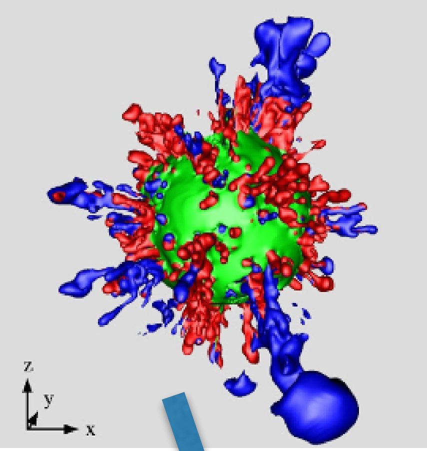
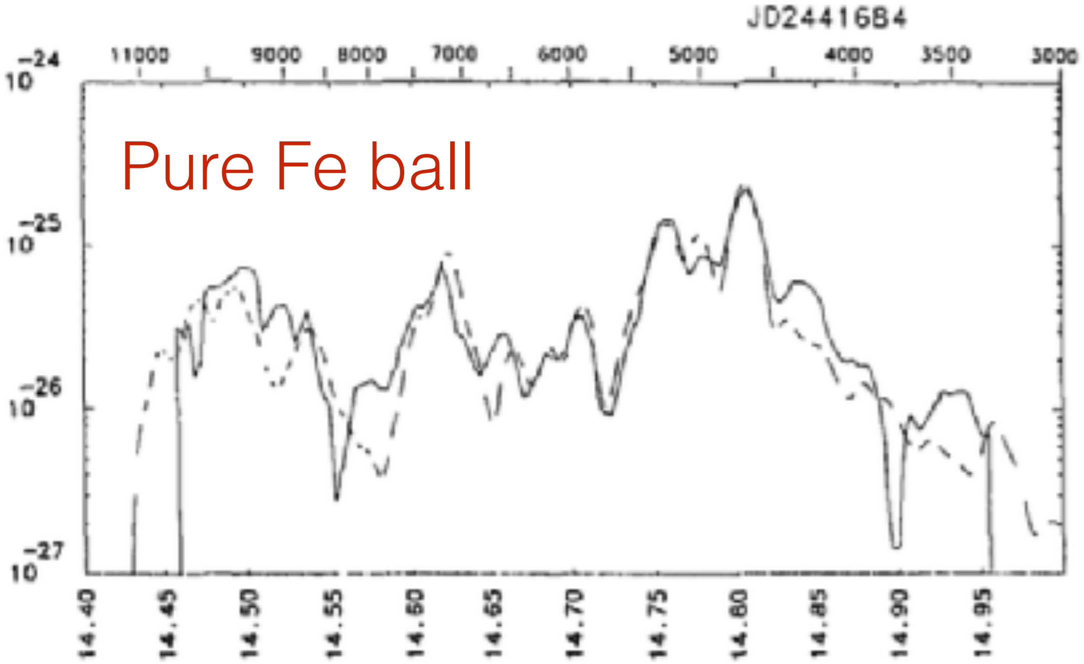
Spectral modelling with SUMO

Anders Jerkstrand
MPA

Late-time spectral modelling : 35 years of progress

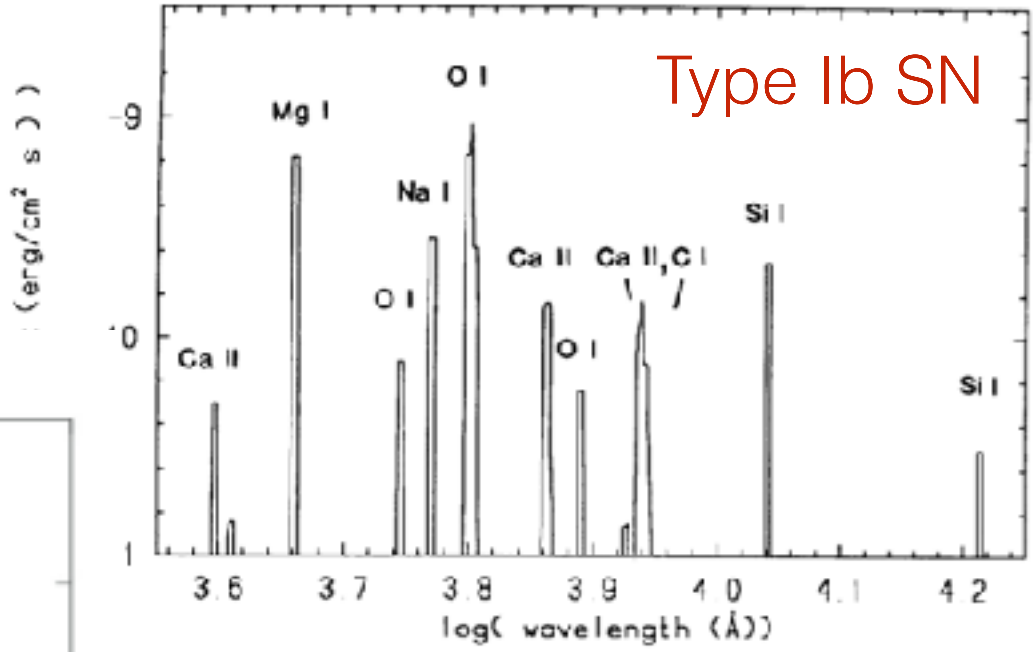


1. **Mixing treatment**
2. **Radioactive deposition**
3. **Non-thermal electrons**
4. **NLTE exc. and ion.**
5. **Temperature**
6. **Radiative transfer**
7. **Atomic data**



