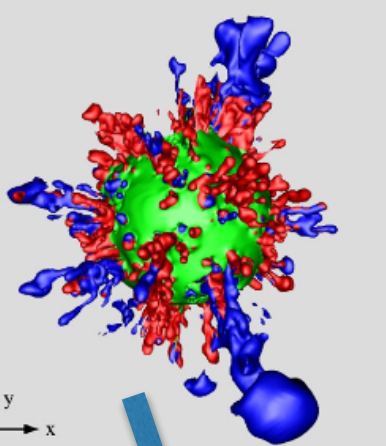


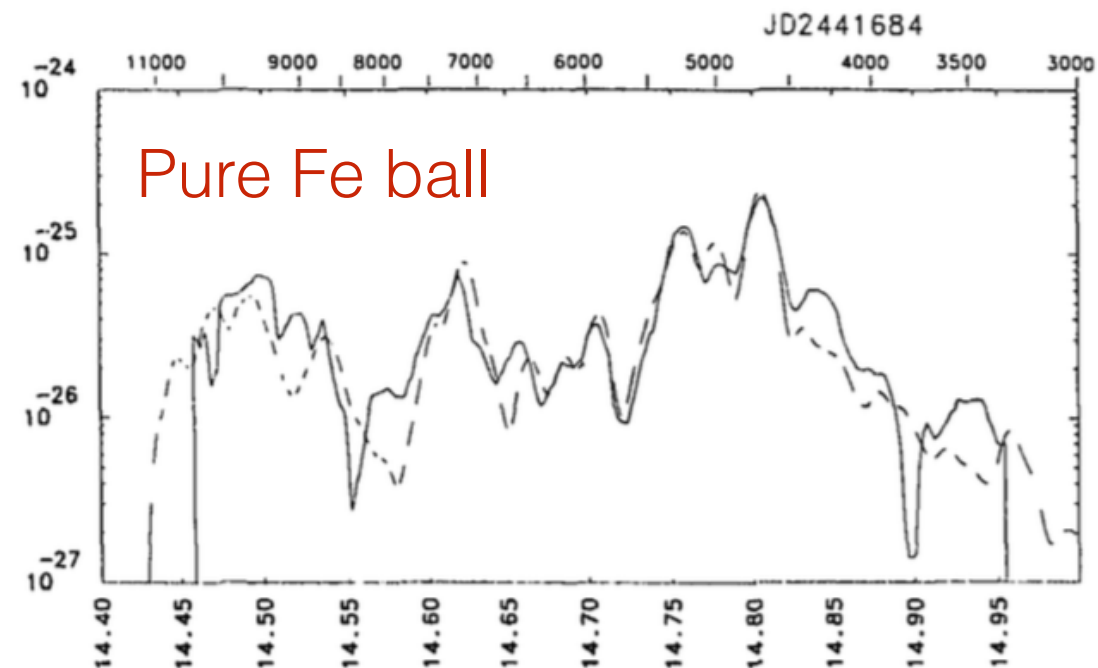
Spectral modelling with SUMO

**Anders Jerkstrand
MPA**

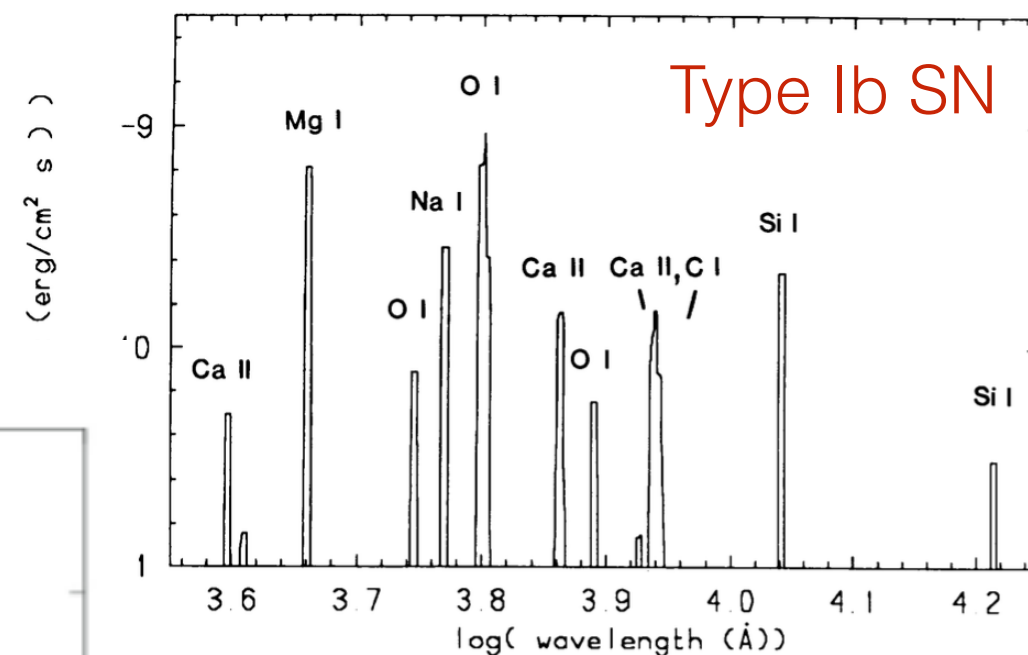
Late-time spectral modelling : 35 years of progress



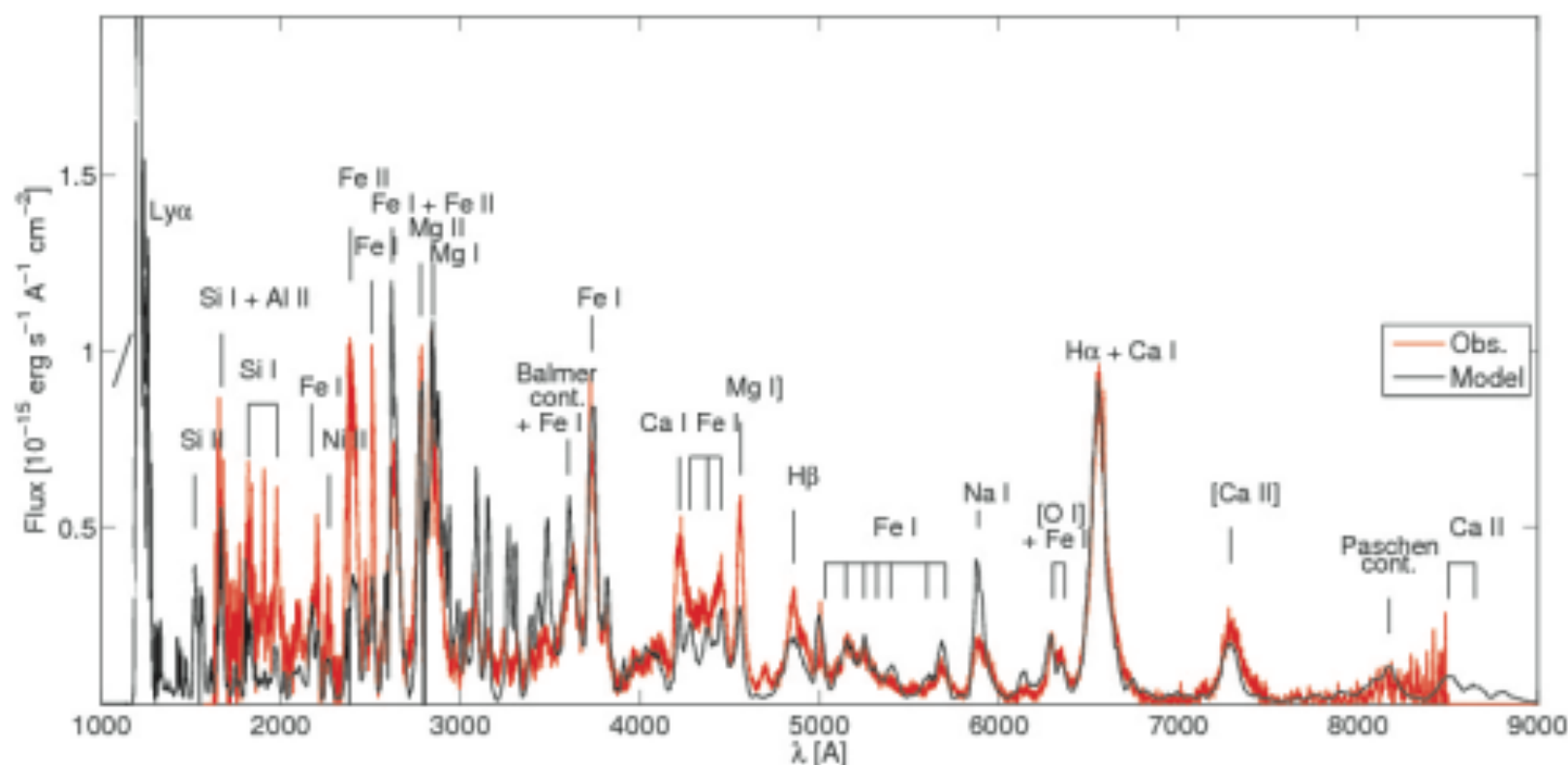
1. Mixing treatment
2. Radioactive deposition
3. Non-thermal electrons
4. NLTE exc. and ion.
5. Temperature
6. Radiative transfer
7. Atomic data



