Understanding Transients Through (UV) Spectroscopy

(with a focus on core-collapse SNe)

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Layout

- Basics of massive star evolution and explosion
- When/how are core-collapse SNe luminous in the UV?
- Insights from modeling:
  - Shock breakout
  - Explosions in a vacuum
  - Explosions in a CSM and proper interacting SNe
  - Late-time interaction
  - TDE (teaser)
- The need for UV data

Massive star evolution

Evolution of the core:

Nuclear burning in deep interior: H -> He -> C, O -> Si -> Fe core

Mixing processes affect surface composition (e.g. N enrichment)

Evolution of the envelope/surface:

$\mathrm{Mdot} \sim 10^{-5} M_{\odot}/\mathrm{yr}$, $v_{\infty}=10-10^{3}$ km/s, $M_{\mathrm{final}} < M_{\mathrm{initial}}$

Close binary interaction:

Mdot up to $\sim 10^{-3} M_{\odot}/\mathrm{yr}$

Wide range of possibilities (Case A,B,C .. mass transfer, Common Envelope, Merger etc)

Massive star properties inferred from SN observations:

$10\text{-}25 M_{\odot}$ RSG (BSG) stars with massive H-rich envelope => Type II-Plateau (few II-pec)

$3\text{-}5 M_{\odot}$ RSG/YSG and WR stars from binaries => Type IIb, Ib, Ic

Huge diversity of interacting SNe (unclear origin) => Type IIn, Ibn (few Icn and Ian)

Chronology of events in the life of a core-collapse SN

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

- **Generic** subsequent Evolution controlled by

Cooling (Expansion & Radiative losses)

versus **Heating** (Radioactive decay / Recombination / CSM interaction / Magnetar …).

modulo Transport (dynamic radiative diffusion --- opacity/composition/ionization)

Their variations cause the diversity of CCSN Light Curves and Spectra

- **Weeks to months**: **Photospheric phase (τ>>1)**
- **After a (few) month(s)**: Transition to **Nebular phase (τ<<1)**

Properties and processes

- At breakout : T_{phot} ~ 10^5-10^6K for R_{star} from 1 to $10^3 R_{sun}$ (WR or RSG)

  => Radiative precursor: flash of X-ray/UV radiation for R_{star}/c (or $\tau R_{star}/c$) => UV luminous

- Adiabatic cooling: T(m) ~ 1/R(m). Steeper with radiative losses + acceleration

  => $T_{phot} > 10^4$K for ~ 0.1–10d (WR-RSG) => Hot BB, ionizing photons => UV luminous

  => Key processes: Photoionization + recombination, electron scattering

  => Photospheric layer conveys information on T, ionization, composition, ρ, R_{star}

  Note: $\rho(m,t) \sim \rho(m,t_0)\,(t_0/t)^3$ so 1d –> 2d comparable to 1yr –> 2yr

- Interaction with atmosphere, wind, or distant CSM:

  => many mechanisms: wave excitation, nuclear flashes, binary effects/RLOF …

  => Potential power source at all times

  => Thermalized shock power comes out in UV and optical => UV luminous

Insights from modeling

Previous work on modeling UV radiation from SNe

- **Pluses**: origin of emission (RS/FS), flash ionization of ER in 87A, N/C ratio (Fransson et al.)
- **Minuses**: Only few SNe modeled (generally SNe with signs of interaction)
  Lack of a physically consistent model

Future work: Aim for global consistency

- Need for a stellar evolution and explosion model (progenitor <-> ejecta <-> CSM)
- Need for Radiation-hydrodynamics (RHD) and Radiative transfer (RT) (light curves and spectra)
- Need to confront to better data (Rapid response, early/late times, UV & optical)
- Need data for **all** core-collapse SN types (so far, brightest objects, usually interacting)

Numerical approaches (personal)

1) Combined RHD + post-processing with RT :
   -> Option 1: assume homologous expansion => nonLTE time-dependent RT (e.g., for SN with no interaction)
   -> Option 2: non-monotonic velocity solver => nonLTE steady-state RT (e.g., for strong interactions)
2) Treatment of shock power in nonLTE time-dependent RT (e.g., for weak interactions)

1D Non-LTE Time-Dependent Radiative Transfer with **CMFGEN**

(Hillier & Miller 1998; Dessart & Hillier 2005ab,2008; Hillier & Dessart 2012)

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

Radioactive decay

Shock power

Energy Equation:

$$\rho \frac{De}{Dt} - \frac{P}{\rho}\frac{D\rho}{Dt} = 4\pi \int_0^\infty \chi_\nu (J_\nu - S_\nu)\, d\nu \quad \underbrace{+\, De_{decay}/Dt + De_{shock}/Dt}_{\text{optional}}$$

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:

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

Non-LTE Time-Dependent Radiative Transfer with **CMFGEN**

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Radioactive decay

power

In case of a **weak** interaction with CSM, we can treat shock power directly in RT (energy equation)

=> Standard nonLTE time-dependent approach

In case of a **strong** interaction with CSM, we must take initial conditions (R, V, T, ρ) from RHD simulation

⇒ Steady state, non-monotonic velocity solver with T set to T_{hydro}

Various approaches offer flexibility to model SNe at different times with different power sources

Radiati

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:

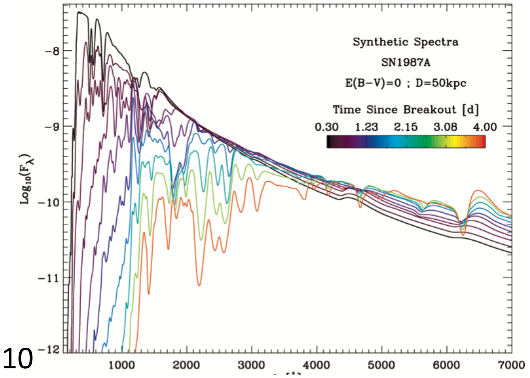
$$\frac{1}{cr^3}\frac{D(r^3 H_\nu)}{Dt} + \frac{1}{r^2}\frac{\partial(r^2 K_\nu)}{\partial r} + \frac{K_\nu - J_\nu}{r} - \frac{\nu V}{rc}\frac{\partial H_\nu}{\partial \nu} = -\chi H_\nu$$

Model LCs and spectra for BSG and RSG explosions – No CSM

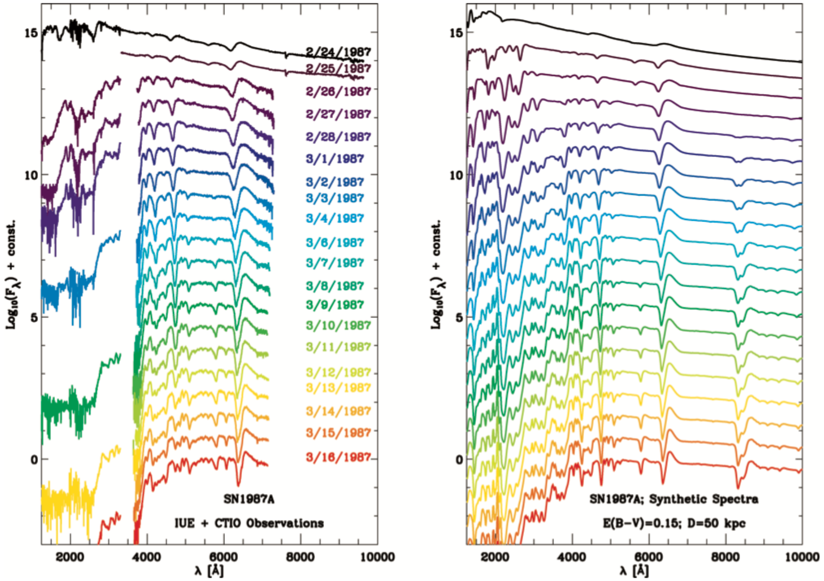
- Method: nonLTE steady-state RT
- Rapid redward color evolution => Probe photosphere cooling
- Increase in line widths (Doppler broadened) => ejecta acceleration
- High ionization lines of He, CNO etc in the UV
- Potential constraints on abundances, metallicity, reddening

Problem: Models are unconstrained at such times : no UV, no optical spectra

SN1987 during the first days

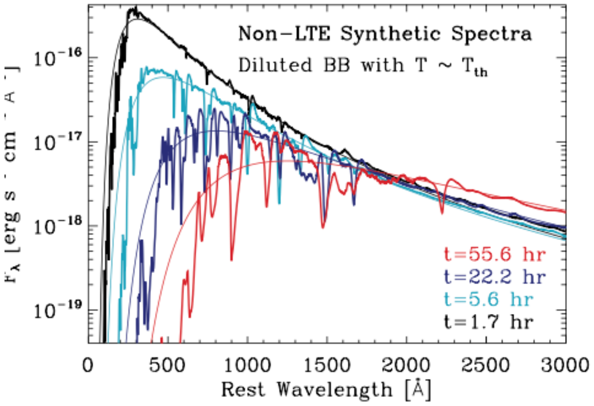


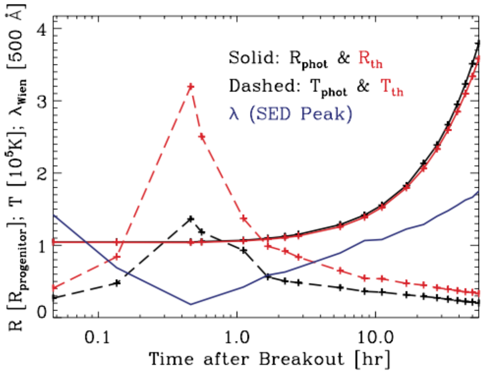
Dessart & Hillier 2010



RSG star explosion; The first hours to days (Gezari+08)

Witnessing the acceleration and cooling of the ejecta



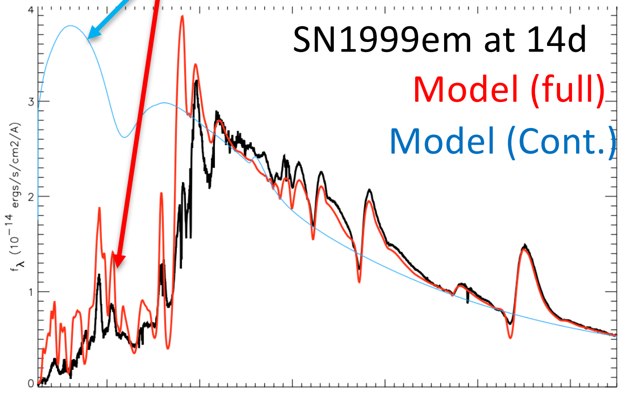


SN II at early times. No CSM

- Method: nonLTE steady state, \`photospheric’ modeling
- Constrain photospheric properties (T, ρ, X_i, V), line formation line blanketing, reddening

Problem: HST spectra too late (too slow response; miss UV bright phase) or only Swift photometry

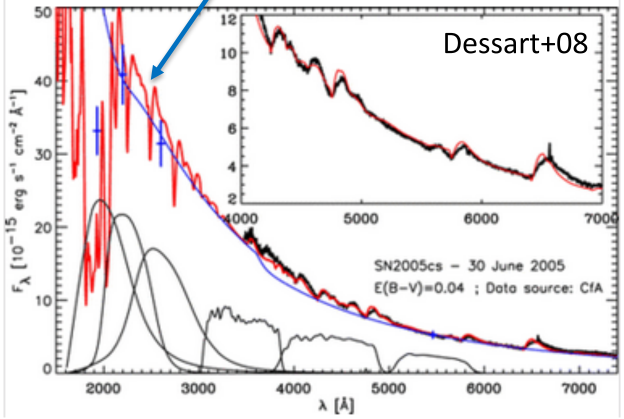
Strong influence of line blanketing in UV
Huge offset Full Flux vs Cont flux.



