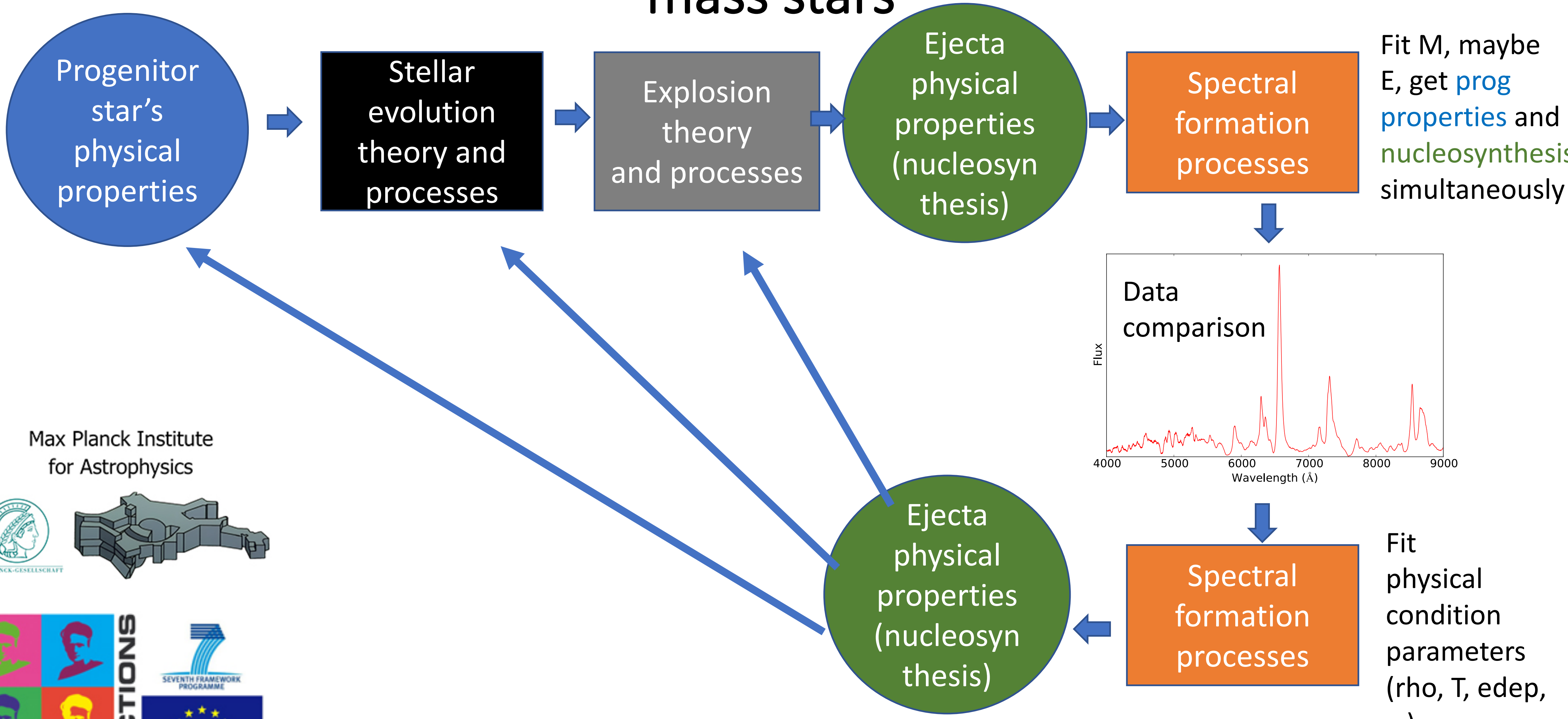
Modelling SN nebular spectra: from the lowest to the highest mass stars



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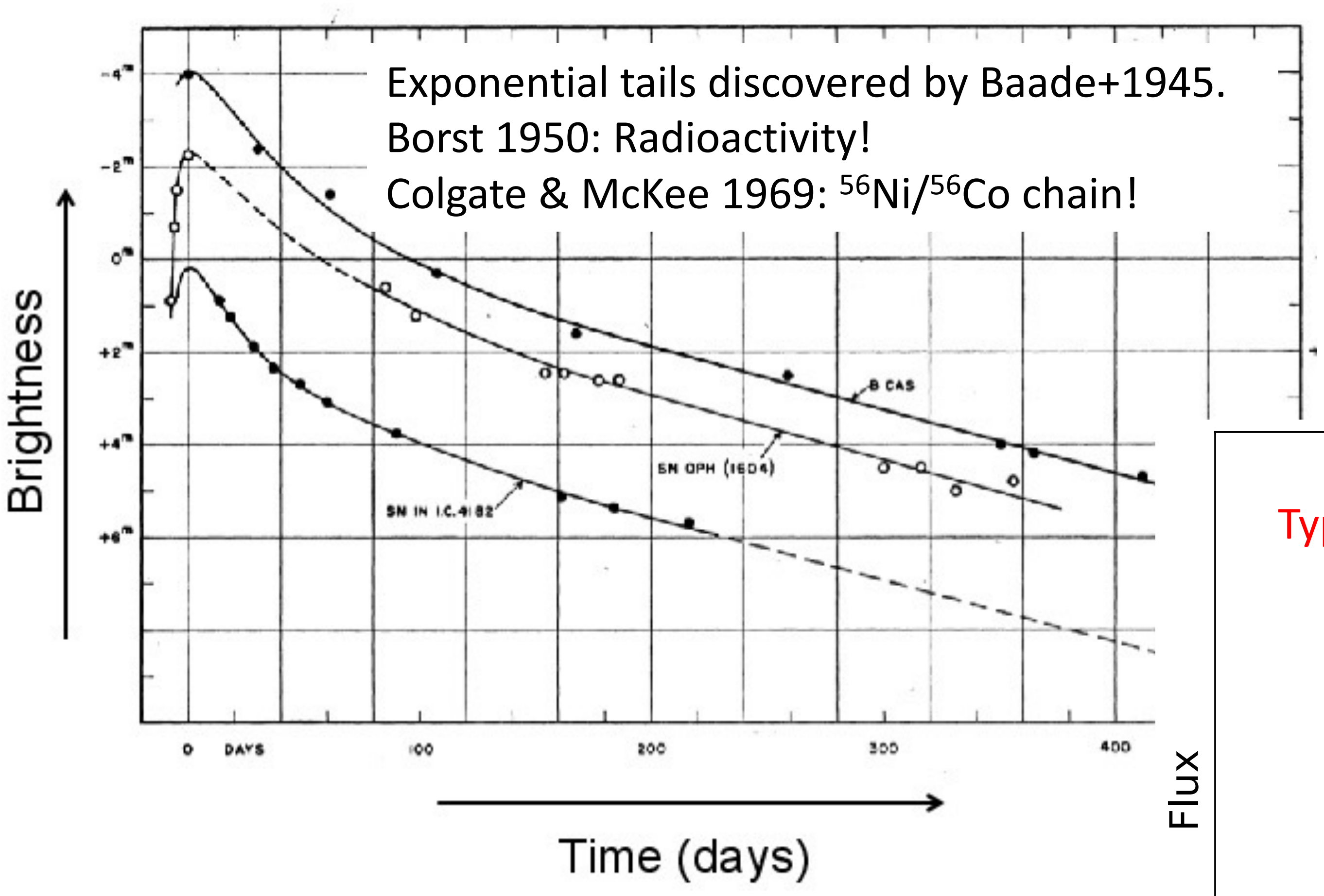
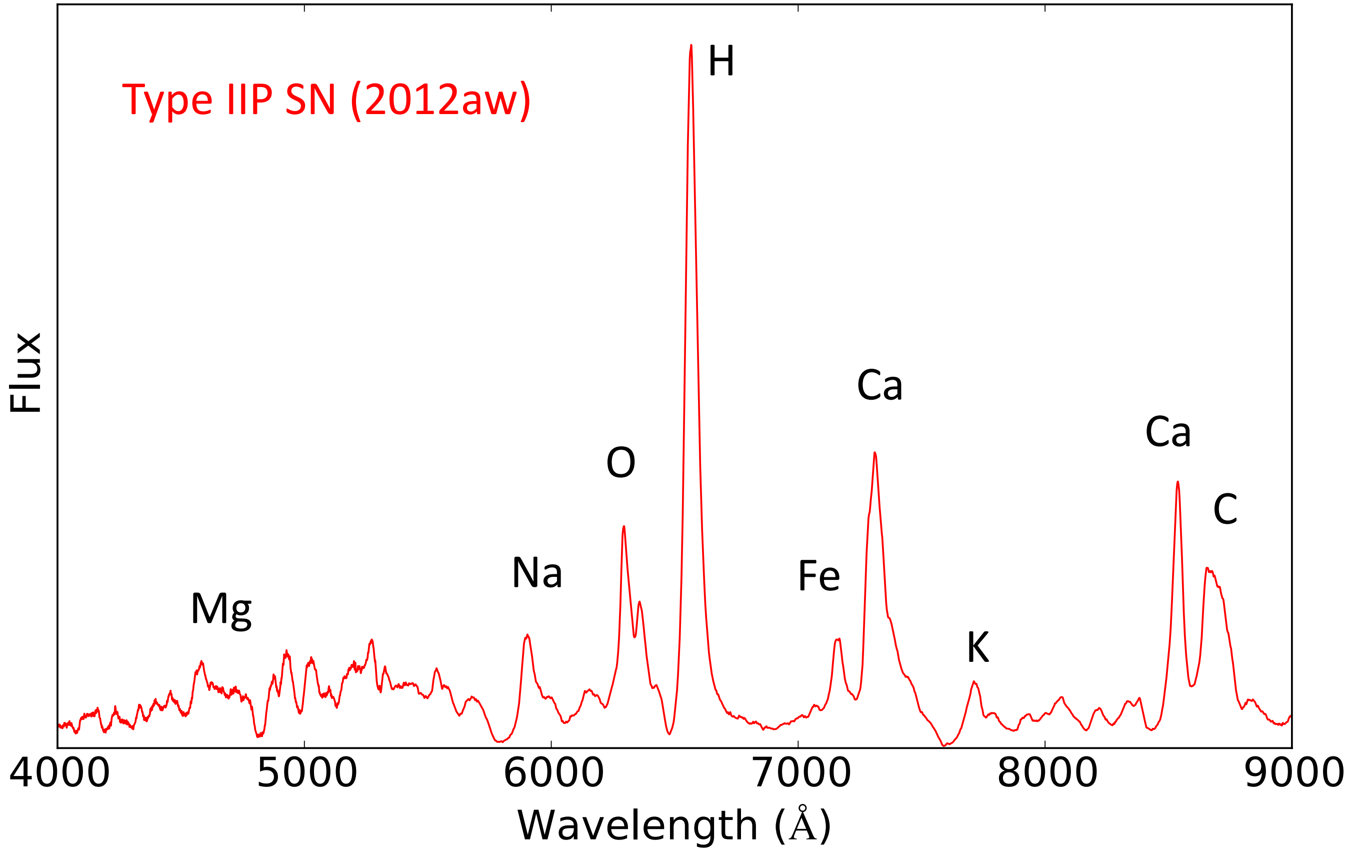
The nebular phase

- 100d – 1000d post explosion
- Emission lines from all nuclear burning regions → our window on nucleosynthesis and ejecta morphology.