Axelrod 1980



Fransson & Chevalier 1987



Jerkstrand+2011

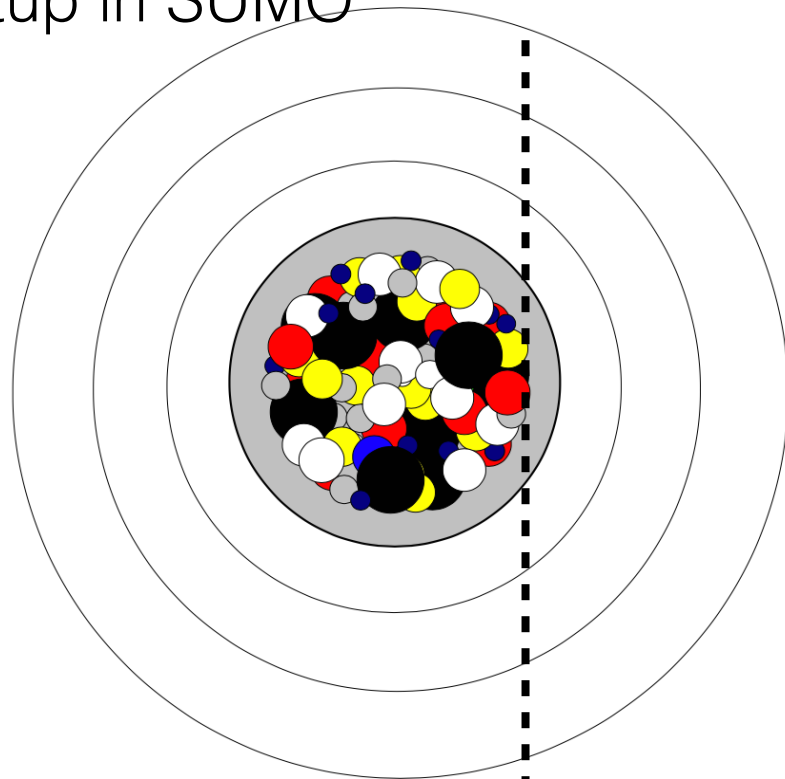
SUMO (*SU*pernova Monte Carlo) :
a steady-state spectral modelling code

1. **Mixing** : Virtual grid method **Jerkstrand+2011, 2012 + updates in later papers**
2. **Gamma-ray deposition** : Compton or gray
3. **Non-thermal electrons** : Spencer-Fano equation (updated Kozma & Fransson 1992 module)
4. **NLTE level populations** : H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, first 3 ion. stages, ~100-600 levels each (9000 total)
 - Includes charge transfer network (150 rates + guessing rule of Pequignot & Aldrovandi 1986)
5. **Temperature** : Cooling = heating
6. **Radiative transfer** : ~300,000 lines, ~3,000 bound-free continua, free-free, electron scattering, and dust.
 - Local : Sobolev approximation modified with continuum (all) and line (Ly-alpha, Ly-beta) destruction probabilities **Hummer & Rybicki 1985, AJ+2012 (App B.5)**
 - Global : Monte Carlo scheme
7. **Atomic data**

1. Mixing : Virtual grid method

Jerkstrand+2011

Setup in SUMO



Impact probability

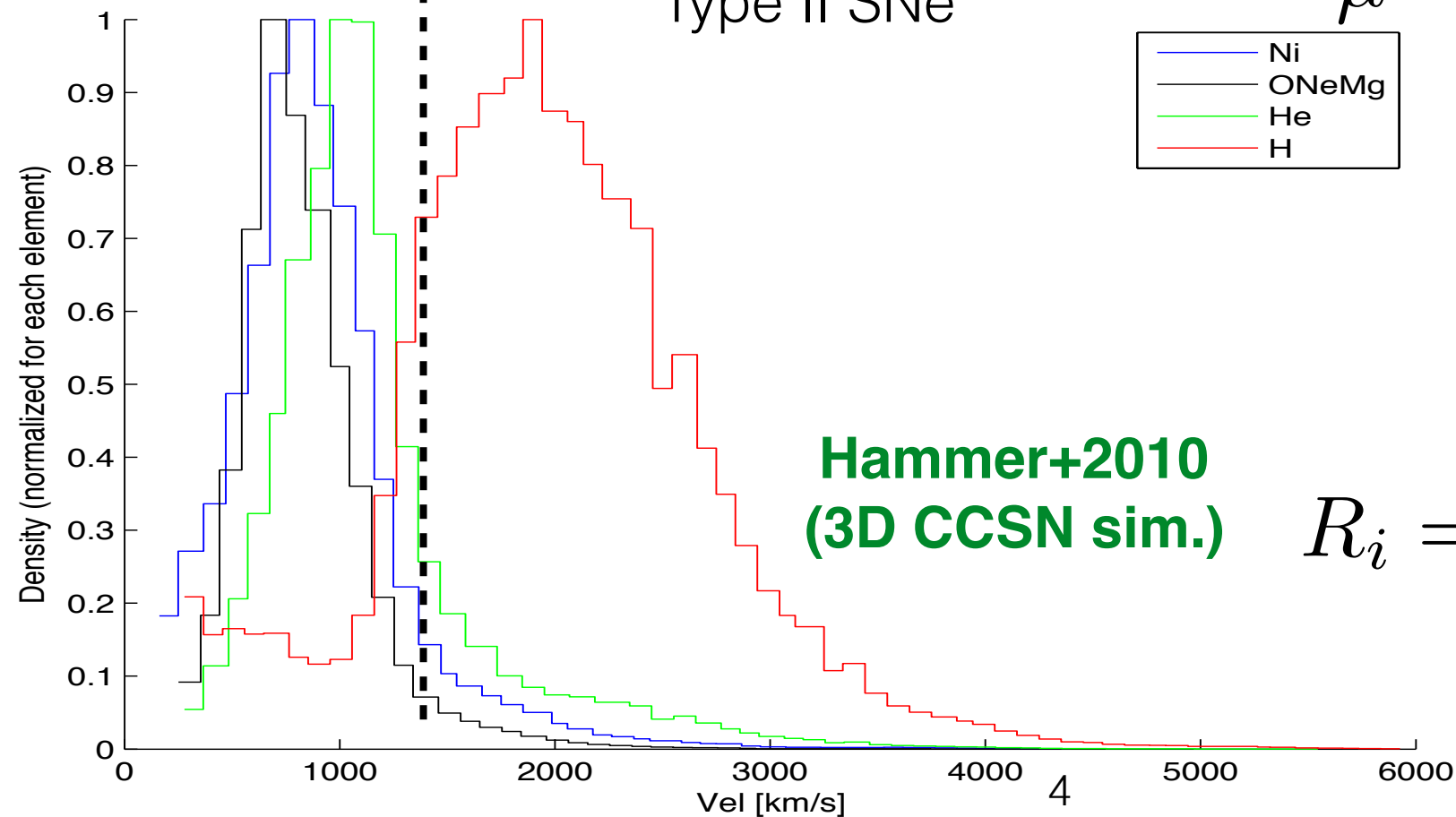
Clump radius

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

Good
method for strong-mixed
Type II SNe

$\mu = z$ Impact angle

Filling factor, clump type i



Hammer+2010
(3D CCSN sim.)

