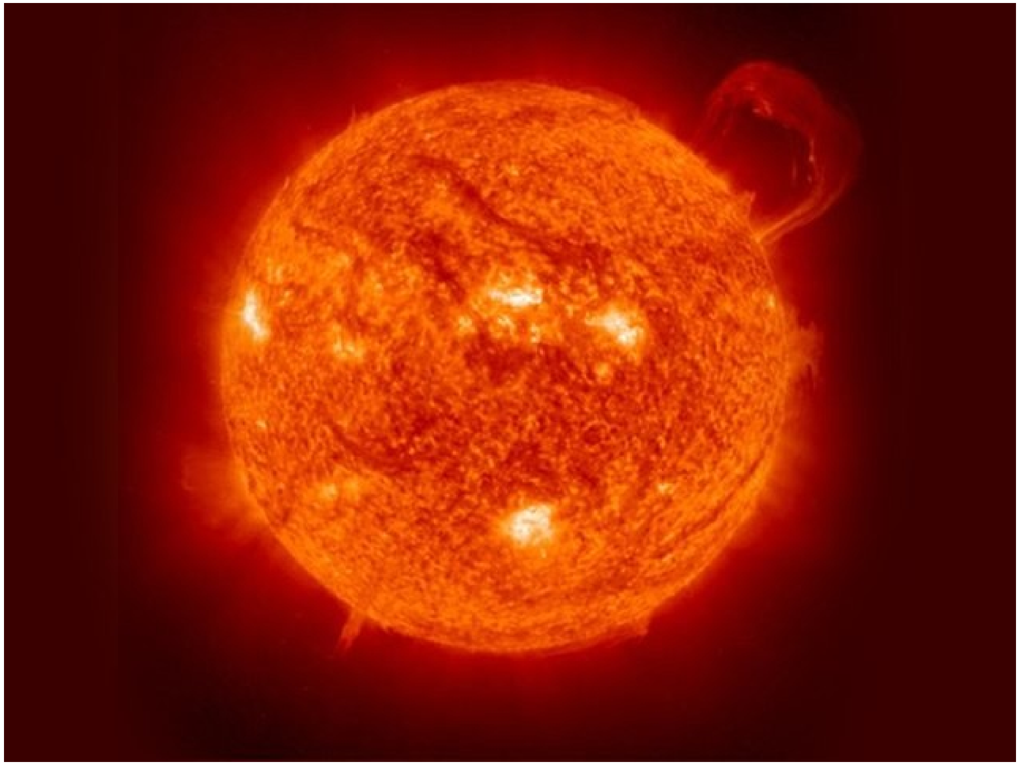
Dark Matter Annihilation in Stars: A New Lease on Life



Mitchell Conference on Collider, Dark Matter, and Neutrino Physics

Texas A&M University

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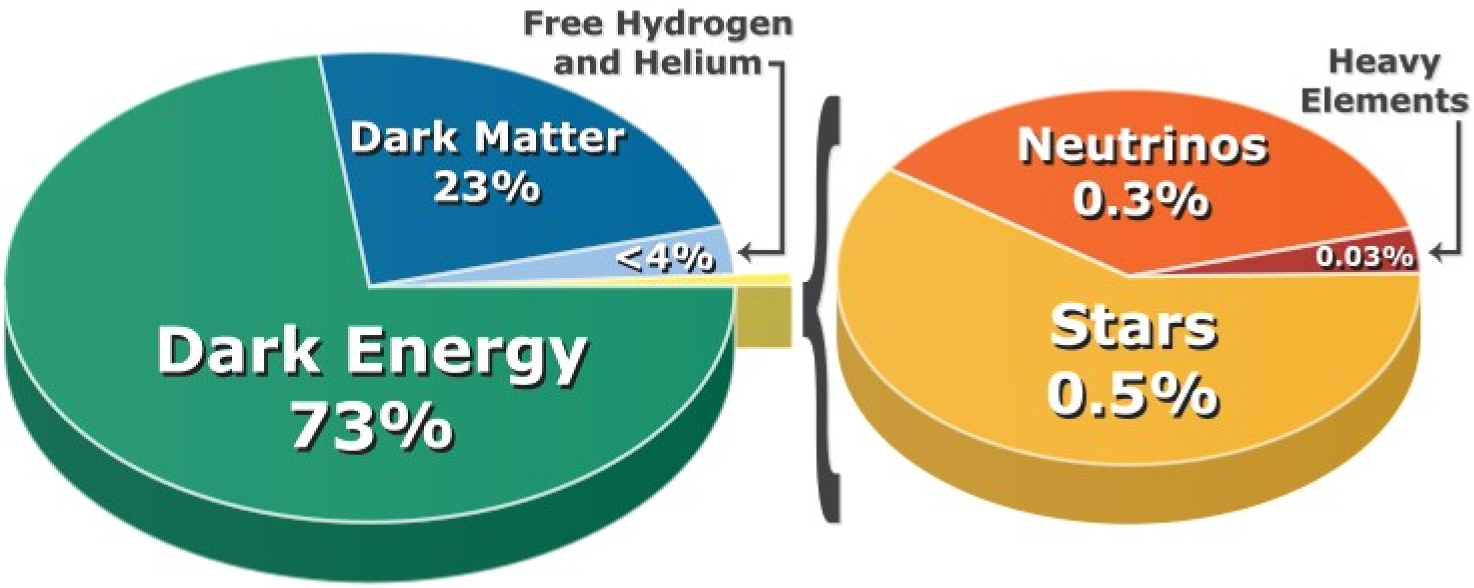
26 May 2022

