Mephisto commissioning observations of interesting supernovae

Brajesh Kumar
(on behalf of Mephisto team)
SWIFAR, Yunnan University

(Mephisto Time-domain workshop, Lijiang, 2024-08-05)

Mephisto (Multi-channel Photometric Survey Telescope)

- It is a 1.6m diameter observing facility.

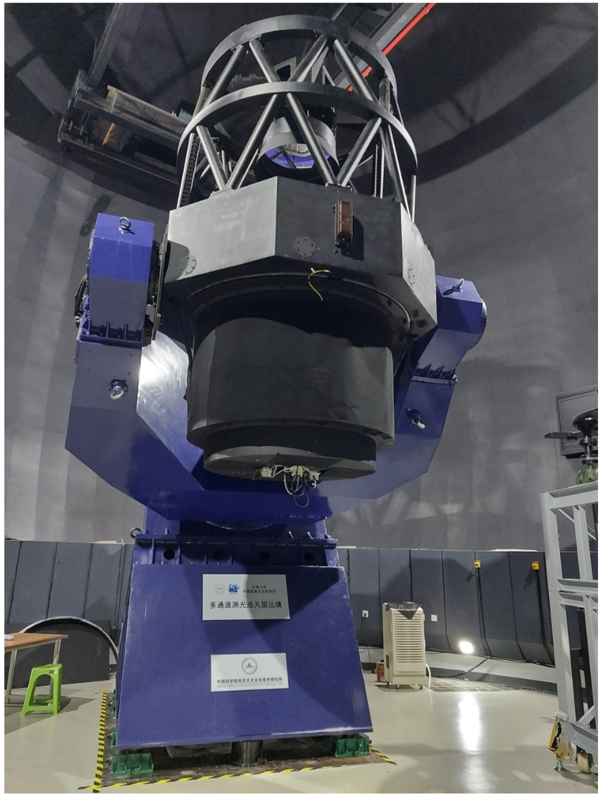
Uniqueness of Mephisto wide and deep multi-band (*uvgriz*) survey:

- Wide multi-channel survey of over 26,000 deg^2 northern hemisphere.

- Multi-channel surveys of transients: cadences of days, hours and minutes.

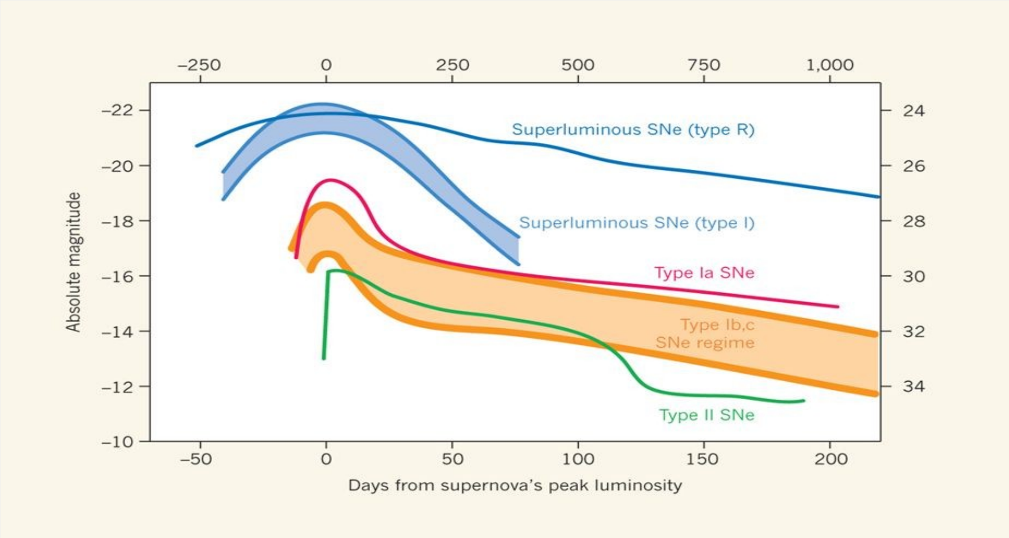
- Deep imaging (limiting mag): *uvgriz* 21.63, 21.65, 22.60, 22.37, 21.99, 21.14 mags (single visits) which can be further improved by co-adding.

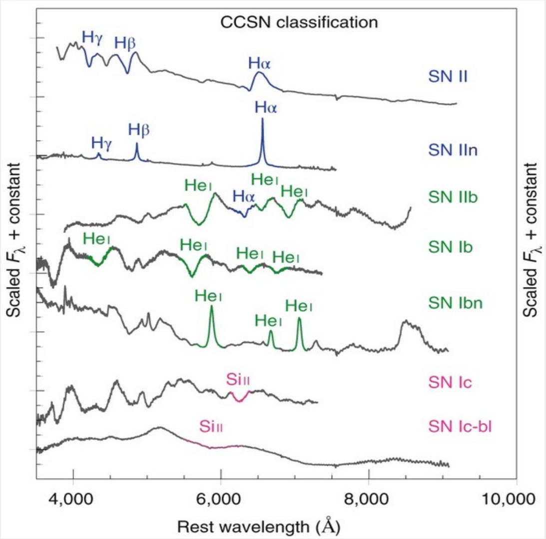
Prompt observations: 1800 deg^2 in three bands per night.



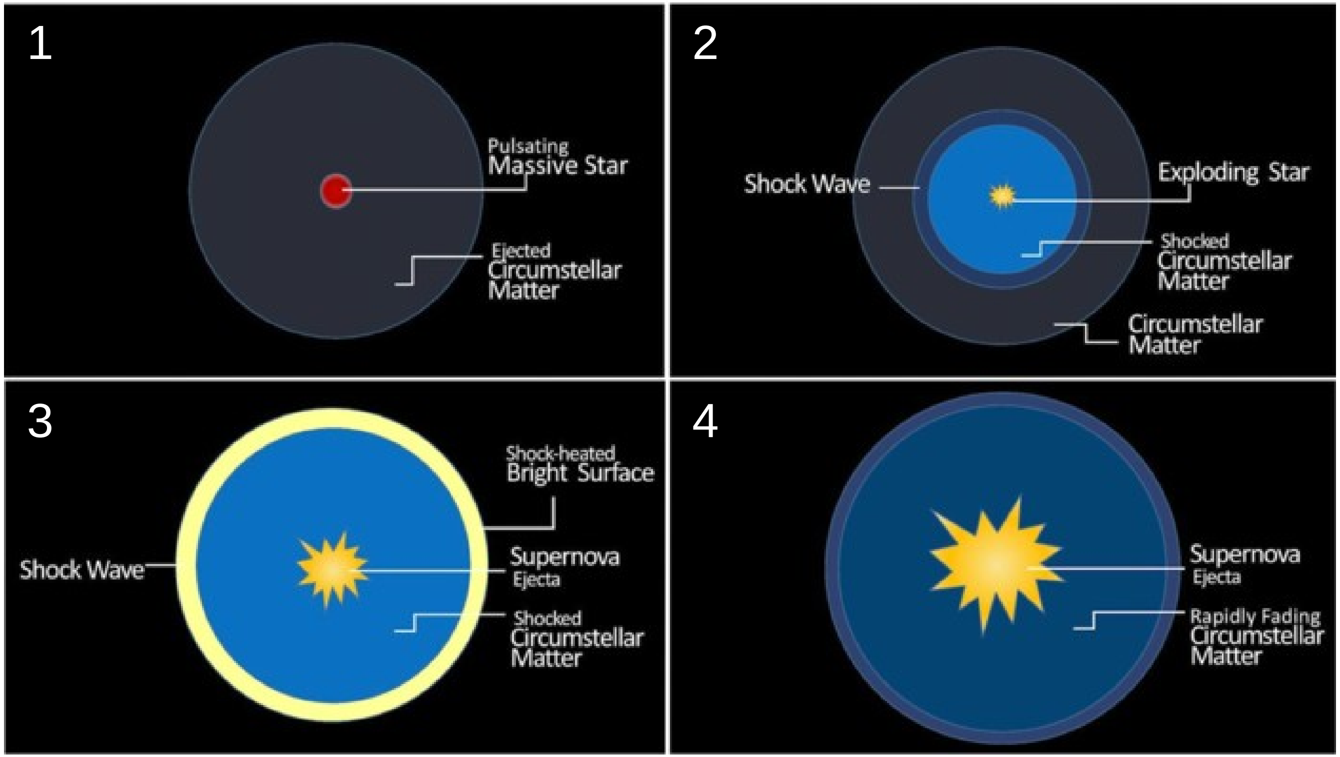
Supernovae: End phase of stars

Core-Collapse SNe (CCSNe): Result due to gravitational collapse of massive star core. SNe classification is based on light curve and spectra (Type: IIP, IIL, IIb, IIn, Ib, Ibn, Ic, Ic-BL). Type IIb, Ib, Ic and Ic-BL are also known as **Stripped Envelope SNe (SE-SNe)** as they strip off their our H/He layers before the explosion.





