The Effects of Asymmetric Dark Matter on Stellar Evolution I: Spin-Dependent Scattering

Troy J. Raen,[1⋆], Héctor Martínez-Rodríguez[1], Andrew R. Zentner[1], Travis J. Hurst[2], Carles Badenes[1], and Rachel Tao[3]

[1] *Department of Physics and Astronomy & Pittsburgh Particle Physics, Astrophysics, and Cosmology Center (Pitt PACC), University of Pittsburgh, Pittsburgh, PA 15260, USA*
[2] *Department of Mathematics and Physics, Colorado State University - Pueblo, Pueblo, C0, 81001*
[3] *Department of Physics, Emory University, Atlanta, GA 30322*

14 June 2019

ABSTRACT
We study the effects of Dark Matter on the evolution of stars with masses 0.8-5.0 $M_\odot$ and find that, in certain environments, main sequence lifetimes can be dramatically altered. [**Troy: Finish writing abstract...**]

Key words: keyword1 – keyword2 – keyword3

[**TO DO: find other stellar textbook(s) to cite.**]

1 INTRODUCTION

[**Andrew: Upon reading this, I think I prefer not to abbreviate dark matter, but you can make the final decision.**]

[**Andrew: I added a number of references to "bib.bib." For some reason, I couldn't open "references.bib."**]

A preponderance of the evidence suggests that approximately 84% of the matter budget of the universe consists of a form of non-baryonic dark matter that has yet to be identified. [**Andrew: Let's cite a few dark matter review articles here including Jungman+96, Bertone+2006, the Cosmic Visions report. Let's also cite some of the standard references for constraints on cosmological parameters, such as the Planck result.**] In the standard picture of cosmological structure formation, galaxies form within the potential wells of large, nearly virialized halos of dark matter (**??**). If the dark matter interacts with standard model particles, it can be captured by stars moving through dark matter halos (**????**). Once captured, continued scattering within the stellar interior contributes to energy transport within the star, potentially altering its evolution (Spergel & Press 1985; Zentner & Hearin 2011) [**Troy: get a few more references**] [**Andrew: Good idea. Look for papers by Fabio Iocco, Ian Shoemaker, Malcolm Fairbairn, Jordi Casanellas, Ilidio Lopez**]. The significance of this energy transport depends on the following properties (in addition to the properties of the star): (1) the dark matter mass, $m_{\rm DM}$; (2) the dark matter-nucleon scattering cross section, $\sigma_{\rm n}$; and (3) the total number of dark matter particles captured by a star, $N_{\rm DM}$, which itself depends on $\sigma_{\rm n}$ as well as the local dark matter environment from which the particles are captured (see § 2). We study the effects of energy transport by asymmetric dark matter (ADM, see below) in stars of mass $0.8 \leqslant M_\star/{\rm M}_\odot \leqslant 5.0$ living within a variety of dark matter environments, using the publicly available code Modules for Experiments in Stellar Astrophysics (`MESA`, Paxton et al. 2011).

Evidence supporting the claim that ∼84% of the matter in the universe is in an unknown form of dark matter is abundant and varied, ranging from the anisotropy of the microwave background radiation to formation and structures of galaxies. [**Andrew: cite reviews here.**] However, dark matter has only been observed indirectly, through its gravitational influence, and much remains to be discovered about its fundamental nature. For several decades, the leading candidate has been the so called Weakly-interacting massive particle (WIMP). The classic WIMP is a heavy ($m_{\rm DM} \sim 10^2 - 10^3$ GeV) thermal relic whose contemporary abundance is set by its annihilation rate in the early universe [**Andrew: cite e.g., Kolb and Turner textbook or some other standard reference for the reader that needs a definition of a thermal relic**]. Therefore, WIMPs are thought to have a fairly well established "standard" annihilation cross section (e.g., **?**). This annihilation, in turn, limits the number of particles that can accumulate

⋆ E-mail: troy.raen@pitt.edu

within a star as the rate of capture of new dark matter particles equilibrates with annihilation in the stellar interior (**?**). Despite numerous, ongoing terrestrial direct detection experiments **[Andrew: cite LUX, CRESST, and so on. maybe ask Brian Batell for references to the very latest results here.]** and efforts to detect dark matter indirectly through its annihilation products **[Andrew: cite the FERMI, HESS, and VERITAS results here as well as IceCube constraints on dark matter]**, dark matter has not been observed non-gravitationally. The available parameter space for classic WIMPs is rapidly shrinking (**?**) **[Troy: Still need to refer to a constraint paper.]**, which has triggered a surge in research into alternatives to the long-favored WIMP.

Asymmetric dark matter (ADM) is an alternative to the classic WIMP in which the relic abundance of the dark matter particle is set by a primordial asymmetry rather than via annihilation (for a review, see **?**, and references therein). If the baryon and dark matter asymmetries are related, then such models have the appealing property that they explain the fact that the contemporary dark matter and baryon abundances are of the same order of magnitude, which is otherwise surprising because these relic abundances are determined by unrelated physics in the WIMP scenario. The variety of specific incarnations of ADM is broad, but ADM models typically predict particle masses smaller than the classic WIMP ($m_{\mathrm{DM}} \sim 1 - 10$ GeV) and no contemporary dark matter annihilation due to the present-day absence of dark matter anti-particles.

These predictions motivate studies to constrain ADM indirectly through stellar astrophysics. The lack of annihilation means that ADM may build up to very large quantities within stars because the capture of ADM is never countered by annihilation. Meanwhile, the relatively low masses compared to the classic WIMP mean captured ADM particles orbit within a significant volume of the star, out to $r_{\mathrm{DM}} \sim X$ **[Andrew: Put number here.]** for a Sun-like star, which means that they experience large differences in ambient temperature throughout their orbits and can thus transport energy outward from the stellar core extremely efficiently (Spergel & Press 1985). These features of ADM have already motivated research into the possibility that ADM may alter stellar evolution (e.g. Zentner & Hearin 2011; **?**; **?**). In this paper we undertake a study of the properties and evolution of stellar populations within halos of ADM. In this first paper on the topic, we further narrow our study to spin-dependent ADM-nucleus scattering. In contrast, spin-independent ADM-nucleus scattering leads to behaviors that are qualitatively distinct; therefore we will present results for this case in a forthcoming manuscript.

We generally find that ADM captured by stars can cool stellar cores to a degree that can have potentially observable effects on stellar populations. In general, the extra cooling due to ADM reduces the MS lifetimes **[Troy: since the intro to stellar models got moved down, the MS hasn't been introduced yet...]** of stars and alters their subsequent evolution **[Q: this last part doesn't make sense to me. The stars cross the sub-giant branch at a lower luminosity but after that the evolution is the same.]**. We summarize our results on stellar lifetimes in Figure 1 and the net effect on stellar populations in the form of stellar isochrones in Figure 4 in § 4. The effects of stellar cooling are particularly large in environments in which the ambient dark matter density is high and velocity dispersion is low, such that the capture of dark matter is extremely efficient. Thus, these effects will be largest in dwarf satellite galaxies and high-redshift galaxies.

In the following section, we summarize the dependence of the capture rate of dark matter within stars on dark matter and stellar properties. In § 3, we describe our simulations of stellar evolution including cooling due to ADM. We present our results in § 4. We discuss our results and draw conclusions in § 5.

[Andrew: I commented out two paragraphs here. I don't think we need them.] [Troy: I'm a bit surprised that you think all of the 2nd paragraph is unnecessary.. I had guessed that this would not be common knowledge to someone who studies dark matter and not stars...?]

