nature astronomy
REVIEW ARTICLE
https://doi.org/10.1038/s41550-019-0856-2

# New regimes in the observation of core-collapse supernovae

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(Group meeting, 2023/12/08)

**Abstract points:** Contributions of wide-field surveys and rapid-response follow-up facilities.

(1) Large statistical samples that enable population studies of the most common SNe and reveal rare (but extremely informative) events that question our standard understanding of the explosion physics involved.
(2) The observations of early SNe emission taken shortly after explosion, which carry signatures of the progenitor structure and mass-loss history has been obtained in some cases.
(3) Future facilities will increase our observational capabilities and allow us to answer many open questions related to these extremely energetic phenomena of the Universe.

# Abbreviations and key terms

- Supernova (SN): SN 2023A, SN 2023Z
- Supernovae (SNe): SNe 2023A, 2023Z, 2023aa ..
- PSN: Possible SN
- Light curve/Bolometric luminosity
- $\Delta m_{15}$ parameter
- Photospheric and nebular phase (early/late)
- Explosion parameters ($M_{ej}$, $^{56}Ni$, $E_{KE}$)

# Supernovae

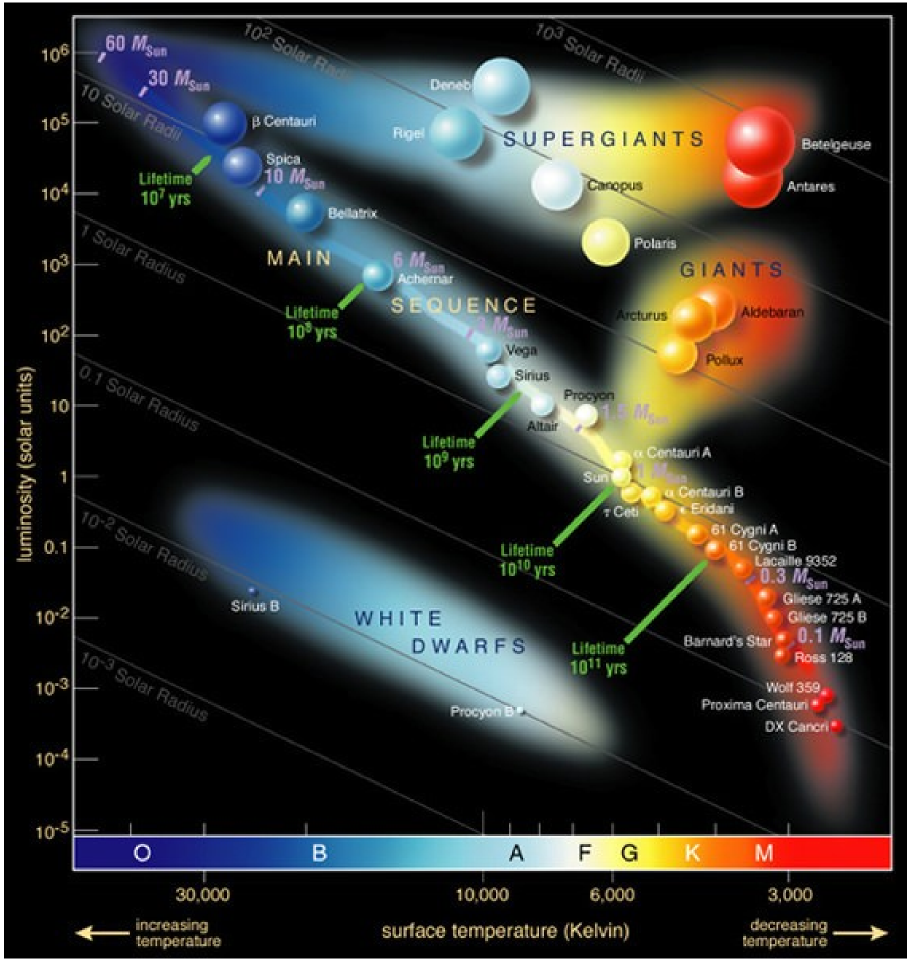
- End phase of a star (stellar evolution).
- They play an essential role in the synthesis of many elements.
- SN ejecta enrich the interstellar medium and the expanding shock produced in the explosion can trigger new star formation.
- Due to their high luminosity, SNe are also served as indicators of extragalactic distances.
- Source of compact objects (neutron star, blackhole).
- An important factor in the physical evolution of galaxies.

