Superluminous Supernovae: Magnetar or not

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Synopsis

1. Methodology: stellar evolution, explosion, radiative transfer
2. Means to produce super-luminous SNe
3. ^{56}Ni decay power: Pair-instability SNe, extreme CCSNe
4. Magnetar-powered SNe
5. Confrontation to SN2007bi (PISN according to Gal-Yam et al.)
6. Standard core-collapse SNe
7. GRB/SNe

Methodology

Stellar evolution from MS to death: MESA (Paxton et al.), STERN (Langer/Yoon), KEPLER (Woosley)

Radiation Hydrodynamics of explosion: V1D (Livne/Waldman/Dessart), KEPLER

1-D Non-LTE time-dependent Radiative transfer with CMFGEN

(Hillier & Miller 1998; Dessart & Hillier 2005,2008, 2010,2011ab; Hillier & Dessart 2012, Dessart et al. 2013abc)

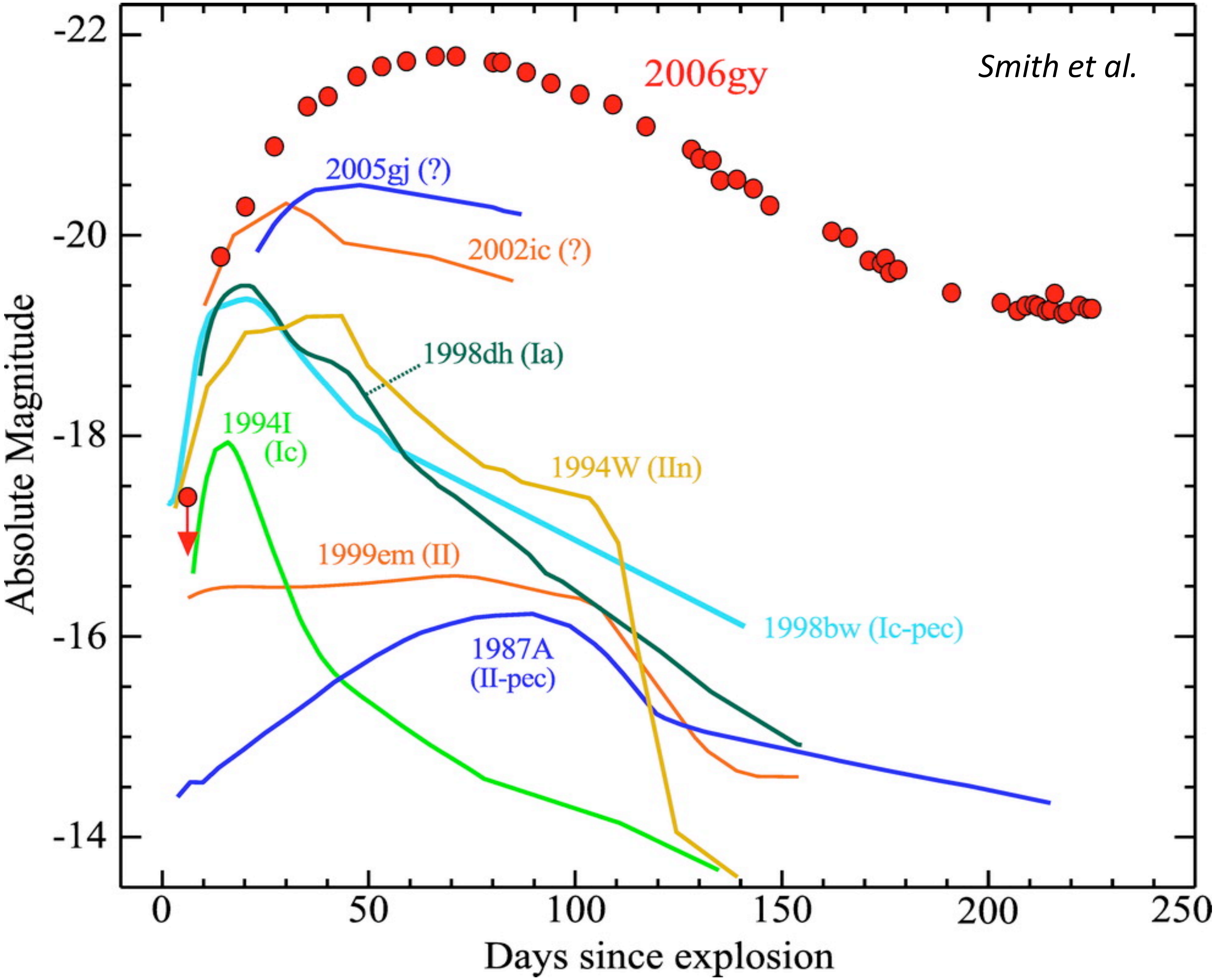
- Non-LTE time-dependent solver: few 1000 (super-) levels (populations and rates)
- Time-dependent transport: moments of RTE with all important terms in v/c, $\partial/\partial t$, $\partial/\partial\nu$,($\partial/\partial\mu$), $\partial/\partial r$
- RTE solved for at ~10^5 frequencies (far-UV to Far-IR)
- Non-local energy deposition (γ-ray transport)
- Non-thermal processes (from radioactive decay).
- Chemical Stratification (H to IGE), 25 ionization stages
- Works for ANY ejecta in homologous expansion (SN Ia/Ib/Ic/II-P/II-pec, PISNe)
- Delivers F(ν,t) => multi-band photometry + spectra over 1-500d

Observations: Diversity of SN Light curves

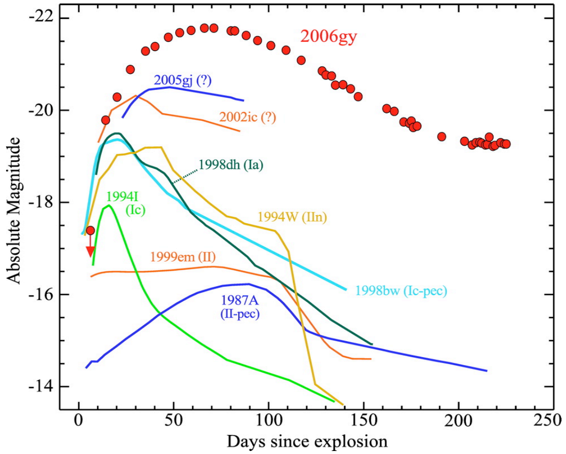
Superluminous SNe
$\int L(t)\,dt \approx 10^{50\text{-}51}$erg

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

Giant star eruptions
e.g. η Car



Superluminous Supernovae: Observations



Huge luminosities

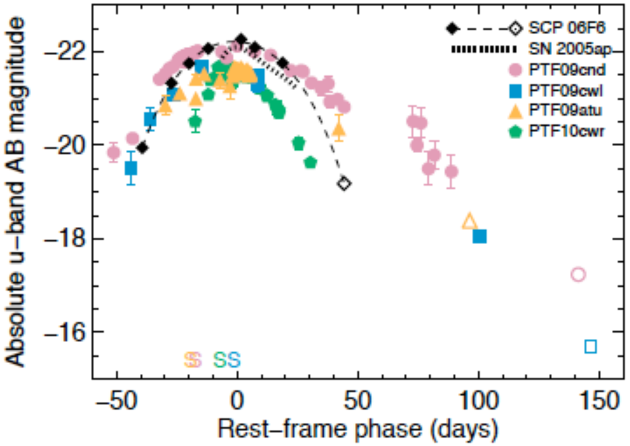
Flux peaks in nUV/optical

Diversity of fading rates after peak

Diversity in SN type: II, IIn, Ib, Ic

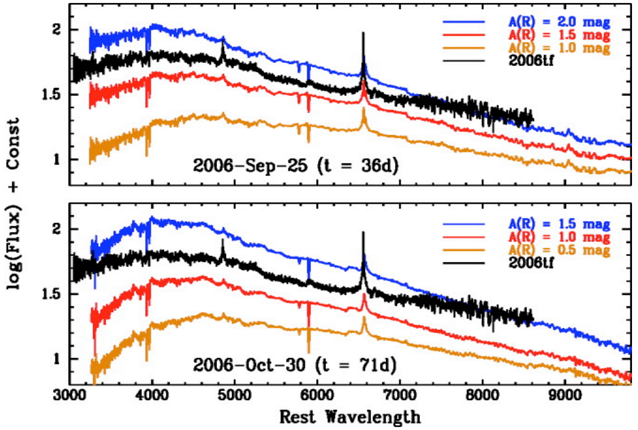
Diversity in color: blue or red

Quimby et al. (2010)



