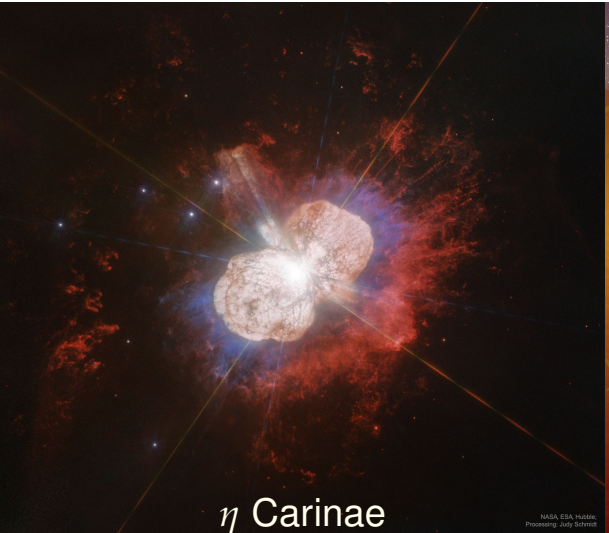
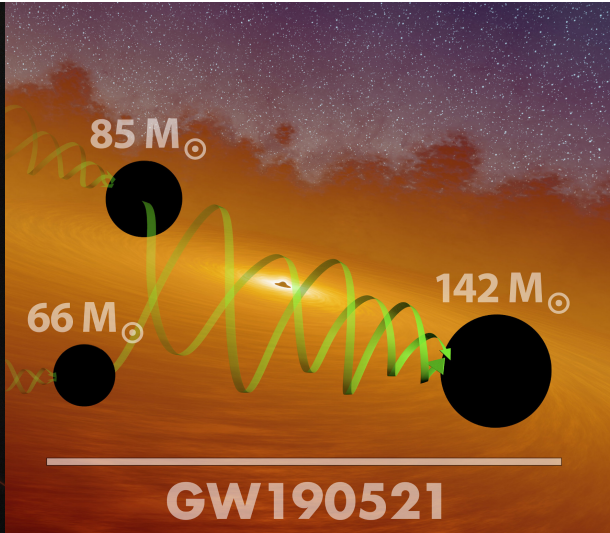
The stellar merger scenario for BHs in the pair-instability gap

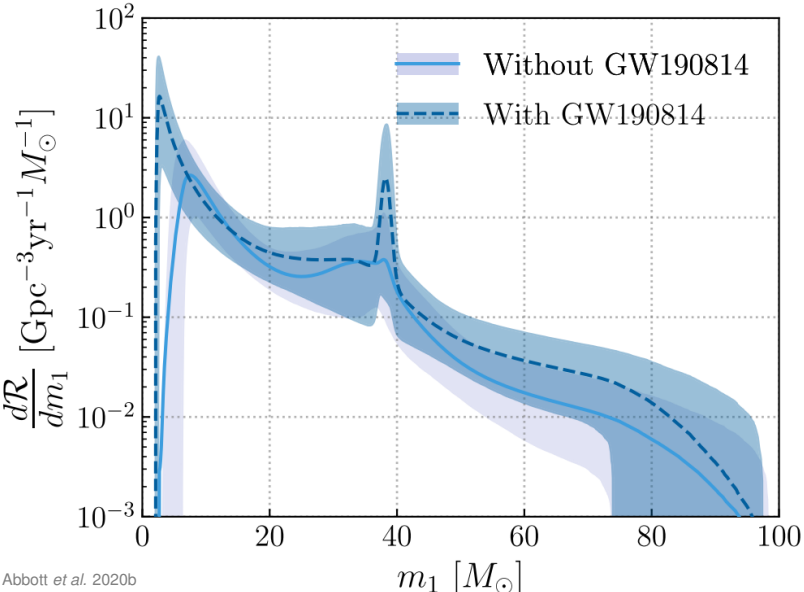
M. Renzo, M. Cantiello, B. D. Metzger, Y.-F. Jiang (姜燕飞)

