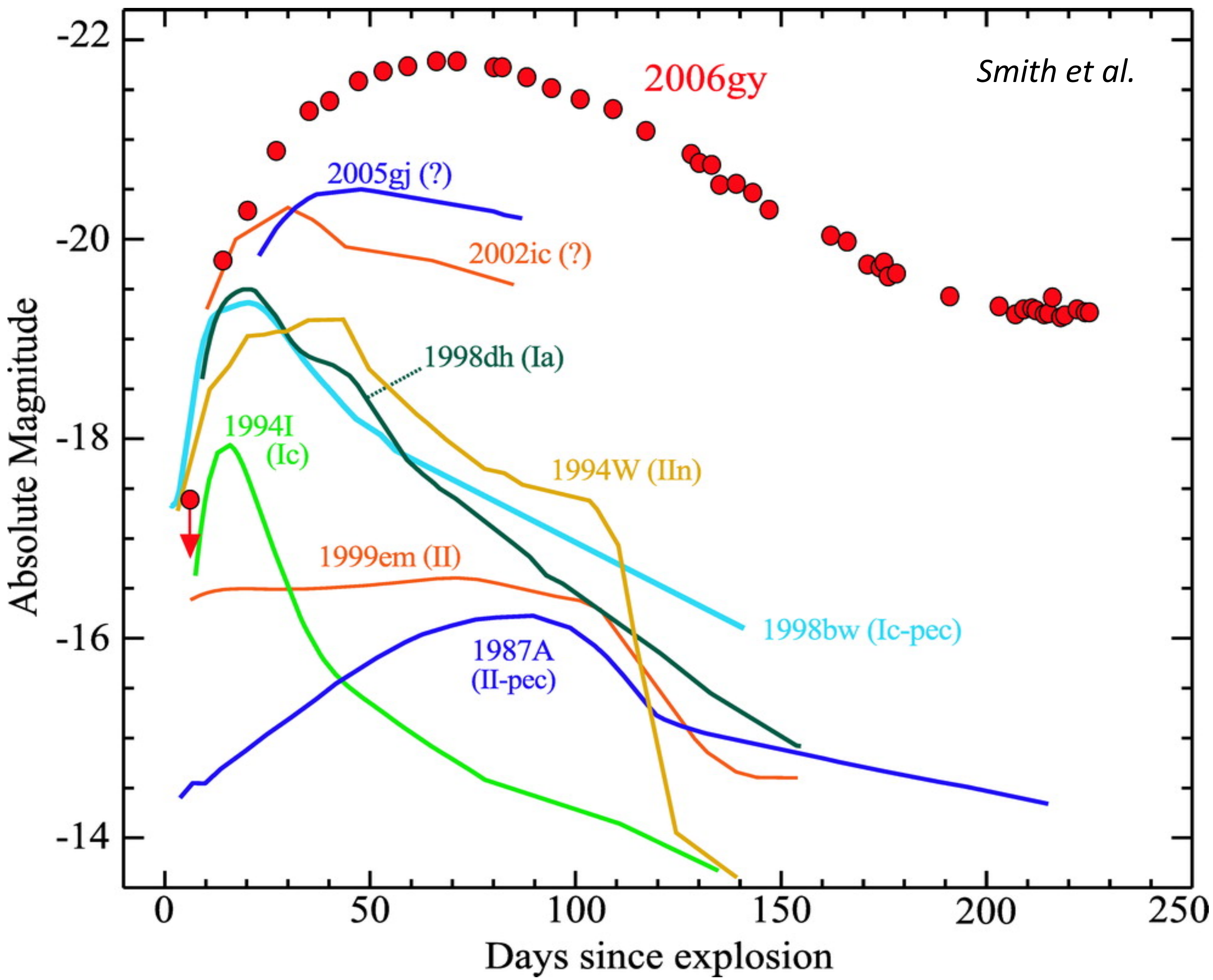
# Super-Luminous Supernovae from Ejecta / CSM interaction

# Diversity of Supernova Light curves

Superluminous SNe
$\int L(t)\,dt \approx 10^{50\text{-}51}$erg

"Standard" SNe
$\int L(t)\,dt \approx 10^{49}$erg

Giant star eruptions
e.g. η Car



# Progenitors and explosion mechanisms

**Thermonuclear runaway (SN Ia: no H, no He, strong SiII):**

- Combustion of ≈1$M_{\odot}$ of C/O to Si/$^{56}$Ni (IME, IGE) releases ≈$10^{51}$erg
- Accreting WD near Mch or merger of two sub-Mch WDs
- Low-mass graveyard
- No remnant
- Association with old stellar populations.

**Gravitational collapse (SN II, IIb, Ib, Ic: H/no-H and/or He/no-He):**

- Collapse of ≈1$M_{\odot}$ Fe core to a neutron star releases $10^{53}$erg.
- Neutrino energy deposition is key.
- Energy from combustion is secondary
- Massive-star graveyard ($M \geq 8M_{\odot}$).
- Neutron star or black hole remnant
- Association with young stellar populations.

# Supernova energy evolution

At shock emergence: $E_{rad} \sim E_{kin}$

Within seconds to days: $dP_{rad}/dr$ ➔ $E_{tot} \sim E_{kin}$

$\Rightarrow$ homologous expansion: $R_{SN} >> R_{\star}$

$V(m) \sim R(m) / t$

$V(m) = const.$

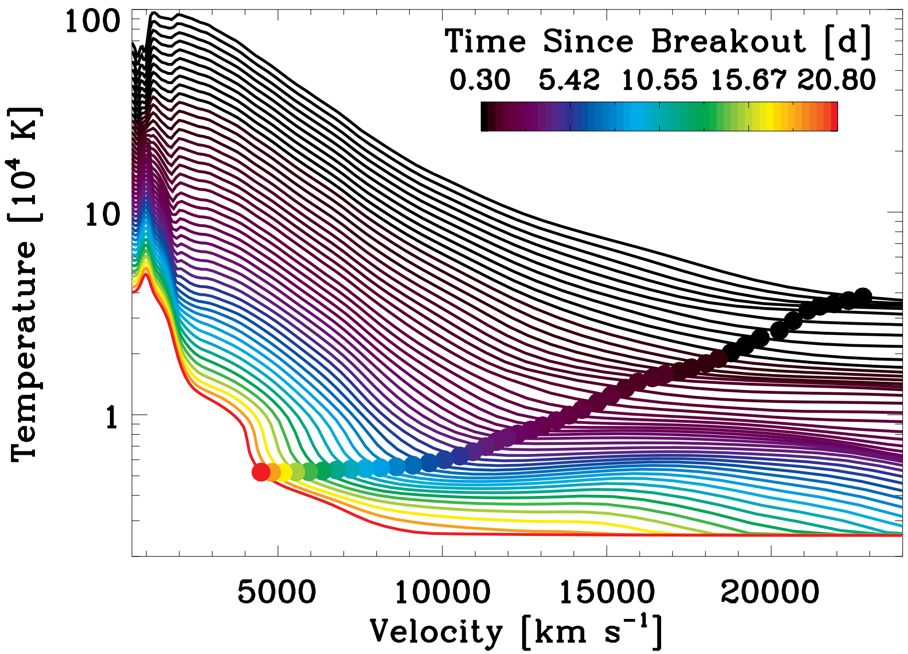
$\rho(m) = \rho_0(m)(t_{expl}/t)^3$

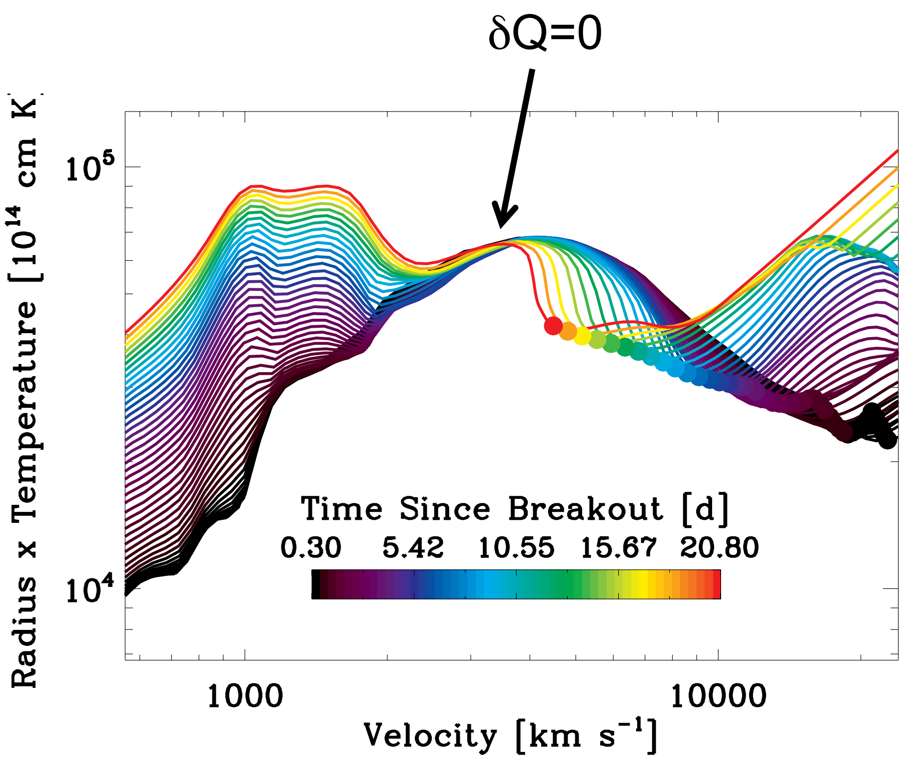
(Isolated) Ejecta Evolution controlled by

- Initial shock-deposited energy
- Cooling
- Heating
- Transport

# SN radiation influenced by cooling

- Cooling through expansion primarily
- $dE=dQ-PdV$ ; $P_{rad} >> P_{gas}$: $E=aT^4V$, $P=aT^4/3$
- => if $dQ=0$ then $dT/T=-1/3\ dV/V$. Since $dV/V=3dR/R$ => $\mathbf{T \approx 1/R}$
- Explosion of a WD: $R_0=10^8$cm, $R_{SN}=10^{15}$cm => $R_{SN}/R_0=10^7$
- => T drops from $10^9$K to room T in ~2 weeks!



# Supernova radiation influenced by heating

- Energy initially deposited by the shock
- Recombination energy: e.g. 13.6eV per HI (weak).
- Radioactive decay energy: $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$.

  $^{56}Ni \rightarrow {}^{56}Co$ : 1.75MeV per decay, half-life=6.07d

  $^{56}Co \rightarrow {}^{56}Fe$ : 3.74MeV per decay, half-life=77.22d

- External sources:

  Magnetar spin-down ($E_{th}$)

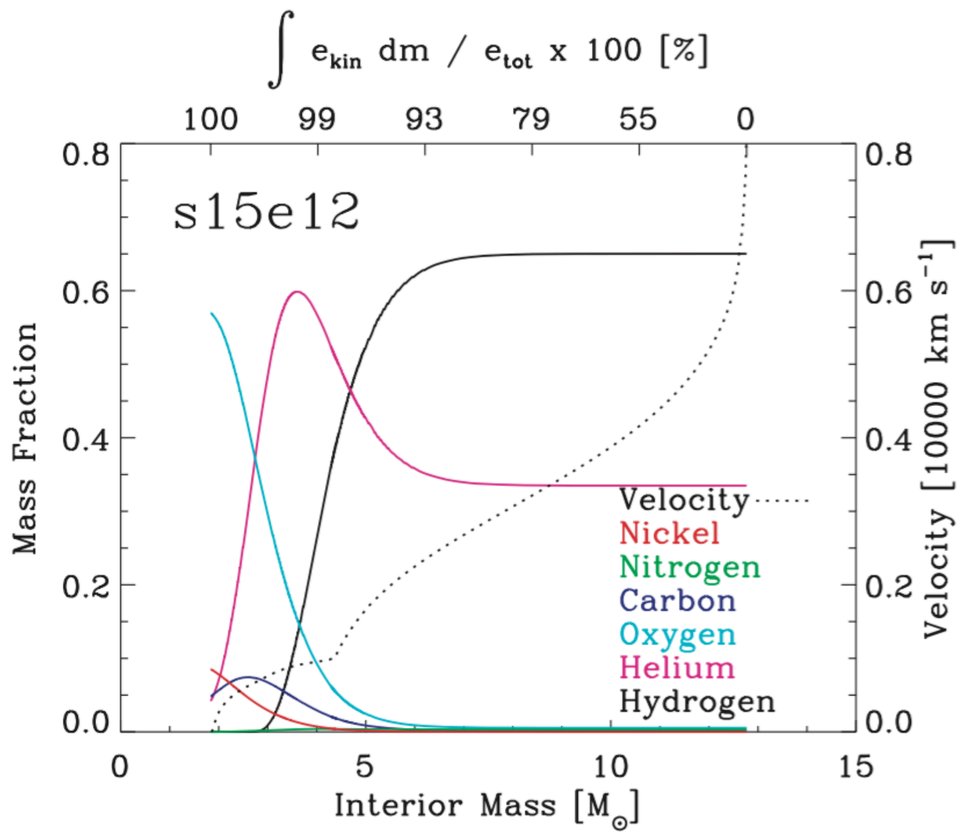
  Ejecta/CSM Interaction ($E_{kin} \rightarrow E_{th}$)

# Superluminous Supernovae: Mechanisms

- Powered by huge $^{56}Ni$ mass : pair-instability SNe or extreme CCSNe
- Powered by magnetar radiation: Delayed energy injection from compact object with large B and $\Omega$ => particle + X-rays/$\gamma$-rays emission
- Powered by interaction with CSM : $E_{kin}$ -> $E_{th}$ -> $E_{rad}$

# Why is ejecta/CSM interaction an efficient engine?

Ekin (~$10^{51}$erg) >> time-integrated Lbol (~$10^{49}$erg)
=> Tapping 1% of Ekin doubles Erad
Interaction taps regions with largest V, lowest RHO



# The diversity of interaction signatures

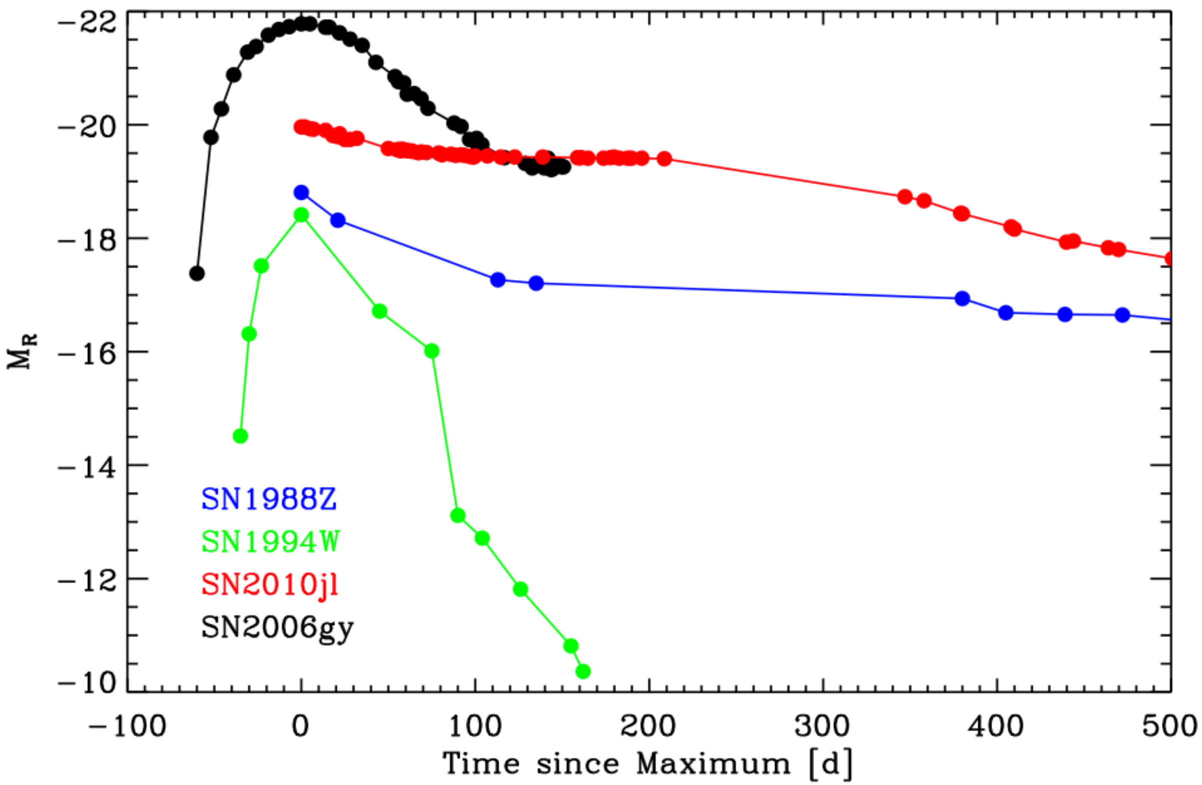
- Interaction inferred from narrow spectral lines (IIn) + huge luminosity
- Range of LC duration, morphology, Lbol maximum etc.
- Cases studies:

⇒ SN 2010jl

⇒ SN1998S

⇒ SN2013fs

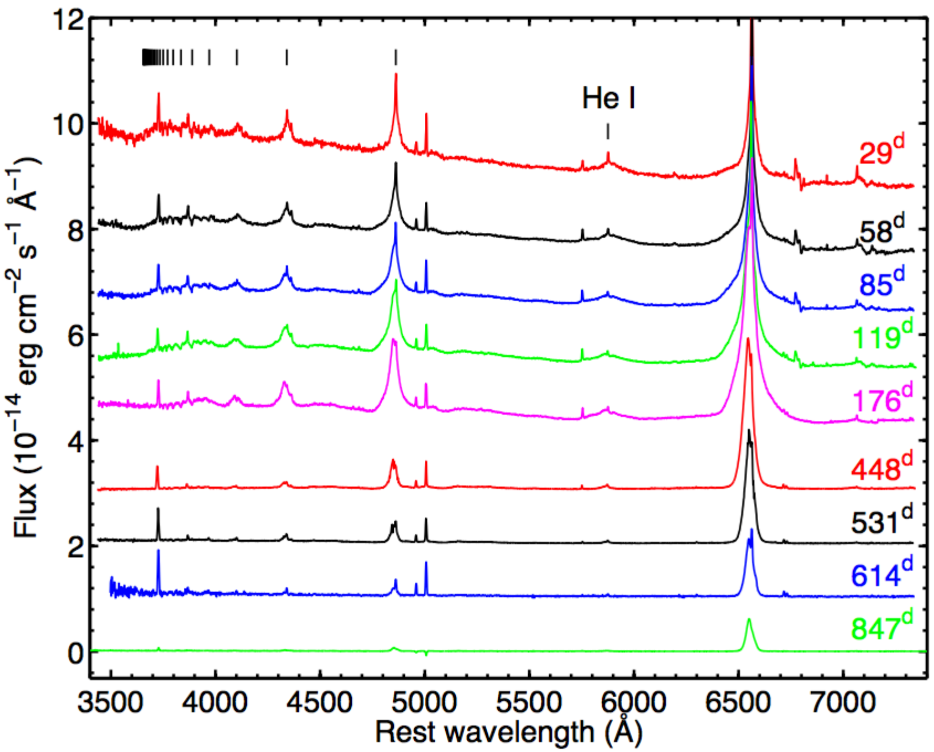
⇒ SN1994W

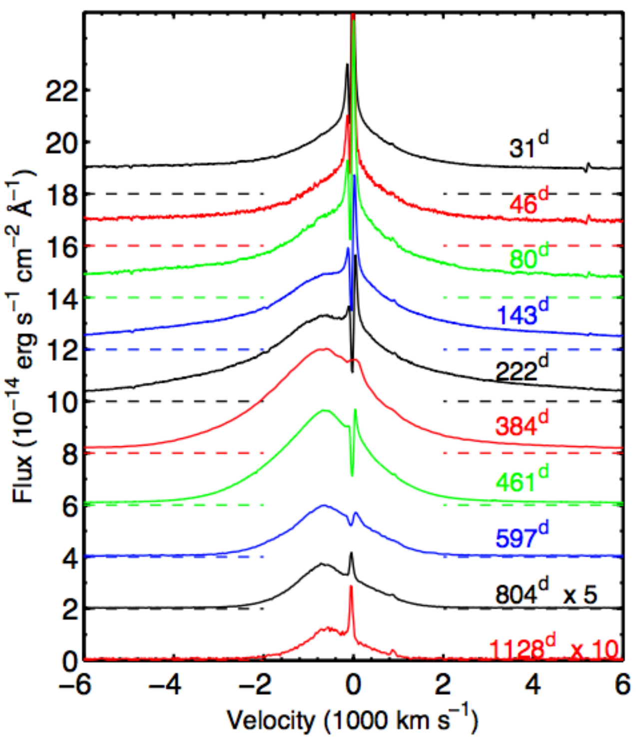


# The diversity of spectral signatures

- SN2010jl: **narrow** symmetric then **broad** bluedshifted lines

Fransson+14

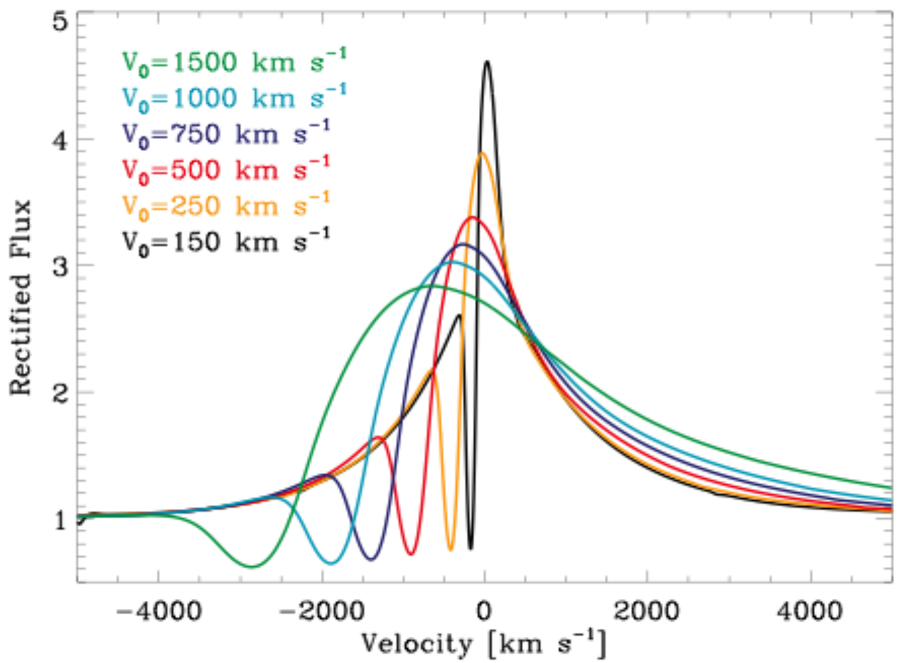


# Effects associated with Electron-scattering: Frequency redistribution

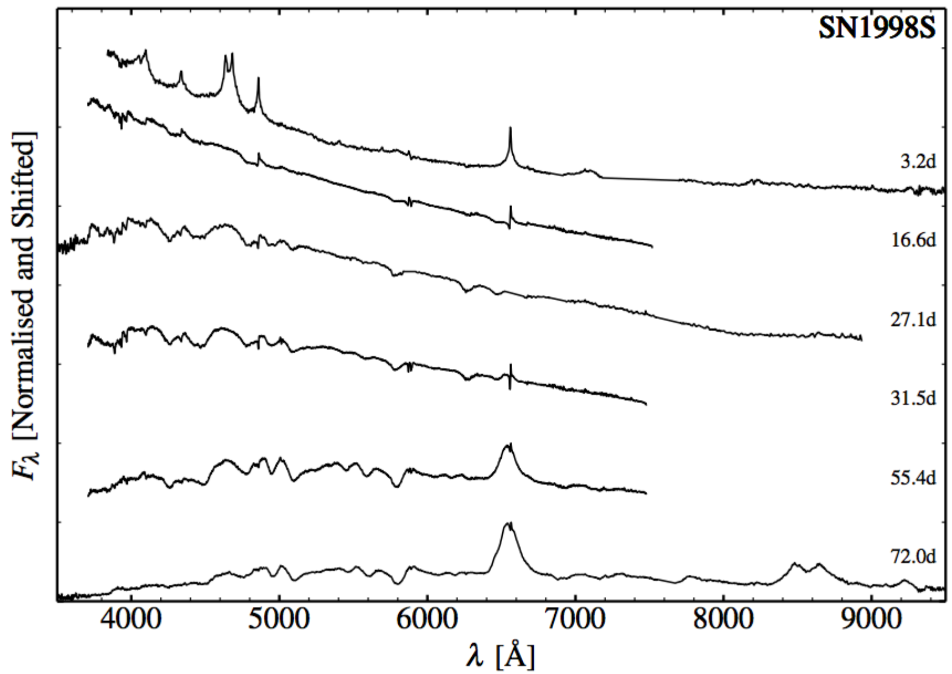
- photon scattering with free electrons causes frequency redistribution
- **Non-coherent scattering** in CMF caused by the thermal motion of scatterers: $V_{thermal}$
- **Coherent scattering** in CMF due to expansion, **Redshift** in Observer's frame: $V_{expansion}$
- $\mathbf{V_{expansion} > V_{thermal}}$ ⇒ 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)

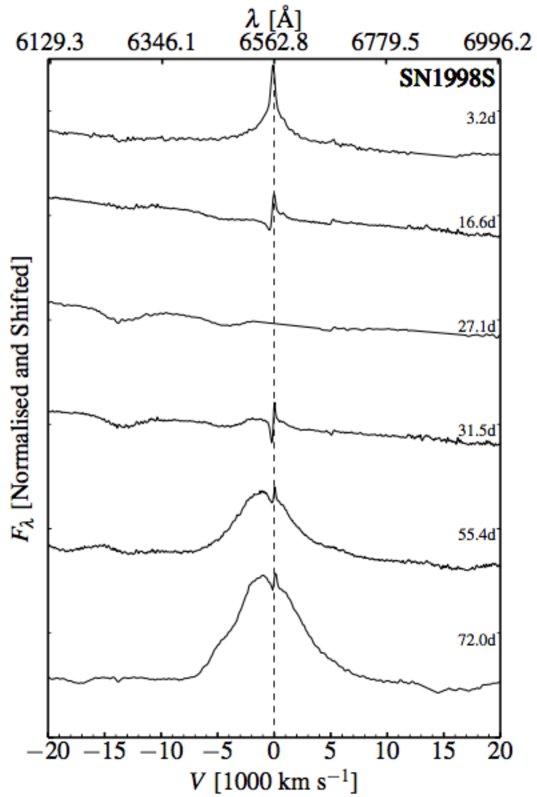
Effect of varying $V_{phot}$ on H$\alpha$ morphology



# The diversity of spectral signatures

- SN1998S: narrow symmetric -> featureless spectra -> `standard’ II-P/II-L spectrum

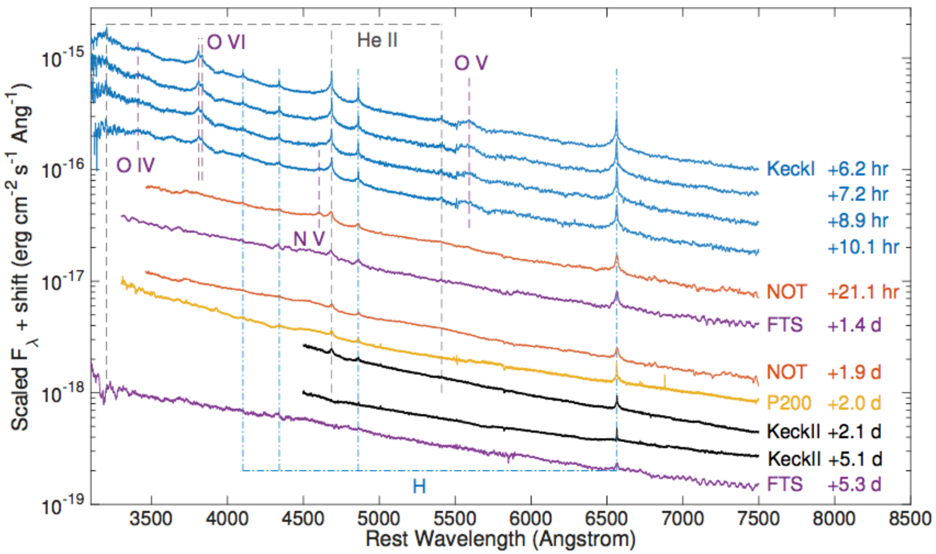


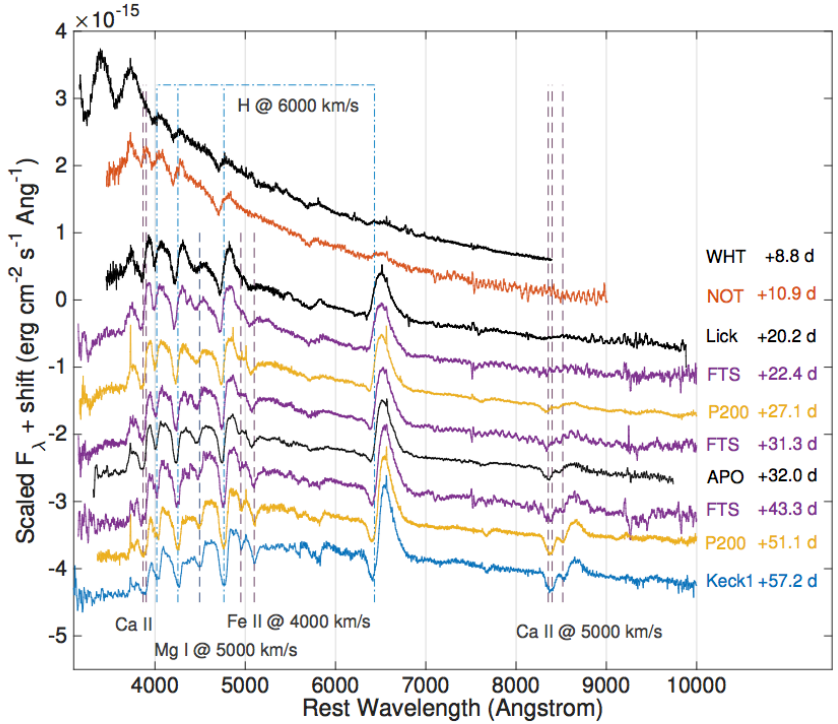
# The diversity of spectral signatures

SN2013fs: Same as SN1998S but more rapid evolution (similar event: SN2013ca)

