Binary merger progenitor- explosion connection
Lessons from SN 1987A

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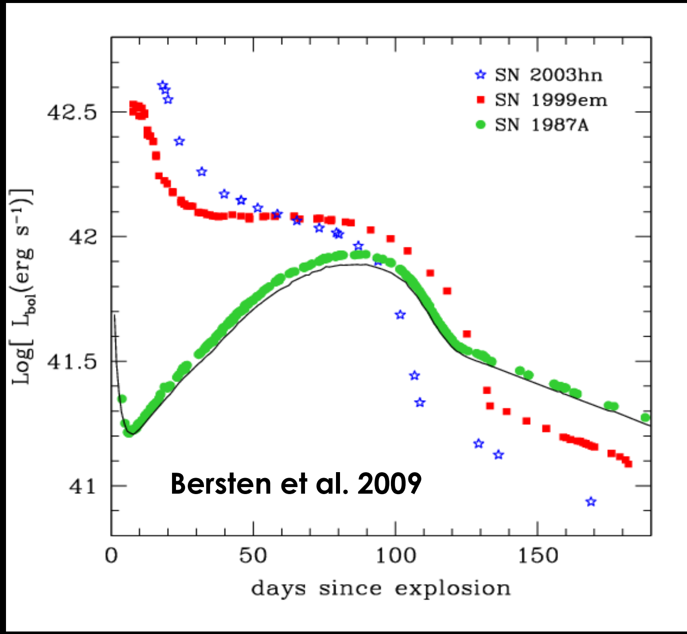
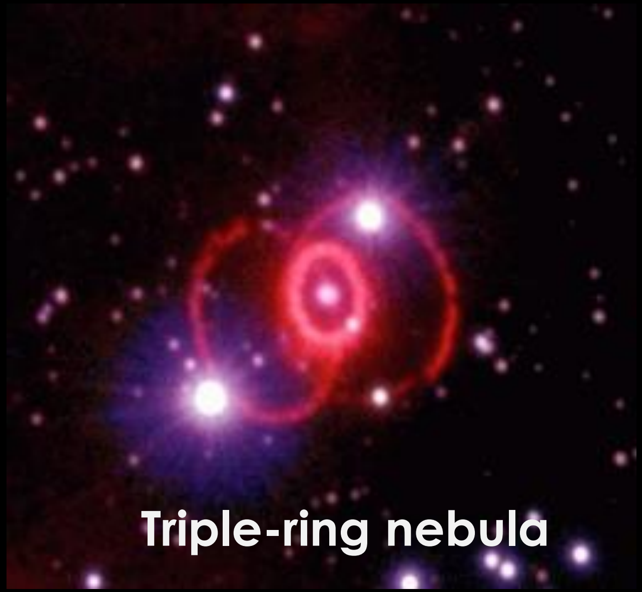
The progenitor, Sanduleak 69^0202





Progenitor was **a hot blue supergiant** (BSG) (T_{eff} = 15,000K – 18,000K)

Unique dome-shaped light curve despite being a Type-II H-rich supernova

Rings ejected by the BSG progenitor-- **Inner ring ejected** at least **20,000 years** before explosion (Burrows+ 1995, Sugerman+ 2005)

Rings **enriched in** helium, nitrogen **(N)** over carbon **(C)** and oxygen **(O)** (Lundqvist & Fransson 1996); N/C = 5±2, N/O = 1.1±0.4

The 30 year story of progenitor evolution of SN 1987A

Single Stars

- Current standard models:
  Eg., Arnett 1987, Woosley et al. 1988, Shigeyama & Nomoto 1990
- Detailed explosion studies
- Ad hoc physics to obtain a blue supergiant pre-SN (rotation, mass-loss, convective overshooting etc.,)
- Cannot explain triple-ring nebula ejection

Binary Stars

- Binary scenario and merger tracks:
  (Podsiadlowski, Joss, Hsu 1992; Podsiadlowski 1992)
- Physics in check, especially for triple-ring nebula (Morris & Podsiadlowski 2007, 2009)
- Merger hydrodynamics (Ivanova+ 2002, 2003)
- No pre-SN models from binary mergers that match all progenitor observations
- No explosion studies

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The quest for blue supergiants: binary merger models for the evolution of the progenitor of SN 1987A

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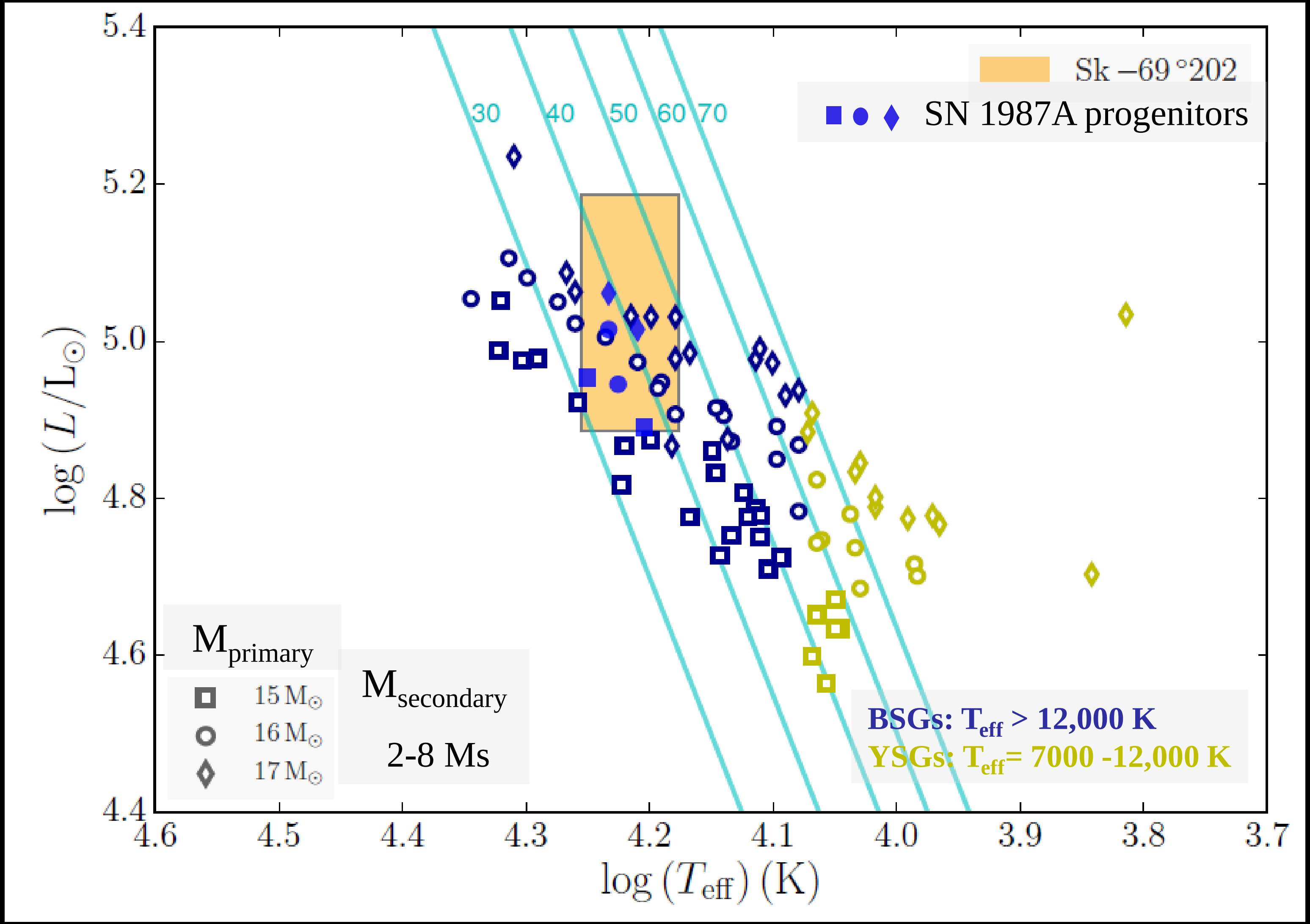
- First systematic stellar-evolution study of Type II progenitors from 84 binary-merger models
  - Which of these models match the progenitor observations of SN 1987A?
    - What conditions can lead to Type II blue supergiant progenitors?