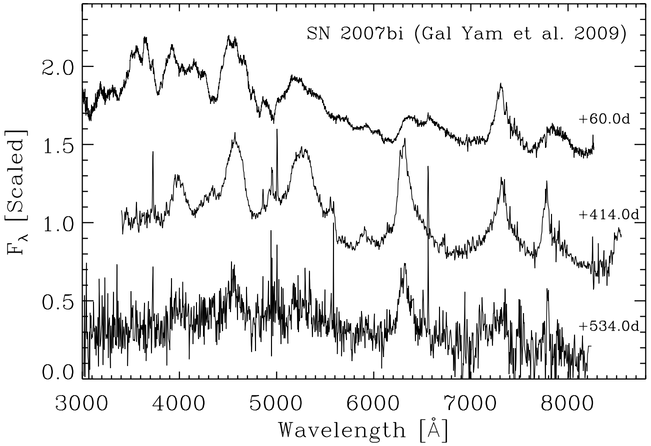
SLSN IIn – 2006gy

H rich – narrow lines



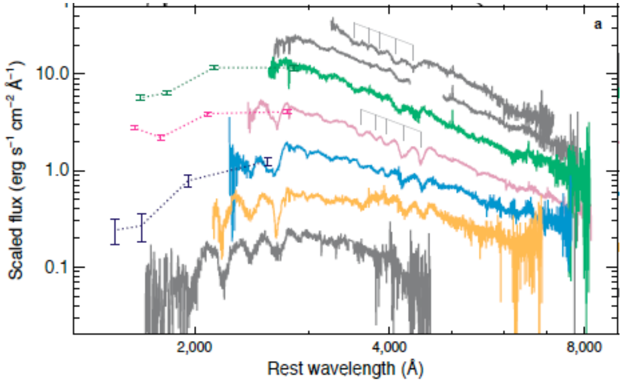
SLSN Ic – 2007bi

Blue - H poor



SLSN – 2005ap/PTF/PS

Very Blue – H poor



Superluminous Supernovae:
Power sources for the luminosity

- Powered by interaction of two “shells”: E_{kin} -> E_{th} -> E_{rad}
- Powered by huge ^{56}Ni mass : pair-instability SNe or extreme CCSNe
- Powered by the radiation of the compact remnant (e.g., magnetar):

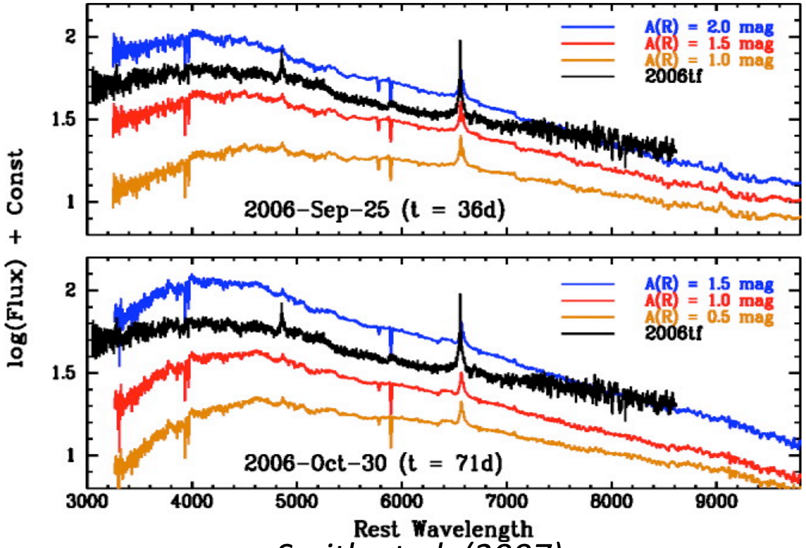
  Delayed energy injection from compact object with large B and Ω

  => particle + X-rays/γ-rays emission

Super-luminous SNe powered by interaction

- Straightforward mechanism: E_{kin} -> E_{th} -> E_{rad}
- Radiation from optically-thick slow moving material at $10^{15\text{-}16}$ cm
- Line broadening by non-coherent electron scattering (NOT expansion)
- Large interacting mass => Large progenitor mass
- Energetics challenge standard explosion (E_{rad}>1B; e.g., 06gy).
- Power source: Pair-instability pulsation; core collapse?

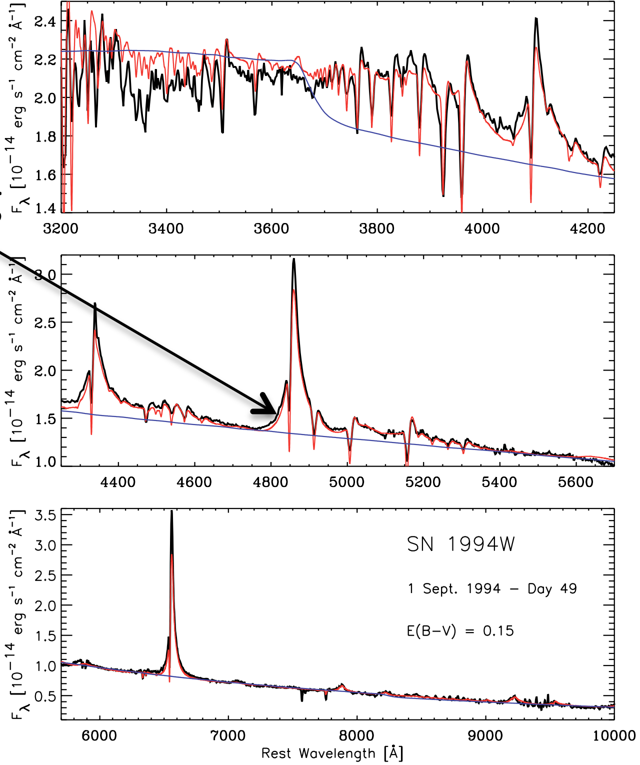
SLSN IIn – 2006gy
H rich – narrow lines



Smith et al. (2007)

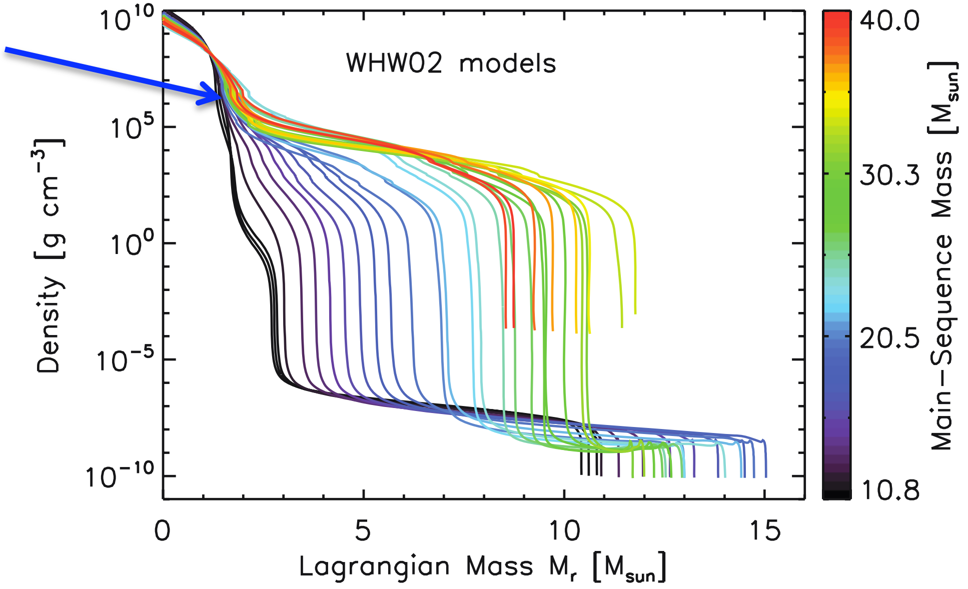
Electron-scattering wings

Dessart et al. (2009)



^{56}Ni powered supernovae

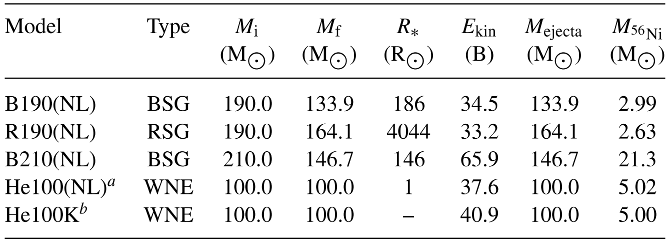
- $<0.2M_\odot$ of ^{56}Ni expected in ν-driven explosion (e.g., Ugliano et al. 2012; $f[M_{init},\rho(m)]$)
- Higher ^{56}Ni mass: magneto-rot explosions but $\rho(m)$ critical?
- Higher ^{56}Ni mass: Pair-production instability in $M>100M_\odot$ stars



