Radiative-transfer Modeling of Massive-star Explosions
Superluminous Supernovae

Luc Dessart[1] and D. John Hillier[2]

[1] :Laboratoire d'Astrophysique de Marseille

[2] :University of Pittsburgh

In collaboration with

Stéphane Blondin (LAM)

Roni Waldman & Eli Livne (Racah Institute, Jerusalem)

Stan Woosley (UC Santa Cruz)

Modeling of SN radiation: Motivation

- Probes for stellar evolution: progenitor star (Id., M_i, M_f, M_{core}), rotation, metallicity, composition (H, He, IME, IGE, s-process)
- Probes for explosion mechanism: energy, nucleosynthesis (^{56}Ni), remnant (NS, BH)
- Probes of their environments: Z, IMF (e.g. first stars)

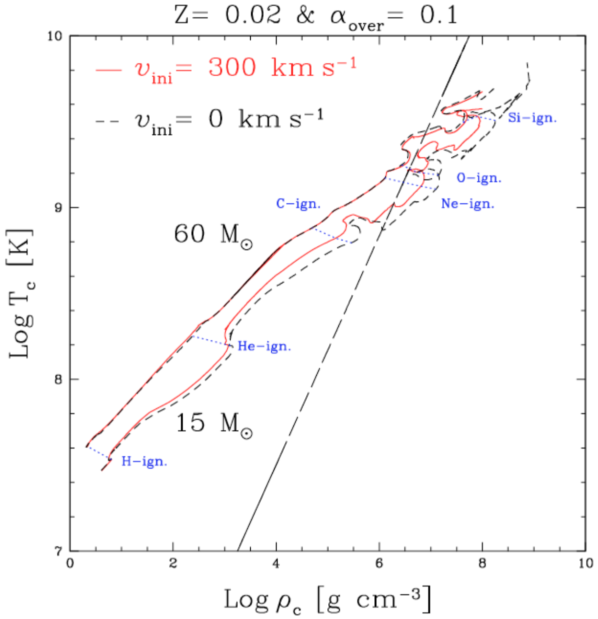
Synopsis

1. The many paths of massive-star evolution
2. Chronology of explosion + SN evolution
3. SN radiation : Light curves and spectra
4. SN radiation modeling : Properties of « standard » SNe II/IIb/Ib/Ic
5. Superluminous SNe : Observations and Mechanisms

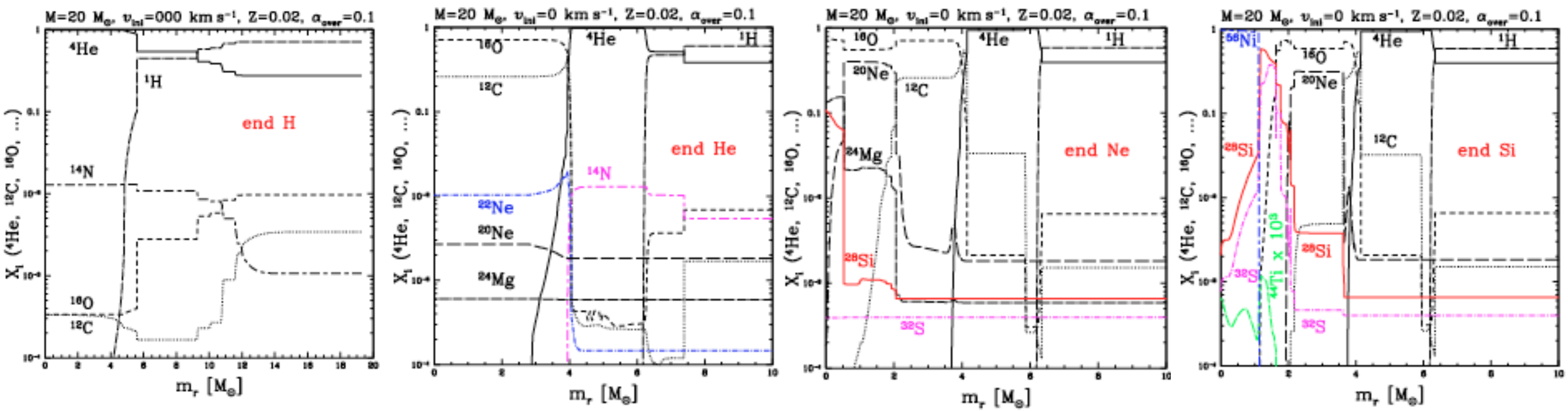
The many paths to massive-star death

Evolution of the core

- Main sequence: M_{MS}>8$M_\odot$, X = 0.7, Y=0.28, Z=0.02 (μ_c=1.36)
- Nuclear burning in core => μ_c, ρ_c, T_c ↗=> compactness ↗
- Star at death: Iron core (μ_c~50) + shells (Si/S, O/Ne/Mg, He, H/He)
- Fe core supported by electron degeneracy pressure



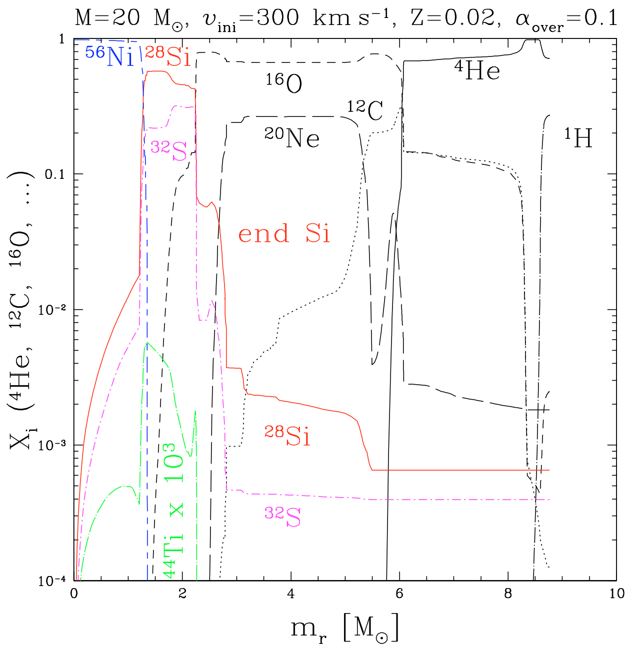
Hirschi et al. (2004)



The many paths to massive-star death
Evolution of the envelope

Radiation-driven Wind mass loss

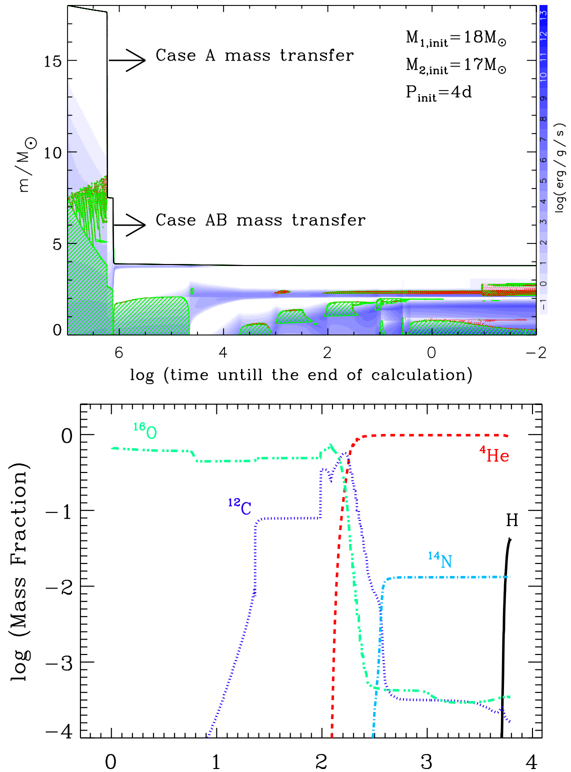
- $dM/dt \sim 10^{-5} M_\odot/yr$; $f(M,Z,\Omega)$
- **Key for higher mass stars**
- **Ex:** $M=20M_\odot$ single, $v_{rot}=300km/s$



Hirschi et al. (2004)

Binary mass transfer

$dM/dt \sim 10^{-4} M_\odot/yr$;
Key for low/moderate-mass stars because weak wind but large R!
Ex: $M=18M_\odot$ binary, slow rot.



Yoon et al. (2010)

Progenitor properties at collapse

- Single stars and wide binaries:

$10\text{-}30 M_\odot$: dies as H-rich RSG/BSG => SNe II-P/II-pec

$>30 M_\odot$: dies as H-deficient WR star of $>10 M_\odot$ => SNe ?

Close Binary systems:

$10\text{-}30 M_\odot$: dies as a low mass H-poor WR star => SNe IIb/Ib/Ic

$>30 M_\odot$: same properties as single WR stars => SNe ?

Core evolution + envelope trimming control SN properties/type

Chronology of events in the life of a CCSN

- **1 sec**: Core collapse, bounce, shock revival
- Shock powered by neutrinos and/or magneto-rotational processes
- **1 min to 1 day**: shock propagates and breaks out (1st EM signature).
- Open question: NS vs. BH formation? Partial fallback?
- **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, $M(^{56}Ni)$ ~ $0.1M_\odot$**

- **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 (τ>>1)**
- **After a (few) month(s)**: Transition to **Nebular phase (τ<<1)**
- **1-10^n years**: SNR, CSM interaction, light echoes

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 $dV/V=3dR/R$ => $T \approx 1/R$
- Explosion of a WD: $R_0=10^8$cm, $R_{SN}=10^{15}$cm => $R_{SN}/R_0=10^7$
- => T drops from 10^9K to room T in ~2 weeks!

SN radiation influenced by heating

1. Recombination energy: e.g. 13.6eV per HI (weak).
2. Radioactive decay energy: $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ (γ-rays,ν, positrons). **Key for Type I SNe!**

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

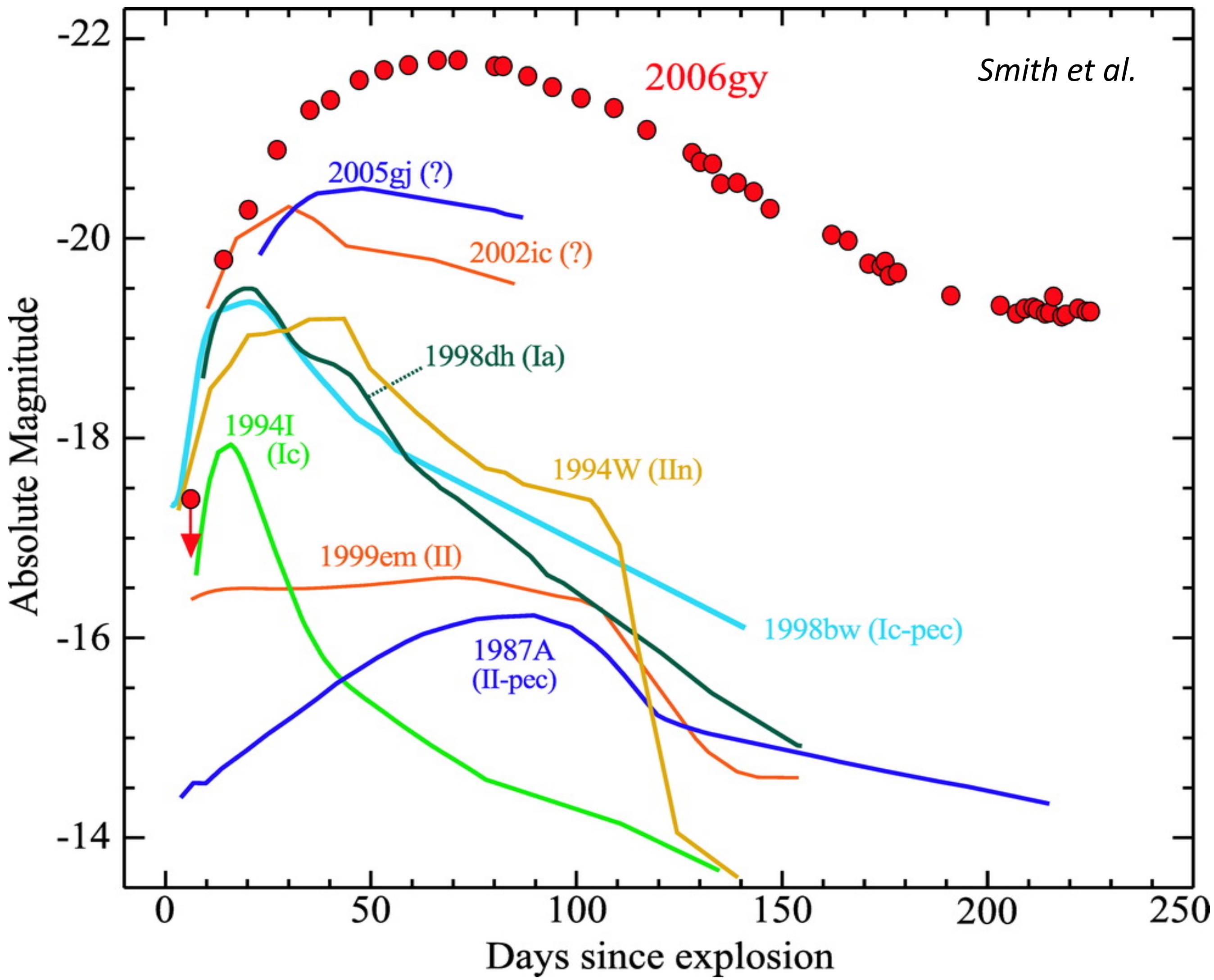
   $^{56}Co \rightarrow {}^{56}Fe$: 3.74MeV per decay, half-life=77.22d
3. Exceptional circumstances: Magnetar spin-down (E_{th}), interaction (Ekin $\rightarrow E_{th}$)

