Monte Carlo Radiative Transfer and Type Ia Supernovae

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Overview

- Introduction and motivation: Type Ia Supernovae
- Radiative Transfer considerations
- Our Monte Carlo radiative transfer code
- Simple tests and applications

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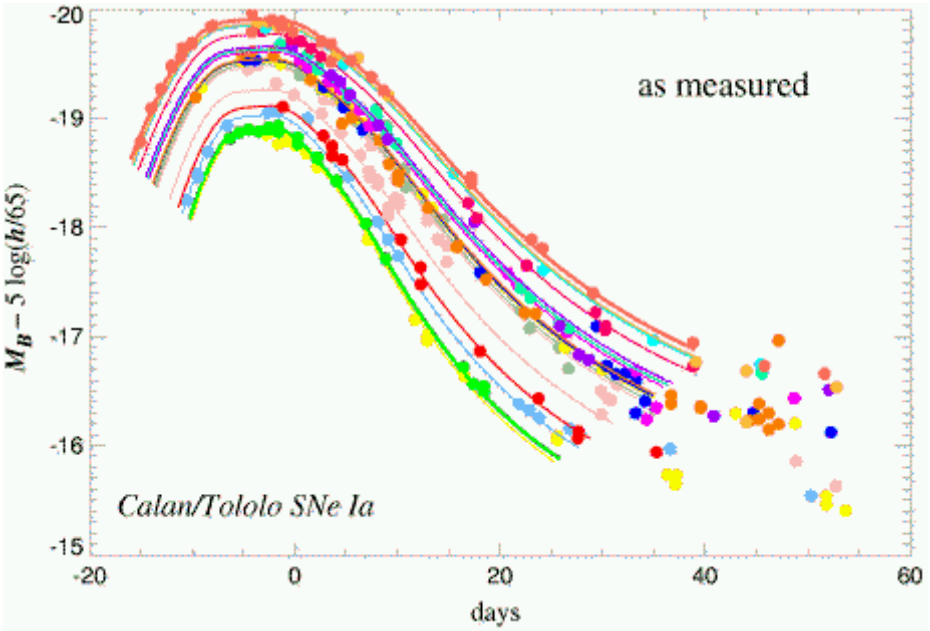

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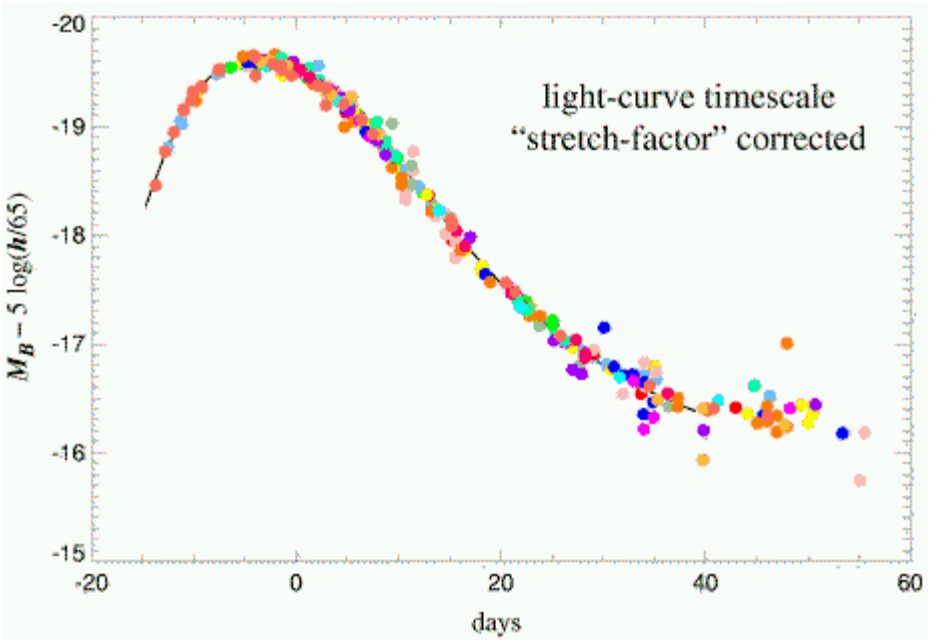

Empirical calibration

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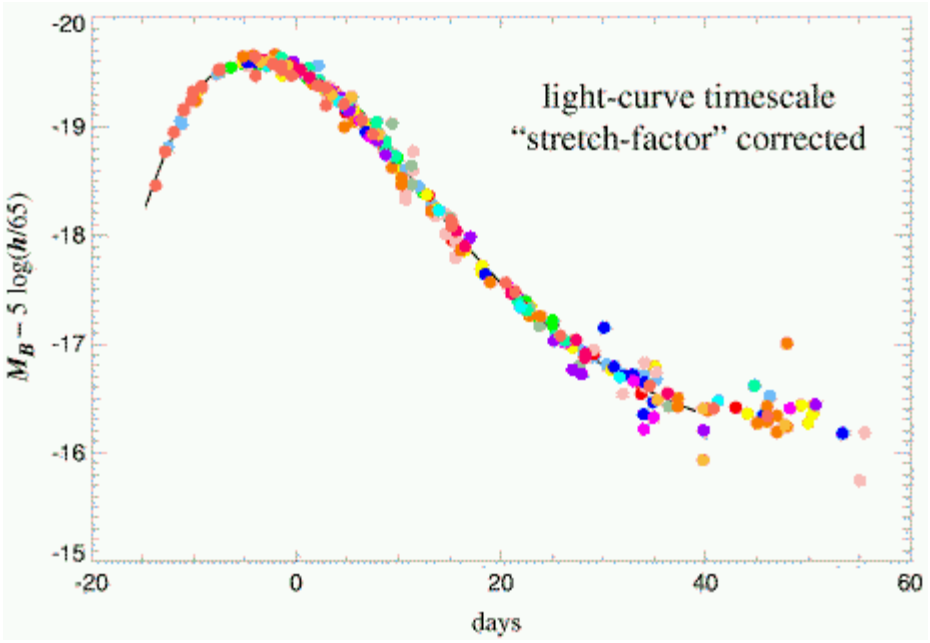

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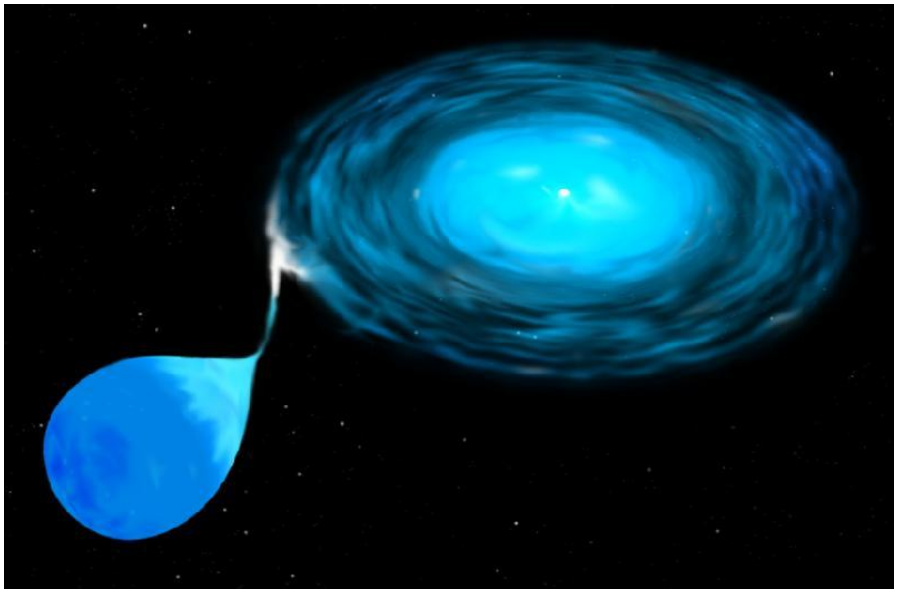

STScI

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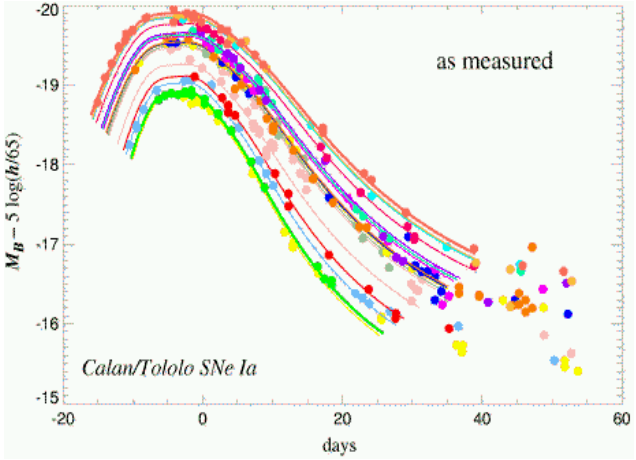
  - What determines the **differences** between events?
  - Why does the **luminosity/light-curve correlation** exists?
  - **Deviations** from standard picture?



