Modelling the spectral evolution of supernova (with the JEKYLL code).

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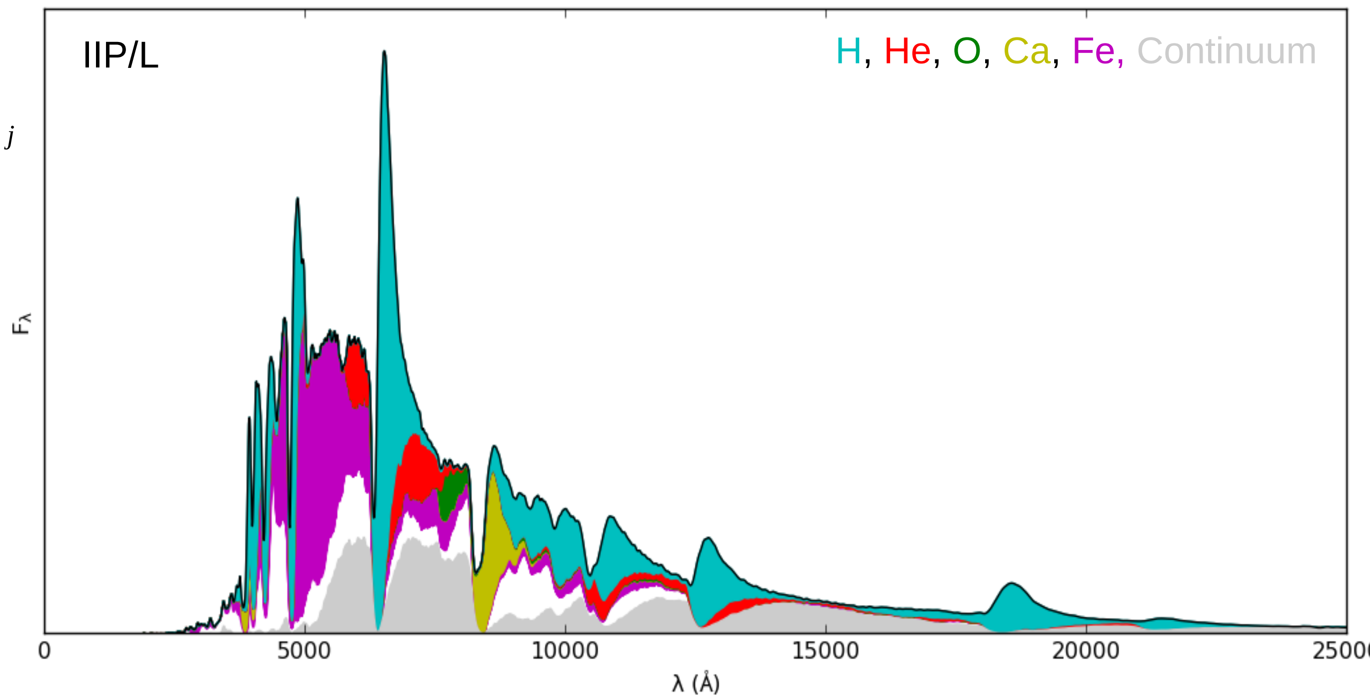
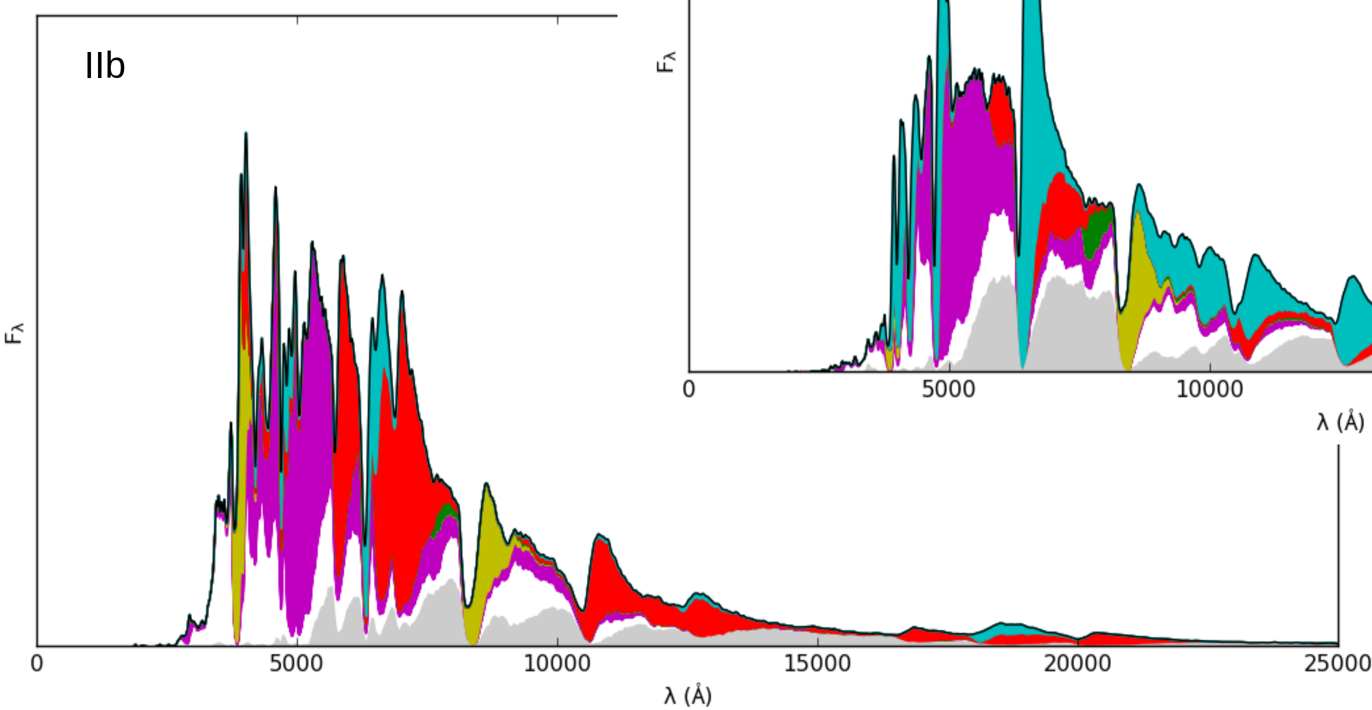
In collaboration with Claes Fransson, Anders Jerkstrand, Markus Kromer, Cecilia Kozma and Kristoffer Spricer

$$\frac{\partial n_i}{\partial t}+\nabla\cdot(n_i\boldsymbol{u})=\sum r_{j,i}n_j-n_i\sum r_{i,j}$$





$$\frac{1}{c}\frac{\partial I}{\partial t}+\boldsymbol{n}\cdot\nabla I=\eta-\chi I$$

The JEKYLL code

What: Realistic* simulations of the spectral evolution and lightcurves of SNe in the photospheric and nebular phase.

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

* Restrictions:

Homologous expansion.
Spherical symmetry.
Steady-state for the matter (work in progress).

NLTE

NLTE: Non-LTE
LTE: Local Thermodynamic Equilibrium

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

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

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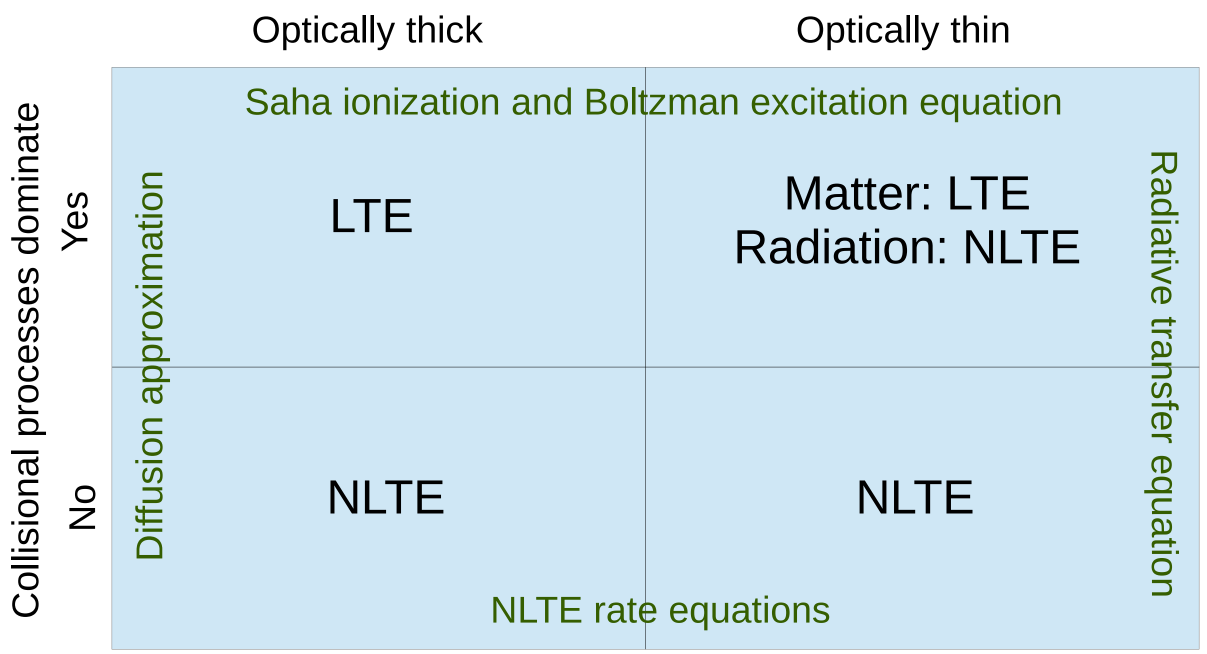

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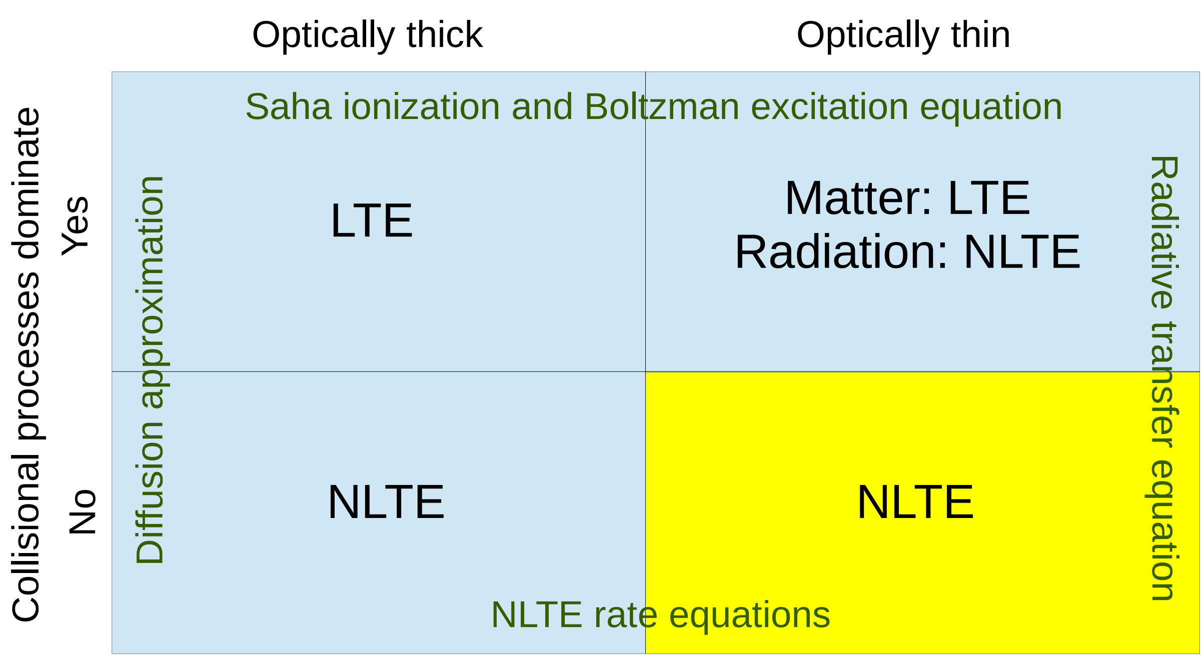
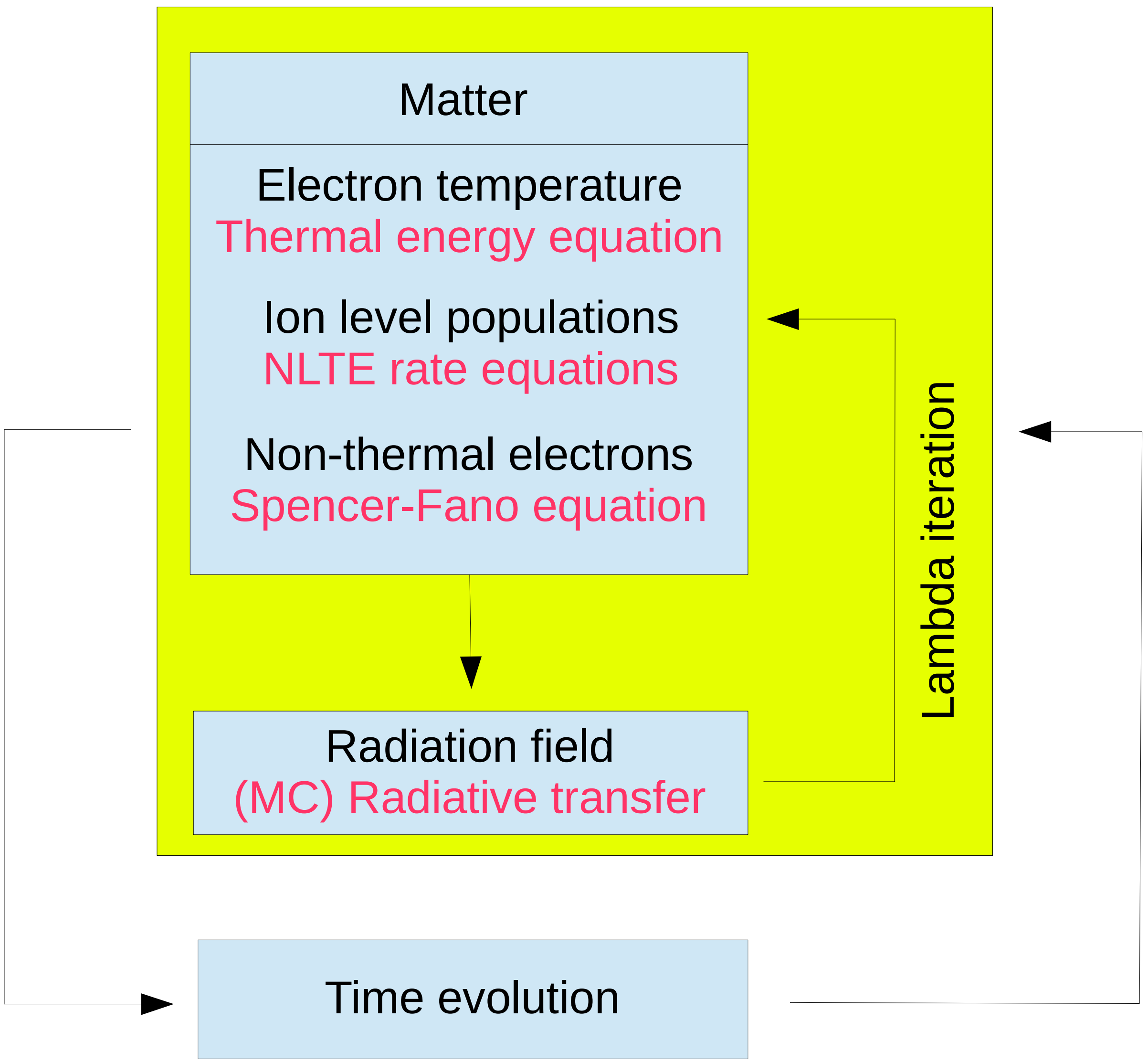


In the outer parts and at late times, SNe ejecta are neither optically thick, nor collisionally dominated,
<u>so a full NLTE solution is required.</u>

Method outline



MC radiative transfer

Following and extending the method by Lucy (2002, 2003, 2005).

