SUMO Ia test calculations

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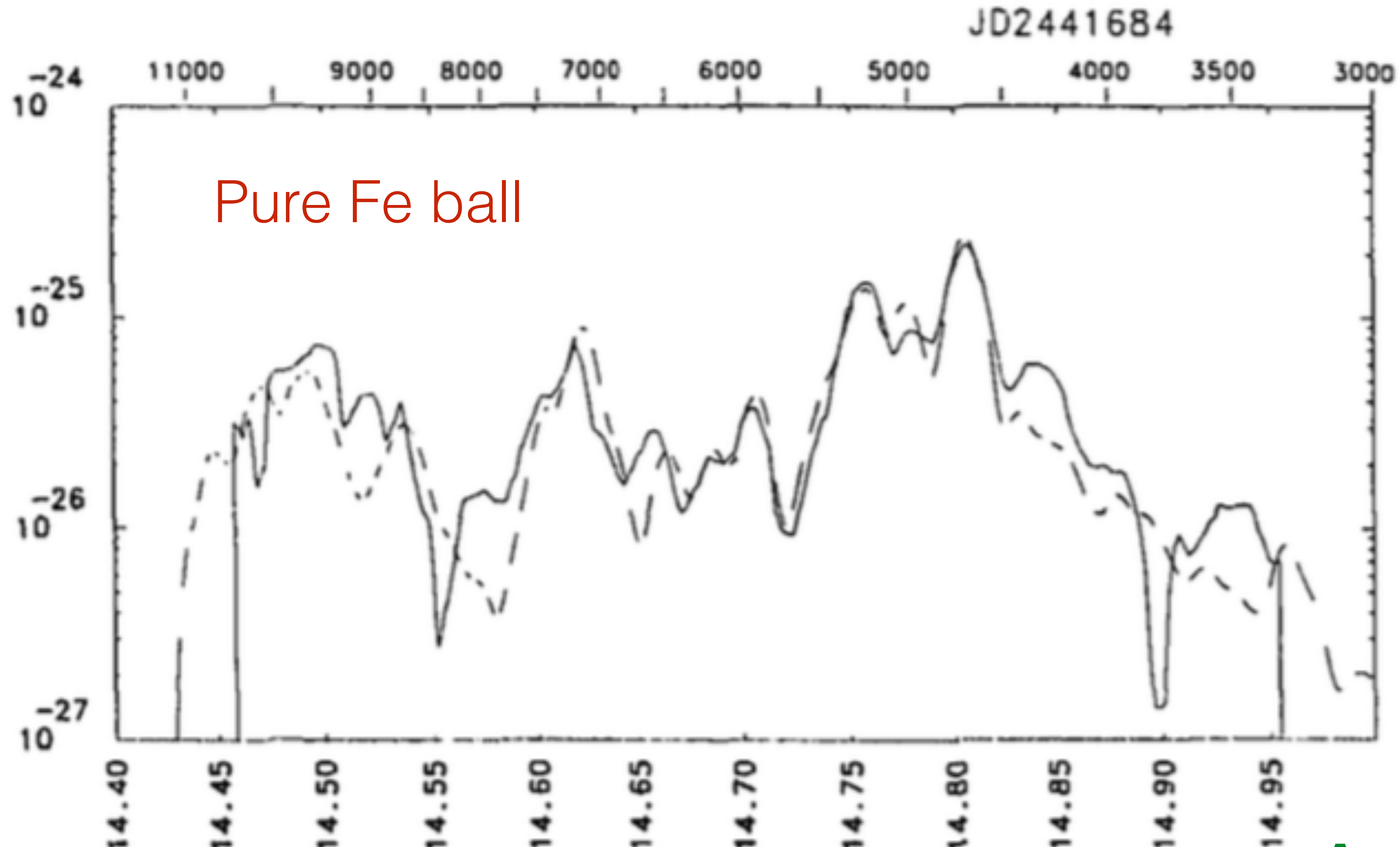
MPA

Late-time spectral modelling : 40 years of progress. How much have we improved on Axelrod for learning about Ia ejecta?



