The circumstellar media of superluminous SNe

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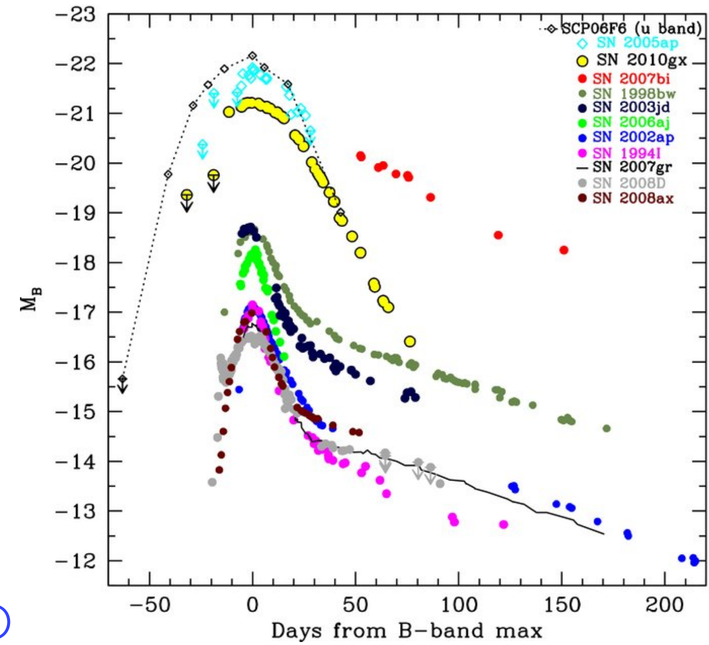
R. Lunnan, P. M. Vreeswijk, S. E. Woosley, S. Schulze, Lin Yan ….
and the iPTF and ZTF SLSN collaborations

Superluminous Type I SNe

Pastorello+ 2010



Mag < -21 → Peak luminosities > 10^{44} erg s^{-1}

Radiated energy up to ~10^{51} ergs

Type I: No H, Type II: Strong H lines

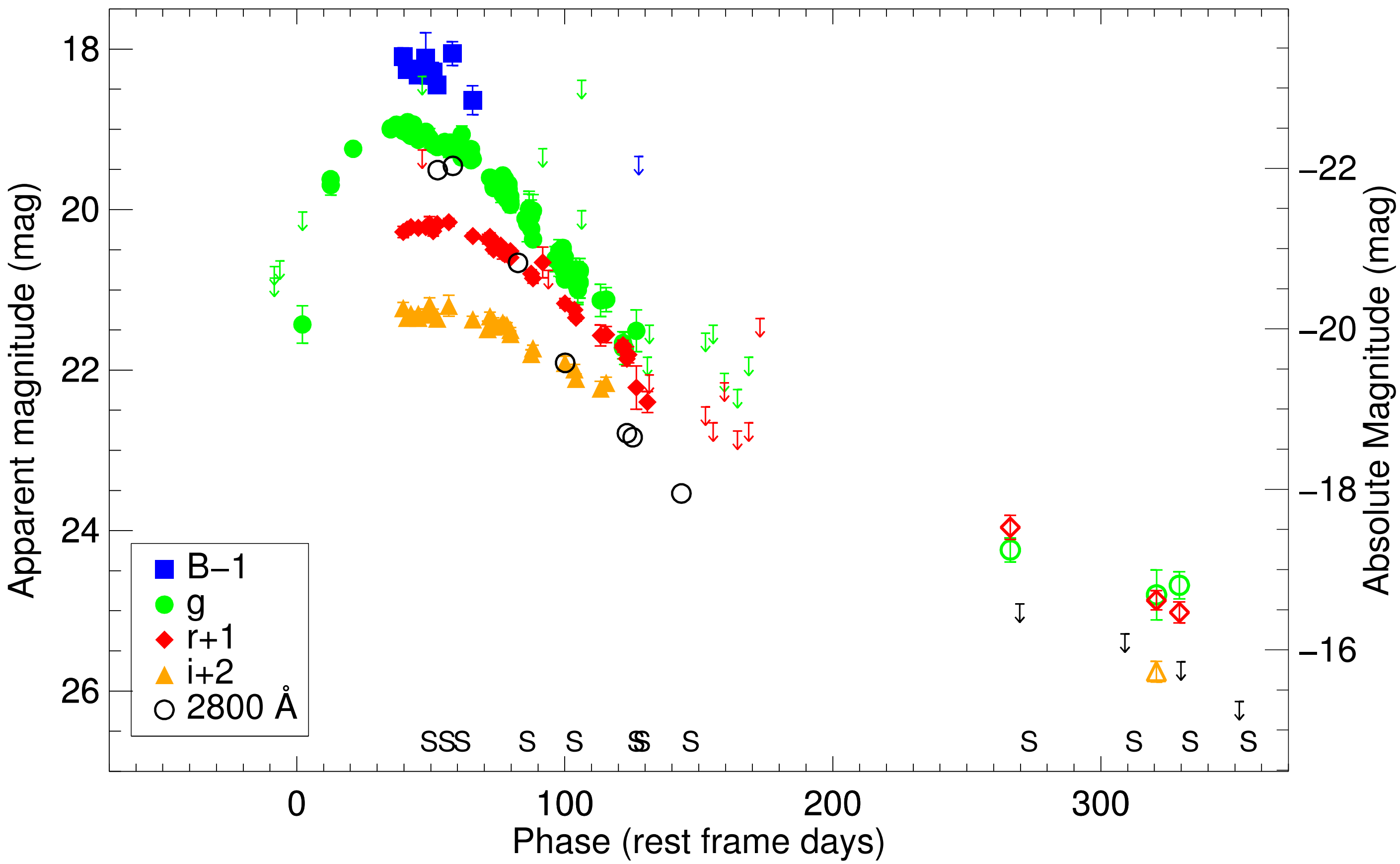
Models:

- Magnetar M_{ZAMS} ?
- Pair instability explosions. $M_{ZAMS} > 140\ M_\odot$
- CS interaction: Works well for Type II (with H) and bright IIns. Proposed for Type I.
- Pulsational pair instability + CC $80 < M_{ZAMS} < 140\ M_\odot$. Probably end as massive 30 – 40 $M_\odot$ (LIGO BHs?)

