Diagnosing nucleosynthesis production in supernovae

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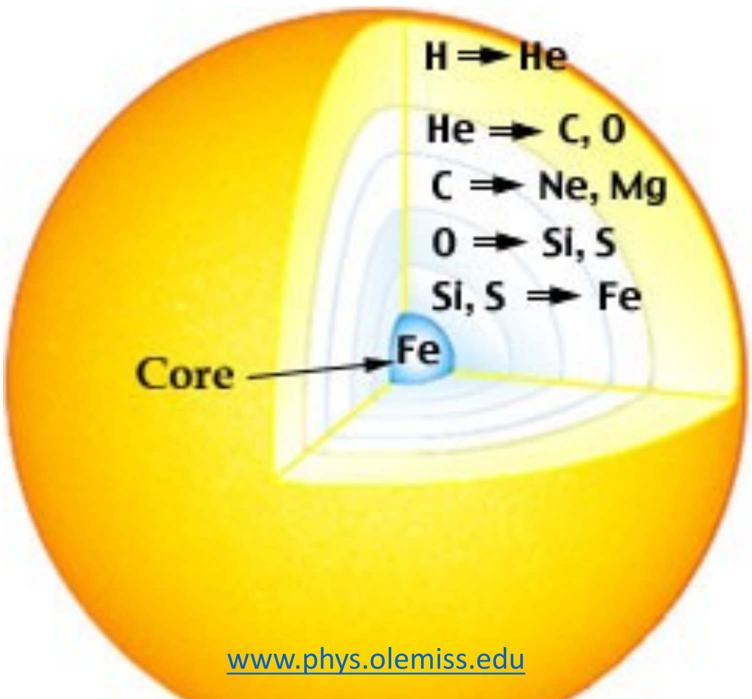
Outline

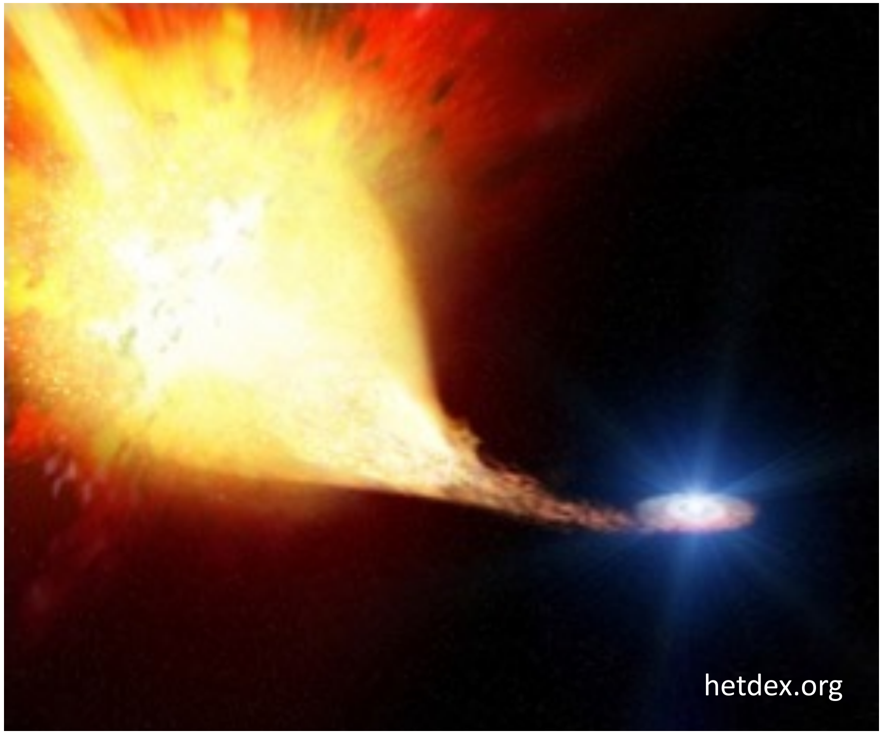
1. Introduction to supernovae and their nucleosynthesis
2. Nebular phase modelling and the SUMO code
3. Results 1. Hydrostatic yields: Oxygen
4. Results 2. Explosive yields: Nickel
5. Outlook : Extending emission line modelling to kilonovae
6. Summary

Supernovae – the deaths of stars

1 Core-collapse of a **massive star** as it runs out of fuel at the end of its life

2 Thermonuclear explosion of a **white dwarf** exceeding the Chandrasekhar limit (1.4 $M_{\odot}$)





More envelope stripping →

Type	**IIP**	**IIL**	**IIb**	**Ib**	**Ic**	**Ia**
Rate	40%	10%	10%	5%	20%	25%

Supernovae – open questions

Stellar origins
- Which stars explode as which Type of SNe?
- How do H-poor SNe lose their H envelopes? How do He-poor lose their He?

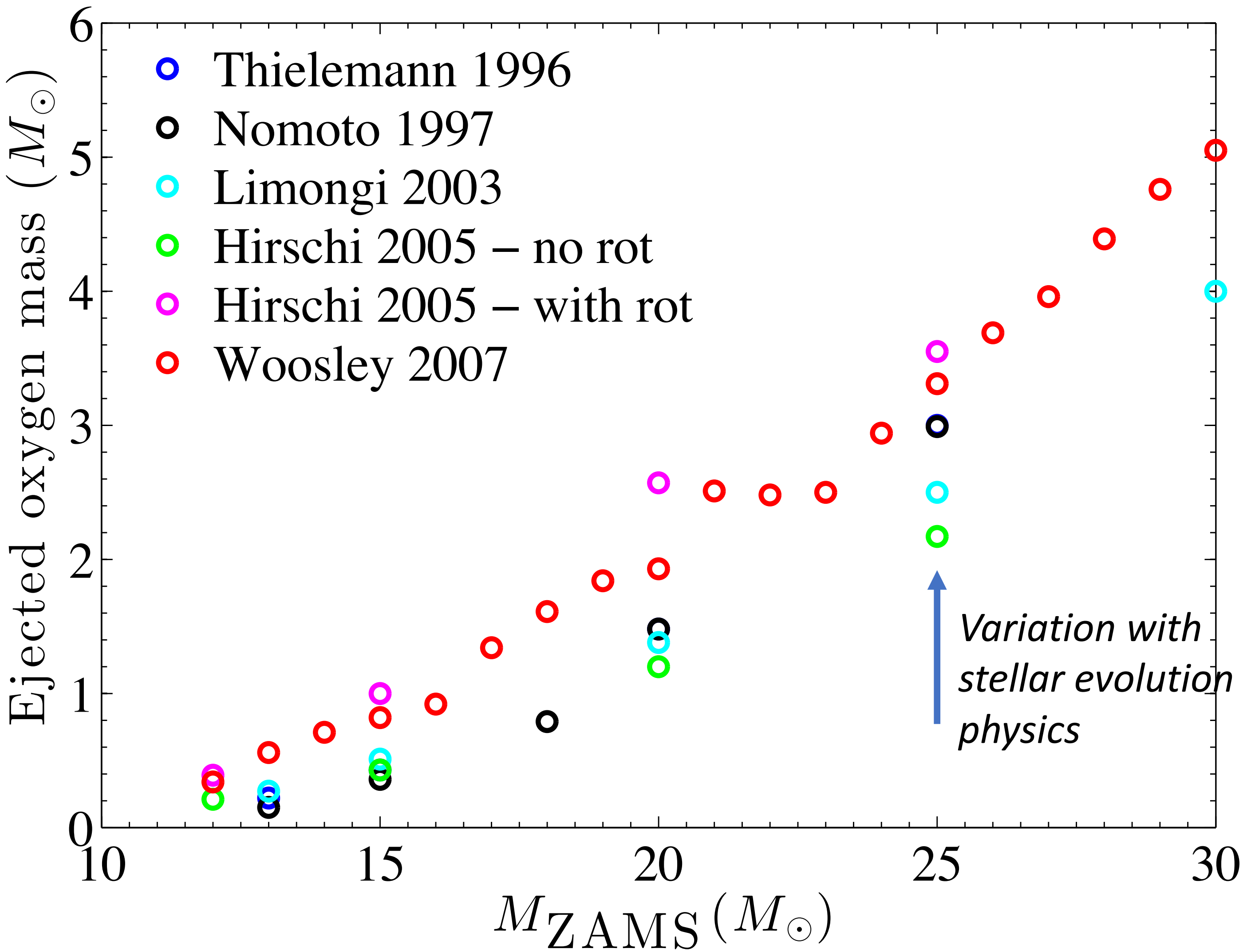
Explosion physics and compact object formation
- How does the explosion happen? Is the neutrino-mechanism the right one? MRI effects?
- How are neutron stars and black holes formed? Which masses, spins, and kicks?

Nucleosynthesis
- Which elements are made in which supernovae?
- Which elements are mainly made by supernovae, and which by other sources?

Application as distance indicators
- How do Type Ia supernovae work, and how accurately can we measure cosmological distances with them?

Exotic physics
- Can the equation of state at high densities be constrained by SNe?
- Do some supernovae form magnetars, quark stars, gamma-ray bursts?