# Two explosion mechanisms

**Type Ia supernovae** are explosions of CO white dwarfs (in binary system) pushed over the Chandrasekhar limit. Here, energy released in the explosion is primarily because of thermonuclear fusion. Typical peak luminosity is of the order of $10^{43}$ erg $s^{-1}$. No stellar remnant.

**Core-collapse supernovae** result due to gravitational collapse of massive star ($M > 8$ solar masses) core. Peak luminosity $\sim 10^{42}$ erg $s^{-1}$. They leave a neutron star or black hole (depending upon mass) stellar remnant (or possibly none).

# Hertzsprung-Russell (H-R) diagram




**High mass stars (>8 $M_{sun}$) evolve as super-giants and explode as core-collapse SNe.**

**Low and intermediate-mass stars (initial masses < 8 $M_{sun}$) → CO white dwarfs (Novae, Ia SNe if in a binary system).**

# Evolution of massive stars

**Mass >75 $M_{Sun}$**

$$O \rightarrow \mathrm{WN(H-rich)} \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN(H-poor)} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN\,Ic}$$

**Mass 40-75 $M_{Sun}$**

$$O \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN(H-poor)} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN\,Ic}$$

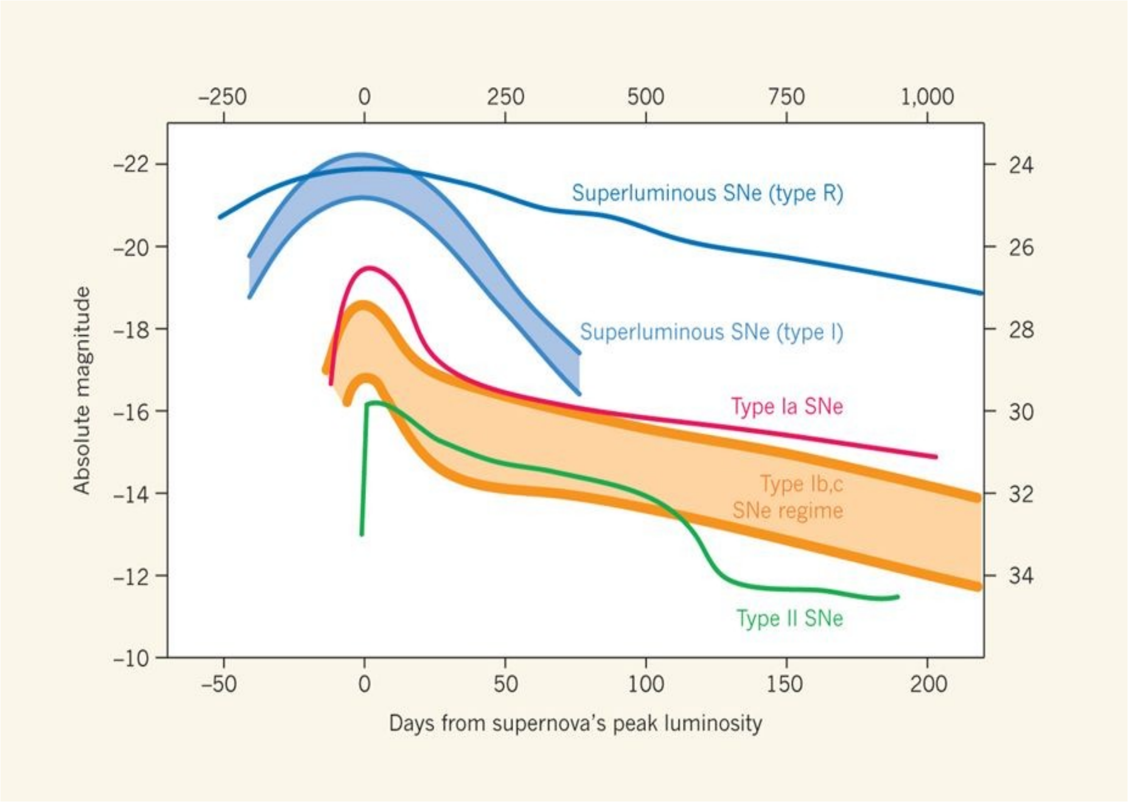
**Mass 25-40 $M_{Sun}$**

$$O \rightarrow \mathrm{LBV/RSG} \rightarrow \mathrm{WN(H-poor)} \rightarrow \mathrm{SN\,Ib}$$

$$O \rightarrow \mathrm{LBV} \rightarrow \mathrm{IIn}\ (?)$$

(Crowther 2006, 2007)

