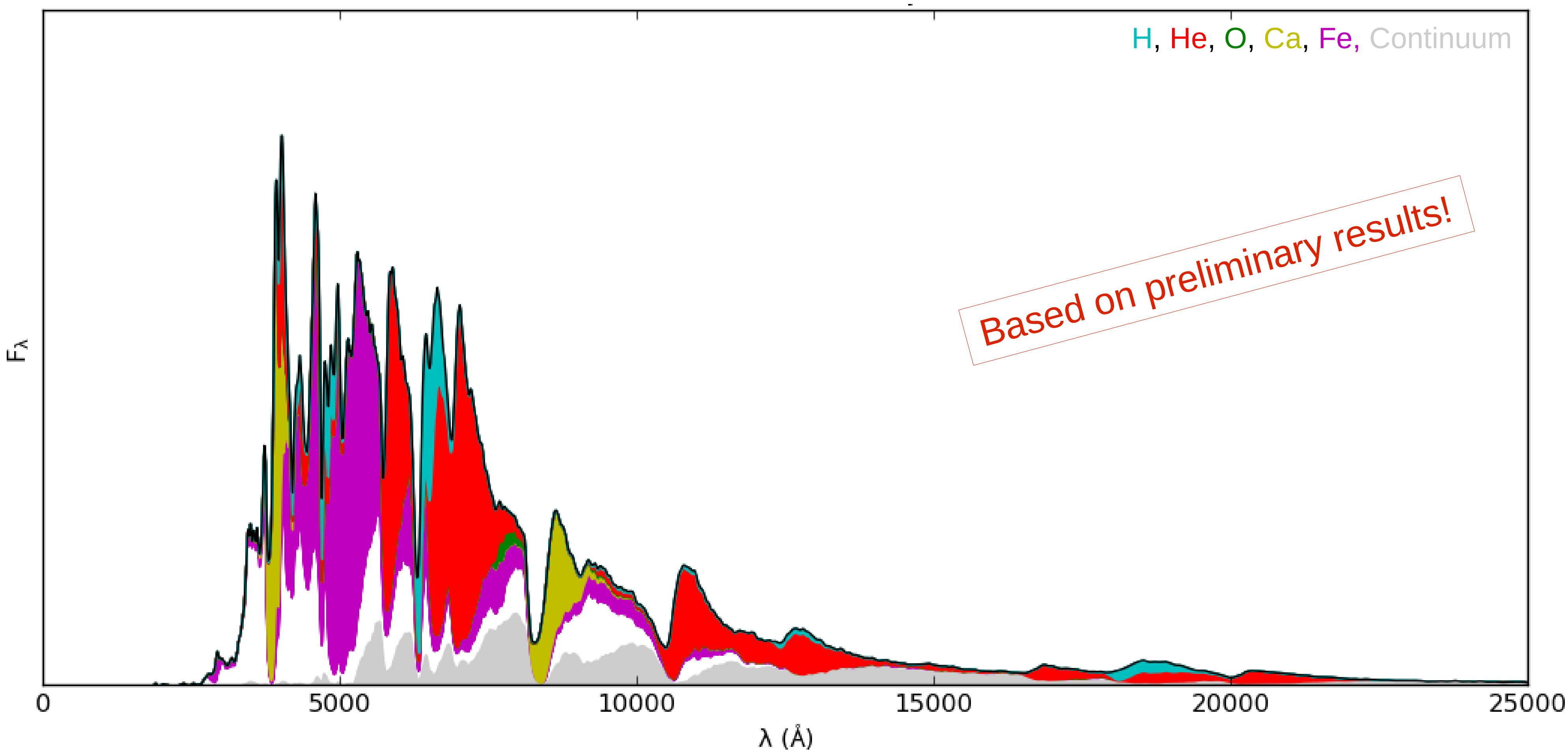
Spectral Synthesis of Core-Collapse Supernovae – The JEKYLL code and its application.

Mattias Ergon

Collaborators: Claes Fransson (physics and software), Markus Kromer (testing), Anders Jerkstrand (testing)



The JEKYLL code

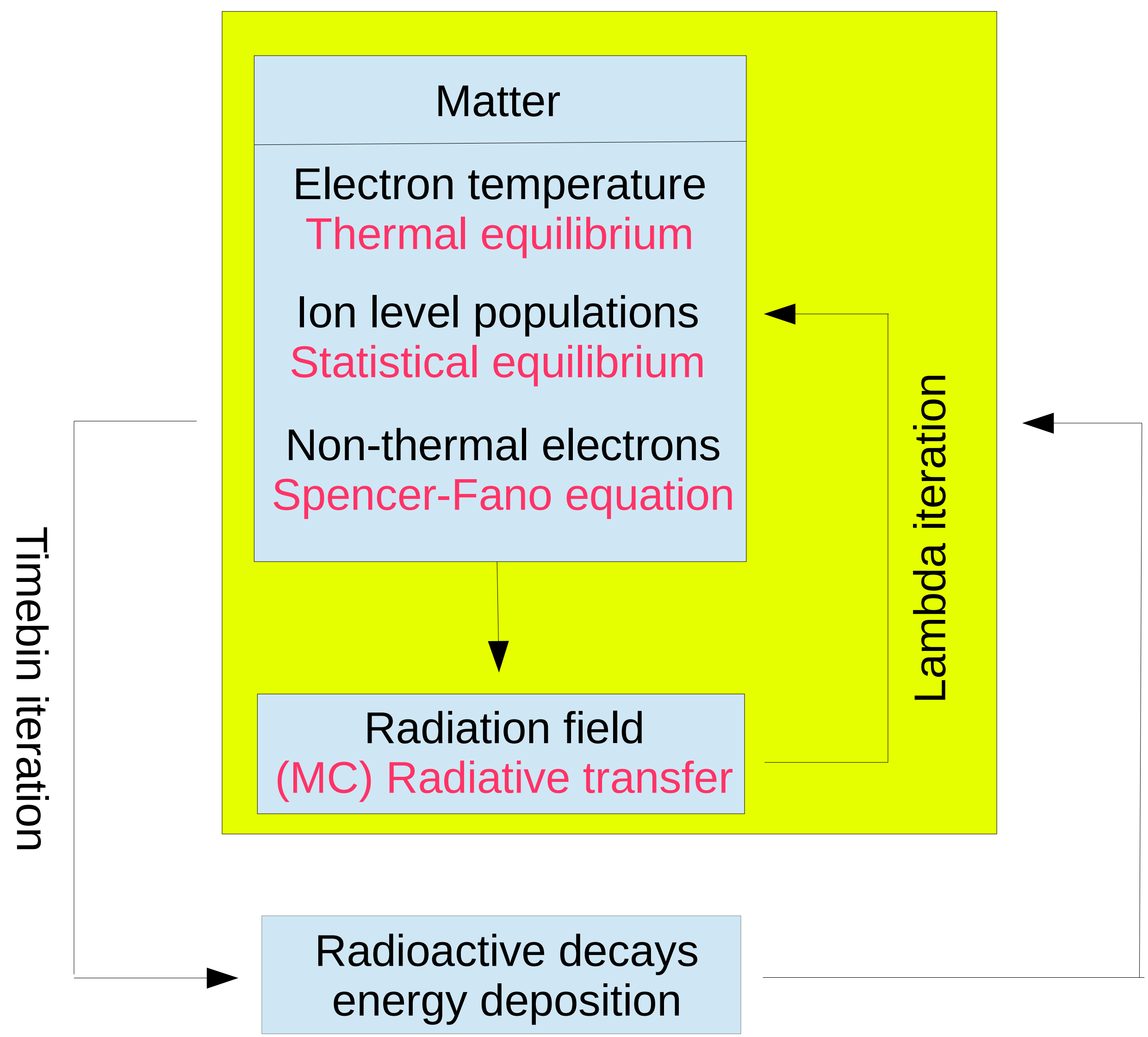
What: Realistic* simulations of the spectral evolution,
and the broad-band and bolometric lightcurves for SNe,
in the photospheric and nebular phase.

How: Full NLTE-solution for the matter and the radiation field,
following (and extending) the method outlined by Leon Lucy (2002, 2003, 2005).

* Restrictions:

Homologues expansion.
Spherical symmetry.
Steady-state for the matter.

Method outline



NLTE

NLTE: Non-LTE
LTE: Local Thermodynamic Equilibrium

In LTE all processes are in (near) equilibrium,
and the state specified by a single parameter, the temperature.

Collisional processes dominate	Optically thick	Optically thin
Yes	LTE	Matter: LTE Radiation: NLTE
No	NLTE	NLTE

NLTE

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Yes	LTE	Matter: LTE Radiation: NLTE
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Saha ionization and Boltzman excitation equation