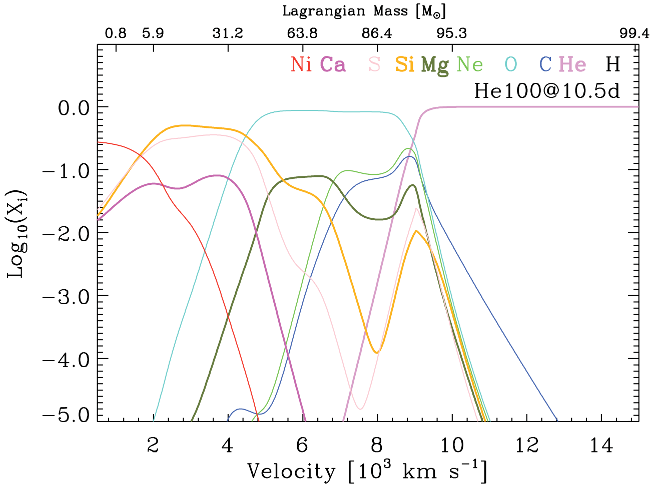
Diversity of $\rho(m)$ above Fe core

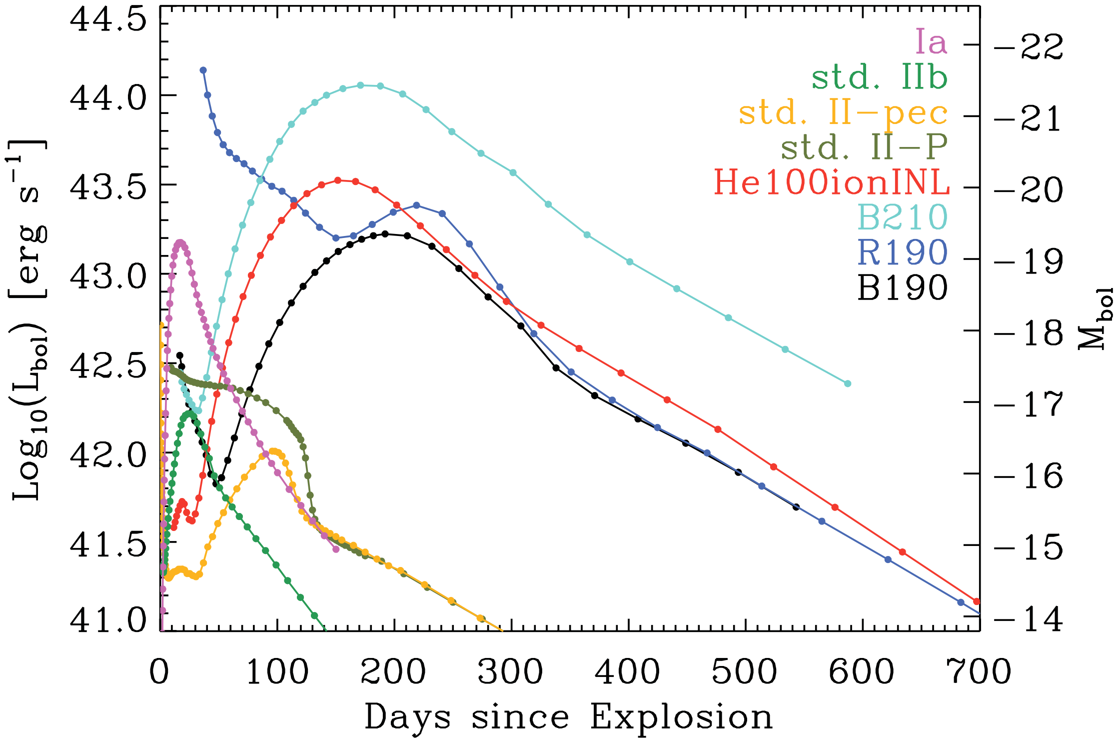
Radiative Signatures of Pair-instability Supernovae

- **Our work**: MESA/V1D/CMFGEN Simulations of ~200M$_\odot$ stars at Z=0.0001 exploding as RSG/BSG/WRs leading to SN II-P, SN II-pec, and SN Ic.
- M(^{56}Ni) ≈ few M$_\odot$ => Huge L$_{peak}$
- Huge energy release (x10) and ejecta mass (x10) => modest E/M and expansion rate
- Large ejecta optical depth => Long rise time, broad LCs, slow evolution



Model	Type	M_i (M$_\odot$)	M_f (M$_\odot$)	R_* (R$_\odot$)	E_{kin} (B)	M_{ejecta} (M$_\odot$)	$M_{^{56}Ni}$ (M$_\odot$)
B190(NL)	BSG	190.0	133.9	186	34.5	133.9	2.99
R190(NL)	RSG	190.0	164.1	4044	33.2	164.1	2.63
B210(NL)	BSG	210.0	146.7	146	65.9	146.7	21.3
He100(NL)[a]	WNE	100.0	100.0	1	37.6	100.0	5.02
He100K[b]	WNE	100.0	100.0	–	40.9	100.0	5.00





(Dessart et al. 2013)

Pair-instability Supernovae: Spectral signatures

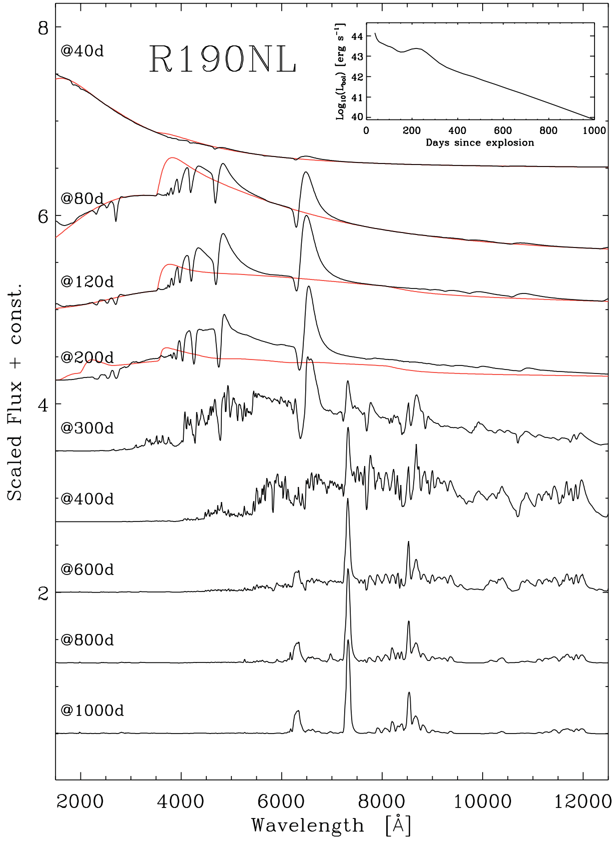
High mass and low/moderate M(^{56}Ni)/M(ejecta)

⇒ Strong chemical stratification. H/He – IMEs - IGEs

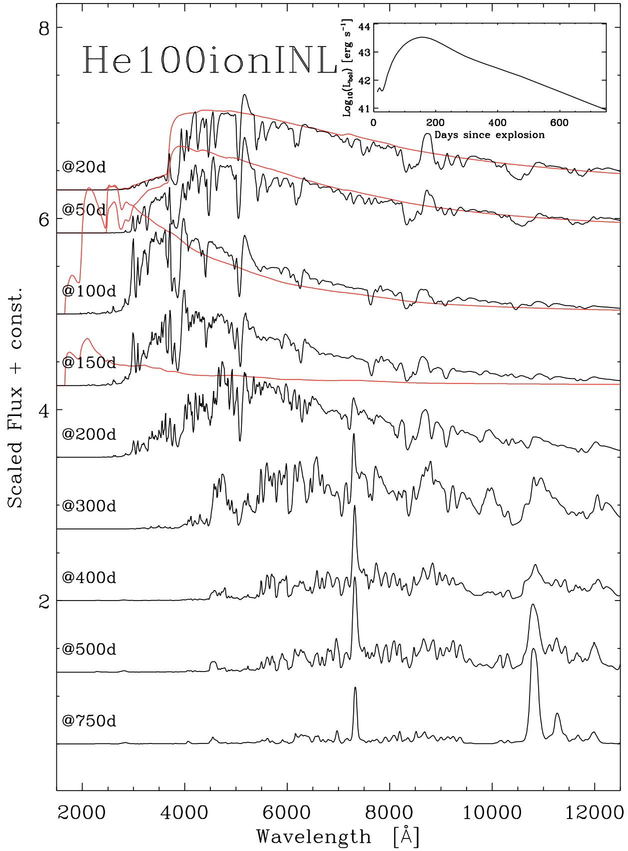
⇒ Cool temperatures and strong metal line opacity at/after peak => Red spectra

⇒ Standard expansion rate, slow inner ejecta => narrow nebular lines

SN II-P



SN Ic

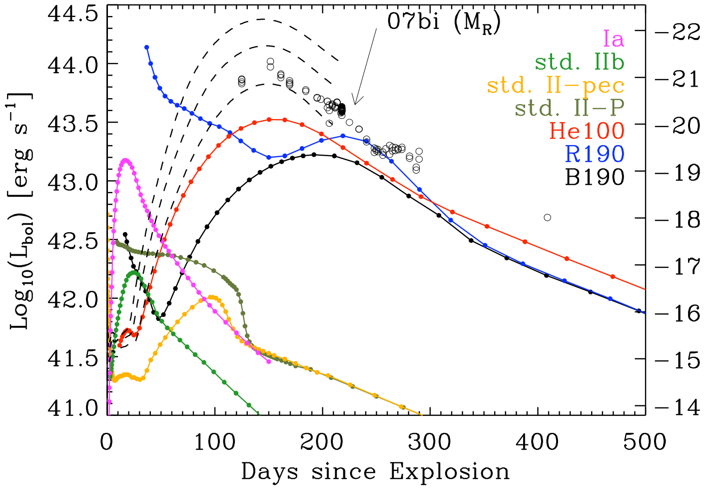


Pair-instability Supernovae

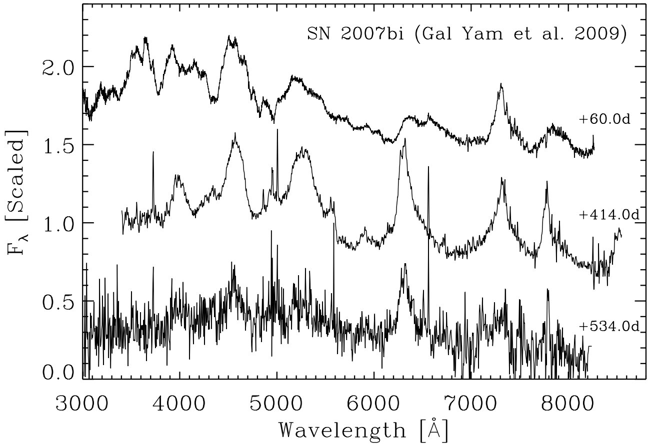
Comparison to SN 2007bi : Proposed as PISN by Gal-Yam et al (2009)

PISN Model:
Dessart et al. (2012,2013)

Light curves

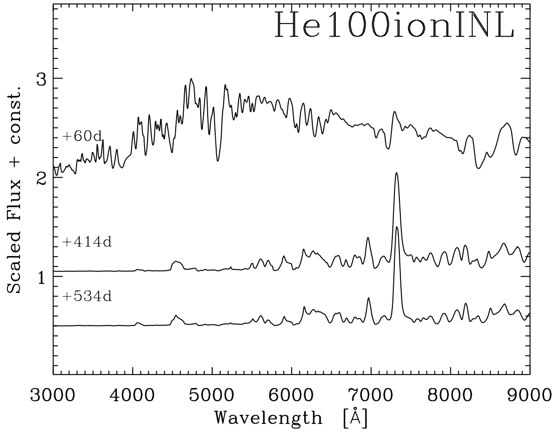


Data:
Gal-Yam et al. (2009)