Yaron+17




Early signatures of interaction

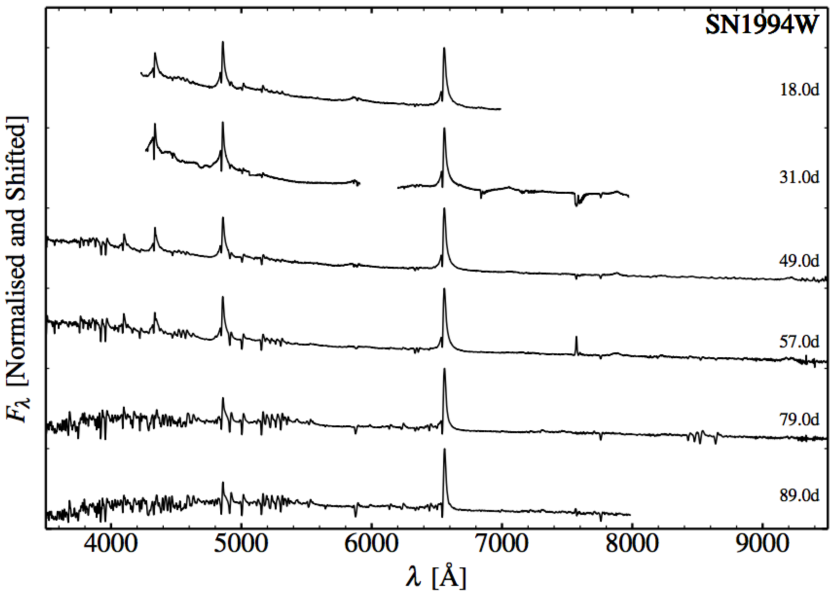


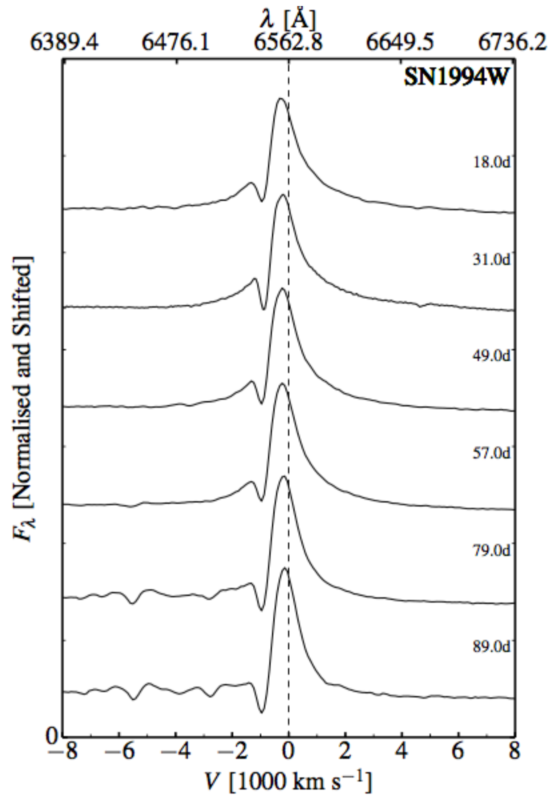

Evolution into a non-interacting / standard Type II

# The diversity of spectral signatures

- SN1994W: **narrow** symmetric lines that become **narrower** with time

(other similar events: 2009kn, 2011A, 2011ht.



# Configurations for CSM / ejecta interactions

- Energetic massive ejecta + high-mass CSM
- Energetic massive ejecta + low-mass CSM
- Energetic massive ejecta + compact/dense CSM
- Energetic light ejecta + massive CSM

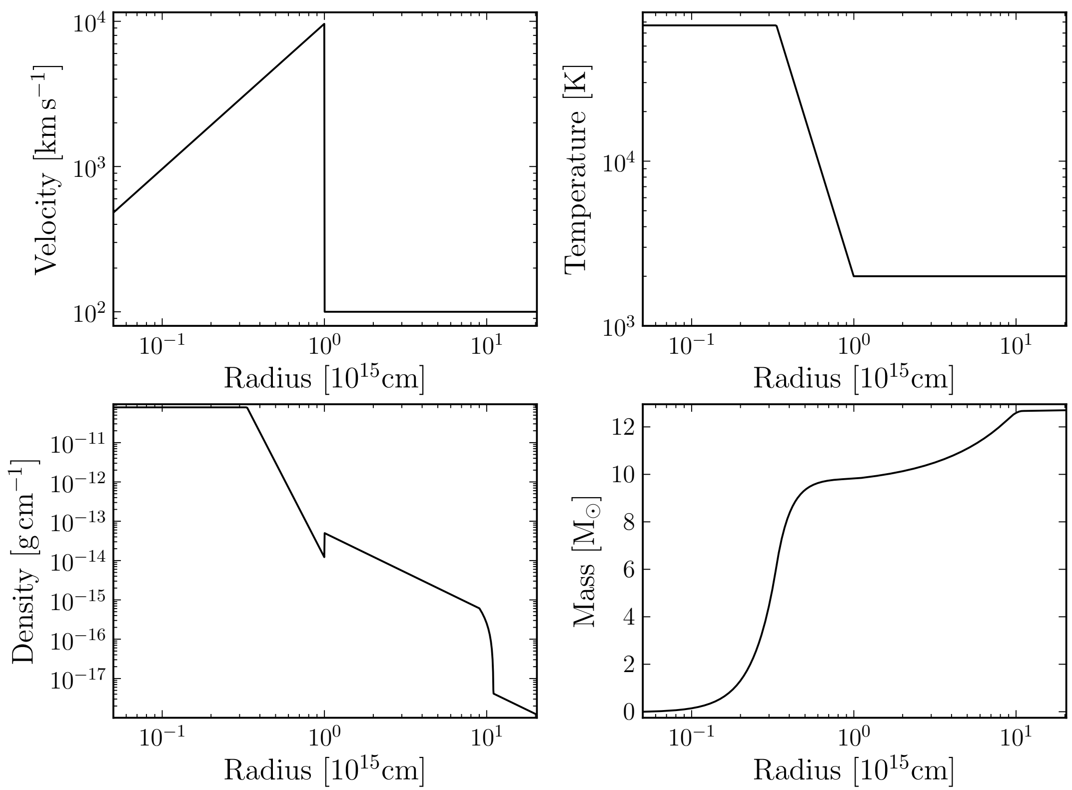
# Numerical Simulations of Interacting Supernovae

- Configuration: Faster inner shell (Ekin) and slower massive outer shell (Mass)
- Strong shock => cooling by radiation
- High mass => large τ => radiation trapping
- Energy-dependent opacity => non-grey approach

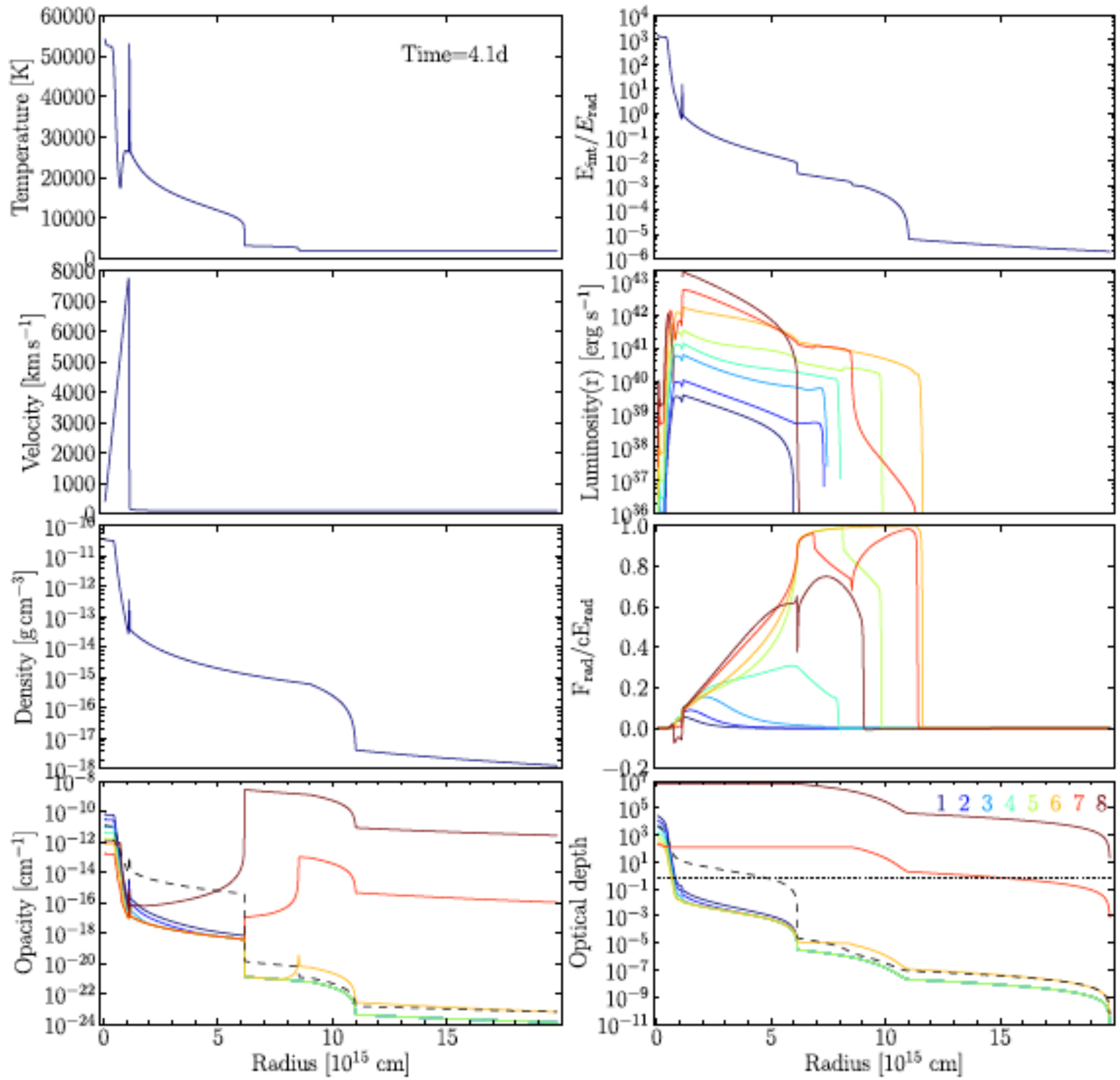
=> Multi-group Radiation hydrodynamics with HERACLES (Audit/Gonzalez)

**Inner shell: SN ejecta**
$10M_{\odot}$, $10^{51}$erg

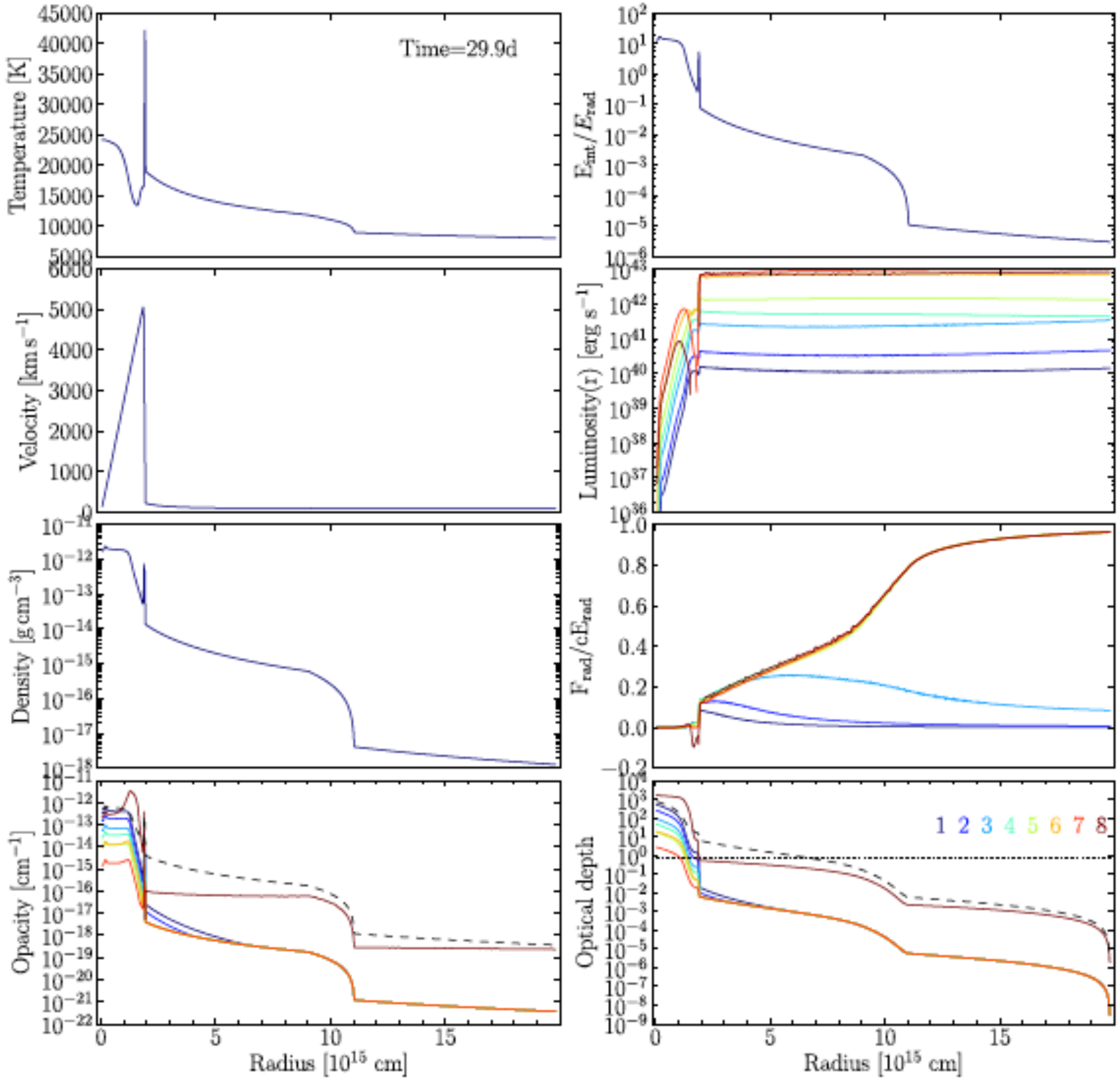
**Outer Shell: strong wind**
$0.1M_{\odot}$/yr, $3M_{\odot}$, vel=100km/s
Uniform H-rich composition



