Supernova radiative-transfer modeling:
A new approach using 1-D, non-LTE, and full time dependence
Illustration for SN1987A and SNe II-P

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In collaboration with Eli Livne, Roni Waldman, & Stan Woosley

Our New Approach in 3 steps

1) Stellar evolution to core collapse / explosion (**KEPLER**)
2) Radiation hydrodynamics of explosion (**KEPLER, V1D**)
3) Gas + radiation evolved to late times using non-LTE time-dependent radiative transfer (**CMFGEN**)

1-D Non-LTE time-dependence using CMFGEN: **Assets**

(Hillier & Miller 1998; Dessart & Hillier 2005,2008)

- **Physical consistency**: stellar-evolution + hydro input: $X_i(m)$, $T(m)$, $\rho(m)$, $v(m)$ $r(m)$

  => use SN light to constrain pre-SN evolution and explosion
- **Full-ejecta simulation**, e.g. no "artificial" boundary conditions, X_i stratification
- **Detailed description of I/J/H**: RTE with all important terms in v/c, $\partial/\partial t$, $\partial/\partial \nu$,$\partial/\partial \mu$, $\partial/\partial r$
- **Detailed description of the gas**: 25 species & 15 ionization stages. **Non-LTE ionization**
- **Non-LTE**: All important radiative + collisional rates included **explicitly**.
- **Non-LTE:** All continuum and line opacity sources included explicitly. Line-blanketing
- **Large model atom**: ~10000 levels and ~200000 transitions. Use of super-levels
- **Decay energy:** Computed with Monte Carlo γ-ray transport code (edep+spectra)
- **Adaptive grid**: ~5 pts per τ-decade at each time (asset over hydro: mass grid)
- RTE solved at ~100000 ν-points. Coverage: ~10A to ~5μm
- Time step: $\Delta t = 0.1t$ => 45-50 steps to go from 0.3 to 21d, or 10 to 1000d => 3 months!

Initial Value problem!

Non-LTE Time-Dependent Radiative Transfer Modeling

Evolution of Gas & Radiation from explosion until nebular phase

Gas

Rate Equation:

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

& charge conservation

Coupling

Energy Equation:

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

+ De_{decay}/Dt

where e = internl energy/unit mass

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

(Excitation + Ionization)

Radiation

RTE 0th moment:

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

RTE 1st moment:

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

Illustration of results for:

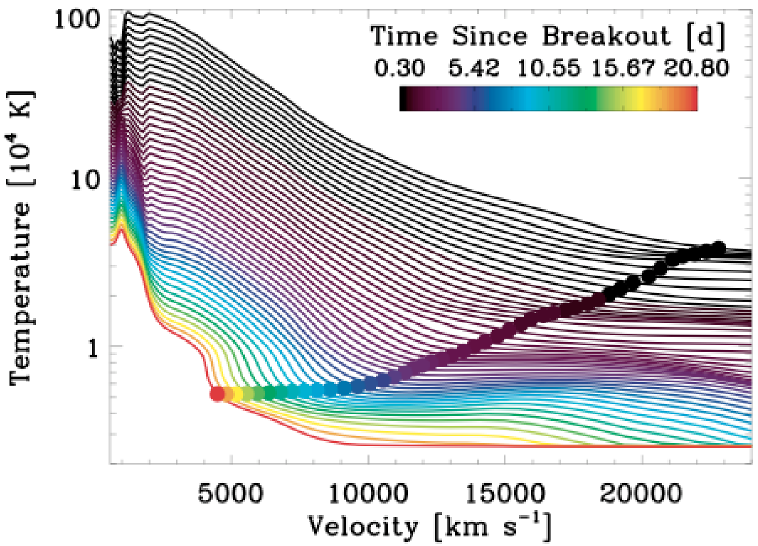
1) SN1987A (model lm18a7Ad from Woosley): evolution from 0.3 to 21d

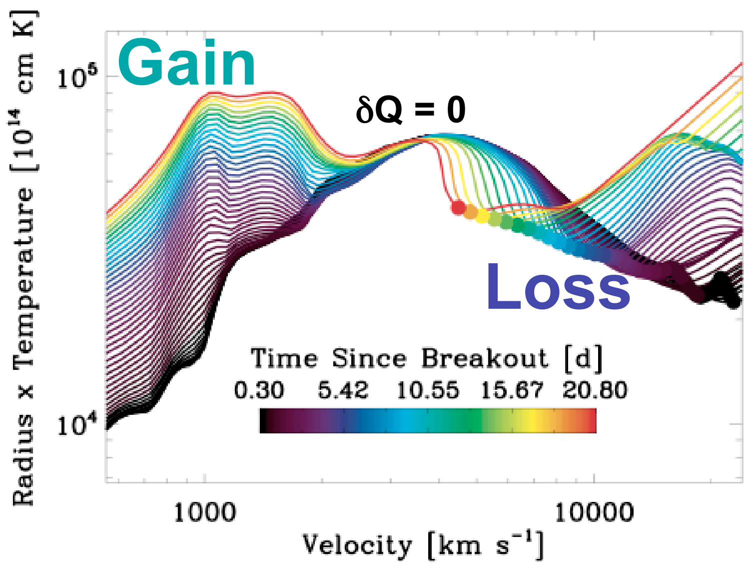
2) 15/25$M_{\odot}$ SN II-P
(model s15 and s25 of WH07 from Woosley): from 10 to 1000d

Full presentation in Dessart & Hillier 2010ab, Dessart, Livne, & Waldman 2010

SN1987A Ejecta Evolution

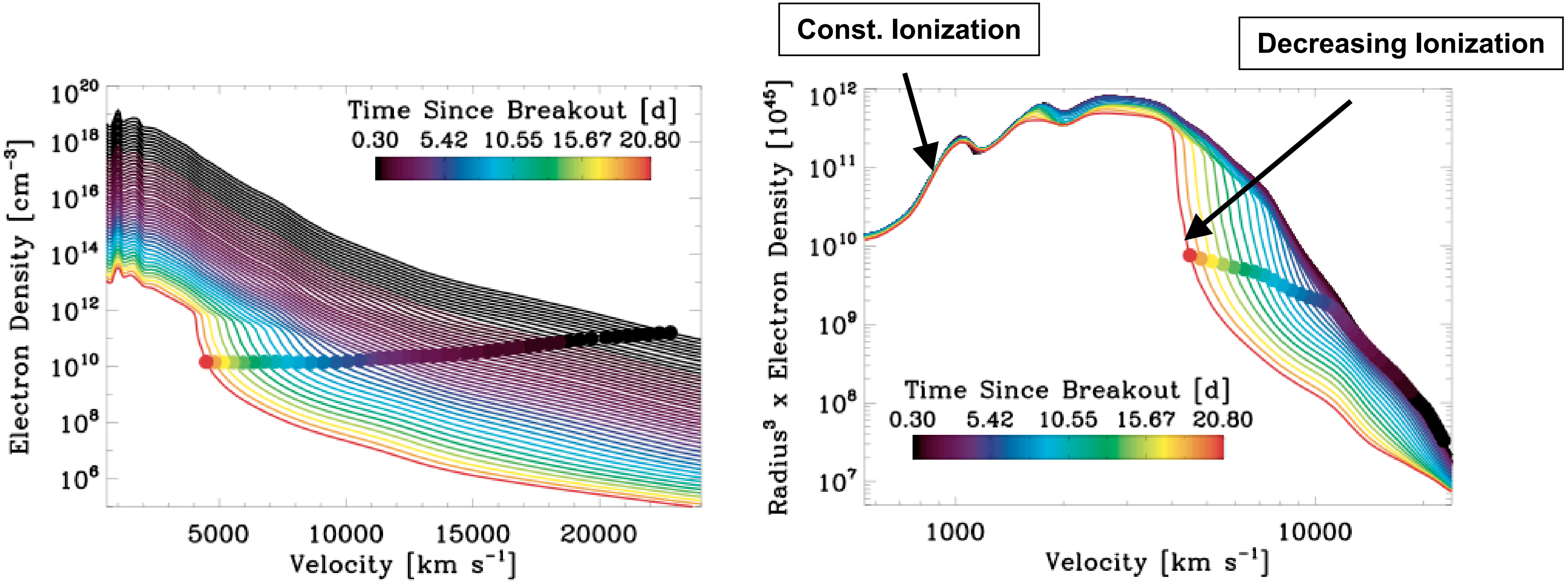
Global cooling due to expansion
Compensated by decay at depth
Exacerbated by radiative losses at surface