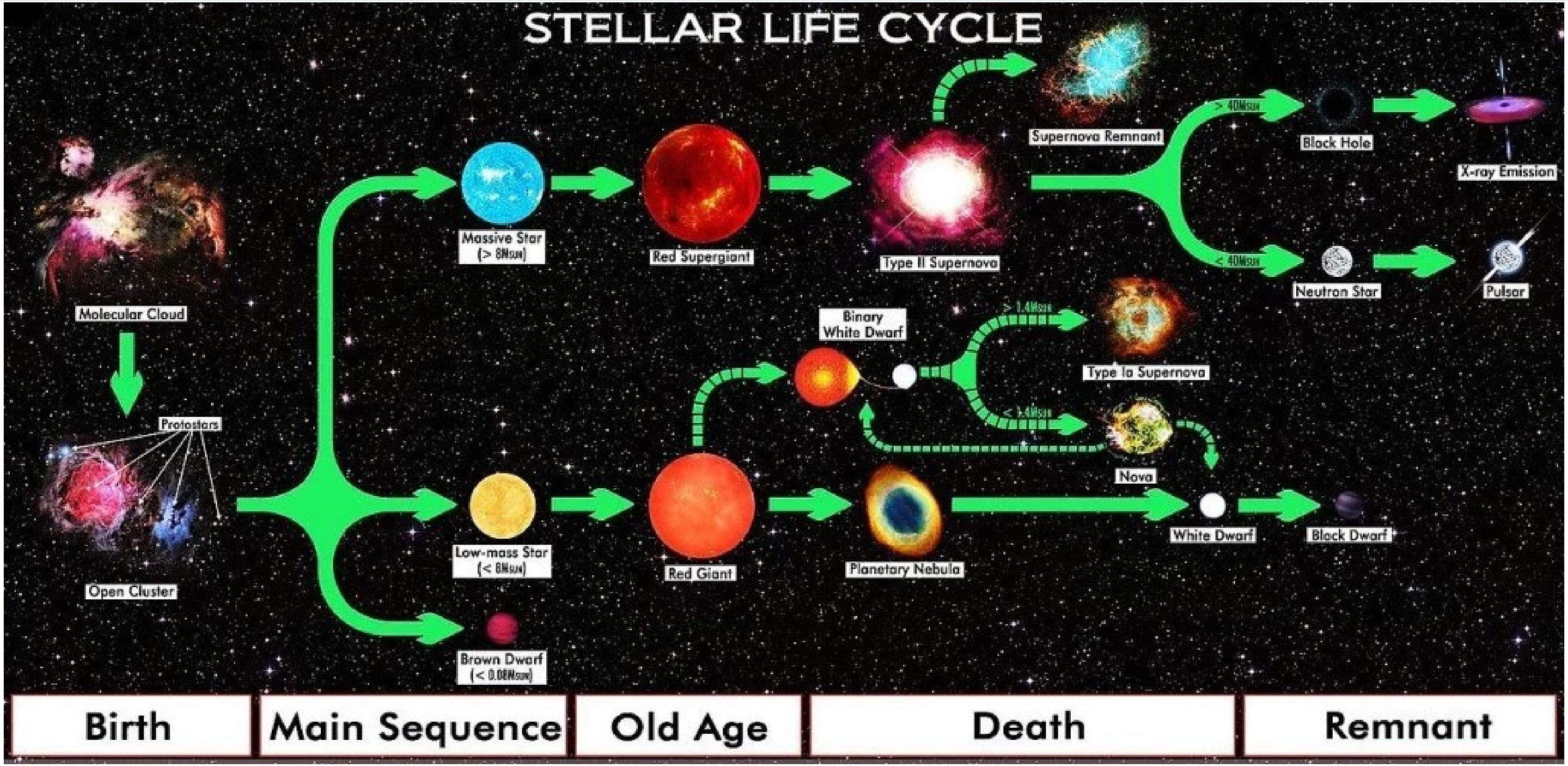
Contents

1. Introduction



- Indirect detection through stellar processes
- Assumptions of dark matter:
  - Annihilation into standard model particles in some way
  - That’s it

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: temperature and density increase due to gravitational forces increases energy production rate
- Collapse occurs when balance breaks down, when contraction of star decreases energy production in the star

