Bumpy Light Curves of Superluminous Supernovae

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Superluminous supernovae (SLSNe)

- SLSNe (Type I (no hydrogen), Type II) are brigher than -21 magnitude in any optical band at the maximum brightness
- Subclasses: SLSN I normal, SLSN I-R, SLSN I - fast,

  SLSN II-n, SLSN IIn-peculiar, SLSN II-L, SN Ia-CSM

- Rise ~ 20-60 d,

  decline ~ 20-500 d,

  E_{rad} ~ (1-10) $\cdot 10^{51}$ erg,

  rate/CC ~ 0.1%,

  ~ 100 SLSNe.

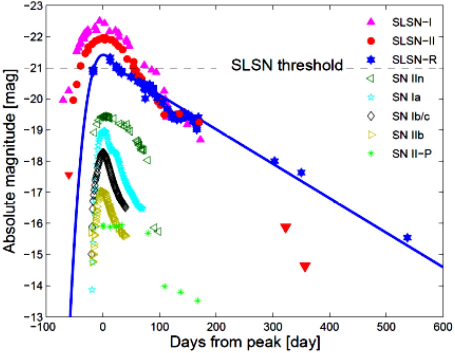
- SLSNe-II: Occur in all galaxies

  SLSNe-I: Exclusively in $M^* < 10^{9.2} M_\odot$,

  $Z < 0.5\ Z_\odot$ galaxies

  (Perley 2016)

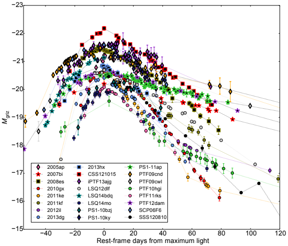
Gal-Yam 2012



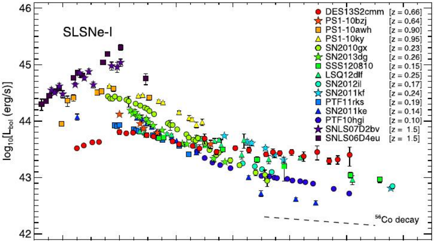
Hydrogen-poor superluminous supernovae

M.Nicholl et al. 2015

griz pseudobolometric light curves



A.Papadopoulos et al. 2015



Observational properties of SLSN-I

- $M_{\rm max} <= -21^m$; $L_{\rm bol,max} > 7 \cdot 10^{43}$ erg/s.
- Typically, they are very blue and emit qiute much in UV range.
- The range of $M_{\rm max}$ is not so large ($\simeq 1^m$); the range of the slopes after max is quite large.
- $V \simeq 10,000$km/s, starting from maximum.
- Many, if not all, of SLSNe has small bump on the rising part of the light curve.
- For some of SLSNe-I: H lines in nebular spectra with $v \simeq 4,000$km/s, $R \simeq 4 \times 10^{16}$cm (iPTF13ehe; Lin+ 2015).

An ideal model must explain all the properties at once.

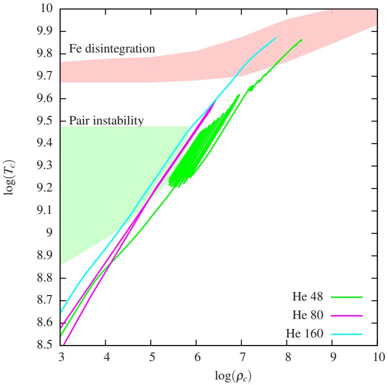
We are still far from the ideal.