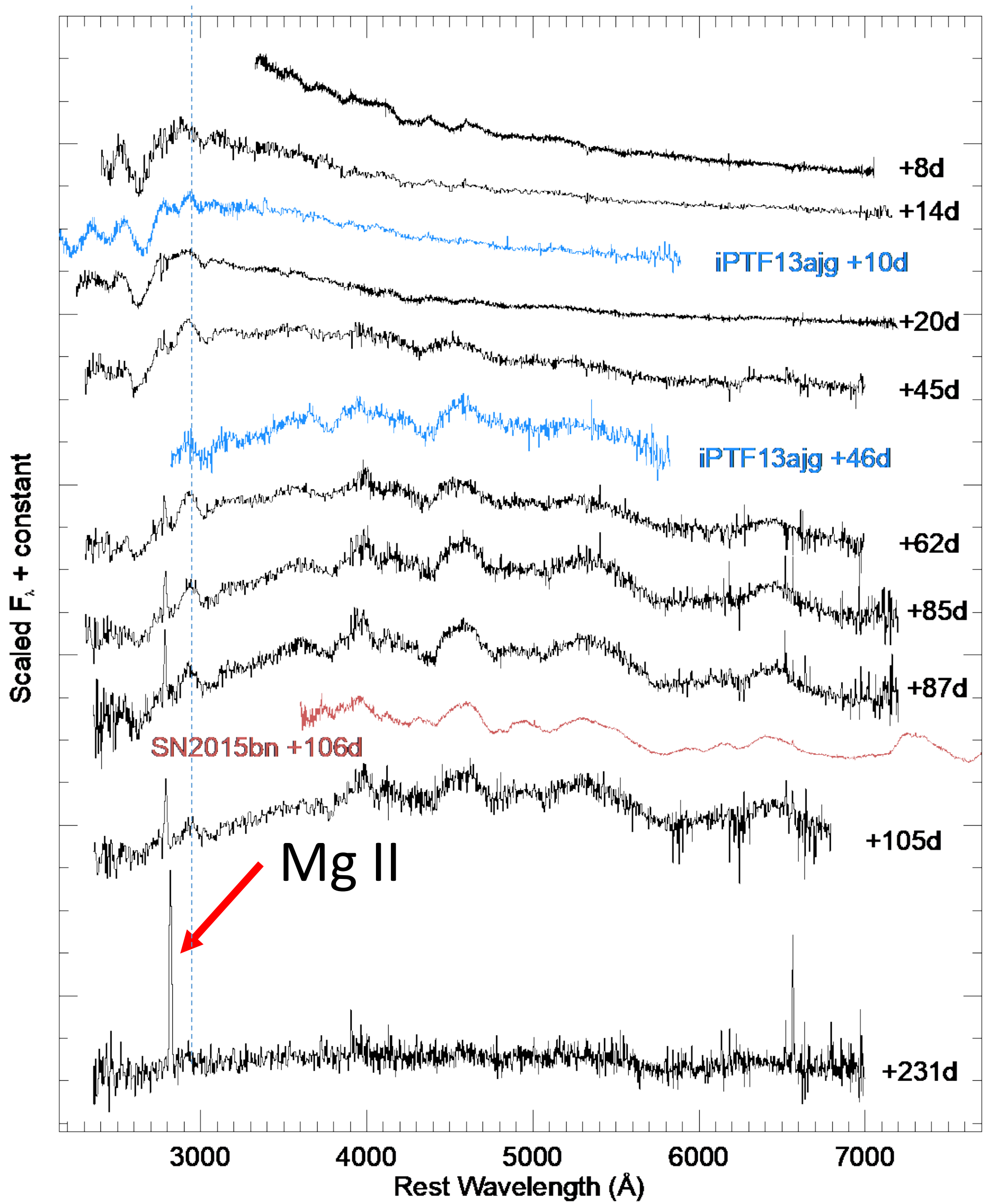
At least the last two require/predict a dense CSM. Where is the direct evidence for this in the Type I SLSNe? No narrow lines seen as for the Type IIn Sne.

The Type I SLSN iPTF 16eh.

