Central Engines and Environment of Superluminous Supernovae

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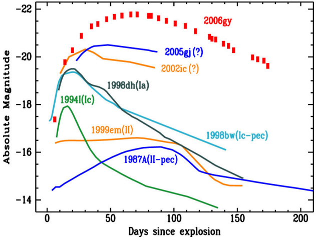
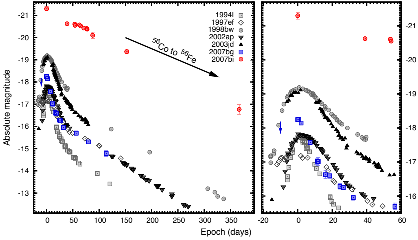
with E.Sorokina, K.Nomoto, P. Baklanov, A.Tolstov, E.Kozyreva, M.Potashov, et al.

Schloss Ringberg, 26 July 2017

First Superluminous Supernova (SLSN) is discovered in 2006



Superluminous SN of type II



Superluminous SN of type I

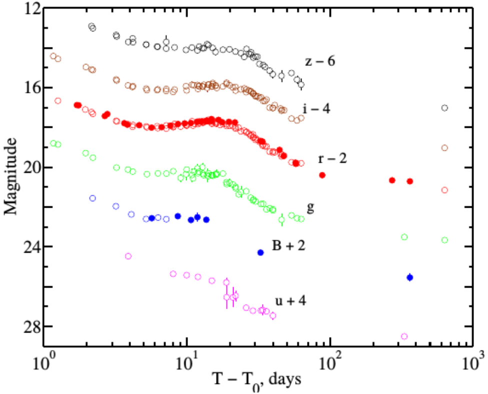
SN2006gy used to be the most luminous SN in 2006, but not now.

Now many SNe are discovered even more luminous.

The number of Superluminous Supernovae (SLSNe) discovered is growing. The models explaining those events with the minimum energy budget involve multiple ejections of mass in presupernova stars. Mass loss and build-up of envelopes around massive stars are generic features of stellar evolution. Normally, those envelopes are rather diluted, and they do not change significantly the light produced in the majority of supernovae.

SLSNe are not equal to Hypernovae

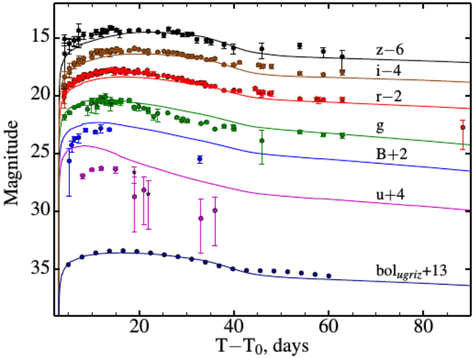
Hypernovae are not extremely luminous, but they have high kinetic energy of explosion.



Afterglow of GRB130702A with bumps interpreted as a hypernova.

Alina Volnova, et al. 2017. Multicolour modelling of SN 2013dx associated with GRB130702A. MNRAS 467, 3500.

Our models of LC with STELLA

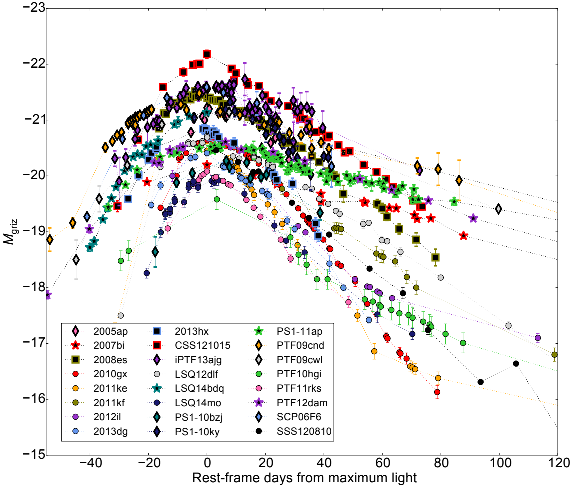


$E \approx 35$ foe. First year light ~ 0.03 foe while for SLSNe it is an order of magnitude larger.

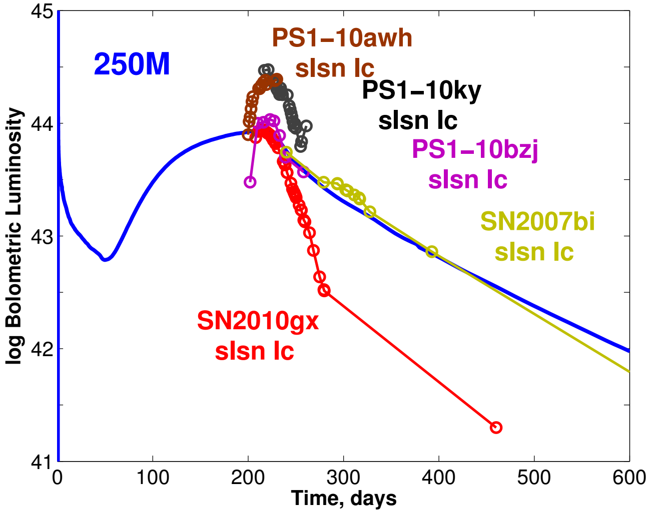
Hydrogen-poor super-luminous supernovae

M.Nicholl et al. 2015

griz pseudobolometric light curves



Path-1 to SLSN: **PISN** e.g. Kozyreva, SB, Langer, Yoon, 2014



It is clear that some SLSNe are not PISN.