Three scenarios proposed for SLSNe-I

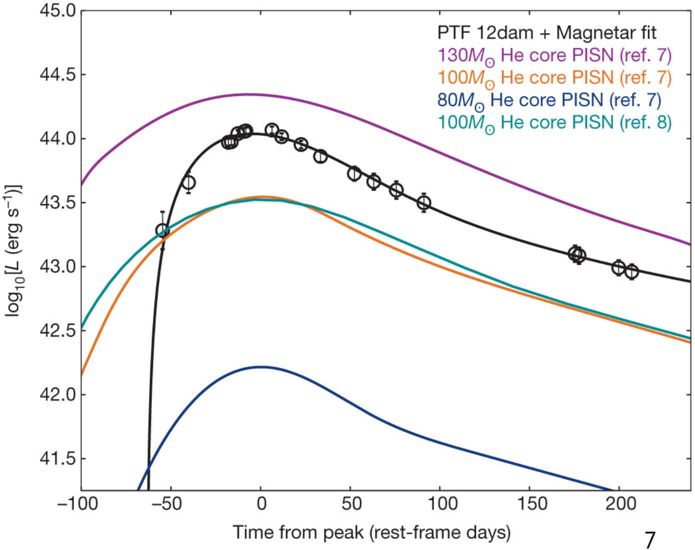
- Pair instability Supernovae, **PISN**
- **"Magnetar"** pumping (BUT observed magnetars are slowly rotating, and here millisecond periods are needed)
- ***Shock interaction*** with CSM, e.g. as a result of Pulsational pair instability, **PPISN**

3 outcomes of pair-instability

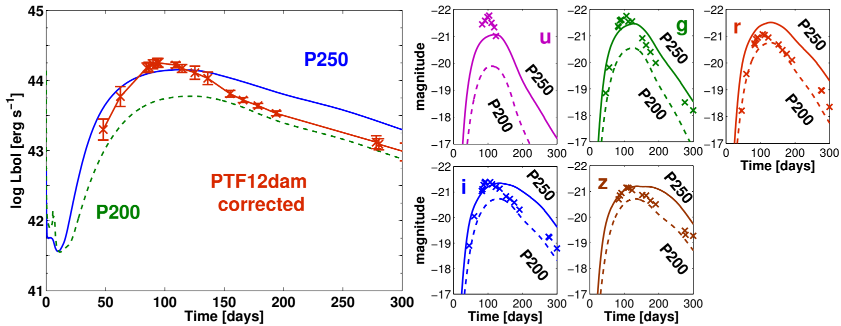
Here are only He-core models, labeled by “He” and the mass of the core. They all reach pair instability, subsequently experiencing 1) pulsations (He48),
2) complete disruption (He80), or
3) direct collapse (He160).



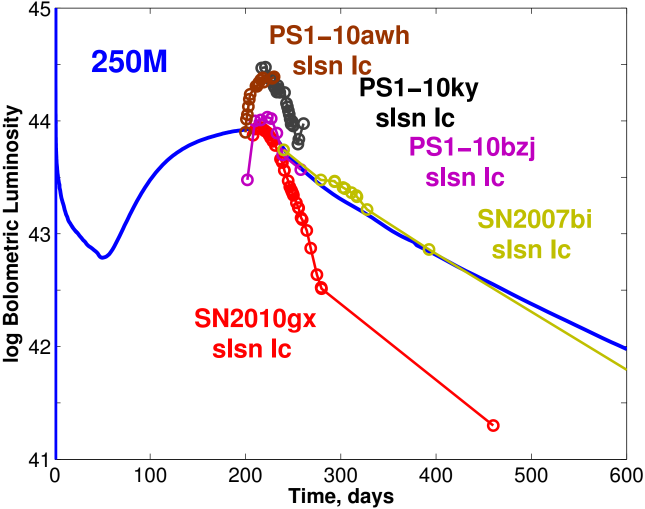
Bolometric light curve and "magnetar" fit for PTF 12dam, Nicholl+, 2013, simple analytical model by S.Jerkstrand, colored curves – PISN models



Compact PISN models with Hydrogen lost; Kozyreva+ 2016



PISN: Kozyreva+ 2014



It is clear that at least some SLSNe are not PISN.

