Light Curve Analysis of a young Type II-L Supernova KSP-ZN7090 from the KMTNet Supernova Program

ESC499 Oral Presentation

Matthew Leung

Supervisor: Prof. Dae-Sik Moon

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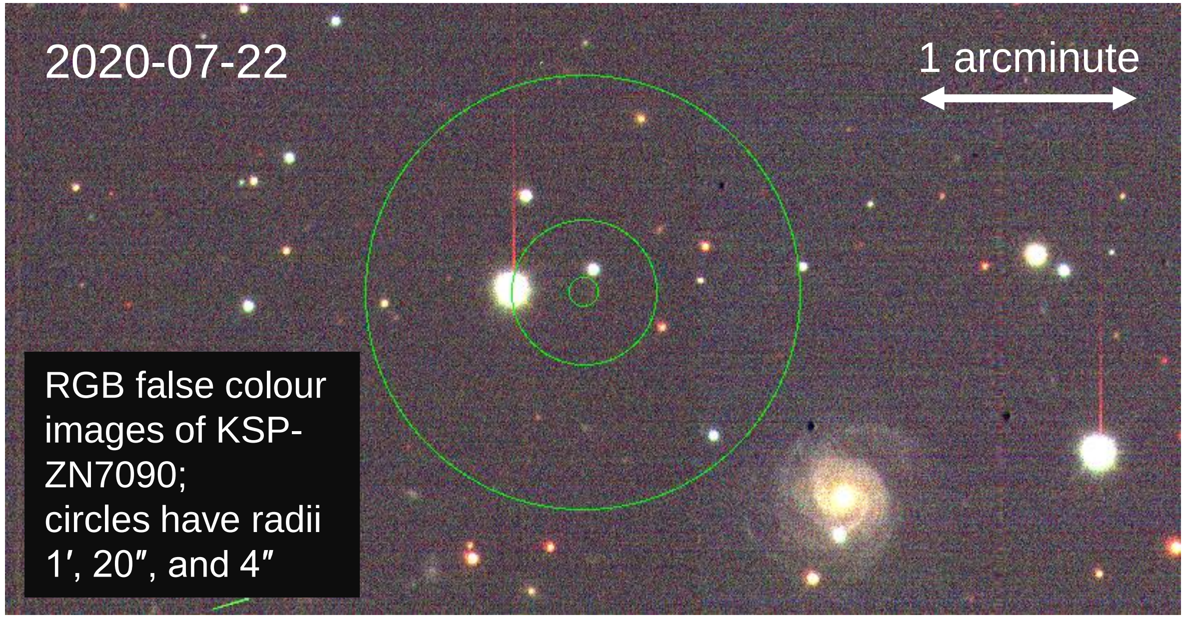
Introduction – Research Gap

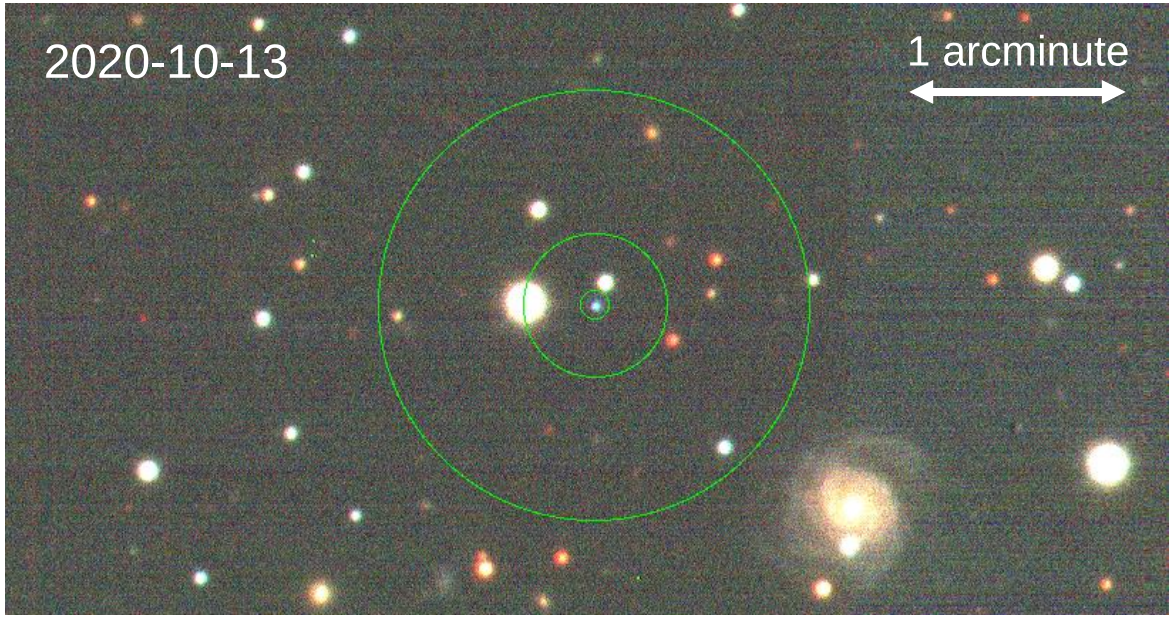
- Massive stars ($\gtrsim 8M_{\odot}$) can explode as **core-collapse SNe (CCSNe)**
- CCSNe explosion mechanism is still not fully understood due to lacking **early** observational data
  - E.g. Neutrino mechanism (the leading theory) fails for **Type II-L SNe**
- Type II-L SNe are **rare** (< 6%-10% of all CCSNe), and their **early** behaviour is “largely uncharted territory”

Introduction – Where KSP-ZN7090 fits in

- KSP-ZN7090
  - First detected by KMTNet on **2020-10-12 14:44 UTC** at location (R.A., decl.) = ($21^h31^m3.05^s$, -53°55′49.91″) (J2000)
  - **Young Type II-L** SN discovered **within ~1 day** of explosion
  - Multi-band (*BVI*) observations from KMTNet



RGB false colour images of KSP-ZN7090;
circles have radii 1′, 20″, and 4″



Introduction – Goals

- Provide information on how KSP-ZN7090 evolves
  - Construct light curve
- Estimate key parameters of KSP-ZN7090
  - Temporal parameters: Epoch of first light, peak epoch, etc.
  - Physical parameters: Nickel-56 mass, ejecta mass, ejecta kinetic energy
- End goal: **Add another SN to the limited sample of Type II-L SNe**

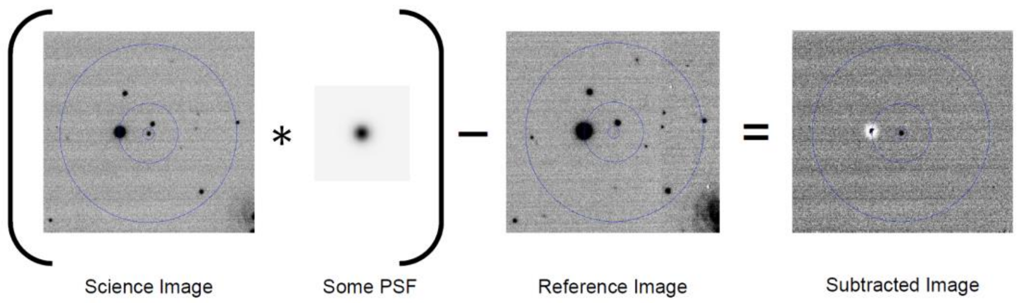
Light Curve Construction

1) Image subtraction
2) PSF Photometry
3) Discarding Bad Quality Images
4) Light Curve Binning and Image Stacking
5) Colour Correction
6) Interstellar Extinction Correction

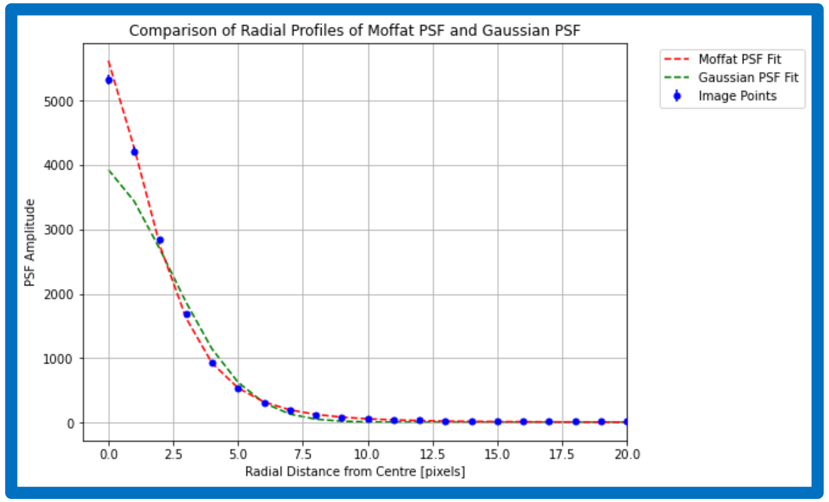
Light Curve Construction

1) **Image subtraction**
2) **PSF Photometry**
3) **Discarding Bad Quality Images**
4) Light Curve Binning and Image Stacking
5) Colour Correction
6) Interstellar Extinction Correction

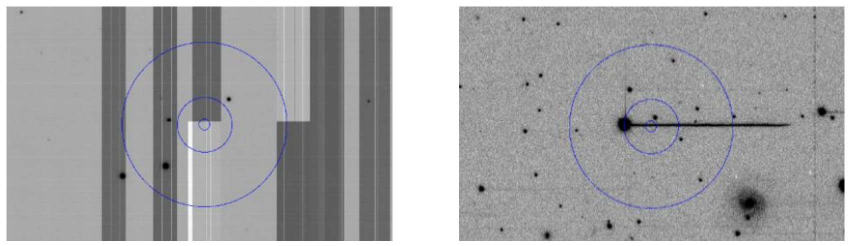
Subtract out background objects



Fit PSFs to objects to find their fluxes

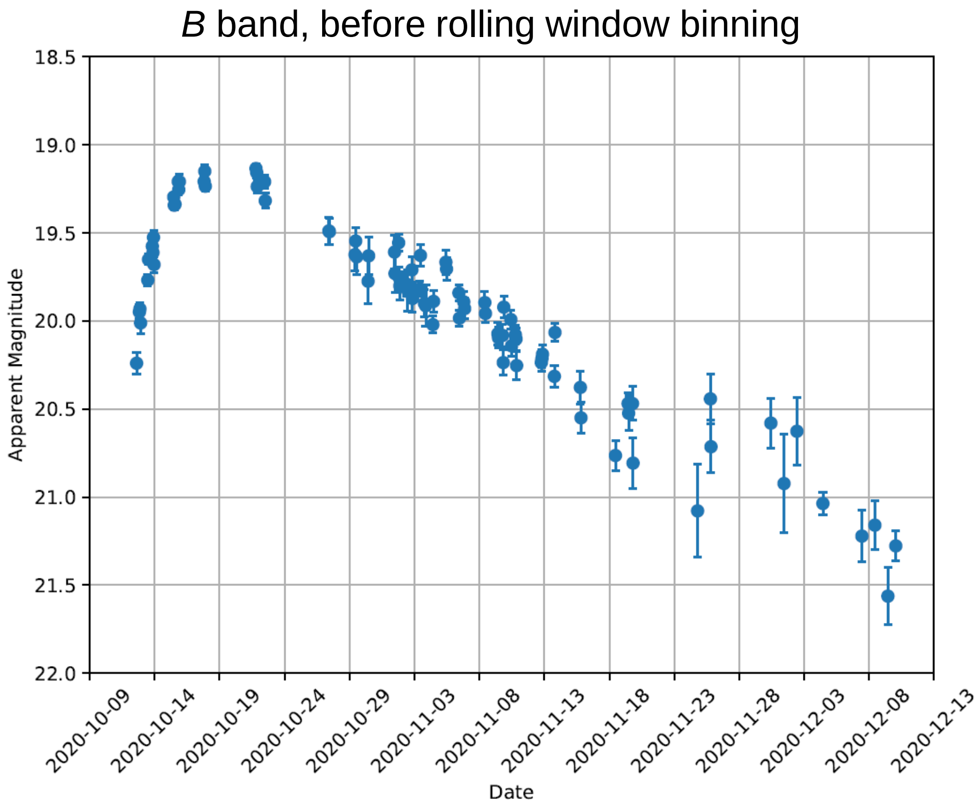


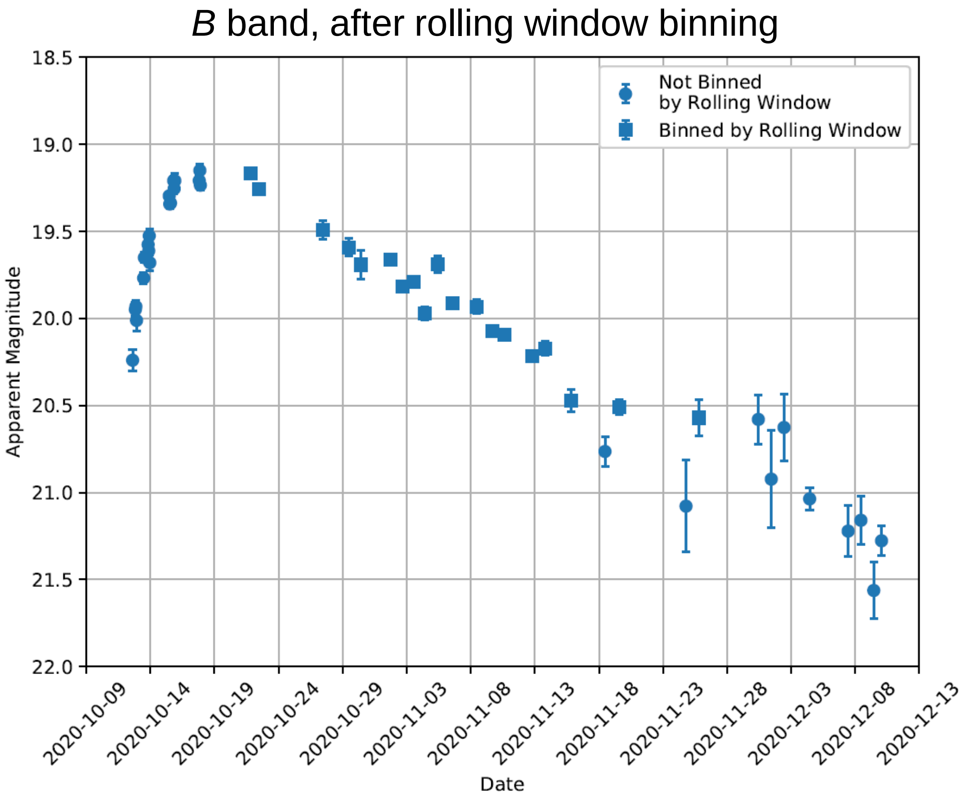
Discard bad images



Light Curve – Binning and Stacking

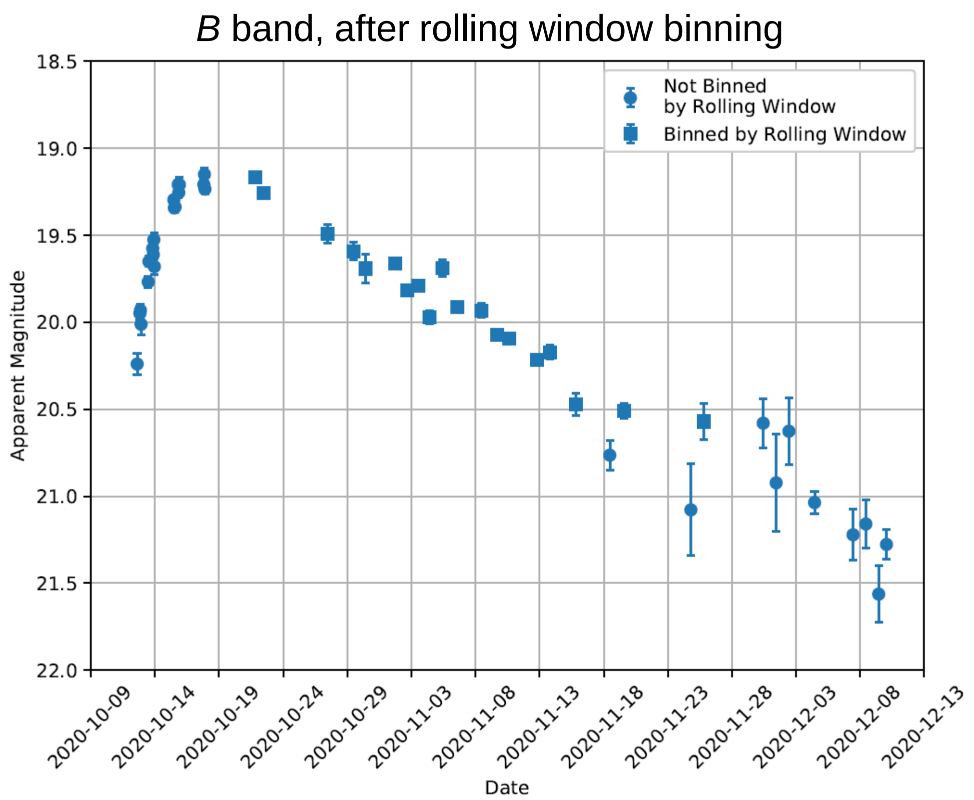
- Data 9 days after first detection was binned with a 24 hour rolling window, using **inverse-variance weighting**
  - Reduced spread in data