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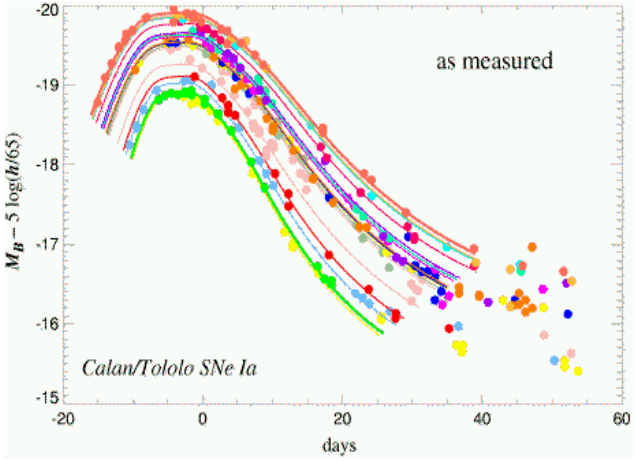
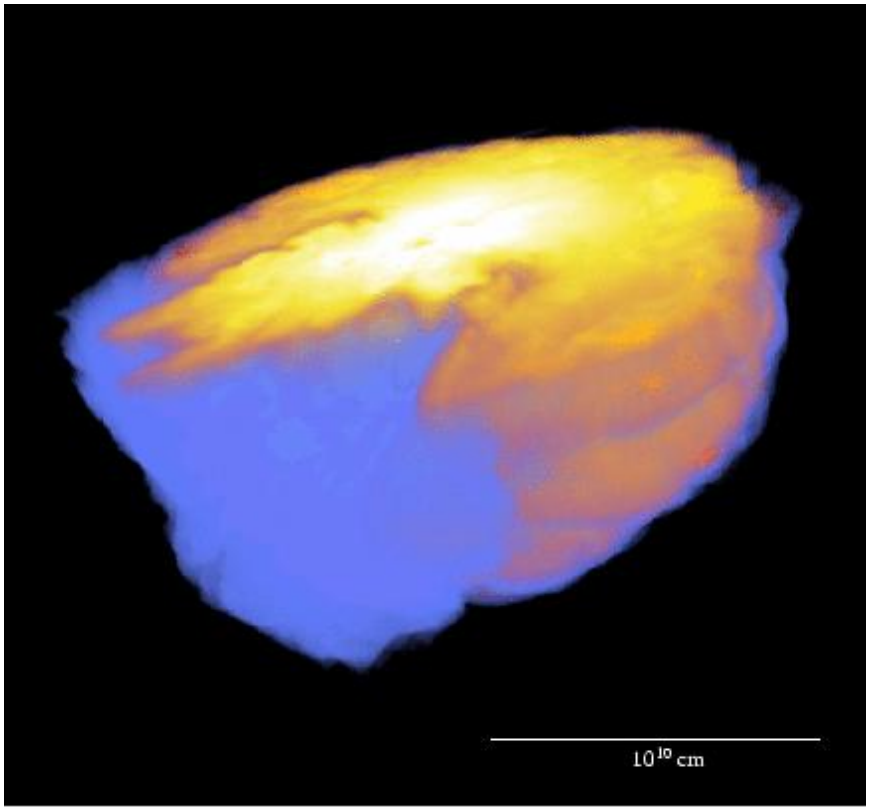


...potential sources of systematic error in the interpretation of SN data

Explosion models versus data



- **State-of-the-art explosion models:**
  - **Fully 3D**; turbulent combustion
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Off-centre deflagration model; courtesy of F. Röpke

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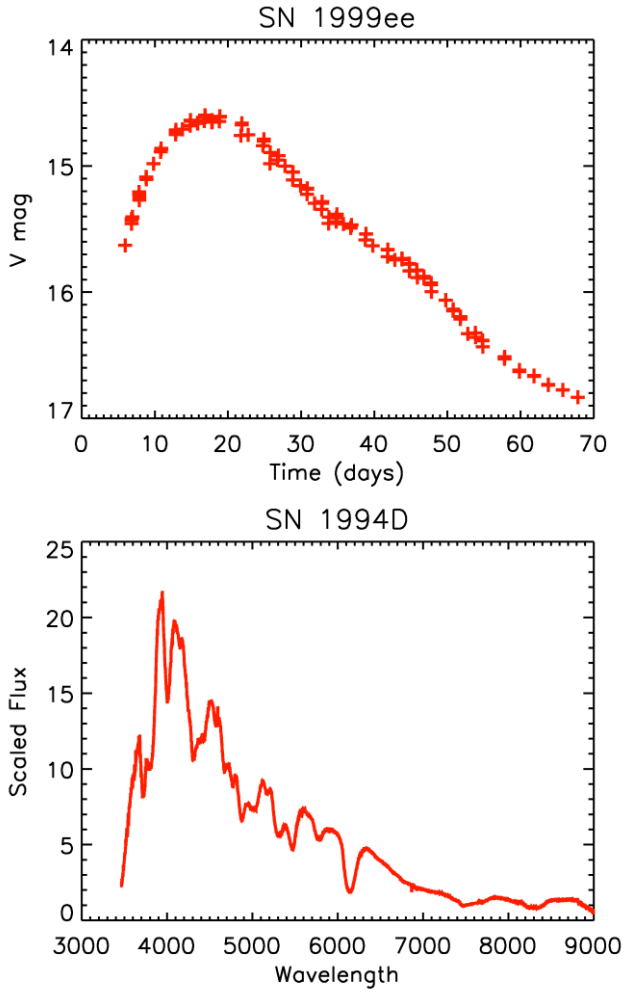

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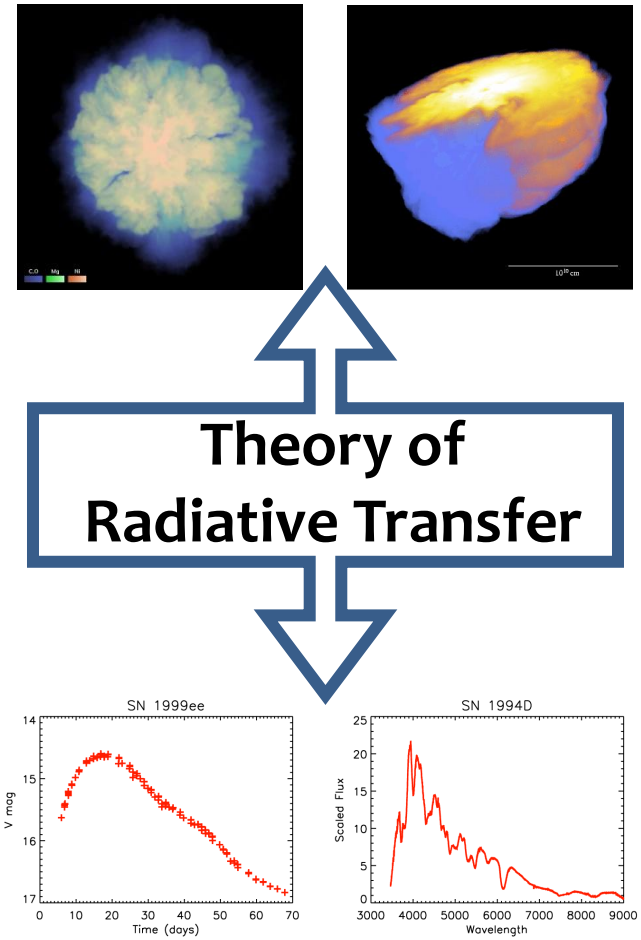

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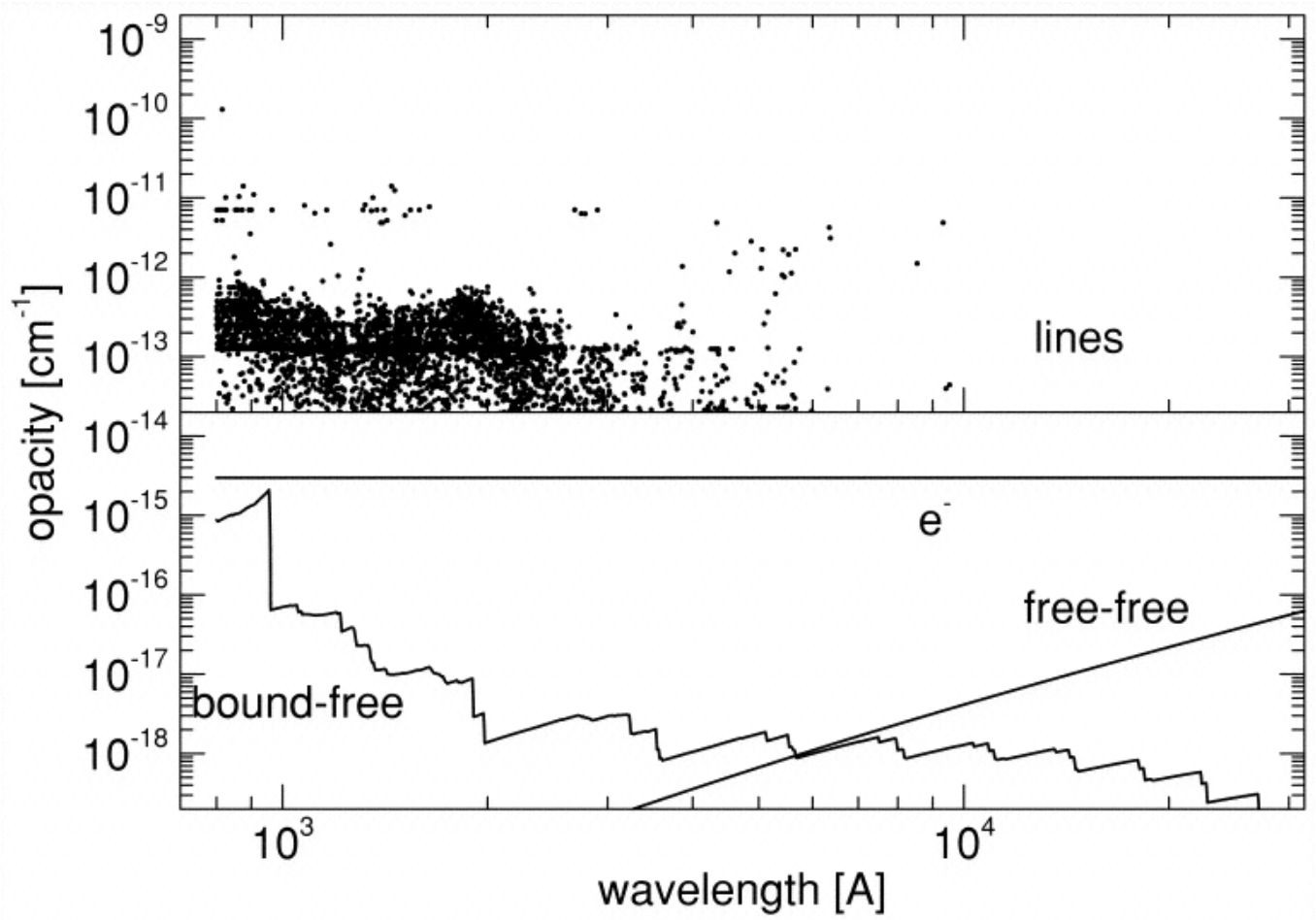

Pinto & Eastman 2000

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  - Departures from LTE inevitable
- **Simplifications**
  - Large velocity gradients: **Sobolev approximation**
  - **Homologous expansion**
  - **Statistical / thermal equilibrium** appropriate

