Radiative transfer for Type Ia supernovae – bridging the gap between explosion models and observations

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Radiative (magneto) hydrodynamic seminar
Ondřejov 21.04.2010

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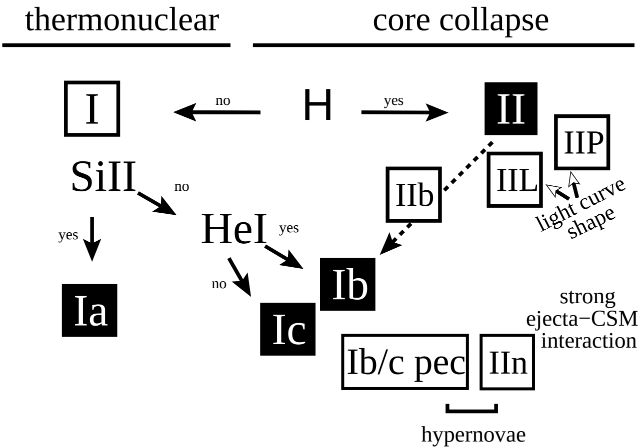
Astrophysical context

- Transient objects of high luminosity
- Explosive deaths of stars
- Important for chemical enrichment of the Universe
- Shock waves influence star formation
- Sources of the galactic component of the cosmic rays

SN 1994D in NGC 4526 (NASA/HST)

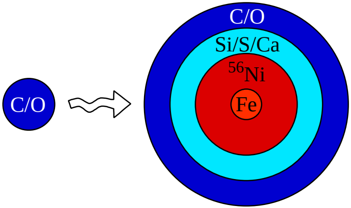
Classification scheme (Turatto 2003)



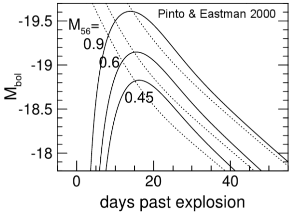
TYPE IA SUPERNOVAE

Basic facts

- No H lines, strong Si II feature
- Thermonuclear explosions of degenerate white dwarf material (Hoyle & Fowler 1960)
- Cosmological distance indicators

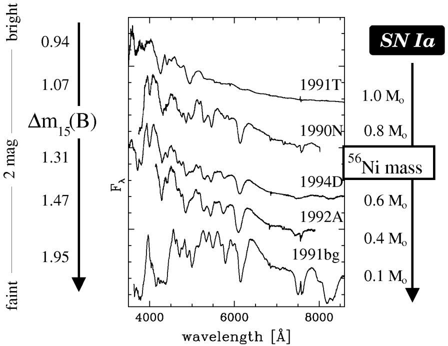


- Light curves powered by γ-rays
  $^{56}\text{Ni} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$
- Luminosity $\propto M(^{56}\text{Ni})$

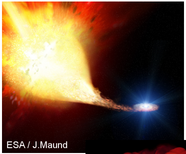


Problems

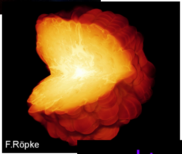
- Origin of observed diversity
- Explosion mechanisms
  - Deflagration
  - Detonation
- Progenitor systems
  - Accreting systems or mergers?
  - Chandrasekhar mass?



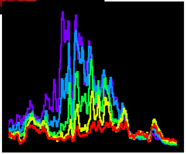
Solving the Ia puzzle by theoretical modelling



Progenitor evolution ($\sim 10^9$ years)
$\Rightarrow$ binary evolution, mass transfer



Explosion phase ($\sim$ seconds)
$\Rightarrow$ hydrodynamics coupled to explosive nucleosynthesis



Formation of spectra and light curves ($\sim 10^2$ days)
$\Rightarrow$ radiative transfer simulations

Outline of the problem

- Multi-wavelength
- Time-dependent

Outline of the problem

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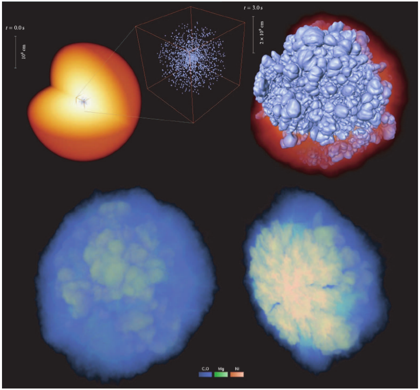

Röpke et al. 2007

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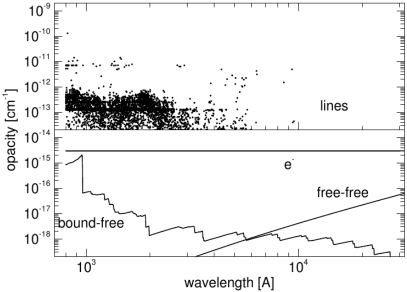

Pinto & Eastman 2000

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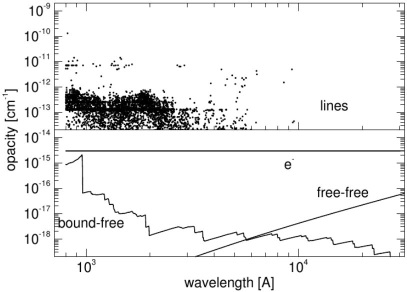

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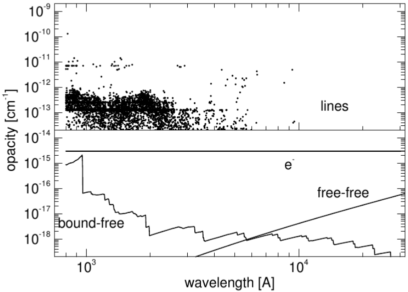
But some simplifications

- Homologous expansion
- Sobolev approximation
- Statistical and thermal equilibrium