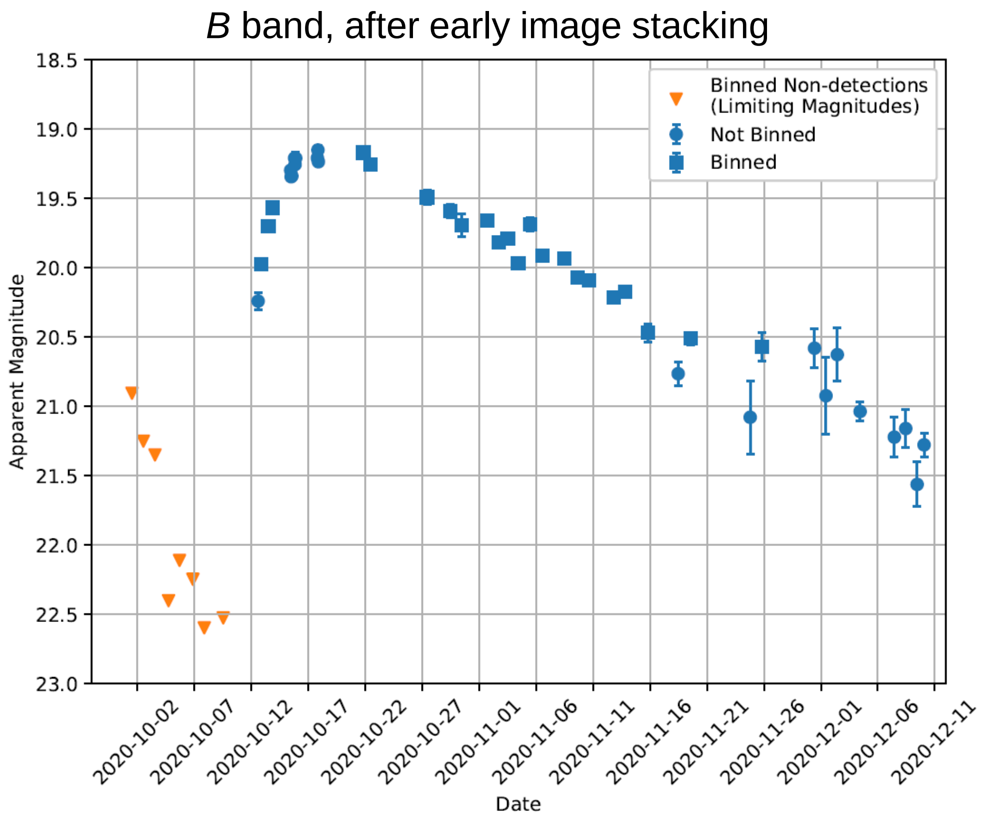




Light Curve – Binning and Stacking

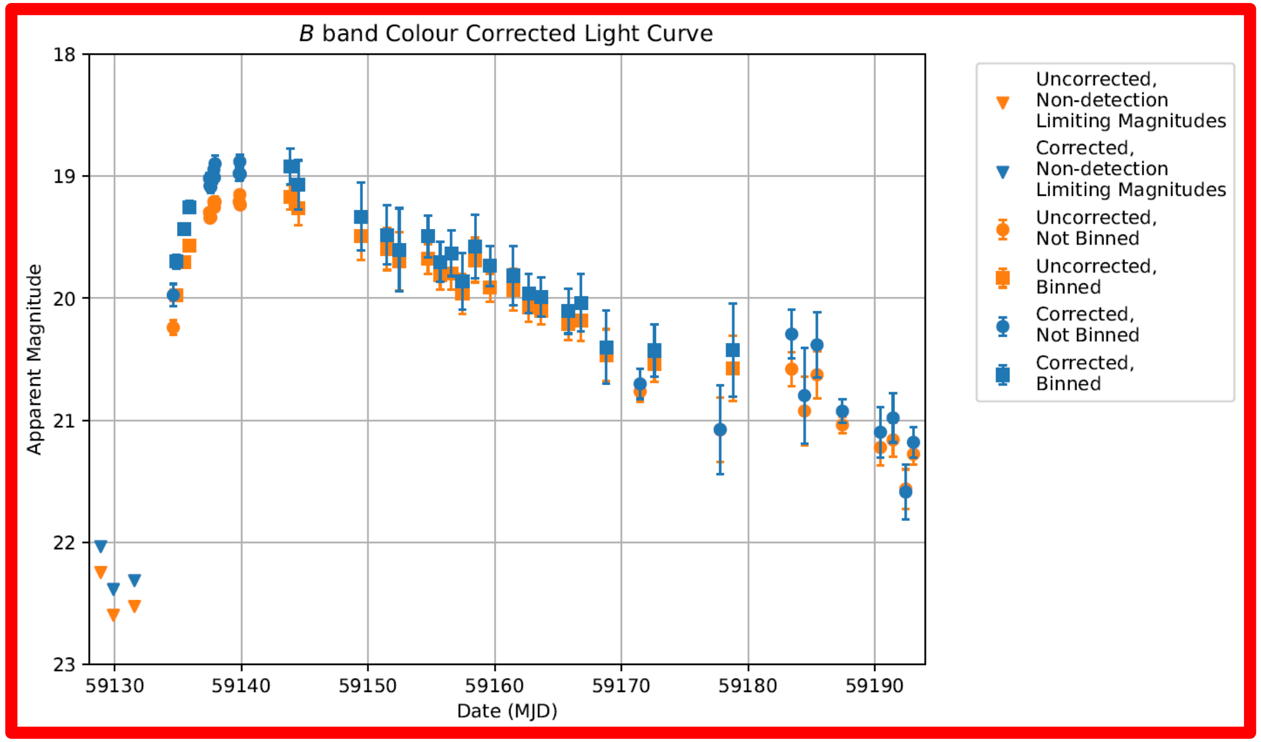
- Early data up to 2 days after first detection were **stacked**
  - Allowed for deeper images
  - Constrained the first light time of SN

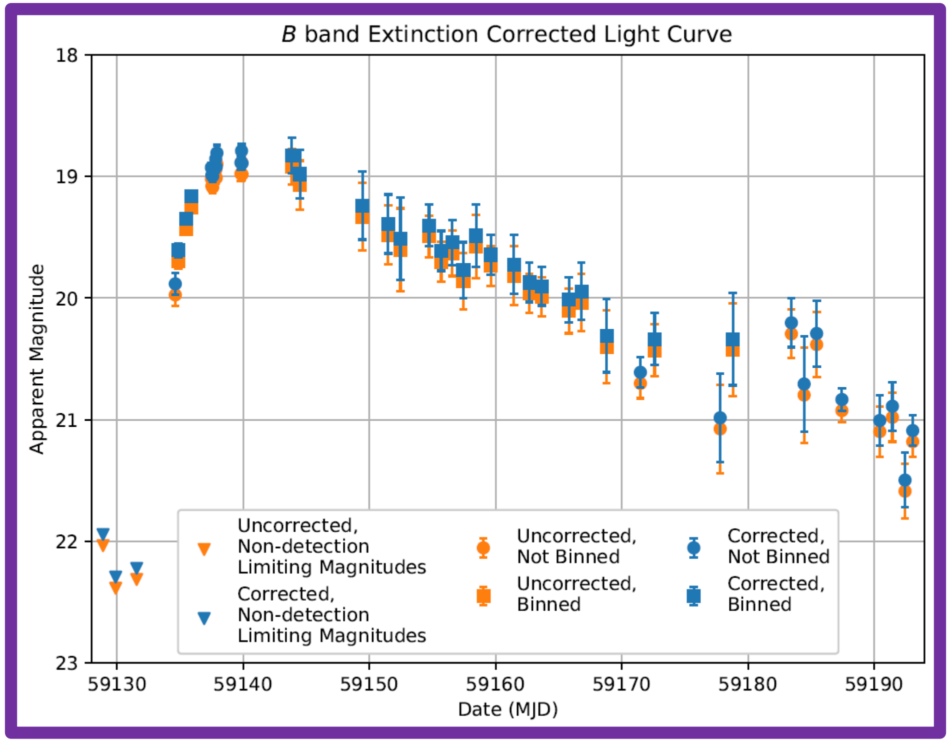




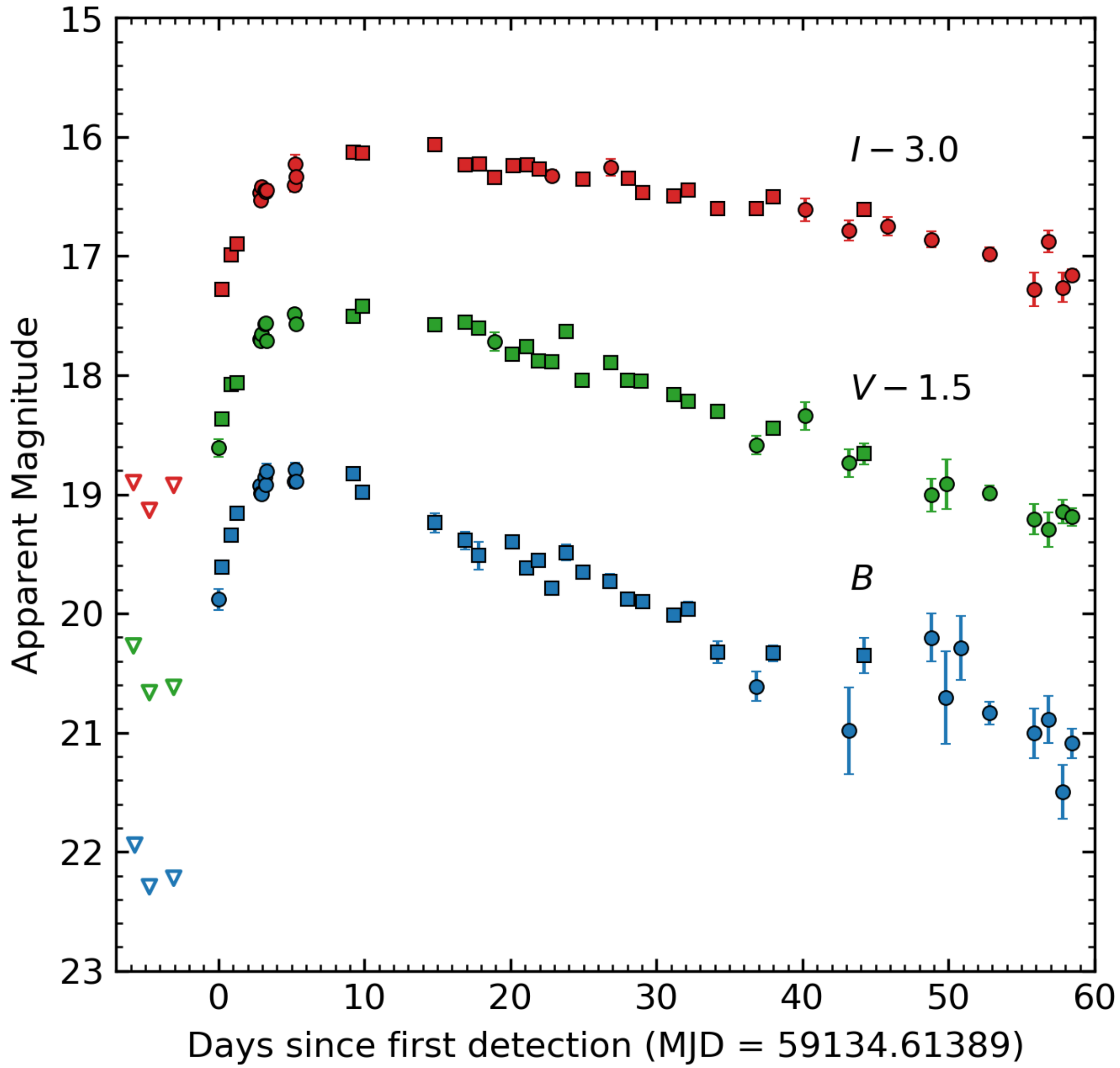
Light Curve – Colour and Extinction Corrections

- Colour correction: KMTNet uses non-standard filters → *B* band required correction
- Extinction correction: Correct for loss in light due to interstellar material between SN and Earth





Final Light Curve



Some observations:

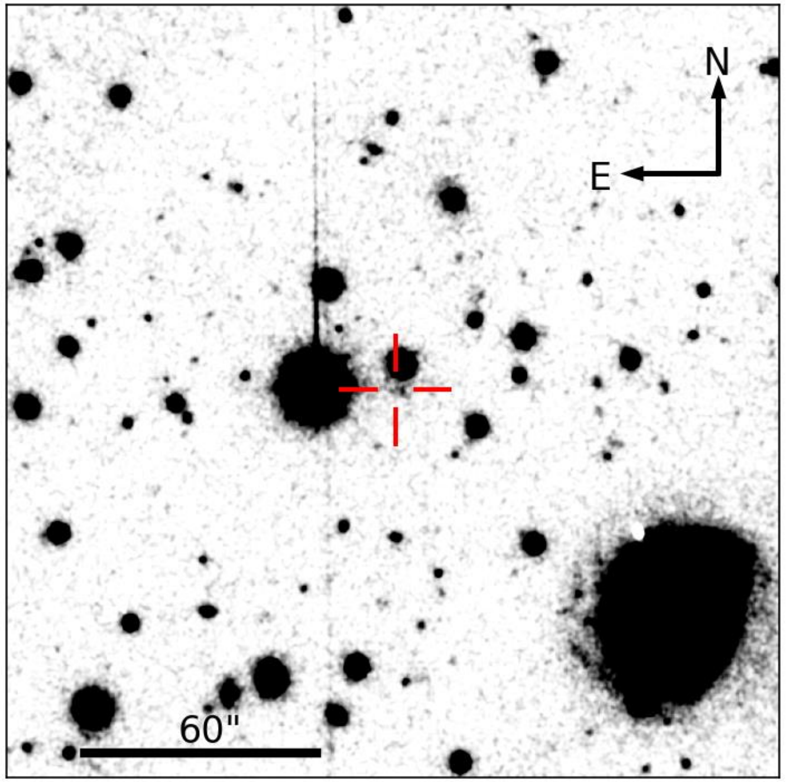
- Fast rise and relatively fast decline
- Clear linear decline post peak, without plateau → likely not II-P
- *V* band declines by > 0.5 mag in first 50 days after explosion → it's II-L (Faran 2014)

For more details, see:
Faran, T., Poznanski, D., Filippenko, A. V., et al. 2014, Monthly Notices of the Royal Astronomical Society, 445, 554, doi: 10.1093/mnras/stu1760

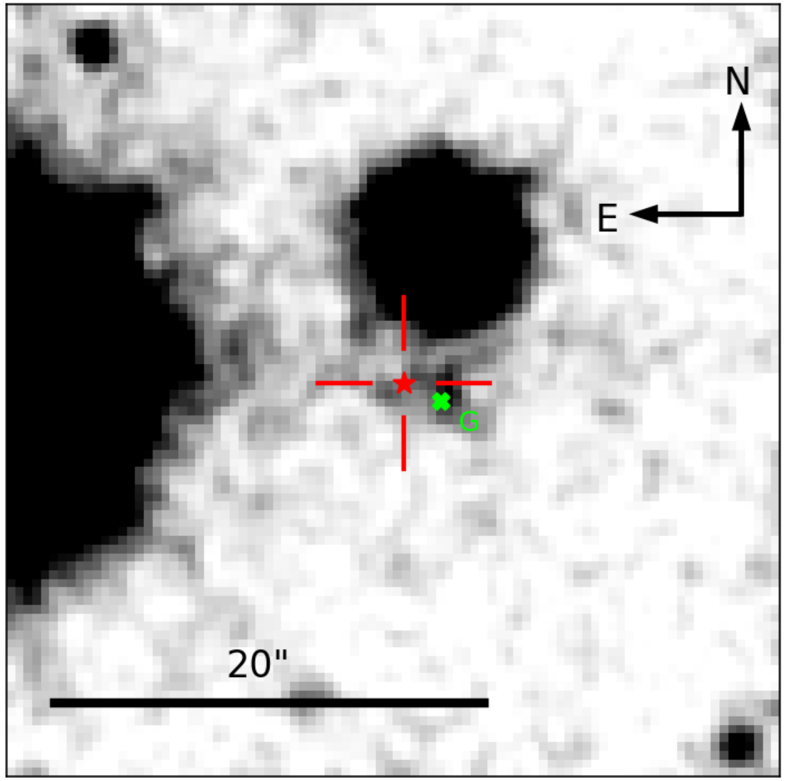
KSP-ZN7090’s Host Galaxy

- At (R.A., decl.) = ($21^h31^m2.86^s$, $-53°55'50.75''$) (J2000)
  - Cf. SN is at (R.A., decl.) = ($21^h31^m3.05^s$, $-53°55'49.91''$); ~3″ positional difference

