Snowmass2021 - Letter of Interest

New Physics and the Black Hole Mass Gap

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Theory Frontier: Astro-Particle Physics and Cosmology

Contact Information (long authors listed after the text)
[Djuna Croon (TRIUMF), LISA, dcroon@triumf.ca] [Maya Fishbach (University of Chicago), LIGO, mfishbach@uchicago.edu] [Sam McDermott (Fermilab), sammcd00@fnal.gov] [Jeremy Sakstein (University of Hawai'i at Manoa), sakstein@hawaii.edu]

Abstract: (must fit on this page)

Present and future gravitational wave detectors may be used to probe the distribution of astrophysical black holes. This population is highly sensitive to the physics of the black hole's stellar progenitors. In particular, this population exhibits a gap in the mass spectrum due to a *pair-instability*, which disrupts cores of stellar progenitors with masses in the range $\sim 60 - 120 \mathrm{M}_{\odot}$. New physics – such as particle production in the stellar interior, or alterations to stellar structure as a result of modified theories of gravity – may strongly affect this process. As a result, the location of the black hole mass gap may be shifted, constituting an observable signature in the astrophysical black hole spectrum. Planned LIGO/Virgo upgrades and the addition of new detectors such as KAGRA and LIGO-India will provide a sub-$\mathrm{M}_{\odot}$ measurement of the mass gap feature, allowing for precision tests of new physics, and opening a new window to the dark sector.

Motivation: The advent of gravitational wave astronomy has opened a revolutionary new window to the universe and affords us an opportunity to observe and characterize the astrophysical black holes of the Universe. Following the first observation of a binary black hole merger in GW150914[1] by the LIGO/Virgo collaboration, the catalog of black hole observations is growing rapidly, with ~ 50 observations expected following the most recent observing run. As additional detectors come online and LIGO and Virgo are upgraded to their design sensitivities over the next few years, thousands of binary black holes can be anticipated.

The topic of this letter of interest is the black hole mass gap (BHMG). The BHMG is a range $45\mathrm{M}_\odot \lesssim M_{\mathrm{BH}} \lesssim 120\mathrm{M}_\odot$ in which no black holes are expected to form by the direct collapse of massive stars, a manifestation of stellar structure theory. The densities and temperatures in the cores of very massive stars ($\gtrsim 50\mathrm{M}_\odot$) are sufficient for the production of electron-positron pairs from the plasma. These reduce the photon pressure, destabilizing the star and causing it to contract. The resulting temperature increase leads to rapid thermonuclear burning of ^{16}O, which releases energy comparable to the star's binding energy. For heavier stars, the thermonuclear explosion is so violent that the entire star becomes unbound, leaving no compact remnant behind. This process is referred to as a pair-instability supernova (PISN). For supermassive stars with core masses above $\sim 120\ \mathrm{M}_\odot$, the PISN is quenched due to energy losses from the photodisintegration of heavy elements, such that black hole remnants reappear above the BHMG.

The handful of binary black hole observations from the first two Advanced LIGO/Virgo observing runs have already provided evidence for a mass gap feature in the distribution of astrophysical black holes[2;3], validating some aspects of stellar structure theory. The mass gap feature will soon be measured with much greater precision – as we will discuss below, that makes it a powerful new tool to test theories of new physics, opening up a new window to the dark side of the universe.

Phenomenological opportunities: Measuring the boundaries of the BHMG provides insights into new physics. To date, the following opportunities have been identified,

- **New light particles** with couplings to the Standard Model would be produced in stellar interiors, and act as an additional source of energy loss. In[4;5] it was shown that such losses drastically alter the late stages of the evolution of massive stars in two important ways. First, the lifetime of helium burning is significantly reduced, resulting in a diminished amount of mass loss due to stellar winds. Second, the pulsations that arise as a result of the pair-instability are weakened and can be quenched entirely for strong-enough couplings. This is due to an increase in the ratio of ^{12}C to ^{16}O at the end of helium burning. The $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction that is active during helium burning has less time to operate, leading to the increase in the ratio of carbon to oxygen. Oxygen is the fuel for the explosive part of the pulsations, whereas carbon acts to quench it, so increasing the C/O ratio has the overall effect of suppressing the pulsations[6]. The end result is that the location of the mass gap (both the upper and lower edge) is raised to higher masses.

- **New heavy particles**, if coupled strongly enough to the Standard Model, may accumulate in the cores of stars and remain in thermal equilibrium with luminous matter. In this case a new instability may be triggered, analogous to the instability from electron-positron pair production. While detailed numerical models of this scenario have not yet been developed,[4] showed through a direct computation of the equation of state that progenitor stars as light as $M \sim 40\ \mathrm{M}_\odot$ could encounter an instability during the hydrogen or helium burning phases. The new instability may lead to an early onset of pulsations or to stellar disruption, depending on the thermonuclear response to the resulting contraction.

- **Modifications of gravity** that could drive the acceleration of the cosmic expansion predict *fifth forces* that alter the dynamics of stars. Leading dark energy paradigms as chameleon, DHOST, and dark matter–baryon interactions include *screening mechanisms*, which predict that the strength of the fifth-force is environment-dependent, allowing for large deviations from GR on cosmological scales while satisfying stringent solar system bounds. In a forthcoming publication it will be shown that the effect of fifth forces on low-metallicity stars in unscreened galaxies is to raise the star's central temperature at fixed mass and central density, moving it deeper into the instability region. This has two effects. First, stars undergoing a PPISN shed more mass, and, second, stars which would have gone PPISN now experience the full PISN, removing their black holes from the spectrum. The ultimate result of these is that the lower edge of the mass gap is significantly lowered below the GR prediction.