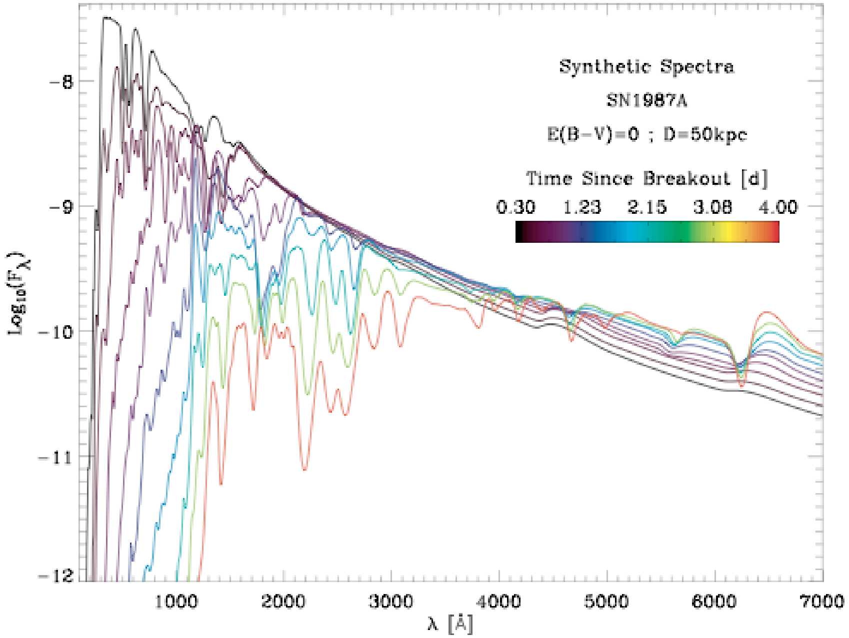
SN1987A Ejecta Evolution

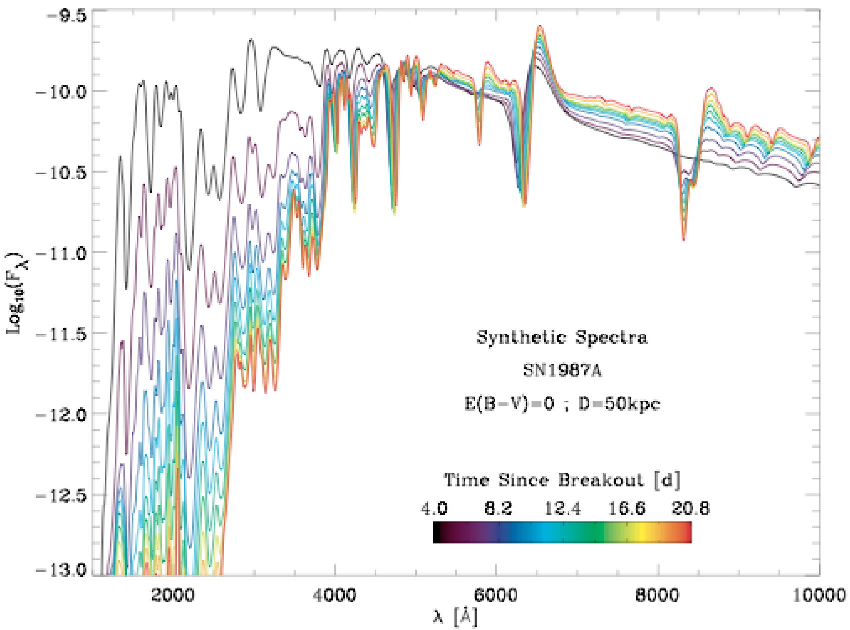
- Set by rate equations and charge conservation (neutrality)
- Mass continuity equation + expansion => Density $\propto 1/R^3$
- Recombination => N_e drops faster than mass density

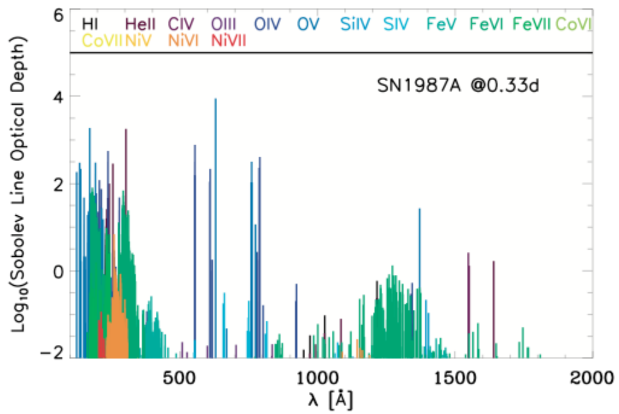


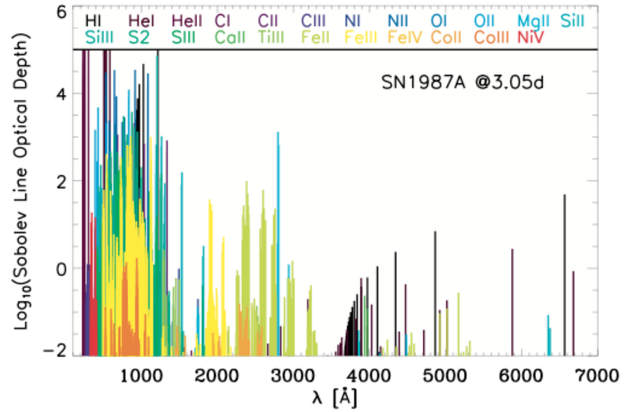
SN1987A Spectroscopic Evolution

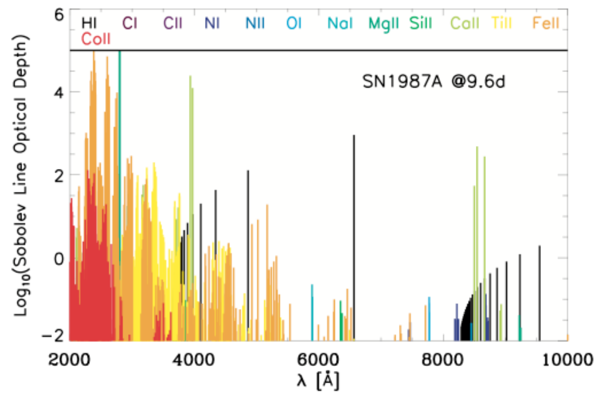
Reflects cooling + ionization shift of opacity sources (line blanketing)