Wide field view around KSP-ZN7090



KSP-ZN7090’s host galaxy marked in green

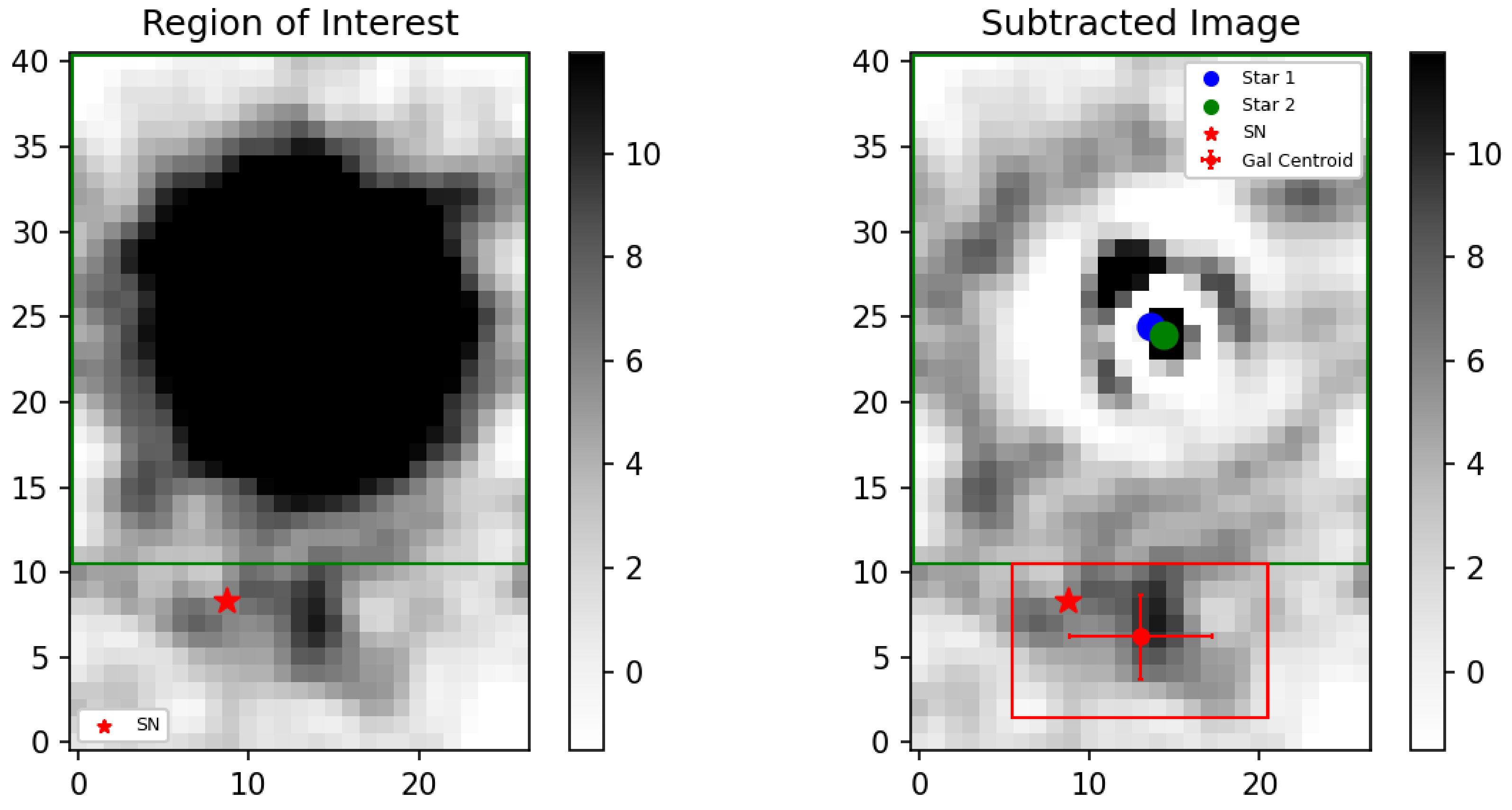


Magnitude of KSP-ZN7090’s host galaxy

Band	Apparent Magnitude	Limiting Magnitude
B	22.165 ± 0.276	21.846
V	22.943 ± 0.283	22.771
I	21.773 ± 0.112	22.569

KSP-ZN7090's Host Galaxy

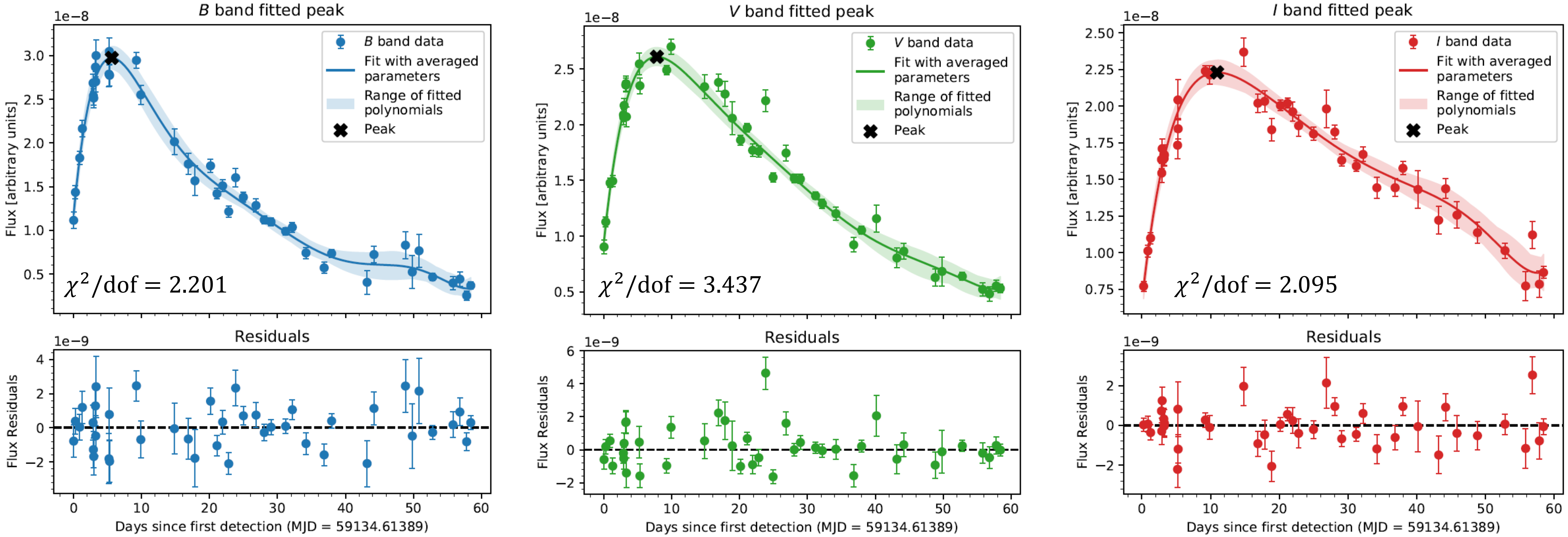
- Fitted a binary star model to nearby bright object and subtracted it out
- In subtracted image, found centroid of region containing host galaxy



Note: The numbers on the axes (excluding the colour bar) represent pixel positions and not actual WCS coordinates

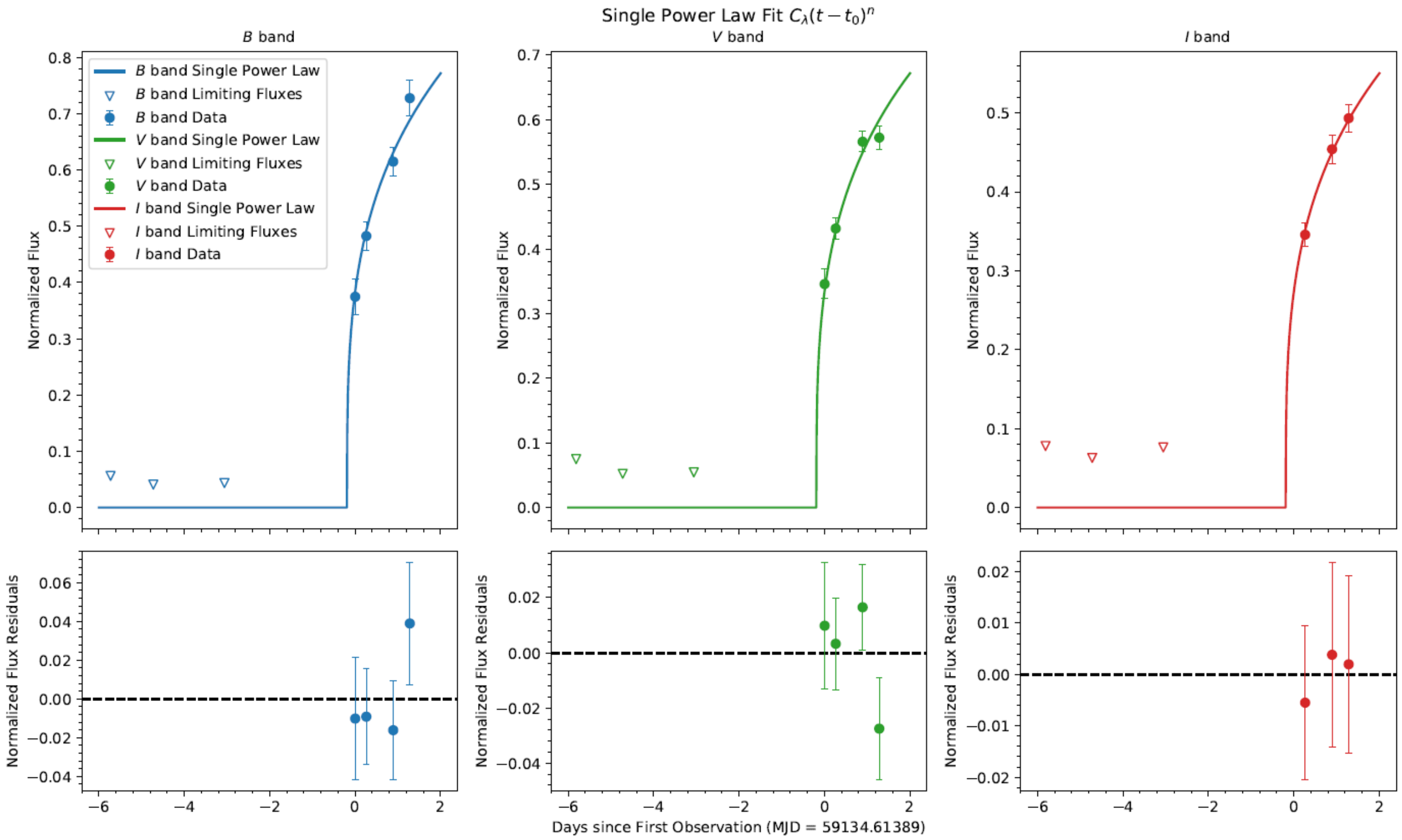
Temporal Parameters – Peak Fitting

- Used Monte Carlo simulations to fit 7th degree polynomial to light curve
- The *B*, *V*, and *I* bands peak at 5.61 ± 0.19, 7.79 ± 0.25, and 10.96 ± 0.35 days respectively



Temporal Parameters – Power Law Fitting

- **Simultaneously** fitted single power law to 3 bands to find epoch of first light t_0
- Epoch of first light is 0.191 ± 0.126 days before first detection



Single power law:

$$f_\lambda(t) = \begin{cases} 0 & \text{if } t < t_0 \\ C_\lambda(t-t_0)^n & \text{if } t \geq t_0 \end{cases}$$

Relevant fitted parameters:

$$t_0 = -0.191 \pm 0.126$$
$$n = 0.285 \pm 0.068$$

Goodness of fit:

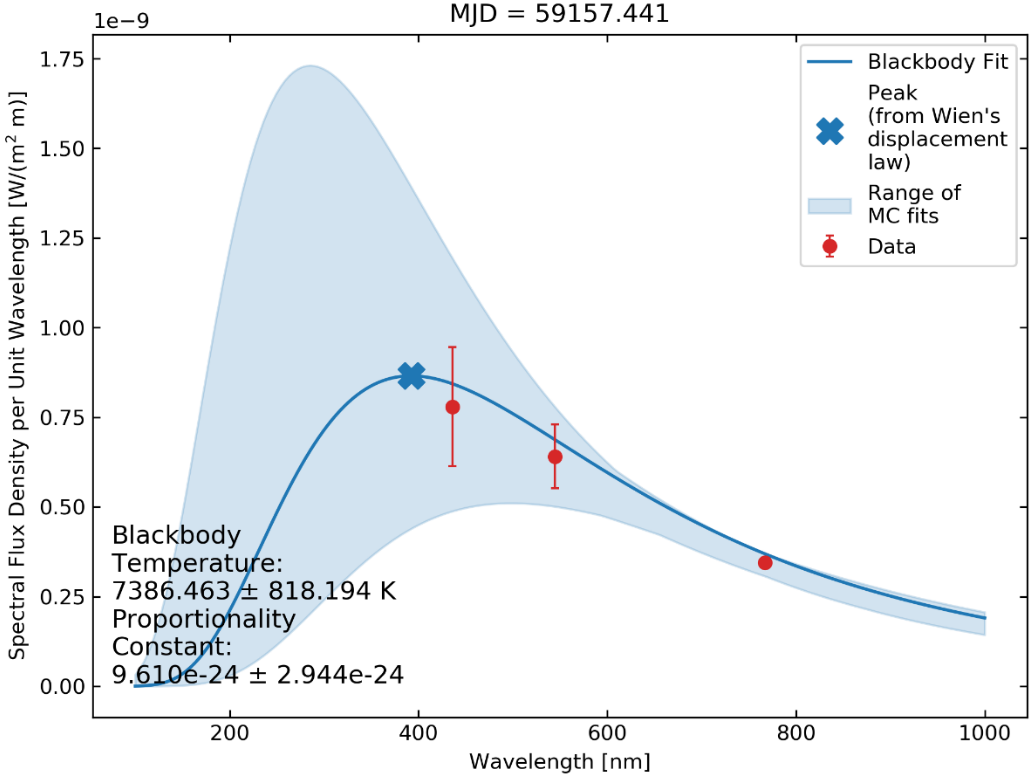
$$\chi^2/\text{dof} = 0.986$$

Bolometric Light Curve

- Required in order to fit models to find physical parameters
- Two methods commonly used:
  - Blackbody Fitting
  - Bolometric Corrections

Bolometric Light Curve – Blackbody Fitting

- **At each epoch**, fitted a blackbody function to *BVI* data points
- From the fitted temperature value and proportionality constant, obtained **bolometric luminosity** as a function of time



Fit function for each epoch (fit parameters are T and A):

$$f_\lambda = AB_\lambda(T) = \frac{2Ahc^2/\lambda^5}{\exp\left[hc/(\lambda k_B T)\right] - 1}$$

