Supernovae (SNe) - observed ZOO: regular types and peculiarities

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Astronomical transients

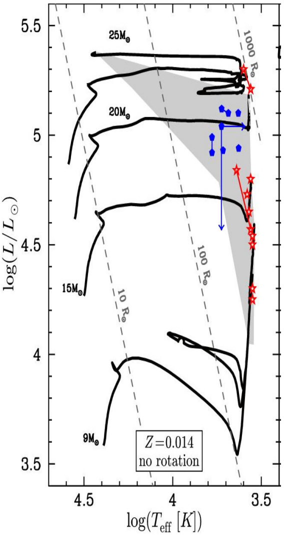
Selected chapters from astrophysics, fall semester, 2022

Talk outline

- What are SNe and why are they important?
- SN ZOO
  - Type Ia
  - Type Ib,c
  - Type II
  - Interacting SNe
  - Superluminous SNe (SLSNe)
  - cf. also the "Handbook of SNe 2017" and the Avishai Gal-Yam's lecture on 35 HUJI (2017)
- Hydrodynamics of SN-CSM interaction
  - Model light curves
  - Model spectral lines
- Conclusions

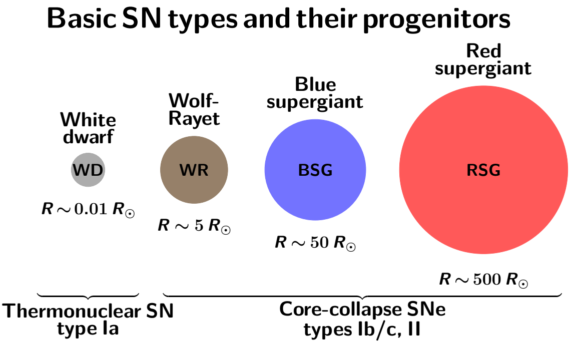
What are SNe and why are they important?

- **Basic classification:**
- SNe of type Ia
  Thermonuclear explosion of C-O white dwarf in a binary system
- SNe of type Ib,c
  Gravitationally collapsing (cc) massive "stripped" stars, He stars, Wolf-Rayet (WR) stars
- SNe of type II
  Gravitationally collapsing very massive stars, mostly red supergiants (RSG, also yellow, blue, and LBVs)
- SNe chemically enrich their host galaxies and drive future generations of star formation
- The SN shock probes the mass loss history of the progenitor system back to $\sim 10^3 - 10^4$ years



Meynet+ 2015

What are sNe and why are they important?

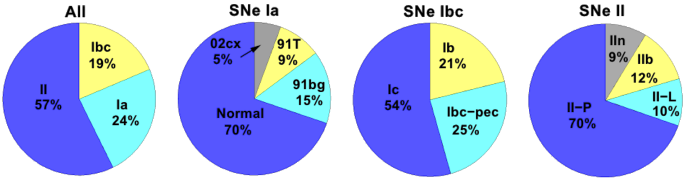


- CC SNe above $\sim 8\ M_\odot$ in general
- CC SNe ~ 8 - $10\ M_\odot$ with a degenerate O+Ne+Mg core - electron capture (ec-) SNe
- CC SNe ~ 10 - $90\ M_\odot$ - iron core collapse $\rightarrow$ various scenarios
- CC SNe over $\sim 100\ M_\odot$ - pair instability SNe (PPISNe, PISNe)

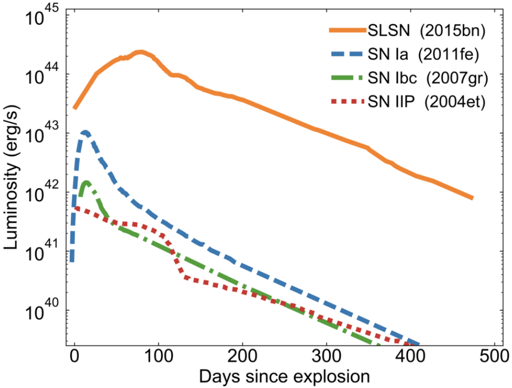
Question: What nebula is this, and what SN is nearby?

- Classification of SNe based almost entirely on V-spectra peak
- First classification: Minkowski 1941 (+ Baade) - **type I/II** (9/5 SNe)
- Classical review - Alex Filippenko 1997
- Modern overview, e.g., in the "*Handbook of Supernovae*" 2017

