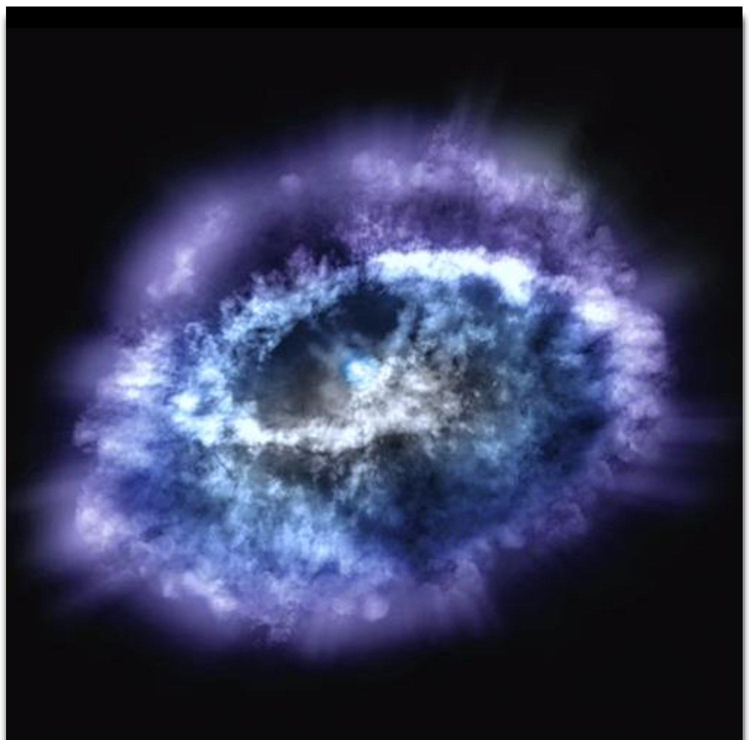
THE UNIVERSITY OF TOKYO

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

From faint to superluminous supernovae: multicolor light curve simulations



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Seminar at IPMU, 7 May 2019

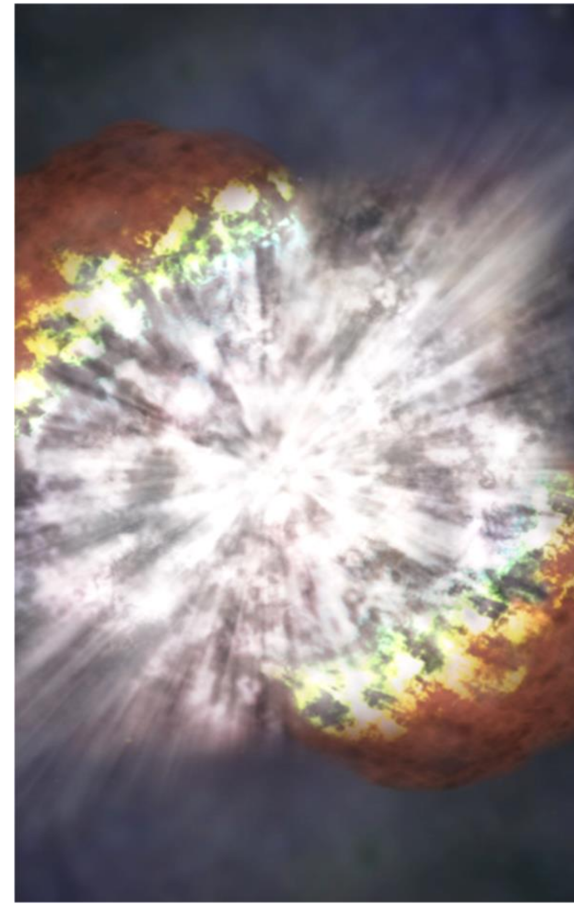
Outline

- Observations of SLSNe and possible scenarios

- Extremely bright in UV SLSN Gaia16apd ($M_{UV} \sim -23$ mag), PTF12dam

- Radiation hydrodynamics simulations of SLSN-I outbursts: multicolor light curves (from X-rays to NIR), color evolution, photospheric temperature and velocity evolution. The influence of opacity, metallicity of CSM

- High-z supernovae: faint/superluminous?



(Image credit: NASA)

Superluminous supernovae (SLSNe)

- SLSNe (Type I (no hydrogen), Type II) are more luminous than -21 magnitude (arbitrary cut) in any optical band at the maximum brightness
- Rise ~ 20-70 d, decline ~ 20-500 d

E_{rad} ~ (1-10) $\cdot 10^{51}$ erg, rate/CC ~ 0.01%

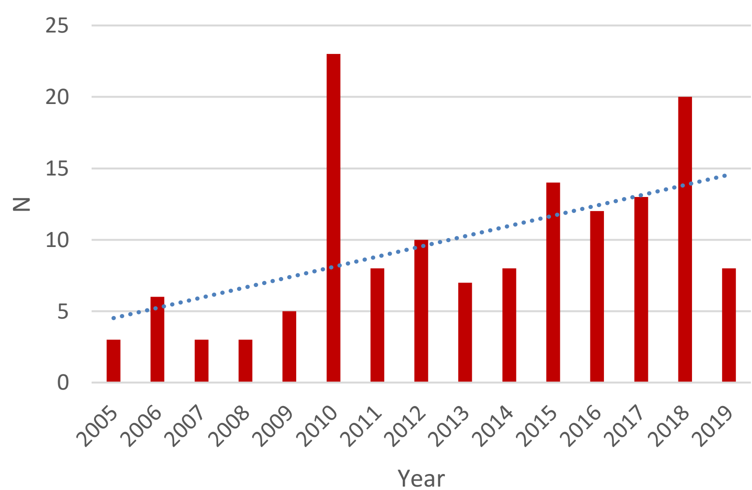
~ 100 SLSNe, z ~ 0.1 – 3.9

(PTF, Pan-STARRS)

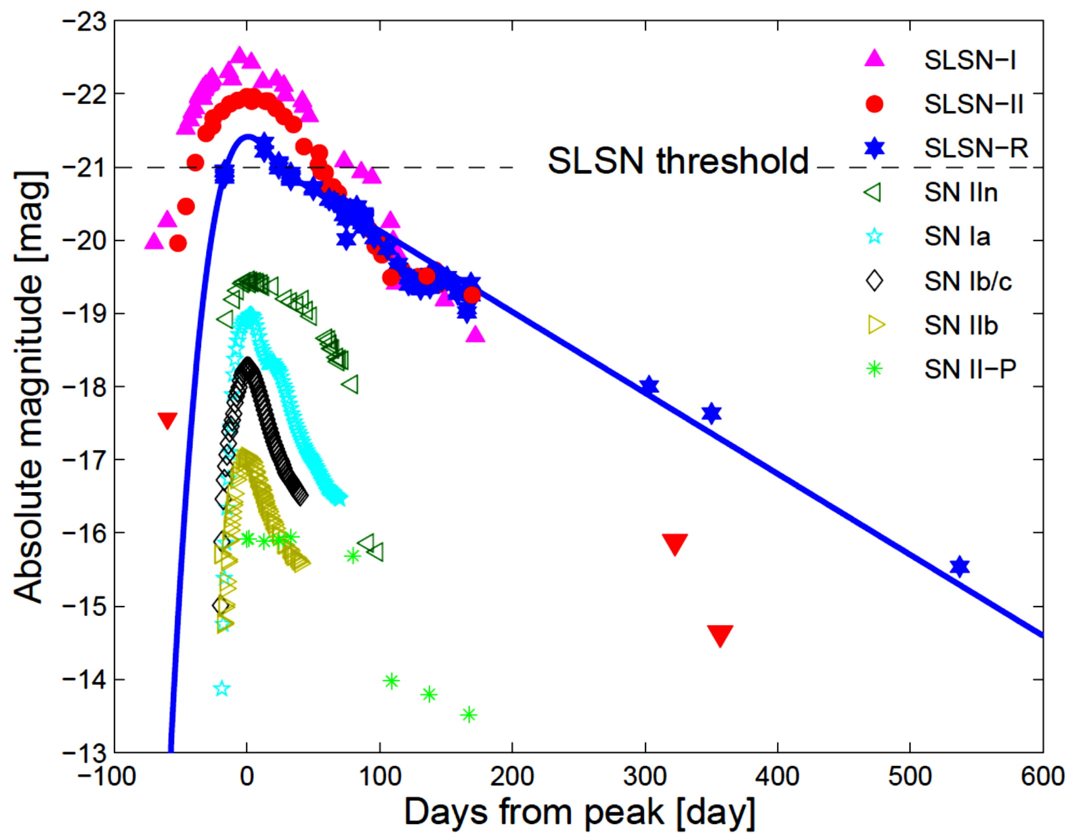
SLSN discoveries:

SN 2006gy (Smith+2007),

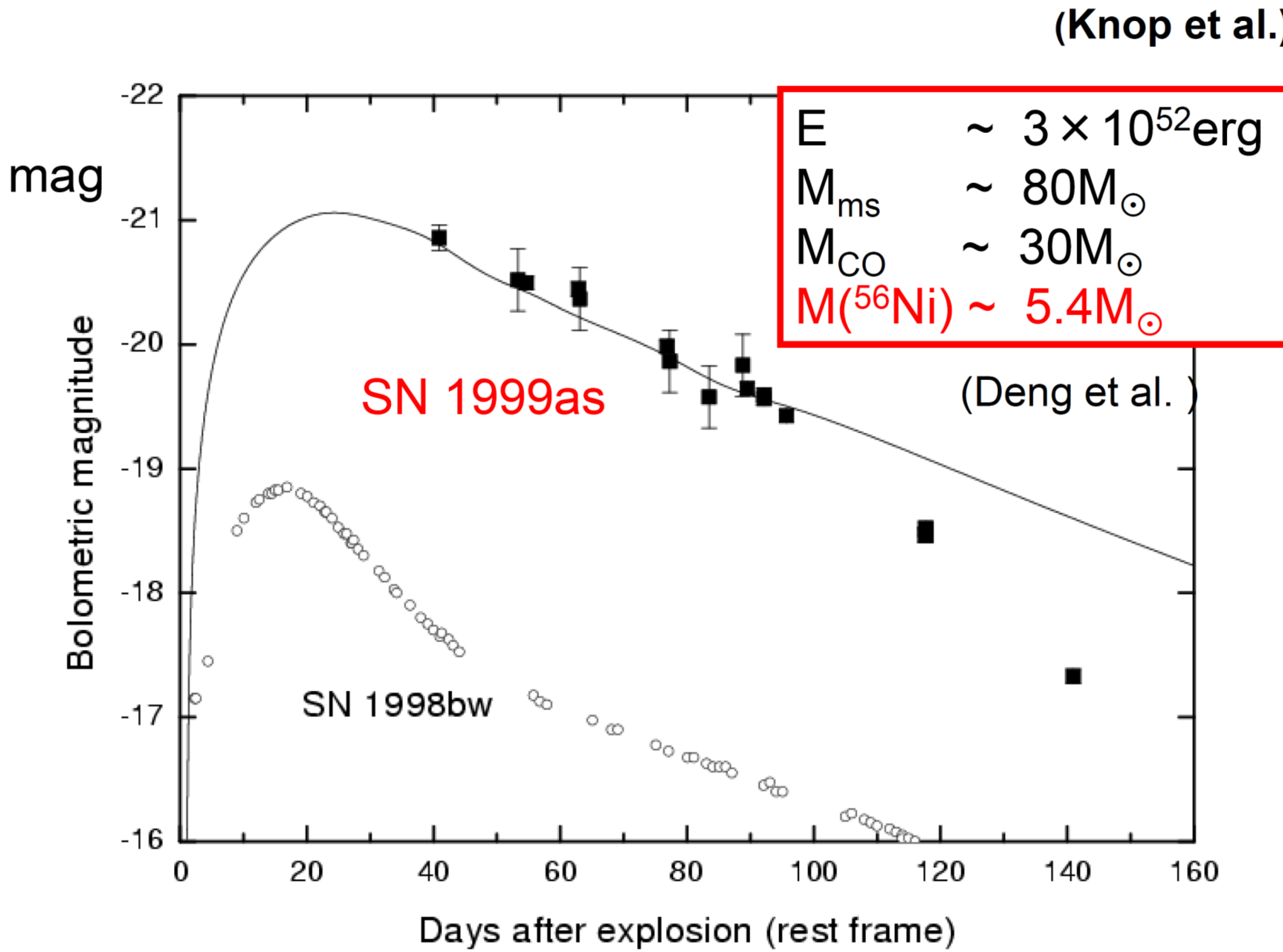
SN 2005ap (Quimby+2007)



Gal-Yam 2012

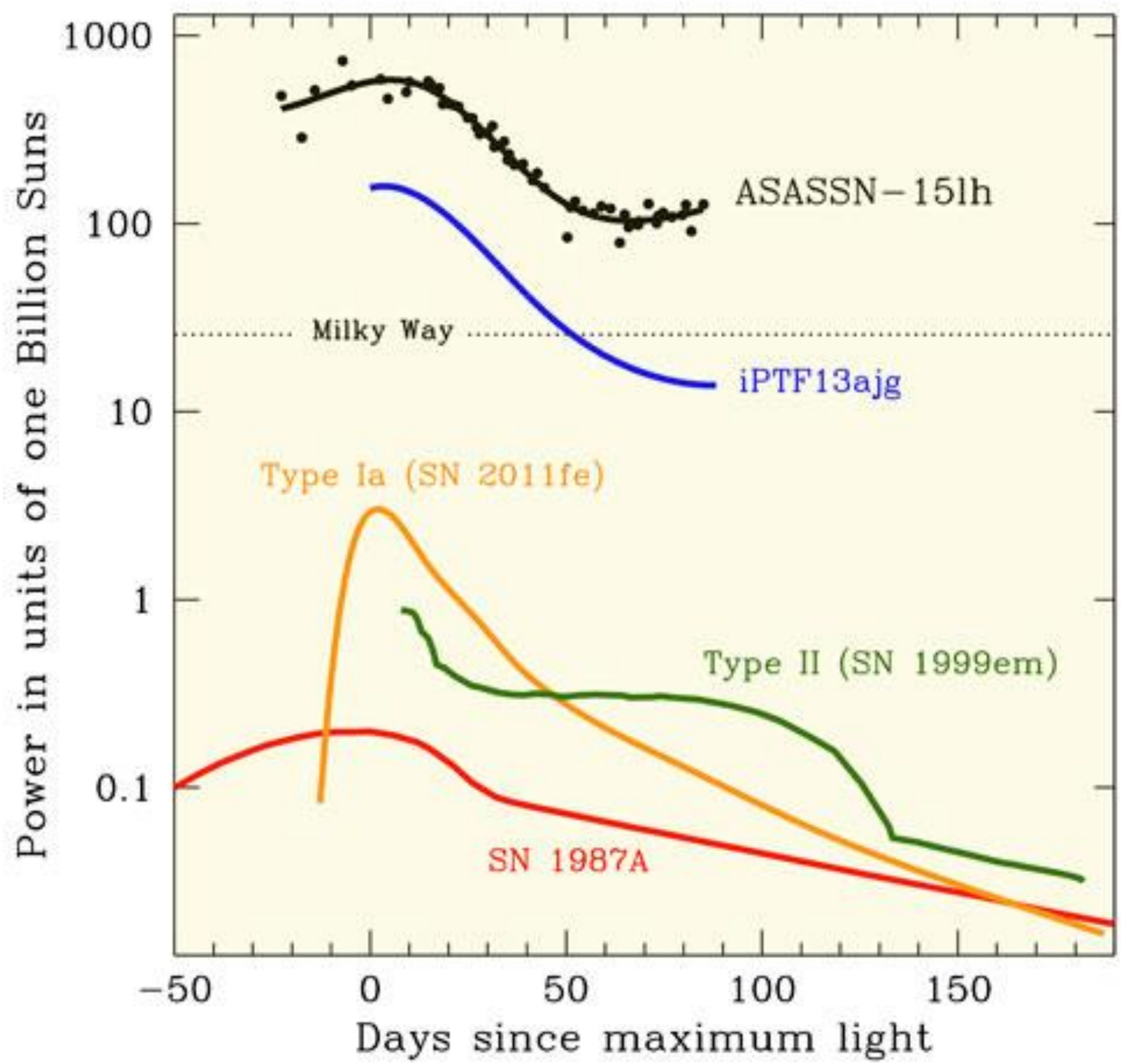


Superluminous SNe: 1999as @z=0.127



$E \sim 3\times10^{52}$erg
$M_{ms} \sim 80M_\odot$
$M_{CO} \sim 30M_\odot$
$M(^{56}Ni) \sim 5.4M_\odot$

Most luminous SLSNe



Credit: The ASAS-SN team

SLSN subclasses

- Type I (no hydrogen), Type II

SLSN I normal
Rapid light curve decay (~20-60 d)
Quimby+2011

SLSN I-R (SN 2007bi-like)
Exponential light curve decay
Gal Yam+2009

SLSN I - fast (PS1-10afx)
Very fast rise and fall (~ 10-20 d)
Chornock+2013
Probably a lensed Ia
Quimby+2013, 2014

SLSN II-n
Narrow/intermediate H lines,
rapid rise, but very slow fall (~100 d)

SLSN IIn-peculiar (SN 2006gy)
Complicated, evolving H profile
Extremely long-lived (~300 d)

SLSN II-L (SN 2008es, CSS121025)
Broad H lines only after peak,
short-lived with fast decay

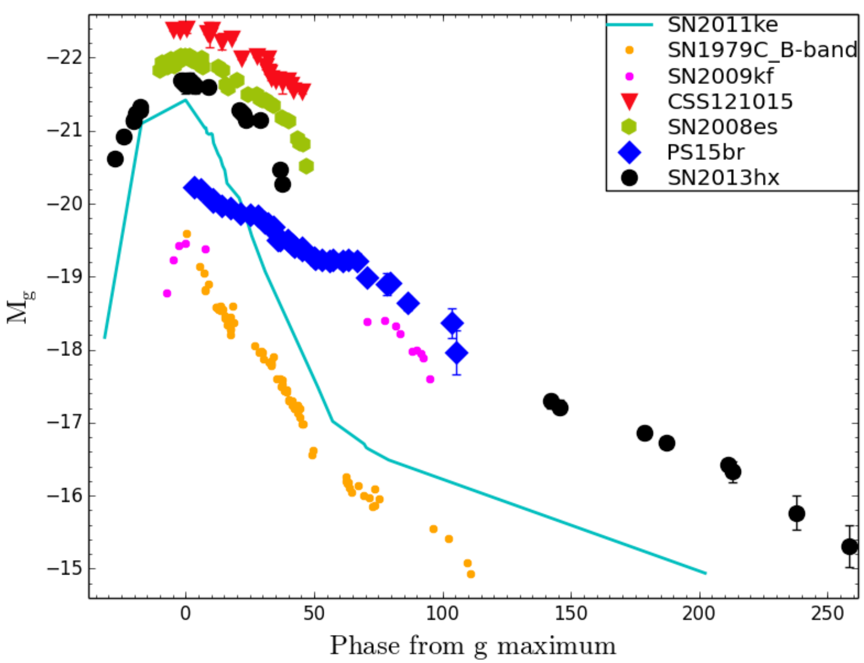
SN Ia-CSM (SN 2012ca)
IIn lines overlying Ia spectrum
e.g. Dilday+2012, Silverman+2013

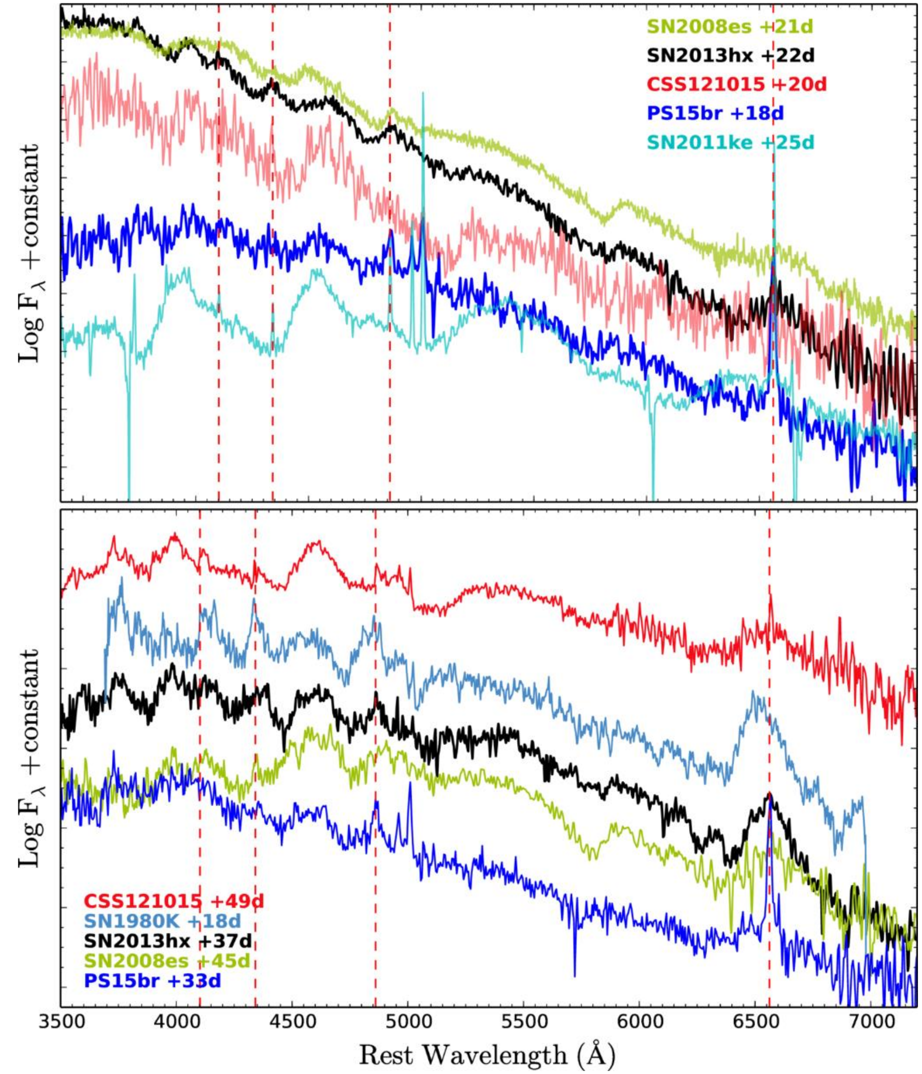
(Perley 2014)

Hydrogen-rich (Type II) SLSNe

- Type IIn (SN 2006gy) are attributed to CSM interaction (narrow and intermediate width hydrogen emission lines)
- The hot blue continuum and high peak luminosity happened early, late interaction for some SLSN-II

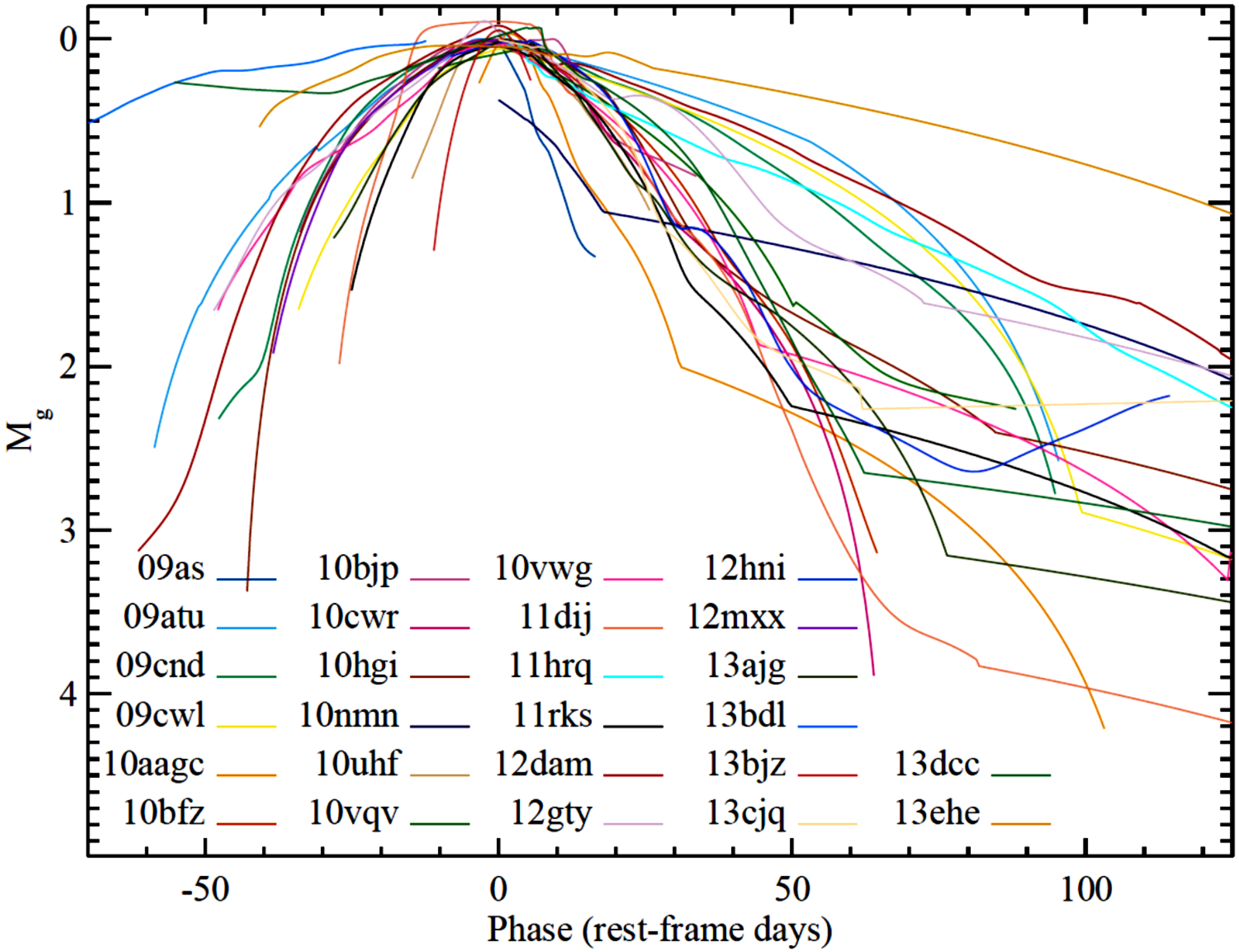
Inserra+ 2016





Hydrogen-poor(Type I) PTF SLSN light curves

- Smoothed light curves of 26 PTF SLSNe normalized at peak **(De Cia+2017)**



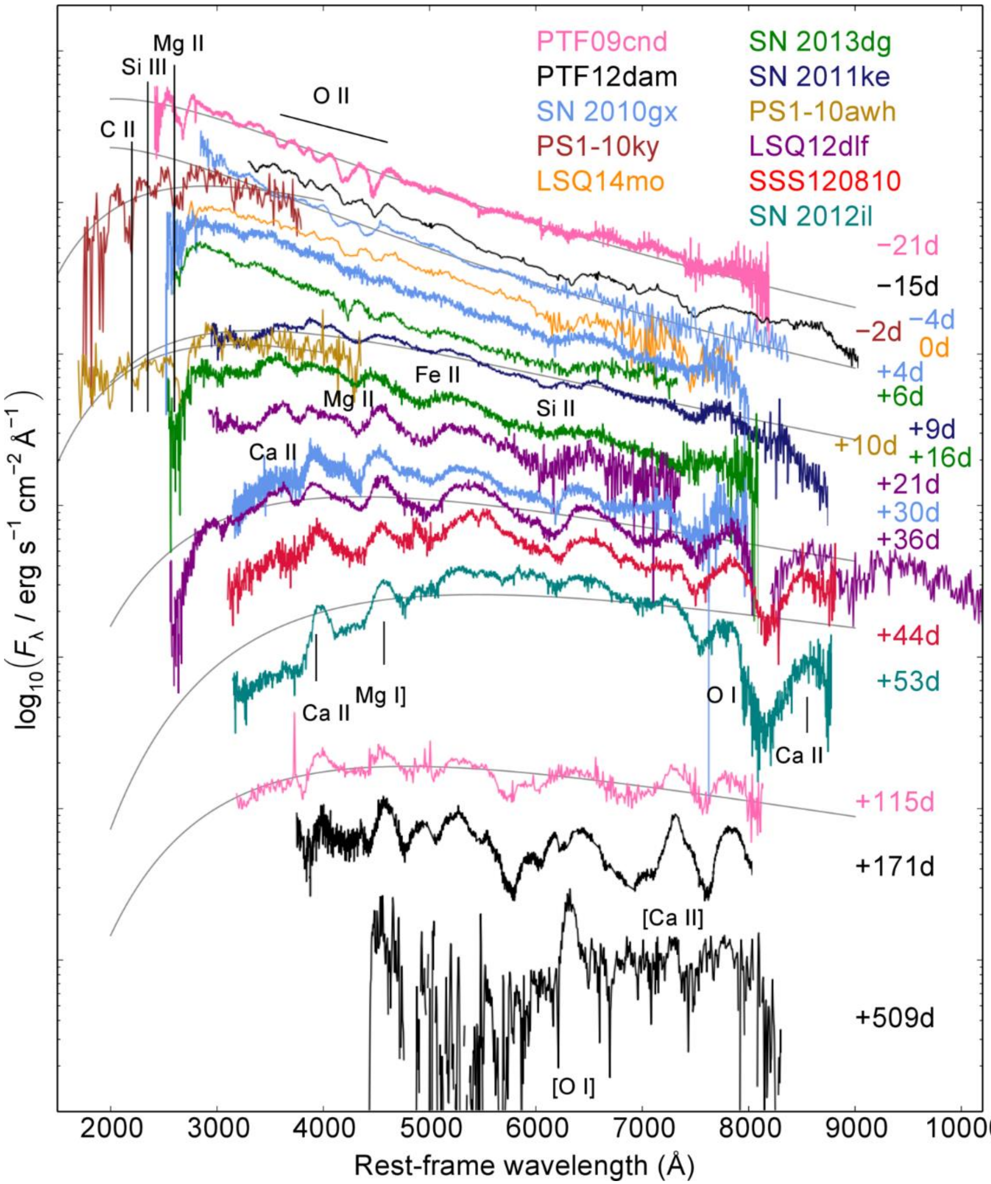
- No obvious gap between rapidly- and slowly-declining events

