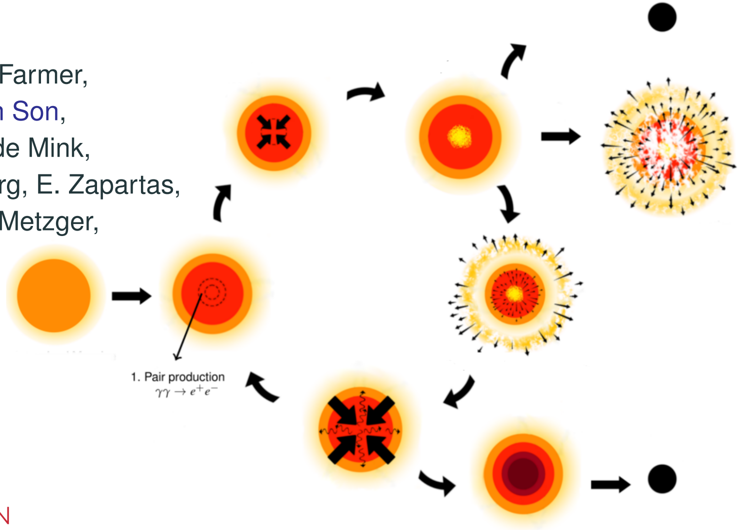
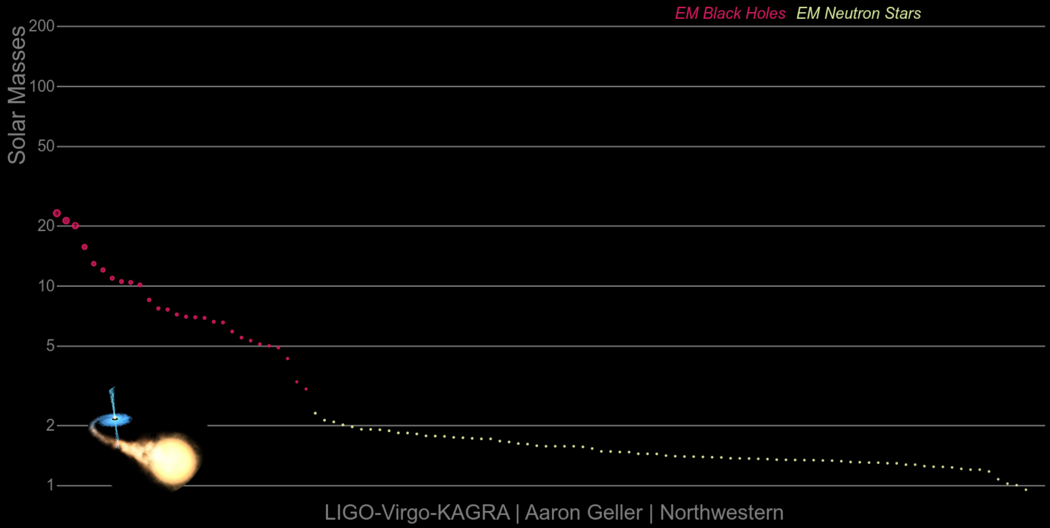
Progenitors of the most massive (stellar-mass) black holes

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



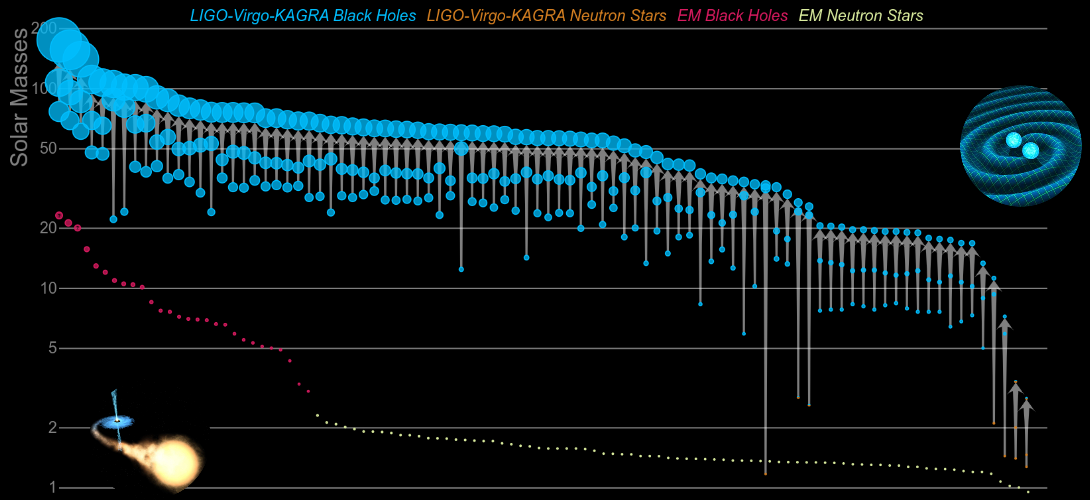
FLATIRON INSTITUTE
Center for Computational Astrophysics

Electromagnetically detected compact object masses



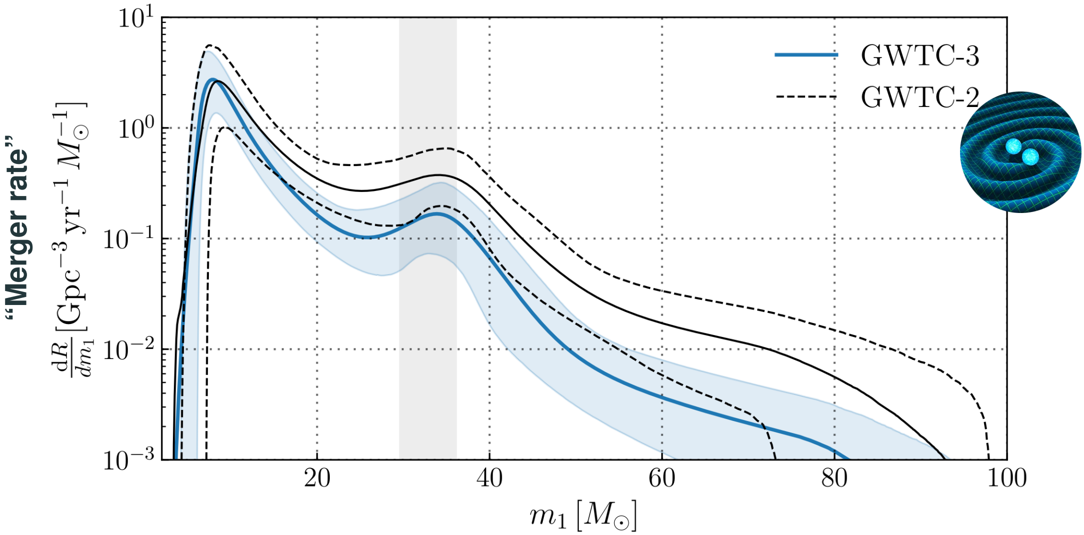
https://media.ligo.northwestern.edu/gallery/mass-plot

Almost all compact object masses



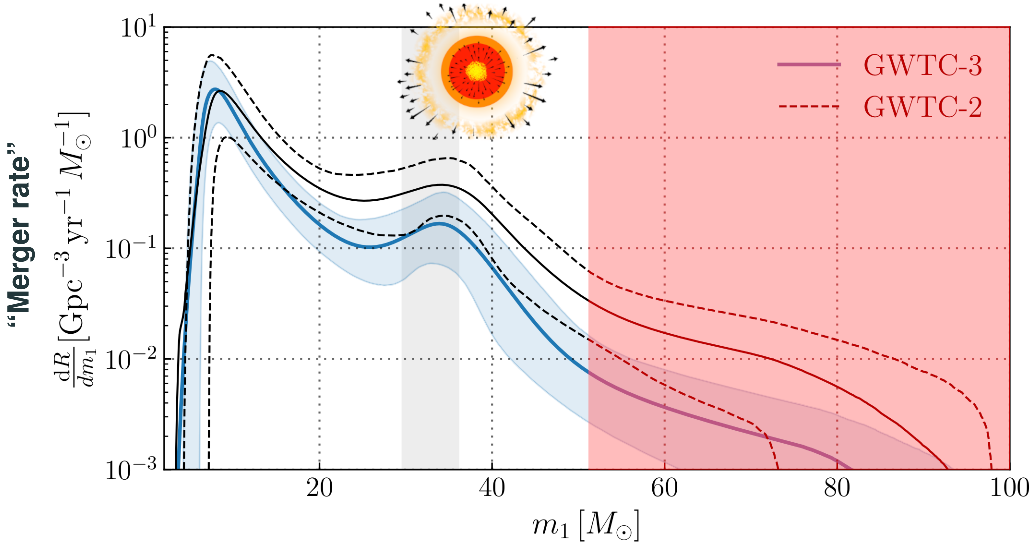
https://media.ligo.northwestern.edu/gallery/mass-plot

Gravitational wave mergers offer an unprecedented view on massive BHs



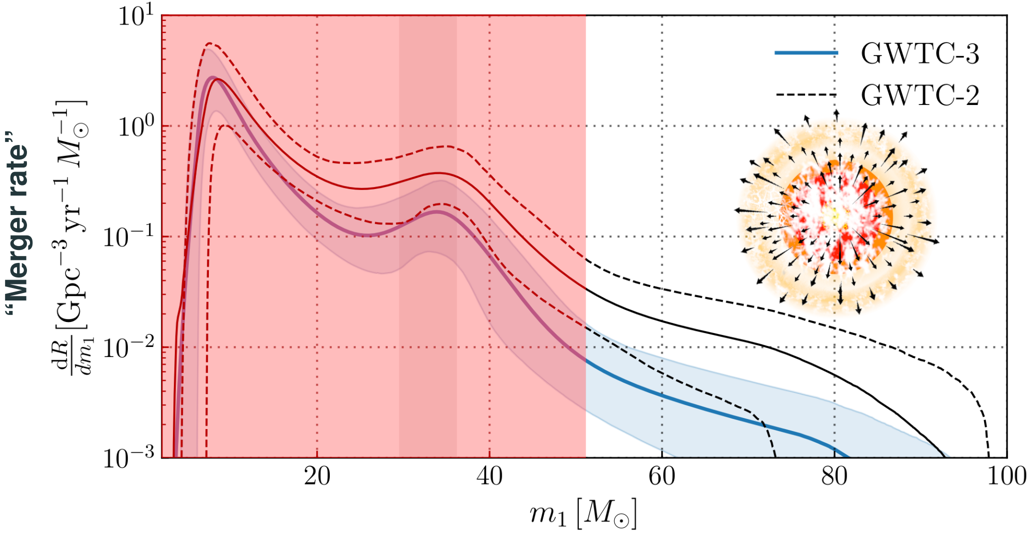
Abbott *et al.* 2022

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

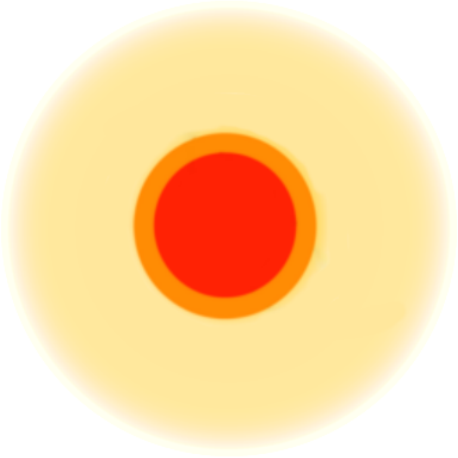
Part 1: (Pulsational) pair instability

Maximum $M_{\rm BH}$ 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

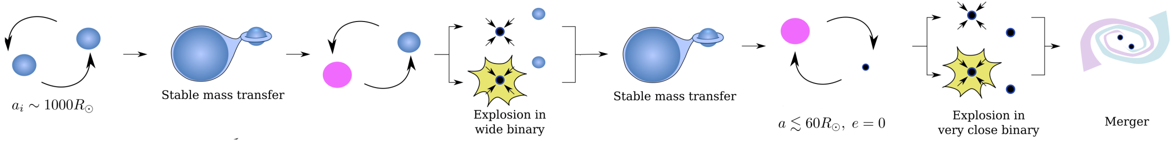
H-rich envelope can be lost to:

- winds
- binary interactions
- first pulse

He cores computed with MESA

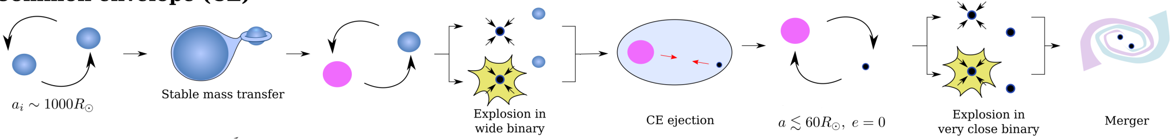
Isolated binary evolution removes the H-envelope anyways

Stable mass transfer (RLOF)

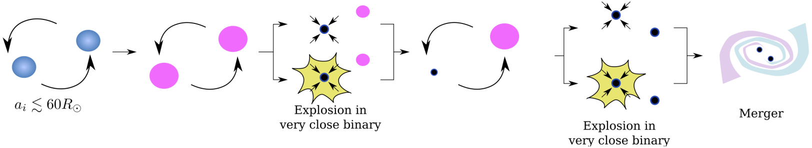


e.g., Klencki *et al.* 2021, van Son *et al.* (incl. MR) 2021, Marchant *et al.* 2021, Gallegos-Garcia *et al.* 2022

Common envelope (CE)



Chemically homogeneous evolution (CHE)



Marchant, MR *et al.* 2019

Pair-instability SNe are the best understood supernovae

Radiation pressure dominated:

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

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

0. Evolved Massive He core

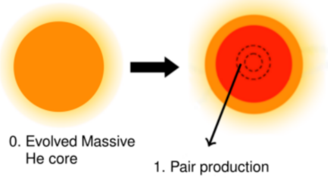
see Fowler & Hoyle 1964, Rakavy & Shaviv 1967, Barkat *et al.* 1967, 1968, Fraley 1968,

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

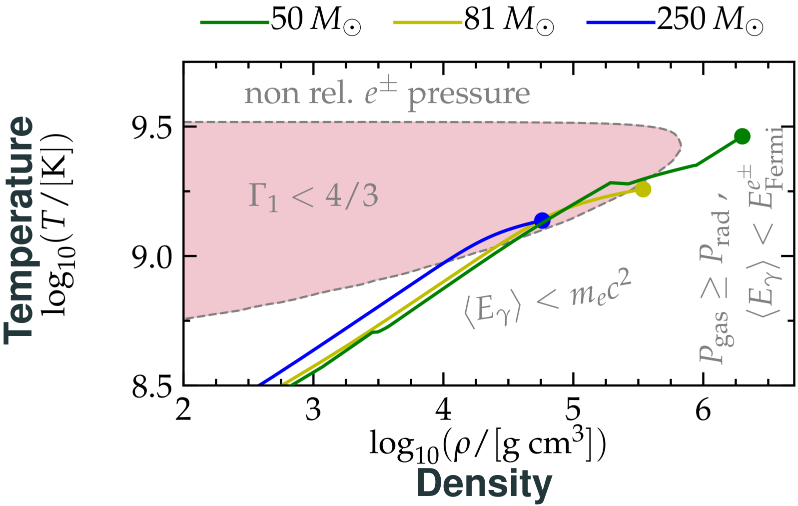
Woosley 2017, 2019, Marchant, MR *et al.* 2019, Farmer, MR *et al.* 2019, 2020, Leung *et al.* 2019, 2020,

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

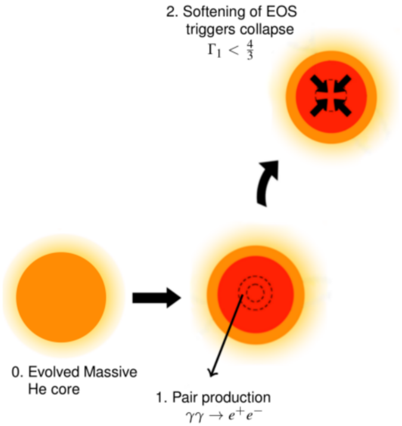
Renzo, Farmer *et al.* 2020b



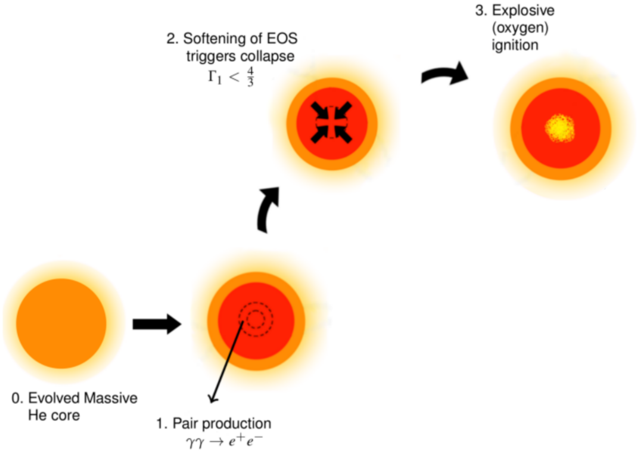
$$\gamma\,\gamma \rightarrow e^{+}\,e^{-}$$