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

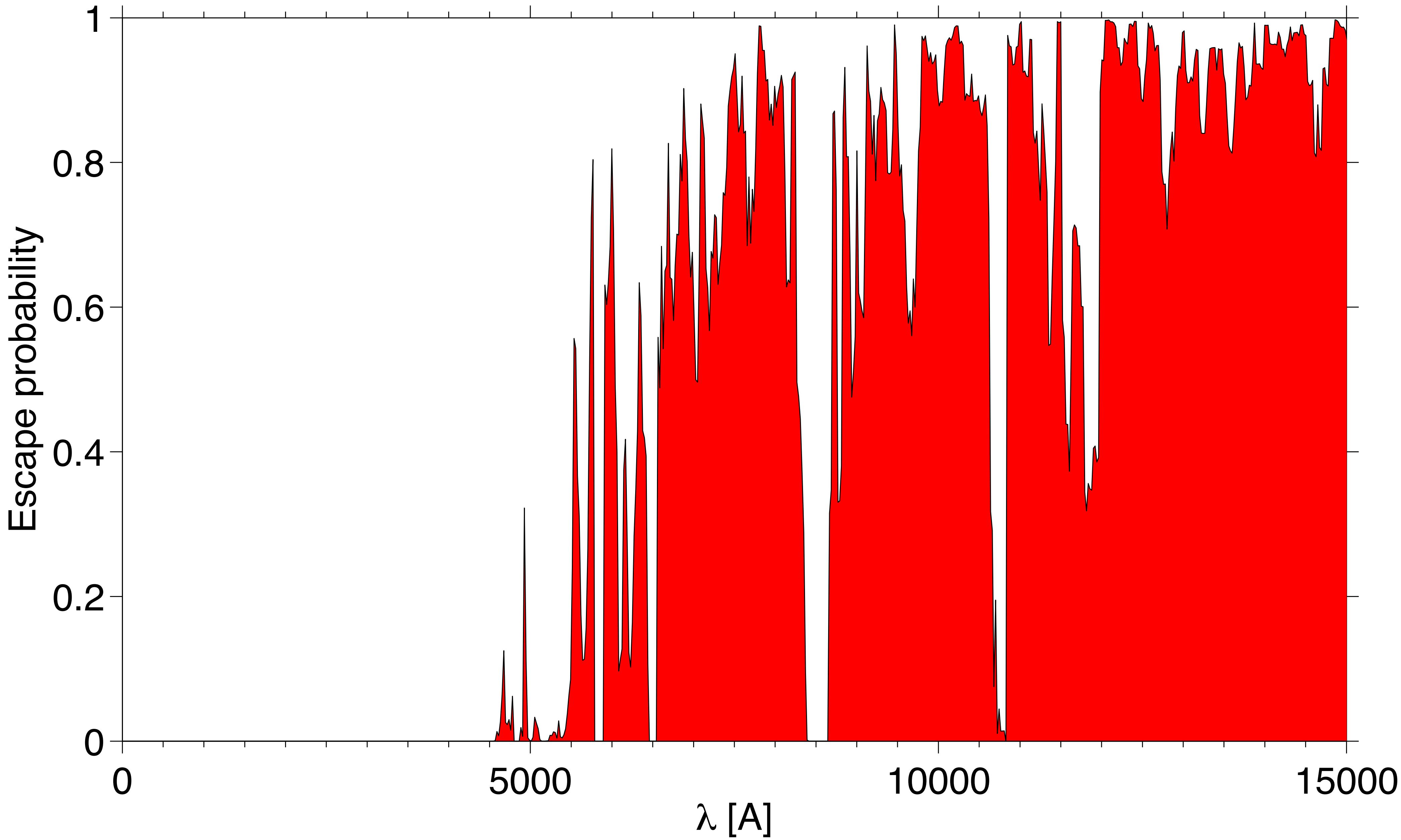
Axelrod 1980: used a "global" escape probability treatment. Avoid NLTE coupling by considering only low-lying (close to LTE) states as absorbing.

