Peering into the Gap: Learning about Dark Matter from the Pair Instability Mass Gap

Joshua Ziegler[1], Katherine Freese[1,2,3]
[1]Texas Center for Cosmology and Astroparticle Physics, Weinberg Institute for Theoretical Physics, University of Texas at Austin
[2]Oskar Klein Center, Department of Physics, Stockholm University
[3]Nordic Institute of Theoretical Physics (NORDITA)

The University of Texas at Austin
Department of Physics
College of Natural Sciences

Introduction

Stellar black holes are expected not to form with masses in the range 50-140 solar masses. During the evolution of the stellar progenitor, pair instability supernovae prevent black holes of these masses from forming. Consequently, the observed mass spectrum of black holes should show a distinct **black hole mass gap** in this range. However, the LIGO and Virgo Collaborations identified a pair of black holes with masses 66 and 85 solar masses in 2019.

Separately, if dark matter annihilates into standard model particles, the energy produced is expected to lead to a phenomenon known as a **dark star**. Dark stars are clouds of gas that are supported entirely by the annihilation of dark matter, and have properties somewhat similar to very large and low density stars. The mechanism behind dark stars naturally produces quite massive objects, but in principle could exist in smaller objects, on the order of hundreds of solar masses for example.

If dark matter annihilation is relevant in stars with these mass ranges, we can hope to find signatures of it both in the black hole mass spectrum and in other astrophysical observations.

Theory

We simulate the evolution of stars of mass 70-300 solar masses with the inclusion of non-nuclear energy. For simplicity, we consider a constant non-nuclear energy of the form,

$$\epsilon(M) = const.$$

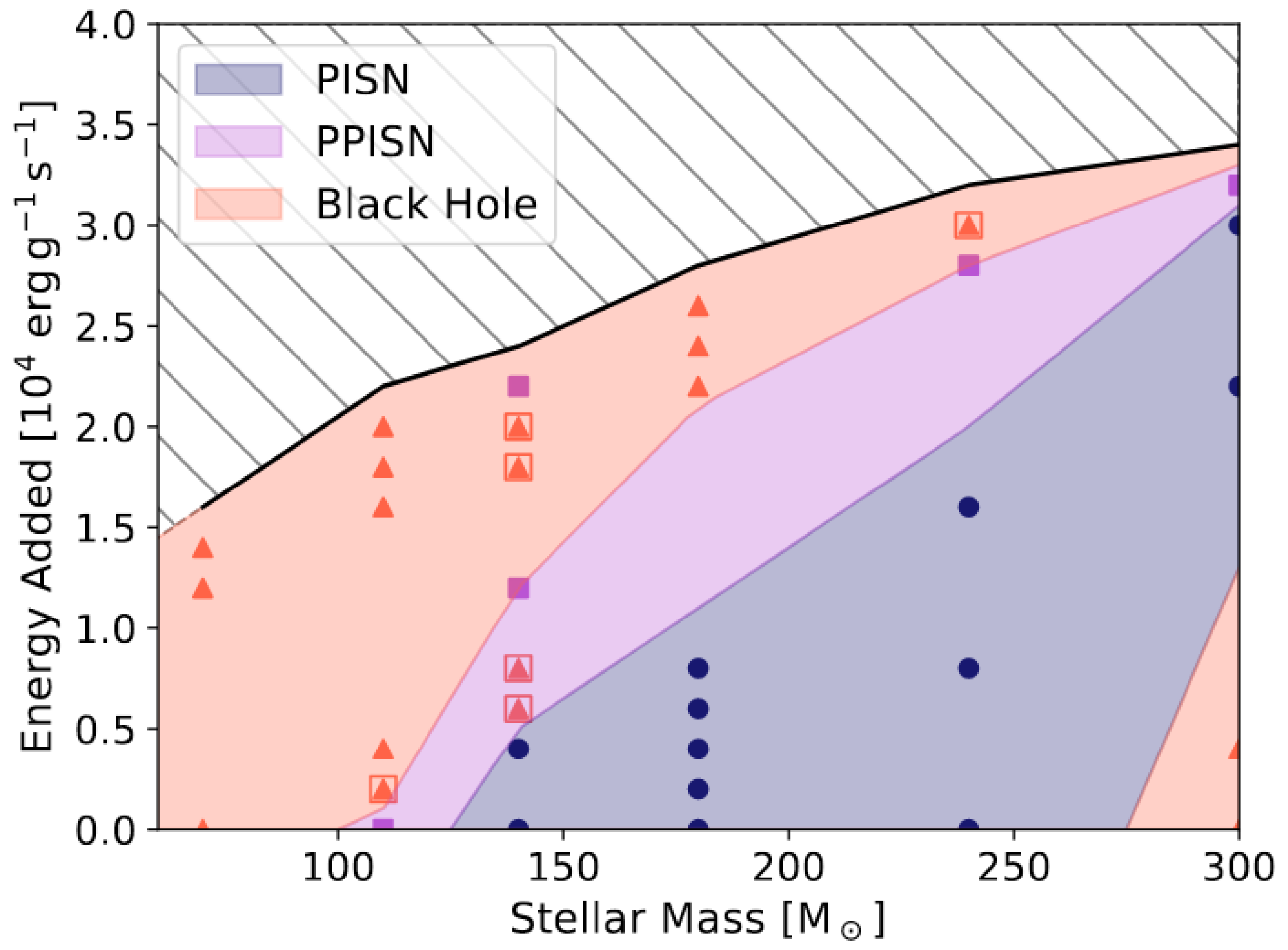
but the results can be extended to more physically reasonable energy profiles.

