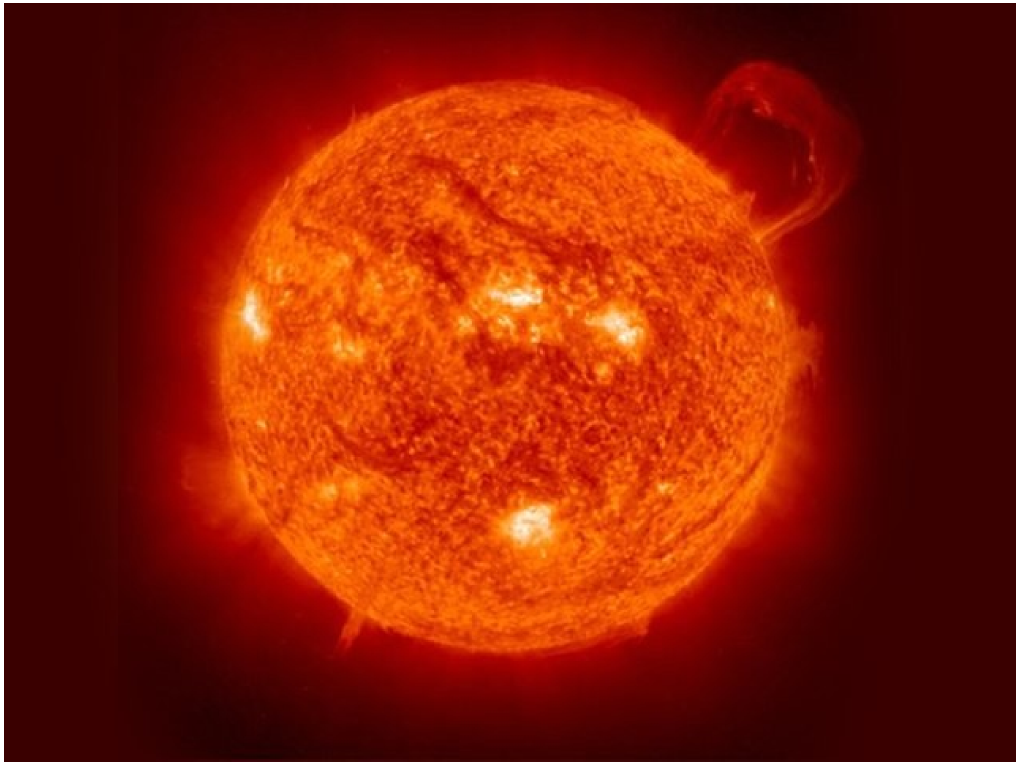
Dark Matter Annihilation in Stars: A New Lease on Life



COSMO 2022,Río de Janeiro

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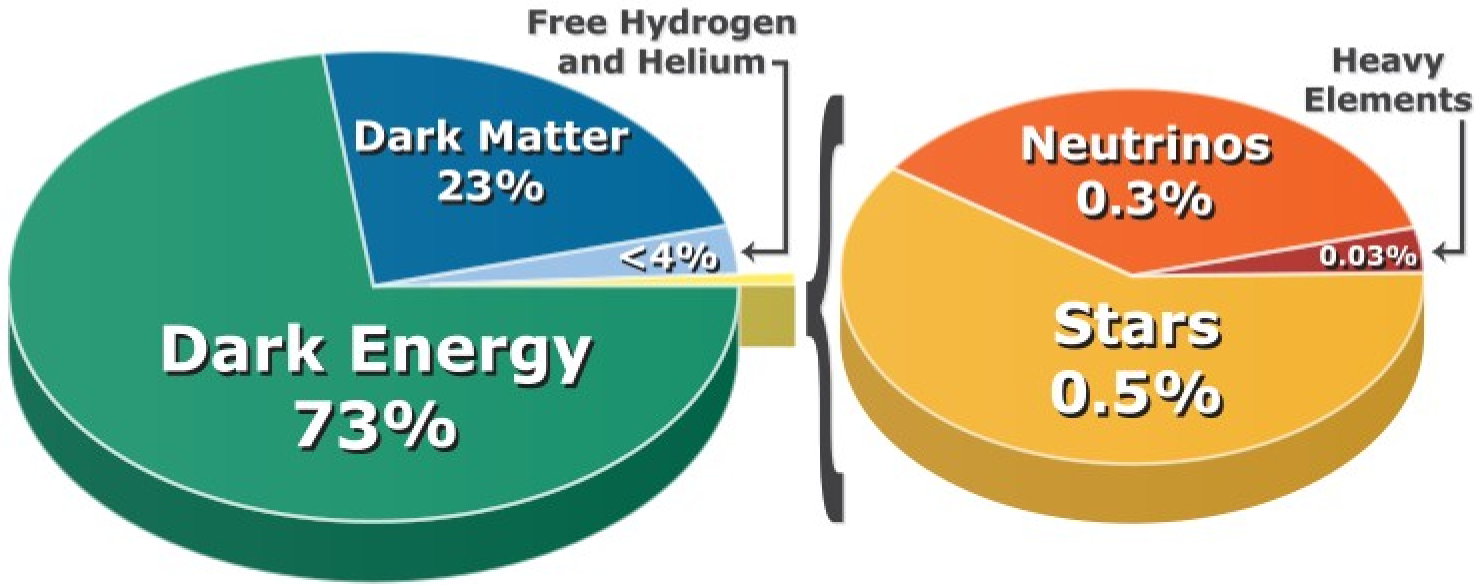
24 Aug 2022

Contents

1. Introduction



- Indirect detection through stellar processes
- Why stars?
  - Easily observable, abundant source
  - Interior of stars dense enough that dark matter effects independent of specific branching ratios
  - Difficult to distinguish effects due to stellar physics from effects due to new physics