R. Lunnan, CF, Vreeijswijk, Woosley+,
Nature Astronomy 2, p. 887, 2018.



At peak g ~ -22.5. Upper range of luminosity

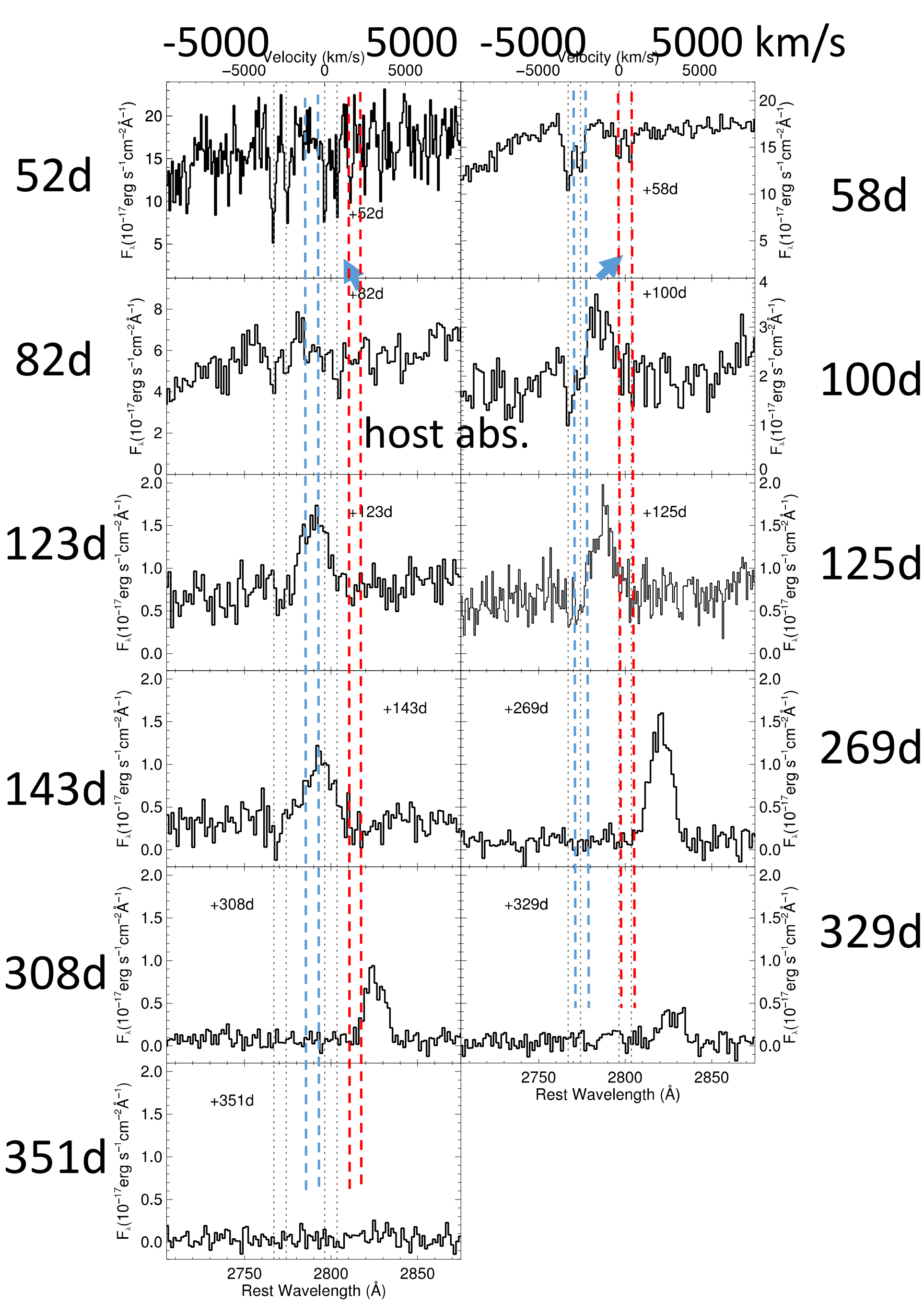


z = 0.428 → UV spectrum to ~2500 Å

No H or He lines: Fairly 'ordinary' superluminous Type I SN

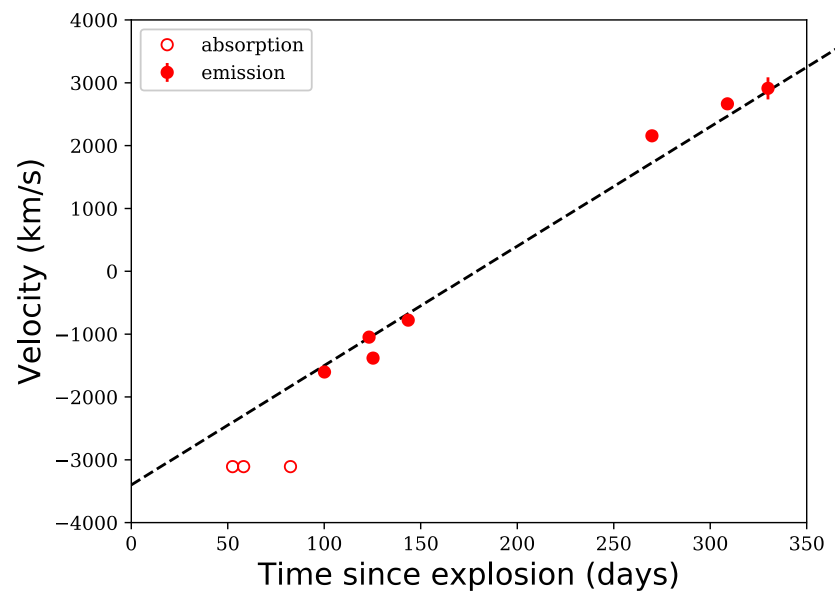
Main exception: Strong Mg II 2795.5, 2802.7 emission at late epochs

Mg II 2795.5, 2802.7 Å

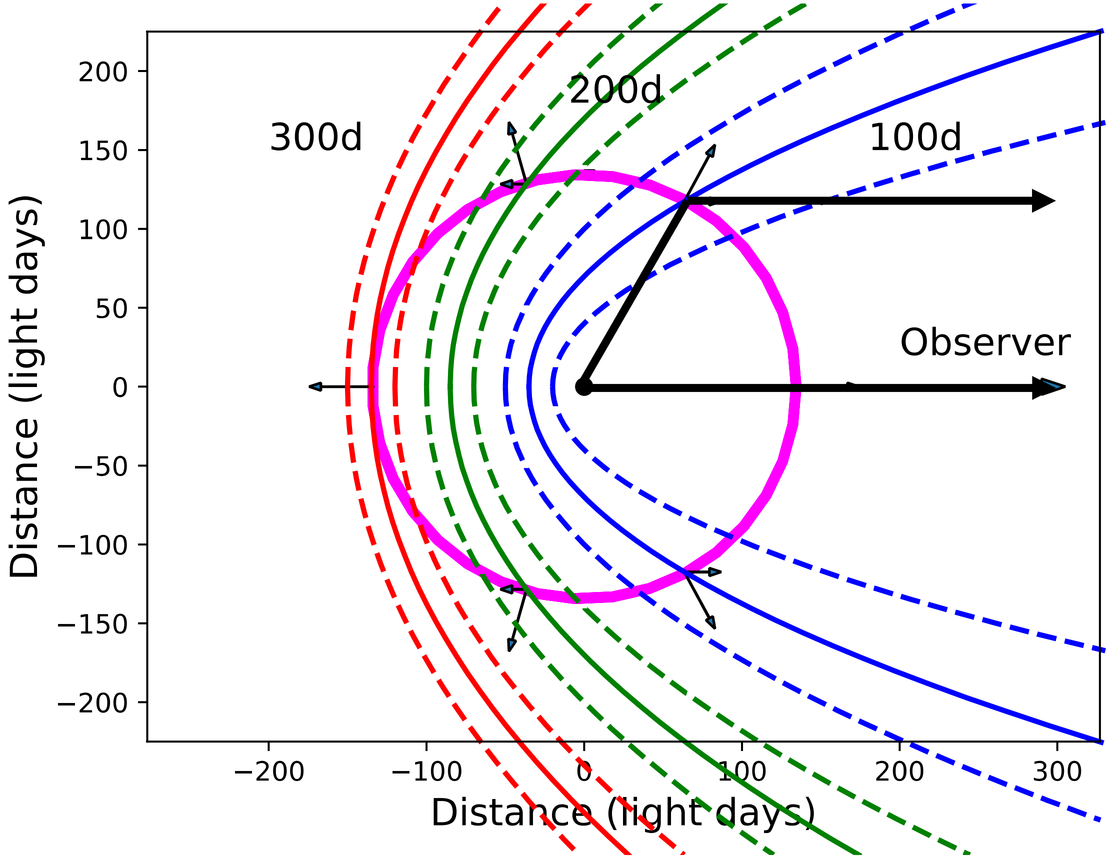


Initially absorption, later emission

Line moves from -3300 km/s to + 3300 km/s during ~350 days



Redshift evolution natural effect of a light echo produced by resonance line scattering.

