Unlocking the secrets of supernovae through their spectra

D. John Hillier & Chendong Li

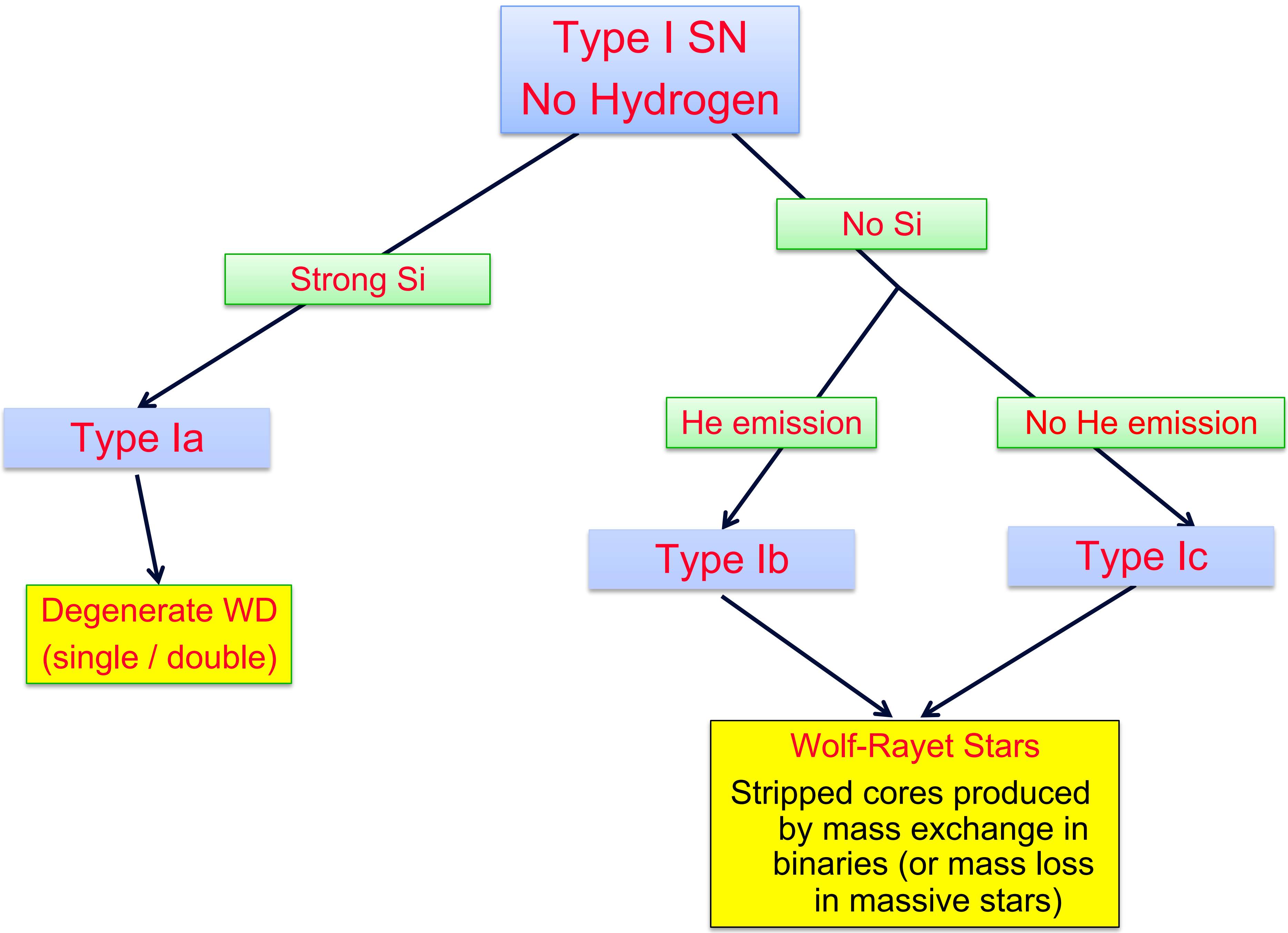
University of Pittsburgh

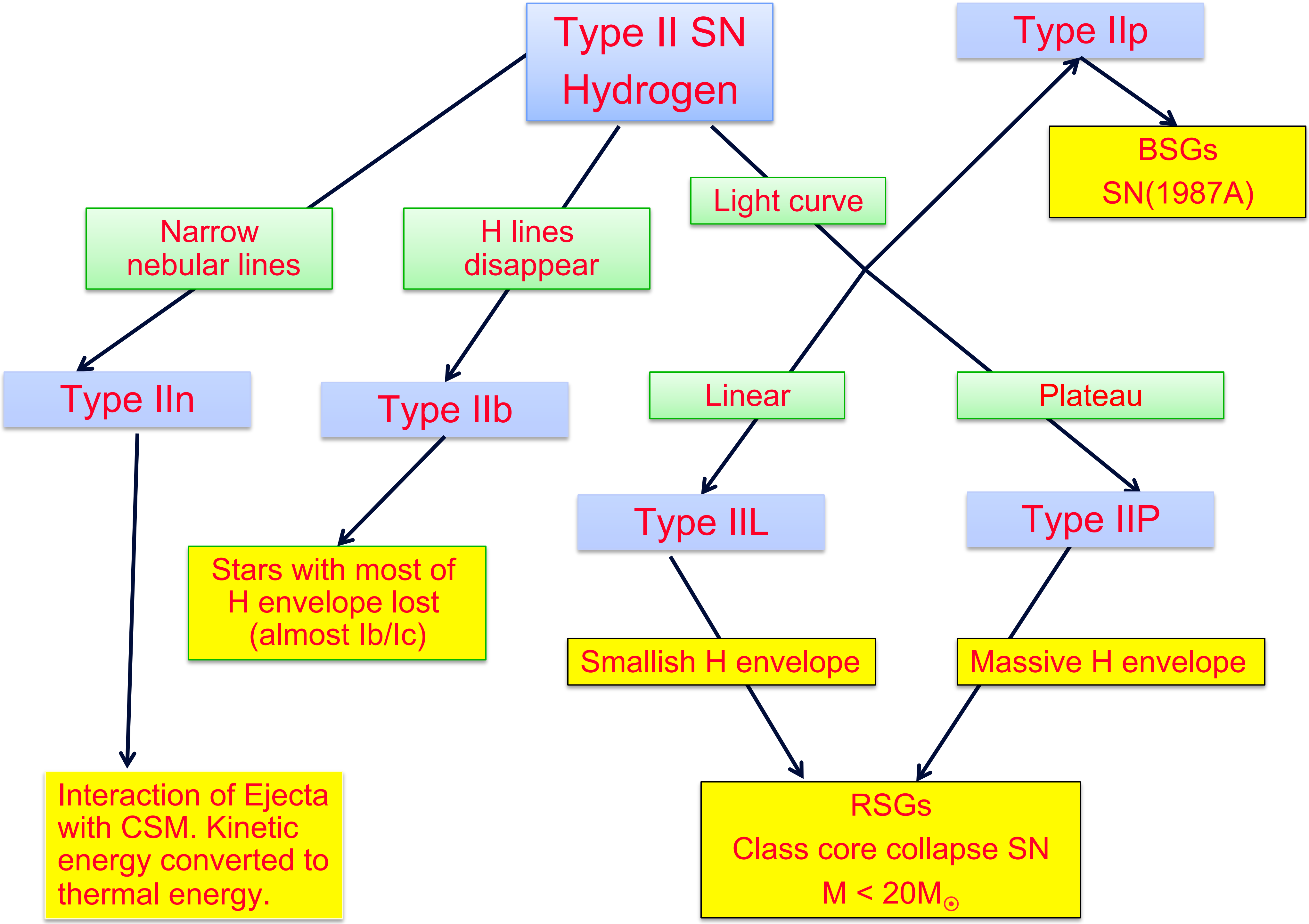
Luc Dessart

Laboratoire d'Astrophysique de Marseille

Stan Woosley, Roni Waldman, Eli Livne, Stéphane Blondin

Special thanks: Atomic data community.


Type I SN
No Hydrogen
Strong Si
No Si
Type Ia
He emission
No He emission
Degenerate WD
(single / double)
Type Ib
Type Ic
Wolf-Rayet Stars
Stripped cores produced by mass exchange in binaries (or mass loss in massive stars)


Type II SN
Hydrogen
Type IIp
BSGs
SN(1987A)
Narrow nebular lines
H lines disappear
Light curve
Type IIn
Type IIb
Linear
Plateau
Type IIL
Type IIP
Stars with most of H envelope lost (almost Ib/Ic)
Smallish H envelope
Massive H envelope
Interaction of Ejecta with CSM. Kinetic energy converted to thermal energy.
RSGs
Class core collapse SN
M < 20M☉

Non-LTE

$$n_i = f\,(\,n_e, T[J], n_1[J], \ldots, n_n[J], J_1, \ldots, J_m)$$

$$J_k = f\,(\,n_e, T, n_1, n_2, \ldots, n_n, \,)$$

Solve rate equations:

2000 levels, 60 depth points

120,000 simultaneous equations!

Must be solved “at the same time” as the radiative transfer equation.

50,000 frequencies.

Include all processes:

photoionizations / recombinations

collisional ionizations /recombinations

dielectronic recombinations

charge exchange reactions, e.g.,

$Fe^{2+} + H \Leftrightarrow Fe^{+} + H^{+}$

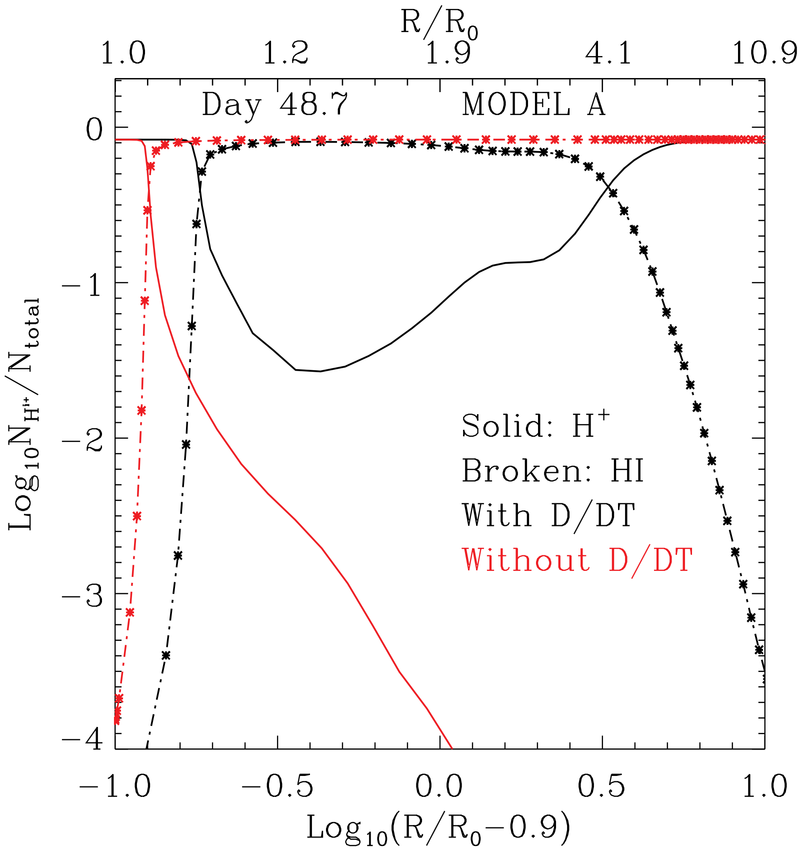
bound-bound transitions

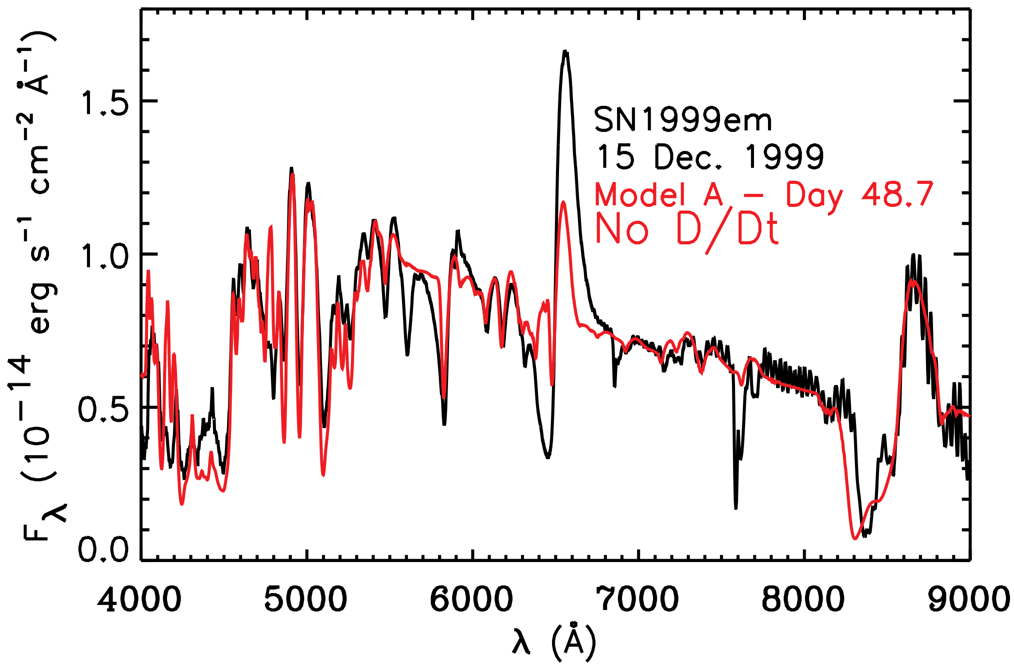
collisional excitations / de-excitations

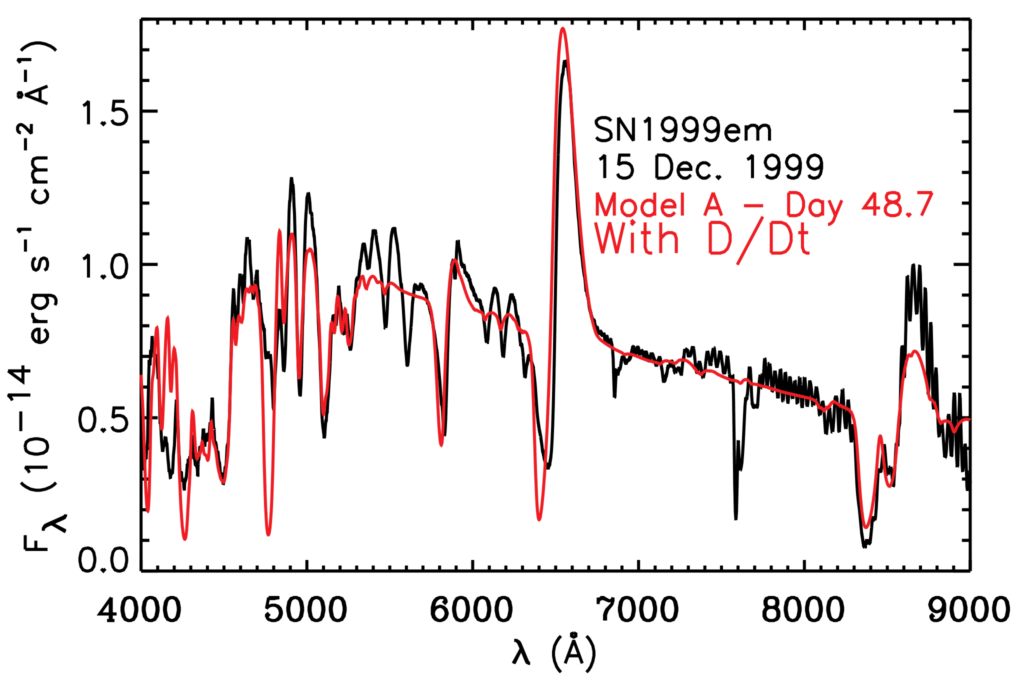
Auger ionizations

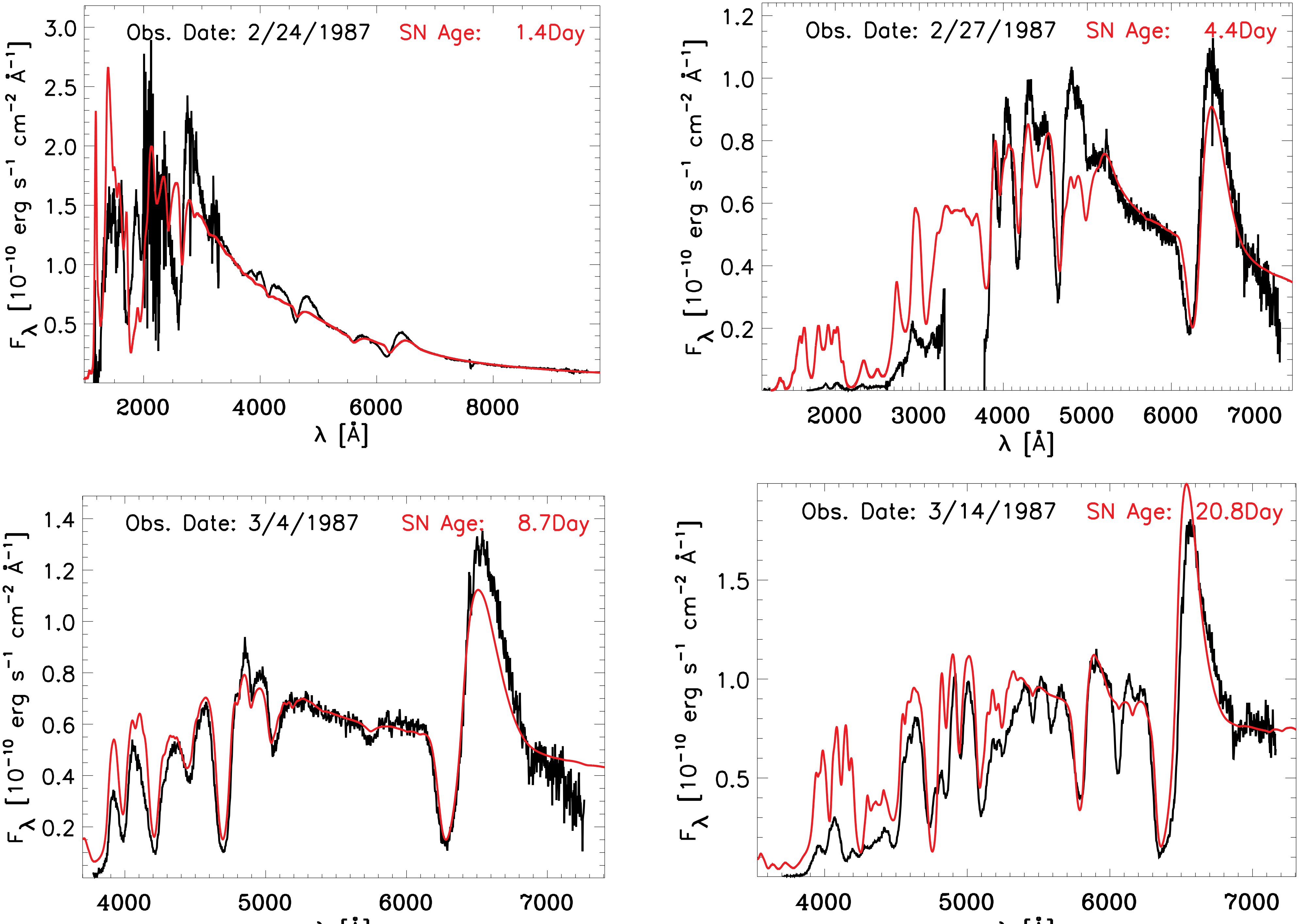
Non-thermal collisions (SN)

Dessart & Hillier (2008, MNRAS, 385,57)





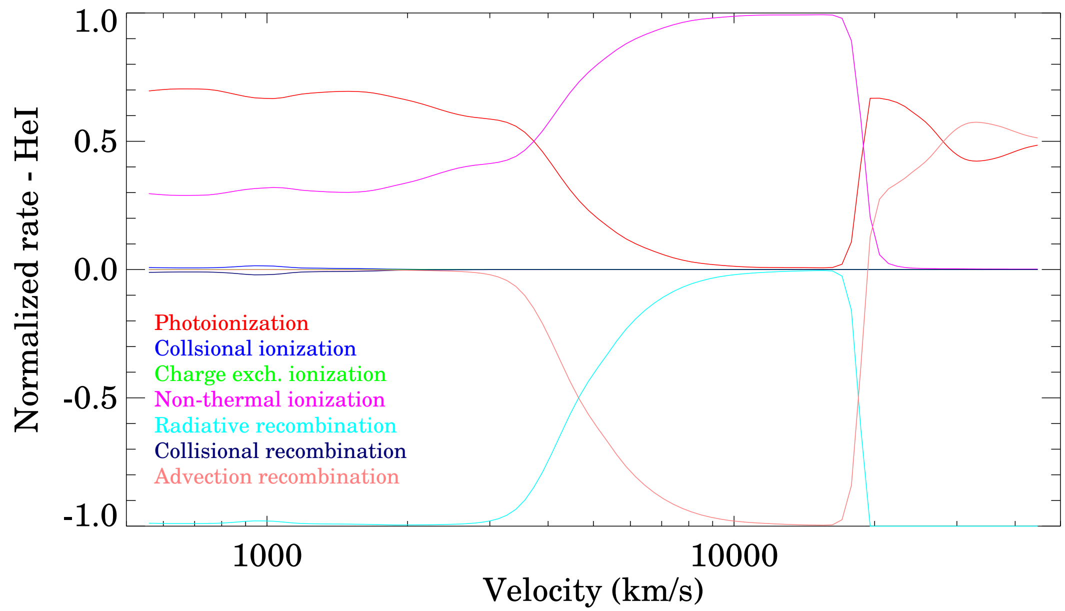


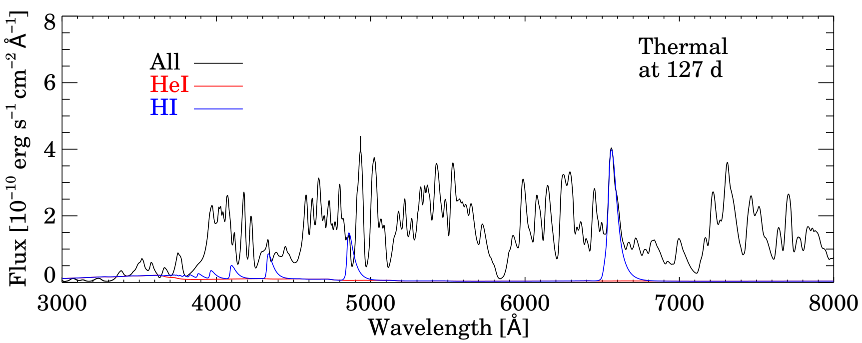

Obs. Date: 2/24/1987
SN Age: 1.4Day
Obs. Date: 2/27/1987
SN Age: 4.4Day
Obs. Date: 3/4/1987
SN Age: 8.7Day
Obs. Date: 3/14/1987
SN Age: 20.8Day
F_λ [10^{-10} erg s^{-1} cm^{-2} Å^{-1}]
λ [Å]

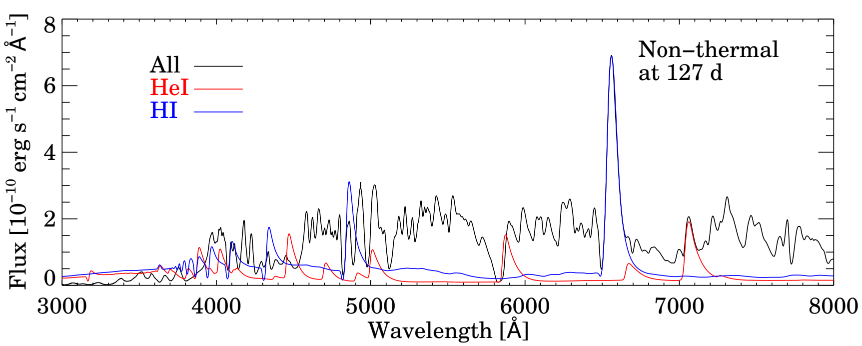
Ionization by Non Thermal Electrons

Important in nebular phase of Type II SN.

