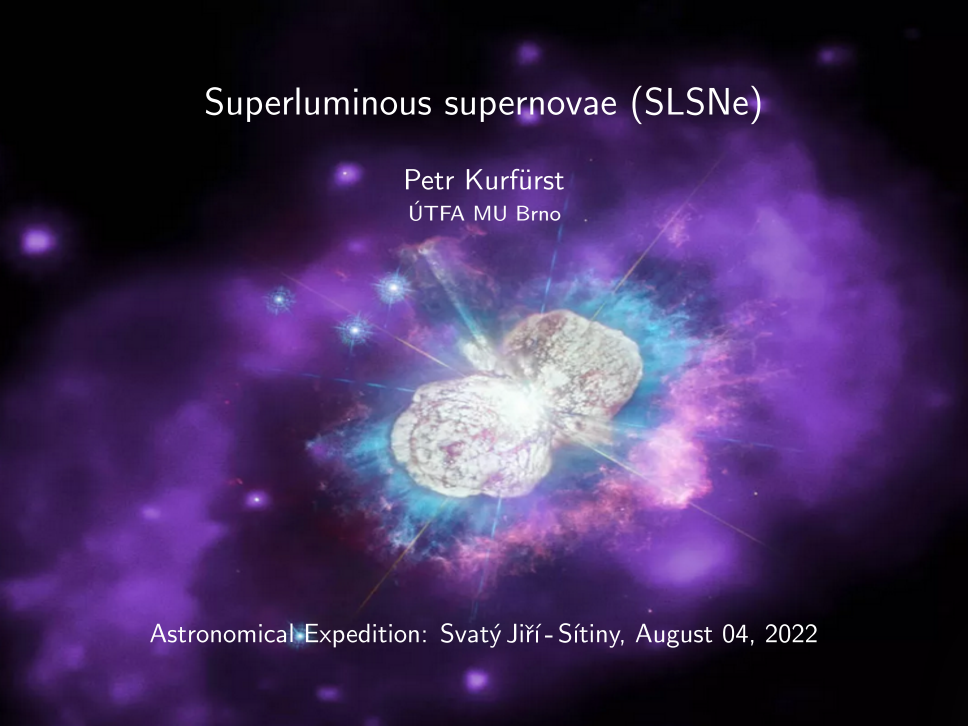

Superluminous supernovae (SLSNe)

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ÚTFA MU Brno

Astronomical Expedition: Svatý Jiří - Sítiny, August 04, 2022

Talk outline

- What are supernovae (SN) and why are they important?
- brief SN ZOO
- SNe that interact with pre-existing circumstellar material
- Hydrodynamics of interactions
- Implications for observations
  - Light curves
  - Spectral line profiles
- Comparison with observed SNe
- Conclusions

What are supernovae and why are they important?

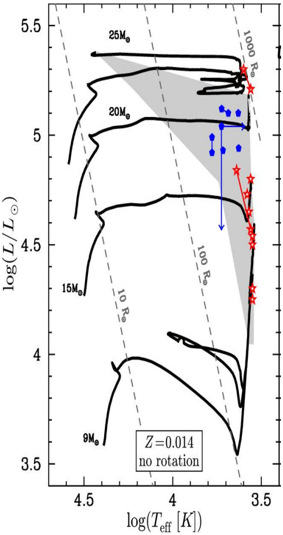
- **First significance in historical "cosmological" context:**
- Cas B: In 1572 occurs Tycho's supernova in Cassiopeia (not the first observed one)
- Contemporary measurement proved that they must be in a "crystal sphere"
- "Artificially precised" and "static" medieval cosmological system began to collapse
- October 9, 1604: Kepler's supernova in Ophiuchus
- Fundamental importance of SNe in the so-called "great debate" (1920, Shapley vs. Curtis) about nature and distance of "nebulae"
- One of the most spectacular events of this kind occurred on Feb 23, 1987: SN 1987A in LMC