Exponential tails discovered by Baade+1945.
Borst 1950: Radioactivity!
Colgate & McKee 1969: ^{56}Ni/^{56}Co chain!





- Data collection rate: ~5-10 per year (<1% of all discovered SNe).
- Current amount of objects: ~50-100

The SUMO code AJ+2011, 2012

Radioactive decay and gamma ray thermalization

NLTE statistical equilibrium
- 22 elements, 3 ion. stages
- 9,000 levels

Degradation of Compton electrons
- Spencer-Fano Equation
- Ionization, excitation, heating

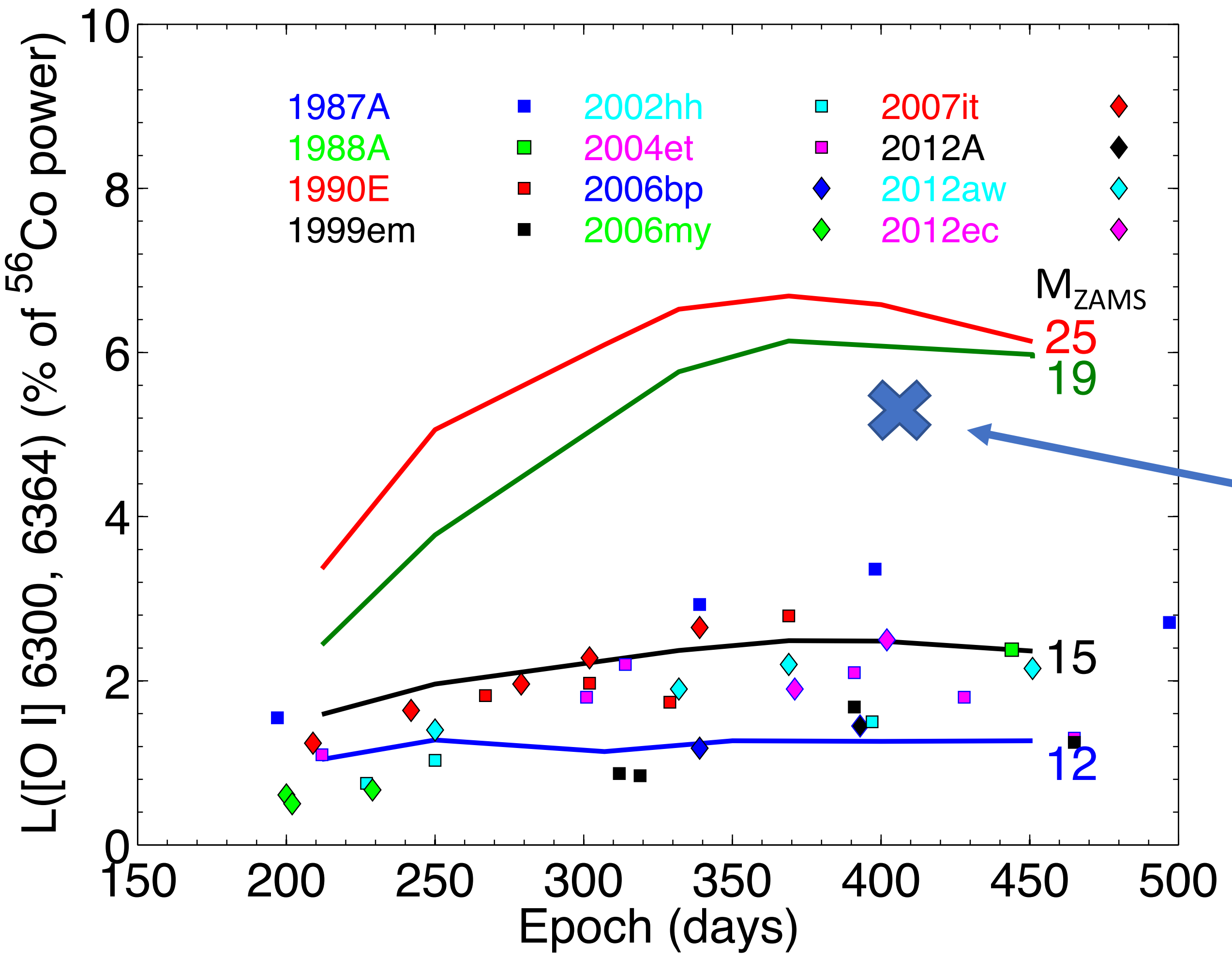
Temperature
- Heating = cooling

Radiative transfer
- Monte Carlo-based
- Sobolev approximation
- 300,000 lines

- Code is 1D but allows treatment of mixing by virtual grid method.

Standard IIP supernovae: explosions of M_{ZAMS} ~ 10-17 $M_{\odot}$ stars

AJ+2015 (MNRAS)



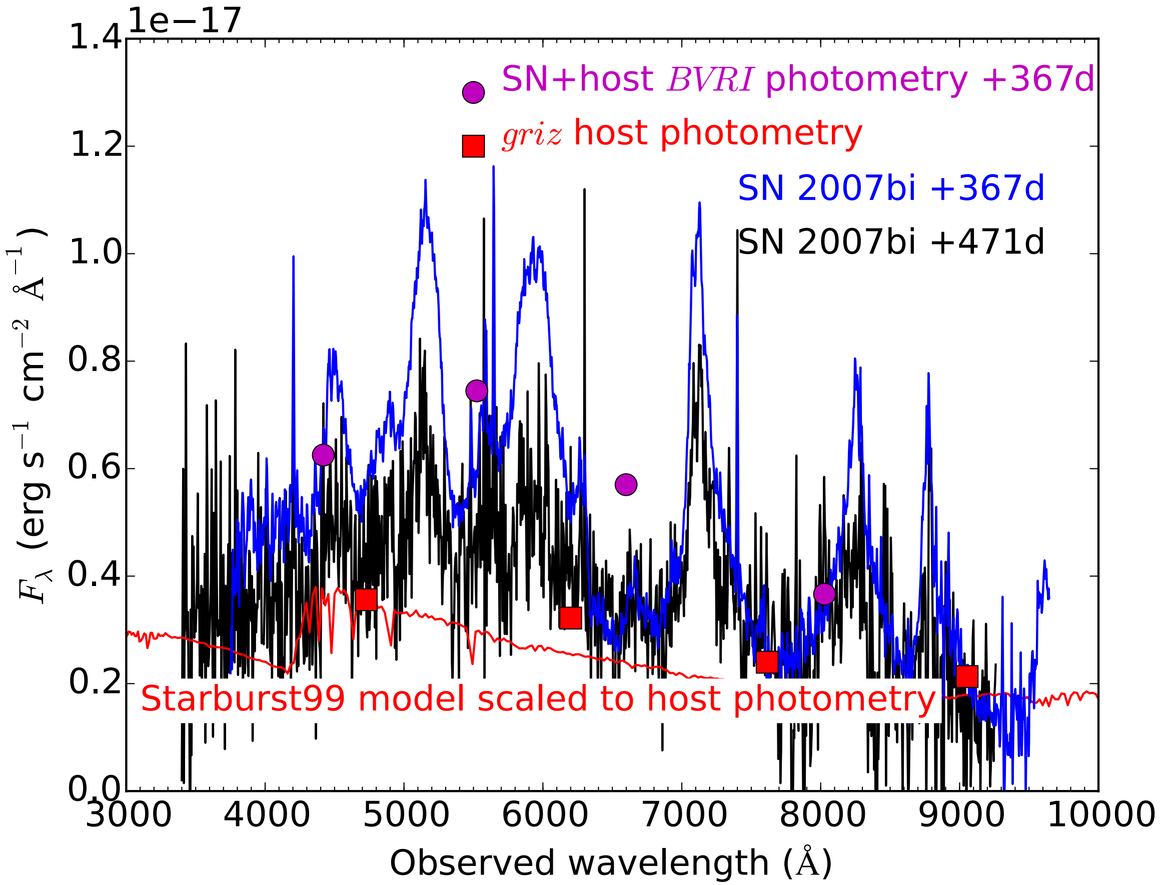
- Can be modelled quite well with virtual grid method in 1D.
- "RSG problem" is real: confirmed from two directions.
- However, first object with possibly M > 20 ~M_{sun} now discovered (Anderson+2018). Low metallicity.
- Same trend for Type IIb SNe (AJ+2015 (A&A))

