

The Degree of Fine-Tuning in our Universe (and possibly others)

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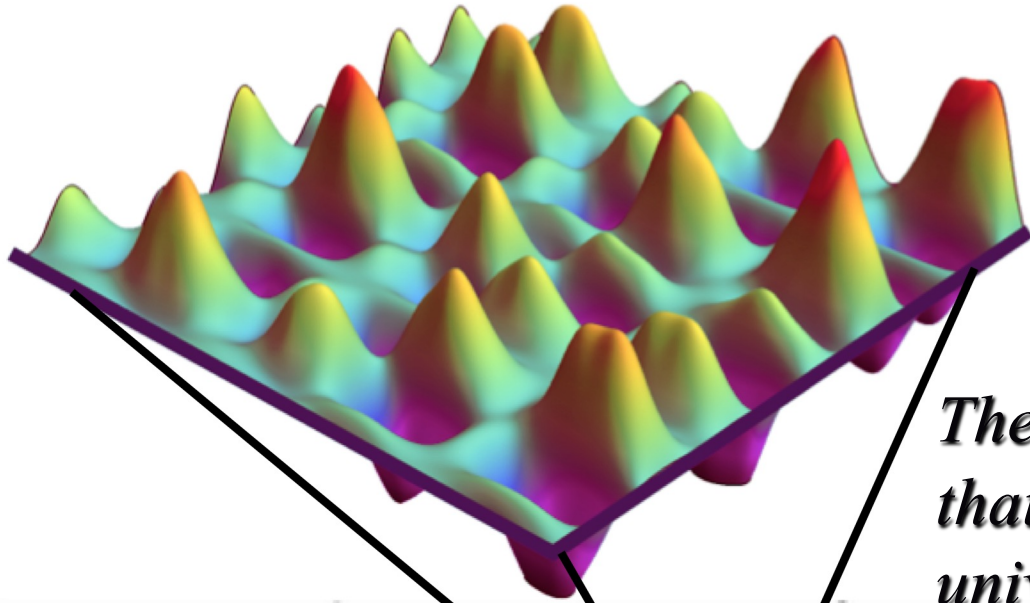
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Introduction

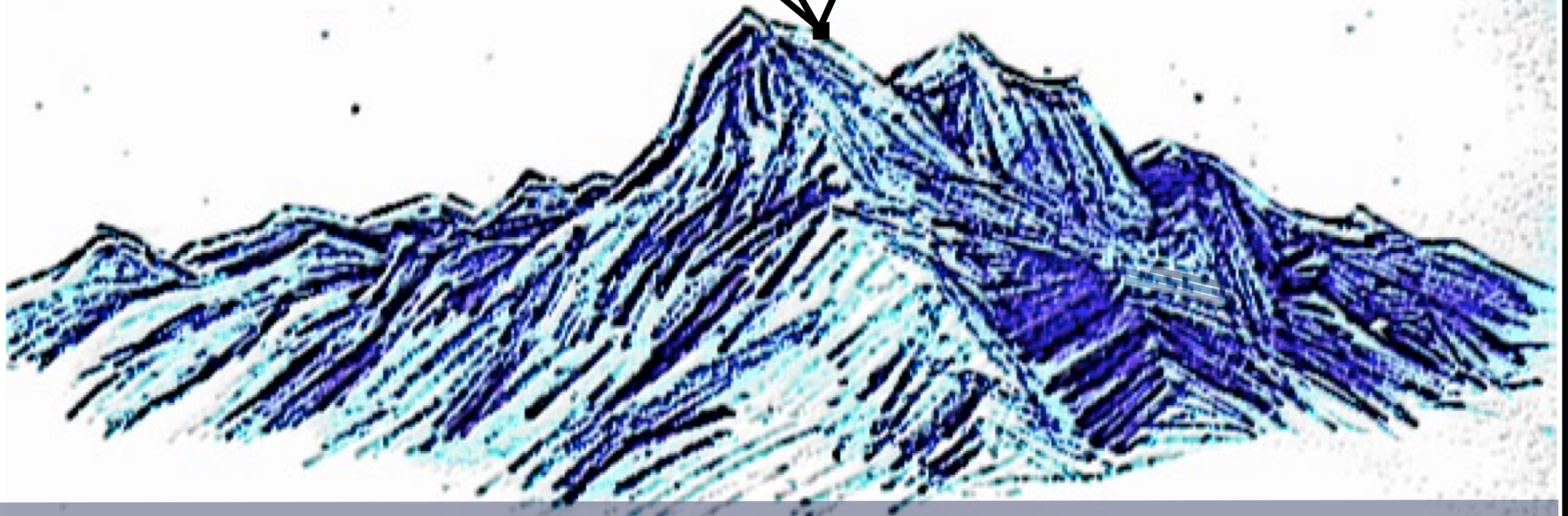
- ◆ Our universe has the right properties for life to develop – we are here
- ◆ Many people say that small changes in our universe would render it lifeless
- ◆ Other universes could exist and could have different laws of physics
- ◆ ***Is our universe fine-tuned for the development of life – by how much?***

*Our universe could be part of a large ensemble of other universes, part of an enormous cosmic archipelago called **THE MULTIVERSE**. The initial conditions, or even the laws of physics, could be different in other universes.*





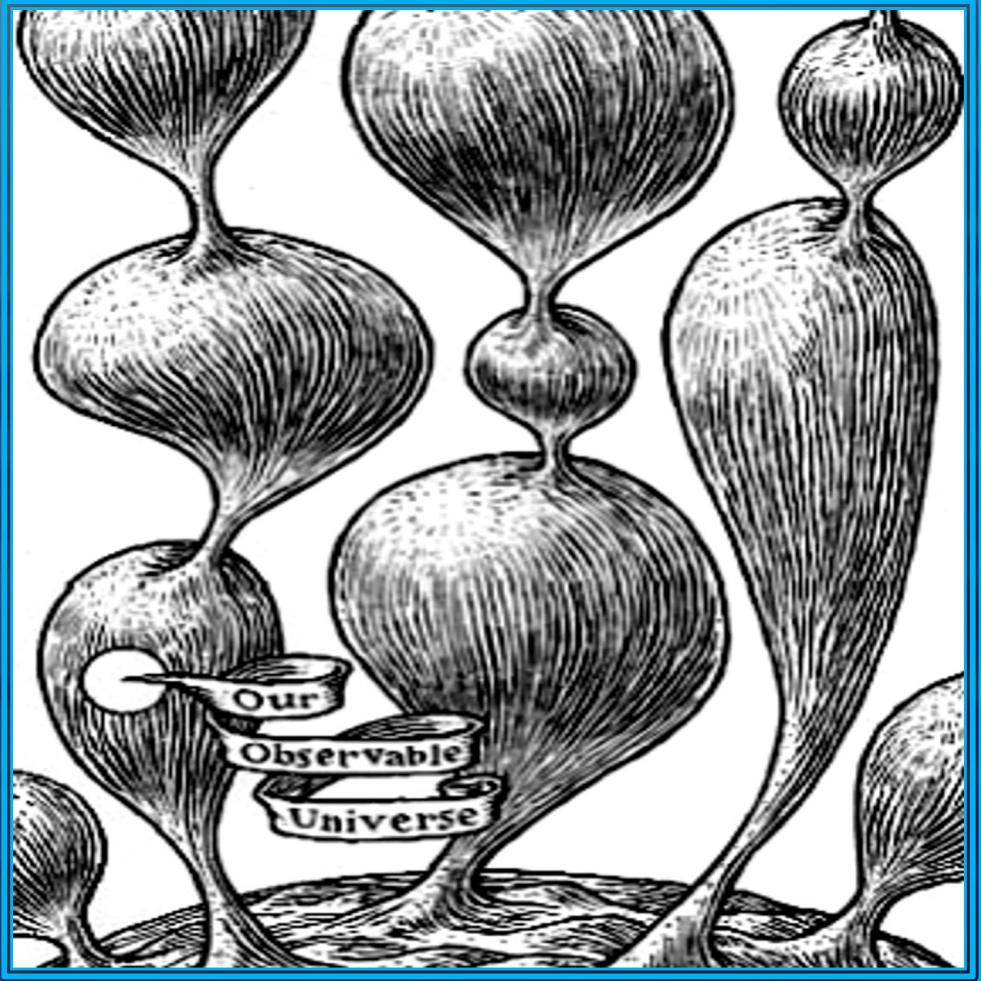
*The fundamental theory
that describes the
universe could have an
entire landscape of
possible vacuum states.*



What versions of the laws of physics allow a universe to support complexity (life)?



*Professor Pangloss confronts the multiverse:
Does our universe really represent the best of
all the possible worlds? Can we do better?*



This Problem Represents a Counterfactual Enterprise

- ◆ Take The Multiverse seriously as a viable working theory (other space-times exist)
- ◆ Anthropic arguments to explain why parameters have observed values
- ◆ Increase fundamental understanding of how astrophysical objects (e.g. stars) operate in our own universe

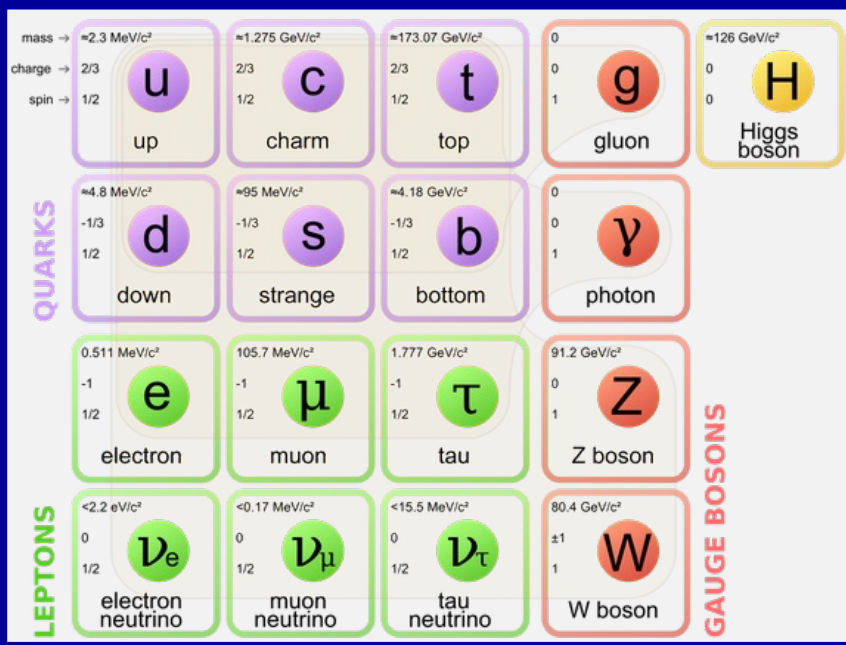


*What parameters are
allowed to vary from
universe to universe?*

Two Approaches

[1] Standard model of particle physics

[2] Astrophysical Phenomenological and Cosmological



$$(\alpha_G, \alpha, \varepsilon_k, B_k, \dots)$$

$$\langle \sigma v \rangle_{jk}$$

(we don't know exactly what can be tuned...)

Structure Constants

$$\alpha \equiv \frac{e^2}{\hbar c}$$

$$\alpha_G \equiv \frac{Gm^2}{\hbar c}$$

$$\frac{\alpha}{\alpha_G} \approx 10^{36} \gg 1$$

Fundamental Parameters

$$\alpha_s = 10$$

$$\alpha_{em} = 10^{-2}$$

$$\alpha_w = 10^{-5}$$

$$\alpha_G = 10^{-38}$$

$$\beta = m_e/m_p = 0.0005$$

$$m_u = 2.3 \text{ MeV}$$

$$m_d = 4.8 \text{ MeV}$$

Cosmological Parameters

$$Q = 10^{-5}$$

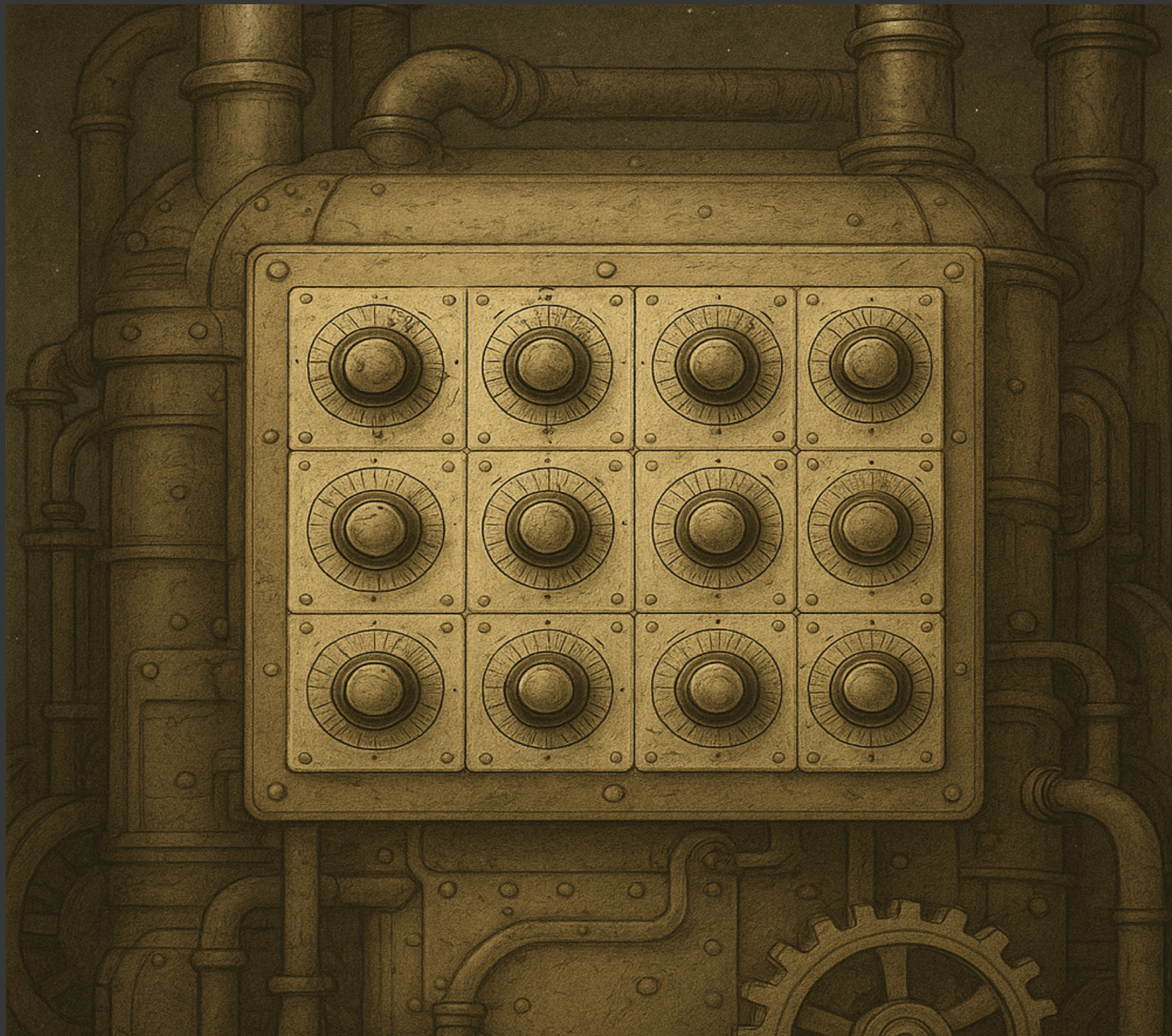
$$\eta = 6 \times 10^{-10}$$

$$\delta = 3 \times 10^{-9}$$

$$\lambda = 0.003 \text{ eV}$$

(assume $\Omega=1$)

nuclear constant C



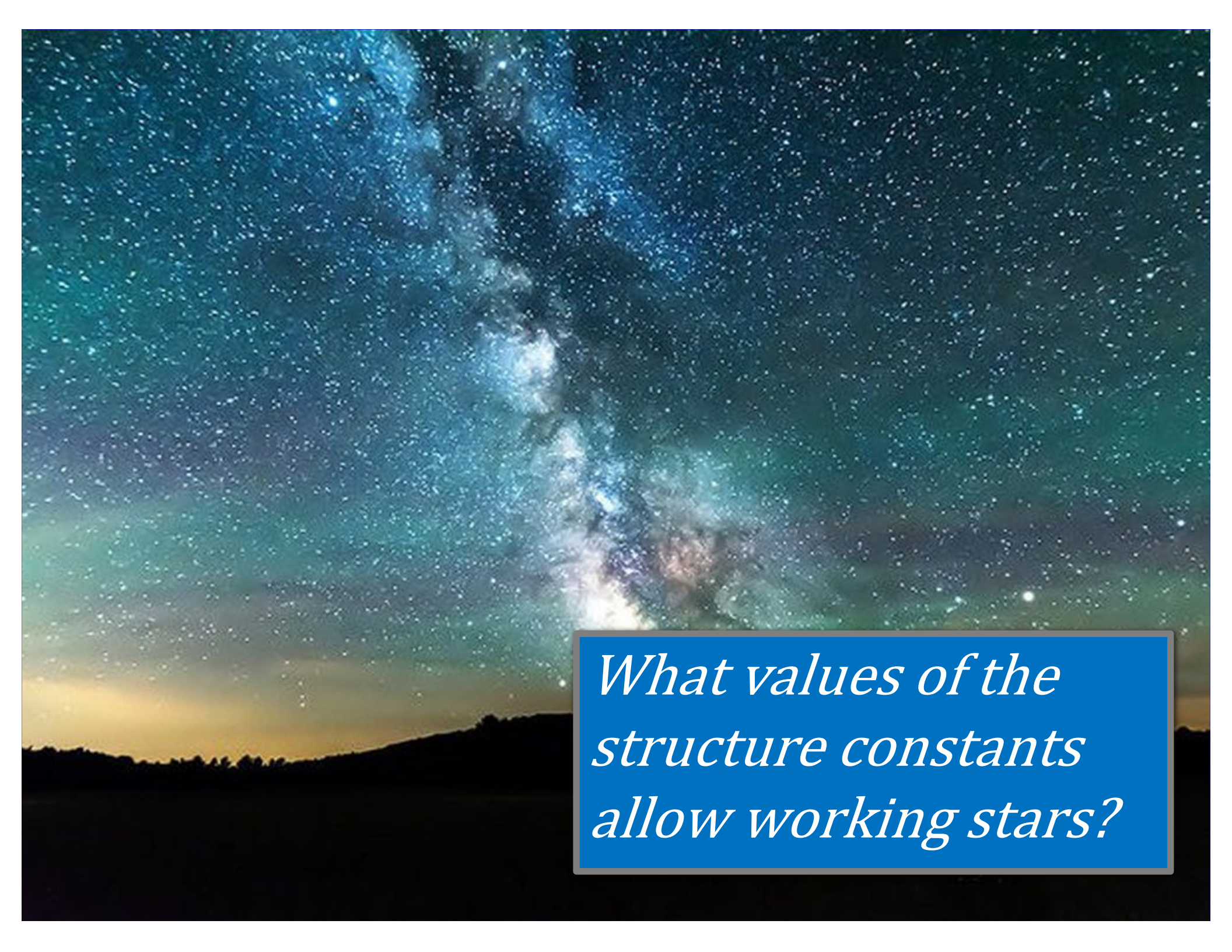


$\alpha_s, \alpha_{em}, \alpha_w, \alpha_G, \beta, m_u, m_d, Q, \eta, \delta, \lambda, C$

How Much Tuning is Fine-Tuning?

