THE UNIVERSITY OF TOKYO

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Superluminous Supernova Models: from X-ray to near-infrared photometry

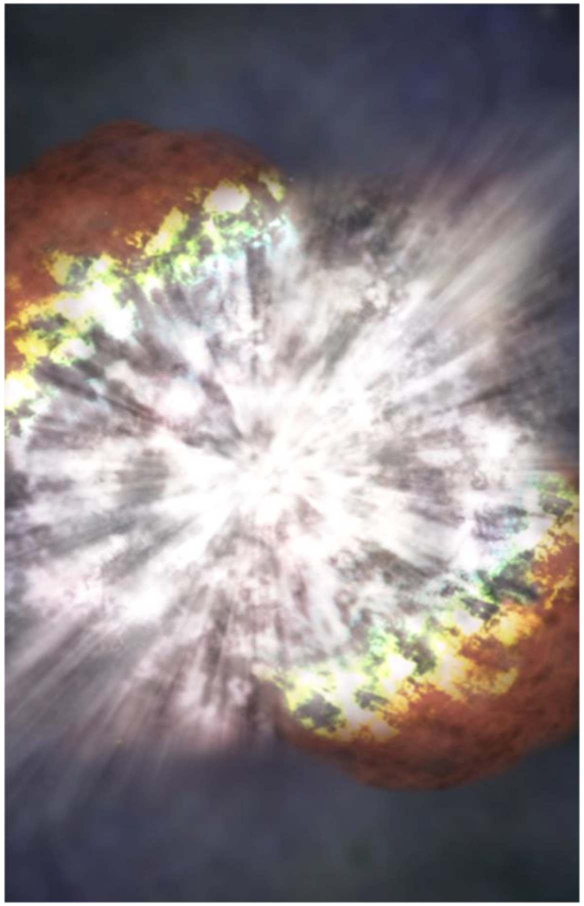
Alexey Tolstov (Kavli IPMU)

Ken'ichi Nomoto (Kavli IPMU)
Sergey Blinnikov (ITEP, Kavli IPMU)
Elena Sorokina (SAI MSU)
Andrey Zhiglo (NSC KIPT, Kavli IPMU)
Robert Quimby (SDSU, Kavli IPMU)
Petr Baklanov (ITEP)
Alexandra Kozyreva (TAU)

Ringberg Workshop on the Progenitor-Supernova-Remnant Connection, July 2017

Outline

- Radiation hydrodynamics simulations of SLSN-I outbursts
- Slow-to-fade SLSN PTF12dam
- Extremely bright in UV SLSN Gaia16apd (M_{UV} ~ -23 mag)
- Multicolor light curves (from X-rays to NIR), color evolution, photospheric temperature and velocity evolution. The influence of opacity, metallicity of CSM
- Constraints on SLSN-I scenarios

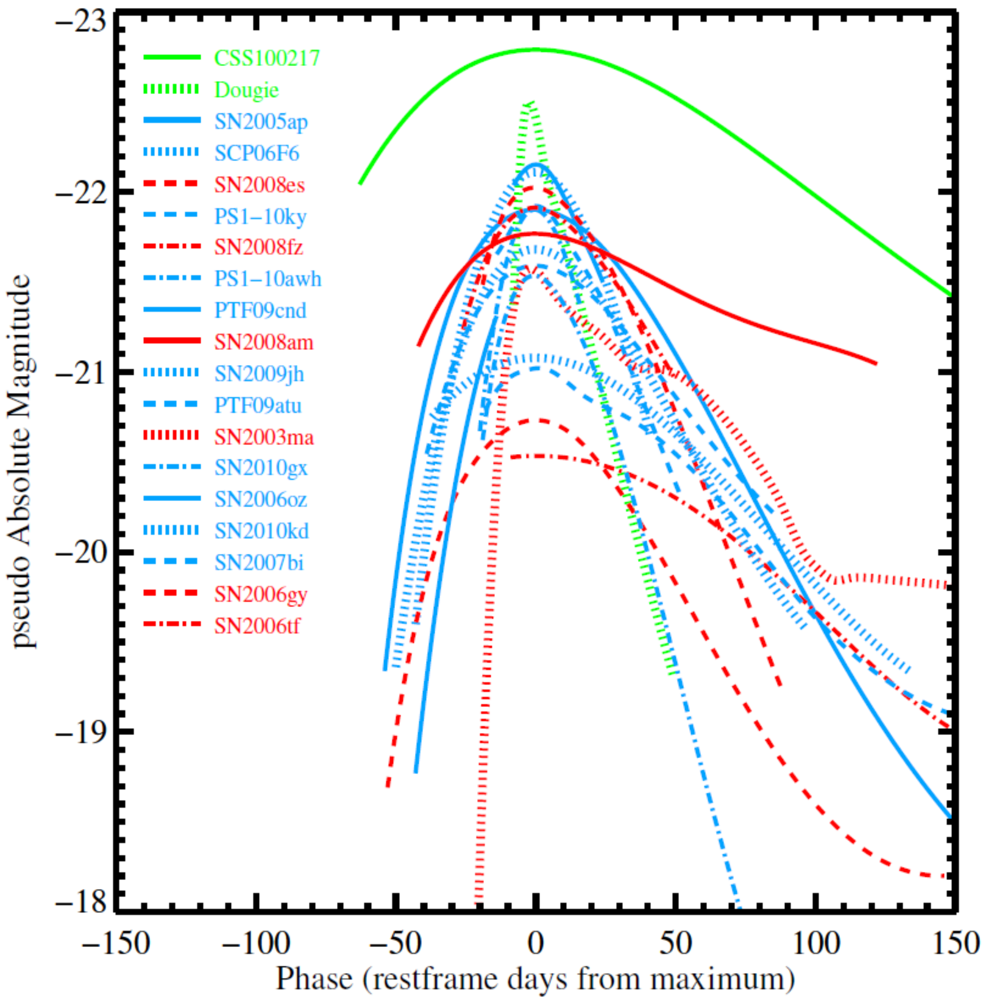


(Image credit: NASA)

Scenarios proposed for SLSN-I (Type I, Type II)

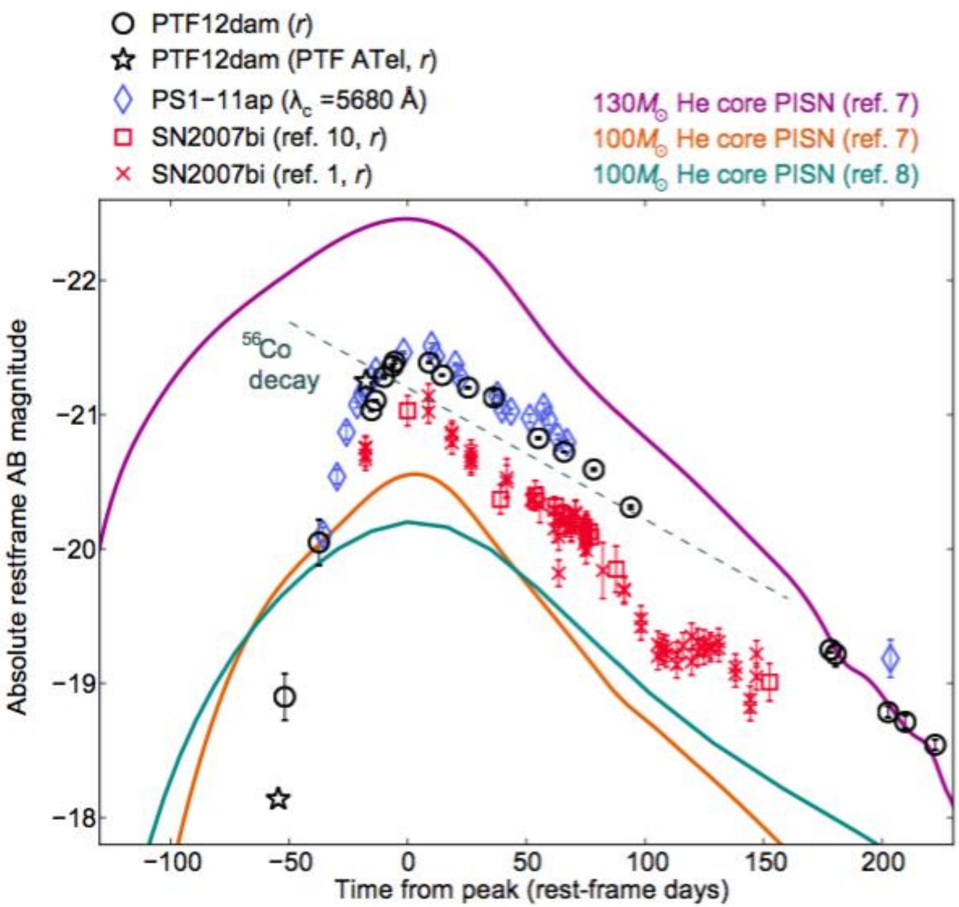
- Pair Instability Supernovae (PISN)
- "Magnetar" pumping (taking in quotes, since observed magnetars are slowly rotating in SGRs, are here millisecond periods are needed)
- Shock interaction with CSM, e.g. Pulsational pair instability (PPISN)

R.Quimby et al. 2013

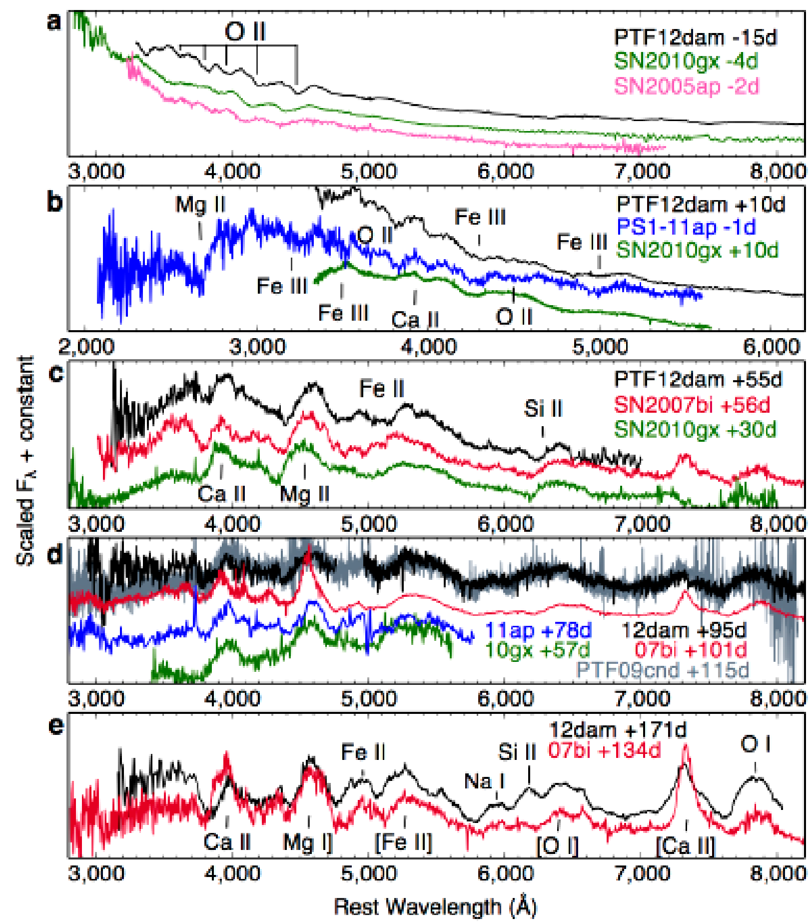


SLSN-I PTF12dam: light curves and spectra

- Optical light curves of slow-fading SLSN (Nicholl et al. 2013)