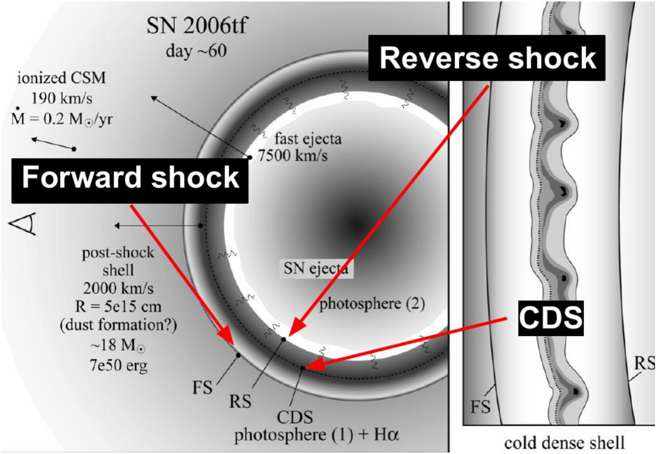
Ejecta–CSM interaction models with modest energy

PISN and magnetar models requires very high explosion energy and extremly high radioactive nickel production.

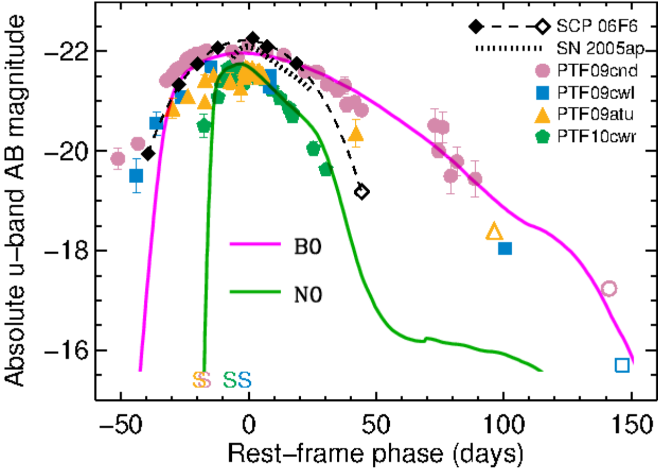
In many cases, CSM interaction scenario doesn’t require so extreme parameters.
Our Lagrangean 1D code STELLA with multigroup radiative transfer allows us to get more economical models.

Sorokina+ 2016, Tolstov+ 2016,2017

Radiative shock waves: a powerful source of light in SLSNe. Cold Dense Shell, Smith et al. 2008, a cartoon