Path-2: **Pulsar pumping supernovae, an old idea**

One of the most popular models for SLSNe is the so called "magnetar" model. It is often forgotten in the current literature that the idea to use a millisecond pulsar with strong magnetic field for pumping the light curves of supernovae was put forward by Shklovskii already in 1971 and elaborated in his paper published in 1975 (English translation in 1976). This is not only the basic idea of current magnetar models for SLSN: they use essentially the same formulae that have been used by Shklovskii more than 40 years ago.


INTERNATIONAL CONFERENCE
"ALL - WAVE ASTRONOMY.
SHKLOVSKY - 100".
A scientific meeting in honour of 100th anniversary of Iosif S. Shklovsky
20 - 22 June 2016, Moscow, Russia
http://shklovsky100.asc.rssi.ru
Topics of the conference
• Cosmic Microwave Background and the Early Universe
• Supermassive black holes and active galactic nuclei
• Sources of cosmic rays generation
• Supernovae and their remnants, gamma-ray bursts, pulsars
• Physics of the interstellar medium
• Stellar evolution and planetary systems
• The SETI problem.

Shklovskii's papers 1972 – 1976

I.S. Shklovskii, Astron. Zh. 49, 913 (1972) [Sov. Astron. 16, 749 (1973)]
I.S. Shklovskii, Astron. Zh. 52, 911 (1975) [Sov. Astron. 19, 554 (1976)]
Shklovskii's idea stems from
N.S. Kardashev 1964
J.P. Ostriker, J.E. Gunn 1969. On the Nature of Pulsars. I. Theory. The Astrophysical Journal 157, 1395.
G.S. Bisnovatyi-Kogan, Astron. Zh. 47, 813 (1970) [Sov. Astron. 14, 652 (1971)] – Magneto-rotational mechanism for supernova explosion

1976SvA....19..554S

Hard radiation by young pulsars as the cause of supernovae optical emission

I. S. Shklovskii

P. K. Shternberg State Astronomical Institute

(Submitted February 10, 1975)
Astron. Zh. **52**, 911–919 (September–October 1975)

Since, according to observations, the masses of the envelopes of type I and II supernovae do not exceed 10^{33} g, their optical thickness in the continuum after the maximum cannot be greater than unity. Therefore, the light curves of supernovae cannot be explained by the passage of a shock wave through the extended envelope of a red supergiant. It is suggested here that energy is pumped into the envelope by the x-ray emission of a young pulsar. A model of the source of this emission is constructed, and a drift of the frequency of the maximum in its spectral distribution follows. The light curves of supernovae of both types after the maximum must follow the power law $L \sim t^{-2.5}$. The ionization of hydrogen (and possible helium) in the envelopes is due to a flux of relativistic protons generated by the young pulsar. There is apparently no fundamental difference between type I and II supernovae. Stars with mass only sightly exceeding the Sun's explode.

Shklovskii 1976 estimates $L \sim 10^{44}$ erg/s

Since the power of the magnetic-dipole emission is

$$L_m = \frac{2}{3c^3} m_\perp^2 \Omega^4, \qquad (2)$$

we have

$$L_m \propto t^{-1} \,(\text{ for } \tau_g < t < \tau_m);$$

$$\tau_g \approx 10^d, \ \tau_m = \frac{3c^3 I}{2m_\perp^2 \Omega^2} \approx 1 \text{ year (see ref. 25)}, \qquad (3)$$

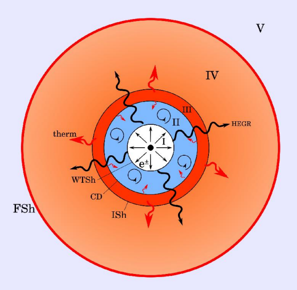
where $m_\perp$ is the component of the magnetic moment m perpendicular to the axis of rotation, and I is the moment of inertia of the neutron star. Assuming a pulsar radius $a = 1.4 \cdot 10^6$ cm, $H = 10^{12}$ G, and $\Omega = 3 \cdot 10^3\ \mathrm{sec}^{-1}$, we find that $L_m \approx 10^{44}$ erg/sec for $t < t_g$, after which L_m will decrease

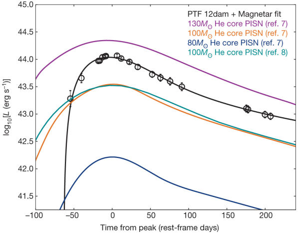
I. S. Shklovskii 556

Ref.25 is Gunn & Ostriker 1969.

“Magnetar” (as a ms pulsar) Powered Supernova

- $E_{\rm rot} = \frac{1}{2} I\Omega^2 \sim 10^{52}$ erg
- $E_{\rm burst} \approx 3 - 10 \cdot 10^{51}$ erg, $L_{\rm rot} = 3 \cdot 10^{45} \left(1 + \frac{t}{10^5 s}\right)^{-2.1} \frac{\rm erg}{\rm s}$
- Magnetized wind $e^{\pm}$ ($\Gamma > 1000$) $\Rightarrow e^{\pm} + B$ – synchrotron, or $e^{\pm} + h\nu_{\rm therm} \rightarrow \gamma$ 100 keV – Compton, 10 TeV $\Rightarrow \gamma + e^{-}$ or $\gamma + h\nu_{\rm therm} \rightarrow$ heat $\Rightarrow h\nu_{\rm therm}, PdV$