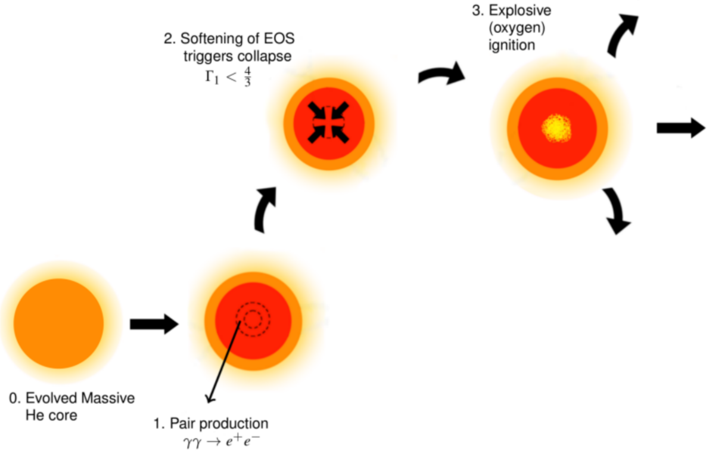
Renzo, Farmer *et al.* 2020b



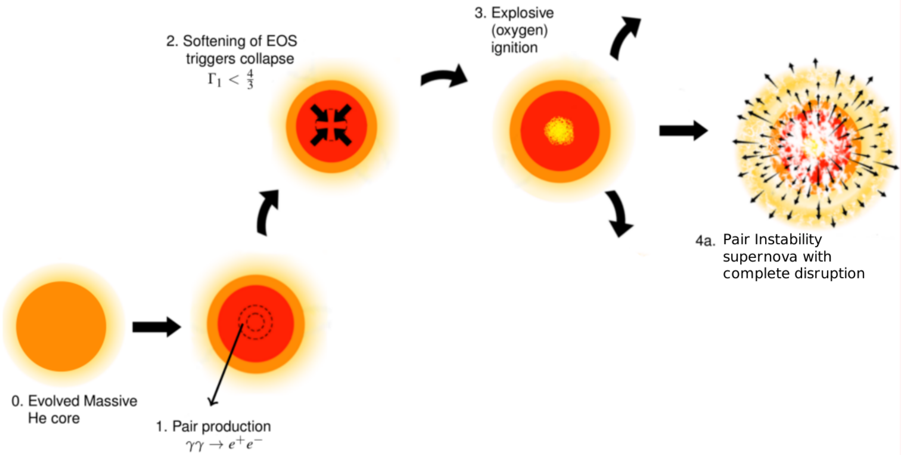
Renzo, Farmer *et al.* 2020b



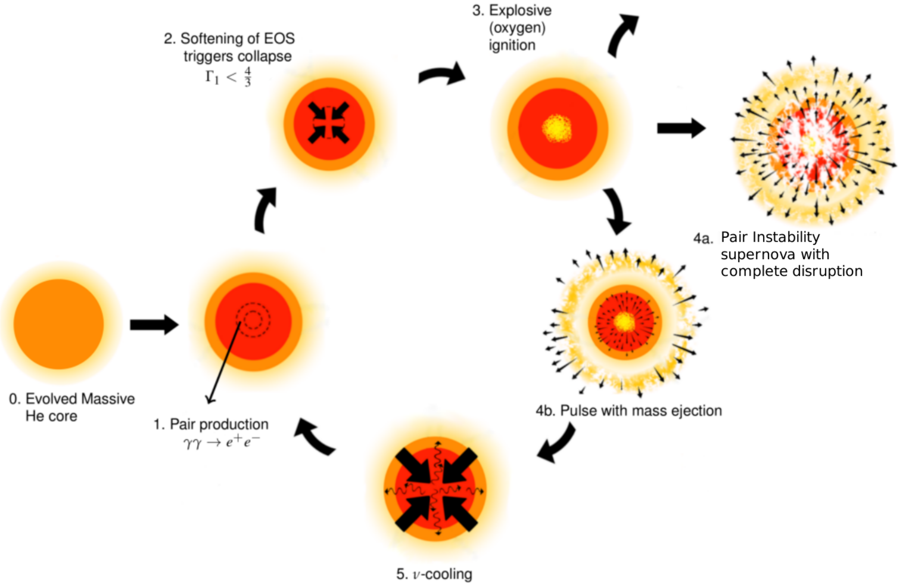
Renzo, Farmer *et al.* 2020b



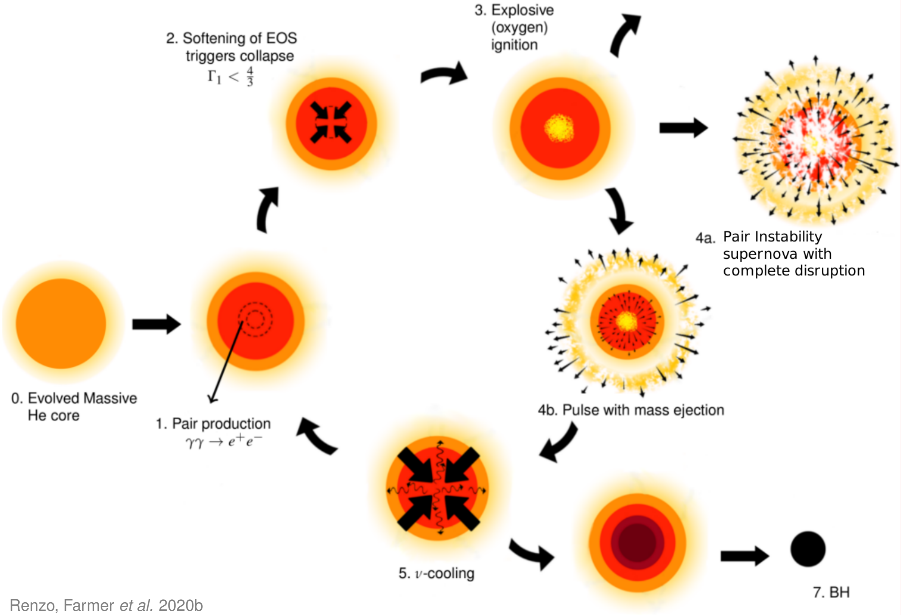
Renzo, Farmer *et al.* 2020b



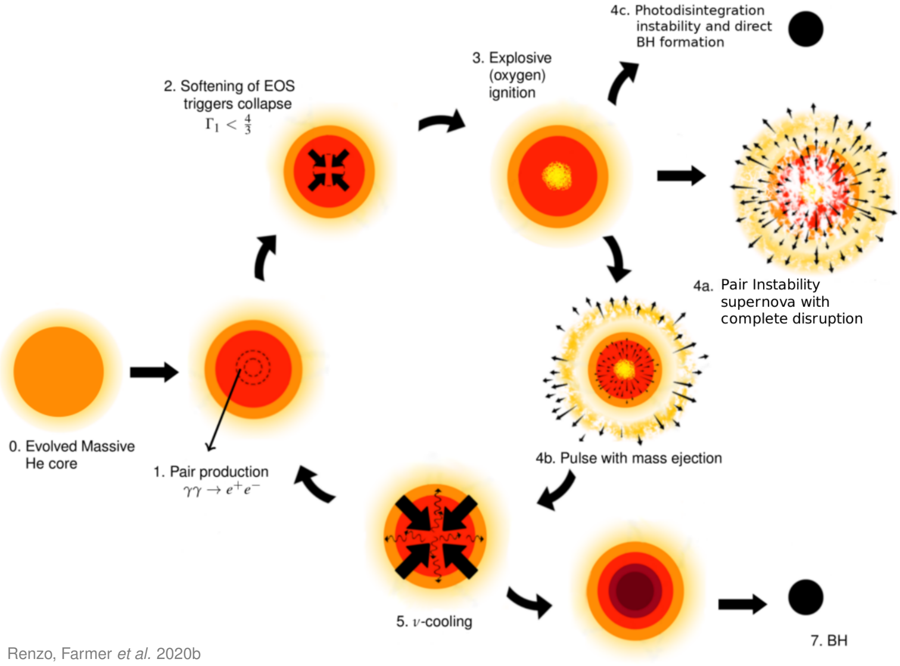
Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b



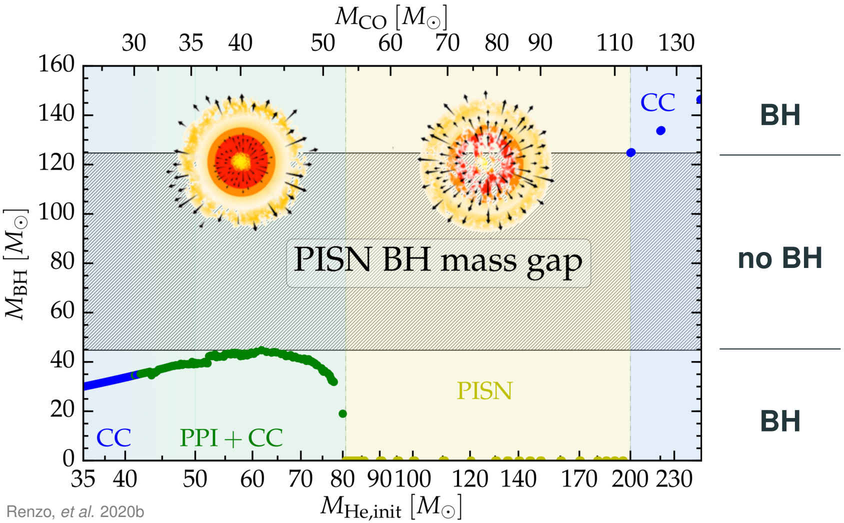
BH

no BH

BH

Renzo, Farmer *et al.* 2020b

Resulting stellar BH masses



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

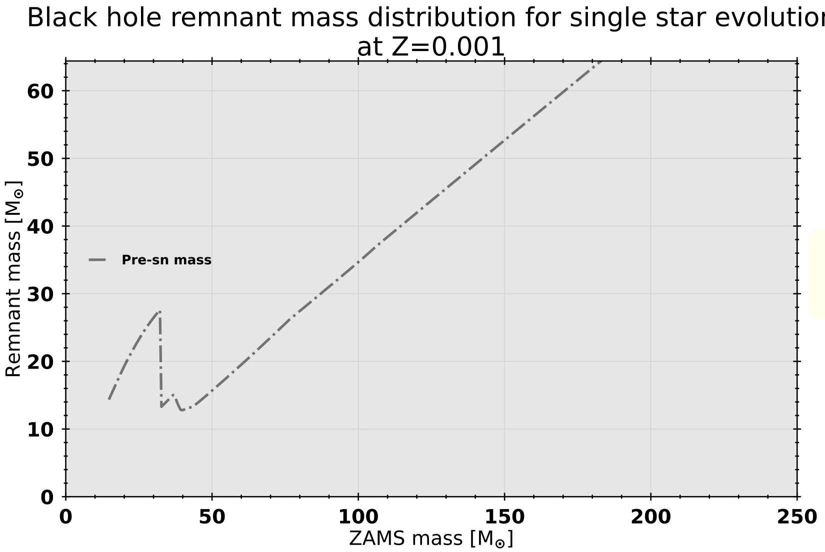
Maximum M_{BH} from single He cores

Implementation in pop. synth.

How robust are these predictions?

$M_{\text{initial}} \rightarrow$ 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_{initial} → CO core mass[†] → BH mass

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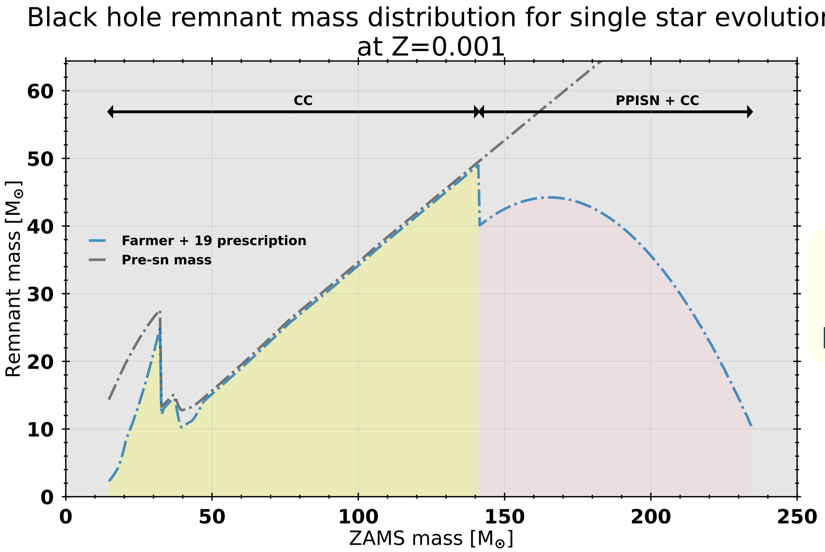

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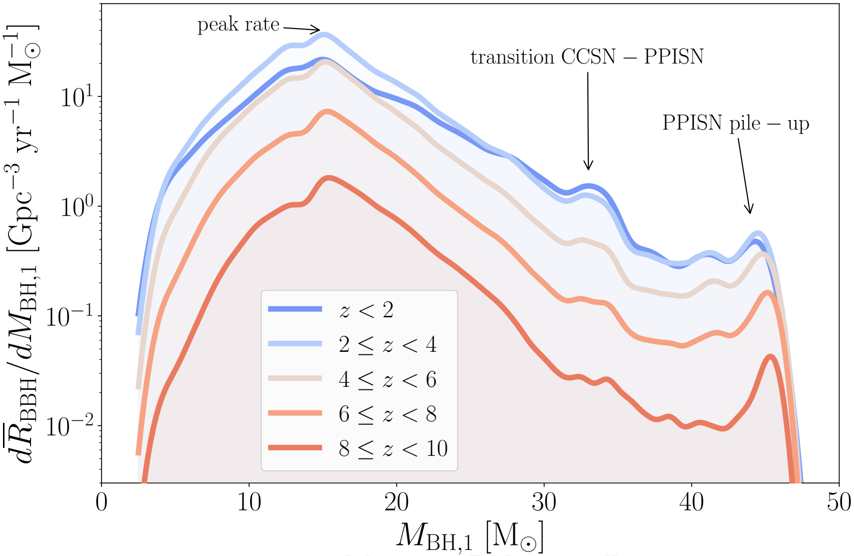
Using “recipes” out-of-the-box leads to artificial features