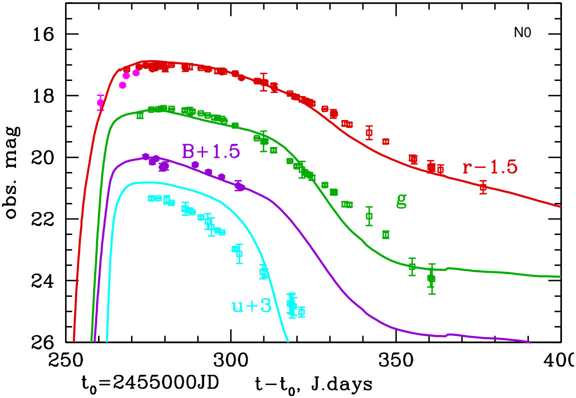


STELLA reproduces the range of SLSNe in shock model: 2 extreme cases



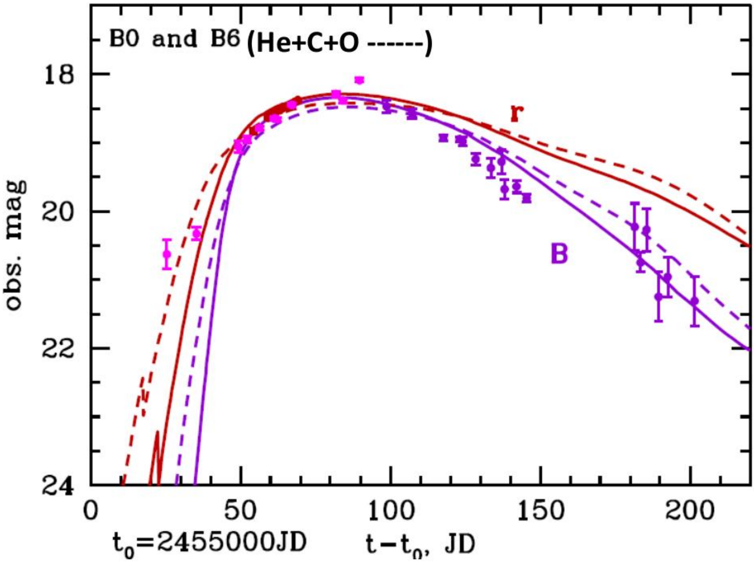
Explosion energy is just 2 - 4 foe

Light curve model for SN2010gx



Synthetic light curves for the model N0, one of the best for SN 2010gx, in r, g, B, and u filters compared with Pan-STARRS and PTF observations. Pan-STARRS points are designated with open squares (u, g, and R bands), PTF points, with filled circles (B and r bands).

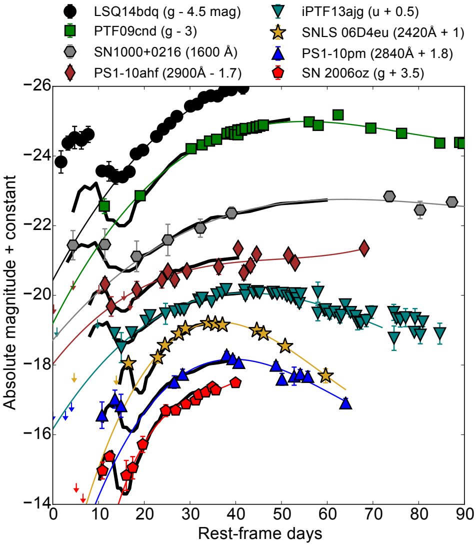
Light Curve Models for PTF09cnd



Circumstellar Interaction

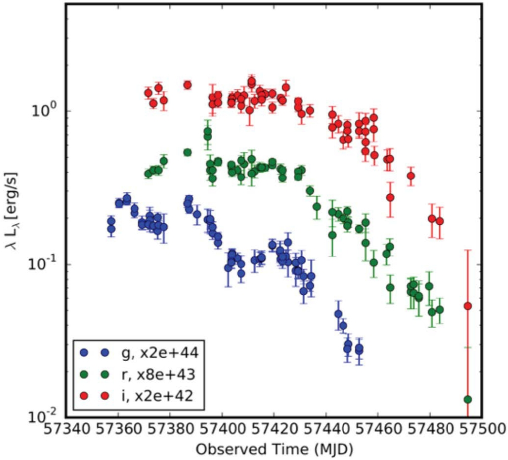
	SN 2010gx (N0)	PTF09cnd (B0)
M(CSM)/$M_\odot$	10	50
M(ejecta)/$M_\odot$	0.7	5
E (10^{51} erg)	2	5
R (CSM)/cm	7×10^{15}	7×10^{15}

Many SLSNe-I have a pre-maximum bump
Nicholl & Smartt 2015



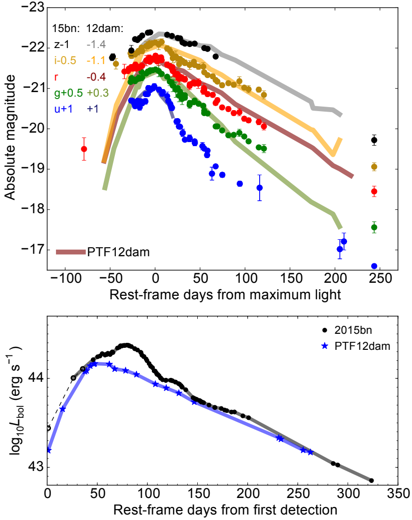
Some others have many bumps on the declining stage