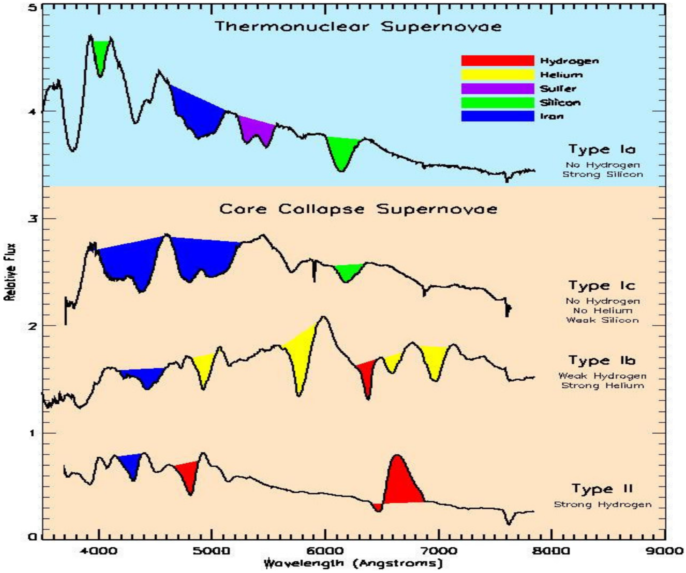
SNe ZOO: "Present day" SN typology



Credit: Dan Kasen

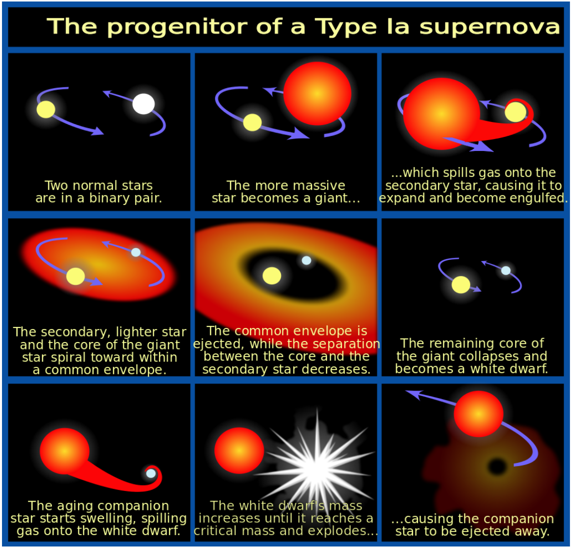


SNe ZOO: "Present day" SN typology



SNe ZOO: Thermonuclear supernovae (type Ia) - no H

single degenerate, double degenerate (super-Chandrasekhar), type Iax

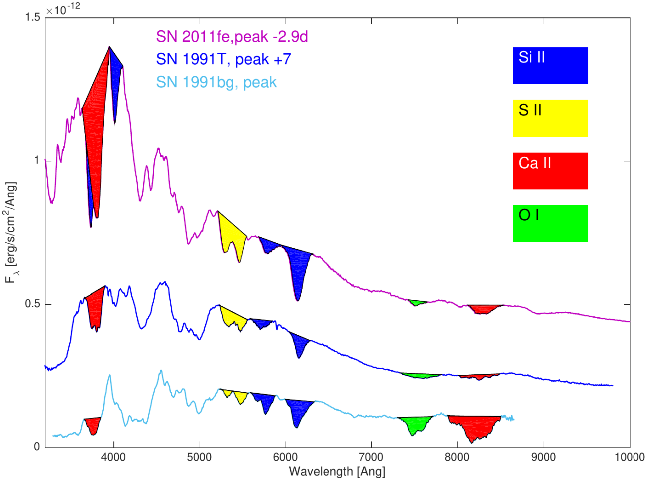


source: NASA

SNe ZOO: Thermonuclear supernovae (type Ia) - no H

- rise time $\sim 17\,\text{-}\,20$ days, $L_{\rm bol,max} \approx 10^{43}\,{\rm erg\,s^{-1}} = 10^{9.4} L_\odot$
- total energies: $E_{\rm rad} \approx 10^{49}$ erg, $E_{\rm kin} \approx 10^{51}$ erg
- maximum emission in V and B filters, "standard" candles
- no traces of H, He in spectra, strong features of intermediate elements (S, Si, Ca) and iron group (Ni, Co, Fe)
- "Brahe" 1572, "Kepler" 1604 $\rightarrow$ probably type Ia Sne
- contribution to Galaxy "metallic" evolution:
  - SNe Ia $\approx 0.5 M_\odot$ of Fe/event, cc SNe $\approx 0.1 M_\odot$ of Fe/event
  - about 2/3 of Fe in local! universe made by SNe Ia
- SN Ia cosmology tests: Riess 1998, Perlmutter 1999
  - SNe distances incosistent with a gravity dominated Universe
  - expansion accelerates!

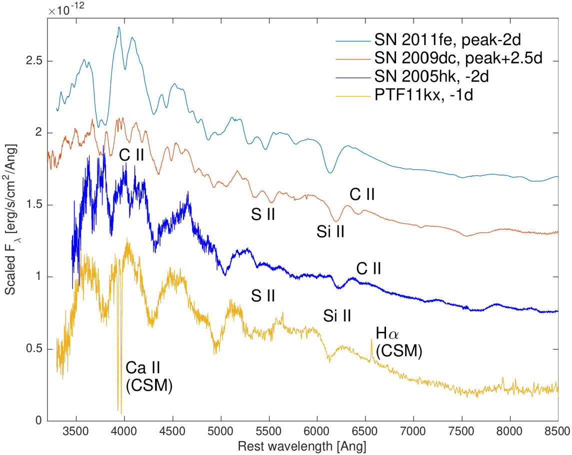
SNe ZOO: Thermonuclear supernovae (type Ia) - no H



Credit: Gal-Yam 2017

- no signs of H, He, strong lines of S, Si, Ca and Ni, Co, Fe
- SN 2011fe - "regular" SN Ia, SN 1991T, 1991bg - "peculiar"

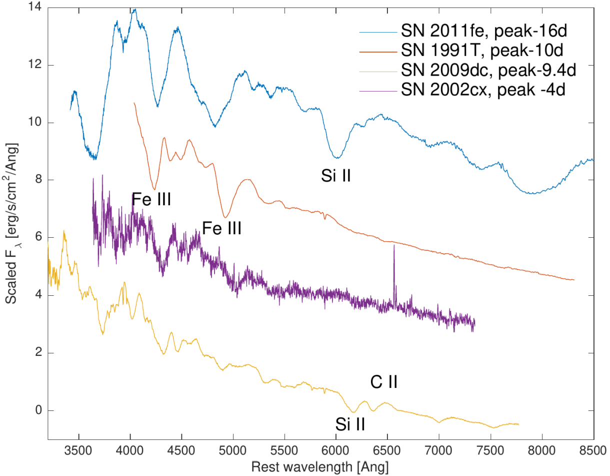
SNe ZOO: Thermonuclear supernovae (type Ia) - no H



Credit: Gal-Yam 2017

- SN 2011fe: "regular" SN Ia, here ∼peak, → over 2 slides ∼late
- SN 2009dc: "super Chandra" SN Ia (slower, brighter, rare, ∼ 1%)
- SN 2005hk: type SN Iax → "zombie star" (fainter, ∼ 10%, 2002cx)
- PTF11kx: SN Ia-CSM ← interacting SN: ∼ 0.1%

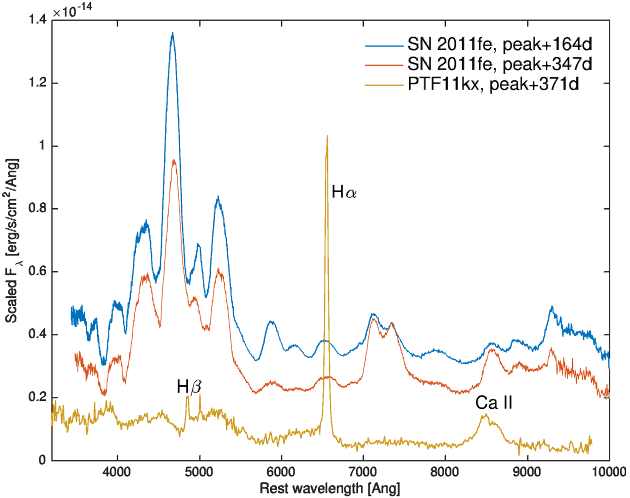
SNe ZOO: Thermonuclear supernovae (type Ia) - no H



Credit: Gal-Yam 2017

- very early phase - before peak
- top to bottom: - regular, SN 1991T, Iax, super-Chandrasekhar

