Stellar death and Supernovae

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- Strong connection to stellar physics, evolution (rotation, B, comp. …)
- Means of explosion: core collapse and combustion
- The transient sky: Old census and recent discoveries
- Future prospects: Modelling and observations

Stellar Explosion

Making use of binding energy

- Gravitational Binding Energy: collapse of a ~$1M_\odot$ WD to a NS releases 10^{53}erg => Collapse of the iron core if the ultimate fate of all massive stars ($M \geq 8M_\odot$). Neutrinos are key for explosion. Young stellar populations.

- Nuclear Binding Energy: combustion of ~$1M_\odot$ of C/O to intermediate/iron-group mass elements releases ~10^{51}erg => Thermonuclear runaway of a Chandrasekhar-mass WD. Combustion is key. Low-mass graveyard (WD+H/He; WD+WD) – Old stellar populations.

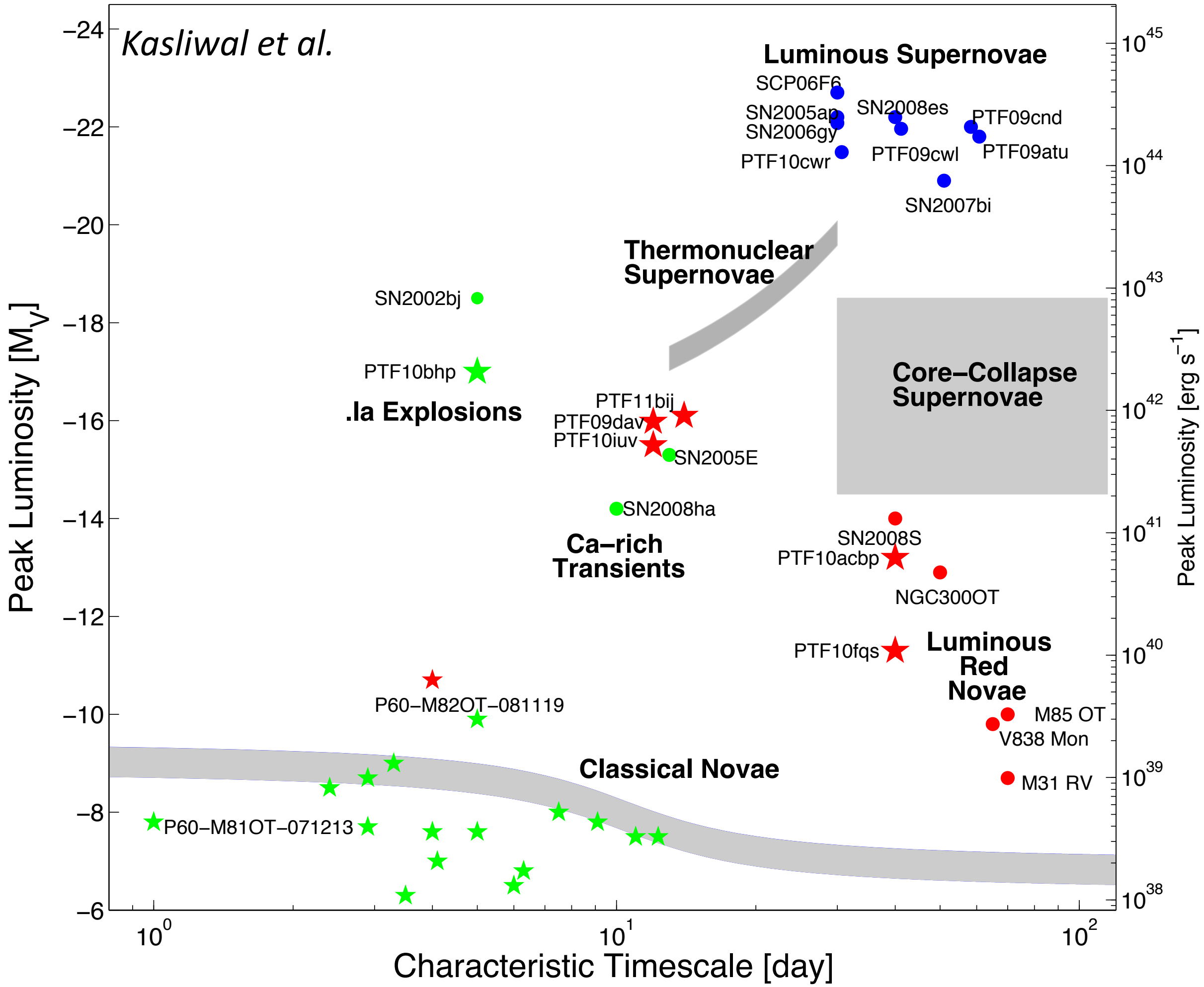
⇒ Energy released unbinds and ejects the star (fully/partially).
⇒ SN radiation powered by shock-deposited and/or radioactive decay energy
⇒ SN radiation influenced by progenitor structure ($M_\star$, $R_\star$)
⇒ Use SN radiation to constrain progenitor and explosion properties

