Chapter X:
Stellar endpoints and gravitational waves

Massive Stars Near and Far
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The Diversity of Massive Stellar Transients Found in Sky-surveys

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Abstract. The recent generation of dedicated wide-field, high-cadence sky-surveys have overwhelmed discovery statistics for all manner of extra-galactic transients, and uncovered new phenomena seemingly linked to the demise of massive stars. For the more established classes of transients, such as core-collapse supernovae, surges in discoveries are allowing true population studies to provide quantitative constraints not only on the explosion properties, but also on the progenitor populations. Crucially, such population insights are benefiting from creation of samples of transients constructed with largely unbiased methods for discovery and characterisation. Surrounding these discoveries are increasing samples of extreme transients that do not fit the standard core-collapse paradigm - requiring the invocation of exotic progenitor stars and placing demands on the stellar evolution of such systems. Here I will provide a high-level observationally-driven overview of recent results related to massive stellar transients.

Keywords. supernovae: general surveys, stars: evolution, techniques: photometric, circumstellar matter

1. Introduction

The relative dearth of massive stars, owing to stellar initial mass function (IMF) considerations, coupled with their short lives, makes the study of their final stages of stellar evolution extremely tricky – chiefly due to the corresponding rarity of suitable targets. At the ultimate end of their nuclear-burning lives massive stars are capable of undergoing spectacular explosive events, vastly increasing their luminosity, albeit for only a brief moment on astronomical time-scales. These explosive astrophysical transients can offer complementary insights into the nature of the final stages of stellar evolution for massive stars, and give us glimpses of the progenitor stars upon explosion. Although linking observables from the transients to the progenitor stars and their final evolution is a more indirect route, the great distances at which transients can be observed allows us to overcome the scarcity problem. Thanks to recent projects dedicated to the discovery of such transients, their study can now provide constraints on, and pose questions of, massive stellar evolution, not just with individual transients of interest, but with populations and statistical studies.

2. Transient sky-surveys

The discovery of transients is a time-domain problem in astrophysics, and requires continual snap-shots of the night-sky in order to pin-point the location of new (or missing) objects. Two axes of performance are ideally maximised for these sky-surveys:

- *Cadence:* A measure of the revisit time between a given location on the sky. A high cadence survey is critical such that observations for a given location recur faster than the time-scale of the transients to be discovered.