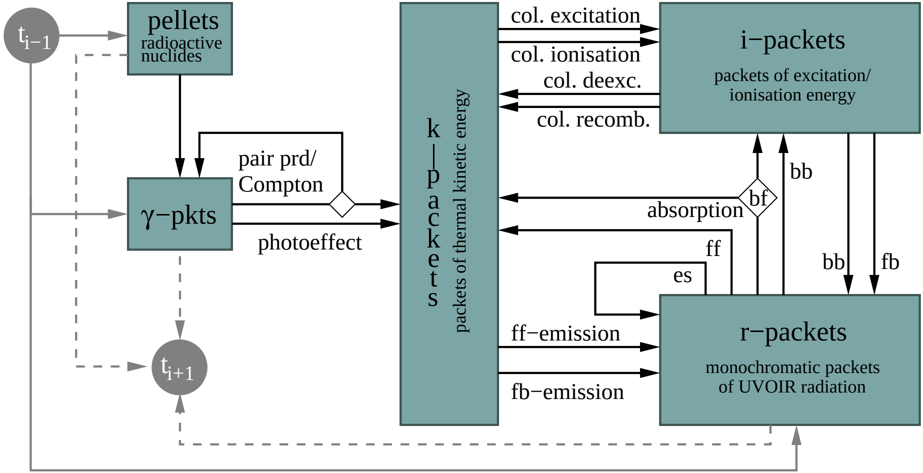
Pinto & Eastman 2000

Monte Carlo method

- Based on quantized energy flow: energy packets
- Follow the packets propagation through the ejecta
- Microphysical description of radiation/matter interactions
  - ⇒ Purely local
  - ⇒ Suitable for complex geometries & time-dependence
- Extract spectra and light curves by binning of escaping packets

- Use indivisible energy packets (Abbott & Lucy 1985; Mazzali & Lucy 1993; Lucy 1999, 2005)
  - ⇒ Implicit energy conservation
  - ⇒ Statistical and thermal equilibrium enforceable (Lucy 2002, 2003)

The framework of ARTIS (Kromer & Sim 2009)



Calculation of transition probabilities requires

1. Specification of atomic data
2. Population numbers (excitation/ionization state of the plasma)
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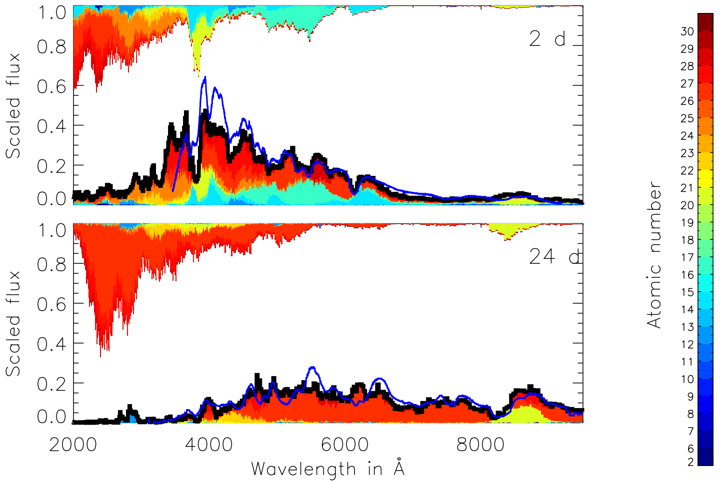
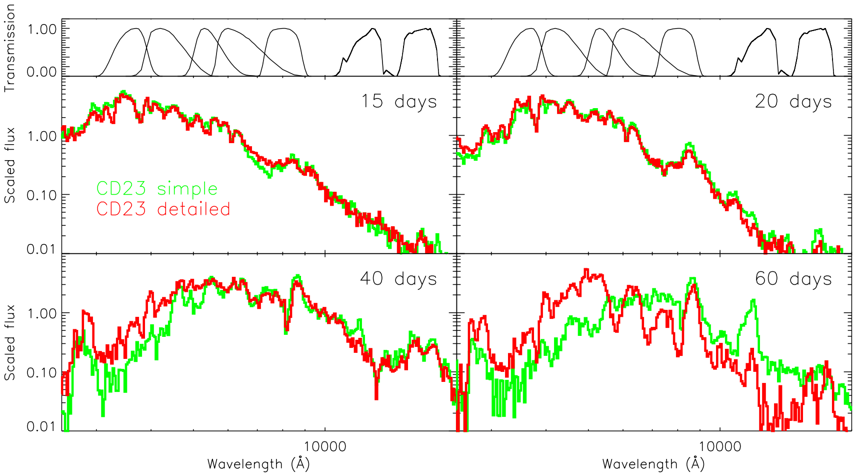
3. Local radiation field J_ν
   - Extractable from MC simulation, but computationally prohibitive
   - Nebular approximation for detailed treatment: $J_\nu = WB_\nu(T_\mathrm{R})$
   - Black body approximation for simple treatment: $J_\nu = B_\nu(T_\mathrm{J})$

Spectral evolution of a standard model



TESTING ARTIS

Influence of ionisation treatment



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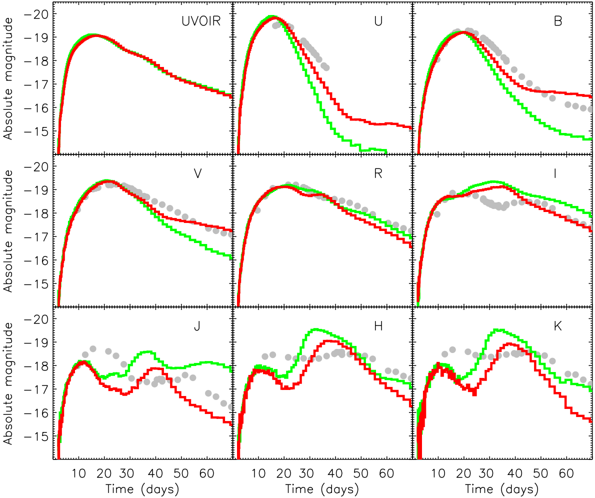

