1D non-LTE time-dependent radiative transfer of supernova ejecta with CMFGEN

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Long-term Goal:

- Design a radiative-transfer tool to model the interaction of radiation and matter in SN ejecta
- Limit to 1D to better focus on physics (e.g. non-LTE etc.)
- Treat all SN types , i.e. thermonuclear or gravitational collapse
- Start from physical input models
- Compute LC and spectra to compare with observations and constrain stellar evolution/explosion
- **CMFGEN** applied/tested for SNe II-pec, II-P, IIb, Ib, and Ic Dessart & Hillier (2005ab,06,08,10,11ab)
- Future work: Type Ia SNe

Synopsis

- Context
- Radiative-transfer issues: line blanketing & opacity, electron-scattering, non-LTE (HeI), time-dependence ($H\alpha$), decay energy & non-thermal processes
- **Steady-state model;** Dependencies
- **Time-dependent models**: LC and spectra for SNe II-pec, II-P, IIb, Ib, and Ic

Chronology of events in the life of a CCSN

- **1 sec**: Core collapse, bounce, shock revival
- **1 min to 1 day**: shock propagates and breaks out (1st EM signature). Fallback? NS vs. BH formation?
- At breakout: $E_{rad} \sim E_{kin}$; $E_{rad} >> E_{th}$; $\tau_{cont} \sim 10^6$
- **Mins to days**: Final ejecta acceleration to homology ($V \propto R$)
- **Ejecta properties: $E_{kin} \sim 10^{51}$erg, $M_{ejecta} \sim$ few $M_\odot$, $V_{exp} \sim 3000$km/s, $M(^{56}Ni) \sim 0.1 M_\odot$**

- **Generic** subsequent Evolution controlled by

  Cooling (Expansion & Radiative losses)

  versus Heating (Radioactive decay & Recombination).

  modulo Transport (dynamic radiative diffusion --- opacity/composition/ionization, dT/dr!)

  Their variations cause the diversity of CCSN Light Curves and Spectra

- **Weeks to months**: **Photospheric phase ($\tau >> 1$)**
- **After a (few) month(s)**: Transition to **Nebular phase ($\tau << 1$)**
- **$1\text{-}10^n$ years**: SNR, CSM interaction, light echoes

Modeling of Light Curves and Spectra: Some Features

- Radiative diffusion $\Rightarrow$ **Time-dependent Transport**, Energy/opacity problem
- Strong collisional proc. at depth $\Rightarrow$ LTE, blackbody SED
- Strong electron scattering $\Rightarrow$ **non-LTE** above R_{phot}, $J \neq B$, flux "dilution"
- Large radii $\Rightarrow$ photospheric density is low (weak collisions) $\Rightarrow$ non-LTE effects
- $\tau_{line} >> \tau_{cont}$ & Expansion $\Rightarrow$ P-Cygni profiles
- Large # of lines and large ejecta velocity $\Rightarrow$ Line overlap and blanketing
- Steep ρ and/or N_e distribution $\Rightarrow$ Line formation, low linear polarization
- High V, low $\rho \Rightarrow t_{rec} \sim R/V \Rightarrow$ time-dependent effects (UC05, DH08)
- γ-rays $\Rightarrow$ High-energy e^- $\Rightarrow$ Non-thermal effects (Lucy 1991)

Non-LTE Time-Dependent Radiative Transfer Modeling with CMFGEN

Co-moving frame formulation for homogously-expanding ejecta (MKH75)

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:

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

1-D Non-LTE time-dependence using CMFGEN

(Hillier & Miller 1998; Dessart & Hillier 2005,2008, 2010,2011ab)

- Simultaneously solves the radiative-transfer equation in the CMF frame, the statistical-equilibrium and the energy equations; Fully implicit solver; partial linearization of SEE.
- **Accurate description of I/J/H**: moments of RTE with all important terms in v/c, $\partial/\partial t$, $\partial/\partial \nu$,$\partial/\partial \mu$, $\partial/\partial r$
- RTE solved for at **~10^5 frequency points** (with coupling). Coverage: ~10A to ~5μm
- **Detailed description of the gas**: 25 species & 15 ionization stages. **Non-LTE ionization**
- **Large model atom**: few 10000 levels and few 100000 transitions.
- Approximation: Use of **Super-Levels.** Easy check on approx by switching to full levels.
- **Non-LTE**: All important radiative + collisional rates included **explicitly**.
- **Non-LTE line blanketing:** All continuum and line opacity sources included explicitly
- Time-dependent terms in SEE ⇒ Time-Dependent Ionization
- Solution of Spencer-Fano equation for **non-thermal heating/ionization/excitation rates**
- **Adaptive grid**: ~7 pts per τ-decade at each time (asset over hydro: mass grid); $\tau \in$ **[10^{-8} to 10^6]**

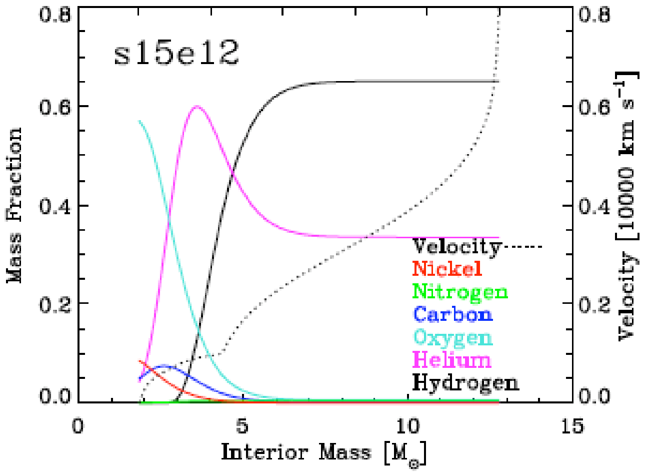
1-D Non-LTE time-dependence using CMFGEN

(Hillier & Miller 1998; Dessart & Hillier 2005,2008, 2010ab)

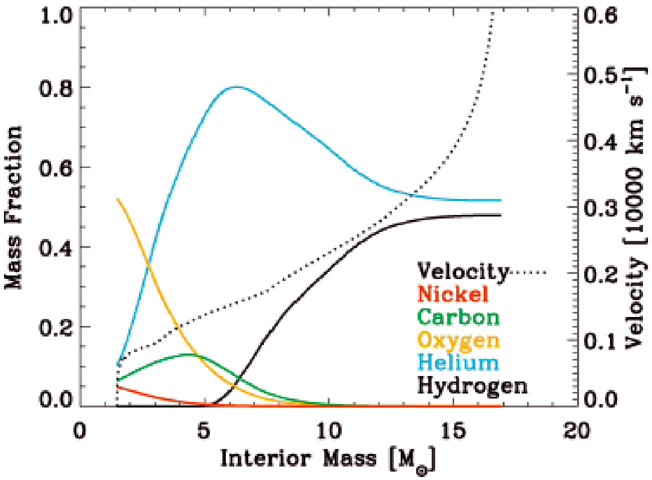
- **Physical consistency**: stellar-evolution + hydro input: X_i(m), T(m), ρ(m), v(m) r(m)

  => use SN light to constrain pre-SN evolution and explosion
- **Full-ejecta simulation**, e.g. no "artificial" boundary conditions, X_i stratification
- **Decay energy:** Computed with Monte Carlo γ-ray transport code (**local or non-local**)
- Model requires **~5-10Gb**, i.e. (NT=2000) x (ND=100) x (NBNDS+1=4) x 8
- Time step: Δt = 0.1t => 45-50 steps to go from 0.3 to 21d, or 10 to 1000d => 3 months!

SN II-P



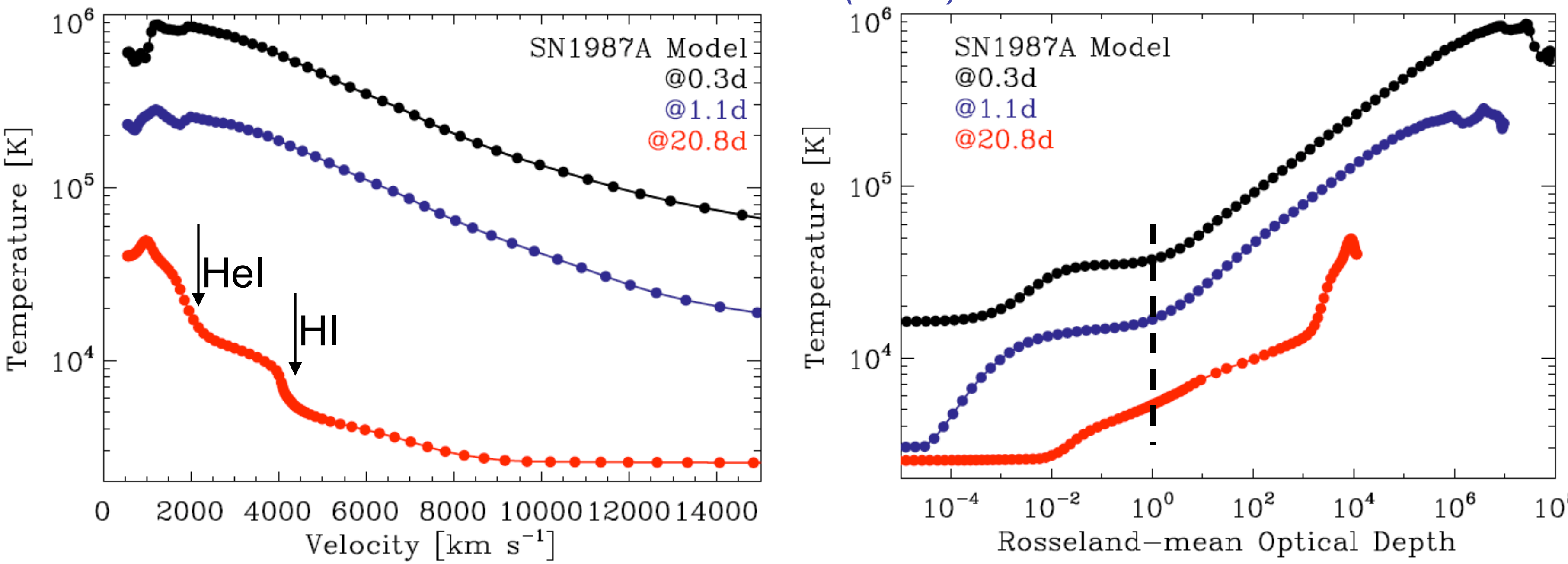
SN1987A



Spatial grid

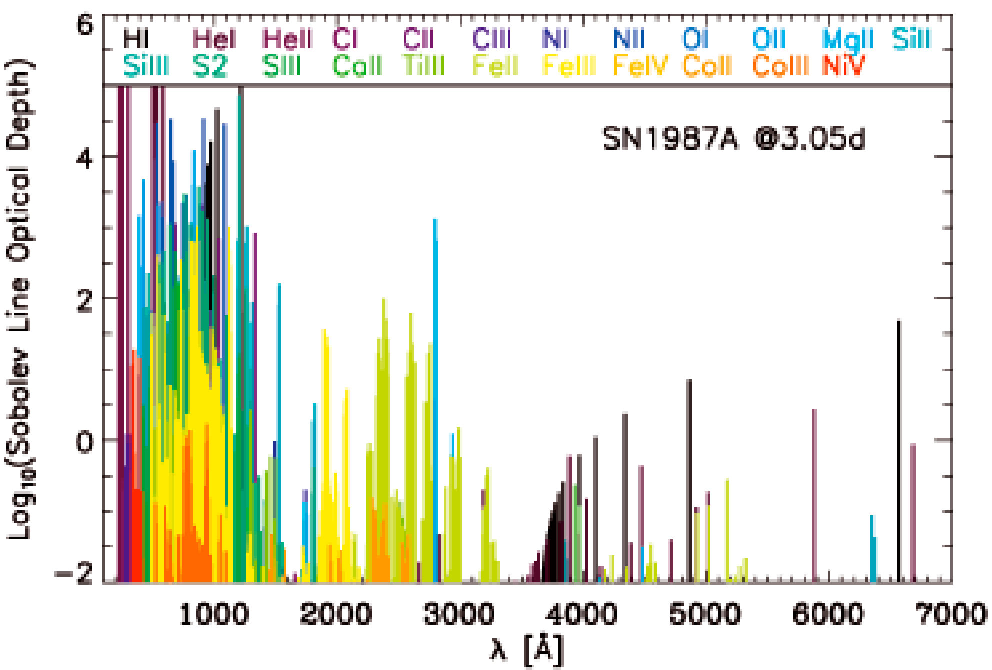
- ✓ Use optical-depth scale, not mass scale (e.g. hydro code)
- ✓ Good resolution of photosphere; **Eddington factors 1/3 →1**
- ✓ Naturally adjusts to resolve recombination fronts
- ✓ Converged results with ~100 depth points.

