Three ways to high emission of SLSN – Superluminous Supernovae

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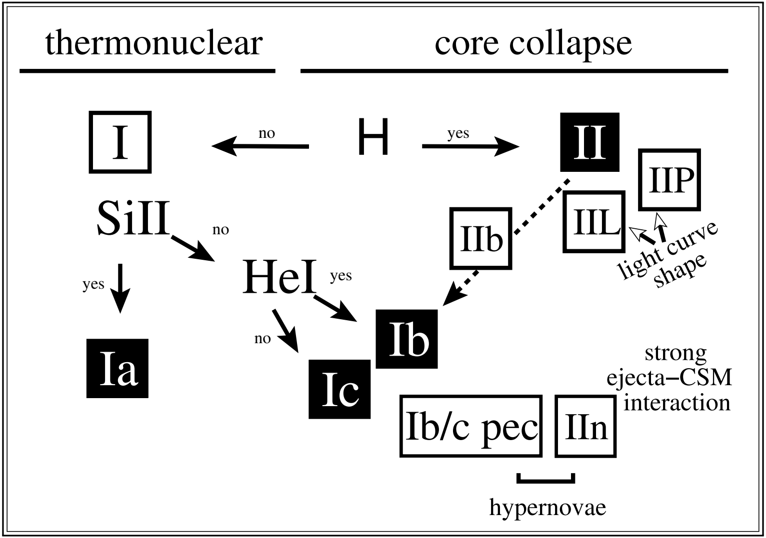
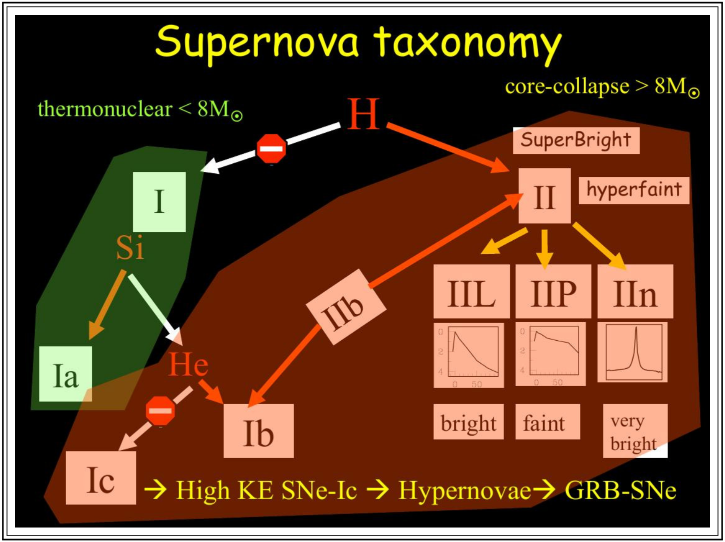
Supernova Classification by Turatto



SN taxonomy

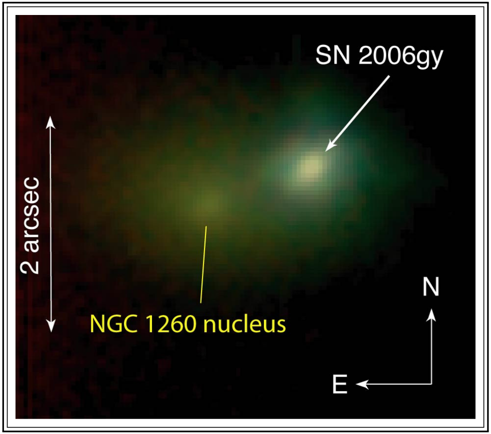

Supernova taxonomy
thermonuclear < 8M☉
core-collapse > 8M☉
H
SuperBright
I
II
hyperfaint
Si
IIL
IIP
IIn
IIb
Ia
He
Ib
Ic
bright
faint
very bright
→ High KE SNe-Ic → Hypernovae→ GRB-SNe

Supernova SN1994D in NGC4526

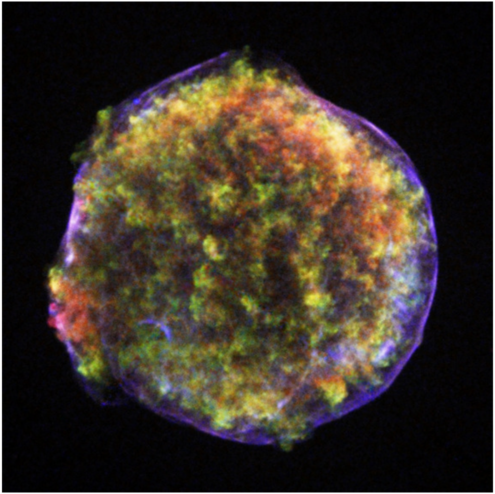
Shocks are not important for light in "Nobel prize" SNe Ia

SN 2006gy

Ofek et al. 2007, ApJL
Smith et al. 2007, ApJ
Shocks are vital for explaining light of those superluminous events for many months...



SNR Tycho in X-rays (Chandra)