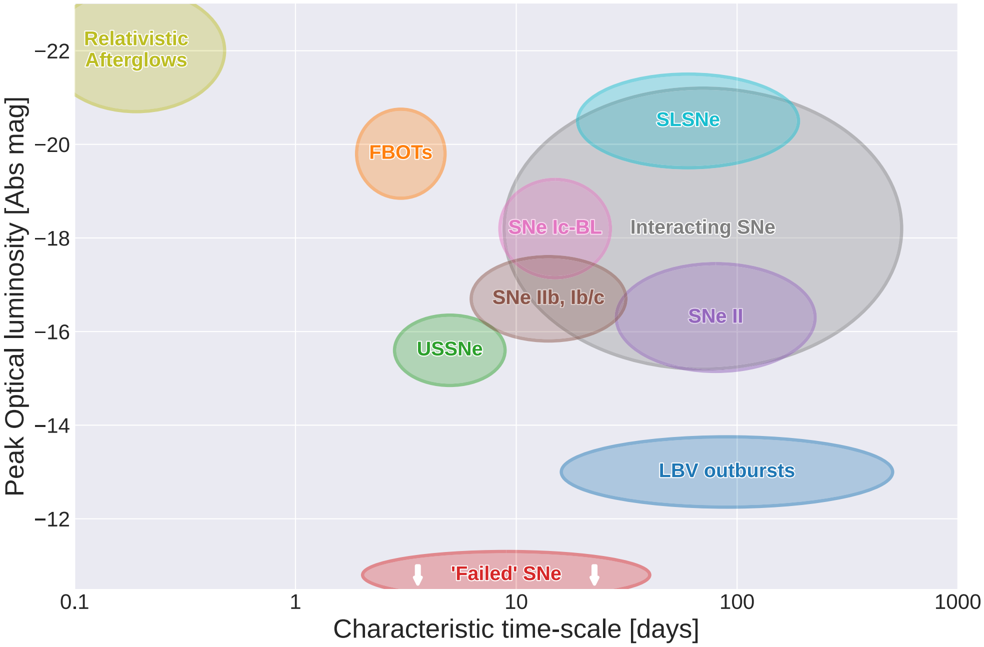

Figure 1. A visualisation of the luminosity-timescale parameter space of transients associated with massive stars. Characteristic time-scale is a loosely defined term, given the varied nature of light curves, but broadly encompasses a full-width-half-maximum-esque parameter – in any case the location of the ellipses for various sub-types are indicative only, and there are notable outliers in various sub-types. Data were collated from Smith et al. (2011b), Kasliwal (2012), Adams et al. (2017), Perley et al. (2020), Yao et al. (2020), Ho et al. (2022), Byrne & Fraser (2022).

- *Volume:* A measure of the volume of Universe probed, in which the observations would be sensitive to a given transient-type. This measure is a product of the area of the night-sky covered by the survey, as well as the flux-depth of the observations.

Each of these is crucial and of course comes with a cost to improve. New technical advances, particularly in the availability of large-format sensors, have had a major impact. Historically, transient surveys were comparatively focussed, typically optimised relatively narrow field-of-view instruments for the discovery of ‘normal’ supernovae. Supernovae evolve on timescales of weeks, and at the time displayed no obviously strong preference where they explode and largely tracing star-formation and/or stellar mass in the local universe (e.g. see review of Anderson et al. 2015). As such, the strategy employed was a sensible one – target massive, nearby galaxies with a recurrence time-scale of a few-days to a week. This intrinsically imposed a strong selection bias away from transients that: a) *do* have a strong preference in host-galaxy or environment (particularly any that favour low-mass/metallicity environments), b) evolve on a timescale of a few days, and/or c) are intrinsically very rare (since the volume probed with is comparatively small).

The typical sky-survey throughout the latter 2010s to current have been of a more synoptic, often multiplexed flavour. With wide fields of view in a single pointing – typically tens of square degree – a galaxy-targeted approach is no longer beneficial, and large swathes of the night sky can be covered in a given night. Prominent current and upcoming such surveys include (alphabetically) ASAS-SN (Shappee et al. 2014), ATLAS (Tonry et al. 2018), BlackGEM (Bloemen et al. 2015), GOTO (Steeghs et al. 2022), PSST (Huber et al. 2015), LSST (LSST Science Collaboration et al. 2009), and ZTF

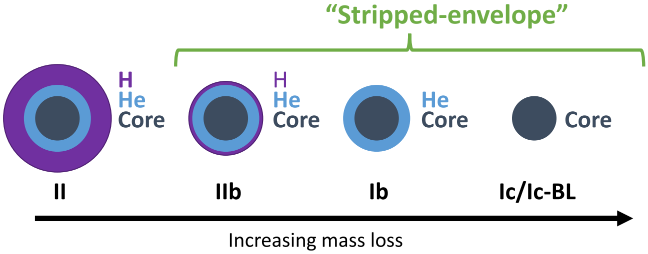

Figure 2. A schematic representation (not to scale) of the progenitor star structure for various CCSN sub-types. Moving from the hydrogen-rich Type II SNe, through to the H- and He-poor Type Ic is a manifestation of additional effects of mass-loss incurred by the progenitor stars prior to undergoing SN. The collectively name "stripped-envelope" CCSNe are indicated.

(Bellm et al. 2019). Each project fulfils a slightly different niche in the cadence and volume search space. Collectively the result is that most of the visible night sky is being observed to an optical depth of $\sim 19 - 21$ mag each night. Future surveys, particularly LSST, will provide additional depth across smaller regions of sky.

To discover transients automatically in the huge data streams from these surveys, *difference imaging* (e.g. Alard & Lupton 1998, Becker 2015, Zackay et al. 2016) is appealed to, where a historical image of the same patch of sky acts as a reference point, with which to compare new observations. Even using difference imaging, the task of finding the astrophysically-interesting objects from the many imaging artefacts, is a huge undertaking and typically requires the use of novel machine- or deep-learning techniques to sift the candidate discoveries in difference images (e.g. Brink et al. 2013, Duev et al. 2019, Killestein et al. 2021). Such measures are essential for the rapid dissemination of a new discovery to human vetters, who can announce to the community and trigger additional follow-up with other facilities. Studying systematically the intrigues of early, short-lived phenomena in transients as well as intrinsically fast-evolving transients, has only therefore only recently started to be possible with such streamlined processes taking us from observation to discovery to follow-up with minimal (and ideally no) human interaction.