# SNe light curves

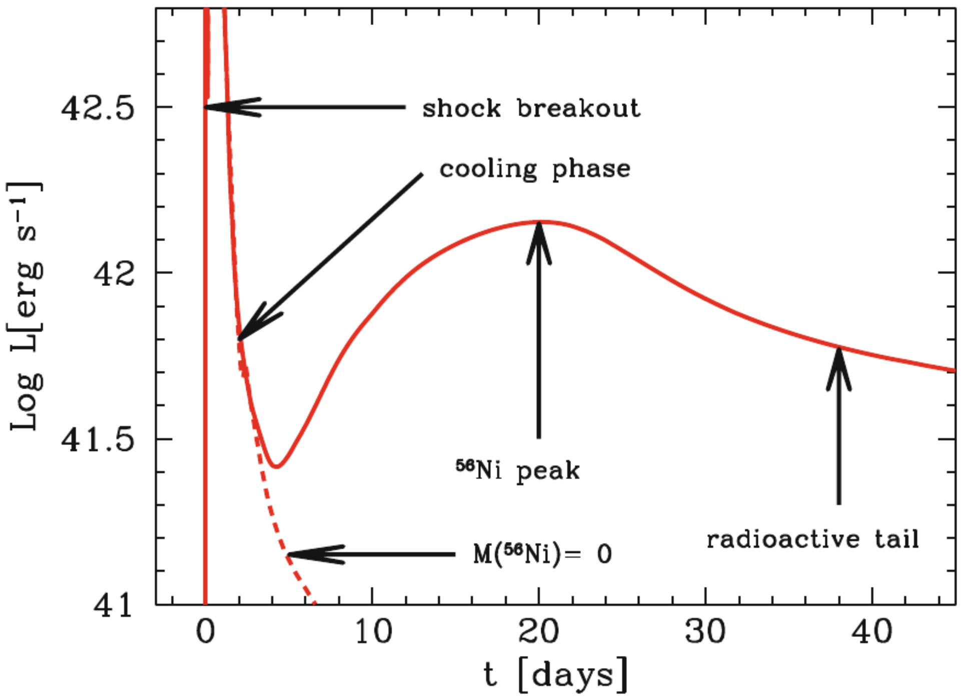



(Smartt, 2012)

- **Observations of different phases are important.**
- **Maximum light phase: Explosion parameters**

# Light curve phases (SNe I)

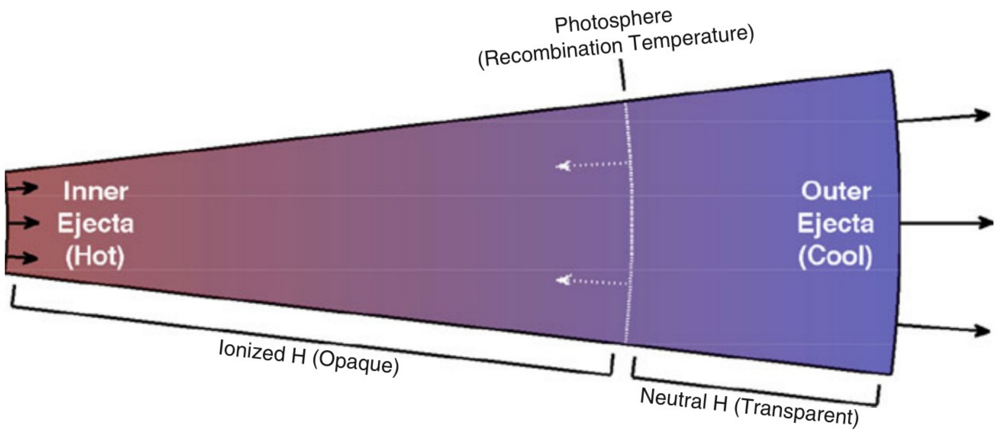
- **The LC of a normal SN I is powered by the shock energy (or explosion energy) and the radioactive decay (mainly of $^{56}Ni$ that is synthesized during the explosion).**
- **Cooling is dominated by the loss of photons and the expansion of the ejecta.**
- **Main peak and beyond, radioactive decay:**
  **$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$**
- **The expanding ejecta becomes optically thin during nebular phase.**

