



JWST Spectroscopy of SNe Ia 2022aaq and 2024gy: Evidence for Enhanced Central Stable Ni Abundance and a Deflagration-to-detonation Transition

Lindsey A. Kwok^{1,39}, Chang Liu (刘畅)^{1,2}, Saurabh W. Jha³, Stéphane Blondin^{4,5}, Conor Larison³, Adam A. Miller^{1,2,6}, Mi Dai⁷, Ryan J. Foley⁸, Alexei V. Filippenko⁹, Jennifer E. Andrews¹⁰, Moira Andrews^{11,12}, Katie Auchettl⁸, Carles Badenes⁷, K. Azalee Bostroem^{13,40}, Thomas G. Brink⁹, Cristine Koelln^{4,14}, Kyle W. Davis⁸, Andreas Flörs¹⁵, Lluís Galbany^{16,17}, Or Graur^{18,19}, D. Andrew Howell^{11,12}, Sahana Kumar²⁰, Réka Könyves-Tóth^{21,22}, Natalie LeBaron^{9,23}, Colin W. Macrie^{3,24}, Keiichi Maeda²⁵, Kate Maguire²⁶, Curtis McCully¹¹, Nicolas E. Meza-Retamal²⁷, Estefania Padilla Gonzalez²⁸, Rüdiger Pakmor²⁹, Jeniveve Pearson¹³, Anthony L. Piro³⁰, Abigail Polin²⁴, Nabeel Rehemtulla^{1,2,6}, César Rojas-Bravo^{31,32}, David J. Sand¹³, Chita Sangkachan³³, Michaela Schwab²⁰, Huei Sears³, Mridweeka Singh³⁴, Bhagya M. Subrayan¹³, Kirsty Taggart⁸, Tea Temim³⁵, Jacco H. Terwel²⁶, Samaporn Tinyanont³³, József Vinkó^{21,22,36,37}, Xiaofeng Wang³⁸, J. Craig Wheeler³⁶, Yi Yang³⁸, and WeiKang Zheng⁹

¹ Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Northwestern University, Evanston, IL 60201, USA; lindsey.kwok@northwestern.edu

² Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA

³ Department of Physics and Astronomy, Rutgers, The State University of New Jersey, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA

⁴ European Southern Observatory, Karl-Schwarzschild-Straße 2, D-85748, Garching bei München, Germany

⁵ Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France

⁶ NSF—Simons AI Institute for the Sky (SkAI), Chicago, IL 60611, USA

⁷ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA

⁸ Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA

⁹ Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA

¹⁰ Gemini Observatory/NSF's NOIRLab, 670 N. A'ohoku Place, Hilo, HI 96720, USA

¹¹ Las Cumbres Observatory, Goleta, CA 93117, USA

¹² Department of Physics, University of California, Santa Barbara, CA 93106-9530, USA

¹³ Steward Observatory, University of Arizona, Tucson, AZ 85721, USA

¹⁴ Technical University of Munich, TUM School of Natural Sciences, Physics Department, D-85748, Garching bei München, Germany

¹⁵ GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany

¹⁶ Institute of Space Sciences (ICE—CSIC), Campus UAB, 08193 Barcelona, Spain

¹⁷ Institut d'Estudis Espacials de Catalunya (IEEC), 08034 Barcelona, Spain

¹⁸ Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciana Building, Portsmouth, PO1 3FX, UK

¹⁹ Department of Astrophysics, American Museum of Natural History, New York, NY 10024, USA

²⁰ Department of Astronomy, University of Virginia, 530 McCormick Rd, Charlottesville, VA 22904, USA

²¹ Konkoly Observatory, HUN–REN Research Center for Astronomy and Earth Sciences, Budapest 1121, Hungary

²² Department of Experimental Physics, Institute of Physics, University of Szeged, Dóm tér 9, Szeged, 6720, Hungary

²³ Berkeley Center for Multi-messenger Research on Astrophysical Transients and Outreach (Multi-RAPTOR), University of California, Berkeley, CA 94720-3411, USA

²⁴ Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA

²⁵ Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan

²⁶ School of Physics, Trinity College Dublin, The University of Dublin, Dublin 2, Ireland, UK

²⁷ Department of Physics and Astronomy, University of California, Davis, CA 95616, USA

²⁸ Johns Hopkins University, Department of Physics and Astronomy, 3400 N. Charles Street Baltimore, MD 21218, USA

²⁹ Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748, Garching, Germany

³⁰ The Observatories of the Carnegie Institution for Science, Pasadena, CA 91101, USA

³¹ School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

³² National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People's Republic of China

³³ National Astronomical Research Institute of Thailand (NARIT), Chiang Mai 50180, Thailand

³⁴ Indian Institute of Astrophysics, Koramangala 2nd Block, Bangalore 560034, India

³⁵ Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

³⁶ Department of Astronomy, The University of Texas at Austin, Austin, TX 78712, USA

³⁷ ELTE Eötvös Loránd University, Institute of Physics and Astronomy, Pázmány Péter sétány 1A, Budapest 1117, Hungary

³⁸ Physics Department, Tsinghua University, Beijing 100084, People's Republic of China

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Abstract

We present optical + near-infrared + mid-infrared (MIR) observations of the normal Type Ia supernovae (SNe Ia) 2022aaq and 2024gy in the nebular phase, continuously spanning 0.35–28 μm . Medium-resolution JWST spectroscopy reveals novel narrow ($v_{\text{FWHM}} < 1500 \text{ km s}^{-1}$) [Ni II] 1.94 and 6.64 μm cores in both events.

³⁹ NASA Hubble Fellow.

⁴⁰ LSST-DA Catalyst Fellow.



The MIR [Ni II] 6.64 μm line exhibits a distinct narrow core atop a broader base, indicating a central enhancement of stable Ni. This structure points to high central densities consistent with a near-Chandrasekhar-mass (M_{Ch}) progenitor or a high-metallicity sub- M_{Ch} progenitor. From detailed line-profile inversions of SN 2024gy, we derive emissivity profiles for stable iron-group elements, radioactive material, and intermediate-mass elements, revealing spatially distinct ejecta zones. The [Ni III] 7.35 μm line shows a shallow-to-steep slope transition—a “broken-slope” morphology—that matches predictions for delayed detonation explosions with separated deflagration and detonation ashes. We also reanalyze and compare to archival JWST spectra of SN 2021aefx and the subluminal SN 2022xkq. From the stable Ni luminosities, we infer that SN 2024gy produced ~ 5 –10 times more stable Ni mass than SN 2022xkq, favoring a near- M_{Ch} scenario for SN 2024gy and a sub- M_{Ch} scenario for SN 2022xkq. These results demonstrate that resolved line profiles, now accessible with JWST, provide powerful diagnostics of explosion geometry, central density, and progenitor mass in SNe Ia.

Unified Astronomy Thesaurus concepts: [White dwarf stars \(1799\)](#); [Type Ia supernovae \(1728\)](#)

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1. Introduction

Type Ia supernovae (SNe Ia) are thermonuclear explosions of white dwarfs (WDs; F. Hoyle & W. A. Fowler 1960). Their nucleosynthetic yields depend sensitively on the density of different layers of the WD during the explosion. At the highest densities ($\gtrsim 10^8 \text{ g cm}^{-3}$, and assuming $T \gtrsim 5 \times 10^9 \text{ K}$, $Y_e = 0.5$), nuclear burning produces stable iron-group elements (IGEs). Slightly lower densities yield radioactive IGEs such as Fe, Co, and Ni, while intermediate-mass elements (IMEs; e.g., Si, Ar, Ca) form at still lower densities. The lowest-density regions contribute low-mass elements (LMEs; Ne, Mg, O) as well as possible unburned C/O material (for a review, see I. R. Seitenzahl & D. M. Townsley 2017).

The central density of the exploding WD is set primarily by its mass, owing to electron degeneracy pressure. Near-Chandrasekhar-mass (M_{Ch}) WDs ignite at higher central densities than sub- M_{Ch} WDs. As a result, at fixed progenitor metallicity, sub- M_{Ch} explosions undergo fewer electron captures and produce smaller yields of stable IGEs (P. Höflich et al. 2004; S. Blondin et al. 2018; K. D. Wilk et al. 2018; L. J. Shingles et al. 2020). The presence and abundance of stable Ni are particularly diagnostic of the explosion conditions: it requires the highest densities and temperatures, and some explosion mechanisms therefore yield little of it at a given metallicity or ^{56}Ni mass (F. Lach et al. 2020; S. Blondin et al. 2022; R. Pakmor et al. 2024). The most common isotope is ^{58}Ni , though ^{60}Ni can be significant at the highest densities and in certain double-detonation models (D. M. Townsley et al. 2019; S. Gronow et al. 2020, 2021). Observations of stable Ni in SNe Ia ejecta thus directly probe both progenitor mass and explosion mechanism.

At late times (>100 days after peak brightness; the nebular phase), the ejecta expand and dilute enough to become optically thin (E. J. C. Bowers et al. 1997; D. Branch et al. 2008; J. M. Silverman et al. 2013; B. Friesen et al. 2014; C. S. Black et al. 2016). Nebular spectra reveal emission lines that trace the geometry of the emitting regions and allow measurements of elemental distributions and kinematics (see A. Jerkstrand 2017 for a review). By this stage, all ^{56}Ni has decayed (half-life of 6.1 days), so Ni emission originates only from stable isotopes.

Stable Ni has been studied in both optical and ground-based near-infrared (NIR) spectra, particularly through the [Ni II] 7378 Å and [Ni II] 1.94 μm lines (K. Maeda et al. 2010b; S. Blondin et al. 2018; S. Dhawan et al. 2018; T. R. Diamond et al. 2018; A. Flörs et al. 2018; K. Maguire

et al. 2018; A. Flörs et al. 2020; S. Blondin et al. 2022; S. Kumar et al. 2026). The 1.94 μm feature was clearly detected in SN 2014J (S. Dhawan et al. 2018; T. R. Diamond et al. 2018), and S. Kumar et al. (2026) extended such analyses to a larger sample using improved telluric corrections. These analyses reveal diversity: for example, A. Flörs et al. (2020) favored sub- M_{Ch} progenitors, while S. Kumar et al. (2026) argued that narrow NIR Ni lines in subluminal events suggest near- M_{Ch} explosions.

A major difficulty in the analysis is line blending. The optical [Ni II] 7378 Å line overlaps with neighboring features, while the NIR [Ni II] 1.94 μm line, though less blended (K. D. Wilk et al. 2018), falls near a strong atmospheric telluric band (for low-redshift SNe). A high signal-to-noise ratio (S/N) and excellent telluric correction are required for robust detection (S. Kumar et al. 2026). JWST removes these limitations, providing access to the 1.94 μm feature without atmospheric contamination and, critically, new stable Ni diagnostics in the mid-infrared (MIR). These include [Ni II] 6.64 μm , [Ni III] 7.35 μm , [Ni IV] 8.40 μm , and [Ni III] 11.00 μm . The MIR also isolates IME lines such as [Ca IV] 3.21 μm , [Ar II] 6.98 μm , [Ar III] 8.99 μm , and [S IV] 10.51 μm , and LME tracers such as [Ne II] 12.88 μm and [Mg II] 9.76 μm (C. L. Gerardy et al. 2007; S. Blondin et al. 2023; J. M. DerKacy et al. 2023, 2024; L. A. Kwok et al. 2023, 2024, 2025; C. Ashall et al. 2024; M. R. Siebert et al. 2024). These lines are all significantly more isolated than optical and NIR lines. Together, these provide the clearest view yet of the chemical structure of SNe Ia ejecta.

In delayed detonation (DDT) models, the explosion begins with a subsonic deflagration that releases energy and causes the star to expand before a detonation front ignites. The high densities during the deflagration phase enhance the production of stable IGEs, while the subsequent detonation synthesizes material at lower densities. As a result, deflagration and detonation ashes occupy distinct regions of the ejecta, with different proportions of stable and radioactive Ni (I. R. Seitenzahl et al. 2013; R. Pakmor et al. 2024).

In contrast, sub- M_{Ch} double-detonation models involve an initial He-shell detonation that triggers a secondary detonation in the C/O core. Stable Ni is synthesized primarily in the central detonation ashes, colocated with radioactive IGEs (S. Gronow et al. 2021; R. Pakmor et al. 2024). These differing burning pathways lead to distinct distributions of nucleosynthetic products, which in turn imprint characteristic signatures on nebular emission-line profiles that are now accessible with JWST.

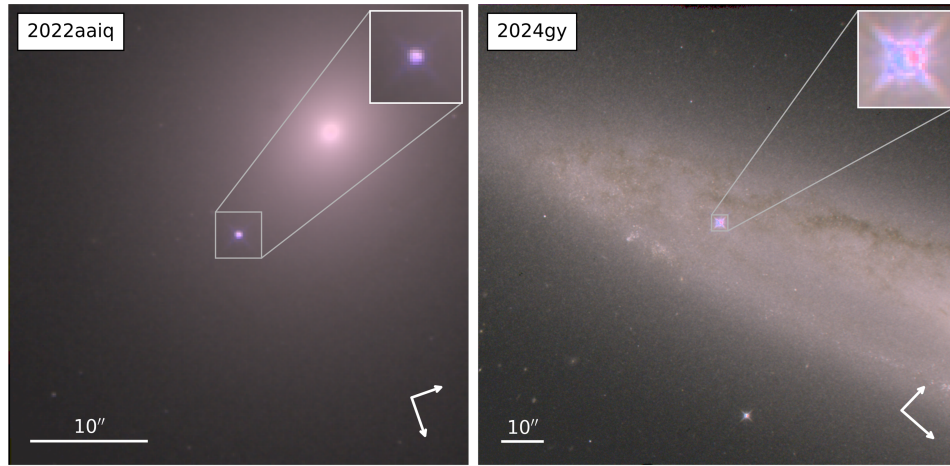


Figure 1. Hubble Space Telescope WFC3/IR NIR images of SN 2022aaiq (left) in its elliptical host galaxy, NGC 5631, and SN 2024gy (right) in its spiral host galaxy, NGC 4216. The red, green, and blue (RGB) channels are mapped from F160W, F140W, and F105W images, respectively. The images are $40'' \times 40''$ and $120'' \times 120''$, respectively, with a scale bar for reference. The orientation is marked by the compass rose with the longer and shorter arms representing north and east, respectively. A $5'' \times 5''$ box is centered on each SN with a zoomed-in image of that region shown in the upper-right corner.

In this paper, we present late-time, medium-resolution NIR + MIR spectroscopy of the normal SNe Ia 2022aaiq and 2024gy from JWST General Observer (GO) programs 2072 (S. W. Jha et al. 2021) and 4516 (S. W. Jha et al. 2023). We focus on the morphologies of the [Ni II] and [Ni III] lines and their implications for explosion models. In both events, [Ni II] shows a narrow core ($v \leq 1500 \text{ km s}^{-1}$), indicative of an enhanced central abundance of stable IGEs, while [Ni III] exhibits a “broken-slope” profile, consistent with predictions of DDT models.

2. Observations

SN 2022aaiq (Figure 1, left; $\alpha = 14^{\text{h}}26^{\text{m}}32^{\text{s}}.011$, $\delta = +56^{\circ}35'03''.17$, J2000) was discovered and reported to the Transient Name Server⁴¹ by P. Wiggins on 2022 November 15 (P. Wiggins 2022; all dates in this work are given in UTC) and was classified as a Type Ia SN on 2022 November 17 by the UCSC team (M. R. Siebert et al. 2022). SN 2022aaiq exploded in NGC 5631, an elliptical galaxy at redshift $z = 0.006485$ (M. Cappellari et al. 2011).

Discovery details for SN 2024gy (Figure 1, right; $\alpha = 12^{\text{h}}15^{\text{m}}51^{\text{s}}.289$, $\delta = +13^{\circ}06'56''.13$, J2000), hosted by the spiral galaxy NGC 4216, are given by L. Li et al. (2026). We adopt a slightly different host-galaxy heliocentric redshift than L. Li et al. (2026), preferring a recent measurement with optical lines at the host nucleus, $z = 0.000385 \pm 0.000045$ or $cz = 116 \pm 14 \text{ km s}^{-1}$ (R. C. E. van den Bosch et al. 2015). Our derived velocities for SN line features in this work are relative to the systemic velocity of the host galaxy, but owing to the unknown velocity of SN 2024gy within its host, we adopt an additional uncertainty of $\sim \pm 200 \text{ km s}^{-1}$ when interpreting line shifts. Additional optical analysis of SN 2024gy is given by L. Li et al. (2026) and J. H. Terwel et al. (2026).

Figure 1 shows SN 2022aaiq and SN 2024gy in their host galaxies with NIR imaging from the Hubble Space Telescope. These observations were taken as part of program 17128 (PI: R. Foley) with WFC3/IR in the F105W, F140W, and F160W passbands.

2.1. JWST Data

SN 2022aaiq and SN 2024gy were each observed at two epochs with the JWST Near Infrared Spectrograph (NIRSpec) fixed slit G235M + G395M gratings (S. M. Birkmann et al. 2022; P. Jakobsen et al. 2022; J. Rigby et al. 2023) and the Mid-Infrared Instrument (MIRI) Medium Resolution Spectrograph (MRS; S. Kendrew et al. 2015; S. Kendrew et al. 2016; J. Rigby et al. 2023), with the same settings and exposure times (MIRI/MRS, 2 hr; NIRSpec gratings, 0.5 hr). SN 2022aaiq was observed by JWST on 2023 April 4 at a phase relative to the *B*-band maximum (2022 December 1; Appendix D) of +125 days and 2023 June 24 at +207 days. SN 2024gy was observed by JWST on 2024 June 9 at +144 days and 2024 December 22 at +337 days postpeak (2024 January 20; Appendix D; L. Li et al. 2026).

For comparison, we also include in our analysis MIRI/MRS data of the normal SNIa 2021aefx and the subluminal (photometrically transitional, spectroscopically SN 1991bg-like; J. Pearson et al. 2024) SNIa 2022xkq from JWST program GO-2114 (C. Ashall et al. 2021) published by C. Ashall et al. (2024) and J. M. DerKacy et al. (2024), respectively. In this work, we use the reductions of these data presented by L. A. Kwok et al. (2025), where the MRS data were reprocessed to improve background subtraction. Differences in the rereduced spectra are discussed in Sections 3.1.3 and 3.1.4.

We processed the MIRI/MRS observations of SN 2021aefx, SN 2022xkq, SN 2022aaiq, and SN 2024gy using a consistent reduction workflow. Starting from the stage2 `*rate.fits` products, we reran the JWST pipeline to generate a single, spatially aligned data cube combining channels 1–4. This step follows Section 3 of the public M. Shahbandeh reduction notebook.⁴² We subtract the background and extract the one-dimensional (1D) SN spectra using `AstroBkgInterp` (B. Nickson et al. 2025),⁴³ which performs interpolation-based background estimation optimized for point-source extraction. We used a fixed aperture radius of five pixels and

⁴¹ <https://www.wis-tns.org>

⁴² https://github.com/shahbandeh/MIRI_MRS/blob/main/MRS_reductions.ipynb

⁴³ <https://github.com/brynickson/AstroBkgInterp>

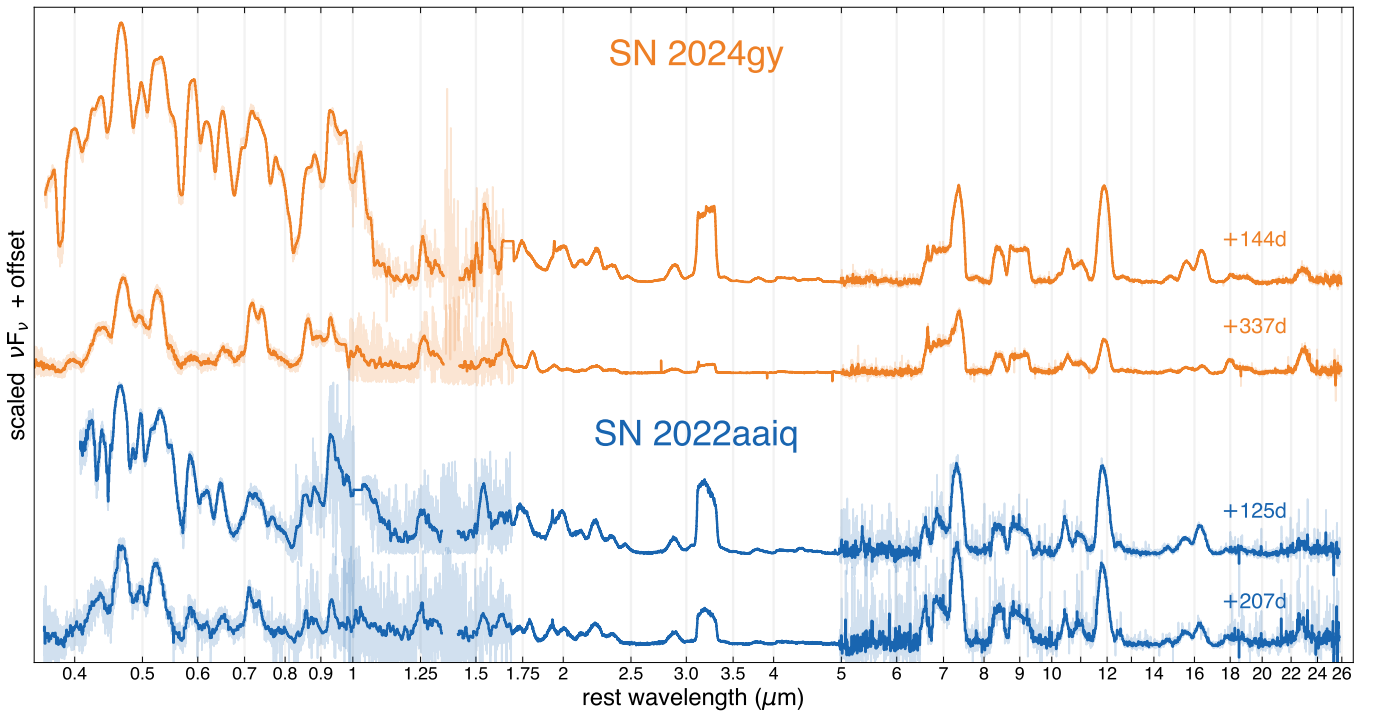


Figure 2. Panchromatic optical + NIR + MIR spectra of the normal SN Ia 2024gy (orange), at +144 days and +337 days postmaximum, and SN 2022aaq (blue) at +125 days and +207 days postmaximum. The unbinned data are shown with low opacity. The spectra are scaled and offset, and the ordinate is given in νF_ν using an arcsinh scaling, for display purposes.

a background annulus width of six pixels. This aperture captures the full SN flux well up to $14\ \mu\text{m}$, but may underestimate the flux at longer wavelengths as the instrument point-spread function (PSF) broadens. While a smaller aperture at longer wavelengths loses a fraction of the SN flux, it significantly improves the isolation of SN emission lines from the high background in channel 4. We therefore caution that the flux calibration is uncertain beyond $\sim 14\ \mu\text{m}$ and do not attempt detailed flux-dependent analysis at these wavelengths. For background subtraction, we adopted the recommended parameters: a polynomial fitting mode of degree 3, a bin size of five, and a cube resolution of high. None of the four SNe exhibits a complex background, and this procedure isolates the SN flux well. Finally, we trimmed each spectrum at wavelengths longer than $26\ \mu\text{m}$, where the noise in channel 4 becomes dominant and no reliable emission features are detected.

