The Maximum Mass of Stellar Black Holes

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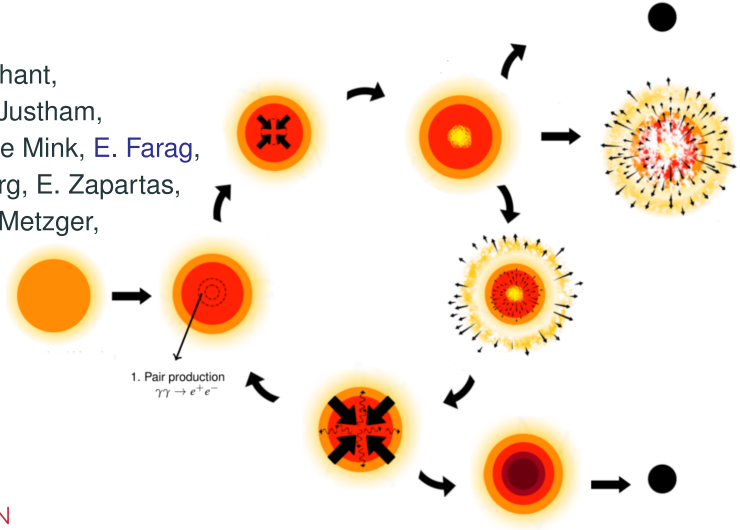
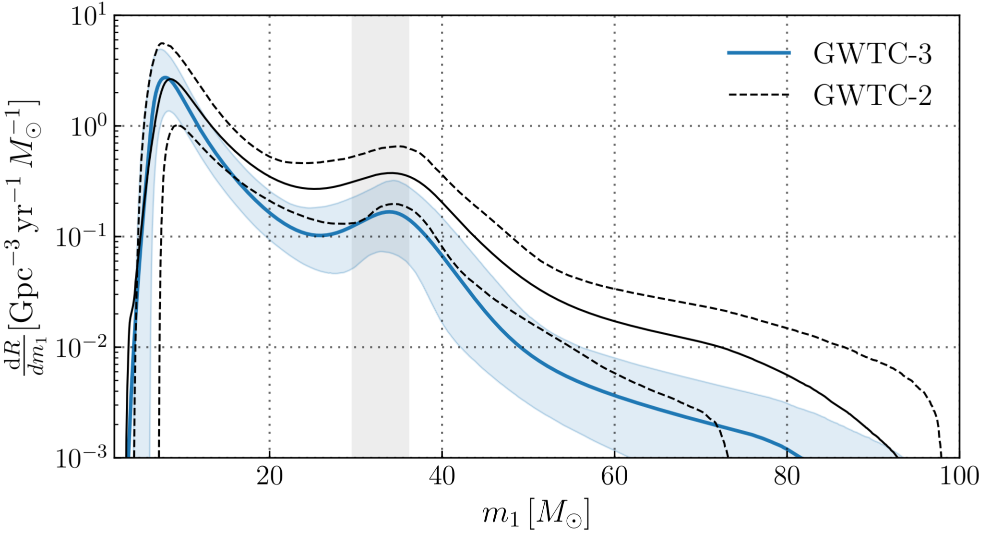
R. Farmer, P. Marchant,
D. D. Hendriks, S. Justham,
L. van Son, S. E. de Mink, E. Farag,
N. Smith, Y. Götberg, E. Zapartas,
M. Cantiello, B. D. Metzger,
Y.-F. Jiang, ...

FLATIRON INSTITUTE
Center for Computational Astrophysics



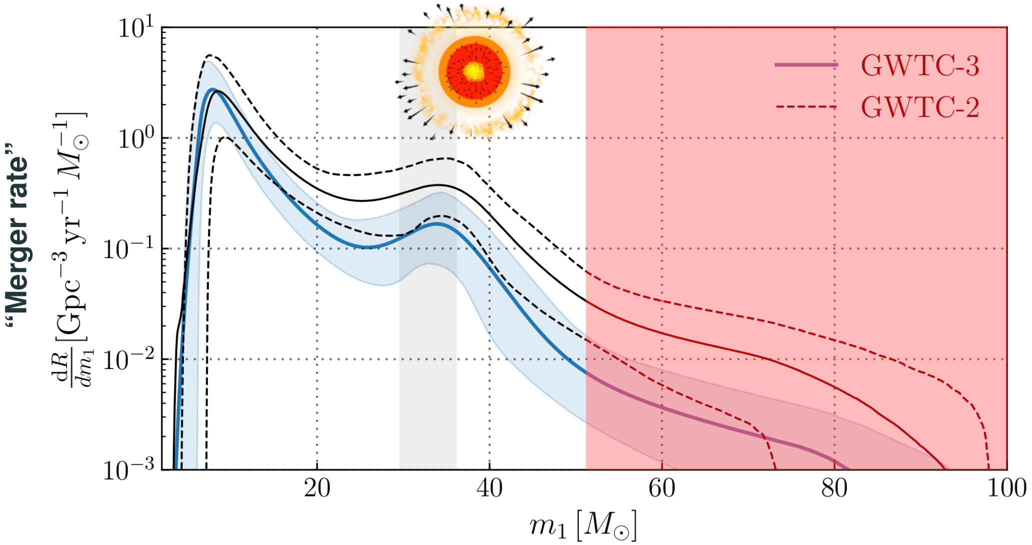
Gravitational wave mergers offer an unprecedented view on massive BHs

“Merger rate”



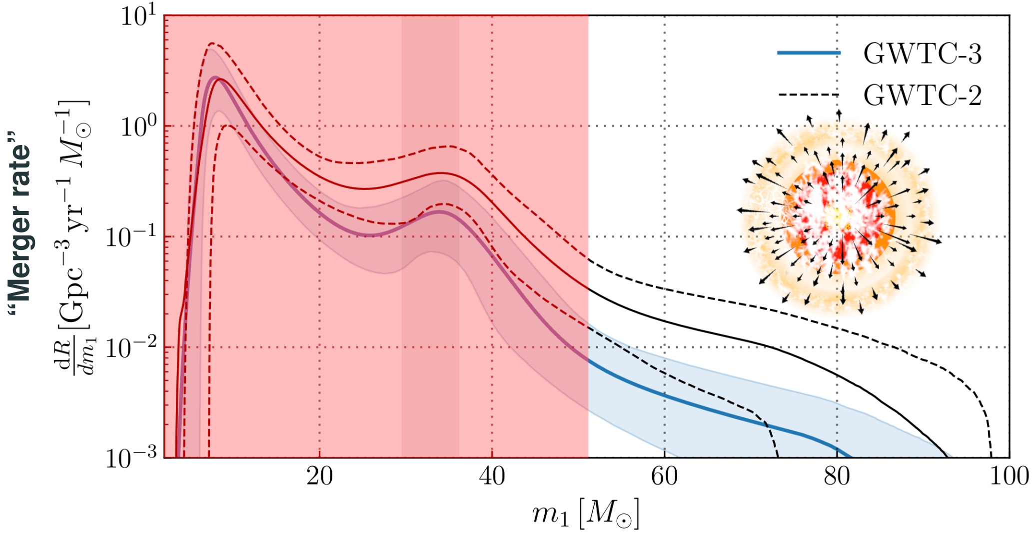
Abbott *et al.* 2022

Part 1: Life and death of the most massive black-hole progenitors



Abbott *et al.* 2022

Part 2: Making "forbidden" black holes ?



Abbott *et al.* 2022

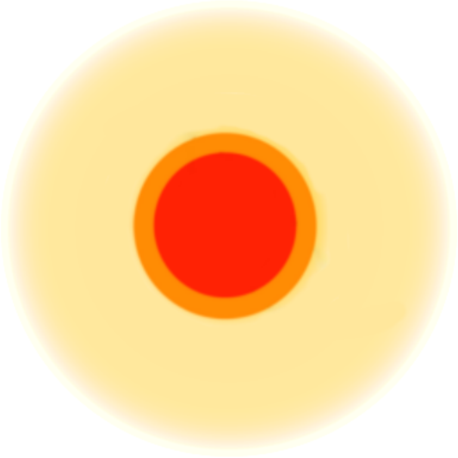
Part 1: (Pulsational) pair instability

Maximum M_{BH} from single He cores

Implementation in pop. synth.

How robust are these predictions?

Pair-production happens in the interior[†] after carbon depletion



[†] can be off-center

Simulating the He core captures the important dynamics

H-rich envelope can be lost to:

- winds
- binary interactions
- first pulse

He cores computed with MESA

Pair-instability SNe are the best understood supernovae

0. Evolved Massive
He core

Radiation pressure dominated:

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

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

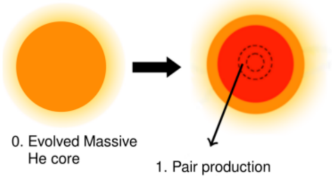
see Fowler & Hoyle 1964, Rakavy & Shaviv 1967, Barkat *et al.* 1967, 1968, Fraley 1968,

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

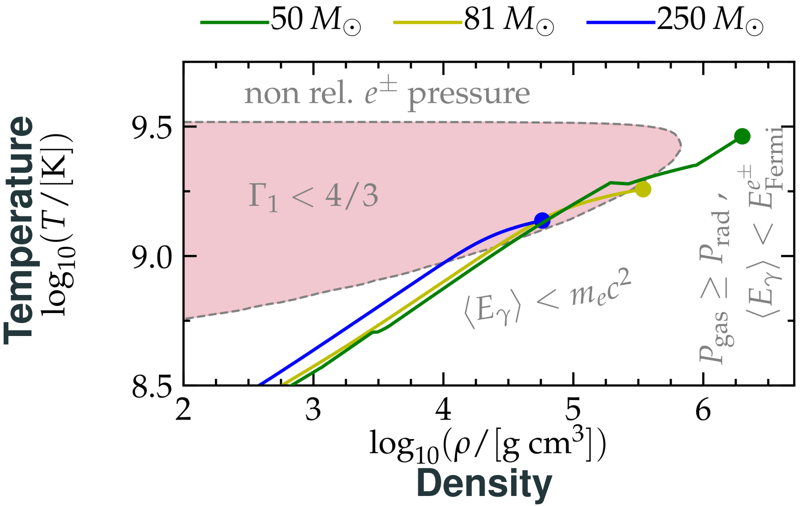
Woosley 2017, 2019, Marchant, MR *et al.* 2019, Farmer, MR *et al.* 2019, 2020, Leung *et al.* 2019, 2020,

Renzo *et al.* 2020a,b, Croon *et al.* 2020a,b, Sakstein *et al.* 2020, 2022, Costa *et al.* 2021, Woosley & Heger 2021, etc...