Important in Type Ib/c almost immediately.





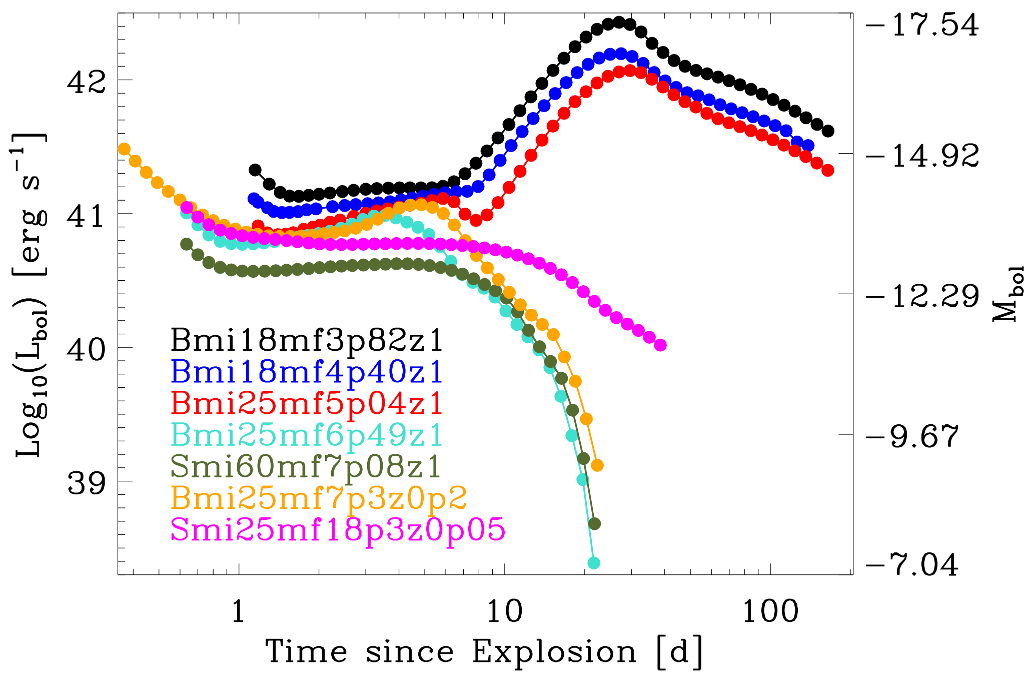


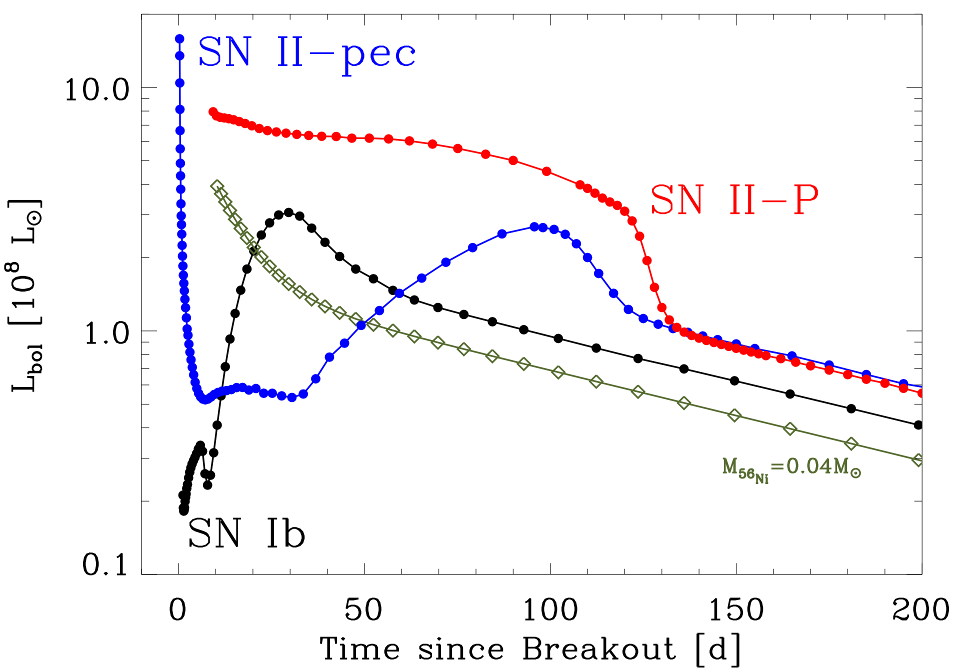
Li, Hillier, Dessart, 2012, MNRAS, in press