Dessart & Hillier (2010)



Model atom --- Line Blanketing

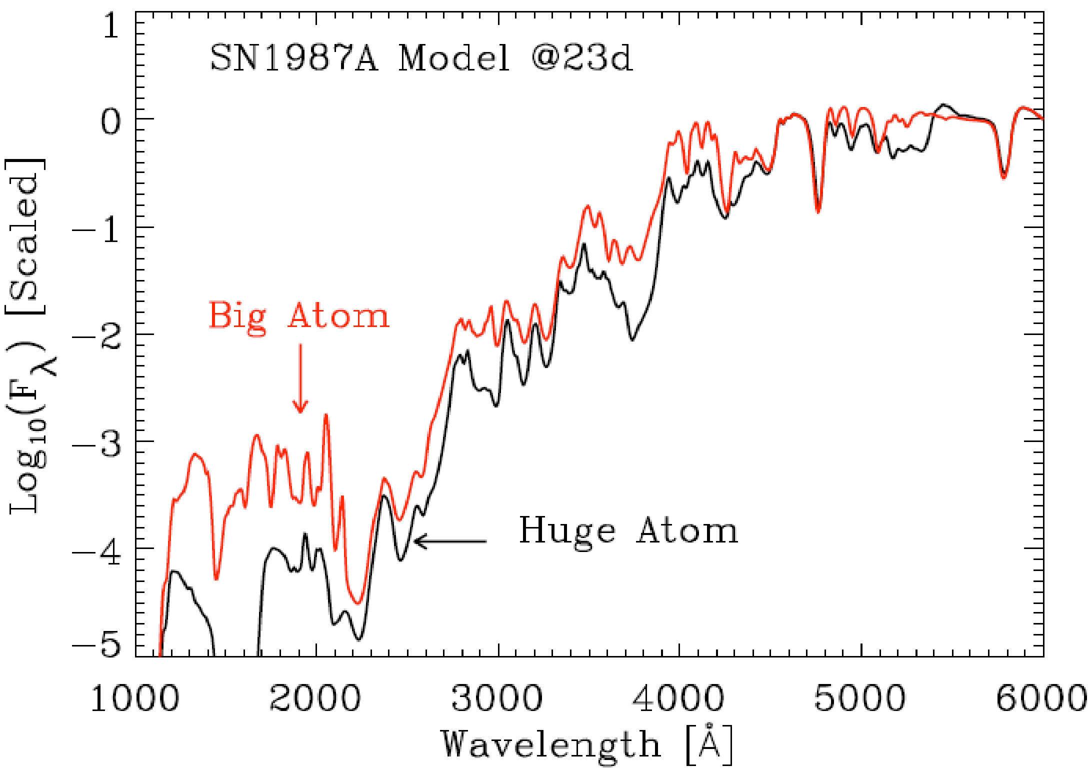
- Many species: H, He, CNO, IME, IGE
- Many ions (I-VII) treated simultaneously
- Huge model atom to account for all species/ions and sources of opacities (lines and continuum).
- Sources of atomic data: Opacity project etc. **Essential.**
- In non-LTE, need for all rates (radiative & collisional)
- Strong line blanketing



Species	N_f	N_s	N_{trans}	Ref	Details
H I	30	20	435		$n \leqslant 30$
He I	51	40	374		$n \leqslant$ 11TRP
He II	30	13	435		$n \leqslant 30$
C I	26	14	120		$n \leqslant 2s2p^3\ {}^3P_0$
C II	26	14	87		$n \leqslant 2s2s4d^2D_{5/2}$
C III	112	62	891		$n \leqslant 2s8f^1Fo$
C IV	64	59	1446		$n \leqslant 30$
N I	104	44	855		$n \leqslant 5f^2Fo$
N II	41	23	144		$n \leqslant 2p^3d^1P_1$
O I	51	19	214		$n \leqslant 2s^22p^3\ {}^4S\ 4f\ {}^3F_3$
O II	111	30	1157		$n \leqslant 2s^22p^2\ {}^3P\ 4d^2D_{5/2}$
O III	86	50	646		$n \leqslant 2p^4f^1D$
O IV	72	53	835		$n \leqslant 2p^2p^3p^2P$
O V	78	41	523		$n \leqslant 2s5f^1Fo_3$
Na I	71	22	1614		$n \leqslant$ 30w2W
Mg II	65	22	1452		$n \leqslant$ 30w2W
Si II	59	31	354		$n \leqslant 3s^2\ {}^1S\ 7g^2G_{7/2}$
Si III	61	33	310		$n \leqslant 3s5g^1Ge_4$
Si IV	48	37	405		$n \leqslant 10f^2Fo$
S II	324	56	8208		$n \leqslant 3s3p^3\ {}^5S\ 4p^6P$
S III	98	48	837		$n \leqslant 3s3p^2\ {}^2D\ 3d\ {}^3P$
S IV	67	27	396		$n \leqslant 3s3p\ {}^3P\ 4p^2D_{5/2}$
Ca II	77	21	1736		$n \leqslant 3p^6$ 30w2W
Ti II	152	37	3134		$n \leqslant 3d^2\ {}^3F\ 5p^4D_{7/2}$
Ti III	206	33	4735		$n \leqslant 3d^6f^3Ho_6$
Fe II	115	50	1437		$n \leqslant 3d^6\ {}^1G1\ 4sd^2G_{7/2}$
Fe III	477	61	6496		$n \leqslant 3d^5\ {}^4F\ 5s^5Fe_1$
Fe IV	294	51	8068		$n \leqslant 3d^4\ {}^5D\ 4d^4G_{5/2}$
Fe V	191	47	3977		$n \leqslant 3d^3\ {}^4F\ 4d^5Fe_3$
Fe VI	433	44	14103		$n \leqslant 3p5\ {}^2P\ 3d^4\ {}^1S\ {}^2Pc_{3/2}$
Fe VII	153	29	1753		$n \leqslant 3p5\ {}^2P\ 3d^3\ b^2D\ {}^1P_1$
Co II	144	34	2088		$n \leqslant 3d^6\ {}^5D\ 4s4p\ {}^7Do_1$
Co III	361	37	10937		$n \leqslant 3d^6\ {}^5D\ 5p^4P_{3/2}$
Co IV	314	37	8684		$n \leqslant 3d^5\ {}^2P\ 4p\ {}^3P_1$
Co V	387	32	13605		$n \leqslant 3d^4\ {}^3F\ 4d^2H_{9/2}$
Co VI	323	23	9608		$n \leqslant 3d^3\ {}^2D\ 4d\ {}^1S_0$
Co VII	319	31	9096		$n \leqslant 3p5\ {}^2P\ d^4\ {}^3F\ {}^2D_{3/2}$
Ni V	183	46	3065		$n \leqslant 3d^5\ {}^2D3\ 4p\ {}^3F_3$
Ni VI	314	37	9569		$n \leqslant 3d^4\ {}^5D\ 4d^4F_{9/2}$
Ni VII	308	37	9225		$n \leqslant 3d^3\ {}^2D\ 4d\ {}^3P_2$
	6426		143054		

Model atom --- Line Blanketing

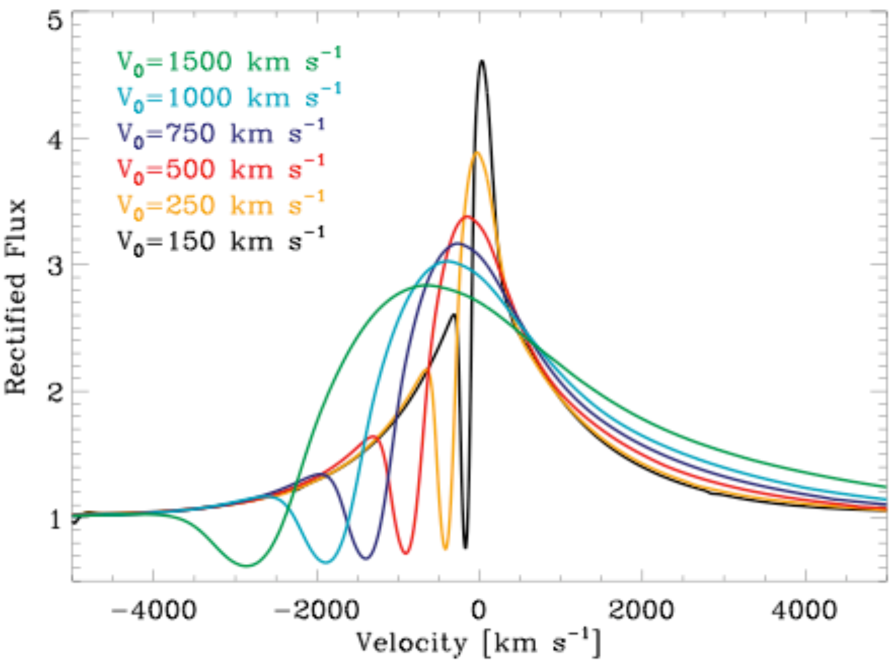
- Difficult to obtain converged results, especially in UV, UB bands
- Accuracy of atomic data?
- Illustration for importance of FeI, NiII and larger FeII model (big → huge atom)



Effects associated with Electron-scattering: Frequency redistribution

- photon scattering with free electrons causes frequency redistribution
- **Non-coherent scattering** in CMF caused by the thermal motion of scatterers: $V_{thermal}$
- **Coherent scattering** in CMF due to expansion, **Redshift** in Observer's frame: $V_{expansion}$
- $\mathbf{V_{expansion} > V_{thermal}}$ ⇒ the redshift dominates: P-Cygni profile with enhanced red-wing flux
- $\mathbf{V_{expansion} < V_{thermal}}$ ⇒ non-coherent redshift/blueshift dominates: Symmetric profile (SNe IIn)

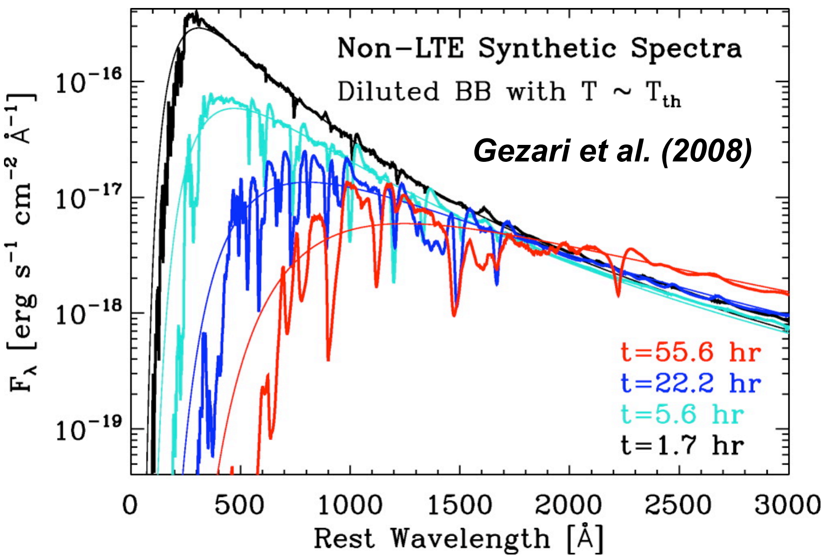
Effect of varying V_{phot} on Hα morphology



Electron-scattering: Flux ‘’Dilution’’

Mihalas book; Dessart & Hillier (2005b)

- Scattering-dominated atmosphere => $\kappa << \sigma$ => $\lambda = \kappa / (\kappa + \sigma) << 1$
- Eddington Approximation and $dB/d\tau$ =const. => Flux $\propto 2\sqrt{\lambda}\ B(\tau=1/\sqrt{3\lambda})$
  - -> $\tau=1/\sqrt{3\lambda}$: thermalization depth
  - -> $2\sqrt{\lambda}$: Factor of “dilution” (<<1)
- Introduce of ‘’dilution’’ factor ξ: $\mathbf{F_{obs} = (\xi R_{phot}/D)^2\ \pi\ B_\nu(T_C)}$; (R_{phot} -> ξR_{phot})

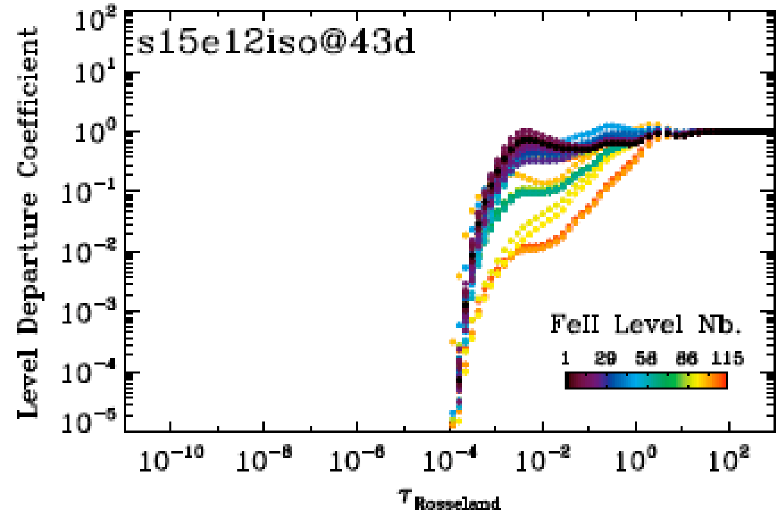


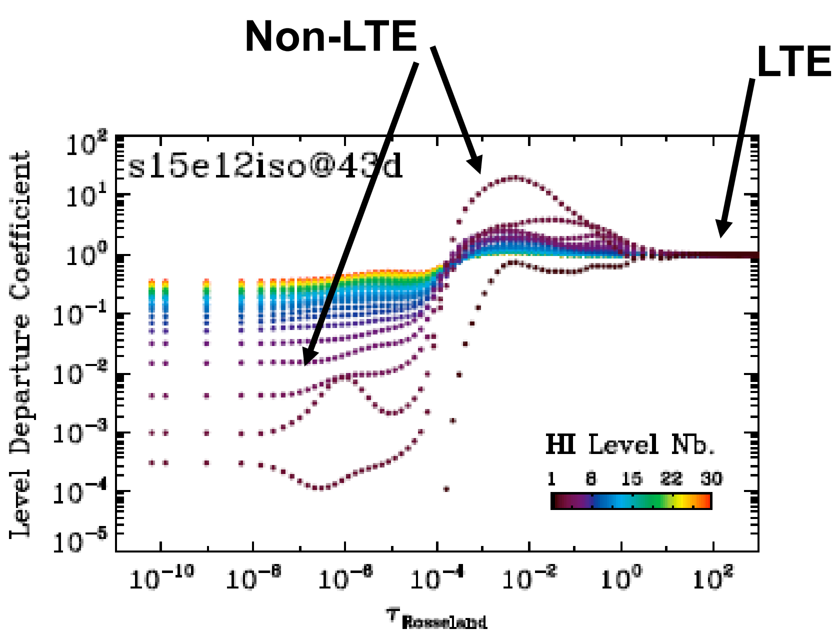
Example with early post-breakout models: SEDs fitted with $B(T_{th})$ and ξ~0.6

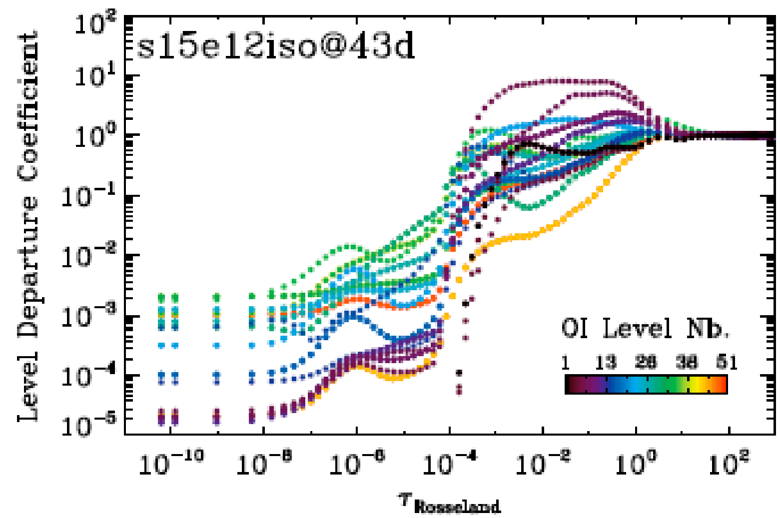
- Solution of the statistical-equilibrium equations using all collisional/radiative rates. About 2000 levels/ variables => Yields non-LTE level populations, ionization, line-blanketing
- High density => Strong collision & weak scattering => LTE
- Low density => weak collision: Dominance of scattering => Drives gas out of LTE
- Large departure coefficients in regions of $\tau<1$ **but we recover LTE at depth!**