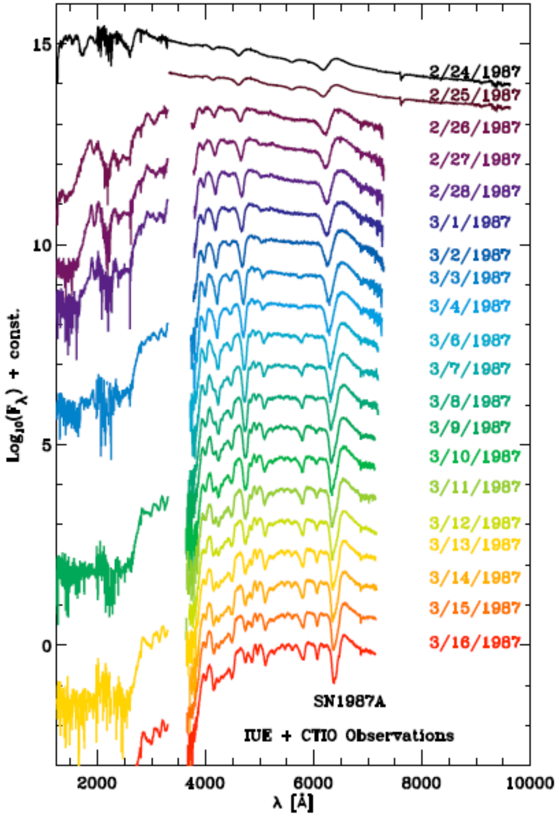


Comparison to observations of SN1987A

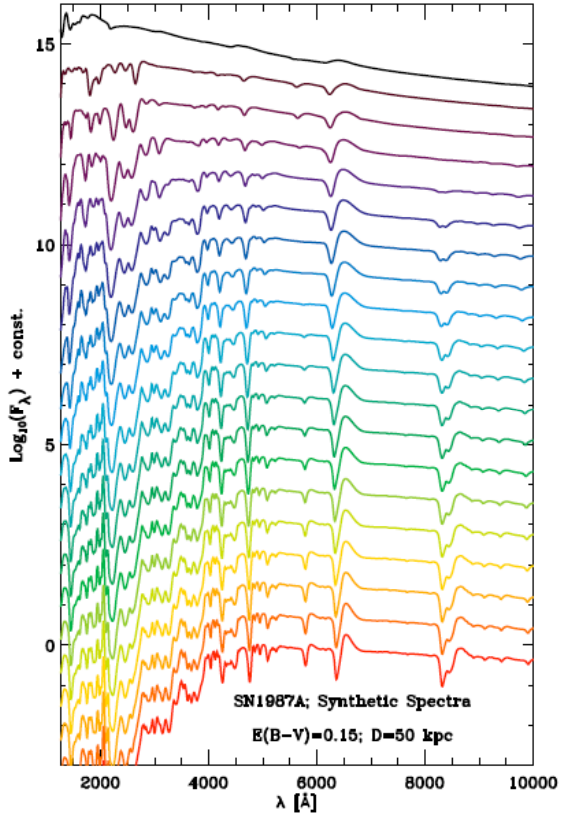
Agreement at 10% level except in the blue

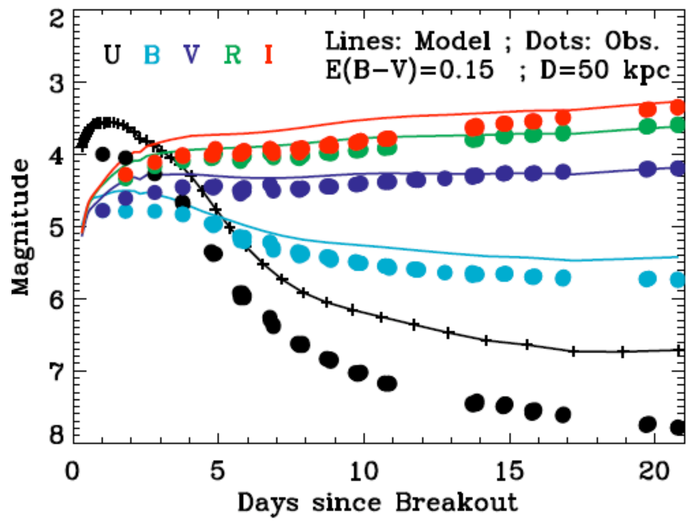
Supports 18$M_{\odot}$ BSG progenitor, R_{*}~50$R_{\odot}$, and E_{expl}~1.2B

Observation



Simulation





Dessart & Hillier (2010a)