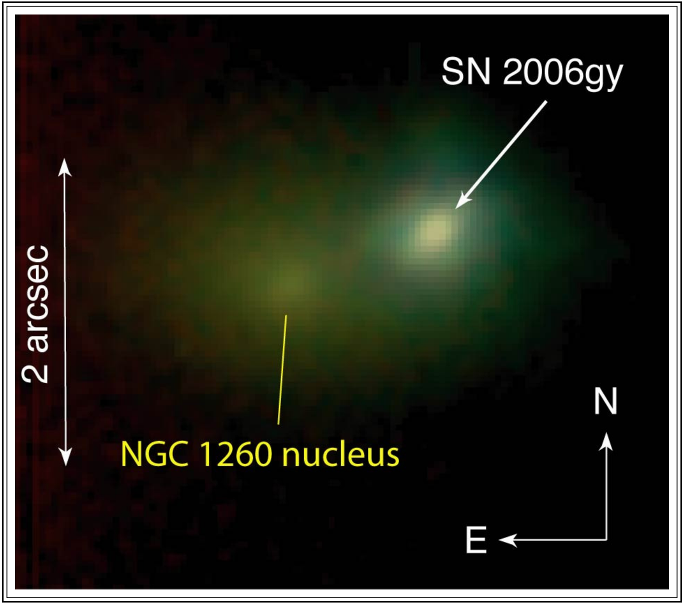


...and thousands of years in SNRs

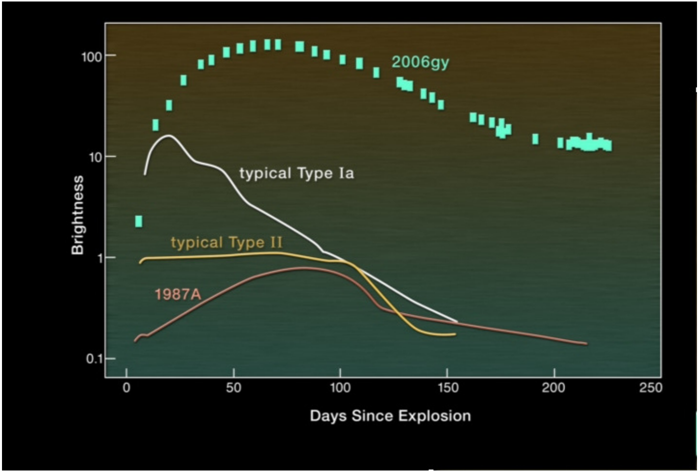
Supernovae: order of events

- Core collapse **(CC)** or explosion
- Neutrino/GW signal, accompanying signals
- Shock creation **if any**, propagation and entropy production inside a star
- Shock breakout (!)
- Diffusion of photons and cooling of ejecta

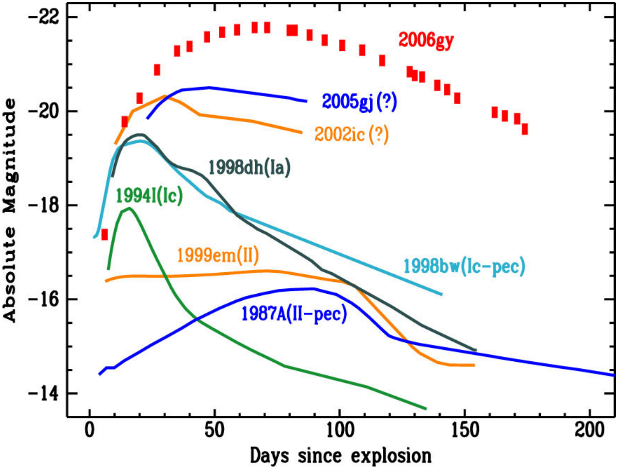
SN 2006gy and the nucleous of its host galaxy



2006: Brightest. Supernova. Ever (N.Smith)

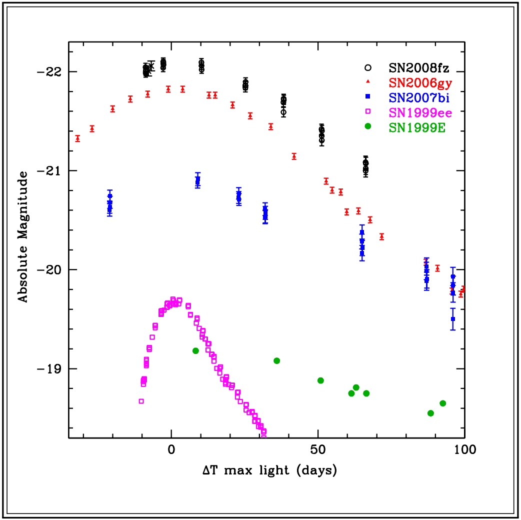


It used to be the Most Luminous SN in 2006, but not now



Now we have many SN events which are more luminous.

Extremely luminous Type IIn SNe

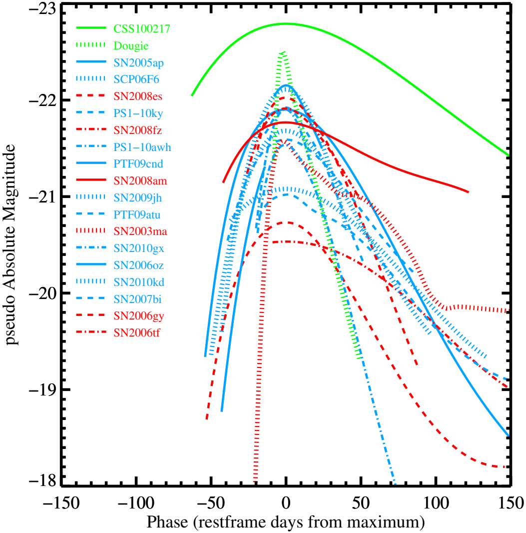


V-band
(Drake et al. 2010)

SN1987A and a typical SNII below the frame!

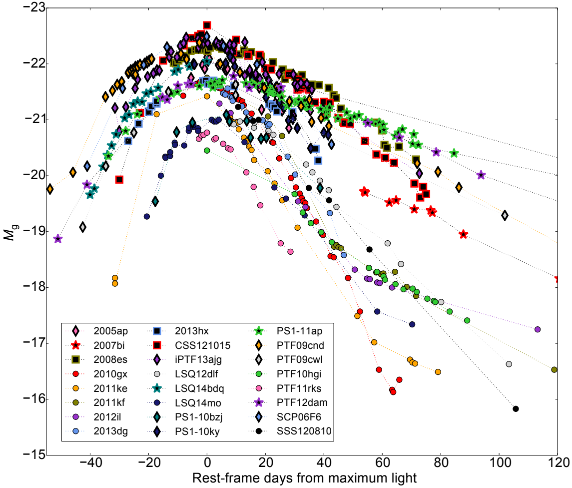
Wide range of super-luminous SNe

R.Quimby et al. 2013



Hydrogen-poor super-luminous supernovae

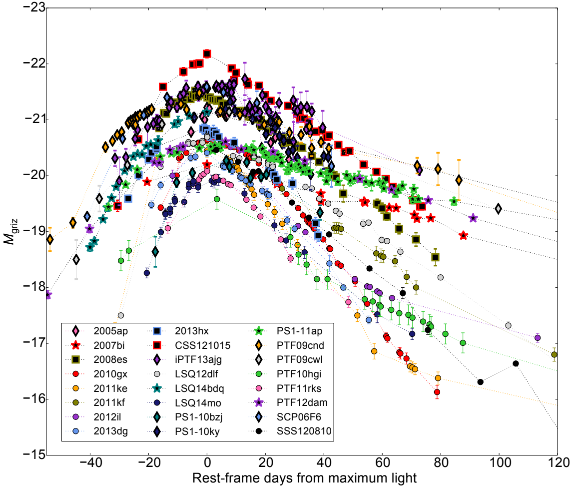
M.Nicholl et al. 2015
g-band light curves