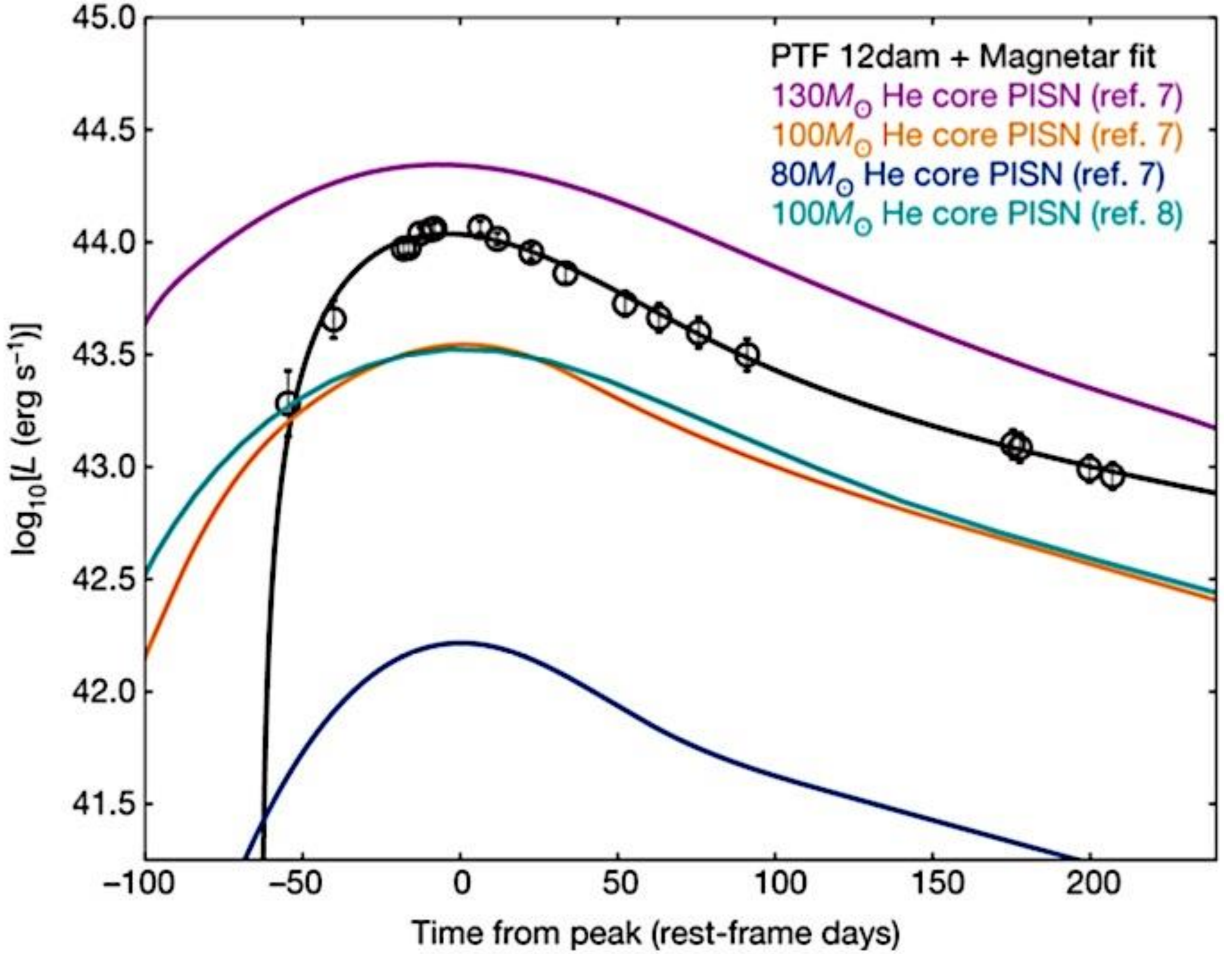


- Spectral evolution of PTF12dam (Nicholl et al. 2013), lack of hydrogen/helium



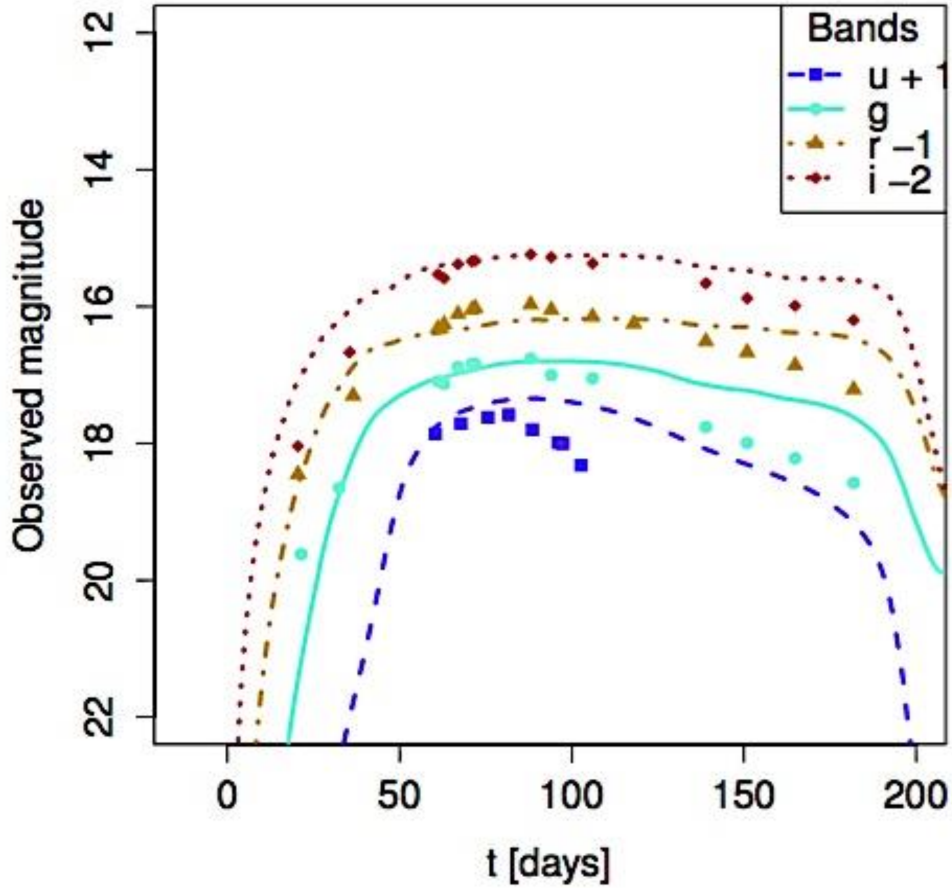
PTF12dam: bolometric light curves and "magnetar" fit

(Nicholl et al. 2013)



- "Magnetar" fits are based on oversimplified models.
- The spin-down energy is converted into shell kinetic energy – **Not into luminosity!** (Badjin, Barkov, Blinnikov, in prep)

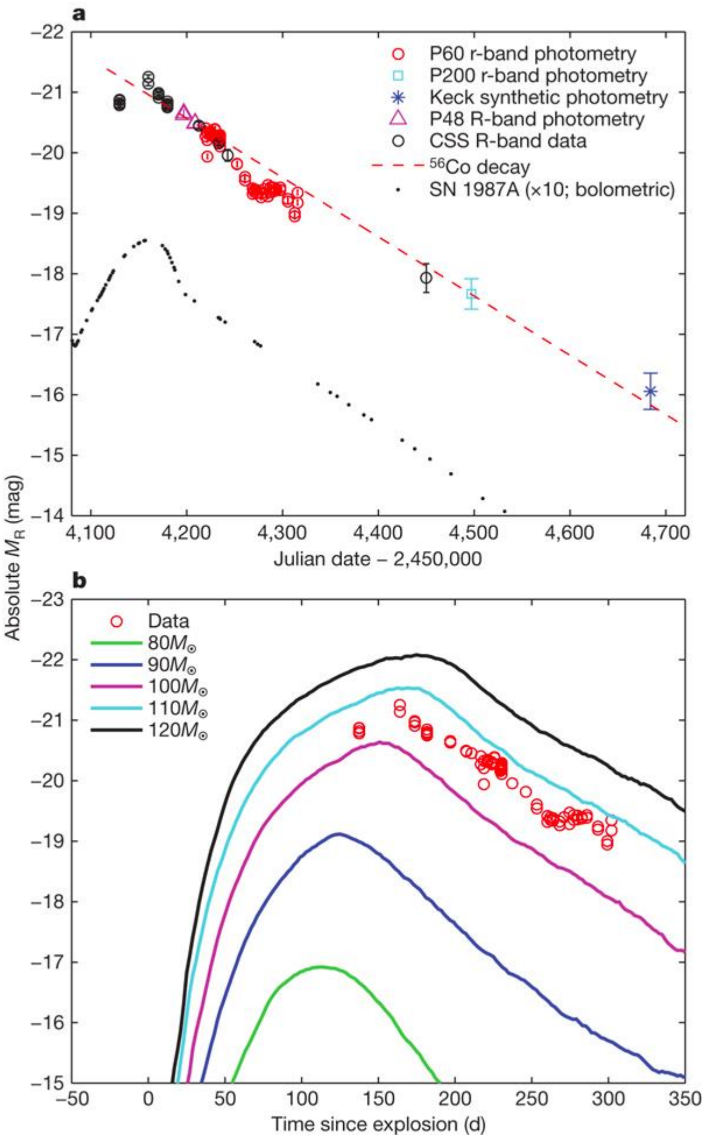
Simulated and observed light curves (Baklanov et al. 2015)



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.

SN 2007bi: PISN, CCSN models

- Gal-Yam et al. 2009



- Moriya et al. 2010

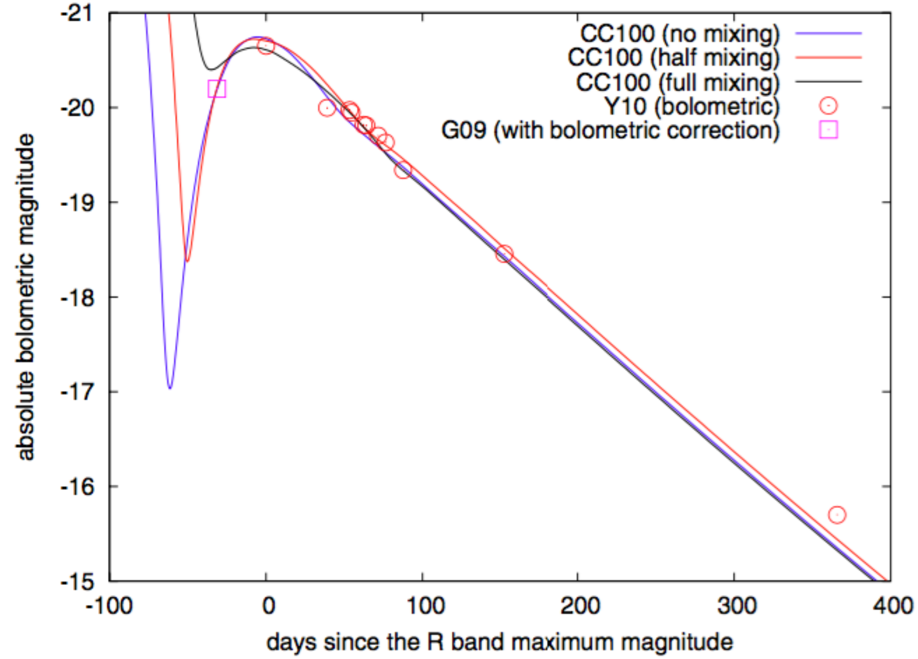
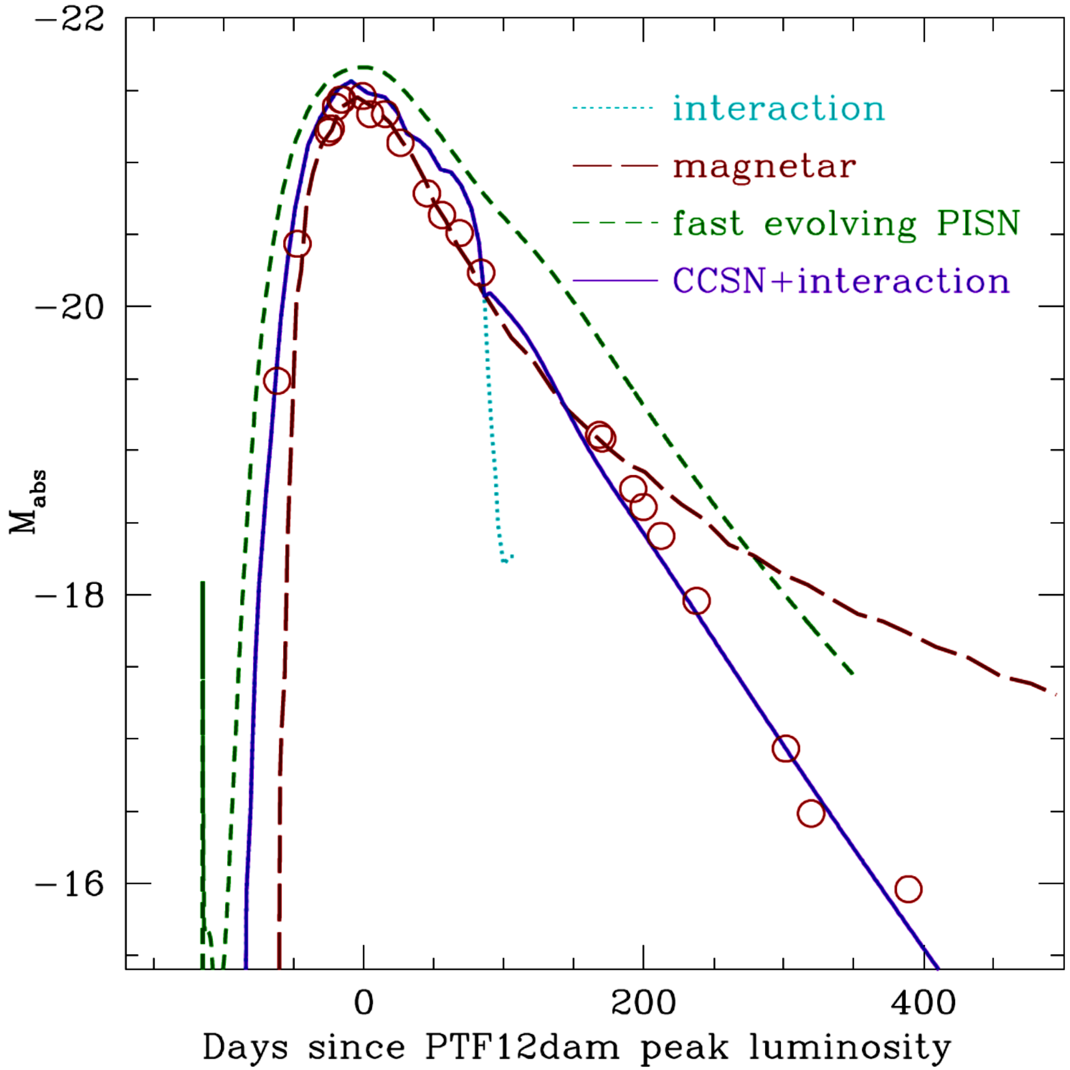


Figure 1. Bolometric LCs of the C+O star SN models CC100 ($M_{ej} = 40\ M_\odot$, $E_{kin} = 3.6 \times 10^{52}$ erg, and $M_{^{56}Ni} = 6.1\ M_\odot$). The observed bolometric LC (open circles) is taken from Y10. The bolometric magnitude of the rising part of SN 2007bi (open square) is estimated from the *R*-band magnitude. All the calculated LCs have the same physical structure but the degrees of mixing are different. The horizontal axis shows the days in the rest frame.

