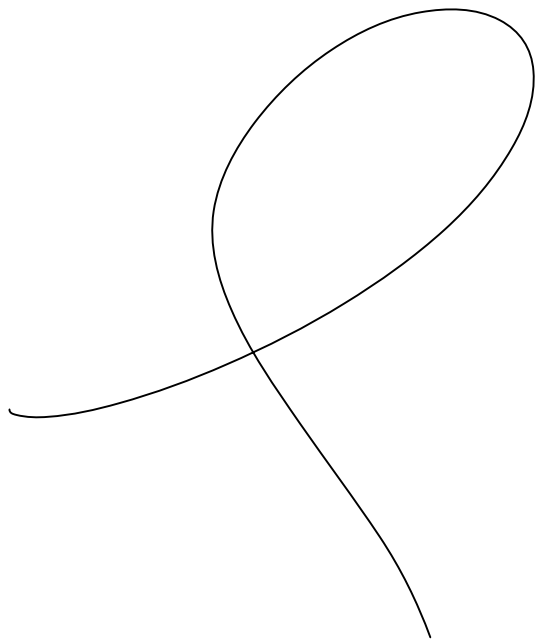
Note Title 5/13/2016



The Fine Structure Constant and Habitable Planets

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Introduction

Multiverse Hypothesis: The laws of physics might be different elsewhere.

Anthropic Principle: We can only live someplace where life can exist.

[Carter, 1983]

[Barrow, Tipler, 1988]

Principle of Living Dangerously:

[Hogan, 2000]

Habitable universes are exceptional

— so —

a slight change in ours would be uninhabitable.

Planets

Reasons it hasn't been done already:

- Extremely messy

- Poorly understood

- Range of environments

Outline

Part I: Planetary Habitability

Part II: Iron

Part III: Radioactivity

Part I: Planetary Habitability

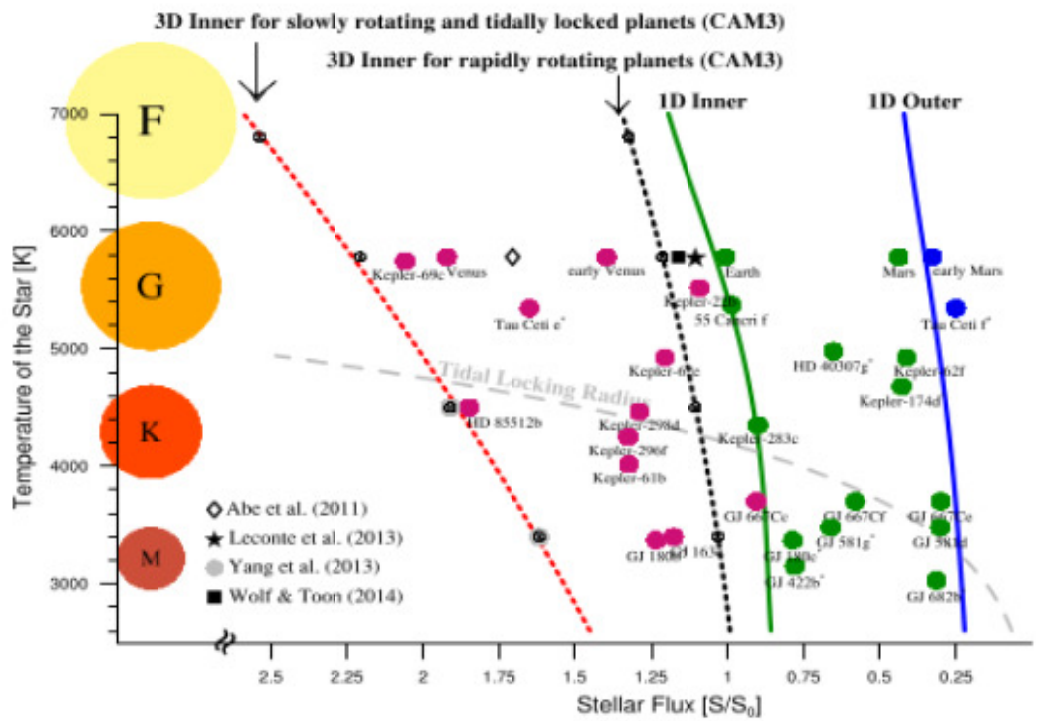
- Habitable Zone
- Eccentricity
- Magnetic Field
- Jupiter
- Metallicity
- Atmosphere
- Plate Tectonics

The Habitable Zone

- A planet must be the right distance from its host star to support liquid water.

