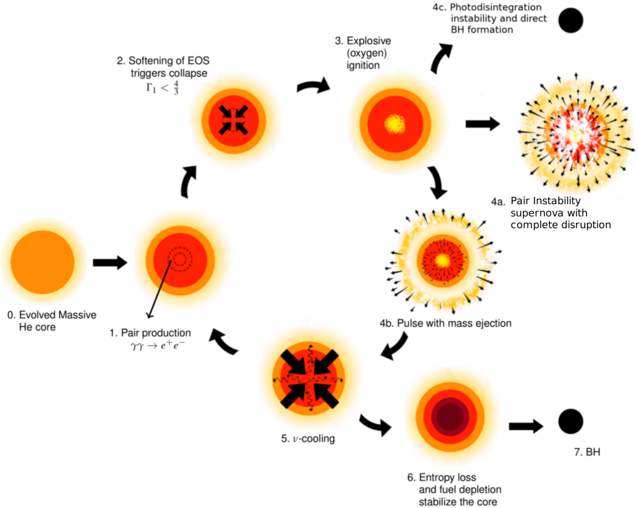
The stars that won’t die: pulsational pair instability supernovae



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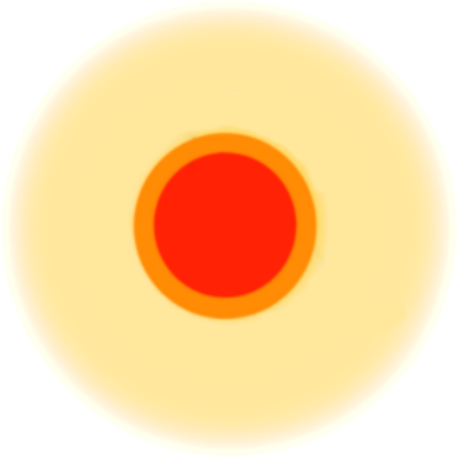
Collaborators: **R. Farmer**, S. Justham, S. E. de Mink , Y. Götberg, E. Zapartas, P. Marchant, M. Cantiello, Y.-F. Jiang, B. D. Metzger, E. C. Laplace, L. van Son, C. Xin

The theoretical picture

Pair-production happens in the interior[†]



[†] can be off-center

Simulating the He core captures the important dynamics

H-rich envelope can be lost to:

- winds
- binary interactions
- first pulse

Pair-instability SNe are the best understood supernovae

0. Evolved Massive He core

Radiation pressure dominated:

$$P_{\mathrm{tot}} \simeq P_{\mathrm{rad}}$$

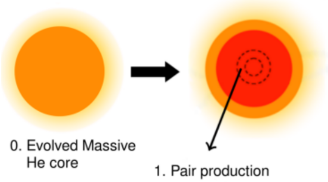
$$M_{\mathrm{He}} \gtrsim 32\,M_{\odot}$$

see Fowler & Hoyle 1964, Rakavy & Shaviv 1967, Barkat *et al.* 1968, Fraley 1968,

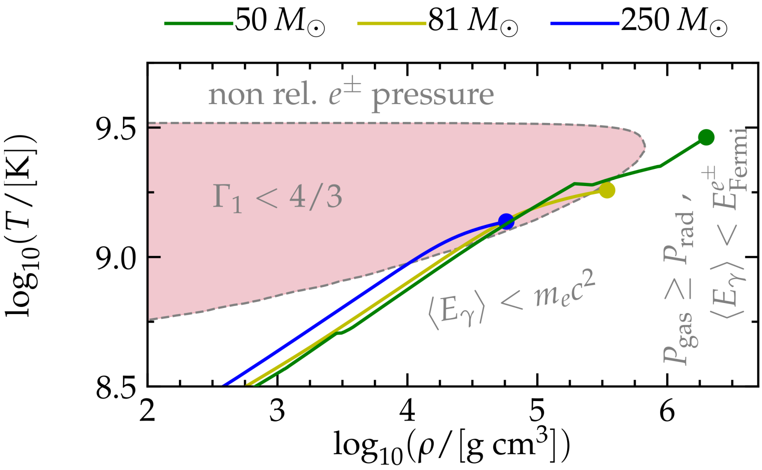
Glatzel *et al.* 1985, **Woosley** *et al.* 2002, 2007, Langer *et al.* 2007, Chatzopoulos *et al.* 2012, 2013, Yoshida *et al.* 2016,

Woosley 2017, 2019, Leung *et al. 2019*, etc...

Renzo, Farmer *et al.* 2020b



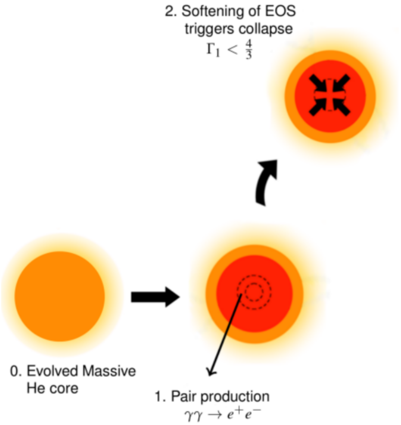
$$\gamma\,\gamma \rightarrow e^{+}\ e^{-}$$



$$\Gamma_1 \overset{\mathrm{def}}{=} \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{\mathrm{s}}$$

Renzo, Farmer *et al.* 2020b

He cores computed with MESA



Collapse on thermal timescale

$$\tau \propto \frac{GM_{\mathrm{He}}^2}{RL_\nu} \quad , \quad L_\nu \gg L$$

(Fraley 68)

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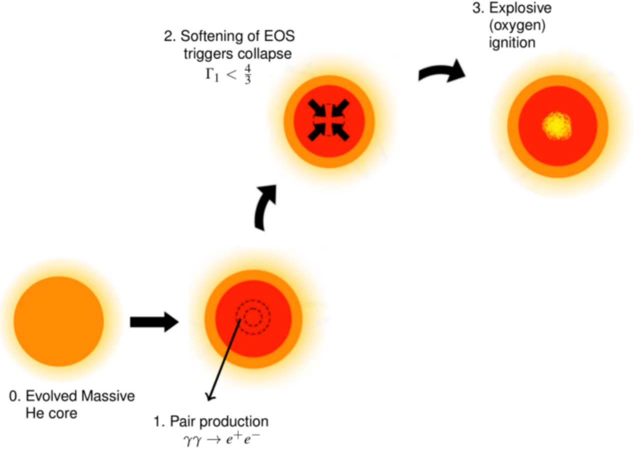


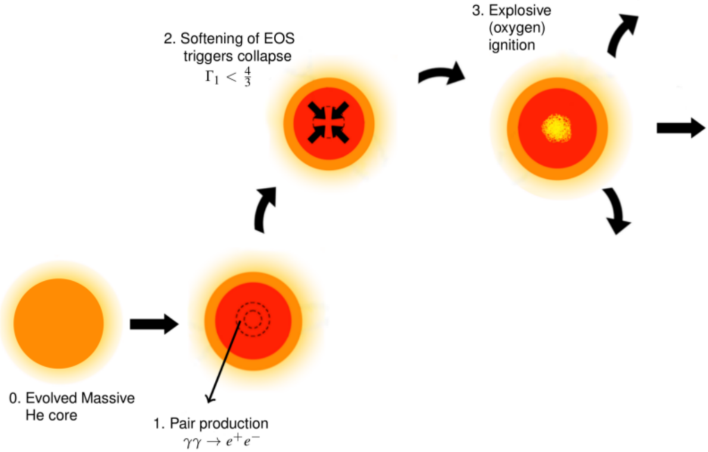
0. Evolved Massive He core

1. Pair production $\gamma\gamma \rightarrow e^+e^-$

2. Softening of EOS triggers collapse $\Gamma_1 < \frac{4}{3}$

3. Explosive (oxygen) ignition

Renzo, Farmer *et al.* 2020b



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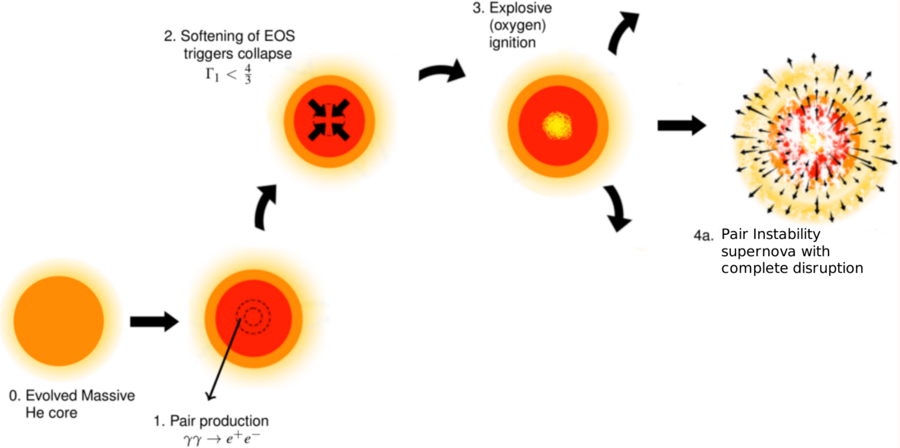

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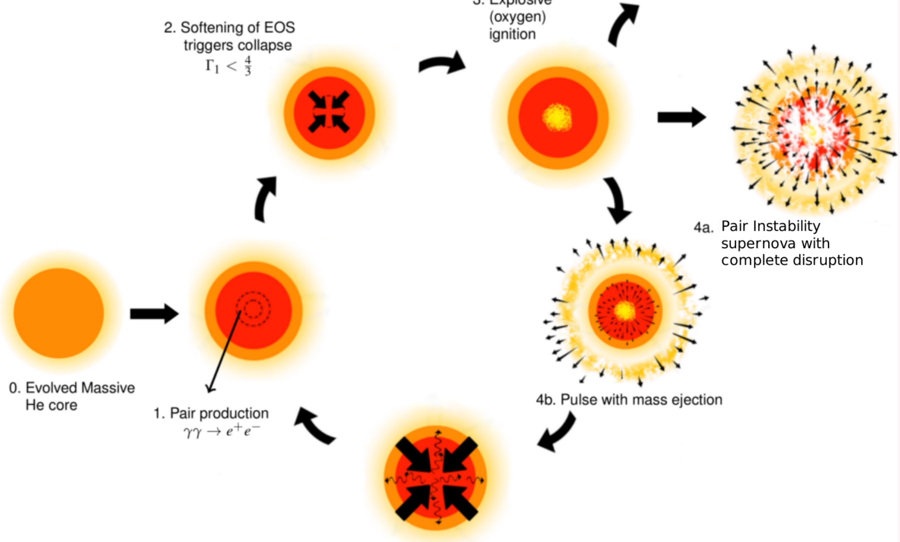
4a. Pair Instability supernova with complete disruption