Hydrogen-poor super-luminous supernovae

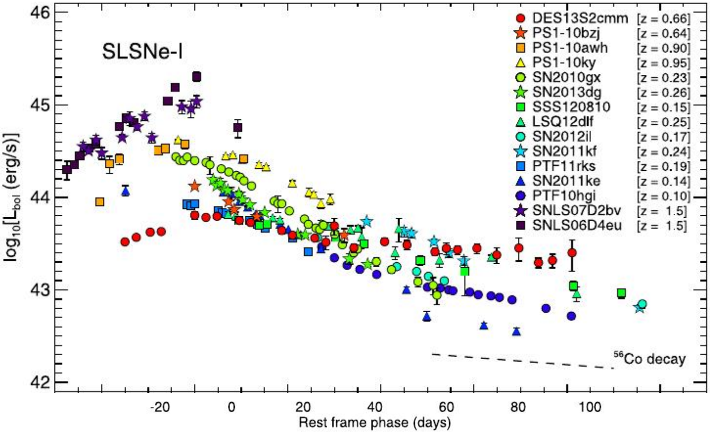
M.Nicholl et al. 2015

griz pseudobolometric light curves



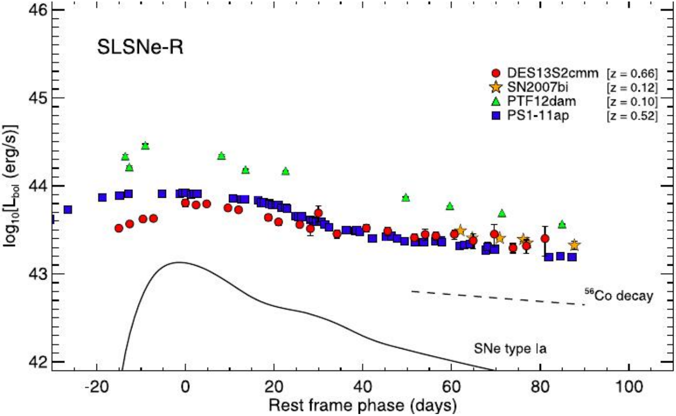
Another set and other units, SLSN-I

A.Papadopoulos et al. 2015



SLSN-R – slow decline

A.Papadopoulos et al. 2015

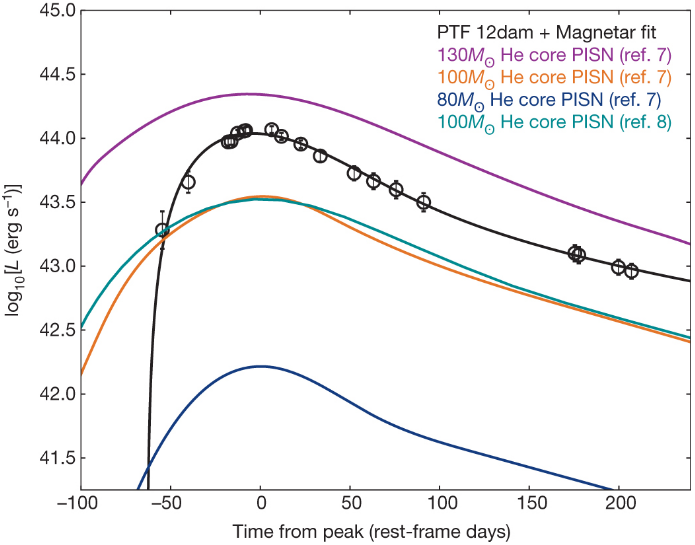


Three ways, i.e. three scenarios proposed for SLSNe

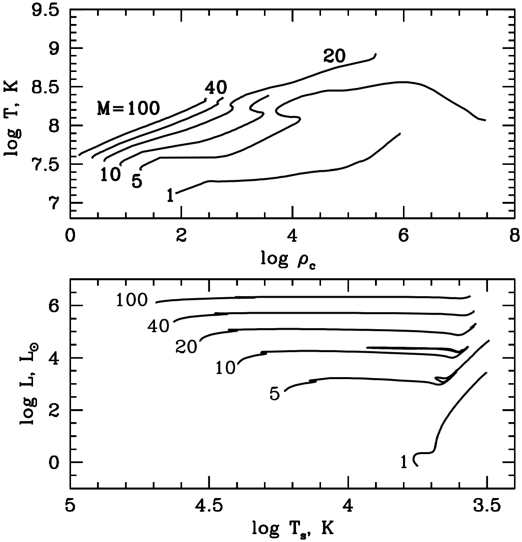
Those objects are called **SLSNe** – Superluminous Supernovae

- Pair instability Supernovae, **PISN**
- "**Magnetar**" pumping (taking in quotes, since observed magnetars are slowly rotating in SGRs, and here millisecond periods are needed)
- **Shock** interaction with CSM, e.g. Pulsational pair instability, **PPISN**

Bolometric light curve and “magnetar” fit for PTF 12dam, Nicholl’ea, 2013



A bit on stellar evolution



One can notice a trend: $T_c \propto \rho_c^{1/3}$.

Mechanical equilibrum

A very crude order-of-magnitude estimate for the attraction force of two halves of a star is

$$F \sim \frac{G_{\mathrm{N}} M^2}{4R^2},$$

this force must be balanced by a gradient of pressure P.
On the surface P is virtually zero, and in the center

$$P_c = \frac{F}{S} = \frac{F}{\pi R^2}.$$

Central Pressure

Omitting all coefficients of order unity, pressure and density in the center are:

$$P_c \simeq \frac{G_{\mathrm{N}} M^2}{R^4},$$

$$\rho_c \simeq \frac{M}{R^3},$$

and we find

$$\boldsymbol{P_c \simeq G_{\mathrm{N}} M^{2/3} \rho_c^{4/3}}.$$

On hydrodynamical instability

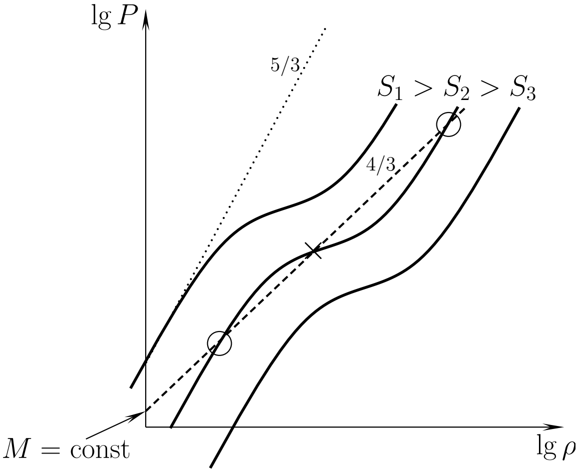
Equilibrium requires (in Newtonian gravity):

$$P_c \simeq G_{\mathrm{N}} M^{2/3} \rho_c^{4/3}.$$

This implies that adiabatic exponent $\gamma < 4/3$ may lead to a hydrodynamical instability.