Figure 2: Radioactive ^{56}Ni and total ejected mass from the light-curve evolution of SN 2007bi are well fitted using PISN models.

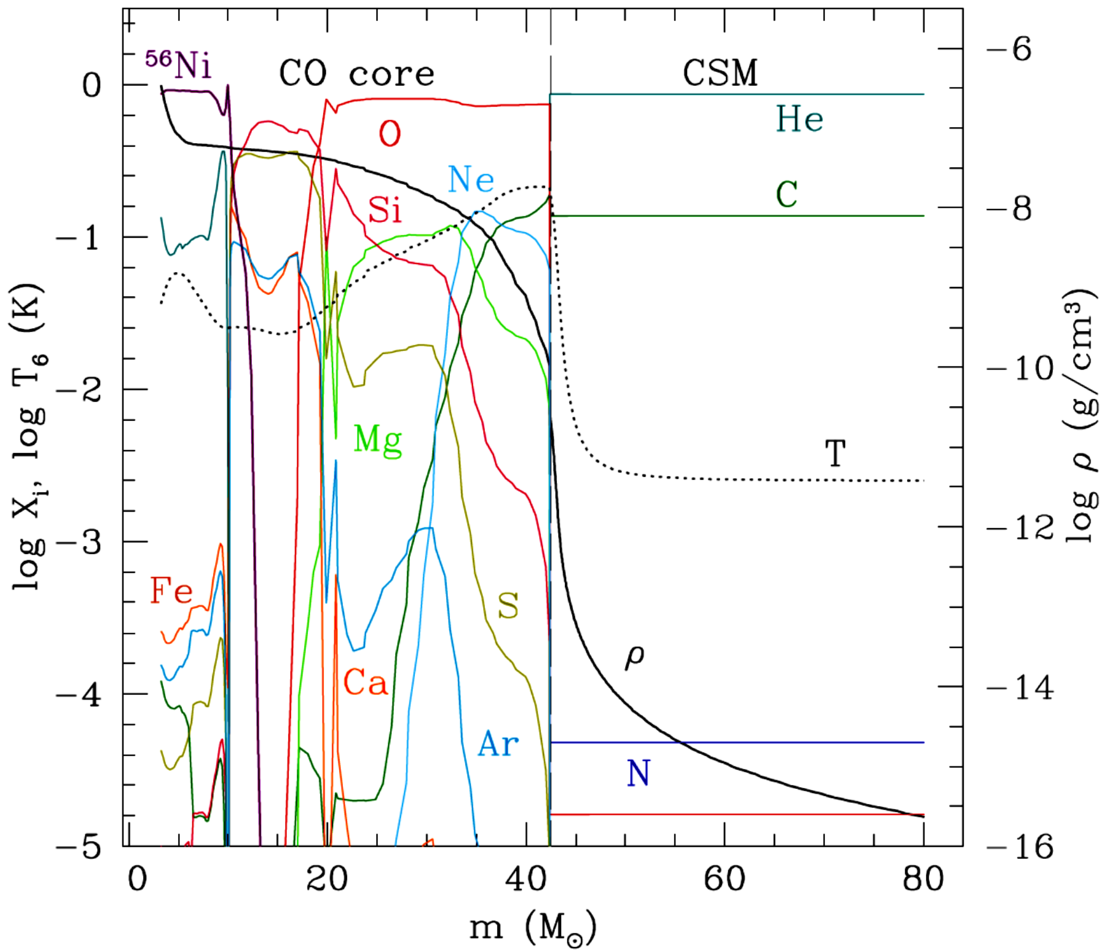
PTF12dam: PISN, CCSN models



- Bolometric light curves of PTF12dam in observations and models (Chen 2014, Nicholl et al 2013, Kozyreva 2017, Baklanov et al 2015)

PTF12dam: composition and structure

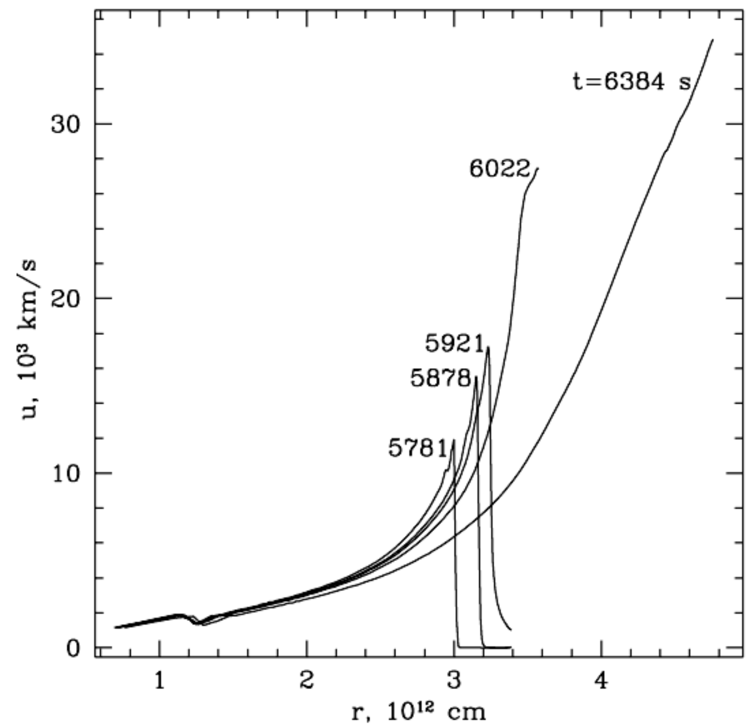
- M_{ZAMS}=100 $M_{\odot}$, Z = $Z_{\odot}$/200
- PTF12dam: pre-SN C+O core (43$M_{\odot}$), M_{cut} =3$M_{\odot}$
- Postprocess explosive nucleosynthesis (used by Moriya et al. (2010) for SN 2007bi)
- 1 day hydro after explosion + extended CSM
- Parameters: M_{CSM}, R_{CSM}, T_{CSM}, M(^{56}Ni), composition of CSM



Numerical code STELLA

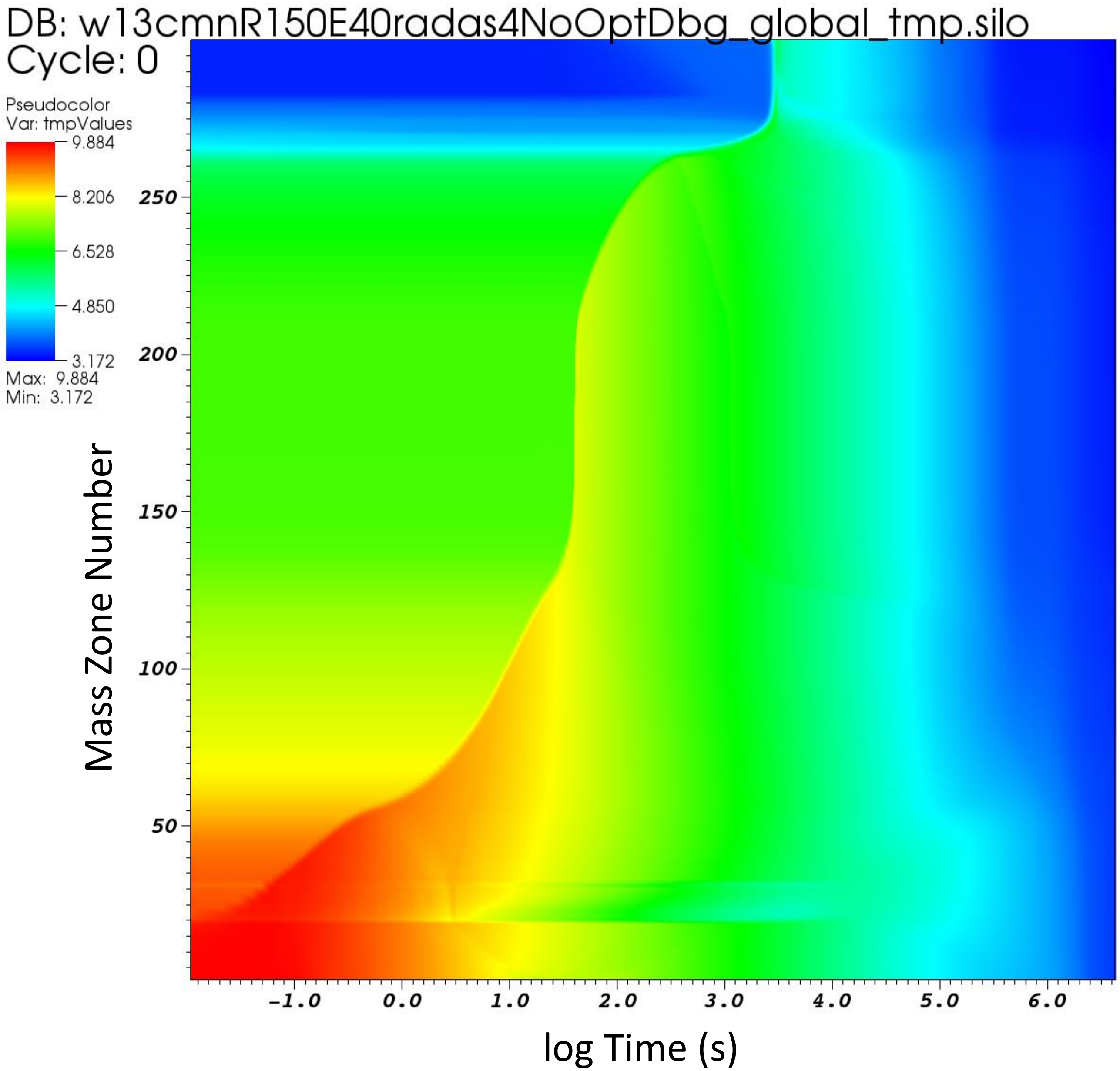
STELLA (STatic Eddington-factor Low-velocity Limit Approximation) (Blinnikov et al. 1998)

- 1D Lagrangian Hydro + Radiation Moments Equations, VEF closure, multigroup (100-300 groups, up to 1000), implicit scheme
- Opacity includes photoionization, free-free absorption, lines and electron scattering (Blandford, Payne 1981). Ionization – Saha's approximation
- STELLA was used in modeling of many SN light curves: SN 1987A, SN 1993J and many others (Blinnikov et al. 2006)