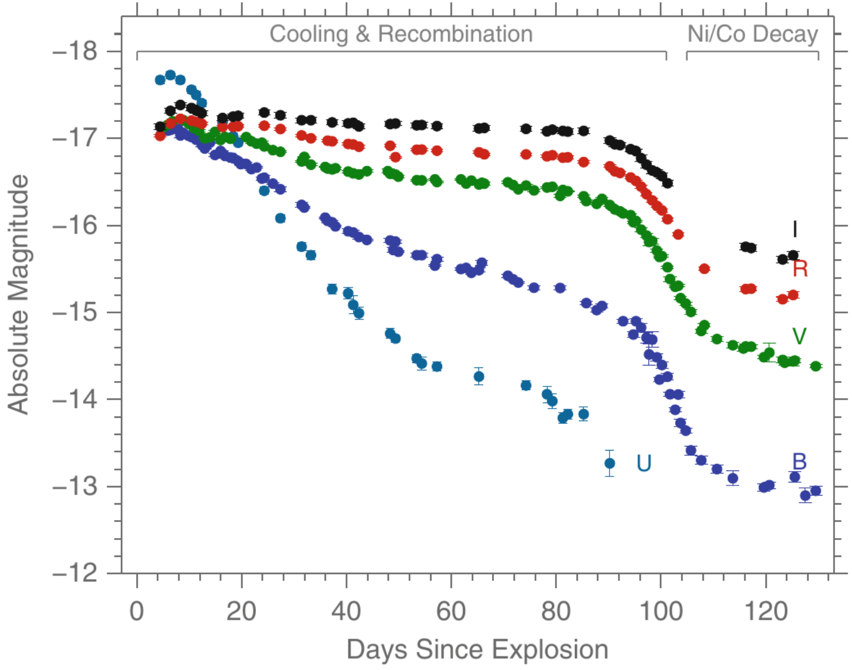



(Bersten et al. 2012)

# Type IIP SNe light curves

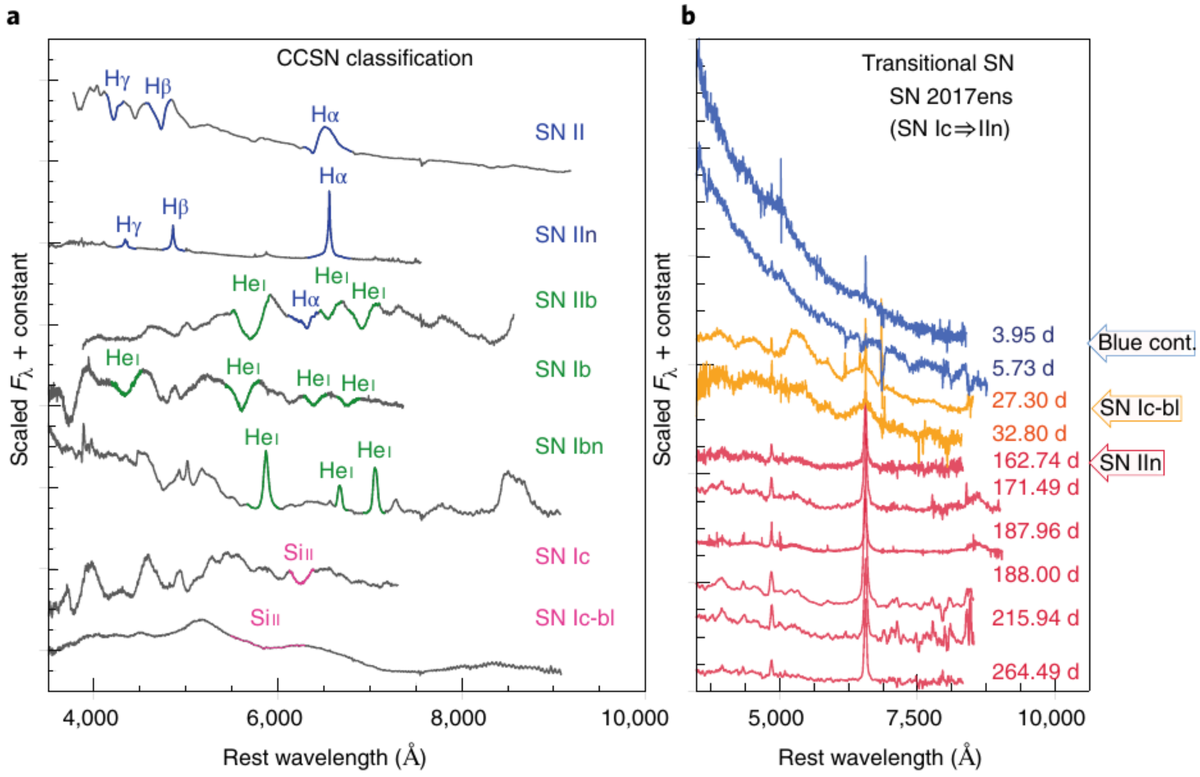
**The shock wave heat and ionizes the hydrogen envelope (T >10,000 K). The envelope expands → Recombination wave moves inwards in mass, staying at roughly the same radius (and temperature).**