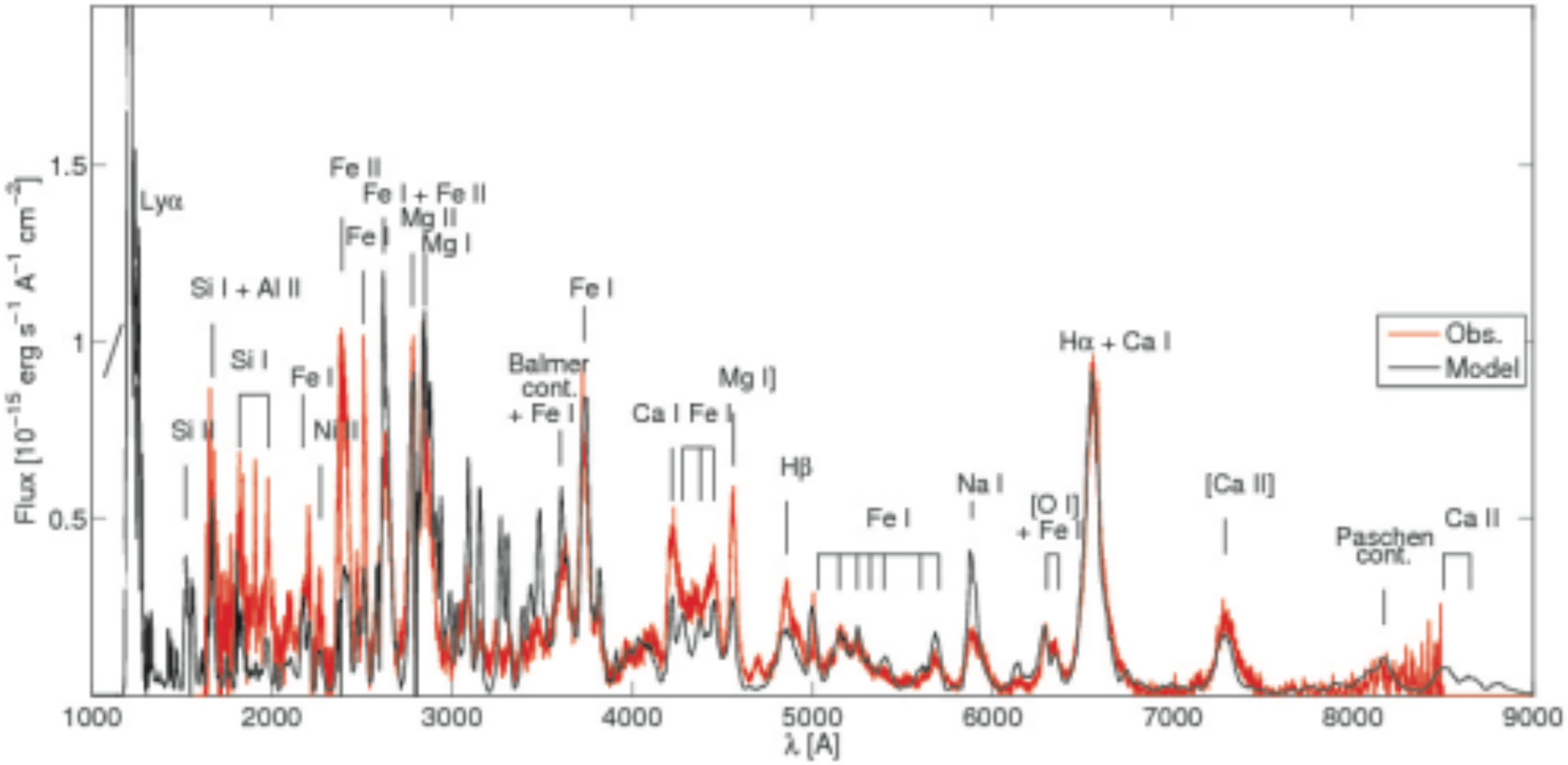
Pure Fe ball

Axelrod 1980



Type Ib SN

Fransson & Chevalier 1987



Jerkstrand+2011

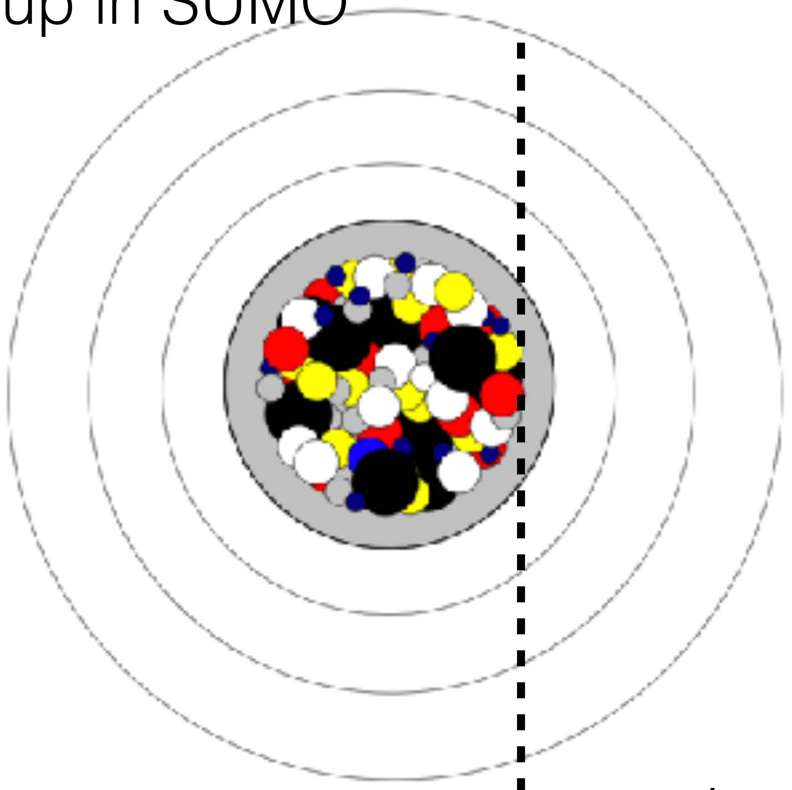
SUMO (*SU*pernova *M*onte *C*arlo) : a steady-state spectral modelling code

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**

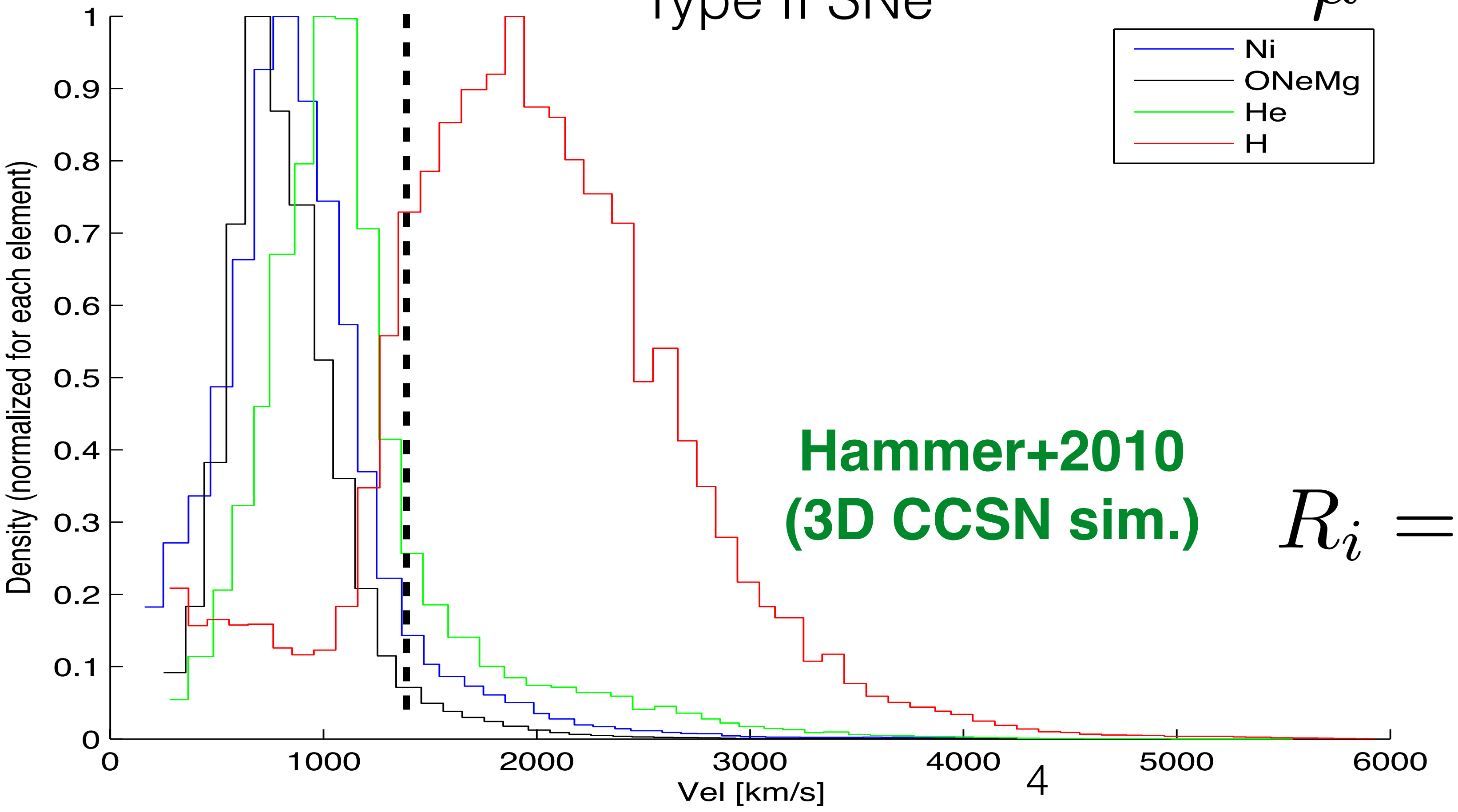
1. Mixing : Virtual grid method

Jerkstrand+2011

Setup in SUMO



Good
method for strong-mixed
Type II SNe



Hammer+2010
(3D CCSN sim.)