Diffusion approximation

Radiative transfer equation

NLTE rate equations

NLTE

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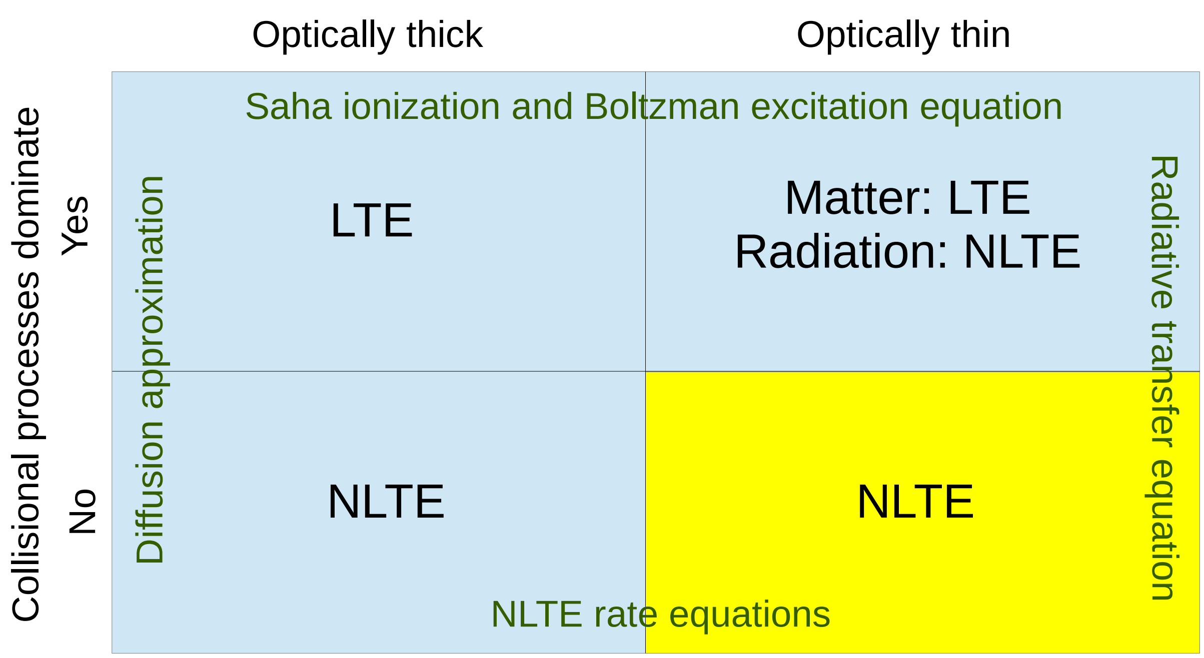
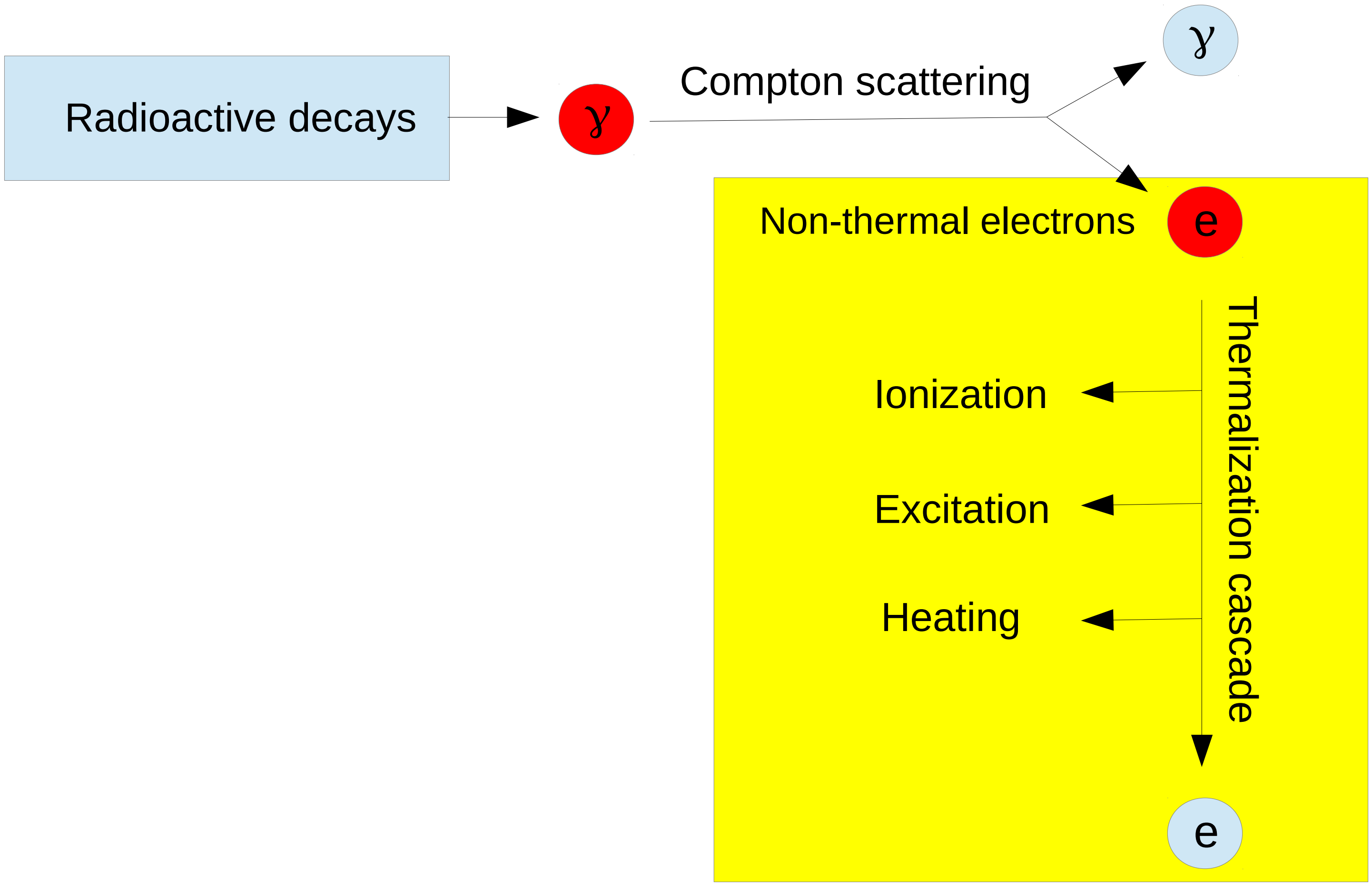
LTE: Local Thermodynamic Equilibrium

In LTE all processes are in (near) equilibrium,
and the state specified by a single parameter, the temperature.

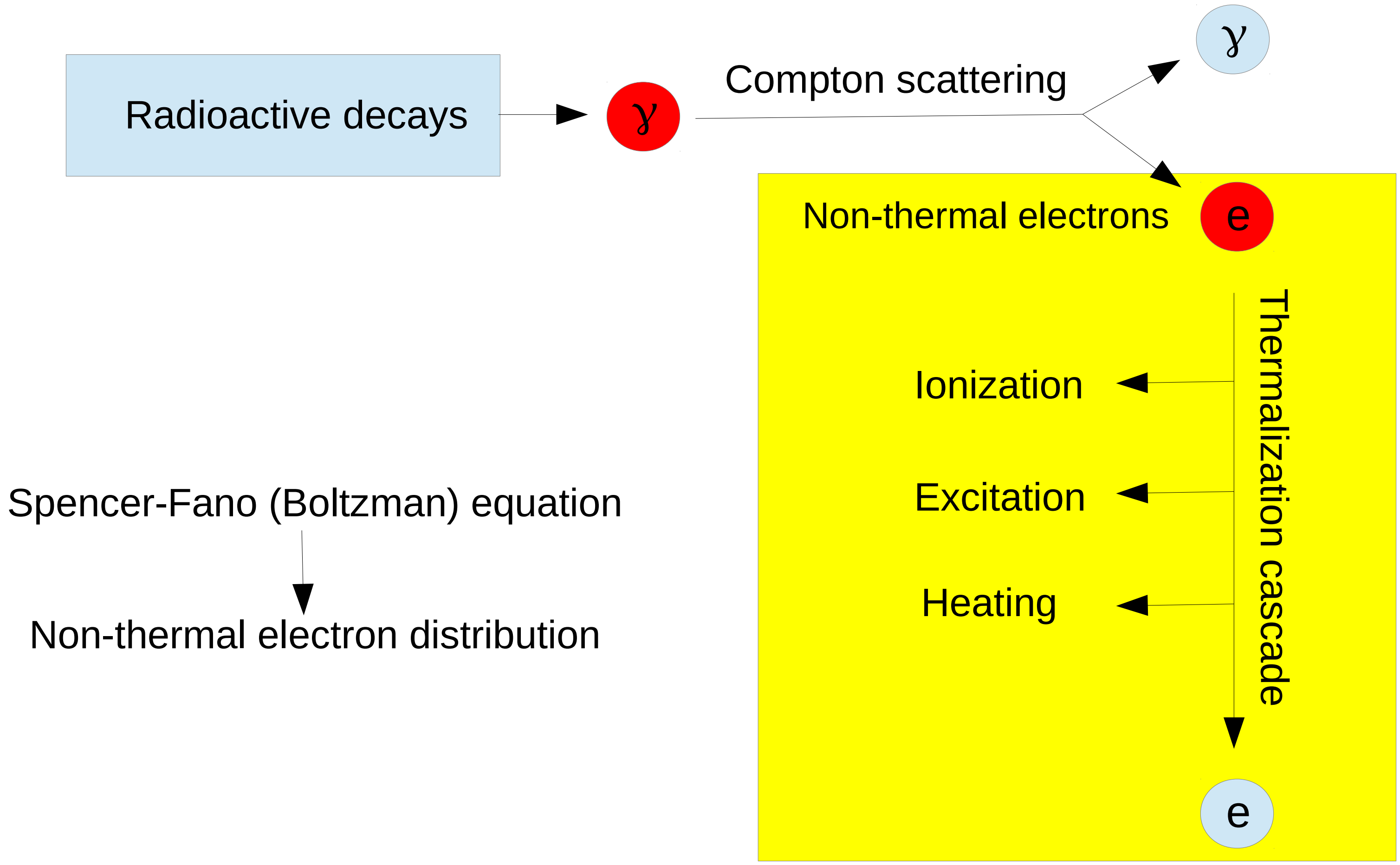


In the outer parts and at late times, SNe ejecta are neither optically thick, nor collisionally dominated,
<u>so a full NLTE solution is required.</u>

Non-thermal electrons



Non-thermal electrons



Problem solved by Kozma & Fransson (1998),
and their original FORTRAN routine has been integrated into JEKYLL.

Other similar codes

SEDONA (Kasen et al. 2006)

Geometry: 3-D
NLTE: No
Non-thermal ionization/excitation: No
Time-dependence: Radiation field
Macroscopic mixing: No
Phase : Photospheric

SUMO (Jerkstrand et al. 2011)

Geometry: 1-D
NLTE: Full
Non-thermal ionization/excitation: Yes
Time-dependence: No
Macroscopic mixing: Yes
Phase: Nebular

JEKYLL (Ergon et al. In prep)

Geometry: 1-D
NLTE: Full
Non-thermal ionization/excitation: Yes
Time-dependence: Radiation field
Macroscopic mixing: Yes
Phase: All

ARTIS (Kromer et al. 2009)

Geometry: 3-D
NLTE: Ionization
Non-thermal ionization/excitation: No
Time-dependence: Radiation field
Macroscopic mixing: Yes
Phase : Photospheric

CMFGEN (Hillier 1998)

Geometry: 1-D
NLTE: Full
Non-thermal ionization/excitation: Yes
Time-dependence: Full
Macroscopic mixing: No
Phase: All

Comparisons

ARTIS

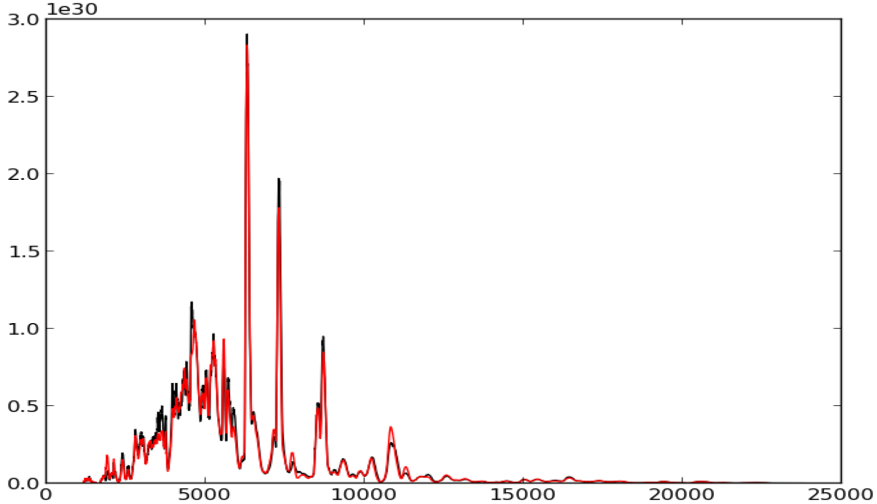
In progress.