(Arcavi et al. 2016, Bose et al. 2015)

# Spectral classification

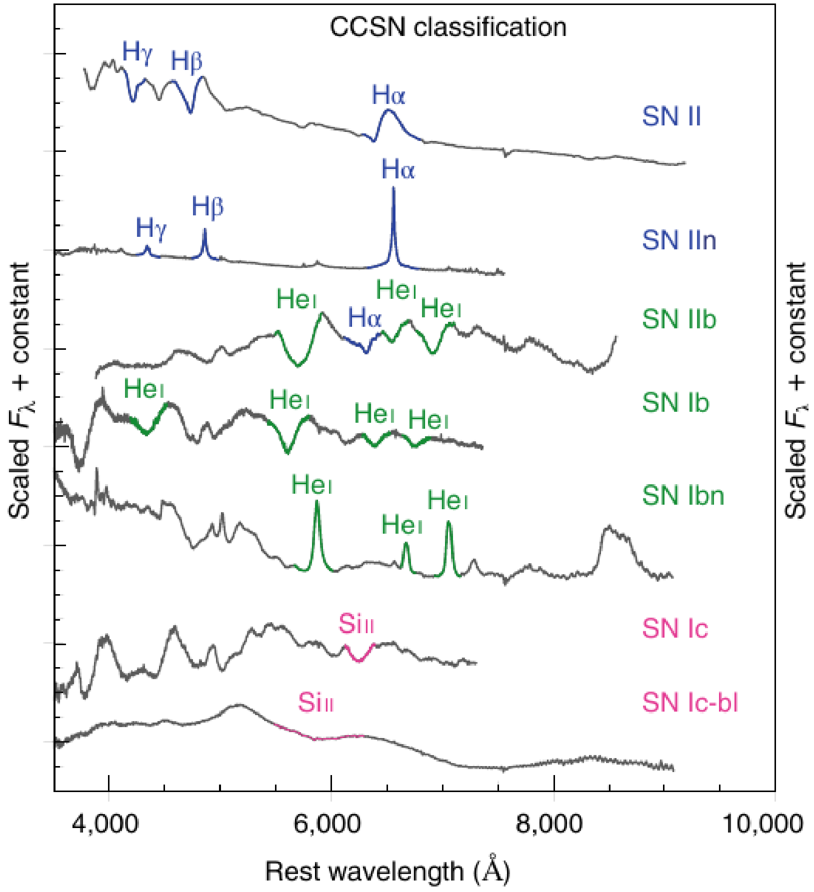



(a) The main classes of CCSNe are marked based on their composition and line profiles. All spectra are at around maximum light, except SN 2006jc (four weeks post-maximum).