Diversity of SN Light curves

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

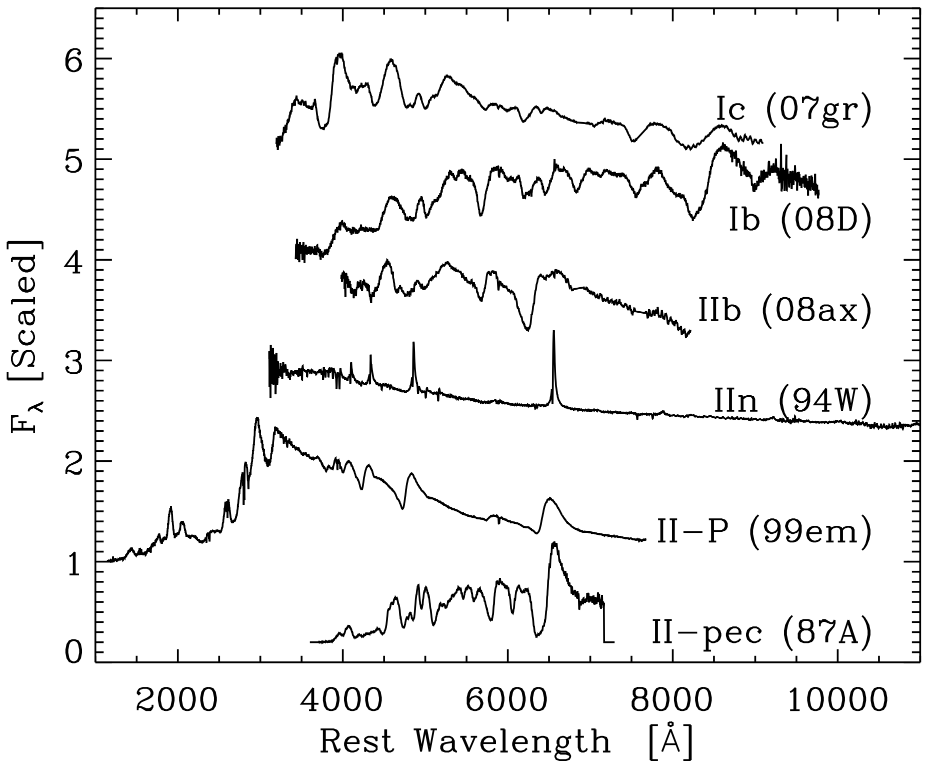
"Standard" SNe
$\int L(t)\, dt \approx 10^{49}$erg

Giant star eruptions
e.g. η Car

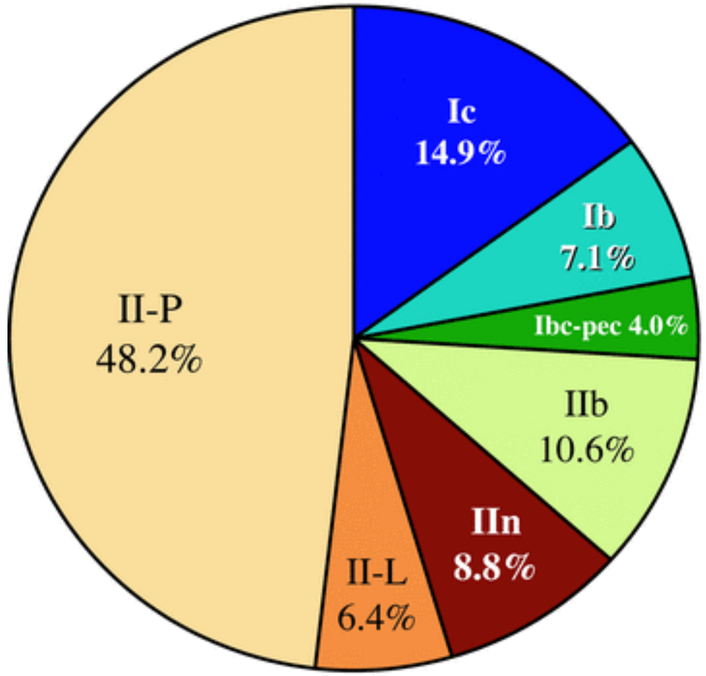


Diversity of CCSN types

Spectral classification reflects variations in composition, ionization, excitation, T, V(m) and light-curve morphology



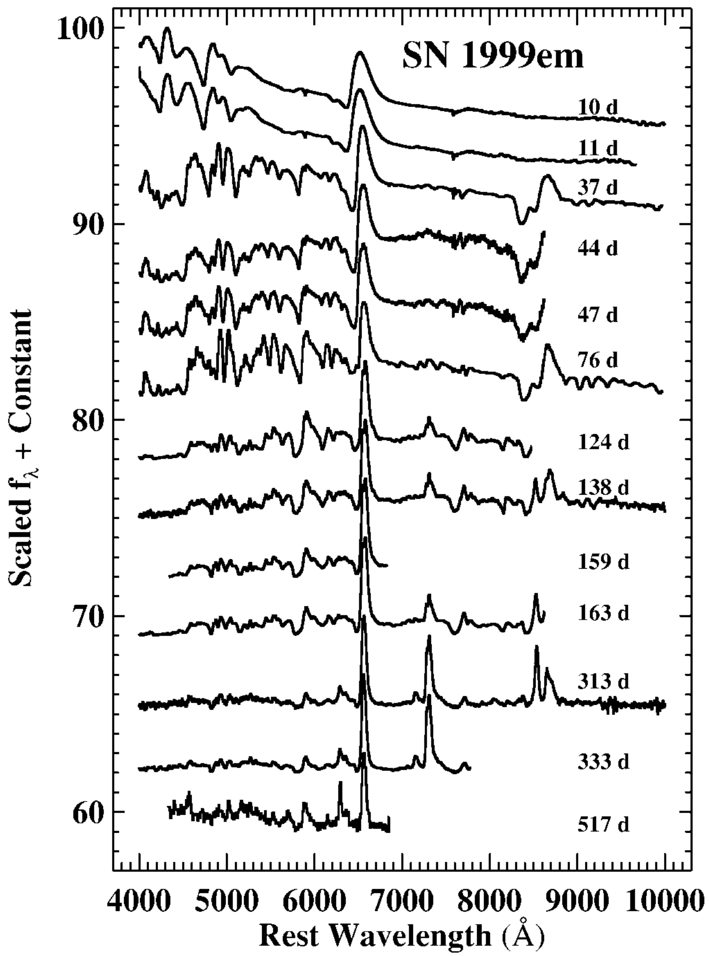
Smith et al. (2011)



Core-Collapse SN Fractions

Basics of Type II SN spectra

Spectral evolution reflects changes in ρ, τ, X_i, V(m)
=> Stellar forensics



Photospheric phase: τ_{cont} >1

Optically-thick outflow=> P-Cygni profiles.
Early: blue cont., weak blanketing
Late: Recombination, strong blanketing
Probe of the envelope (primordial comp.)

Nebular phase: τ_{cont} <1

Pseudo-continuum from lines (FeI, FeII)
P-Cygni profiles for thick lines
Boxy profiles for forbidden (thin) lines
Emission from inner ejecta
τ_{line} >1 even if τ_{cont} <1
Probe of the core (evolved comp.)

1-D Non-LTE time-dependence with CMFGEN

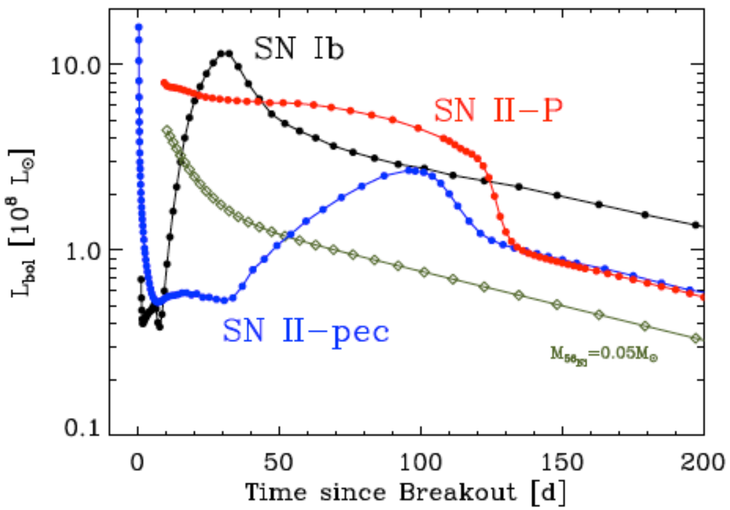
(Hillier & Miller 1998; Dessart & Hillier 2005,2008, 2010,2011ab; Hillier & Dessart 2012)

- **GOAL**: SN radiation modeling to constrain progenitor and explosion properties
- Time-dependent transport: moments of RTE with all important terms in v/c, $\partial/\partial t$, $\partial/\partial \nu$,($\partial/\partial \mu$), $\partial/\partial r$
- Non-LTE solver: solve for 10000+ levels (explicitly account of collisional-radiative rates)
- Non-LTE time-dependent ionization (selection of 25 species & 15 ionization stages)
- RTE solved for at ~10^5 frequencies (far-UV to Far-IR)
- Line blanketing
- Non-local energy deposition and Non-thermal processes.
- **Initial conditions:** Stellar evolution from main seq. + Hydrodynamics of explosion
- Full-ejecta simulation, e.g. no "artificial" boundary conditions, X_i stratification
- Time evolution: ~1 d to few 100d after explosion (Δt = 0.1t)

Basics of core-collapse SN light curves

	pre-SN Star	$M_\star$ [$M_\odot$]	$R_\star$ [$R_\odot$]	M_{ejecta} [$M_\odot$]	E_{kin} [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	15.5	1.2	0.08
SN Ib	WN	25 (binary)	10	3.6	1.2	0.24

(DH10,DH11a)



- Shock-breakout burst followed by rapid fading (expansion cooling)
- Post-breakout plateau: f($R_\star$)
- Potential re-brightening from ^{56}Ni/^{56}Co decay. Delay function of mixing.
- High-brightness phase function of $M_\star$ (large τ), $R_\star$ (cooling), $M_{^{56}Ni}$ (heating)
- Transition to nebular phase when $\tau_{cont} \leq 1$; Flux f($M_{^{56}Ni}$,γ-ray trapping)
- Not considered: external power from CSM interaction, external radiation etc.