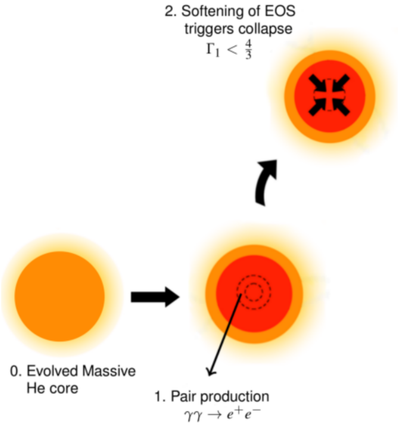
Renzo, Farmer *et al.* 2020b



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



Renzo, Farmer *et al.* 2020b

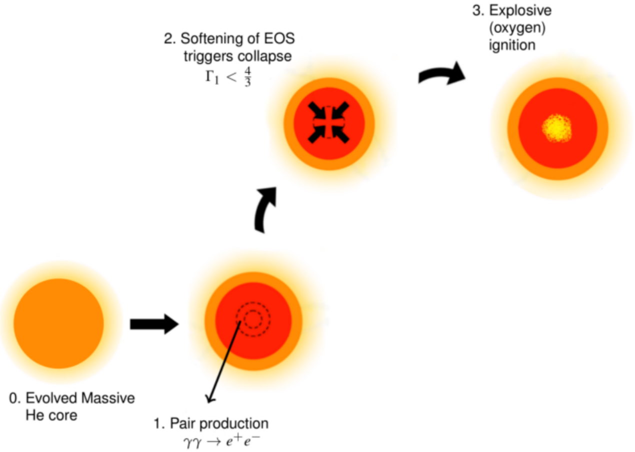


2. Softening of EOS triggers collapse $\Gamma_1 < \frac{4}{3}$

0. Evolved Massive He core

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

Renzo, Farmer *et al.* 2020b



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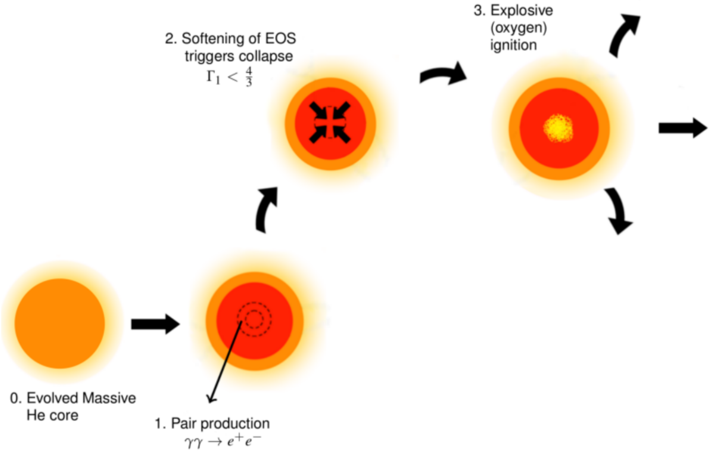
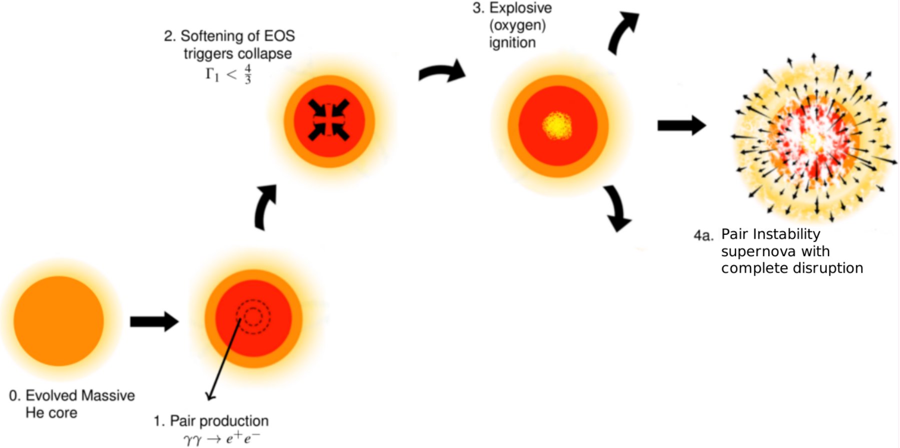
3. Explosive (oxygen) ignition

Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b



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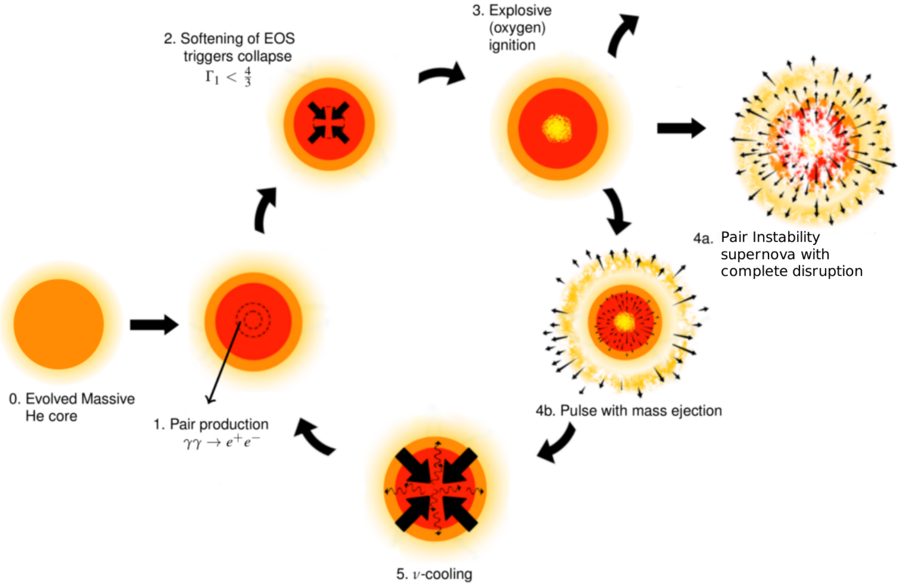
4a. Pair Instability supernova with complete disruption

Renzo, Farmer *et al.* 2020b



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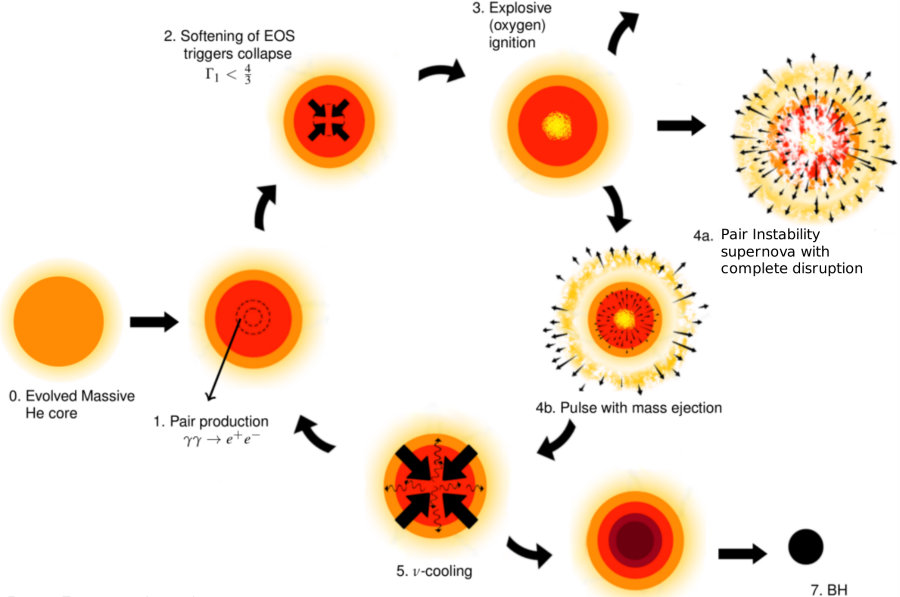
4b. Pulse with mass ejection

5. ν-cooling

Renzo, Farmer *et al.* 2020b



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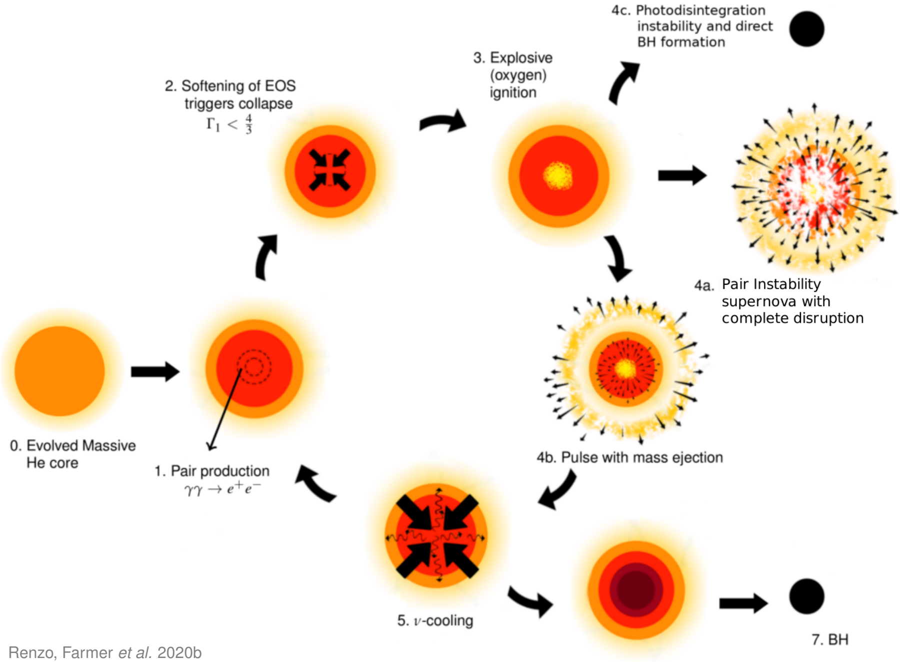
7. BH

Renzo, Farmer *et al.* 2020b



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

4a. Pair Instability supernova with complete disruption

4b. Pulse with mass ejection

4c. Photodisintegration instability and direct BH formation

5. ν-cooling

7. BH

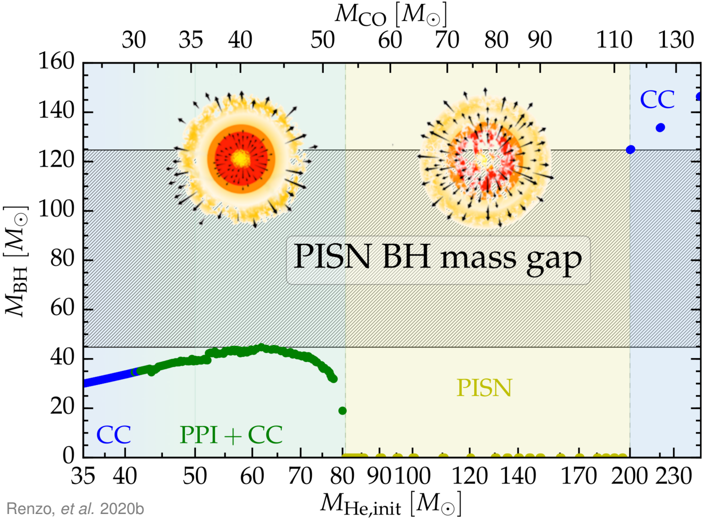
Renzo, Farmer *et al.* 2020b

BH

no BH

BH

Resulting stellar BH masses



BH

no BH

BH

Renzo, *et al.* 2020b

see also:

Rakavy & Shaviv 1967, Fraley 1968, Woosley *et al.* 2002, 2007, Woosley 2017, 2019, Marchant, MR *et al.* 2019, Leung *et al.* 2019, Farmer, MR *et al.* 2019, 2020, MR 2020a, Stevenson *et al.* 2019, Spera & Mapelli 2019, van Son *et al.* (incl. MR) 2020, Costa *et al.* 2021, Woosley & Heger 2021, Mehta *et al.* 2022

Part 1: (Pulsational) pair instability

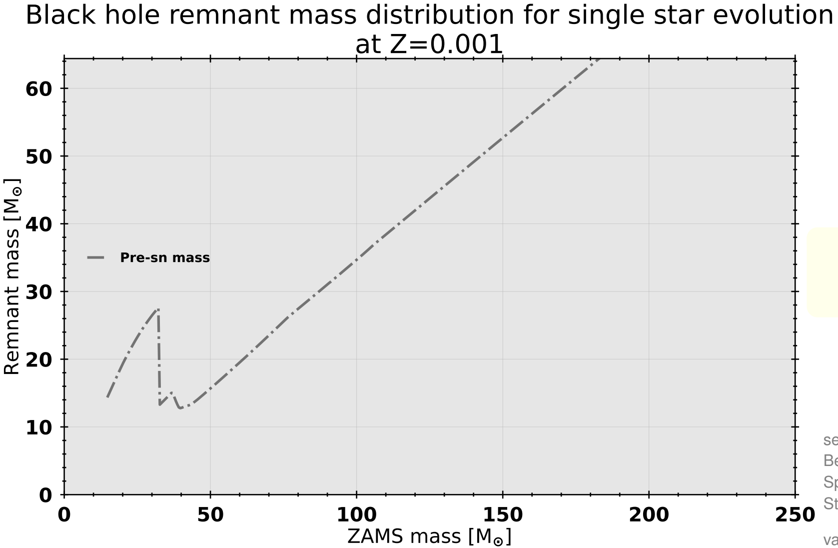
Maximum M_{BH} from single He cores

Implementation in pop. synth.