- How do the structures of binary merger models compare with single star models?

Distribution in HR diagram of all 84 merger pre-SN models



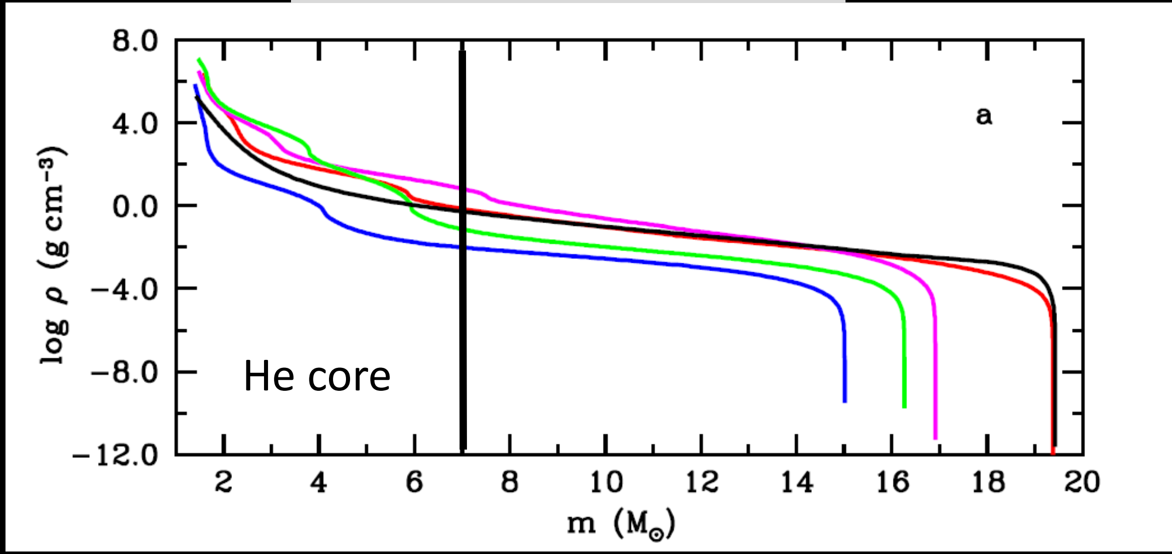
- Only chose initial parameters
- No fine tuning during evolution; pre-SN models come naturally from simulations

SN 1987A progenitors

- HRD position
  N/C, N/O values in surface
  Lifetime >15,000 yr

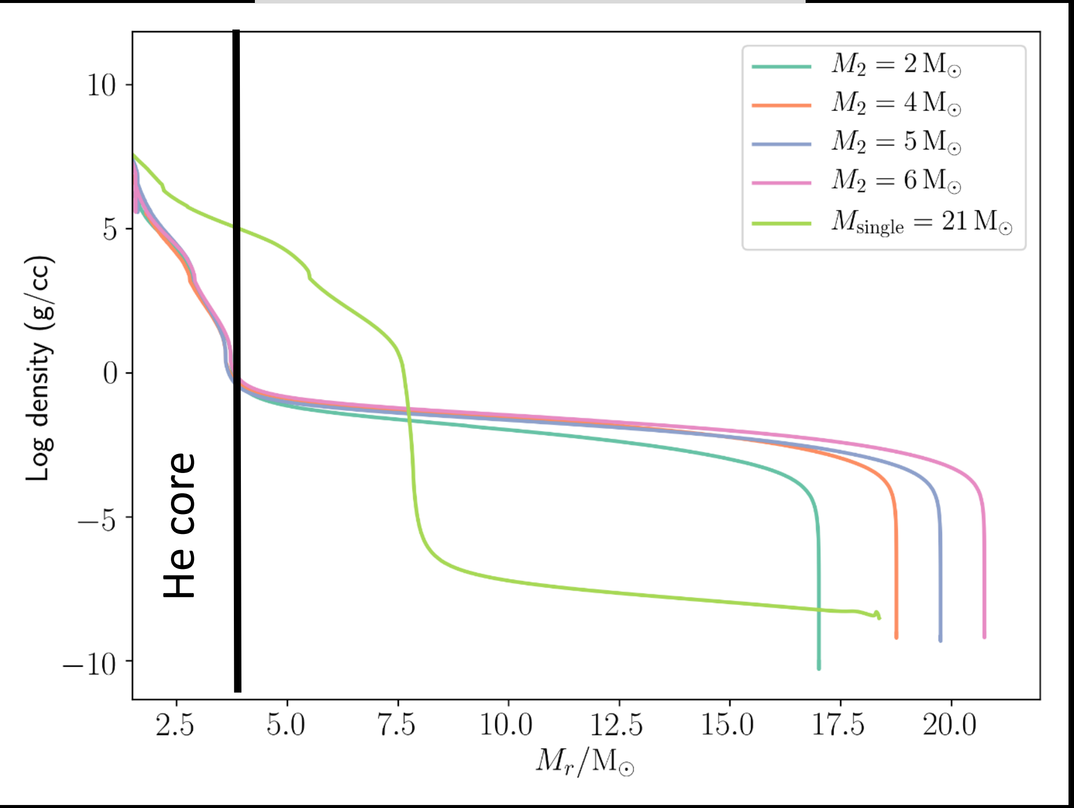
Density profiles comparison of SN 1987A pre-SN models

Single star models,
(Utrobin et al. 2015)

