# ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

## Lecture 26 • Our place in the Universe and the anthropic principle

12/7/2021

# Logistics

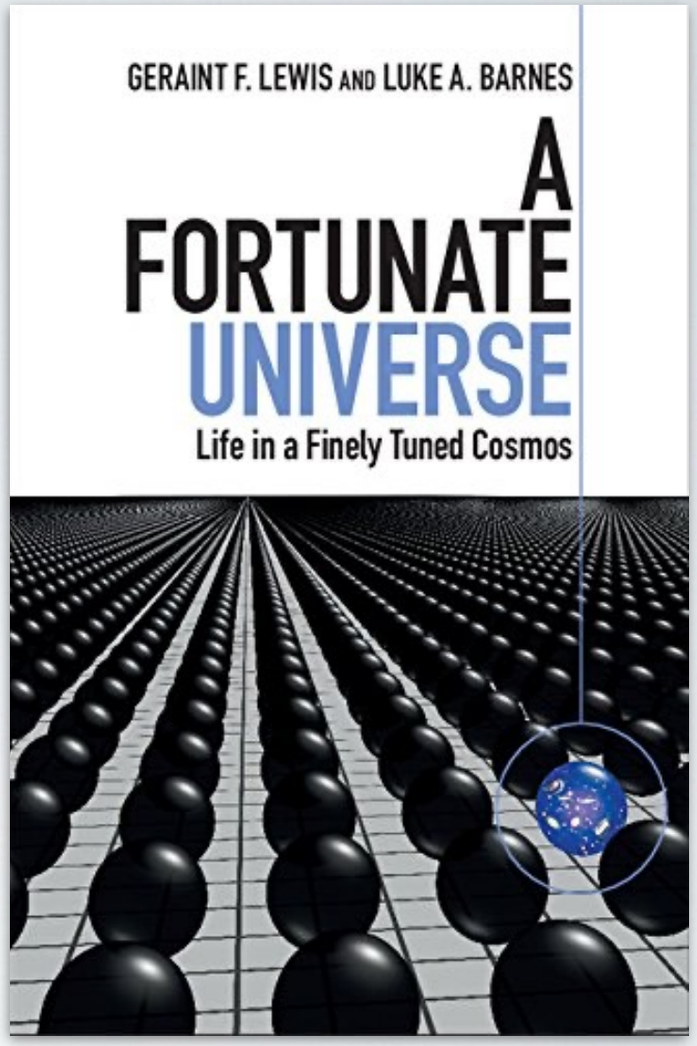
- Course evaluations are now open
  - Until 12/14
  - https://www.courseevalum.umd.edu

# Final Logistics

- If you miss the final for a documented emergency, please let me know as soon as possible
- You need a doctor's note for medical absences
- Please make sure you are on time
- Bring a calculator

# Today

- Life and the anthropic principle
- Fine-tuning the Universe
- Possible solutions to fine-tuning



# Part 1: Life and the anthropic principle

# The anthropic principle

**Given our existence as observers, the physical laws and constants underlying the Universe must be such that they allow for life to form.**

- Alternative version: Our location in the Universe is privileged as it must be compatible with our existence as observers
(a counterpoint to the Copernican principle)
- Our existence tells us very little about the rest of the Universe or other Universes; if we did not exist, we would not be able to make this observation!

