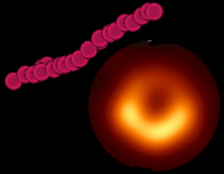
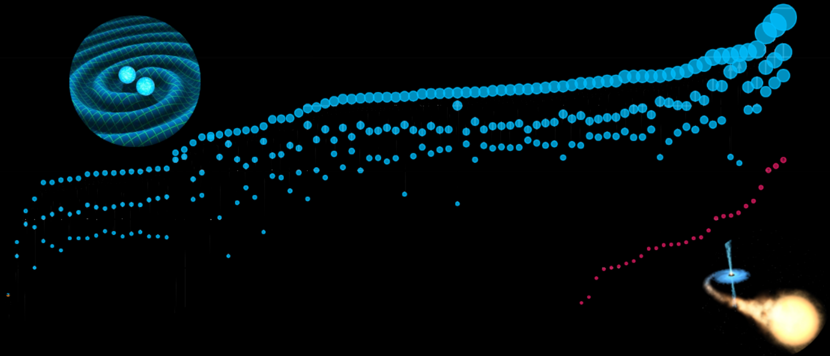
Big Black Holes: from stars to super-massive seeds

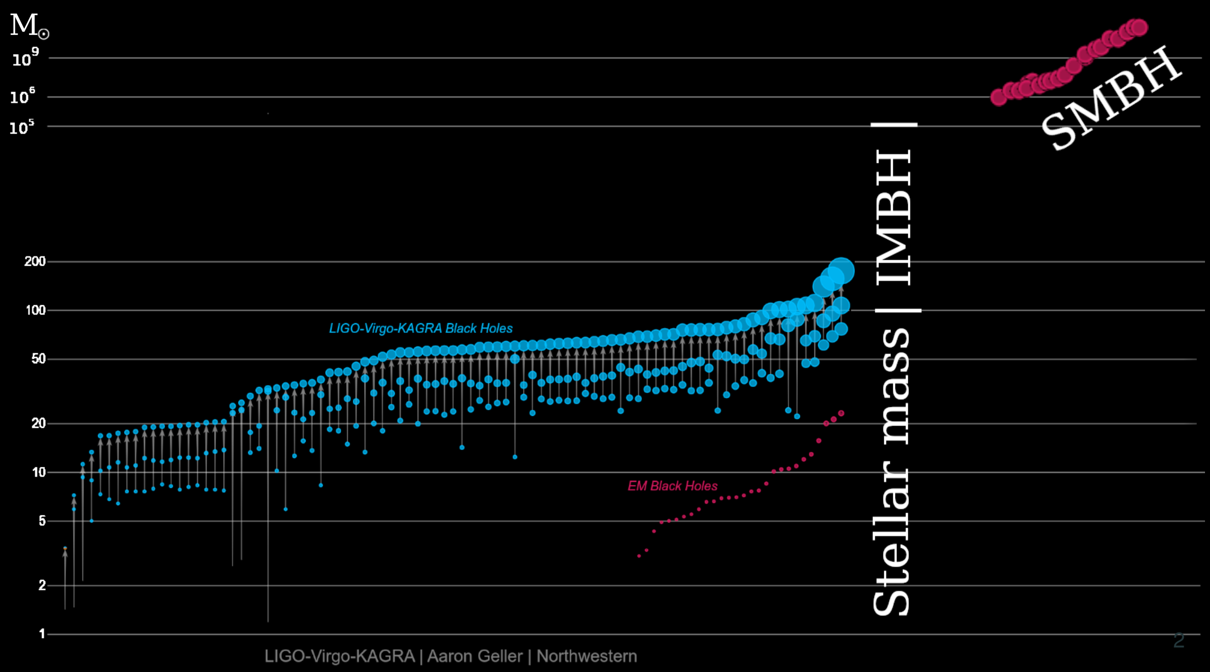


Mathieu Renzo

FLATIRON INSTITUTE
Center for Computational Astrophysics



Collaborators: **L. van Son**, **D. D. Hendriks**, **E. Farag**, R. Farmer, Y. Götberg, E. Zapartas, S. Ford, B. D. Metzger, M. Cantiello, S. Justham, S. E. de Mink, W. M. Farr, P. Marchant, N. Smith, J. Bellovary



M⊙
10^9
10^6
10^5
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA Black Holes
EM Black Holes
Stellar mass | IMBH |
SMBH
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Maximum mass of stellar BHs

(Pulsational) pair-instability evolution

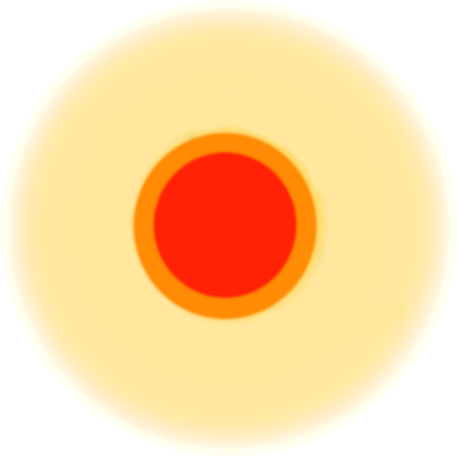
Implementation in pop. synth.

How robust are these predictions?

Filling the gap “from above”

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

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

Renzo, Farmer *et al.* 2020b

Radiation pressure dominated:

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

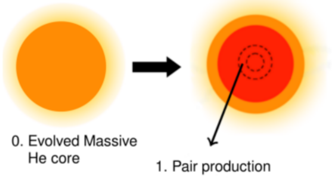
$$M_{\rm He} \gtrsim 32\, M_{\odot}$$

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

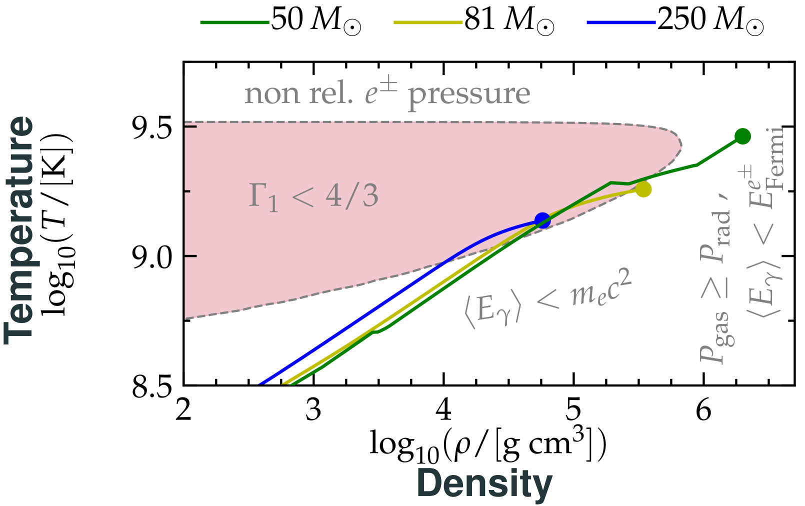
Glatzel *et al.* 1985, **Woosley** *et al.* 2002, 2007, Langer *et al.* 2007, Chatzopoulos *et al.* 2012, 2013, Yoshida *et al.* 2016,

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

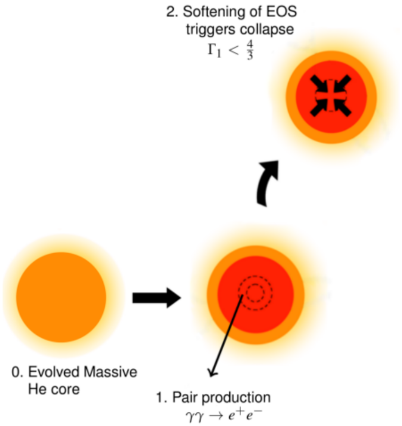
Renzo *et al.* 2020a,b, Croon *et al.* 2020a,b, Sakstein *et al.* 2020, 2022, Costa *et al.* 2021, Woosley & Heger 2021, etc...