Monte Carlo method

- ***Discretise energy flow*** *into* ***indivisible quanta*** *and simulate propagation*
  - Leon Lucy's method (Abbott & Lucy '85; Mazzali & Lucy '93; Lucy '99, '02, '03, '05)
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$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = \epsilon_\nu - \kappa_\nu I_\nu$$

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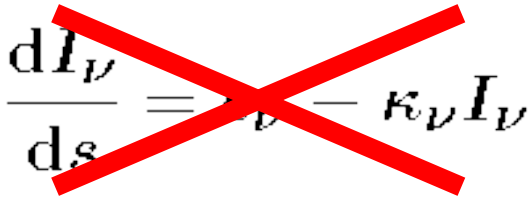

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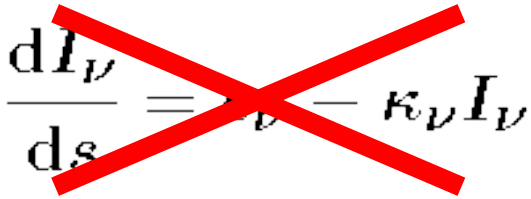

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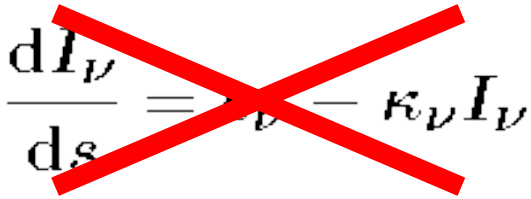

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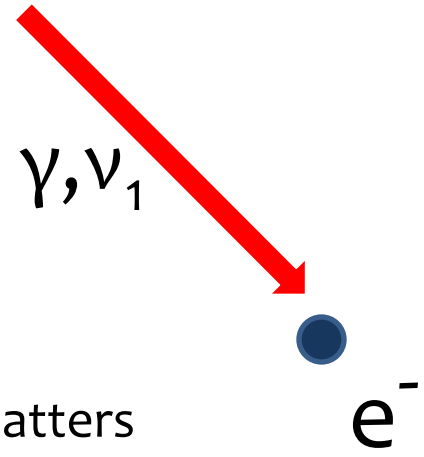
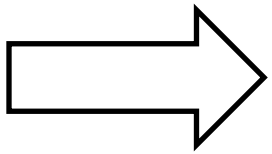
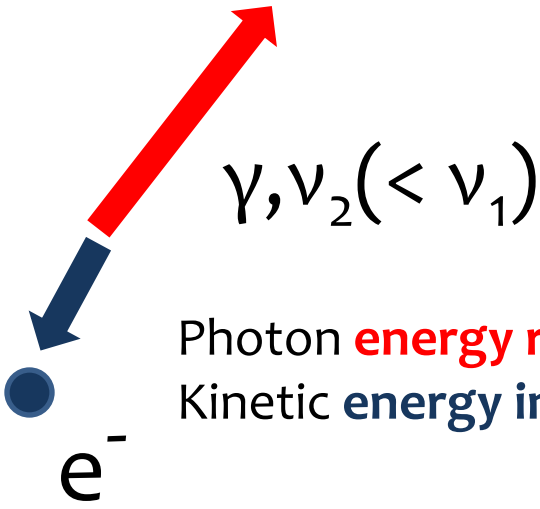
Example: Compton scattering



Photon scatters on **cold electron**.





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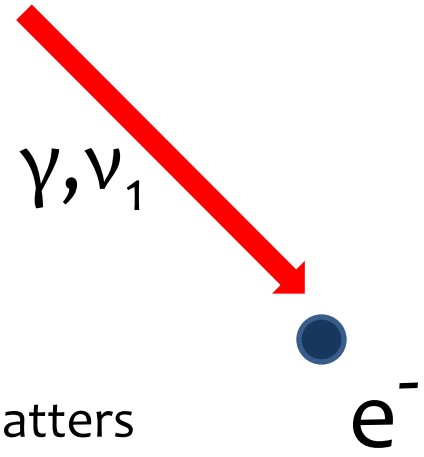

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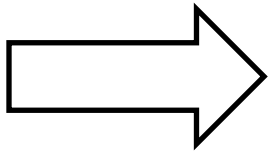

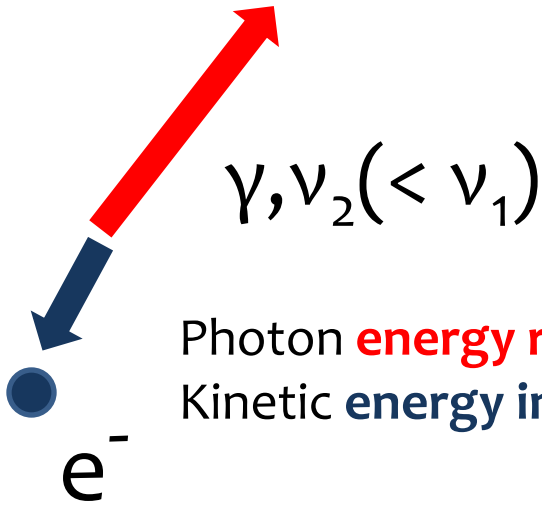

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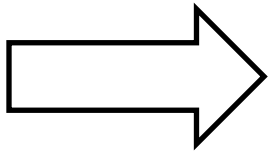
(ε_0, ν_1)



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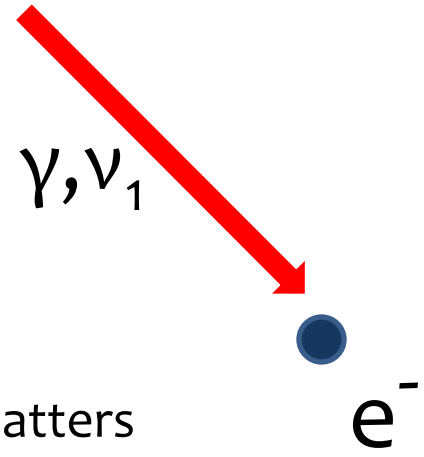

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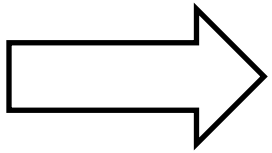

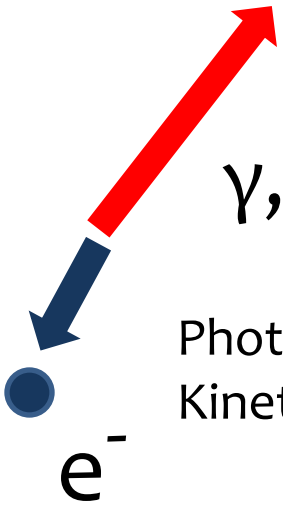

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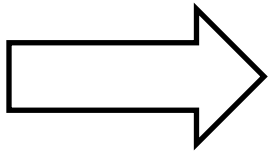


γ–packet
(ε_0, ν_2)

Prob = ν_2/ν_1

OR

***k*–packet**
(ε_0)

$(1 - \nu_2/\nu_1)$

Quanta types for SN Ia scheme

- **γ–packet** (high energy photons; monochromatic)
- **r-packet** (ultraviolet – infrared radiation; monochromatic)
- ***k*–packet** (thermal kinetic energy)
- **i-packet** (excitation/ionization energy)
- **Radioactive pellet** (radioactive nuclei yet to decay)

Concept readily generalized... (e^-–packet, e^+–packet etc.)

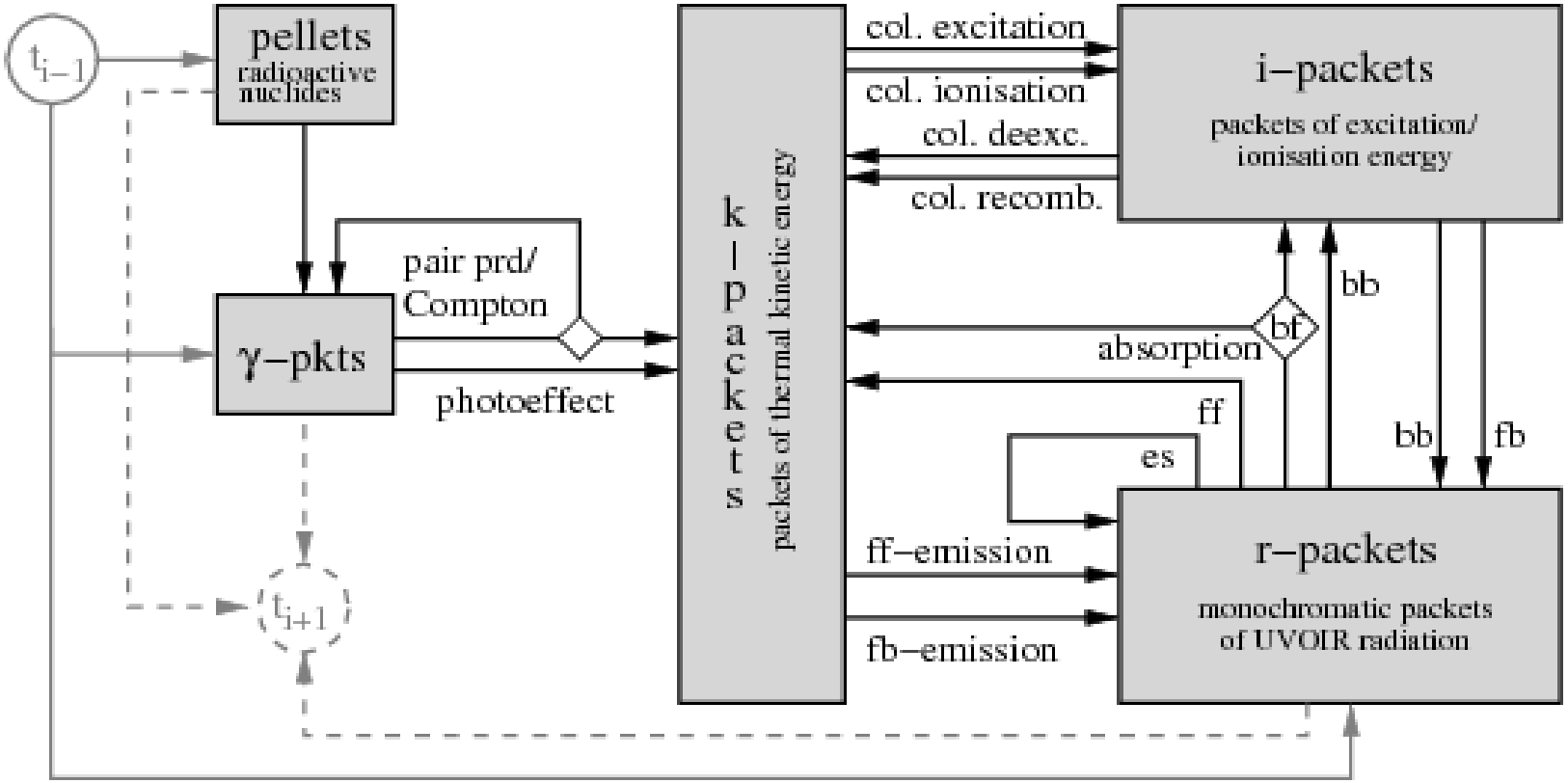
For further details see Lucy 02, 03 and 05

