Probing pre-supernovae mass loss using double-peaked Type Ibc SNe from ZTF

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Zwicky Transient Facility (ZTF): A Supernovae Factory

ZTF | Fast *(30s exp.)* & Large *(full visible sky)* [Not Deep]

- Two **legacy-scale** survey projects:

§ **Bright Transient Survey** (BTS/"RCF")

: Magnitude-limited Survey

§ **Census of the Local Universe** (CLU)

: Volume-limited Survey

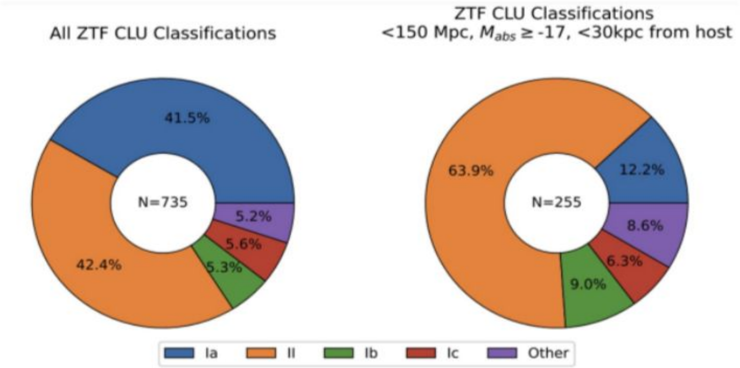
Census of the Local Universe Survey

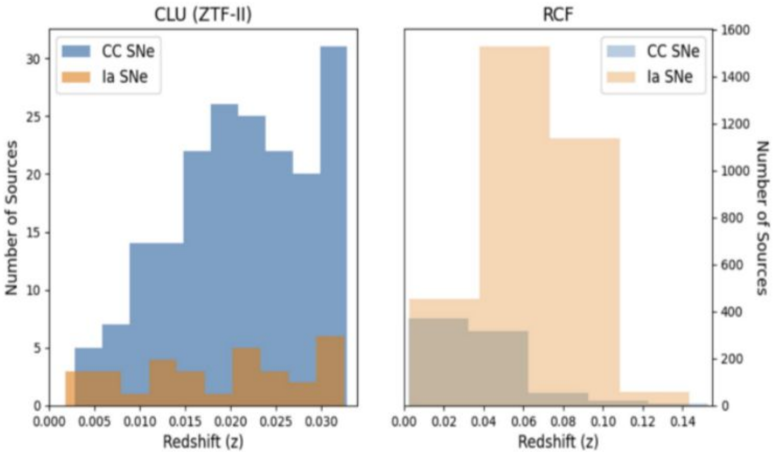
- Record every transient < 200 Mpc (based on galaxy crossmatch)

- Classify every transient < 150 Mpc unless brighter than -17 mag

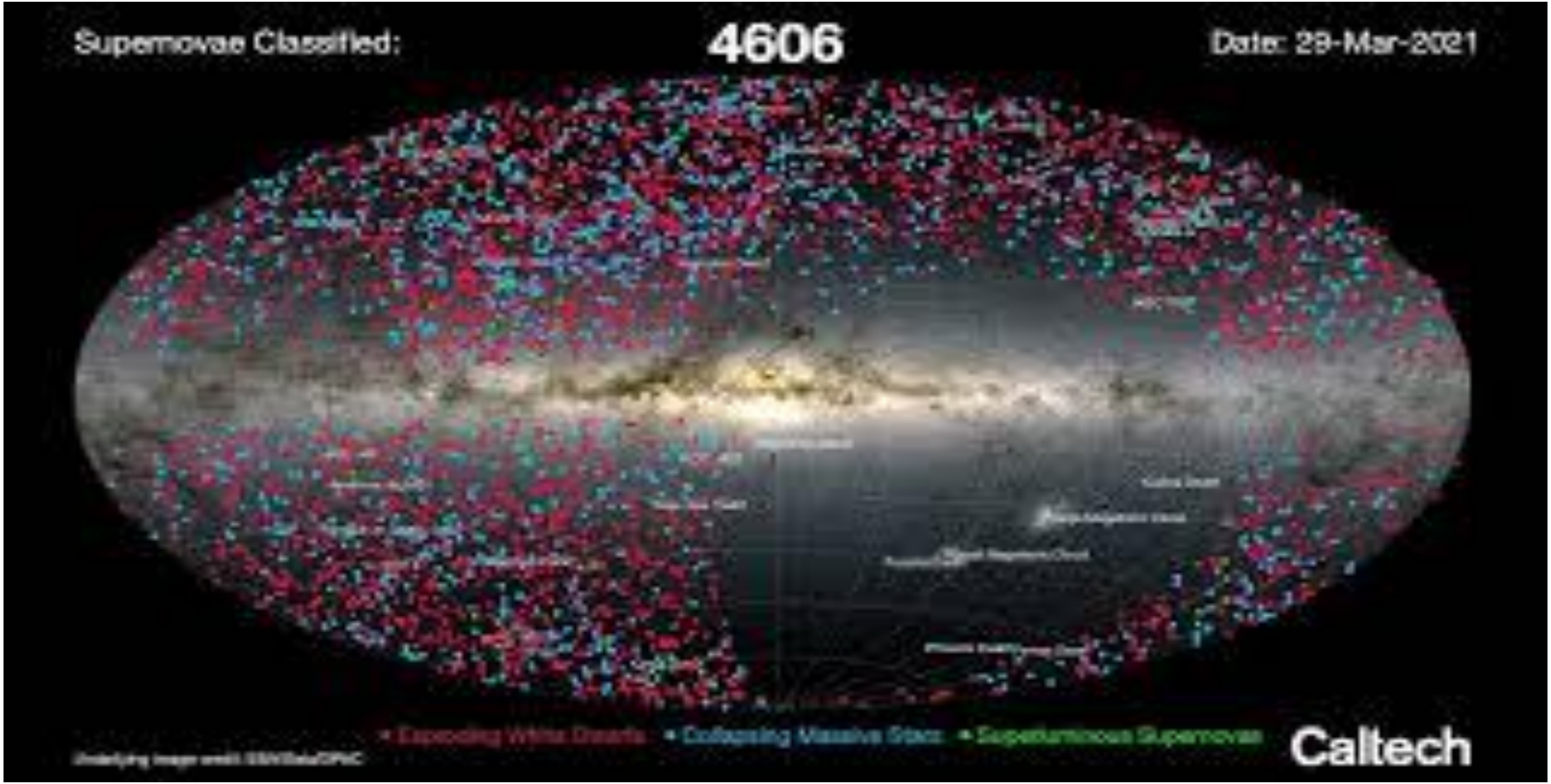
Crucial for the faintest transient Populations:

- Obscured SNe
- Low-luminosity SNe (faint end LF)
- "Gap" transient populations



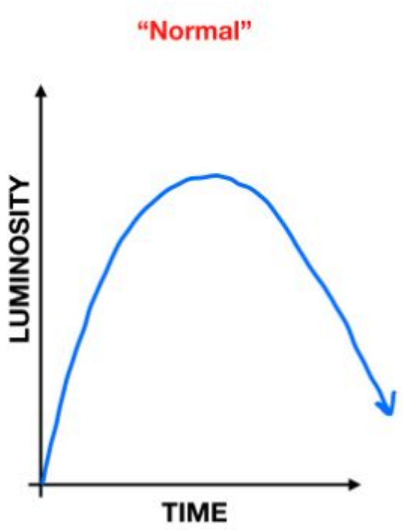


ZTF: A Supernovae Factory

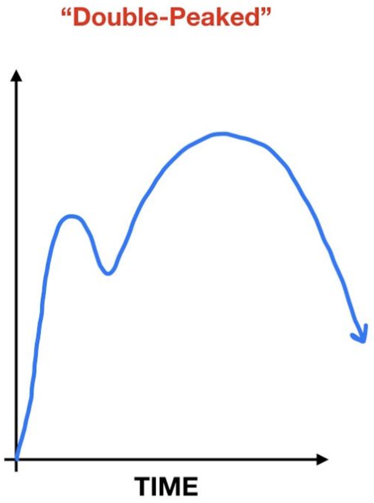


Credits: Christoffer Fremling

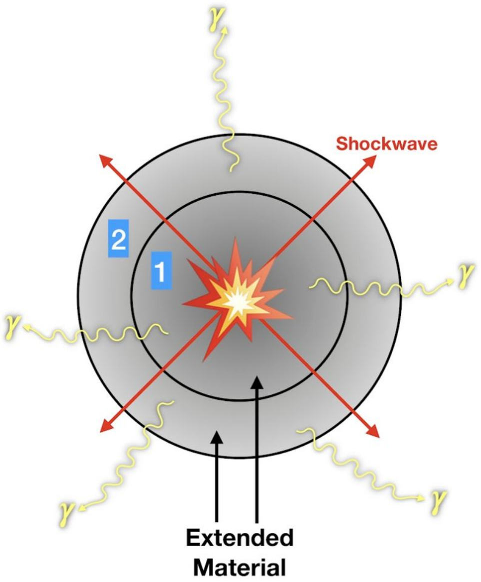
MOTIVATION: WHAT ARE DOUBLE-PEAKED SN?



Powered by radioactive decay



Early bump is too fast, bright and blue



After core-collapse, a shockwave runs through outer layer, and in its wake the layer cools

Source: astrobites.org

MOTIVATION

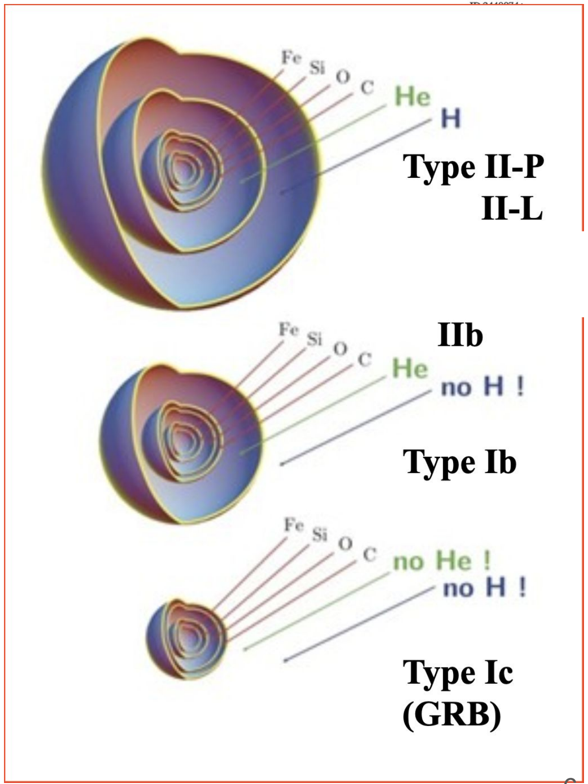
Type IIb SNe -> extended envelope -> early bump common

Type Ibc SNe are thought to arise from compact stars,

What gives rise to the first-bump in Type Ibc SNe?

Pre-SN mass loss?

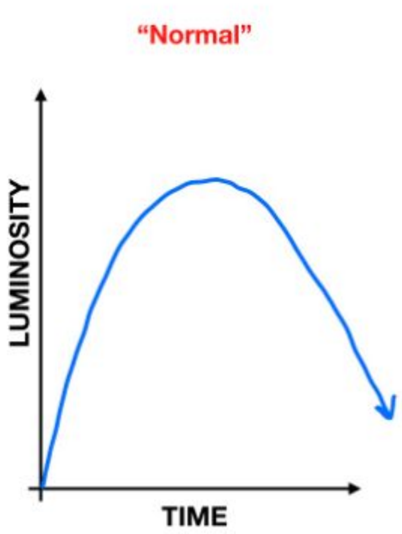
Here, the envelope/CSM is more likely to be extended material that was ejected in a mass-loss episode



SUPERNOVA INTERACTING WITH STELLAR MATERIAL

Credit: ALMA

MOTIVATION: WHAT ARE DOUBLE-PEAKED SN?



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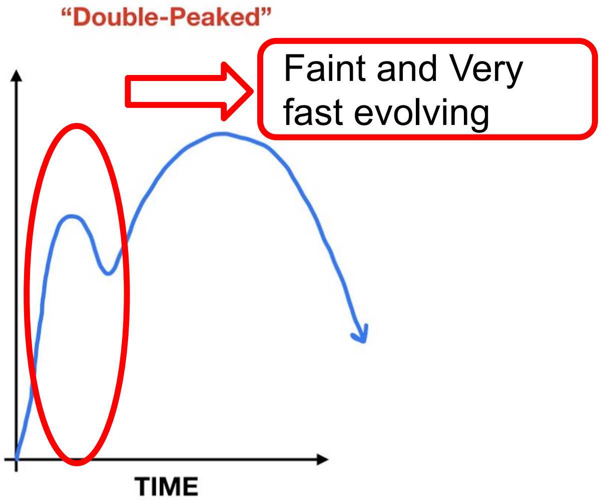