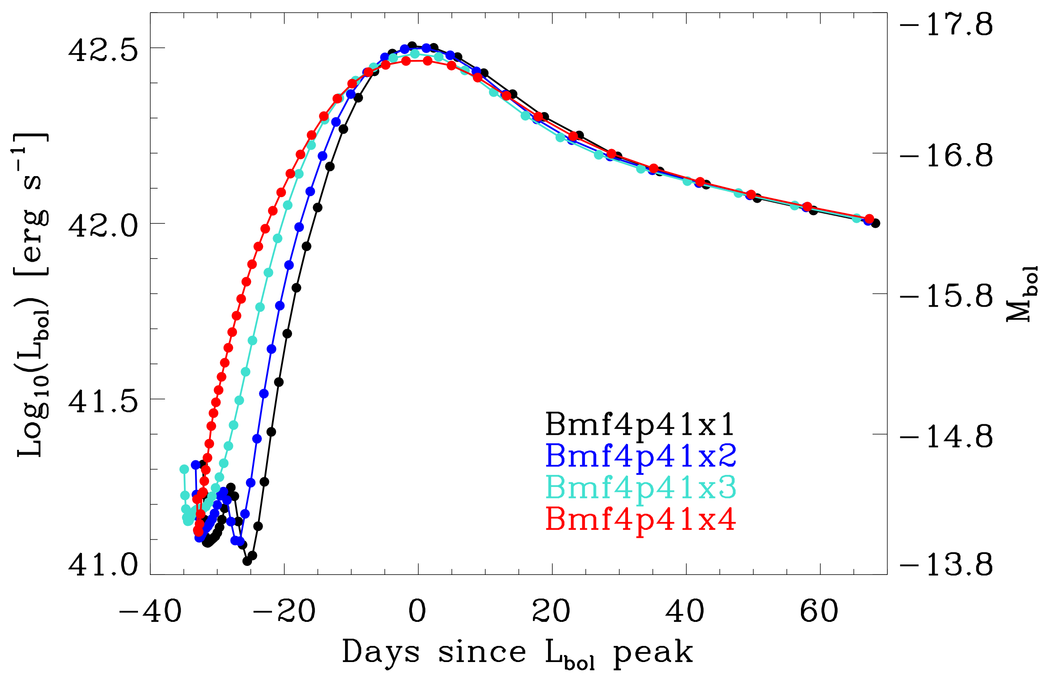
Modeling Ibc SNe

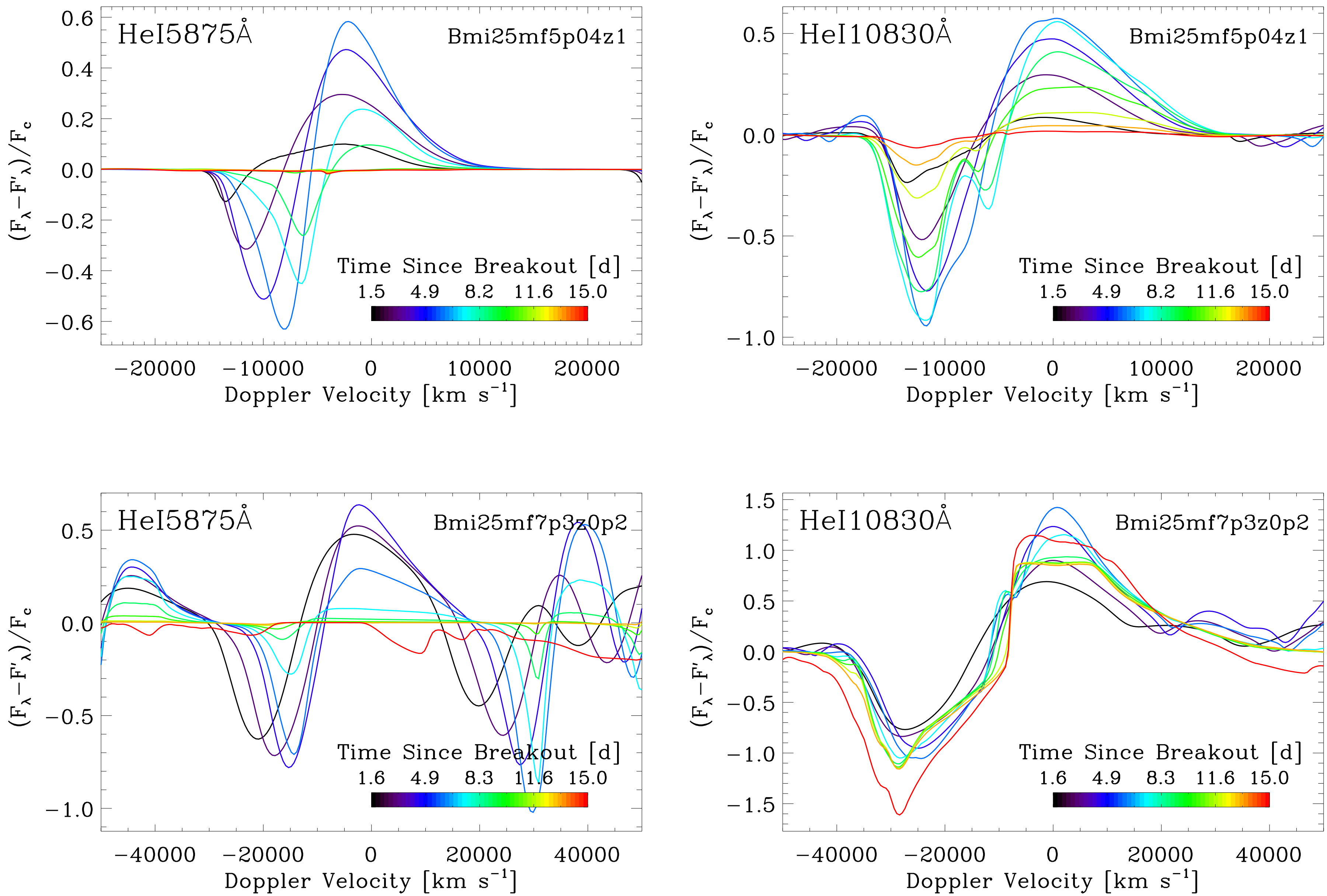
Dessart et al, 2011, MNRAS, 414, 2985

Dessart, Hillier, Li, Woosley, 2010, MNRAS, submitted





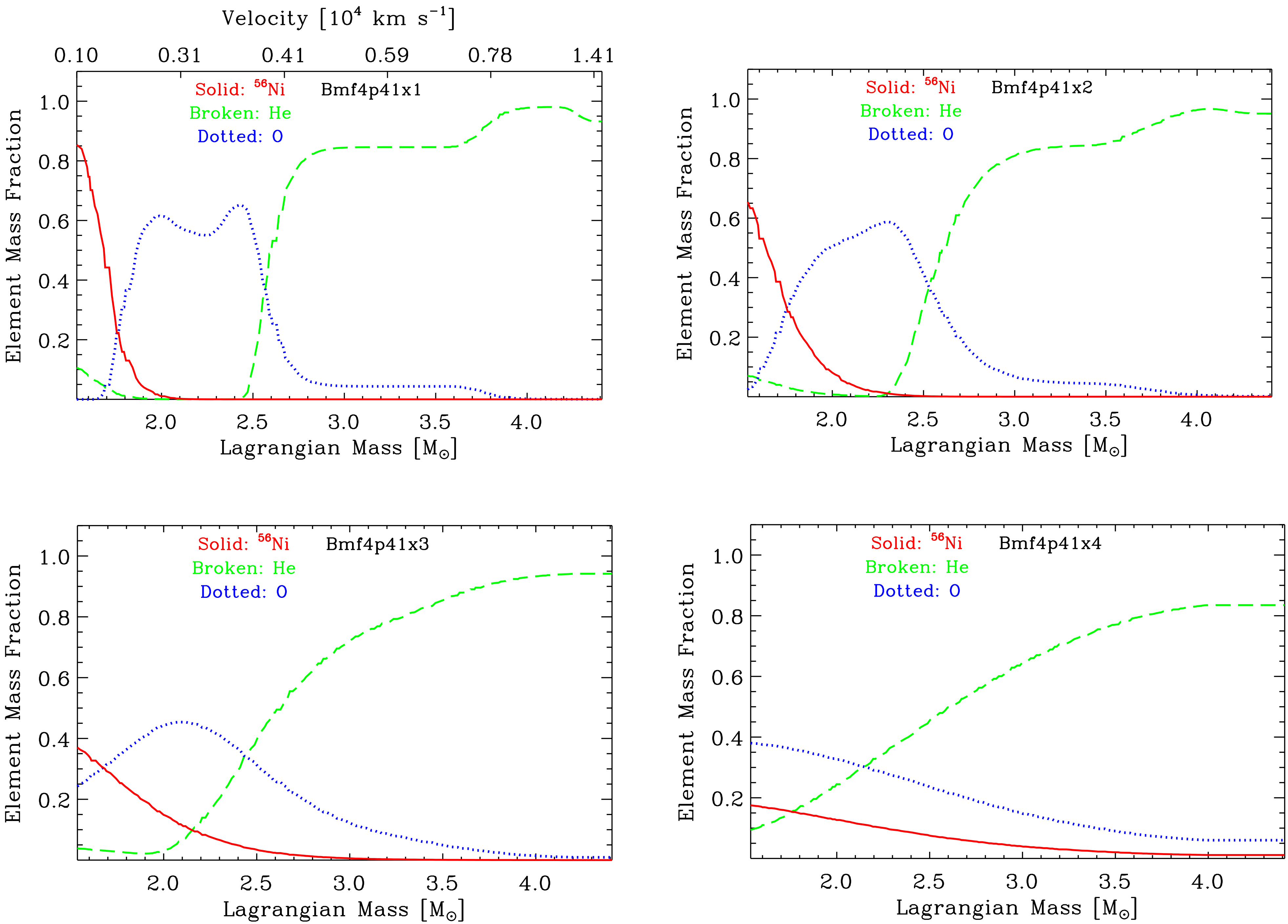




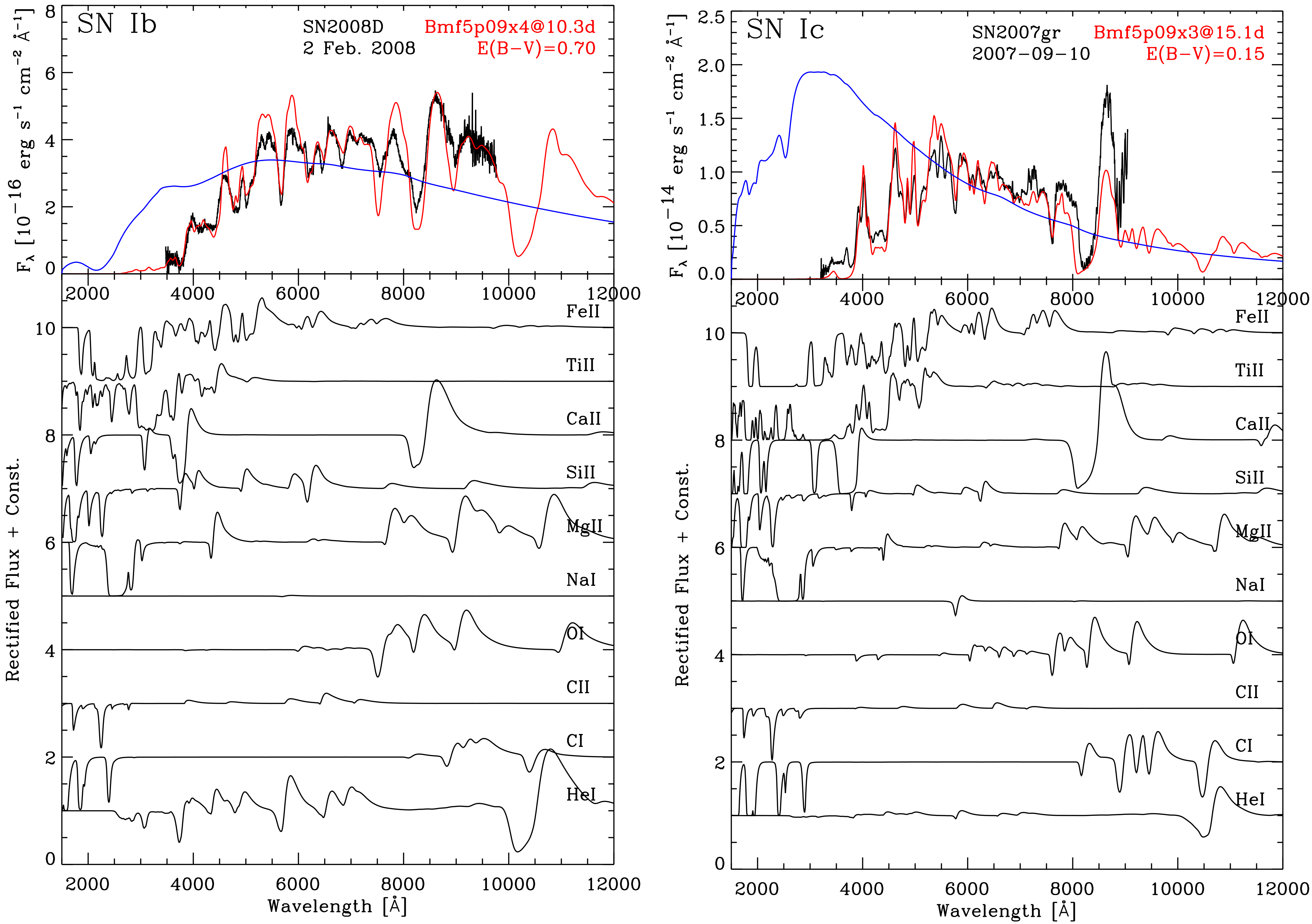
Crucial for detecting He

Observations of He I 10830Å

Early observations

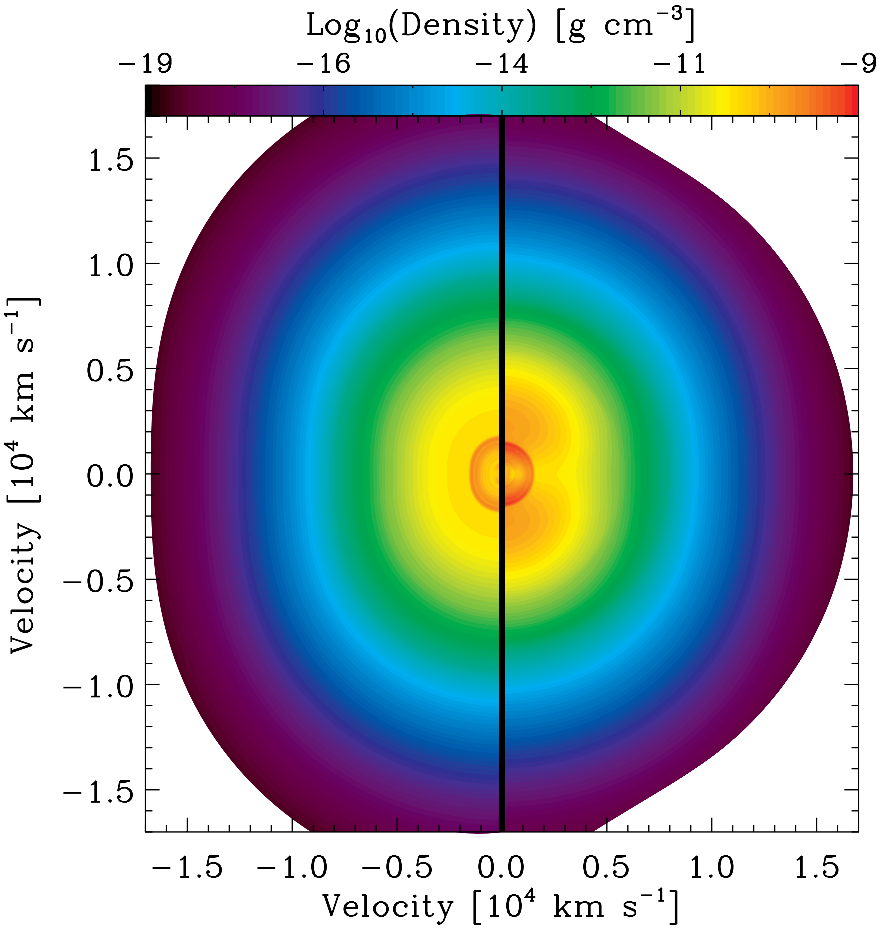


Velocity [10^4 km s^{-1}]
0.10 0.31 0.41 0.59 0.78 1.41
Solid: ^{56}Ni
Broken: He
Dotted: O
Bmf4p41x1
Bmf4p41x2
Bmf4p41x3
Bmf4p41x4
Element Mass Fraction
Lagrangian Mass [$M_\odot$]