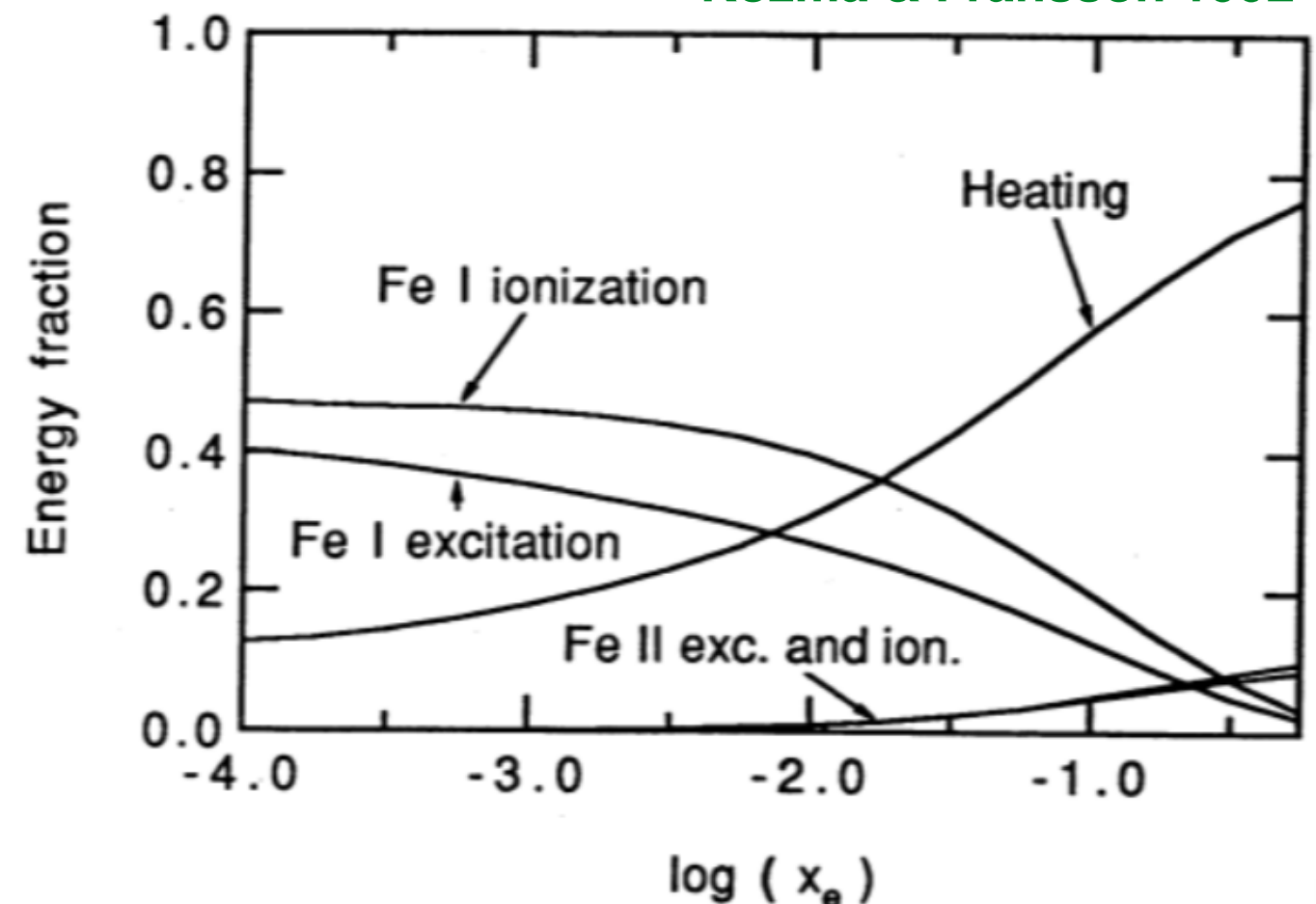
$$R_i = \left(\frac{3V f_i}{4\pi N} \right)^{1/3}$$

Number of clumps
of each type

3. Non-thermal electron degradation : Spencer-Fano equation

- Energy loss by 3 channels: **ionization**, **excitation** and **heating**.
- Important properties:
 - Occurs fast (see **Axelrod 1980**) — > ignore time dep. and ignore spatial transport.
 - Insensitive to nature of primary particle (as long as $> \sim 1$ keV).
 - Insensitive to electron density.
- Approximations:
 - *Differential* ionization cross section, same form for all elements (**Opal 1971**).
 - Bethe approx. where no cross sections.
 - With few exceptions, ignore ion. to excited states

Kozma & Fransson 1992



In Ia SNe, x_e is always $> \sim 0.1$ so heating fraction close to unity —>

- Heating rate robustly calculated
- Ionization and exc. rates less so

4. NLTE level populations

- Rate equations (element i , ion stage j , level k):

$$\frac{dn_{ijk}}{dt} - \frac{n_{ijk}/\rho}{d\rho/dt} = \sum_{i'} \sum_{j'} \sum_{k'} n_{i'j'k'} \mathcal{R}_{i'j'k',ijk} - n_{ijk} \sum_{i'} \sum_{j'} \sum_{k'} \mathcal{R}_{ijk,i'j'k'}$$

$$\mathcal{R}_{ion} = R_{photo-ion.} + C_{thermal ion.} + C_{non-thermal ion.} + C_{charge transfer, ion.}$$

$$\mathcal{R}_{rec} = R_{stim. rec.} + R_{rad. rec.} + R_{diel. rec.} + C_{3-body rec.} + C_{charge transfer, rec}$$

$$\mathcal{R}_{exc} = R_{photo-exc.} + C_{thermal exc.} + C_{non-thermal exc.}$$

$$\mathcal{R}_{de-exc.} = R_{stim. em.} + R_{spont. decay} + C_{thermal de-exc.}$$

- SUMO : Steady state : LHS = 0. Eventually breaks down due to slow recombination and slow cooling (few years years post-explosion).
- R rates either from A) Counting in Monte Carlo (standard, avoids ambiguity with “blue wing” definition) or B) radiation field reconstruction (less noise). *Counting: compensate for stim. emiss:*
- No simplifications (e.g. superlevels).

$$R_{i,k,l,u} = \frac{N_{i,k,l,u}}{n_{i,k,l}} \left(1 - \frac{g_{k,l} n_{i,k,u}}{g_{k,u} n_{i,k,l}} \right)^{-1}$$

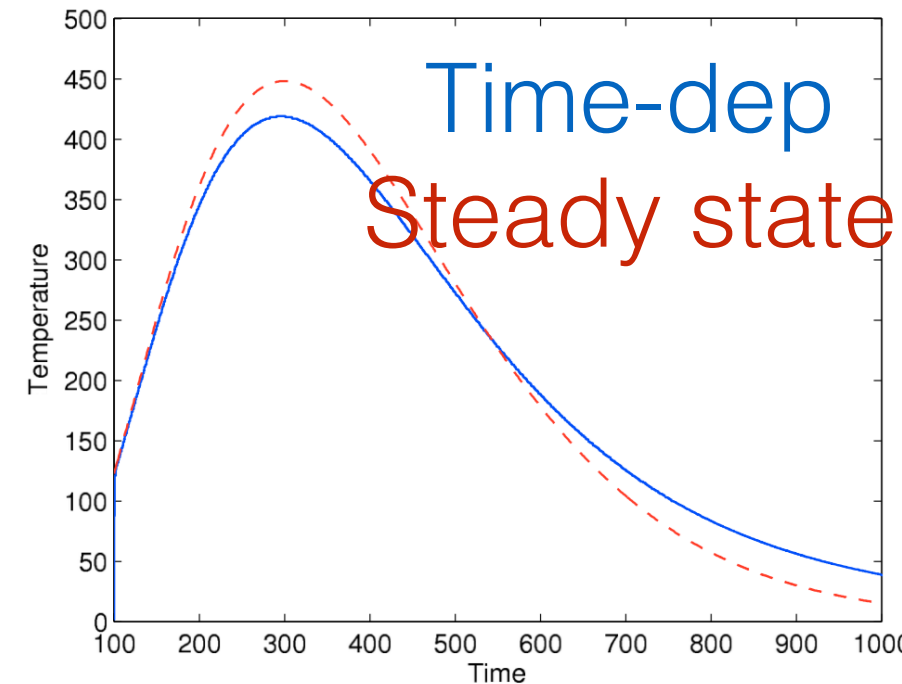
5. Temperature : steady-state

- **First law of thermodynamics** for homology and perfect, monoatomic gas:

$$\frac{dT(t)}{dt} = \frac{H(T) - C(T)}{\frac{3}{2}kn(t)} - \frac{2T(t)}{t} - \frac{T(t)}{1 + x_e(t)} \frac{dx_e(t)}{dt}$$