For a given parameter we want to calculate the range -- the factor by which the parameter can vary and still allow for a working universe.

Tuning an FM radio requires the frequency to be specified to about 0.5 percent, or a factor of 1.005



*What values of the
structure constants
allow working stars?*

Stellar Structure Model

- ◆ Build robust, semi-analytic stellar model
- ◆ Polytropic model of mechanical structure
- ◆ Only one nuclear burning species
- ◆ Radiative energy transport
- ◆ Define solution space: 4 forces of nature reduced to 3 parameters:

$$(G, \alpha, C)$$

What fraction of this parameter space allows for existence of working stars?

STELLAR OVERVIEW

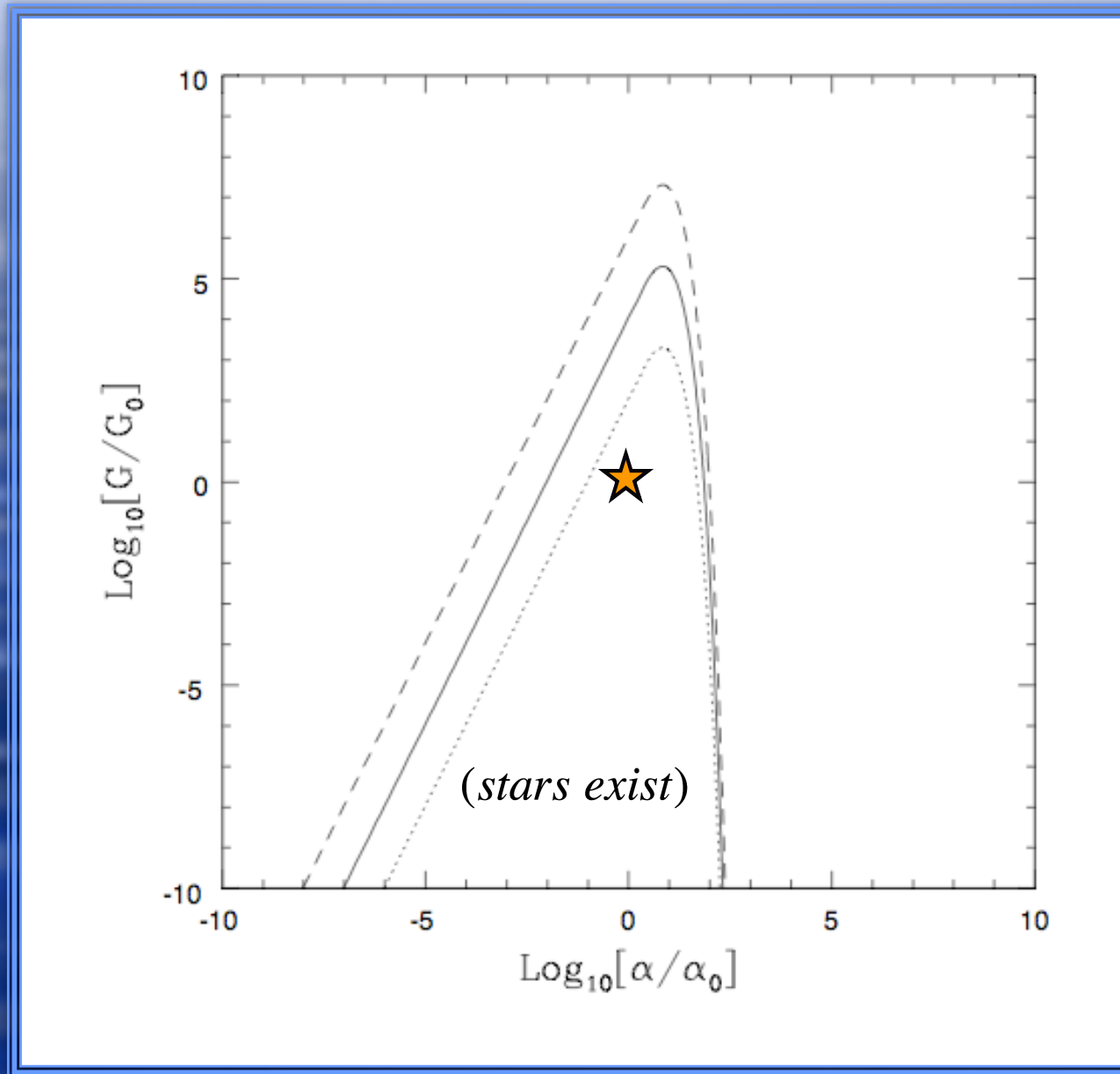
Solution space:

4 forces of nature reduced to
3 parameters:

$$(G, \alpha, C)$$

What ranges of the parameters (G, α, C)
allow for the existence of working stars?

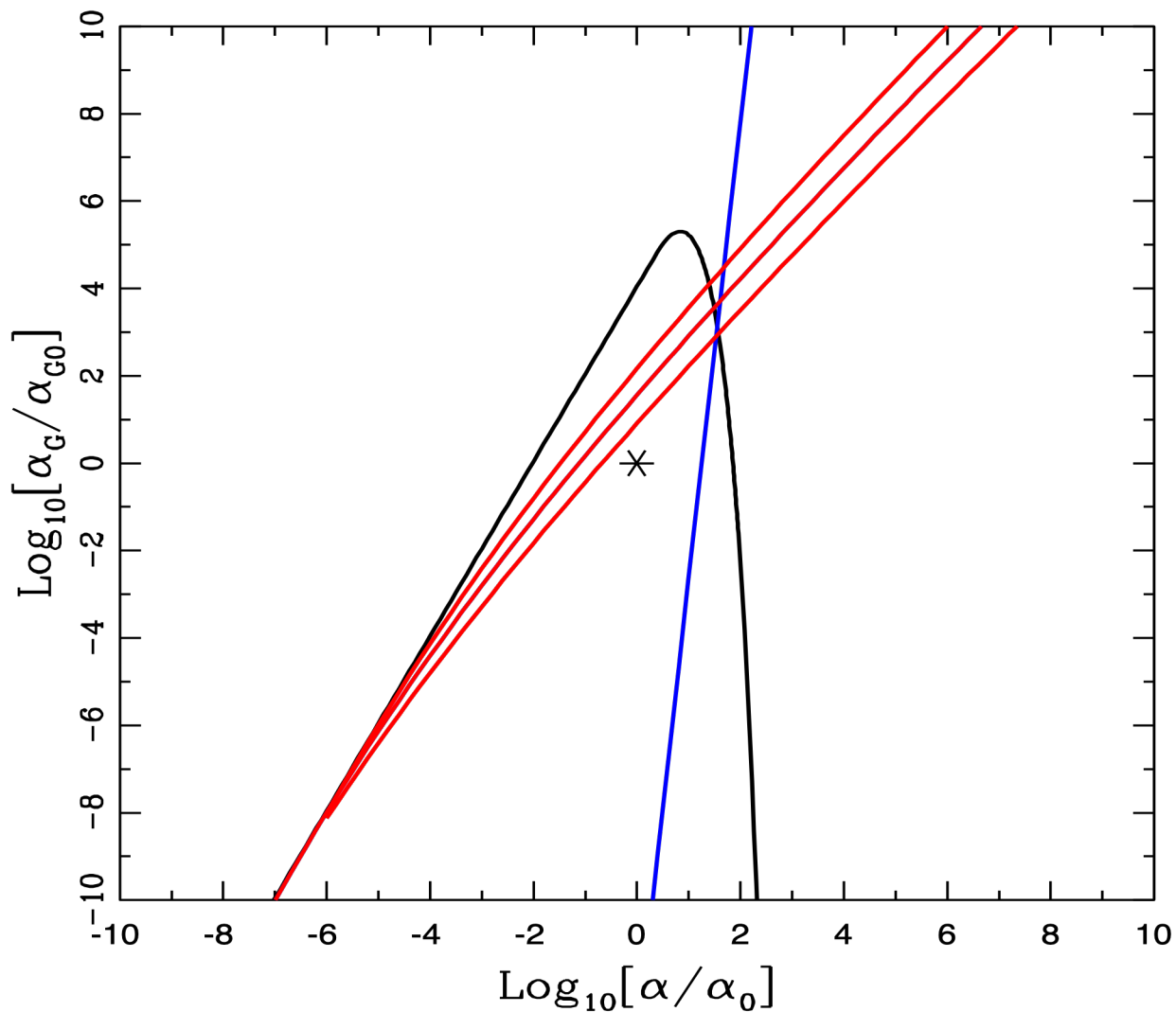
Allowed Region of Parameter Space



Additional Constraints on Stars for Universe to be Habitable

- ◆ Stars must be hot enough to allow for habitable planets – the surface temperature must be larger than that required to drive chemical reactions
- ◆ Stars must live long enough for life to develop, which takes about 1 Gyr or 10^{33} ticks of the atomic clock

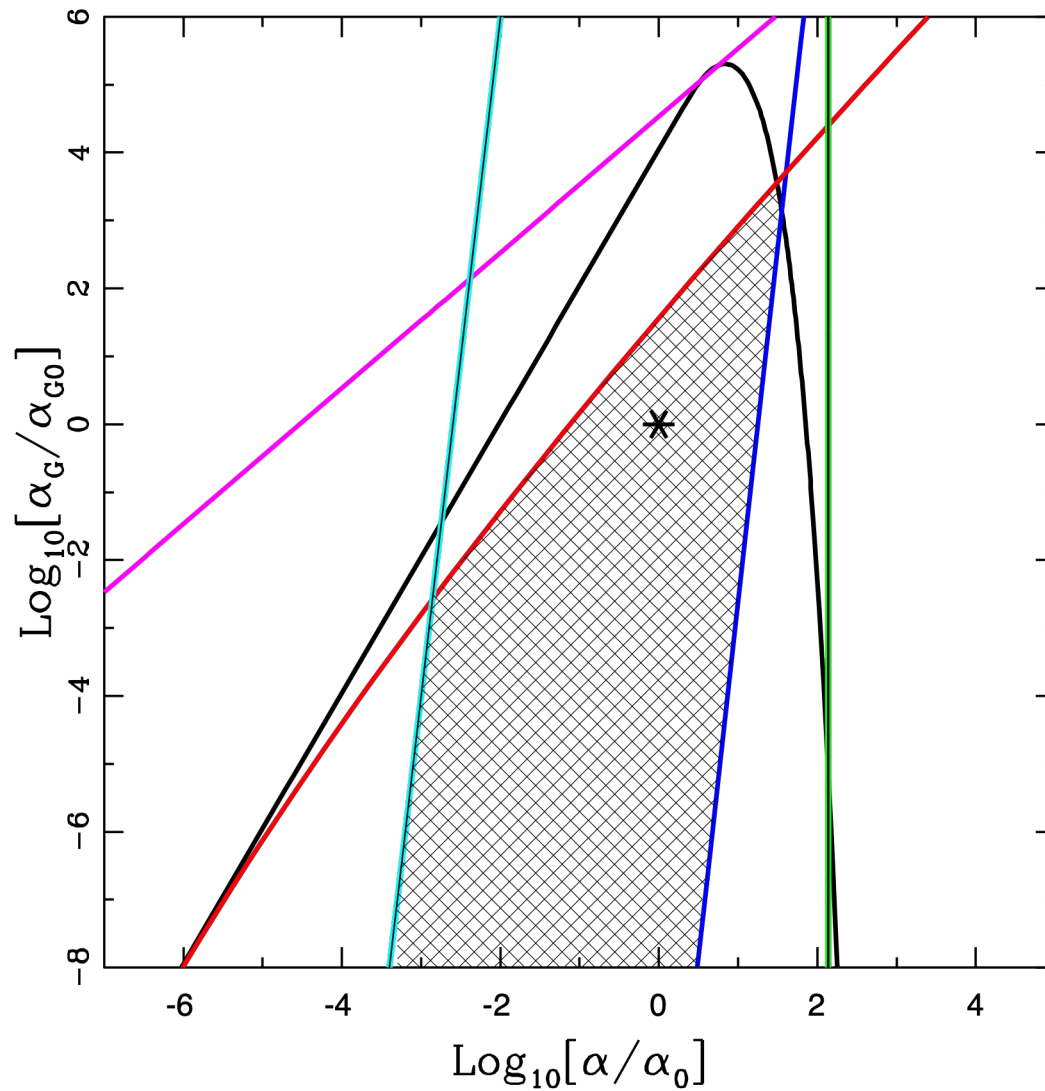
Lifetime and Temperature Constraints



Constraints on Planets/Stars for Universe to be Habitable

- ◆ Planets must be large enough to hold onto their atmospheres and small enough to not be degenerate
- ◆ Planets must be sufficiently complex
- ◆ Planets must be smaller than stars
- ◆ Stars must be smaller than their host galaxies, where galactic mass is set by its cooling time scale

Combined Stellar Constraints



Stellar Constraints

- ◆ Stable long-lived stars exist
- ◆ Stars are sufficiently long-lived
- ◆ Stellar photospheres are sufficiently hot
- ◆ Planets large -- to retain atmospheres
- ◆ Planets remain non-degenerate
- ◆ Planets are smaller than their host stars
- ◆ Planets large enough for complexity
- ◆ Galaxies can cool and produce stars



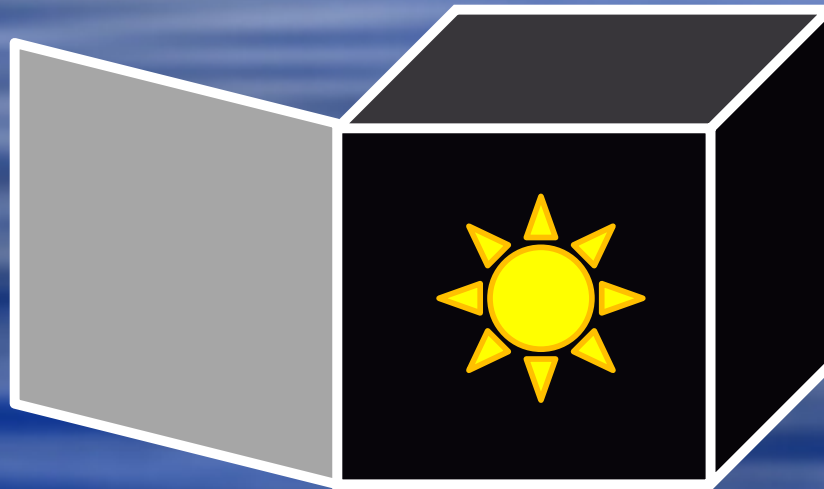
*Triple alpha process,
stable diprotons,
unstable deuterium.*

TRIPLE ALPHA PROBLEM

- ◆ In our universe Be-8 is unstable
- ◆ Stars allow small population of Be-8 in NSE
- ◆ Carbon made via $\text{Be-8} + \text{He-4} \rightarrow \text{C-12}$
- ◆ Need Hoyle resonance to get reaction fast enough to get observed carbon abundance

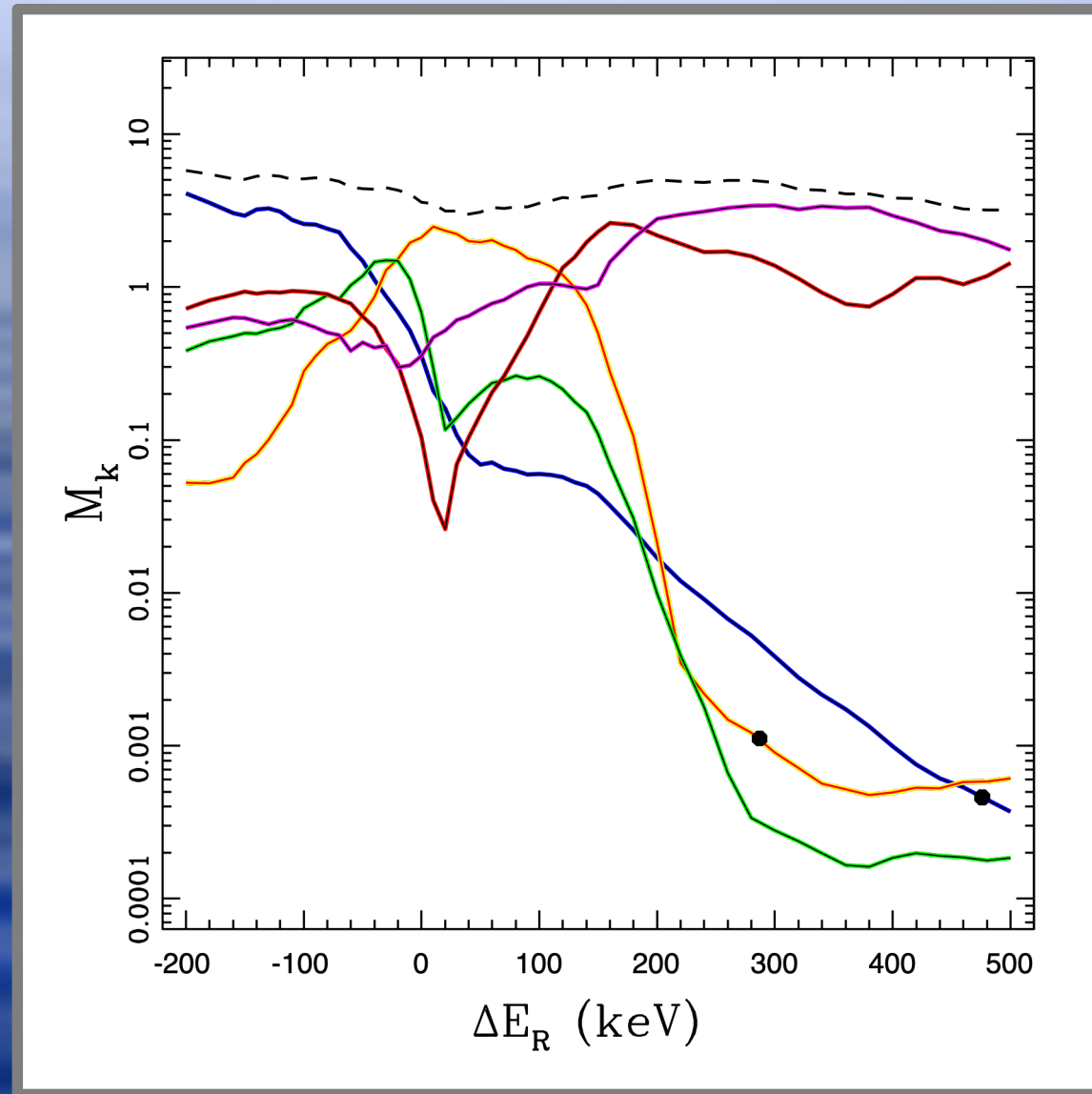
If the energy level of the C-12 resonance changes too much, stars do not produce observed abundance of carbon.