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

Jerkstrand+2011, 2012 + updates in later papers

1. **Mixing** : Virtual grid method (see 2011 paper)
   1. **Gamma-ray deposition** : Gray (0.06Y_e for ^{56}Co)
2. **Non-thermal exc. and ion.** : Spencer-Fano equation (Kozma & Fransson 1992 method + more cross sections).
3. **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 (~8000 total). Includes charge transfer network (150 rates + guessing rule of Pequignot & Aldrovandi 1986). Continuum-modified Sobolev approx. Steady-state.
4. **Temperature** : Cooling (<u>bb</u>+rec.+ff) = heating (<u>nt</u> + ff + p.i. + c.d. + c.t.). Steady-state.
5. **Radiative transfer** : Hybrid Monte Carlo/ray-tracing with ~300,000 lines (explicit), ~3,000 bound-free continua, free-free, electron scattering, dust. Sobolev approximation modified with continuum (all) and line (Ly-alpha, Ly-beta) destruction probabilities **Hummer & Rybicki 1985, AJ+2012 (App B.5)**
6. **Atomic data** *See later slide.*

Is transfer needed at ‘nebular’ times?

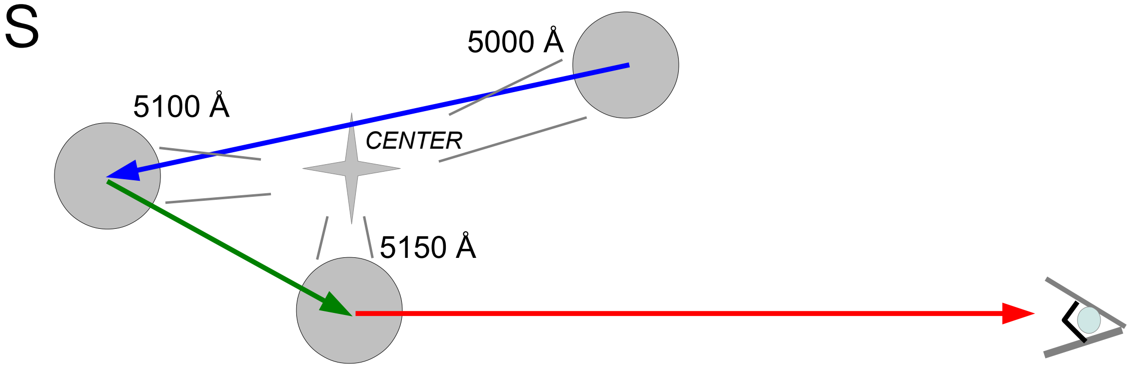


Escape probability in a Type II SN model at 300d

AJ Thesis 2011

The radiative transfer

- **Monte Carlo method** with (Sobolev) lines electron scattering, free-free, photo-ionization, dust.

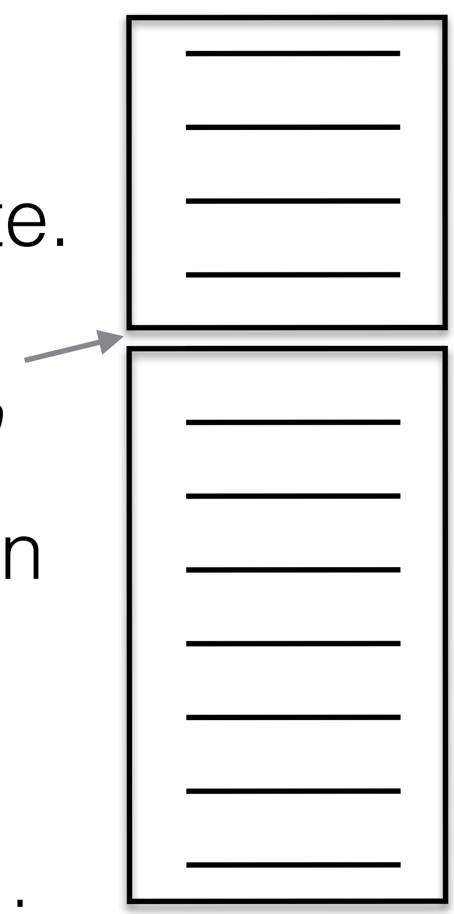


- All lines treated <u>explicitly</u> (no expansion opacity). Absorption events split into two groups:

1. <u>Abs. to low and mid-lying levels</u>: Attenuate packet, increase photoexc. rate. ("full NLTE coupling")

2. <u>To high levels</u>: Fluorescence cascade calibrated to enforce energy conservation ("no NLTE coupling").
   - $E_{in} = E_{out} + E_{coll.\ deexc.}$
   - Recursive method to ensure emission in all fluorescence channels.

Typical cap at 200-300 levels



High levels: uncoupled pop. solutions
$E_{out} = E_{in} + E_{coll.\ deex}$
Allow full fluorescence

Mid/low levels: Coupled pop. solutions
Attenuate packet, accumulate photoexcitation rates

- Photoion.+free-free : Full coupling (pure attenuation). Electron scattering: on-the-fly.

Atomic data

- **Energy levels** Mostly Kurucz CD 23 + “NIST”
- **A-values** Mostly Kurucz CD 23 + “NIST”
- **Thermal collision strengths** e.g. Pradhan*. Generic: Allowed: Regemorter. Forbidden: 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, Arnauld & Raymond 92.
- **Photoionization cross sections** Verner et al. 1996 + TOPBASE + hydrogenic.
- **Recombination rates** e.g. Nahar **
- **Charge transfer rates** e.g. Arnauld & Rothenflug 1985, Swartz 1994, Kingdon & Ferland 1996, Zhao 2004

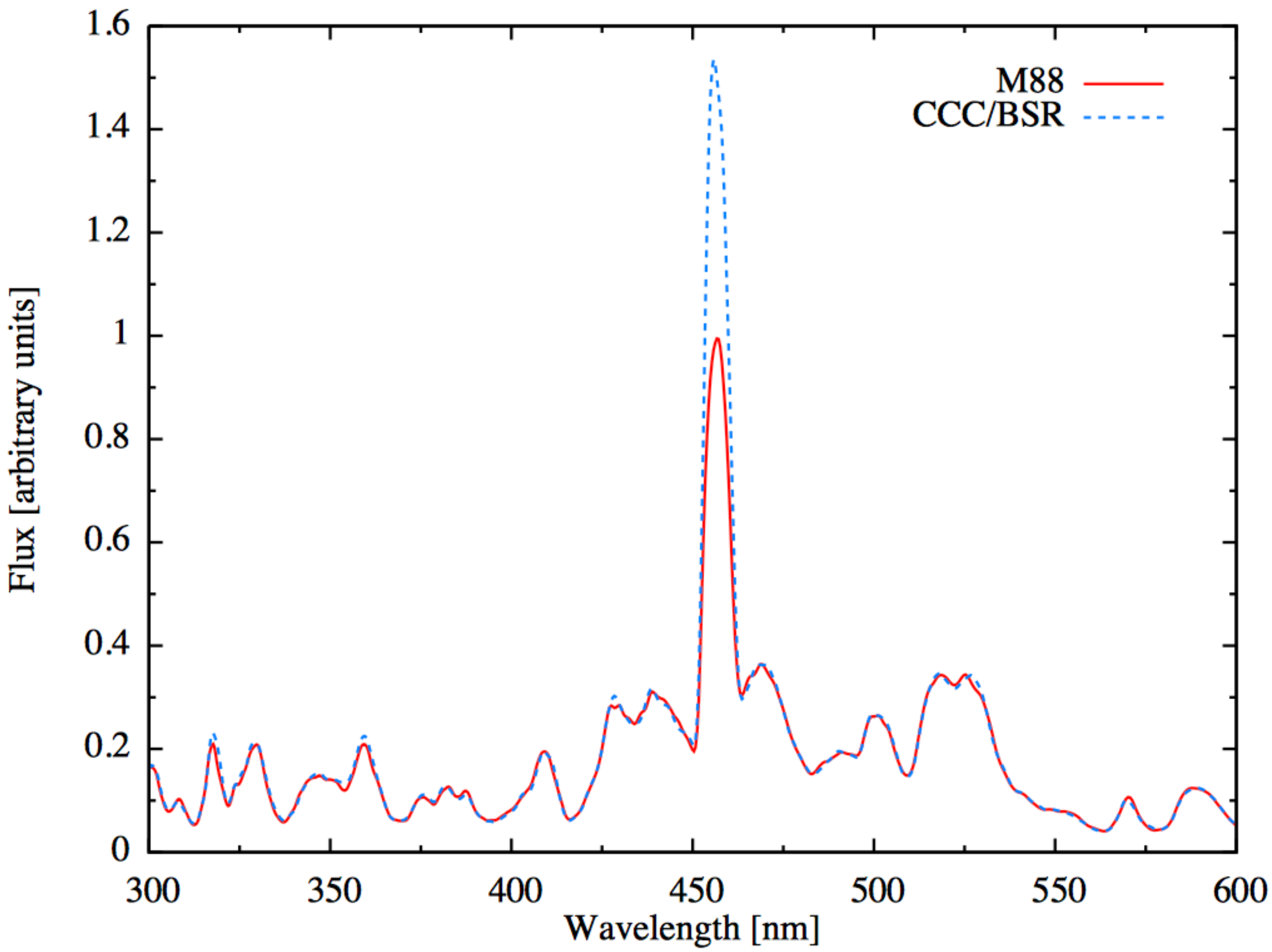
Current overview of data sources maintained at