Numerical implementation

Specify:

- **Input model: density, chemical composition**
  - **Discretised in time and space (3D Cartesian grid)**
  - **Energy begins as radioactive pellets**
- **Atomic processes**
  - **Set of MC rules for each process**
  - **Atomic data (atomic models from Kurucz database)**

ARTIS Code: flow chart



Kromer & Sim 09

Excitation/Ionization state

Required to compute optical depths:

- **Obtainable** from equations of **statistical/thermal equilibrium**

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = \sum_{j \neq i} n_j R_{j \to i} - n_i \sum_{j \neq i} R_{i \to j} = 0$$

Excitation/Ionization state

Required to compute optical depths:

- **Obtainable** from equations of **statistical equilibrium**
  - Complete set of NLTE rate equations **too expensive**
  - We restrict ourselves to **photoionization balance**
  - Adopt **Boltzmann excitation** populations

$$\frac{n_i}{n_0} = \frac{g_i}{g_0} \exp\left(-\frac{\epsilon_i - \epsilon_0}{k_{\mathrm{B}} T_{\mathrm{J}}}\right)$$

Application: the W7 model

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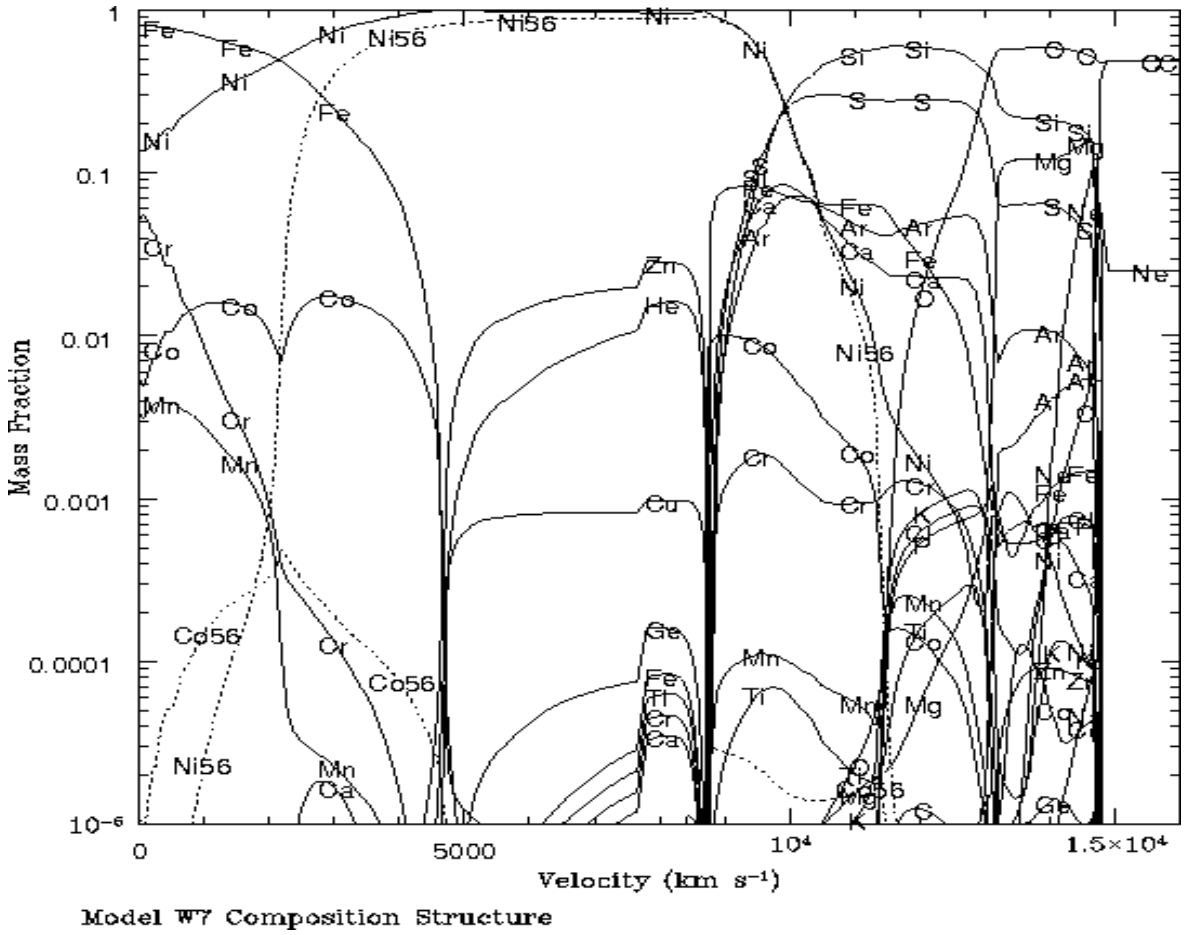
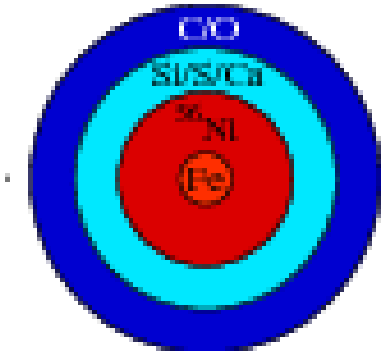


Well-known 1D SN Ia explosion model



Nomoto et al. 84
Thielemann et al. 86

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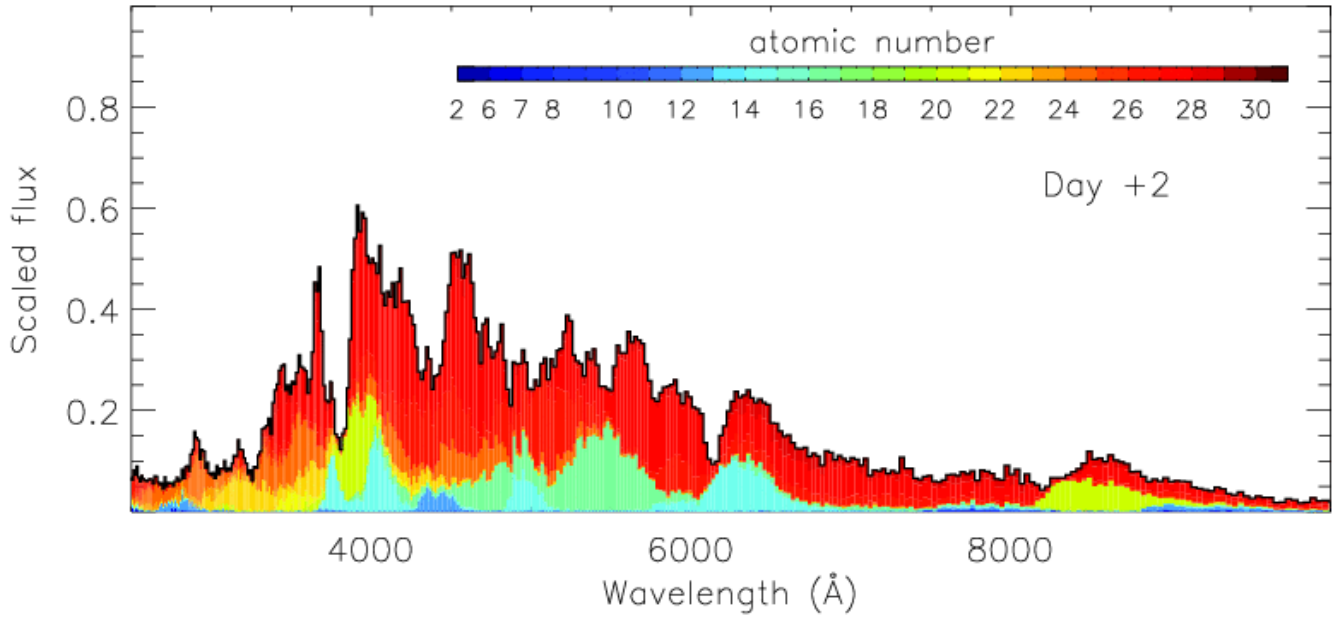