MESA SIMULATIONS



Thanks: Frank Timmes et al, Evan Grohs

Alpha Element Yields vs Resonance



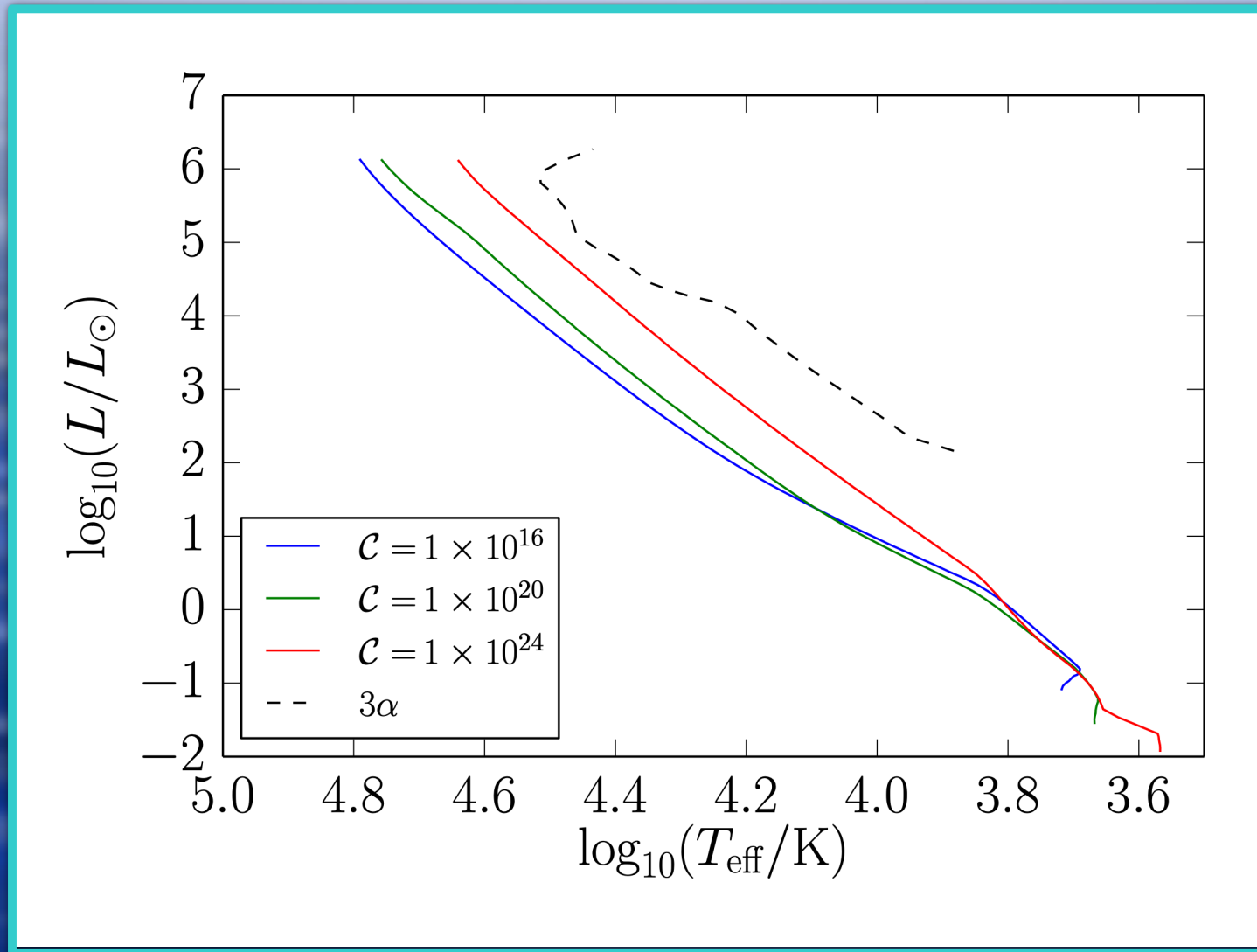
Huang, Adams, & Grohs 2019, *AstroPartPhys*, 105, 13

TRIPLE ALPHA SOLUTION

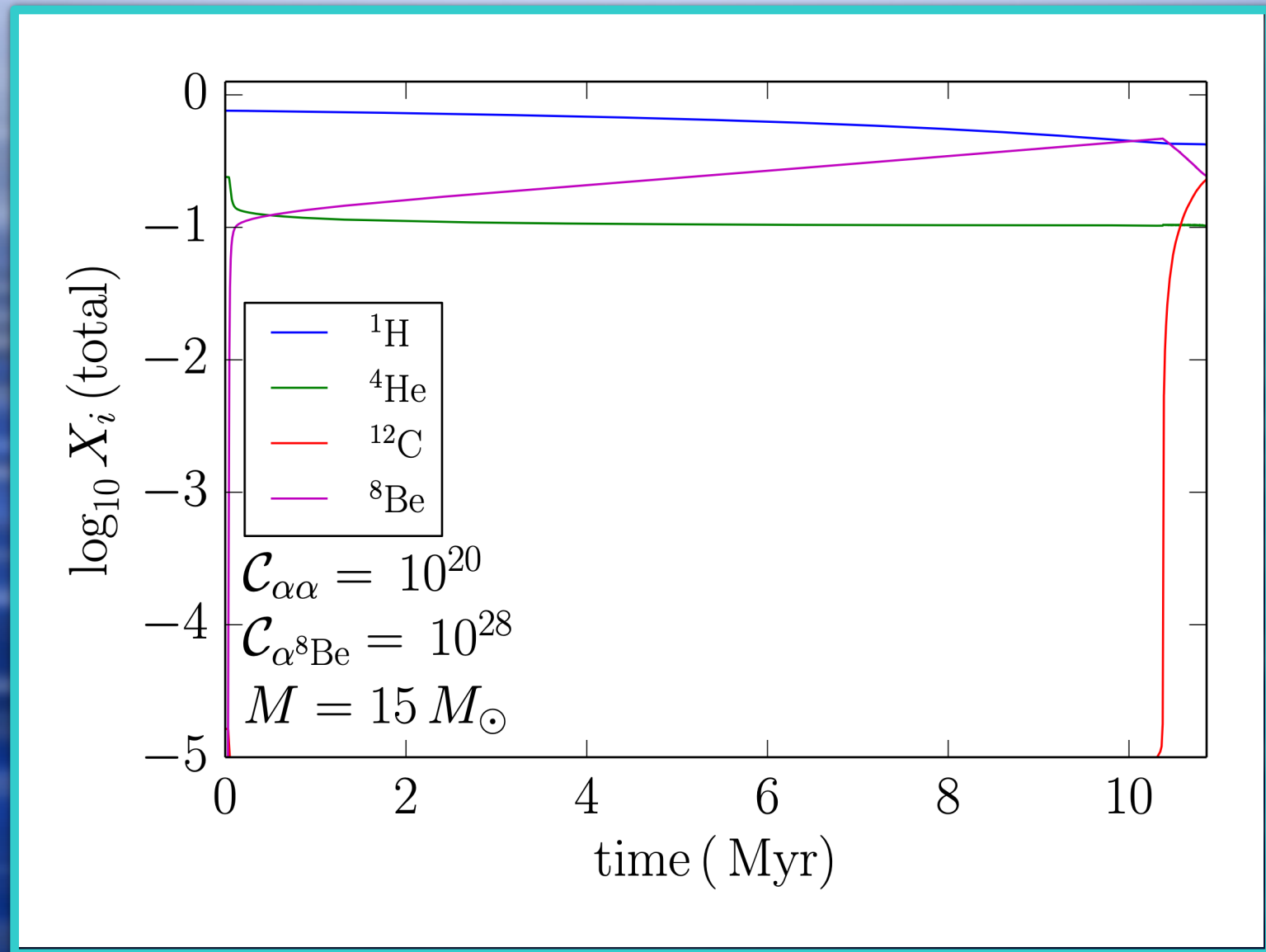
- ◆ Change in resonance of -300 keV is OK
- ◆ Change in resonance of +500 keV leads to less carbon than observed (but still some!)
- ◆ Lower resonances lead to more carbon...
- ◆ Be-8 fails to be stable by only 92 keV

It's 'easier' to make Be-8 stable than to compromise carbon production via triple alpha, but a universe with stable Be-8 does not need the triple alpha process.

H-R Diagram for $2(\text{He-4}) \rightarrow \text{Be-8}$



Chemical Evolution with Stable Be-8



Deuterium Fine-Tuning Problem

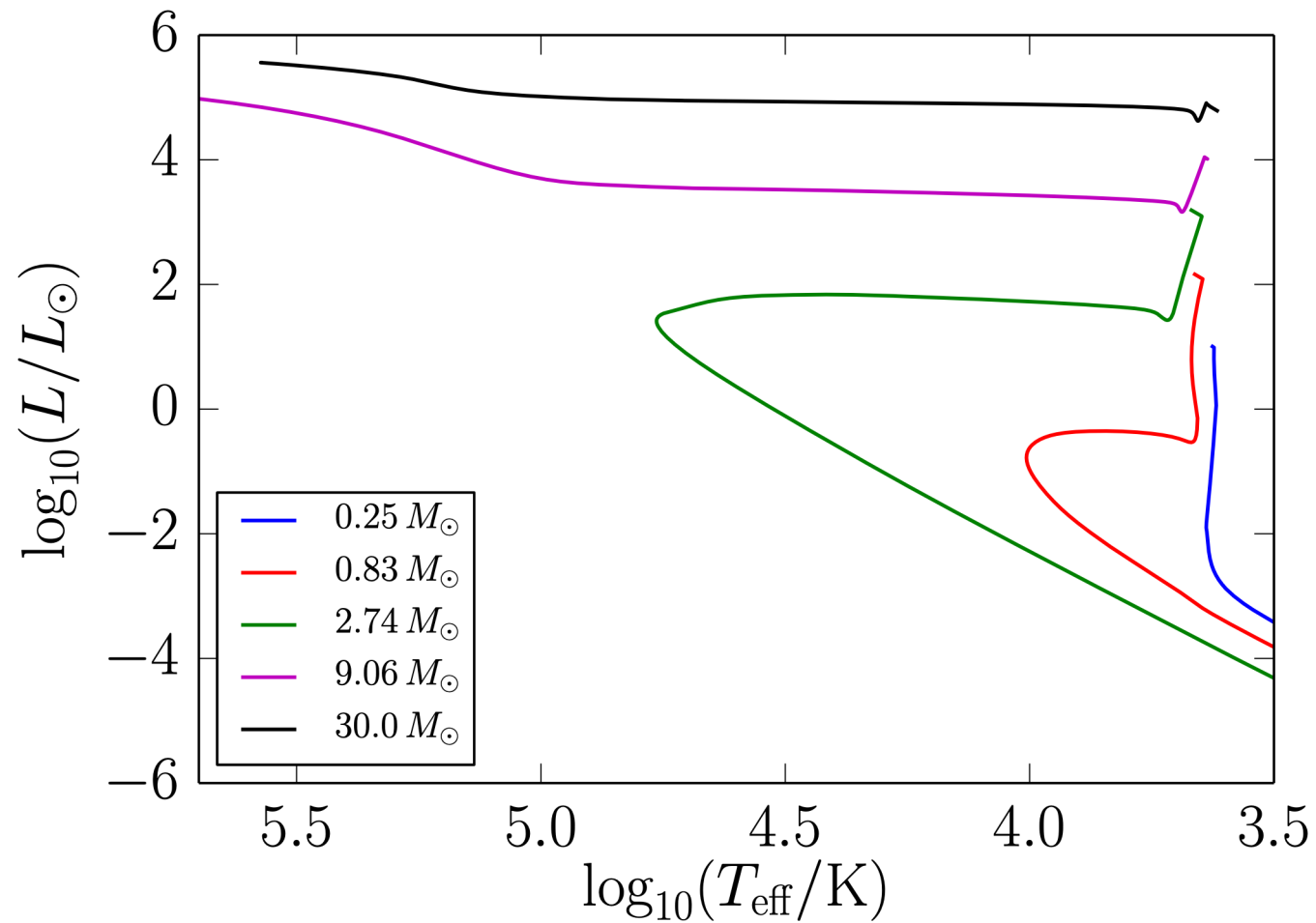
- ◆ Deuterium production is the first step in making heavy nuclei, both in BBN and in stellar interiors
- ◆ CLAIM: If deuterium is unstable, then the first step in the chain fails, and no heavy elements can be produced

Deuterium-Free Stellar Evolution

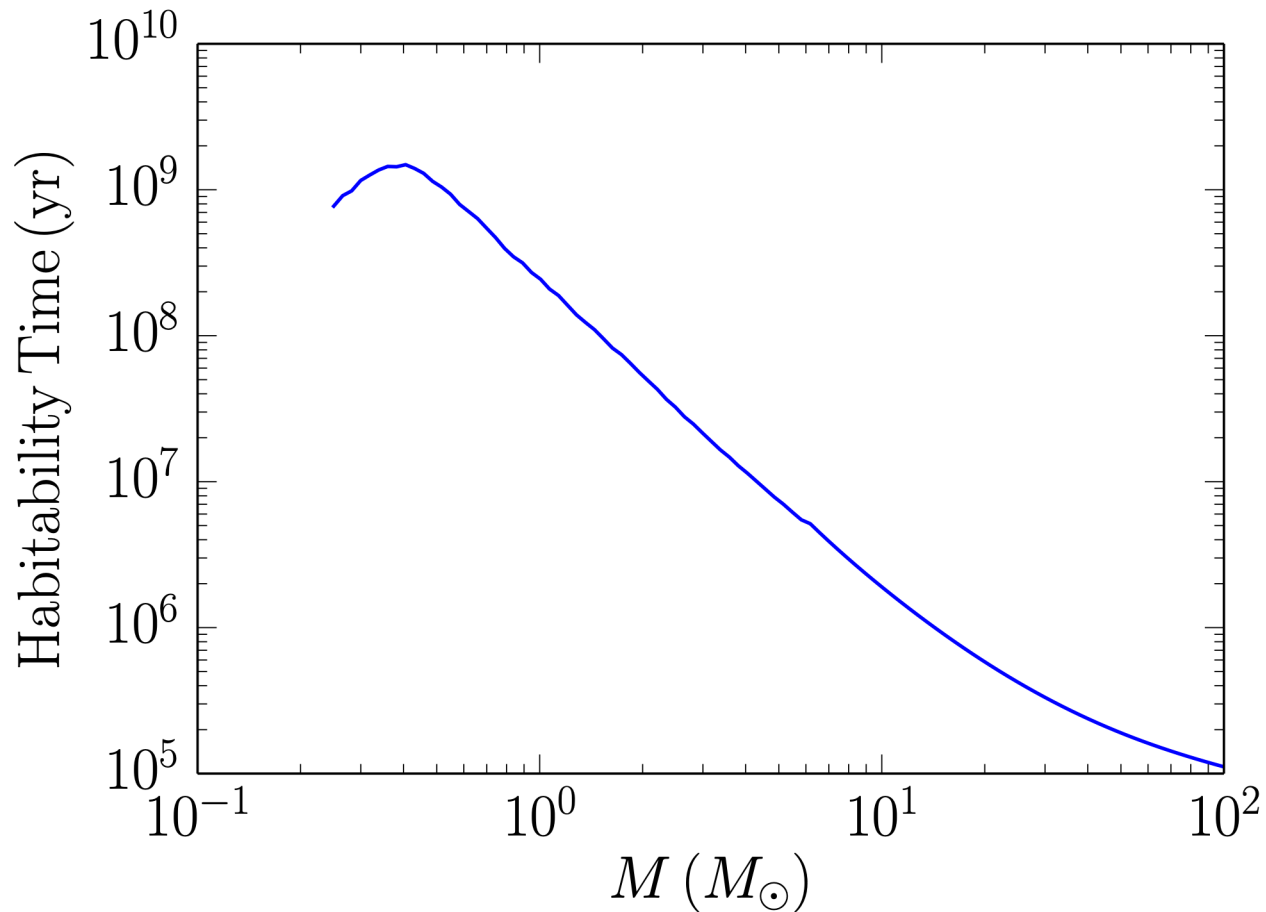


- ◆ In the absence of any nuclear reactions, stars will still generate energy via gravitational contraction.
- ◆ Are these stars bright enough, and live long enough, for life to develop?
- ◆ How do complex nuclei develop if the stars are powered by gravity?