2 DARK MATTER PROPERTIES AND CAPTURE IN STARS

Probing the parameter space of ADM with simulations of stellar evolution is computationally expensive. Consequently, we show results for a representative set of ADM parameters chosen to: (1) make the effects of ADM on stellar evolution significant; and (2) remain consistent with contemporary constraints on dark matter properties. For our models we choose $m_{\mathrm{DM}} = 5$ GeV ($\approx 5 m_p$) and a spin-dependent scattering cross section of $\sigma_{\mathrm{p}} = 10^{-37}$ cm^2. **[Q: I see that you took out the footnote explaining that the overwhelming majority of spin-dependent DM scattering events in MS stars are with protons. Is that so obvious that it doesn't need to be stated?]** We assume that ADM self-interactions are negligible throughout; however, it is likely that self-interactions would lead to enhanced cooling (e.g., Zentner 2009) and exploring such models would constitute a potentially interesting follow-up to this work.

[Troy: Need something here on current m$_x$ and σ_x constraints.] [Andrew: Yes, we need something here. It should just be a sentence saying that these parameters are just below the contemporary constraints on spin-dependent dark matter-nucleon scattering and give a citation to the latest result. I'm guessing you got this from Brian already, but the Cosmic Visions report from last year gives a nice summary along with links to all of the relevant experiments.]

The energy transported by dark matter is proportional to the amount of ADM within the star. In ADM models, in which annihilation of dark matter within the star is negligible, the number of dark matter particles within the star at time, t, is given by $N_{\mathrm{DM}} = C_{\mathrm{DM}} t$ where C_{DM} is the capture rate. We use the capture rate from Zentner & Hearin (2011), which is a simplified form valid for dark matter particle masses $m_{\mathrm{DM}} \lesssim 20$ GeV (see Gould 1992; Zentner 2009, for more complete capture rates):

$$C_{\rm DM} = C_{\odot}\Big(\frac{\rho_{\rm DM}}{0.4\ {\rm GeV\ cm^{-3}}}\Big)\Big(\frac{270\ {\rm km\ s^{-1}}}{\bar{v}}\Big) \times \Big(\frac{\sigma_{\rm P}}{10^{-43}\ {\rm cm^2}}\Big)\Big(\frac{5\ {\rm GeV}}{m_{\rm DM}}\Big) \times \Big(\frac{v_{\rm esc}}{618\ {\rm km\ s^{-1}}}\Big)^2\Big(\frac{M_\star}{{\rm M}_\odot}\Big) \quad (1)$$

where $C_\odot = 5\times10^{21}\ {\rm s^{-1}}$, $\rho_{\rm DM}$ is the DM density in the stellar environment, $\bar{v}$ is the velocity dispersion of dark matter particles in the stellar neighborhood, and $v_{\rm esc}$ is the escape speed from the surface of the star.

The first line of Eq. (1) gives the dependence of the capture rate on stellar environment. Both $\rho_{\rm DM}$ and $\bar{v}$ are properties of the local stellar environment. Moreover, these properties are degenerate with one another in Eq. (1); a higher ambient density of dark matter leads to a higher rate of capture, while a lower relative velocity between the star and the infalling dark matter leads to a higher probability for capture. Therefore it is convenient to parameterize a star's local dark matter environment by an overall factor (Zentner & Hearin 2011; Hurst et al. 2015),

$$\Gamma_B = \Big(\frac{\rho_{\rm DM}}{0.4\ {\rm GeV\ cm^{-3}}}\Big)\Big(\frac{270\ {\rm km\ s^{-1}}}{\bar{v}}\Big). \quad (2)$$

Normalized in this way, Γ_B specifies the capture rate, $C_{\rm DM}$, relative to the rate that would be realized in the solar neighborhood for the same star. From this point on we will characterize a star's dark matter environment using Γ_B due to the fact that density and velocity dispersion are degenerate in Eq. (1). In general, we will be most interested in values of $\Gamma_B > 1$, so we will refer to Γ_B as the environmental boost factor. A value of $\Gamma_B = 0$ describes a stellar environment with no DM (hereafter referred to as 'standard models' and labeled 'NoDM'), and $\Gamma_B = 1$ describes the solar neighborhood. A value of $\Gamma_B = 10^2$ may specify an environment in which the dark matter density is 100 times that in the solar neighborhood at the same velocity dispersion, an environment in which the velocity dispersion is 1/100 that of the solar neighborhood at the same density, or any of an infinite number of other possible combinations.

It is interesting to consider the range of Γ_B values that would be considered reasonable. If the distribution of dark matter within galaxies such as the Milky Way follows a profile that diverges as the **?**, NFW density profile, then one might expect to find a dark matter environment near the Galactic center with densities significantly higher than the local value and velocity dispersions significantly lower than the local value, giving $\Gamma_B \gg 1$. However, stellar populations near the Galactic Center are difficult to observe and any assumption about the dark matter density profile in the inner regions of any galaxy must be considered highly speculative. Interestingly, Local Group dwarf galaxies are extremely dark matter-dominated and have well constrained dark matter profiles and velocity dispersions. In some cases, the Local Group dwarfs have densities $\sim 2-3$ orders of magnitude higher than the dark matter density in the Solar neighborhood and have velocity dispersions that are at least ~ 2 orders of magnitude smaller than the local value. This suggests that values of $\Gamma_B \sim 10^{5-6}$ could be realized within Local Group dwarfs and has the further merit that Γ_B within Local Group dwarfs can be **[Q: measured?]** more precisely in the future. **[Andrew: TO DO: Address Γ_B in high-redshift galaxies.]** Finally, while we have focused on the boost parameter Γ_B as a proxy for the dark matter environment in which a star is embedded, we note that values of $\Gamma_B \neq 1$ can also be mimicked through dark matter physics. In particular, dark matter self-interactions can enhance the capture rates of dark matter within stars (Zentner 2009).

3 METHODS

[Andrew: I'm not sure I understand the purpose of the following paragraph. How does it advance our story? It seems unnecessary to me.] **[Troy: I'm trying to give the reader a sense of how MESA works because I refer to some (or maybe just one) of these pieces later on. The first sentence here might be so obvious that it doesn't need to be included. The second sentence could be moved here, along with the paragraph that follows.]** While we cannot directly observe stellar interiors, standard models have been developed and refined over the last century that match observations quite well. They are based on solving a set of coupled differential equations that describe energy and mass conservation, energy transport, and hydrostatic equilibrium using equations of state, tabulated opacities, and the (evolving) compositions of stellar interiors (see Pols 2011 for details). **[Andrew: I would also cite some of the classic textbooks here, because most of what you are discussing is available in standard textbooks on stellar evolution. My favorite book is the bible of stellar evolution, Kippenhahn and Weigert, but there are several good books on this topic.]**

[Andrew: I think we should move this more detailed discussion of low-mass vs. high-mass stars to the results section. So, let's remove everything starting here *]** Stars spend most of their lifetimes on the main sequence (MS), a near equilibrium state powered by hydrogen burning in the core. This conversion of hydrogen to helium happens via two main channels: the proton–proton (pp-) chain and the carbon–nitrogen–oxygen (CNO) cycle. The CNO cycle is much more sensitive to the temperature, as can be seen by the approximate scaling relations of the burning rates:

$$\epsilon_{pp} \propto T^4 \quad (3)$$

$$\epsilon_{CNO} \propto T^{18} \quad (4)$$

This has several important consequences:

(i) The pp-chain (CNO cycle) dominates in stars with central temperatures, T_c, less (greater) than $\approx 2\times10^7$ K.

(ii) The stable stellar structures in the two regimes are different. In CNO-dominated stars, radiative transport is insufficient to carry such large amounts of energy away from the central burning region, requiring these stars to have convective cores. In contrast, pp-dominated stars are stable with purely radiative cores.