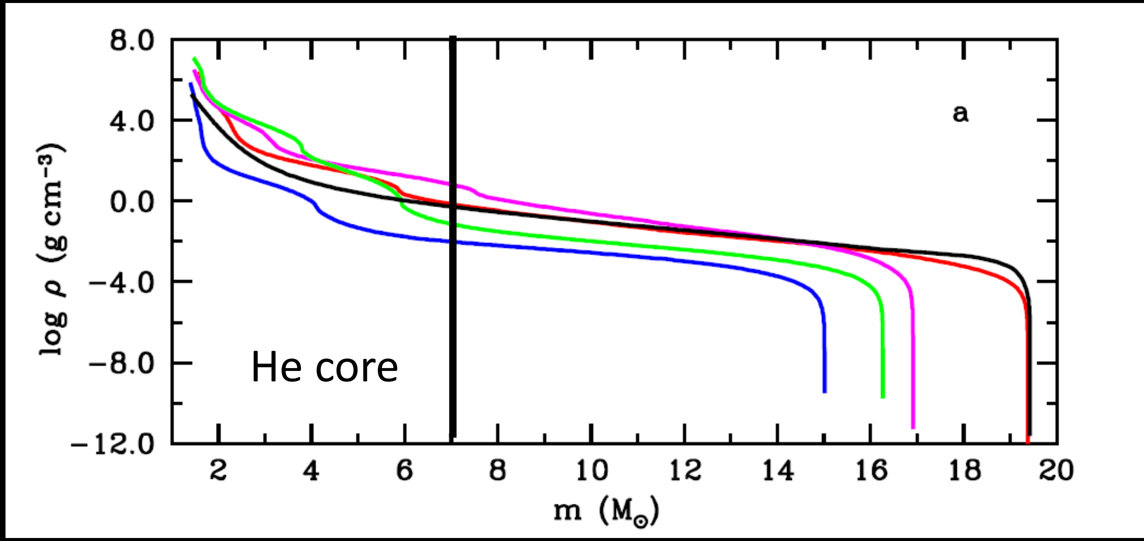


Density profiles comparison of SN 1987A pre-SN models

Binary merger models
M_1=16 $M_\odot$



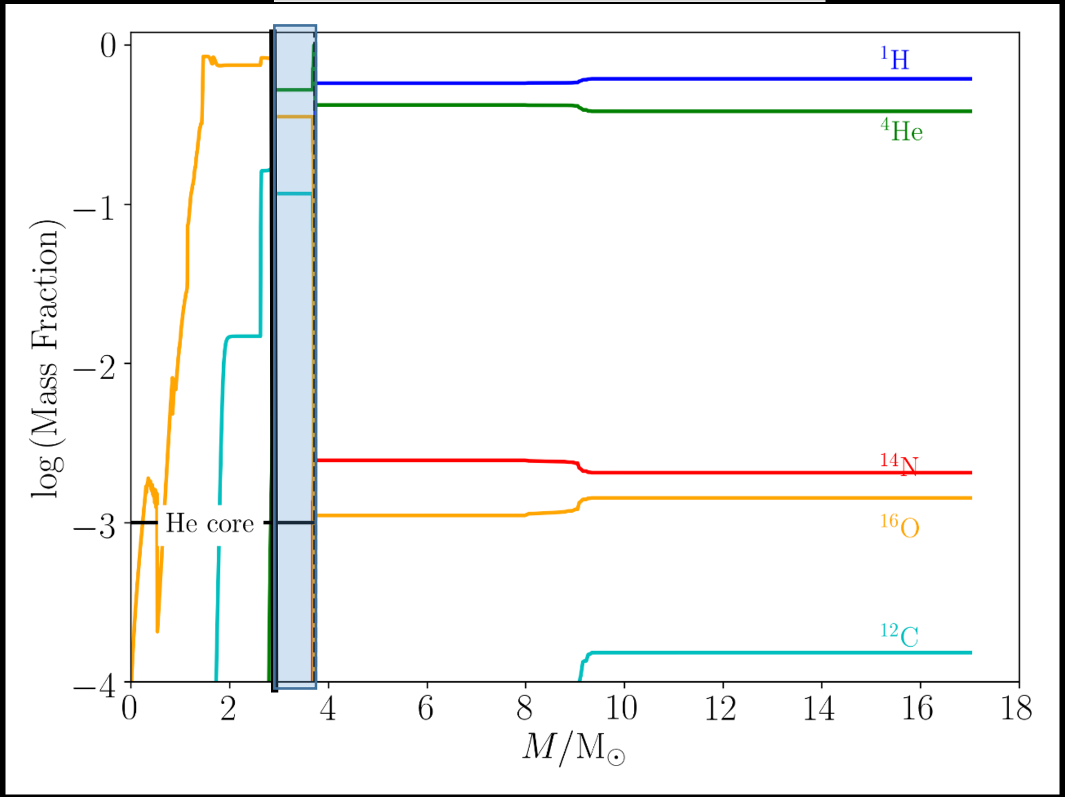
Single star models



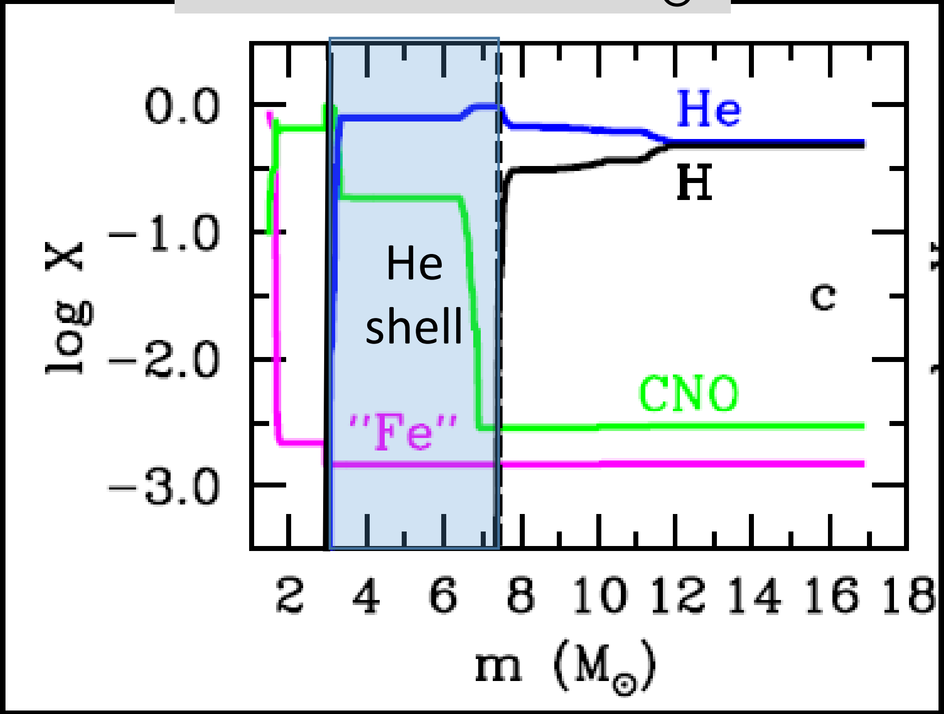
Parameter	Binary mergers	Single stars
He core mass (Ms)	2.9 – 4.1	~5-7
Envelope mass (Ms)	15 – 20	10-15

Chemical composition comparison

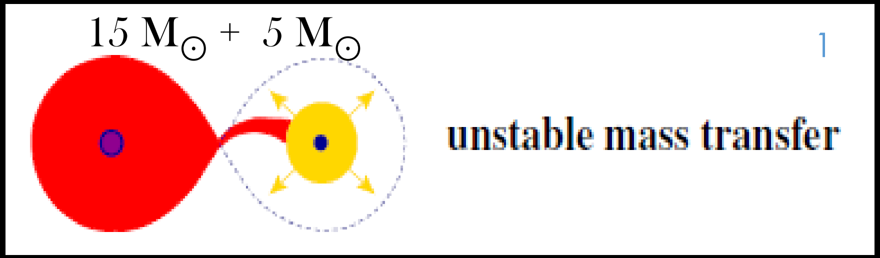
Binary merger model
16 + 2 $\mathbf{M_\odot}$

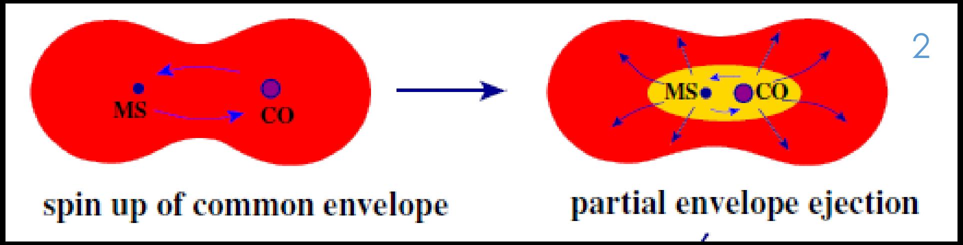


Single star model
Woosley 1988, 18 $M_\odot$



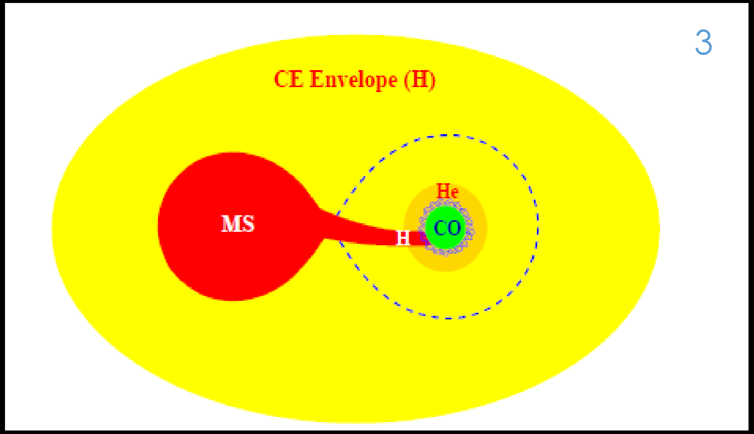
Binary merger scenario
Podsiadlowski and Ivanova papers





(Podsiadlowski et al. 2007)

Primary Red supergiant with CO core +
Secondary main sequence



Blue Supergiant
pre-SN ?