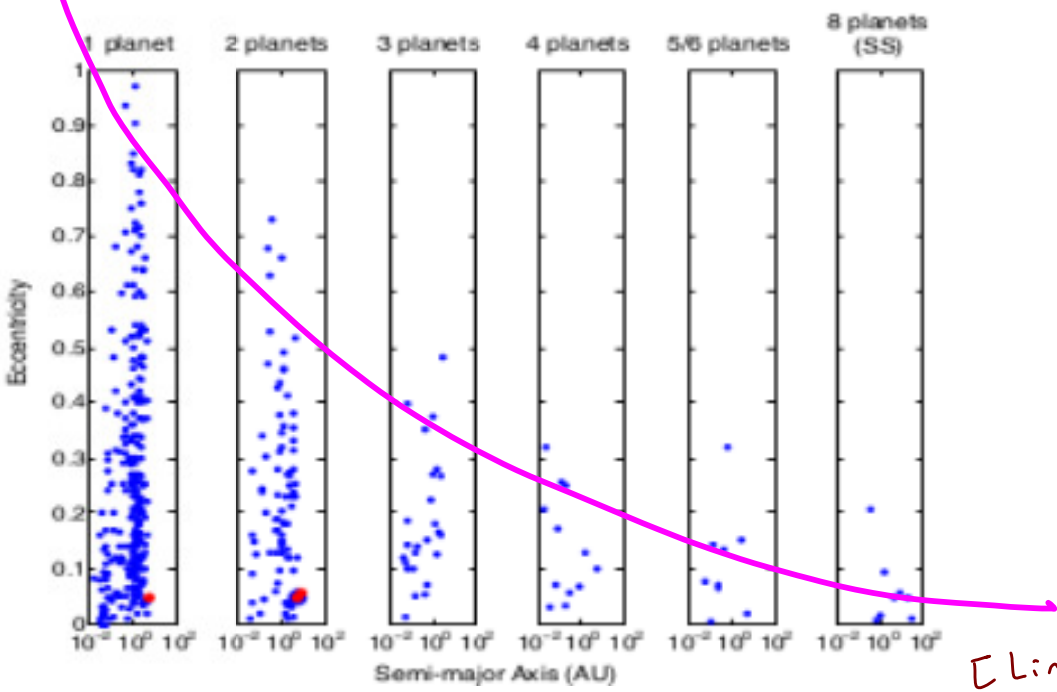
Depends on how fast the planet is spinning

[Yang et al, 2014]



Eccentricity

- Orbit must be sufficiently circular so that it stays in the HZ: $e < .1$
- $e_\oplus \sim .01$ — 10x smaller than required!



Correlation between e and # planets

[Limbach & Turner, 2014]

Magnetic Field

- Shields against harmful cosmic and solar rays

- Does not affect biosphere directly, but without it atmosphere would erode.

- Earth's B field is created by the dynamo effect by a spinning Iron core.

[MAVEN 2015] Mars's atmosphere stripped by sun

Jupiter

- Friend or Foe?

  ↳ Collects comets

  ↳ Also destabilizes their orbit

  Is this good or bad for life?