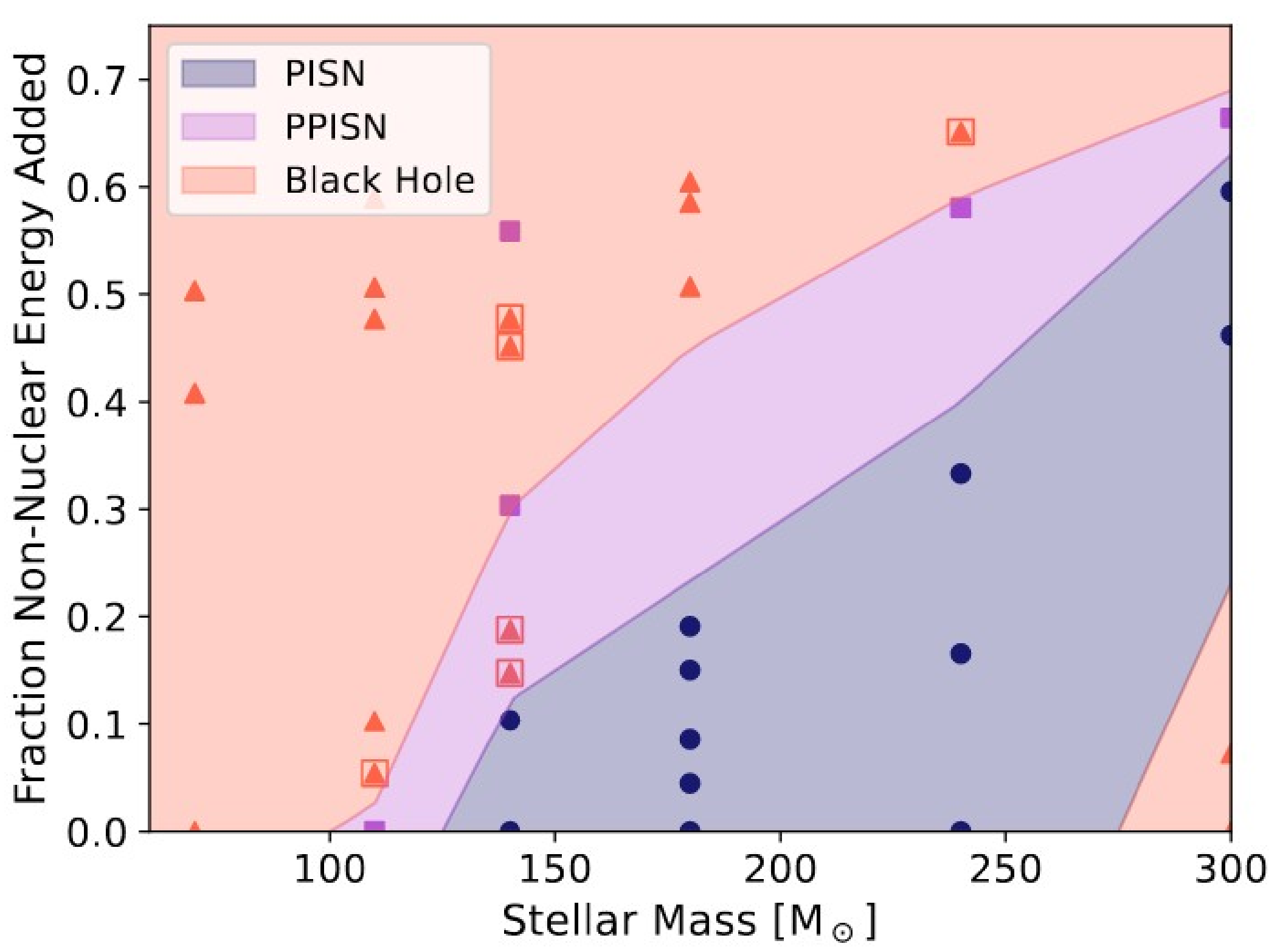
To simulate the stellar evolution, we use the one dimensional stellar evolution equations:

$$\frac{\partial r}{\partial M} = \frac{1}{4\pi r^2 \rho}$$
$$\frac{\partial P}{\partial M} = -\frac{GM}{4\pi r^2} - \frac{\partial^2 r}{\partial t^2}\frac{1}{4\pi r^2}$$
$$\frac{\partial L}{\partial M} = \epsilon - C_p \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t} + \epsilon_{non-nuc}$$
$$\frac{\partial T}{\partial M} = -\frac{GMT}{4\pi r^4 P}\nabla$$

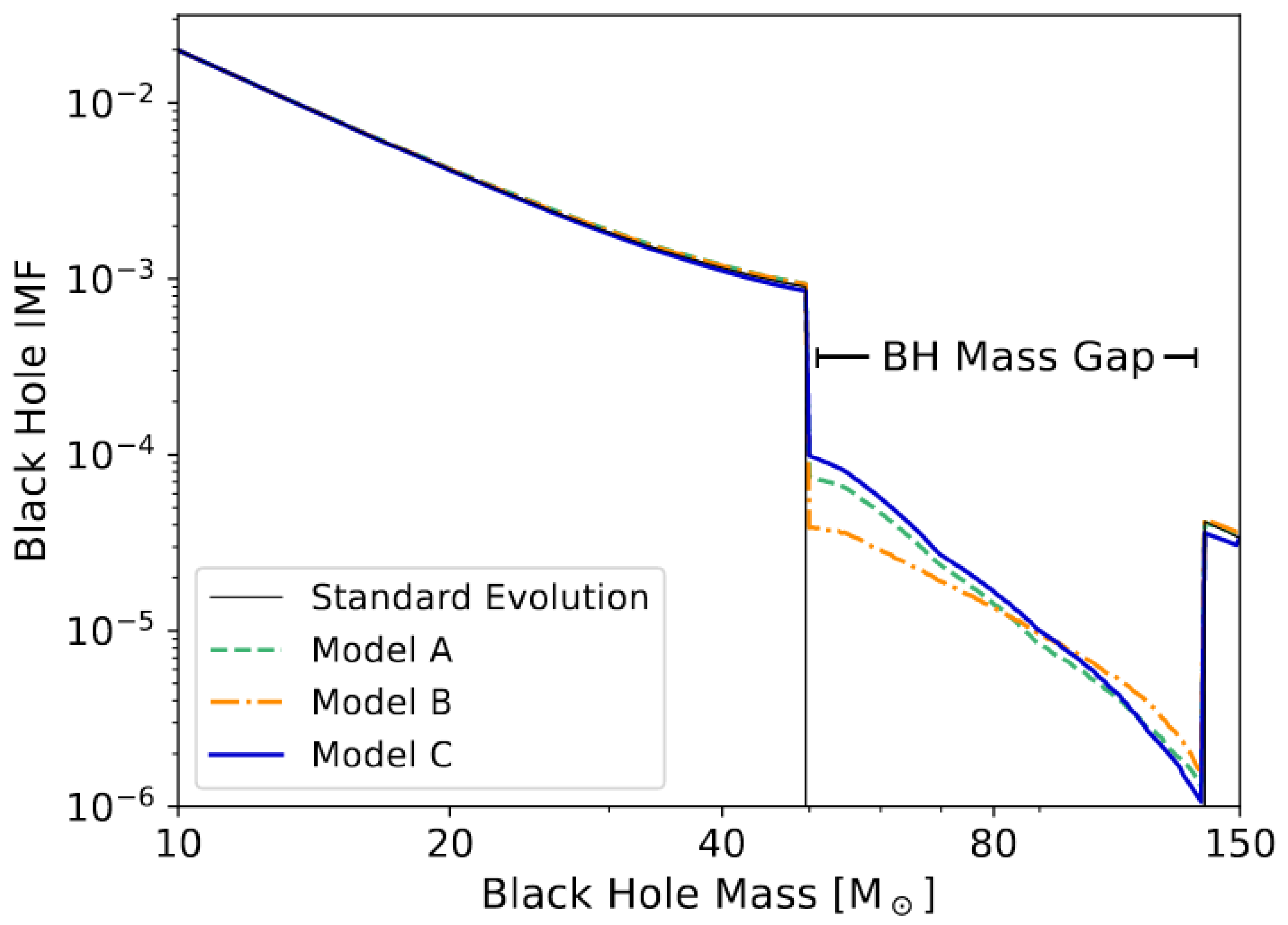
Inclusion of non-nuclear energy causes slight changes to the stellar evolution throughout the lifetime of the star, but the most noticeable effects occur near the end of a star's lifetime.