Merger: Order of 100 years

He core is dredged up→ He core shrinks after merger
Seen in 3D simulations of Ivanova (2002, 2003)

Merger

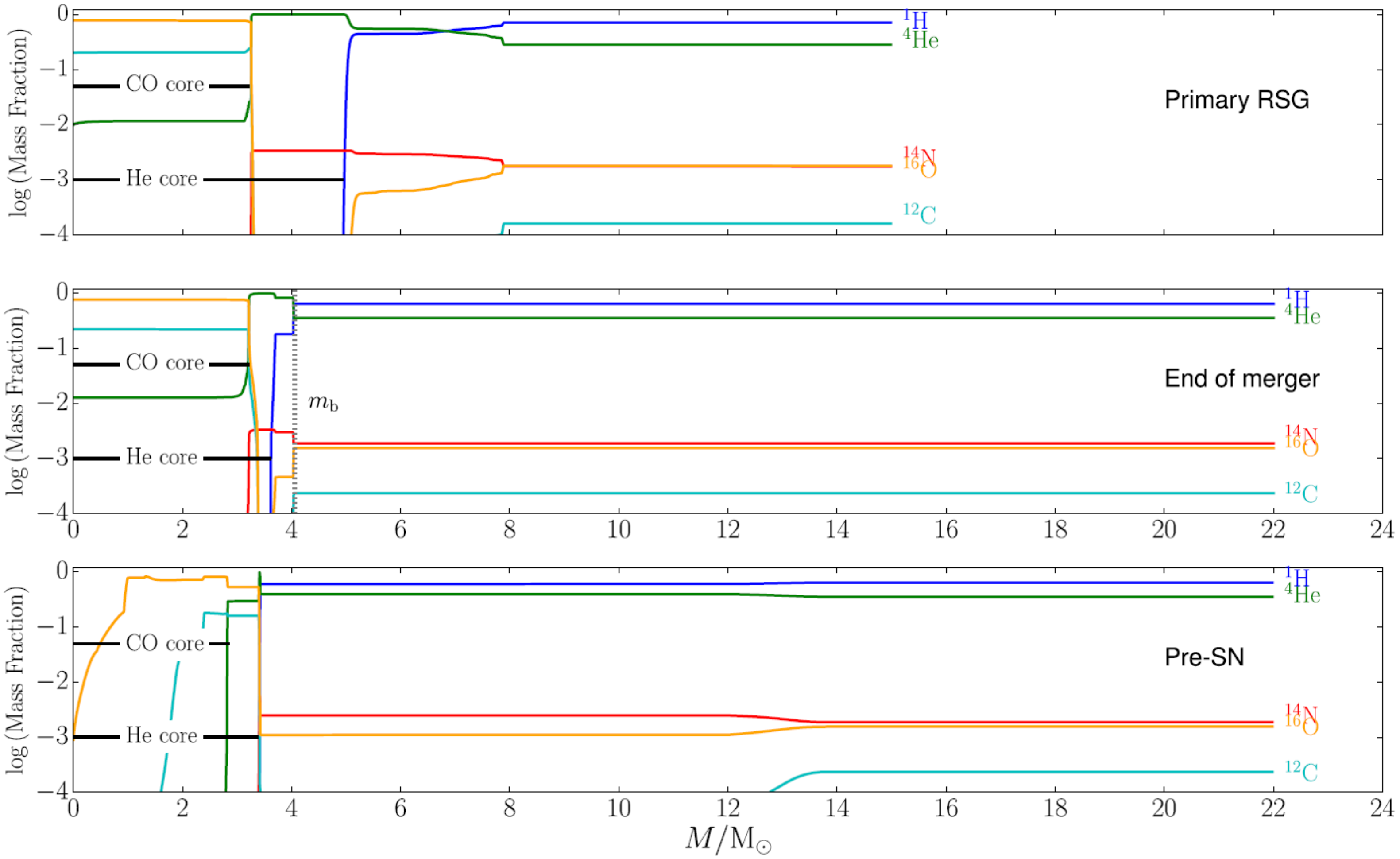


Figure 1. Top panel, stage B in Fig. 4: Composition of the RSG model from a primary of $M_1 = 16\,\mathrm{M}_\odot$ consisting of a He core of $M_{\mathrm{He\,c},1} = 4.92\,\mathrm{M}_\odot$ just prior to the merger. Middle panel, stage C in Fig. 4: Composition at the end of the merger with $M_2 = 7\,\mathrm{M}_\odot$. The boundary of mixing m_b (dotted vertical line) is set for $f_\mathrm{c} = 16.6\%$. At the end of the merger, the star has a smaller He core of mass $3.41\,\mathrm{M}_\odot$. Bottom panel, stage D in Fig. 4: Composition of the pre-SN model. The surface composition of the star does not change much from the one at the end of the merger.

M_1=16 $\mathbf{M_\odot}$ **,rotating at v/vc= 0.30**

M_2=7 $\mathbf{M_\odot}$

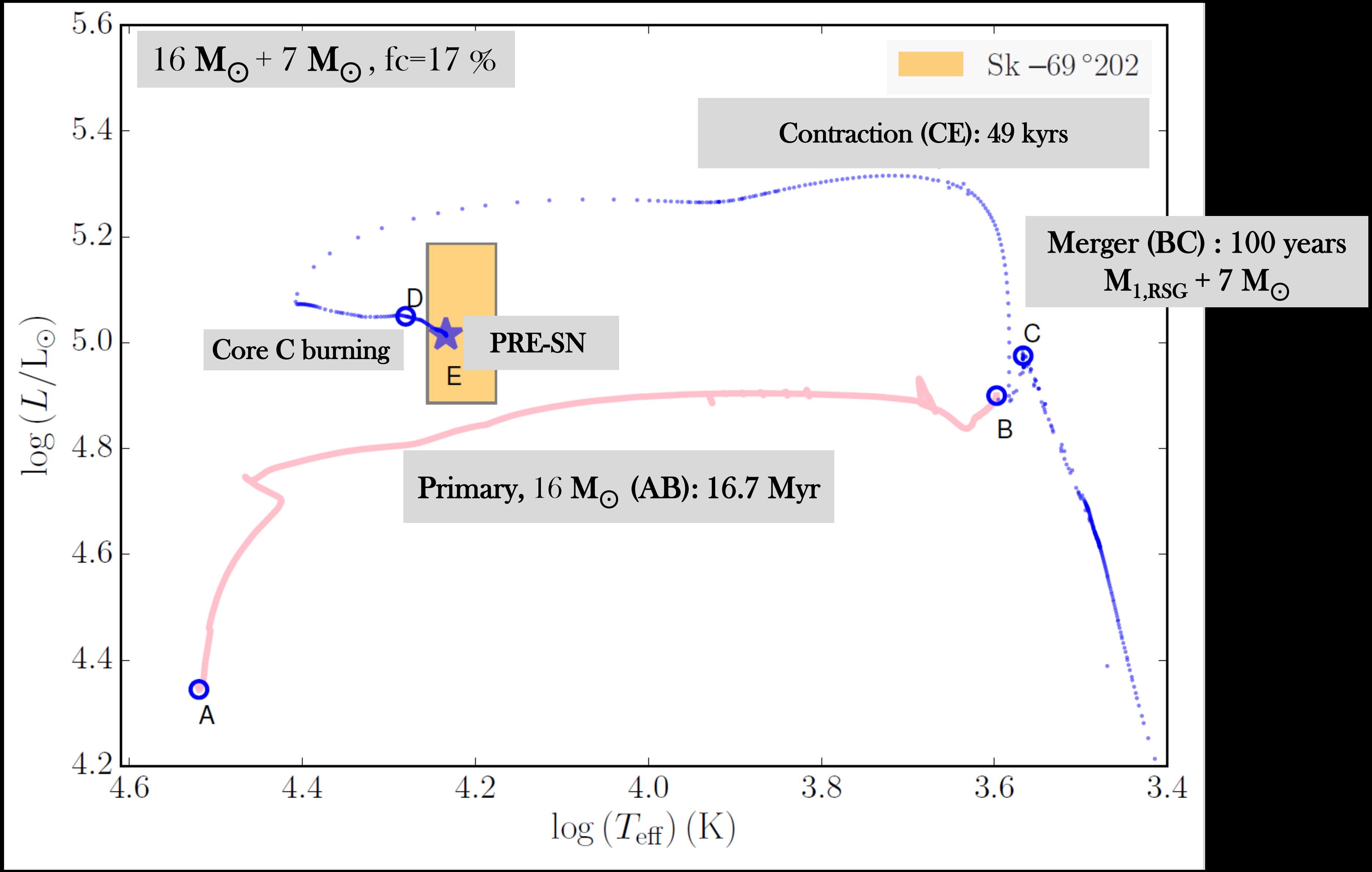
fc=17 % → mixing boundary

(m_b)= 3.7 $\mathbf{M_\odot}$

(No common envelope physics included)