Observations of the Transient Sky

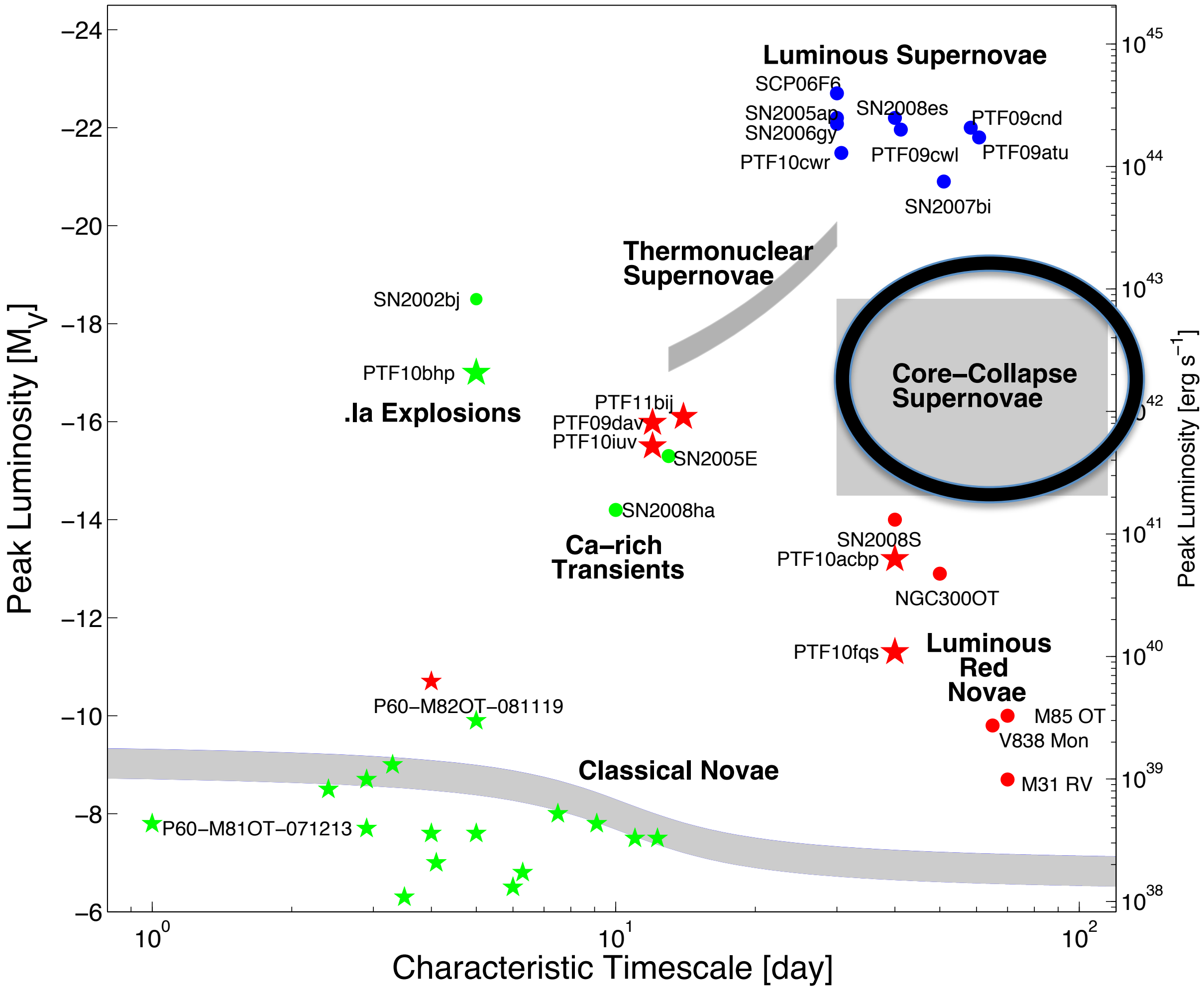
Ongoing transient surveys (many un-targeted):

e.g., Palomar Transient Factory, Pan-STARRS, La Silla Quest, CHASE, Catalina survey