CMFGEN

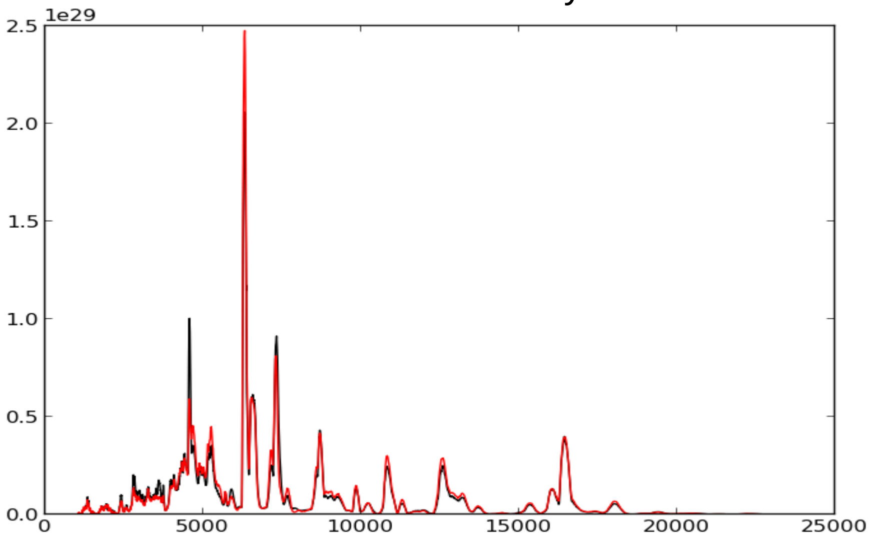
T.B.D.

SUMO

Model 13G at 200 days



Model 13G at 400 days

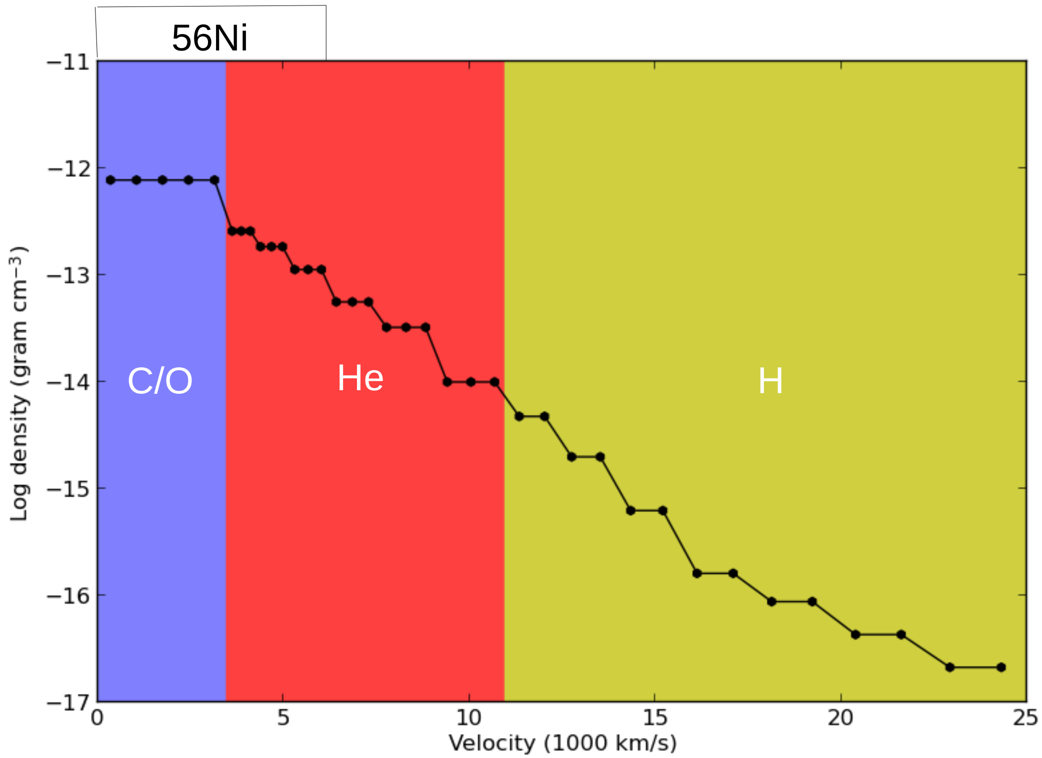


Type IIb models: Background

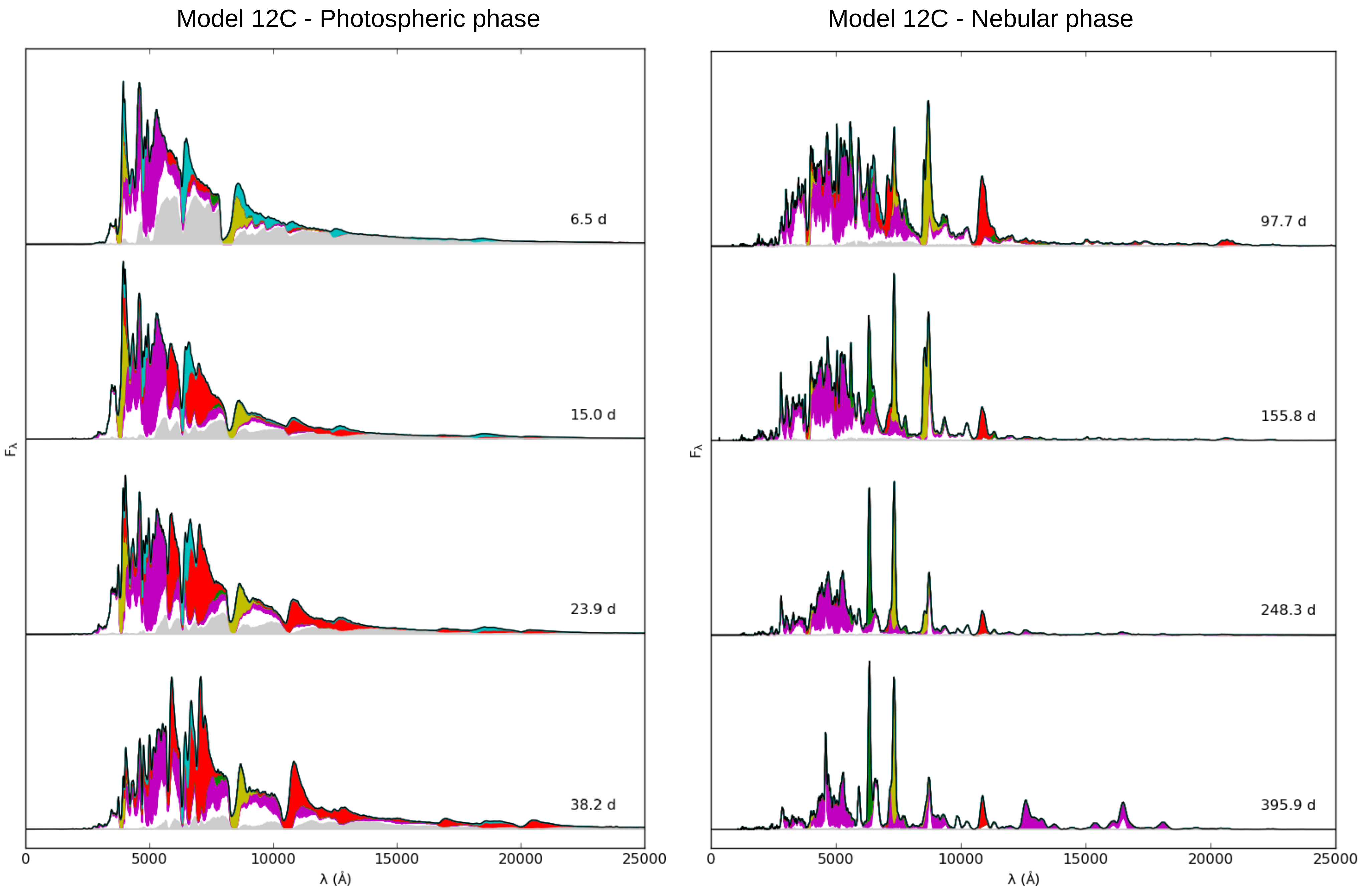
Constructed and evolved through the nebular phase with SUMO in Jerkstrand et al. (2015).

Evolved through the photospheric phase with JEKYLL in Ergon et al. (in prep).

In the following I show some results for model 12C,
which showed a reasonable agreement with SN 2011dh in the nebular phase.