Fig 1. from Menon & Heger, MNRAS, 2017

HR diagram



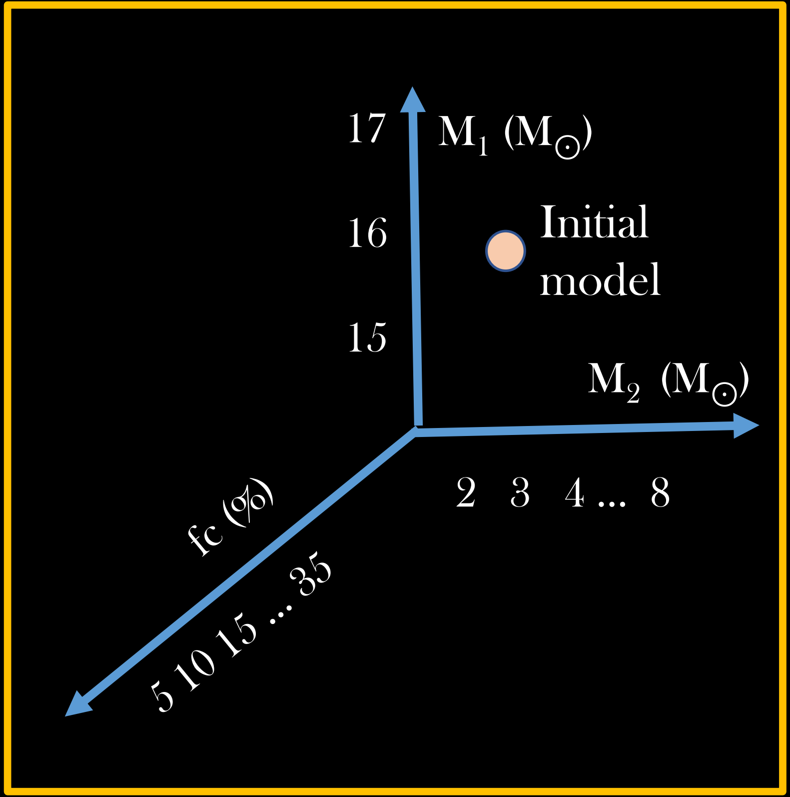
16 M⊙ + 7 M⊙ , fc=17 %
Sk −69 °202
Contraction (CE): 49 kyrs
Merger (BC) : 100 years
M1,RSG + 7 M⊙
Core C burning
PRE-SN
Primary, 16 M⊙ (AB): 16.7 Myr
A
B
C
D
E
log (L/L⊙)
log (Teff) (K)
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.6
4.4
4.2
4.0
3.8
3.6
3.4

Methodology

1. Choose a combination of three initial parameters:
   - -primary mass (M_1)
   - -secondary mass (M_2)
   - -fraction of He core-dredged up (f_c): mixing boundary, He core mass after merger

KEPLER
(Woosley, Heger & Weaver 2002; Heger, Woosley & Spruit 2005)

2. Merge primary and secondary stars (no common envelope physics included)
3. Follow evolution until pre-SN stage (i.e. just before iron-core collapse)
4. Check if pre-SN model matches observational criteria of Sk-69^0 202



LMC composition, Z=0.0055

CRAB (Utrobin 2004; Utrobin 2007)

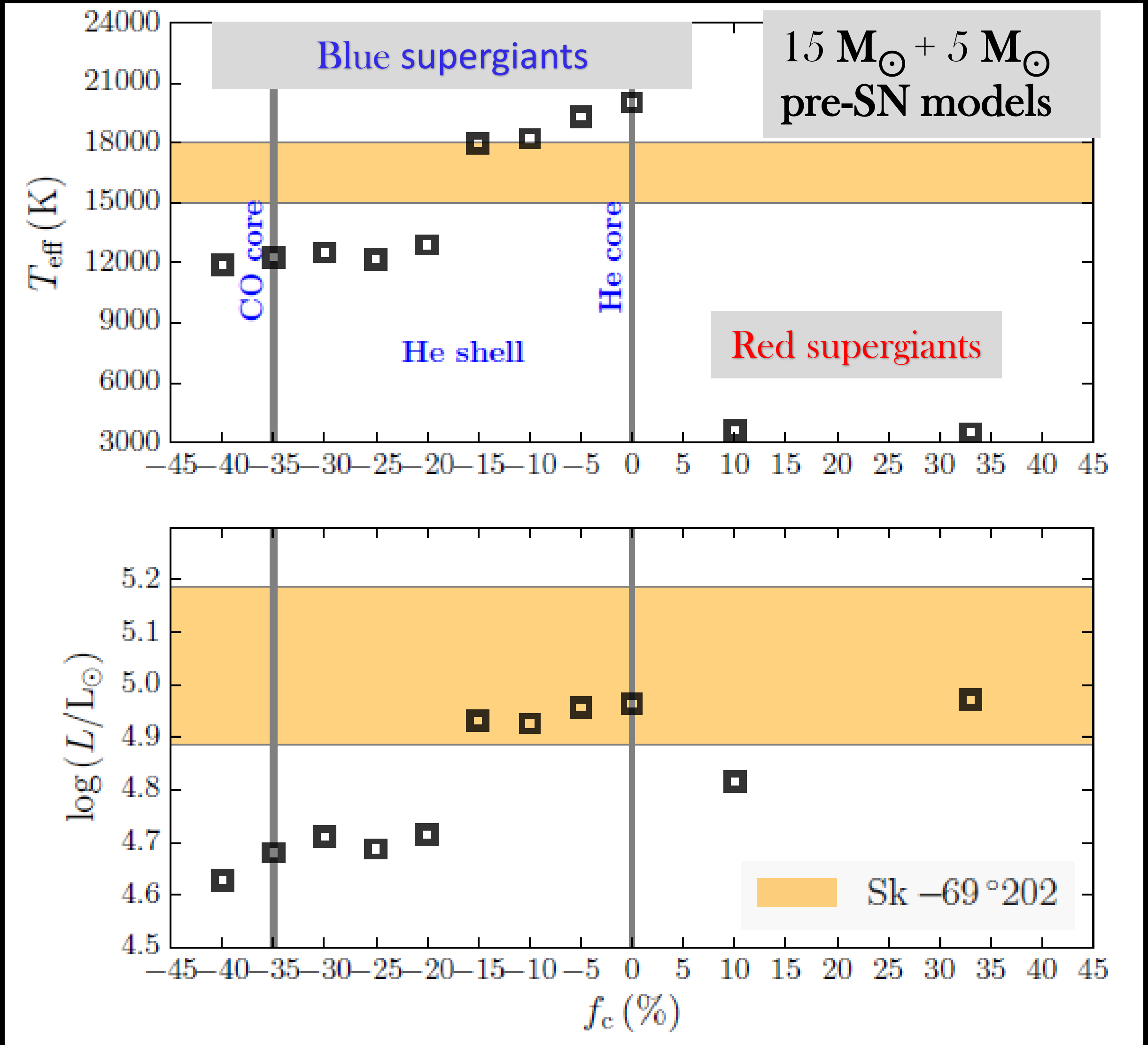
5. Explode these models (Victor Utrobin)

What causes pre-supernova models to become blue?

And how do their explosions look?

