Testing general relativity using the black hole mass gap

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Introduction

General relativity (GR) has passed all observational tests to date, but cosmic mysteries such as the Hubble tension and the existence of dark energy might indicate that GR breaks down on cosmological scales. **Modified gravity theories**, such as theories that predict that the strength of gravity is environment dependent, are a promising solution. We test how changing the gravitational constant *G* affects the stars that collapse to form black holes.

Electron-positron pair production in massive stars decreases the pressure and results in an instability that causes the star to pulse and lose mass before collapsing to form a black hole. The most massive stars explode violently in a **pair-instability supernova (PISN)**, leaving behind no black hole. As a result, there is an absence of black holes in a certain mass range.

We study this **black hole mass gap (BHMG)** as a new way to test gravity using LIGO's gravitational wave observations of black holes.

Methods

We use the stellar structure code MESA to simulate the late evolutionary stages of black hole progenitors to study the effects of changing *G* on the location of the BHMG. We modify MESA to change *G* to $(1+\Delta G/G_N)G_N$. In these simulations, we use metallicity $Z = 10^{-5}$, which corresponds to the lower edge of the BHMG in GR.

Results

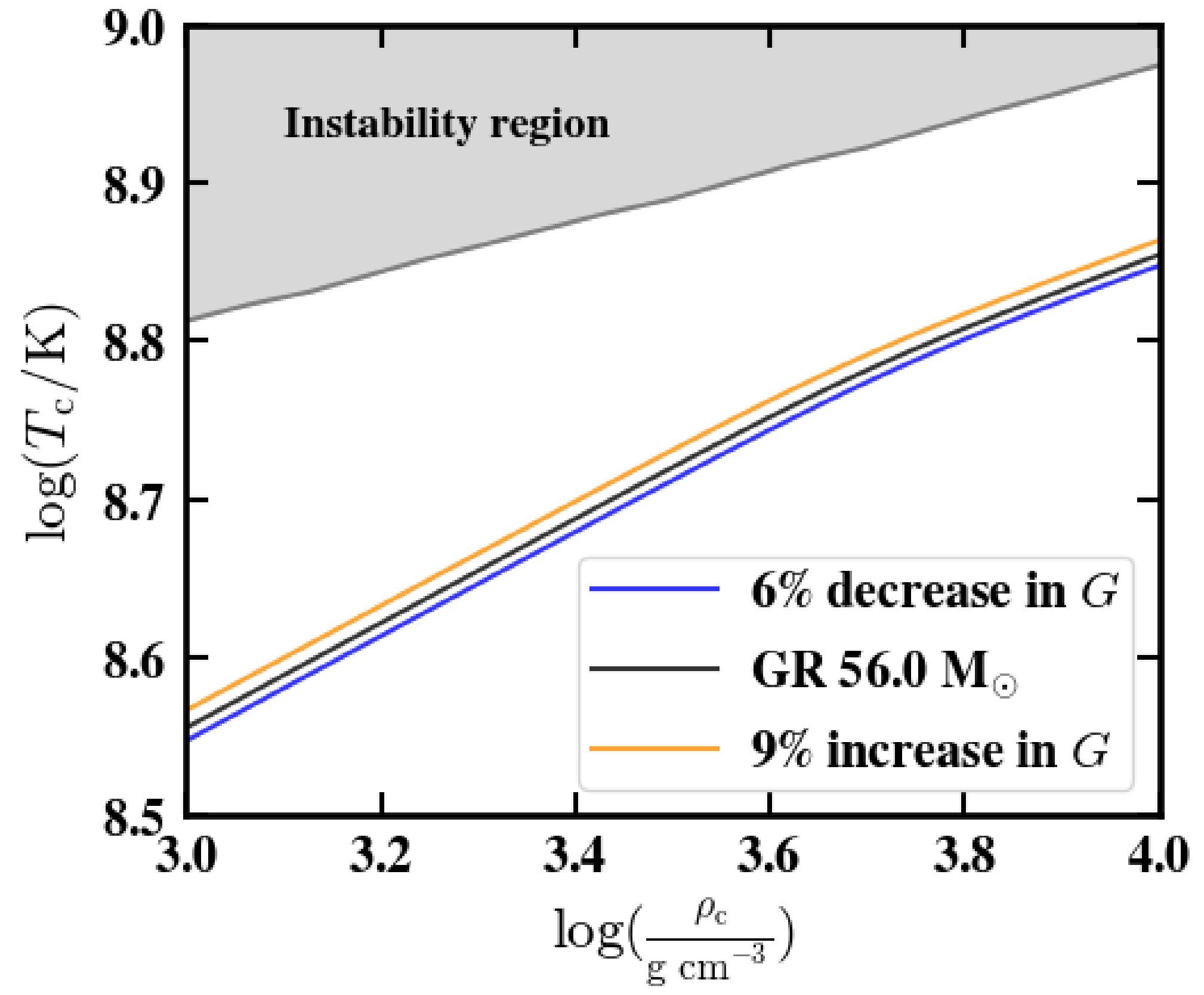

Figure 1 Our results reveal that increasing *G* raises the star's central temperature at a fixed central density, moving the stellar tracks closer to the instability region. A stronger instability will cause more mass to be lost during pulsations.