More massive stars produce much more nucleosynthesis



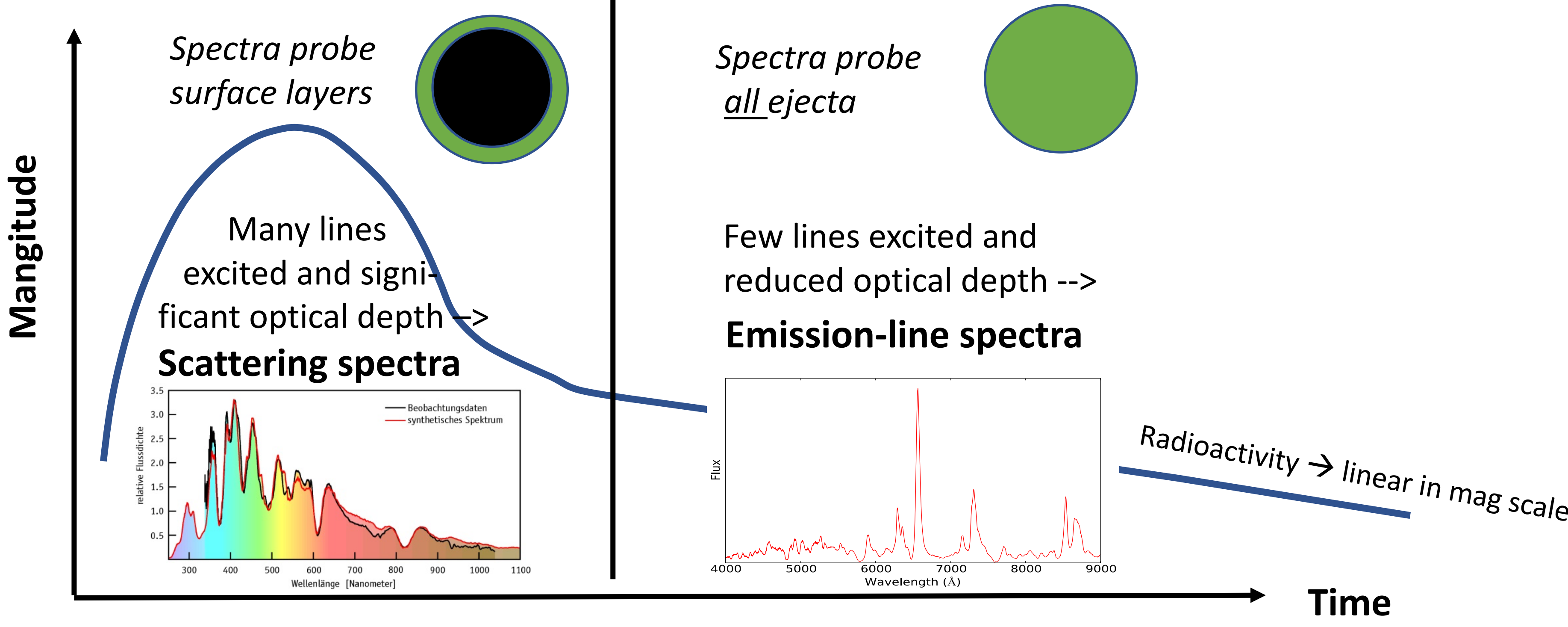
Two main supernova phases

Photospheric phase

Long escape time for radiation
→ a diffusion light curve

Nebular phase

Short escape time for radiation
→ a steady-state tail

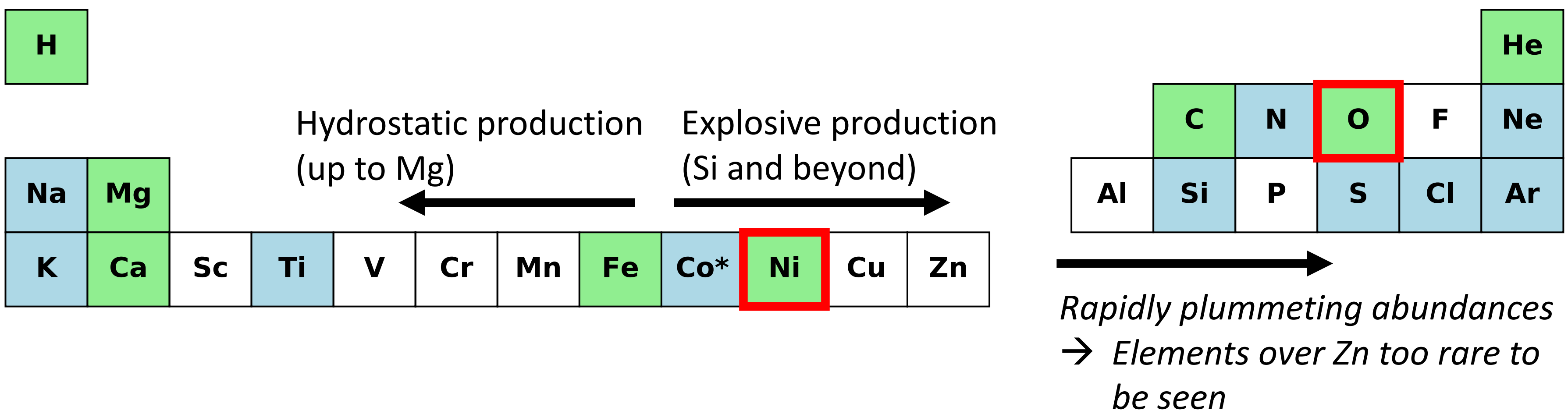


Simple microphysics (~LTE)

Complex microphysics (NLTE)

Transition epochs: H-rich SNe: ~**150d**, H-poor SNe: ~**30d**, Kilonovae: ~**2d**

Elements currently diagnosed from supernova emission-line spectra



Good diagnostic situation

Moderate diagnostic situation

Poor diagnostic potential

See Jerkstrand 2017,chapter in Handbook of supernovae, for a review of key results

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

Jerkstrand+2011, 2012

Radioactive decay and gamma-ray thermalization

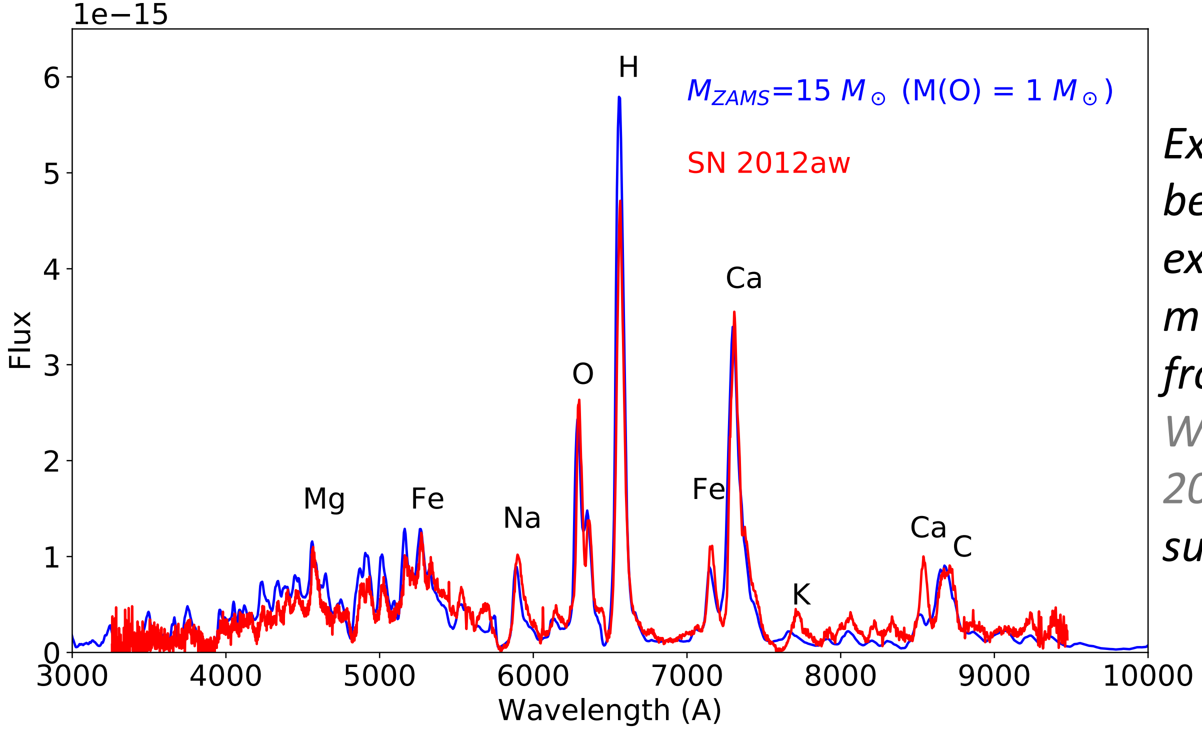
Degradation of Compton electrons
- Spencer-Fano Equation
- Ionization, excitation, heating

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

Temperature
- Heating = cooling

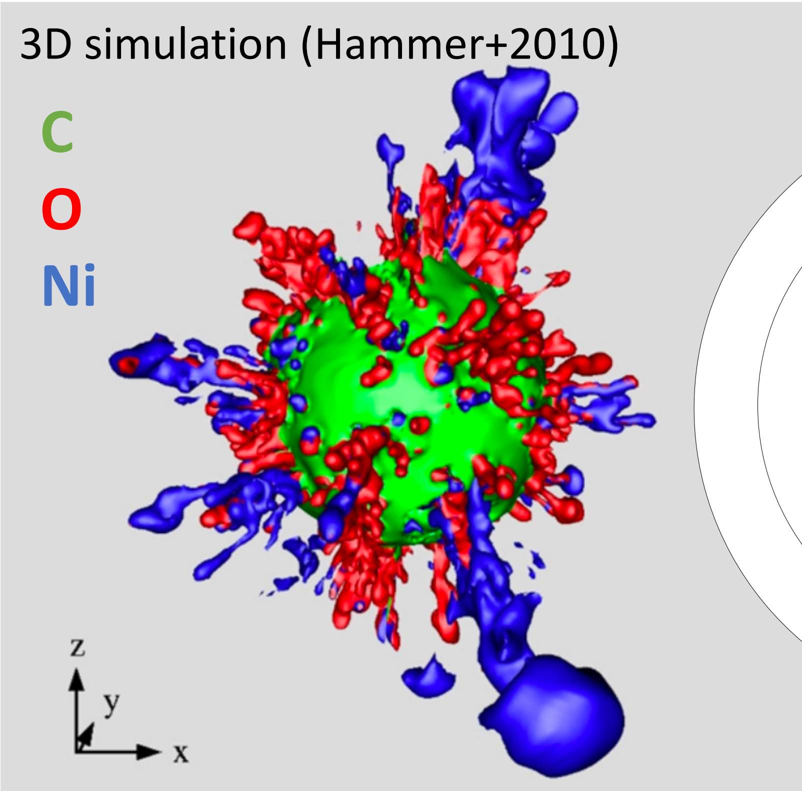
Radiative transfer
- Monte Carlo-based, Sobolev approximation, 300,000 lines

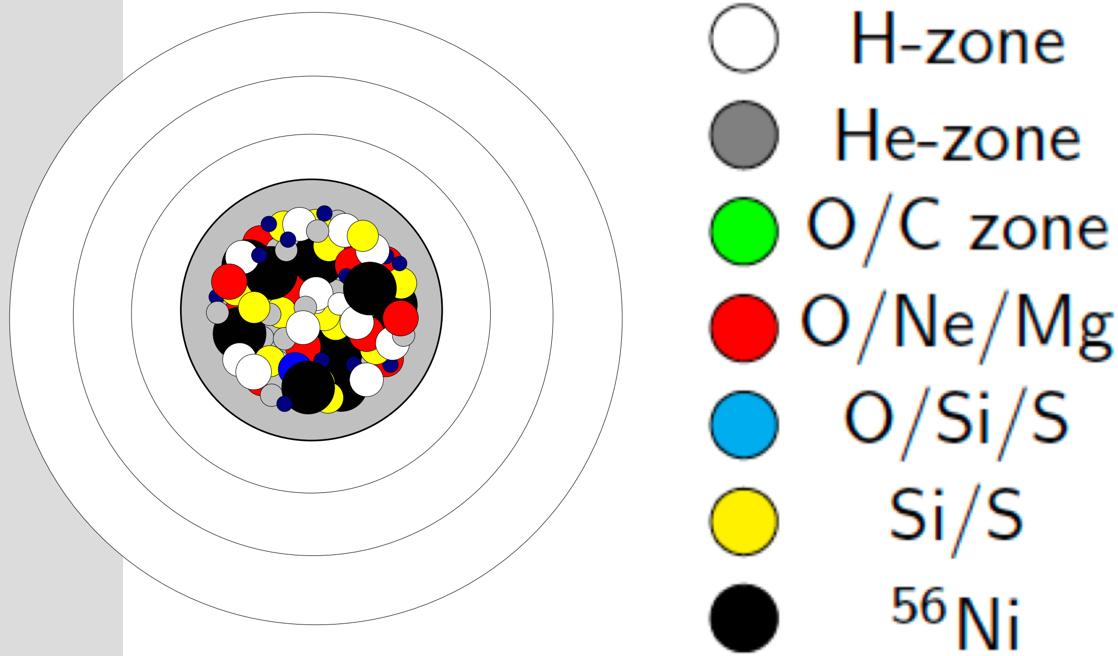
- Code is 1D but allows approximate treatment of mixing by *virtual grid method*.



Example of best-fitting explosion models (this one from KEPLER, Woosley & Heger 2007) to a Type IIP supernova.

