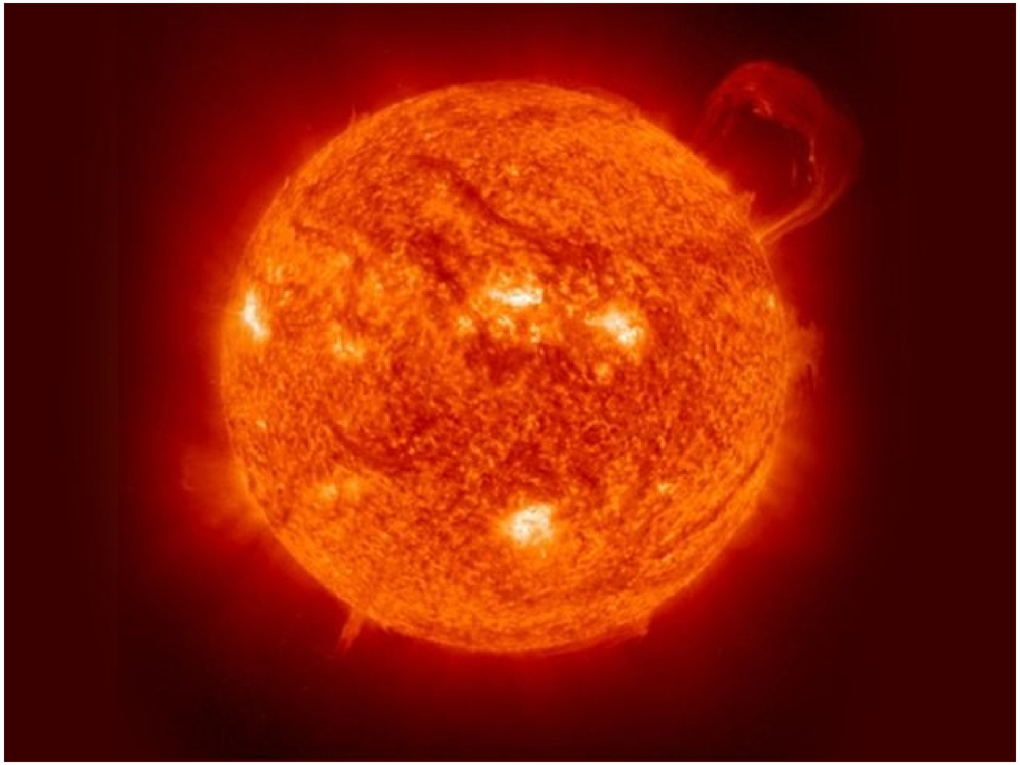
Dark Matter Annihilation in Stars:
A New Lease on Life



TeV Particle Astrophysics

Queen’s University

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11 Aug 2022

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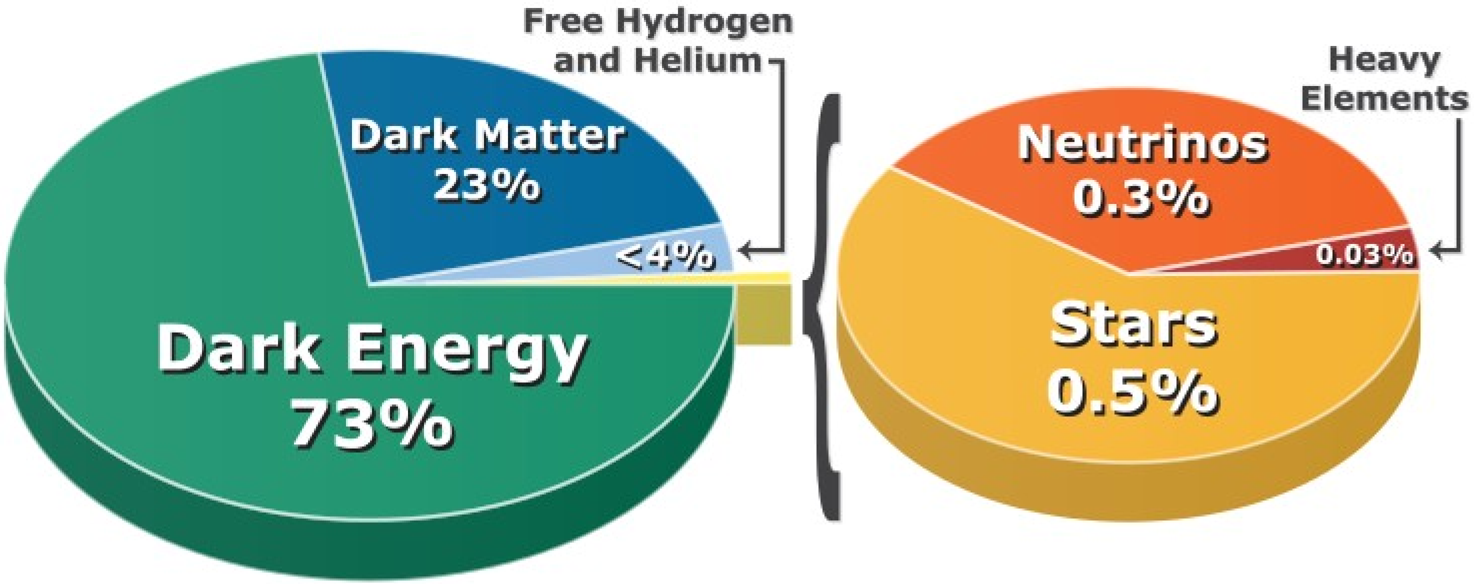
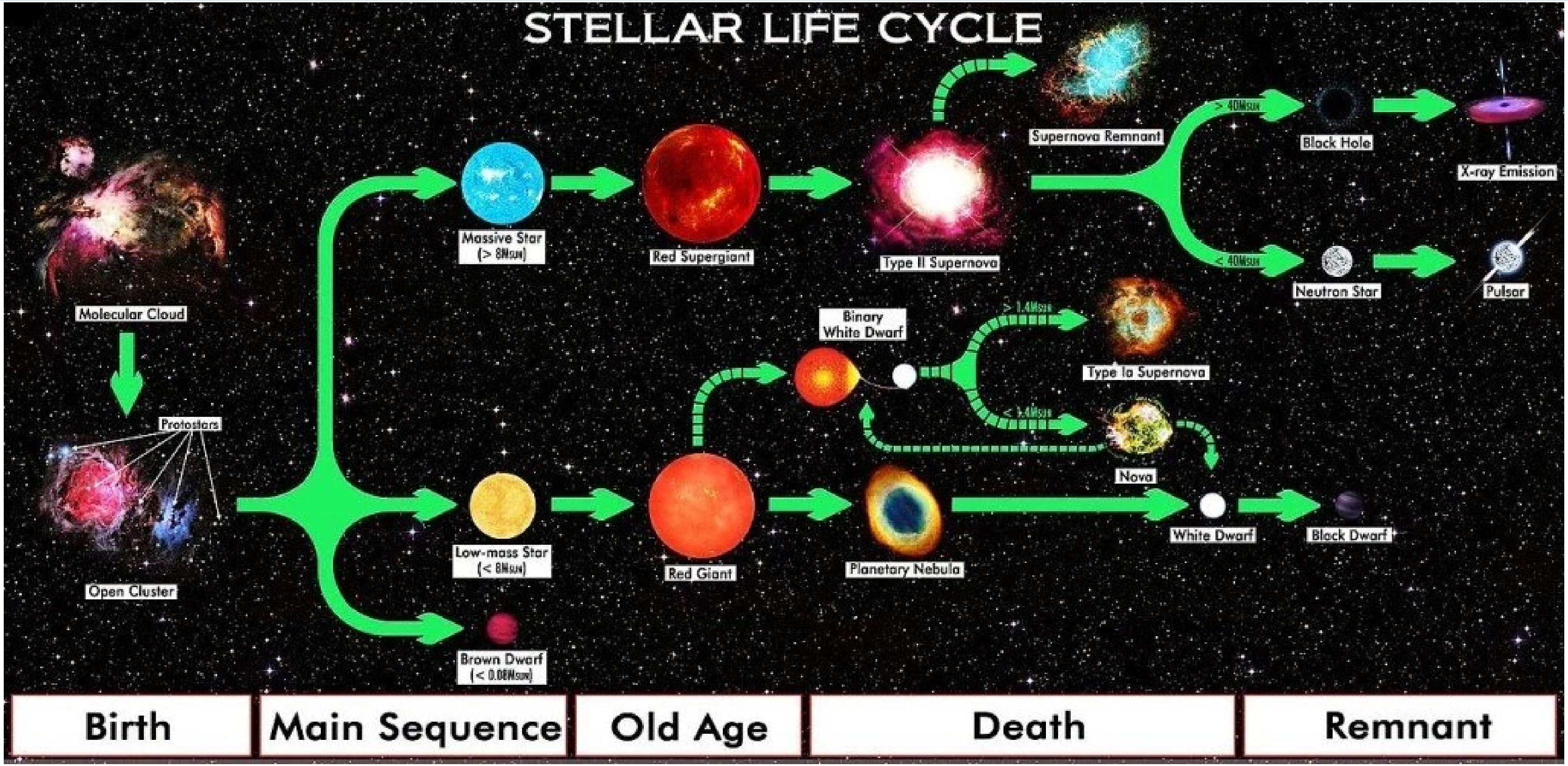
1. Introduction