- **Post-explosion observational features are mainly governed by the pre-explosion activities of the progenitor star.**

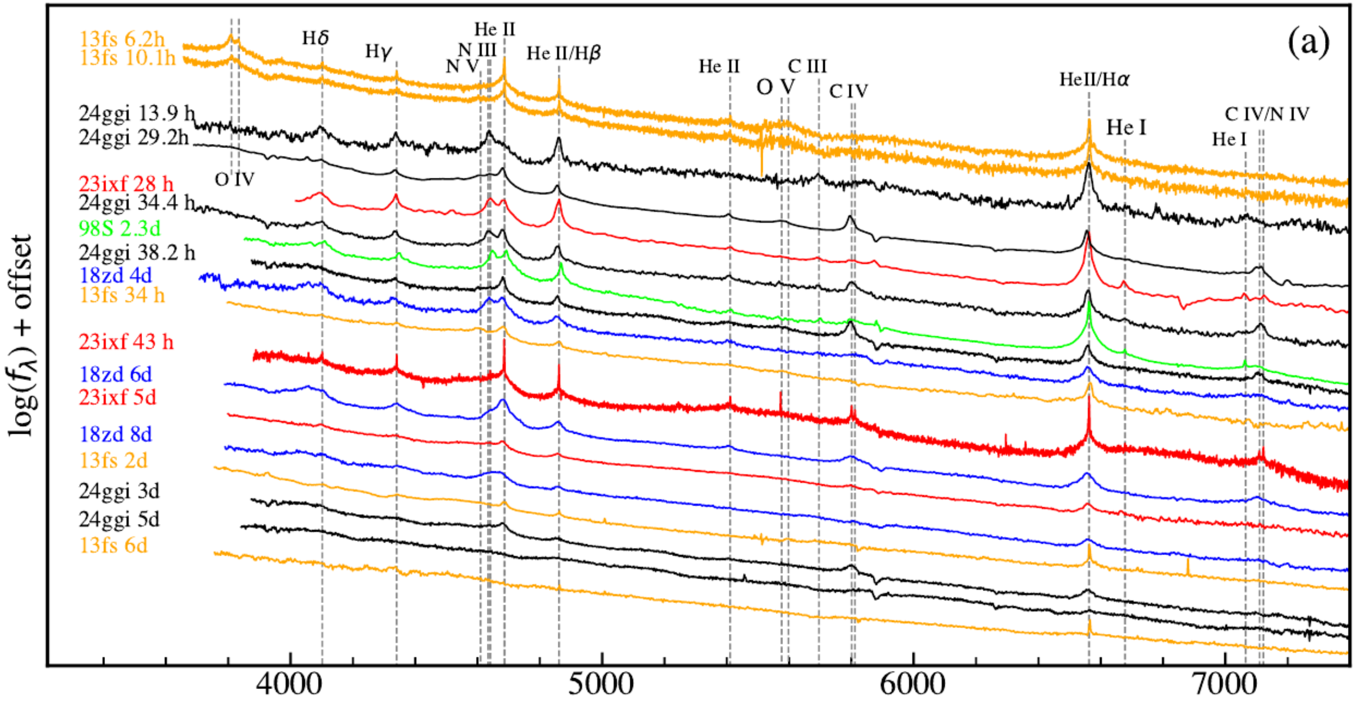


Credit: Shing-Chi Leung

1. A massive star undergoes large pulsations (before explosion) and ejects some material to form dense circumstellar matter (CSM).
2. The star explodes to form a shock wave, which propagates through the CSM.
3. When the shock wave reaches the surface of the CSM, the kinetic energy is converted to the thermal and radiation energy. Then the surface of the CSM shines very bright.
4. CSM rapidly expands and fades. Supernova ejecta also expands and fades.

“Flash” features in spectra

The propagating shock finally breaks out of the stellar surface and **ionizes the surrounding CSM, which consequently appears as “flash” features in the spectra** (Quimby et al. 2007; Gal-Yam et al. 2014; Yaron et al. 2017; Jacobson-Galán et al. 2024a).



(Zhang+ 2024)

Comparison (SNe 2023ixf, 2024ggi) of flash features

Supernovae observations with Mephisto facility

- We followed up **more than a dozen of different types** (Ia, IIb, IIP, IIn, etc.) of supernovae.
- The target selection was based on notices from Transient Name Server (early discovered events).
- Considering the peculiarity of targets in some case continuous monitoring was performed.
- We used pilot camera for SNe observations (**Note:** all three channels were available from Dec 2023).
- **Newly developed Mephisto data reduction pipeline** was used for preprocessing and calibration of images.

SN 2023ixf observations with Mephisto and 50 cm array

The Astrophysical Journal, 969:126 (10pp), 2024 July 10
https://doi.org/10.3847/1538-4357/ad4be3

Multiband Simultaneous Photometry of Type II SN 2023ixf with Mephisto and the Twin 50 cm Telescopes

Yuan-Pei Yang[1,5], Xiangkun Liu[1,5], Yu Pan[1], Xinzhong Er[1], Dezi Liu[1], Yuan Fang[1], Guowang Du[1], Yongzhi Cai[2,3,4], Xian Xu[1], Xinlei Chen[1], Xingzhu Zou[1], Helong Guo[1], Chenxu Liu[1], Yehao Cheng[1], Brajesh Kumar[1], and Xiaowei Liu[1]

- SN 2023ixf is one of the nearest (~6.7 Mpc) SN in last two decades which exploded in Messier 101.
- Discovered very early (a few hours) after the explosion (Itagaki, 2023).
- Multi-wavelength observations and detailed study of this SN was done by many groups.
- SN 2023ixf was monitored (~270 days) with Mephisto facilities.

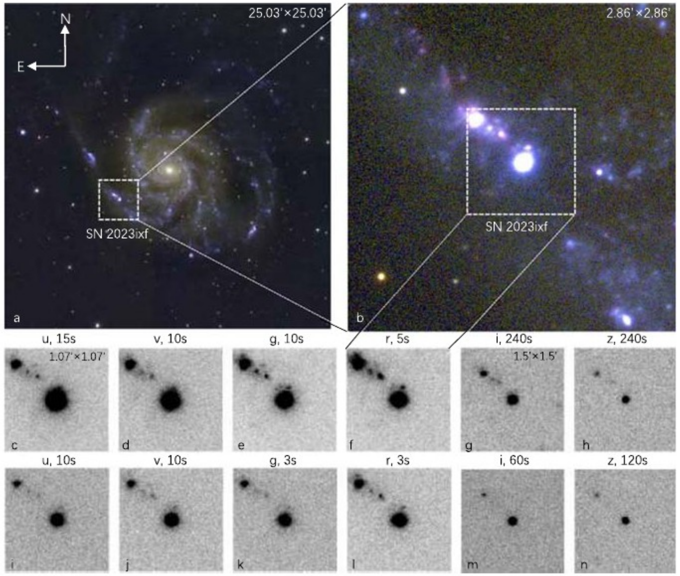
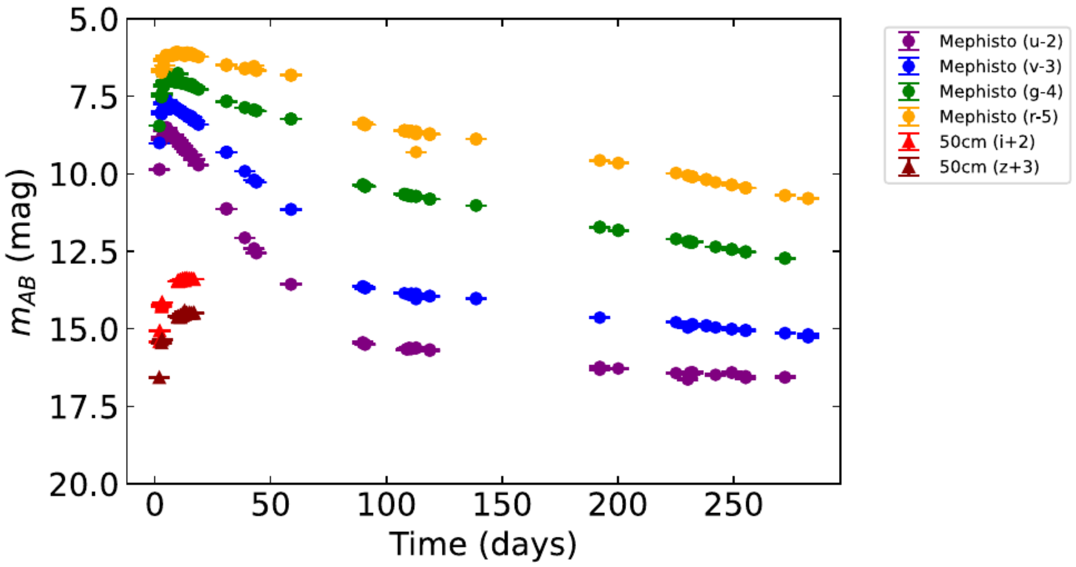