SUMO:

Steady-state approx : $H(T) = C(T)$



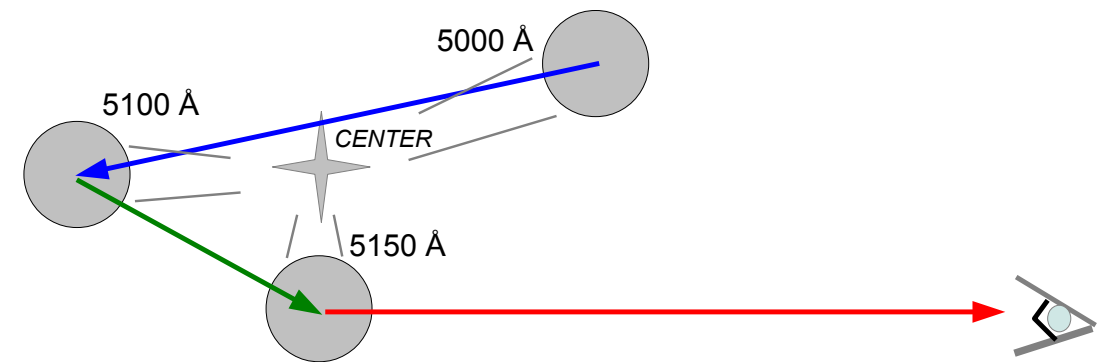
$$H = H_{\text{non-thermal}} + H_{\text{photoion}} + H_{\text{CT(net)}} + H_{\text{coll.deexc}} + H_{\text{free-free}}$$

$$C = C_{\text{coll.exc(net)}} + C_{\text{rec}} + C_{\text{free-free}}$$

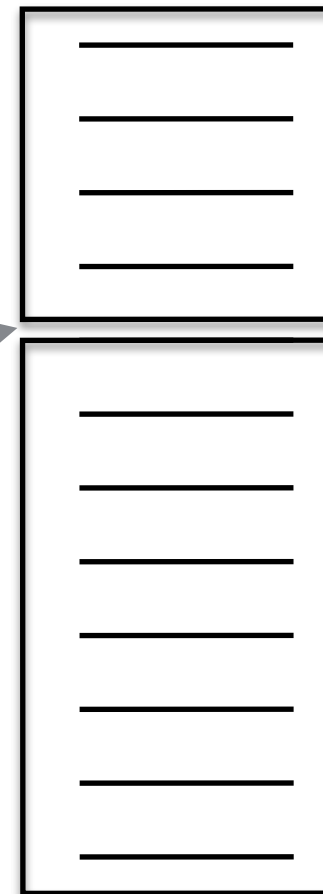
Typically $H_{\text{non-thermal}}$ and $C_{\text{coll.exc(net)}}$ dominant terms.

6. Radiative transfer

- **Monte Carlo method** with (Sobolev) lines, electron scattering, free-free, photon.
- All lines treated explicitly (no expansion opacity). Absorption events split into two groups:
 1. Abs. to low and mid-lying levels: Attenuate packet, increase photoexc. rate. (“full NLTE coupling”)
 2. To high levels: Fluorescence cascade calibrated to radiative equilibrium (“no NLTE coupling”).
 - $E_{\text{in}} = E_{\text{out}} + E_{\text{coll. deexc.}}$
 - Recursive method to ensure signal in all fluorescence steps.
- Continuum : Full coupling (pure attenuation).



Typical cap at 200-300 levels



High levels: uncoupled pop. solutions

$E_{\text{out}} = E_{\text{in}} + E_{\text{coll. deexc}}$
Allow full fluorescence

Mid/low levels: Coupled pop. solutions

Attenuate packet, accumulate photoexcitation rates

7. Atomic data

- Energy levels **Mostly Kurucz CD 23 + “NIST”**
- A-values **Mostly Kurucz CD 23 + “NIST”**
- Thermal collision strengths **e.g. Pradhan*.. Allowed: Regemorter. Forb: 0.004g1g2 (Axelrod)**
- Non-thermal b-b collisions **Specific: HI, HeI, OI, NaI, MgI, MgII, CaI, CaII, FeI. Rest: Bethe approximation.**
- Non-thermal b-f collisions **Mostly Arnaud & Rothenflug 1985**
- Photoionization cross sections **Verner et al. 1996 + “TOPBASE”**
- Recombination rates **e.g. Nahar**..**
- Charge transfer rates **e.g. Arnaud & Rothenflug 1985, Swartz 1994, Kingdon & Ferland 1996, Zhao 2004**