How robust are these predictions?

M_{initial} $\rightarrow$ CO core mass† $\rightarrow$ BH mass

†and composition! (Patton & Sukhbold 2020)



"Initial mass"

David D. Hendriks

Univ. Surrey

Fryer *et al.* 2012

Fryer *et al.* 22, Olejak *et al.* 22

see also:
Belczynski *et al.* 2016,
Spera & Mapelli 2017,
Stevenson *et al.* 2019,

van Son *et al.* (incl. MR) 2022, ...

Hendriks, van Son, MR *et al.*, in prep.

$M_{\text{initial}} \rightarrow$ CO core mass† $\rightarrow$ BH mass

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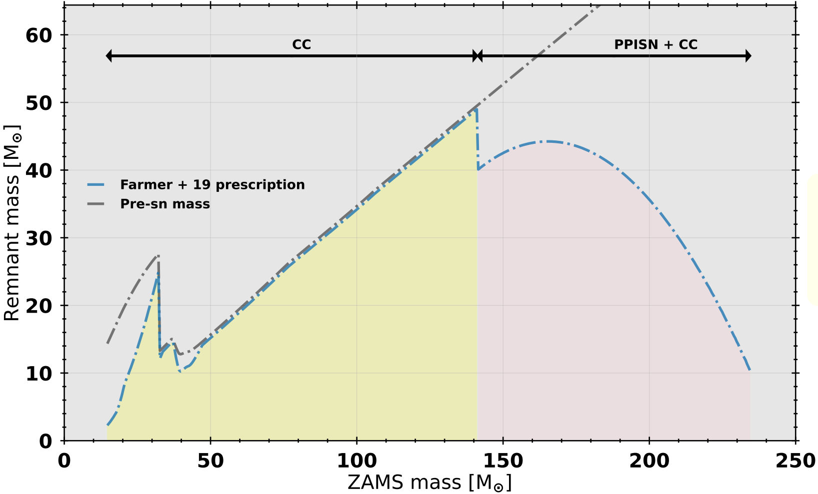
David D. Hendriks

Univ. Surrey

Black hole remnant mass distribution for single star evolution
at Z=0.001



"Initial mass"

Fryer *et al.* 2012
+
Farmer, MR *et al.* 2019

see also:
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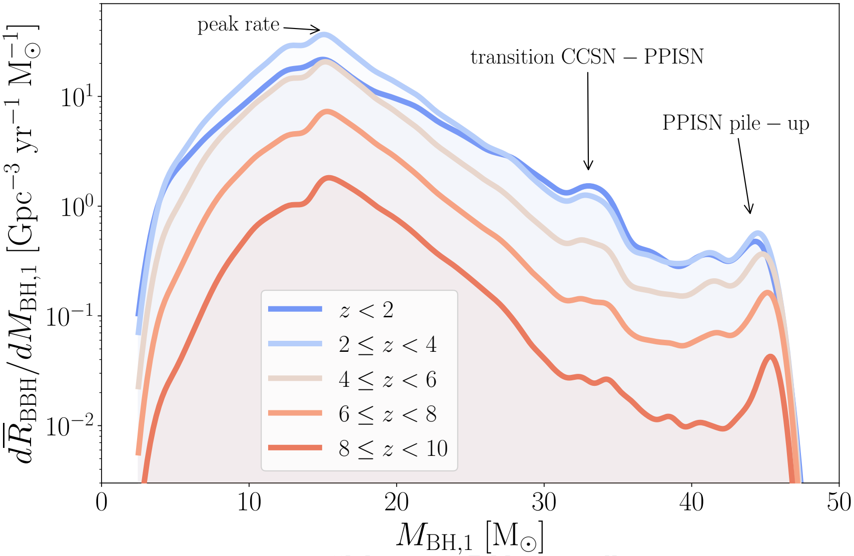
van Son *et al.* (incl. MR) 2022, ...

Hendriks, van Son, MR *et al.*, in prep.

Using “recipes” out-of-the-box leads to artificial features



“Binary BH merger rate”

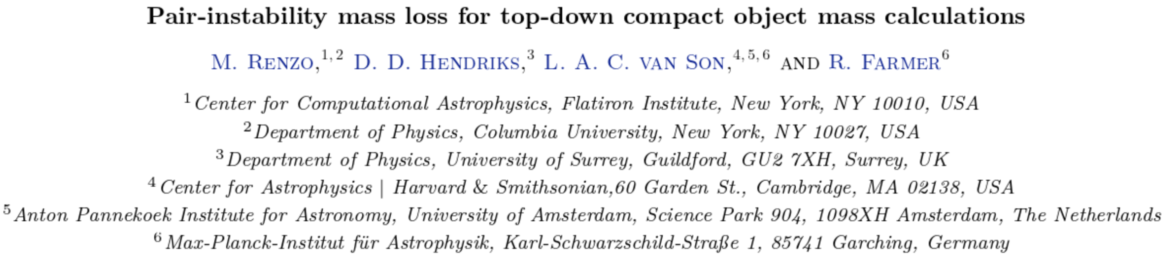
“biggest BH mass”

Lieke van Son

Harvard

van Son *et al.* (incl. MR) 2022

see also Tanikawa *et al.* 2020, 2021, 2022



Pair-instability mass loss for top-down compact object mass calculations

M. Renzo,[1,2] D. D. Hendriks,[3] L. A. C. van Son,[4,5,6] and R. Farmer[6]

[1] Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA
[2] Department of Physics, Columbia University, New York, NY 10027, USA
[3] Department of Physics, University of Surrey, Guildford, GU2 7XH, Surrey, UK
[4] Center for Astrophysics | Harvard & Smithsonian,60 Garden St., Cambridge, MA 02138, USA
[5] Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098XH Amsterdam, The Netherlands
[6] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85741 Garching, Germany

$$M_{\mathrm{BH}} = M_{\mathrm{proto-NS}} + M_{\mathrm{fallback}}$$

(Fryer *et al.* 2012, 2022)

$$\Downarrow$$

$$M_{\mathrm{BH}} = M_{\mathrm{pre-explosion}} - \left(\Delta M_{\mathrm{SN}} + \Delta M_{\nu,\mathrm{core}} + \Delta M_{\mathrm{env}} + \Delta M_{\mathrm{PPI}} + \cdots\right)$$

New fit to Farmer, MR *et al.* 2019

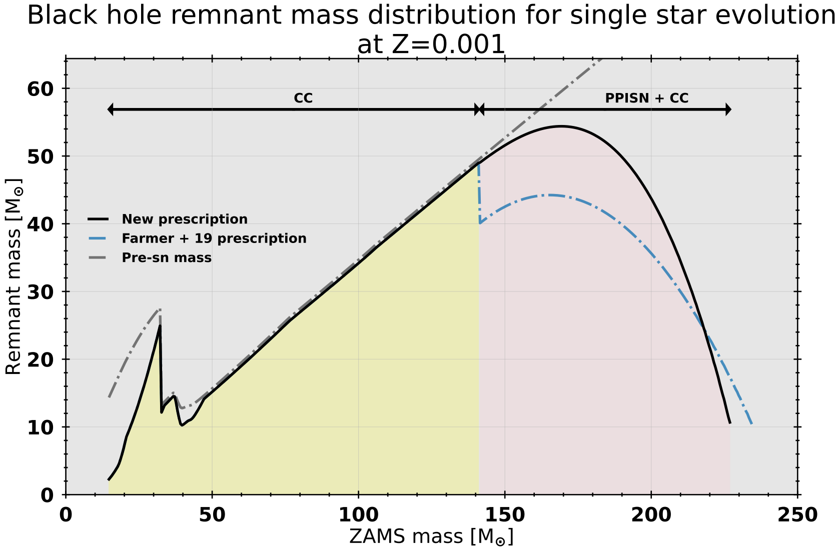
Renzo *et al.* 2022, RNAAS

$M_{\text{initial}} \rightarrow$ CO core mass† $\rightarrow$ BH mass

† and composition! (Patton & Sukhbold 2020)

David D. Hendriks

Univ. Surrey



“Initial mass”

Hendriks, van Son, MR *et al.*, in prep.

M_{initial} → CO core mass† → BH mass

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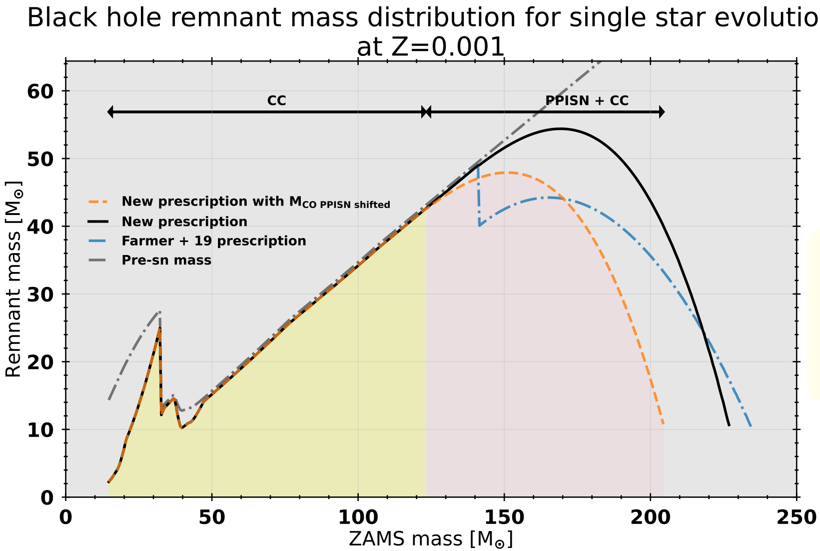


“Initial mass”

David D. Hendriks

Univ. Surrey

Fryer *et al.* 2012

\+

~~Farmer, MR *et al.* 2019~~

Renzo *et al.* 2022

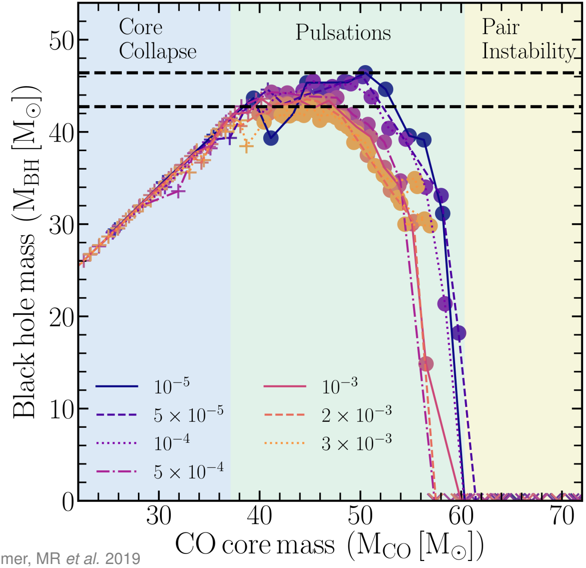
Hendriks, van Son, MR *et al.*, in prep.