Impact probability

Clump radius

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

$$\mu = z$$

Impact angle

Filling factor, clump type *i*

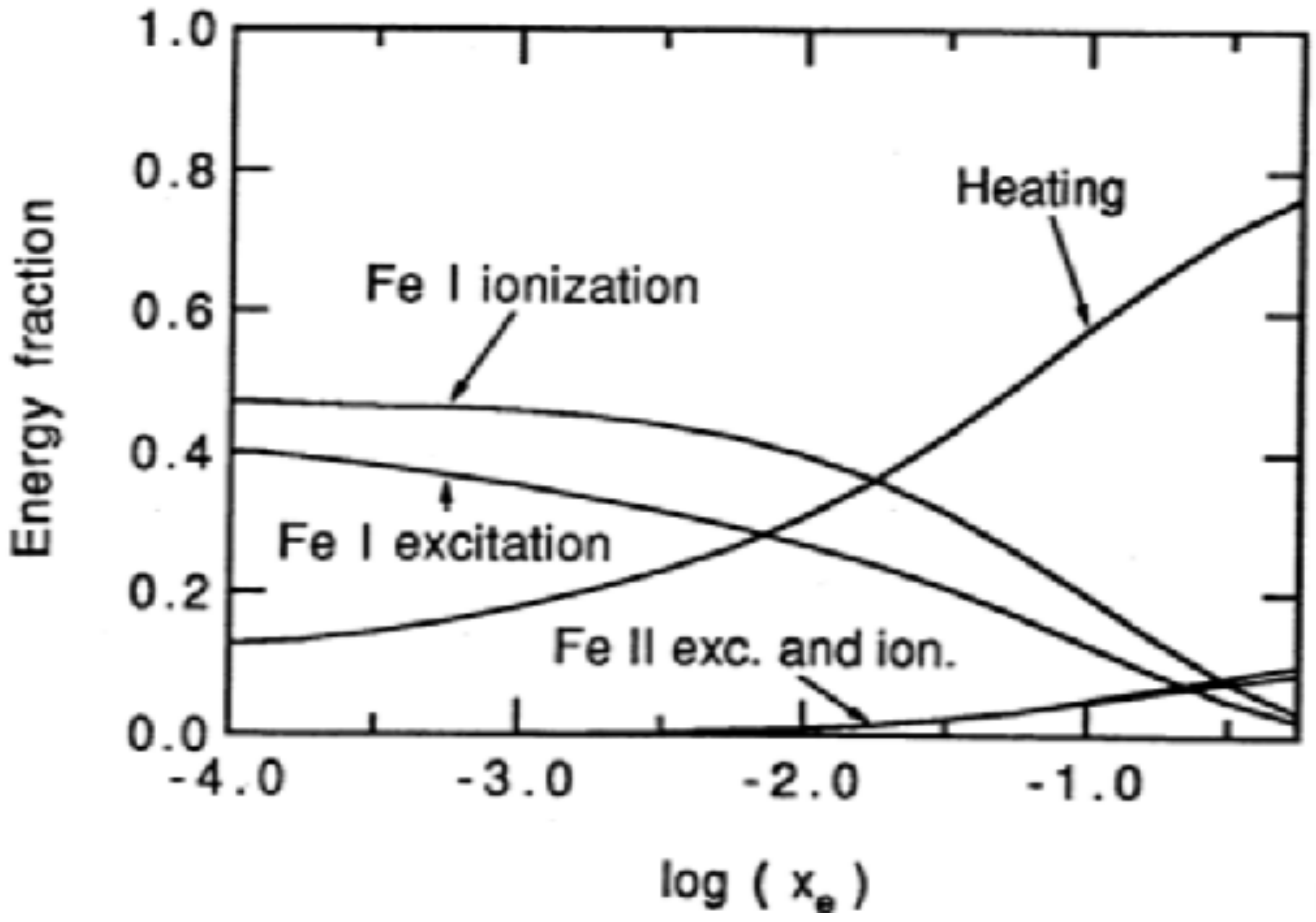
$$R_i = \left(\frac{3Vf_i}{4\pi N}\right)^{1/3}$$

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 >~ 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 >~ 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*):

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

$$\begin{aligned}
\mathcal{R}_{ion} &= R_{photo-ion.} + C_{thermal\ ion.} + C_{non-thermal\ ion.} + C_{charge\ transfer,ion.}\\
\mathcal{R}_{rec} &= R_{stim.\ rec.} + R_{rad.\ rec.} + R_{diel.\ rec.} + C_{3-body\ rec.} + C_{charge\ transfer,rec}\\
\mathcal{R}_{exc} &= R_{photo-exc.} + C_{thermal\ exc.} + C_{non-thermal\ exc.}\\
\mathcal{R}_{de-exc.} &= R_{stim.\ em.} + R_{spont.\ decay} + C_{thermal\ de-exc.}
\end{aligned}$$

- 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).

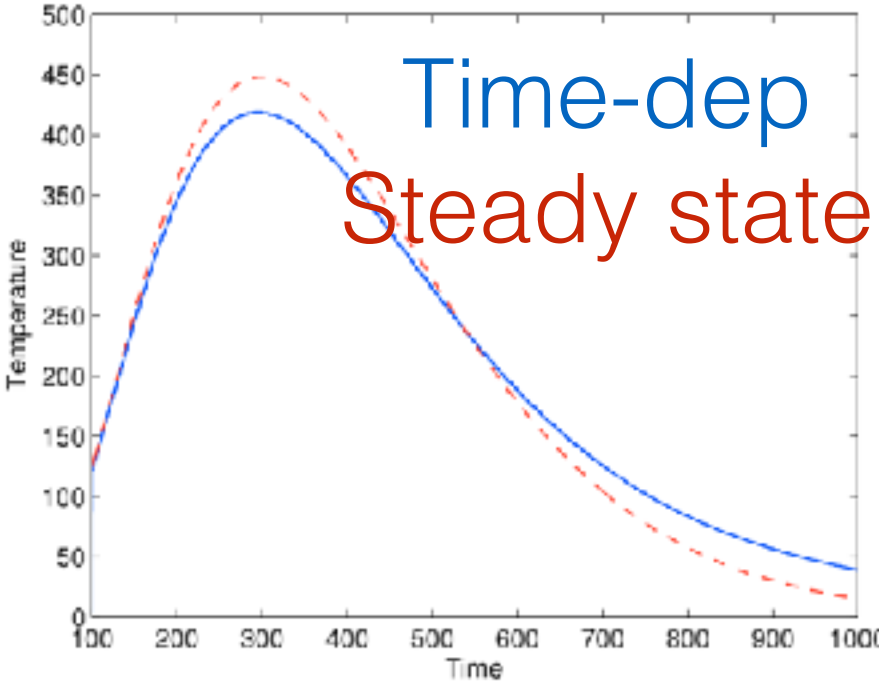
Counting: compensate for stim. emiss:

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

- No simplifications (e.g. superlevels).

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

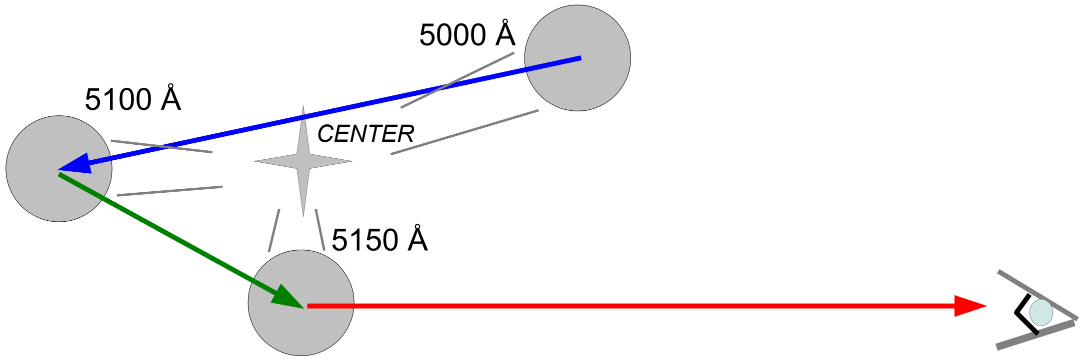
- **Monte Carlo method** with (Sobolev) lines, electron scattering, free-free, photon.