Non-LTE effects

Dessart & Hillier (2011)

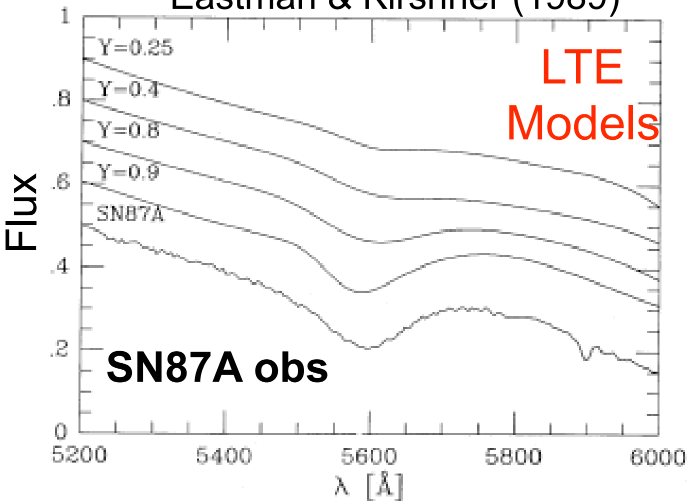






non-LTE effects: Influence on HeI lines at early times

Eastman & Kirshner (1989)

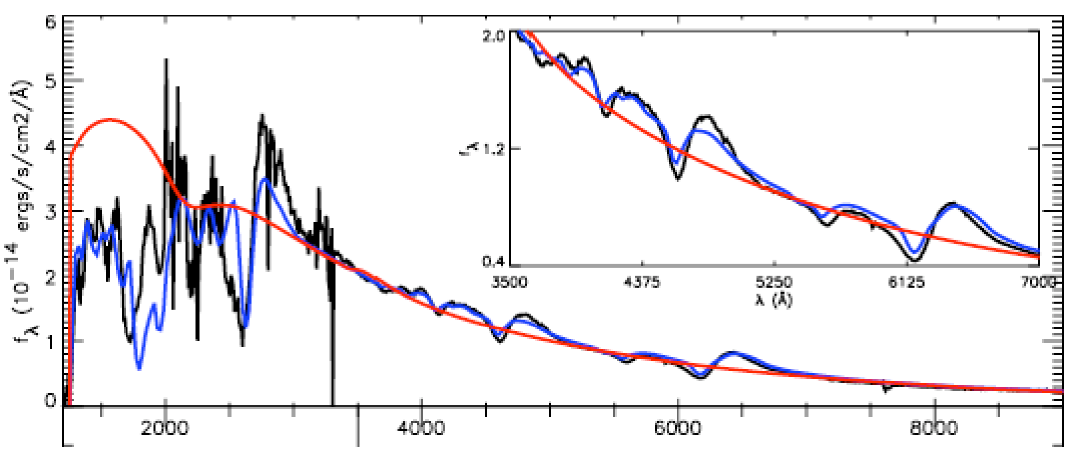


→ non-LTE: Account of radiative rates in the determinations of level populations

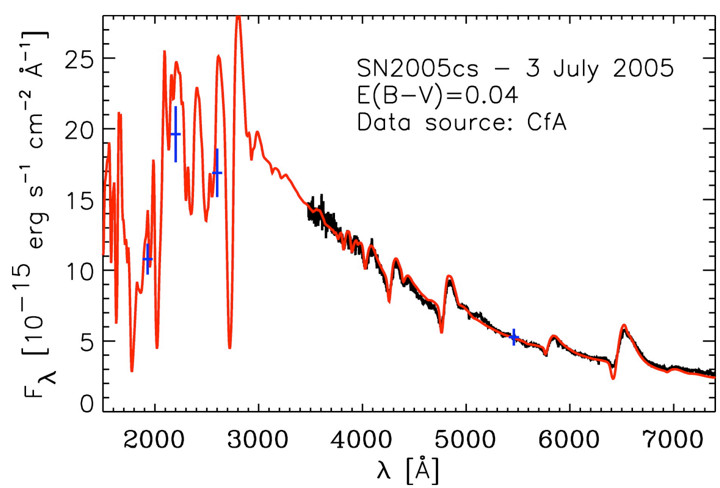
→ non-LTE allows good fit to HeI lines using a "standard" BSG/RSG He abundance **at early times**

⇒ non-LTE key for abundance determinations

Dessart & Hillier (2005): non-LTE model for SN87A

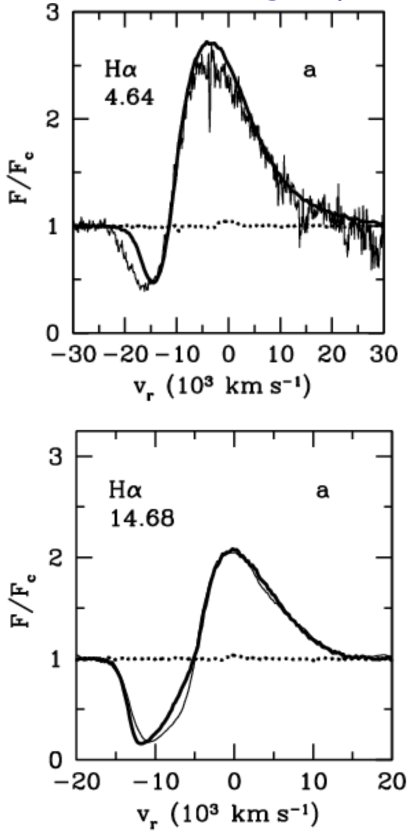


Dessart et al. (2008)
non-LTE model for 05cs

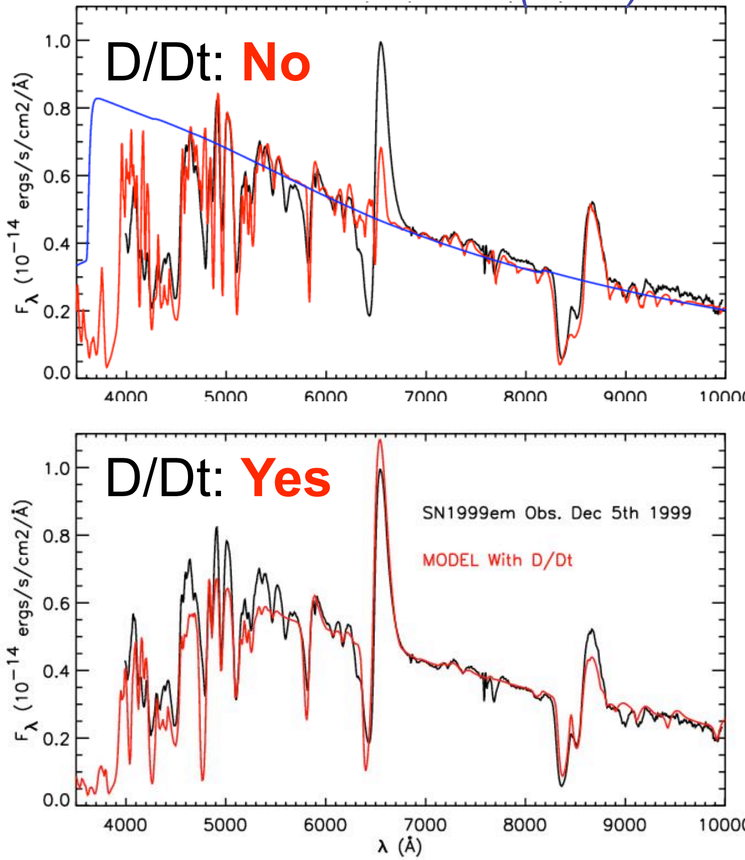


Spectral Modelling: time-dependent effects

Utrobin & Chugai (2005)



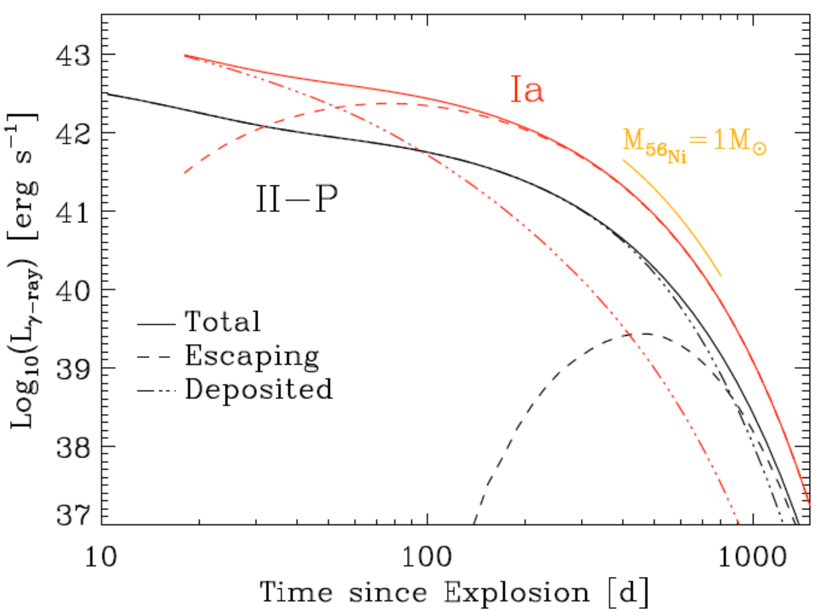
Dessart & Hillier (2008)

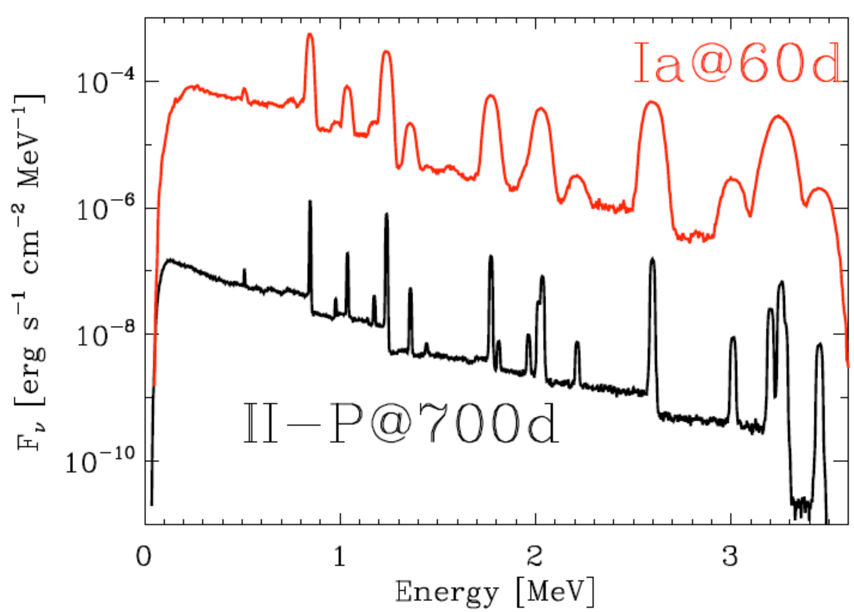


- High V, low $\rho \Rightarrow t_{rec} \sim R/V \Rightarrow$ time-dependent effects (UC05, DH08)
- Retain D/Dt terms in SSE and Energy equations
- Key to yield strong recombination lines **in the absence of Lyman/Balmer flux**
- Hα strength at rec. epoch sensitive to N_e rather than ρ profile

Treatment of Energy Deposition: γ-ray Monte-Carlo transport code

- 2-step decay chain: $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ ($\tau_{1/2}$=6.1 and 77.27d)
- β+ decay, electron capture ⇒ γ-rays, neutrinos, positrons, pairs
- Monte-Carlo code to follow γ-rays trough ejecta subject to Compton Scattering and photoelectric absorption
- **τ_γ>>1: assume local deposition as heat**. **τ_γ<1: non-local, non-thermal**

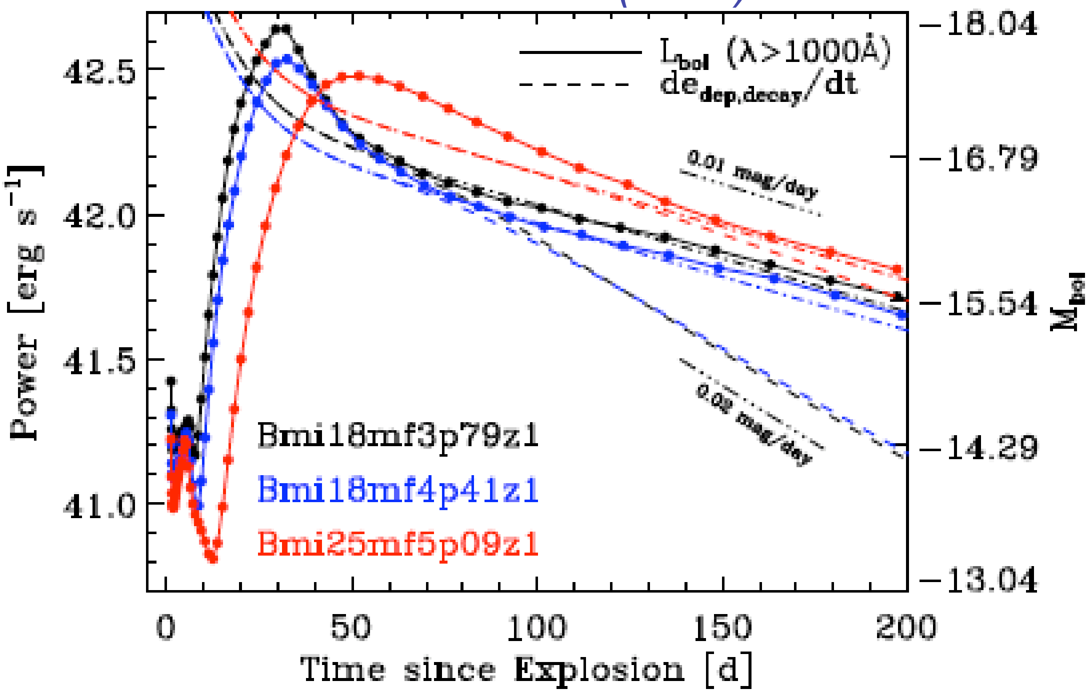




γ-ray escape and the nebular-phase decline rate

- Full γ-ray trapping in SNe II-P and II-pec up to ~700d
- γ-ray escape as early as ~50d in SNe IIb/Ib/Ic
- Key diagnostic of ejecta mass (insensitive to ionization issues)
- Fast-declining SNe IIb/Ib/Ic LCs points to low-mass progenitors