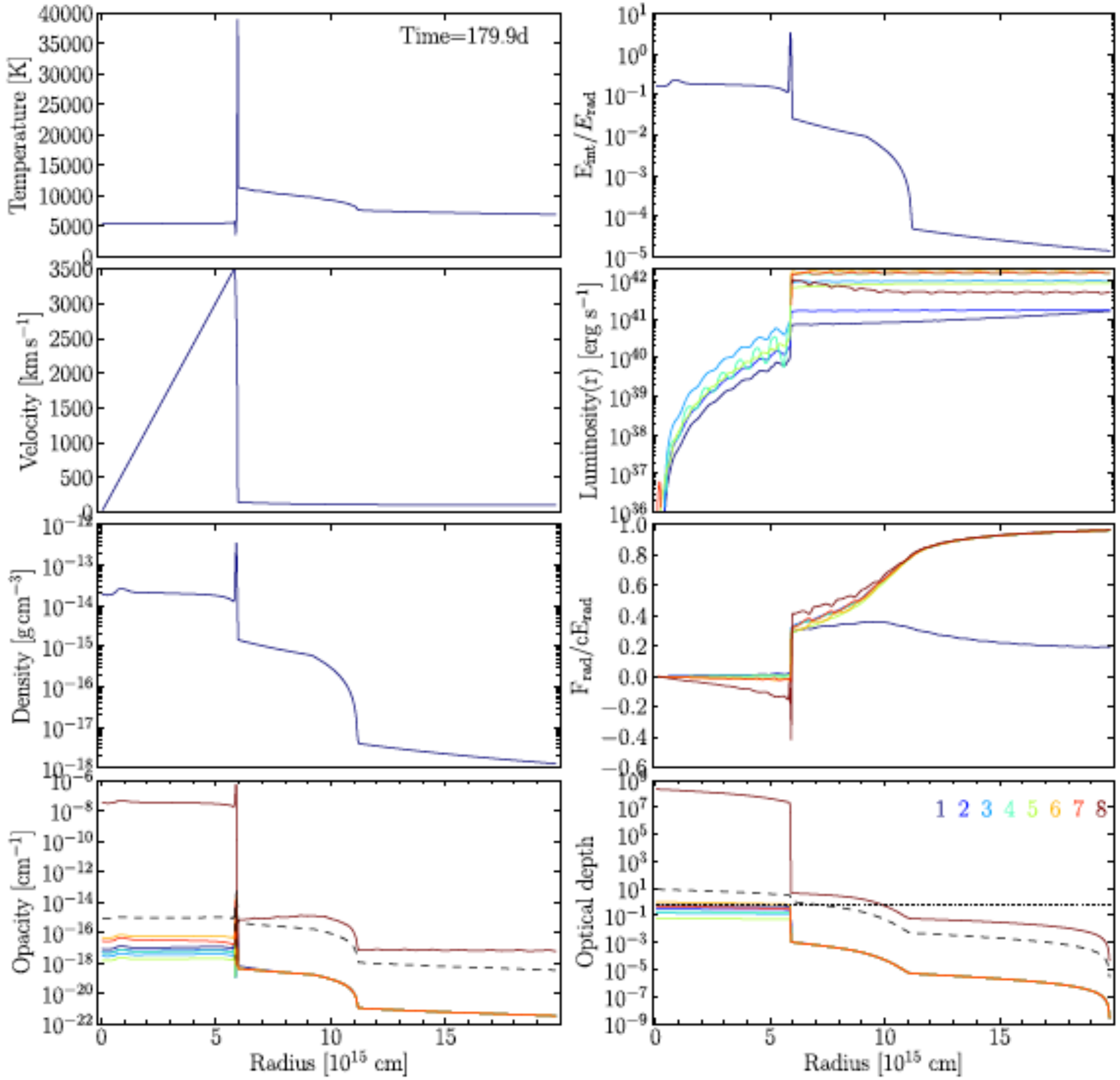
# Evolution of interaction: Day 4.1



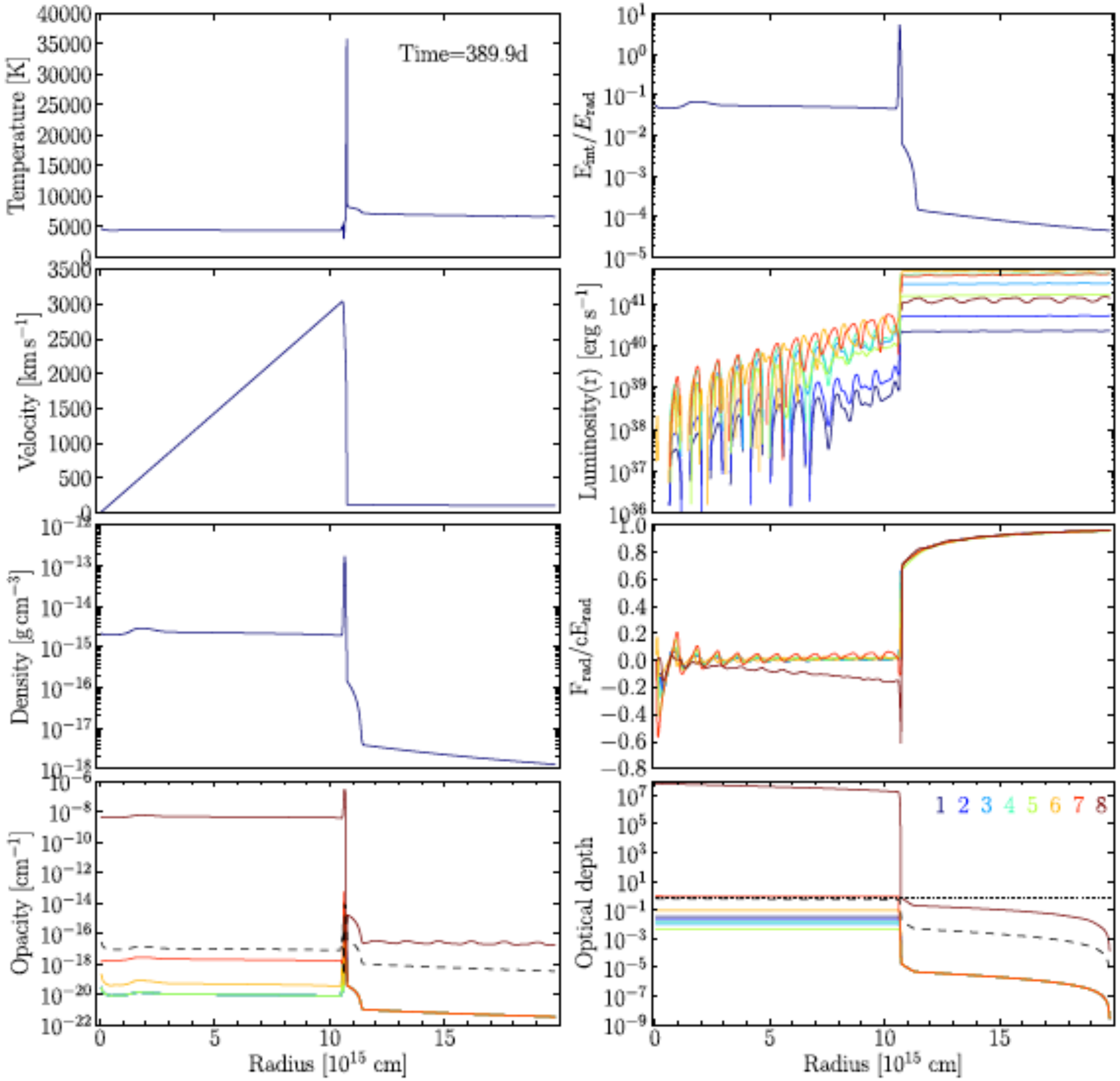
# Evolution of interaction: Day 29.9



# Evolution of interaction: Day 179.9

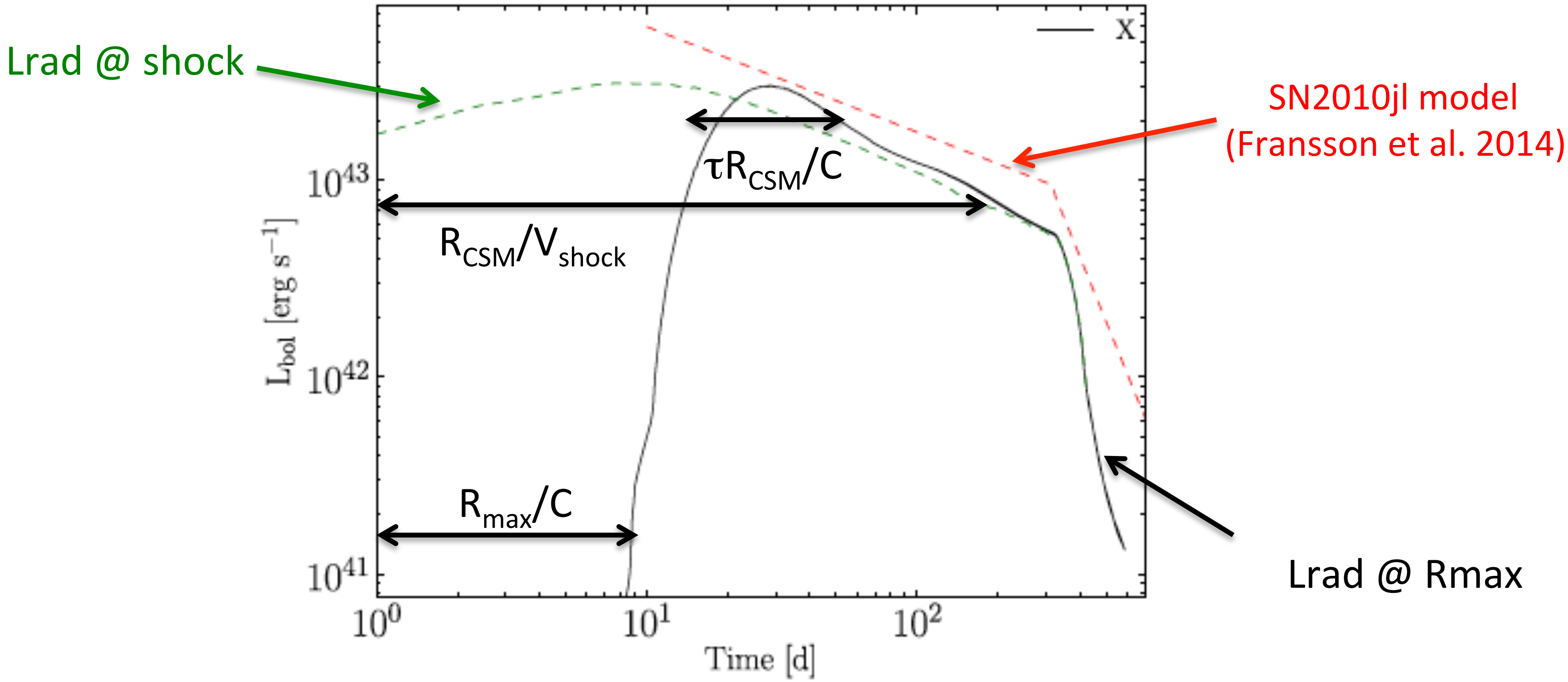


# Evolution of interaction: Day 389.9

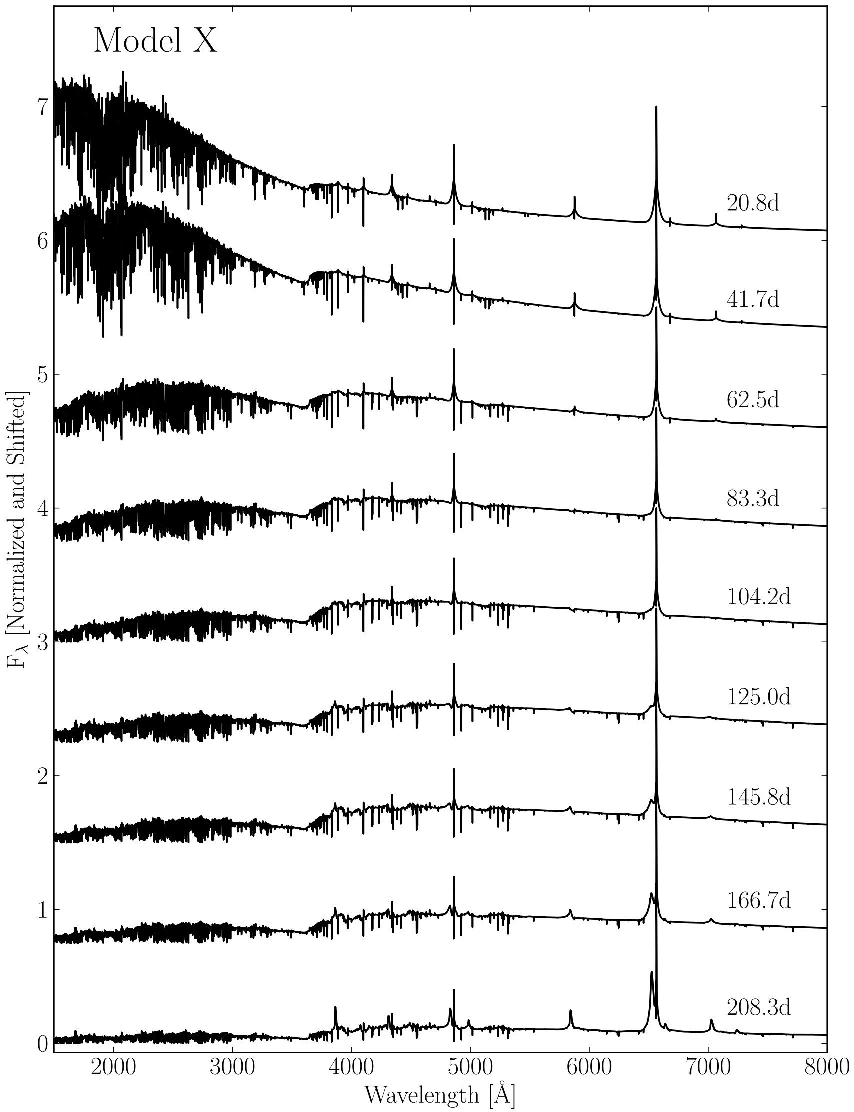


# Numerical Simulations of Interacting Supernovae

- Shock powered luminosity: $L_{\rm shock} \sim 2\pi r^2 \rho_{\rm csm} v_{\rm shock}^3$
- Optical depth effects : $L_{bol}<L_{shock}$ for $t<t_{diff}$
- LC break when shock leaves dense CSM

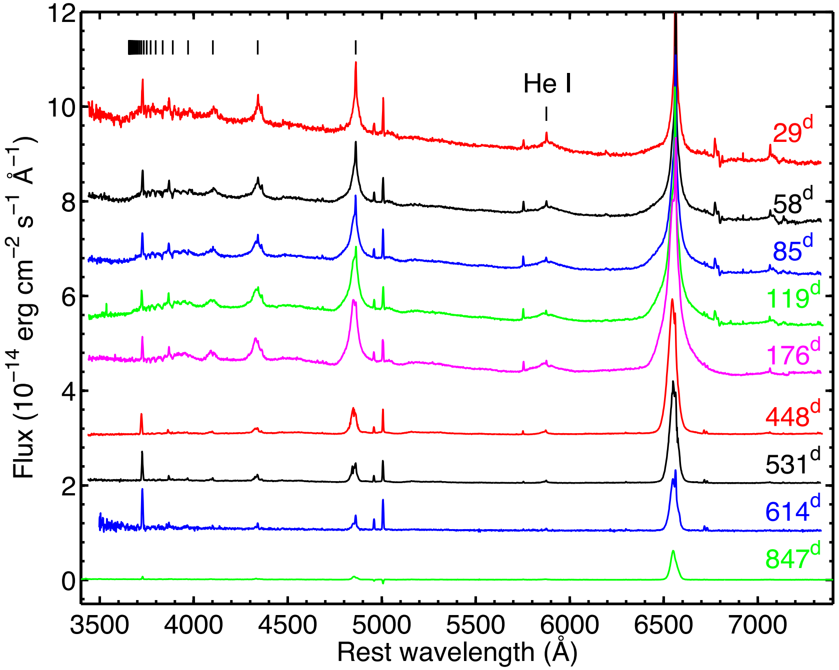


# Spectral evolution




Reproduction of narrow symmetric profiles
Very slow spectral evolution
Evolution to lower T/color (fixed $R_{phot}$)