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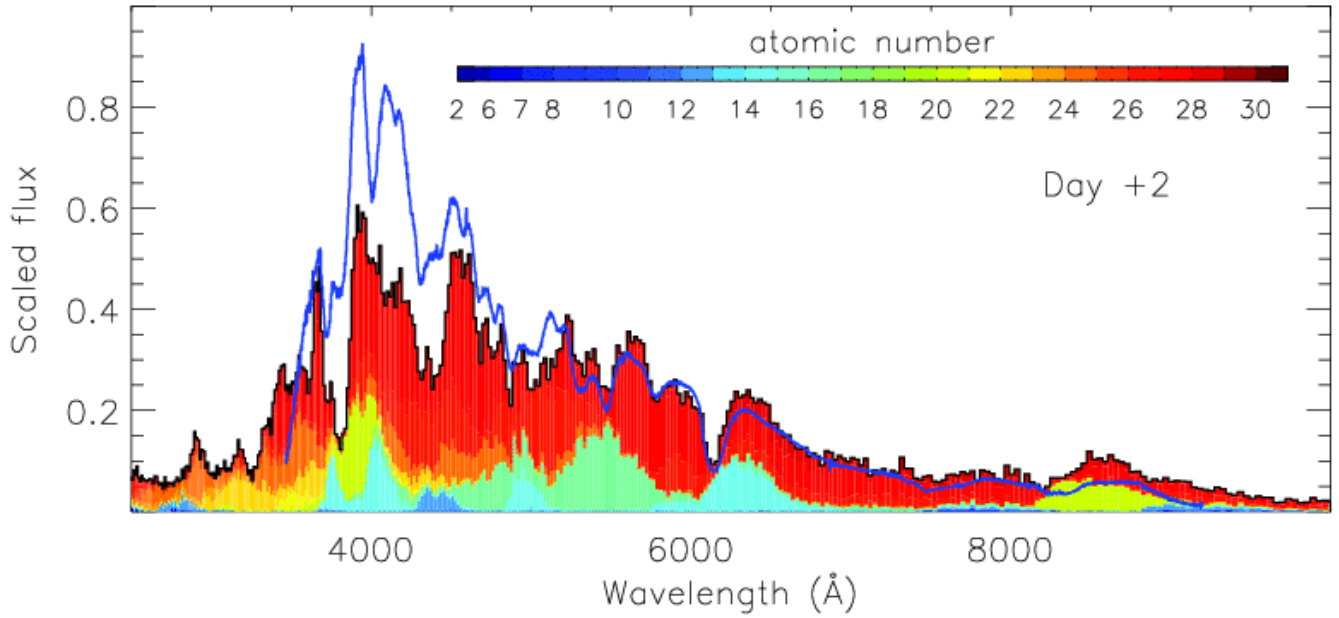

SN 1994D

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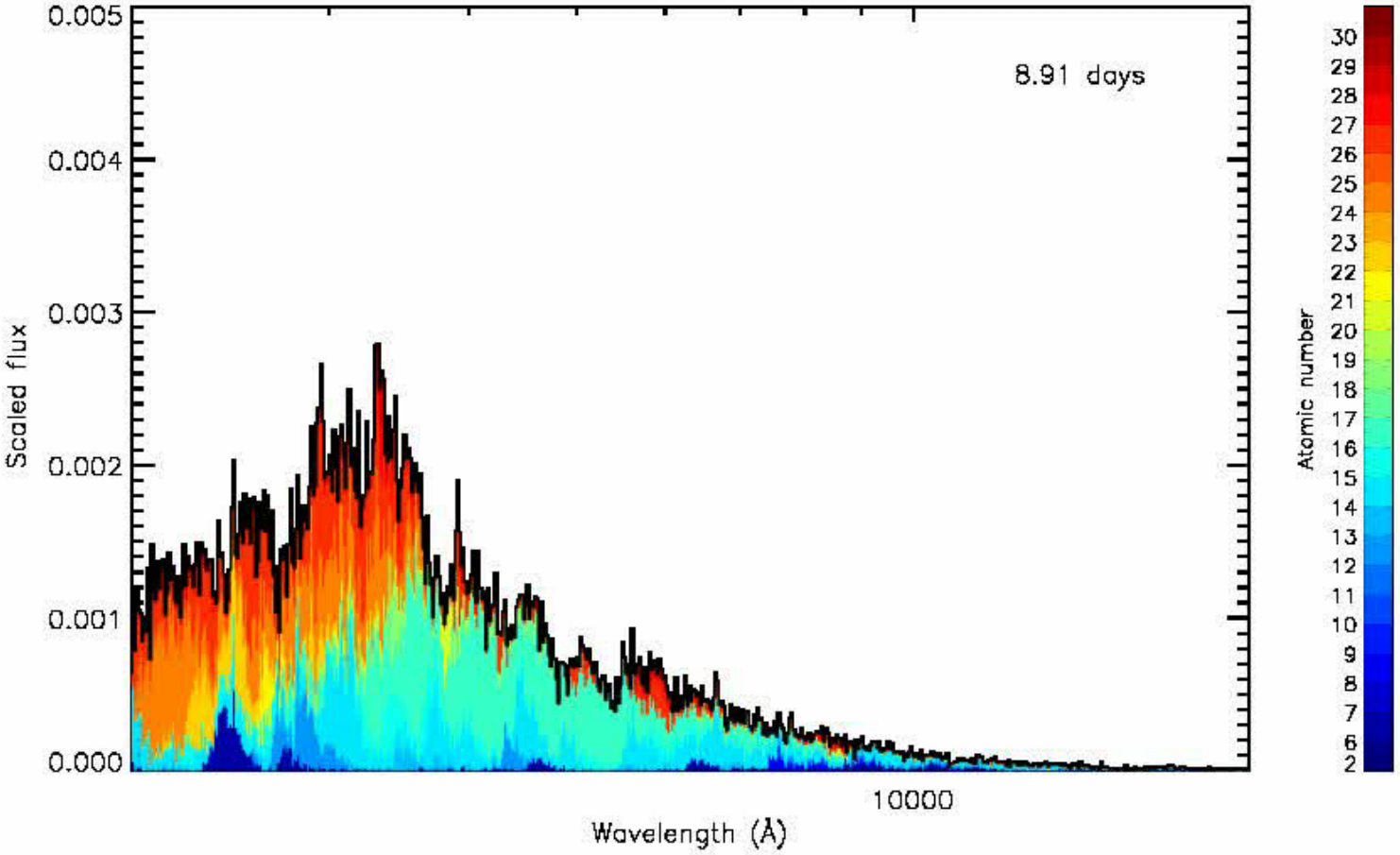
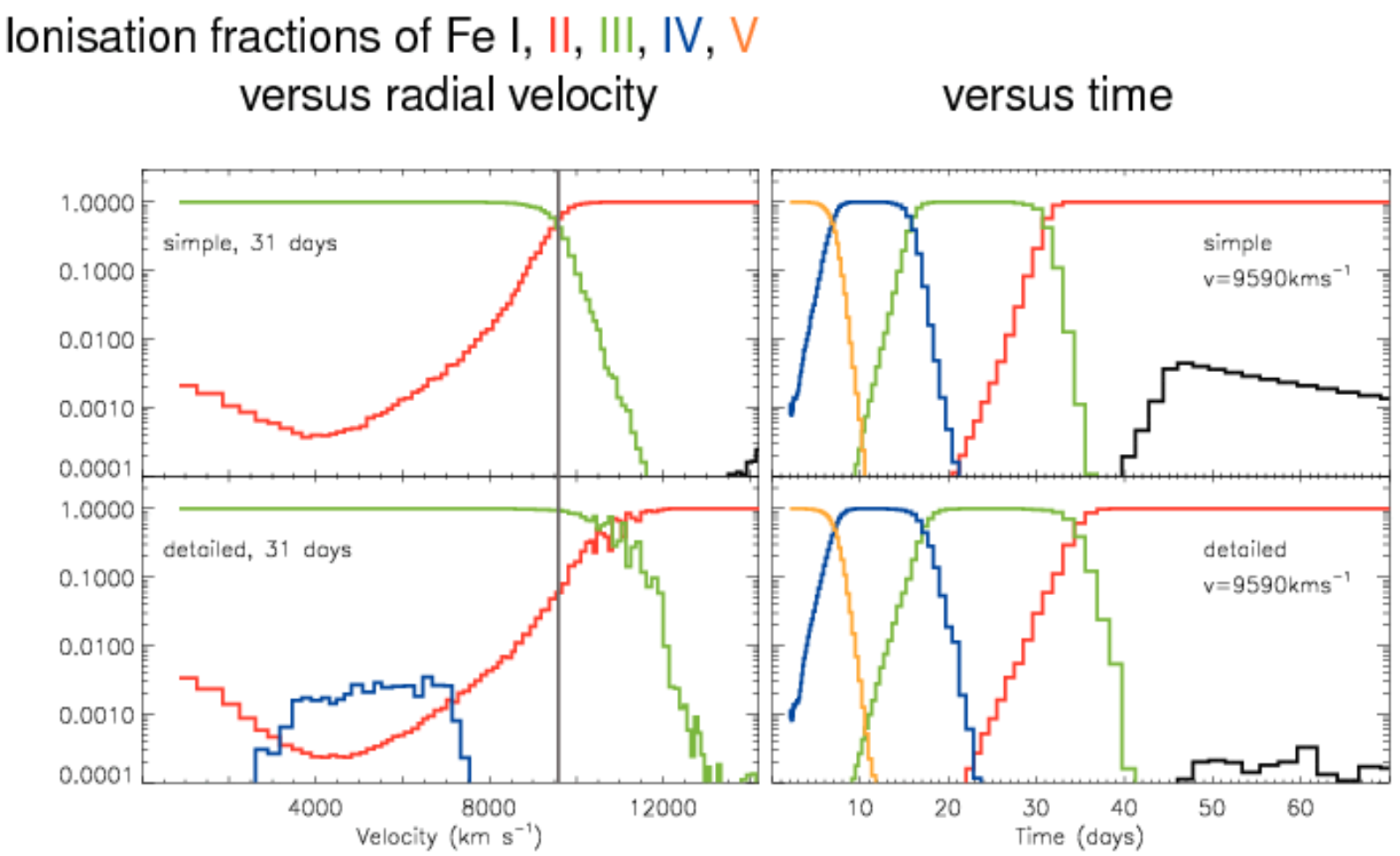