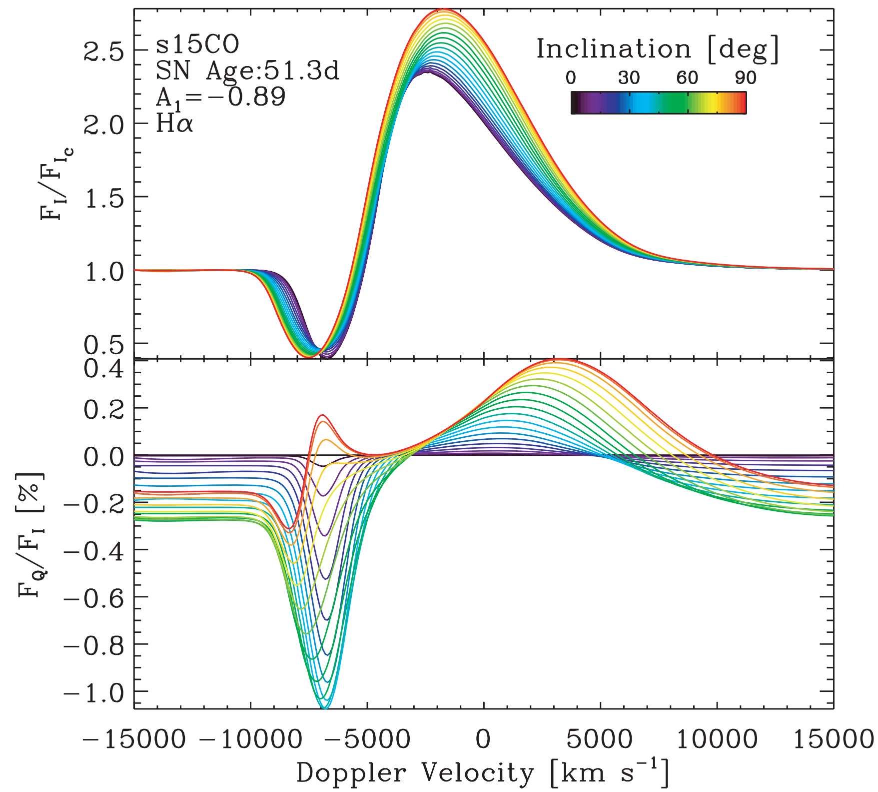
SN Ib
SN2008D
2 Feb. 2008
Bmf5p09x4@10.3d
E(B−V)=0.70
SN Ic
SN2007gr
2007−09−10
Bmf5p09x3@15.1d
E(B−V)=0.15
FeII
TiII
CaII
SiII
MgII
NaI
OI
CII
CI
HeI
Rectified Flux + Const.
Wavelength [Å]

Polarization

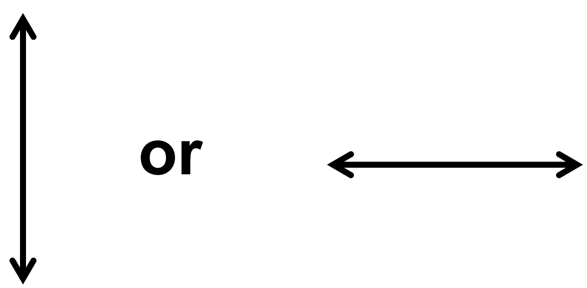


Non-spherical explosions

- Ia – some asymmetry.
- Ibc – strongly asymmetric
- II – asymmetric below H core?



Polarization can flip sign!



Dessart, Hillier, 2011, MNRAS, 415, 3497

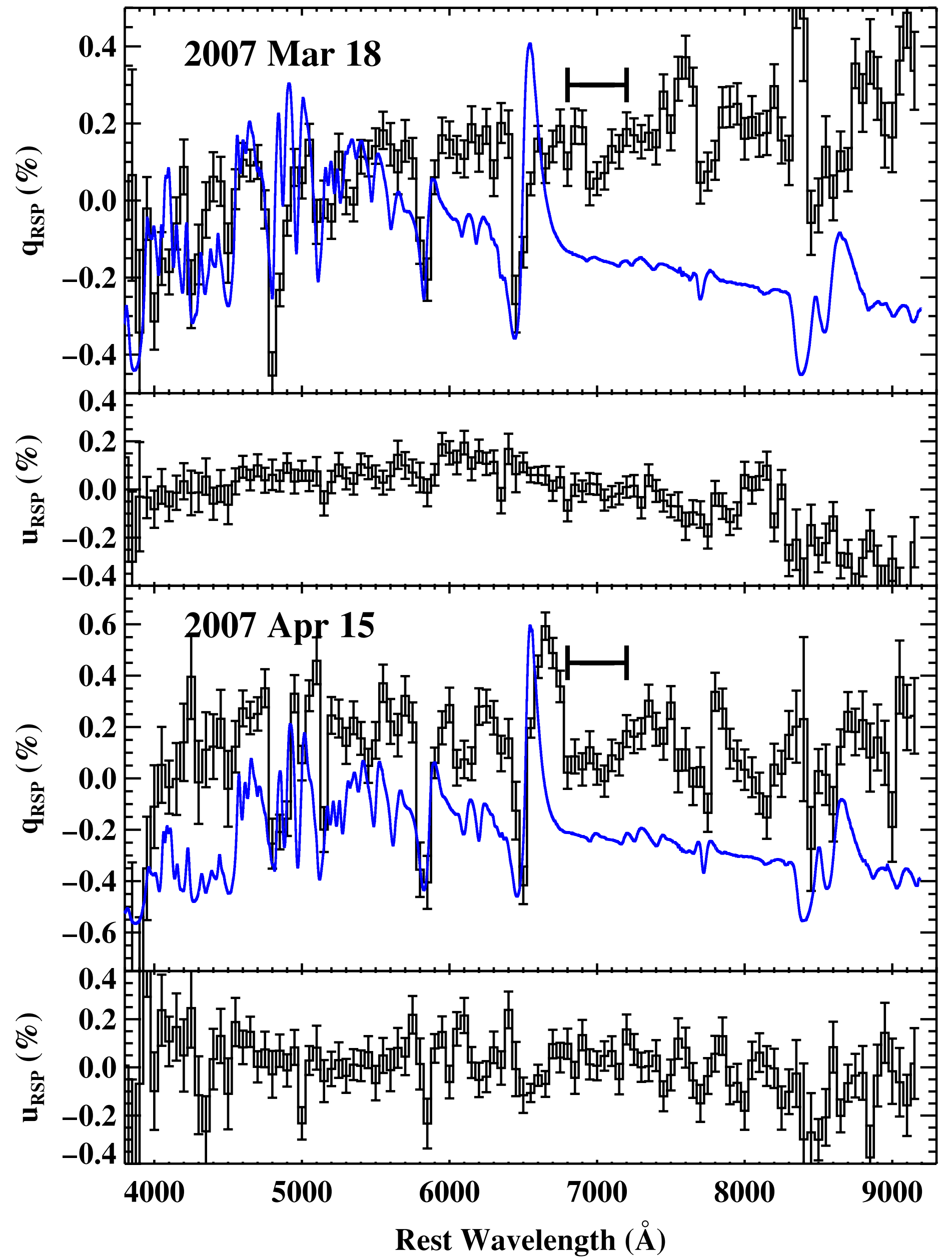
Optically thin scattering:

$$p \propto \tau(1 - 3\gamma)\sin^2 i$$

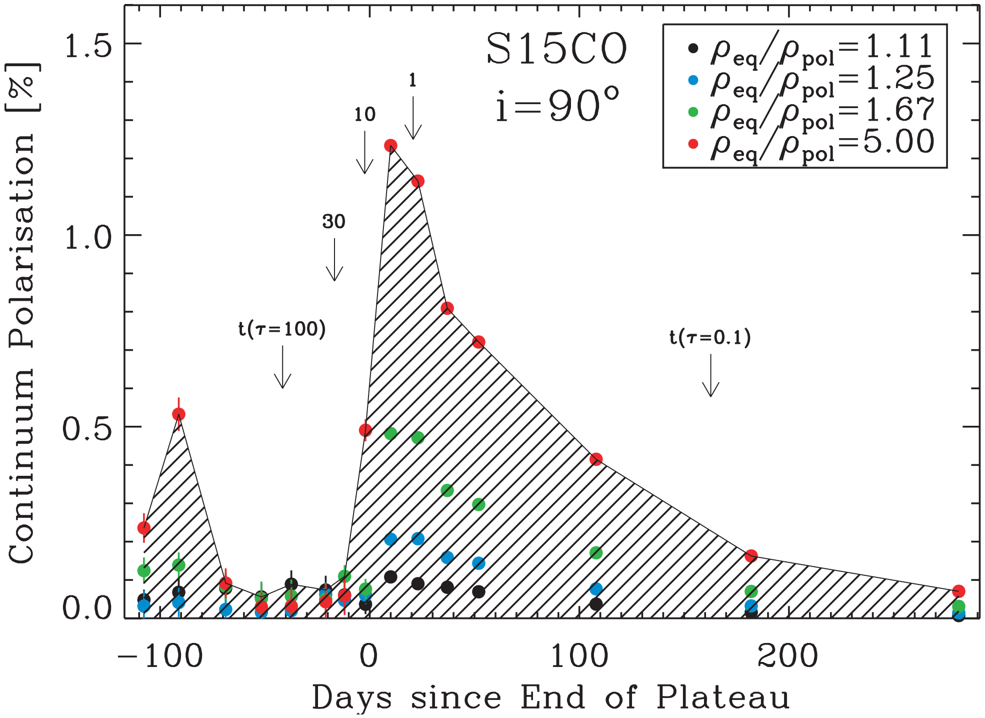
γ is a shape factor – geometry of envelope.
i – inclination rel. to sym. axis.
(Brown & McLean 1977).

SNe ejecta are not thin (epoch dependent). Thus simple formula DOES NOT necessarily apply.

Polarization can be both aligned and perpendicular to symmetry axis in the same object.

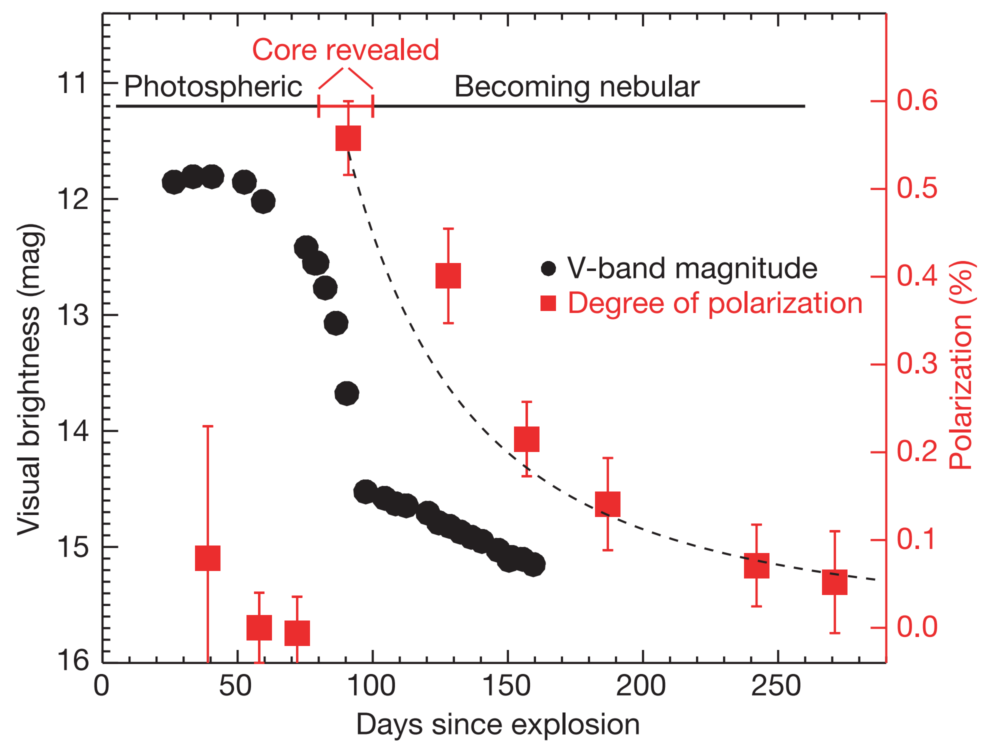


2007aa
Chornock, et al., 2010, ApJ, 713,1363



IIP model

Dessart, Hillier, 2011, MNRAS, 415, 3497



SN 2004dj (Type IIP)

Leonard, Filippenko, Ganeshalingam, et al., 2006, Nat., 440, 505

Atomic data

Ideal world

- Superb atomic data
- Discrepancies only related to astrophysics / model assumptions.

