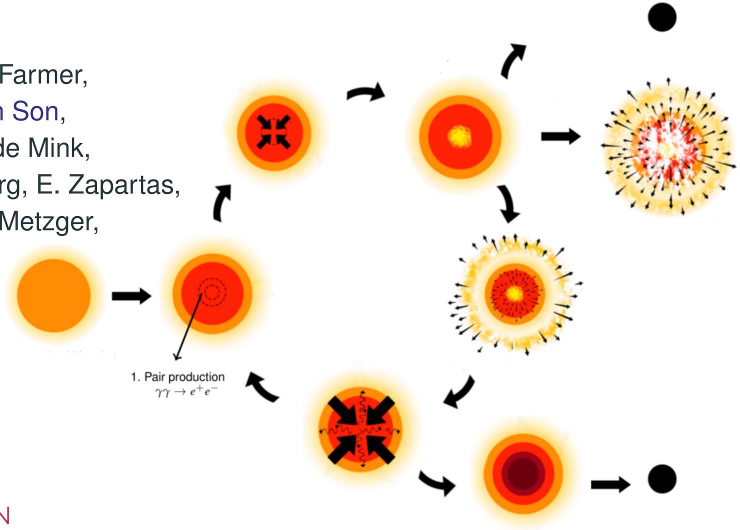
Progenitors of the most massive (stellar-mass) black holes

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

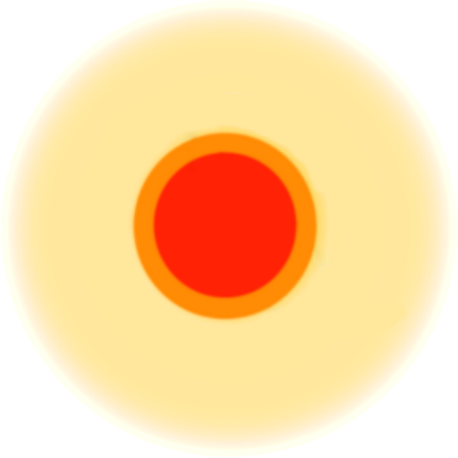
(Pulsational) pair instability

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

Radiation pressure dominated:

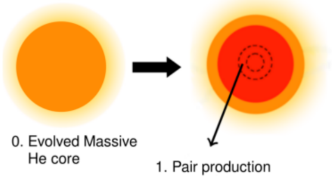
$$P_{\rm tot} \simeq P_{\rm rad}$$

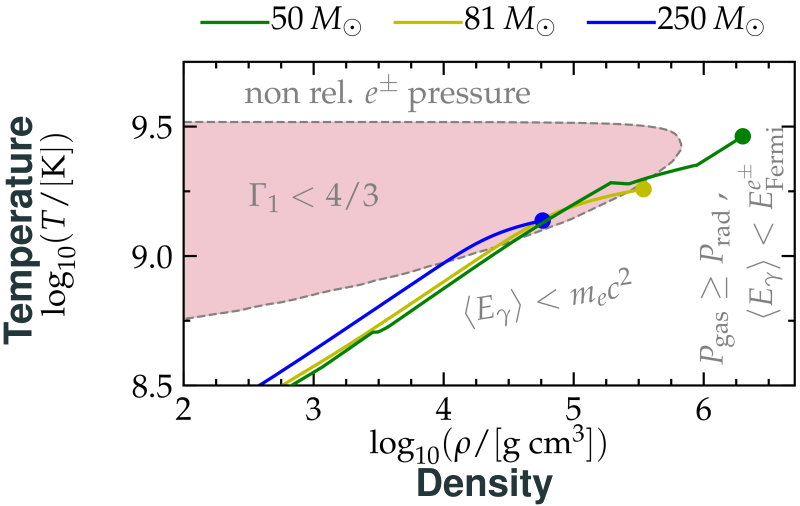
$$M_{\rm He} \gtrsim 32\,M_\odot$$

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...