Part 1: (Pulsational) pair instability

- Maximum M_{BH} from single He cores
- Implementation in pop. synth.
- **How robust are these predictions?**

Metallicity? Small effect

Focus on lower edge of the gap



Farmer, MR *et al.* 2019

Metallicity shift

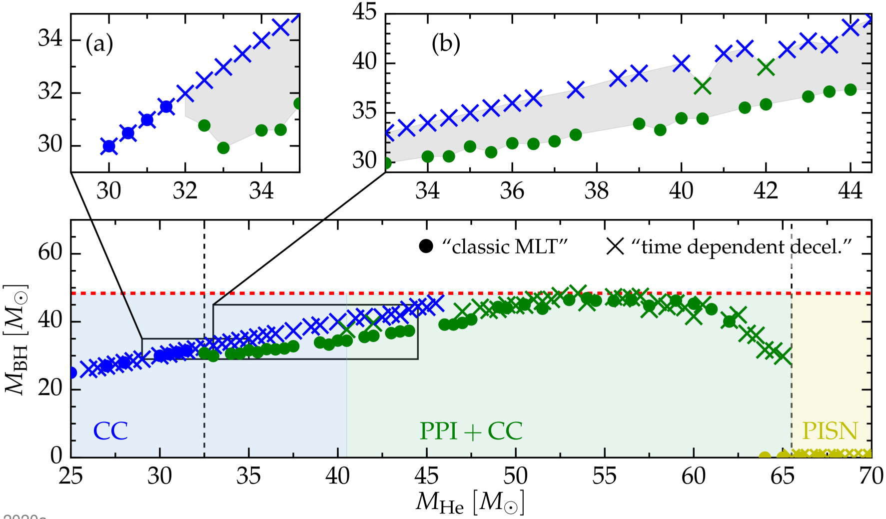
$\Delta\max\{M_{\rm BH}\}\sim$7%

over 2.5 orders of magnitude

Comparable or smaller effects:
mixing, winds, nuclear reaction network size, rotation, code used, etc..

Treatment of time-dependent convection? Not the edge

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

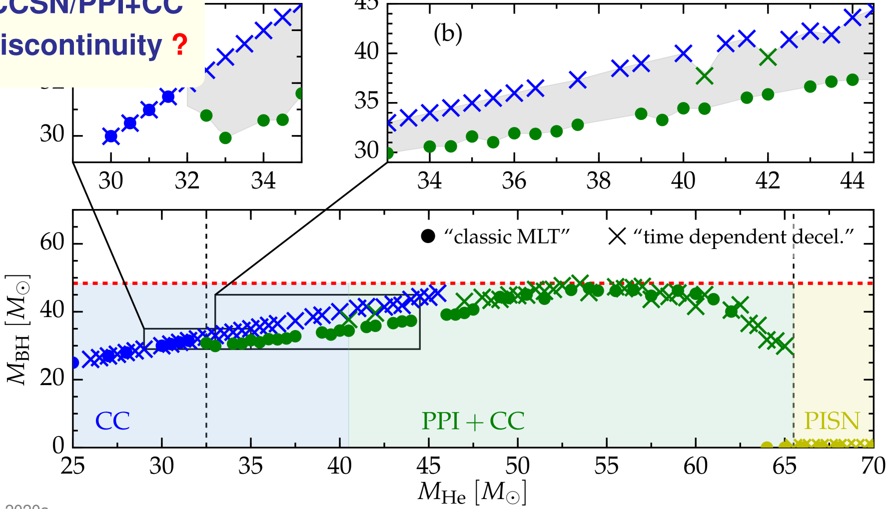


Renzo, Farmer *et al.* 2020a

Treatment of time-dependent convection? Not the edge

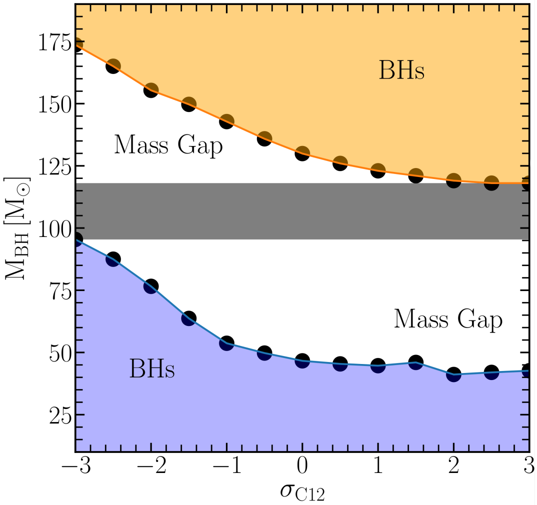
Matters for least massive PPI, not for the most massive BH progenitors

CCSN/PPI+CC discontinuity ?



Renzo, Farmer *et al.* 2020a

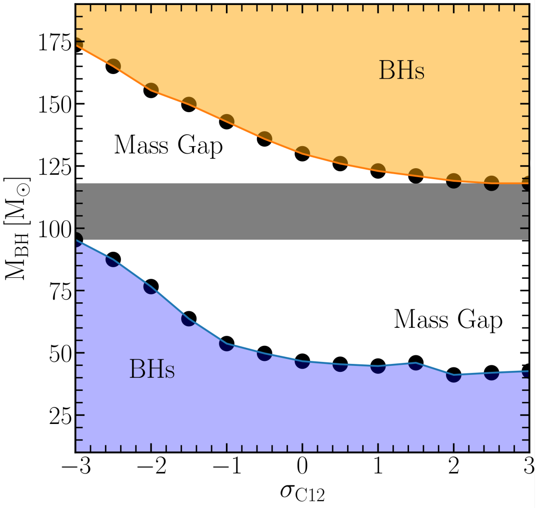
The input physics that matters: $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate



⇐ **lower** **Rate** **higher** ⇒

Farmer, MR *et al. 2020*, see also Farmer, MR *et al.* 2019, Costa *et al.* 2021, Woosley & Heger 2021, Farag, MR *et al.* submitted

$^{12}C(\alpha,\gamma)^{16}O$ reaction rate was undersampled in tables



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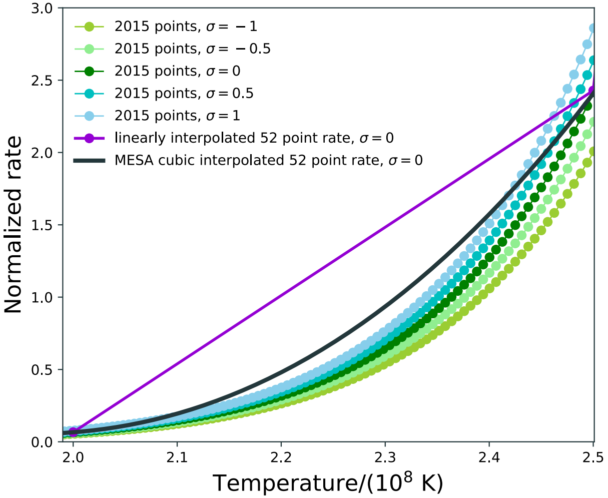
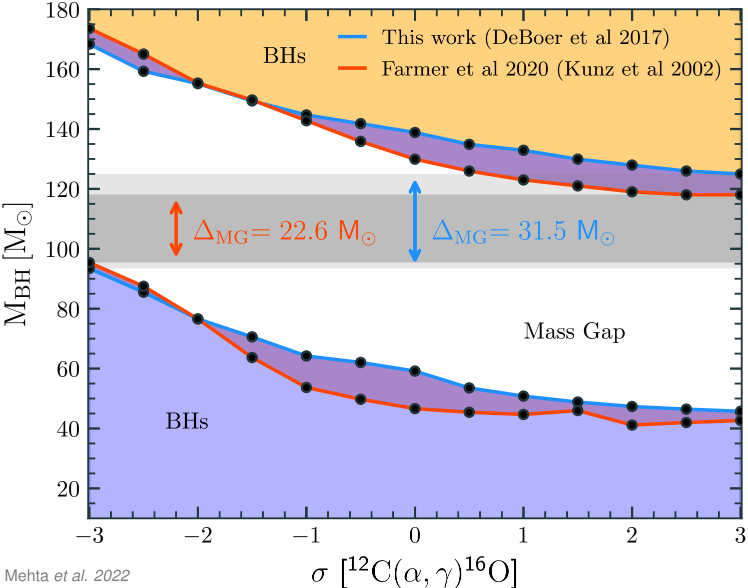


Farmer, MR *et al. 2020*, see also Farmer, MR *et al.* 2019, Costa *et al.* 2021, Woosley & Heger 2021, Farag, MR *et al.* submitted

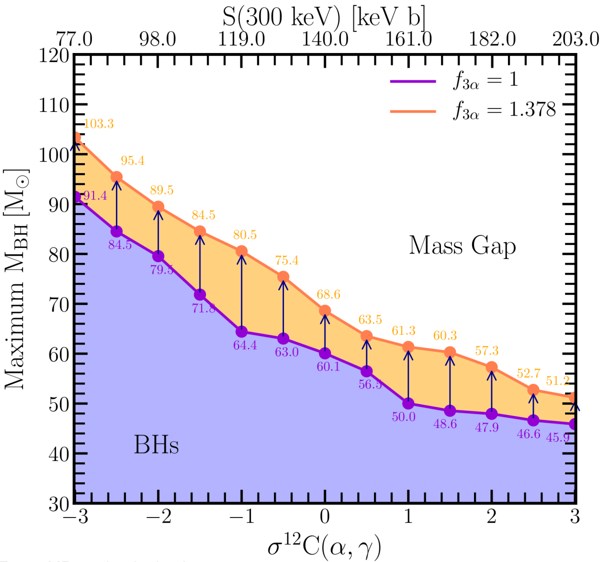
Mehta *et al. 2022*

BH mass gap from single He cores with updated $^{12}C(\alpha,\gamma)^{16}O$ rate



Mehta *et al. 2022*

Pushing further up with 3α rate uncertainties



Ebrahim “Eb” Farag

Arizona State Univ.

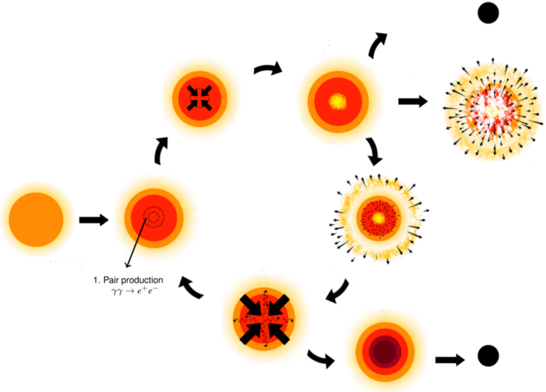
New lower edge of the gap:

$$\max(M_{\rm BH}) = 69^{+34}_{-18}\,M_\odot$$

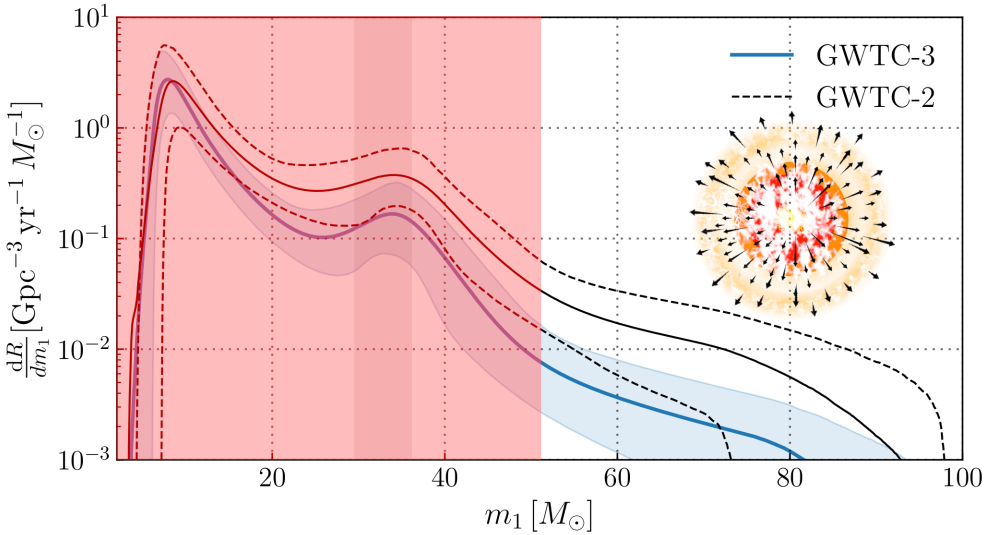
Farag, MR *et al.* submitted

Conclusions on the physics of (pulsational) pair-instability

- Pair-instability evolution of single He cores is robustly understood.
- Main uncertainties are time-dependent convection, and nuclear reactions rates
- $\max(M_{\rm BH})$ below the gap: $69^{+34}_{-18}\,M_\odot$
- $\min(M_{\rm BH})$ above the gap: $139^{+30}_{-14}\,M_\odot$



Part 2: Making forbidden black holes ?