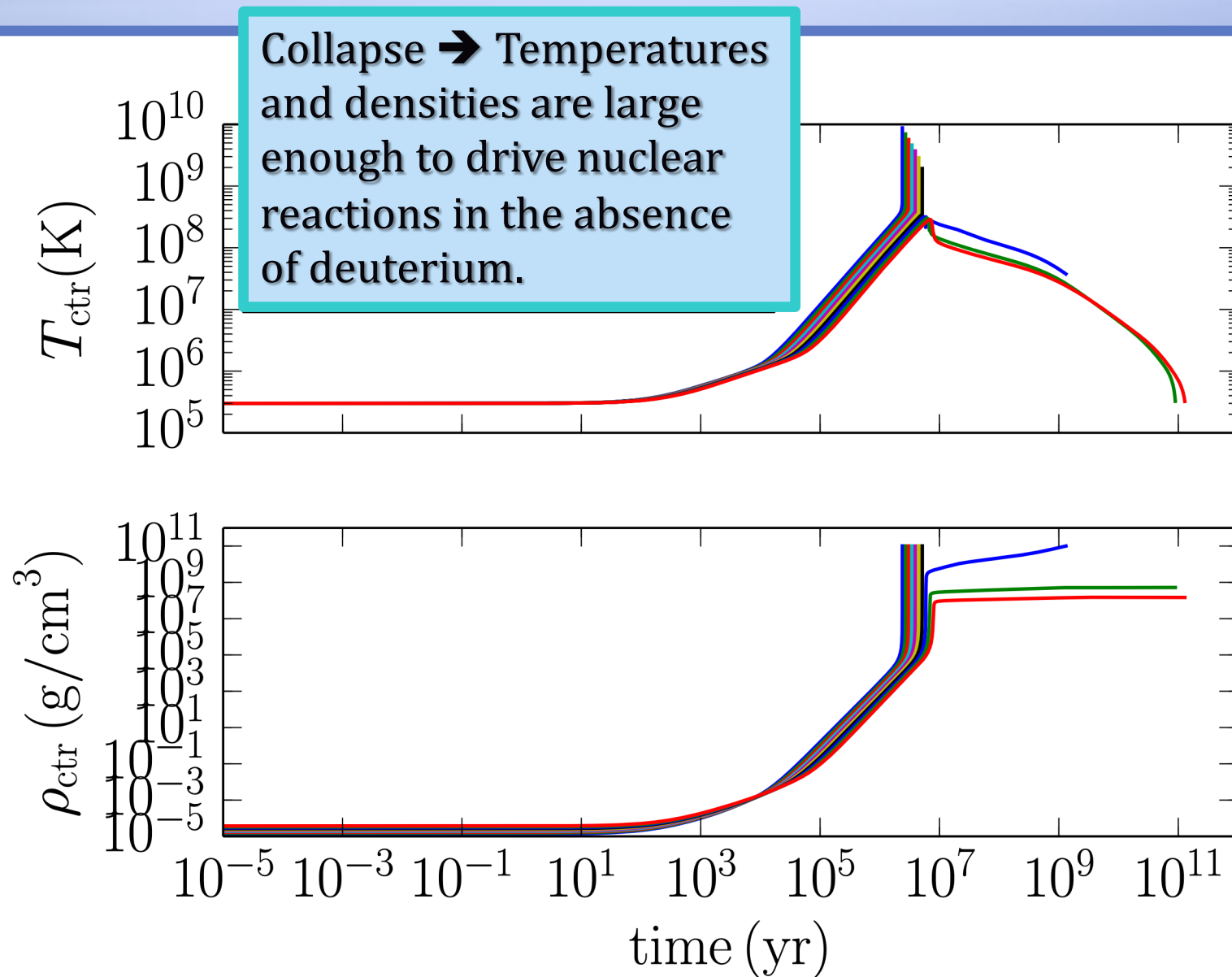
Stellar Evolution – Gravity Only



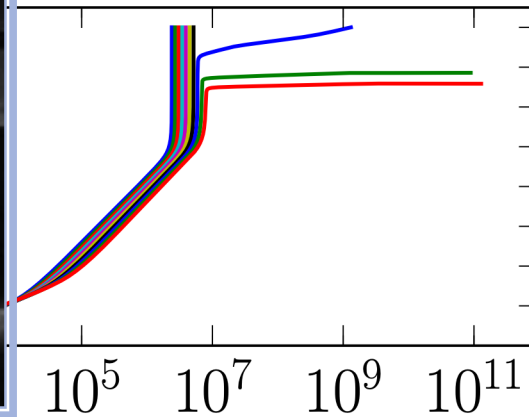
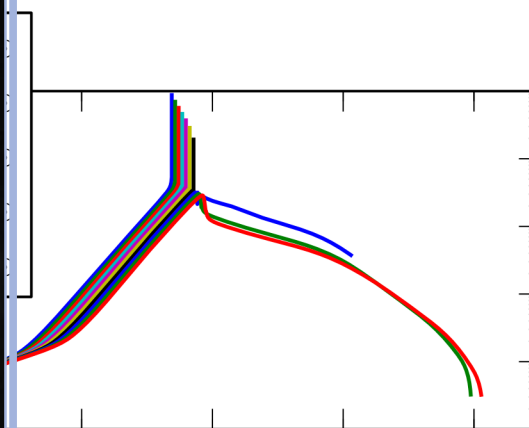
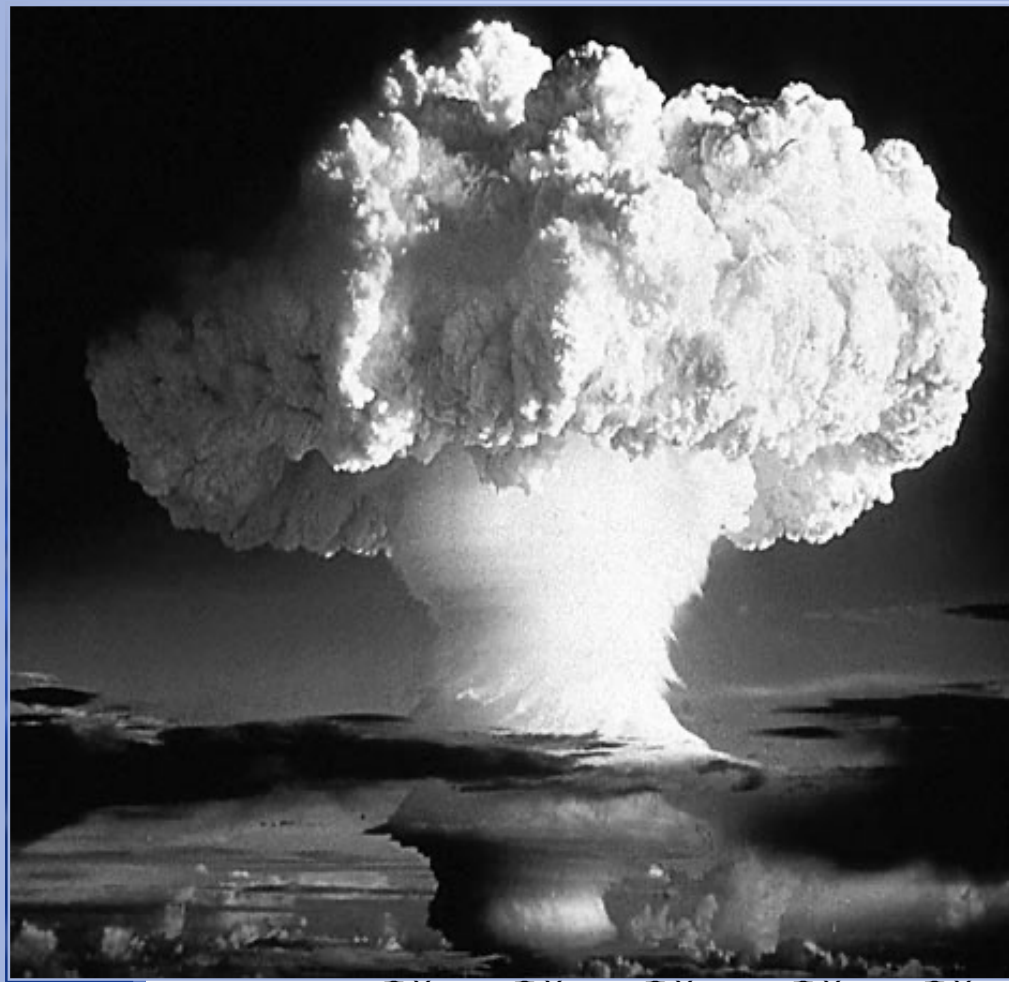
Stellar Evolution Time vs Mass



Properties of the Stellar Core

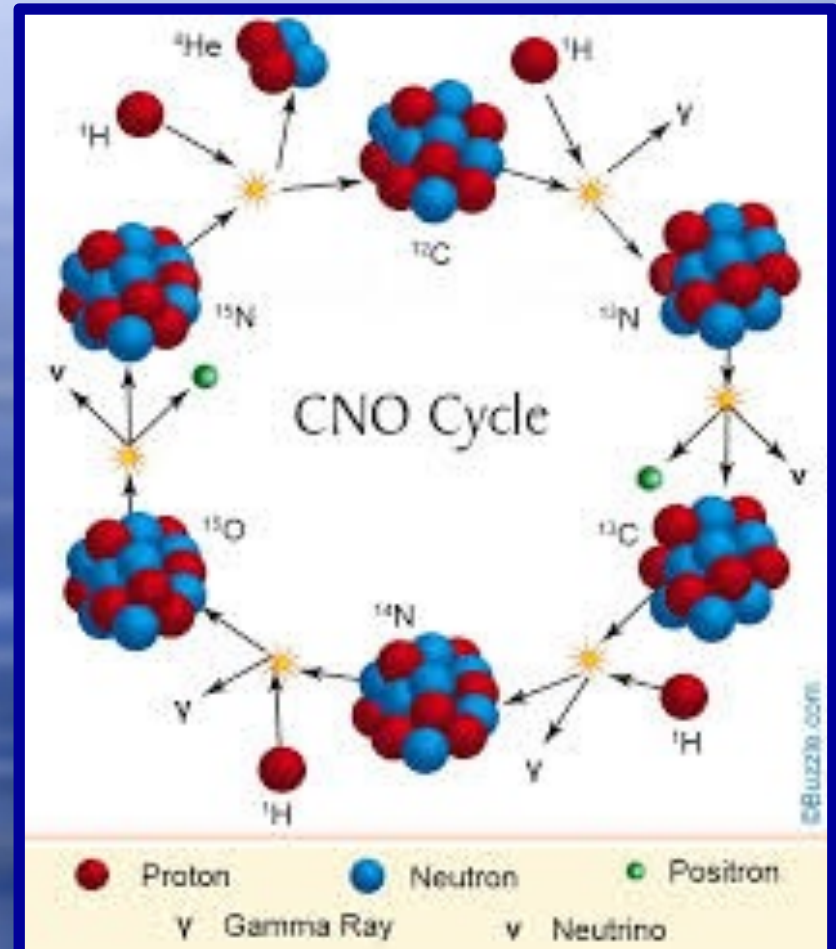
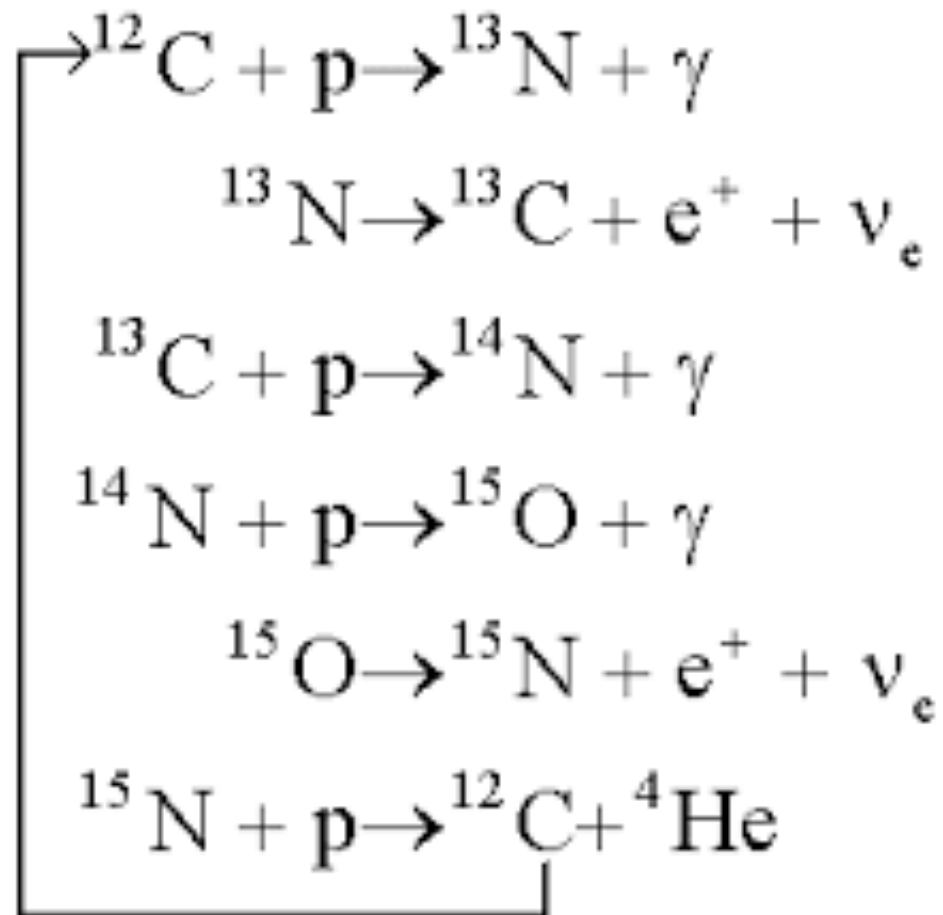


Explosive Nucleosynthesis

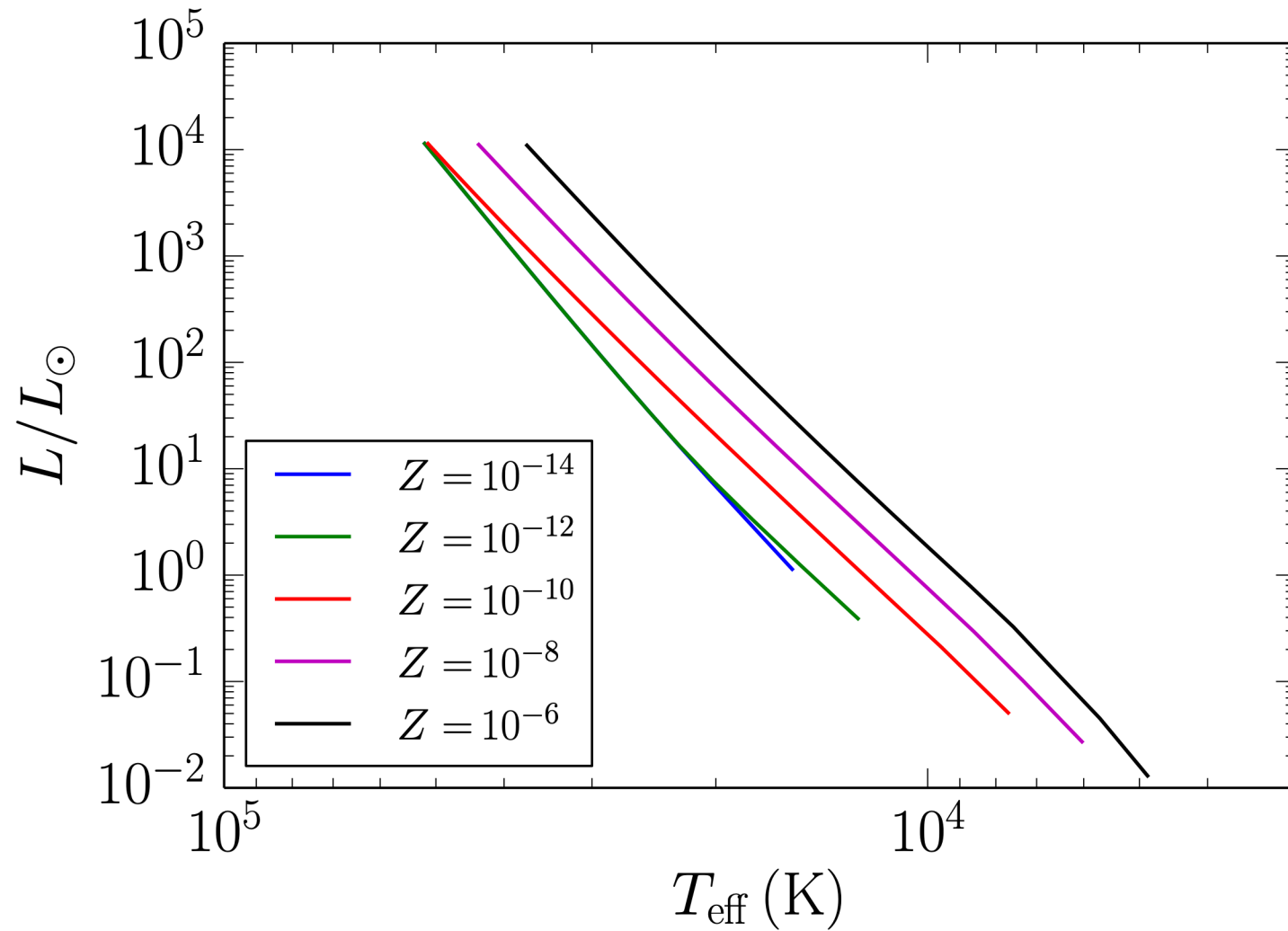


time (yr)

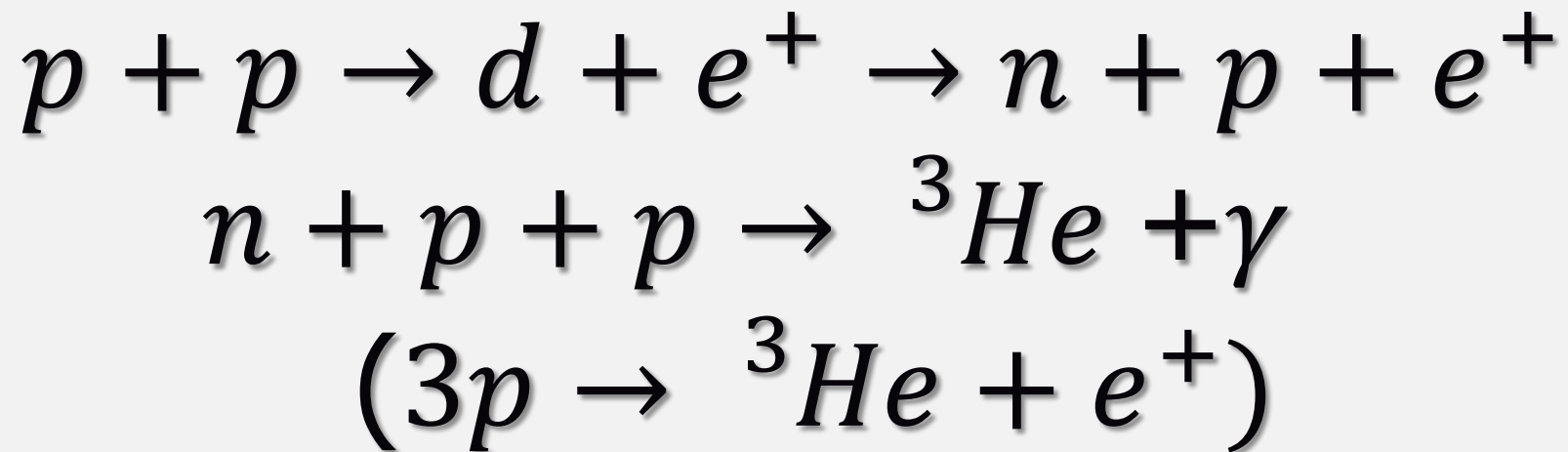
Stellar Evolution via the CNO Cycle



Extreme CNO Main Sequence



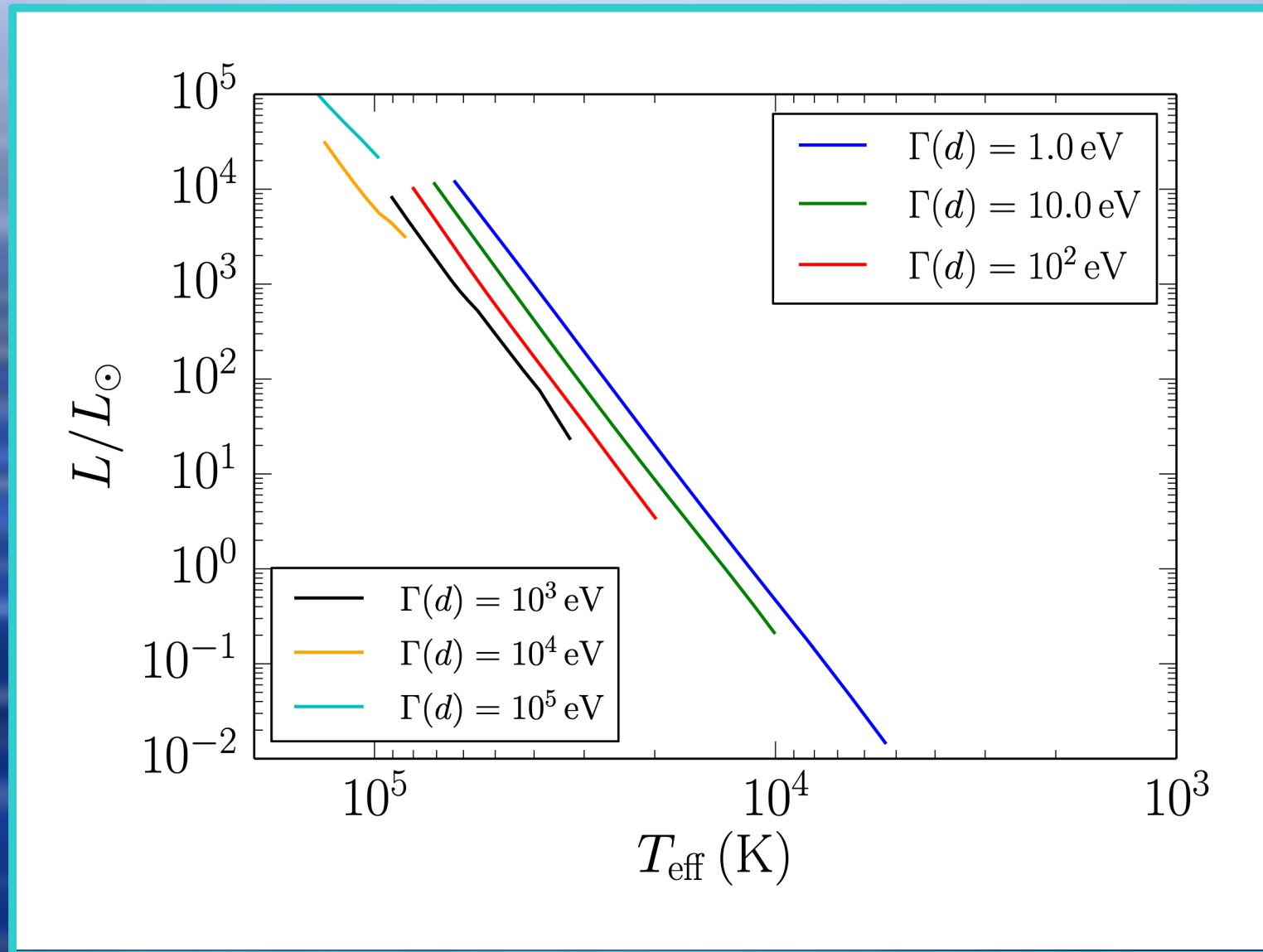
Triple Nucleon Reactions: Standing population of Neutrons