arXiv:2010.00705





GW reveal a BH population in the gap



Abbott *et al.* 2020b

$97.1^{+1.7}_{-3.4}\%$ have $M_1 < 45\,M_\odot$

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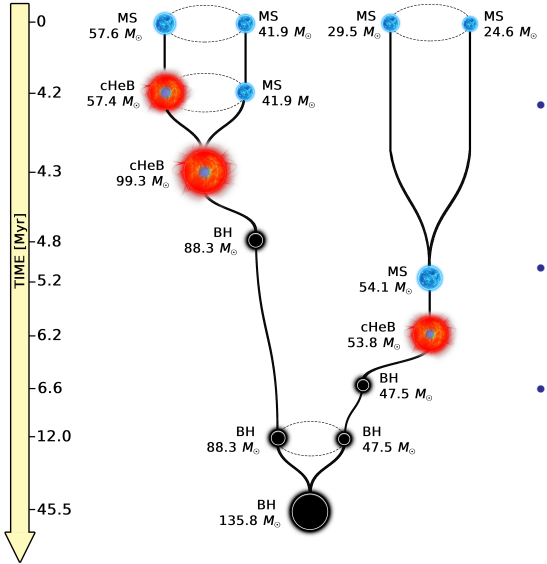
How to form the others **?**

The “stellar merger scenario”

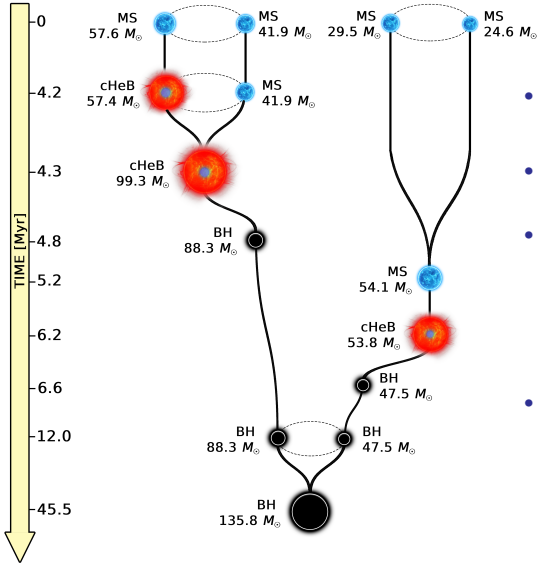


- Make a star with a small core and oversized envelope to avoid PPISN
- Collapse it to a BH in the gap
- Pair it in a GW source with dynamics

di Carlo *et al.* 20a

See also Spera *et al.* 19, di Carlo *et al.* 19, 20b, see also Kremer *et al.* 20, Mapelli *et al.* 20, Renzo *et al.* 20c

Four challenges of the “stellar merger scenario”



- Mass loss (and rejuvenation) ? Assumed zero
- Wind and eruptions ? Assumed zero
- Loss of envelope at core-collapse ?

  Because of ν losses – Assumed zero

  see Nadhezin 1980, Lovegrove & Woosley 2013

- Need dynamics to pair with 2nd BH

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  Requires nuclear cluster and/or AGN disk?

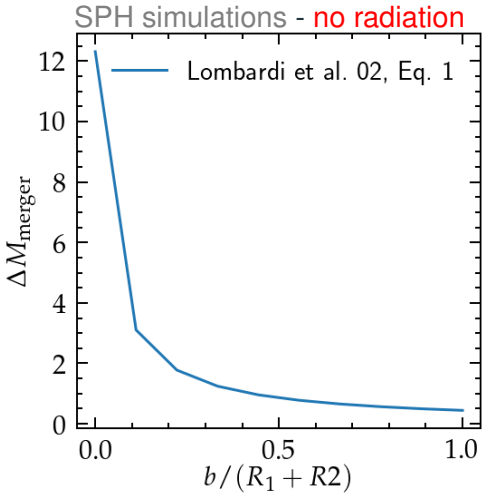
di Carlo *et al.* 20a

See also Spera *et al.* 19, di Carlo *et al.* 19, 20b, see also Kremer *et al.* 20, Mapelli *et al.* 20, Renzo *et al.* 20c