Tycho Brahe


Johannes Kepler

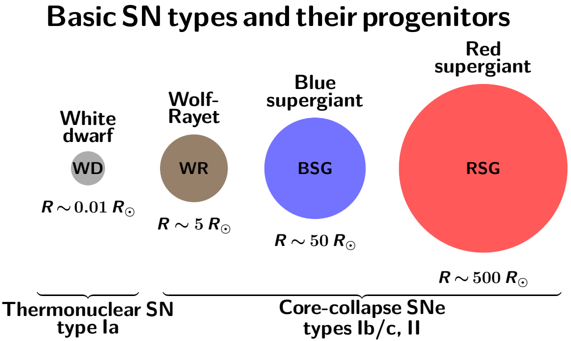
What are supernovae and why are they important?

- **Basic classification:**
- Supernovae of type Ia
  Thermonuclear explosion of C-O white dwarf in a binary system
- Supernovae of type Ib,c
  Gravitationally collapsing massive "stripped" stars, He stars, Wolf-Rayet (WR) stars
- Supernovae of type II
  Gravitationally collapsing very massive stars, mostly red supergiants (also yellow, blue, and LBVs)
- Supernovae (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



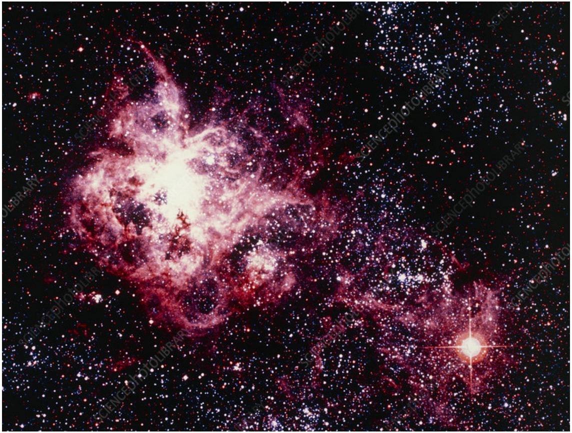
Meynet+ 2015

What are supernovae and why are they important?



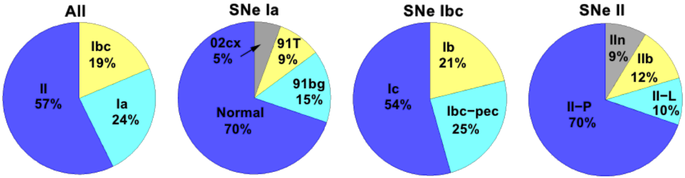
- cc SNe above $\sim 8\ M_\odot$ in general
- cc SNe ~ 8 - $10\ M_\odot$ with a degenerate O+Ne+Mg core - electron capture (ec-) SNe
- cc SNe ~ 10 - $90\ M_\odot$ - iron core collapse $\rightarrow$ various scenarios
- cc SNe over $\sim 100\ M_\odot$ - pair instability SNe (PPISNe, PISNe)

SNe ZOO: What nebula is this, and what SN is nearby?