B. Carter • Barrow & Tipler • Lewis & Barnes

# The big question

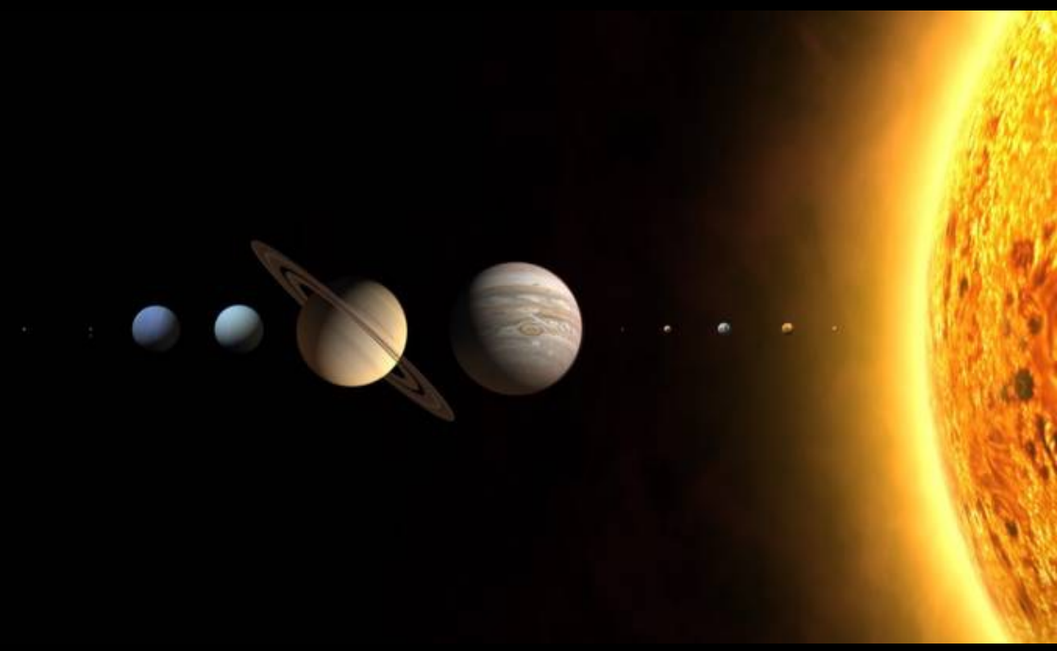
- Our theories leave a lot to be explained
  - Why are physical laws the way they are?
  - Free parameters in standard model of particles (masses, forces etc)
  - Free parameters in cosmology (how much matter, dark energy etc)
- This raises uncomfortable questions for physics and cosmology:
  - Do our theories naturally predict Universes that can create life?
  - What happens when we change the free parameters?
  - More technically: out of the set of all possible physics, is the subset that would permit life to develop large or small?
  - More succinctly:

**Is the Universe fine-tuned to allow for our existence?**

Lewis & Barnes

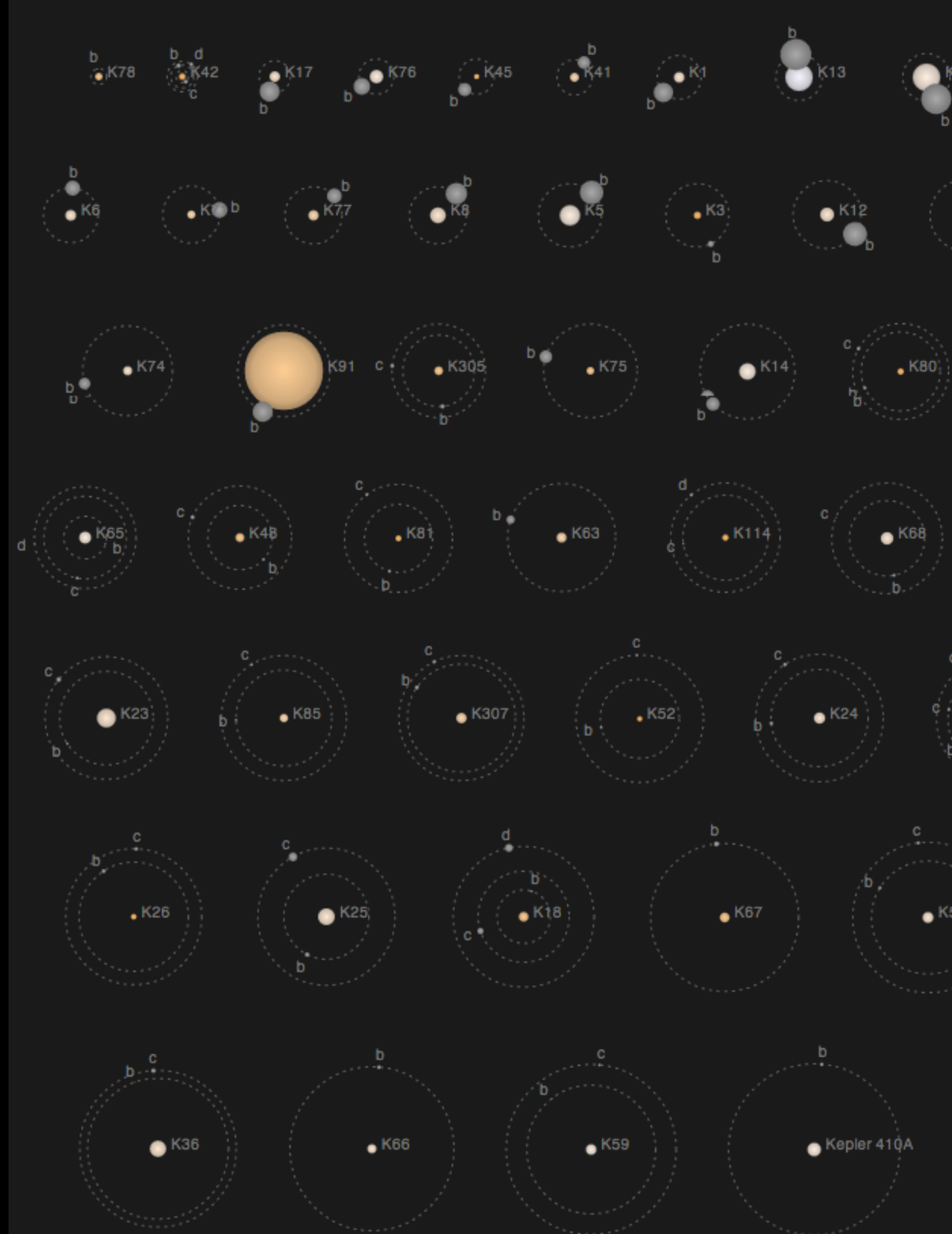
# Conditions for human life on our Earth

- A **star** with just the right mass
  - two times larger and its lifetime would be too short (took ~3 billion years for human life to develop)
  - two times smaller: to have liquid water, Earth would need to be so close to star that rotation would be tidally locked (hot day side, cold night side)
- A **planet**…
  - with the right mass and composition
  - in the “habitable zone” around its star
- Large **Moon**
  - keeps tilt of Earth’s axis relatively steady; otherwise widely varying seasons
- A benevolent **Jupiter**
  - shields us from many impacts (extinctions)
  - bad Jupiters (large gas planets) drive interior planets into star
- Right place in **Galaxy**
  - close to the nucleus, too many supernova and gamma-ray bursts
  - in halo and globular clusters, few heavy elements
- And so on…