Ionization treatment: the W7 model



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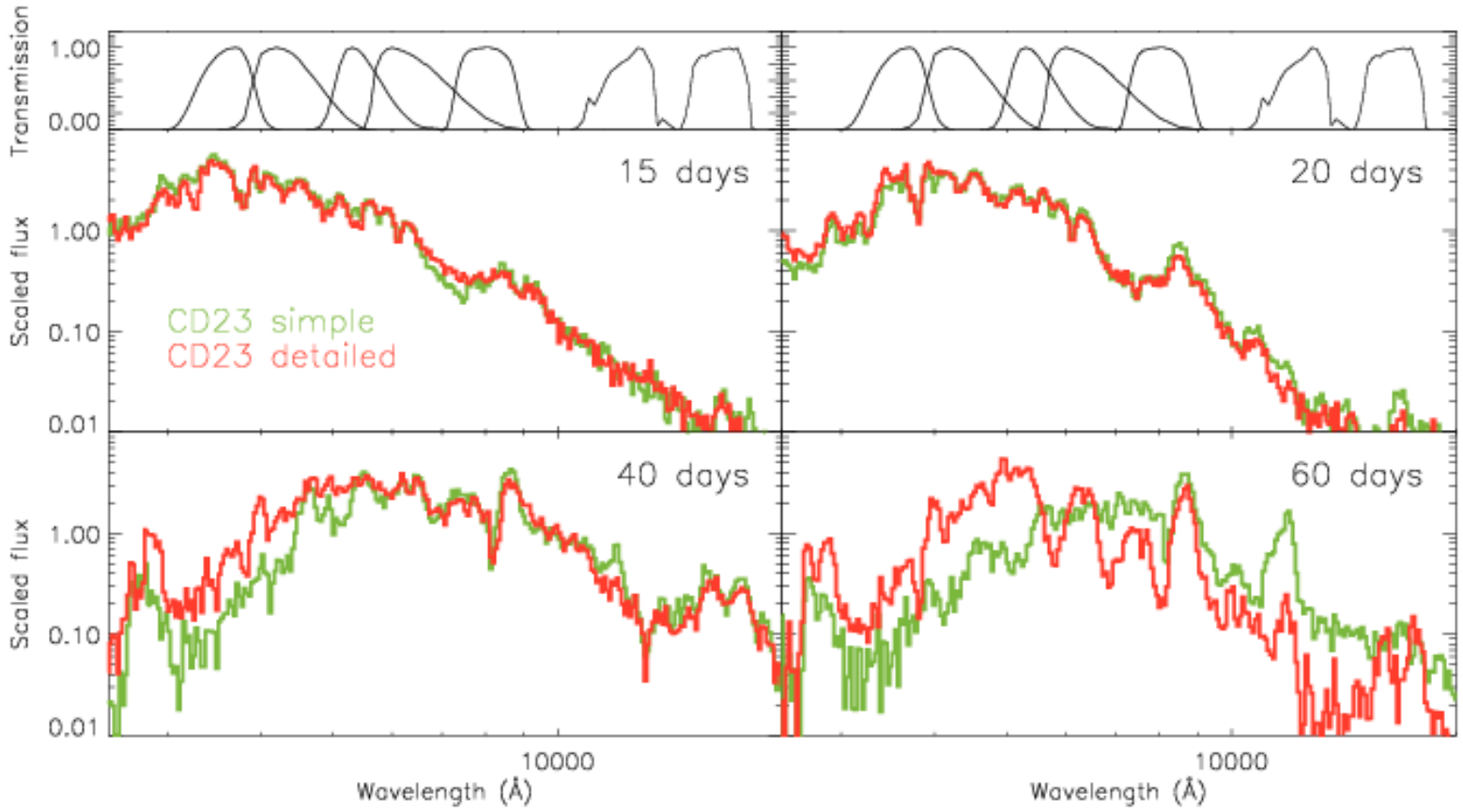

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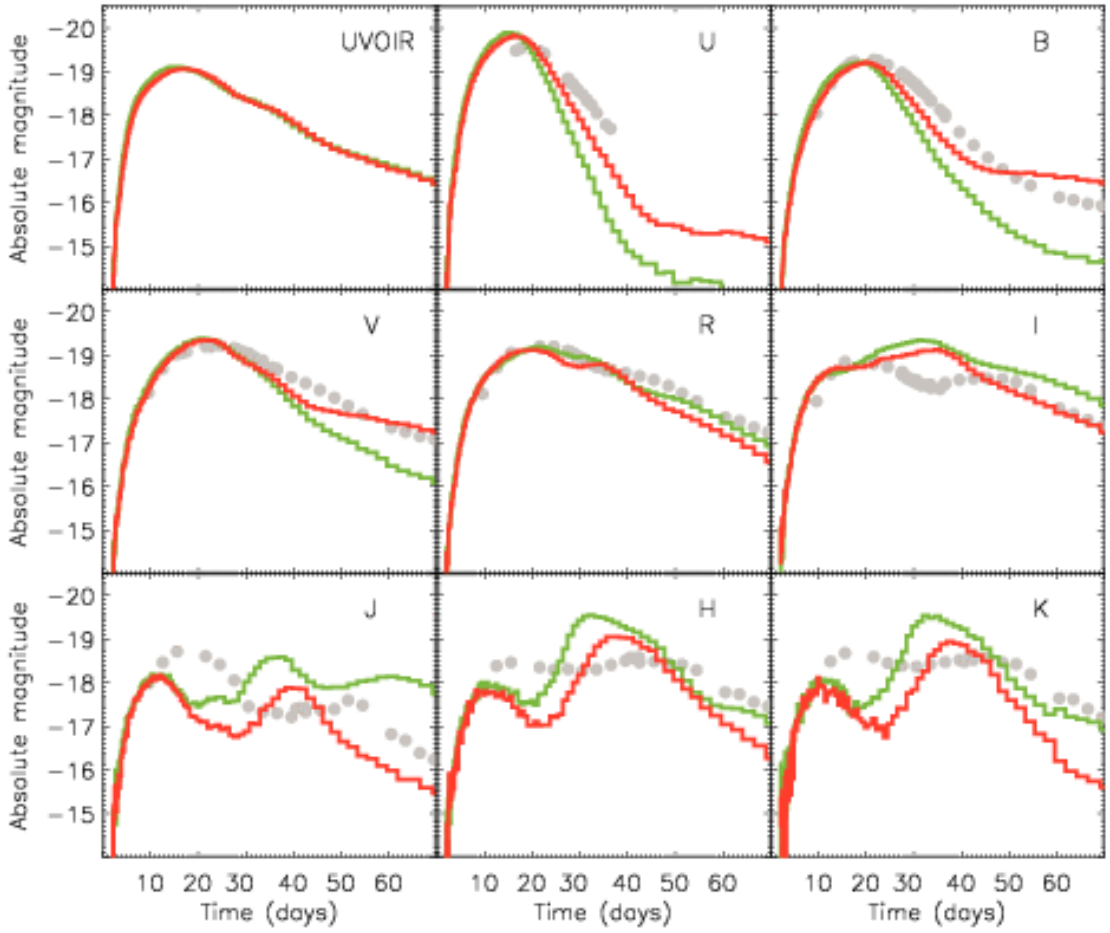
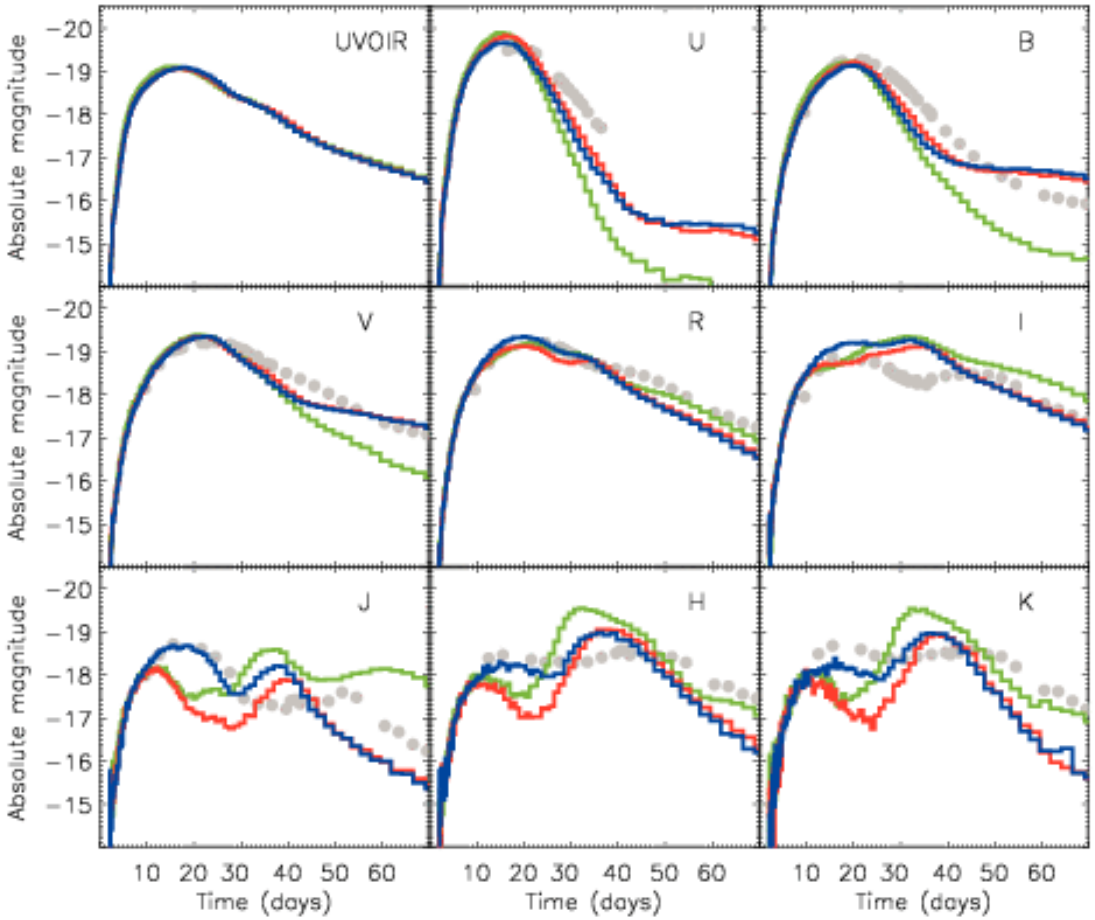