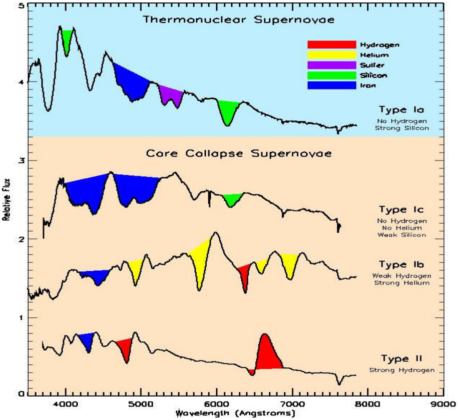


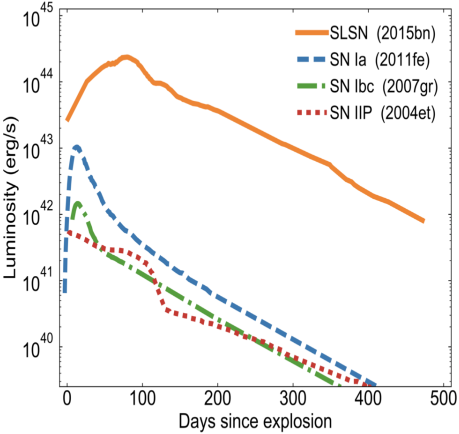
- Classification of SNe based almost entirely on V-spectra peak
- First classification: Minkowski 1941 - type I/type II (9/5 SNe)
- Classical review - Alex Filippenko 1997
- Modern overview e.g., in the "Handbook of SNe" 2017

SNe ZOO: "Present day" SN classification



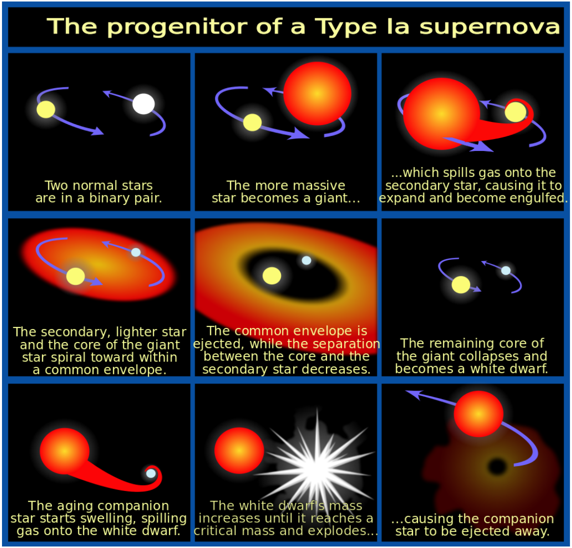
Credit: Dan Kasen





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

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

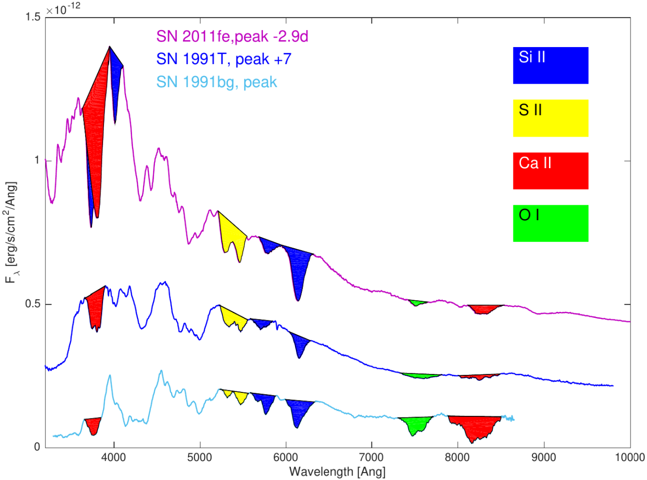


source: NASA

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

- rise time $\sim$ 17 - 20 days, $L_{\rm bol,max} \approx 10^{43}\,{\rm erg\,s^{-1}} = 10^{9.4}\,L_\odot$
- total energies: $E_{\rm rad} \approx 10^{49}\,{\rm erg}$, $E_{\rm kin} \approx 10^{51}\,{\rm erg}$
- 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!

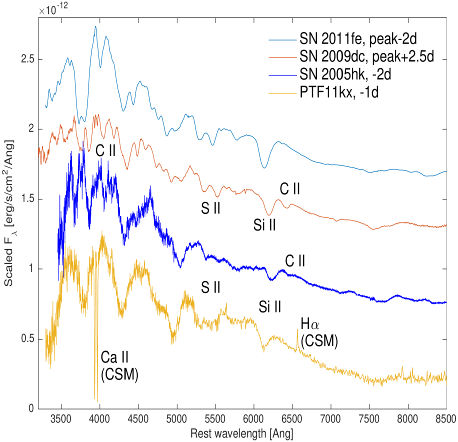
SNe ZOO: Thermonuclear supernovae (type Ia) - no H