1st challenge: the merger

Mass and angular momentum budget

Estimates of mass loss for stellar collisions: $\Delta M_{\rm merger} \lesssim 10\%$



"Impact parameter"

Lombardi *et al.* 02, see also Glebbeek *et al.* 13

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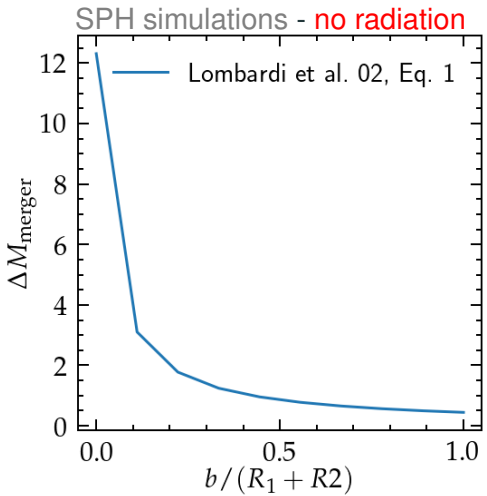

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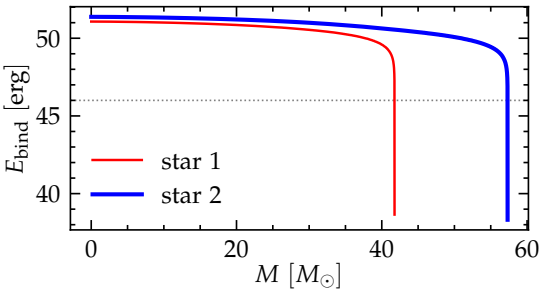

Energetic estimate

$$E_{\rm kin} \sim \frac{1}{2}\frac{M_1 M_2}{M_1 + M_2} v^2 \lesssim 10^{46}\,{\rm erg} \ll E_{\rm bind}$$

Using $v \lesssim 10\,{\rm km\ s^{-1}}$, $M_1 = 58\,M_\odot$, $M_2 = 42\,M_\odot$

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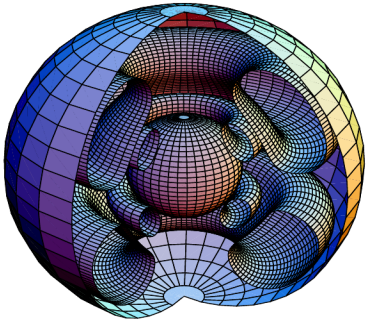
I will assume $\Delta M_{\rm merger} \equiv 0$

Lombardi *et al.* 02, see also Glebbeek *et al.* 13

Angular momentum distribution



Maeder & Meynet 2000

Possible issues

- **Surface:** Centrifugally driven mass loss

  Heger *et al.* 00

- **Core:** Core-growth by mixing

  de Mink *et al.* 09, de Mink & Mandel 16, Marchant *et al.* 16

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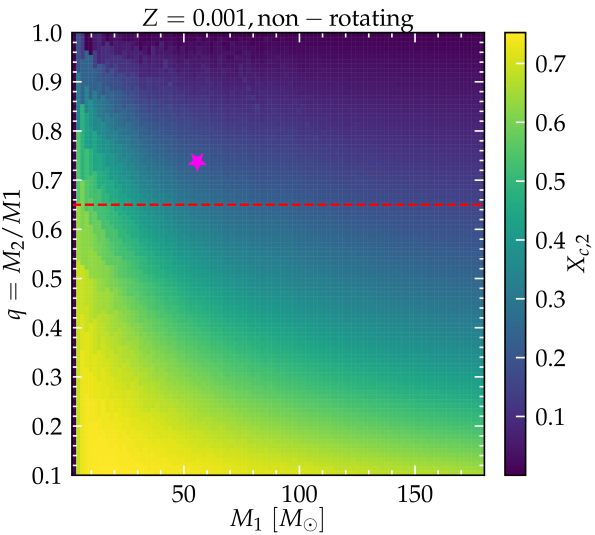
I will assume no rotation