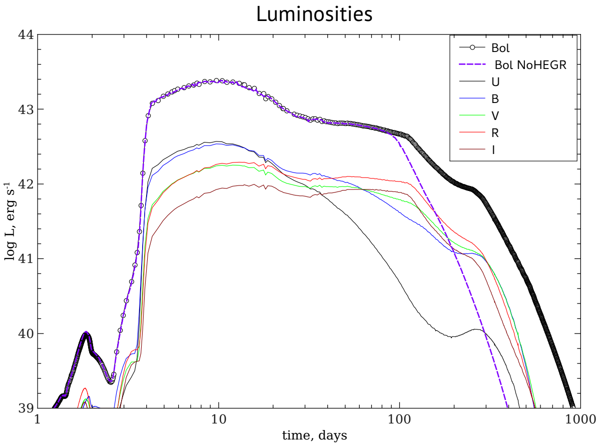




- Analogy with γ-ray heating from decays
- Contribution of $L_{\rm rot}$ directly into thermal luminosity fits nicely the observed light curves (M Nicholl et al. *Nature*, 2013)
- **But!** This must be checked in detail...

Badjin, Barkov, SB, Khangulyan (in prep.): $15 M_{\odot}$, E=3 foe: thermal emission

- The optimism of the community is premature
- Magnetar manifests itself on the "tail" – only for the latest epochs (> typical time-scale of ^{56}Ni$\to ^{56}$Co$\to ^{56}$Fe$\sim 10^2$ days.)



Why the primitive "magnetar" does not work?

Thus, a more detailed consideration (in comparison with the simple deposition of spin-down losses into heat) has certain difficulties in explaining the high luminosities observed.
This is because **a huge number of thermal photons yields a very high pair-creation opacity for gamma-rays** and hence **prevents** them from entering the expanding shell itself.
The spin-down energy is converted into relativistic plasma pressure and the work it makes upon the shell, and therefore into the shell kinetic energy.

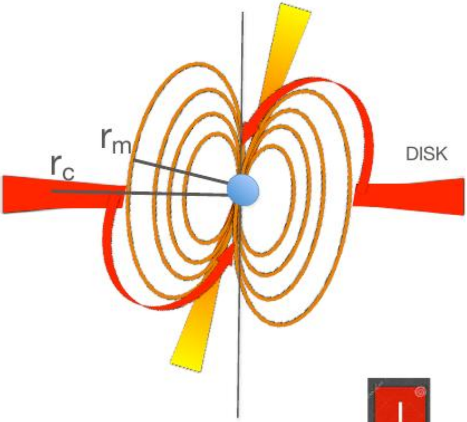
Not into luminosity! Details in http://wwwmpa.mpa-garching.mpg.de/hydro/NucAstro/PDF_16/Badjin.pdf

Magnetar may work as an accretor, not ejector

Accreting magnetars as source of GRB power

⇒ **Accretion phase**

$r_m < r_c$



Bernardini et al., 2013

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Borrowed from Bernardini+ (2013, 2015, 2017)

A third path to SLSN – Double explosion: an old idea for SNIIn

Grasberg & Nadyozhin (1986)

Models were proposed for SLSNe with the explosion energy tens times higher than in usual SNe, and presupernovae were suggested ten times more massive, with a huge amount of radioactive ^{56}Ni produced in the explosion. This is possible in pair-instability SNe, **PISNe**.

However, in many cases those extreme parameters are not needed. Our Lagrangian 1D code STELLA with multigroup radiative transfer allows us to get more economical models

The latest papers with our results are

Sorokina, Blinnikov, Nomoto, Quimby, Tolstov 2016, ApJ 829, 17 “Type I Superluminous Supernovae as Explosions inside Non-hydrogen Circumstellar Envelopes”,

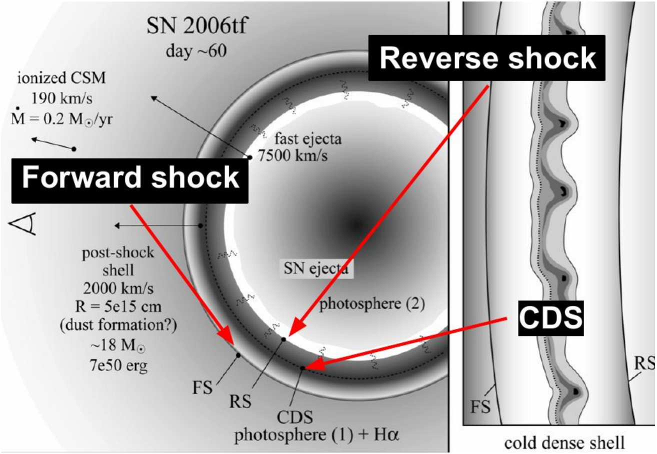
Tolstov+2017, ApJ 835, 266 “Pulsational Pair-instability Model for Superluminous Supernova PTF12dam: Interaction and Radioactive Decay”

Repeated explosions: a mechanisms for Superluminous Supernovae

In some cases, large amounts of mass are expelled just a few years before the final explosion. Then the slowly expanding envelopes around supernovae may be quite dense. The **shock waves** produced in collisions of supernova ejecta and those dense shells may provide the required power of light to make the supernova much **more luminous** than a "naked" supernova without pre-ejected surrounding material.