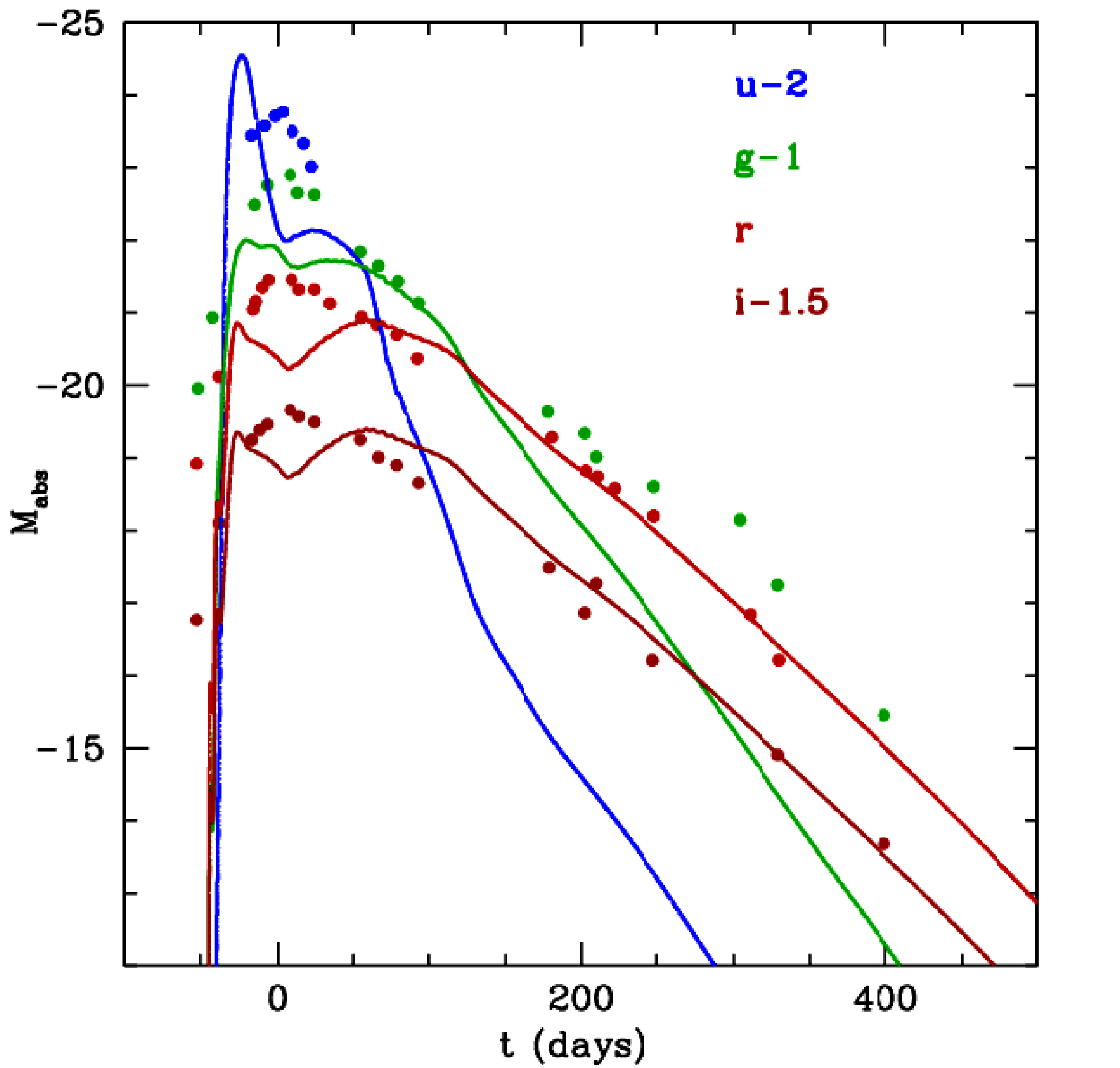
- Matter velocity at the epoch of shock breakout versus Eulerian radius r (bottom) in the model for SN 1987A from Blinnikov (1999). The proper time is given near the curves.

Numerical code STELLA. Temperature diagram



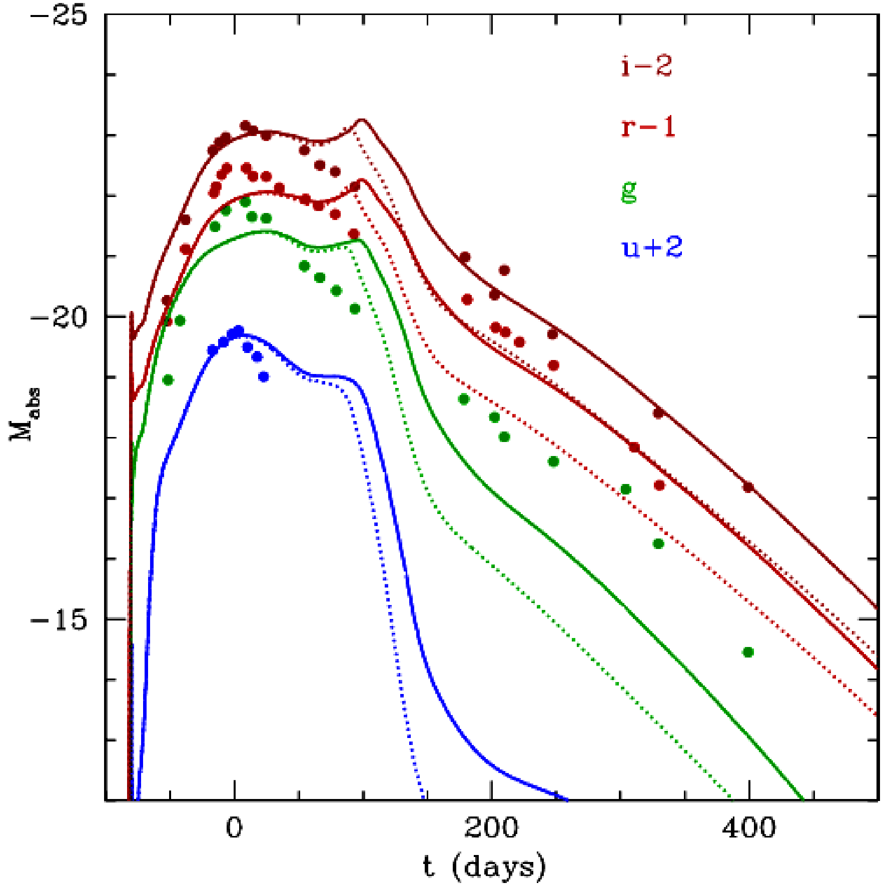
PTF12dam: multicolor light curve simulations

Params	Value
M_ej, $M_\odot$	40
M_CSM, $M_\odot$	10
T_CSM, K	2500
log R_CSM, cm	16.15
p	2
E_51	20
M(^{56}Ni) , $M_\odot$	6
AMHT, $M_\odot$	10
X_CSM	C:O=1:4