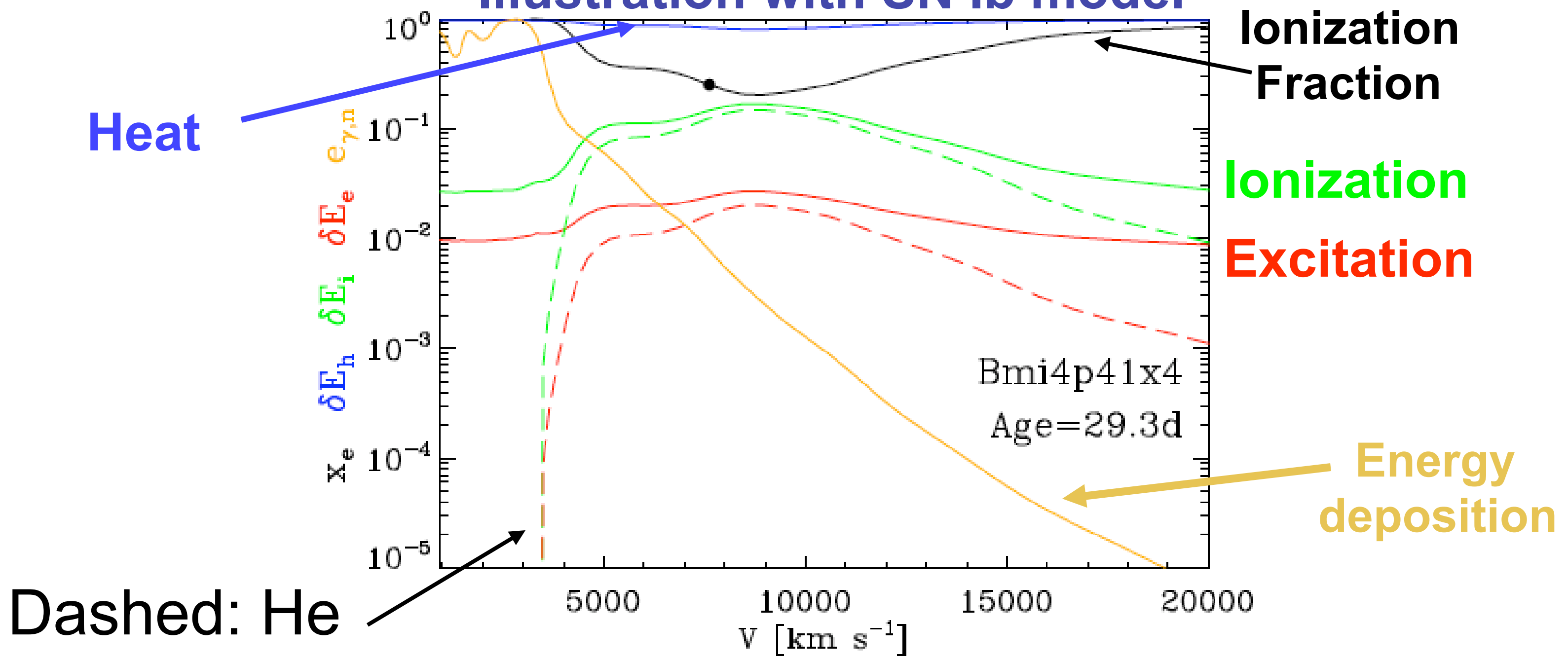
Dessart et al. (2011)



Non-thermal processes

- Solution of the Spencer-Fano Equation (1954) following Kozma & Fransson (1992)
- Determination of contribution to **heat** (thermal energy) and **ionization/excitation** (non-thermal) for all non-LTE atoms/ions/levels
- Treatment of corresponding terms in energy and SEE equations
- On/Off switch in CMFGEN
- Key property: **Non-thermal electrons deposit the bulk of their energy as heat**

Illustration with SN Ib model



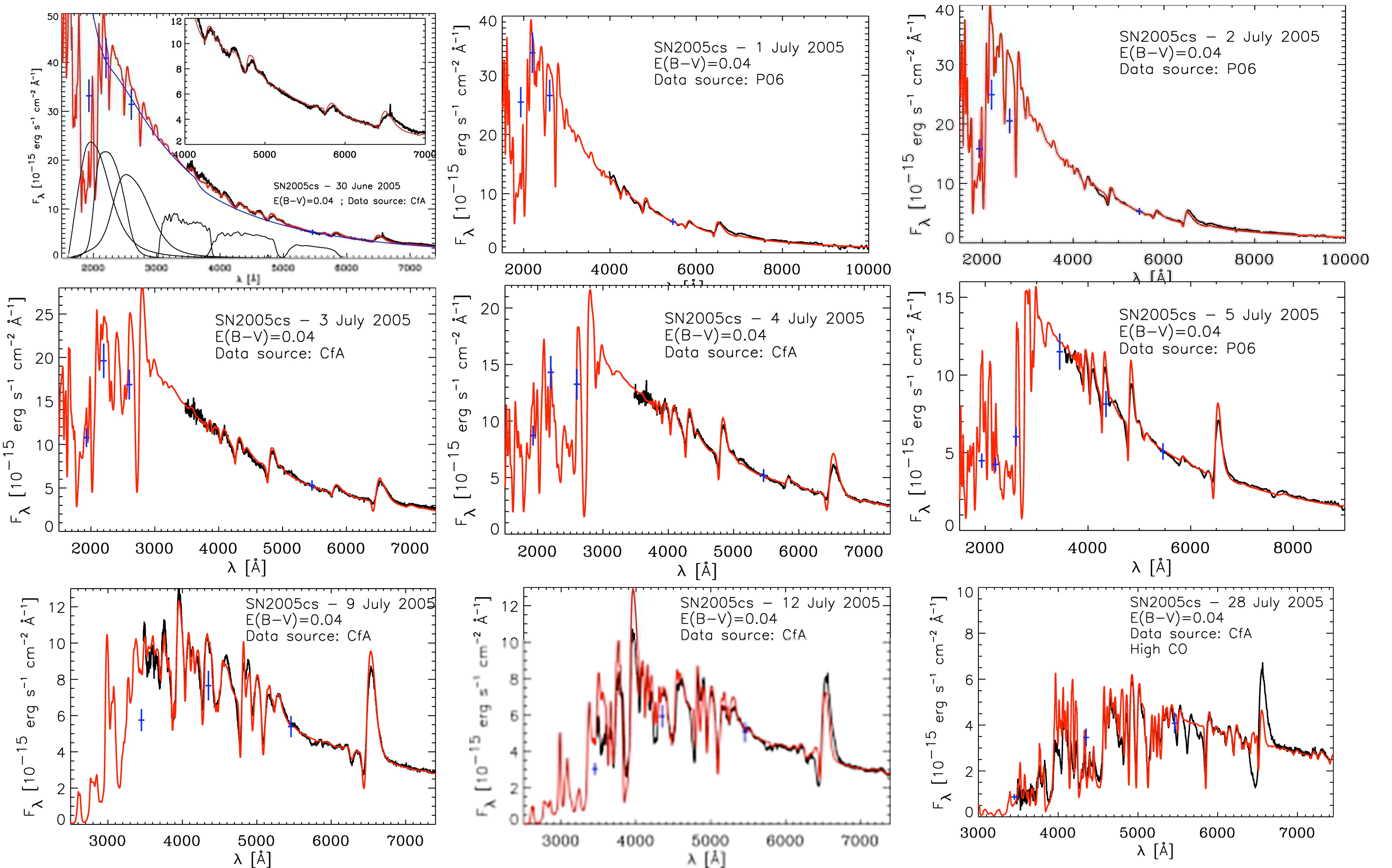
Illustrations with non-LTE Steady-state approach

1. Application to SNe II-P (SN2005cs)
2. Exploration on spectral dependencies

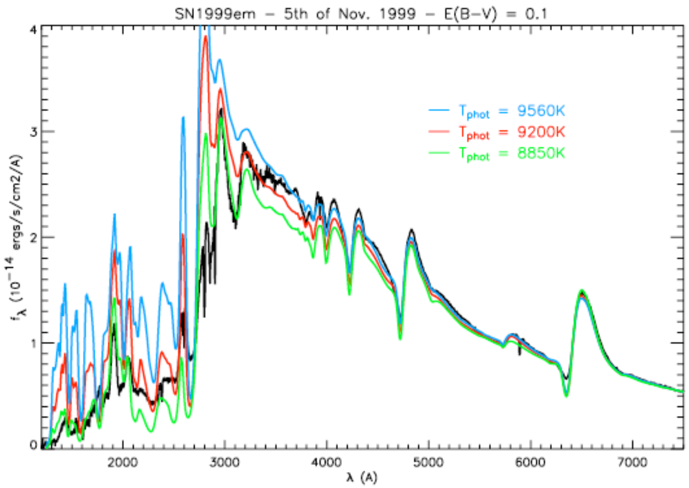
Non-LTE Steady State Approach

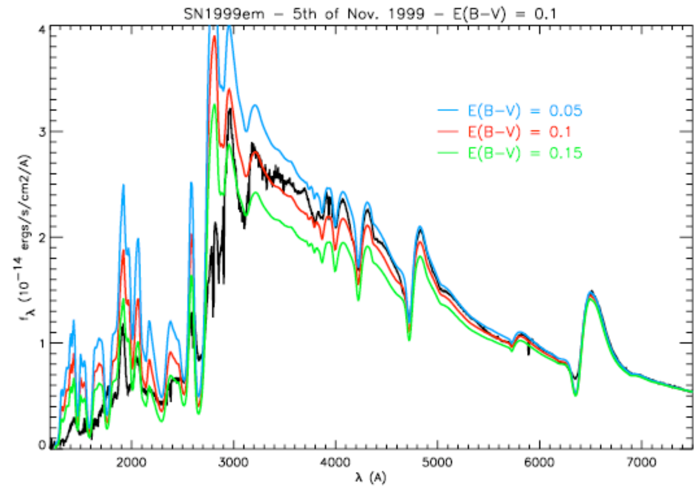
Application: Modeling of Young Type II SNe

The case of the Type II-P SN 2005cs in NGC 5194 (Dessart et al. 2008)



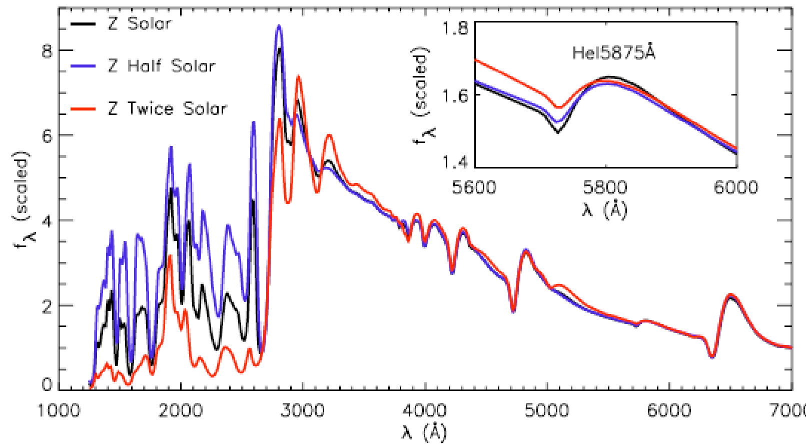
SN II-P spectra: Dependencies

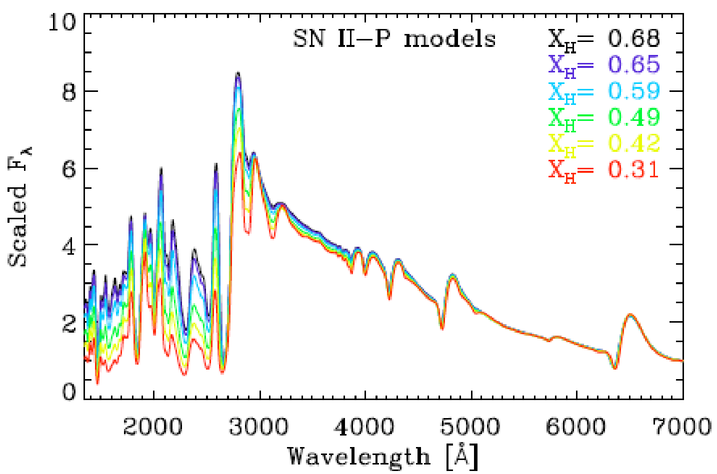


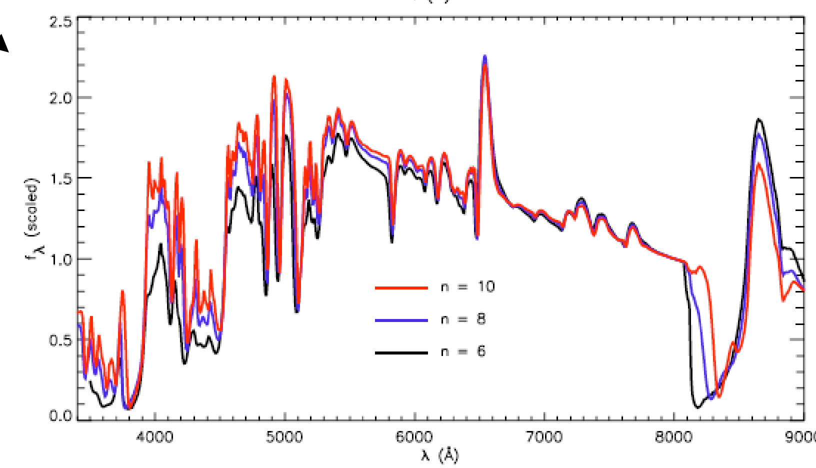


Degenerate effect of E(B-V) and T. **Use lines**

- Z modulates metal-line blanketing
- $\rho(v)$ modulates τ_{line} and τ_{cont}
- H/He in SN II-P: influences UV flux but HI lines poorly sensitive