SNe ZOO: Thermonuclear supernovae (type Ia) - no H



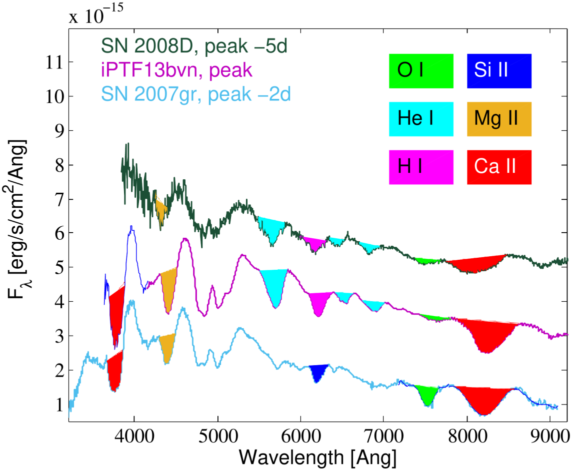
Credit: Gal-Yam 2017

- PTF11kx: SN Ia-CSM ← interacting SN, $\sim 0.1\%$, late H_α emission enhancement

SNe ZOO: Core-collapse supernovae

- hydrodynamics and turbulence - post bounce conditions
- regions of instabilities, innermost ejecta decelerates $\rightarrow$ falls back $\rightarrow$ convective engine $\rightarrow$ shock decelerates $\Rightarrow$ reverse shock (dimensional analysis) $\rightarrow$ even if SN is exploding, material accretes onto proto-NS
- convection $\Rightarrow$ explosion energy up to 100 foe (most of them $\sim$ 1 foe)
- EOS $\rightarrow$ dense nuclear matter
- neutrino transport and corresponding cross sections $\rightarrow$ Boltzmann equation, numerical transport techniques
- nuclear burning
- magnetic fields $\rightarrow$ affect the fluid flow, strong B fields in proto-NS can alter the ν transport, magnetars!

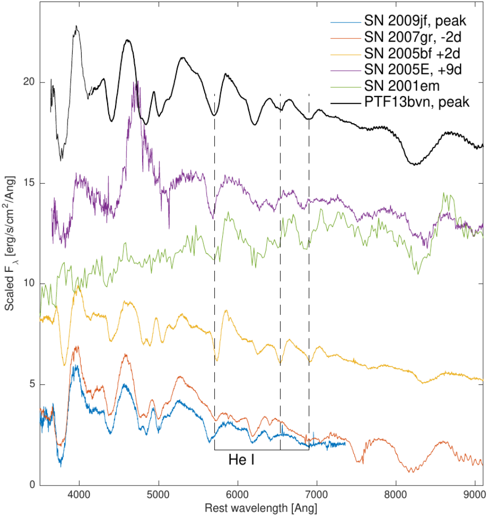
SNe ZOO: Core-collapse supernovae - type Ib,c (no H)



Credit: Gal-Yam 2017

- SN 2008D, iPTF13bvn: “regular” SN Ib with prominent He lines
- SN 2007gr: type SN Ic (no He lines)
- peculiar Ib SNe: for example Ca-rich type Ib (progenitor not certain)

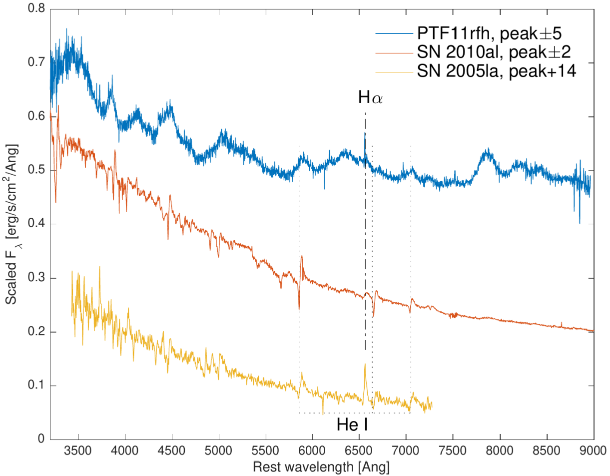
SNe ZOO: Core-collapse supernovae - type Ib,c (no H)



Credit: Gal-Yam 2017

- Ca-rich type Ib SNe
- SN 2001em: peculiar Ca-rich type Ib (progenitor not certain)

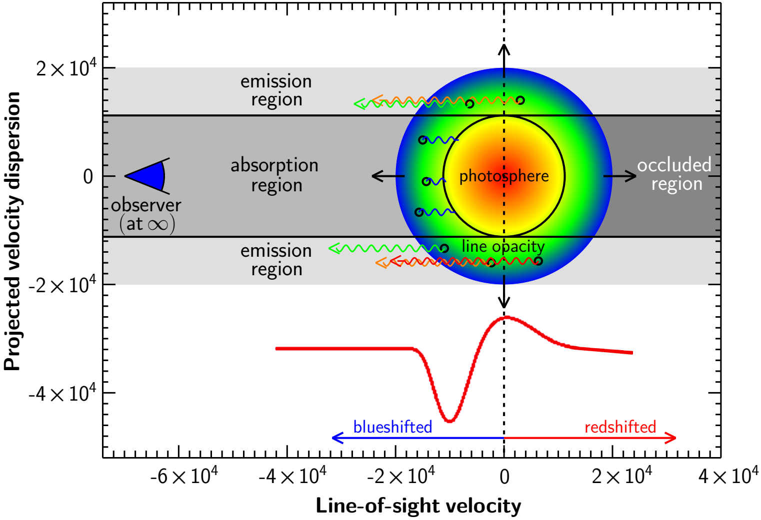
SNe ZOO: Core-collapse supernovae - type Ib,c (no H)



Credit: Gal-Yam 2017

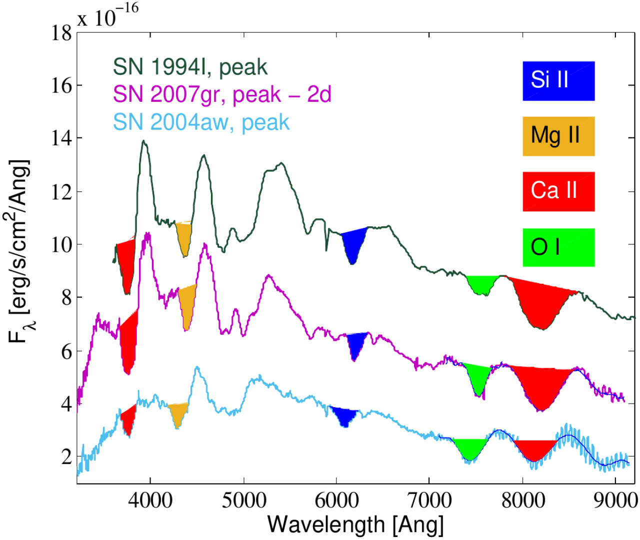
- PTF11frh: type Ibn - broad He lines, narrow Hα emission
- SN 2010al: Ibn - narrow P-Cygni profiles oh He lines
- SN 2005la: Ibn - broader P-Cygni He lines + broader Hα emission

