Evaluation of anthropic arguments in the multiverse

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Motivated by the possible existence of other universes as part of the multiverse framework, we investigate how changing quantities in nuclear physics can change the prospects for the existence of astrophysical structures. We focus on nucleosynthesis and consider changing binding energies and reaction rates for both big bang nucleosynthesis (BBN) and stellar nucleosynthesis. We find the resulting differences in nuclear abundances in these two settings. The abundance yields are used to assess the strength of anthropic arguments or infer the prospects of habitability in other universes.

Stable $^8\mathbf{Be}$ (arXiv:1608.04690)

Highlights

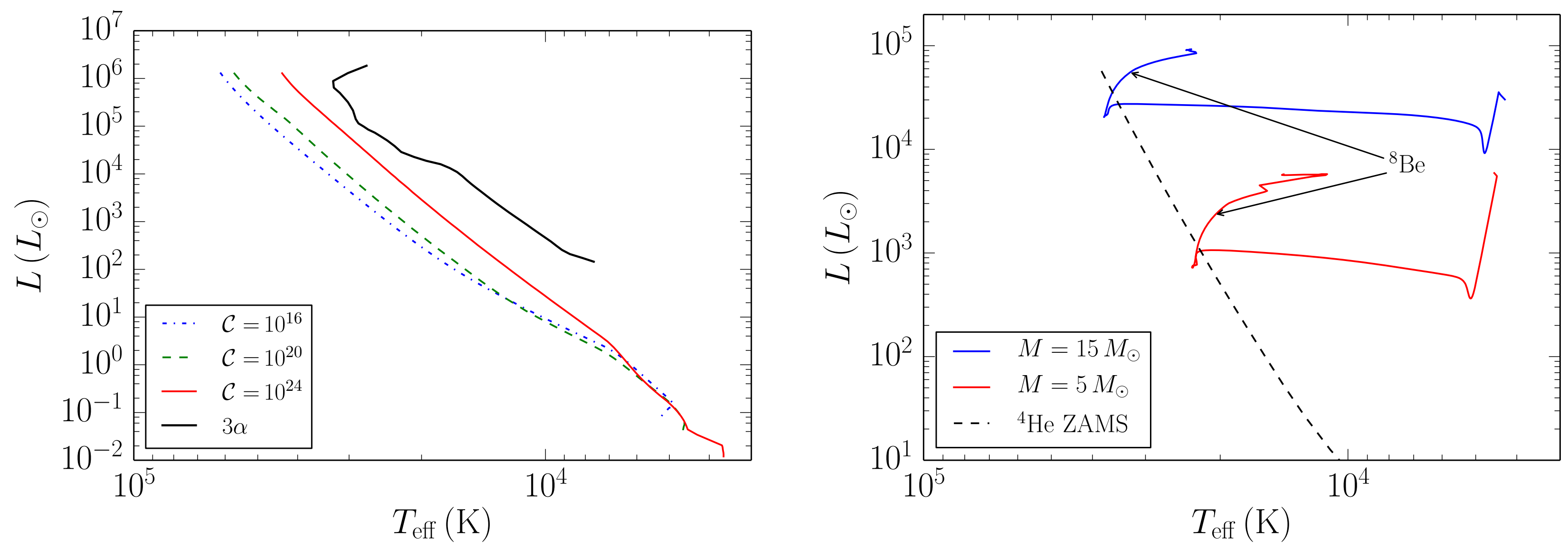
- In our universe, no stable $A = 8$ nuclear configuration; $^8\mathbf{Be}$ unstable by $\sim 90\,\mathrm{keV}$
- Stars synthesize $^{12}\mathbf{C}$ directly from 3 α particles via the Hoyle resonance in $^{12}\mathbf{C}$
- If a stable $^8\mathbf{Be}$ isotope exists, it could obviate the need for the Hoyle resonance in $^{12}\mathbf{C}$

Reactions with $^8\mathbf{Be}$

With a stable $^8\mathbf{Be}$ nucleus, there are two new reactions and corresponding integrated cross sections ($\langle\sigma v\rangle$) to consider: $\alpha(\alpha,\gamma)^8\mathrm{Be}$ and $^8\mathrm{Be}(\alpha,\gamma)^{12}\mathrm{C}$. We take $\langle\sigma v\rangle$ from Nomoto et al (1985) for each individual reaction. The overall strength of each $\langle\sigma v\rangle$ is set using two nuclear burning parameter, $\mathcal{C}$ for $\alpha(\alpha,\gamma)^8\mathrm{Be}$ and $\mathcal{C}_C$ for $^8\mathrm{Be}(\alpha,\gamma)^{12}\mathrm{C}$. The two additional reactions are added to the *MESA* reaction network, and the triple-alpha reaction is eliminated, while we add $^8\mathrm{Be}$ to the isotope list. *MESA* evolves stars of varying mass with low metallicity.