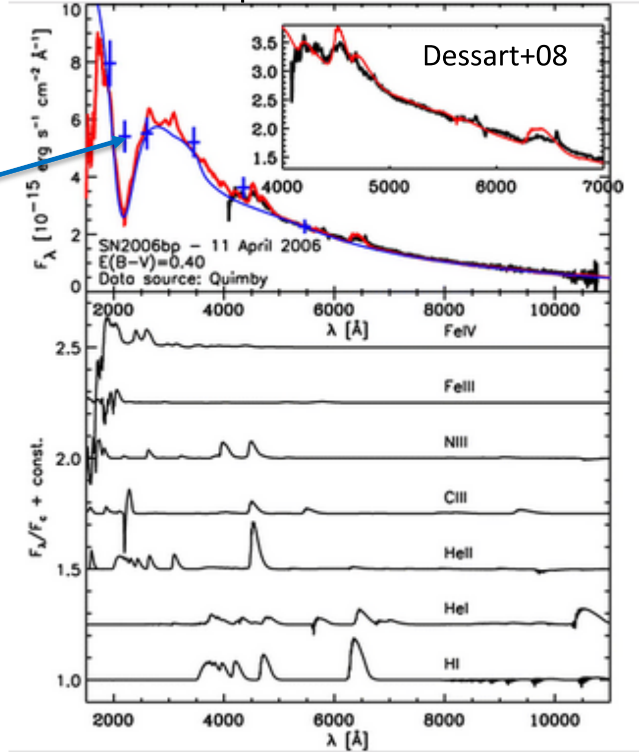
Dessart & Hillier (2005)

Only Swift data in UV

SN2005cs at 5d



SN2006bp at 3d



Quimby+08

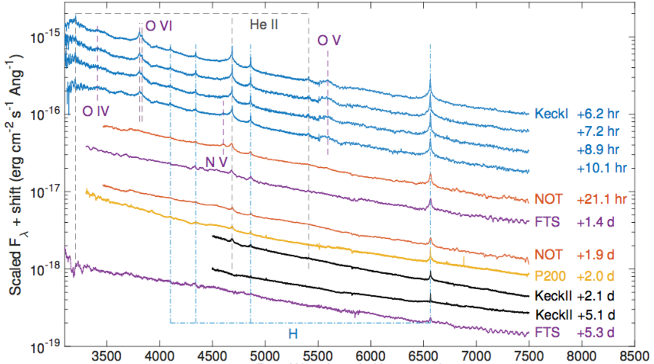
Type II SNe with CSM

Method: RHD + post-treatment with RT (Non-monotonic velocity solver)

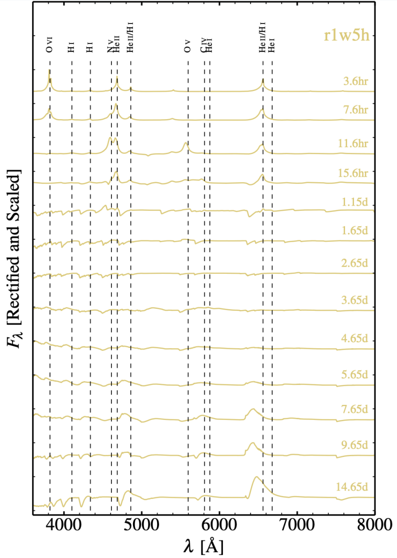
Strong UV flux, weaker optical flux, electron-scattering broadened lines
=> Probe of CSM, mass loss, atmospheric structure
Rapid evolution on day timescale

Problems: **rarely** observed in optical, **never** observed in UV
Fast response essential

SN2013fs in optical range (Yaron+17)