“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

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

(Fryer *et al.* 2012, 2022)

$$\Downarrow$$

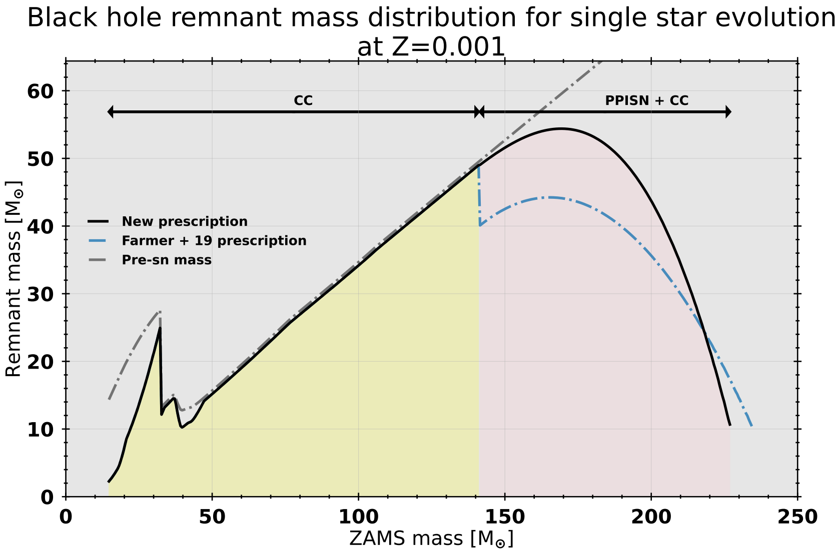
$$M_{\rm BH} = M_{\rm pre-explosion} - \left(\Delta M_{\rm SN} + \Delta M_{\nu,\rm core} + \Delta M_{\rm env} + \Delta M_{\rm PPI} + \cdots\right)$$

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)



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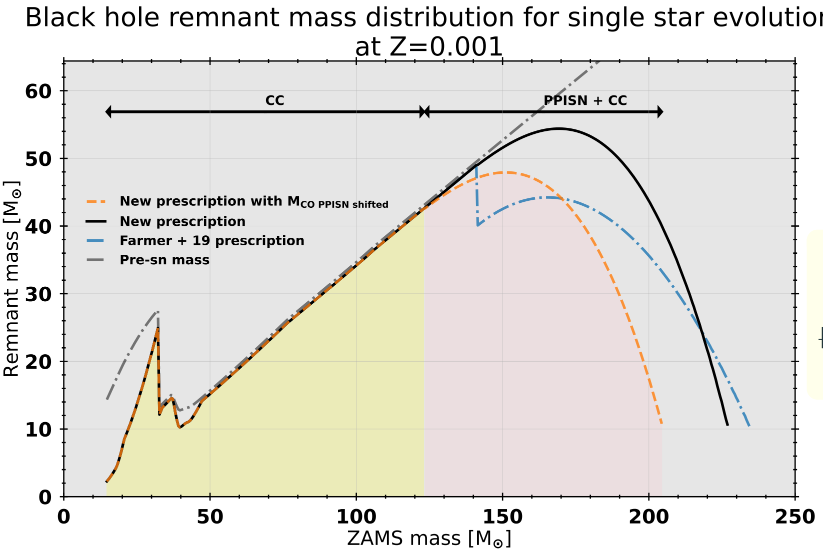

"Initial mass"

David D. Hendriks

Univ. Surrey

Fryer *et al.* 2012

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

Renzo *et al.* 2022

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

Part 1: (Pulsational) pair instability

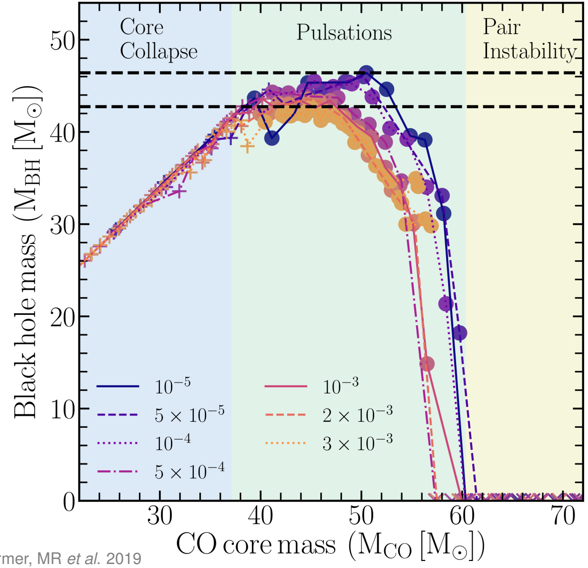
Maximum M_{BH} from single He cores

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

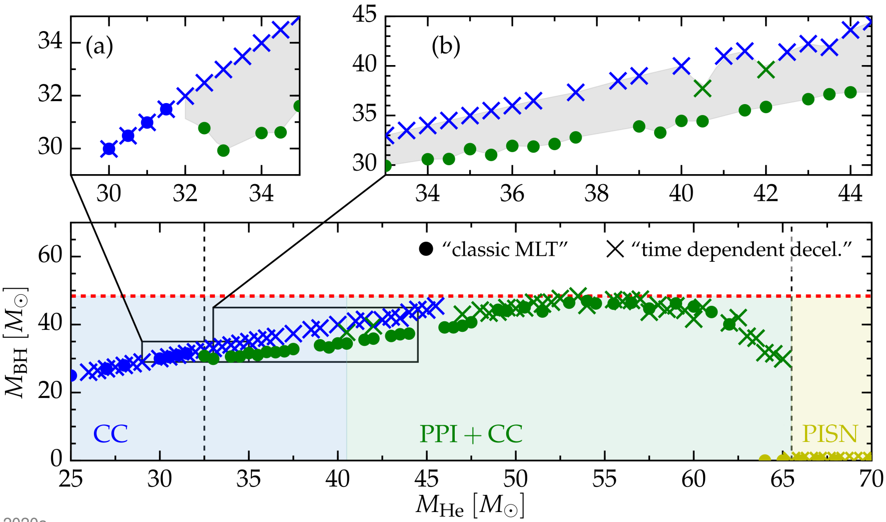
$\Delta \max\{M_{\rm BH}\} \sim 7\%$

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

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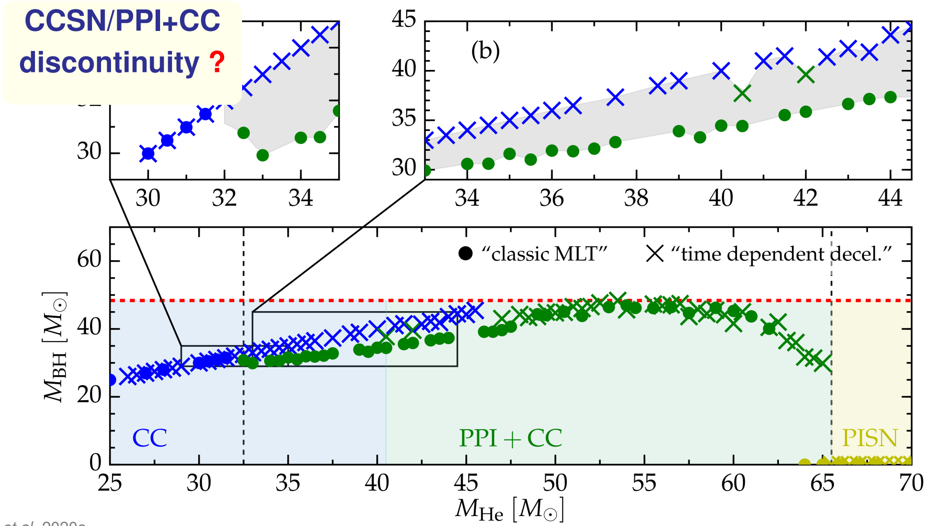
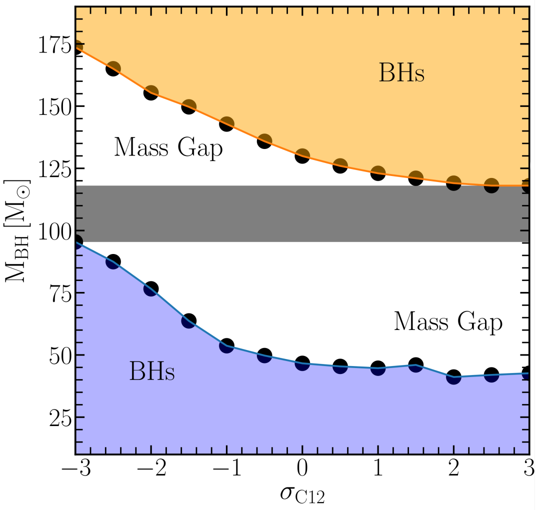


Renzo, Farmer *et al.* 2020a

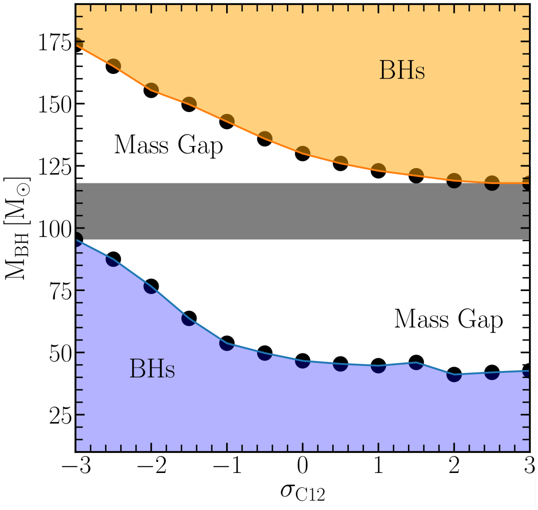
The input physics that matters: $^{12}C(\alpha,\gamma)^{16}O$ reaction rate

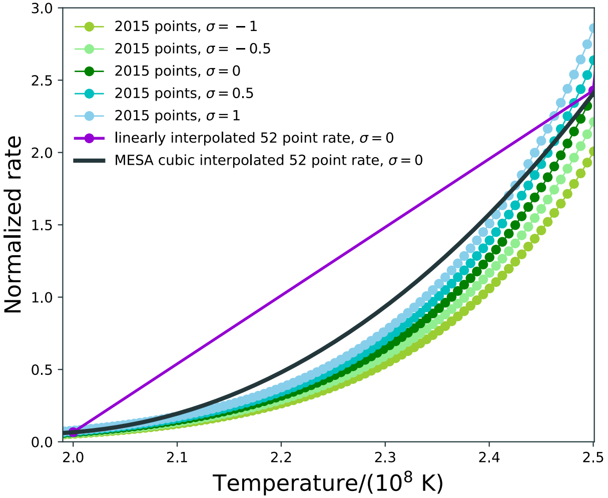


⇐ **lower** **Rate** **higher** ⇒

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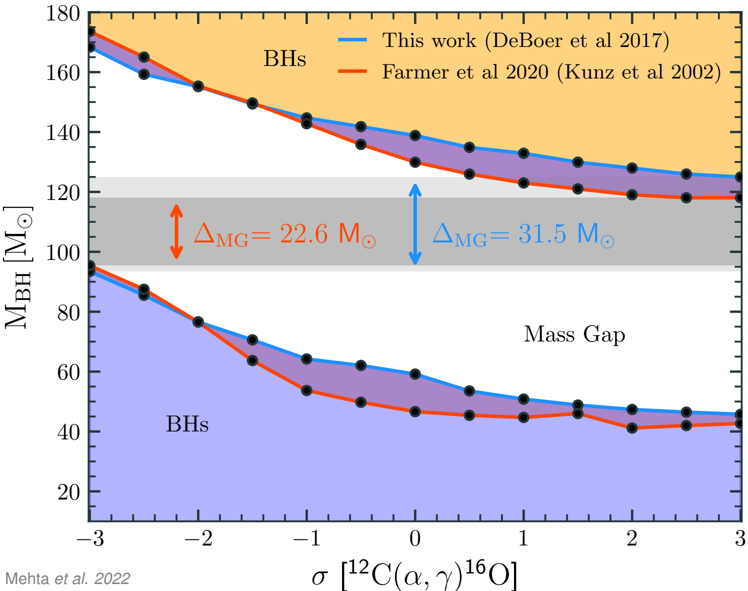
Farmer, MR *et al. 2020*, see also Farmer, MR *et al.* 2019, Costa *et al.* 2021, Woosley & Heger 2021, Farag, MR *et al.* submitted

