Optically thin ejecta

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Physics of optically thin ejecta

- Steady state conditions : Power out = Power in.

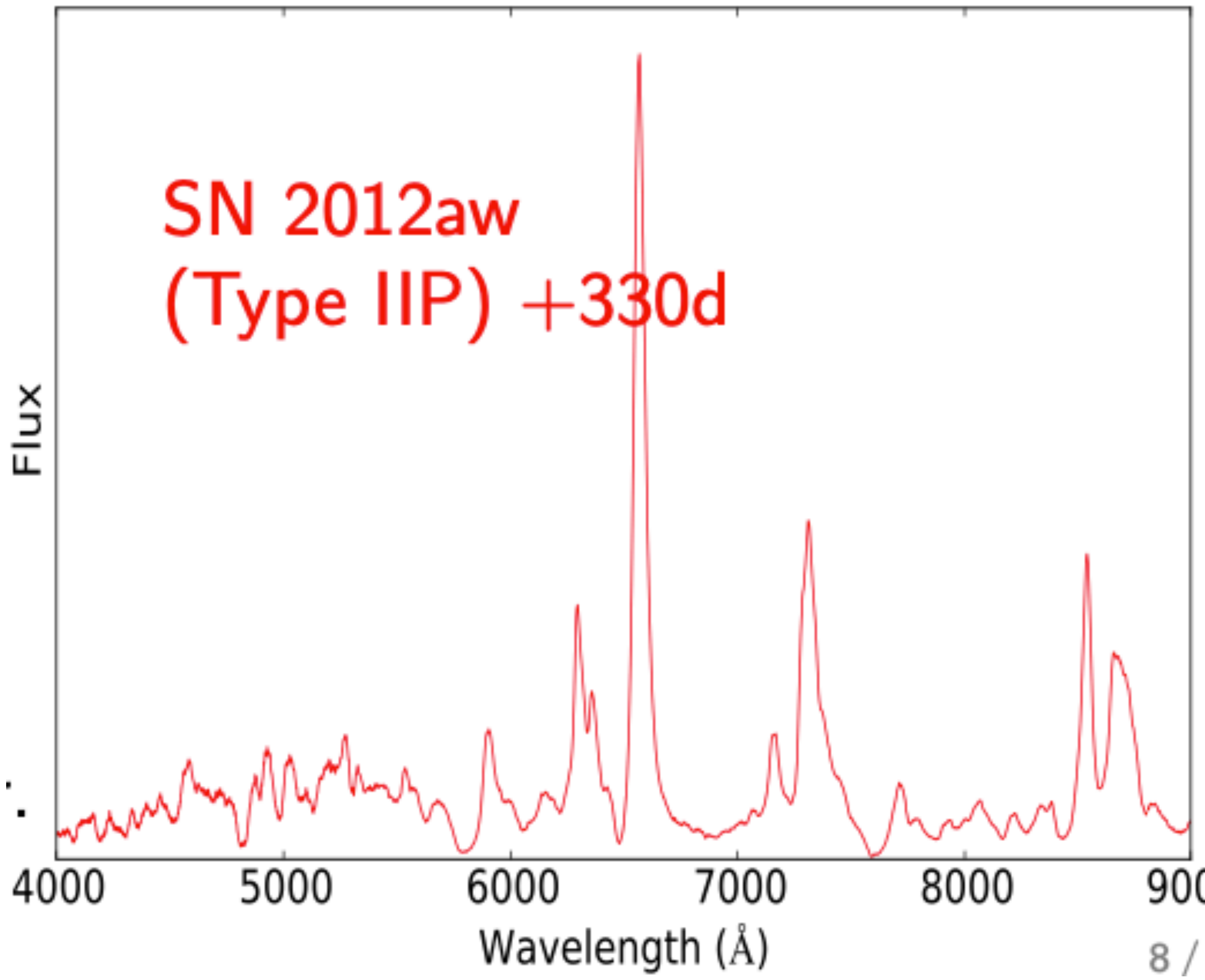
- Radioactivity heats, ionises and excites the gas: reemission mainly by low-lying forbidden lines of common elements.

- Line luminosities can probe
  - Element mass
  - Volume of emission region
  - Density

- Low density —> NLTE conditions —> atomic data (A-values, collision cross sections, photoionisation cross sections, charge transfer rates) important.

  - Supernovae: Atomic data situation medium-good: in several applications not the main limiting factor.

  - Kilonovae: Atomic data main bottleneck to more accurate results.



Pros

- **Probes the core** where the star's nucleosynthesis - hydrostatic and explosive - can be inferred.
- **Line profiles** diagnostic of core's 3D structure and link to explosion physics.
- **Lower velocities** than photospheric phase —> less line blending (and lower *T* gives fewer active lines).
- **Steady state conditions** : no sensitivity to thermodynamic history of ejecta.
- **Limited radiative transfer effects** —> "clean view" and for computational aspect, rapid convergence even in a Lambda iteration.

Cons

- **Complex (NLTE) modelling**, and associated challenge in getting physical conditions right.
- **Highly non-linear emissivities** : small error in *T* can give big error in e.g. inferred mass.
- **Complex mixing** in the explosion (mainly macroscopic) —> most modelling so far limited to 1D with artificial mixing and can only partly account for this.
- **Illumination bias**: We see mainly what is illuminated by gamma rays.
- **SNe rapidly dim** —> limited S/N in observed spectra.

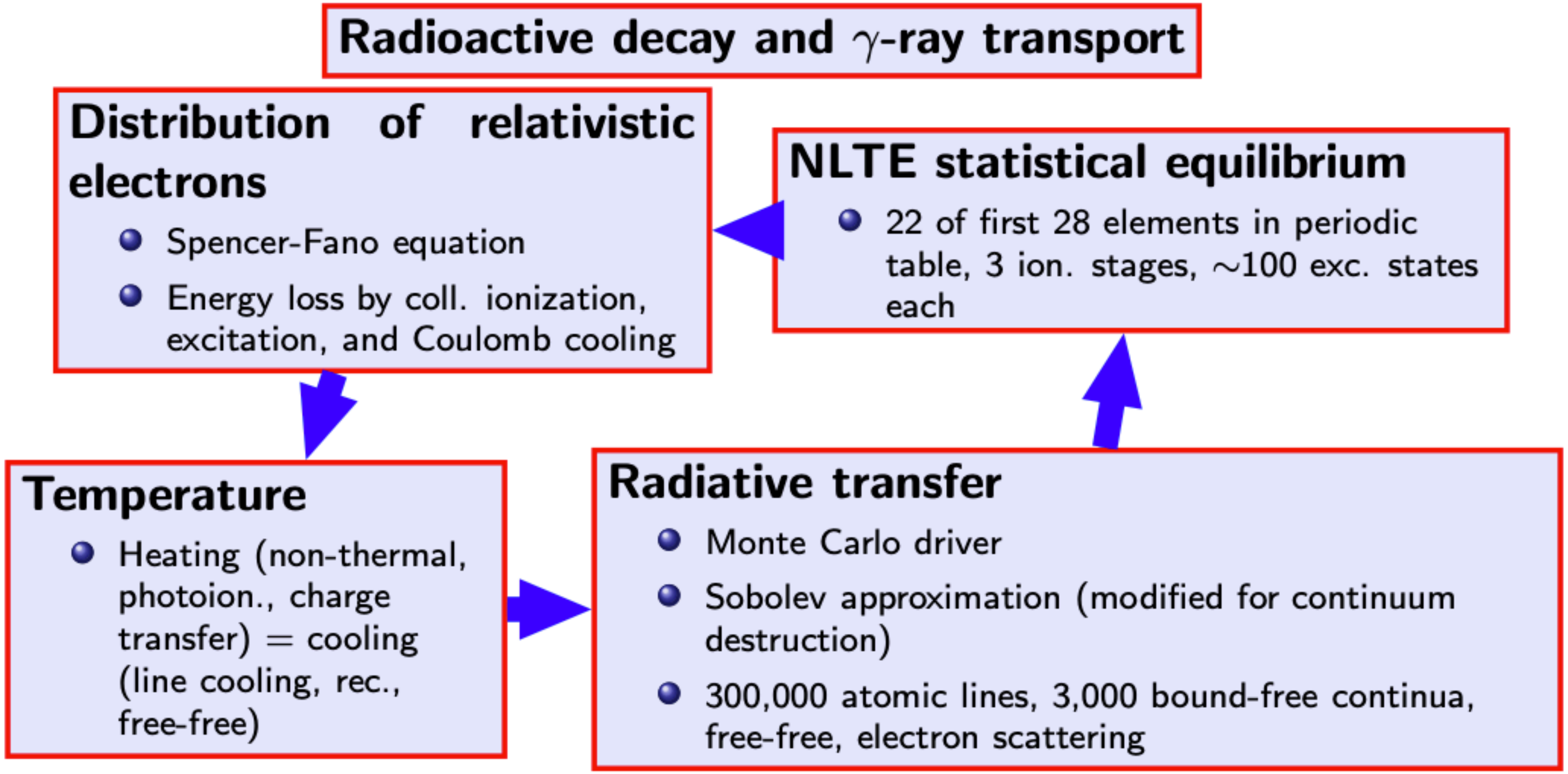
Radiative transfer codes for late phases

- **1-zone models** (Axelrod, Mazzali, Maeda)
- **1D models**
    - Monte Carlo (SUMO, SEDONA, ARTIS)
    - Grid-based (CMFGEN)
- **3D models**
    - Monte Carlo (SEDONA, ARTIS, SUMO-LIGHT)

- Self-consistent explosion models or crafted ejecta (both density profile and composition)?
- Optically thin or with radiative transfer?
- Thermalization calculated or parameterised?
- Size and quality of atomic data library?

