Diagnosing nucleosynthesis production in supernovae

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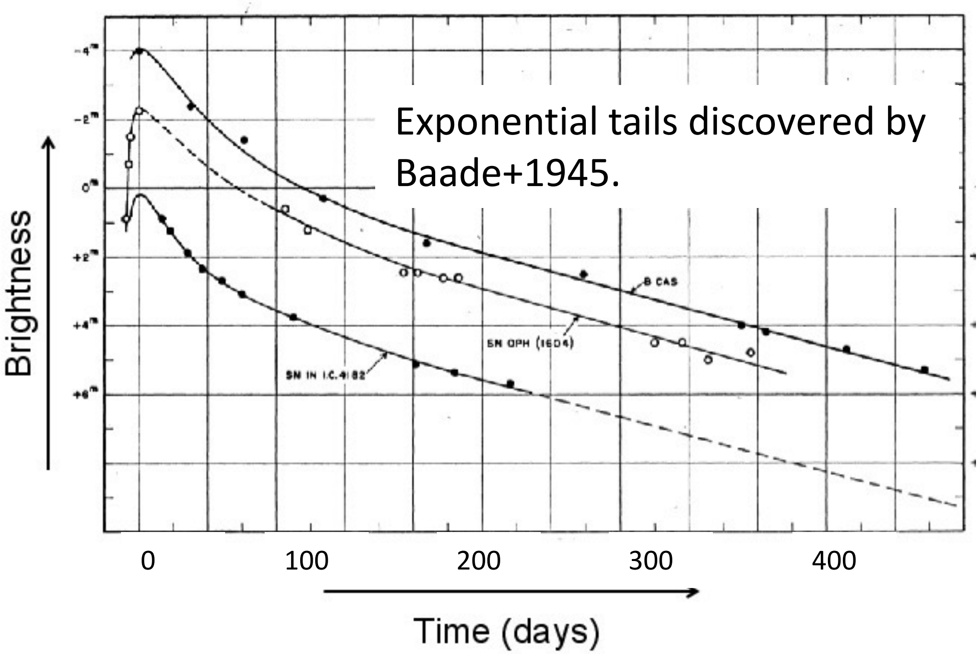
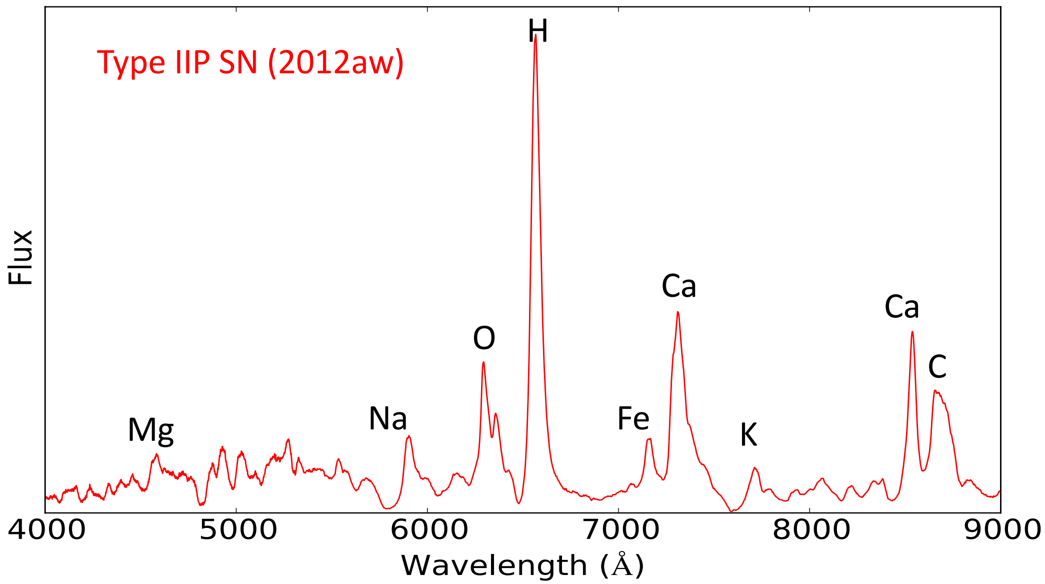
MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

The nebular phase : our window on stellar nucleosynthesis



- 100d – 1000d post explosion.
- Emission lines from all nuclear burning regions visible.
- Data collection rate: ~5-10 per year (<1% of all discovered SNe).
- Current amount of objects: ~50-100



The SUMO code : a state-of-the-art forward modelling tool

Jerkstrand+2011, 2012

Radioactive decay and gamma-ray thermalization

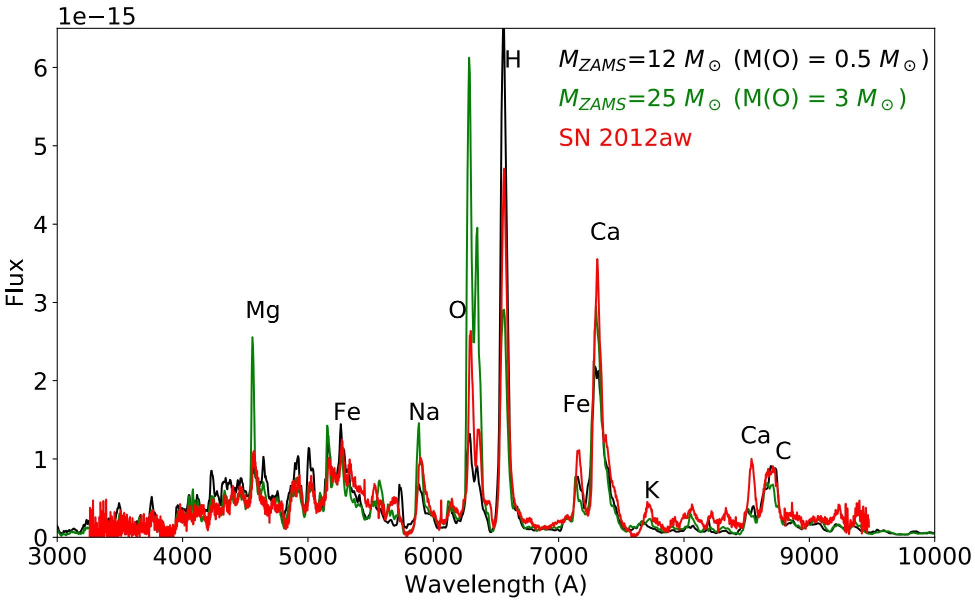
Degradation of Compton electrons
- Spencer-Fano Equation
- Ionization, excitation, heating

