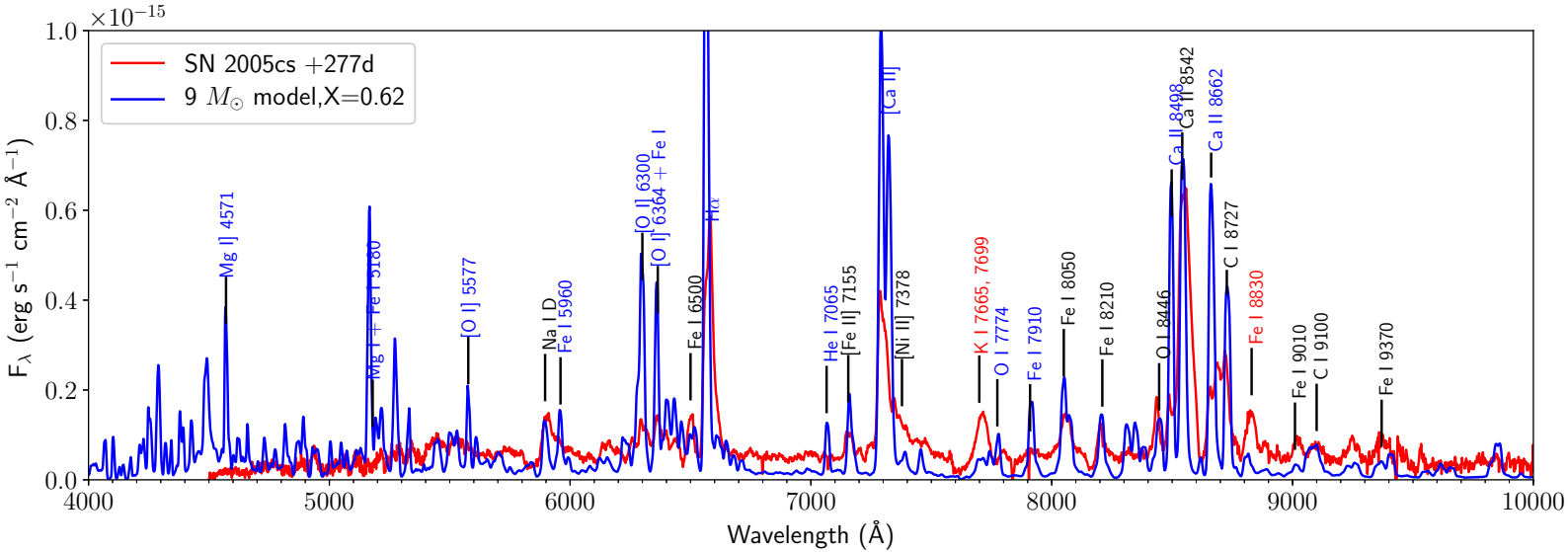
Important with high S/N, high-resolution spectra of subluminous IIP SNe

Comparison to **SN 2008bk**



- Dust forms around 400d
- As convincing as SN 1997D
- Mg, O, Na, C all strong → Fe core progenitor

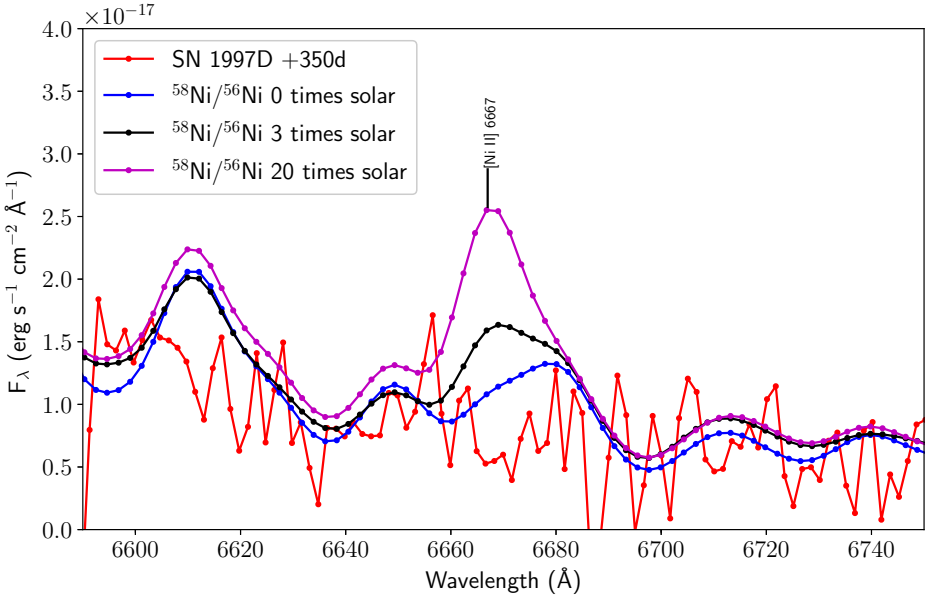
SN 2005cs: poor fits to 9 $M_\odot$ model