The recent increase in statistics for common transient types, and the uncovering of rare, exotic explosions from these surveys is pushing forward and questioning our understanding of massive stars at the ends of their lives. A visual representation of luminosity-timescale parameter space for transients that is being evermore populated is shown in Figure 1. A few highlights for sub-types will be picked out in the following sections – more in-depth discussion of specific subtypes can be found elsewhere in this issue.

3. Core-collapse Supernovae

Core-collapse supernovae (CCSNe) are the most well-established transient associated with massive stars. An enduring, observationally driven classification scheme (Filippenko 1997, Modjaz et al. 2019) is used to discriminate sub-types largely based on the structure of the progenitor star upon explosion – specifically the degree of stripping the outer hydrogen- and helium-rich layers have undergone prior to SN. This is visually represented in Figure 2, where it is shown the distinction of Type II SNe (SNe II) from "stripped-envelope" SNe (SESNe). From single stellar evolution, an increase in mass loss would be expect to be driven primarily by an increase in zero-age main sequence (ZAMS) mass, or metallicity of the star. Following this, we may expect a mass and/or metallicity dependence of the progenitor star on the resultant CCSN type observed. However, it was noted already from earlier sky-surveys (e.g. LOSS (Filippenko et al. 2001)) that $\mathcal{R}\frac{\mathrm{SESNe}}{\mathrm{SNe\ II}}$ – i.e. the relative rate of SESNe – is larger than one might expect

(Li et al. 2011). Using straight-forward IMF arguments, and assuming a mass-segregation of the SNe II vs SESNe progenitors, the high relative abundance of SESNe requires a lower mass-limit of progenitors much lower than the observed and theoretical mass range of Wolf-Rayet (WR) stars (Smith et al. 2011a). WR stars possess sufficiently strong winds and mass-loss that they can strip themselves of their hydrogen and helium layers prior to SN and so appear as SESNe, but at lower masses another channel must be contributing to the creation of SESNe. This high relative rate of SESNe has survived the creation of larger and more homogeneously-selected samples of CCSNe (e.g. Perley et al. 2020), and remains significantly above that which is comfortable for single stellar evolution at around one quarter to one third.

The mechanism appealed to, in order to relieve the tension in relative rates of CCSN sub-types, has been the effect of binary stellar evolution on the progenitor stars (e.g. Yoon et al. 2010, Eldridge et al. 2013, Yoon et al. 2017) – an expected influential process given the prevalence of binary interactions in massive stars (e.g. Sana et al. 2012). The presence of a (close) binary companion to a SN progenitor strongly influences its evolution, and causes the binary parameters (i.e. mass and separation of companion) to be the dominating factor influencing its mass-loss rate. This will act towards washing out a strong ZAMS mass-dependence between CCSN sub-types. SESNe, therefore, are expected to have a large contribution of binary progenitors, and producing them in single star systems may actually be quite difficult, except for the most massive progenitors (Beasor & Smith 2022). It should be noted that other factors, such as top-heavy IMFs or a strong metallicity dependence on the observed CCSN sub-type may also explain the high SESN rate, but these factors would consequently come with a strong environmental and/or host-galaxy dependence on sub-type. The presence (or not) of such a dependence has been varyingly reported in the literature (e.g. Graur et al. 2017, Schulze et al. 2021), suggesting at least that, if present, they are not likely to be dominant factors.

In addition to volumetric rates, properties of the luminous SN signature also infer constraints on nature of the progenitor systems. In particular, following analytical relations describing the diffusion time-scale for SESNe (e.g. Arnett 1982, Khatami & Kasen 2019) an estimate for the ejecta mass can be obtained from the width of the bolometric light curve and photospheric velocity – the analytical estimate naturally coming with significant assumptions on the nature of the explosion. This prescription, although simplfied (see caveats in, e.g., Afsariardchi et al. 2021), does allow for population studies of large quantities of SESNe. A common theme in such studies is a distribution of low ejecta masses, typically clustered around 2–4 $M_\odot$ (e.g. Drout et al. 2011, Lyman et al. 2016, Taddia et al. 2018, Prentice et al. 2019). This is at odds with expectations of single, massive WR progenitors, which may be expected to expel $\sim$8–10 $M_\odot$, and points to the prevalence of more moderate mass progenitors producing the bulk of SESNe. New results from systematic sky-surveys however are revealing a significant population of spectroscopically-normal, broad-light curve SESNe that *are* consistent with explosions of very massive progenitors (Karamehmetoglu et al. in prep).