PTF SLSN-I spectroscopy

(Nicholl+ 2015)

- Series of 5 lines of O II, which may persist until shortly after maximum light (signature of the class?).
- After oxygen recombination (around 15,000 K) maximum Ca II H&K, Mg II, Si II, and Fe II. A few weeks after maximum, SLSNe-I start to resemble SNe Ic at maximum light
- Velocities are comparable to normal Ic:

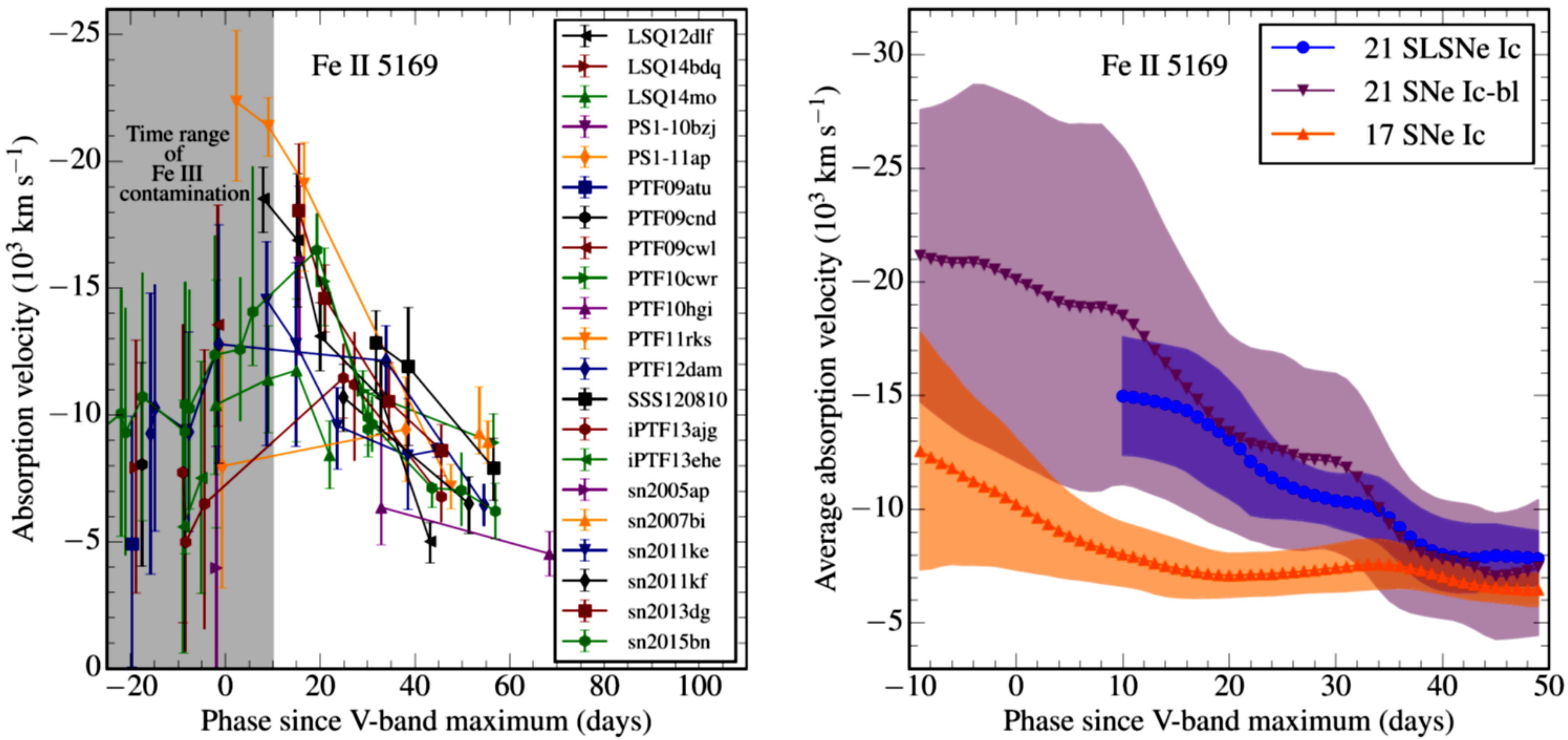
10500±3100km/s for SLSNe,
9800±2500km/s for Ic,
slower decline for SLSNe



Fe II λ5169Å absorption velocities

(Liu+ 2017)

- No systematic difference in velocities for SLSNe Ic between fast-declining light curves and slow-declining light curves.
- Similarities in observations indicate that SLSNe Ic and SNe Ic-bl may have similar explosion engines, which is consistent with a multi-D magnetar model in Suzuki & Maeda (2017).



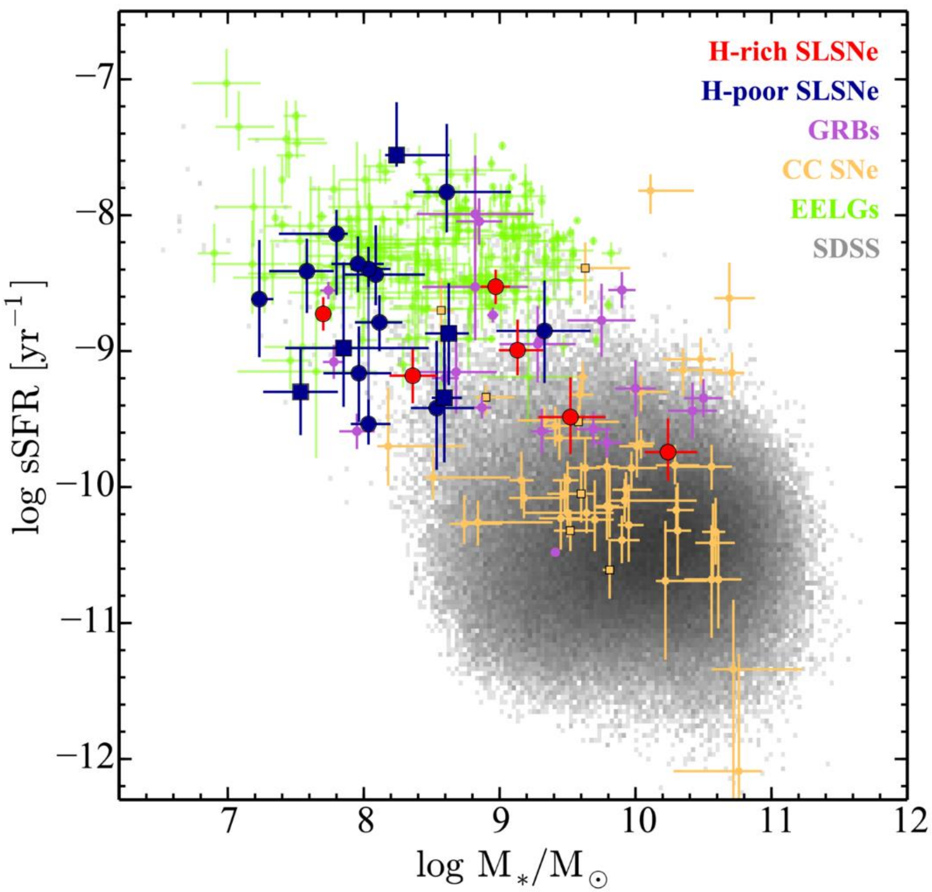
SLSN Host Galaxies

(Perley 2017)

- **High metallicity strongly suppresses SLSNe-I**
  Low (<1/2 Solar), but not *very* low

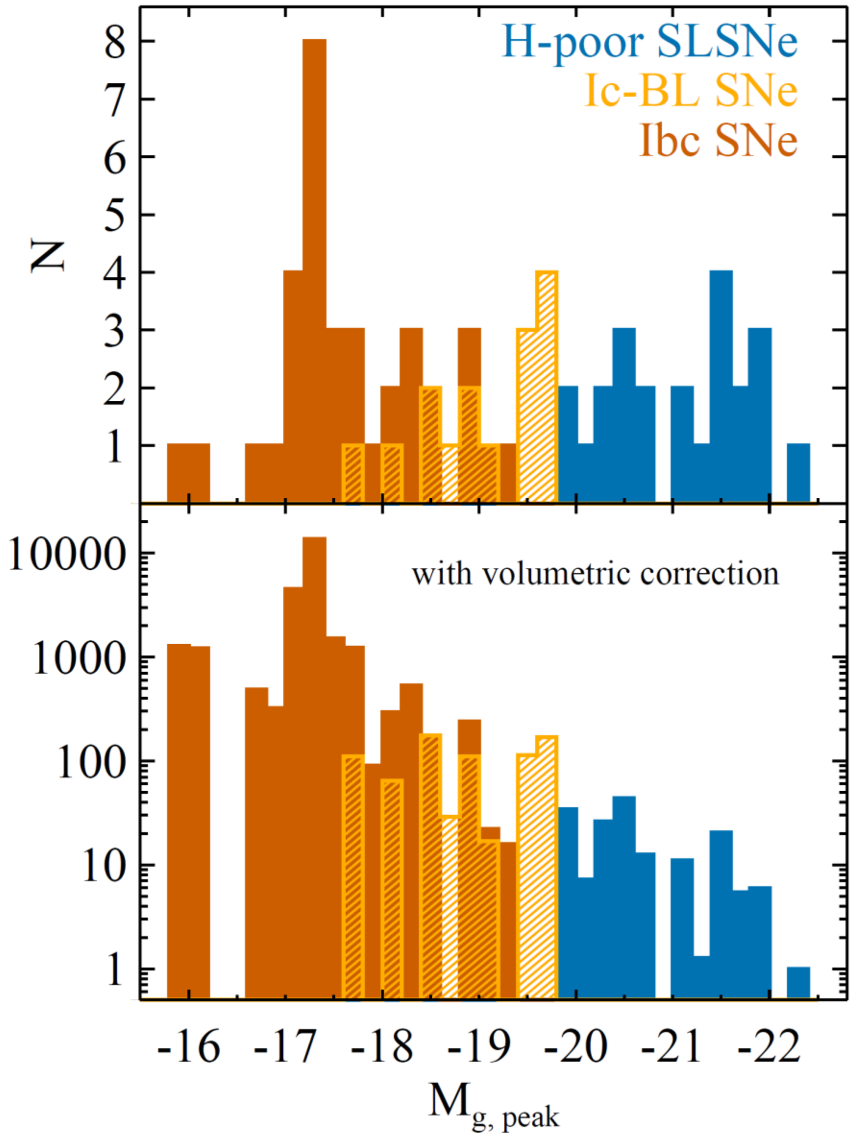
(Leloudas+2005)

- **The approximate cosmic rate is low, but significant**
  ~1/3000 supernovae at z~0, on average. But, ~1/600 in metal-poor galaxies.
- **SLSNe-I have distinct environments from other SNe**
  SLSNe-I, SLSN-II, GRBs, and (other) cc-SNe all have statistically different host populations
- **SLSNe-I may prefer the most intensely star-forming galaxies**
  Partially (entirely?) a side-effect of metallicity preference.

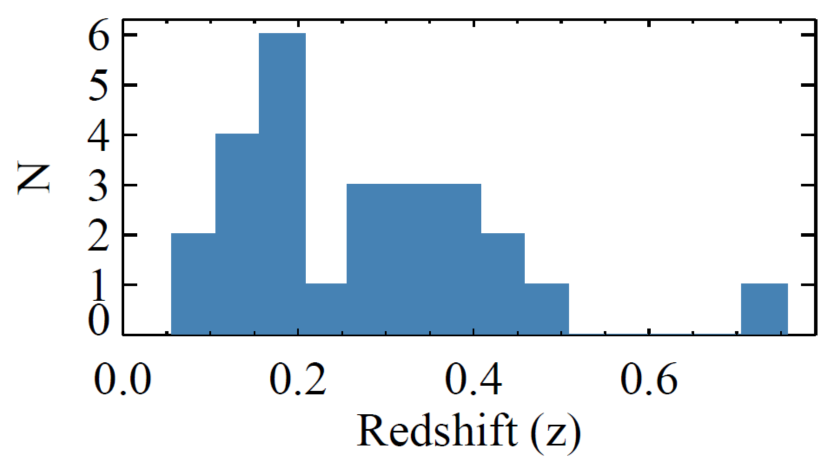


Peak – magnitude and redshift distributions (PTF)

(De Cia+ 2017)



- Higher redshift (up to z ~ 4). JWST is expected to be able to detect SLSNe out to z ~ 20 (Abbott+ 2017).
- PTF typically discovers SLSNe below z < 1.
- Pan-STARRS1 SLSNe tend to be at higher redshift (z > 0.5).



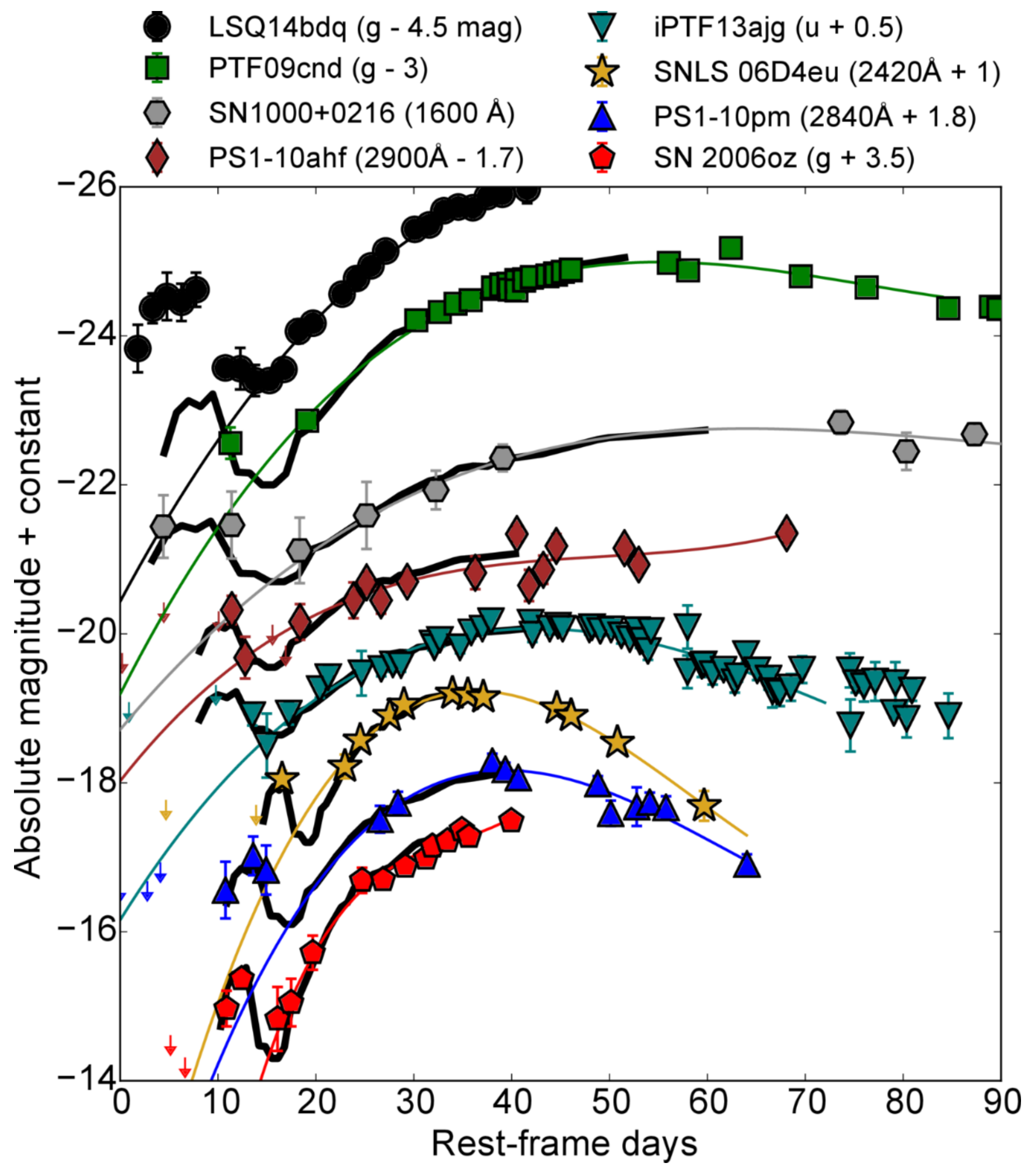
Doubled peak of SLSN-I

- 8 of 14 SLSN-I with early data

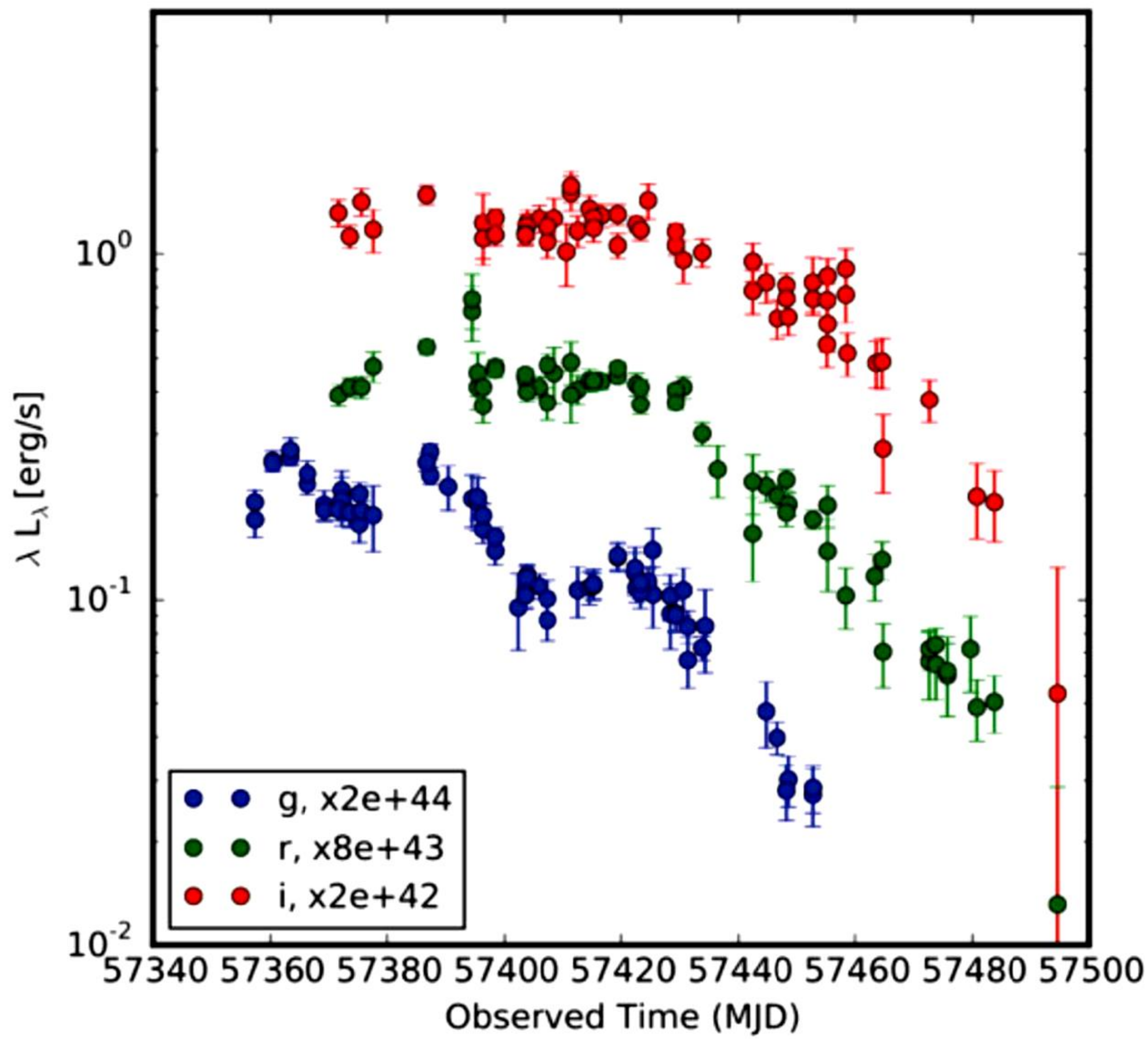
- Shock breakout
- Postshock cooling
- Interaction with CSM

- T ~ 20,000 K and rapid cooling, consistent with a shock in extended materia (Smith+2016)

(Nicholl+2016)



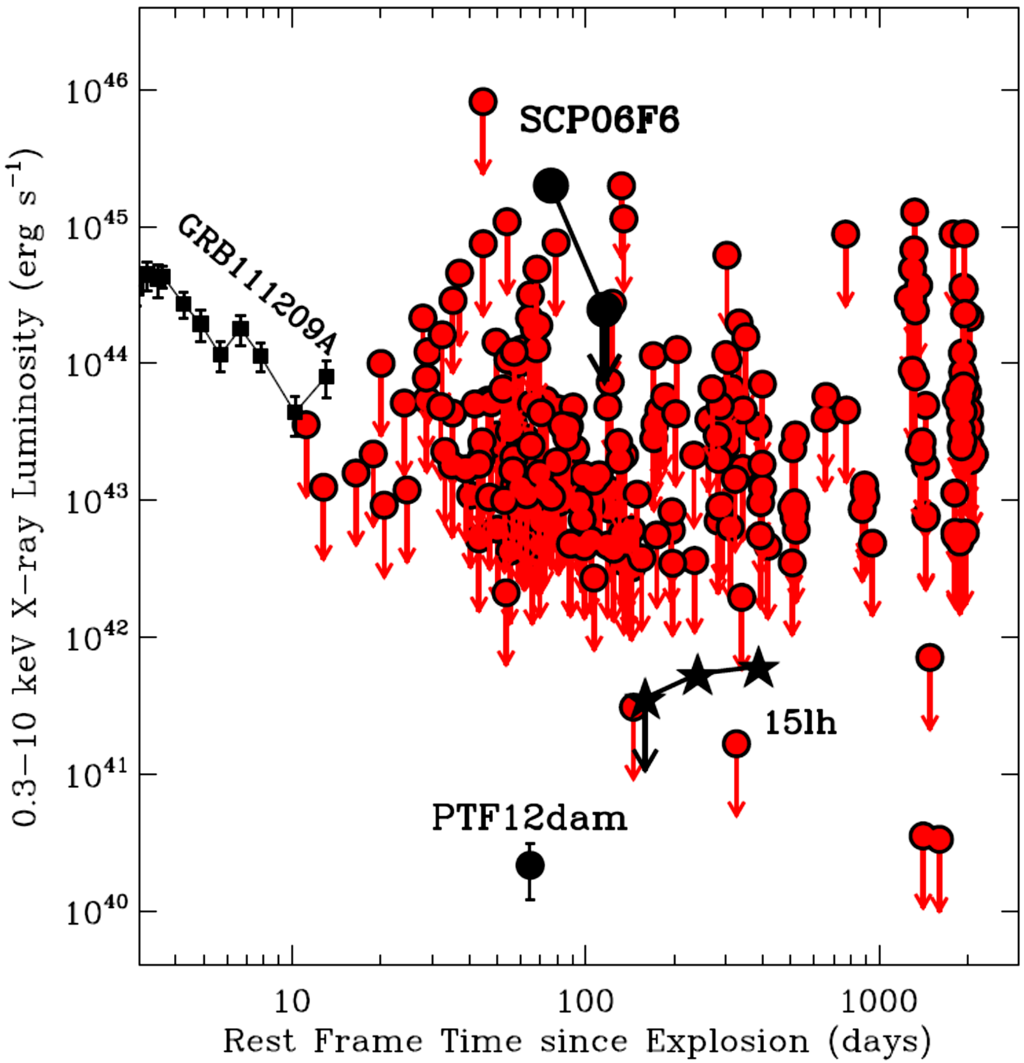
SLSN-I PTF15esb: bumpy light curve



(Yan+16)

- Multiple-shell CSM interaction model. Late-time H (+100d). He?