1D Non-LTE Time-Dependent Radiative Transfer of Supernova Ejecta with CMFGEN: Results

Dessart & Hillier 2010,2011; Dessart et al. 2011ab

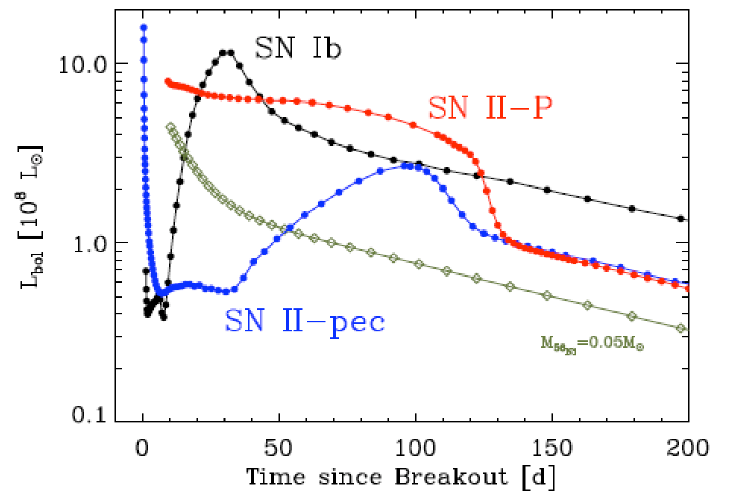
1. SN II-pec (87A): evolution from 0.3 to 21d of BSG-progenitor model lm18a7Ad (Woosley, priv. comm.)
2. SN II-P: evolution from 10 to 1000d of 1.2B explosion of 15 and 25$M_{\odot}$ RSG progenitors.
3. SNe IIb/Ib/Ic: evolution from 1 to 100d of 1.2B explosion of (quasi) hydrogen-less cores produced from binary-star evolution (Yoon et al. 2010).

Light-curve evolution of SNe II-P, II-pec, Ib: Radiative-transfer simulations on full ejecta using physical input models

Inputs

(DH10,DH11a; Dessart et al. 2011)

	pre-SN Star	M_* $[M_\odot]$	R_* $[R_\odot]$	M_{ejecta} $[M_\odot]$	E_{expl} [B]	$M_{^{56}Ni}$ $[M_\odot]$
SN II-P	RSG	15 (single)	830	10.9	1.2	0.08
SN II-pec (87A)	BSG	18 (single)	47	15.6	1.2	0.08
SN Ib	WN	25 (binary)	10	3.6	1.2	0.24



- Rapid fading after shock breakout
- Post-breakout plateau: $L_{Plateau}$ function of R_*
- Possible re-brightening from $^{56}Ni/^{56}Co$ decay. Delay function of mixing.
- High-brightness phase function of M_* (large τ), R_* (cooling), $M_{^{56}Ni}$ (heating)
- Transition to nebular phase when $\tau \sim 1$; $L_{nebular}$ function of $M_{^{56}Ni}$ and γ-ray trapping
- Not considered: binary (Kasen 2010) or CSM interaction, Magnetar radiation (Maeda et al. 07)

Confrontation of simulations to observations => M_*, R_*, E_{expl}, ^{56}Ni

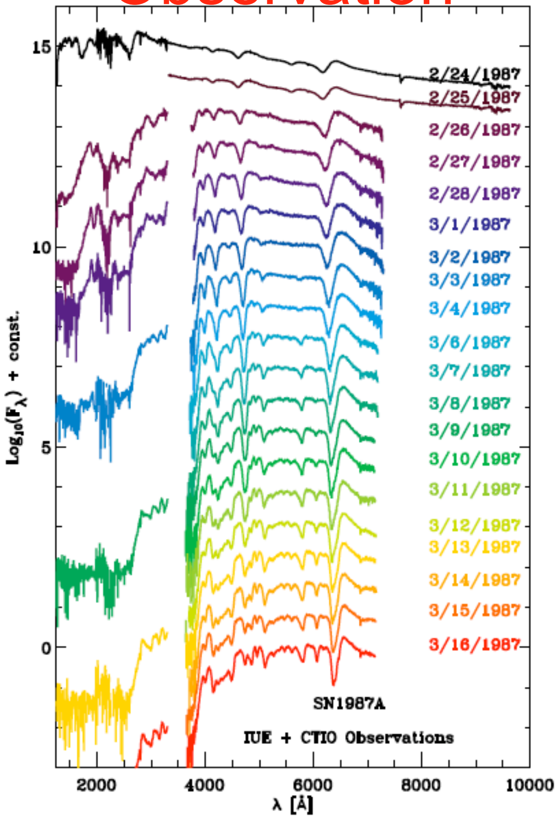
LCs are degenerate/ambiguous: confusion Ia/b/c, difference M_* & M_{ejecta} etc.

Comparison to observations of SN1987A

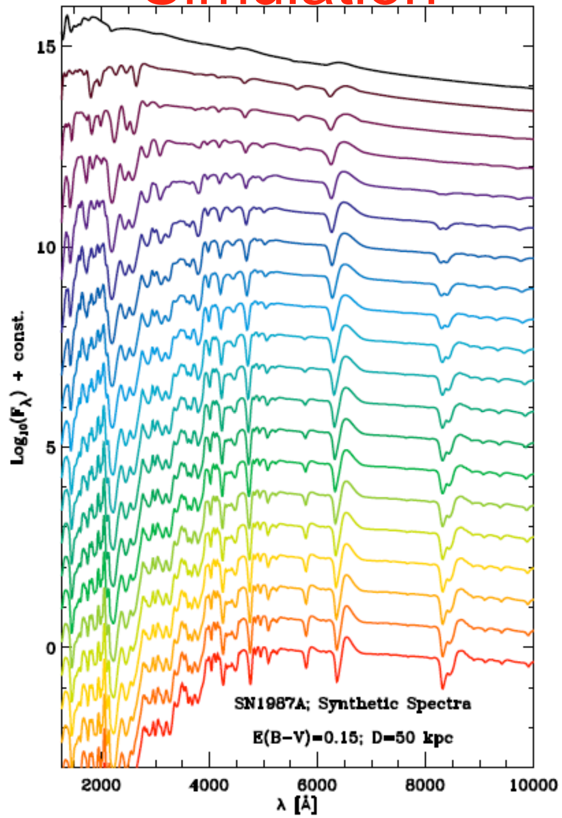
Agreement at 10% level except in the blue (opacity issue)

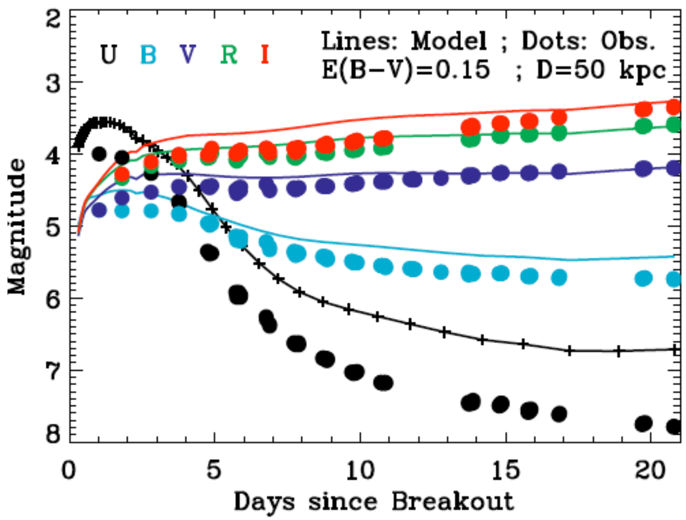
Supports $18M_\odot$ BSG progenitor, R_*~$50R_\odot$, and E_{expl}~1.2B

Observation



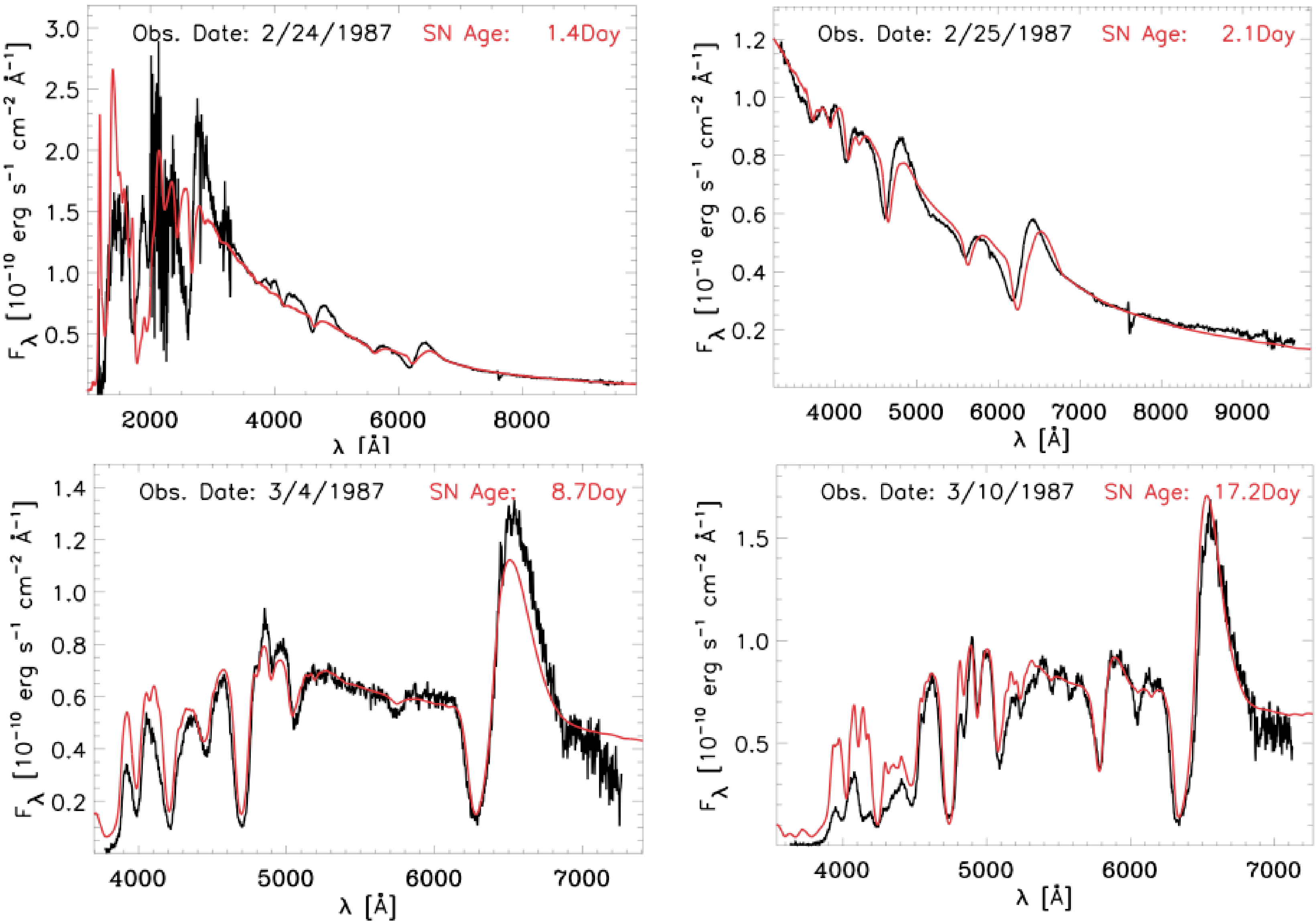
Simulation





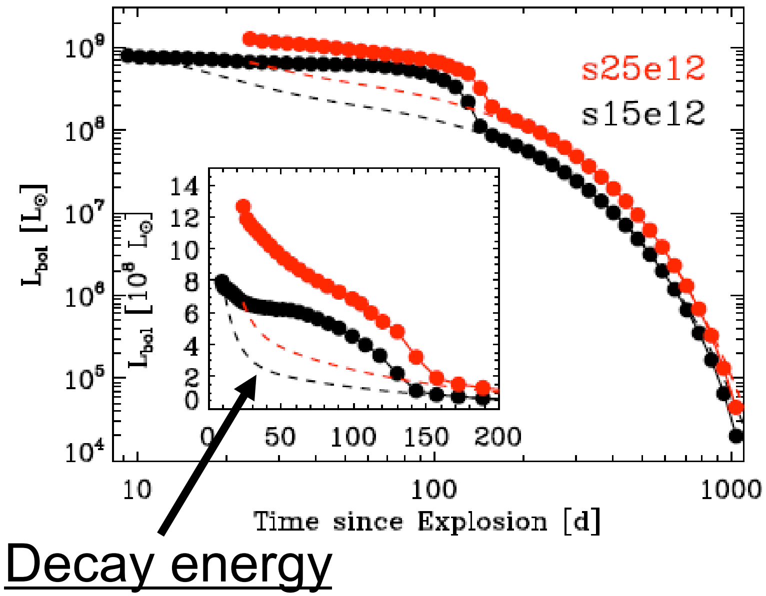
Dessart & Hillier (2010a)