- 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. Stellar Evolution



R.N. Bailey/Wikimedia Commons

- Balance between energy/pressure and gravitational force
- Two types of evolution:
  - Stable equilibrium: fusion balances gravity
  - Contraction/collapse: temperature and density increase due to gravitational forces increases energy production rate

2.1 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

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

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

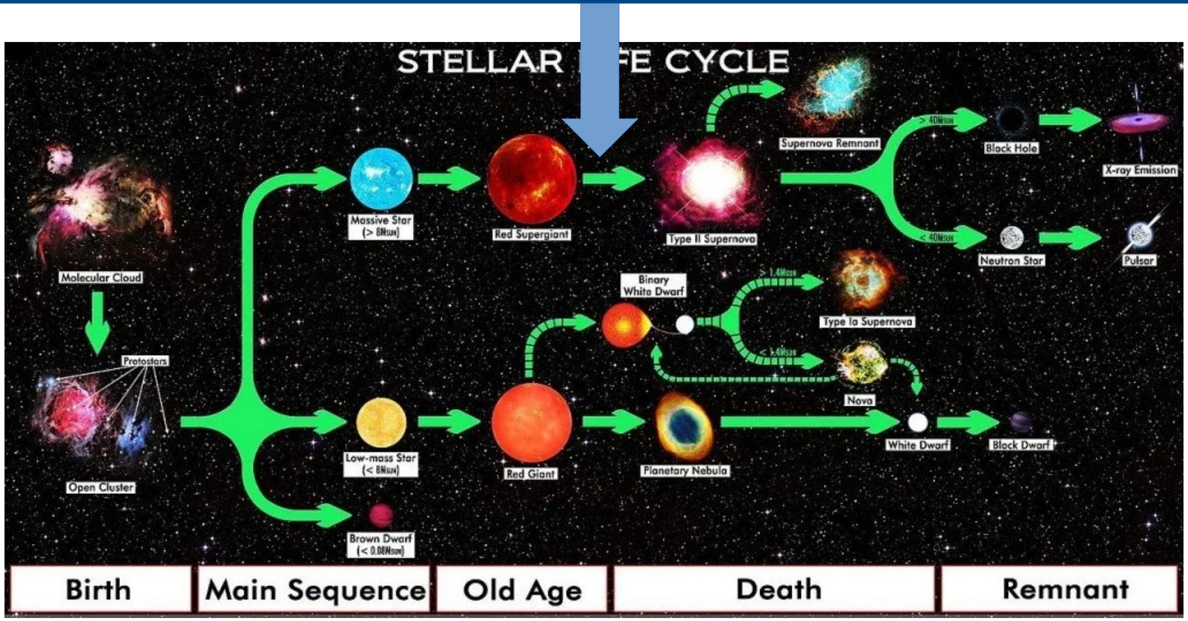
$$\frac{\partial L}{\partial M} = \epsilon - C_P\frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t}$$