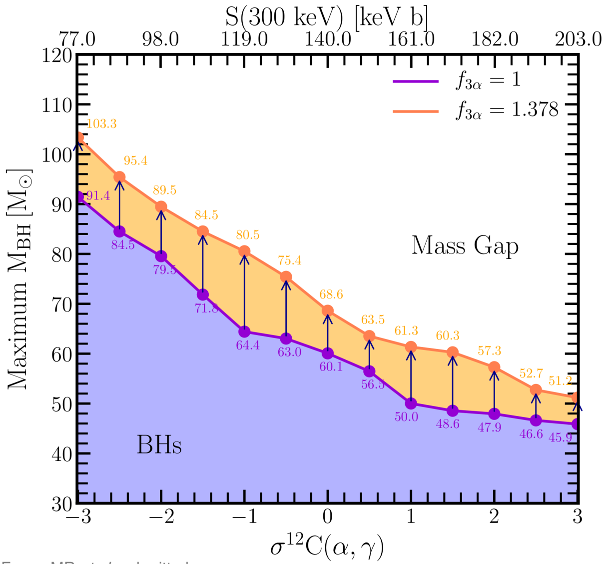
Mehta *et al. 2022*

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

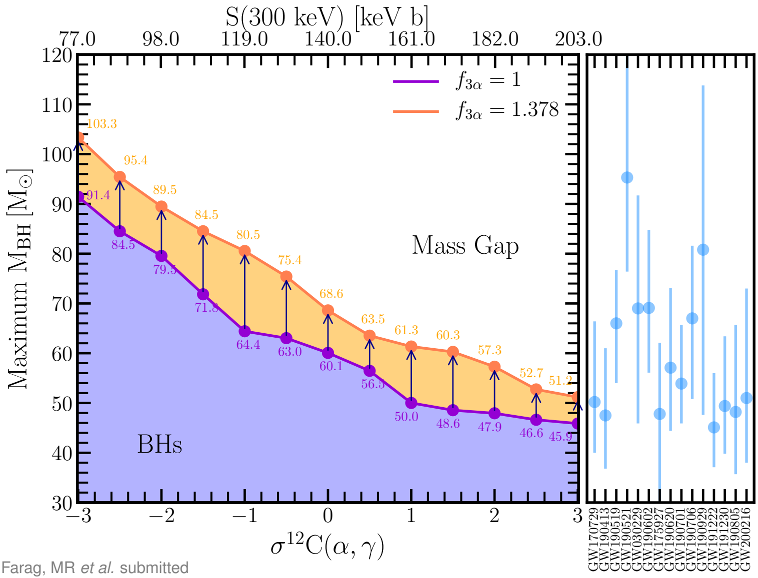
Arizona State Univ.

New lower edge of the gap:

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

Farag, MR *et al.* submitted

Pushing further up with 3α rate uncertainties



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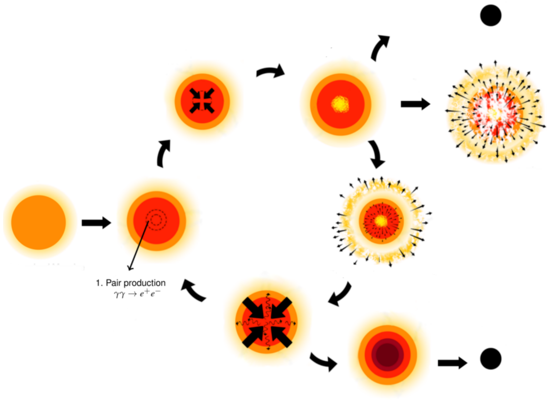
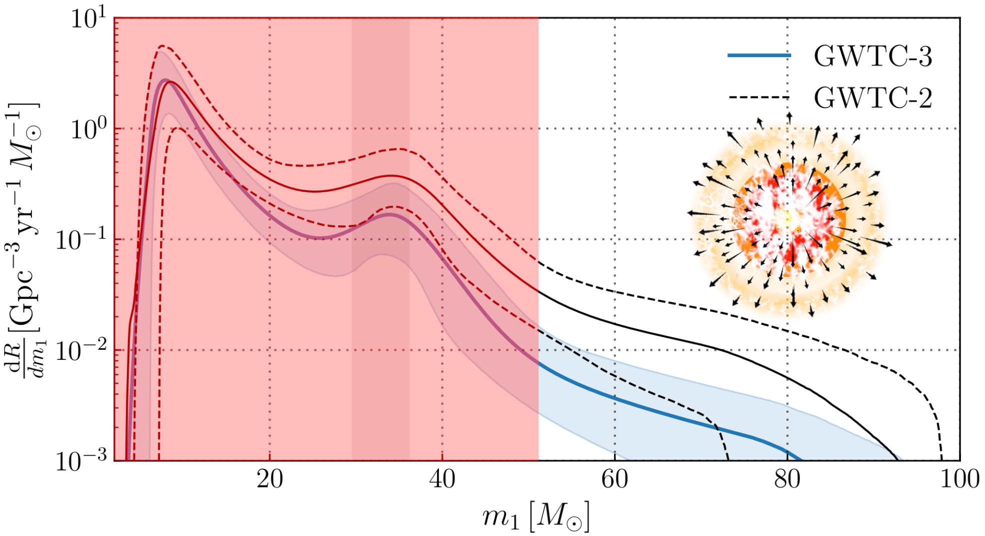
Conclusions on the physics of (pulsational) pair-instability

- 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 $^{12}C(\alpha,\gamma)^{16}O$

  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"

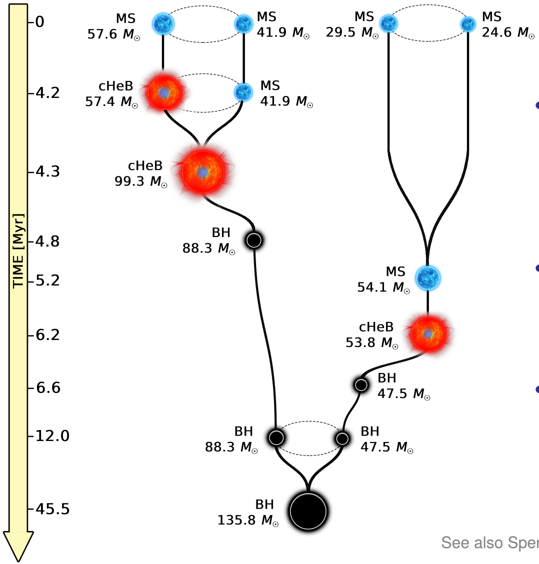
More ideas than events

The stellar merger scenario

Filling the gap "from above"

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

The stellar merger scenario

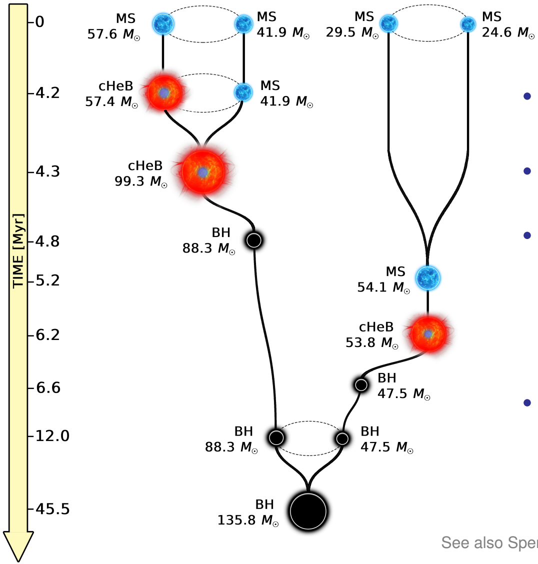


di Carlo *et al.* 20a

- 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

Four challenges of the “stellar merger scenario”



- Mass loss (and core structure) **?**
- Wind and eruptions **?**
- Loss of envelope at BH-formation **?**

  Because of ν losses – Assumed zero

  see Nadhezin 1980, Lovegrove & Woosley 2013

- Need dynamics to pair with 2^{nd} BH

  $\Downarrow$

  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, 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 $\dot{M}$