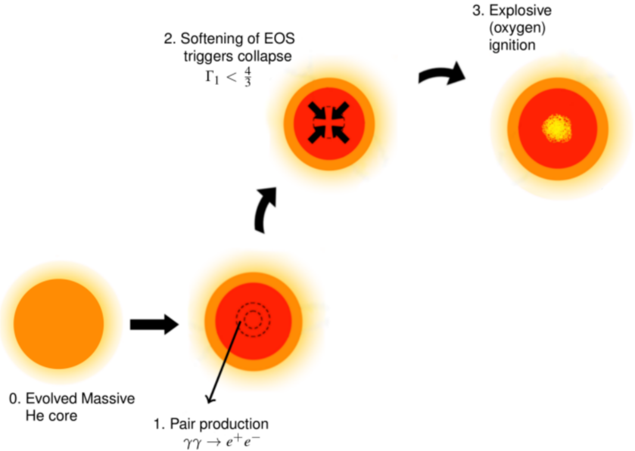
$$\gamma\,\gamma \rightarrow e^+\,e^-$$



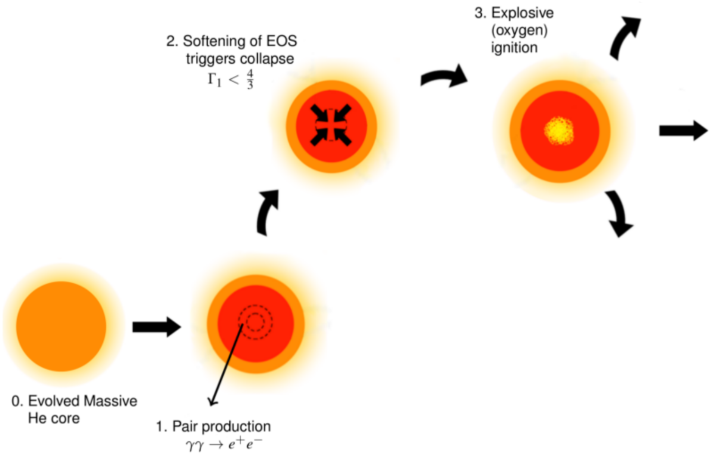
Renzo, Farmer *et al.* 2020b



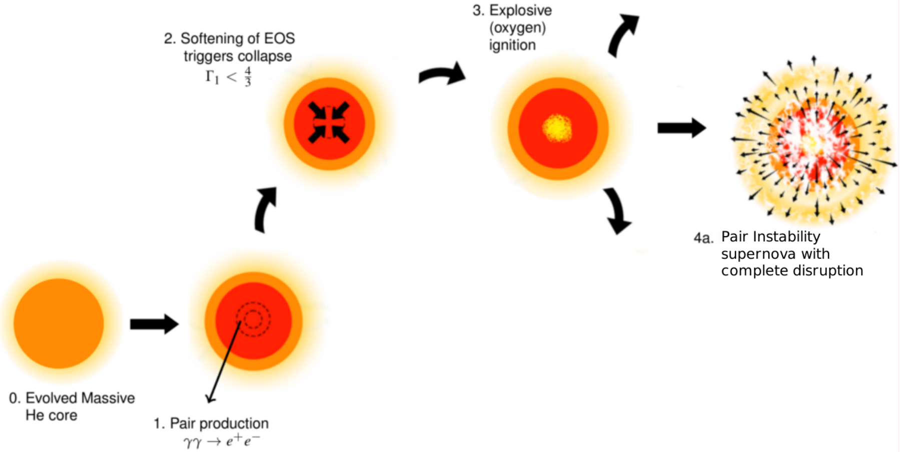
Renzo, Farmer *et al.* 2020b



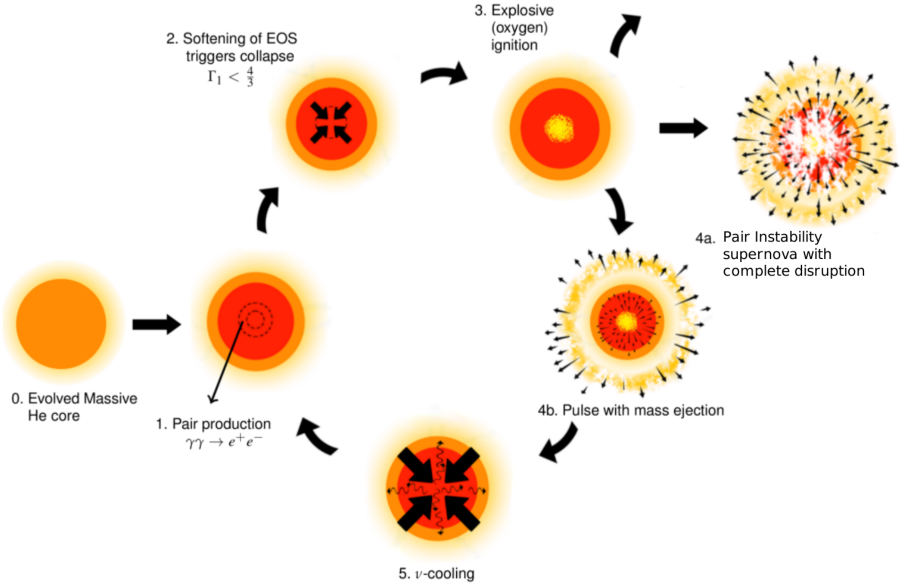
Renzo, Farmer *et al.* 2020b



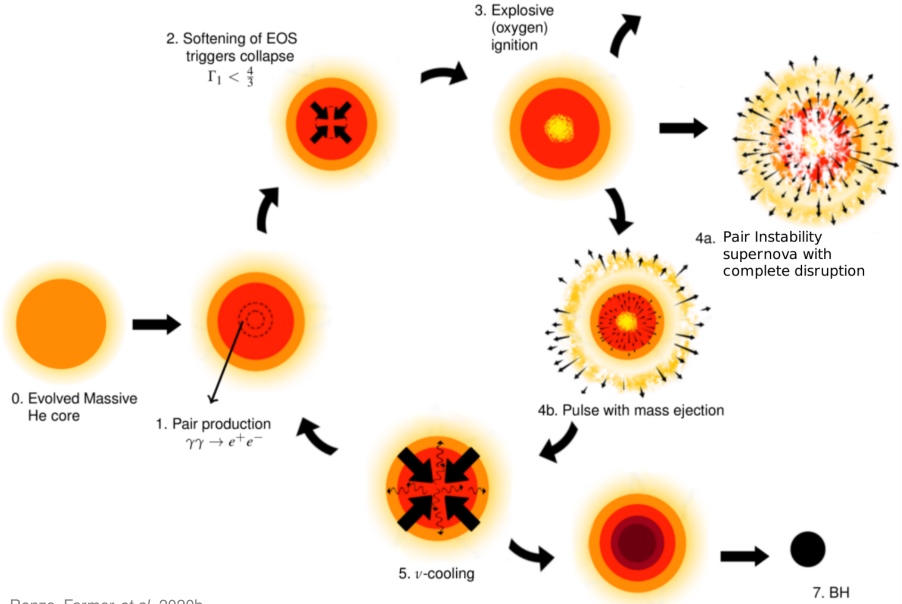
Renzo, Farmer *et al.* 2020b



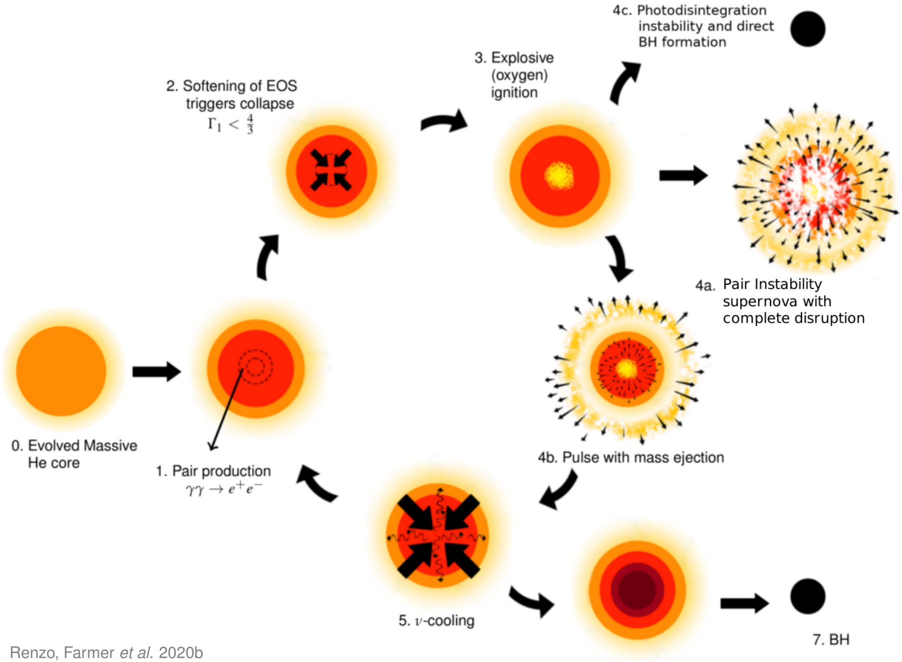
Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b



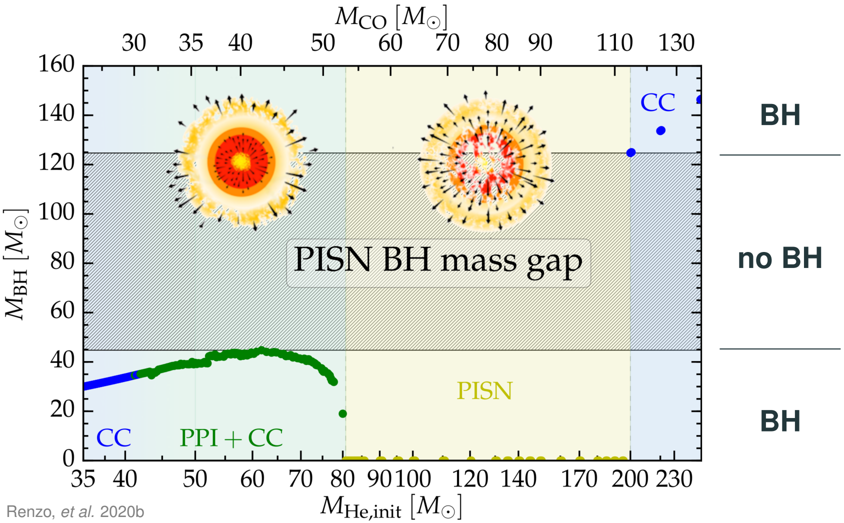
BH

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

Maximum mass of stellar BHs

(Pulsational) pair-instability evolution

Implementation in pop. synth.

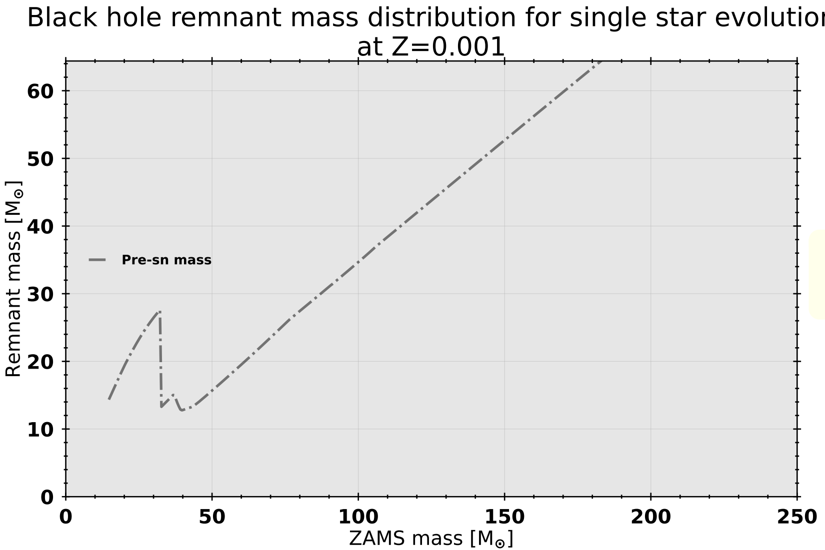
How robust are these predictions?

Filling the gap "from above"

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

$M_{\text{initial}} \rightarrow$ 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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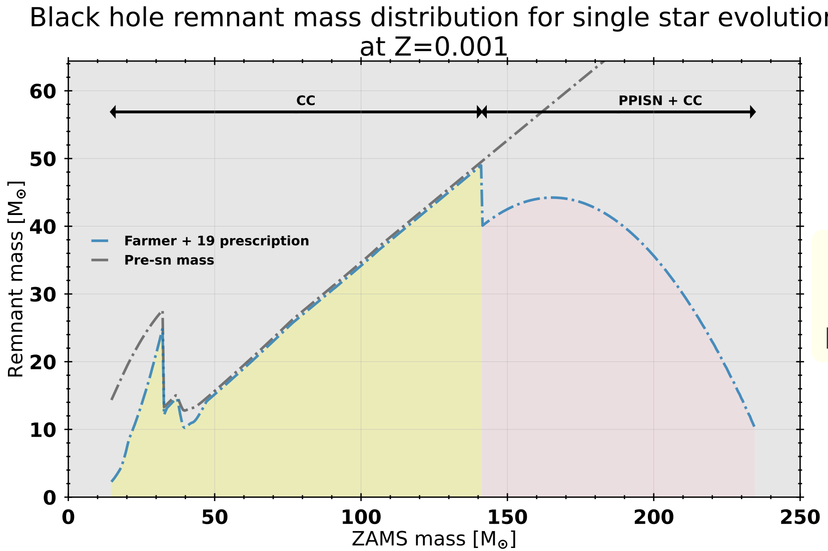


"Initial mass"

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

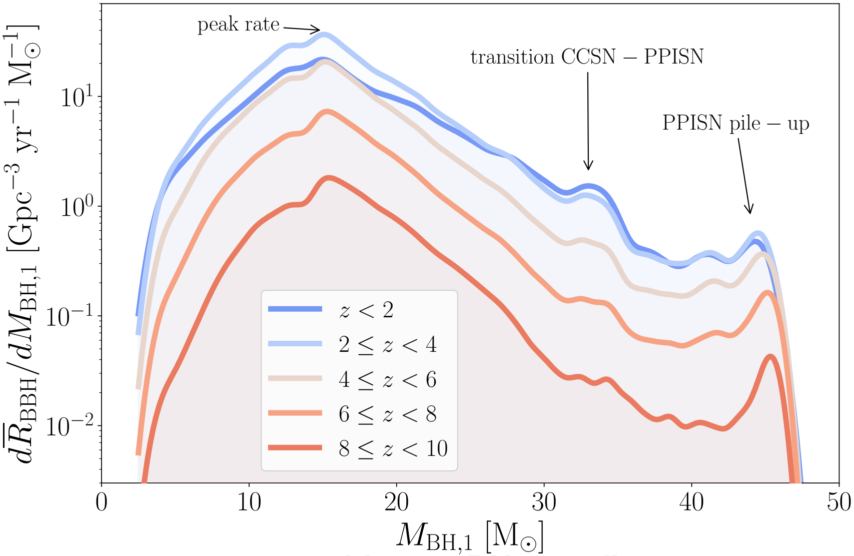
Fryer *et al.* 2012
+
Farmer, MR *et al.* 2019

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

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

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)

$$\Downarrow$$

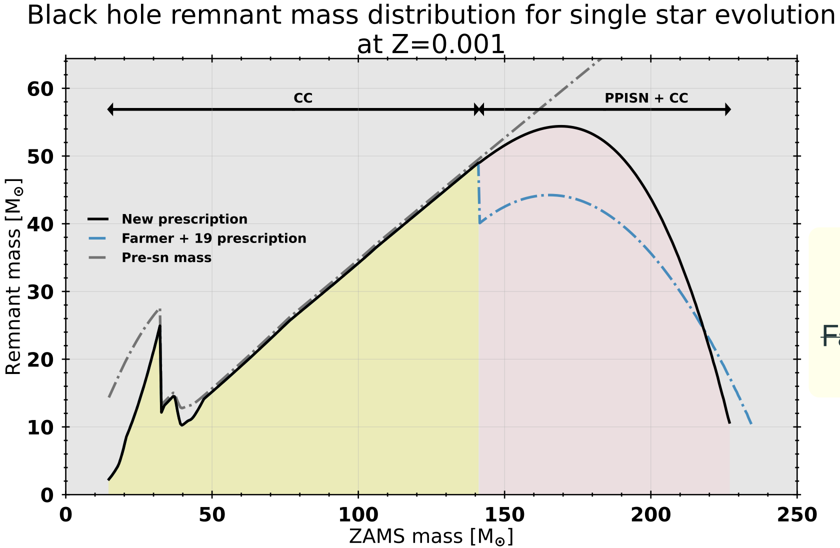
$$M_{\mathrm{BH}} = M_{\mathrm{pre-explosion}} - \left(\Delta M_{\mathrm{SN}} + \Delta M_{\nu,\mathrm{core}} + \Delta M_{\mathrm{env}} + \Delta M_{\mathrm{PPI}} + \cdots\right)$$

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

Renzo *et al.* 2022, RNAAS

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

† and composition! (Patton & Sukhbold 2020)



"Initial mass"

David D. Hendriks

Univ. Surrey

Fryer *et al.* 2012

+

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

Renzo *et al.* 2022

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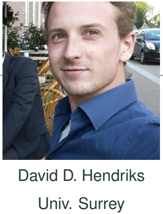
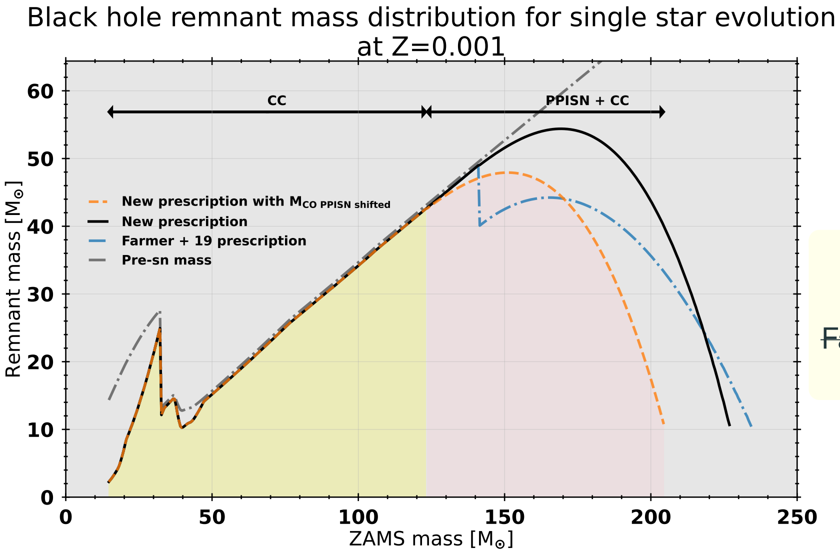




"Initial mass"

Fryer *et al.* 2012

\+

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

Renzo *et al.* 2022

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

Maximum mass of stellar BHs

(Pulsational) pair-instability evolution

Implementation in pop. synth.