Figure 2. Images of SN 2023ixf with Mephisto ((a)–(f), (i)–(l)) in the *uvgr* bands and the twin 50 cm telescopes ((g), (h), (m), (n)) in the *iz* bands. Panel (a): the *vgr*-band composite image of the Pinwheel Galaxy Messier 101 with Mephisto on 2023 May 20. Panel (b): the image of the region near SN 2023ixf. Panels (c)–(h): images of SN 2023ixf in the *uvgriz* bands with different exposures on 2023 May 21. Panels (i)–(n): images of SN 2023ixf in the *uvgriz* bands with different exposures on 2023 June 4.

Light curve and color-color evolution of SN 2023ixf

- Both photospheric and nebular phases were covered.



LC evolution of SN 2023ixf

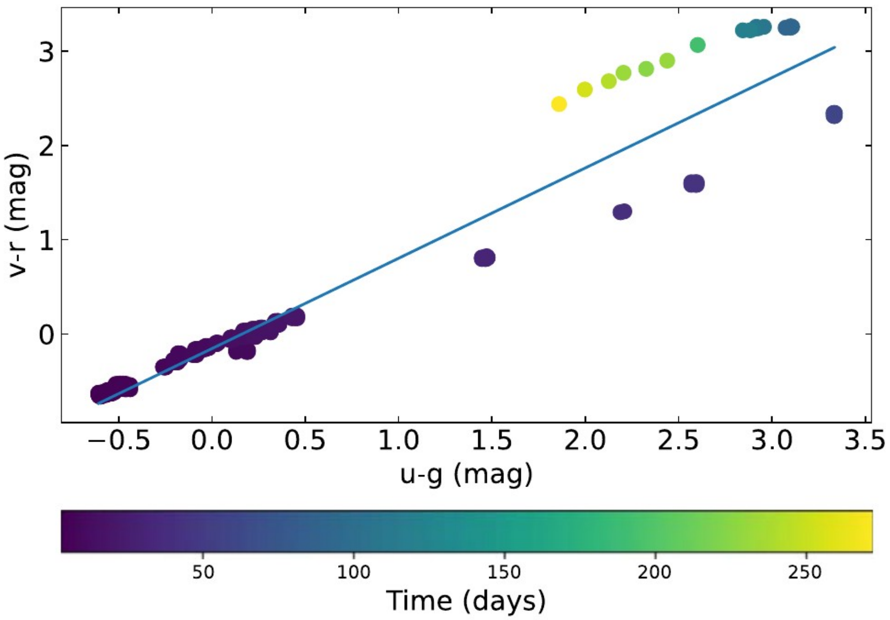


Figure 6. The evolution of SN 2023ixf in the $(u - g) - (v - r)$ color–color diagram. The epoch of the measurement after phase zero with Mephisto is represented by the color of the data point. The solid line corresponds to the theoretical prediction of blackbody radiation based on Equation (4).

SN 2023ixf: Key findings

- Analytical models were used to estimate progenitor properties and explosion parameters of SN 2023ixf.
- The bolometric luminosity reached the maximum value of 3×10^{43} erg s^{-1} at 3.9 days after the explosion and fully settled onto the radioactive tail at ~90 days.
- Based on the radioactive tail, the initial nickel mass was estimated as M_{Ni} ~0.098 M_{Sun}.
- The explosion energy and the ejecta mass are estimated to be E; (1.0–5.7) × 10^{51} erg and M_{ej}; (3.8–16) M_{Sun}, respectively.
- The peak bolometric luminosity is proposed to be contributed by the interaction between the ejecta and the circumstellar medium (CSM).
- Shocked CSM mass M_{CSM} ~ 0.013 M_{Sun}
- Mass loss rate of the progenitor ~ 0.022 M yr^{-1}

SN 2024ggi

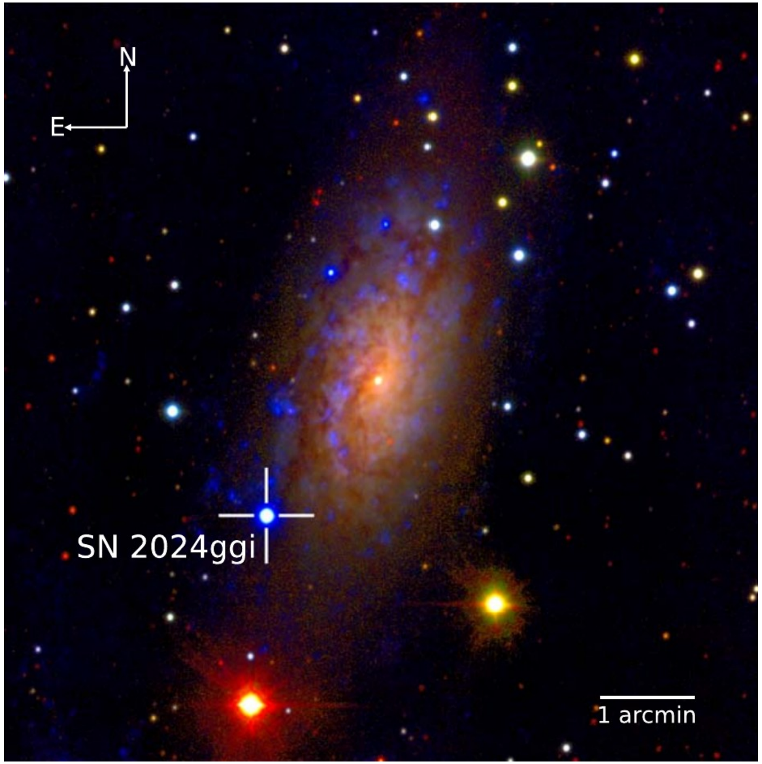
The Astrophysical Journal Letters, 971:L2 (8pp), 2024 August 10 https://doi.org/10.3847/2041-8213/ad62f7

CrossMark

Early-phase Simultaneous Multiband Observations of the Type II Supernova SN 2024ggi with Mephisto

Xinlei Chen[1], Brajesh Kumar[1], Xinzhong Er[1], Helong Guo[1], Yuan-Pei Yang[1], Weikang Lin[1], Yuan Fang[1], Guowang Du[1], Chenxu Liu[1], Jiewei Zhao[2], Tianyu Zhang[1], Yuxi Bao[1], Xingzhu Zou[1], Yu Pan[1], Yu Wang[1], Xufeng Zhu[1], Kaushik Chatterjee[1], Xiangkun Liu[1], Dezi Liu[1], Edoardo P. Lagioia[1], Geeta Rangwal[1], Shiyan Zhong[1], Jinghua Zhang[1], Jianhui Lian[1], Yongzhi Cai[3,4,5], Yangwei Zhang[1], and Xiaowei Liu[1]