- circles: SN 2001el (Krisciunas 2003)
- CD23 simple
- CD23 detailed

Atomic data: the W7 model



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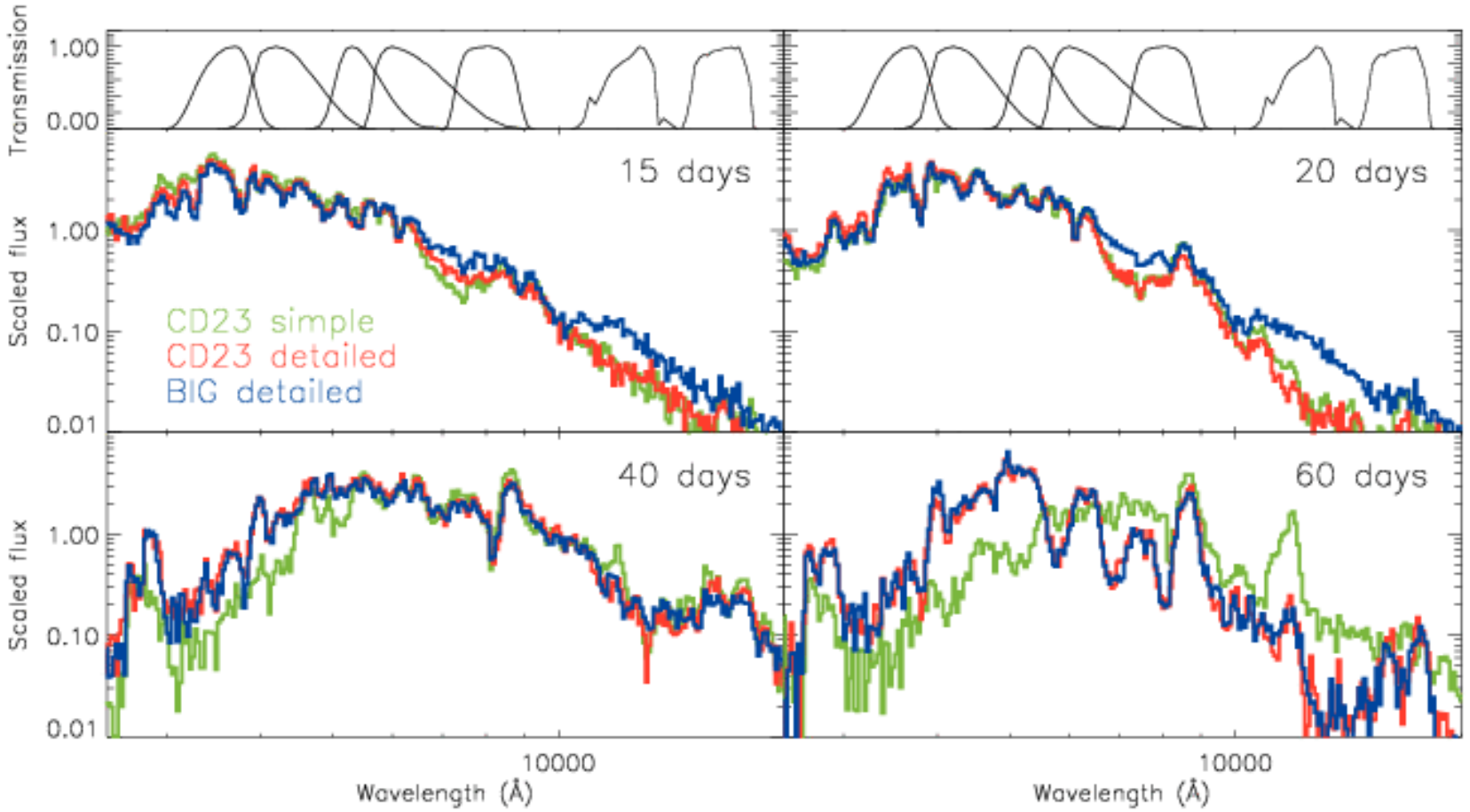
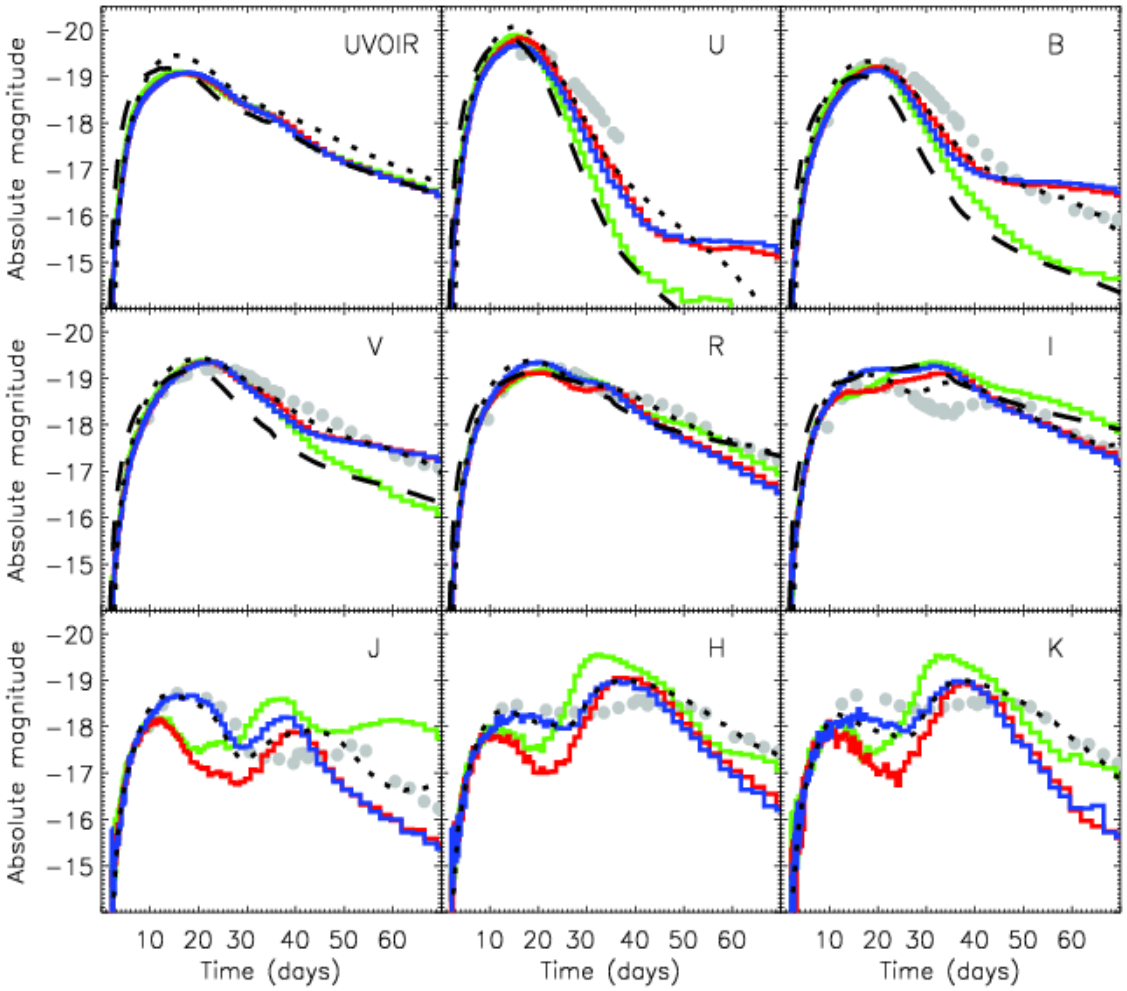


Comparison with other codes



Dashed lines

STELLA

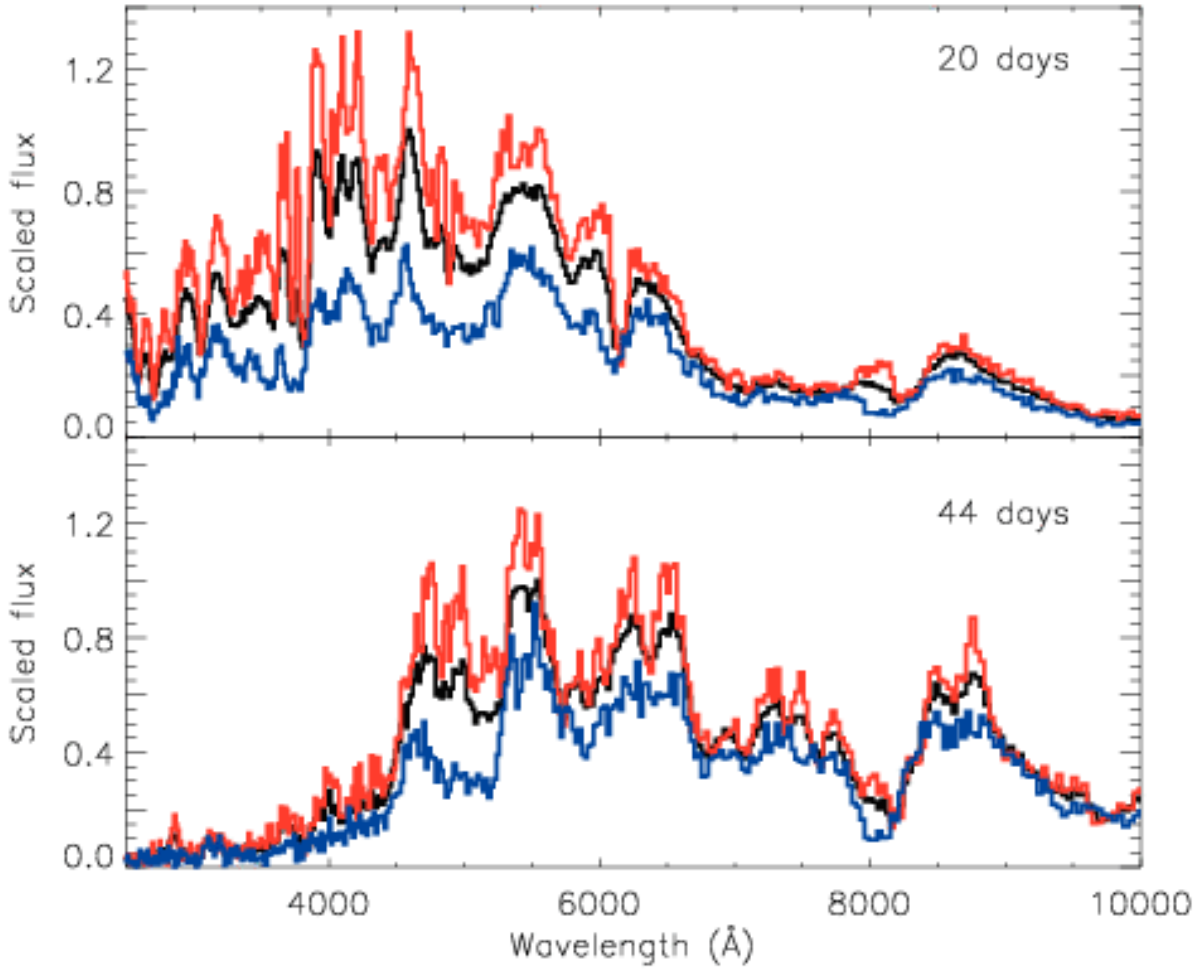
(Sorokina/Blinnikov)