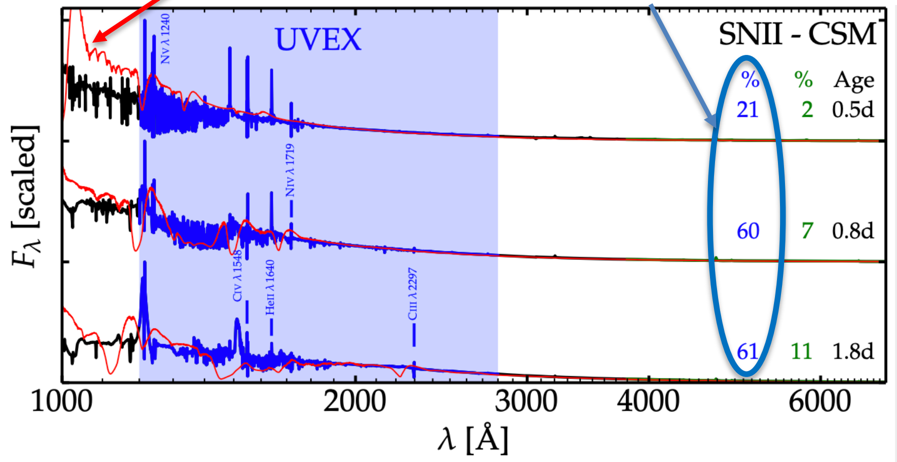


Simulation from Dessart+17
$\dot{M}$~$10^{-2}$$M_\odot$/yr within 5x$10^{14}$cm



NoCSM case

Fractional UV flux



Dessart+17

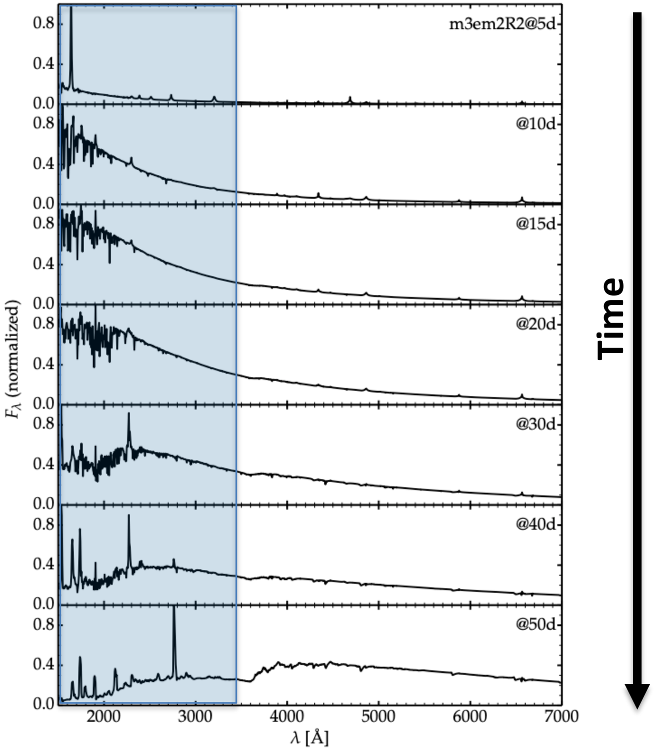
RSG star explosion in extended CSM (e.g. SN1998S)

Spectrum formation in CSM, then dense shell, then ejecta (witnessed in SN1998S)

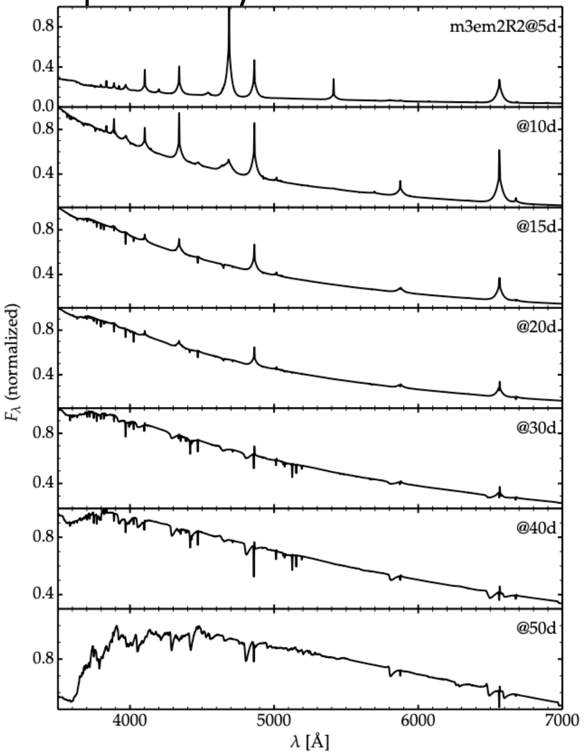
UV flux >> Optical Flux for many days

Never observed in UV

UV + optical



Optical only



Unique spectral evolution

Already observed (SN1998S,Leonard+00; SN2020tlf, Jacobson-Galan+22)

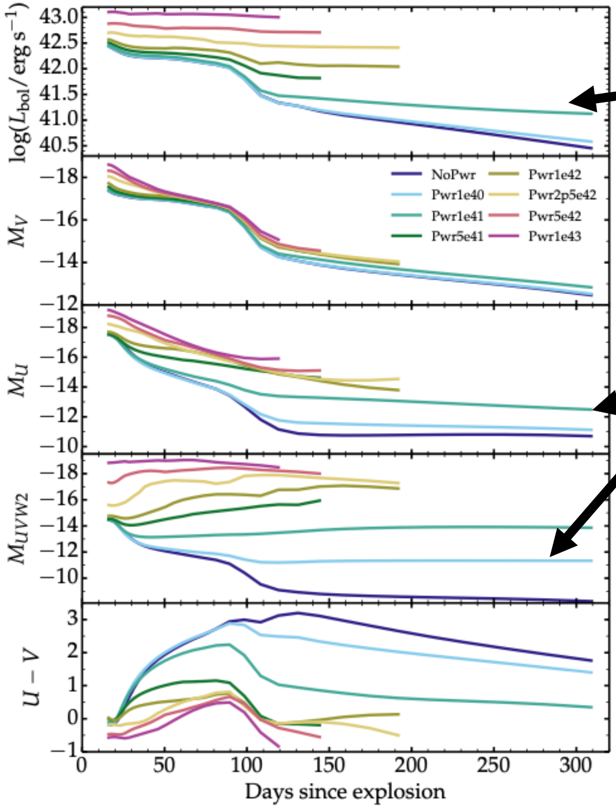
Note: Information in optical is not bad.
Rapid response is the main challenge

Time-dependent nonLTE radiative-transfer with shock power

Dessart+22

Method: nonLTE time dependent RT with constant shock power injected in outer dense shell

Tests from 10^{40} to 10^{43}erg/s (Mdot from 10^{-6} to $10^{-3}M_{\odot}$/yr)



At the end, interaction always wins!