see de Mink *et al.* 13, Schneider *et al.* 19

Making a merger with MESA

A very simple approach

Very massive stars have very similar lifetimes

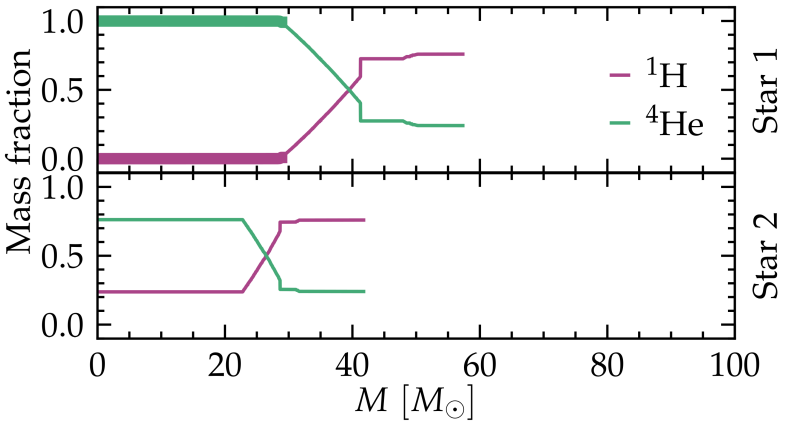


"Hydrogen left in the center of star 2"

If the He core is not allowed to grow,
Where does the He of star 2 go?

(also overshooting dependent)

Merger model from two stars

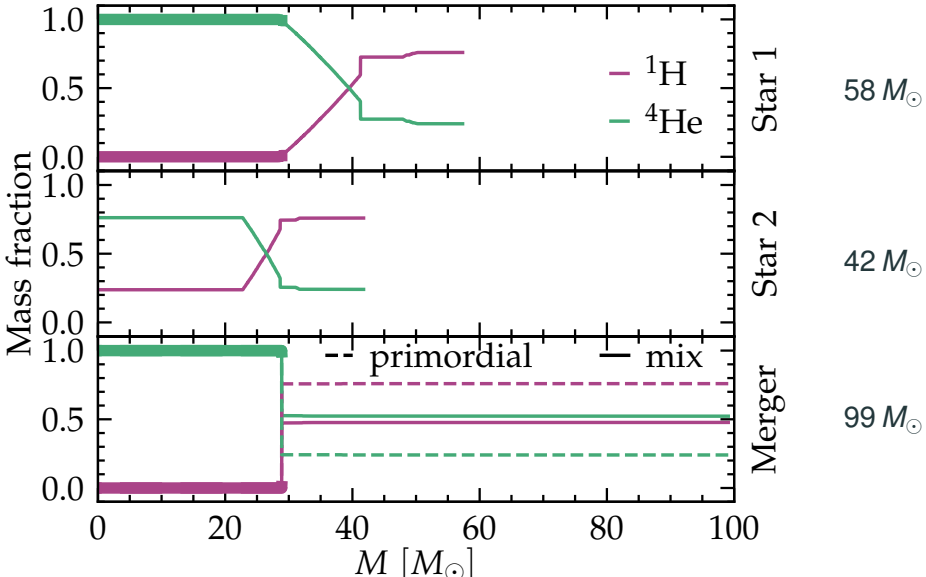


58 $M_\odot$

42 $M_\odot$

Renzo, Cantiello *et al.* 20

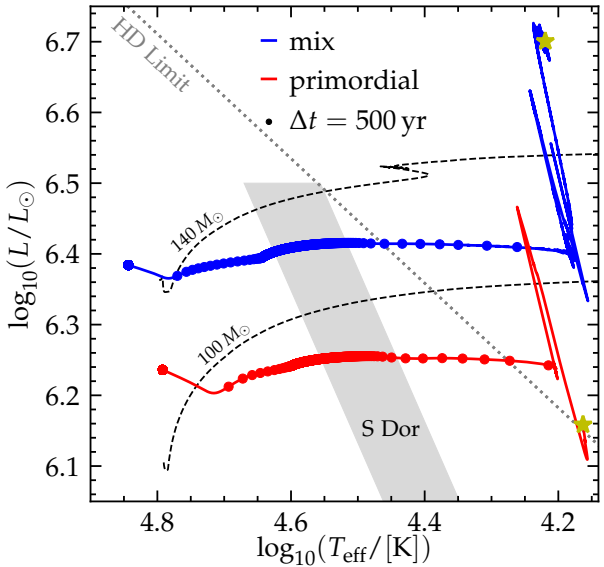
Merger model in two steps: (1) grow mass and (2) set composition



2nd challenge: the evolution

Keeping the mass on the star

Merger products are He-rich and blue ⇒ envelope instabilities?