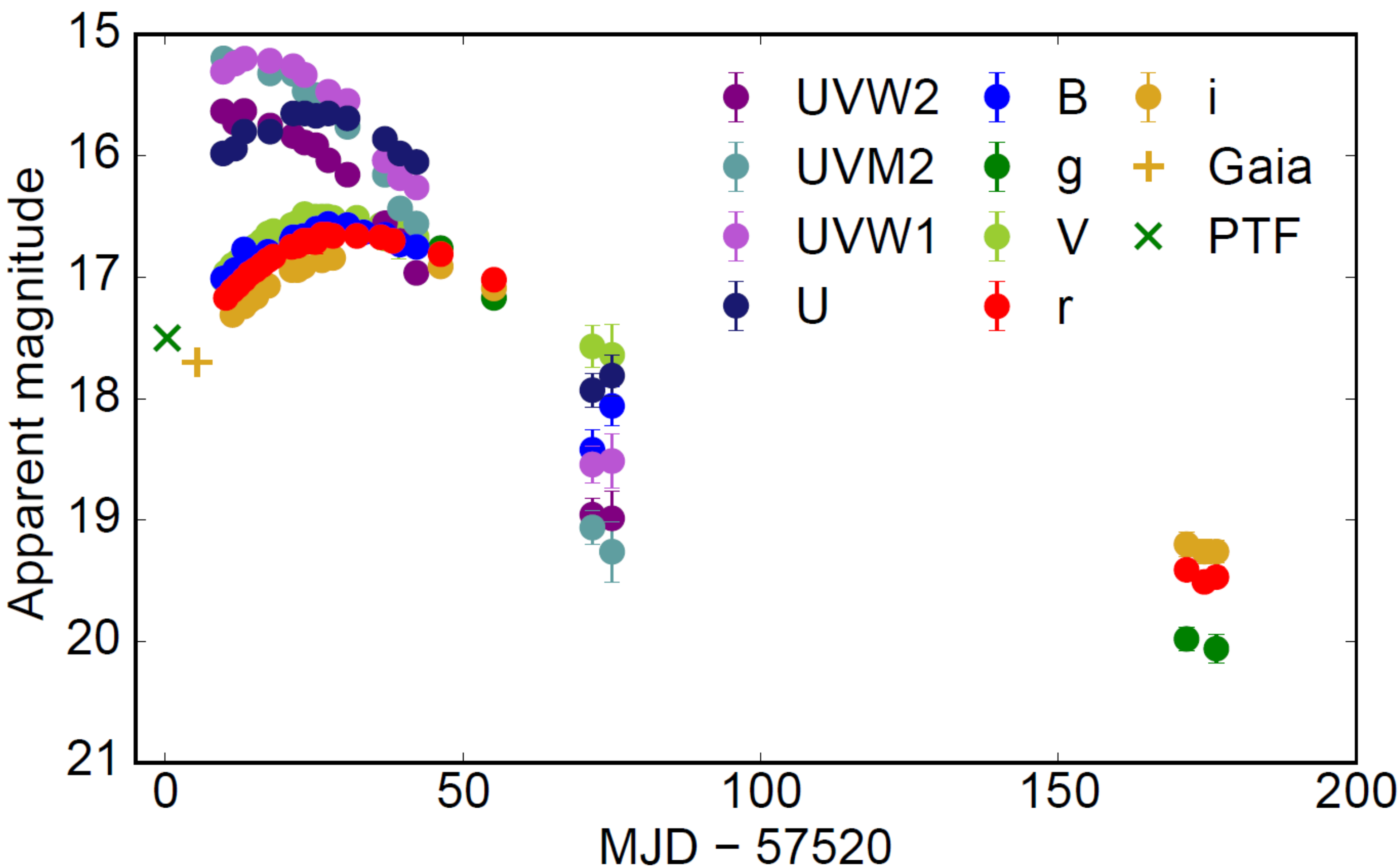
X-ray observations of SLSN-I



- 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

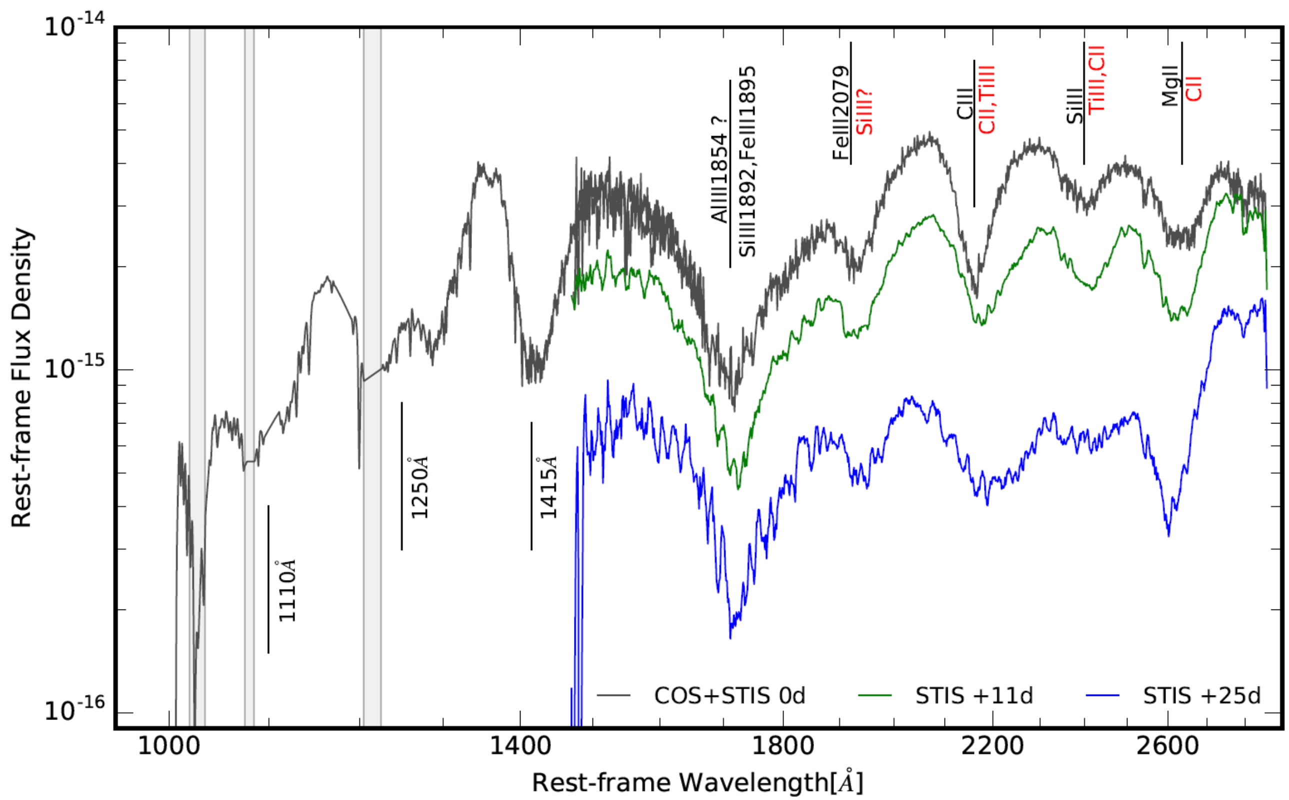
Hydrogen-poor UV-bright Gaia16apd

- Extraordinarily UV-bright emission among superluminous supernovae (Kangas et al. 2017; Yan et al. 2017; Nicholl 2017)



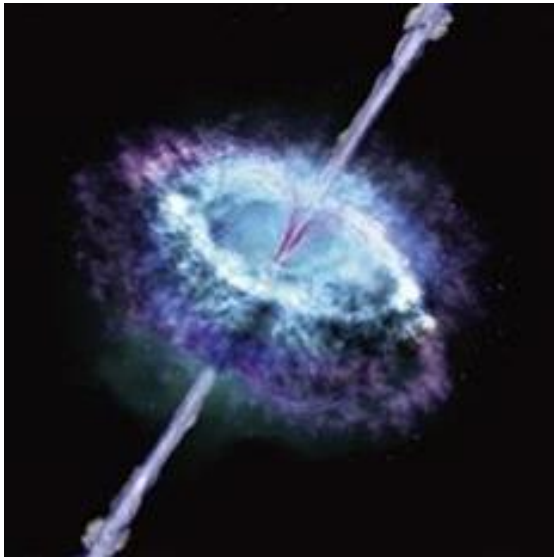
Gaia16apd far-UV spectrum (Yan+17)

- The complete and reliable identification of the UV absorption features requires future detailed modeling
- Tentative comparison with the published synthetic UV spectra (made available by D. Kasen) suggests that Gaia16apd may be an explosion of a massive C+O core with a sub-solar metal abundance



SLSN-I Gaia16apd (SN 2016eay)

- (Yan+17) z=0.1018, $L=3\cdot10^{44}$ erg, t_{rise}=33d (uncertain up to 72d), 50% luminosity in 1000-2500A. Spectrum is similar to PS1-11bam, 6 spectral features similar to SN1992A, SN2017fe (SNIa), ejecta velocity 14,000 km/s, no X-rays
- (Kangas+17), spectroscopically similar to PTF12dam, v=15,600…19,800 km/s from -16.2d to +2.8d; 12,700-12,400 from +2.8d to +43d; v=10,000 at +150d
- Interaction? Magnetar? PISN?

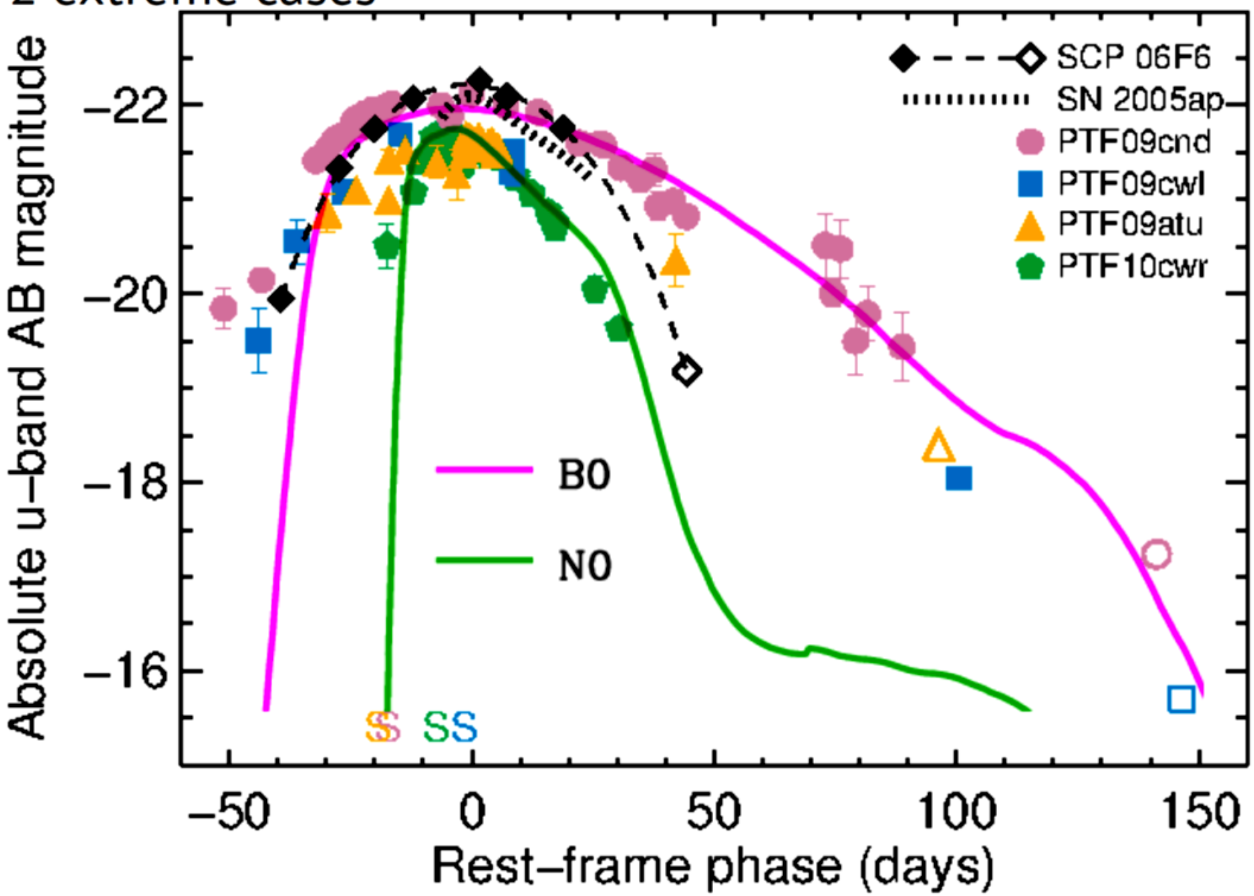




(Image credit: Kavli IPMU)

Arguments for interaction model

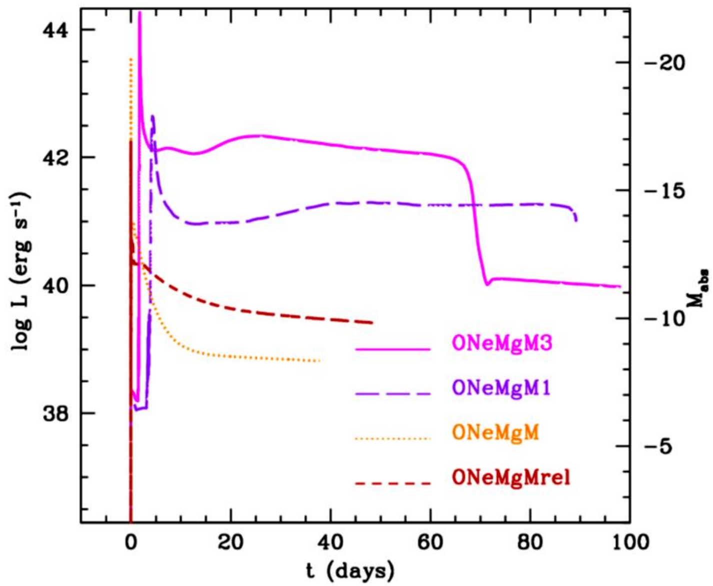
(Sorokina+ 2016)

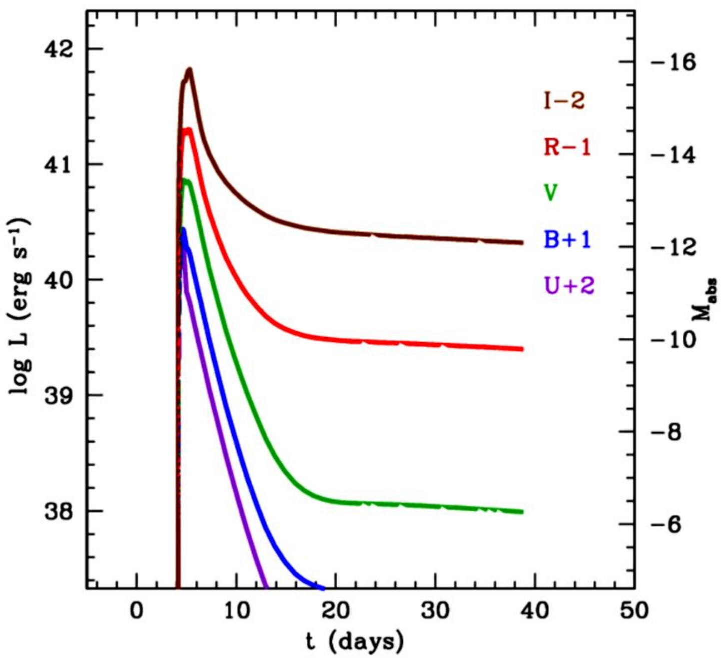
- STELLA reproduces a wide range of SLSNe in the interaction model: 2 extreme cases



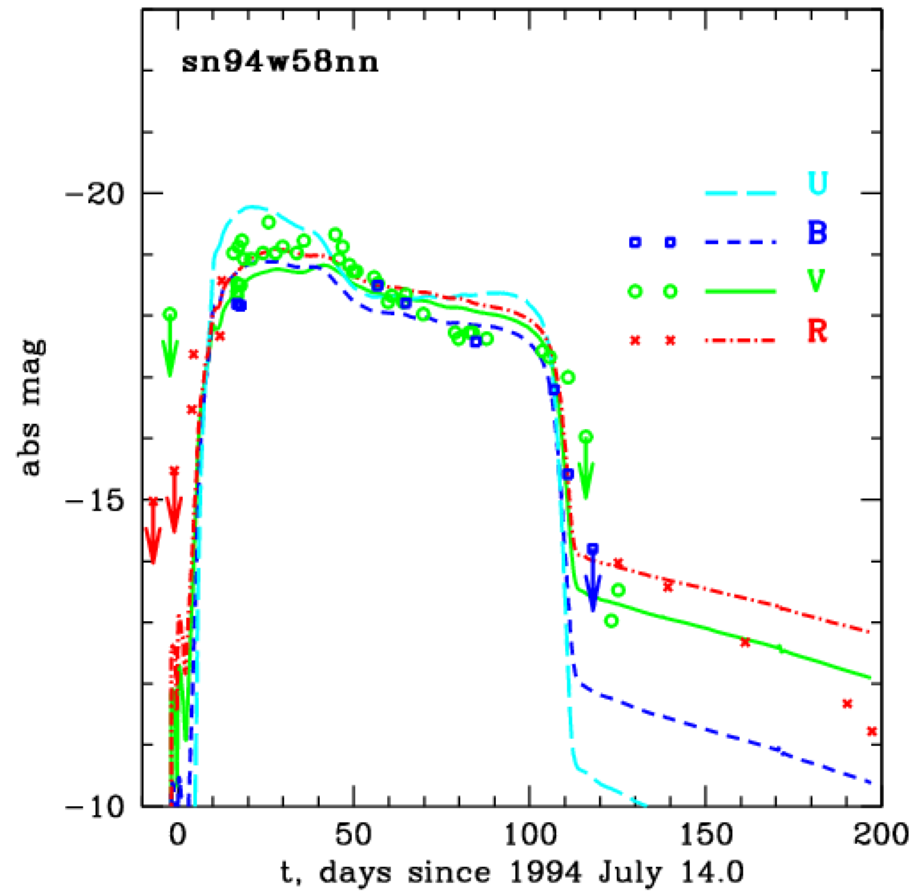
Explosion energy is just 2 - 4 foe

Multicolor light curves: models with mass loss



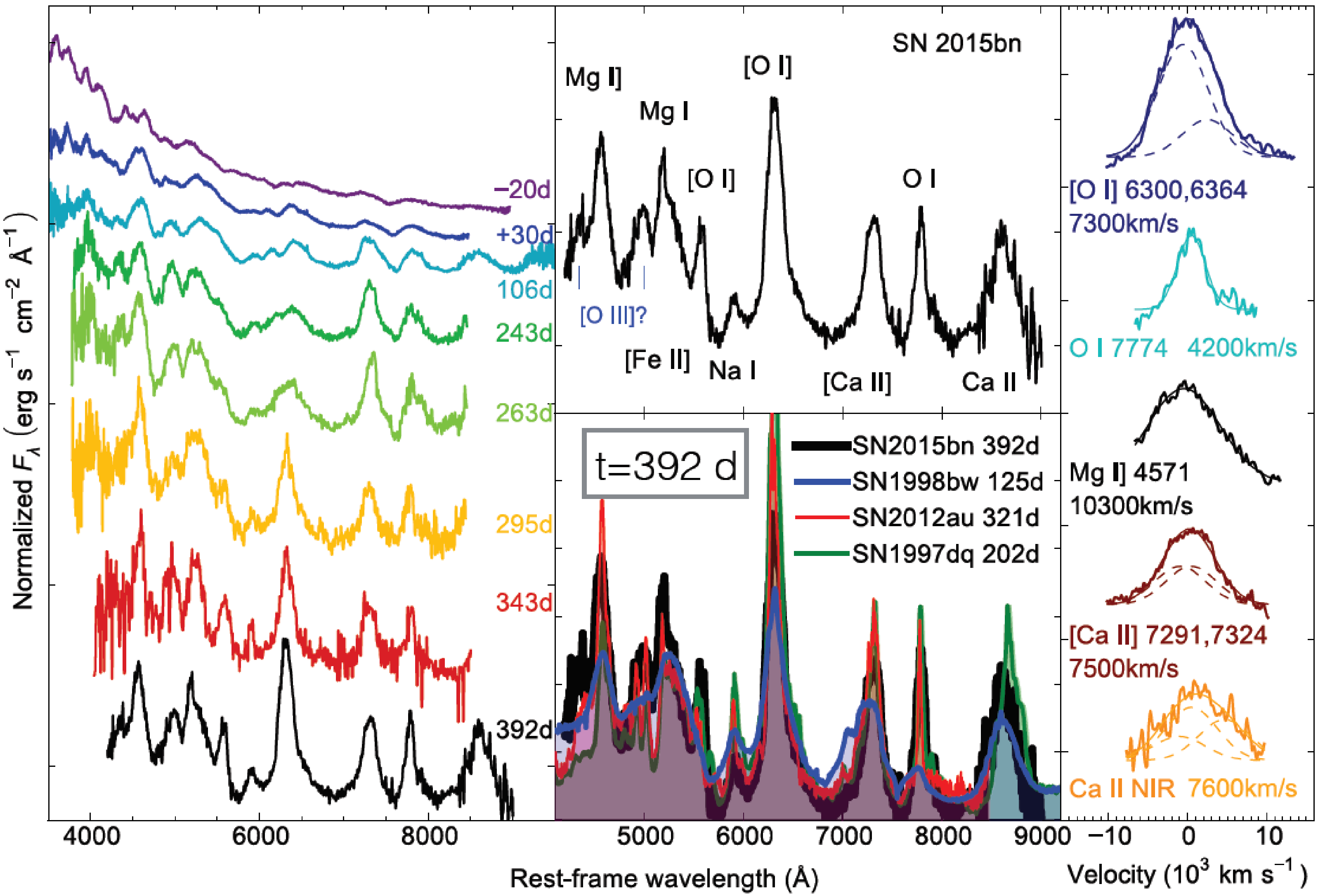


- ONeMg core + envelope (model for SN 1054, Tominaga+ 2013)
- Rapidly-evolving faint transients started to be observed (Drout2013)



- SN 1994W model of Chugai&Blinnikov2004

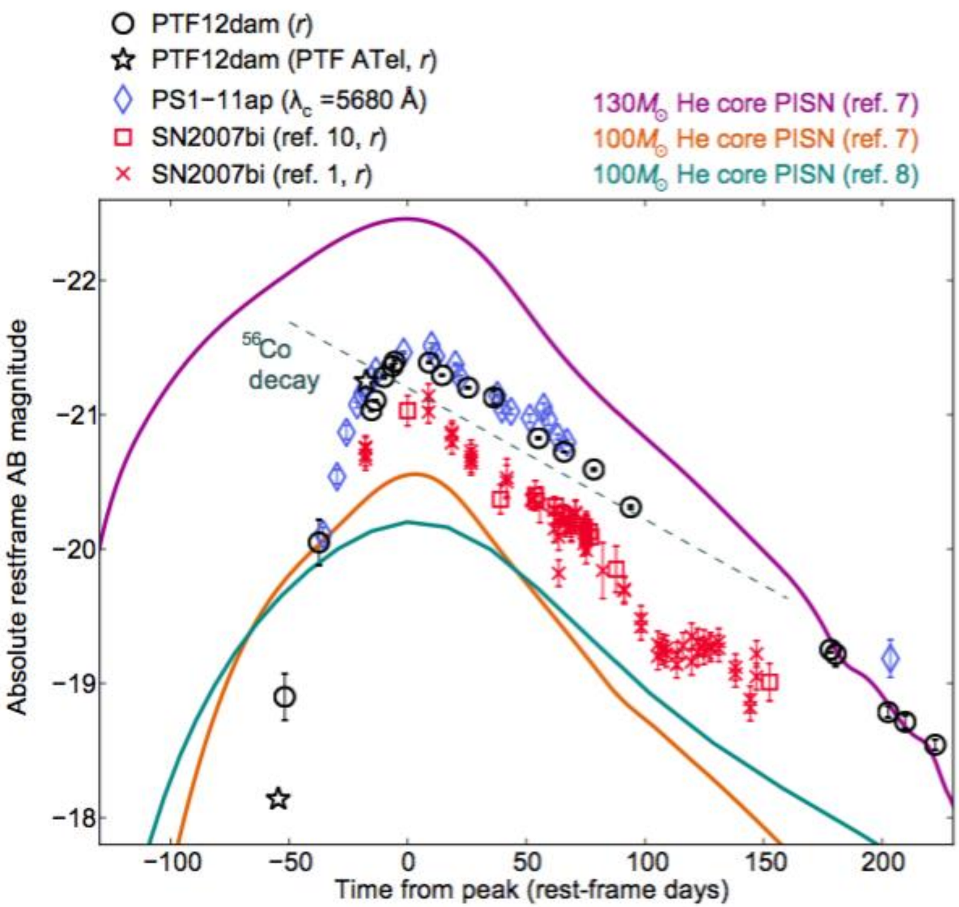
Similarity of SLSN2015bn to "Hypernovae" at late times (by R. Margutti)