Light curves of CCSNe (Ib/c/II-pec/II-P) reflect variations of a few in $M_\star$, 10 in E_{kin} and M(^{56}Ni), but **up to 1000 in $R_\star$**

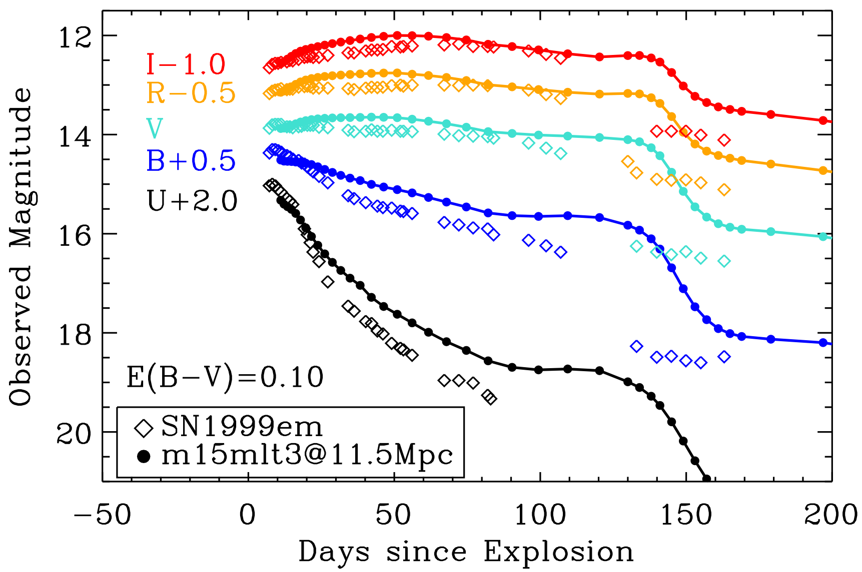
Case study of SNII-P 1999em

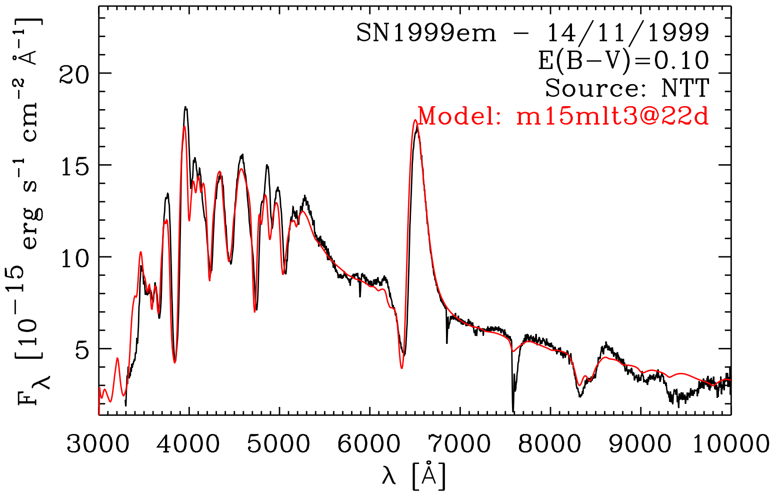
1.2B ejecta from

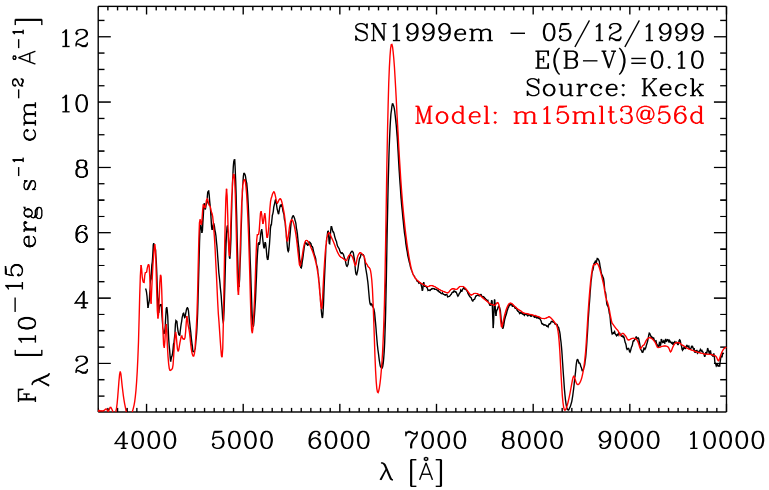
$500R_\odot$ $15M_\odot$ RSG.

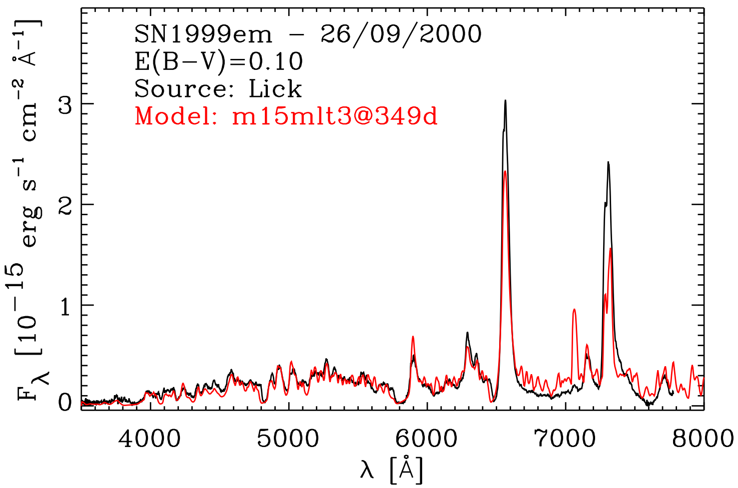
Dessart & Hillier (2011), Dessart et al. (in prep.)

- Good match to SED, line profiles, ionization
- Non-thermal processes key for Hα at late times
- Nebular spectra OK => Core properties suitable
- LC OK for colors but plateau too long – M(H-env.)





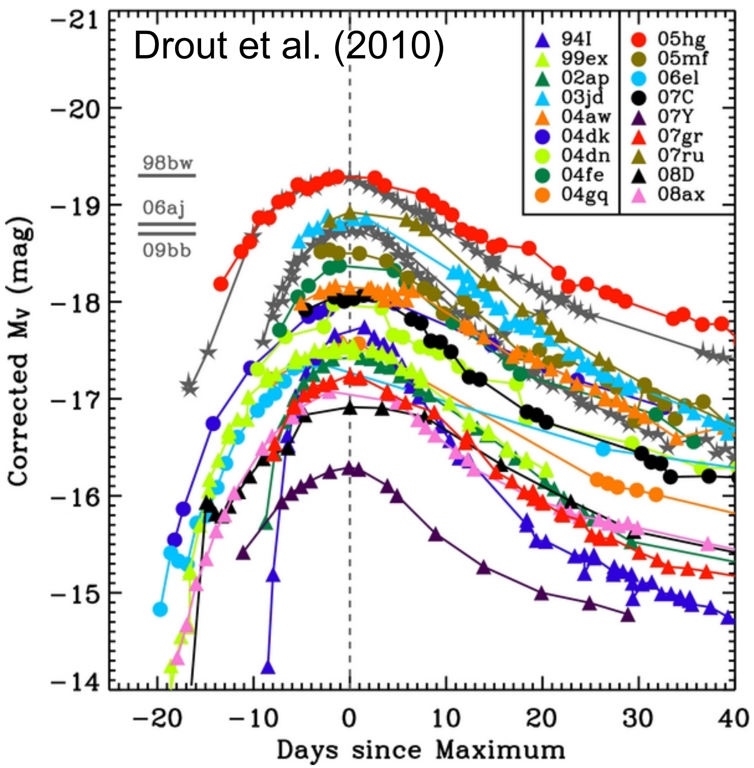




SN IIb/Ib/Ic Light curves: Observations vs. models

Observations

- Rise time to peak of ~20 days
- Narrow peak (20d).
- SNe IIb/Ib/Ic have similar LC props.
- Scatter in peak brightness



Models

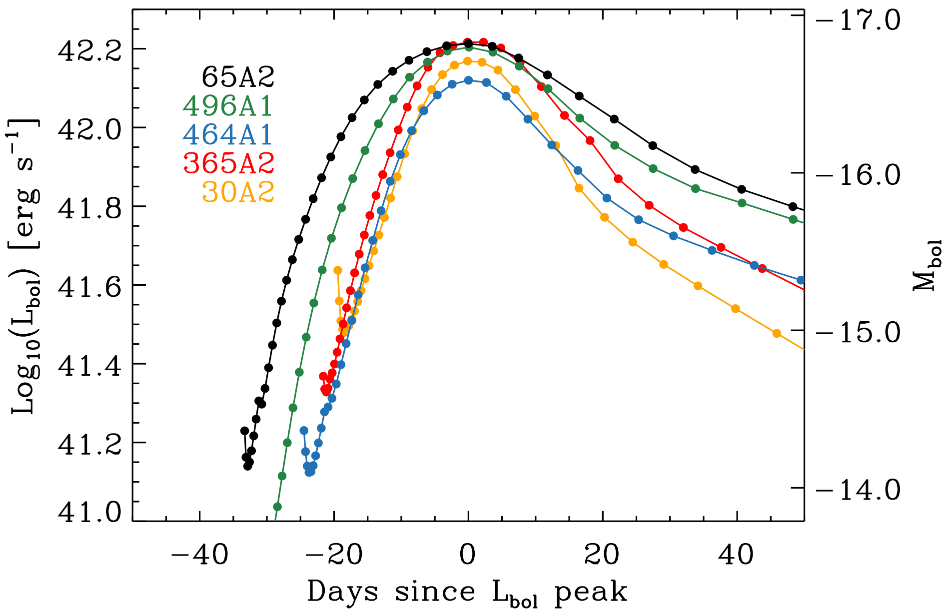
Early, narrow peak with

fast nebular decline

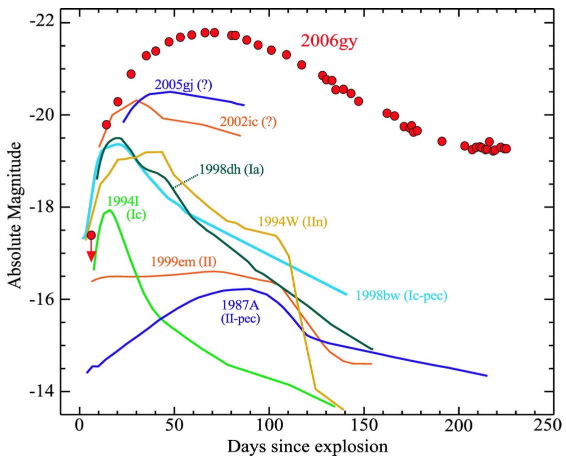
⇒ low-mass ejecta(<5M$_\odot$)

⇒ **Binary star progenitors**

Dessart et al. (2011,2012, in prep.)