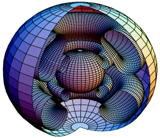
  Langer 88, Heger *et al.* 00

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

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

$\Downarrow$

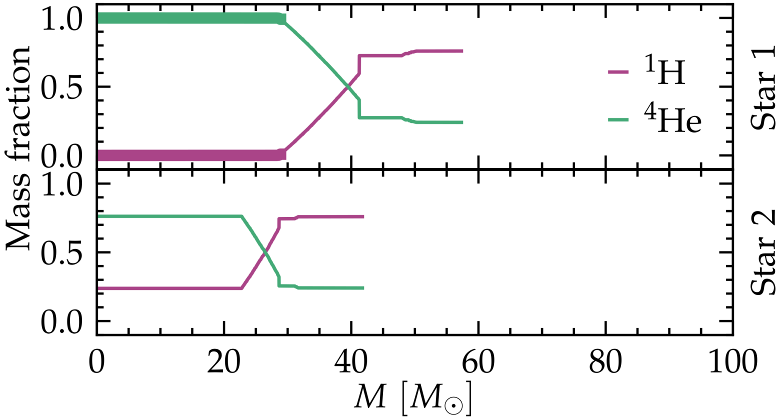
I will assume no rotation



Maeder & Meynet 2000

Ballone *et al.* 22

Merger model: the pre-merger stars



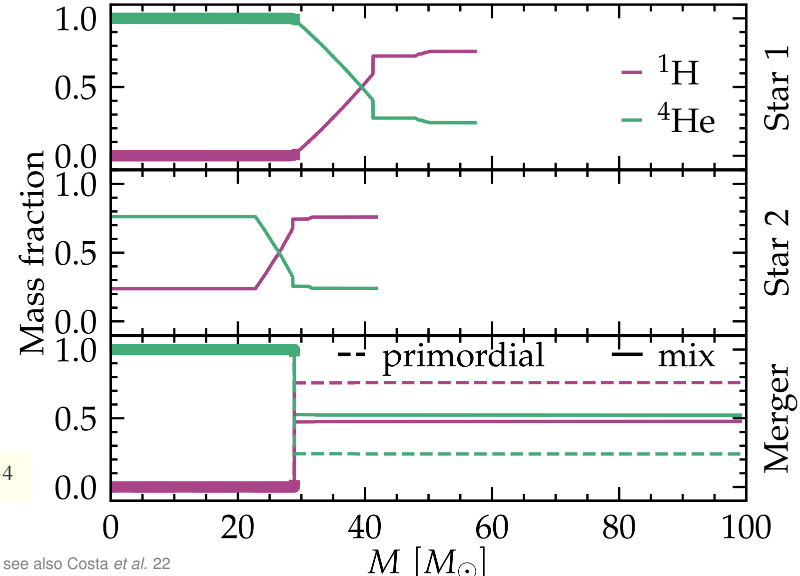
$58\,M_\odot$

$42\,M_\odot$

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

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

Merger model: composition of the merger



$58\,M_\odot$

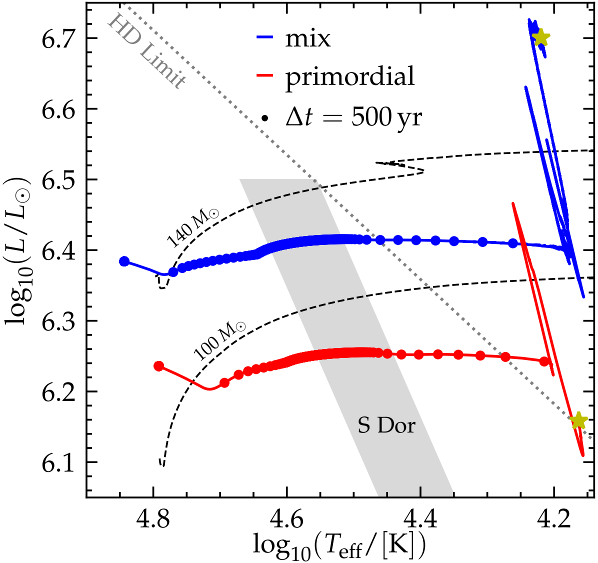
$42\,M_\odot$

$99\,M_\odot$

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

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

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



Very massive stars are hardly stable

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

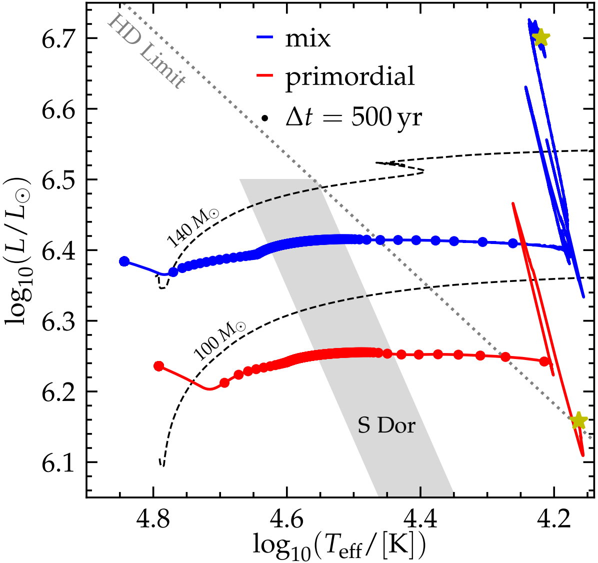
⇓

- LBV eruptions, helped by He opacity?

Jiang *et al.* 18

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

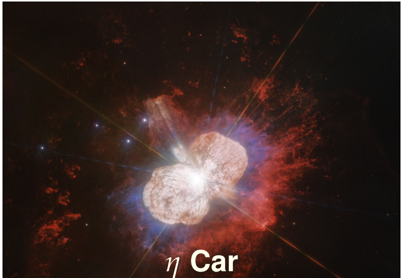
Very massive stars are hardly stable

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

⇓

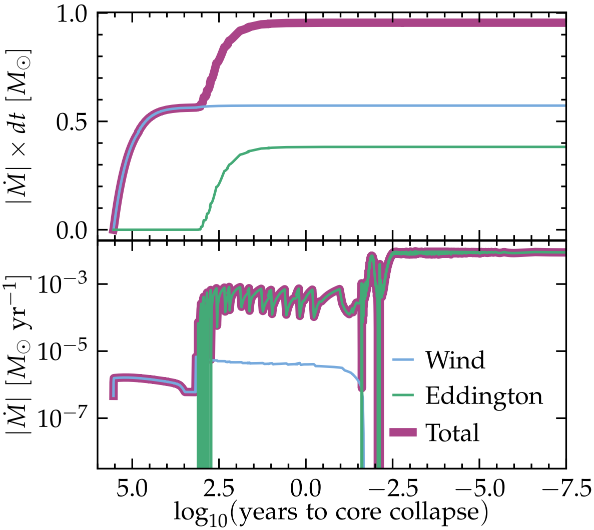
- LBV eruptions, helped by He opacity?

Jiang *et al.* 18



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?

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

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

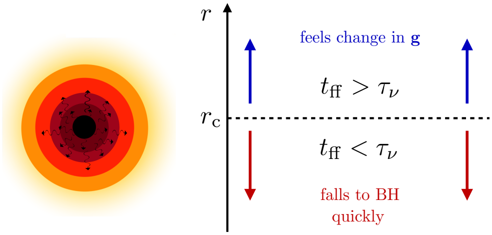
- weak fallback powered explosion

  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

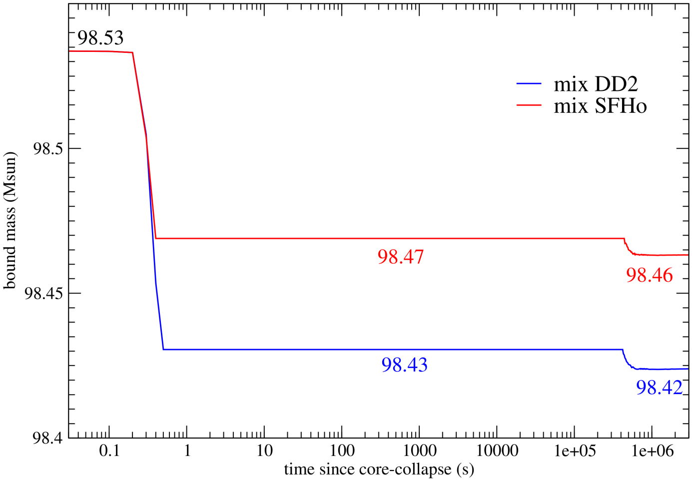
Accretion disks and ν-driven shocks remove little mass for BSG

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



Fernàndez *et al.* 2018

MESA → GR1D+FLASH credits: R. Fernàndez



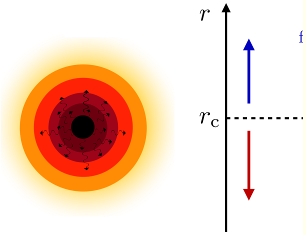
Nadhezin 1980, Lovegrove & Woosley 2013, Piro *et al.* 2013, Coughlin *et al.* 2018, Fernàndez *et al.* 2018, Ivanov & Fernàndez 2021

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

$M_{\mathrm{BH},0} \simeq M_{\mathrm{cor}}$ ...

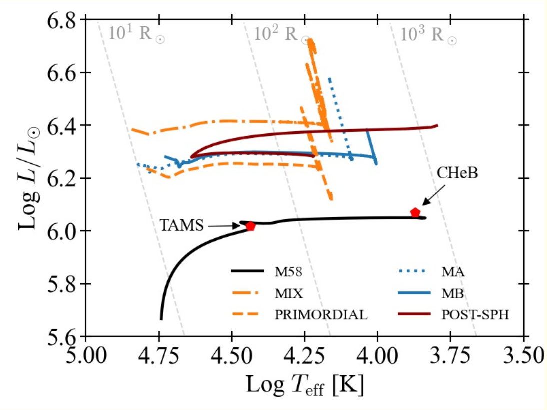
MESA → GR1D+FLASH

credits: R. Fernàndez

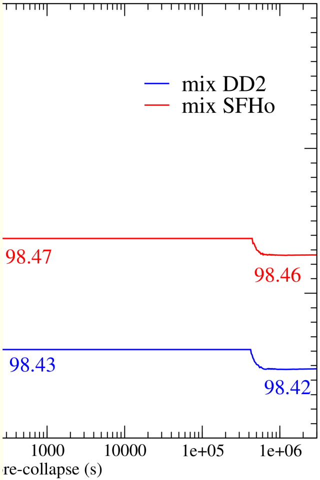


Fernàndez *et al.* 20...