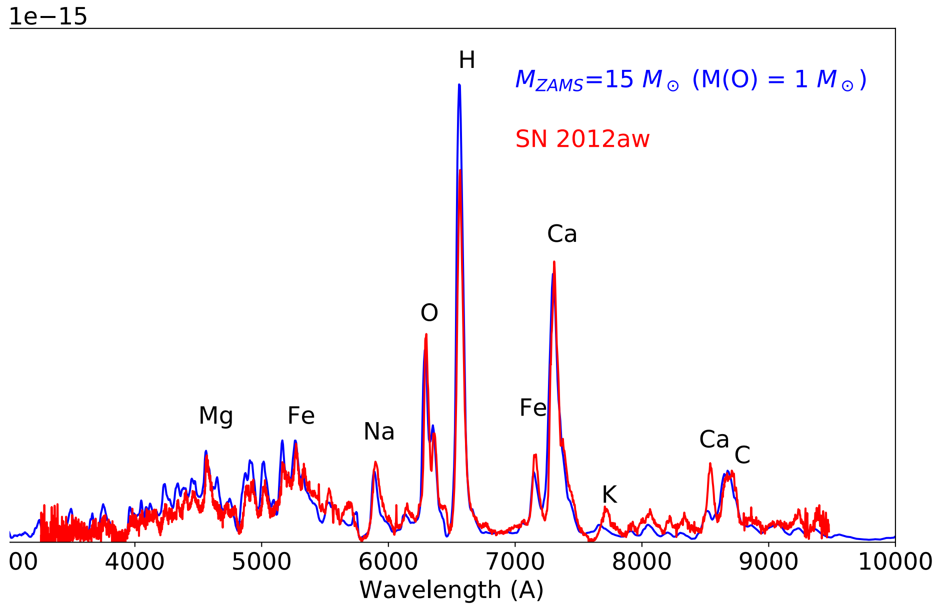
NLTE statistical equilibrium
- 22 elements, first three ionization stages
- 10,000 levels

Temperature
- Heating = cooling

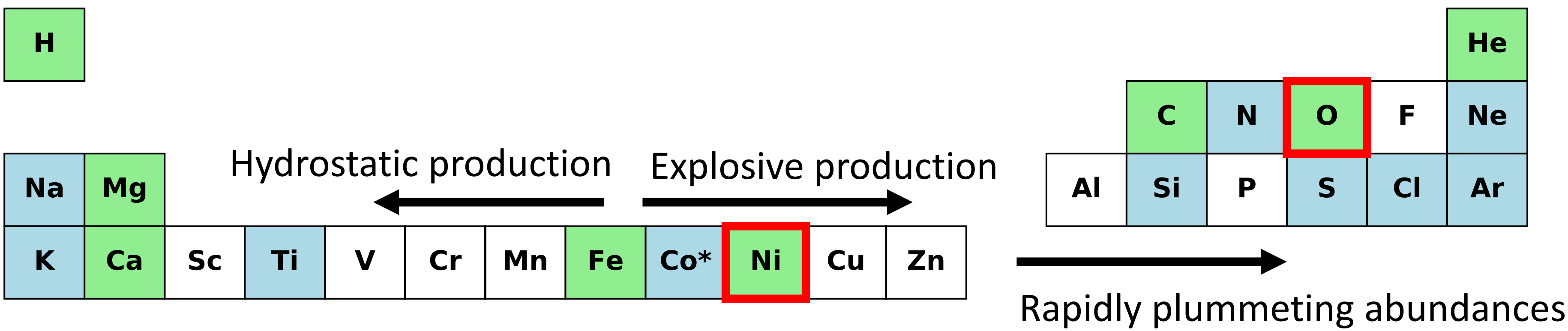
Radiative transfer
- Monte Carlo-based, Sobolev approximation, 300,000 lines