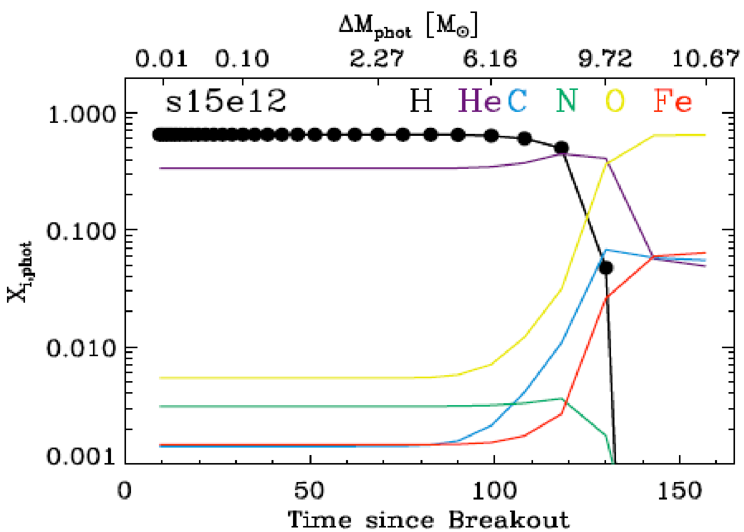
Comparison with SN1987A spectra

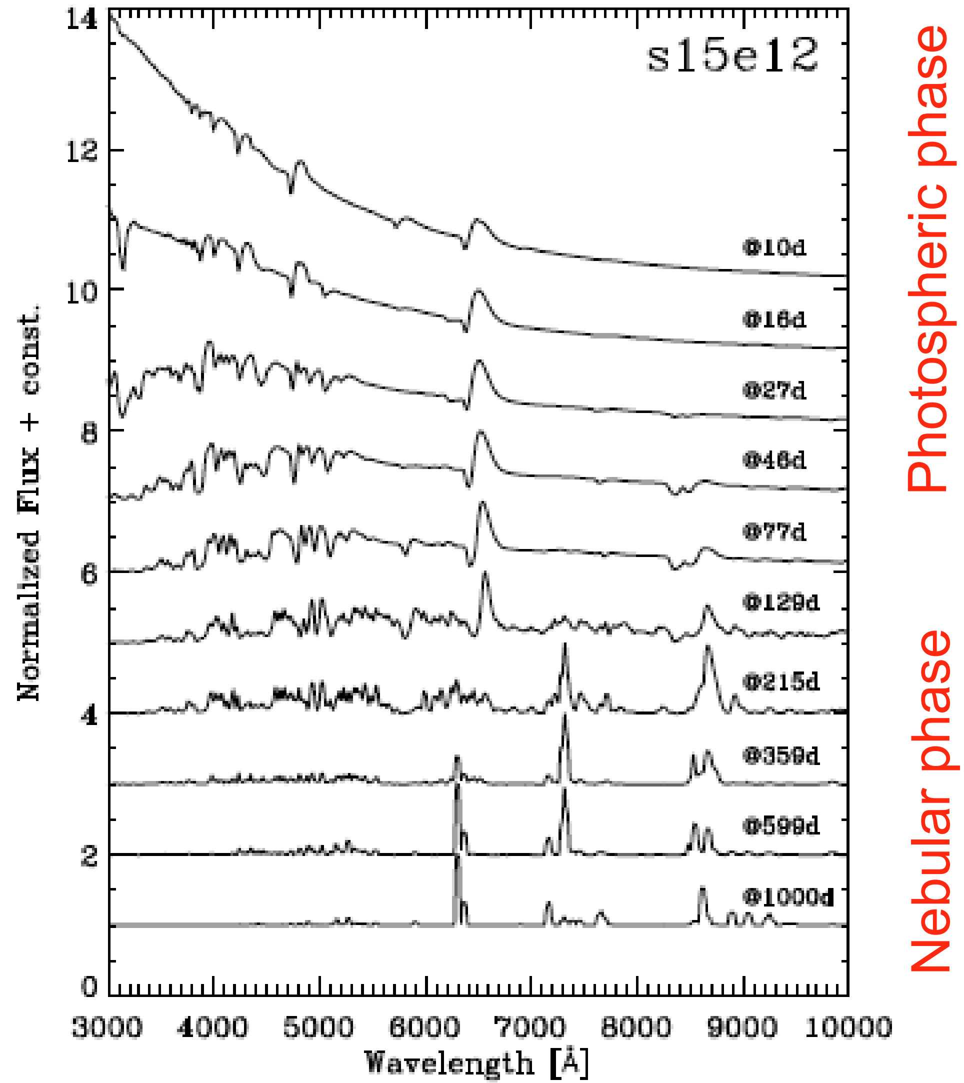


Simulations of SNe II-P based on 15 and 25$M_\odot$ progenitor stars

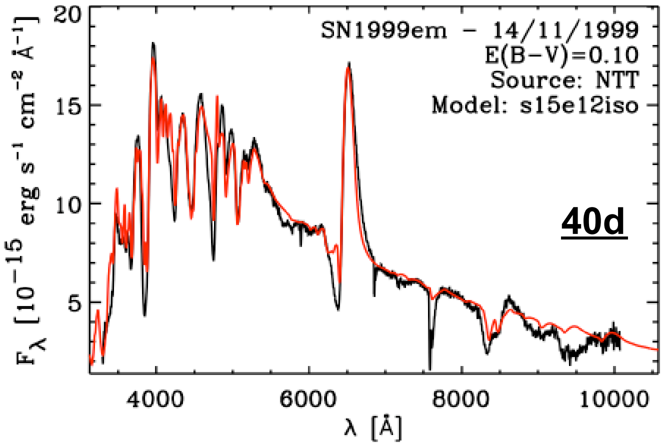
Dessart & Hillier (2011)



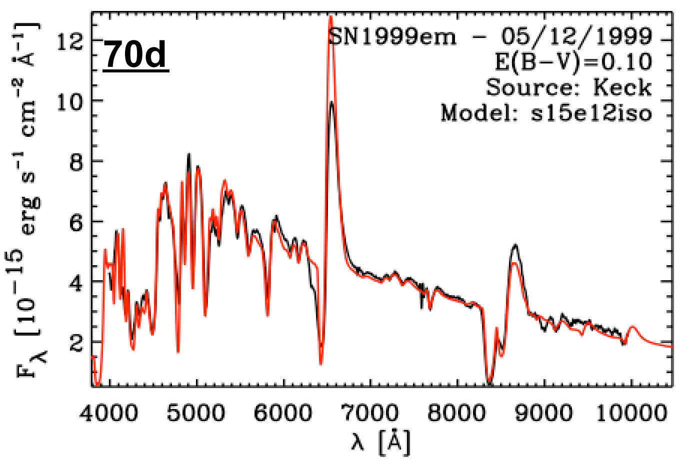


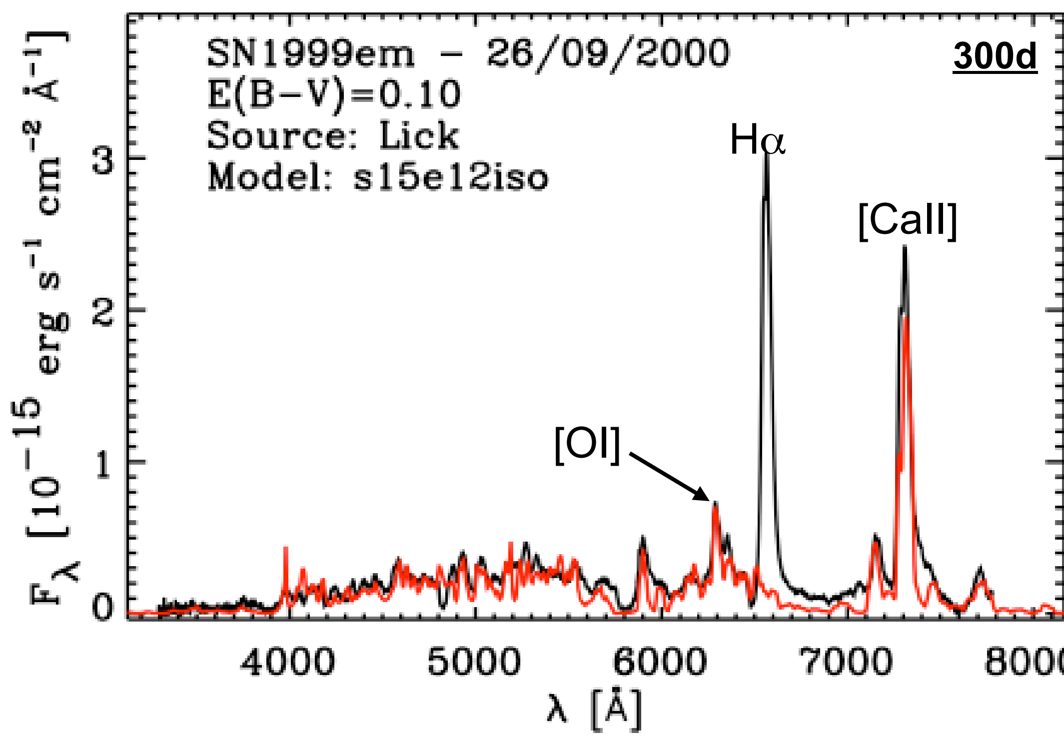


Comparison to SN 1999em (II-P) spectra



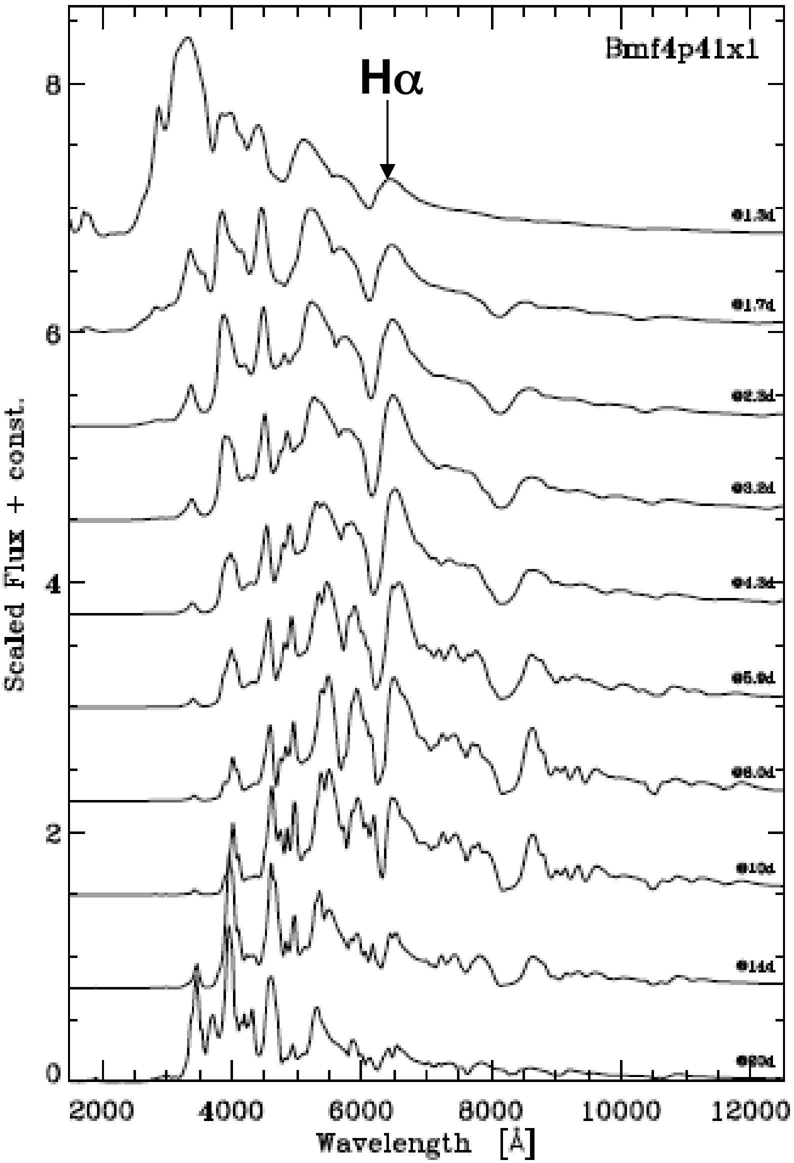
- General agreement at all times
- Specific disagreement with Hα at nebular times: neglect of non-thermal processes
- [OI]: important line from He-core oxygen





Simulations of SNe IIb based on binary-star evolution models

Dessart et al. (2011)



- Binary-star progenitor model
- $M_* = 18 M_\odot$, $R_* = 12 R_\odot$; $M_{ejecta} = 2.91 M_\odot$
- $M(He) = 1.63\ M_\odot$, $M(H) = 0.006 M_\odot$,
- $X(H) = 0.05$ at 50000 km/s
- $X(H) < 0.001$ at 10000 km/s
- $M(^{56}Ni) = 0.18 M_\odot$ (unmixed); **thermal processes only**

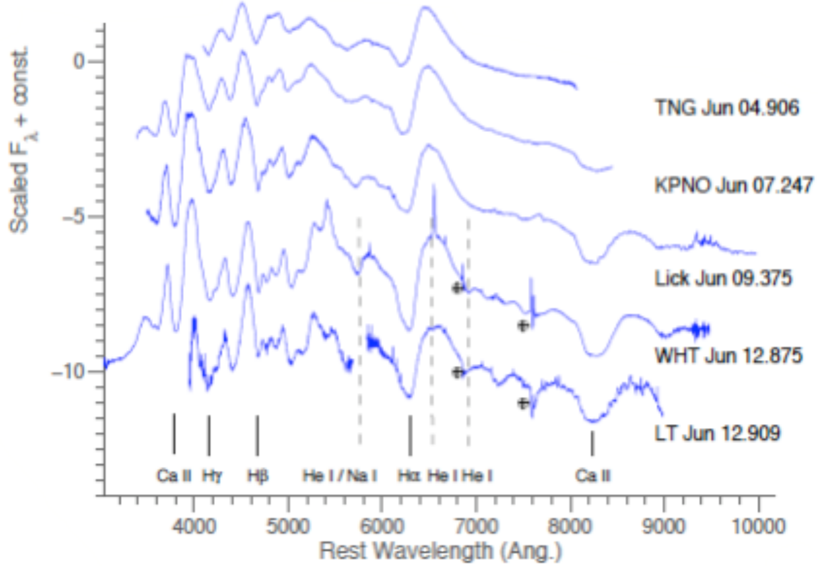
Results

- Hα present for ~20 days, HeI lines for ~10d
- Hα present for X(H) as low as 0.01
- Non-LTE time-dependent effects are key
- Non-thermal effects irrelevant/unlikely for Hα
- If fast LC + HI lines ⇒ low-mass ejecta & prog. because of He-core structure

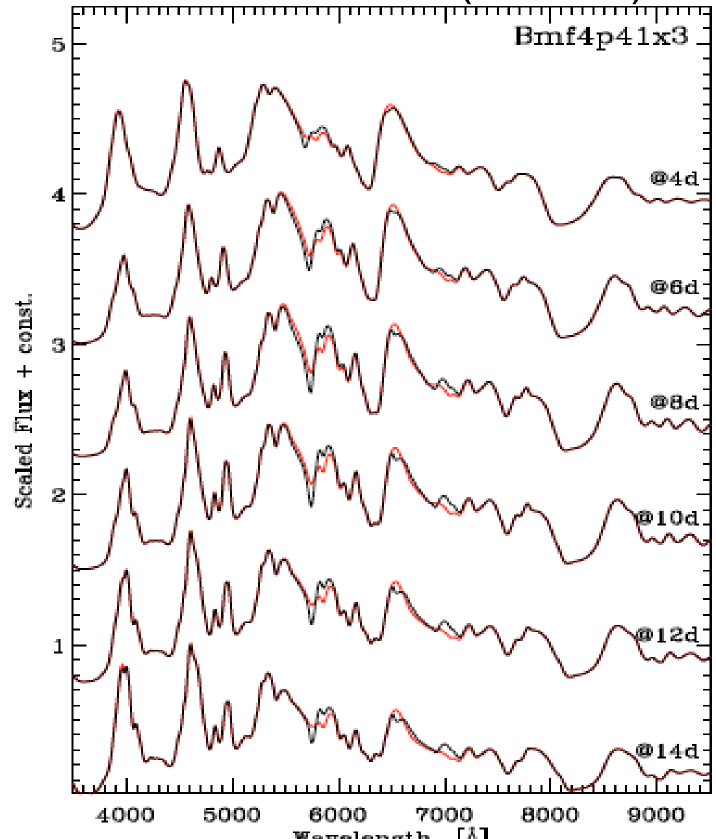
Comparison with SN IIb 2011dh

Encouraging match to SN 2011dh with SN IIb model 4.4Msun model of Dessart et al. (2011ab) for optical and near-IR ranges.