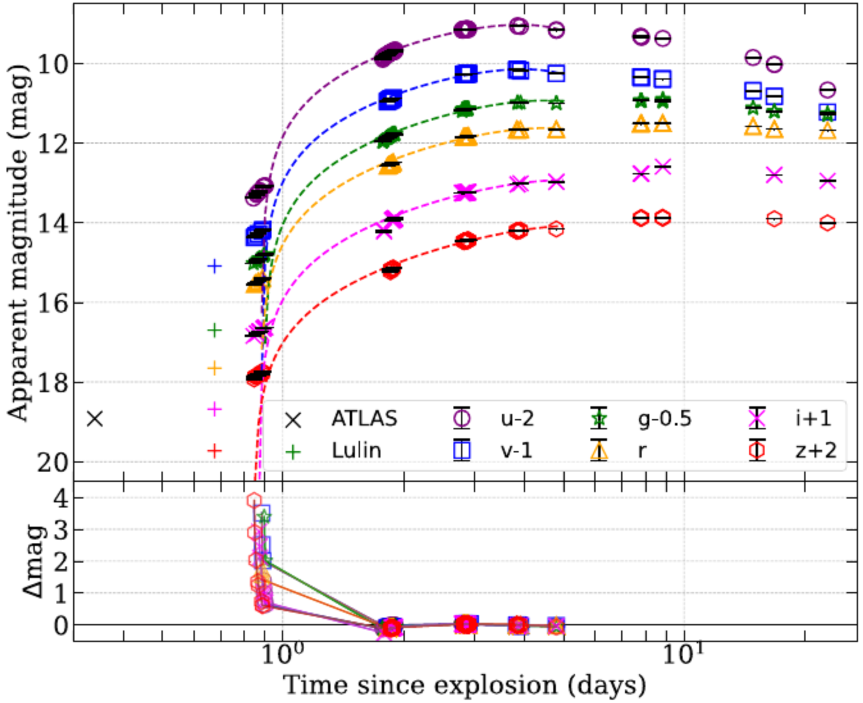
- SN was discovered (Srivastav et al. 2024; Tonry et al. 2024) in NGC 3621 on MJD 60411.14 (UT 2024 April 11.14) by the ATLAS survey group with a discovery magnitude ~19.
- The early spectra taken within a few hours suggest a Type II SN with **flash features** (Hoogendam et al. 2024; Zhai et al. 2024).
- Mephisto was triggered just after receiving the TNS notice. On Initial nights continuous observations were performed.



Color composite image (ugi) of the host

Light curve properties of SN 2024ggi

- u and v band reached a peak within 4 days and then started to decrease.
- A fireball model (Goldhaber 1998; Riess et al. 1999) was used to fit the initial 5 days of photometric data points.
- The fitting curves can represent the observed light curves from the **second to the fifth** day but **inconsistency** on the first day in all bands.
- During the first day, the differences between the observed and fitted v- and z- band light curves reached **4 magnitudes**.
- An eruption or instability activity in the progenitor before the gravitational collapse of the core (mass loss) and/or strong influence of CSM interaction.



The shock-cooling model of Morag et al. (2023) was fitted to the early photometry using a Markov Chain Monte Carlo routine implemented in the Light Curve Fitting Package (Hosseinzada et al. 2023).

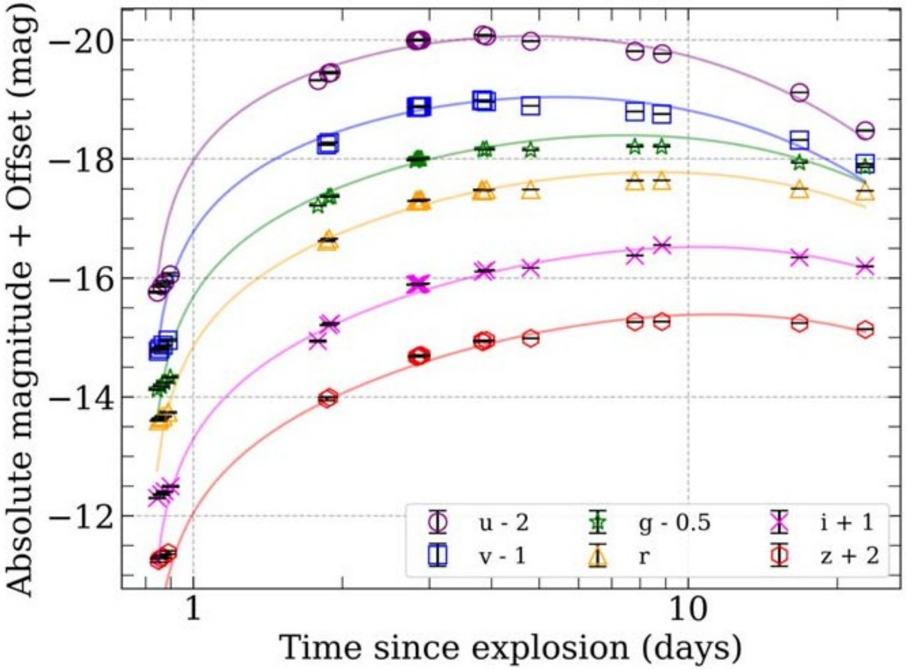


Table 1

The Best Fitting Values of the Shock Cooling Model (see Section 3.1)

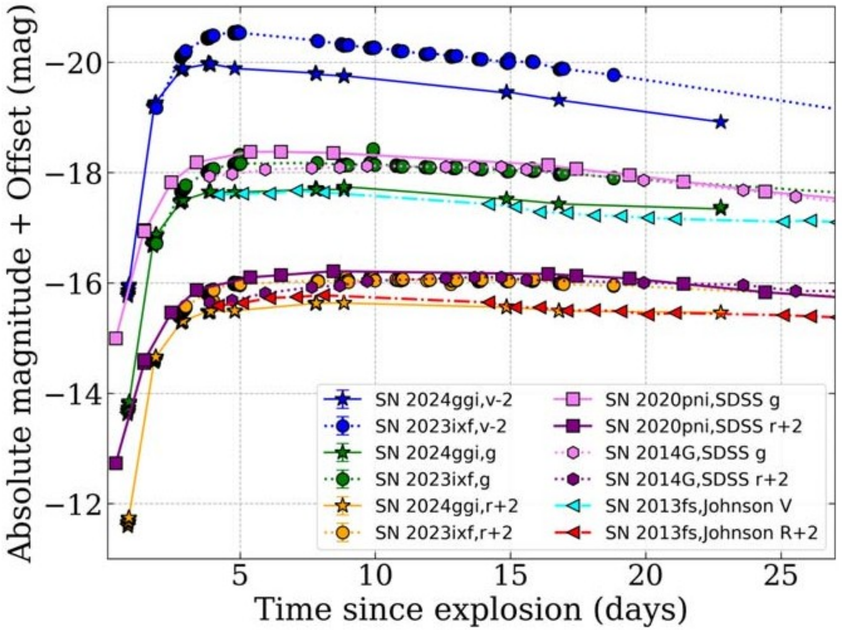
Parameter	Variable	Result
Shock speed (10^8 cm s^{-1})	v_s	$5.60^{+0.09}_{-0.13}$
Envelope mass ($M_\odot$)	M_{env}	$1.66^{+0.03}_{-0.03}$
Ejecta mass×factor ($M_\odot$)	$f_\rho M$	$1.2^{+0.3}_{-0.2}$
Progenitor radius ($R_\odot$)	R	547^{+14}_{-10}
Explosion epoch (day)	t_0	$60411.61^{+0.0001}_{-0.0001}$

Comparison of LCs

- Multiband light curves of SN 2024ggi with other well-studied events with flash features (SNe 2023ixf, 2020pni, 2014G and 2013fs).

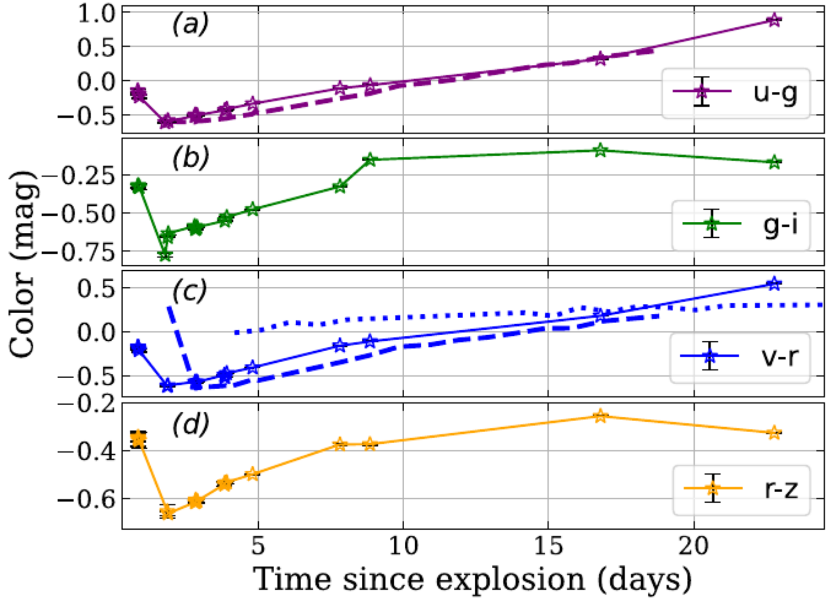
- The peak absolute magnitude is −17.75 ± 0.2 in the g band, while SN 2023ixf reached the peak after 5 days (M_g = –18.43). Both are toward the brighter end of the average peak absolute magnitude (V band) of normal Type II SNe.