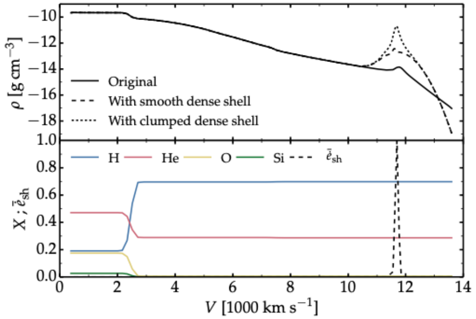
Weak impact in optical

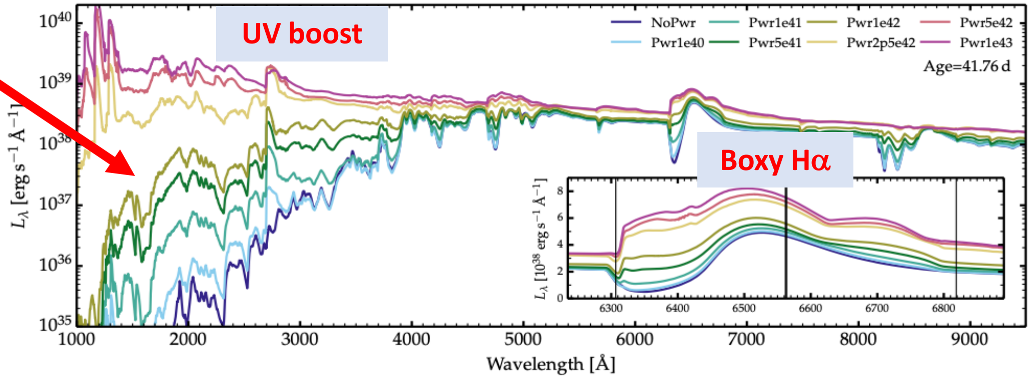
Strong impact in the blue

Critical information in the UV

Heuristic approach

Inject shock power in outer dense shell

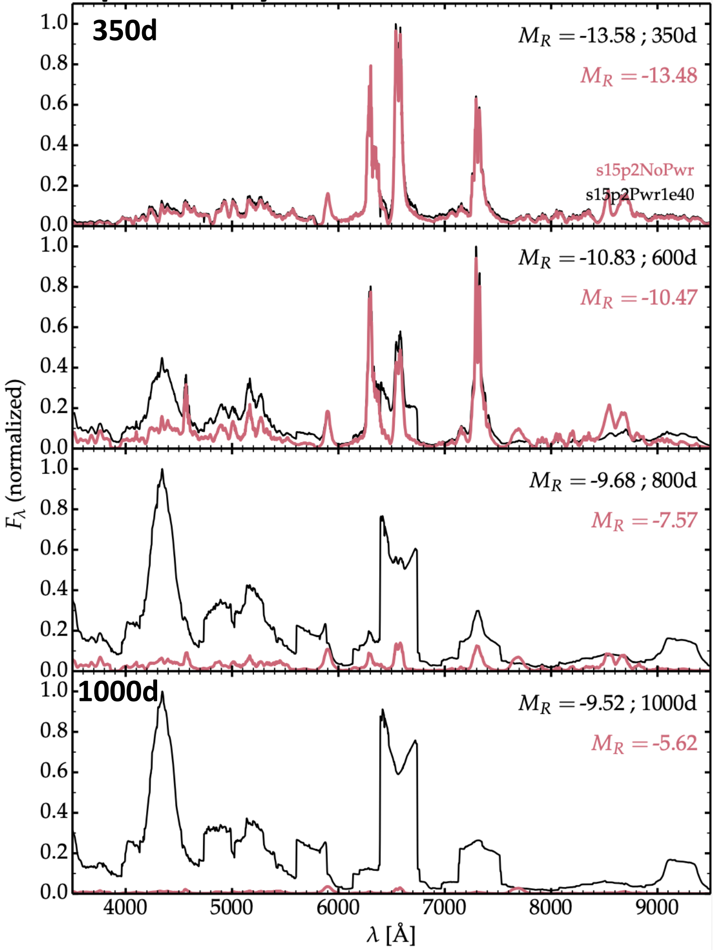




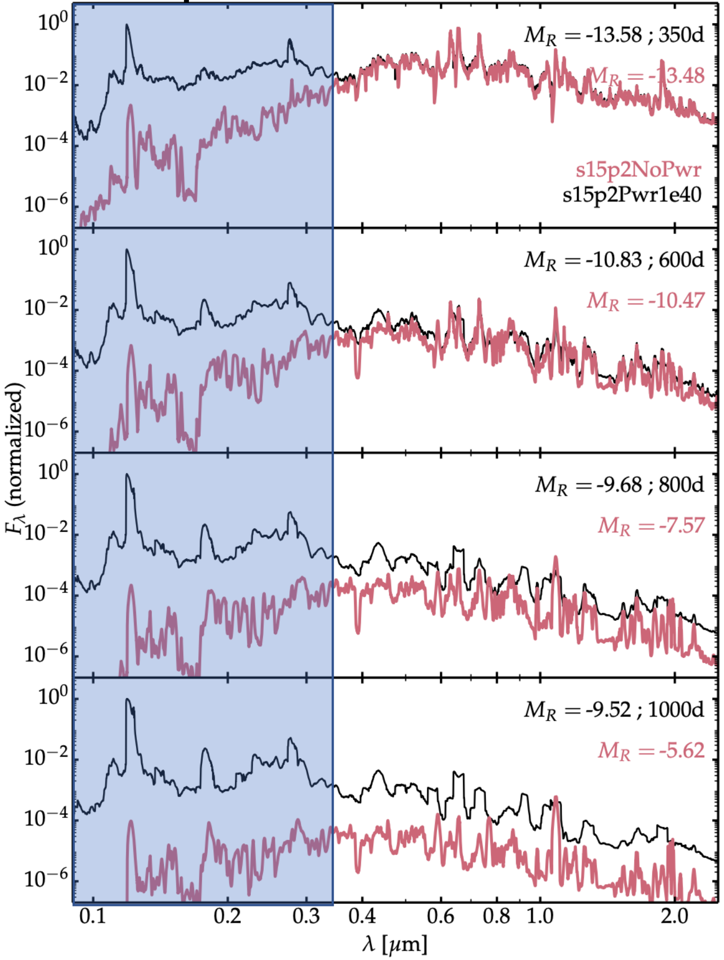
Spectroscopic evolution in UV and optical until 3 years