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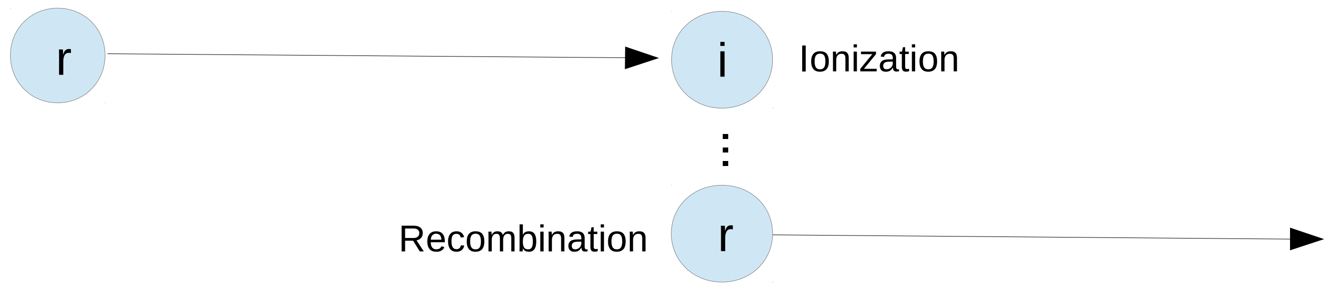
The MC packets carry energy.

Radiation packets are propagated and interacts with the matter.

When absorbed, packets are converted into excitation, ionization or thermal energy.

When emitted, packets are converted into radiation energy.



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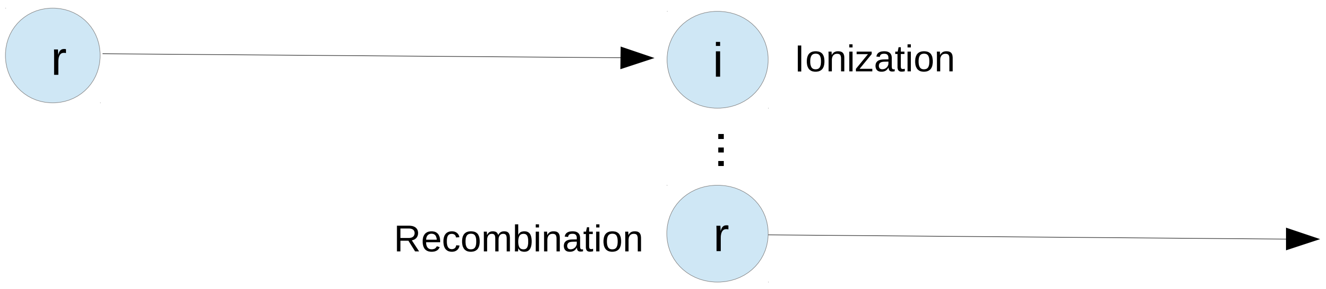
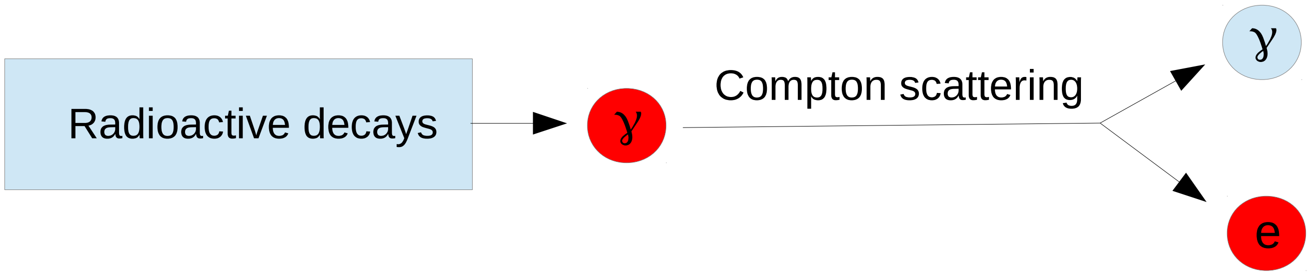
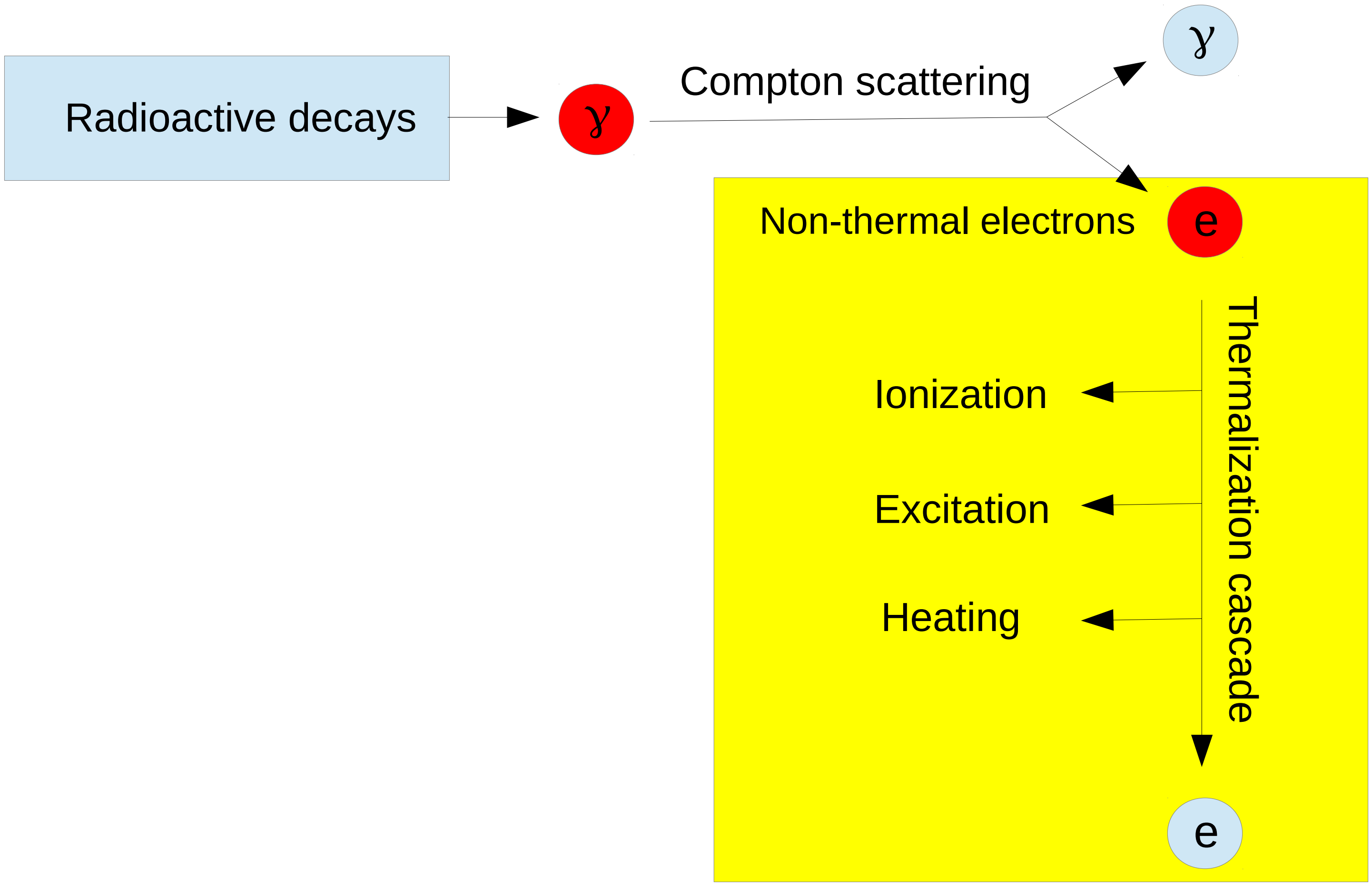


Rule number one: The MC packet energy is conserved.

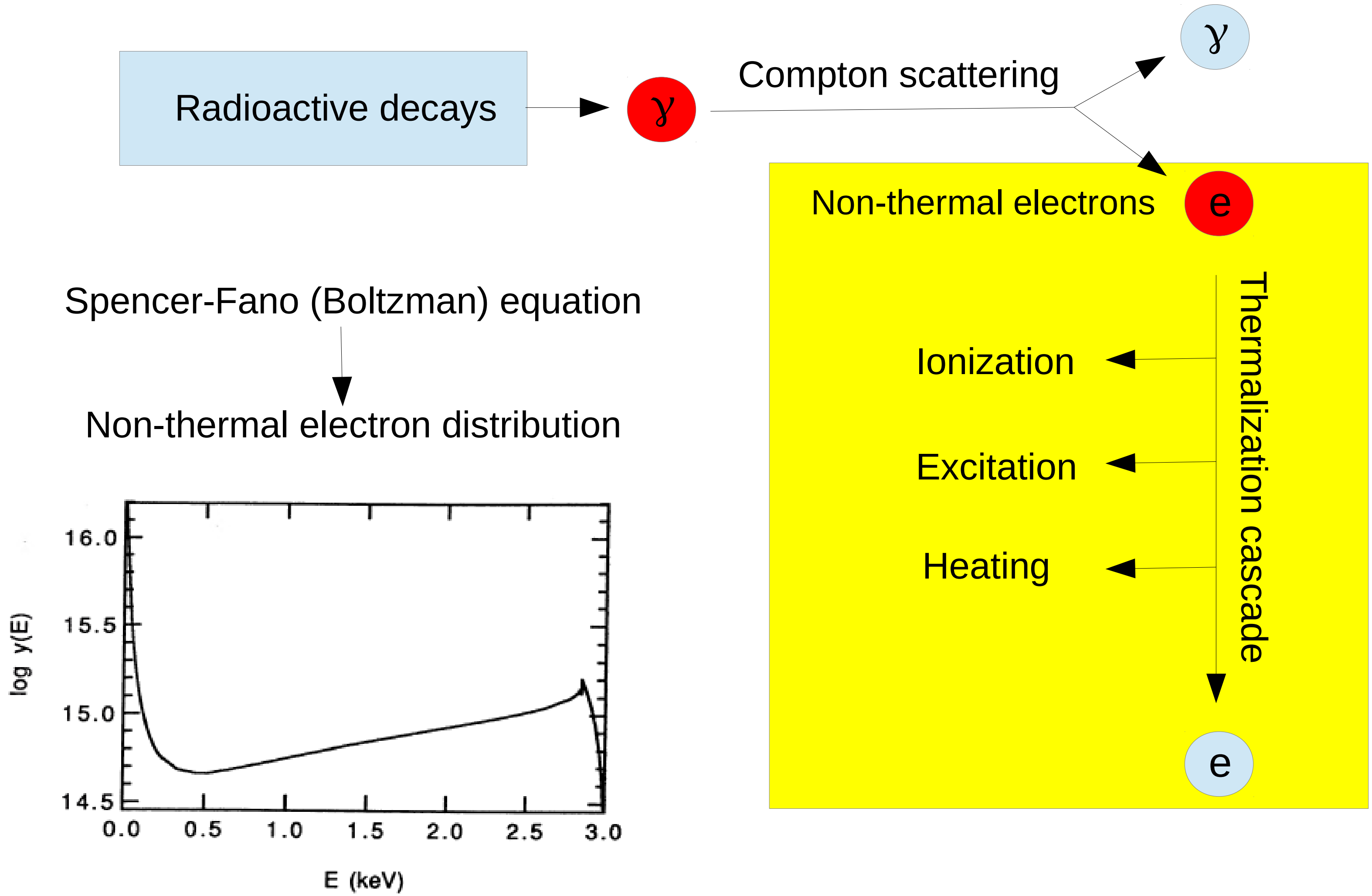
Non-thermal electrons



Non-thermal electrons

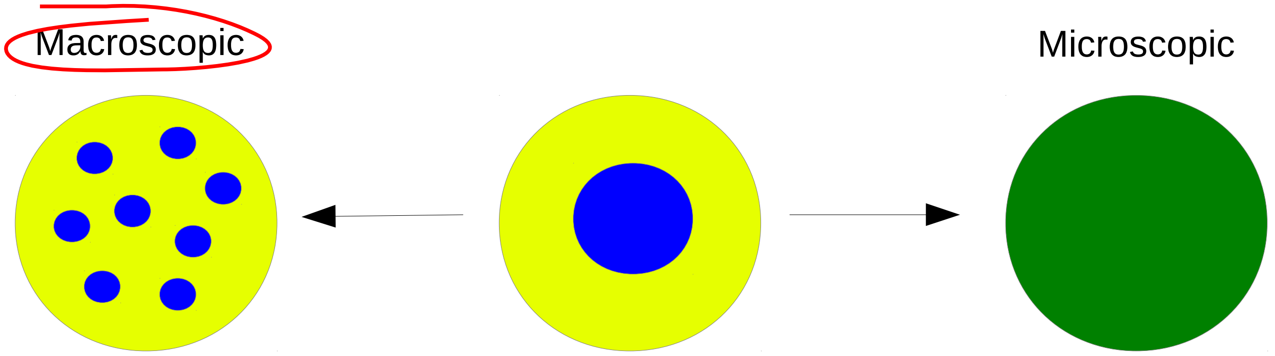


Non-thermal electrons



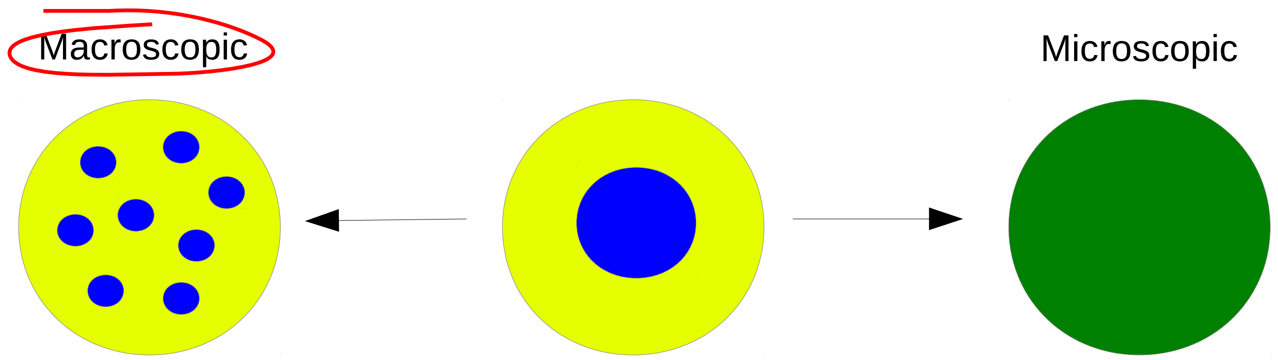
Problem solved by Kozma & Fransson (1998),
and their original FORTRAN routine has been integrated into JEKYLL.