SUMO

Jerkstrand+2011,2012



Radioactive decay and γ-ray transport

Distribution of relativistic electrons

- Spencer-Fano equation
- Energy loss by coll. ionization, excitation, and Coulomb cooling

NLTE statistical equilibrium

- 22 of first 28 elements in periodic table, 3 ion. stages, ~100 exc. states each

Temperature

- Heating (non-thermal, photoion., charge transfer) = cooling (line cooling, rec., free-free)

Radiative transfer

- Monte Carlo driver
- Sobolev approximation (modified for continuum destruction)
- 300,000 atomic lines, 3,000 bound-free continua, free-free, electron scattering

CMFGEN

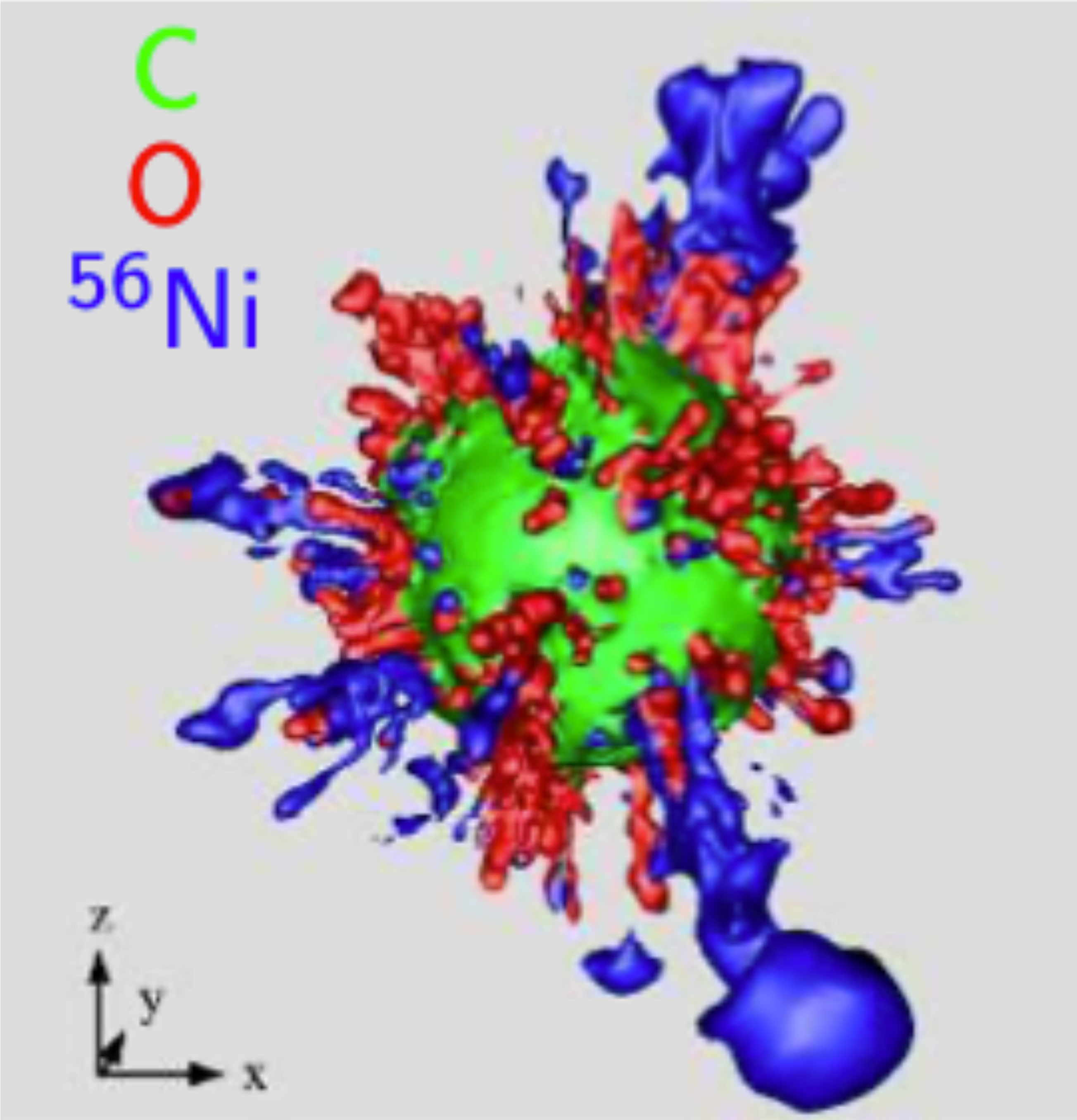
Hillier & Millier (1998); Hillier & Dessart (2012)

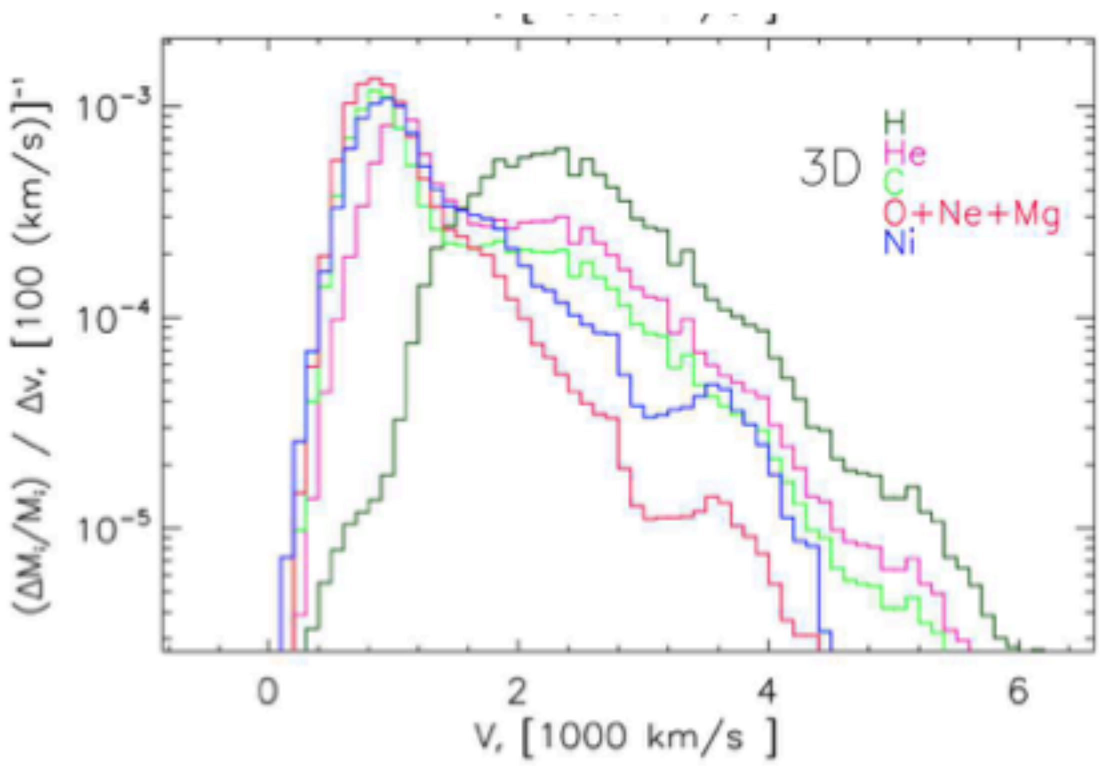
- Solution of moments of radiative-transfer equation + closure. Yields I_ν, J_ν, F_ν versus depth from far-UV to far-IR (10^5 to 10^6 frequencies).
- Time-dependent or steady state mode.
- Solution of statistical equilibrium equations (O(1000) unknowns at each depth).
- Complex model atoms and processes.
- Non-local γ-ray energy deposition + non-thermal processes.
- Initial conditions from progenitor/explosion model in homologous expansion (most elements up to Ni + Ba; multiple ionization stages treated).
- Optical-thin conditions: special treatment of mixing.