Model comparison with/without shock power of 10^{40}erg/s

Optical only

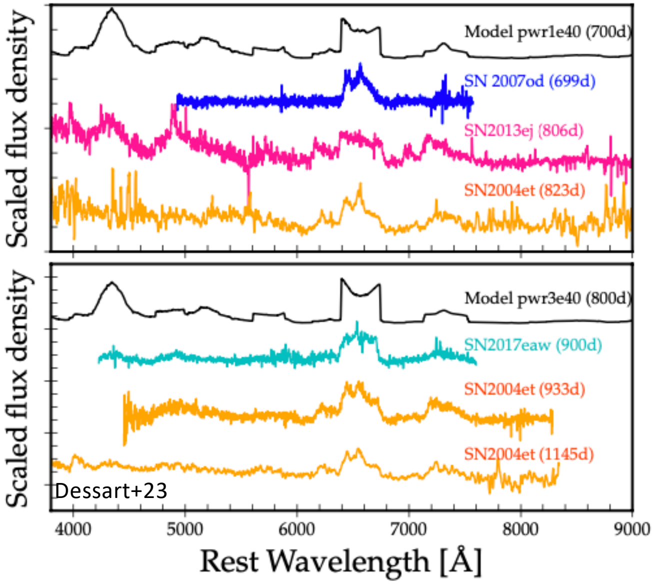


UV+ Optical + NIR



Objects with late time interaction
show Hα emission
But UV flux should be much greater
Method needs improvement

Optical observations vs models at 3 yr



Dessart+23

Spectroscopic evolution in UV and optical until later times

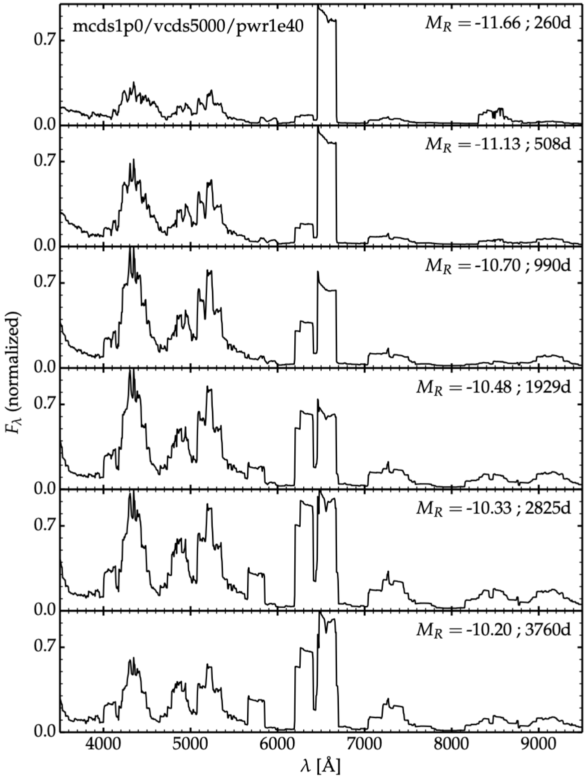
Work in progress (configuration analogous to SN1998S):

Evolution of ejecta/CSM until the birth of a remnant (10-20yr)

Shock power injected in $1M_{sun}$ dense shell => strong thermalization

Fails to produce high ionization lines from low density CSM: more work needed

Optical only

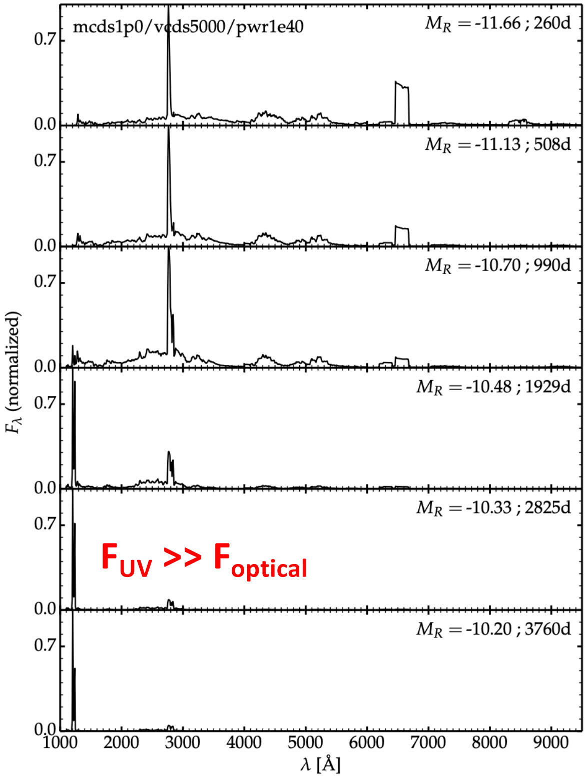


~1yr

~3yr

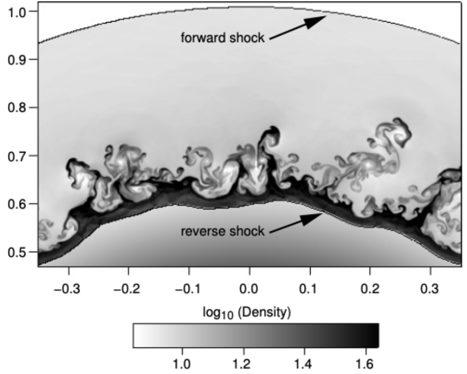
~10yr!