Mixing



Hydrodynamical instabilities → <u>Macroscopic mixing</u> of the nuclear burning zones.

Mixing



Hydrodynamical instabilities → <u>Macroscopic mixing</u> of the nuclear burning zones.

Macroscopic vs Microscopic mixing

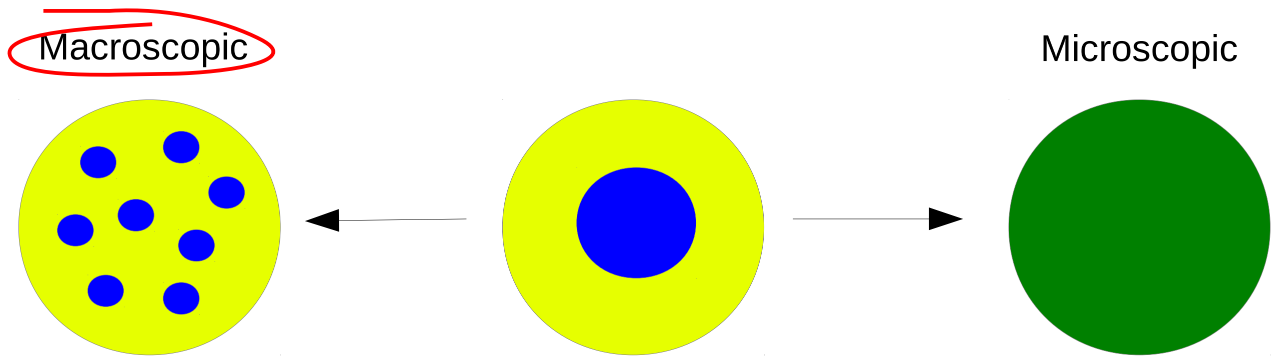
↓

Different composition and (possibly) density

↓

Different temperature, degree of ionizaton etc.

Mixing



Hydrodynamical instabilities → Macroscopic mixing of the nuclear burning zones.

Macroscopic vs Microscopic mixing

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Different composition and (possibly) density

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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.

Other similar codes

SEDONA (Kasen et al. 2006)

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

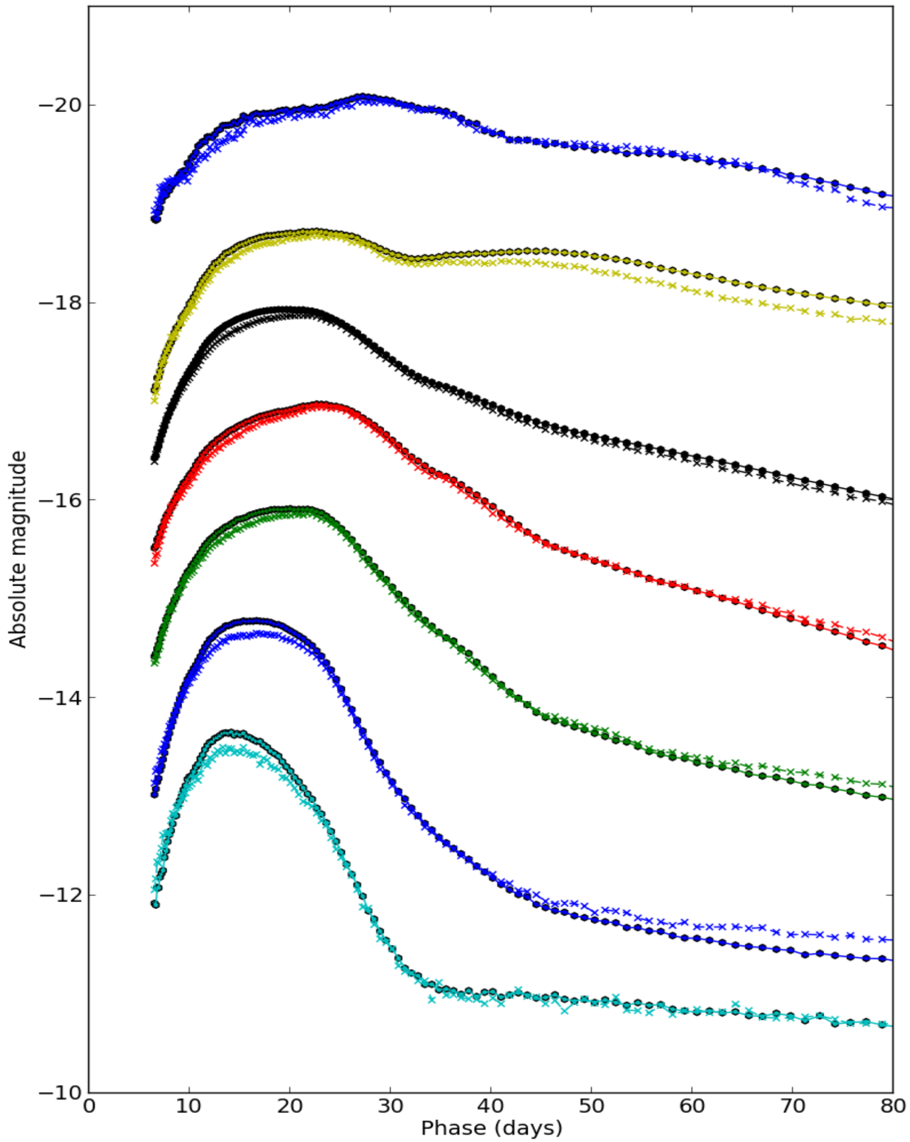
CMFGEN (Hillier 1998)

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

+ Mazzali (2000,2001), Kerzendorf et al. (2014) and more.

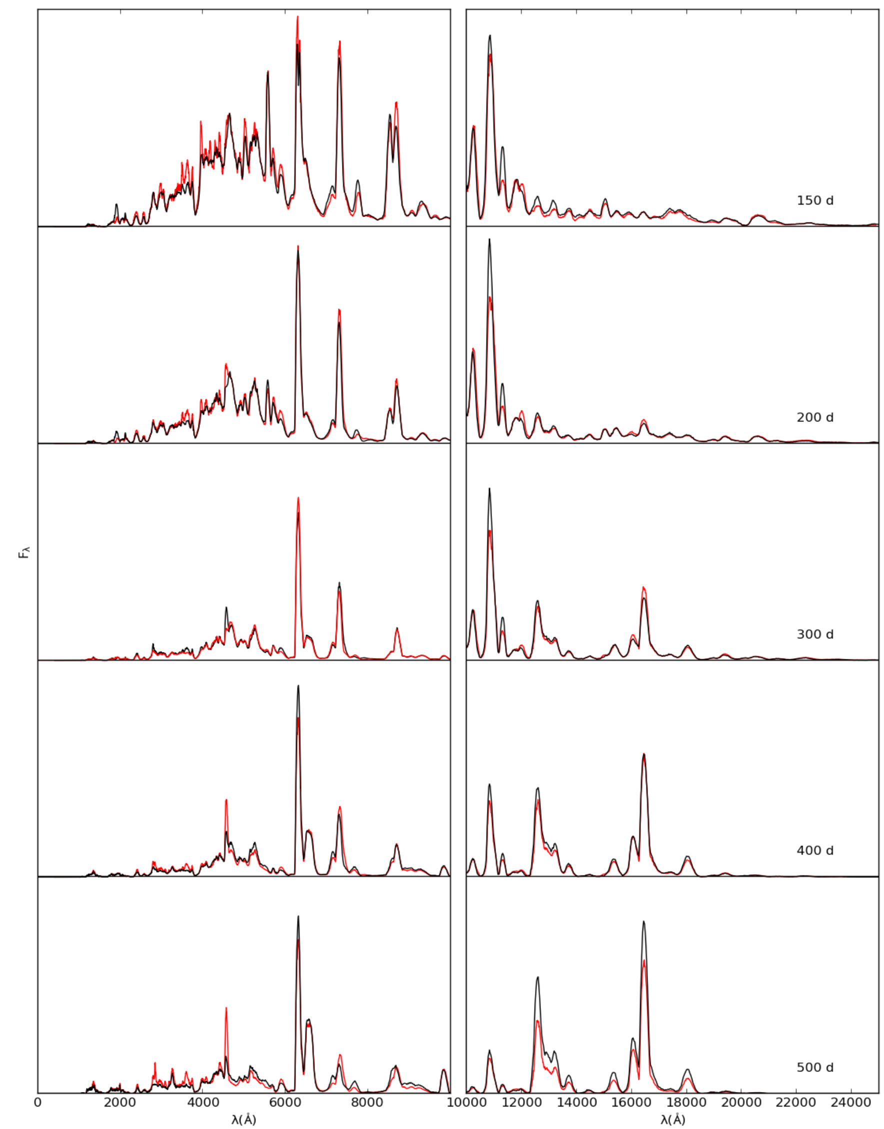
Comparisons

JEKYLL (circles) and ARTIS (crosses)