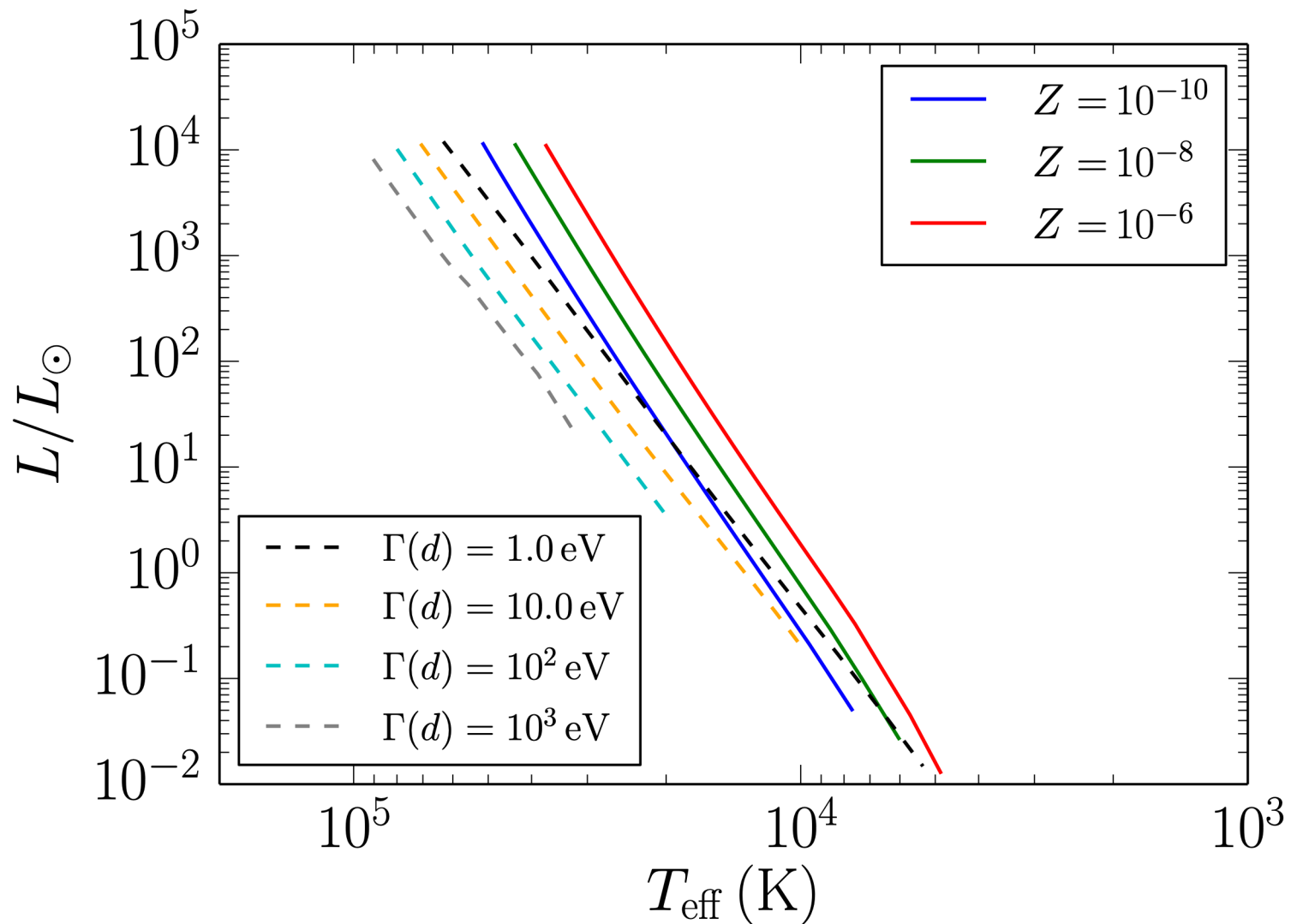
$p+p \rightarrow d$ weak interaction

$p+n \rightarrow d$ strong interaction

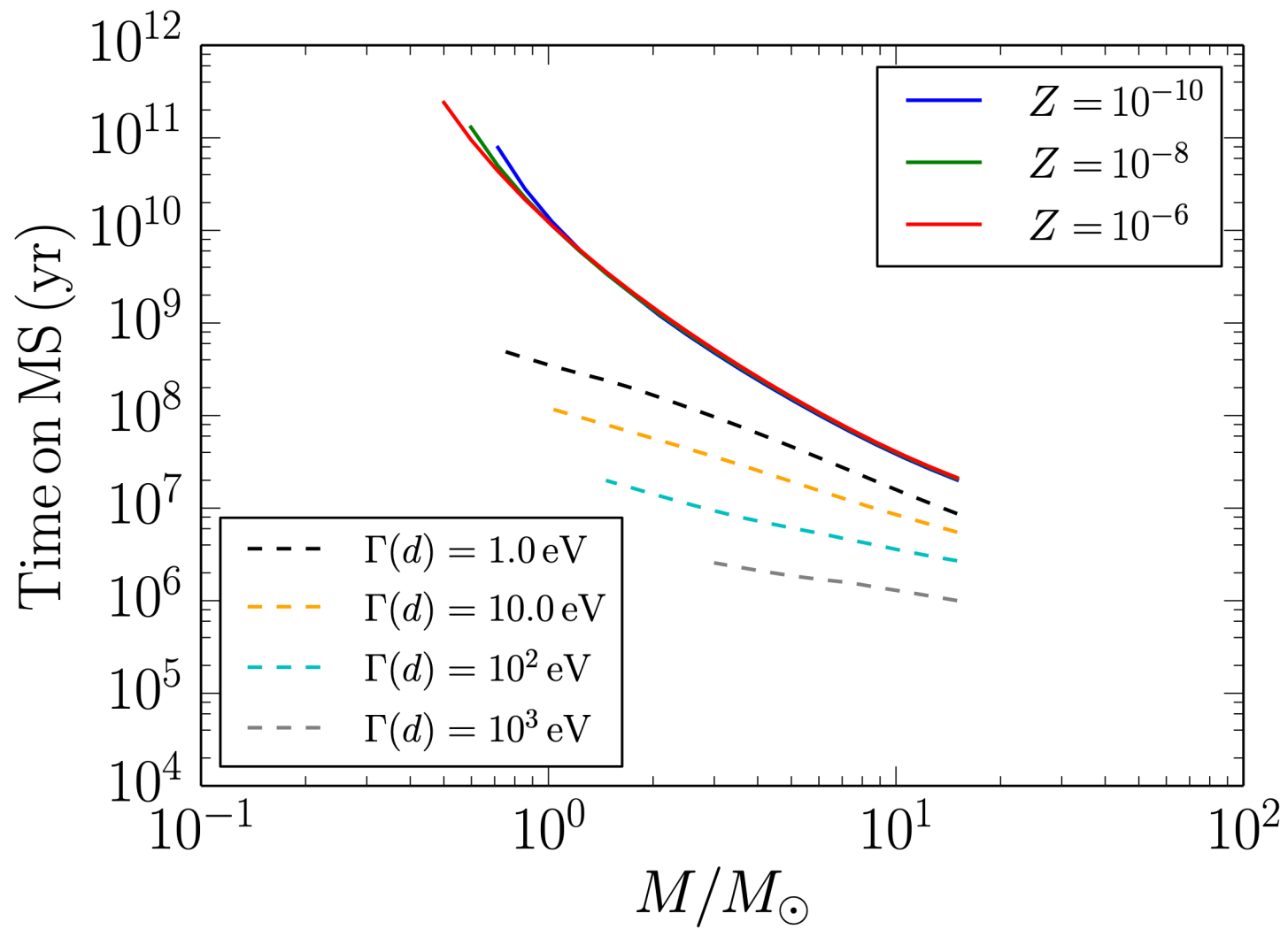
Extreme Triple Nucleon Main Sequence



Main Sequence Comparison



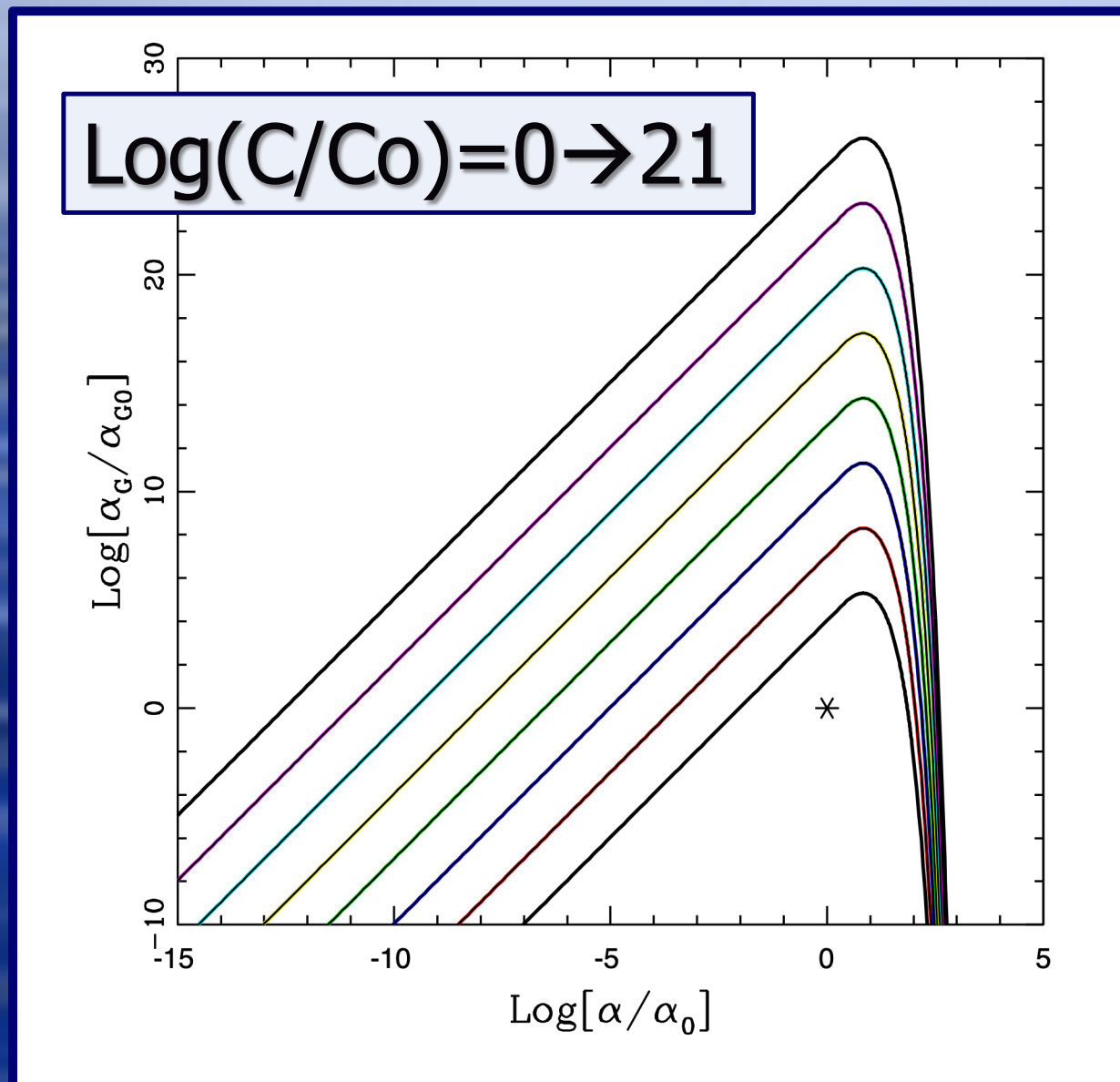
Main Sequence Lifetimes



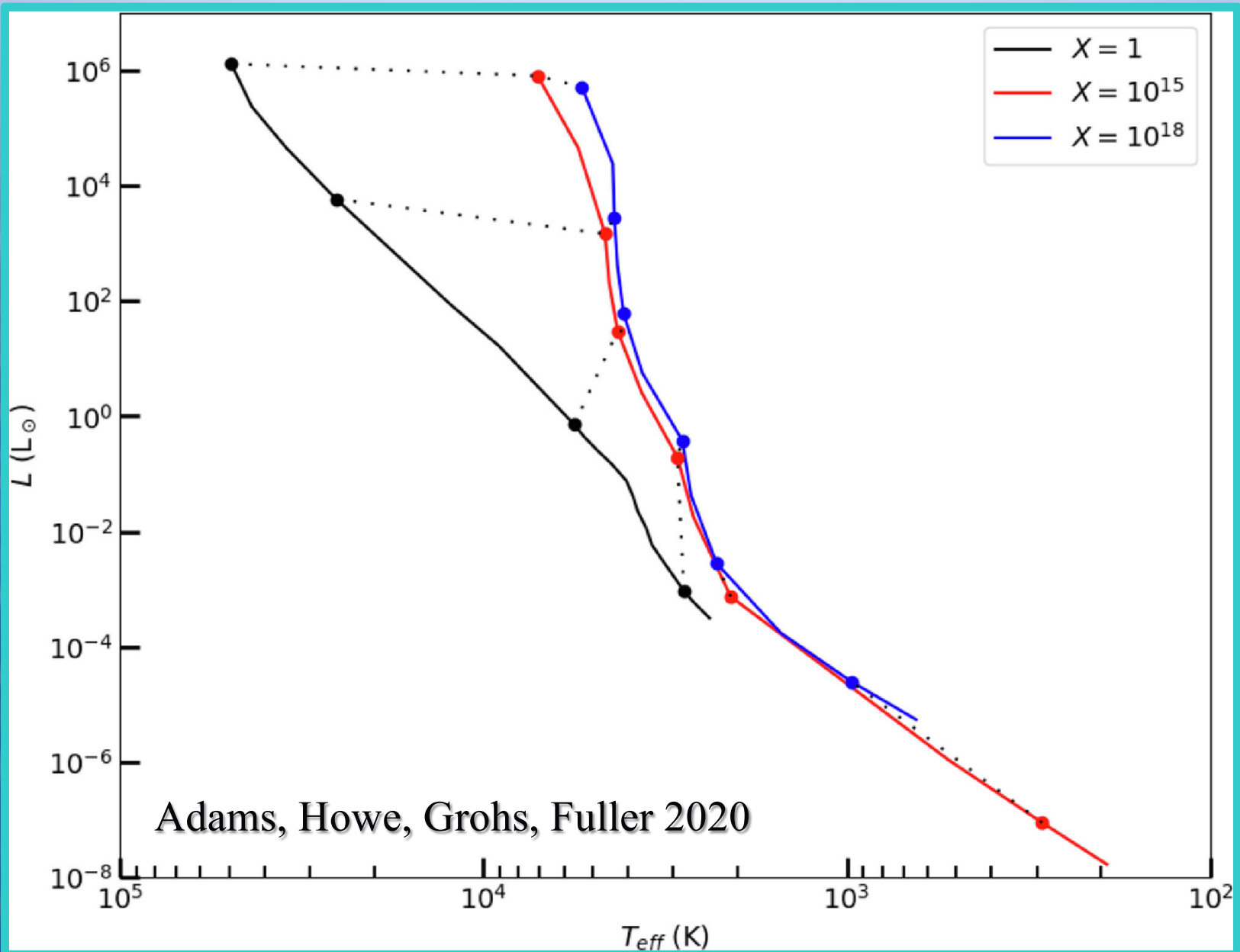
Diproton Fine-Tuning Problem

- ◆ If diprotons are stable, then nuclear burning can proceed via the strong interaction, which has large cross section
- ◆ CLAIM: If cross section larger (by 16 – 18 orders of magnitude) then stars will live short lives

Stars with Stable Diprotons



Stars with Stable Diprotons: Main Sequence



Bottom Line

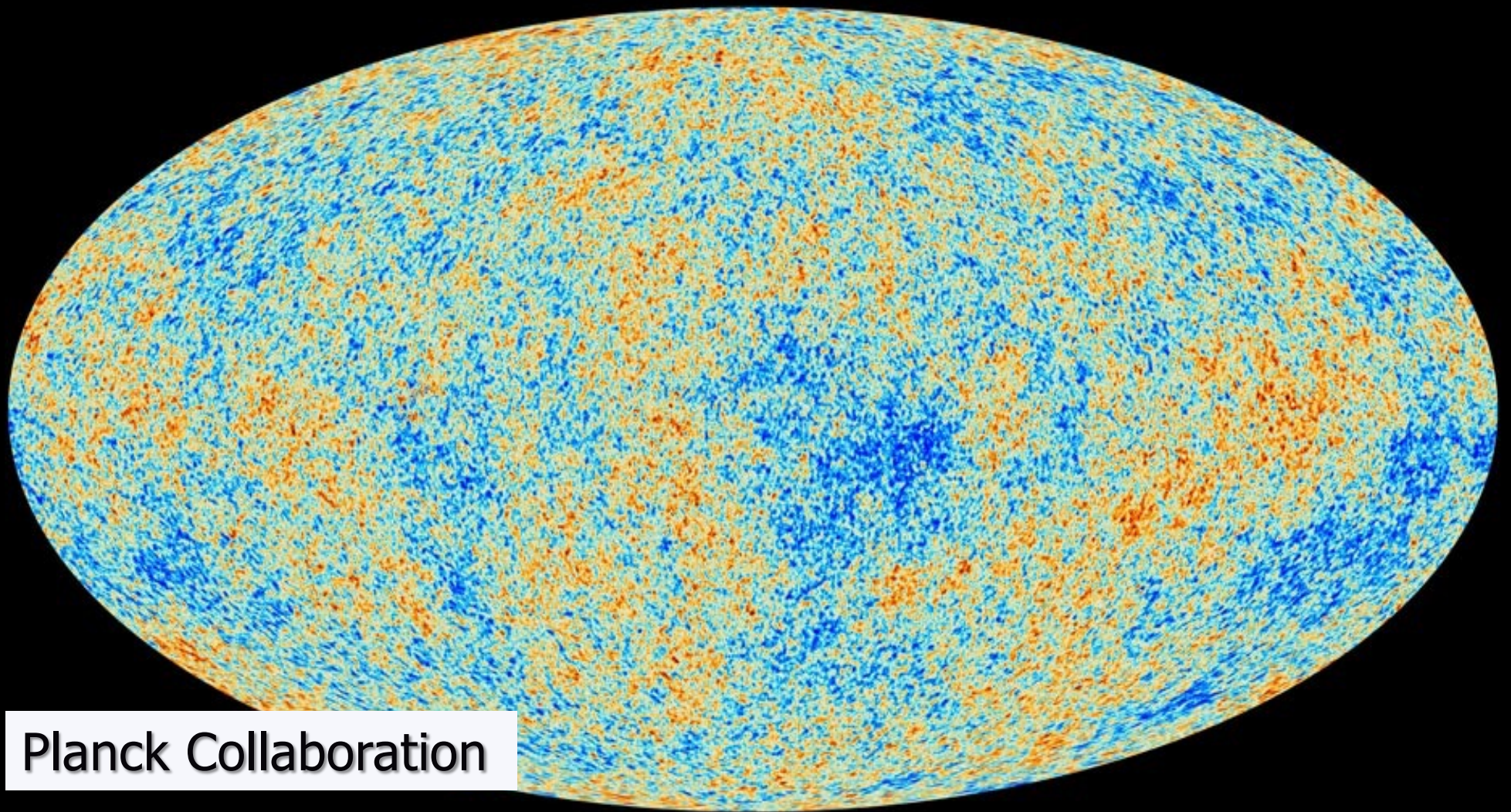
Stars in other universes are not rare as sometimes claimed: Parameter space for working stars spans orders of magnitude.



