The Maximum Mass of Stellar Black Holes

Mathieu Renzo
R. Farmer, P. Marchant,
D. D. Hendriks, S. Justham,
L. van Son, S. E. de Mink, E. Farag,
N. Smith, Y. Götberg, E. Zapartas,
M. Cantiello, B. D. Metzger,
Y.-F. Jiang, ...
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 1: (Pulsational) pair instability

Maximum $M_{BH}$ from single He cores
Implementation in pop. synth.
How robust are these predictions?
Pair-production happens in the interior\(^\dagger\) 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
Pair-instability SNe are the best understood supernovae

Radiation pressure dominated:

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

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

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

Temperature

$\log_{10}(T/[K])$

Density

$\log_{10}(\rho/[g \text{ cm}^{-3}])$

$\Gamma_1 < 4/3$

$\langle E_\gamma \rangle < m_e c^2$

$P_{\text{gas}} \geq P_{\text{rad}}$, $\langle e^\pm_\text{Fermi} \rangle 

Renzo, Farmer et al. 2020b
2. Softening of EOS triggers collapse

\[ \Gamma_1 < \frac{4}{3} \]

0. Evolved Massive He core

1. Pair production

\[ \gamma \gamma \rightarrow e^+ e^- \]
0. Evolved Massive He core

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

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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
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5. \( \nu \)-cooling

7. BH

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

Renzo, et al. 2020b
see also:
Part 1: (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 $Z=0.001$

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

see also:
Belczynski et al. 2016,
Spera & Mapelli 2017,
Stevenson et al. 2019,
von Son et al. (incl. MR) 2022, ...
Black hole remnant mass distribution for single star evolution at Z=0.001

Farmer + 19 prescription
Pre-sn mass

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

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. Farmer6

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

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

(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
$M_{\text{initial}} \rightarrow \text{CO core mass}^+ \rightarrow \text{BH mass}$

and composition! (Patton & Sukhbold 2020)

Black hole remnant mass distribution for single star evolution at $Z=0.001$
$M_{\text{initial}} \rightarrow \text{CO core mass}^+ \rightarrow \text{BH mass}$

and composition! (Patton & Sukhbold 2020)

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

New prescription with $M_{\text{CO PPISN shifted}}$

Farmer + 19 prescription

Pre-sn mass

Fryer et al. 2012

Farmer, MR et al. 2019

Renzo et al. 2022
Part 1: (Pulsational) pair instability

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

Farmer, MR et al. 2019

Metallicity shift

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

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
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: \( ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \) reaction rate

\( ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \) reaction rate was undersampled in tables.
BH mass gap from single He cores with updated $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate

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

$\Delta_{MG} = 22.6 \ M_\odot$
$\Delta_{MG} = 31.5 \ M_\odot$
Pushing further up with $3\alpha$ rate uncertainties

New lower edge of the gap:

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

• \( \max(M_{\text{BH}}) \) below the gap: \( 69^{+34}_{-18} M_\odot \)

• \( \min(M_{\text{BH}}) \) 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

### 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, 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

### 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

- Make a star with a small core and oversized envelope to avoid PPISN
- Collapse it to a BH in the gap
- Pair it in a GW source with dynamics

See also Spera et al. 19, di Carlo et al. 19, 20b, see also Kremer et al. 20, Mapelli et al. 20, Renzo et al. 20c, Costa et al. 22, Ballone et al. 22
Estimates of mass loss for stellar collisions: $\Delta M_{\text{merger}} \lesssim 12\%$

SPH simulations - no radiation
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
Merger model: the pre-merger stars

\[ Z = 2 \times 10^{-4} \]

\[ 21 \]

Renzo, Cantiello et al. 20, see also Costa et al. 22
Merger model: composition of the merger

\[ Z = 2 \times 10^{-4} \]

Renzó, 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

- ~ $10^5$ 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?

Very massive stars are hardly stable
- \( \sim 10^5 \) years in S Dor instability strip
- reach core-collapse as BSG
  \( \downarrow \)
- LBV eruptions, helped by He opacity?

Jiang et al. 18

Renzo, Cantiello et al. 20, see also Costa et al. 22
The estimated radiation-driven mass loss is not significant

\[ \dot{M} = \frac{L - L_{\text{Edd}}}{v_{\text{esc}}^2} \]

\( L > L_{\text{Edd}} \) 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?

Possible causes for mass ejection at BH formation:

- $\nu$-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

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

see also Adams et al. 17 & Basinger et al. 20 for possible EM counterpart to BH formation
Accretion disks and $\nu$-driven shocks remove little mass for BSG

$$M_{BH,0} \approx M_{core} - \frac{E_\nu}{c^2}$$

$M_{BH,0}$ falls to BH quickly.