SLSN-I PTF15esb: bumpy light curve



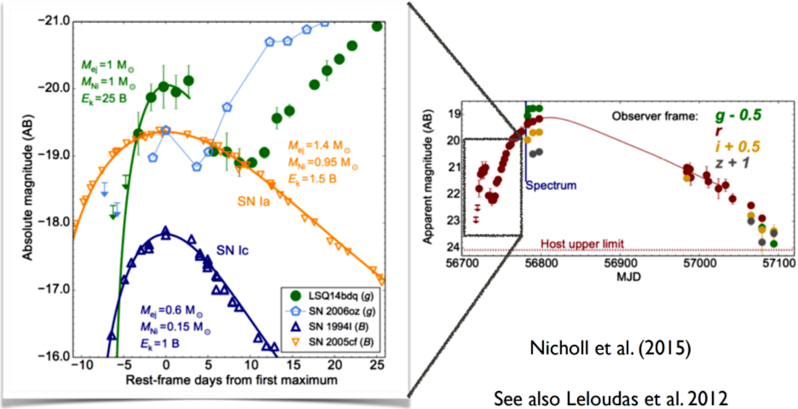
(Yan+16)

SN 2015bn – another example of very bumpy SLSN (Nicholl+ 2015). Pre- and post-maximum bumps might have similar or differnt origin.



Radioactive origin of pre-maximum bump?

Doubled peak of SLSN-I (by R. Quimby)



Nicholl et al. (2015)

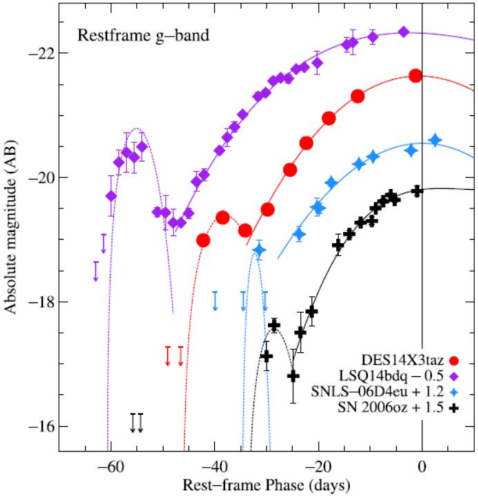
See also Leloudas et al. 2012
Nicholl & Smartt 2016
Kasen et al. 2016

Some more realistic explanaitions of bumps

- 1st bump - shock break-out through an extended pre-SN envelope, main max - another (whichever) main source of energy.
- Two (or more) subsequent explosions/ejections (quite natural for PPISN scenario – see recent paper by Woosley 2017, with lots of models)
- Stratification of ejected elements along the radius:
  Innermost layes of CO-rich gas become opaque at lower T, then photosphere stalls waiting for helium layers to become opaque at higher T.

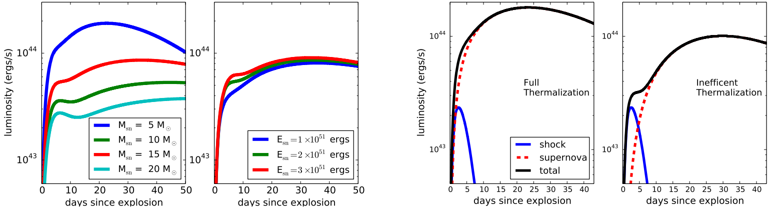
Shock breakout – analytical formula

Double Peaks (Smith et al. 2016)