A crucial challenge: considering 3D effects



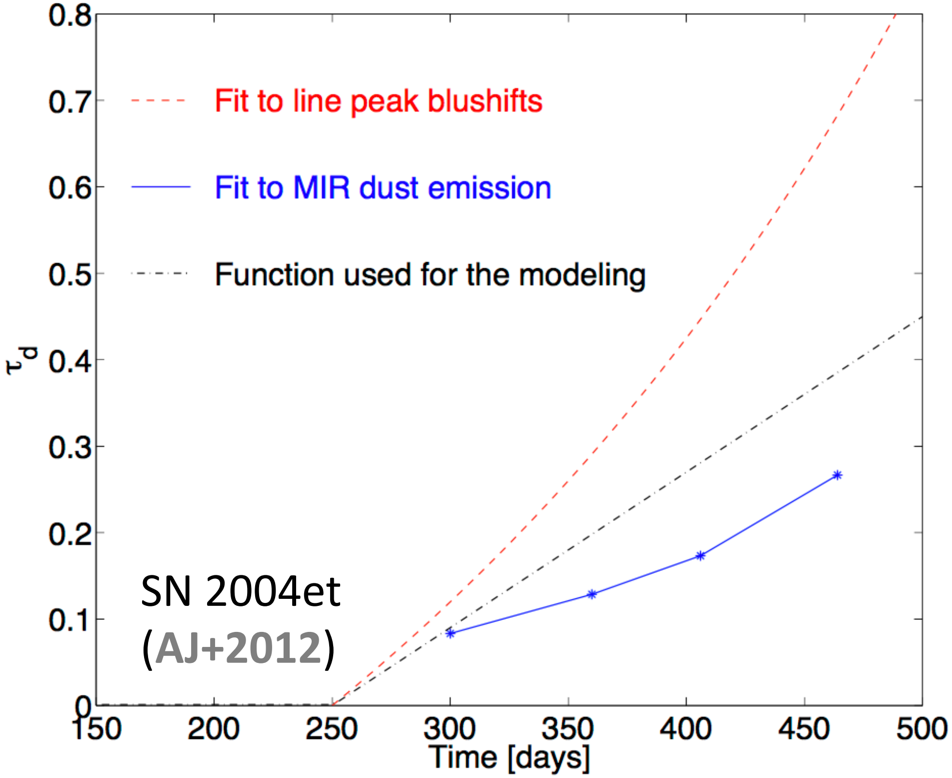


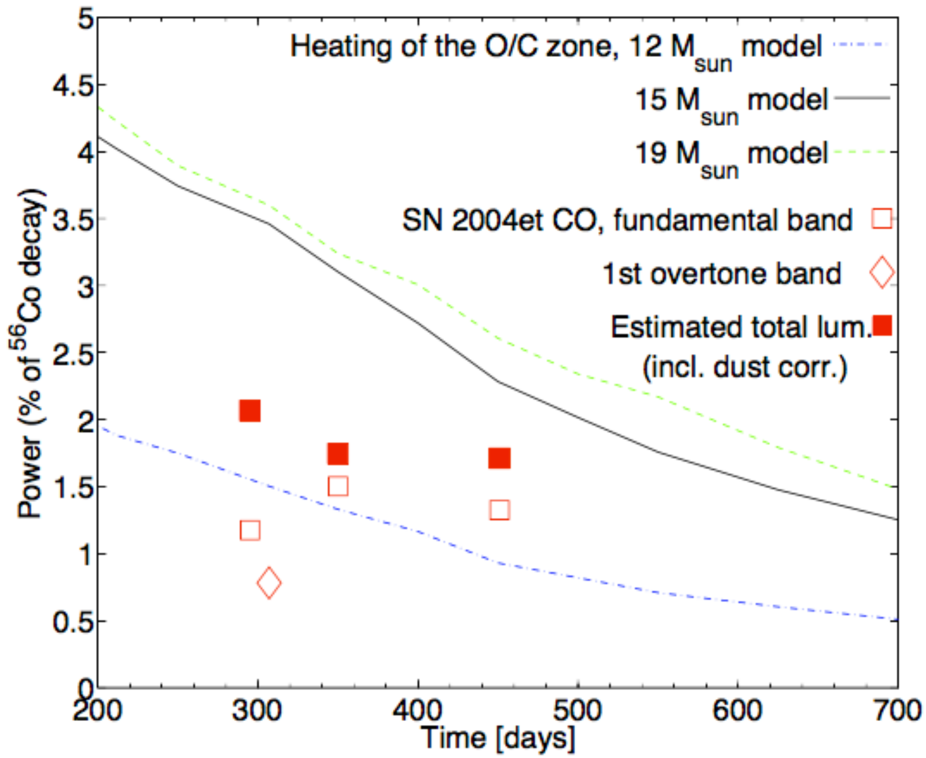
Set-up in SUMO

- In Monte-Carlo codes, one option it to treat clumps in a *statistical manner* (Jerkstrand et al. 2011)
- Use 3D simulations as guide to set up the probability functions using radial averages of distributions.

Treatment of molecules and dust

Jerkstrand+2012





<u>Dust:</u>

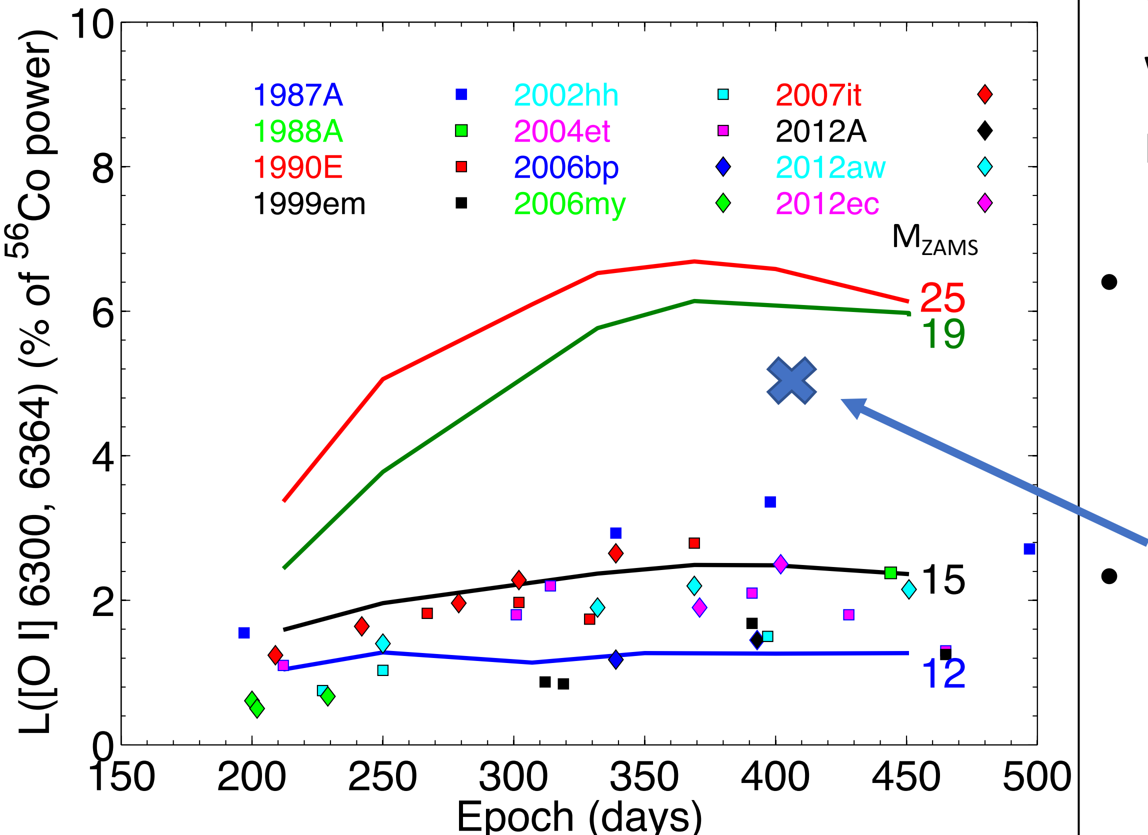
- Apply a gray, time-dependent absorption coefficient.
- Value can be inferred from line shifts and IR observations.

<u>Molecules:</u>

- Assume O/Si and O/C zones to be mainly cooled by SiO and CO (a result from chemistry codes).
- Can be tested in few cases (e.g. SN 1987A, SN 2004et).

Oxygen : Standard Type II supernovae from explosions of M_{ZAMS} =10-17 $M_\odot$ stars. M(O) = 0.1 – 1 $M_\odot$.

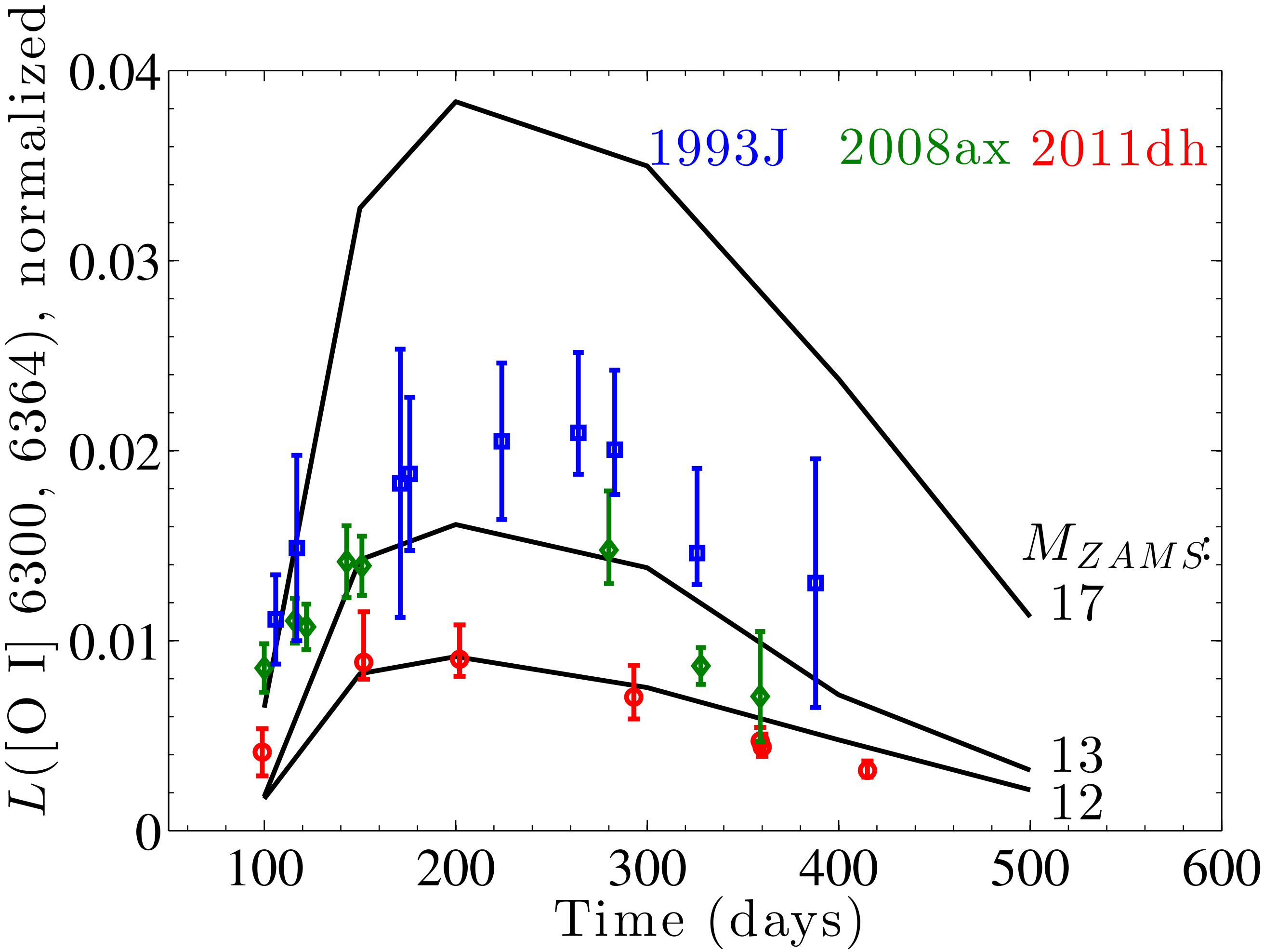
AJ+2015 (MNRAS)



- Can be modelled quite well with approximate mixing methods in 1D.
- **"Red Supergiant problem"** (Smartt 2009) appears confirmed.
- However, first object with possibly M > 20 ~$M_\odot$ now discovered (Anderson+2018). Low metallicity (0.05 $Z_\odot$).

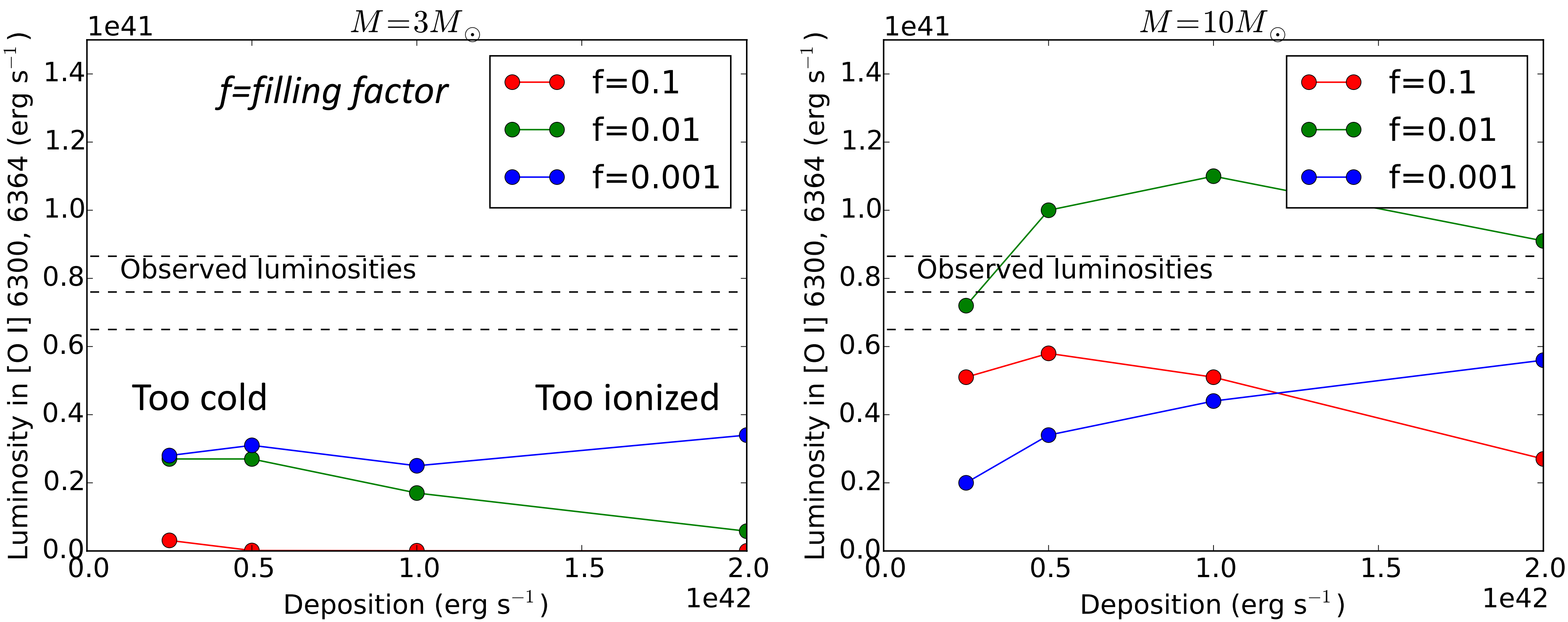
Oxygen: Same picture for hydrogen-poor (Type Ib/IIb) SNe: these appear to be mainly *mass donors to a companion* from low-mass progenitor range (10-20 $M_\odot$).