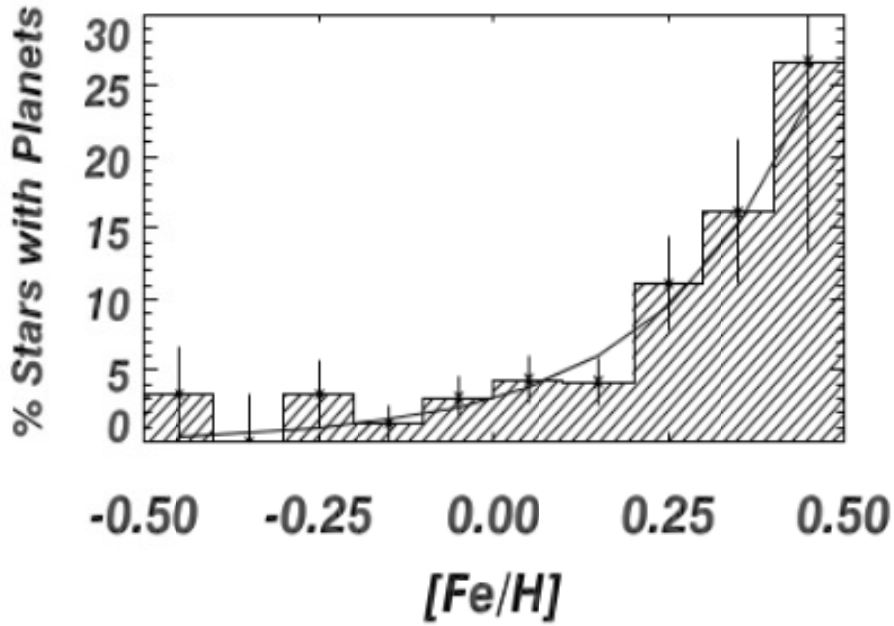
[ROSETTA 2014] Earth's water not from comets

Metallicity

- "Hot Jupiters" —

giants that migrated inwards are correlated with metallicity

[Fischer & Valenti 2005]



- Migration would have destroyed Earth.

$\Rightarrow$ Need low metallicity

Atmosphere

- Composed of variety: H, He, H_2O, O_2, CO_2, ...

Too large: H & He bound — Mini-Neptune

Too small: H_2O unbound — Mars

Earth: escape velocity $\approx$ thermal velocity

$\Rightarrow \quad .7 < \frac{R}{R_\oplus} < 1.6$

[Rogers 2014]

[Marcy et al 2014]

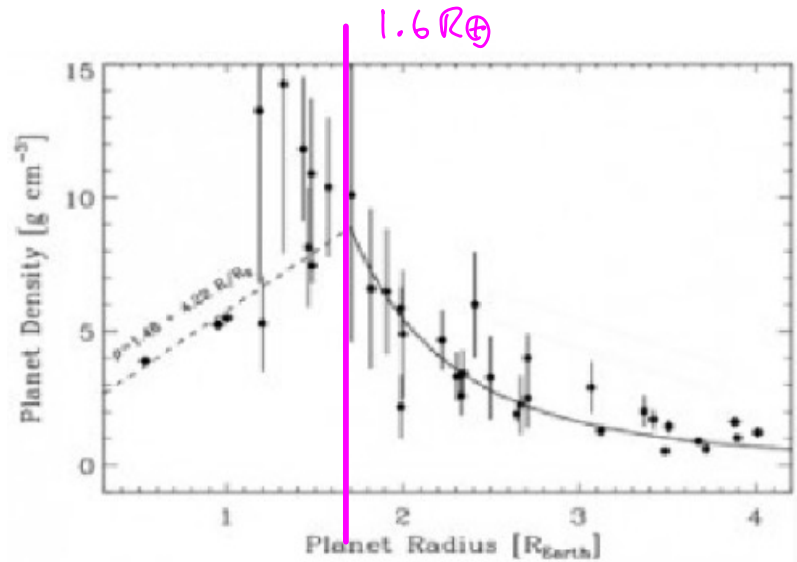


Plate Tectonics

- Recycles minerals into biosphere
- Created continents
- Stabilizing climate feedback loop

$$CO_2 + CaSiO \longrightarrow CaCO + SiO_2$$

- "A living Rock"

$$.7 < \frac{R}{R_\oplus} \lesssim 2.5$$

[O'Neill, Lenardic, 2007]

[Foley, Bercovici, Landuyt, 2012]

[Alibert, 2014]

Two narrow windows happen to overlap

Part II: Iron

Why Iron?

- Earth is 30% Fe by weight because

- Iron is the endpoint of stellar fusion because

- Iron has the highest binding energy* because

- A balance between Coulomb and Fermi Repulsion

  ⟶ Changing α would change this balance!