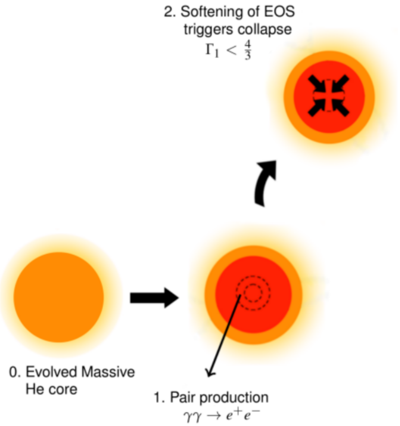
Renzo, Farmer *et al.* 2020b



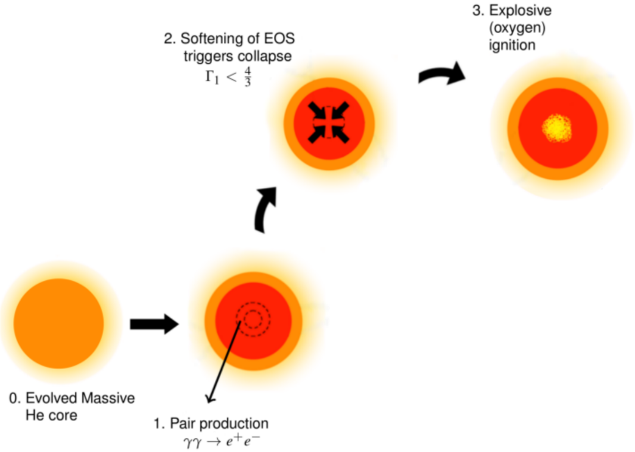


$$\gamma\ \gamma \rightarrow e^+\ e^-$$

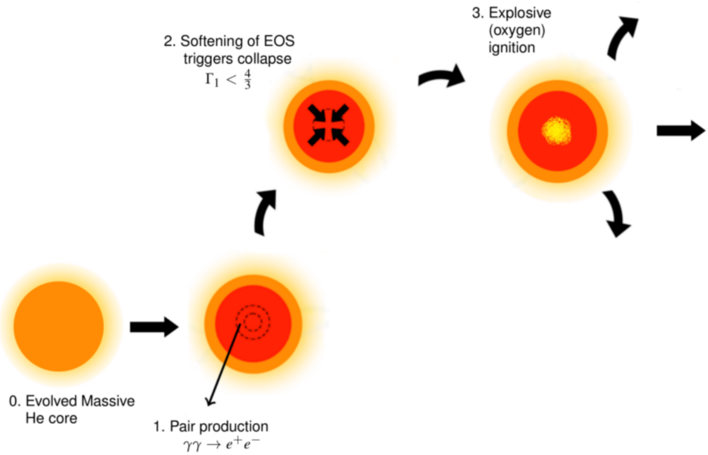
Renzo, Farmer *et al.* 2020b



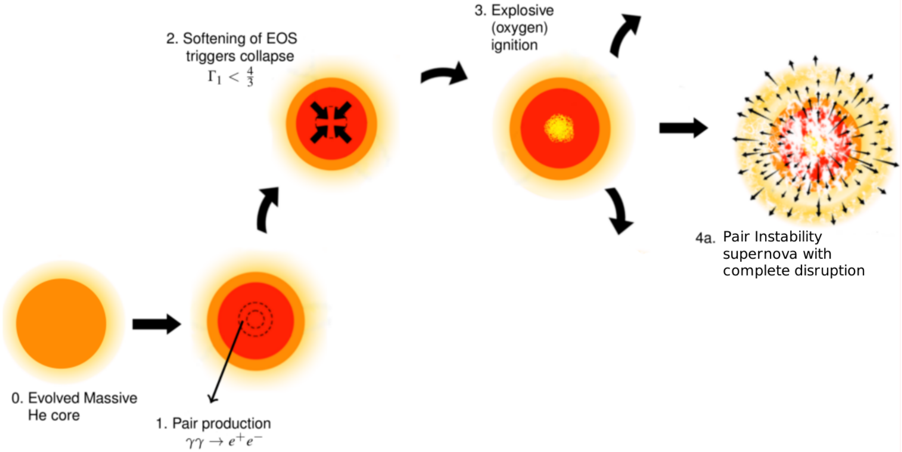
Renzo, Farmer *et al.* 2020b



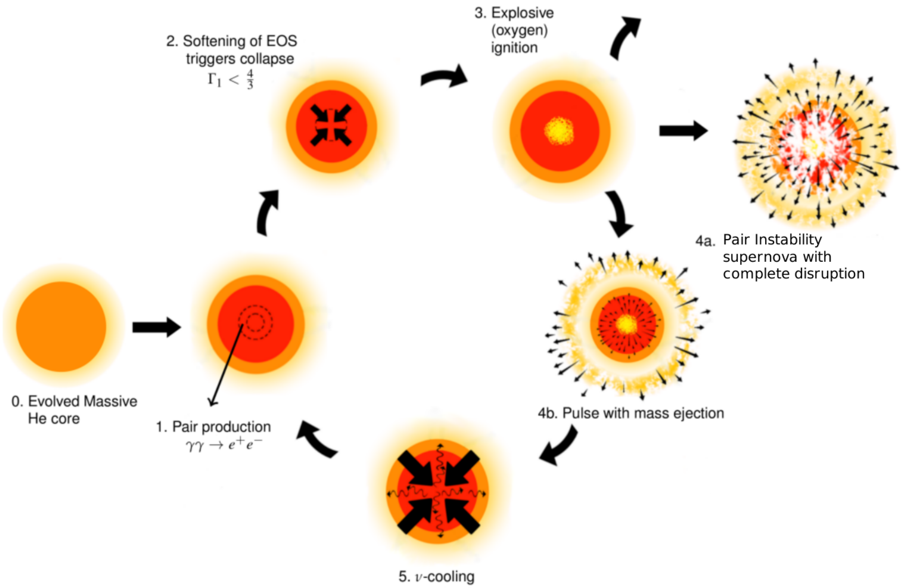
Renzo, Farmer *et al.* 2020b



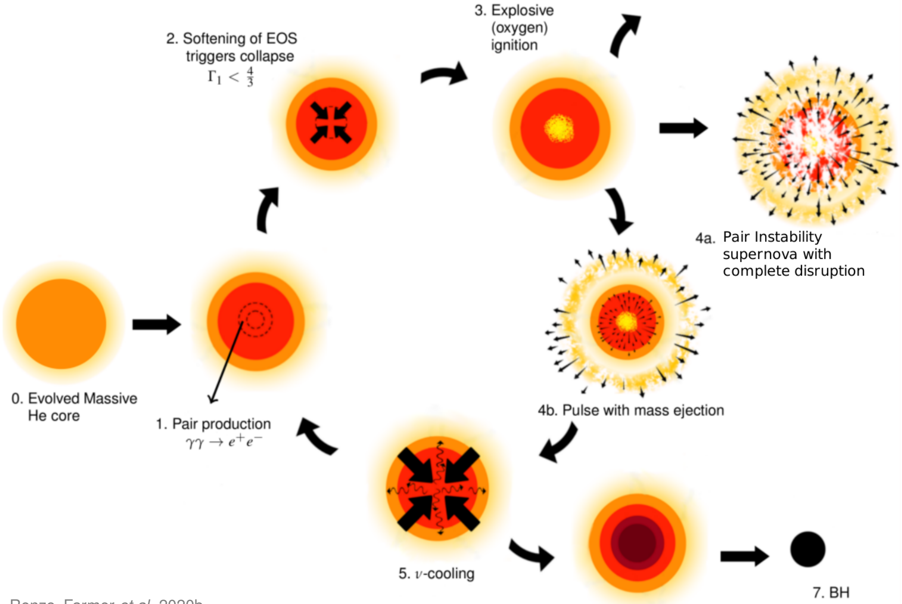
Renzo, Farmer *et al.* 2020b



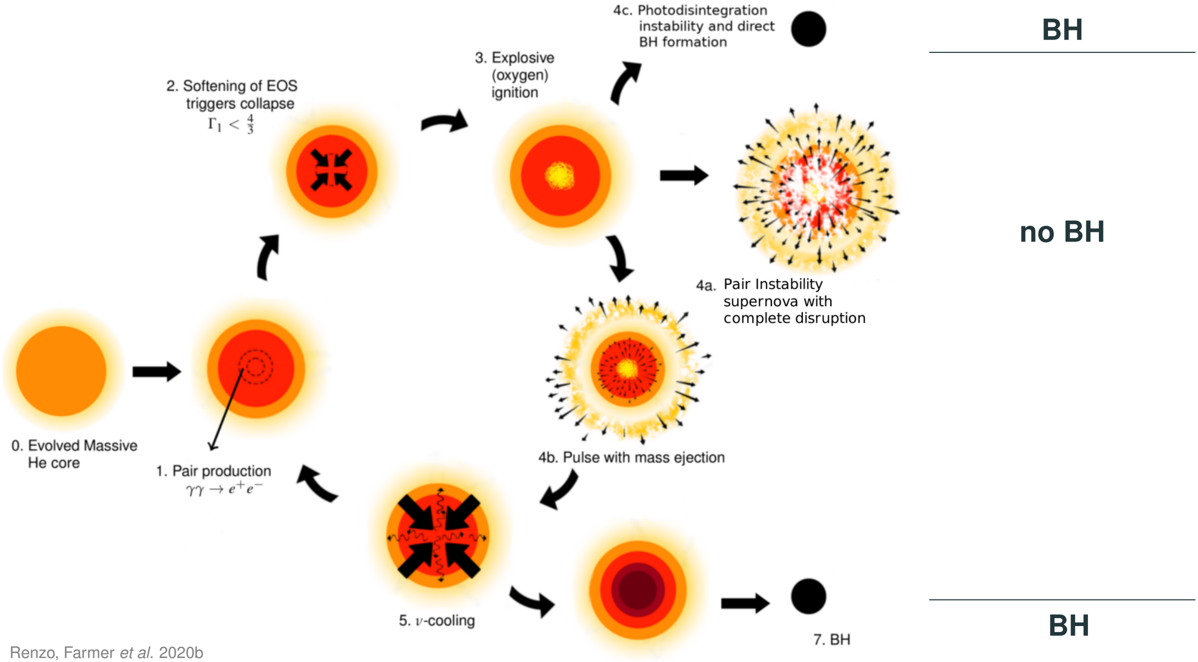
Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b