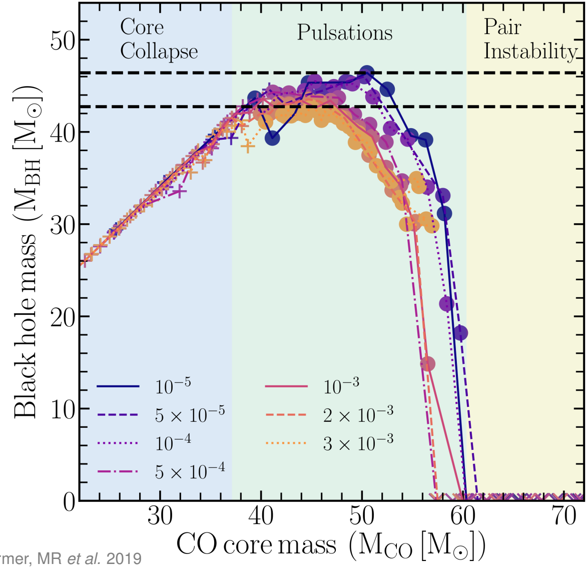
How robust are these predictions?

Filling the gap “from above”

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

Metallicity? Small effect

Focus on lower edge of the gap



Metallicity shift

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

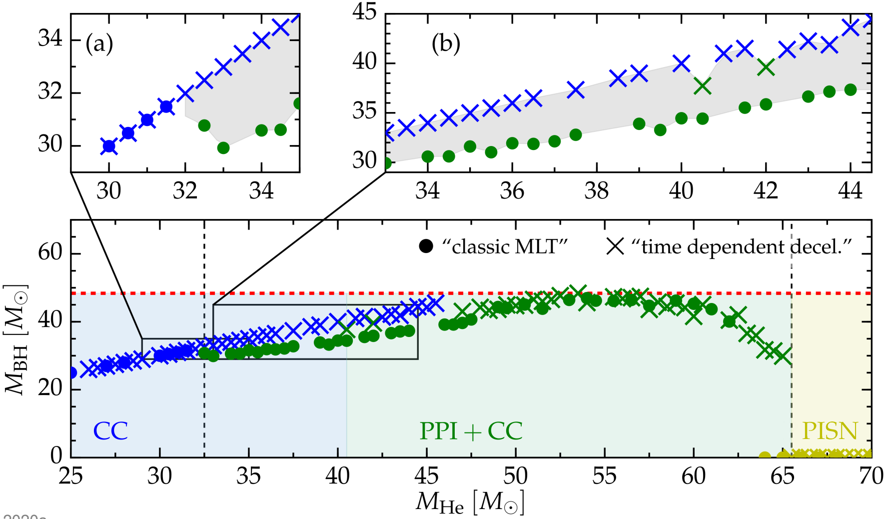
over 2.5 orders of magnitude

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

Farmer, MR *et al.* 2019

Treatment of time-dependent convection? Not the edge

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

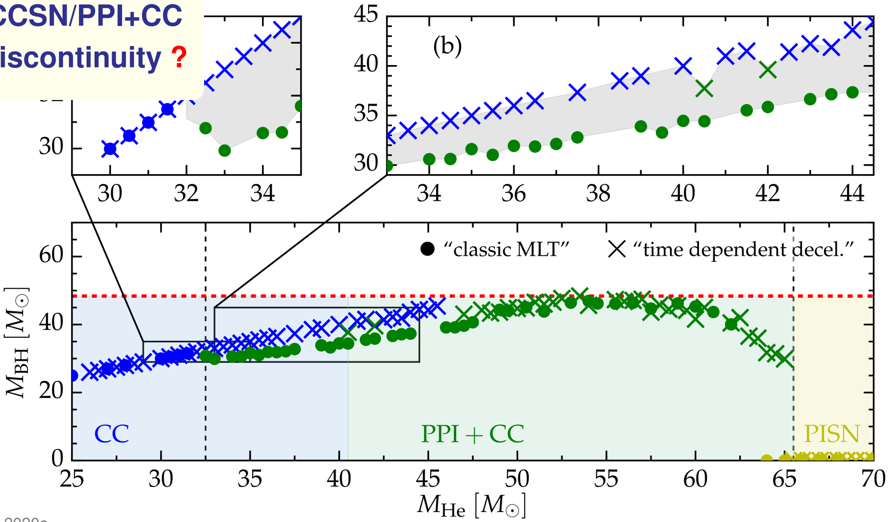


Renzo, Farmer *et al.* 2020a

Treatment of time-dependent convection? Not the edge

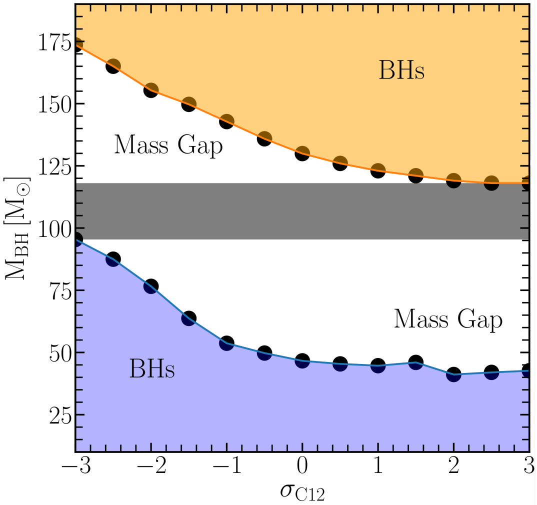
Matters for least massive PPI, not for the most massive BH progenitors

CCSN/PPI+CC discontinuity ?



Renzo, Farmer *et al.* 2020a

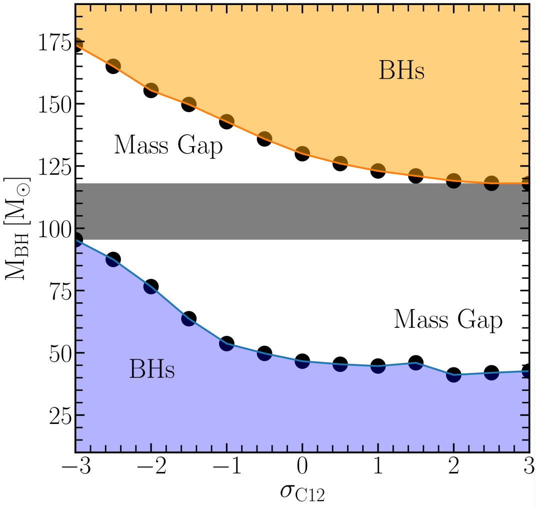
The input physics that matters: $^{12}C(\alpha,\gamma)^{16}O$ reaction rate

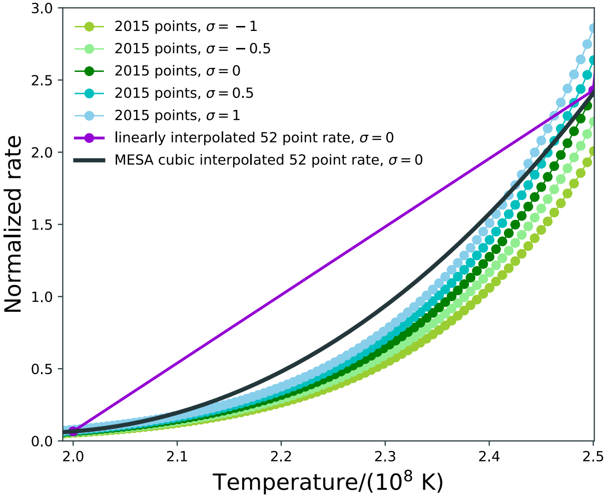


⇐ **lower** **Rate** **higher** ⇒

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



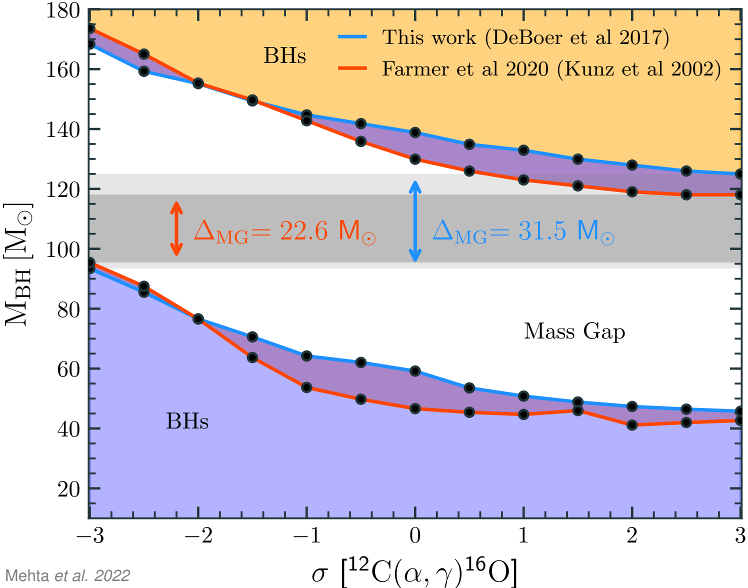


⇐ **lower** **Rate** **higher** ⇒

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

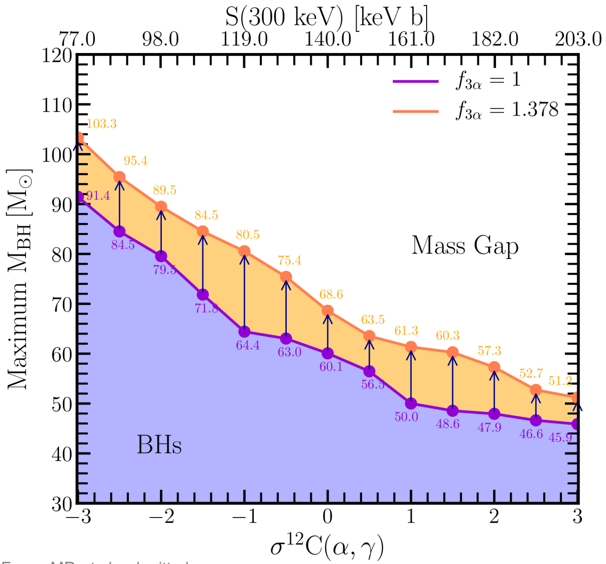
Mehta *et al. 2022*

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.

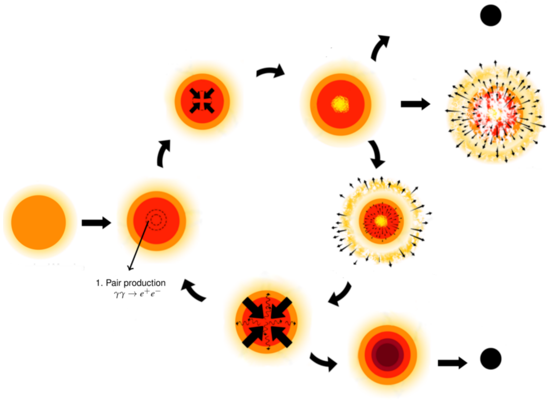
New lower edge of the gap:

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

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: $139^{+30}_{-14}\,M_\odot$



What is the fate of the H-rich envelope at BH formation?

