New physics and the Black Hole Mass Gap

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LIGO/Virgo’s biggest discovery yet: the *impossible* black holes
GW190521

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... let’s wind back a bit
Binary mergers in LIGO/Virgo O1+O2

“The Stellar Graveyard”
Binary mergers in LIGO/Virgo O1+O2

Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

“Mass Gap”

“Mass Gap”

“Stellar Graveyard”
Binary mergers in LIGO/Virgo O3a

Mass Gap?

“Mass Gap”

LIGO-Virgo Neutron Stars

LIGO-Virgo Black Holes

“The Stellar Graveyard”
What populates the stellar graveyard?

• In the LIGO/Virgo mass range: remnants of heavy, low-metallicity population-III stars
  • Primarily made of hydrogen (H) and helium (He)
  • Would have existed for $z \gtrsim 6$, $M \sim 20 - 130 M_\odot$
  • Have not been directly observed yet (JWST target)

• Collapsed into black holes in core-collapse supernova explosions. *(Or did they?)*

• We study their evolution from the Zero-Age Helium Branch (ZAHB)
Evolution of old population-III stars

Stellar evolution simulated with MESA 12778*

*M. Paxton et al., arXiv:1710.08424 [astro-ph.SR]
Evolution of old population-III stars

Main nuclear reactions:

\[ +^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \]

Stellar evolution simulated with MESA 12778*

Evolution of old population-III stars

Main nuclear reactions:

\[ ^{12}C + ^{12}C \rightarrow ^{16}O + 2 \, ^{4}He \]

\[ \rightarrow ^{20}Ne + ^{4}He \]

\[ \rightarrow ^{23}Na + p^+ \]

\[ \rightarrow ^{23}Mg + n \]

\[ \rightarrow ^{24}Mg + \gamma \]

\[ M_{\text{in}} = 120M_\odot \]

\[ M_{\text{in}} = 40M_\odot \]

\[ M_{\text{in}} = 70M_\odot \]

Stellar evolution simulated with MESA 12778*

Evolution of old population-III stars

\[ M_{\text{in}} = 120 M_\odot \]

\[ M_{\text{in}} = 40 M_\odot \]

\[ M_{\text{in}} = 70 M_\odot \]

Stellar evolution simulated with MESA 12778*

Pair-instability

• The high temperatures of the pop-III stars lead to **electron-positron pair creation** in the thermal plasma via $\gamma \gamma \rightarrow e^+ e^-$ ($2m_e \approx 10^{10} \text{K}$)

• Stars supported by radiation pressure $\Gamma = (\partial P/\partial \rho)_s \approx 4/3$

• Instability occurs for $\Gamma < 4/3$
  ‣ Non-relativistic electrons destabilize the star
  ‣ Rapid thermonuclear burning of $^{16}\text{O}$ follows
Evolution of old population-III stars

\[ M_{in} = 120M_\odot \]
\[ M_{in} = 40M_\odot \]
\[ M_{in} = 70M_\odot \]

\[ \gamma \gamma \rightarrow e^+ e^- \quad (2m_e \approx 10^{10}K) \]
softens the equation of state

\[ \Gamma < \frac{4}{3}, \text{ unstable} \]

He ignition

C ignition

Stellar evolution simulated with MESA 12778*

Extremely massive stars ($M_{\text{in}} > 200M_\odot$)

Very, very massive stars ($M_{\text{in}} > 90M_\odot$)

Very massive stars ($M_{\text{in}} > 50M_\odot$)

Adapted from Renzo et al [2002.05077]
Pair-instability and the BHMG

\[ Z = \frac{Z_\odot}{10} = 1.42 \times 10^{-3} \]
Known physics dependence of the BHMG

- Astrophysical + nuclear + numerical uncertainties
- Most important uncertainty: $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate
- Using updated deBoer et al rate, BHMG found at $51^{+0}_{-4}\text{M}_\odot$

*deBoer et al arXiv:1709.03144 [hep-ex]*

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\[\text{deBoer et al arXiv:1709.03144 [hep-ex]}

\[\text{But GW190521?!}
What about new physics?