Renzo, Farmer *et al.* 2020b



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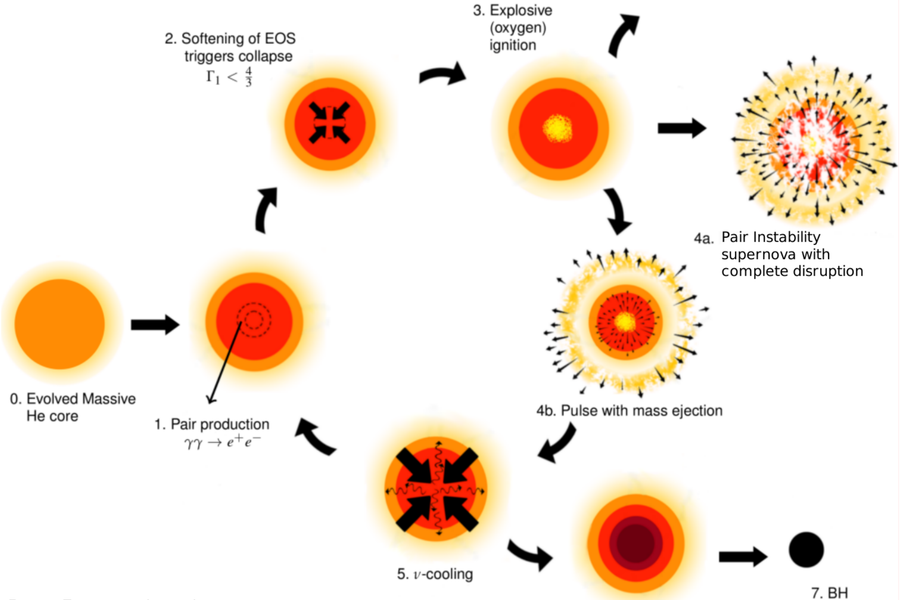
4b. Pulse with mass ejection

5. ν-cooling

Renzo, Farmer *et al.* 2020b



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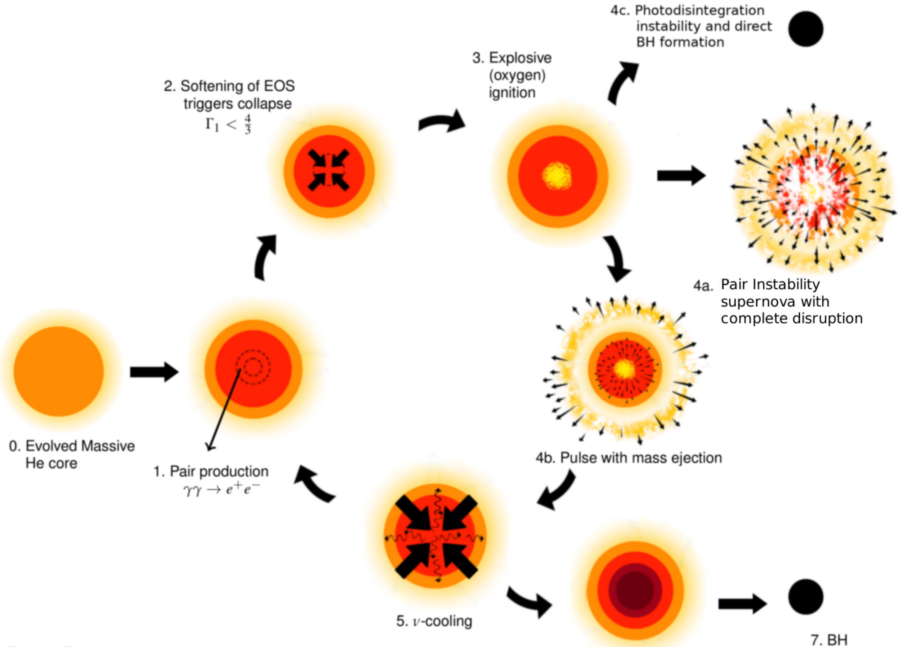
5. ν-cooling

7. BH

Renzo, Farmer *et al.* 2020b



BH

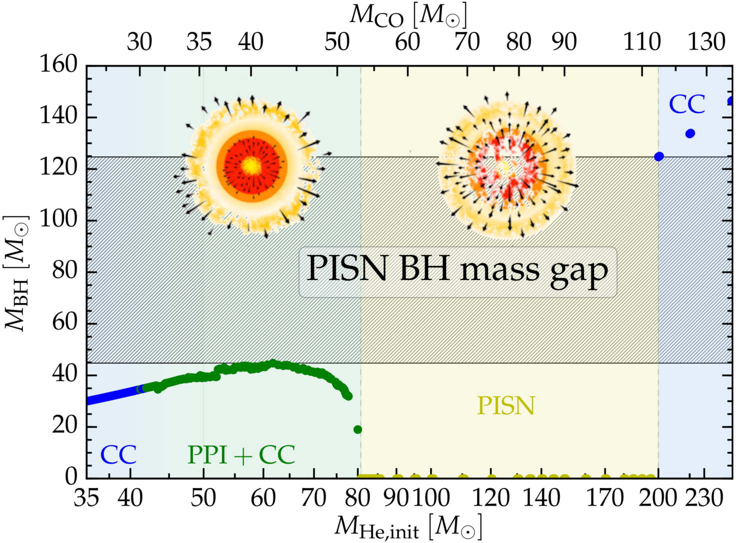
no BH

BH

Renzo, Farmer *et al.* 2020b

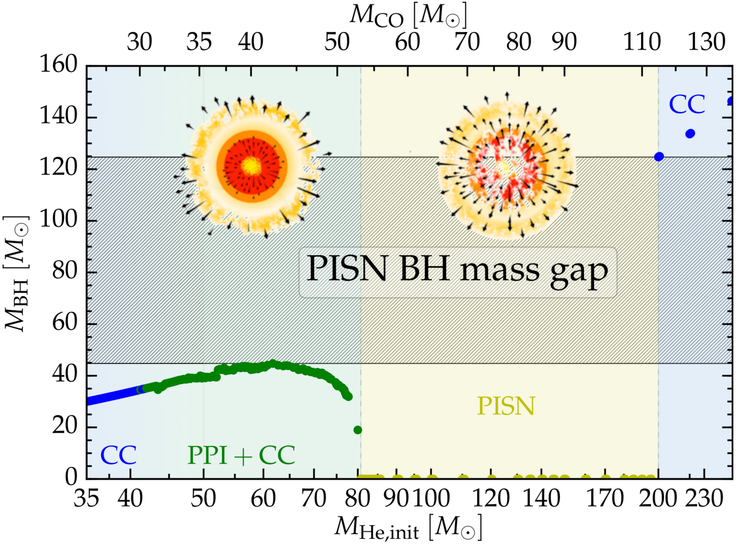
The pair-instability BH mass gap

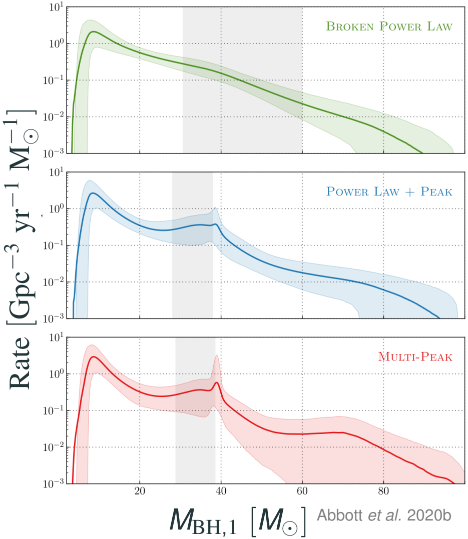
The distribution of stellar BH masses



Renzo, Farmer, *et al.* 2020b

The distribution of stellar BH masses





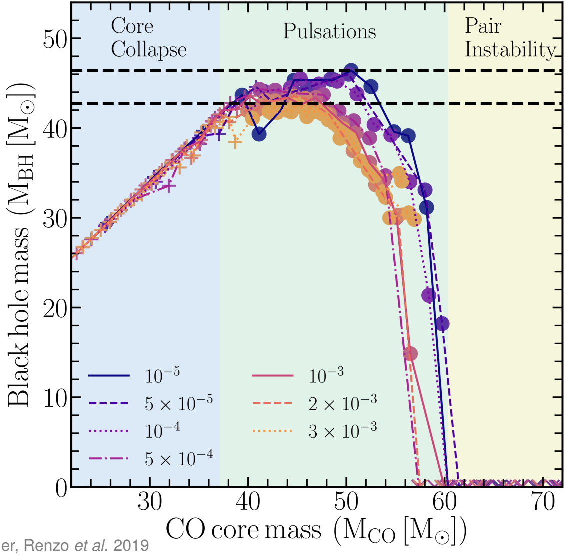
Abbott *et al.* 2020b

Renzo, Farmer, *et al.* 2020b

How robust are these predictions?

Metallicity? Small effect

Focus on lower edge of the gap



Farmer, Renzo *et al.* 2019

Metallicity shift

$\Delta \max\{M_{\rm BH}\} \sim 7\%$

over 2.5 orders of magnitude

Comparable or smaller effects: mixing, resolution, winds, nuclear reaction network size, etc..

EM signatures of PPISN

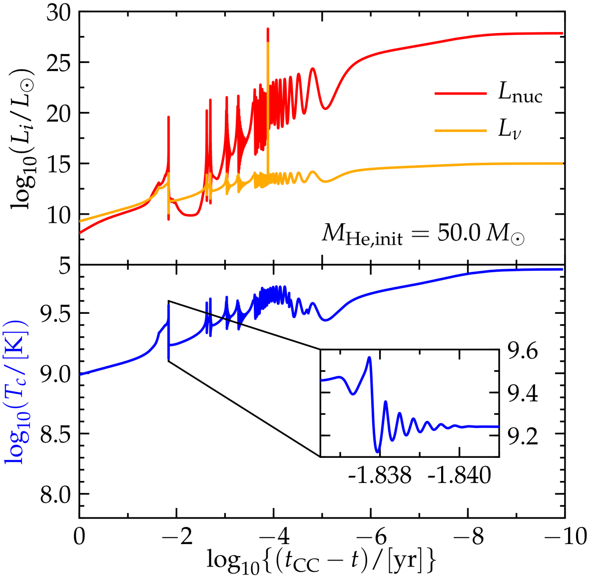
What is a pulse? Can we count them?