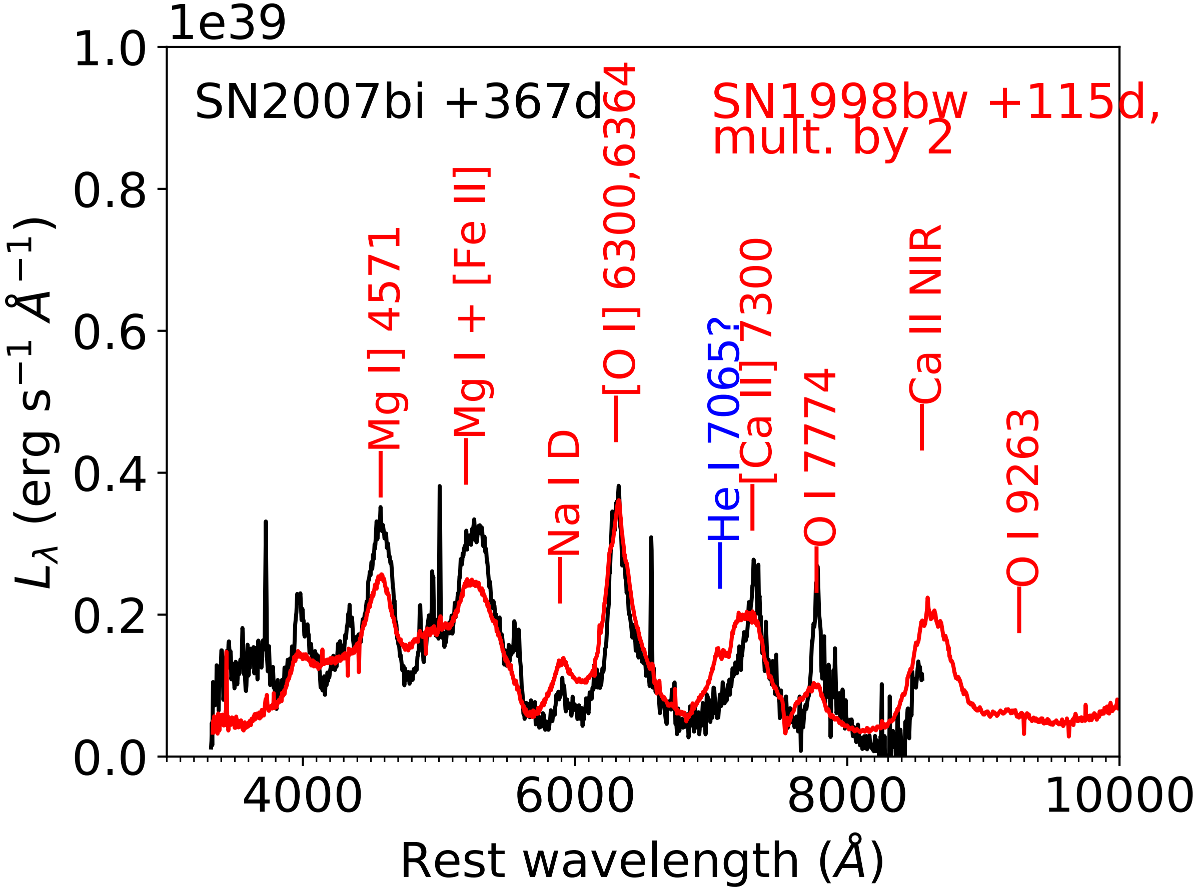
The monsters

Superluminous Type Ic supernovae

Nebular spectra of SLSN Ic: *with galaxy subtraction prototype SN 2007bi (Gal-Yam+2009) is very similar to SN 1998bw*

AJ+2017



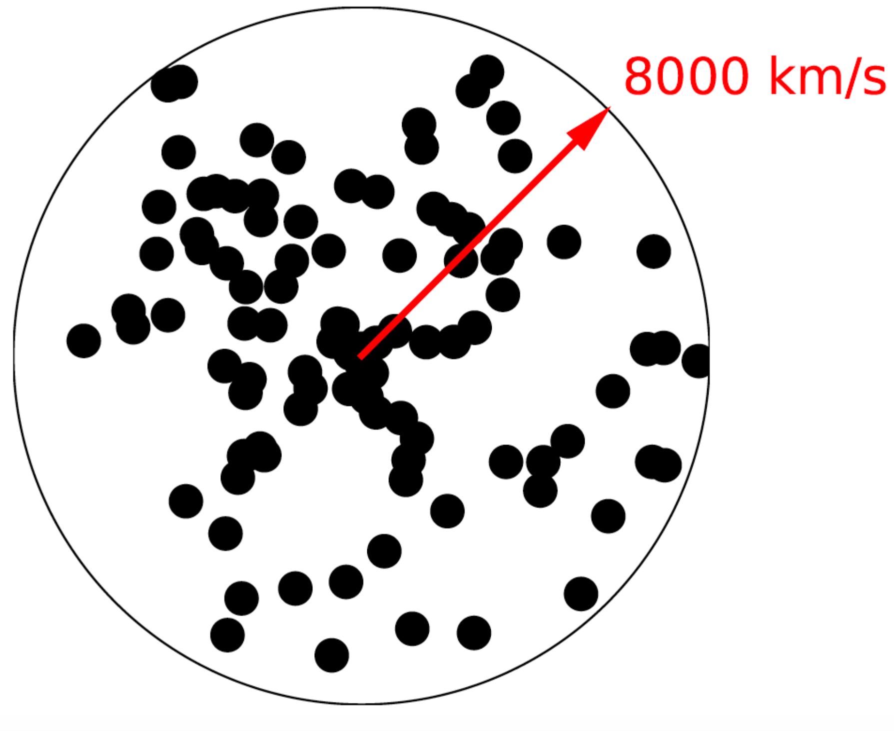


[O I] lines → Very large inferred O masses ($\gtrsim 10\ M_\odot$) → Origin in very massive stars ($M_{ZAMS} \gtrsim 40\ M_\odot$)

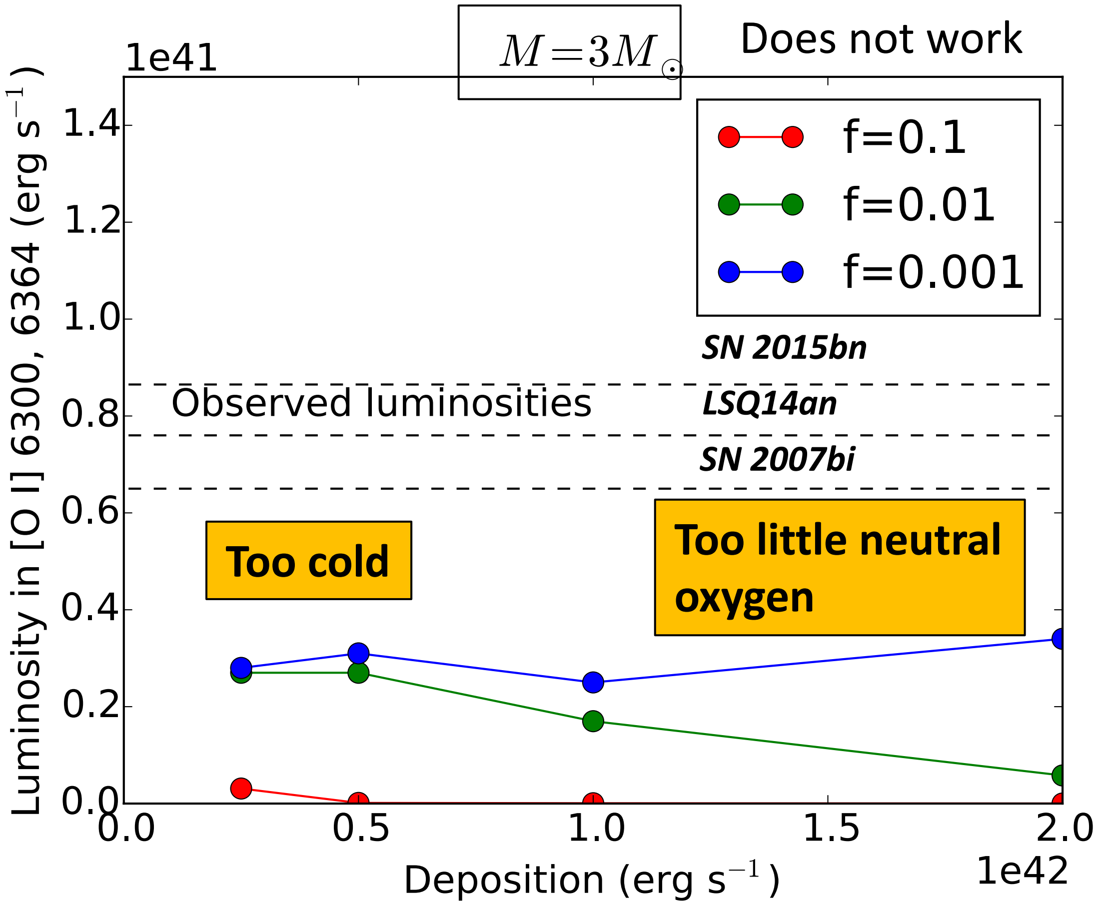
AJ+2017

Three parameters:

- Mass
- Energy deposition
- f (filling factor)



Clumps with C-burning composition



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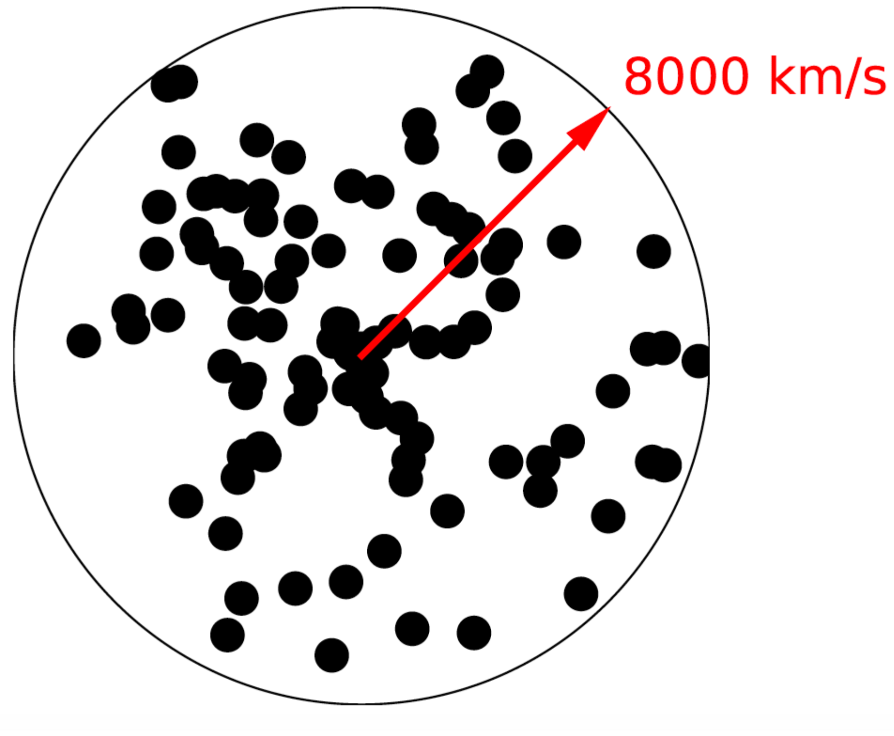