4. Superluminous Supernovae

The emergence of discoveries in the mid-2000s of extremely luminous supernovae (e.g. Quimby et al. 2007, Ofek et al. 2007) called into question the limits of the core-collapse scenario, and promoted more niche explosion mechanisms in order to explain these events. Since then, the recent and current generations of sky-surveys have figuratively exploded the detection rate of such luminous events – dubbed super-luminous SNe (SLSNe). Initially defined based on an peak luminosity cut (Gal-Yam 2012), the burgeoning SLSN population, inevitably, has since grown in observational diversity and a classification now includes a revised consideration of the peak luminosity (Gal-Yam 2019) as well as a search for spectroscopic signatures not typically seen in CCSNe (Quimby et al. 2011).

SLSNe are found as both H-rich and H-poor, designated Type I and II analogously to CCSNe. Succinctly, SLSNe-I display peak optical luminosities $M \lesssim 20$ mag, have longer rise times than CCSNe (in some cases much longer) and display hot photospheric spectra through peak, evolving at later times to resemble SESNe Type Ic. Another unusual feature are the presence of "bumps" in the light curves, both at early- (Nicholl & Smartt 2016) and late-times (Nicholl et al. 2016). SLSNe-II appear similar to SNe Type IIn (Section 6), albeit at higher luminosities and consequently different inferred circumstellar medium properties. Notable examples exist of broad H lines in SLSNe-II (e.g. SN 2008es Miller et al. 2009, Gezari et al. 2009), although as a whole SLSNe are the much poorer-studied of the type SLSN types.

Quickly it was established that the traditional energy deposition from radioactive decay – primarily ^{56}Ni – was unable to explain most SLSNe. For all but the most slowly evolving SLSNe (rise-times of months), the timescales of radioactive deposition and diffusion are too long when attempting to power their peak luminosities, and require implausibly high mass ratios of synthesised radioactive material to ejecta. In the case of the most slowly evolving SLSNe, a very high $M(^{56}\mathrm{Ni}) \simeq$ several $\mathrm{M}_{\odot}$ (cf. $\lesssim$0.1–0.2 $\mathrm{M}_{\odot}$ for CCSNe Lyman et al. 2016, Anderson 2019, Afsariardchi et al. 2021) is required, invoking $\mathrm{M}_{\mathrm{ej}} \simeq 100\,\mathrm{M}_{\odot}$. These properties are plausible in the pair-instability supernova (PISN) explosion of very massive stars ($M_{\mathrm{ZAMS}} > 100\,\mathrm{M}_{\odot}$). A very small handful of objects have been proposed as consistent with the PISN scenario (e.g. Kozyreva et al. 2018). The observational favourability of detecting these events in the current and future generation of sky-surveys, owing to their huge and long-lived luminosities, is tempered by the expected rate of such events, even from IMF arguments alone.

For SLSNe-II in particular, the dominance of narrow balmer emission lines in the spectra indicates an additional powering component from interaction of the ejecta with a slow-moving, dense pre-existing medium. Powerful, potentially episodic, mass-loss prior to explosion can furnish massive stars with a dense circumstellar-medium (CSM; Smith 2014), and it is likely similar phenomena seen in other interaction-driven SNe is at play, albeit with more extreme CSM properties driven by exteme mass-loss from more massive progenitors (Woosley et al. 2007) to power the high luminosities. The presence of hydrogen-free CSM can also allow interaction to contribute towards the energy-budget of SLSNe-I, and indeed may provide a means of explaining late time bumps in the light curves Inserra et al. (2017).

Another popular model that has emerged to explain SLSNe, particularly SLSNe-I, is through the presence of a nascent magnetar, formed during the collapse of the progenitor, which is able to inject an additional energy source into the SN ejecta via spin-down of the magnetar (e.g. Woosley 2010). With $P \sim$milli-seconds, and $B \sim 10^{14}$, satisfactory magnetar-powered models can reproduced the light curves (Inserra et al. 2013) and spectra (Dessart et al. 2012) of many SLSNe-I. The energy injection may also provide a means of powering the early light curve bumps (Kasen et al. 2016), although can have difficulty reproducing observed photospheric velocity evolution (Liu et al. 2017).