SN2011dh; Arcavi et al (2011)



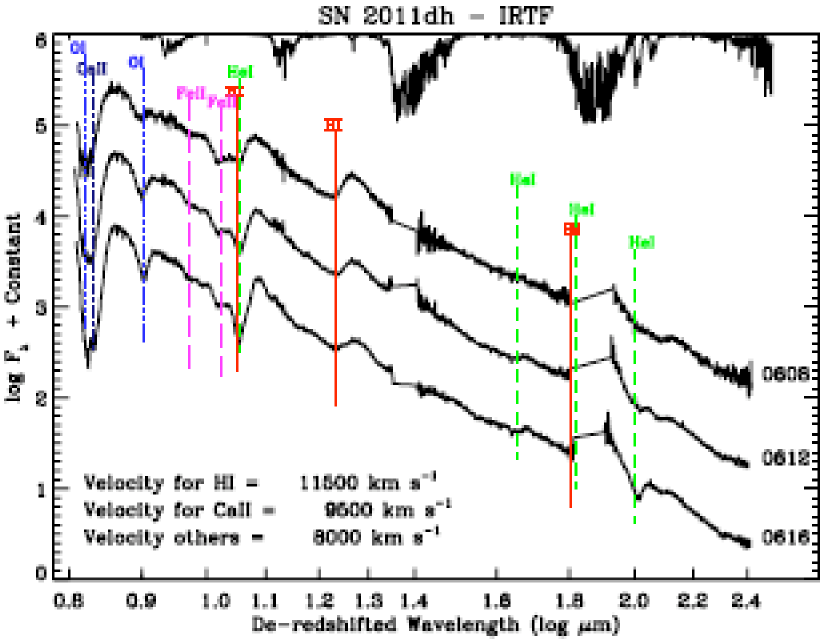
Dessart et al. (2011ab)



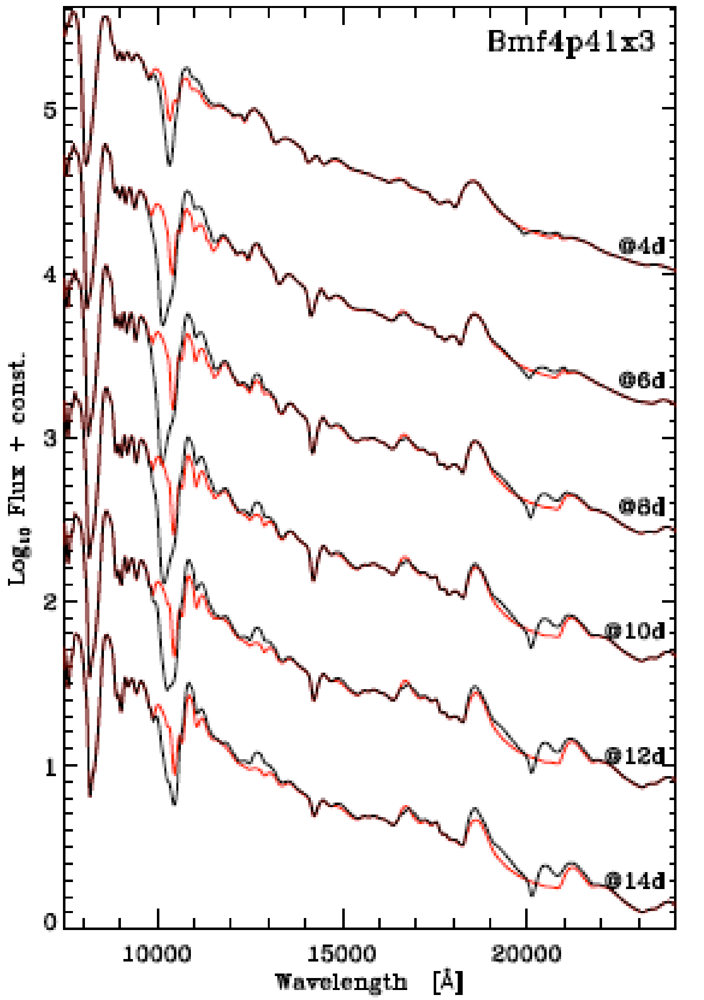
Comparison with SN IIb 2011dh

Encouraging match to SN 2011dh with SN IIb model 4.4Msun model of Dessart et al. (2011ab) for optical and near-IR ranges.

SN2011dh; Marion et al. (ATel)



Dessart et al. (2011ab)



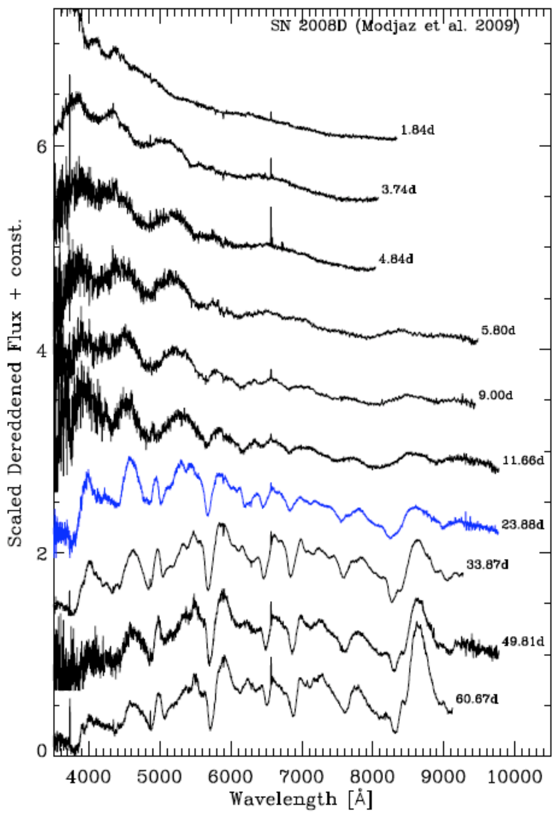
Simulations of SNe Ib based on binary-star evolution models

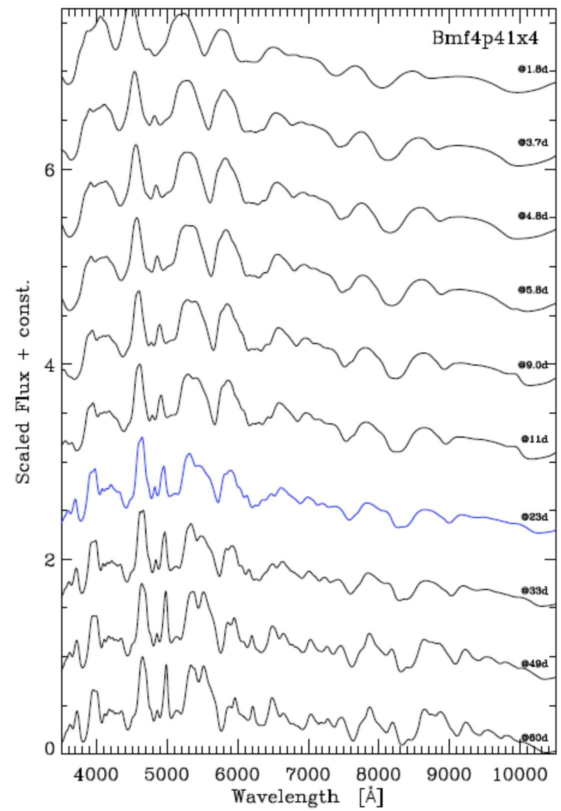
Dessart et al. (in prep)

Strongly mixed SN Ib model
Modeling with non-thermal processes.

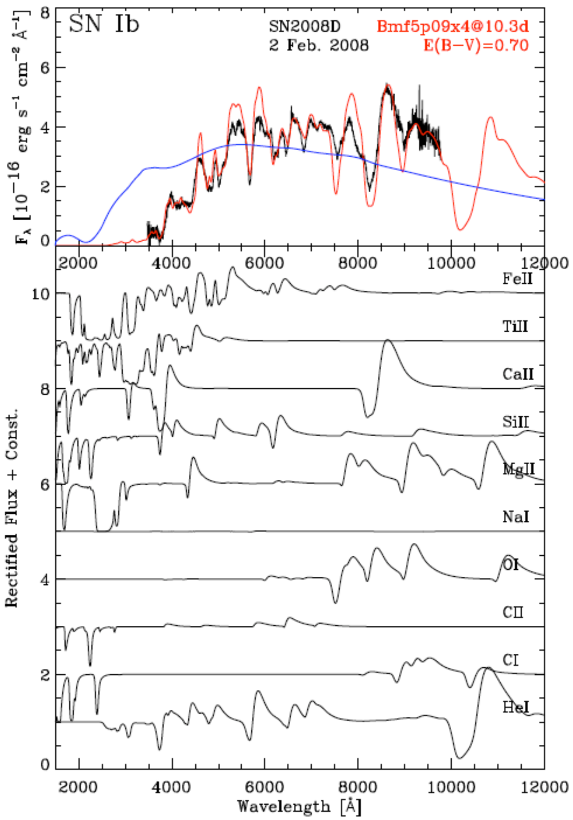
SN 2008D:
Blue featureless SED (intriguing...),
Appearence/persistence of HeI lines,
Fast transition to nebular (red SED)

Structured SED
Appearance/persistance of HeI lines
(mixing, non-thermal effects),
Slower transition to nebular (M, ^{56}Ni))
SED too blue at late time (^{56}Ni)





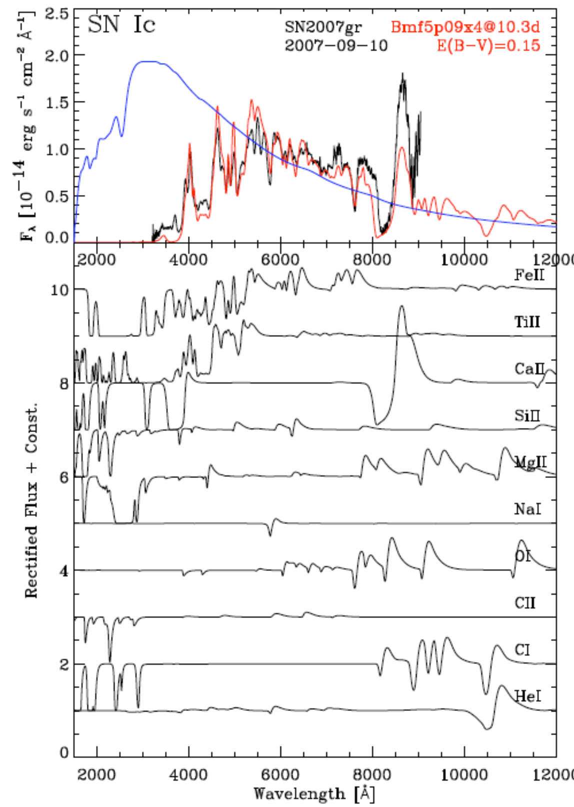
Strong Mixing



Effect of mixing in Helium-rich ejecta

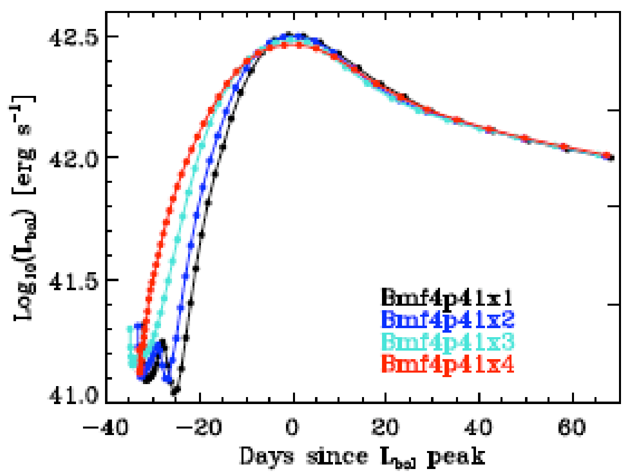
Dessart et al. (in prep)

Moderate Mixing



Models

- 5.1$M_\odot$ **He-rich** pre-SN star model
- 1.2B ejecta with 2 levels of mixing
- **Affects ^{56}Ni strongly, He weakly**
- Non-thermal treatment



Strong Mixing: SN Ib

- No post-breakout plateau
- Prompt rise to peak
- Redder colors and broader spectral lines at peak
- **Un-ambiguous presence of numerous HeI lines**
- **HeI/FeII/SiII in 6000A region but HeI stronger**
- Numerous CI/OI/MgII/CaII lines at 7000-9000A

Moderate Mixing: SN Ic

- post-breakout plateau.
- Re-brightening delayed
- Bluer colors and narrower spectral lines at peak
- **HeI lines present but weak**
- **NaI/OI/HeI/FeII/SiII in 6000A region: Messy!**
- Numerous CI/OI/MgII/CaII lines at 7000-9000A

What distinguishes SN Ib from SN Ic ejecta/progenitors?