Abbott *et al.* 2022

Part 2: Filling the BH mass "gap"

More ideas than events

The stellar merger scenario

Filling the gap "from above"

Siegel *et al.* (incl. MR) 2021

Filling the PISN BH 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, Costa *et al.* 21

- Beyond standard model physics

Choplin *et al.* 17, Croon*et al.* 20a,b, Sakstein *et al.* 20,22
Straight *et al.* 20, Ziegler *et al.* 20

Avoid pair-instability

- “wet” stellar merger scenario

Spera & Mapelli 2019, di Carlo *et al.* 19, 20a,b, Renzo *et al.* 20c,
Kremer *et al.* 20, Costa *et al.* 22, Ballone *et al.* 22

- pop. III/low winds Farrell *et al.* 20, Kinugawa *et al.* 20,
Belczynski *et al.* 20, Vink *et al.* 21

- Mass loss from above the gap

Shibata *et al.* 21, Siegel *et al.* (incl MR) 21

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.* (incl. MR) 2020
- in halos Safarzadeh & Haiman 20

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

“Impostor” GW events: High eccentricity merger? Lensing?

Part 2: Filling the BH mass “gap”

More ideas than events

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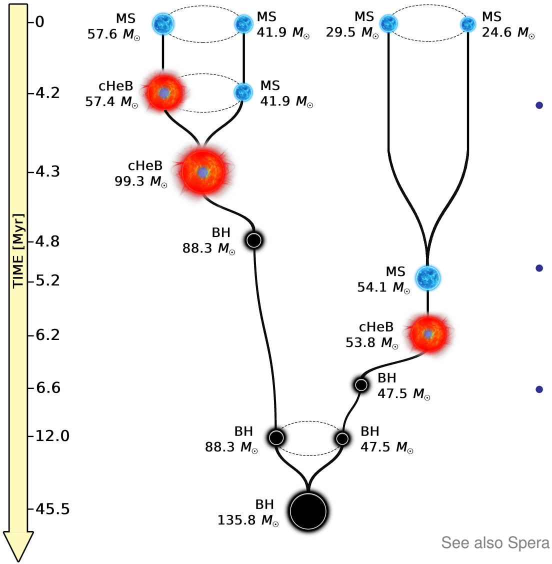
Filling the gap “from above”

Siegel *et al.* (incl. MR) 2021

The stellar merger scenario



di Carlo *et al.* 20a

- 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

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, Costa *et al.* 22, Ballone *et al.* 22

Estimates of mass loss for stellar collisions: $\Delta M_{\rm merger} \lesssim 12\%$

SPH simulations - no radiation

Ballone *et al.* 22

Angular momentum budget of the merger

SPH simulations - no radiation

Angular momentum

- **Surface:** Centrifugally-driven $\dot{M}$

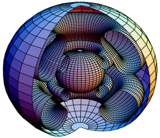
Langer 88, Heger *et al.* 00

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

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

$\Downarrow$

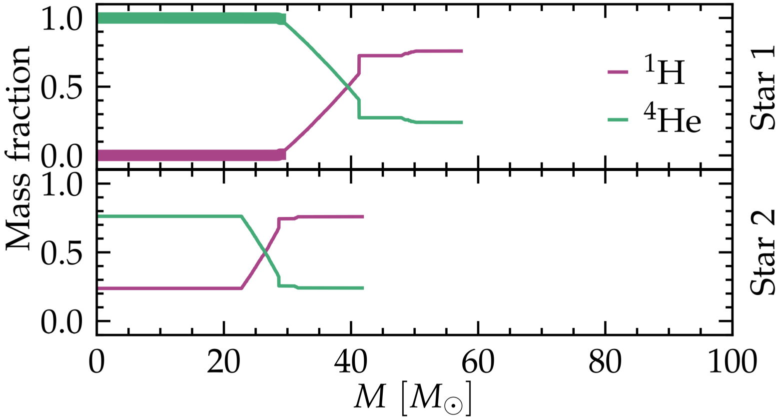
I will assume no rotation



Maeder & Meynet 2000

Ballone *et al.* 22

Merger model: the pre-merger stars



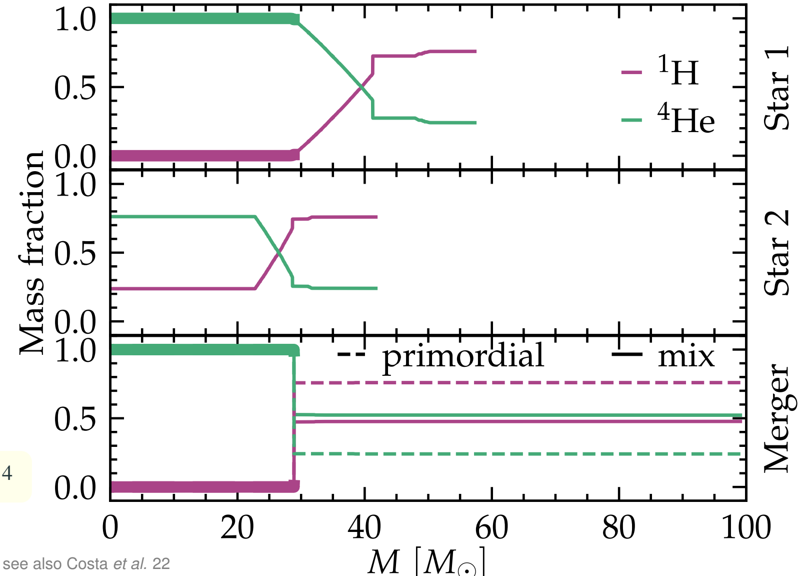
$58\,M_\odot$

$42\,M_\odot$

$Z = 2 \times 10^{-4}$

Renzo, Cantiello *et al.* 20, see also Costa *et al.* 22

Merger model: composition of the merger



$58\,M_\odot$

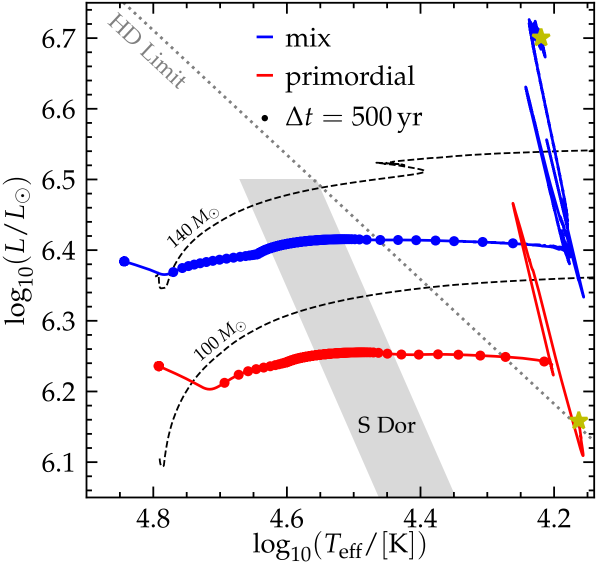
$42\,M_\odot$

$99\,M_\odot$

$Z = 2 \times 10^{-4}$

Renzo, Cantiello *et al.* 20, see also Costa *et al.* 22

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



Renzo, Cantiello *et al.* 20, see also Costa et al. 22

Very massive stars are hardly stable

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

⇓

- LBV eruptions, helped by He opacity?

Jiang *et al.* 18

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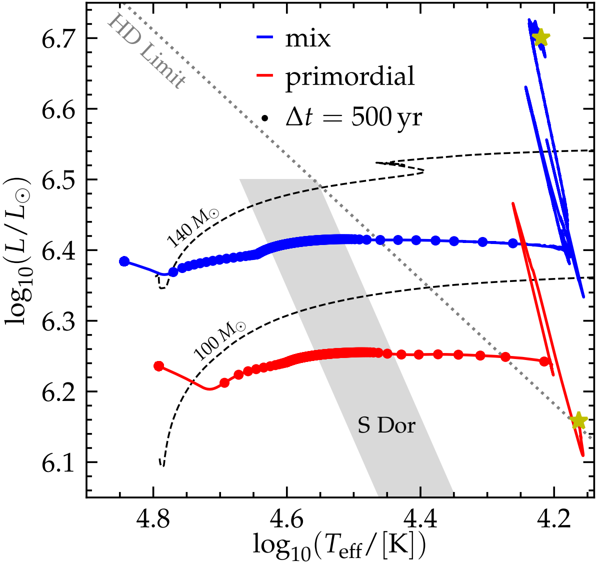

Renzo, Cantiello *et al.* 20, see also Costa et al. 22

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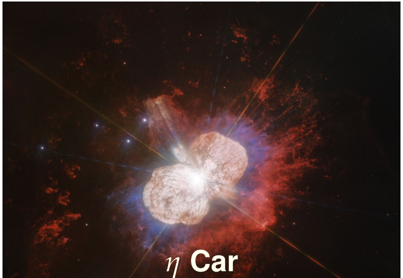
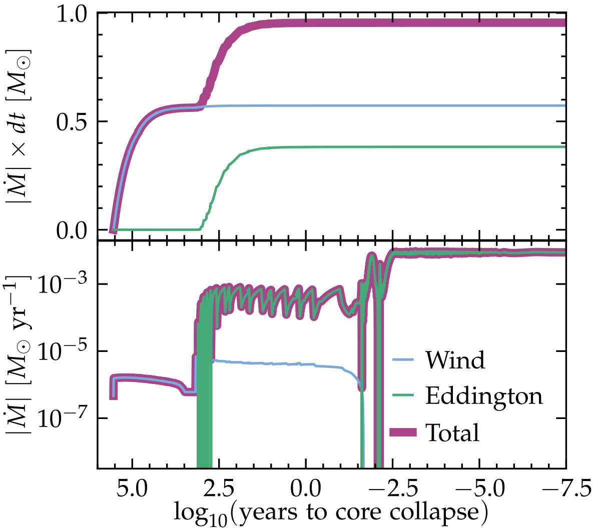


Hirai *et al.* 2021

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

Do BHs form via a failed, weak, or full blown SN explosion?