Very massive stars are hardly stable

- $\sim 10^5$ years in S Dor instability strip
- reach core-collapse as BSG

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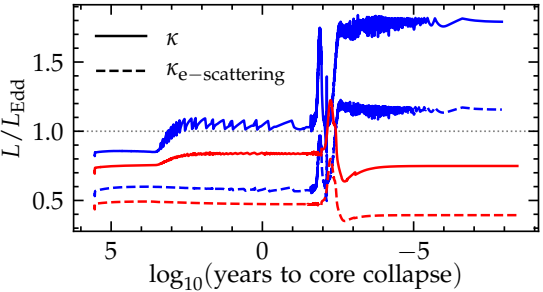
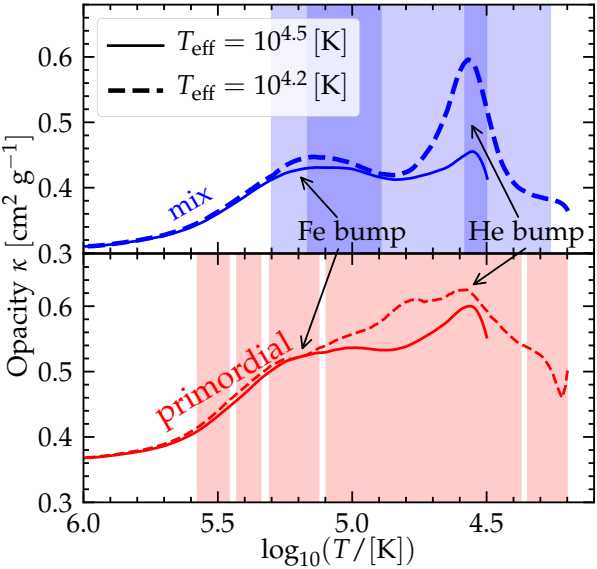
- LBV eruptions, aided by He opacity?