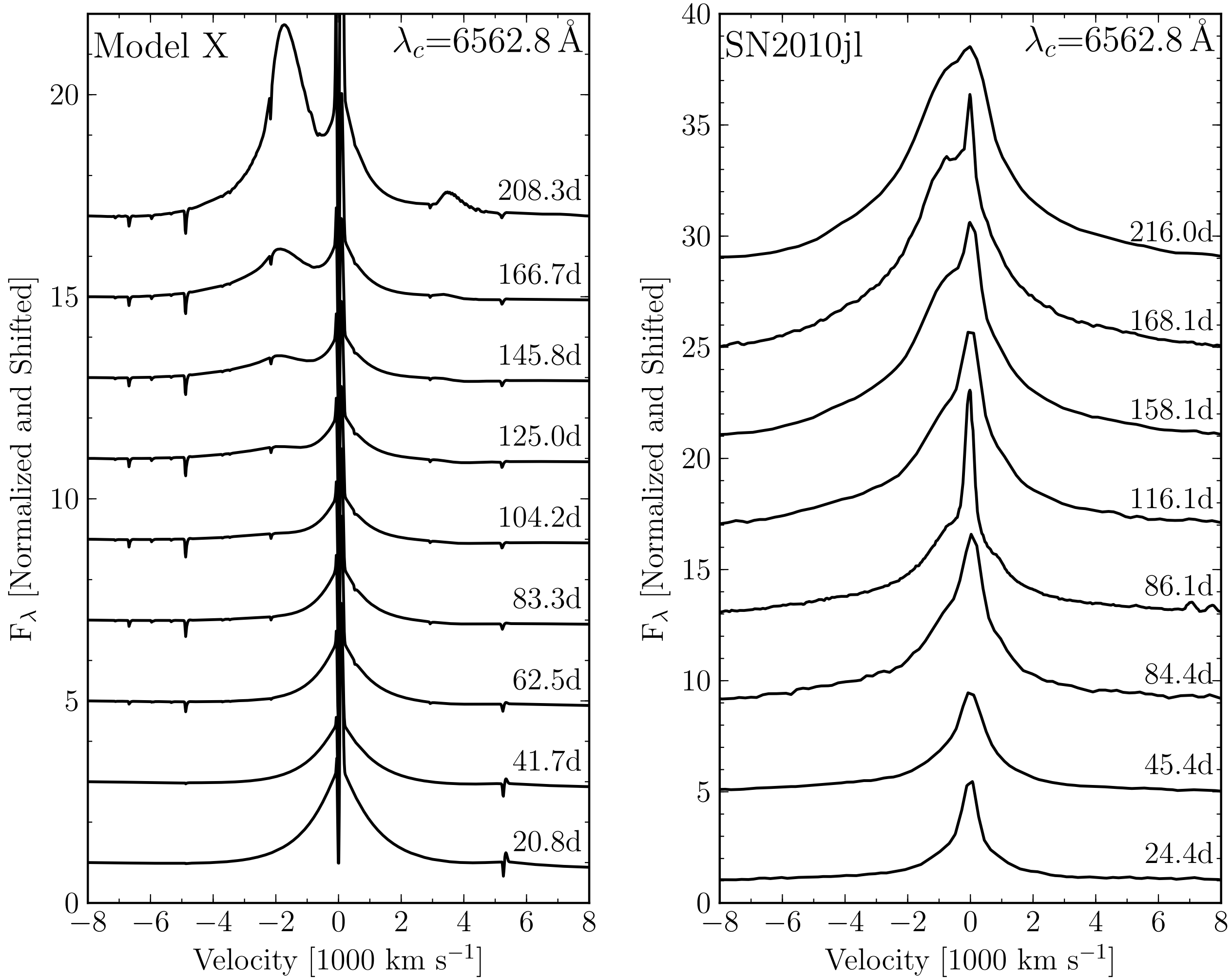
SN2010jl Fransson et al (2014)



# Comparison to SN 2010jl

Reproduces narrow line core & broad wings: electron scattering + emission in CSM.

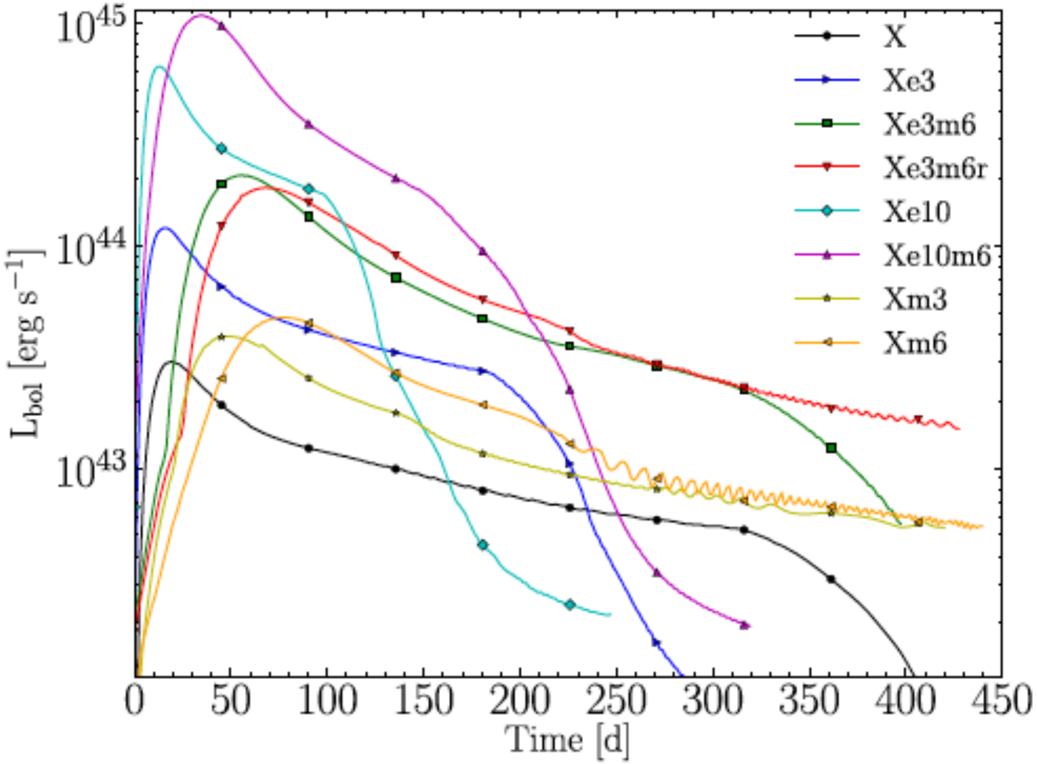
Reproduces (qualitatively) the emission blueshift: Contribution from dense shell.



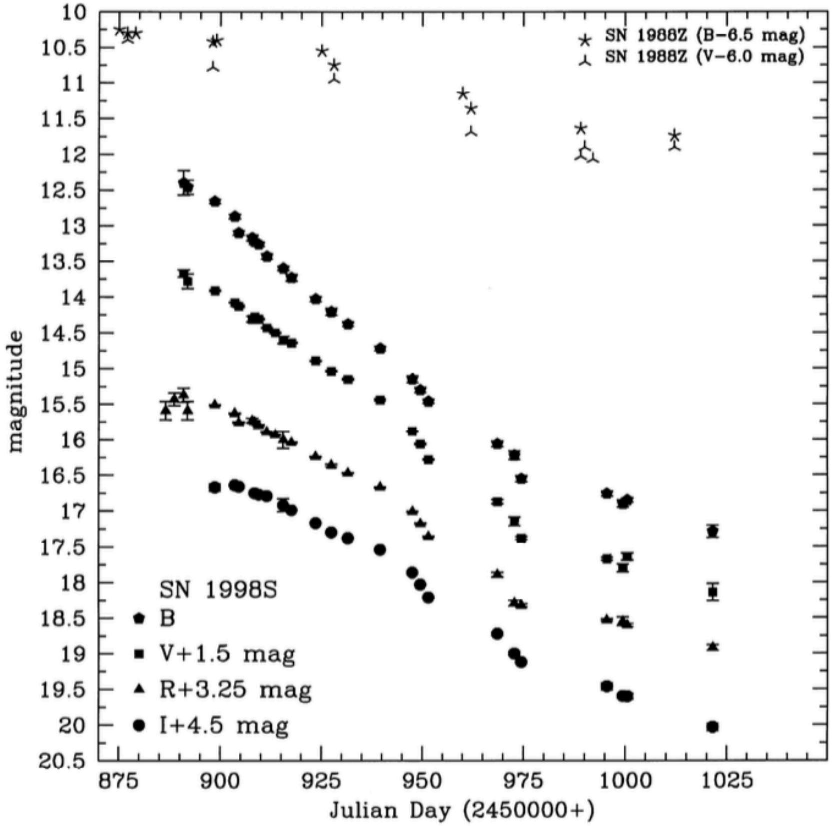
# Numerical Simulations of Interacting Supernovae

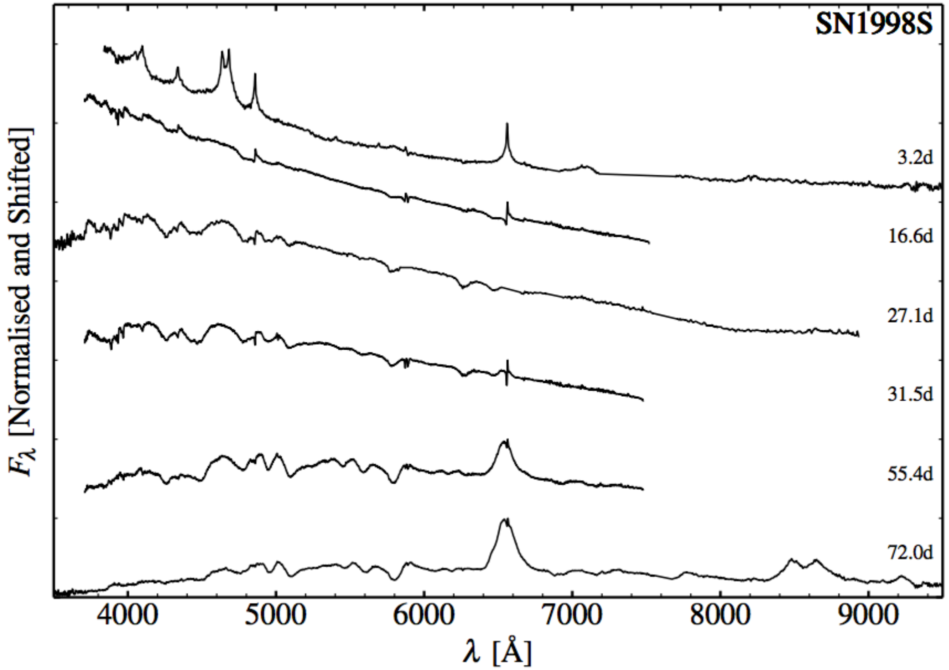
| model | $E_{\rm kin,SN}$ [$10^{51}$ erg] | $V_{\rm max,SN}$ [km s$^{-1}$] | $E_{\rm kin,CSM}$ [$10^{51}$ erg] | $M_{\rm CSM}$ [$M_\odot$] | $\dot{M}_{\rm CSM,in}$ [$M_\odot$ yr$^{-1}$] | $\dot{M}_{\rm CSM,out}$ [$M_\odot$ yr$^{-1}$] | $L_{\rm bol,peak}$ [erg s$^{-1}$] | B.C.$_{\rm @peak}$ [mag] | $(V-I)_{\rm @peak}$ [mag] | $t_{\rm peak}$ [d] | $\int L dt$ [$10^{51}$ erg] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| X | 1 | 9608 | 5.17(-4) | 2.89 | 0.1 | 0.001 | 3.024(43) | -1.06 | 0.15 | 19.4 | 0.32 |
| Xe3 | 3 | 16642 | 9.70(-4) | 2.89 | 0.1 | 0.001 | 1.204(44) | -1.35 | 0.11 | 15.7 | 0.88 |
| Xe3m6 | 3 | 16642 | 5.15(-3) | 17.31 | 0.6 | 0.006 | 2.080(44) | -1.39 | 0.01 | 55.7 | 2.05 |
| Xe3m6r | 3 | 16642 | 6.08(-3) | 26.73 | 0.6 | 0.006 | 1.818(44) | -1.05 | 0.06 | 68.3 | 2.13 |
| Xe10 | 10 | 30384 | 2.55(-3) | 2.89 | 0.1 | 0.001 | 6.399(44) | -1.46 | 0.13 | 12.7 | 2.92 |
| Xe10m6 | 10 | 30384 | 1.31(-2) | 17.31 | 0.6 | 0.006 | 1.091(45) | -1.80 | -0.04 | 34.2 | 6.89 |
| Xm3 | 1 | 9608 | 1.46(-3) | 8.66 | 0.3 | 0.003 | 3.906(43) | -0.84 | 0.13 | 47.9 | 0.49 |
| Xm6 | 1 | 9608 | 2.87(-3) | 17.31 | 0.6 | 0.006 | 4.751(43) | -0.80 | 0.27 | 77.5 | 0.63 |

- Huge diversity from variations in ejecta Ekin and CSM mass.
- Similar spectral evolution to 2010jl
- Ekin conversion efficiency of 30-70%



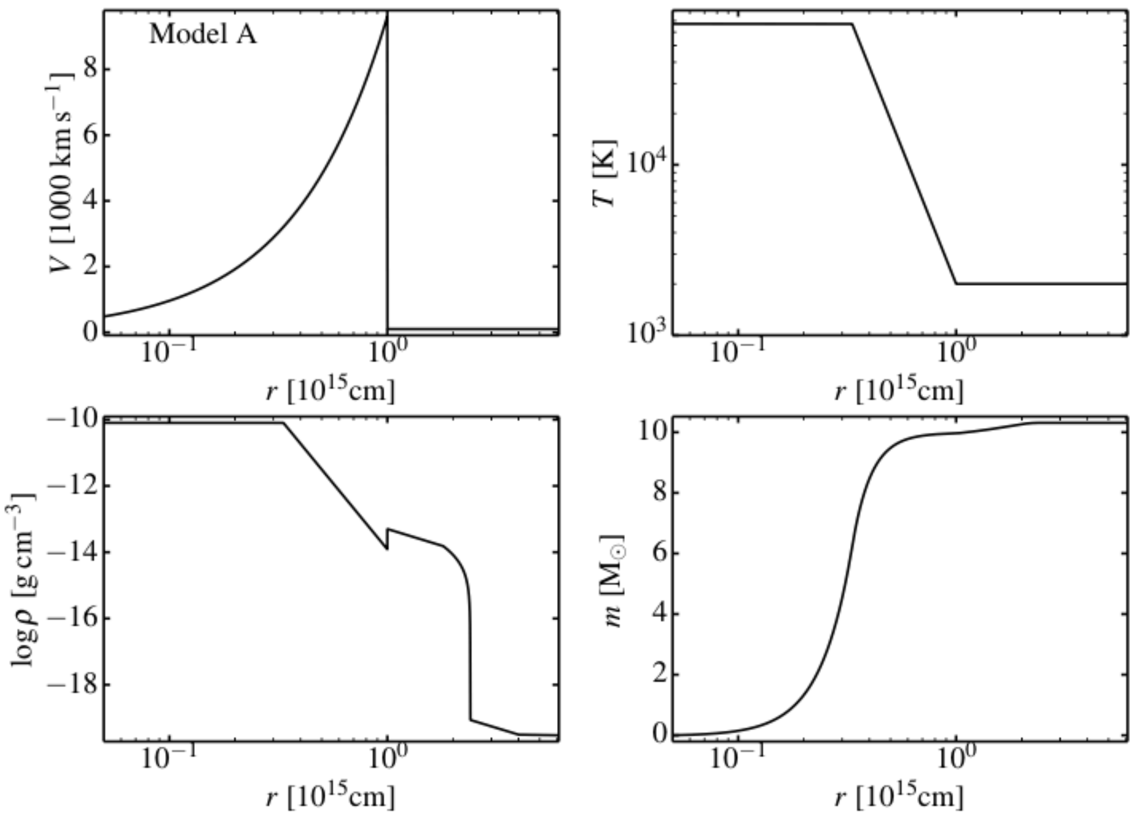
# The case of a lower CSM mass/extent: SN1998S