All JWST data presented here were obtained from the Mikulski Archive for Space Telescopes⁴⁴ at the Space Telescope Science Institute. The specific observations can be accessed via doi:10.17909/tzsy-x483. The data of SN 2022aaq, SN 2024gy, SN 2021aefx, and SN 2022xkq are shown in Figures 2, 3, and 4, respectively. The JWST spectra of SN 2022aaq and SN 2024gy continuously span $1.7\text{--}28\ \mu\text{m}$. In stitching together the spectra, we switch from NIRSpec to MIRI at $5\ \mu\text{m}$.

2.2. Ground-based Data

2.2.1. Optical Photometry

Optical photometry for SN 2022aaq and SN 2024gy was obtained through the Global Supernova Project (GSP)

collaboration using the Las Cumbres Observatory (LCO; T. M. Brown et al. 2013) 0.4 m and 1 m telescopes. Preprocessing, including bias correction and flat-fielding, was handled by the BANZAI pipeline (C. McCully et al. 2018). Further data reduction was carried out using *lcofotpipe* (S. Valenti et al. 2016), a photometric reduction pipeline that uses PSF photometry (P. B. Stetson 1987) to calculate zero-points, color terms, and extracted magnitudes.

In this work, we do not analyze the light curves in detail. We use them to estimate distance and extinction for dereddening and calibrating the spectra used to measure stable Ni luminosities in Section 5.3. We estimate the distance to SN 2024gy using *BayeSN*, a hierarchical Bayesian SN Ia light-curve model (K. S. Mandel et al. 2022; M. Grayling et al. 2024). We favor using *BayeSN* because SN 2024gy is located near the center of NGC 4216 and it explicitly models host-galaxy dust extinction separately from intrinsic SN spectral energy distribution variations, unlike alternatives like SALT2 (J. Guy et al. 2007).

Using the *BayeSN* model trained by S. M. Ward et al. (2023), fitting the light curve of SN 2024gy yields a distance modulus to NGC 4216 of $\mu = 31.18 \pm 0.11\ \text{mag}$, which corresponds to a distance of $17.2 \pm 0.9\ \text{Mpc}$ that we adopt for our analysis of SN 2024gy. This distance agrees within the uncertainties with measurements from L. Li et al. (2026). The *BayeSN* fit to SN 2024gy results in a host-galaxy extinction of $A_V = 0.72 \pm 0.06\ \text{mag}$ (with $R_V = 2.55 \pm 0.10$) and a time of *B*-band maximum light of MJD = 60329.19 ± 0.05 corresponding to 2024 January 20 (Appendix D).

We similarly fit SN 2022aaq with *BayeSN*, using LCO and Zwicky Transient Facility (ZTF) photometry, the latter obtained via the ZTF forced-photometry service (F. J. Masci et al. 2019, 2023). Given sparser data than for SN 2024gy, we

⁴⁴ <https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

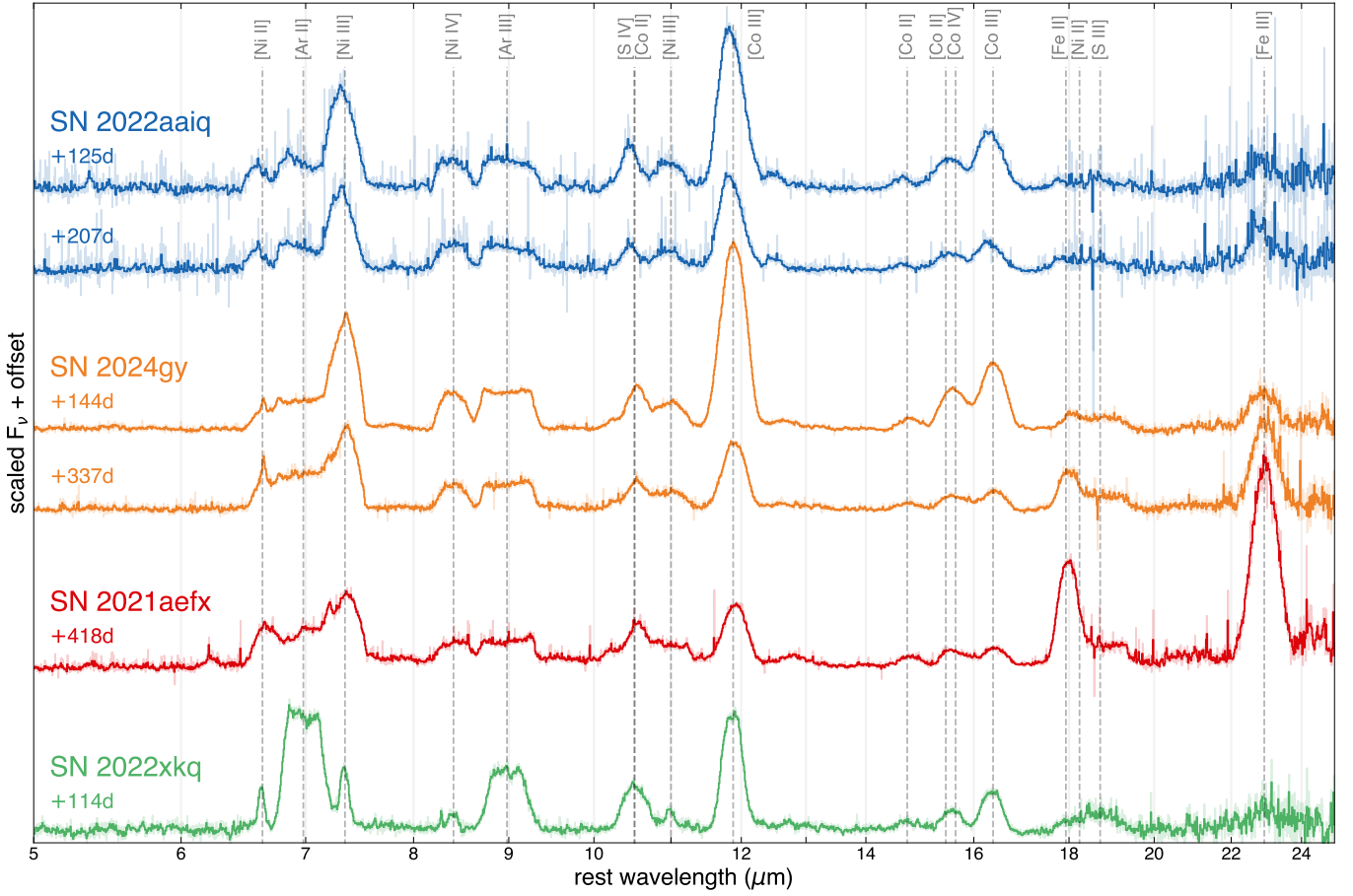


Figure 3. Comparison and identifications of prominent lines for JWST/MIRI MRS spectra of normal SNe Ia 2022aaig (blue), 2024gy (orange), and 2021aefx (red), and SN 1991bg-like SN 2022xkq (green). A narrow component of [Ni II] 6.64 μm is detected in SN 2024gy. Low opacities show the unbinned data. Owing to differences in phase and distance, we scale the spectra and offset for display purposes. A linear (not arcsinh) flux scaling is used.

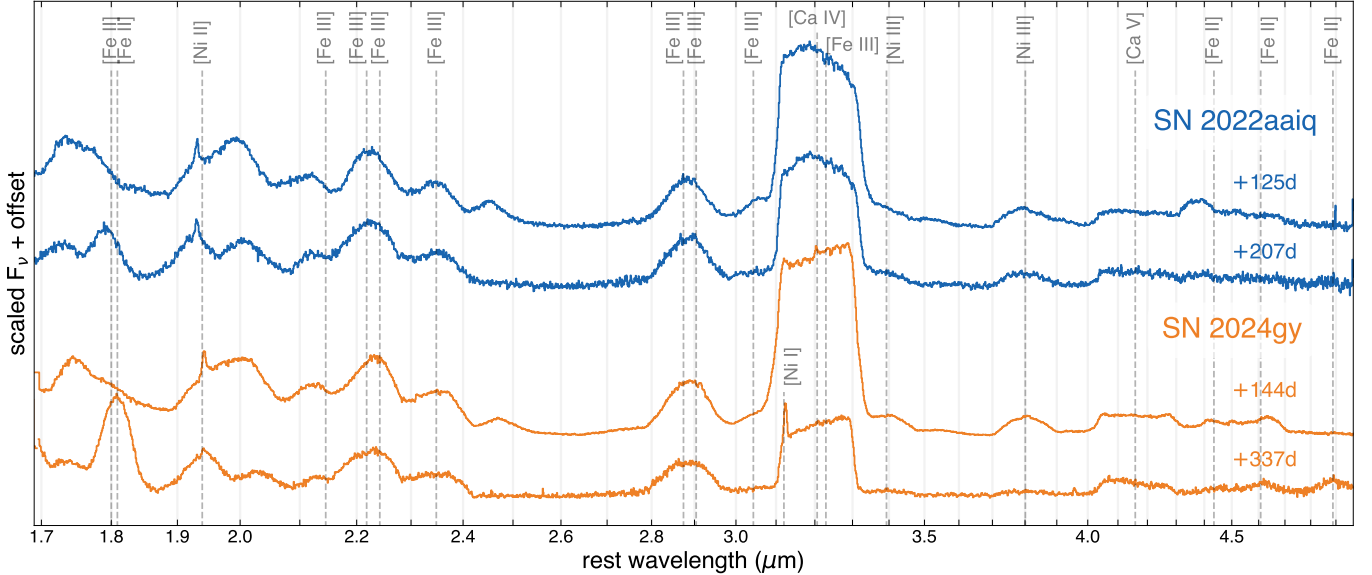


Figure 4. Comparison and identifications of prominent lines for the JWST/NIRSpec G235M + G395M spectra of normal SNe Ia 2022aaig (blue) and 2024gy (orange). Narrow features from [Ni II] 1.94 μm are detected in both epochs for SN 2022aaig and SN 2024gy. A narrow [Ni I] 3.12 μm spike is also detected in SN 2024gy at +337 days. Owing to differences in phase and distance, we scale the spectra and offset for display purposes. An arcsinh flux scaling is also applied to more clearly show weaker lines.

fix R_V to the BayeSN training sample mean value of 2.7 and find A_V to be consistent with 0. We recover a distance modulus of $\mu = 32.76 \pm 0.10$ mag, corresponding to a distance of

35.6 ± 1.7 Mpc. This distance is longer than other redshift-independent distances reported in the NASA Extragalactic Database but is within 2σ agreement to the recent surface-

brightness-fluctuation-based distance from R. B. Tully et al. (2013, $\mu = 32.27 \pm 0.14$ mag).⁴⁵ The time of the maximum *B*-band light is MJD = 59914 $\pm$ 0.09, corresponding to 2022 December 1. We present the BayeSN fit alongside that of SN 2024gy in Appendix D.

2.2.2. Optical Spectroscopy

We obtained contemporaneous optical spectra at similar phases to the JWST observations of SN 2022aaiq and SN 2024gy. Spectra of SN 2024gy were taken with the Low Resolution Imaging Spectrometer (LRIS; program PIs: A. V. Filippenko, A. A. Miller; J. B. Oke et al. 1995) on the Keck I 10 m telescope on 2024 June 6, 2024 June 13, 2024 June 28, and 2025 January 1. We combine the first two LRIS observations to complement the first JWST epoch and pair the last LRIS observation with the second JWST epoch (Figure 2). We analyze the 2024 June 28 LRIS spectrum, which has the highest S/N, in more detail in Section 4.6. This spectrum is reduced with the `PyPeIt` package (J. X. Prochaska et al. 2020), and we use `hostsub_gp`⁴⁶ to remove the host-galaxy contamination (C. Liu & A. A. Miller 2026).

Contemporaneous optical spectra for both JWST observations of SN 2022aaiq were taken with the Low Resolution Spectrograph 2 (LRS2; program PI: J. C. Wheeler T. S. Chonis et al. 2014) mounted on the Hobby–Eberly Telescope (HET; L. W. Ramsey et al. 1998) located at McDonald Observatory on 2023 March 31 and 2023 June 25 (Figure 2). The LRS2 Integral Field Unit data were reduced by the `Panacea`⁴⁷ pipeline. For each wavelength slice in the three-dimensional (3D) data cube, we mask out the SN position with a 3'' diameter circular aperture and estimate the underlying galaxy flux by linearly interpolating from the surrounding pixels. This process is repeated independently for each slice. The resulting “host-only” cube is subtracted from the original data cube before extracting the 1D SN spectrum.

A contemporaneous optical spectrum of SN 2022aaiq was also taken with the Echelle Spectrograph and Imager (ESI; program ID: U177, program PI: R. J. Foley A. I. Sheinis et al. 2002) on the Keck II 10 m telescope on 2023 March 27. Observations were taken with the 0.75'' slit, aligned to the parallactic angle (A. V. Filippenko 1982). Spectra were reduced in a standard manner using the tools in our custom spectroscopy pipeline⁴⁸ (M. R. Siebert et al. 2019). All 10 orders were extracted, wavelength calibrated, flux calibrated, and telluric corrected, and then combined into a single continuous spectrum. This spectrum was combined with the optical HET spectrum and the first JWST epoch for SN 2022aaiq.

We rescale the optical spectra to match photometry using a low-order spline function (“spectral mangling”). We correct for Galactic extinction using the F19 model from E. L. Fitzpatrick et al. (2019) with $R_V = 3.1$ and $E(B - V) = 0.028$ mag, and for host extinction using the parameters inferred from BayeSN. In Section 4.6, we also utilize a Magellan Baade optical spectrum of SN 2022xkq from J. Pearson et al. (2024) taken on 2023 March 5 at a

similar phase to the JWST observation. This spectrum is also calibrated to photometry and dereddened for the extinction given by J. Pearson et al. (2024).

2.2.3. NIR Spectroscopy

Our contemporaneous ground-based NIR spectra for both JWST epochs of SN 2022aaiq were obtained from the Near-Infrared Echellette Spectrometer (NIREs) on the Keck II 10 m telescope through the Keck Infrared Transient Survey (KITS) program (S. Tinianont et al. 2024). SN 2022aaiq was observed with NIREs on 2023 March 30 and 2023 June 7. SN 2024gy was observed with NIREs through the KITS program on 2024 December 15, similar in phase to the second JWST epoch. All NIREs spectra were reduced using procedures outlined by S. Tinianont et al. (2024).

An NIR spectrum contemporaneous with the first JWST epoch for SN 2024gy was obtained on 2024 June 5 with the Folded-port InfraRed Echelle Spectrograph (FIRE; program PI: A. Polin; R. A. Simcoe et al. 2013) mounted on the 6.5 m Magellan Baade Telescope at Las Campanas Observatory in Chile. The FIRE spectrum was reduced using the IDL pipeline `firehose` (R. A. Simcoe et al. 2013).

3. Spectral Analysis

3.1. Line Identifications

We identify lines using the predictions of S. Blondin et al. (2023). Most prominent MIR forbidden lines arise from ground-state or low-lying transitions. The four SNe studied here (SNe 2022aaiq, 2024gy, 2021aefx, and 2022xkq) all show the same dominant features, though relative strengths vary with the SN and phase (see Figure 3). Many lines have been previously reported (S. Blondin et al. 2023; J. M. DerKacy et al. 2023, 2024; L. A. Kwok et al. 2023; C. Ashall et al. 2024); here, we highlight those clarified or newly detected in our data. Notably, the JWST spectra of SN 2022aaiq and SN 2024gy reveal narrow components in several Ni lines.

3.1.1. Narrow Stable Nickel

Our medium-resolution JWST spectra of SN 2022aaiq and SN 2024gy show a narrow [Ni II] 1.94 μm line rising above the surrounding broad emission (Figures 4 and 5). This feature, difficult to isolate from the ground owing to telluric absorption and line overlap, is cleanly detected and resolved here with a high S/N, confirming the results of S. Kumar et al. (2026). Its velocity offset is consistent with all other Ni lines across the NIR and MIR (Section A.1), blueshifted by ~ 1000 km s^{−1} in SN 2022aaiq and redshifted by ~ 500 km s^{−1} in SN 2024gy, likely reflecting viewing-angle effects.

The [Ni II] 6.64 μm line also shows a narrow central component (consistent in velocity offset and width) superimposed on a broad base (Figures 3, 5, and 6). This narrow component is robustly detected in both epochs for SN 2024gy and more tentatively in SN 2022aaiq. Following S. Taubenberger et al. (2009), we refer to a narrow feature atop a broader base as a “narrow-core” profile. The more isolated MIR line clarifies that the [Ni II] 1.94 μm feature must also comprise both broad and narrow components. As S. Kumar et al. (2026) note, their detection criteria, which favor narrow features rising above broader emission, likely underestimate the

⁴⁵ https://ned.ipac.caltech.edu/byname?objname=NGC+5631&hconst=67.8&omegam=0.308&omegav=0.692&wmap=4&corr_z=1

⁴⁶ https://github.com/slowdivePTG/HostSub_GP

⁴⁷ <https://github.com/grzeimann/Panacea>

⁴⁸ https://github.com/msiebert1/UCSC_spectral_pipeline/tree/esi

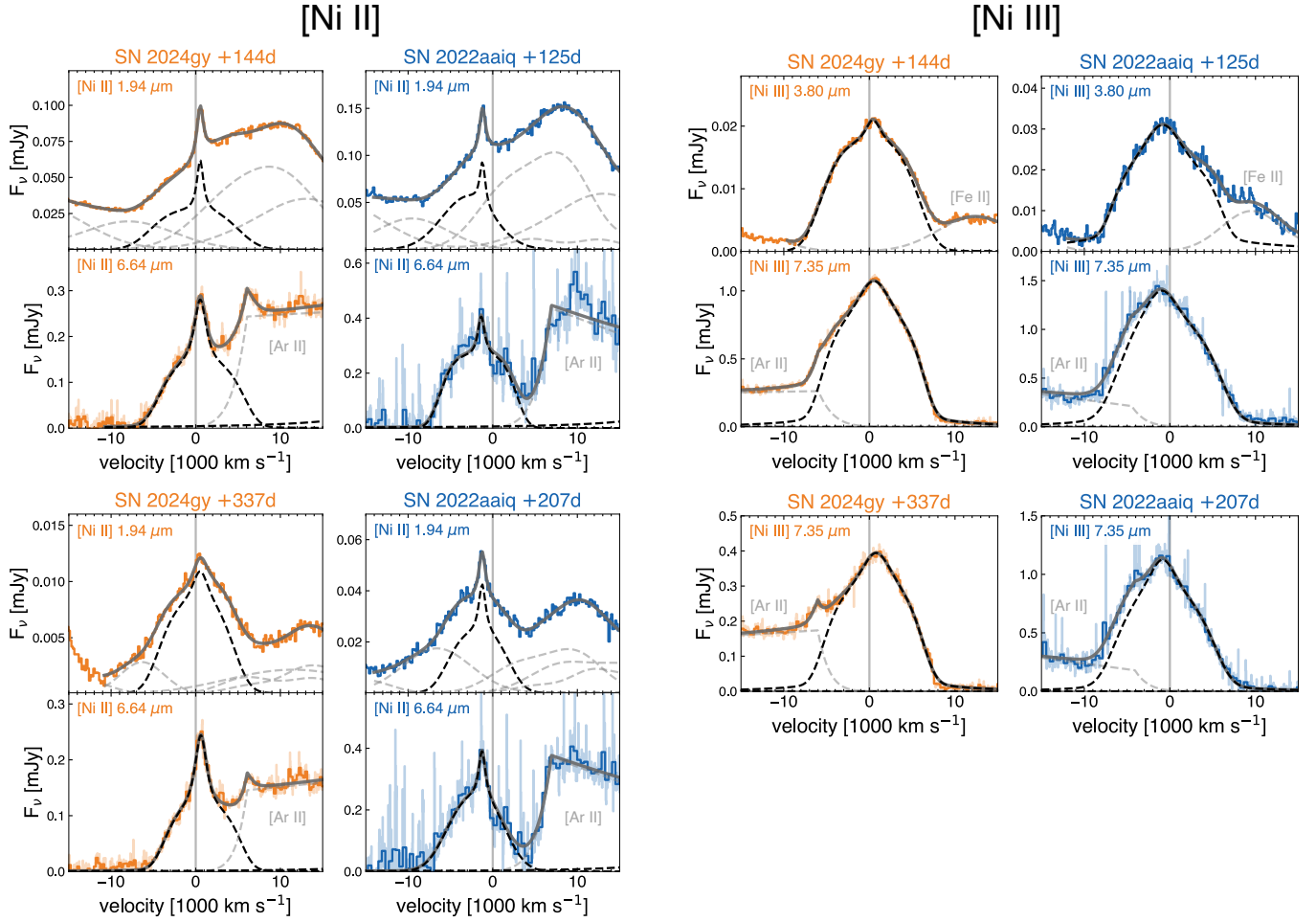


Figure 5. Line-profile fits for [Ni II] 1.94 and 6.64 μm (left) and [Ni III] 3.80 and 7.35 μm (right) in SN 2024gy (orange) at +144 and +337 days and SN 2022aaig (blue) at +125 and +207 days. The contribution from Ni is shown in dashed black, and contributions from other nearby lines are shown in dashed gray. The composite fit is shown in solid gray.

incidence of [Ni II] 1.94 μm in their sample; future analyses should account for both components.