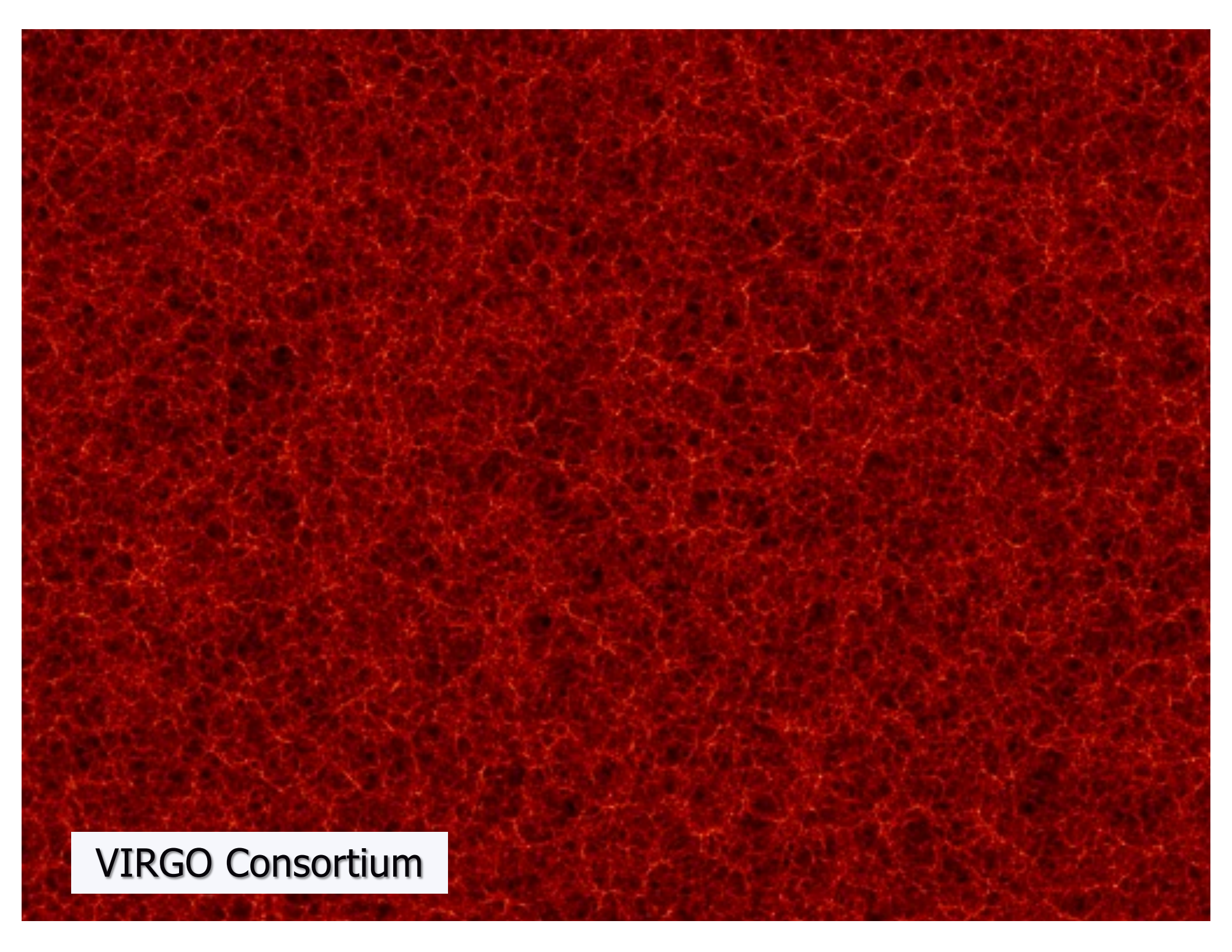


*What values of Q
allow for habitable
galaxies?*

The Cosmic Microwave Background Radiation



Planck Collaboration



VIRGO Consortium



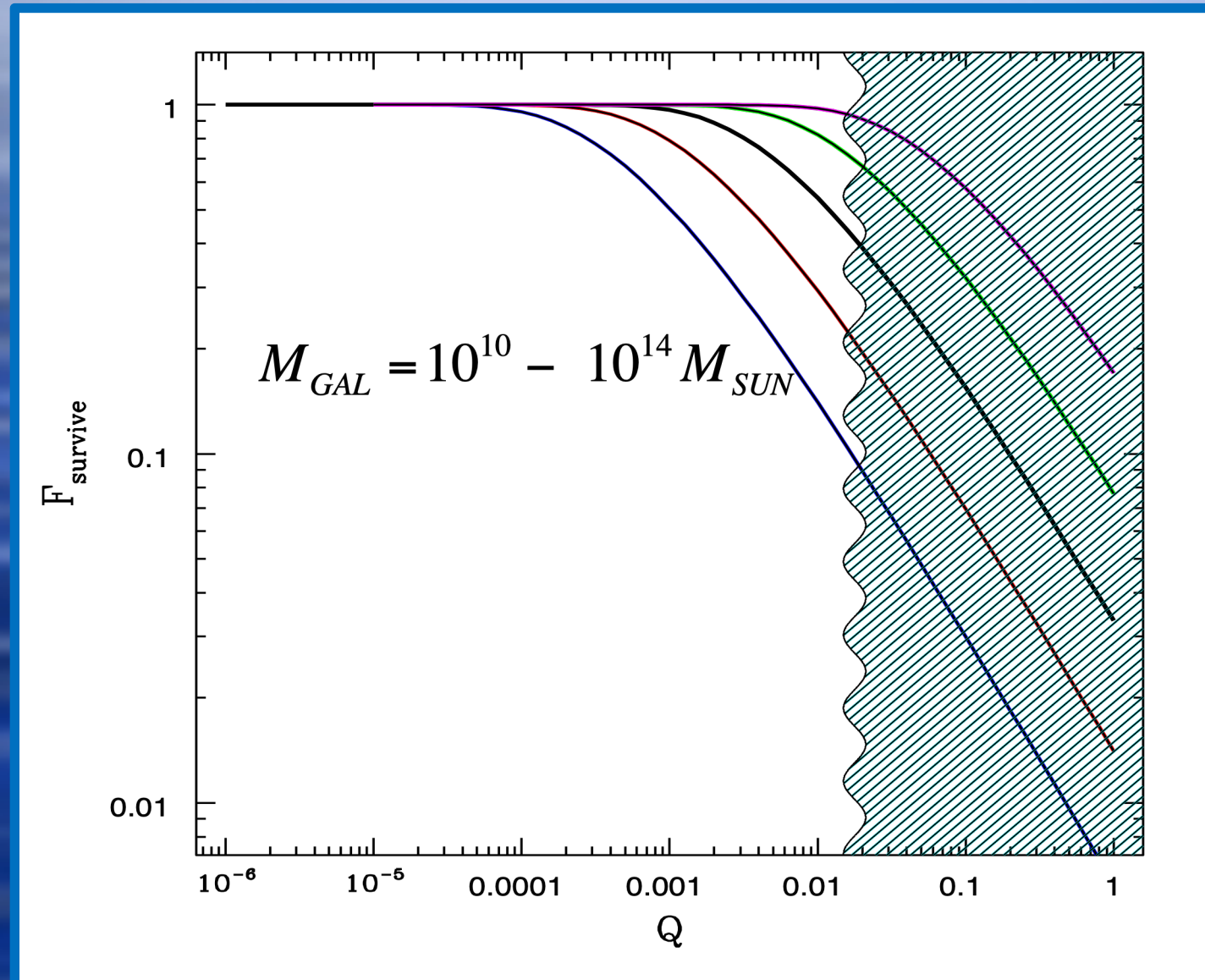
Hubble Space Telescope

$$Q = \frac{\Delta T}{T} = \frac{\Delta \rho}{\rho} \approx 10^{-5}$$

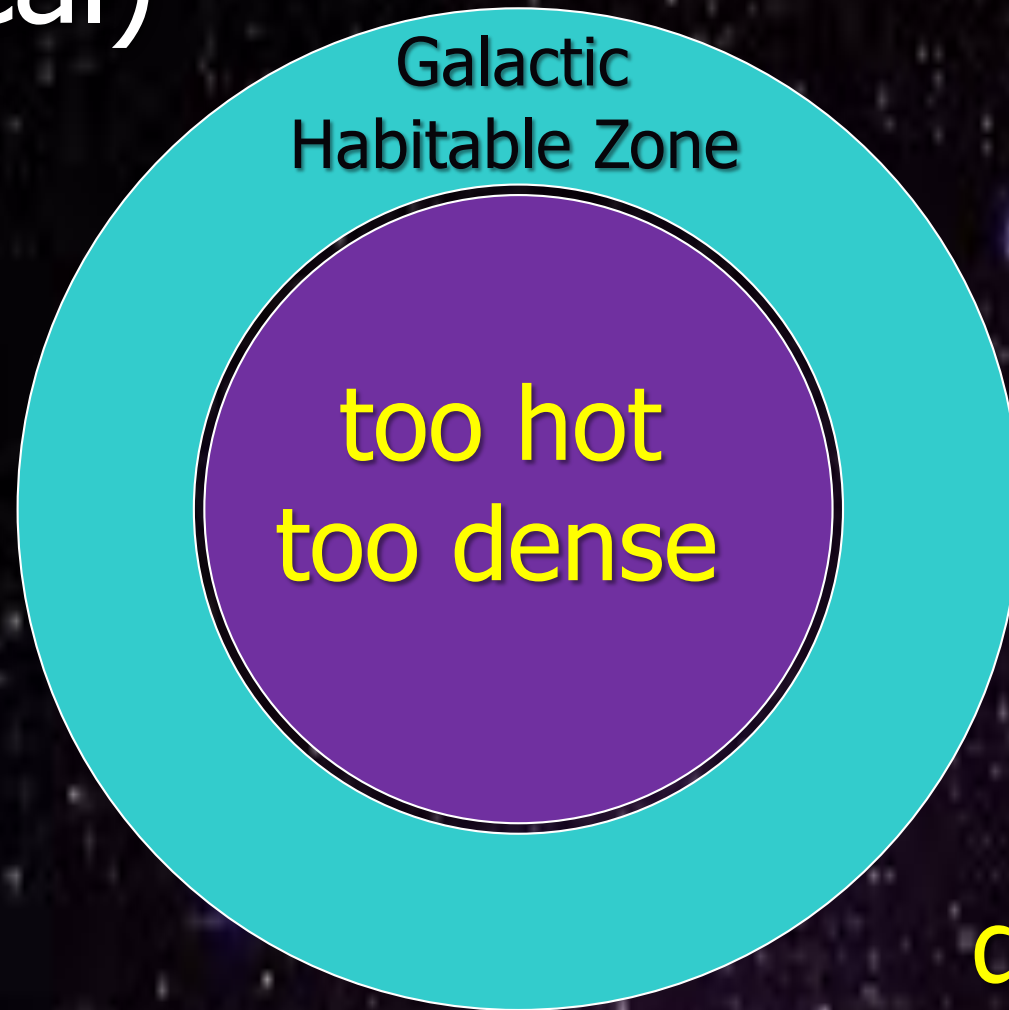
- ◆ Fluctuation amplitude Q sets starting point for collapse of halos – galaxy formation
- ◆ Larger Q leads to earlier collapse, which in turn leads to denser galaxies
- ◆ Denser galaxies can disrupt habitability by stripping earth-like planets from their stars
- ◆ Original claim: Q cannot be more than 10 times larger than the value in our universe

(Tegmark & Rees 1998, 2006)