Real world

- Atomic data of mixed quality.
- Discrepancies: atomic physics or astrophysics?

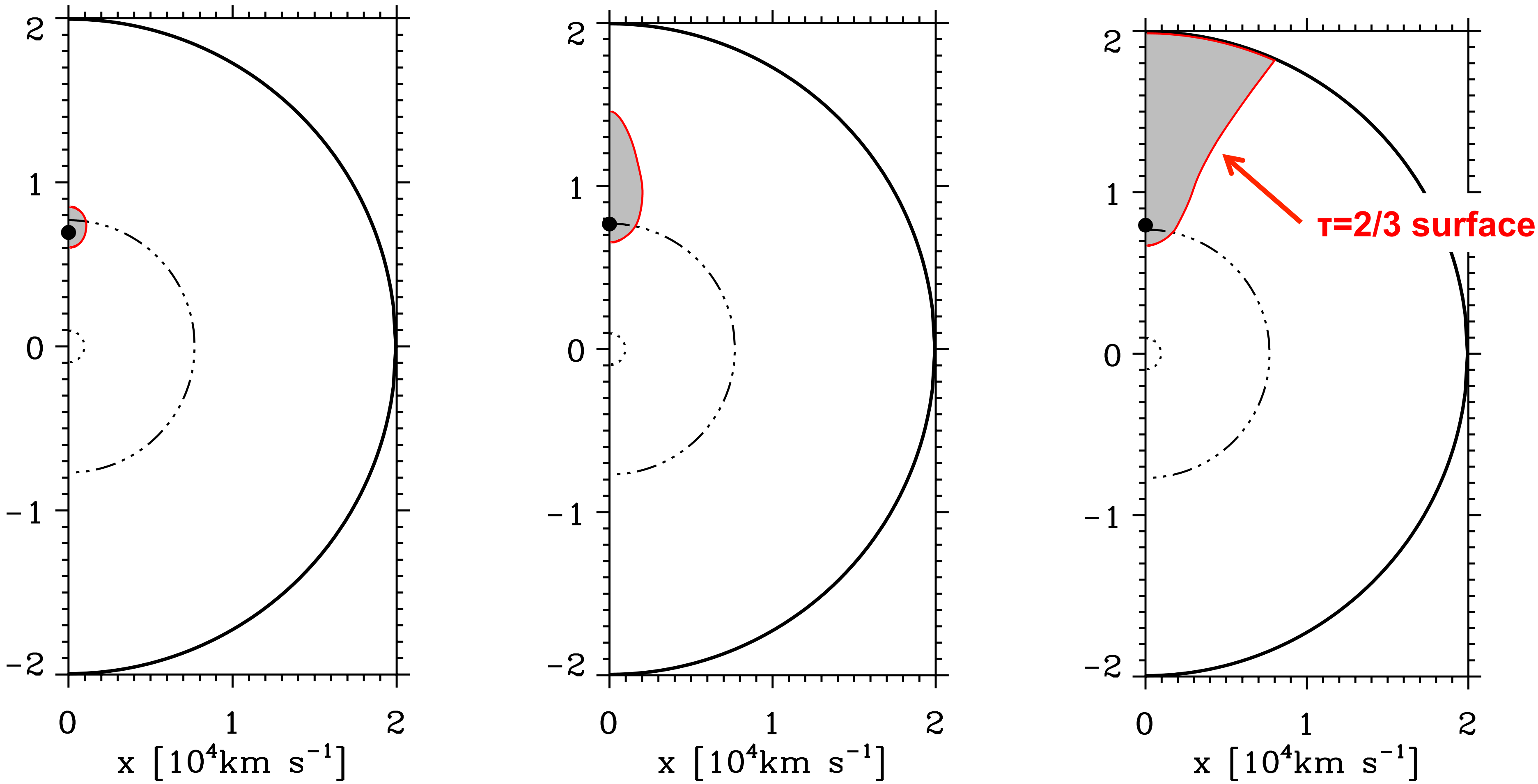
What's needed

- Accurate energy levels & wavelengths
  - Resonances in photoionization cross-sections.
- gf values
- Most important elements
  - H, He, CNO, Si, S, Ti, Fe, Co, Ni
  - Need photoionization cross-sections, collisional data (IRON project).
- Collisional data is generally lacking
- Charge exchange reactions in H poor environments (O, C, Si, Fe, Co, Ni).
  - Need channel information.

THE

END

Gamma-Rays
Local or non-Local?

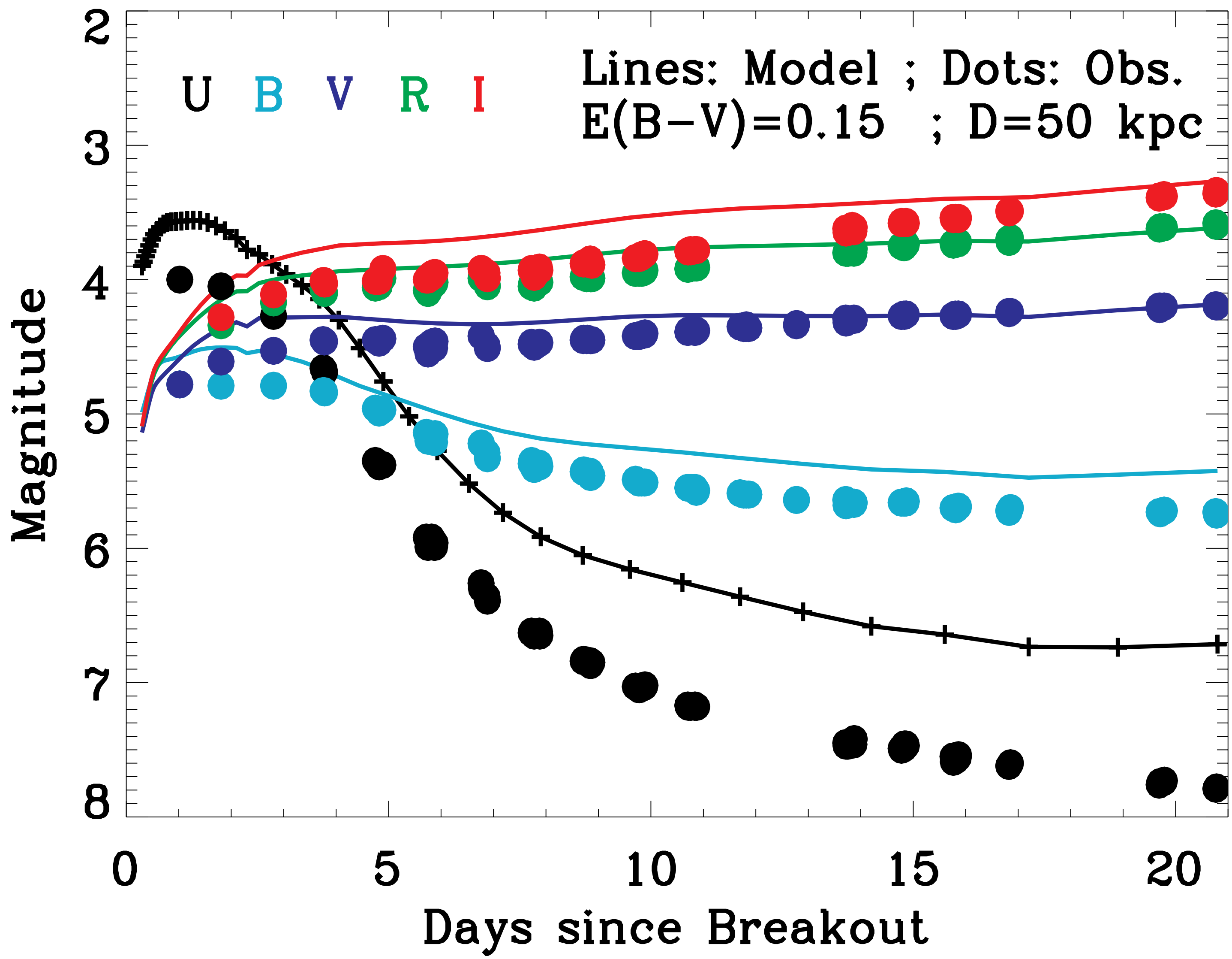


Bmi18mf4p41z1 -- Day 27

In the inner region gamma-rays are absorbed locally. Only in outer ejecta can gamma-rays travel freely.

SN1987A

Dessert & Hillier (2010, MNRAS, astroph, in press)



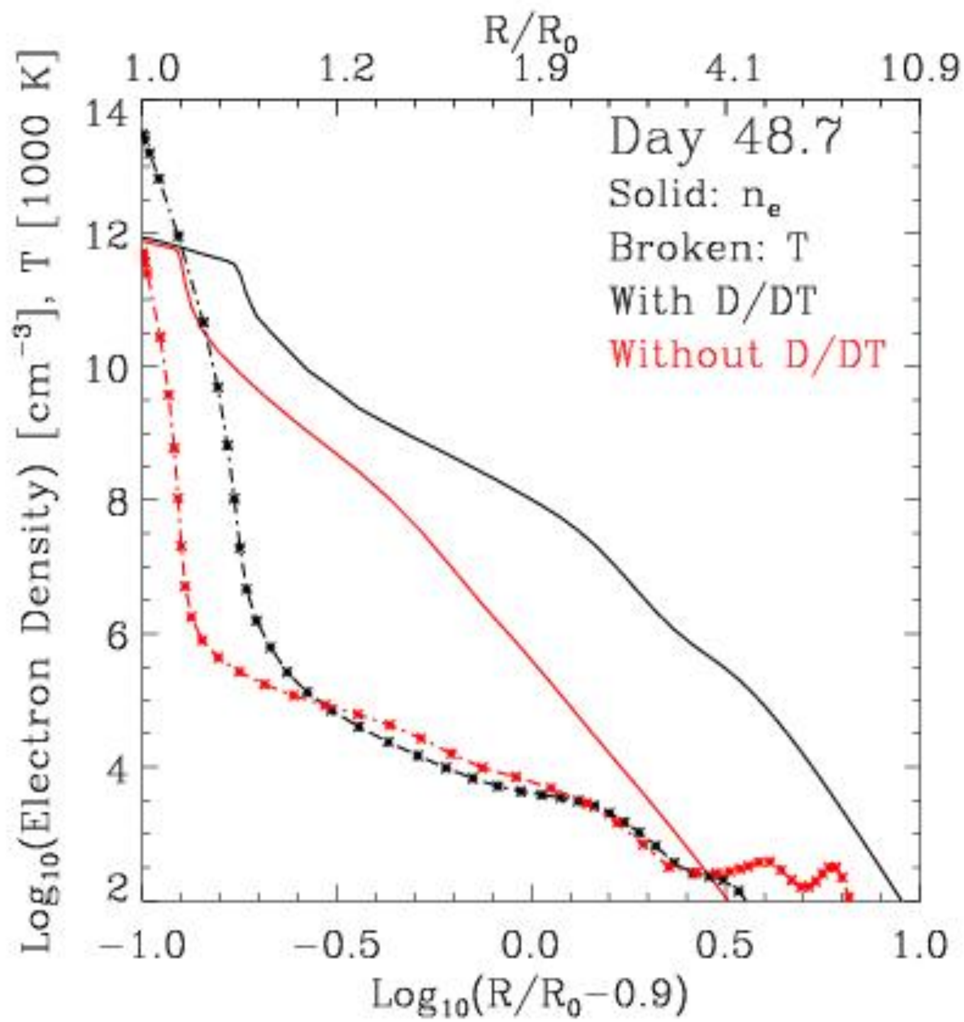
Energy Equation

$$\rho \frac{De}{Dt} - \frac{P}{\rho}\frac{D\rho}{Dt} = 4\pi\int_0^\infty \chi_\nu (J_\nu - S_\nu)\, d\nu$$