2.1 1D Stellar Evolution

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

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

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

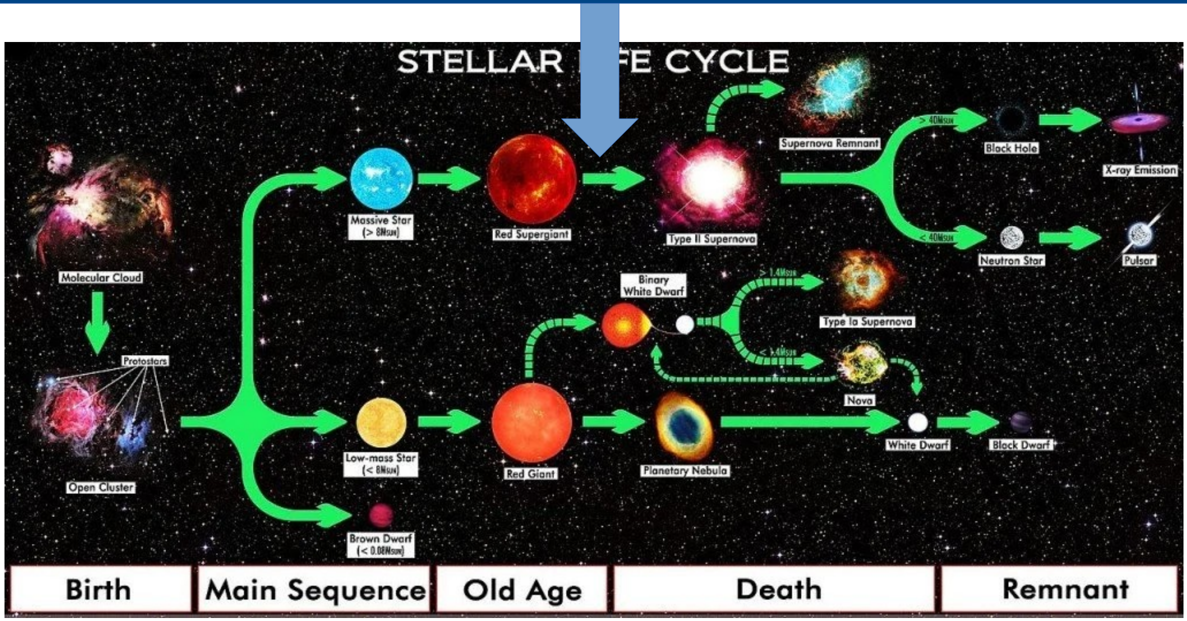
$$\frac{\partial L}{\partial M} = \epsilon - C_P \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t}$$

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

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

∇ Function related to energy transport and opacity within star

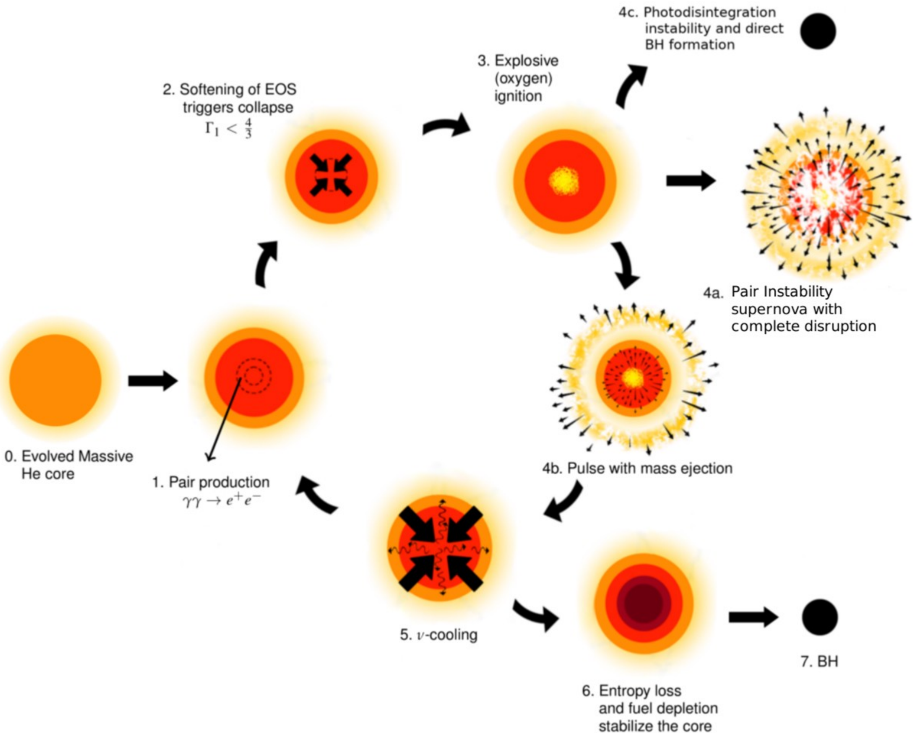
2.3 Pair Instability



- 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, which leads to violent bounce