Not everything that happens inside the star influences the surface...

$\simeq$

...the internal structure can readjust

1 st pulse definition: thermonuclear ignition

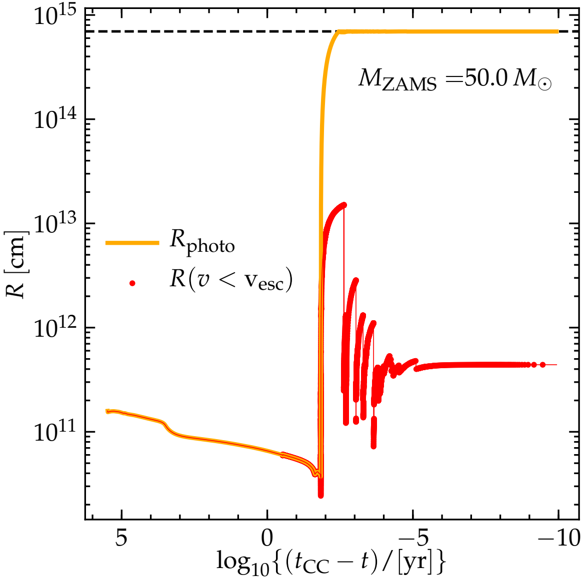


- Typical fuel ^{16}O but can be ^{28}Si
- Possible neutrino signal

Wright 2017, Leung *et al.* 2020

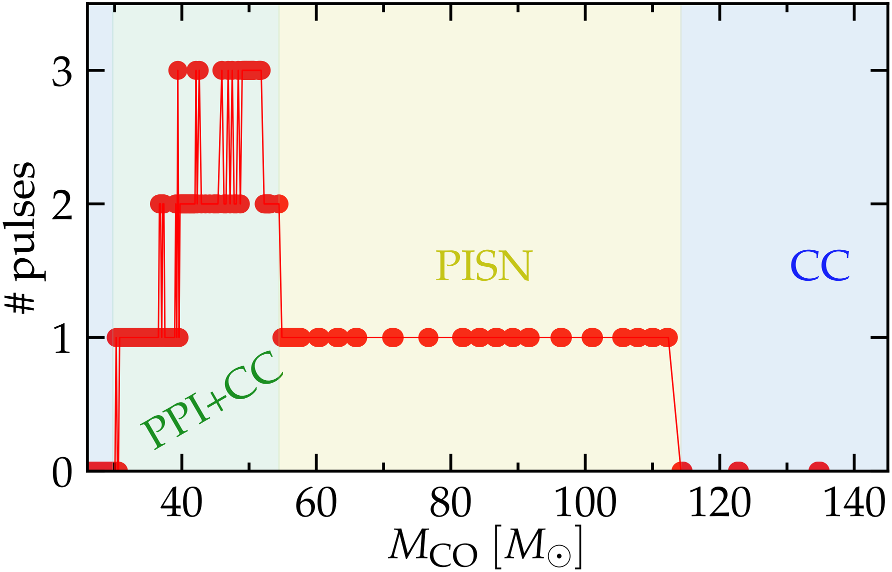
- Hard to count the maxima (and maybe not informative?)

2^{nd} pulse definition: radial expansion



- Large radial expansion
- Can be hidden by a pseudo-photosphere
- Important for binary interactions

3^{rd} pulse definition: dynamical mass ejection ($\Delta M_{\mathrm{pulse}} \gtrsim 10^{-6} M_{\odot}$)

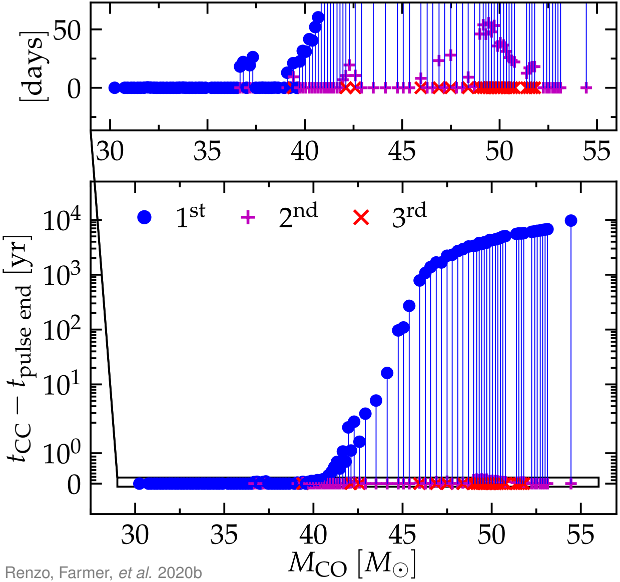


$\lesssim$ 3 distinct mass ejections

EM signatures of PPISN

When do the pulses occur?

Interpulse delays range from $0 \lesssim t \lesssim \tau_{\mathrm{KH}}$



Renzo, Farmer, *et al.* 2020b

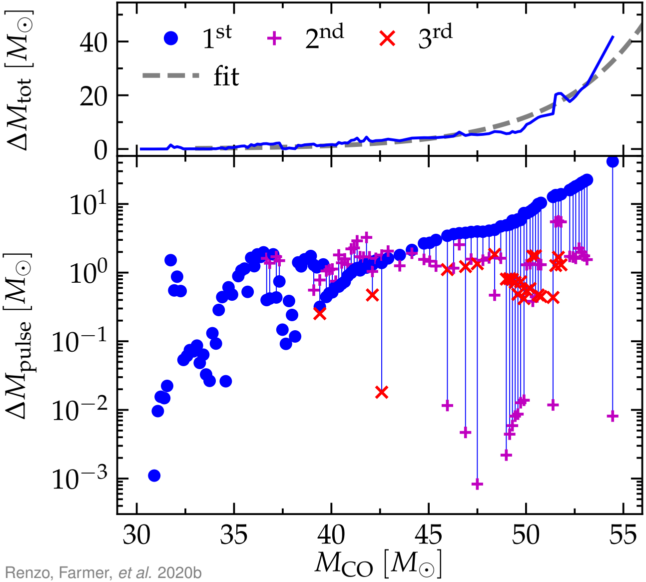
Many in the ∼ month delay timescale

Larger M_{CO} ⇒ stronger explosions ⇒
larger departure from equilibrium ⇒
longer delay up to τ_{KH}

EM signatures of PPISN

Amount of mass loss

The amount of mass lost is a steep function of the core mass



Renzo, Farmer, *et al.* 2020b

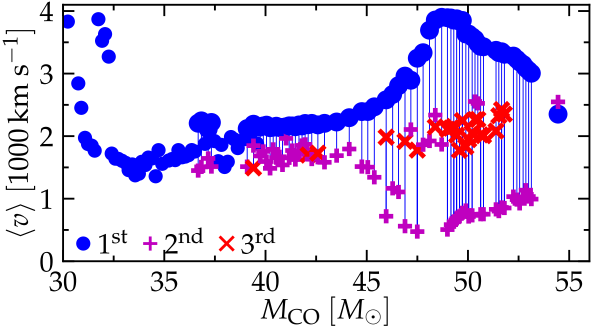
From the He core!

- H-envelope gone to winds, binarity, or at 1st pulse
- Winds not included
- ΔM_pulse large, but relevant for M_BH only for $M_\mathrm{CO} \gtrsim 40\ M_\odot$

EM signatures of PPISN

Ejecta velocity

Typical velocities $\langle v \rangle \simeq v_{\rm esc} \simeq 10^3\,\mathrm{km\ s^{-1}}$

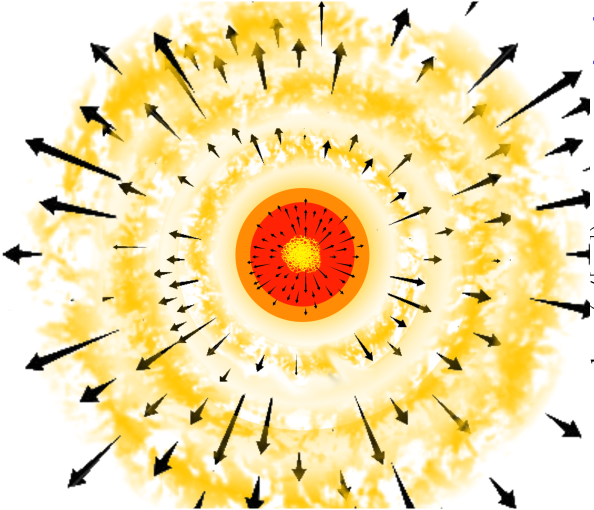


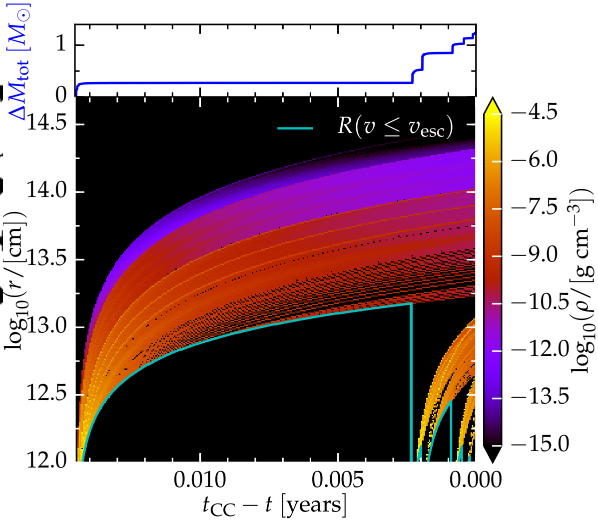
Connection to (some) SNIbn ?

Caveats: No radiative effects, assumes constant post-ejection velocity

Renzo, Farmer, *et al.* 2020b

Can shells collide with each other?