We also detect [Ni I] 3.12 μm for the first time in a normal SN Ia.⁴⁹ It appears in the +337 day spectrum of SN 2024gy as a narrow feature at the blue edge of [Ca IV] 3.21 μm (Figures 4 and 7). The wings of the [Ca IV] profile maintain the same shape, narrowing only marginally from the previous epoch, indicating no accompanying broad [Ni I] component at this phase. The [Ni I] feature matches the offsets and widths of the narrow [Ni II] components. By contrast, the [Ni III] 3.80 μm line of SN 2024gy at +144 days shows a narrow-core profile with a less pronounced narrow spike atop an even broader base; this is less clear in the [Ni III] 7.35 μm line. We quantify kinematic properties in Section 4 and interpret the central Ni emission in Section 7.

3.1.2. SN 2022aaig and SN 2024gy

Beyond the narrow Ni features, both SNe show several new or clarified lines. We detect [S IV] 10.51 μm and [S III] 18.71 μm with flat-topped profiles similar to Ar (Figure 3). The [S IV] feature produces the subtle shoulder near 10.2 μm and contributes to blending near 11 μm . In the

+337 days spectrum of SN 2024gy, [Fe II] 17.93 μm emerges atop the blue side of [S III] 18.71 μm , while [Fe III] 22.92 μm grows in strength in both SNe. The predicted 14–17 μm Co complex (comprised of [Co II] 14.74 μm , [Co II] 15.46 μm , [Co IV] 15.64 μm , and [Co III] 16.39 μm ; S. Blondin et al. 2023) is present in both objects.

Our NIRSpec observations also reveal weak lines in the range 3–5 μm (Figure 4). [Ni III] 3.39 and 3.80 μm are detected in both SNe; at early phases, when [Ni III] 3.80 μm is measured with a good S/N, it provides a relatively clean tracer of [Ni III]. Several [Fe II] lines appear near 4.5 μm . We further identify a flat-topped feature near 4.15 μm as [Ca V] 4.16 μm using the Atomic Line List⁵⁰ (P. A. M. van Hoof 2018). Although highly ionized, this ground-state transition shows morphology consistent with that of other IME lines. [Ca V] was not included in the CMFGEN models of S. Blondin et al. (2023).

3.1.3. SN 2022xkq

As background-subtraction techniques for MRS data have improved, we reassess several identifications for SN 2022xkq from J. M. DerKacy et al. (2023) using our rereduction. We now detect weak [Ni IV] 8.40 μm and [Ni III] 11.00 μm lines.

⁴⁹ L. A. Kwok et al. (2023) identified this line in SN 2021aefx, but it was reclassified as [Ca IV] 3.21 μm by S. Blondin et al. (2023).

⁵⁰ <https://linelist.pa.uky.edu/newpage/>

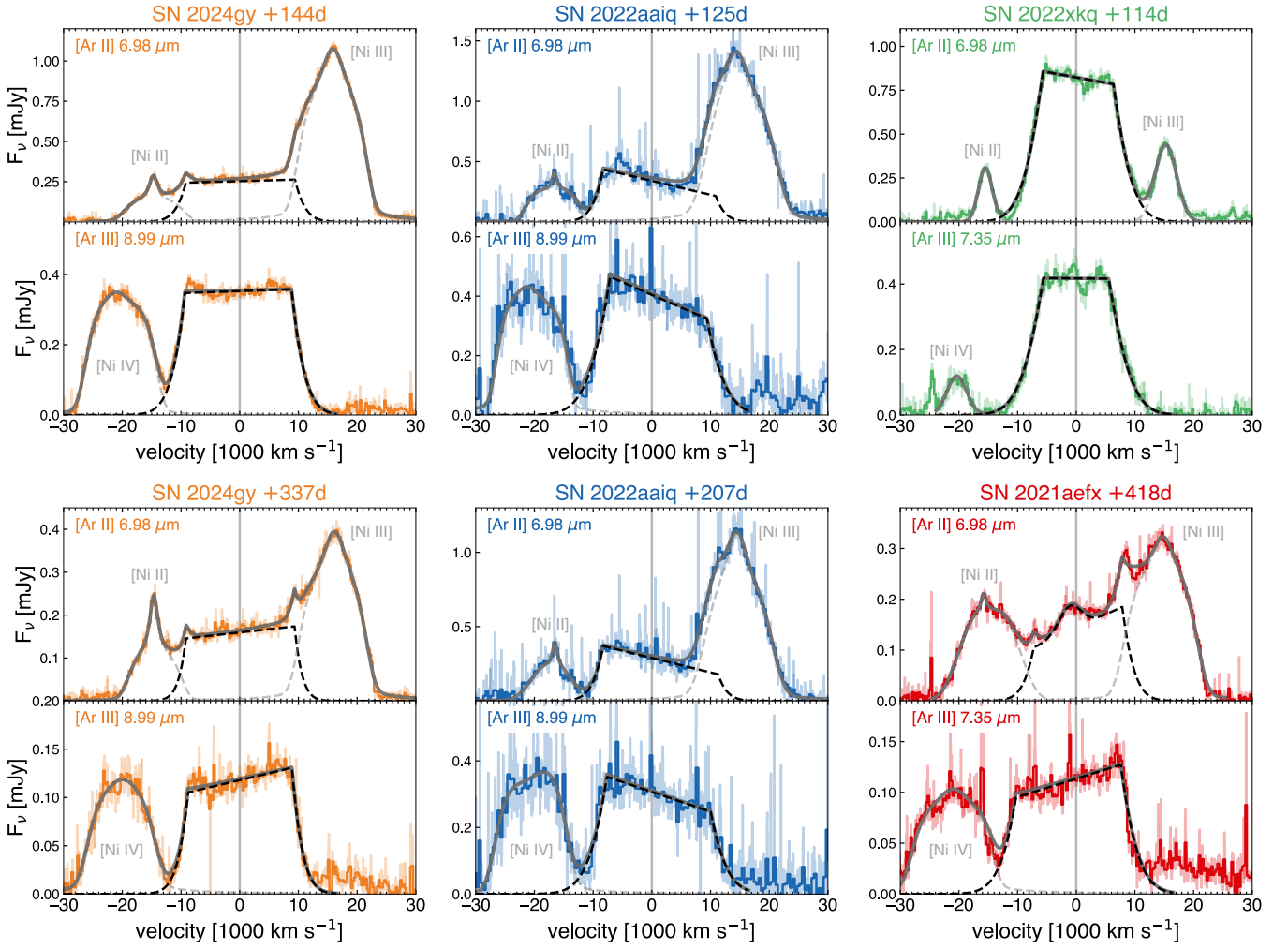


Figure 6. Line-profile fits for [Ni II] 6.98 μm , [Ar II] 6.98 μm , [Ni III] 7.35 μm , [Ni IV] 8.40 μm , and [Ar III] 8.99 μm in SN 2024gy (orange) at +144 and +337 days, SN 2022aaq (blue) at +125 and +207 days, SN 2022xkq (green) at +114 days, and SN 2021aefx (red) at +418 days. The contribution from Ar is shown in dashed black, and contributions from Ni lines are shown in dashed gray. The composite fit is shown in solid gray. The [Ar II] and [Ar III] lines are well fit by slanted flat-topped profiles, indicating a mildly asymmetric shell. The [Ni II] lines in SN 2022aaq and SN 2024gy are well fit by a narrow core atop a broad base, indicating enhanced central emission. The [Ni III] lines in SN 2022aaq, SN 2024gy, and SN 2021aefx are well fit by a broken-slope profile with a broad base that narrows toward the peak.

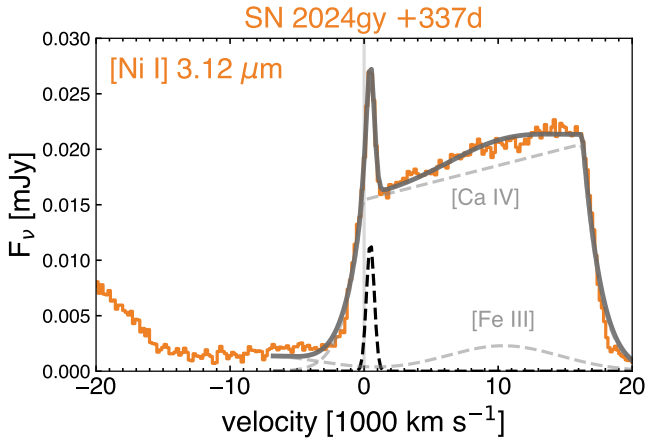


Figure 7. Line-profile fit for [Ni I] 3.12 μm in SN 2024gy (orange) at +337 days. The contribution from Ni is shown in dashed black, and contributions from other nearby lines are in dashed gray. The composite fit is displayed in solid gray. The [Ni I] line is well fit by only a narrow component (without a broad base), suggesting that it is only present in the centermost regions.

The [Ni IV] 8.40 μm profile shows an extremely narrow feature on its blue side (see Section A.1). Lacking a convincing separate identification, we suggest it may be part of the [Ni IV] emission, potentially from a higher-velocity clump or nugget. We also detect the full Co complex between 14 and 17 μm .

Our rereduction further shows that [Ar III] 8.98 μm lacks the strong blue peak previously attributed to [Ni IV] 8.95 μm , [Ti II] 8.92 μm , or [Ti II] 9.19 μm (J. M. DerKacy et al. 2024). We do not find clear evidence for these lines. Given the weakness of [Ni IV] 8.40 μm (expected to be the strongest [Ni IV] transition) and the absence of other Ti features, we attribute the 9 μm feature almost entirely to [Ar III]. Fluctuations atop the Ar lines had been suggested to arise from weak lines, including neutral ions (J. M. DerKacy et al. 2023); however, we do not detect other expected neutral transitions (e.g., [Ni I] 7.51 μm , which would be isolated at the velocities of SN 2022xkq), and the phase (+114 days) is likely too early for such low ionization (e.g., [Ni I] appears in SN 2024gy at +337 days but not in SN 2022aaq at +207 days). We therefore favor ejecta inhomogeneities and asymmetries as the

source of these variations (e.g., J. M. Pollin et al. 2026; K. Simotas et al. 2025).

Finally, the rereduction reduces the noise in the continuum between prominent lines. J. M. DerKacy et al. (2024) discuss a pseudocontinuum from a lingering photosphere; however, we find that the continuum in SN 2022xkq is not more pronounced than in the later-epoch observations of the other SNe.

3.1.4. SN 2021aefx

SN 2021aefx was observed at a later phase than the other SNe. It shows strong [Fe II] 17.93 μm and [Fe III] 22.92 μm , consistent with the time evolution seen in SN 2022aaq and SN 2024gy. Our rereduction more clearly reveals flat-topped [S III] 18.71 μm beneath [Fe II] 17.93 μm , as well as the 14–17 μm Co complex. Near 7 μm , there is an excess above expectations for a flat-topped [Ar II] 6.98 μm , given the [Ar III] 8.99 μm line profile (Figure 6). This bump has been present since +255 days (J. M. DerKacy et al. 2023; L. A. Kwok et al. 2023; C. Ashall et al. 2024), but earlier epochs had lower resolution. The excess is not consistent with [Ni II] 6.92 μm , a weak nearby line. We suggest this excess may be additional central [Ar II] emission, perhaps due to mixing.

3.2. Comparisons

The spectra of SN 2022aaq, SN 2024gy, and SN 2021aefx are broadly similar despite their phase differences. They share the same dominant lines with comparable morphologies: IME features are flat topped, while IGE features are centrally peaked. Yet within this similarity, variations emerge that are physically meaningful—for example, tilted IME profiles and skewed [Co III] 11.88 μm indicate mild asymmetries, consistent with off-center explosions viewed at different angles (J. M. DerKacy et al. 2023). A detailed multiobject comparison will be presented in future work; here, we predominantly focus on the Ni lines.

By contrast, the subluminous, spectroscopically SN 1991bg-like (A. V. Filippenko et al. 1992; B. Leibundgut et al. 1993) SN 2022xkq (J. Pearson et al. 2024) shows marked differences. Its Ni lines are single component and narrower than the broad bases of normal SNe Ia yet broader than their narrow Ni cores. Relative to [Ni III] 7.35 μm and [Co III] 11.88 μm , the [Ar II] 6.98 μm and [Ar II] 8.99 μm lines are much stronger than in normal SNe Ia. Velocity measurements and an interpretation are given in Section 4.5 and Section 7.

4. Emission-line Profiles

4.1. Line-fitting Procedure

We model the nebular spectra using the fitting approach from L. A. Kwok et al. (2023, 2024, 2025) in which blended spectral lines are fit simultaneously. We choose wavelength intervals for our fits that encompass all relevant overlapping transitions (e.g., 6.4–7.8 μm for [Ni II] 6.64 μm , [Ar II] 6.98 μm , and [Ni III] 7.35 μm in Figure 6). If multiple transitions of the same ion fall within the specified spectral window, they are required to share the same kinematic parameters (velocity offset, width, and profile shape), while their relative line strengths are fixed according to a model line list computed from the N100 DDT model (I. R. Seitenzahl et al. 2013) at 165 days postexplosion (see Section 6).

The overall normalization of each ion is free. Thus, the fits determine the velocity centroid, characteristic width, and relative flux contribution of individual lines.

Different ions are described by functional forms chosen to reproduce their observed profile shapes. Specifically, [Ar II] and [Ar III] are modeled with a slanted flat top plus Gaussian wings, [Co II] and [Co III] with a Gaussian, and [Ni II], [Ni III], and [Ni IV] with a Lorentzian plus super-Gaussian (described below). All velocities are measured relative to the adopted heliocentric systemic velocity of the host galaxy, and JWST transitions are fit using vacuum rest wavelengths.

4.2. Ni and Ar in SN 2024gy and SN 2022aaq

The 6–9.5 μm spectral window contains the dominant [Ni II] 6.64 μm , [Ar II] 6.98 μm , [Ni III] 7.35 μm , [Ni IV] 8.40 μm , and [Ar III] 8.99 μm transitions. While [Ar II] is blended on both sides, the blue wing of [Ni II] and red wing of [Ni III] in SN 2022aaq and SN 2024gy are relatively clean and reveal a two-component structure: a narrow central peak superimposed on a broader base.

We therefore fit the Ni profiles with a two-component function consisting of a Lorentzian (narrow core) and a super-Gaussian (broad base), allowing independent velocity centroids and widths for each component (see Section A.2 for functional details). Alternative representations, such as narrow + broad Gaussians, do not simultaneously reproduce the observed sharp narrow component and steep outer wings. Our Lorentzian + super-Gaussian provides a more flexible empirical description for the line shape, without affecting centroid measurements.

We constrain [Ar II] 6.98 μm using the nearly isolated [Ar III] 8.98 μm line, adopting its best-fit kinematic parameters as priors ($\pm 500 \text{ km s}^{-1}$). Applying the two-component Ni model described above, we then fit the full 6–9.5 μm complex in both SNe, shown in Figure 6 (and see Section A.2). We find that [Ni II] is systematically narrower than [Ni III] at a given phase, consistent with ionization stratification in which recombination occurs more efficiently in the denser inner ejecta. This trend is also observed in the narrow components of the NIR transitions [Ni II] 1.94 μm and [Ni III] 3.80 μm .

In Figure 5, we use MIR-derived parameters (with $\pm 500 \text{ km s}^{-1}$ priors on [Ni II] narrow-component parameters, and $\pm 1000 \text{ km s}^{-1}$ priors for others) and find that the NIR lines can be fit well with these kinematic constraints. Without MIR constraints, the narrow component in [Ni II] 1.94 μm is still well constrained, but the broad base becomes highly sensitive to bounds and blending, showing that the NIR alone cannot robustly constrain it. Additional details and a discussion of the NIR line fitting is given in Section A.2.

4.3. [Ni I] in SN 2024gy

Figure 7 shows our fit to the narrow [Ni I] 3.12 μm line in SN 2024gy at +337 days. The line sits on the blue edge of [Ca IV] 3.21 μm , which itself is blended on the red side with [Fe III] 3.23 μm . We find no evidence for a broad [Ni I] component (see Section 3.1.1), and therefore fit only a Lorentzian. The line is nearly identical in width and offset to the narrow [Ni II] components, supporting ionization stratification: at this epoch, only the physical conditions in the core (temperature, density, nonthermal processes, etc.) permit recombination to [Ni I]. Taken together, the line profiles show

an ionization-dependent trend: the narrow-core contribution increases toward lower ionization states.

4.4. SN 2021aefx and SN 2022xkq

At +418 days, SN 2021aefx exhibits Ni profiles broadly similar to those of SN 2022aaiq and SN 2024gy, though the [Ni II] narrow core is only marginally detected and the two components in [Ni III] are less distinct. The [Ar II] 6.98 μm line in SN 2021aefx exhibits an additional central component not present in the other objects (Figure 6). The nearby [Ni II] 6.92 μm transition is too weak and velocity inconsistent to account for this excess, leaving its origin uncertain. This feature may reflect some inward mixing of Ar into lower-velocity regions.

In contrast, SN 2022xkq (a transitional SN 1991bg-like event) shows [Ni II] 6.64 μm and [Ni III] 7.35 μm lines that are well described by single Gaussians with no narrow cores and that are substantially narrower than in the normal events (Figure 6). The Ar lines are likewise narrower but relatively stronger compared to Ni. These widths indicate that stable Ni in SN 2022xkq is confined to the low-velocity inner ejecta and that the overall ejecta velocities are reduced relative to normal SNe Ia.

Additional details and a discussion of the line fitting for SN 2021aefx and SN 2022xkq is given in Section A.3.

4.5. Kinematic Trends

Figure 8 presents our measurements of the velocity offset, v_{off} , and the full width at half-maximum (FWHM) from the fitted profiles of the dominant emission lines for SN 2024gy (orange; top left), SN 2022aaiq (blue; top right), SN 2021aefx (red; bottom left), and SN 2022xkq (green; bottom right). These quantities are derived from the fitted line profiles obtained by simultaneously fitting the 6.5–17 μm spectral range, with uncertainties estimated via a bootstrap method (L. A. Kwok et al. 2023, 2025). Several physically meaningful trends emerge.

In each SN, the FWHM measurements reveal a clear ion-dependent velocity stratification, with the IMEs (Ar and S) exhibiting significantly broader profiles than the IGEs. SN 2024gy, SN 2022aaiq, and SN 2021aefx share a similar structure in which the IMEs extend to $\sim 20,000 \text{ km s}^{-1}$, while the IGEs (Ni and Co) cluster around $8000\text{--}13,000 \text{ km s}^{-1}$. In contrast, SN 2022xkq shows a more pronounced separation between nucleosynthetic layers: the IMEs extend to $\sim 16,000 \text{ km s}^{-1}$, the radioactive IGEs (Co) to $\sim 8000 \text{ km s}^{-1}$, and the stable IGEs (Ni) to only $\sim 4000 \text{ km s}^{-1}$. This suggests that, in the more luminous explosions, the radioactive and stable IGEs are broadly cospatial, whereas in the subluminous SN 2022xkq, the nucleosynthetic layers remain more distinctly separated.

Notably, in SN 2024gy and SN 2022aaiq, the narrow-core component of [Ni II] is even narrower than the Ni emission observed in SN 2022xkq. This indicates that, although stable Ni and radioactive Co extend to similar velocities overall, a portion of the stable Ni remains highly concentrated in the innermost ejecta while Co is more broadly distributed.

The v_{off} measurements show that the IGEs tend to exhibit larger velocity offsets than the IMEs. In SN 2024gy and SN 2022aaiq, the lowest ionization states ([Ni II] and [Co II]) have the largest offsets, with the narrow [Ni II]

core displaying a similar shift to their broader counterparts. This behavior is consistent with expectations for a modestly off-center ignition ($\sim 500\text{--}1500 \text{ km s}^{-1}$). The magnitude and sign of the offsets (redshift versus blueshift) vary between the SNe, consistent with viewing-angle effects. Among the objects studied here, SN 2022aaiq exhibits the strongest trend in v_{off} ; its Ar profiles are also the most strongly tilted and are slanted opposite to those of SN 2024gy and SN 2021aefx, with the velocity offsets showing a similar reversal.

These results support the findings of K. Maeda et al. (2010b) and K. Maguire et al. (2018) and provide independent MIR evidence for spatially distinct emitting regions of nucleosynthetic products, ionization-dependent stratification, and velocity offsets driven by off-center ignition and viewing-angle effects.

4.6. Optical [Ni II] Fits

The most prominent Ni feature in the optical is [Ni II] $\lambda 7378$, which is heavily blended with lines from [Fe II] and [Co III]. Estimating its flux therefore requires joint modeling of the full 7300 $\text{\AA}$ complex, accounting for contributions from multiple species. In our fitting, we do not find any need for contributing emission from [Ca II]. The optical data were taken from the ground, so we analyze this region with respect to the air wavelengths of the transitions. We model this region using the Bayesian fitting code `sn_line_velocities`⁵¹ (C. Liu et al. 2023), incorporating priors on line velocities and widths informed by the isolated NIR and MIR lines, but not fixing them. Specifically, the [Ni II] 6.64 μm and [Co III] 11.88 μm lines provide central velocity (v_μ) and FWHM constraints for those ions, while [Fe II] parameters are averaged over multiple NIR transitions. We fit the 5750–7600 $\text{\AA}$ rest-frame region with single-Gaussian components for [Fe II], [Ni II], and [Co III], fixing each ion to share the same v_μ and dispersion across its transitions. The line list and relative strengths for each species are based on late-time models of a normal SN Ia, SN 2015F (A. Flörs et al. 2020). Gaussian priors of $\mathcal{N}(v_{\mu,\text{IR}}, 500) \text{ km s}^{-1}$ and $\mathcal{N}[\ln(\text{FWHM}_{\text{IR}}/2.355), 0.05]$ are adopted for v_μ and $\ln v_\mu$, respectively. We fix the continuum level to zero in the fit, as host-galaxy contamination was removed prior to fitting using `hostsub_gp` (see Section 2.2.2; C. Liu & A. A. Miller 2026).