+ Large programs: e.g. ESO/PESSTO



Core-collapse supernovae from massive star explosions

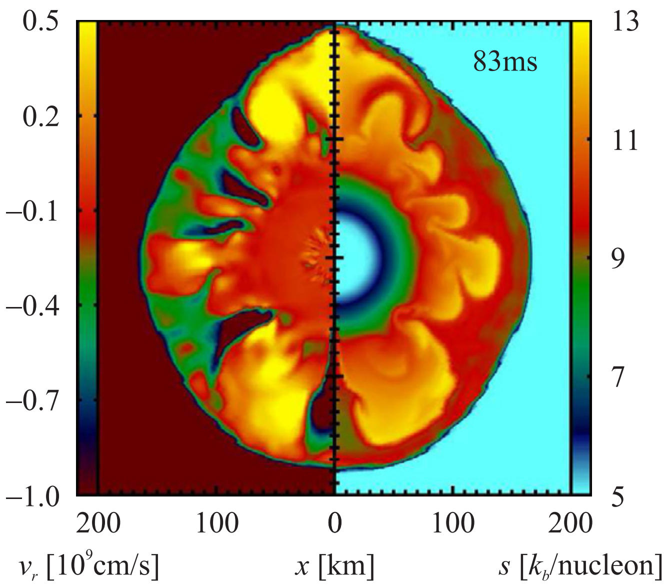


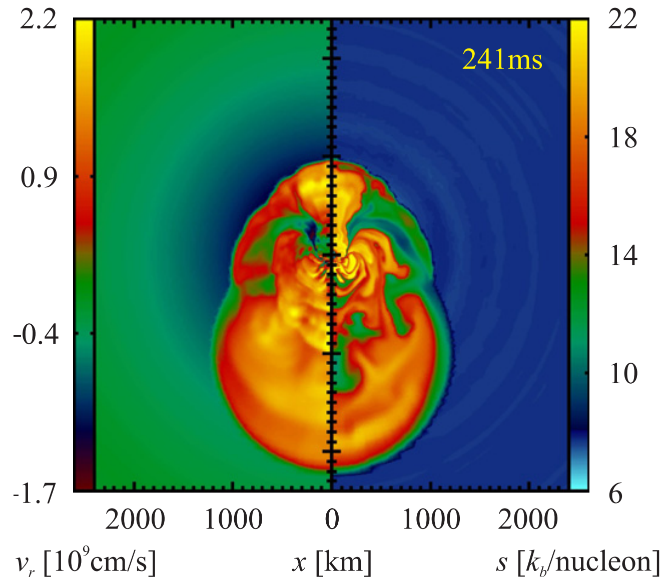
The core-collapse explosion mechanism

- Neutrino-driven explosion mechanism probably for all standard core-collapse SNe
- Numerical challenge (multi-D effects, neutrino transport)
- Dependency on core structure / compactness => pre-SN star (M, single/binary)?
- Maximum MS mass for successful explosion? Could be as low as 20-25$M_{\odot}$

Core collapse does NOT imply a successful supernova explosion

$8M_{\odot}$ progenitor *(Mueller et al. 2012)*

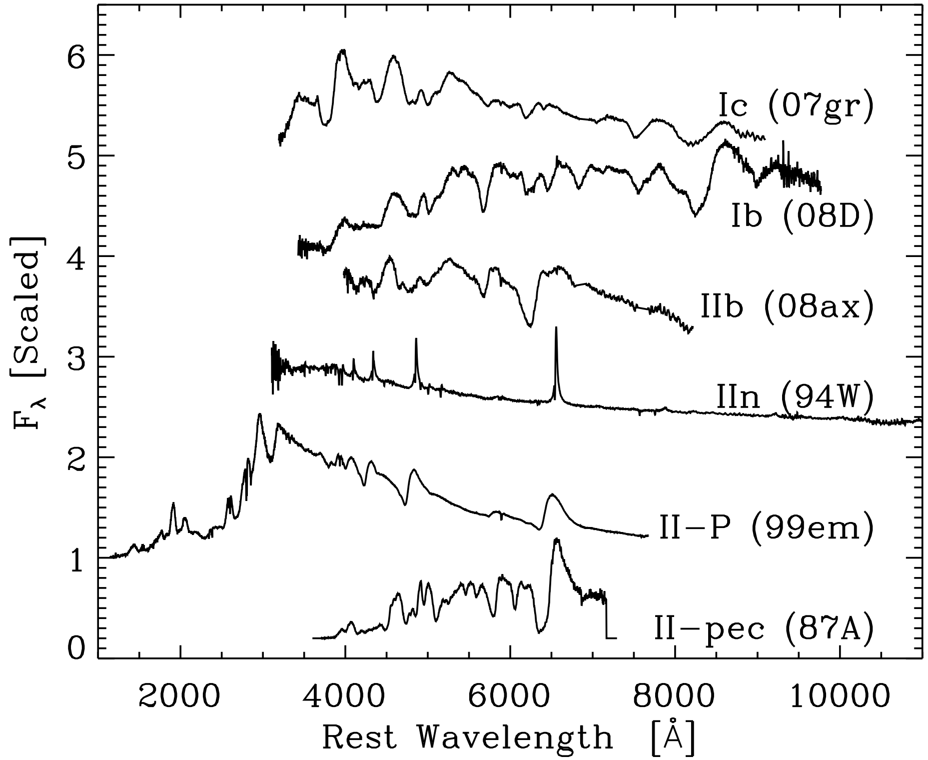




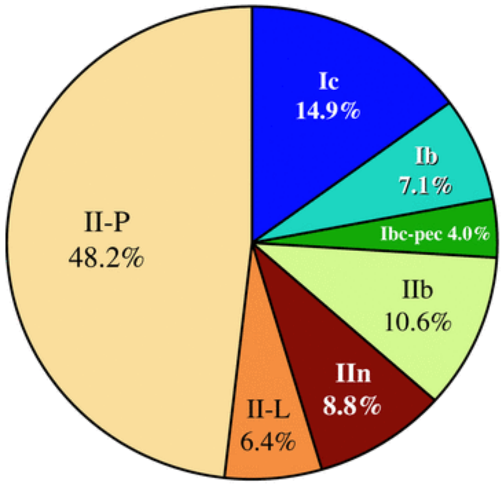
Diversity of observed core-collapse supernovae

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

=> Connection to pre-SN evolution + explosion



Smith et al. (2011)