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- CD23 simple
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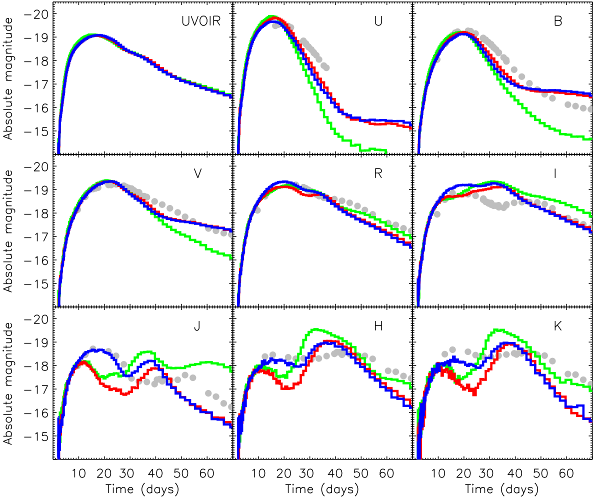

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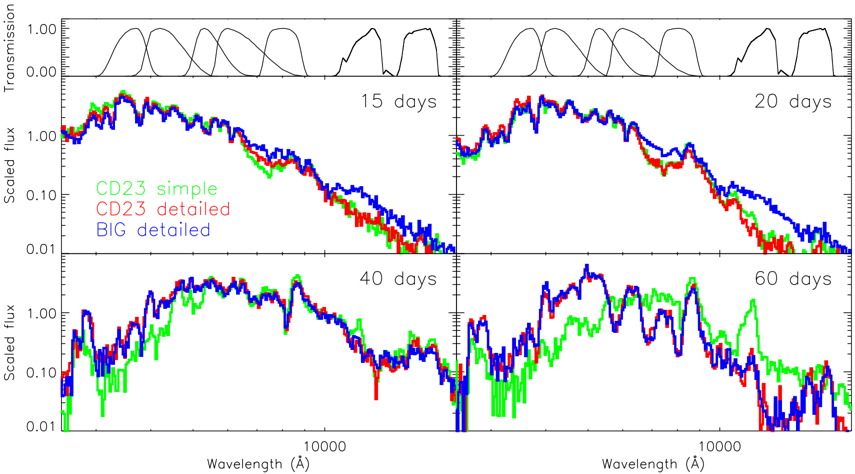

Now apply ARTIS to study outcome of different progenitor scenarios and explosion mechanisms

- Single degenerate Chandrasekhar-mass model
- Double degenerate mergers
- Double detonation sub-Chandrasekhar-mass model

The basic picture

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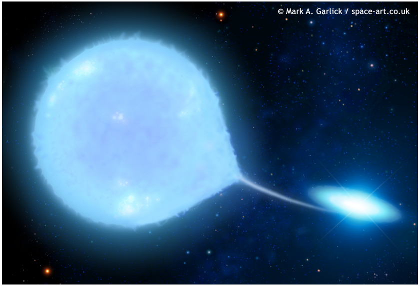
- Ignition at Chandrasekhar mass



SINGLE DEGENERATE CHANDRASEKHAR MASS MODEL

The basic picture

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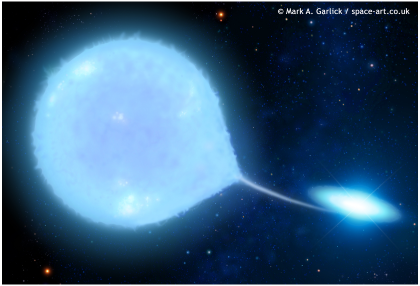
- Ignition at Chandrasekhar mass

- How does the explosion work?
  - Detonation
  - Deflagration



Pure detonation

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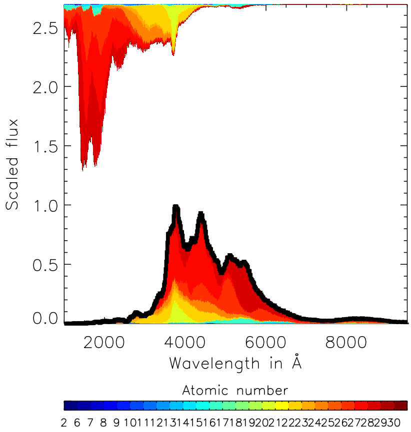

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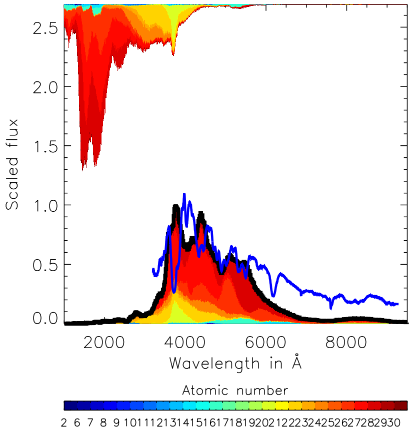
⇒ Cannot explain SNe Ia (Arnett 1969)



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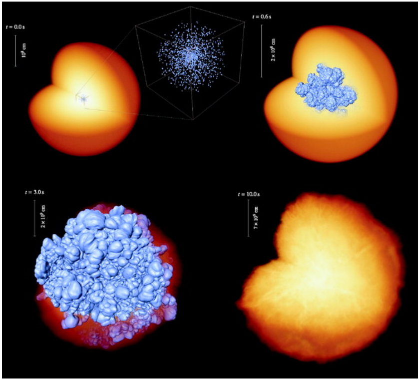

Röpke et al. 2007

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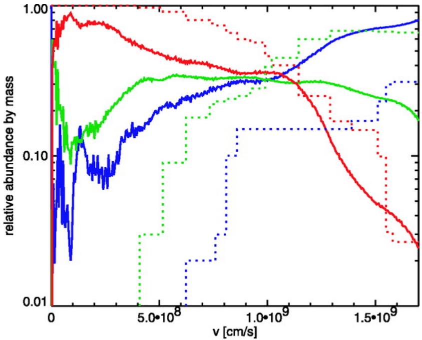