*subject to availability constraints

Nuclear Physics

- Proceeds through Helium accretion:

  makes nuclei with # protons = # neutrons

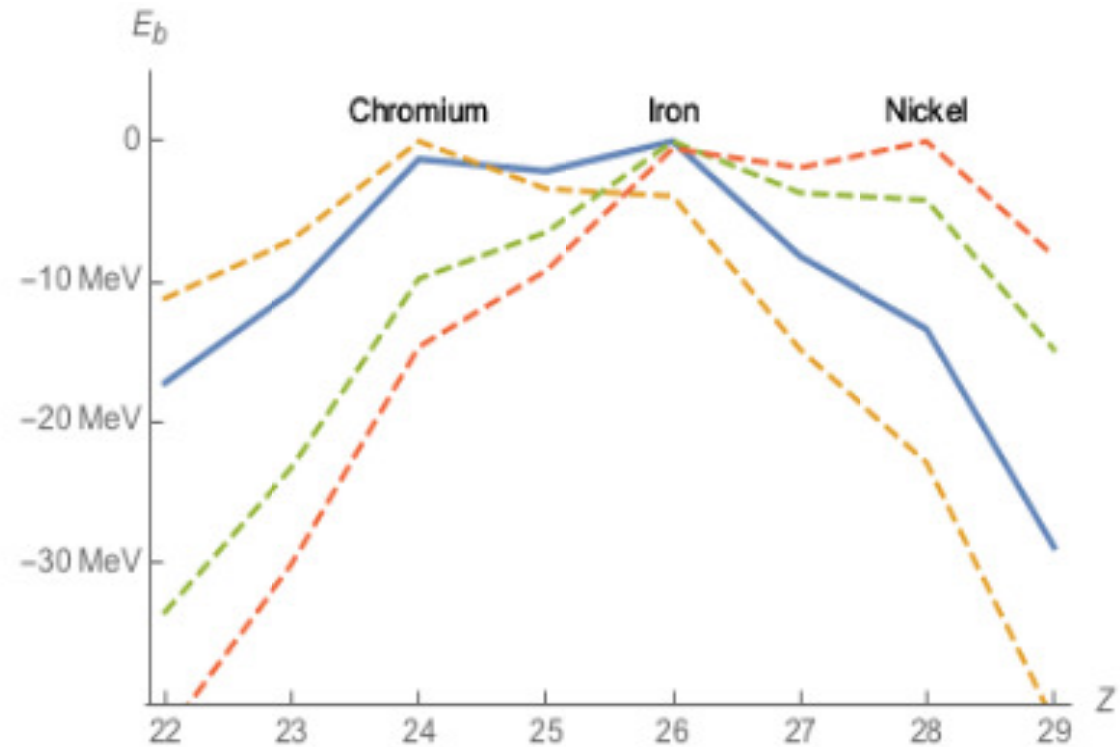
- Stops at "doubly magic" Nickel-56

- $Ni56 \xrightarrow[\text{week}]{\beta} Co56 \xrightarrow[\text{months}]{\beta} Fe56$

- Semi-Empirical Mass Formula:

$$E_{binding}(A,z) = a_c \frac{z(z-1)}{A^{1/3}} - a_{sym} \frac{(A-2z)^2}{A} + \dots$$

Binding Energies



$\alpha_0 = \frac{1}{137}$

$Z_{min} = 28$ for $\alpha > \frac{1}{95}$ Nickel never decays

$Z_{min} = 24$ for $\alpha < \frac{1}{205}$ Iron decays to Chromium

Why is Iron Special? (1/3)

Geophysics:

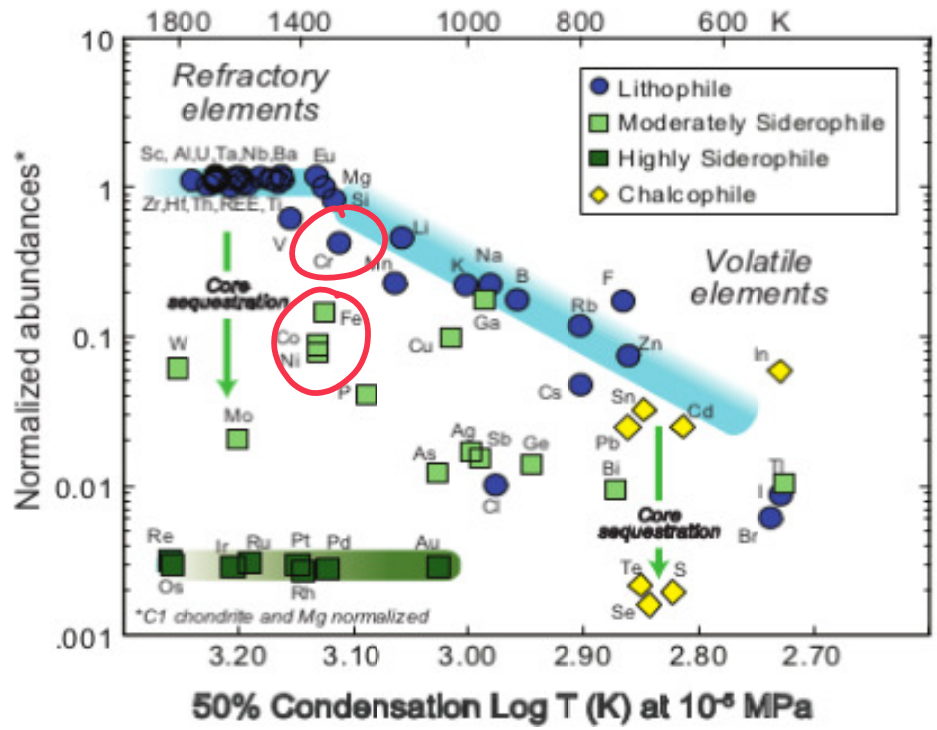
- Magnetic properties are not very different between Cr, Fe, Ni

- Cr is "lithophilic" - it sticks to rocks

- Core may never have formed if

$$\alpha < \frac{1}{205}$$

[Bellini et al, 2013]



Why is Iron Special? (2/3)

Biochemistry:

- Iron is essential to all life:

  copying DNA, transporting oxygen, cofactor, ...

- Often the limiting

  nutrient for

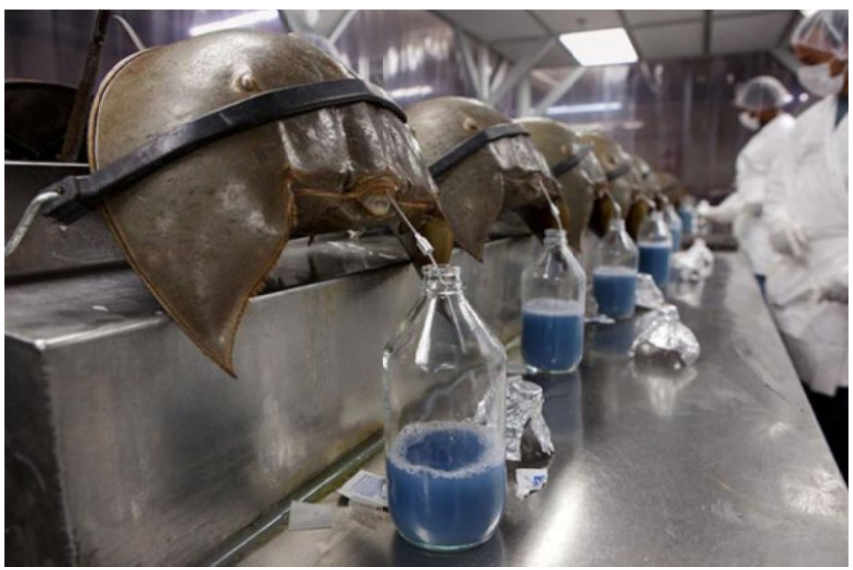
  algal communities

HOWEVER

- Borrelia burgdorferi

(Lyme disease)

uses Mg instead



- Horseshoe crabs use Cu instead in their blood

Why is Iron Special? (3/3)

Abiogenesis:

- Iron might have been crucial for origin of life

↳ Iron-Sulfur World [Wächtershäuser, 1998]

↳ Speeds up RNA world [Hsiao et al, 2013]

↳ Catalyzes glycolysis in Archean ocean [Keller et al, 2019]

Part III : Radioactivity

Earth's Heat

- Generated by

  (i) residual gravitational heat from formation

  (ii) radioactive decay

Using geoneutrinos [KAMLAND, 2011] we can now measure the relative magnitudes of the two

	HEAT	HALFLIFE	
U238:	8 TW	4.5 Gy	} α decays
Th232:	8 TW	14.1 Gy	
K40:	4 TW	1.3 Gy	} β decay
TOTAL:	20 TW	out of 47 TW	

