Expanding Horizons

Transforming Astronomy in the 2040s

Core-Collapse Supernovae in the 2040s

Scientific Categories: Time-domain

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Abstract:

A next-generation spectroscopic facility is essential to decode the fundamental physics of core-collapse supernovae by capturing their rapid spectral evolution from shock breakout to the nebular phase. The core science requires continuous UV–K-band coverage to track the full thermal and chemical evolution of the ejecta. A critical capability is dynamic spectral resolution: a low-resolution mode (R $\approx$ 1000) is paramount for securing early-time, photon-starved flash-ionization spectra, which directly probe the progenitor's circumstellar environment and radius. The facility must then rapidly switch to higher resolution (R $\geq$ 5000) to resolve the kinematic structure of the ejecta, measuring asymmetries and velocities that constrain the explosion mechanism itself. Finally, sustained high-resolution observations into the nebular phase are necessary to measure precise chemical yields, linking the products of nucleosynthesis unambiguously to the progenitor's mass and the explosion dynamics. This comprehensive, time-domain approach systematically connects pre-explosion mass loss to final chemical output, transforming supernovae into calibrated laboratories for stellar death and cosmic chemical enrichment.

1 Introduction and Background

Core-collapse supernovae (CCSNe) mark the end of massive stars ($M \geq 8\,M_{\odot}$), triggered by iron-core collapse into a proto-neutron star or black hole. Current spectroscopic facilities cannot adequately trace their **rapid, multi-epoch evolution**—from shock breakout and ejecta–circumstellar material (CSM) interaction to late-time nucleosynthesis.

A next-generation spectroscopic facility, optimized for rapid response and broad wavelength coverage, is essential to advance stellar evolution, explosion physics, and nucleosynthesis. Looking to the 2040s, future surveys will open new discovery space, driving the need for **dedicated, high-efficiency follow-up** capable of addressing key questions: how progenitor and binary evolution shape CCSN diversity; how final-stage mass loss and CSM interaction influence the explosion; and how multi-messenger observations (gravitational-wave, neutrino, electromagnetic) can be synergistically combined.

Early-time spectroscopy probes the progenitor environment. Flash spectroscopy of ionized circumstellar material within days of explosion directly traces pre-supernova mass loss. Current data show features in only ∼14% of Type II SNe, but this likely reflects observational limits—not true rarity. A dedicated time-domain facility with rapid UV-optical spectroscopy would reveal their true prevalence and diversity. Similarly, UV spectroscopy of events like SN 2023ixf resolves shock breakout and early cooling. Rapid, coordinated spectra are therefore essential to understand massive-star death.

2 Open Science Questions in the 2040s

What physical processes drive the explosion mechanism of core-collapse supernovae?

Core-collapse supernova explosions arise from complex interactions between neutrino heating, hydrodynamic instabilities (e.g. SASI), and, in some cases, magneto-rotational effects. Neutrino heating is the dominant mechanism [Bethe and Wilson, 1985, Müller, 2016], while progenitor structure, rotation, and magnetic fields modulate explosion asymmetries, nucleosynthesis, and remnant properties [Burrows, Vartanyan et al., 2019].

Similarly, shock breakout (SBO), the first electromagnetic signal when the shock reaches the stellar surface or CSM, encodes key information about the progenitor radius, explosion energy, and the surrounding density [Klein and Chevalier, 1978, Matzner and McKee, 1999]. Observations of SBOs in diverse progenitors (e.g., Wolf–Rayet stars, red supergiants, dense CSM) show a continuum from classical surface breakout to CSM-mediated events [Soderberg et al., 2008, Yaron et al., Ofek et al., 2010]. Early-time spectroscopy (≤ 1 day) of SBOs is thus crucial for constraining radiative transfer, pre-supernova mass loss, and linking progenitor structure to explosion physics—key objectives for next-generation time-domain spectroscopic facilities.

Supernova progenitors constraints

The presence and properties of CSM around supernovae provide direct insight into the final stages of progenitor evolution, including mass loss history or binary interactions. Dense CSM around progenitors manifests in distinctive early photometric and spectroscopic signatures, as exemplified by the detailed modelling of SN 2023ixf, which constrained the mass, density structure, and interaction timescales of its CSM [Zimmerman et al., 2024]. In stripped-envelope supernovae, binary interactions fundamentally shape the circumstellar environment; the periodic modulations

in the light curve and spectral evolution of SN 2015ap, for instance, reveal a structured CSM indicative of non-conservative mass transfer in a binary progenitor system [Ragosta et al., 2025]. CSM mass, density, and spatial distribution affect the shape of the light curve [Khatami and Kasen, 2024] and of the spectral lines, where it appears as asymmetries and multiple peaks in the emission profiles [Andrews et al., 2017, Andrews and Smith, 2018]. High CSM densities can even mask the internal powering mechanism, to the point that even a non-terminal outburst could mimic a faint core-collapse SN or even a thermonuclear explosion [Silverman et al., 2013].