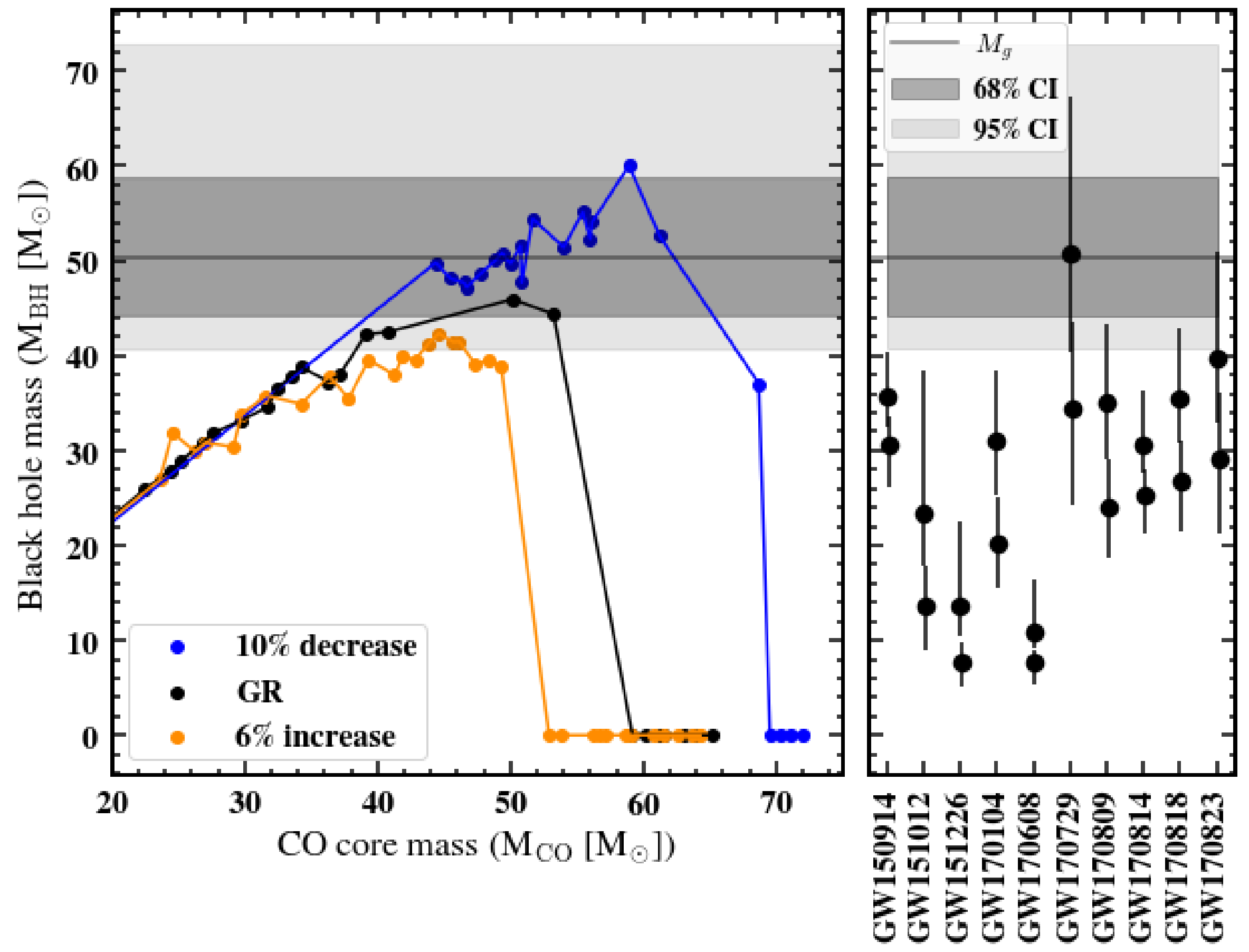

Figure 2 Our grids of masses for different values of *G* show that increasing *G* results in lower mass black holes and lower mass stars going PISN. The right panel shows black hole masses observed by LIGO, and the shaded region represents the constraint on the maximum black hole mass from observations.