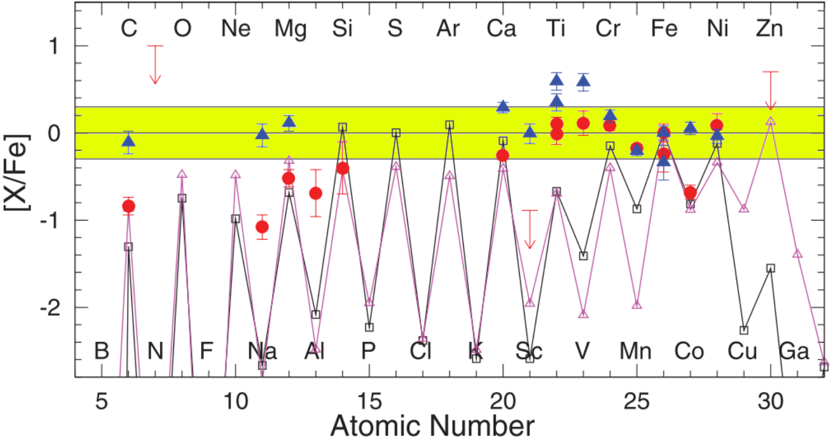




Woosley *et al.* 07, Chen *et al.* 14, Woosley 17, Renzo, Farmer *et al.* 2020b

Another possible observable: “Odd-even” effect in low *Z* stars

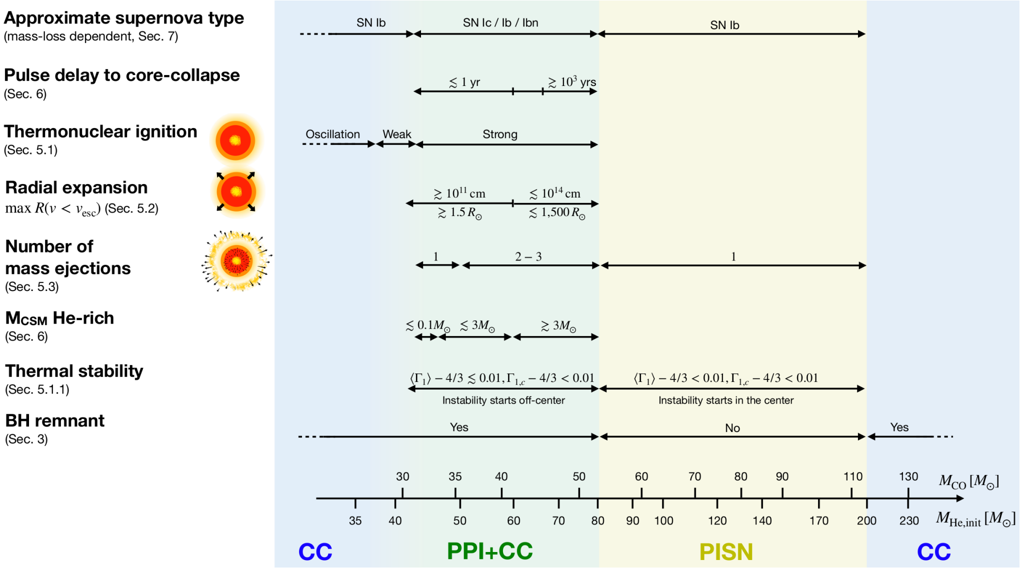
Nucleosynthesis without neutrons around ⇒ hard to make odd *A* elements



PISN predictions

adapted from Aoki *et al.* 14, predictions from Heger & Woosley 2002

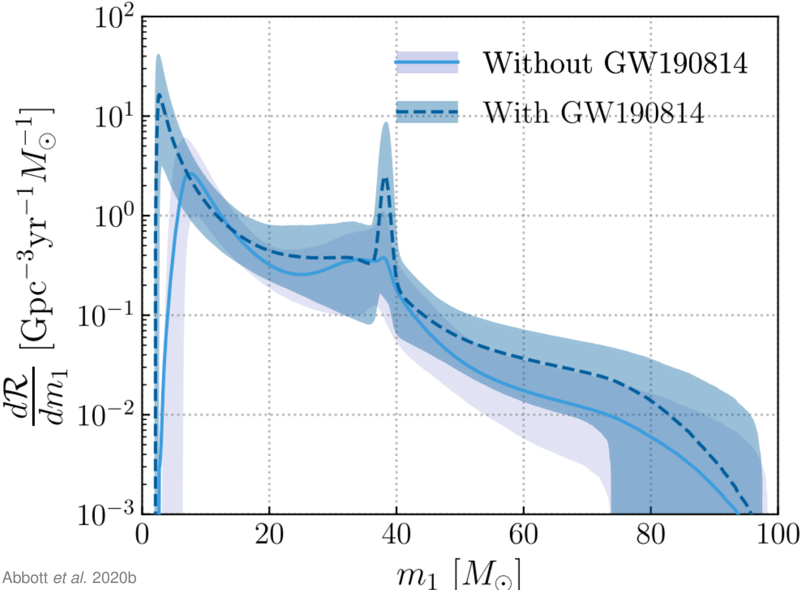
Summary of EM transients



Renzo, Farmer *et al.* 2020b

Filling the PISN mass gap

GW reveal a BH population in the gap



Abbott *et al.* 2020b

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

$\Downarrow$

How to form the others ?

Possible ways to fill the PISN mass gap

pre-BH formation

post-BH formation

Possible ways to fill the PISN mass gap

pre-BH formation

Move the gap

- decrease by $\sim 2.5\sigma$ the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

Farmer et al. 20, Belczynski 20

- Beyond standar model physics

Choplin *et al.* 17, Croon*et al.* 20a,b, Sakstein *et al.* 20,

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Straight *et al.* 20, Ziegler *et al.* 20

Avoid pair-instability

- stellar merger scenario

see Spera & Mapelli 2019, di Carlo *et al.* 19, 20a, 20b, Renzo *et al.* 20c

- population III Farrell *et al.* 20, Kinugawa *et al.* 20
- Quench winds Belczynski *et al.* 20, Vink *et al.* 20

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post-BH formation

Accretion:

- in proto-cluster Roupas & Kazanas 2019a,b
- PBHs before re-ionization de Luca *et al.* 2020
- in isolated binary van Son *et al.* 2020
- in halos Safarzadeh & Haiman 20

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Multiple generations of BBH mergers

- in clusters — Fragione *et al.* 20, Liu & Lai 20
- in nuclear clusters — Perna *et al.* 19
- in AGN disks

McKernan *et al.* 12, Bartos *et al.* 17, Stone *et al.* 19

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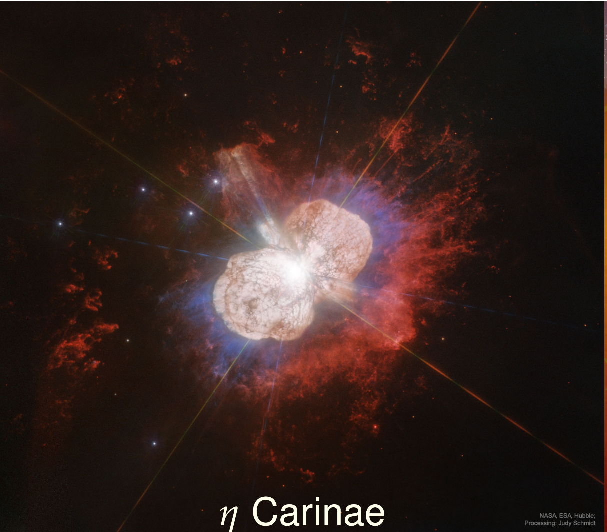
"Impostor" GW events: High eccentricity merger? Lensing?

Filling the PISN mass gap

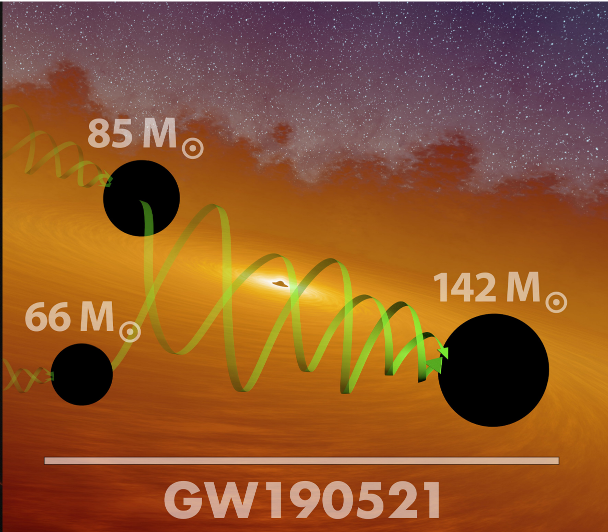
The “stellar merger” scenario

Merge stars below the gap to get large envelope and small core

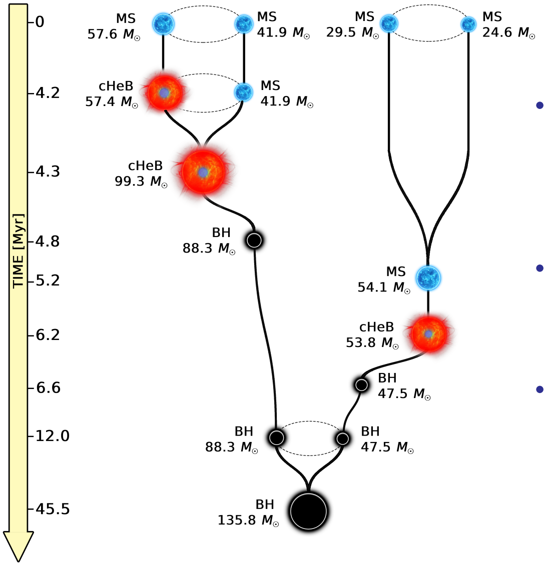
see Spera & Mapelli 2019, Di Carlo *et al.* 2020a,b, Kremer *et al.* 2020
see also issues in Renzo, Cantiello *et al.* 2020



NASA, ESA, Hubble;
Processing: Judy Schmidt



The “stellar merger scenario”

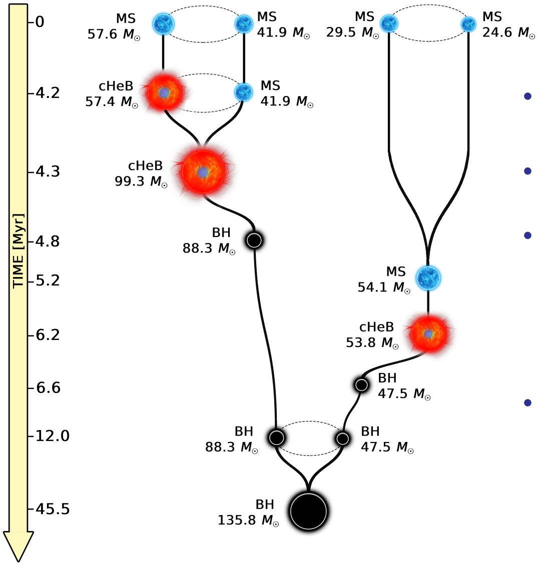


- Make a star with a small core and oversized envelope to avoid PPISN
- Collapse it to a BH in the gap
- Pair it in a GW source with dynamics

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

  ⇓

  Requires nuclear cluster and/or AGN disk?