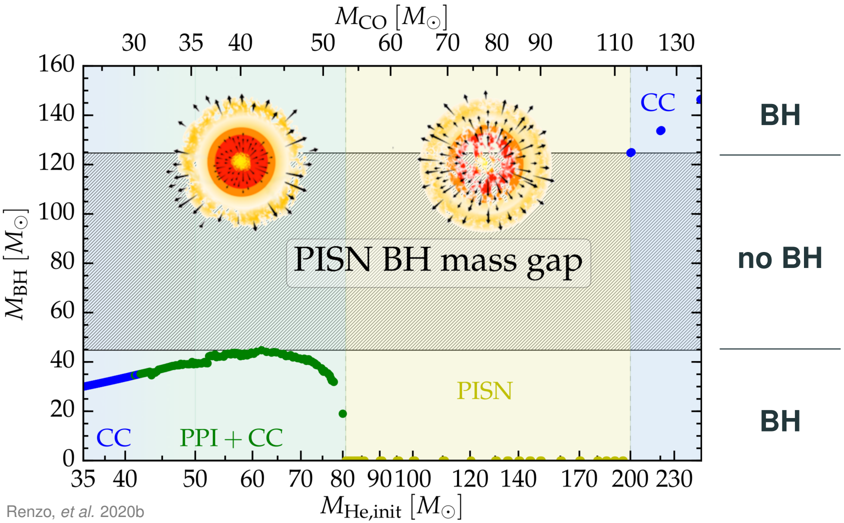


Renzo, Farmer *et al.* 2020b



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

(Pulsational) pair instability

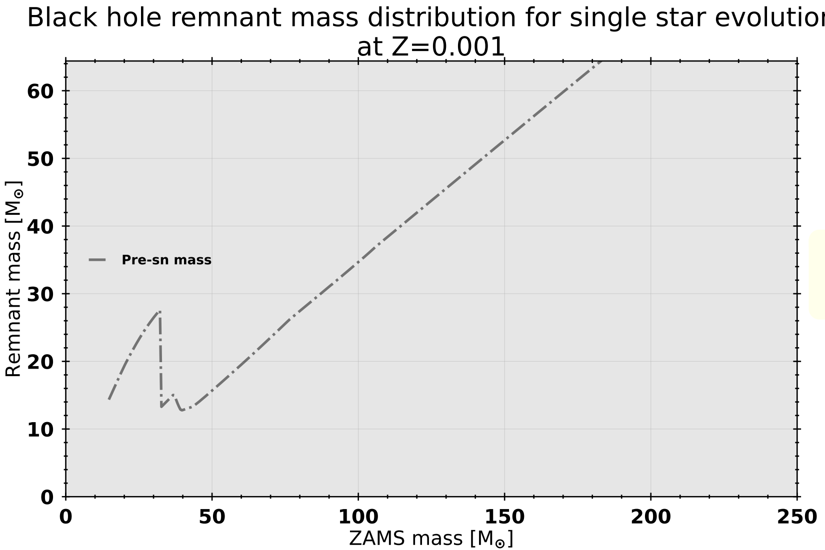
Maximum M_{BH} from single He cores

Implementation in pop. synth.

How robust are these predictions?

$M_{initial}$ → CO core mass† → BH mass

† and composition! (Patton & Sukhbold 2020)



"Initial mass"

David D. Hendriks

Univ. Surrey

Fryer *et al.* 2012

see also 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) 2021, Olejak *et al. 2022*, ...

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

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

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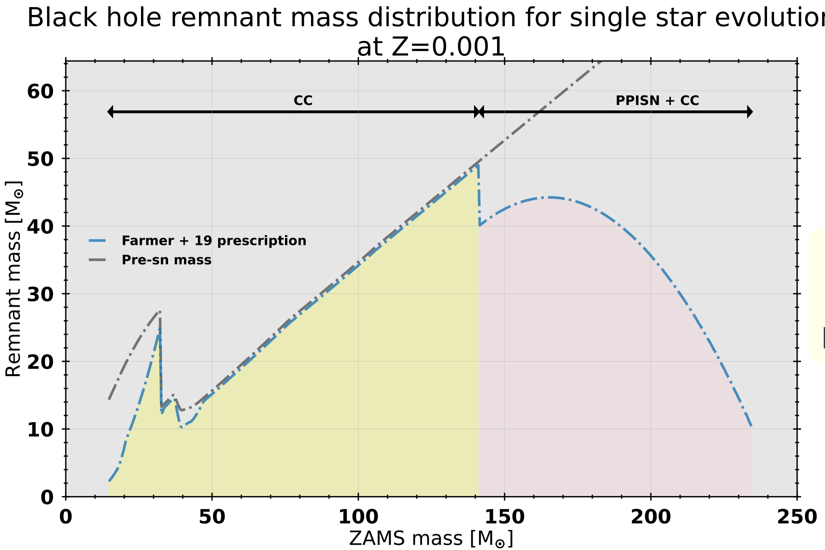

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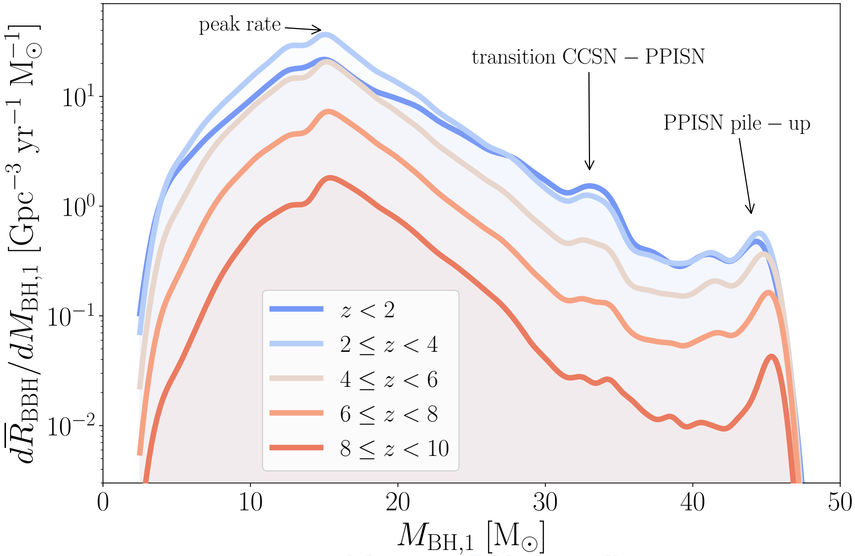
Hendriks, van Son, MR *et al.*, in prep.

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) 2021

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)

$$\Downarrow$$

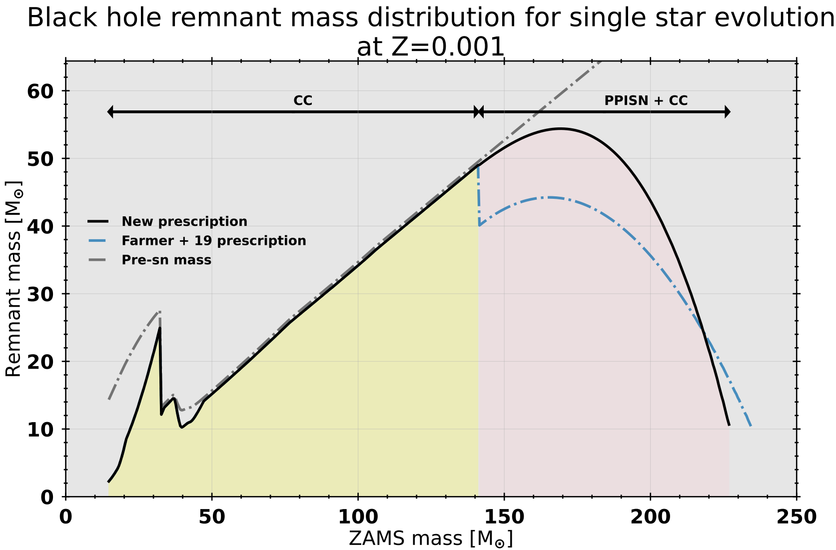
$$M_{\rm BH} = M_{\rm pre-explosion} - \left(\Delta M_{\rm SN} + \Delta M_{\nu,\rm core} + \Delta M_{\rm env} + \Delta M_{\rm PPI} + \cdots \right)$$

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)



"Initial mass"

David D. Hendriks
Univ. Surrey

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

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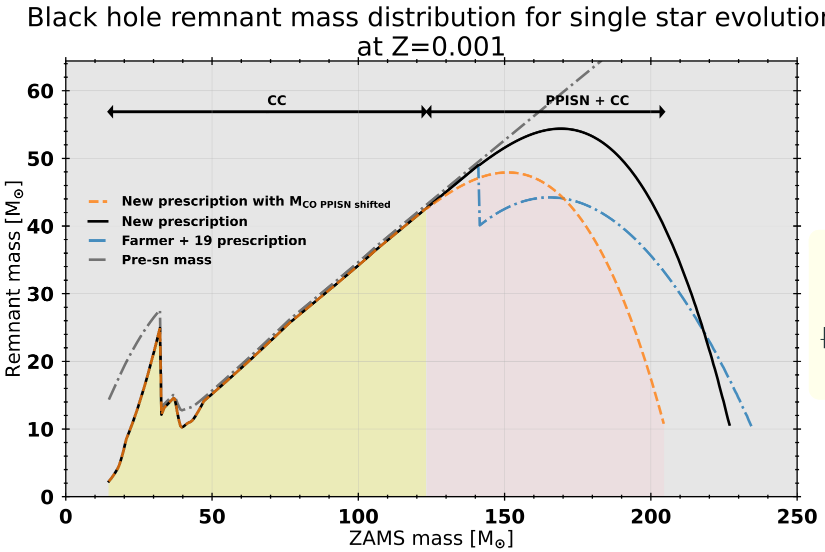