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

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

∇ Function related to energy transport and opacity within star

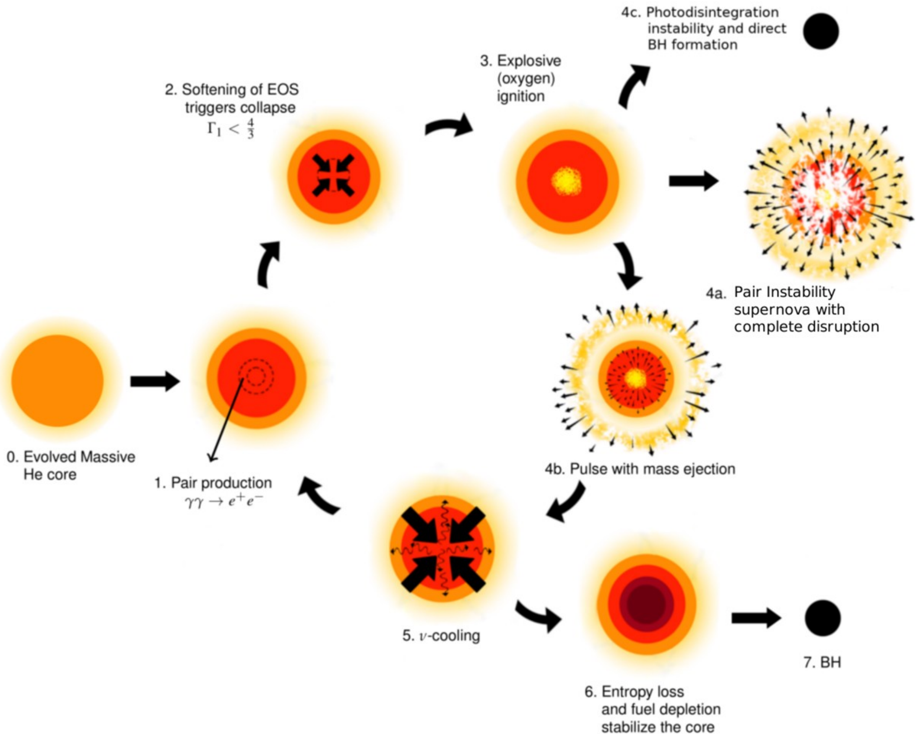
2.3 Pair Instability



- Massive stars (~140 – 240 $M_\odot$) reach temperatures and densities such that electron-positron pairs are produced late in their life
- $\gamma\gamma \to e^- e^+$
- Leads to a pair instability collapse
- Collapse triggers fusion of oxygen and silicon, which leads to violent bounce

2.2 Pair Instability

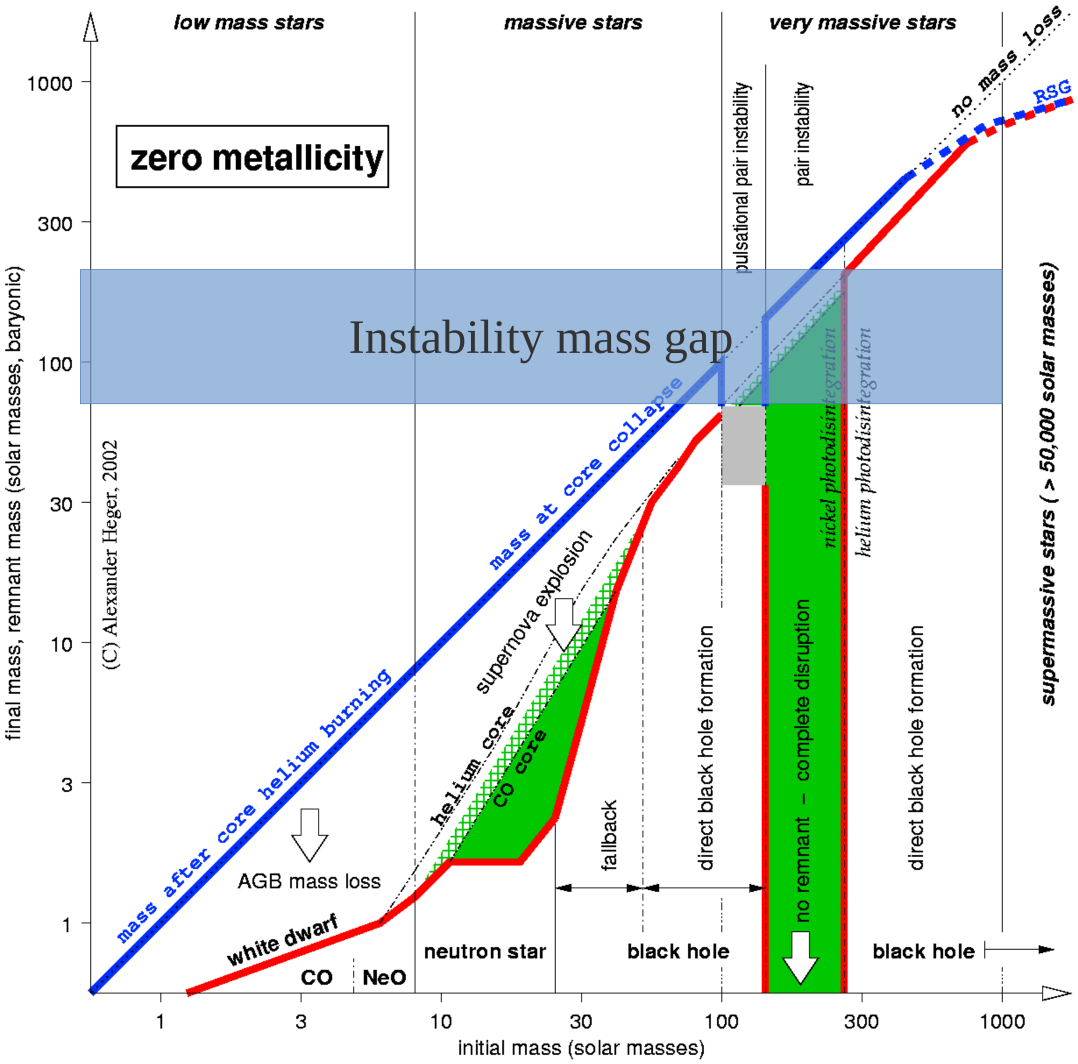
- Core-collapse supernova
  - No pair instability
  - Star continues fusing heavier and heavier elements until it reaches iron and cannot produce energy from fusion
  - Loss of radiation in the core leads to less pressure, and star undergoes runaway collapse
- PISN: Pair instability supernova
  - Oxygen burning produces more energy than gravitational binding energy
  - Leads to complete destruction of the star, with no remnant
- PPISN: Pulsational pair instability supernova
  - Initial oxygen burning episode does not provide enough energy to completely destroy the star, but does provide enough to significantly reduce the mass of the star
  - Star expands, cools, and then contracts again, leading to another pair instability episode and subsequent explosion. Can happen multiple times
  - Each pulse reduces mass of star until some small portion of the star survives, leads to black hole



Predictions for the hydrogen-free ejecta of pulsational pair-instability supernovae. M. Renzo, R. Farmer, S. Justham, Y. Gotberg, S.E. de Mink, E. Zapartas, P. Marchant, and N. Smith, Astron. Astrophys. **640**, A56 (2020).