2. 1D Stellar Evolution

- Assume spherical symmetry, no magnetic fields, no rotation
- Zero metallicity (Type III stars)
- MESA: Modules for Experiments in Stellar Astrophysics
  - Choice of input masses, chemical compositions, nuclear networks, thermal properties, etc.
  - Produces time series of stellar structure

$$\frac{\partial r}{\partial M} = \frac{1}{4\pi r^2 \rho}$$

$$\frac{\partial P}{\partial M} = -\frac{GM}{4\pi r^2} - \frac{\partial^2 r}{\partial t^2}\frac{1}{4\pi r^2}$$

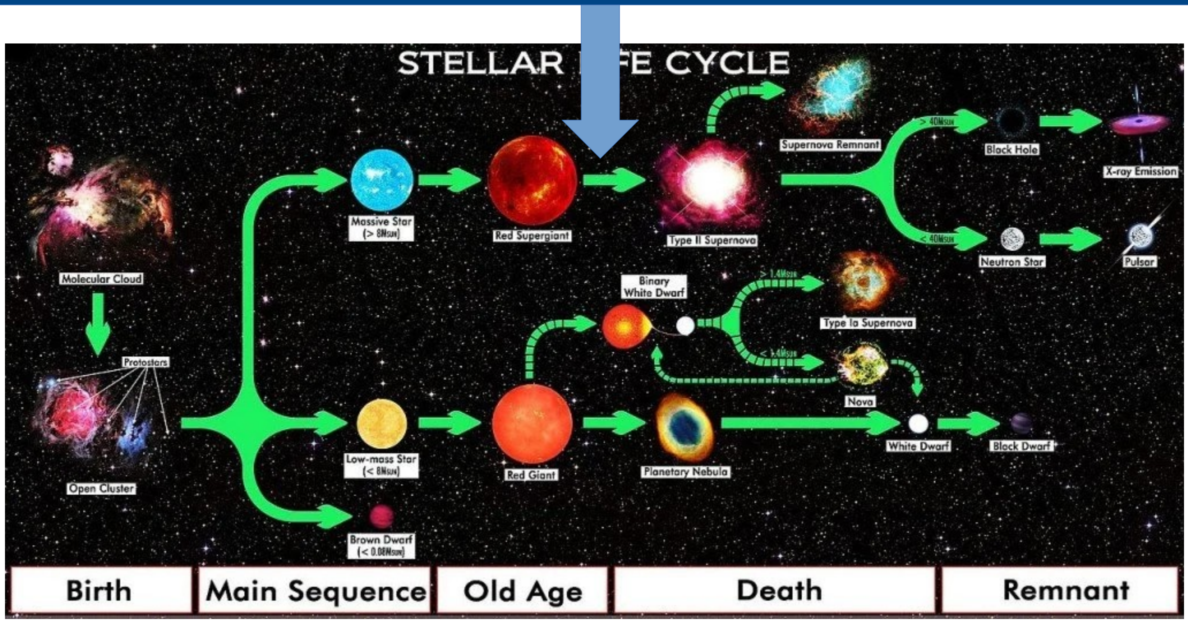
$$\frac{\partial L}{\partial M} = \epsilon - C_P\frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t}$$

$$\frac{\partial T}{\partial M} = -\frac{GMT}{4\pi r^4 P}\nabla$$

ϵ Specific energy production rate (erg g^{-1} s^{-1})