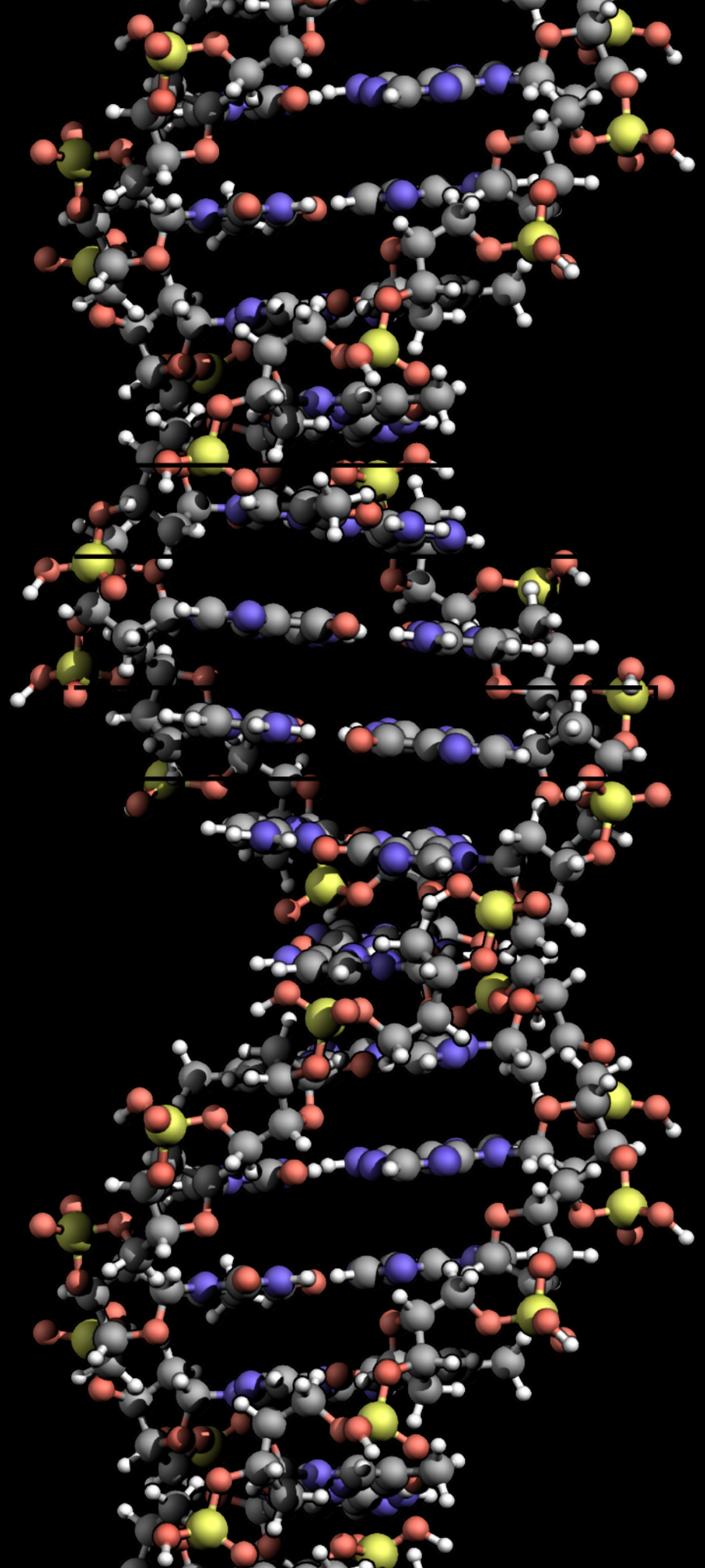


# Coincidence?

- Can all of this be a coincidence?
  - **Yes!!!**
- There are **$10^{10}$ stars in the Milky Way** alone, and most have planets
- There are **galaxies** wherever we look
- The question becomes irrelevant if we consider an **infinite Universe**