Figure 9 demonstrates that both SN 2022xkq and SN 2024gy are well described by this three-ion model. For SN 2022xkq, small residuals near 7500 $\text{\AA}$ ($\sim 5000 \text{ km s}^{-1}$; Figure 9, right panel) may reflect deviations in [Fe II] ratios due to its lower ionization. The distinct secondary peak at $\sim 7400 \text{\AA}$, centered near zero velocity, is reproduced by the [Ni II] multiplet with a velocity dispersion of $\text{FWHM} = 2320 \pm 80 \text{ km s}^{-1}$ —significantly narrower than the [Fe II] and [Co III] components ($\sim 10^4 \text{ km s}^{-1}$). This is consistent with the MIR spectra, where [Ni II] is also much narrower ($\text{FWHM} \approx 3000 \text{ km s}^{-1}$) than [Co III] ($\text{FWHM} \approx 8000 \text{ km s}^{-1}$).

In SN 2024gy, the overall 7300 $\text{\AA}$ complex is similarly well fit with [Fe II], [Ni II], and [Co III]. A narrow [Ni II] component (thick black line, Figure 9, left panel) is detected at a velocity offset of $\sim +500 \text{ km s}^{-1}$, consistent with that measured in the NIR and MIR [Ni II] lines. We detect optical

⁵¹ https://github.com/slowdivePTG/sn_line_velocities

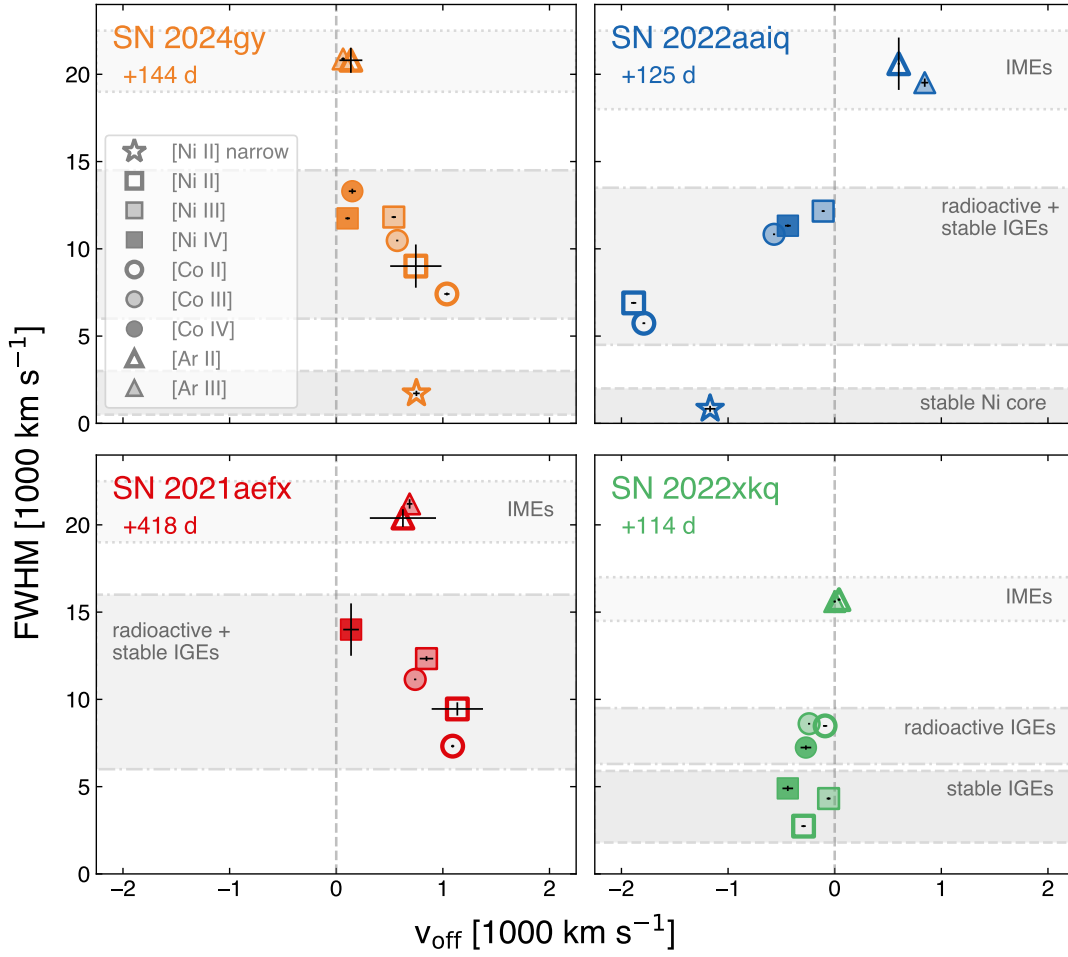


Figure 8. Kinematic offsets (v_{off}) and FWHM measurements from fits to the emission-line profiles of SN 2024gy (orange), SN 2022aaiq (blue), SN 2021aefx (red), and SN 2022xkq (green). For multicomponent fits, the plotted FWHM corresponds to the broader component, except for the narrow [Ni II] component, which is marked by a star. Highly blended or poorly constrained lines (e.g., [S IV]) are omitted. Elements are distinguished by marker shape, while ionization stage is indicated by fill. SN 2024gy, SN 2022aaiq, and SN 2021aefx exhibit clear stratification between IMEs and IGEs, while SN 2022xkq shows additional separation between radioactive and stable IGEs. In all objects, IGEs exhibit larger velocity offsets than IMEs, consistent with off-center ignition. Values for the fit measurements can be found in Table 2.

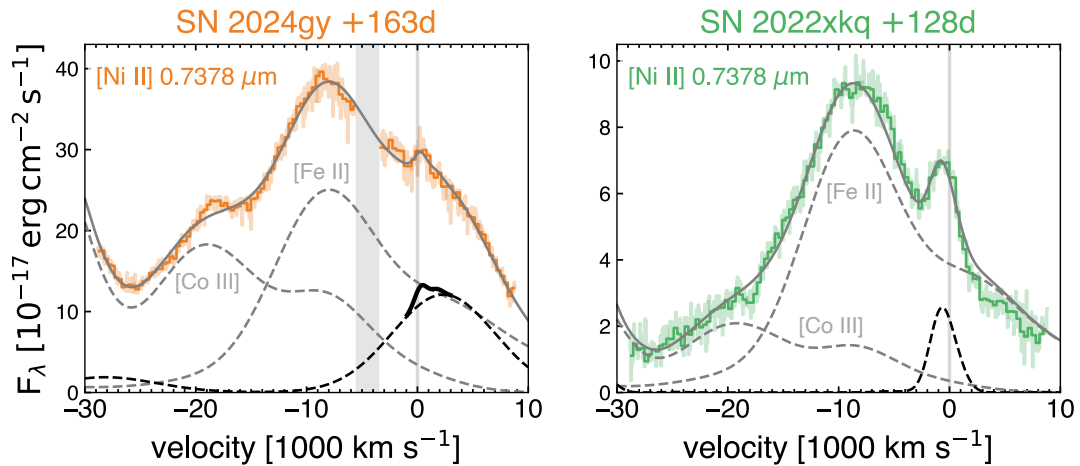


Figure 9. Line-profile fit for [Ni II] $0.7378 \mu\text{m}$ in SN 2024gy (orange) at +163 days (left) and SN 2022xkq at +128 days (right). The contribution from Ni is shown in dashed black, and contributions from other nearby lines are in dashed gray. The composite fit is displayed in solid gray. Left: the solid thick black line shows the narrow component of the [Ni II] emission that we detect in our Keck/LRIS spectrum of SN 2024gy.

[Ni II] $\lambda 7378$ emission in both SN 2022xkq and SN 2024gy, and find—as expected—that the optical and NIR [Ni II] lines share all velocity characteristics in our fits. The close

correspondence across wavelengths establishes that the narrow-core [Ni II] emission discovered with JWST is also present in the optical.

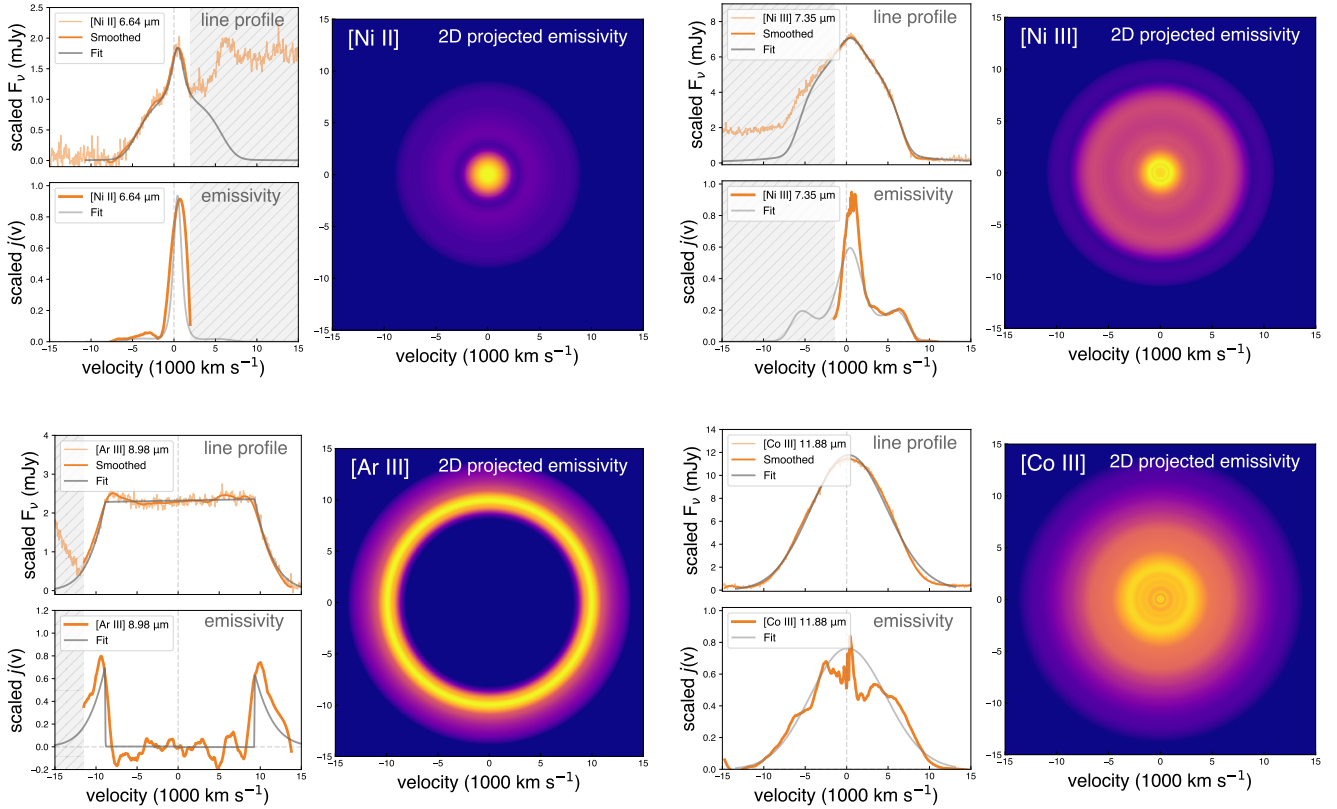


Figure 10. Line profile, emissivity, and 2D projected emissivity of [Ni II] 6.64 μm (upper left), [Ni III] 7.35 μm (upper right), [Ar III] 8.99 μm (lower left), and [Co III] 11.88 μm (lower right) for SN 2024gy at +144 days. For each ion, the upper-left panel displays the line profile, the lower-left panel shows the emissivity $j(v)$, and the right panel indicates the emissivity projected into 2D. The data are shown in light orange, the smoothed data in dark orange, our line fits in gray, and regions contaminated by line overlap in hatched light gray. Radial symmetry is imposed on the 2D projected emissivities, which are visual aids rather than physically accurate.

5. Line-profile Inversions

Nebular line profiles directly trace the emissivity of the ejecta along the line of sight. In principle, they can be inverted to recover the emissivity distribution $j(v)$ and ultimately the density structure $\rho(v)$. In practice, this is difficult because (i) lines may be blended, (ii) deprojecting the line of sight requires symmetry assumptions, and (iii) connecting $j(v)$ to $\rho(v)$ requires knowledge of temperature $T(v)$ and electron density $n_e(v)$ (A. Jerkstrand 2017).

C. Fransson & R. A. Chevalier (1989) showed that, assuming symmetry about the line-of-sight axis and homologous expansion, the emissivity as a function of velocity can be estimated from the derivative of the line profile. Rearranging Equation 8 of A. Jerkstrand (2017) gives

$$j(v) \propto \frac{1}{v} \frac{dF_v(v)}{dv}. \quad (1)$$

We apply this method to the JWST/MIRI data of SN 2024gy. The high resolution and S/N of our MRS observations, together with several minimally blended MIR lines, make this approach particularly effective for probing ejecta structure. We focus on four representative ions: [Ni II] 6.64 μm (clean blue side), [Ni III] 7.35 μm (clean red side), [Ar III] 8.99 μm (minor blue overlap only), and [Co III] 11.88 μm (essentially uncontaminated). These trace stable IGEs (Ni), radioactive IGEs (Co), and IMEs (Ar). The nearly flat [Ar III] 8.99 μm profile supports spherical symmetry as a reasonable first-order assumption for this object. However, this approach relies on

symmetry assumptions. In particular, Equation (1) depends on the 3D velocity, whereas in practice we use the line-of-sight velocity as a proxy, introducing additional uncertainty. Fully capturing the true ejecta structure will therefore require future multidimensional modeling.

5.1. Emissivity Profiles: SN 2024gy

Figure 10 shows the observed line profiles (upper left), derived emissivity profiles (lower left), and 2D projections (right; for visualization purposes). To mitigate sensitivity to noise, the data were gently smoothed before differentiation; results are insensitive to smoothing parameter choices. Velocities were offset by the value where the derivative crosses zero, consistent with a bulk offset of the explosion center, and the $v = 0 \text{ km s}^{-1}$ bin was interpolated to avoid division by zero. Regions affected by line overlap (hatched gray) are excluded from the derivative, though overplotted fits (gray) from Section 4 illustrate approximate contributions. We show the same calculation for emissivity based on the fits and find that it reveals subtle shortcomings in our fitted shapes. The two-dimensional (2D) projected emissivity visualization panels in Figure 10 are generated assuming radial symmetry, and we stress that they are a visual guide more than physically accurate.

In this work, we do not attempt to derive ion abundance or density profiles from our emissivity profiles owing to the large number of model-dependent assumptions that are required. Instead, our analysis stays closer to the data, and we suggest

that modeling comparisons be made between the output emissivity profiles or nebular lines themselves.

5.1.1. [Ni II]: Enhanced Central Emissivity

The [Ni II] 6.64 μm emissivity profile (Figure 10, top left) shows strong enhancement in the inner few thousand km s^{-1} , corresponding to the narrow core. The broader base reflects a shell-like distribution at larger velocities, with a thin gap in emission between the core and outer material. We construct the radially symmetric 2D projected emissivity using only the clean blue side of the line. This morphology indicates a centrally concentrated reservoir of stable Ni.

5.1.2. [Ni III]: Broken-slope Structure

The [Ni III] 7.35 μm profile (Figure 10, top right) displays a broken-slope morphology: a shallower inner slope that steepens beyond $\sim 4000 \text{ km s}^{-1}$. The emissivity dips only slightly between the two slopes, creating a broad, double-peaked structure. Compared to [Ni II], the [Ni III] emission is more extended, consistent with expected ionization stratification. We construct the radially symmetric 2D projected emissivity using only the clean red side of the line.

5.1.3. [Co III]: Extended Radioactive IGEs

The [Co III] 11.88 μm line (Figure 10, bottom right) is effectively isolated and shows weaker central emission than either Ni line, with slight asymmetry between blue and red wings. The profile suggests that radioactive IGEs (80%–90% of Co is radioactive at this phase; S. Blondin et al. 2023) are more evenly distributed and less centrally concentrated than stable Ni. Emission in the innermost regions is weaker than predicted by a Gaussian fit, consistent with high-density material being converted to stable Ni at the expense of radioactive Ni, which rapidly decays to radioactive Co (C. L. Gerardy et al. 2007).

5.1.4. [Ar III]: Shell-like IMEs

The [Ar III] 8.99 μm line (Figure 10, bottom left) exhibits a nonuniform shell morphology: emissivity peaks near the inner-shell edge at $\sim 8000 \text{ km s}^{-1}$, shows a clear shoulder, and falls steeply at the outer boundary. The nearly colocated [Ar III] inner-shell edge and outer extent of Ni emission highlights the layered structure of IMEs surrounding stable IGEs.

For centrally filled emission, the inversion in Equation (1) relies on directly mapping the line-of-sight velocity to the 3D velocity. However, for flat-topped profiles indicating shell-like emission, material with $v_{\text{los}} \approx 0$ arises mostly from ejecta at large 3D velocities nearly perpendicular to the line of sight, rather than from the center. Applying the standard $1/v$ factor at line-of-sight velocities smaller than the inner-shell boundary therefore overestimates the emissivity at small radii. To account for this projection effect, we impose a floor on v and compute

$$j(v) \propto \begin{cases} \frac{1}{v_{\text{inner}}} \frac{dF_\nu}{dv} & \text{if } v < v_{\text{inner}} \\ \frac{1}{v} \frac{dF_\nu}{dv} & \text{if } v \geq v_{\text{inner}} \end{cases},$$

where v_{inner} is the inner velocity boundary of the shell. This approach preserves the form of the inversion while incorporating the expected shell geometry.

5.2. Line-profile Derivatives

While emissivity profiles are useful for visualization, line-profile derivatives provide an assumption-independent way to highlight subtle changes in slope and morphology. In Figure 11, we compare the line profiles and derivatives of [Ni III] 7.35 μm , [Ar III] 8.99 μm , and [Co III] 11.88 μm in SN 2024gy to four representative explosion models from S. Blondin et al. (2023):

1. *Delayed detonation (DDT)*. A Chandrasekhar-mass ($1.4 M_\odot$) WD ignited at 100 points, based on the N100 model of I. R. Seitenzahl et al. (2013).
2. *Double detonation (DBLDET)*. A $1.0 M_\odot$ C/O WD with a $0.2 M_\odot$ He shell, following S. Gronow et al. (2021).
3. *Gravitationally confined detonation (GCD)*. Ignition offset at 10 km in a $1.4 M_\odot$ WD with central density of 10^9 g cm^{-3} (F. Lach et al. 2022).
4. *Violent merger (MERGER)*. Dynamic disruption of two WDs with masses $1.1 M_\odot$ and $0.9 M_\odot$ (R. Pakmor et al. 2012).

Each model was rerun at 165 days postexplosion to match our first epoch of SN 2024gy, and Figure 11 shows the isolated single-ion nebular line profiles. Distinct profile morphologies arise from the different ejecta compositions and structures produced by each explosion mechanism. Slight tilts in the model [Ar III] profiles reflect relativistic effects (S. Blondin et al. 2023).

None of the models reproduces all details of the observed line widths, ionization balance, or relative line strengths. These discrepancies likely reflect limitations in current nebular radiative-transfer calculations and model assumptions (discussed further in Section 6). By contrast, the overall morphology of the nebular lines—set by how different elements are distributed in velocity space—is uniquely imprinted by the explosion physics. The line morphologies are one of the most discriminating signatures of the explosion mechanism.

5.2.1. SN 2024gy: Signatures of a Delayed Detonation

Against this model backdrop, we examine the line morphologies of SN 2024gy in detail. The high S/N and resolution of our MRS data of SN 2024gy allow us to recover subtle features in the line morphologies. Both the line profiles and their derivatives carry the same diagnostic information, but the derivatives highlight slope changes more clearly.

The [Ni III] 7.35 μm profile derivative shows a shallower slope at inner velocities that steepens by roughly a factor of 2 at higher velocities. This broken-slope behavior, also visible directly in the profile, is a characteristic feature of the DDT model (Figure 11, top row). The velocity of the slope break and the overall line width are somewhat smaller in SN 2024gy than in the DDT model, but the qualitative shape, with distinct inner and outer stable Ni components, is strikingly similar.