Early bump is too fast, bright and blue

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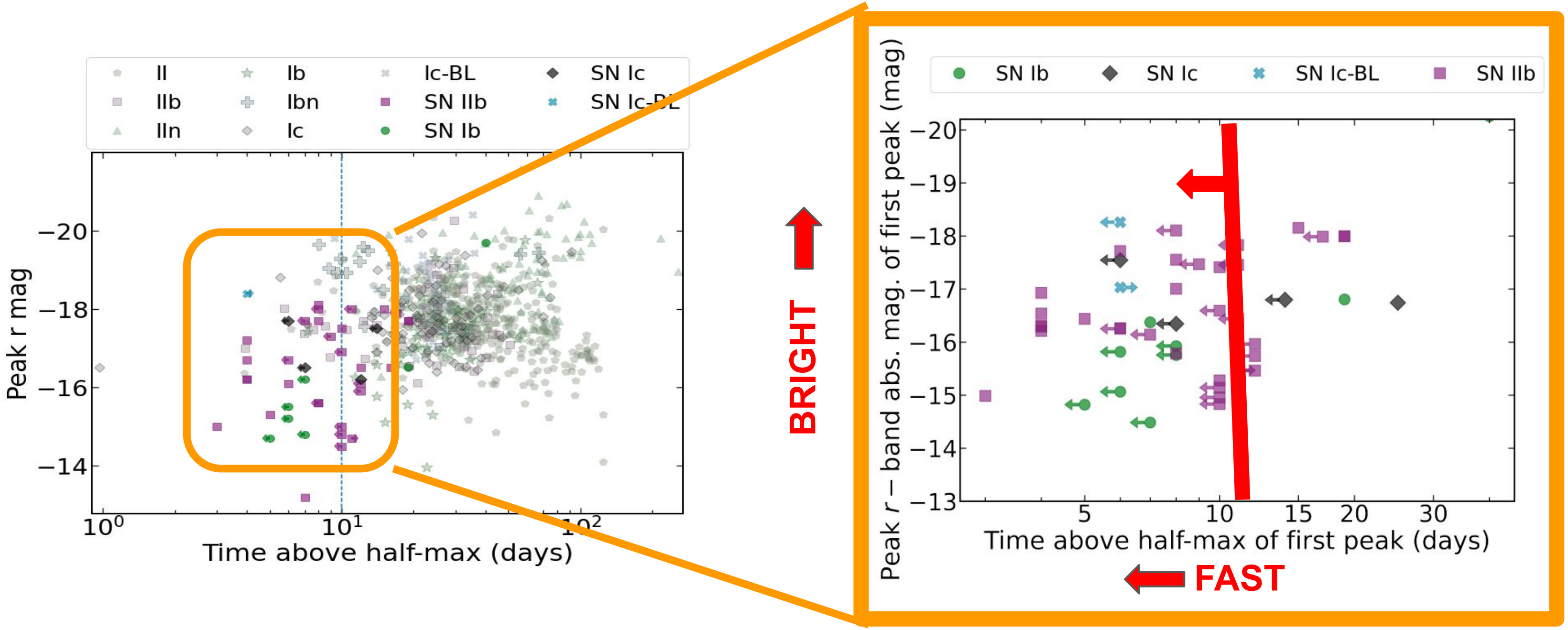
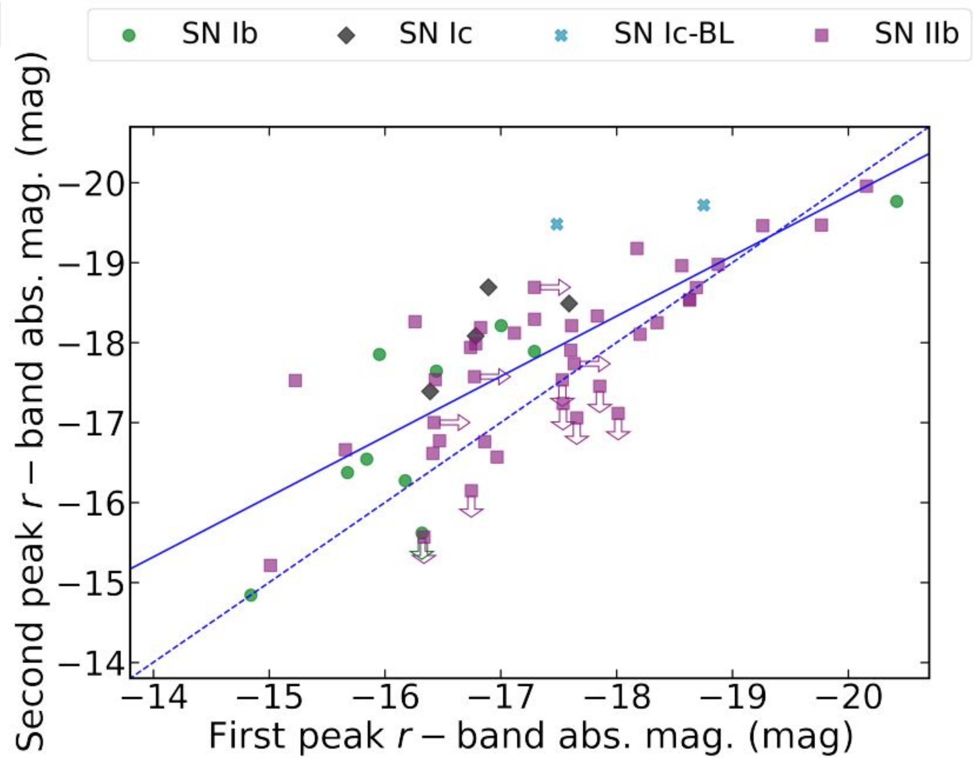
SAMPLE of DOUBLE-PEAKED TYPE Ibc SNe



17 double-peaked Type Ibc SNe out of 475 Type Ibc SNe in ZTF

Can be confused with other fast transients (e.g. kilonova) when follow-up during the first peak

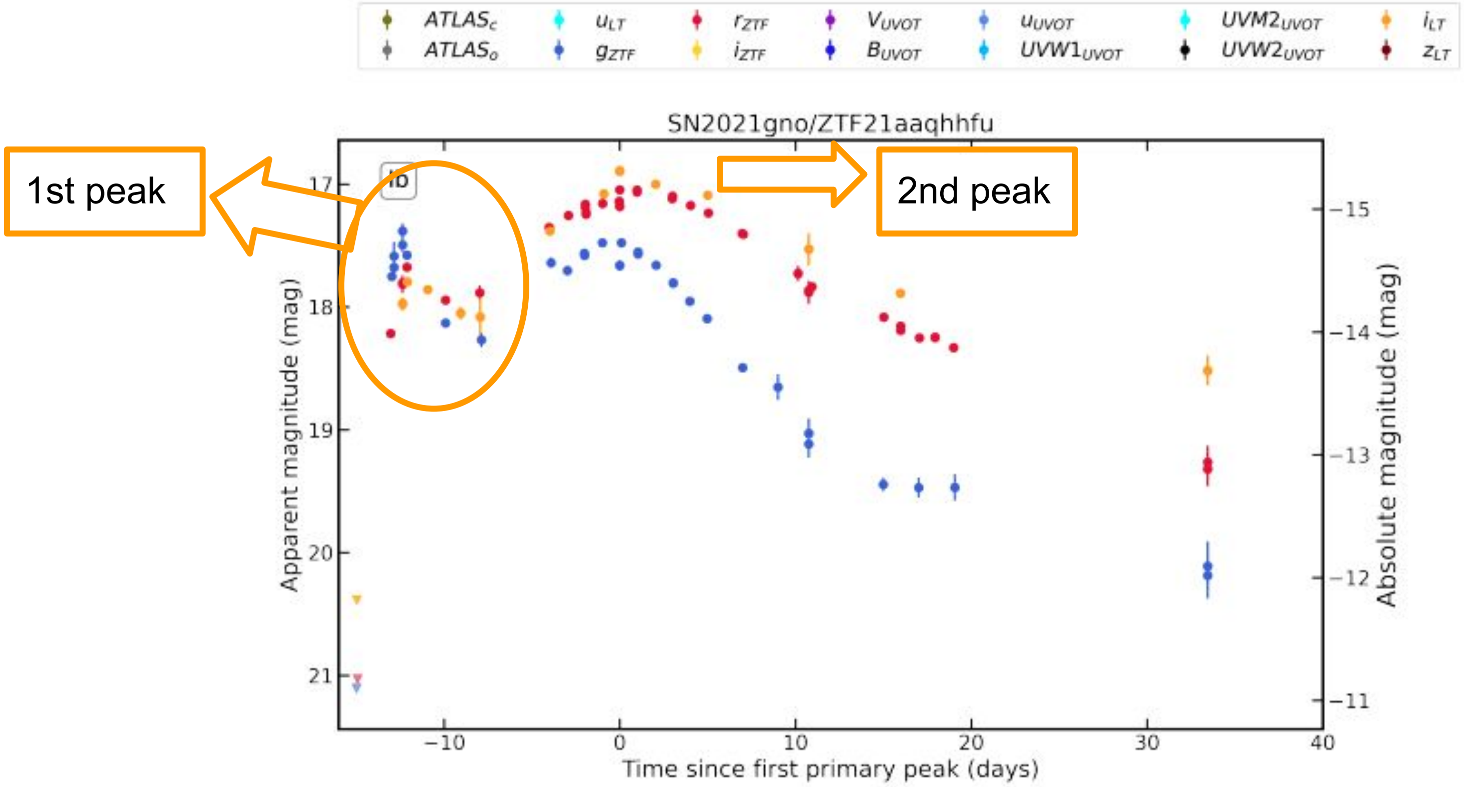
CORRELATION BETWEEN TWO PEAKS



Reason for correlation unclear

He-star main sequence?