“Initial mass”

David D. Hendriks

Univ. Surrey

Fryer *et al.* 2012

+

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

Renzo *et al.* 2022

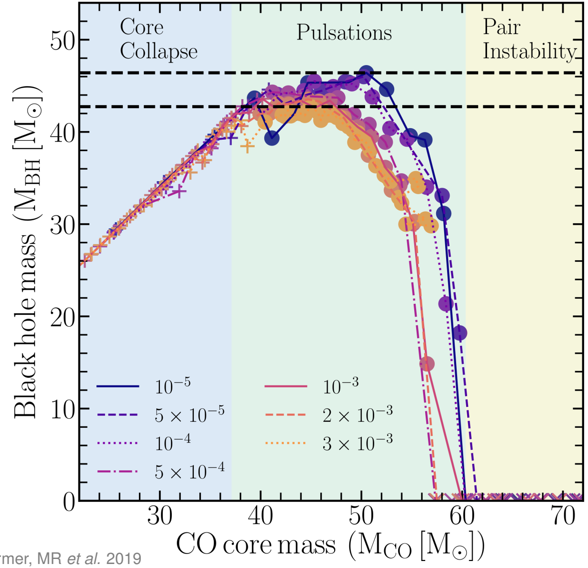
Hendriks, van Son, MR *et al.*, in prep.

(Pulsational) pair instability

- Maximum $M_{\rm BH}$ 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

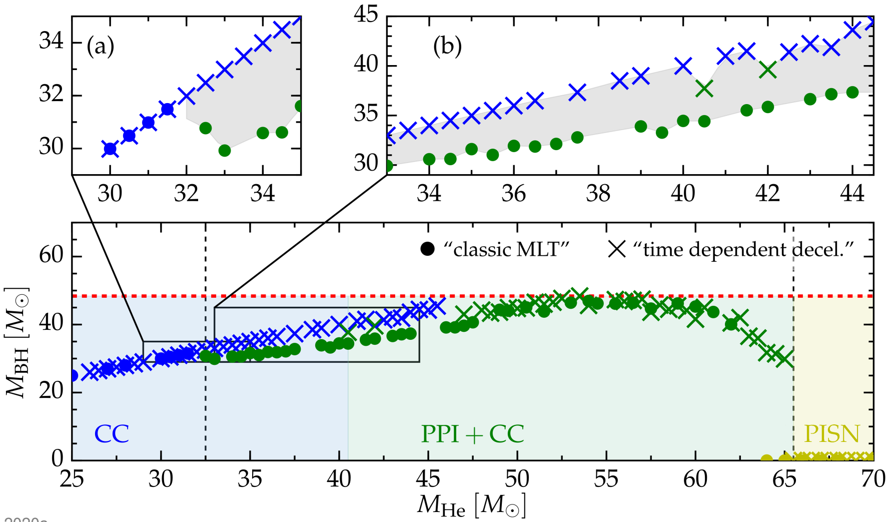
$\Delta\max\{M_{\rm BH}\}\sim$7%

over 2.5 orders of magnitude

Comparable or smaller effects: mixing, resolution, 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

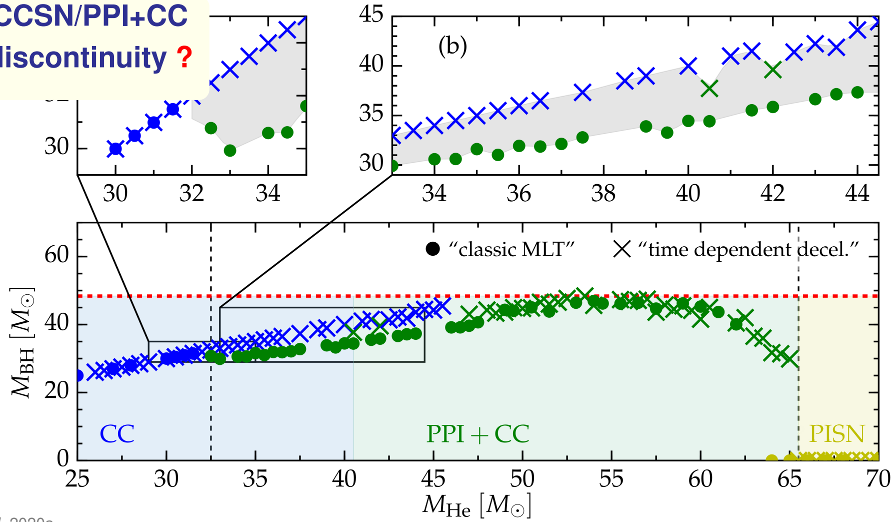


Renzo, Farmer *et al.* 2020a

Treatment of time-dependent convection? Not the edge

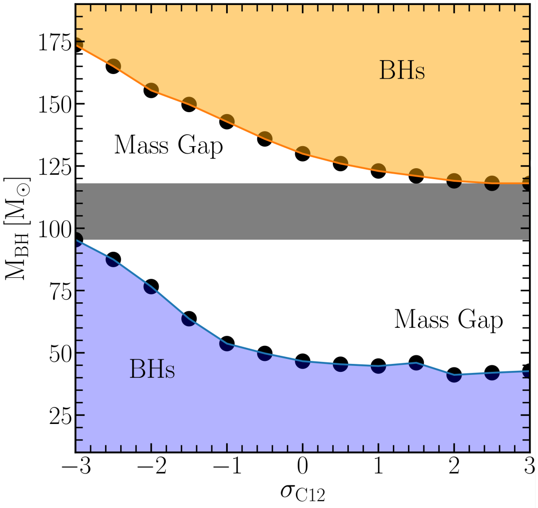
Matters for least massive PPI, not for the most massive BH progenitors

CCSN/PPI+CC discontinuity ?



Renzo, Farmer *et al.* 2020a

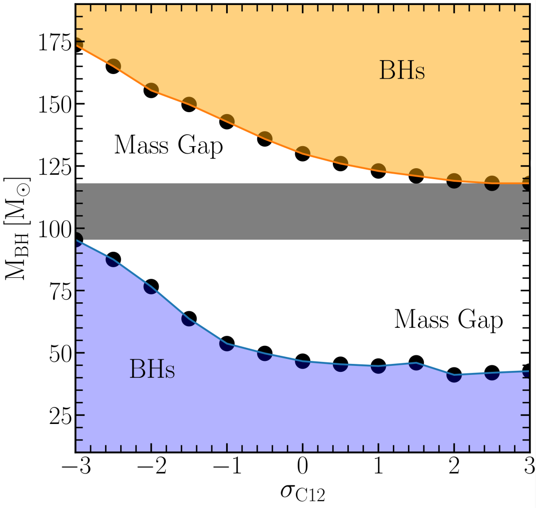
The only input physics that matters: $^{12}C(\alpha,\gamma)^{16}O$ reaction rate