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





Elements currently diagnosed from supernova emission line spectra



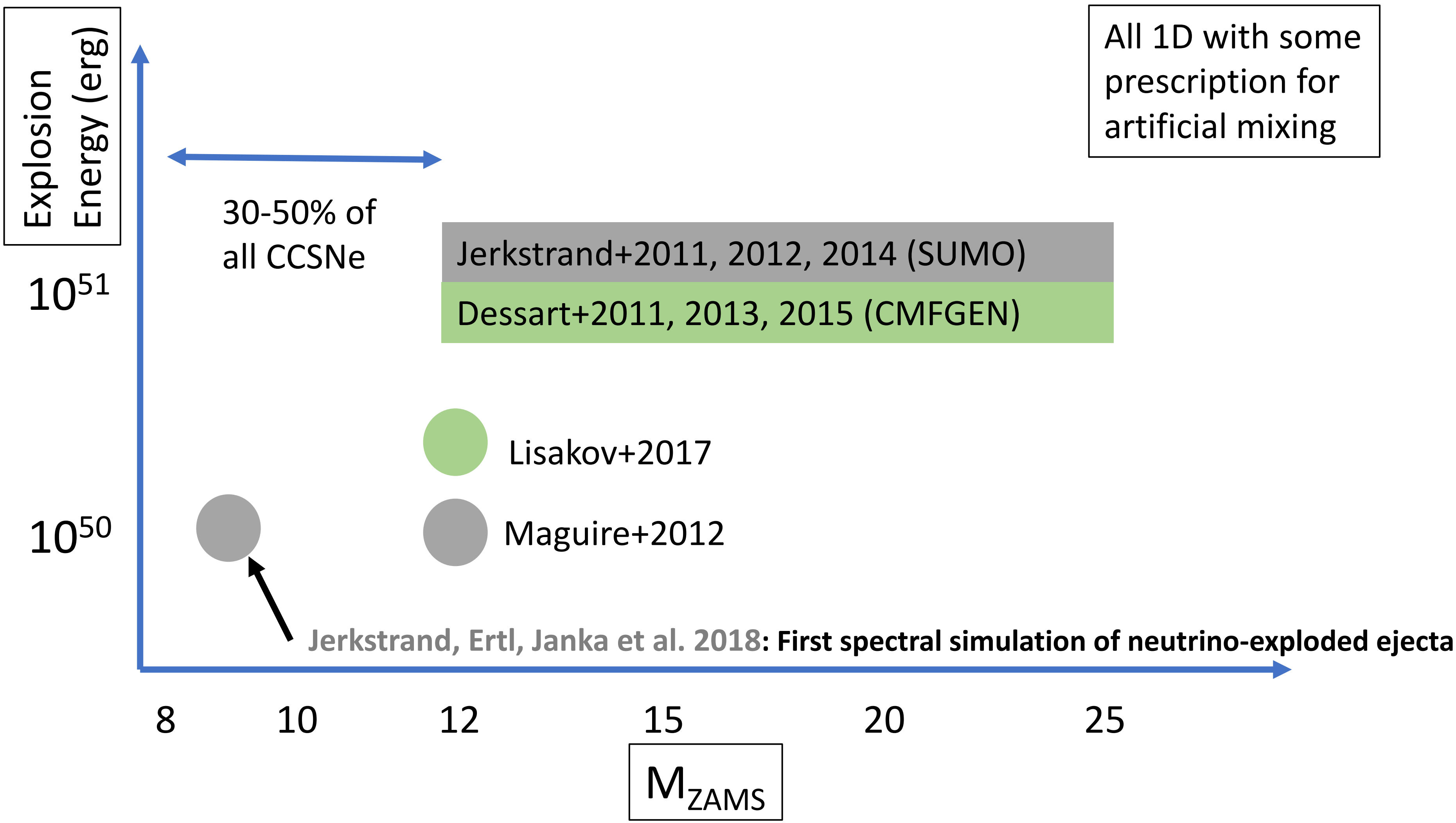
Good diagnostic situation

Moderate diagnostic situation

Poor diagnostic potential

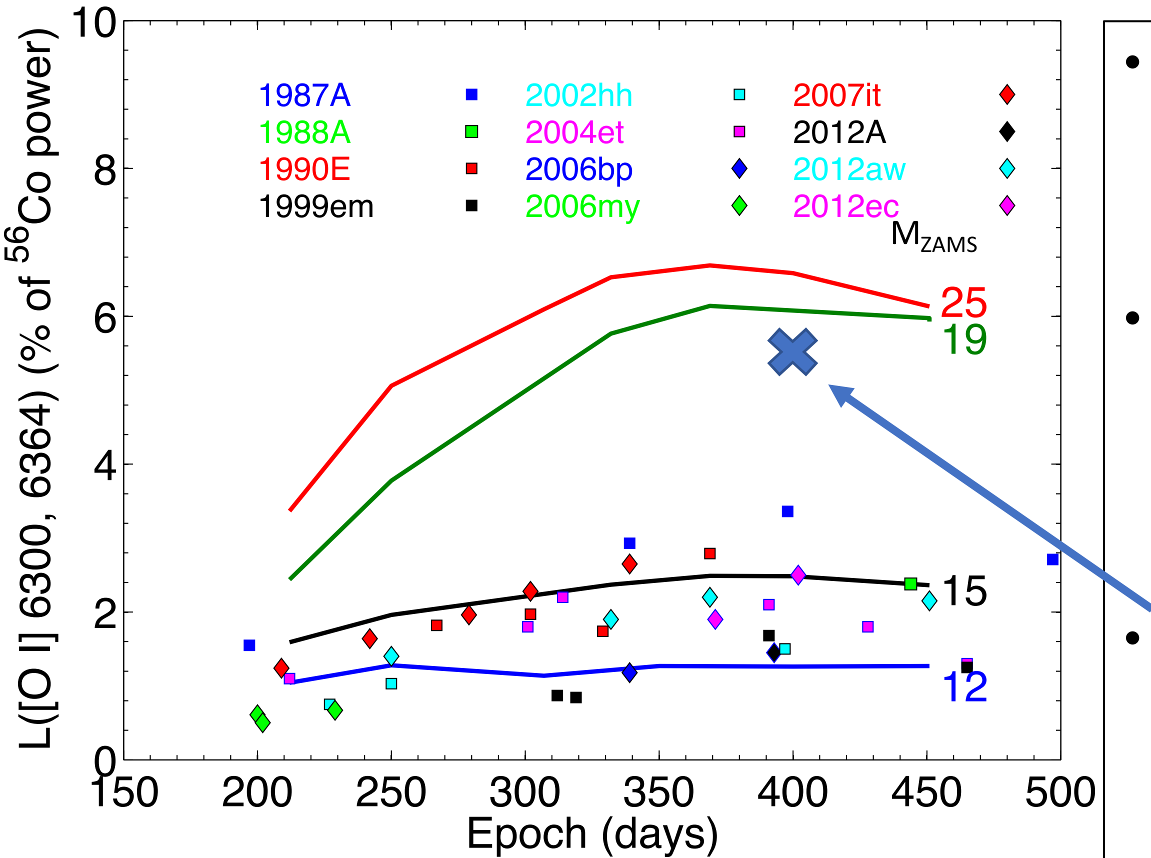
Jerkstrand 2017,
Handbook of supernovae

Available late-time spectral models for Type II SNe



Oxygen : Standard Type II supernovae from explosions of M_{ZAMS} =10-17 $M_{\odot}$ stars. <M(O)> ~ 0.5 $M_{\odot}$.