PISN Model:
Dessart et al. (2012,2013)

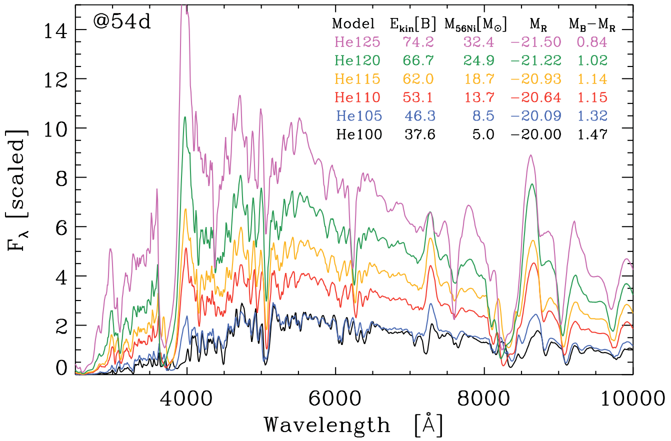
Spectra



- SN2007bi: Proposed as PISN by Gal-Yam et al (2009)
- LC fit SN Ic model (He100) with 5$M_\odot$ 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



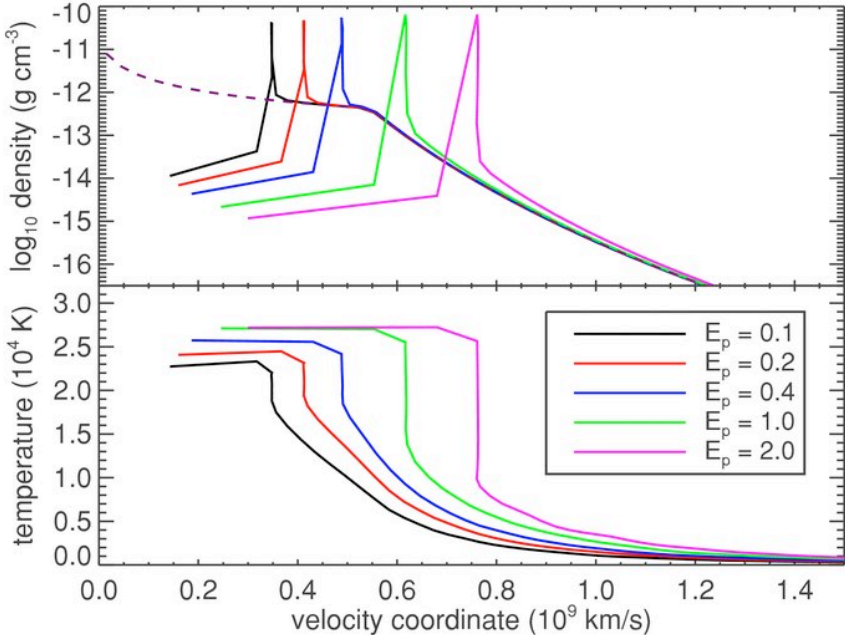
Magnetar-powered Supernovae

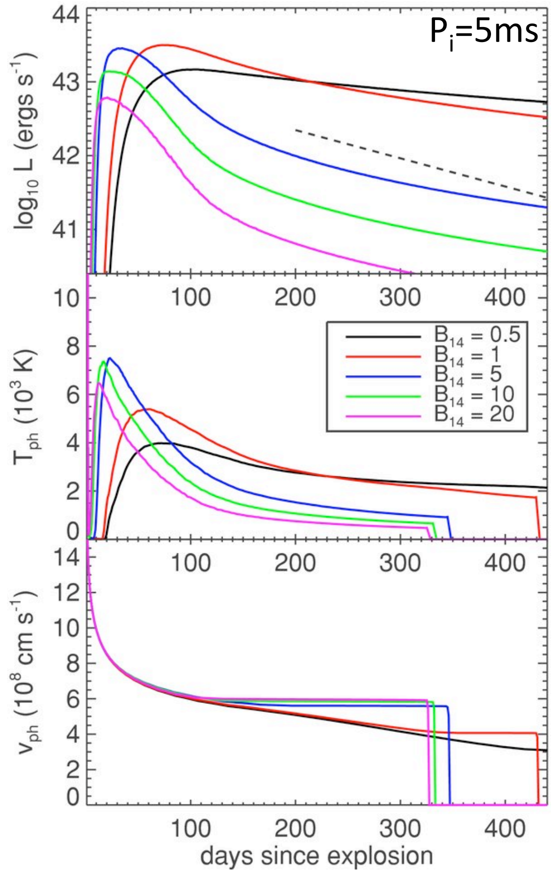
- Very different constraints: B and Period, not M
- Fast-spinning magnetar at birth: $E = I\omega^2/2 = 2\times10^{50}\ (P/10\text{ms})^{-2}$ erg
- Dipole radiation: $dE/dt = 10^{45}\ (B/10^{15}\text{G})^2(P/10\text{ms})^2$ erg/s
- Spin down time: $E/(dE/dt) = 4.8\text{d}\ (B/10^{15}\text{G})^{-2}(P/10\text{ms})^{2}$ => ≈half-life ^{56}Ni!
- SLSNe: 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 & Bildsten (2010)





Radiative signatures of magnetar-powered Supernovae

Model: Delayed energy injection in the 1B explosion of a 9$M_\odot$ WC star

Huge luminosities

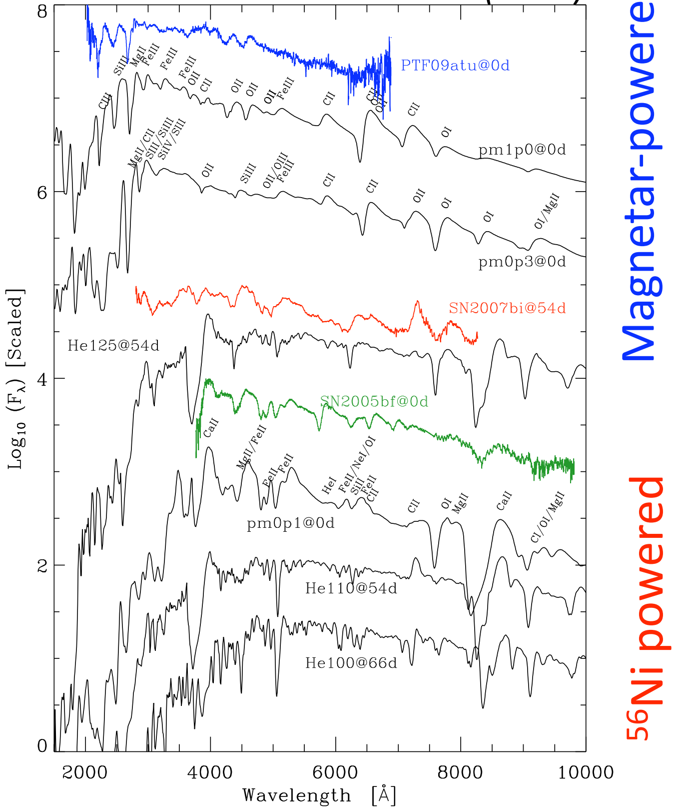
High E, moderate M => Fast rise to peak

Fast ejecta => broad lines at all times

High temperature and weak blanketing => blue colors/spectra

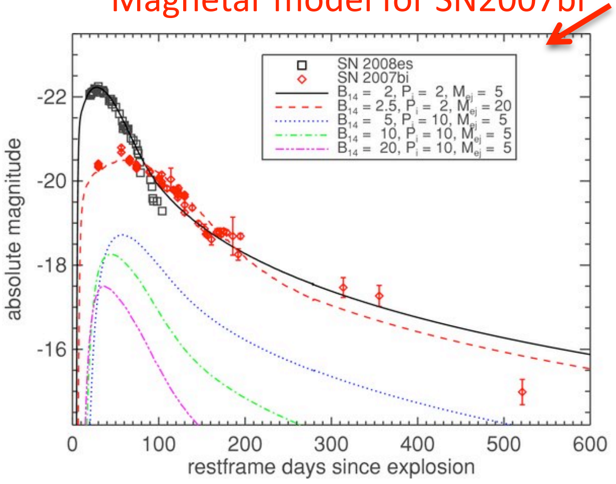
=> Stark contrast with PISN signatures!