2.3 Black Hole Mass Gap

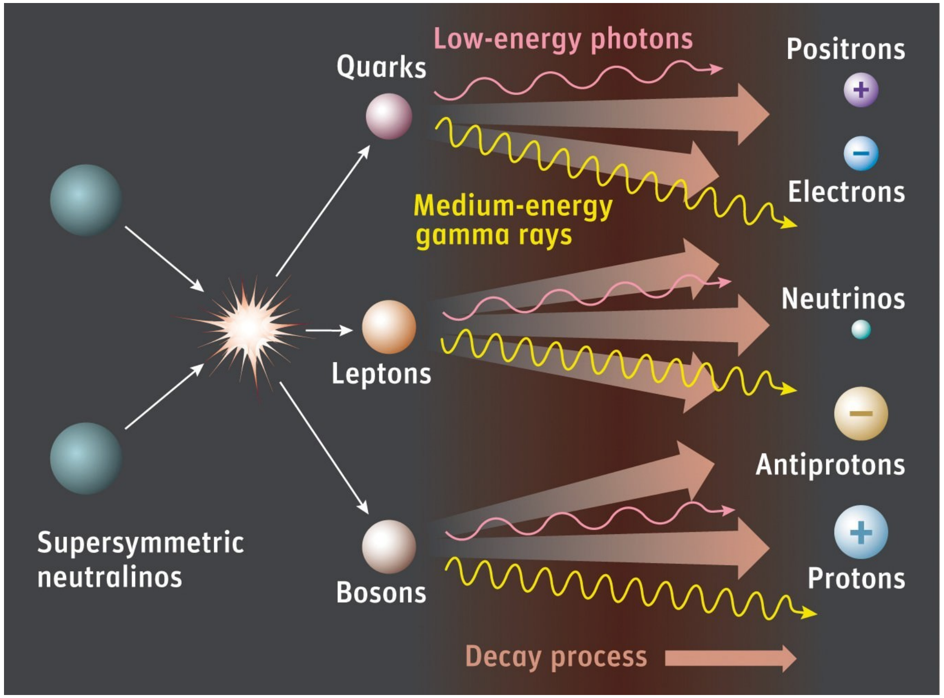
- Due to PISN and PPISN, black holes cannot form with (initial) masses between ~50 and 140 $M_\odot$
- Black holes can exist in the mass gap (e.g. GW190521):
  - Multiple mergers
  - Uncertainties
  - New physics
- Population statistics of black holes may offer test of these explanations



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

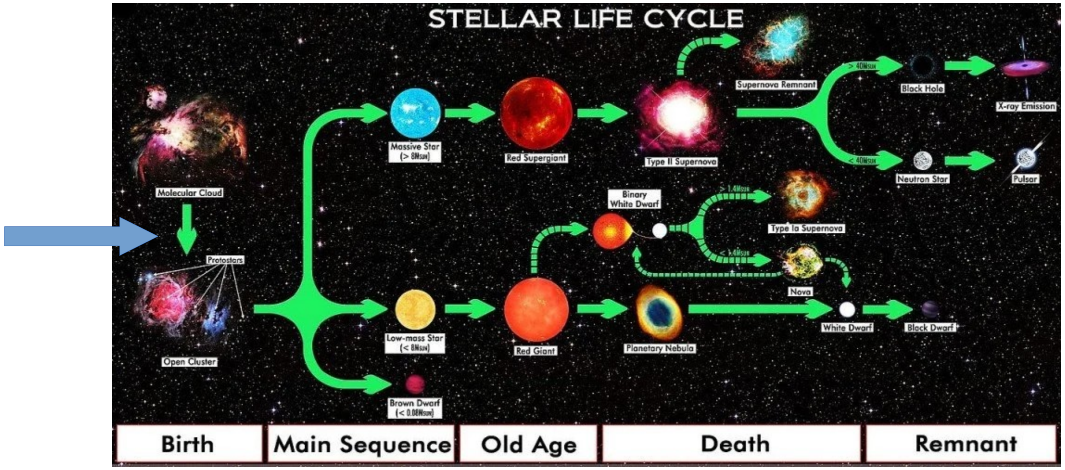
3.1 Dark Matter Model

- Only requirement is that dark matter annihilates to standard model
- Regardless of exact decay chain, products will eventually be some combination of charged particles, photons, and neutrinos.
- Neutrinos escape, but electrons and photons quickly thermalize with gas, causing temperature to rise
- Very efficient source of energy within a star