The nature of current and future sky-surveys being agnostic to any pre-existing "targets" to search for transients (i.e. nearby, massive galaxies) has contributed immensely to the discovery of large numbers of SLSNe, with detections now in their hundreds. When we assess the locations of SLSNe, they are dominated by a population of low-mass, and consequently low-metallicity, host galaxies (Angus et al. 2016, Chen et al. 2017). Identifying SLSNe early in their evolution is not trivial, yet is crucial to properly characterise fleeting phenomena such as their early bumps. Future progress will need to begin to take automated advantage of environmental information, particularly taking

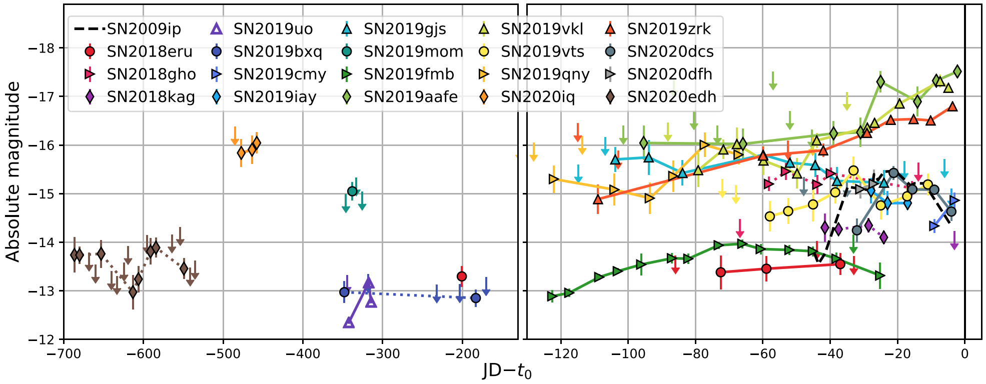

Figure 3. Precursor light curves for a sample of interaction-driven CCSNe from ZTF reproduced from Strotjohann et al. (2021). t_0 indicates the detection time of supernova. There is a prevalence of outbursts in the final few months of the stars' lives (5-69% of the analysed sample showed this behaviour), with indications of some comparatively luminous outbursts years prior to supernova. © AAS. Reproduced with permission.

advantage of wide-field multi-colour and multi-object-spectroscopic surveys to allow for rapid identification of luminous outbursts in faint galaxies.

5. Ultra-Stripped Supernovae

Evolving on comparatively short timescales, ultra-stripped SNe (USSNe) are a new classification of extra-galactic transient that bear many hall-marks of SESNe. Observationally, they bear many signatures of SESNe albeit on a compressed timescale: rising in a few days and transitioning to the nebular phase in a matter of weeks. Although detailed follow-up is sparse, their spectra and later-time luminosity evolution, which is described well by a radioactive power source, conform closely to what is seen in SNe Ic. SN 2005ek, one of the first, and most extreme examples of this empirical class exemplifies these properties (Drout et al. 2013). The proposed model for these events involves the core-collapse of an almost bare core, marginally above the Chandrasekhar limit, which expels only a few tenths of a solar mass of ejecta (Tauris et al. 2013; 2015). This scenario is extremely unlikely for single stellar evolution, and invokes exotic binary pathways where the neutron star remnant of a primary supernova in a binary acts to strongly strip its companion, prior to its own supernova. It is currently unclear how much USSNe can be said to arise from a separate stellar evolution channel to that of regular SESNe, or if there is a continuum of core-collapse events down to very low ejecta-masses. USSNe, more than most transient discussed here, demand high-cadence sky-survey data, and rapid identification procedures in order to grow the population of known events.

The interest in USSNe is compounded to by their potential role as progenitors of neutron star mergers – now being detected by the current generation of gravitational wave detectors (Abbott et al. 2017) – since the binary evolution pathways required for the system to undergo a high degree of He star stripping naturally leads to the formation of close binary neutron star (BNS) system (Tauris et al. 2017, Jiang et al. 2021). Indeed, the USSNe themselves are not too dissimilar (in the grand scheme of transient diversity) from the electromagnetic kilonovae arising from BNS mergers, WHICH CAN lead to their discovery and follow-up as interlopers within the electromagnetic follow-up campaigns of gravitational wave triggers (ENGRAVE collaboration in prep).