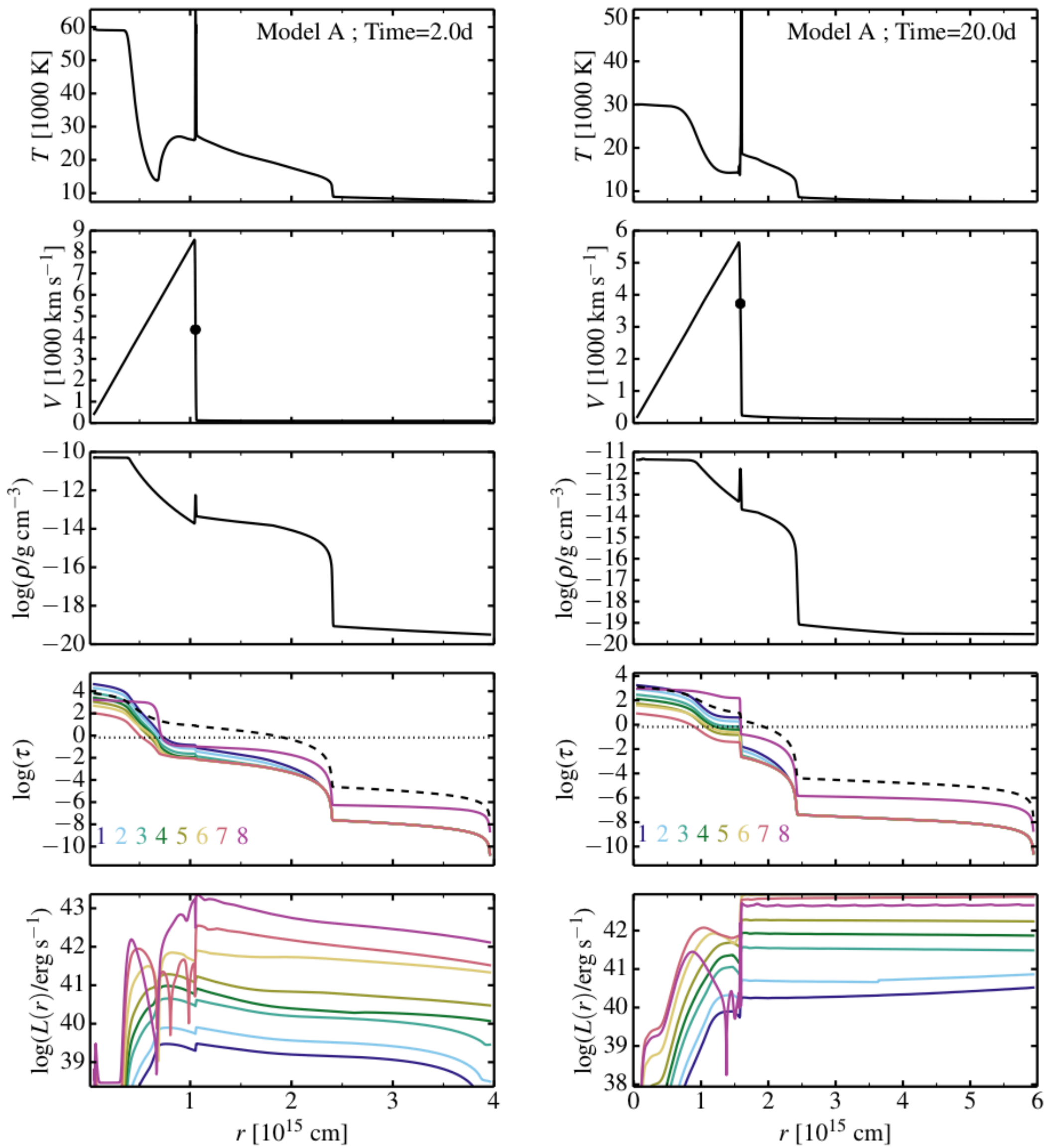



# Initial ejecta/CSM configuration for SN1998S
# 10Msun 10^51erg RSG explosion in 0.3Msun CSM

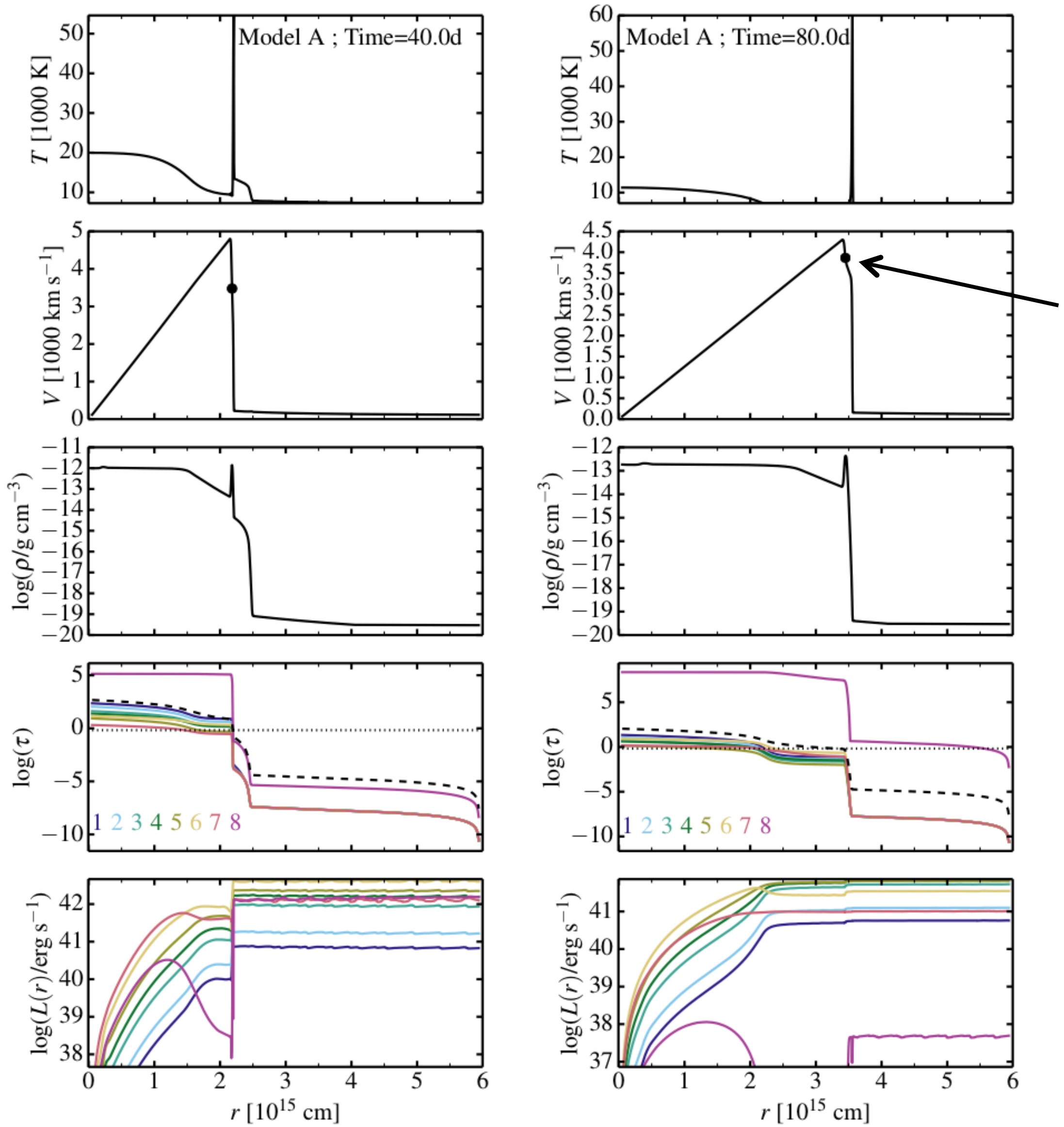
| | Inner shell | | | | | | Outer shell | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model | Type | Age [d] | $E_{\rm kin}$ [erg] | $M_{\rm tot}$ [$M_\odot$] | $V_{\rm m}$ [km s$^{-1}$] | $R_{\rm t}$ [$10^{15}$ cm] | Type | Age [d] | $E_{\rm kin}$ [erg] | $M_{\rm tot}$ [$M_\odot$] | $\dot{M}$ [$M_\odot$ yr$^{-1}$] | $V_{\rm m}$ [km s$^{-1}$] |
| A | Ejecta | 12.0 | 1.00(51) | 9.96 | 3000 | 1.00 | Wind | 1157.4 | 3.49(46) | 0.35 | 0.1 | 100 |



# Results from Radiation Hydro

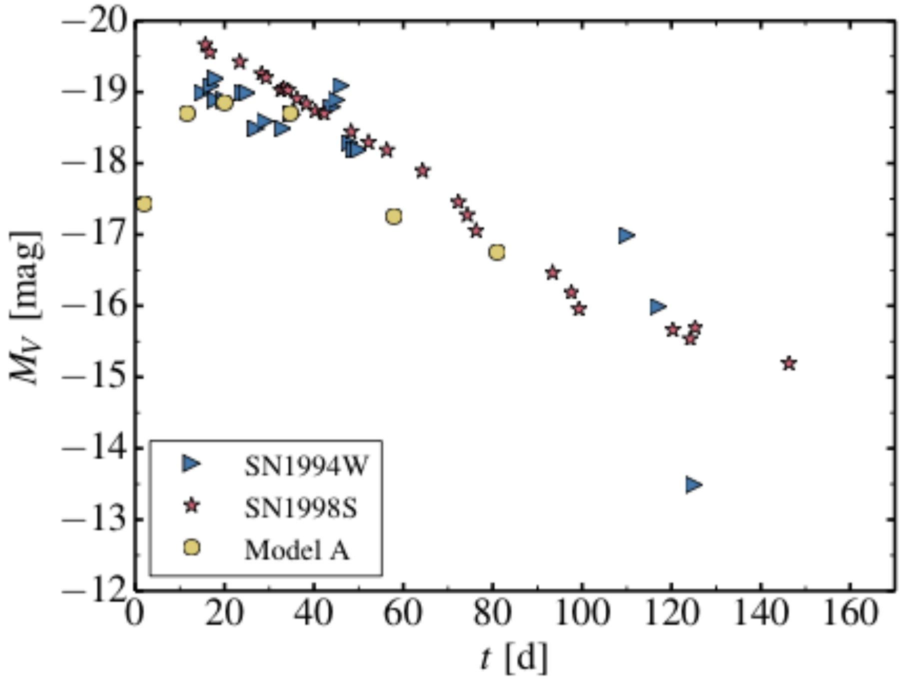


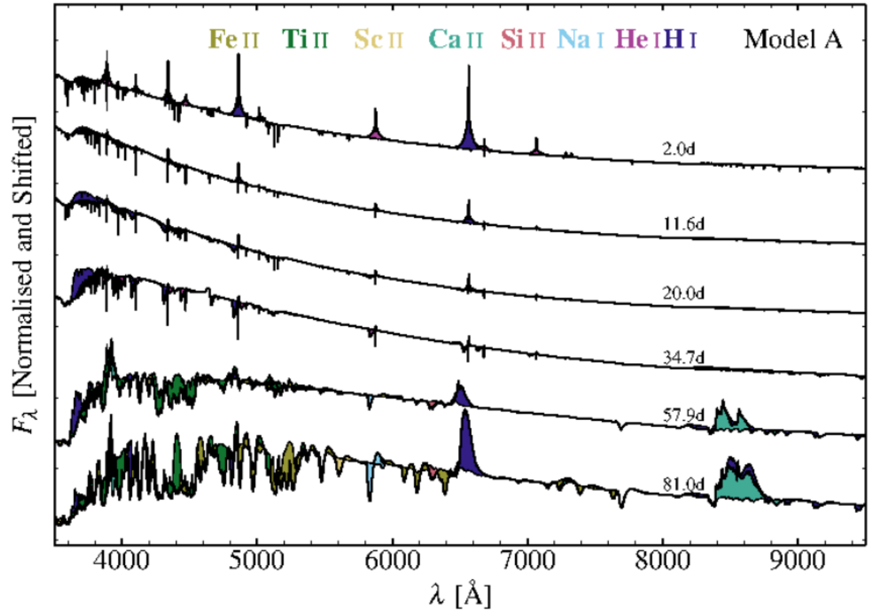
# Results from Radiation Hydro

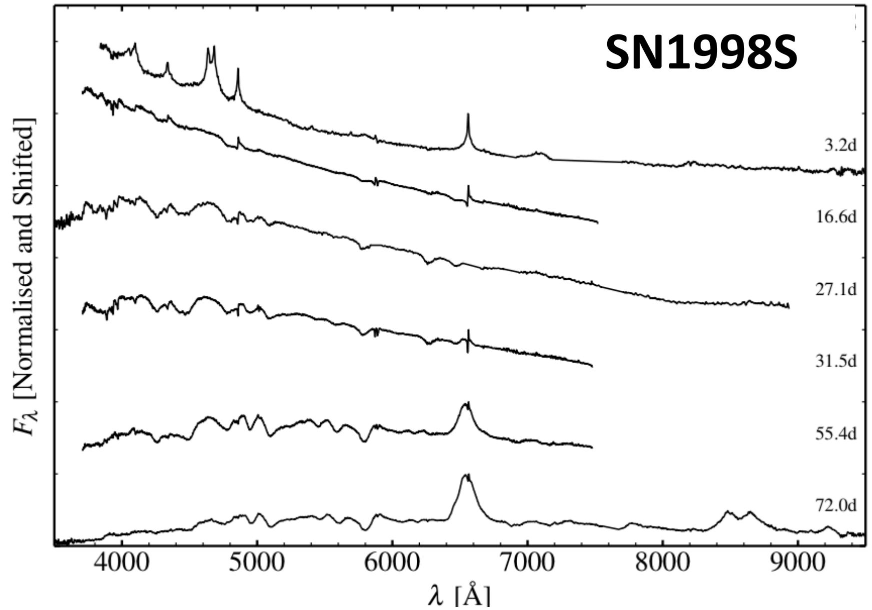



Dot: V(CDS)

# LC and spectral comparison for SN1998S




Model matches LC and spectra of 98S
Model matches LC of 94W but not the spectra (broad lines at late times)