Alpha Decays

- Geiger-Nuttall: half life depends exponentially on binding energy:

$$\log t_{1/2} = \frac{a\,Z}{\sqrt{\Delta E_b}} - b$$

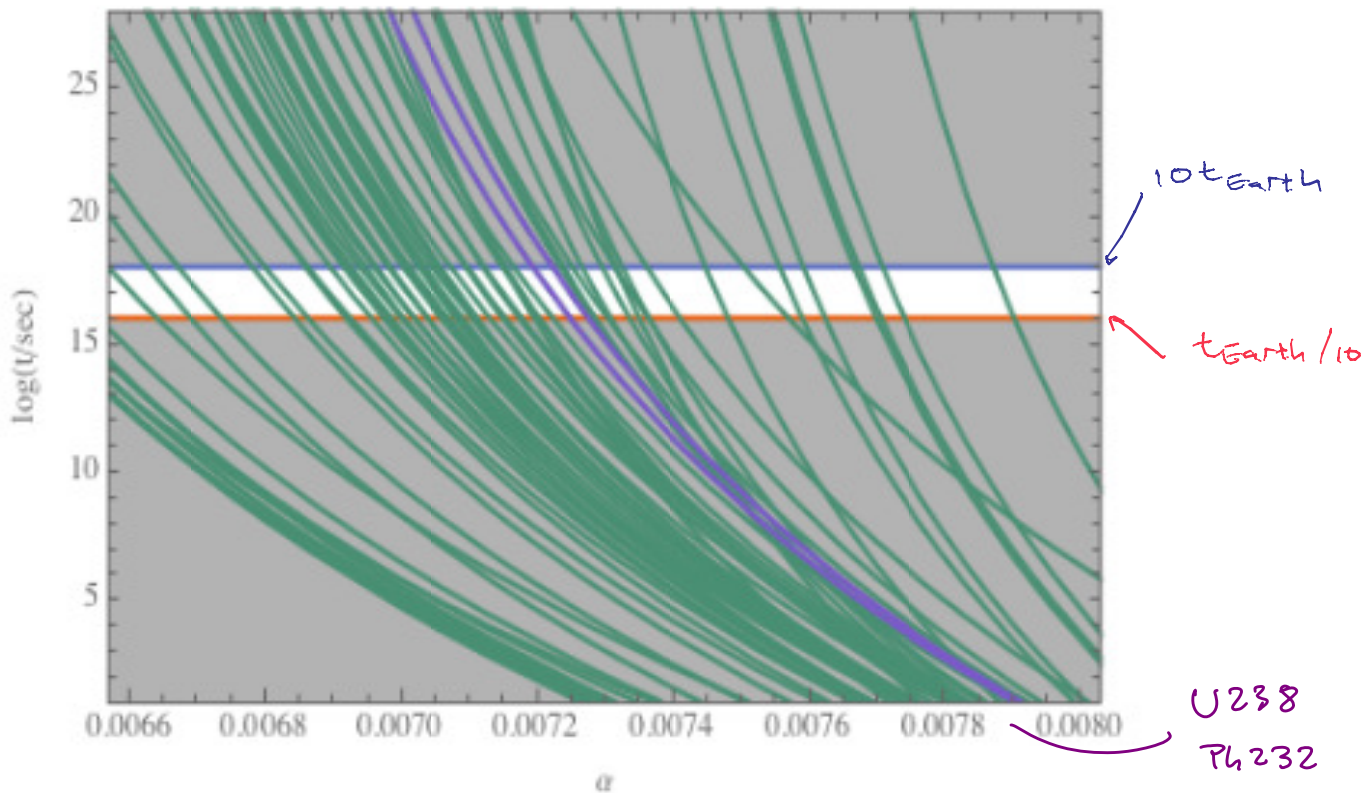
U238:

$\Delta\alpha = +.2\% \Rightarrow t_{1/2} = \frac{t_{Earth}}{10}$ – would have decayed already

$\Delta\alpha = -.2\% \Rightarrow t_{1/2} = 10\, t_{Earth}$ – would be practically stable