PHOTOMETRY: Example lightcurve



PROGENITOR MASS CONSTRAINTS FROM NEBULAR SPECTRA

The nebular phase	> 100 DAYS AFTER EXPLOSION.

Nebular Phase [O I] lum. strongly depends on progenitor mass

Low [O I] luminosity

↓

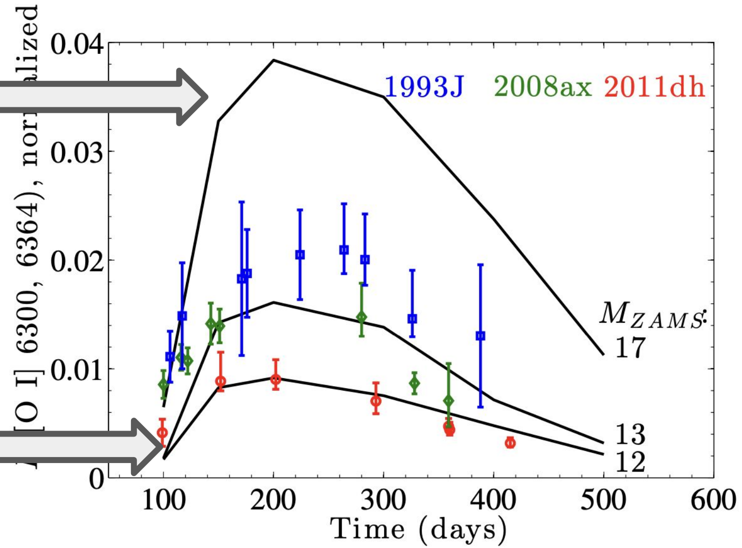
Low O mass

↓

Low progenitor mass

17 Msun

12 Msun

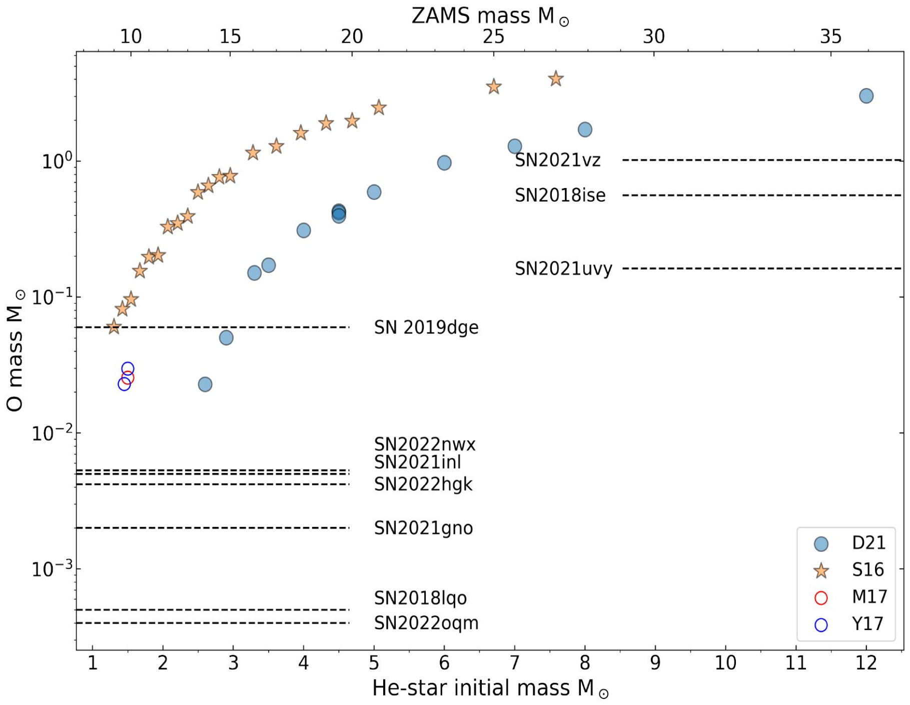


CONSTRAINING PROGENITOR MASS

Obtain nebular spectra from 100 to 300d after explosion with LRIS, Keck

Measure nebular [O I] luminosity to constrain progenitor mass

Six SNe with ZAMS mass < 12 Msun



EJECTA MASS - NICKEL MASS DISTRIBUTION

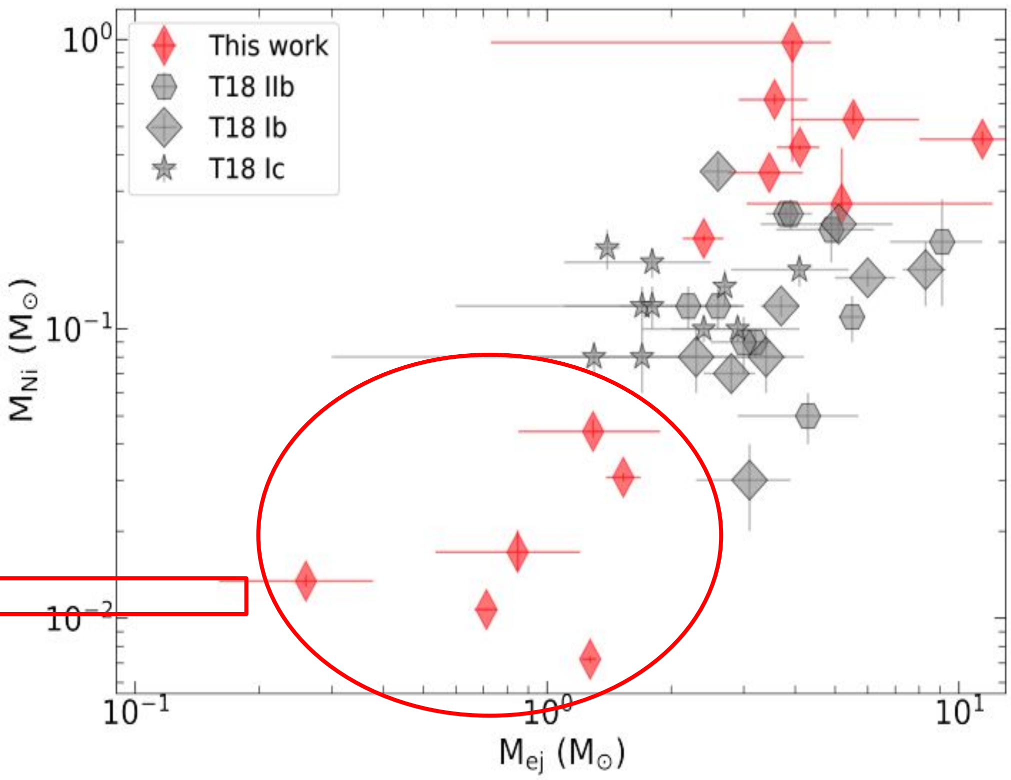
Radioactive decay powered second-peak

Six SNe with low Mej (< 1.4 Msun)