SUMO

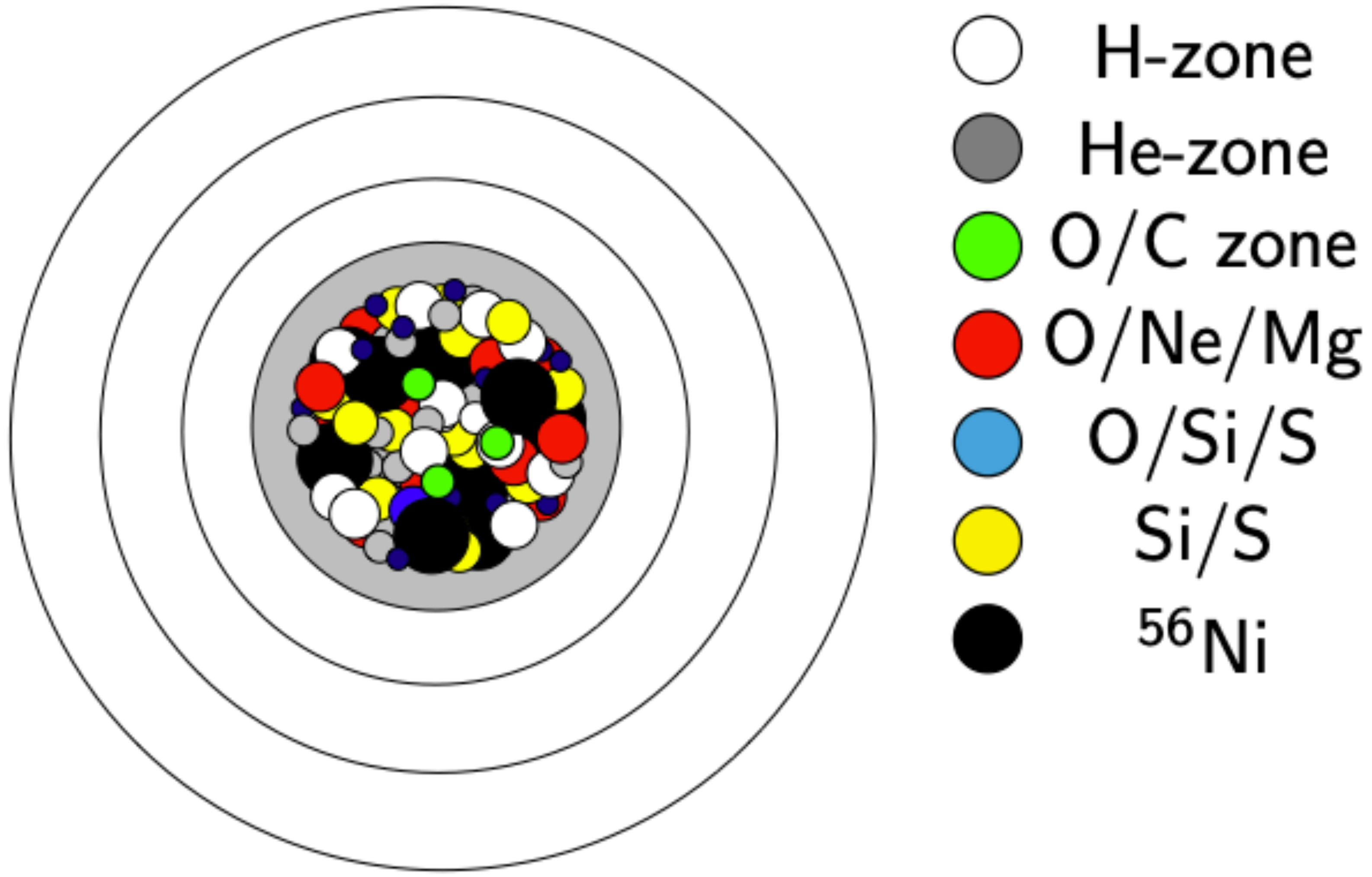
Jerkstrand+2011

Treat mixing statistically to avoid microscopic mixing : unique approach possible with Monte Carlo only.