Hydrodynamical stability

Mechanical stability



Relativistic particles lead to $\gamma \to 4/3$

We have $\gamma \sim 4/3$ due to high entropy S (photons and e^+e^- pairs).
At low $S \to 0$ we have $\gamma \to 4/3$ due to high Fermi energy of degenerate electrons at high density ρ.

$T_c \propto M^{2/3}\rho_c^{1/3}$ in non-degenerate stars

So if we have a classical ideal plasma with

$$P = \mathcal{R}\rho T/\mu,$$

where $\mathcal{R}$ is the universal gas constant, and μ – mean molecular mass,

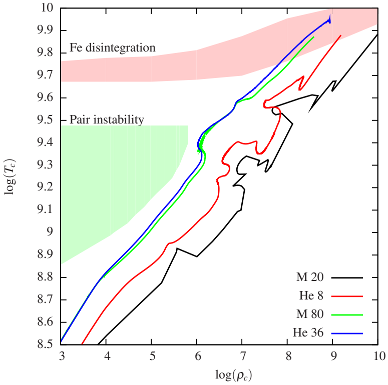
$$T_c \simeq \frac{G_{\mathrm{N}} M^{2/3} \rho_c^{1/3} \mu}{\mathcal{R}}.$$

Thus,

$$\boldsymbol{T_c \propto \rho_c^{1/3}}$$

The same 1/3 power for radiation-dominated massive stars (but with $M^{1/6}$).

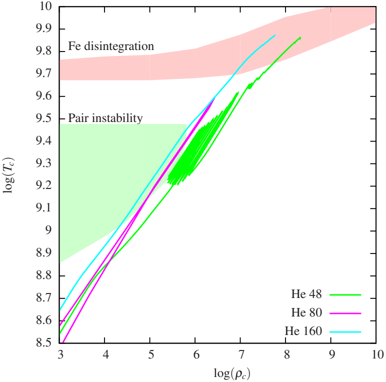
Massive stars and their He-cores



Each line is labeled “M” for stellar models and “He” for He-core models, followed by the mass of the model or of the core. Here are stars that reach core collapse avoiding pair instability.

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).

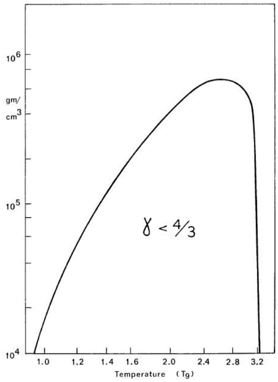


Pairs in Stellar Stability

Bisnovatyi-Kogan, G. S., Kazhdan, Y. M. 1967. Critical Stellar Parameters. Soviet Astronomy 10, 604.

Gary S. Fraley 1968. Pair-instability SNe

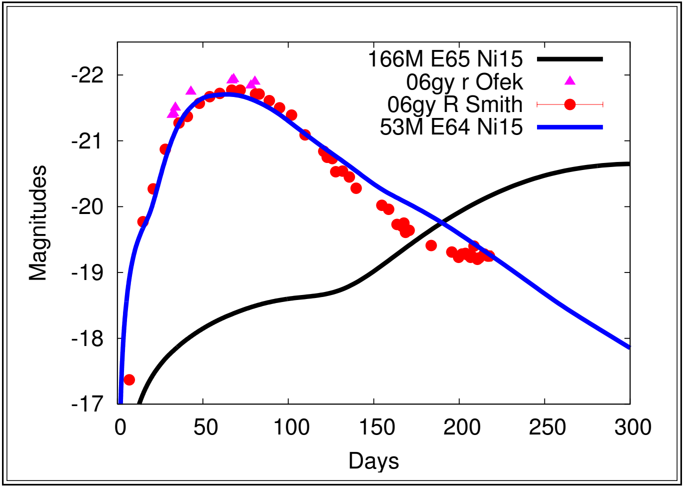
SUPERNOVAE EXPLOSIONS INDUCED BY PAIR-PRODUCTION INSTABILITY



The area in which γ becomes less than $\frac{4}{3}$ due to electron-positron pair production

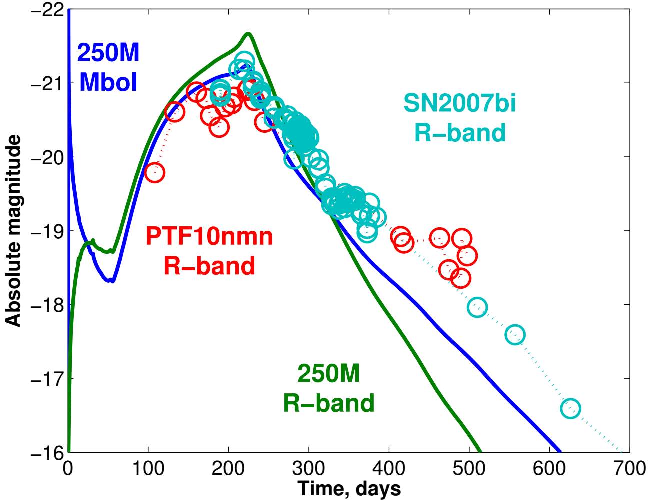
Pair Instability Supernova = PISN

K. Nomoto, N. Tominaga, M. Tanaka, K. Maeda, H. Umeda, 2007



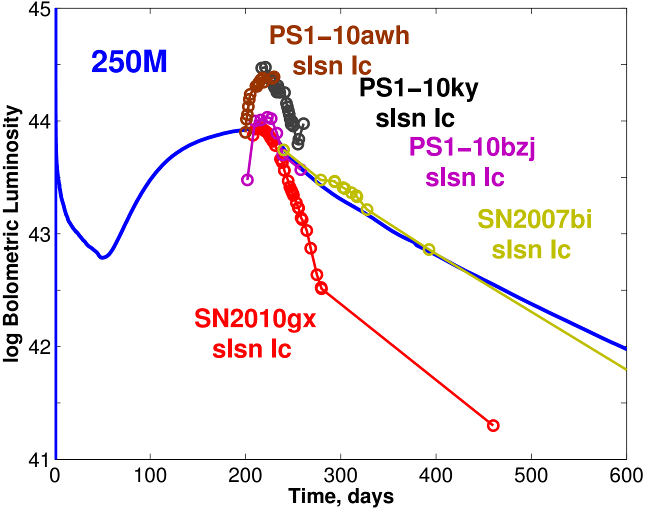
Huge mass must be stripped, large energy and ^{56}Ni mass.
Predicted velocity too high for SNIIn.