Dessart etal. (2012)



Kasen & Bildsten (2010)

Magnetar model for SN2007bi



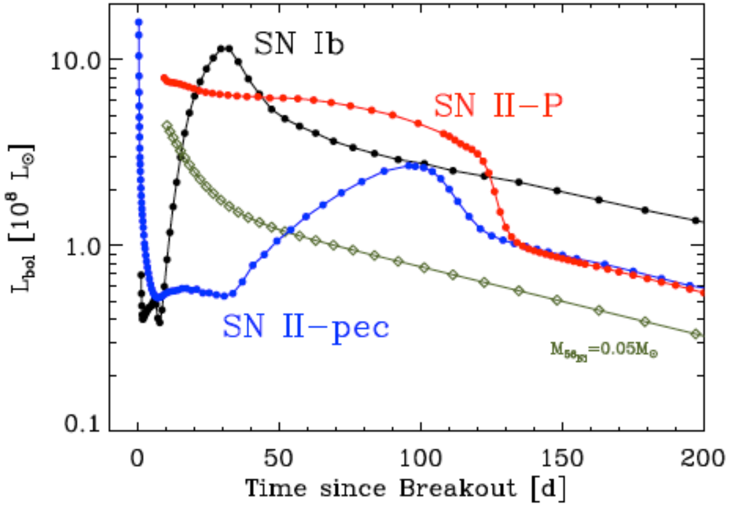
Massive star properties at death

- Fe core: 1.4-2$M_\odot$
- Envelope structure/composition f(M_{init},dM/dt, Ω, Z)
- He/CO-core mass f(M_{init},dM/dt)
- Single vs. binary star evolution
- dM/dt: wind ($10^{-(7-5)} M_\odot$/yr) or RLOF ($10^{-(5-3)} M_\odot$/yr)
- Final mass ≈2 to few 10 $M_\odot$

- Standard explosion: 1B and 0.1 $M_\odot$ of ^{56}Ni

⇒ Death as compact/extended light/heavy H-rich/deficient stars (WR vs. BSG/RSG)

⇒ Diversity of standard SN light curve and spectra connected to progenitor diversity



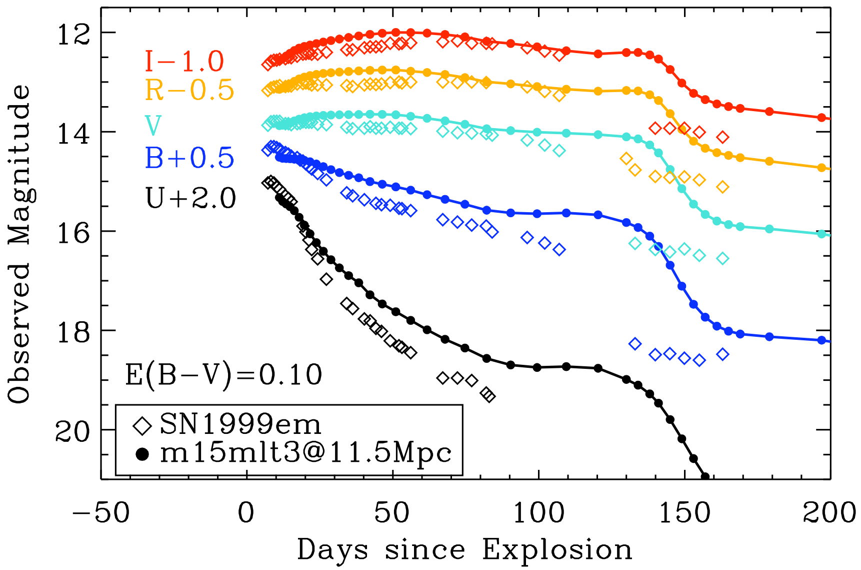
Case study of SNII-P 1999em

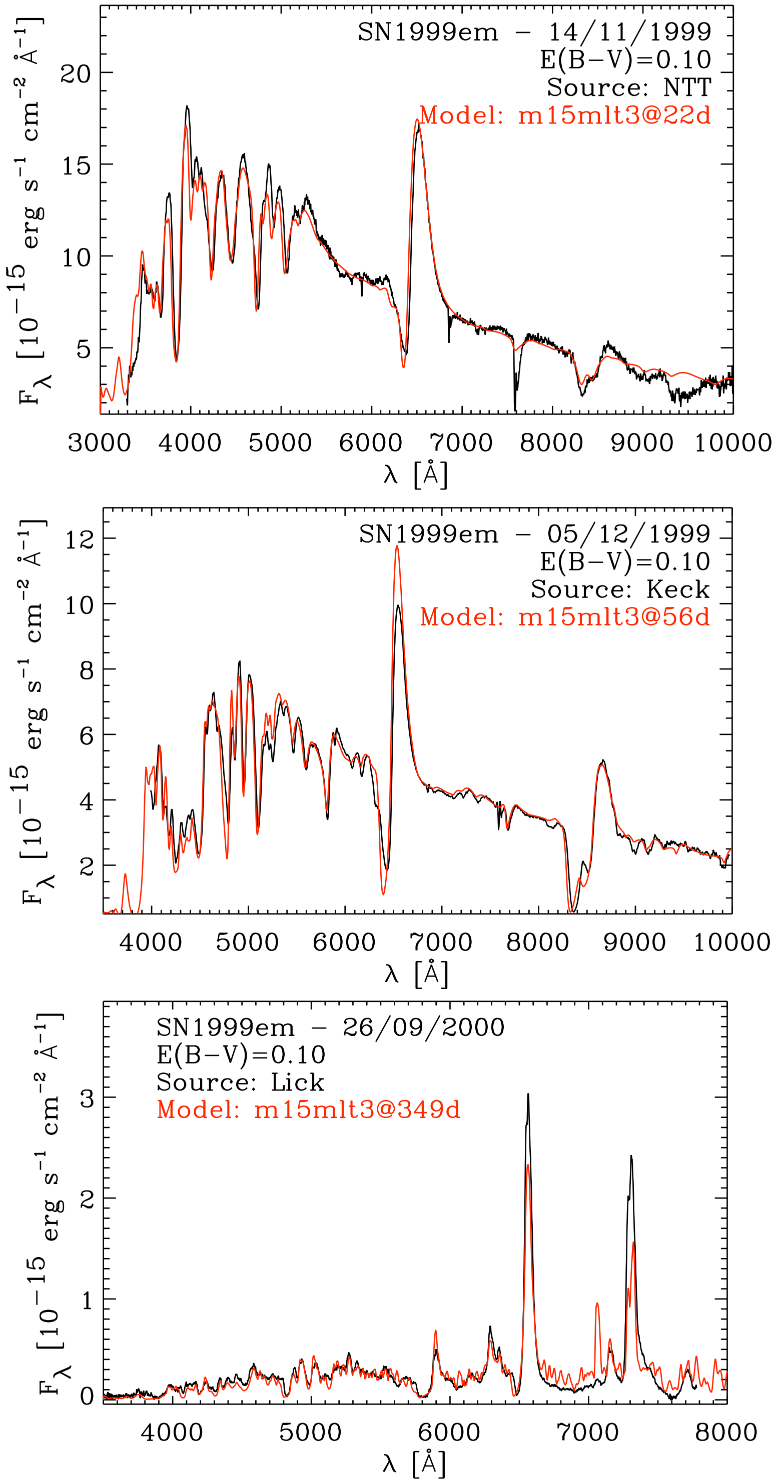
1.2B ejecta from

500R$_\odot$ 15M$_\odot$ RSG.

Dessart & Hillier (2011), Dessart et al. (2013)

- Good match to flux, 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.)

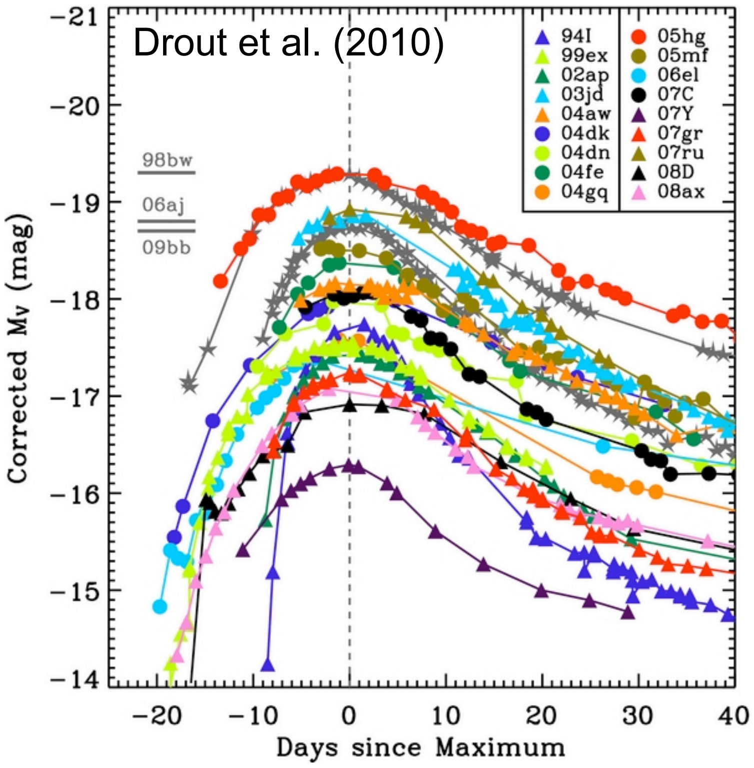




SN IIb/Ib/Ic Light curves: Observations vs. models

Observations

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



Drout et al. (2010)