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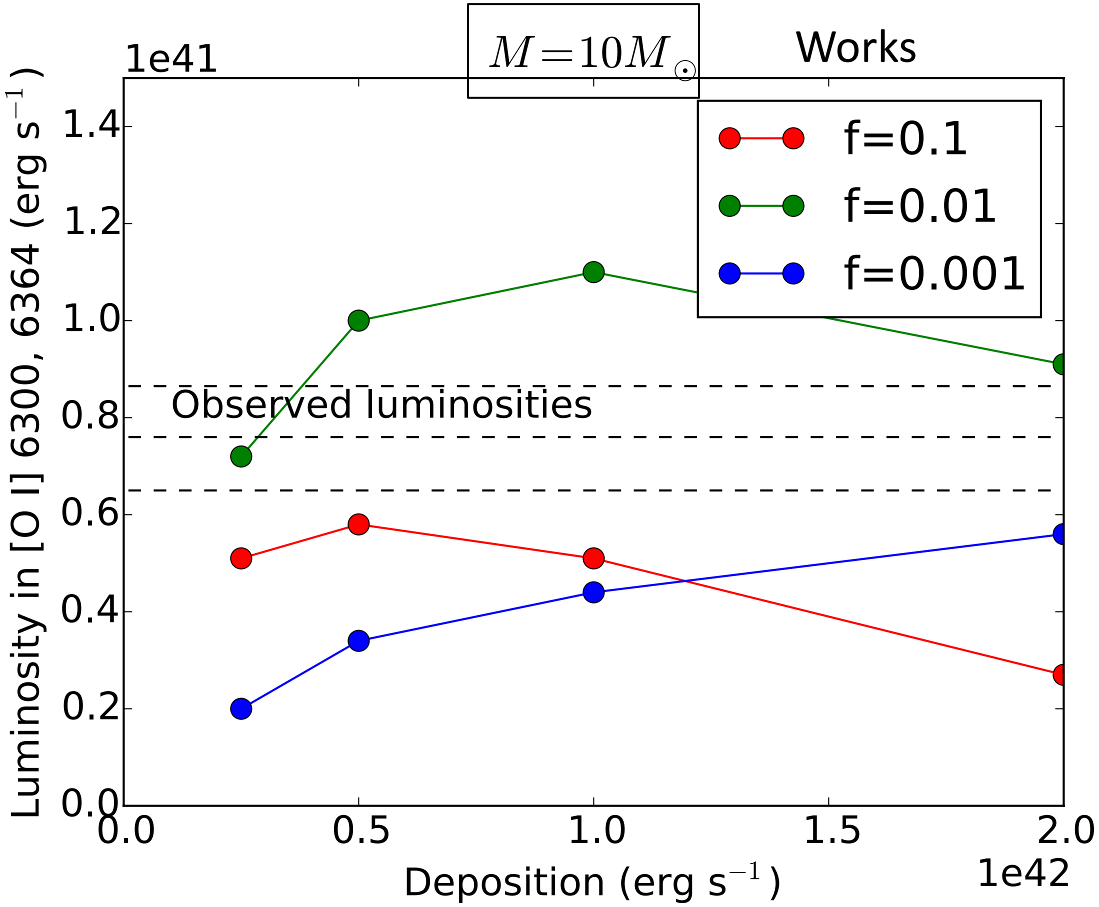
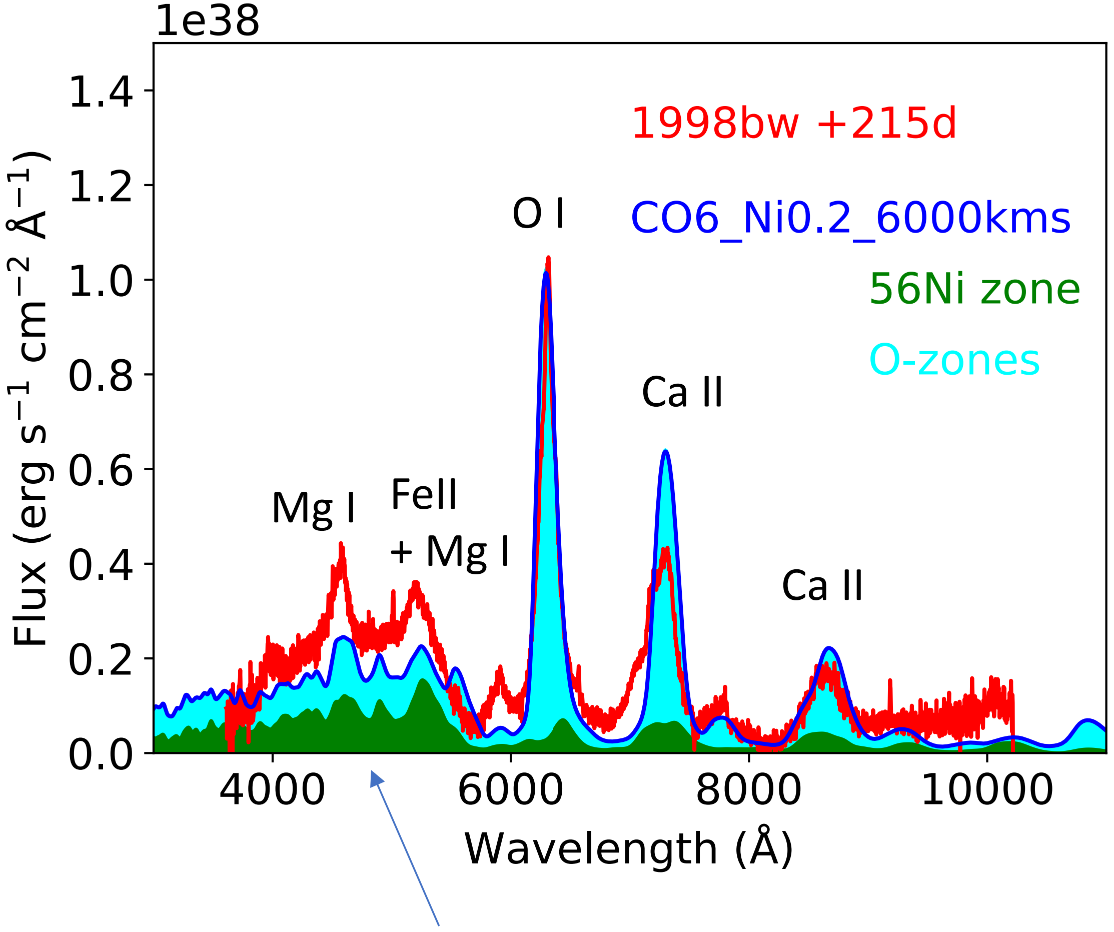


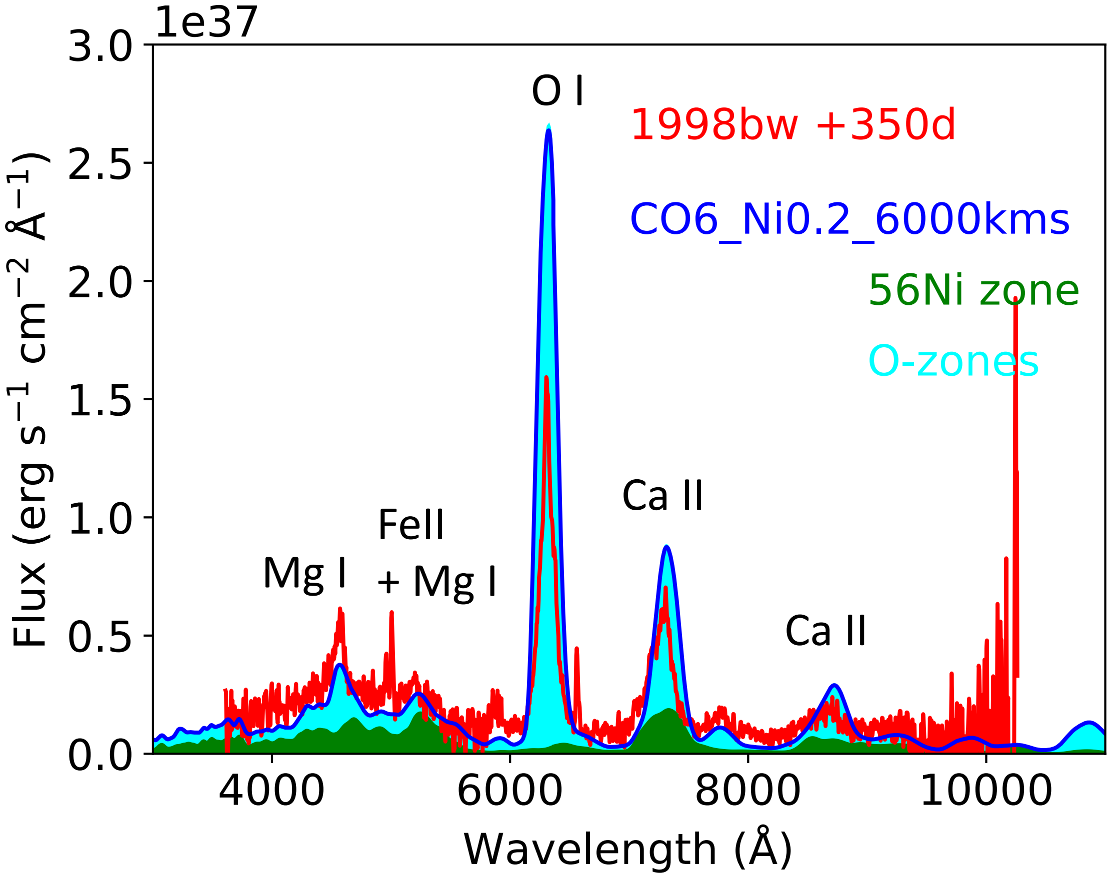
- Independent support from large inferred Mg masses (1.5-15 M_{sun})
- Recombination lines suggest material is clumped or compressed in shells ($f \lesssim 0.01$).