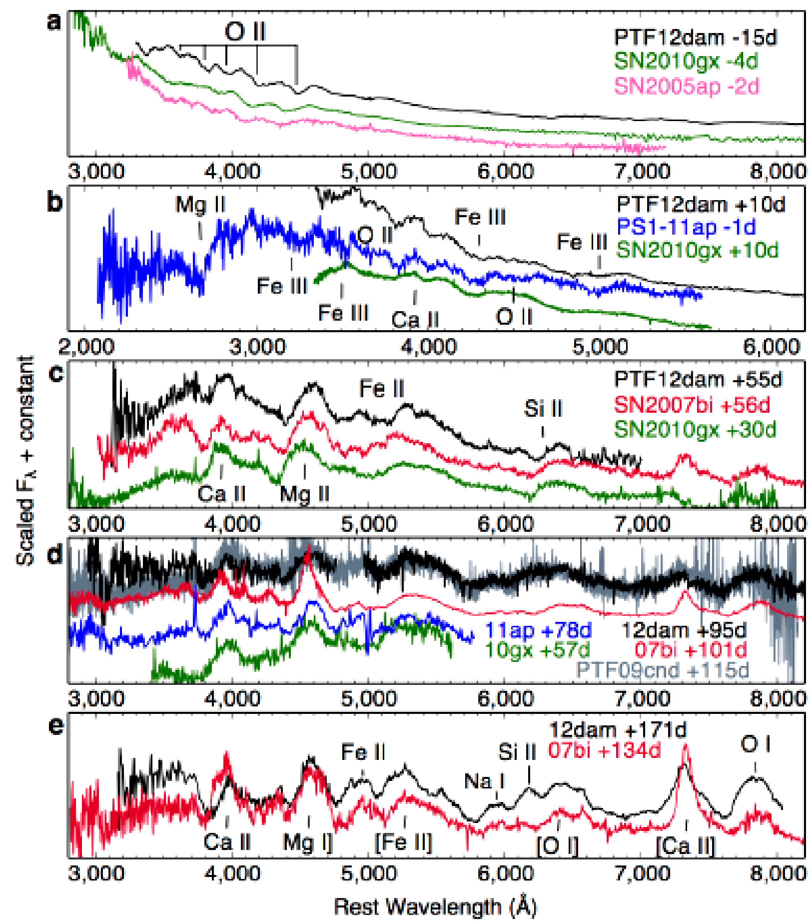
Nicholl+2016

SLSN I-R PTF12dam: light curves and spectra

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

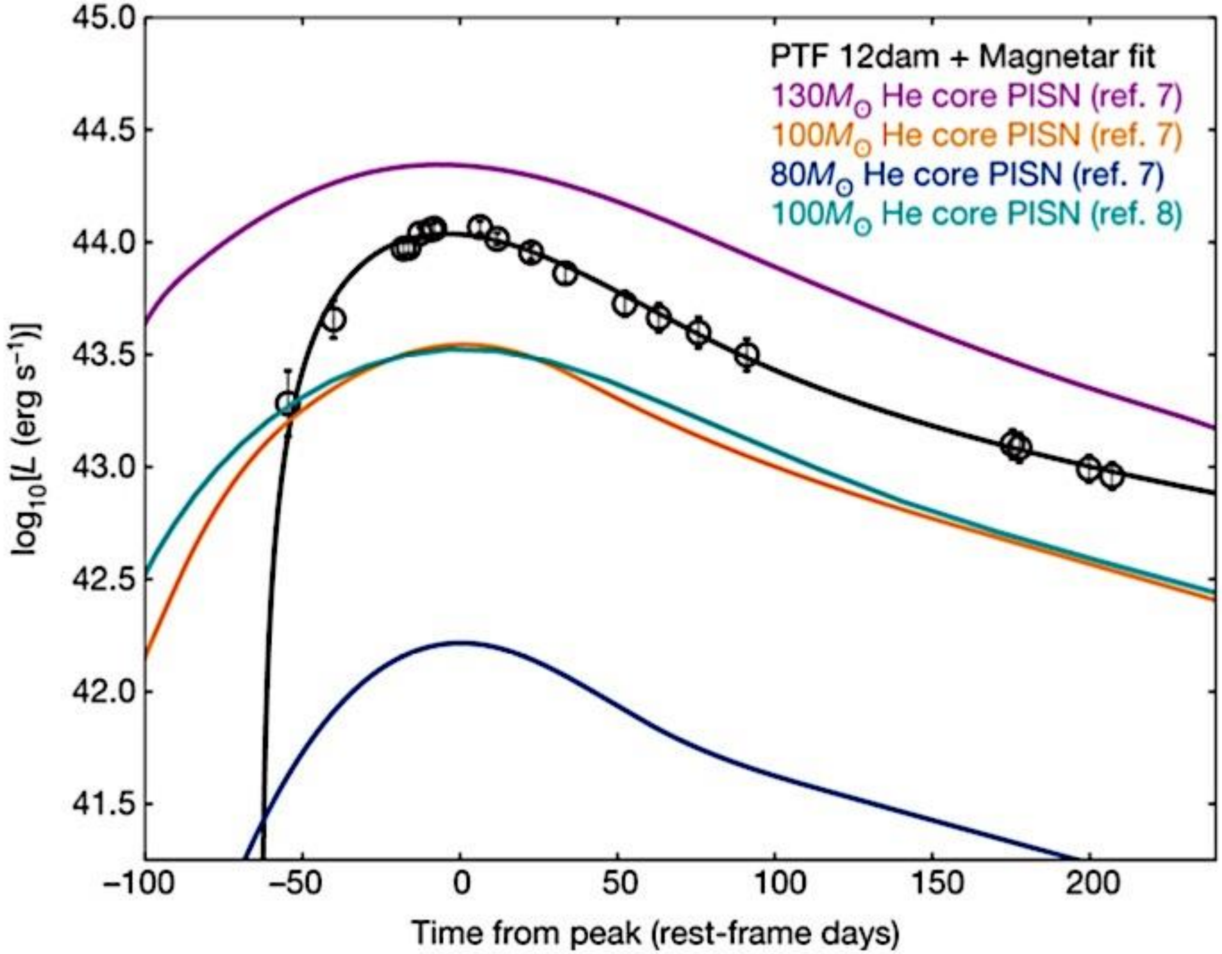


- Spectral evolution of PTF12dam (Nicholl et al. 2013), lack of hydrogen/helium



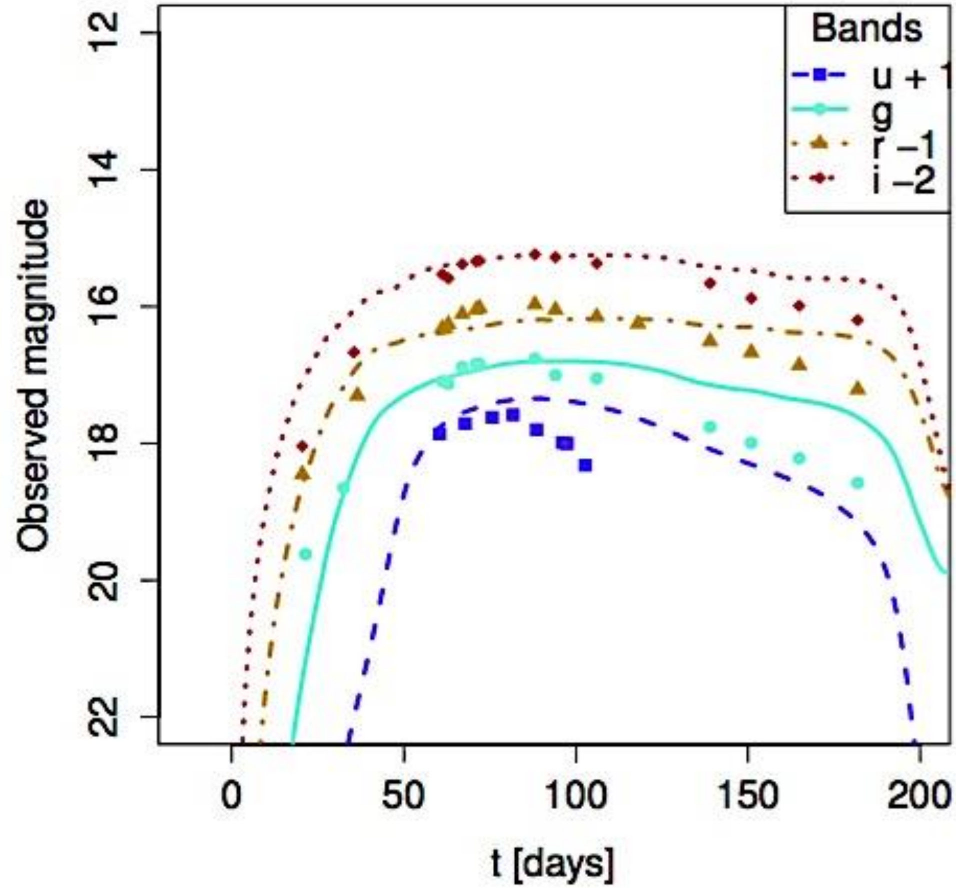
PTF12dam: bolometric light curves and “magnetar” fit

(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)

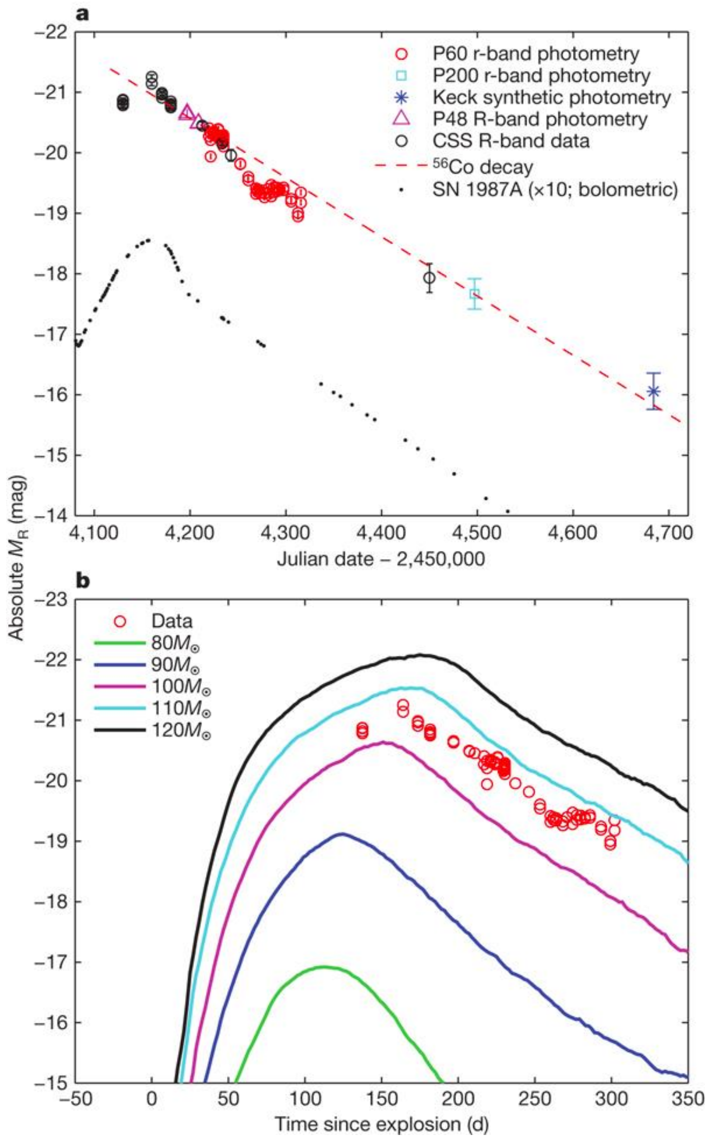
Simulated and observed light curves (Baklanov et al. 2015)



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

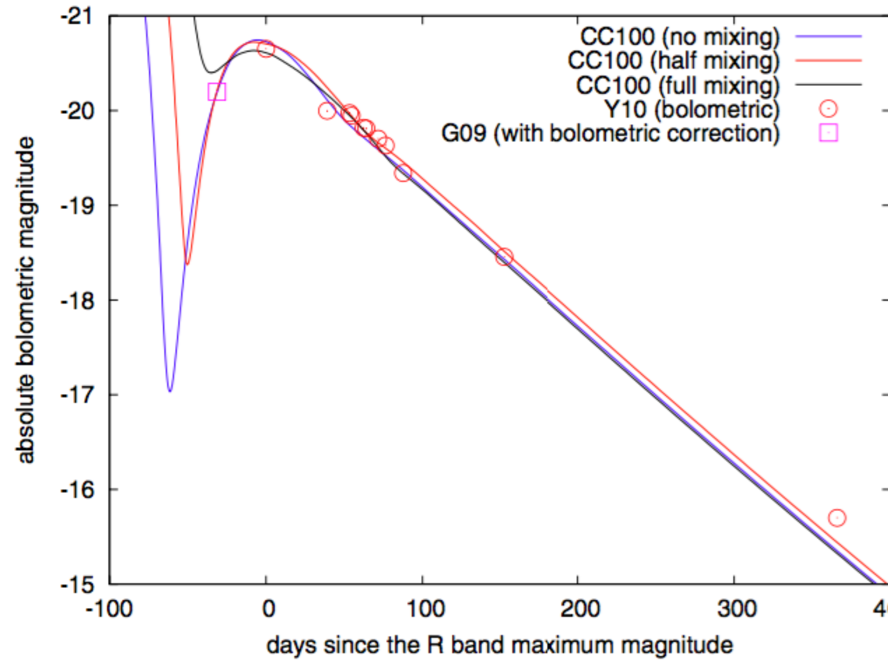
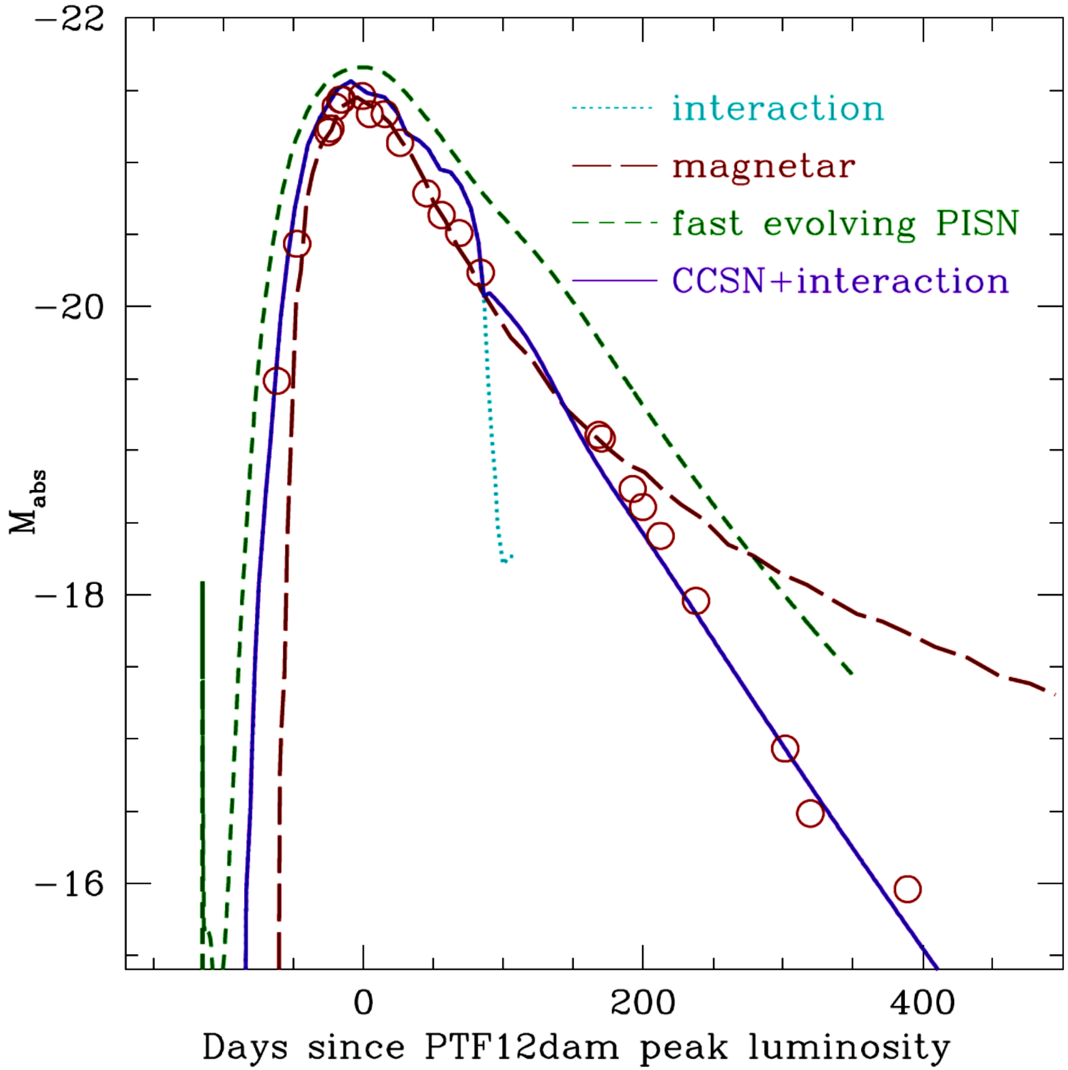


Figure 1. Bolometric LCs of the C+O star SN models CC100 ($M_{\rm ej} = 40\ M_\odot$, $E_{\rm kin} = 3.6 \times 10^{52}$ erg, and $M_{^{56}\rm Ni} = 6.1\ M_\odot$). The observed bolometric LC (open circles) is taken from Y10. The bolometric magnitude of the rising part of SN 2007bi (open square) is estimated 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.

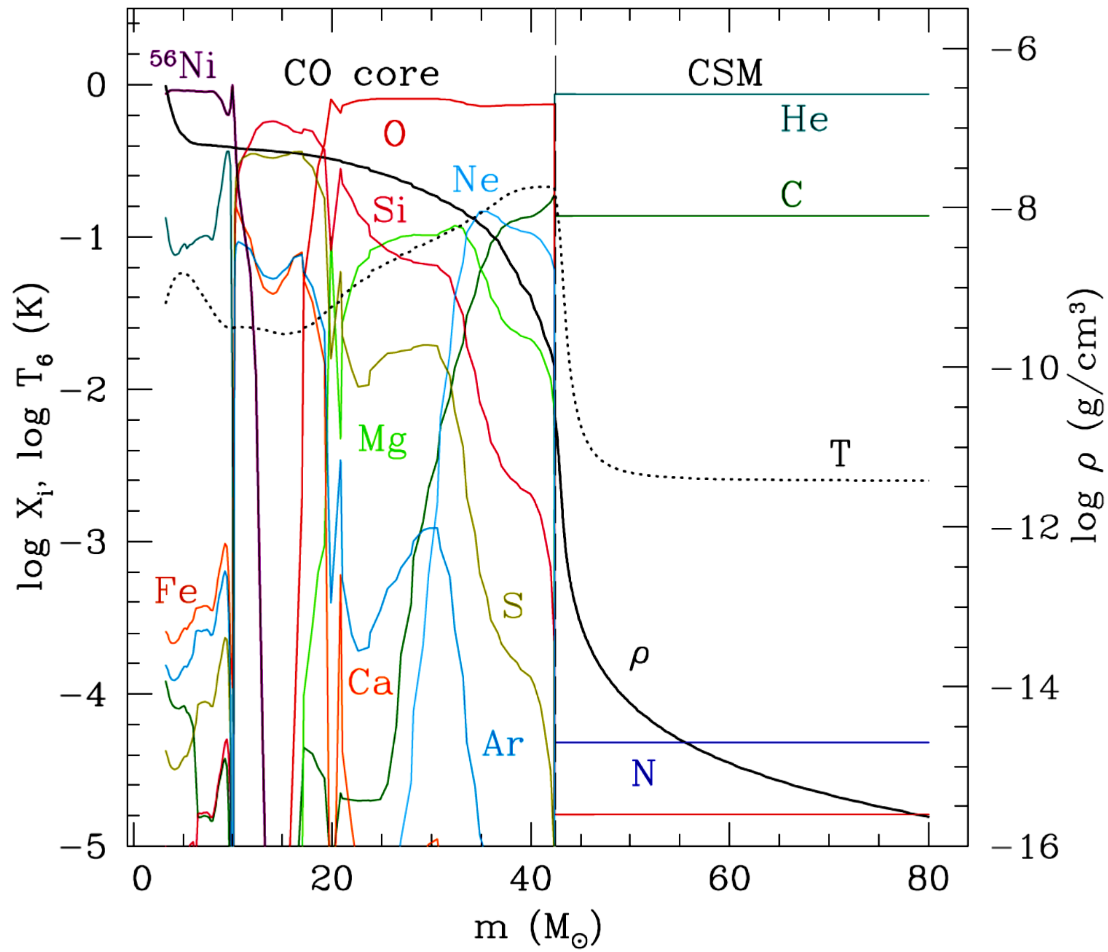
PTF12dam: PISN, CCSN models



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

Interaction model: composition and structure of pre-SN

- M_{ZAMS}=100 $M_\odot$, Z = $Z_\odot$/200 (Umeda&Nomoto 2008)
- PTF12dam: pre-SN C+O core ($43M_\odot$), M_{cut} =$3M_\odot$
- 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

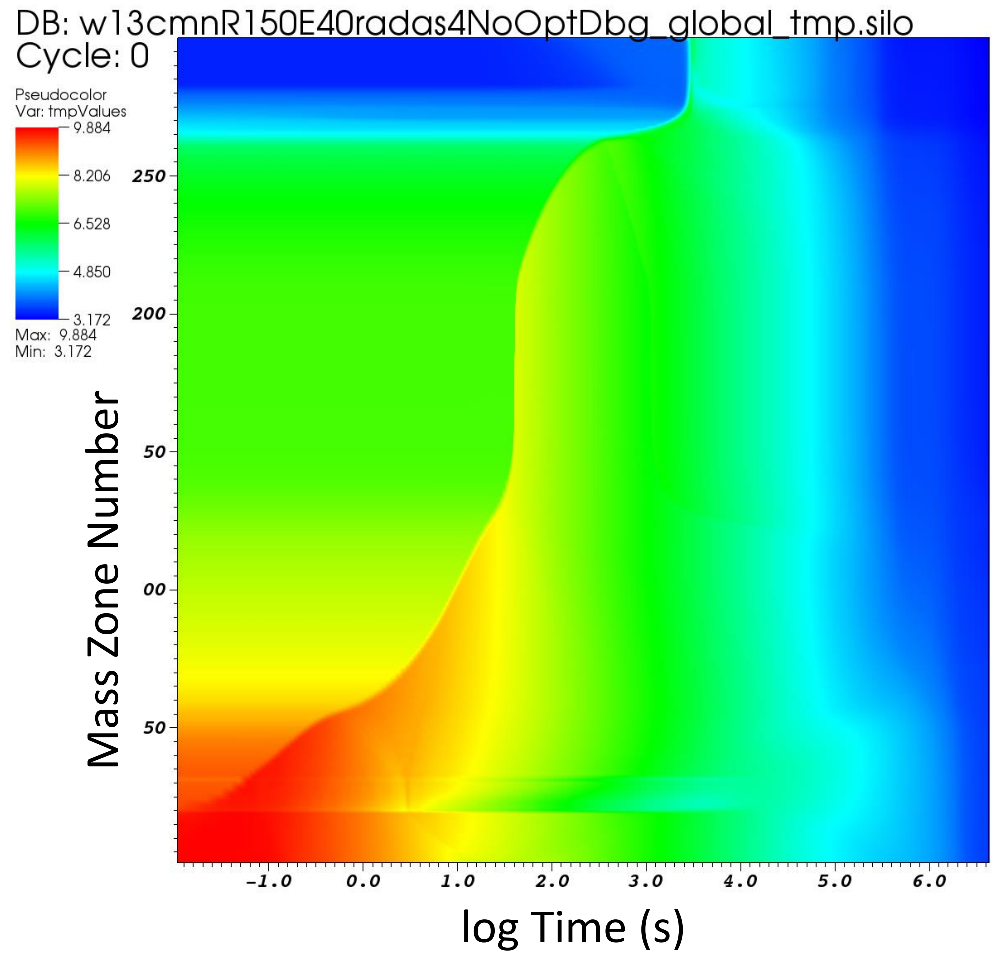


Numerical code STELLA

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

- 1D Lagrangian Hydro + Radiation Moments Equations (2D), 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)

Temperature evolution



Comoving radiative transfer equation (Mihalas 1980)

Transfer equation:

$$\frac{\gamma}{c}(1+\beta\mu_0)\frac{\partial I_0(\mu_0,\nu_0)}{\partial t}+\gamma(\mu_0+\beta)\frac{\partial I_0(\mu_0,\nu_0)}{\partial r}$$
$$+\gamma(1-\mu_0{}^2)\left[\frac{(1+\beta\mu_0)}{r}-\frac{\gamma^2}{c}(1+\beta\mu_0)\frac{\partial\beta}{\partial t}-\gamma^2(\mu_0+\beta)\frac{\partial\beta}{\partial r}\right]\frac{\partial I_0(\mu_0,\nu_0)}{\partial\mu_0}$$
$$-\gamma\left[\frac{\beta(1-\mu_0{}^2)}{r}+\frac{\gamma^2}{c}\mu_0(1+\beta\mu_0)\frac{\partial\beta}{\partial t}+\gamma^2\mu_0(\mu_0+\beta)\frac{\partial\beta}{\partial r}\right]\nu_0\frac{\partial I_0(\mu_0,\nu_0)}{\partial\nu_0}$$
$$+3\gamma\left[\frac{\beta(1-\mu_0{}^2)}{r}+\frac{\gamma^2\mu_0}{c}(1+\beta\mu_0)\frac{\partial\beta}{\partial t}+\gamma^2\mu_0(\mu_0+\beta)\frac{\partial\beta}{\partial r}\right]I_0(\mu_0,\nu_0)$$
$$=\eta_0(\nu_0)-\chi_0(\nu_0)I_0(\mu_0,\nu_0)\,.$$