Models

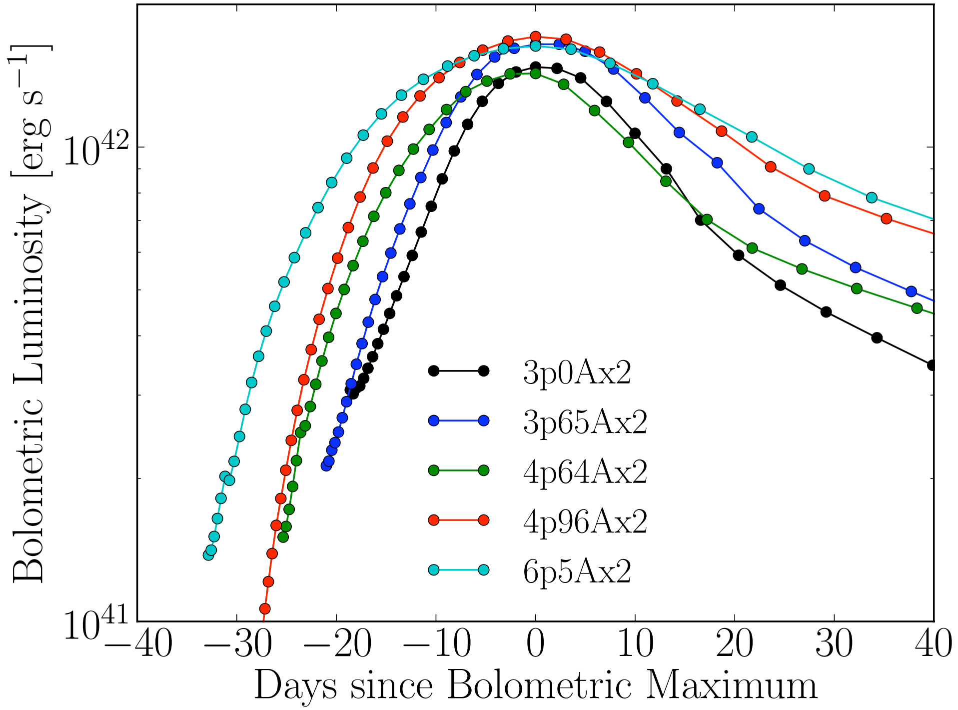
Early, narrow peak with

fast nebular decline

⇒ low-mass ejecta($<5M_\odot$)

⇒ **Binary star progenitors**

Follow-up to Dessart et al. (2011,2012)



Progenitors of CCSNe

Diversity of std CCSN: LC primarily f(Rstar), spectra primarily f(composition, ionization)

SNe II-P: RSGs from single star evolution, $M_{init} \approx 10\text{-}25 M_\odot$

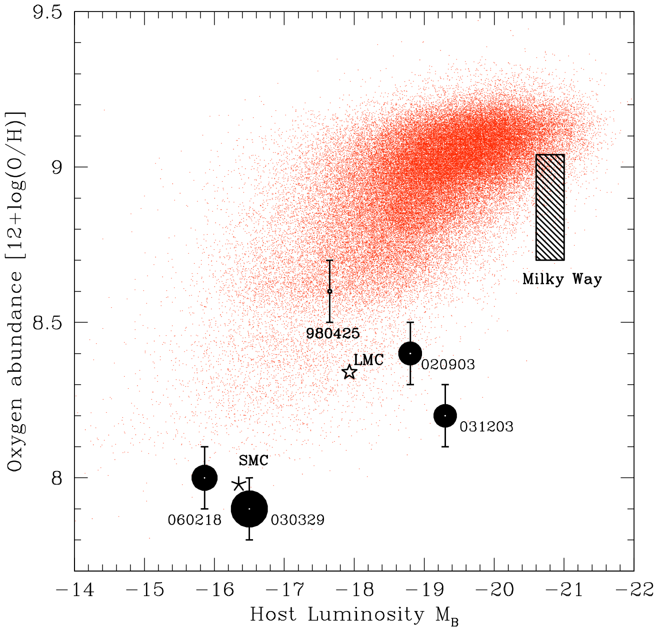
SNe Ib/c: "He cores" from binary-star evolution, $M_{init} \approx 10\text{-}25 M_\odot$

Fate of higher mass stars unknown.

LGRB/SN progenitors
Collapsar versus magnetar

- Rotation proposed as key for LGRBs/SNe
- Collapsar model: failed explosion, **BH formation**, disk formation, GRB, SN powered from disk wind. Huge rotation + core compactness *(Woosley 1993)*
- Magnetar model: GRB + SN powered by fast-spinning proto-magnetar *(Wheeler et al. 2000).*
- Reduce dL/dt by quenching dM/dt at low Z => $M_i \approx M_f$

Stanek et al. (2006)



Yoon et al. (2006)

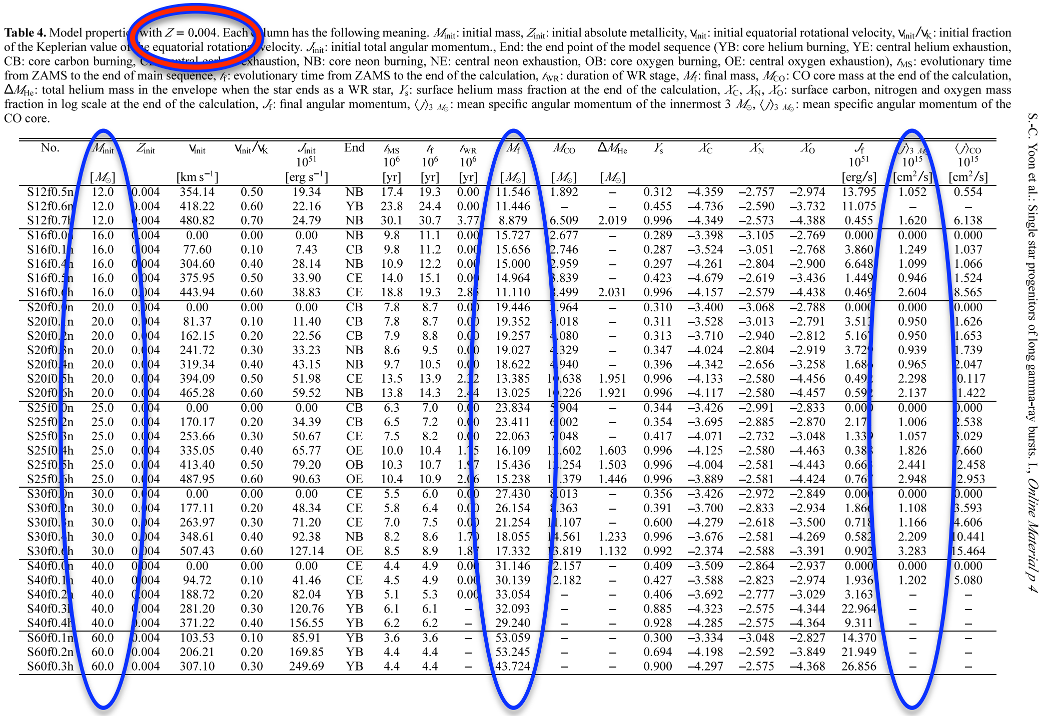


Table 4. Model properties with $Z = 0.004$. Each column has the following meaning. $M_{\rm init}$: initial mass, $Z_{\rm init}$: initial absolute metallicity, $v_{\rm init}$: initial equatorial rotational velocity, $v_{\rm init}/v_{\rm K}$: initial fraction of the Keplerian value of the equatorial rotational velocity. $J_{\rm init}$: initial total angular momentum., End: the end point of the model sequence (YB: core helium burning, YE: central helium exhaustion, CB: core carbon burning, CE: central carbon exhaustion, NB: core neon burning, NE: central neon exhaustion, OB: core oxygen burning, OE: central oxygen exhaustion), $t_{\rm MS}$: evolutionary time from ZAMS to the end of main sequence, $t_{\rm f}$: evolutionary time from ZAMS to the end of the calculation, $t_{\rm WR}$: duration of WR stage, $M_{\rm f}$: final mass, $M_{\rm CO}$: CO core mass at the end of the calculation, $\Delta M_{\rm He}$: total helium mass in the envelope when the star ends as a WR star, $Y_{\rm s}$: surface helium mass fraction at the end of the calculation, $X_{\rm C}$, $X_{\rm N}$, $X_{\rm O}$: surface carbon, nitrogen and oxygen mass fraction in log scale at the end of the calculation, $J_{\rm f}$: final angular momentum, $\langle j \rangle_{3\,M_\odot}$: mean specific angular momentum of the innermost 3 $M_\odot$, $\langle j \rangle_{3\,M_\odot}$: mean specific angular momentum of the CO core.