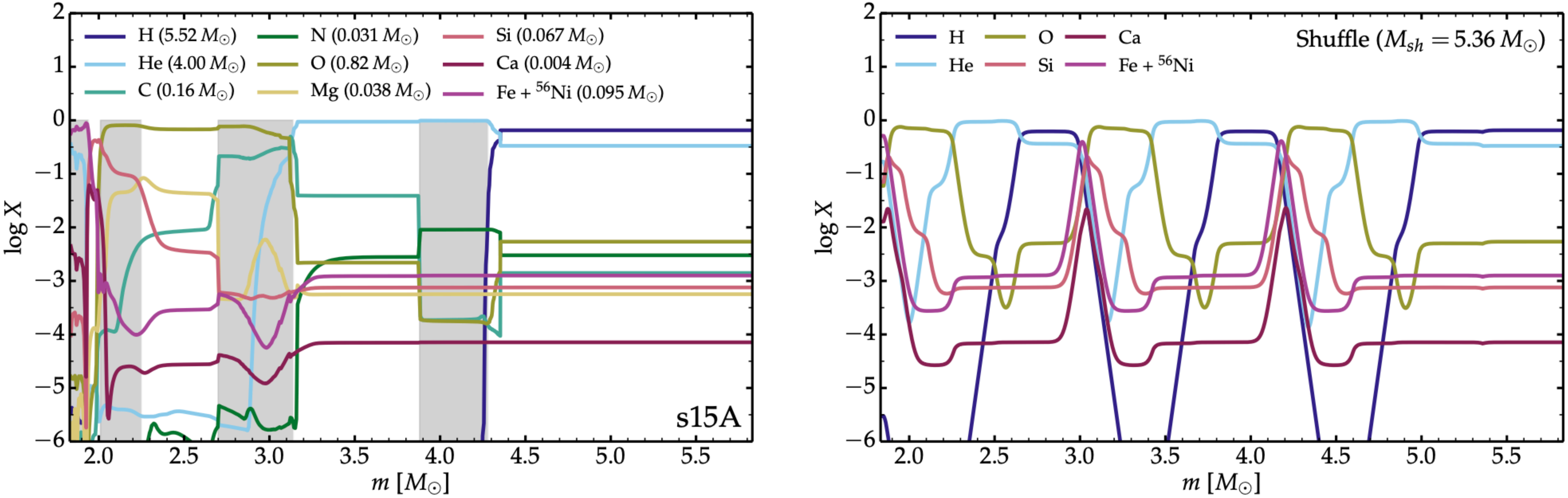
Hammer+2010, 3D model



Ejecta setup in SUMO

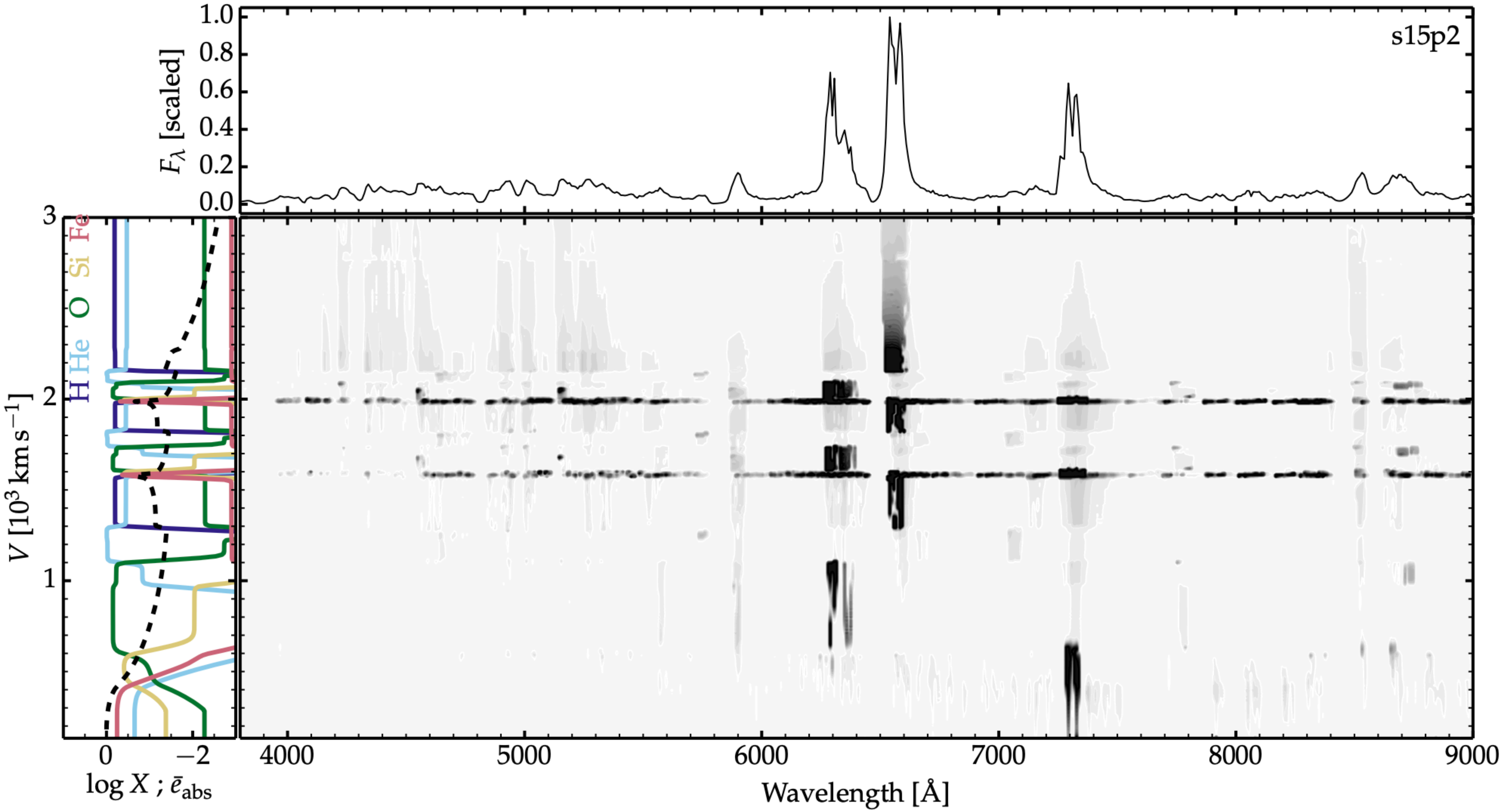
CMFGEN

- Chemical segregation treated with a “shuffled-shell” approach: macroscopic mixing but NO microscopic mixing (see Dessart & Hillier 2020).