SNe ZOO: Core-collapse supernovae - type Ib,c (no H)



- **P-Cygni** line profile formation mechanism

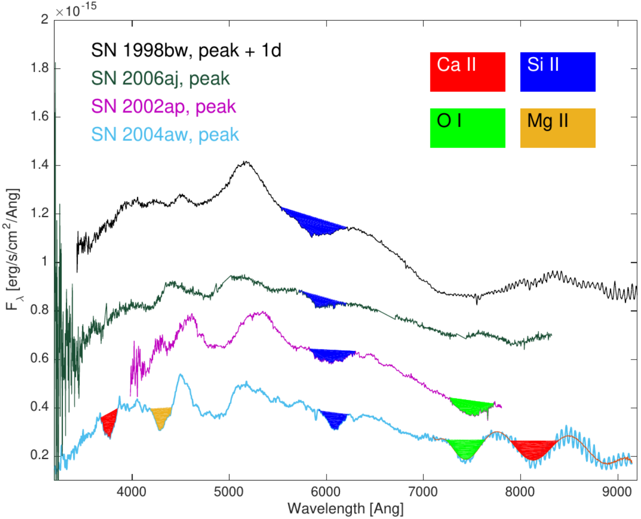
SNe ZOO: Core-collapse supernovae - type Ib,c (no H)



Credit: Gal-Yam 2017

- **type Ic**: typicals - lines in “red” get broader

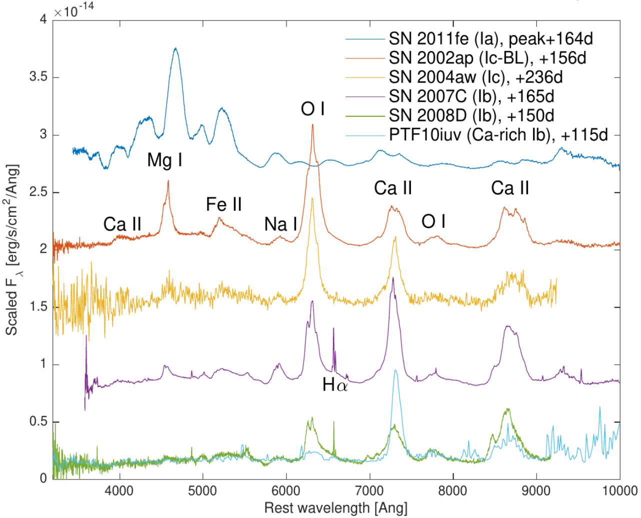
SNe ZOO: Core-collapse supernovae - type Ib,c (no H)



Credit: Gal-Yam 2017

- type Ic - broad lines: (Ic-BL) → associated with GRBs

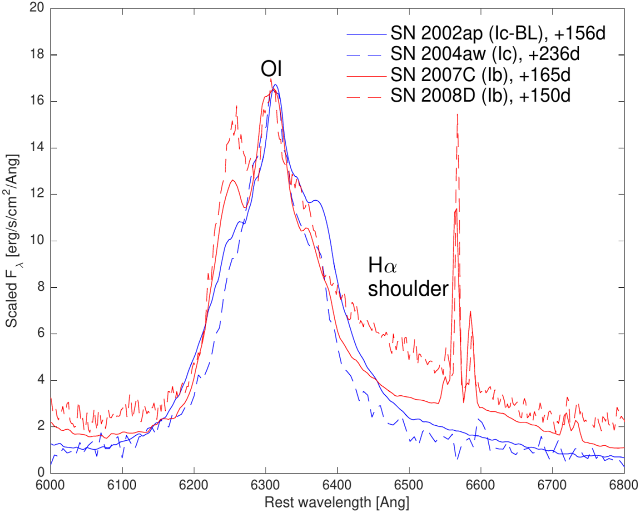
SNe ZOO: Core-collapse supernovae - type Ib,c (no H)



Credit: Gal-Yam 2017

- **Nebular spectra** - SN 2007C regular Ib, PTF 10iuv Ca-rich Ib
- **Type I a,b,c - clearly distinguishable** at late times

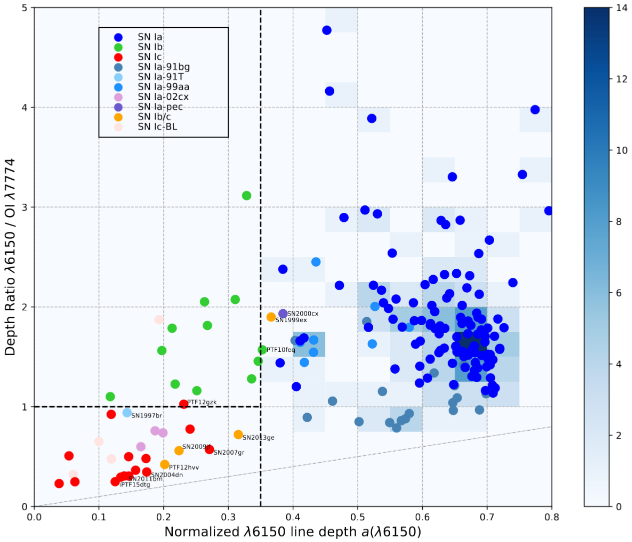
Hydrogen in SNe Ib in the nebular phase



Credit: Gal-Yam 2017

- **Type Ib SNe** with late H emission shoulder in red wing (Ic not)