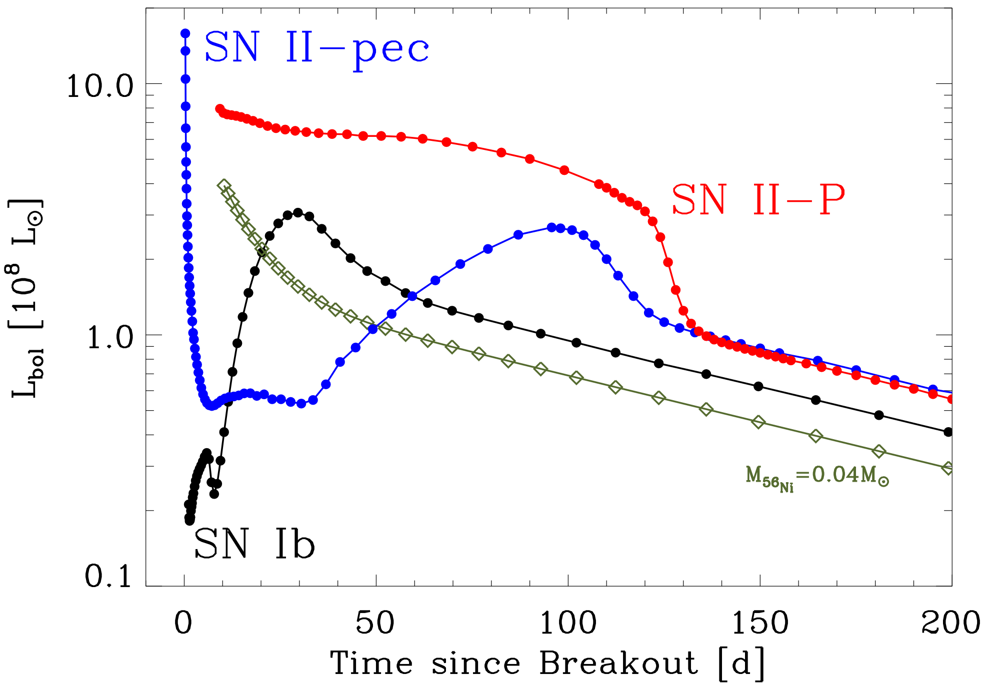
where

$$e = \text{internl energy/unit mass}$$

$$= \frac{\frac{3}{2}kT(n+n_e)}{\mu m_H n} + \frac{\sum n_i E_i}{\mu m_H n}$$

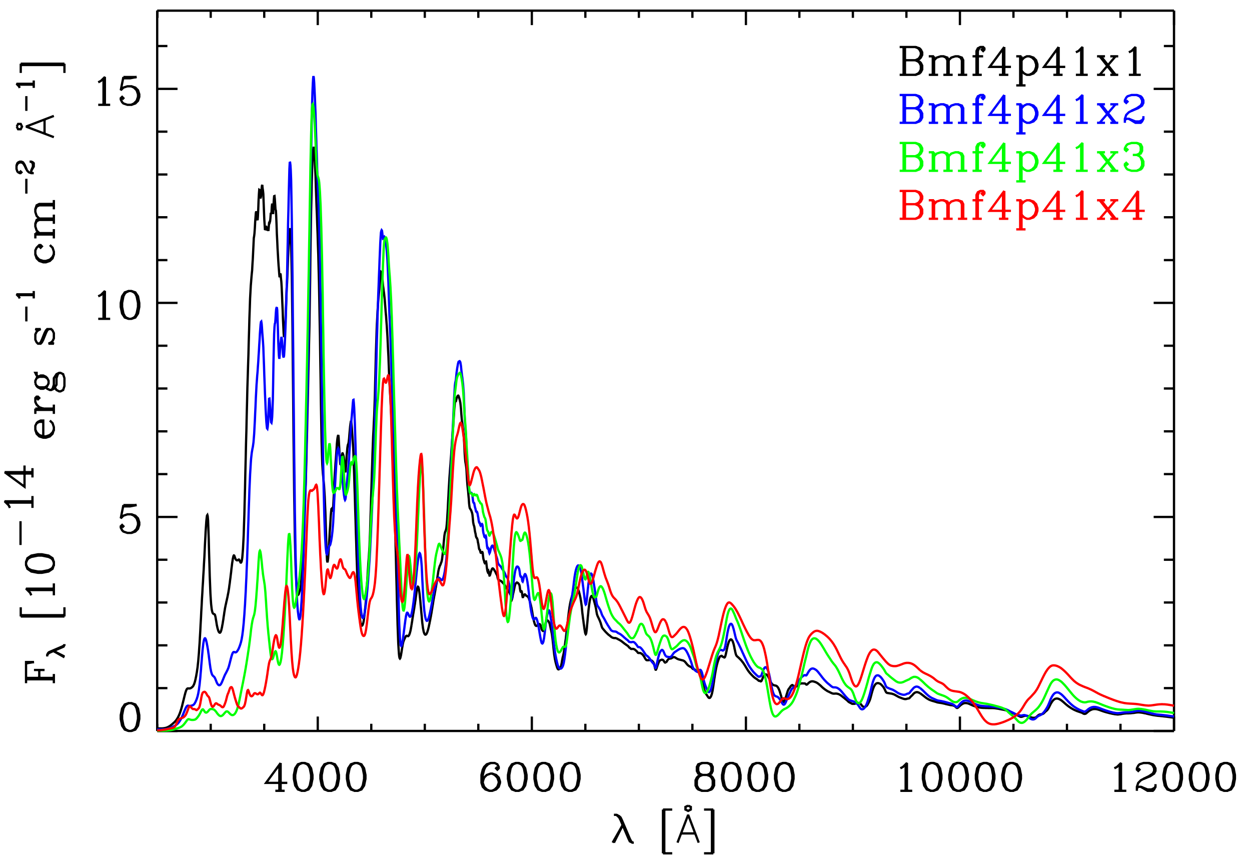


Energy released as H recombines can be important.



SN II−pec
SN II−P
SN Ib
$M_{^{56}Ni}$=0.04$M_\odot$
10.0
1.0
0.1
L_{bol} [10^8 $L_\odot$]
0
50
100
150
200
Time since Breakout [d]

Influence of Mixing



Absorption and Emission Coefficients

Extinction Coefficient, χ_ν

Defined such an element of cross section dA and length ds removes from a beam propagating perpendicuar to dA into a solid angle dω removes an amount of energy, dE:

$$dE = \chi_\nu(r,\vec{n})\, I_\nu(r,\vec{n})\, dA\, ds\, d\omega\, d\nu\, dt$$

$1/\chi$ has the units cm and gives an indication of how far a photon can travel before it is absorbed – a mean free path.

Extinction process normally split into 2 classes:

(1) Absorption processes (photon is destroyed)

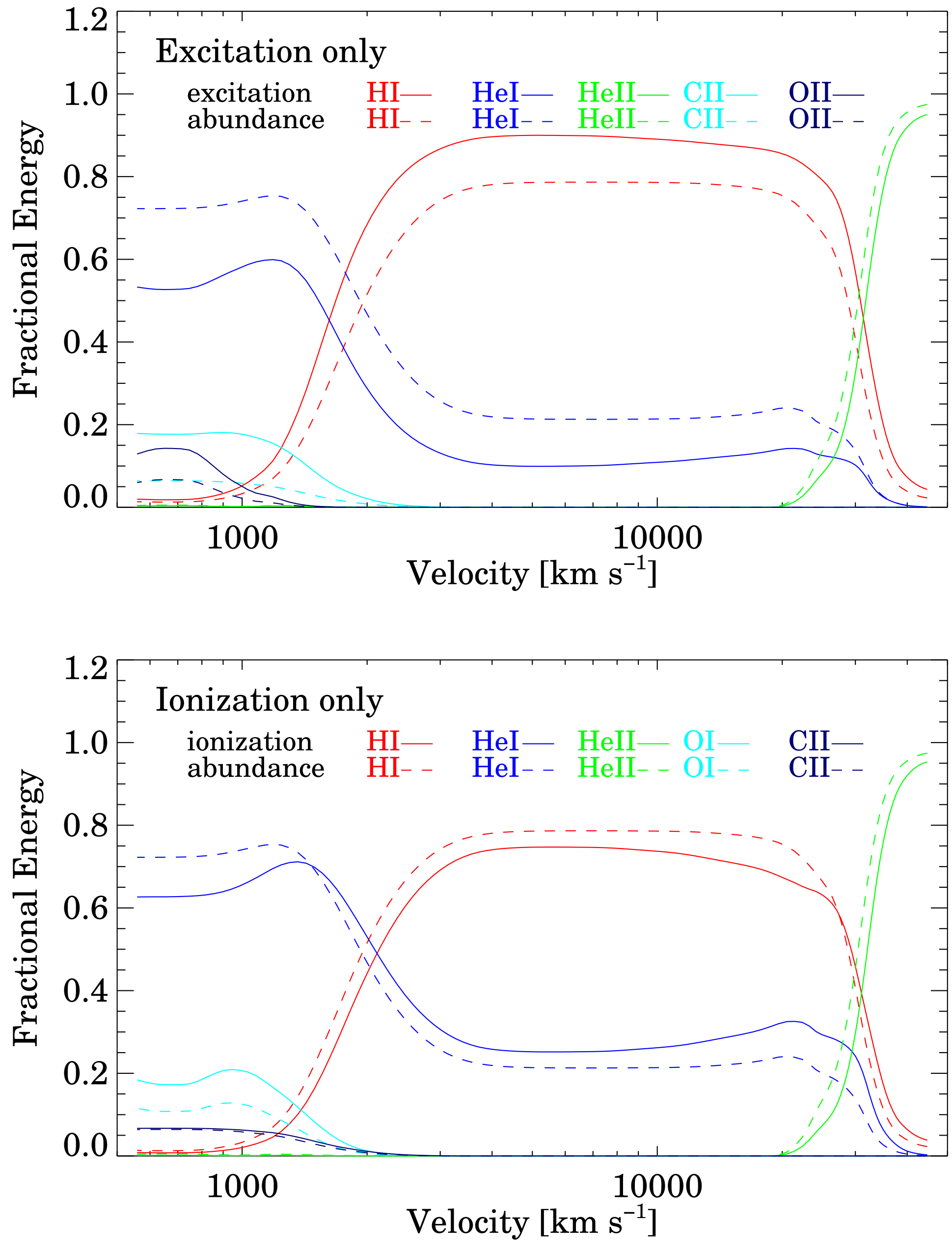
(2) Scattering processes (photons direction of travel is altered).

Emission Coefficient, η_ν

$$dE = \eta_\nu(r,\vec{n},t)\, dA\, ds\, d\omega\, d\nu\, dt$$

dE is the energy emitted into solid angle dω about in frequency interval dν and dt from a volume of cross-section dA and length ds.

In LTE, $\eta_\nu=\chi_\nu S_\nu = \chi_\nu B_\nu(T)$


Excitation only
excitation HI HeI HeII CII OII
abundance HI HeI HeII CII OII
Fractional Energy
Velocity [km s^{-1}]
1000
10000
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Ionization only
ionization HI HeI HeII OI CII
abundance HI HeI HeII OI CII
Fractional Energy
Velocity [km s^{-1}]

Atomic data

What's needed

- Accurate energy levels & wavelengths
  - Resonances in photoionization cross-sections.
- gf values
- Most important elements
  - H, He, CNO, Si, S, Ti, Fe, Co, Ni
  - Need photoionization cross-sections, collisional data (IRON project).
- Collisional data is generally lacking
- Charge exchange reactions in H poor environments (O, C, Si, Fe, Co, Ni).
  - Need channel information.