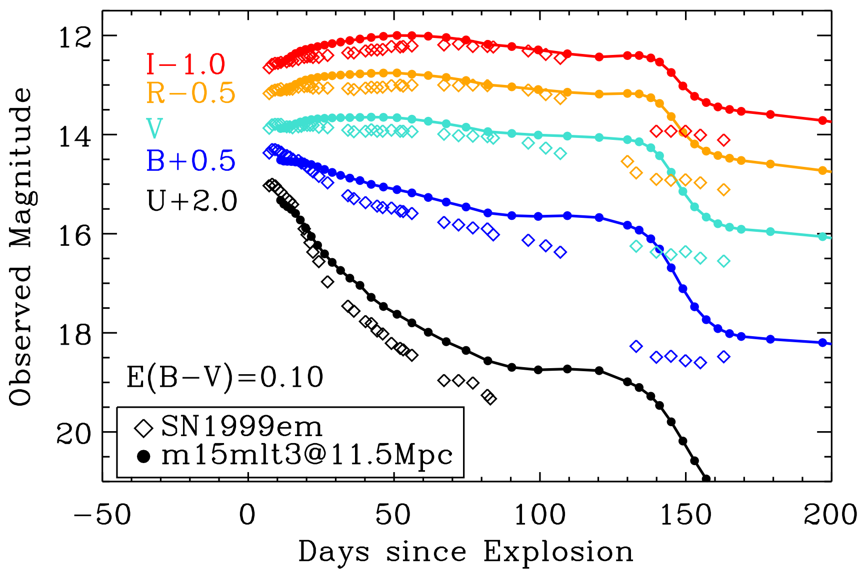
Core-Collapse SN Fractions

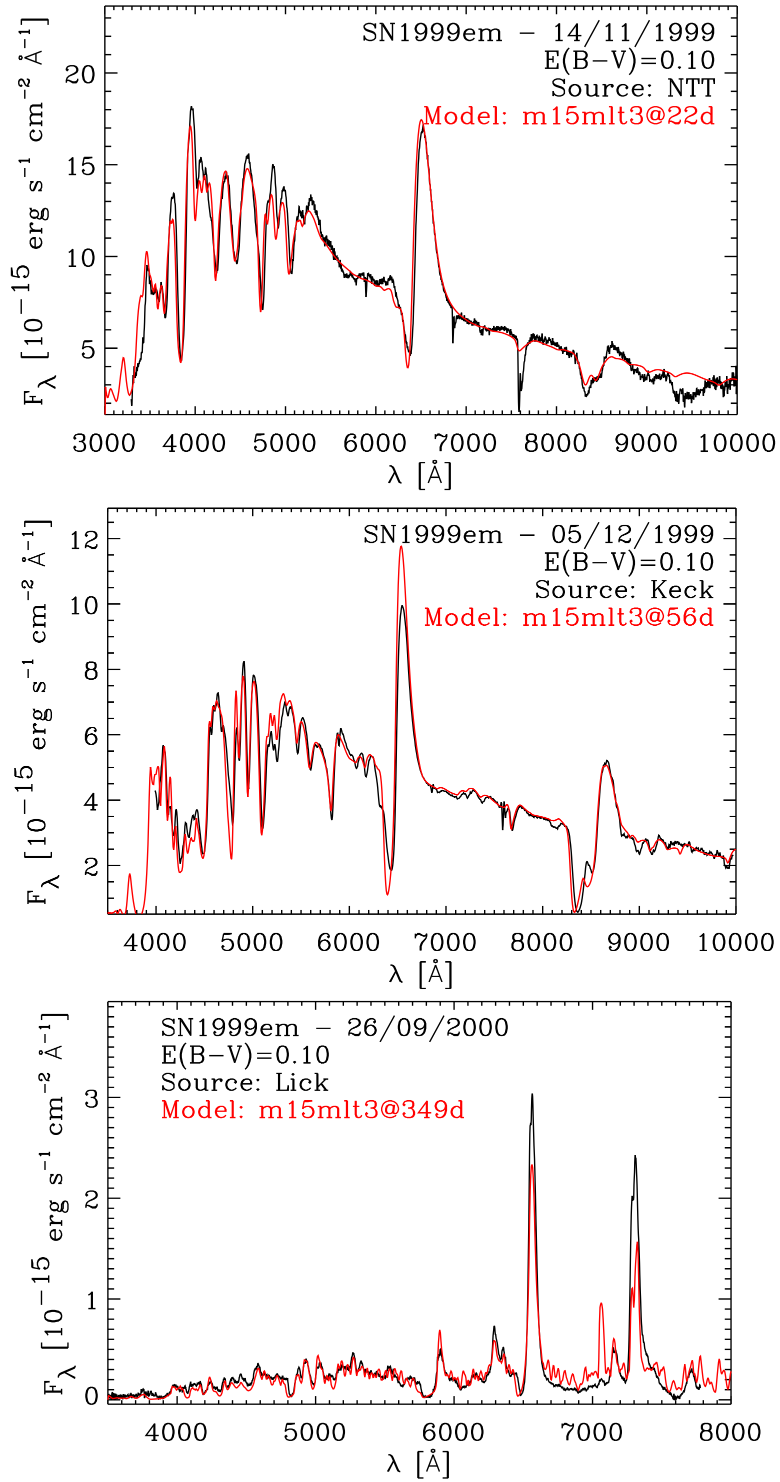
Red-supergiant stars are progenitors of Type II-Plateau Supernovae