The [Ar III] 8.99 μm profile also resembles the DDT model in overall morphology, though with notable differences: the observed Ar shell begins significantly farther out and is

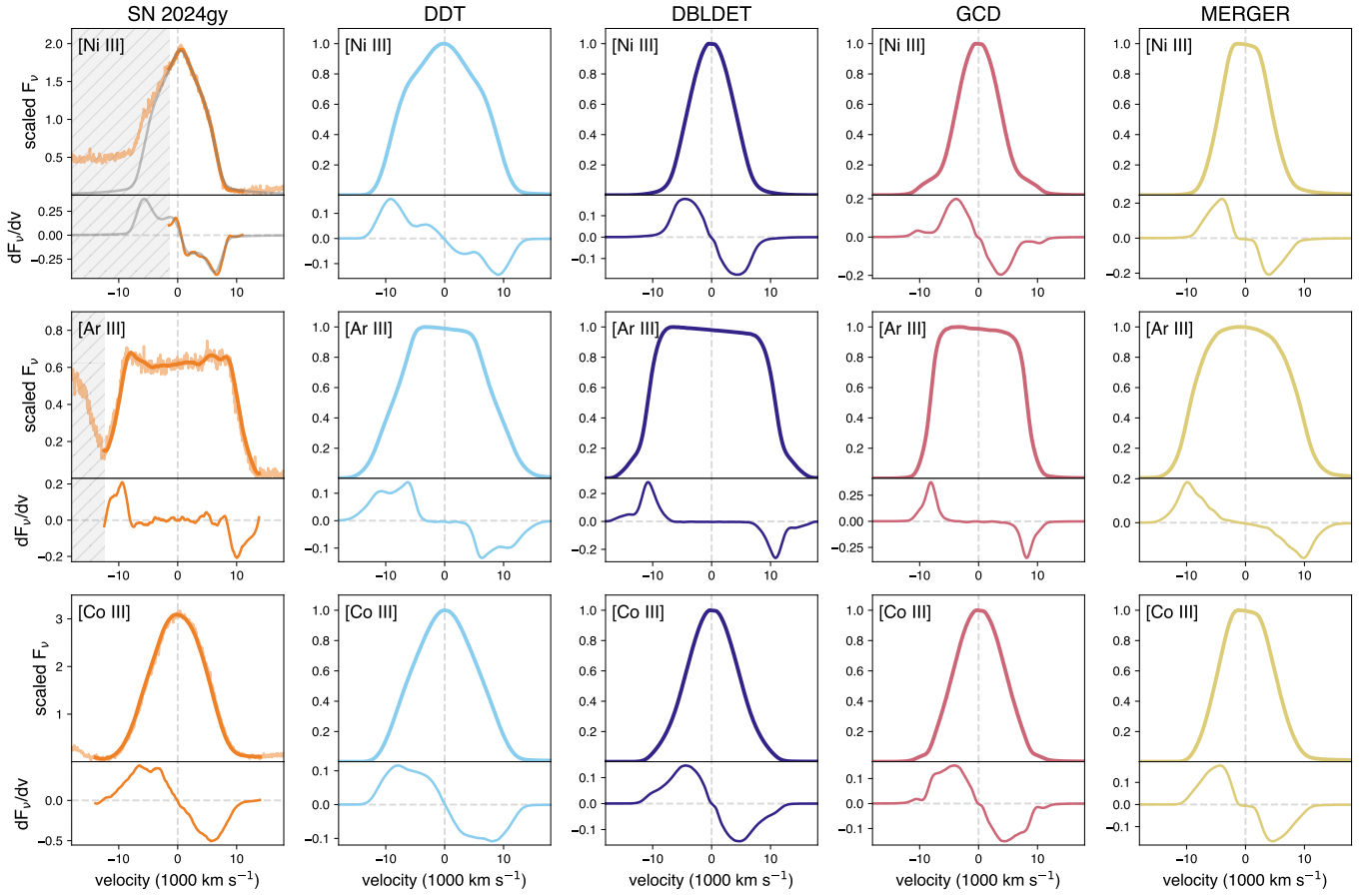


Figure 11. Line profiles (upper panels) and their derivatives (lower panels) for [Ni III] $7.35 \mu\text{m}$, [Ar III] $8.99 \mu\text{m}$, and [Co III] $11.88 \mu\text{m}$ for SN 2024gy at +144 days (orange), and the DDT (cyan), DBLDET (green), gravitationally confined detonation (GCD; pink), and MERGER (yellow) models from S. Blondin et al. (2023). For SN 2024gy, the data are shown in light orange, the smoothed data in dark orange, our fit to the [Ni III] profile in gray, and regions contaminated by line overlap in hatched light gray. The derivative morphologies of SN 2024gy are most similar to those of the DDT model. Owing to the 1D nature of CMFGEN, the model line profiles are symmetric about zero velocity, with a slight blueward tilt because of relativistic effects (S. Blondin et al. 2023).

confined to a smaller velocity range than in the model (Figure 11, middle row). In both data and model, the profile shows a peak at the inner-shell edge, followed by a weaker shoulder that drops off. The extent of the observed [Ar III] shell actually more closely matches the DBLDET model, which places Ar at higher velocities, although the derivative shape of the wings differs. This suggests that some aspects of the Ar distribution may be captured better by certain double-detonation realizations.

The [Co III] $11.88 \mu\text{m}$ profile in SN 2024gy is faintly double peaked, with a notch on the red side and a slight inner shoulder on the blue side (Figure 11, bottom row). The DDT model predicts an intermediate derivative shape between these two observed sides. The DBLDET and GCD models also show some similarity here, indicating that the distribution of radioactive material between models may be more similar and this line less discriminatory.

Taken together, the line morphologies of SN 2024gy—particularly the broken-slope [Ni III] profile—most closely resemble those of the DDT model. However, the observed [Ar III] extent and, to some degree, the [Co III] profile bear similarities to the DBLDET model. Since we consider only one realization of each scenario, further exploration of a broader landscape of models may reproduce these features more fully. We therefore conclude that the overall evidence favors a DDT origin for SN 2024gy, but recommend more

detailed modeling for confirmation. In Section 7, we further discuss implications for explosion mechanisms.

5.2.2. SN 2022xkq, SN 2022aaiq, and SN 2021aefx

SN 2022xkq has a sufficiently high S/N for derivative analysis (see Appendix C). Its MIR [Ni II] and [Ni III] profiles are single component and significantly narrower than those of normal SNe Ia, though broader than the narrow [Ni II] core seen in SN 2024gy and SN 2022aaiq. The [Ni III] derivative most closely resembles the DBLDET morphology (albeit at a smaller velocity width), while [Ar III] shows features more consistent with the DDT, including hints of an inner peak and outer shoulder. In contrast, the [Co III] profile exhibits sharper, more triangular derivatives reminiscent of MERGER models. Taken together, SN 2022xkq shows mixed morphological signatures across Ni, Ar, and Co lines and does not appear consistent with any of the models we investigated, and it is markedly different from SN 2024gy. We therefore regard its origin as inconclusive, consistent with the conclusion of J. Pearson et al. (2024) that no existing explosion model fully explains its optical photometric and spectroscopic dataset.

SN 2022aaiq and SN 2021aefx provide additional context (see Appendix C for full derivative comparisons). The lower S/N of SN 2022aaiq limits robust conclusions, though the presence of a narrow [Ni II] component similar to that of SN 2024gy may indicate a related origin, potentially viewed

Table 1
Measured Stable Ni Fluxes and Derived Quantities

SN	Distance (Mpc)	Phase (days)	F_{Ni} ($\text{erg s}^{-1} \text{cm}^{-2}$)	L_{Ni} (erg s^{-1})	$L_{\text{Ni}}(+130 \text{ days})$ (erg s^{-1})
SN 2024gy	17.2 ± 0.9	+144	$(9.4 \pm 0.5) \times 10^{-14}$	$(3.3 \pm 0.4) \times 10^{39}$	$\sim 4.1 \times 10^{39}$
SN 2022xkq	31 ± 2	+114	$(5.8 \pm 0.9) \times 10^{-15}$	$(6.7 \pm 1.3) \times 10^{38}$	$\sim 5.4 \times 10^{38}$

Note. Luminosities are computed using the adopted distances listed below.

from a different angle. SN 2021aefx, observed at a later phase (+418 days), exhibits [Ni III] and [Co III] derivative structures broadly consistent with the DDT model, though with some differences in the [Ar III] morphology that may reflect phase-dependent visibility of outer ejecta. This interpretation is consistent with J. M. DerKacy et al. (2023) and C. Ashall et al. (2024), who also suggest a DDT origin for SN 2021aefx.

5.3. Stable Ni Luminosities and Mass Estimates

S. Blondin et al. (2023) showed that the total Ni luminosity (integrated over the range $0.3\text{--}30 \mu\text{m}$ at ~ 270 days postexplosion) correlates tightly with the stable Ni mass across a wide range of explosion models (see their Figure 13). We use this relation to estimate the relative stable Ni production for SN 2024gy and SN 2022xkq.

Before proceeding, we emphasize several limitations. The DDT points shown in Figure 13 of S. Blondin et al. (2023) do not represent seven independent explosion models, but rather one 3D model reconstructed in 1D along multiple viewing directions. These nonspherically averaged realizations were designed to probe asymmetry effects (S. Blondin et al. 2023) and may not represent fully self-consistent explosion models. As a result, the Ni luminosity–mass relation is model dependent, and we therefore use the roughly linear relationship only in a comparative sense. Future work should investigate this relationship and its application to observations in more systematic detail.

Using the optical, NIR, and MIR line fits from Section 4, we integrate the observed [Ni I] (negligible contribution), [Ni II], [Ni III], and [Ni IV] emission to obtain total stable Ni fluxes. The measured fluxes and derived luminosities are given in Table 1.

For SN 2024gy, we estimate the total Ni flux at +144 days to be $(9.4 \pm 0.5) \times 10^{-14}$, with [Ni II] 7378 Å and [Ni III] $7.35 \mu\text{m}$ being the dominant contributors. For SN 2022xkq, we estimate the total Ni flux at +114 days to be $(5.7 \pm 0.9) \times 10^{-15} \text{erg s}^{-1} \text{cm}^{-2}$, using the optically thin ratio between [Ni II] $\lambda 7378$ and $1.94 \mu\text{m}$ of 5.67 to account for missing NIR coverage (other NIR Ni lines contribute $<3\%$ in SN 2024gy, so we neglect them in SN 2022xkq).

Using the adopted distances (Table 1, from our BayeSN fits, and J. Pearson et al. 2024), we compute total Ni luminosities at the observed phases. To adjust for the phase difference, we extrapolate the luminosities to a common phase of +130 days, using a late-time decline rate of 1.5 mag per 100 days for both objects. We consider a range of plausible late-time decline rates ($\sim 1.2\text{--}1.8$ mag per 100 days), informed by the objects themselves and by similar events in the literature (e.g., E. Cappellaro et al. 1997; J. C. Lair et al. 2006; G. Leloudas et al. 2009; O. Graur et al. 2020) and find that reasonable choices within this range do not significantly alter the qualitative comparison between the two objects. The resulting

Ni luminosities at +130 days are $\sim 4.1 \times 10^{39} \text{erg s}^{-1}$ for SN 2024gy and $\sim 5.4 \times 10^{38} \text{erg s}^{-1}$ for SN 2022xkq.

Comparing SN 2024gy and SN 2022xkq at the extrapolated common phase of +130 days, we find that the stable Ni emission in SN 2024gy is 5–10 times more luminous than in SN 2022xkq. Despite significant systematic uncertainties in the absolute values, the tight luminosity–mass correlation for stable Ni ensures a robust relative comparison: SN 2024gy produced substantially more stable Ni than SN 2022xkq. Combined with the low ^{56}Ni mass ($0.22 \pm 0.03 M_{\odot}$) inferred by J. Pearson et al. (2024), the small stable Ni yield of SN 2022xkq disfavors the suggested high-density DDT origin (J. M. DerKacy et al. 2024) and instead may favor a sub- M_{Ch} explosion scenario. The origin of SN 2022xkq is further discussed in Section 7.4.

6. Radiative-transfer Experiments

To explore the origin of the narrow [Ni II] cores, we perform controlled radiative-transfer experiments using 1D non-LTE calculations with CMFGEN (D. J. Hillier & L. Dessart 2012) applied to spherically averaged DDT models from I. R. Seitenzahl et al. (2013), following S. Blondin et al. (2023) and L. A. Kwok et al. (2025). These calculations are not intended to be fully self-consistent. Rather, they are designed to test how specific modifications to the inner ejecta structure affect the emergent nebular line profile.

Several limitations must be kept in mind. The underlying explosion models are 3D simulations that have been spherically averaged prior to 1D radiative-transfer calculations. As a result, the calculations do not capture intrinsic asymmetries present in the original 3D models. In addition, 1D nebular radiative-transfer calculations are known to exhibit systematic ionization discrepancies, often producing spectra that are more highly ionized than typically observed (e.g., L. J. Shingles et al. 2022; S. Blondin et al. 2023). These discrepancies primarily affect relative line strengths but have a smaller impact on velocity-space morphology, which is the primary diagnostic considered here.

Based on results from Section 5 suggesting a DDT origin for SN 2024gy, we perform our radiative-transfer experiments on the N100_ddt model and its lower and higher central density variants (N100L_ddt and N100H_ddt; I. R. Seitenzahl et al. 2013), available on the Heidelberg Supernova Model Archive⁵² (M. Kromer et al. 2017). We note, however, that the qualitative result of the experiments described below—that enhancing the stable Ni abundance at the lowest velocities produces a narrow [Ni II] core—is not specific to these particular DDT models. Any explosion model with a centrally concentrated stable Ni distribution, with energy deposited from radioactive decay, would be anticipated to exhibit similar

⁵² <https://hesma.h-its.org>

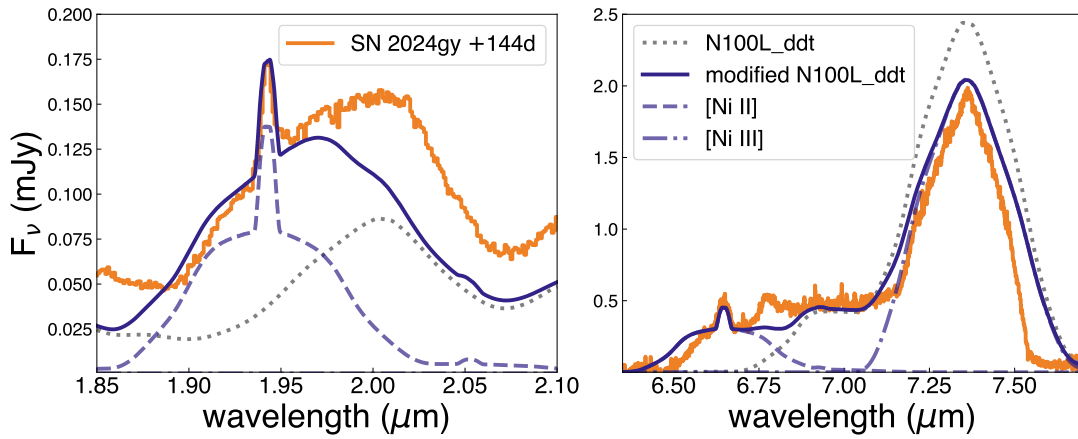


Figure 12. SN 2024gy at +144 days (~ 165 days postexplosion; orange) compared to our radiative-transfer N100L_ddt model (dotted gray) and our modified N100L_ddt model (solid indigo) at 165 days postexplosion. In our modified N100L_ddt model, we artificially adjust the [Ni II] and [Ni III] ion populations to match the observed [Ni II]/[Ni III] line strength ratio and increase the abundance of ^{58}Ni in the innermost $v < 1000 \text{ km s}^{-1}$ by $10^{-3} M_{\odot}$ to match the strength of the narrow feature in the [Ni II] 1.94 and 6.64 μm lines. The individual contributions of [Ni II] and [Ni III] to the composite features are shown in dashed indigo and dotted-dashed indigo, respectively. The model lines have been redshifted by 500 km s^{-1} to match the observed offset in SN 2024gy.

qualitative morphological behavior, although the quantitative details would depend on the underlying density and abundance structure.

In the DDT models from I. R. Seitenzahl et al. (2013), the number of ignition kernels sets the strength of the deflagration phase: fewer kernels yield less preexpansion, higher central densities, and a higher abundance of ^{56}Ni while stable Ni yields remain similar. These differences in burning strength produce distinct element and isotope distributions (see Figure 8 of I. R. Seitenzahl et al. 2013) that imprint directly on nebular line profiles. Among them, the N100 model shows the most prominent broken-slope morphology in [Ni III] 7.35 μm (Figure 11), while the lower and higher central density variants (N100L_ddt and N100H_ddt) display subtler versions. The N100L_ddt case produces narrower lines, closer to the [Ni III] widths we observe, and retains a slope break. We therefore adopt this model for further modification, calculated at 165 days postexplosion to match the first epoch of JWST observations of SN 2024gy.

We first test whether raising the density of the innermost ejecta ($v \lesssim 1000 \text{ km s}^{-1}$) can reproduce the narrow [Ni II] cores. Scaling the central density with a Gaussian of FWHM $\approx 1000 \text{ km s}^{-1}$ to add $0.01\text{--}0.1 M_{\odot}$ enhances central emission, but in *all* IGE lines. This contradicts the data: in SN 2024gy, no comparable narrow peak is seen in [Co II] 10.52 μm , despite sufficient sensitivity to detect one. Pure density enhancement therefore fails to explain the observations, unless the core is composed almost entirely of stable Ni, and not radioactive Co.

We next enhance the abundance of ^{58}Ni in the innermost layers ($v < 1000 \text{ km s}^{-1}$), conserving total mass by reducing the Fe fraction. Adding $10^{-3} M_{\odot}$ of stable Ni—a factor of ~ 10 above the original $10^{-4} M_{\odot}$ present—to a region of total mass $0.006 M_{\odot}$ significantly boosts the local Ni mass fraction. However, this corresponds to only a percent-level perturbation of the total stable Ni mass in the model. Variations in ignition configuration alter the central ejecta structure and stable IGE distribution in the model suite (I. R. Seitenzahl et al. 2013), indicating that central stable Ni concentration is sensitive to ignition configuration within the DDT framework. This modification produces the desired morphology: a narrow

[Ni II] core atop a broad base, while leaving other lines unaffected, in agreement with the observed line profiles.

As shown in Figure 12, the unmodified N100L_ddt model (dotted gray) underpredicts the [Ni II] flux, consistent with the ionization discrepancy noted above (e.g., L. J. Shingles et al. 2022). To isolate the morphological effect of enhanced central stable Ni, we follow S. Blondin et al. (2022) and adjust the Ni ionization state for comparison purposes. With this adjustment, the enhanced-Ni model reproduces both the absolute strength and the relative narrow-to-broad structure of the [Ni II] 1.94 and 6.64 μm lines.

These experiments demonstrate that introducing additional stable Ni at the lowest velocities naturally produces a narrow [Ni II] core atop a broader base, while leaving other lines unaffected. The narrow [Ni II] cores in SN 2024gy and SN 2022aaq therefore point to an enhanced concentration of stable Ni in the innermost ejecta. Possible physical origins for such central Ni enhancement are discussed in Section 7.

7. Discussion

Our JWST MRS observations provide new constraints on the distribution of stable IGEs, radioactive IGEs, and IMEs in SNe Ia. The line morphologies—particularly the presence of narrow [Ni II] cores and broken-slope [Ni III] profiles—carry diagnostic information about the explosion physics. Below we interpret these results in the context of different explosion scenarios.

7.1. Interpretation of Narrow Cores

Narrow emission cores are common in nebular spectra of stripped-envelope SNe (SNe Ib/c), most notably in [O I] $\lambda\lambda 6300, 6364$. S. Taubenberger et al. (2009) attribute them to several possible geometries: (a) enhanced central density in nearly spherical ejecta; (b) an equatorial torus or disk viewed face on; or (c) clumps ejected perpendicular to the line of sight. The latter two are strongly viewing-angle dependent and would statistically produce narrow peaks substantially offset from the line center. By contrast, all three SNe Ia in our sample show narrow cores with $|v_{\text{off}}| < 1300 \text{ km s}^{-1}$, more consistent with enhanced central density in a mildly off-center ignition. The likelihood of this occurring

purely from orientation effects is low, though larger samples are needed to confirm this. By analogy with the dense O cores inferred in SNe Ib/c (K. Iwamoto et al. 2000; P. A. Mazzali et al. 2000, 2007a, b; K. Maeda et al. 2003), we find an enhanced central concentration of stable Ni to be the most compelling explanation for our SNe Ia.

The observed ionization dependence of Ni line widths supports this interpretation. In SN 2024gy at +337 days, [Ni III] lines are broader than [Ni II], which in turn are broader than the purely narrow [Ni I], consistent with recombination proceeding most efficiently in the densest central regions at a given epoch. The line morphologies also depend on energy deposition from radioactive material, predominantly ^{56}Co at these epochs. Since Co emission is strong and broadly distributed, most layers of the ejecta remain illuminated, implying that the Ni cores are not artifacts of uneven energy input.

We next consider whether the narrow Ni cores could instead arise solely from ionization effects. In SN 2024gy at +144 days, the [Ni III] $3.80\ \mu\text{m}$ line shows a weaker, flatter narrow component than [Ni II] 1.94 and $6.64\ \mu\text{m}$, hinting at stratification within the core. However, some degree of ionization stratification is expected even if the narrow feature results from an abundance enhancement. The widths of the [Ni II] narrow components remain constant in both SN 2022aaiq and SN 2024gy—an evolution spanning nearly 200 days—and in SN 2024gy the [Ni I] width matches that of [Ni II]. Ionization-driven changes would instead produce continuous temporal evolution and systematic width differences between ions as the density and temperature change. Moreover, no comparable narrow feature is seen in [Co II] despite sufficient sensitivity.

Taken together, these results indicate that ionization effects modulate line strengths and relative contributions from broad and narrow components but cannot by themselves account for the narrow cores. Their persistence across multiple ions and epochs, combined with their absence in Co, point to an intrinsic enhancement of stable Ni abundance in the innermost ejecta.

7.2. Delayed Detonation Models

In 2D and 3D DDT simulations, buoyant deflagration ashes rise through Rayleigh–Taylor (RT) instabilities, mixing outward while unburned C/O fuel flows inward. When the detonation follows, it burns the remaining fuel almost instantaneously, converting the core entirely into detonation ashes (e.g., K. Maeda et al. 2010a; I. R. Seitenzahl et al. 2013; R. Pakmor et al. 2024).

In 3D simulations, the central ejecta are therefore dominated by detonation ashes, while deflagration ashes occupy higher velocities, overlapping at intermediate regions in velocity space through rising plumes. The broken-slope morphology of [Ni III] in the DDT model (Figure 11) directly reflects this two-zone structure. One-dimensional models also produce two distinct zones, but the geometry is inverted: deflagration ashes are artificially confined to the center and surrounded by detonation ashes (K. Maeda et al. 2010a; R. Pakmor et al. 2010; S. Blondin et al. 2013). R. Pakmor et al. (2024) argue that such confinement is inherently unphysical. P. Höflich et al. (2021) calculate the deflagration phase assuming spherical symmetry, suggesting that strong magnetic fields might suppress RT instabilities and retain deflagration ashes in

the core. Whether such fields can arise self-consistently in 3D remains uncertain.

In 3D DDT models, the deflagration phase produces $\sim 15\%$ – 20% stable Ni, while the detonation phase—occurring at lower densities after expansion—produces only $\sim 5\%$ (R. Pakmor et al. 2024). The [Ni II] and [Ni III] profiles of SN 2024gy indicate that stable Ni is distributed across three regions: outer (~ 4000 – $8000\ \text{km s}^{-1}$), inner (~ 1500 – $4000\ \text{km s}^{-1}$), and a compact central core ($\lesssim 1500\ \text{km s}^{-1}$). The broken-slope [Ni III] morphology, with distinct inner and outer components, is qualitatively consistent with detonation ashes in the center and deflagration ashes farther out. However, the presence of an additional narrow core implies that the innermost layers burned at densities high enough to synthesize stable IGEs. This presents a challenge for current 3D DDT models, as it would require either (i) confinement of some deflagration ashes in the core—via an as-yet unidentified mechanism—or (ii) recompression of the core to high density prior to detonation, perhaps through pulsations or other dynamic processes.