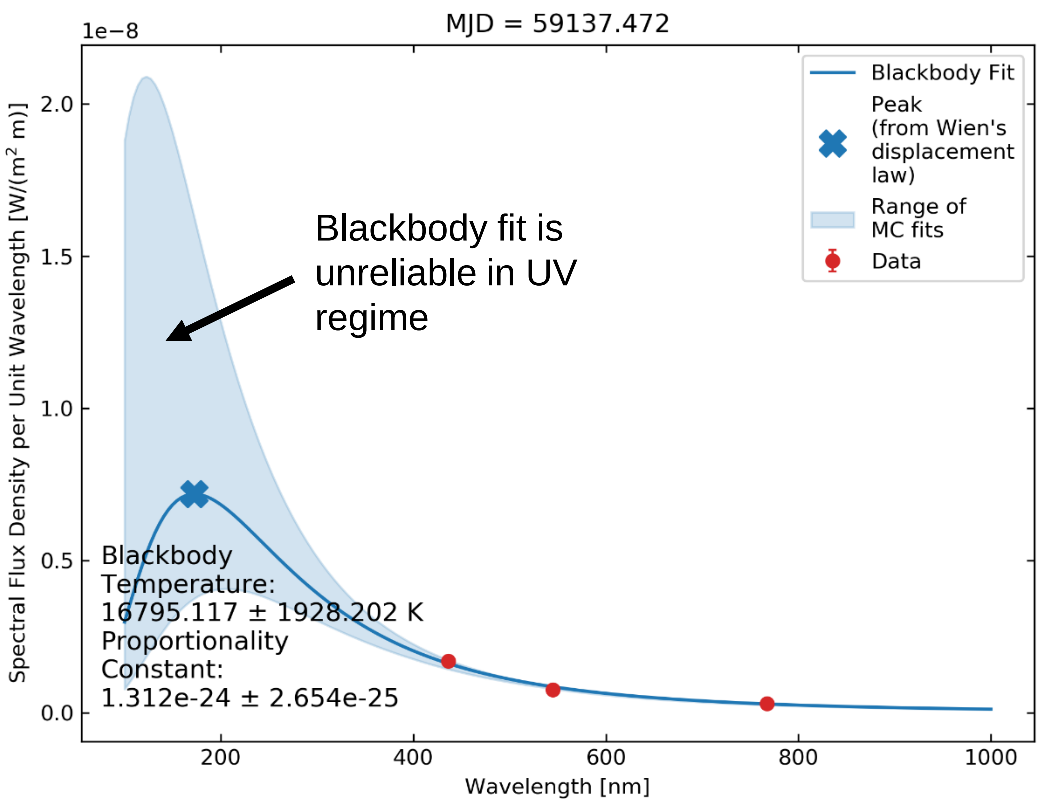
Bolometric luminosity calculation:

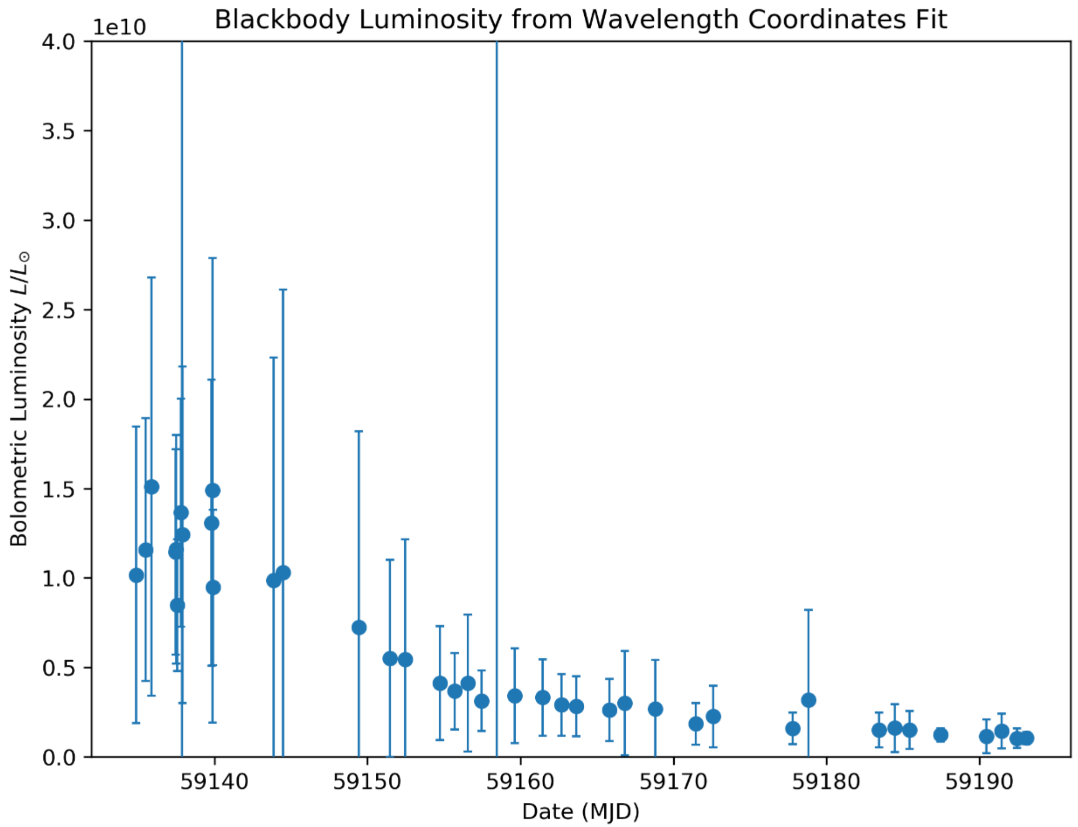
$$L_{\mathrm{bol}} = 4\pi r^2 F_{\mathrm{bol}} = \frac{8Ahc^2\pi^5 r^2}{15(hc/(k_B T))^4}$$

r is the luminosity distance to SN

Bolometric Light Curve – Blackbody Fitting

- Results had high uncertainty because blackbody was not well constrained
  - Blackbody peak is not always constrained
- Usually, this method is effective if there are observations in more bands

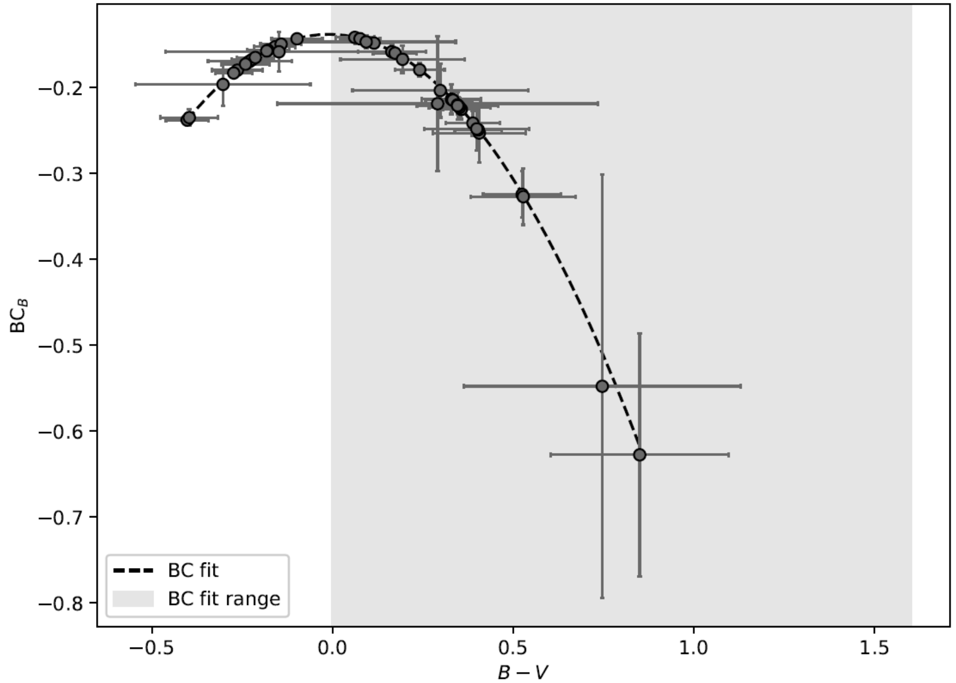




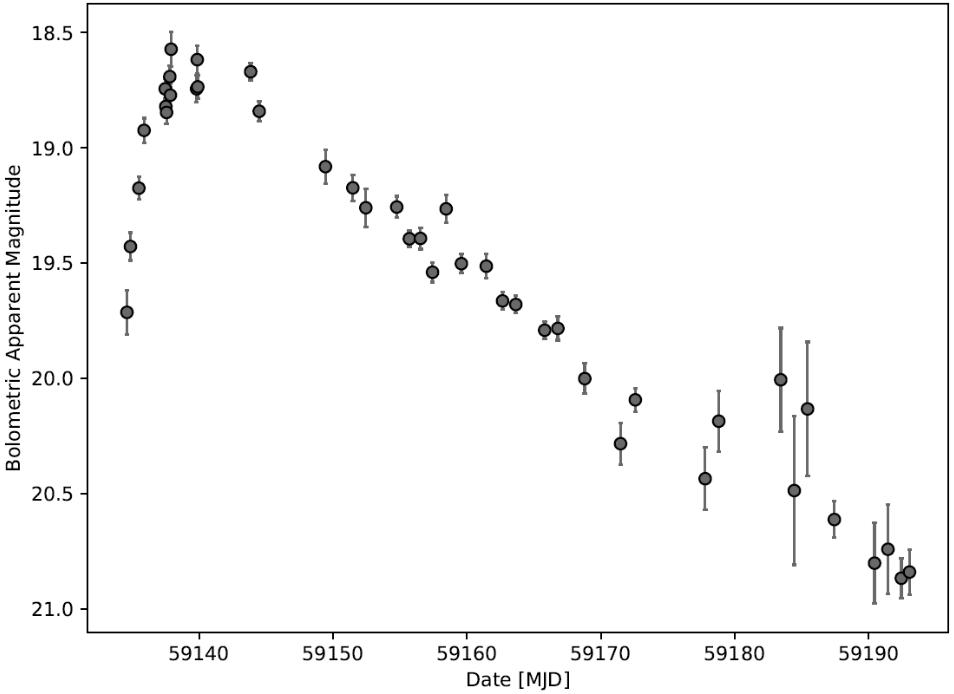
Bolometric Light Curve – Bolometric Corrections

- Added a **correction term** (polynomial function of colour) to a certain band to obtain bolometric light curve
  - $m_{\mathrm{bol}} = m_B + \mathrm{BC}_B = m_B + \sum_{k=0}^{n} c_k (m_B - m_V)^k$
  - Coefficients for the polynomial are given in the literature

Bolometric correction term for *B* band as a polynomial function of (*B* – *V*)



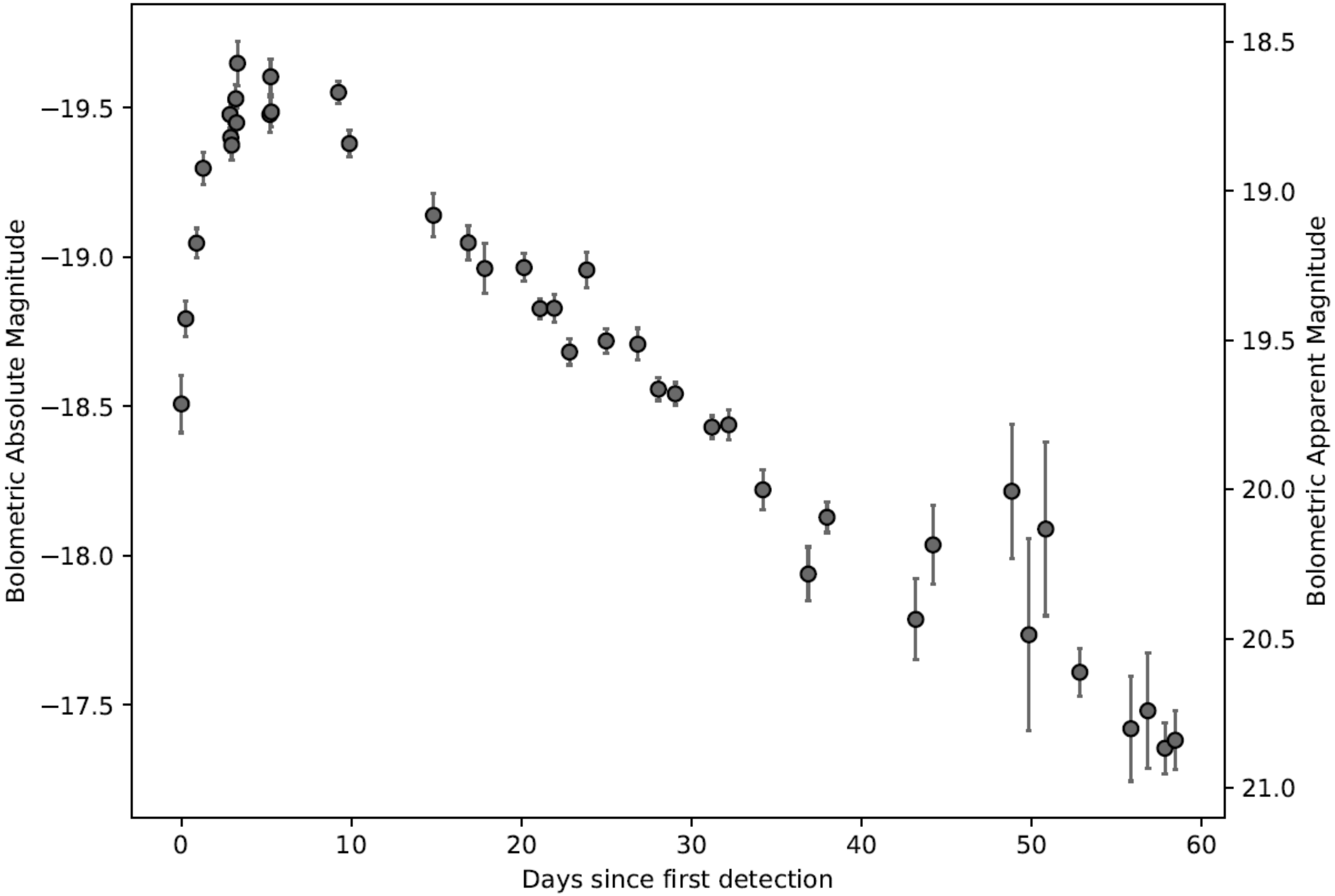
Bolometric Light Curve



Bolometric Light Curve

- Clear linear decline
- Not at nebular phase yet
  - Some models not usable

Bolometric light curve assuming SN is at $z = 0.1$



Physical Parameters – Valenti et al. (2008) Model

- Modified version of Arnett (1982) model originally for Type Ia SNe without hydrogen recombination phase
- Model shown below (fit parameters are in red):

$$L(t) = M_{\mathrm{Ni}} \exp\left(-\left[\frac{t}{\tau_m}\right]^2\right) \times \left[(\epsilon_{\mathrm{Ni}} - \epsilon_{\mathrm{Co}}) \int_0^{t/\tau_m} 2z \exp(-2zy + z^2)\, dz + \epsilon_{\mathrm{Co}} \int_0^{t/\tau_m} 2z \exp(-2zy + 2zs + z^2)\, dz\right]$$

$$y \equiv \tau_m/(2\tau_{\mathrm{Ni}}) \qquad s \equiv \tau_m(\tau_{\mathrm{Co}} - \tau_{\mathrm{Ni}})/(2\tau_{\mathrm{Co}}\tau_{\mathrm{Ni}})$$

$$\tau_m = \left(\frac{\kappa_{\mathrm{opt}}}{\beta c}\right)^{\frac{1}{2}} \left(\frac{10 M_{\mathrm{ej}}^3}{3 E_{\mathrm{k}}}\right)^{\frac{1}{4}} \qquad E_{\mathrm{k}} = \frac{3 M_{\mathrm{ej}} v_{\mathrm{ph}}^2}{10}$$

Note: Arnett (1982) and Valenti et al. (2008) both have incorrect equations for ejecta kinetic energy and ejecta mass. The correct equation can be found in Toy et al. (2016)

References:

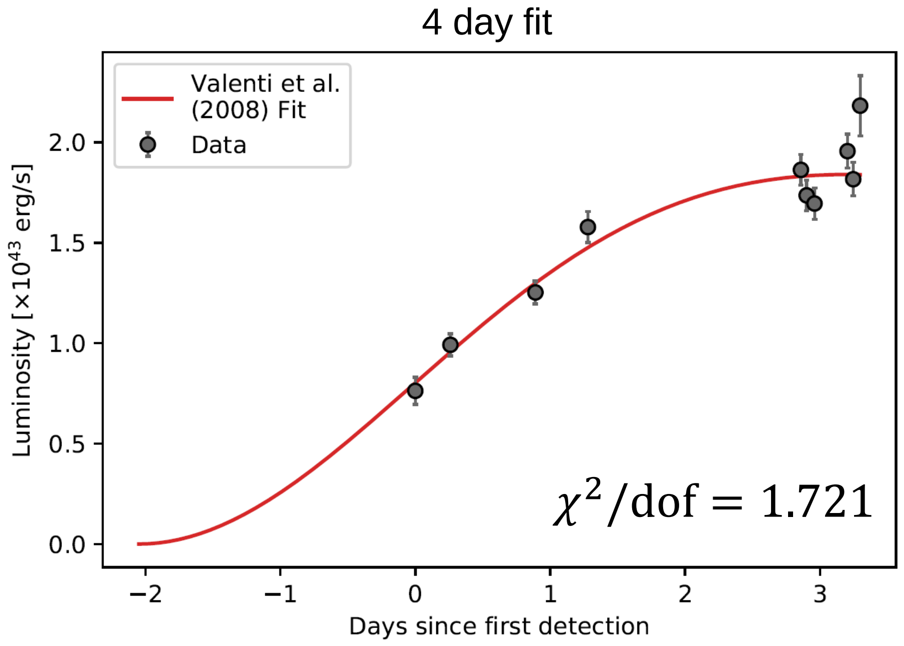
Arnett W. D., 1982, ApJ, 253, 785, doi: 10.1086/159681

