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

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S. Justham, S. E. de Mink,
N. Smith, Y. Götberg, E. Zapartas,
M. Cantiello, B. D. Metzger,
Y.-F. Jiang, ...
(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\(^\dagger\) after carbon depletion

\(^\dagger\) 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
Radiation pressure dominated:

\[ P_{\text{tot}} \sim P_{\text{rad}} \]

\[ M_{\text{He}} \gtrsim 32 M_\odot \]

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

Renzo, Farmer et al. 2020b
0. Evolved Massive He core

1. Pair production
   \[ \gamma \gamma \rightarrow e^+ e^- \]

2. Softening of EOS triggers collapse
   \[ \Gamma_1 < \frac{4}{3} \]
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3. Explosive (oxygen) ignition

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4a. Pair Instability supernova with complete disruption

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4b. Pulse with mass ejection

5. \( \nu \)-cooling

Renzo, Farmer et al. 2020b
Resulting stellar BH masses

Renzo, et al. 2020b
see also:
(Pulsational) pair instability

Maximum $M_{\text{BH}}$ from single He cores
Implementation in pop. synth.
How robust are these predictions?
$M_{\text{initial}} \rightarrow \text{CO core mass}^{\dagger} \rightarrow \text{BH mass}$

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

see also Fryer et al. 2012, 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, ...
$M_{\text{initial}} \rightarrow \text{CO core mass}^\dagger \rightarrow \text{BH mass}$

and composition! (Patton & Sukhbold 2020)

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

Farmer + 19 prescription

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

van Son et al. (incl. MR) 2021
Pair-instability mass loss for top-down compact object mass calculations

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\[ M_{\text{BH}} = M_{\text{proto-NS}} + M_{\text{fallback}} \]

(Fryer et al. 2012, 2022)

\[ \downarrow \]

\[ M_{\text{BH}} = M_{\text{pre-explosion}} - (\Delta M_{\text{SN}} + \Delta M_{\nu,\text{core}} + \Delta M_{\text{env}} + \Delta M_{\text{PPI}} + \cdots) \]

New fit to Farmer, MR et al. 2019
$M_{\text{initial}} \rightarrow \text{CO core mass}^{†} \rightarrow \text{BH mass}$

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

- New prescription
- Farmer + 19 prescription
- Pre-sn mass

$M_{\text{initial}}^{†}$ and composition! (Patton & Sukhbold 2020)

David D. Hendriks
Univ. Surrey

Hendriks, van Son, MR et al., in prep.
\( M_{\text{initial}} \rightarrow \text{CO core mass}\uparrow \rightarrow \text{BH mass} \)

and composition! (Patton & Sukhbold 2020)

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

- New prescription with \( M_{\text{CO PPISN shifted}} \)
- New prescription
- Farmer + 19 prescription
- Pre-sn mass

Fryer et al. 2012
Farmer, MR et al. 2019
Renzo et al. 2022

David D. Hendriks
Univ. Surrey
(Pulsational) pair instability

Maximum $M_{\text{BH}}$ from single He cores
Implementation in pop. synth.
How robust are these predictions?
Metallicity? Small effect

Focus on lower edge of the gap

Metallicity shift

$$\Delta \max \{ M_{\text{BH}} \} \sim 7\%$$
over 2.5 orders of magnitude

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

Farmer, MR et al. 2019
Treatment of \textbf{time-dependent convection}? Not the edge

Matters for least massive PPI, not for the most massive BH progenitors
Treatment of time-dependent convection? Not the edge

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

CCSN/PPI+CC discontinuity?
The only input physics that matters: $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rate

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\( ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \) reaction rate was undersampled in tables.
BH mass gap with updated nuclear reactions

\[ \Delta_{MG} = 22 \sigma_6 M_\odot \]
\[ \Delta_{MG} = 31 \sigma_5 M_\odot \]

This work (DeBoer et al. 2017)
Farmer et al. 2020 (Kunz et al. 2002)

\( \sigma \left[ ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \right] \)
BH mass gap with updated nuclear reactions

\[ \Delta_{MG} = 22 \sigma_6 M_\odot \]
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\[ \sigma [^{12}\text{C}(\alpha, \gamma)^{16}\text{O}] \]