PISN: A. Kozyreva, SB, Langer, Yoon, 2014



$M_{\rm in}/M_{\rm f} = 250/169$, $E_{\rm expl} = 70$, $E_{\rm kin} = 44$, Mass of ^{56}Ni $= 19 M_{\odot}$

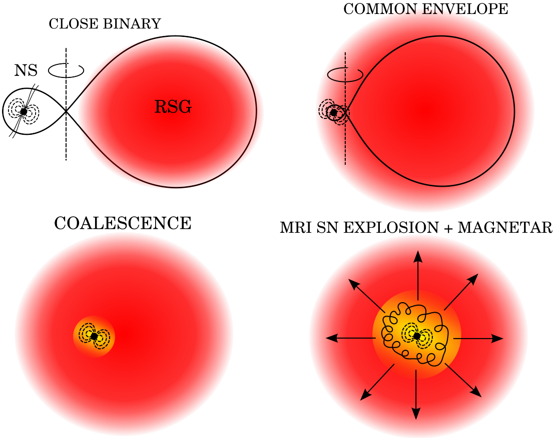
PISN: A. Kozyreva, SB, Langer, Yoon, 2014



It is clear that some SLSNe are not PISN.

“Magnetar” Powered Supernova

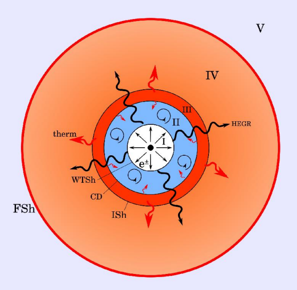
Scenario outline

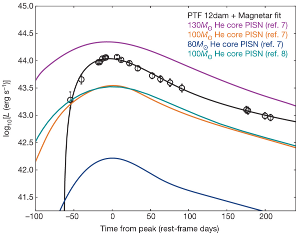


Barkov M.V. & Komissarov S.S., *Mon.Not.Roy.Astron.Soc.*, 2011, **415**, pp.944-958

"Magnetar" Powered Supernova

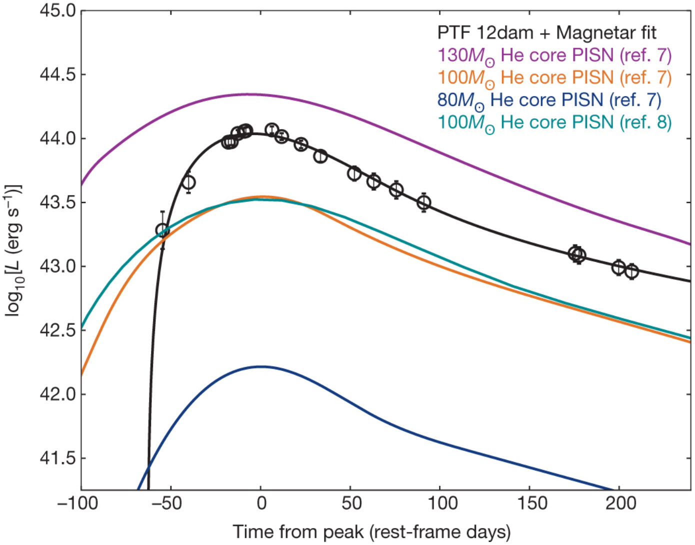
- $E_{\rm rot} = \frac{1}{2} I \Omega^2 \sim 10^{52}$ erg
- $E_{\rm burst} \approx 3 - 10 \cdot 10^{51}$ erg,
  $L_{\rm rot} = 3 \cdot 10^{45} \left(1 + \frac{t}{10^5 s}\right)^{-2.1} \frac{\text{erg}}{\text{s}}$
- Magnetized wind $e^{\pm}$ $(\Gamma > 1000) \Rightarrow e^{\pm} + B$ – synchrotron, or $e^{\pm} + h\nu_{\rm therm} \to \gamma$ 100 keV – Compton, 10 TeV $\Rightarrow \gamma + e^{-}$ or $\gamma + h\nu_{\rm therm} \to$ 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, **502**, pp.346-349)
- **But!** This must be checked in detail...

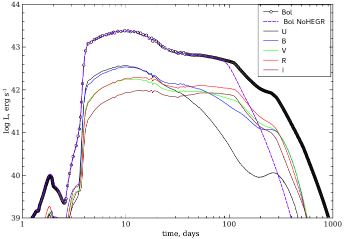
Bolometric light curve and “magnetar” fit for PTF 12dam, Nicholl’ea, 2013



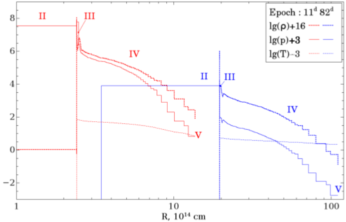
Badjin, Barkov: $15M_{\odot}$, 3 foe: thermal emission

- The optimism of the community is premature
- Magnetar manifests itself only on the “tail” – only for the latest epochs (> typical time-scale of ^{56}Ni→^{56}Co→^{56}Fe$\sim 10^2$ days.)
- The most efficient heat source is photo-production of pairs in the thermal background. While the shell (III and IV) is not quite as cold, its thermal background traps γ -rays in the wind (II) and does not allow it to, after that - it is transparent and weakly absorbing. The energy of γ-rays heats up not the shell, but the lepton plasma of the wind and this energy is spent for work on its expansion rather than the thermal radiation of the gas
- Near the contact of the wind and the matter ($II - III$) a dense radiative layer is formed

luminosities



profiles ρ, p, T



Why the primitive “magnetar” does not work?

A more detailed consideration (in comparison with simple deposition – vsazhivaniem – 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 great pair-creation opacity for gamma-rays and hence prevent them to enter 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.

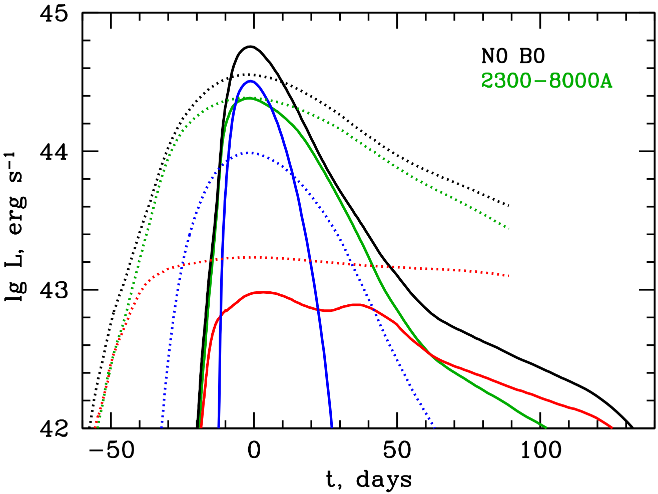
Not into luminosity!