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

Possible causes for mass ejection at BH formation:

- ν-driven shocks

  Nadhezin 80, Lovegrove & Woosley 13, Piro 13, Fernandez *et al.* 18

- Jets, (even without net rotation)

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

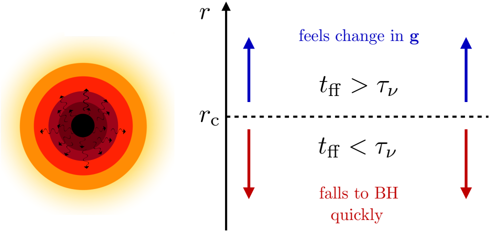
- weak fallback powered explosion

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

see also Adams *et al.* 17 & Basinger *et al.* 20 for possible EM counterpart to BH formation

Accretion disks and ν-driven shocks remove little mass for BSG

$$M_{\mathrm{BH},0} \simeq M_{\mathrm{core}} - E_\nu / c^2$$



feels change in **g**

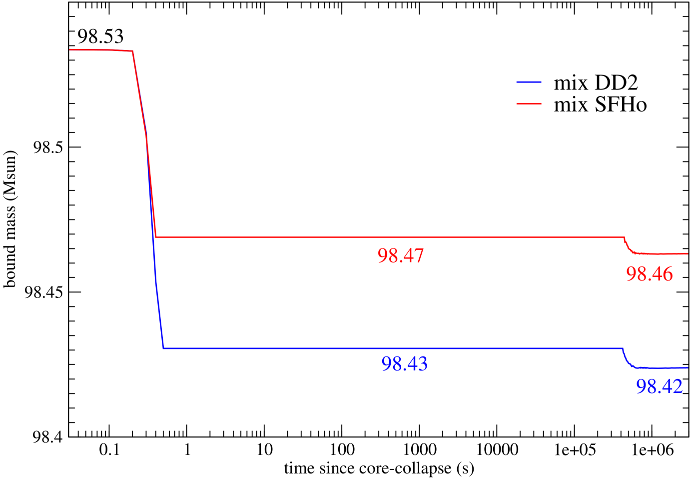
$t_{\mathrm{ff}} > \tau_\nu$

$t_{\mathrm{ff}} < \tau_\nu$

falls to BH quickly

Fernàndez *et al.* 2018

MESA → GR1D+FLASH credits: R. Fernàndez



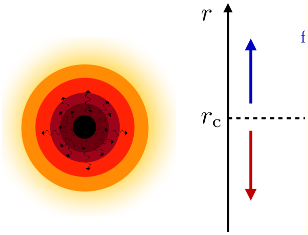
Nadhezin 1980, Lovegrove & Woosley 2013, Piro 2013, Coughlin *et al.* 2018, Fernàndez *et al.* 2018, Ivanov & Fernàndez 2021

Accretion disks and ν-driven shocks remove little mass for BSG

$M_{\rm BH,0} \simeq M_{\rm cor}$

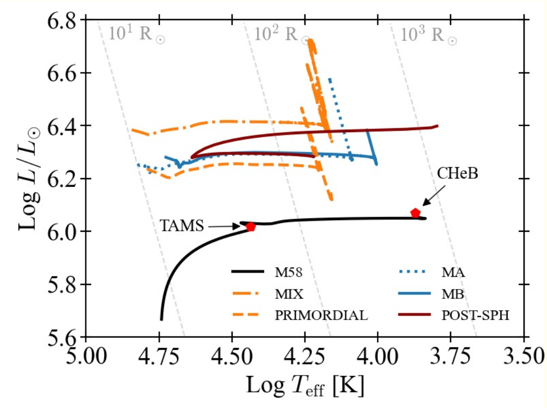
MESA → GR1D+FLASH

credits: R. Fernàndez

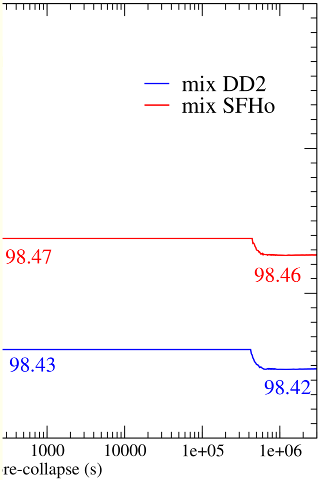


Fernàndez *et al.* 20

BSG/RSG depends on energy transport in $L > L_{\rm Edd}$ layers



Costa *et al.* 22



Nadhezin 1980, Lovegrove & Woosley 2013, Piro 2013, Coughlin *et al.* 2018, Fernàndez *et al.* 2018, Ivanov & Fernàndez 2021

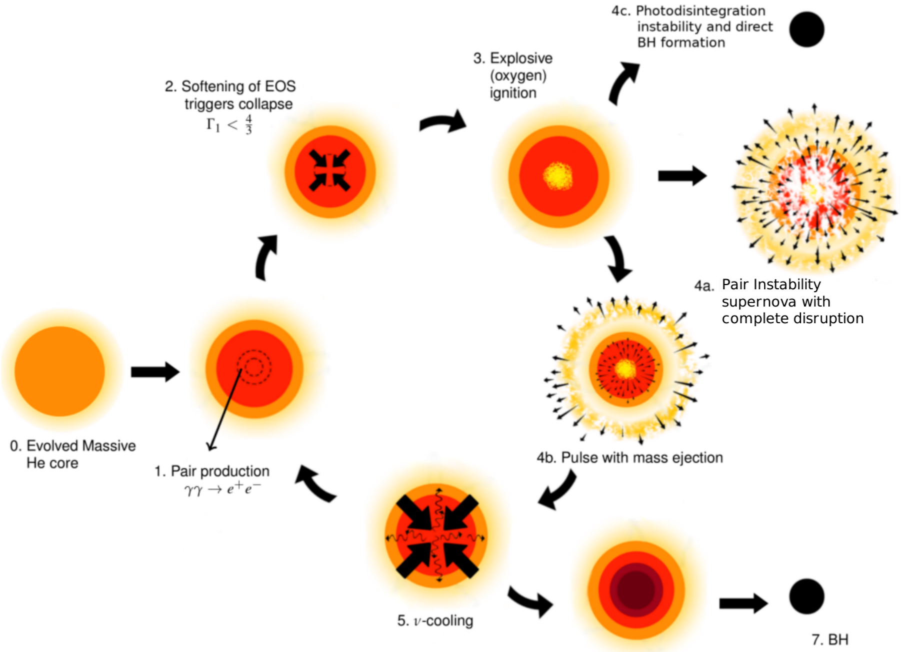
Part 2: Filling the BH mass “gap”

More ideas than events

The stellar merger scenario

Filling the gap “from above”

Siegel *et al.* (incl. MR) 2021


4c. Photodisintegration instability and direct BH formation
2. Softening of EOS triggers collapse $\Gamma_1 < \frac{4}{3}$
3. Explosive (oxygen) ignition
4a. Pair Instability supernova with complete disruption
4b. Pulse with mass ejection
0. Evolved Massive He core
1. Pair production $\gamma\gamma \rightarrow e^+e^-$
5. ν-cooling
7. BH

BH

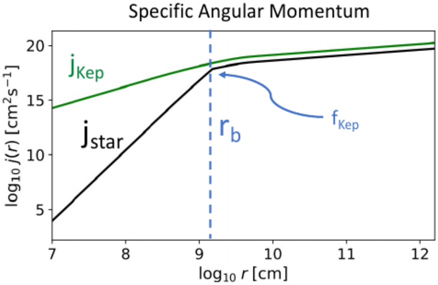
no BH

BH

Extrapolation of long-GRB models to progenitors above the gap

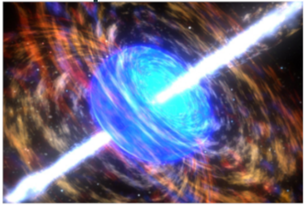
above the gap
(with no rotation)

+



=

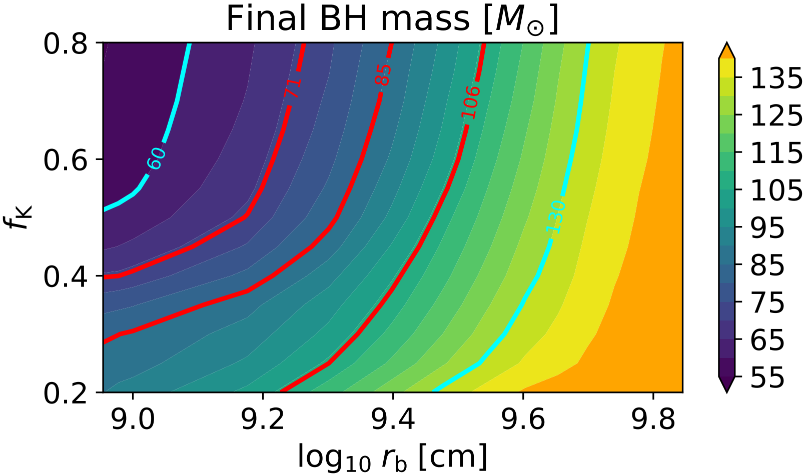
“super-kilonova”



Disk so massive it
self-neutronize
and does r-process

Siegel *et al.* (incl. MR), 2021

Result: BH in the gap, r-process nucleosynthesis, and observable transient



$M_{^{56}\mathrm{Ni}} \sim 10 - 60\, M_\odot$

$M_{\mathrm{r-process}} \sim 1 - 20\, M_\odot$

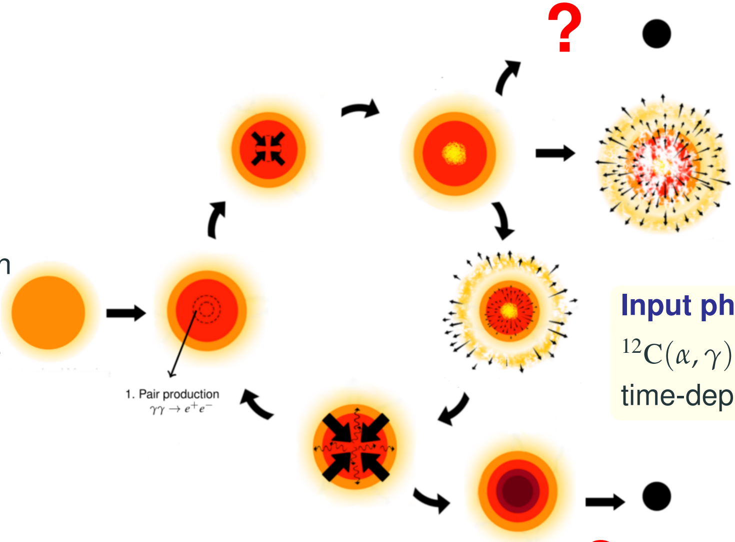
Rubin & Roman rate:

$\sim 10^{-2}$-few/year

Siegel *et al.* (incl. MR), 2021

Conclusions

(Pulsational) pair instability is well understood – but questions remain



Progenitor evolution
& pre-PPISN
binary interactions
?

Input physics:

$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ rate ?

time-dependent conv. ?

Final BH formation & fate of H-rich envelope ?