The BHMG and new physics

• Scenario 1: new, light particles coupled to material in the star introduce new loss channels

• Case studies:
  • the electrophilic axion $\mathcal{L}_{ae} = -ig_{ae}\bar{\psi}_e\gamma_5\psi_ea$ (will also work with $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$ for convenience)*
  
  $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$

  • the photophilic axion $\mathcal{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$ (will also define $g_{10} \equiv 10^{10}g_{a\gamma}$ GeV)
  
  • the hidden photon $\mathcal{L}_{A'\gamma} = -\frac{\epsilon}{2}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}^2}{2}A_\mu A^\mu$ (and define nothing)


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Energy loss due to electrophilic axions

• Semi-Compton scattering, $e + \gamma \rightarrow e + a$:

$$Q_{SC} = \frac{40 \zeta_6 \alpha_{EM} g_a^2}{\pi^2} \frac{Y_e T^6}{m_N m_e^4} F_{\text{deg}} \approx 33 \alpha_{26} Y_e T_8^6 F_{\text{deg}} \text{erg g}^{-1} \text{s}^{-1}$$

$$F_{\text{deg}} = \frac{2}{n_e} \int \frac{d^3 p}{(2\pi)^3} f_e - (1 - f_{e^-}), \text{ where } f_e^- \text{ is the Fermi-Dirac distribution}$$

• Bremsstrahlung, $e + (Z, A) \rightarrow e + (Z, A) + a$:

$$Q_{b,ND} = \frac{32 \alpha_{EM} g_a^2 \rho T_8^{5/2}}{45 \sqrt{\frac{\pi^3}{2} m_N^2 m_e^7/2}} F_{b,ND} \approx 582 \alpha_{26} \rho_6 T_8^{5/2} F_{b,ND} \text{ erg g}^{-1} \text{s}^{-1}$$

$$Q_{b,D} = \frac{\pi Z^2 \alpha_{EM} g_a^2 T^4}{60 A m_N m_e^2} F_{b,D} \approx 10.8 \alpha_{26} T_8^4 F_{b,D} \text{ erg g}^{-1} \text{s}^{-1}$$
Energy loss due to electrophilic axions

- Semi-Compton scattering, $e + \gamma \rightarrow e + a$:

$$Q_{\text{SC}} = \frac{40 \zeta_6 \alpha_{\text{EM}} g_a^2}{\pi^2} \frac{Y_e T^6}{m_N m_e^4} F_{\text{deg}} \simeq 33 \alpha_{26} Y_e T_8^6 F_{\text{deg}} \frac{\text{erg}}{\text{g} \cdot \text{s}}$$

$$F_{\text{deg}} = \frac{2}{n_e} \int \frac{d^3 p}{(2\pi)^3} f_e(1 - f_{e^-})$$, where $f_{e^-}$ is the Fermi-Dirac distribution

$$0 < F_{\text{deg}} < 1$$

Semi-Compton emission dominates throughout the Helium burning phase
Energy loss due to photophilic axions

- Primakov effect \((Z, A) + \gamma \rightarrow (Z, A) + a\)

\[
Q_{a\gamma} = \frac{g_\alpha^2 T^7}{4\pi^2 \rho} \left( \frac{k_s}{2T} \right)^2 f[(k_s/2T)^2] \approx 283.16 \frac{\text{erg}}{\text{g} \cdot \text{s}} g_{10}^2 T_8^7 \rho_{3^{-1}} \left( \frac{k_s}{2T} \right)^2 f[(k_s/2T)^2]
\]

- With Debye momentum

\[
\left( \frac{k_s}{2T} \right)^2 = 0.166 \frac{\rho_3}{T_8^3} \sum_j Y_j Z_j^2
\]

Screened at high \(T\) and low \(\rho\)
Energy loss due to hidden photons

- Plasma production, dominated by longitudinal modes (in a non-relativistic plasma)

\[ Q_{A'} = \frac{e^2 m_{A'}^2}{4\pi \rho} \frac{\omega_p^3}{e^{\omega_p/T} - 1} \approx \frac{e^2 m_{A'}^2}{4\pi} \frac{\omega_p^2 T}{\rho} \approx 1.8 \times 10^3 \frac{\text{erg}}{\text{g} \cdot \text{s}} \frac{Z}{A} T_8 \left( \frac{e}{10^{-7} \text{ meV}} \right)^2 \]

In the limit \( \omega_p \ll T \)