Current overview of data sources maintained at

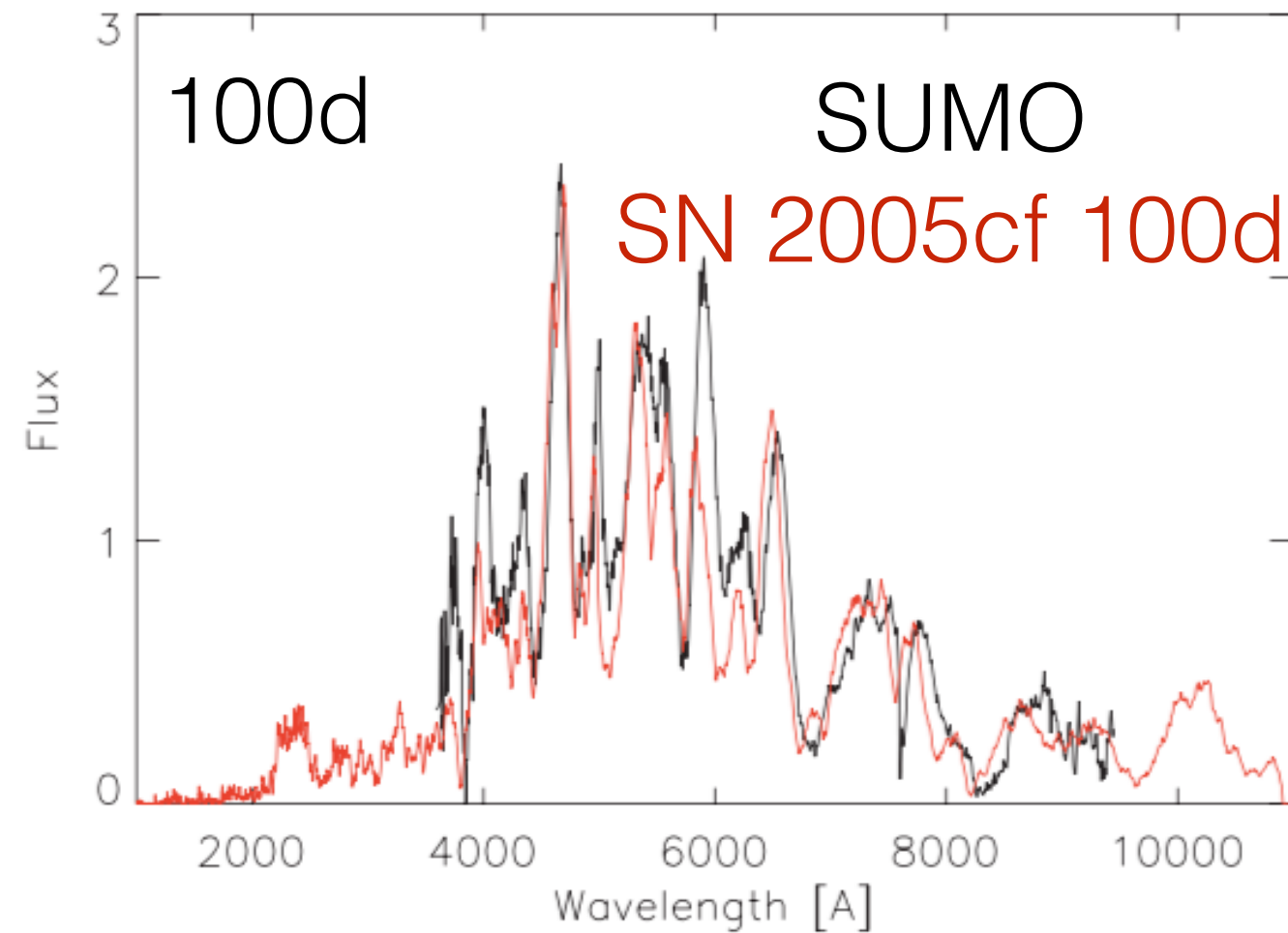
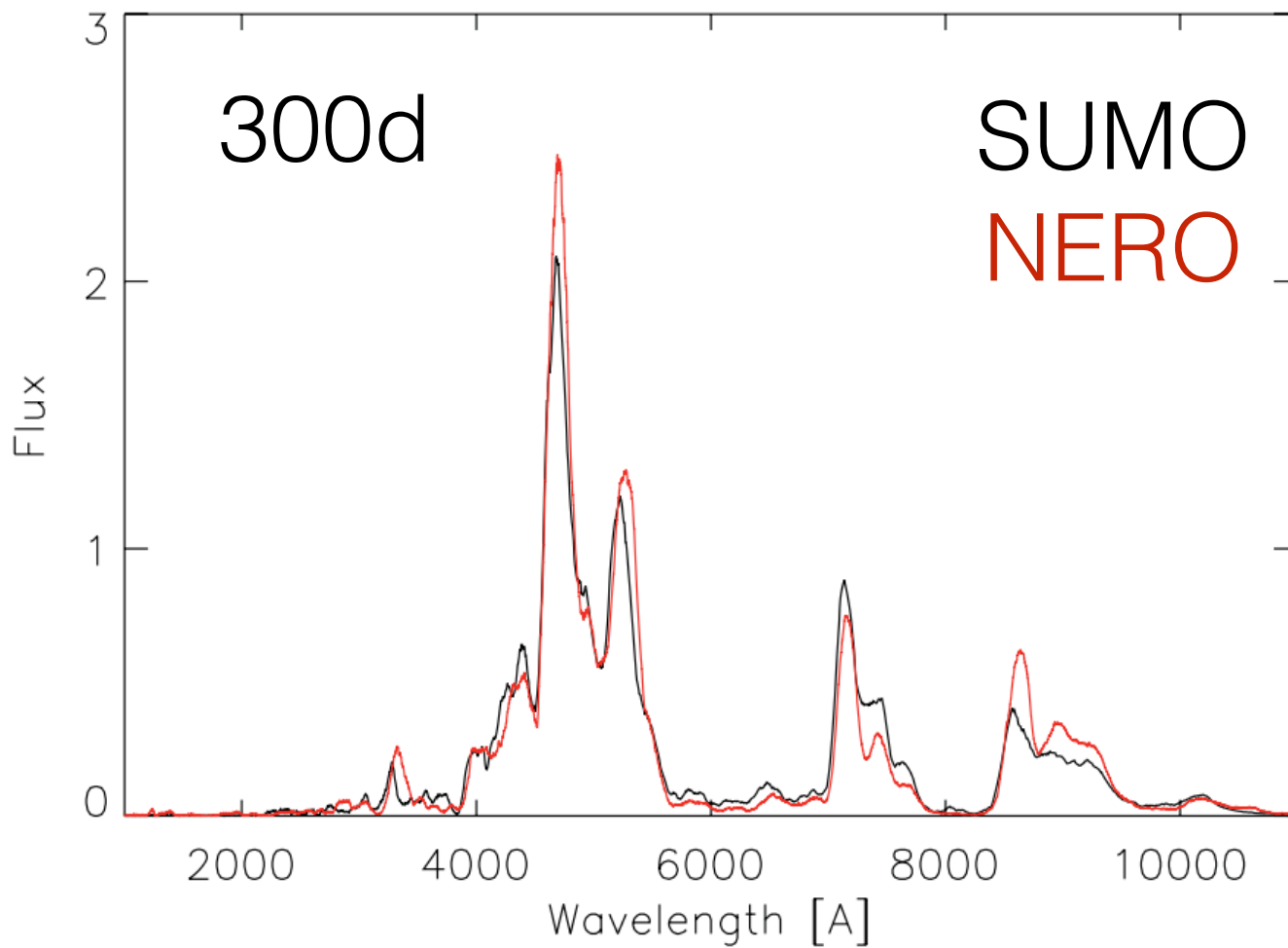
<https://star.pst.qub.ac.uk/wiki/doku.php/users/ajerckstrand/start>