Röpke et al. 2007

Fe-group; intermediate mass; C,O

Model: solid

SN 2002bo: dotted

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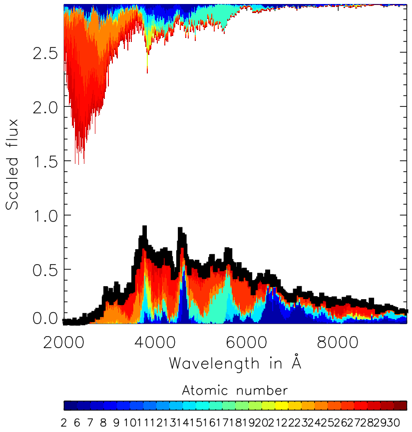

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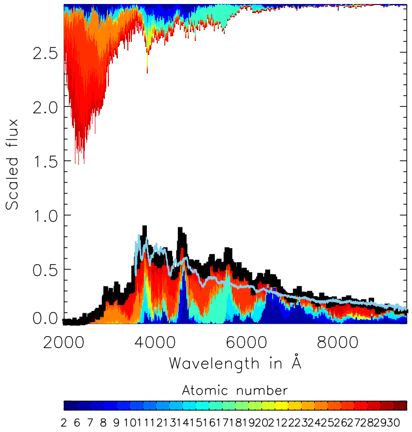

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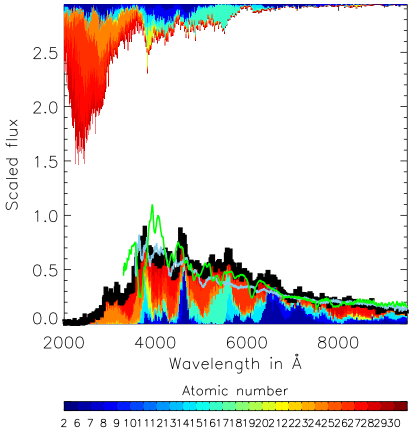
⇒ Maybe



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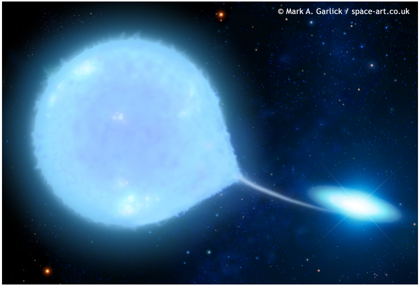

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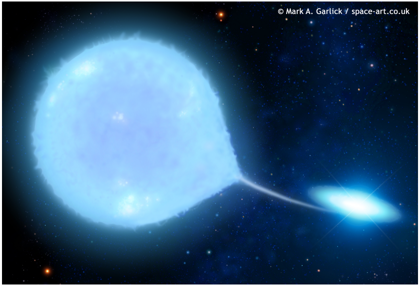

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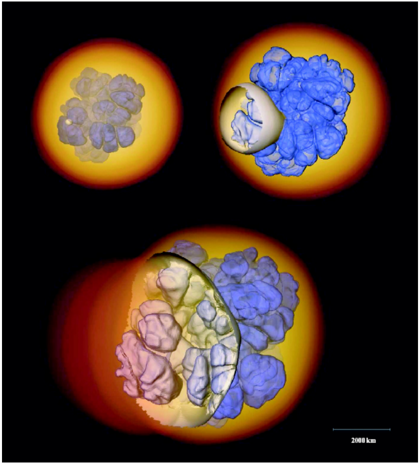
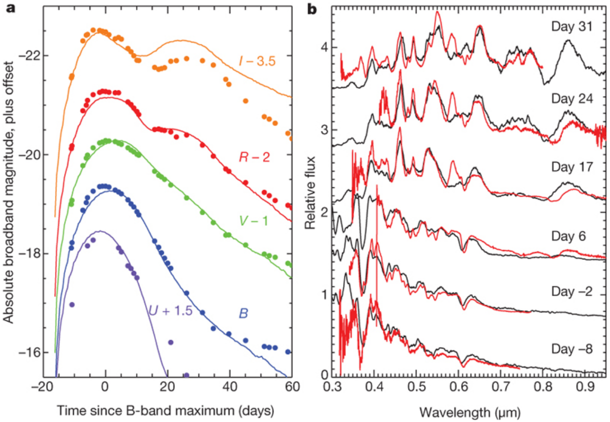
  - ⇒ Delayed-detonation



Röpke & Bruckschen 2008

SINGLE DEGENERATE CHANDRASEKHAR MASS MODEL

Observational outcome of delayed detonations



Kasen, Röpke & Woosley 2009

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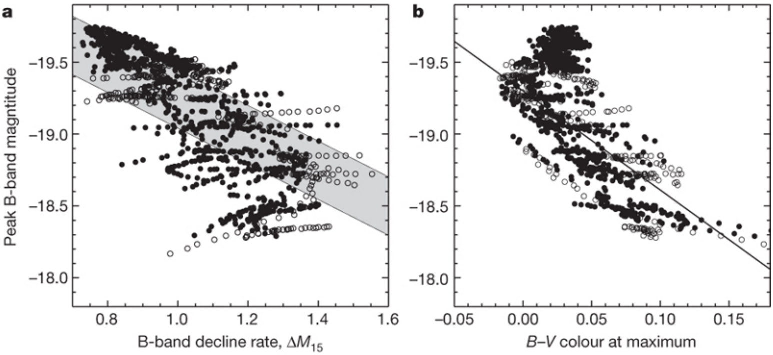