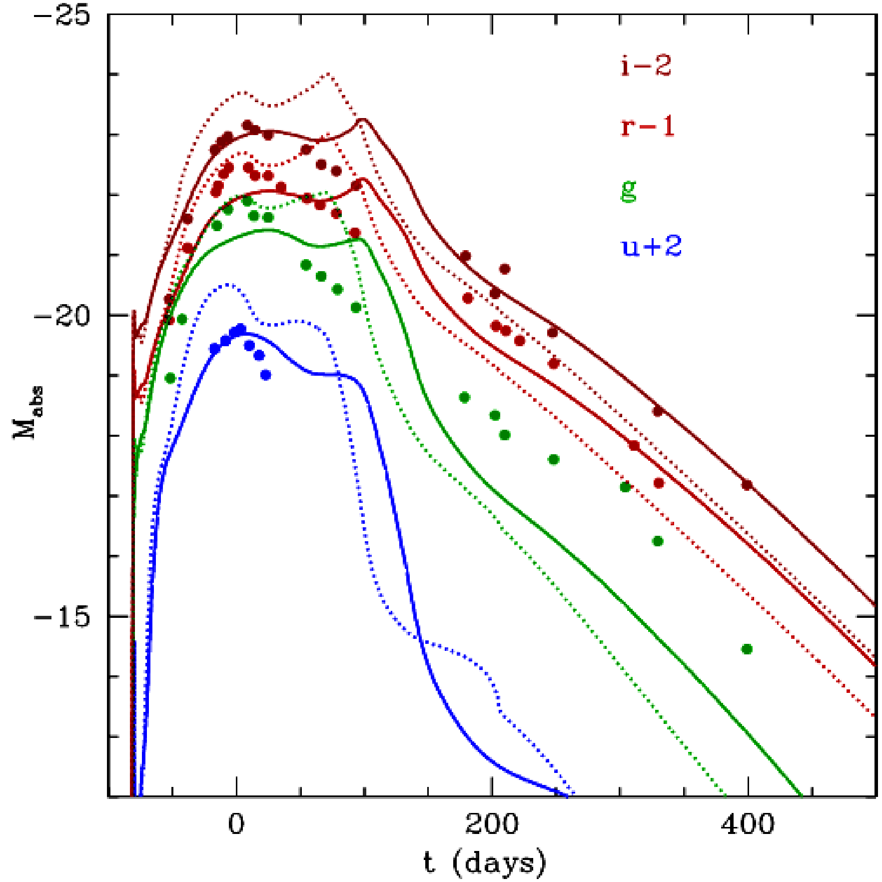


Multicolor light curves: modeling

- Lower ^{56}Ni mass – fainter tail

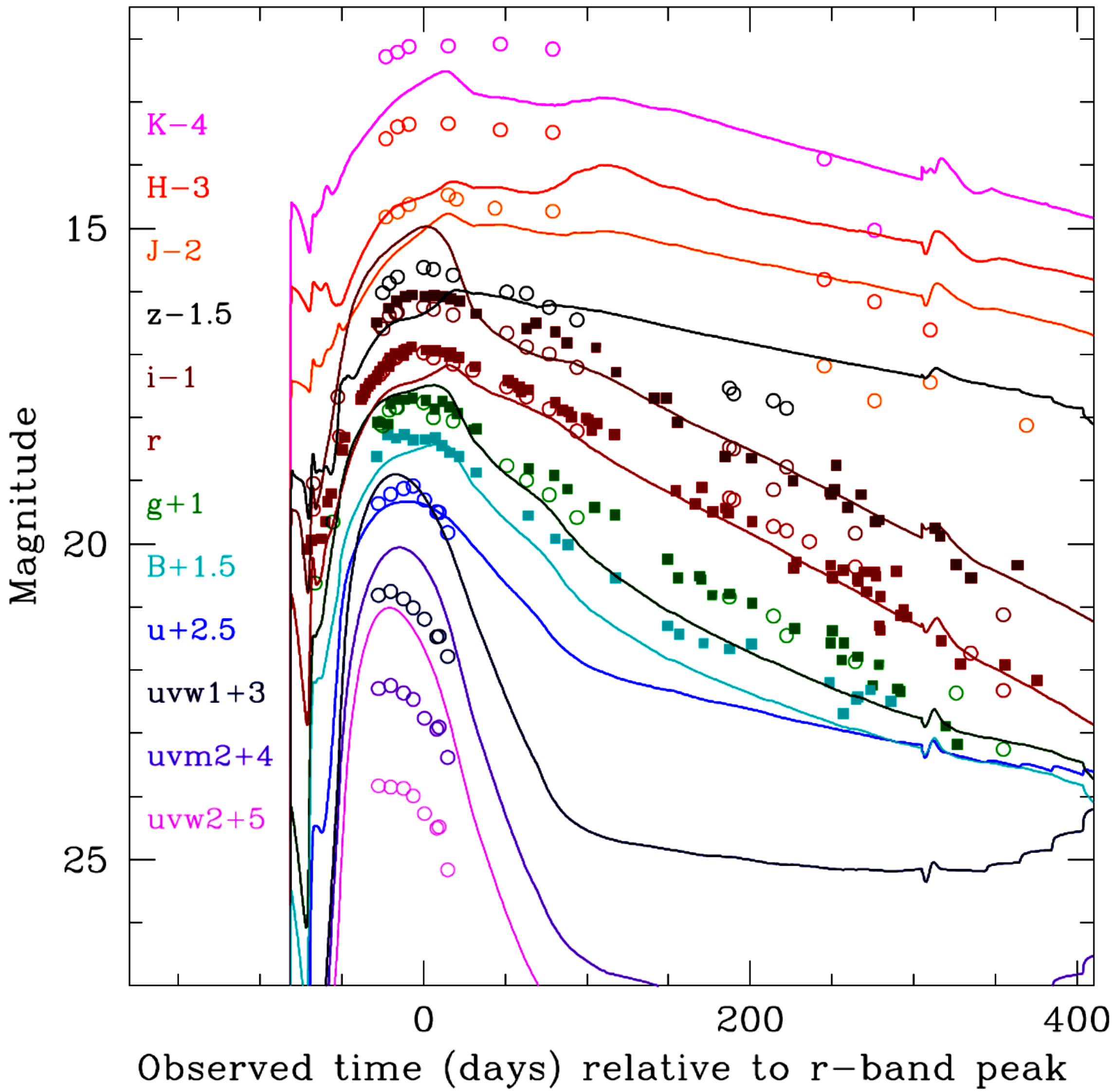


- Larger energy – brighter peak



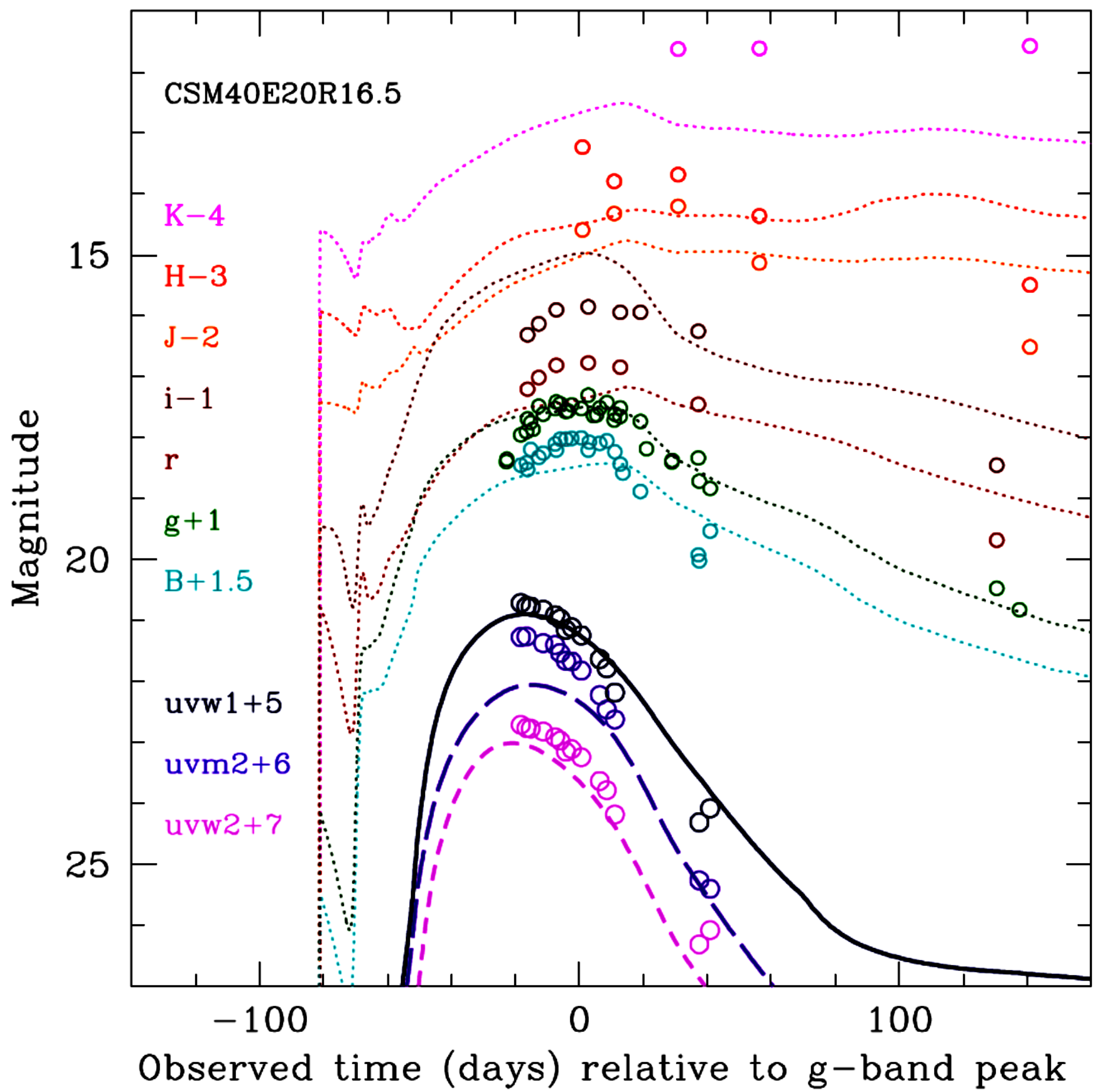
PTF12dam R16 model. Multicolor light curves

Params	Value
M_ej, $M_\odot$	40
M_CSM, $M_\odot$	38
T_CSM, K	2500
lg R_CSM, cm	16.5
p	2
E_51	20
M(^{56}Ni) , $M_\odot$	6
AMHT, $M_\odot$	10
X_CSM	He:C=9:1



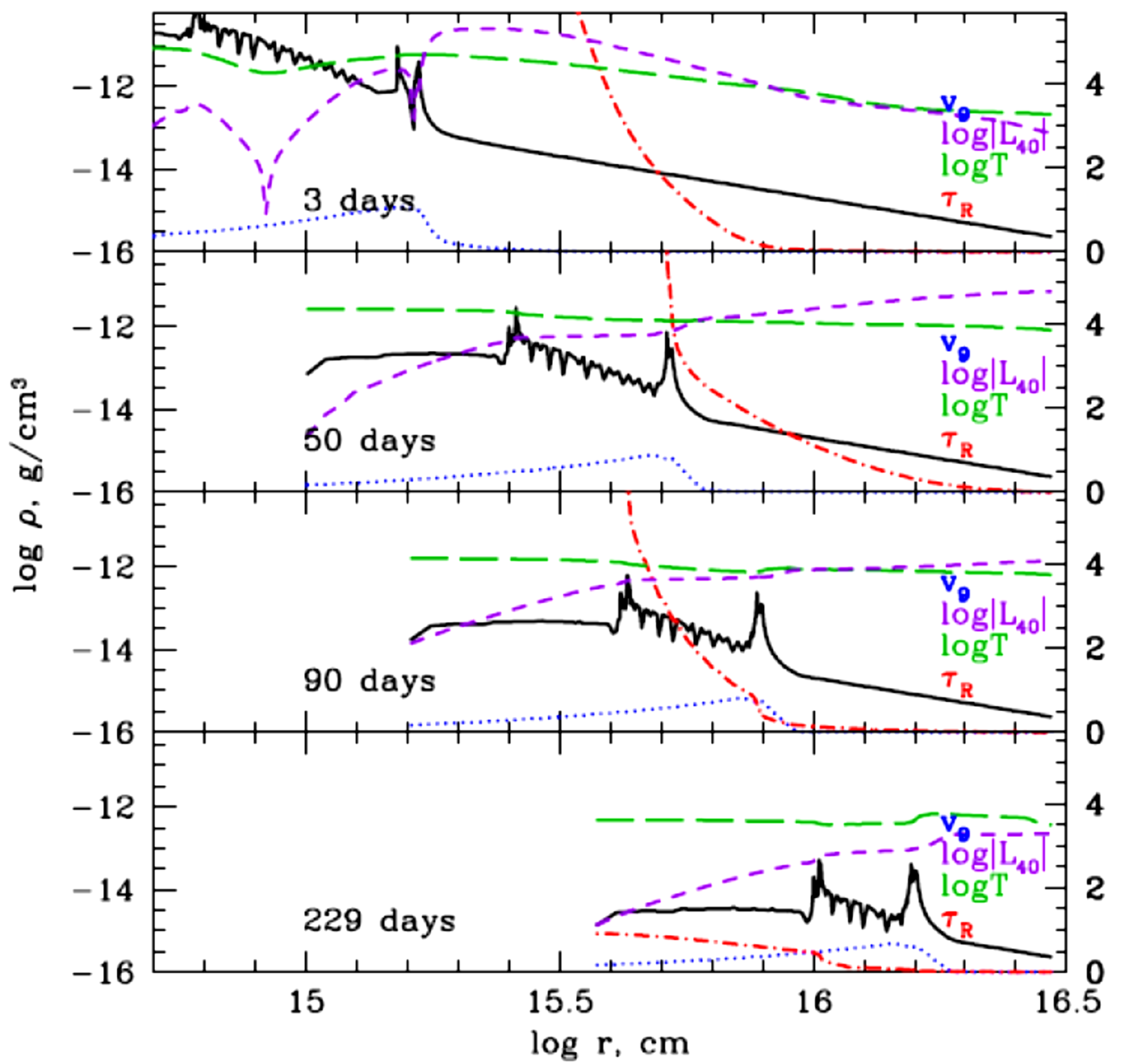
Gaia16apd R16 model. Multicolor light curves

Params	Value
M_ej, $M_\odot$	40
M_CSM, $M_\odot$	38
T_CSM, K	2500
lg R_CSM, cm	16.5
p	2
E_51	20
$M(^{56}Ni)$, $M_\odot$	6
AMHT, $M_\odot$	10
X_CSM	He:C=9:1

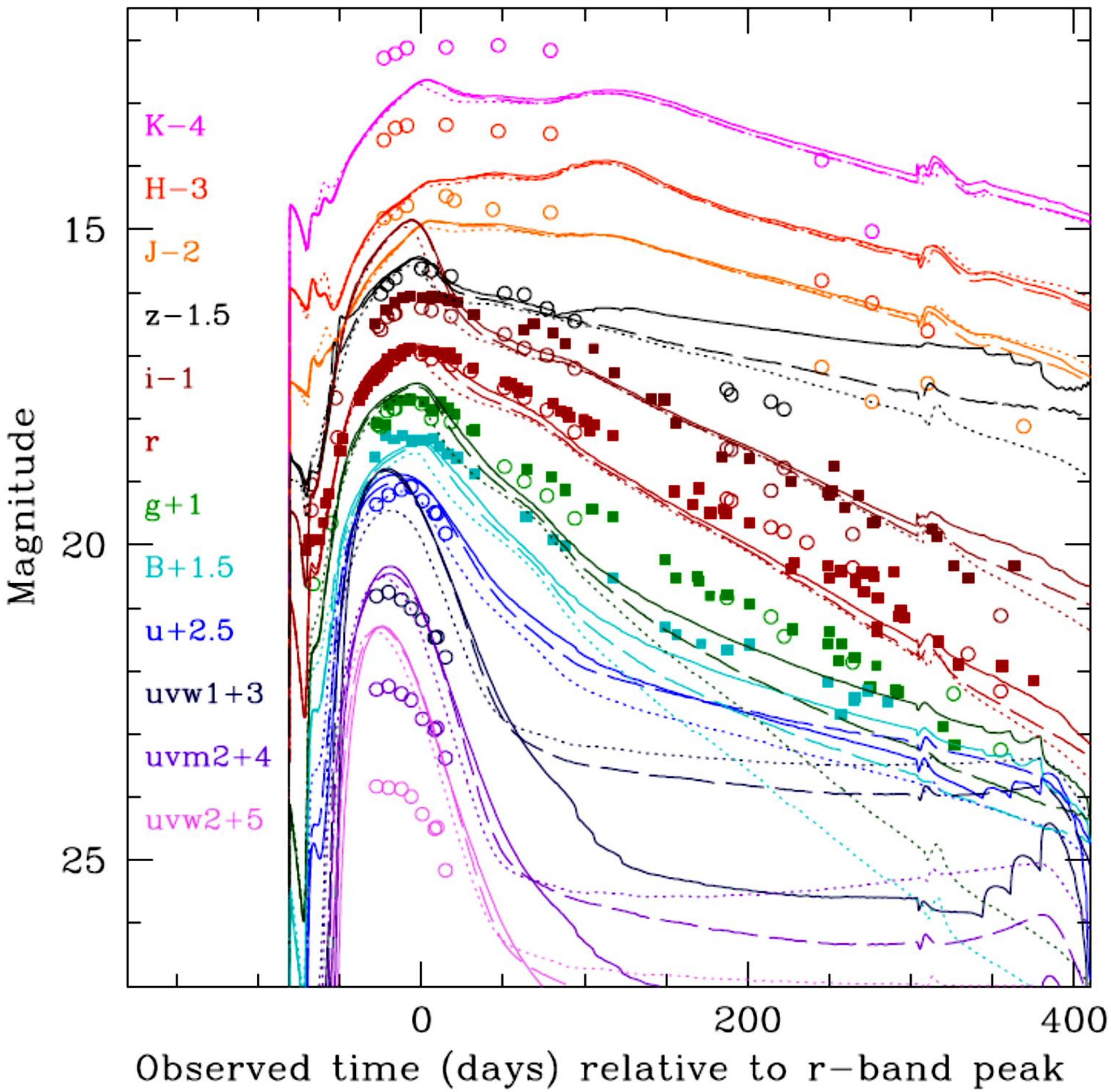


PTF12dam R16 model. Shock wave hydro

- Emission heats the gas
- Near the peak luminosity
- After the peak luminosity
- Light curve decline (radioactive decay of ^{56}Ni to ^{56}Co to ^{56}Fe)