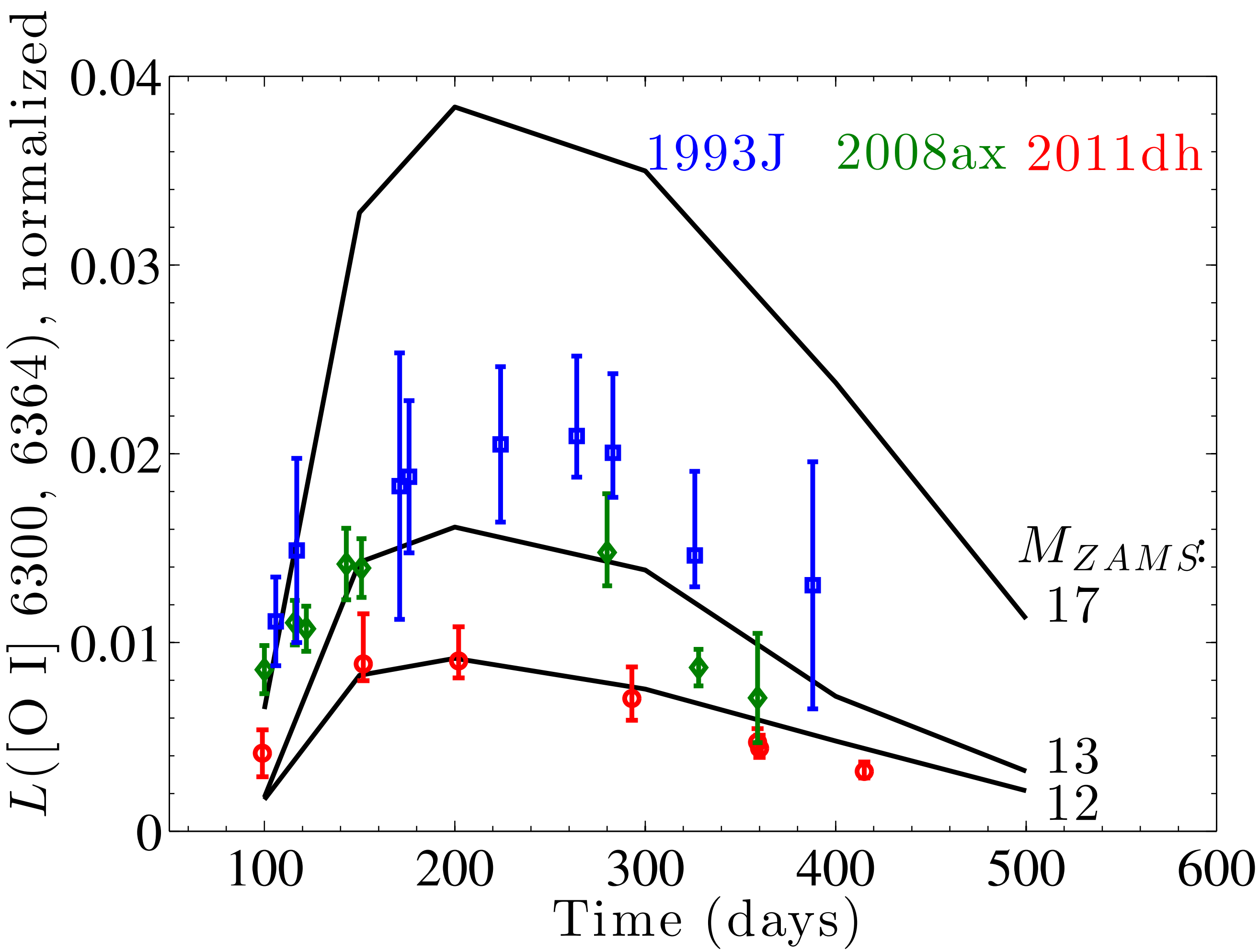
AJ+2012,2014,2015 (MNRAS)



- Type II can be modelled quite well with approximate mixing methods in 1D.
- "**Red Supergiant problem**" (Smartt 2009) appears confirmed from nucleosynthesis view.
- However, first object with possibly M > 18 M_{sun} now discovered (Anderson+2018). Low metallicity ($0.05Z_{sun}$).