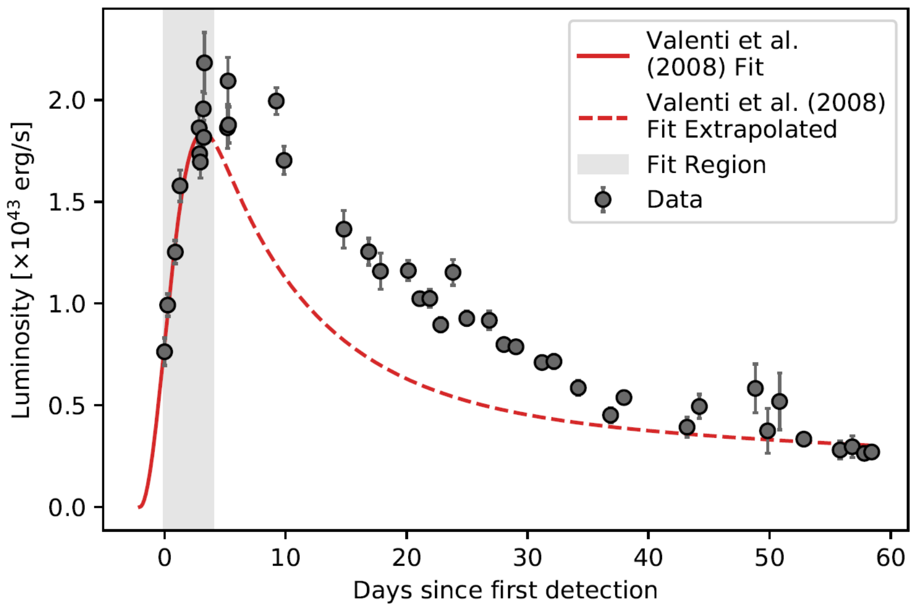
Toy, V. L., Cenko, S. B., Silverman, J. M., et al. 2016, The Astrophysical Journal, 818, 79, doi: 10.3847/0004-637x/818/1/79

Valenti, S., Benetti, S., Cappellaro, E., et al. 2008, Monthly Notices of the Royal Astronomical Society, 383, 1485, doi: 10.1111/j.1365-2966.2007.12647.x

Physical Parameters – Valenti et al. (2008) Model

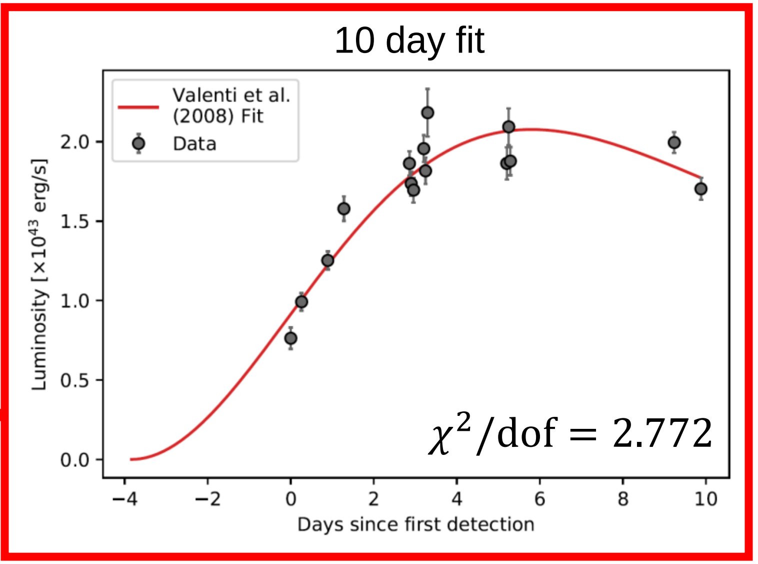
- Assumptions: $v_{\mathrm{ph}} = 10000$ km/s, constant opacity $\kappa = 0.34$ cm^2/g due to Thompson scattering
- Results: $M_{\mathrm{Ni}} = (0.382 \pm 0.041)\, M_{\odot}$, $\tau_m = 3.368 \pm 0.854$ days, $t_{SBO} = 2.049 \pm 0.521$ days before first detection
- Fit to first 4 days after first detection





Physical Parameters – Valenti et al. (2008) Model

- Results are inconsistent with other Type II-L SNe
- This model may not be too applicable
  - Originally for Type Ia/Ic SNe
  - Assumes light curve rise is mainly due to energy from radioactive decay
  - Does not capture light curve rise well for longer fit intervals



Comparison of Results

	SN KSP-ZN7090	SN 2013ej	SN 2013hj	SN 2014G	SN 2017ahn
Type	II-L	II-L	II-L	II-L	II
M_{Ni} [$\times M_\odot$]	0.382 ± 0.041	0.020 ± 0.002	0.08 ± 0.01	0.059 ± 0.003	0.041 ± 0.006
M_{ej} [$\times M_\odot$]	0.016 ± 0.008	12	9.6	4.8	12.52
E_{k} [$\times 10^{51}$ erg]	0.009 ± 0.005	2.3 *	2 *	2.0	1.35

* total energy (kinetic + thermal)

Next Steps

- Fast rise and incompatibility of Valenti et al. (2008) model suggests that light curve rise could be due to shock-heated cooling
- Try analytic models such as Nakar & Sari (2010) and Rabinak & Waxman (2011)
    - These models have been widely used in the literature for Type II SNe with good results

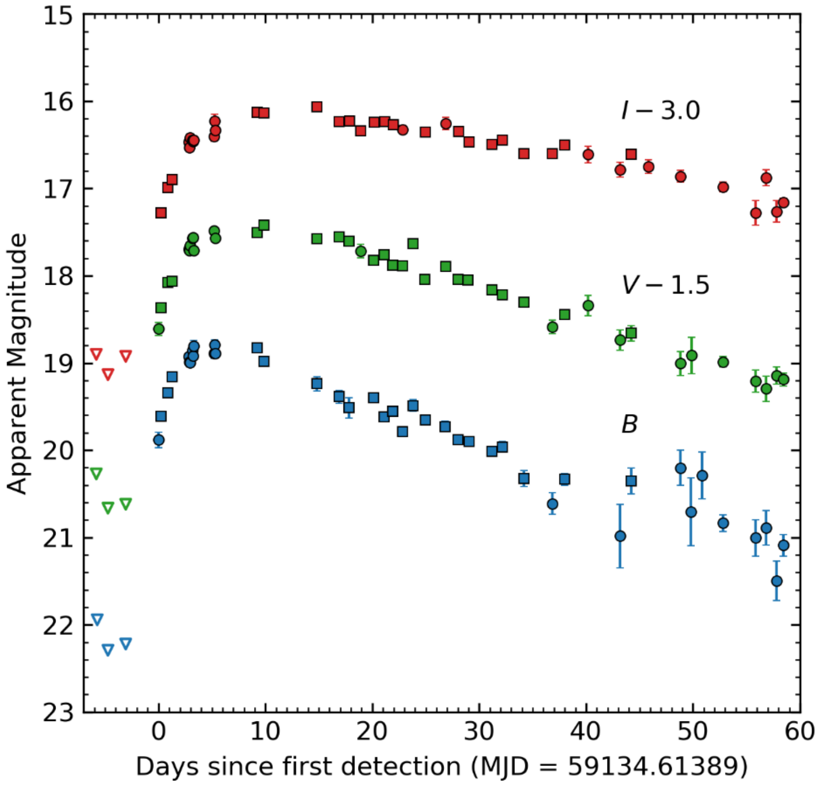
References:

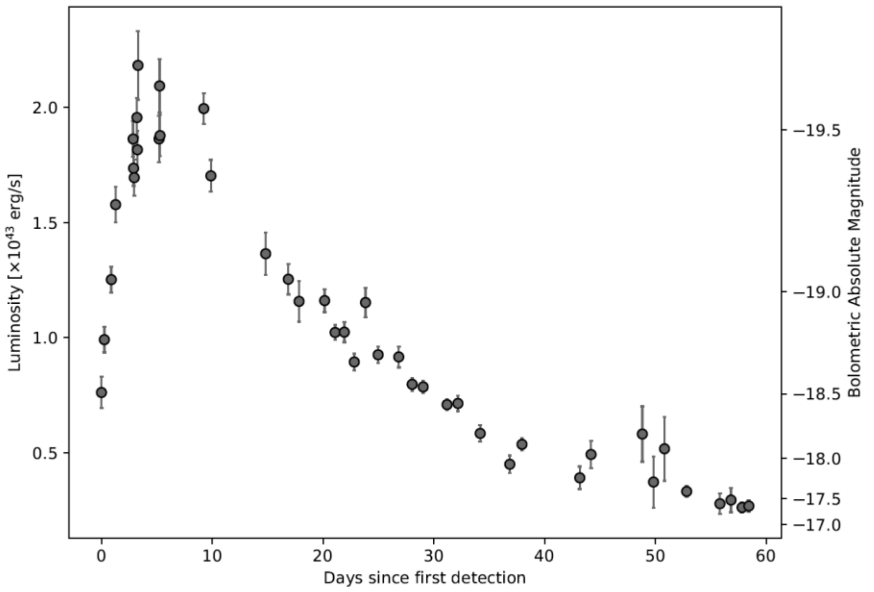
Nakar, E., & Sari, R. 2010, The Astrophysical Journal, 725, 904, doi: 10.1088/0004-637x/ 725/1/904

Rabinak, I., & Waxman, E. 2011, The Astrophysical Journal, 728, 63, doi: 10.1088/0004- 637x/728/1/63

Conclusion

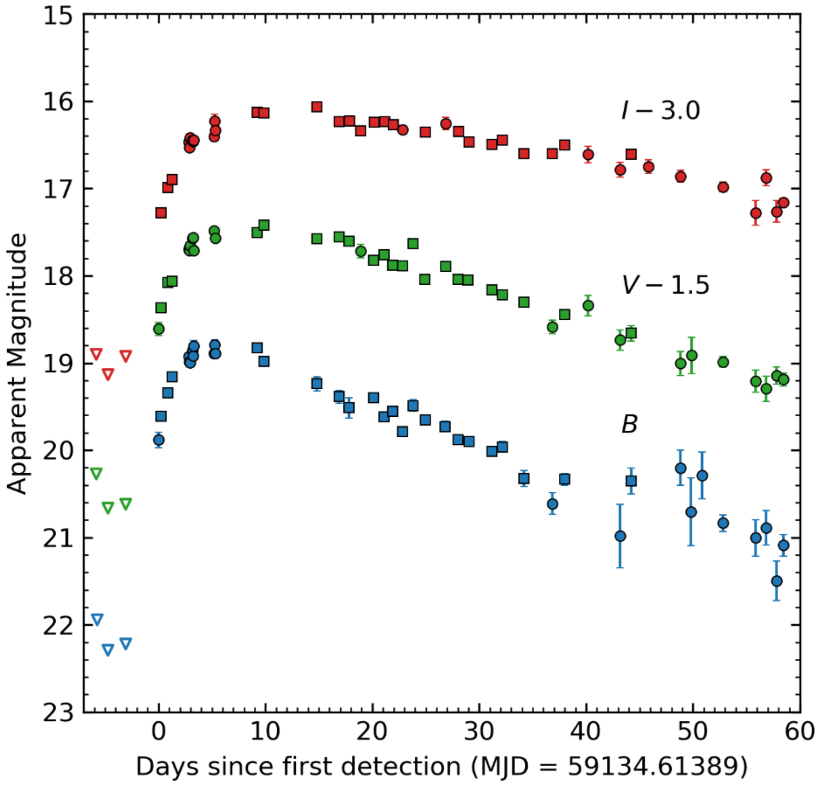
- Constructed *BVI* light curves
- Estimated temporal parameters
  - Epoch of first light
  - Peak epoch
- Created bolometric light curve
- Roughly estimated physical parameters
  - Likely that light curve rise is not only due to radioactive decay

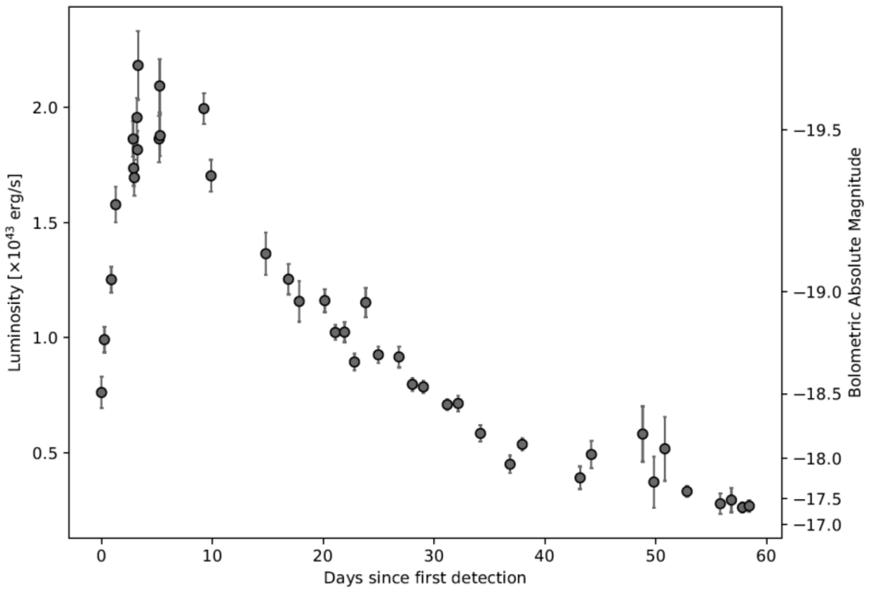




Conclusion

- **Constructed *BVI* light curves**
- Estimated temporal parameters
  - Epoch of first light
  - Peak epoch
- **Created bolometric light curve**
- Roughly estimated physical parameters
  - Concluded that light curve rise is probably not only due to radioactive decay
- **Added another SN to the limited sample of Type II-L SNe**





Thank you!