Ejecta Mass: 0.2 – 7 Msun

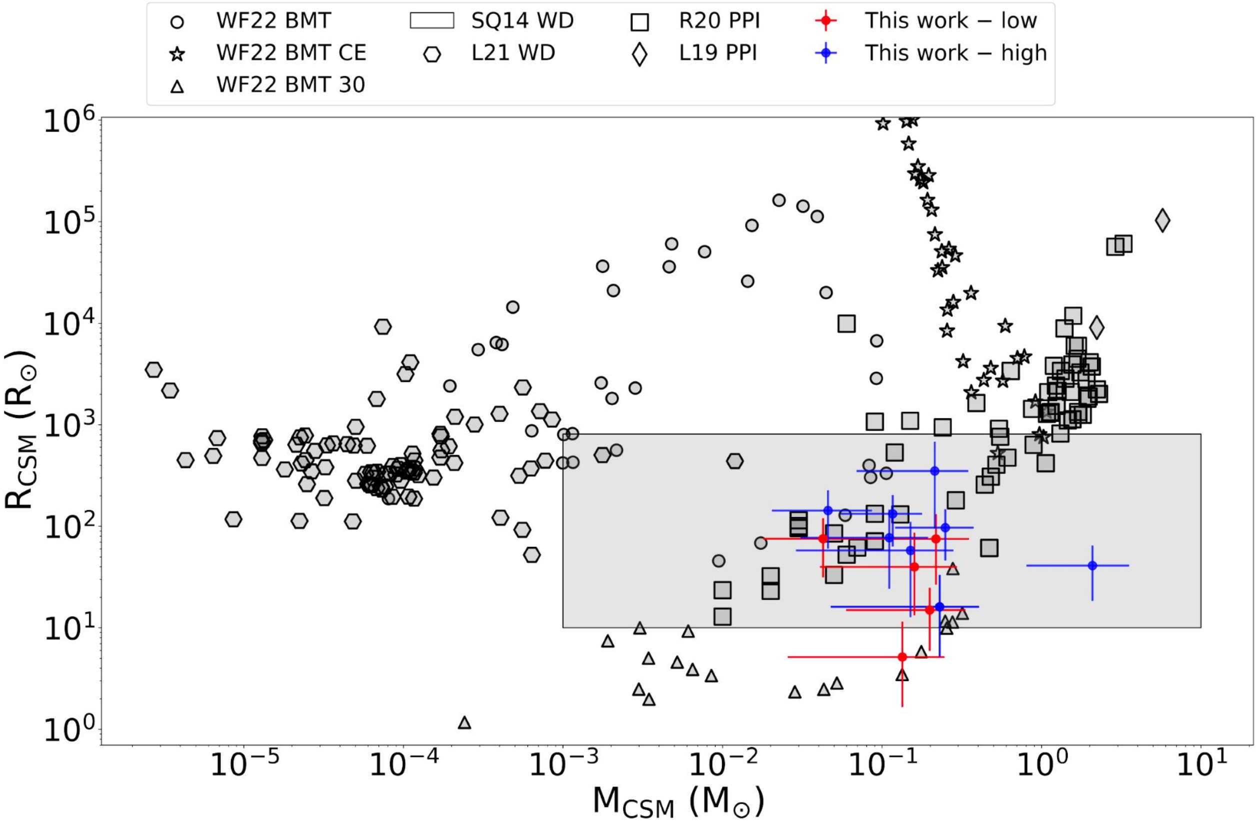
Nickel Mass: 0.01 – 0.5 Msun

Progenitor mass < 12 Msun



MASS LOSS SCENARIOS

- **Late-time binary mass transfer**
- **Wave-instability driven mass-loss**
- **Pulsational Pair-instability driven mass loss**
- **Wolf rayet wind driven mass loss**



MASS LOSS SCENARIOS

What gives rise to the first-peak?

↓

Interaction with external stellar bound/unbound material ejected in a pre-SN mass event

SNe with ZAMS < 12 Msun

- Mass transfer in binary evolution ✓
- Wave-heating mass loss ✓

SNe with ZAMS > 12 Msun

- Wave-heating mass loss ✓
- Pulsation Pair Instability ✓ ✗
- WR wind ✗

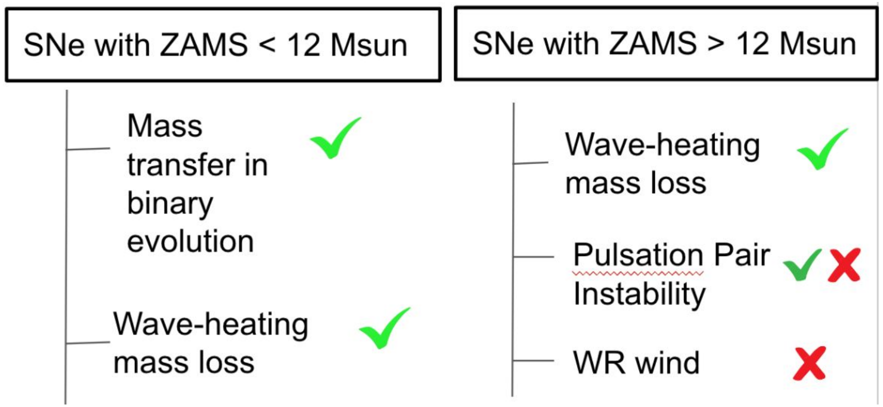
Summary/Conclusion

- **Sample of 17 double-peaked Type Ibc SNe out of a total of 475 Type Ibc SNe in ZTF.**

- **Rate ~ 3 – 9 % of all stripped-envelope SNe.**

- **Strong correlation exists between peak magnitude of the first and second peaks.**