Superluminous Supernovae: The facts

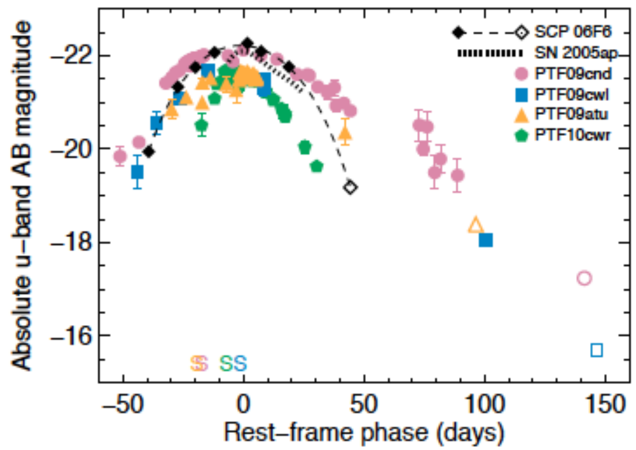


Huge luminosities

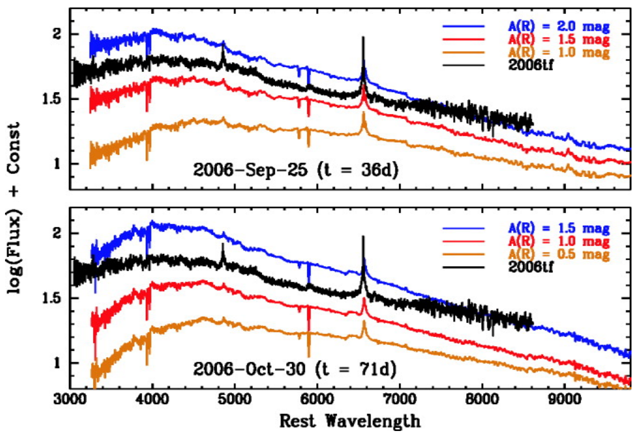
Diversity of fading rates after peak

Diversity in SN type: II, IIn, Ic

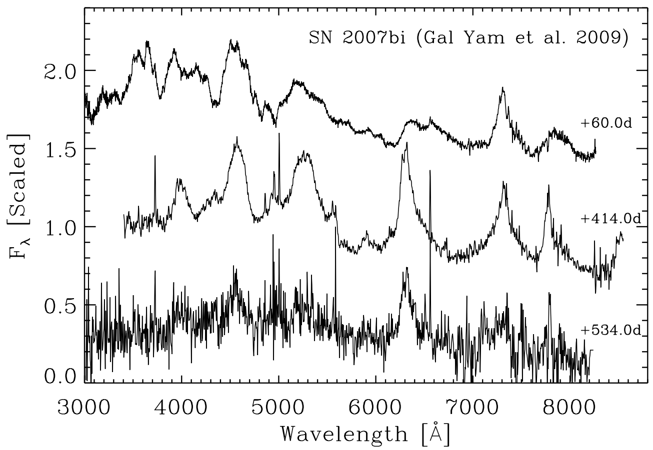
Diversity in colors: blue or red



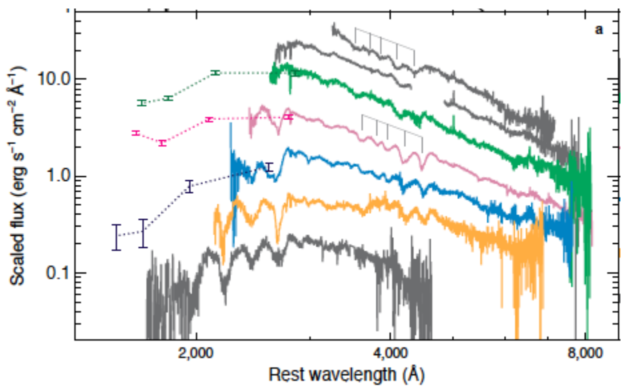
SLSN IIn – 2006gy
H rich – narrow lines



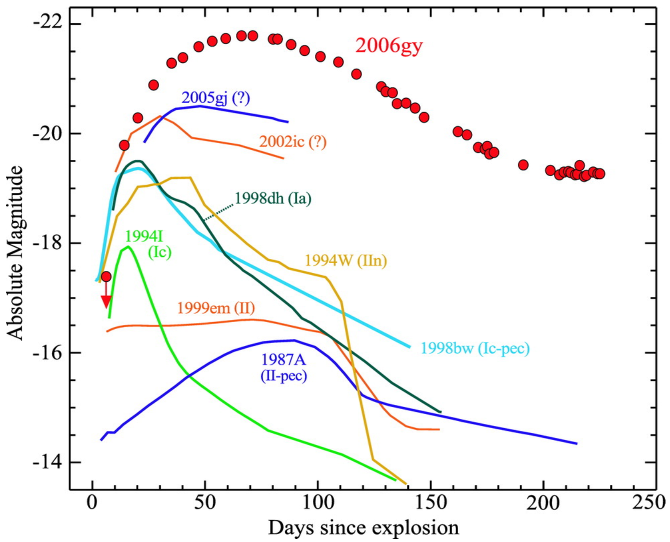
SLSN Ic – 2007bi
Blue - H poor

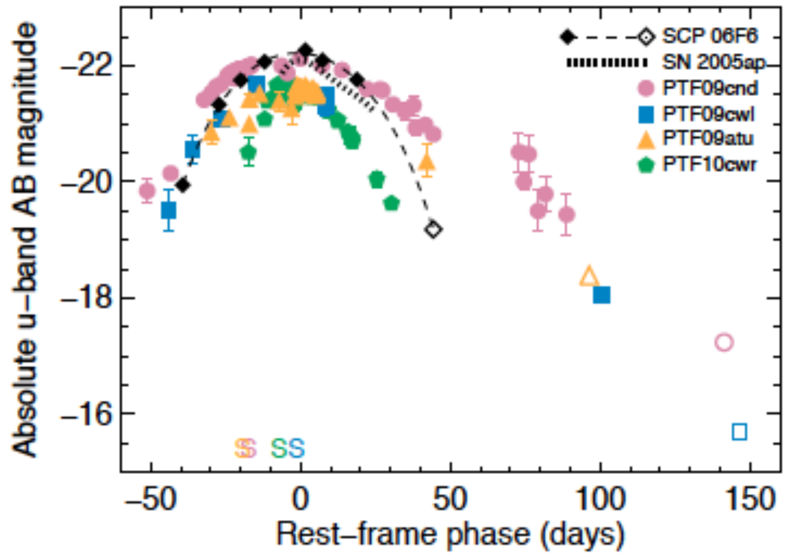


SLSN – 2005ap/PTF
Very Blue – H poor



Superluminous Supernovae: Mechanisms





Trick: Heat up the gas once it has expanded to a SN radius

(recall about PdV losses)

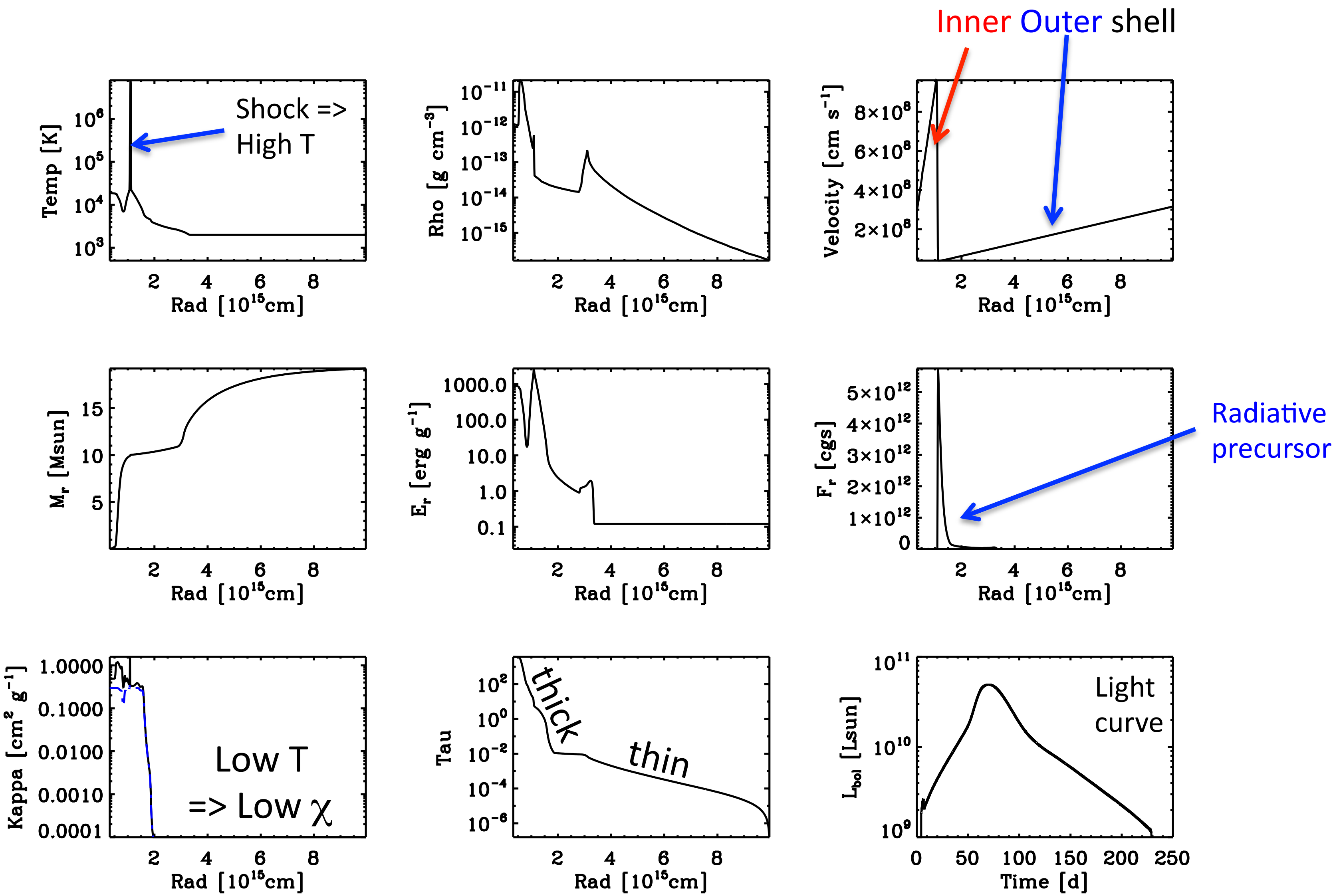
- Powered by interaction with CSM : E_{kin} -> E_{th} -> E_{rad}
- Powered by huge ^{56}Ni mass : pair-instability SNe or extreme CCSNe
- Powered by magnetar radiation: Delayed energy injection from compact object with large B and Ω => particle + X-rays/γ-rays emission

Superluminous SNe through CSM interaction

- CSM interaction => Photosphere formation at huge R => huge L
- Deceleration => Massive slow outer shell + fast inner shell (SN)
- Power: E_{kin} -> E_{th} -> E_{rad}
- High mass => large τ => coupling between gas and radiation
- Radiation hydrodynamics: Modeling with HERACLES (Audit/Gonzalez)
- Interaction between 2 eruptions in a $60M_{\odot}$ star:
- Inner shell ($3.5x10^{51}$erg & $10M_{\odot}$) vs. outer shell ($2x10^{50}$erg & $9M_{\odot}$)