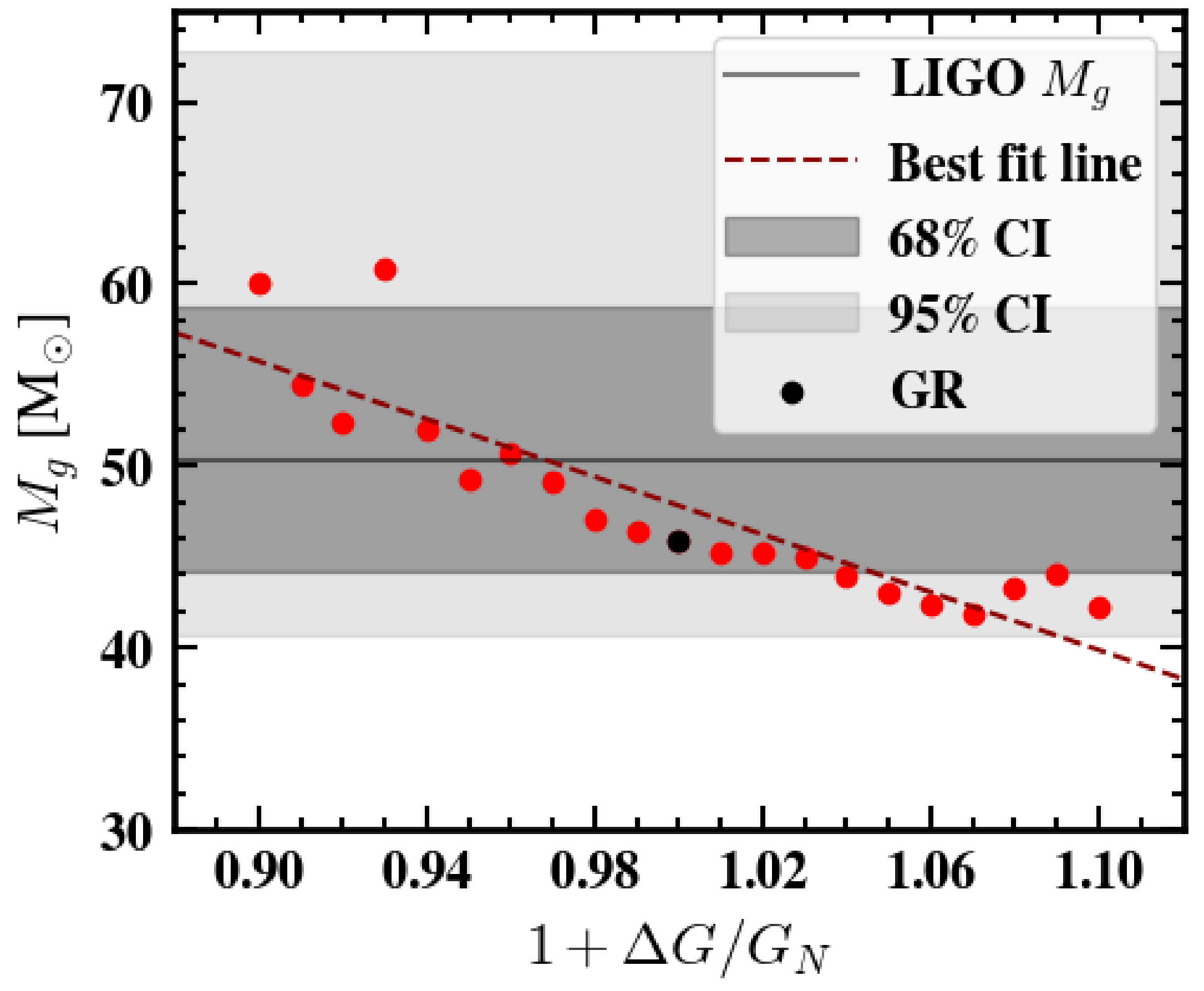

Figure 3 For each grid, we extract the maximum black hole mass, which defines the lower edge of the BHMG. We find that increasing *G* causes stronger pulsations and produces less massive black holes, while the opposite is true for decreasing *G*. This trend persists throughout the range of *G* values we test.

Conclusion

We use a Bayesian analysis to find a posterior probability distribution for *G*. Assuming the relationship shown by the best fit line in Figure 3, we constrain *G* by ~10%. This demonstrates the usefulness of the BHMG for studying gravity and motivates further study.