di Carlo *et al.* 20a

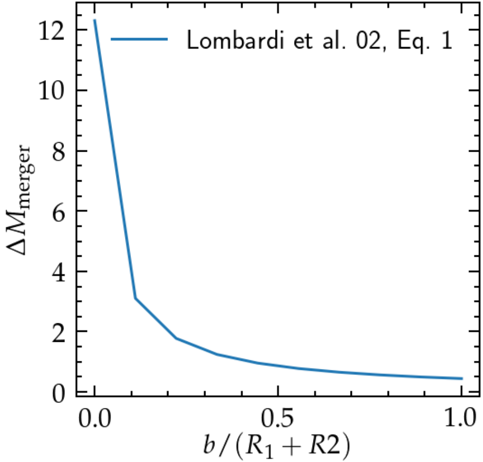
See also Spera *et al.* 19, di Carlo *et al.* 19, 20b, see also Kremer *et al.* 20, Mapelli *et al.* 20, Renzo *et al.* 20c

The “stellar merger” scenario

1^{st} challenge: merger mass and angular momentum budget

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

SPH simulations - no radiation



“Impact parameter”

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

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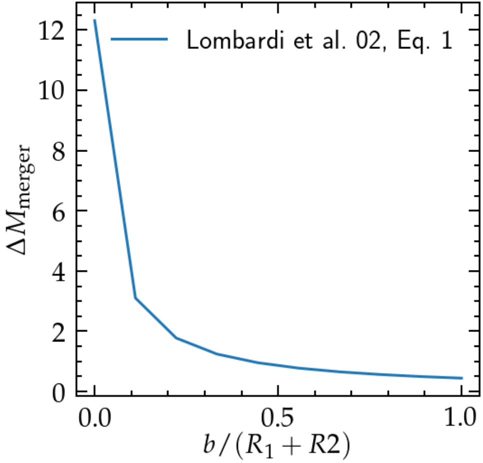

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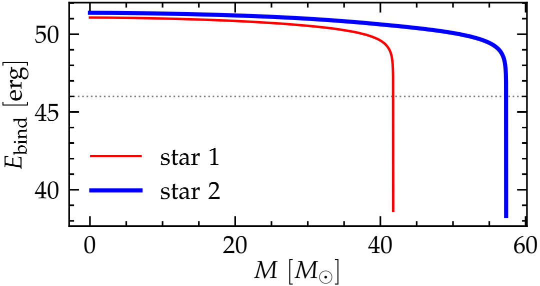


Energetic estimate

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

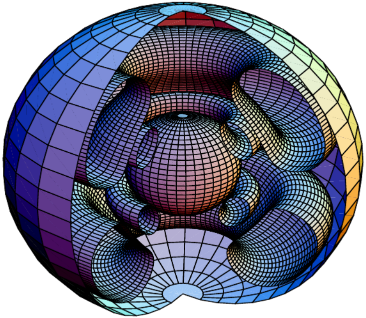
Using $v \lesssim 10\,\mathrm{km\ s^{-1}}$, $M_1 = 58\,M_\odot$, $M_2 = 42\,M_\odot$

$$\Downarrow$$

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

⇓

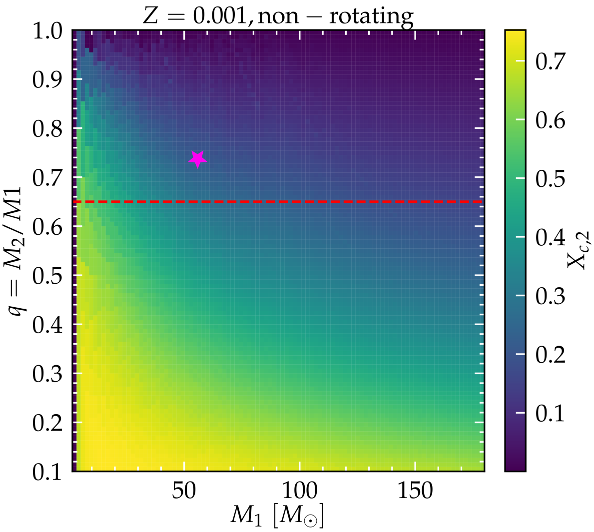
I will assume no rotation

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

The “stellar merger” scenario

Simplified MESA mergers

Very massive stars have very similar lifetimes

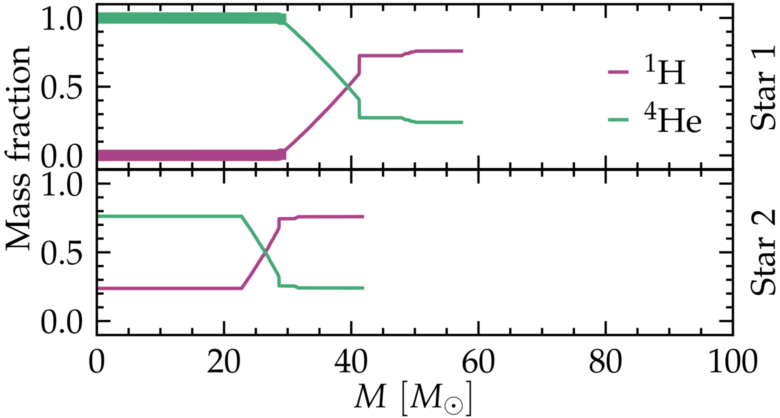


“Hydrogen left in the center of star 2”

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

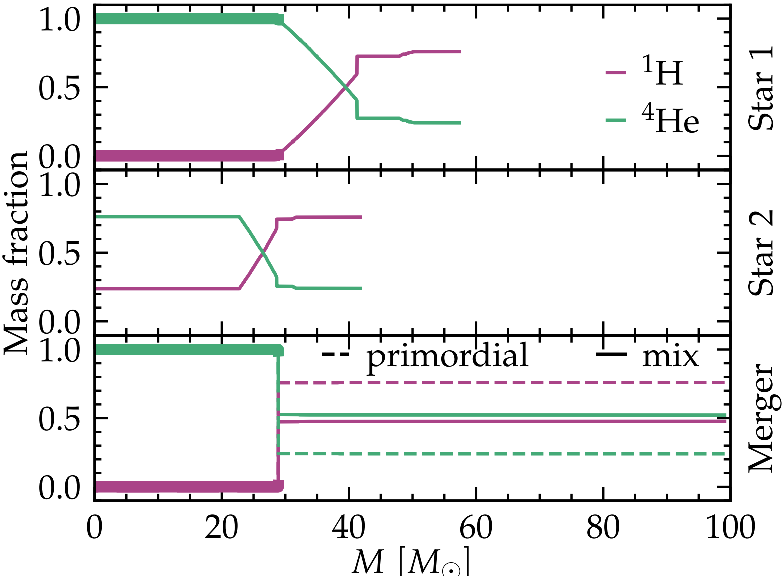


$58\ M_\odot$

$42\ M_\odot$

Renzo, Cantiello *et al.* 20

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



58 $M_\odot$

42 $M_\odot$

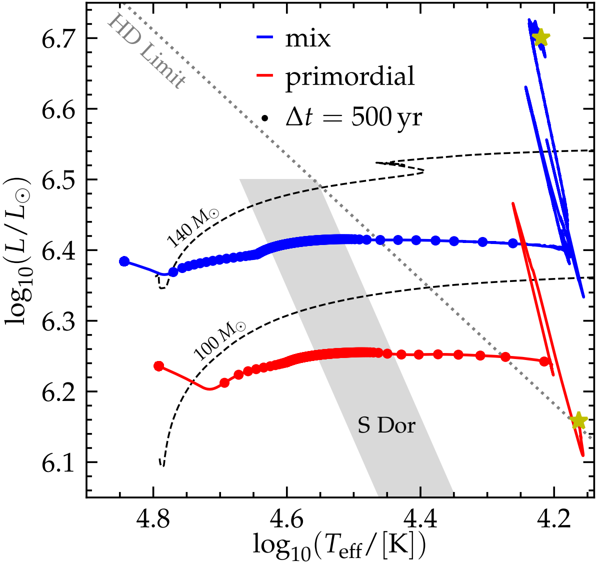
99 $M_\odot$

Renzo, Cantiello *et al.* 20

The “stellar merger” scenario

2nd challenge: Keeping the mass

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



Renzo, Cantiello *et al.* 20

Very massive stars are hardly stable

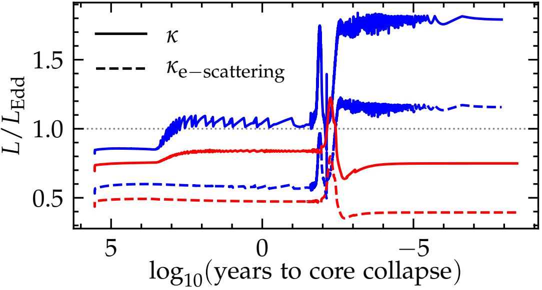
- $\sim 10^5$ years in S Dor instability strip
- reach core-collapse as BSG

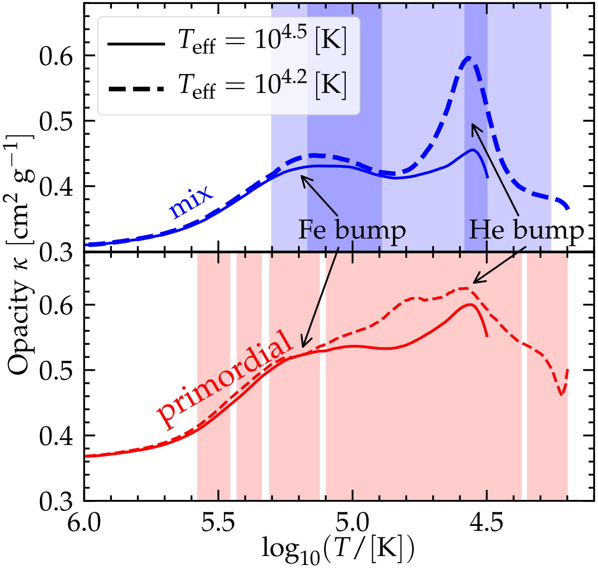
⇓

- LBV eruptions, aided by He opacity?