We are able to reproduce the range of SLSNe in shock interaction with CSM models with **modest energy**

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, but first let us overview briefly alternatives.

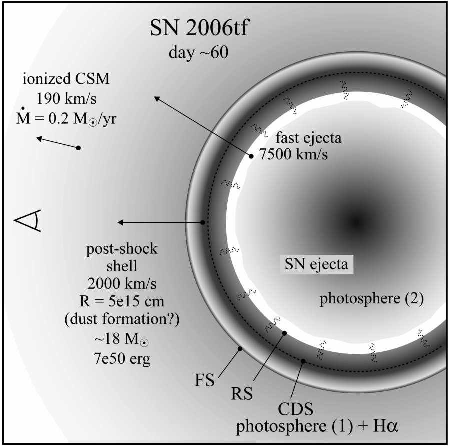
STELLA reproduces the range of SLSN in shock model: 2 extreme cases

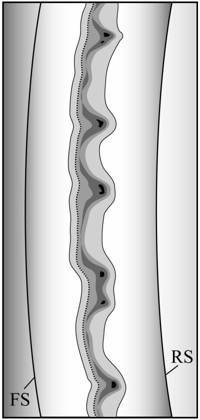


Explosion energy is just 2 - 4 foe

Radiative shock waves: a powerful source of light in SLSNe. Cold Dense Shell

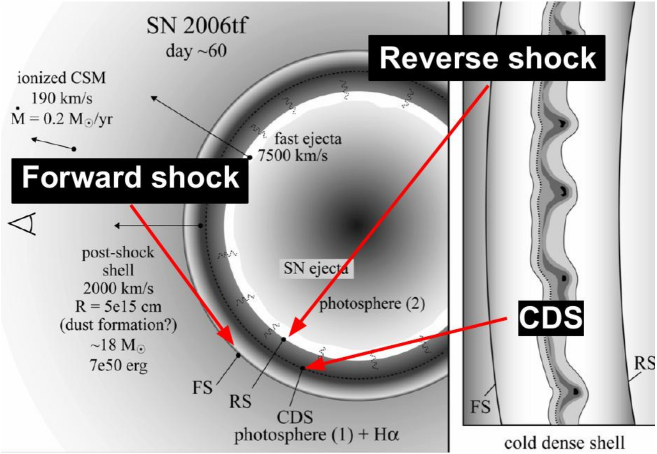
A cartoon:





cold dense shell

Radiative shock waves: a powerful source of light in SLSNe. Cold Dense Shell



Baklanov et al. PTF12dam

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Original Russian Text © P.V. Baklanov, E.I. Sorokina, S.I. Blinnikov, 2015, published in Pis'ma v Astronomicheskiĭ Zhurnal, 2015, Vol. 41, Nos. 3–4, pp. 113–122.

Hydrogenless Superluminous Supernova PTF12dam in the Model of an Explosion inside an Extended Envelope

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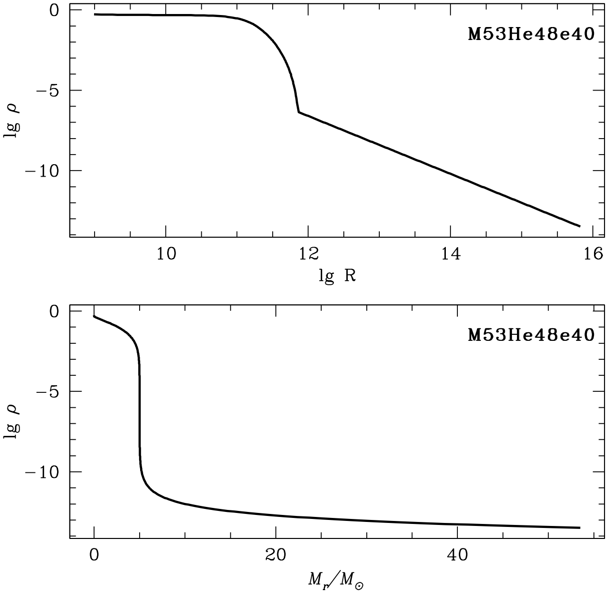
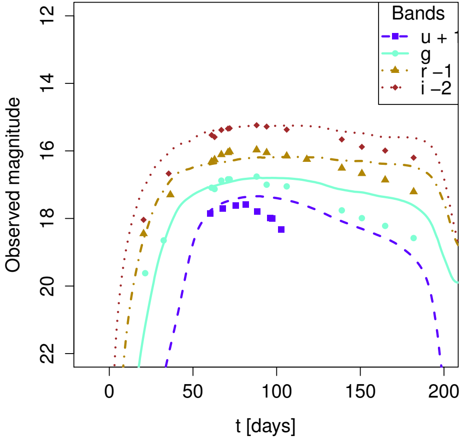
Assumed preSN and “wind” structure

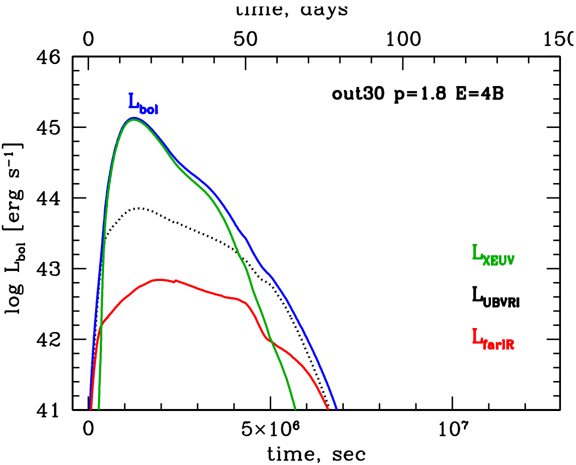


Simulated a



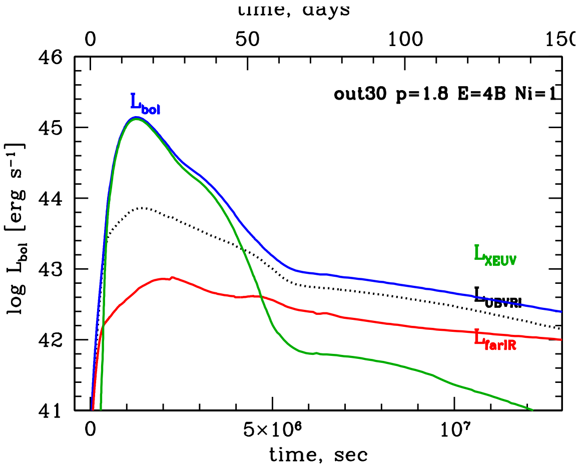
Ejecta 5 $M_\odot$, “wind” 48 $M_\odot$ of He, explosion 4 foe. Perhaps not He, but C/O, and larger mass may be needed for long “tail”. Here radioactive heating may help.