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

Possible causes for mass ejection:

- ν-driven shocks

  Nadhezin 80, Lovegrove & Woosley 13, Piro 13, Fernandez *et al.* 18, Ivanov & Fernandez 21

- Jets (even without net rotation)

  Gilkis & Soker 2014, Perna *et al.* 18, Quataert *et al.* 19, Antoni & Quataert 22

- weak fallback powered explosion

  Ott *et al.* 18, Kuroda *et al.* 18, Chan *et al.* 20, 21

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

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Different predicted outcomes for RSG/BSG

$\Rightarrow$ Z-dependence

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

Maximum mass of stellar BHs

(Pulsational) pair-instability evolution
Implementation in pop. synth.
How robust are these predictions?
Filling the gap "from above"

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

Filling the PISN BH mass gap: more ideas than events

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:

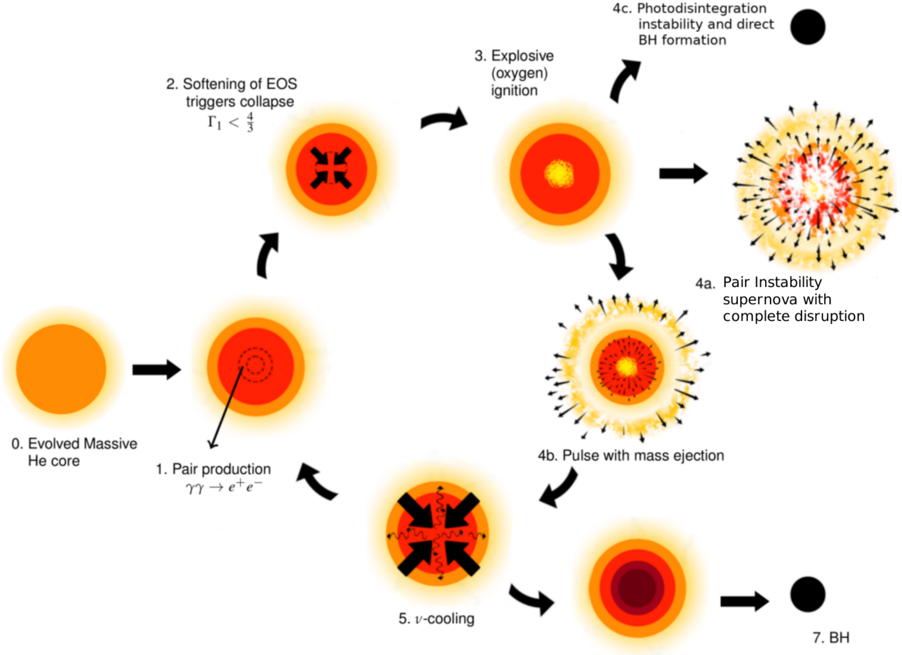
- in proto-cluster Roupas & Kazanas 2019a,b
- PBHs before re-ionization de Luca *et al.* 2020
- in isolated binary van Son *et al.* (incl. MR) 2020
- in halos Safarzadeh & Haiman 20

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?


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

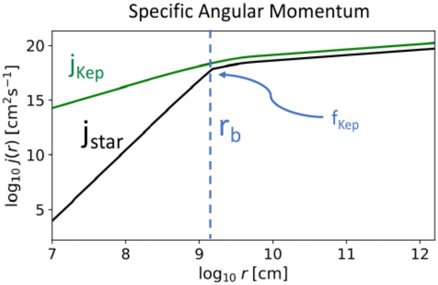
no BH

BH

Extrapolation of long-GRB models to progenitors above the gap

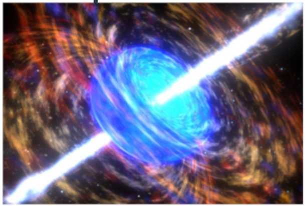
above the gap
(with no rotation)

+



=

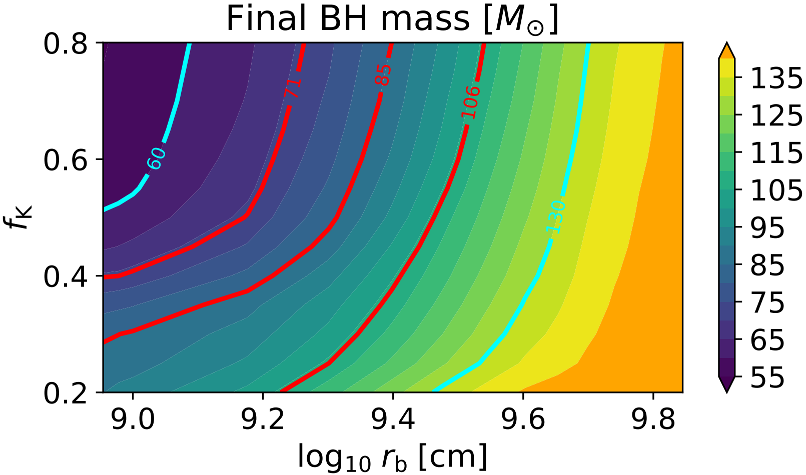
"super-kilonova"



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

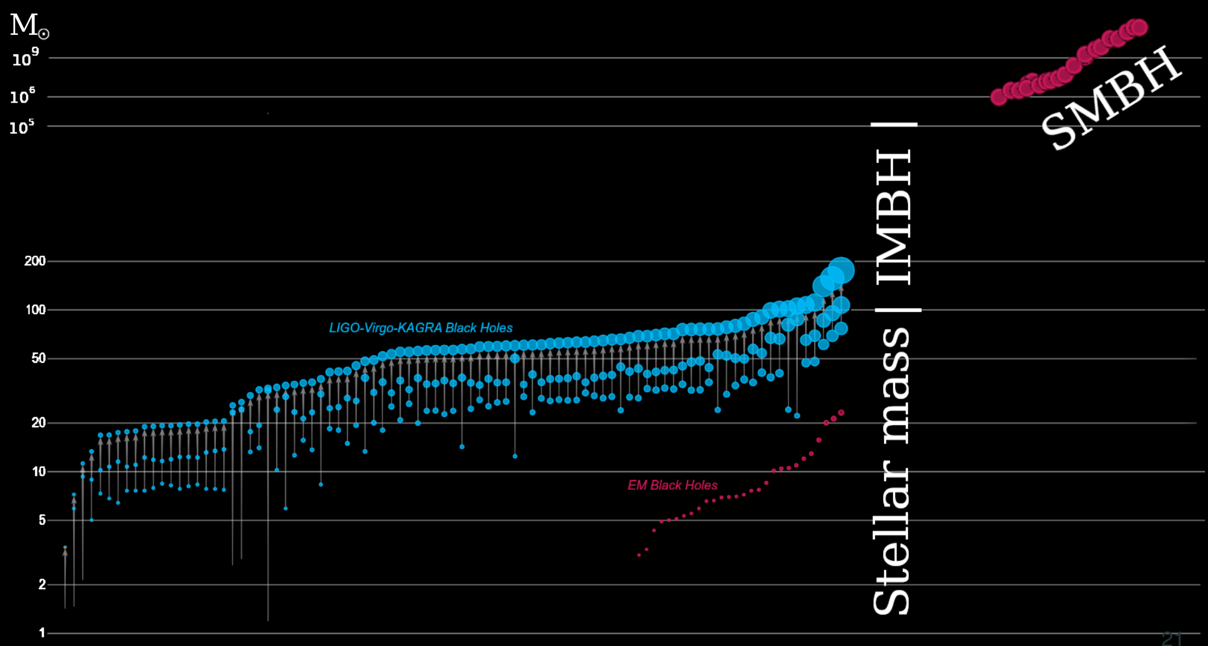
Siegel *et al.* (incl. MR), 2021

Observing IMBH

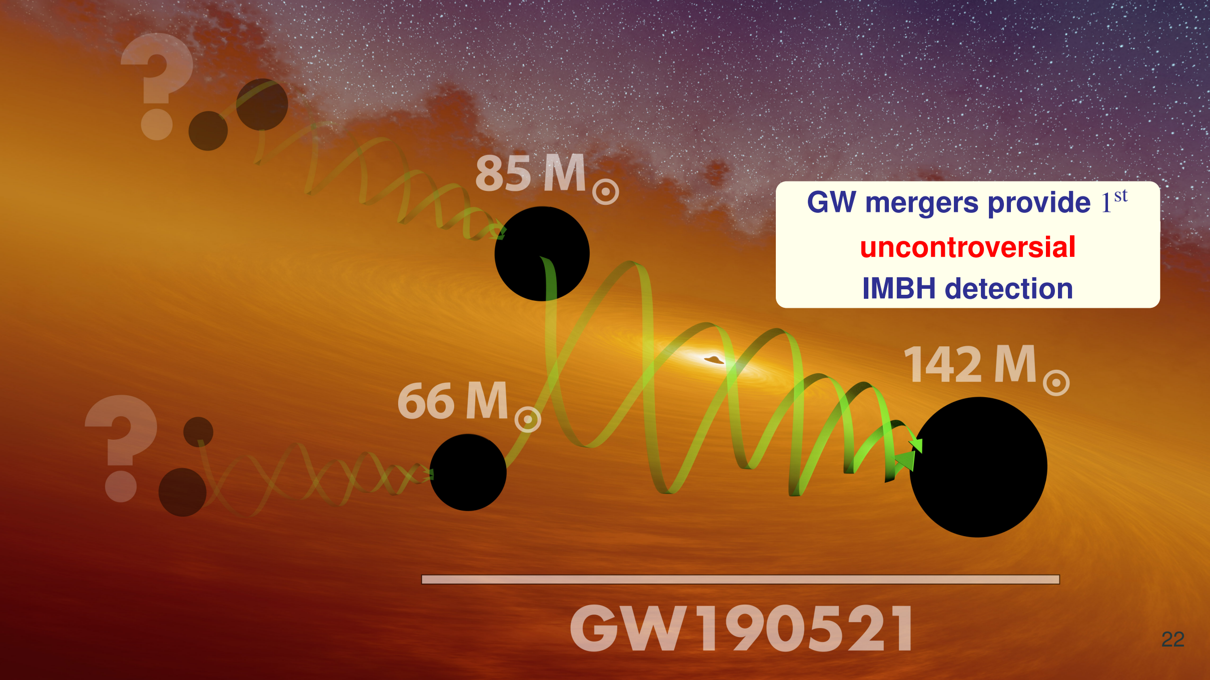
Gravitational waves

Dynamics and accretion signatures

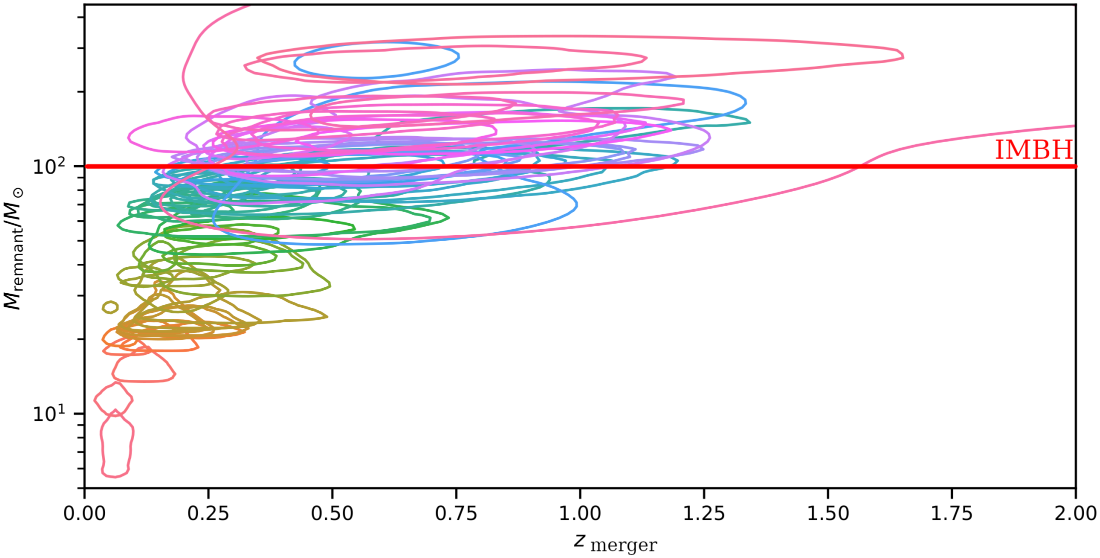
Hyper-velocity stars



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern


85 M⊙
66 M⊙
142 M⊙
GW mergers provide 1^{st}
uncontroversial
IMBH detection
GW190521

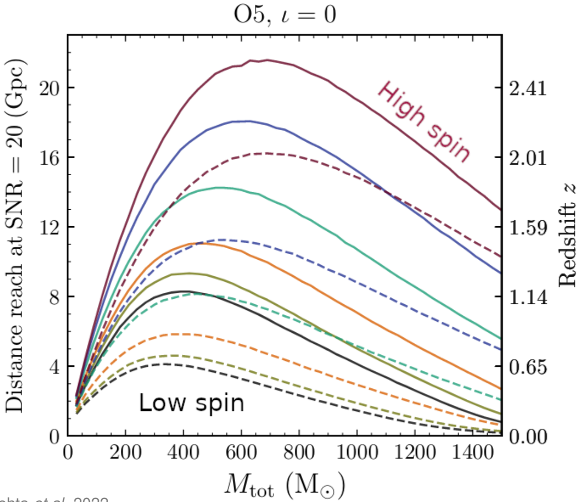
Not just one event: a population of post-merger IMBH is appearing