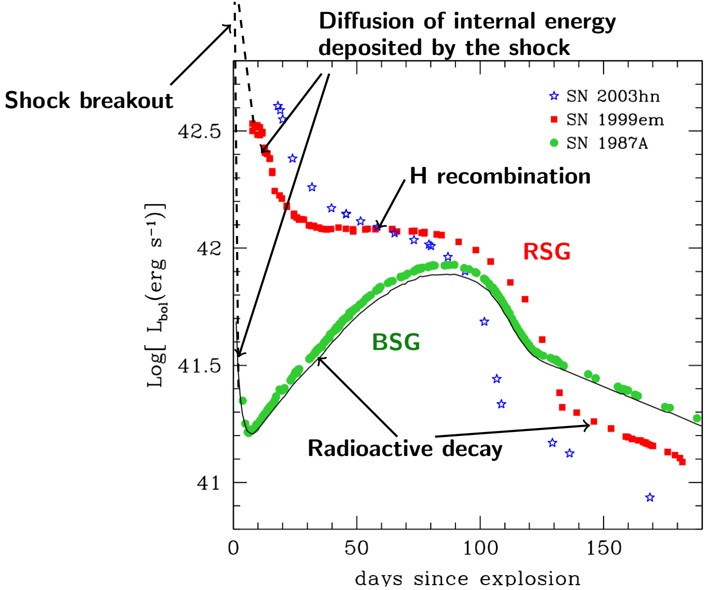
Quantitative separation of type I SNe



Credit: Sun+ 2017

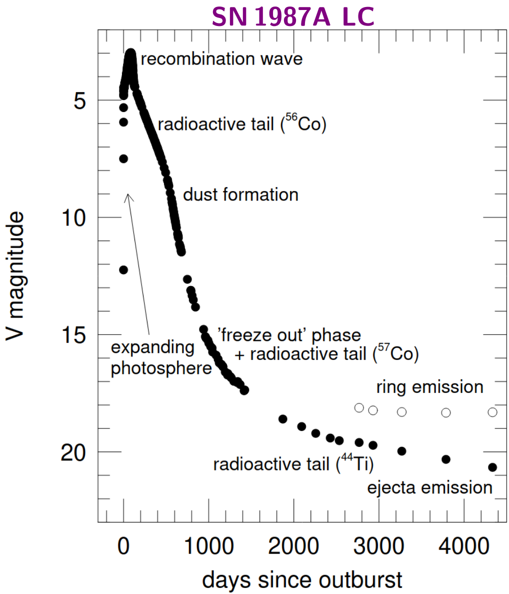
- **O and Si lines** - important feature for distinguishing the types

SNe ZOO: Core-collapse supernovae - type II (H rich)



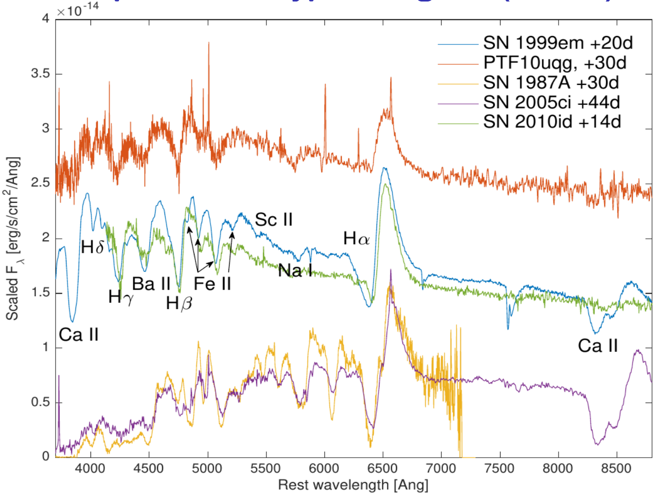
Credit: Bersten & Hamuy 2009

SNe ZOO: Core-collapse supernovae - type II (H rich)



Credit: Leibundgut & Suntzeff 2001

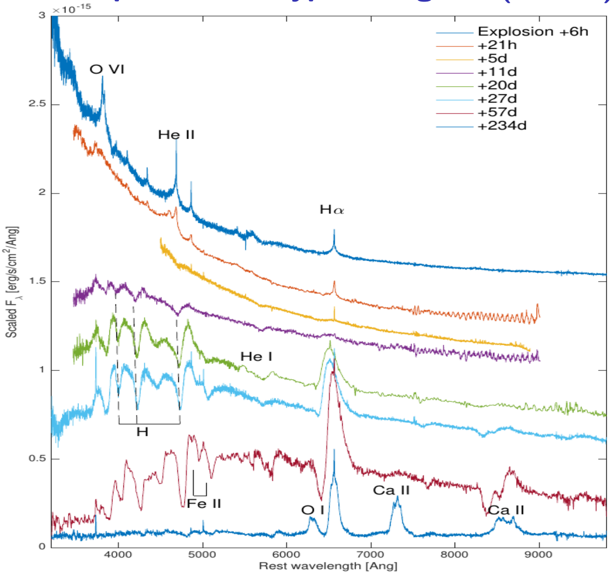
SNe ZOO: CC supernovae - type II regular (H rich)



Credit: Gal-Yam 2017

- regular SNe II: top - type II-L, no absorption in Hα, emission only
- middle: type II-P, strong P-Cygni lines
- bottom: BSGs - slow rise to maximum (up to 70-80 days)

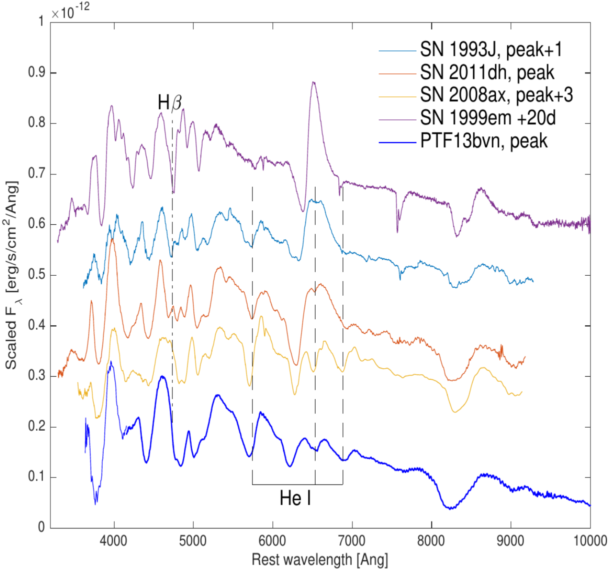
SNe ZOO: CC supernovae - type II regular (H rich)



Credit: Gal-Yam 2017

- **type II evolution** to late times

SNe ZOO: CC supernovae - type IIb transitional



Credit: Gal-Yam 2017

- **type IIb**: transition between types II (early) and Ib (late)

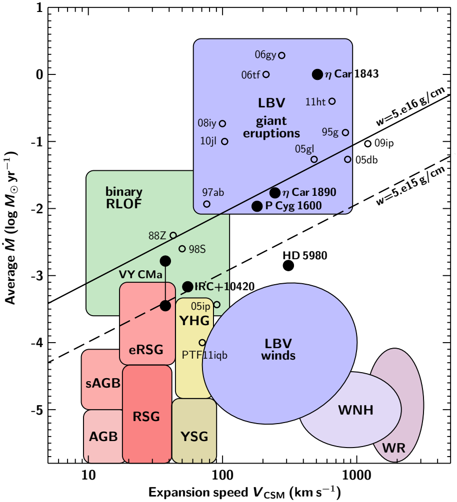
SNe interacting with CSM (type IIn, Ibn, hypothetically Icn)

- The chief reason that they are extremely interesting is because they their progenitor may be wildly unstable long before explosion