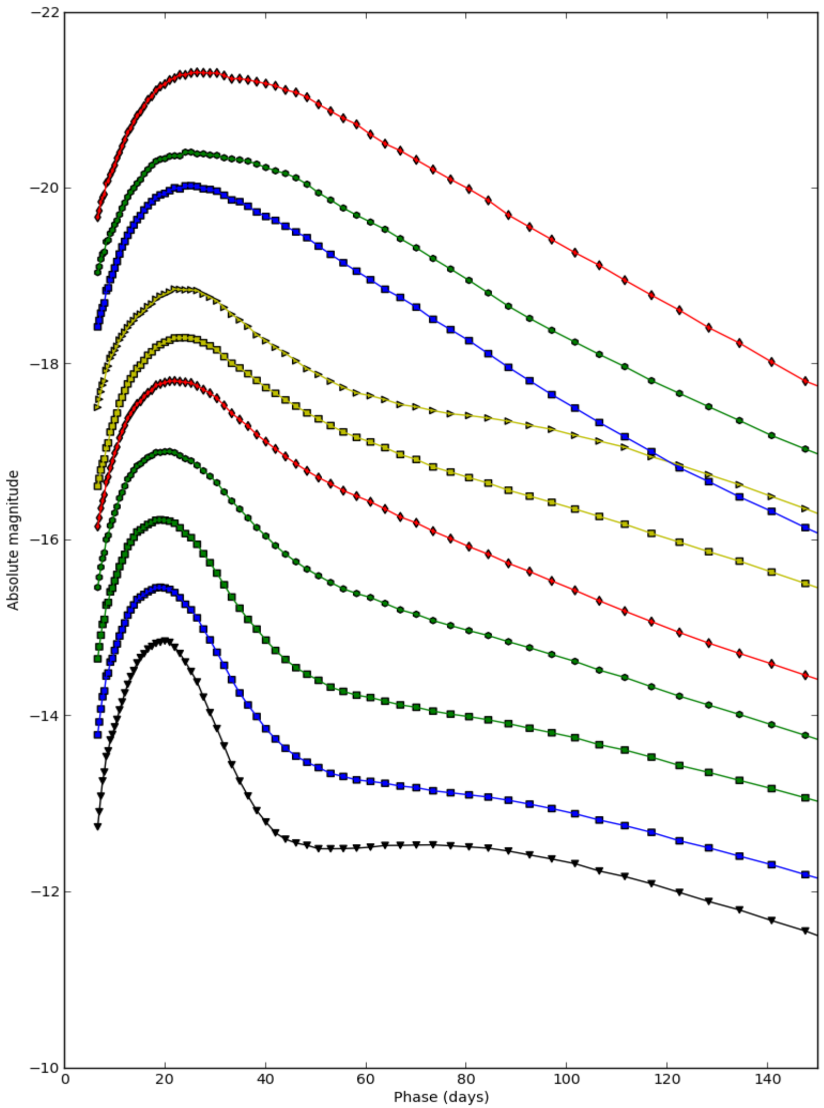


Type IIb models: Spectral evolution

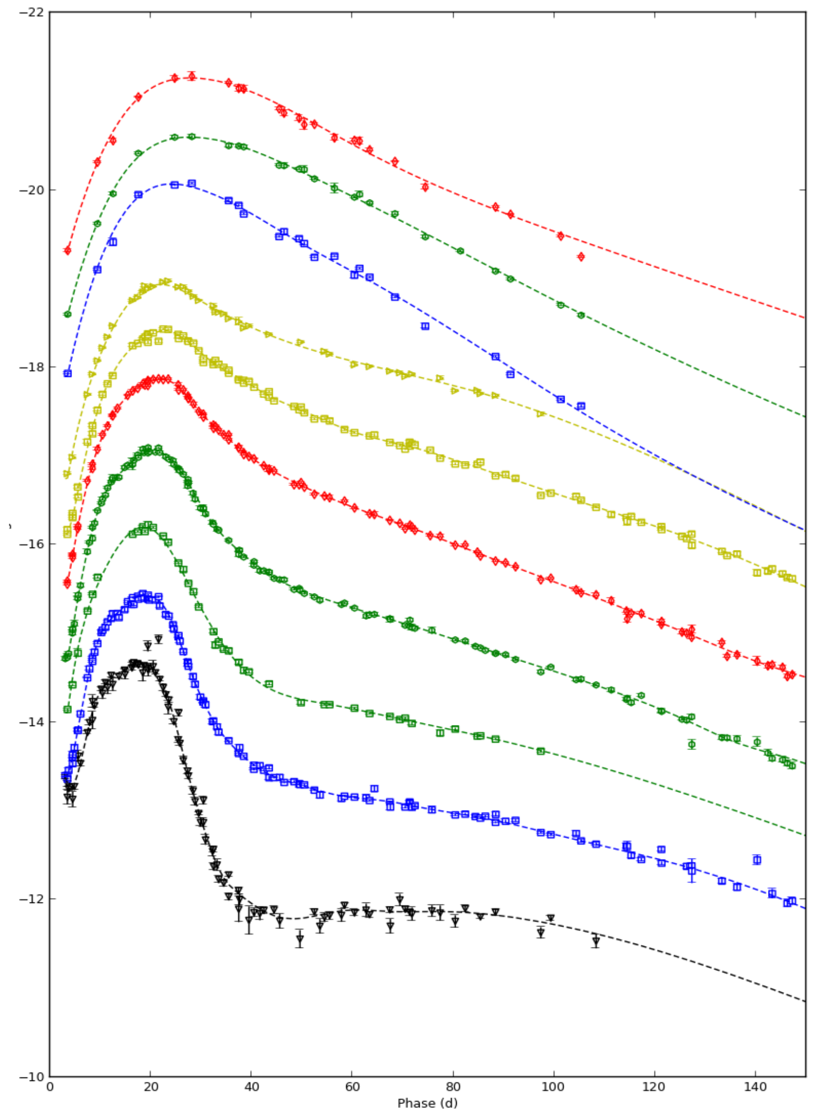


Type IIb models: Broad-band lightcurves

Model 12C: 3-150 days

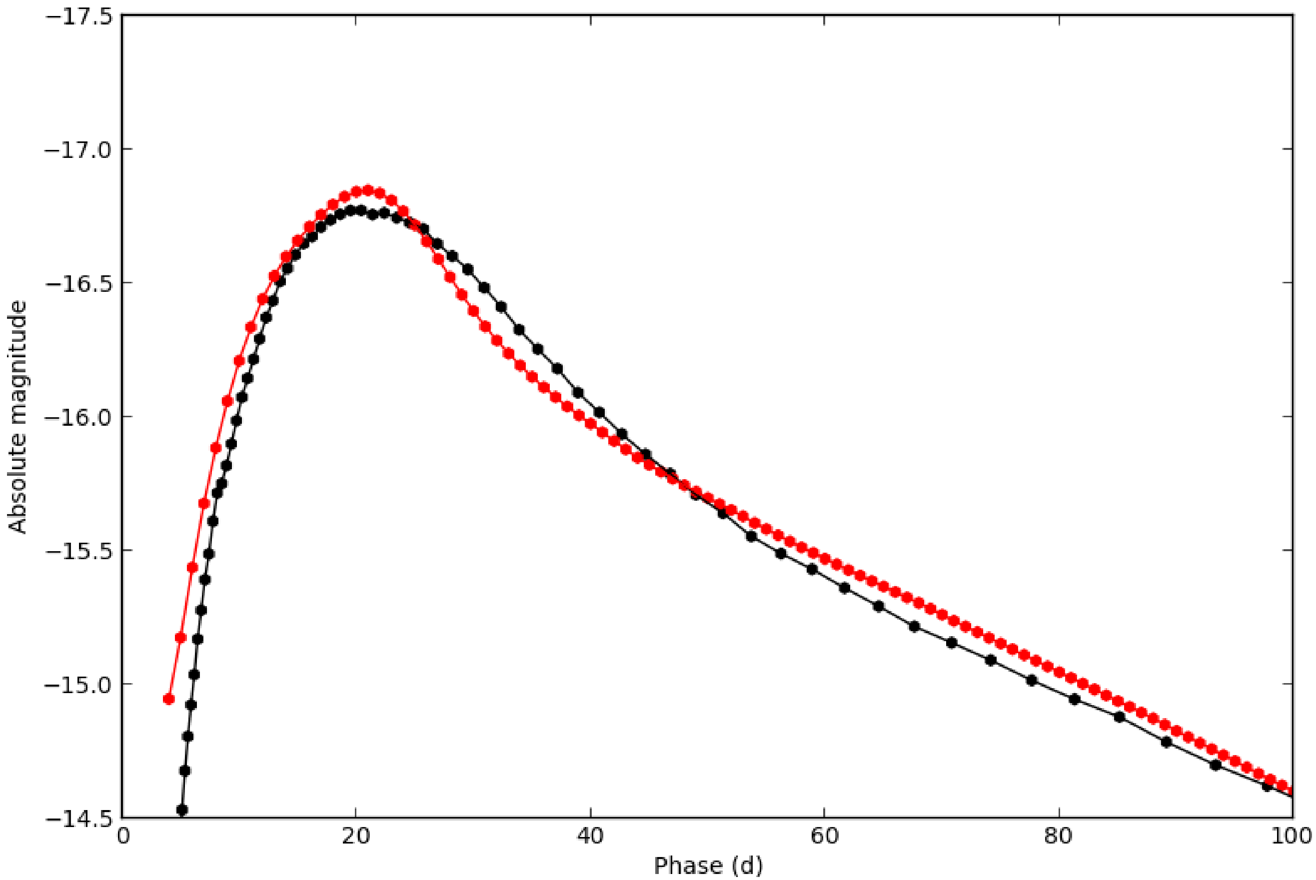


SN 2011dh: 3-150 days



Type IIb models: UV-MIR pseudo-bolometric lightcurve