(iii) Smaller energy production rates in pp-dominated stars also means that DM energy transport can be significant at much lower values than in CNO-dominated stars.

T_c generally increases with stellar mass, and the temperature threshold in (i) is equivalent to $M_\star \approx 1.3\ {\rm M}_\odot$. This means that our mass range includes two qualitatively distinct groups, which we will refer to as low-mass stars ($0.8 \leqslant M_\star/\mathrm{M}_\odot \lesssim 1.3$) and high-mass stars ($1.3 \lesssim M_\star/\mathrm{M}_\odot \leqslant 5.0$) for the purposes of this paper **[Q: Is this ok or should I really call them low-mass and intermediate-mass stars?]**. **[Andrew: *** and ending here. This can be moved.]**

We study the impact of dark matter on the evolution of $0.8 \leqslant M_\star/\mathrm{M}_\odot \leqslant 5.0$ stars through the thermal pulse (or equivalent) phase using the publicly-available code Modules for Experiments in Stellar Astrophysics (`MESA`), (Paxton et al. 2011). `MESA` models stellar evolution by simultaneously solving the coupled stellar structure and composition equations. We base our models on the `MESA` inlist used in Choi et al. (2016)[1] (see also Dotter 2016); however, we turn off rotation and diffusion and use a hard net **[TO DO: explain this better]**. Our results are robust to these changes. **[TO DO: double check diffusion and hard net results]**. This choice makes our models and our isochrones comparable to those published by Dotter. We use a solar metallicity of z=0.014. DM energy transport is calculated as described in 3.1 and passed to `MESA` using the native `other_energy_implicit` hook which includes this energy self-consistently when solving the coupled equations.

The size of each time step in a `MESA` model can vary by orders of magnitude, and so output for different `MESA` runs may contain information at drastically different times. To generate isochrones we must interpolate output from a range of initial stellar masses, with all other parameters held constant. We accomplish this using code written by Dotter (2016)[2]. It takes a set of `MESA` runs and uses key evolutionary phases to guide the interpolation. This helps to ensure that phases with shorter time scales are properly represented in the interpolation.

3.1 Energy Transport by Dark Matter

The energy transported by captured ADM can, in principle, be computed by solving the Boltzmann equation; however, this strategy is too computationally intensive to combine with a full-scale simulation of the evolution of stellar structure. To reduce the computational costs of our simulations, we estimate ADM energy transport using the approximations of Spergel & Press (1985). In particular, we assume a Maxwellian phase-space distribution for the ADM and calculate an orbit-averaged temperature, T_{DM}, by requiring that the distribution satisfy the first moment of the Boltzmann equation. This amounts to a requirement on energy conservation: ADM should neither inject nor remove a net energy from the star. The rate of energy transfer (per unit mass) from dark matter to protons is then

$$\epsilon_{\mathrm{DM}}(r) = 8\sqrt{\frac{2}{\pi}}\frac{n_{\mathrm{DM}}(r)n_p(r)}{\rho(r)}\frac{m_{\mathrm{DM}}m_p}{(m_{\mathrm{DM}}+m_p)^2}\sigma_{\mathrm{p}} \times\left(\frac{m_p kT_{\mathrm{DM}} + m_{\mathrm{DM}}kT(r)}{m_{\mathrm{DM}}m_p}\right)^{1/2} k(T_{\mathrm{DM}} - T(r)), \tag{5}$$

where $n(r)$ is a number density, $\rho(r)$ is the mass density, k is Boltzmann's constant, and the subscript p refers to protons. (See Spergel & Press 1985, for a detailed derivation).

Generally, n_p, n_{DM}, and T all peak at the center (exceptions noted below), so the energy transport is most efficient here. The number density of dark matter particles, n_{DM} increases in proportion with N_{DM}, so we can expect the effects to increase with both Γ_B and stellar age through the MS, while hydrogen is abundant. As a star leaves the MS, n_p drops in the core and spin-dependent ADM energy transport is greatly diminished because there are relatively few protons left with which dark matter may scatter[3]. A standard MS temperature profile decreases monotonically with distance from the star's center, but it can become temporarily inverted when ADM moves large amounts of energy away from the center (requires $\Gamma_B \gg 1$) **[Q: should I mention any standard conditions that cause this? degeneracy?]**. **[Andrew: You can give guidelines if you know them. But if not, it is ok.]**

The sign of $\epsilon_{\mathrm{DM}}(r)$ is given by the final term in (5), $T_{\mathrm{DM}} - T(r)$, which is used to define an ADM characteristic radius, r_{DM}, implicitly as

$$T(r_{\mathrm{DM}}) = T_{\mathrm{DM}}. \tag{6}$$

Then dark matter takes energy from $r < r_{\mathrm{DM}}$ and deposits it at $r > r_{\mathrm{DM}}$ for a standard MS temperature profile. With our chosen ADM parameters we see typical values:

$$r_{\mathrm{DM}} \sim \mathcal{O}(0.1R_\star) \tag{7}$$

$$l_{\mathrm{DM}} = (\sigma_{\mathrm{p}} n_p)^{-1} \sim \mathcal{O}(1R_\star) \tag{8}$$

[Q: is this a right/good way to write this? also, should $R_\star$ be in Roman font here?] **[Andrew: Looks good to me.]** **[TO DO: check that the data agree with these estimates]** where l_{DM} is the ADM mean free path (implying that it completes several orbits between scattering events). These values allow dark matter to travel much larger distances than photons or ions within the star (which have $l \lesssim 10^{-10}R_\star$) and to traverse qualitatively distinct regions of the star. This large mean free path is what enables dark matter to serve as such an effective coolant despite being far less numerous than either photons or ions (**?**). **[Q: should I mention anything else here? like seeing a significant temperature gradient or something related to the convection effects?]** **[Andrew: I think this is good.]**

[TO DO: orphaned: dm probes temp diffs over large portion of star. so temp gradient shallow at center dm energy transport can still be efficient. contrary to standard stellar evolution.]

[TO DO: check that old plots are xluminosity and not xheat.]

[Andrew: We should probably mention that our (your) software module will be made available through the standard MESA portal. Do you also want to point to a github page for your module?]

[1] `http://waps.cfa.harvard.edu/MIST/`
[2] `https://github.com/aarondotter/iso`

[3] This is one of the primary reasons that spin-dependent and spin-independent scattering gives qualitatively distinct results. As the star burns H on the MS, the number of protons is reduced, reducing the importance of spin-dependent scattering processes. In the case of spin-independent scattering, the effect gets more important as helium is produced from H burning during the MS.

4 RESULTS

[TO DO: still need to re-write this paragraph.] We find that, for stars significantly affected by ADM energy transport, the general effect is to shorten MS lifetimes (see Figure 1) so that, for a stellar populations of a given age, the MS turn-off happens at a lower mass and the stars evolve through the sub-giant branch at a lower luminosity (see Figure **??**) when ADM cooling is operative. This causes isochrones of clusters in high Γ_B environments to appear older than their standard model counterparts. This becomes noticeable in the highest Γ_B environments around 0.2 Gyr as stars with M $\approx$ 4 M$_\odot$ begin to leave the MS. Prior to this the stars have not had enough time to capture a sufficient number of WIMPs for ADM-driven energy transport to be a significant contribution to the overall energy transfer within the star.

[Andrew: In what follows, an important change will be that we should discuss the figures in the order in which they appear. This is very standard practice and I don't think we should deviate from that.]