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

Atomic data



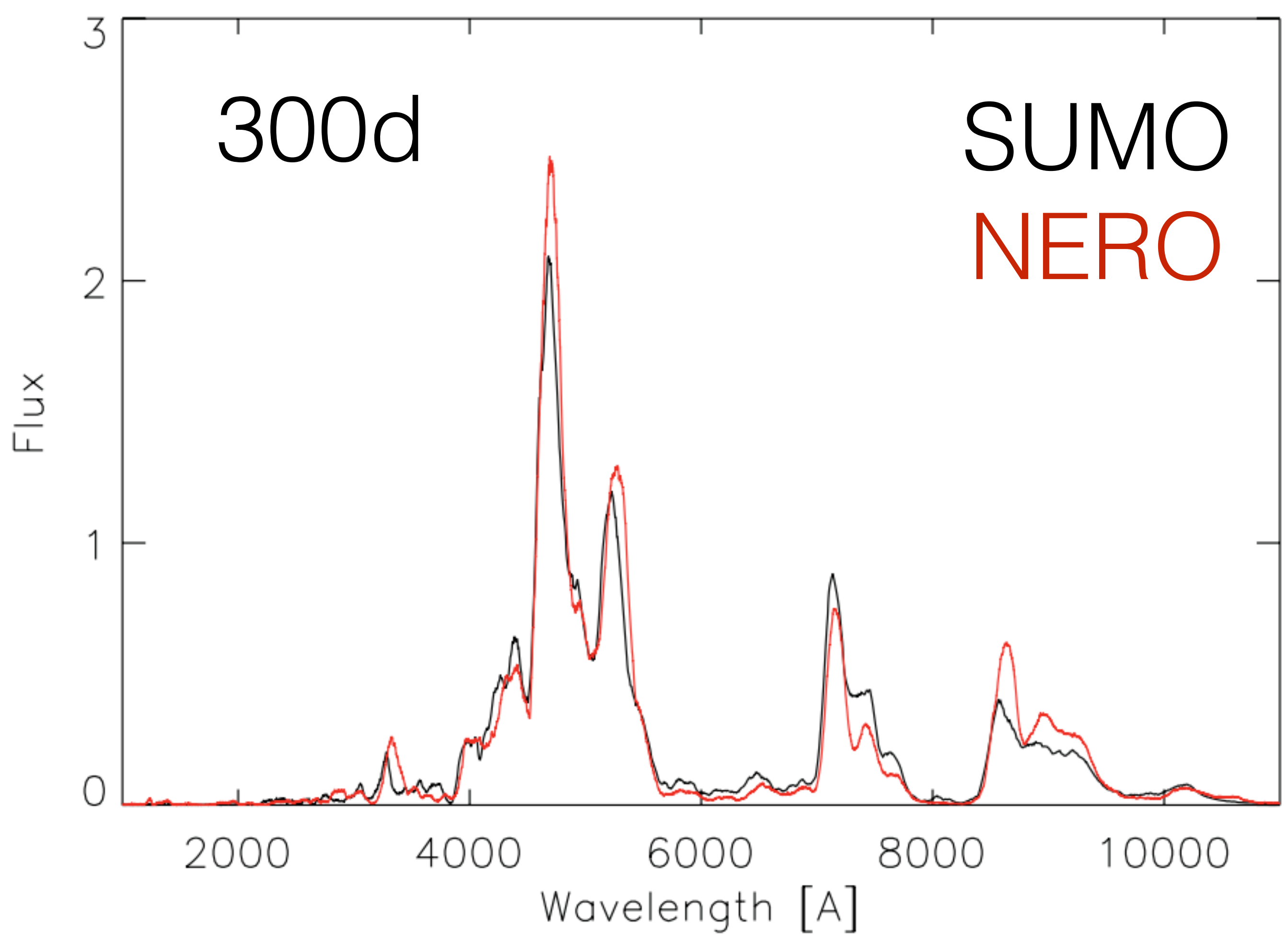
Barklem+2018 : update Mg I thermal coll. strengths