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



Costa *et al.* 22



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

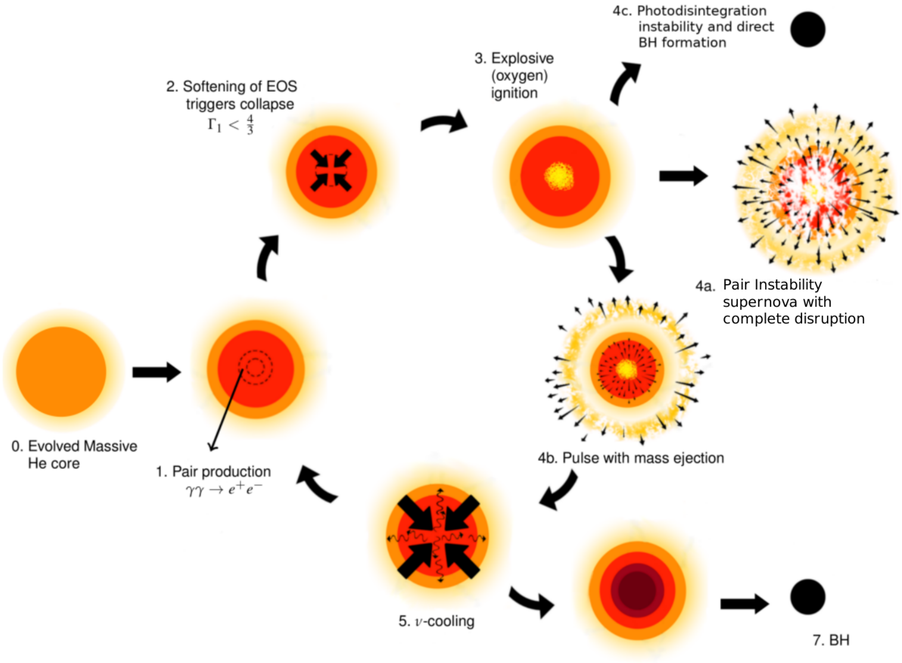
Part 2: Filling the BH mass "gap"

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
0. Evolved Massive He core
1. Pair production $\gamma\gamma \rightarrow e^+e^-$
4b. Pulse with mass ejection
5. ν-cooling
7. BH

BH

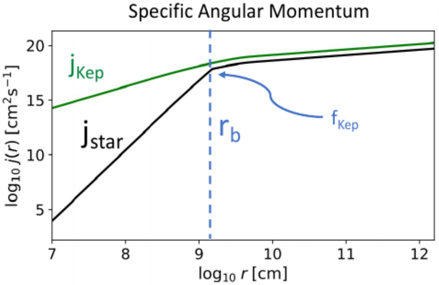
no BH

BH

Extrapolation of long-GRB models to progenitors above the gap

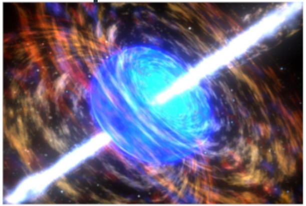
above the gap
(with no rotation)

+



=

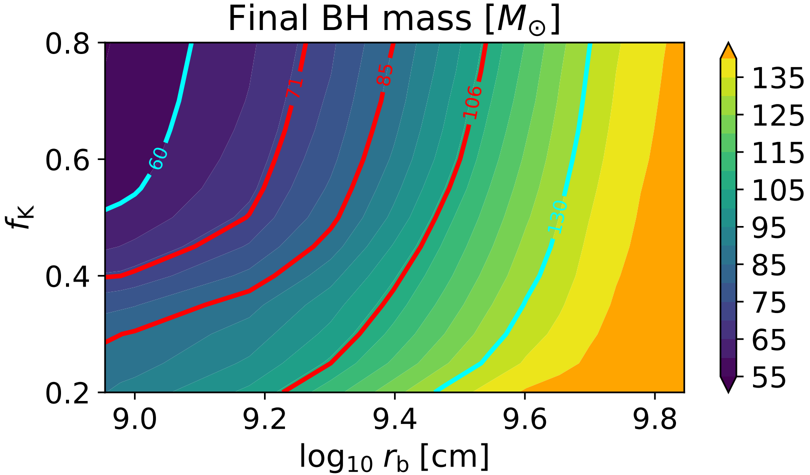
"super-kilonova"



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

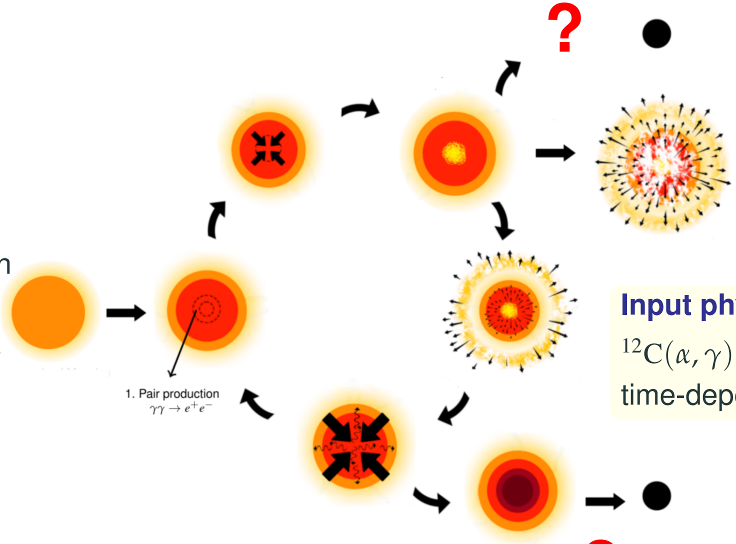
Siegel *et al.* (incl. MR), 2021

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

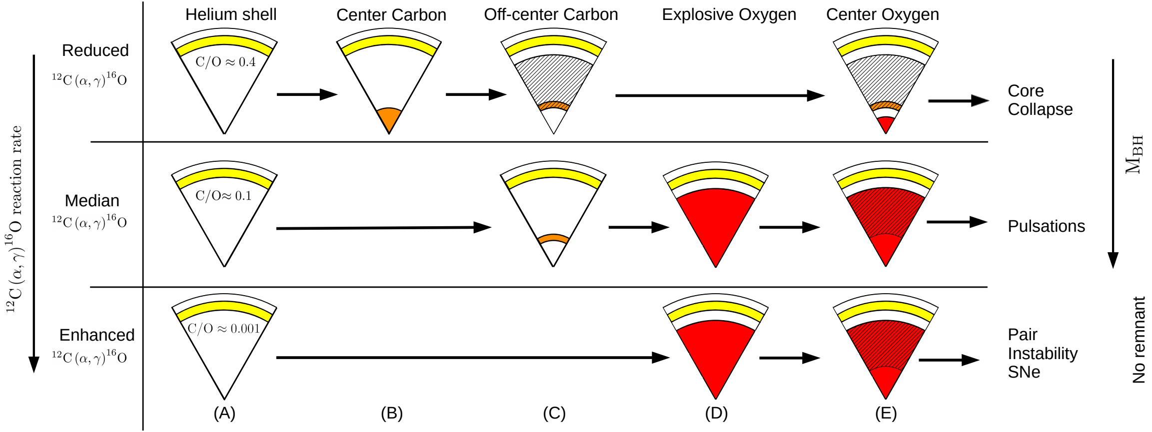
  McKernan *et al.* 12, Bartos *et al.* 17, Stone *et al.* 19

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

Backup slides

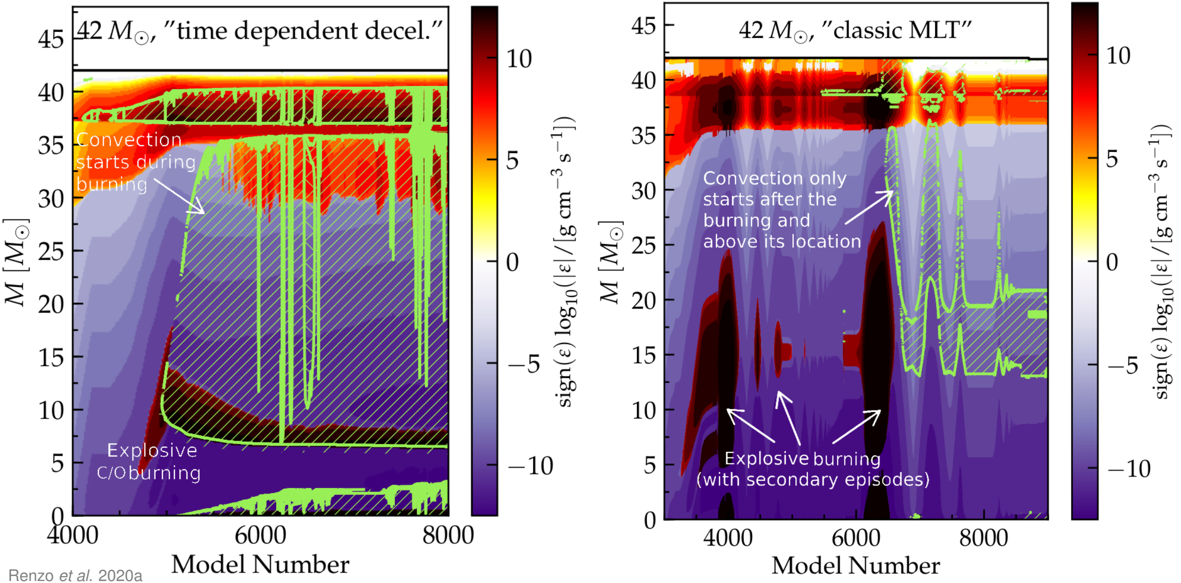
The $^{12}C(\alpha,\gamma)^{16}O$ ends He core burning

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



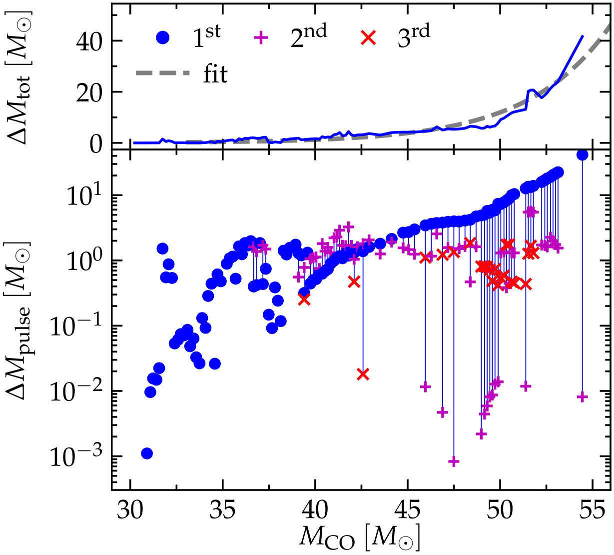
Farmer, Renzo *et al.* 2020

Convection during the pulses quenches the PPI mass loss



Renzo *et al.* 2020a

Amount of mass lost per pulse



Larger cores

⇓

More energetic pulses

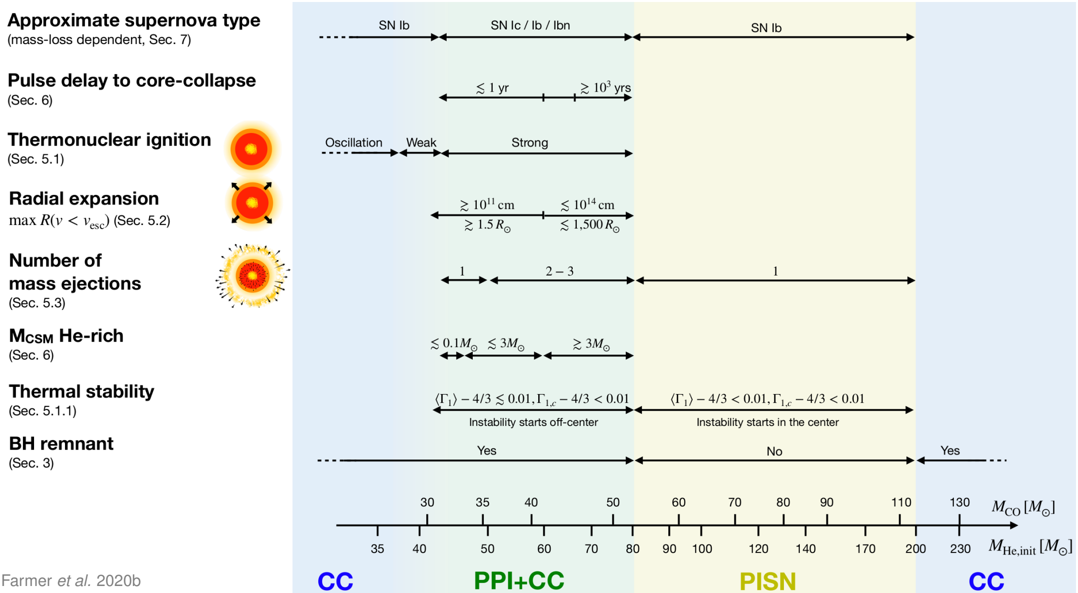
⇓

More mass loss

(and longer delays)