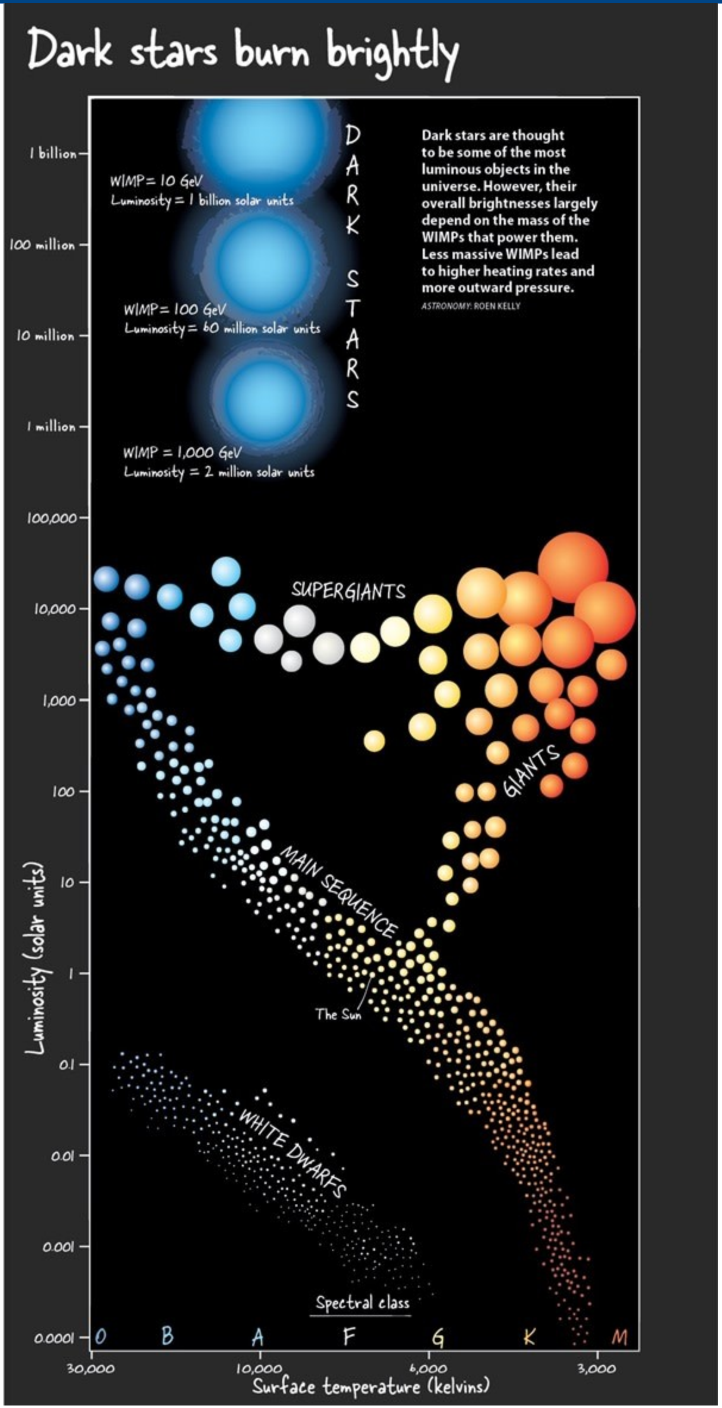


Sky and Telescope, Gregg Dinderman
https://www.universetoday.com/116293/marco-view-makes-dark-matter-look-even-stranger/

3.2 Dark Stars



- Stellar objects that form as gas and dust contract to form a star, but before fusion can begin.
- Low temperature, low density, but very large
- Little ionizing radiation → stars do not stop growing, can reach masses of $10^5 M_\odot$
- We're interested in stars with less dark matter than these, where dark matter annihilation and fusion produce comparable energy


Dark stars burn brightly

Dark stars are thought to be some of the most luminous objects in the universe. However, their overall brightnesses largely depend on the mass of the WIMPs that power them. Less massive WIMPs lead to higher heating rates and more outward pressure.

ASTRONOMY: ROEN KELLY

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

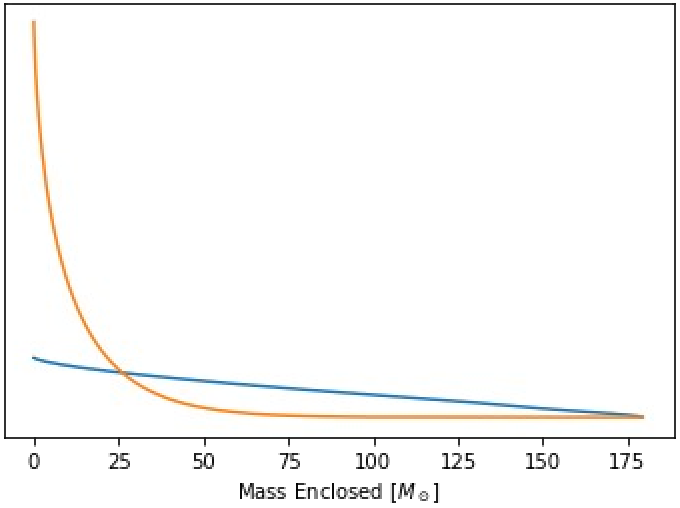
- Approximate the energy produced through dark matter as a constant energy production rate density
- Compared to nuclear energy, which is strongly centrally peaked, treating energy from dark matter as a constant is reasonable