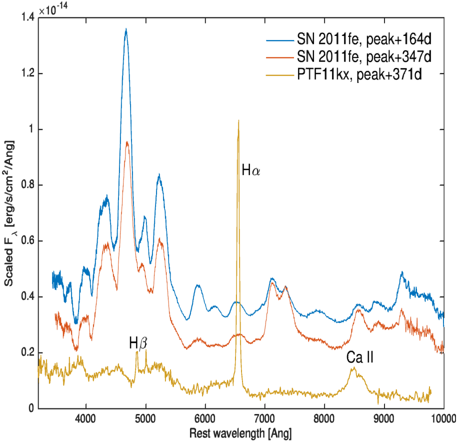


Credit: Gal-Yam 2017

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

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





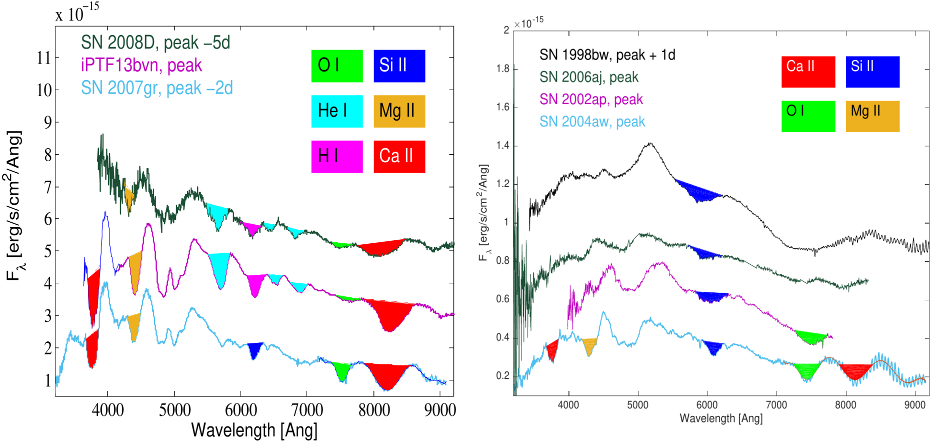
Credit: Gal-Yam 2017

- SN 2011fe: “normal” SN Ia
- SN 2009dc: “super Chandra” SN Ia (slower, brighter, rare, $\sim$ 1%)
- SN 2005hk: type SN Iax $\rightarrow$ “zombie star” (fainter, $\sim$ 10%, 2002cx)
- PTF11kx: SN Ia-CSM $\leftarrow$ interacting SN, $\sim$ 0.1%

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!

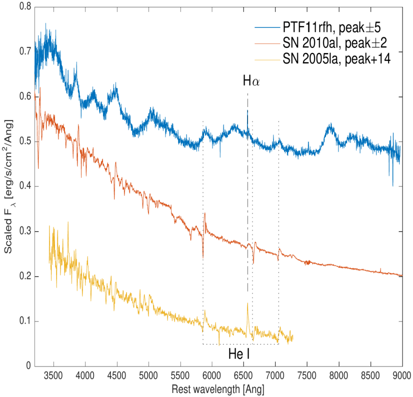
SNe ZOO: Core-collapse supernovae - type Ib,c (no H)

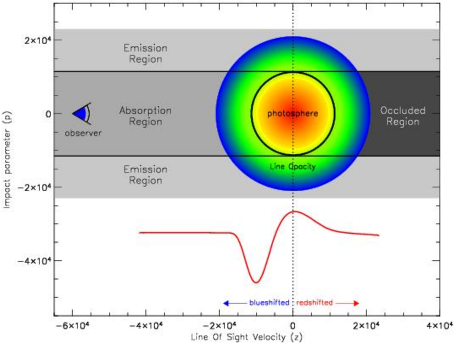


Credit: Gal-Yam 2017

- 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)
- right panel: type Ic - broad lines (Ic-BL) $\rightarrow$ associated with GRBs

