Maximum Black Hole mass across Cosmic Time

by

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Outline

1. LIGO: What have we observed so far?
2. How are BH binaries formed?
3. A new way to make massive BHs in very massive stars
4. Summary & Conclusions
LIGO: what have we observed so far?
The dawn of GW astronomy

LIGO Hanford Data (shifted)

LIGO Livingston Data
Observed BHs so far...
How are BH binaries formed?
How is one BH formed?

<table>
<thead>
<tr>
<th>STELLAR NEBULA</th>
<th>MASSIVE MAIN SEQUENCE STAR</th>
<th>RED SUPER GIANT</th>
</tr>
</thead>
<tbody>
<tr>
<td>When massive nebulae become unstable, they collapse and <em>a star is born</em></td>
<td>Massive stars evolve ~90% close to the main sequence, burning hydrogen</td>
<td>When they run out of hydrogen, they become cold and large, and burn heavier elements</td>
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</tbody>
</table>
How is one BH formed?

Langer 2012
Other things to consider about BH binary progenitors...

To get a binary BH system to **merge within a Hubble time**, you need to form two BHs close together.

Massive stars that make black holes are complicated to study because they have **stellar winds**, which regulate the distribution of BH masses.

Our understanding of **mixing processes** can alter their evolution.
What can we expect the distribution of mergers to look like?

Massive stars also make supernovae

The lowest mass BH formed by massive stars should correspond to the transition between systems that form NS+SNe, and those that collapse into BHs

Ertl et al. 2016
Lower mass gap
How is one BH formed?
What can we expect the distribution of mergers to look like??

Very massive stars experience pair instability in their cores. This leads to a runaway thermonuclear process that leads to an explosion that leaves behind no remnants.

Stars close to this limit experience pulsations caused by this instability, which limits the maximum BH mass.
What can we expect the distribution of mergers to look like??
Higher mass gap

GW 190521: How did this happen??

GW 190521 parameters: (Abbott et al. 2020)
85$^{+21}_{-14}$ M$_\odot$ and 66$^{+17}_{-18}$ M$_\odot$
A new way to make massive BHs in very massive stars
Key points

● Previous studies assume that VMSs lose their hydrogen envelopes during their evolution in binary interactions or during an LBV phase, which may not happen at low Z.

● Mixing parameters are uncertain. If VMSs have low overshooting, they will evolve to have relatively small cores.
Key points

● Previous studies assume that VMSs lose their hydrogen envelopes during their evolution in binary interactions or during an LBV phase, which may not happen at low Z

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\[ f_{ov} = 0.01 \]

\[ Z = 0.1 \, Z_{\odot} \]

MLT++

Physically motivated reduction of stellar winds
Results

$M_{\text{CO}} = 32.7 \, M_\odot$

$M_{\text{env}} = 42.9 \, M_\odot$

$M_{\text{fin}} = 80 \, M_\odot$
Results

Low mass loss and overshooting allow the star to avoid the RSG region, where mass loss is stronger.
Results

![Graph showing BH mass vs. metallicty (Z/Z_☉)]

- New limit set by PI
- Previous limit
- Maximum CO core mass
- Limit set by winds

BH mass (solar masses)

Metallicity (Z/Z_☉)
Caveats

- The numerical treatment of mixing and energy transport is uncertain
- The actual mass loss rates for VMSs at low Z is very uncertain
- It is not trivial to assume that the final stellar mass is equal to the BH mass
- The role of binarity is omitted
- There are other channels to produce such events with the assumptions of previous works (e.g. triple stellar systems, dynamical mergers in dense stellar systems)
Summary & conclusions
Summary & conclusions

- The authors find that the **upper mass limit for BH masses** coming from VMSs depends on mass loss and mixing, and can be increased up to around **90 M☉**

- Their channel relies on stars at low Z that have **small cores** and **massive envelopes**, and evolve as **blue supergiants**

- Could potentially have large implications on how we interpret GW observations, but more theoretical work is required