^{56}Ni vs. Shock wave heating



no ^{56}Ni

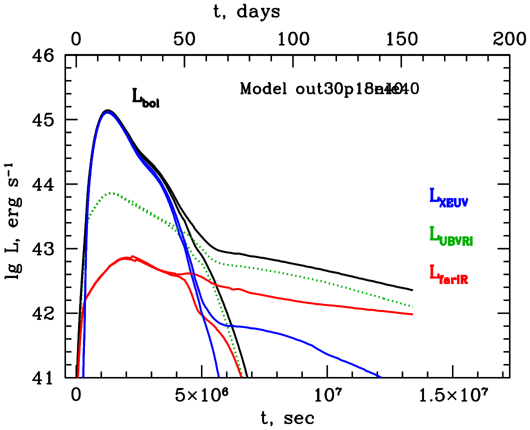
^{56}Ni vs. Shock wave heating



$M(^{56}\text{Ni}) = 1 M_\odot$ in the ejecta

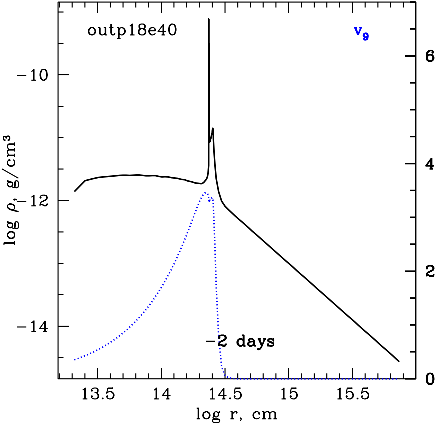
^{56}Ni vs. Shock wave heating

2 previous plots combined

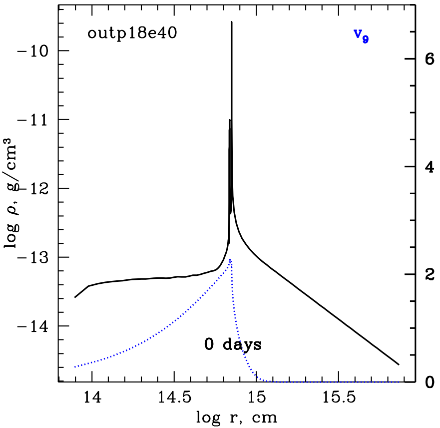


$M(^{56}\mathrm{Ni}) = 1 M_\odot$ added to the ejecta

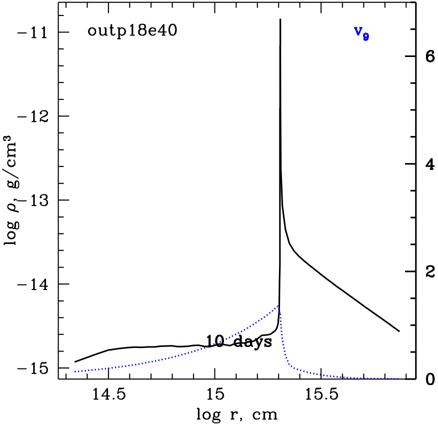
Long Living Dense shells-1 Sorokina et al.



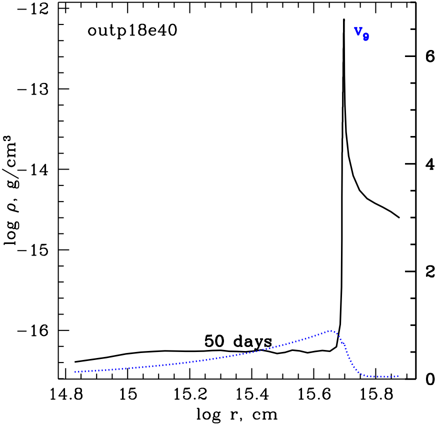
Long Living Dense shells-2 Sorokina et al.



Long Living Dense shells-3 Sorokina et al.



Long Living Dense shells-4 Sorokina et al.



How would behave thin shells in 3D reality?

In general, there may be **instabilities**, destroying the picture.
How do they affect the production of light?

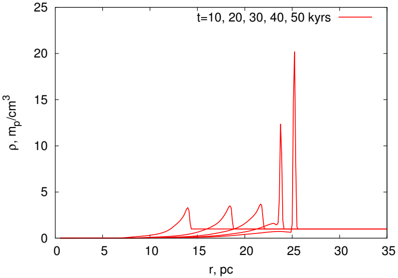
Therefore, we begin a multidimensional program of study of those shells.

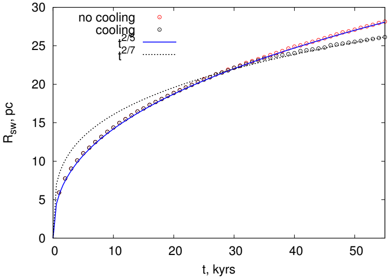
For a while we use an Eulerian approach in our 2D and 3D simulations.

For simplicity, we consider first not the SLSNe, but Supernova Remnants, SNRs, at a stage of *catastrophic cooling* when similar thin dense shells are formed.

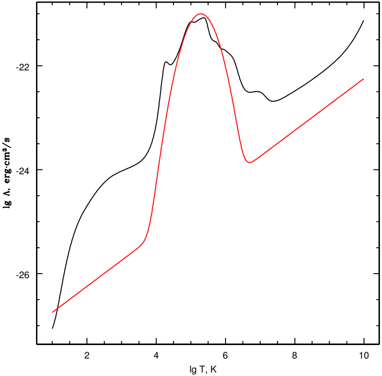
Strong radiating shock in SNR

- Radiative cooling in optically thin medium ($\tau \ll 1$)
- Density jump develops $\rho_2/\rho_1 \gg (\gamma+1)/(\gamma-1)$
- The solution for $R(t)$ goes from Sedov $\propto t^{2/5}$ to the radiative one $\propto t^{2/7}$



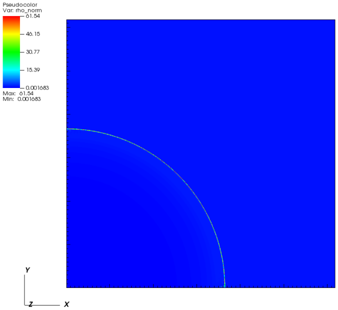


The shape of cooling function

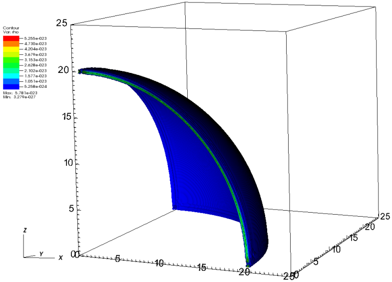


Dependence of cooling function on temperature. Red line is approximation by Straka, and the black one – T.Plewa based on the CLOUDY package.