These case studies disclose the full usage of all the phases from the photometric and spectroscopic evolution of the transient. Early-time light curves and spectra are particularly sensitive to circumstellar density and recent mass-loss episodes, whereas late-time evolution and nebular features constrain envelope composition, asymmetry, and potential surviving companions.

Current surveys are limited by heterogeneous instrumentation (including varying spectral resolutions), irregular cadence, a lack of near-IR coverage, and varying depth. This makes it difficult to detect low-level precursor variability, episodic mass loss, or rapid changes in circumstellar structure—all of which carry crucial information about the progenitor.

By the 2040s, addressing the outstanding questions in supernova progenitor physics will require systematic, high-cadence, and uniform monitoring of nearby galaxies. Dedicated time-domain capabilities—providing stable image quality, consistent depth, and cadence optimised for the erratic variability of massive stars—will enable the detection of subtle pre-explosion activity, the resolution of binary-driven mass-loss signatures, and precise confirmation of progenitor disappearance after explosion. Such a focused approach will transform our ability to connect pre-explosion behaviour directly to the observed transient evolution, moving the field from reactive characterisation toward predictive time-domain astrophysics, where we can identify which stars are likely to explode and under what physical conditions.

Chemical evolution of supernovae across time

Supernovae play a pivotal role in driving the chemical evolution of galaxies, acting as the primary sources of heavy elements and dust throughout cosmic history [Gall et al., 2011, Gall and Hjorth, 2018]. CCSNe from massive stars dominate the enrichment of α-elements (O, Ne, Mg, Si, S, Ca) in the early Universe. Recent advances in time-domain astronomy and nebular-phase spectroscopy have revealed significant diversity in nucleosynthetic outputs, even among similar explosion types, pointing to complex dependencies on progenitor metallicity, rotation, and explosion asymmetry [Jerkstrand et al., 2015, Sieverding et al., 2020]. There is a need for a high-to-mid resolution spectroscopic facility capable of systematically characterizing the composition of supernova ejecta across a wide temporal and wavelength baseline, spanning a range of metallicities. This facility would connect studies of the local Universe with the epoch of reionisation, providing the potential to constrain the evolution of heavy-element production over cosmic time.

3 Technology and Data Handling Requirements

A next-generation spectroscopic facility for time-domain supernova science would be advantageous to be built around a multiplexed array of telescopes to ensure continuous temporal and full-sky coverage. This architectural framework is crucial for conducting an impartial census of transient populations. The spectroscopic instrument suite requires continuous UV to K band (0.32–2.4 μm) coverage to capture all critical phases. We prioritize mid- to high-resolution spectroscopy (R $\approx$ 3000-10000; 100-30 km s^{-1}) for detailed kinematic studies and nucleosynthetic diagnostics, moving beyond the capabilities of existing low-resolution instruments. A secondary, low-resolution

mode (R $\approx$ 1000) is essential for high-sensitivity studies of early-time flash-ionization spectra. However, to fully resolve kinematic structure, a high-resolution mode (R $\gtrsim$ 5000) is required. The combined light-collecting power of a dedicated time-domain facility uniquely enables this crucial high-resolution spectroscopy of faint, early transients, transforming these signals into detailed maps of circumstellar density and velocity to link pre-explosion mass loss to the supernova event. To characterize transients from their earliest phases, the instrument must be optimized for rapid-response operation. Achieving the necessary cadence for shock-breakout and early CSM studies requires an interrupt-driven system with slew capabilities of several degrees per second and full spectroscopic readiness within minutes. Detector readout must support low-noise, high-speed operation, with frame times $\lesssim$ 5 s to enable flexible exposure control during rapidly evolving phases. High quantum efficiency in the blue and near-UV ($\lambda \leq 400$ nm) is crucial for capturing fleeting ionized CSM recombination features that dissipate within hours of explosion. The optical design must therefore prioritize UV-optimized coatings, minimal reflective surfaces, and maximized system throughput (goal: $\geq$35–40% end-to-end efficiency).

Given the expected high volume of transient alerts from future time-domain surveys—where the focus of 2040s astrophysics may shift from mere discovery to comprehensive characterization—a multiplexed observational approach is essential. This refers primarily to a coordinated array of multiple telescopes that provides fundamental flexibility in time and sky coverage. A secondary instrument-level multiplexing capability, via a fiber-fed or multi-slit architecture enabling simultaneous spectroscopy of 10–50 targets within a single field of view, would further enhance demographic studies. Stable and automated calibration systems—including arc lamps, continuum flats, and real-time environmental monitoring—are required to maintain wavelength and flux stability across nightly operations, especially under queue-scheduled and dynamically prioritized follow-up.

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