No.	$M_{\rm init}$ [$M_\odot$]	$Z_{\rm init}$	$v_{\rm init}$ [km s^{-1}]	$v_{\rm init}/v_{\rm K}$	$J_{\rm init}$ 10^{51} [erg s^{-1}]	End	$t_{\rm MS}$ 10^6 [yr]	$t_{\rm f}$ 10^6 [yr]	$t_{\rm WR}$ 10^6 [yr]	$M_{\rm f}$ [$M_\odot$]	$M_{\rm CO}$ [$M_\odot$]	$\Delta M_{\rm He}$ [$M_\odot$]	$Y_{\rm s}$	$X_{\rm C}$	$X_{\rm N}$	$X_{\rm O}$	$J_{\rm f}$ 10^{51} [erg/s]	$\langle j \rangle_{3\,M_\odot}$ 10^{15} [cm^2/s]	$\langle j \rangle_{\rm CO}$ 10^{15} [cm^2/s]
S12f0.5n	12.0	0.004	354.14	0.50	19.34	NB	17.4	19.3	0.00	11.546	1.892	–	0.312	−4.359	−2.757	−2.974	13.795	1.052	0.554
S12f0.6n	12.0	0.004	418.22	0.60	22.16	YB	23.8	24.4	0.00	11.446	–	–	0.455	−4.736	−2.590	−3.732	11.075	–	–
S12f0.7h	12.0	0.004	480.82	0.70	24.79	NB	30.1	30.7	3.77	8.879	6.509	2.019	0.996	−4.349	−2.573	−4.388	0.455	1.620	6.138
S16f0.0n	16.0	0.004	0.00	0.00	0.00	NB	9.8	11.1	0.00	15.727	2.677	–	0.289	−3.398	−3.105	−2.769	0.000	0.000	0.000
S16f0.1n	16.0	0.004	77.60	0.10	7.43	CB	9.8	11.2	0.00	15.656	2.746	–	0.287	−3.524	−3.051	−2.768	3.860	1.249	1.037
S16f0.4n	16.0	0.004	304.60	0.40	28.14	NB	10.9	12.2	0.00	15.000	2.959	–	0.297	−4.261	−2.804	−2.900	6.648	1.099	1.066
S16f0.5n	16.0	0.004	375.95	0.50	33.90	CE	14.0	15.1	0.00	14.964	3.839	–	0.423	−4.679	−2.619	−3.436	1.449	0.946	1.524
S16f0.6h	16.0	0.004	443.94	0.60	38.83	CE	18.8	19.3	2.85	11.110	3.499	2.031	0.996	−4.157	−2.579	−4.438	0.469	2.604	8.565
S20f0.0n	20.0	0.004	0.00	0.00	0.00	CB	7.8	8.7	0.00	19.446	3.964	–	0.310	−3.400	−3.068	−2.788	0.000	0.000	0.000
S20f0.1n	20.0	0.004	81.37	0.10	11.40	CB	7.8	8.7	0.00	19.352	4.018	–	0.311	−3.528	−3.013	−2.791	3.513	0.950	1.626
S20f0.2n	20.0	0.004	162.15	0.20	22.56	CB	7.9	8.8	0.00	19.257	4.080	–	0.313	−3.710	−2.940	−2.812	5.167	0.950	1.653
S20f0.3n	20.0	0.004	241.72	0.30	33.23	NB	8.6	9.5	0.00	19.027	4.329	–	0.347	−4.024	−2.804	−2.919	3.729	0.939	1.739
S20f0.4n	20.0	0.004	319.34	0.40	43.15	NB	9.7	10.5	0.00	18.622	4.940	–	0.396	−4.342	−2.656	−3.258	1.686	0.965	2.047
S20f0.5h	20.0	0.004	394.09	0.50	51.98	CE	13.5	13.9	2.32	13.385	10.638	1.951	0.996	−4.133	−2.580	−4.456	0.492	2.298	10.117
S20f0.6h	20.0	0.004	465.28	0.60	59.52	NB	13.8	14.3	2.44	13.025	10.226	1.921	0.996	−4.117	−2.580	−4.457	0.592	2.137	11.422
S25f0.0n	25.0	0.004	0.00	0.00	0.00	CB	6.3	7.0	0.00	23.834	5.904	–	0.344	−3.426	−2.991	−2.833	0.000	0.000	0.000
S25f0.2n	25.0	0.004	170.17	0.20	34.39	CB	6.5	7.2	0.00	23.411	6.002	–	0.354	−3.695	−2.885	−2.870	2.171	1.006	2.538
S25f0.3n	25.0	0.004	253.66	0.30	50.67	CE	7.5	8.2	0.00	22.063	7.048	–	0.417	−4.071	−2.732	−3.048	1.339	1.057	3.029
S25f0.4h	25.0	0.004	335.05	0.40	65.77	OE	10.0	10.4	1.75	16.109	12.602	1.603	0.996	−4.125	−2.580	−4.463	0.383	1.826	7.660
S25f0.5h	25.0	0.004	413.40	0.50	79.20	OB	10.3	10.7	1.97	15.436	12.254	1.503	0.996	−4.004	−2.581	−4.443	0.663	2.441	12.458
S25f0.6h	25.0	0.004	487.95	0.60	90.63	OE	10.4	10.9	2.06	15.238	11.379	1.446	0.996	−3.889	−2.581	−4.424	0.767	2.948	12.953
S30f0.0n	30.0	0.004	0.00	0.00	0.00	CE	5.5	6.0	0.00	27.430	8.013	–	0.356	−3.426	−2.972	−2.849	0.000	0.000	0.000
S30f0.2n	30.0	0.004	177.11	0.20	48.34	CE	5.8	6.4	0.00	26.154	8.363	–	0.391	−3.700	−2.833	−2.934	1.866	1.108	3.593
S30f0.3n	30.0	0.004	263.97	0.30	71.20	CE	7.0	7.5	0.00	21.254	11.107	–	0.600	−4.279	−2.618	−3.500	0.718	1.166	4.606
S30f0.4h	30.0	0.004	348.61	0.40	92.38	NB	8.2	8.6	1.70	18.055	14.561	1.233	0.996	−3.676	−2.581	−4.269	0.582	2.209	10.441
S30f0.6h	30.0	0.004	507.43	0.60	127.14	OE	8.5	8.9	1.87	17.332	13.819	1.132	0.992	−2.374	−2.588	−3.391	0.902	3.283	15.464
S40f0.0n	40.0	0.004	0.00	0.00	0.00	CE	4.4	4.9	0.00	31.146	12.157	–	0.409	−3.509	−2.864	−2.937	0.000	0.000	0.000
S40f0.1h	40.0	0.004	94.72	0.10	41.46	CE	4.5	4.9	0.00	30.139	12.182	–	0.427	−3.588	−2.823	−2.974	1.936	1.202	5.080
S40f0.2h	40.0	0.004	188.72	0.20	82.04	YB	5.1	5.3	0.00	33.054	–	–	0.406	−3.692	−2.777	−3.029	3.163	–	–
S40f0.3h	40.0	0.004	281.20	0.30	120.76	YB	6.1	6.1	–	32.093	–	–	0.885	−4.323	−2.575	−4.344	22.964	–	–
S40f0.4h	40.0	0.004	371.22	0.40	156.55	YB	6.2	6.2	–	29.240	–	–	0.928	−4.285	−2.575	−4.364	9.311	–	–
S60f0.1n	60.0	0.004	103.53	0.10	85.91	YB	3.6	3.6	–	53.059	–	–	0.300	−3.334	−3.048	−2.827	14.370	–	–
S60f0.2n	60.0	0.004	206.21	0.20	169.85	YB	4.4	4.4	–	53.245	–	–	0.694	−4.198	−2.592	−3.849	21.949	–	–
S60f0.3h	60.0	0.004	307.10	0.30	249.69	YB	4.4	4.4	–	43.724	–	–	0.900	−4.297	−2.575	−4.368	26.856	–	–

S.-C. Yoon et al.: Single star progenitors of long gamma-ray bursts. I., *Online Material p 4*

LGRB/SN progenitors
Collapsar versus magnetar

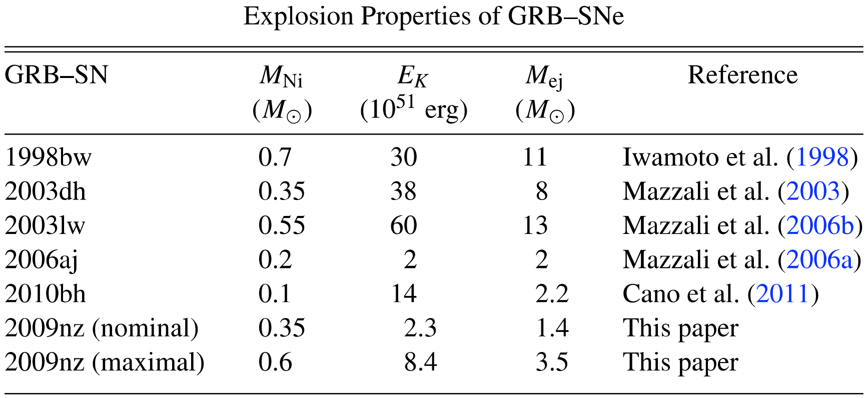
- Reduce dL/dt by quenching dM/dt at low Z => $M_i \approx M_f$
- GRB/SNe ejecta masses: 2-15$M_\odot$
- But:

⇒ Can we form BHs from a 10-20$M_\odot$ fast-spinning progenitor?

⇒ Do they have the right core structure?

⇒ Can they escape a magneto-rotational explosion and produce a SLSN?

Berger et al. (2011)

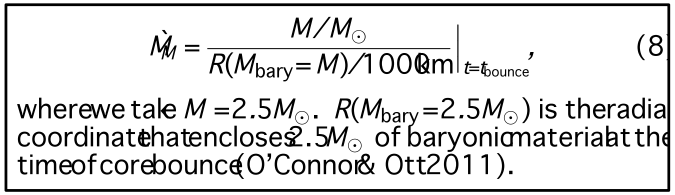


Explosion Properties of GRB–SNe

GRB–SN	$M_{\rm Ni}$ ($M_\odot$)	E_K (10^{51} erg)	$M_{\rm ej}$ ($M_\odot$)	Reference
1998bw	0.7	30	11	Iwamoto et al. (1998)
2003dh	0.35	38	8	Mazzali et al. (2003)
2003lw	0.55	60	13	Mazzali et al. (2006b)
2006aj	0.2	2	2	Mazzali et al. (2006a)
2010bh	0.1	14	2.2	Cano et al. (2011)
2009nz (nominal)	0.35	2.3	1.4	This paper
2009nz (maximal)	0.6	8.4	3.5	This paper

GRB/SN progenitors of Woosley & Heger (2006)

Likelihood of BH formation in collapsar progenitors

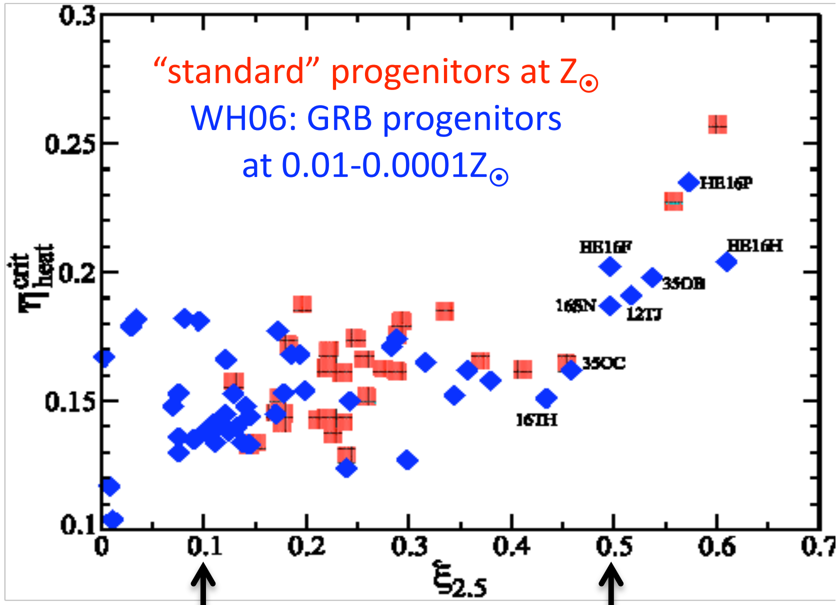


$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary}=M)/1000\,{\rm km}}\bigg|_{t=t_{\rm bounce}}, \qquad (8$$

where we take $M = 2.5M_\odot$. $R(M_{\rm bary}=2.5M_\odot)$ is the radia
coordinate that encloses $2.5M_\odot$ of baryonic material at th
time of core bounce (O'Connor & Ott 2011).