Moment equations:

$$\frac{\gamma}{c}\left[\frac{\partial J_0(\nu_0)}{\partial t}+\beta\frac{\partial H_0(\nu_0)}{\partial t}\right]+\gamma\left[\frac{\partial H_0(\nu_0)}{\partial r}+\beta\frac{\partial J_0(\nu_0)}{\partial r}\right]$$
$$-\gamma\nu_0\left\{\frac{\beta}{r}\left[\frac{\partial J_0(\nu_0)}{\partial\nu_0}-\frac{\partial K_0(\nu_0)}{\partial\nu_0}\right]+\frac{\gamma^2}{c}\frac{\partial\beta}{\partial t}\left[\frac{\partial H_0(\nu_0)}{\partial\nu_0}+\beta\frac{\partial K_0(\nu_0)}{\partial\nu_0}\right]+\gamma^2\frac{\partial\beta}{\partial r}\left[\frac{\partial K_0(\nu_0)}{\partial\nu_0}+\beta\frac{\partial H_0(\nu_0)}{\partial\nu_0}\right]\right\}$$
$$+\gamma\left\{\frac{2}{r}[H_0(\nu_0)+\beta J_0(\nu_0)]+\frac{\gamma^2}{c}\frac{\partial\beta}{\partial t}[H_0(\nu_0)+\beta J_0(\nu_0)]+\gamma^2\frac{\partial\beta}{\partial r}[J_0(\nu_0)+\beta H_0(\nu_0)]\right\}$$
$$=\eta_0(\nu_0)-\chi_0(\nu_0)J_0(\nu_0)$$

$$\frac{\gamma}{c}\left[\frac{\partial H_0(\nu_0)}{\partial t}+\beta\frac{\partial K_0(\nu_0)}{\partial t}\right]+\gamma\left[\frac{\partial K_0(\nu_0)}{\partial r}+\beta\frac{\partial H_0(\nu_0)}{\partial r}\right]$$
$$-\gamma\nu_0\left\{\frac{\beta}{r}\left[\frac{\partial H_0(\nu_0)}{\partial\nu_0}-\frac{\partial N_0(\nu_0)}{\partial\nu_0}\right]+\frac{\gamma^2}{c}\frac{\partial\beta}{\partial t}\left[\frac{\partial K_0(\nu_0)}{\partial\nu_0}+\beta\frac{\partial N_0(\nu_0)}{\partial\nu_0}\right]+\gamma^2\frac{\partial\beta}{\partial r}\left[\frac{\partial N_0(\nu_0)}{\partial\nu_0}+\beta\frac{\partial K_0(\nu_0)}{\partial\nu_0}\right]\right\}$$
$$+\gamma\left\{\frac{1}{r}[3K_0(\nu_0)-J_0(\nu_0)+\beta H_0(\nu_0)+\beta N_0(\nu_0)]+\frac{\gamma^2}{c}\frac{\partial\beta}{\partial t}[J_0(\nu_0)+2\beta H_0(\nu_0)-\beta N_0(\nu_0)]\right.$$
$$\left.+\gamma^2\frac{\partial\beta}{\partial r}[2H_0(\nu_0)-N_0(\nu_0)+\beta J_0(\nu_0)]\right\}=-\chi_0(\nu_0)H_0(\nu_0)$$

SRRHD. Radiation-dominated mildly-relativistic shock

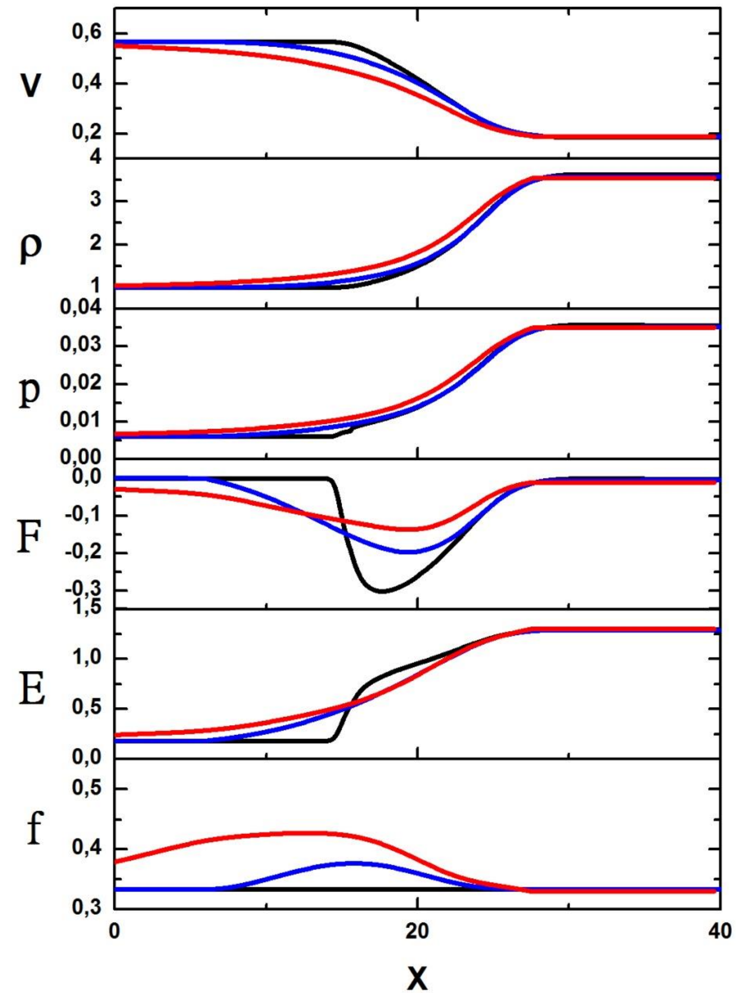
Semi-analytic relativistic hydro +
Relativistic radiation transfer
(no closure condition) (Tolstov et al. 2015)

Shock tube configuration
(Farris et al., 2008), $P_r/P_g \approx 10$

Γ	κ^a	Left state^c	Right State^c
5/3	0.08	$\rho_0 = 1.0$	$\rho_0 = 3.65$
		$P = 6.0 \times 10^{-3}$	$P = 3.59 \times 10^{-2}$
		$u^x = 0.69$	$u^x = 0.189$
		$E = 0.18$	$E = 1.30$

Closure condition: P = fE

- Eddington approximation: f = 1/3
- M1-closure (Levermore, 1984)
  f = f(E,F) joins "optically thin"
  and "thick" cases
- **Photon Boltzmann equation**



STELLA RADA integration (Tolstov2010)

STELLA

Hydro

Radiation Moments

Static Eddington factors

Fluxes in comoving frame

Output: Fluxes o(v/c) in observer frame

HD relativistic corrections
(Misner & Sharp, 1969)
$V \rightarrow V/[1+(V/C)^2]^{1/2}$
Doppler effect

RADA (relativistic, time-dependant)

Boltzmann transport equation

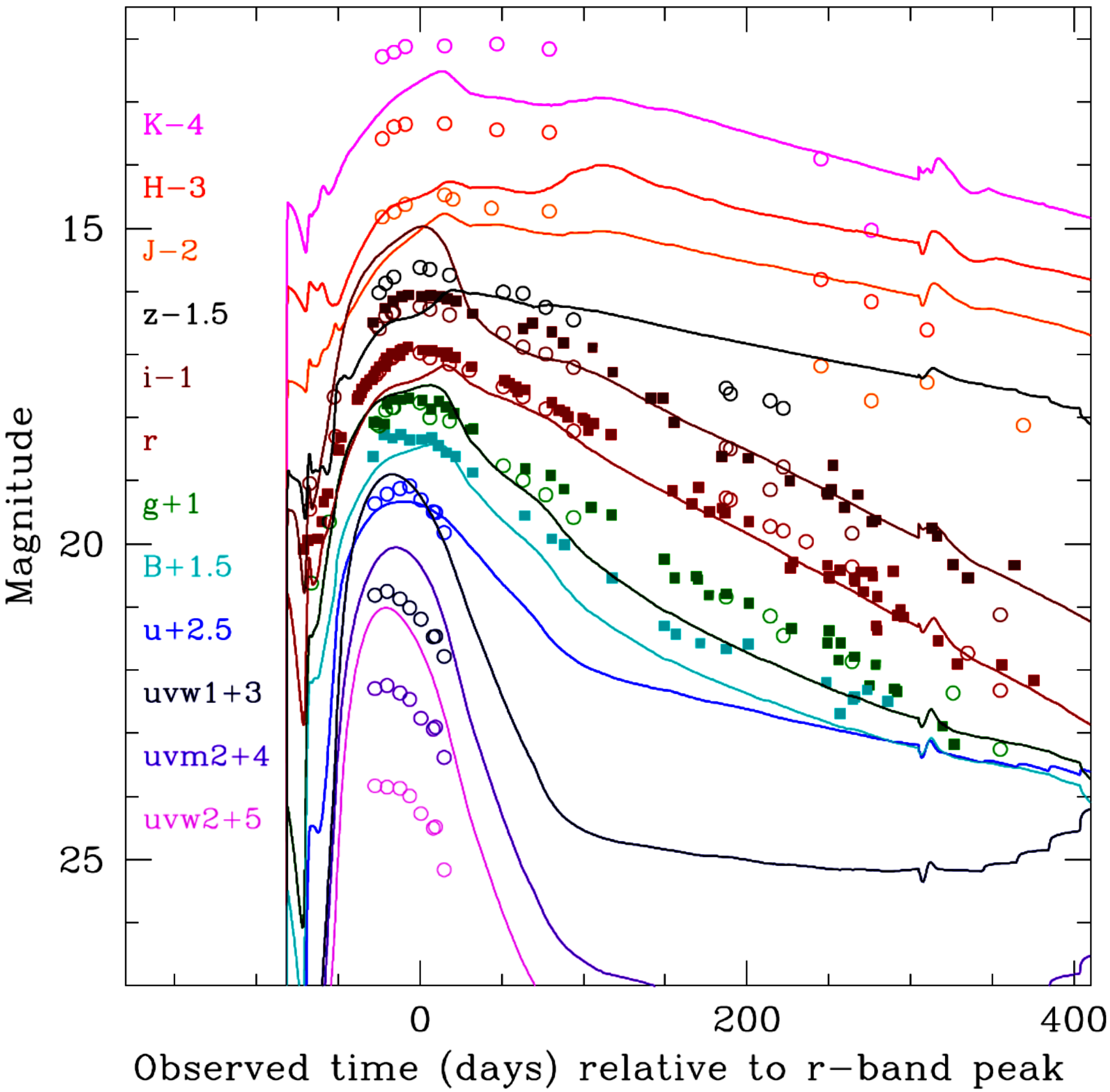
Time-dependent Eddington factors

Fluxes in comoving frame

Output: Fluxes in observer frame

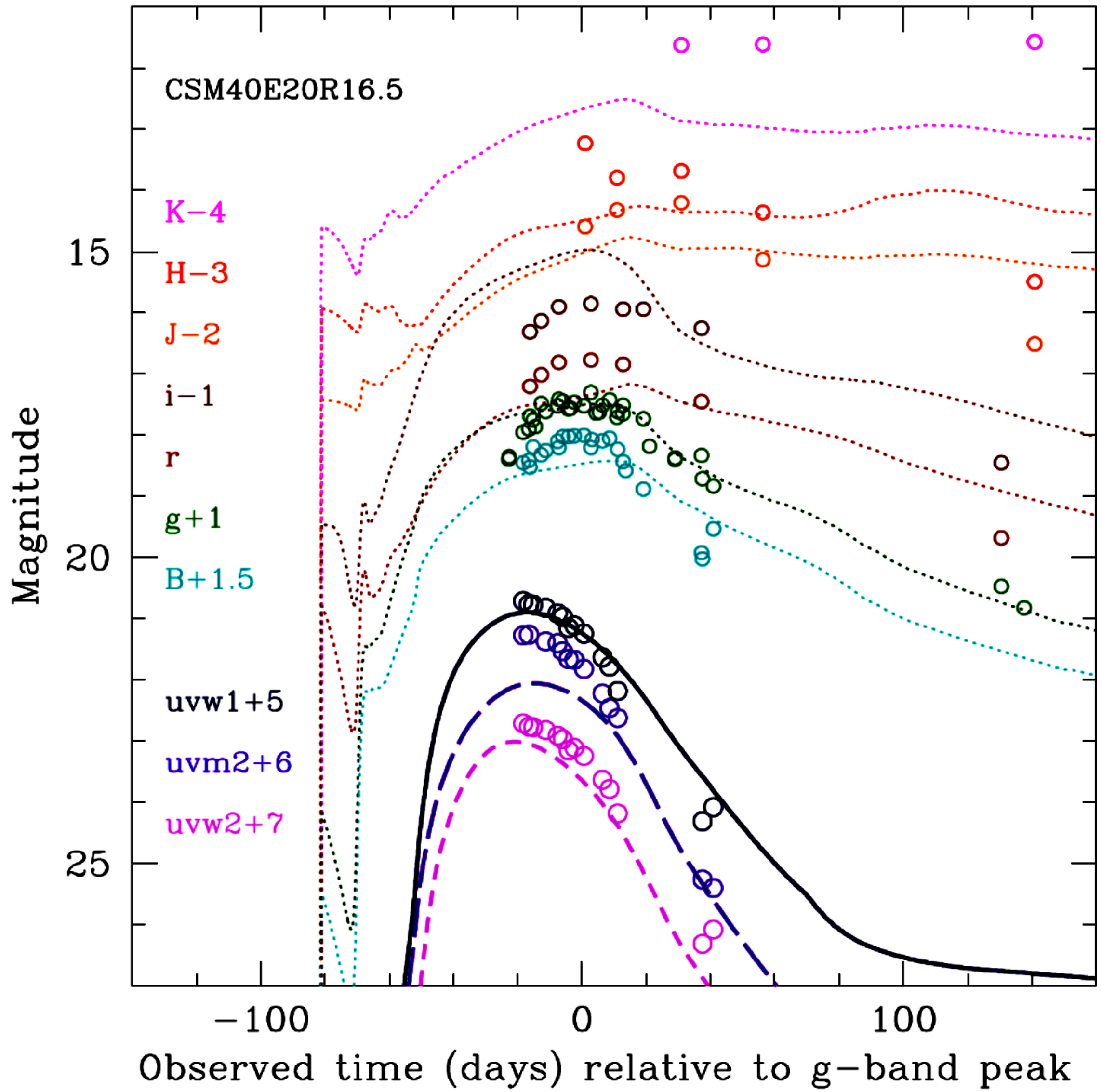
PTF12dam R16 model. Multicolor light curves

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



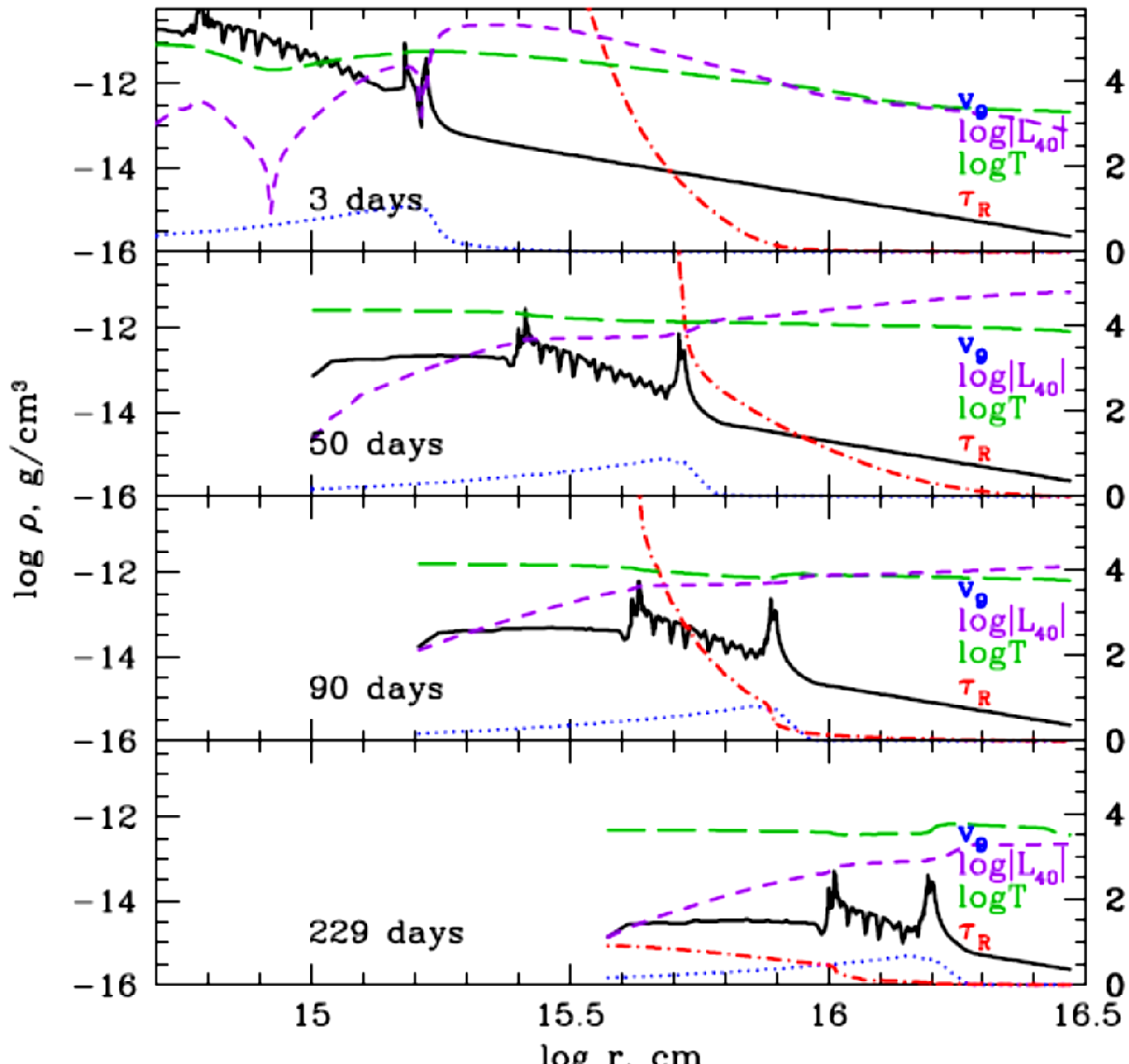
Gaia16apd R16 model. Multicolor light curves

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

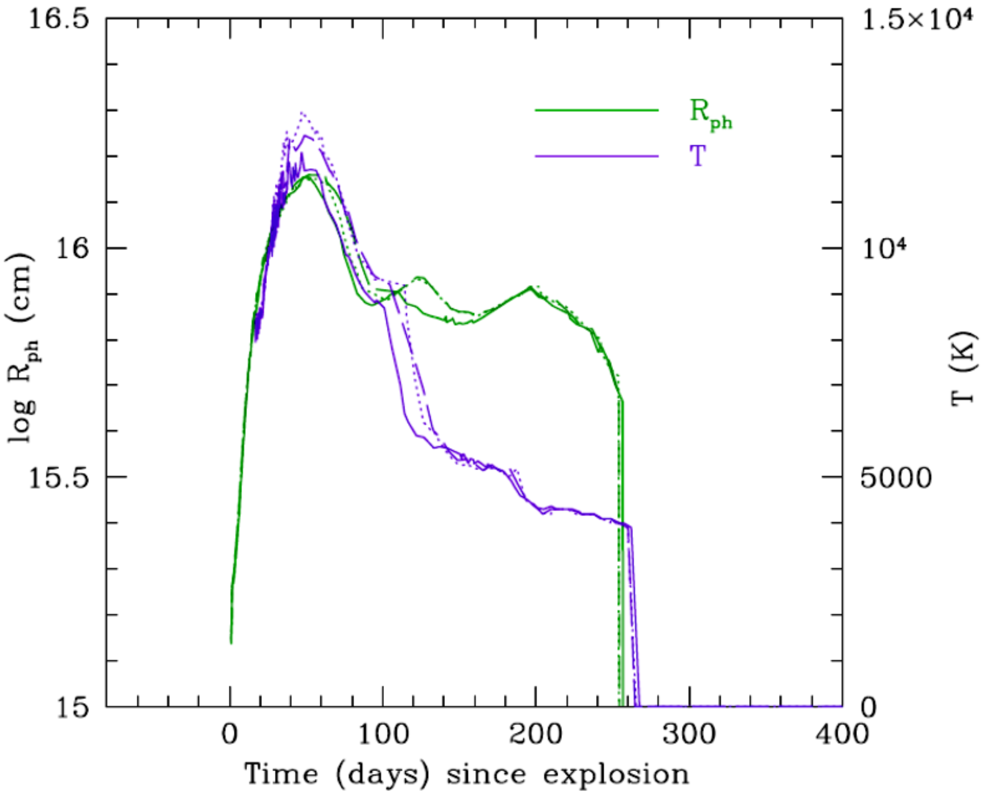


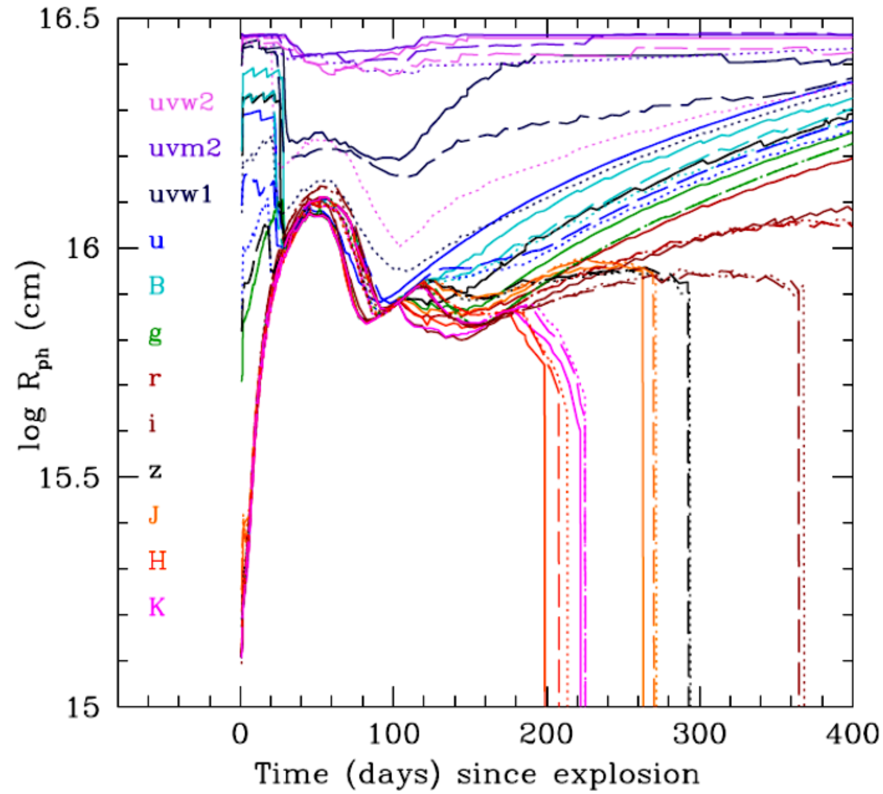
PTF12dam R16 model. Shock wave hydro

- 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)



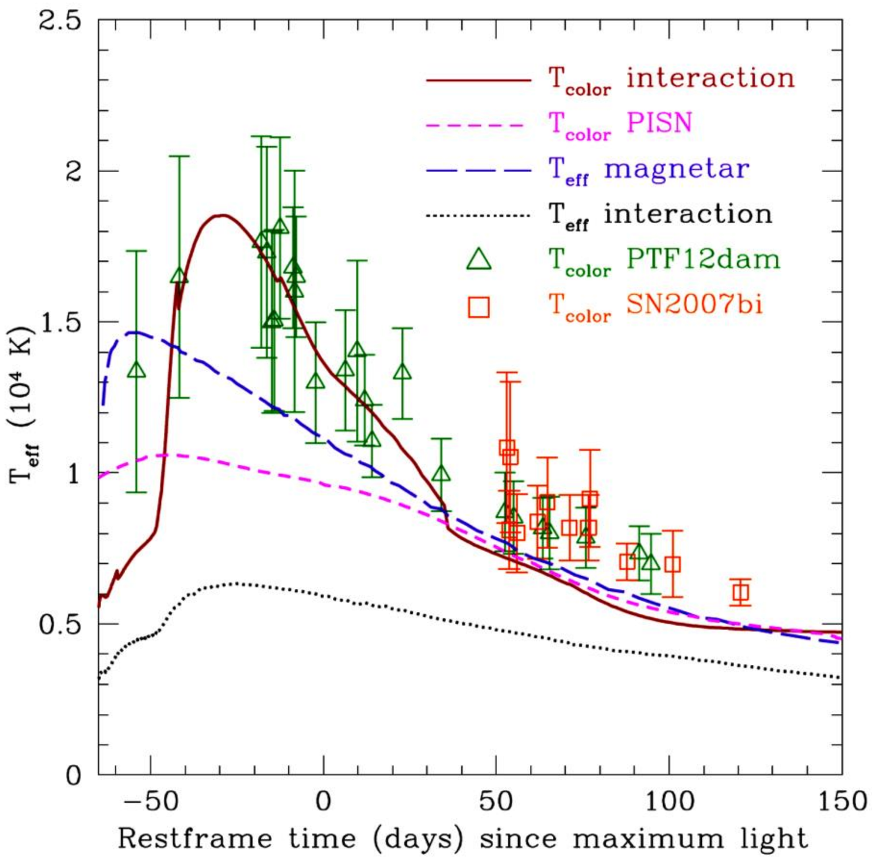
Photosperic temperature and radius



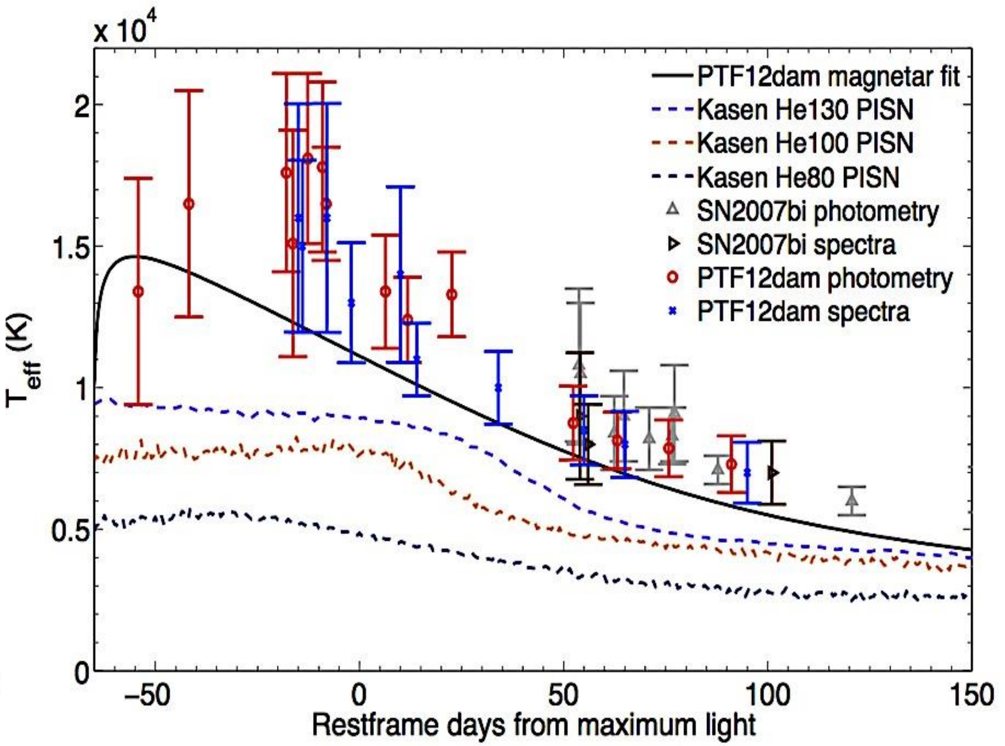


PTF12dam R16 model. Temperature evolution

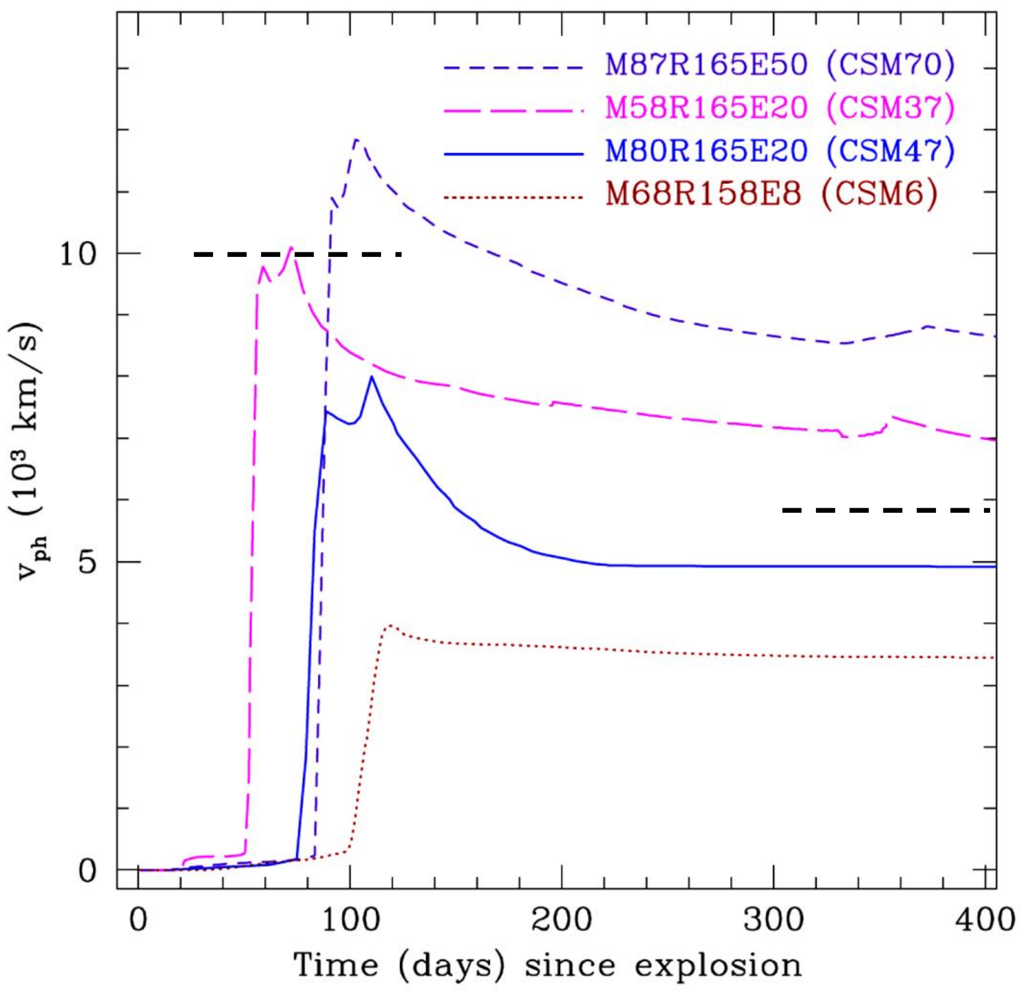
- Color and effective temperature evolution of PTF 12dam and SN 2007bi compared with interaction model