2.2 Pair Instability

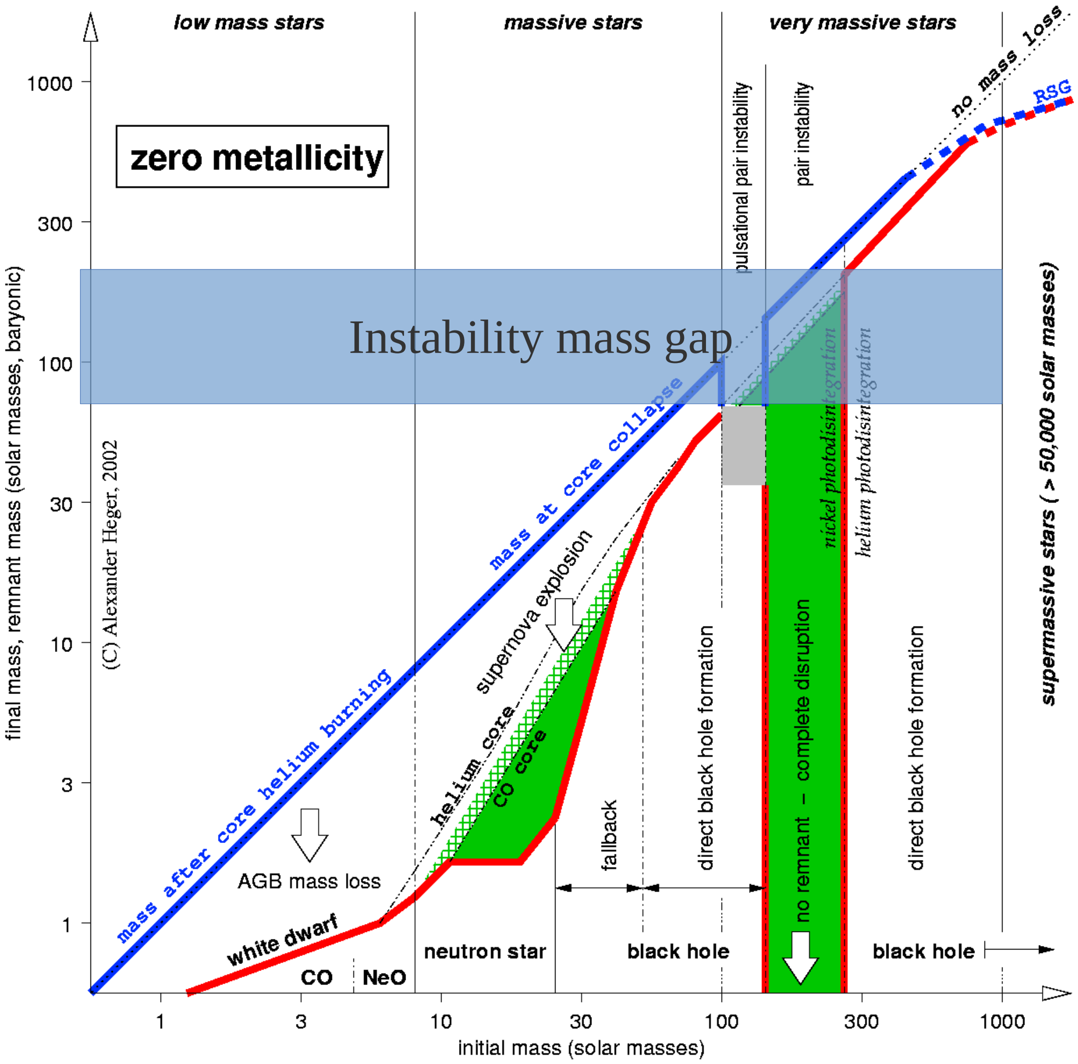
- PISN: Pair instability supernova
  - Oxygen burning produces more energy than gravitational binding energy
  - Leads to complete destruction of the star, with no remnant
- PPISN: Pulsational pair instability supernova
  - Initial oxygen burning episode does not provide enough energy to completely destroy 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
- 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



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

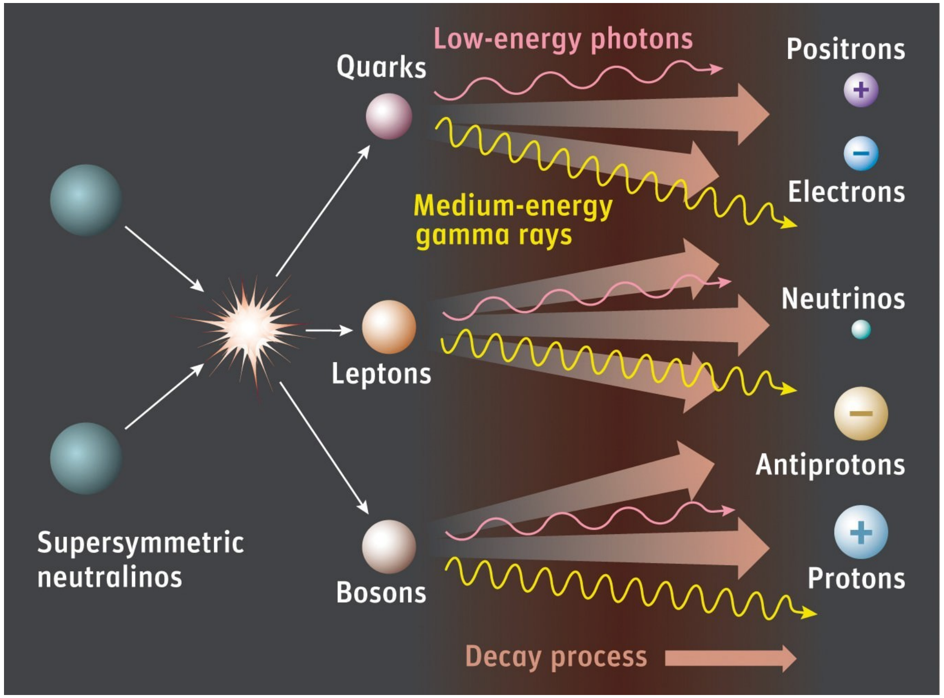
- Due to PISN and PPISN, black holes cannot form with (initial) masses between ~50 and 140 $M_\odot$
- Black holes can exist in the mass gap (e.g. GW190521):
  - Multiple mergers
  - Uncertainties
  - New physics
- Population statistics of black holes may offer test of these explanations