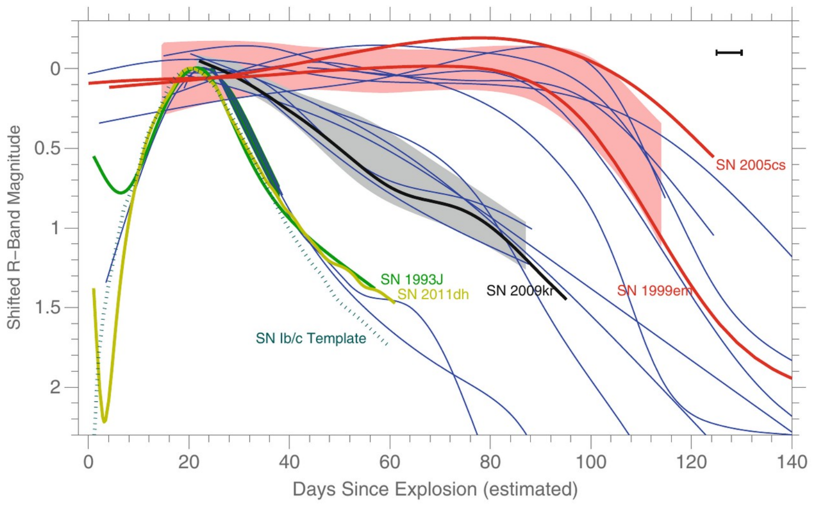
(b) Some objects defy classification as a single type, such as SN 2017ens, which initially displayed a blue continuum, then the spectrum of a SN Ic-bl, and then that of a SN IIn.

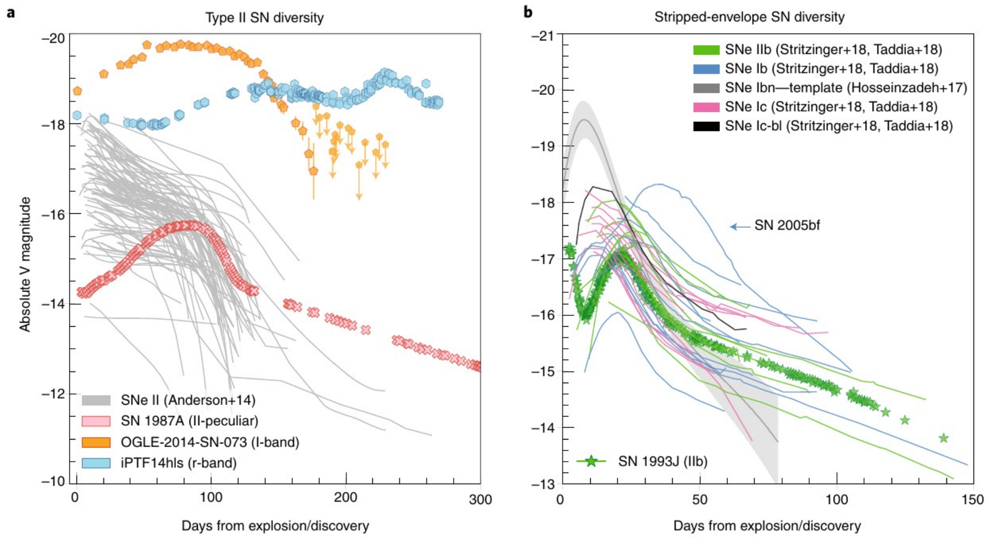
# Stripped envelope supernovae (SE-SNe):

- Ib, Ic, Ic-BL and IIb are collectively known as SE-SNe as their progenitors stripped off (partially or fully) H/He envelope before the explosion.



# Photometric diversity




Two separate populations, two overlapping populations or a single continuous one?

A large diversity in luminosity and light curve shape.

The double-peaked light curve of SN 2005bf might be the result of a double-peaked Ni distribution or of a magnetar powering the second peak.

# Peculiar event

- OGLE-2014-SN-073:

  Classified as SNe II based on the presence of hydrogen in the spectra. However, the light curves and spectral evolution were highly unusual.