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



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

AJ+2017 (ApJ)

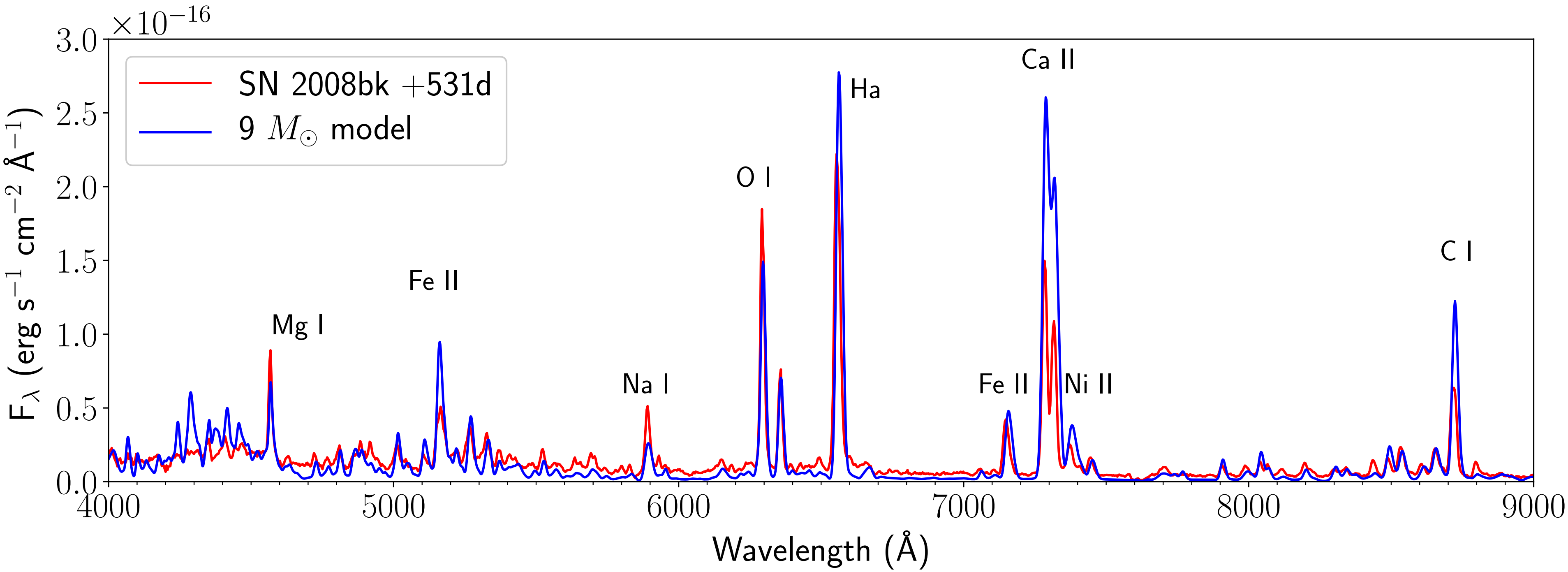


- Independent support from large inferred Mg masses (1 - 10 $M_\odot$) from standard recombination lines theory.

- **Implication**: *Some* high-mass stars do explode somehow (but most probably collapse directly to black holes)

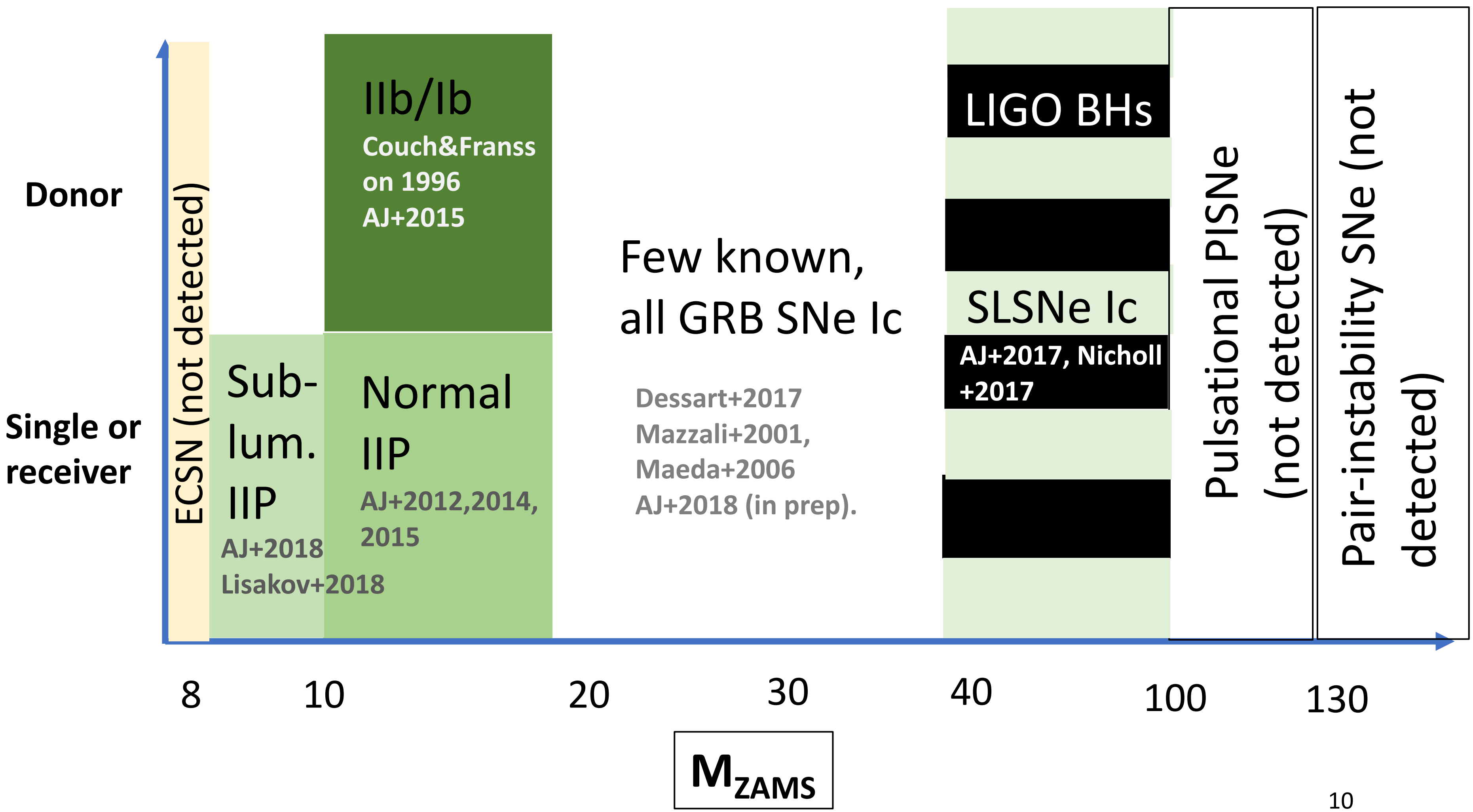
Low-velocity Type II SNe: match models for 8-10 $M_\odot$ progenitors

AJ+2018

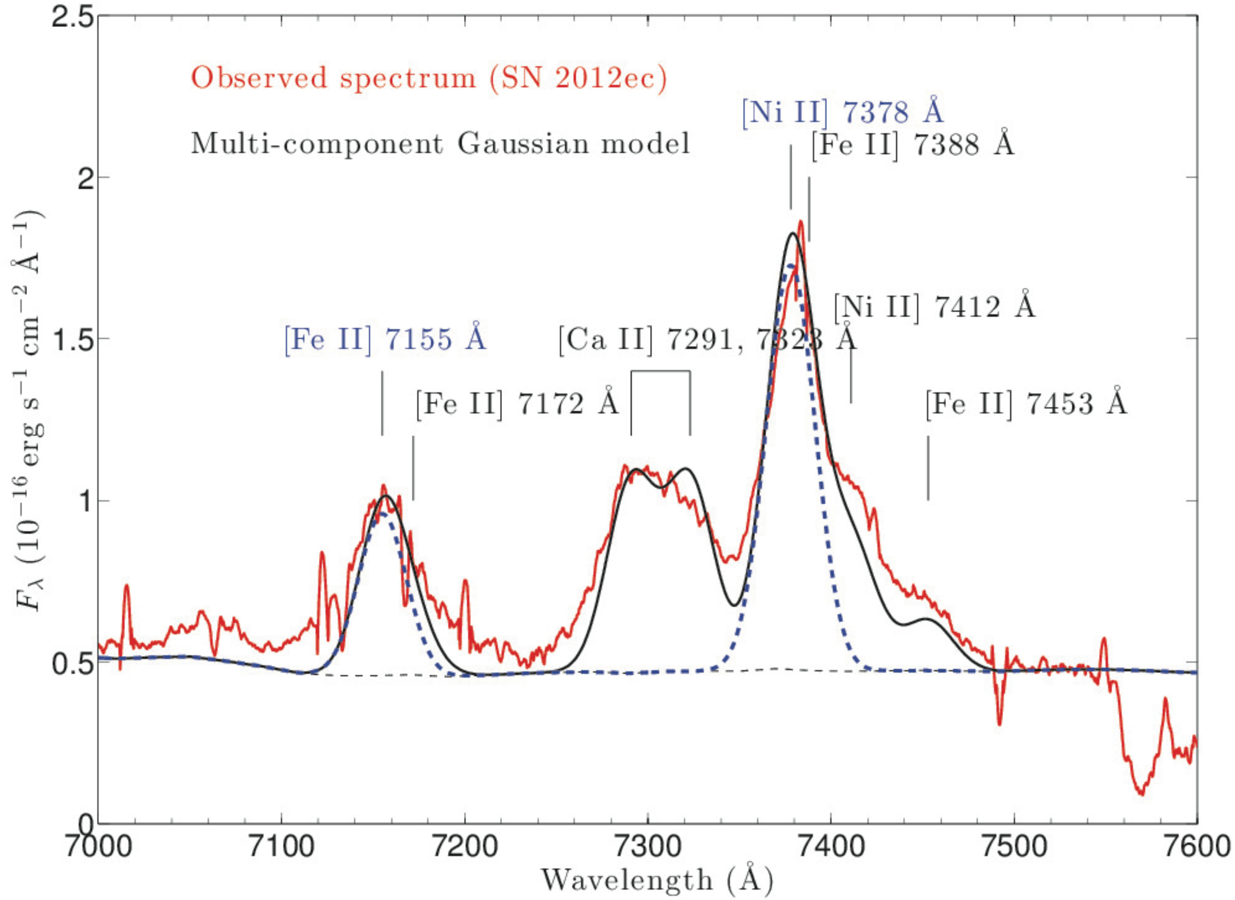


- Mg, O, Na, C lines all strong → ***Fe core progenitors, not ONeMg cores*** *(more later)*

The progenitor landscape (local Universe, $Z \sim Z_{\odot}$) from inferred hydrostatic nucleosynthesis yields



Nickel: a unique tracer of the innermost layers and the explosion



- Forward modelling shows Fe and Ni lines formed in LTE and optically thin → can use analytic method.