Standard ^{56}Ni-powered models, explosions of 6-10 M_{sun} CO cores fit SN 1998bw quite well.

AJ+2018, in prep.

See also Mazzali+2001,Maeda+2006, Dessart+2018.





<5500 Å region dominated by radiative transfer effects

Broad-lined Ic (e.g. 1998bw)

M(CO) ~ 6 M_{sun}
MZAMS ~ 25 M_{sun}

SLSN Ic fast

??
No nebular data

SLSN Ic slow

M(CO) >~ 15 M_{sun}
MZAMS ~ 40-100 M_{sun}

Upper limit set by PPISN limit. Association with PISN (>130 M_{sun}) not likely (AJ+2016).

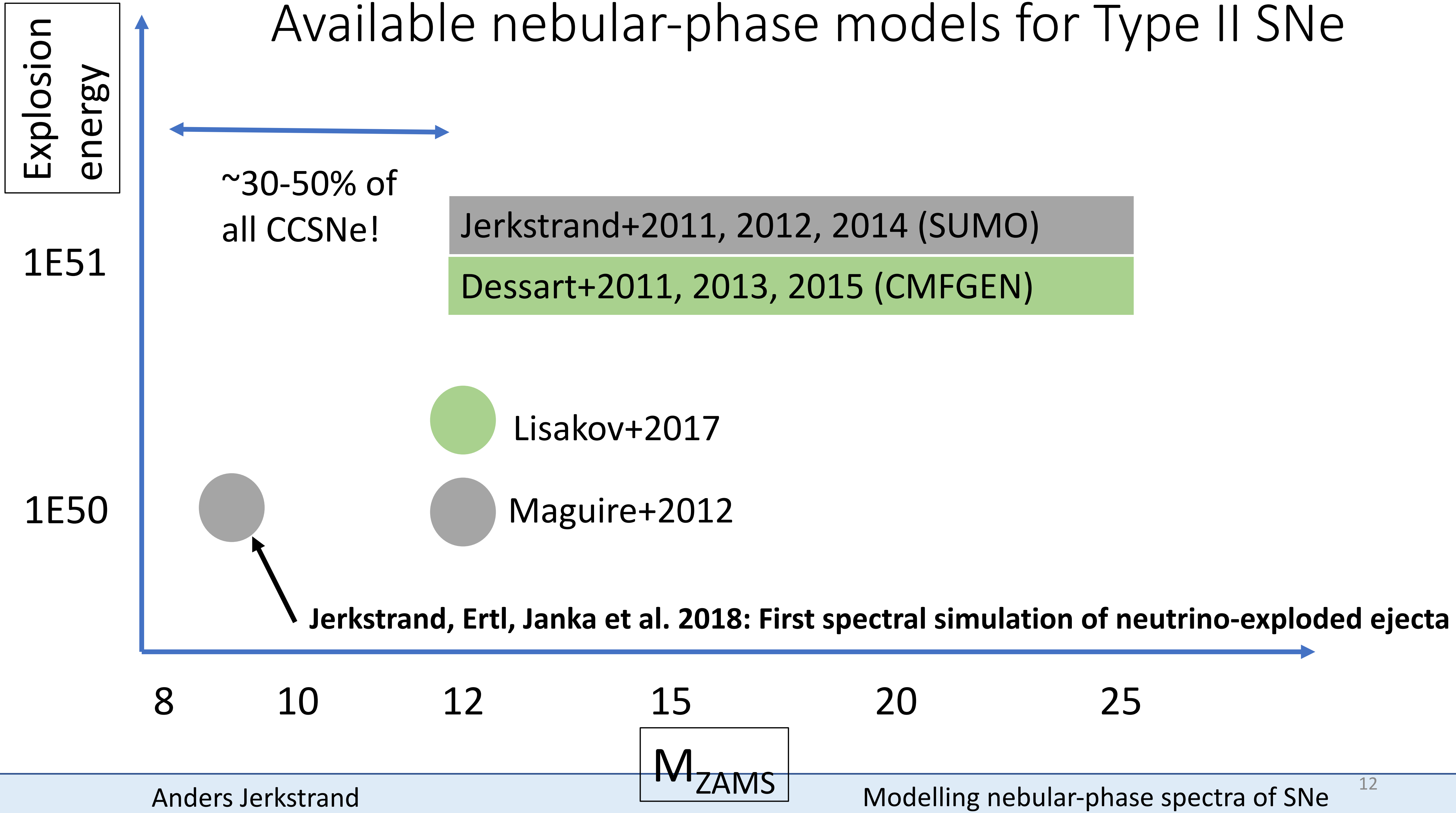
The mice

Subluminous Type II supernovae

20 years of speculation:
low-mass progenitors
or high-mass stars with
weak explosions and fallback?

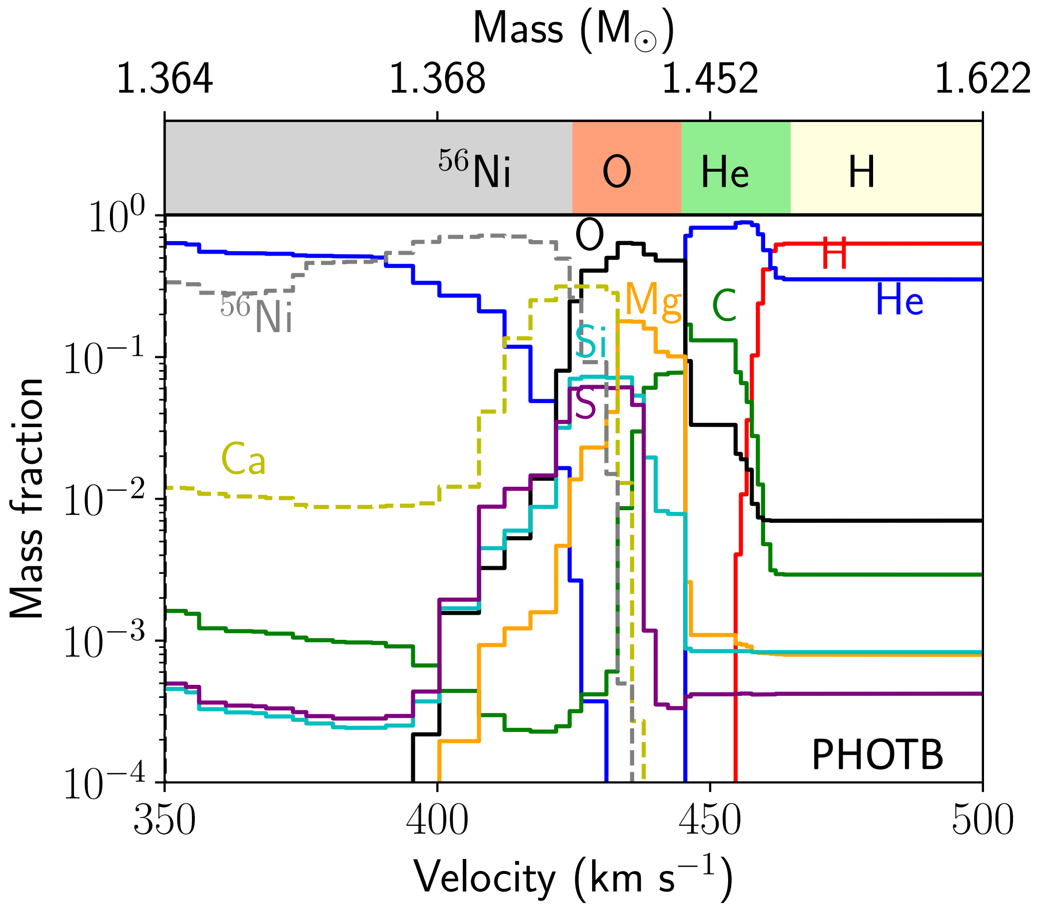
e.g. Turatto+1998,
Chugai & Utrobin 2000,
Zampieri 2003,
Pastorello 2004,2006,2009,
Nomoto+2013,
Spiro+2013

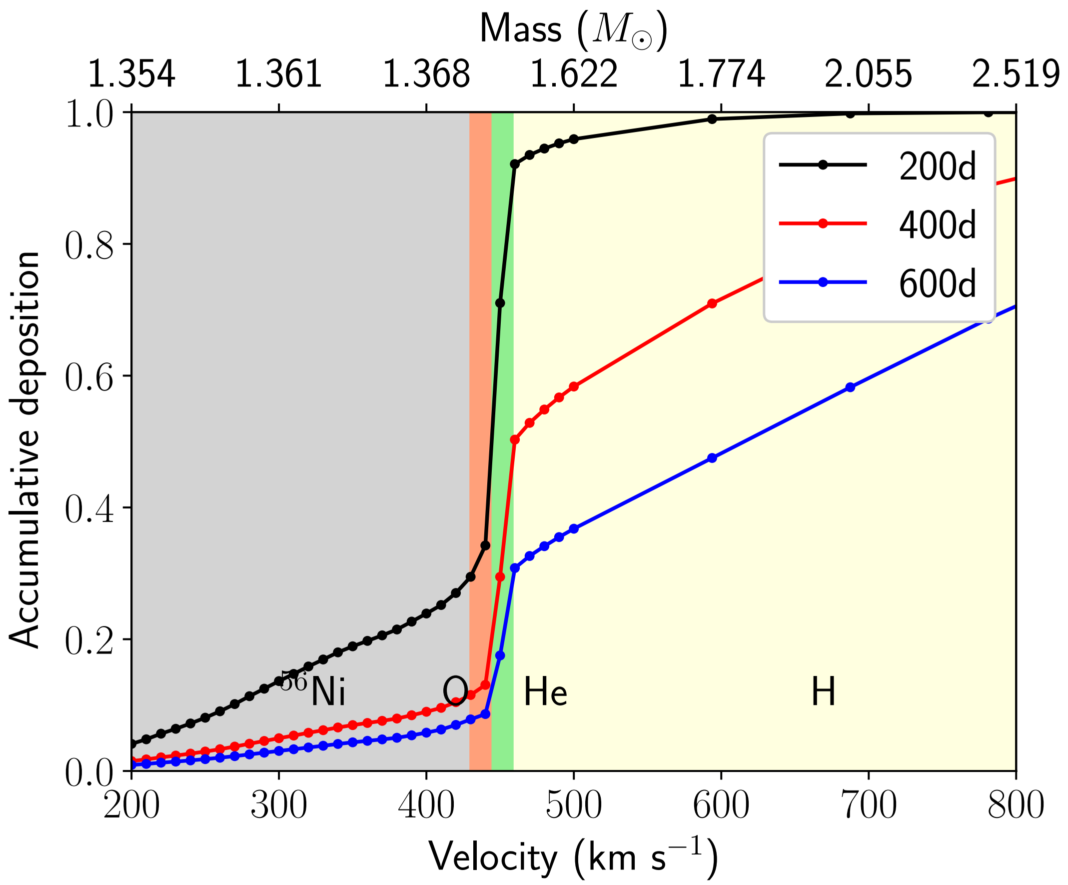
Available nebular-phase models for Type II SNe