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

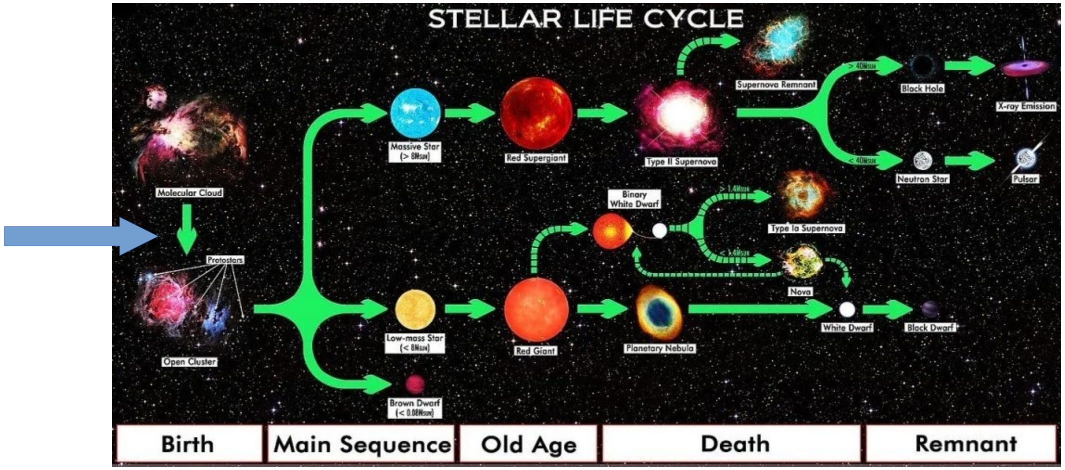
3.1 Dark Matter Model

- 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

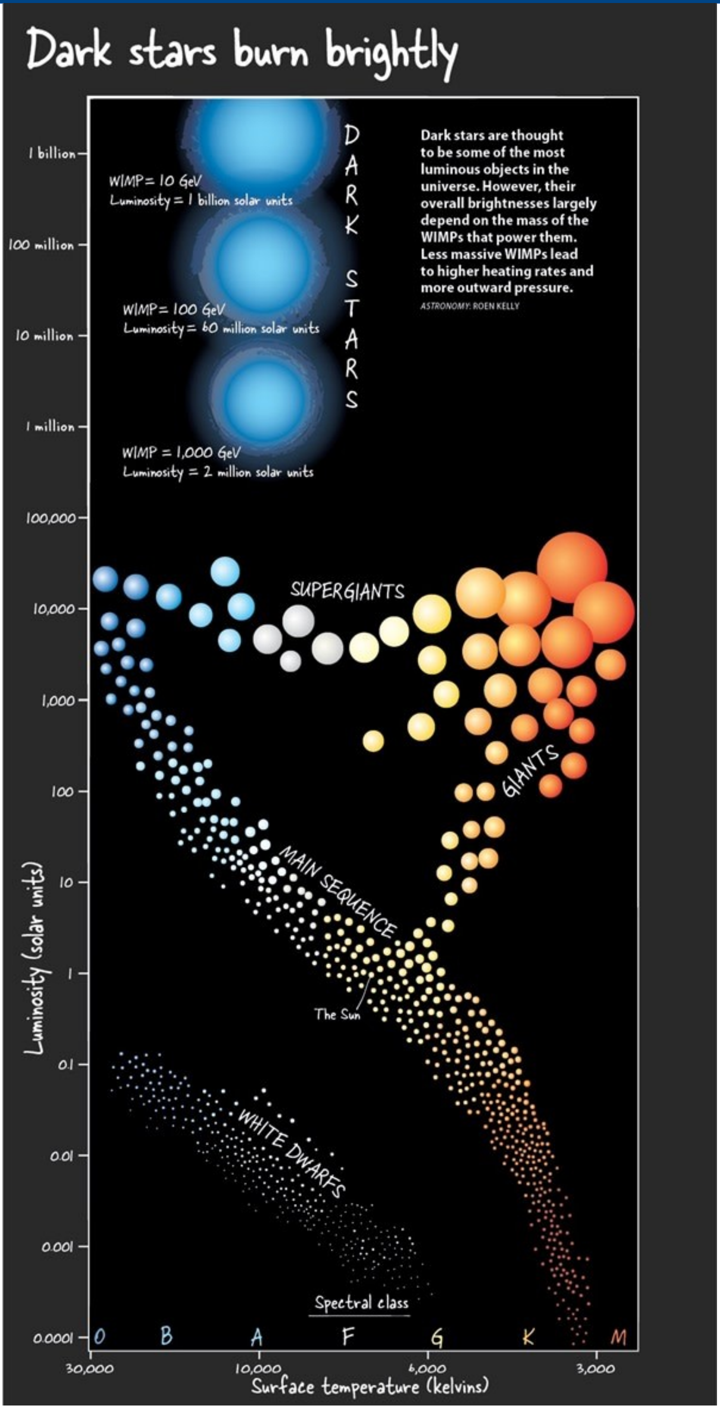


Sky and Telescope, Gregg Dinderman
https://www.universetoday.com/116293/marco-view-makes-dark-matter-look-even-stranger/