The two-component Ni distribution inferred from the [Ni III] broken slope, together with the high inferred stable Ni mass of SN 2024gy (Section 5.3), points to a DDT origin as the most plausible scenario. The narrow cores require enhanced stable Ni in the innermost ejecta, but whether this originates from confined deflagration ashes or high-density detonation ashes remains uncertain. Current 3D simulations do not reproduce this structure, and further work is needed to test mechanisms such as suppression of RT instabilities or pulsational compression prior to detonation.

7.3. Double-detonation Models

Sub- M_{Ch} double detonations predict a distinct distribution of stable IGEs compared to near- M_{Ch} DDTs, with stable IGEs concentrated in the C/O core detonation ashes and colocated with radioactive IGEs. The resulting nebular line profiles are more nearly single-component Gaussians (Figure 11). A small amount of stable Ni may also form in the outer He-burning ashes, but these layers are at low density and unlikely to be detectable in nebular spectra.

An important distinction from M_{Ch} explosions is that sub- M_{Ch} models generally produce less total stable Ni, owing to their lower progenitor masses and consequently lower burning densities (e.g., P. Höflich et al. 2004; S. Blondin et al. 2018; K. J. Shen et al. 2018; S. Gronow et al. 2021). However, in double detonations, the initial He-shell detonation can exert additional pressure that compresses the underlying C/O core, allowing the inner regions to reach densities high enough for stable Ni synthesis (e.g., J. Morán-Fraile et al. 2024). As a result, the C/O core detonation in some double-detonation models can produce a comparable amount of stable Ni to the detonation phase of DDT models (R. Pakmor et al. 2024). The key difference is that DDTs also form stable Ni during the preceding deflagration phase, which sub- M_{Ch} explosions lack. Progenitor metallicity can further modify this outcome: higher metallicity increases the initial neutron excess, enhancing the production of stable Ni even in lower-mass WDs (F. X. Timmes et al. 2003; S. Blondin et al. 2022).

Double-degenerate scenarios in which both WDs undergo double detonation (e.g., K. J. Shen et al. 2024) could, in principle, produce two distinct Ni-rich regions, as the secondary WD detonates within the ashes of the primary. In practice, however, the secondary WD burns at much lower

densities and is not expected to synthesize significant stable Ni in the scenario from K. J. Shen et al. (2024). This scenario would also introduce an intervening layer of IMEs between the two Ni zones—contrary to our observed [Ar III] profiles in SN 2024gy, which do not show such a structure. More equal binary mass ratios would lead to more stable Ni produced in the secondary WD, but would also likely lead to bulk asymmetries (e.g., L. A. Kwok et al. 2024).

While the broken-slope [Ni III] morphology is difficult to reproduce in a double-detonation framework, a potential mechanism for producing a narrow Ni core in sub- M_{Ch} progenitors is gravitational settling of ^{22}Ne . In near- M_{Ch} WDs, a convective simmering phase homogenizes isotopes prior to explosion (S. E. Woosley et al. 2004; A. L. Piro & P. Chang 2008), but in lower-mass WDs (which lack vigorous convection), neutron-rich ^{22}Ne can gravitationally settle toward the center (L. Bildsten & D. M. Hall 2001; E. García-Berro et al. 2008). This enrichment could seed enhanced neutronization during burning and increase the yield of stable Ni in the innermost ejecta.

We cannot rule out sub- M_{Ch} double detonations, particularly if ^{22}Ne settling enhances central neutronization. However, existing sub- M_{Ch} models predict smaller stable Ni masses and lack the observed broken-slope morphology. Future 3D simulations, coupled with late-time JWST MIR spectroscopy, will be essential to distinguishing between these possibilities.

7.4. Origin of SN 2022xkq

SN 2022xkq is spectroscopically distinct from the other SNe Ia in our sample. Its [Ni II] and [Ni III] profiles are well described by single-Gaussian components with FWHM $\approx 3000 \text{ km s}^{-1}$ —narrower than the broad bases typical of normal SNe Ia, yet broader than the narrow [Ni II] cores seen in SN 2022aaiq and SN 2024gy. The line-profile derivatives do not closely resemble any of the explosion models in Figure 11. Consistent with this, J. Pearson et al. (2024) found that no existing model reproduces the full early-time optical photometric and spectroscopic dataset of SN 2022xkq. These single-component, moderately narrow Ni features, together with comparatively strong Ar emission, indicate a meaningful physical difference in the explosion mechanism relative to the brighter events.

J. M. DerKacy et al. (2024) proposed a high-central-density DDT model to explain the narrow Ni features, arguing that they require little to no central mixing. However, the deflagration phase in that model was computed in 1D (imposing spherical symmetry) and therefore cannot capture the mixing behavior expected in 3D deflagrations. This raises the possibility that the limited central mixing instead reflects detonation-dominated burning. Moreover, the model fit from J. M. DerKacy et al. (2024) is degraded when compared with the rereduced spectra: Ti lines are not clearly present, and the model predicts [Ni I] $7.51 \mu\text{m}$ emission that is not observed. The absence of this line, even at late times in SN 2024gy when [Ni I] $3.12 \mu\text{m}$ is detected, may indicate that the modeled central densities are too high.

From our analysis, combined with previous measurements by L. Li et al. (2026) and J. Pearson et al. (2024), SN 2024gy produces both more ^{56}Ni and more ^{58}Ni than SN 2022xkq. A sub- M_{Ch} origin could naturally explain the relatively narrow single-component Ni lines. However, J. Pearson et al. (2024) reported persistent carbon absorption in SN 2022xkq, which is

challenging to reconcile with standard sub- M_{Ch} models (S. Blondin et al. 2017; A. Polin et al. 2019). It should also be noted that we do not explore the full diversity of DDT models in this work, and we cannot rule out that a DDT scenario with differing conditions could explain the differences between SN 2022xkq and the brighter events.

The NIR [Ni II] $1.94 \mu\text{m}$ line provides additional context. S. Kumar et al. (2026) found strong, narrow [Ni II] emission in subluminescent SNe Ia and suggested it might be evidence for DDTs of near- M_{Ch} WDs. Their detection method, however, favors narrower features that rise above blended neighboring lines. Our JWST/MIRI data reveal that [Ni II] emission can include both broad and narrow components, suggesting their method may overlook objects with substantial amounts of stable Ni, but no strong narrow component, such as SN 2021aefx. In subluminescent events such as SN 2022xkq, the lower ejecta velocities and ionization state likely enhance the visibility of [Ni II] by reducing blending and allowing it to dominate cooling over [Ni III]. The faster transition to optically thin conditions may further isolate the line.

Taken together, these observations suggest that SN 2022xkq occupies a physically distinct regime from the DDT-like SNe 2022aaiq and 2024gy. We suggest that double-detonation models remain potentially viable—especially those incorporating ^{22}Ne settling, which could enhance central neutronization and produce the observed narrower, stable Ni lines without a broader base component. Further multidimensional modeling and time-dependent radiative-transfer calculations will be essential to determine whether such sub- M_{Ch} explosions can fully reproduce the Ni morphology and luminosity of SN 2022xkq.

7.5. Asymmetries

The small sample of JWST/MRS observations of SNe Ia analyzed in this work reveals that, while the main MIR lines are broadly similar, even normal SNe Ia exhibit notable variations. One key difference is the presence of asymmetries in several line profiles, especially [Ar III] $8.99 \mu\text{m}$ and [Co III] $11.88 \mu\text{m}$, reflecting intrinsic asymmetries in the ejecta. Our line-inversion analysis in Section 5 assumes spherical symmetry—an inherently unphysical approximation for a 3D explosion, but also a good place to start. In addition to the lower S/N of the SN 2022aaiq MRS data, such asymmetry may explain why the analysis performs well for SN 2024gy but yields a less coherent result for SN 2022aaiq.

The line profiles in SN 2022aaiq are less symmetric than those in SN 2024gy or SN 2021aefx, most clearly in [Ar III] $8.99 \mu\text{m}$, which appears distinctly slanted in SN 2022aaiq but comparatively flat in SN 2024gy. Even in SN 2024gy, the [Co III] $11.88 \mu\text{m}$ emissivity and derivative profiles deviate from perfect symmetry. J. M. DerKacy et al. (2023) demonstrated that similar asymmetries in SN 2021aefx can arise from viewing-angle effects in an off-center ignition. The [Ar III] $8.99 \mu\text{m}$ line in SN 2021aefx slopes upward toward the red, whereas it slopes to the blue in SN 2022aaiq and is flatter in SN 2024gy. Such variation is consistent with a population of off-center explosions viewed from different orientations. SN 2022aaiq may therefore represent a more intrinsically asymmetric event, or we may simply view SN 2024gy from a direction where it appears more symmetric. Asymmetries may also become more pronounced at later

times, as seen in SN 2024gy where the [Ar III] 8.99 μm line is more slanted in the +337 days observation.

Recently, J. M. Pollin et al. (2026) computed multi-dimensional models and nebular-phase spectra for the dynamically driven double-degenerate double-detonation (D^6) model. They found that multidimensional effects significantly influence the ionization, velocity, and width of emission features, producing distinct line-profile morphologies depending on viewing angle. This underscores the need for further 3D modeling and radiative-transfer postprocessing across multiple explosion channels. Our comparison of SN 2024gy with angle-averaged 3D model outputs demonstrates that assuming spherical symmetry can still provide valuable insights, but improved approximations that better reflect fully 3D geometries will be essential for interpreting the asymmetries observed in JWST spectra.

While asymmetries may arise from the explosions themselves (i.e., off-center ignition), K. Simotas et al. (2025) showed that certain asymmetric signatures detectable with JWST/MRS could instead result from wakes formed as the ejecta encounter and flow around a companion star. The predicted line-profile distortions from such wakes depend strongly on the viewing angle and should appear consistently across lines from multiple ions. We exclude this scenario as the origin of the narrow [Ni II] cores in SN 2022aaq and SN 2024gy: no corresponding features are seen in the Ar and Co lines, and the narrow Ni peaks are centered in both objects despite different inferred viewing angles from the [Ar III] lines. Nonetheless, companion-induced wakes remain an intriguing observational signature to test in future JWST/MRS studies of SNe Ia.

8. Summary and Conclusions

We have presented medium-resolution JWST NIR + MIR spectroscopy of the normal SNe Ia 2022aaq (+125 and +207 days) and 2024gy (+144 and +337 days), which reveal novel narrow-core ($v_{\text{FWHM}} < 1500 \text{ km s}^{-1}$) emission in both the NIR and MIR [Ni II] lines. The relative isolation of the MIR [Ni II] 6.64 μm line shows that this narrow feature sits atop a broader base of emission. A later epoch of SN 2024gy further reveals [Ni I] 3.12 μm emission composed solely of this narrow component. The high S/N and spectral resolution of the SN 2024gy data also reveal a broken-slope line profile in [Ni III], indicating distinct inner and outer regions of stable IGEs.

The emissivity and derivative profiles we derive for SN 2024gy show close agreement with predictions from DDT models, though the narrow-core Ni component remains challenging to explain with current models. We summarize several new observational signatures from SN 2022aaq and SN 2024gy.

1. The narrow-core + broad-base [Ni II] structure demonstrates that stable Ni extends to intermediate velocities, while the innermost $v < 1500 \text{ km s}^{-1}$ exhibits a concentrated enhancement of stable Ni mass.
2. The narrow-core Ni peak is blueshifted by $\sim 1000 \text{ km s}^{-1}$ in SN 2022aaq and redshifted by $\sim 500 \text{ km s}^{-1}$ in SN 2024gy. These small offsets suggest mildly off-center ignition, as expected for DDT explosions (e.g., K. Maeda et al. 2010b,a; J. M. DerKacy et al.

2023, 2024). The direction of the offset likely depends on the viewing angle.

3. The derived emissivity and derivative profiles for SN 2024gy reveal three distinct Ni-emitting zones: an innermost core ($\lesssim 1500 \text{ km s}^{-1}$), an inner region ($\sim 1500\text{--}3000 \text{ km s}^{-1}$), and an outer region ($\sim 3000\text{--}8000 \text{ km s}^{-1}$). In the [Ni III] 7.35 μm line, these inner and outer regions appear as a “broken-slope” morphology, matching the separation between detonation and deflagration ashes predicted by DDT models. The [Ar III] 8.99 μm and [Co III] 11.88 μm lines, albeit more tentatively, show signatures consistent with this interpretation.
4. The [Co III] 11.88 μm emissivity profile, tracing radioactive ^{56}Co decay, differs from the Ni profiles: it shows less emission in the core and more at high velocities.
5. Only the innermost, stable Ni-dominated regions—traced primarily by [Ni II] and, at later epochs, [Ni I]—show a narrow enhancement. The [Ni III] and [Ni IV] lines, which trace less-dense outer regions, lack strong narrow components. No narrow cores are detected in [Co II] or [Co III], which trace radioactive material. Radiative-transfer models reproduce the observed narrow [Ni II] component by artificially increasing the inner Ni abundance by $10^{-3} M_{\odot}$ within $v < 1000 \text{ km s}^{-1}$, roughly a tenfold enhancement.
6. The [Ar III] 8.99 μm and [Co III] 11.88 μm lines exhibit asymmetries, differing in slope and skew between SN 2022aaq, SN 2024gy, and SN 2021aefx. These variations are consistent with off-center ignition and viewing-angle effects predicted for DDT explosions, suggesting that even normal SNe Ia can display moderate large-scale asymmetries in their ejecta.

Overall, we favor a near- M_{Ch} progenitor undergoing a DDT with mild off-center ignition for both SN 2022aaq and SN 2024gy. The narrow [Ni II] cores trace enhanced stable Ni in the innermost ejecta, while the broken-slope [Ni III] profiles record the separation of deflagration and detonation ashes. Ionization effects alone likely cannot reproduce the persistent narrow component, implying a compositional concentration of stable Ni at low velocities. The narrow-core Ni remains a key challenge for current 3D DDT models, requiring either confinement of deflagration ashes or recompression of the core before detonation. Although we cannot entirely rule out sub- M_{Ch} origins, our findings most strongly support near- M_{Ch} DDTs for SN 2024gy, and more tentatively for SN 2022aaq and SN 2021aefx.

The X-ray spectra of some SN remnants (SNRs) thought to be of SNe Ia origin have also provided interesting constraints on the mass of the exploding WDs. Notably, H. Yamaguchi et al. (2015) found that the Ni/Fe and Mn/Fe mass ratios inferred from the X-ray spectrum of SNR 3C397 effectively rule out a sub- M_{Ch} origin (see also V. Mehta et al. 2024). Using a more indirect method based on the Ca/S mass ratio, which is sensitive to the level of neutronization in the SN ejecta, H. Martínez-Rodríguez et al. (2017) found independent evidence for high neutronization in three SNRs: 3C397 and G337.2-0.7 in the Milky Way, and N103 in the Large Magellanic Cloud. This evidence for high neutronization in the relatively small sample of X-ray bright SNRs in the Milky Way and the Magellanic Clouds suggests that there is a near- M_{Ch} channel to SNe Ia, and that this channel makes a

significant contribution to the SN Ia rate in star-forming galaxies.

We encourage high S/N observations between ~ 100 and 200 days postpeak in the optical and NIR to search for narrow [Ni II] components. A weak narrow feature in [Ni II] 7378 Å is detected in our highest S/N Keck/LRIS spectrum of SN 2024gy, and S. Kumar et al. (2026) reported a similar feature in SN 2011iy in the NIR. Because JWST samples will be comparatively limited, establishing the frequency of narrow-core [Ni II] emission should also be pursued by ground-based facilities.

The origin of the subluminal SN 2022xkq remains uncertain. Additional modeling—including sub- M_{Ch} double-detonation scenarios—should be explored to understand its narrow, single-component Ni lines and the implications for the SN 1991bg-like subclass.

This analysis demonstrates that detailed mapping of stable Ni emission is possible only with the medium-resolution modes of JWST/MIRI (Appendix B). Ni lines in the optical and NIR are too blended, while low-resolution JWST modes, though efficient for large samples, wash out diagnostic structure. MRS observations are essential for detailed case studies of the nearest SNe Ia. Expanding this sample will provide critical tests of explosion models and progenitor masses in shaping SNe Ia diversity.

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Facilities: JWST (NIRSpec/MIRI), Keck:I (LRIS), Keck:II (NIRES), Keck:II (DEIMOS, ESI), LCOGT/GSP.

Software: Astropy (Astropy Collaboration et al. 2013, 2018, 2022), Matplotlib (J. D. Hunter 2007), NumPy (T. E. Oliphant 2006), PyRAF (Science Software Branch at STScI 2012), PySALT (S. M. Crawford et al. 2010), dust extinction (K. Gordon et al. 2022), jwst (H. Bushouse et al. 2022), YSE-PZ (D. A. Coulter et al. 2022, 2023), CMFGEN (D. J. Hillier & L. Dessart 2012), ChatGPT (OpenAI 2025).

Appendix A

Additional Line Comparisons and Fits

A.1. All Optical, NIR, and MIR Stable Ni Lines

Figure 13 shows all NIR and MIR Ni lines in SN 2024gy, SN 2022aaiq, SN 2021aefx, and SN 2022xkq. All Ni lines peak at a consistent velocity across a large wavelength range. This agreement in velocity confirms that the narrow spike in the NIR spectra of SN 2022aaiq and SN 2024gy is [Ni II] 1.94 μm .

A.2. Fitting [Ni II] and [Ni III] in SN 2022aaiq and SN 2024gy

In Figure 5, the unblended [Ni II] wing reveals a narrow-core profile: a sharp central peak atop a broader base. The sharp narrow peak is better modeled by a Lorentzian than a Gaussian, while the base shows a bend near 3000 km s^{-1} and steeper wings than a Gaussian, empirically motivating the use of a super-Gaussian. Thus, [Ni II] is fit with a Lorentzian + super-Gaussian function,

$$f(v) = A [\text{Lorentzian}(v) + R \text{ Super-Gaussian}(v)], \quad (\text{A1})$$

where

$$\text{Lorentzian}(v) = \frac{1}{1 + \left(\frac{2(v - v_L)}{\text{FWHM}_L}\right)^2}, \quad (\text{A2})$$

$$\text{Super-Gaussian}(v) = \exp \left[- \left(\frac{2(\ln 2)^{1/(2n)}(v - v_{\text{SG}})}{\text{FWHM}_{\text{SG}}} \right)^{2n} \right]. \quad (\text{A3})$$

Here, A is the line amplitude, R is the Lorentzian-to-super-Gaussian ratio, v_L and v_{SG} are velocity offsets, FWHM_L and FWHM_{SG} are the FWHM intensity, and n is the order of the super-Gaussian, which controls flatness near the peak and steepness of the falloff. This six-parameter fit captures the sharp core and broad wings, and is flexible enough for both [Ni II] and [Ni III].

The [Ni III] lines show a less pronounced core and a more pronounced bend around 4000 km s^{-1} (Figure 5, right panel). We refer to this bend in the line profile (seen clearly in the derivative in Section 5) as a “broken-slope” profile. At +144 days, the red side of the [Ni IV] 8.40 μm line in SN 2024gy also shows a broken slope (Figure 6).

In our fits, we constrain [Ar II] 6.98 μm using the nearly isolated [Ar III] 8.98 μm line, which is well fit by a slanted flat top with Gaussian wings. Allowing $\pm 500 \text{ km s}^{-1}$ bounds around the parameters of this fit for [Ar II], and adopting Lorentzian + super-Gaussian profiles for Ni, we fit the full 6–8 μm complex in both SNe. Fit results are shown in Figure 6 and Figure 5.

The sharp uptick on the blue edge of [Ar II] is likely overfit; a similar feature appears in [Ar III] 8.99 μm and [Ca IV] 3.21 μm , suggesting ejecta inhomogeneity or asymmetry. Offsets between Lorentzian and super-Gaussian centers are allowed but remain small (Figure 5, left panel). Allowing such offsets and tilted flattops implicitly assumes axisymmetry along the line of sight.

We extend these fits to the NIR. Using MIR-derived parameters as bounds ($\pm 500 \text{ km s}^{-1}$ for [Ni II] narrow components, $\pm 1000 \text{ km s}^{-1}$ for others), we fit [Ni II] 1.94 μm and [Ni III] 3.80 μm with the same two-component profiles (Figure 5). Emission from the same ion should arise from the same ejecta regions, making these constraints physically well motivated. This is especially important for [Ni II] 1.94 μm , where blending with [Co III] and [Fe II] lines complicates the fit. Without MIR constraints, the narrow [Ni II] component is still well constrained, but the broad base becomes highly sensitive to bounds and blending, showing that the NIR alone cannot robustly constrain it. At much later phases (>400 days), the [Ni II] 1.94 μm line becomes more isolated (S. Dhawan et al. 2018), but it is also much fainter and therefore challenging to observe.