- **Six SNe with ejecta mass < 1.5 Msun and ZAMS mass < 12 Msun.**



EXTRA

INTERACTION WITH ***UNBOUND*** STELLAR MATERIAL

MASS LOSS SCENARIOS

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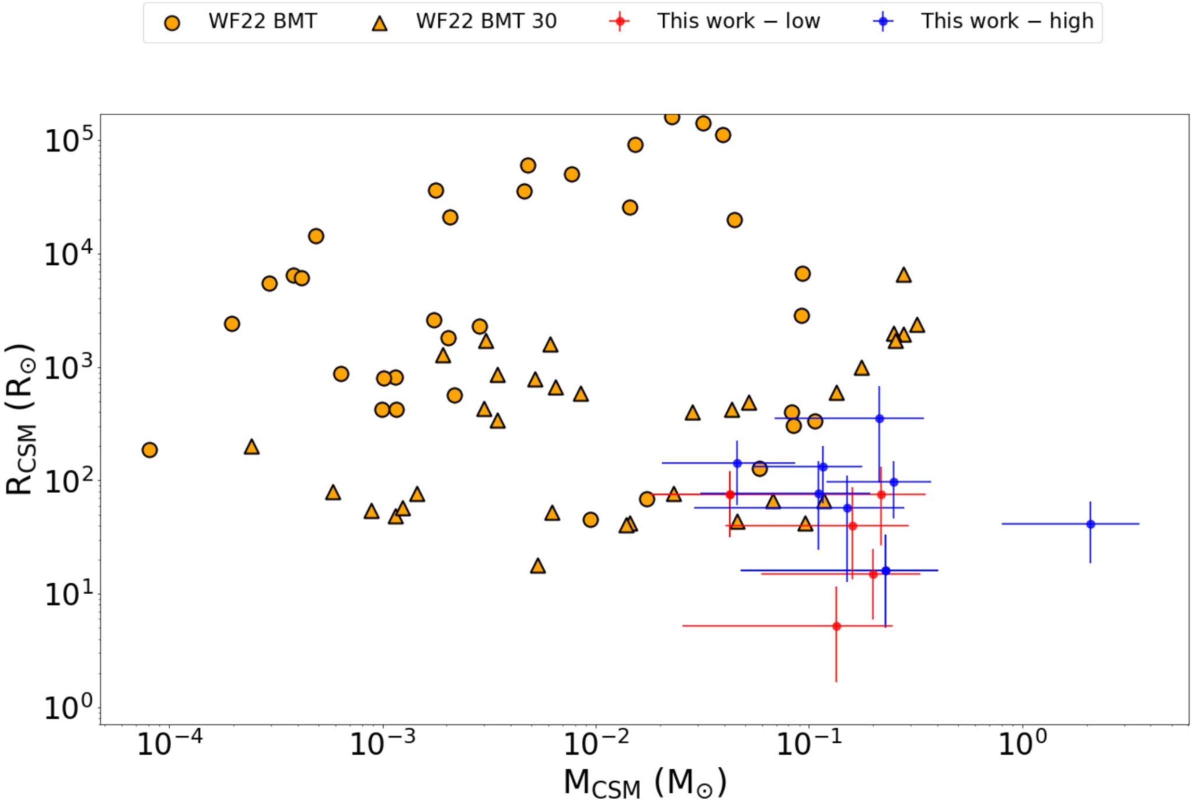
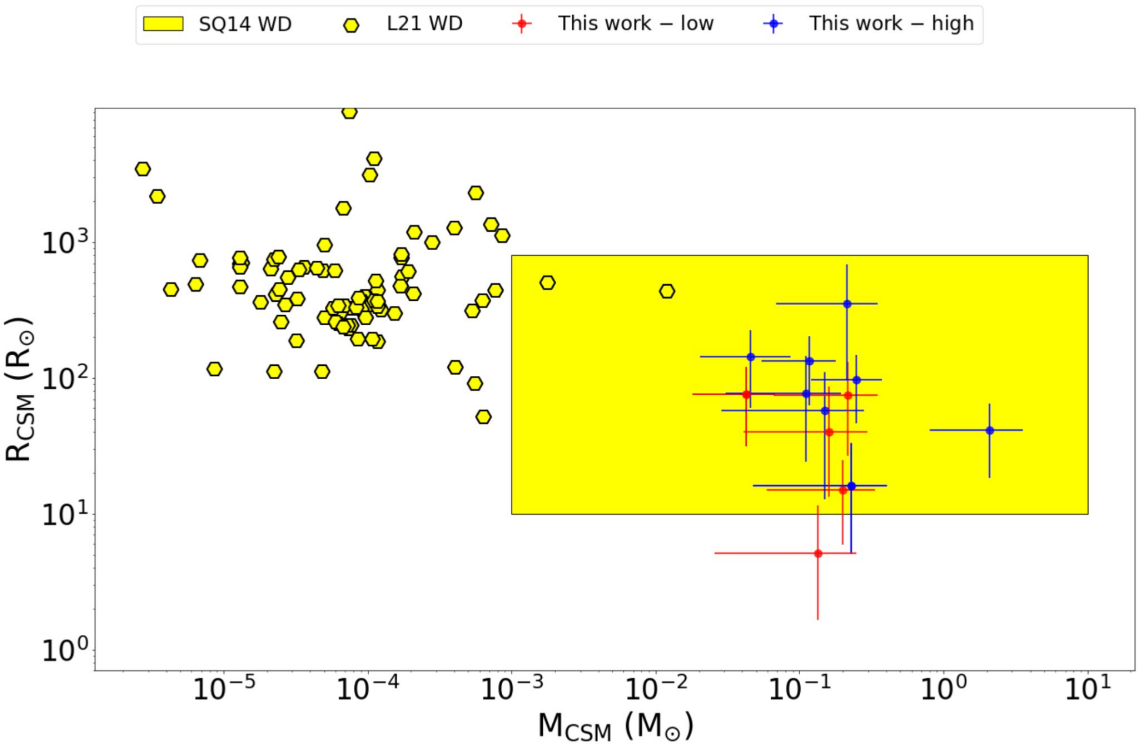
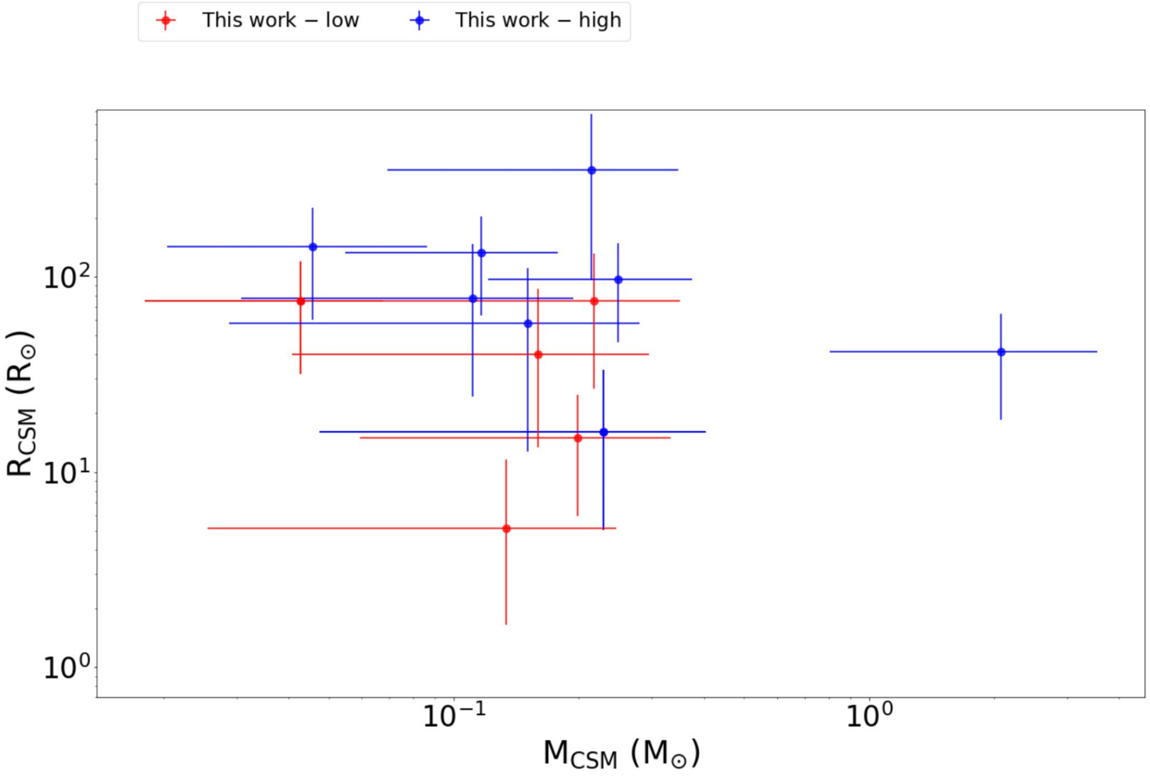