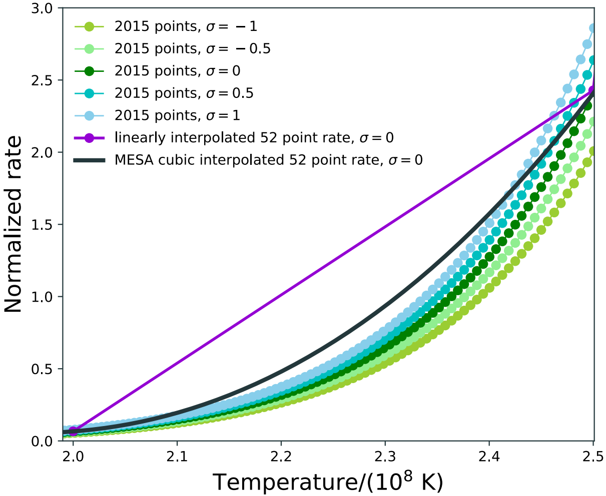


⇐ **lower** **Rate** **higher** ⇒

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

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





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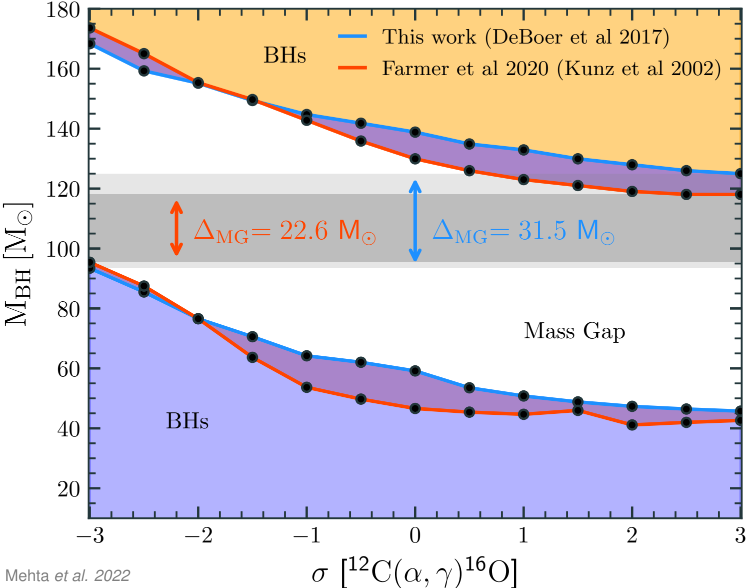
Mehta *et al. 2022*

BH mass gap with updated nuclear reactions



Mehta *et al.* 2022

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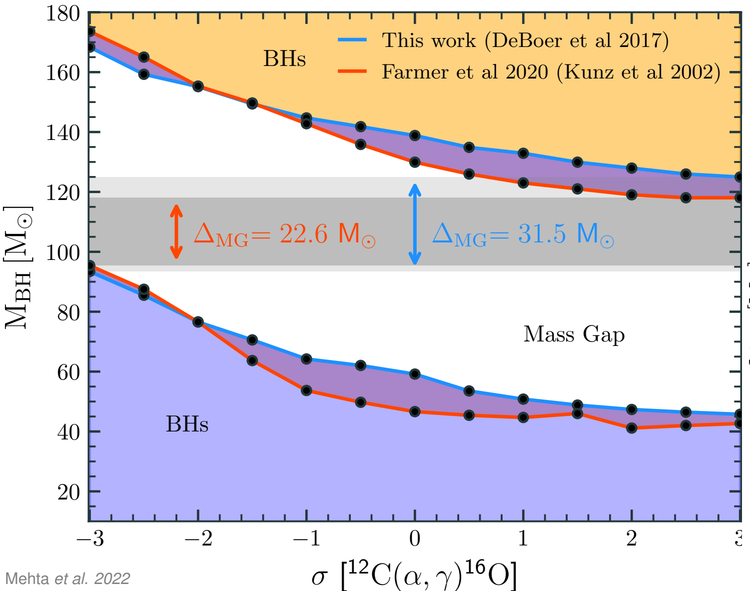
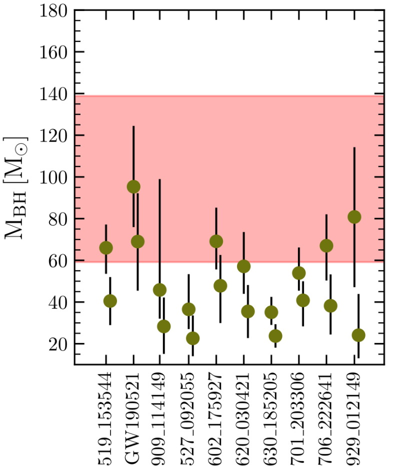




Mehta *et al. 2022*

Filling the PISN BH mass “gap”

More ideas than events

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, 20b, Renzo *et al.* 20c,

  Kremer *et al.* 20, Costa *et al.* 22, Ballone *et al.* 22

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

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

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

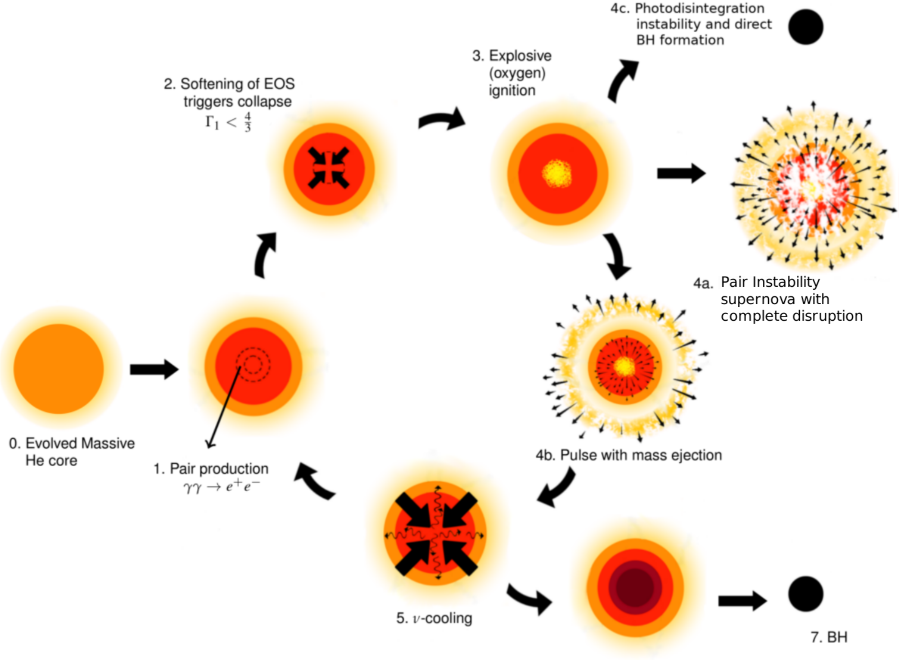
"Impostor" GW events: High eccentricity merger? Lensing?

Filling the PISN BH mass “gap”

More ideas than events

Filling the gap “from above”

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



4c. Photodisintegration instability and direct BH formation
3. Explosive (oxygen) ignition
2. Softening of EOS triggers collapse
$\Gamma_1 < \frac{4}{3}$
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

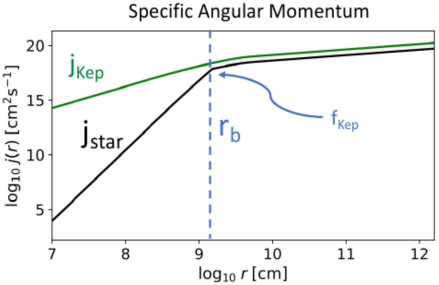
no BH

BH

Extrapolation of long-GRB models to progenitors above the gap

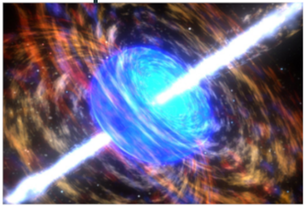
above the gap
(with no rotation)