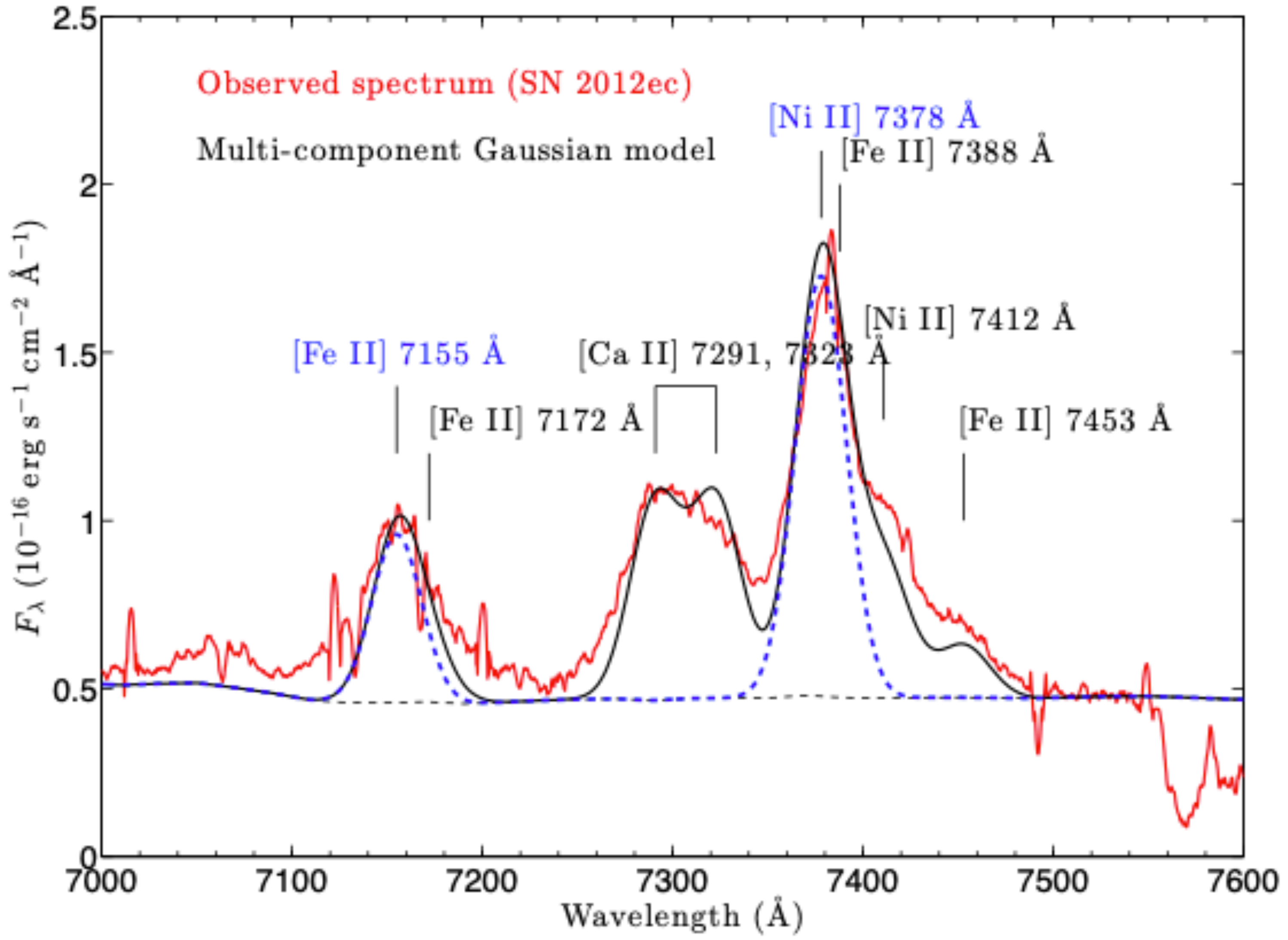
CMFGEN

Spectrum formation regions in a 15.2 $M_\odot$ RSG explosion model at 350d



Results examples

Explosive nucleosynthesis

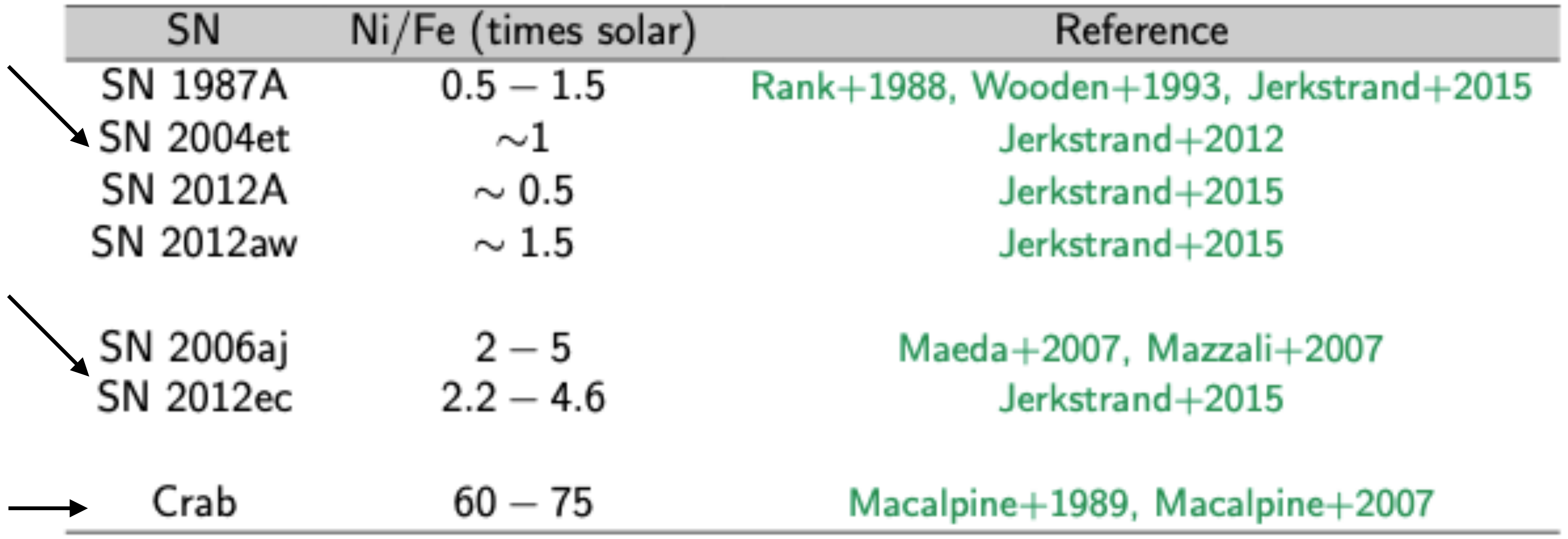


Jerkstrand+2015

Solar

Super-Solar

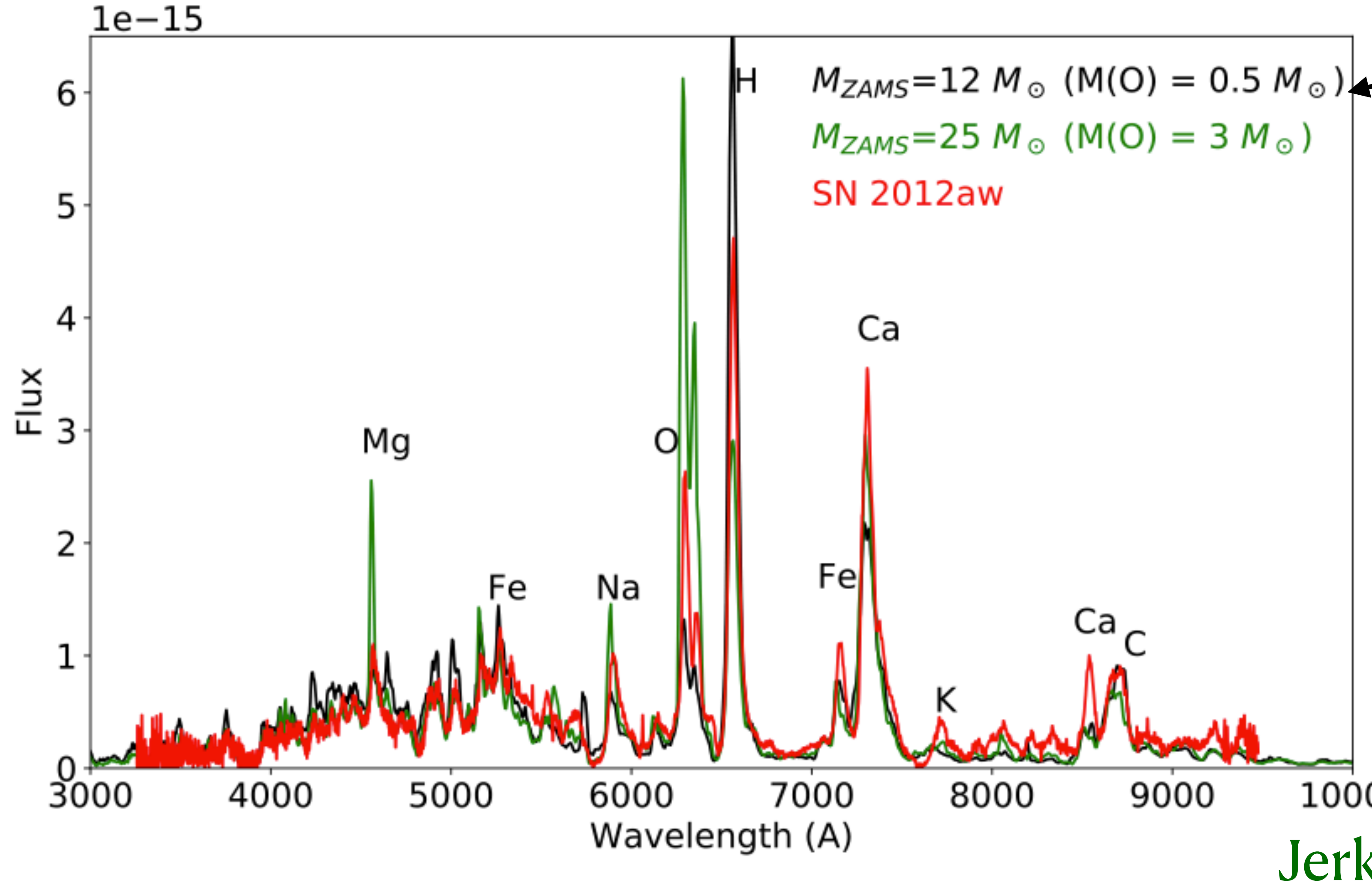
Extreme



SN	Ni/Fe (times solar)	Reference
SN 1987A	0.5 – 1.5	Rank+1988, Wooden+1993, Jerkstrand+2015
SN 2004et	~1	Jerkstrand+2012
SN 2012A	~ 0.5	Jerkstrand+2015
SN 2012aw	~ 1.5	Jerkstrand+2015
SN 2006aj	2 – 5	Maeda+2007, Mazzali+2007
SN 2012ec	2.2 – 4.6	Jerkstrand+2015
Crab	60 – 75	Macalpine+1989, Macalpine+2007

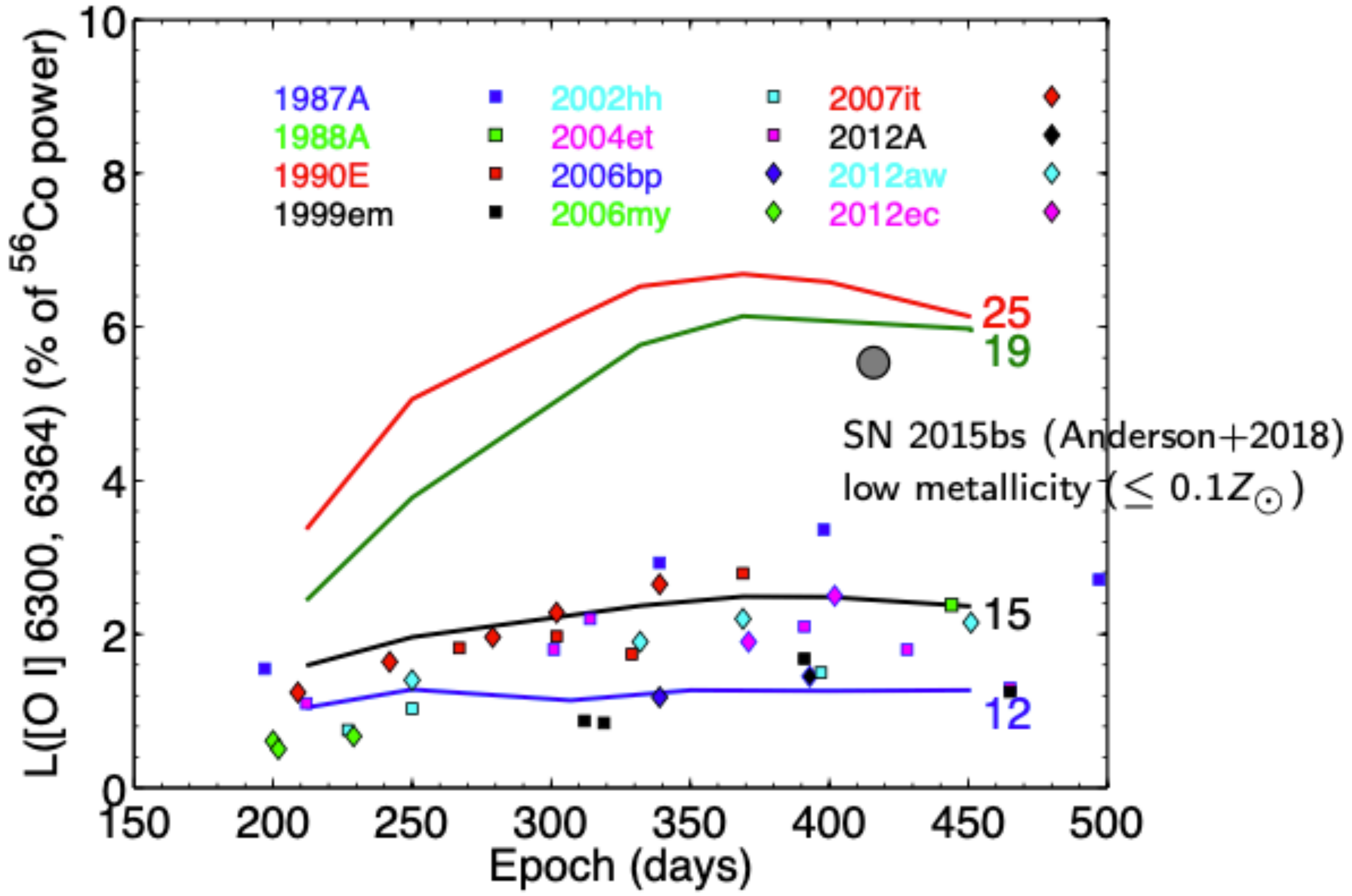
Elements diagnosed: **Si, S, Ca, Fe, Co, ^{56}Ni, ^{44}Ti**