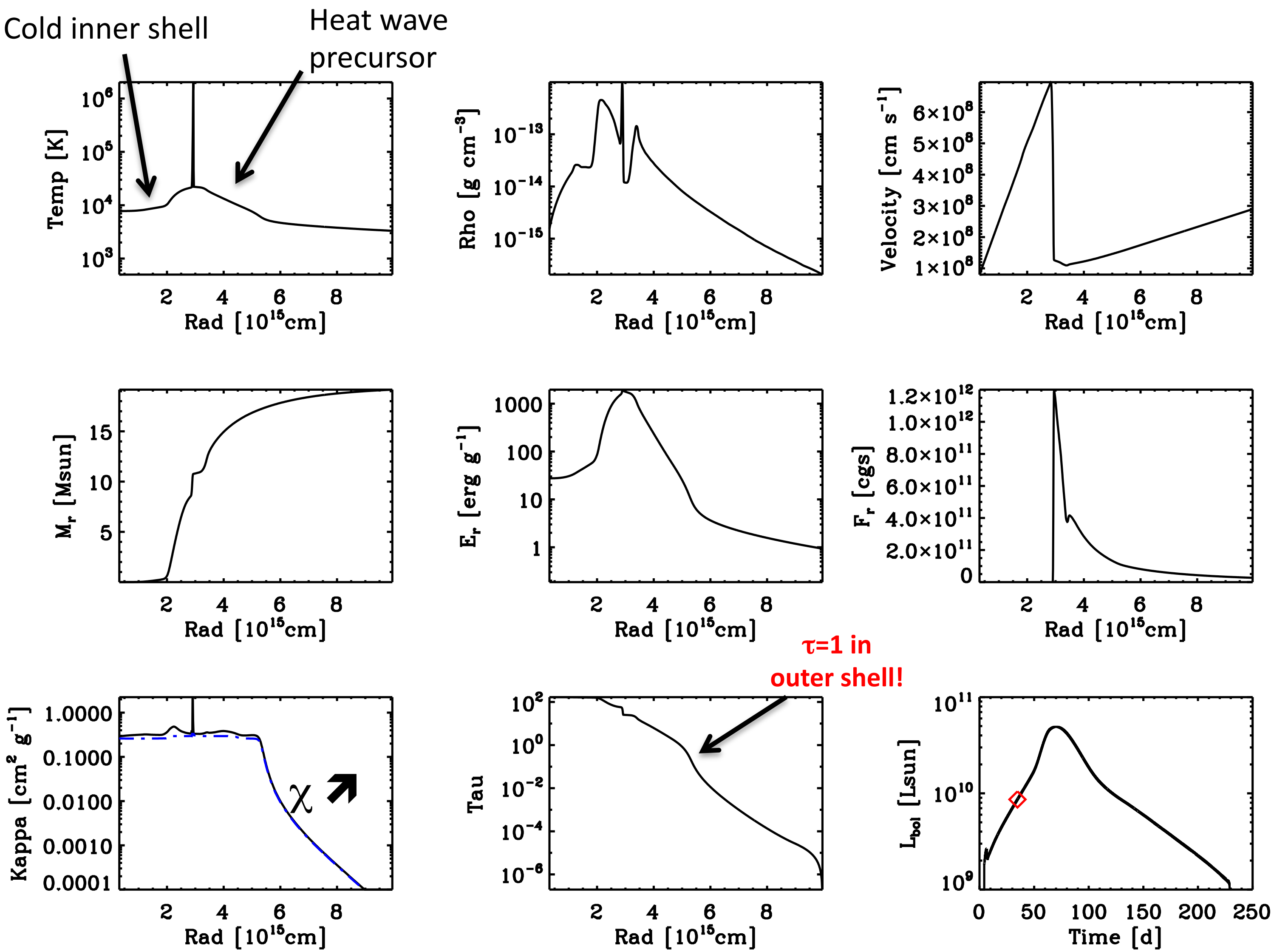
Superluminous SNe through CSM interaction

At 1 day after the start of the interaction



Superluminous SNe through CSM interaction

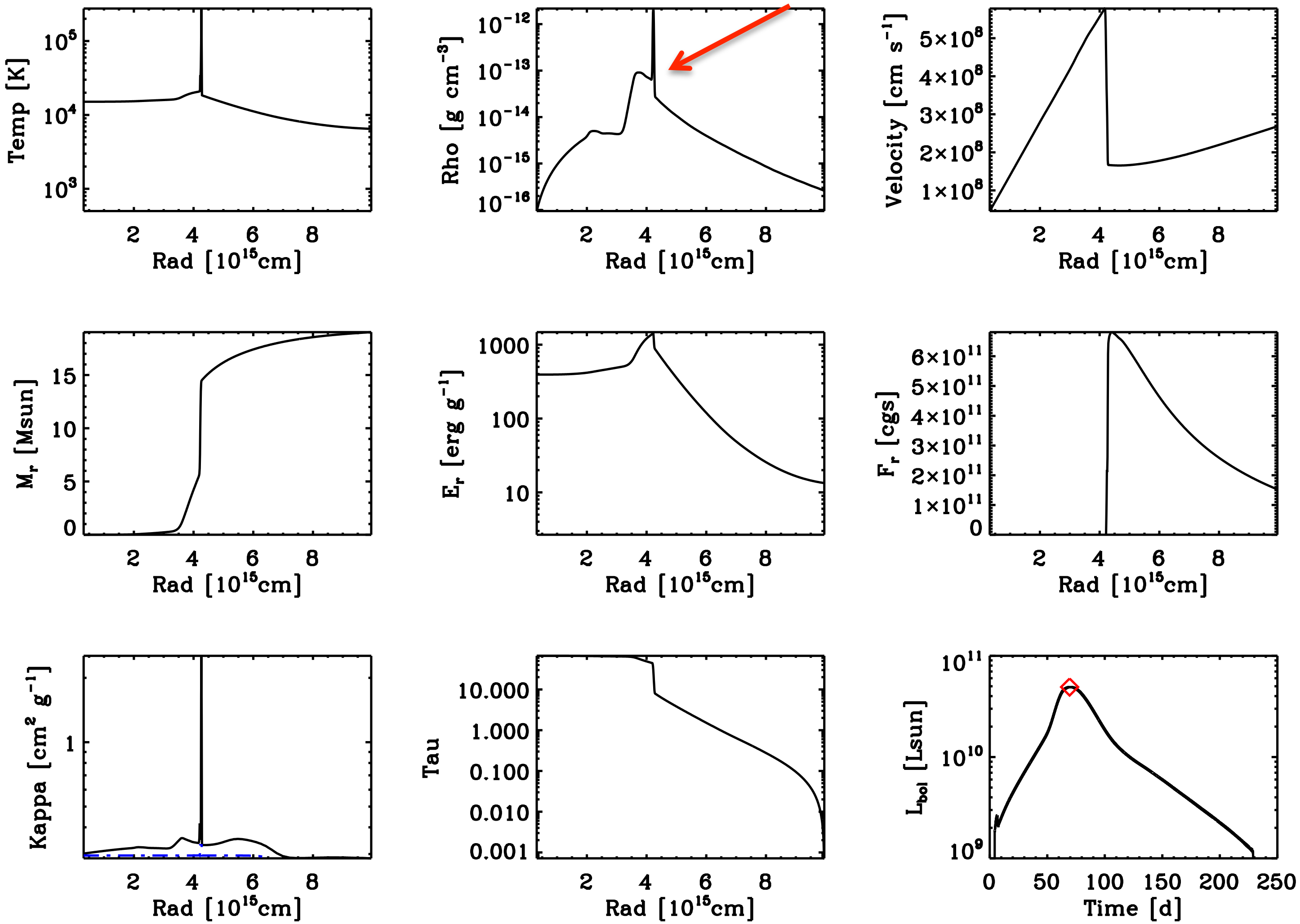
At 1 month after the start



Superluminous SNe through CSM interaction

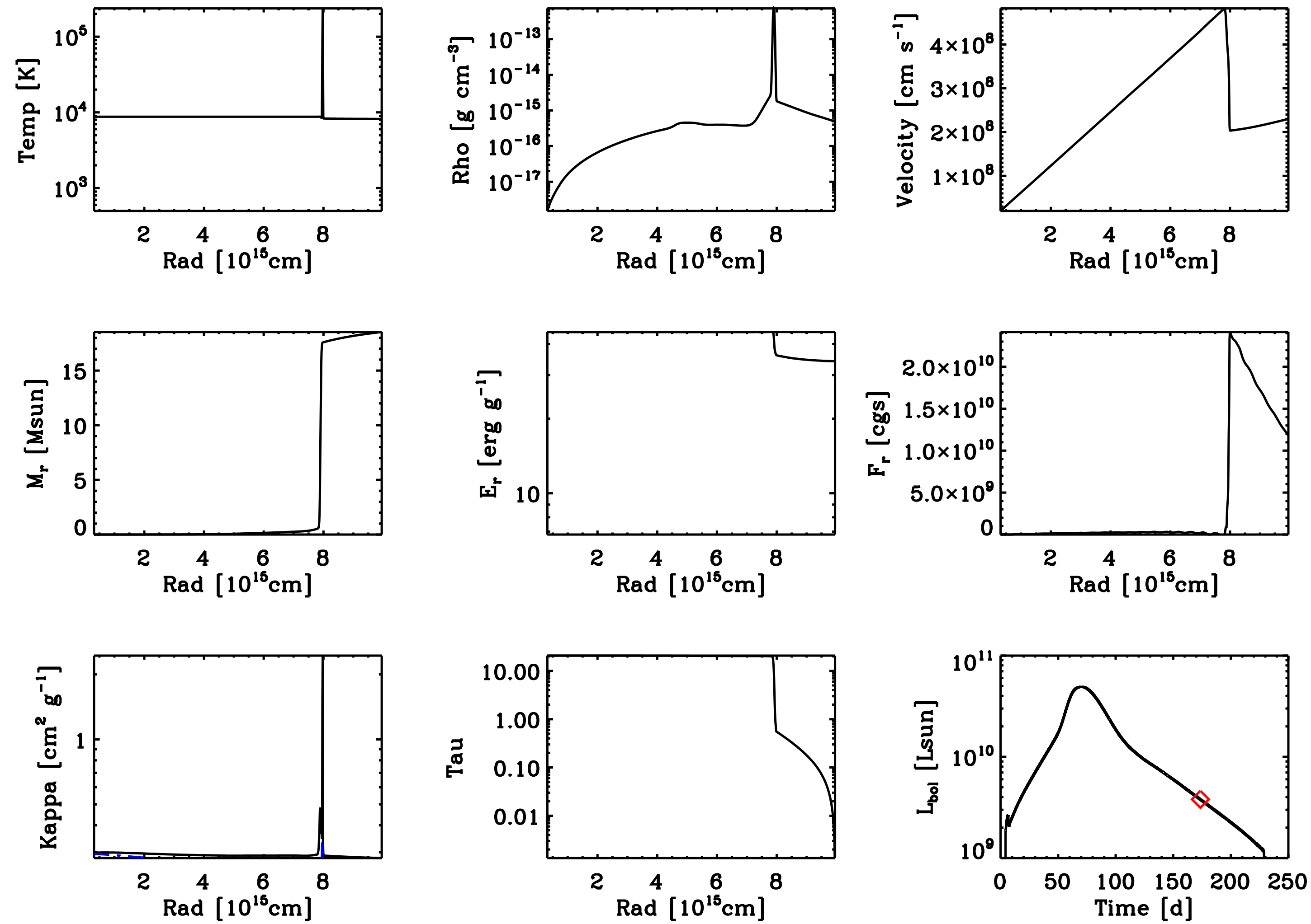
At the peak of the bolometric light curve