- 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



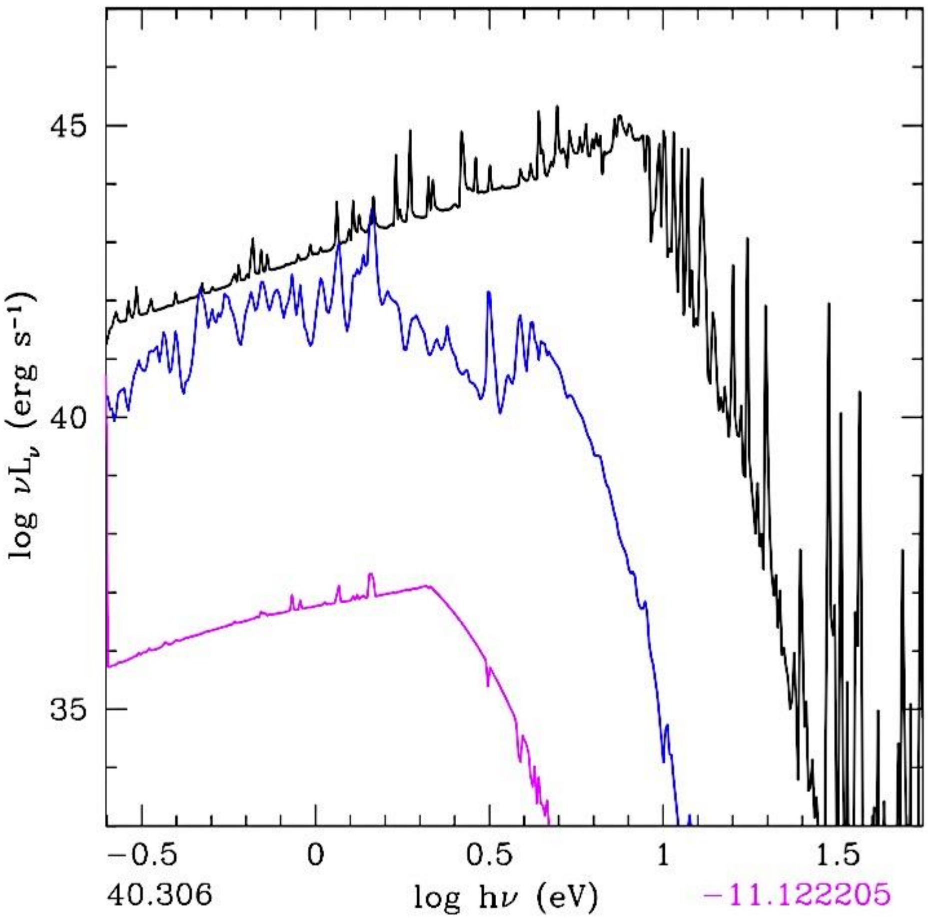
- Flux measurements of the broad SN lines of PTF12dam in the GTC spectrum taken at +509d (Chen 2014).

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**	$\mathbf{6.0 \pm 0.4 \times 10^{-16}}$

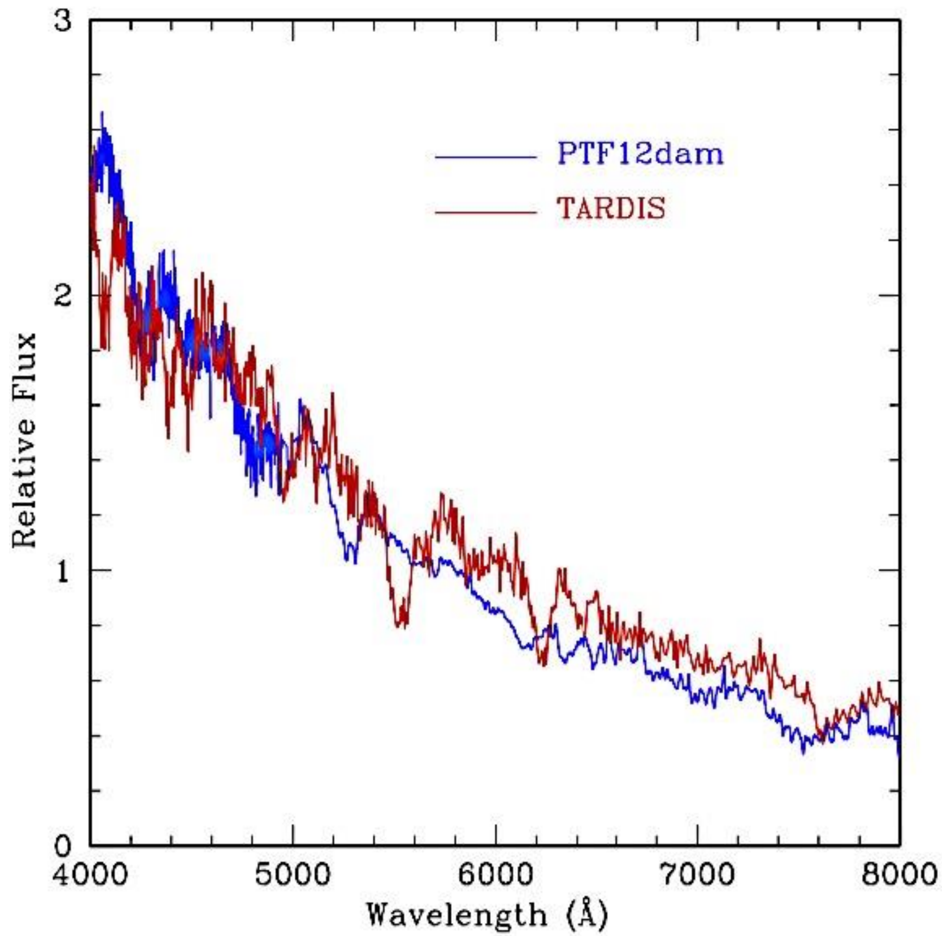
SN Name	EW (Å)	FWHM (Å)	Velocity (km s^{-1})	Luminosity ± Error (erg s^{-1})
PTF12dam (+509d)	187	74	~ 4000	$1.9 \pm 0.2 \times 10^{38}$
	332	**137**	**~ 5800**	$\mathbf{1.3 \pm 0.1 \times 10^{39}}$
	71	102	~ 4000	$2.9 \pm 0.3 \times 10^{38}$
	78	109	~ 4200	$3.3 \pm 0.4 \times 10^{38}$
SN 2007bi (+470d)	**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 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+17, Nicholl+17, Kangas+17).

- **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): $M_{ej} = 40\ M_{\odot}$, $M_{CSM} = 3 \ldots 100\ M_{\odot}$, $\log R_{CSM} = 14 \ldots 17$ cm, $E_{51,kin} = 5 \ldots 60$, CO / He composition, $M(^{56}\mathrm{Ni}) = 0 \ldots 6\ M_{\odot}$.

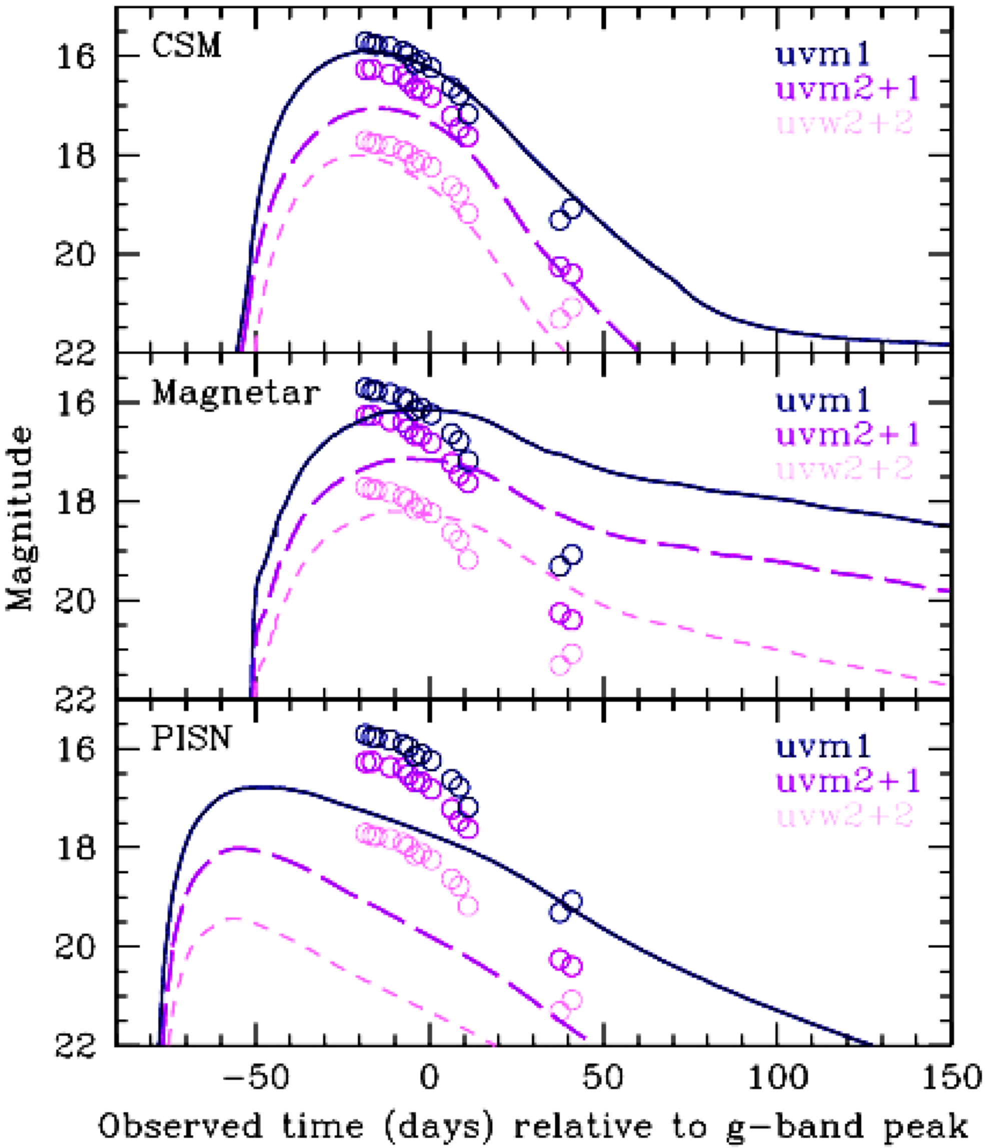
  - **Magnetar pumping**

  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**

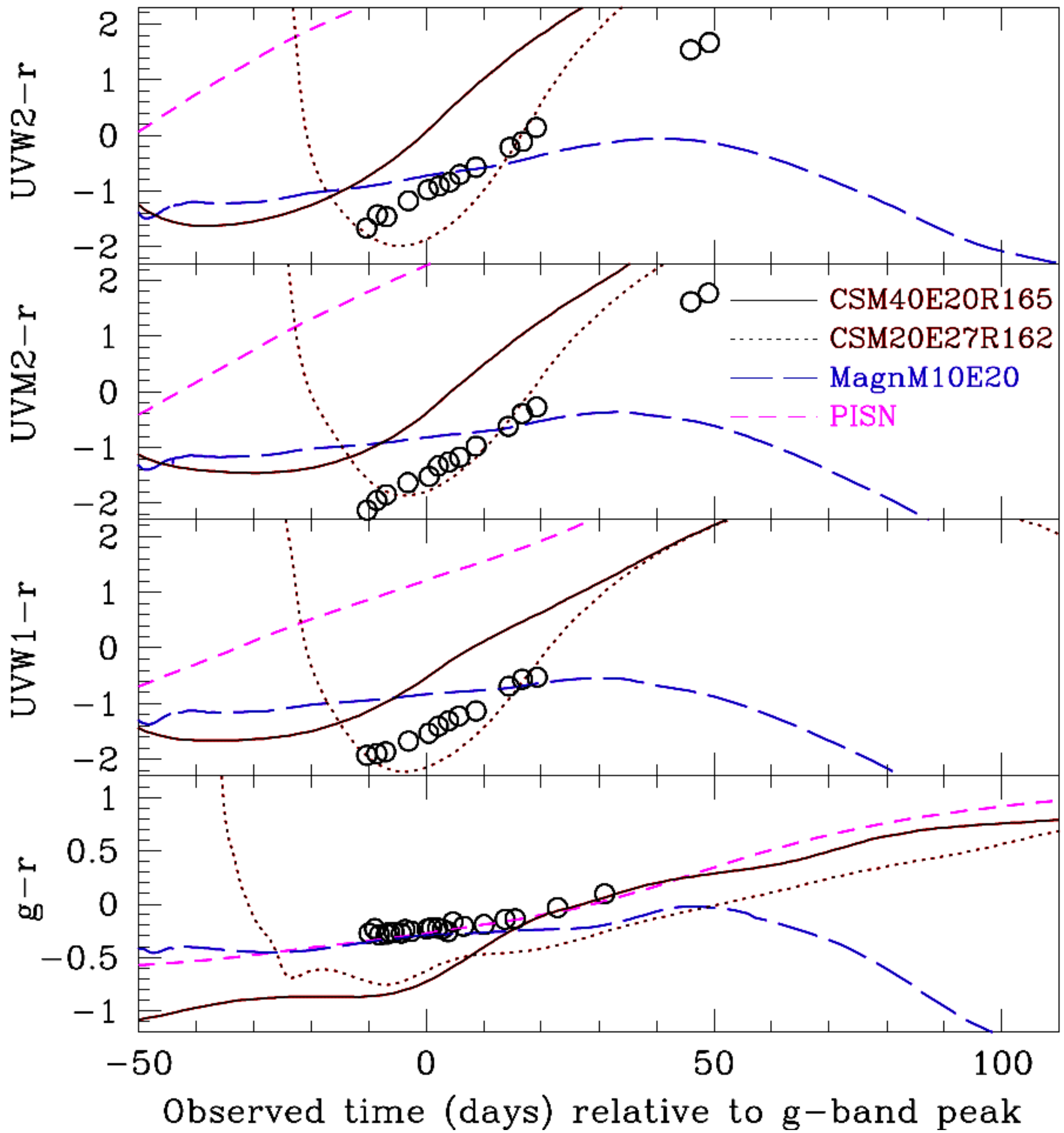
  He130Ni55 progenitor model (Heger&Woosley 2002), $R = 4\ R_{\odot}$, $M(^{56}\mathrm{Ni}) = 55\ M_{\odot}$, $M = 57\ M_{\odot}$, $E_{51,dep} = 44$.

Ultraviolet Emission of Gaia16apd



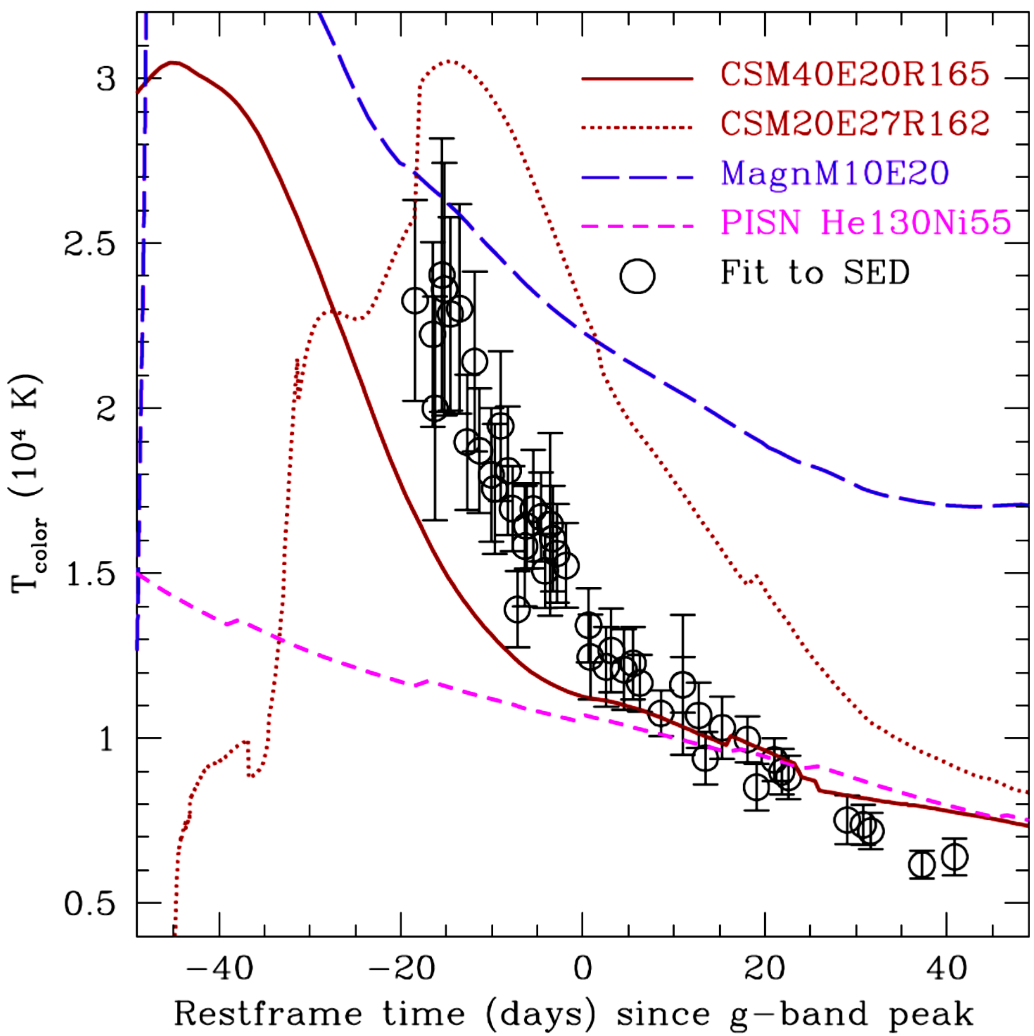
- **Which model best fits the UV data?**
  - Shock interaction with CSM
  - Magnetar pumping
  - Pair-instability supernova
- The best-fit (chi-squared minimization) of UV and optical light curves to Gaia16apd among ~ 150 models.
- **Conclusion**: interaction model is the most promising to explain extreme UV luminosity of Gaia16apd.

Gaia16apd color evolution



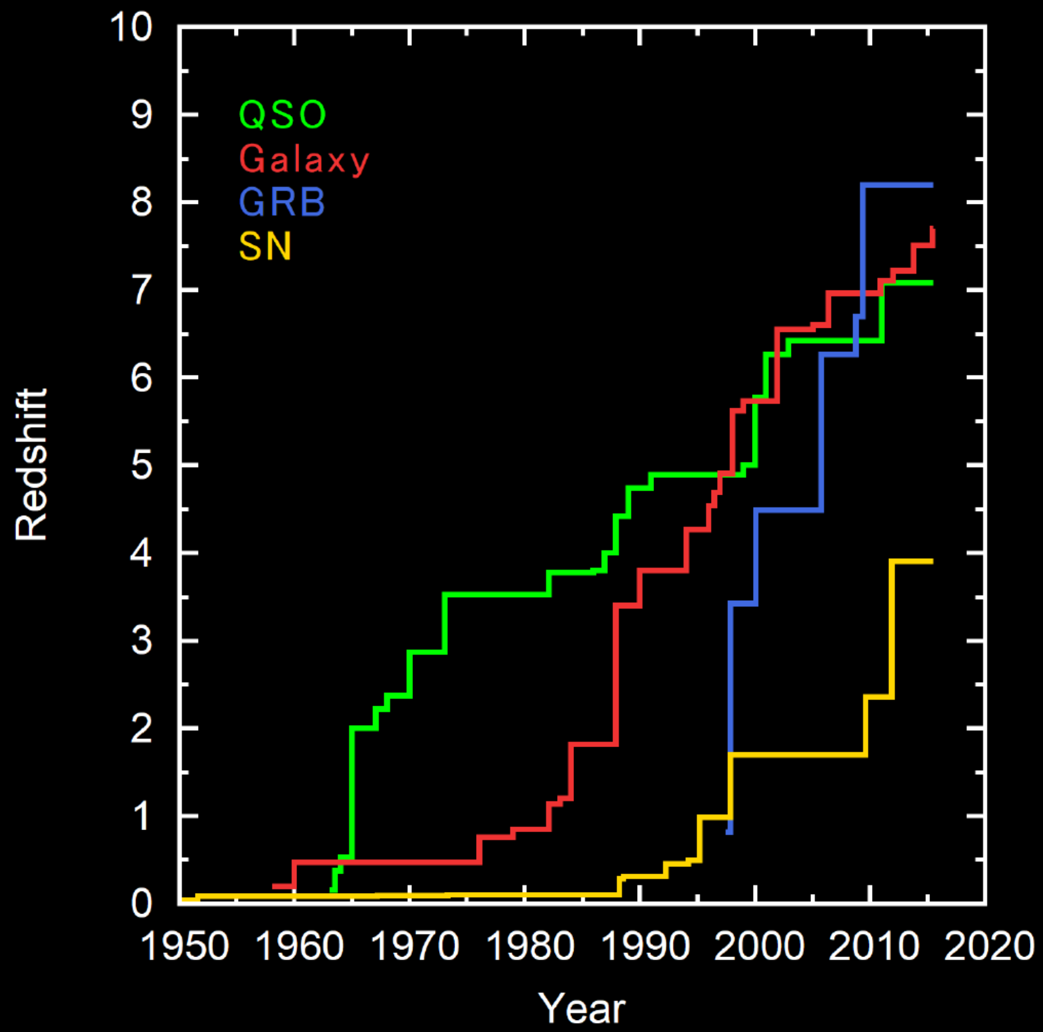
- The interaction model (CO) is in better agreement with observations.
- The magnetar model has a slower reddening than observations.
- The PISN model is in good agreement with the observed reddening rate, but the model evolves about 50 days earlier than the observed one.
- g - r color evolution is more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

Gaia16apd color temperature evolution



- T_{color} - temperature of the blackbody whose SED most closely fits the data; $T_{eff} = (L/(4\pi\sigma R^2))^{1/4}$
- The temperature decline rate is a better fit to the observed values in interaction models
- Variation of chemical composition of CSM.
- The interaction models do not produce X-ray emission: radiation-dominated shock wave, T_{ej} ~ 20,000-30,000 K

Timeline of redshift records

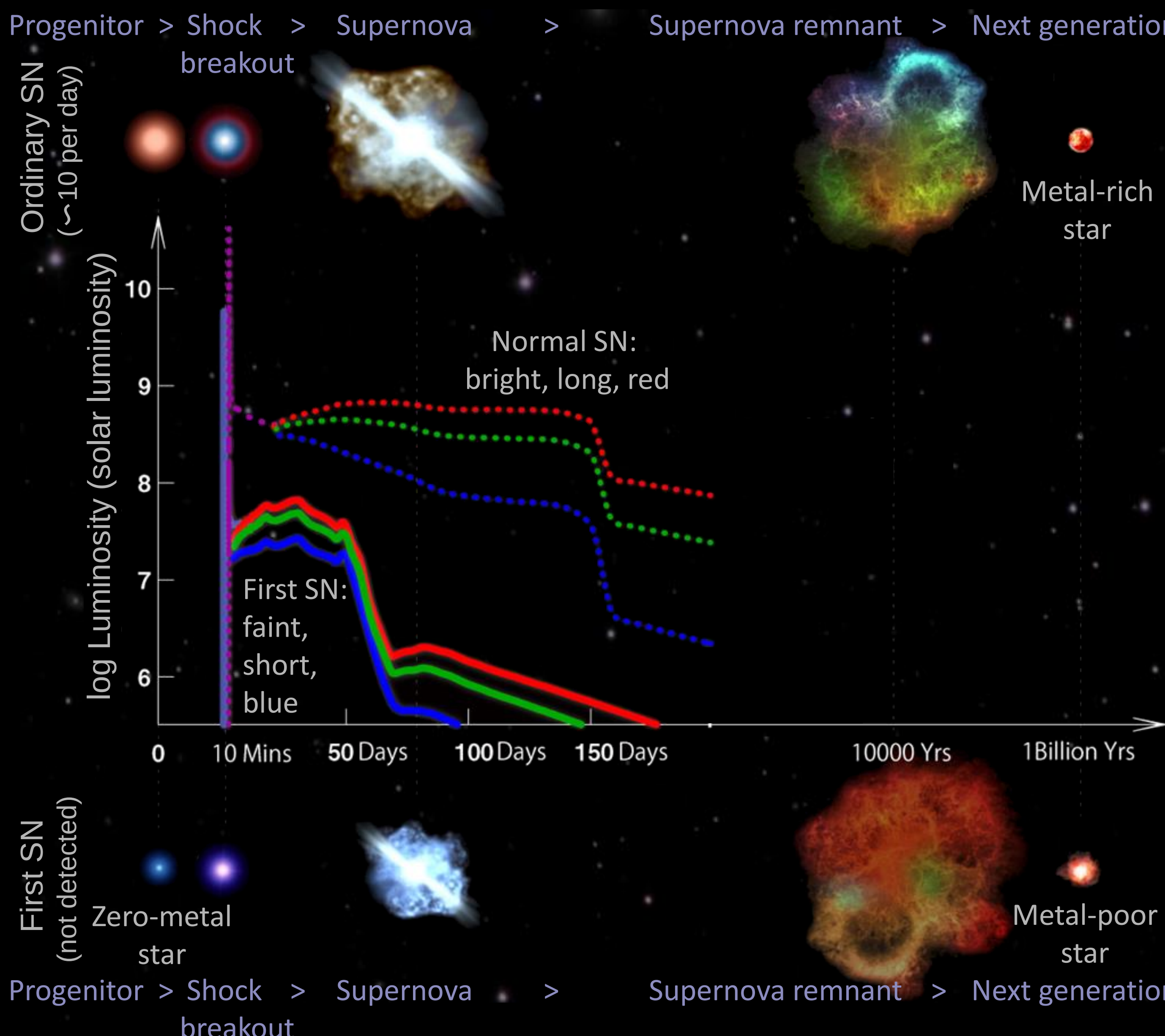


High-Redshift SNe

- High Redshift SNe z = 3.9 (Cooke+ 2012)
- Superluminous SNe?
- CSM interaction?