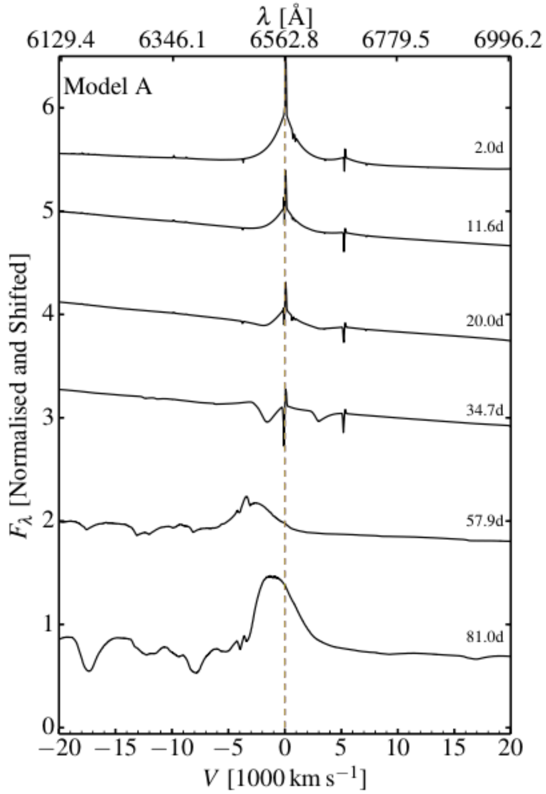
# Results from Radiative Transfer

Narrow lines: IIn

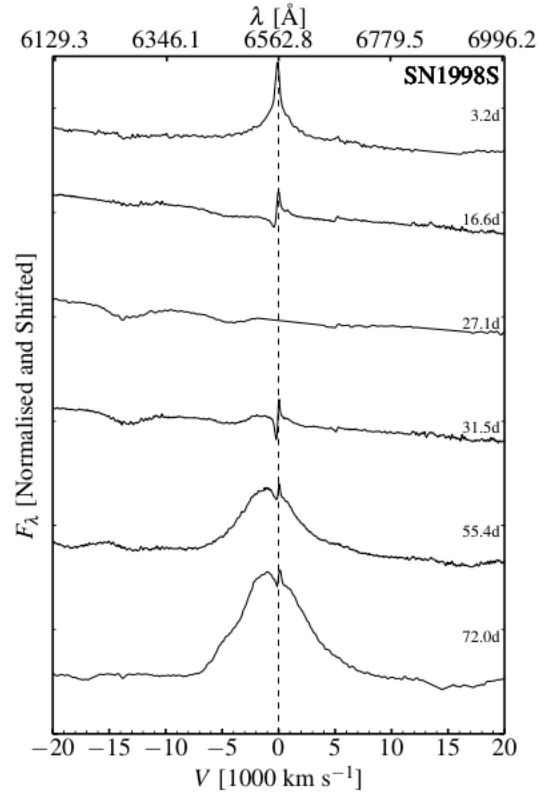
Pure absorption lines

**Broad** lines at late times

**Model A**



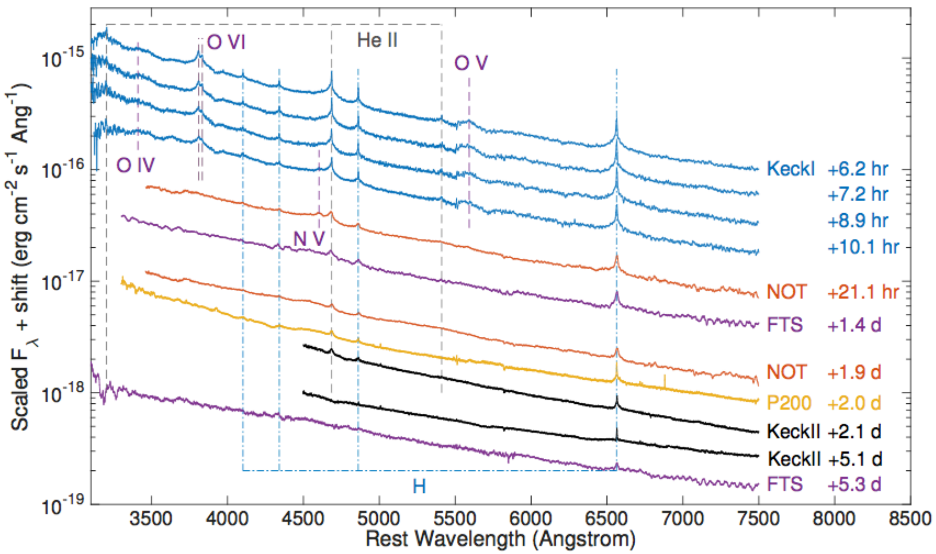

**Obs: SN1998S**



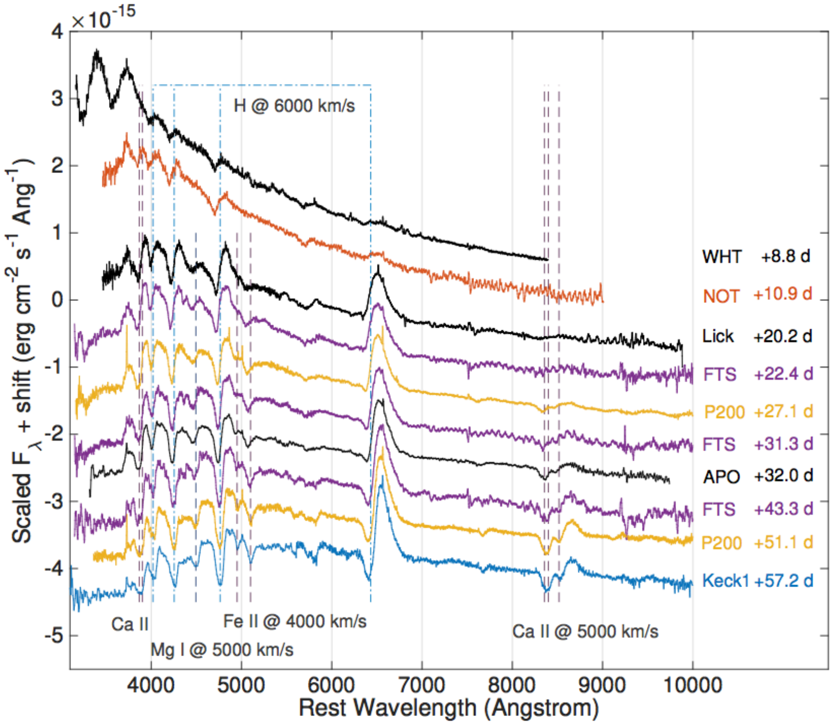
# Explosion in the RSG wind/atmosphere: SN2013fs

SN2013fs: Same as SN1998S but more rapid evolution (similar event: SN2013ca)

Yaron+17



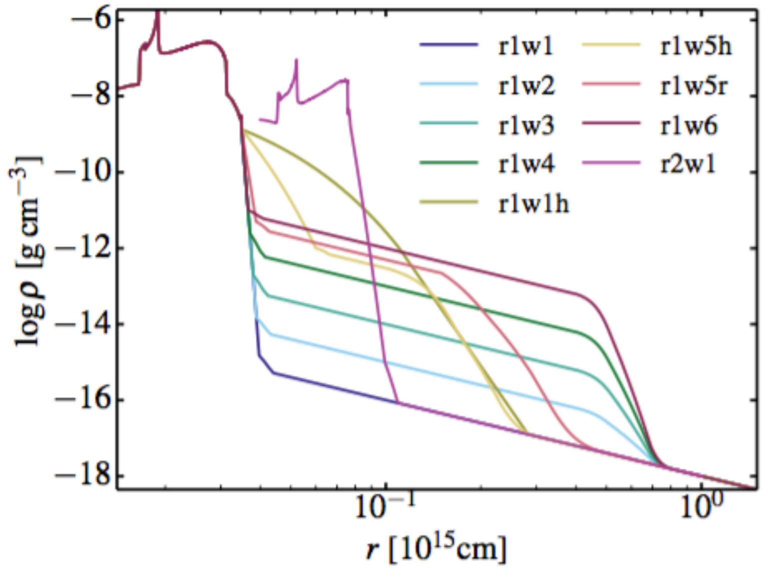

Early signatures of interaction




Evolution into a non-interacting / standard Type II

# Explosion in the RSG wind/atmosphere: SN2013fs

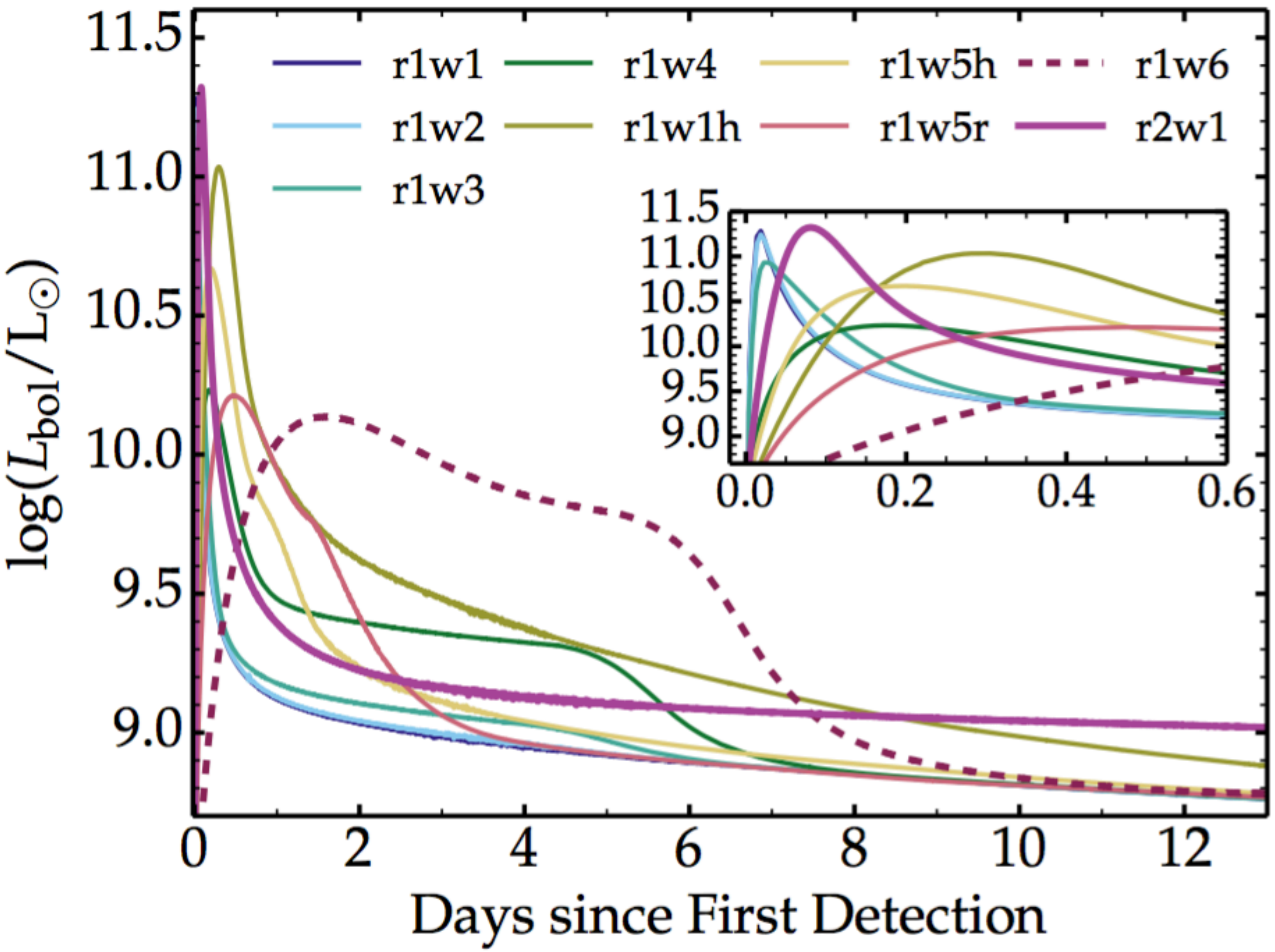
Put 0.001-0.1Msun of material on top of the RSG surface (wind/atmosphere), i.e., within 5-10Rstar




| Model | $t_{rise}$ [d] | $\Delta t_{max}$ [d] | $L_{bol,max}$ [erg s$^{-1}$] | $f_{drop}$ | $\int L_{bol}\,dt$ [erg] | $R_\star$ [$R_\odot$] | $M_{ejecta}$ [$M_\odot$] | $E_{kin}$ [erg] | $H_\rho$ [$R_\star$] | $n_\rho$ | $\dot{M}$ [$M_\odot$ yr$^{-1}$] | $M_{ext}$ [$M_\odot$] | $\tau_{ext}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| r1w1 | 0.018 | 0.062 | 7.38(44) | 146.2 | 6.65(48) | 501 | 12.52 | 1.35(51) | 0.01 | ... | 1(-6) | 2.75(-3) | 160 |
| r1w2 | 0.019 | 0.068 | 6.71(44) | 130.4 | 6.68(48) | 501 | 12.52 | 1.35(51) | 0.01 | ... | 1(-5) | 2.79(-3) | 160 |
| r1w3 | 0.025 | 0.15 | 3.30(44) | 57.4 | 6.66(48) | 501 | 12.52 | 1.35(51) | 0.01 | ... | 1(-4) | 3.05(-3) | 160 |
| r1w4 | 0.186 | 5.11 | 6.53(43) | 5.61 | 8.67(48) | 501 | 12.52 | 1.35(51) | 0.01 | ... | 1(-3) | 5.59(-3) | 169 |
| r1w1h | 0.30 | 0.755 | 4.16(44) | 11.98 | 2.10(49) | 501 | 12.52 | 1.35(51) | 0.3 | 12 | 1(-6) | 1.62(-1) | 4780 |
| r1w5h | 0.21 | 1.03 | 1.79(44) | 8.72 | 1.10(49) | 501 | 12.52 | 1.35(51) | 0.1 | ... | 3(-3) | 3.57(-2) | 1600 |
| r1w5r | 0.53 | 2.36 | 6.25(43) | 1.74 | 9.48(48) | 501 | 12.52 | 1.35(51) | 0.01 | ... | 5(-3) | 1.02(-2) | 353 |
| r1w6 | 1.94 | 7.00 | 5.24(43) | 2.02 | 1.99(49) | 501 | 12.52 | 1.35(51) | 0.01 | ... | 1(-2) | 3.04(-2) | 246 |
| r2w1 | 0.081 | 0.179 | 8.03(44) | 84.91 | 1.44(49) | 1107 | 12.57 | 1.24(51) | 0.01 | ... | 1(-6) | 6.14(-2) | 956 |

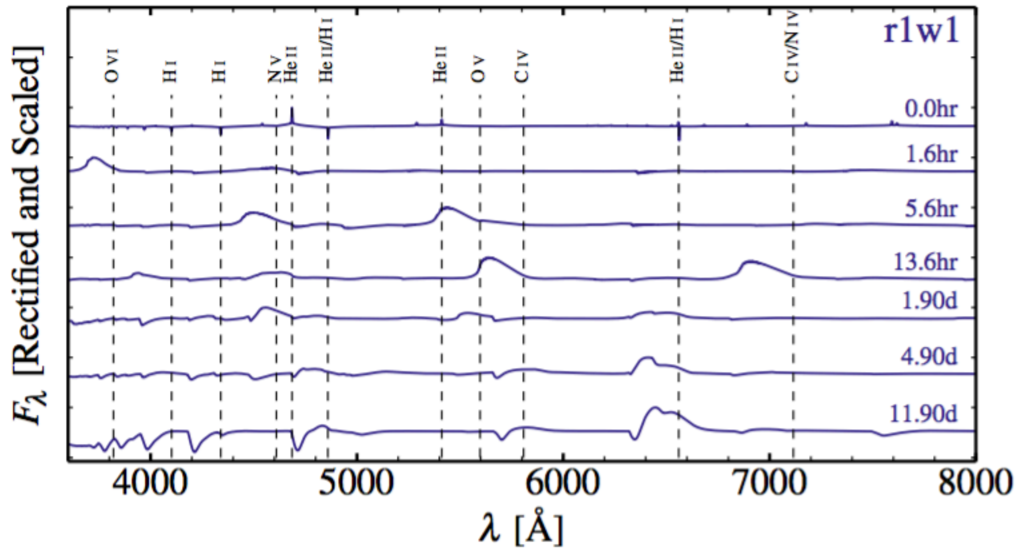
# Explosion in the RSG wind/atmosphere: SN2013fs