[Andrew: For this first paragraph, I might attempt to do something like the following. I think this gives a nice introduction to the basic result, incorporates what the reader needs to know about low-and high-mass stars (so we can remove that part from the introduction), and segues into the separate subsections about low- and high-mass stars. This may need some editing, but I hope you get the idea.] In general, we find that ADM within stars alters stellar MS lifetimes and post-MS evolution. The alteration of MS lifetimes is shown in Figure 1. For the purposes of this figure, we have defined the MS to end when the core abundance of hydrogen falls below XXXXX. In Fig. 1, it is apparent that in most, but not all, scenarios that we study, MS lifetimes are reduced due to ADM. Examining Fig. 1 more closely, stellar lifetimes relative to the standard case with no ADM increase from low masses until they turn over and decrease again. The mass at which this decrease occurs varies based upon the environmental boost factor Γ_B, which is a proxy for the strength of the cooling effect. However, the reason for the turnover is related to a fundamental distinction between low-mass stars and high-mass stars.

[Andrew: Maybe you want to add a discussion of Figure 2 right here as well?]

To understand this feature better, consider standard stellar evolution in which there is no influence from dark matter of any kind. In this case, stars burn hydrogen to produce helium through two channelsl, namely the proton-proton (pp) chain and the carbon-nitrogen-oxygen (CNO) cycle **[Andrew: Cite one or more standard references on stellar structure here. I am partially to Kippenhahn, but whatever you like is fine.]**. The pp chain dominates energy production in stars with core temperatures $T_c \lesssim 2\times10^7$K and the rate of burning scales with temperature very roughly as $\epsilon_{pp} \propto T^4$. The CNO cycle dominates nuclear burning in stars with higher core temperatures and CNO burning rates scale much more strongly with temperature: $\epsilon_{CNO} \propto T^{16-20}$. The core temperature that separates the CNO cycle from the pp chain corresponds to a stellar mass of approximately $M_\star \approx 1.3$ M$_\odot$. This distinction in burning rates corresponds to a fundamental difference in stellar structure. In pp-dominated stars with $M_\star \lesssim 1.3$ M$_\odot$, the transport of energy from the core burning region is dominated by photon diffusion. Energy transport in the cores of such stars is said to be radiative. In CNO-dominated stars with $M_\star \gtrsim 1.3$ M$_\odot$, radiative energy transport is insufficient to carry away the energy produced by hydrogen burning. Consequently, these high-mass stars have convective cores. In what follows, we will consider results for high-mass stars and low-mass stars separately and we will demonstrate that ADM has distinct effects on the evolution of low- and high-mass stars.

4.1 High-Mass Stars: $1.3 \lesssim M_\star/\mathrm{M}_\odot \leqslant 5.0$

In standard models, MS stars with $M_\star \gtrsim 1.3$ M$_\odot$ are powered primarily by the CNO cycle. This has several important consequences: (1) the burning rate is much higher than in pp-dominated stars; (2) the burning rate is extremely sensitive to core temperature; and (3) stellar cores must be convective in order to carry away the energy produced by core hydrogen burning. Central convection typically extends beyond the burning region, giving the star a source of new nuclear fuel as hydrogen from outside of the core is mixed into the stellar center. **[Andrew: A better way to say this that may eliminate the need for any footnote might be to say something along the lines of "This influx of unburnt hydrogen into the stellar core extends the MS lifetime of the star beyond what it would have been had there been no convection.]** As a result, convection extends the MS lifetimes [4]. Once hydrogen throughout the convective zone is depleted, the star exits the MS. At this point, the burning rate rapidly decreases and the star loses more energy at its surface than is being generated by burning. Gravity temporarily dominates and the star contracts until the internal temperature increase is sufficient to ignite hydrogen in a shell outside the depleted core. This can be seen in the 'NoDM' models (light blue **[Q: green? yellow?]** **[Andrew: light blue]**) in Figure 5. **[Andrew: Tell the reader how they see this effect. What is the reader looking for?]** **[Q: why does the convective region shrink while burning rate increases?]** The contraction causes a temporary increase in T_{eff} and a feature in the star's HR diagram called the convective hook (see Figures 3 and 4). See Pols (2011) for more details. **[Andrew: If you want to discuss Figure 5 prior to discussing the isochrones, then we should switch the order in which the figures appear in the paper. Figure 5 will need a detailed caption and/or a more detailed description in the main text of the paper.]**

If a star captures enough ADM, the combination of dark matter + radiative energy transport becomes sufficient to carry the flux from nuclear burning. Convection disappears from the center first (where ADM energy transport is most efficient) and retreats away from the core, into a narrowing shell. Without convective mixing, the central hydrogen supply depletes and so the burning also shifts into a shell,

[4] This extension is subdominant. Central temperatures increase with stellar mass, causing the burning rates to increase dramatically which shortens standard model stellar lifetimes so they decrease approximately as $\tau \propto M_\star^{-2.5}$.

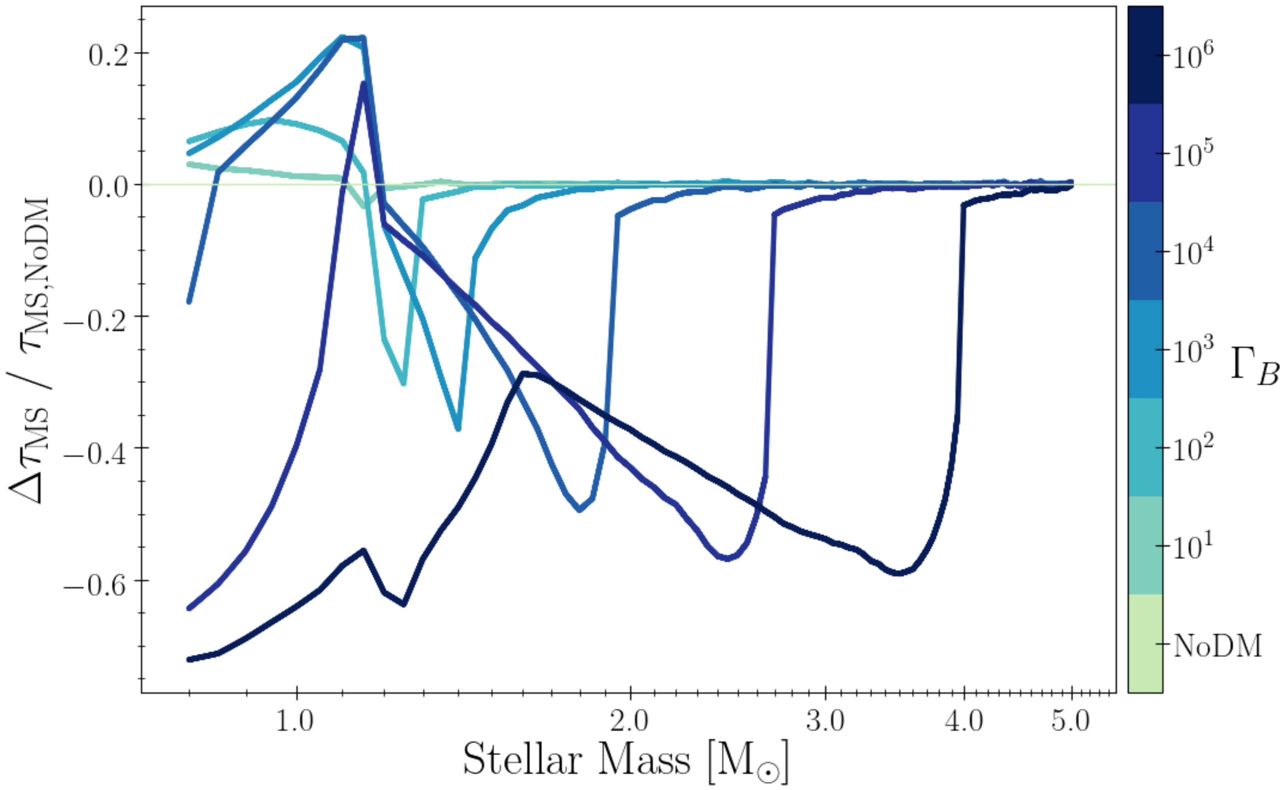

Figure 1. CHANGES: yaxis label remove 'MS', don't italicize 'NoDM'. xaxis label -> Star Mass, values -> 1,2,.. need more tick marks. Colorbar rotate gammaB to face up. **[Andrew: x-axis should be logarithmically spaced, but we don't want the "$\times 10^0$" on the labels.]** Change in MS lifetime relative to NoDM model. The presence of DM generally shortens the MS lifetime. Differences in the two categories of stars in this mass range can be seen here in the non-monotonicity around roughly 1.3 Msun.