Jiang *et al.* 18

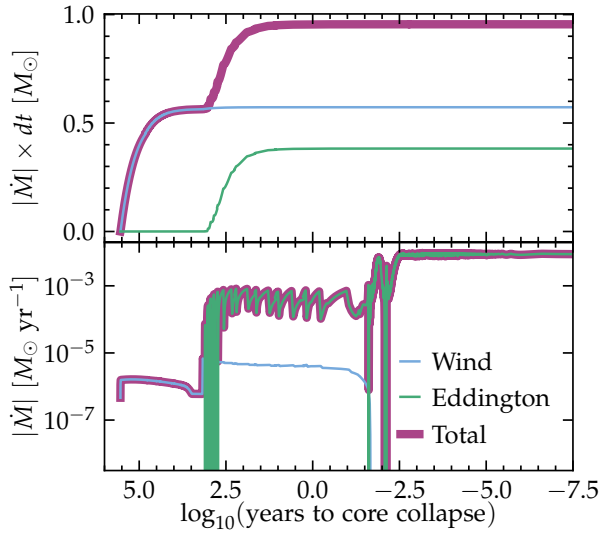
Renzo, Cantiello *et al.* 20

Eddington ratio and Opacity structure





The estimated radiation-driven mass loss is not significant



$$\dot{M} = \frac{L - L_{\mathrm{Edd}}}{v_{\mathrm{esc}}^2}$$

$L > L_{\mathrm{Edd}}$ only for few 100 years

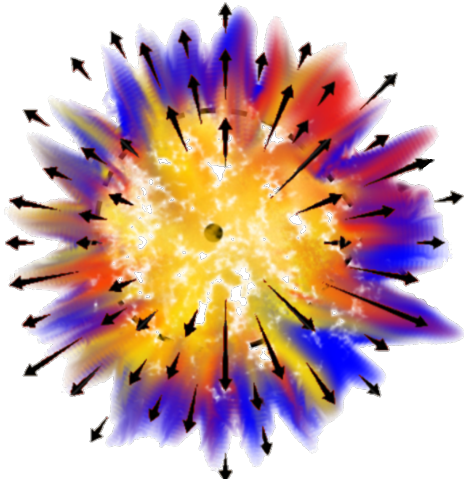
(higher $Z \Rightarrow$ higher $\kappa \Rightarrow$ higher $\dot{M}$)

Renzo, Cantiello *et al.* 20

3rd challenge: BH formation

What is the fate of the H-rich envelope?

Do BHs form via a failed, weak, or full blown SN explosion? (Work in progress)



$\Delta E_\nu \simeq 10^{53}\,\mathrm{erg}$

Possible causes for mass ejection at BH formation:

- ν-driven shocks

  Nadhezin 80, Lovegrove & Woosley 14, Fernandez *et al.* 18

- Jets, (even without net rotation)

  Gilkis & Soker 2014, Perna *et al.* 18, Quataert *et al.* 19

- weak fallback powered explosion

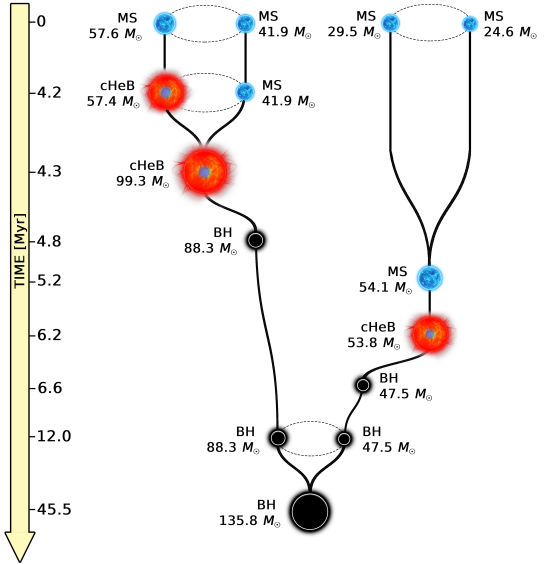
  Ott *et al.* 18, Kuroda *et al.* 18, Chan *et al.* 20

see also Adams *et al.* 17 for possible EM counterpart to BH formation

4^{th} challenge: forming a binary BH

Dynamics needed

Massive BHs are dynamically active: short merger time or cluster ejection



di Carlo *et al.* 20a

- $\tau_{\rm merger} \simeq$ few $\times$ 10 Myr
- 6% of BH formed at $Z < 0.002$ have masses in the gap ($\lesssim$ 1% at $Z_\odot$)
- depends also on initial cluster density

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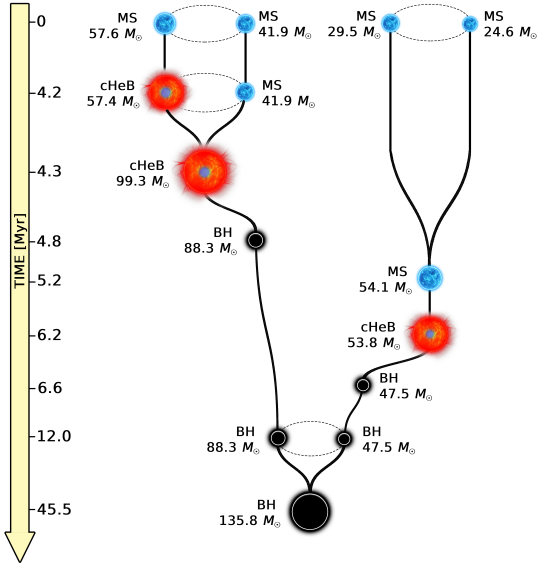