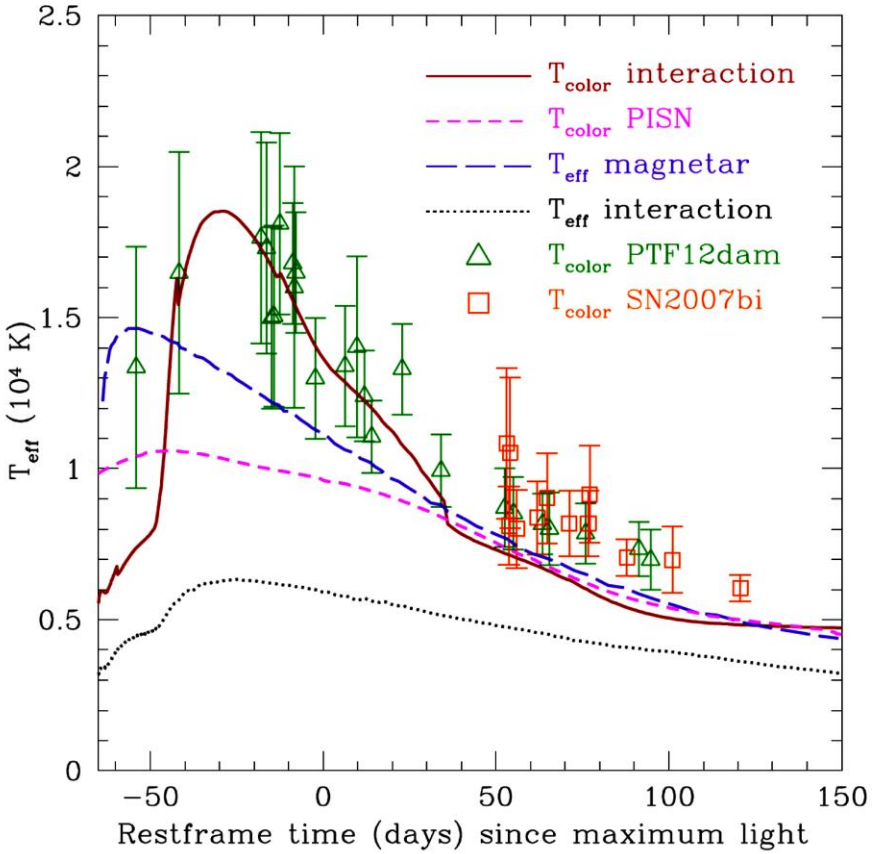
Metallicity of CSM



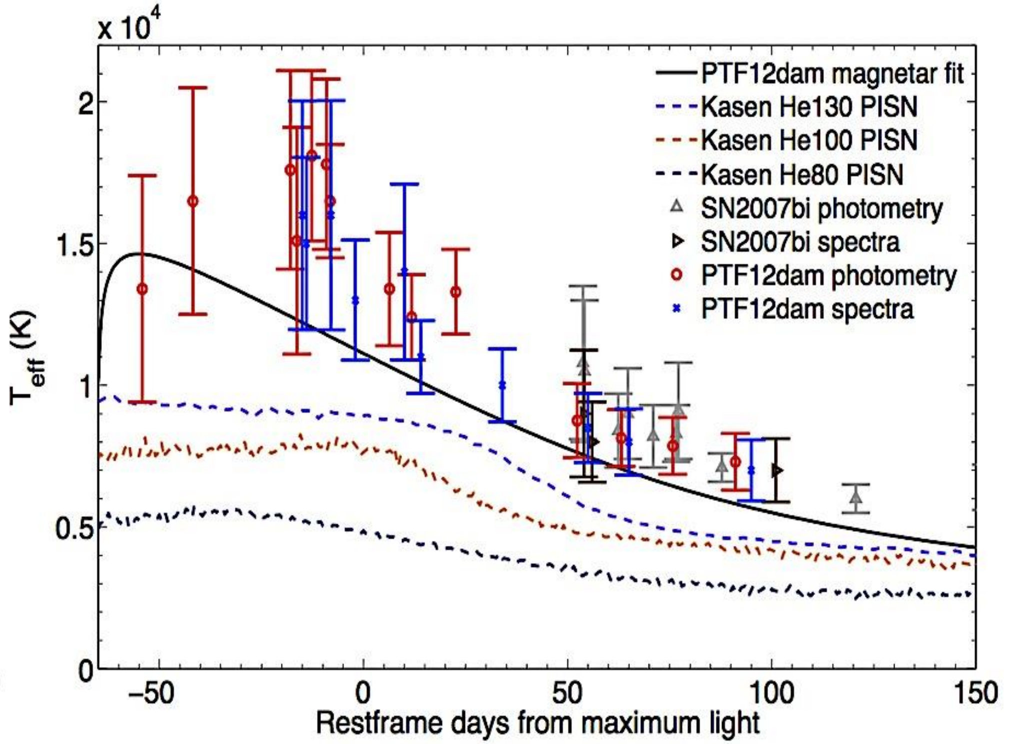
- Solar metallicity (solid line), low $Z=Z_{\odot}/200$ (dashed line), zero metallicity (dotted line).
- Due to lower opacity, the CSM cools down faster and the optical light curve decline increases.
- The decrease of the radius of the photosphere, especially in UV wavelengths. The temperature of internal CSM layers is higher, that leads to higher luminosity at UV wavelengths.

PTF12dam R16 model. Temperature evolution

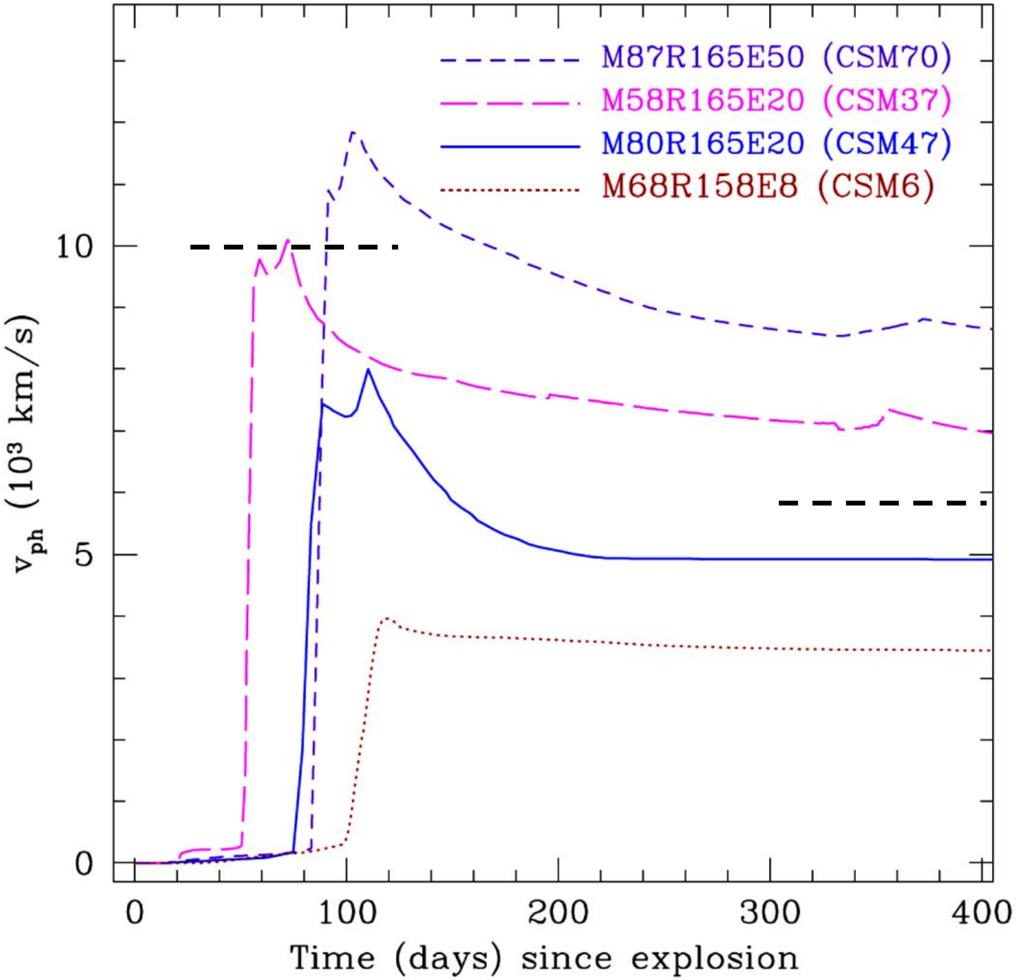
- Color and effective temperature evolution of PTF 12dam and SN 2007bi compared with interaction model



- Effective temperature evolution of PTF 12dam and SN 2007bi compared with magnetar-powered and PI models (Nicholl 2013)
- T_{color} - temperature of the blackbody whose SED most closely fits the data; $T_{eff} = (L/(4\pi\sigma R^2))^{1/4}$



PTF12dam R16 model. Velocity evolution

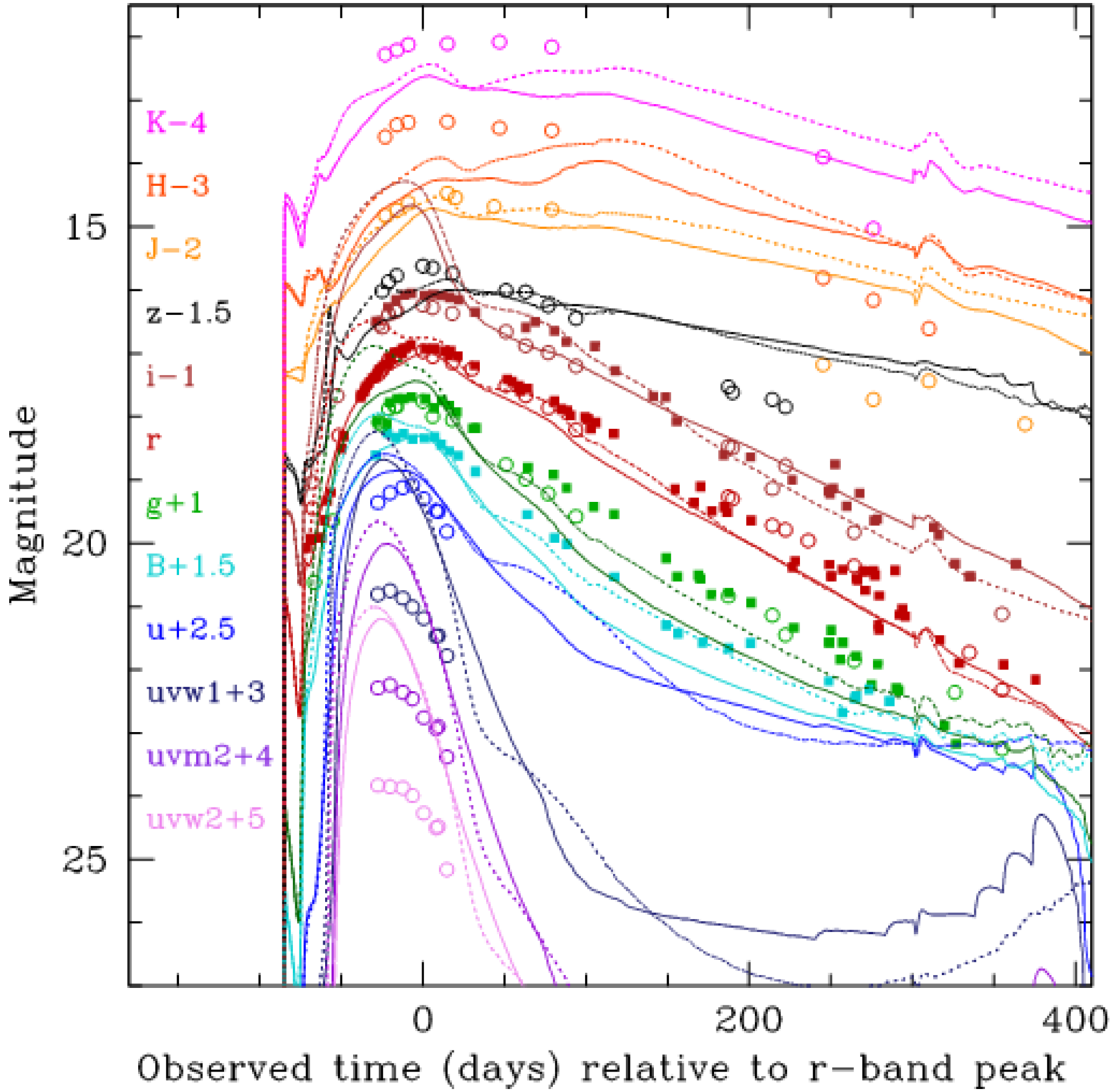


- Flux measurements of the broad SN lines of PTF12dam in the GTC spectrum taken at +509d (Chen 2014).