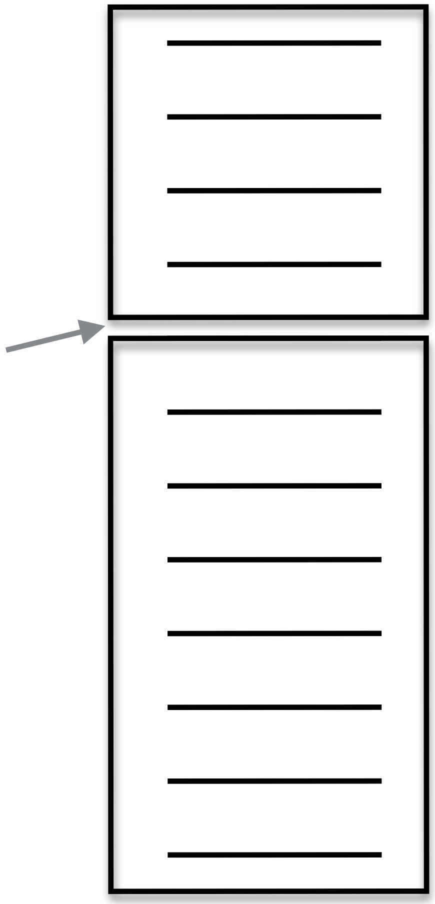
- All lines treated explicitly (no expansion opacity). Absorption events split into two groups:

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

$E_{\text{out}} = E_{\text{in}} + E_{\text{coll. deex}}$

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, FeII. 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. Arnauld & Rothenflug 1985, Swartz 1994, Kingdon & Ferland 1996, Zhao 2004**

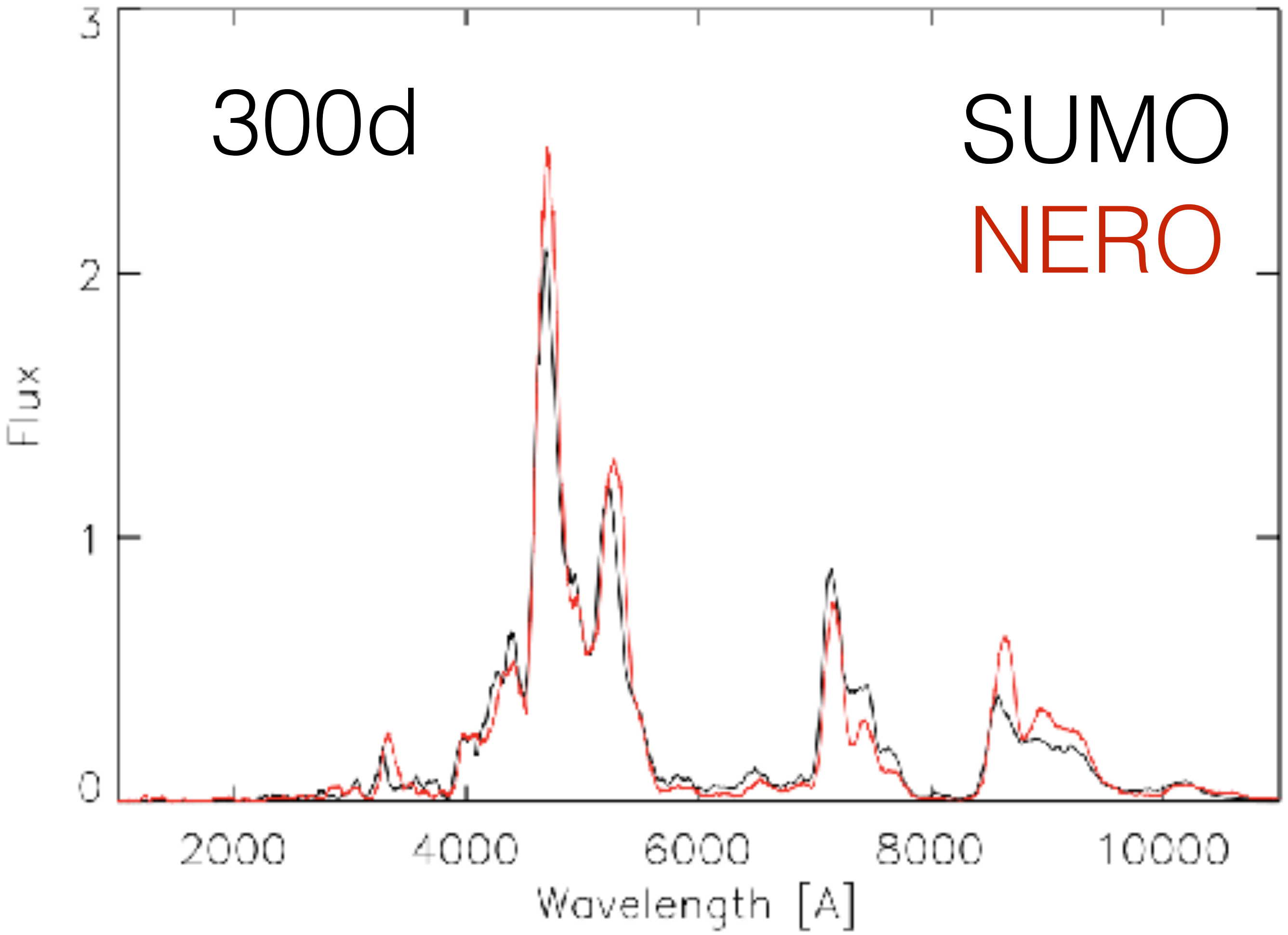
Current overview of data sources maintained at

https://star.pst.qub.ac.uk/wiki/doku.php/users/ajerkstrand/start

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

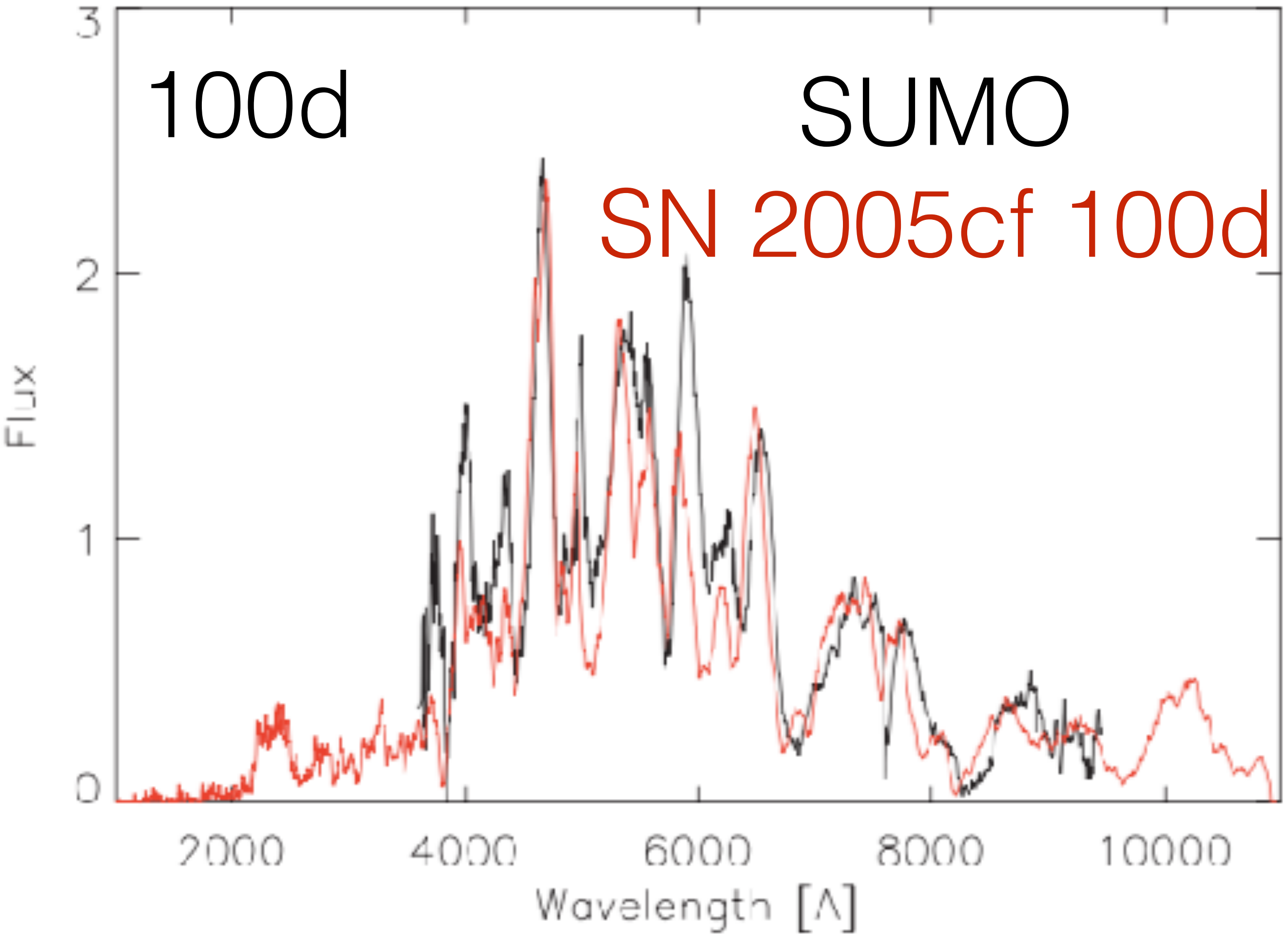
** http://www.astronomy.ohio-state.edu/~nahar/nahar_radiativeatomicdata/index.html