Case study of SN1999em

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

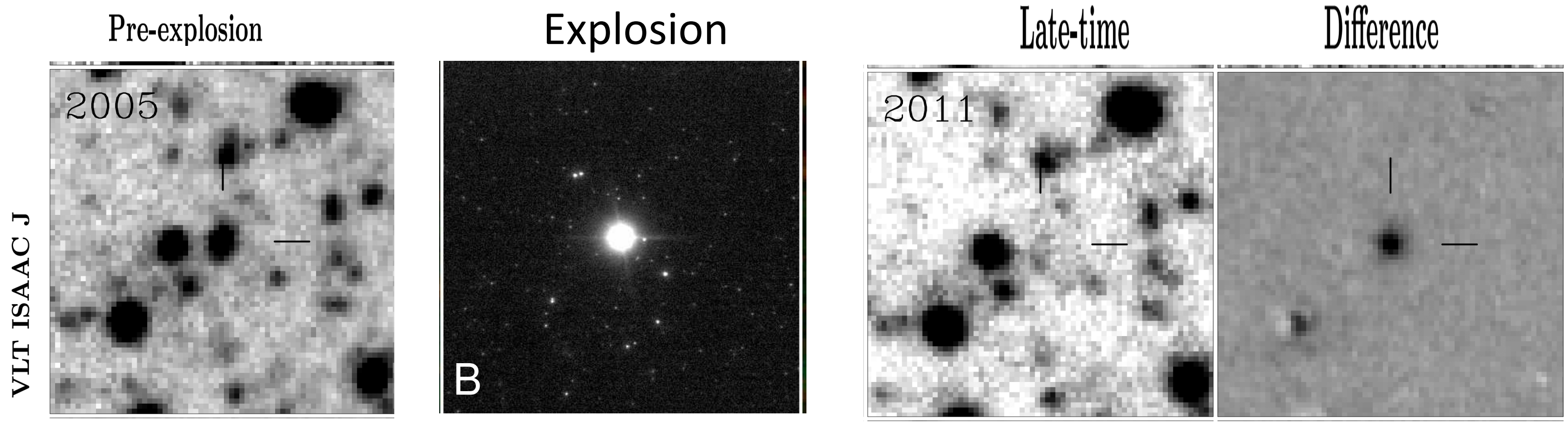
Modeling supports a $500R_{\odot}$ $15M_{\odot}$ RSG turned into a $\sim10^{51}$erg ejecta





RSG progenitors of SNe II-P identified on pre-explosion images

Smartt, van Dyk, Leonard and Co



SN 2008bk

- **A handful of SNe II-P progenitors identified photometrically as RSG stars (inferred mass <18$M_{\odot}$).**
- **Supergiant progenitors of SNe IIb also detected (e.g., SN 1993J)**
- **But no SN Ia/Ib/Ic progenitor detected yet….**

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

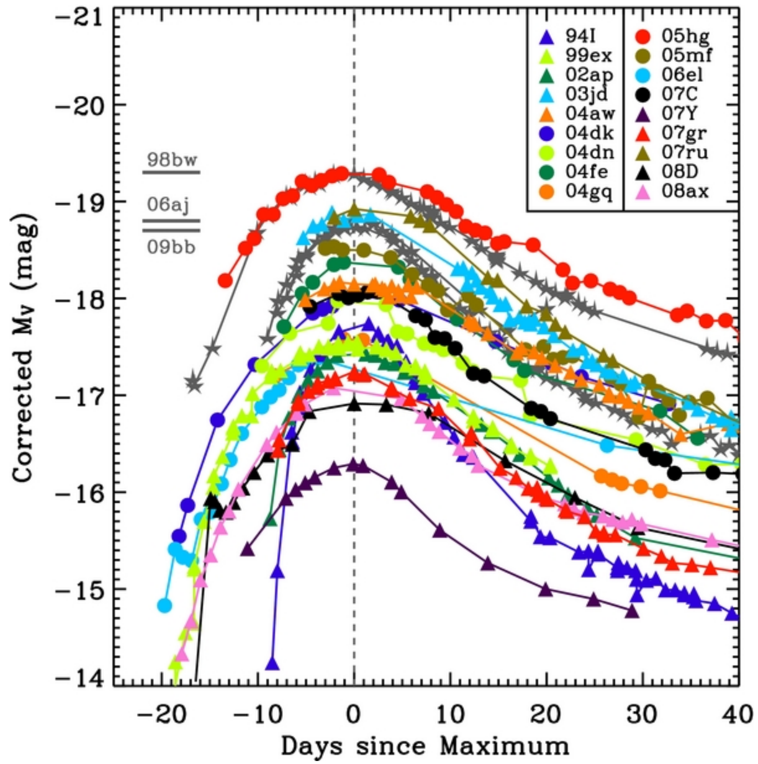
⇒ Narrow light curves suggest low mass ejecta

⇒ Single WR stars probably too massive at death

⇒ SN IIb/Ib/Ic rates hard to reconcile with single stars and standard IMF

⇒ **Solution: interacting binaries**

Drout et al. (2010)

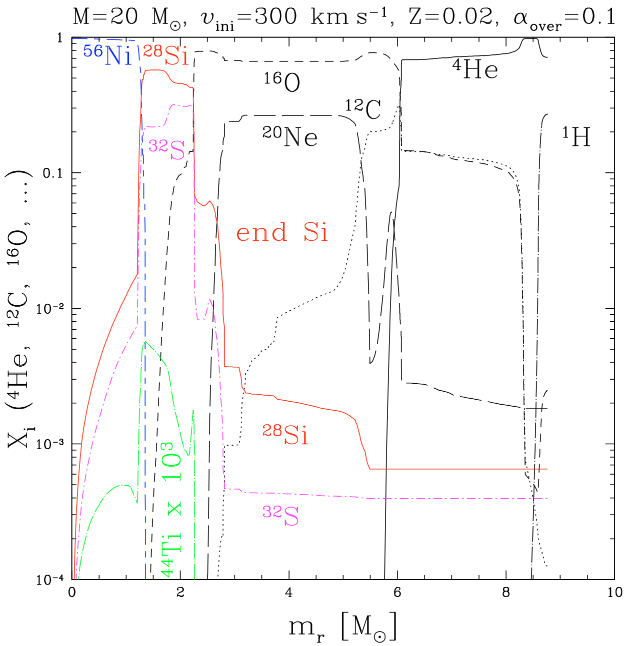


Importance of mass loss for envelope stripping

Radiation-driven Wind mass loss

- dM/dt ~$10^{-5} M_\odot$/yr ; f(M,Z,Ω)
- Key for higher mass stars
- **Final mass of 10-20$M_\odot$**

Ex. 20$M_\odot$ single + rot.