Backup Slides

Additional Content for Q&A

CCSNe Explosion Mechanism Overview

- Once a massive star's iron core is above Chandrasekhar mass, nuclei would undergo **photodisintegration** → core begins collapsing rapidly in **runaway process**
- Inner core collapses until it's limited by repulsive **strong nuclear force**, which rebounds the falling inner core and sends a **shock wave** outwards
- This shock wave will soon crash supersonically into outer material which is still falling, leading to a **stall (accretion shock)**
- **Some mechanism** allows the shock wave to **continue moving outwards**, overcoming the stall, and allowing us to ultimately observe the SN

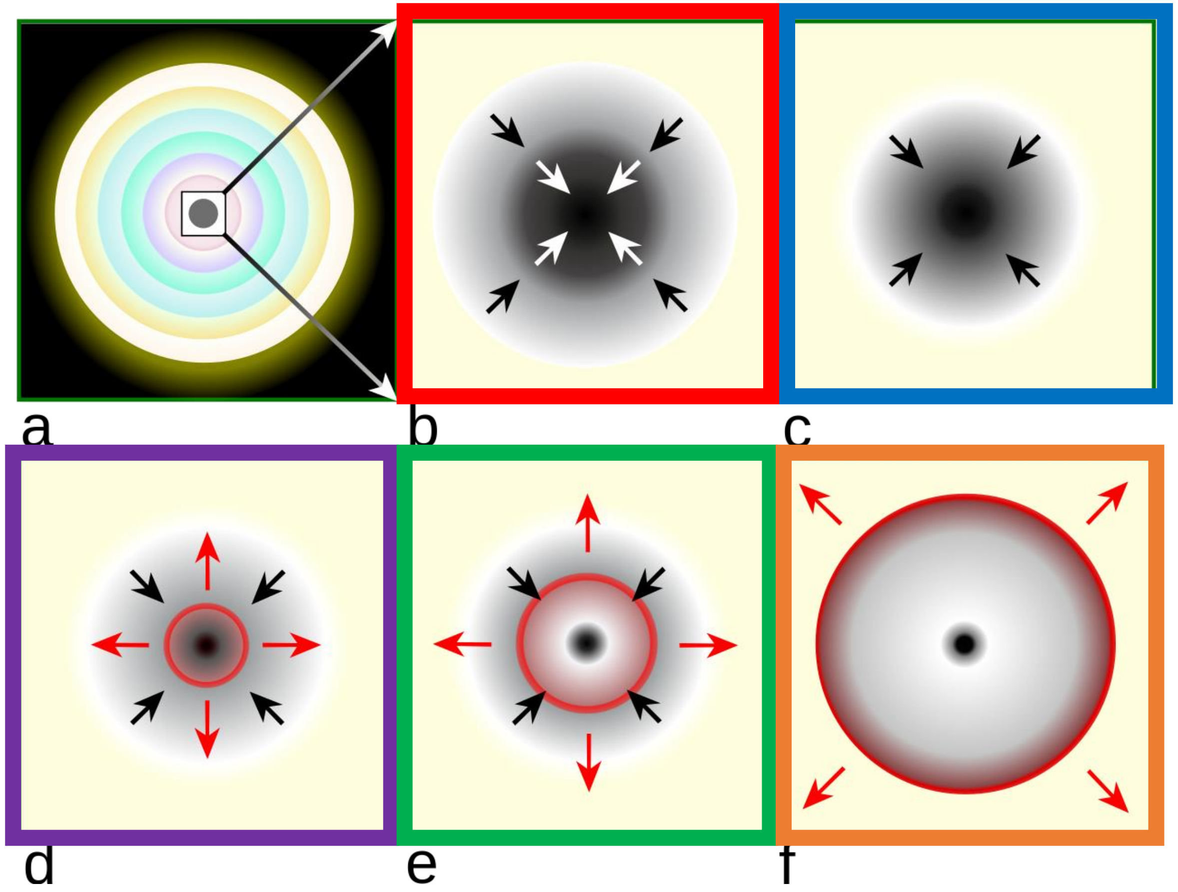


Image Credit: R.J. Hall

The "Supernova Problem"

- How can the stalled shock wave continue moving outwards and ultimately provide observable characteristics? (Couch 2017)
- Leading solution: **Neutrino mechanism** (Colgate & White 1966)
  - Most of energy set free by gravitational core collapse is radiated by neutrinos
  - Neutrino energy deposited in material behind shock front allows it to continue outwards
  - Problems: "Uncertain and controversial" (Janka et al. 2007); has not been fully verified with simulations and real observational data; fails for some SNe types like Type II-L SNe (Sukhbold et al. 2016)

Additional Info:

Colgate, S. A., & White, R. H. 1966, The Astrophysical Journal, 143, 626, doi: 10.1086/ 148549

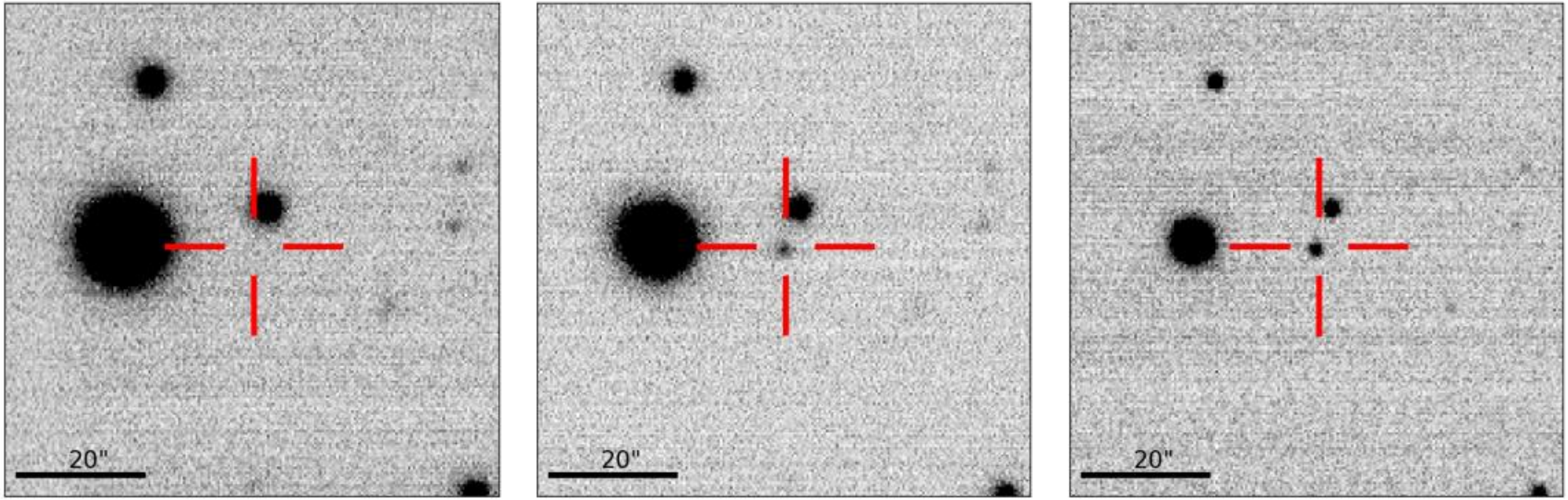
Couch, S. M. 2017, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 375, 20160271, doi: 10.1098/rsta.2016.0271

Janka, H.-T., Langanke, K., Marek, A., Martinez-Pinedo, G., & Muller, B. 2007, Physics Reports, 442, 38, doi: https://doi.org/10.1016/j.physrep.2007.02.002

Sukhbold, T., Ertl, T., Woosley, S. E., Brown, J. M., & Janka, H.-T. 2016, The Astrophysical Journal, 821, 38, doi: 10.3847/0004-637x/821/1/38

Ugliano, M., Janka, H.-T., Marek, A., & Arcones, A. 2012, The Astrophysical Journal, 757, 69, doi: 10.1088/0004-637x/757/1/69

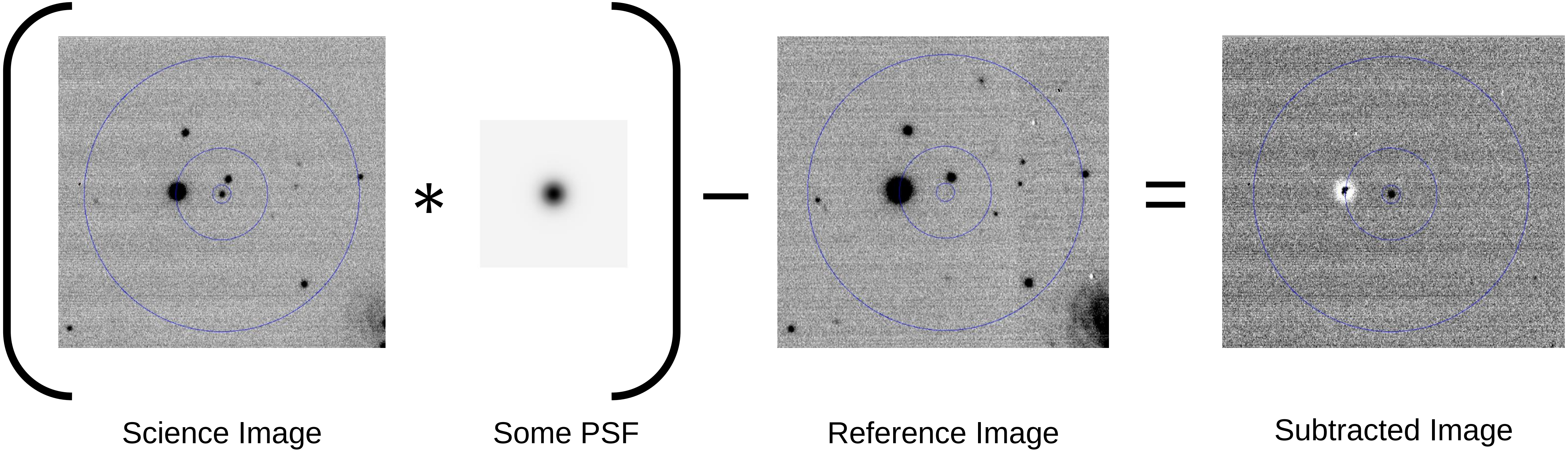
KSP-ZN7090 Images at Key Epochs



(a) B band last non-detection (b) B band first detection (c) B band peak brightness

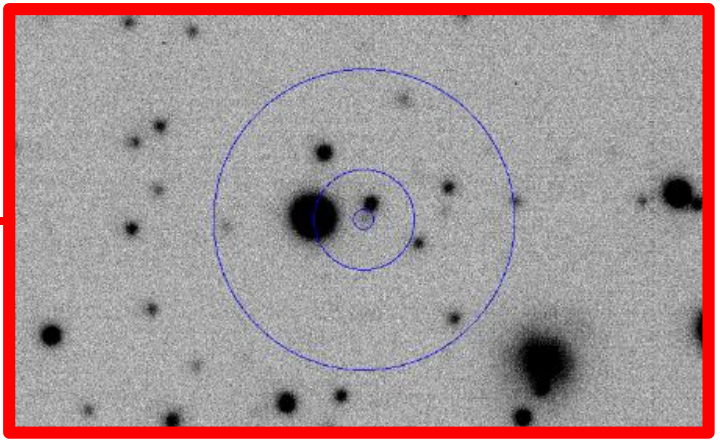
Light Curve – Image Subtraction

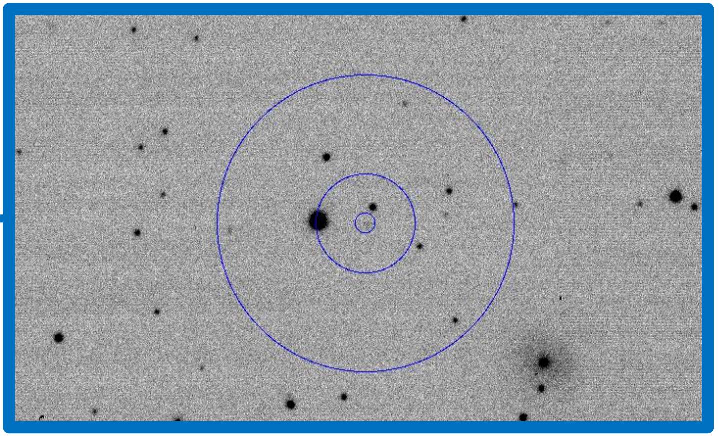
- **Sources nearby** KSP-ZN7090 → need to do image subtraction
  - Light from other objects can spill over to SN
- Image subtraction done with **HOTPANTS**

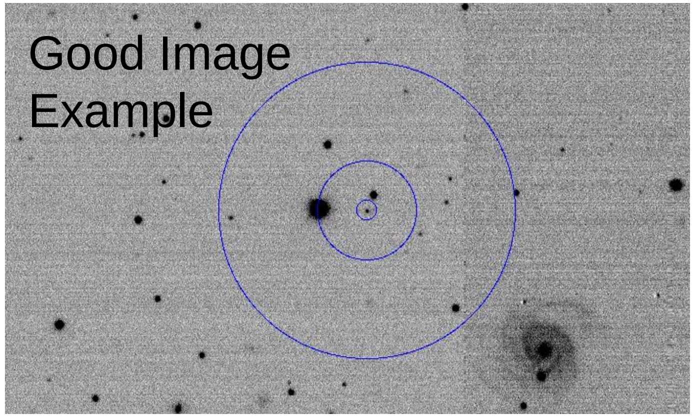


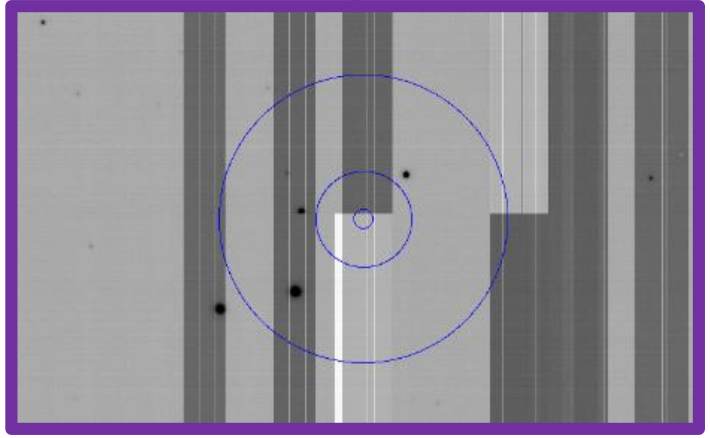
Light Curve – Discard Bad Images

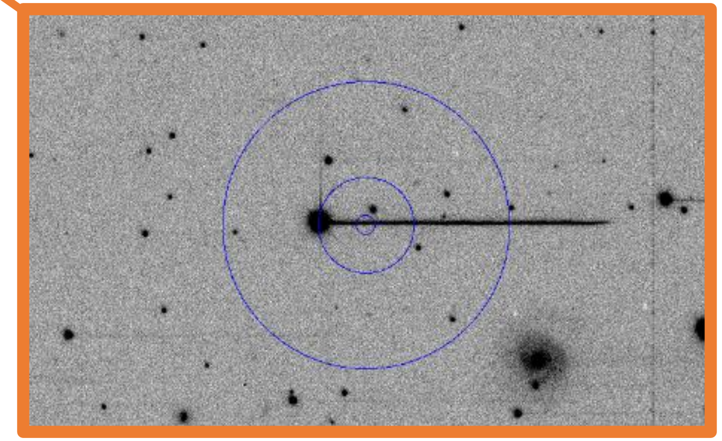
- Sky Conditions
  - Bad seeing (Average FWHM $\gtrsim 4''$)
  - Low limiting magnitude ($m_{\mathrm{lim}} \lesssim 20.5$)
- Detector issues and image artifacts
  - Streaks
  - Bad pixels
  - Random gradients











Light Curve – Binning and Stacking

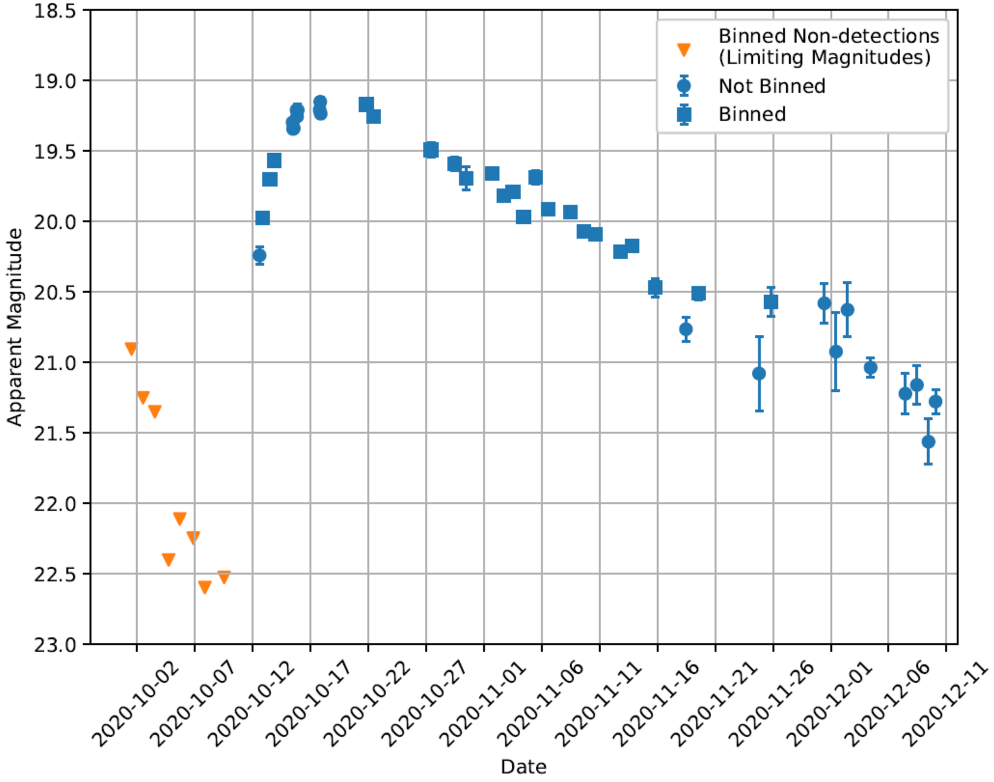
- Early data up to 2 days after first detection were **stacked** using SWarp, with a `COMBINE_TYPE` flag of `AVERAGE`
- Data 9 days after first detection was binned with a 24 hour rolling window, using **inverse-variance weighting**