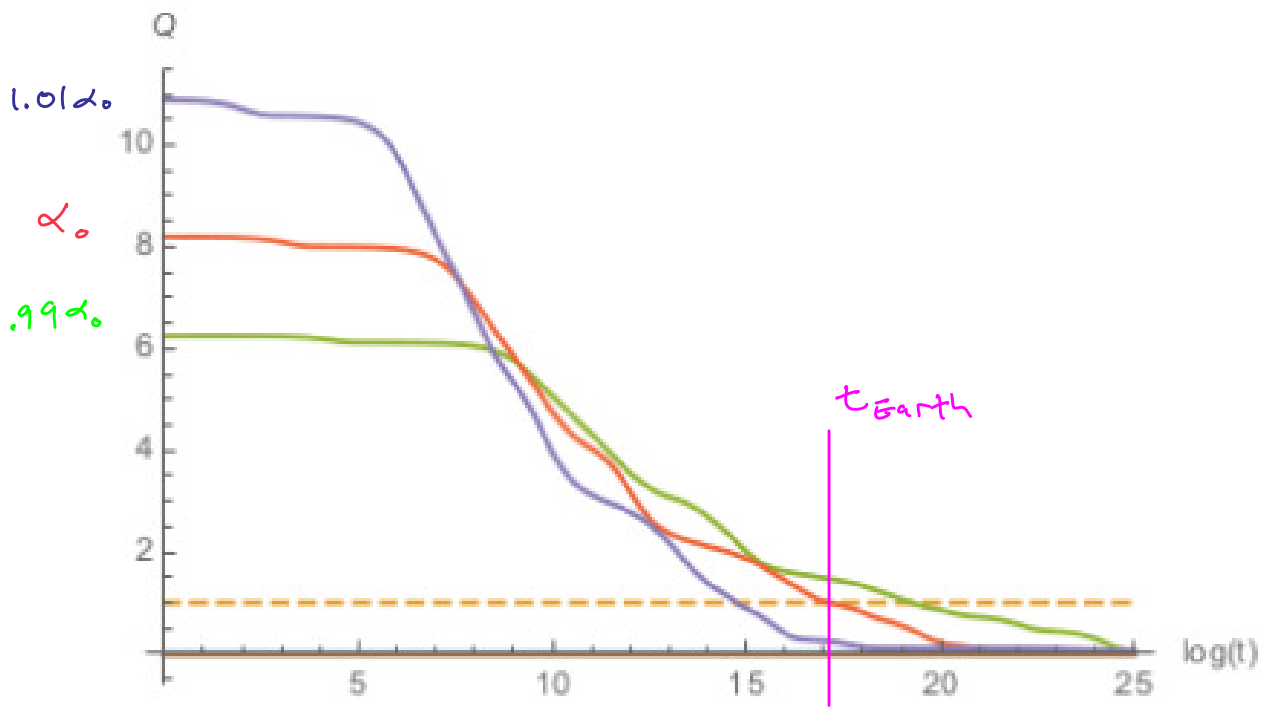
All Elements (1/3)

- Actually 65 α decays: the relevant ones match the age of the Earth.