- Where photons have plasma mass \( \omega_p \approx \sqrt{\frac{4\pi \alpha_{\text{EM}} n_e}{m_e}} \approx 654\text{eV} \sqrt{\frac{Z}{A} \rho_3} \)

Loss rates

Electrophilic axion: $Q_{ae} \propto T^6$

Photophilic axion: $Q_{a\gamma} \propto T^4$

Hidden photon: $Q_A' \propto T$

Central losses: $Q_{ae}$, $Q_{a\gamma}$, $Q_A'$ (erg g$^{-1}$ s$^{-1}$)

Example track of $M_{in} = 55$ M$_\odot$ progenitor
Implications of enhanced losses

![Graph showing wind loss and pulsation loss against T(K).]

- $\alpha_{26} = 0$
- $\alpha_{26} = 72$
- $\alpha_{26} = 100$

- $2 \times 10^8$ to $4 \times 10^8$
- $3 \times 10^9$ to $4 \times 10^8$
Implications of enhanced losses

The pulsation losses are much lower

The wind losses are a bit lower
What does the extra energy loss do?

Electrophilic axion: $m_a \ll \text{keV}, Z = 10^{-5}$

Greater energy losses lead to shorter He-burning phases

Extra dissipation scales linearly with $\alpha_{26}$

Less time for $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$: C/O is larger at the time of helium depletion (HD)
The BHMG and new physics

Enhanced losses, larger C/O at HD

Helium shell  →  Center Carbon  →  Off-center Carbon  →  Explosive Oxygen  →  Center Oxygen

C/O ≈ 0.4  →  C/O ≈ 0.1  →  C/O ≈ 0.001

Core Collapse  →  Pulsations  →  Pair Instability SNe

Enhanced losses → greater progenitors collapse → larger black holes
For light axions in strong tension with stellar cooling constraints but interesting complementary probe in light of XENON1T.
Photophilic axion: $m_a \ll \text{keV}, Z = 10^{-5}$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\end{figure}

- $g_{10} = 0$
- $g_{10} = 3$
- $g_{10} = 1$
- $g_{10} = 5$
Hidden photon: $m_{A'} = 10^{-2}\text{eV}, Z = 10^{-5}$
New physics and the black hole mass gap

Electrophilic axion: $m_a \ll \text{keV}, Z = 10^{-5}$

Photophilic axion: $m_a \ll \text{keV}, Z = 10^{-5}$

Hidden photon: $m_{A'} = 10^{-2} \text{ eV}$

Astrophysical BH

Mass gap

Astrophysical BH

Mass gap

Astrophysical BH

Mass gap

$Q_{ae} \propto T^6$

$Q_{a\gamma} \propto T^4$

$Q_{A'} \propto T$

Potentially large shifts of the mass gap!

Heavier degrees of freedom may instead be thermalized in the core.

Then, they may give rise to an instability in the same way that electron-positron pairs do.

Equilibration time (vector):

\[ t_{A'} \approx \frac{1}{\Gamma_{A'}^{-1}} \approx \left( \epsilon^2 \sigma_{T} n_{e} e^{-m_{A'}/T_{c}} \right)^{-1} \]

so for \( \epsilon = 3 \times 10^{-12} \), we find \( t_{A'} \approx 10^5 \) years, a timescale similar to the lifetime of helium burning.

Heavier degrees of freedom of freedom?

Heavier degrees of freedom?

May probe this parameter space

The BHMG and new physics

• Scenario 2: screened modified gravity (MG)

• Increased local strength of gravity → need larger pressure gradient to maintain hydrostatic equilibrium → larger core temperature at fixed density

• Pair instability is exacerbated → Lighter black holes

• Decreased local strength of gravity works in reverse → Heavier black holes

Straight, Sakstein, Baxter, in progress
GW190521, the impossible black holes

... and Beyond the Standard Model physics

Hidden photon: $\epsilon m_A/10^{-9}$ eV

Photophilic axion: $g_{10}$

Electrophilic axion: $\alpha_{26}$

Extra dimensions: $M_5$/TeV

$\nu$ – magnetic moment: $\mu_\nu/10^{-9}$

Modified gravity: $\Delta G/G_N$

$M_{\text{BHMG}}$ ($M_\odot$)