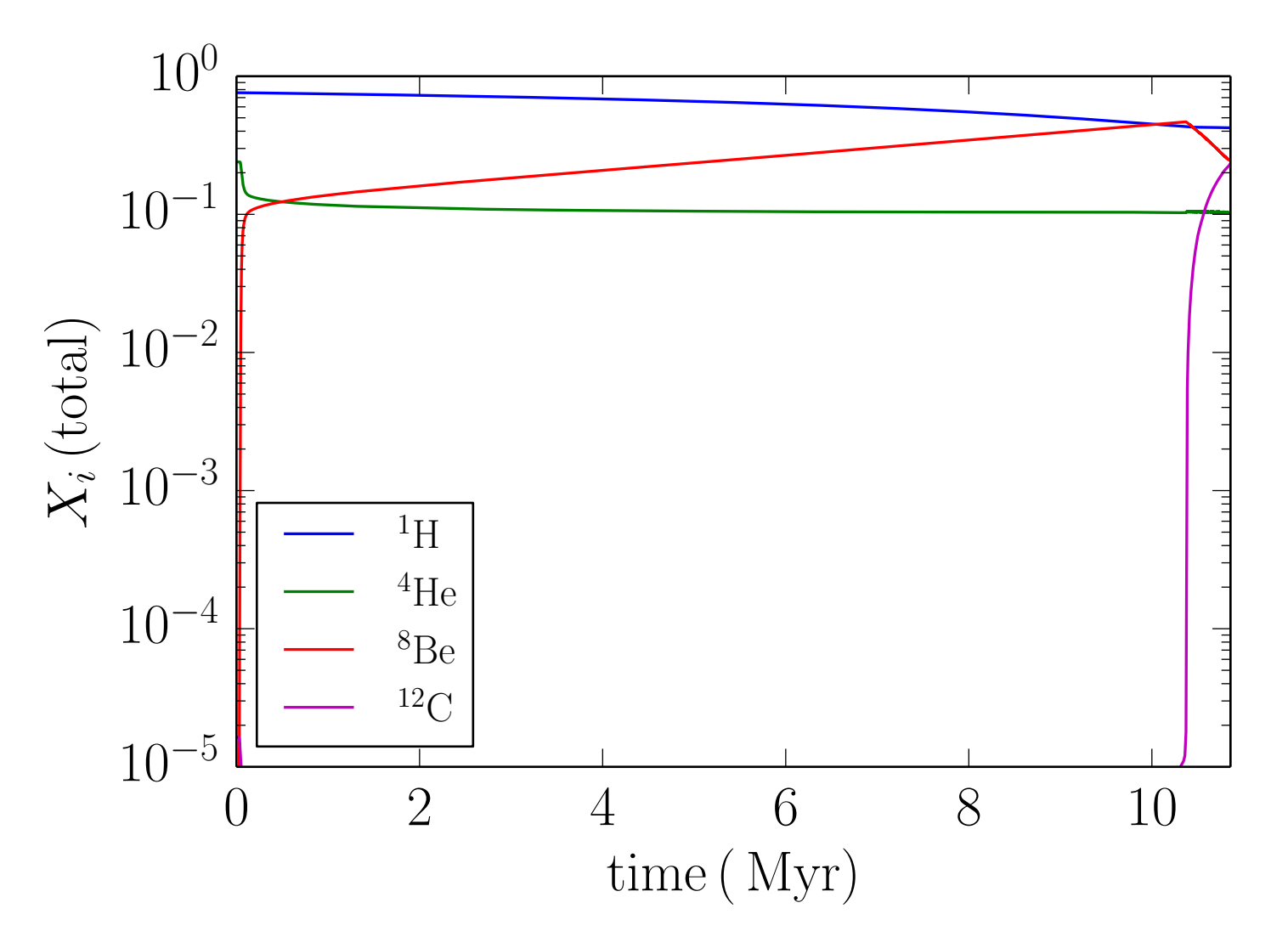
Main sequences

Left: Three Hertzsprung Russell (HR) diagrams of the Zero Age Main Sequence (ZAMS) for $^4\mathrm{He}$ burning. The colored lines correspond to different values of $\mathcal{C}$. The ZAMS ranges from 0.25 up to 100 $M_\odot$. Plotted for comparison is a solid black line of the ZAMS for $^4\mathrm{He}$ burning with the triple-alpha reaction in our universe. *Right*: HR tracks for two stars with different masses. For both stars, $\mathcal{C} = 10^{20}$ and $\mathcal{C}_C = 10^{28}$ in cgs units. The black dashed line gives the ZAMS for $^4\mathrm{He}$ burning. The $^8\mathrm{Be}$ label shows when the composition of the star reaches 50% $^8\mathrm{Be}$ by mass. The termination of each track is when the $^{12}\mathrm{C}$ mass fraction reaches 50% in the stellar core.



Mass fraction evolution

The evolution of mass fractions (averaged over the total volume of the star) as a function of time for a 15 $M_\odot$ star. $\mathcal{C} = 10^{20}$ and $\mathcal{C}_C = 10^{28}$ in cgs units. The initial composition is 24% $^4\mathrm{He}$, which burns into $^8\mathrm{Be}$.