- This has not been included in standard stellar evolution models

- Another reason they are interesting is because CSM interaction is a very efficient engine for making extremely bright super-luminous transients

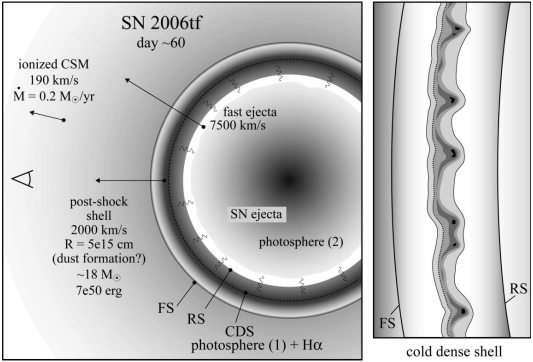
- The CSM interaction may also be highly non-spherical, perhaps linked to binarity of the progenitor system



Plot of mass-loss rate as a function of wind velocity, comparing values for interacting SNe to those of known types of stars (Smith 2014)

SNe interacting with CSM - basic physical picture

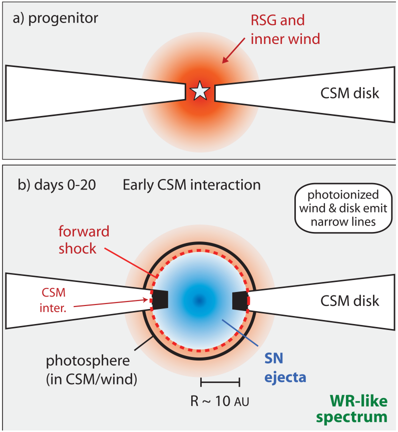
- When a SN explodes inside a dense CSM, four zones are delineated in the simplest picture (Smith+ 2008):

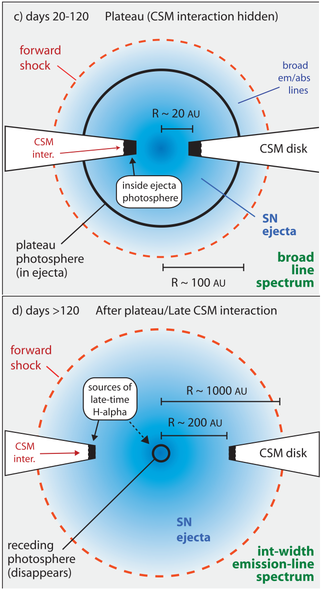


- The unshocked CSM outside the forward shock (FS) (photoionized)
- The swept-up CSM between FS and "cold dense shell" (CDS)
- The decelerated SN ejecta encountering the reverse shock (RS)
- The freely expanding SN ejecta inside RS

SNe interacting with CSM - basic physical picture

Sketch of the asymmetric SN-CSM interaction (Smith+ 2015)

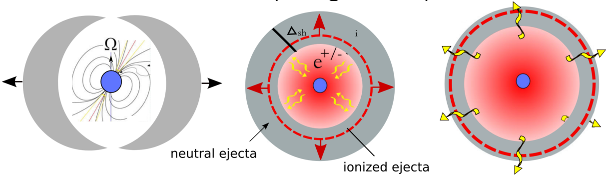




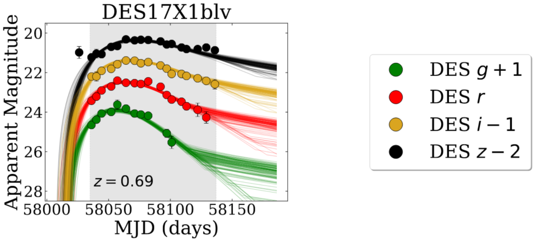
- After a few days, the SN photosphere envelopes the SN-disk interaction
- At late times, the SN-disk interaction may be exposed again (higher $V_{\rm SN}$)

Magnetar powered SLSNe - basic physical picture

(Metzger+ 2014)



- mass $M_{ej} \sim 0.01 - 0.1\, M_\odot$ is ejected with $V_{ej} \sim 0.1\, c$
- Non-thermal UV and X-ray photons thermalize within ejecta
- Optical and X-ray photons diffuse out of the nebula

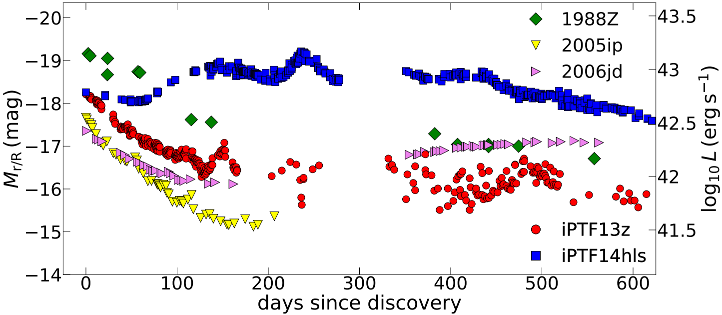


- Multi-band light curves of SLSNe with magnetar model (Hsu+ 2021)

Type IIn SNe, SLSNe

Comparison of light curves of five prominent long-lasting type IIn SNe

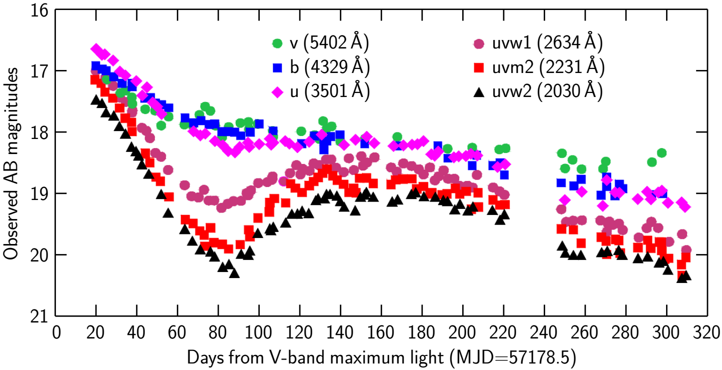
(Aretxaga+ 1999, Stritzinger+ 2012, Smith+ 2009, Nyholm+ 2017, Guillochon+ 2017)



- Most of the SNe (except iPTF14hls) are of type IIn, they showed a steep initial decline followed by a long slower decline
- Undulations and bumps in SN IIn light curves are rare but have been observed in a few cases (Nyholm+ 2017)