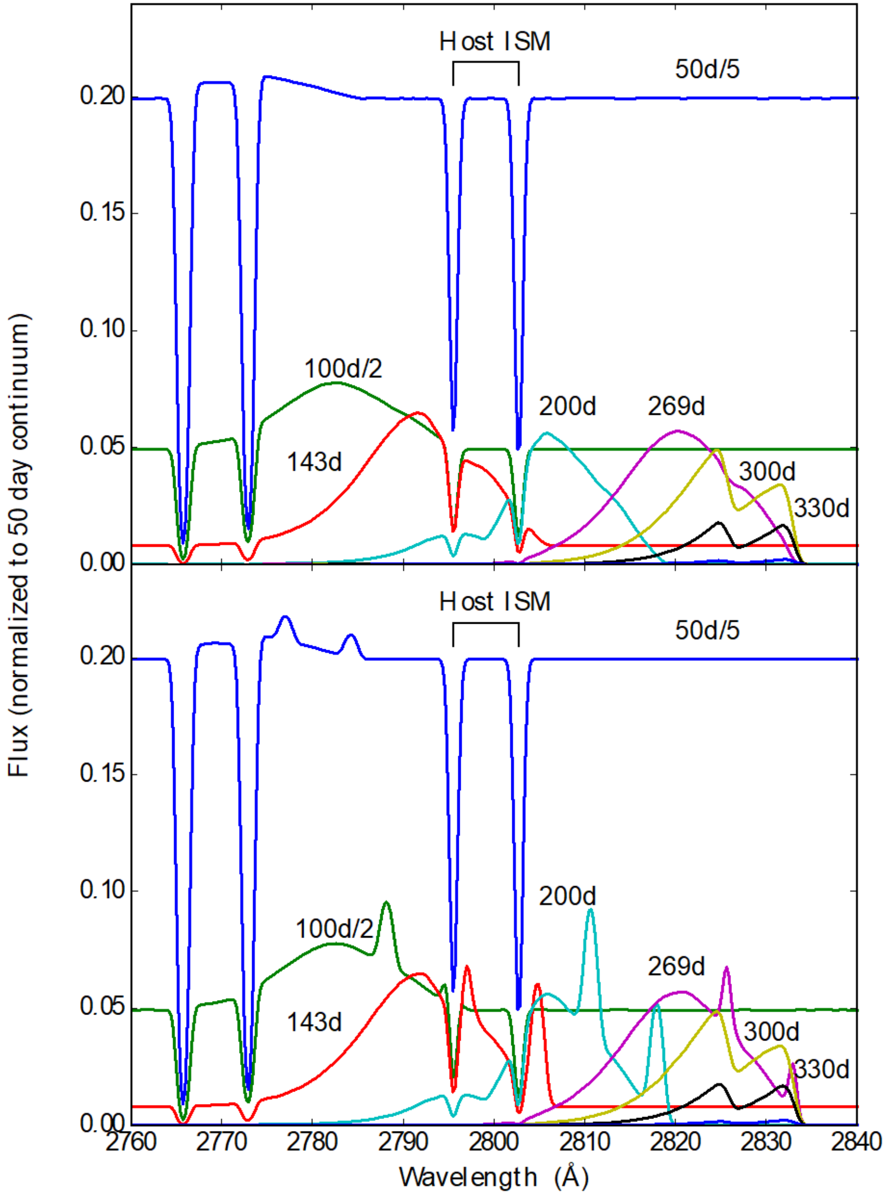


Requires the shell to be expanding and $t_{SN} << R_{shell}/c$

Early emission: blueshifted (if photospheric emission strong: absorption)

Late emission: redshifted

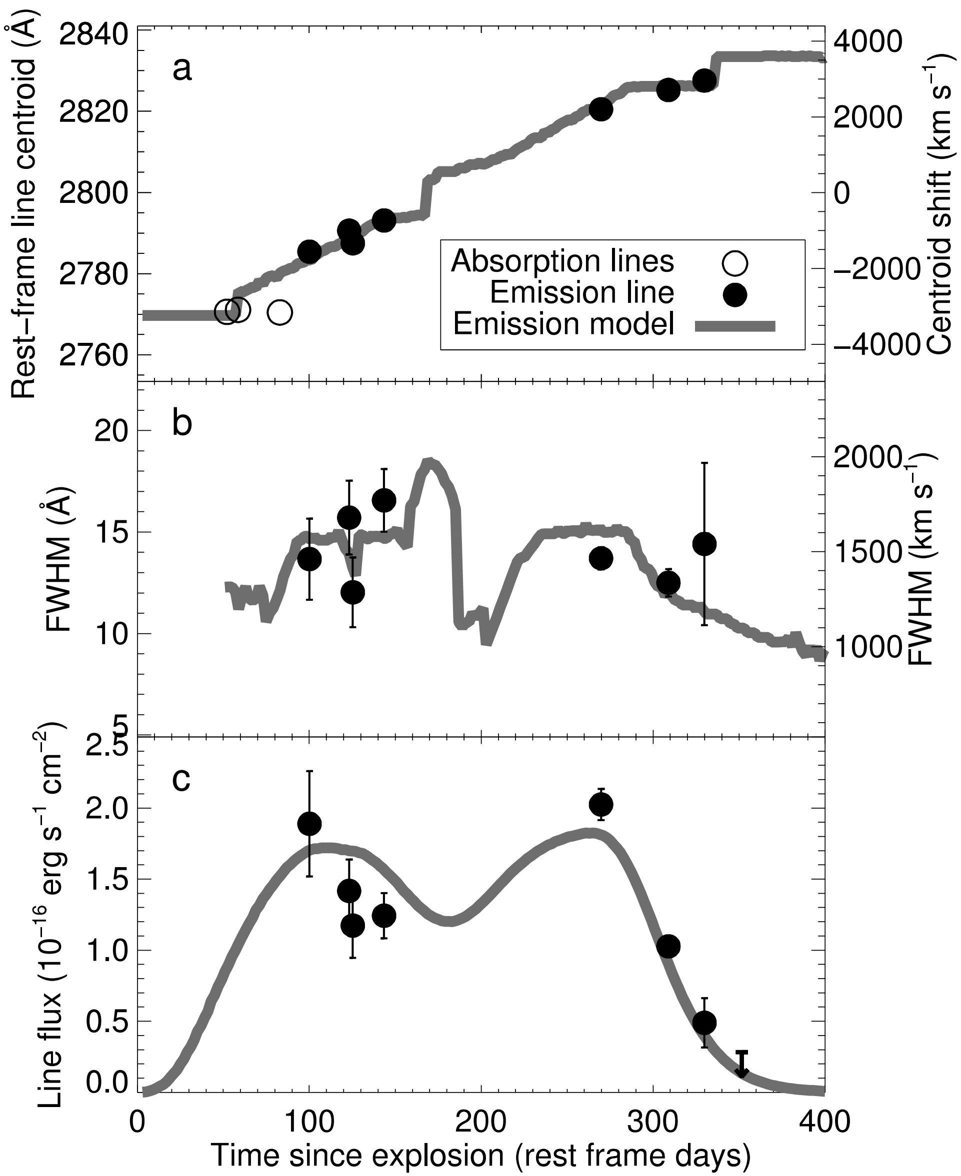
Monte Carlo calculation of line scattering of photospheric continuum at 2800 by Mg II 2795.5, 2802.7 Å from CS shell