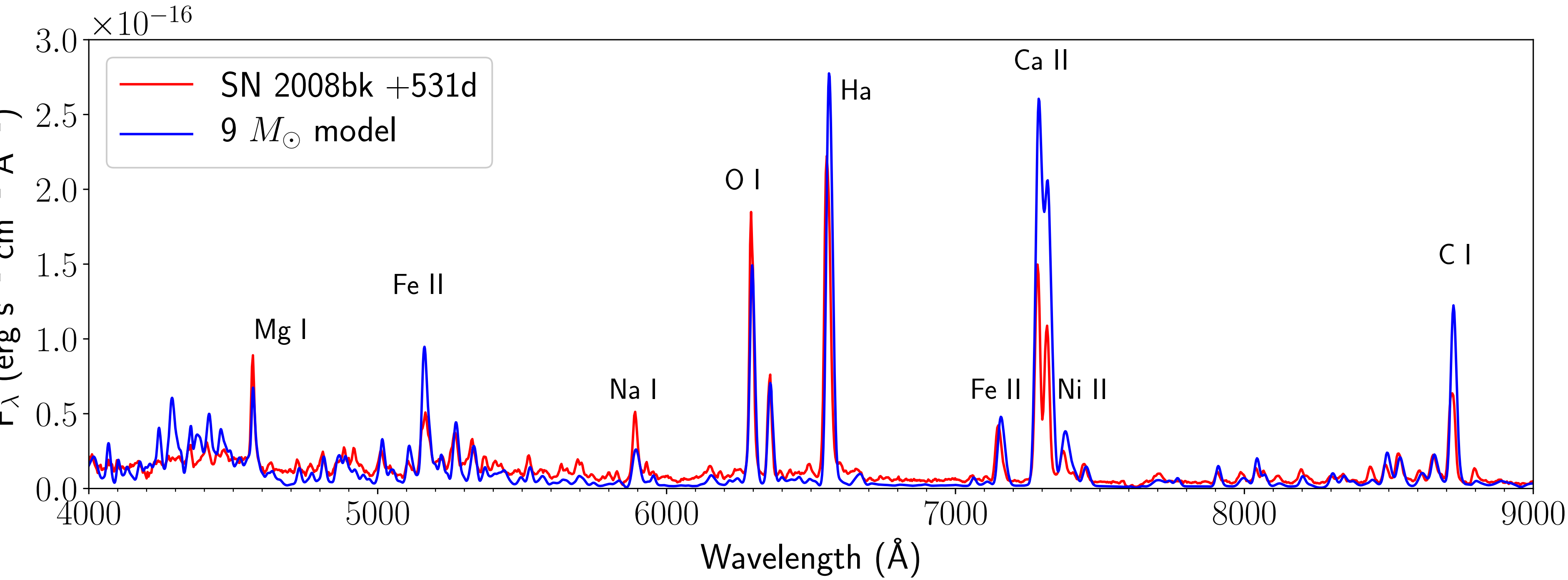
Oxygen: Same picture for Type Ib/IIb SNe: these are mainly *mass donors* from low-mass progenitor range.

AJ+2015 (A&A)
Ergon+2015 (A&A)



“Weak” Type II SNe: from 8-10 $M_\odot$ stars

Jerkstrand, Ertl, Janka+2018



Data: Maguire+2012

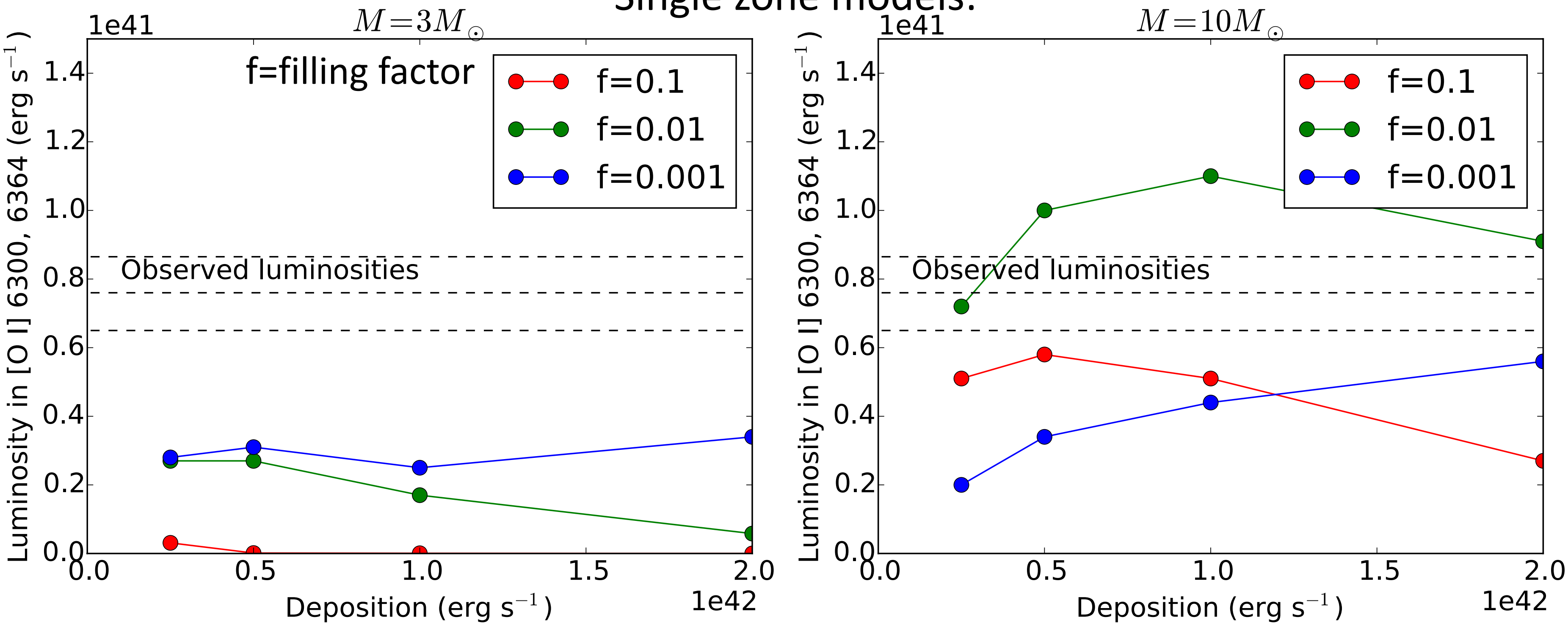
- Mg, O, Na, C all strong → ***Fe core progenitors, <u>not</u> ONeMg core progenitors*** *(more later)*
- Competing hypothesis that these would be fall-back SNe from massive stars has little current support.