Credits: W. M. Farr

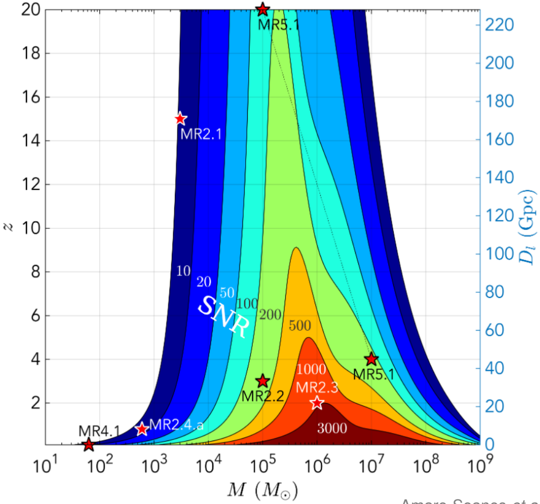
Future detectors will reveal a population of low-mass IMBH

Merger: ground-based



Mehta *et al.* 2022

Inspiral: space-based



Amaro-Soanes *et al.* 2017

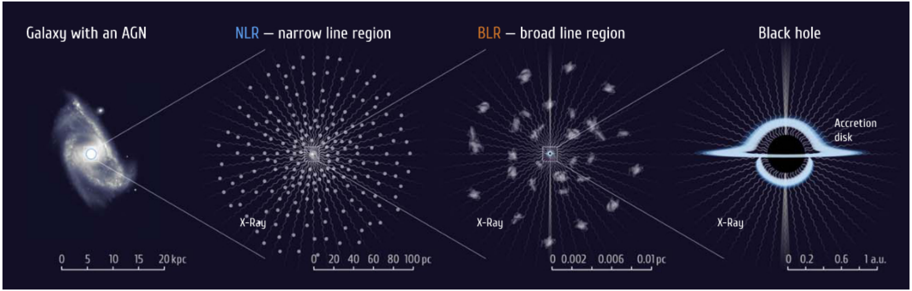
Observing IMBH

Gravitational waves

Dynamics and accretion signatures

Hyper-velocity stars

Study of low mass active galactic nuclei yields many candidates



Chilingarian *et al.* 18

Require confirmation with accretion signatures

Upcoming large spectral surveys + X-ray mission will help sieve through

Globular clusters IMBH may form through collisions

e.g., Portegies-Zwart & McMillan 2002

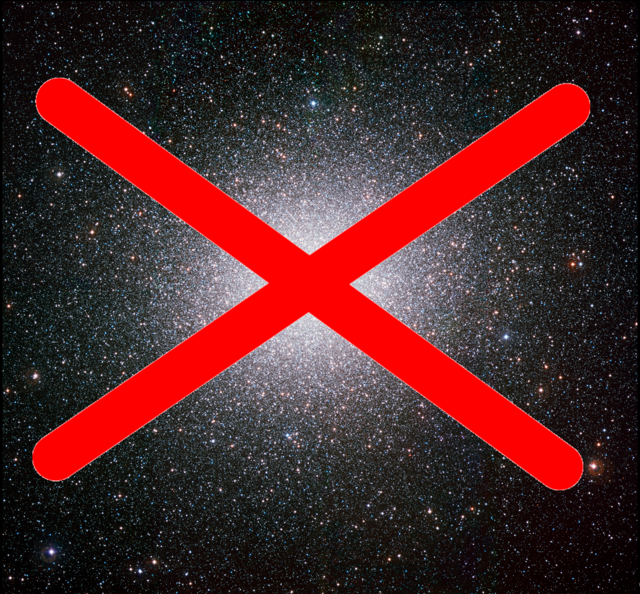
ω Centauri, credits: ESO

Measure σ_v with stars (or pulsars!)

Confirm with accretion signatures
(X-ray or radio)

No confirmed IMBH in globular clusters so far

Greene *et al.* 2020



Future prospects

SKA & ATHENA may soon help probe accretion

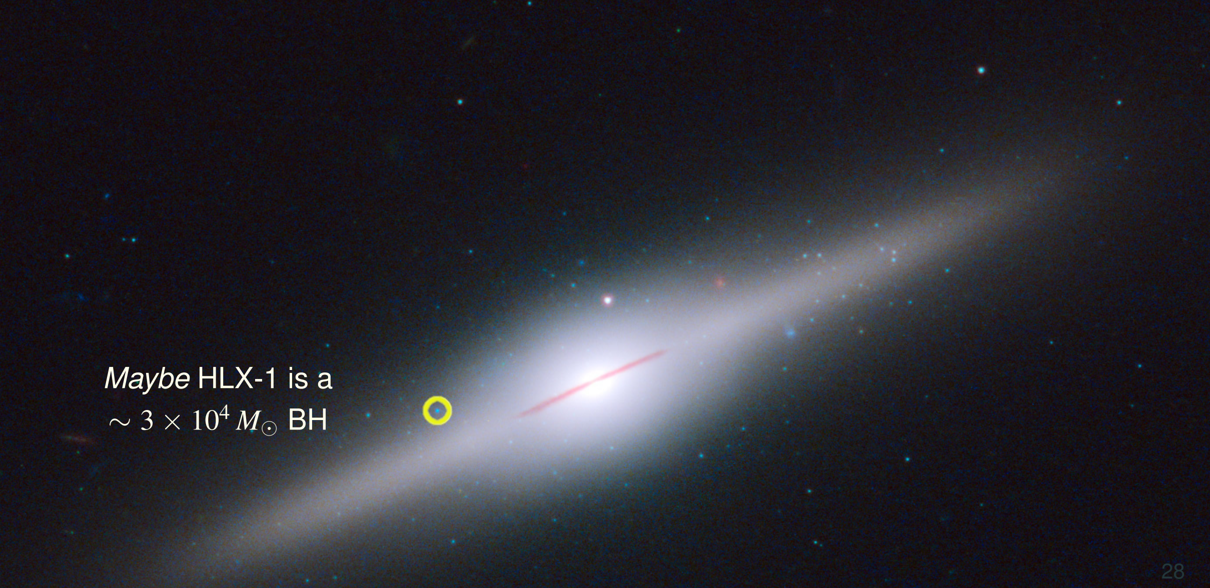
+

JWST may see Pop III clusters

See also Renuka's talk!

ω Centauri, credits: ESO

ULXs: they have pulsations ⇒ solid surfaces, not IMBH



Farrell *et al.* 09

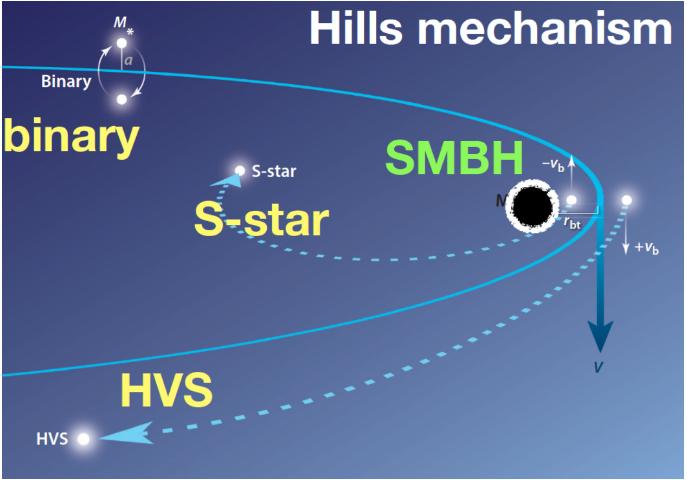
Observing IMBH

Gravitational waves

Dynamics and accretion signatures

Hyper-velocity stars

Hyper-velocity stars may form through binary+SMBH interaction

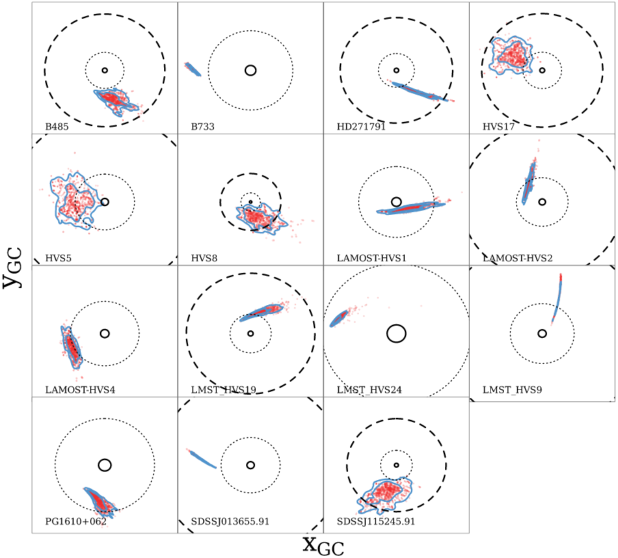


$\Rightarrow$ HVS should come from the Galactic center!

Hills 1988

Only one found from the Galactic center!

(see Koposov *et al.* 2020)



Evans, MR, Rossi 2020

Fraser Evans

Univ. of Leiden

Are some HVS signatures of IMBH in the Galaxy?

Other possibilities:

- **Binaries**: not for the entire population

  see Tauris 2015, Evans, MR, Rossi 2020

- **Extragalactic origin**: likely for some

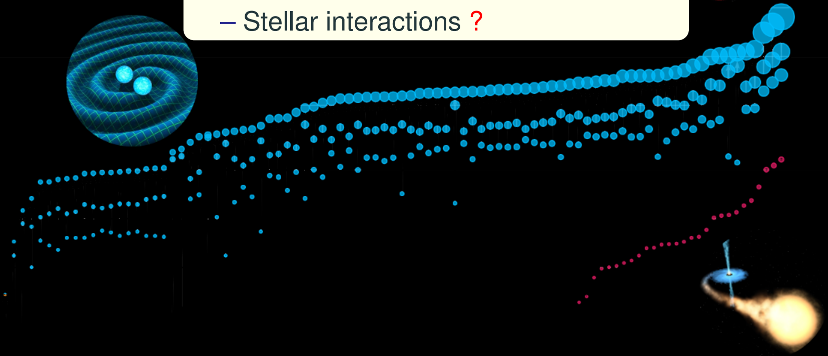
  see Boubert *et al.* 2017

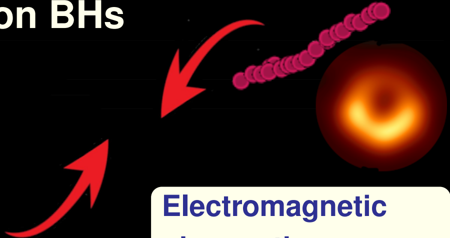
Conclusions

Recent and ongoing explosions of data on BHs

Gravitational waves

- Probe IMBH from the bottom
- Challenge understanding of PPISN
  - Input or explosion physics ?
  - Stellar interactions ?