- CC SN 1000+0216, z=3.8993
- Type Ia SN UDS10Wil, z=1.914

The first supernova explosions



First supernovae (SNe): near future detections!
How do they explode?
How to identify them?

- Simulations:
  - first supernovae - explosions of first stars (compact, zero-metal stars)
- Purpose:
  Photometric easy-to-use indicator of first SN explosions for current and future surveys (HSC/Subaru, LSST, WFIRST, JWST).

Pop III stars – Pop III GRB – Pop III SNe

$M > 10^5 M_\odot$:SMS (Super Massive Stars)

→ GR instability → Collapse

$M \sim 300 - 10^5 M_\odot$:

→ Collapse (& Explosion) → IMBH → SMBH ?

→ **Pop III GRBs ?**

$M \sim 140 - 300 M_\odot$:

→ **Pair Instability SNe** → Complete Disruption

$M \sim 8 - 140 M_\odot$:

→ Core Collapse → **Pop III GRBs, Hypernovae**

→ **SNe II**

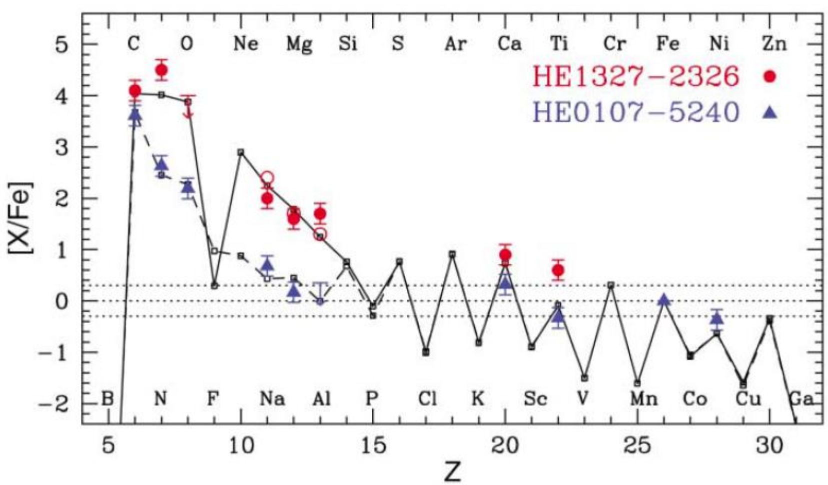
Heger & Woosley 2002, Joggert+11, Joggert+12, Yoon+12, Whalen+13, Whalen+14, Smidt+14, Chen+14, Hirano+15, Chen+16, Hartwig+17

First stars

- **400 million years after Big Bang**
  Direct insight into the age of galaxy formation

Image credit: NASA/WMAP

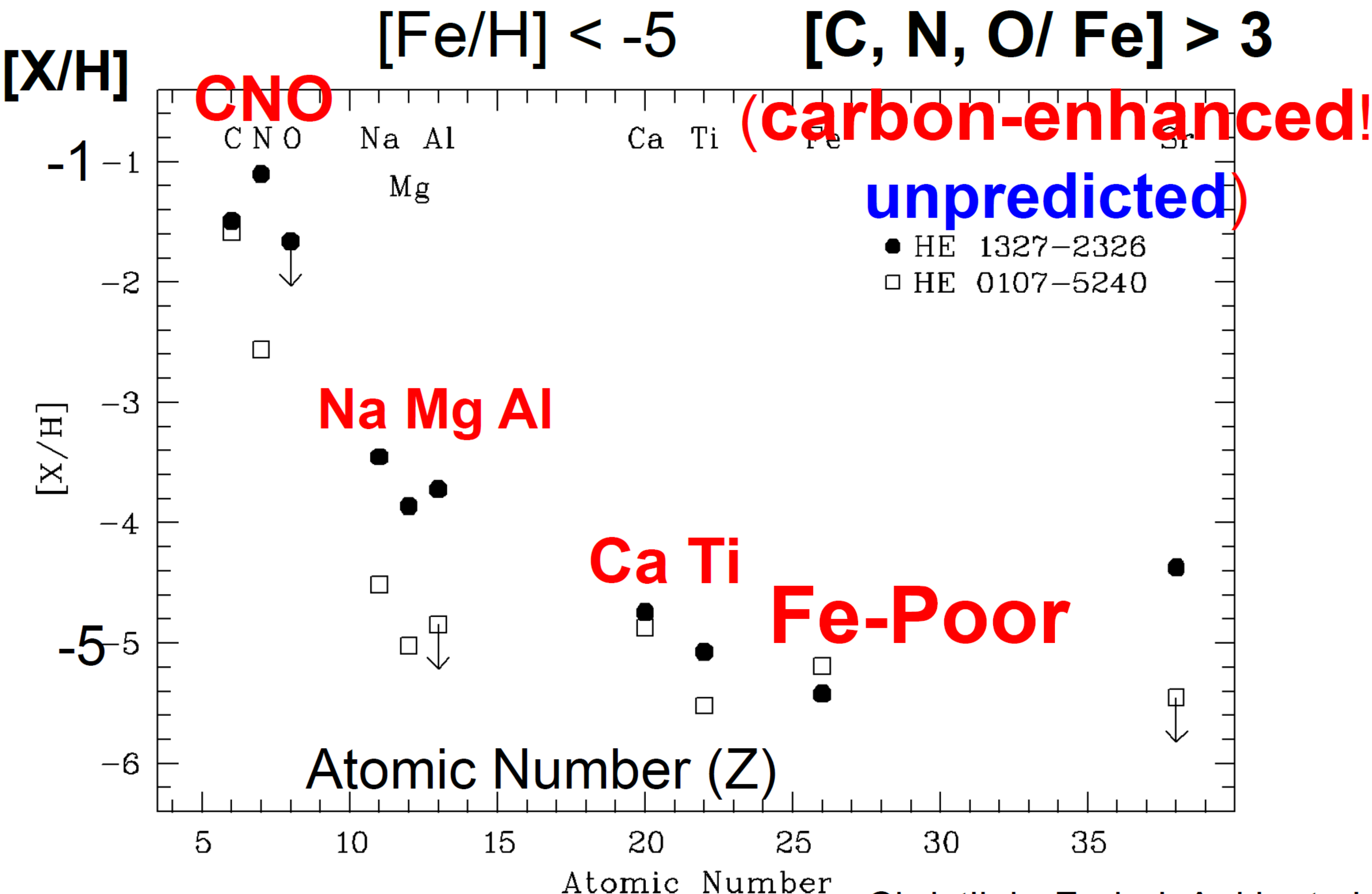
- **Elemental abundance ratio in EMP stars (Iwamoto et al., 2003, 2005)**



- 2nd generation (low mass) extremely metal-poor (EMP, [Fe/H]<-3) stars: abundance pattern and distribution (mixing)
- Abundance pattern of EMP stars provides constraints on mass, explosion energy of first supernovae
- Light curves and spectra of first supernovae (including shock breakout)
- Observational signature of first supernovae (M, E, abundance) expected from 1st stars
- Rough IMF and constraints on star formation rate

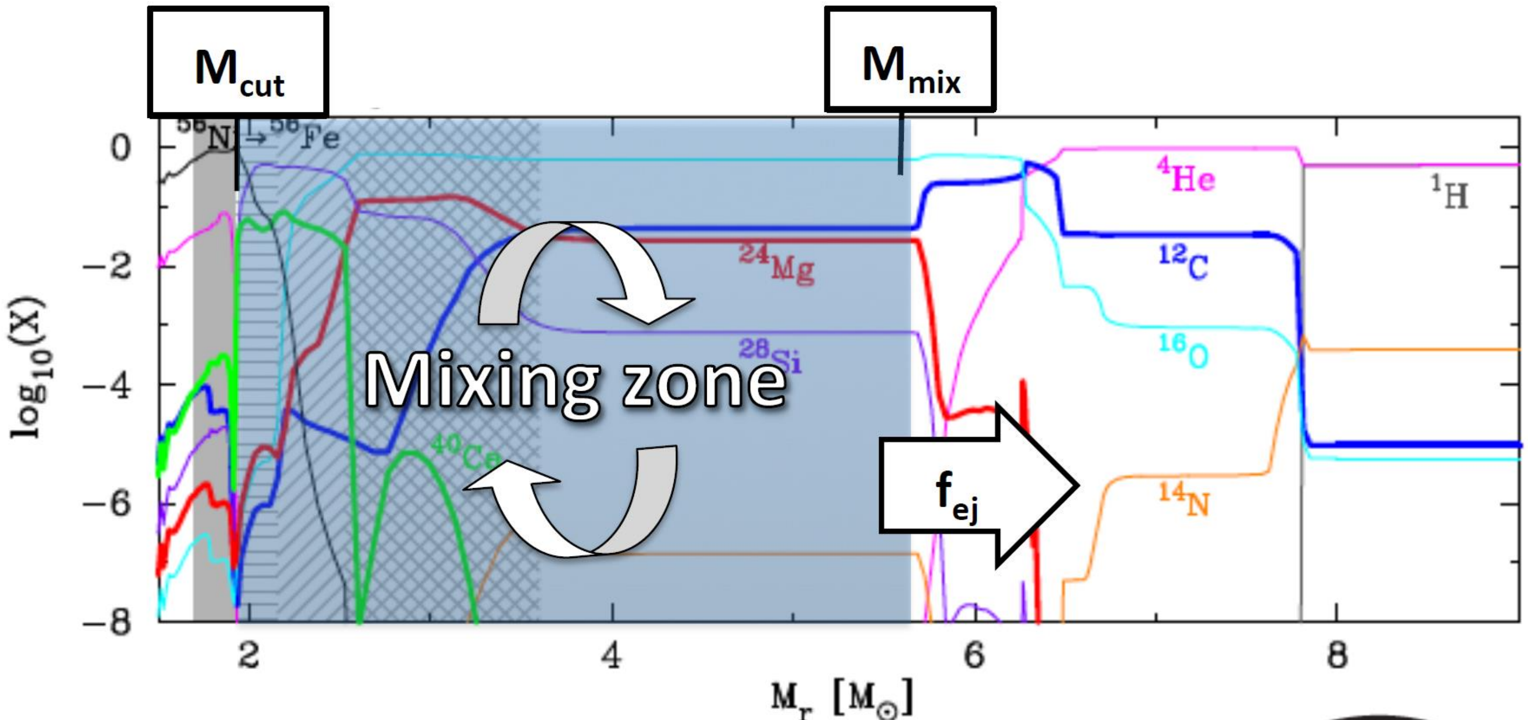
Understanding of the earliest star formation and the chemical enrichment history of the Universe!

Hyper Metal Poor (HMP) stars



Christlieb, Frebel, Aoki, et al.

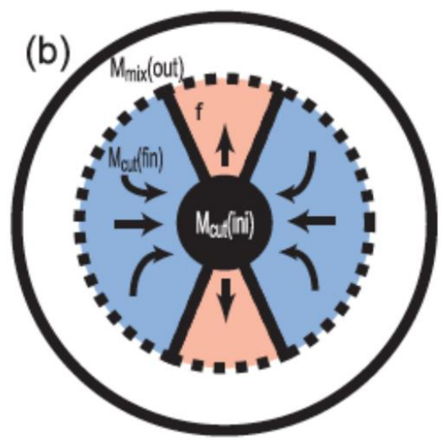
The mixing-fallback model



- ❑ M_{cut}: Inner boundary of the mixing zone
- ❑ M_{mix}: Outer boundary of the mixing zone
- ❑ f_{ej}: ejected fraction (fraction of mass ejected in the mixing zone)

➡ Mass of a compact remnant (e.g. NS or BH):

$$M_{rem}=M_{cut}+(1-f_{ej})(M_{mix}-M_{cut})$$

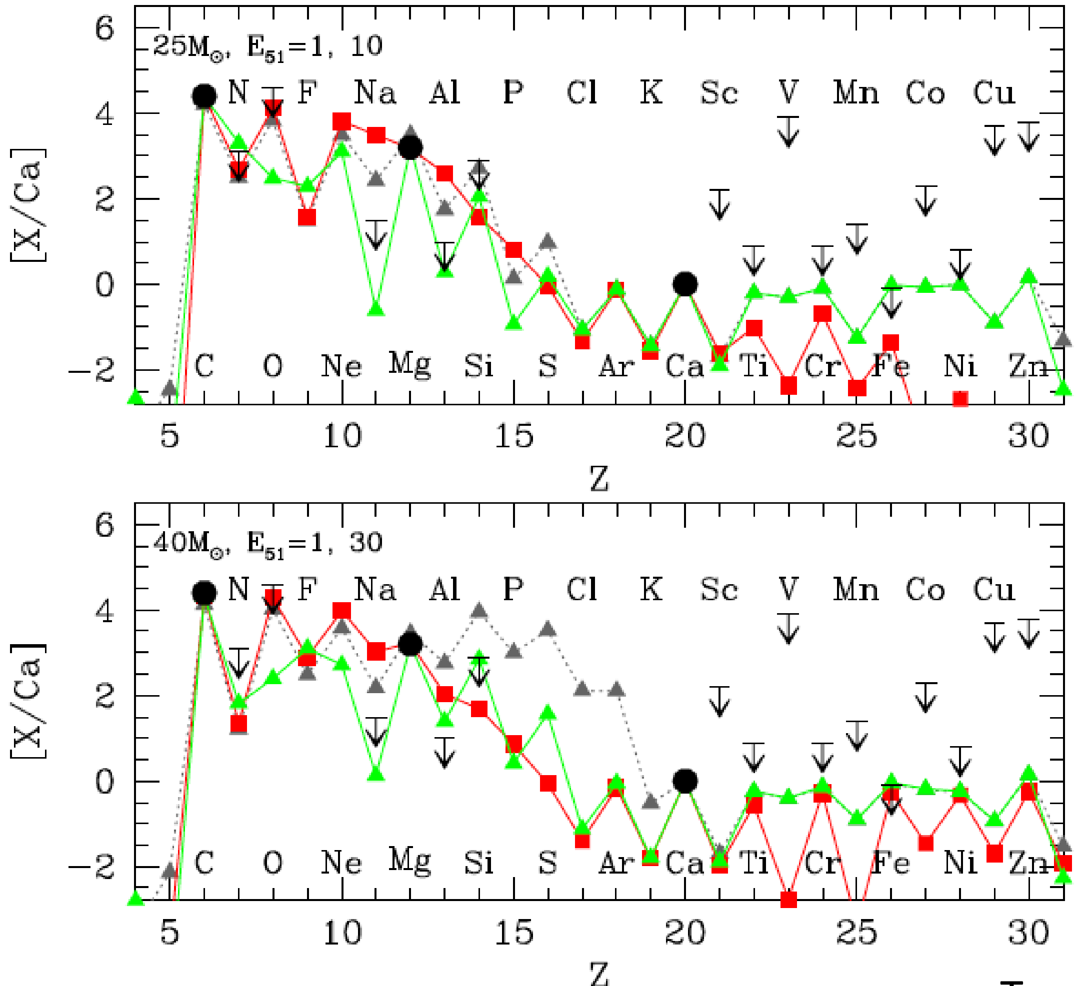


Tominaga et al. 2007

Nucleosynthesis signatures. SM 0313-6708 vs. Pop III SN yields M=25M$_\odot$ and 40M$_\odot$

■: E_{51}=1 (supernova)

▲: E_{51}= 10 (hypernova)

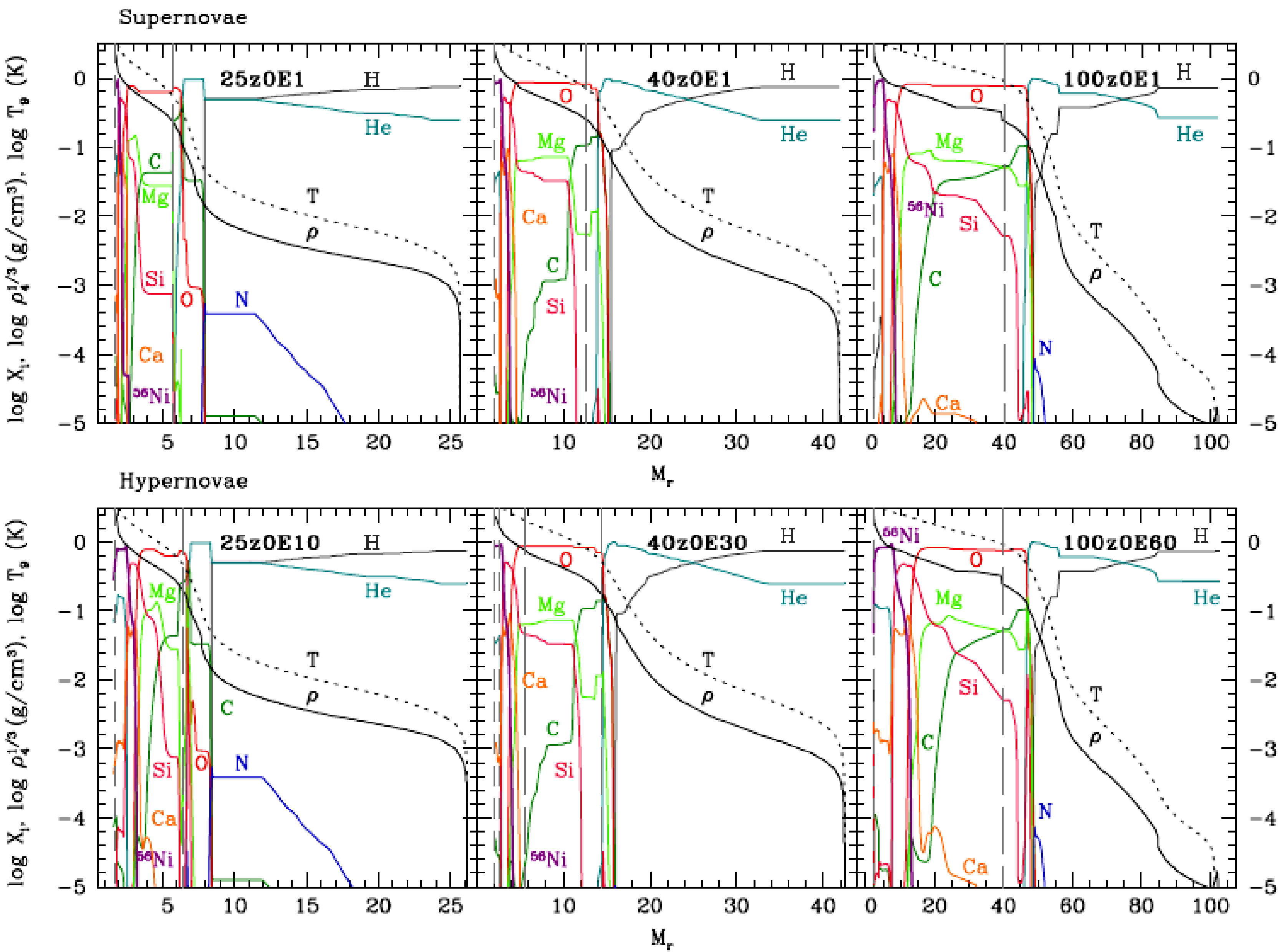


- The majority of the EMP stars are better explained by the Pop III star models with < 40 M$_\odot$
- Jet-like SN explosion or week explosion

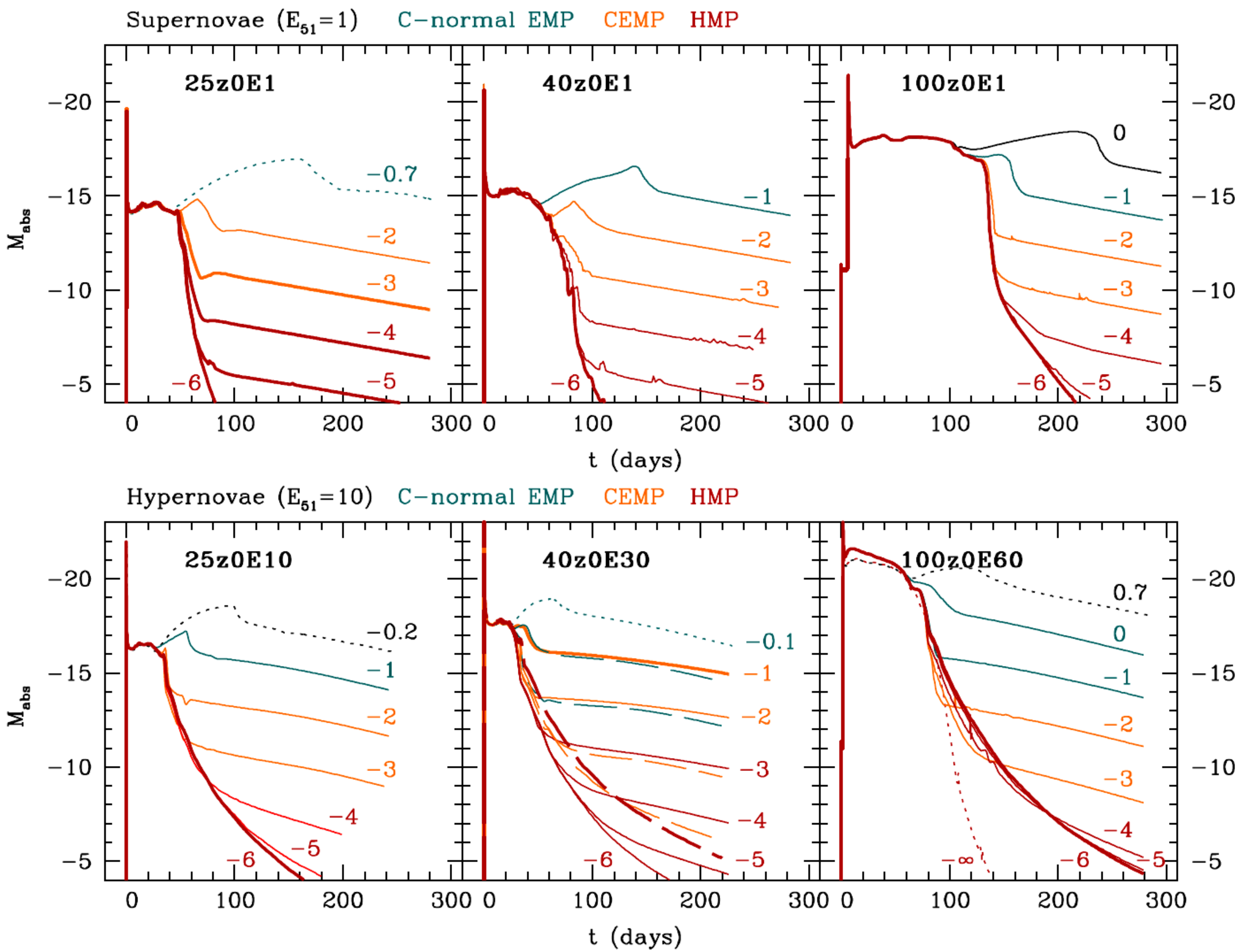
$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}$$