See also Lisakov et al 2017, 2018

Oxygen : Very large production only inferred in a rare class of *superluminous supernovae*

Jerkstrand+2017, ApJ

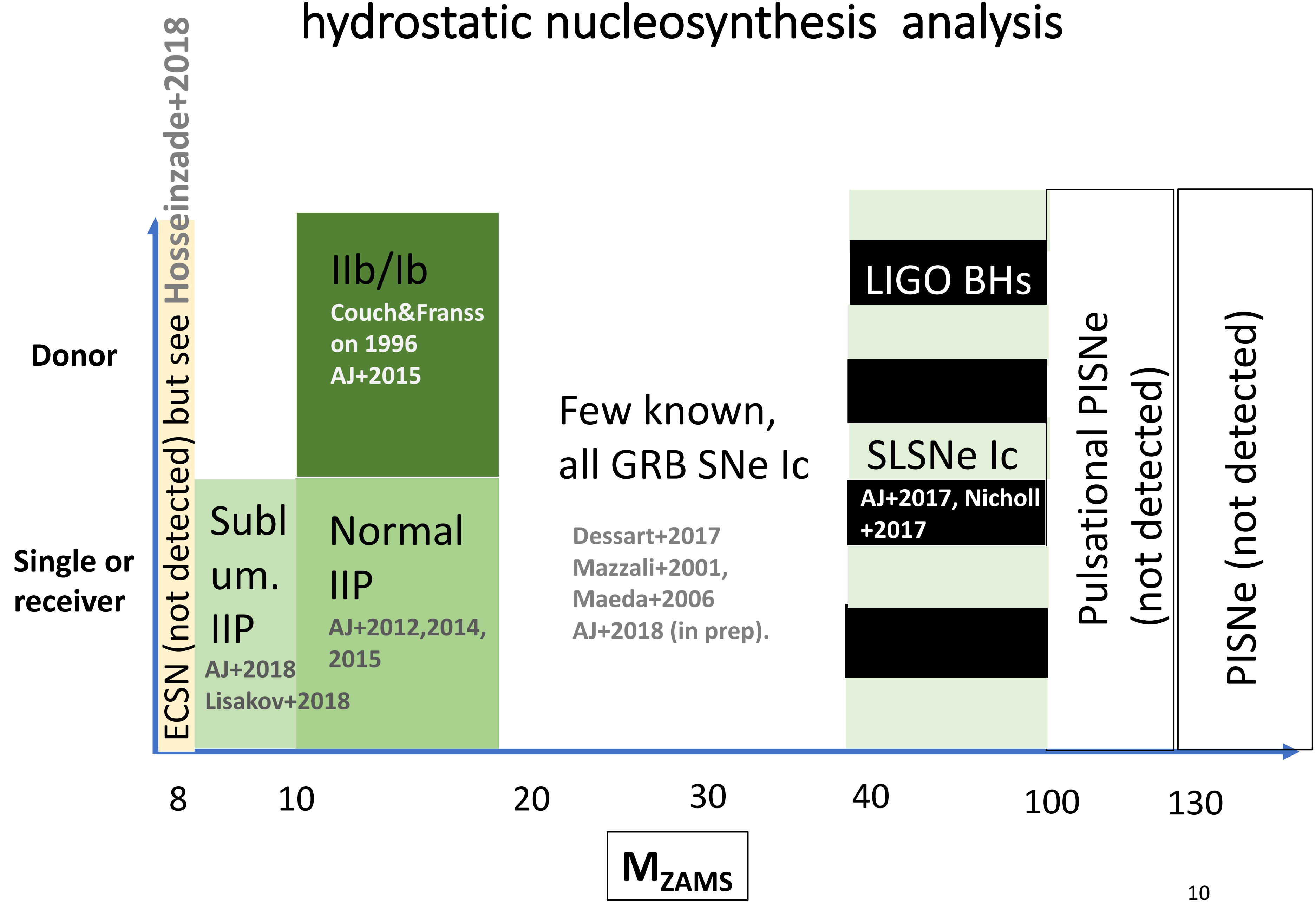
Single zone models:



- Independent support from large inferred Mg masses (1-10 M_{sun})

- Implication : *Some* high-mass stars (M_{ZAMS} >~ 40 M_{sun}) do explode somehow.
- Superluminous supernovae are probably too rare to impact GCE.

The progenitor landscape (local Universe, $Z \sim Z_{sun}$) from hydrostatic nucleosynthesis analysis