* <http://www.astronomy.ohio-state.edu/~pradhan/table2.ps>

** http://www.astronomy.ohio-state.edu/~nahar/nahar_radiativeatomicdata/index.html

Code tests with W7

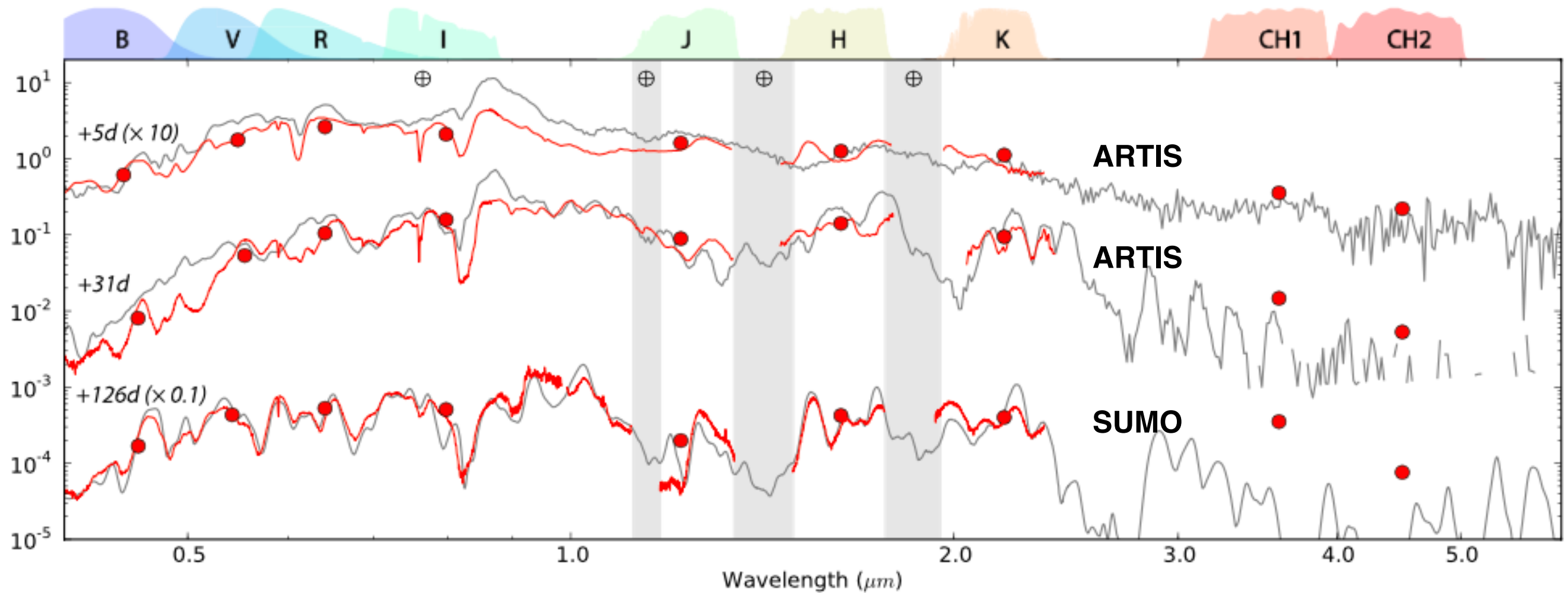
Maurer, Jerkstrand
et al. +2011



SN 2014J

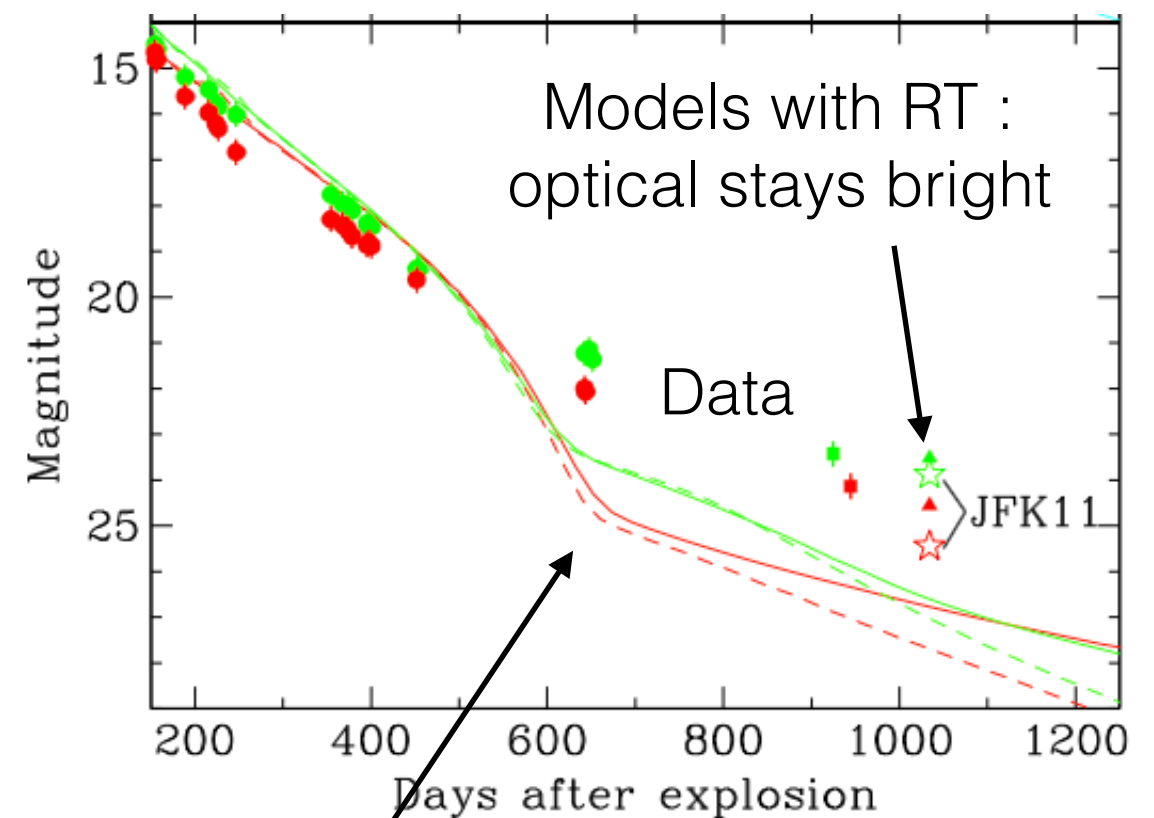
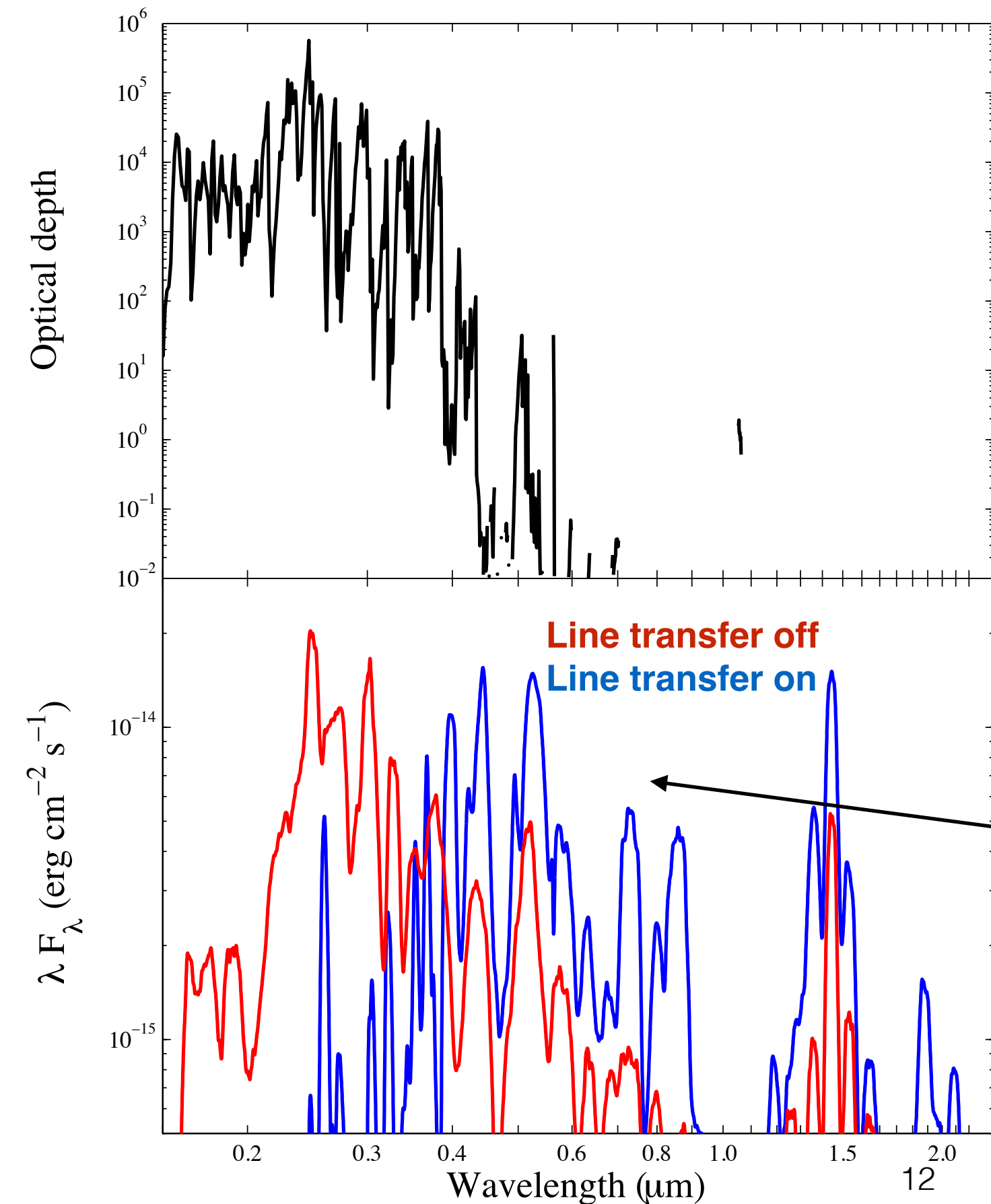
Johansson (incl. AJ)+2017

