WHY CC SUPERNOVAE ARE IMPORTANT

- Final deaths of massive ($M > 8 \, M_\odot$) stars
- Formation of compact objects (i.e., NS/BH)
- Galactic nucleosynthesis— they expel newly-formed elements back into the ISM
- The kinetic energy of SNe is a major input of energy and driver of turbulence in the interstellar medium
- Tracers and probes of the sites of massive star formation
CORE-COLLAPSE SUPERNOVA TYPES

- Three basic flavors of CC SNe:
  - Thick H envelope
  - Stripped envelope
  - Dominated by CSM interaction (not illustrated)
If single stars dominate, most massive stars will explode as RSGs due to steepness of IMF

Smartt 2009
BUT OBSERVATIONS SHOW:

WR-like progenitors?
Probably stripped via binary interactions

Strong interactions ($M_{CSM} \sim 0.01-1 \, M_\odot$)

- Binary evolution and/or extensive mass loss in last years before explosion modify the appearance of stars/SNe
O stars: $M_{\text{ZAMS}} > 15M_{\odot}$

Cumulative fraction of O stars at birth

- Effectively single ~29%
- Envelope stripping ~33%
- Merge ~24%
- Accretion & spin up or CE ~14%

Adopted limit for severe stripping before supernova

Adopted limit for interaction during main sequence

Intrinsic probability density

Initial orbital period (d)
A star is present at the SN position in pre-explosion imaging, but vanishes afterwards.

In this case $M_{\text{init}} \sim 18 M_\odot$

This has been done for ~20 or so SNe now.
THE ROLE OF LSST

Note the SN landscape in the early 2020’s—many bright (nearby) SN searches will be operational (ASASSN, ATLAS, etc.) and the initial run of ZTF will have already happened

- Massive number of SN discoveries
  - Well-defined subsamples
- Uniformly high-quality photometry for free
  - Both in photometric precision and quality of subtractions
- Large dynamic range
  - Light curve points when SNe are either really young or old
- Ability to be modeled
  - Mitigating some selection biases
**COSMIC SFR PROBED BY CCSNE**

- CC SN rate is proportional to the star formation rate

Graur et al. 2015

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Strolger et al. 2015
CORRELATIONS WITH ENVIRONMENTS

- Locations within hosts are related to the mass of the progenitors
- Other environmental effects: e.g., fraction of stripped-envelope SNe vs. host metallicity

Kelly et al. 2008
A WELL-SAMPLED SN II LIGHT CURVE

CSP: Anderson et al. 2014
SN IIP THEORETICAL LIGHT CURVE

- Hot, cooling envelope at early times (large progenitor radius ~ few $\times 10^{13}$ cm)

  e.g., Eastman et al. 1994

  Rubin et al. 2016
SN IIP THEORETICAL LIGHT CURVE

- ~100 day plateau powered by H recombination (large hydrogen envelope ~ $10 \, M_\odot$)

  e.g., Eastman et al. 1994

  Leonard et al. 2002
PLATEAU SCALINGS

\[ t_{sn} \propto E^{-1/6} M_{ej}^{1/2} R_0^{1/6} \kappa^{1/6} T_i^{-2/3}, \]
\[ L_{sn} \propto E^{5/6} M_{ej}^{-1/2} R_0^{2/3} \kappa^{-1/3} T_i^{4/3}. \]  \( (8) \)

- Arnett (1980); Popov (1993); Kasen & Woosley (2009) and more derived analytic scaling relationships for the plateau
- Above assumes radiative diffusion and recombination releasing shock-deposited thermal energy
- Note: effects of nickel heating extend the plateau by \(~20\%\)!
SN IIP THEORETICAL LIGHT CURVE

- Radioactive decay tail at late times

e.g., Eastman et al. 1994
Barbon et al. (1979) defined 2 classes of SNe II based on blue light curves: IIP have a plateau with duration ~100 days vs. IIL.

Lots of authors have proposed similar, but not identical, criteria.
LARGE LIGHT CURVE SAMPLES

Pan-STARRS1: Sanders et al. 2015
CSP: Anderson et al. 2014
LARGE LIGHT CURVE SAMPLES

Pan-STARRS1: Sanders et al. 2015

CSP: Anderson et al. 2014
A VARIETY OF DECLINE RATES

Pan-STARRS1: Sanders et al. 2015

CSP: Anderson et al. 2014

No statistical evidence for bimodality!
Faster decline on plateau = more “IIIL-ish” = more luminous

Pan-STARRS1: Sanders et al. 2015
CSP: Anderson et al. 2014
Models from Kasen & Woosley (2009) compared to data from PS1 (Sanders et al. 2015)

Very few of the models overlap in parameter space with the data!
Most objects have plateau durations of $90 \pm 20$ days.

Model grids generally produce a wider variety of plateau durations (e.g., 0.3B explosions with 180d plateaus: Kasen & Woosley 2009; Dessert et al. 2013).

This may reveal hidden correlations, see Poznanski (2013).
NICKEL PRODUCTION

- $M_{\text{Ni}}$ is perhaps the easiest fundamental observable to measure— can easily scale to 87A

- 2 orders of magnitude spread in nickel production: few $\times 10^{-3} M_{\odot}$ — few $\times 0.1 M_{\odot}$

PS1: Sanders et al. 2015

Müller et al. 2017
Inferred mass of nickel correlates with plateau luminosity and with Fe velocity—both proxies for explosion energy (Hamuy 2003).

- Inferred mass of nickel correlates with plateau luminosity and with Fe velocity—both proxies for explosion energy (Hamuy 2003)

Valenti et al. 2016

Pejcha & Prieto 2015
Basic idea to apply Baade-Wesselink method for variable stars (Kirshner & Kwan 1974)

$L = 4\pi R^2 \sigma T^4$

$R$ from velocity $\times$ time

$T$ from color

But $T_{\text{col}} \neq T_{\text{eff}}$, so correction factors are required
A single measurement of the Fe II velocity on the plateau or the decline rate on the plateau (combined with a color) gives a respectable correlation with luminosity.
SNE II IN LSST

- Light curves of Type IIP supernovae are easy to recognize and classify with high confidence even in the absence of a spectrum.

- But note the negative consequences of long intrinsic timescales (plus some time dilation) and short observing seasons.

- Also, the fast rise is not well-suited to the “standard” LSST cadence.