UV + optical



$F_{UV} >> F_{optical}$

Interaction simulation by John Blondin



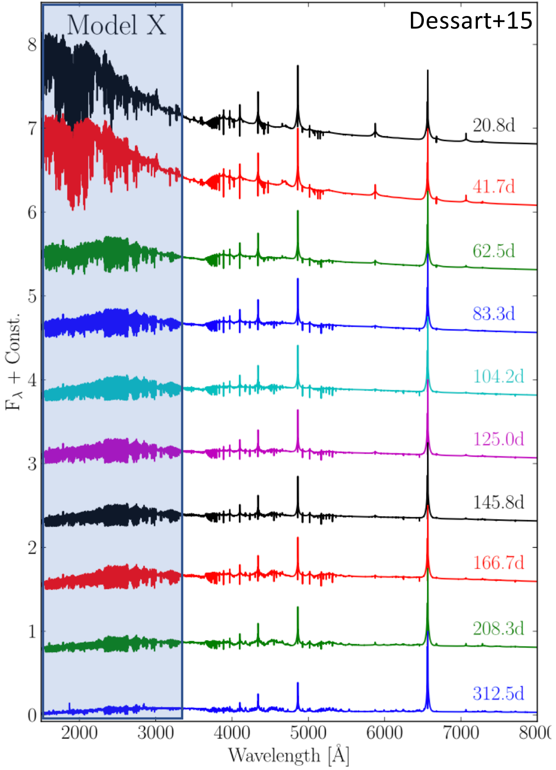
=> Need calibration with 3D RHD simulations

Super-luminous Type IIn SN and Type Ibn SNe

RHD + RT with non-monotonic velocity solver
Line formation in CSM and dense shell
Narrow lines first and broad (blue-shifted) lines later
“Scaled-up” version of SN1998S

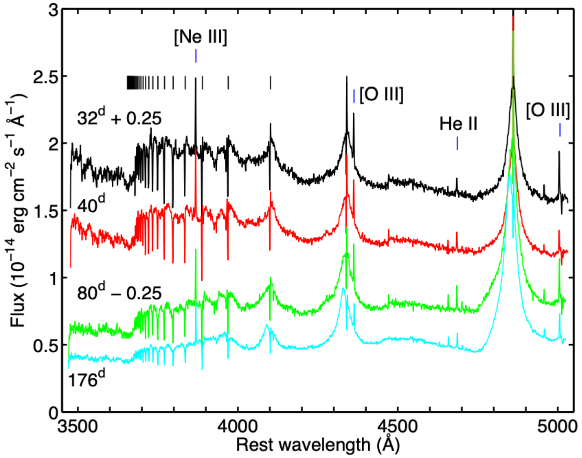
Type Ibn SN2020nxt
HST + ground based
Tough to match the UV (missed early phase)
Wang+ in prep.

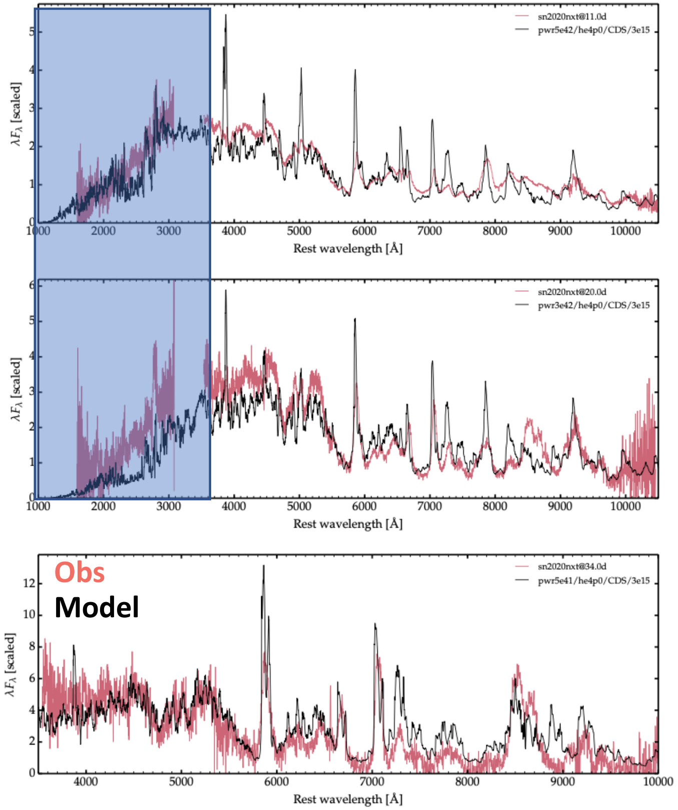
Model for explosion in a dense wind



Type IIn SN2010jl:
Model for explosion in a dense wind

Observations (Fransson+14)





Tidal Disruption Events

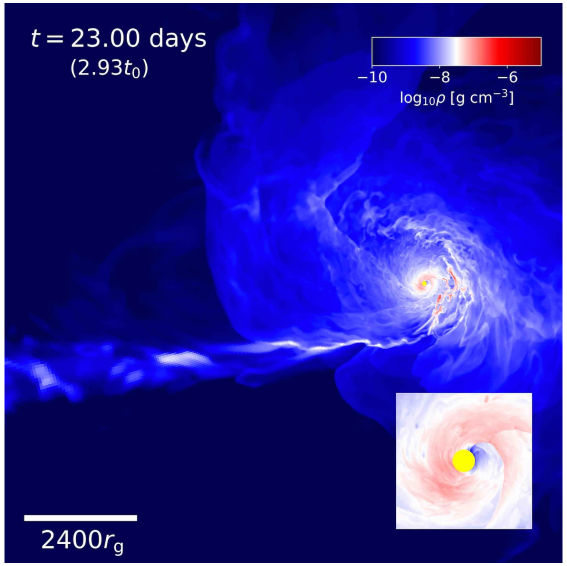
Work in progress (with Taeho Ryu and Suvi Gezari)