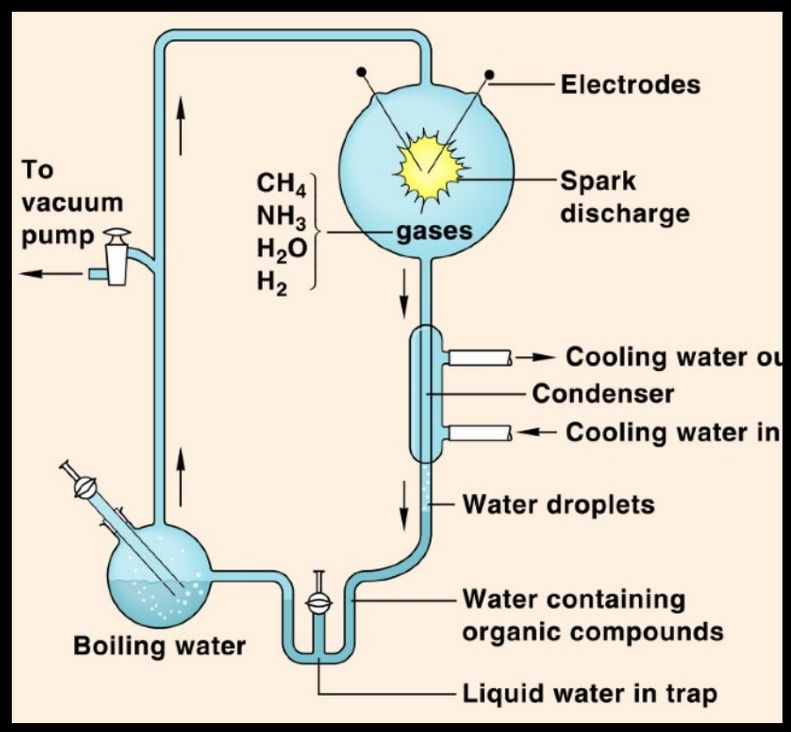



Kepler / New York Times



# But what about life?

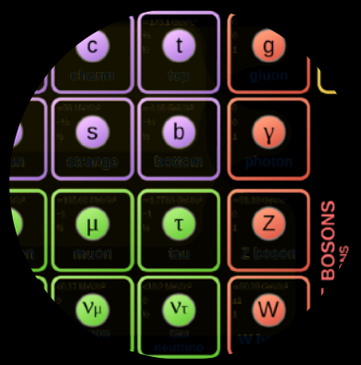
- We can ask many more detailed questions:
  - Which **planets** can host life?
  - What **elements** to we need exactly (C, O, N…)?
  - What does it take to make **DNA**?
- These are **not the questions we are asking!**
  - We assume that life can emerge if some **fundamental conditions** are given
  - Miller-Urey experiment showed that organic compounds are formed under generic conditions



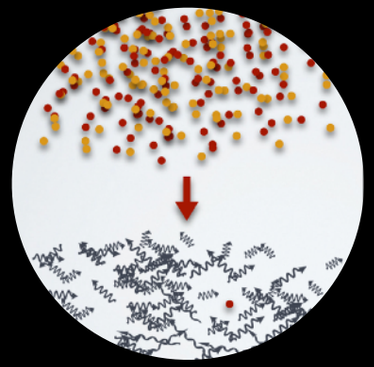

Miller-Urey experiment

# Why do we exist?

(according to this class)