Photospheric continuum from observations (after ~50 days)

Standard light curve

With early burst. Can be excluded!



- Peak velocity of absorption/emission line shift from -3200 to + 3400 km s^{-1} on a time scale of ~350 days
- FWHM nearly constant ~ 1500 km s^{-1}
- Emission line flux

Distance to shell ~ 130 light days, i.e. 3.4×10^{17} cm

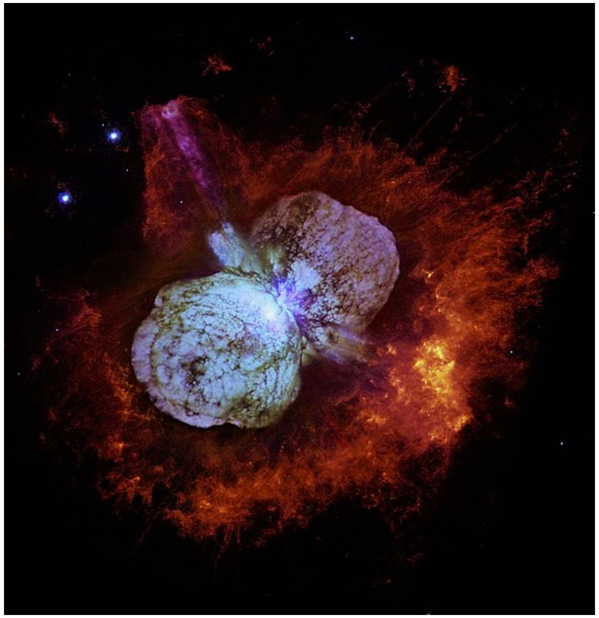
Thin shell 130 – 137 light days

Linear velocity evolution → Close to spherical.

Velocity ~ 3300 km s^{-1} → Time scale since ejection ~ 32 years.

Origin of shell:

Previous LBV-like ejection? Cf. Eta Car (shell velocity 2000-6000 km s^{-1}). Likely to be too asymmetric for velocity and light curve evolution



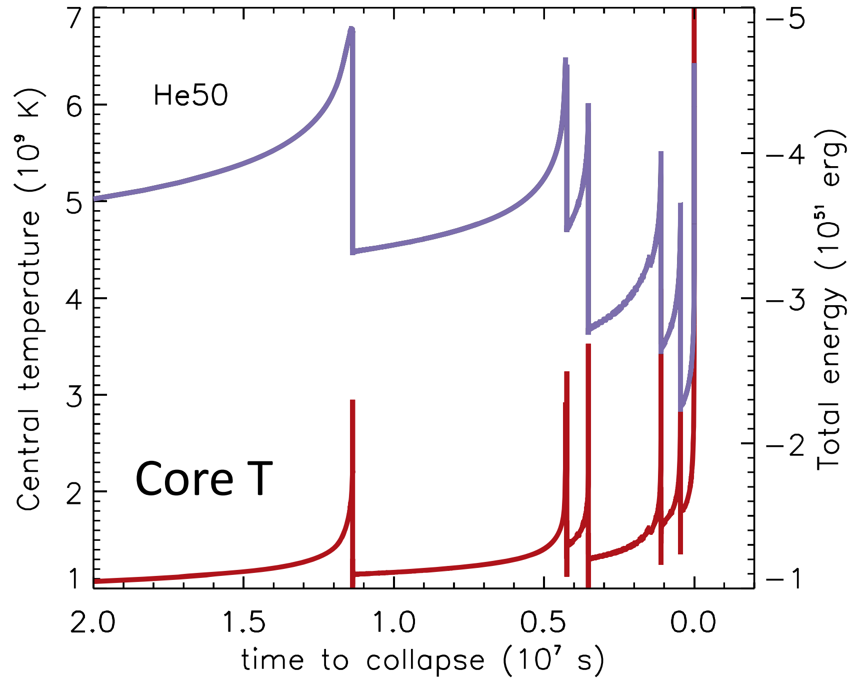
N. Smith

Pulsational pair-instability ejection

(e.g., Woosley, Blinnikov, Heger 2007, Woosley 2017, Sorokina+ 2016, Leung+ 2019…).

$40\ M_\odot < M(\mathrm{He}) < 65\ M_\odot$
Pair creation removes pressure
→ collapse, increase in T →
unstable O burning →
expansion and mass ejection