Looking ahead…

Posterior PDFs using the first 4 BBH mergers, and assuming a power law mass distribution, $p(m_1 | \alpha) \propto m_1^{-\alpha}$

With the complete O3 data set (and beyond), the field of black hole population studies will really take off!

from Fishbach & Holz, arXiv:1709.08584 [astro.ph]
To conclude,

- Gravitational waves offer an **exciting new opportunity** to study open questions in particle astrophysics and cosmology

- Binary mergers allow for black hole population studies

- **The black hole mass gap** is an exciting probe of new physics, which will come into focus in the next few years

- **GW190521** constitutes an intriguing puzzle which could be (partially) explained by BSM physics
Thank you!

...ask me anything you like!

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Helium burning rates as a function of $T$

![Graph showing helium burning rates as a function of temperature $T$. The graph includes two curves: one for $^{12}\text{C}^{16}\text{O}$ and another for triple $\alpha$. The x-axis represents temperature $T$ in Kelvin, ranging from $10^8$ to $10^{10}$, and the y-axis represents rate in units of cm$^3$ Mol$^{-1}$ s$^{-1}$, ranging from $10^{-30}$ to $10^5$. The source of the data is the STARLIB catalogue.]

(Kunz is currently used in STARLIB)

Fitting GW190521 masses $m_1$ and $m_2$
(Kunz is currently used in STARLIB)

Fitting GW190521 masses $m_1$ and $m_2$
Large black hole in LB-1?

- Last year, a $70\,M_\odot$ black hole was reported in a binary with a high-metallicity smaller star (from the radial velocity variability of the $H\alpha$ emission line, suggesting an accretion disk)
- It was suggested (1911.12357) that it was formed due to the core-collapse of a high metallicity progenitor with reduced stellar winds
- However, those simulations did not include pulsations (they were stopped at carbon burning)
- The observation has since also been disputed (1912.04185 and 1912.03599) - apparent shifts instead originate from shifts in the luminous star’s $H\alpha$ absorption line
Binary merger events ($M_1 \approx M_2$)

- $>50$ LIGO/Virgo observations
  - 2017 Nobel Prize in Physics

- *Can be used to learn about new physics in various ways*

- Most GW radiation from the **inspiral phase**, ending in $f_{\text{ISCO}}$

- Solvable in a $(v/c)$ expansion
  - Weak gravity, small velocity

\[
f_{\text{ISCO}} = \frac{C_*^{3/2}}{3^{3/2} \pi G_N (M_1 + M_2)}
\]
Compact object merger sensitivity

- Best detection prospects for
  \[ f_{\text{min}} < f_{\text{peak}} \sim f_{\text{ISCO}} < f_{\text{max}} \]
- Defines an CO sensitivity band
  \[ f_{\text{ISCO}} = \frac{C_*^{3/2}}{3^{3/2} \pi G_N (M_1 + M_2)} \]
  \[ C_* = \frac{G_N M_*}{R_*} \]
  \[
  \begin{align*}
  C_\odot &= 2 \times 10^{-6} & C_{\text{BH}} &= 0.5 \\
  C_\odot &= 7 \times 10^{-10} & C_{\text{NS}} &\sim 0.1
  \end{align*}
  \]
- Sensitivity determined by masses, compactness and luminosity distance

Giudice, McCullough, Urbano [JCAP, 1605.01209]
What can we learn from the *inspiral* waveform?

*A lot, for example,*

1. Component masses
2. Tidal effects $\rightarrow$ equation of state
3. Dynamical friction $\rightarrow$ environmental effects
4. Long-range (dark) forces $\rightarrow$ BSM effects
5. Extra dissipation channels $\rightarrow$ BSM effects
6. Redshift distribution of events $\rightarrow$ age of objects
7. “Hair”: multipolar metric deviations (EMRIs) $\rightarrow$ tests of GR

So what about new physics? May show up in various ways, I will give a (unabashedly biased) selection of examples.

Hints of mass-gap mergers:
- GW190814 $\rightarrow$ downgraded mass gap probability $<1\%$ $\rightarrow$ publication June ’20
- GW190924 (24 September ’19)
- GW190930 (30 September ’19)

Further information could come (for example) from multi-messenger signals (or absence thereof), or post-merger quasi-normal modes or “echoes”