Code tests with W7 Maurer, Jerkstrand et al. +2011


300d

SUMO

NERO


100d

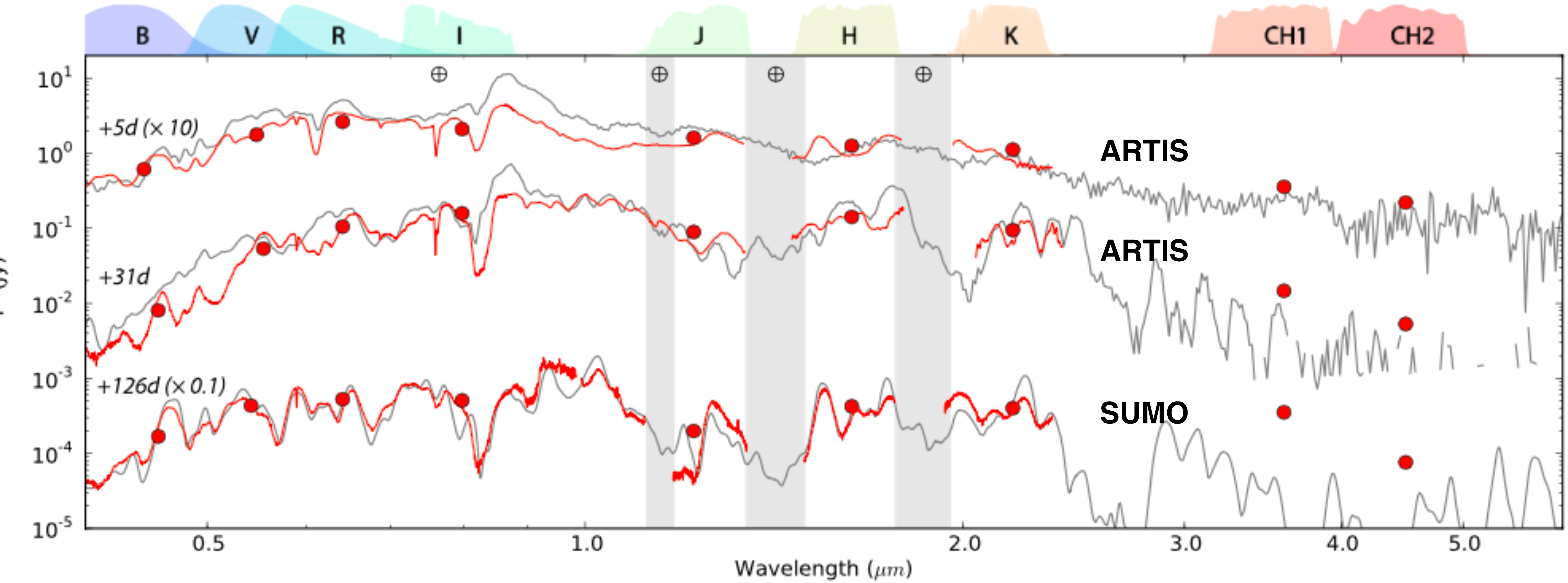
SUMO

SN 2005cf 100d

SN 2014J

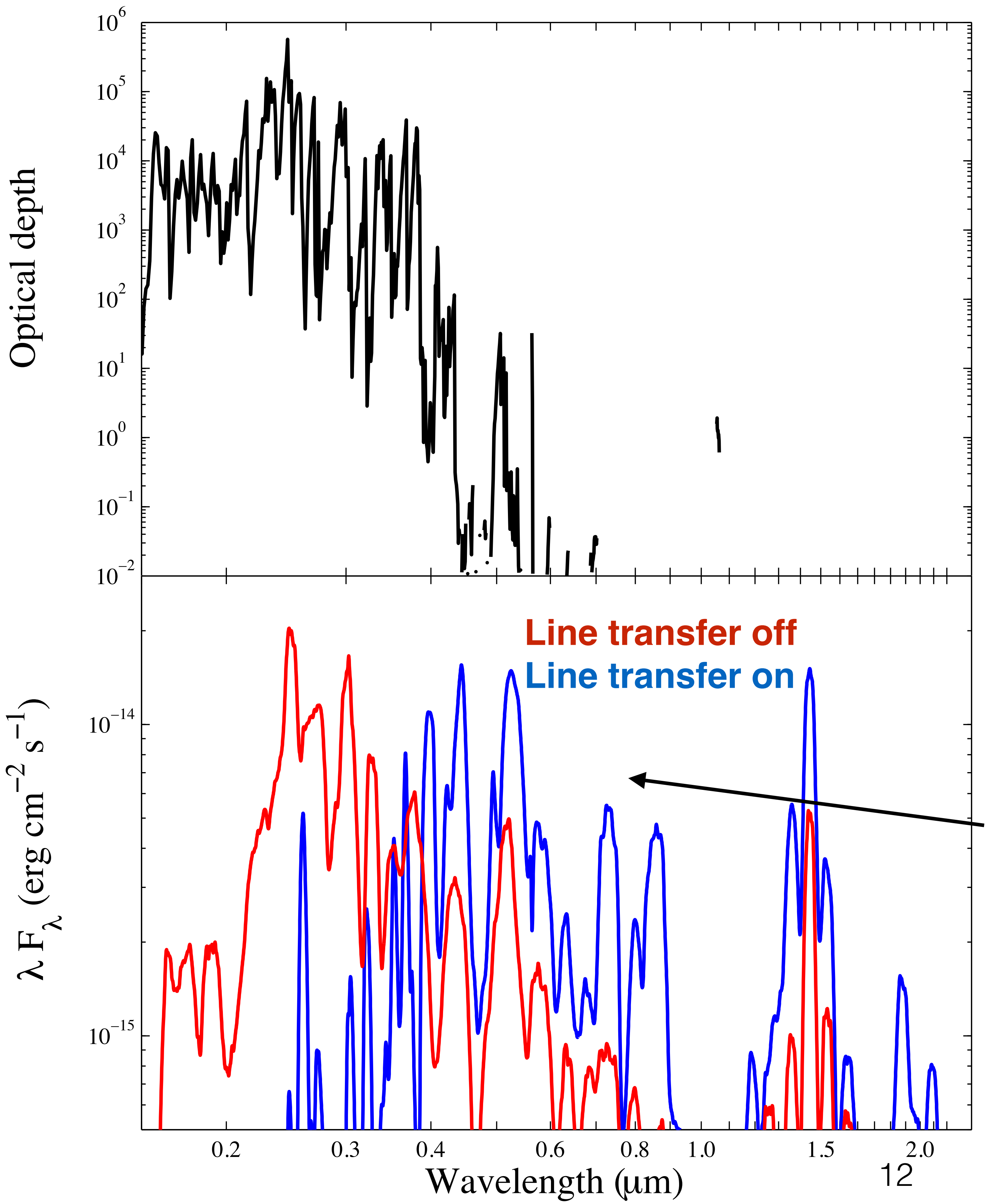
Johansson (incl. AJ)+2017