Mass ejections after each pulse.
Ejected mass 1 – 10 $M_\odot$,

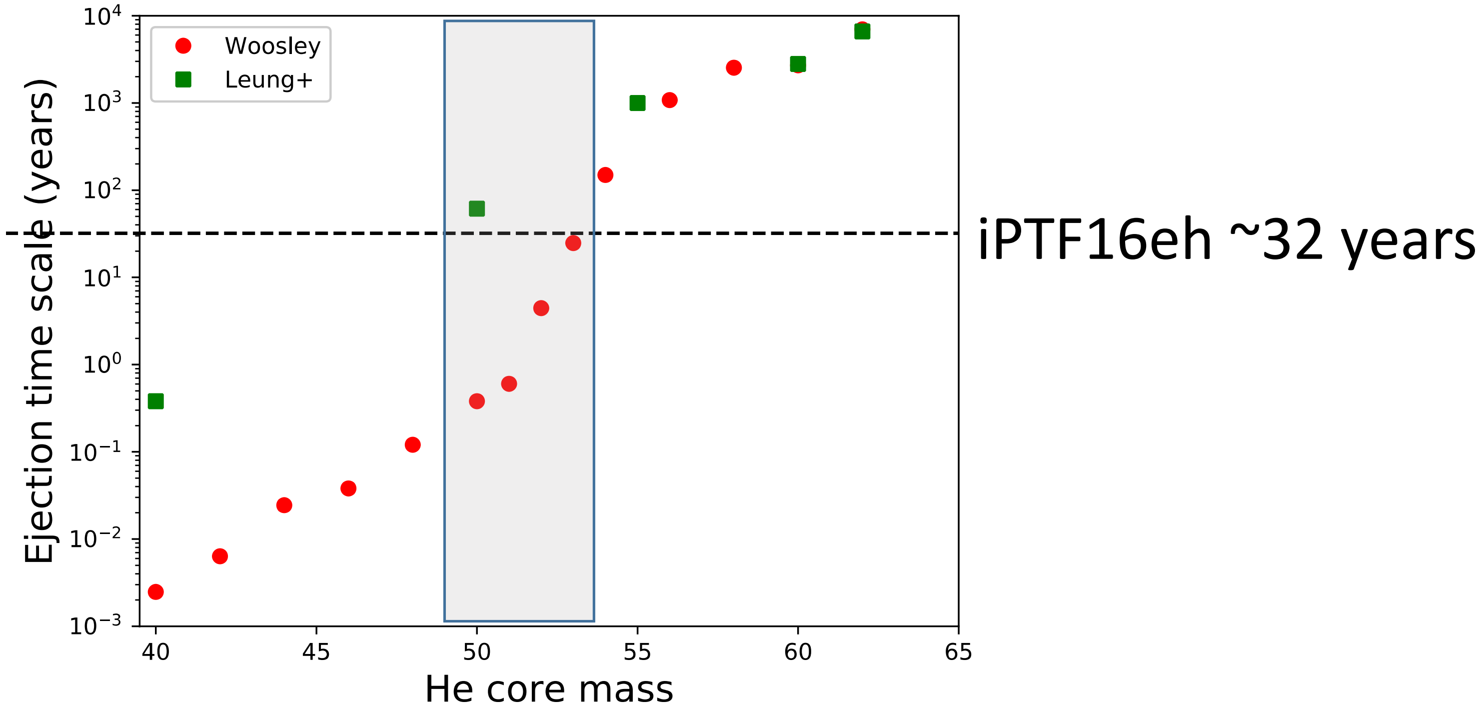


Woosley 2017

Time scale between last major pulse and core collapse sensitive to He core mass

Woosley 2017

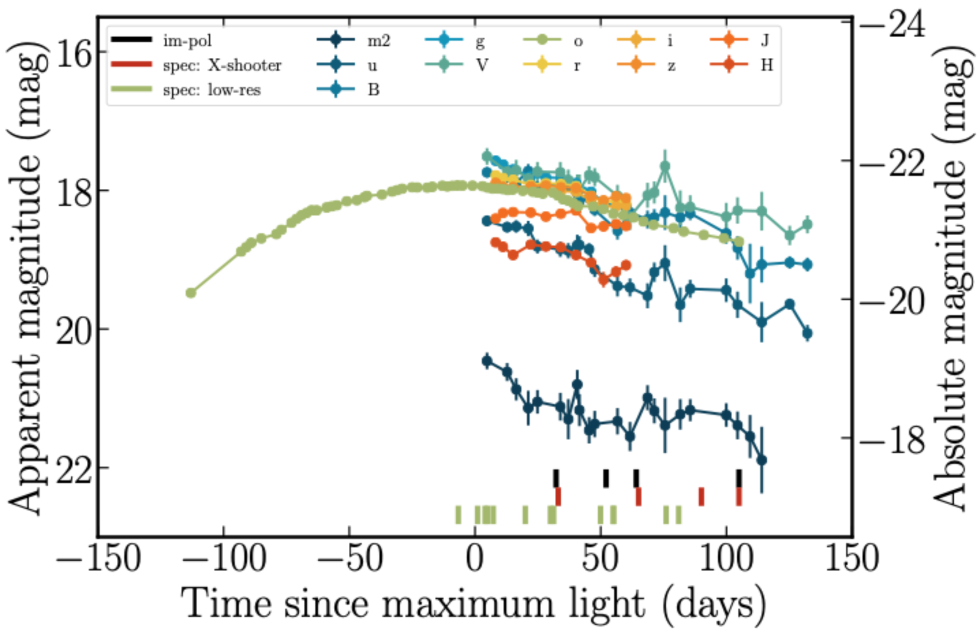
Leung et al. 2019

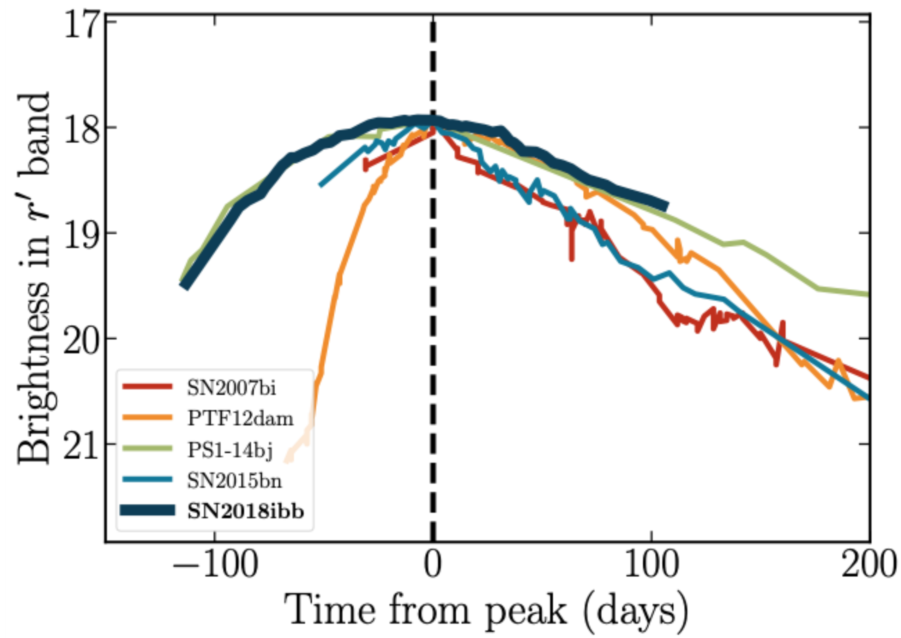


- Time scale of 32 years consistent with final ejection from a ~ 50 - 54 $M_{\odot}$ He-core model (ZAMS-mass 100-120 $M_{\odot}$).
- Velocity 2000 - 3000 km/s, insensitive to He-core mass for bare He-cores. Close to observed.