Interaction with densest part of outer shell



Superluminous SNe through CSM interaction

At 6 months after the start

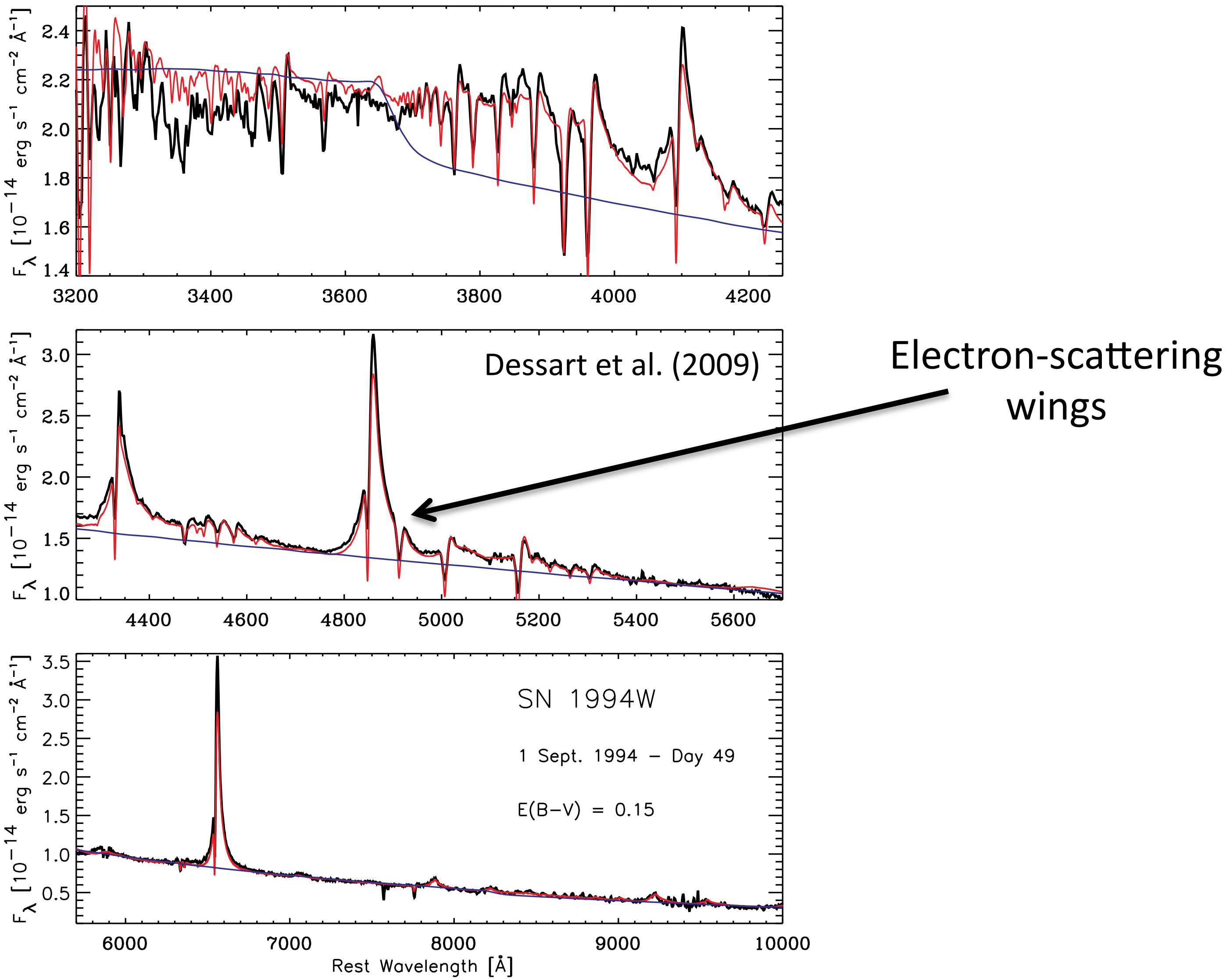


Superluminous SNe through CSM interaction

- Radiative precursor. Modifies outer shell (T, χ, v)
- Piles up all the mass in dense shell – stability?
- High T region at shock: thin => X-rays OR thick => optical photons
- Wind (v const.) vs. eruption (V≈R): modifies shock/Lbol at late times
- Huge time-integrated L_{bol} (≈10^{50}erg), f(E_{kin}, M)
- Clear signatures for SNe IIn: Narrow lines but huge R & L

SN IIn: 1994W

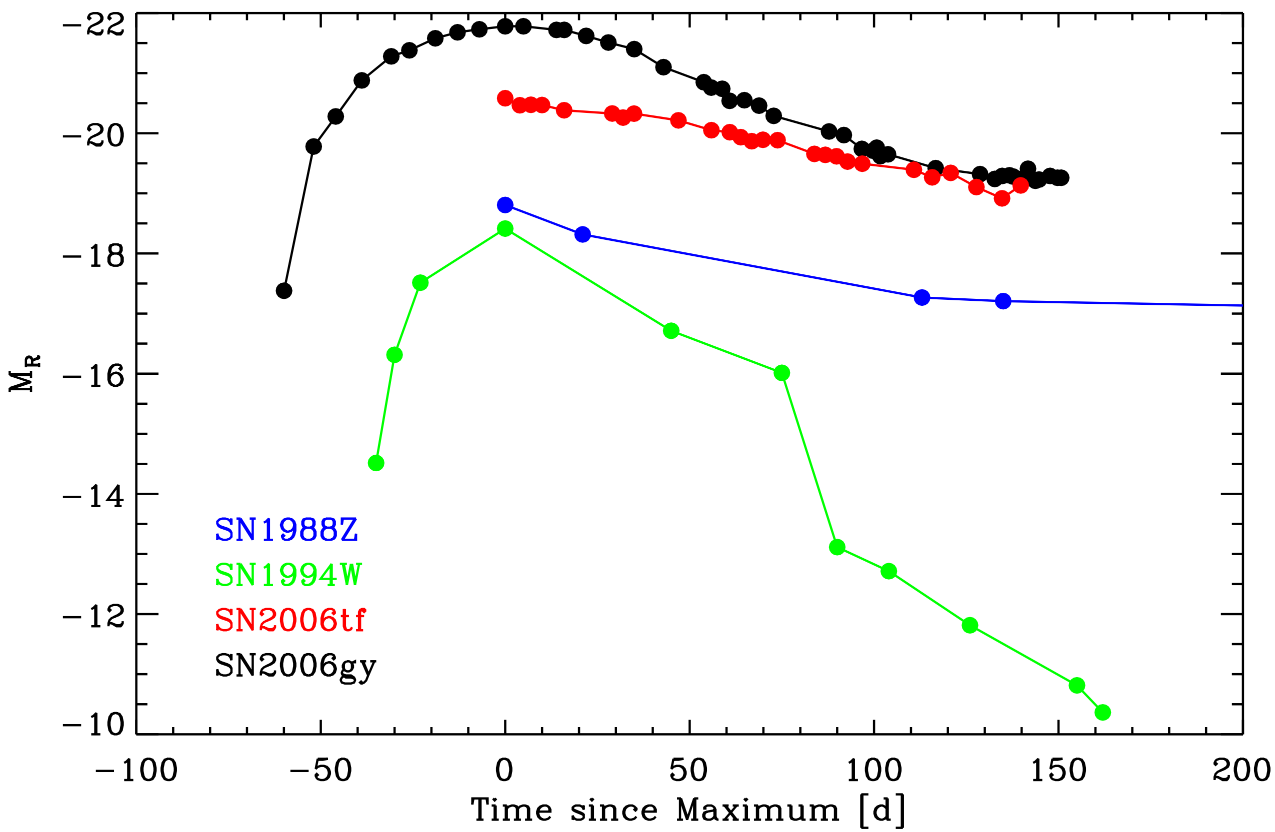
Radiation from optically-thick layer (dense shell and above)
Hybrid profile morphology well understood



Diversity of SNe IIn light curves

⇒ Suggests range in inner/outer shell properties: X, Y, M, extent (ρ), E_{kin}, dv/dr

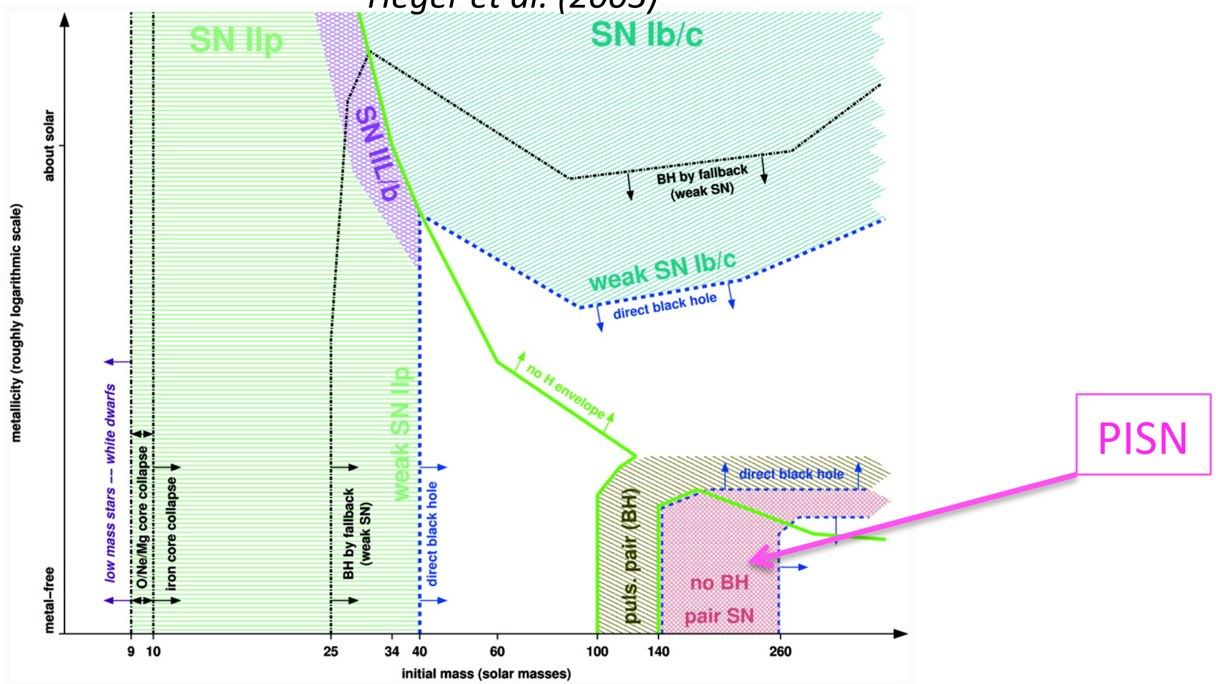
⇒ Reflects complexity of stellar evolution and stellar stability



Pair-instability Supernovae

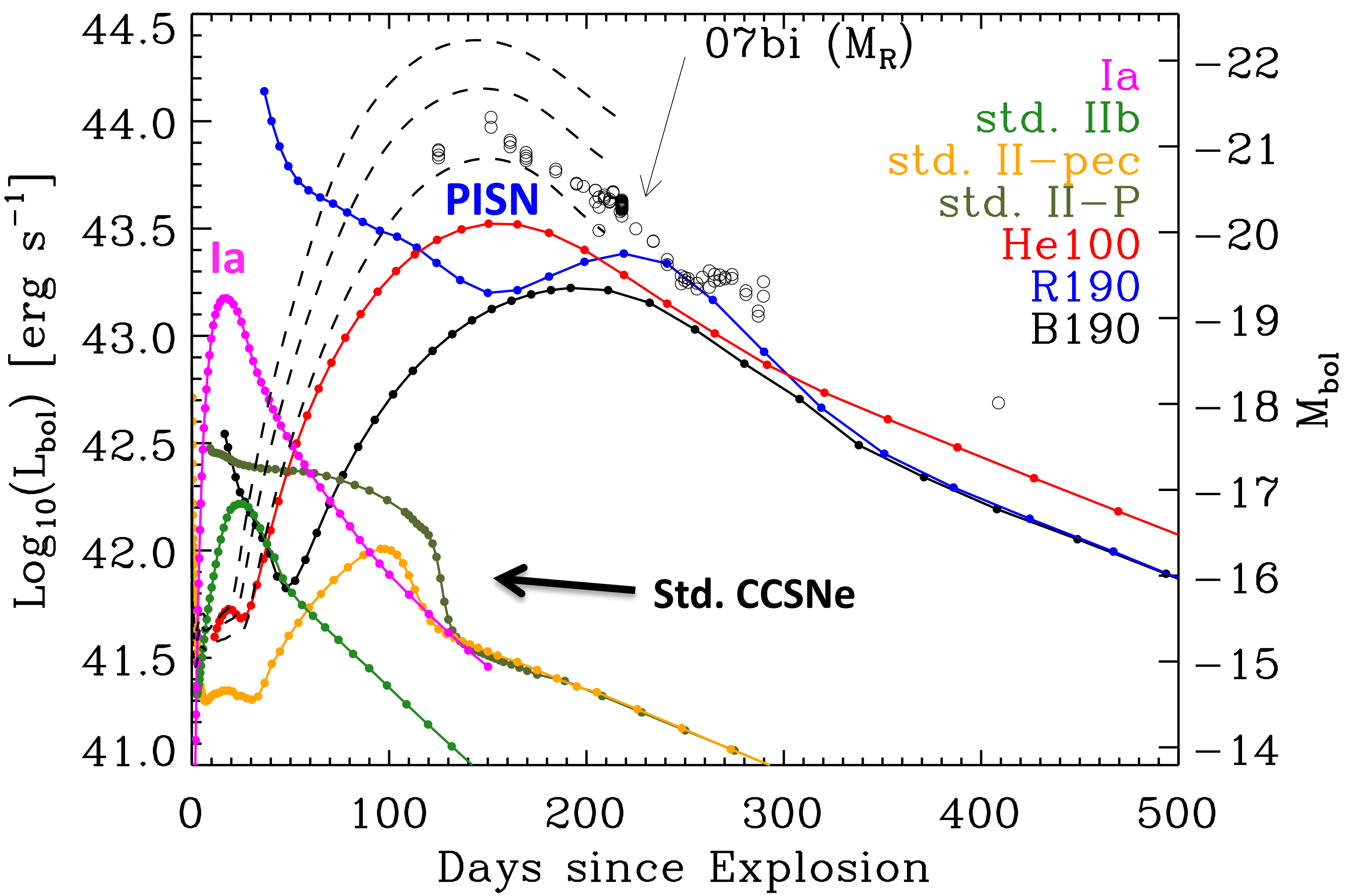
- Associate with top-heavy IMF of first stars? Mergers? Function of redshift?
- 140-260$M_\odot$ objects that collapse during C/Ne/O-core burning due to electron/positron pair production
- Thermonuclear runaways leaving no remnant
- Burn several $M_\odot$ of O to ^{56}Ni and Si: Combustion energy of few 10^{52}erg!
- Unclear status at death: RSG -> SN II-P or WR -> SN Ibc