∇ Function related to energy transport and opacity within star

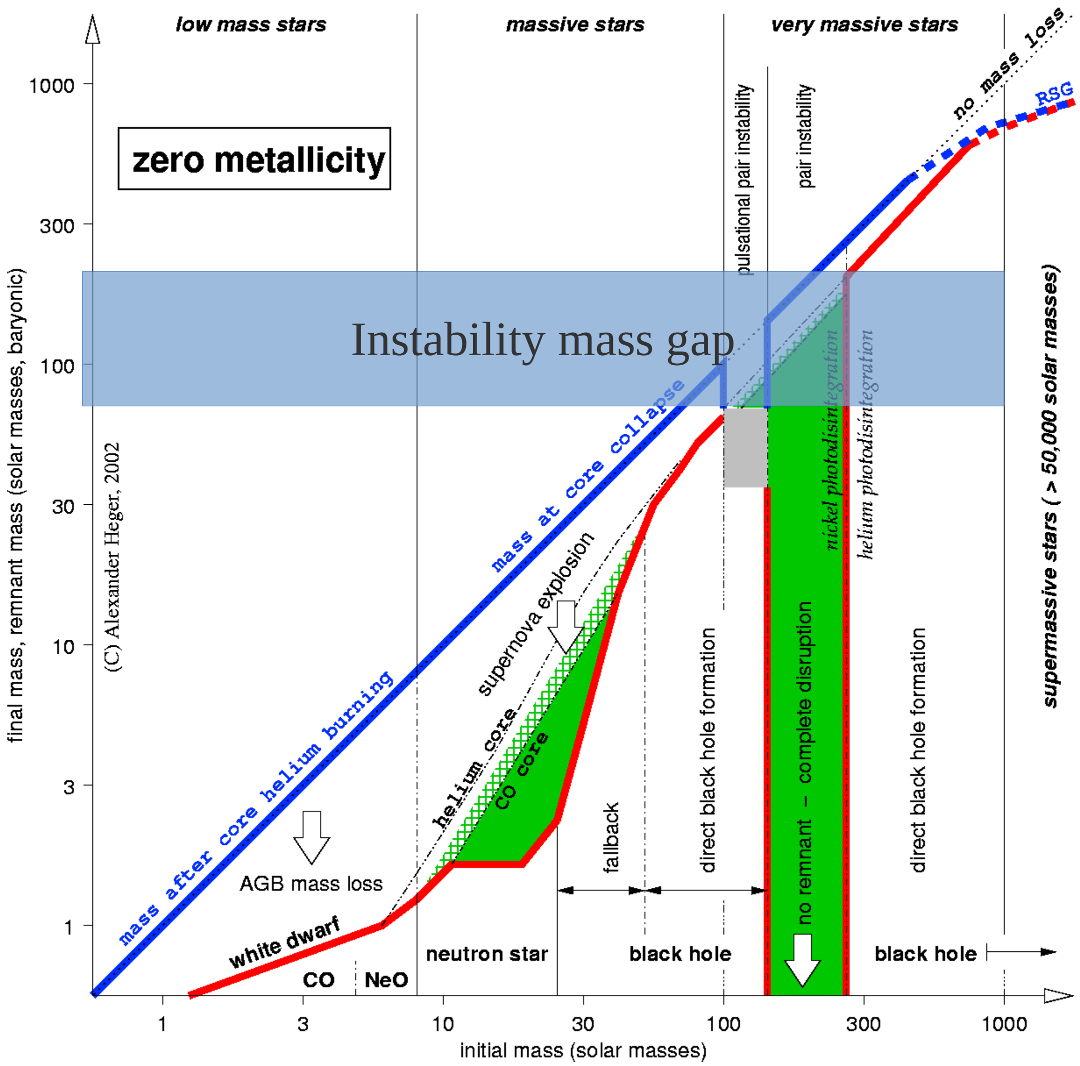
2. Pair Instability



- Massive stars (~140 – 240 $M_{\odot}$) reach temperatures and densities such that electron-positron pairs are produced late in their life
- $\gamma\gamma \rightarrow e^{-}e^{+}$
- Leads to a pair instability collapse
- Collapse triggers fusion of oxygen and silicon, which leads to violent bounce
  - Complete destruction of star: pair instability supernova (PISN)
  - Ejection of part of star: pulsational pair instability supernova (PPISN)

2. Black Hole Mass Gap

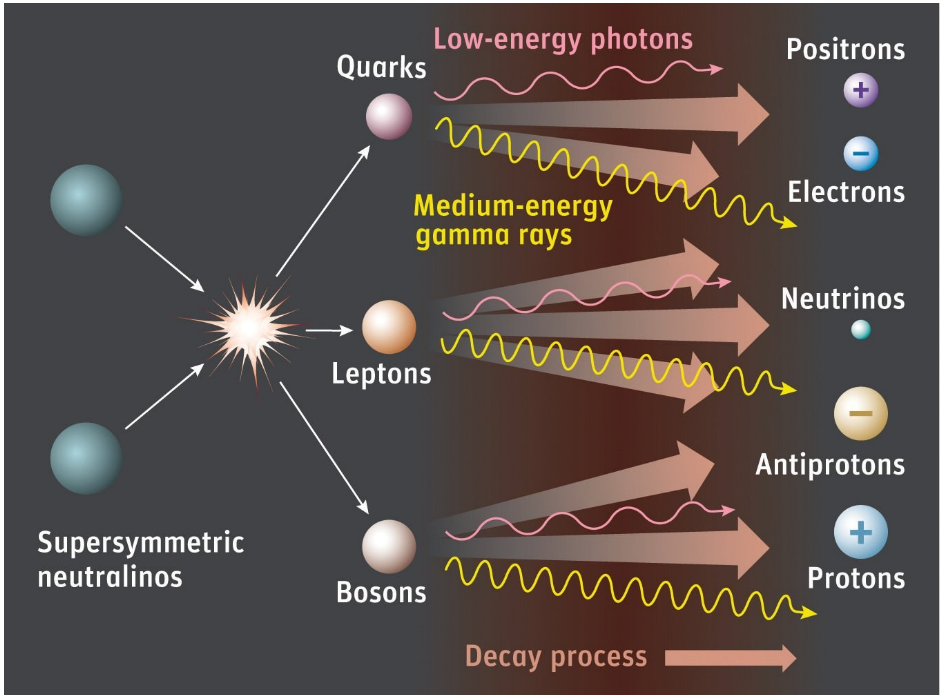
- Due to PISN and PPISN, black holes cannot form with (initial) masses between ~50 and 140 $M_\odot$
- Black holes can exist in the mass gap (e.g. GW190521):
  - Multiple mergers
  - Uncertainties
  - New physics
- Population statistics of black holes may offer test of these explanations



The evolution and explosion of massive stars. S.E. Woosley, A. Heger, T.A. Weaver, Mod. Rev. Phys. **74**, 1015 (2002).

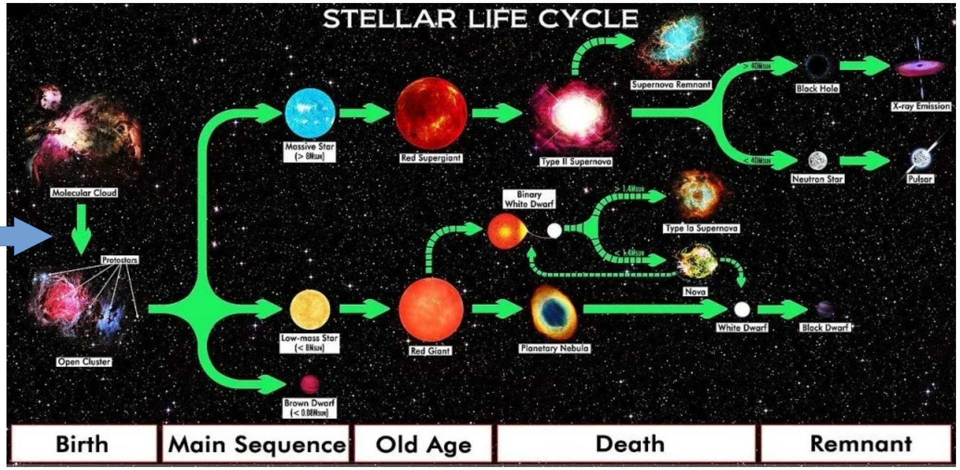
3. Dark Matter Model

- Minimal assumptions about dark matter:
  - Particles
  - Either self-annihilate or non-negligible amount of anti-particle
  - Annihilation products include some fraction of charged SM particles
- All charged particles heat up star
- Energy produced from one annihilation = twice DM mass, efficient source of energy