Post-process 3D GR-hydro simulations with 1D…

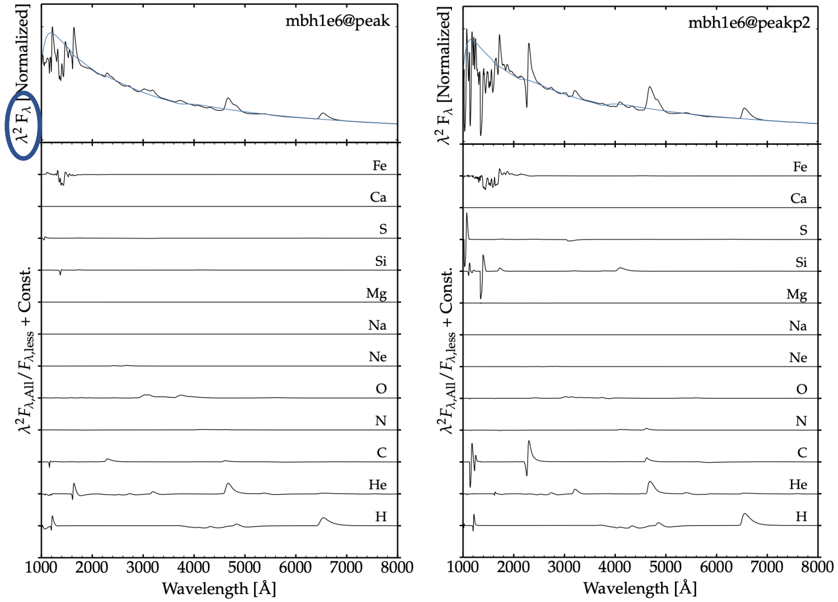
RT assumes steady state, T=T$_{hydro}$, Z$_\odot$

Equatorial slice through 3D GR-Hydro of TDE of 3M$_\odot$ star and 10^{5}M$_\odot$ BH

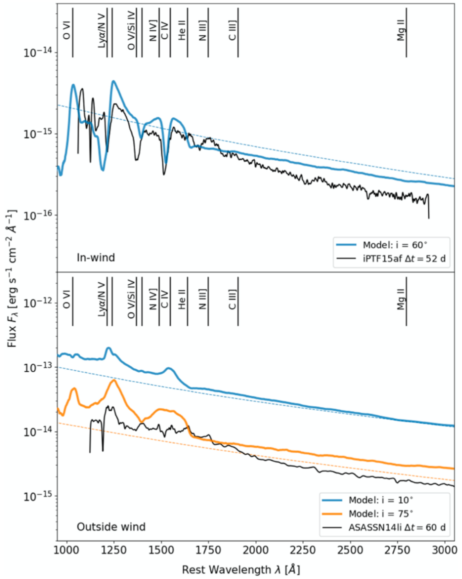
Ryu+ in prep



1D RT exploration for two epochs

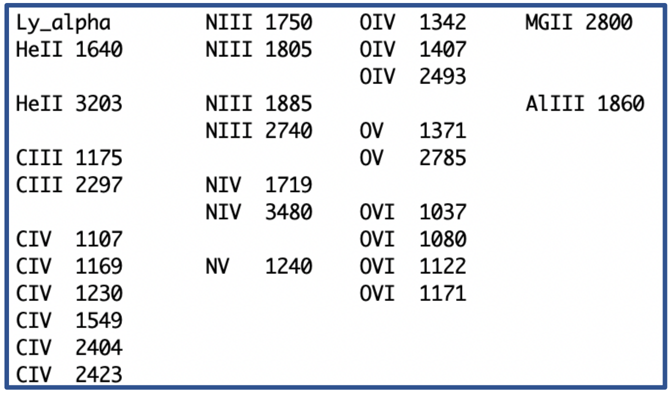


2D RT calculations for disk wind from TDE (Parkinson+22)



The need for UV data

- Most Type II SNe should be very luminous in UV for days (II-P) or years (IIn)
- Line diagnostics: Resonance transitions (high density; CDS) & Forbidden lines (low density, CSM)
- Any hope to include MgII2800 in the UV spectrograph?
- UV range critical to constrain bolometric luminosity => SN ‘Engine’ (ideally need X-ray+UV+optical+IR)
- UV range is essential to reveal interaction => mass loss / CSM
- Rapid-response to catch the SN while hot and luminous
- Observe from early to late times (wind/CSM on all scales?)
- Follow all core-collapse SN types (-> late-time interaction)
- Strong diversity of SNe in optical => Probably huge in UV
- UV spectra: an uncharted territory for transients



```
Ly_alpha          NIII 1750    OIV  1342    MGII 2800
HeII 1640         NIII 1805    OIV  1407
                               OIV  2493
HeII 3203         NIII 1885                 AlIII 1860
                  NIII 2740    OV   1371
CIII 1175                      OV   2785
CIII 2297         NIV  1719
                  NIV  3480    OVI  1037
CIV  1107                      OVI  1080
CIV  1169         NV   1240    OVI  1122
CIV  1230                      OVI  1171
CIV  1549
CIV  2404
CIV  2423
```

The need for UV data

But

UV range very difficult to model

Sensitive to T, ρ, ionization, composition, reddening => Strong blanketing

UV flux: Continuum vs. lines

Need for model development in coming years