SN Name	Line	λ (Å)	Flux ± Error (erg s^{-1} cm^{-2})
PTF12dam (+509d)	[O I]	5577	$7.0 \pm 0.5 \times 10^{-18}$
	[O I]	**6300 6363**	$\mathbf{4.6 \pm 0.3 \times 10^{-17}}$
	[Ca II]	7291 7324	$1.1 \pm 0.1 \times 10^{-17}$
	O I	7771-7775	$1.2 \pm 0.1 \times 10^{-17}$
SN 2007bi (+470d)	**[O I]**	**6300 6363**	$\mathbf{2.4 \pm 0.3 \times 10^{-16}}$
SN 2007bi (+367d)	**[O I]**	**6300 6363**	$\mathbf{6.0 \pm 0.4 \times 10^{-16}}$

SN Name	EW (Å)	FWHM (Å)	Velocity (km s^{-1})	Luminosity ± Error (erg s^{-1})
PTF12dam (+509d)	187	74	~ 4000	$1.9 \pm 0.2 \times 10^{38}$
	332	**137**	**~ 5800**	$\mathbf{1.3 \pm 0.1 \times 10^{39}}$
	71	102	~ 4000	$2.9 \pm 0.3 \times 10^{38}$
	78	109	~ 4200	$3.3 \pm 0.4 \times 10^{38}$
SN 2007bi (+470d)	**190**	**143**	**~ 6100**	$\mathbf{9.5 \pm 1.0 \times 10^{39}}$
SN 2007bi (+367d)	**358**	**182**	**~ 8100**	$\mathbf{2.4 \pm 0.2 \times 10^{40}}$

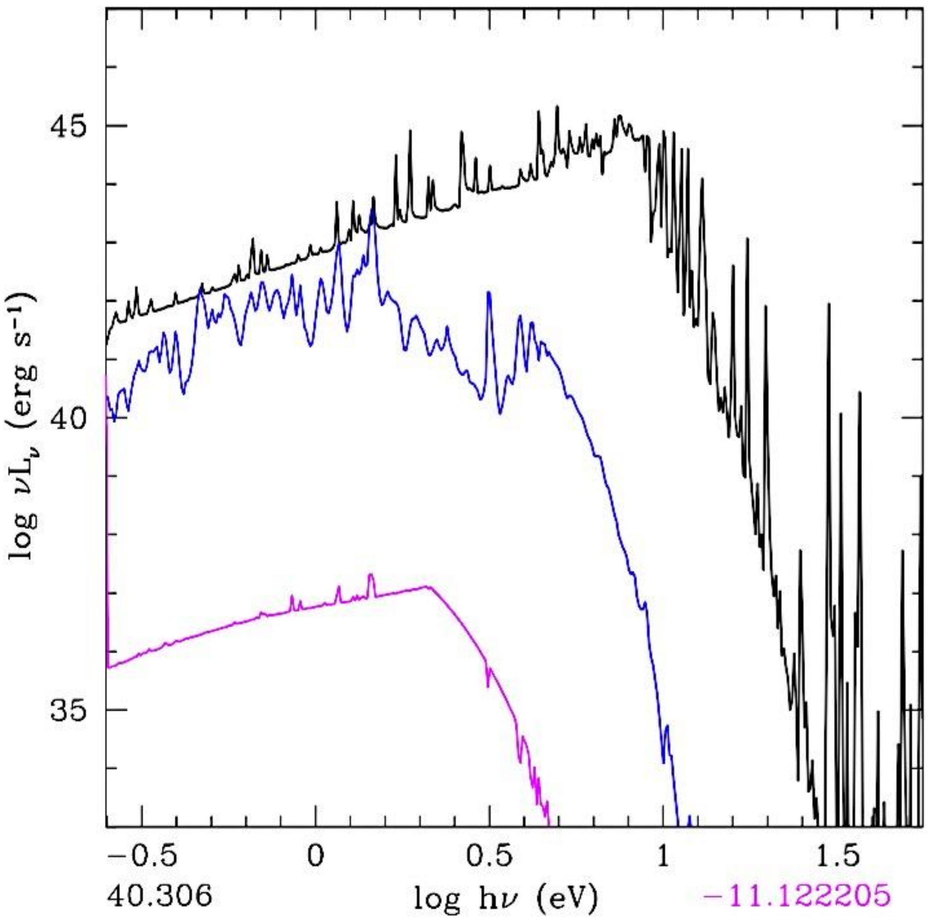
PTF12dam light curves. Opacity

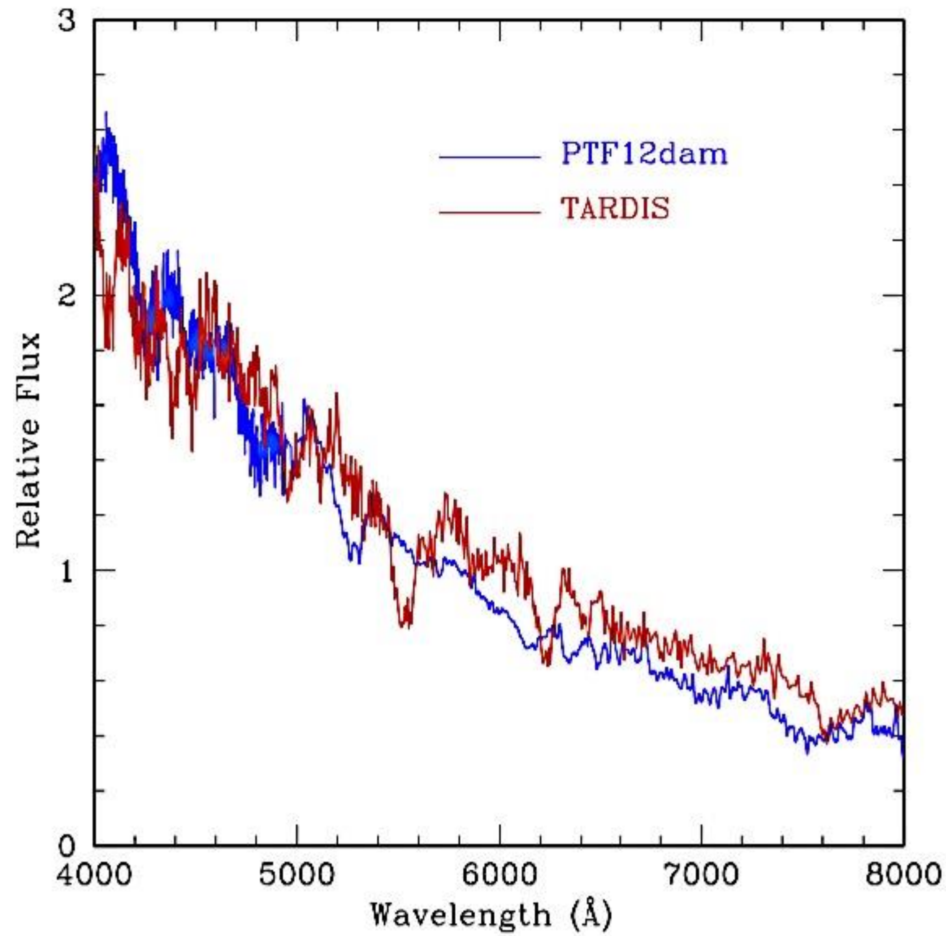


- 100,000 -> 26,000,000 lines (Sorokina 2016)
- Brighter peak in all the bands ~ 0.5 mag

PTF12dam R16 model. Spectral synthesis (in progress)

- STELLA run-time calculations (1000 groups): before shock breakout, near the peak luminosity, +350d after maximum
- TARDIS code (Kerzendorf & Sim 2014) post-process calculations: comparison with the observed spectrum near maximum light





Models of Gaia16apd

- **Gaia16apd**: extremely luminous UV emission among SLSNe (Yan+16, Nicholl+16, Kangas+16).

- **Simulations**: multicolor radiation hydrodynamics. Comparison of light curves, color temperature evolution and photospheric velocities.

  - **Shock interaction with CSM**

  Interaction models ($N \sim 100$) (Tolstov+2017): $M_{ej} = 40\ M_{\odot}$, $M_{CSM} = 3...100\ M_{\odot}$, $\log R_{CSM} = 14...17$ cm, $E_{51,kin} = 5...60$, CO / He composition, $M(^{56}Ni) = 0...6\ M_{\odot}$.

  - **Magnetar pumping**

  Magnetar models ($N \sim 30$) constructed from SN 1998bw ejecta $M_{ej} \sim 10\ M_{\odot}$ with various magnetar parameters around $P = 1$ ms, $B = 10^{14}$ G.

  - **Pair-instability supernova**

  He130Ni55 progenitor model (Heger&Woosley 2002), $R = 4\ R_{\odot}$, $M(^{56}Ni) = 55\ M_{\odot}$, $M = 57\ M_{\odot}$, $E_{51,dep} = 44$.

Magnetar model

(Kasen & Bildsten 2010)

- For PISN and interaction model the energy deposition rate $L_{dep} = E_{dep}/t_{dep}$ during $t_{dep} \sim 0.1$s.

- The energy deposition rate L_{dep} in magnetar model is

$$L_{dep} \sim E_{dep}/(1 + t/t_m)^2,$$

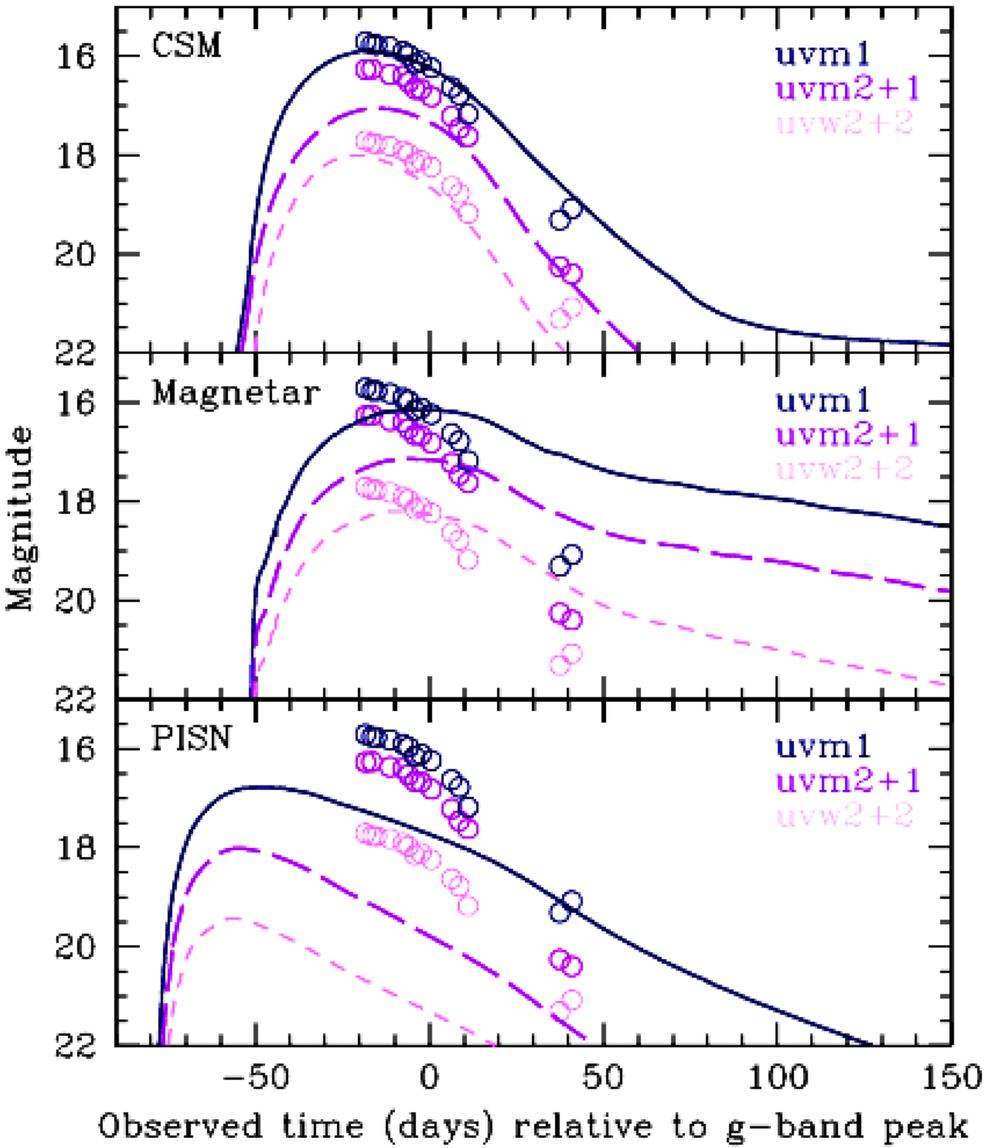
where the total spin energy E_m and spin-down timescale t_m is connected with pulsar spin period P and its magnetic field B:

$$E_m \approx 2 \times 10^{52} P_{ms} \text{ ergs},$$
$$t_m \approx 5 \, B_{14} P_{ms} \text{ days},$$

where $P_{ms} = P/1$ ms and $B_{14} = B/10^{14}$ G.