Stable nickel: a unique tracer of the innermost layers and the explosion

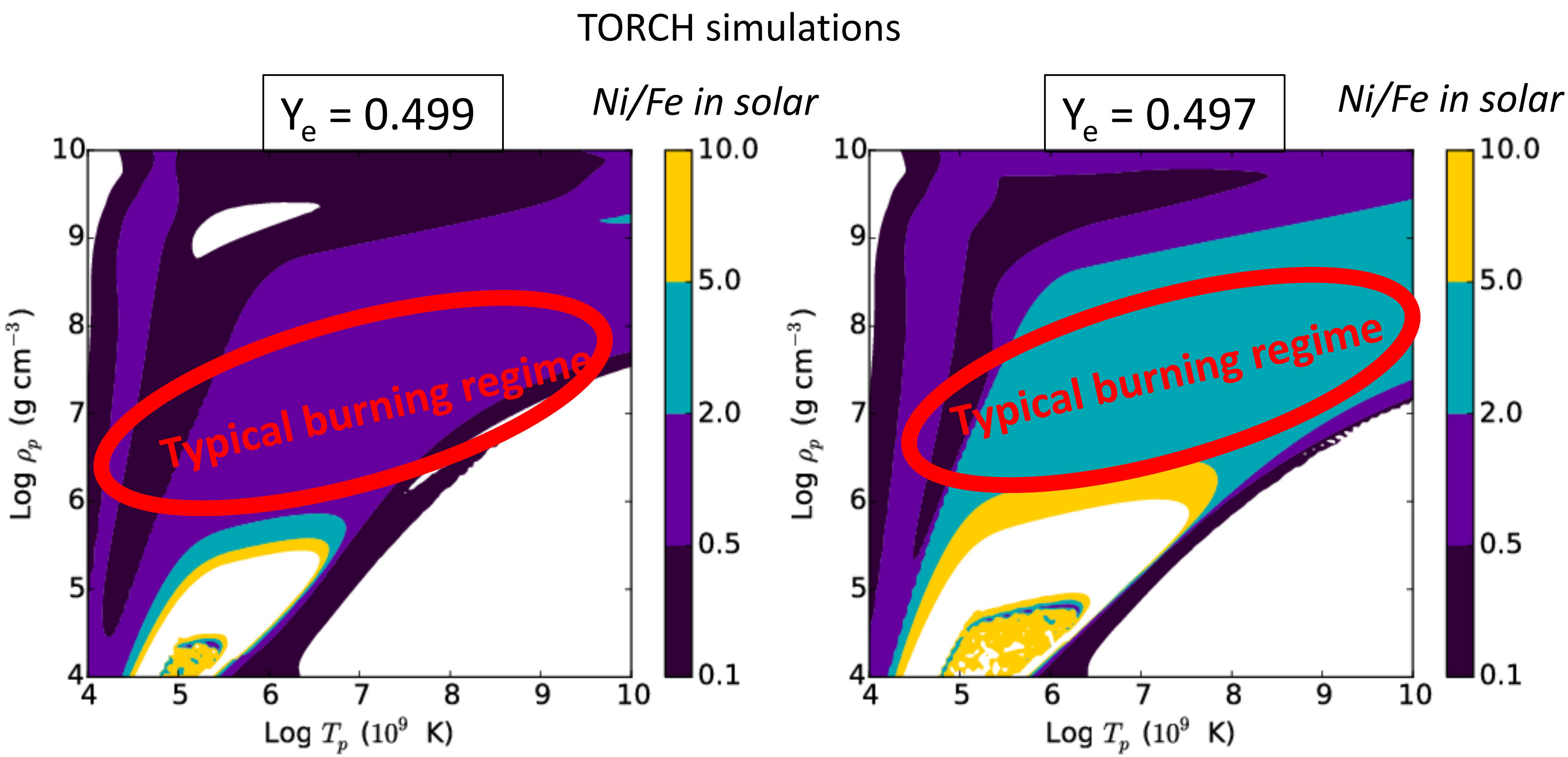
AJ+2015 (MNRAS)

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

- Average ratio ≥ solar. If true in larger sample, Type Ia SNe must make Ni/Fe ≤ solar → constraints on both CC and TN explosions models.
- Sometimes significantly larger: what does it mean?

Stable nickel: a unique tracer of the innermost layers and the explosion

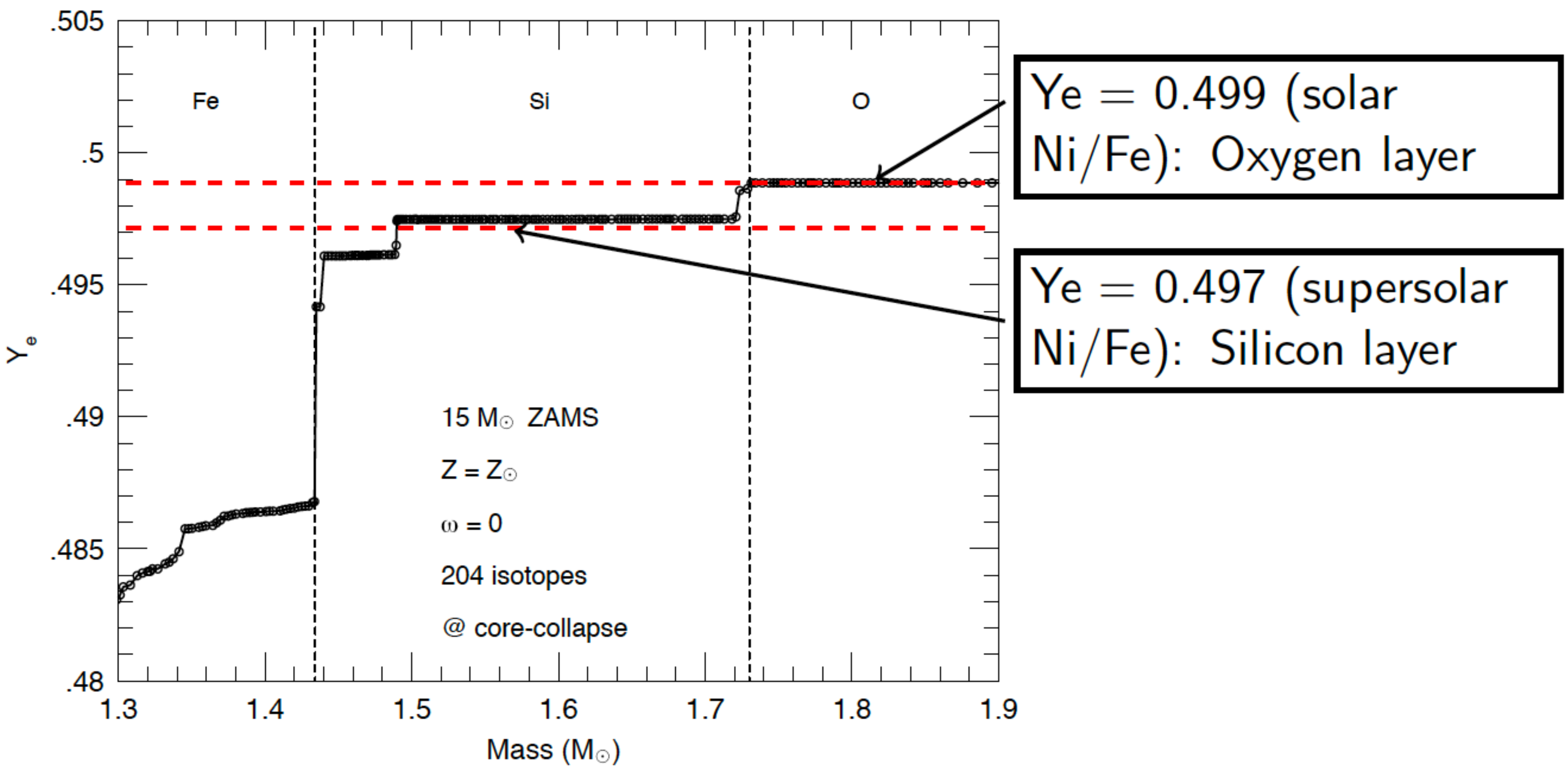
AJ,Magkotsios,Timmes+2015 (ApJ)