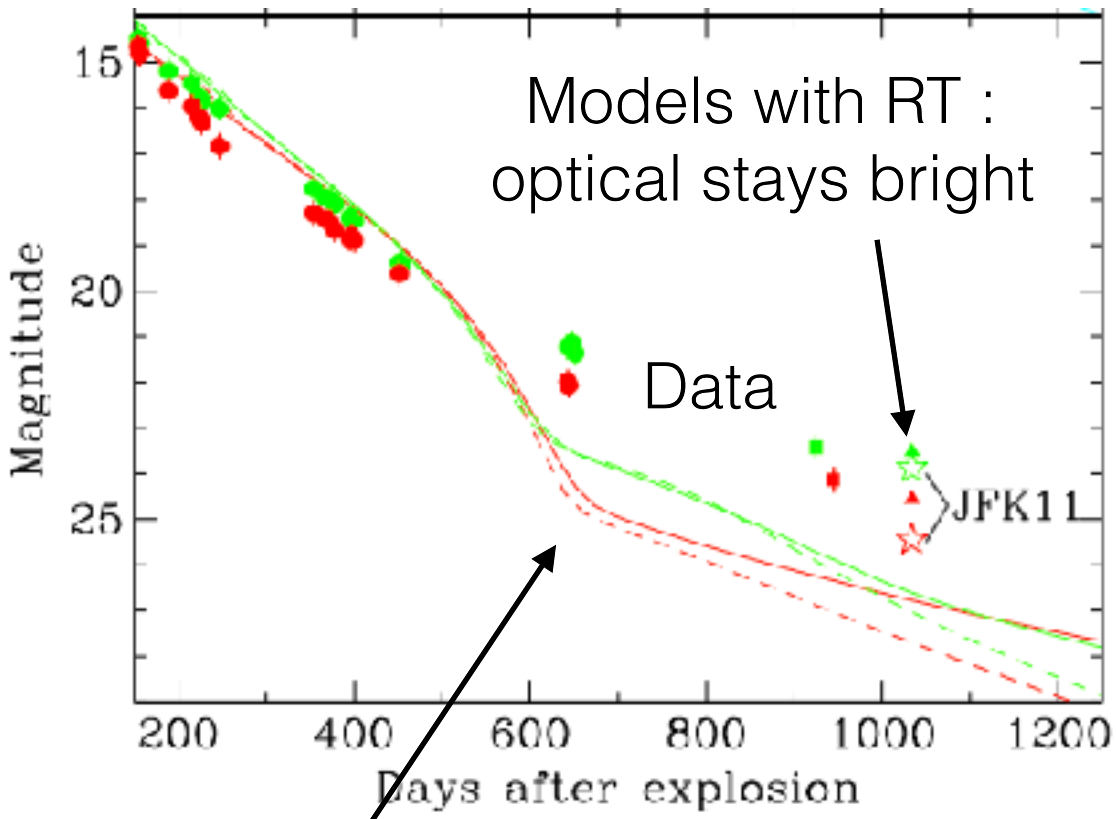
Model = W7



Ia spectra at 1000d

Fransson & Jerkstrand 2015





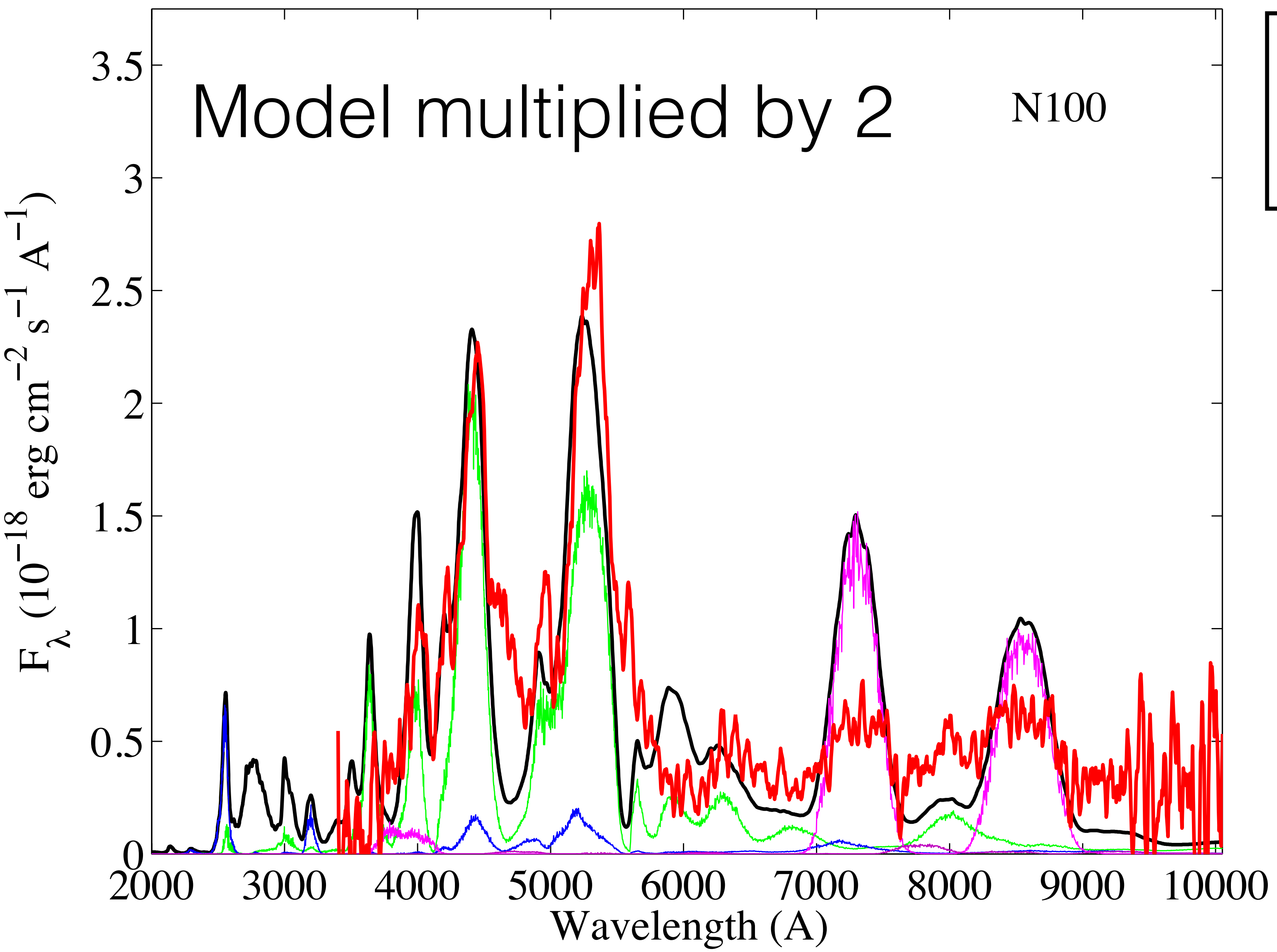
Models with RT : optical stays bright

Data

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?