Is iPTF16eh unique? SN2018ibb

S. Schulze et al 2019, in prep.





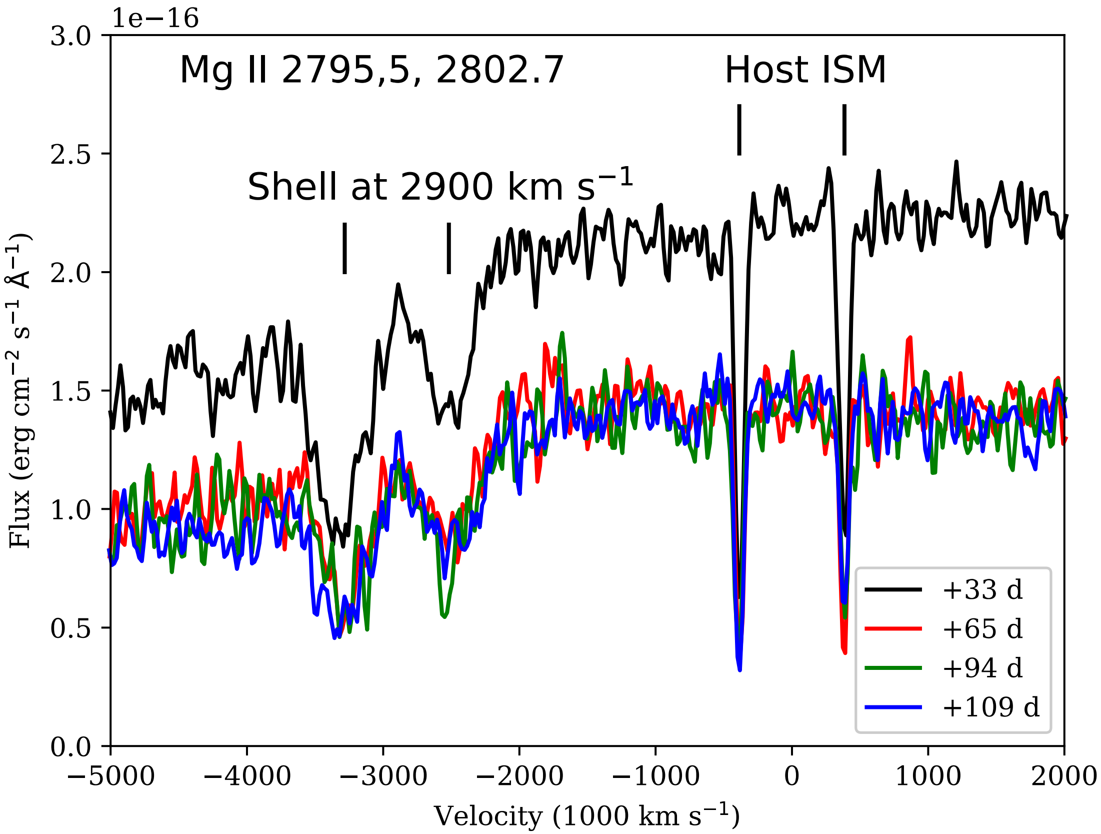
Discovered Nov. 2018

z = 0.166

Peak magnitude r -21.8

Very slow evolution, similar to SN 2015bn

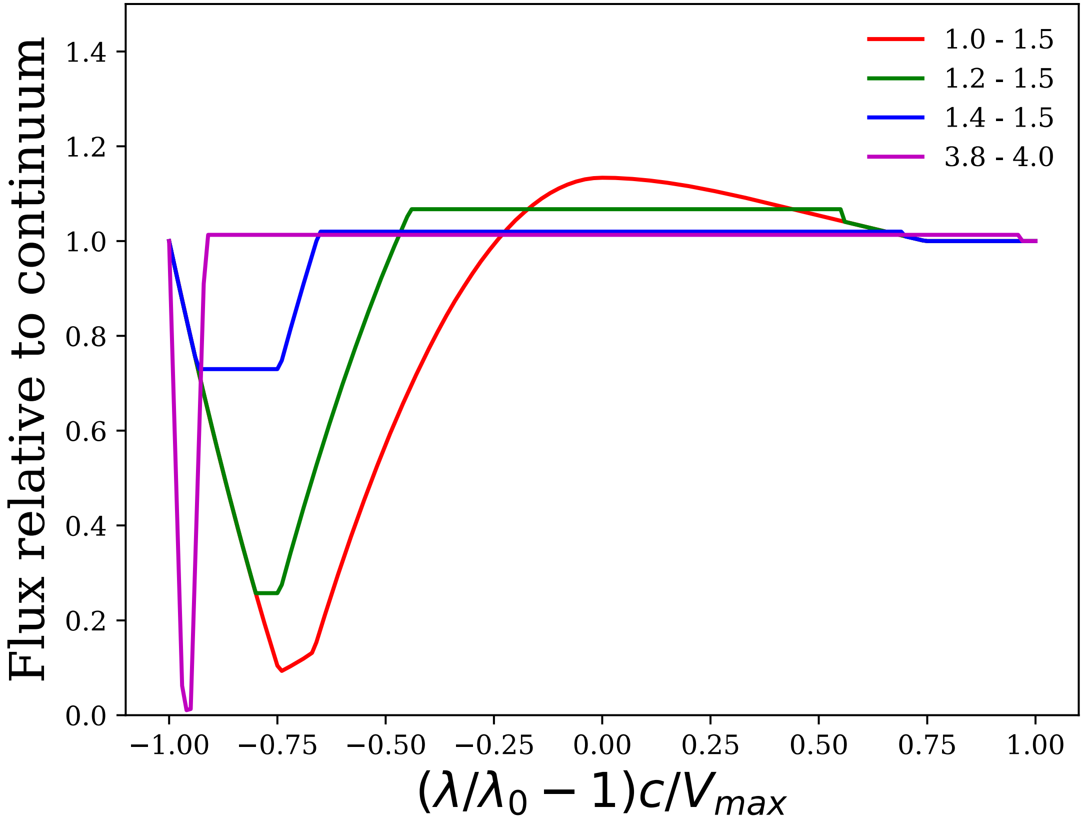
At high resolution: VLT X-shooter spectra



Schulze et al 2019, in prep.