(Light curve models by Victor Utrobin using CRAB)

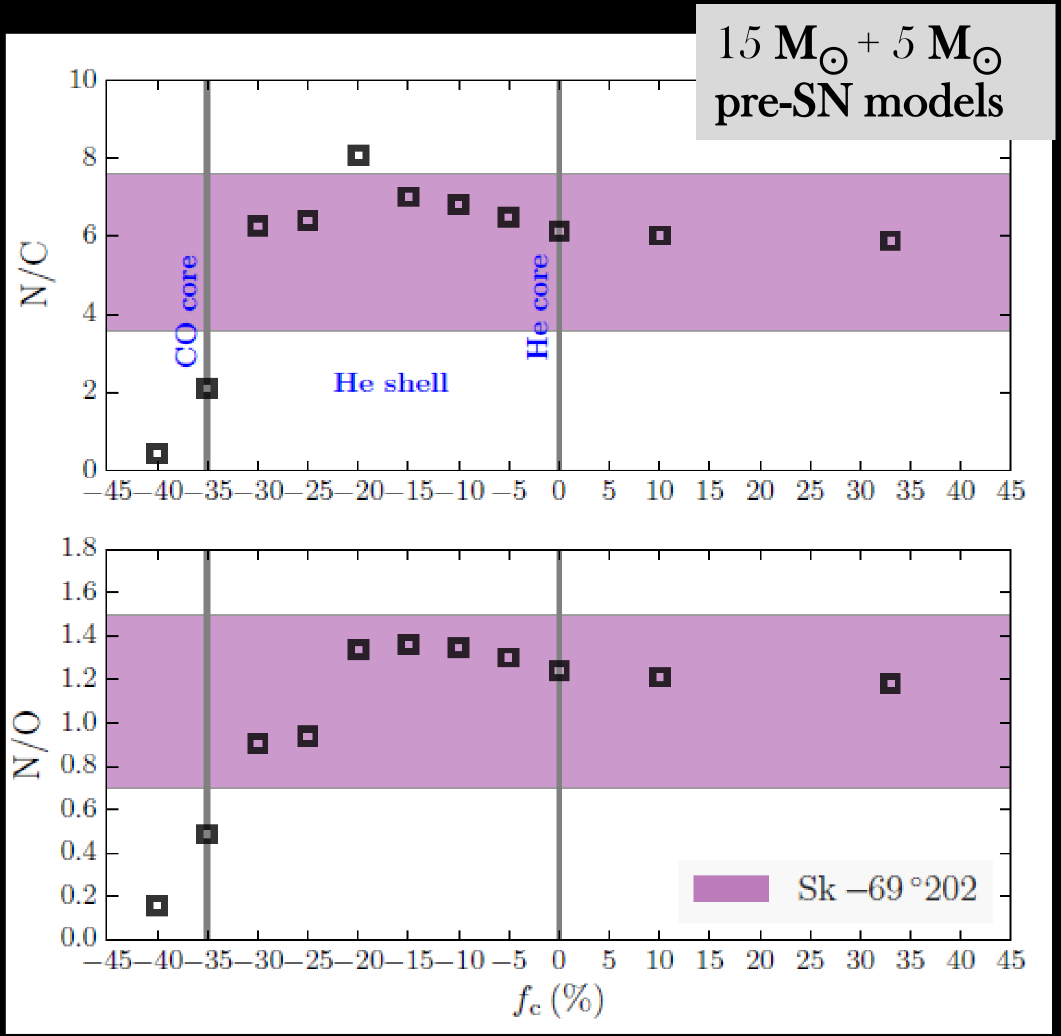
Fraction of He core dredged up (fc)



Increasing M_{core}/M_{env}

- Relation between M_{core}/M_{env} and T_{eff} is not monotonic
- For a given M_1, M_2, decreasing fc decreases T_{eff}
- Accretion alone, without core dredge up, makes RSGs from mergers

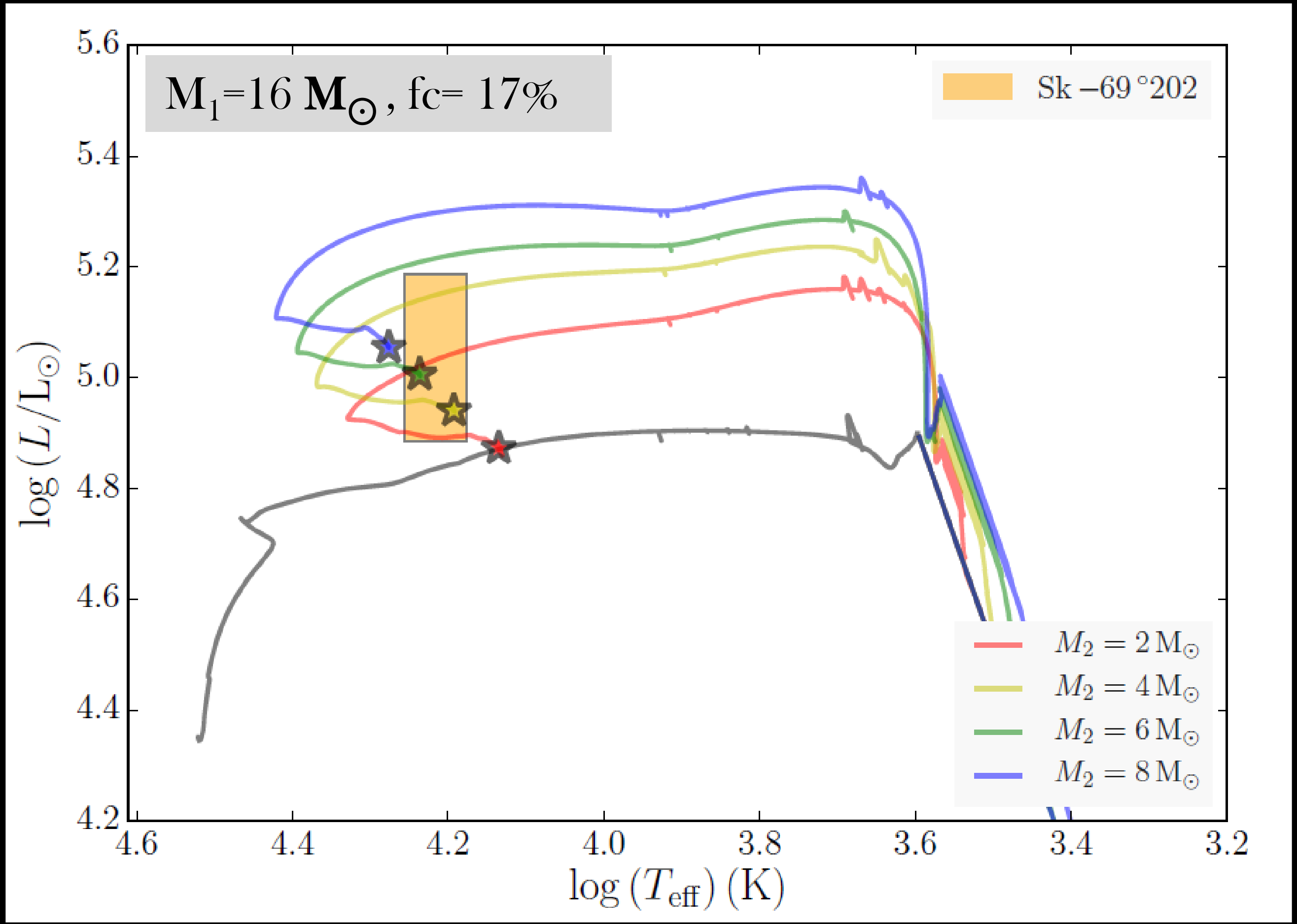
Fraction of He core dredged up (fc)