Spectral formation in a M_{ZAMS}=9 $M_\odot$ model

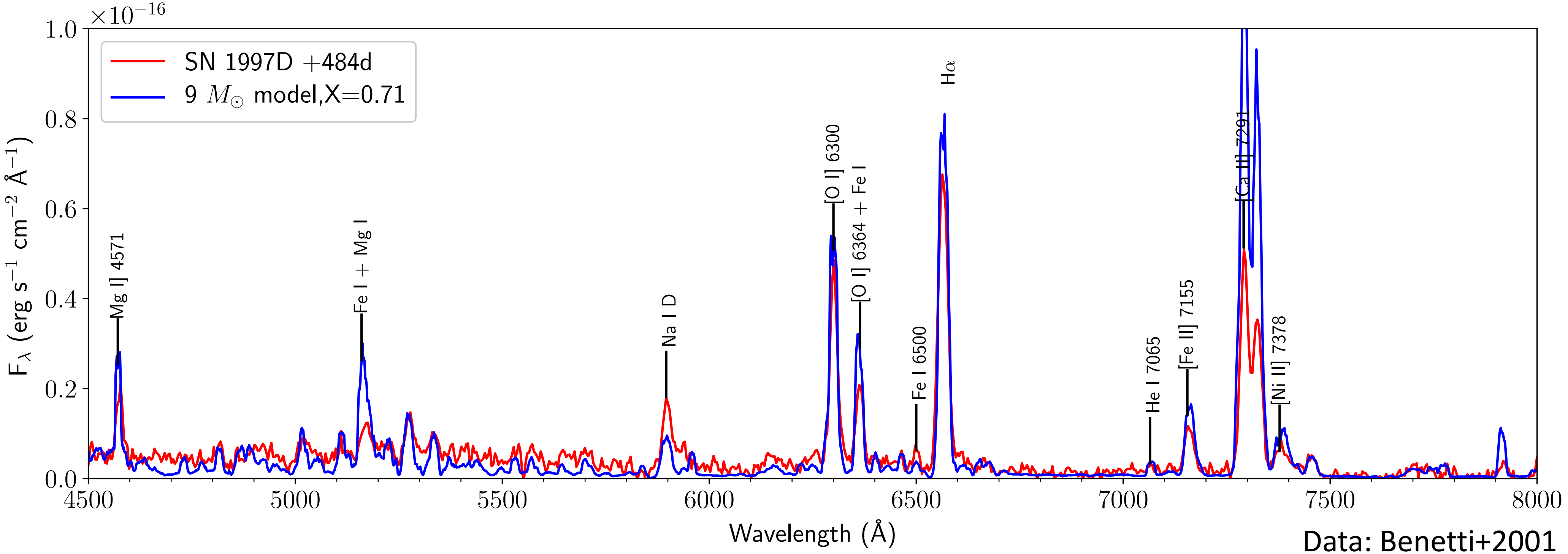
AJ+2018





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

Comparison to object 1 of 3: **SN 1997D** (the prototype for the subluminous IIP class)



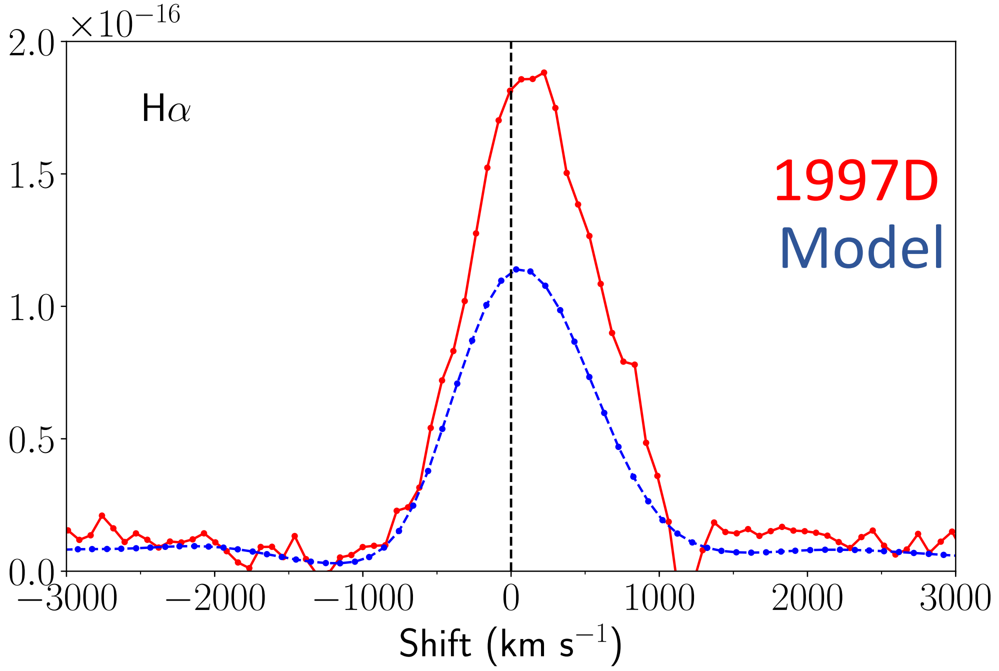
AJ+2018

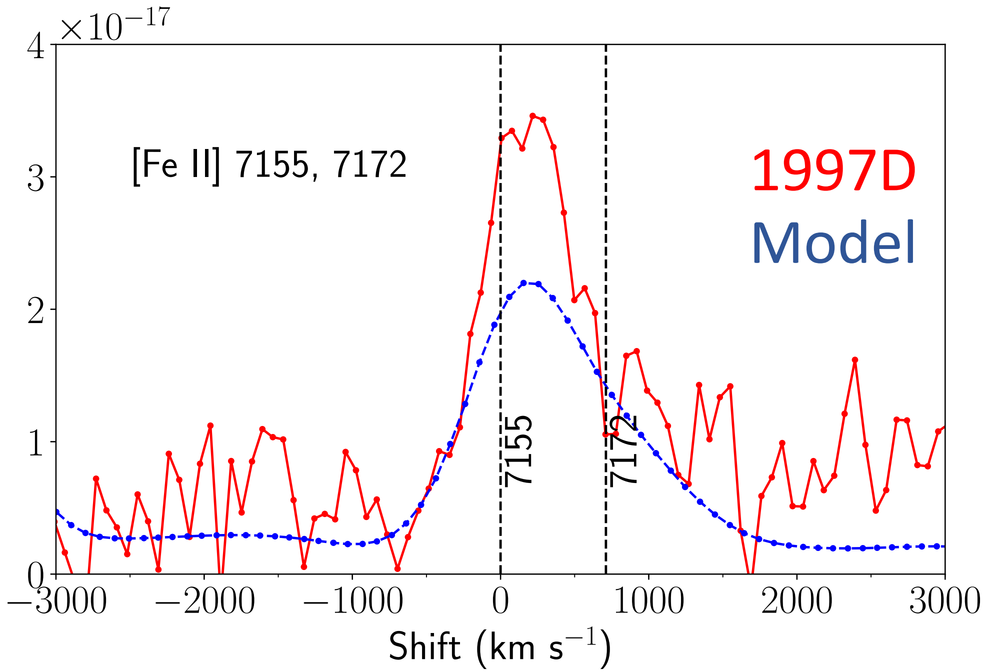
Data: Benetti+2001

- Mg and O lines in good agreement
- He I 7065 is seen → He shell is present
- <u>1997D convincingly linked to low-mass progenitor (no tuning)</u>

Testing explosion models through line profiles

AJ+2018





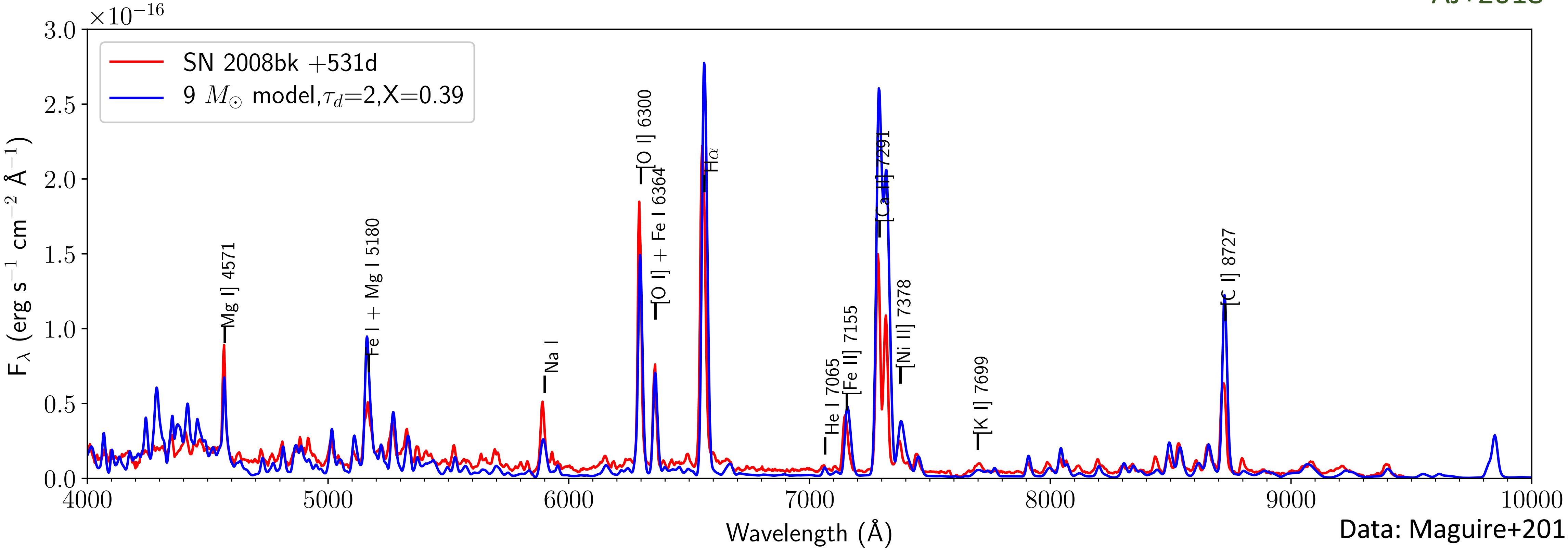
Line	FWHM (km s^{-1})	FWHM$_{dec.}$ (km s^{-1})	Model (km s^{-1})
Hα	1020	820	1100
He 7065	950	740	900
O I 6300,6360	940	720	900
Ca II 7291	820	560	900
Fe II 7155	730	420	800

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

3D tests now in preparation.