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

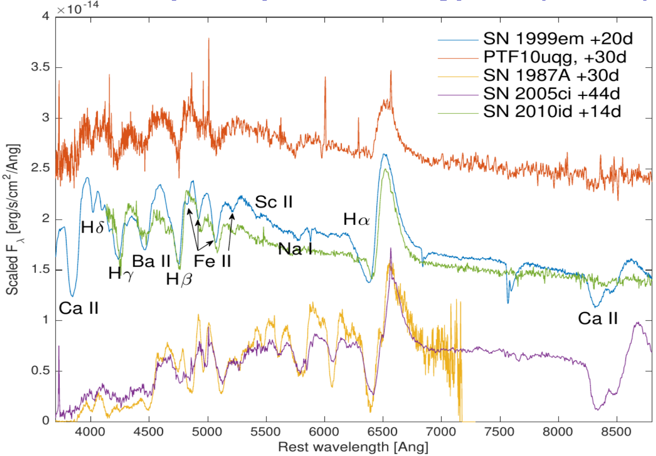




Credit: Gal-Yam 2017

- 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 profiles of He lines + broader Hα emission
- right panel: P-Cygni line profile formation mechanism

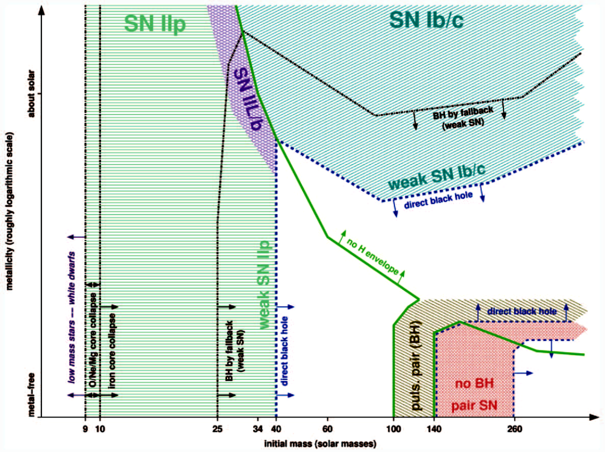
SNe ZOO: Core-collapse supernovae - type II (H rich)

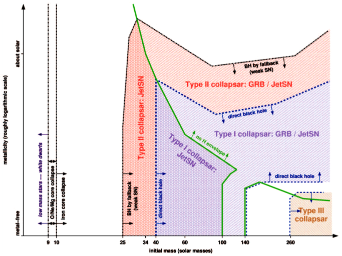


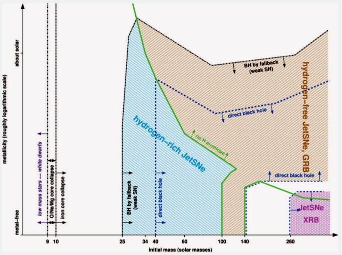
Credit: Gal-Yam 2017

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

SNe ZOO: Core-collapse supernovae



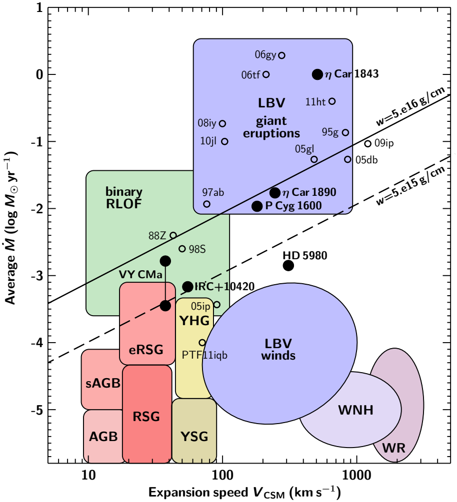




- left: graphs of SNe by initial mass vs. metallicity
- top right: graphs of collapsar types
- bottom right: jet-driven types of SNe (all Heger+ 2003)