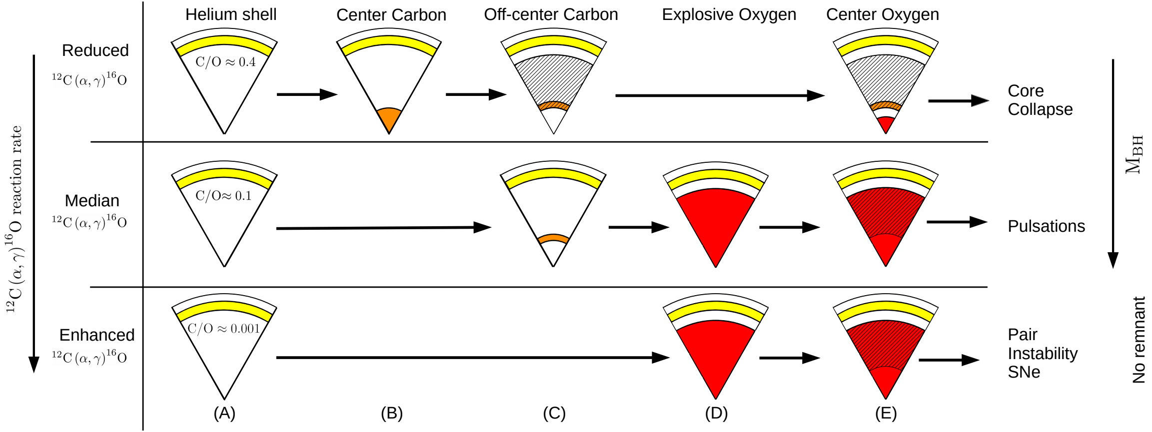
Electromagnetic observations

- Probe IMBH from the top
- Accretion and dynamics from new observatories:
  - JWST
  - Athena
  - *Gaia*
  - ZTF+SDSS

Backup slides

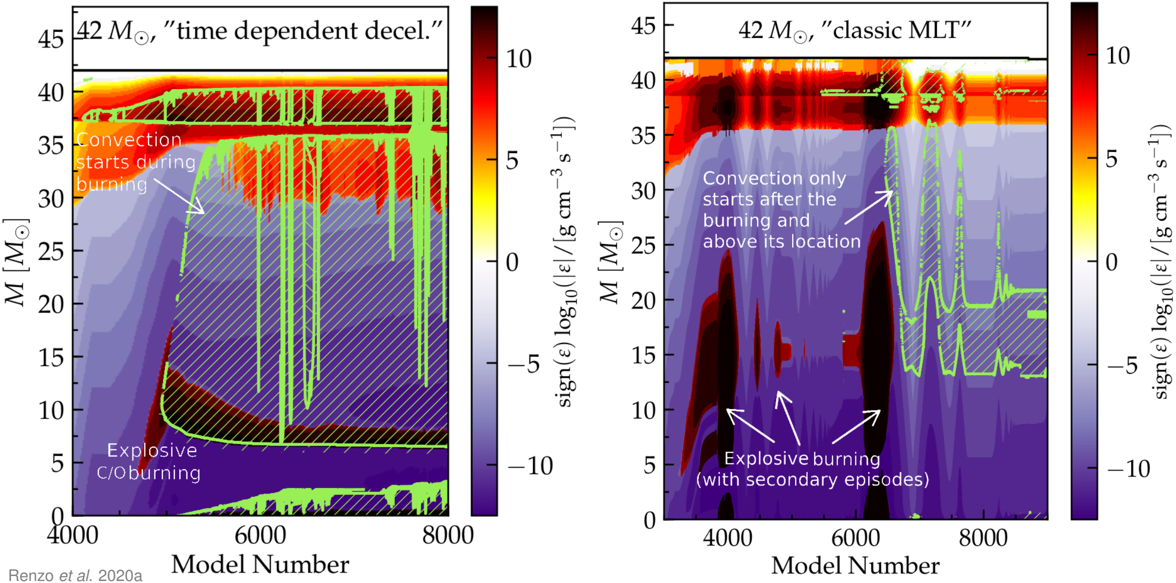
The $^{12}C(\alpha,\gamma)^{16}O$ ends He core burning

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



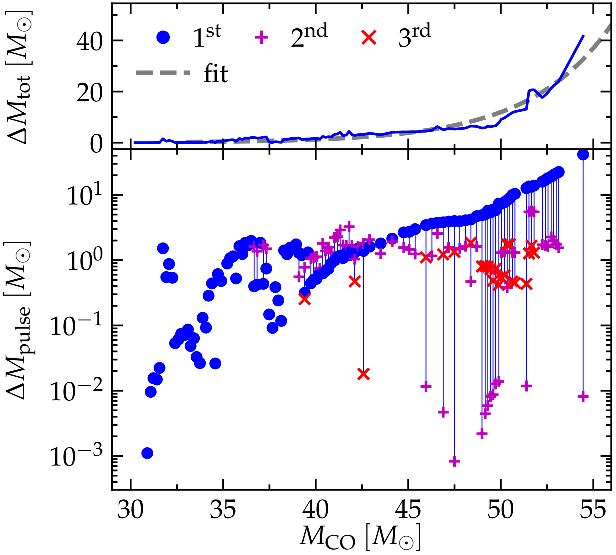
Farmer, Renzo *et al.* 2020

Convection during the pulses quenches the PPI mass loss



Renzo *et al.* 2020a

Amount of mass lost per pulse



Larger cores

$\Downarrow$

More energetic pulses

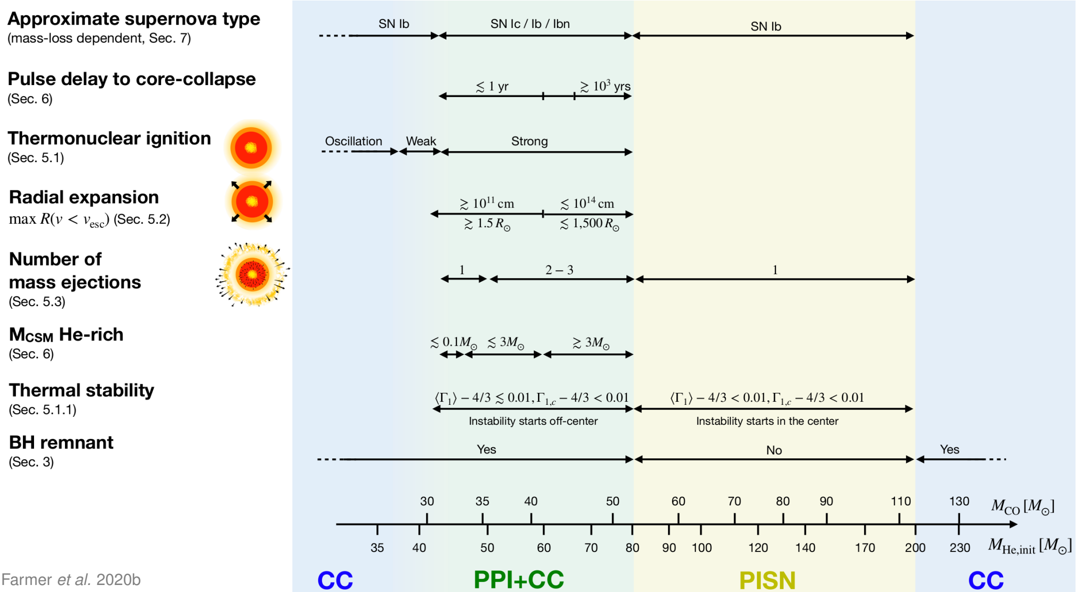
$\Downarrow$

More mass loss

(and longer delays)

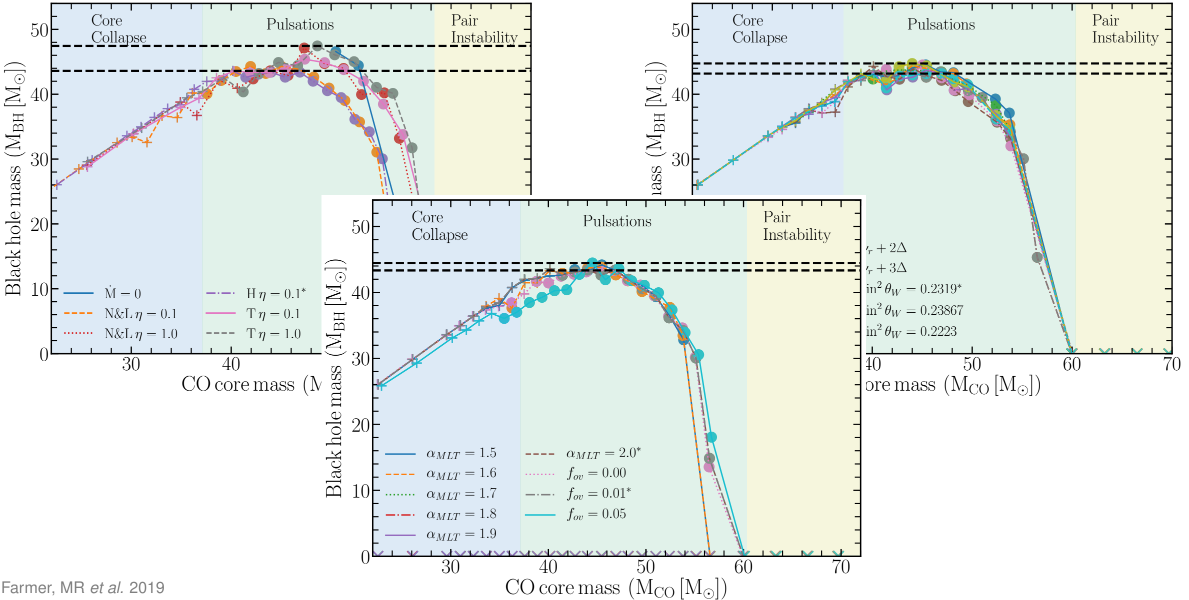
Renzo, Farmer *et al.* 2020b

Summary of EM transients



Renzo, Farmer *et al.* 2020b

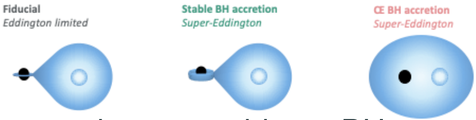
Winds, mixing, ν physics? Also small effects



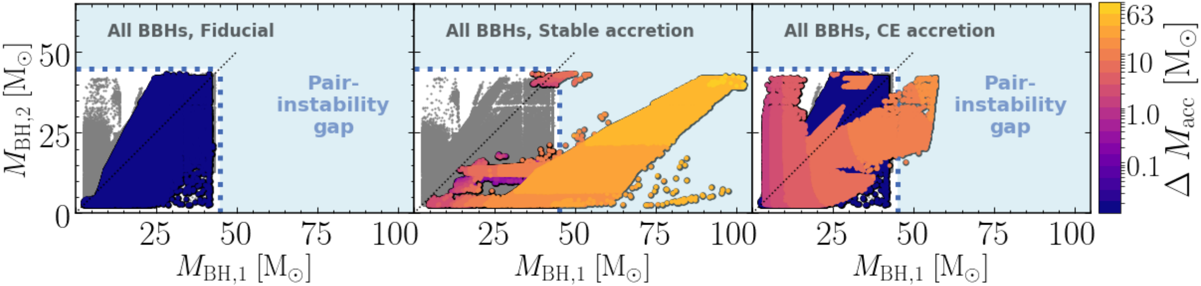
Farmer, MR *et al.* 2019

Can isolated binary evolution "pollute" the gap?

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

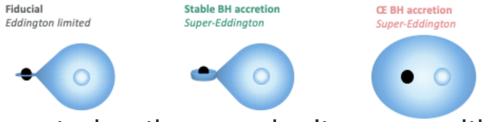


With unlimited accretion, some binary BHs can enter the gap...

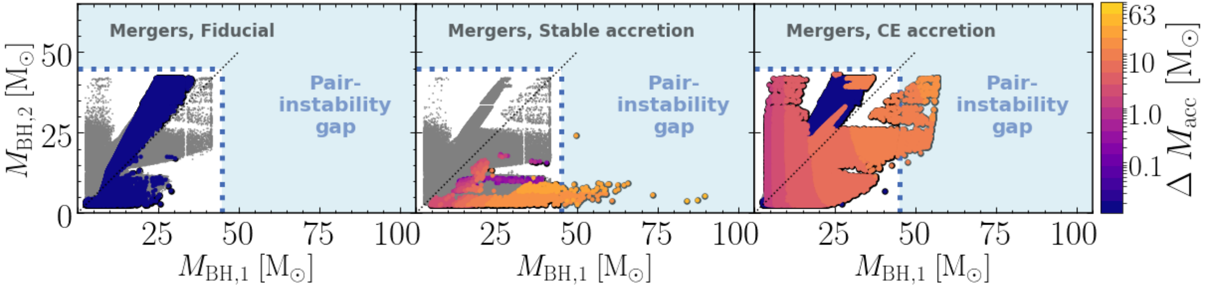


Can isolated binary evolution "pollute" the gap?