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

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

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

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

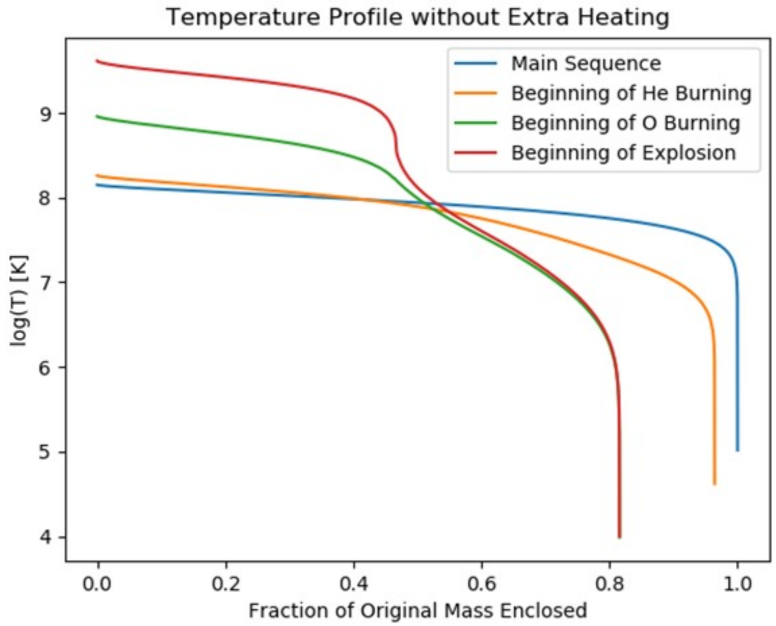


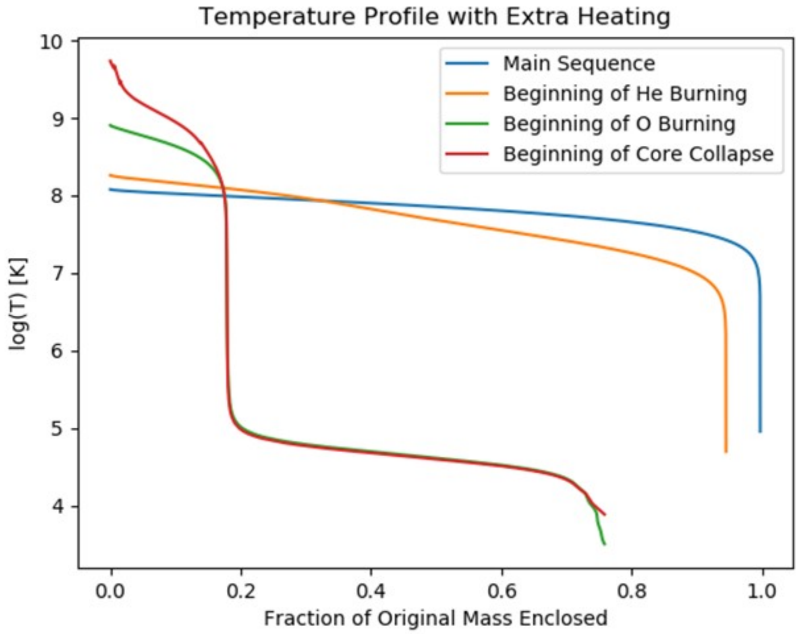
Assuming WIMP dark matter and adiabatic contraction