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

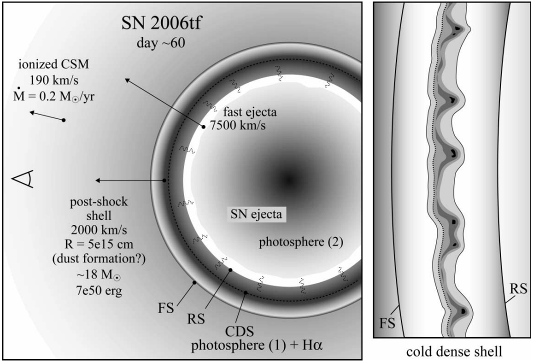
- The chief reason that they are extremely interesting is because they their progenitor may be wildly unstable long before explosion
- This has not been included in standard stellar evolution models
- Another reason they are interesting is because CSM interaction is a very efficient engine for making 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

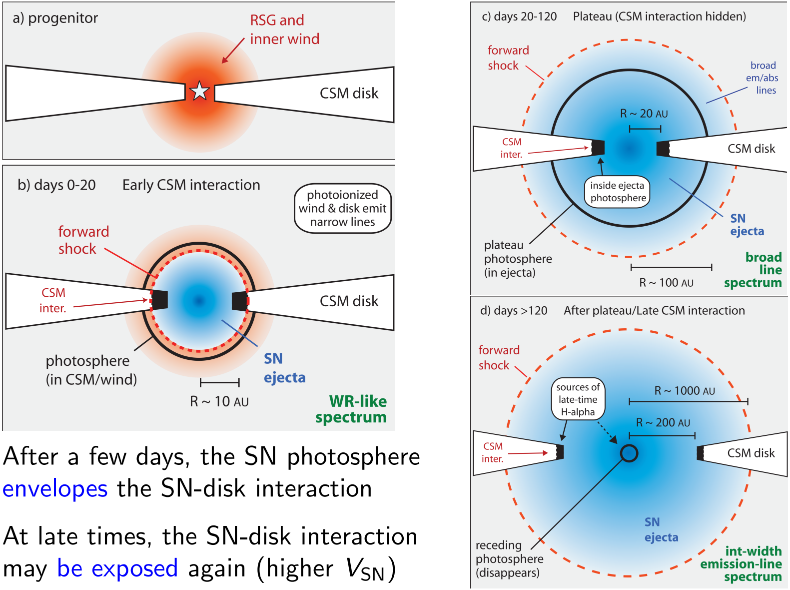
- When a SN explodes inside a dense CSM, four zones are delineated in the simplest picture (Smith+ 2008):



- 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

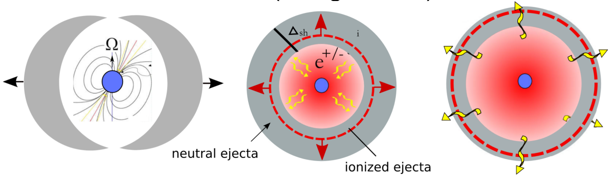
Sketch of the asymmetric SN-CSM interaction (Smith+ 2015)



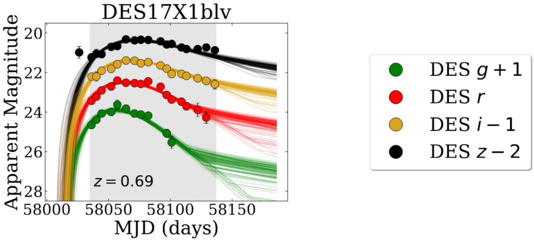
- After a few days, the SN photosphere envelopes the SN-disk interaction
- At late times, the SN-disk interaction may be exposed again (higher V_{SN})

Magnetar powered SLSNe - basic physical picture

(Metzger+ 2014)