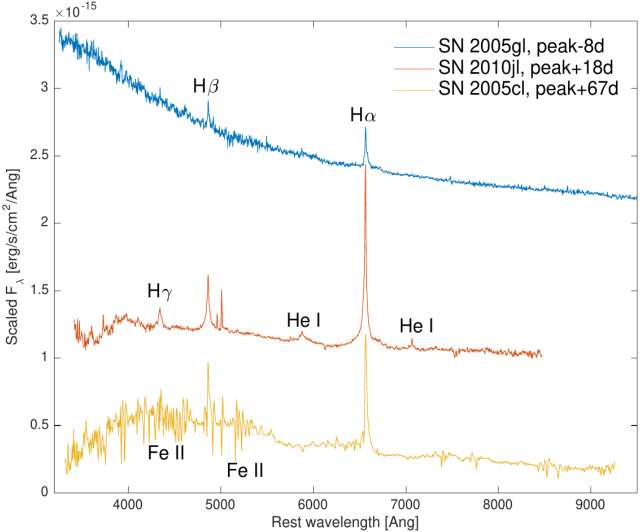
Type IIn SNe, SLSNe

Example of type IIn ASASSN-15lh light curves in 6 bands (Brown+ 2016)



- UVOT light curves in AB magnitudes
- Late-time rebrightenings brighter than $M = -21$ mag
- Interaction of SN ejecta with clumpy CSM (cf. Calderón+ 2016, 2020) is also expected to produce bumps in the light curves

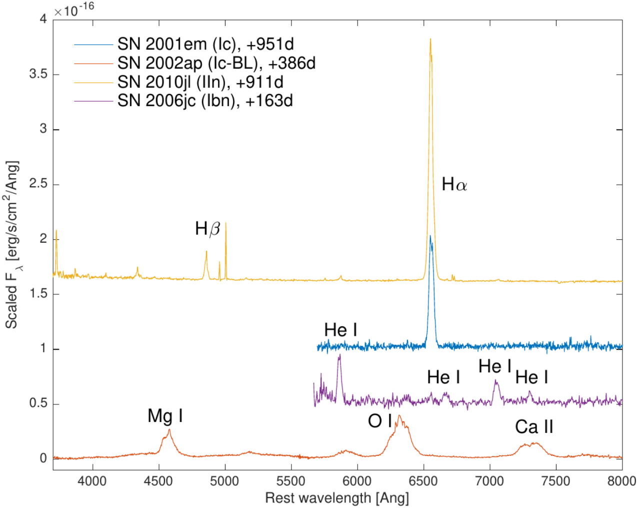
Typical IIn - pre-peak phase: interactors



Credit: Gal-Yam 2017

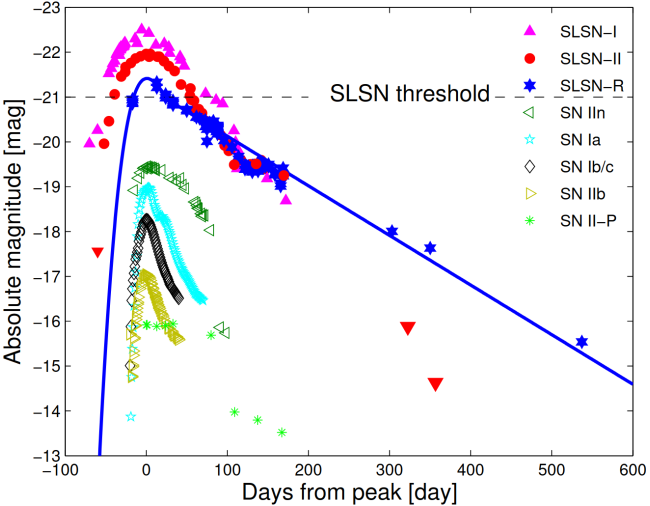
- **Typical IIn SNe - spectra** - @ pre-peak

Type I and II - nebular phase: interactors



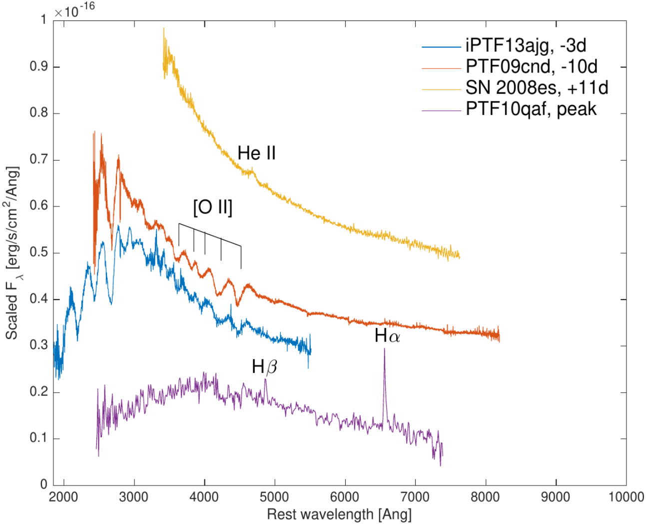
- Type IIn, Ic reg., Ibn, Ic-BL (from top) (corrected for their host-galaxy recession velocities and for extinction, Gal-Yam 2017)
- The classification of SN at late time may differ from the peak

SLSNe - LCs around peak luminosity



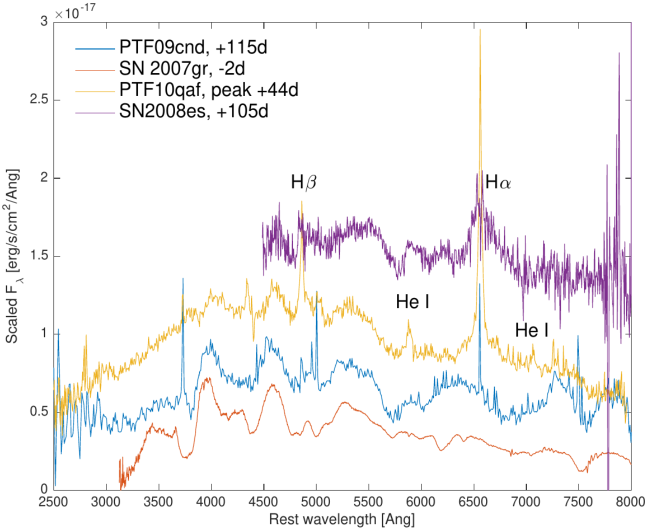
- Comparison of SLSNe LCs to other “normal” types (Gal-Yam 2017)