Hydrostatic nucleosynthesis



KEPLER models
with artificial
mixing
processed by
SUMO

Jerkstrand+2014,2015

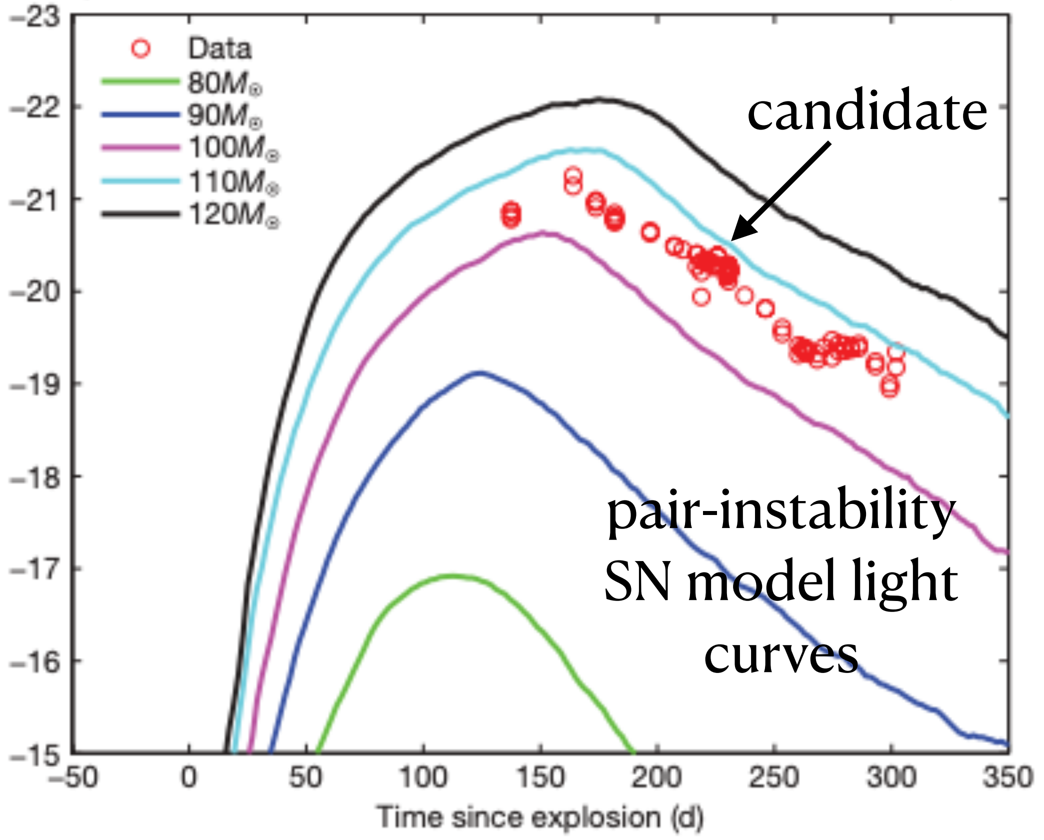


Elements diagnosed: **He, C, N, O, Na, Mg**

Results examples

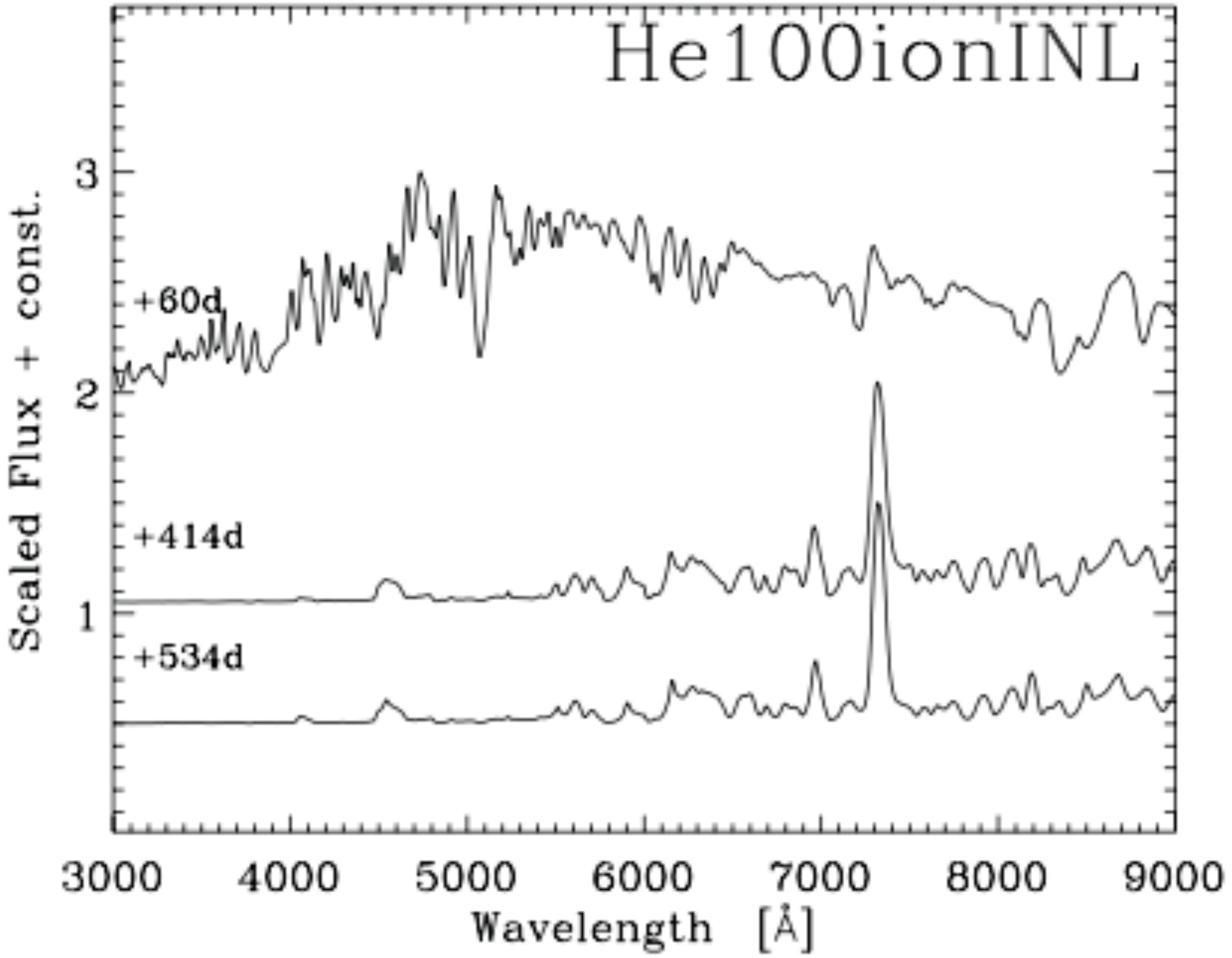
Important final tests for models that have passed reproduction of photospheric light curves and spectra: here pair-instability SN models shown to fail reproduction of candidate events