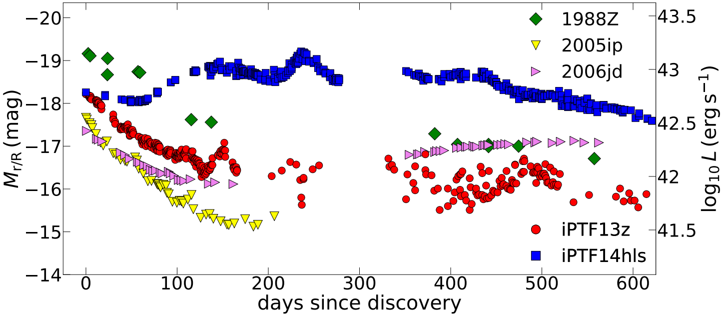
- mass $M_{ej} \sim 0.01 - 0.1\, M_\odot$ is ejected with $V_{ej} \sim 0.1\, c$
- Non-thermal UV and X-ray photons thermalize within ejecta
- Optical and X-ray photons diffuse out of the nebula



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

Type IIn SNe, SLSNe

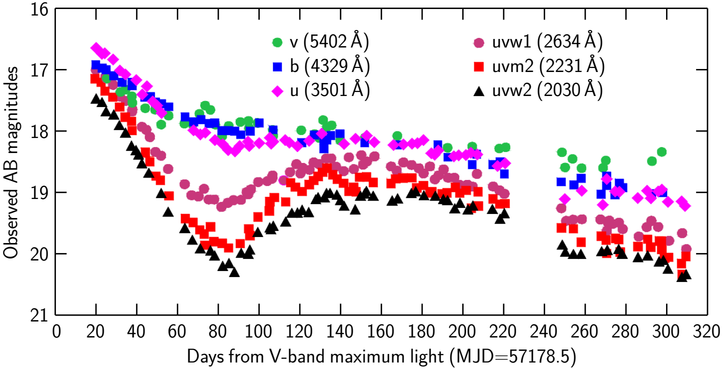
Comparison of light curves of five prominent long-lasting type IIn SNe
(Aretxaga+ 1999, Stritzinger+ 2012, Smith+ 2009, Nyholm+ 2017, Guillochon+ 2017)



- 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)

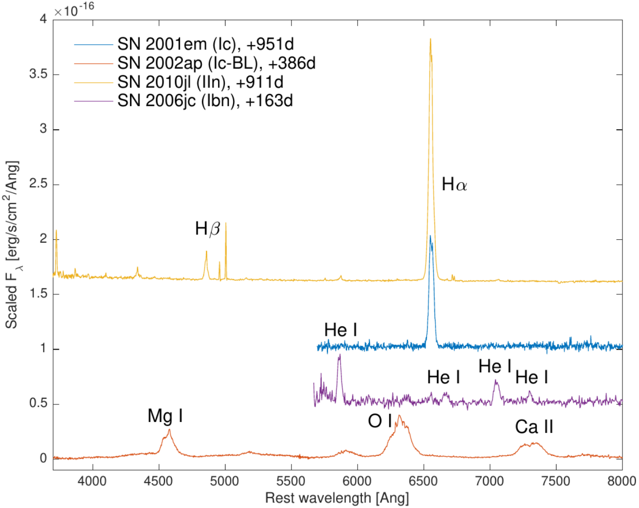
Type IIn SNe, SLSNe

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

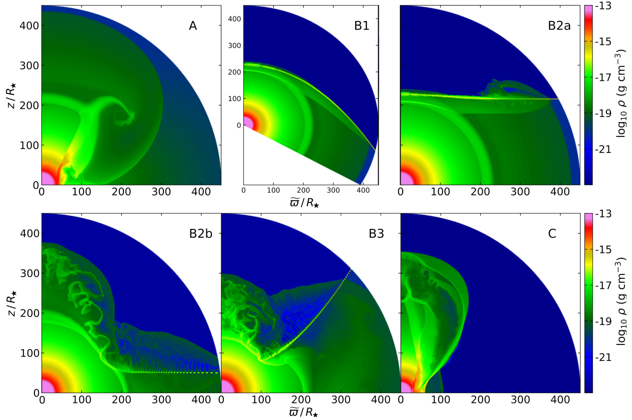
Type I and II - nebular phase: interactors