Unstable $^2\mathbf{H}$ (arXiv:1612.04741)

Highlights

- In our universe, deuterium is the smallest nucleus with $A > 1$; bound by only $\sim 2.2\,\mathrm{MeV}$
- Deuterium is the first step in BBN [via $n(p,\gamma)^2\mathrm{H}$] and stellar nucleosynthesis [via $p(p,e^+\nu_e)^2\mathrm{H}$]
- Without stable deuterium, stars could still synthesize $^4\mathrm{He}$ and heavier elements through other means

Triple nucleon reaction

Unstable deuterium decays into constituent nucleons. To overcome the $A = 2$ mass gap, we propose a triple-nucleon reaction for $^3\mathrm{He}$ production

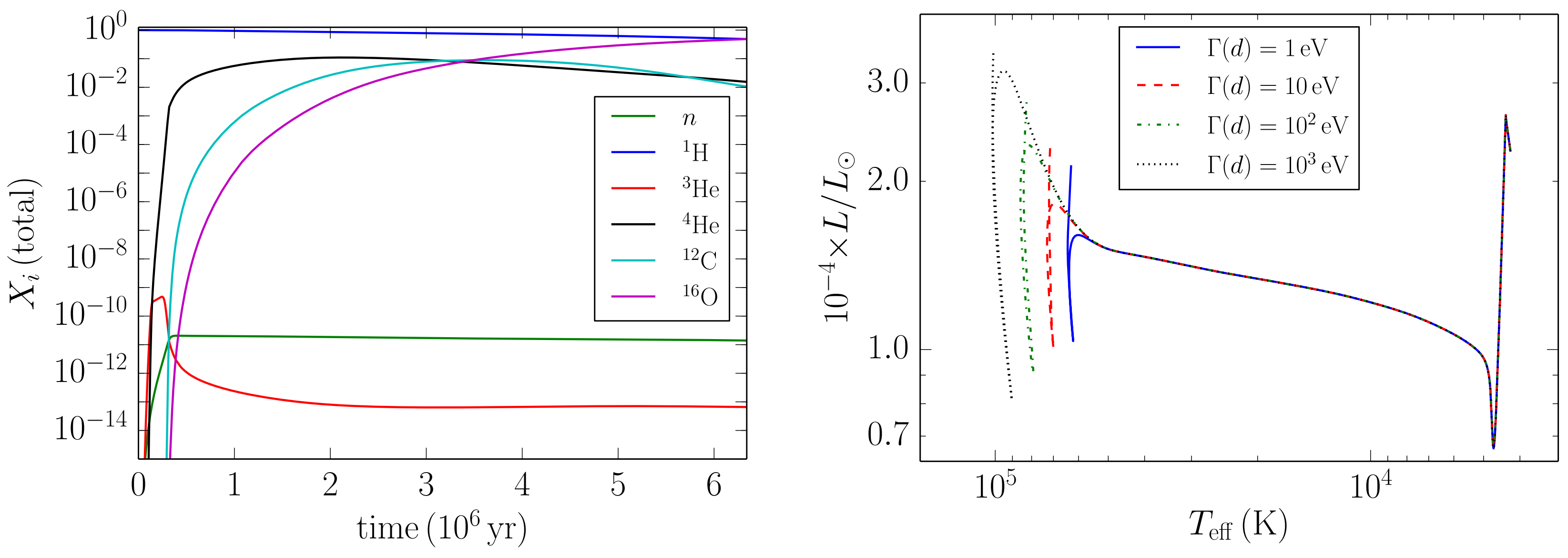
$$n + p + p \to {}^3\mathrm{He} + \gamma$$

$$\left.\frac{dY_3}{dt}\right|_+ = Y_n Y_P^2 \frac{\rho_b^2 N_A^2}{2\Gamma(d)} \langle np\rangle\langle dp\rangle$$

$\Gamma(d)$ is the decay width and a parameter in the model. The reaction is added into the *MESA* network for stars, and the *BURST* network for BBN, while any reactions with $^2\mathrm{H}$ are eliminated.

Stars with triple nucleon reaction

Left: The evolution of mass fractions (averaged over the entire volume of the star) as a function of time for a 15 $M_\odot$ star. The initial composition is pure hydrogen. There exists a sea of neutrons produced from a modified version of the pp reaction, namely $p + p \to p + n + e^+ + \nu_e$. The decay width is $\Gamma(d) = 10.0\,\mathrm{eV}$. *Right*: HR tracks of a 15 $M_\odot$ star with varying decay widths. A larger decay width dictates hotter core temperatures, and as a result, hotter surface temperatures. The tracks terminate when the amount of metals in the core reaches 50% by mass.



BBN with triple nucleon reaction

The languidness of the triple-nucleon reaction is not able to synthesize $^3\mathrm{He}$ at the level that $n(p,\gamma)^2\mathrm{H}$ and $^2\mathrm{H}(p,\gamma)^3\mathrm{He}$ are able to in our universe. $^4\mathrm{He}$ is suppressed by 13 orders of magnitude for a decay width $\Gamma(d) = 1\,\mathrm{eV}$.