Gal-Yam 2009

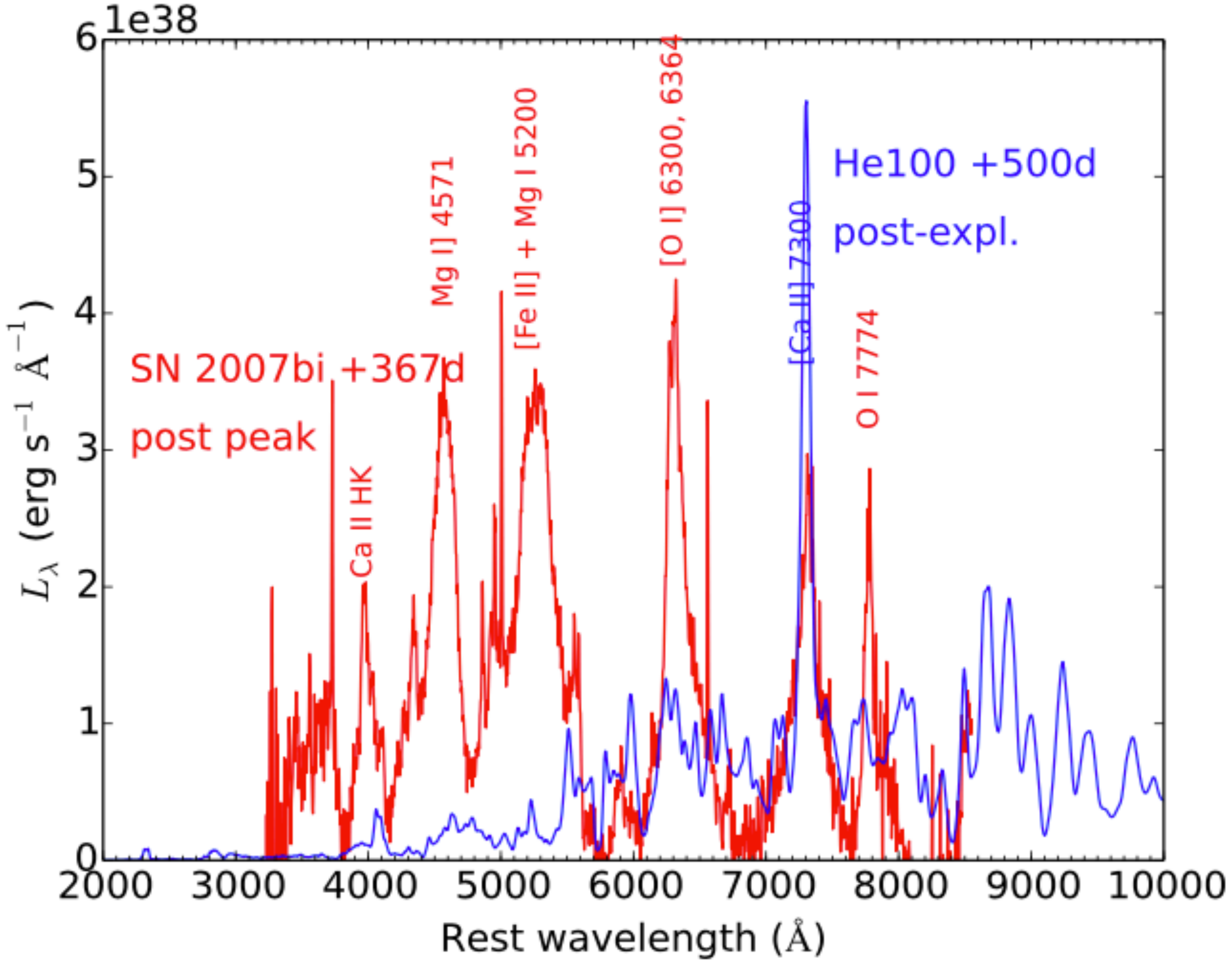


candidate

pair-instability SN model light curves



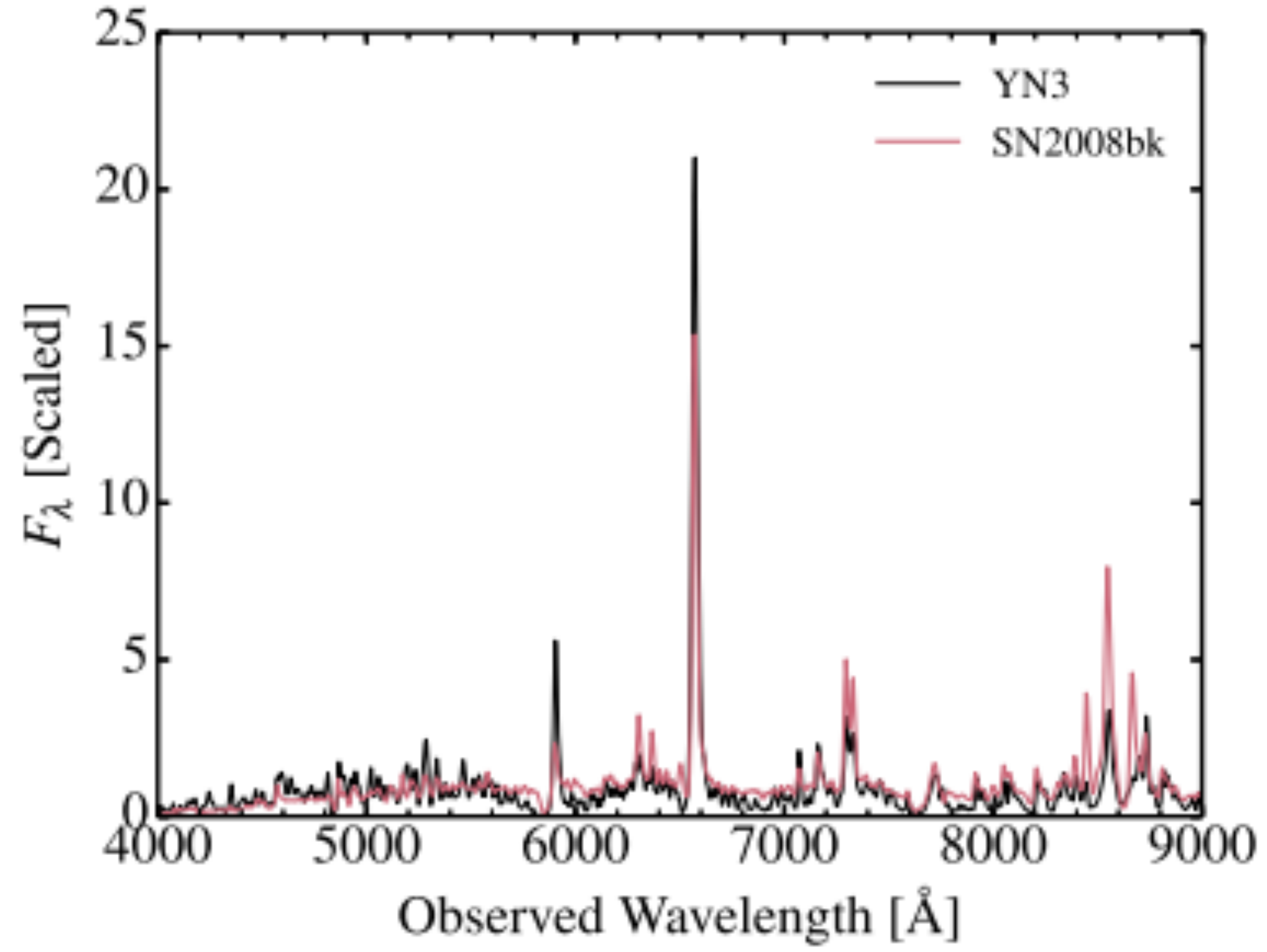
Dessart+2013



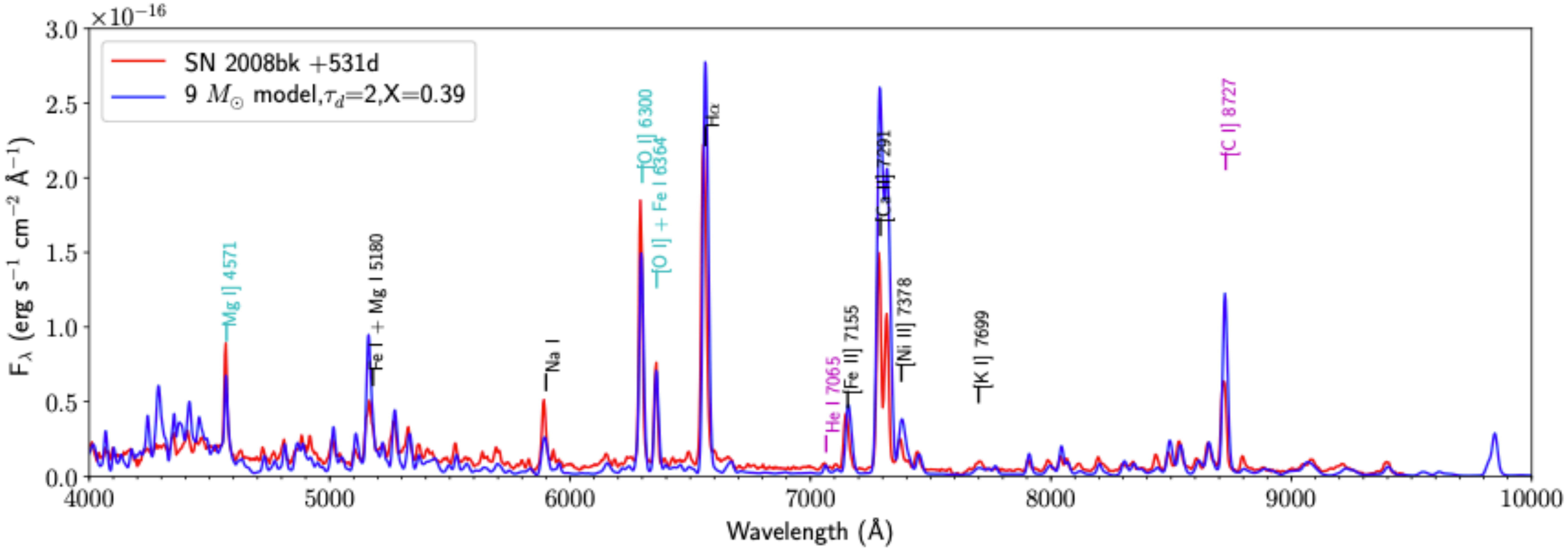
Jerkstrand+2016

Results examples

SNe from the lowest masses, ~8-10 M_{sun}, now well matched with **subluminous IIP class.**
Confirm ~10^{50} erg explosions. No electron-capture SNe yet seen.