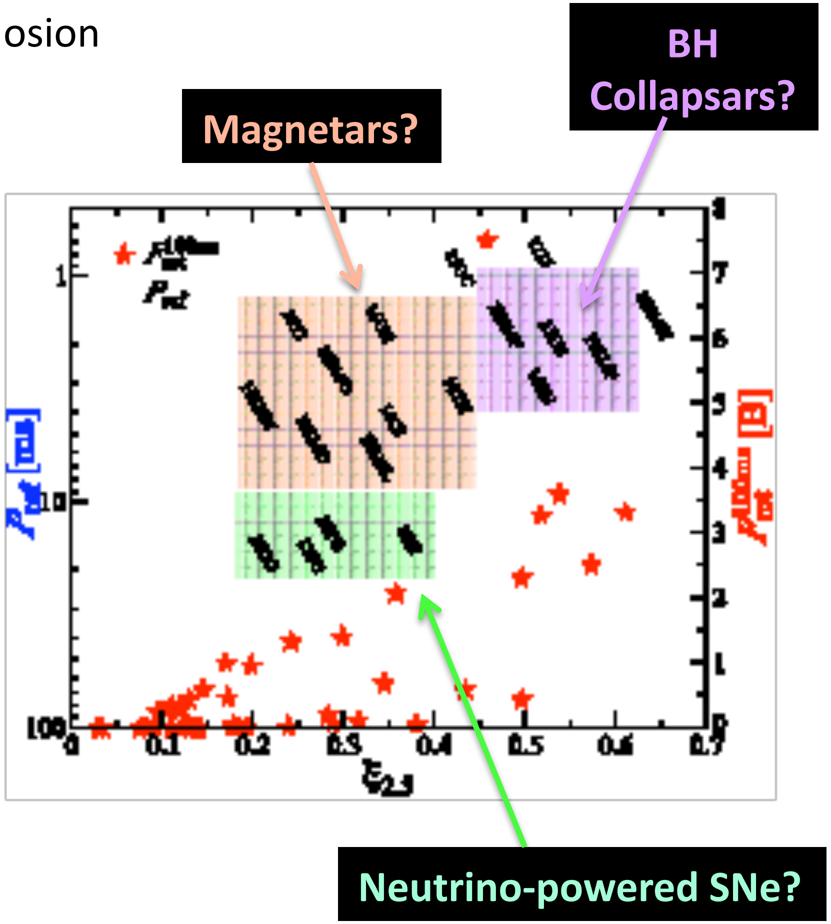
- BH formation is key for collapsar model
- Indicator: core compactness $\xi_{2.5}$
- Most GRB progenitors (WH06) have small Fe core and $\xi_{2.5}$; Overlap with $Z_\odot$ progenitors!
- But huge core rotation to produce a MHD explosion

Dessart, O'Connor & Ott (2012)



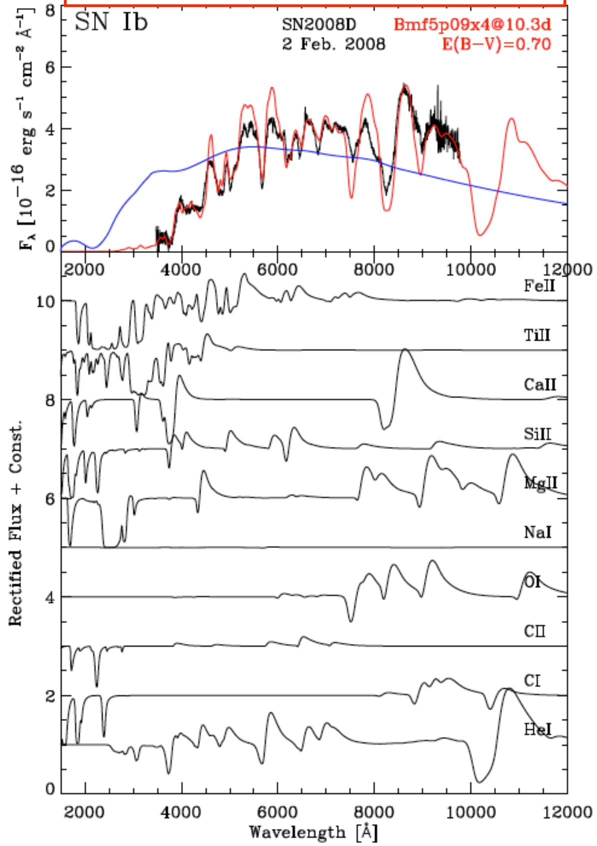
$R_{2.5}$=25000km

$R_{2.5}$=5000km

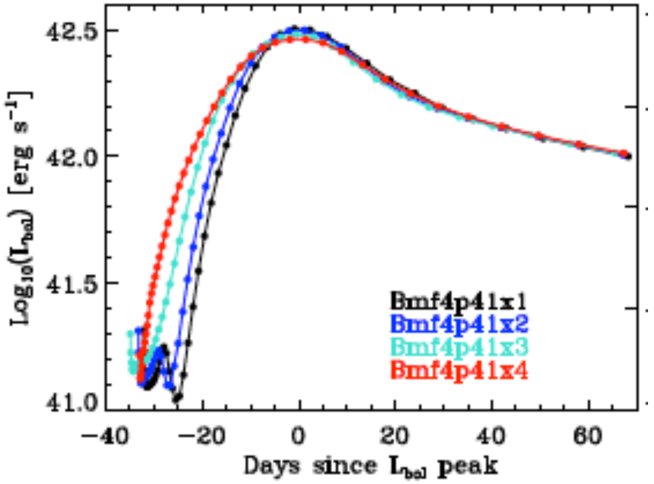


Sensitivity of SN Ib/Ic classification; Effect of mixing in a $3M_\odot$ He-rich ejecta

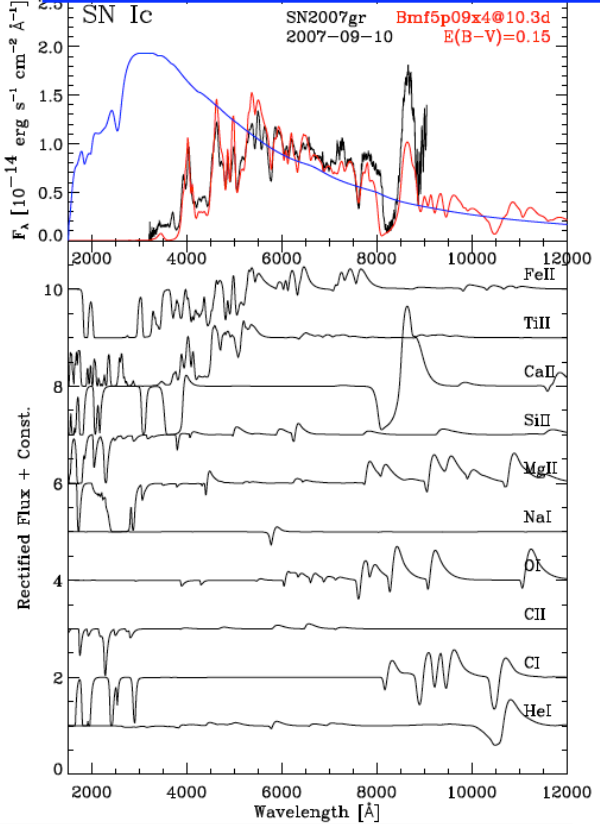
Strong Mixing: SN Ib



Dessart et al. (2011,2012)



Moderate Mixing: SN Ic



Mixing modulates:

- Bolometric rise time and brightening slope
- Spectral colors
- Width of lines (effect on ionization) => Inferrence of E_{kin}
- **Non-thermal excitation of HeI lines => SN Ib or Ic classification**

Summary

- SN radiation Modeling: tool to infer progenitor and explosion properties
- Superluminous SNe from CSM interaction, extreme M(^{56}Ni), magnetar radiation
- CSM interaction => SNe IIn: H-rich, narrow lines (some Ibn and Ian too).
- PISNe: broad luminous light curves with red colors. Slow expansion. Yet to be seen?
- Magnetar-powered SNe: diverse LCs (B, Ω), short rise time, blue colors, fast expansion (broad nebular lines).

=> ^{56}Ni power vs. « Magnetar » power produce different signatures

- Fast core rotation + low $M_{\rm init}$/low compactness good for magnetar formation + SLSNe; suitable for black holes?
- Helium in SNe Ic? Problem of mixing and/or CO core mass. Probably present in all SNe Ic.