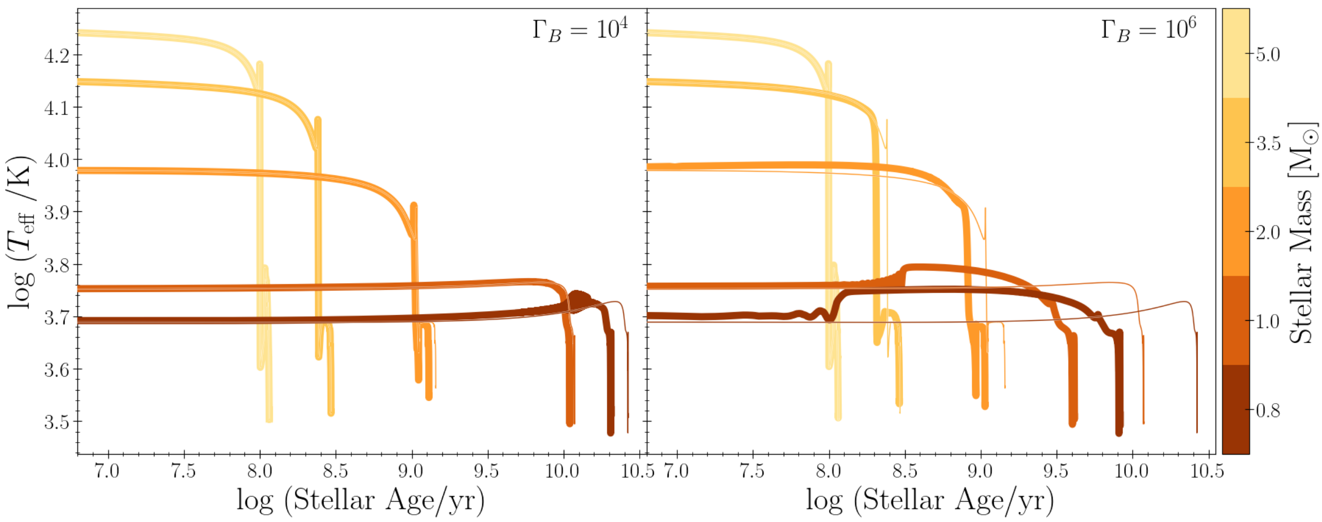

Figure 2. CHANGES: increase all font sizes. yaxis label Teff italicized / K. xaxis lower limit 7. Perhaps remove c4 panel and make the 3rd panel a zoom-in that includes c4?

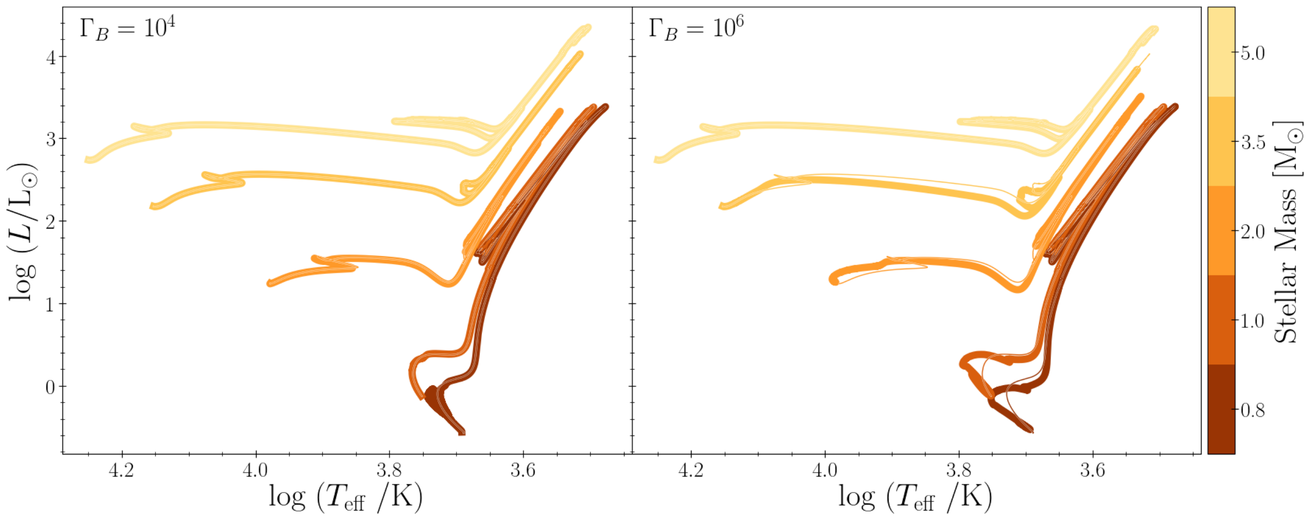

Figure 3. CHANGES: all font sizes bigger except plot labels. axis labels log(variable (italic)/ unit). Add and label ZAMS line.

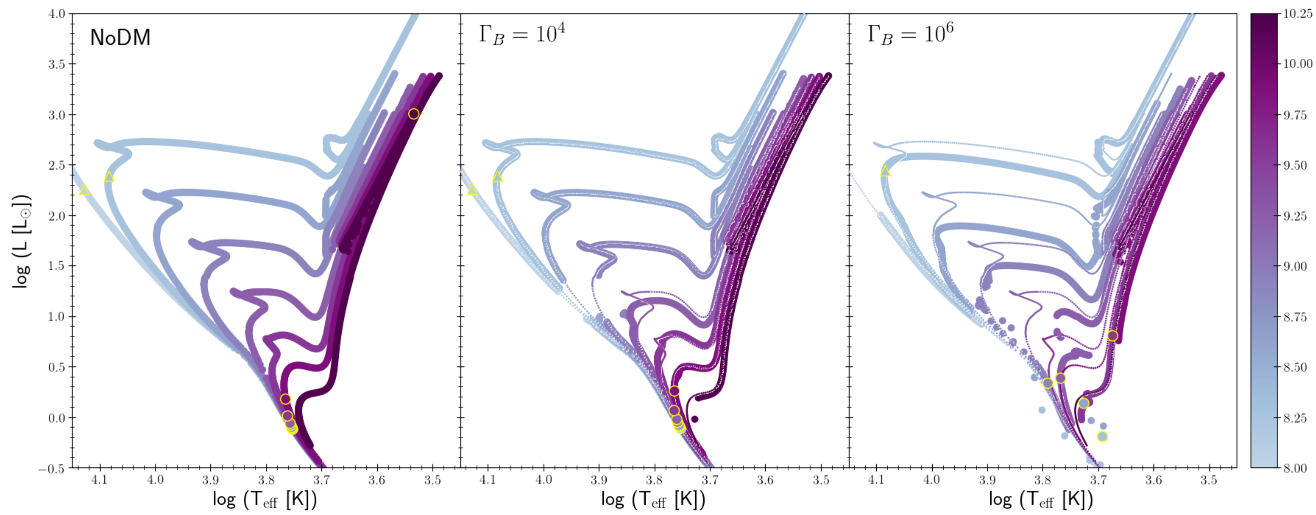

Figure 4. CHANGES: all font sizes bigger except plot labels. axis and colorbar labels log(variable (italic)/ unit). Consider zoom in of lower right on c6 plot. Triangles are 3.5 M$_\odot$, circles are 1.0 M$_\odot$. There is missing data where the isochrone code did not interpolate. This is due to non-monotonicity in the initial mass - age relation of a given EEP (equivalent evolutionary phase), which is a known problem that Dotter discusses in his paper.

following the lower boundary of the convective zone (Figure 5). The result is that these stars leave the MS earlier and at a lower luminosity, and they skip the convective hook altogether (Figure 3). This makes the isochrones appear older than their 'NoDM' counterparts (Figure 4). The effects disappear as $M_\star$ approaches 5 M$_\odot$ because stellar lifetimes become too short for a sufficient amount of ADM to build up.