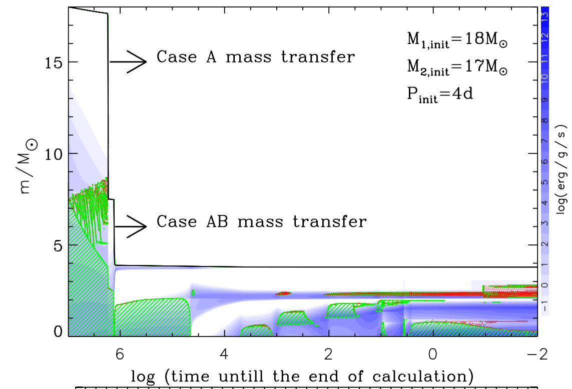


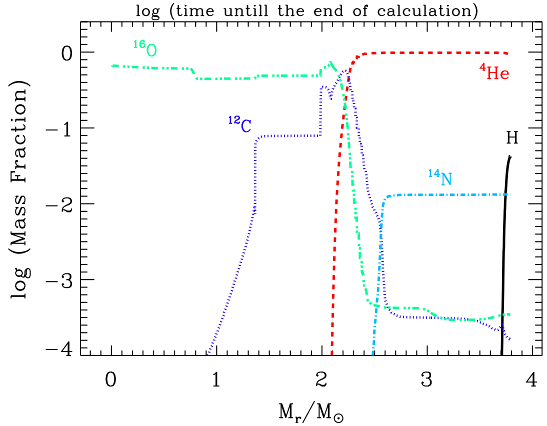
Hirschi et al. (2004); Georgy et al. (2011)

Binary mass transfer

- 70% of massive stars in binary systems
- dM/dt ~$10^{-4} M_\odot$/yr ;
- Key for lower mass stars
- **Final mass as low as 2-3$M_\odot$**

Ex: 18$M_\odot$+ 17$M_\odot$ binary





Yoon et al. (2010)