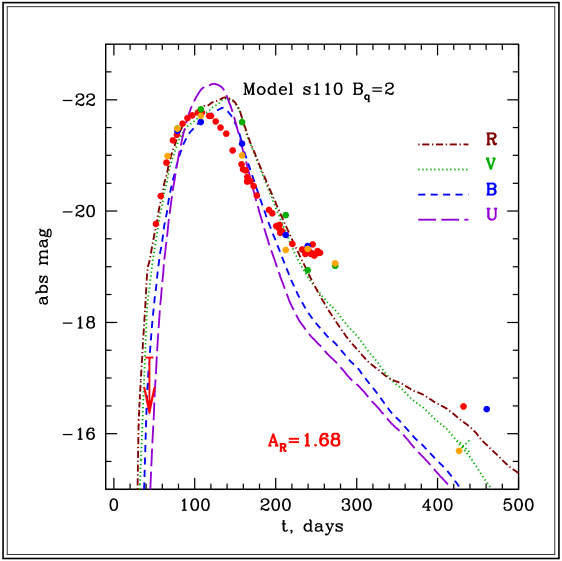
This class of the models is referred to as **"interacting" supernovae**. We show in a detailed radiation hydro modelling (E.Sorokina, S.Blinnikov, K.Nomoto, R.Quimby, & A.Tolstov - ApJ 829, 17, 2016) that the interacting scenario is able to explain both fast and slowly fading SLSNe, so the large range of these intriguingly luminous objects can in reality be almost ordinary supernovae placed into extraordinary surroundings.

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

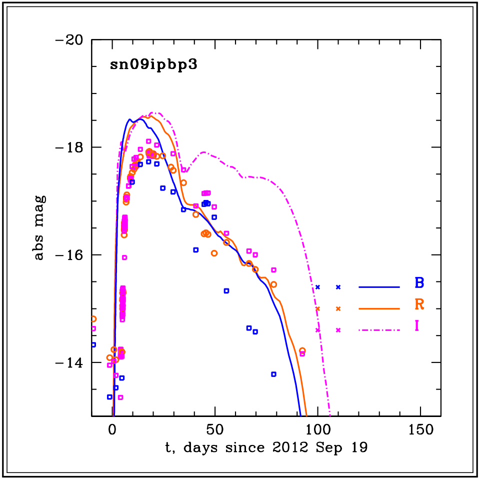


SNIIn: LCs for SN2006gy in shock-interaction model by STELLA

new runs



SNIIn: An example of an ‘impostor’ SN 2009ip

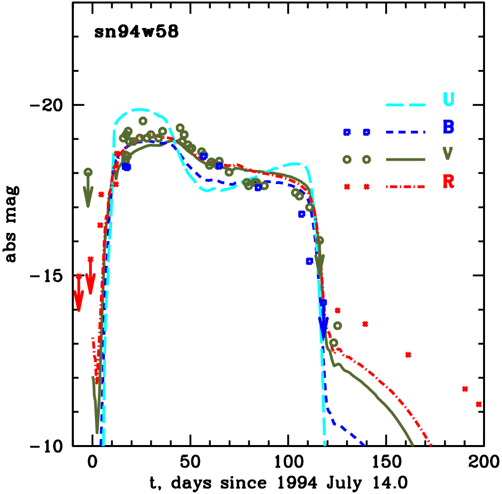


– almost no extinction. Model by STELLA in Baklanov+ (2013)

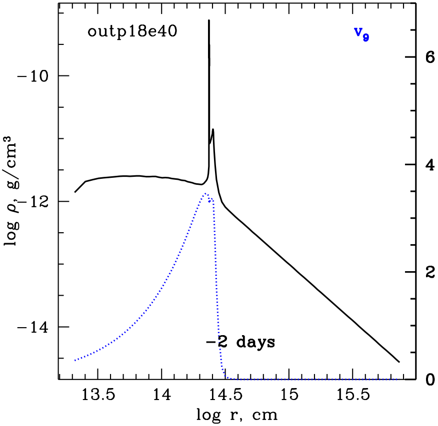
Real explosion September 2012

SNIIn: Light Curve of SN 1994W

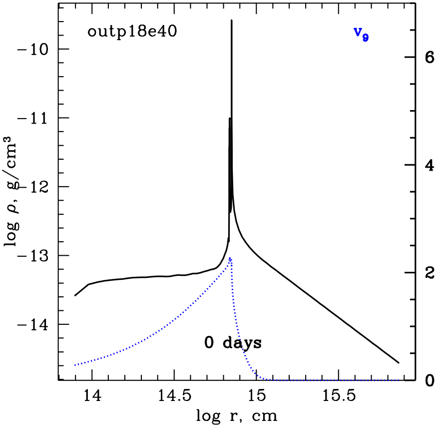
Light curves for the run sn94w58 (Chugai,SB+ 2004). Fluxes in BV filters converge – contrary to SNIIP, a good feature to distinguish SNIIn before spectroscopic observations.



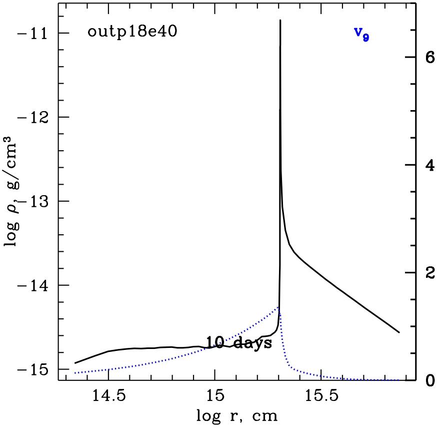
Long Living Dense shells-1 Sorokina et al.