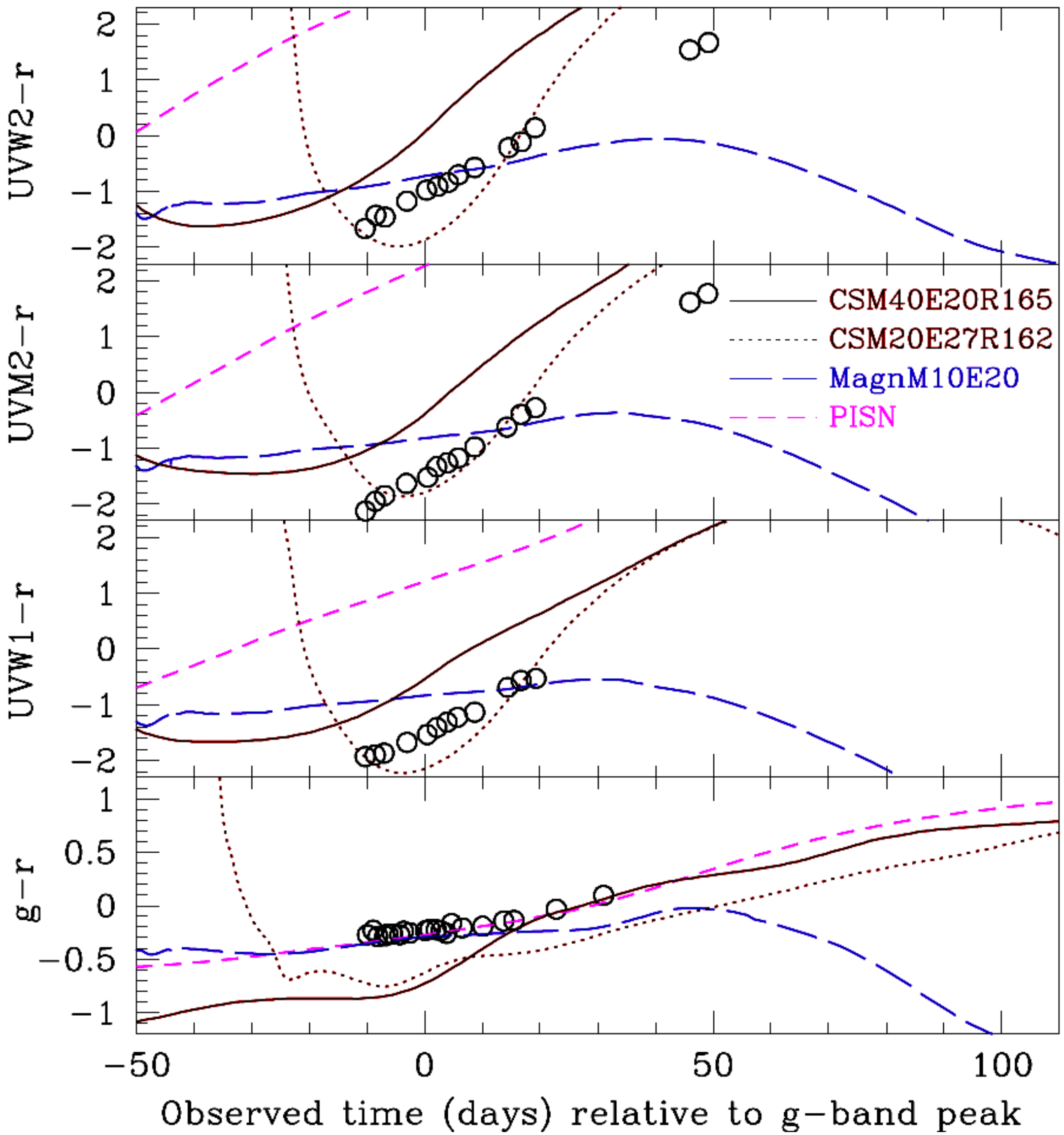
- We assume that all spin-down energy is thermalized in the ejecta.

Ultraviolet Emission of Gaia16apd



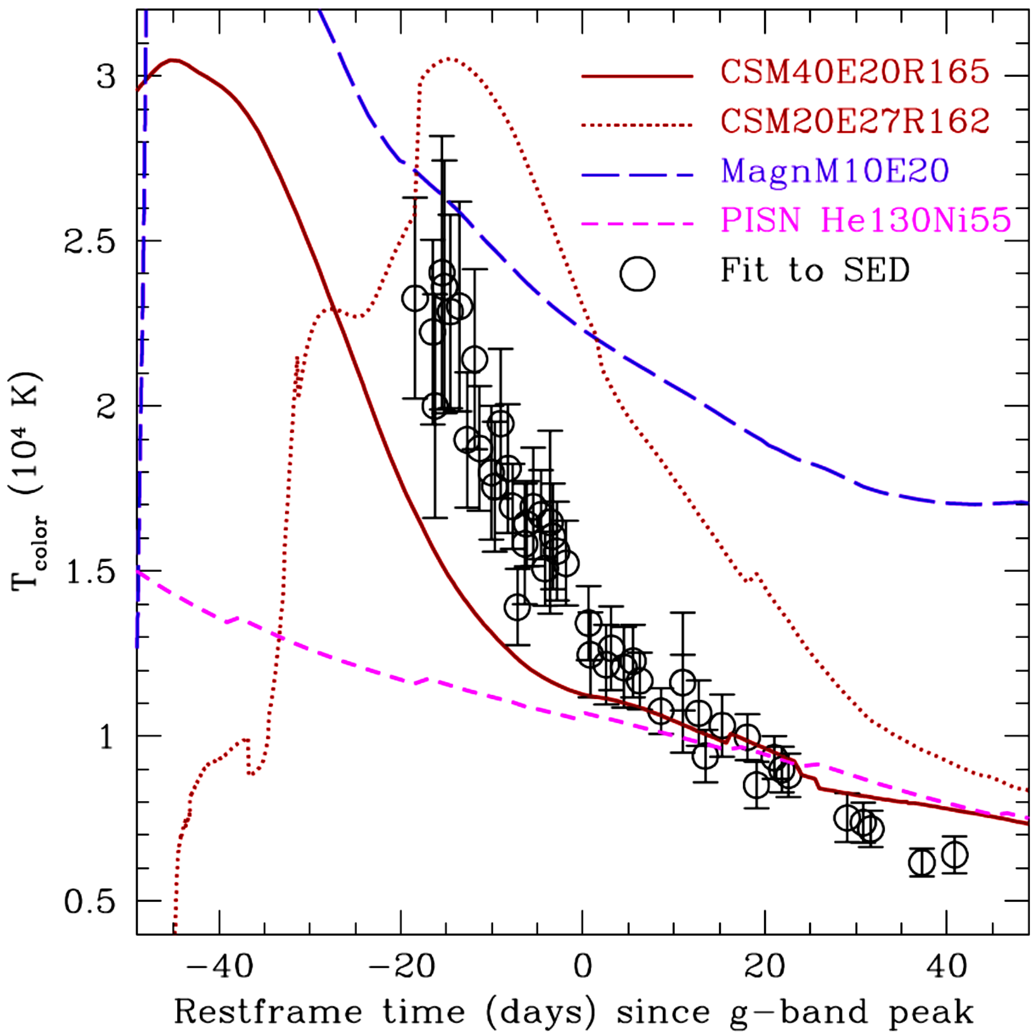
- **Which model best fits the UV data?**
  - Shock interaction with CSM
  - Magnetar pumping
  - Pair-instability supernova
- The best-fit (chi-squared minimization) of UV and optical light curves to Gaia16apd.
- **Conclusion**: interaction model is the most promising to explain extreme UV luminosity of Gaia16apd.

Gaia16apd color evolution



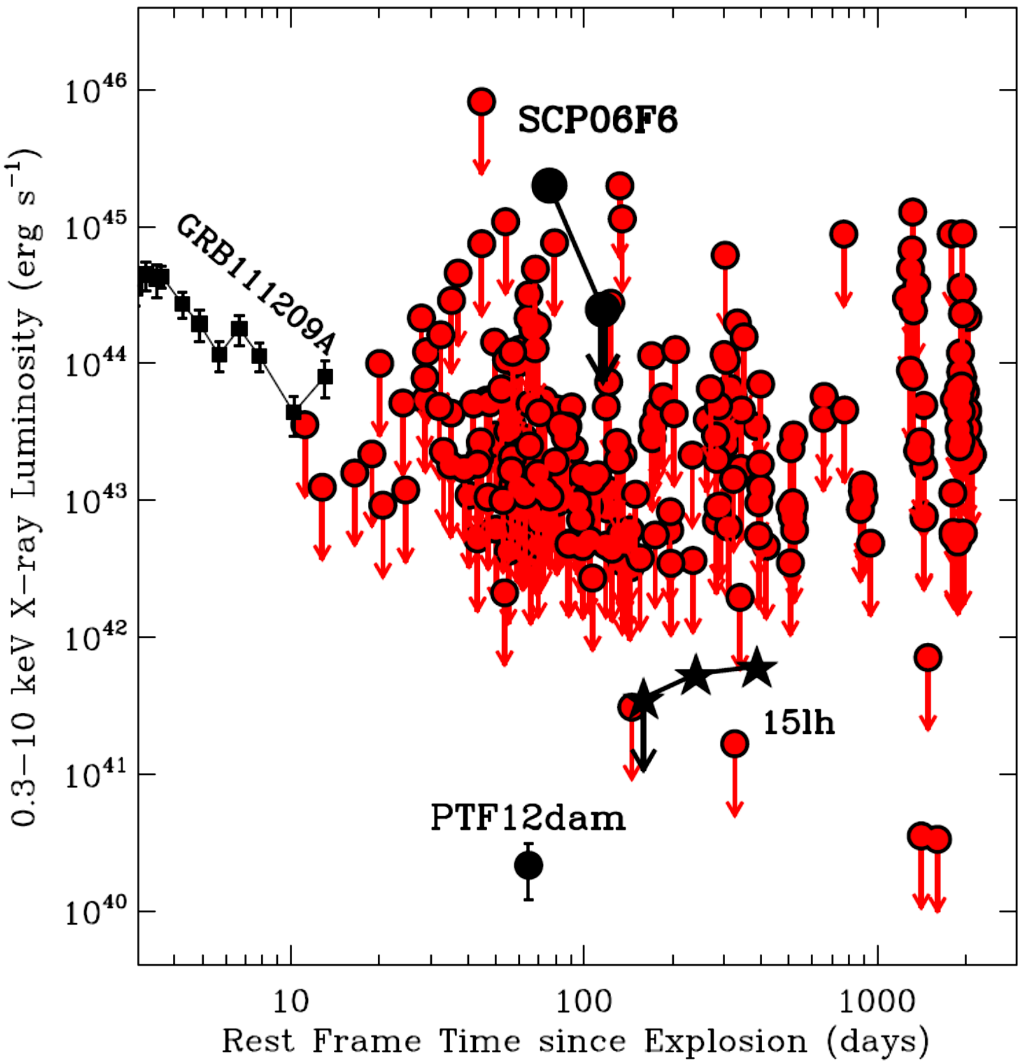
- The interaction model (CO) is in better agreement with observations.
- The magnetar model has a slower reddening than observations.
- The PISN model is in good agreement with the observed reddening rate, but the model evolves about 50 days earlier than the observed one.
- g - r color evolution is more consistent with the magnetar and the PISN model.

Gaia16apd color temperature evolution



- The temperature decline rate is a better fit to the observed values in interaction models
- Variation of chemical composition of CSM.

X-ray observations of SLSN-I



- 26 nearby SLSN-I with Swift, Chandra and XMM (Margutti 2017)
- X-ray observations of SLSNe-I spanning the time range 10-2000 days (red circles for upper limits, black circles for detections) show that superluminous X-ray emission of the kind detected at the location of SCP06F6

- The interaction models do not produce X-ray emission: radiation-dominated shock wave, $T_{ej} \sim$ 20,000-30,000 K

Summary

- We propose that PTF12dam and Gaia16apd are PPISNe, where the outer envelope of a progenitor is ejected during the pulsations. It is powered by double energy source: radioactive decay of ^{56}Ni and a radiative shock in a dense circumstellar medium.
- Parameters: E_{51}=20…30, M_{ej+env}=40$M_{\odot}$+20…40$M_{\odot}$, M(^{56}Ni)=6…7 $M_{\odot}$, R = 10^{16} cm.
- Open questions: CO/He composition, “dark helium”, time scale of the formation of the envelope and its radius, density and temperature profiles, asymmetric explosion.
- The magnetar model requires more detailed simulations of high-energy effects: pair-productions, spectral transport of gamma-rays, inverse Compton, coupling of wind and plasma.
- Combined multicolor light curve and spectra modeling are required to identify the scenario of SLSNe, parameters of supernovae (E, M, Z).