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

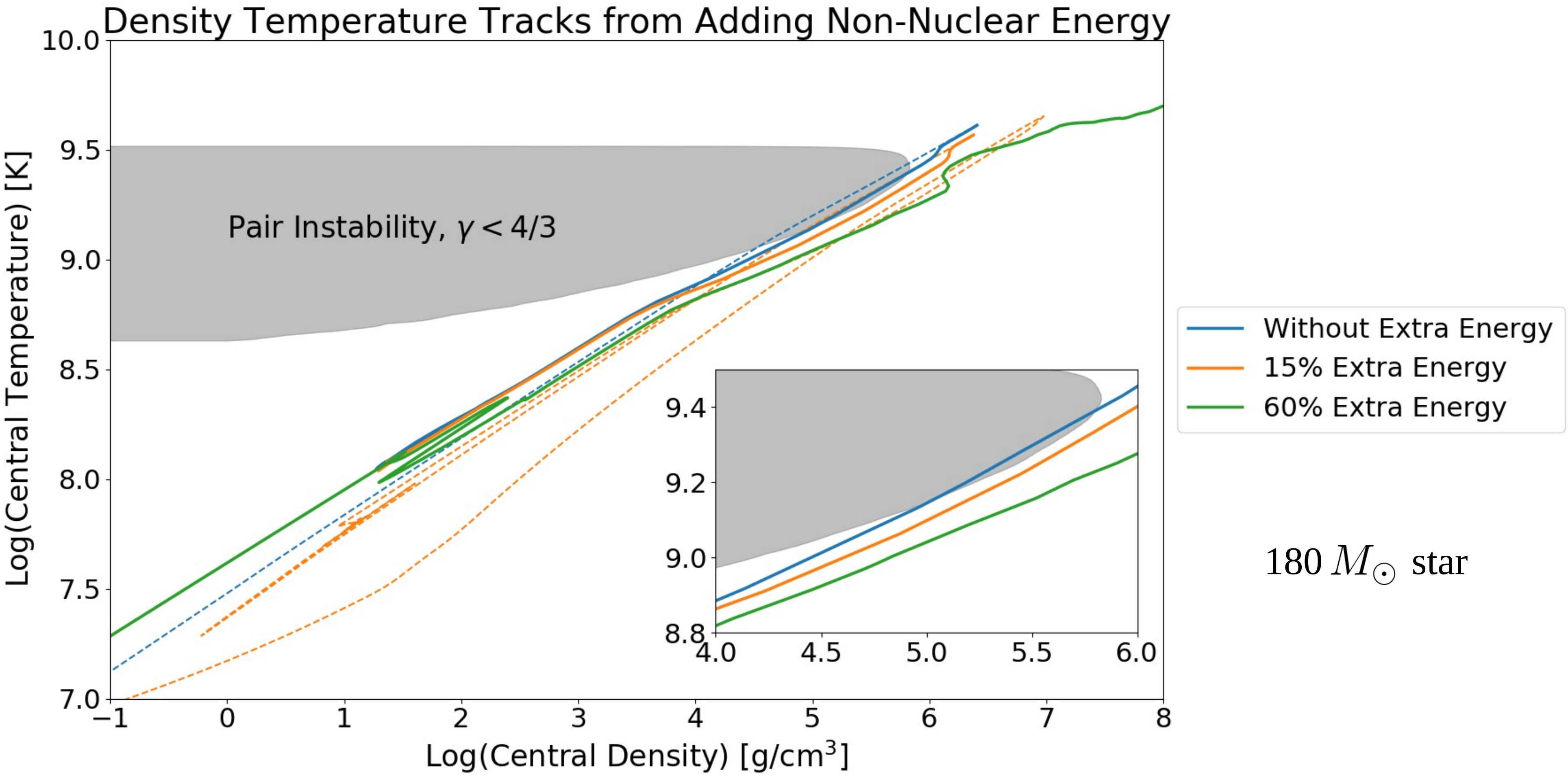
4.1 Structural Changes

- 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



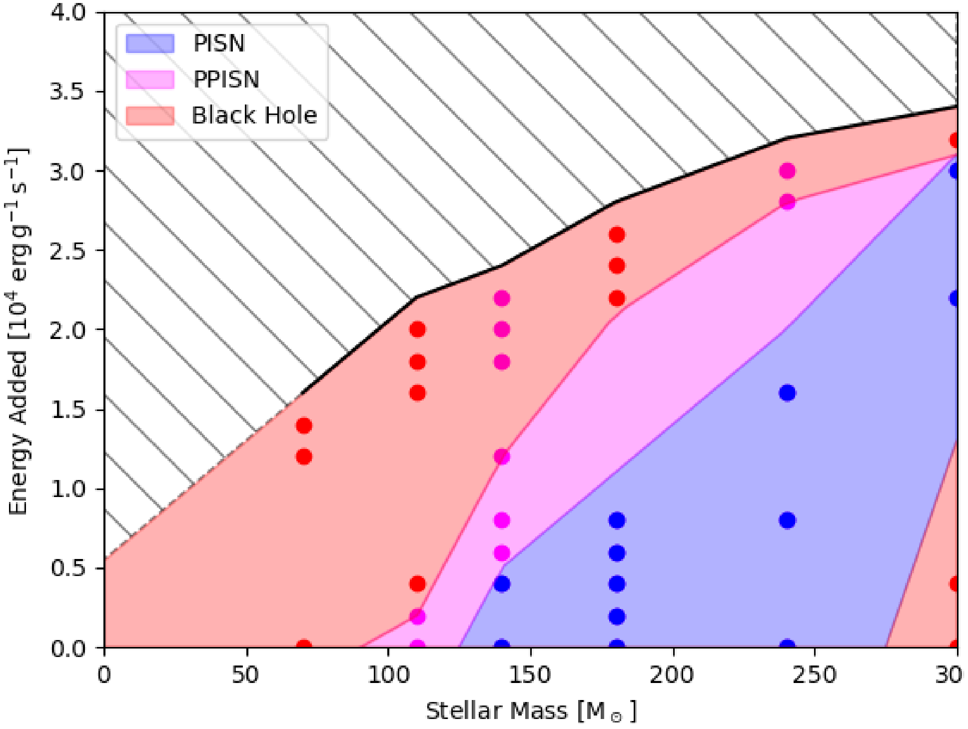


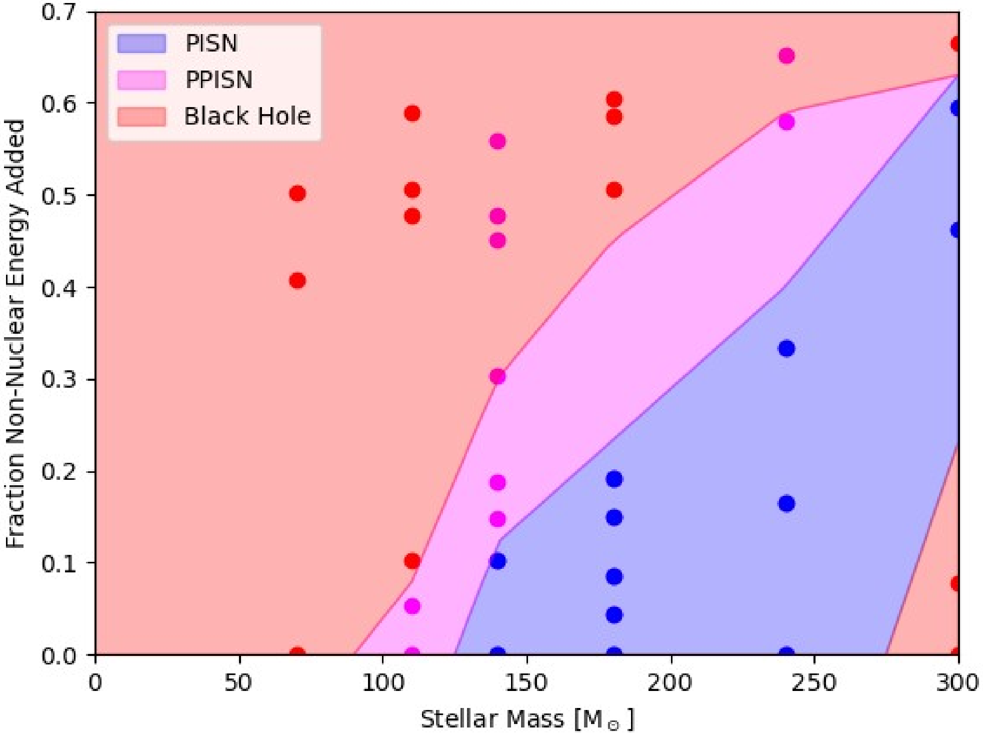
4.1 Avoiding Pair Instability



$180\ M_\odot$ star

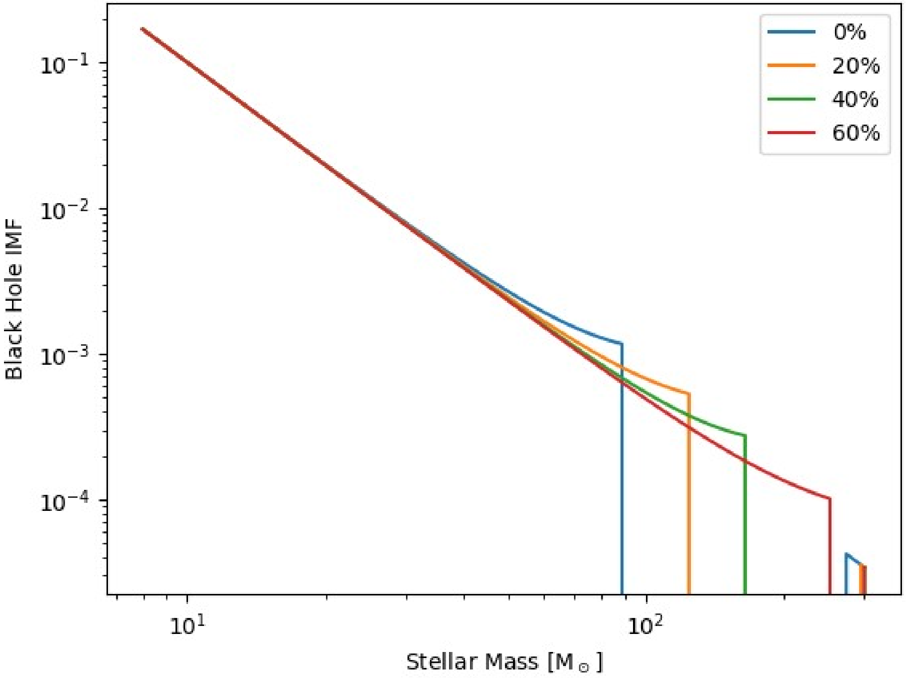
4.2 How unique is this result?