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

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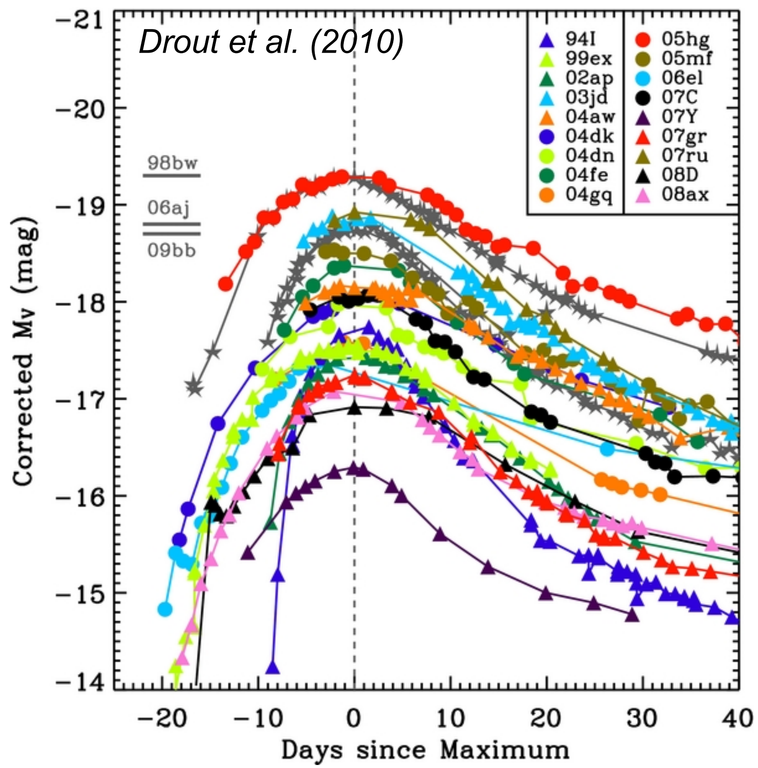
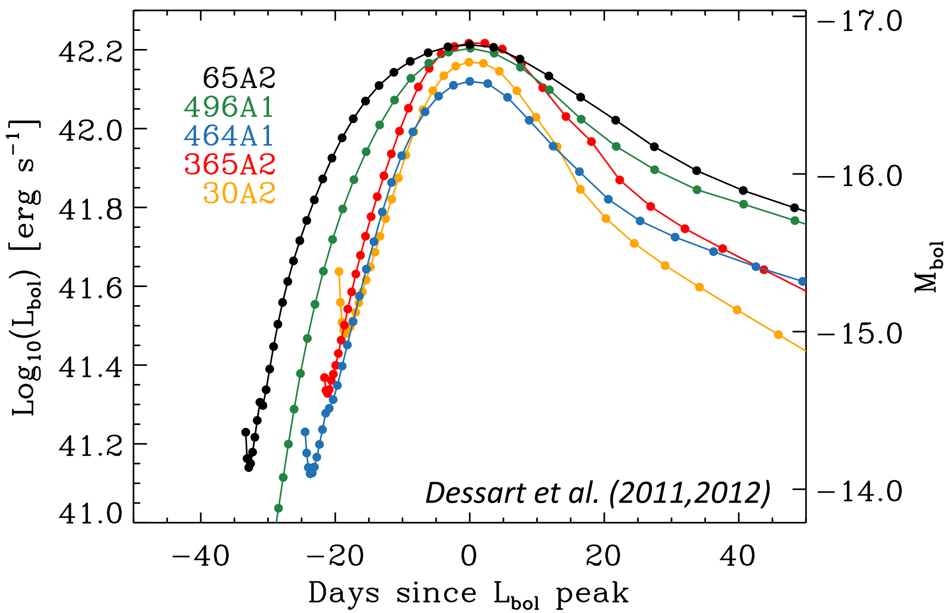
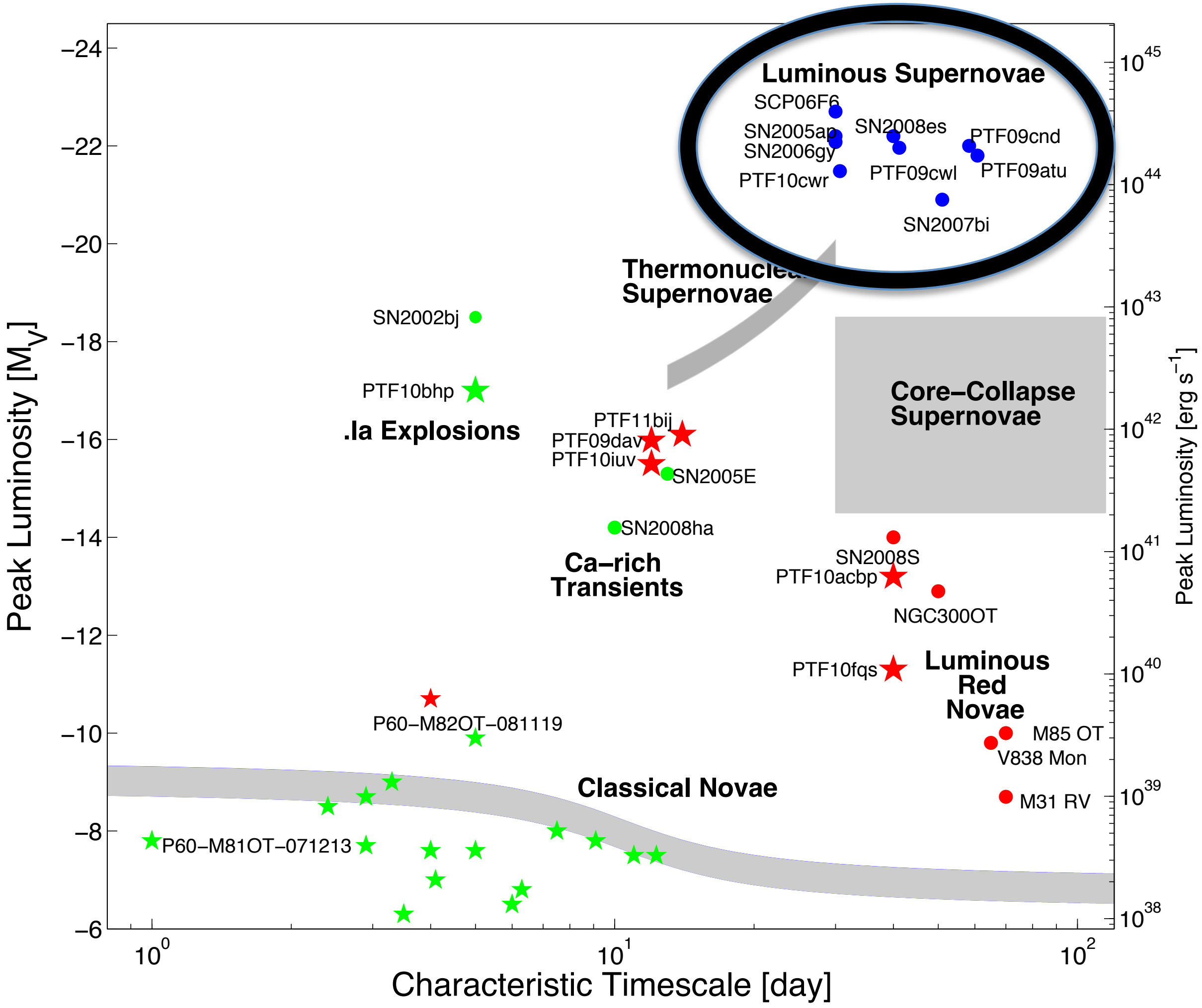


Models

- Inputs: binary stars of 15-25$M_\odot$
- Early, narrow peak with fast nebular decline
- low-mass ejecta(<5$M_\odot$)
- Favors Binary star progenitors (single WRs too massive at death)
- Confirms expectations form SN populations (Eldridge, Smith etc.)



Core-collapse supernovae from massive star explosions



LGRB/SNe: Collapsar and/or magnetar?