Filling the PISN BH 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, Costa *et al.* 21
- Beyond standard model physics

  Choplin *et al.* 17, Croon*et al.* 20a,b, Sakstein *et al.* 20,22 Straight *et al.* 20, Ziegler *et al.* 20

Avoid pair-instability

- “wet” stellar merger scenario

  Spera & Mapelli 2019, di Carlo *et al.* 19, 20a,b, Renzo *et al.* 20c, Kremer *et al.* 20, Costa *et al.* 22, Ballone *et al.* 22
- pop. III/low winds Farrell *et al.* 20, Kinugawa *et al.* 20, Belczynski *et al.* 20, Vink *et al.* 21
- Mass loss from above the gap

  Shibata *et al.* 21, Siegel *et al.* (incl MR) 21

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.* (incl. MR) 2020
- in halos Safarzadeh & Haiman 20

Multiple generations of BBH mergers

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

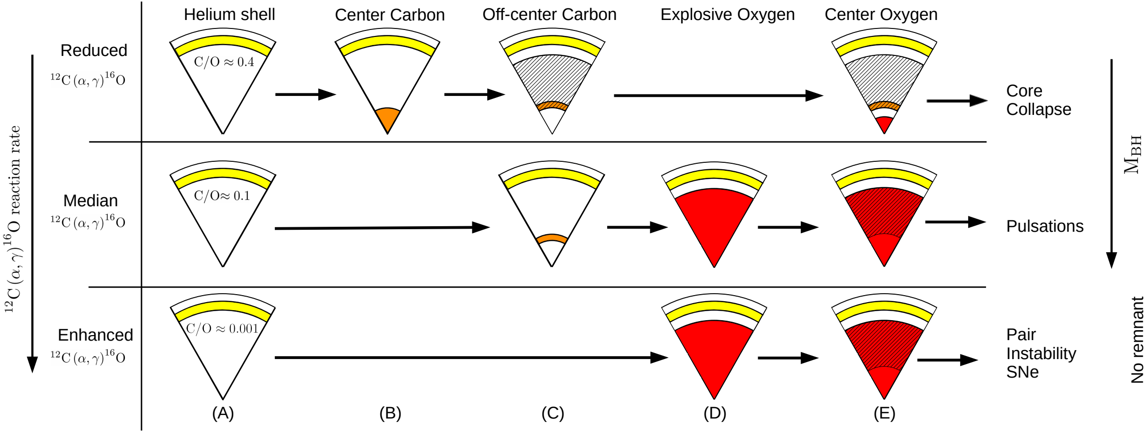
  McKernan *et al.* 12, Bartos *et al.* 17, Stone *et al.* 19

“Impostor” GW events: High eccentricity merger? Lensing?

Backup slides

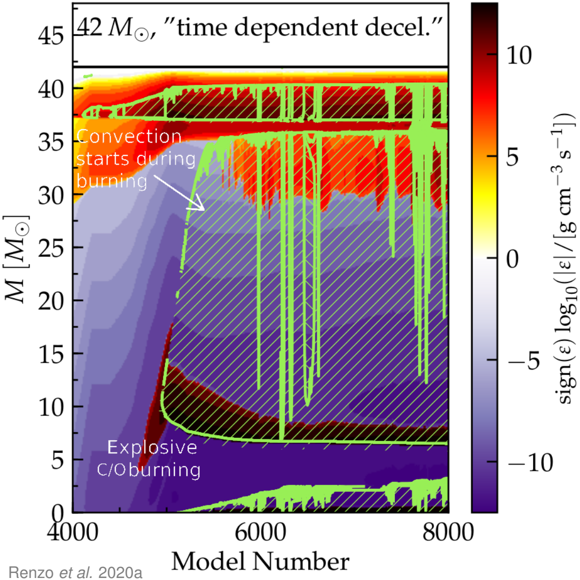
The $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ ends He core burning

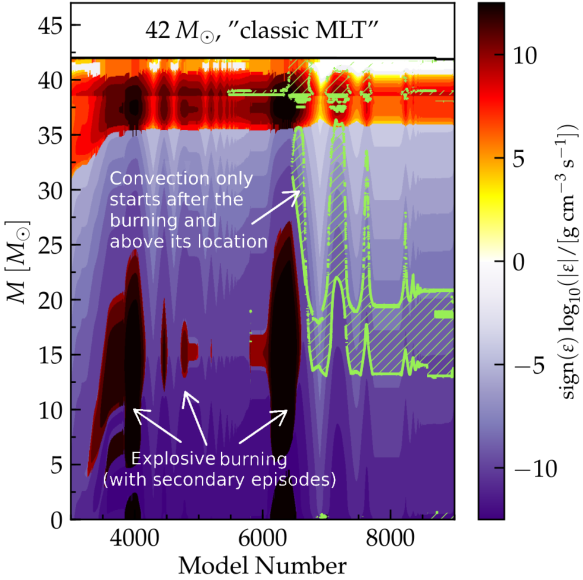
More $^{12}\mathrm{C} \Rightarrow$ C shell burning delays $^{16}\mathrm{O}$ ignition to higher ρ



Farmer, Renzo *et al.* 2020

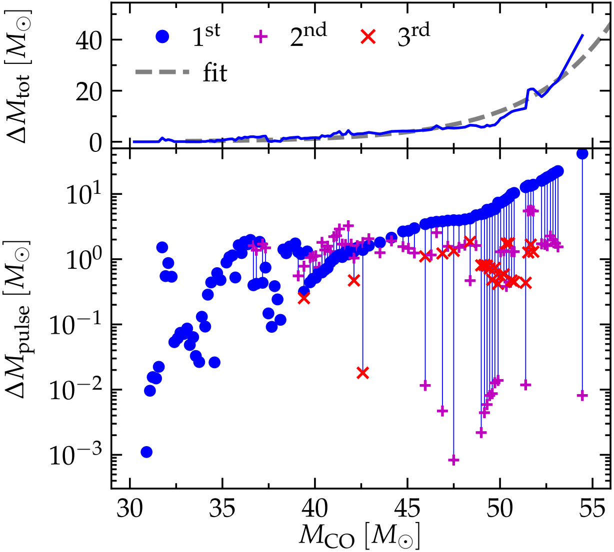
Convection during the pulses quenches the PPI mass loss





Renzo *et al.* 2020a

Amount of mass lost per pulse



Larger cores

$\Downarrow$

More energetic pulses

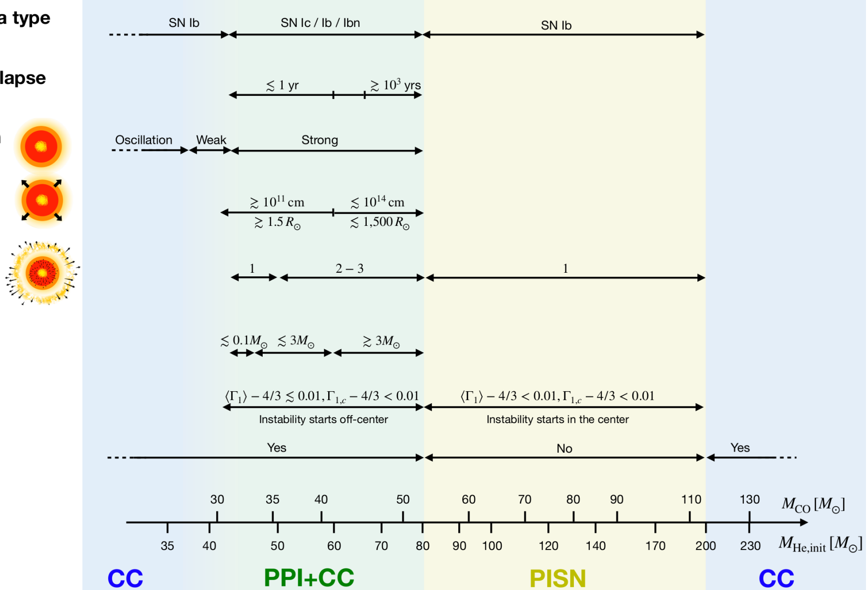
$\Downarrow$

More mass loss

(and longer delays)

Renzo, Farmer *et al.* 2020b

Summary of EM transients



Approximate supernova type
(mass-loss dependent, Sec. 7)

Pulse delay to core-collapse
(Sec. 6)

Thermonuclear ignition
(Sec. 5.1)

Radial expansion
max $R(v < v_{\rm esc})$ (Sec. 5.2)

Number of mass ejections
(Sec. 5.3)

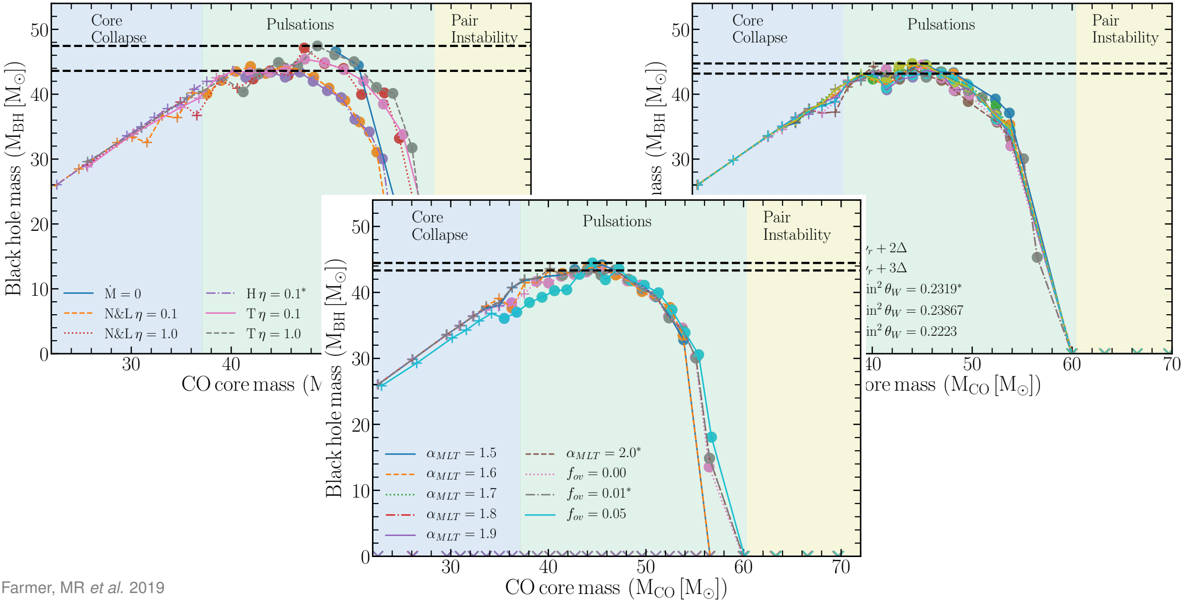
$M_{\rm CSM}$ He-rich
(Sec. 6)

Thermal stability
(Sec. 5.1.1)

BH remnant
(Sec. 3)

Renzo, Farmer *et al.* 2020b

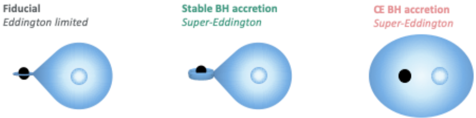
Winds, mixing, ν physics? Also small effects



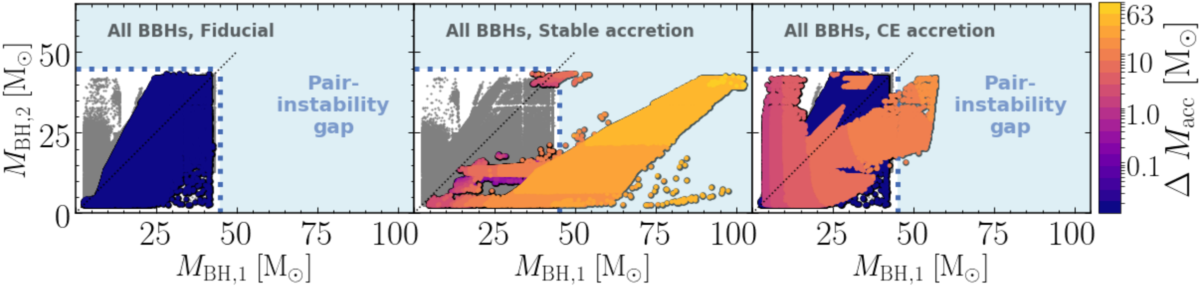
Farmer, MR *et al.* 2019

Can isolated binary evolution “pollute” the gap?

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

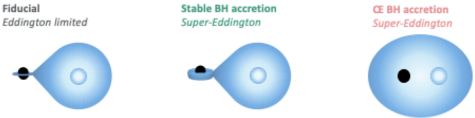


With unlimited accretion, some binary BHs can enter the gap...