- **Dark energy**, through its effects on the cosmic expansion, can be probed by gravitational-wave *standard sirens*, so named because the gravitational-wave signal from a binary black hole merger directly encodes the luminosity distance of the source[7;8]. If a measurement of the source's redshift is also available, the combination of redshift and distance yields a measurement of the expansion rate of the universe.[9] proposed that the location of the BHMG can provide the necessary redshift measurement. Because gravitational waves measure redshifted masses, whereas the physics of the BHMG depends on the source-frame mass, a gravitational-wave catalog alone will be able to provide both distances and redshifts of black hole mergers. This method will enable an independent measurement of the cosmic expansion at redshifts $z \lesssim 1$, and is expected to provide a $\sim 10\%$-level measurement of the dark energy equation of state with 5 years of Advanced LIGO/Virgo observations[9].

Standard Model Uncertainties: The BHMG is also sensitive to Standard Model effects, most notably:
Metallicity and Wind Loss: Metallicity affects the remnant BH mass $M_{\rm BH}$ because the mass lost to winds during core helium burning scales as $Z^{0.85}$[10–12]. The lower edge of the mass gap is relatively robust against changes in metallicity, shifting only by $\sim 3\mathrm{M}_\odot$ for $10^{-5} < Z < 3 \times 10^{-3}$[13]. In addition, the wind loss efficiency parameter η may vary due to clumping[14]; however, variations in the wind loss prediction leads to differences $\lesssim 3\mathrm{M}_\odot$ for three different mass loss prescriptions and $\eta = \{0.1, 1\}$[13].
Nuclear physics: The physics of the pair-instability renders the final black hole mass sensitive to the ratio of ^{12}C to ^{16}O present when pulsations begin[6;13], and the predicted accuracy of the location of the mass gap is potentially limited by the understanding of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate. Using errors derived in[15] the mass gap varies by $-4(+0)\mathrm{M}_\odot$[6]. Further improving the accuracy and precision of this reaction rate (and other potentially limiting rates[6]) should be a high priority for future theoretical and experimental work.
"Pollution" from astrophysical effects: Common envelope evolution and super-Eddington accretion may "pollute" the BHMG[16;17], but population synthesis models indicate that these astrophysical effects have a limited impact on the location of the mass gap[18]. Meanwhile, hierarchical mergers taking place in young star clusters or globular clusters can create black holes in the mass gap. Such mergers will leave a distinctive signature on the spins of the black holes as well as their masses, and can be disentangled from the first generation that formed from direct stellar collapse when recovering the location of the BHMG[19–22].
Other physics: Other uncertain physics such as convective mixing, electroweak uncertainties on the neutrino loss rate, and numerical resolution have only a minor impact on the lower edge of the mass gap, changing its location by $1\mathrm{M}_\odot$ or less[13]. Stellar rotation and the efficiency of angular momentum transport may also vary the location of the BHMG by a few percent[23]. This effect may manifest as a correlation between black hole masses and spins, which may be possible to measure with a catalog of BBH sources.

Observational Prospects: The first handful of LIGO/Virgo detections have begun to probe the location of the BHMG, with evidence for a feature at $\sim 45\mathrm{M}_\odot$. While the location and shape of this feature remains uncertain, future gravitational wave observations may reveal correlations between BH masses, spins, and redshifts, and disentangle the various theoretical uncertainties discussed above. These observations may also constrain the upper edge of the gap[24;25]. Within a few years of observation at design sensitivity, the location of the BHMG will be measured with sub-$\mathrm{M}_\odot$ precision[26], providing a novel probe of new physics.

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Authors and endorsers (names and institutions):
Eric Baxter (University of Hawai'i at Manoa)
Emanuele Berti (Johns Hopkins University)
Alessandra Buonanno (Max Planck Institue for Gravitational Phyiscs)
Vitor Cardoso (Instituto Superior Técnico)
Djuna Croon (TRIUMF)
Kristina D. Launey (Louisiana State University)
Nicolas Fernandez (UIUC)
Maya Fishbach (University of Chicago)
Kurt Hinterbichler (Case Western)
Daniel Holz (University of Chicago)
Jonathan J. Heckman (University of Pennsylvania)
Richard J. deBoer (University of Notre Dame)
Austin Joyce (University of Amsterdam)
Joachim Kopp (CERN / JGU Mainz)
Ajit Kumar Mehta (Max Planck Institue for Gravitational Phyiscs)
Jason Kumar (University of Hawaii)
Jose M. Ezquiaga (University of Chicago)
Will M. Farr (Stony Brook University / CCA)
Sam McDermott (Fermilab)
Hector O. Silva (UIUC)
Antonella Palmese (Fermilab)
Aditya Parikh (Harvard University)
Marco Raveri (UPenn)
David Rubin (University of Hawai'i at Mānoa)
Jeremy Sakstein (University of Hawai'i at Manoa)
B.S. Sathyaprakash (Penn State)
Marcelle Soares-Santos (University of Michigan)
Mark Trodden (University of Pennsylvania)
Yu-Dai Tsai (Fermilab) Nico Yunes (UIUC)