Comparison with SN1987A spectra

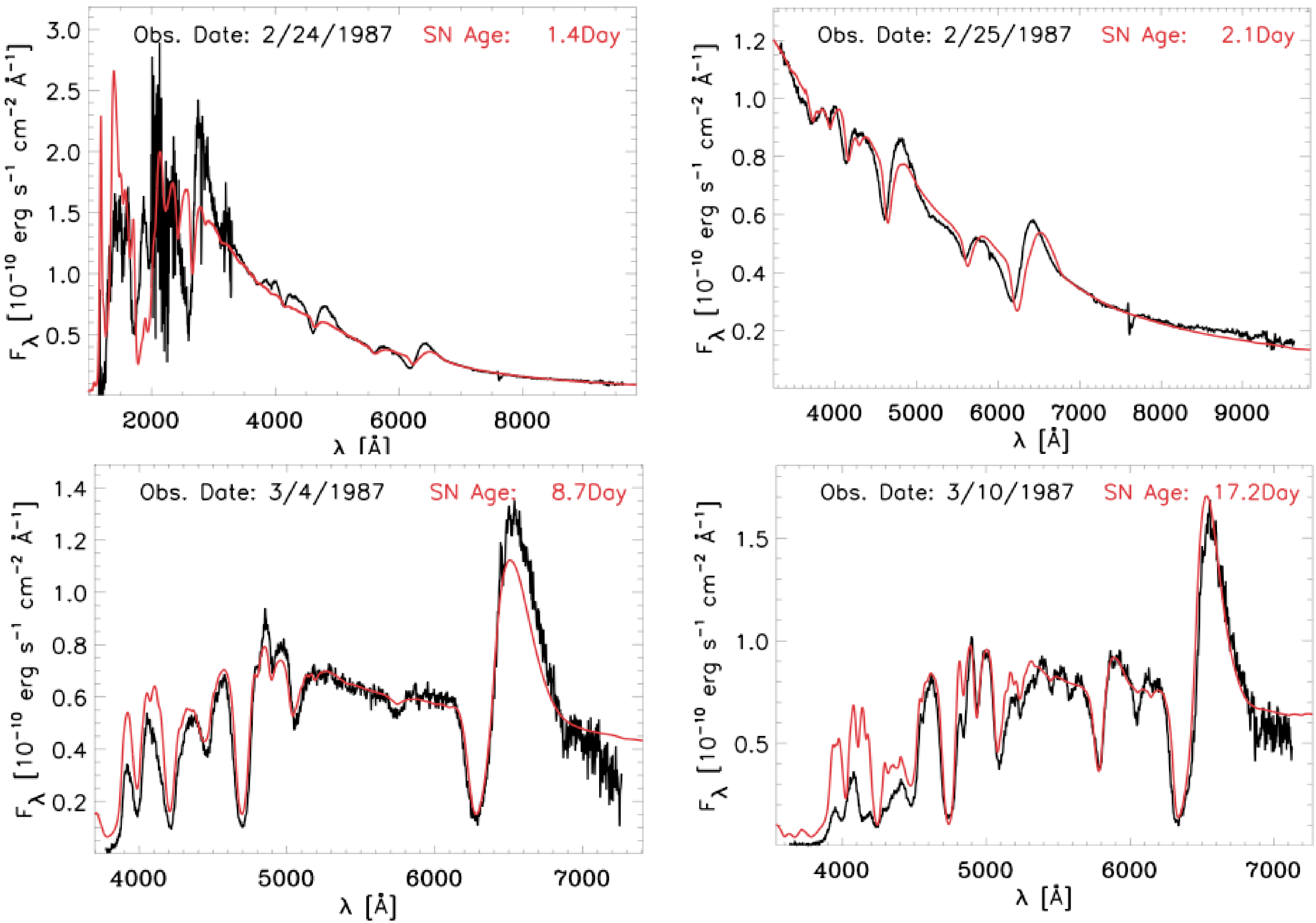


Illustration of results for:

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evolution from 10 to 1000d

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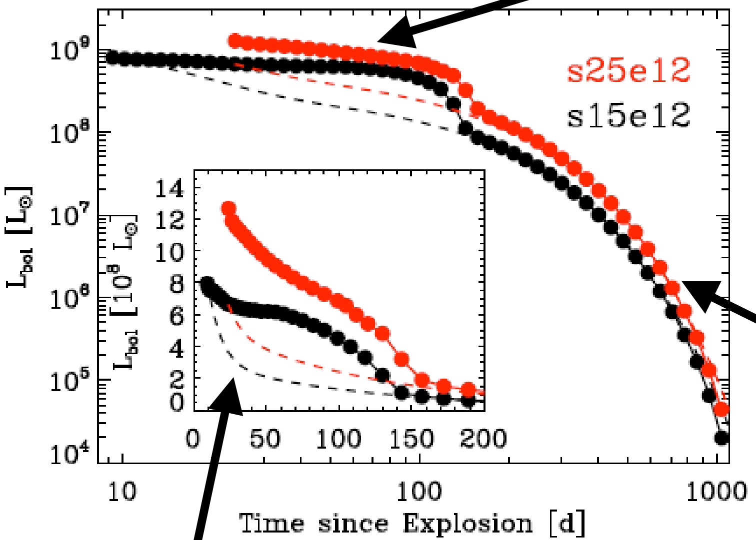
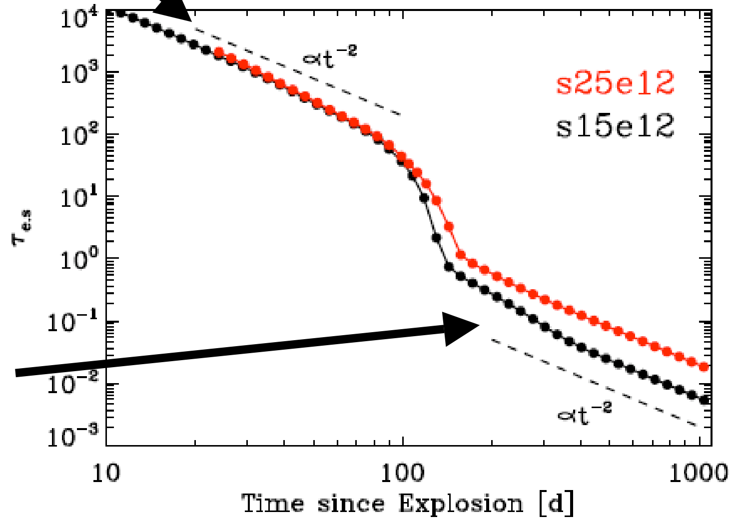
Simulations of SNe II-P
based on 15 and 25$M_\odot$ progenitor stars