Early lightcurves for Type IIb model 12C

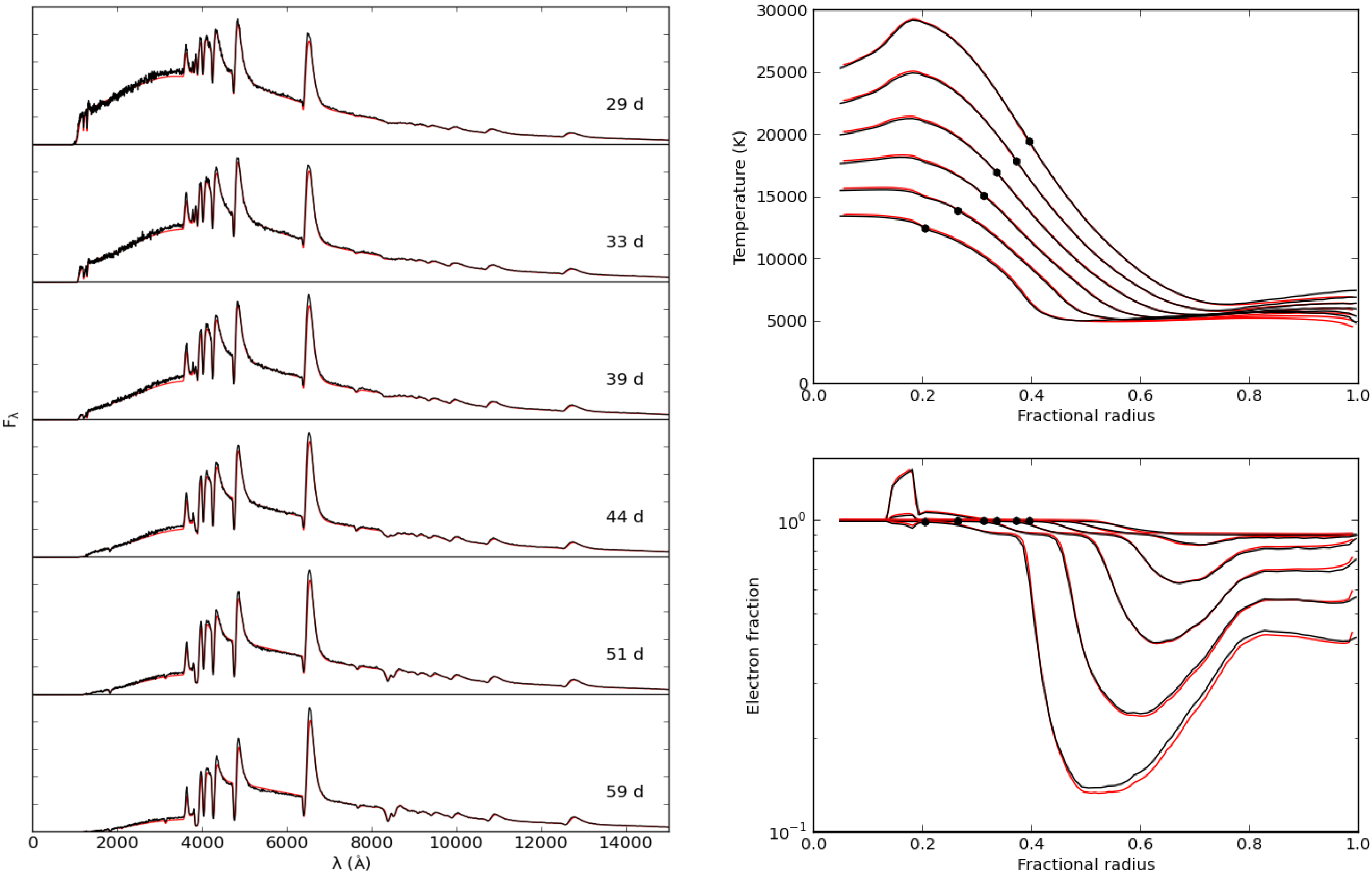
JEKYLL and SUMO



Nebular spectra for Type IIb model 13G

Comparisons

JEKYLL and CMFGEN

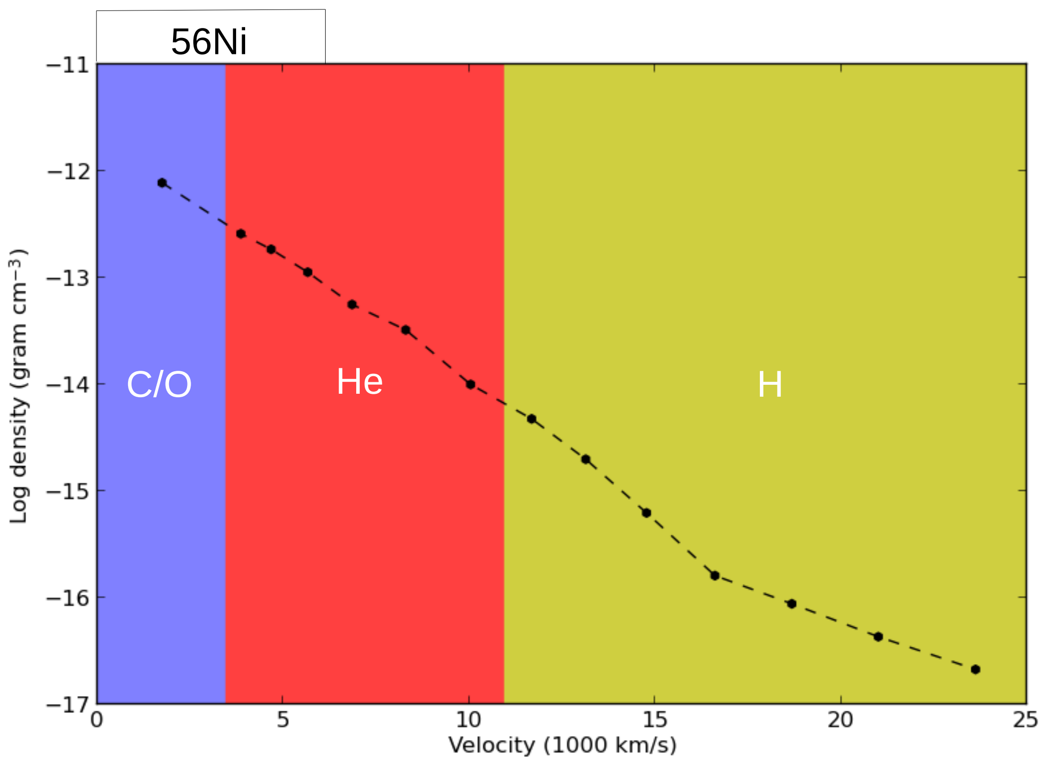


Type IIb models: Background

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



$M_{In} = 12\,M_\odot$

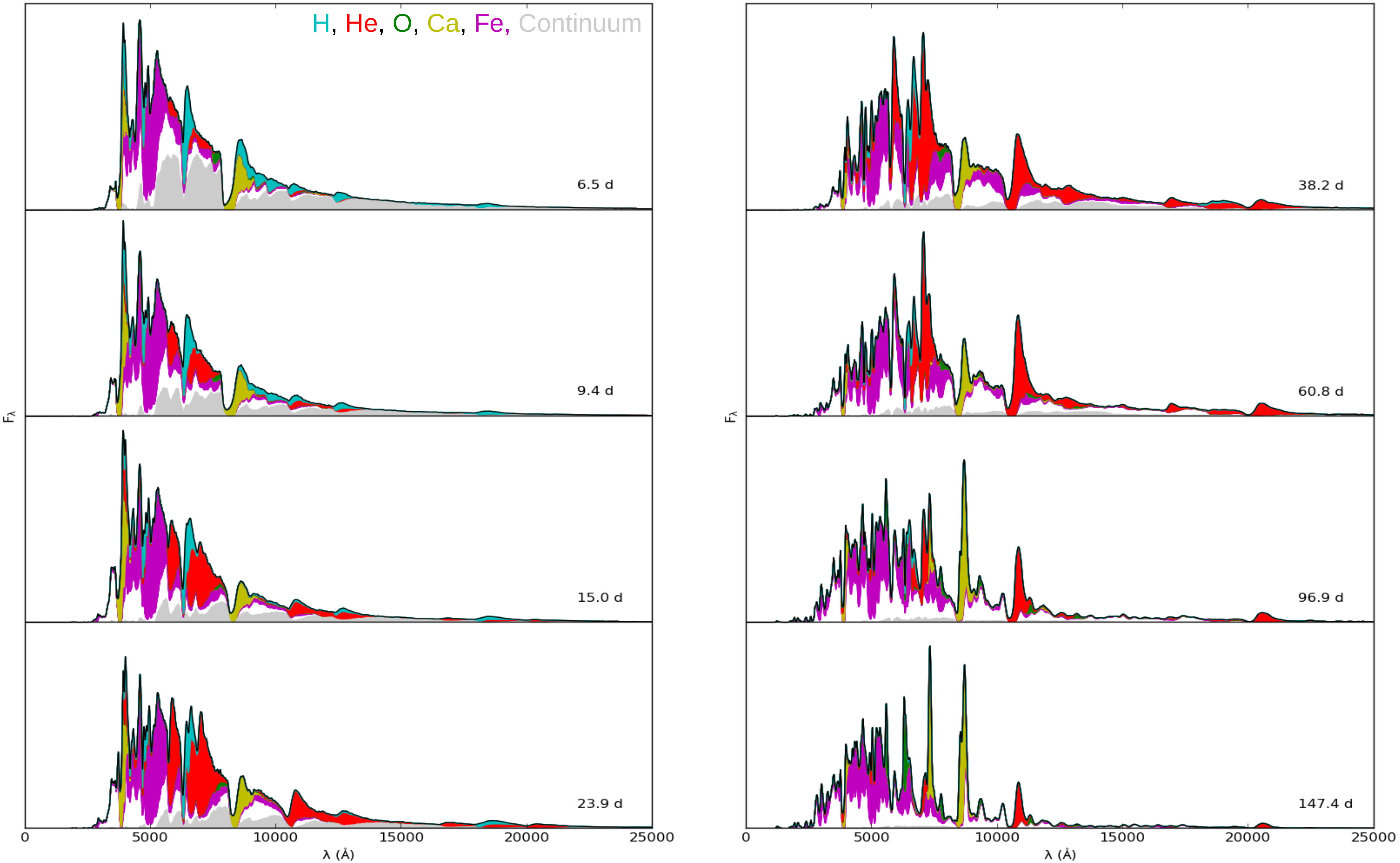
$M_{Ej} = 1.7\,M_\odot$

$M_{Ni} = 0.075\,M_\odot$

$E_K = 6.8 \times 10^{50}$ erg

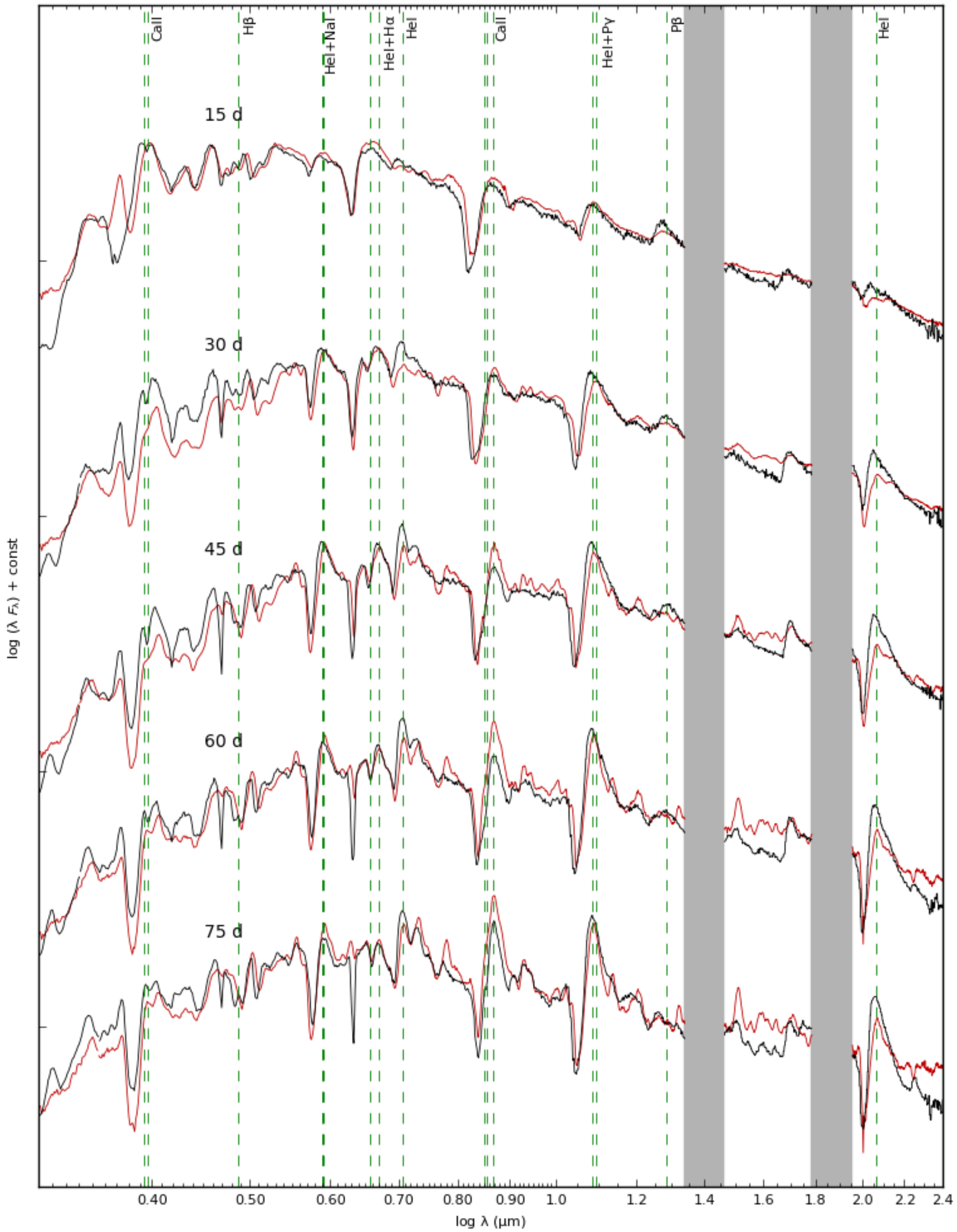
Type IIb models: Spectral evolution

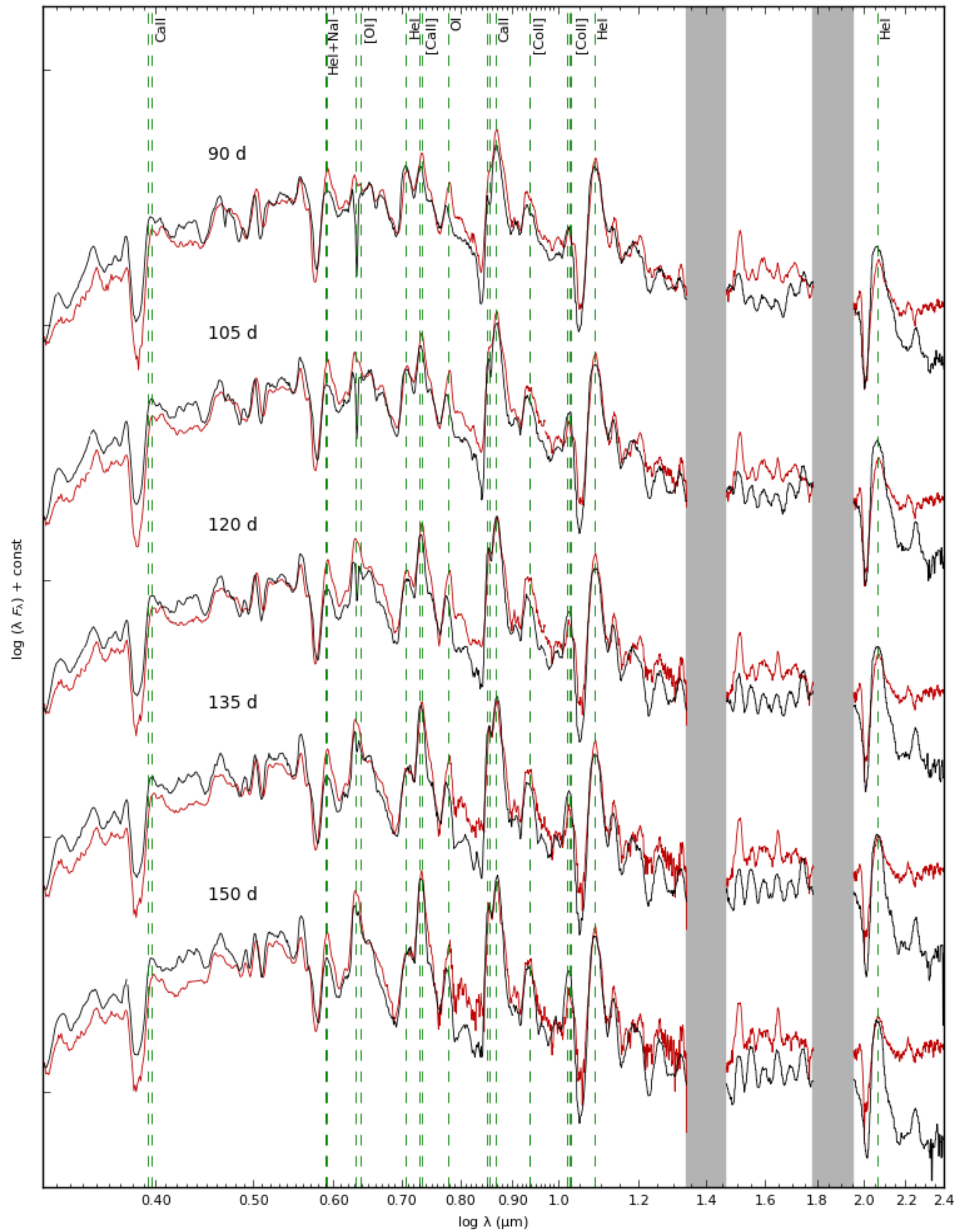
Model 12C: Before 150 days



Comparison to SN 2011dh: Spectral evolution

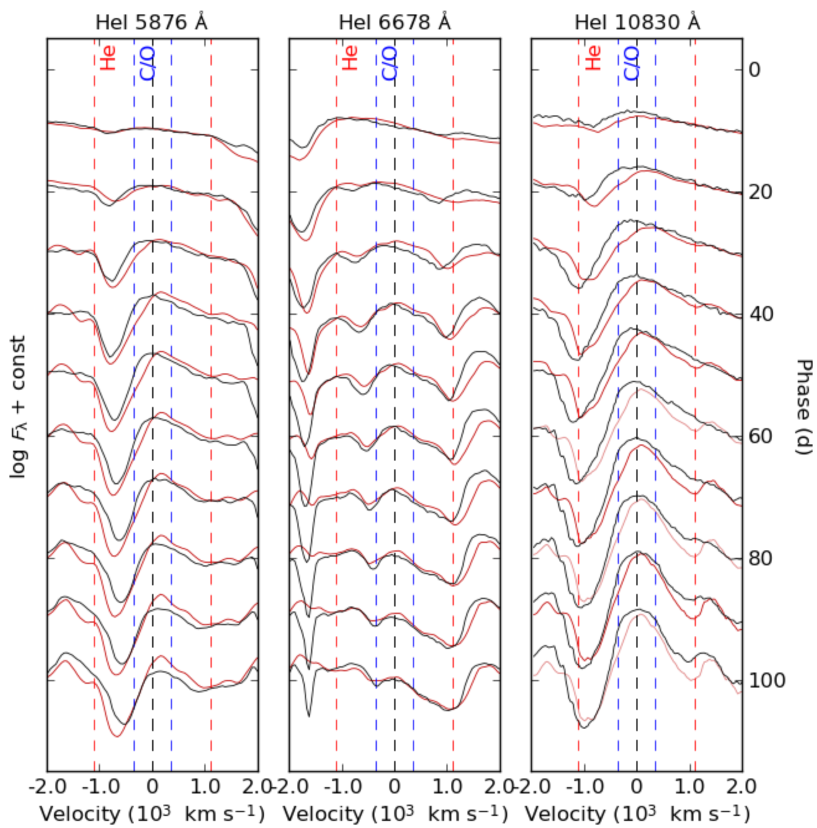
Model 12C and SN 2011dh – Before 150 days