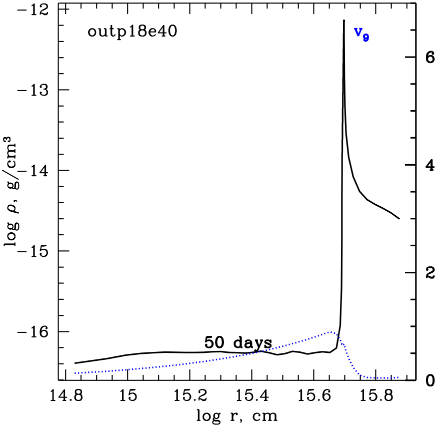
Long Living Dense shells-2 Sorokina et al.



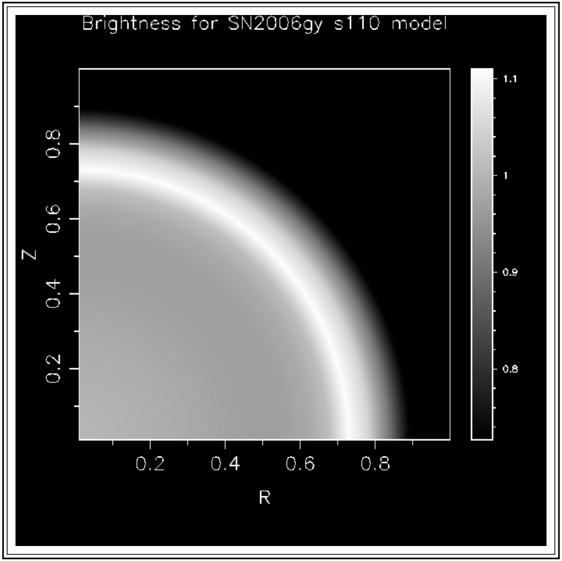
Long Living Dense shells-3 Sorokina et al.



Long Living Dense shells-4 Sorokina et al.

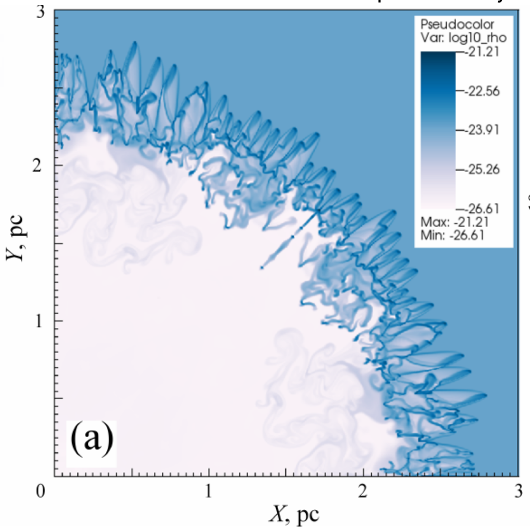


‘Visible’ disk of SN 2006gy



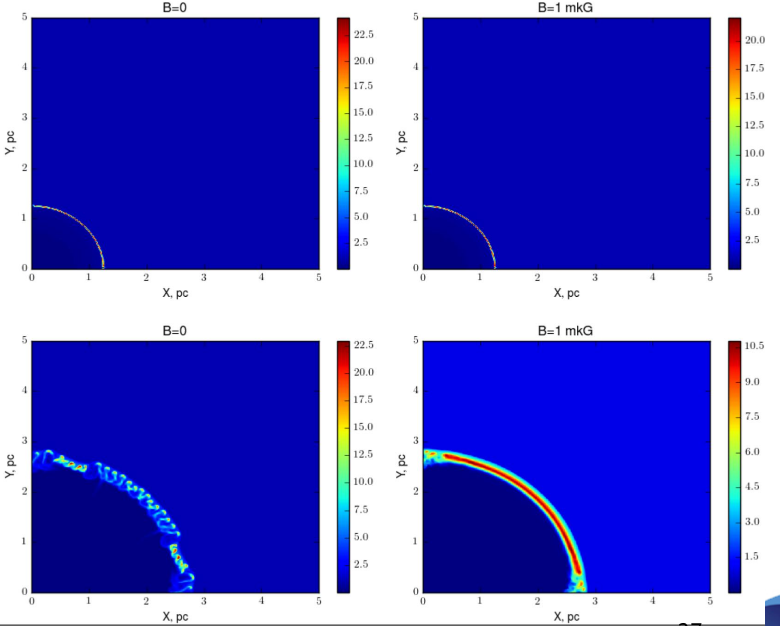
Development of new patterns of 3D-instability

We begin realistic multi-D simulations. The picture may be like this:



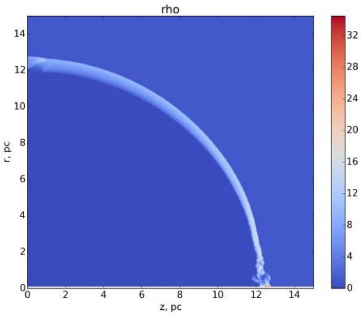
Details in Badjin, Glazyrin, Manukovsky, SB, MNRAS 2016

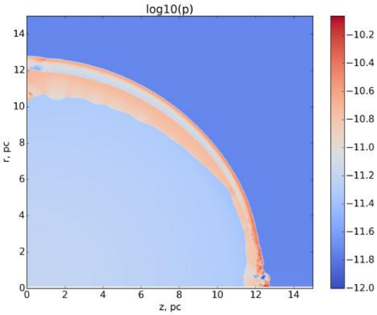
Influence of magnetic field: B along z-axis in 2D-simulations