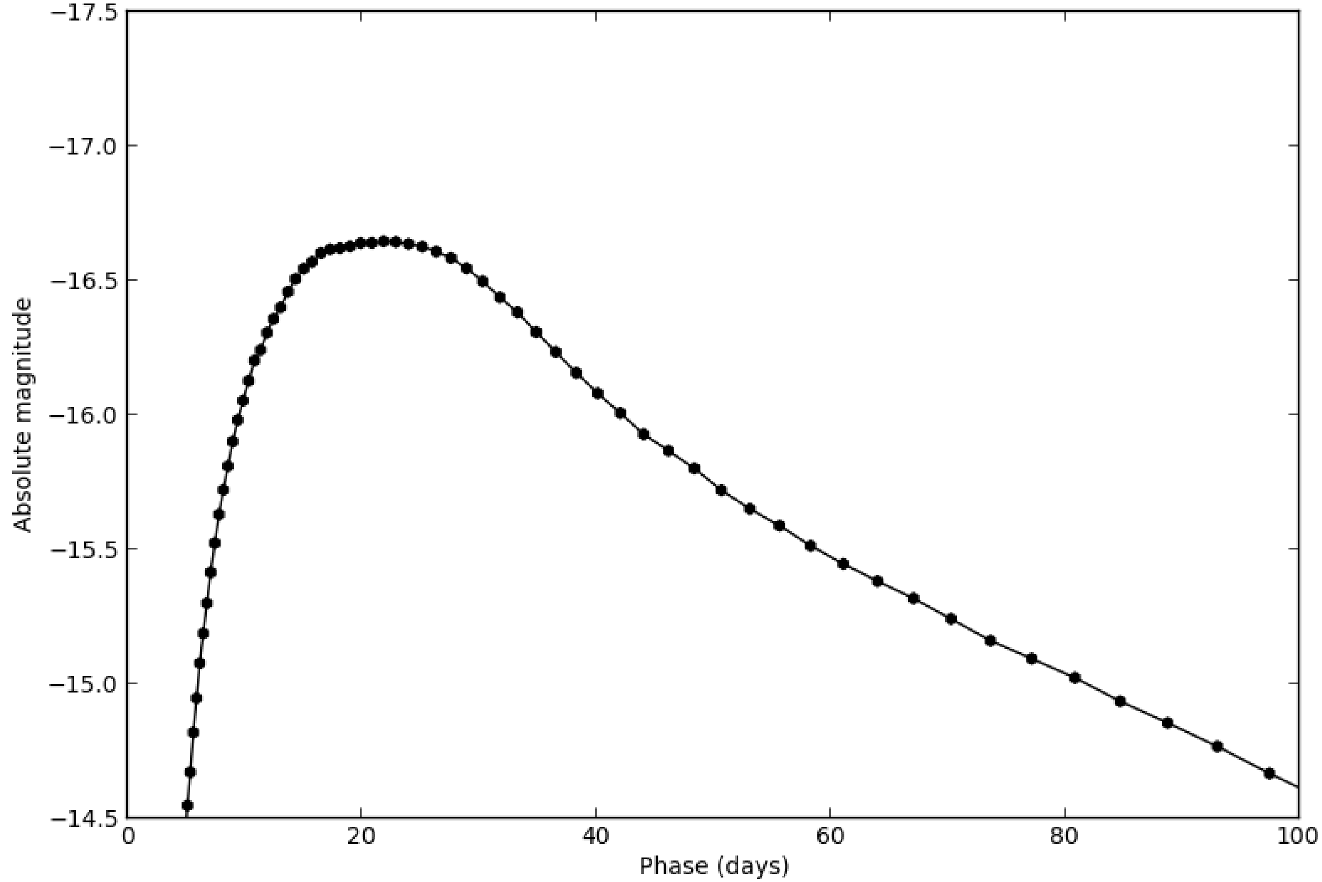
Model 12C: 3-100 days



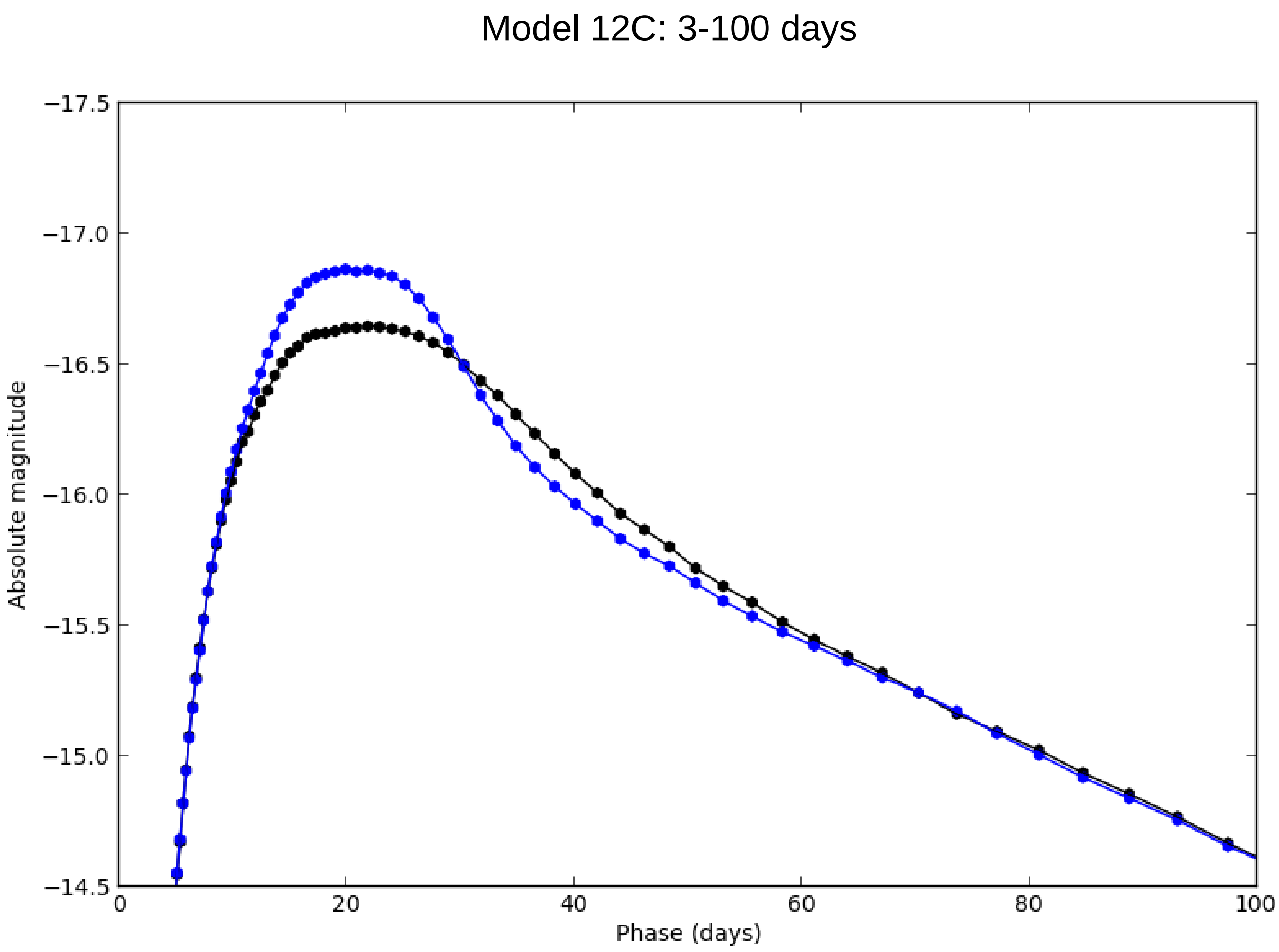
SN 2011dh: 3-100 days

Effect of NLTE: Bolometric lightcurve

Model 12C: 3-100 days

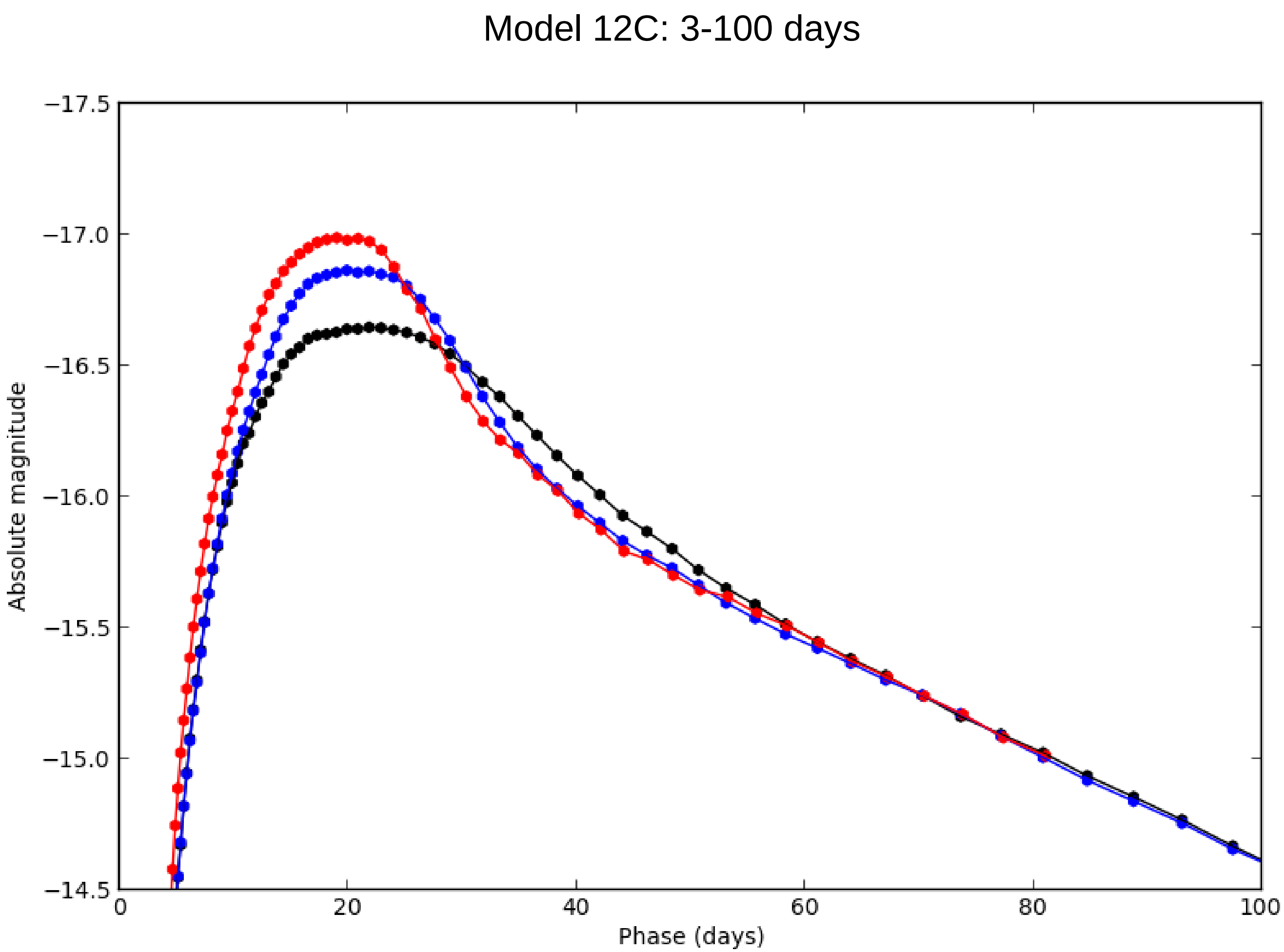


Effect of NLTE: Bolometric lightcurve



Non-thermal ionization/excitation - Off

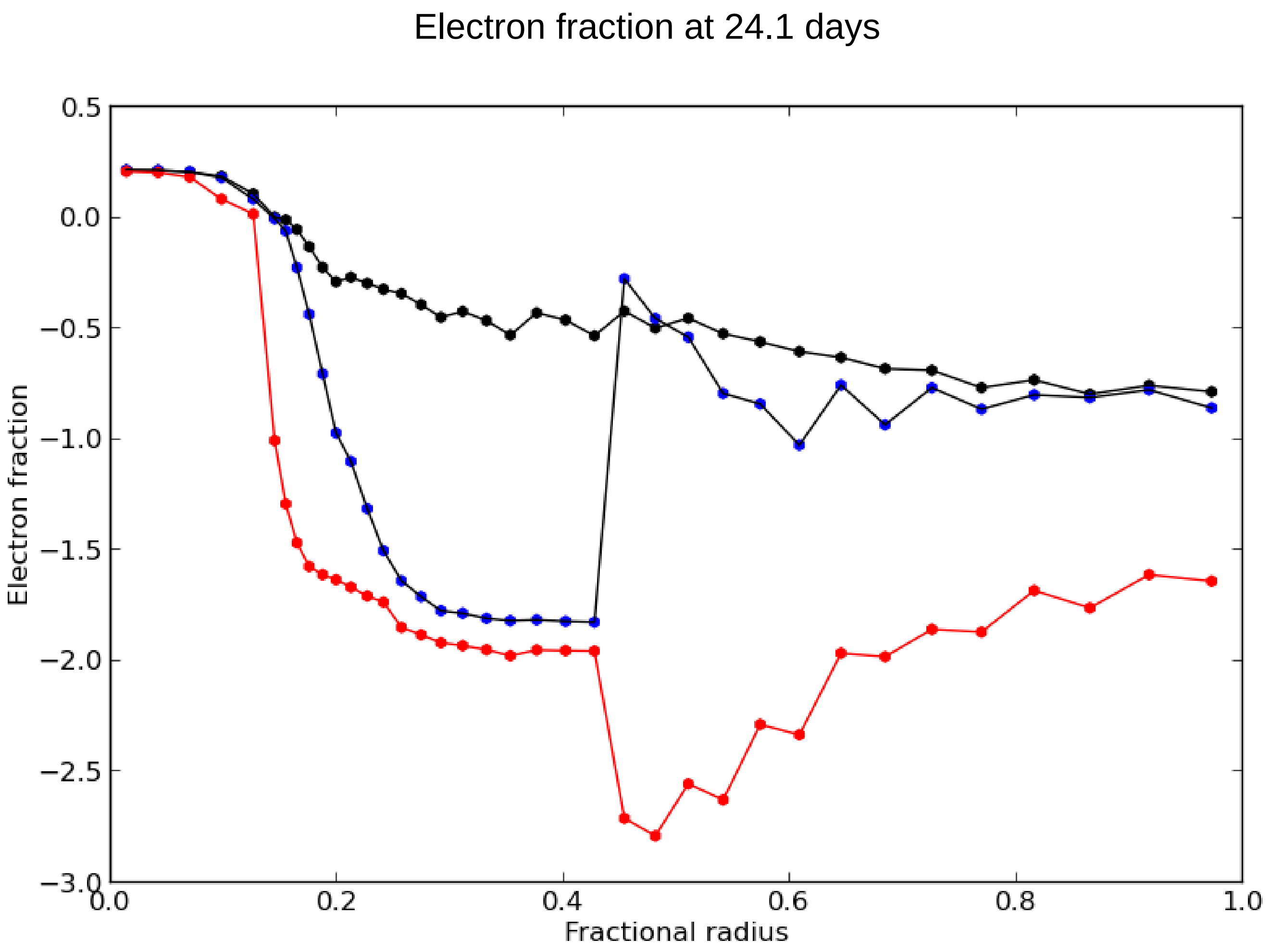