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

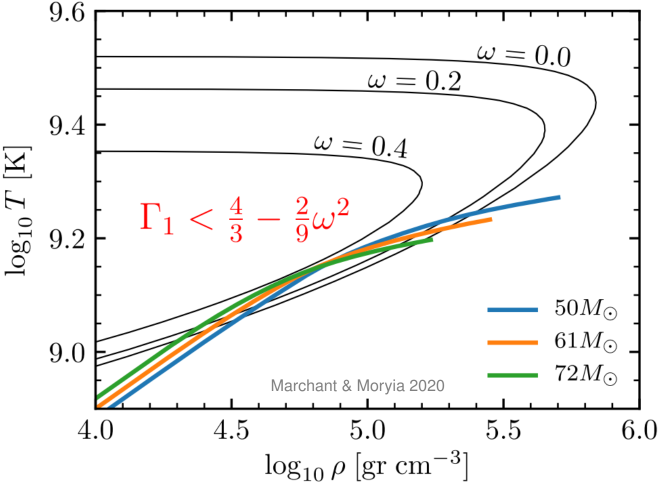
even with the most optimistic assumptions:

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

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:

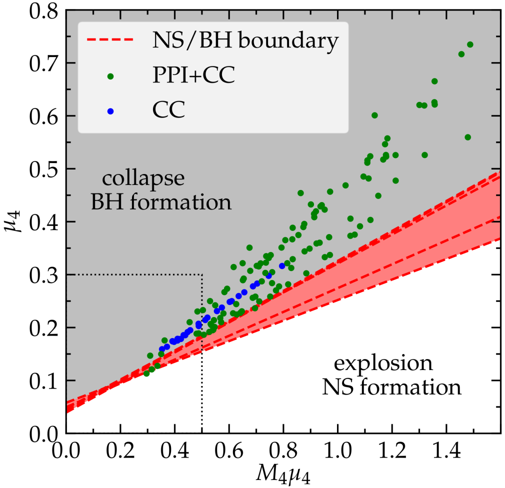
- No core-envelope coupling
- large initial rotation
- low Z ($\simeq$ no winds)

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

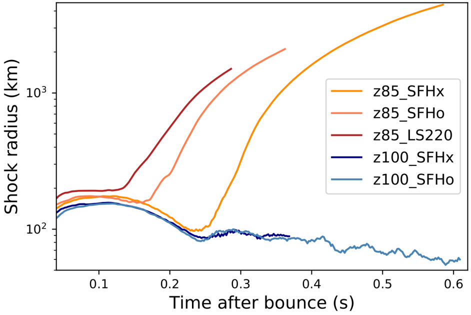
see also Glatzel *et al.* 1985

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

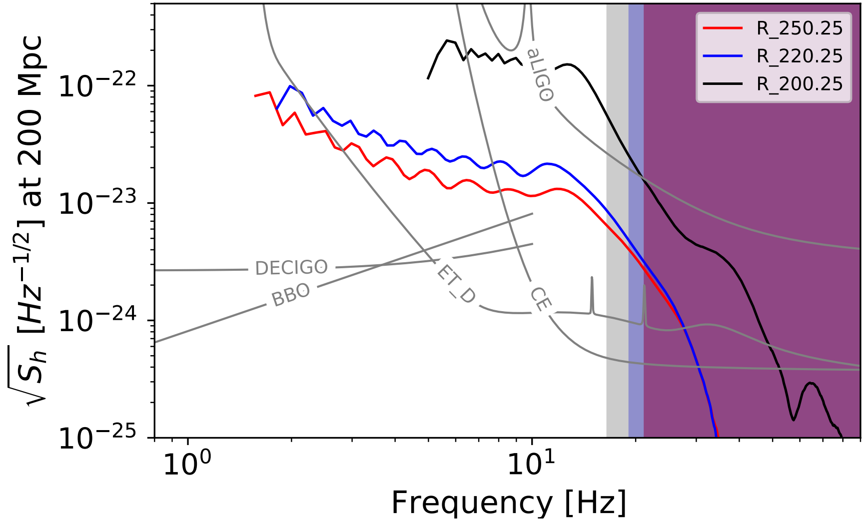
$$\max \Delta M_{CC} \lesssim 3.5\, M_\odot$$

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

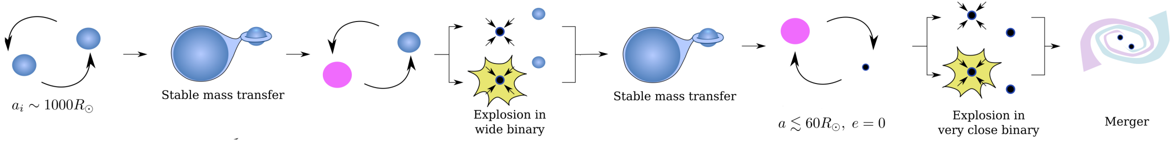


"sad trombone"
ν decreases
as BH and its ISCO
grow

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

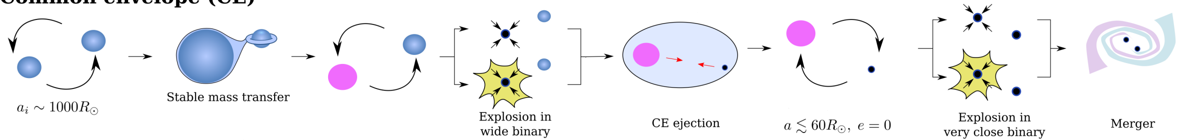
Isolated binary evolution removes the H-envelope anyways

Stable mass transfer (RLOF)

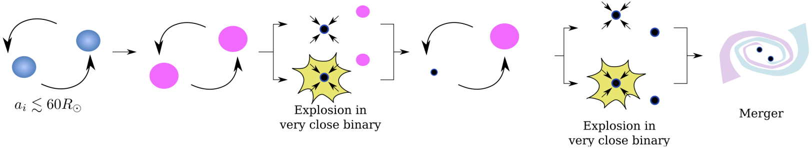


e.g., Klencki *et al.* 2021, van Son *et al.* (incl. MR) 2021, Marchant *et al.* 2021, Gallegos-Garcia *et al.* 2022

Common envelope (CE)

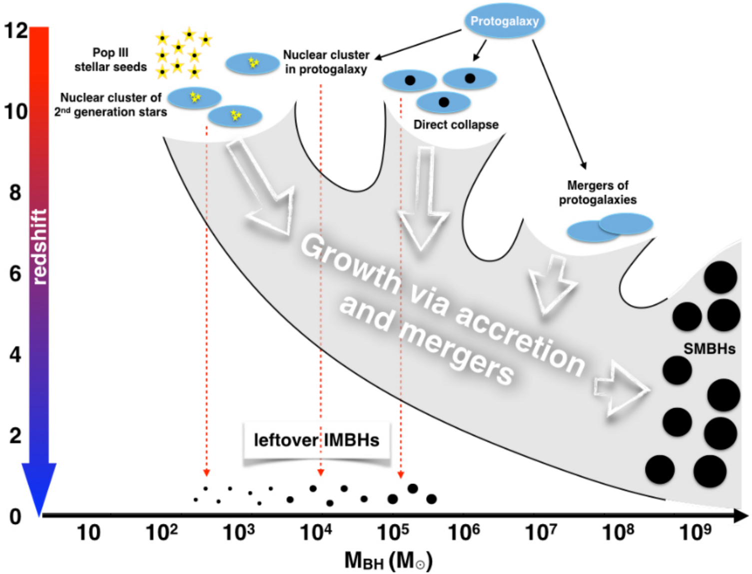


Chemically homogeneous evolution (CHE)



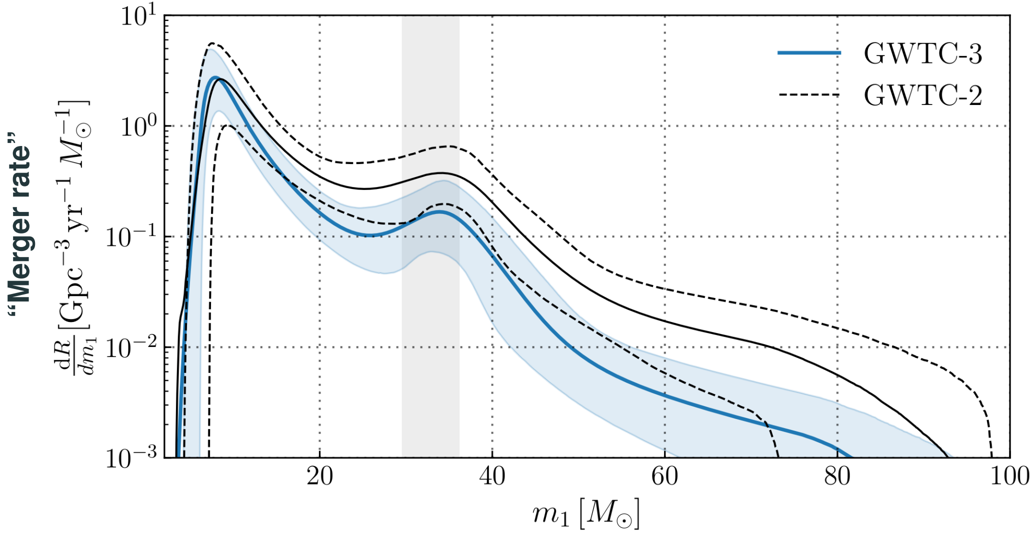
Marchant, MR *et al.* 2019

SMBH formation scenario can be distringuished based on their leftovers



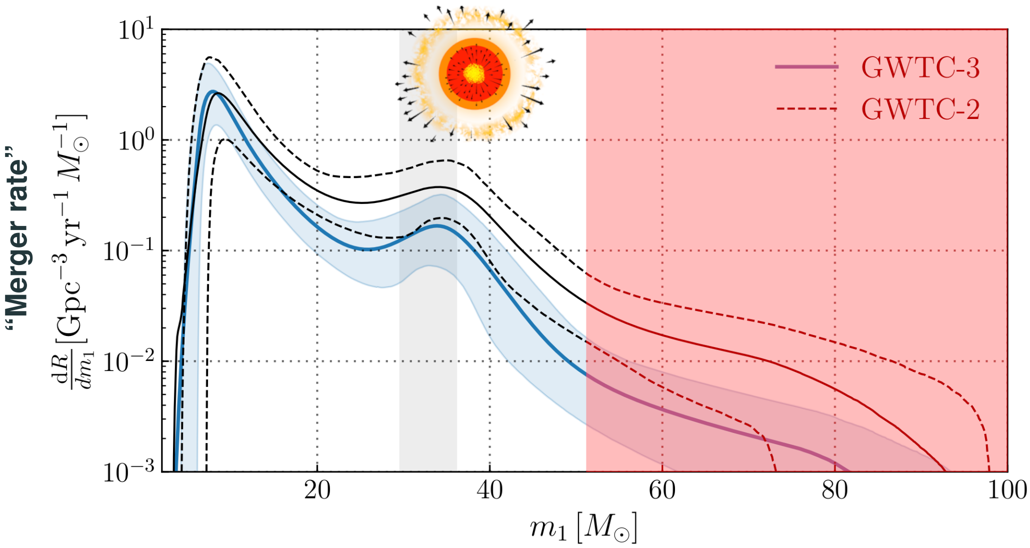
Mezcua 2017

Gravitational wave mergers offer an unprecedented view on massive BHs



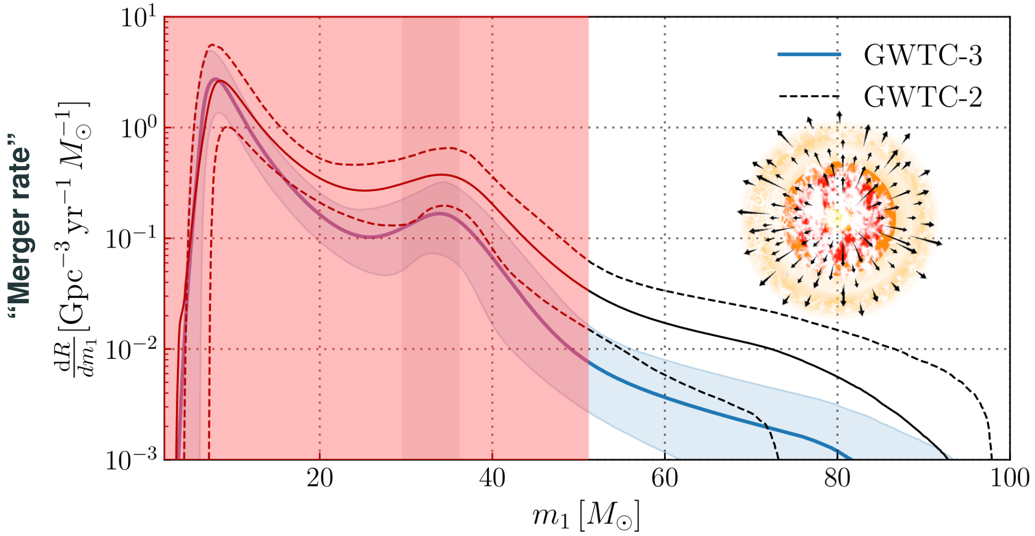
Abbott *et al.* 2022

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



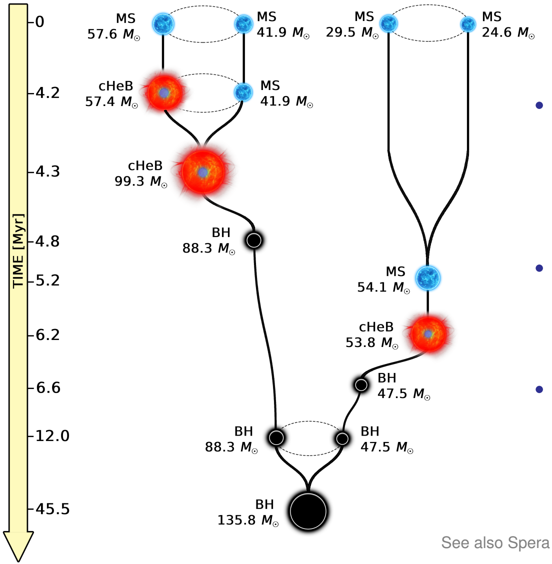
Abbott *et al.* 2022

Part 2: Making forbidden black holes ?