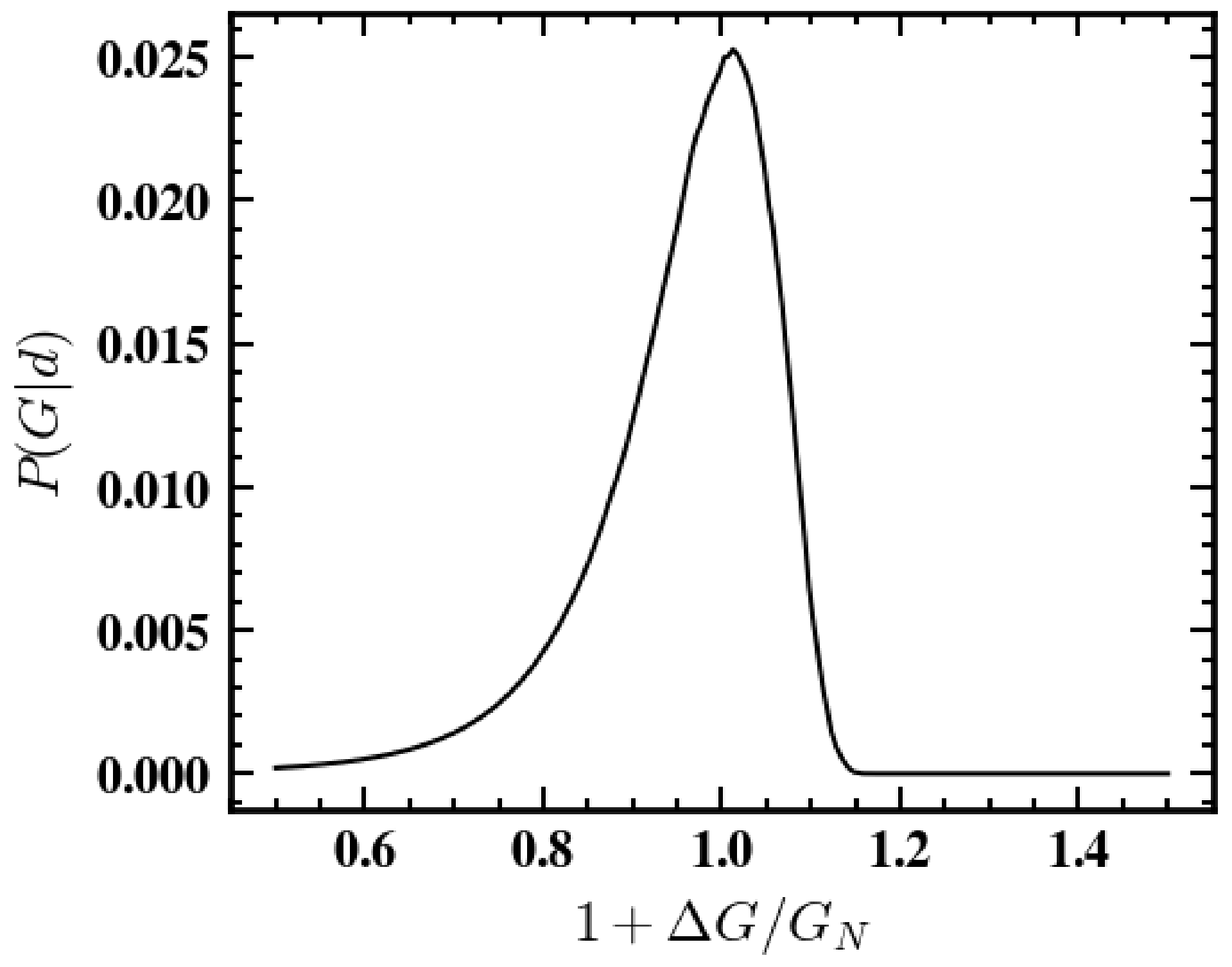

Figure 4 We find $1+\Delta G/G_N = 0.98^{+0.06}_{-0.09}$ for a 68% confidence interval.

Future Work

- Quantify systematics such as nuclear reaction rates, metallicity, and binarity
- Cross correlate LIGO signal with galaxy clustering maps to test environmental dependence of *G*

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References

R. Farmer, M. Renzo, S. de Mink, P. Marchant, and S. Justham. Mind the gap: The location of the lower edge of the pair instability supernovae black hole mass gap. 10 2019. doi: 10.3847/1538-4357/ab518b.

M. Fishbach and D. E. Holz. Where Are LIGO's Big Black Holes? Astrophys. J. Lett., 851(2):L25, 2017.doi: 10.3847/2041-8213/aa9bf6.

B. Paxton et al. Modules for Experiments in Stellar Astrophysics (MESA): Convective Boundaries, Element Diffusion, and Massive Star Explosions. Astrophys. J. Suppl., 234(2):34, 2018. doi: 10.3847/1538-4365/aaa5a8.