Jiang *et al.* 18

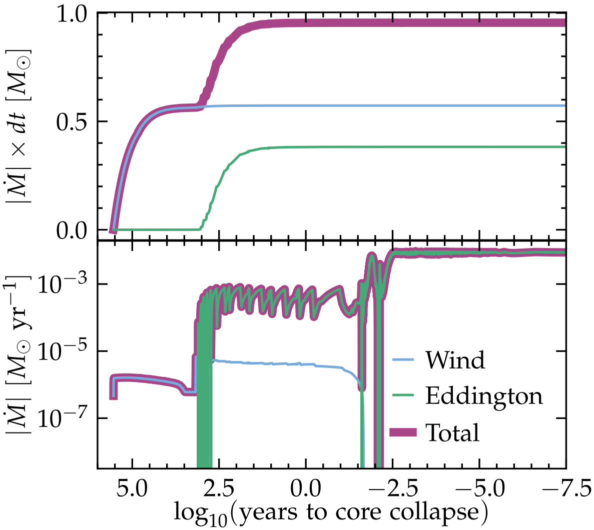
Eddington ratio and Opacity structure





Renzo, Cantiello *et al.* 20

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

The “stellar merger” scenario

3rd challenge: envelope fate at BH formation

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

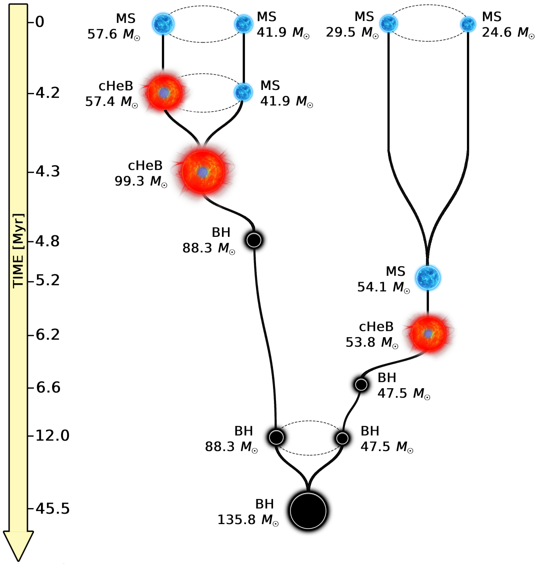
  Ott *et al.* 18, Kuroda *et al.* 18, Chan *et al.* 20

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

The “stellar merger” scenario

4th challenge: forming a binary BH

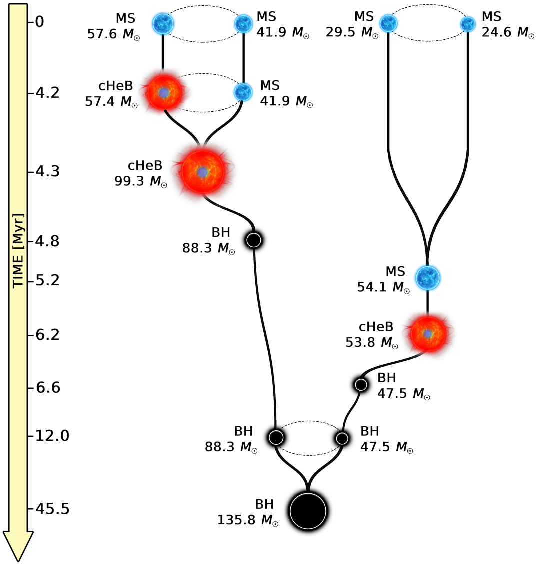
Massive BHs are dynamically active: short merger time or cluster ejection



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

di Carlo *et al.* 20a

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



di Carlo *et al.* 20a

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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

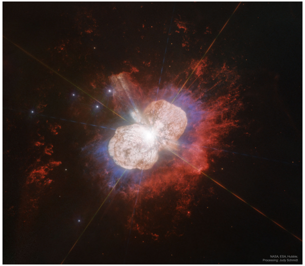
$$\Downarrow$$

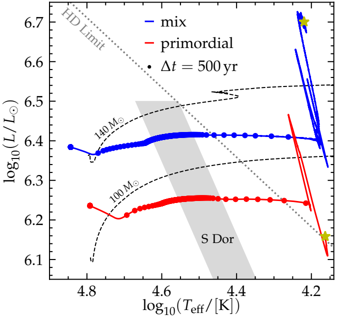
Stellar merger scenario twice ?

Conclusions

for the “stellar merger” scenario

The stellar merger scenario is very speculative





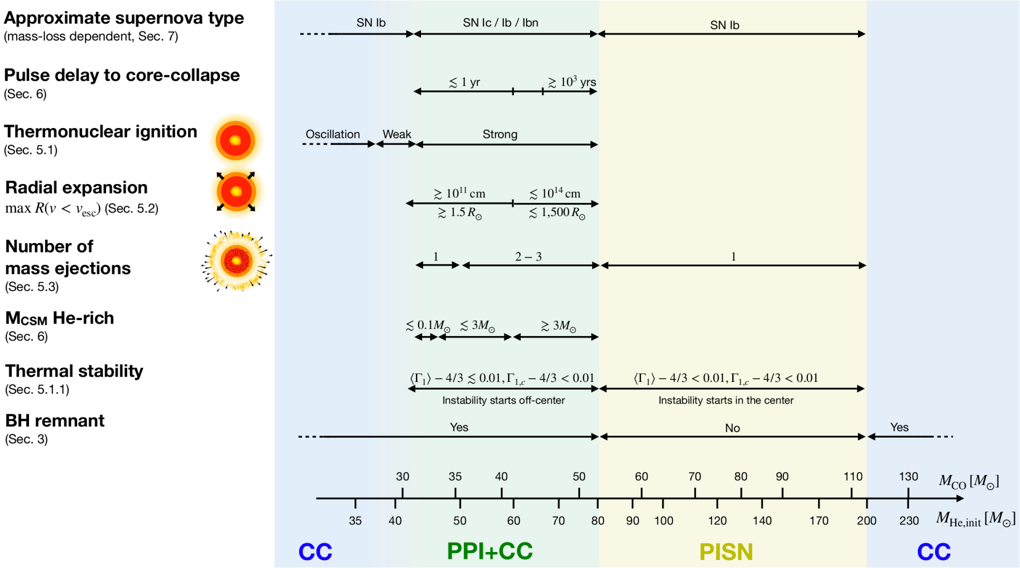
- Similar lifetimes of massive stars $\Rightarrow$ where does the He go?
- If He mixed in the envelope $\Rightarrow$ BSG with high L/L_Edd
- Estimated $\Delta M_\mathrm{radiation} \lesssim 1\,M_\odot$ at $Z = 0.0002$

$\Rightarrow$ LBV-like eruption at very low Z?

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

- Need better simulations of merger process and BH formation

Summary of EM transients



Approximate supernova type
(mass-loss dependent, Sec. 7)
SN Ib | SN Ic / Ib / Ibn | SN Ib

Pulse delay to core-collapse
(Sec. 6)
$\lesssim 1$ yr | $\gtrsim 10^3$ yrs

Thermonuclear ignition
(Sec. 5.1)
Oscillation | Weak | Strong

Radial expansion
$\max R(v < v_{\rm esc})$ (Sec. 5.2)
$\gtrsim 10^{11}$ cm | $\lesssim 10^{14}$ cm
$\gtrsim 1.5\,R_\odot$ | $\lesssim 1{,}500\,R_\odot$

Number of mass ejections
(Sec. 5.3)
1 | 2 – 3 | 1

$M_{\rm CSM}$ He-rich
(Sec. 6)
$\lesssim 0.1 M_\odot$ | $\lesssim 3 M_\odot$ | $\gtrsim 3 M_\odot$

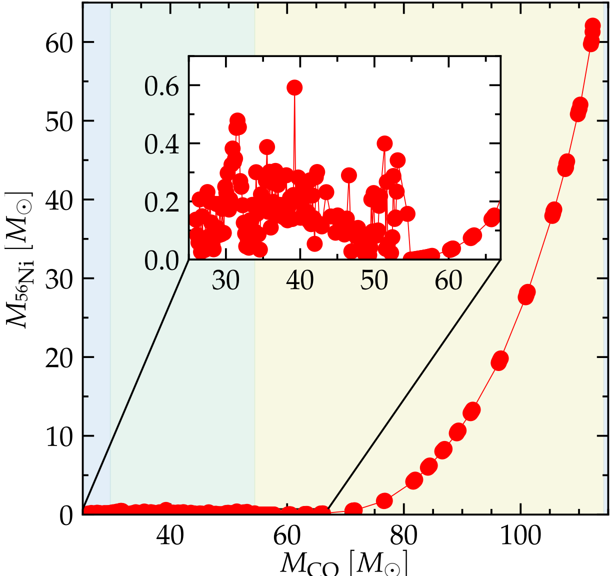
Thermal stability
(Sec. 5.1.1)
$\langle\Gamma_1\rangle - 4/3 \lesssim 0.01, \Gamma_{1,c} - 4/3 < 0.01$
Instability starts off-center
$\langle\Gamma_1\rangle - 4/3 < 0.01, \Gamma_{1,c} - 4/3 < 0.01$
Instability starts in the center

BH remnant
(Sec. 3)
Yes | No | Yes

Renzo, Farmer *et al.* 2020b

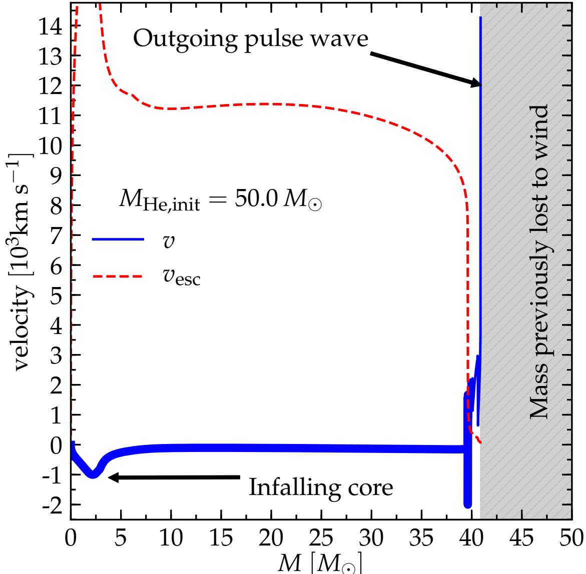
Backup slides

^{56}Ni production



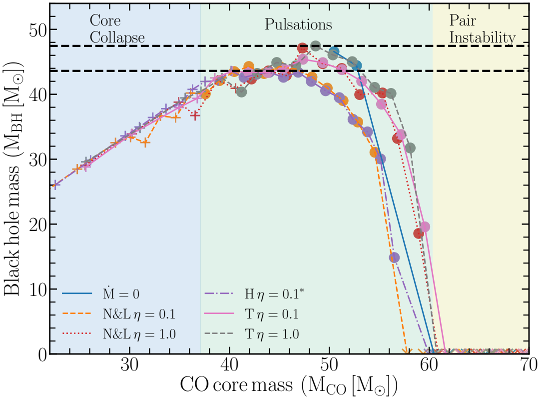
Farmer, Renzo *et al.* 2020b

Velocity profile at core-collapse after PPI



Farmer, Renzo *et al.* 2020b

Winds, mixing, ν physics? Also small effects



Farmer, Renzo *et al.* 2019

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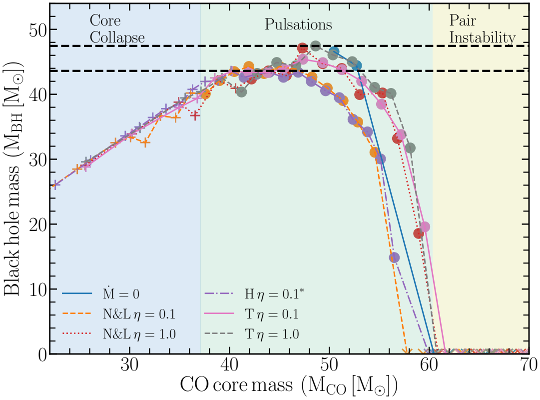