Heger et al. (2003)



Pair-instability Supernovae

- Our work: Simulations of 3 PISNe from RSG/BSG/WR progenitors at $10^{-4} Z_{\odot}$
- Large ^{56}Ni mass => Huge L_{peak}
- Huge ejecta mass and energy release => modest E/M and large τ => broad LCs

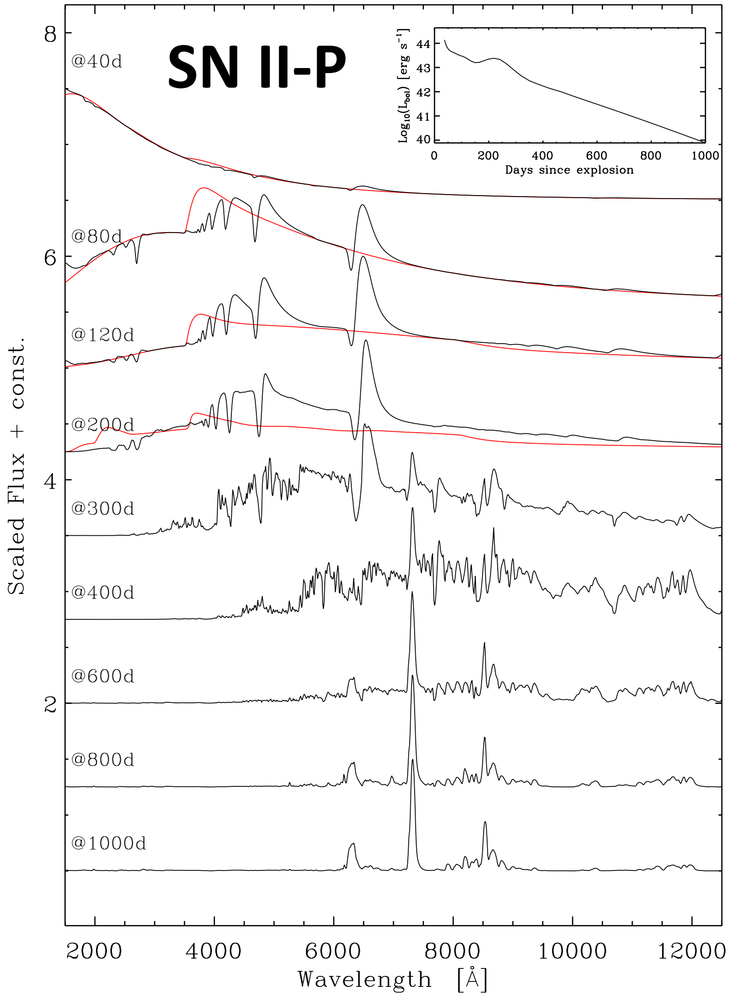


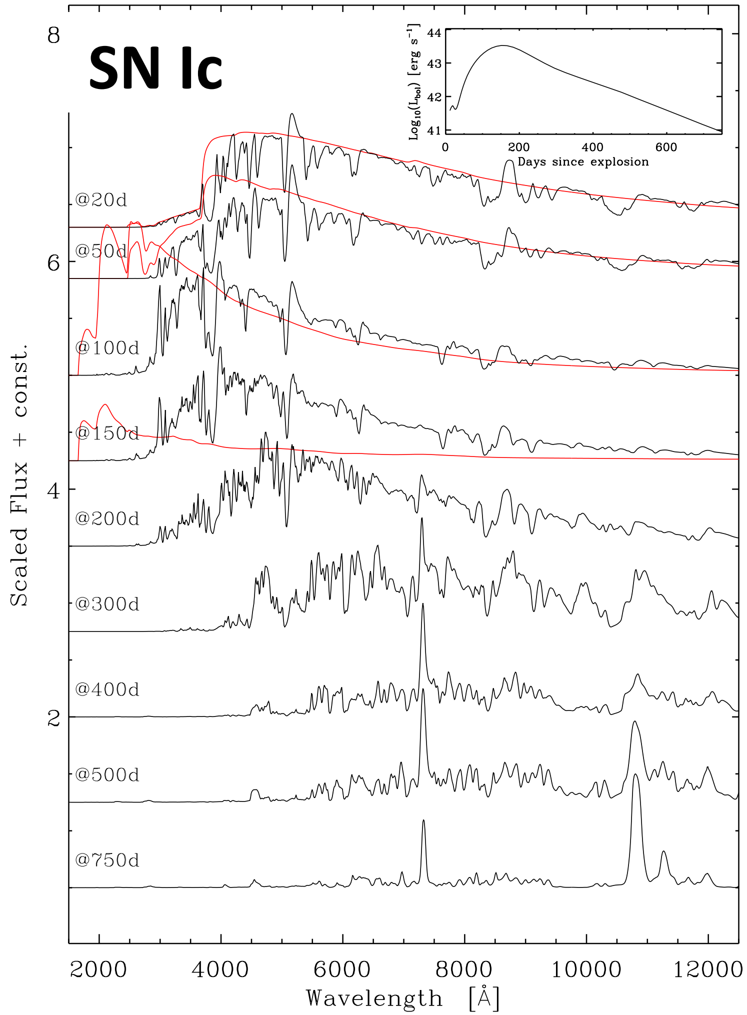
Pair-instability Supernovae
Spectral signatures

High mass and low/moderate M(^{56}Ni)/M(ejecta)

⇒ Cool temperatures and strong metal line opacity at/after peak => Red spectra

⇒ More difficult to detect at large redshifts

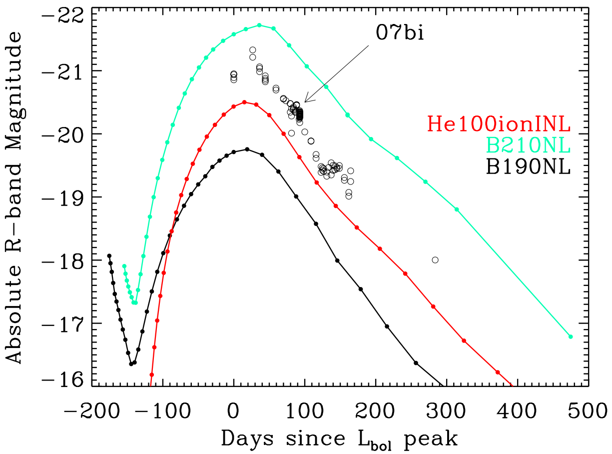




Pair-instability Supernovae

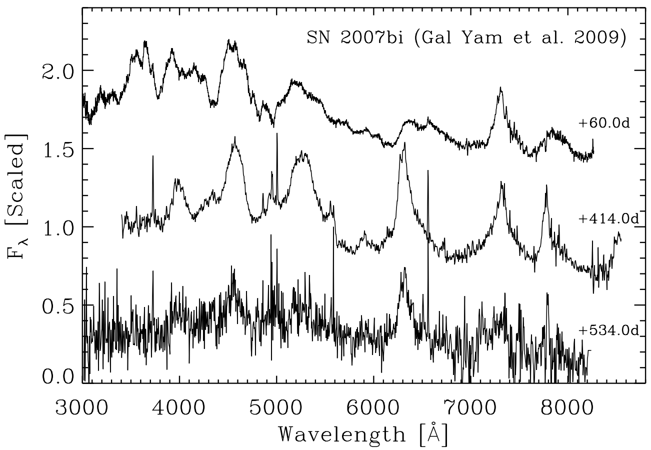
Comparison to SN 2007bi

Light curves



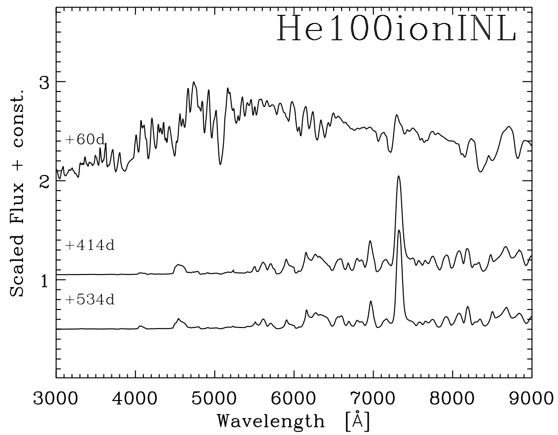
Data:

Gal-Yam et al. (2009)



PISN Model:

Dessart et al. (2012cd)