Bolometric light curves from radiation hydrodynamics simulation

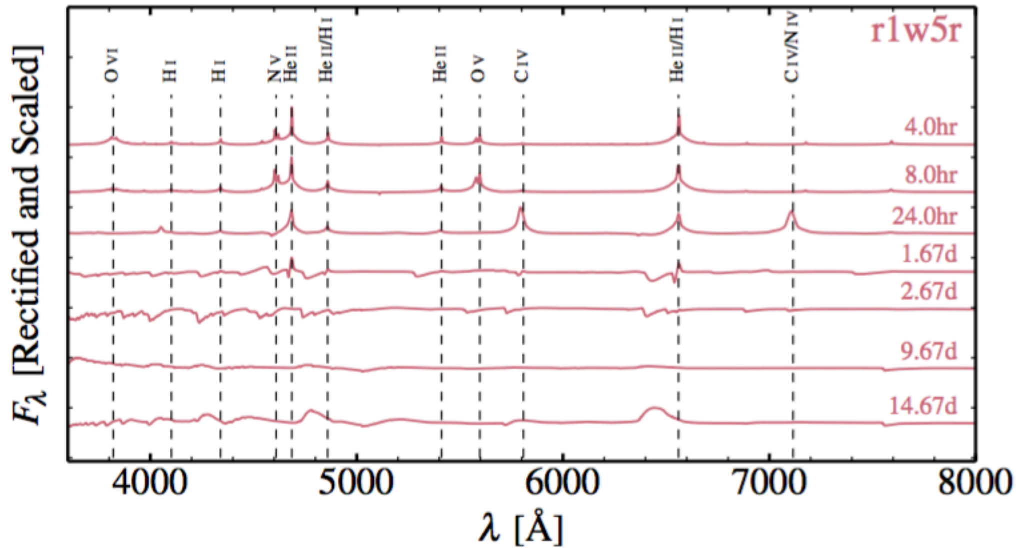


# Explosion in the RSG wind/atmosphere: SN2013fs

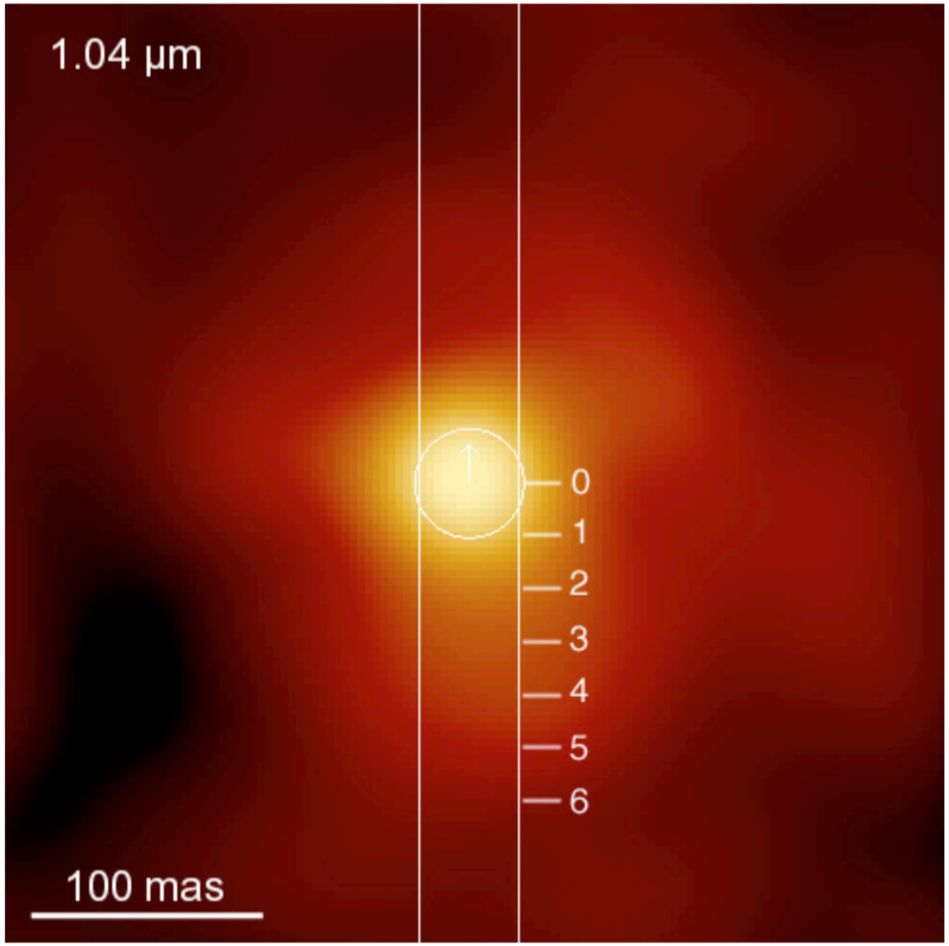
Low-density environment: Doppler-broadened blueshifted emission lines at all times




High-density environment: electron-scattering symmetric line profiles at early times



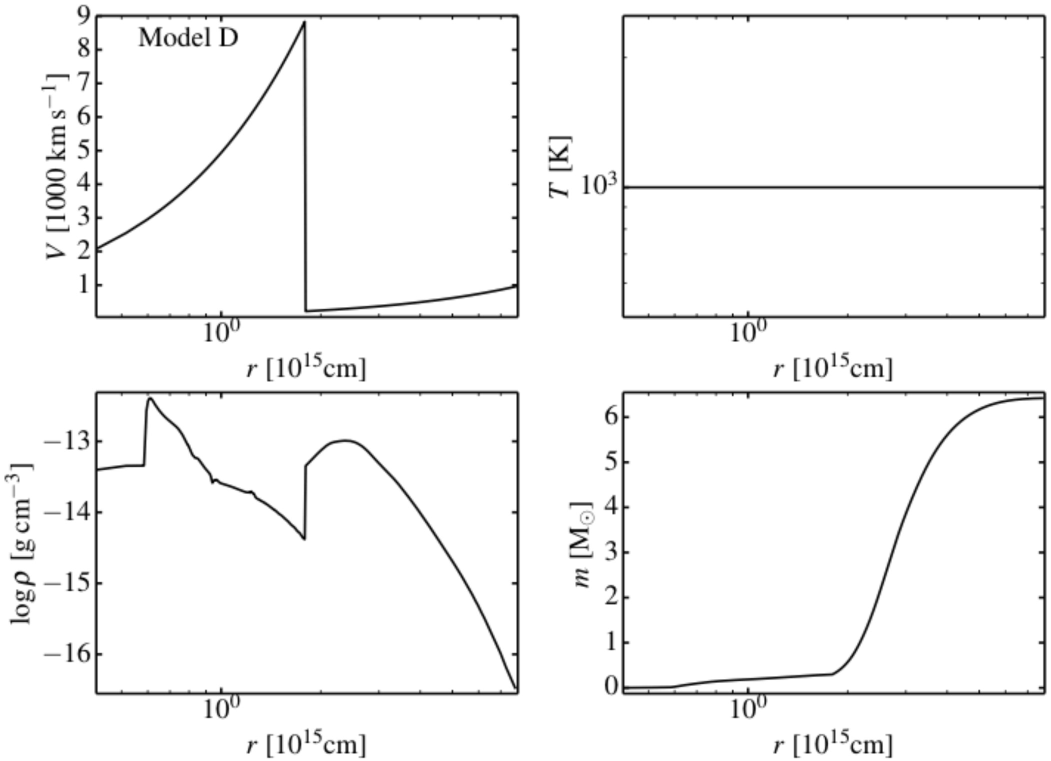
# Environment of Betelgeuse




Kervella+09

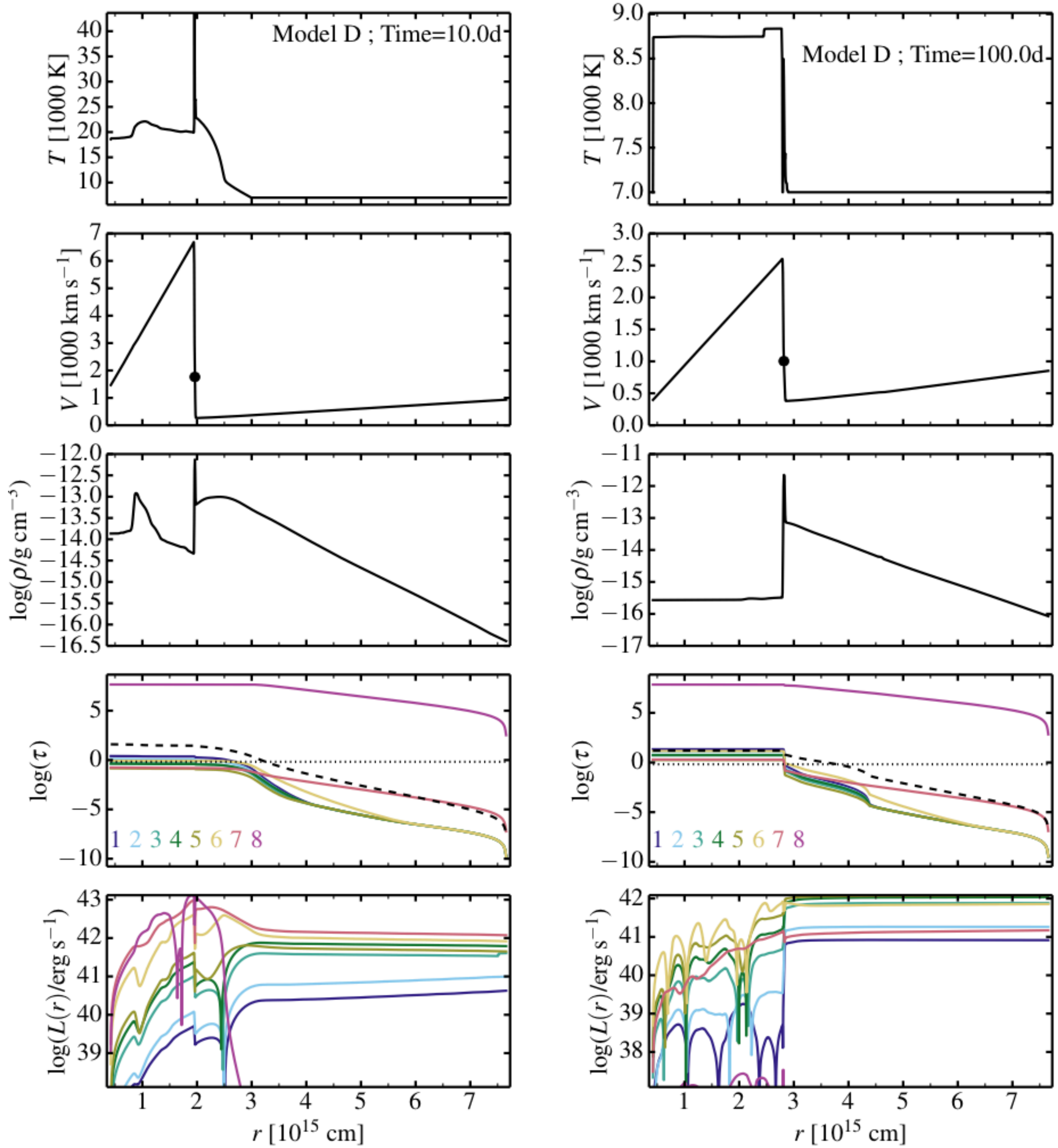
# Explosion of a He-core inside detached massive CSM

| | Inner shell | | | | | | Outer shell | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model | Type | Age [d] | $E_{kin}$ [erg] | $M_{tot}$ [$M_\odot$] | $V_m$ [km $s^{-1}$] | $R_t$ [$10^{15}$ cm] | Type | Age [d] | $E_{kin}$ [erg] | $M_{tot}$ [$M_\odot$] | $\dot{M}$ [$M_\odot$ $yr^{-1}$] | $V_m$ [km $s^{-1}$] |
| D | Ejecta | 23.4 | 6.77(49) | 0.29 | 4730 | 1.80 | Ejecta | 941.7 | 0.94(49) | 6.1 | ... | 377 |



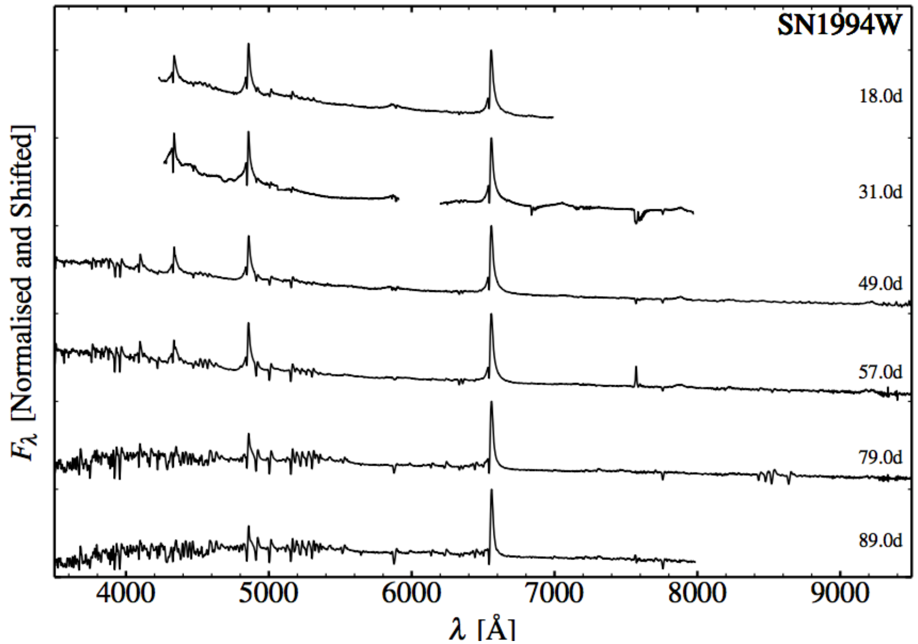
# SN1994W - Results from Radiation Hydro

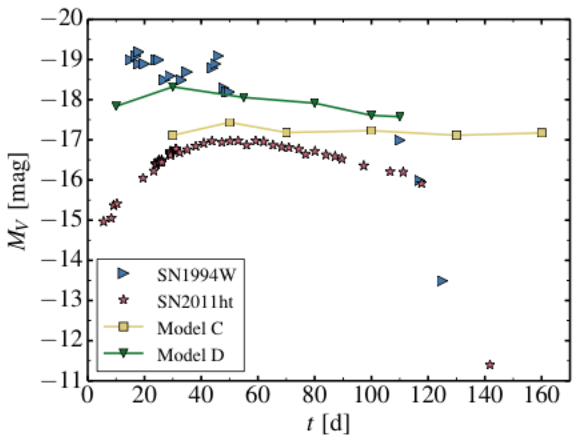
Strong deceleration of inner shell
Huge conversion efficiency of Ekin to Erad

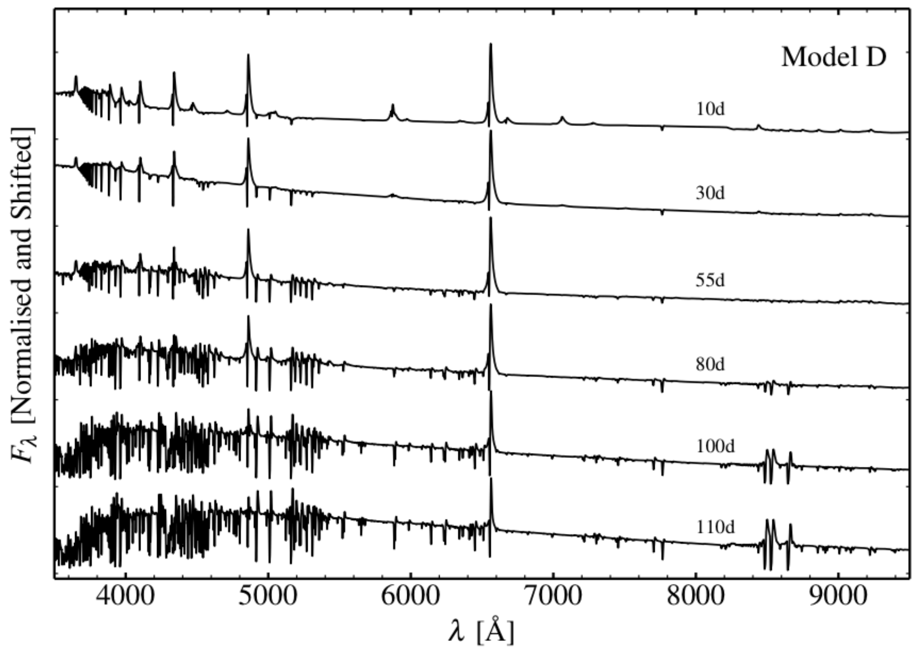


# SN1994W - Results from Radiative transfer

OK match to 94W light curve
Narrow lines at all times



# SN1994W - Results from Radiative transfer

Narrow Halpha getting narrower with time