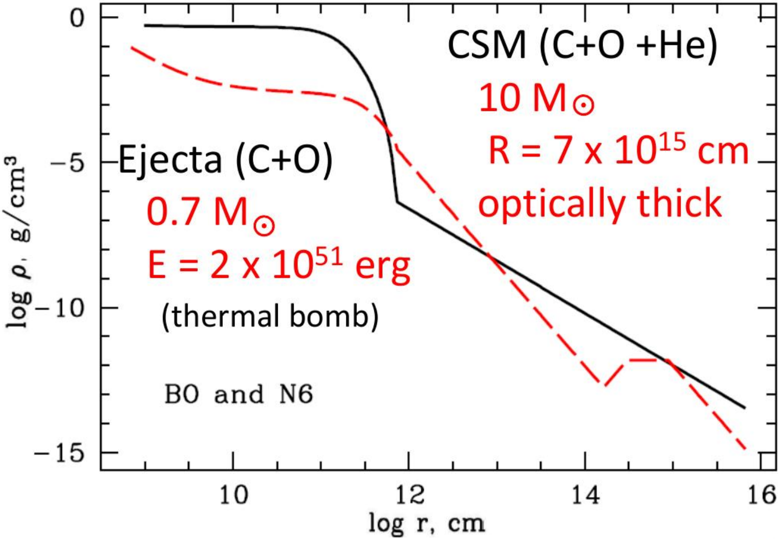
2D RZ simulations

$\longrightarrow \mathrm{B}$





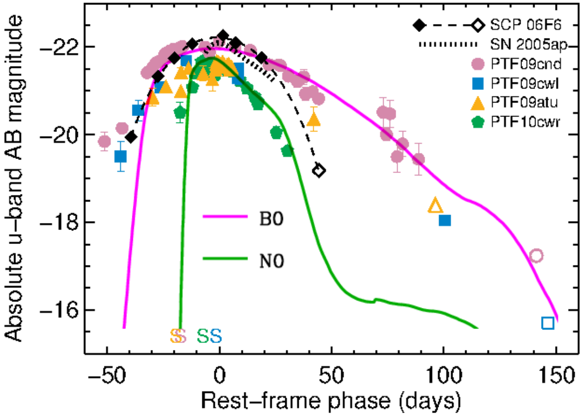
Circumstellar Interaction model for SN 2010gx (Sorokina et al. 2016: STELLA)



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}

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



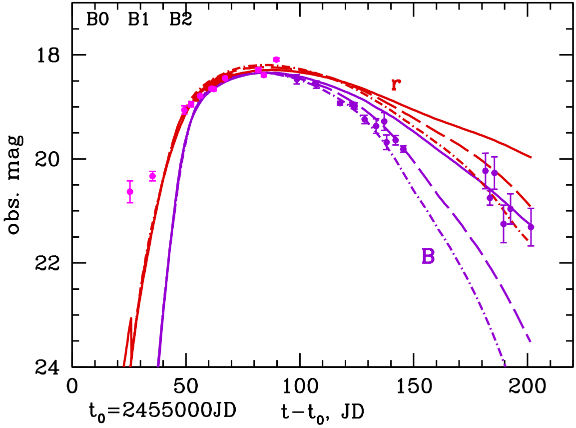
Explosion energy is just 2 - 4 foe.

Static vs. expanding CSM for PTF09cnd

B0 (static);

B1 (Ew=0.1 foe, v_{max}=750 km/s);

B2 (Ew=0.3 foe, v_{max}=1,300 km/s)



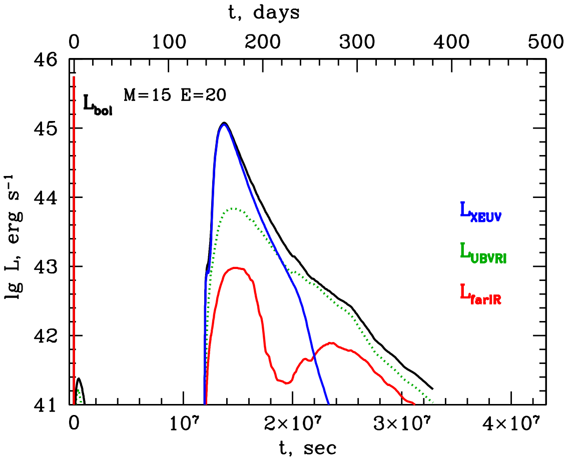
Sorokina+ (2016)

Problems with high photospheric velocity in SLSNe

Many SLSNe-I have photospheric velocity of order 10^4 km/s which is hard to explain in interacting models with modest energy of explosion. Our new set of radiation hydro models (SB, Sorokina, Nomoto in prep.) demonstrates that a strong explosion (on the observed **hypernova** scale) within a dense envelope produced by previous weaker explosions explains naturally both high luminosity and high photospheric velocity of SLSNe. Observed hypernovae are associated with **GRBs**.