Inverse-variance weighting:

$$m_{\mathrm{avg}} = \frac{\sum_i (m_i/[\delta m_i]^2)}{\sum_i (1/[\delta m_i]^2)}$$

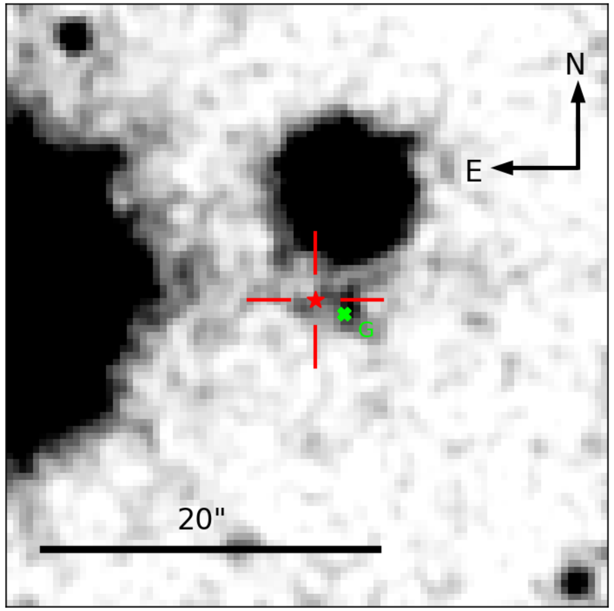
$$\delta m_{\mathrm{avg}} = \sqrt{\frac{1}{\sum_i (1/[\delta m_i]^2)}}$$

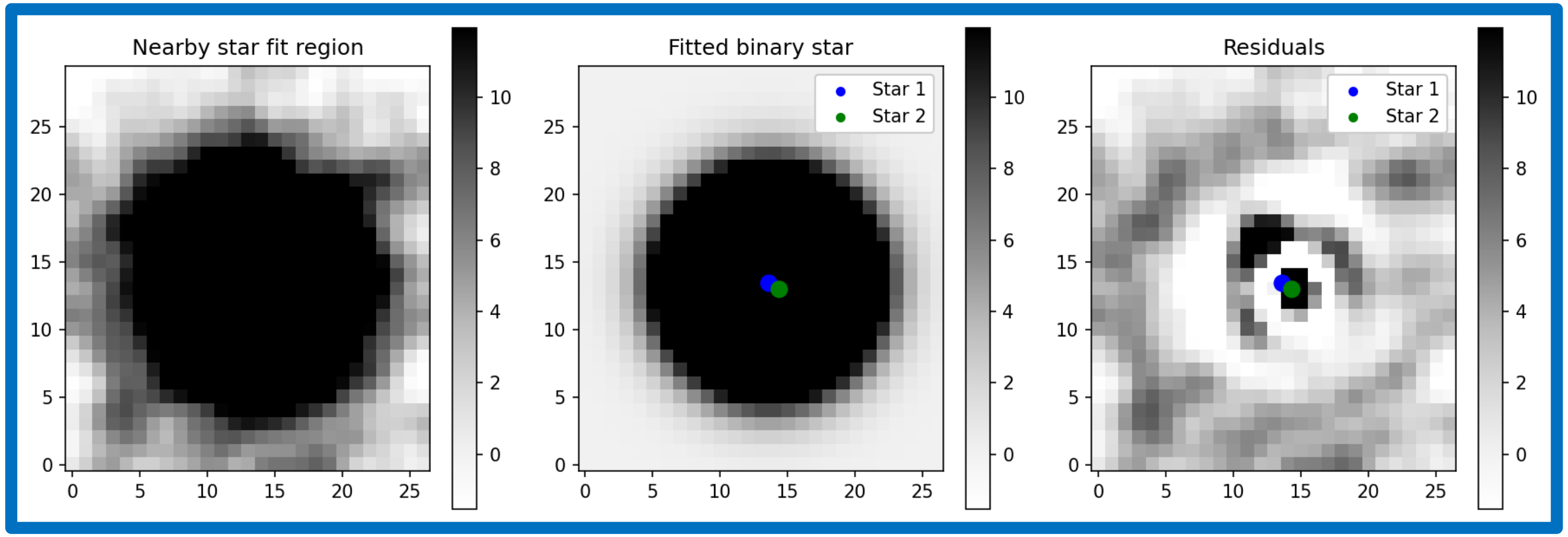
B band, after stacking and binning

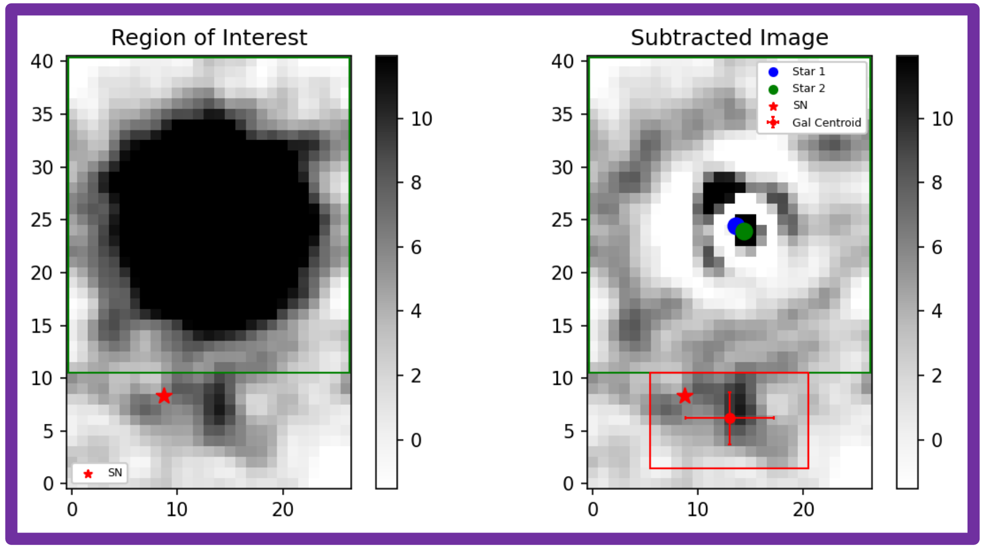


KSP-ZN7090’s Host Galaxy

- Fitted binary star model to nearby object, and subtracted it out
- Calculated centroid in cropped region of subtracted image



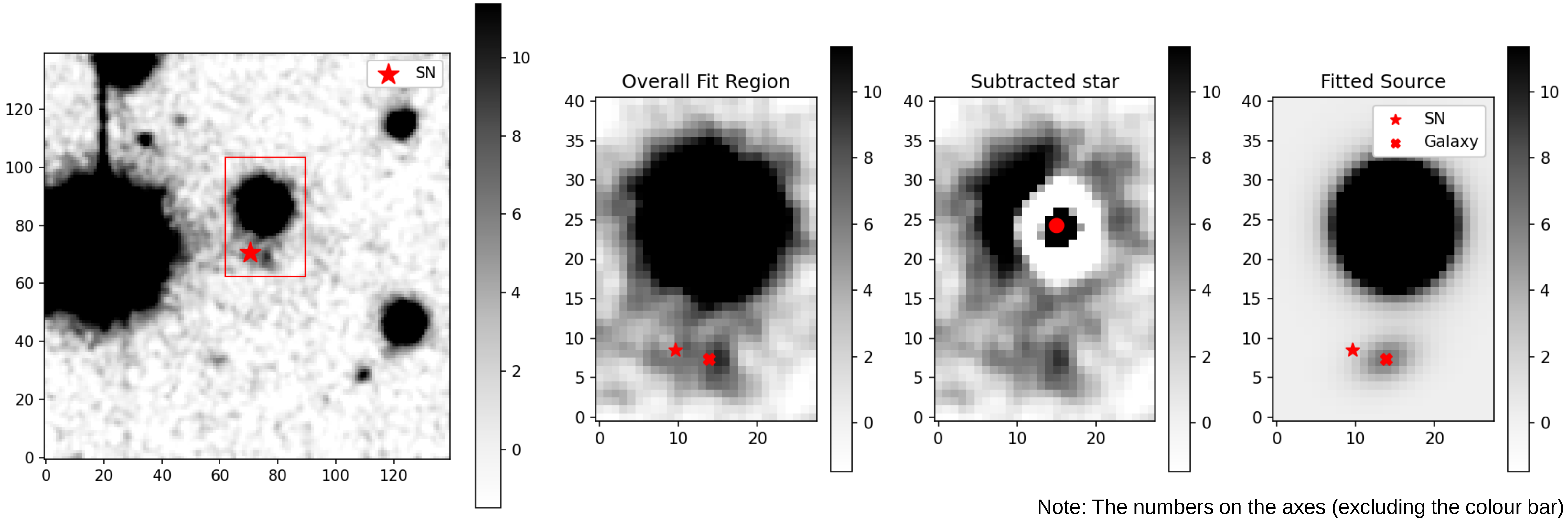




Note: The numbers on the axes (excluding the colour bar) represent pixel positions and not actual WCS coordinates

KSP-ZN7090's Host Galaxy

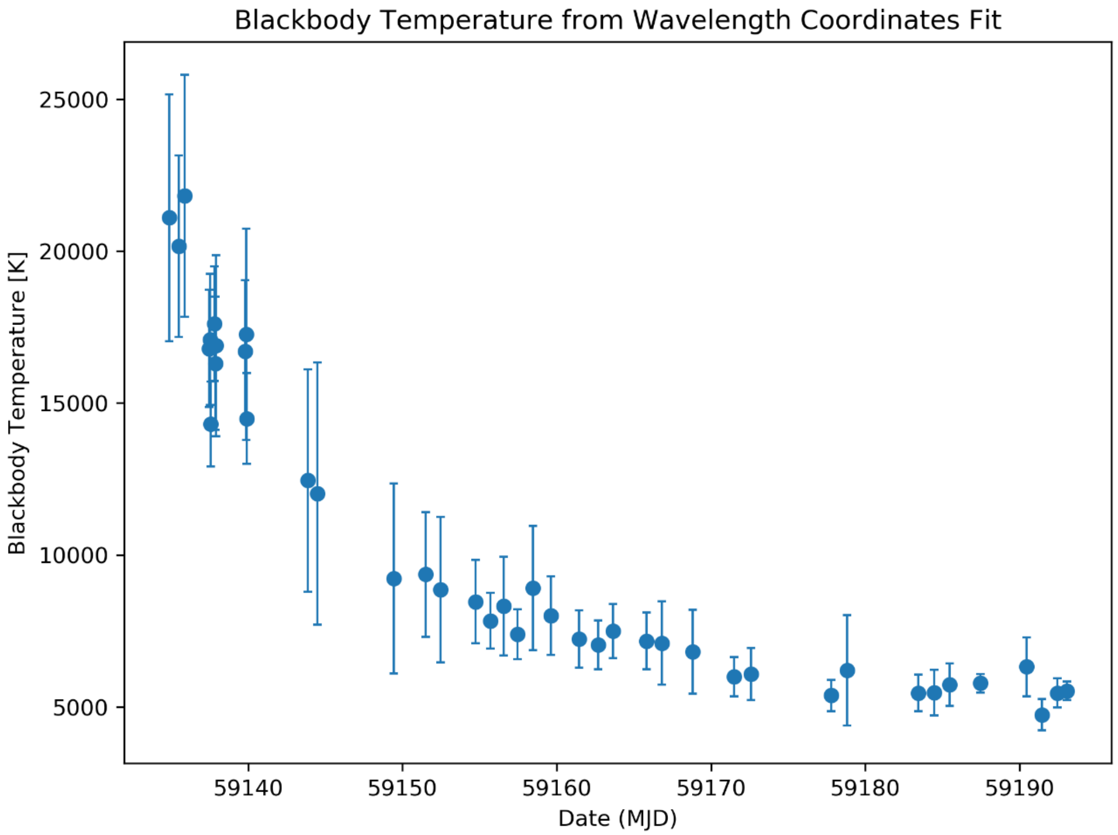
- Why use a binary star?
  - Reason: When it was assumed that the nearby object was a single star (e.g. assuming that the object was a Gaussian PSF), the subtraction did not work well

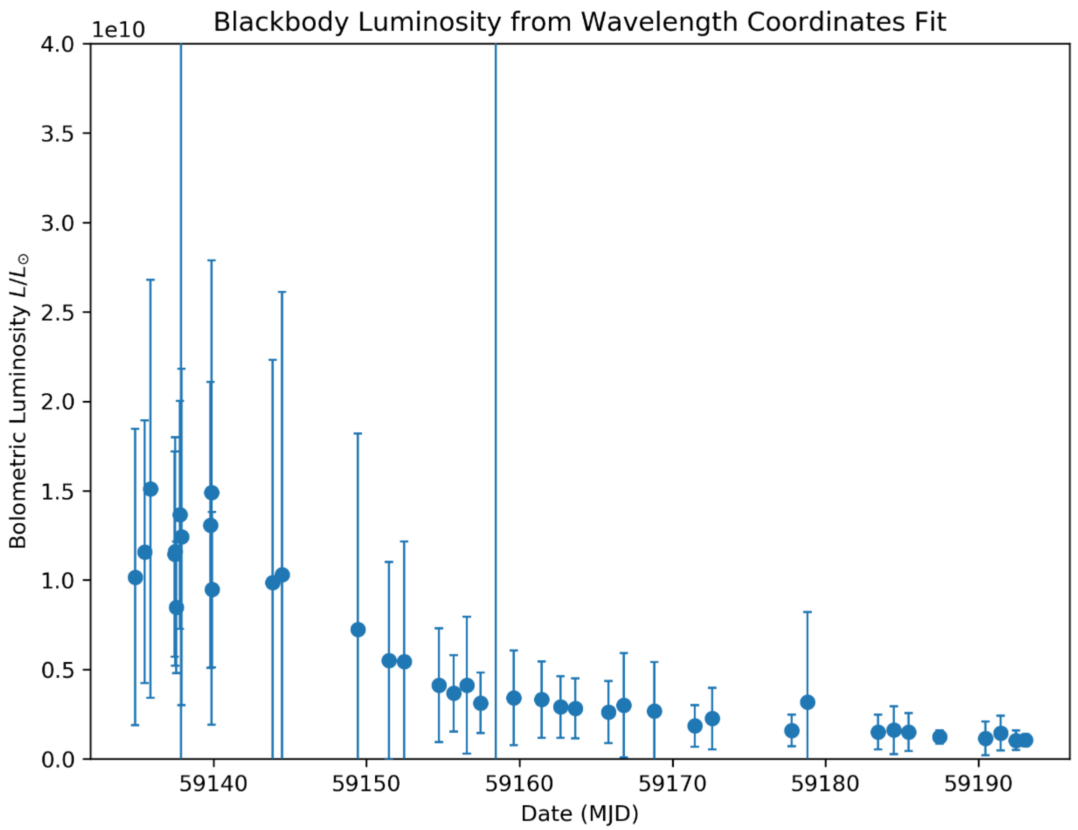


Note: The numbers on the axes (excluding the colour bar) represent pixel positions and not actual WCS coordinates

Bolometric Light Curve – Blackbody Fitting

- Both the T and A fit parameters had high uncertainty
- Blackbody function fit unreliable in UV regime





Bolometric Light Curve – Bolometric Corrections (BC)

- Tried BCs from 2 papers in the literature: Martinez et al. (2021) and Lyman et al. (2013)
- Martinez BC is better suited for Type II-P SNe; consists of 3 phases: cooling, plateau, and nebular
  - BC polynomials are much steeper and lead to higher uncertainties when outside the suggested fit range
  - Plateau phase and nebular phase are not applicable to KSP-ZN7090
- Lyman BC has 2 phases: cooling, and radiatively-/radioactively-powered
  - Radiatively-/radioactively-powered phase was ultimately used, with the assumption that the light curve's rise is mainly caused by energy released by radioactive decay
- See next slide

References:

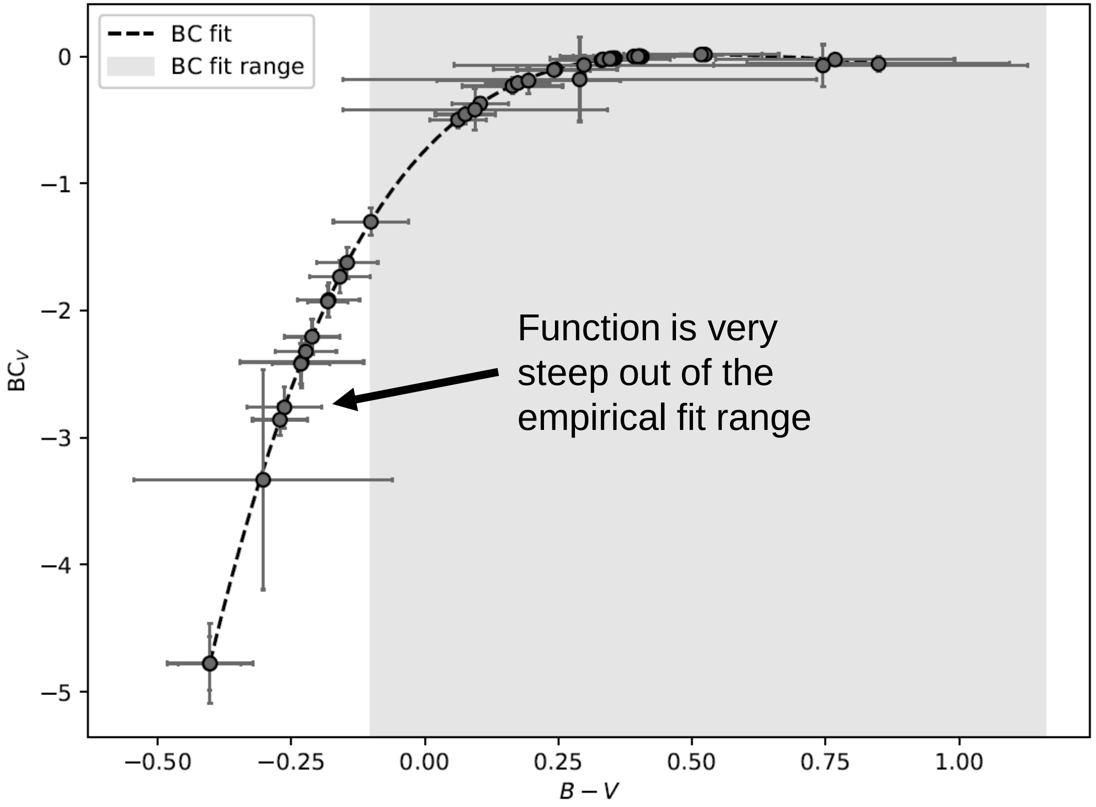
Lyman, J. D., Bersier, D., & James, P. A. 2013, Monthly Notices of the Royal Astronomical Society, 437, 3848, doi: 10.1093/mnras/stt2187

Martinez, L., Bersten, M. C., Anderson, J. P., et al. 2021, Astronomy & Astrophysics, doi: 10.1051/0004-6361/202142075

Bolometric Light Curve – Bolometric Corrections (BC)

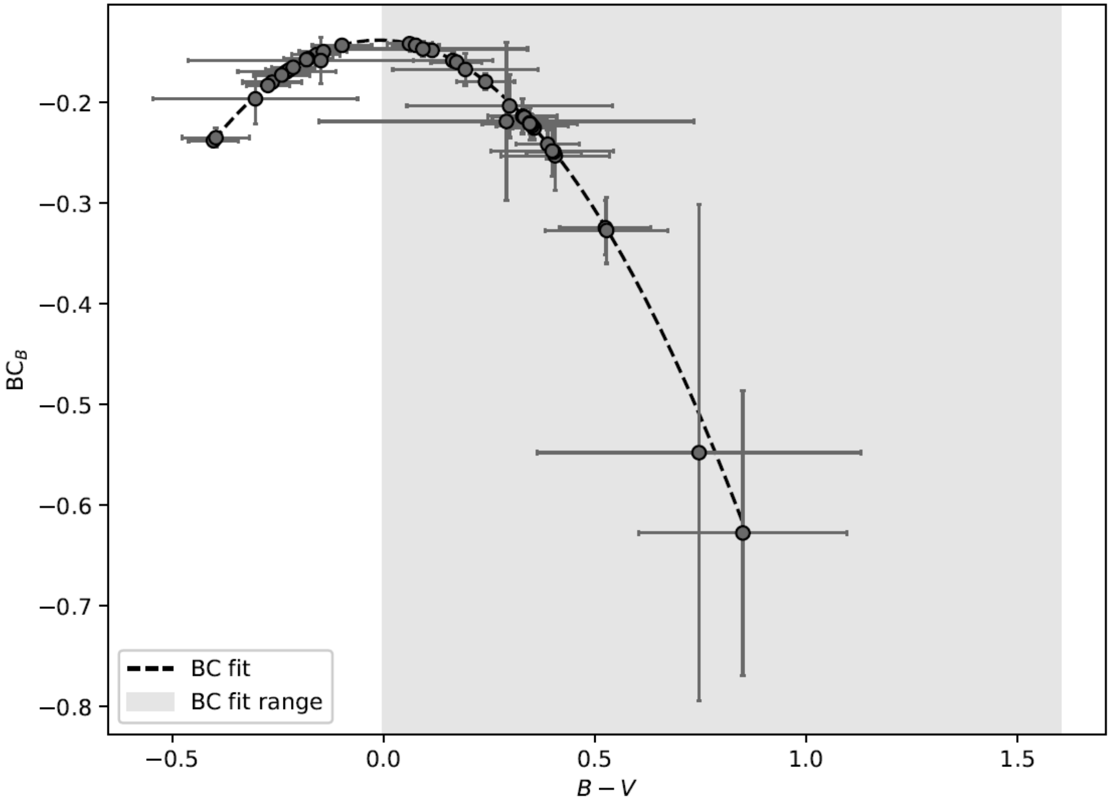
- Bolometric corrections as a polynomial function of colour:

Bolometric correction term from Martinez et al. (2021), cooling phase



Function is very steep out of the empirical fit range

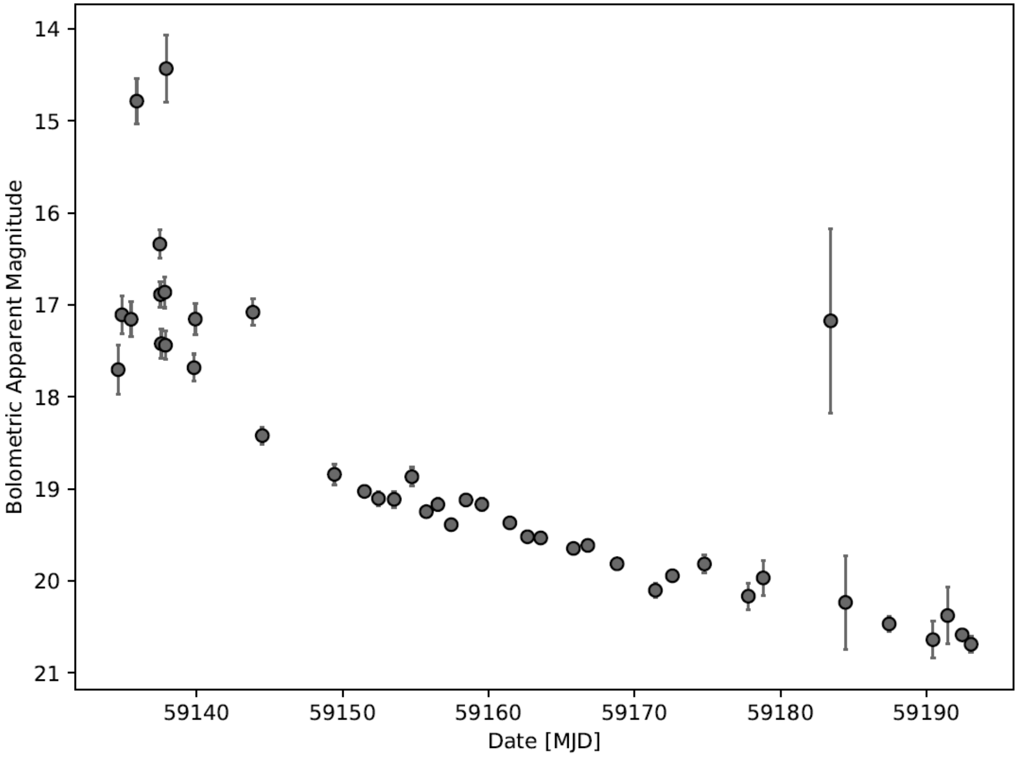
Bolometric correction term from Lyman et al. (2013), radiatively-/radioactively-powered phase



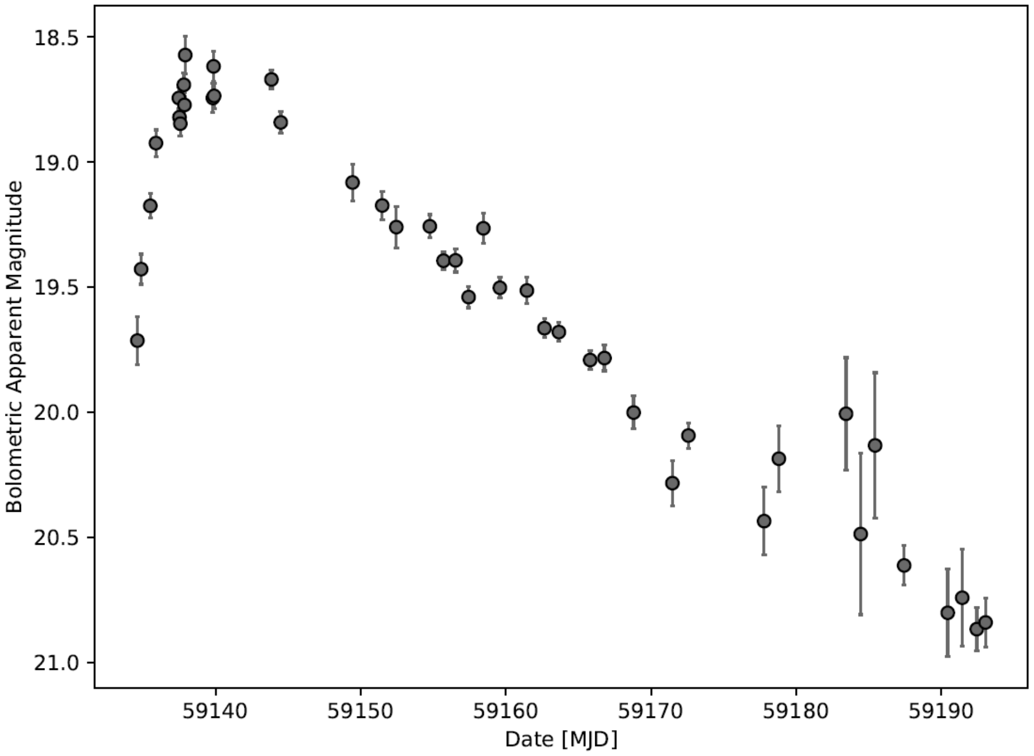
Bolometric Light Curve – Bolometric Corrections (BC)

- Bolometric light curves following methods in Martinez et al. (2021) and Lyman et al. (2013):

Bolometric light curve using bolometric correction from Martinez et al. (2021), cooling phase



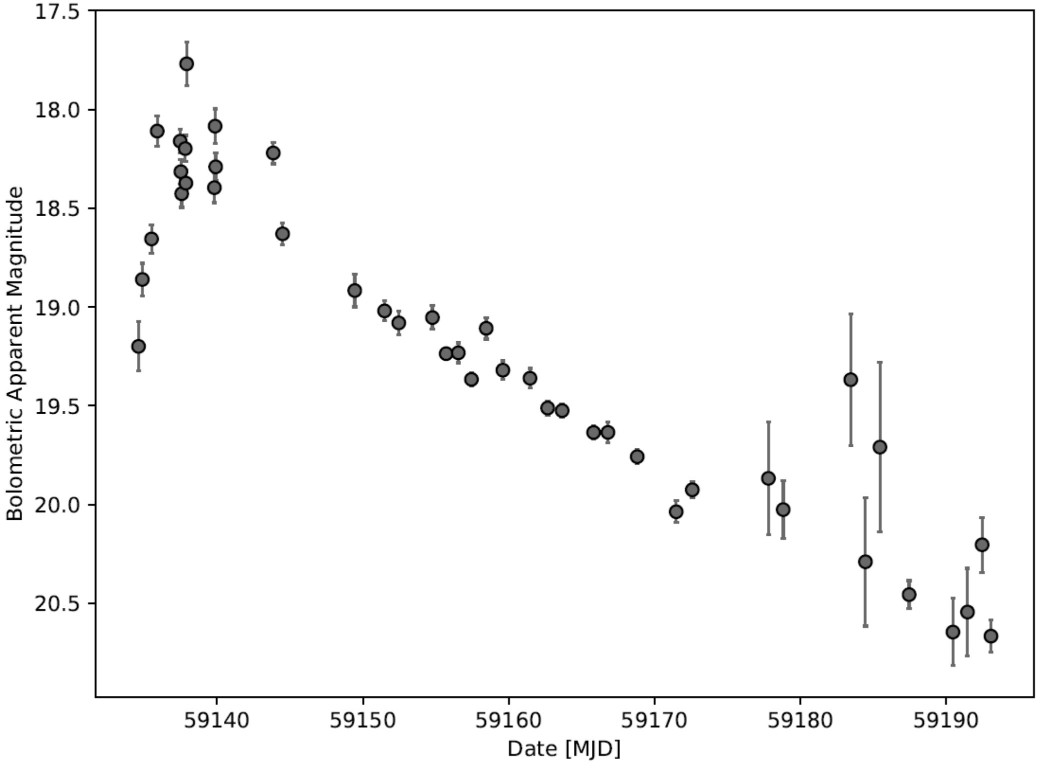
Bolometric light curve using bolometric correction term from Lyman et al. (2013), radiatively-/radioactively-powered phase



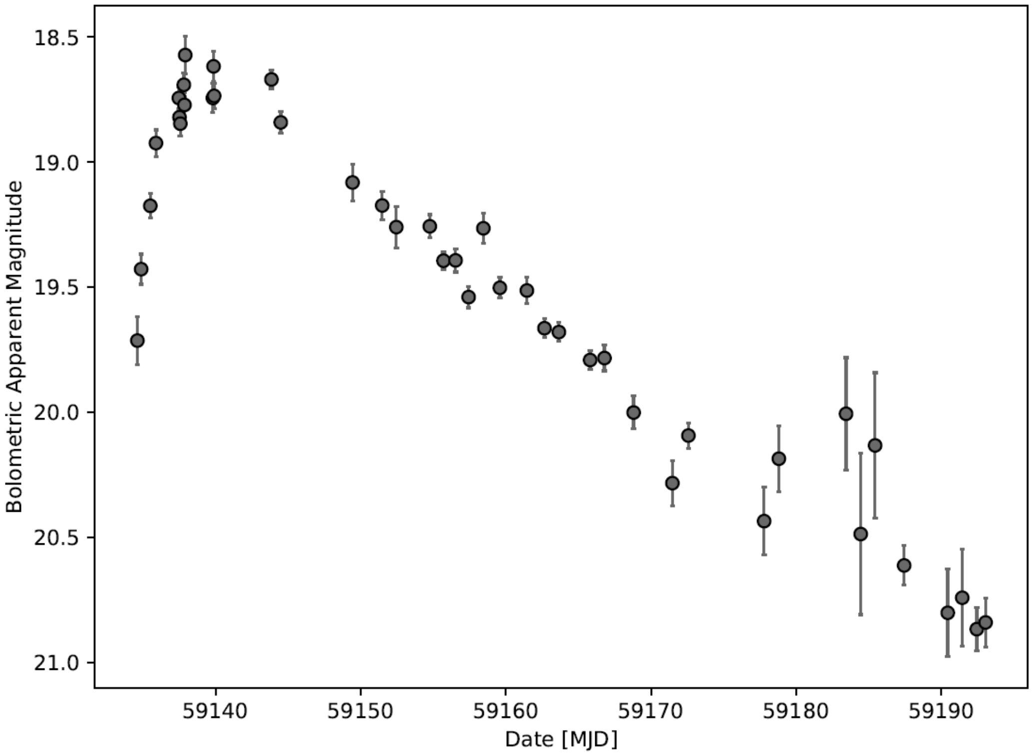
Bolometric Light Curve – Bolometric Corrections (BC)

- Comparison between cooling and radiatively-/radioactively-powered phase for Lyman et al. (2013):

Bolometric light curve using bolometric correction term from Lyman et al. (2013), cooling phase



Bolometric light curve using bolometric correction term from Lyman et al. (2013), radiatively-/radioactively-powered phase



Physical Parameters – Valenti et al. (2008) Model

- Fit fails to capture rise of light curve well
- Note that Type Ic SNe usually peak at longer times (e.g. ~20 days)