Nickel: a unique tracer of the innermost layers and the explosion

AJ+2015 (MNRAS)

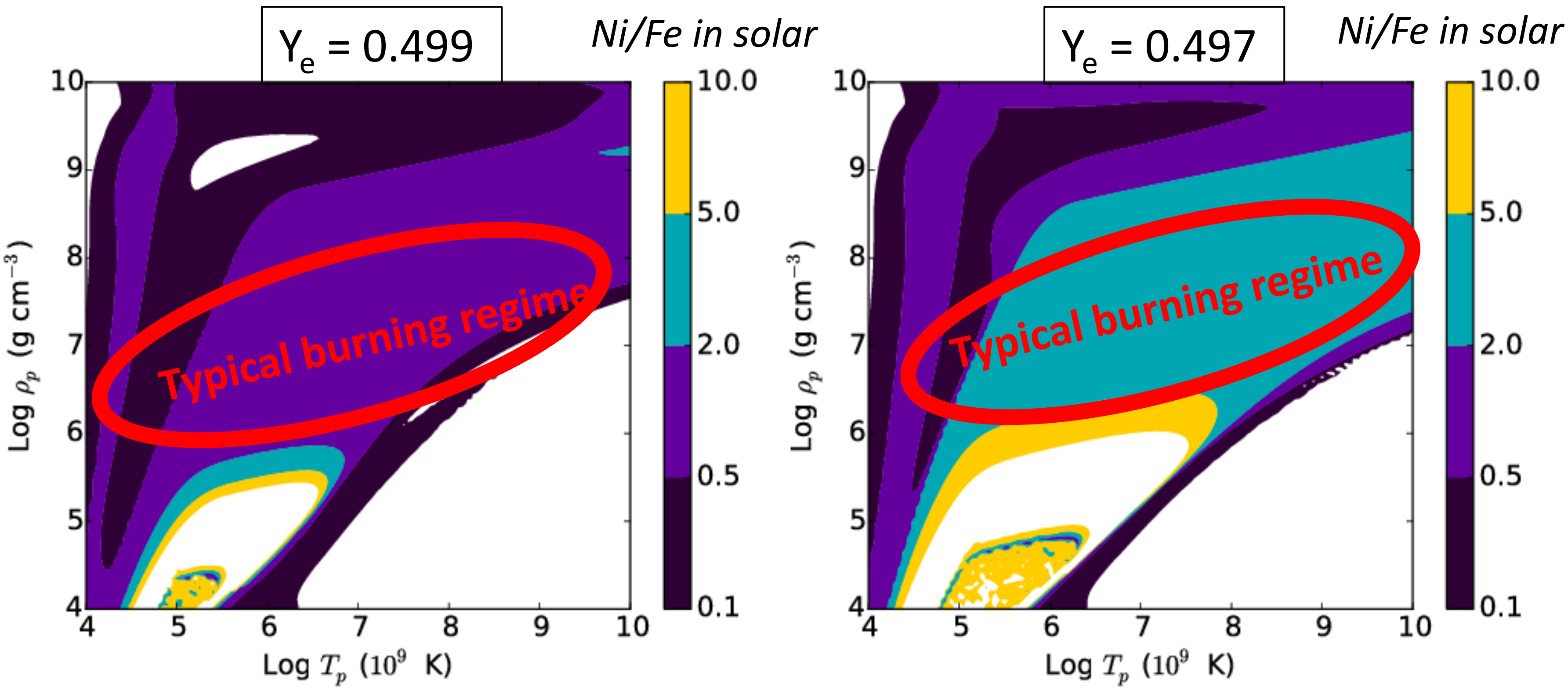
SN	Ni/Fe (times solar)	Reference
Crab	$60 - 75$	Macalpine 1989, Macalpine 2007
SN 1987A	$0.5 - 1.5$	Rank1988, Wooden1993, AJ+2015
SN 2004et	~ 1	AJ+2012
SN 2006aj	$2 - 5$	Maeda+2007, Mazzali+2007
SN 2012A	~ 0.5	AJ+2015
SN 2012aw	~ 1.5	AJ+2015
SN 2012ec	$2.2 - 4.6$	AJ+2015

- Average ratio ≥ solar. If true in larger sample, Type Ia SNe must make Ni/Fe ≤ solar → *constraints on both core-collapse and thermonuclear explosions models*.
- But sometimes significantly larger than solar: what does it mean?

Nickel: a unique tracer of the innermost layers and the explosion

AJ,Magkotsios,Timmes+2015 (ApJ)

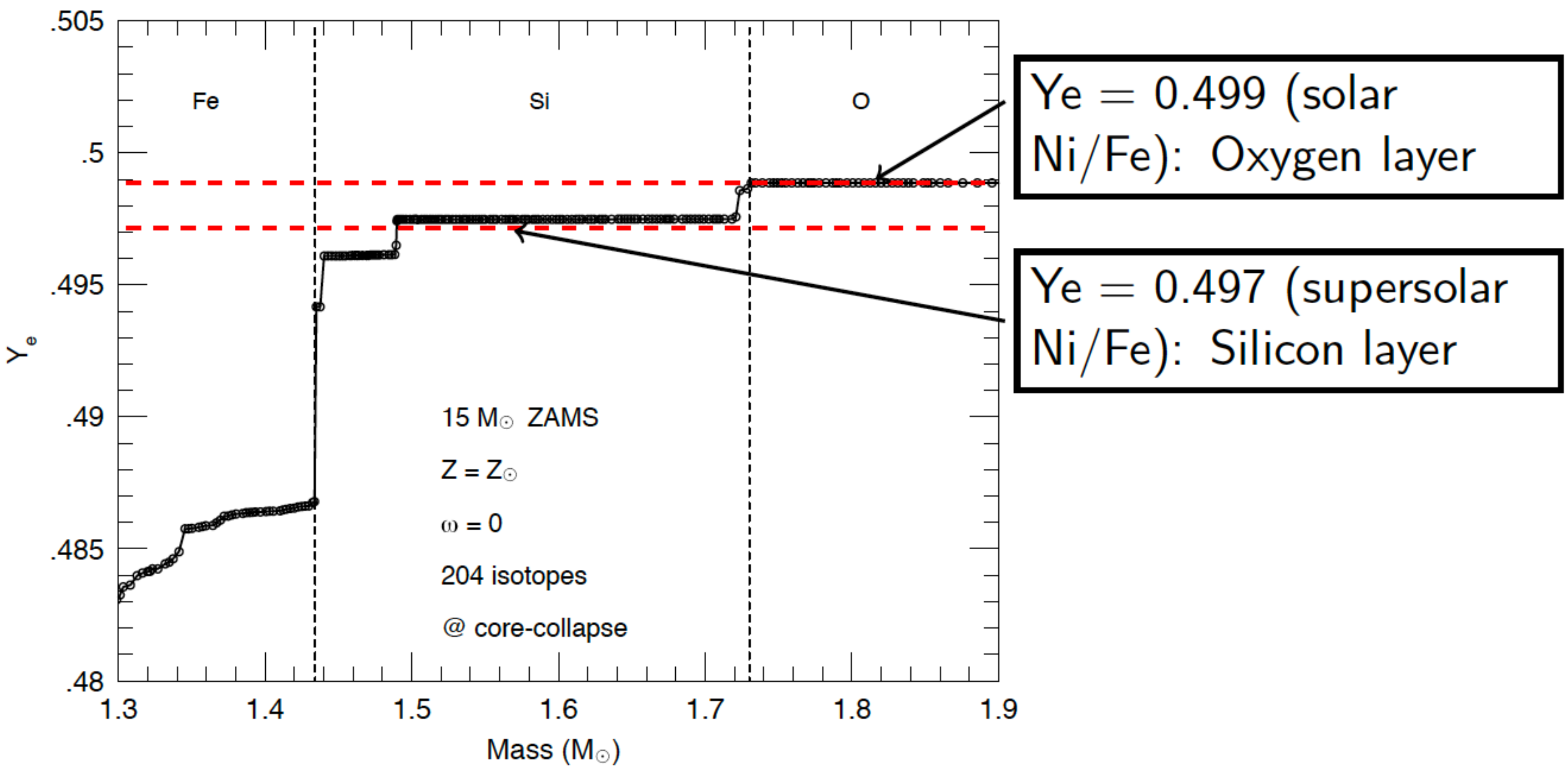
TORCH simulations, vary electron fraction Y_e, tempesature, density



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

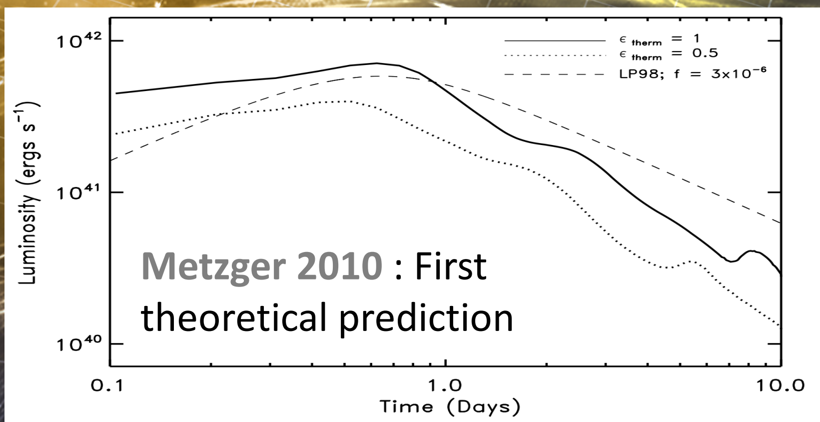
Nickel: The Ni/Fe ratio tells us which progenitor layer was explosively burned

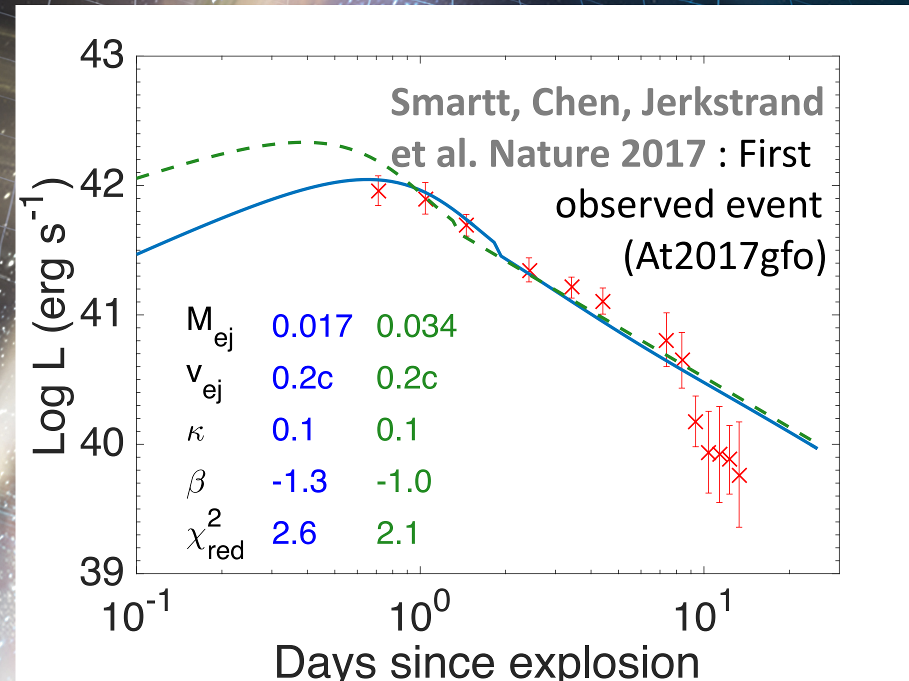
AJ,Magkotsios,Timmes+2015 (ApJ)



- Can help on constraining mass cuts used in galactic chemical evolution models and understand late shell burning physics. For example, KEPLER grid gives [Ni/Fe]=+0.1-0.3 dex depending on piston location (Woosley & Heger 2007).

Kilonovae





Production sites for the r-process elements?
Makers of short gamma-ray bursts?