- The rise time (in the u and v bands) of ~4 days in SN 2024ggi is significantly shorter than the average peak rise time of ~10 days (V-band) of normal Type II events (Valenti et al. 2016).

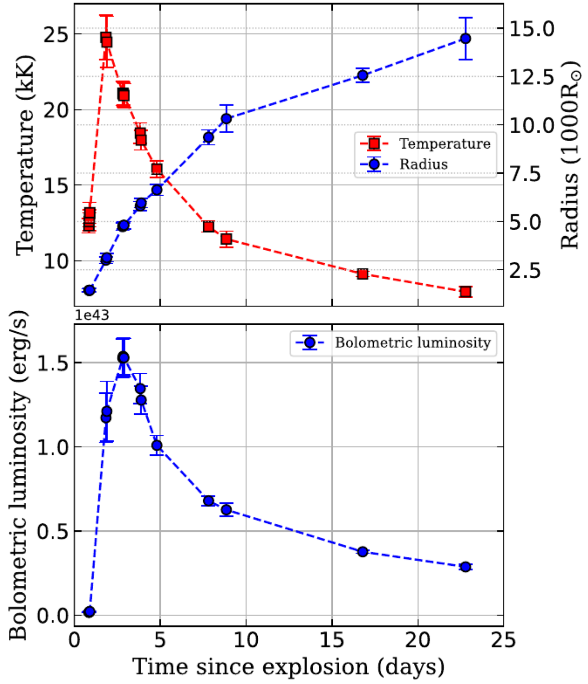


Color and Temperature Evolution

- SN 2024ggi became bluer rapidly in all colors during the first 2 days.
- The color evolution rate in SN 2023ixf is faster than other events in the beginning, and both SN 2024ggi and SN 2023ixf are bluer than SN 2013fs.
- The temperature evolution (initial rise and drop) in SN 2024ggi is indicative of a possible shock break out inside a compact and dense CSM surrounding the progenitor.

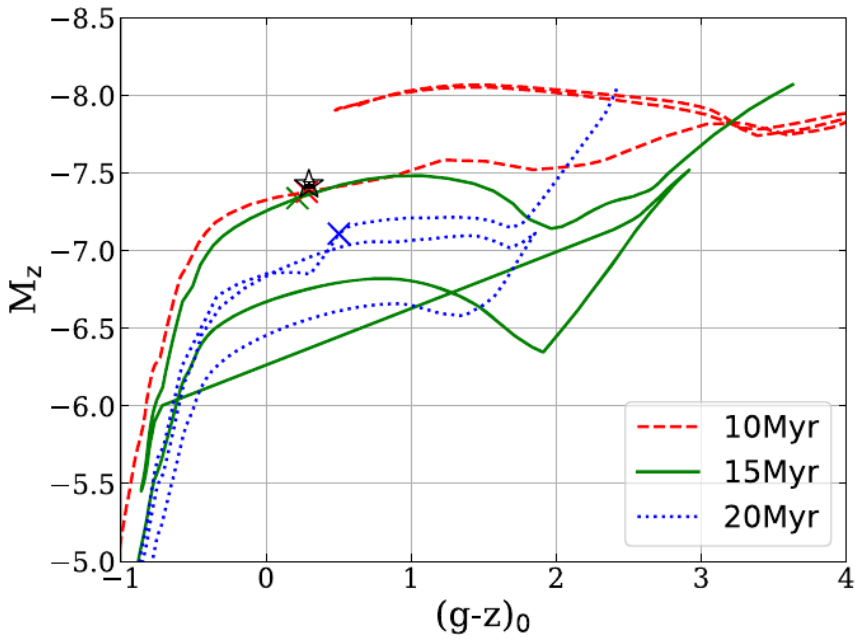


Comparison of colors of SNe 204ggi (star), 2023ixf and 2013fs



Possible progenitor of SN 2024ggi

- A possible progenitor has been identified at the location of SN 2024ggi in the images of the Dark Energy Camera Legacy Survey Data.
- A clear detection in the g, r, i, and z bands has been noticed.
- PARSEC stellar evolutionary isochrones (Bressan et al. 2012) were used to estimate the mass of the progenitor.
- The isochrones that match the measurement best have an age of ~10 (red) or 15 (green) Myr, with an initial mass of 17 or 14 M_{Sun} and a metallicity of Z = 0.025 or Z = 0.01.
- The lower mass limit (14 M_{Sun}) is similar to Xiang et al. (2024) (progenitor investigation of SN 2024ggi using the HST and Spitzer Space Telescope archival images.



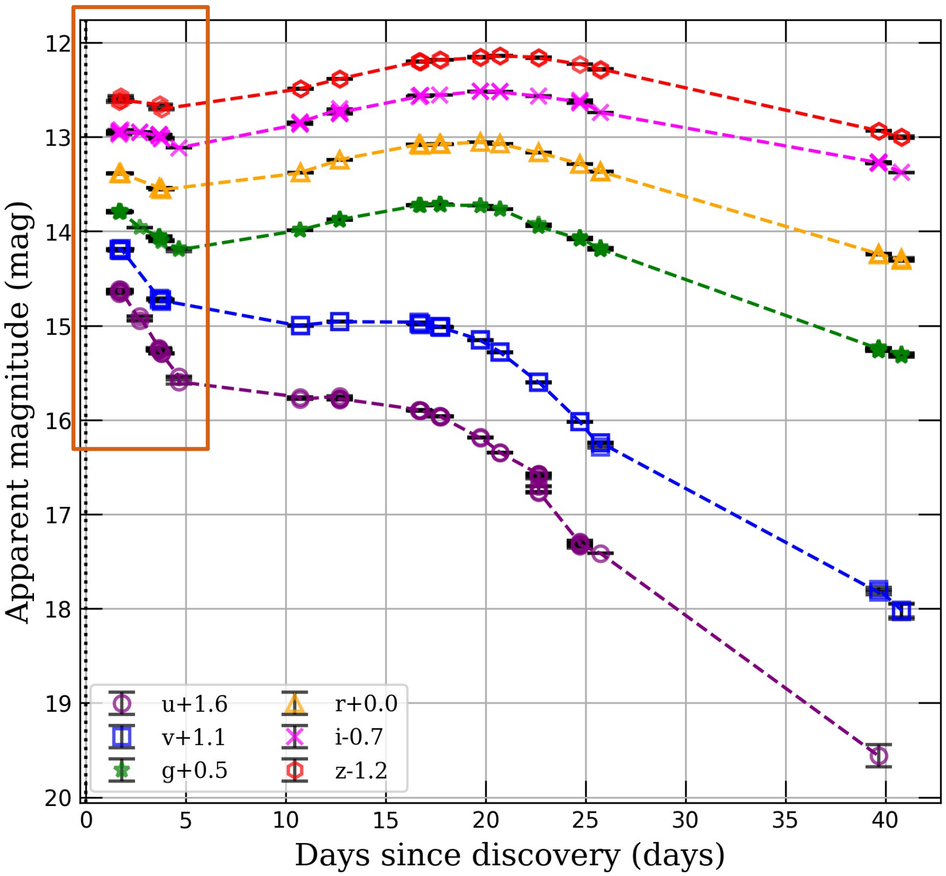
Color–magnitude diagram of 10, 15, and 20 Myr PARSEC stellar evolutionary isochrones

SN 2024ggi: Key findings

- SN 2024ggi is another nearby supernova after SN 2023ixf which was discovered early after the explosion.
- The u − g, g − i, v − r, and r − z color evolution of SN 2024ggi demonstrate a blue excess in the beginning (2 days after first light).
- The blackbody (optical) temperature increases from 12,500 to 25,000 K in 2 days after the explosion and thereafter decreases.
- The best-fit progenitor radius ~547 R_{Sun} is consistent with an RSG.
- The comprehensive photometric properties of SN 2024ggi indicate that **pure shock-cooling emission may not be attributed to them. Rather, a delayed shock break out from a dense CSM is favorable.**
- The possible progenitor mass of SN 2024ggi was estimated in the **mass range 14-17 M_{Sun}**