4.2 Low-Mass Stars: $0.8 \leqslant M_\star/\mathrm{M}_\odot \lesssim 1.3$

Standard model stars in this mass range have relatively low central temperatures and so are powered primarily by the pp-chain, which is much less sensitive to the temperature. This means the burning does not peak as strongly at the center and radiative transport is sufficient to carry the energy flux, so the core is not convective. Without convective mixing, hydrogen depletes first at the very center and the burning shifts outward gradually, avoiding the instability that causes the convective hook in standard CNO-powered stars. This behavior is very similar to high-mass stars that collect large amounts of ADM, which contributes to isochrones appearing older as Γ_B gets large.

Since the burning rate is much lower, the same number of captured dark matter particles have a larger effect in this mass range. As stars with Γ_B as low as 10^2 **[TO DO: check this number for several masses]** enter the MS, ADM is already transporting a significant amount of energy away from the center ($\epsilon_{\rm DM} \approx \epsilon_{pp}$ near $r = 0$) and depositing it in a shell at $m(< r) \approx 0.1$ M$_\odot$. This causes the temperature, and therefore the burning rate, to be lower at the center

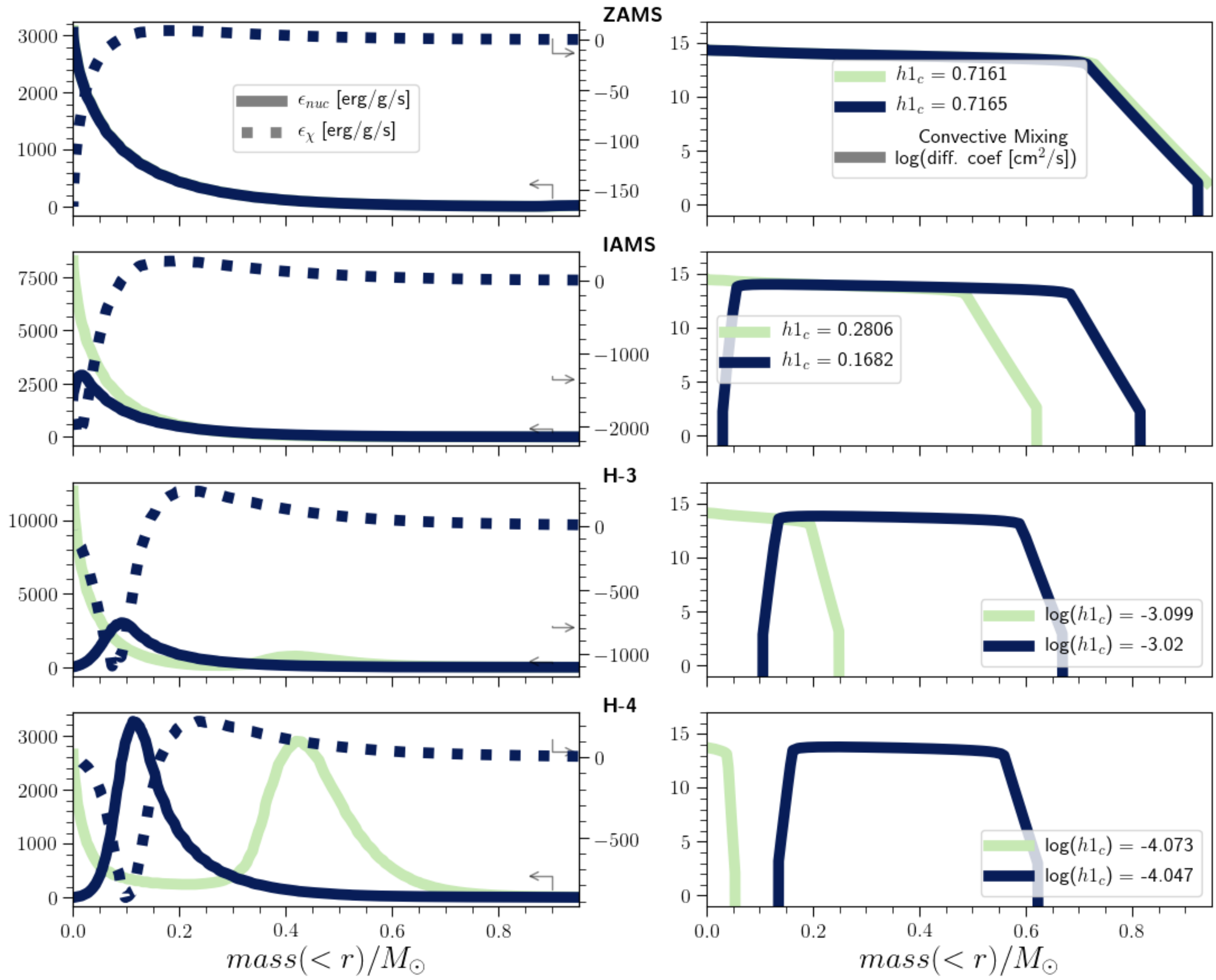

Figure 5. CHANGES: main title ". column titles 'energy production and transport', 'convection'. yaxes label with units, remove them from legend. put 0 line on epschi for c0. fix the scale? xaxis label m(<r)/Msun. reduce linewidth. increase space between rows, maybe decrease height of plots. CAPTION: 3.5Msun. Cboost colors are the same as the previous plots. Time moves down the page. Left column (note large scale changes): eps nuc is on the left axis, DM energy transport is on the right. Negative (positive) values of epschi indicate DM is removing (depositing) energy. Right column: convective mixing (log(D) where D is diffusion coefficients of convection + overshoot.). As the radiative core grows in the c6 model, the burning gradually shifts outward to shell burning, following the inner edge of the convective shell. The hydrogen supply is not replenished outside the convective zone. NOTES: I'll put the grey arrows in exactly the right place once we settle on which time steps to show. The $h1_c$ legend is just a check to make sure the specific profile used is close enough to the one I wanted. I will remove this for the final plot.

and higher in a shell relative to standard models. Stars in environments with $\Gamma_B \lesssim 10^4$ are able to remain stable in this configuration. See Figure 6.