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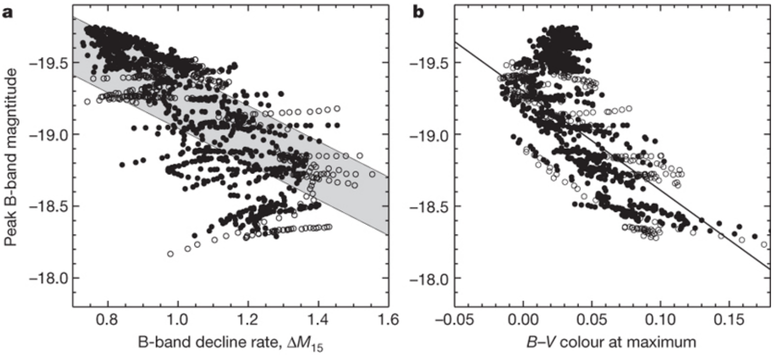

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⇒ Delayed-detonation Chandrasekhar mass models reproduce the observed diversity of normal SNe Ia

But not all is perfect

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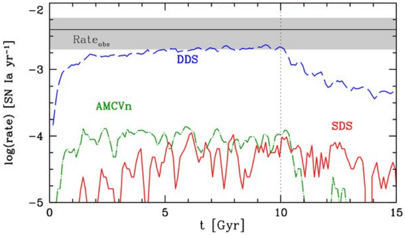


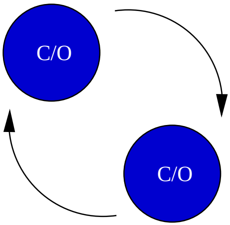
Ruiter, Belczynski & Fryer 2009

The basic picture

- Close WD binaries merge due to emission of gravitational waves
- Possible Ia progenitors if $M_1 + M_2 > M_{\text{Ch}}$ (Iben & Tutukov 1984, Webbink 1984)

- Observationally very few objects known
- So far simulations yielded no explosions (e.g. Motl 2007, Yoon 2007)

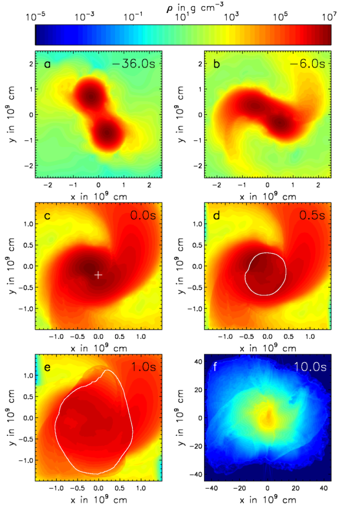
- Fate depends strongly on $q = M_2/M_1$
  - $q < q_{\text{crit}}$ stable mass transfer
  - $q_{\text{crit}} < q < q_{\text{merge}}$ disruption of secondary
  - $q_{\text{merge}} < q$ violent merger



DOUBLE DEGENERATE MERGERS

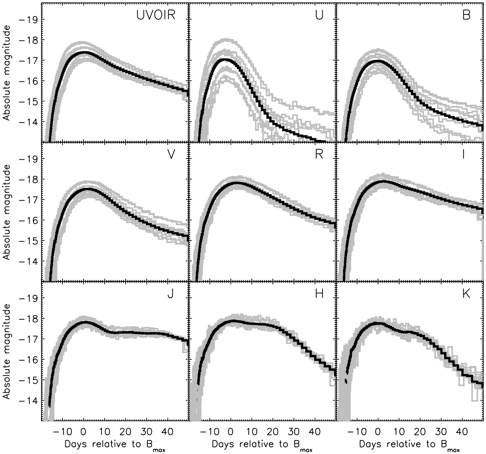
Merging two 0.9 $M_\odot$ WDs (Pakmor et al. 2010)

- SPH simulation to model coalescence of WDs
- Trigger detonation
- Follow explosion with a grid code
- Energy release unbinds the object
- Nucleosynthesis postprocessing yields $0.1 M_\odot$ ^{56}Ni
- Similar evolution for $0.93 < q < 1$ ($q_{\rm merge}$?)



DOUBLE DEGENERATE MERGERS

Synthetic light curves



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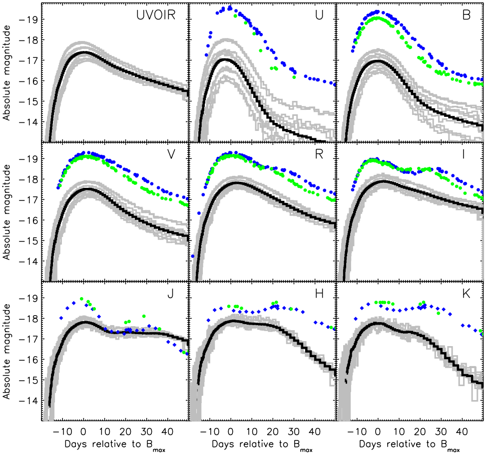

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- Do not follow Phillips relation
- Red colours
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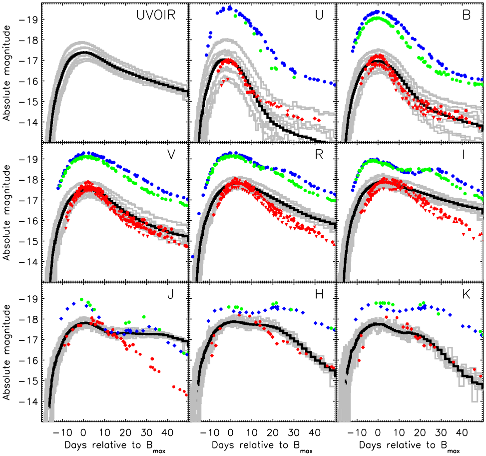

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⇒ Fit to subluminous 1991bg-like objects

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- Spectroscopically peculiar
- “Strong” continuum polarization
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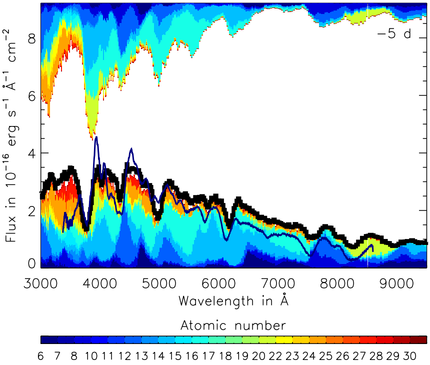