+



=

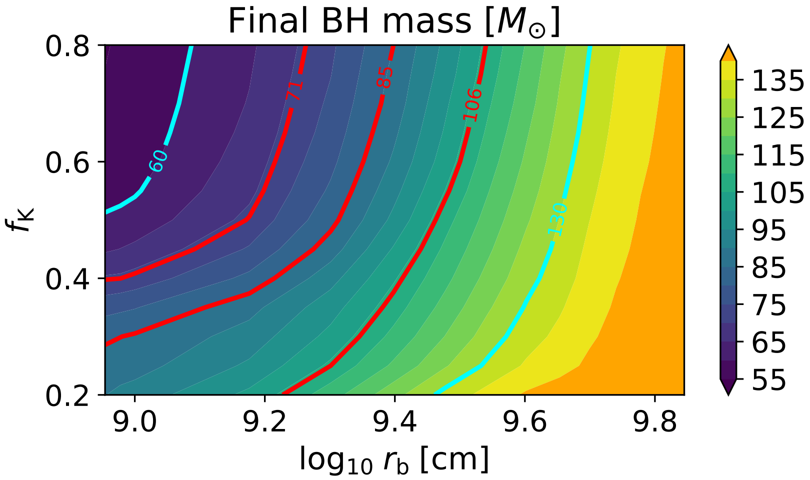
"super-kilonova"



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

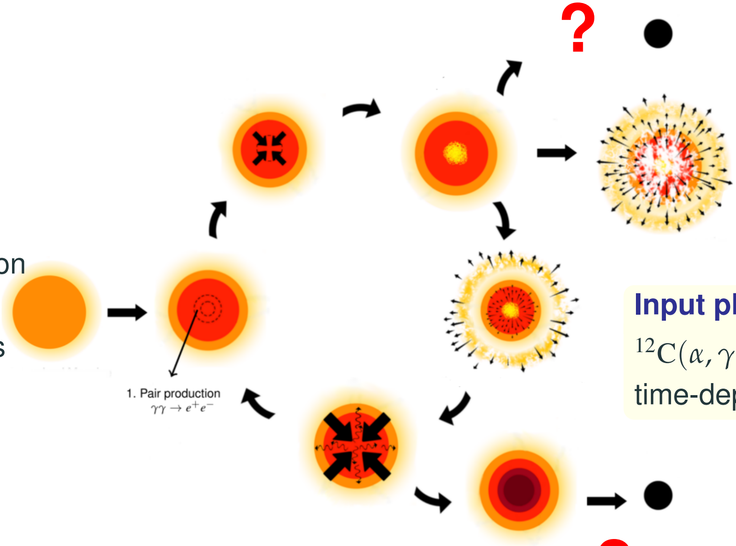
Siegel *et al.* (incl. MR), 2021

Conclusions

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

Progenitor evolution
& pre-PPISN
binary interactions

?



Input physics:

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

time-dependent conv. ?

Final BH formation & fate of H-rich envelope ?

Filling the PISN BH mass gap

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Farmer *et al.* 20, Belczynski 20, Costa *et al.* 21

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Avoid pair-instability

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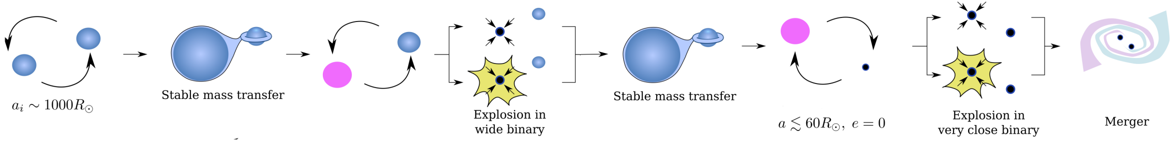
"Impostor" GW events: High eccentricity merger? Lensing?

Backup slides

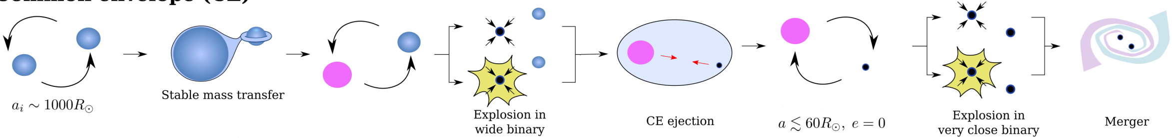
Isolated binary evolution removes the H-envelope anyways

Stable mass transfer (RLOF)

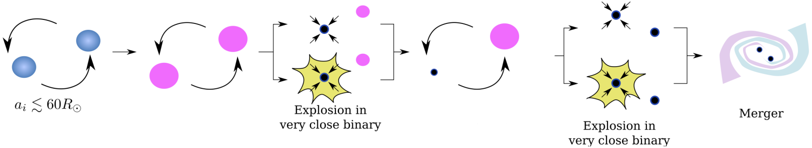


e.g., Klencki *et al.* 2021, van Son *et al.* (incl. MR) 2021, Marchant *et al.* 2021, Gallegos-Garcia *et al.* 2022

Common envelope (CE)



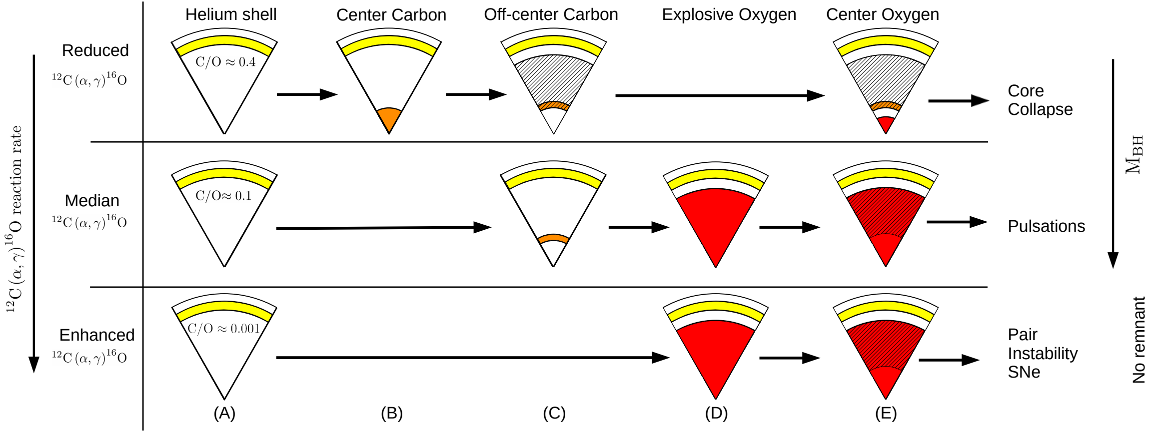
Chemically homogeneous evolution (CHE)



Marchant, MR *et al.* 2019

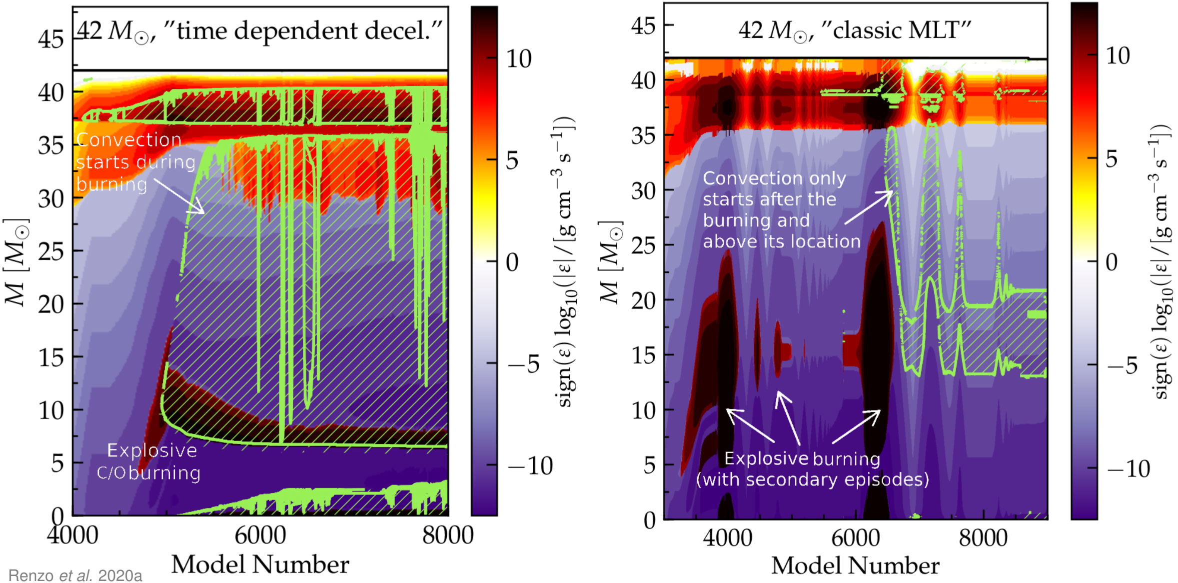
The $^{12}C(\alpha,\gamma)^{16}O$ ends He core burning