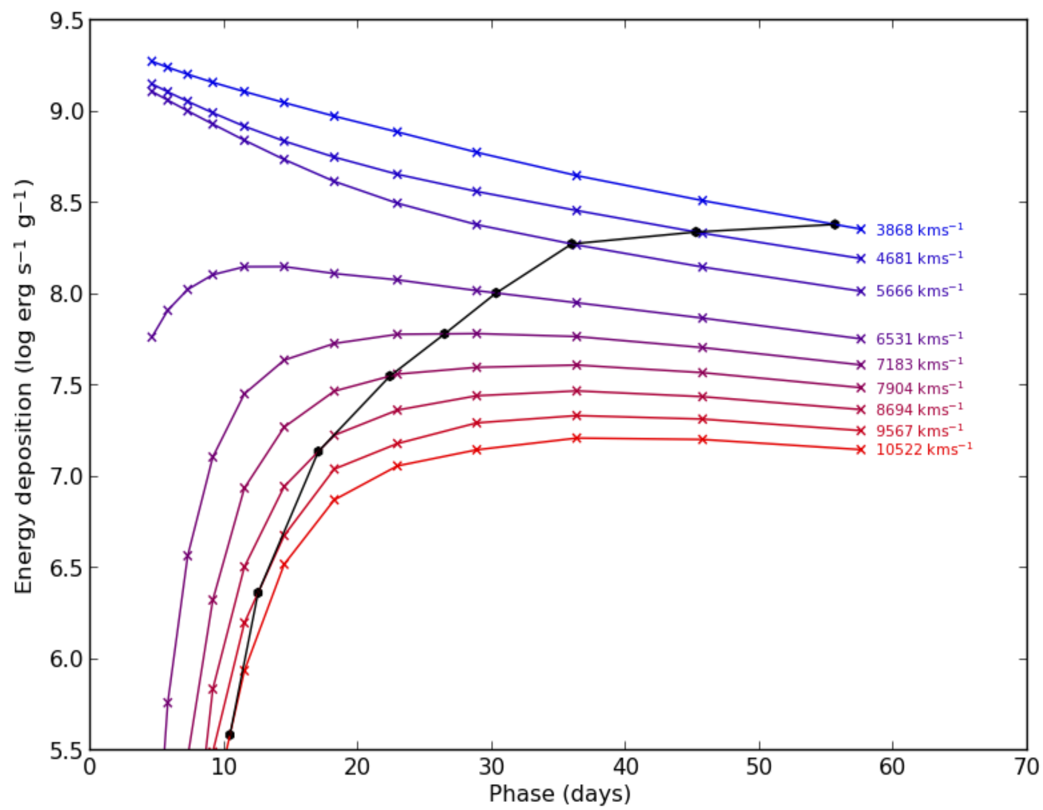


Comparison to SN 2011dh: Helium lines

Model 12C and SN 2011dh – Before 100 days

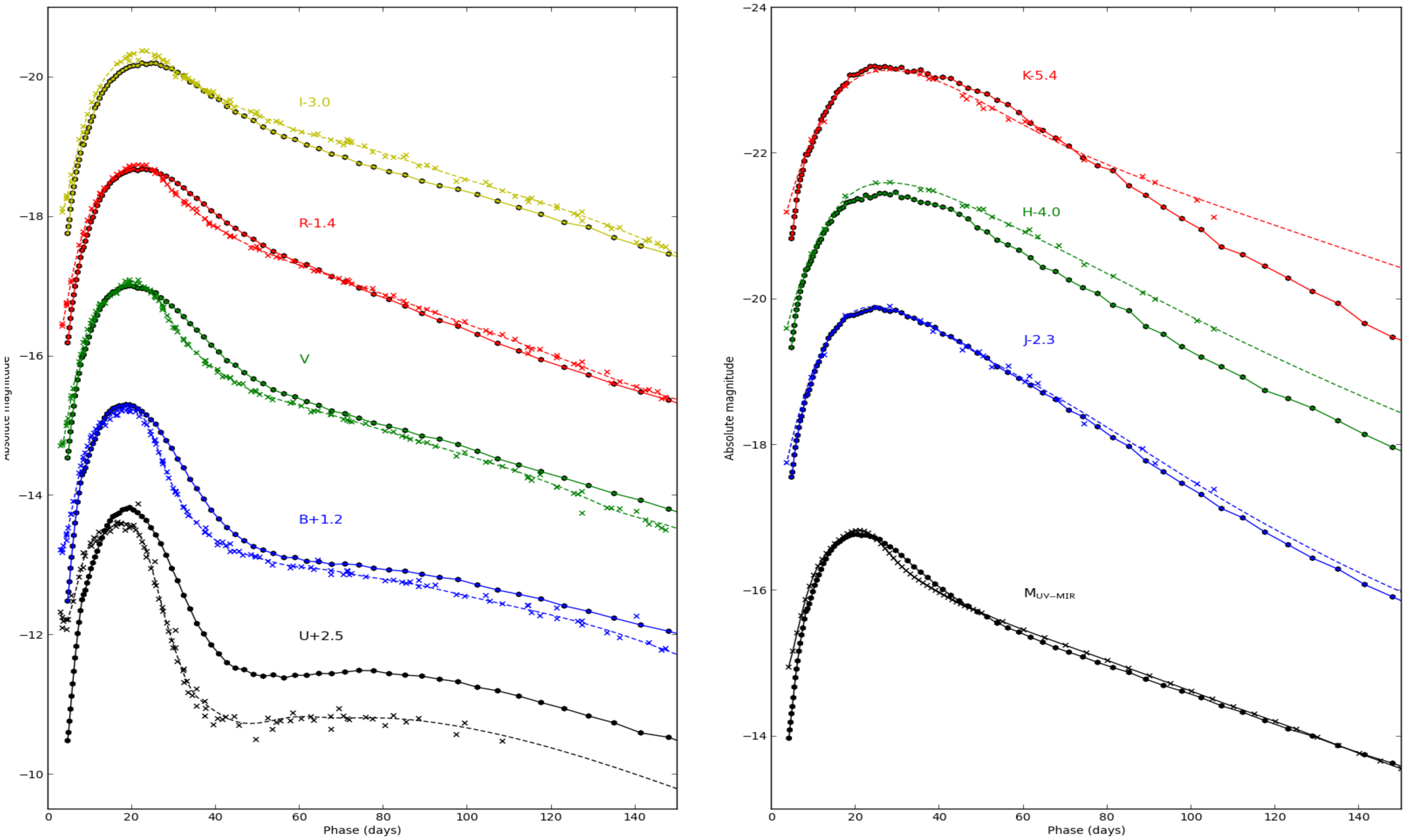


Radioactive energy deposition in the helium envelope

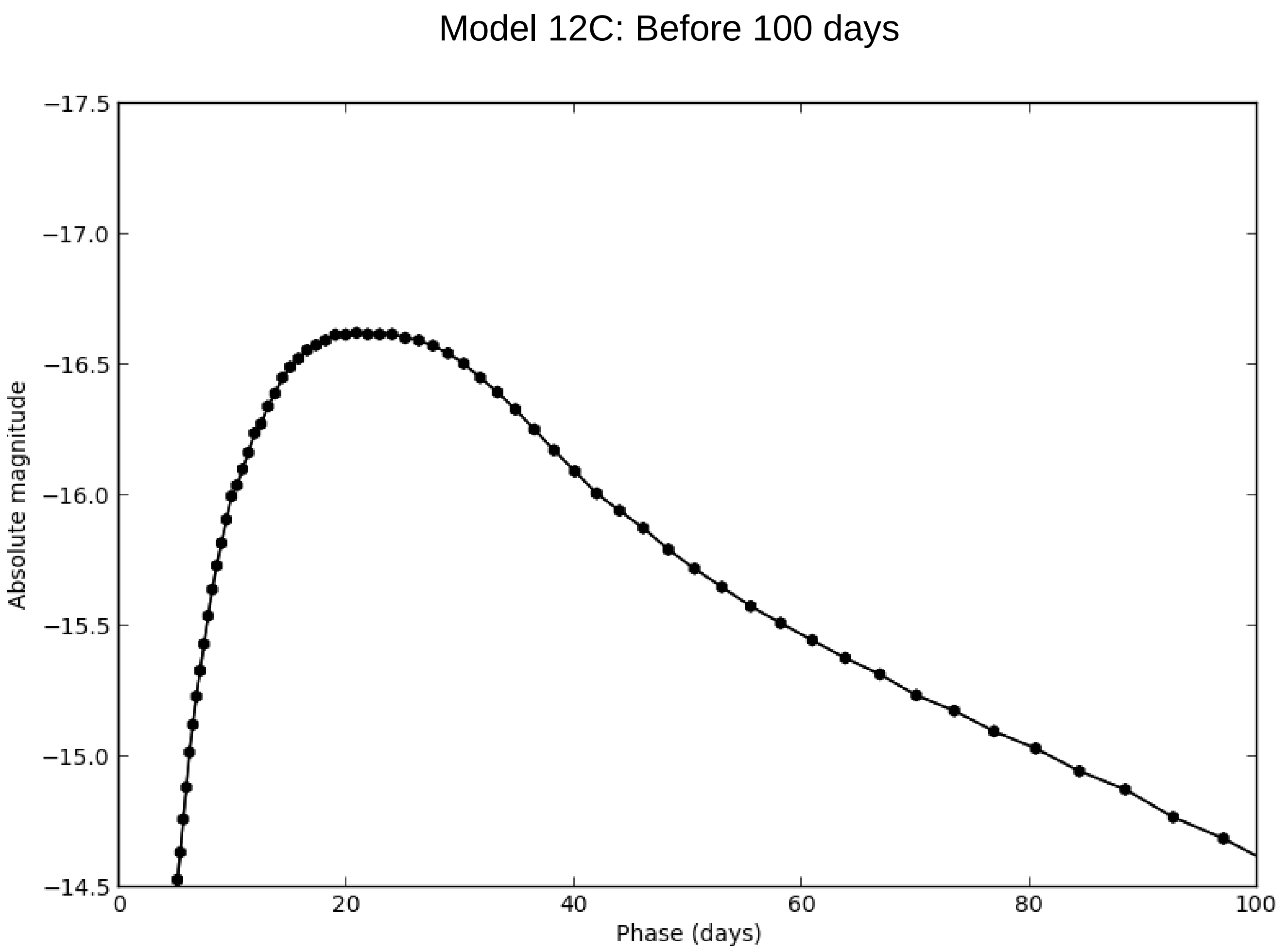


Comparison to SN 2011dh: Lightcurves

Model 12C (circles) and SN 2011dh (crosses): Before 150 days



Effect of NLTE: Bolometric lightcurve



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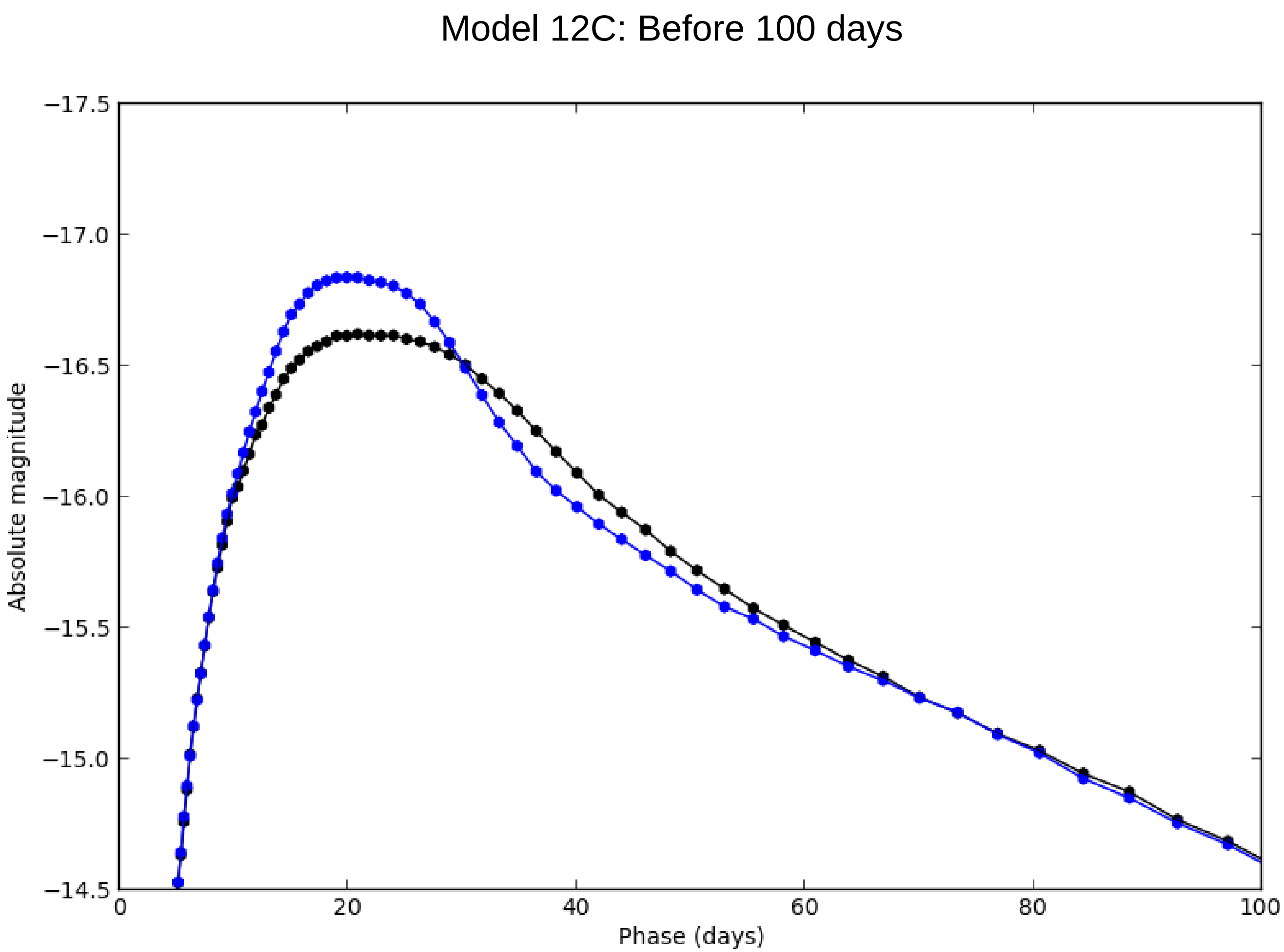
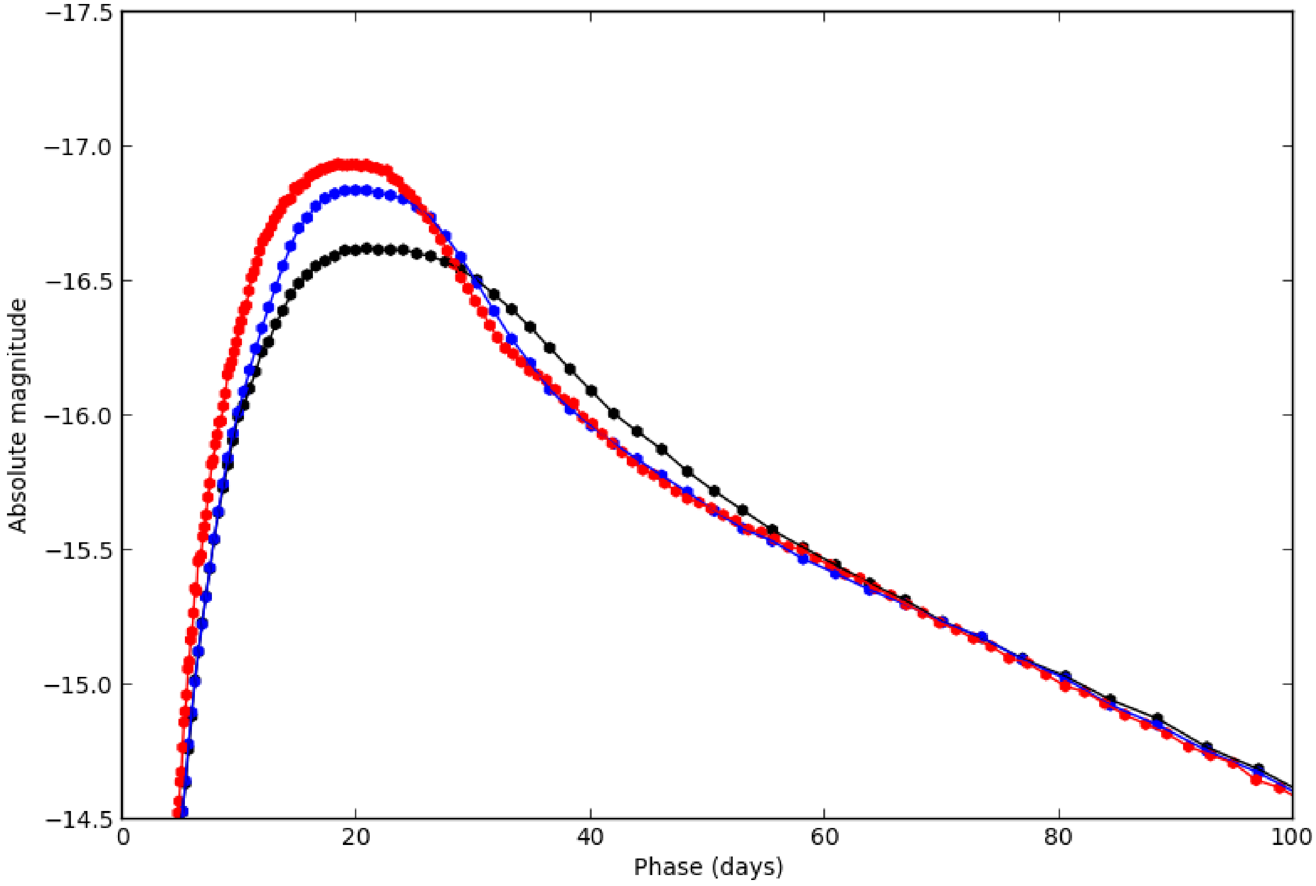