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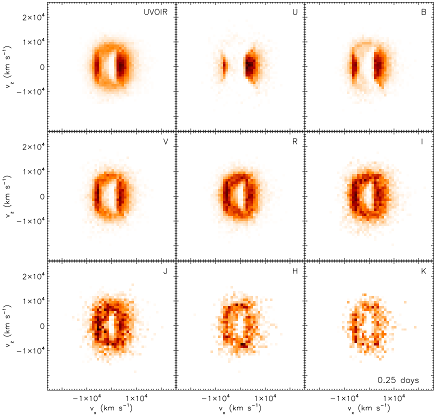

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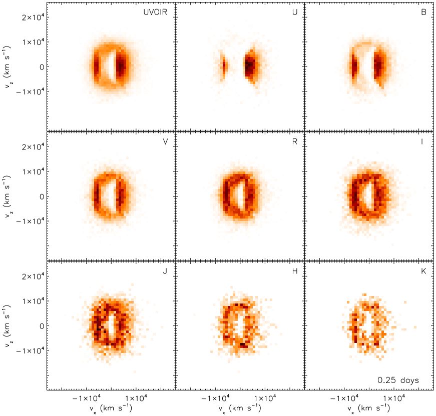

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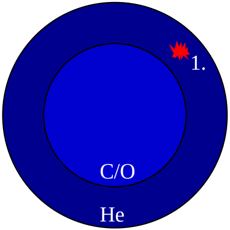
⇒ Violent mergers ($q > q_{\mathrm{merge}}$) lead to 1991bg-like objects

How to make the bulk of normal SNe Ia?

The basic picture

- CO WD accretes $\sim 0.2 M_\odot$ He from a He-rich companion star
- Primary detonation triggers in the He-shell



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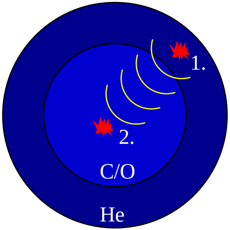

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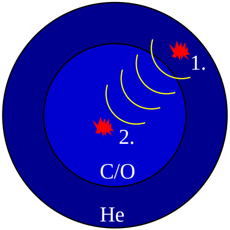
- Robustness of core ignition?
- Problems in fitting observational data

(Höflich & Khokhlov 1996, Nugent et al. 1997)



New hydro simulations (Fink et al., in press)

- Set of minimum shell mass models (Bildsten et al. 2007)

Model	$M_{tot} / M_{\odot}$	$M_{core} / M_{\odot}$	$M_{shell} / M_{\odot}$
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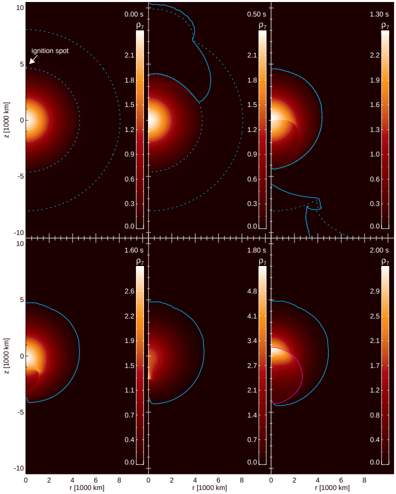
2	1.004	0.920	0.084
3	1.080	1.025	0.055
4	1.164	1.125	0.039
5	1.293	1.280	0.013
6	1.389	1.385	0.004



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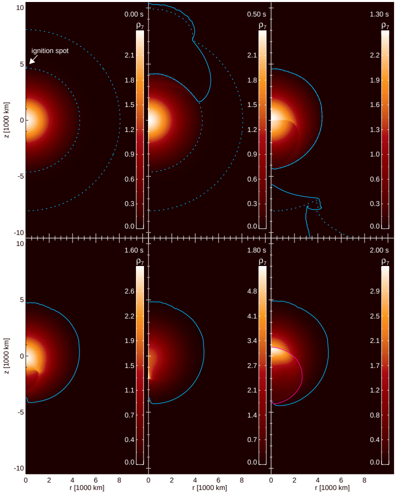
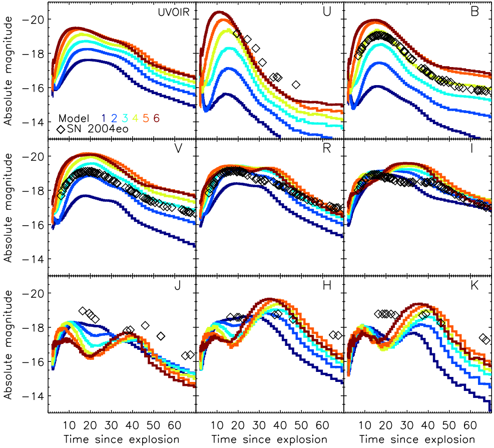
- All models successfully ignite the core detonation



Observational outcome of the Fink et al. models



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- Despite low mass, time-evolution OK

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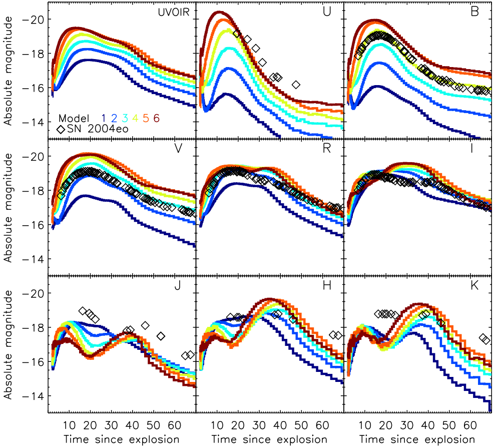