Models with $\Gamma_B \gtrsim 10^4$ capture enough ADM so that $\epsilon_{\rm DM} \gg \epsilon_{pp}$ near $r = 0$ which destabilizes the core and sets up a series of oscillations. **[TO DO: check different masses, particularly 0.8Msun for which the effect may extend down to c4.]** (see Figure 7 Time 2, left plot). As T_c continues to decrease, the temperature profile inverts and the center is no longer the hottest region in the star. Eventually, $T_c < T_{\rm DM}$ and dark matter begins moving energy back towards the center ($\epsilon_{\rm DM}(r = 0) > 0$, see Time 3 in Figure 7 **[TO DO: possibly pick this time a little later, after xheat at center >0]**). This increases both the central temperature and burning rate until $T_c > T_{\rm DM}$ and the cycle starts over. The effects propagate out to the surface where L, T_{eff}, and $R_\star$ all oscillate in response to changes in the core. Similar oscillatory behavior was noted in Iocco et al. (2012) **[Q: seems like I need to say more here, but I'm not sure what. The Iocco paper (arXiv:1201.5387v1) states the following: "In spite of our efforts, we have not been able to fully understand the reason of the oscillations seen in Figure 3, whether they are a physical effect arising from the "bouncing" of the central temperature on the WIMP temperature floor, or a numerical artifact.**

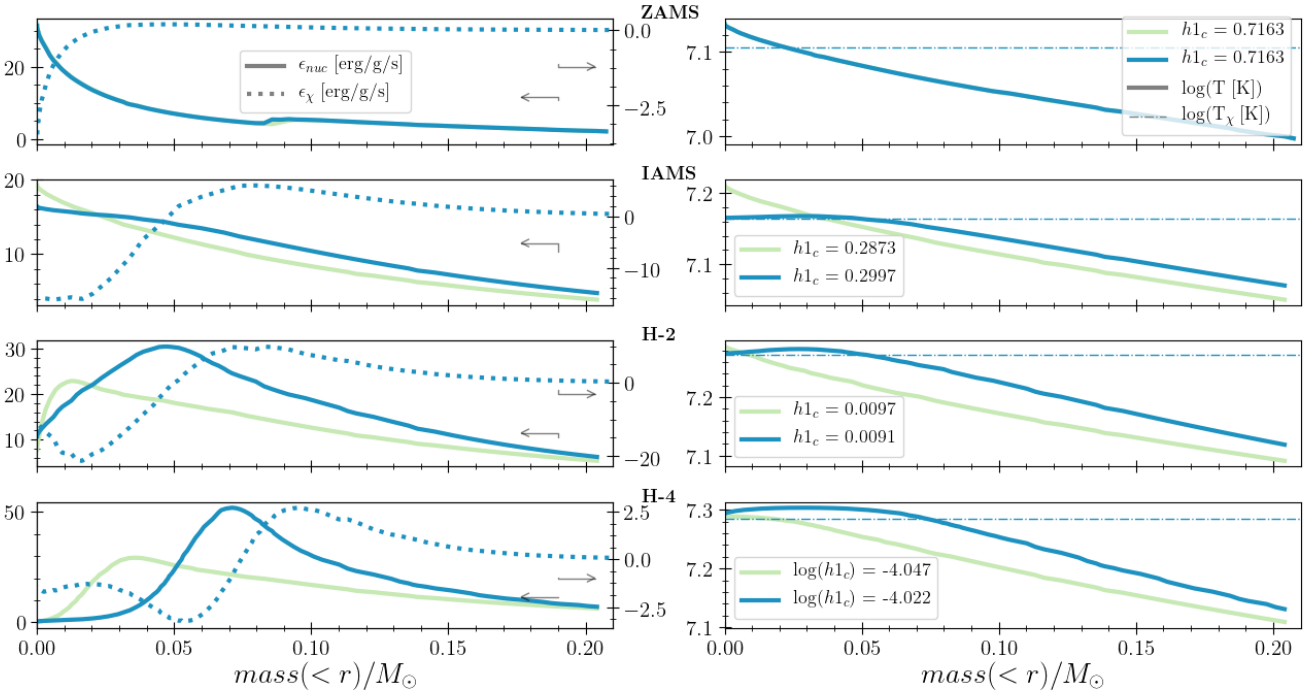

Figure 6. 1.0Msun. Cboost colors are the same as the previous plots. Time moves down the page. Left column: (same as previous plot) eps nuc is on the left axis, DM energy transport is on the right (note large scale changes here). Right column: temperature (DM temperature marked as thin dotted line. DM energy transport decreases the burning in the core and pushes the burning into a shell more quickly than the reference models.

We have however checked that the existence of oscillations does not affect our results nor does change our conclusions. Beside the theoretical consistency of the intepretation presented in the paper, one can be convinced of the actual physical consistency of our results with observations based on several numerical experiments we have performed: ..."].

The process repeats, with increasing amplitude, until the central temperature falls low enough that the core becomes significantly degenerate. Once electron degeneracy pressure can support the core, the temperature decouples from the equation of state and the star quickly settles into a more stable configuration with a significant temperature inversion (see Time 4 in Figures 7 and 8).

Overall, the ADM captured by these stars causes burning in a larger volume and at a higher rate than in standard models (see Figure 8). The stars then burn through the central hydrogen supply faster and leave the MS earlier: by 2.5 Gyr, solar mass stars with $\Gamma_B = 10^6$ have already left the MS and are climbing the red-giant branch. Note that the 2.5 Gyr, $\Gamma_B = 10^6$ isochrone is most similar the 10 Gyr, NoDM isochrone (Figure 4).

Notes: hydrogen depletes in shell first.

Possible work for future: 1. vary DM mass and cross section (given observational constraints) to see how quick the effects vanish. 2. model iso curves and quantify how much older they look.

5 DISCUSSION AND CONCLUSIONS

[**Andrew: I think that most of your conclusions section could be (1) a summary of our results and (2) speculations on how to turn this into a constraint in the future.**]

ACKNOWLEDGEMENTS

REFERENCES

Choi J., Dotter A., Conroy C., Cantiello M., Paxton B., Johnson B. D., 2016, The Astrophysical Journal, 823, 1

Dotter A., 2016, The Astrophysical Journal Supplement Series, 222, 8

Gould A., 1992, The Astrophysical Journal, 388, 338

Hurst T. J., Zentner A. R., Natarajan A., Badenes C., 2015, Physical Review D - Particles, Fields, Gravitation and Cosmology, 91

Iocco F., Taoso M., Leclercq F., Meynet G., 2012, Physical Review Letters, 108, 1

Paxton B., Bildsten L., Dotter A., Herwig F., Lesaffre P., Timmes F., 2011, Astrophysical Journal, Supplement Series, 192

Pols O., 2011, Utrecht University, Lecture Notes: Stellar Structure and Evolution. No. September, `http://www.astro.ru.nl/{~}onnop/education/stev{_}utrecht{_}notes/`

Spergel D. N., Press W. H., 1985, The Astrophysical Journal, 294, 663

Zentner A. R., 2009, Physical Review D - Particles, Fields, Gravitation and Cosmology, 80

Zentner A. R., Hearin A. P., 2011, Physical Review D - Particles, Fields, Gravitation and Cosmology, 84, 3