MASS LOSS SCENARIOS

- **Late-time binary mass transfer**

- **Wave-instability driven mass-loss**

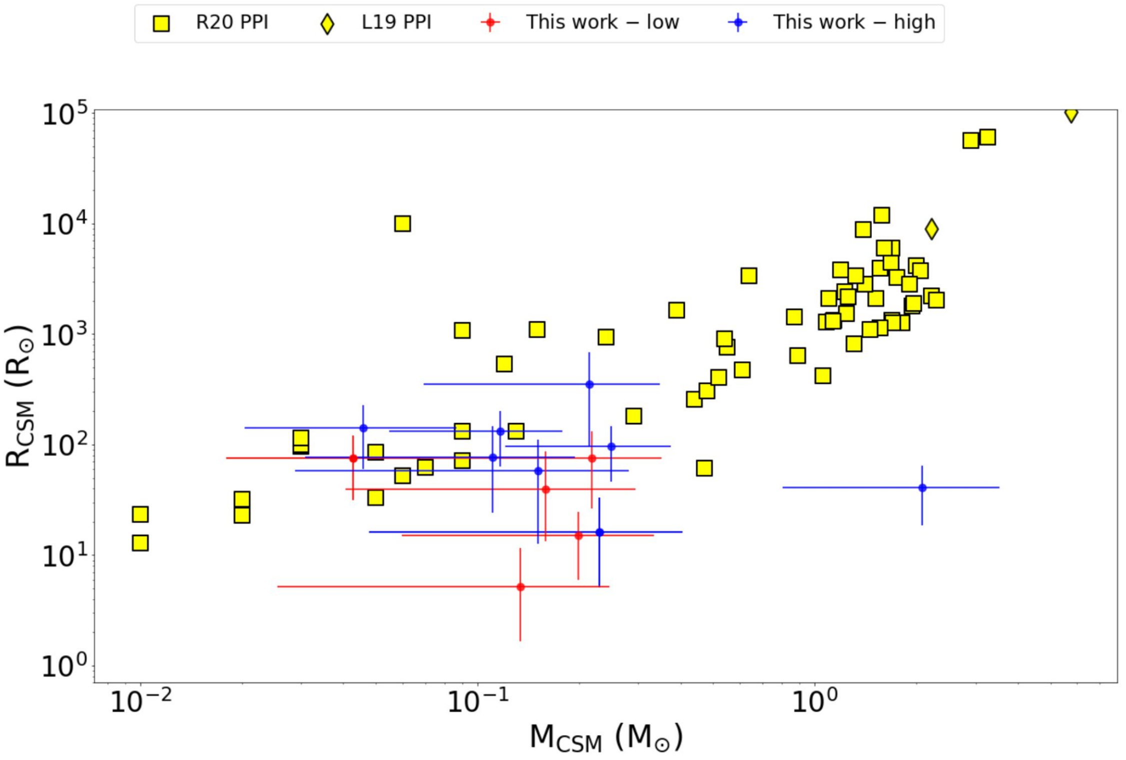




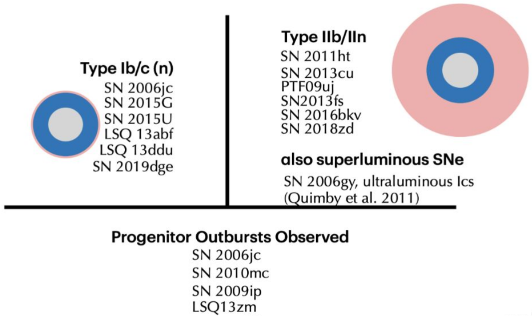
This work − low
This work − high
R_{CSM} ($R_\odot$)
10^0
10^1
10^2
10^{-1}
10^0
M_{CSM} ($M_\odot$)

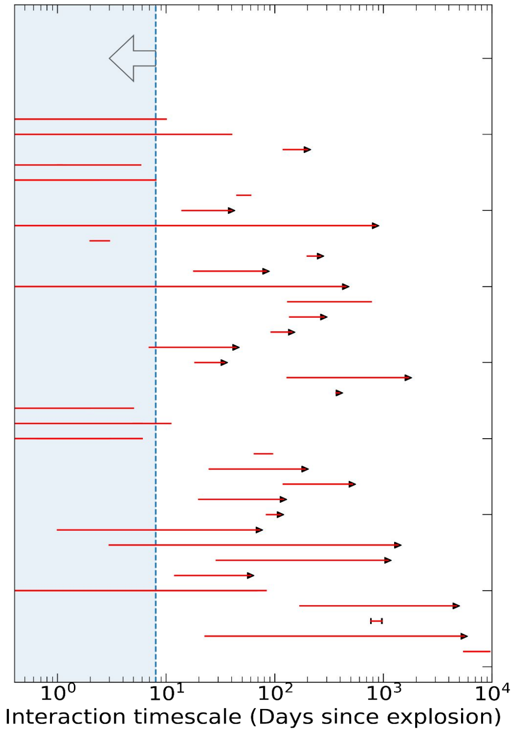
MASS LOSS SCENARIOS

- **Late-time binary mass transfer**
- **Wave-instability driven mass-loss**
- **Pulsation Pair-instability driven mass loss**



Literature





Probing interaction early on.

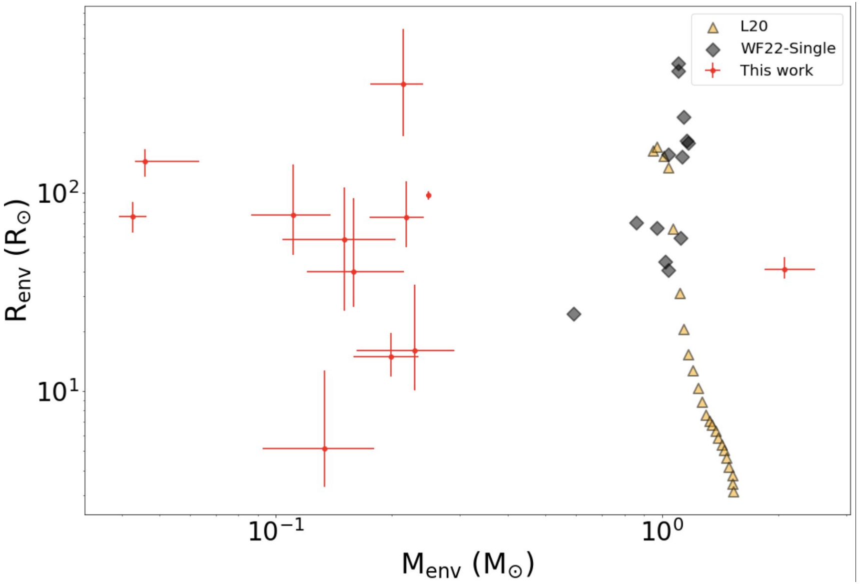
Variety of observational “tracers”.

Systematic study.

MASS LOSS SCENARIOS: 1. For SNe with progenitor mass < 12 Msun

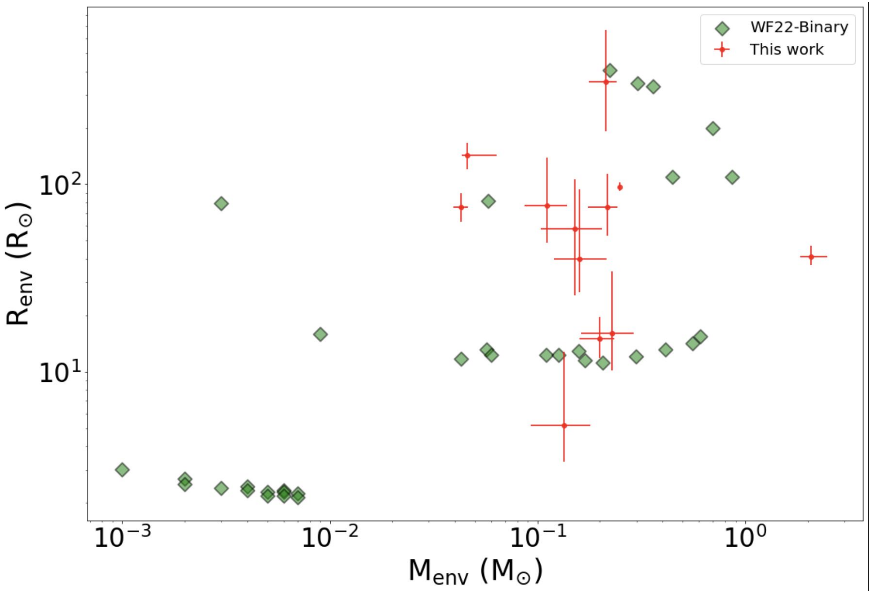
INTERACTION WITH ***BOUND*** STELLAR MATERIAL