Fraction of Galaxy that Survives Disruption via Scattering Encounters



Anatomy of a (spherical) Galaxy

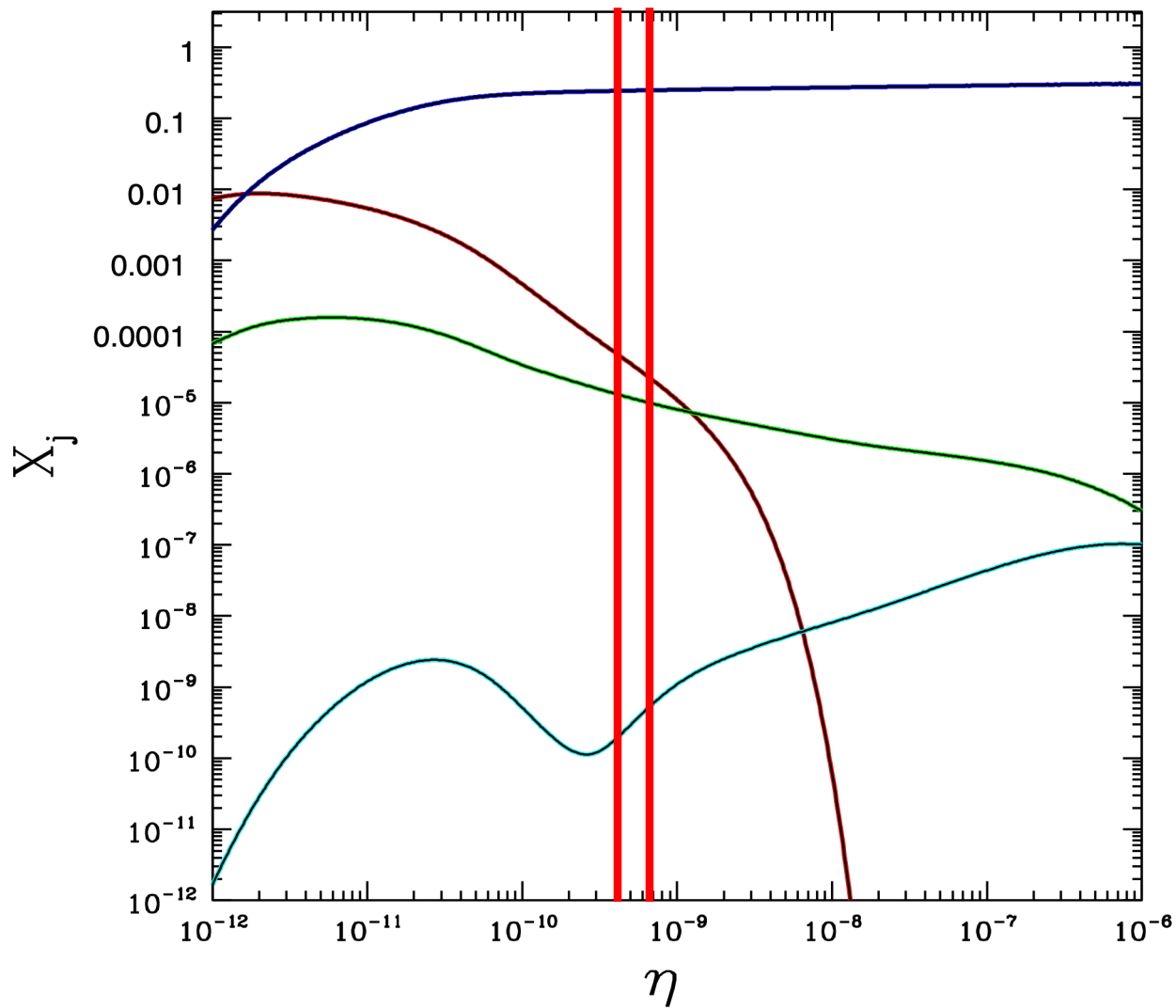


dark and
empty

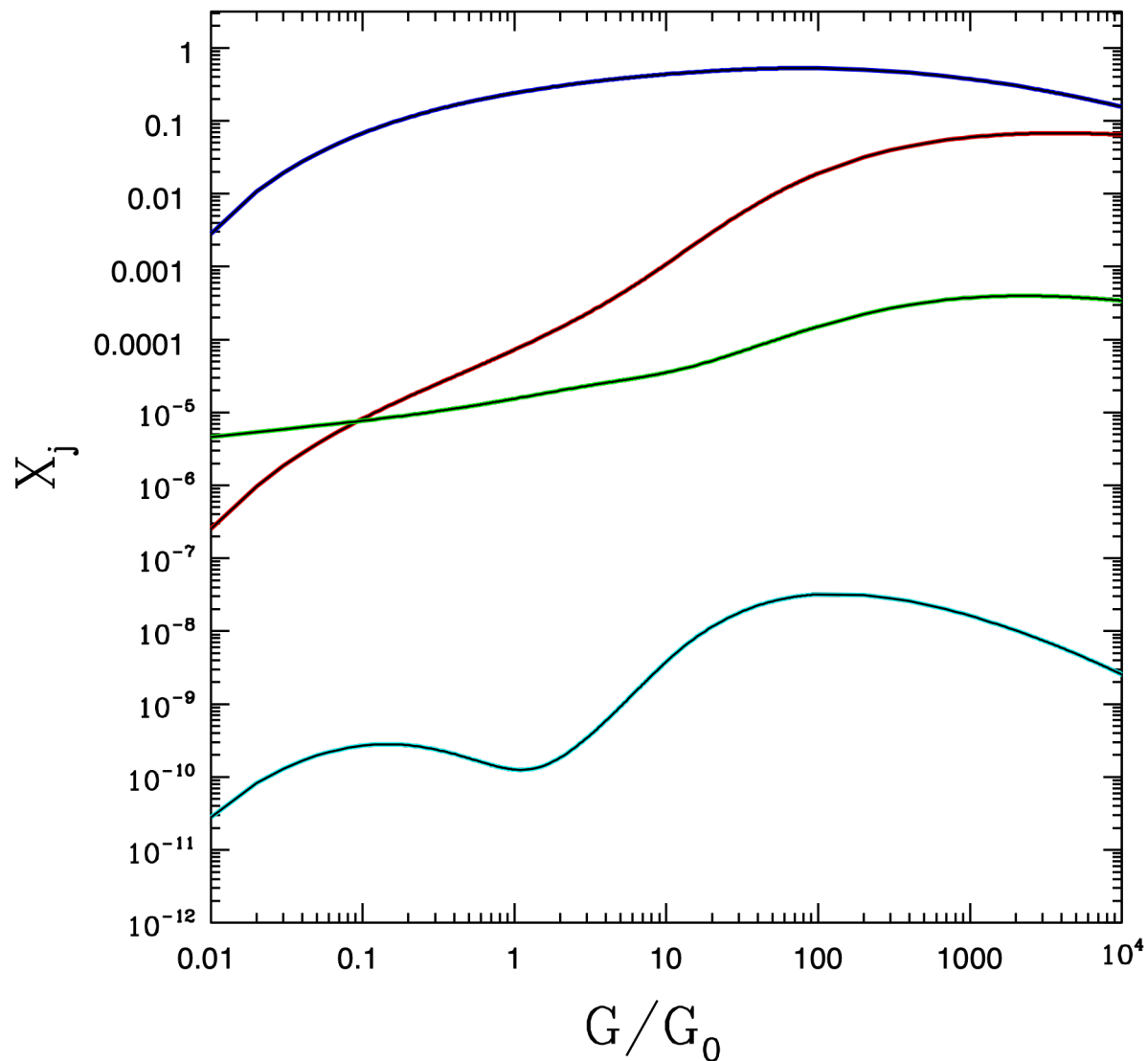


*What parameters allow
successful Big Bang
Nucleosynthesis?*

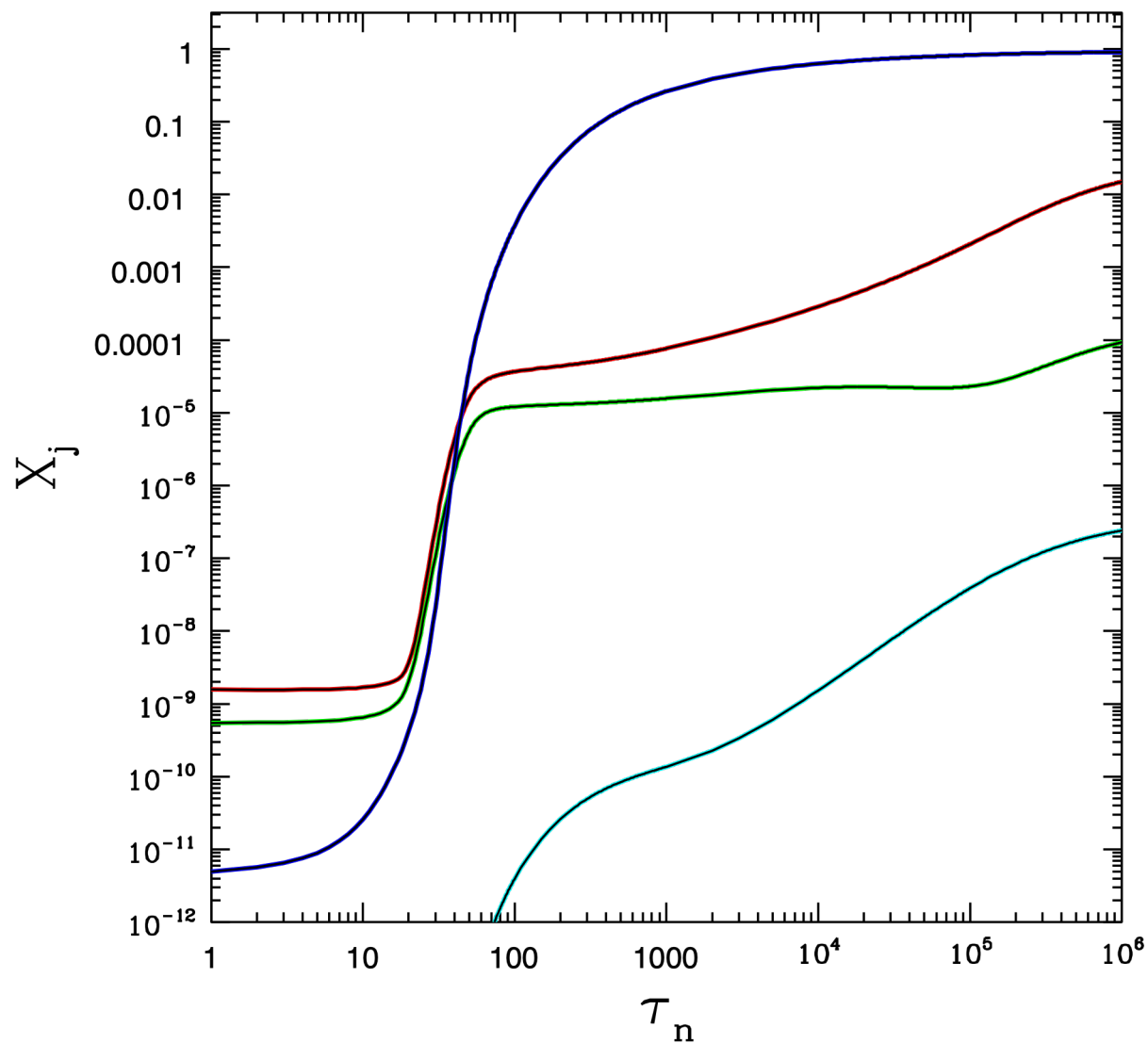
BBN Yields vs Baryon Fraction



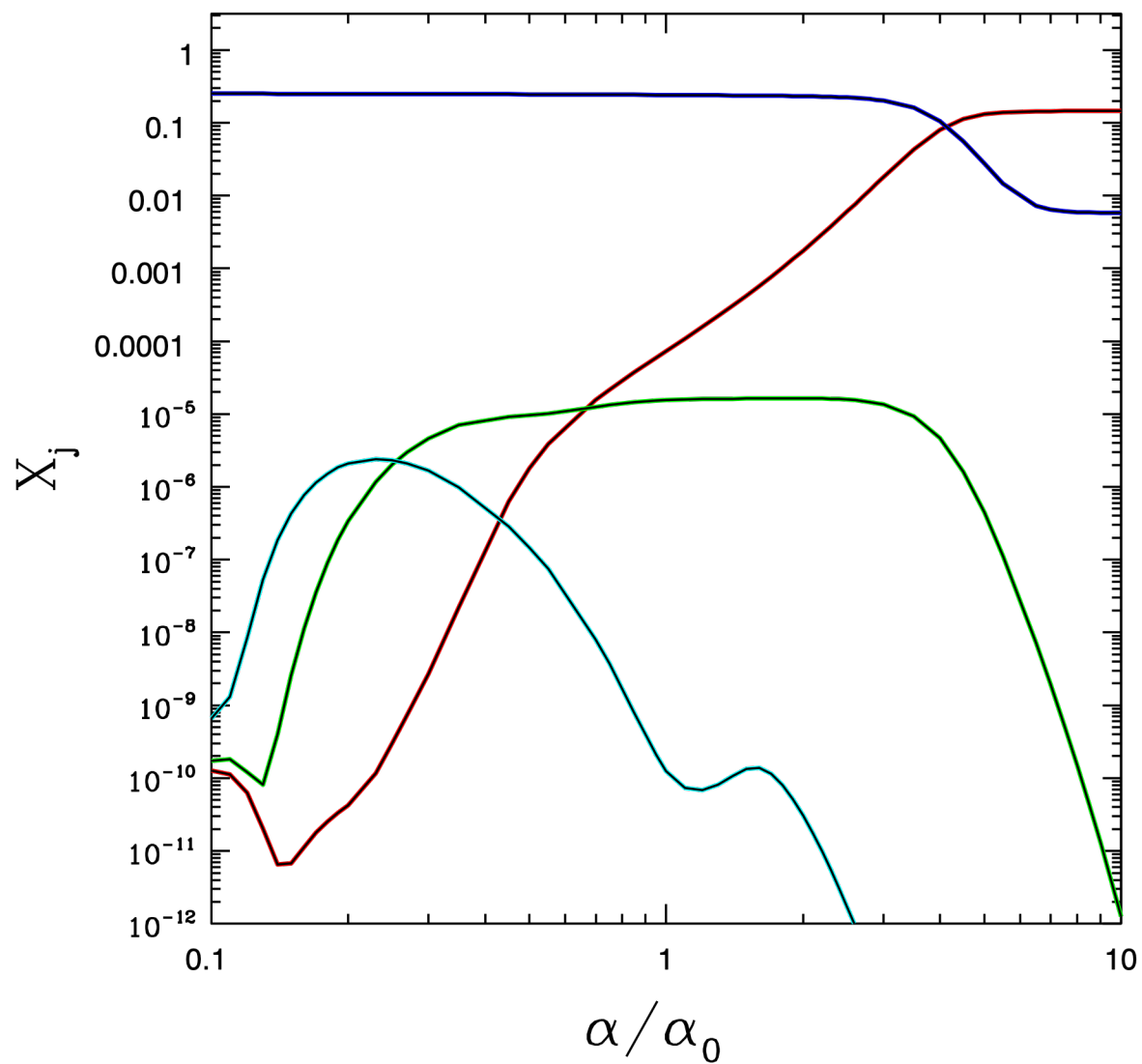
BBN Yields vs Gravity



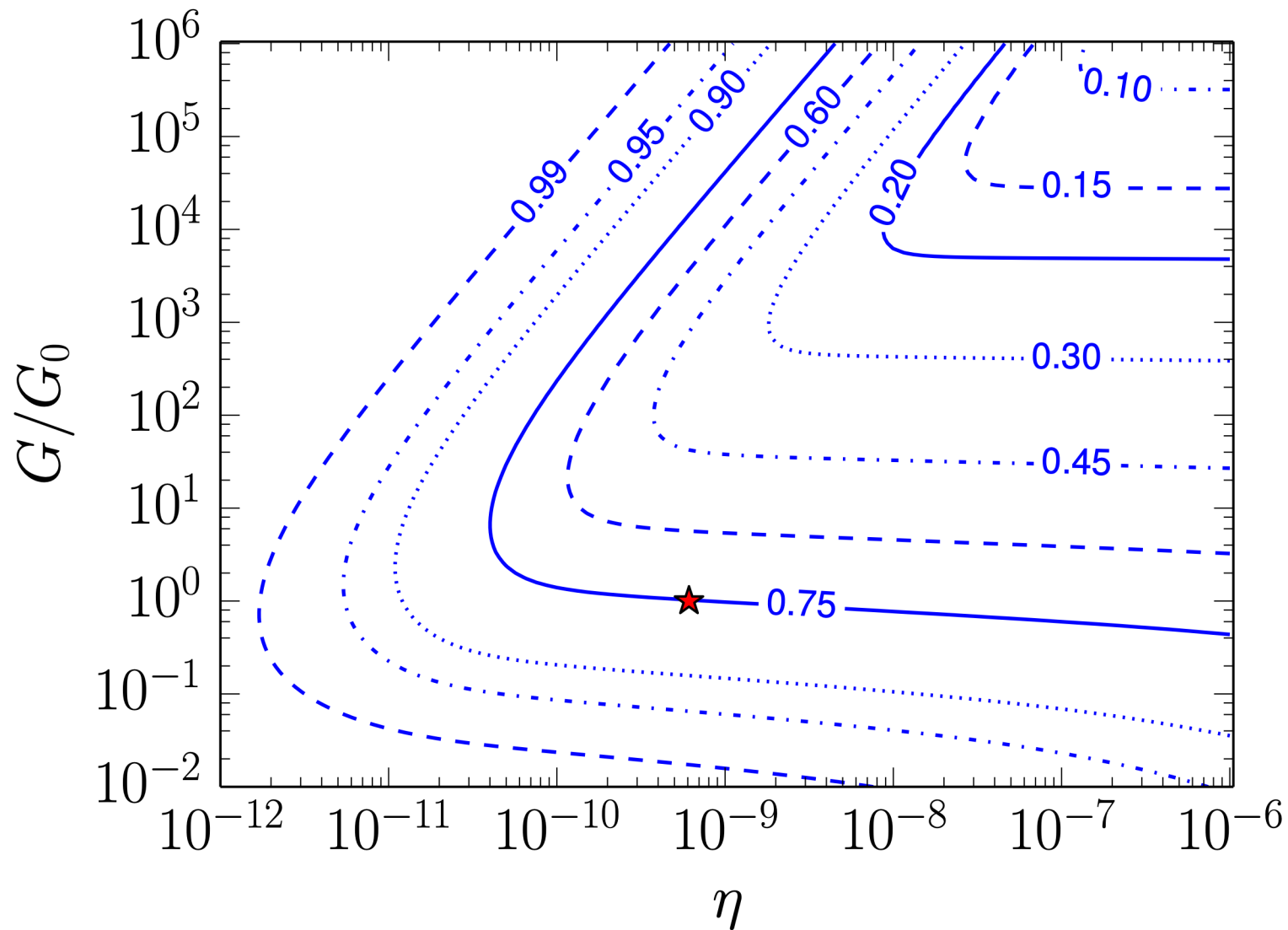
BBN Yields vs Neutron Lifetime

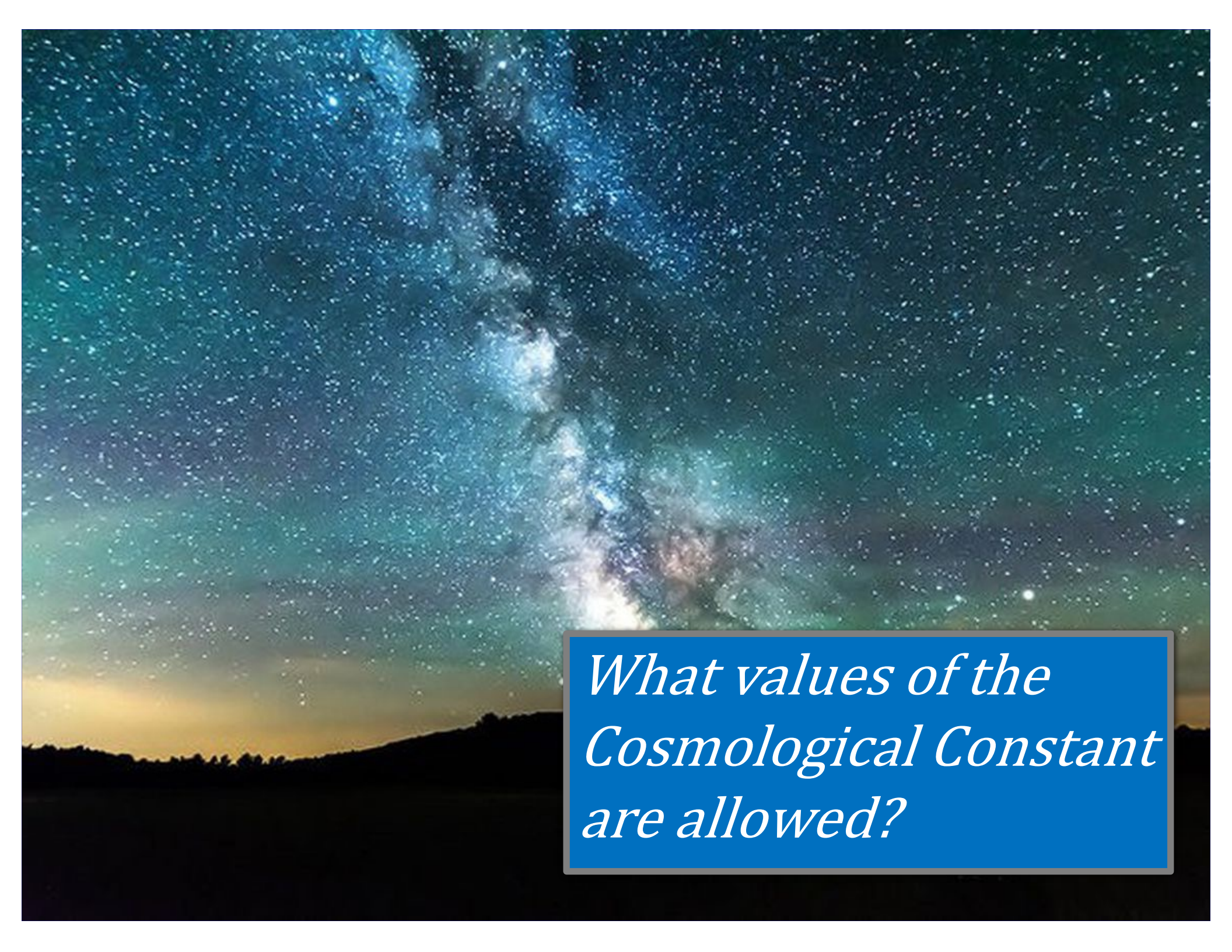


BBN Yields vs Alpha



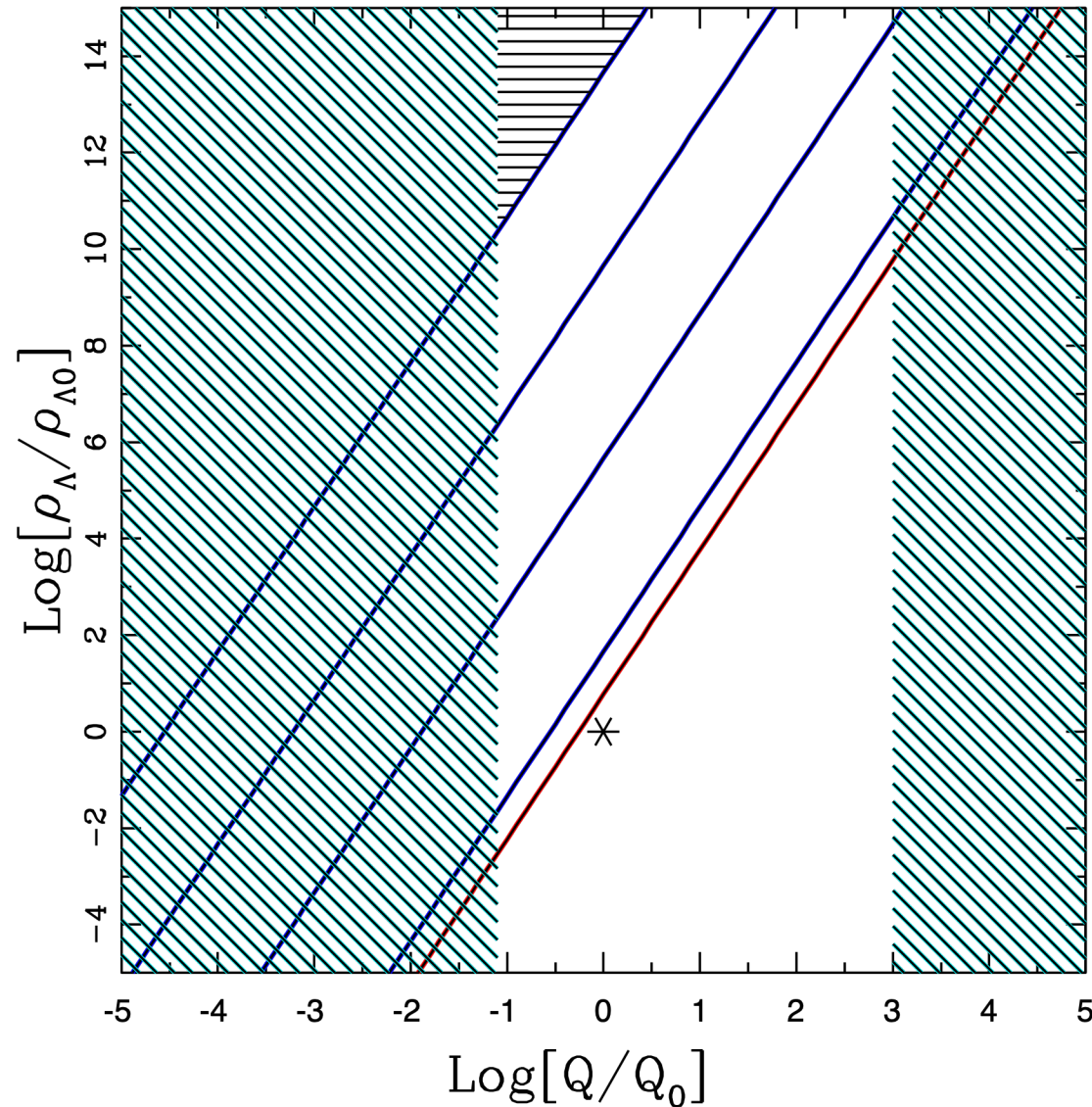
Hydrogen survival in η - G plane

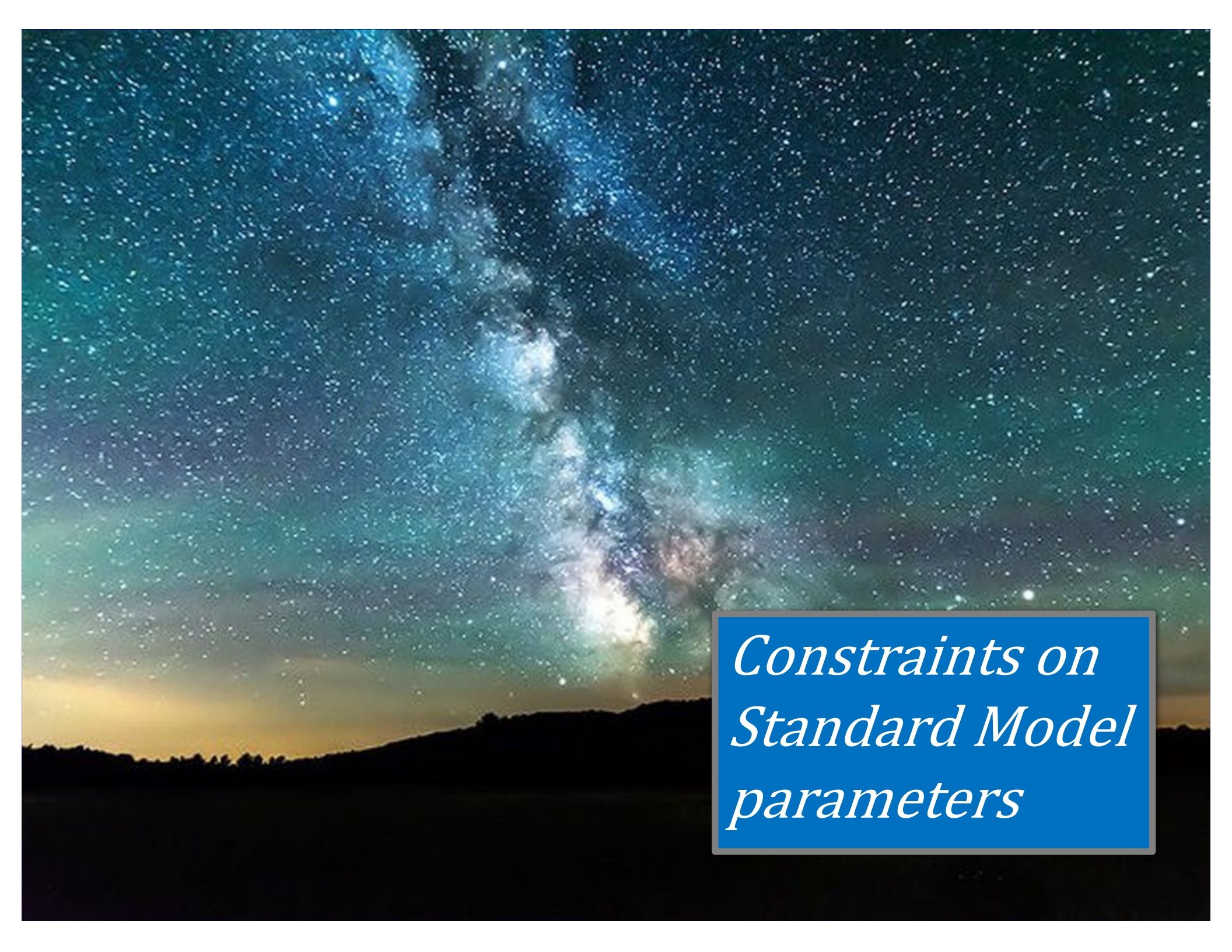




*What values of the
Cosmological Constant
are allowed?*

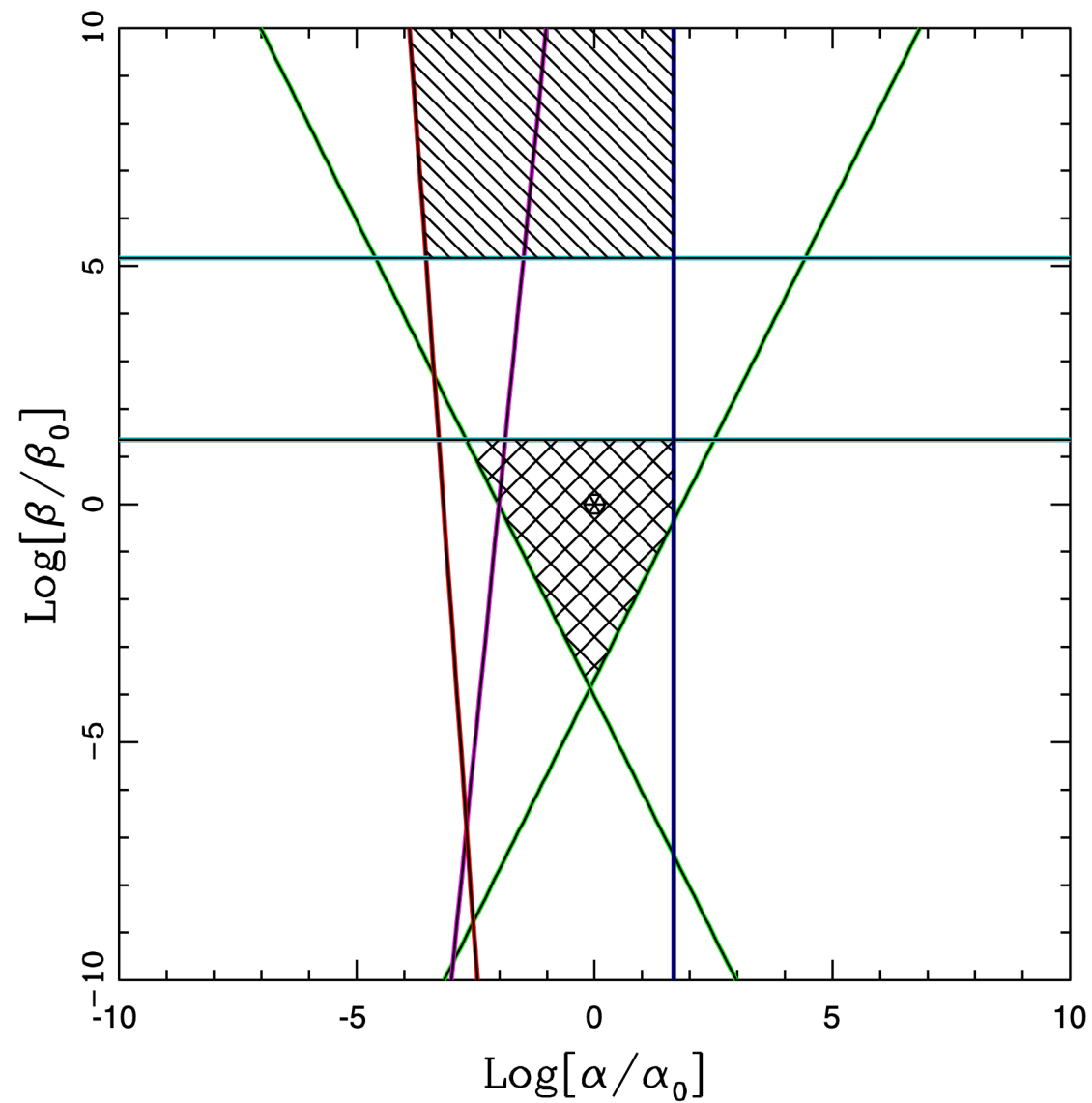
Cosmological Constant Constraint



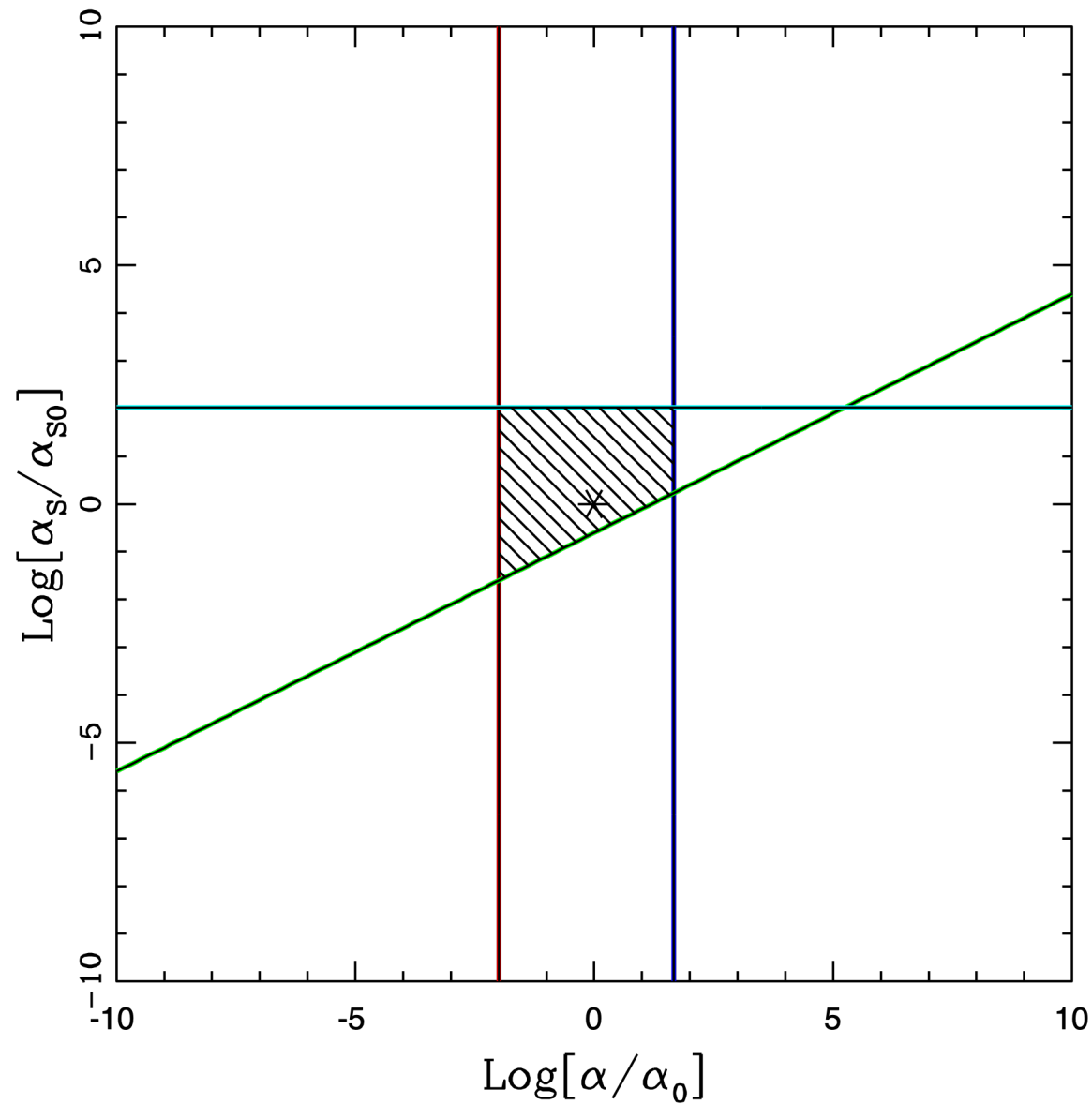


*Constraints on
Standard Model
parameters*

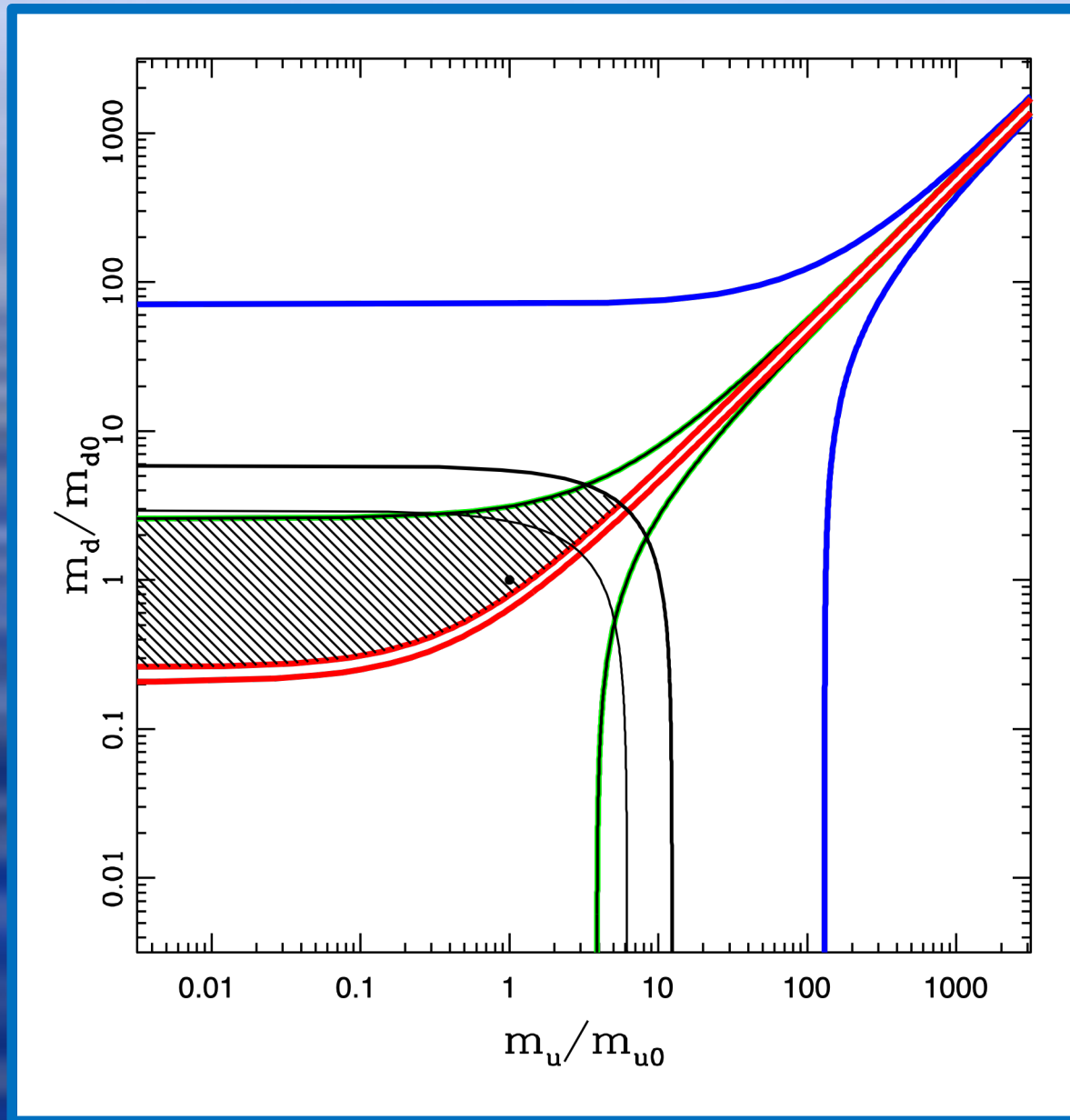
The $\alpha - \beta$ Plane



The $\alpha - \alpha_s$ Plane



Constraints on Quark Masses



Summary of Constraints

Ranges of Parameter Values for Viable Universes

quantity	symbol	observed value	range (decades)
Up quark mass	m_u	2.3 MeV	> 3
Down quark mass	m_d	4.8 MeV	0.85
Electron-proton mass ratio	β	1/1836	5