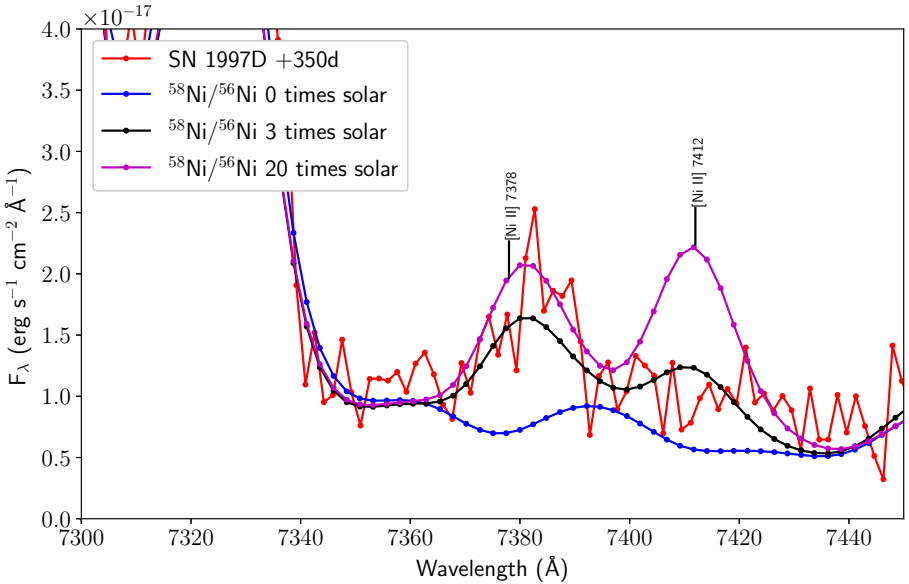


Data: Pastorello+2009

- No Mg, O, He lines have emerged at latest epoch (+277d)
- C I looks to be there → Fe core progenitor
- Maund+2005: $M_{pro} \sim 9\ M_{sun}$ from pre-explosion imaging
- Utrobin & Chugai 2008 : $M_{pro} >\sim 20\ M_{sun}$ from light curve modelling

No observed object shows explosive nucleosynthesis expected from electron-capture SNe





Summary

- First nebular-phase spectral models for **8-10 $M_\odot$ range** calculated. Important development: neutrino explosion simulations.
- Of the three low-velocity IIP SNe with observed nebular spectra, 2 show good agreement with a 9 $M_\odot$ model (1997D & 2008bk). The third, SN 2005cs less clear.
- **Strong indications that (most) *subluminous IIP SN* correspond to the lowest mass CCSNe, 8-12 $M_\odot$ (see also Lisakov+2017, 2018).**
- Nucleosynthesis suggests **iron core progenitors**, rather than ONeMg ECSNe.
- It is not currently clear whether electron capture SNe occur in Nature:
  - No observed subluminous IIP matches expected spectra
  - Crab neutron star kick not compatible (Gessner & Janka 2018)
  - New stellar evolution models highlight difficulties to reach this end point (Delta $M_{ZAMS} < 0.5\ M_\odot$, Poelarends 2008, Doherty 2015)
  - Mechanism may not work (Jones+2016)