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GW190521

$M_1 = 85^{+21}_{-14}\,M_\odot \qquad M_2 = 66^{+17}_{-18}\,M_\odot$

both in the PISN gap

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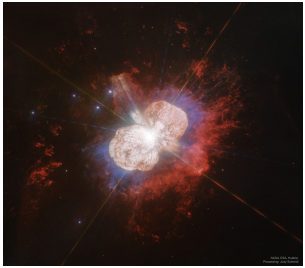
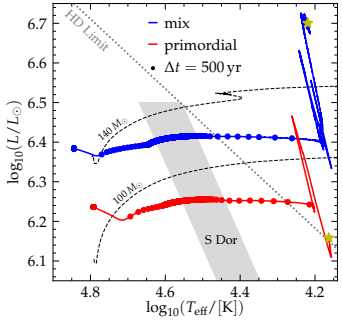
Stellar merger scenario twice **?**

Conclusions

Take home points

The stellar merger scenario is speculative





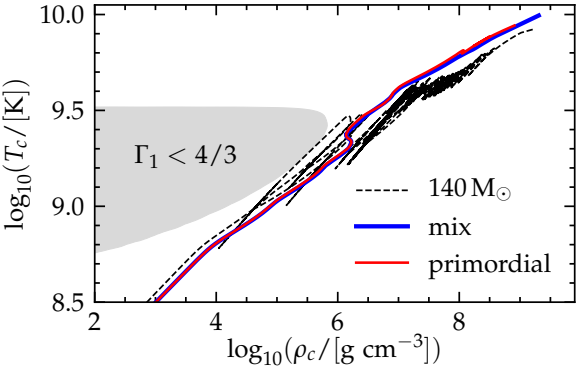
- Similar lifetimes of massive stars $\Rightarrow$ where does the He go?
- If He mixed in the envelope $\Rightarrow$ BSG with high $L/L_{\rm Edd}$
- Estimated $\Delta M_{\rm radiation} \lesssim 1\,M_\odot$ at $Z = 0.0002$

Renzo, Cantiello, *et al.* 20, arXiv:2010.00705

- Need better simulations of merger process and BH formation

Backup slides

Core evolution of merger models



By construction avoid PPISN

$$\langle\Gamma_1\rangle = \frac{\int_0^{R_*} P(r)\Gamma_1(r)\,dr}{\int_o^{R_*} P(r)\,dr} > 4/3$$

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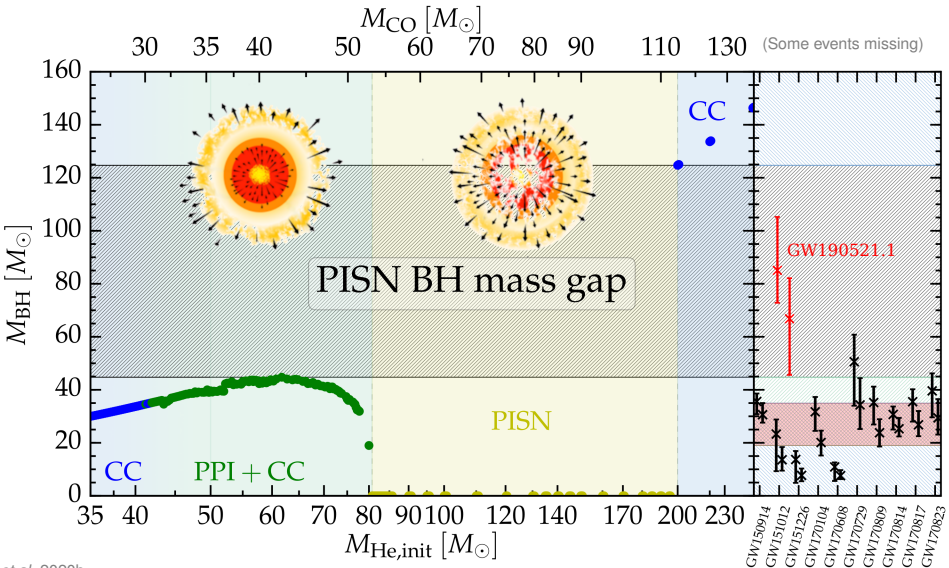
Global stability against pair-production

The pair-instability BH mass gap



Renzo, Farmer, *et al.* 2020b