Non-thermal ionization/excitation - Off

Effect of NLTE: Bolometric lightcurve

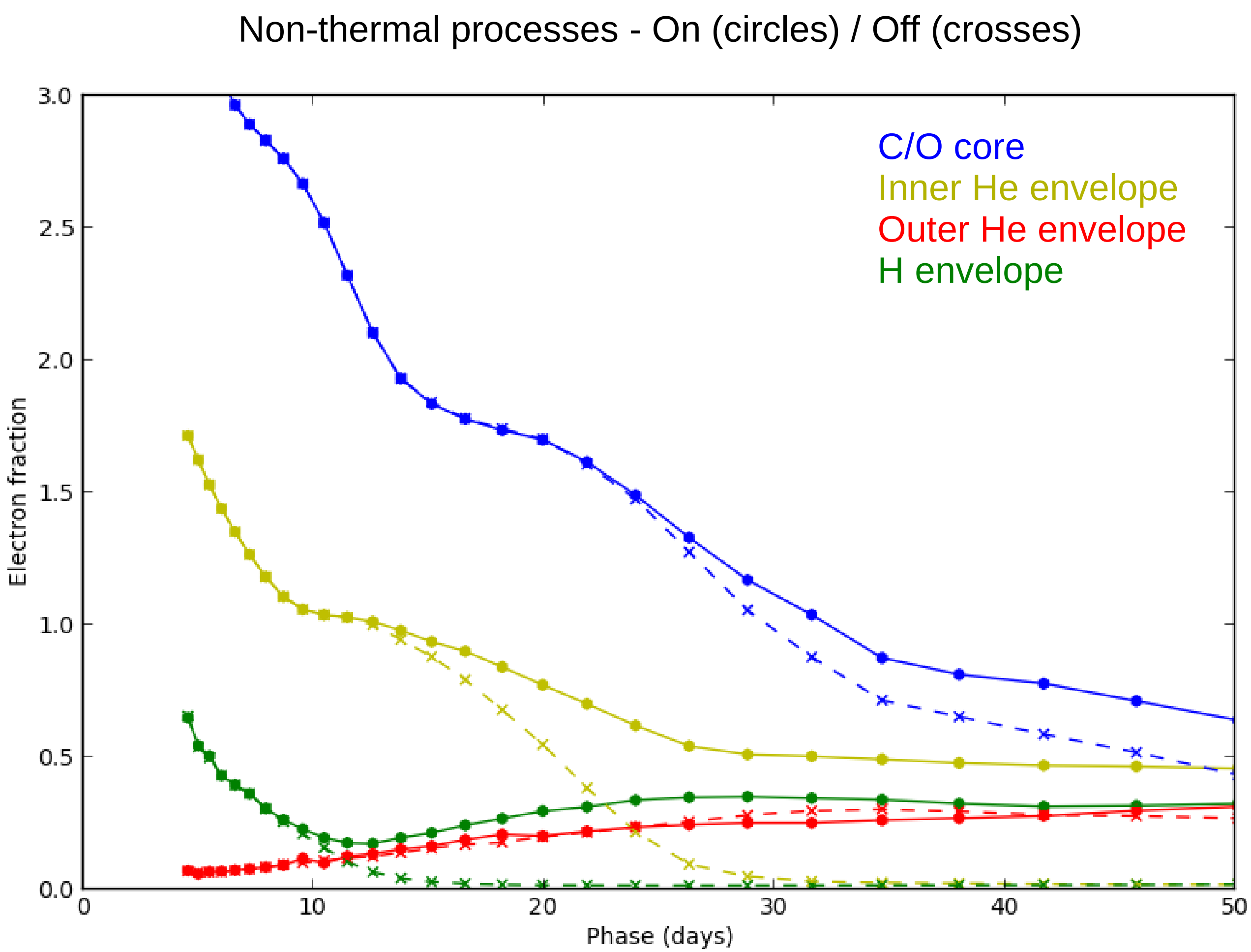
Model 12C: Before 100 days



Non-thermal ionization/excitation - Off

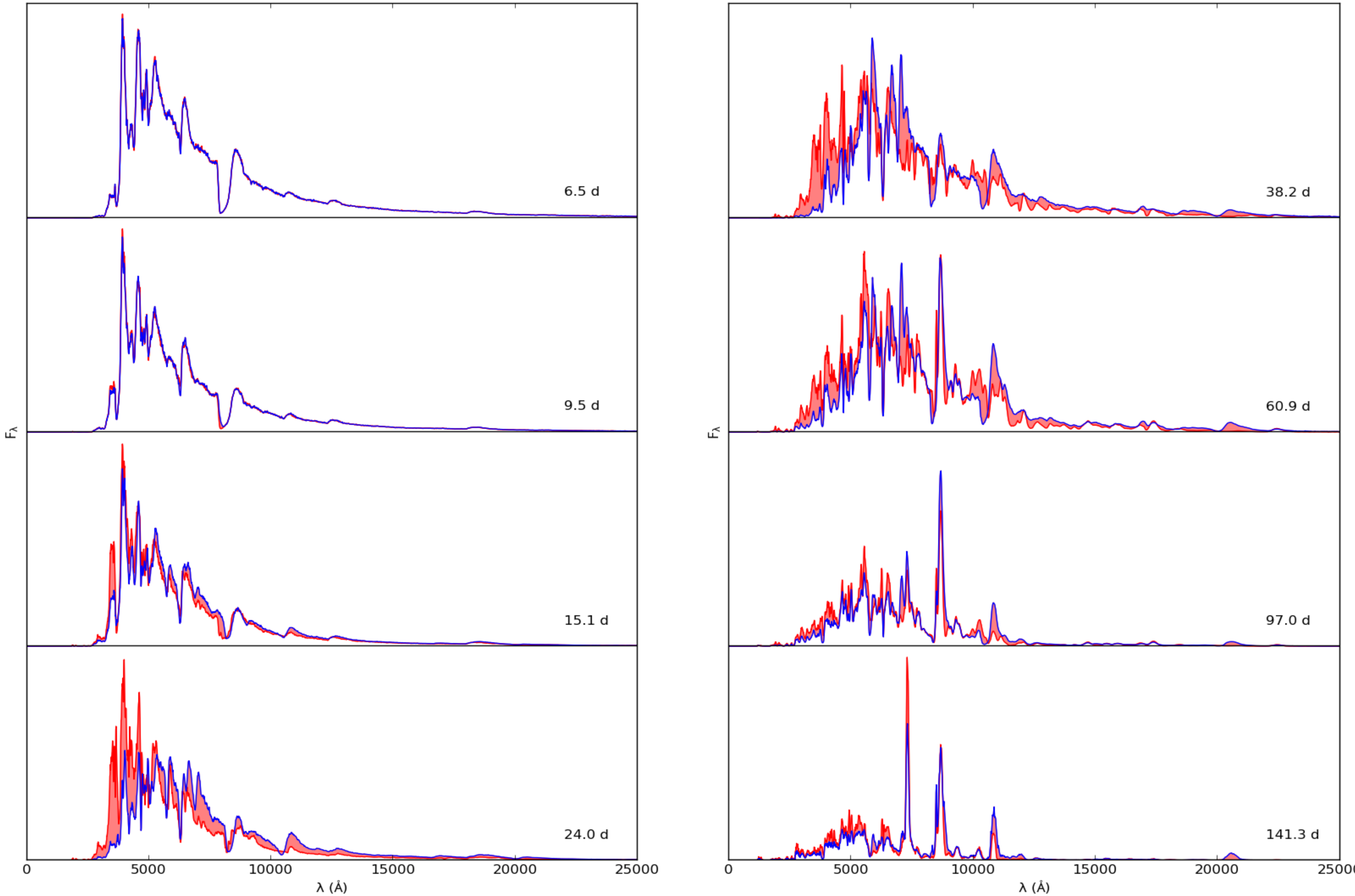
LTE

Effect of NLTE: Ionization



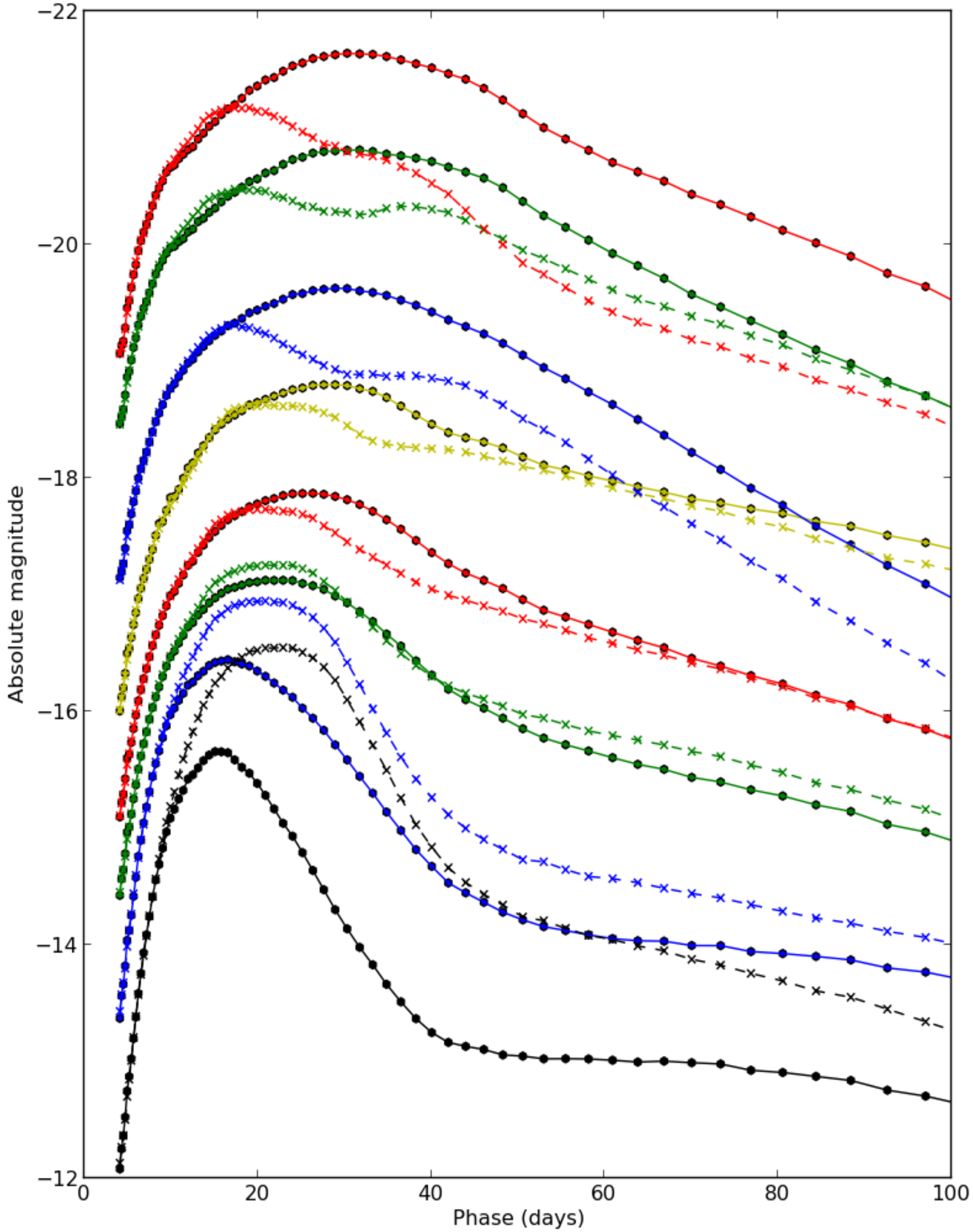
Effect of NLTE: Spectral evolution