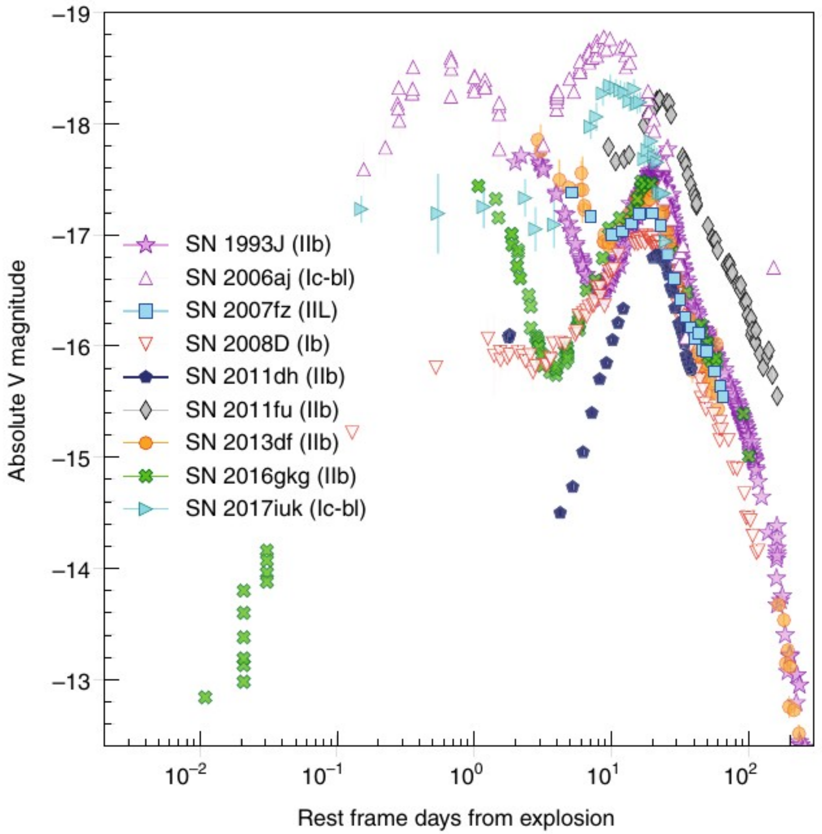
  It showed a light curve similarity with SN 1987A-like objects, but approximately four magnitudes brighter than SN 1987A, while the spectra showed no evolution during the first ~160 days.

  Not fit into any known class and are hard to explain with current explosion models, as canonical Ni-decay power cannot produce the observed properties. **Different alternative power sources, such as a magnetar spindown, fallback accretion, electron–positron pair production, hidden interaction with material ejected by the star before its explosion, and jets are being considered.**

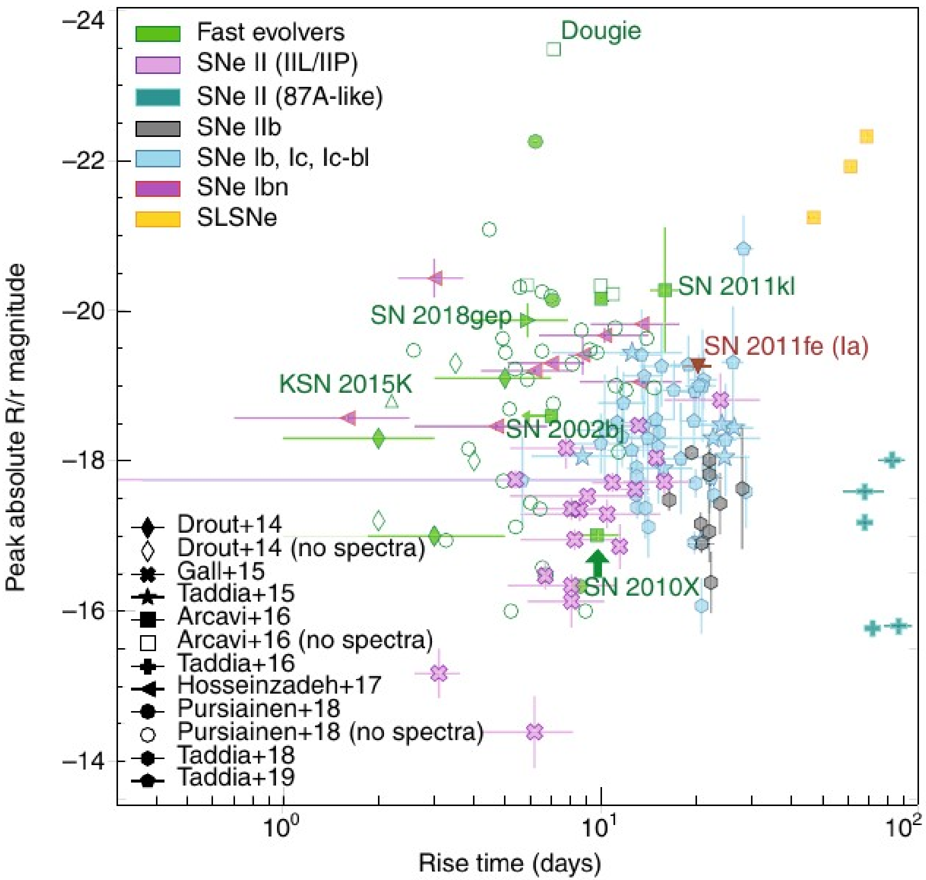
# Very early and  high-cadence observations

An additional new and exciting capability enabled by recent wide-field transient surveys and rapid-response follow-up facilities is that of **observing SNe very soon (in hours) after explosion. This allows us to probe the early emission from SNe**, which, in stripped events is often powered by mechanisms different to those responsible for the main peak of the light curve (which is powered by the radioactive decay of nickel to cobalt to iron).