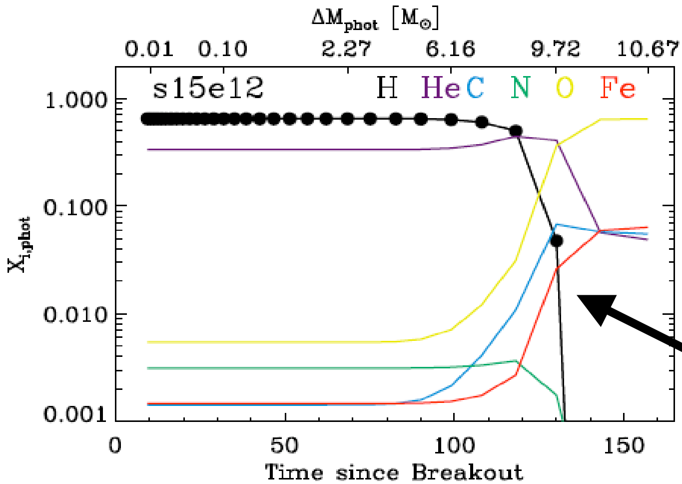
Photospheric phase





Nebular phase

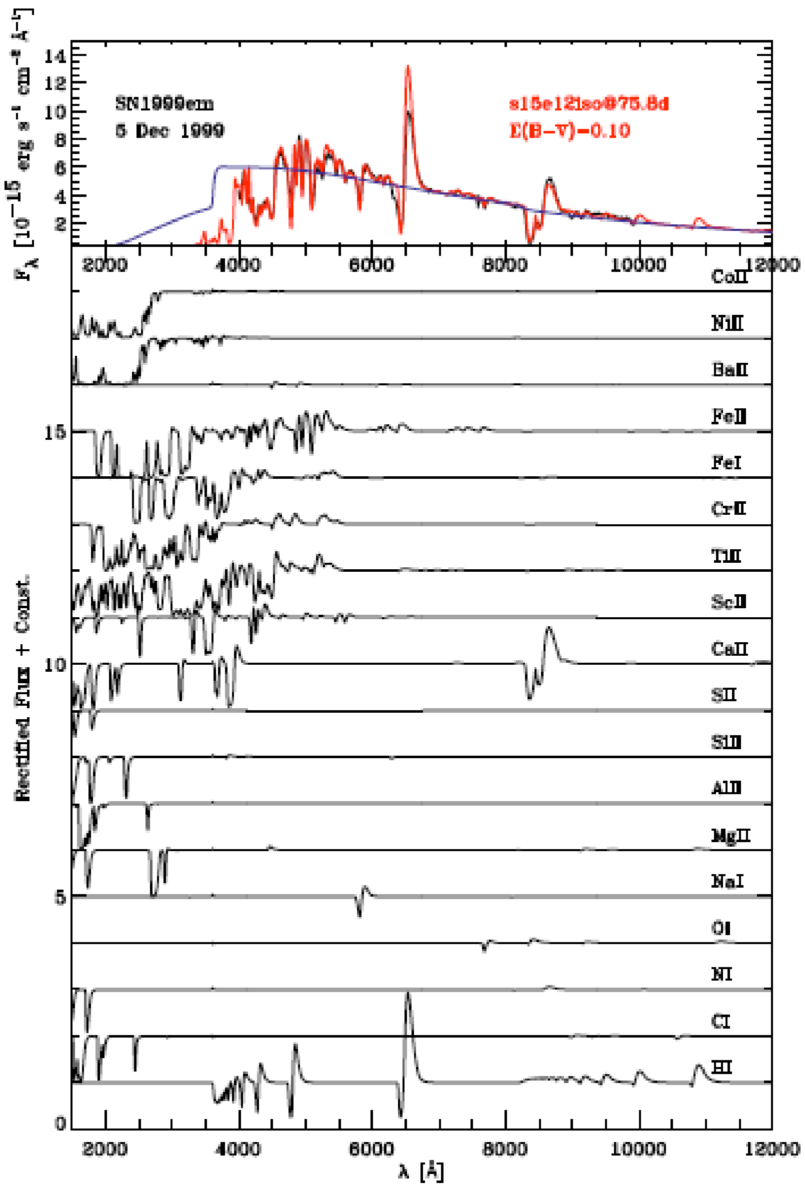
Decay energy

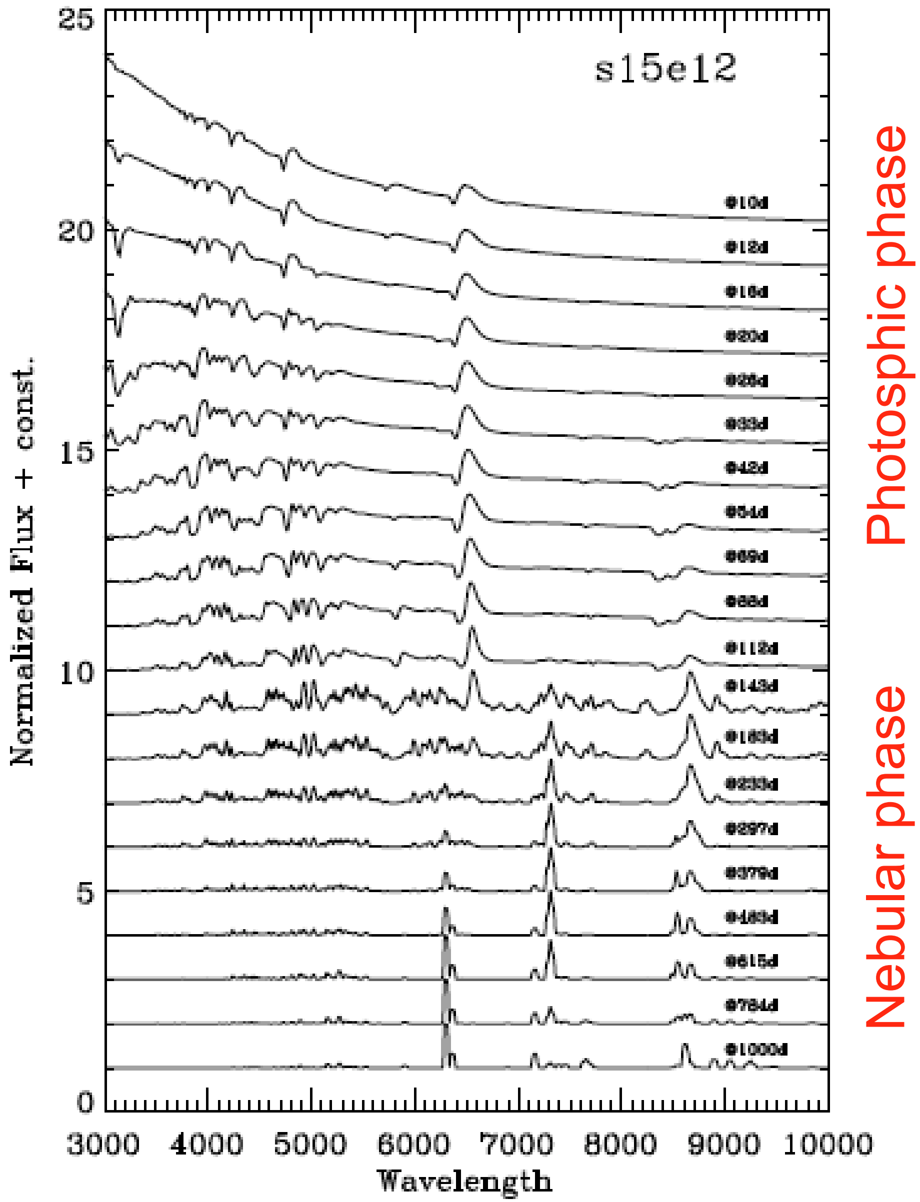


End of Phot. Phase

Dessart & Hillier (2010b)

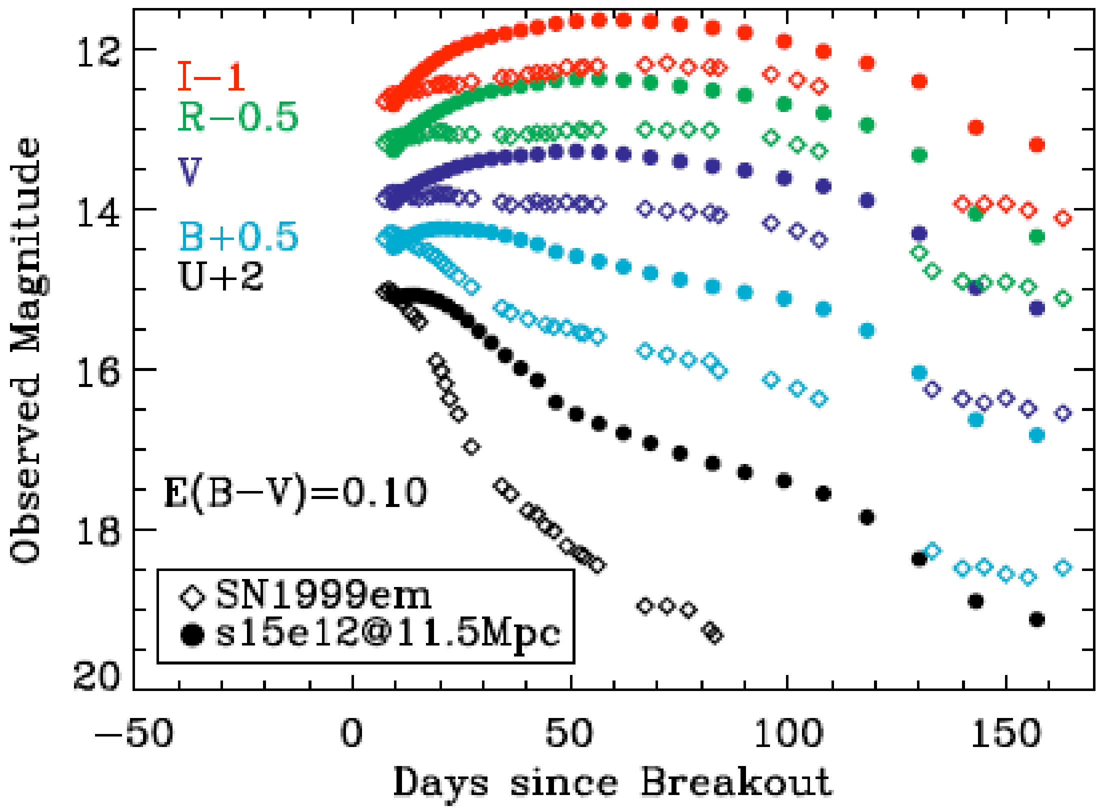
Simulations of SNe II-P
Line-blanketing and spectral evolution