Effect of NLTE: Bolometric lightcurve



Non-thermal ionization/excitation - Off

NLTE excitation - Off

Effect of NLTE: Ionization

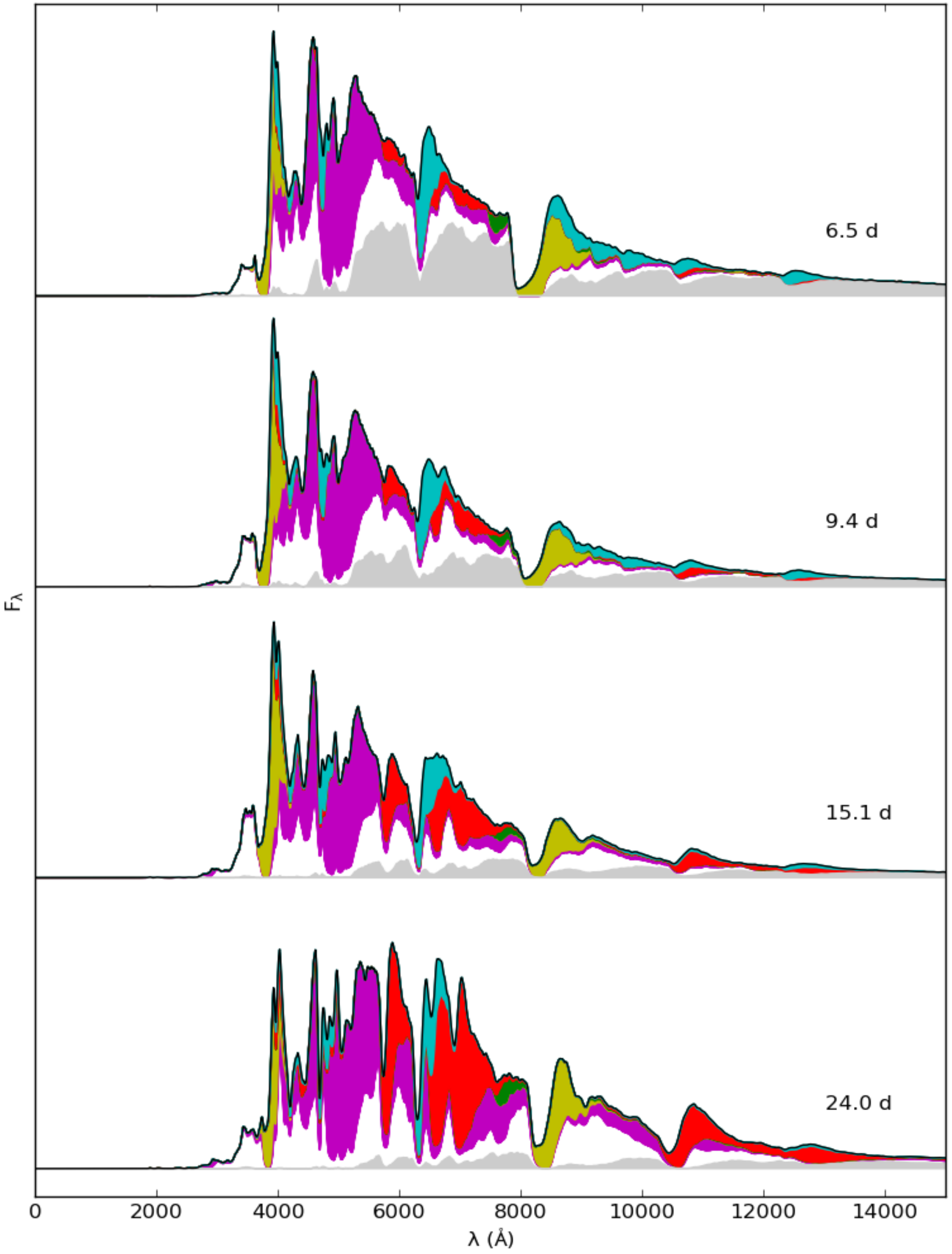


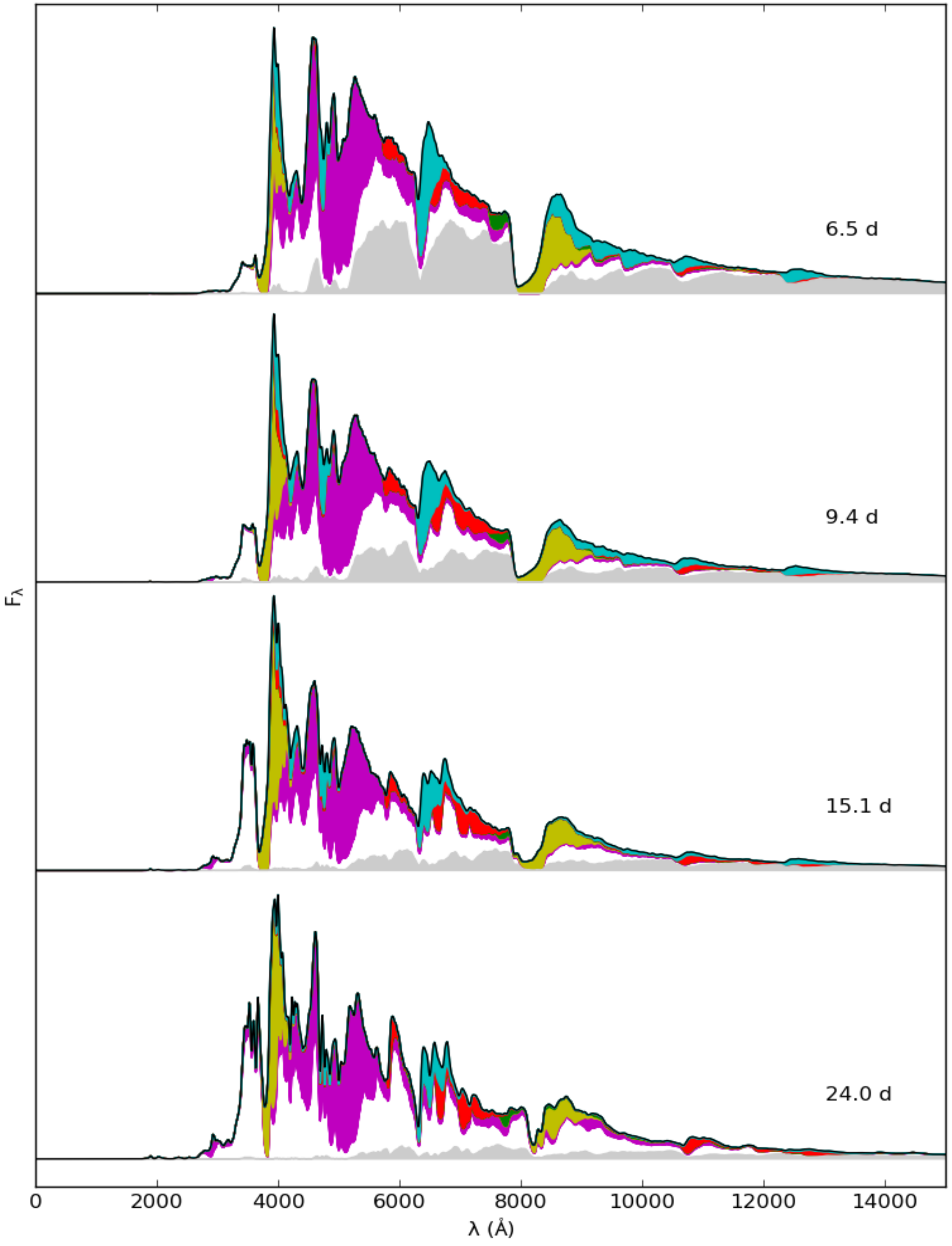
Non-thermal ionization/excitation - Off

NLTE excitation - Off

Effect of NLTE: Spectral evolution