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 $10^5 M_\odot$
- Eventually dark matter content reduced, star contracts, stellar evolution can occur



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

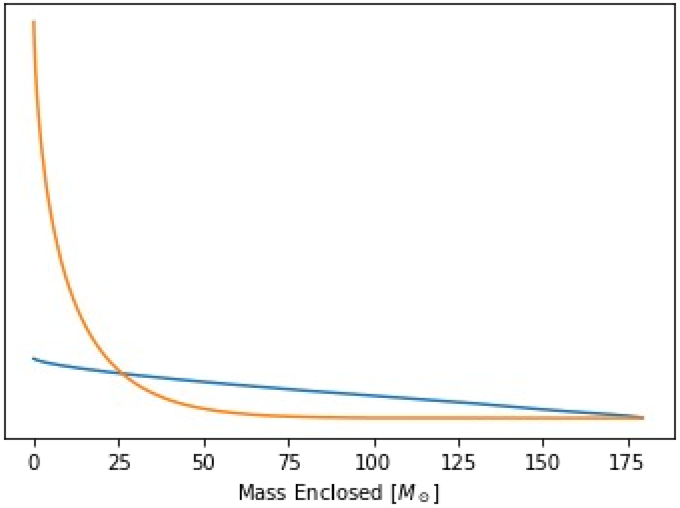
- Approximate the energy produced through dark matter as a constant energy production rate density
- Compared to nuclear energy, which is strongly centrally peaked, treating energy from dark matter as a constant is reasonable

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

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

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

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

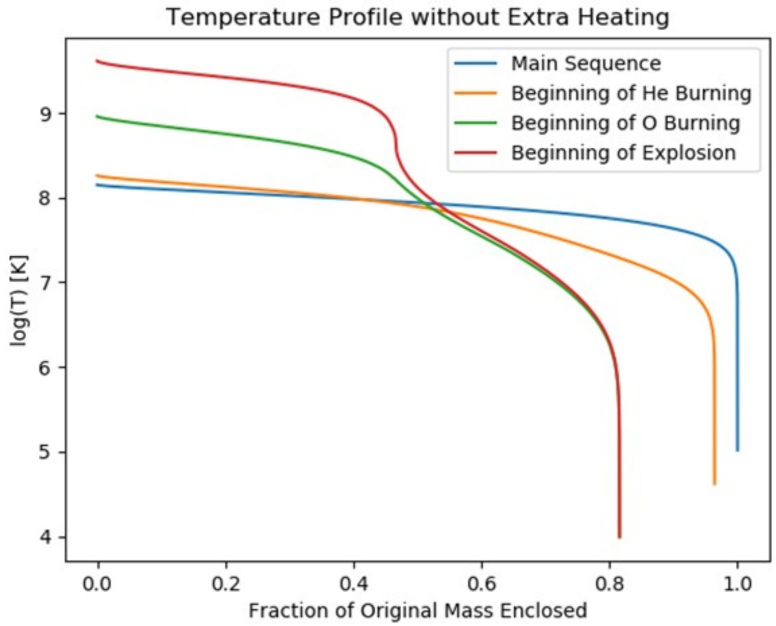


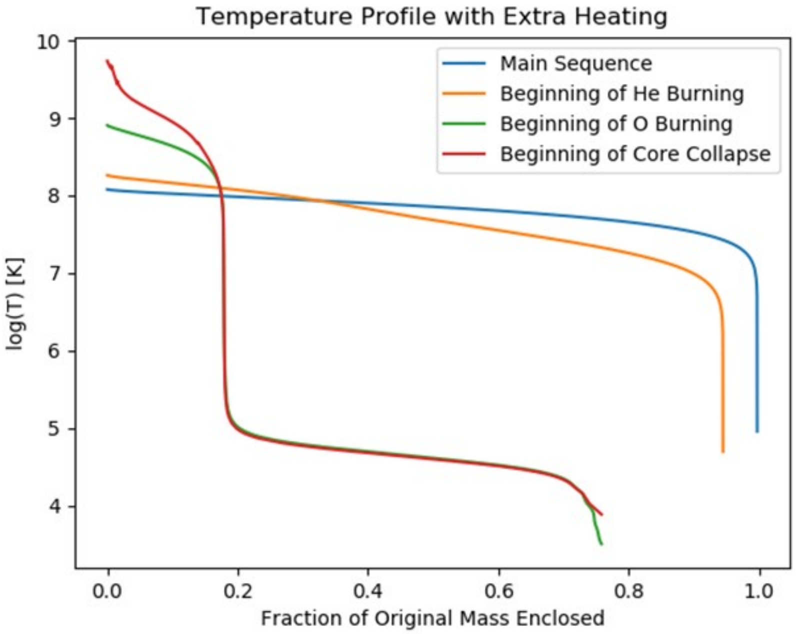
Assuming WIMP dark matter and adiabatic contraction