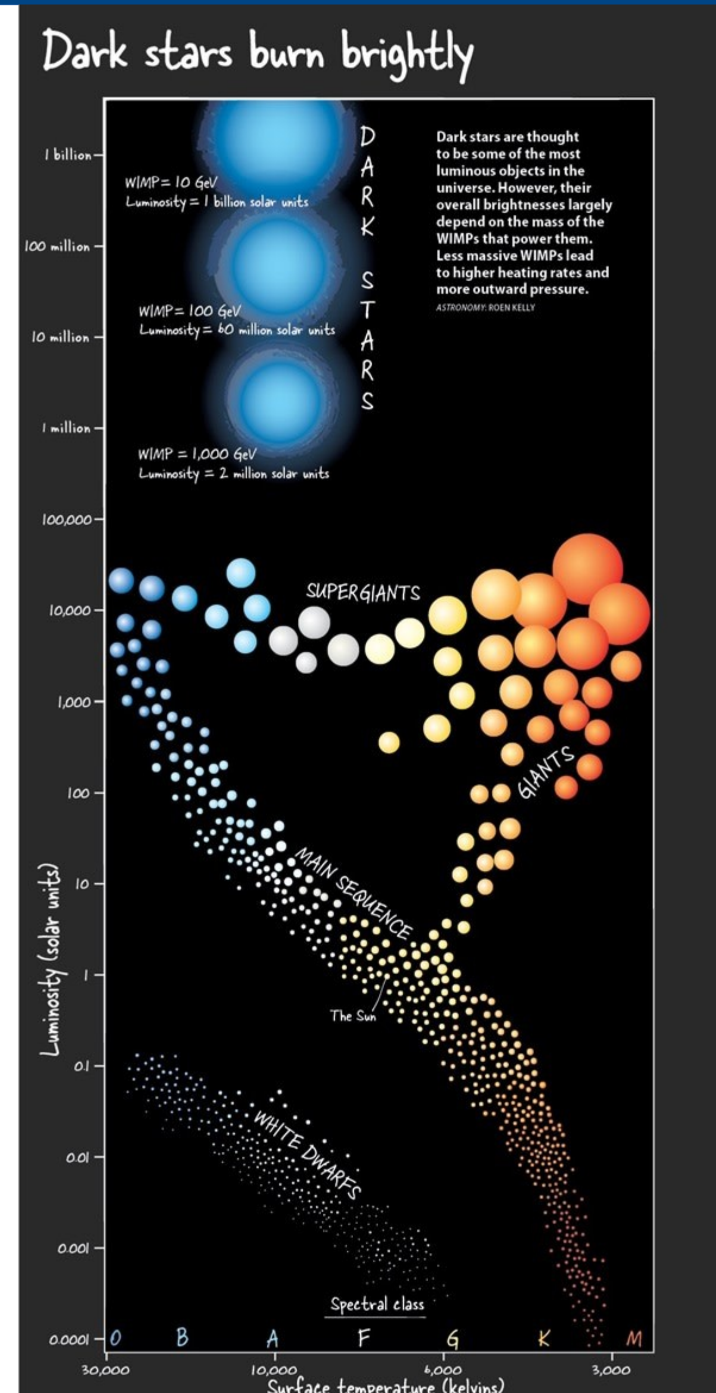


Sky and Telescope, Gregg Dinderman
https://www.universetoday.com/116293/marco-view-makes-dark-matter-look-even-stranger/

3. Dark Stars



- First stars in proto-galaxies, but only one per galaxy
- Dark matter annihilation fully supports cloud of gas and dust against gravity before fusion starts
- Cold and fluffy object produces little feedback to stop growing
- Requires adiabatic contraction to increase DM density enough for annihilation to be important



Astronomy, Roen Kelly
https://www.discovermagazine.com/the-sciences/the-early-universe-may-have-been-filled-with-dark-matter-stars

4. Stellar Evolution with Extra Energy

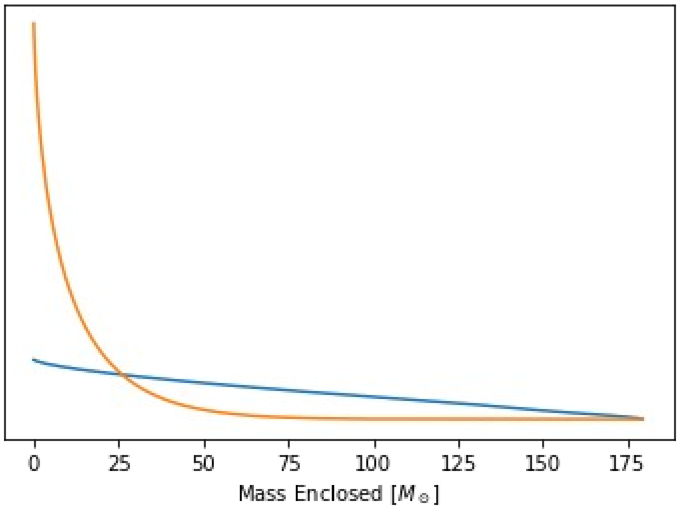
- Approximate the energy produced through dark matter as a constant energy production rate density
- Compared to nuclear energy, which is strongly centrally peaked, treating energy from dark matter as a constant is reasonable

$$\frac{\partial r}{\partial M} = \frac{1}{4\pi r^2 \rho}$$

$$\frac{\partial P}{\partial M} = -\frac{GM}{4\pi r^2} - \frac{\partial^2 r}{\partial t^2}\frac{1}{4\pi r^2}$$