Increasing M_{core}/M_{env}

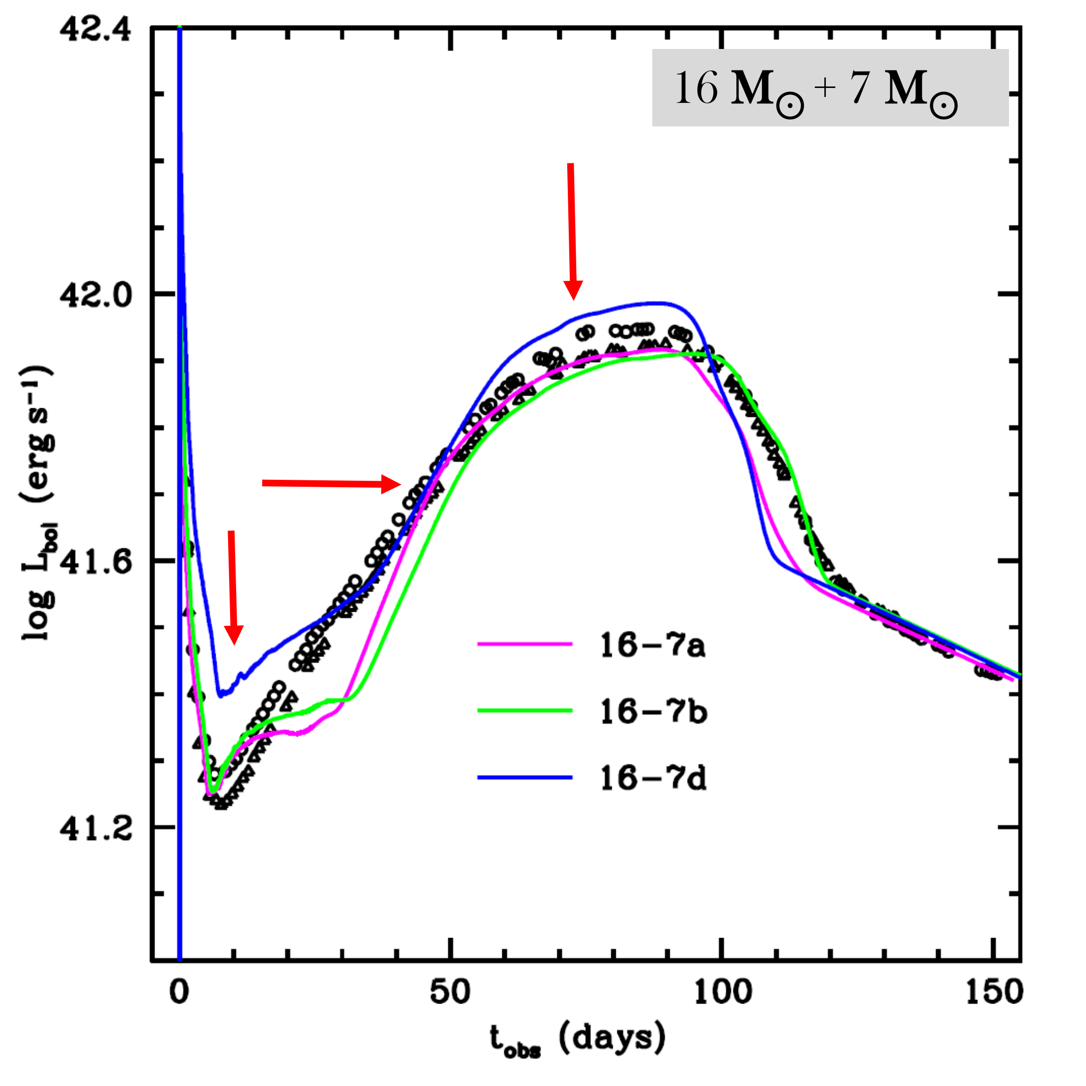
Dredge-up from CO core will decrease N/C and N/O

Secondary Mass (M_2)



Fixed M_1, fc, monotonic increase in T_{eff} and L, with increasing M_2

Light curves by changing He core fraction (fc)



Initial models

Model	R_{pre-SN} ($R_\odot$)	$M_{He-core}$ ($M_\odot$)	M_{pre-SN} ($M_\odot$)
16-7a	29.4	3.8	22
16-7b	36.8	3.4	22
16-7d	60.0	3.0	22

Explosion parameters

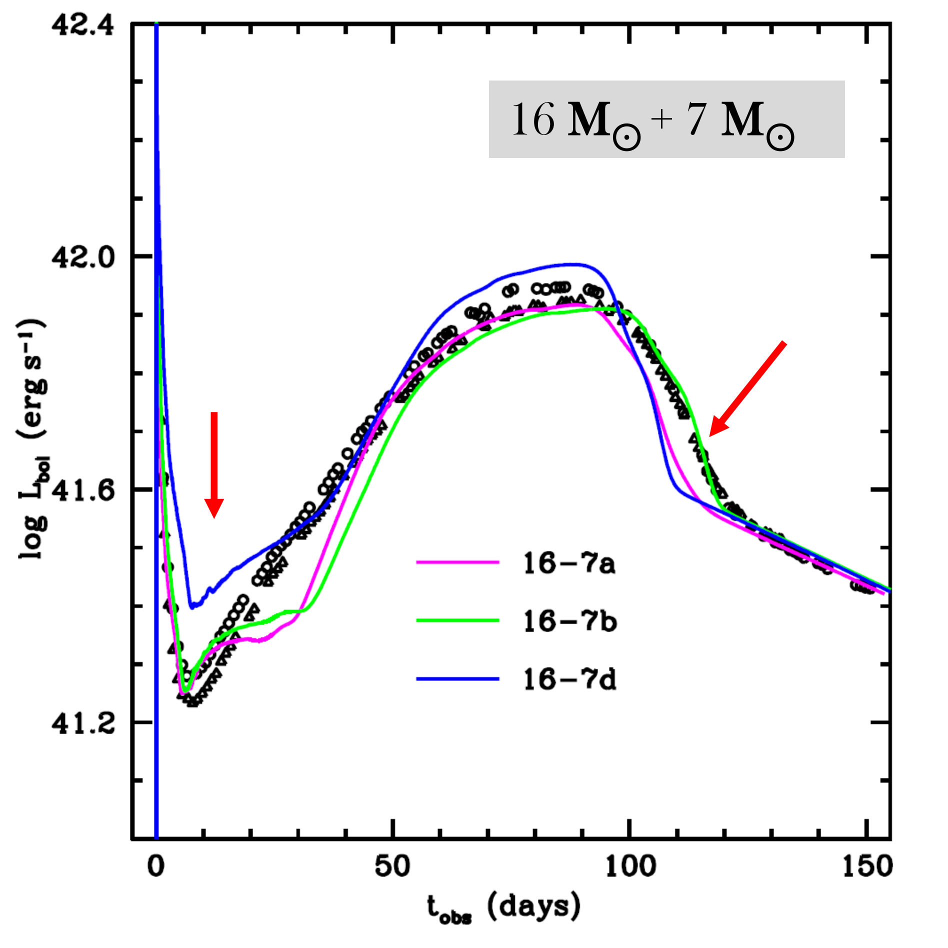
E_exp/ M_ejecta= 1.5×10^{51} erg/18$M_\odot$