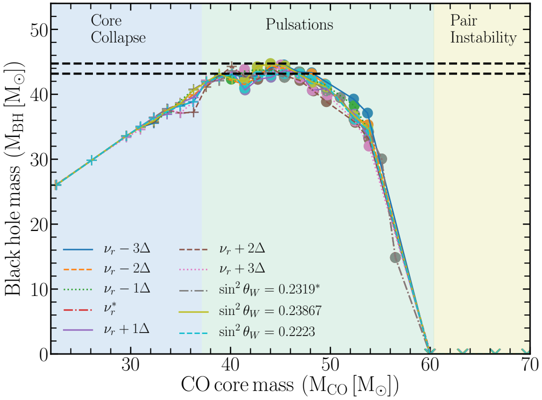

Farmer, Renzo *et al.* 2019

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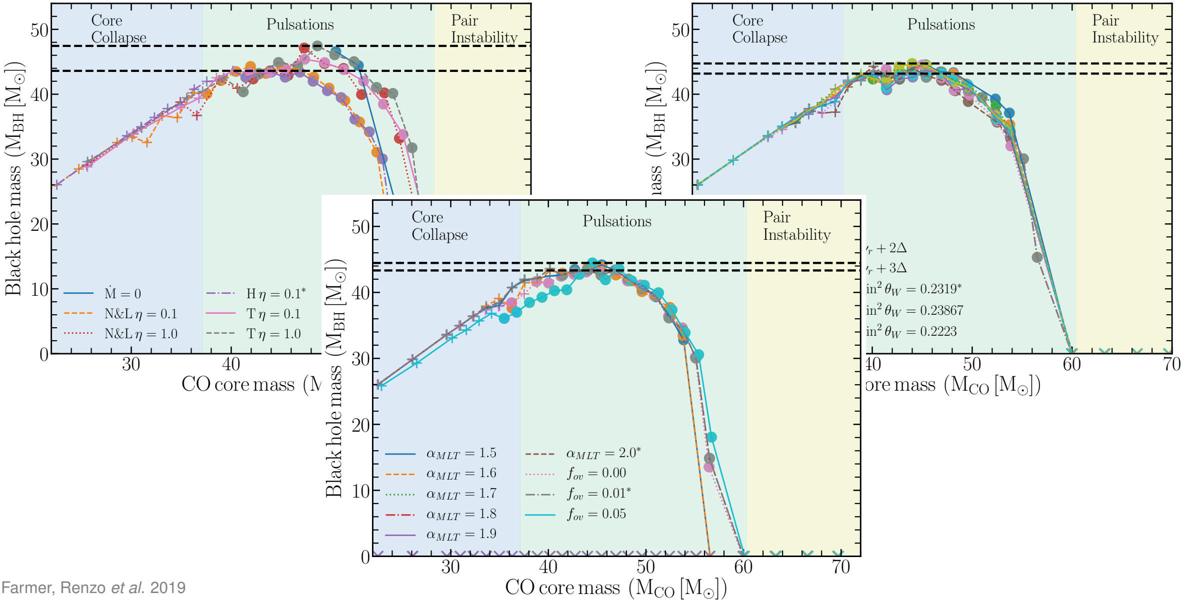
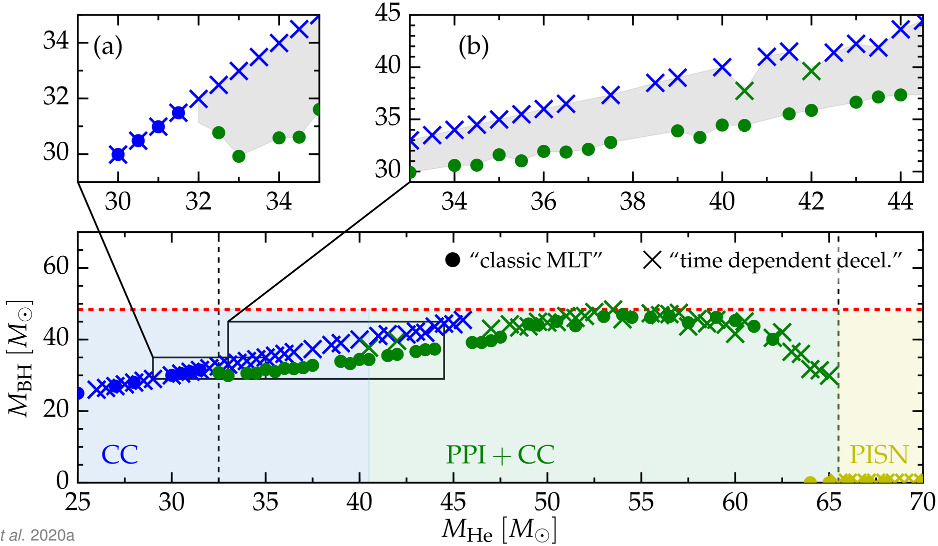


Farmer, Renzo *et al.* 2019

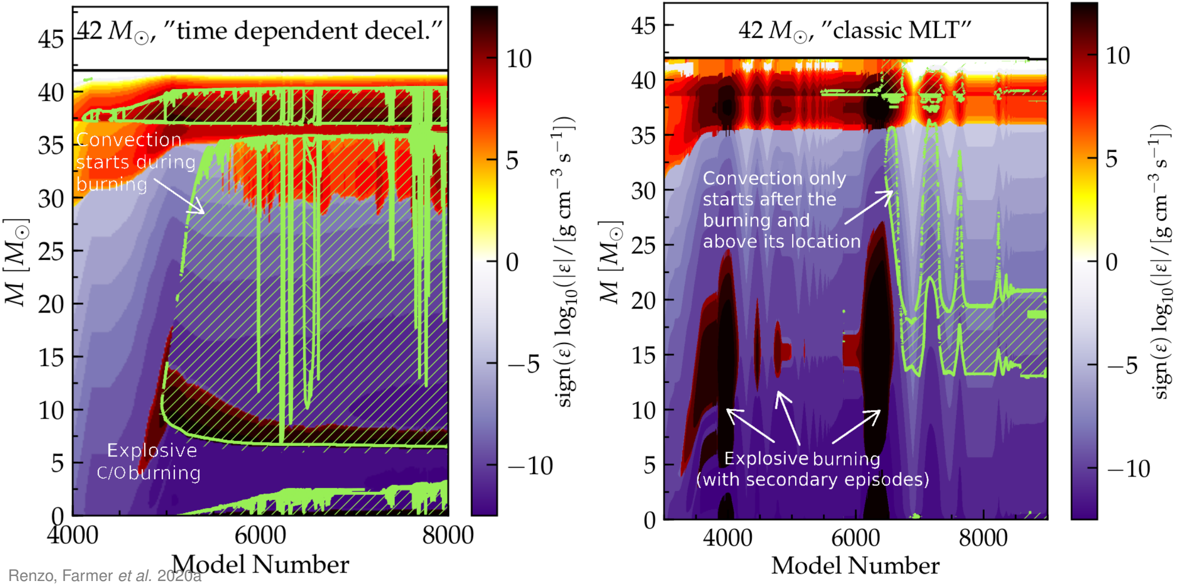
Treatment of time-dependent convection? Not the edge

Matters for least massive PPI, not for the most massive BH progenitors



Renzo, Farmer *et al.* 2020a

Convection during the pulses quenches the PPI mass loss



42 $M_\odot$, "time dependent decel."

Convection starts during burning

Explosive C/O burning

42 $M_\odot$, "classic MLT"

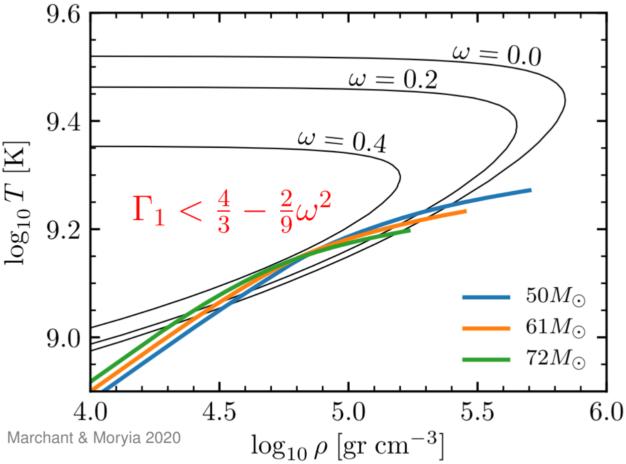
Convection only starts after the burning and above its location

Explosive burning (with secondary episodes)

Renzo, Farmer *et al.* 2020a

Can rotation move the gap? Barely...