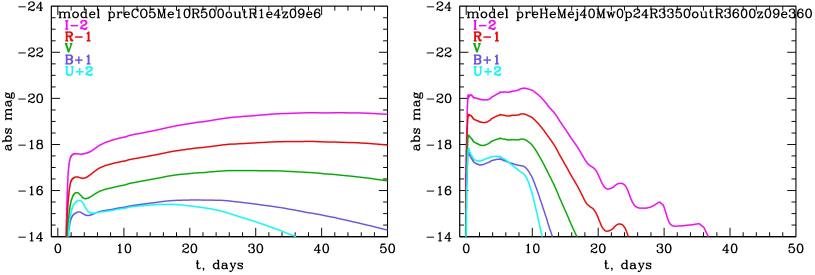


Shock breakout looks similar for any energy source

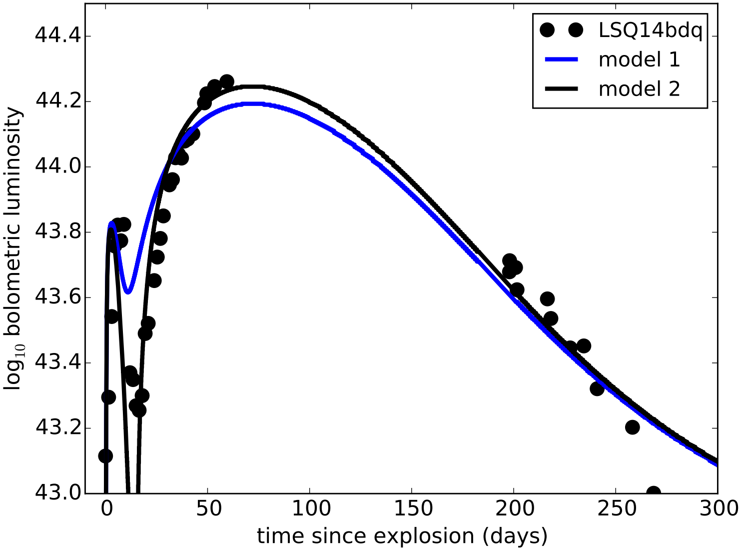
Magnetar inside:



Thermal bomb:

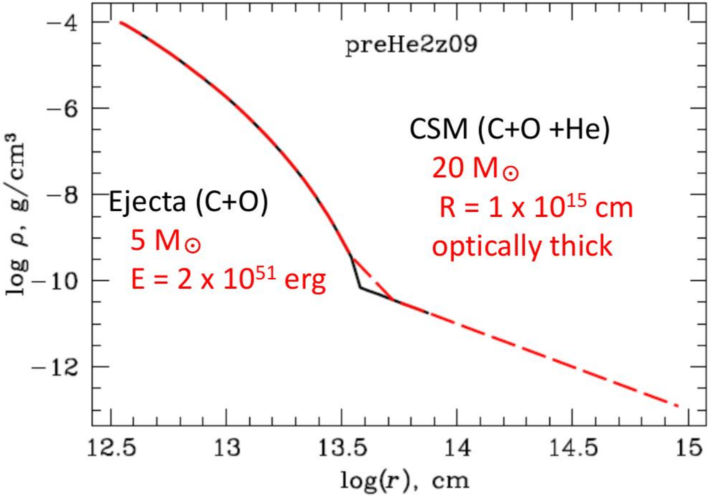


Shock breakout

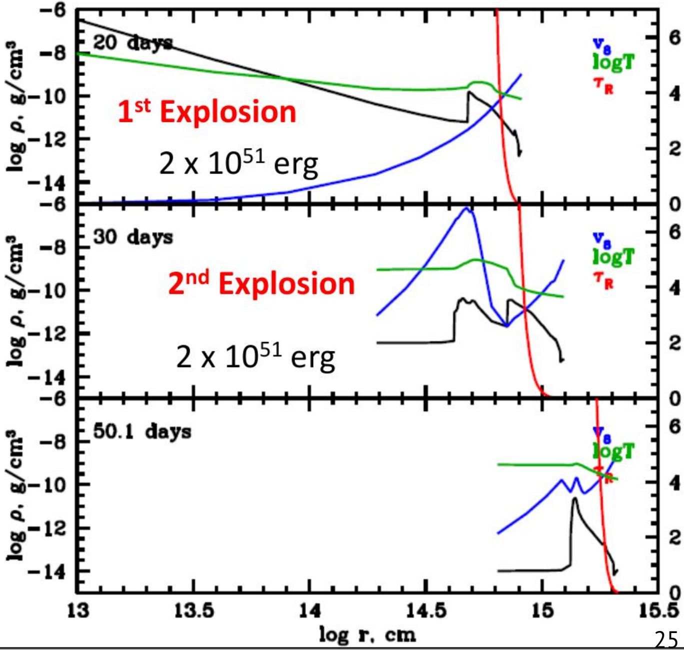


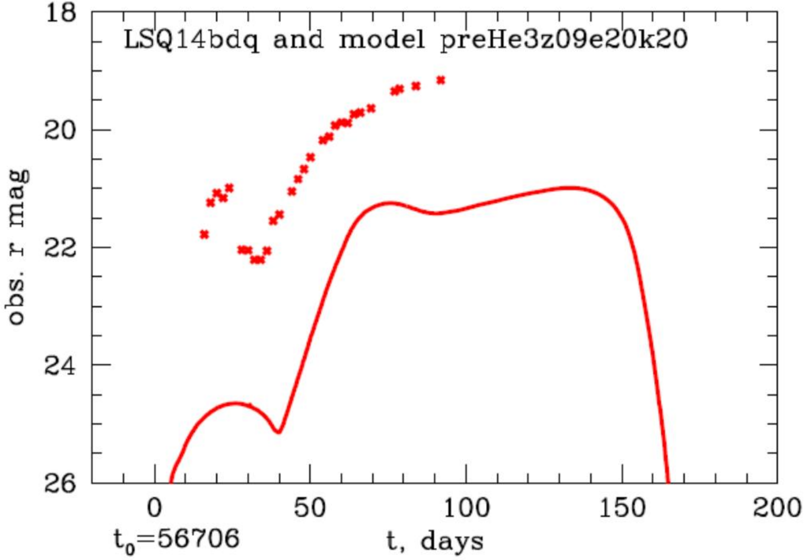
Kasen+ 2016 (Magnetar model)

Two Explosions in CSM (Sorokina+16)

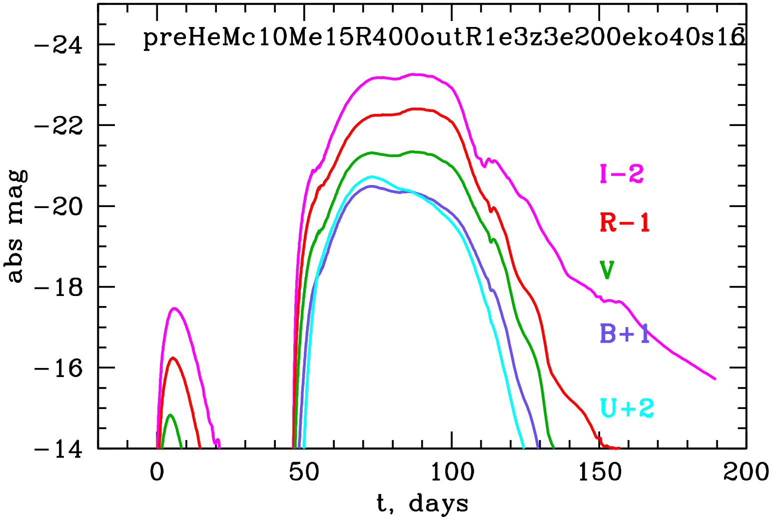


Two explosions details




LSQ14bdq and model preHe3z09e20k20
obs. r mag
18
20
22
24
26
0
50
100
150
200
t, days
t_0=56706

1st piston with $E = 4B$, then thermal bomb with $E = 20B$



Problems with 2-explosion models

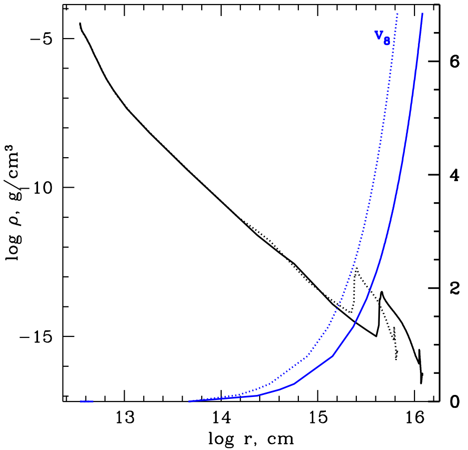
It is the easiest model for light curve calculation,
BUT it is unclear if it is physically possible to produce 2 energetic explosion or mass ejection so close in time
and WHY this time delay and brightness ratio of two maxima are so similar for many SLSNe.