NSF/LIGO

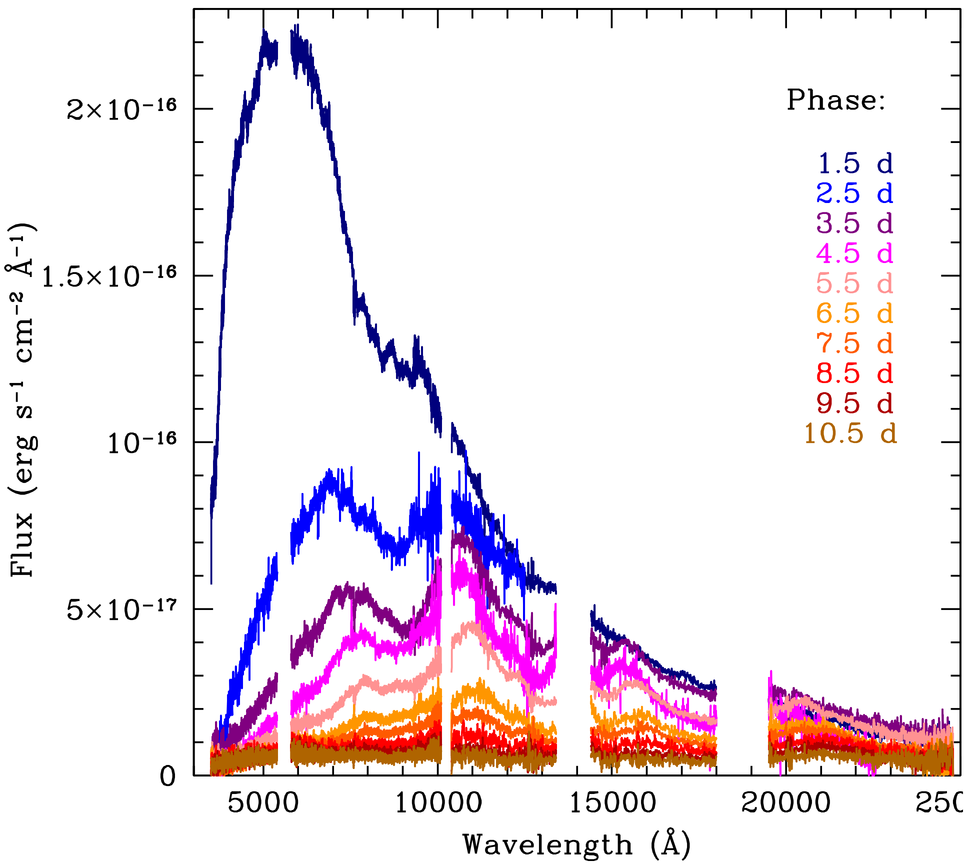
From supernovae to kilonovae

	SNe	KNe
Homology	~1 day	~10 sec
Mass	1-10 M_{sun}	~0.01 M_{sun}
Velocity	0.01c	(0.1-0.3)c
Powering	^{56}Ni	r-process
Composition	Z=1-30	Z=40-90
t_peak	10 days	1 day
rho_peak	10^{-10} g/cm^3	**10^{-14} g/cm^3**

Much lower densities than SNe —> NLTE more important

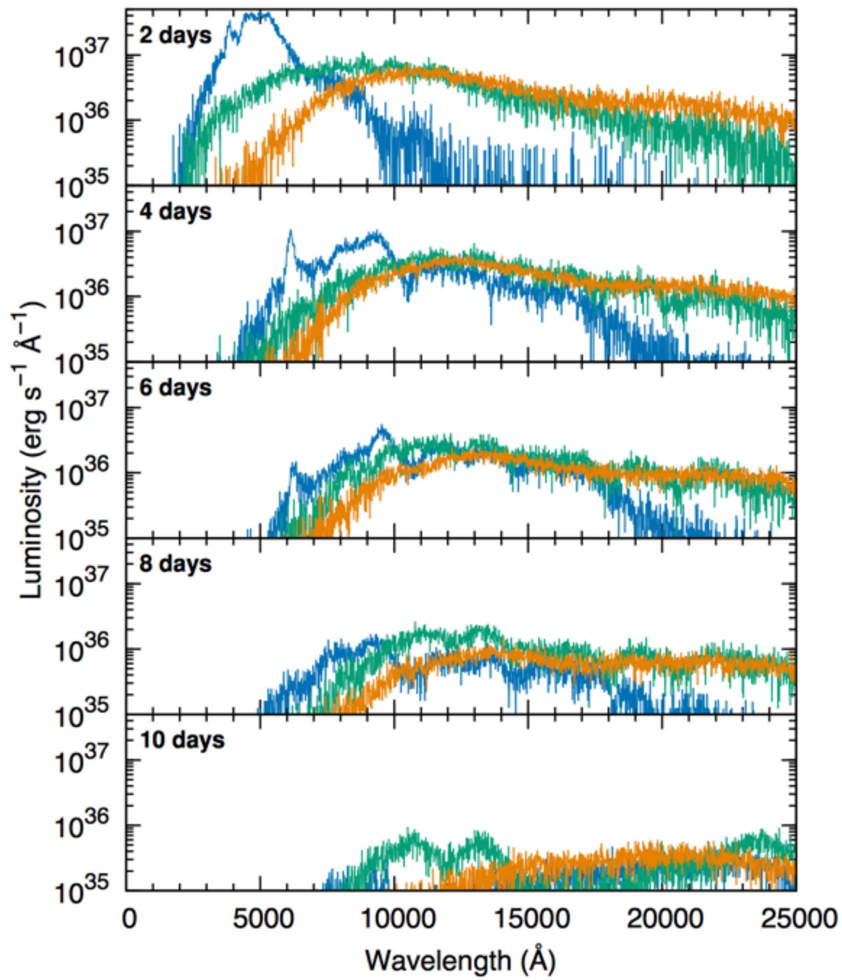
Kilonovae: the challenge to understand the spectra

AT 2017gfo: observed spectra



Courtesy E. Pian

Models, three different ejecta.



Tanaka+2017

Summary

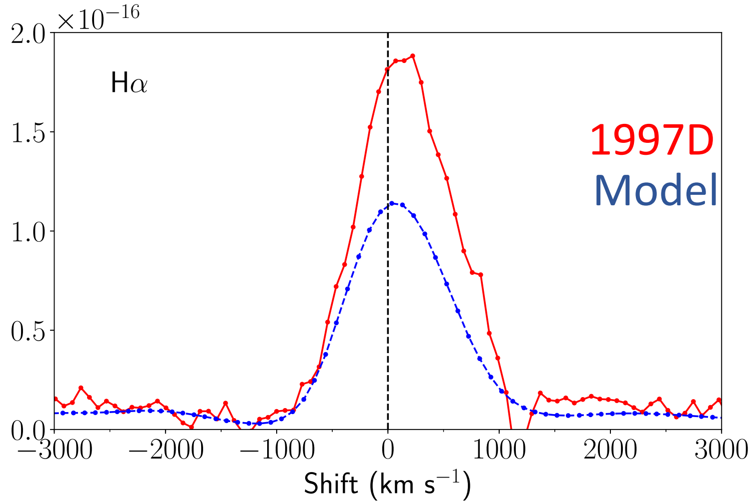
- Stellar element production and supernova explosion physics can be directly diagnosed by **nebular-phase spectroscopy** of supernovae to determine their yields and morpjology.
- **H, He, C, N, O, Ne, Na, Mg, Si, S, Cl, Ar, K, Ca, Fe, Co, Ni** have so far been diagnosed to various extents.
- The **SUMO code** provides state-of-the-art synthetic spectra of explosion models.
- **Oxygen** (An important diagnostic of hydrostatic burning yields):
  - Type II SNe produce 0.1-1 $M_\odot$ O and appear to arise from 8-17 $M_\odot$ 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 explosive silicon burning fuel: *oxygen* (gives solar Ni/Fe) or *silicon* (gives supersolar Ni/Fe).
- **Kilonovae**: The community is currently transitioning tools to model ejecta from *neutron star mergers*. Can we identify these as the main sources of r-process elements in the Universe?

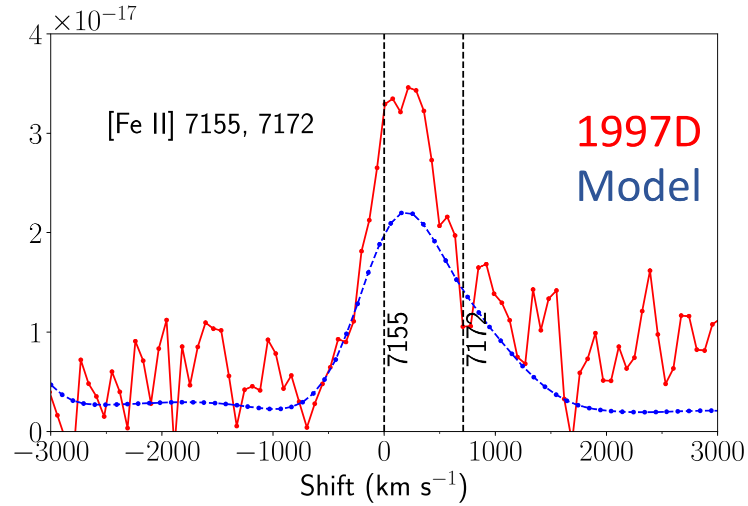
THANK YOU FOR LISTENING

Reserve slides

Testing explosion models through line profiles

AJ+2018



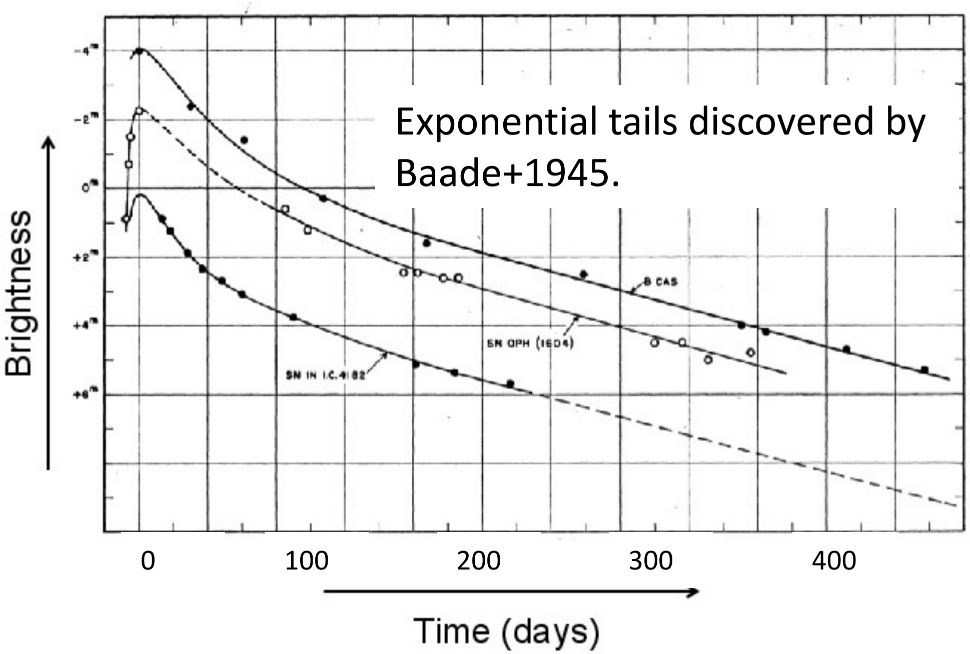


Line	FWHM (km s^{-1})	FWHM$_{dec.}$ (km s^{-1})	Model (km s^{-1})
Hα	1020	820	1100
He 7065	950	740	900
O I 6300,6360	940	720	900
Ca II 7291	820	560	900
Fe II 7155	730	420	800

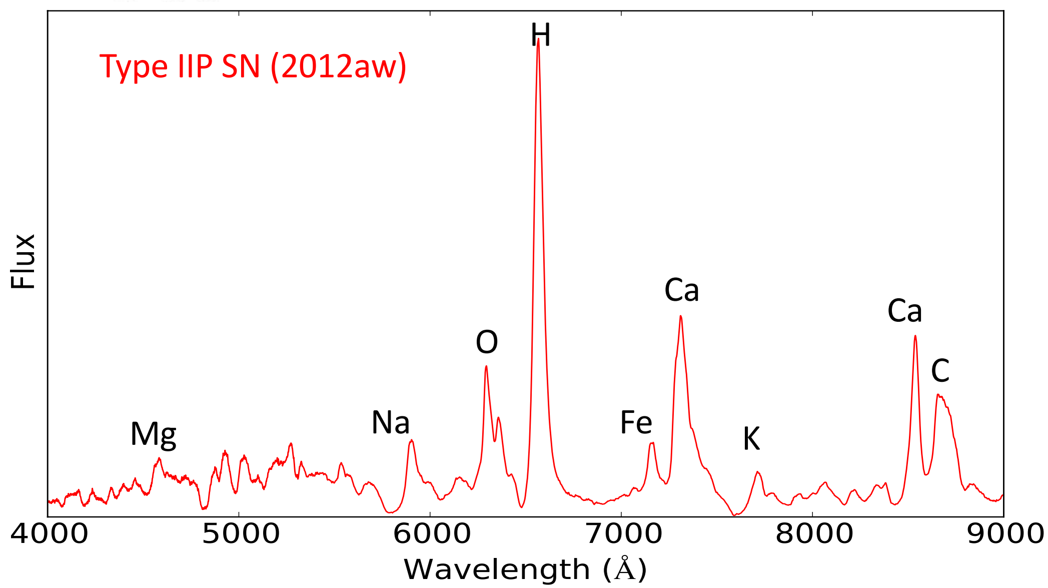
Table 3. Observed line profile widths in SN 1997D, at +350d, compared to the model (unconvolved) values.