Non-thermal ionization/excitation - On/Off

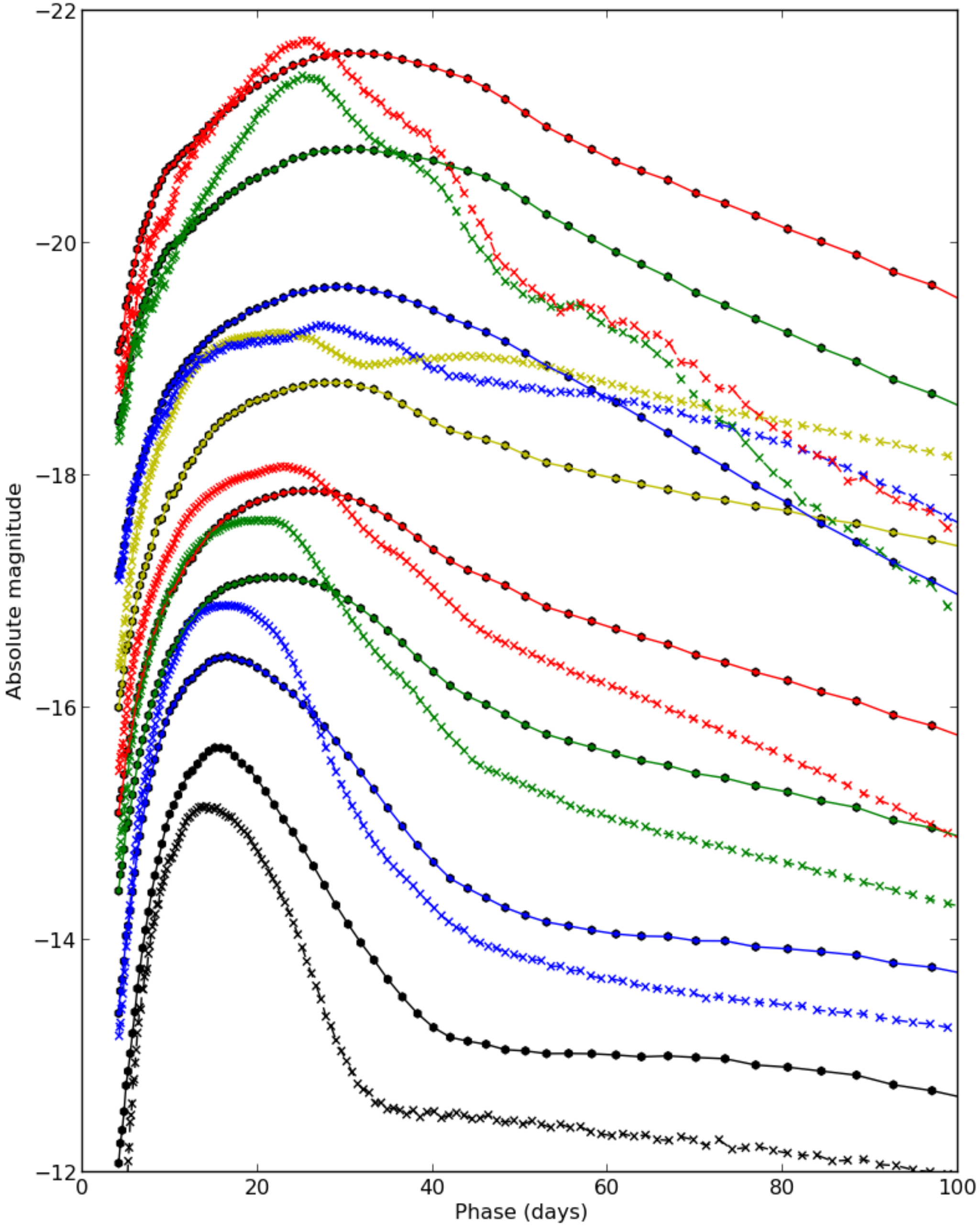


Effect of NLTE: Broadband lightcurves

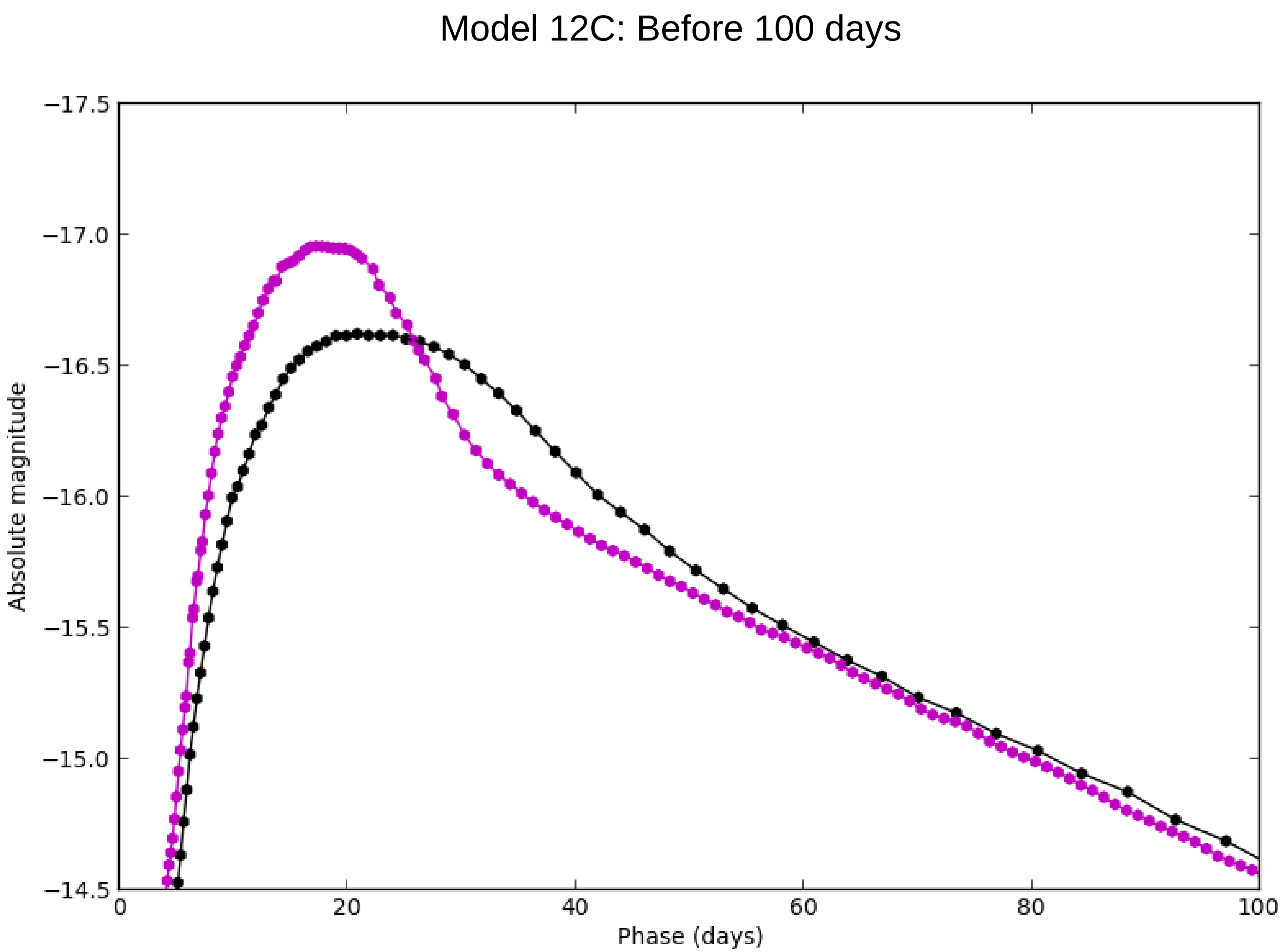
Non-thermal processes - On (circles) / Off (crosses)



NLTE (circles) / LTE (crosses)

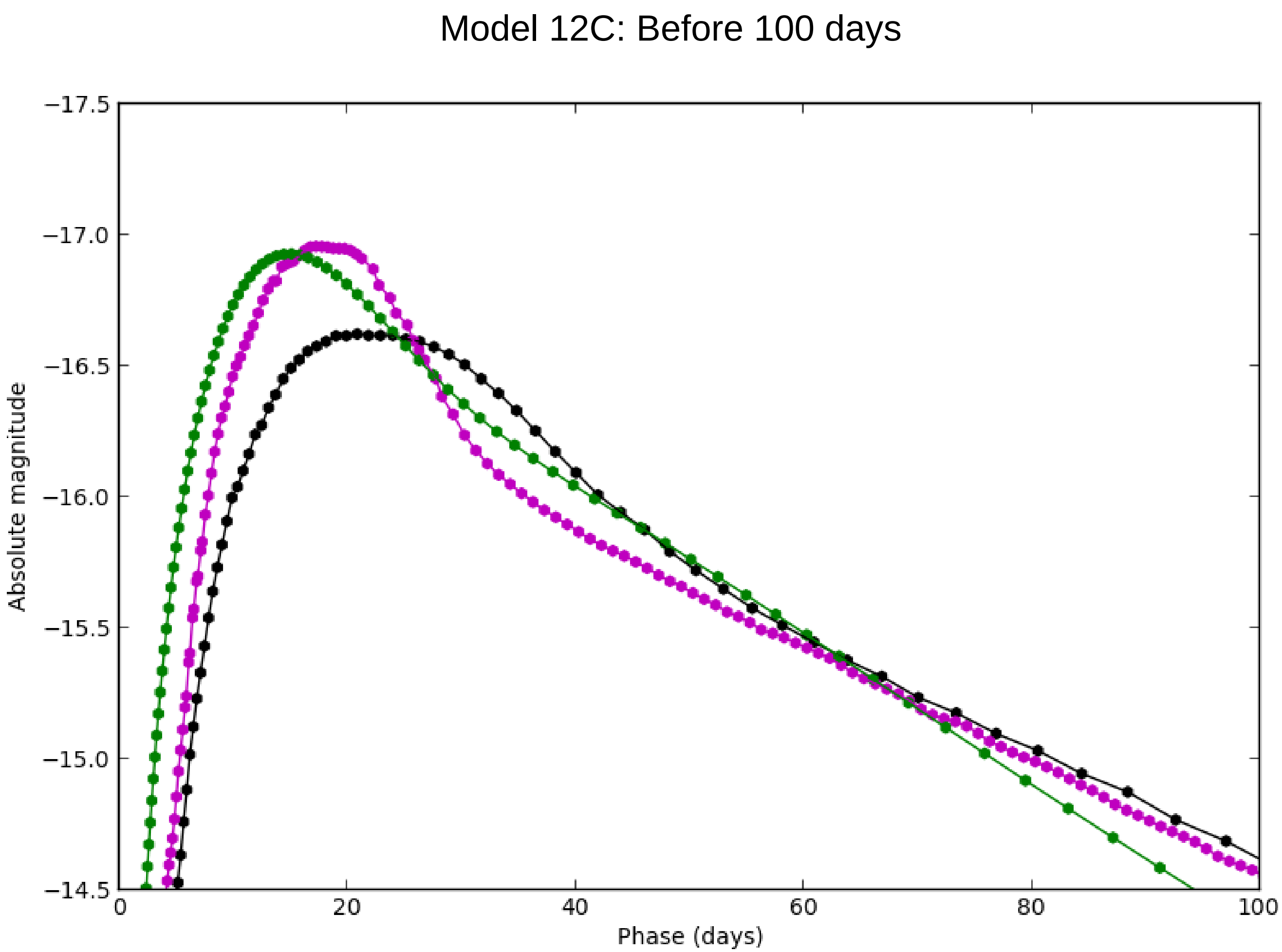


Effect of NLTE: Bolometric lightcurve



LTE + Opacity floor (HYDE)