Lisakov 2017

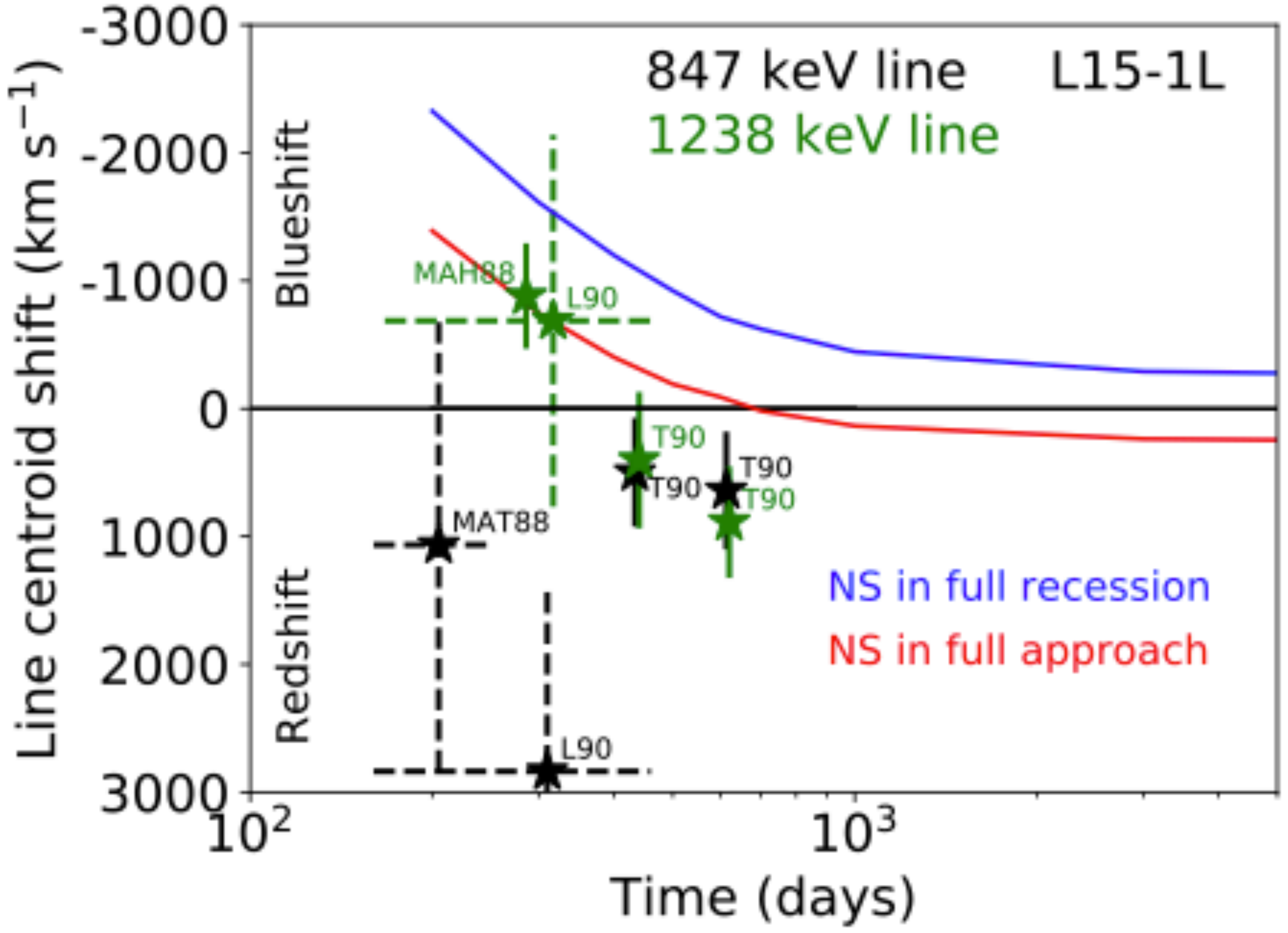


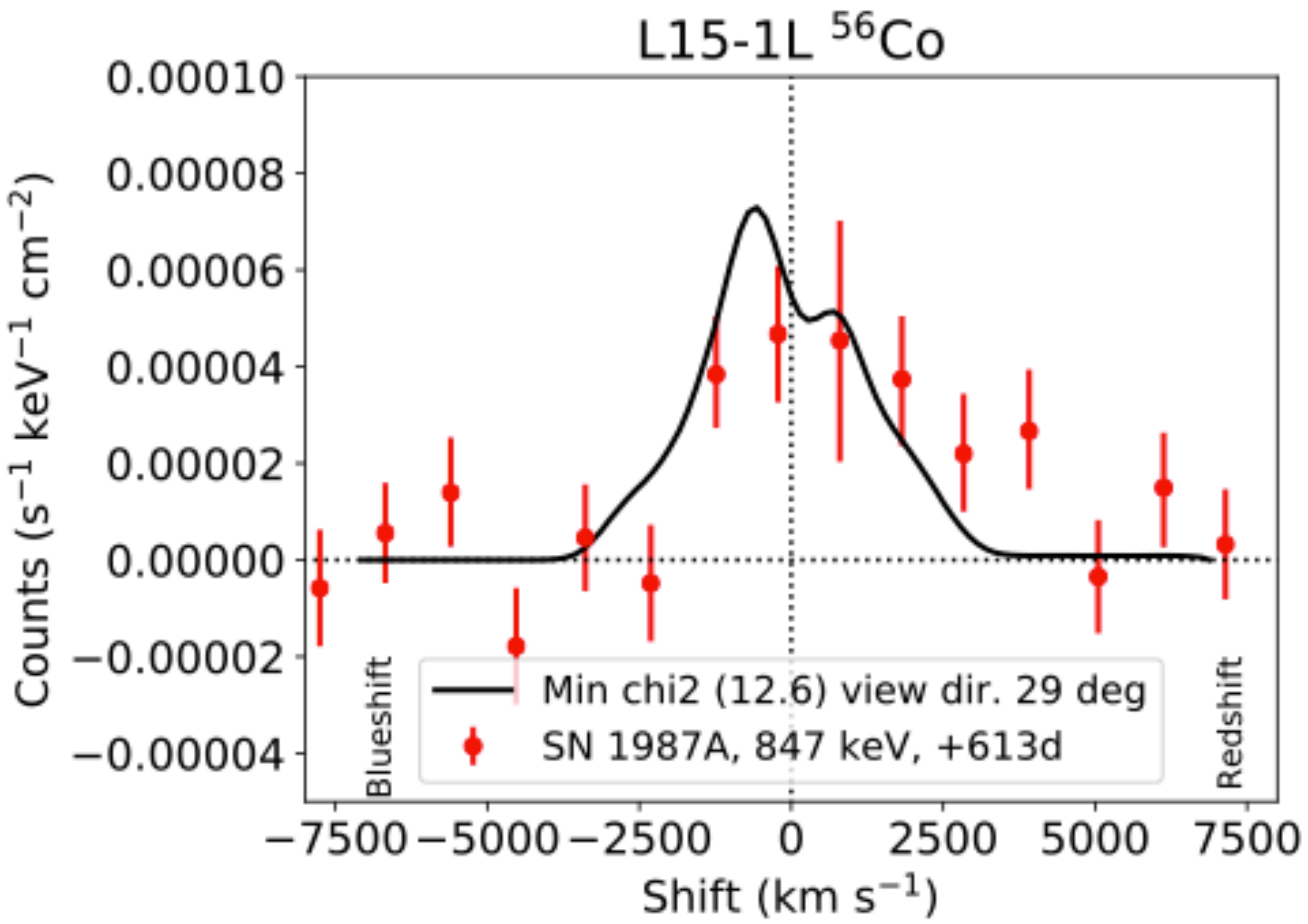
Jerkstrand 2018

Results examples

Tests of 3D explosion models -
So far only simple applications such as gamma ray line profiles.

3D models for SN 1987A by
Garching group.





Jerkstrand+2020

Ongoing for Ia SNe since few years (Botyanski 2017/2018, Shingles 2020)

Outlook

- 1D codes have relatively good artificial mixing schemes, and 3D nebular RT codes emerging.
- Need for 3D explosion simulations evolved at least until shock breakout or (better) until the onset of “homology”. ^{56}Ni/^{56}Co decay influences dynamics for ~weeks.
- Need for detailed nucleosynthesis: sensitivity of composition to nuclear network, dynamics, resolution, neutrino effects, ..
- Cover full mass range, single vs. binary evolution (CCSN)
- Major limitation for KN spectra is the scarcity of atomic data for r-process elements => Need for an “Opacity Project”? How accurate is existing data?
- KN thermalization : ground work laid by Berkeley group.
- Community dissemination: published explosion/merger/progenitor simulations preferably made public to allow for post-processing, code comparison etc.