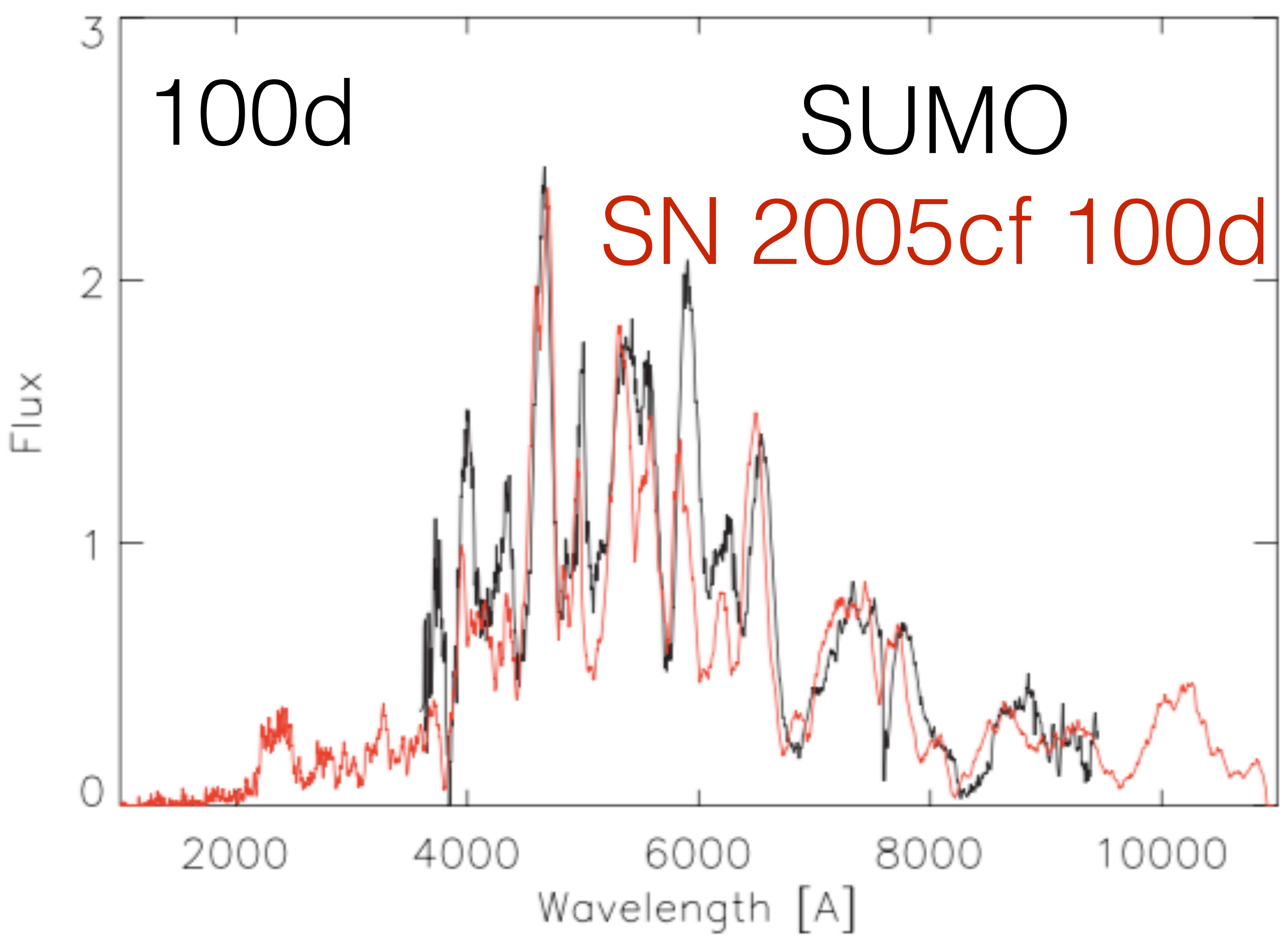
Atomic data : Fe/Co/Ni

- **Energy levels** FeI: CD23(496), FeII: NIST (528), FeIII: KO (168), CoI: CD23 (317), CoII: CD23 (108), CoIII: KO (306), NiI: NIST (136), NiII: CD23 (500), NiIII: NIST (8).
- **A-values** FeI: CD23(496), FeII: Fuhr&Wiese 2006, FeII: KO, CoI: CD23, CoII: Quinet 1998, CoIII: KO, NiI: NIST, NiII: NIST + Nussbaumer & Storey 1982, Ni III: NIST.
- **Thermal collision strengths** FeI: Pelan & Berrington 1997, FeII: Zhang&Pradhan 1995, FeIII: Zhang&Pradhan1995b, CoI/II/III: generic, NiI: generic*, NiII: Cassidy 2010/2011 NiIII: Bautista 2001