Effect of NLTE: Bolometric lightcurve

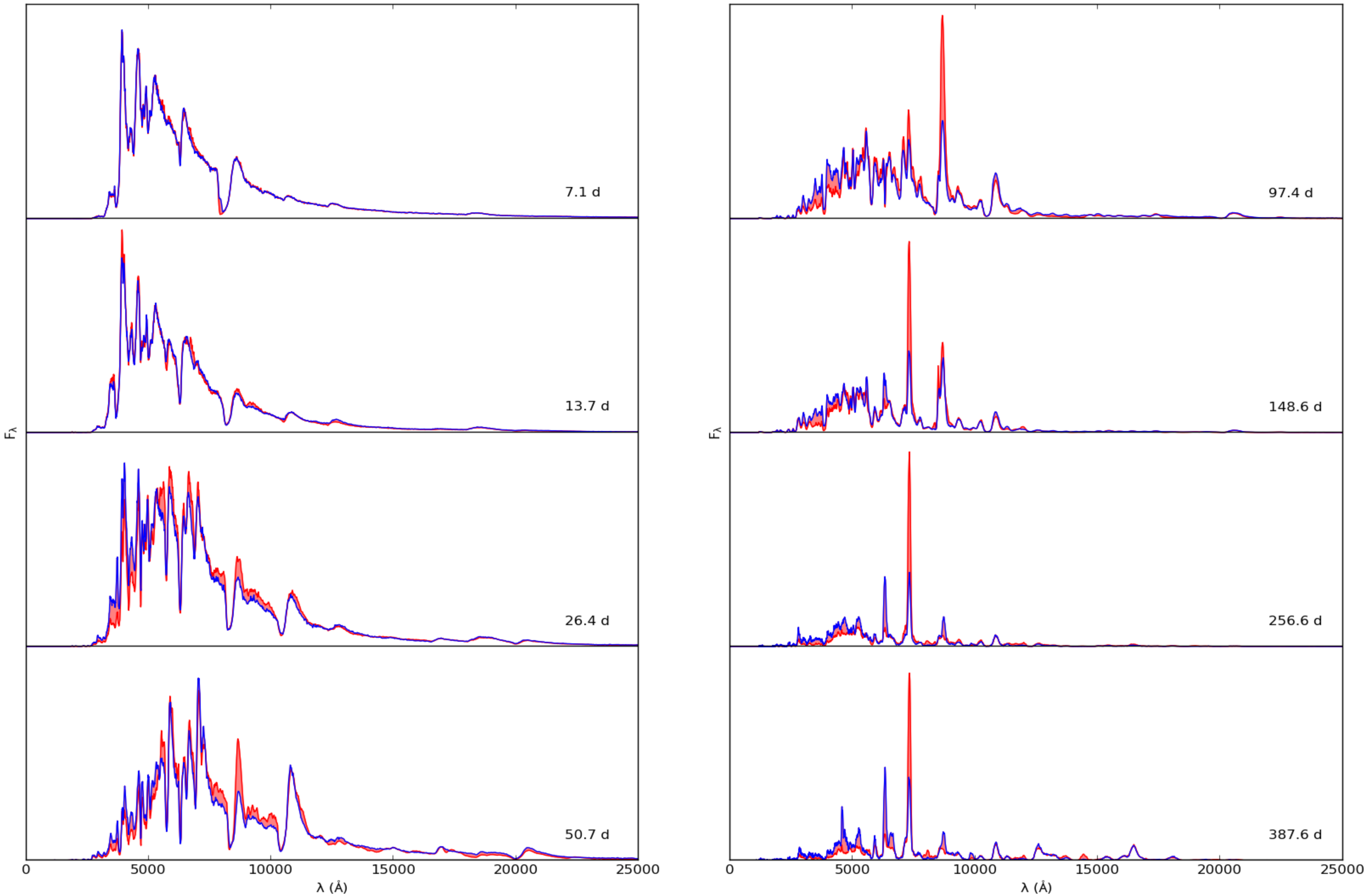


LTE + Opacity floor (HYDE)

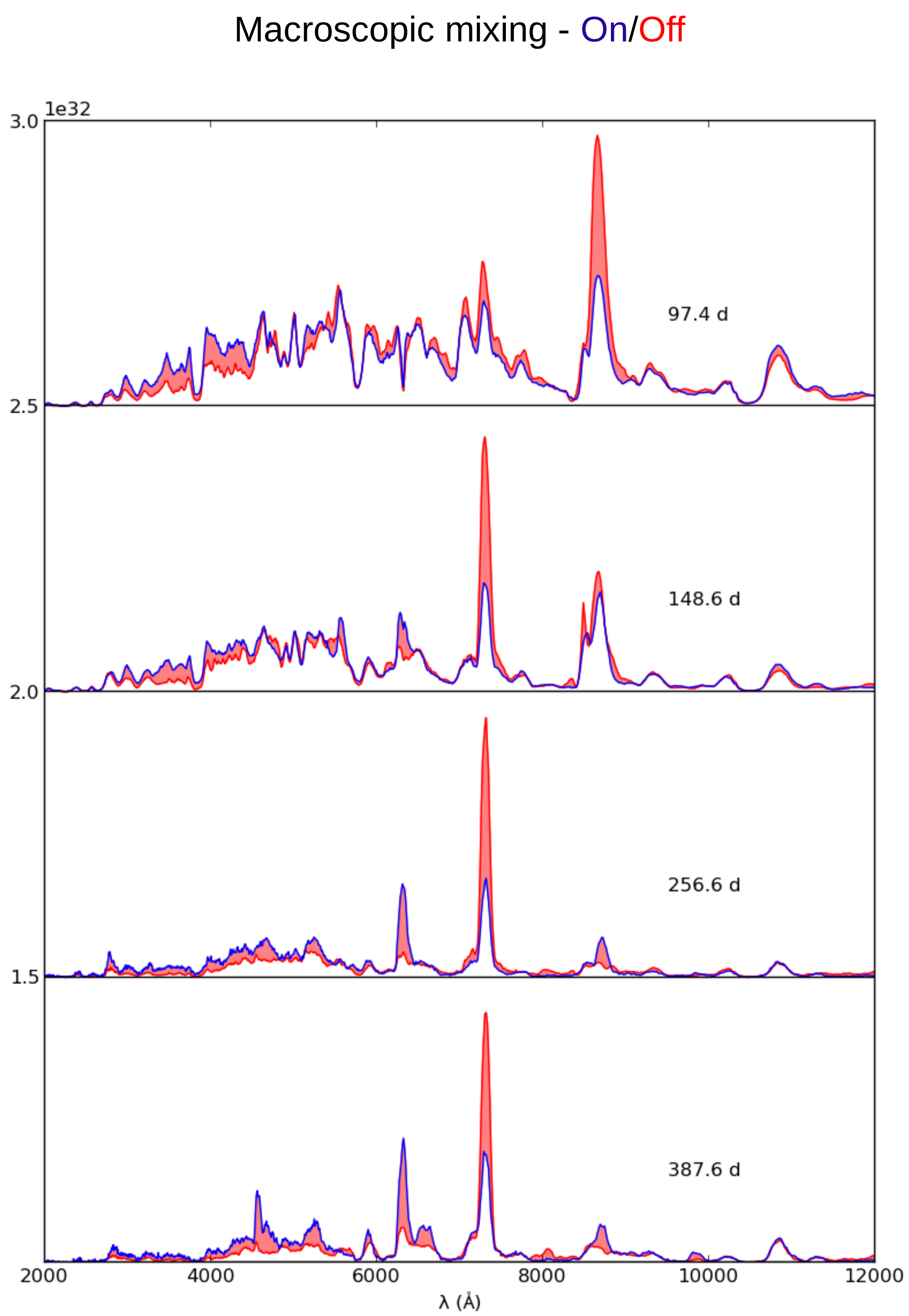
Arnett (1982) + Popov (1991)

Effect of macroscopic mixing: Spectral evolution

Macroscopic mixing - On/Off

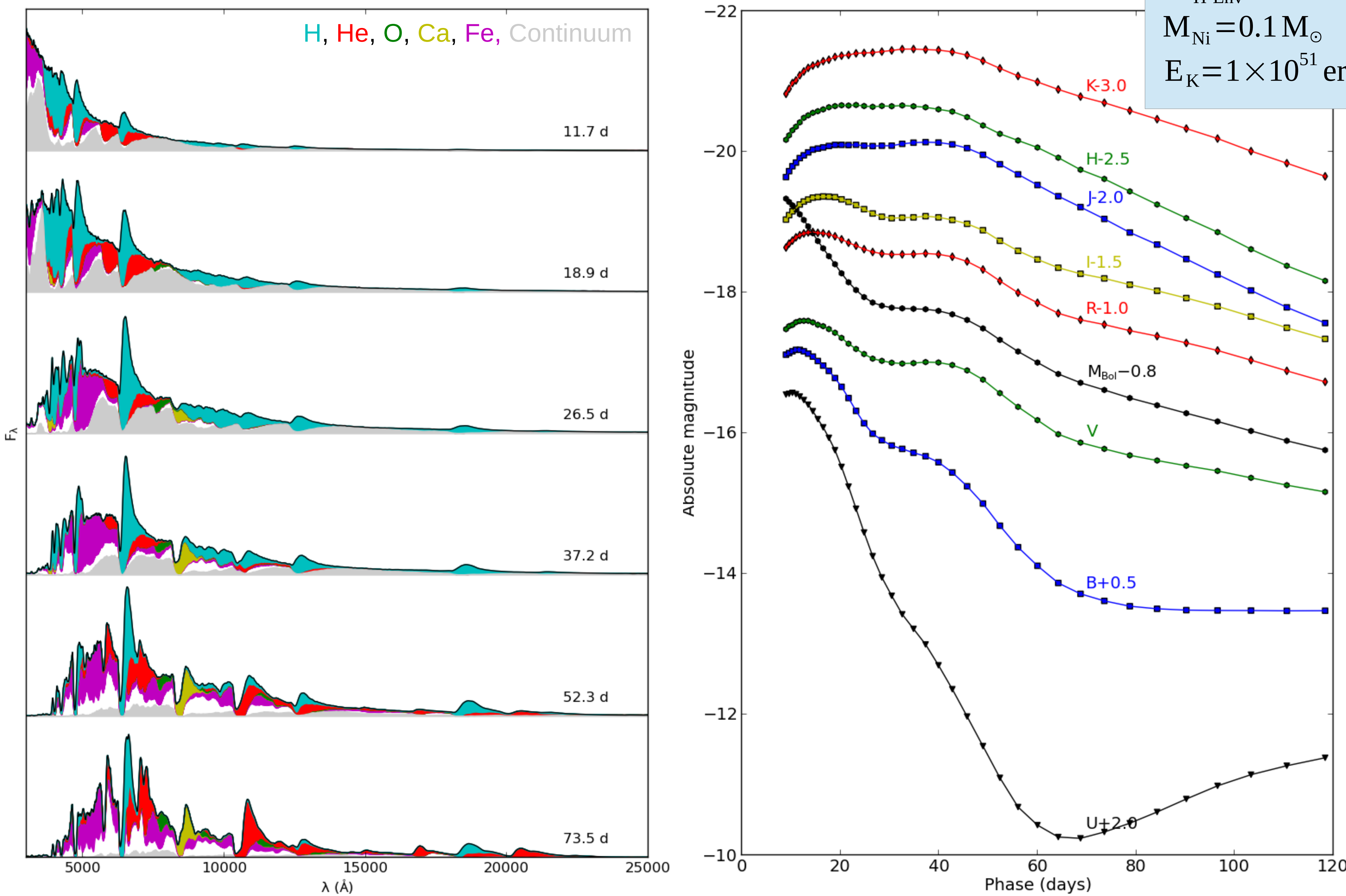


Effect of macroscopic mixing: Spectral evolution



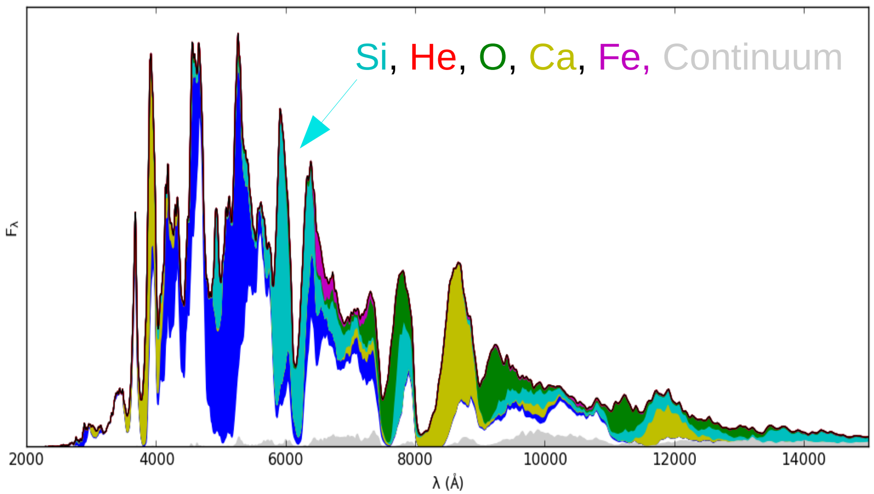
Type IIL SNe: A model with strong He lines

$M_{\text{He-Core}} = 4.0\,M_\odot$
$M_{\text{H-Env}} = 0.8\,M_\odot$
$M_{\text{Ni}} = 0.1\,M_\odot$
$E_K = 1\times10^{51}$ erg

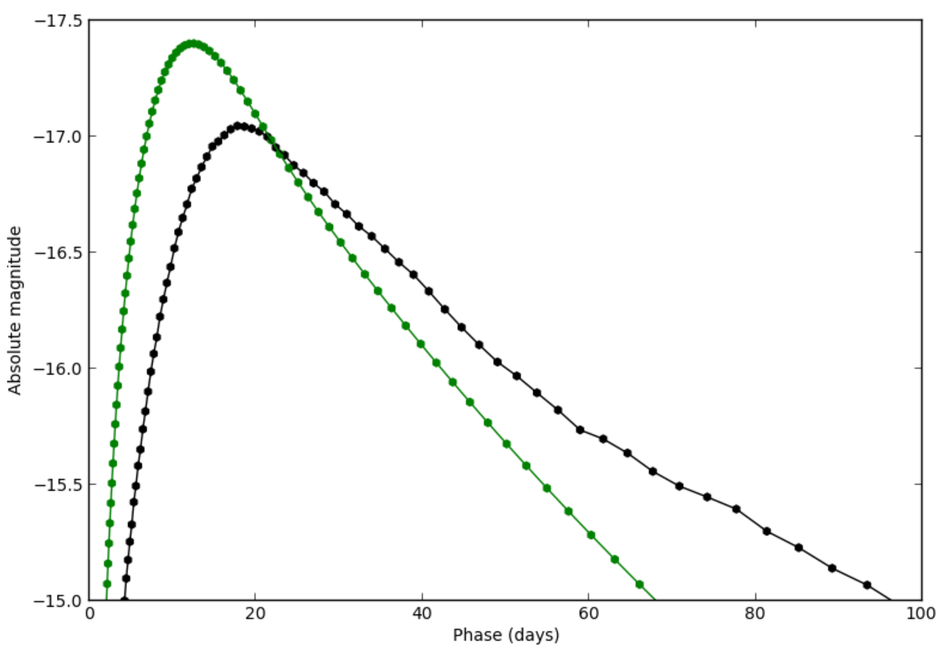


Type Ic SNe: A model with strong Si lines

Spectrum @ max



Bolometric lightcurve



Arnett (1982) + Popov (1991)

$M_{C/O\text{-}Core} = 2.9\,M_\odot$

$M_{Ni} = 0.1\,M_\odot$

$E_K = 1 \times 10^{51}$ erg