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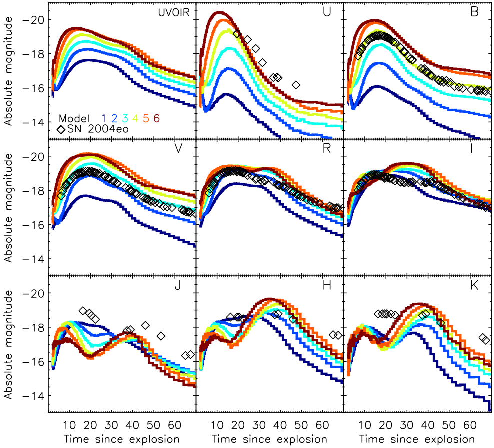

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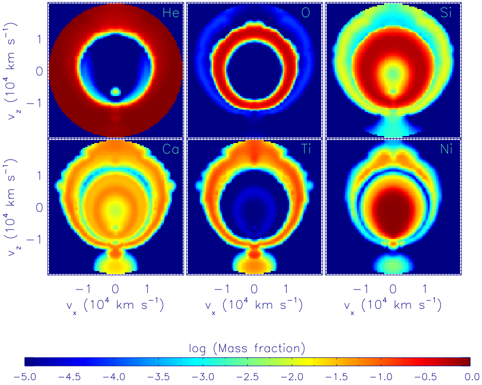

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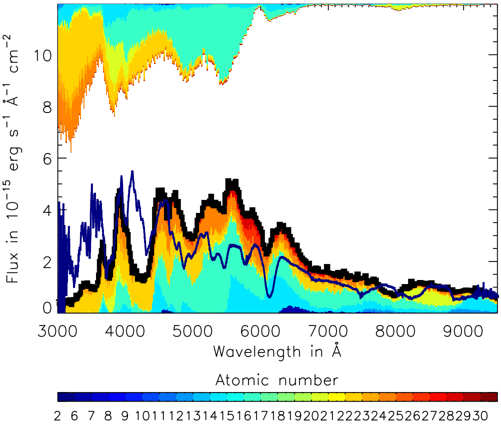

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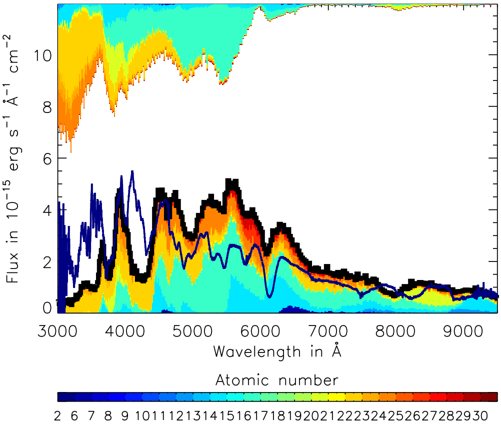

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- Can we understand this?
  - ⇒ Fe-rich shell material redistributes flux
- As they stand these models are bad

Nucleosynthesis in the shell depends strongly on

- Initial composition
- Density
- Better understanding of progenitor evolution needed to pin down those

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- Initial composition
- Density
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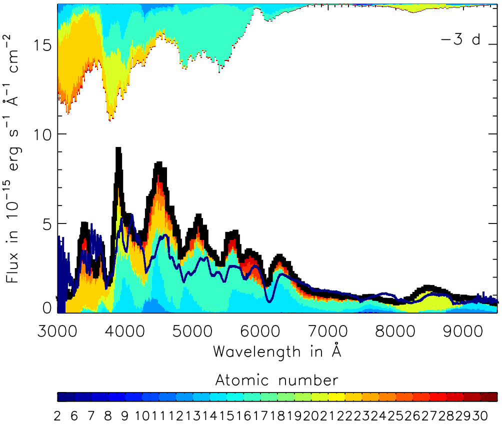
- But modified model looks promising
- This is pure speculation



New MC RT code (ARTIS, Kromer & Sim 2009)

- Parameter-free
- Time-dependent
- Fully 3D
- Multi-wavelength: γ to NIR
- Detailed solution of ionisation and thermal balance equation (crucial to match observations)
- Detailed treatment of radiation/matter interactions
- Need extensive line list to simulate redistribution properly

- Prediction of synthetic observables from explosion models possible
- We just began to do detailed comparison of models and observations

Status on different explosion models

- Pure detonations: ruled out
- Pure deflagrations: ruled out for normal SNe Ia, but maybe realized in 2002cx-likes
- Delayed detonations: synthetic observables match normal SNe Ia, but rate problems
- Mergers: violent mergers do work and explain 91bg-like events
- Sub-Chandras: give “healthy” explosions, but peculiar observables (strongly dependent on shell composition)

- How to explain the bulk of normal SNe Ia?
- How to explain the diversity?
- Progenitors?

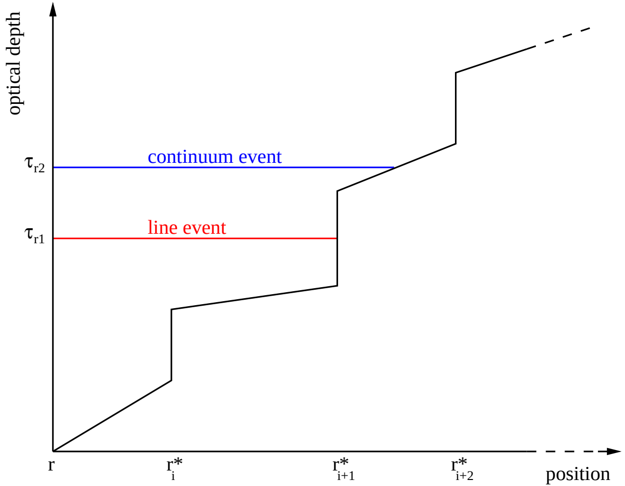
Where to go in the future?