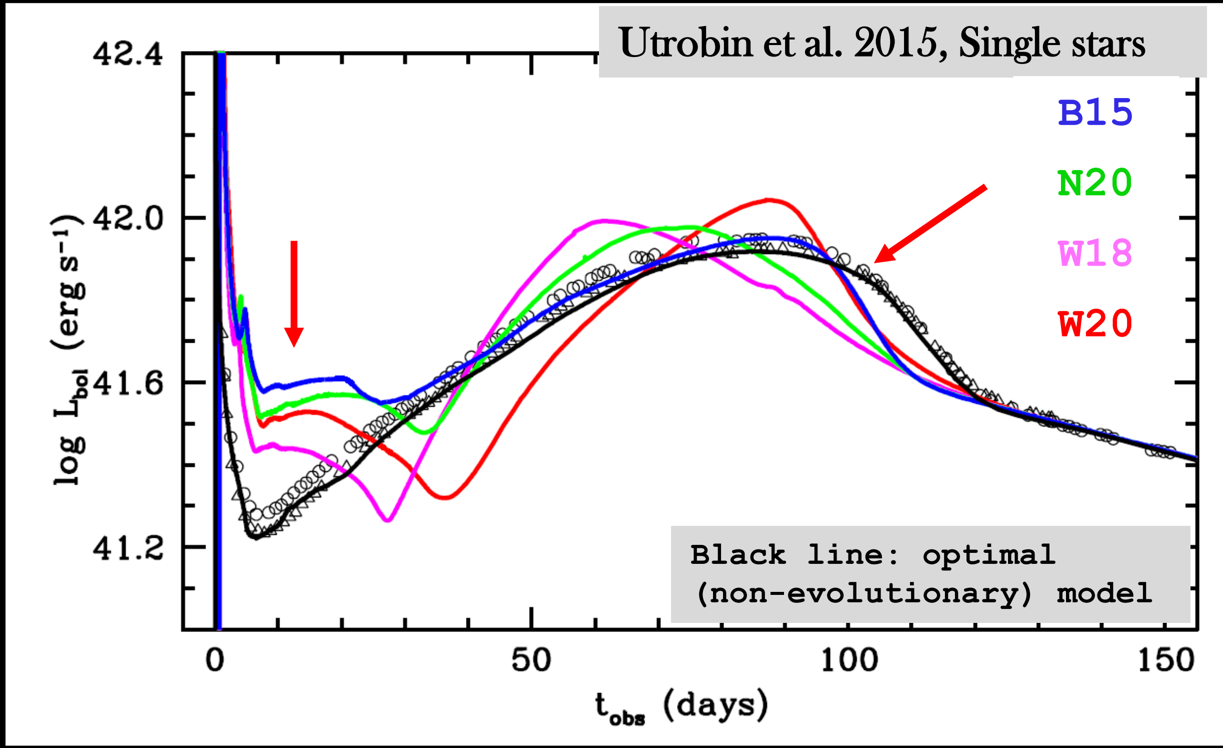
Mixing width = 2 $\mathbf{M_\odot}$

Nickel mixing velocity = 3000 km/s

M_{Ni} in ejecta = 0.073 $\mathbf{M_\odot}$

Light curves comparison between binary mergers and single stars





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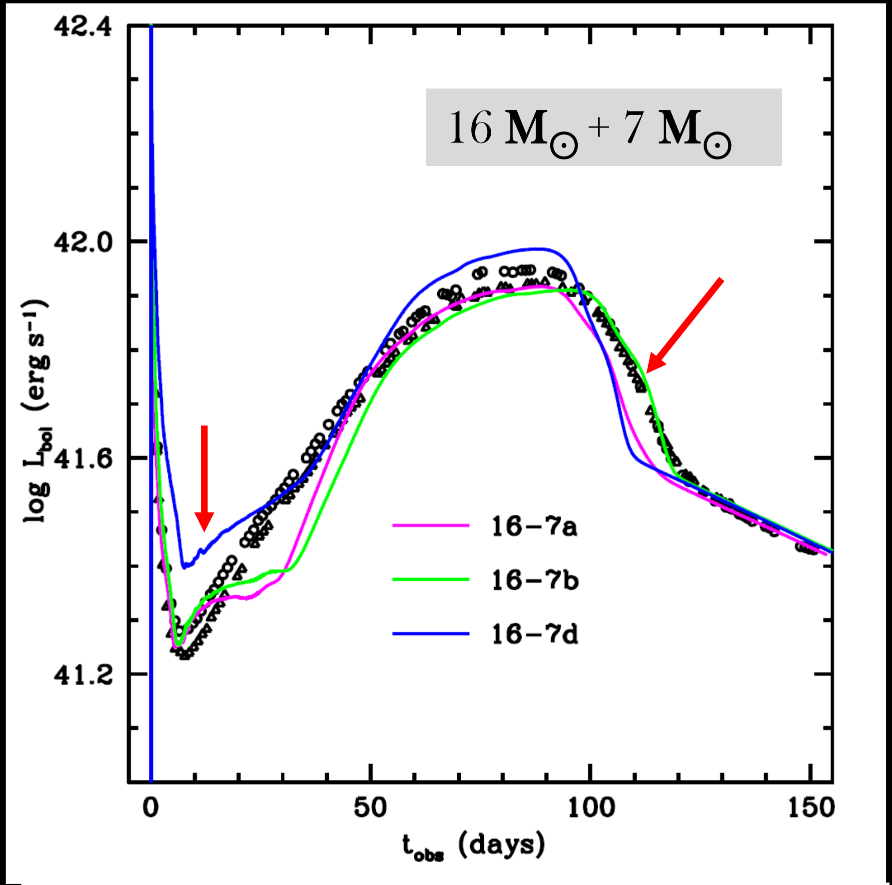

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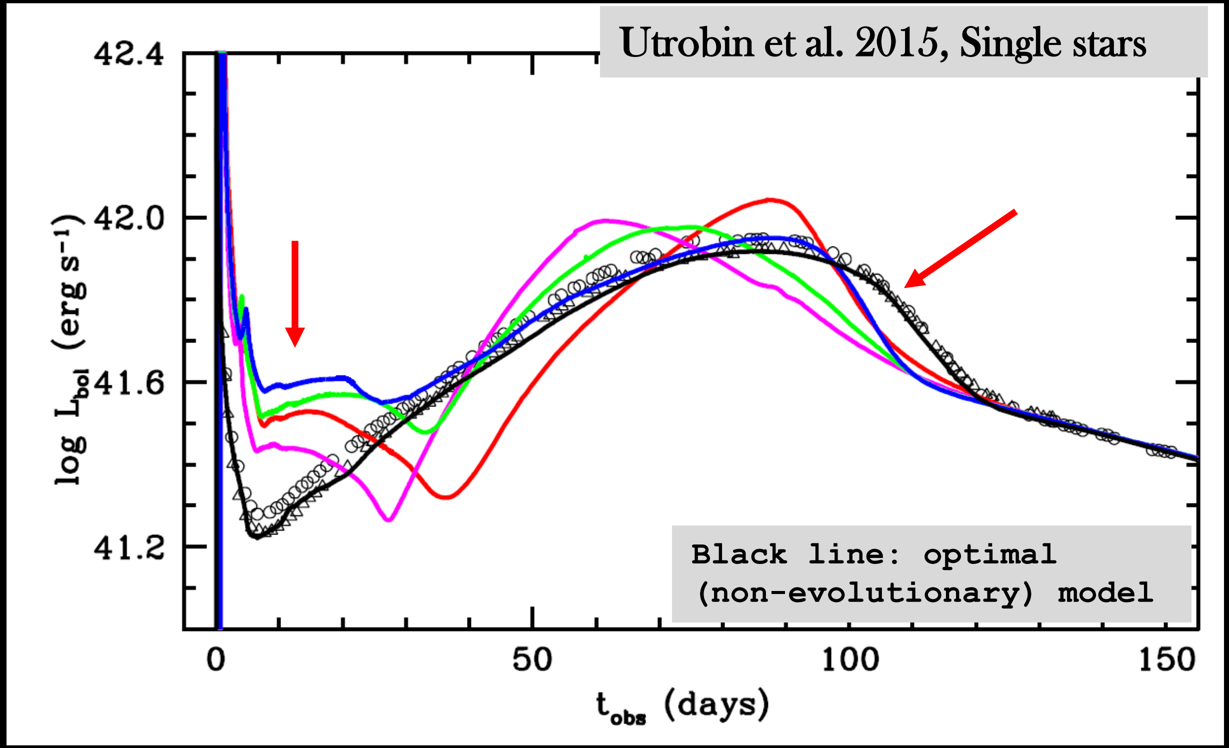


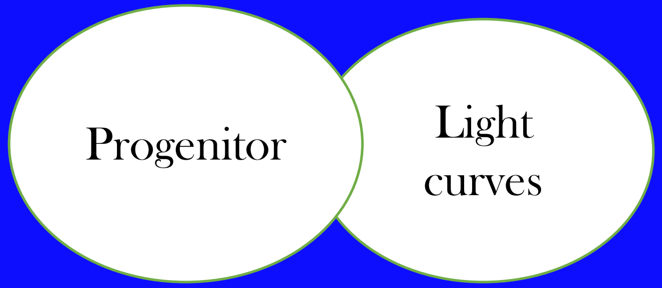
Model	R_{pre-SN} ($R_\odot$)	$M_{He-core}$ ($M_\odot$)	M_{pre-SN} ($M_\odot$)
B15	56.1	4.0	15.0
N20	47.9	6.0	16.3
W18	46.8	7.4	16.9
W20	64.2	5.8	19.4

Conclusions

Stellar evolution

- Blue supergiants are highly favoured via mergers, in the parameter space studied
- **Six models match the progenitor observations of SN 1987A**
- Sensitive to fraction of He core dredged up and secondary mass accreted
- More massive and smaller He core masses compared to single star models

Binary merger scenario



Supernova explosions

- Light curves fit better with merger models
- Important consequences for 3D simulations (Janka, Utrobin, et al., work in progress)
- What are the other consequences/implications for supernova studies?