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



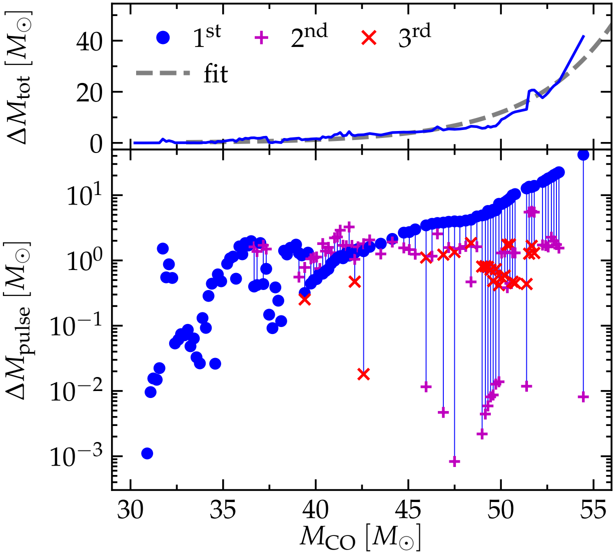
Farmer, Renzo *et al.* 2020

Convection during the pulses quenches the PPI mass loss



Renzo *et al.* 2020a

Amount of mass lost per pulse



Larger cores

⇓

More energetic pulses

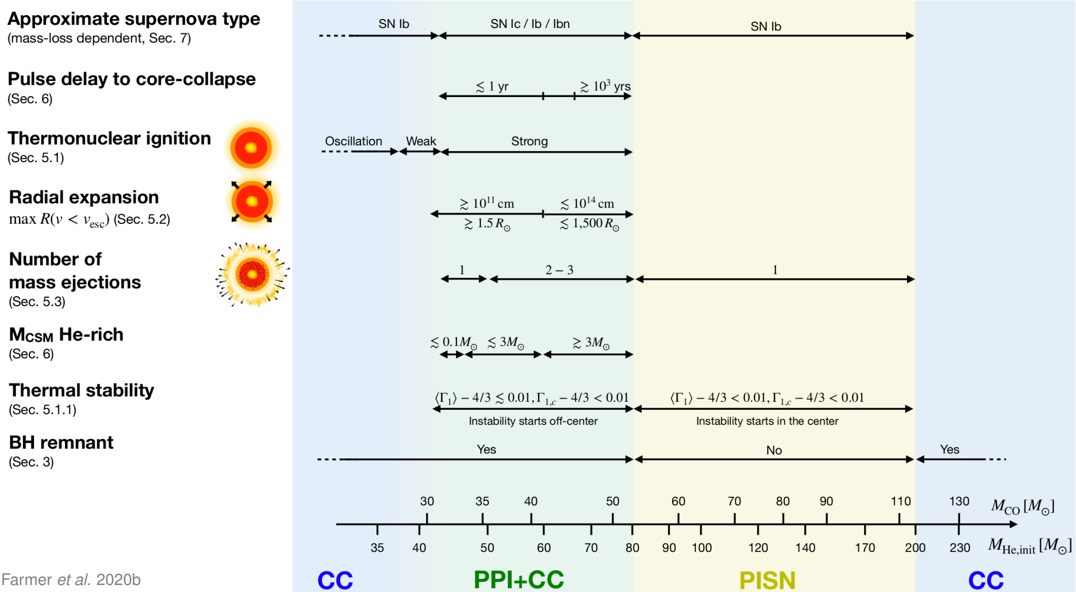
⇓

More mass loss

(and longer delays)

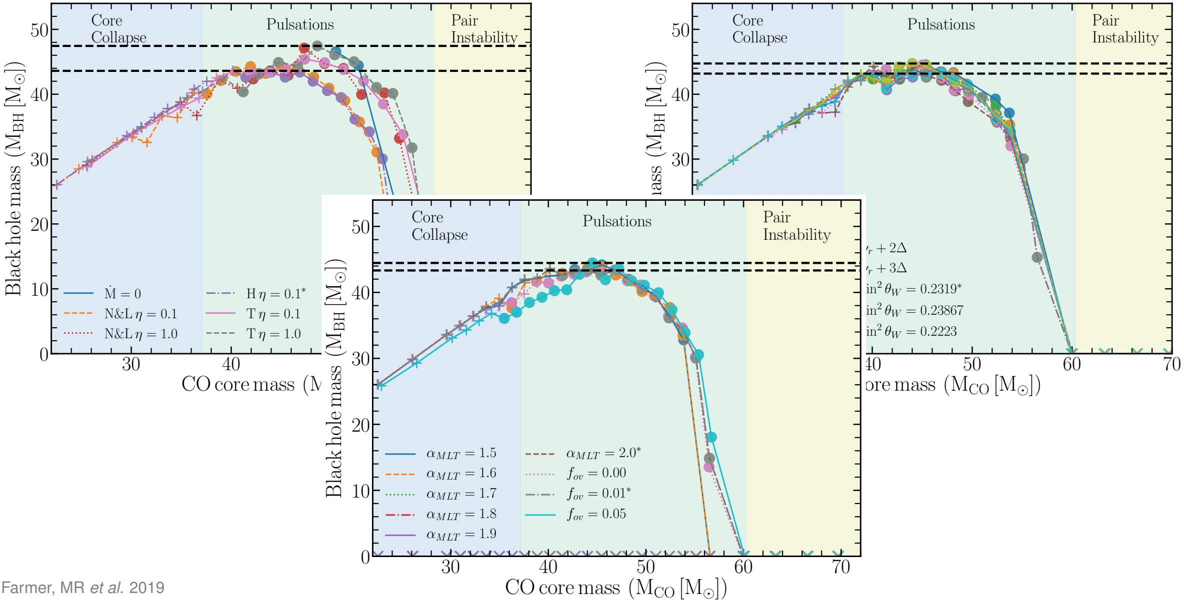
Renzo, Farmer *et al.* 2020b

Summary of EM transients



Renzo, Farmer *et al.* 2020b

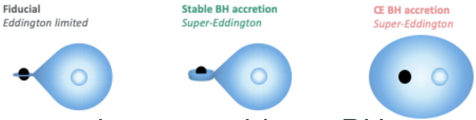
Winds, mixing, ν physics? Also small effects



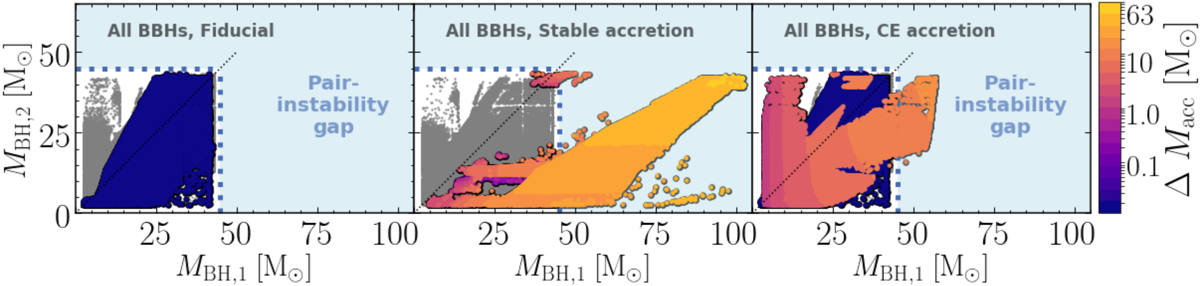
Farmer, MR *et al.* 2019

Can isolated binary evolution “pollute” the gap?