**The Shock breakout and cooling emission encodes information about the radius and internal density structure of the progenitor right before explosion.**

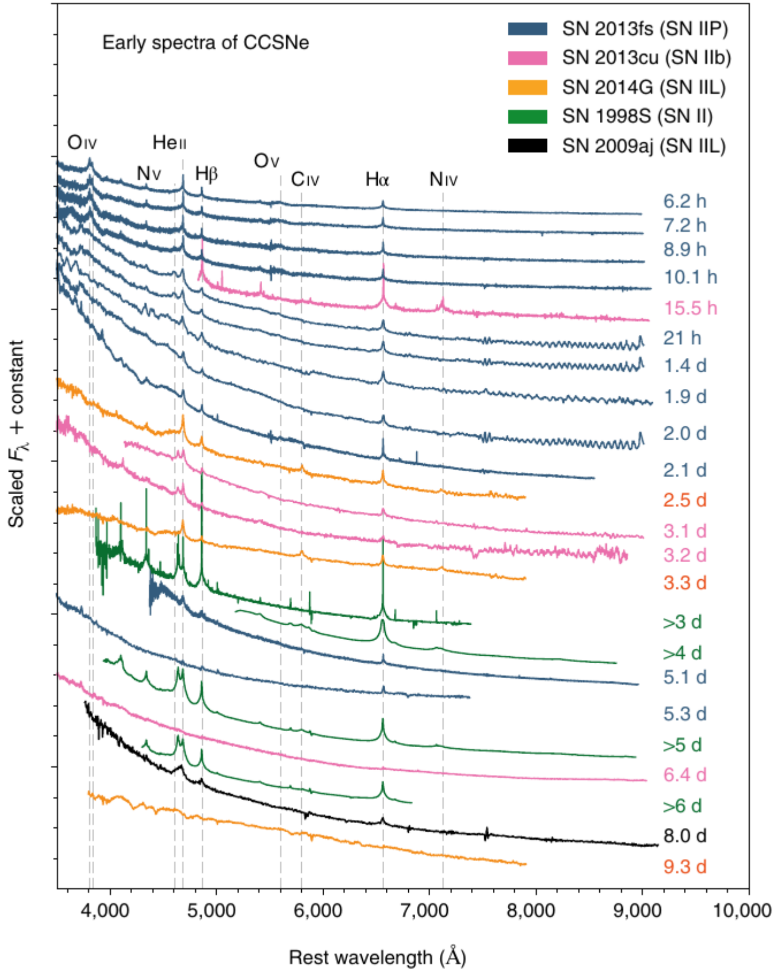


# New phase space



# Flash spectroscopy of infant SNe

- Early-time spectra of CCSNe showing narrow lines reveal the presence, composition and extent of confined CSM ejected by the progenitor shortly before explosion. This information is a crucial constraint on the late stages in stellar evolution models.
- Narrow CSM lines slowly broaden as the confined CSM is accelerated by the SN ejecta.



# A bright, fast and abundant future

Despite lots of progress in the quality and quantity of observations of CCSNe, there are still a number of outstanding questions:

- What are the stellar systems that give rise to these explosions?
- What are the dominant mechanisms by which the outer layers of stripped envelope SN progenitors are removed?
- Which kinds of stars are able to produce SNe with jets and GRBs?
- How ubiquitous is CSM around CCSN progenitors and what are its properties?

**The upcoming surveys shall be very helpful in this direction.**

# Further readings

- Hand book of supernovae: Athem W. Alsabti • Paul Murdin
- Supernova Explosions: David Branch • J. Craig Wheeler
- Classification of supernovae: A. V. Filippenko, 1997, ARA&A, 35, 309
- Observational and Physical Classification of Supernovae: Avishay Gal-Yam