Comparison to **SN 2008bk**

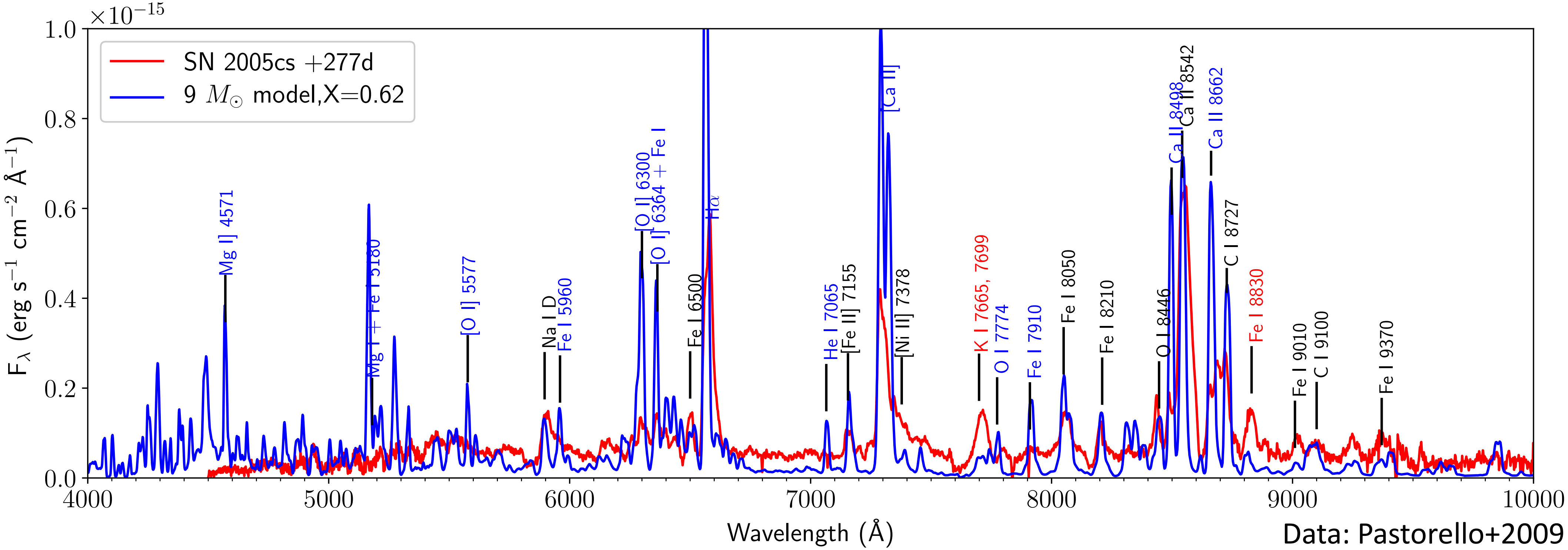
AJ+2018



Data: Maguire+2012

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

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



AJ+2018

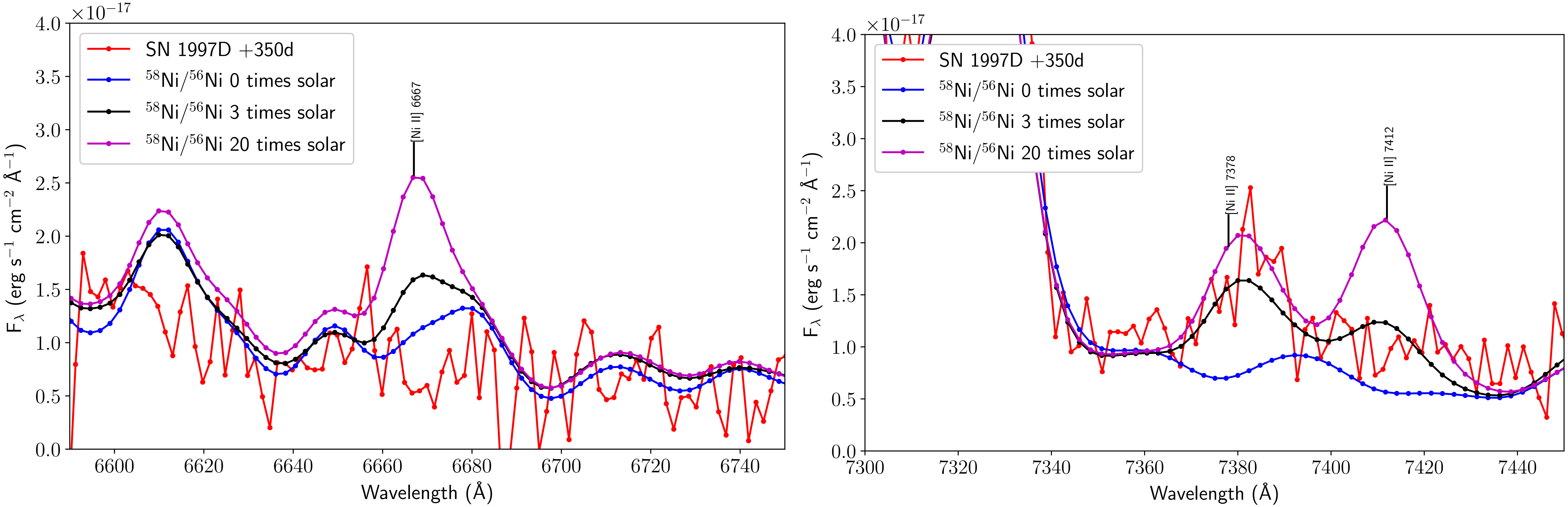
Data: Pastorello+2009

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

Unclear and contradictory

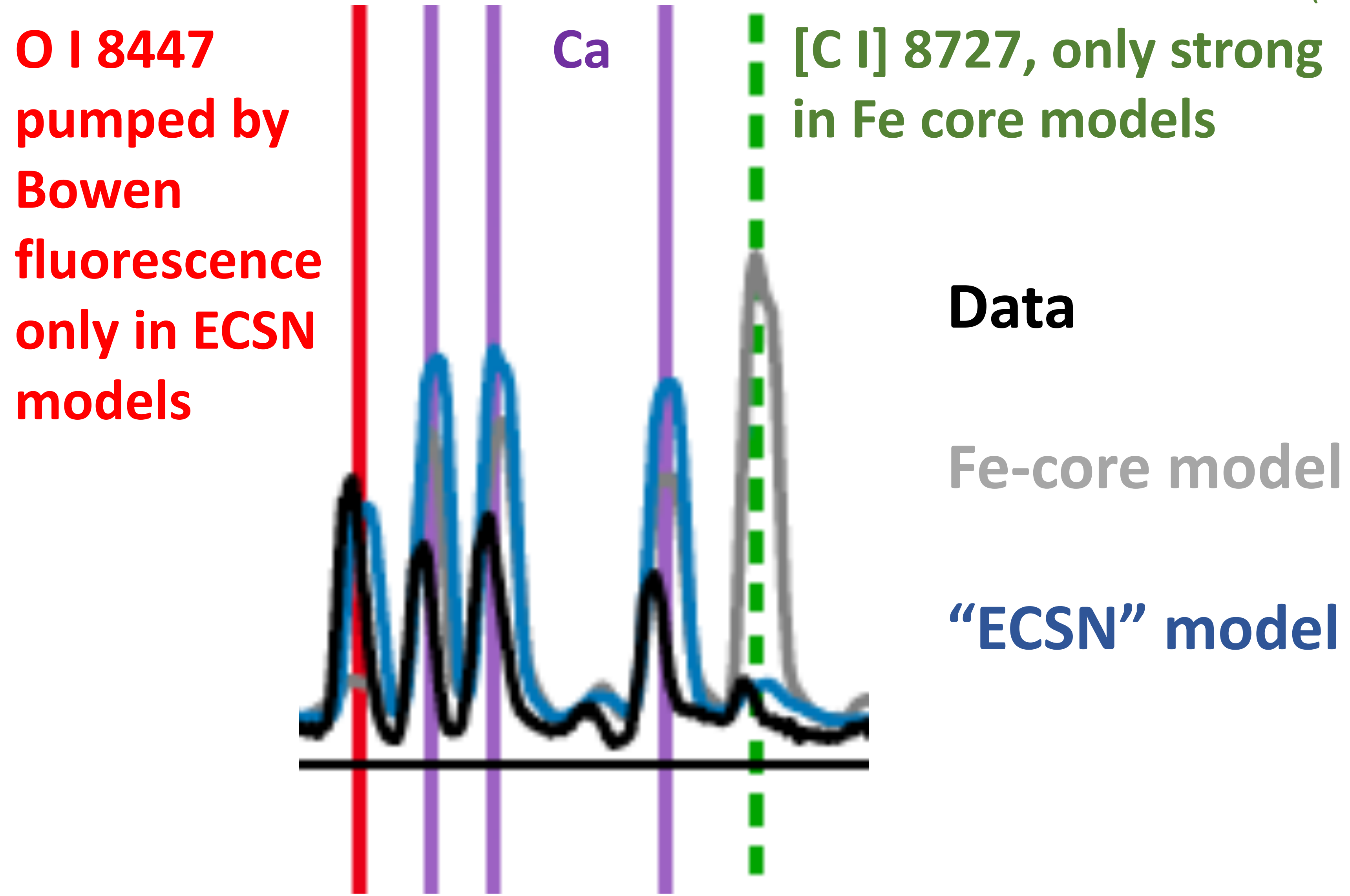
No observed object shows <u>explosive</u> nucleosynthesis (^{58}Ni) expected from electron-capture SNe