Before late-time binary mass transfer



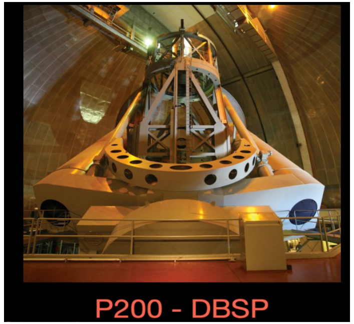
Envelope mass is higher

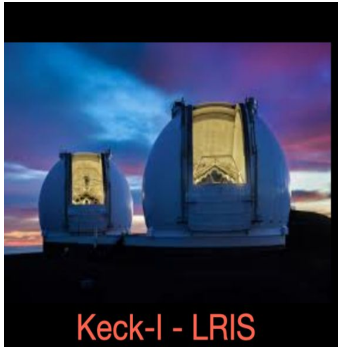
After late-time binary mass transfer

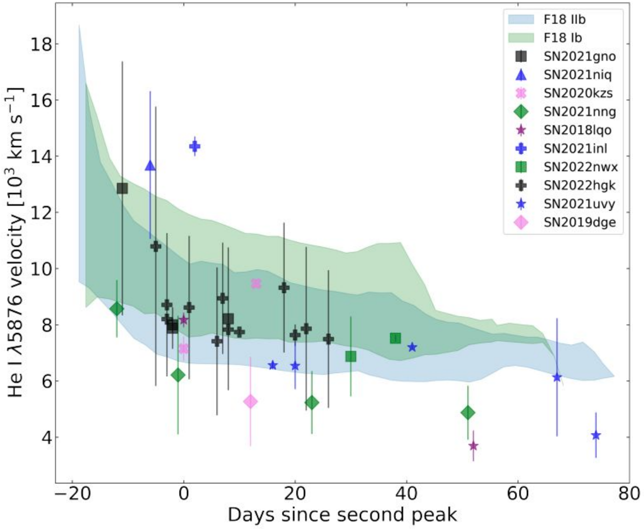


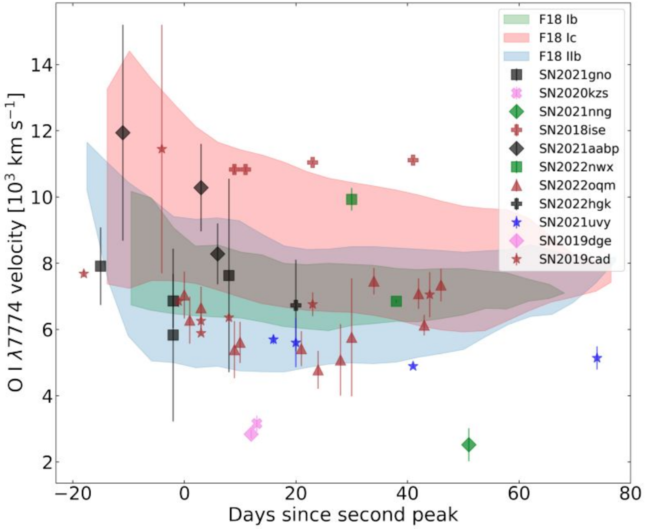
Some models are consistent

PHOTOSPHERIC VELOCITY MEASUREMENT



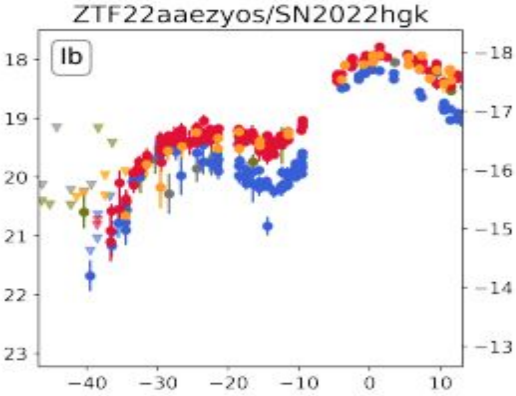


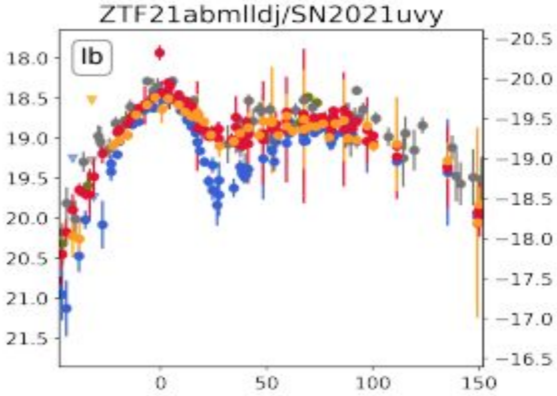


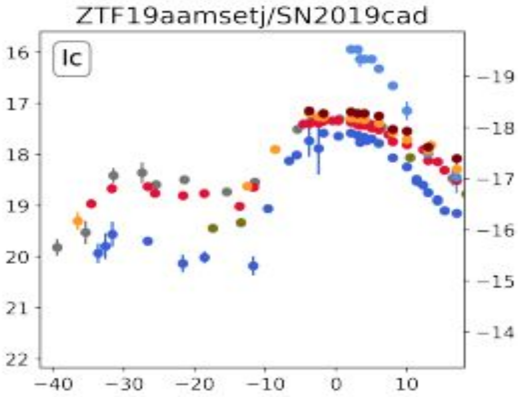


Consistent with canonical Type Ibc SNe

Very long-lasting first-peak : Not Shock Cooling







*Lightcurve analysis of these 3 SNe not part of this work

Order Of Magnitude Consistency

Shock breakout cooling

The bulk of photons emerge from the layer where τ ~ c/vext.

:Upper limits of
$$t \sim \left(\frac{3}{4\pi} \frac{\kappa M_{\rm ext}}{v_{\rm ext} c} \right)^{1/2}$$

Shock deposits energy Edep into the layer, which then cools from expansion.

Assume that the deposited energy is half the kinetic energy of the shock

$$L_{\rm cool} \sim \frac{v_{\rm ext} R_{\rm ext} M_{\rm ext}}{4t^2}.$$

:Lower limit of Rext

Consistent within OOM to Piro 2020 fits.

Rule out Shock breakout from CSM

shock crossing timescale is t_cross ~ R_CSM/v_s, ~ 0.01 days;

Shock heats the CSM with an energy density that is roughly half of the kinetic energy of the shock, so the energy density of the CSM ~ $(1/2)(\rho v^2/2)$

$$L_{\rm BO} \sim \frac{v_s^3}{4} \frac{dM}{dR}$$

NOT consistent

Summary/Conclusion

17 double-peaked Type Ibc(BL) SNe out of a total of 475

Signature of pre-SN mass loss

Rate ~ 3 – 9 % of all stripped-envelope SNe

~ 1 – 2 % of all core-collapse SNe

Strong correlation exists between peak magnitude of the first and second peaks.

Absence of first-peak mean => Binary evolution?

Need UV surveys: ULTRASAT, UVEX?