Model = W7



Ia spectra at 1000d

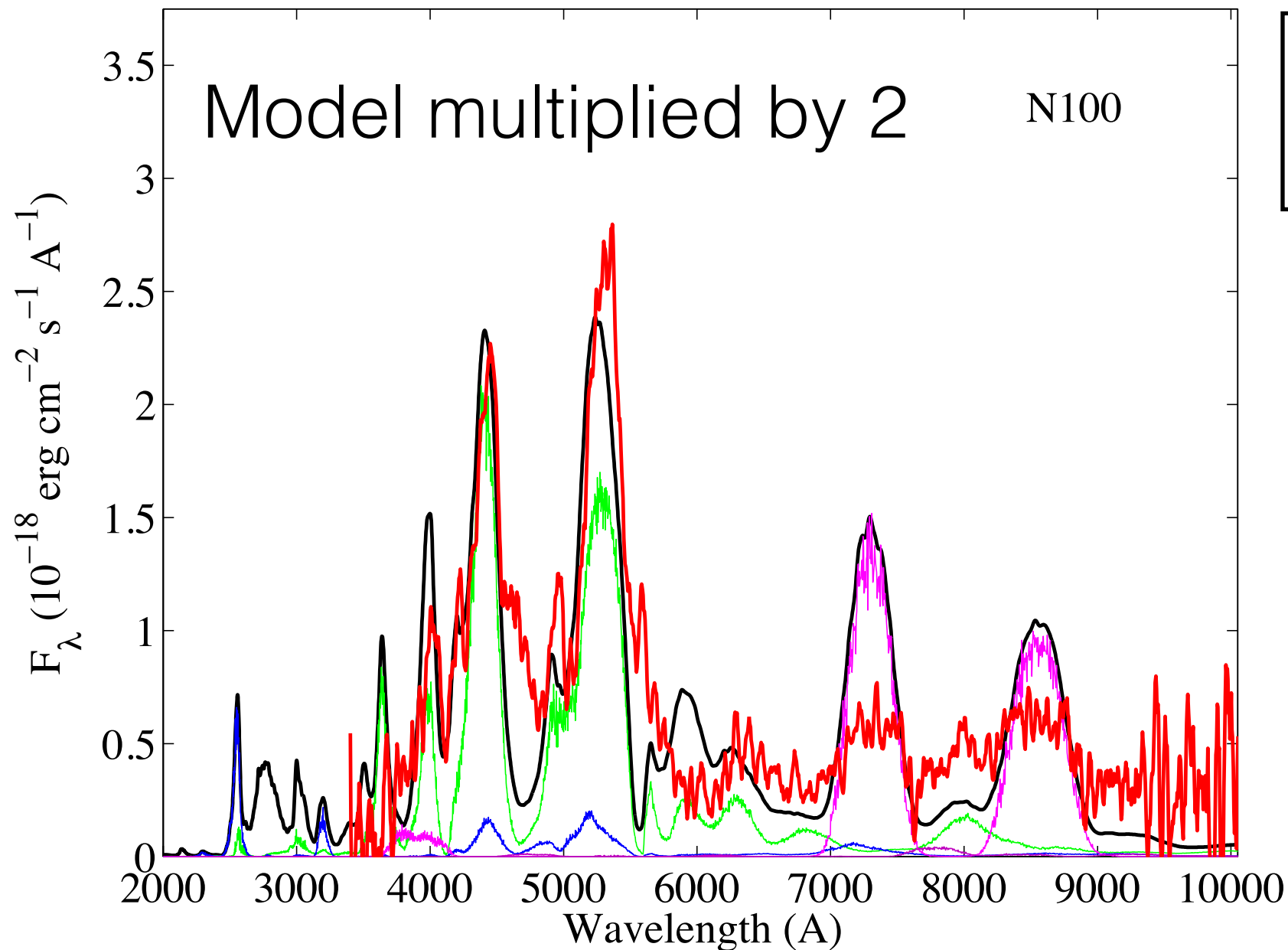
Fransson & Jerkstrand 2015



Models with no RT : optical flux decreases strongly at ~700d

**Fluorescence boosts optical/NIR
by factor ~10.
Optical carries ~20% in SUMO
models.**

^{57}Ni mass in SN 2011fe?



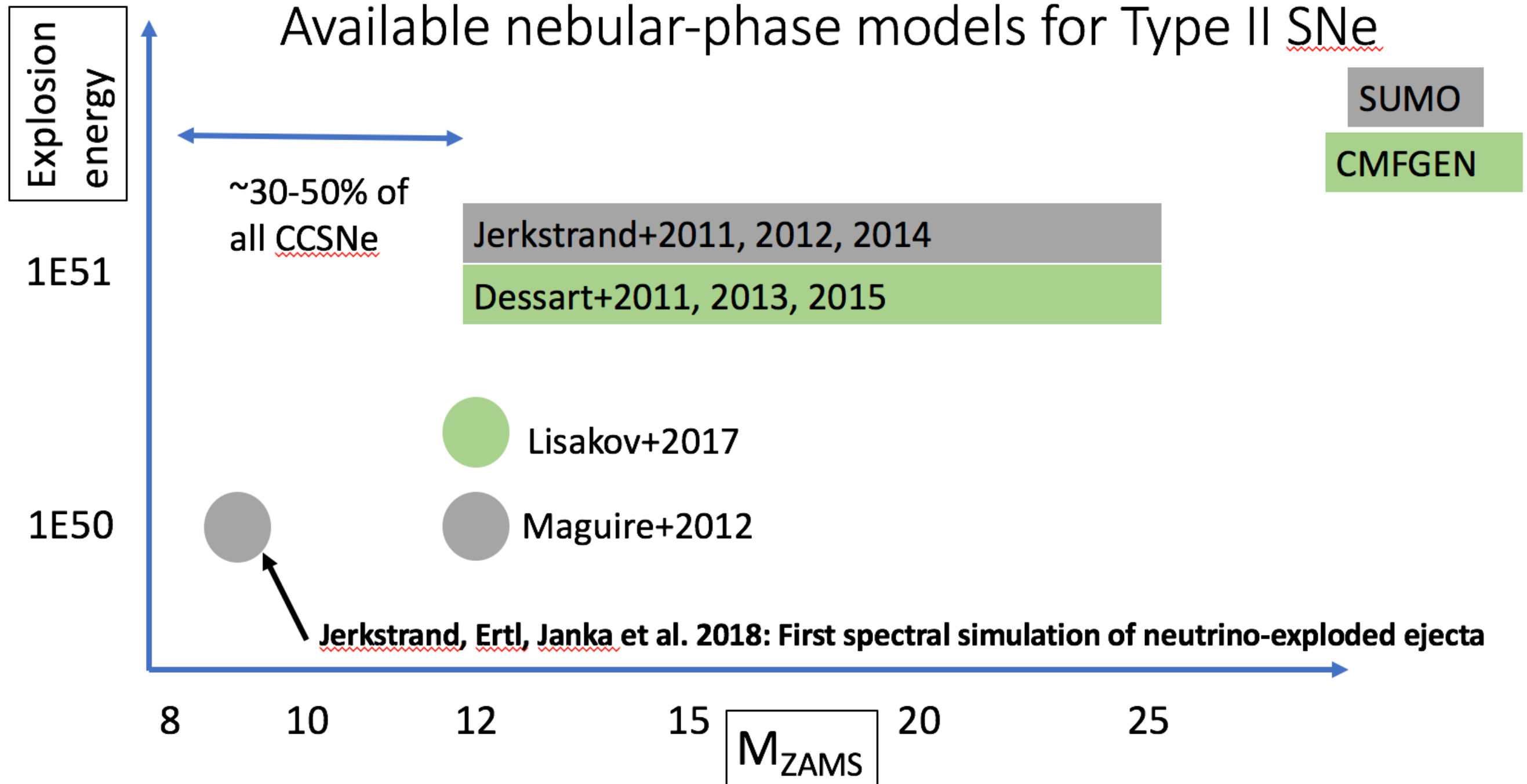
$$M(^{56}\text{Ni}) = 0.60 M_{\text{sun}}$$
$$M(^{57}\text{Ni}) = 0.018 M_{\text{sun}}$$