- 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

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 $0 \lesssim \theta \lesssim 2\pi/3$

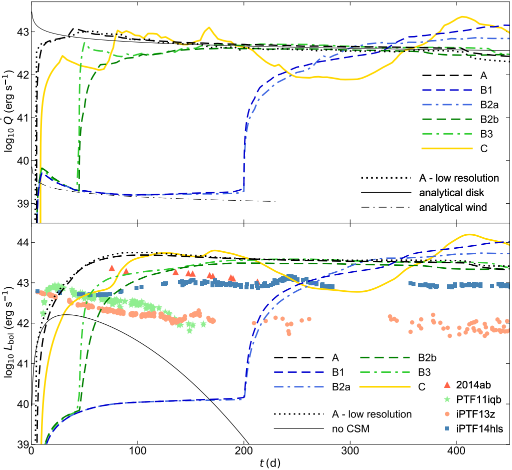
Hydrodynamics of interaction

Animations of various models of SN interactions with asphercal CSM
(the previous quantity with V_r, V_θ ,T, and $\dot{q}$):

- SN - circumstellar disk: model_A.mp4
- SN - colliding wind shell oriented to SN: model_B1.mp4
- SN - distant planar colliding wind shell: model_B2a.mp4
- SN - closer planar colliding wind shell: model_B2b.mp4
- SN - colliding wind shell oriented away from SN: model_B3.mp4
- SN interacting with bipolar lobes: model_C.mp4

Shock power as an internal power source

Estimates of shock heating rates and light curves from our simulations:



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

Models:

A - SN-disk

B1 - SN-colliding wind shell oriented to SN

B2a - SN-distant planar colliding wind shell

B2b - SN-closer planar colliding wind shell

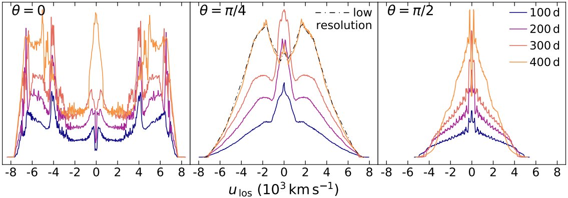
B3 - SN-colliding wind shell oriented away from SN

C - SN-bipolar lobes

Spectral line profiles

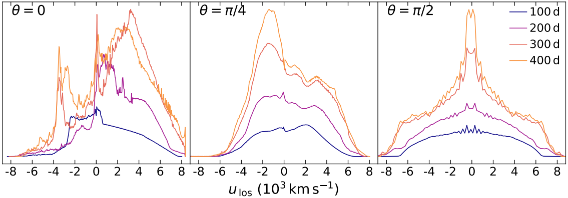
- Line-of-sight velocity distributions for our models:

A



SN - disk

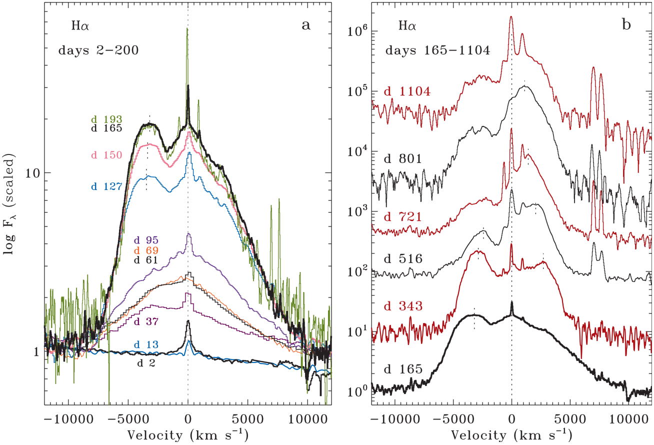
B2b



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

Summary

Thank you for your interest (or patience)

Summary

Thank you for your interest (or patience)

...and keep your enthusiasm for astronomy!