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

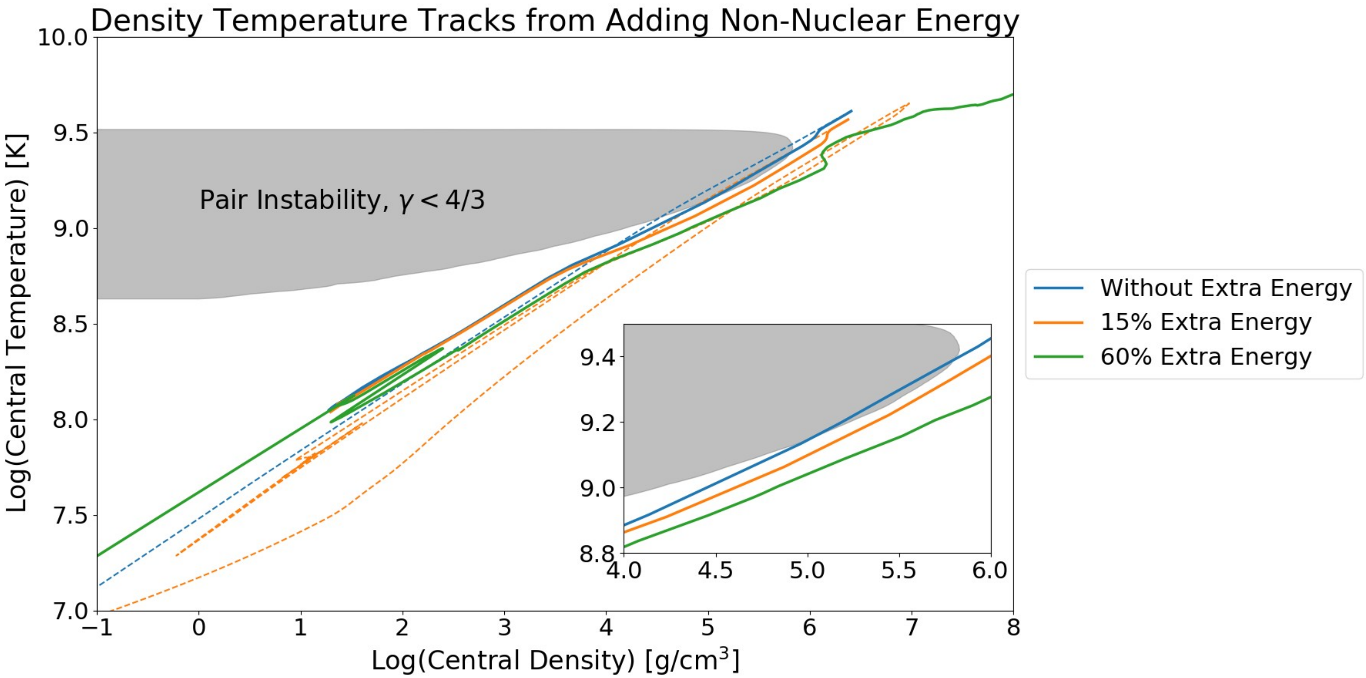
4.1 Structural Changes

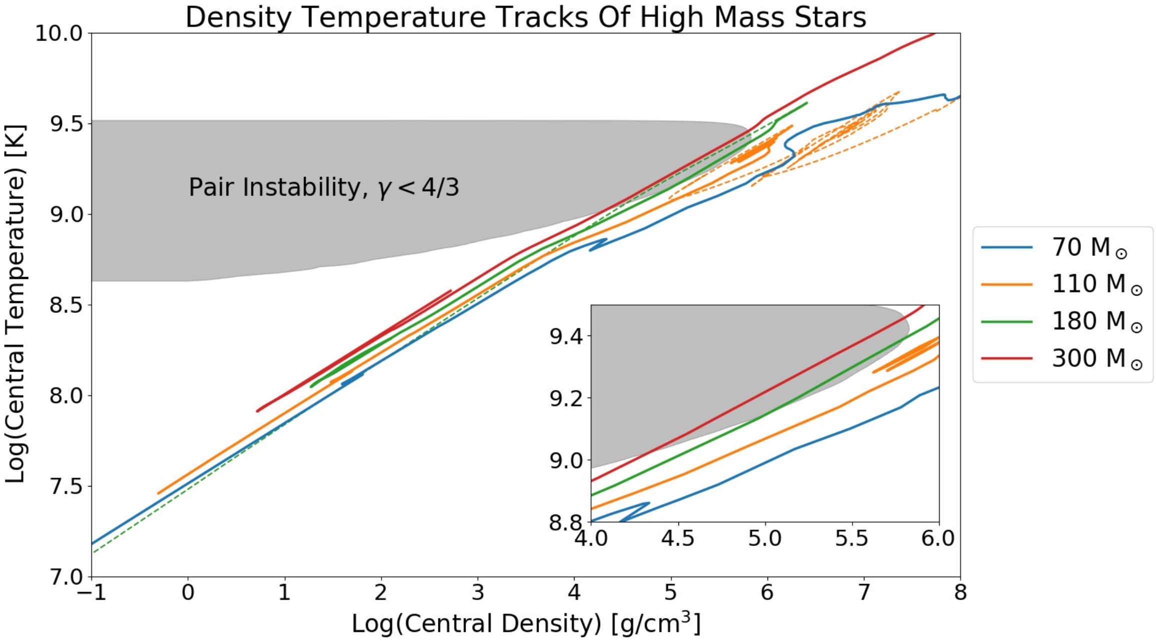
- Extra energy in the star → less energy required from nuclear reactions
- Effectively reducing size of core, relative to overall mass of star