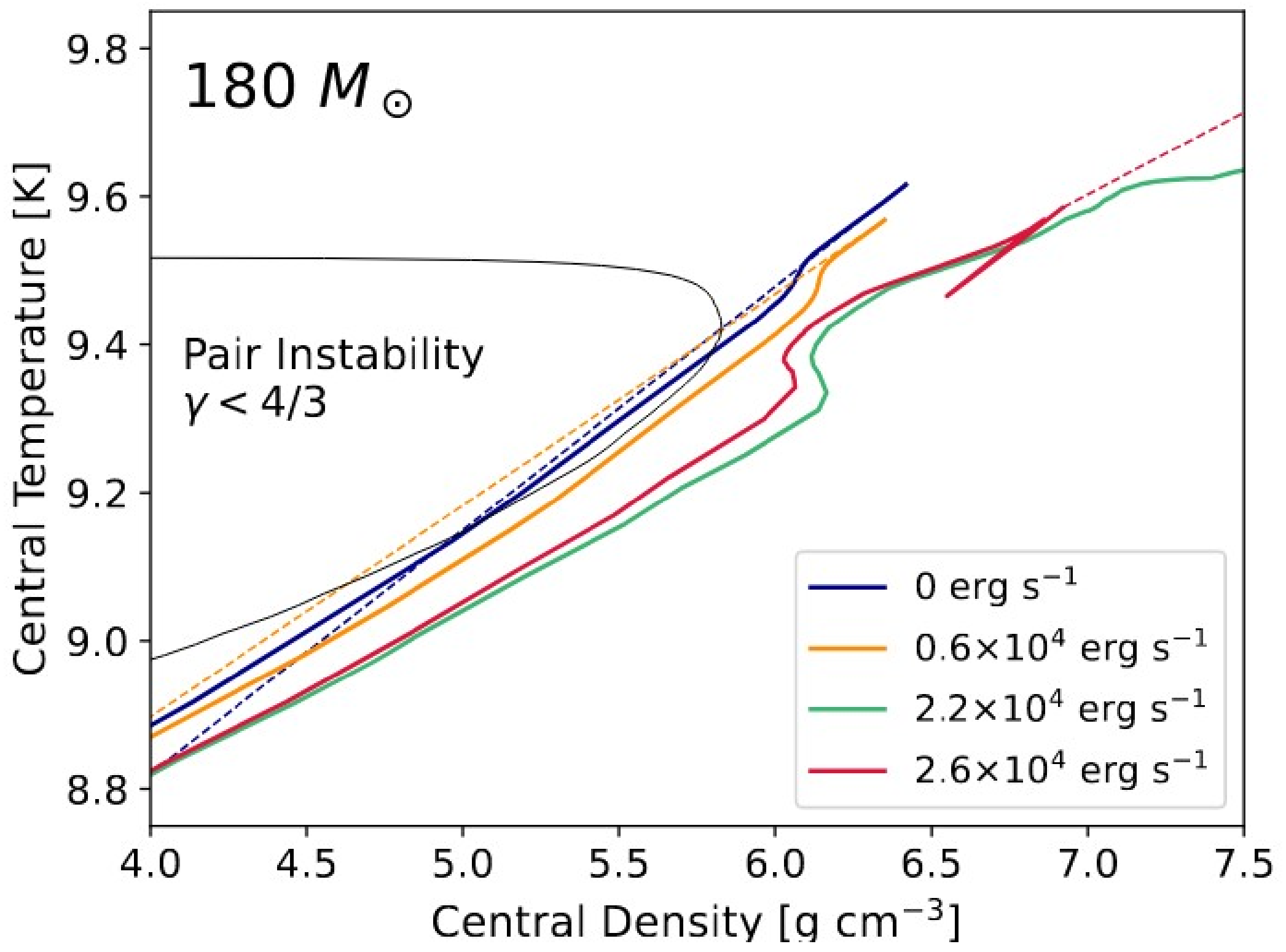
Black Hole Mass Spectrum





Stars in this mass range can experience one of three evolutionary behaviors.
Core-Collapse Supernova (CCSN): When iron core reaches sufficient mass, it collapses. Infall is halted when core reaches nuclear degeneracy pressures, and infalling material bounces outward. The outgoing shockwave is the source of the observable supernova. The mass of the resulting compact object is comparable to the mass of the stellar progenitor.
Pair Instability Supernova (PISN): Core temperatures are sufficiently high that photons in the core pair produce electrons and positrons. The loss of pressure causes the core to collapse. Increased temperature allows oxygen to fuse, which produces a shockwave that leads to a supernova. Notably, this type of supernova leaves behind no compact remnant.
Pulsational Pair Instability Supernova (PPISN): Similar to a PISN, electron-positron pair production causes core to collapse. However, a smaller fraction of radiation converts to electron-positron pairs, so oxygen fusion does not produce as powerful of a shockwave. A portion of the star is ejected, but the remainder starts evolving again at a lower core temperature. Repeated episodes of pair instability produces a pulsing effect that leads to a black hole with significantly lower mass than the progenitor star.





Inclusion of non-nuclear energy leads stars to have a more massive envelope (and consequently less massive core) than than fusion-only stars of the same initial mass. As a result, higher amounts of non-nuclear energy produces effects similar to those achieved in higher mass stars. Consequently, stars that include non-nuclear energy can avoid pair instability at higher masses than stars without non-nuclear energy. This could allow black holes in the pair instability mass gap, as long as sufficient numbers of stars include non-nuclear energy. With sufficient numbers of black hole observations, we may be able to place constraints on dark matter properties.