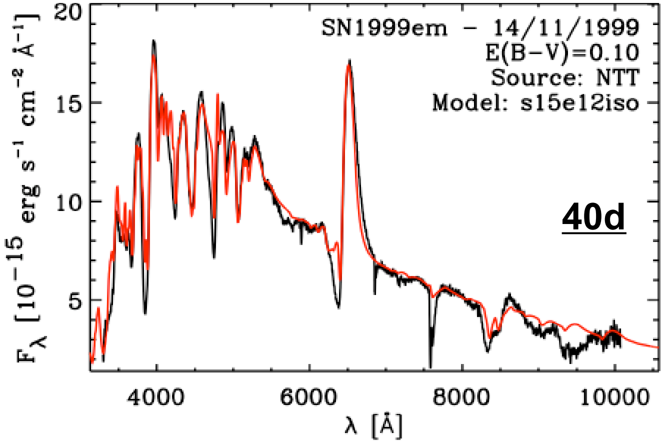


Comparison to SN 1999em (II-P)

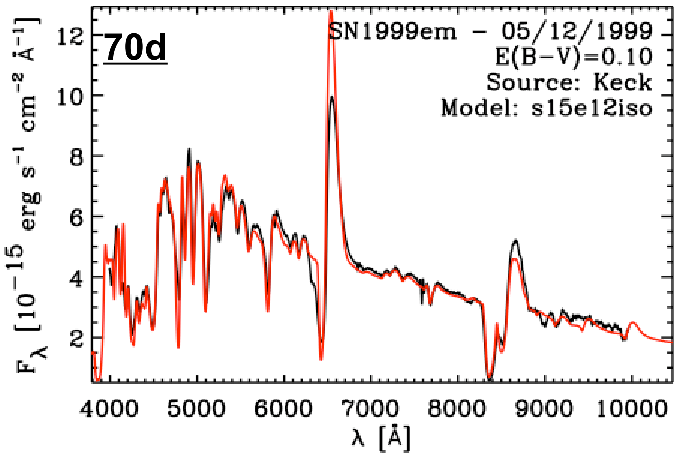
Good qualitative agreement but quantitative offset:
too blue, too bright, and bright for too long
=> pre-SN model R_* too big?

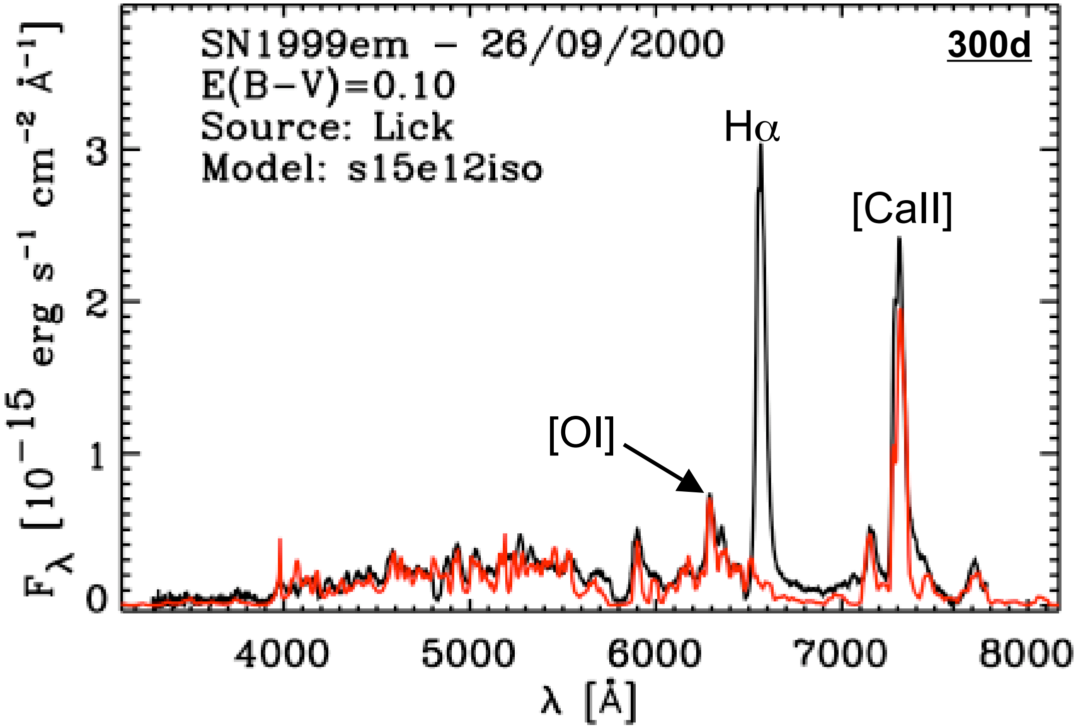


Comparison to SN 1999em (II-P) spectra



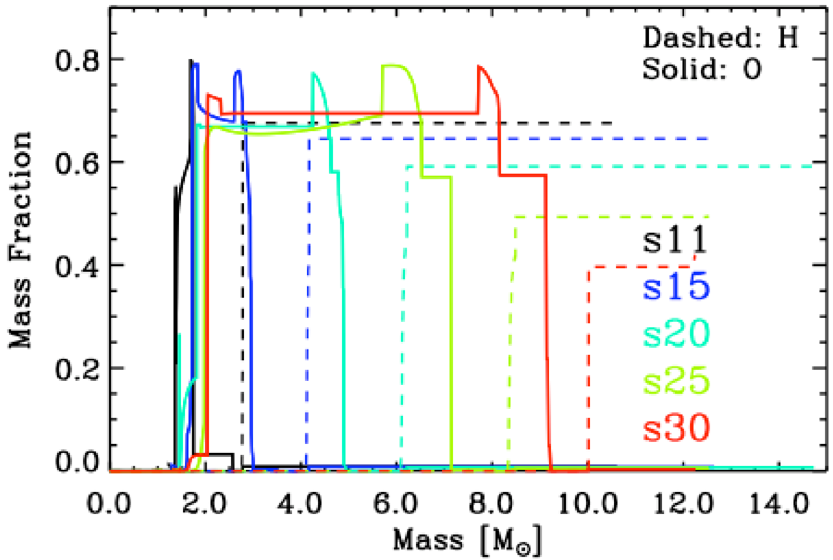
- o General agreement at all times
- o Specific disagreement with Hα at nebular times: neglect of non-thermal processes
- o [OI]: important line from He-core oxygen





SN II-P ejecta kinematics: V_{phot} vs. [OI] width

- Higher-mass progenitors have bigger helium cores
- Higher-mass progenitors lose more mass
- All SNe II-P RSG progenitors die with a comparable total mass but varying core/H-envelope masses
- Higher-mass progenitors expel oxygen at a larger velocity