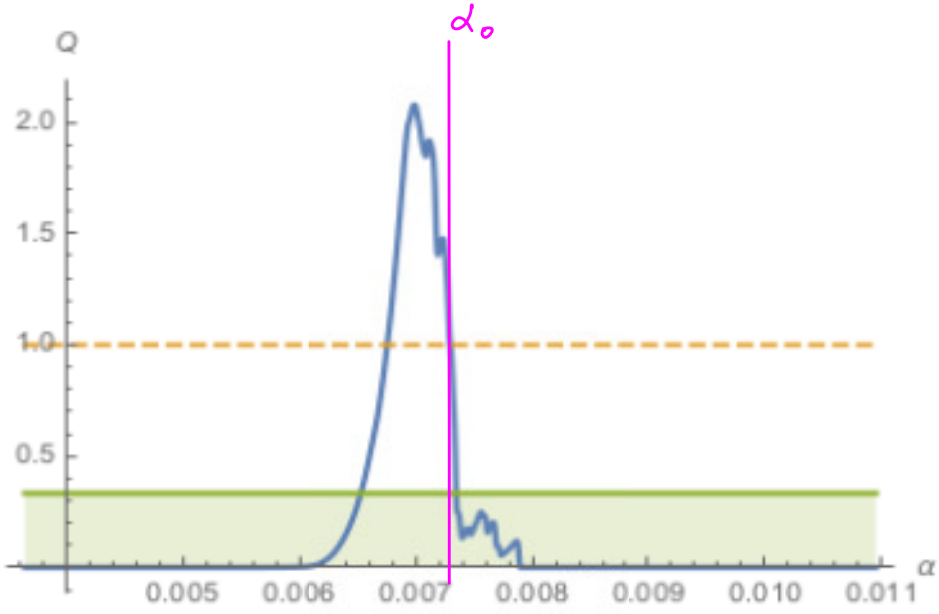


All Elements (2/3)

- Can find total heat generated as a function of α:



All Elements (3/3)



Once Q drops to 1/3 its current value, plate tectonics will grind to a halt

[Valencia et al, 2007]

- This restricts

$$\frac{1}{153} < \alpha < \frac{1}{136}$$

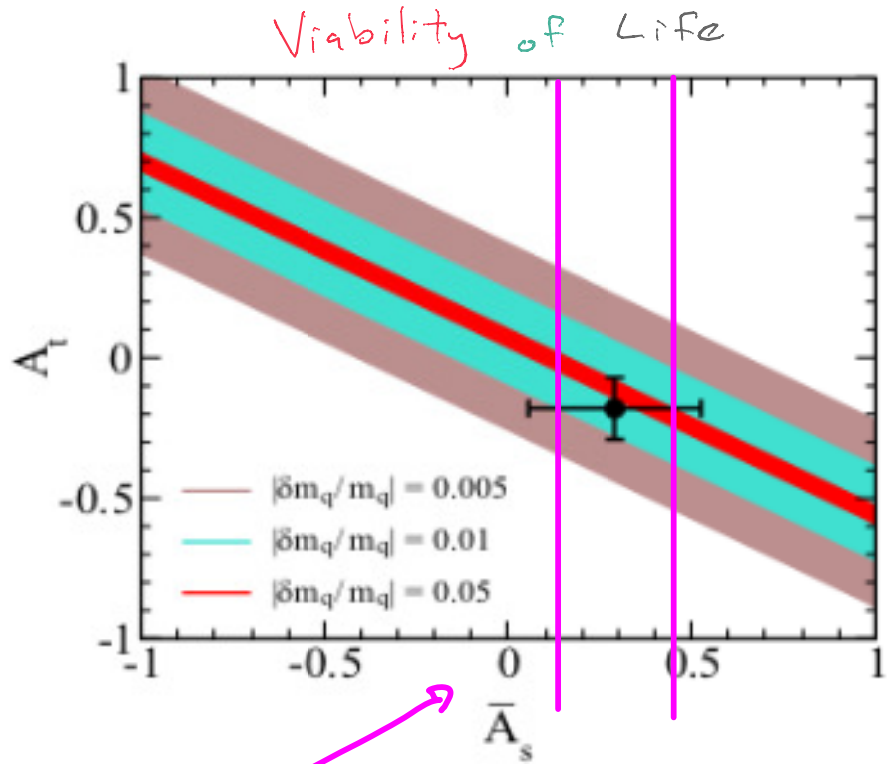
Note the actual value almost coincides with the upper bound.

Comparison to Other Bounds

- Most stringent bound comes from Carbon production in stars:

$$|\Delta\alpha| \lesssim 3\text{-}4\,\%$$

- However, this can be compensated by changing quark masses.



[Epelbaum et al, 2013]

- Our bounds break this degeneracy

Grand Unified Theories

- Strength of forces change with energy, meet at a high scale.

The GUT window: $\frac{1}{180} < \alpha < \frac{1}{85}$

- If $\alpha < \frac{1}{180}$, $M_{GUT} > M_{Planck}$

- Proton decay: If $\alpha > \frac{1}{85}$, $t_{proton} < t_{stars}$

is comparable to the iron window $\frac{1}{205} < \alpha < \frac{1}{95}$

and the two overlap. Flexible GUTs?

Outlook

- Advances in planetary science this past decade allow us to finally address long standing questions about the universe.

- We will learn even more this coming decade, especially about exoplanet atmospheres

  TESS, CHEOPS, JWST, ...

- What else will this teach us about fundamental physics?