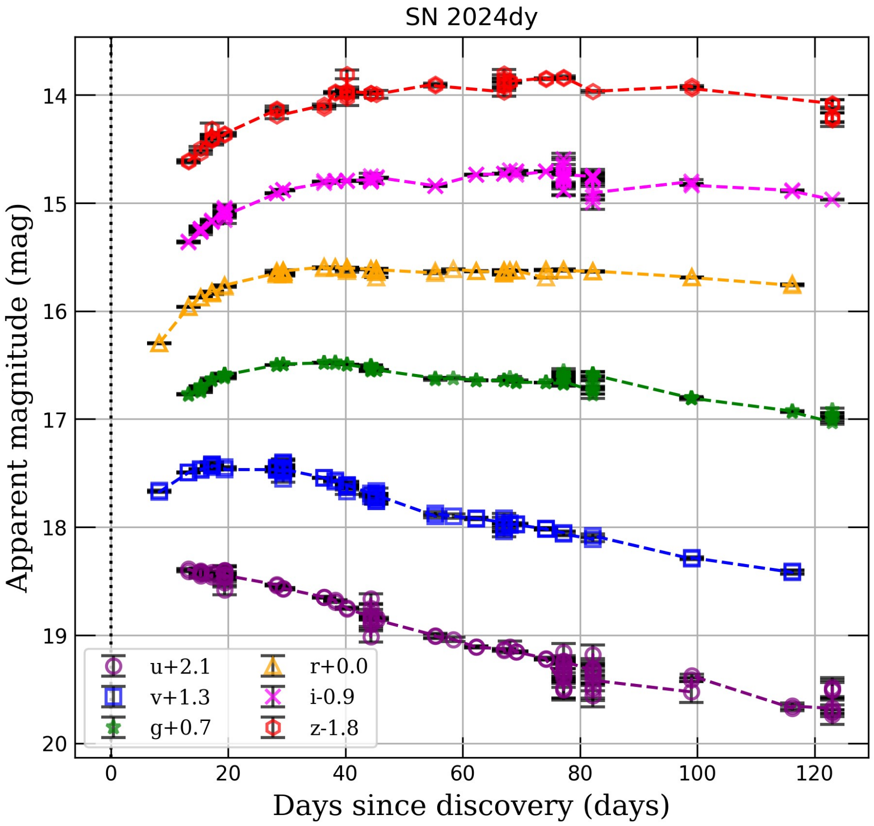
SN 2024iss

- Discovery 2024-05-12 (GOTO group).
- It was classified as a Type IIb supernova.
- SN 2024iss was monitored (uvgriz bands) with Mephsito ~45 days (after discovery). Further observations are planned after the rainy season.
- Type IIb SNe usual LC feature of two peaks was observed with Mephisto. The interesting **adiabatic cooling phase** was detected in all bands.
- Further analysis is in progress.



SN 2024dy

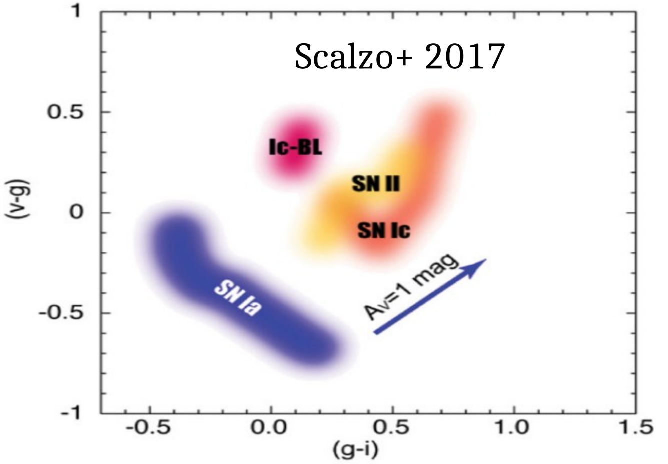
- Discovery 2024-01-02 (ATLAS group).
- It was classified as a Type IIn supernova.
- SN 2024dy was monitored (uvgriz bands) with Mephsito for 4.5 months after the discovery. As LC evolution is slow, further observations are planned in new observing cycle.
- The LC evolution is slow in redder bands.



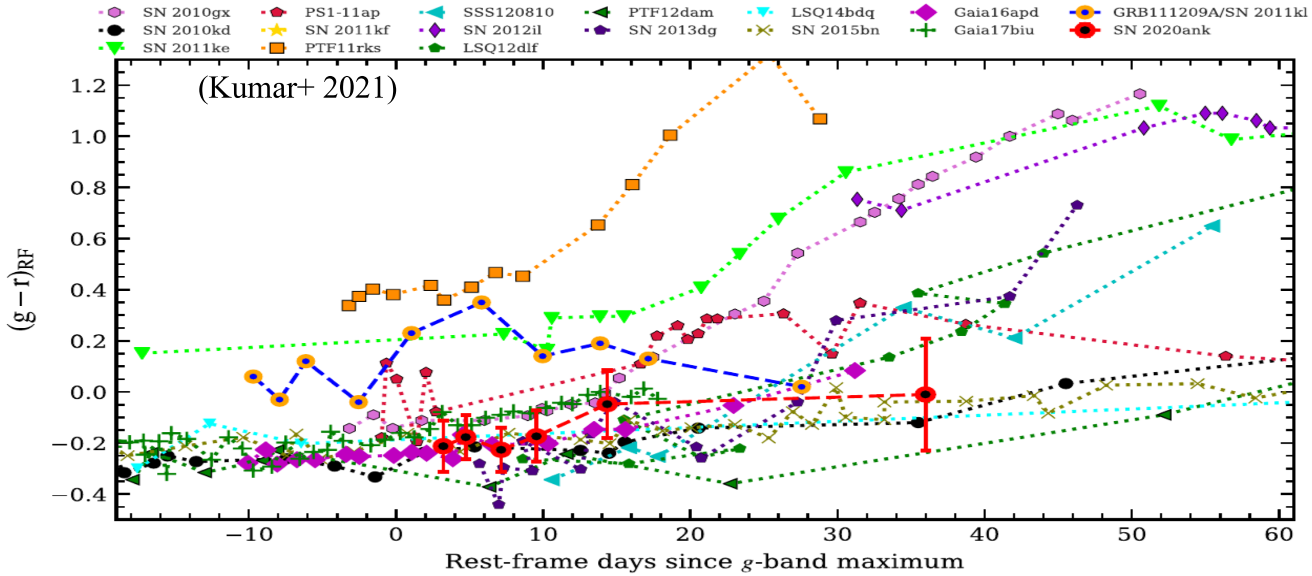
LC evolution of SN 2024dy

Mephisto colors and transient science

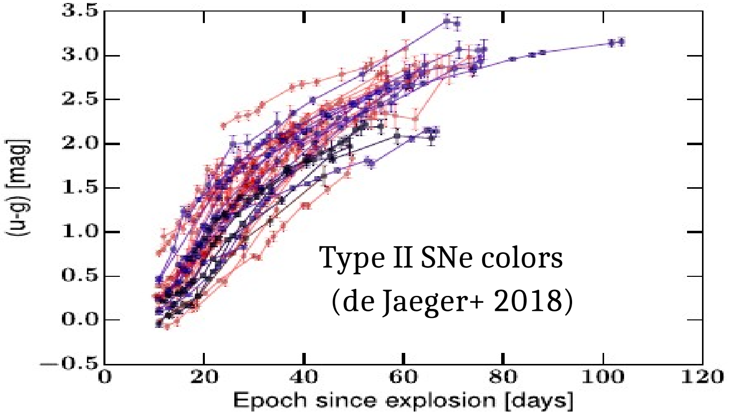
- The color evolution of SNe provides substantial information about the temperature, chemical composition of the ejecta, and shock interaction with CSM in the vicinity of the progenitor.
- Mephisto real-time and color accuracy (0.2-0.5%) → very useful for transient classifications and further monitoring.
- Multi-band monitoring (colors) will be useful for transient science.