$t_{ff} > \tau_\nu$ feels change in $g$

$t_{ff} < \tau_\nu$ falls to BH quickly

Fernández et al. 2018

MESA $\rightarrow$ GR1D+FLASH


Credits: R. Fernández
Accretion disks and $\nu$-driven shocks remove little mass for BSG

\[ M_{\text{BH},0} \approx M_{\text{cor}} \]

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

\[ r < r_c \]

\[ r_c \]

Fernández et al. 2018

MESA $\rightarrow$ GR1D+FLASH

Credits: R. Fernández


Costa et al. 22
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
1. Pair production
\[ \gamma\gamma \rightarrow e^+e^- \]

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\[ \Gamma_1 < \frac{4}{3} \]

3. Explosive (oxygen) ignition

4a. Pair Instability supernova with complete disruption

4b. Pulse with mass ejection

5. \( \nu \)-cooling

6. 3. Explosive (oxygen) ignition

7. BH

4c. Photodisintegration instability and direct BH formation

no BH

BH
Extrapolation of long-GRB models to progenitors above the gap

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

\[ M_{\text{56Ni}} \sim 10 - 60 M_\odot \]

\[ M_{\text{r-process}} \sim 1 - 20 M_\odot \]

Rubin & Roman rate:

\[ \sim 10^{-2}\text{-few/year} \]
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

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

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- **in halos**
  
  Safarzadeh & Haiman 20

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- **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 $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ 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
- Center Carbon
- Off-center Carbon
- Explosive Oxygen
- Center Oxygen
- Core Collapse

Median $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- Helium shell
- Center Carbon
- Off-center Carbon
- Explosive Oxygen
- Center Oxygen
- Pulsations

Enhanced $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- Helium shell
- Center Carbon
- Off-center Carbon
- Explosive Oxygen
- Center Oxygen
- Pair Instability

Farmer, Renzo et al. 2020
Convection during the pulses quenches the PPI mass loss.
Amount of mass lost per pulse

Larger cores \[\downarrow\] More energetic pulses \[\downarrow\] More mass loss (and longer delays)

Renzo, Farmer et al. 2020b
## Summary of EM transients

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

<table>
<thead>
<tr>
<th>SN Ib</th>
<th>SN Ic / Ib / Ibn</th>
<th>SN Ib</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤ 1 yr</td>
<td>≥ 10^3 yrs</td>
</tr>
</tbody>
</table>

### Pulse delay to core-collapse
(Sec. 6)

<table>
<thead>
<tr>
<th>Oscillation</th>
<th>Weak</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 10^11 cm</td>
<td>≤ 10^4 cm</td>
<td></td>
</tr>
<tr>
<td>≥ 1.5 ( R_\odot )</td>
<td>≤ 1,500 ( R_\odot )</td>
<td></td>
</tr>
</tbody>
</table>

### Thermonuclear ignition
(Sec. 5.1)

<table>
<thead>
<tr>
<th>Number of mass ejections</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Sec. 5.3)</td>
</tr>
</tbody>
</table>

| 1 | 2 – 3 | 1 |

### Radial expansion
\( \max R(v < v_{cc}) \) (Sec. 5.2)

<table>
<thead>
<tr>
<th>( M_{\text{CSM}} ) He-rich</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Sec. 6)</td>
</tr>
</tbody>
</table>

| \( \leq 0.1 M_\odot \) | \( \leq 3 M_\odot \) | \( \geq 3 M_\odot \) |

### Thermal stability
(Sec. 5.1.1)

<table>
<thead>
<tr>
<th>( \langle \Gamma_1 \rangle - 4/3 \leq 0.01, \Gamma_{1e} - 4/3 &lt; 0.01 )</th>
<th>( \langle \Gamma_1 \rangle - 4/3 &lt; 0.01, \Gamma_{1e} - 4/3 &lt; 0.01 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instability starts off-center</td>
<td>Instability starts in the center</td>
</tr>
</tbody>
</table>

### BH remnant
(Sec. 3)

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>( M_{\text{He, init}} [M_\odot] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 35 )</td>
</tr>
<tr>
<td>CC</td>
</tr>
</tbody>
</table>

Renzo, Farmer et al. 2020b
Winds, mixing, $\nu$ physics? Also small effects
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

Mass accretion leads to orbital widening

even with the most optimistic assumptions:

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

van Son et al., incl. MR, 2020
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 $\sim 20\%$ 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.

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

from \( \nu \)-driven engines

3D simulations not conclusive yet

Gravitational waves from super-kilonova

Siegel et al. (incl. MR), 2021

"sad trombone"}

$\nu$ decreases as BH and its ISCO grow
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
Isolated binary evolution removes the H-envelope anyways

Stable mass transfer (RLOF)

$\dot{a}_i \sim 1000 R_\odot$

Stable mass transfer

Explosion in wide binary

Stable mass transfer

$\dot{a}_i \lesssim 60 R_\odot$, $e \approx 0$

Explosion in very close binary

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)

$\dot{a}_i \sim 1000 R_\odot$

Stable mass transfer

Explosion in wide binary

CE ejection

$\dot{a}_i \lesssim 60 R_\odot$, $e \approx 0$

Explosion in very close binary

Merger

Chemically homogeneous evolution (CHE)

$\dot{a}_i \lesssim 60 R_\odot$

Explosion in very close binary

Explosion in very close binary

Merger

Marchant, MR et al. 2019