Post-shock-breakout cooling, then interaction

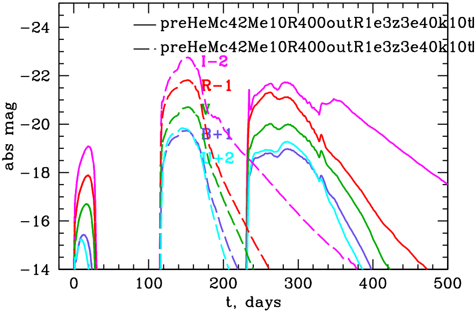
(or subsequent interactions with several ejections)

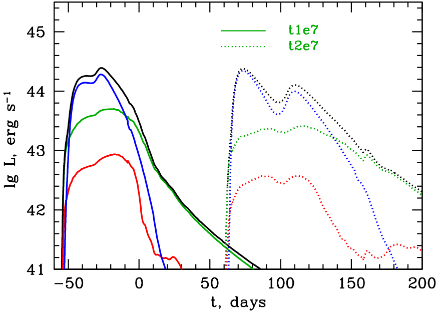
Piston expands 8 Msun of He-envelope with $E = 1B$;

density distribution in 1e7 s and 2e7 s

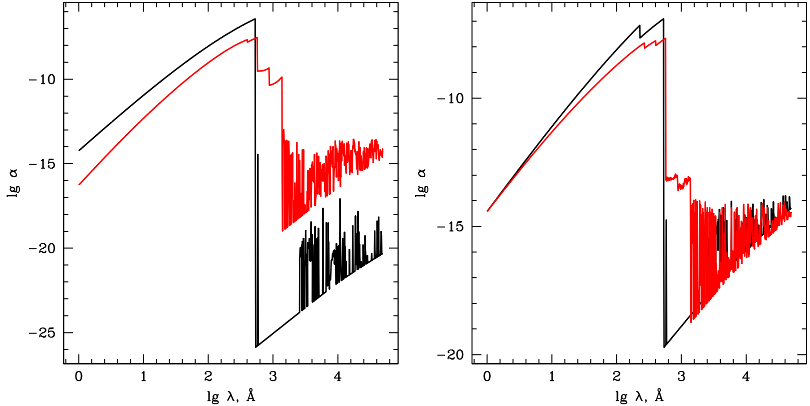


Then 2nd explosion produces the whole light curve





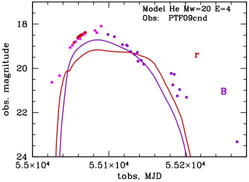
Opacities of CO mixture (red) and He (black)



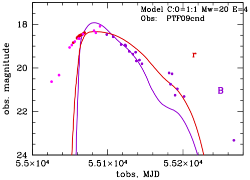
T=7000K

T=11000K

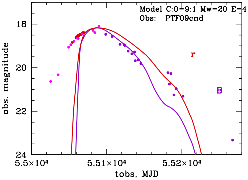
Different composition



Helium



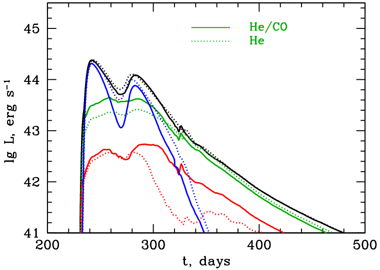
C:O=1:1

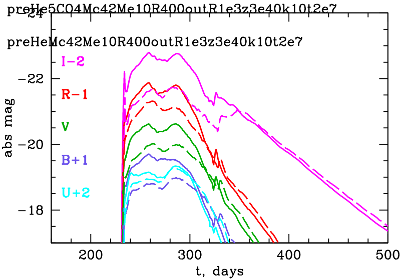


C:O=9:1

Sorokina+ (2016)

Pure helium vs. CO/He models





Conclusions

- Interaction models are able to reproduce both narrow and wide LCs of SLSNe. They require quite large mass of CO-rich material ejected within few months to years before the final explosion. The problem of high velocities will be discussed in the next talk.
- The origin of pre-maximum bumps still remain questionable.
- Most natural explanation of the post-maximum bump is the interaction of SCM layers or bullets.
- The combination of the SLSN scenarios is promising.
- The ideal scenario have to explain ALL observational features at once: LCs including bumps, high velocities, etc.

The work is in progress

Thank you!