$$\frac{\partial L}{\partial M} = \epsilon - C_P \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t} + \boxed{\epsilon_{non-nuc}}$$

$$\frac{\partial T}{\partial M} = -\frac{GMT}{4\pi r^4 P}\nabla$$

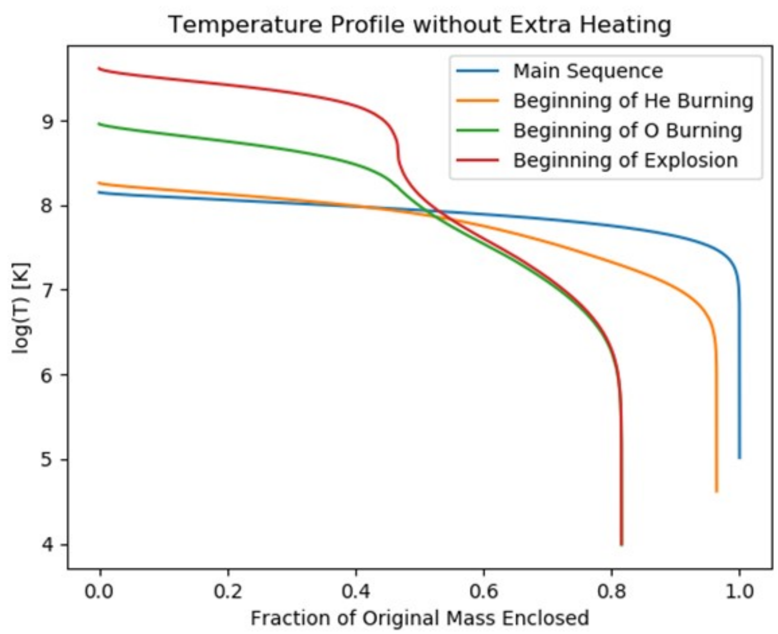


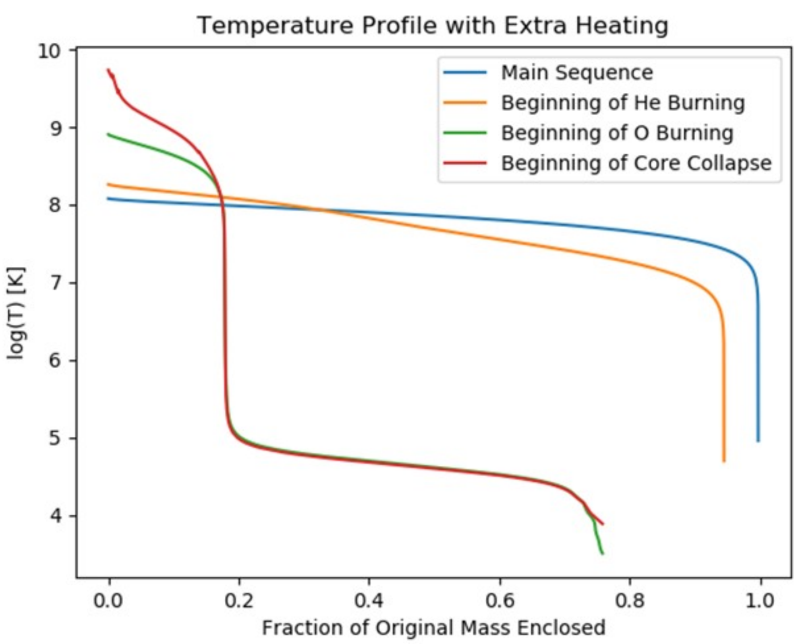
Assuming WIMP dark matter and adiabatic contraction