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



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



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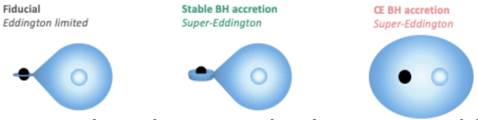
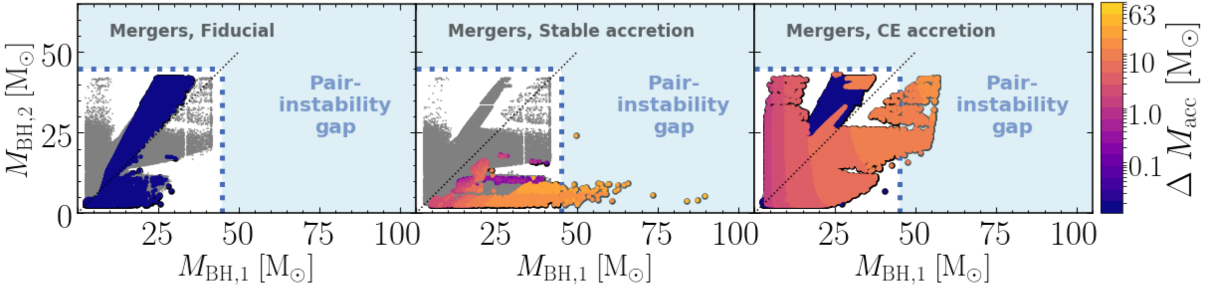


... but those entering the gap don't merge within 13.7 Gyr



Mass accretion leads to orbital widening

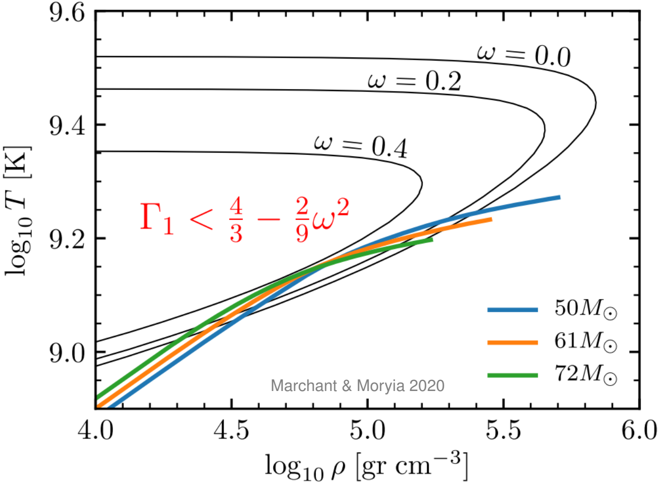
even with the most optimistic assumptions:

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

Can rotation move the gap? Barely...

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

Chatzopoulos *et al.* 2012, 2013



Rotation stabilizes only for *very* extreme assumption:

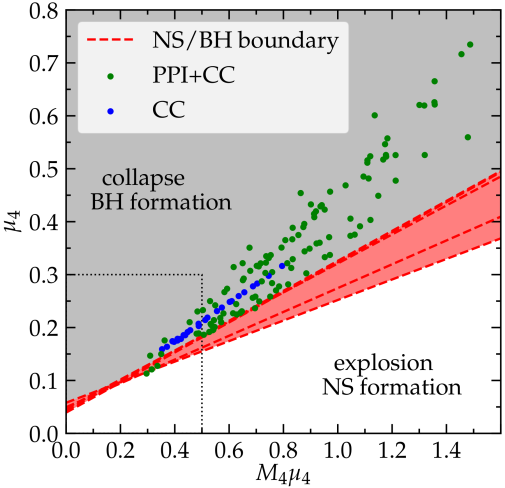
- No core-envelope coupling
- large initial rotation
- low Z ($\simeq$ no winds)

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

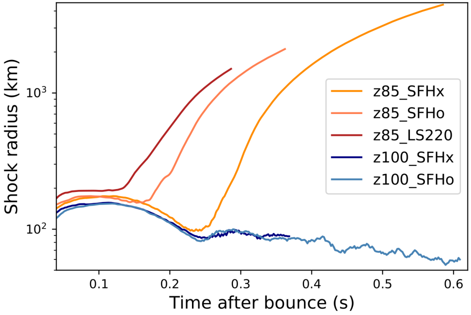
see also Glatzel *et al.* 1985

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

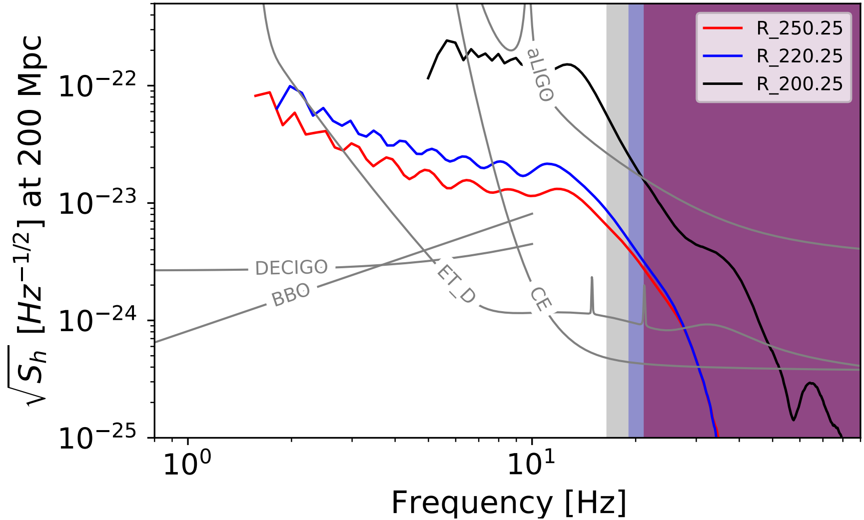
$$\max \Delta M_{CC} \lesssim 3.5\, M_\odot$$

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

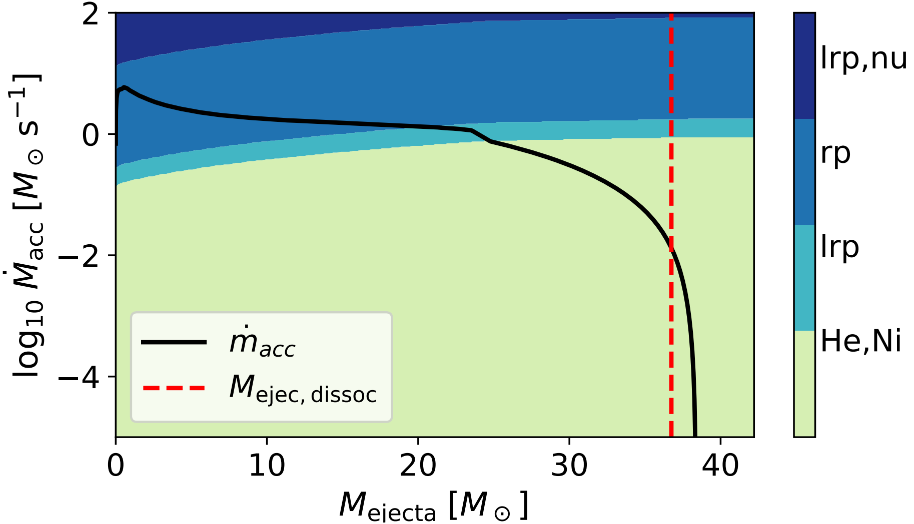
Gravitational waves from super-kilonova



"sad trombone"
ν decreases
as BH and its ISCO
grow

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

Disk self-neutronization allows for r-process nucleosynthesis



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