- **Solar production** requires Y_e ~ 0.499, whereas **supersolar** requires Y_e ~ 0.497.

The Ni/Fe ratio may tell us which progenitor layer was explosively burned

AJ,Magkotsios,Timmes+2015 (ApJ)

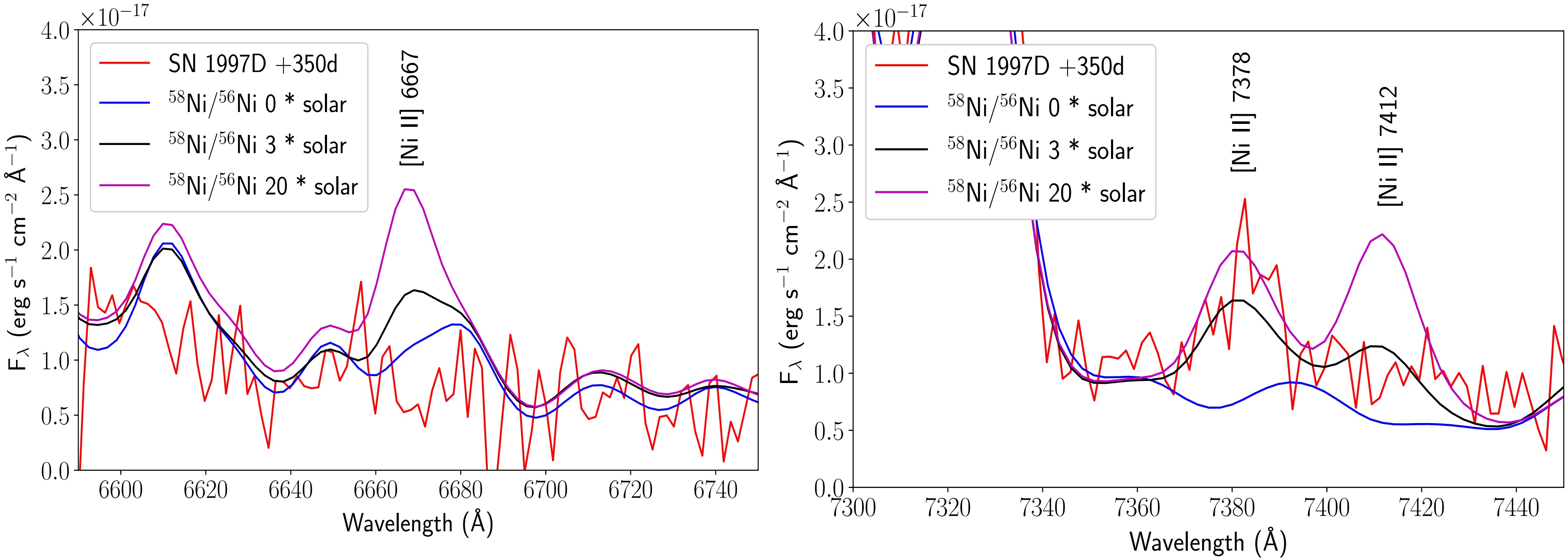


Can help on constraining mass cuts used in GCE models and late shell burning physics.

For example, KEPLER grid gives [Ni/Fe]=+0.1-0.3 dex depending on piston location (Woosley & Heger 2007).

An exception: Electron capture supernovae have predicted Ni/Fe >> solar. But no SN yet observed shows this.

Jerkstrand, Ertl, Janka+2018



Summary

- Stellar element production and supernova explosion physics can be directly diagnosed by **nebular-phase spectroscopy** of supernovae.
- **H**, **He**, **C**, **N**, **O, Ne, Na, Mg**, **Si, S, Cl, Ar, K, Ca**, **Fe, Co, Ni** have so far been diagnosed to various extents.
- The **SUMO code** provides state-of-the-art synthetic spectra of explosion models.
- **Oxygen**: Good diagnostic lines, and strongest indicator of MS mass and hydrostatic burning yields.
  - Type II SNe produce 0.1-1 M_{sun} O and appear to arise from 8-17 M_{sun} stars.
- **Nickel**:
  - An important diagnostic of explosive burning.
  - A sample of CCSNe show mostly solar Ni/Fe, but sometimes several times larger. This may be explained by which progenitor layer provided the main explosivesilicon burning fuel: *oxygen* (gives solar) or *silicon* (gives supersolar).

THANK YOU FOR LISTENING