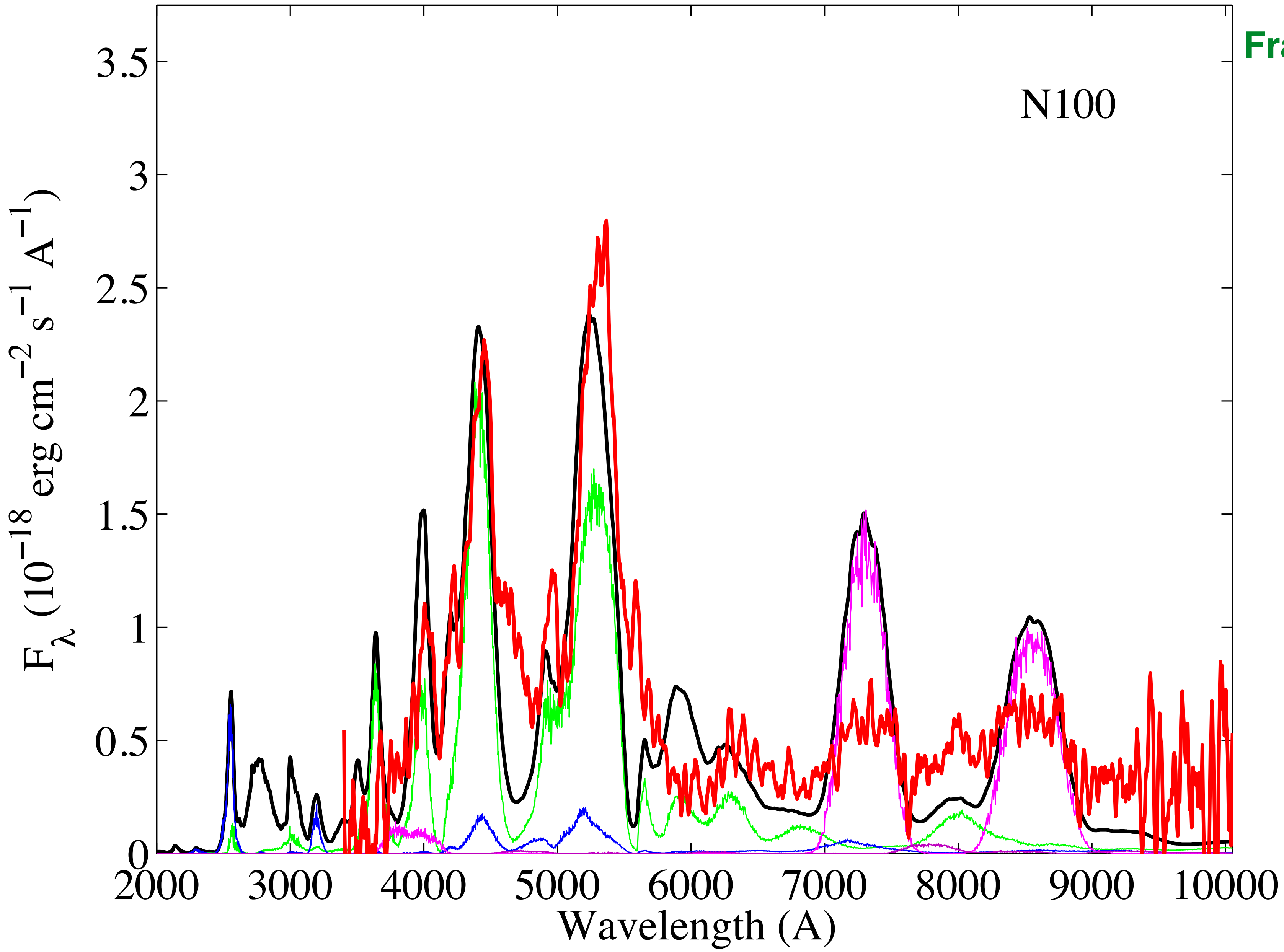
  **.. Allowed: Regemorter. Forbidden: 0.004g1g2 (Axelrod)*
- **Non-thermal b-b collisions** FeII: Ramsbottom 2005/2007, others: Bethe approximation.
- **Non-thermal b-f collisions** FeI/II/III: Arnaud & Raymond 1992, CoI/II/III: Source of data unclear, NiI/II/III: Arnold & Rothenflug 1985.
- **Photoionization cross sections** FeI/II: Nahar & Pradhan 1995. CoI/II/NiI/NiII: Verner (GS)+ hydrogenic (excited).
- **Recombination rates** FeI/FeII: Nahar1997, CoI/CoII/NiI/NiII: generic.

Old code tests with W7 Maurer, Jerkstrand et al. +2011





Example of a Type Ia application: ^{57}Ni mass in SN 2011fe



Fransson & Jerkstrand 2015

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) ~ 0.06 M_{sun}
If freeze-out important : M(^{57}Ni) ~ 0.02 M_{sun}

Test calculation status

Toy01: 100-400d done
Toy06: 100-400d done
DDC10: In progress
DDC25: In progress

Issues:

- No triply ionized (or higher) ions in SUMO
- In standard setting slow convergence at earlier times —> limit to 100d.
- So far only quite low-resolved ejecta done (500 km/s shells)

Choices

Ejecta resolution:

* How thick shells? *500 km/s*
* Maximum velocity? *10,000 km/s*

RT resolution:

* dlambda/lambda *1E-3*
* tau_tresh *1E-3*

Physical processes

* Charge transfer *off*

Coupling radfield-NLTE:

* Photoexcitation *Standard*
* Npis *50*

Example output : toy06