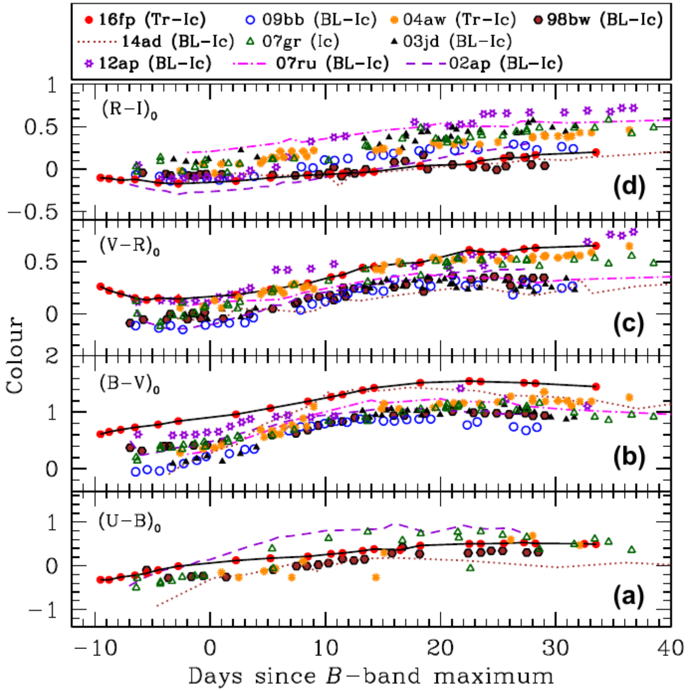
Color evolution of different SNe

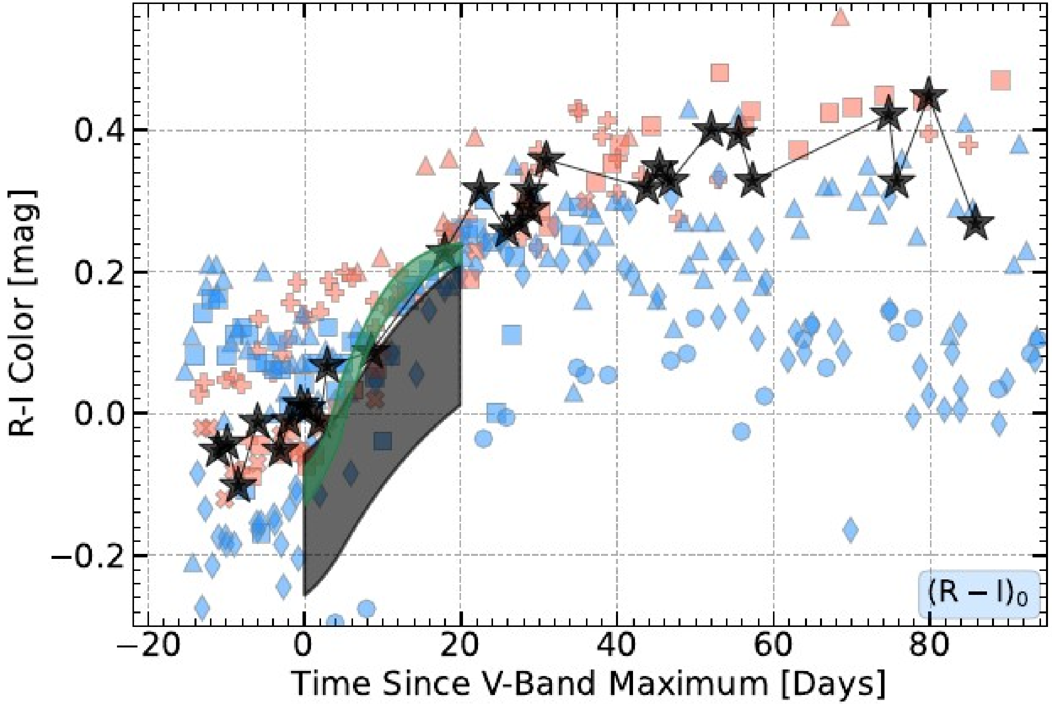


SLSNe-I color evolution



SE-SNe colors



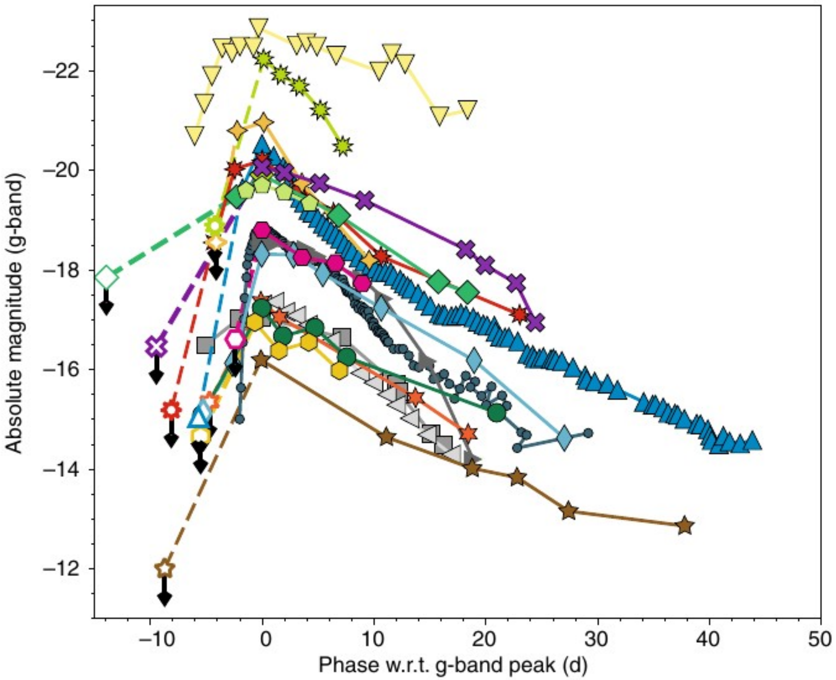


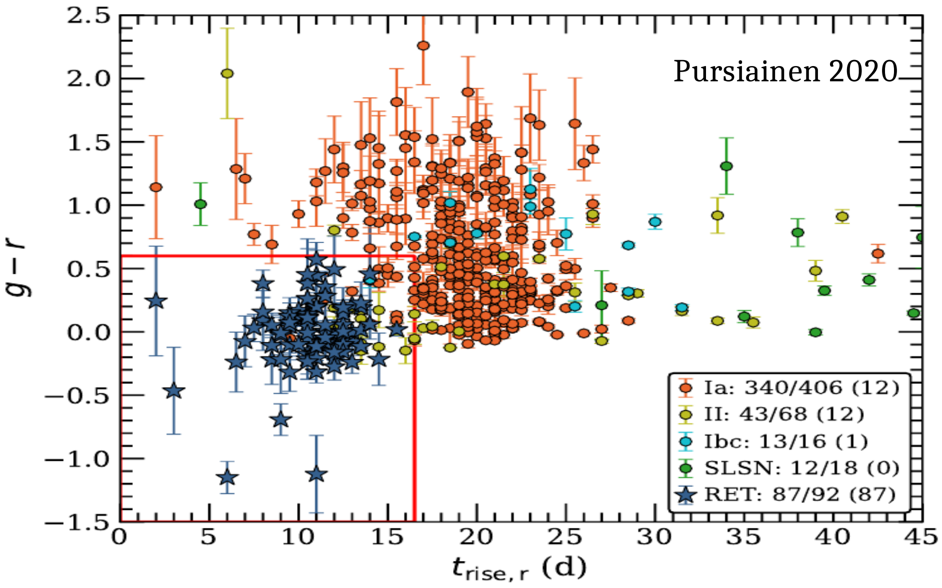
(Kumar+ 2018, Stritzinger+ 2018, Anjasha+ 2023)

- Diversity in color evolution is likely due to the varying nature of the expansion and cooling of the SN photosphere.

Mephisto and rare transients (FBOT)

- Fast Blue Optical Transients (FBOTs) are very rare events. These are usually characterized by **a rapid light curve rise to the peak** (≲10 days from the last non-detection) and an exponential decline within 30 days after peak.
- Blue at peak and slowly becomes redder.
- Explosion of an ultra-stripped progenitor.