Time Dependent Radiative Transfer

(comoving-frame)

For Homologous expansion:

$$\frac{1}{cr^3}\frac{D(r^3 J_\nu)}{Dt} + \frac{1}{r^2}\frac{\partial(r^2 H_\nu)}{\partial r} - \frac{\nu V}{rc}\frac{\partial J_\nu}{\partial \nu} = \eta_\nu - \chi_\nu J_\nu$$

$$\frac{1}{cr^3}\frac{D(r^3 H_\nu)}{Dt} + \frac{1}{r^2}\frac{\partial(r^2 K_\nu)}{\partial r} + \frac{K_\nu - J_\nu}{r} - \frac{\nu V}{rc}\frac{\partial H_\nu}{\partial \nu} = -\chi_\nu H_\nu$$

100,000 equations!

Grey transfer:

$$\frac{1}{cr^4}\frac{D(r^4 J)}{Dt} + \frac{1}{r^2}\frac{\partial(r^2 H)}{\partial r} = \overline{\chi}(S - J)$$

$$\frac{1}{cr^4}\frac{D(r^4 H)}{Dt} + \frac{1}{r^2}\frac{\partial(r^2 K)}{\partial r} + \frac{K - J}{r} = -\overline{\chi} H$$

Unanswered questions

Type Ia SN

- Progenitor?
  - Single degenerate
  - Double degenerate (M> 1.4 $M_\odot$)
  - Double degenerate (M< 1.4 $M_\odot$)
- Why such standardizable candles?
- Deflagration / Detonation
- Mixing / Asymmetries

Type Ib/Ic

- Progenitor
  - Wolf-Rayet (W-R) star?
  - Binary channel W-R star?
- Helium abundance
- Mixing / Asymmetries

Type II P

- Progenitors (M < 20 $M_\odot$) – Why?
- Explosion mechanism
- Asymmetries
- Mixing

Pair Instability SNe (PISN)

- Observed?
- Metallicity?

Luminous SNe

- PISN?
- IIn?

Type IIn SN

- Interaction with circumstellar medium?
- Cause of CSM
- Progenitor

SNe imposters

- Luminous explosions – LBV like
- Mechanisms

Bright Future

Surveys

SNe factory
Polamar Transient Factory
SkyMapper
Pan-Stars
LSST

Experiment

Raleigh-Taylor instabilities
Instabilities
Magnetic fields

Theory

Explosions

- 2D/3D
- Need constraints on progenitors
- Mixing/resolution

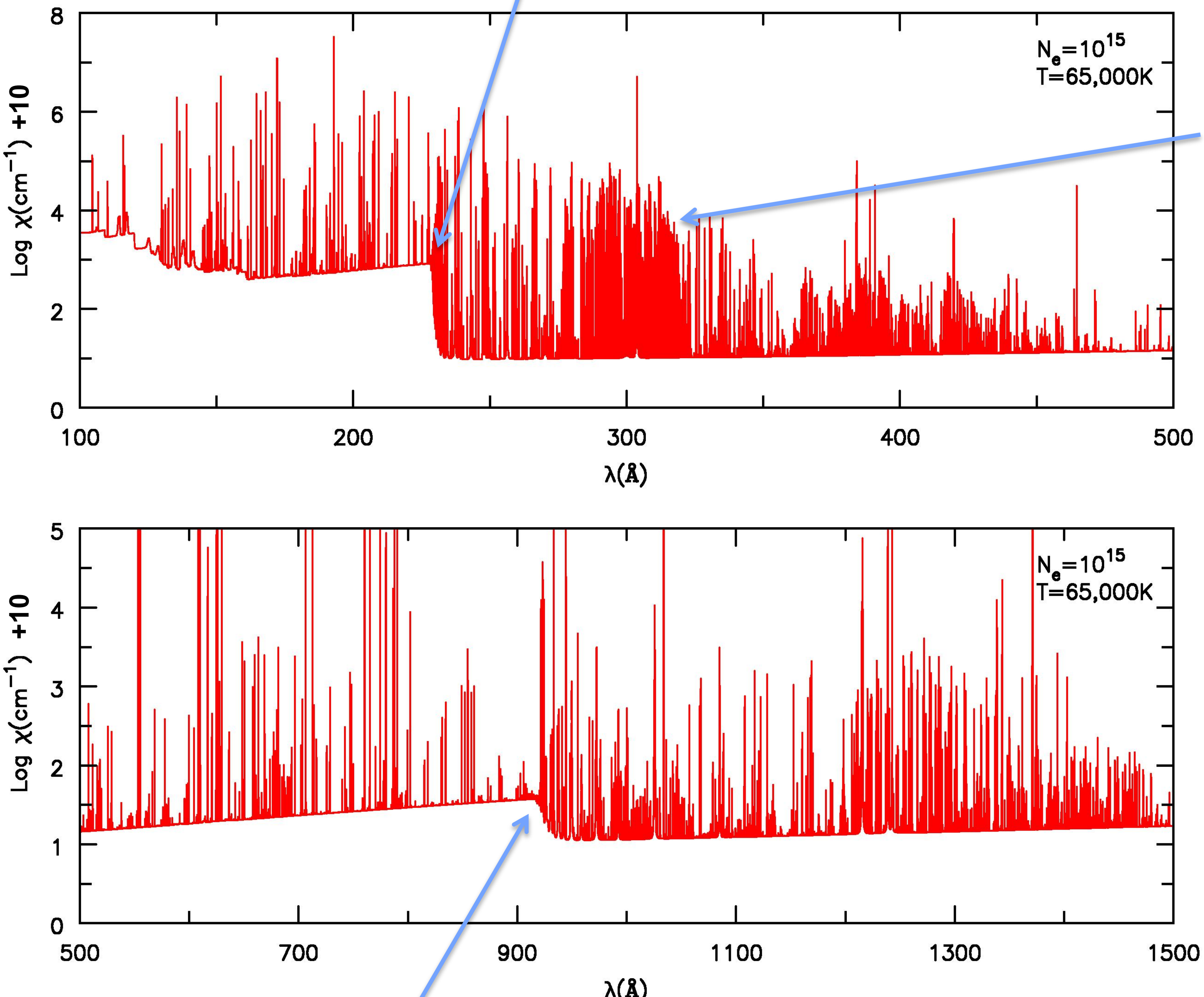
Light curves / Spectra

- 1D / 3D Monte Carlo
- Ray tracing (1D/3D)
- LTE / non-LTE / LTE with scattering.

Illustration of opacity for a real stellar atmosphere.

Bound-Free Jump (n=1 state in He II)

Forrest of bound-bound transitions.



Lyman Jump (n=1 state in H)

Time Dependent Statistical Equilibrium Calculations

Utrobin & Chugai (2005, A&A, 441,271)

Rate equation

$$\frac{\partial n_i}{\partial t} + \nabla.(n_i\vec{V}) = \sum_{j\neq i}(n_j R_{ji} - n_i R_{ij})$$

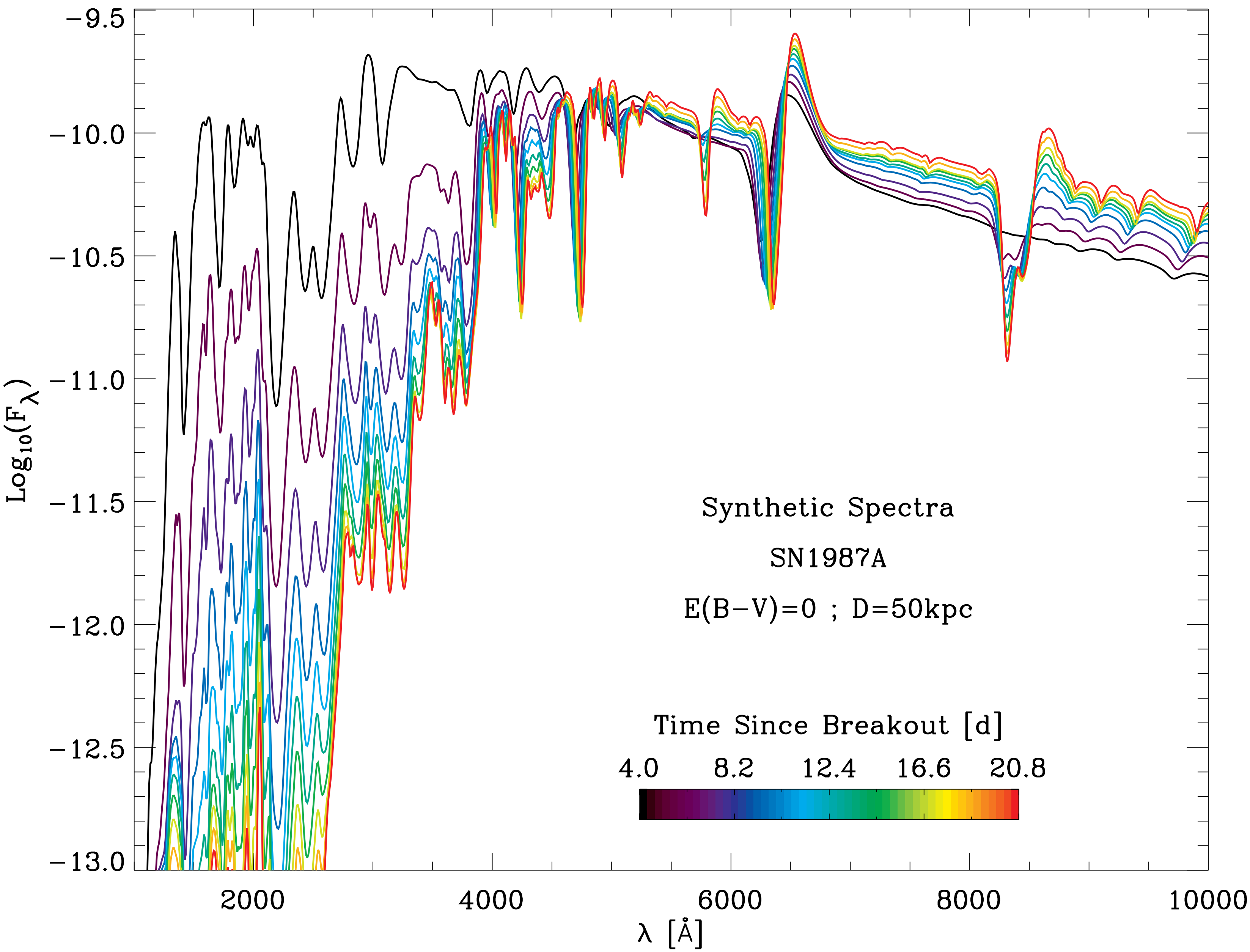
Lagrangian Frame:

$$\rho \frac{D(n_i/\rho)}{Dt} = \frac{1}{r^3}\frac{D(r^3 n_i)}{Dt} = \sum_{j\neq i}(n_j R_{ji} - n_i R_{ij})$$

One such equation for each level (all species & Ionization stages)

Note:

Primarily effects ionization balance. Recombination processes generally much slower than radiative processes coupling levels in a given ionization stage.



Synthetic Spectra
SN1987A
E(B−V)=0 ; D=50kpc
Time Since Breakout [d]
4.0
8.2
12.4
16.6
20.8
−9.5
−10.0
−10.5
−11.0
−11.5
−12.0
−12.5
−13.0
2000
4000
6000
8000
10000
λ [Å]
Log10(Fλ)