Powering $\sim 50/50$
by ^{56}Co positrons
and ^{57}Co electrons

If freeze-out unimportant : $M(^{57}\text{Ni}) \sim 0.06 M_{\text{sun}}$

If freeze-out important : $M(^{57}\text{Ni}) \sim 0.02 M_{\text{sun}}$

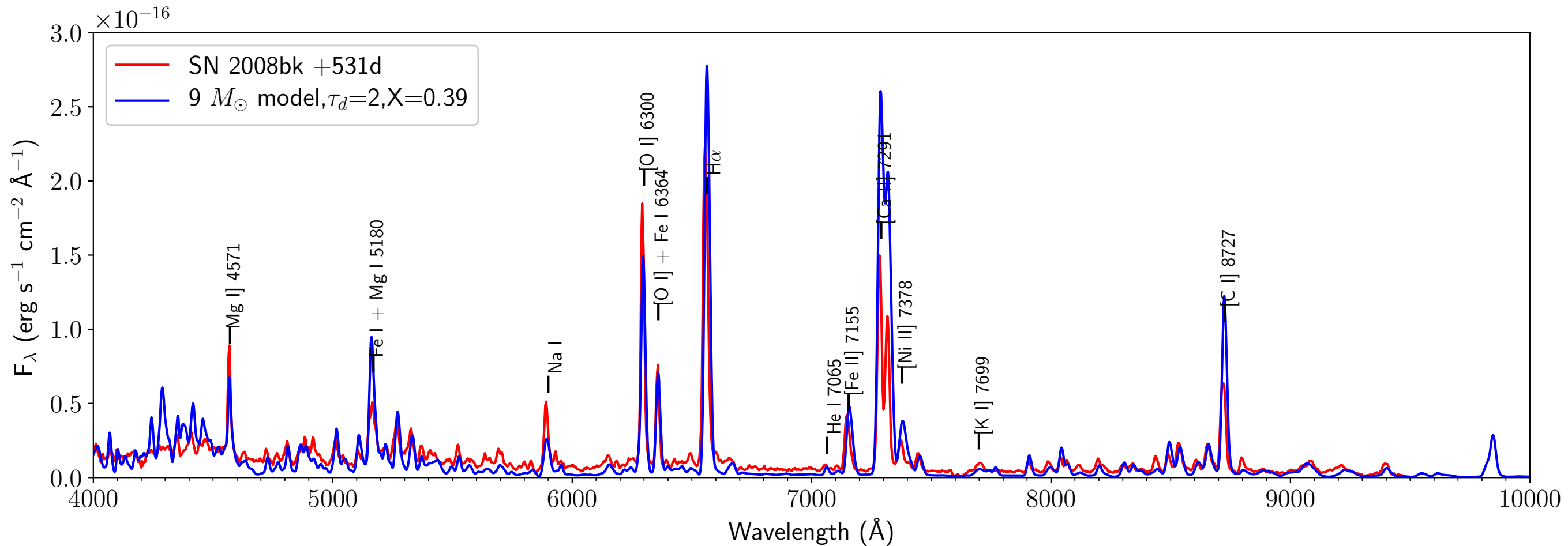
Available nebular-phase models for Type II SNe



Subluminous IIP SNe: good fits to low-mass progenitors

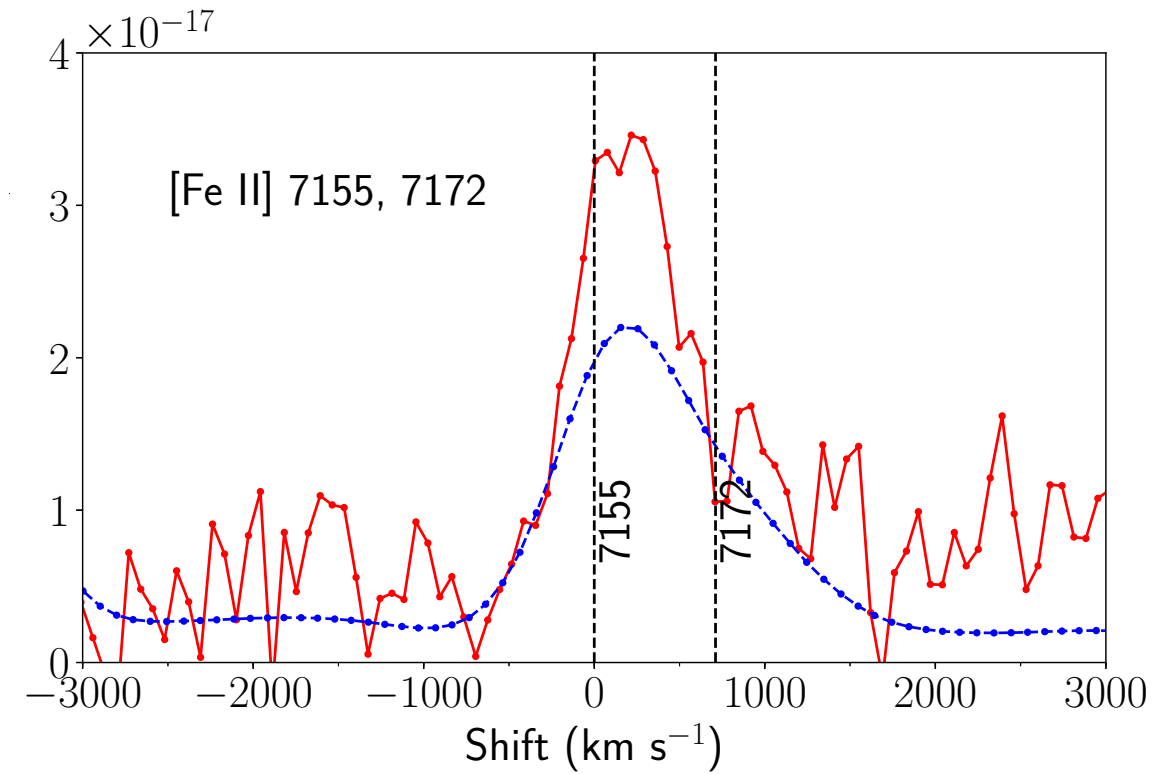
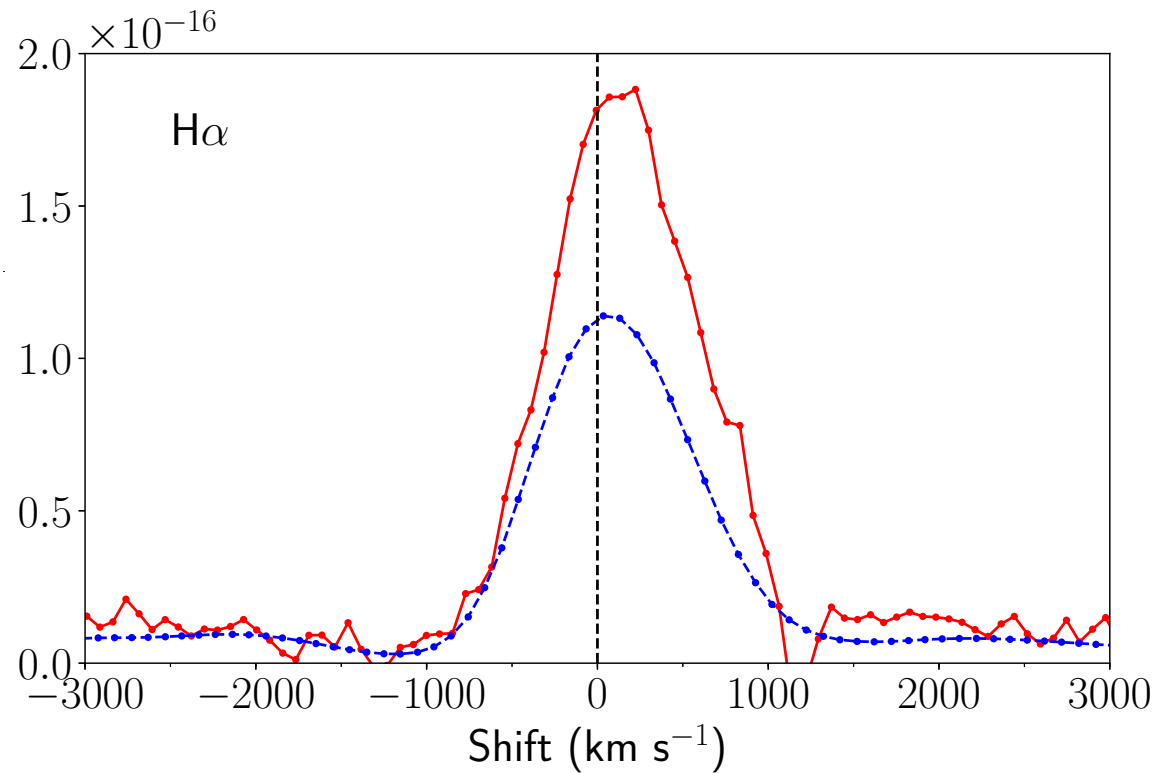
AJ+2018

See also Lisakov+2017,2018



Self-consistent explosions: can probe line profiles

AJ+2018



3D tests now in preparation.

Line	FWHM (km s ⁻¹)	FWHM _{dec.} (km s ⁻¹)	Model (km s ⁻¹)
H α	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.