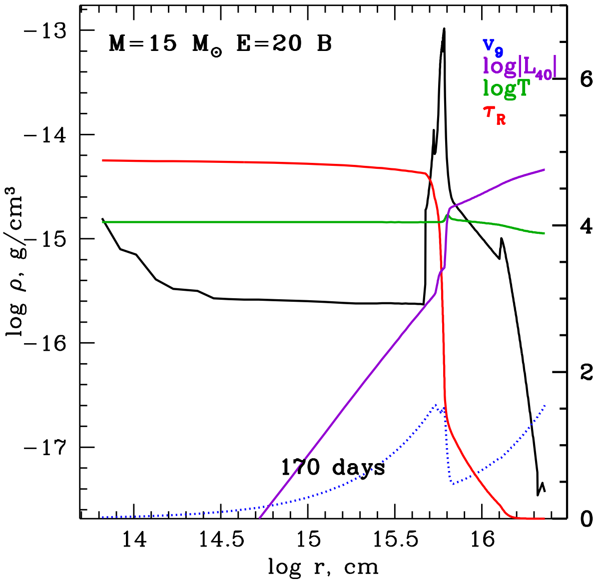
We conclude that the main features observed in SLSNe near maximum light are explained by a GRB-like central engine, embedded in a dense envelope and shells ejected prior the final collapse of a massive star.

High energy of explosion is needed for explaining high velocity

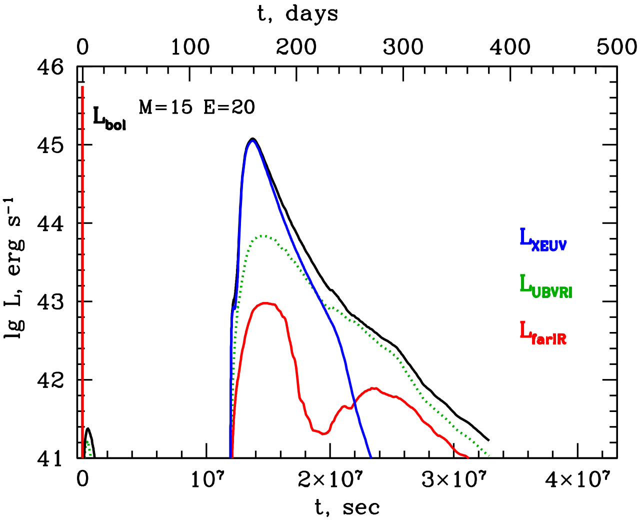


He-rich ejecta: 1st explosion is modelled with a kinetic bomb $E = 4$ foe, then a thermal bomb with $E = 20$ foe for producing high photospheric velocity (bolometric and quasi-bolometric LCs)

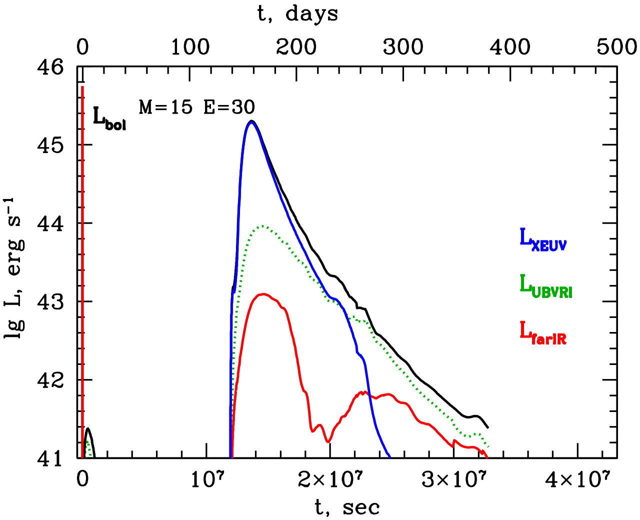
Radiation hydro profiles for high velocities, E=20 foe