$$\epsilon_\chi \sim \rho^{0.62}$$

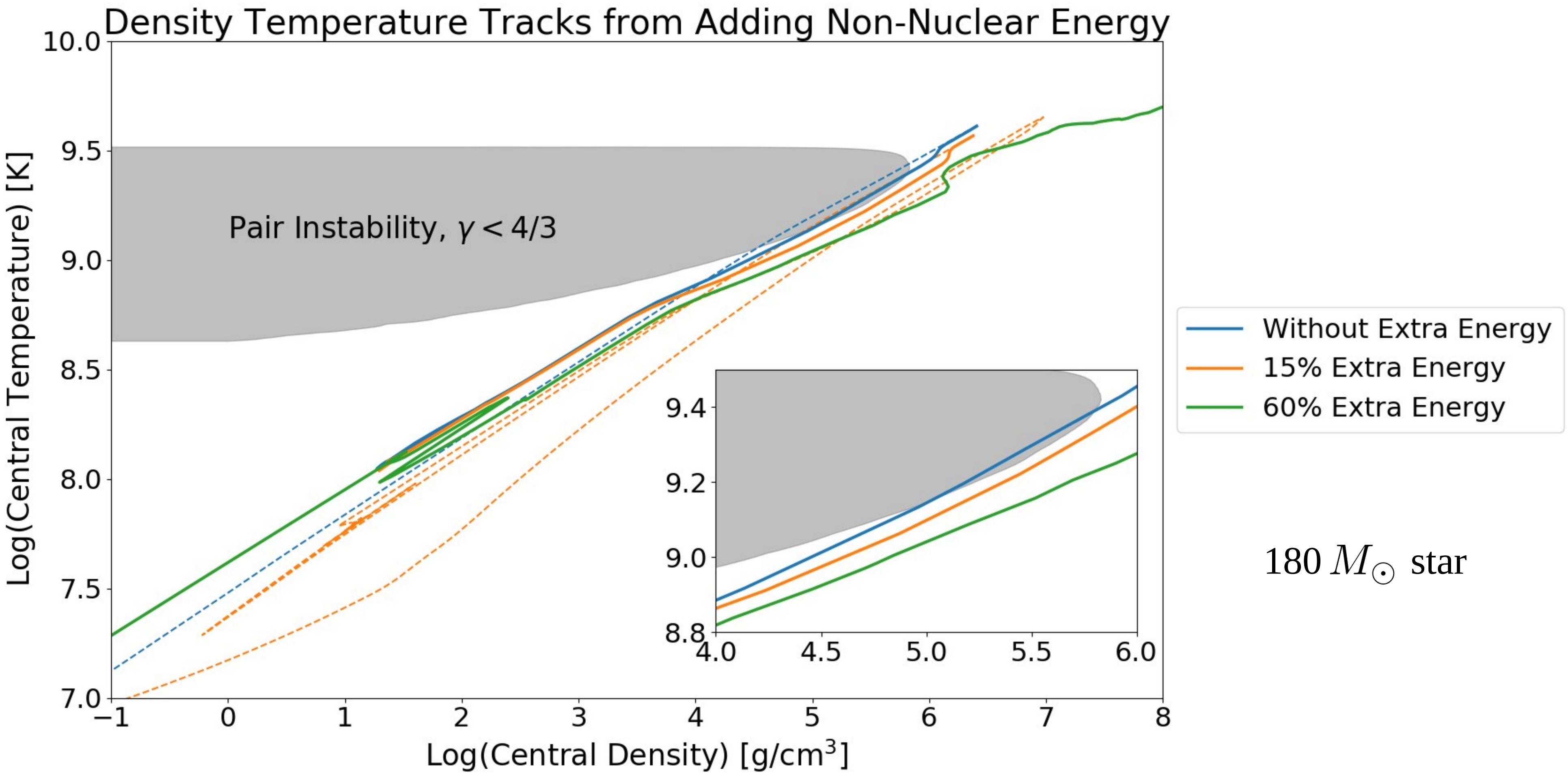
4. Structural Changes

- Extra energy in the star → less energy required from nuclear reactions
- Effectively reducing size of core, relative to overall mass of star
- In some cases, changes to temperature and density gradients increase convective mixing in star and can further reduce core mass