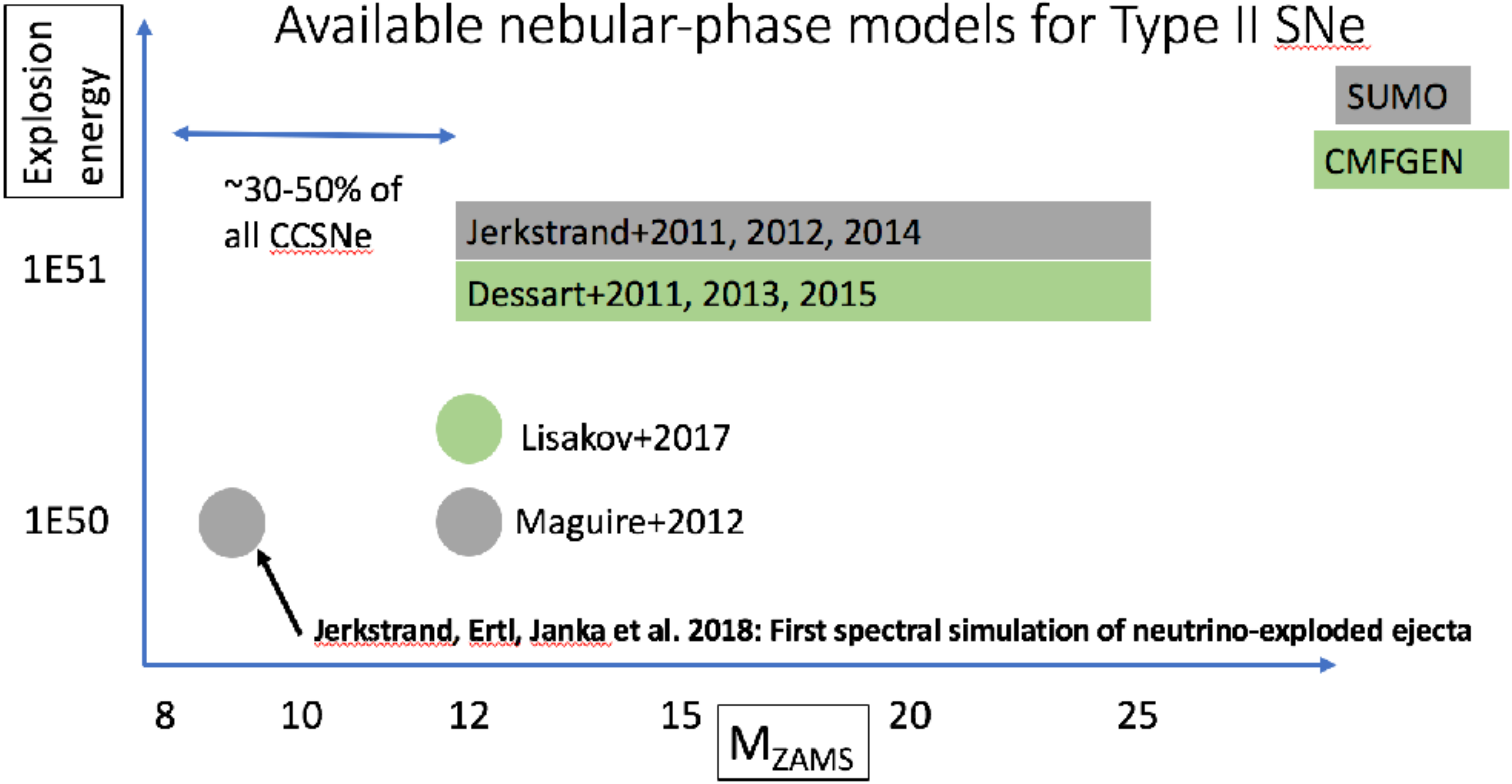


$M(^{56}Ni) = 0.60\ M_{sun}$
$M(^{57}Ni) = 0.018\ M_{sun}$

Powering ~ 50/50
by ^{56}Co positrons
and ^{57}Co electrons

If freeze-out unimportant : $M(^{57}Ni) \sim 0.06\ M_{sun}$
If freeze-out important : $M(^{57}Ni) \sim 0.02\ M_{sun}$

Available nebular-phase models for Type II SNe



SUMO

CMFGEN

Explosion energy

1E51

1E50

~30-50% of all CCSNe

Jerkstrand+2011, 2012, 2014

Dessart+2011, 2013, 2015

Lisakov+2017

Maguire+2012

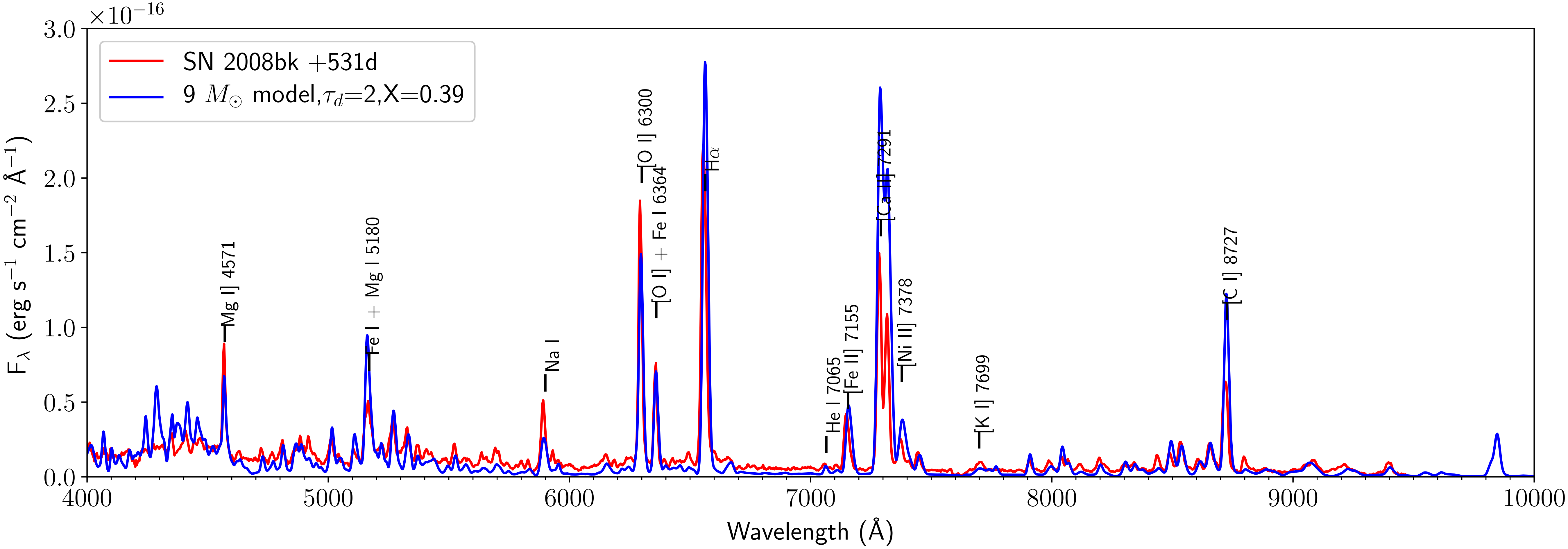
Jerkstrand, Ertl, Janka et al. 2018: First spectral simulation of neutrino-exploded ejecta