3D tests now in preparation.

The nebular phase : our window on stellar nucleosynthesis



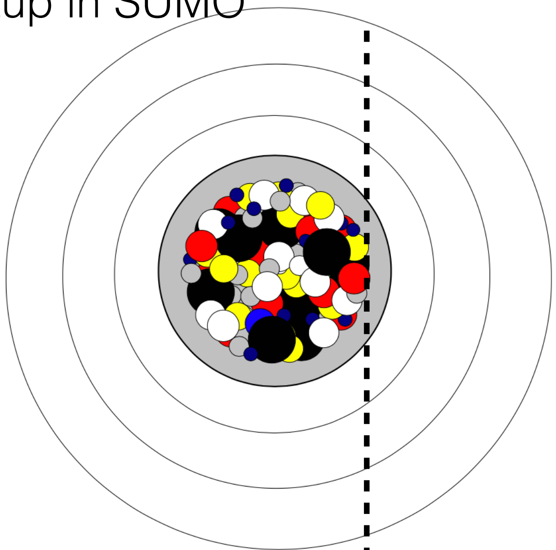
- 100d – 1000d post explosion
- Emission lines from all nuclear burning regions
- Data collection rate: ~5-10 per year (<1% of all discovered SNe).
- Current amount of objects: ~50-100



1. Mixing : Virtual grid method

Jerkstrand+2011

Setup in SUMO



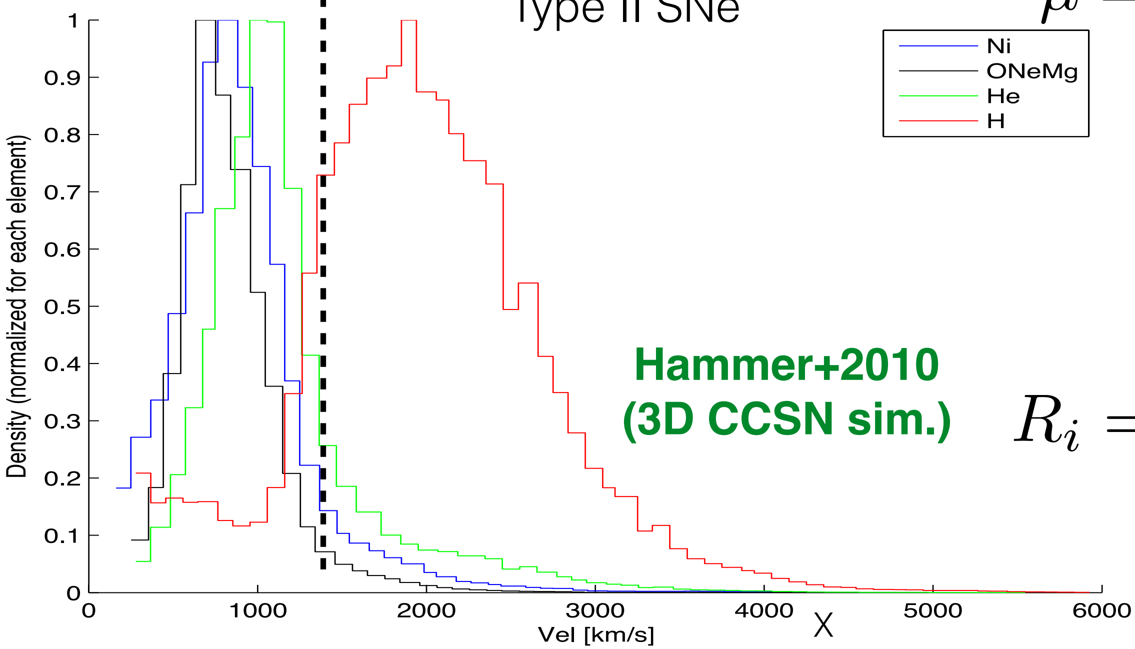
Impact probability

Clump radius

$$p_i = \frac{R_i^2}{\sum_i R_i^2}$$

Good method for strong-mixed Type II SNe

$$\mu = z$$ Impact angle



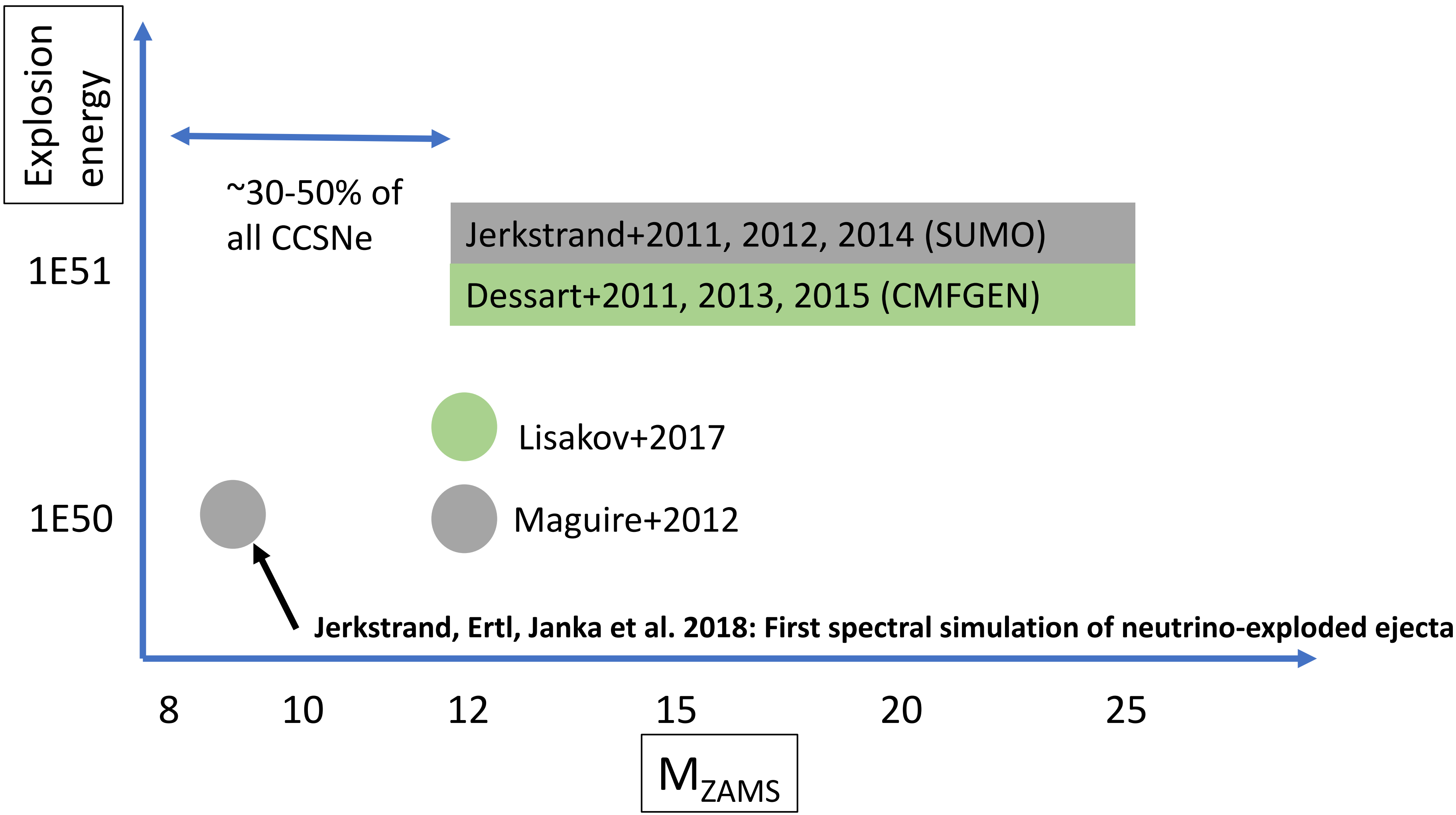
Hammer+2010 (3D CCSN sim.)

Filling factor, clump type *i*

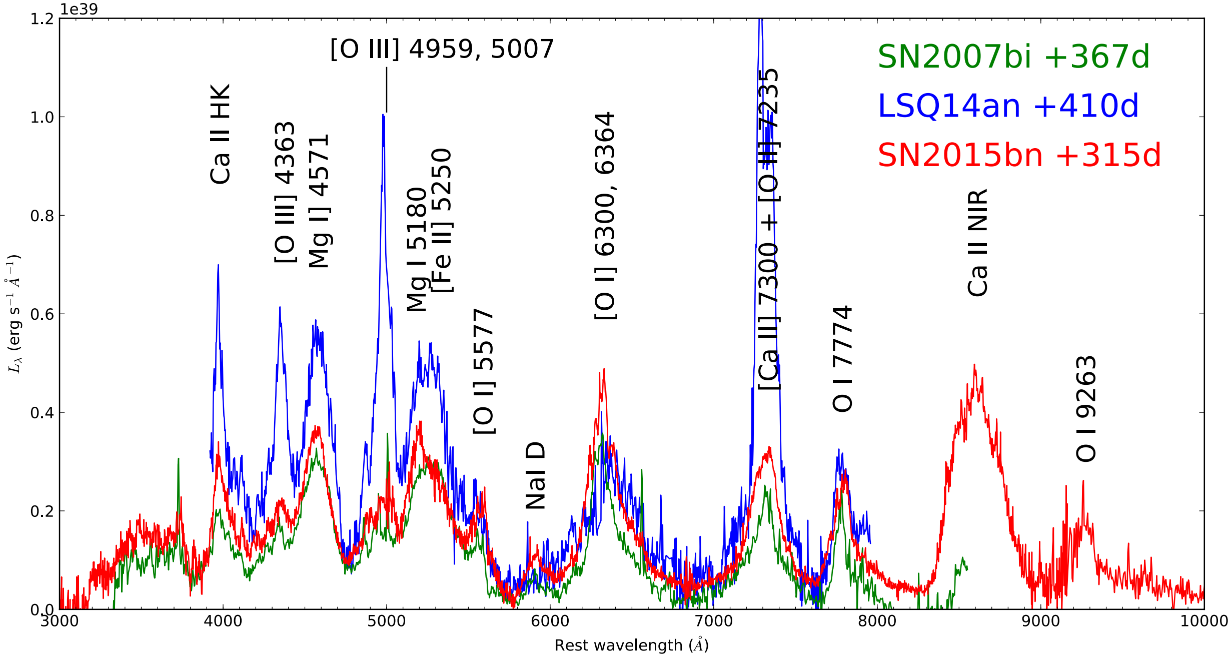
$$R_i = \left(\frac{3Vf_i}{4\pi N}\right)^{1/3}$$