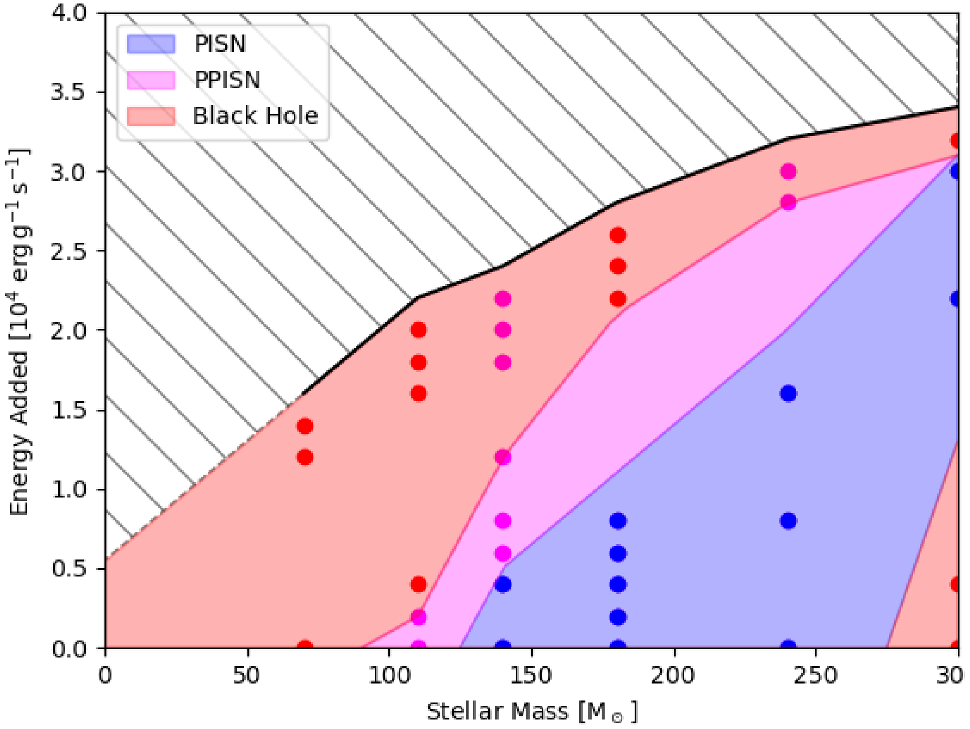


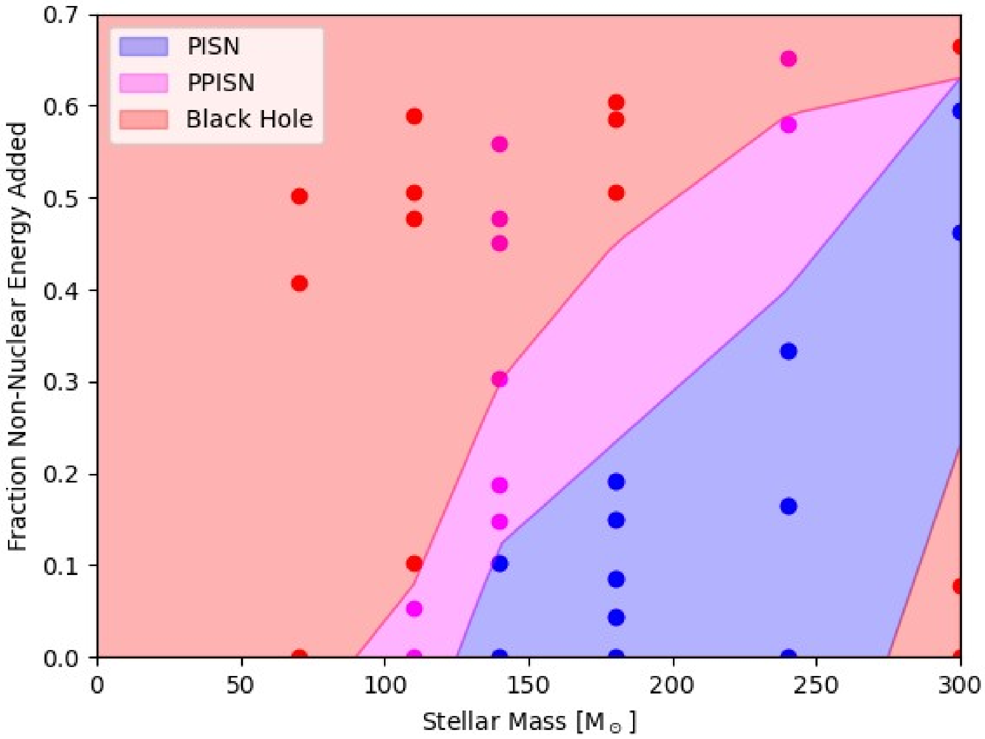
4. Avoiding Pair Instability



180 $M_\odot$ star

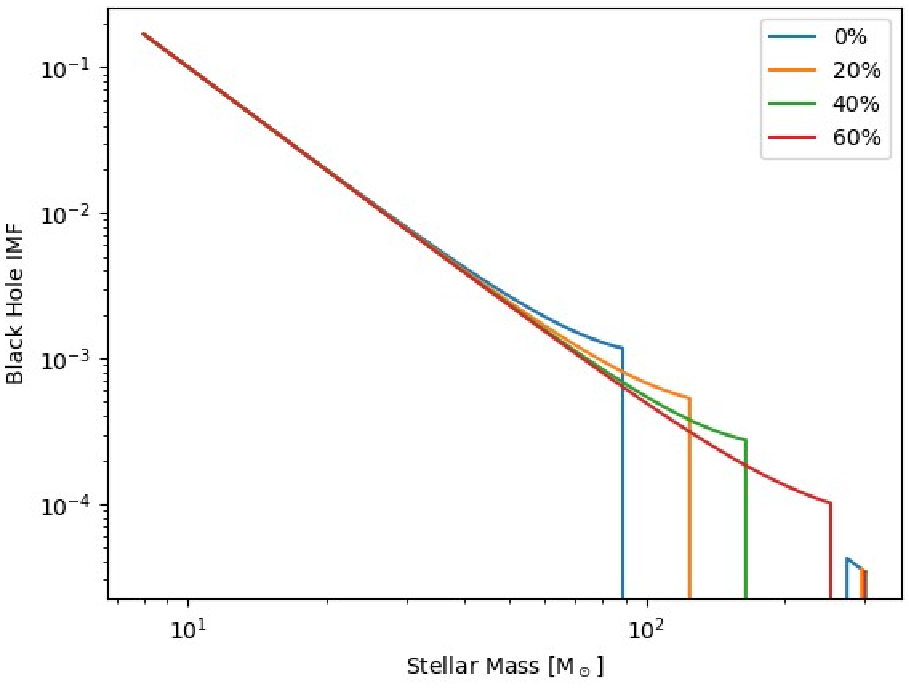
4. How unique is this result?



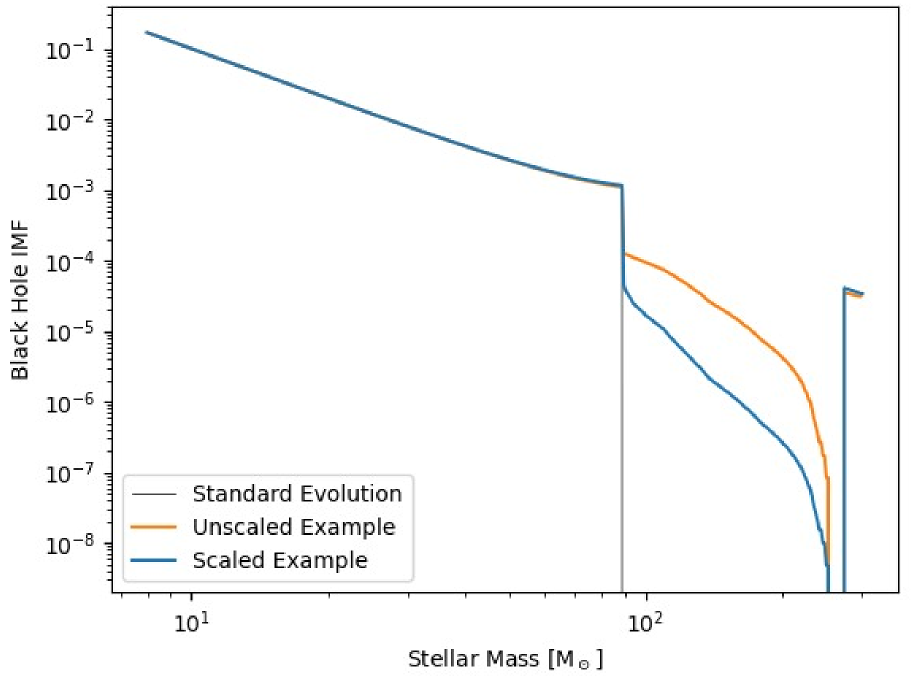


4. Potential Tests

- Black hole population statistics (BHIMF)
- Depends significantly on dark matter astrophysics



Assuming all stars include non-nuclear energy



Illustrative examples:

Unscaled: 0.1% of stars with non-nuclear energy, uniform distribution of energy fractions

Scaled: fraction of stars with non-nuclear energy ranges from 1% to 0.01% inversely with non-nuclear energy fraction

Fine print: these plots show (core-collapse) supernova precursors, rather than black hole mass