Tominaga 2007, Ishigaki+ 2015, 2017

Pop III presupernova composition and structure



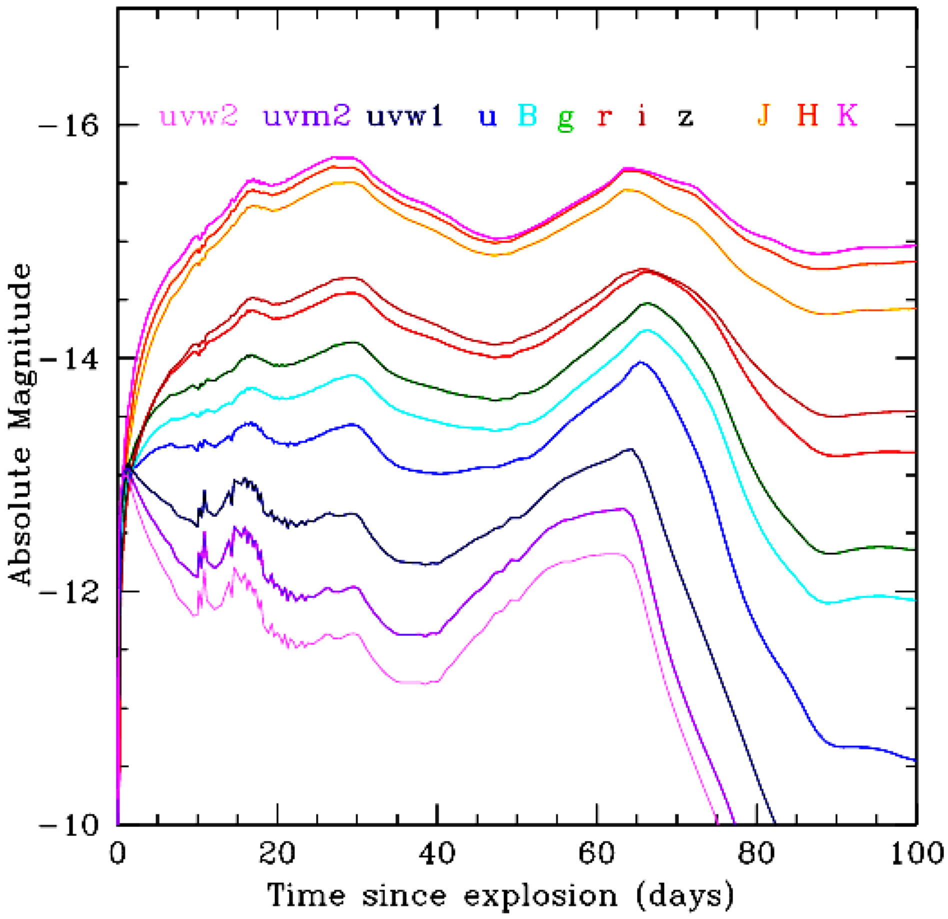
Bolometric light curves of z0 SNe

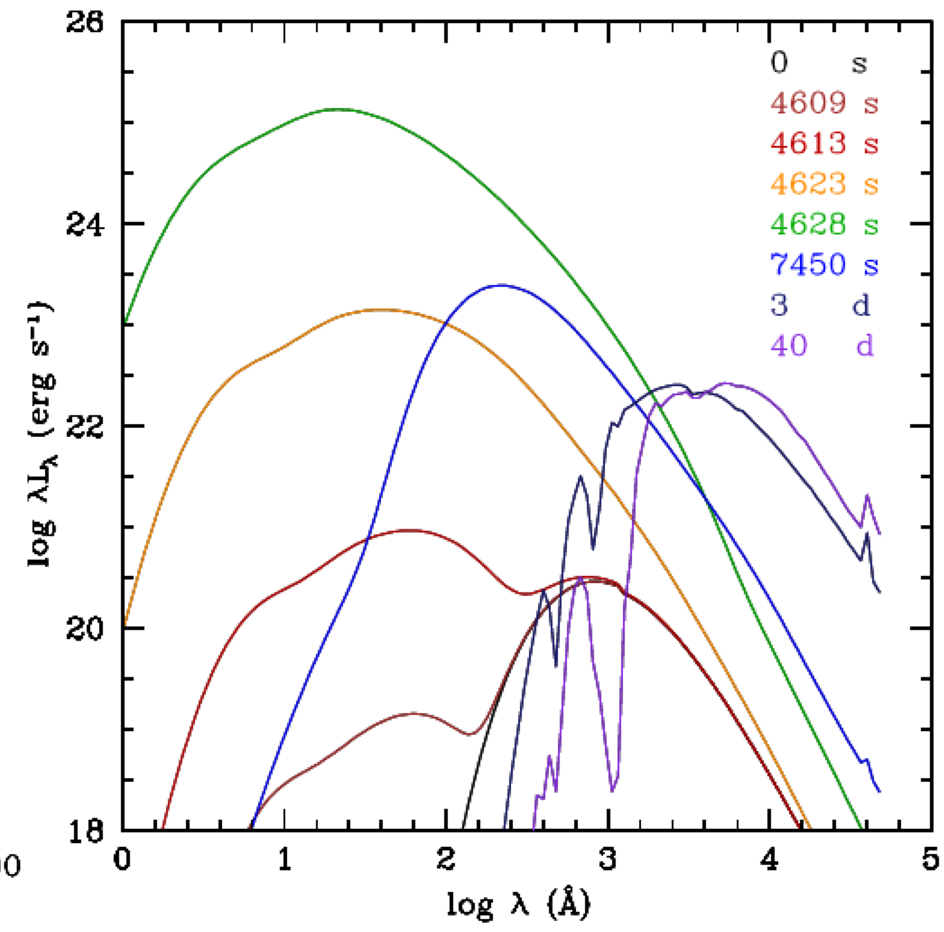


Light curves and spectra M=25$M_\odot$

- Light curves: $M(^{56}Ni) = 0.01\ M_\odot$
  Bumps due to zero metallicity

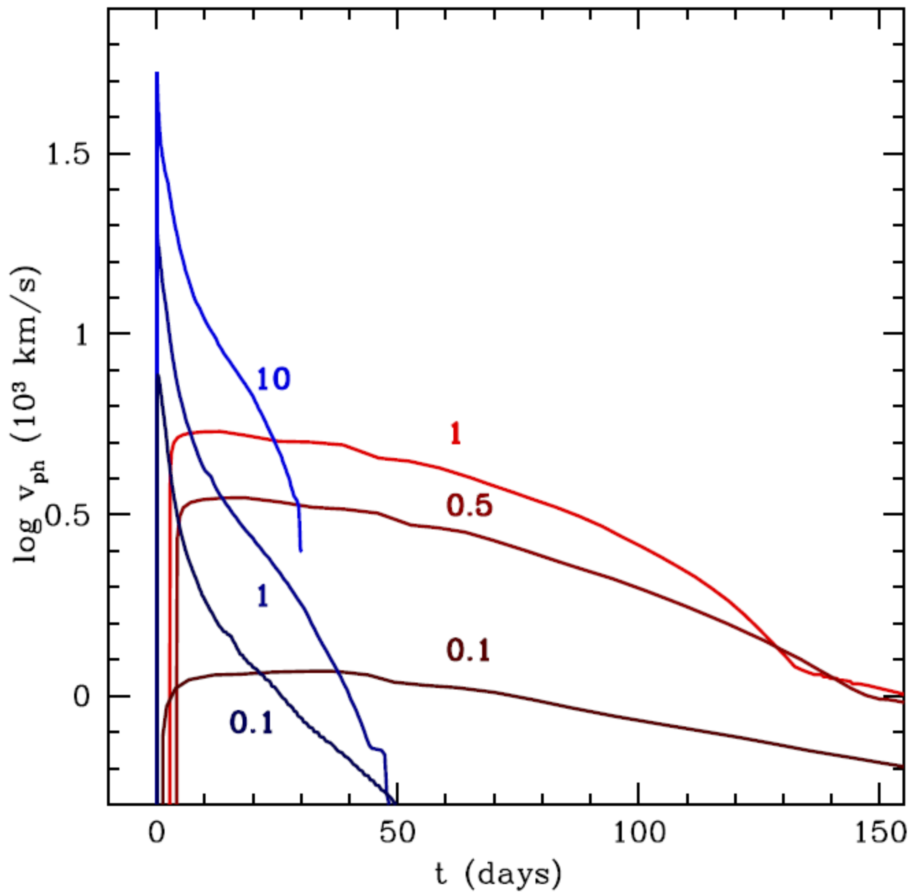
- SED evolution from shock breakout to “plateau” phase



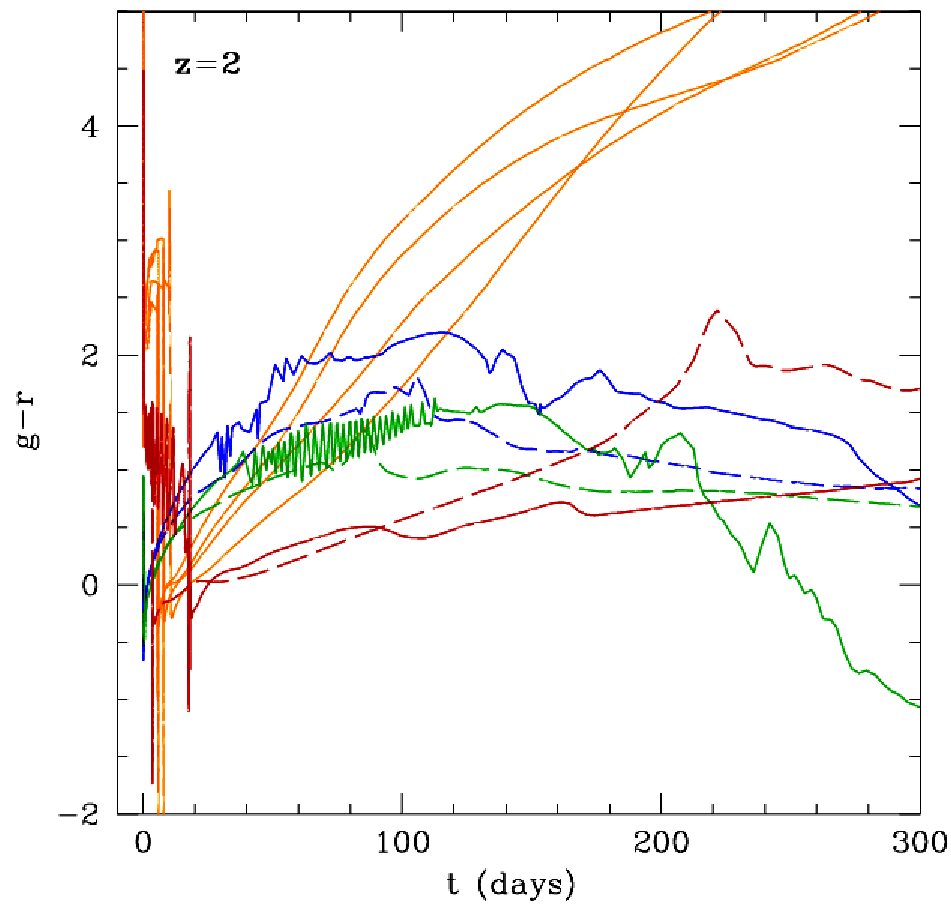


Zero vs solar metallicity

- Photospheric velocities zero-metallicity and solar metallicity progenitors, parametrized by the explosion energy *E*51, M=25M$_\odot$

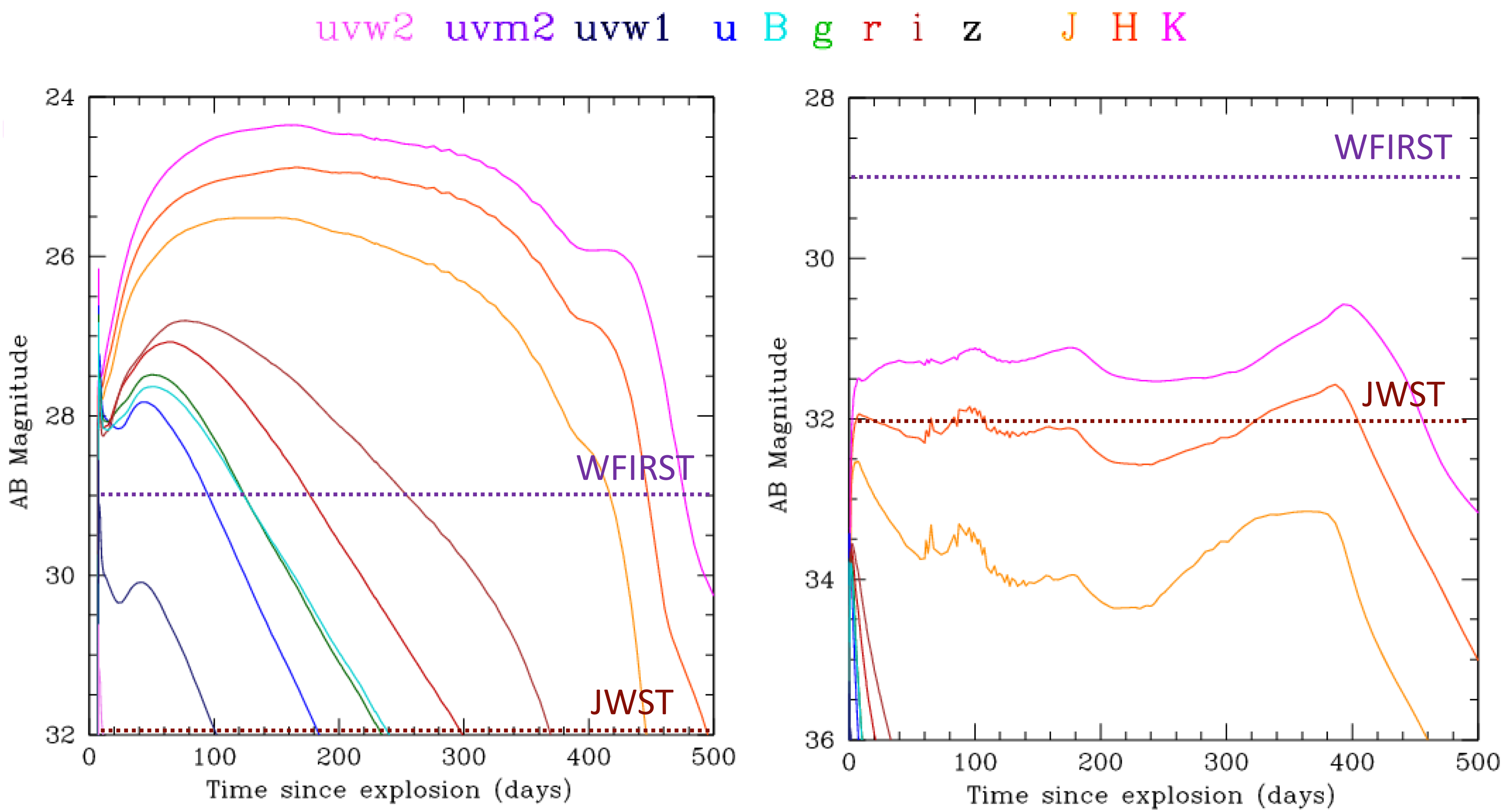


- Color evolution light curves, z=2. Solar metallicity (20-25 M$_\odot$) and zero-metallicity (25 $M_\odot$, 40 $M_\odot$, 100 $M_\odot$) models. SNe -solid lines, HNs - dashed lines.

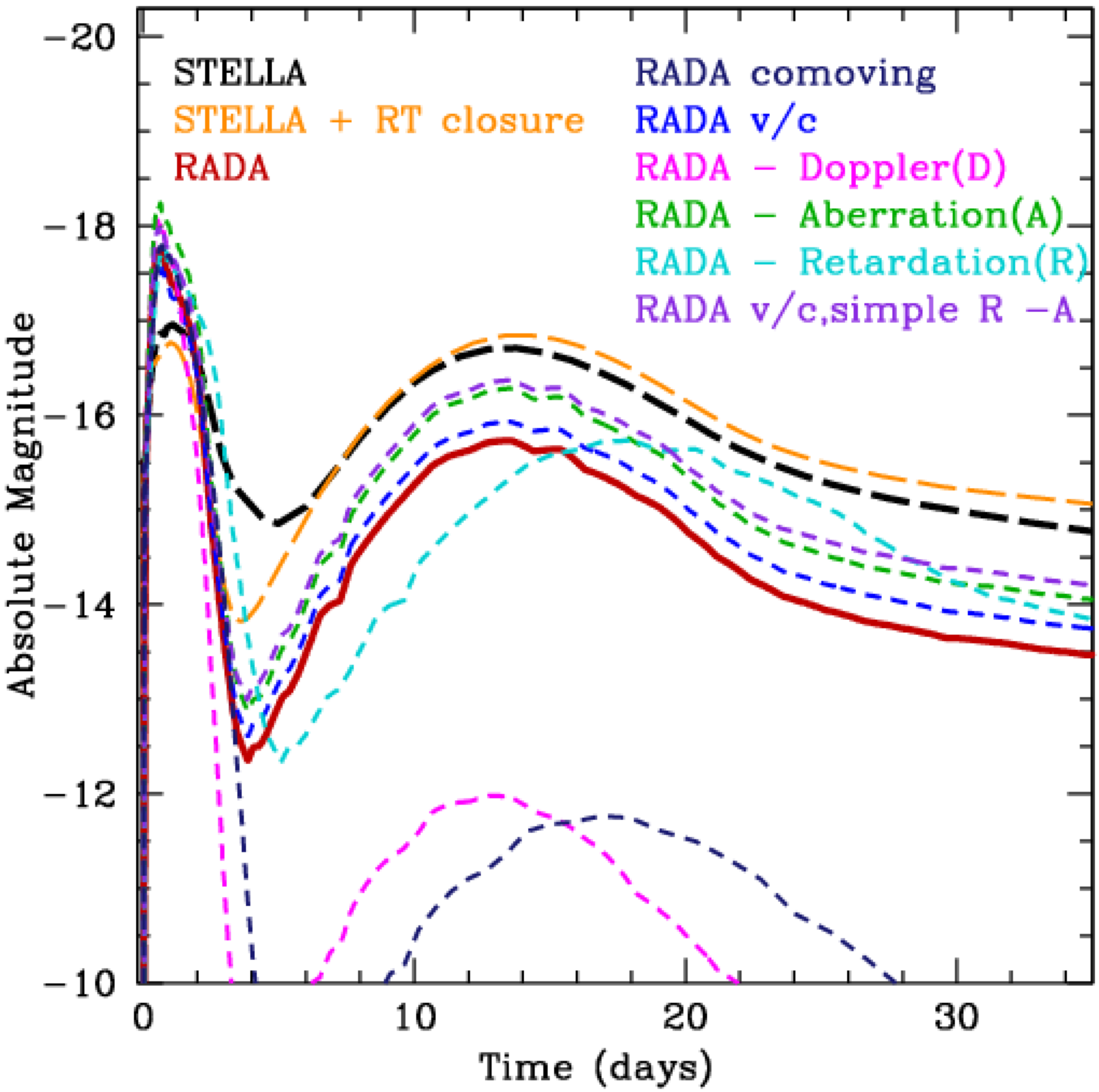


Light curves at redshift z=5, $100M_\odot$ HN vs $25M_\odot$ SN

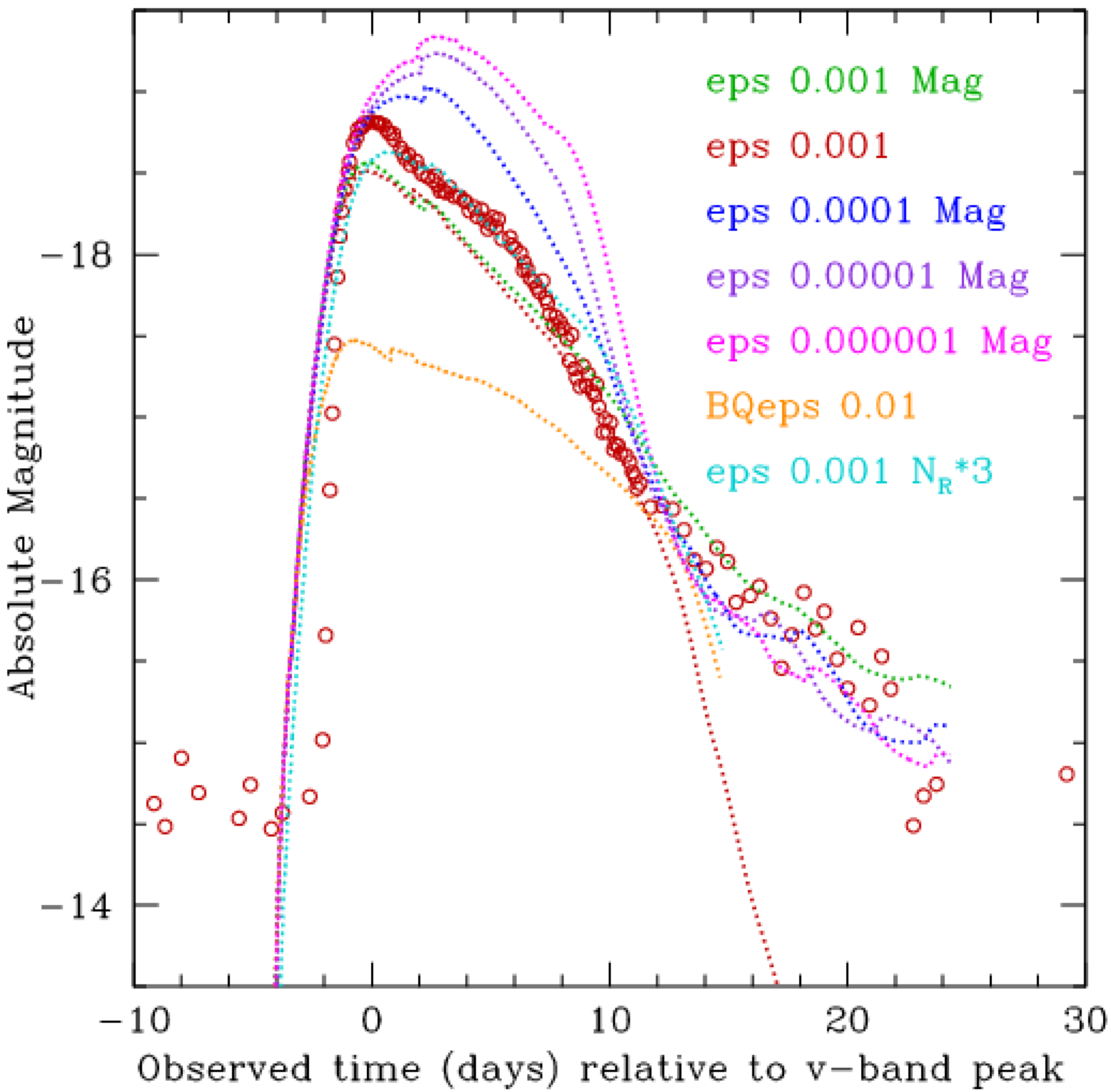
- Light curves: M(56Ni)=0.01 $M_\odot$



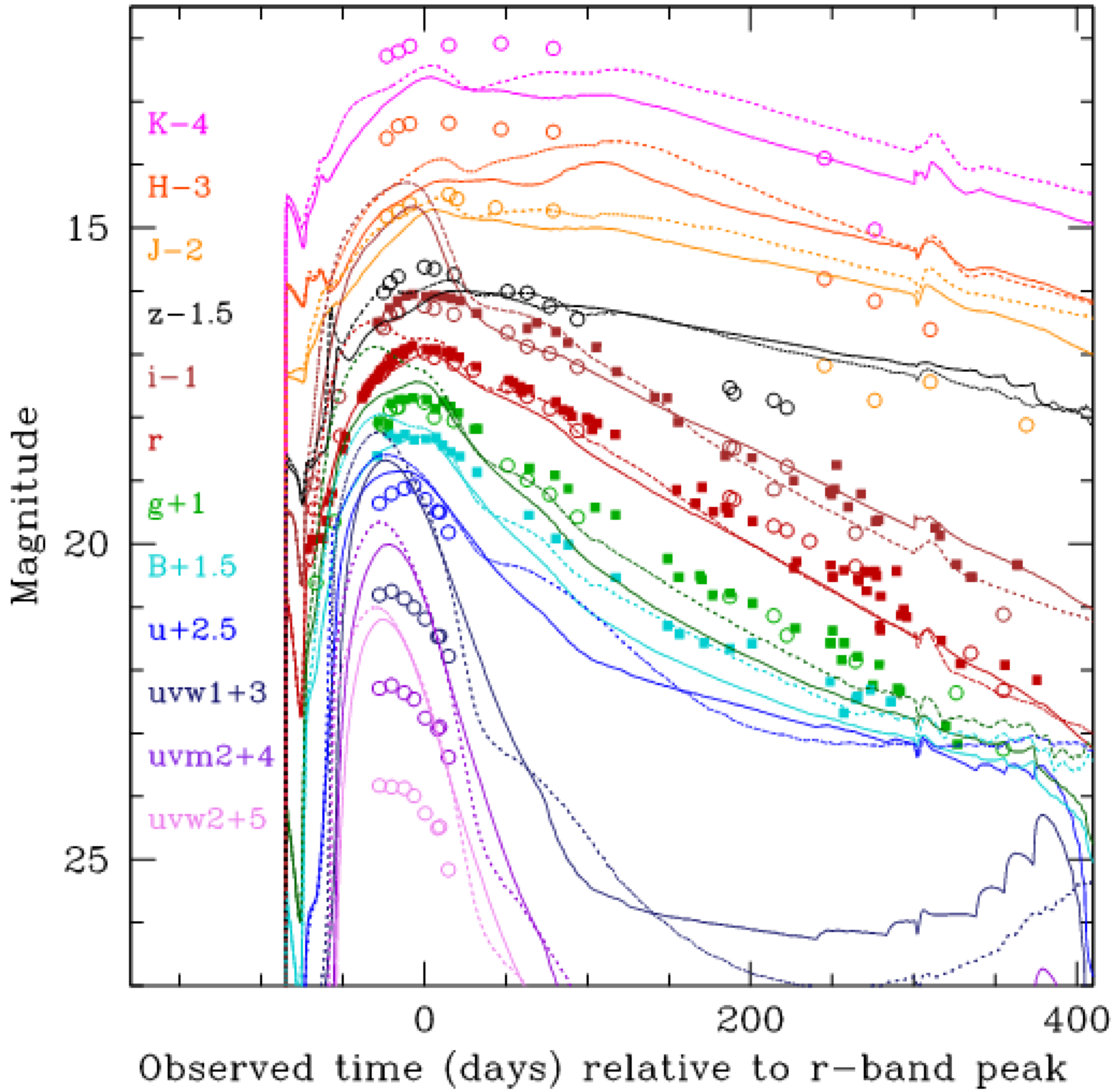
Relativistic effects



Multidimensional effects



Opacity effects



Summary

- We propose that some SLSNe (PTF12dam, Gaia16apd) are PPISN, where the outer envelope of a progenitor is ejected during the pulsations. UV light curves, color and temperature evolution fit the observations. 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, velocities.
- 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.
- Both searches of local faint SNe and very luminous SNe at high z should be performed.
- Pop III core-collapse SNe with $M_{\rm MS} \lesssim 40$–$60\ M_\odot$: shorter, bluer, and fainter than ordinary SNe.
- The plateau phase is common to both BSG and RSG, but can be bumpy.