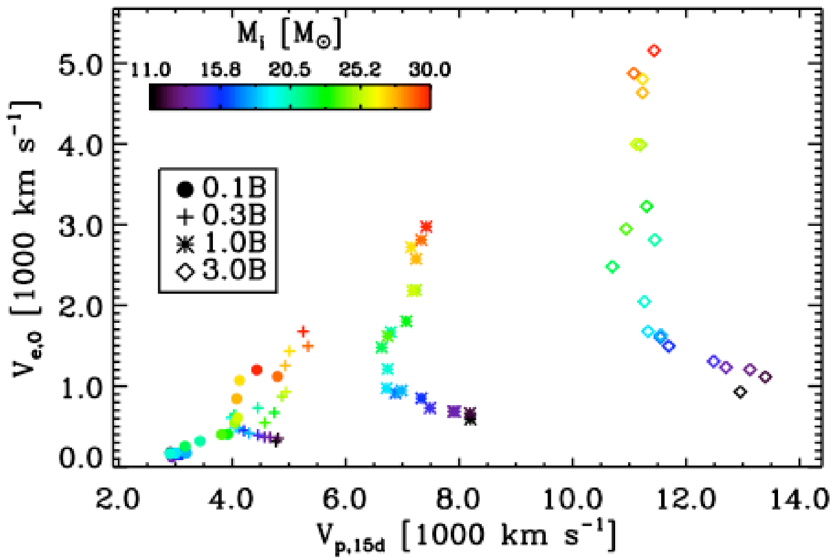
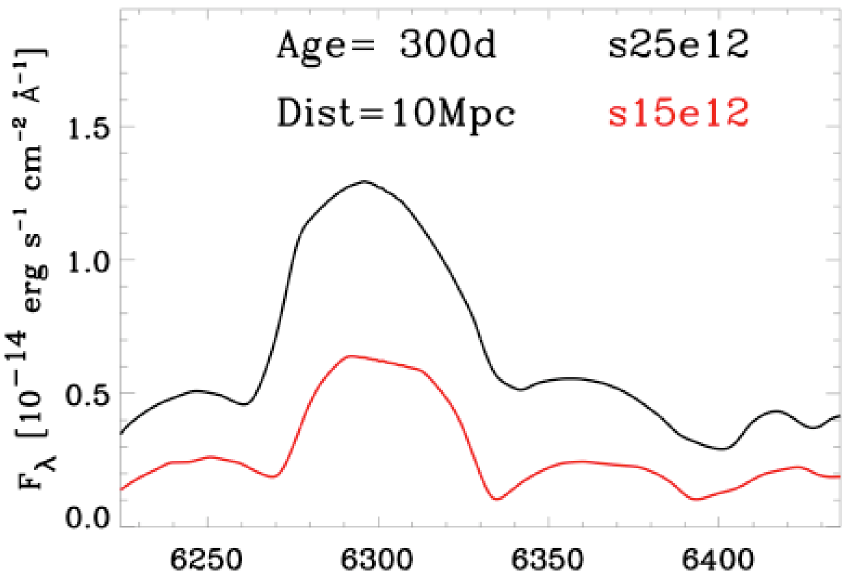
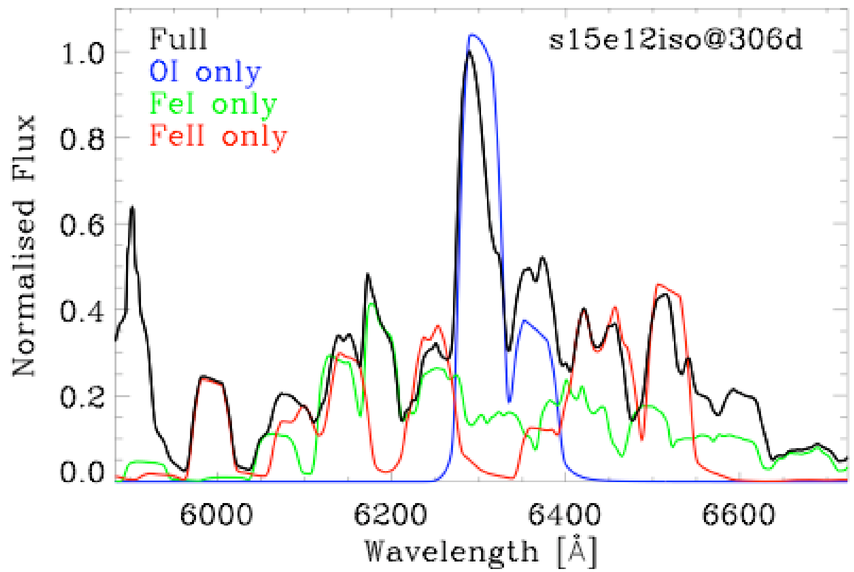


Illustration with [OI] from CMFGEN simulations

- Broader/stronger [OI] line in more massive progenitors
- Modulations: ^{56}Ni (heating), clumping, line overlap





Conclusions

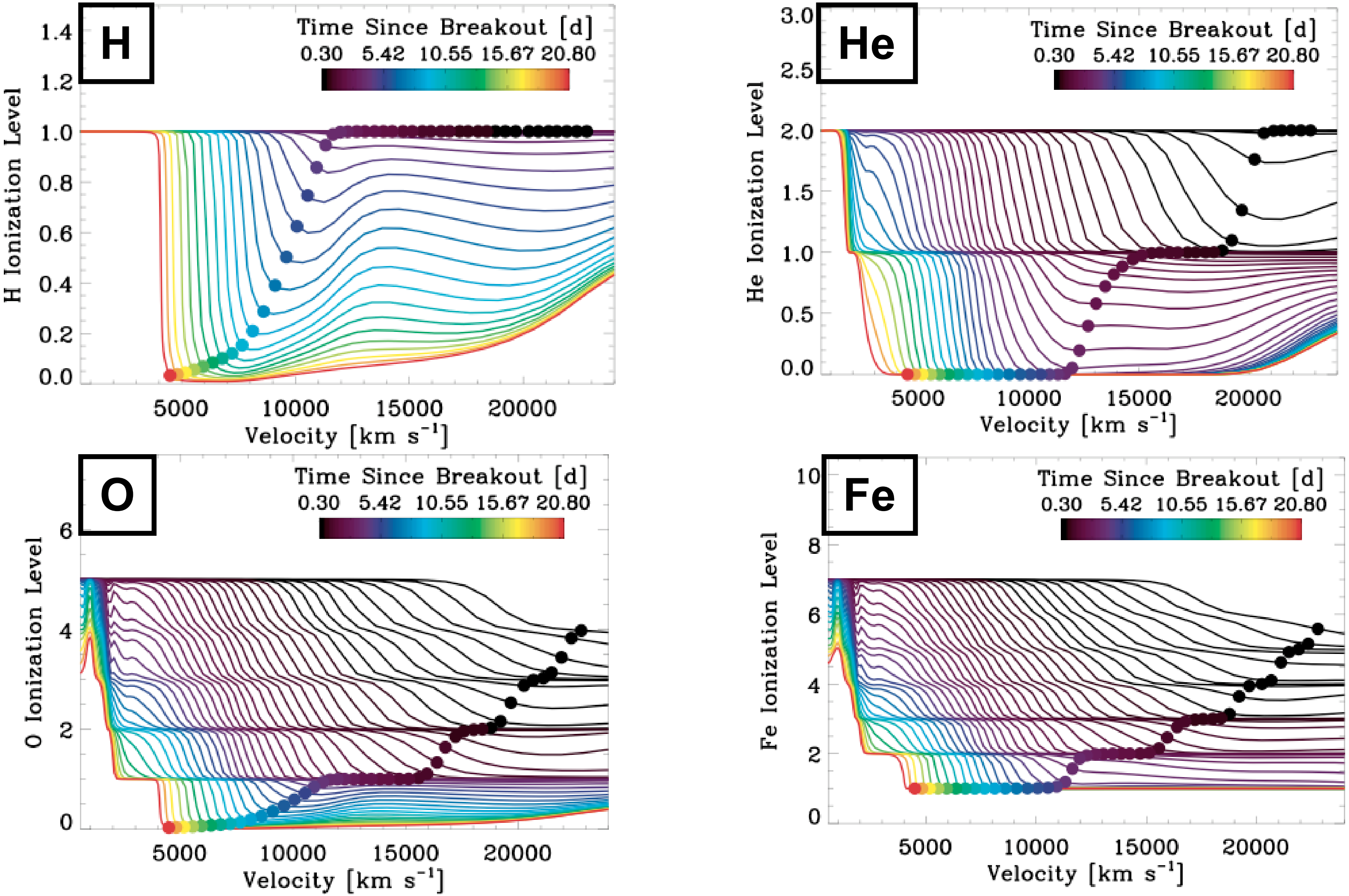
- CMFGEN passes a stringent set of tests, reproducing well the evolution of spectra and LCs of SN1987A.
- Outstanding problem with UV & B-band fluxes
- Reproduction of HI/HeI lines (H/He, non-LTE)
- Reproduction of line widths, e.g. Hα (E_{kin})
- No direct/indirect effect of ^{56}Ni/^{56}Co for initial 20 days
- No evidence for asymmetry at early times