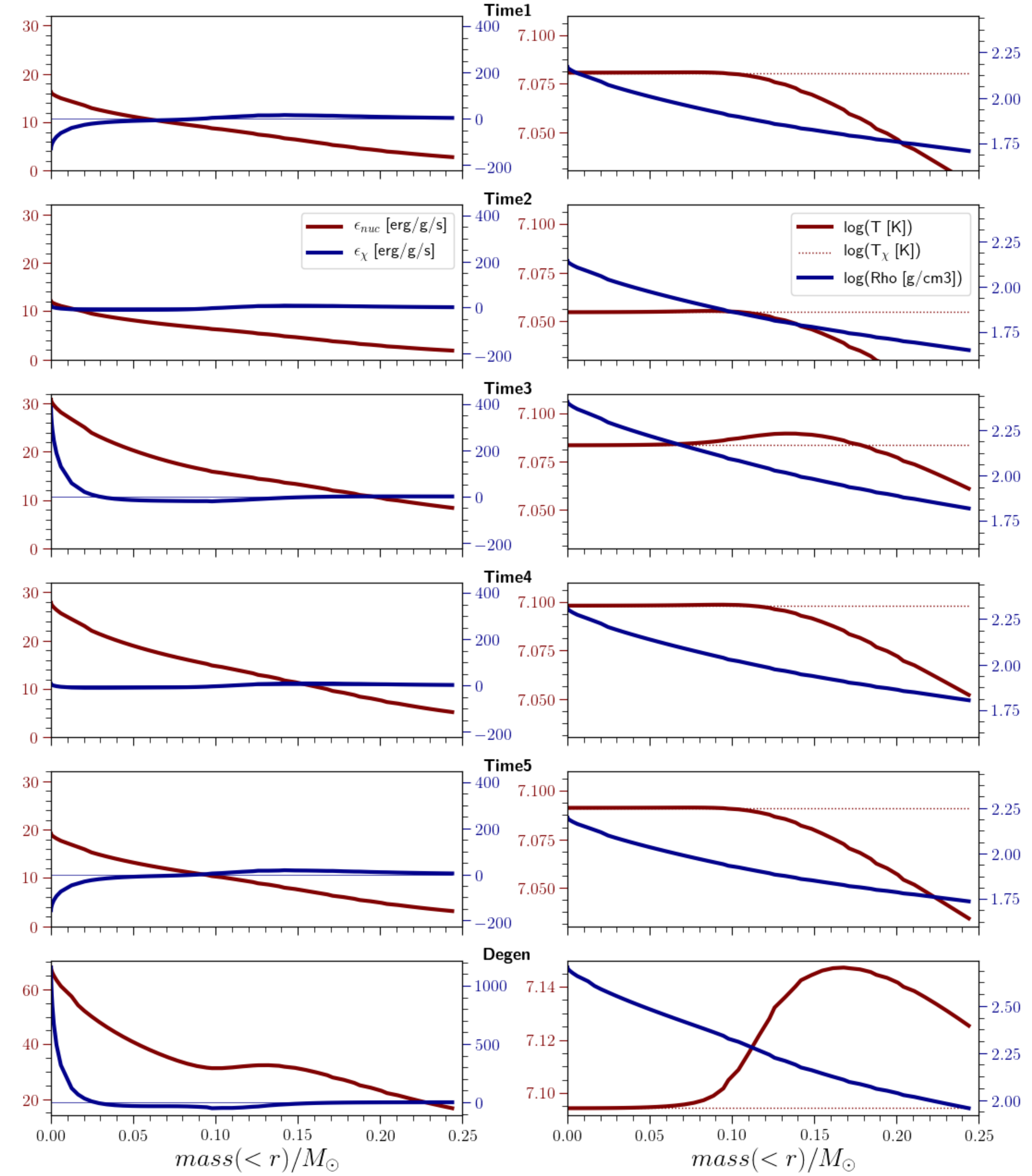

Figure 7. Star mass 1.0Msun, $\Gamma_B = 10^6$ (colors are different than previous plots). Time moves down the page with rows correspond to times from figure 8. 'Time1-5' were chosen to show the progression and extremes of DM energy transport during one oscillation cycle. Scales are fixed for ease of comparison. 'Degen' shows conditions after the oscillations stop, when electron degeneracy pressure is supporting the core (note scale changes). Left column has ϵ_{nuc} on left axis (red) and DM energy transport on the right (blue). Right column has logT on left axis (red, with T$_x$ marked with thin dotted line) and logRho on the right axis (blue).

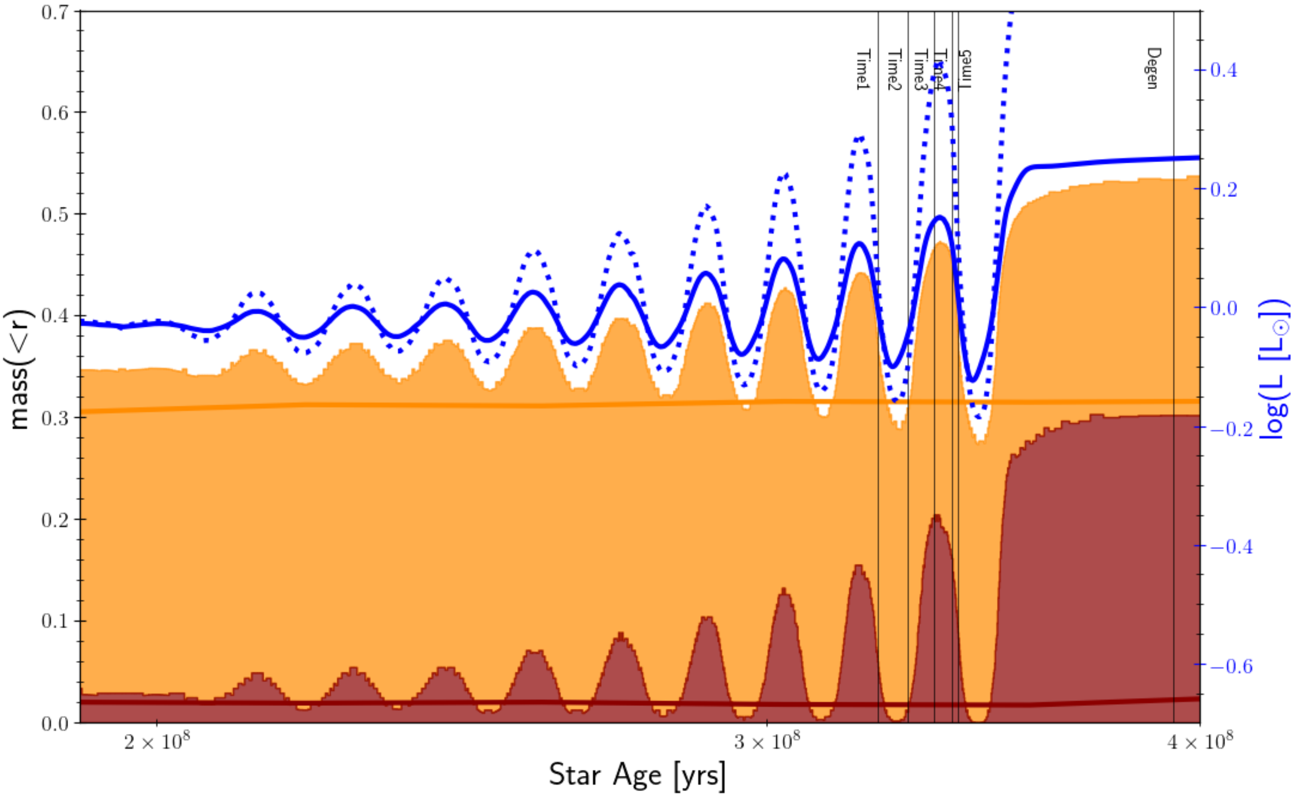

Figure 8. Star mass 1.0Msun, $\Gamma_B = 10^6$. Figure 7 shows profiles of the star at the times marked here by vertical black lines. Yellow and red show burning intensity as a function of age and mass coordinate (left axis) (I believe the burning thresholds are 1 erg/g/s and 10 erg/g/s respectively, but I'm a little confused about the mesa output and I need to check with Héctor or Carles.) Darker yellow and red lines mark the burning extent of the NoDM model over this time period. Blue line is luminosity (right axis). NOTE: Dotted blue line is hydrogen burning luminosity (I will probably remove this line for the final plot, but I want to check with Carles to make sure the behavior makes sense. I think the explanation is: When LH>L star is producing more energy than it is losing, causing it to expand, and . I have a separate plot of the radius that we can look at if needed. Actually could add logR to this plot.)

This paper has been typeset from a TEX/LATEX file prepared by the author.