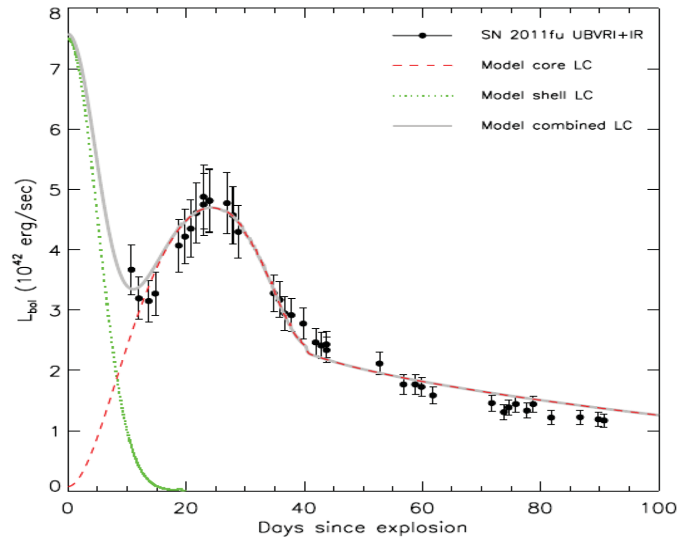




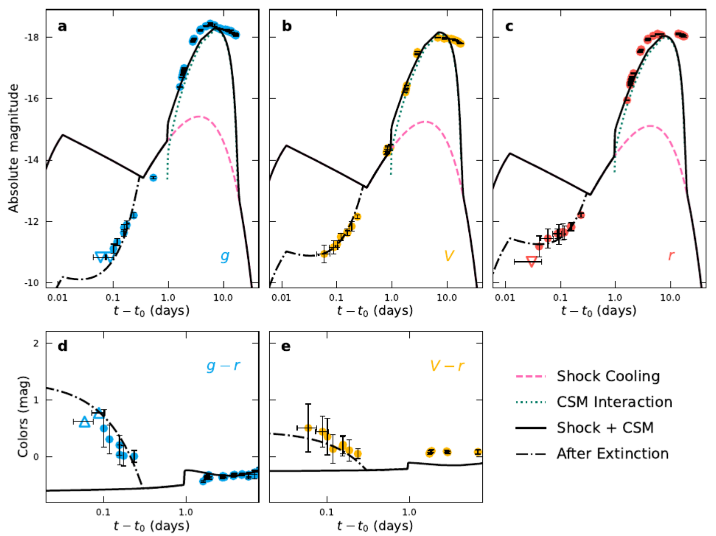
Color evolution of SNe and FBOTs

Mephisto early phase observations

- It is possible to detect early phase shock breakout phase with MEPHISTO survey (c.f. min-hr cadence).
- The fast, initial decline is result of the radiation of the cooling outer envelope (which is initially heated by the shock wave passing through it after the explosion).
- We can estimate various **physical parameters of the explosion** and **properties of the progenitor**.

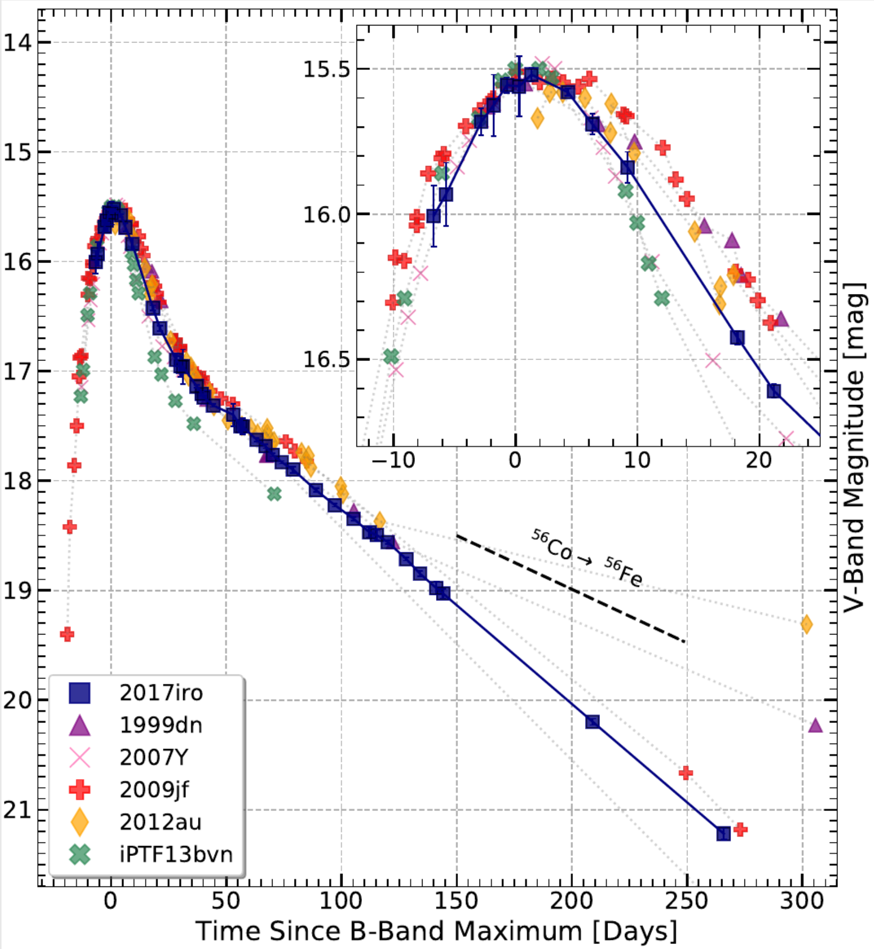


Two component model fitting on SN 2011fu (Kumar+ 2013)



Hybrid model fit on early LC of SN 2023ixf (Li+ 2024).

Late phase light curve heterogeneity in SE-SNe?



- SE-SNe declines faster than the expected decay rate of 0.98 mag/100 d from ^{56}Co →^{56}Fe i.e. lower opacity of the ejecta for the γ-rays (incomplete trapping).

- Late-time decay rate: Two group of events?

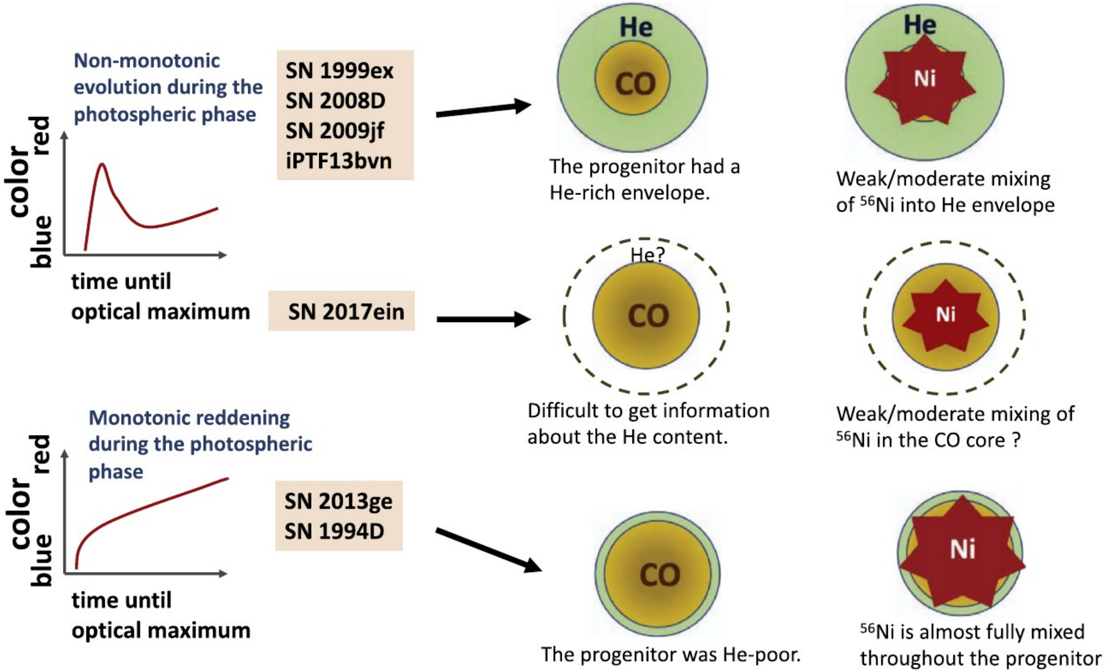
➔ Slow declining (SNe 2012au, 1999dn)
An additional source of energy (interaction of the ejecta with the CSM/magnetar).

➔ Fast declining (SNe 2017iro, 2009jf, 2007Y and iPTF13bvn)
Due to incomplete trapping of γ-rays in the SN ejecta.

(Kumar+ 2021)

Effect of Nickel mixing on the early-time Color evolution of SN Ib/c

Yoon et al. 2019 investigated the effects of ^{56}Ni mixing with the STELLA code on the early-time color evolution of SNe Ib/Ic. They show that the early-time color evolution of SN Ib/Ic sensitively depends on the ^{56}Ni distribution, and can be a powerful probe of ^{56}Ni mixing in SN Ib/Ic.



(Yoon+ 2019)

Summary and future perspective

- Mephisto is a unique facility. It is already contributing with important data of transients (SNe) during the commissioning phase observations.
- Once fully operational, it will scan a large and deep sky area in multi-bands (ugi and vrz) simultaneously.
- It is possible to discover various transients (cf. image subtraction), their classification (based on colors) and further monitoring with Mephisto.
- Mephisto early phase observations will be helpful in providing information on the progenitor properties and late phase observations can provide important information on possible heterogeneity in the nebular phase.
- Mephisto multi-band light curves can be used to constrain various explosion parameters.
- For a detailed study of peculiar events, followup observations (multi-wavelength) with other facilities will be crucial and a collaborative approach will be useful.