- Mg II lines shifted by 2900 km/s to blue
- Weak P-Cygni emission
- Wide lines ~ 700 km/s (too wide for intervening galaxies)
- Little evolution in line profile or velocity shift from +33 to +109 days

- No echo seen, but need the SN to fade.
- Absorption line profile gives information about location relative to SN and velocity within the shell. Modeling ongoing.



Singlet line with different shell extents relative photosphere
1 – 1.5
1.2 – 1.5
1.4 – 1.5
3.8 – 4.0

Other cases of CSM signatures: Hα in iPTF13ehe

Yan et al., 2015, 2017

Strong, broad Hα ~ 325 days from explosion

Velocity width > 4000 km s^{-1}

Shell radius ~ 4×10^{16} cm

Excitation not clear: Shocks, X-ray photoion., ….

How common are shells around Type I SLSNe?

Many selection effects against shell detections:

- Mg II 2795, 2803 → $z > 0.15$
- Bright enough for high resolution spectroscopy
- Frequent monitoring especially at late epochs for echo when SN faded
- For echo $R_{shell} > c\, t_{decay}$
- Large variety in ejection time scale and therefore R_{shell} from PPI models (months to decades)

Can be very common.

Conclusions

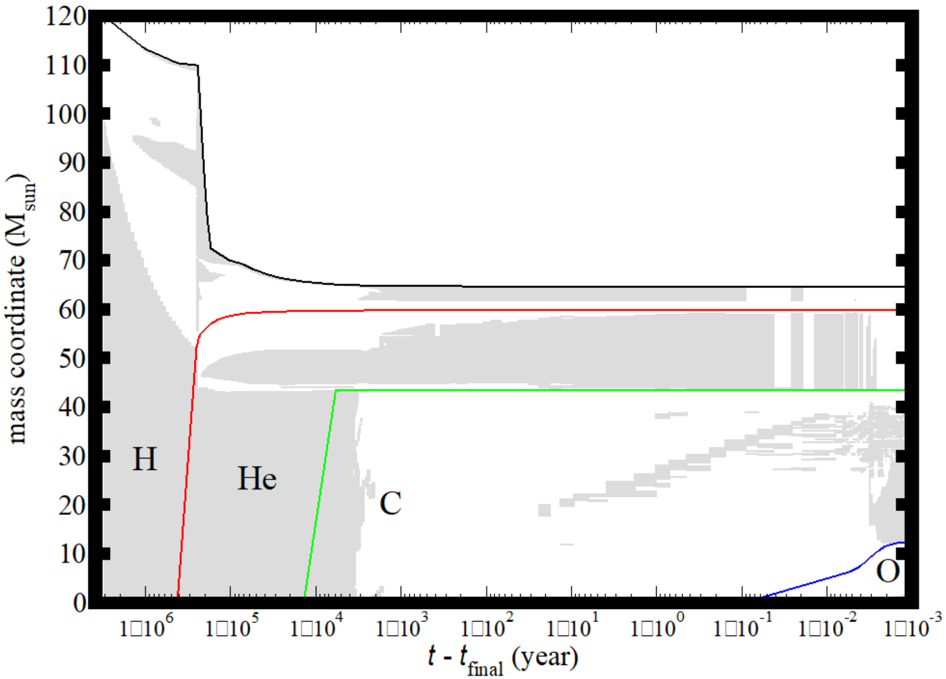
Resonance line echoes very useful for deriving shell properties

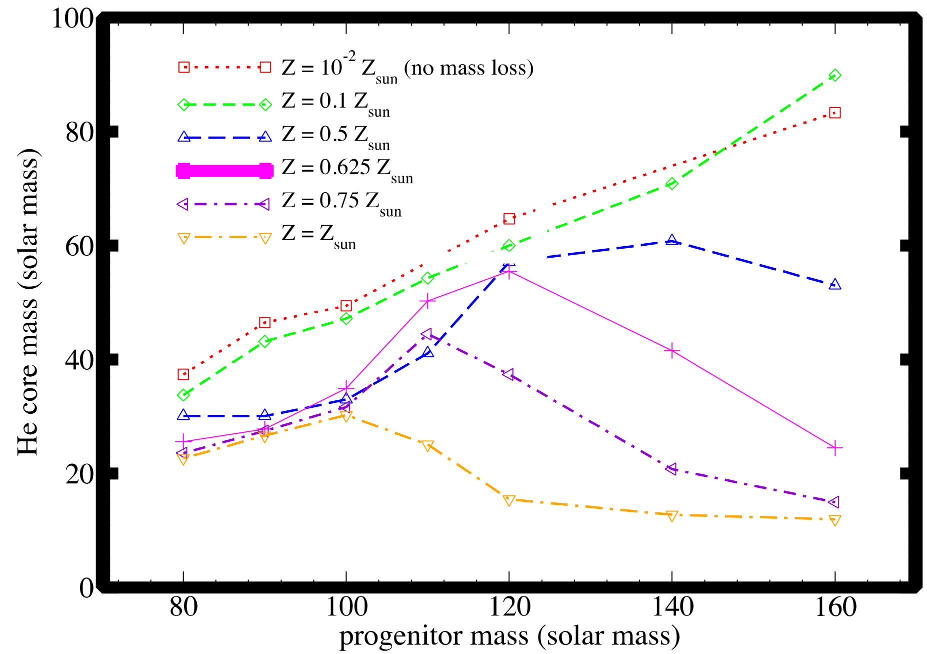
Shell in iPTF16eh consistent with pulsational pair instability ejection of ~ 53 $M_\odot$ He core (~100-120 $M_\odot$). Likely to have collapsed to a massive BH.

iPTF16eh not alone, but only one with an echo (yet)

At least some Type I SLSNe have massive shells. This fraction can be large due to selection effects. More monitoring of luminous cases needed.

Far UV best region: Chemical composition, strong lines… Many resonance lines from high (C IV, NV, Si IV..) and low (C II, O I, Fe II) ionization ions in UV → HST


mass coordinate (M_{sun})
H
He
C
O
t - t_{final} (year)


Z = 10^{-2} Z_{sun} (no mass loss)
Z = 0.1 Z_{sun}
Z = 0.5 Z_{sun}
Z = 0.625 Z_{sun}
Z = 0.75 Z_{sun}
Z = Z_{sun}
He core mass (solar mass)
progenitor mass (solar mass)