But

- Pre-SN RSG models (generally?) too big or H/He too large. Discussion?
- Spectroscopy essential for inferring SNe II-P progenitor properties

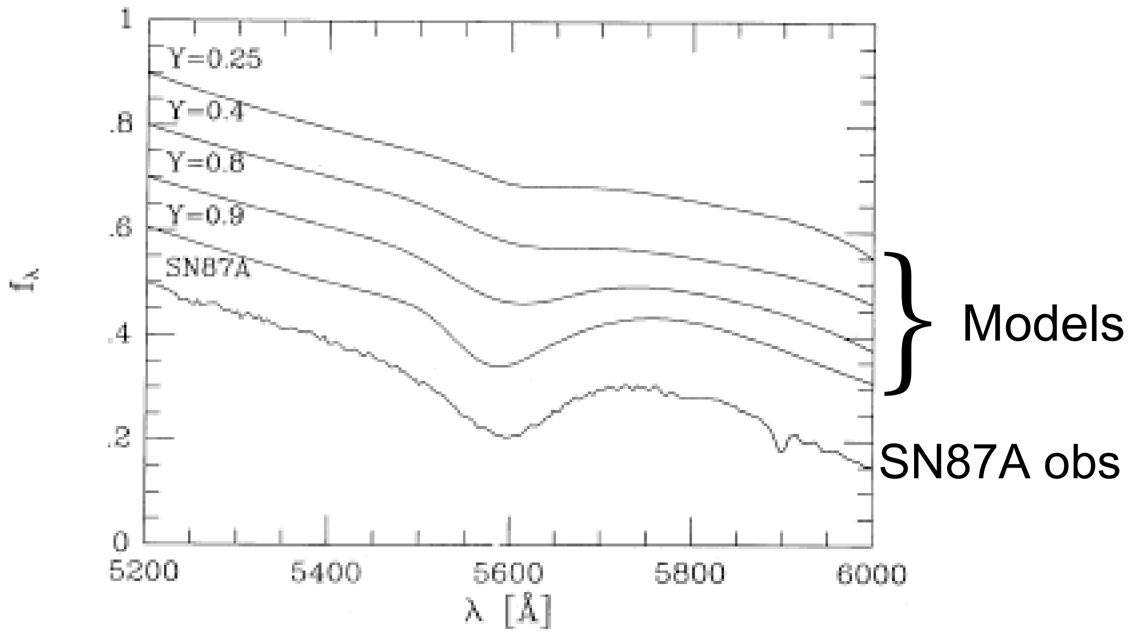
SN1987A: Strong ionization stratification

Stratification both in **composition** and **ionization**



Previous radiative-transfer studies of SN1987A

Eastman & Kirshner (1989): LTE & d/dt=0 approach
Unacceptable helium enrichments to fit HeI lines



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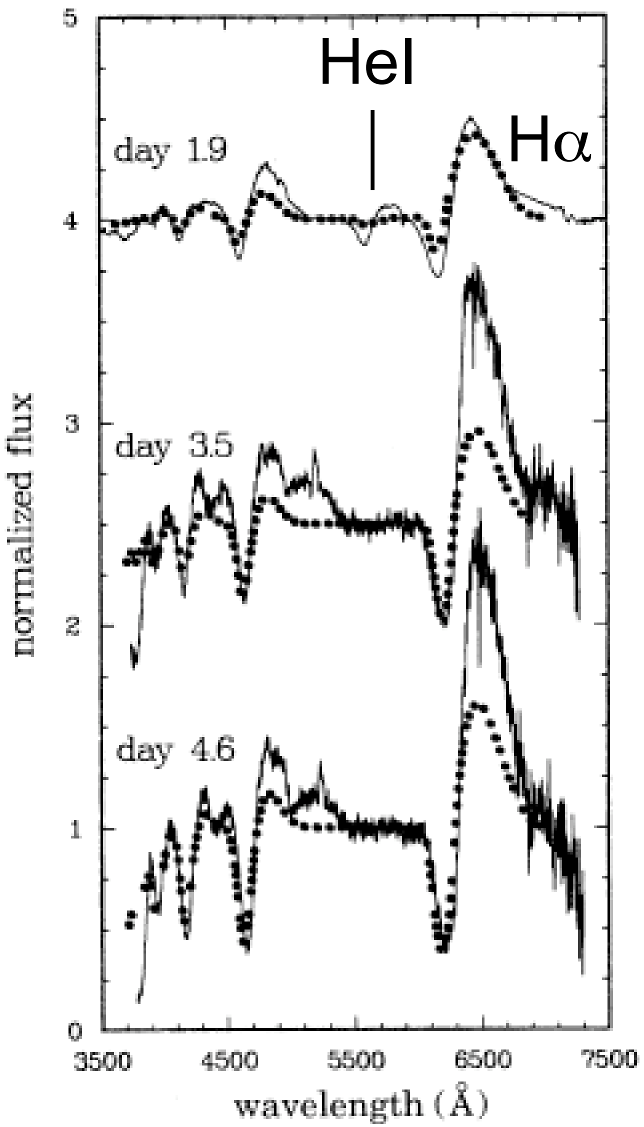

Schmutz et al. (1990)
quasi-LTE & d/dt=0 approach
Problem with HeI & HI line strength

Previous radiative-transfer studies of SN1987A

Utrobin & Chugai (2005)
non-LTE for H & de/dt≠0 & dn/dt≠0 approach
(coarse treatment of the radiation field)
=> Time-dependent ionization effects