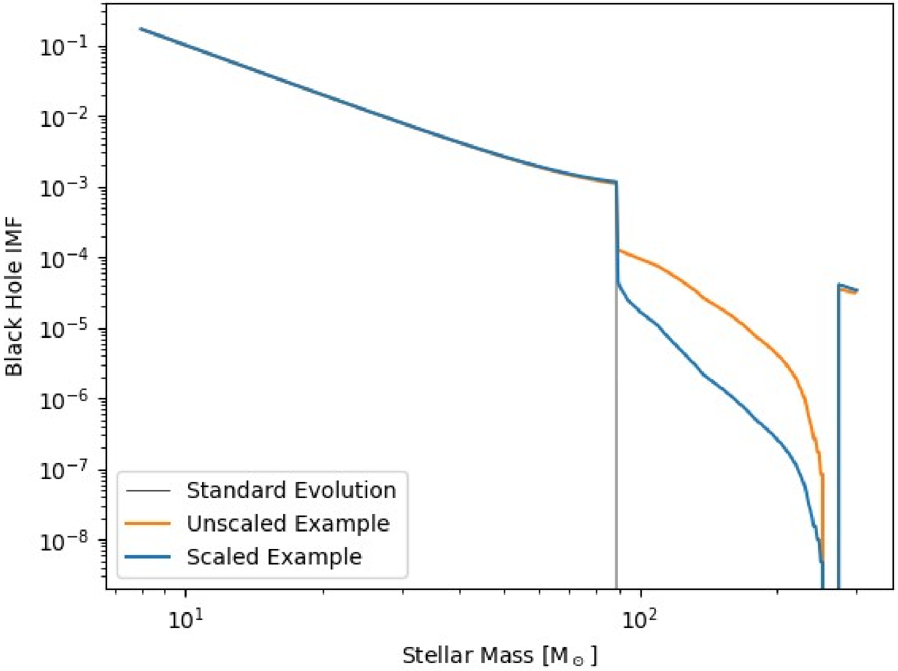


4.3 Potential Tests

- 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

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

6. References

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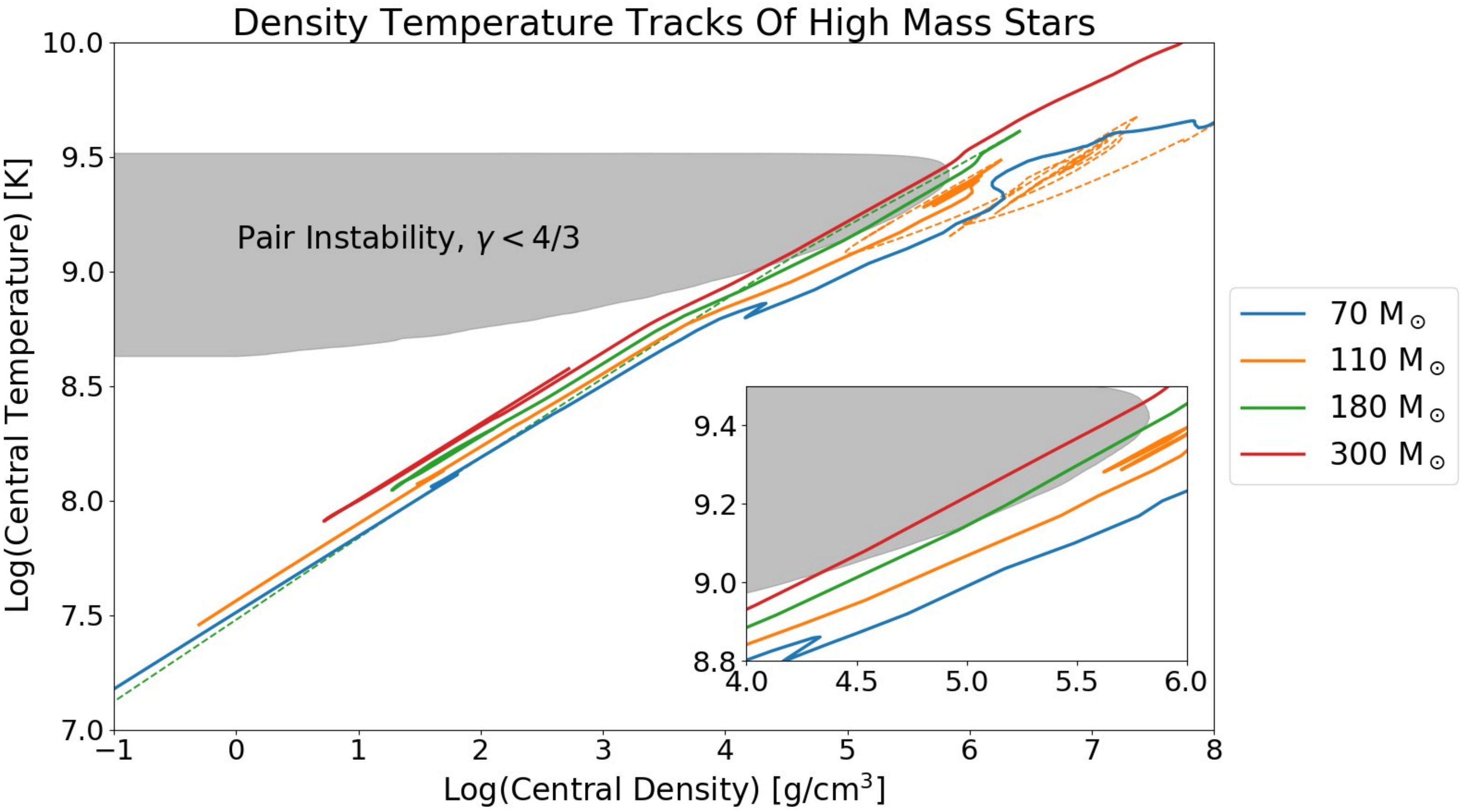
  https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.043015

- 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
Pair Instability, $\gamma < 4/3$
Log(Central Temperature) [K]
Log(Central Density) [g/cm^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 $M_\odot$
110 $M_\odot$
180 $M_\odot$
300 $M_\odot$

Dark Matter as energy source

- 180 $M_\odot$ star 60% extra energy: approximately 10^{53} erg produced over the lifetime of the star
- On average: 5×10^{42} GeV s^{-1} or ~1 GeV cm^{-3} s^{-1}

- Possible environments with high enough dark matter density:
  - Centers of early proto-galaxies
  - Dark matter spikes around supermassive black holes