AJ+2018

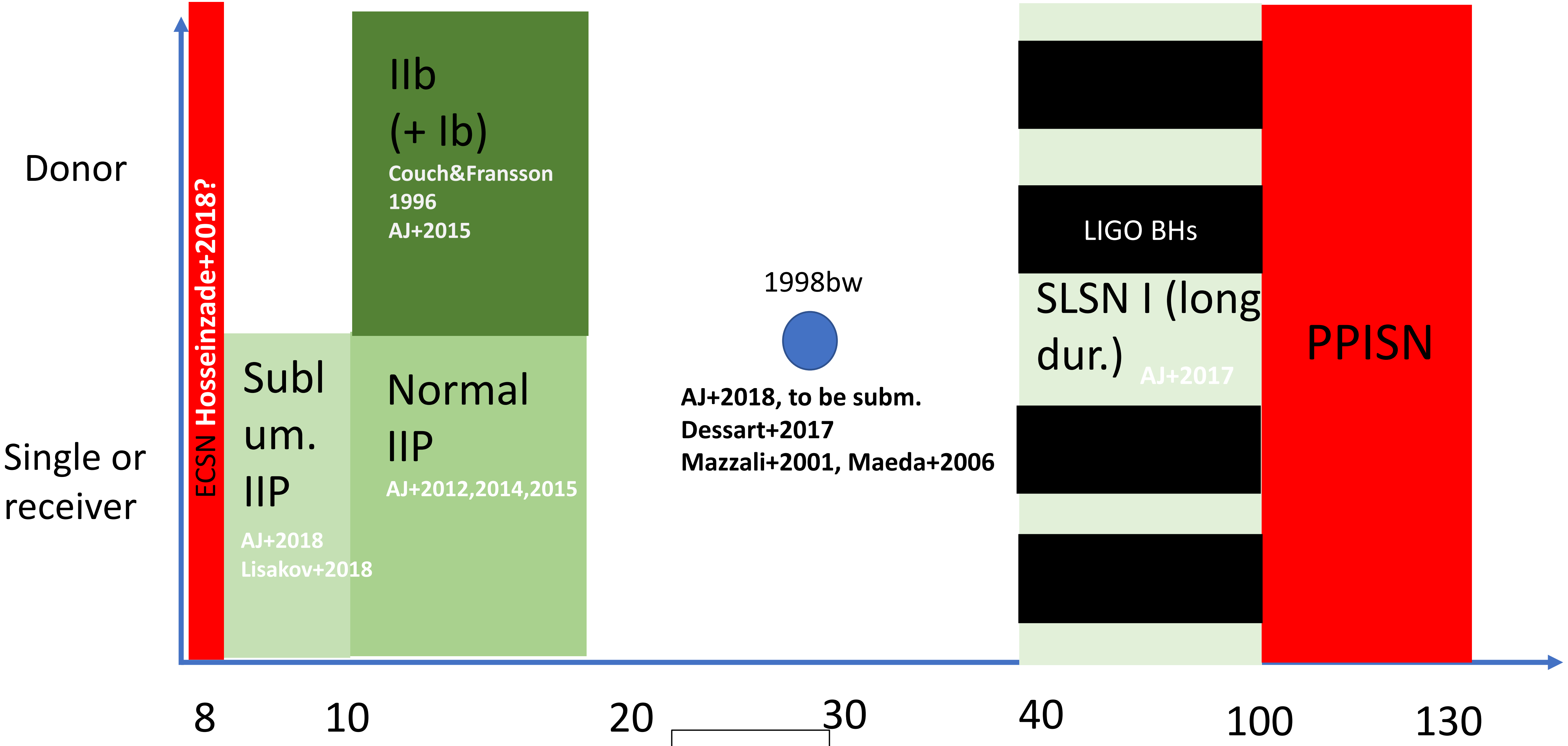


However: is SN 2016bkv the first discovered electron-capture SN?

Hosseinzade+(incl. AJ) 2018

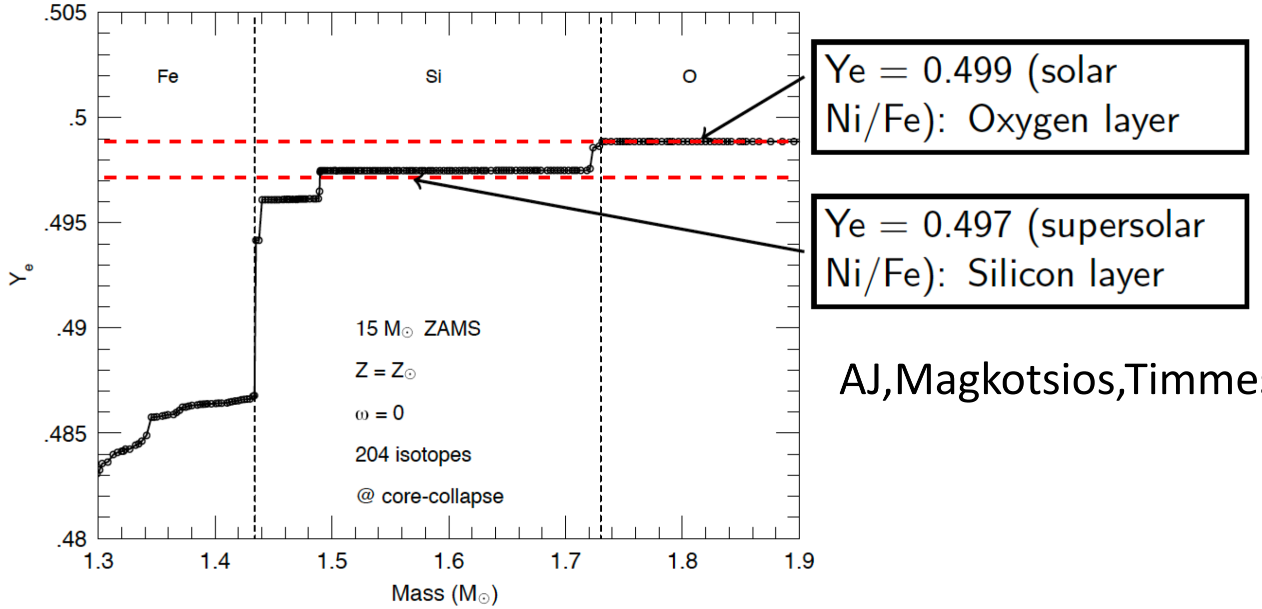


The landscape from nucleosynthesis analysis



^{58}Ni : a unique tracer of explosion

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	∼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



AJ,Magkotsios,Timmes+2015 (ApJ)

Summary

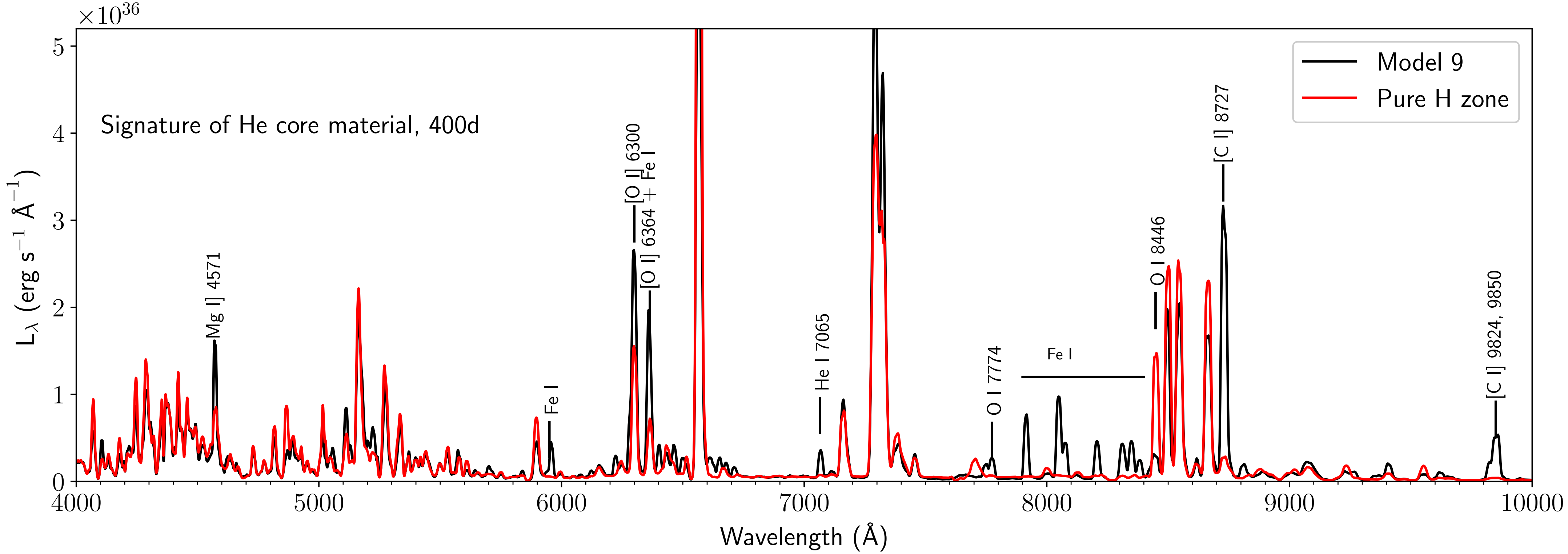
- High-mass end: Long-duration superluminous Ic SNe undoubtedly the explosions of very massive stars, M_{ZAMS} >~ 40 M_{sun}.
  - Which massive stars collapse to the LIGO BHs, which make SNe?
  - Why do SLSN look similar to 1998bw?

- Low-mass end: 8-12 M_{sun} range now opened up for modelling (30-50% of all CCSNe). First models show good agreement with “subluminous IIP” class.
  - Explosions of iron cores in the 9-12 M_{sun} range appears robust.
  - Electron capture supernovae not yet clearly discovered (but SN 2016bvn is a strong candidate)

THANK YOU

Nucleosynthesis signatures

AJ+2018



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