- Pure deflagrations: detailed comparison to 2002cx-like objects
- Delayed detonations: improve understanding of DDT physics
- Mergers: explore parameter space
- Sub-Chandras: can we avoid the shell effects?

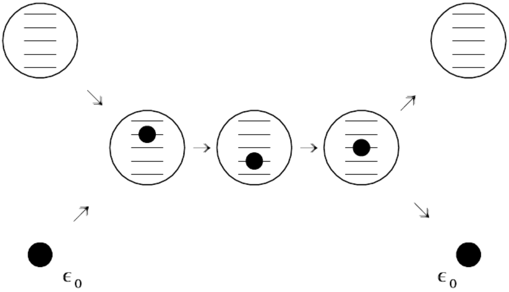
- Nucleosynthesis in the regime of incomplete burning

- Influence of multi-dimensional effects on observables
- Late-time spectra and polarization

Selecting the next event



Macro atom formalism



Lucy 2002

Excitation/ionisation treatment

- detailed solution of the ionisation balance
  - assume photoionisation equilibrium

$$\frac{N_{j,k}}{N_{j+1,k} n_\mathrm{e}} = \frac{\alpha^\mathrm{sp}_{j,k}}{\Gamma_{j,k}}$$

  - derive $\Gamma_{j,k}$ from Monte Carlo simulation

$$\Gamma_{j,k} \equiv \frac{g_{0,j,k}}{U_{j,k} n_{0,j,k}} \cdot \sum_{i=0}^{\mathcal{N}_{j,k}} n_{i,j,k} \gamma_{i,j,k}$$

- simultaneous solution of the thermal balance equation $\Rightarrow T_\mathrm{e}$
  - heating rates from Monte Carlo simulation
  - cooling rates evaluated at T_e
- use Boltzmann formula evaluated at $T_\mathrm{J} = \frac{\pi}{\sigma^4} \langle J \rangle$ for excitation

Radiation field

- exact radiation field extractable by Monte Carlo estimators

$$J_\nu \mathrm{d}\nu = \frac{1}{4\pi \Delta t V} \sum_{\mathrm{d}\nu} \epsilon_\nu^{\mathrm{cmf}} \mathrm{d}s$$

- *but*: computationally prohibitive

⇒ parameterise local radiation field in nebular approximation

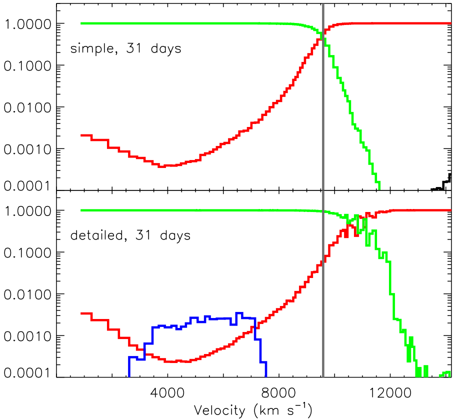
$$J_\nu = W \cdot B_\nu \left(T_R\right)$$

dilution factor W and radiation temperature T_R defined as

$$W = \frac{\pi}{\sigma T_\mathrm{R}^4} \langle J \rangle \qquad T_\mathrm{R} = \frac{h \langle \nu \rangle}{3.832 k_\mathrm{B}}$$

Influence of ionisation treatment

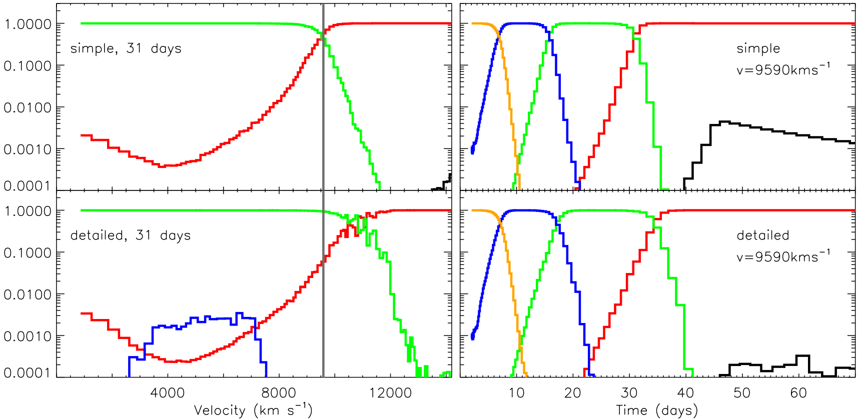
Ionisation fractions of Fe I, II, III, IV, V
versus radial velocity



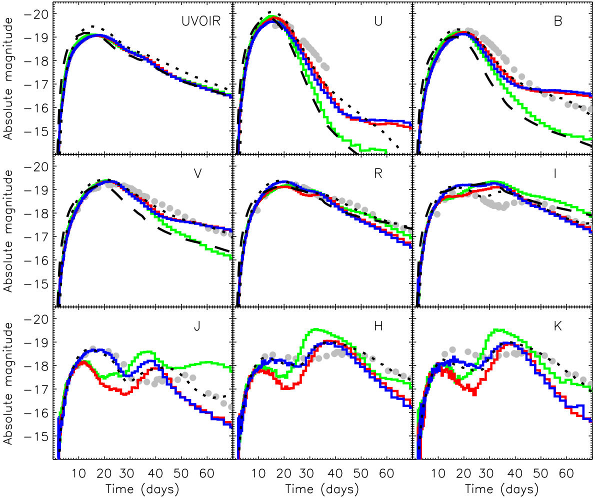
Influence of ionisation treatment

Ionisation fractions of Fe I, II, III, IV, V

versus radial velocity versus time



Broad-band light curves



- blue: big detailed
- red: CD23 detailed
- green: CD23 simple
- dashed: STELLA (Blinnikov 1998)
- dotted: SEDONA (Kasen 2006)
- circles: SN 2001el (Krisciunas 2003)

TESTING THE CODE

Flux redistribution