Formation of GW190521 via gas accretion onto population III stellar black hole remnants born in high-redshift minihalos

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FORMATION OF GW190521 VIA GAS ACCRETION ONTO POPULATION III STELLAR BLACK HOLE REMNANTS BORN IN HIGH-REDSHIFT MINIHALOS

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For information on the discovery, properties and implications...

Properties and astrophysical implications of the 150 $M_\odot$ binary black hole merger GW190521

LIGO Scientific Collaboration and Virgo Collaboration
What’s so important about GW190521?

credit: LIGO
What’s so important about GW190521?

$142^{+28}_{-16} \, M_\odot$

- falls into the class of intermediate-mass black holes
- between the stellar-mass BHs and SMBHs
- “seeds” SMBHs?
What’s so important about GW190521?

Masses: \(~85\, M_\odot\) and \(~66\, M_\odot\)

L+V: 99% of simulated BH primaries have masses below \(45\, M_\odot\)

Cause: pair-instability mass gap

Question: how can we get two companions in the gap?
A possible scenario... Hierarchical mergers

Rare and requires really dense environments such as:

- young star clusters (e.g., Fragione+20)
- AGN accretion disks (e.g., McKernan+12)
- globular clusters (e.g., Kimball+20)
Other scenarios

- Wrong assumptions during GW analysis: eccentricity and heads-on collisions (e.g., Calderón Bustillo et al. 2020)
- Gravitational lensing due to a galaxy or a galaxy cluster (e.g., Ng et al. 2018)
- Primordial BHs from dark-matter overdensities (e.g., Carr & Hawking 1974)
- Uncertainties in binary evolution?
A new scenario: Pop III stars formed in a minihalo

Population III stars (z > 10) with zero metallicity:

- suppressed fragmentation = **massive stars** are more common (Hirano+15)
- **higher binary fraction** (Sana+12)
- decreased stellar winds and evolution = **massive BH remnants** (Farrell+20)

Dark matter minihalos:

- $10^5 - 10^6 \, M_\odot$, hosting Pop III stars (e.g., Inayoshi+19)
- proposed for forming SMBHs, but... **radiative feedback**, SN explosions, **escaping BHs** (e.g., Whalen+08, Alvarez+09, Smith+18)
The toy model: environment

Once upon a redshift (>15) in a minihalo far far away…
a Pop III binary is born

When (z~10) the minihalo builds up, accretion is efficient

\[ u_{\text{esc}} > 10 \text{ km s}^{-1} \]

\[ u_{\text{rel}} = 10 \text{ km s}^{-1} \]

\[ n_c \sim 2.5 \times 10^{10} \text{ cm}^{-3} \]

\[ T_g = 10^4 \text{ K} \]

\[ M_{\text{mh}} = 10^7 - 10^8 \, M_\odot \]

\[ \rho_g(r) = \frac{\rho_c}{1 + (r/r_c)^2} \]
Drag force (gas) $\rightarrow$ system falls in the central region

**two cases**: $10M_\odot + 10M_\odot$ and $40M_\odot + 40M_\odot$

\[
\tau_{df}(r) \approx 2 \times 10^4 \left( \frac{M_{bh}}{M_\odot} \right)^{-1} \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right] \text{ yr}
\]
The toy model: accretion near the dense core

**Bondi-Hoyle-Lyttleton accretion**

\[
\dot{M}_{\text{bh}} = \frac{4\pi G^2 M_{\text{bh}}^2 \rho_g}{(c_s^2 + v_{\text{rel}}^2)^{3/2}}
\]

**Eddington accretion rate**

\[
\dot{M}_{\text{Edd}} = 2.2 \times 10^{-8} \left( \frac{M}{M_\odot} \right) M_\odot \text{yr}^{-1}
\]

**Hyper-Eddington accretion**

Photon trapping suppresses radiative feedback when BHL accretion rate is >500x the Edd.

\[
n_c \sim 2.5 \times 10^{10} \text{ cm}^{-3}
\]

\[
r \sim \text{pc}
\]

\[
n \sim 10^3 \text{ cm}^{-3}
\]
Which binary is favored?

For different galactocentric distances:

- 20$M_\odot$ binary: dynamical friction $<<$ accretion timescale to reach $150M_\odot$ (GW190521)
  
- Similar timescales for $80M_\odot$ binary
  
- Only a few thousand years of Hyper-Eddington accretion are need for the more massive case
Predicted merger rates

SFR density
$10^4$-$10^5 \, M_\odot \, yr^{-1} \, Mpc^{-3}$ at $z=10-20$

Pop III metallicity
$Z_{\text{crit}} = 3 \times 10^{-4} \, Z_\odot$

Canonical delay-time distributions
(3 choices of slope/minimum time)

Standard $\Lambda$CDM parameters
Discussion / Conclusion

- **Merger rate** and other properties (q / spin) consistent with the L+V result

- Simulations: BBHs spend most of their time in low-density regions, and can orbit away: this model requires **only a few Myrs** to be spent in the dense core

- **3D** simulations with inhomogenous gas distributions to verify this scenario

- Extension: dynamically-captured isolated BHs close to the core

- Even more massive BHs can be formed: lower-f detectors needed (e.g. LISA)