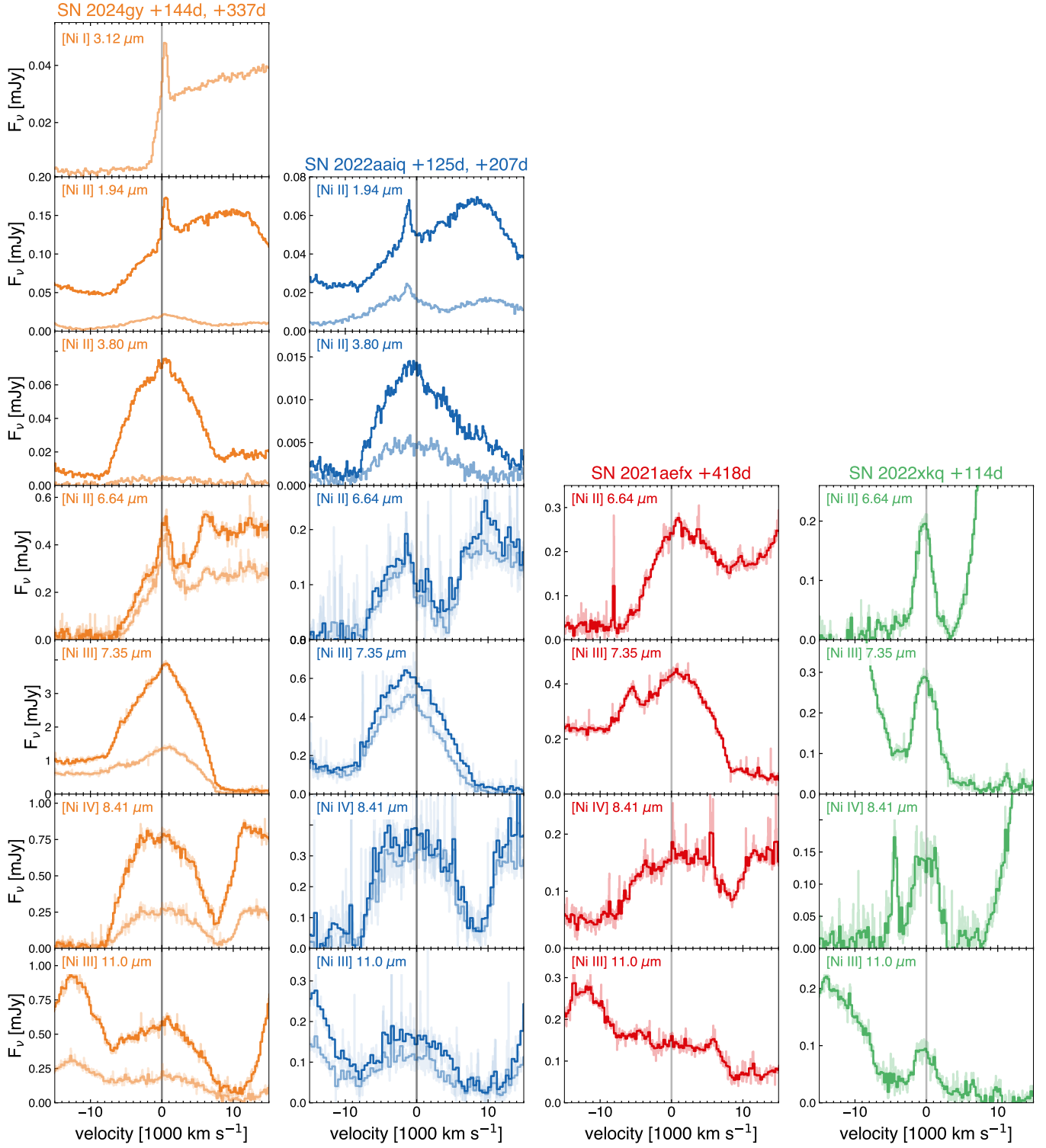


Figure 13. All prominent Ni lines in the JWST data of the normal SN 2024gy at +144 days (orange) and +337 days (light orange), SN 2022aaiq at +125 days (blue) and +207 days (light blue), and SN 2021aefx at +418 days (red), and the subluminal SN 2022xkq at +114 days (green). For each SN, the velocity of the peak agrees for all lines.

The [Ni III] 3.80 μm line, newly accessible with NIR-Spec, is well isolated (Figure 5, right panel). It shows a distinct narrow peak like [Ni II], though with smaller relative strength. Unlike many of the strong MIR lines, this transition does not terminate at the ground state; instead, it connects an excited upper level to a lower excited

state. This may explain why its narrow component appears more prominent than in [Ni III] 7.35 μm . By the second epoch in both SN 2024gy and SN 2022aaiq, the line weakens and flattens (see Figure 13, lower opacity lines), so we do not fit the [Ni III] 3.80 μm line at these epochs in Figure 5 (right panel).

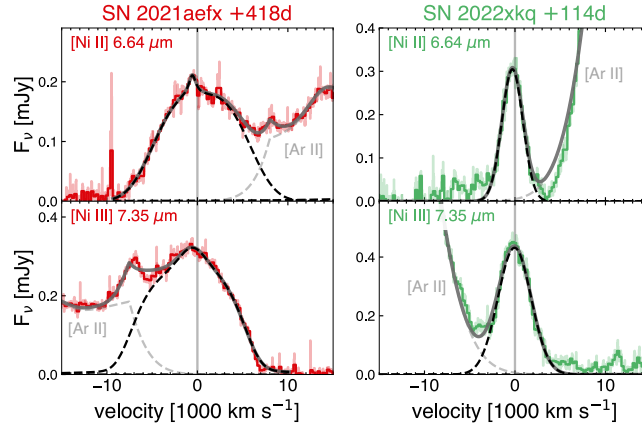


Figure 14. Line-profile fits for [Ni II] 6.64 μm and [Ni III] 7.35 μm in SN 2021aefx (red) at +418 days and SN 2022xkq (green) at +114 days. The contribution from Ni is shown in dashed black, and contributions from other nearby lines are in dashed gray. The composite fit is displayed in solid gray. The SN 2021aefx Ni lines display a similar shape to SN 2024gy and SN 2022aaiq, but have less contribution from the narrower components. The SN 2022xkq Ni lines are well fit by a simple Gaussian.

A.3. Fitting [Ni II] and [Ni III] in SN 2021aefx and SN 2022xkq

For SN 2021aefx, our fits reproduce the overall [Ni II] and [Ni III] line profiles. We marginally detect a weak [Ni II] narrow core, and the two-component structure in [Ni III] is only weakly developed, with a bend near $\sim 5000 \text{ km s}^{-1}$ (Figure 14). The blue wing of [Ar III] 8.99 μm appears to decline more steeply than permitted by the adopted profile shape, so the blue wing of [Ar II] 6.98 μm likely does as well.

To reproduce the central excess in [Ar II] 6.98 μm , we include an additional component modeled as a slanted flat-topped profile with parabolic wings plus a central Gaussian (Figure 6).

For SN 2022xkq, the [Ni II] 6.64 μm and [Ni III] 7.35 μm lines are well described by single Gaussians, with [Ni II] slightly narrower than [Ni III] (Figure 14). The narrow width of the [Ar II] feature allows clean separation of the Ni and Ar contributions. Fit parameters are given in Table 2.

Table 2
Best-fit MIR Line-profile Parameters for Each Ion from Figure 8

Ion	Profile	Outer		Inner		v_{inner}	v_c	Ratio ($A_{\text{out}}/A_{\text{in}}$)	n
		FWHM	v_{off}	FWHM	v_{off}				
SN 2024gy +144 d									
[Ni II]	L + SG ^a	9.01 ± 1.24	0.75 ± 0.24	1.57 ± 0.24	0.77 ± 0.03	...	...	1.44 ± 0.74	3.27 ± 0.92
[Ni III]	L + SG ^a	11.82 ± 0.06	0.54 ± 0.02	5.98 ± 0.08	0.74 ± 0.03	...	...	1.20 ± 0.04	5.56 ± 0.13
[Ni IV]	L + SG ^a	11.75 ± 0.07	0.11 ± 0.02	7.68 ± 0.33	0.40 ± 0.20	...	...	3.00 ± 0.01	5.38 ± 0.14
[Co II]	Gaussian	7.41 ± 0.08	1.04 ± 0.02	...	...	...	...	...	...
[Co III]	Gaussian	10.48 ± 0.01	0.57 ± 0.01	...	...	...	...	...	...
[Co IV]	Gaussian	13.30 ± 0.14	0.15 ± 0.03	...	...	...	...	...	...
[Ar II]	Flat top	20.80 ± 0.72	0.14 ± 0.11	...	...	9.30 ± 0.06	0.04 ± 0.02	...	...
[Ar III]	Flat top	20.88 ± 0.09	0.06 ± 0.02	...	...	9.07 ± 0.03	0.05 ± 0.01	...	...
SN 2022aaq +125 d									
[Ni II]	Gaussian	6.90 ± 0.06	−1.89 ± 0.02	0.83 ± 0.17 ^b	−1.17 ± 0.05 ^b	...	...	...	...
[Ni III]	L + SG ^a	12.16 ± 0.05	−0.11 ± 0.01	6.76 ± 0.07	−0.83 ± 0.03	...	...	1.16 ± 0.04	4.33 ± 0.08
[Ni IV]	Gaussian	11.32 ± 0.06	−0.44 ± 0.03	...	...	...	...	...	...
[Co II]	Gaussian	5.73 ± 0.04	−1.79 ± 0.01	...	...	...	...	...	...
[Co III]	Gaussian	10.83 ± 0.01	−0.57 ± 0.01	...	...	...	...	...	...
[Ar II]	Flat top	20.61 ± 1.50	0.60 ± 0.01	...	...	9.51 ± 0.06	−0.65 ± 0.20	...	...
[Ar III]	Flat top	19.52 ± 0.24	0.84 ± 0.03	...	...	8.56 ± 0.09	−0.50 ± 0.03	...	...
SN 2021aefx +418 d									
[Ni II]	Gaussian	9.45 ± 0.38	1.14 ± 0.24	...	...	...	...	...	...
[Ni III]	Gaussian	12.34 ± 0.14	0.85 ± 0.06	...	...	...	...	...	...
[Ni IV]	Gaussian	14.00 ± 1.50	0.14 ± 0.07	...	...	...	...	...	...
[Co II]	Gaussian	7.32 ± 0.08	1.09 ± 0.01	...	...	...	...	...	...
[Co III]	Gaussian	11.14 ± 0.03	0.74 ± 0.01	...	...	...	...	...	...
[Ar II]	FT + G ^c	20.39 ± 0.51	0.63 ± 0.31	8.00 ± 1.50	0.16 ± 0.06	9.54 ± 0.31	0.50 ± 0.20	1.33 ± 0.27	...
[Ar III]	Flat top	21.20 ± 0.27	0.69 ± 0.03	...	...	8.89 ± 0.05	0.45 ± 0.02	...	...
SN 2022xkq +114 d									
[Ni II]	Gaussian	2.74 ± 0.06	−0.29 ± 0.02	...	...	...	...	...	...
[Ni III]	Gaussian	4.32 ± 0.07	−0.06 ± 0.02	...	...	...	...	...	...
[Ni IV]	Gaussian	4.90 ± 0.15	−0.44 ± 0.05	...	...	...	...	...	...
[Co II]	Gaussian	8.48 ± 0.05	−0.09 ± 0.02	...	...	...	...	...	...
[Co III]	Flat top	8.60 ± 0.02	−0.24 ± 0.01	...	...	2.12 ± 0.03	0.20 ± 0.02	...	...
[Co IV]	Gaussian	7.24 ± 0.12	−0.27 ± 0.05	...	...	...	...	...	...
[Ar II]	Flat top	15.72 ± 0.06	0.04 ± 0.01	...	...	6.00 ± 0.03	−0.14 ± 0.01	...	...
[Ar III]	Flat top	15.61 ± 0.05	0.00 ± 0.01	...	...	5.56 ± 0.03	−0.01 ± 0.01	...	...

Notes. All velocity quantities are given in units of 1000 km s^{-1} . Columns that are not relevant to a given profile type are marked with an ellipsis. The reported uncertainties may underestimate the true uncertainties, as they do not include potential systematic effects (e.g., peculiar velocities within the host galaxy) or additional sources of uncertainty in the fitting procedure. The v_c parameter, which controls the slope of the flat top, represents the velocity offset of the plateau with respect to v_{off} while v_{inner} represents the radius of the inner edge of the shell.

^a Lorentzian + super-Gaussian (Equation (A1)).

^b Parameter is from the narrow core of the NIR [Ni II] $1.94 \mu\text{m}$ line.

^c Flat top + Gaussian.

Appendix B Impact of Spectral Resolution

Medium-resolution JWST modes (NIRSpec gratings and MIRI/MRS; $R \approx 1000\text{--}3000$) provide an order-of-magnitude increase in resolving power compared to low-resolution modes (NIRSpec/PRISM and MIRI/LRS; $R \approx 40\text{--}300$). This increased resolution is essential for resolving low-velocity features, such as the narrow [Ni II] emission and detailed line-profile structure. The tradeoff is that medium-resolution observations are significantly more time intensive, requiring high S/N targets that are typically nearby.

This is illustrated by SN 2024gy ($\sim 17.2 \text{ Mpc}$) and SN 2022aaq ($\sim 36 \text{ Mpc}$): for the same exposure times,

SN 2024gy achieves a substantially higher S/N. Its MIRI/MRS spectrum clearly resolves the broad-base, narrow-core structure of [Ni II] $6.64 \mu\text{m}$, whereas the narrow core is much less clearly distinguishable in SN 2022aaq.

As shown in Figure 15, degrading the spectra to the resolving power of MIRI/LRS and NIRSpec/PRISM significantly blurs both the narrow [Ni II] core and the broken-slope structure of [Ni III] $7.35 \mu\text{m}$, preventing separation of narrow and broad components. The [Ni II] $1.94 \mu\text{m}$ line is detected with NIRSpec/G235M, but blending with nearby features complicates isolation of the broad component.

Although the [Ni II] $1.94 \mu\text{m}$ line is accessible from the ground, strong telluric absorption in this region makes such

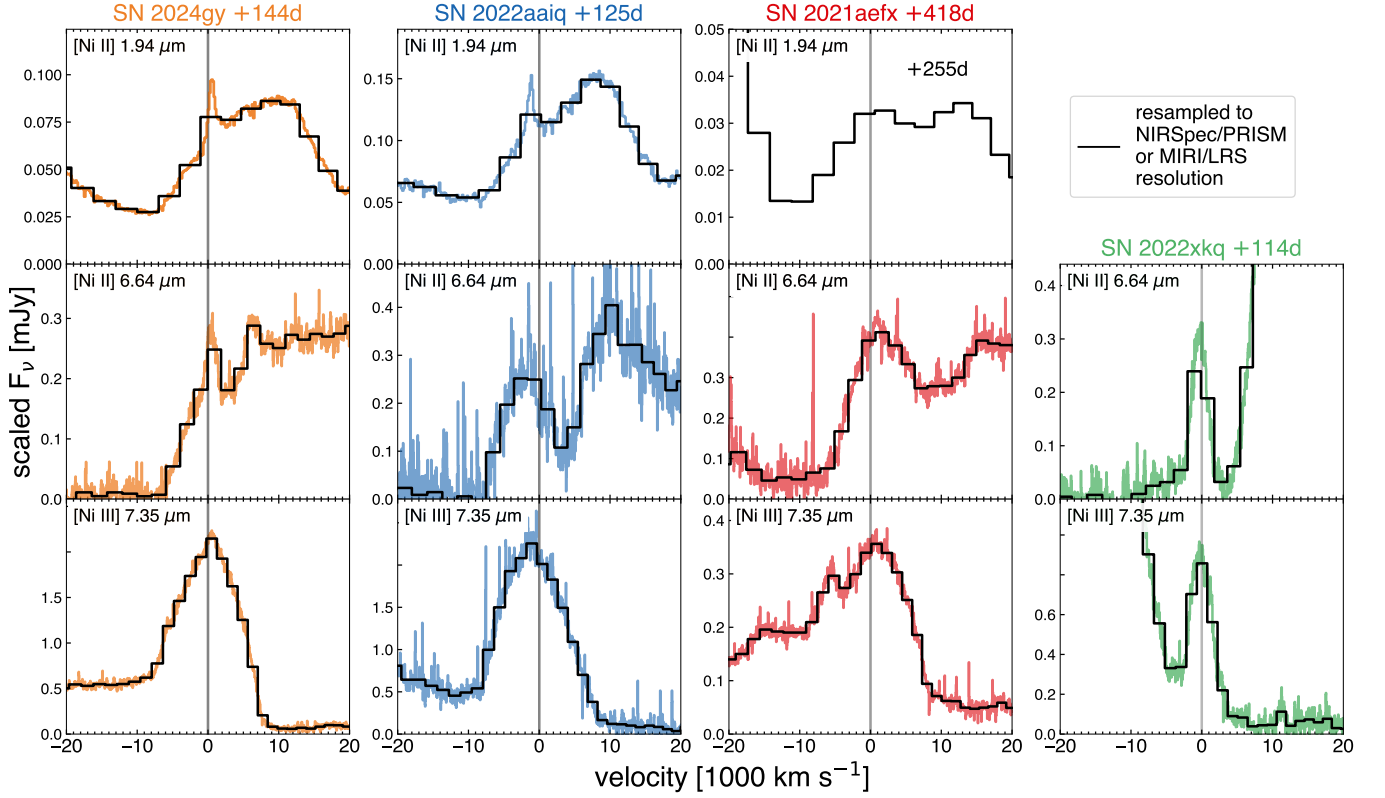


Figure 15. JWST NIRSpec/G235M grating and MIRI/MRS data of SN 2024gy (orange), SN 2022aaiq (blue), SN 2021aefx (red), and SN 2022xkq (green) resampled onto the low-resolution wavelength grids of NIRSpect/PRISM and MIRI/LRS (black). The low-resolution modes cannot capture fine details such as narrow lines.

observations challenging (e.g., S. Kumar et al. 2026). We therefore recommend JWST NIRSpec/G235M as the optimal mode for future observations of this feature.

Appendix C

Line-profile Derivatives for SN 2022aaiq, SN 2021aefx, and SN 2022xkq

Figure 16 presents the line-profile derivatives for SN 2022aaiq, SN 2021aefx, and SN 2022xkq, with comparisons to DDT, DBLDET, GCD, and MERGER models (see Figure 16).

For SN 2022xkq, the [Co III] profile exhibits a flat-topped structure at $v \lesssim 2000 \text{ km s}^{-1}$ and sharper, more triangular derivatives than seen in normal SNe Ia. While some features resemble DDT or DBLDET morphologies, the combination of

Ni, Ar, and Co structures differs from both SN 2024gy and the N100 DDT model (I. R. Seitenzahl et al. 2013), underscoring the distinct nature of SN 1991bg-like events.

For SN 2022aaiq, the [Ni III], [Ar III], and [Co III] profiles appear more asymmetric than in SN 2024gy. The [Co III] line shows a possible notch feature reminiscent of DDT or GCD models, though the limited S/N precludes a firm interpretation.

SN 2021aefx, observed at +418 days, shows a double-peaked [Ni III] derivative with a shallow-to-steep slope break, similar to SN 2024gy and DDT models. The [Co III] profile also exhibits a notch-like feature, while the [Ar III] line has a steeper red wing without a clear outer shoulder. At this late phase, reduced density in the outer ejecta may suppress higher-velocity emission, and we therefore regard the derivative-based interpretation as tentative.

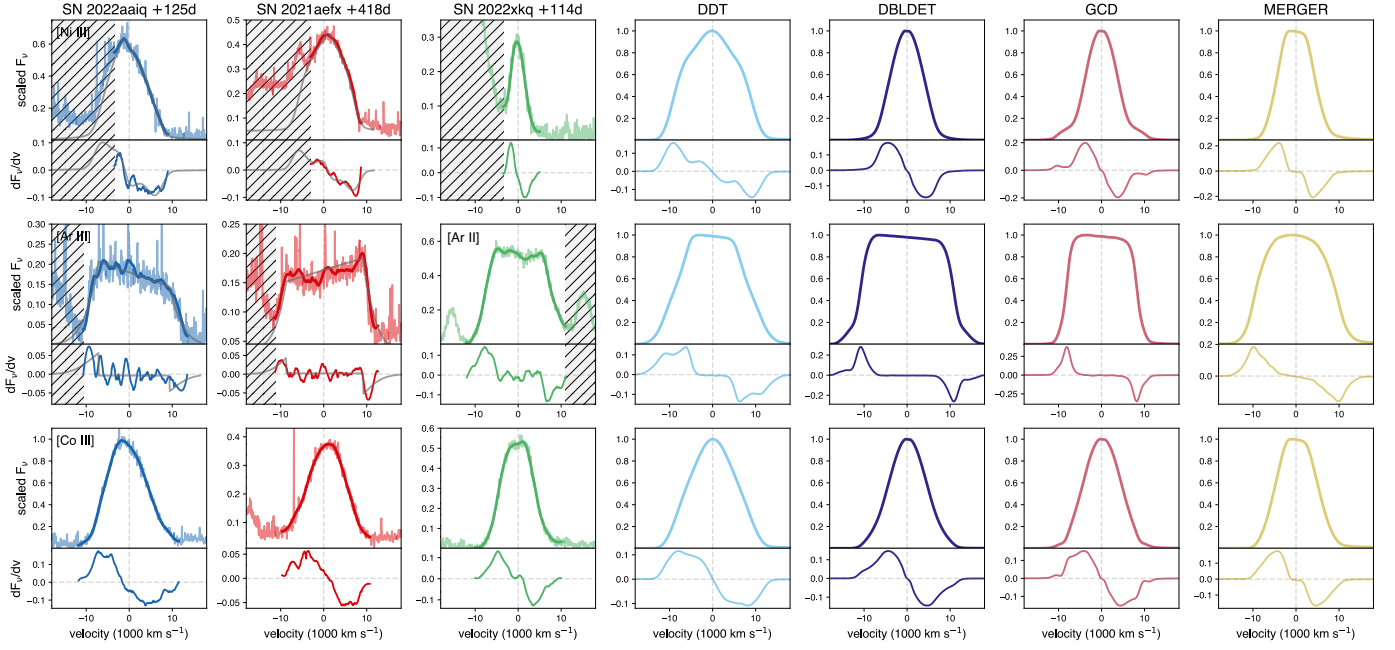


Figure 16. Line profiles (upper panels) and their derivatives (lower panels) for [Ni III] 7.35 μm , [Ar III] 8.99 μm , and [Co III] 11.88 μm for SN 2022aaiq at +125 days (blue), SN 2021aefx at +418 days (red), SN 2022xkq at +114 days (green), and the DDT (cyan), DBLDET (green), GCD (pink), and MERGER (yellow) models from S. Blondin et al. (2023). The data are shown in lower opacity and the smoothed data in full opacity. Our fits to blended lines are shown in gray and regions contaminated by line overlap in hatched light gray.

Appendix D

BayeSN Fits to SN 2022aaiq and SN 2024gy Photometry

Figure 17 shows our BayeSN fits to the light curves of SN 2022aaiq and SN 2024gy from Section 2. The photometry is given in Tables 3 and 4. Photometry in the *BV* bands is reported

in Vega magnitudes using standards from P. B. Stetson (2000), while *gri*-band data are presented in AB magnitudes (J. B. Oke & J. E. Gunn 1983), calibrated against Sloan Digital Sky Survey sources (J. A. Smith et al. 2002).