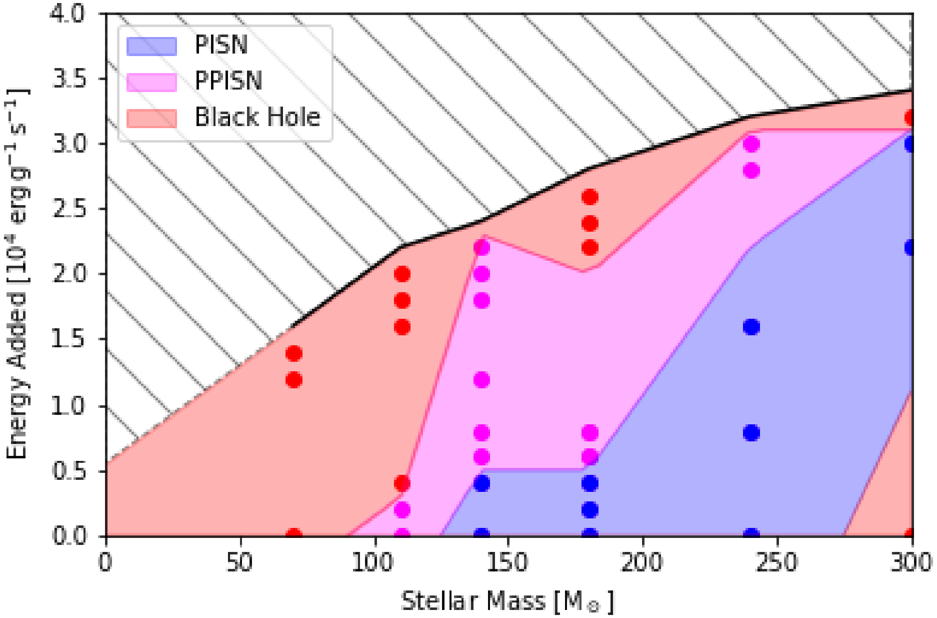


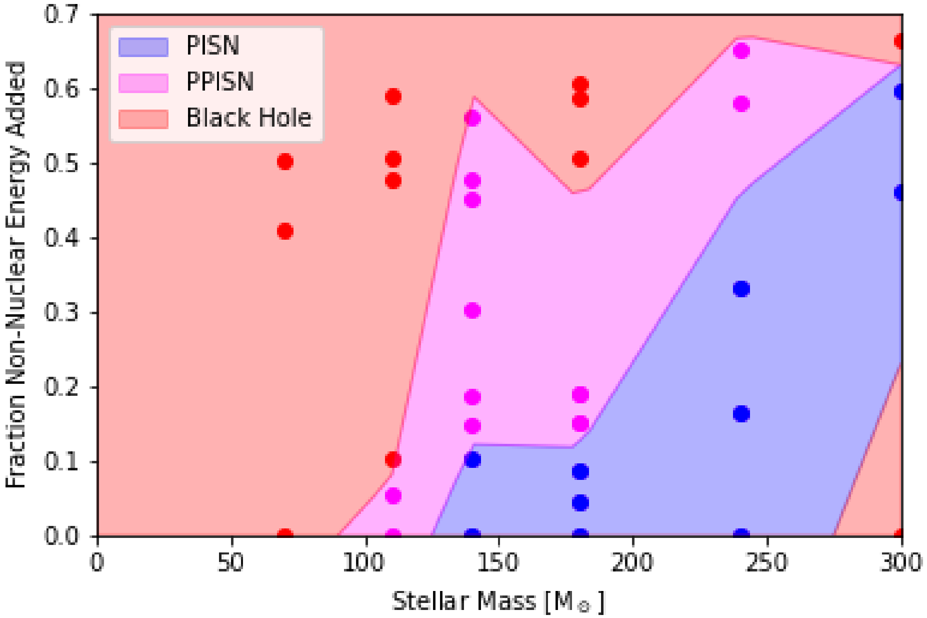
4.1 Avoiding Pair Instability





4.2 How unique is this result?





preliminary

4.3 Potential Tests

- Black hole population statistics (BHIMF)
- Supernova observations as a function of metallicity/redshift
- Chemical composition in low-metallicity environments

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)

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- 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