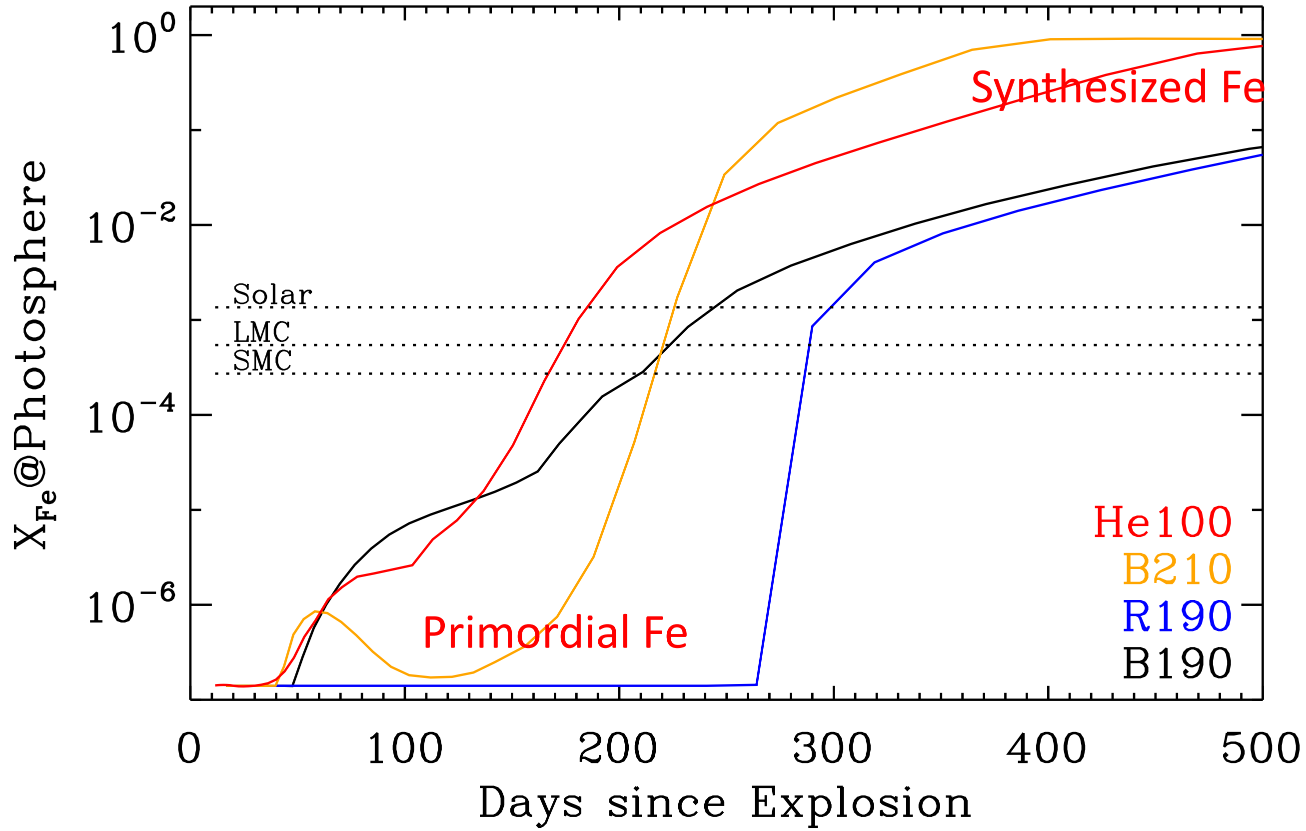
- LC fit SN Ic model (He100) with $5M_\odot$ of ^{56}Ni
- Spectra of SN 2007bi are blue with broad lines
- Contemporaneous model spectra are red with narrow lines

⇒ **SN 2007bi probably not a PISN.**

⇒ Lesson: Hard to produce a blue SN with lots of ^{56}Ni

Pair-instability Supernovae

Cosmological probes



- Huge evolution of X_{Fe} @ photosphere => Probe of Z
- Very exciting prospects for the future
- First stars difficult to detect. First SNe should be easier

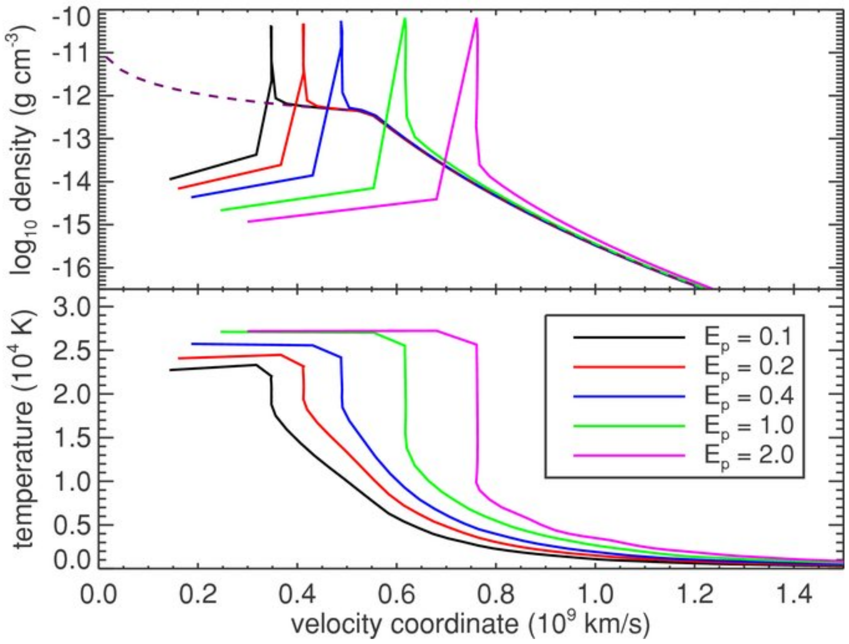
Magnetar-powered Supernovae

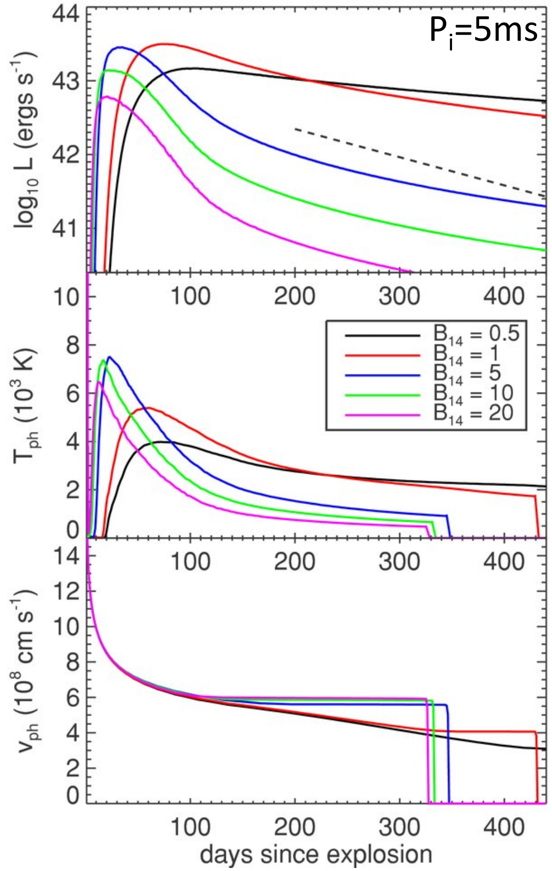
- Fast-spinning magnetar at birth: E = Iω^2/2 = 2x10^{50} (P/10ms)$^{-2}$ erg
- Dipole radiation: dE/dt = 10^{45} (B/10^{15}G)^2(P/10ms)^2 erg/s
- Spin down time: E/(dE/dt) = 4.8d (B/10^{15}G)$^{-2}$(P/10ms)^2 => ≈half-life ^{56}Ni!
- Goal: moderate B,P to have large E, dE/dt

  Spin down time ~ expansion time: R/V ≈ 10d
- Effects: Snow-plow of inner ejecta => Fast dense shell at base

  Injection of internal energy => High ejecta temperatures

Kasen & Bildsen (2010)





Magnetar-powered Supernovae

Signatures: Delayed energy injection => Huge luminosities

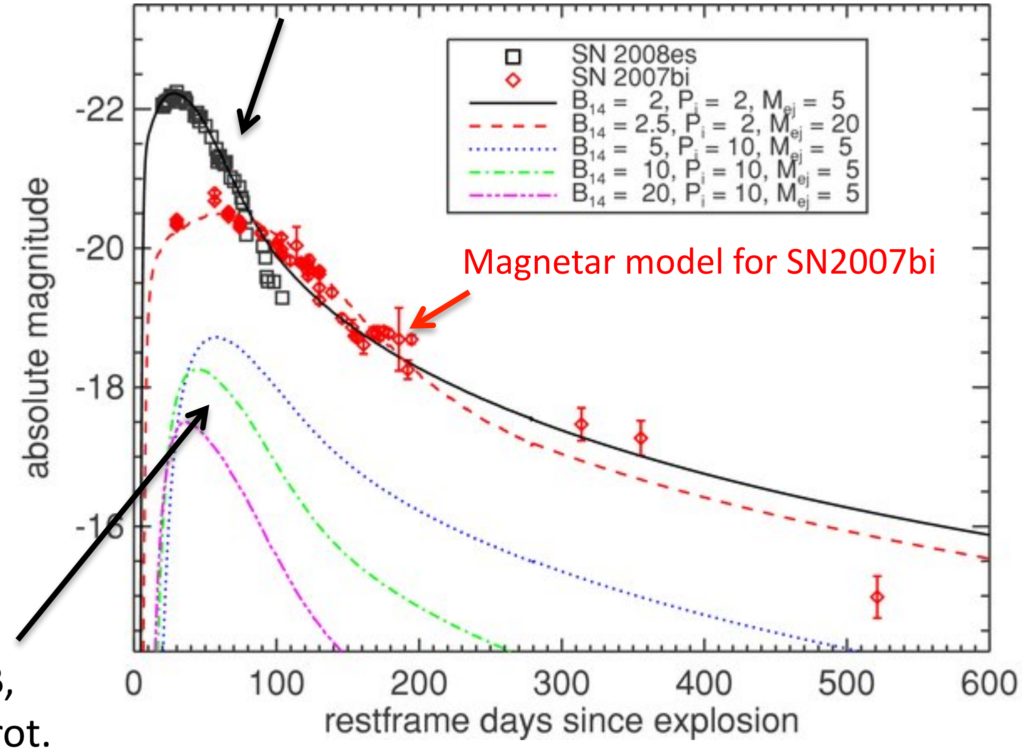
High temperature and weak blanketing => blue colors and spectra

fast ejecta => broad lines at all times

=> Stark contrast with PISN signatures!

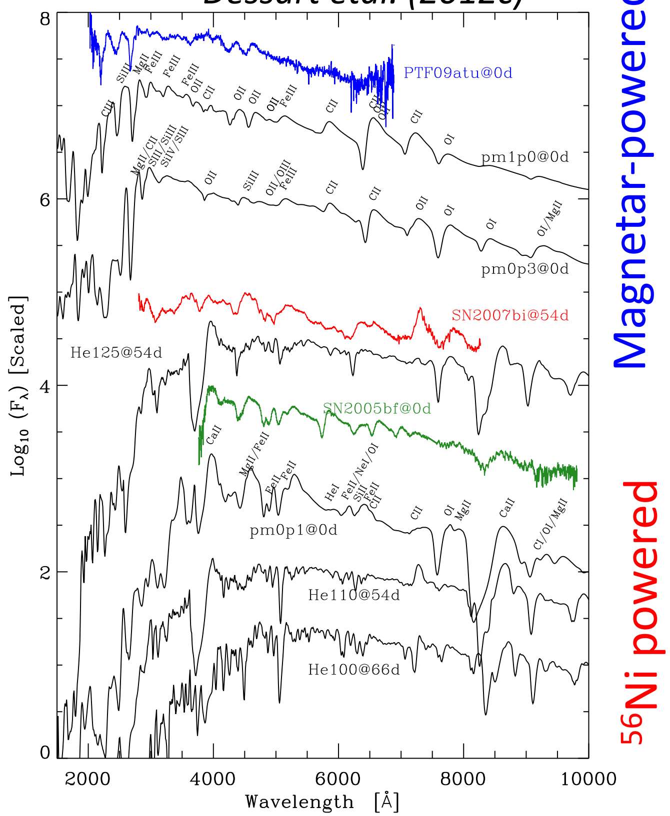
Lower B, Faster rot.

Kasen & Bildsten (2010)



higher B, Slower rot.

Dessart etal. (2012c)



Summary

- SN radiation Modeling: tool to infer progenitor and explosion properties
- SN II SNe: primarily from 10-25$M_\odot$ single stars that die as RSGs
- SNe IIb/Ib/Ic: primarily from 10-25$M_\odot$ close binary stars that die as low-M WR
- Superluminous SNe from CSM interaction, extreme M(^{56}Ni), magnetar radiation
- CSM interaction => SNe IIn: H-rich, narrow lines
- PISNe: broad luminous light curves with red colors. Slow expansion.
- Magnetar-powered SNe: diverse LCs but blue colors. Fast expansion.
- Favor search for first stellar explosions rather than first stars.

SLSNe from
CFHT legacy survey
Deep field
(Cooke et al. (2012)