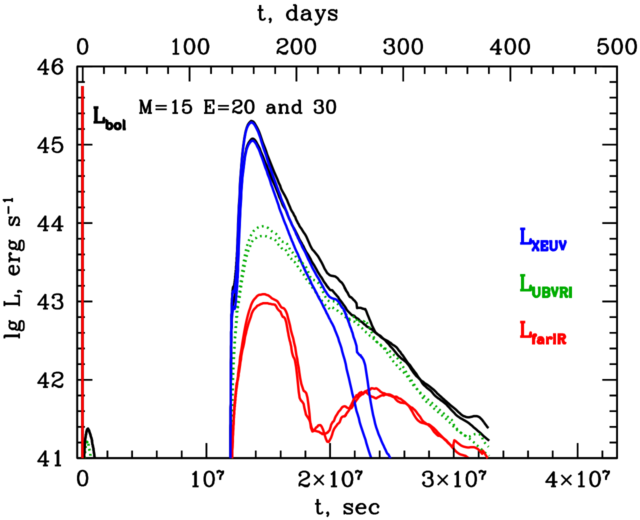
Effect of larger energy



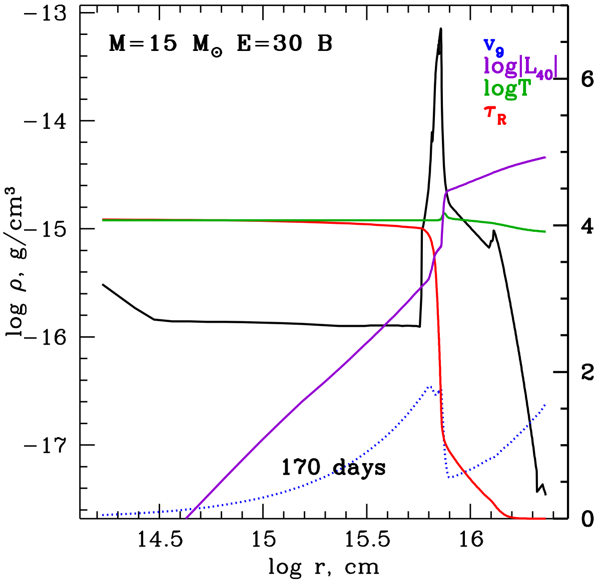
Effect of larger energy



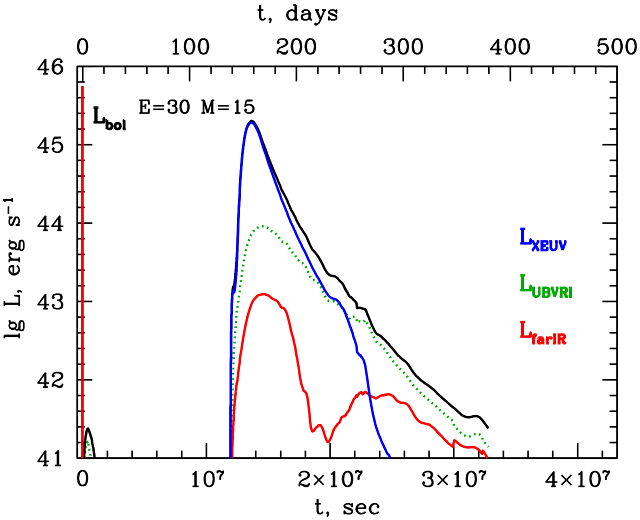
Effect of larger energy



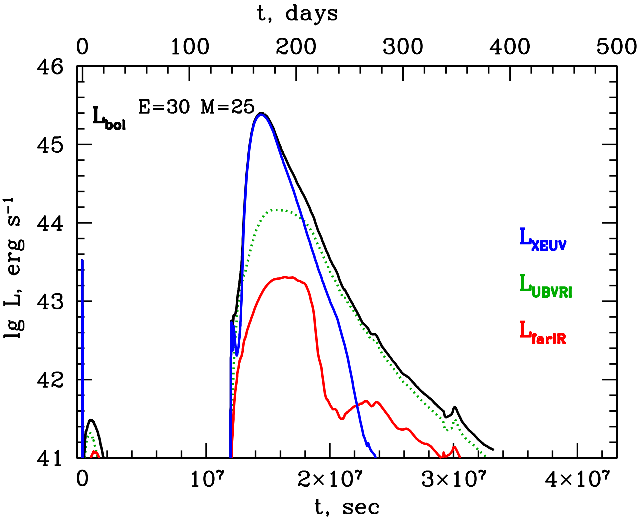
Radiation hydro profiles for high velocities, E=30 foe



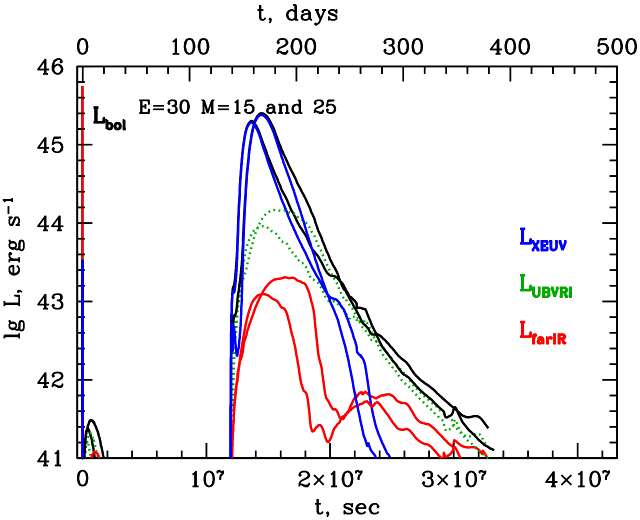
Effect of larger mass



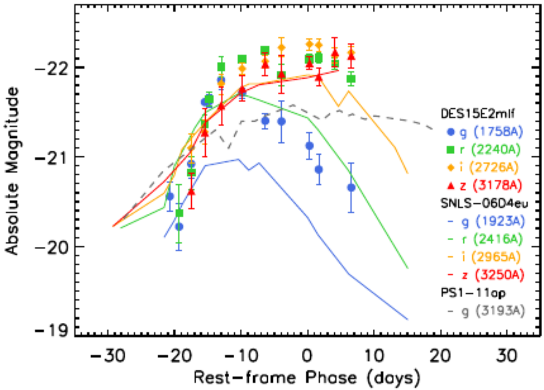
Effect of larger mass



Effect of larger mass



DES15E2mlf at z=1.86, Pan+ (2017)



LC in UV faster than in visible light (in restframe)

Conclusions

- 'Magnetar' model for Superluminous Supernovae (SLSNe) perhaps works if the central engine is an accreting magnetized NS, not an ejecting ms pulsar. It requires a lot of work before it will give reliable predictions. In any case, it seems to be useful for explaining tails on SLSN light curves.
- Models for SLSNe involving interaction with circumstellar matter are able to reproduce a broad class of SLSN light curves, but photospheric velocities are rather low for $E < 4$ foe.
- High photospheric velocities may be explained for $E \gtrsim 20$ foe, i.e. on the energy scale of hypernovae and GRBs.
- One should expect different behaviour in X-rays for low velocity SLSNe (like SNe IIn) and high velocity SLSN I.

Thank you!