Dessart et al. (in prep)

- Binary evolution scenario (Yoon et al. 2010) for production of low-mass Ib/c ejecta to match LCs (Ensman & Woosley 1988, Shigeyama et al. 1990, Dessart et al. 2011), rates (Smith et al. 2010).
- **Ib versus Ic** conditioned by progenitor (mass, composition) and explosion (mixing) properties.

SNIb

- $X_{^{56}Ni} \geq 0.01$ at **He-rich** photosphere to yield HeI lines ⇒ Hard to make a SN Ib
- **High $X_{^{56}Ni}$ ⇒ SNe Ib likely from lower-mass progenitors (small cores) + efficient mixing**
- SN Ib progenitors: low-mass ''WR'' in binaries (weak winds, low L)? Undetected by current WR searches. Associated with a massive star companion at explosion.

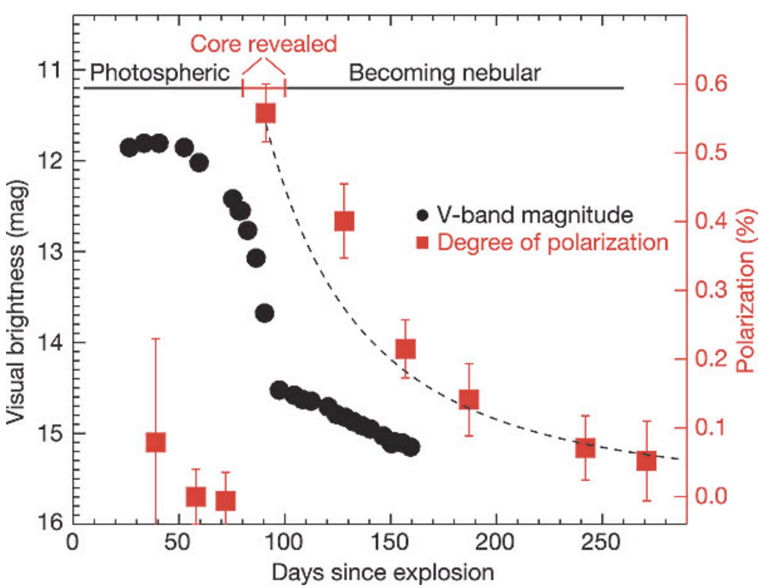
SNIc

SNe Ic likely from **higher mass progenitors** (larger O buffer between He and ^{56}Ni) or ejecta that are **He deficient or insufficiently mixed**. SNe Ic easier to make.

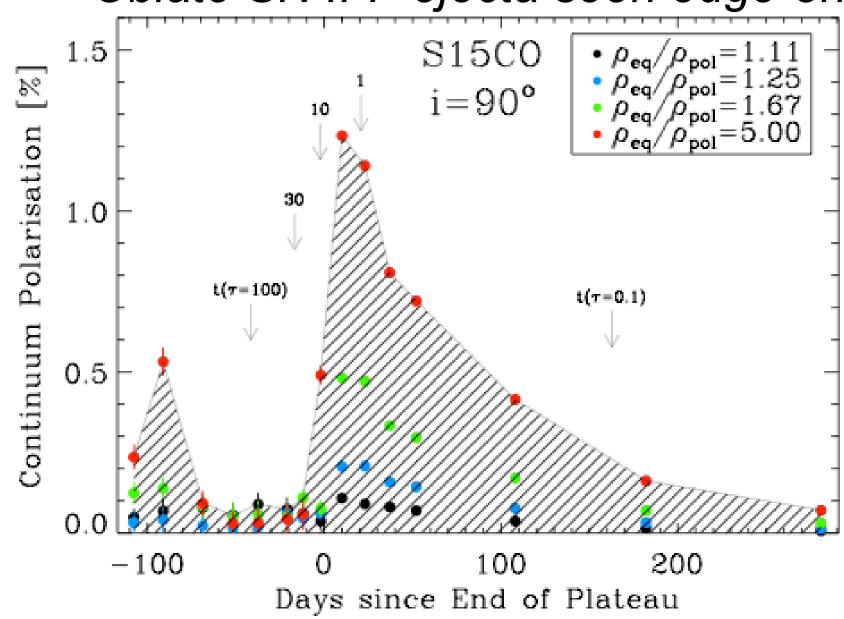
Spectro-polarimetry: Explore departures from spherical symmetry

- Inputs from non-LTE time-dependent SN II-P simulations (DH11a)
- Fixed imposed asymmetry
- Polarization due to electron scattering
- Plateau-phase: Low-polarization due to strong cancellation effects, optical depth effects, steep mass-density and/or electron-density distribution
- For a **fixed** asymmetry, **polarization jumps at onset of nebular phase**
- Nebular-phase: polarization commensurate to magnitude of asymmetry

Leonard et al. (2006) - Type IIP SN2004dj



Dessart & Hillier (2011b)
Oblate SN II-P ejecta seen edge-on

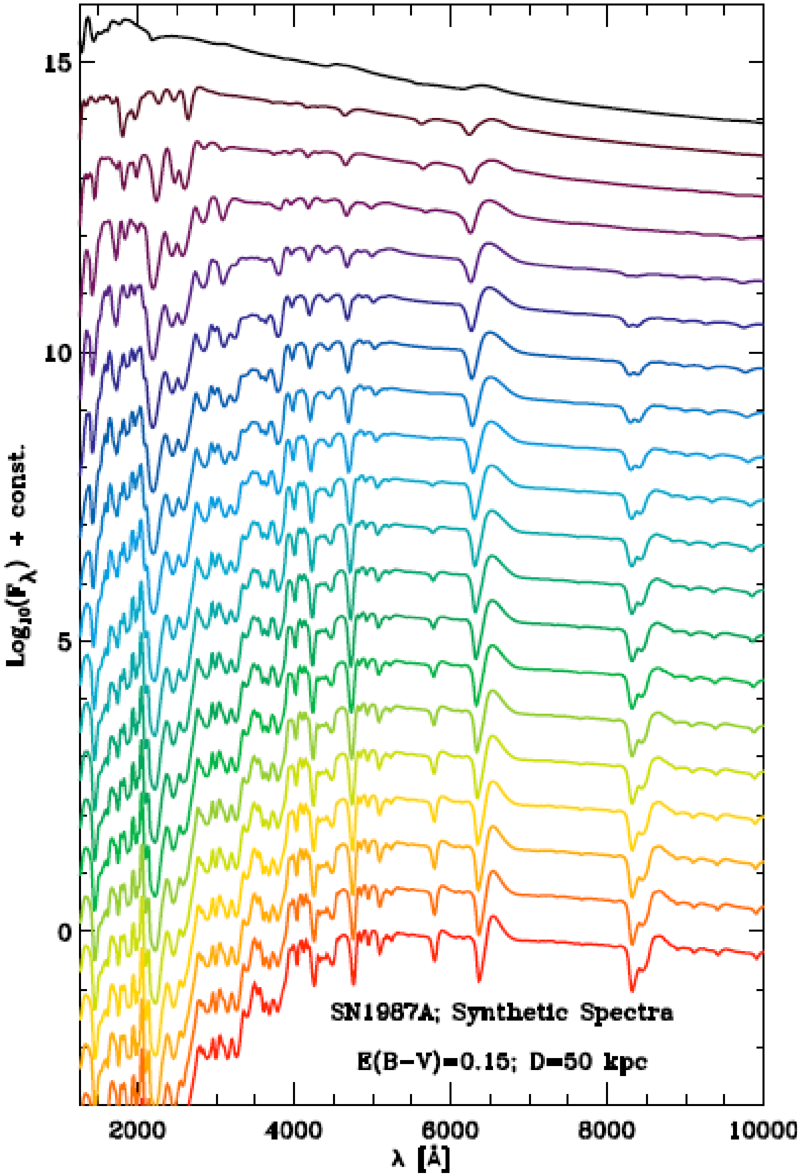


Summary

- Original goals met. CMFGEN ''works'' for all SN types, fully non-LTE, fully time-dependent, treatment of non-thermal processes, local/non-local energy deposition
- Code **benchmarked** against 87A (!) and SNe II-Plateau observations.
- Non-LTE and steady state adequate at early times in Type II SN. Allows "good fits" through tuning parameters. Good for distance determinations with Type II SNe. Dependencies.
- Late-time modeling requires time-dependent treatment (e.g. Dn/Dt) => Ionization freeze-out
- Non-thermal processes key in low-ionized conditions (SNe II, Ib, Ic).

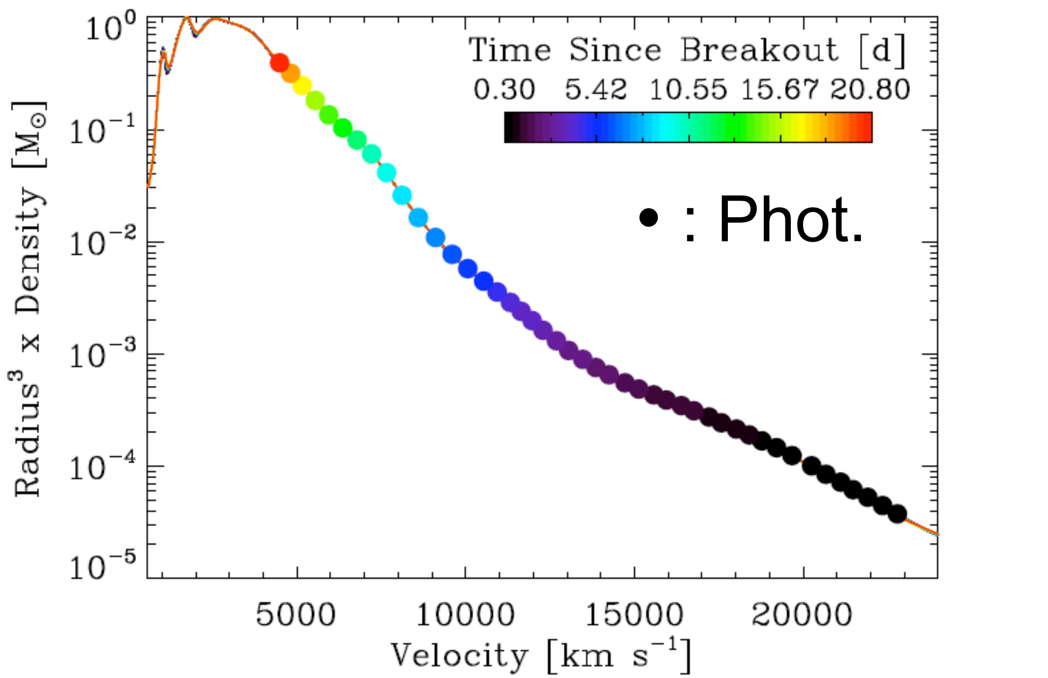
- Higher physical consistency with "Full-Ejecta" simulations based on hydrodynamical inputs of pre-SN evolution and explosion. NO artificial inner-boundary condition.
- Versatile tool for **simultaneous** spectroscopic and light-curve modeling of SNe.
- Great tool when combined with radiation-hydrodynamics (hydro inputs) and stellar evolution models (pre-SN star)
- Gear-up for current/forthcoming blind surveys: PTF, PAN-STARRS, Sky-Mapper, and LSST

Comparison to observations of SN1987A



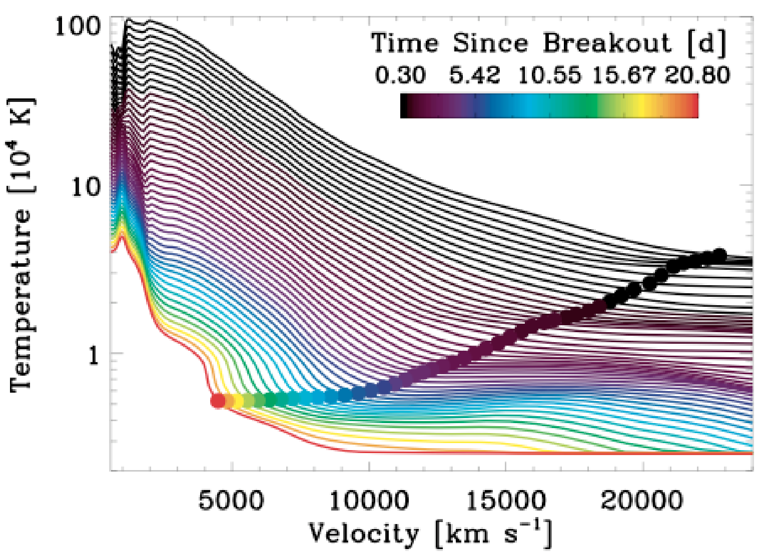
Dessart & Hillier (2010a)

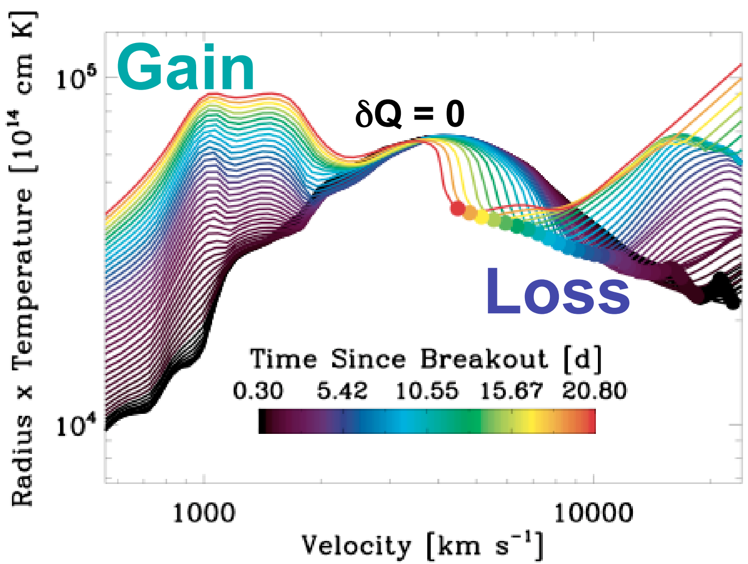
Strengthening of Hα caused by time-dependent effects rather than changes in density distribution at photosphere



SN1987A Full-Ejecta Evolution

Global cooling due to expansion: $T \propto 1/R$
Compensated by decay at depth
Exacerbated by radiative losses at surface





SN1987A Ejecta Evolution

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