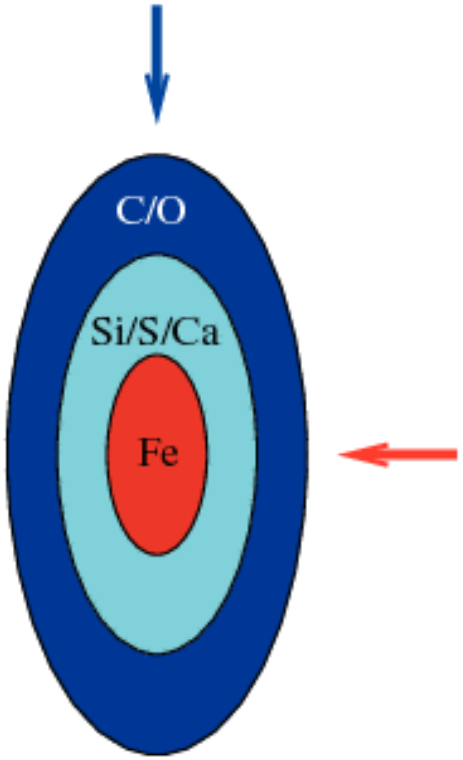
Dotted lines

SEDONA

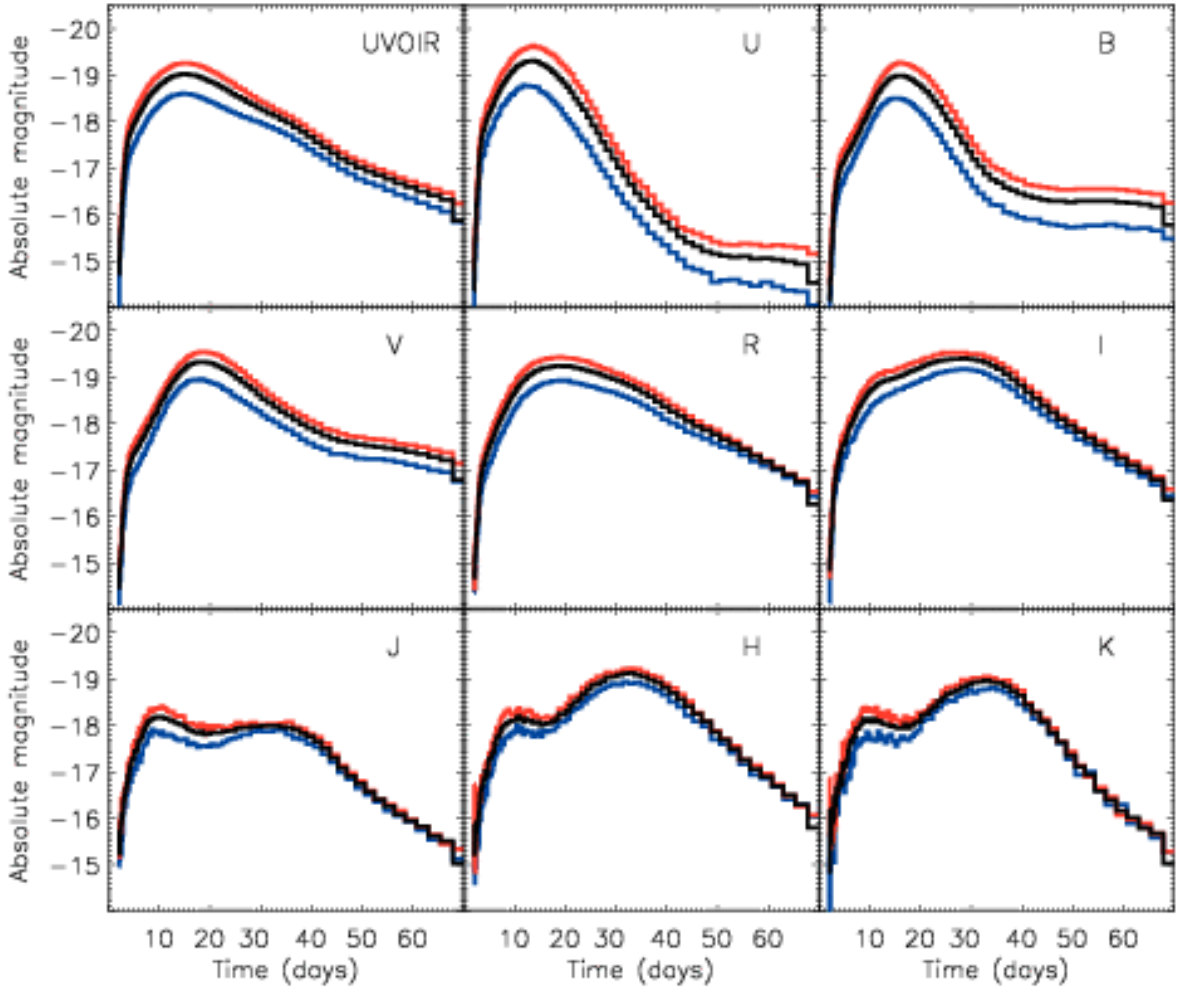
(Kasen)

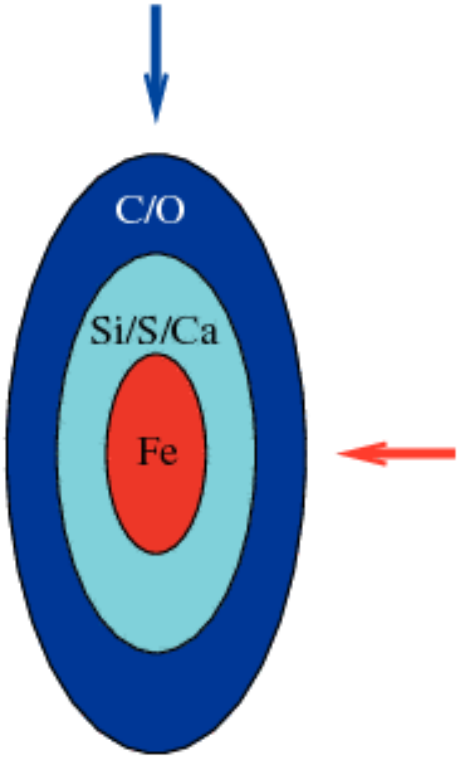
Test: an ellipsoidal model



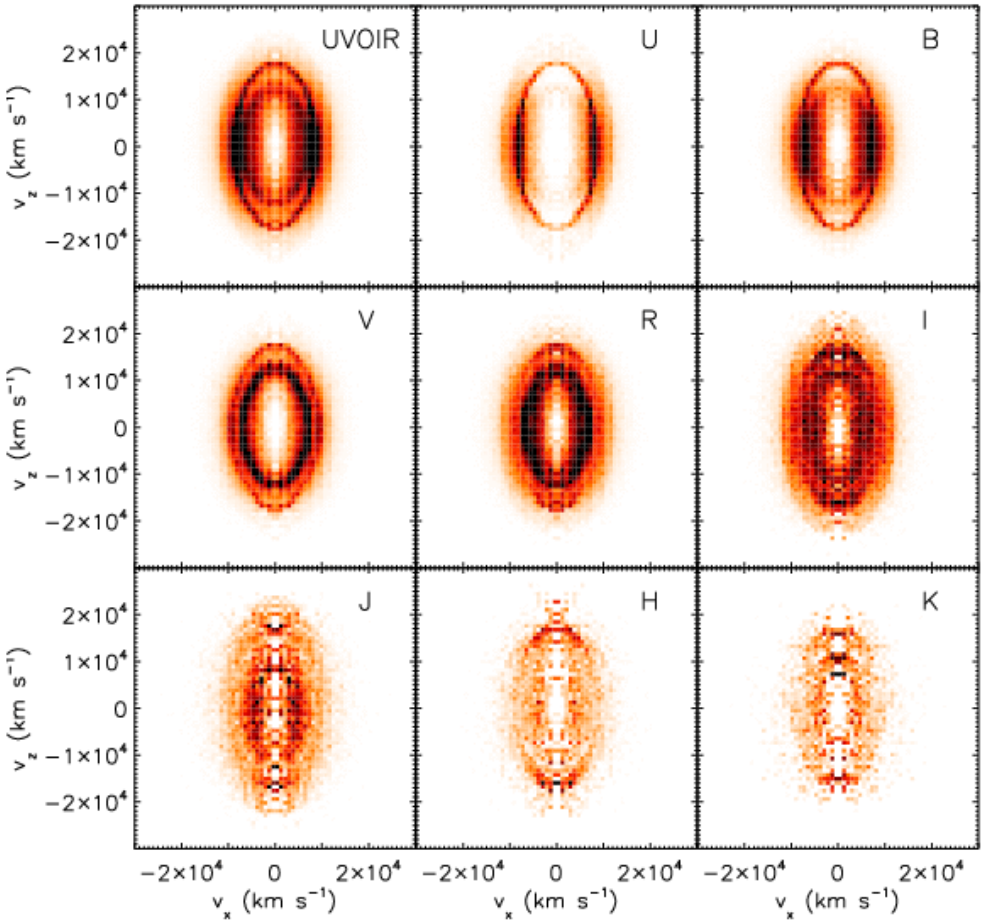


Test: an ellipsoidal model





Test: an ellipsoidal model



Summary

- Radiative transfer **links physical models** with **observables**
- **Monte Carlo** methods can treat all necessary physics
  - **Conservation laws** directly applied
  - **Multi-D** easily implemented
- Developed a new code for application to SN Ia (ARTIS)
  - 3D; time-dependent (Sim 2007, Kromer & Sim 2009)
  - Detailed treatment of **ionization/thermal balance**
- Test calculations in 1D agree well with other codes (and observations)
  - Confirmed importance of ionization
- Departures from spherical symmetry have **observable consequences**
- Now beginning work with **real explosion models**
- Working on application of method to **other astrophysical systems**