M_{ZAMS}

Sublumimous IIP SNe: good fits to low-mass progenitors

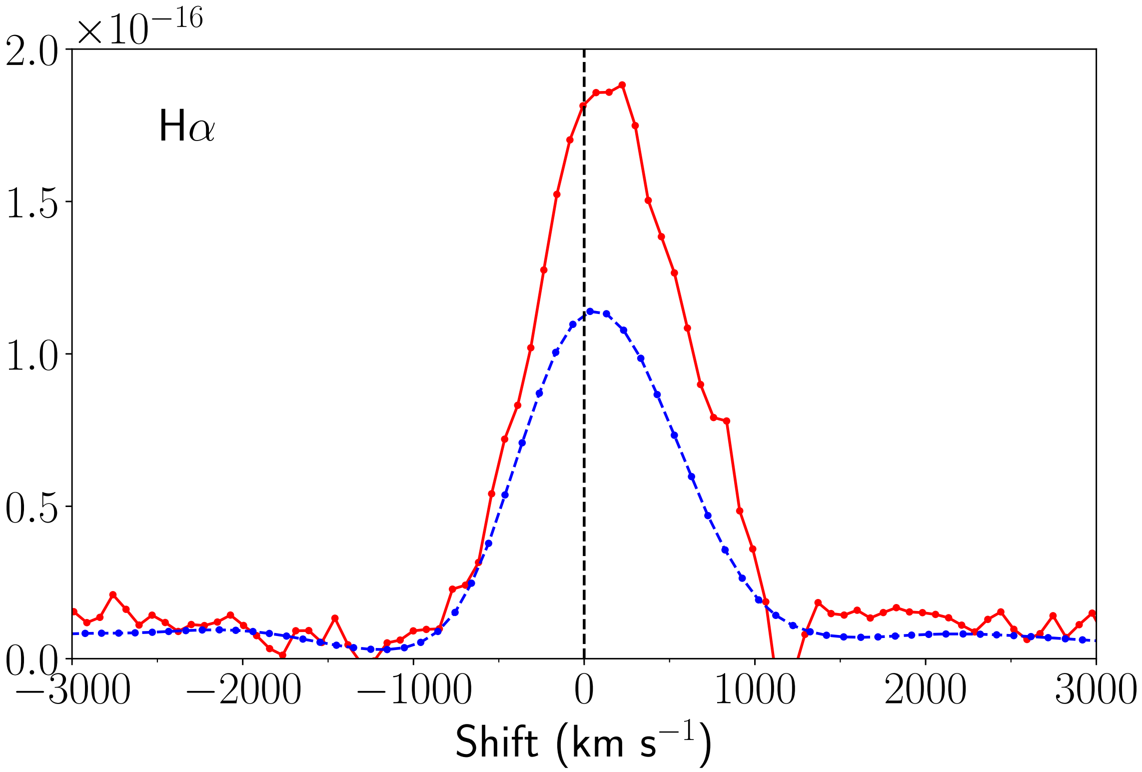
AJ+2018

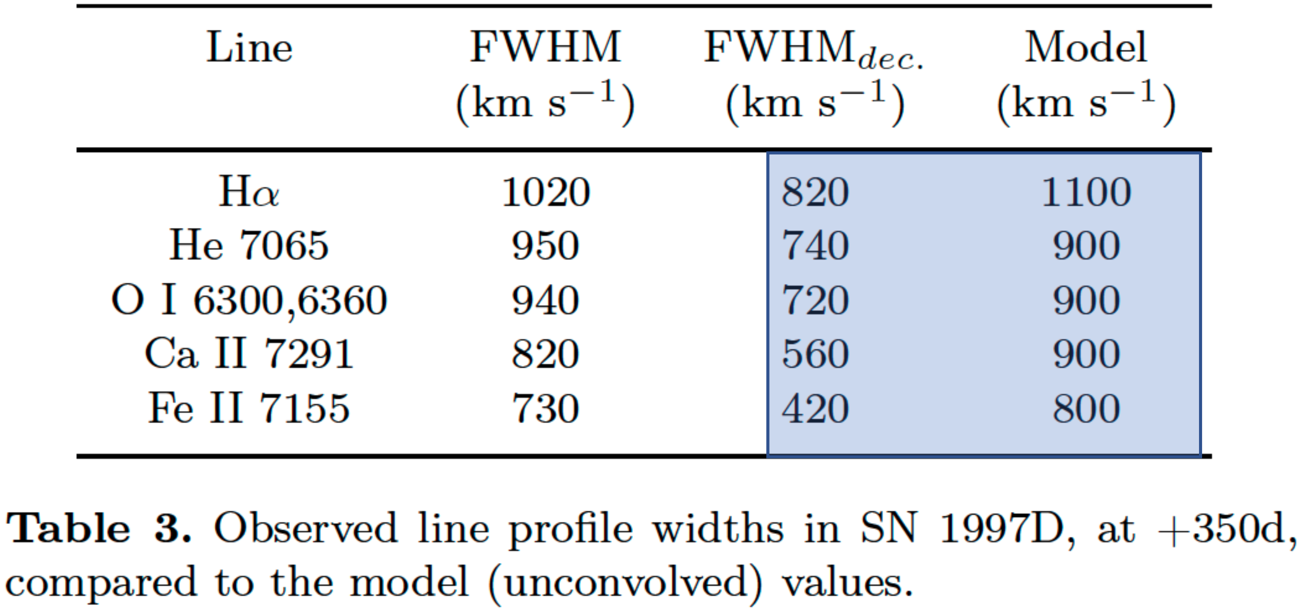
See also Lisakov+2017,2018



Self-consistent explosions: can probe line profiles

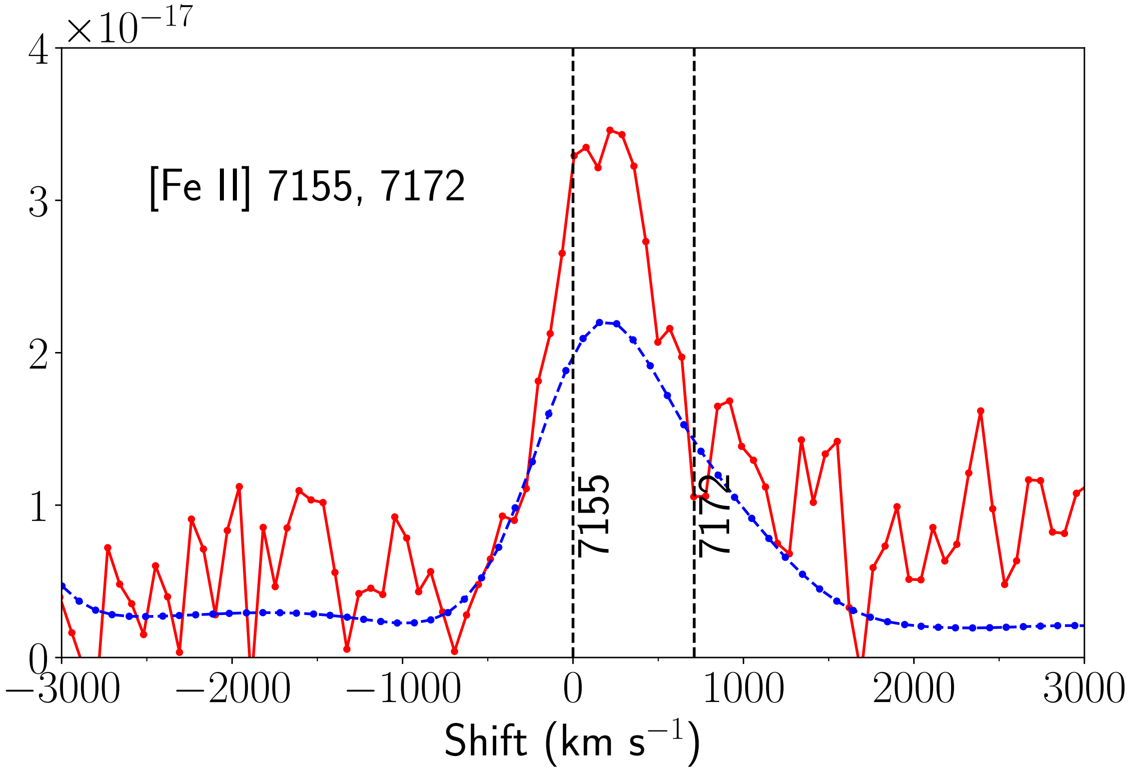
AJ+2018





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.