Up-down quark mass difference	δm	2.5 MeV	1
Gravitational constant	α_G	6×10^{-39}	> 10
Weak coupling constant	α_w	10^{-5}	6+
Fine structure constant	α	1/137	4
Strong coupling constant	α_s	15	3
Fluctuation amplitude	Q	10^{-5}	4
Baryon to photon ratio	η	6×10^{-10}	6
Dark matter abundance	δ	3×10^{-9}	6
Vacuum energy scale	λ	0.003 eV	10+
AM Radio	f_{AM}	535 – 1605 kHz	0.0043
FM Radio	f_{FM}	88 – 108 MHz	0.00087

Alpha Must be Small

- ◆ Stable stars require QM tunneling
- ◆ Stars must have sufficiently hot surface temperatures
- ◆ Large atomic nuclei would not exist
- ◆ Electrons would be relativistic in heavy elements → different chemistry
- ◆ Planets smaller than their host stars

$\therefore \alpha < 1 \rightarrow QED \text{ perturbative}$

The Bottom Line

- ◆ The fine-tuning of our universe for life is not as extreme as previous workers have suggested
- ◆ A wide range of parameters allows for working universes
- ◆ A range of different scenarios allows for working universes

Our Universe is NOT the best of all possible Universes

- ◆ More logical universe would have:
- ◆ Larger Q (more natural)
- ◆ More habitable planets (GHZ)
- ◆ Stable Be-8 nuclei
- ◆ Less vacuum energy (more LSS)
- ◆ More stars

References:

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