6. Interaction-driven Supernovae

Transients borne of massive stellar progenitors are more than likelyy to be conceived in complex environments. They may be still embedded within the comparatively dense interstellar medium of their natal star-formation complex, and they will have the history of their mass-loss (and that of their companion) imprinted in the immediate circumstellar surroundings – into both their freshly exploded ejecta will propagate. Such interaction between the fast-moving SN ejecta ($10^4 - 4.5\,\mathrm{km\ s^{-1}}$) and the surrounding media ($10^1 - 3\,\mathrm{km\ s^{-1}}$) will produce shocks and sources of luminosity that will imprint on the multi-wavelength photometric and spectroscopic evolution of the supernova (Chevalier 1977; 1982). Concurrent analysis of these multi-wavelength components can reveal the nature of the ambient medium (e.g. Tsuna et al. 2021).

Of relevance for extra-galactic transient timescales is the interaction with a circumstellar medium (CSM). The CSM of massive stars are dense, and can show varying profiles depending on the state of mass-loss history – primarily characterised as steady-state and/or eruptive. One of the most distinctive features of interaction-driven SNe is the presence of narrow emission lines, characterised by the velocity of the ambient medium. As such, the 'n' designation for the SNe type is used to indicate 'narrow' lines. This has been most prominently displayed by SNe IIn – those with narrow Balmer lines (Schlegel 1990) – but more recently, signatures of interaction with H-poor CSM have been found. The Ibn subclass are instead characterised by narrow He lines (Pastorello et al. 2008), and the even more recent Icn discoveries (Gal-Yam et al. 2022, Perley et al. 2022) display narrow C and O lines, and a conspicuous absence of H or He lines. Such H-poor CSM would be most naturally explained by WR progenitor stars, and indeed the inferred high density and velocity ($10^3\,\mathrm{km\ s^{-1}}$) of the media surrounding these SNe also agrees with this picture. The fast nature of these events, however, contradicts expectations of purported very massive WR progenitors. These latter sub-classes are therefore currently provoking resurgence in models of massive stellar collapse with significant fallback onto a nascent black-hole (Perley et al. 2022) and compact object accretion from WR stars (Metzger 2022), among others.

As well as impacting the SN itself, extensive mass-loss throughout a massive star's life may be responsible for the production of 'precursor' outbursts. The study of Strotjohann et al. (2021) found a high-occurrence of outbursts in the months preceding an interaction-driven SN (Figure 3). The cause of these outbursts is likely to be linked to eruptive mass-loss events, similar to that seen to occur in local massive stars, particularly luminous blue variable and η Car-like stars. Collisions between an euptive mass-loss event and the ambient medium could themselves also produce a weaker cousins of an interaction-powered SNe, manifesting as outbursts. The cause of such eruptive mass-loss is less clear. Late stage, unstable nuclear burning can drive strongly super-Eddington winds from stars (Fuller 2017, Fuller & Ro 2018), however in some cases the timescales for the precursors pre-date these late nuclear burning stages, and additionally appear much more luminous than may be expected. Constraints on pre-explosion outbursts, and even the variability of the progenitor star (e.g. Kilpatrick et al. 2021) will become more common place particularly with the commencement of the Vera Rubin Observatory and could give us the best means of studying the rare, final few years of massive stellar evolution.

Acknowledgements

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Discussion

HIRSCHI: What are the environments of interacting supernovae?

LYMAN: For the H-poor events we do not have populations to draw significant conclusions as yet. The Type IIn SNe interesting display an extremely wide range of environments, and we see a much larger proportion of them, compared to SE SNe, for example, that occur in the outskirts of their host galaxies, or away from regions of ongoing star formation.

FRASER: There is the issue that what we label a Type IIn SN is probably an extremely heterogeneous collection of objects, ranging from faint SN 2008S-like events up to SLSNe.

Brennan: What are the causes of the pre-outburst bumps that have been seen?

Lyman: Likely related to mass-loss events, but the underlying cause of those events is less clear. Certain luminosity and timescale constraints are expected from, e.g., late-stage unstable burning, and having much longer time-scale pre-SN variability constraints is needed to address this.