- Massive stars associated with LGRBs/SNe
- Key role of Rotation :

1) Collapsar model: failed explosion, BH formation, disk formation, GRB, SN powered from disk wind. Huge rotation + core compactness *(Woosley 1993)*

2) Magnetar model: GRB + SN powered by fast-spinning proto-magnetar *(Wheeler et al. 2000)*. **Magneto-rotation explosion** *(Dessart et al. 2008).*

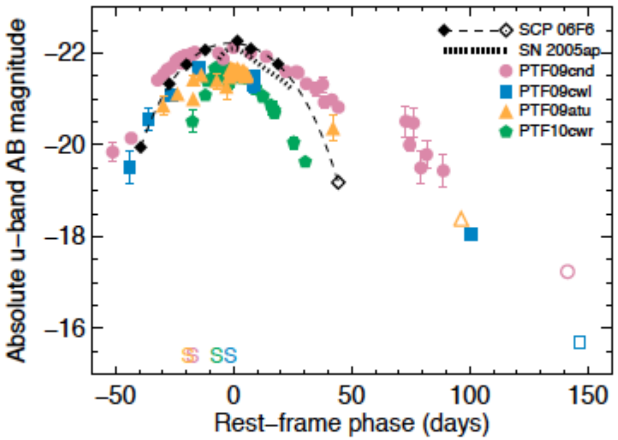
- **Reduce dL/dt by quenching dM/dt at low Z => $M_i \approx M_f$**
- GRB/SNe show diverse ejecta masses and energies (host Z?)
- BH formation uncertain for lower mass progenitors => Favors magnetars?

Berger et al. (2011)

Explosion Properties of GRB–SNe

GRB–SN	M_{Ni} ($M_\odot$)	E_K (10^{51} erg)	M_{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

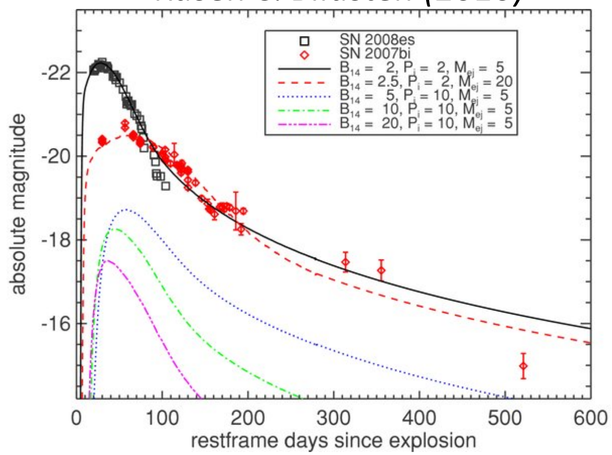
Superluminous Supernovae: Mechanisms



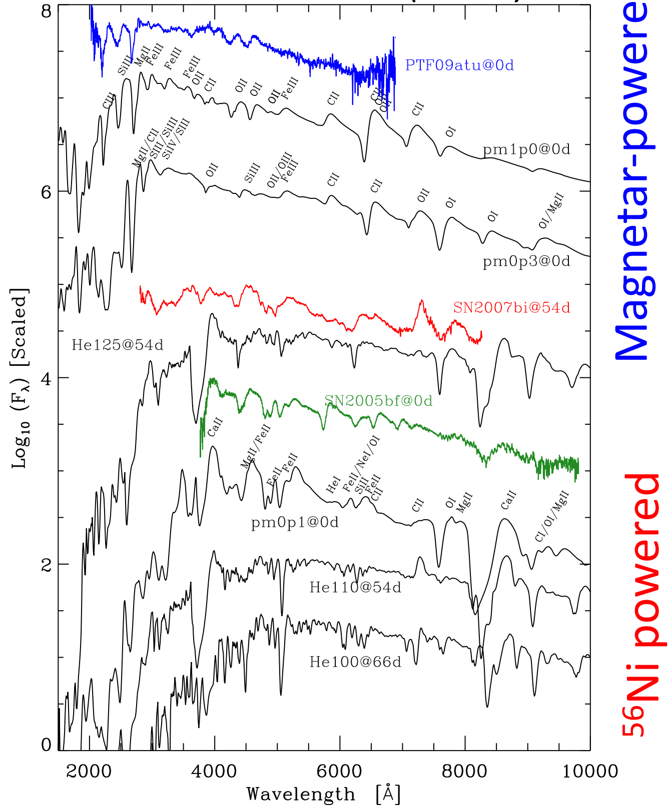
SLSNe Ic at z~1

(*Quimby et al. 2010*)

Kasen & Bildsten (2010)



Dessart etal. (2012c)



- 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

Summary

- Huge progress on observational side: Wide-field high-cadence surveys. **LSST, ELT!**
- CCSNe come from low/moderate mass massive stars either single or binaries
- Fate of more massive stars unclear. Complete collapse to a black hole?
- GRB/SN progenitors: BH formation not guaranteed. Collapsar or Magnetar?
- Super-luminous SNe at z~1: Magnetar powered? Probes of distant universe.
- Diversity of faint/fast transients: variety of burning configurations in WDs. Tough numerical challenge for RT and hydro.
- Need to understand stellar explosions to understand the chemical evolution of the Universe, the formation of compact objects (BH, pulsars, magnetars), the origin of LGBRs etc.

=> Strong need for radiative-transfer modeling of SN light curves and spectra + multi-D hydro modeling of explosion