Number of clumps of each type

Available late-time spectral models for Type II SNe



Nebular data sample of SLSN Ic now 3

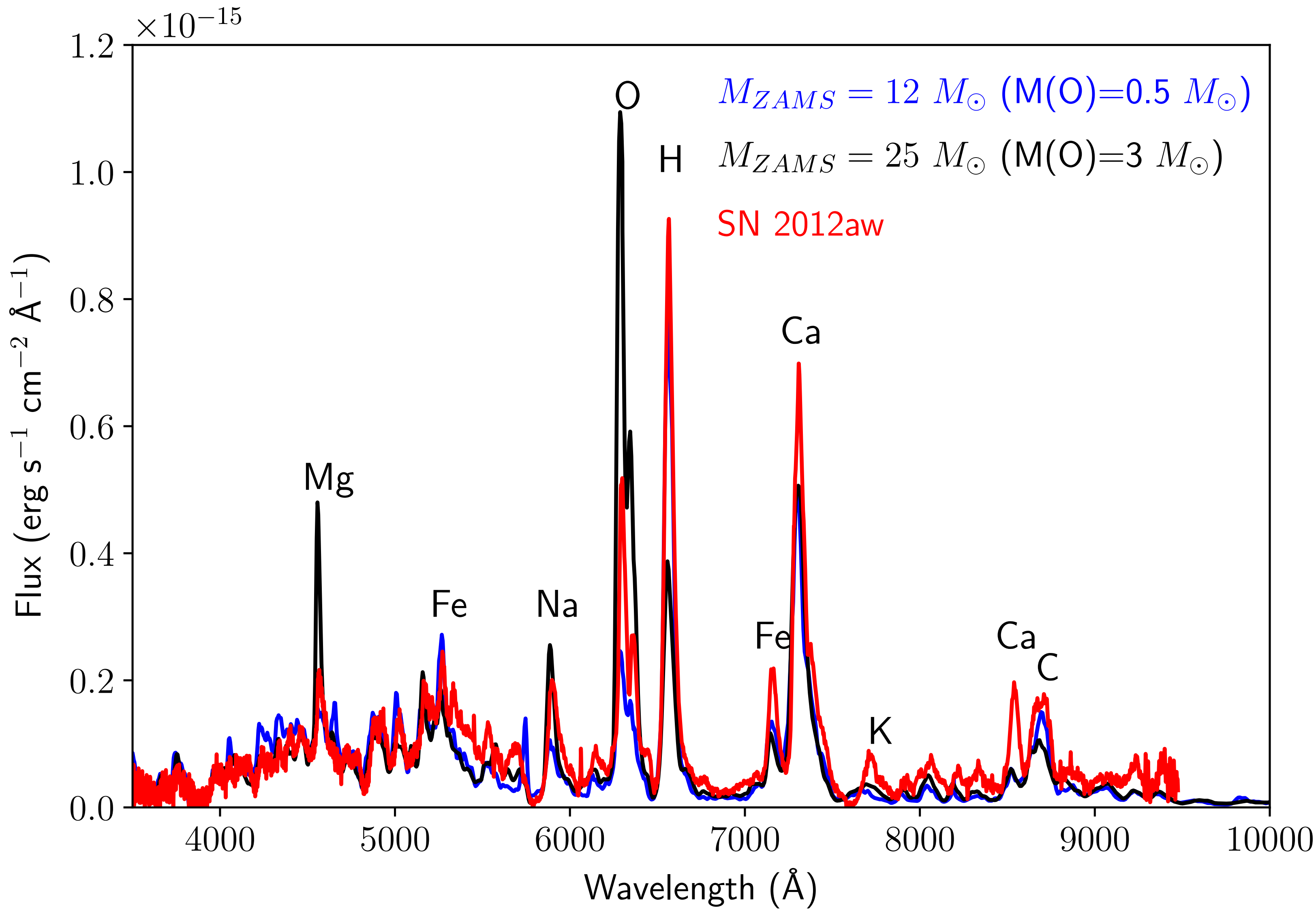


Jerkstrand+2017
z=0.11-0.16

- SN 2015bn virtual clone of SN 2007bi (see also Nicholl+2016).
- LSQ14an: additional [O II] and [O III] lines (see also Lunnan+2016 for PS1-14bj case)

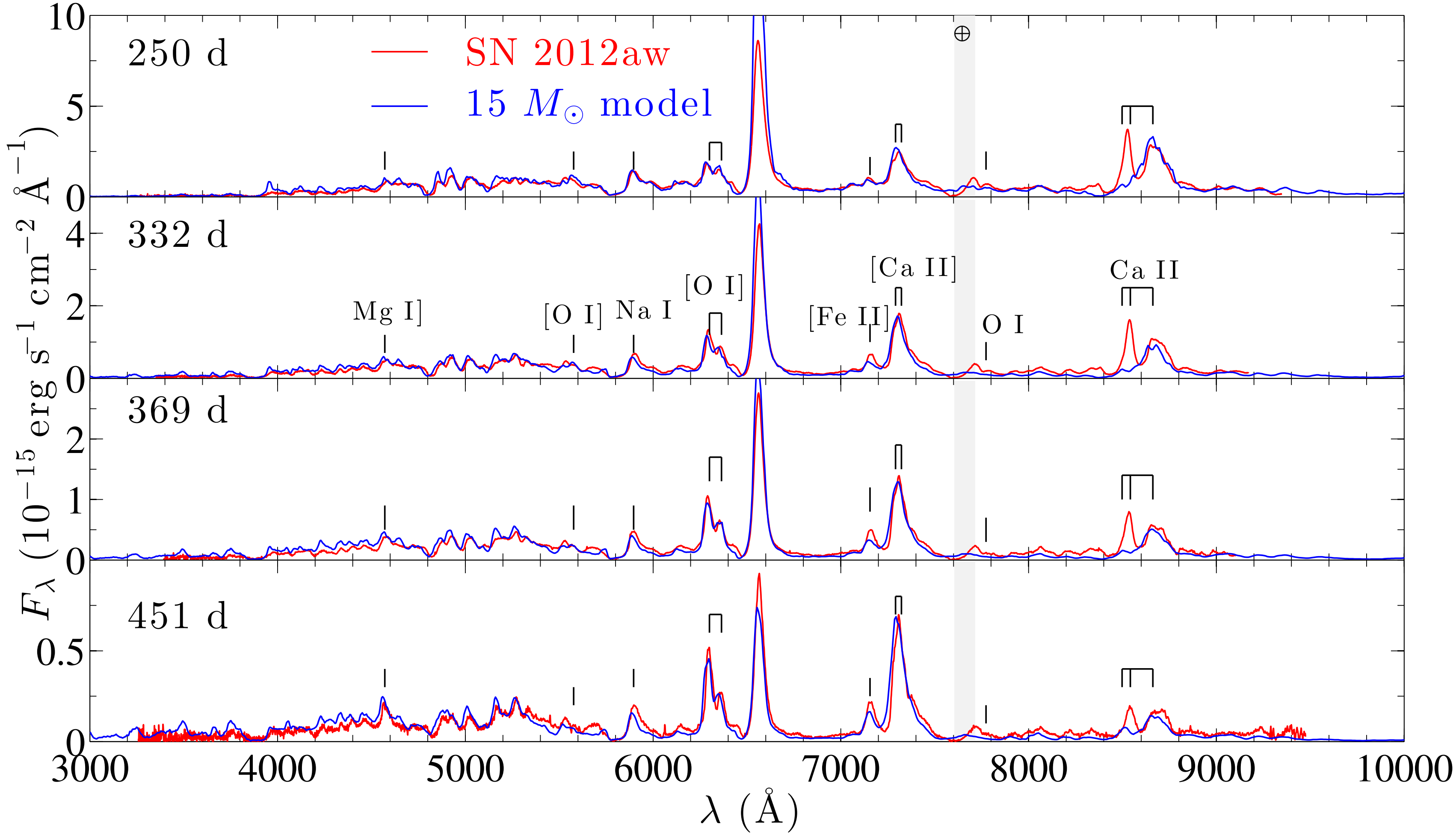
200-250d:
iPTF13ehe (Yan+2015) z = 0.34
PS1-14bj (Lunnan+2016) z= 0.52
iPTF15esb (Yan+2017) z = 0.22
iPTF16bad (Yan+2017) z= 0.25
Gaia16adp (Kangas+2017) z=0.10

Can start to make detailed model comparisons, e.g. find best-fitting M_{ZAMS}



AJ+2014.

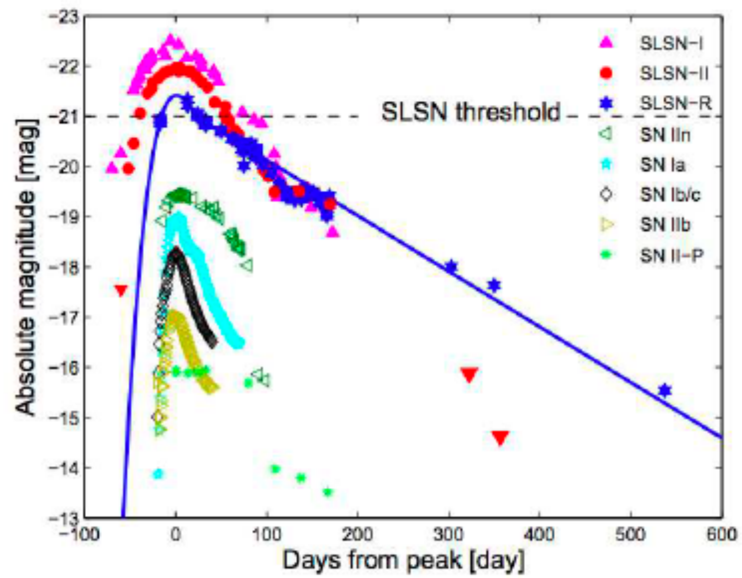
Type II supernovae. Breakthrough a few year ago: *Model spectra start to agree quite well with observed spectra*



AJ+2014. See also Dessart+2013.

SLSNe

- A new class of extremely bright SNe
- Emit 100 times more energy than no
- Type IIn or Type Ic
- Power source is unknown. Candidate



Radioactivity

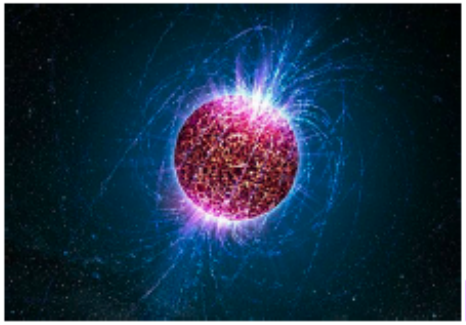
$E \approx$
$10^{51}\left(\frac{M(^{56}\mathrm{Ni})}{5M_{\odot}}\right)$

Gamma-ray thermalization.

Neutron sta

rotation ene

$E \approx$
$10^{51}\left(\frac{P}{5\ \mathrm{ms}}\right)$



Magnetic

spin-down +

thermalization of

Circumstellar interaction + X-ray thermalization.

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

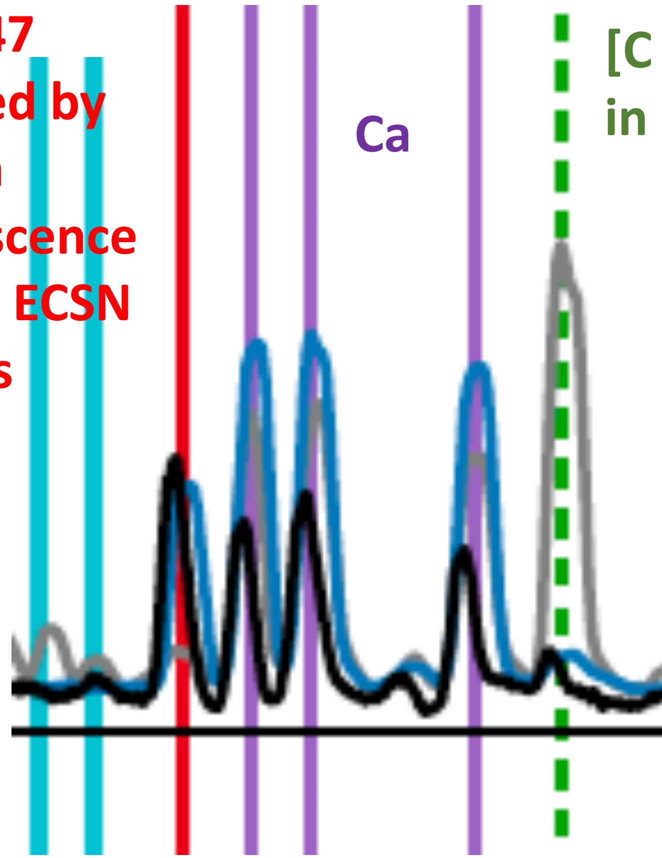
Hosseinzade+(incl. AJ) 2018

O I 8447 pumped by Bowen fluorescence only in ECSN models

Ca

[C I] 8727, only strong in Fe core models

nickel lines?



SN 2016bkv

Fe-CCSN model

“ECSN” model

How can we determine element masses in SN ejecta from their nebular spectra?

Methods:

1. Measure line luminosities + assume uniform conditions and analytic forms valid in certain limits (e.g. LTE, optically thin) *Important complement but not accurate enough on its own*
2. Forward modelling : free composition in single zone *Simple and fast, but many free parameters and to some extent unphysical*
3. Forward modelling : multi-zone explosion models with self-consistent nucleosynthesis *Recent progress (Dessart & Hillier 2011, AJ 2011 (PhD thesis), Maurer 2011 (PhD thesis), AJ+2012, 2014, 2015a, 2015b, 2016)*

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

AJ, Ertl, Janka+2018