SLSNe - typical early spectra



- Peak SLSNe spectra (Gal-Yam 2017) - types II, I, I, IIn

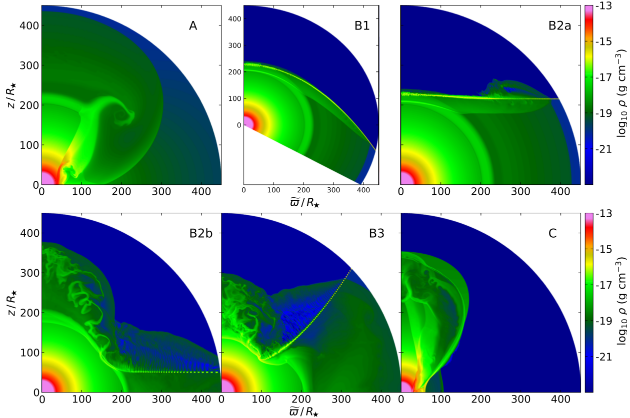
SLSNe - post-peak spectra



- Post-peak and somewhat later SLSNe spectra (Gal-Yam 2017) - types II, IIn, I, I

Hydrodynamics of interaction

- Hydro sims of a SN interacting with six forms of aspherical CSM



- Numerical setup: Own Eulerian hydro code with radial grid composed of 60 zones below $R_\star$, and 6000 zones between $R_\star$ and outer boundary (Kurfürst+ 2020)
- Uniform polar grid with 480 grid cells covers $0 \lesssim \theta \lesssim \pi/2$ and 640 cells for $0 \lesssim \theta \lesssim 2\pi/3$

Hydrodynamics of interaction

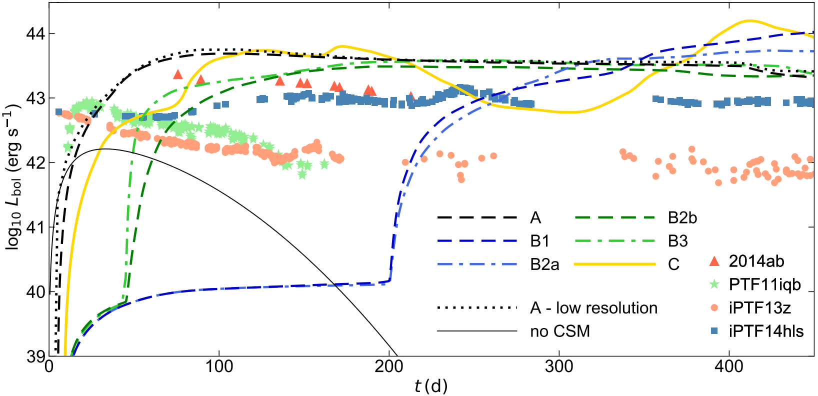
SN - disk interaction

SN - η Car-like bipolar lobes interaction

(Kurfürst+ 2020)

Shock power as an internal power source

Estimates of light curves from our simulations:



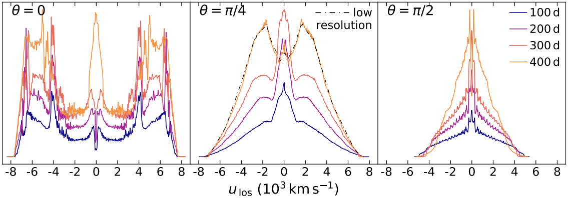
Compared observed LCs (Bilinski+ 2020, Smith+ 2015, Nyholm+ 2017, Arcavi+ 2017)

- A - SN-disk
- B1 - SN-concave colliding wind (CW) shell
- B2a - SN-distant planar CW shell
- B2b - SN-closer planar CW shell
- B3 - SN-convex CW shell
- C - SN-bipolar lobes

Spectral line profiles

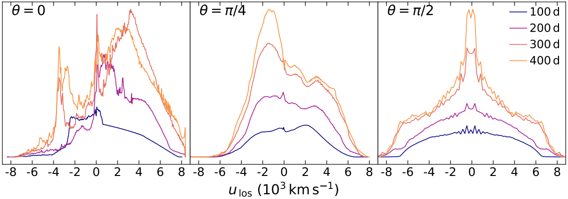
- Line-of-sight velocity distributions for our models:

A



SN - disk

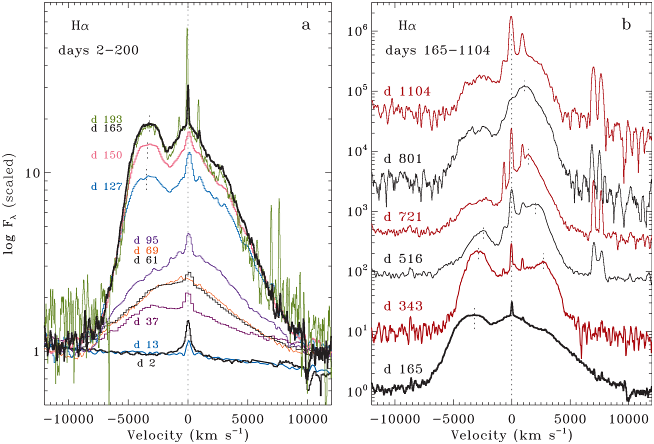
B2b



SN - colliding winds planar shell

- Linearly scaled normalized distributions on the vertical axes
- Each column represents different viewing polar angle θ

Comparison with observed supernovae



PTF11iqb
(Smith+ 2015)

- Initially a blueshifted peak of Hα emission, after $\sim$ 500 days a redshifted peak appeared and eventually dominated the emission
- Interaction with a colliding wind shell could consistently explain PTF11iqb (compare our models B2b and B3)

Summary

- Supernovae played a "historical" role in revealing the nature of the Universe, their "Renaissance" observations ended the epoch of "Aristotelian cosmology"
- In the early 20th century, they helped to reveal the nature of distant galaxies and the size of (at least) nearby Universe
- SNe play crucial role in cosmic nucleosynthesis, in dynamical and chemical evolution of the Universe, in triggering the formation of new stars, etc.
- From the observational point of view, SNe have been most roughly classified into two basic types - type I (no H in spectra) and type II (with H present)
- The up-to-date canonical classification distinguishes mainly type Ia ($\sim$ 25%, TNR of exploding WDs), types Ib,c ($\sim$ 20%), and type II ($\sim$ the rest, all connected with cc of massive stars); the observational rate differs due to the systematically higher peak luminosity of the type Ia

Summary

- Many other subclasses or transition types spectroscopically identified in recent 2-3 decades; the most important for us are the "interacting" types IIn and SLSNe; they may exceed the peak brightness of "normal" SNe up to 2 orders of magnitude
- They also show extraordinarilly long duration of their bright luminosity, the dimming of their light curves often does not drop below 2 magnitudes within 1 year
- They also often show undulations, bumps, and rebrightenings in their light curves; the explanation of the physical origin is an extremely interesting challenge
- Deriving the pre-explosion CSM morphologies and properties will lead to understanding the pre-explosions more or less violent processes in the progenitor stars; a fundamental contribution to understanding the stellar and cosmological evolution