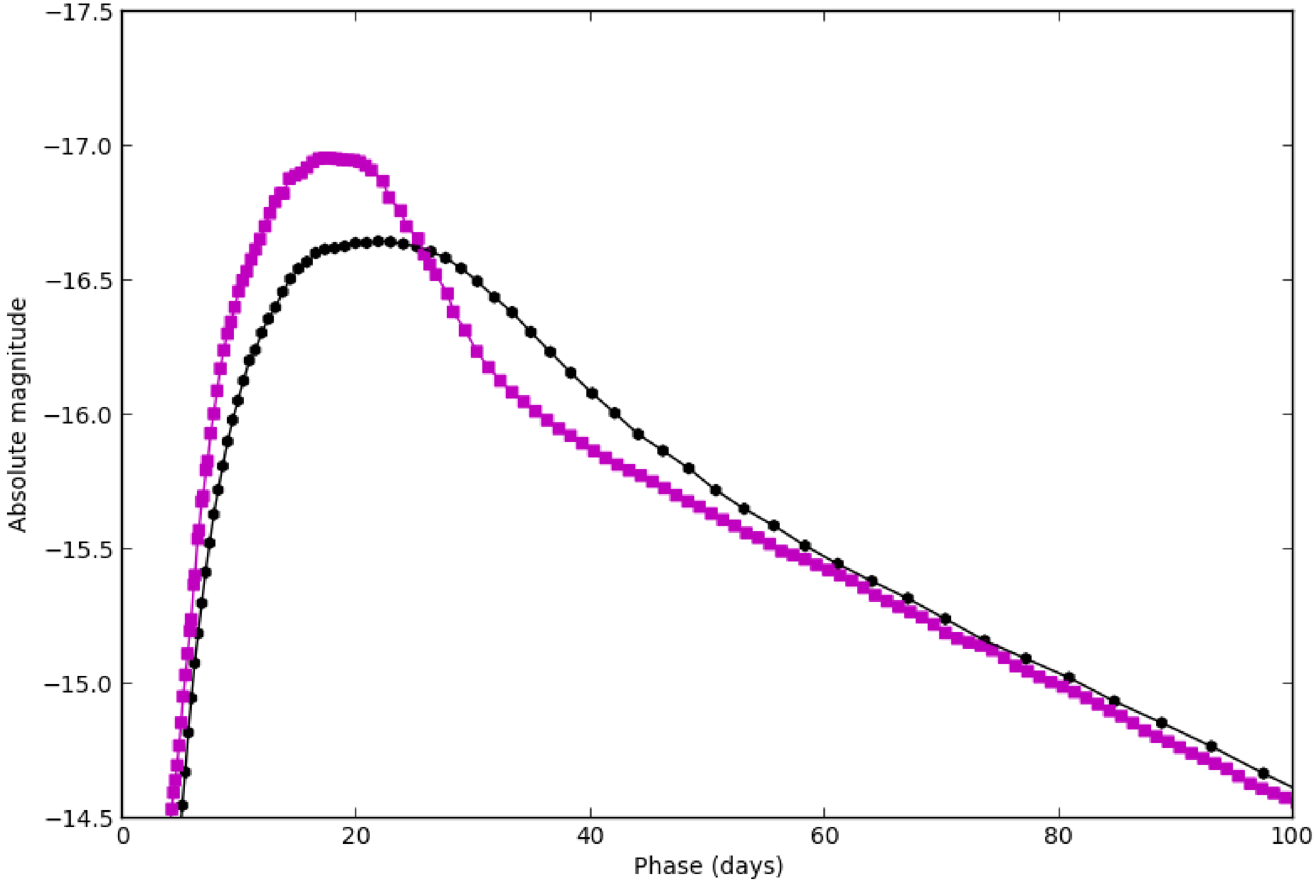
Non-thermal ionization/excitation - Off





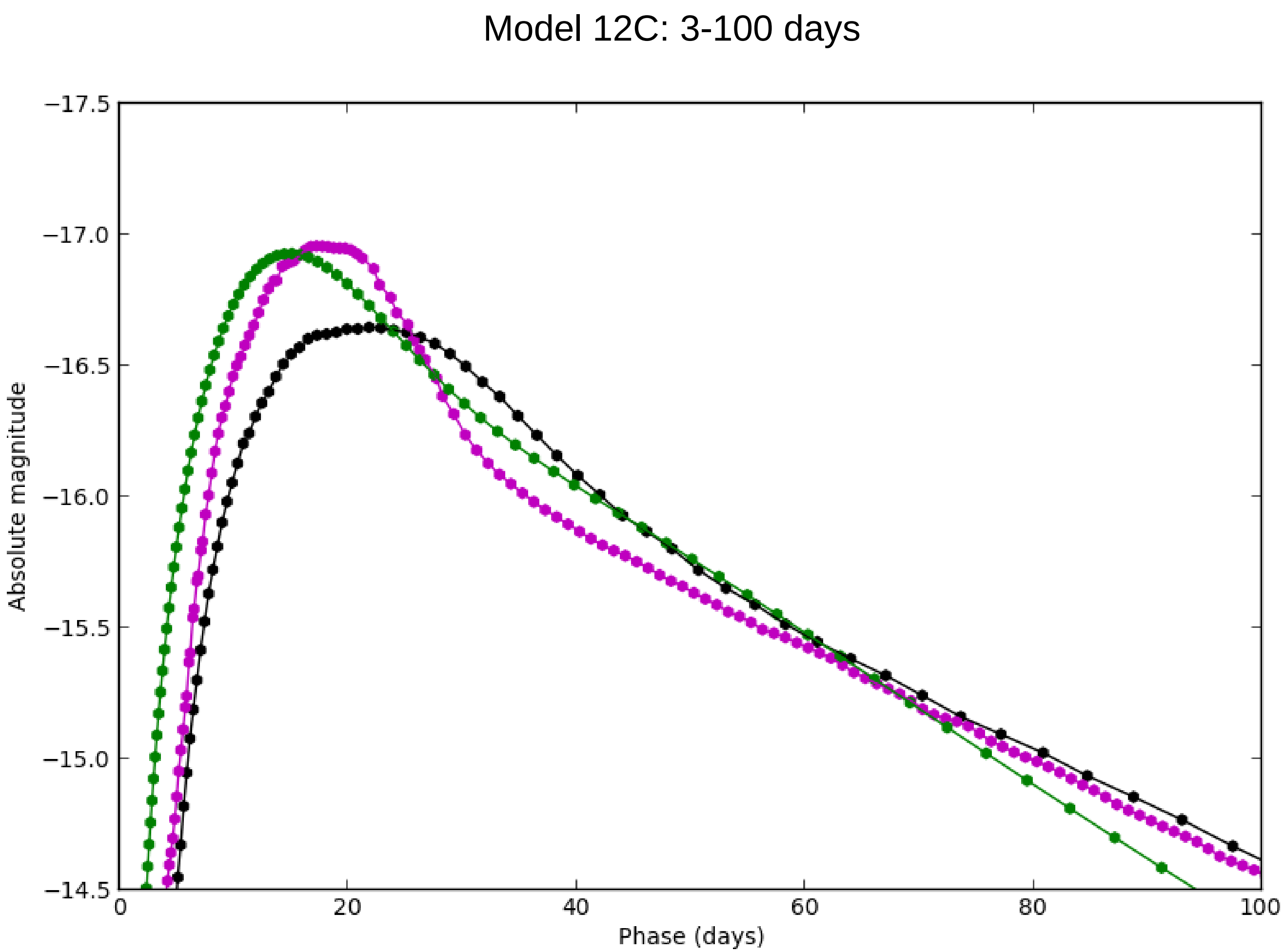
Effect of NLTE: Bolometric lightcurve

Model 12C: 3-100 days



LTE + Opacity floor (HYDE)

Effect of NLTE: Bolometric lightcurve

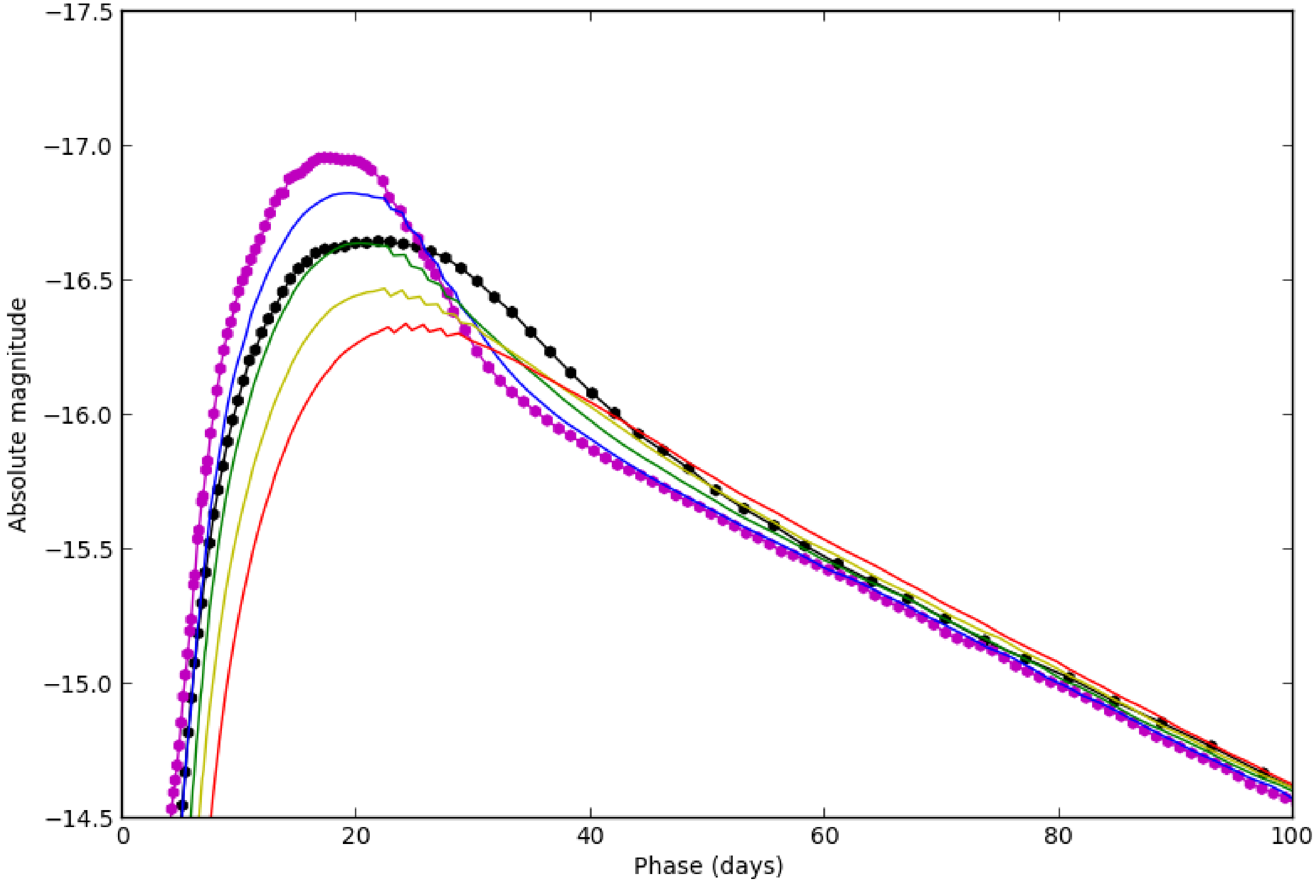


LTE + Opacity floor (HYDE)