Abbott *et al.* 2022

The stellar merger scenario

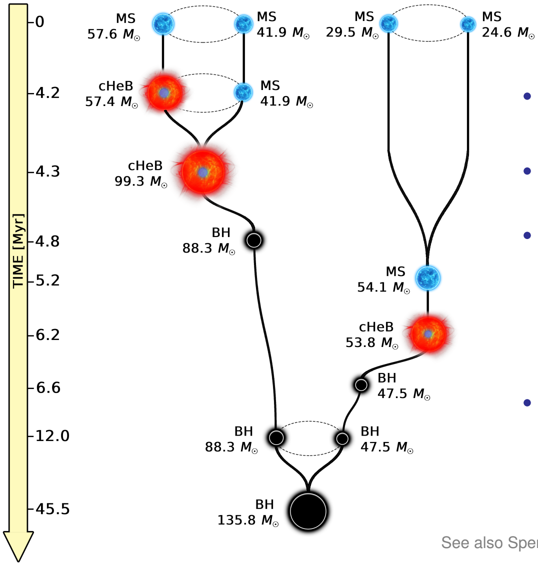


di Carlo *et al.* 20a

- 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"



di Carlo *et al.* 20a

- 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?

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 $\dot{M}$

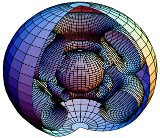
Langer 88, Heger *et al.* 00

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

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

$\Downarrow$

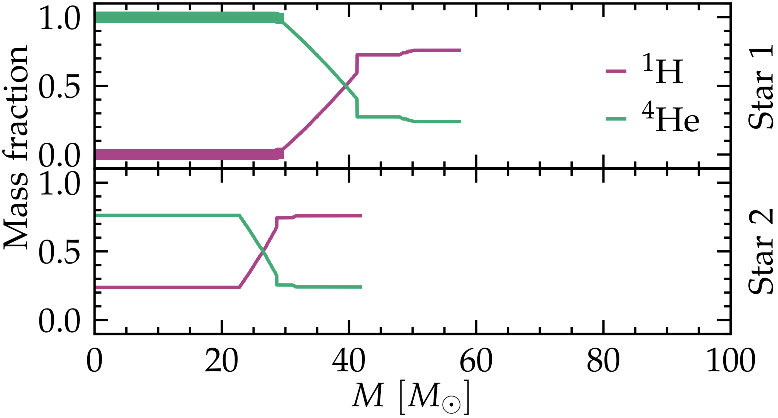
I will assume no rotation



Maeder & Meynet 2000

Ballone *et al.* 22

Merger model: the pre-merger stars



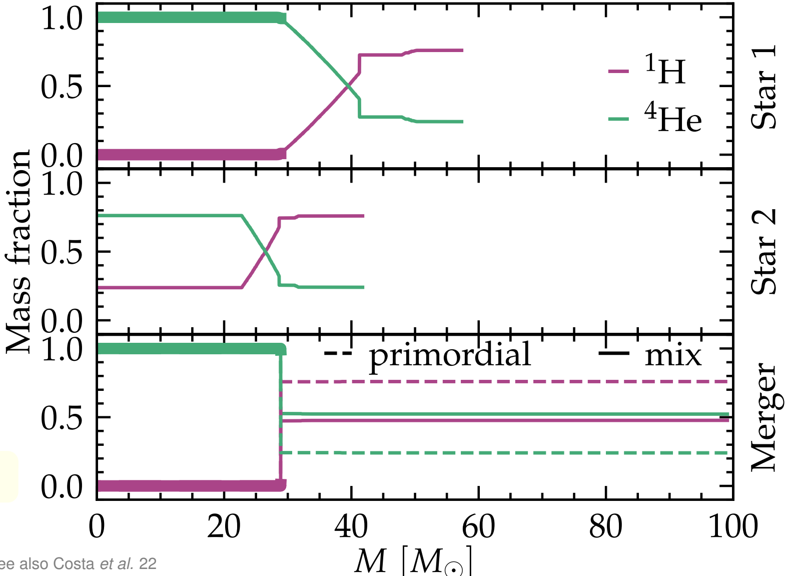
$58\,M_\odot$

$42\,M_\odot$

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

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

Merger model: composition of the merger



$58\,M_\odot$

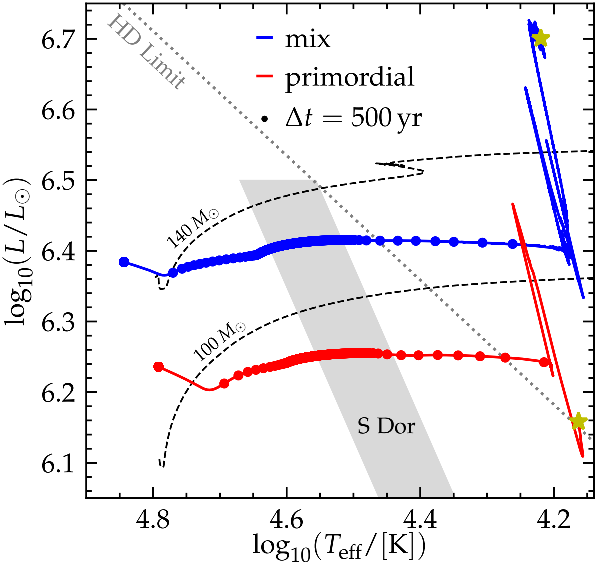
$42\,M_\odot$

$99\,M_\odot$

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

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

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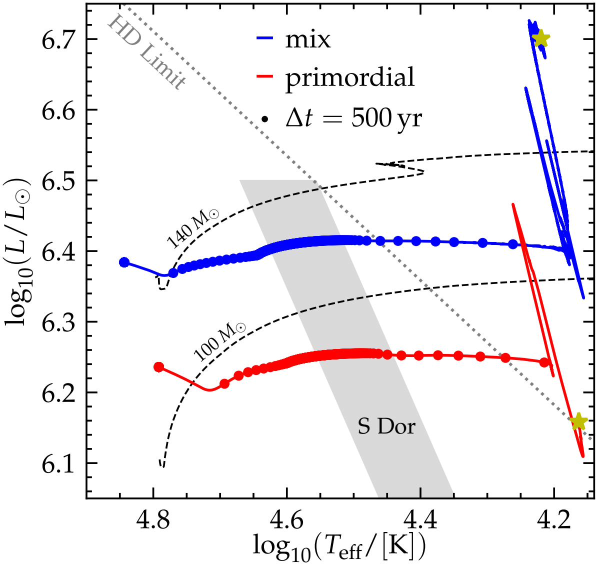

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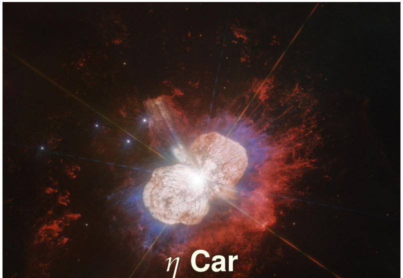
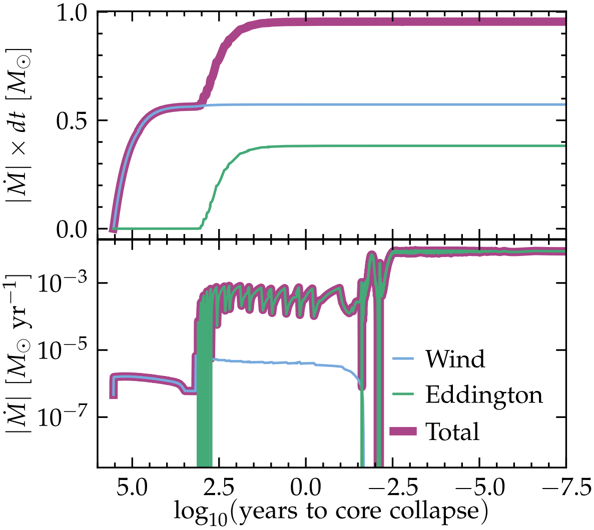


Hirai *et al.* 2021

The estimated radiation-driven mass loss is not significant



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

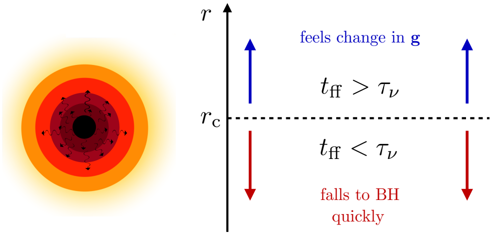
$L > L_{\mathrm{Edd}}$ only for few 100 years

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

Renzo, Cantiello *et al.* 20

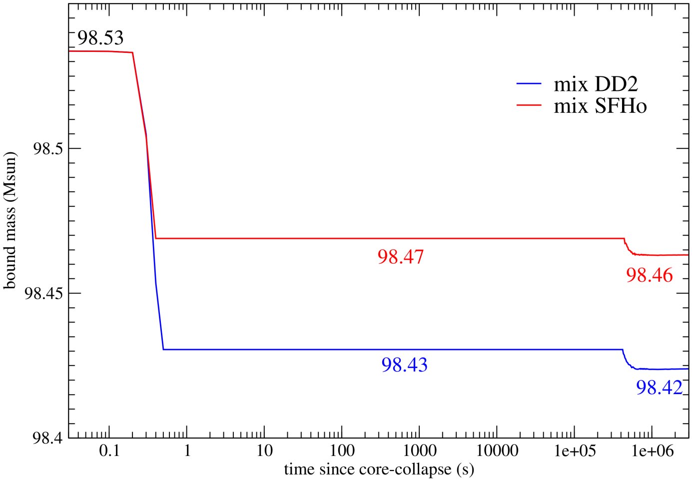
Accretion disks and ν-driven shocks remove little mass for BSG

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



Fernàndez *et al.* 2018

MESA → GR1D+FLASH credits: R. Fernàndez

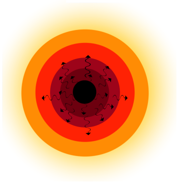


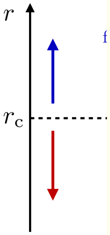
Nadhezin 1980, Lovegrove & Woosley 2013, Piro 2013, Coughlin *et al.* 2018, Fernàndez *et al.* 2018, Ivanov & Fernàndez 2021

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

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

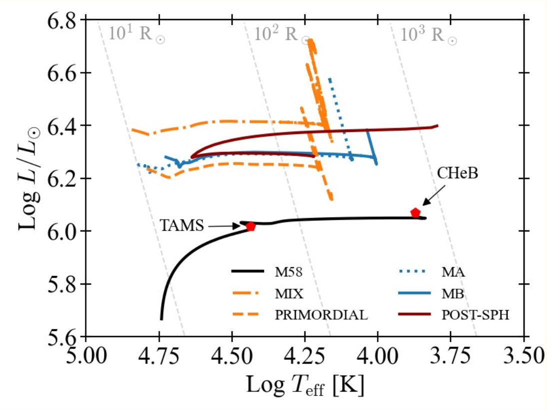
MESA → GR1D+FLASH credits: R. Fernàndez



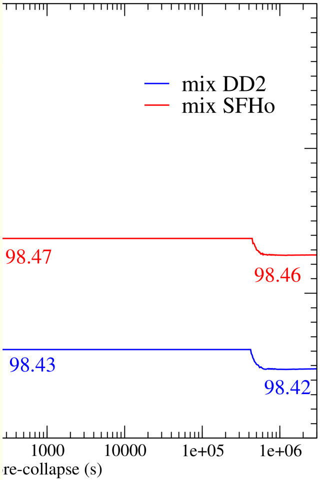


Fernàndez *et al.* 20

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



Costa *et al.* 22



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