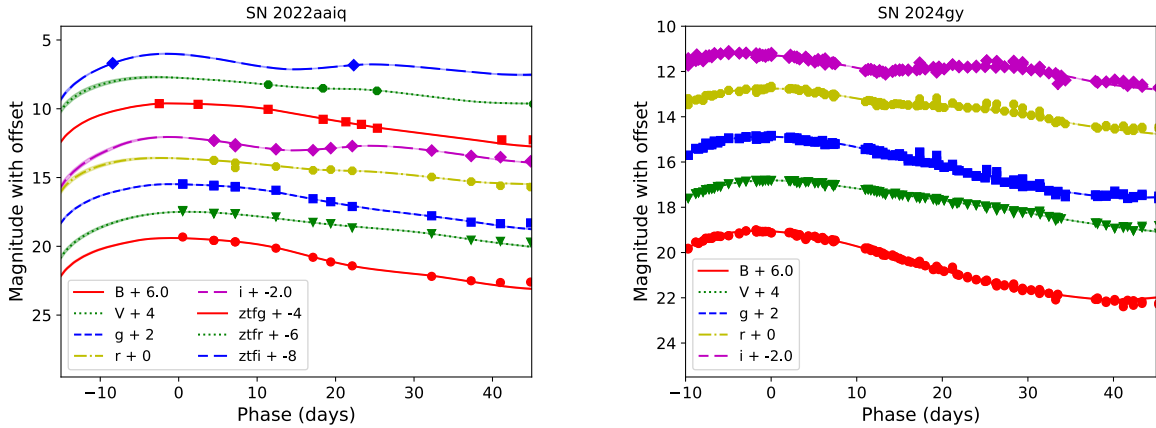


Figure 17. Left: LCO (from the GSP collaboration) and ZTF photometry for SN 2022aaiq. The BayeSN light-curve fit is overplotted and the filters are offset for clarity. Right: light-curve fit for SN 2024gy (with only LCO data). The data are in the rest-frame phase for each SN.

Table 3
Optical Photometry for SN 2022aaq

MJD	Phase (days)	Magnitude (mag)	Filter
59912.516	−1.5	13.32 ± 0.01	<i>B</i>
59912.519	−1.5	13.40 ± 0.02	<i>V</i>
59912.520	−1.5	13.46 ± 0.02	<i>V</i>
59912.521	−1.5	13.48 ± 0.01	<i>g</i>
59912.522	−1.5	13.46 ± 0.01	<i>g</i>
59916.514	2.5	13.57 ± 0.01	<i>B</i>
59916.515	2.5	13.57 ± 0.01	<i>B</i>
59916.517	2.5	13.63 ± 0.02	<i>V</i>
59916.518	2.5	13.60 ± 0.02	<i>V</i>
59916.519	2.5	13.56 ± 0.01	<i>g</i>
...	...	...	...

Note. Phases are relative to the *B*-band maximum MJD 59914.0.

(This table is available in its entirety in machine-readable form in the [online article](#).)

Table 4
Optical Photometry for SN 2024gy

MJD	Phase (days)	Magnitude (mag)	Filter
60314.310	−15.2	16.74 ± 0.02	<i>B</i>
60314.310	−15.2	16.72 ± 0.02	<i>B</i>
60314.310	−15.2	15.89 ± 0.03	<i>V</i>
60314.310	−15.2	15.91 ± 0.03	<i>V</i>
60314.320	−15.2	16.27 ± 0.01	<i>g</i>
60314.320	−15.2	16.25 ± 0.01	<i>g</i>
60314.320	−15.2	15.77 ± 0.02	<i>r</i>
60314.320	−15.2	15.74 ± 0.01	<i>r</i>
60314.320	−15.2	15.71 ± 0.03	<i>r</i>
60314.320	−15.2	16.21 ± 0.02	<i>i</i>
...	...	...	...

Note. Phases are relative to the *B*-band maximum MJD 60329.5.

(This table is available in its entirety in machine-readable form in the [online article](#).)

ORCID iDs

Lindsey A. Kwok <https://orcid.org/0000-0003-3108-1328>
 Chang Liu (刘畅) <https://orcid.org/0000-0002-7866-4531>
 Saurabh W. Jha <https://orcid.org/0000-0001-8738-6011>
 Stéphane Blondin <https://orcid.org/0000-0002-9388-2932>
 Conor Larison <https://orcid.org/0000-0003-2037-4619>
 Adam A. Miller <https://orcid.org/0000-0001-9515-478X>
 Mi Dai <https://orcid.org/0000-0002-5995-9692>
 Ryan J. Foley <https://orcid.org/0000-0002-2445-5275>
 Alexei V. Filippenko <https://orcid.org/0000-0003-3460-0103>
 Jennifer E. Andrews <https://orcid.org/0000-0003-0123-0062>
 Moira Andrews <https://orcid.org/0000-0002-1895-6639>
 Katie Auchettl <https://orcid.org/0000-0002-4449-9152>
 Carles Badenes <https://orcid.org/0000-0003-3494-343X>
 K. Azalee Bostroem <https://orcid.org/0000-0002-4924-444X>
 Thomas G. Brink <https://orcid.org/0000-0001-5955-2502>
 Cristine Koelln <https://orcid.org/0009-0000-9117-8995>
 Kyle W. Davis <https://orcid.org/0000-0002-5680-4660>
 Andreas Flörs <https://orcid.org/0000-0003-2024-2819>
 Lluís Galbany <https://orcid.org/0000-0002-1296-6887>

Or Graur <https://orcid.org/0000-0002-4391-6137>
 D. Andrew Howell <https://orcid.org/0000-0003-4253-656X>
 Sahana Kumar <https://orcid.org/0000-0001-8367-7591>
 Réka Könyves-Tóth <https://orcid.org/0000-0002-8770-6764>
 Natalie LeBaron <https://orcid.org/0000-0002-2249-0595>
 Colin W. Macrie <https://orcid.org/0000-0002-9209-2787>
 Keiichi Maeda <https://orcid.org/0000-0003-2611-7269>
 Kate Maguire <https://orcid.org/0000-0002-9770-3508>
 Curtis McCully <https://orcid.org/0000-0001-5807-7893>
 Nicolas E. Meza-Retamal <https://orcid.org/0000-0002-7015-3446>
 Estefania Padilla Gonzalez <https://orcid.org/0000-0003-0209-9246>
 Rüdiger Pakmor <https://orcid.org/0000-0003-3308-2420>
 Jeniveve Pearson <https://orcid.org/0000-0002-0744-0047>
 Anthony L. Piro <https://orcid.org/0000-0001-6806-0673>
 Abigail Polin <https://orcid.org/0000-0002-1633-6495>
 Nabeel Rehemtulla <https://orcid.org/0000-0002-5683-2389>
 César Rojas-Bravo <https://orcid.org/0000-0002-7559-315X>
 David J. Sand <https://orcid.org/0000-0003-4102-380X>
 Chita Sangkachan <https://orcid.org/0009-0007-7934-1543>
 Michaela Schwab <https://orcid.org/0009-0002-5096-1689>
 Huei Sears <https://orcid.org/0000-0001-8023-4912>
 Mridweeka Singh <https://orcid.org/0000-0001-6706-2749>
 Bhagya M. Subrayan <https://orcid.org/0000-0001-8073-8731>
 Kirsty Taggart <https://orcid.org/0000-0002-5748-4558>
 Tea Temim <https://orcid.org/0000-0001-7380-3144>
 Jacco H. Terwel <https://orcid.org/0000-0001-9834-3439>
 Samaporn Tinyanont <https://orcid.org/0000-0002-1481-4676>
 József Vinkó <https://orcid.org/0000-0001-8764-7832>
 Xiaofeng Wang <https://orcid.org/0000-0002-7334-2357>
 J. Craig Wheeler <https://orcid.org/0000-0003-1349-6538>
 Yi Yang <https://orcid.org/0000-0002-6535-8500>
 WeiKang Zheng <https://orcid.org/0000-0002-2636-6508>

References

- Ashall, C., Baron, E., Hoefflich, P. A., et al. 2021, *JWST Proposal Cycle 1*, 2114
 Ashall, C., Hoefflich, P., Baron, E., et al. 2024, *ApJ*, 975, 203
 Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, *ApJ*, 935, 167
 Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, *AJ*, 156, 123
 Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33
 Bildsten, L., & Hall, D. M. 2001, *ApJL*, 549, L219
 Birkmann, S. M., Giardino, G., Sirianni, M., et al. 2022, *SPiE*, 12180, 121802P
 Black, C. S., Fesen, R. A., & Parrent, J. T. 2016, *MNRAS*, 462, 649
 Blondin, S., Bravo, E., Timmes, F. X., Dessart, L., & Hillier, D. J. 2022, *A&A*, 660, A96
 Blondin, S., Dessart, L., & Hillier, D. J. 2018, *MNRAS*, 474, 3931
 Blondin, S., Dessart, L., Hillier, D. J., & Khokhlov, A. M. 2013, *MNRAS*, 429, 2127
 Blondin, S., Dessart, L., Hillier, D. J., & Khokhlov, A. M. 2017, *MNRAS*, 470, 157
 Blondin, S., Dessart, L., Hillier, D. J., Ramsbottom, C. A., & Storey, P. J. 2023, *A&A*, 678, A170
 Bowers, E. J. C., Meikle, W. P. S., Geballe, T. R., et al. 1997, *MNRAS*, 290, 663
 Branch, D., Jeffery, D. J., Parrent, J., et al. 2008, *PASP*, 120, 135
 Brown, T. M., Baliber, N., Bianco, F. B., et al. 2013, *PASP*, 125, 1031
 Bushouse, H., Eisenhamer, J., Dencheva, N., et al. 2022, *JWST Calibration Pipeline*, v1.7.0, Zenodo, doi:10.5281/zenodo.7038885

- Cappellari, M., Emsellem, E., Krajnović, D., et al. 2011, *MNRAS*, **413**, 813
- Cappellari, E., Mazzali, P. A., Benetti, S., et al. 1997, *A&A*, **328**, 203
- Chonis, T. S., Hill, G. J., Lee, H., Tuttle, S. E., & Vattiat, B. L. 2014, *SPIE*, **9147**, 26
- Coulter, D. A., Jones, D. O., McGill, P., et al. 2022, YSE-PZ: An Open-source Target and Observation Management System, v0.3.0, Zenodo, doi:10.5281/zenodo.7278430
- Coulter, D. A., Jones, D. O., McGill, P., et al. 2023, *PASP*, **135**, 064501
- Crawford, S. M., Still, M., Schellart, P., et al. 2010, *SPIE*, **7737**, 25
- DerKacy, J. M., Ashall, C., Hoefflich, P., et al. 2023, *ApJL*, **945**, L2
- DerKacy, J. M., Ashall, C., Hoefflich, P., et al. 2024, *ApJ*, **961**, 187
- Dhawan, S., Flörs, A., Leibundgut, B., et al. 2018, *A&A*, **619**, A102
- Diamond, T. R., Hoefflich, P., Hsiao, E. Y., et al. 2018, *ApJ*, **861**, 119
- Filippenko, A. V. 1982, *PASP*, **94**, 715
- Filippenko, A. V., Richmond, M. W., Branch, D., et al. 1992, *AJ*, **104**, 1543
- Fitzpatrick, E. L., Massa, D., Gordon, K. D., Bohlin, R., & Clayton, G. C. 2019, *ApJ*, **886**, 108
- Flörs, A., Spyromilio, J., Maguire, K., et al. 2018, *A&A*, **620**, A200
- Flörs, A., Spyromilio, J., Taubenberger, S., et al. 2020, *MNRAS*, **491**, 2902
- Fransson, C., & Chevalier, R. A. 1989, *ApJ*, **343**, 323
- Friesen, B., Baron, E., Wisniewski, J. T., et al. 2014, *ApJ*, **792**, 120
- García-Berro, E., Althaus, L. G., Corsico, A. H., & Isern, J. 2008, *ApJ*, **677**, 473
- Gerardy, C. L., Meikle, W. P. S., Kotak, R., et al. 2007, *ApJ*, **661**, 995
- Gordon, K., Larson, K., McBride, A., et al. 2022, karllark/dust_extinction: NIRSpectralExtinctionAdded, v1.1, Zenodo, doi:10.5281/zenodo.6397654
- Graur, O., Maguire, K., Ryan, R., et al. 2020, *NatAs*, **4**, 188
- Grayling, M., Thorp, S., Mandel, K. S., et al. 2024, *MNRAS*, **531**, 953
- Gronow, S., Collins, C., Ohlmann, S. T., et al. 2020, *A&A*, **635**, A169
- Gronow, S., Collins, C. E., Sim, S. A., & Röpke, F. K. 2021, *A&A*, **649**, A155
- Guy, J., Astier, P., Baumont, S., et al. 2007, *A&A*, **466**, 11
- Hillier, D. J., & Dessart, L. 2012, *MNRAS*, **424**, 252
- Hoefflich, P., Ashall, C., Bose, S., et al. 2021, *ApJ*, **922**, 186
- Hoefflich, P., Gerardy, C. L., Nomoto, K., et al. 2004, *ApJ*, **617**, 1258
- Hoyle, F., & Fowler, W. A. 1960, *ApJ*, **132**, 565
- Hunter, J. D. 2007, *CSE*, **9**, 90
- Iwamoto, K., Nakamura, T., Nomoto, K., et al. 2000, *ApJ*, **534**, 660
- Jakobsen, P., Ferruit, P., Alves de Oliveira, C., et al. 2022, *A&A*, **661**, A80
- Jerkstrand, A. 2017, in *Handbook of Supernovae*, ed. A. W. Alsabti & P. Murdin (Springer)
- Jha, S. W., Badenes, C., Camacho-Neves, Y., et al. 2021, *JWST Proposal Cycle 1*, **2072**
- Jha, S. W., Badenes, C., Camacho-Neves, Y., et al. 2023, *JWST Proposal Cycle 2*, **4516**
- Kendrew, S., Scheithauer, S., Bouchet, P., et al. 2015, *PASP*, **127**, 623
- Kendrew, S., Scheithauer, S., Bouchet, P., et al. 2016, *SPIE*, **9904**, 990443
- Kromer, M., Ohlmann, S., & Röpke, F. K. 2017, *MmSAI*, **88**, 312
- Kumar, S., Hsiao, E. Y., Ashall, C., et al. 2026, *ApJ*, **1000**, 178
- Kwok, L. A., Jha, S. W., Temim, T., et al. 2023, *ApJL*, **944**, L3
- Kwok, L. A., Siebert, M. R., Johansson, J., et al. 2024, *ApJ*, **966**, 135
- Kwok, L. A., Singh, M., Jha, S. W., et al. 2025, *ApJL*, **989**, L33
- Lach, F., Callan, F. P., Sim, S. A., & Röpke, F. K. 2022, *A&A*, **659**, A27
- Lach, F., Röpke, F. K., Seitzzahl, I. R., et al. 2020, *A&A*, **644**, A118
- Lair, J. C., Leising, M. D., Milne, P. A., & Williams, G. G. 2006, *AJ*, **132**, 204
- Leibundgut, B., Kirshner, R. P., Phillips, M. M., et al. 1993, *AJ*, **105**, 301
- Leloudas, G., Stritzinger, M. D., Sollerman, J., et al. 2009, *A&A*, **505**, 265
- Li, L., Wang, Z., Liu, J., et al. 2026, *ApJ*, **996**, 10
- Liu, C., & Miller, A. A. 2026, *PASP*, **138**, 024503
- Liu, C., Miller, A. A., Polin, A., et al. 2023, *ApJ*, **946**, 83
- Maeda, K., Mazzali, P. A., Deng, J., et al. 2003, *ApJ*, **593**, 931
- Maeda, K., Röpke, F. K., Fink, M., et al. 2010a, *ApJ*, **712**, 624
- Maeda, K., Taubenberger, S., Sollerman, J., et al. 2010b, *ApJ*, **708**, 1703
- Maguire, K., Sim, S. A., Shingles, L., et al. 2018, *MNRAS*, **477**, 3567
- Mandel, K. S., Thorp, S., Narayan, G., Friedman, A. S., & Avelino, A. 2022, *MNRAS*, **510**, 3939
- Martínez-Rodríguez, H., Badenes, C., Yamaguchi, H., et al. 2017, *ApJ*, **843**, 35
- Masci, F. J., Laher, R. R., Rusholme, B., et al. 2019, *PASP*, **131**, 018003
- Masci, F. J., Laher, R. R., Rusholme, B., et al. 2023, arXiv:2305.16279
- Mazzali, P. A., Iwamoto, K., & Nomoto, K. 2000, *ApJ*, **545**, 407
- Mazzali, P. A., Foley, R. J., Deng, J., et al. 2007a, *ApJ*, **661**, 892
- Mazzali, P. A., Kawabata, K. S., Maeda, K., et al. 2007b, *ApJ*, **670**, 592
- McCully, C., Volgenau, N. H., Harbeck, D. R., et al. 2018, *SPIE*, **10707**, 107070K
- Mehta, V., Sullivan, J., Fisher, R., et al. 2024, *MNRAS*, **532**, 1087
- Morán-Fraile, J., Holas, A., Röpke, F. K., Pakmor, R., & Schneider, F. R. N. 2024, *A&A*, **683**, A44
- Nickson, B., Engesser, M., Pierel, J., & Larson, K. 2025, brynickson/AstroBkgInterp: V 1.0.0 - First Light, Zenodo, doi:10.5281/zenodo.17410170
- Oke, J. B., Cohen, J. G., Carr, M., et al. 1995, *PASP*, **107**, 375
- Oke, J. B., & Gunn, J. E. 1983, *ApJ*, **266**, 713
- Oliphant, T. E. 2006, *A Guide to NumPy* (Trelgol Publishing)
- OpenAI 2025, ChatGPT (GPT-5.1) [Large Language Model], <https://chat.openai.com/>
- Pakmor, R., Kromer, M., Röpke, F. K., et al. 2010, *Natur*, **463**, 61
- Pakmor, R., Kromer, M., Taubenberger, S., et al. 2012, *ApJL*, **747**, L10
- Pakmor, R., Seitzzahl, I. R., Ruiter, A. J., et al. 2024, *A&A*, **686**, A227
- Pearson, J., Sand, D. J., Lundqvist, P., et al. 2024, *ApJ*, **960**, 29
- Piro, A. L., & Chang, P. 2008, *ApJ*, **678**, 1158
- Polin, A., Nugent, P., & Kasen, D. 2019, *ApJ*, **873**, 84
- Pollin, J. M., Sim, S. A., Shingles, L. J., et al. 2026, *MNRAS*, **548**, stag735
- Prochaska, J. X., Hennawi, J. F., Westfall, K. B., et al. 2020, *JOSS*, **5**, 2308
- Ramsey, L. W., Adams, M. T., Barnes, T. G., et al. 1998, *SPIE*, **3352**, 34
- Rigby, J., Perrin, M., McElwain, M., et al. 2023, *PASP*, **1046**, 048001
- Science Software Branch at STScI 2012, PyRAF: Python alternative for IRAF, Astrophysics Source Code Library, ascl:1207.011
- Seitzzahl, I. R., Ciaraldi-Schoolmann, F., Röpke, F. K., et al. 2013, *MNRAS*, **429**, 1156
- Seitzzahl, I. R., & Townsley, D. M. 2017, in *Handbook of Supernovae*, ed. A. W. Alsabti & P. Murdin (Springer), **1955**
- Sheinis, A. I., Bolte, M., Epps, H. W., et al. 2002, *PASP*, **114**, 851
- Shen, K. J., Boos, S. J., & Townsley, D. M. 2024, *ApJ*, **975**, 127
- Shen, K. J., Kasen, D., Miles, B. J., & Townsley, D. M. 2018, *ApJ*, **854**, 52
- Shingles, L. J., Flörs, A., Sim, S. A., et al. 2022, *MNRAS*, **512**, 6150
- Shingles, L. J., Sim, S. A., Kromer, M., et al. 2020, *MNRAS*, **492**, 2029
- Siebert, M. R., Davis, K. W., Foley, R. J., Brink, T., & Filippenko, A. 2022, *TNSCR*, **2022-3347**, 1
- Siebert, M. R., Foley, R. J., Jones, D. O., et al. 2019, *MNRAS*, **486**, 5785
- Siebert, M. R., Kwok, L. A., Johansson, J., et al. 2024, *ApJ*, **960**, 88
- Silverman, J. M., Nugent, P. E., Gal-Yam, A., et al. 2013, *ApJS*, **207**, 3
- Simcoe, R. A., Burgasser, A. J., Schechter, P. L., et al. 2013, *PASP*, **125**, 270
- Simotas, K., Bildsten, L., & Prust, L. J. 2025, *ApJ*, **994**, 23
- Smith, J. A., Tucker, D. L., Kent, S., et al. 2002, *AJ*, **123**, 2121
- Stetson, P. B. 1987, *PASP*, **99**, 191
- Stetson, P. B. 2000, *PASP*, **112**, 925
- Taubenberger, S., Valenti, S., Benetti, S., et al. 2009, *MNRAS*, **397**, 677
- Terwel, J. H., Maguire, K., O'Donnell, C., et al. 2026, *A&A*, in press (arXiv:2606.03589)
- Timmes, F. X., Brown, E. F., & Truran, J. W. 2003, *ApJL*, **590**, L83
- Tinyanont, S., Foley, R. J., Taggart, K., et al. 2024, *PASP*, **136**, 014201
- Townsley, D. M., Miles, B. J., Shen, K. J., & Kasen, D. 2019, *ApJ*, **878**, L38
- Tully, R. B., Courtois, H. M., Dolphin, A. E., et al. 2013, *AJ*, **146**, 86
- Valenti, S., Howell, D. A., Stritzinger, M. D., et al. 2016, *MNRAS*, **459**, 3939
- van den Bosch, R. C. E., Gebhardt, K., Gültekin, K., Yıldırım, A., & Walsh, J. L. 2015, *ApJS*, **218**, 10
- van Hoof, P. A. M. 2018, *Galax*, **6**, 63
- Ward, S. M., Thorp, S., Mandel, K. S., et al. 2023, *ApJ*, **956**, 111
- Wiggins, P. 2022, *TNSR*, **2022-3322**, 1
- Wilk, K. D., Hillier, D. J., & Dessart, L. 2018, *MNRAS*, **474**, 3187
- Woosley, S. E., Wunsch, S., & Kuhlen, M. 2004, *ApJ*, **607**, 921
- Yamaguchi, H., Badenes, C., Foster, A. R., et al. 2015, *ApJL*, **801**, L31