2D and 3D simulations



Density at $t = 41 \times 10^3$ yrs. Grid 1600x1600, FRONT3D.



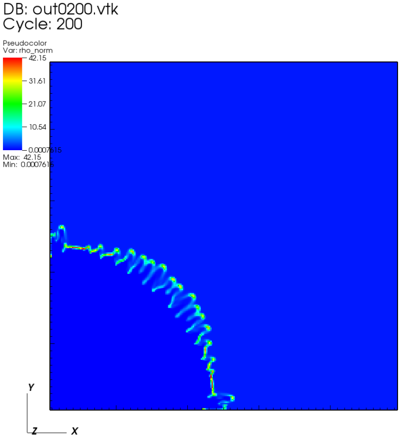
3D simulations. Density at $t = 40 \times 10^3$ yrs. Grid 512^3, FRONT3D.

Radiative shock in 2D

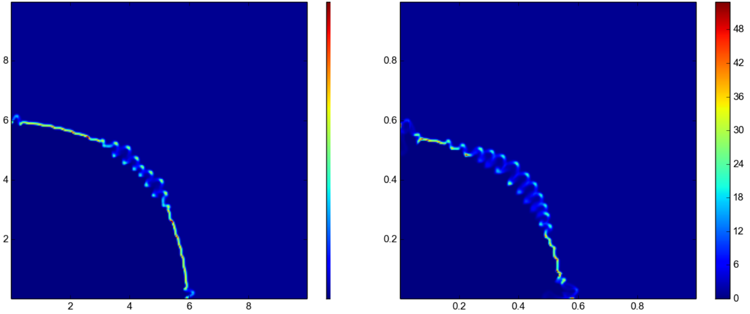
Instability develops due perturbations induced by the Cartesian grid.

Spherical symmetry is not destroyed in $R - \phi$ grid!

Initial density 1 baryon/cm^3, and the size is 80 pc. Simulations by FRONT3D.



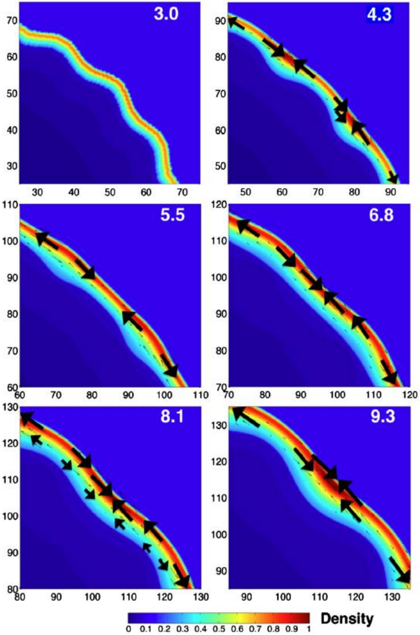
Simulations by PLUTO4



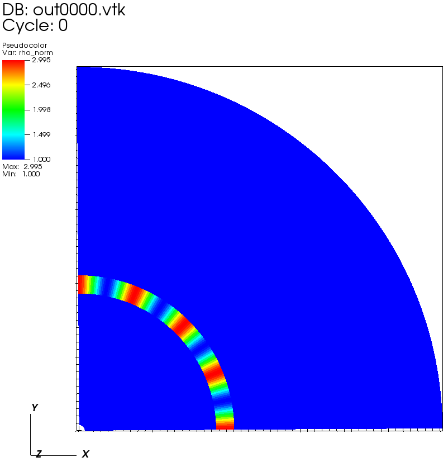
Grid 256x256 for CLOUDY cooling function $n_0 = 1$, $\gamma = 5/3$, left, and $n_0 = 10$, $\gamma = 1.4$, right.

Vishniac Instability?

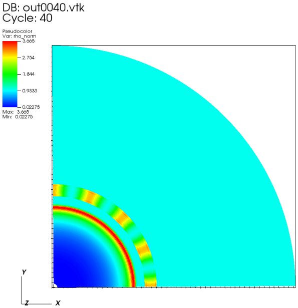
The Astrophysical Journal, 759:78 (16pp), 2012 November 10 Michaut et al.

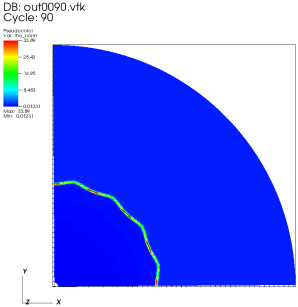


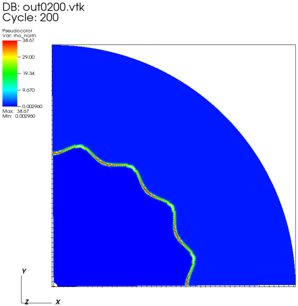
Regular perturbations of initial density

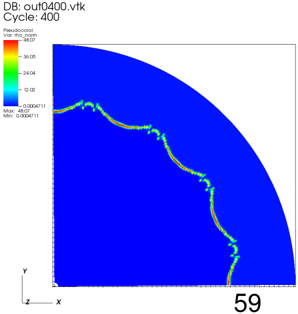


Vishniac instability does not develop (grid $R - \phi$)









Conclusions

- Radiative Shock model is most promising for the variety of SLSNe. Problems appear with this model if high velocity is measured on photosphere.
- Instability of thin shells between radiative shock waves develops in the presence of the grid-induced or physical disturbances.
- The character of instability does not correspond to oscillatory pattern of Vishniac instability (overstability), but rather to a thermal instability.
- For the conditions of superluminous supernovae (SLSN) an accurate accounting of radiative transfer is needed for the investigation of the instability of the shell.
- It is interesting to conduct simulations in a Lagrangian scheme, since Eulerian schemes understate the density contrast in thin layers.

Thank you!