PRELIMINARY

4. Dark Matter as energy source

- $\epsilon_{DM}\rho_{gas}=\langle\sigma v\rangle(\rho_\chi)^2/m_\chi$
- Necessary density is $\rho_\chi \sim 10^{-7}\, g\, cm^{-3} \left(\frac{3\times10^{-26} cm^3 s^{-1}}{\langle\sigma v\rangle}\right)^{1/2} \left(\frac{m_\chi}{1GeV}\right)^{1/2}$

- Possible environments with high enough dark matter density:
  - Centers of (small/dwarf) proto-galaxies
  - Dark matter spikes around intermediate- or super-massive black holes
  - High scattering cross-section

5. Conclusion

- Adding a non-nuclear energy source to a star can provide a means to circumvent pair instability and avoid a pair instability supernova
- It seems that this behavior appears at all stellar masses: there always exists an amount of energy such that pair instability can be avoided.
- Potential opportunities to detect include black hole population statistics, from gravitational wave observatories
- Although rare, environments where dark matter density is high enough that this could potentially occur have been proposed.

- Potentially allows probes of:
  - Dark matter distribution within halo
  - Properties of dark matter (scattering vs annihilation cross section)
  - Stellar processes

6. References

- J. Ziegler and K. Freese, Phys. Rev. D **104**, 043015 (2021).

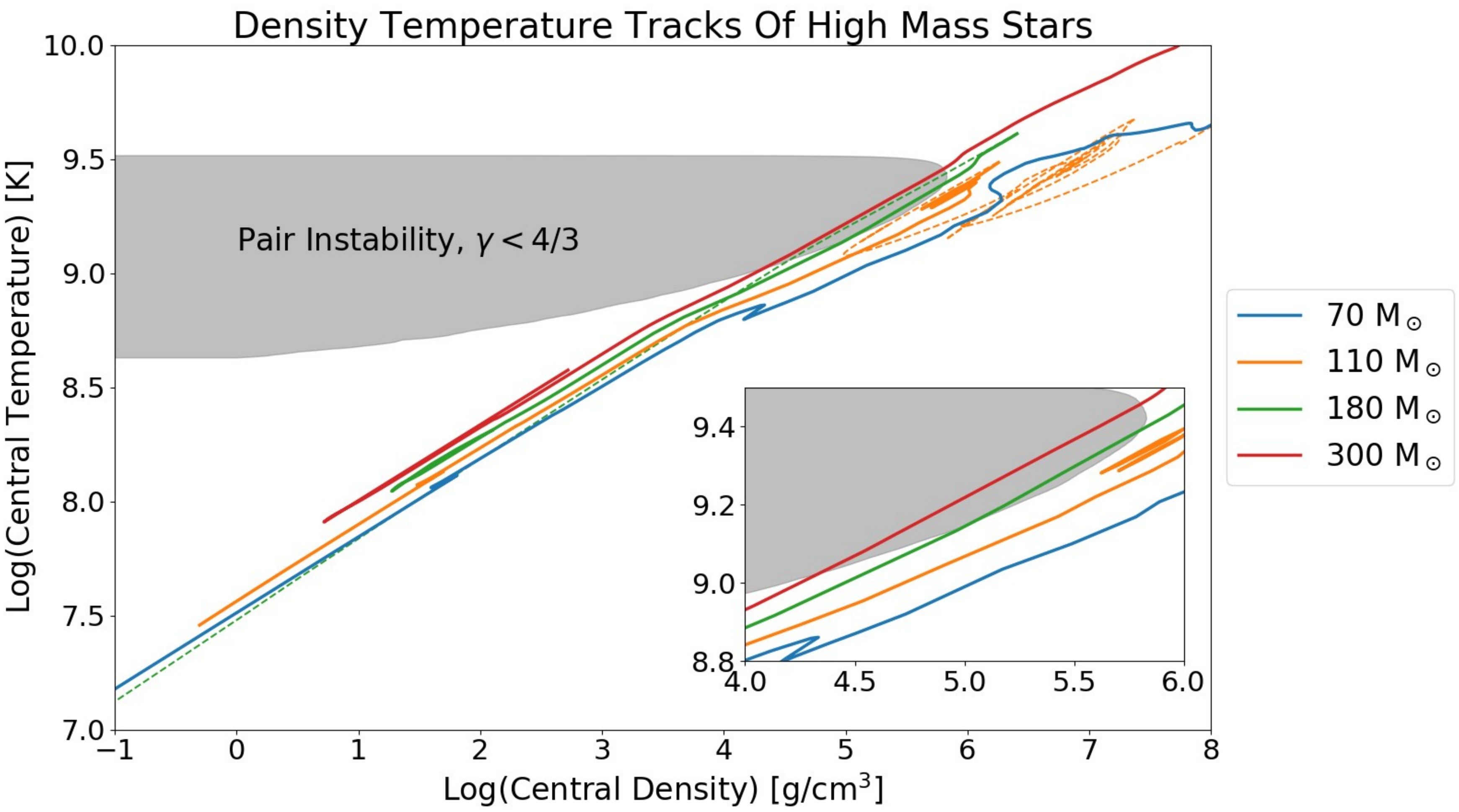
  https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.043015

- R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. **125**, 101102 (2020)

  https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.101102

- S. E. Woosley, A. Heger, and T. A. Weaver, Rev. Mod. Phys. **74**, 1015 (2002).

  https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.74.1015



Density Temperature Tracks Of High Mass Stars
Log(Central Temperature) [K]
Log(Central Density) [g/cm³]
Pair Instability, γ < 4/3
10.0
9.5
9.0
8.5
8.0
7.5
7.0
−1
0
1
2
3
4
5
6
7
8
9.4
9.2
9.0
8.8
4.0
4.5
5.0
5.5
6.0
70 M⊙
110 M⊙
180 M⊙
300 M⊙