Rotation $\Rightarrow$ **bigger** M_{He} $\Rightarrow$ can increase the rates



Marchant & Moryia 2020

Chatzopoulos *et al.* 2012, 2013

Rotation stabilizes only for *very* extreme assumption:

- No core-envelope coupling
- large initial rotation
- low Z ($\simeq$ no winds)

$\Downarrow$

only $\sim$20% shift of instability

$\lesssim$4% for “realistic” coupling

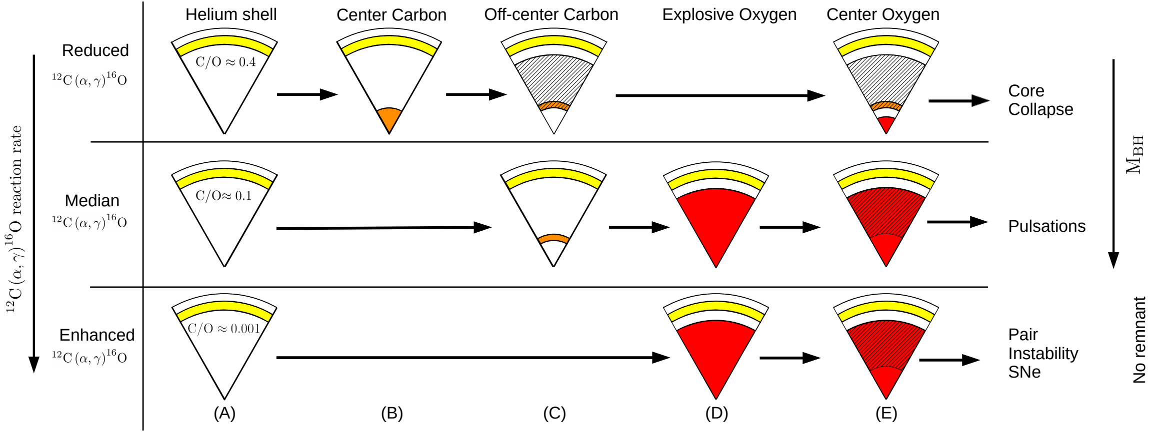
see also Glatzel *et al.* 1985

The only known large uncertainty

Nuclear reaction rates

The $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ ends He core burning

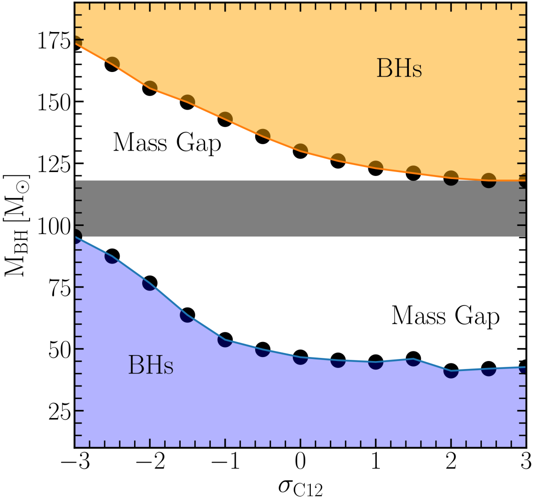
More $^{12}\mathrm{C} \Rightarrow$ C shell burning delays $^{16}\mathrm{O}$ ignition to higher ρ



Farmer, Renzo *et al.* 2020

The most important reaction $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate

Change in C/O ratio ⇒ different C-shell behavior



GW can constrain nuclear rates with the gap...

...if other channels don't pollute it too much

Farmer, Renzo *et al.* 2020, see also Takahashi 2018, Farmer, Renzo *et al.* 2019

The most important reaction $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate

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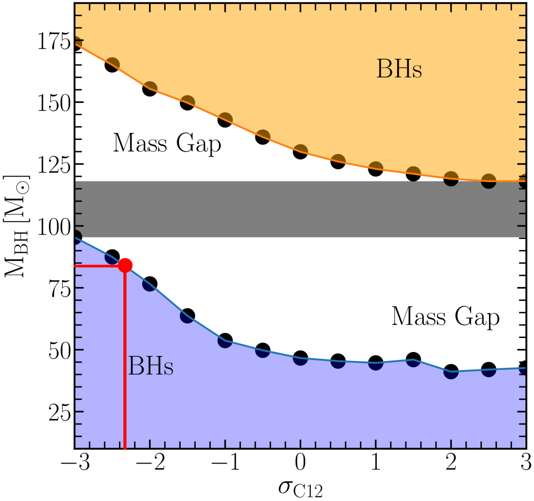


$M_{\mathrm{BH}} \simeq 85\,M_\odot$ requires **decreasing** rate by $\sim 2.5\,\sigma$

GW can constrain nuclear rates with the gap...

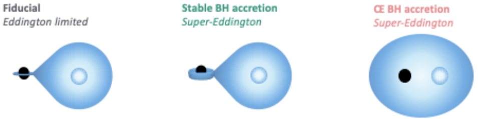
...if other channels don't pollute it too much

Farmer, Renzo *et al.* 2020, see also Takahashi 2018, Farmer, Renzo *et al.* 2019

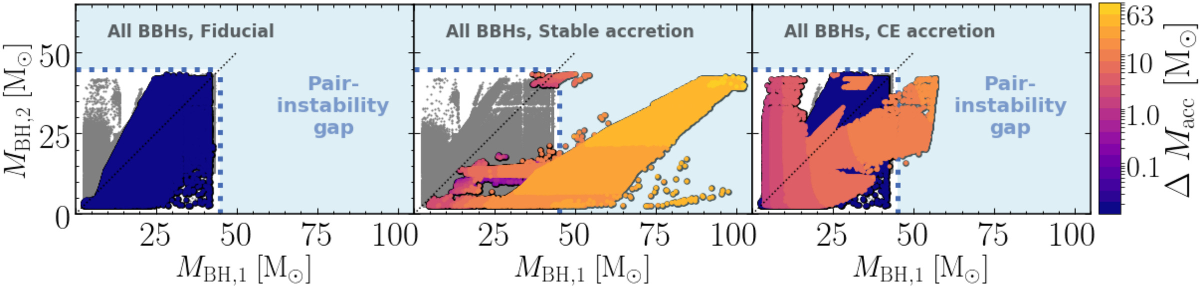
Possible ways to bridge the gap

Does binarity move the gap?

Can isolated binary evolution “pollute” the gap?

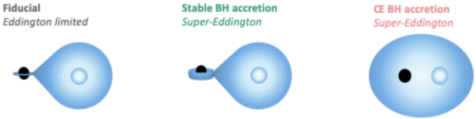


With unlimited accretion, some binary BHs can enter the gap...

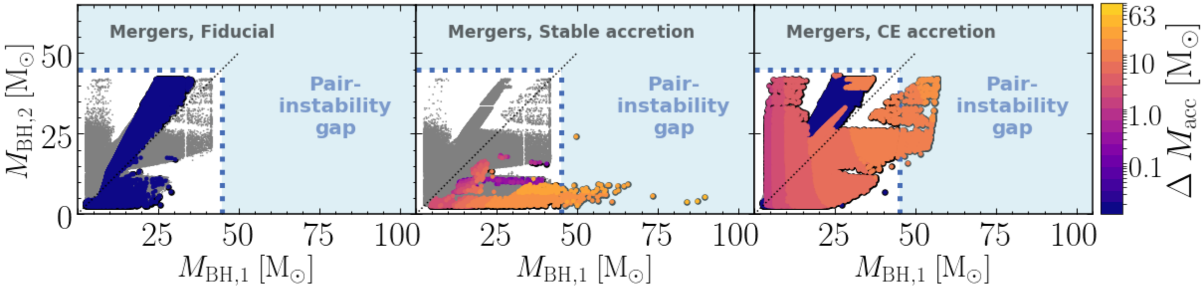


van Son *et al.*, incl. MR, 2020

Can isolated binary evolution “pollute” the gap?



... but those entering the gap don’t merge within 13.7 Gyr



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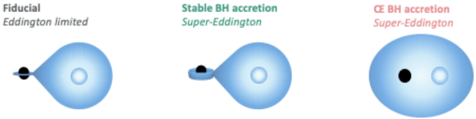

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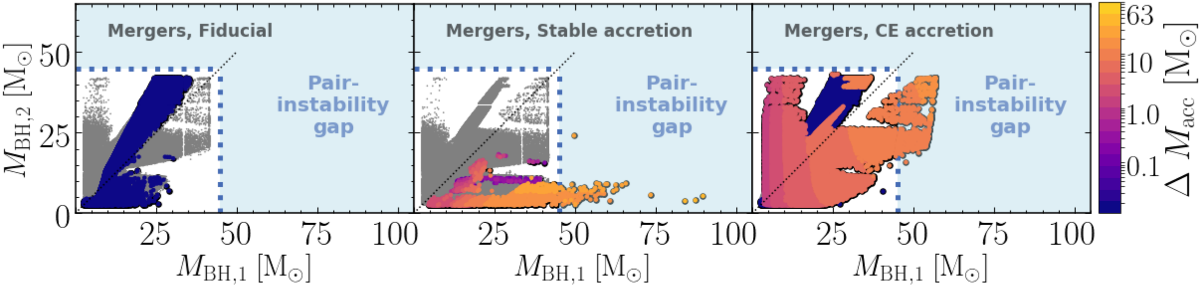


Mass accretion leads to orbital widening

even with the most optimistic assumptions:

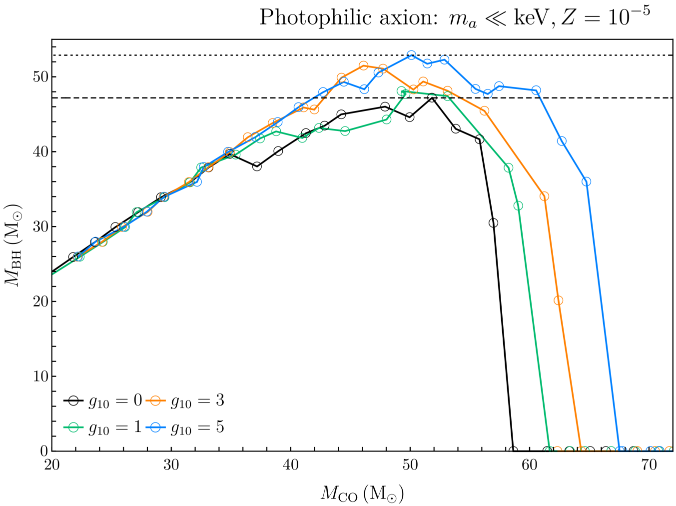
- $\lesssim 1\%$ systems with $M_{\mathrm{tot}} \gtrsim 90\, M_\odot$
- No systems with $M_{\mathrm{tot}} > 100\, M_\odot$

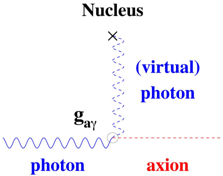
van Son *et al.*, incl. MR, 2020

Possible ways to bridge the gap

Beyond standard-model physics ?

Effectively change the cooling during He core burning





Choplin *et al.* 2017

Affects C/O ratio, $T - \rho$ structure, decrease $P_{\mathrm{rad}} / P_{\mathrm{tot}}$

Other possibilities:

- dark photons
- other axions
- change G
- ν magnetic moment
- extra dimensions

Croon *et al.* 2020a, see also Croon *et al.* 2020b, Sakstein *et al.* 2020