Astrophysical Predictions

Oscillating Burst Event: in some cases, we predict an outflow of stellar material from the core of a star shortly before a core collapse supernova. We ended our simulations prior to allowing this outflow to reach the surface (in most cases), so it is unclear how this observable signature would present. In the most optimistic scenarios, we can hope that this signature would be observable in highly resolved supernova light curves.
Dredge-up: In some cases, the inclusion of non-nuclear energy encouraged greater mixing between the core and envelope of a star. Eventually, this leads the surface composition of the star to be metal-rich, compared to the initial metallicity of the star. This may appear observationally as a population of very massive stars with unexpectedly high metallicity

Conclusion

- Stars that are partially supported by non-nuclear energy exhibit different evolutionary behaviors than their fusion only counterparts.
- Differences in evolution can potentially lead to black holes in the pair instability mass function
- Evolution may offer astrophysically observable signatures.
- If observable, these evolutionary differences may be used to probe the source of the non-nuclear energy, potentially allowing relatively model-independent constraints on dark matter.

Acknowledgments

K.F. is Jeff & Gail Kodosky Endowed Chair in Physics at the University of Texas at Austin, and K.F. and J.Z. are grateful for support via this Chair. K.F. and J.Z. acknowledge support by the U.S. Department of Energy, Office of Science, Office of High Energy Physics program under Award Number DE-SC-0022021 as well as support from the Swedish Research Council (Contract No. 638-2013-8993).

References

- J. Ziegler and K. Freese, arXiv:2212.13903 (to be published).
- J. Ziegler and K. Freese, Phys. Rev. D **104**, 043015 (2021). [arXiv:2010.00254]
- S.E. Woosley, A. Heger, and T.A. Weaver, Reviews of Modern Physics **74**, 1015 (2002).