BHs
Mass Gap

\(M_{\text{BH}}\) [M\(_\odot\)]
Filling the PISN BH mass “gap”

More ideas than events

Filling the gap “from above”

Siegel et al. (incl. MR) 2021
### Move the gap

- **decrease by $\sim 2.5\sigma$ the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$**
  
  Farmer et al. 20, Belczynski 20, Costa et al. 21

- **Beyond standard model physics**
  
  Choplin et al. 17, Croonet 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

### 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
0. Evolved Massive He core

1. Pair production \( \gamma \gamma \rightarrow e^+ e^- \)

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3. Explosive (oxygen) ignition

4a. Pair Instability supernova with complete disruption

4b. Pulse with mass ejection

4c. Photodisintegration instability and direct BH formation

5. \( \nu \)-cooling

7. BH

no BH
Extrapolation of long-GRB models to progenitors above the gap (with no rotation)

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

“super-kilonova”

Siegel et al. (incl. MR), 2021
Result: BH in the gap, r-process nucleosynthesis, and observable transient

Final BH mass [$M_\odot$]

- $M_{56\text{Ni}} \sim 10 - 60 M_\odot$
- $M_{r\text{-process}} \sim 1 - 20 M_\odot$
- 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

Final BH formation & fate of H-rich envelope

Input physics:
$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate ?
time-dependent conv. ?
### Filling the PISN BH mass gap

#### Move the gap
- **Pre-BH formation**
  - decrease by $\sim 2.5\sigma$ the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
    - 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. 20,22
  - Kremer et al. 20, Costa et al. 22, Ballone et al. 22
- population III
  - Farrell et al. 20, Kinugawa et al. 20
- Quench winds
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#### 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
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  - Perna et al. 19
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  - McKernan et al. 12, Bartos et al. 17, Stone et al. 19

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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)

Stable mass transfer

Explosion in wide binary

Stable mass transfer

Merger

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)

Stable mass transfer

Explosion in wide binary

CE ejection

Merger

Chemically homogeneous evolution (CHE)

Explosion in very close binary

Explosion in very close binary

Merger

Marchant, MR et al. 2019
The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ ends He core burning

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

Reduced $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- Helium shell
  - $C/O \approx 0.4$
- Center Carbon
- Off-center Carbon
- Explosive Oxygen
- Center Oxygen
- Core Collapse

Median $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- $C/O \approx 0.1$
- Pulsations

Enhanced $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- $C/O \approx 0.001$
- Pair Instability SNe
- No remnant

(A) (B) (C) (D) (E)

Farmer, Renzo et al. 2020
Convection during the pulses quenches the PPI mass loss
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

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

Pulse delay to core-collapse
(Sec. 6)

Thermonuclear ignition
(Sec. 5.1)

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

Number of mass ejections
(Sec. 5.3)

$M_{\text{CSE}}$ He-rich
(Sec. 6)

Thermal stability
(Sec. 5.1.1)

BH remnant
(Sec. 3)
Winds, mixing, $\nu$ 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?

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

van Son et al., incl. MR, 2020

Mass accretion leads to orbital widening

even with the most optimistic assumptions:

- $\lesssim 1\%$ systems with $M_{\text{tot}} \gtrsim 90 M_\odot$
- No systems with $M_{\text{tot}} > 100 M_\odot$
Can rotation move the gap? Barely...

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

Rotation stabilizes only for very extreme assumption:

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

only $\sim20\%$ shift of instability
$\lesssim4\%$ 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.

\[ \max \Delta M_{CC} \lesssim 3.5 M_\odot \]

from \( \nu \)-driven engines

\[ \rho \]

3D simulations not conclusive yet

\[ \rho \]

Powell, Müller, Heger 2021

Rahman, et al. 2021

Gravitational waves from super-kilonova

Siegel et al. (incl. MR), 2021

“sad trombone” 
\( \nu \) decreases as BH and its ISCO grow
Disk self-neutronization allows for r-process nucleosynthesis

Siegel et al. (incl. MR), 2021