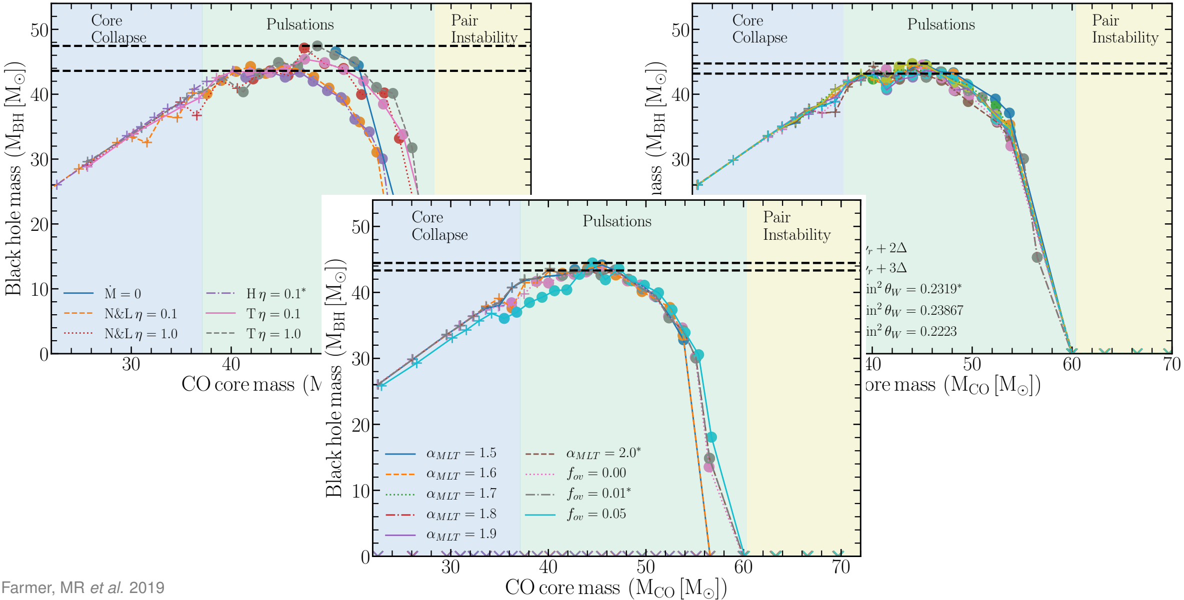
Renzo, Farmer *et al.* 2020b

Summary of EM transients



Renzo, Farmer *et al.* 2020b

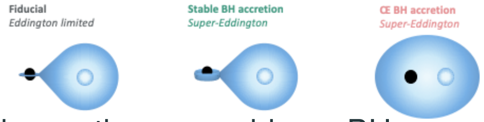
Winds, mixing, ν physics? Also small effects



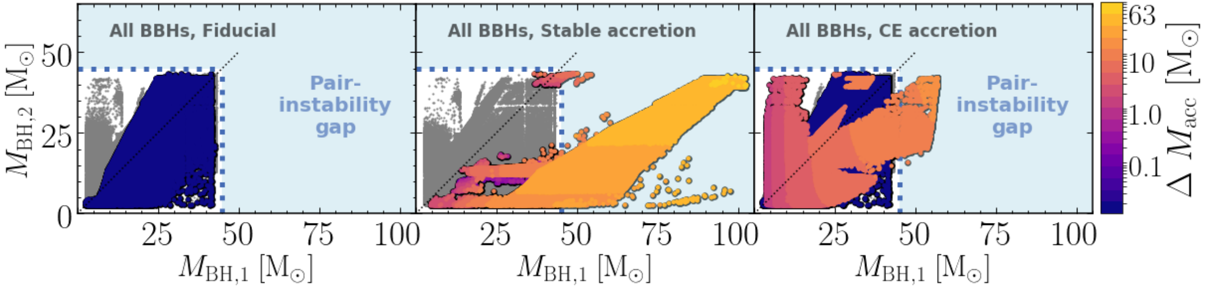
Farmer, MR *et al.* 2019

Can isolated binary evolution "pollute" the gap?

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

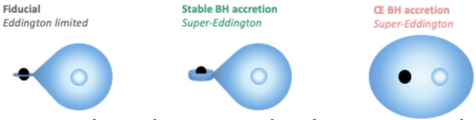


With unlimited accretion, some binary BHs can enter the gap...

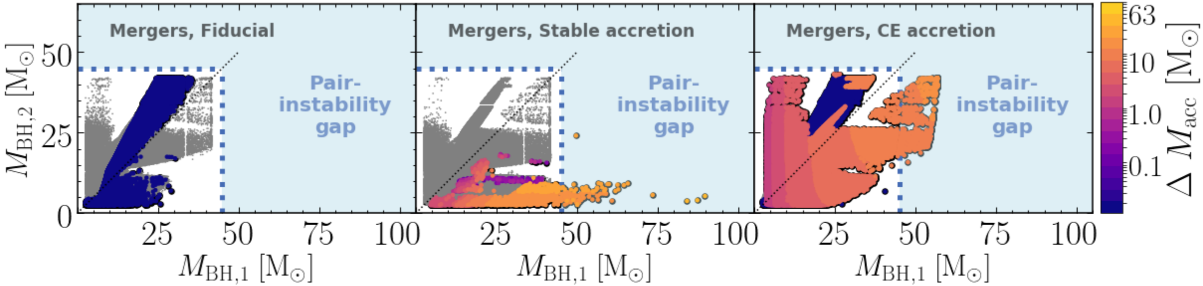


Can isolated binary evolution "pollute" the gap?

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

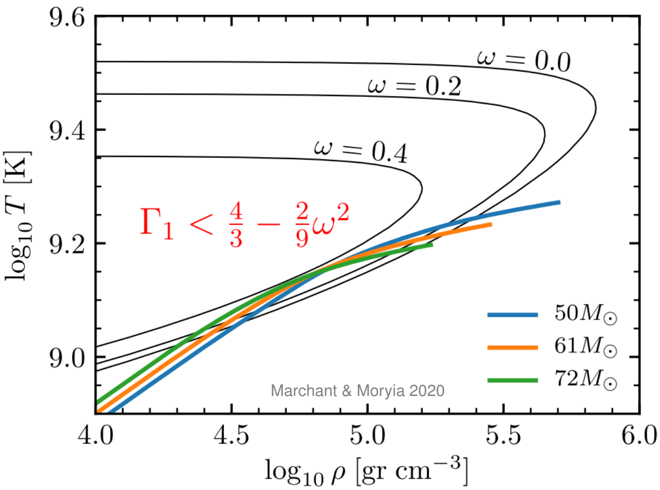
even with the most optimistic assumptions:

• $\lesssim 1\%$ 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** $M_{\rm He}$ $\Rightarrow$ can increase the rates

Chatzopoulos *et al.* 2012, 2013



Rotation stabilizes only for *very* extreme assumption:

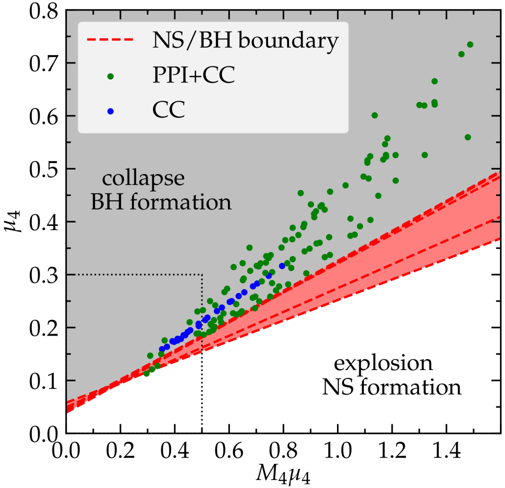
- No core-envelope coupling
- large initial rotation
- low Z ($\simeq$ no winds)

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

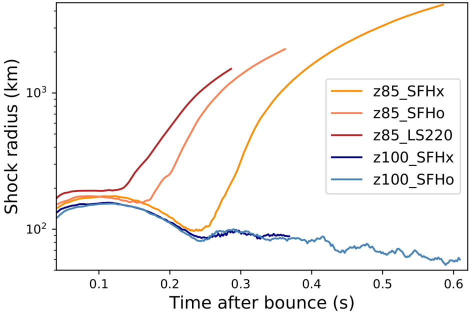
see also Glatzel *et al.* 1985

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

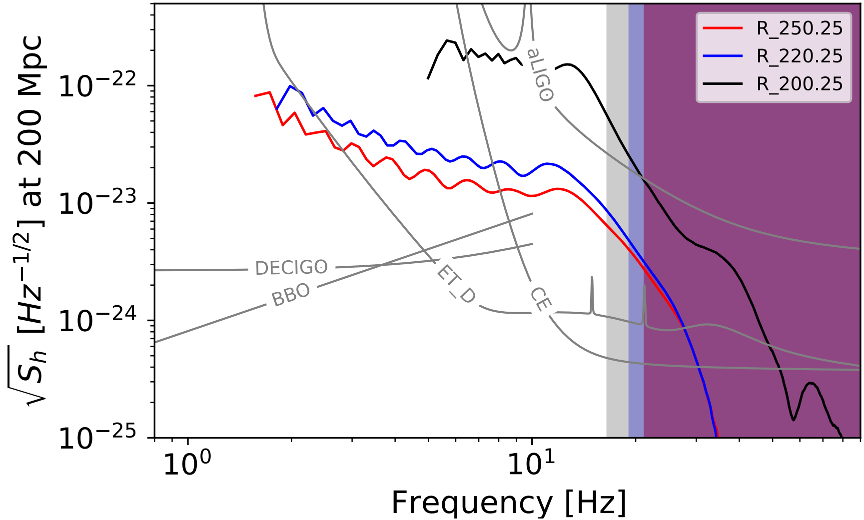
$$\max \Delta M_{CC} \lesssim 3.5\, M_\odot$$

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