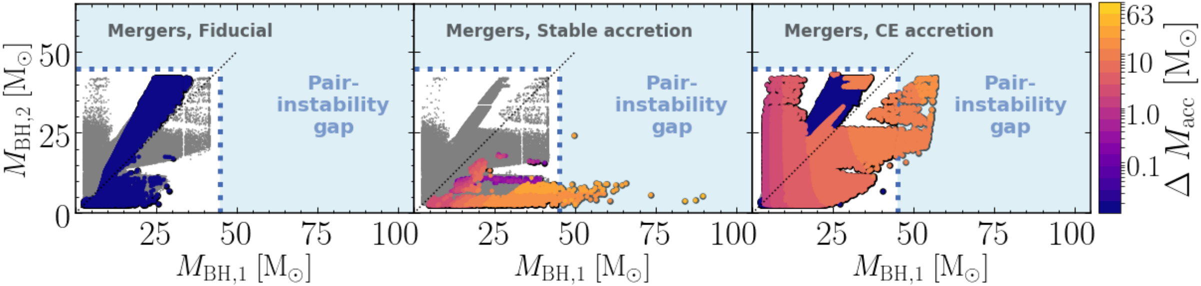


Can isolated binary evolution "pollute" the gap?

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



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



Mass accretion leads to orbital widening

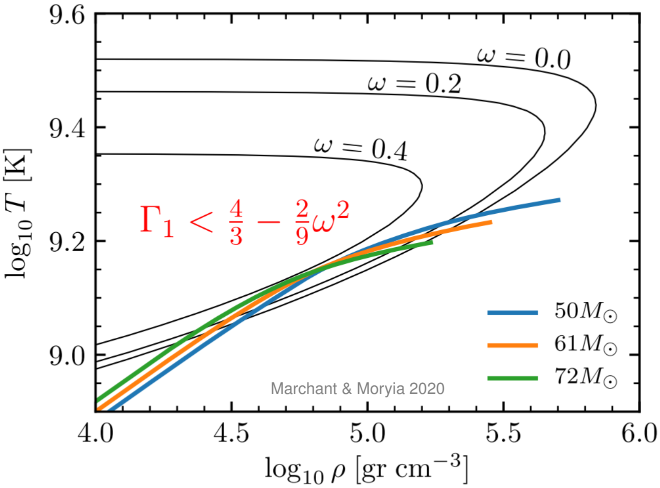
even with the most optimistic assumptions:

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

Can rotation move the gap? Barely...

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

Chatzopoulos *et al.* 2012, 2013



Marchant & Moryia 2020

Rotation stabilizes only for *very* extreme assumption:

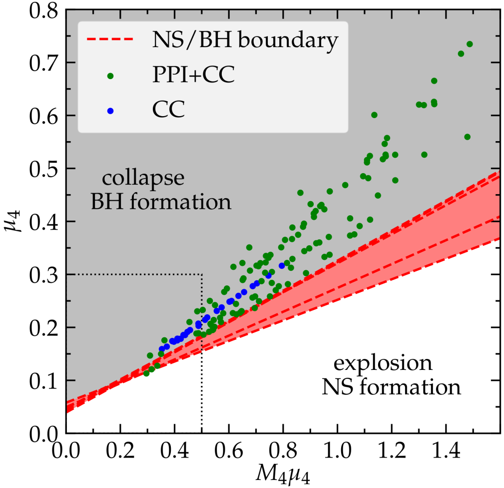
- No core-envelope coupling
- large initial rotation
- low Z ($\simeq$ no winds)

only $\sim$20% shift of instability
$\lesssim$4% for "realistic" coupling

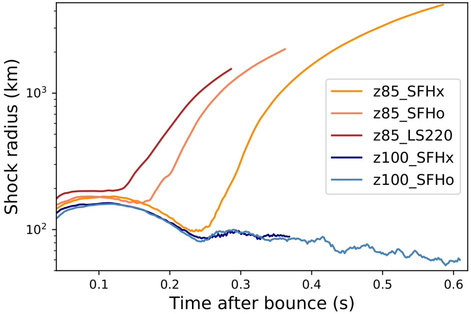
see also Glatzel *et al.* 1985

Can the final core-collapse result in an explosion?

Parametric 1D explodability criteria
are not really applicable.



3D simulations not conclusive yet



Powell, Muëller, Heger 2021

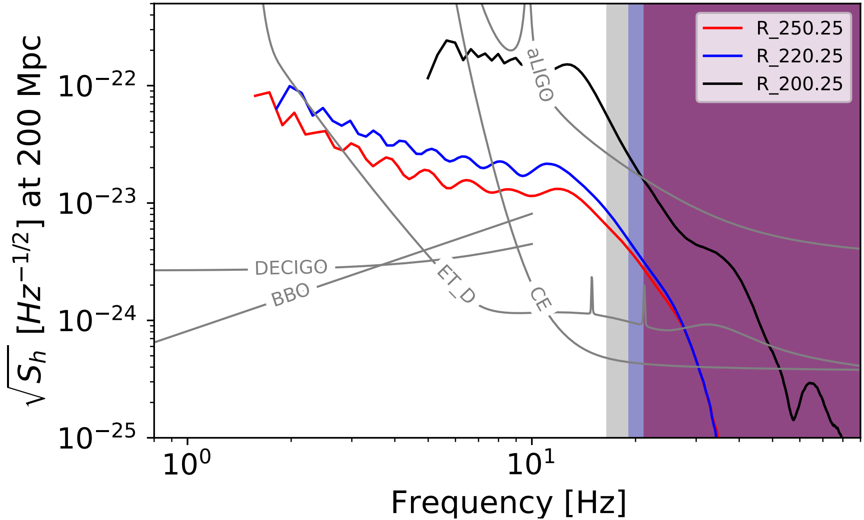
$$\max \Delta M_{CC} \lesssim 3.5\,M_{\odot}$$

from ν-driven engines

Rahman *et al.*, 2021

Renzo, Farmer, *et al.* 2020b, see also Ertl *et al.* 2016,2020, O'Connor & Ott 2011, Müller & Mandel 2020, Couch *et al.* 2020

Gravitational waves from super-kilonova



“sad trombone”

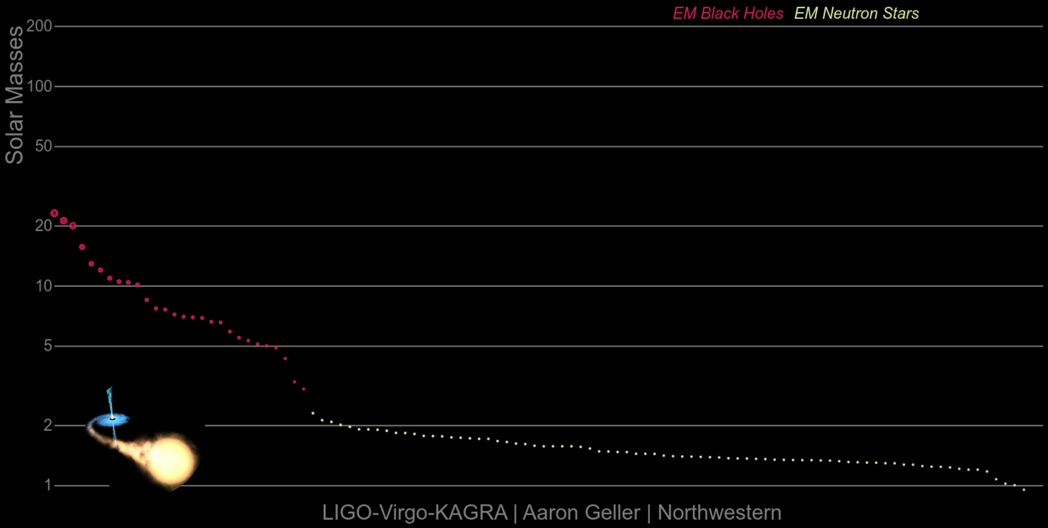
ν decreases

as BH and its ISCO

grow

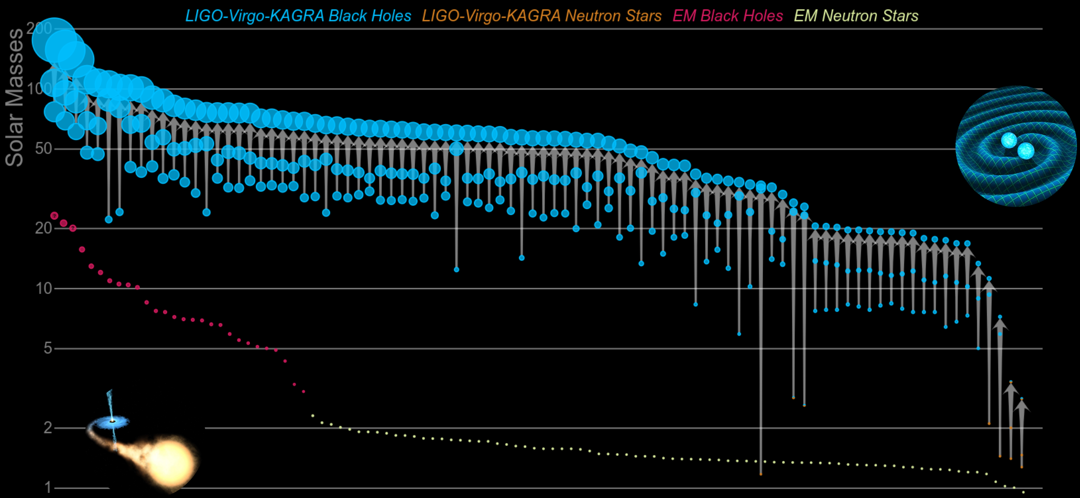
Siegel *et al.* (incl. MR), 2021

Electromagnetically detected compact object masses



https://media.ligo.northwestern.edu/gallery/mass-plot

Almost all compact object masses

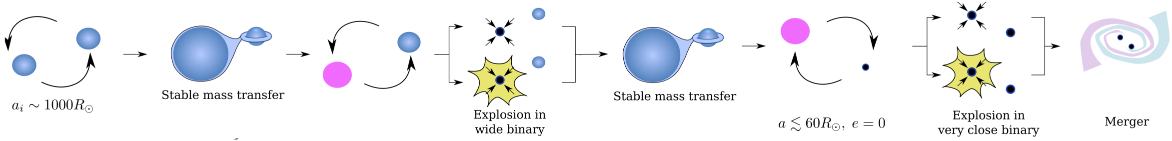


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

https://media.ligo.northwestern.edu/gallery/mass-plot

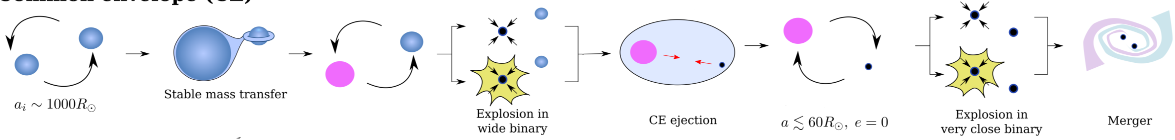
Isolated binary evolution removes the H-envelope anyways

Stable mass transfer (RLOF)

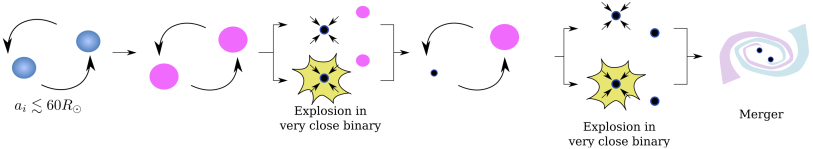


e.g., Klencki *et al.* 2021, van Son *et al.* (incl. MR) 2021, Marchant *et al.* 2021, Gallegos-Garcia *et al.* 2022

Common envelope (CE)



Chemically homogeneous evolution (CHE)



Marchant, MR *et al.* 2019