Arnett (1982) + Popov (1991)

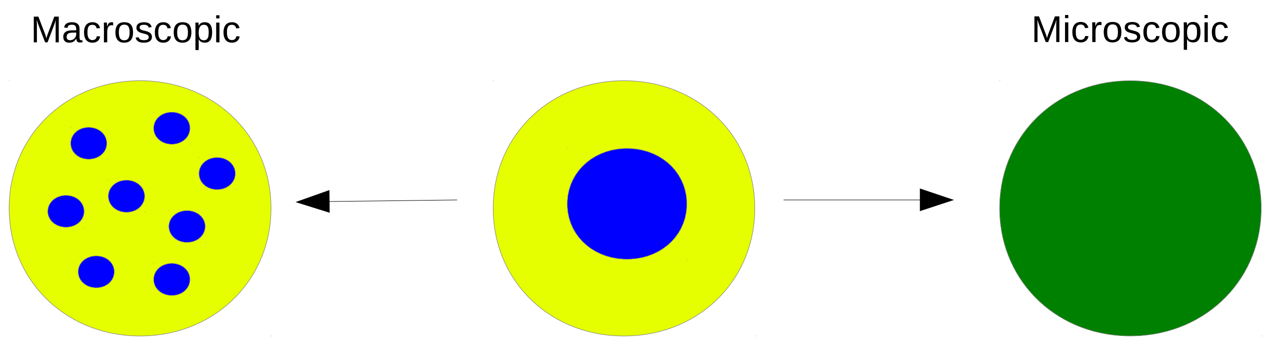
Effect of NLTE: Bolometric lightcurve

Model 12C: 3-100 days



HYDE opacity floor : 0.024, 0.05, 0.1, 0.15, 0.2 cm^2 gram^-1

Mixing



Hydrodynamical instabilities → Macroscopic mixing of the nuclear burning zones.

Macroscopic vs Microscopic mixing

↓

Different composition and (possibly) density

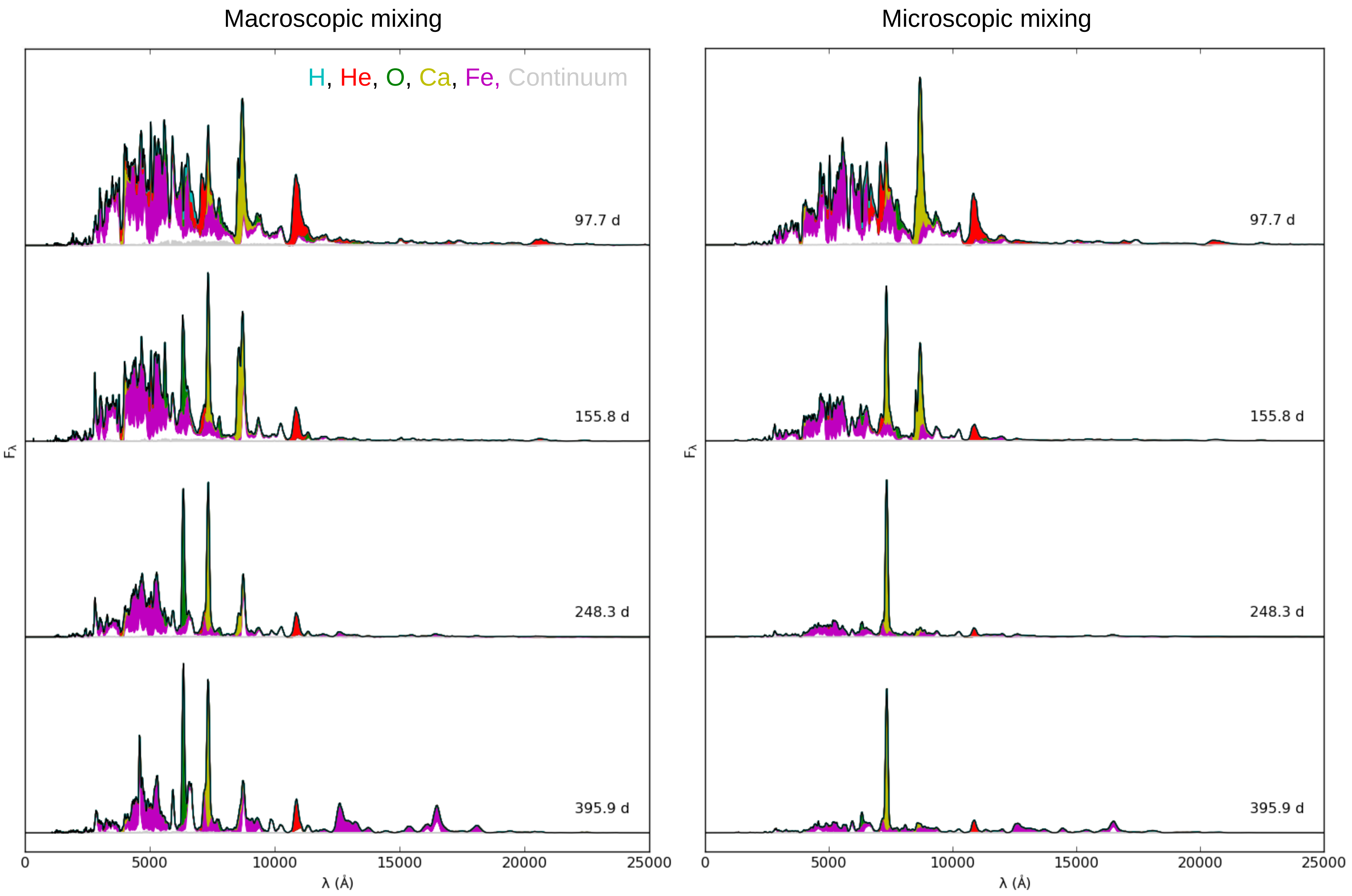
↓

Different temperature, degree of ionizaton etc.

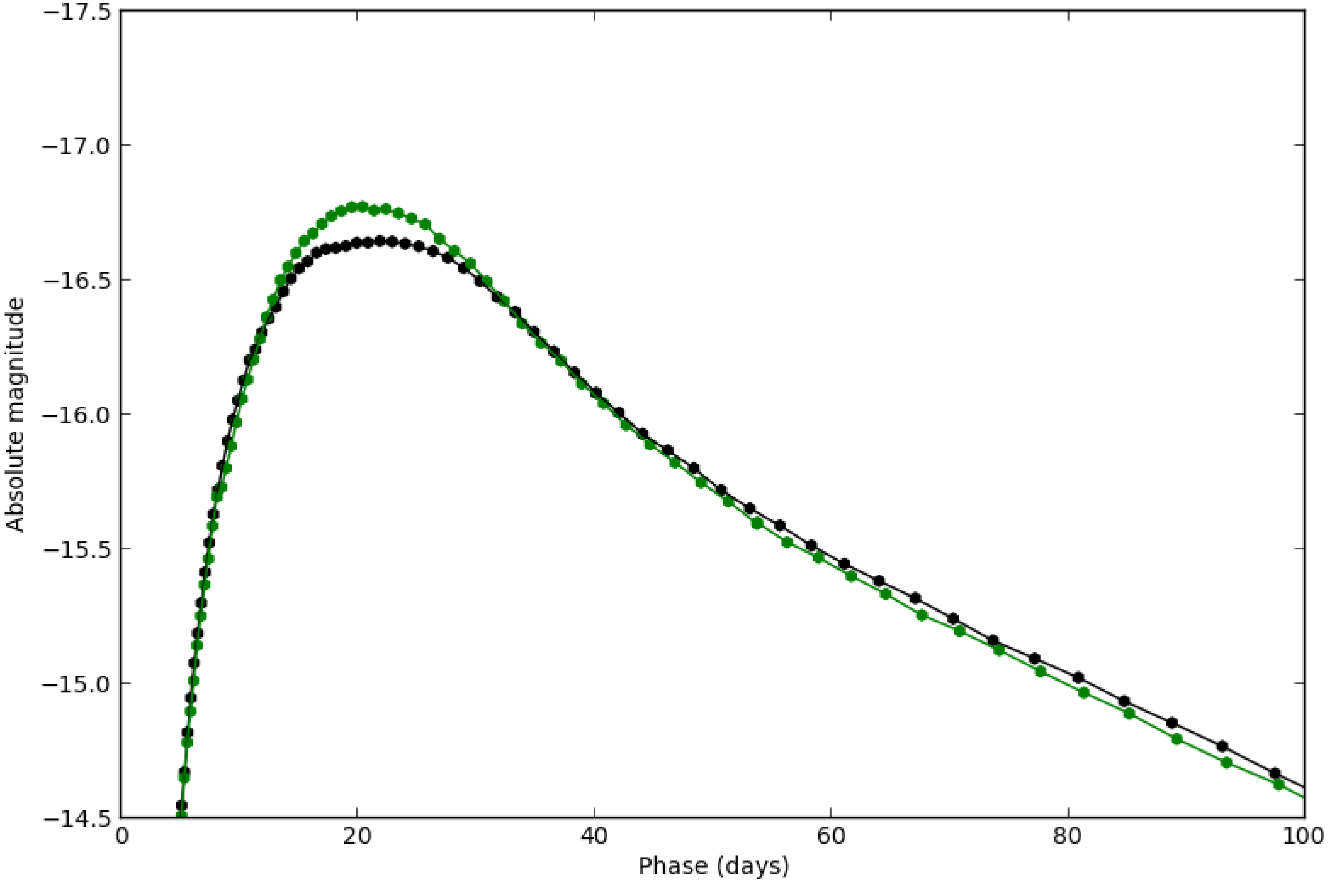
To simulate macroscopic mixing, JEKYLL supports virtual cells (Jerkstrand et al. 2011).

Virtual cells represents clumps of macroscopically mixed material,
and are randomly selected while the photons traverse the otherwise spherically symmetric ejecta.

Effect of mixing: Spectral evolution



Effect of mixing: Bolometric lightcurve



Microscopic Mixing

Macroscopic Mixing

More to come ...