fundamental particles

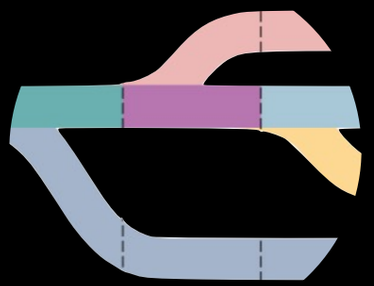


matter-antimatter asymmetry

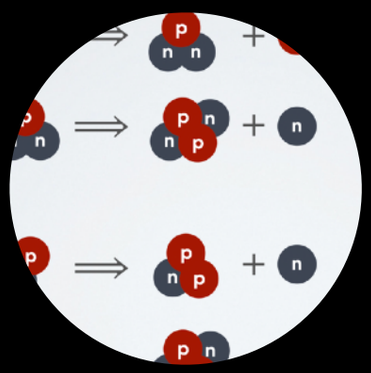
galaxy formation

star formation and supernovae

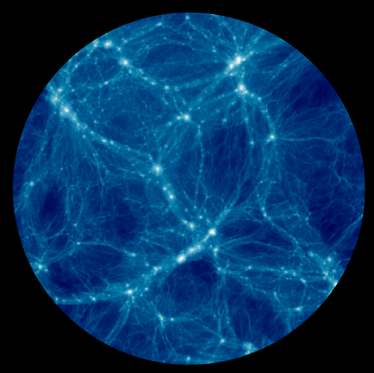
stars with many higher elements



fundamental forces



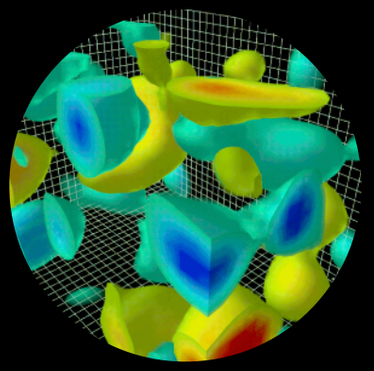

Big Bang nucleosynthesis



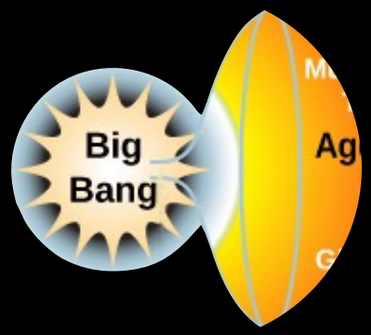
gravitational collapse


higher elements

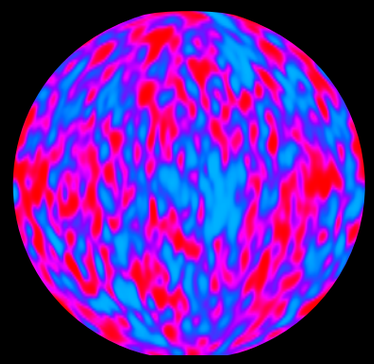
rocky planets



quantum fluctuations




inflation



inhomogeneities at recombination

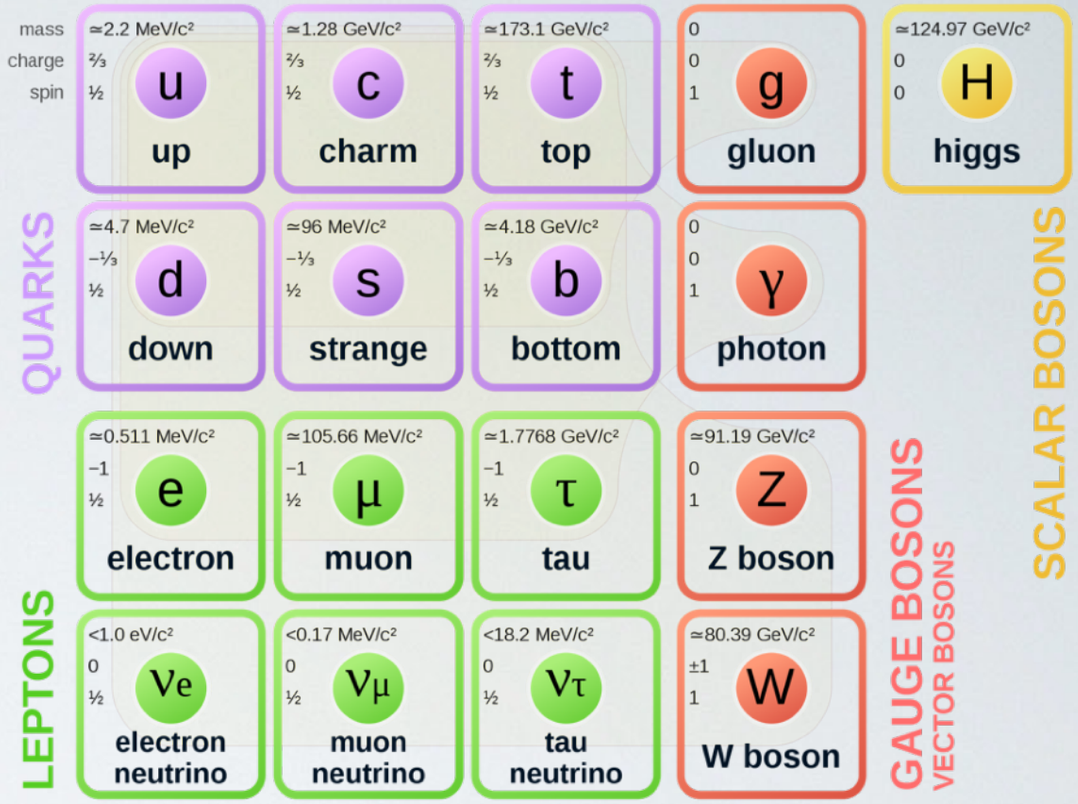
# Conditions for (any kind of) life in the Universe

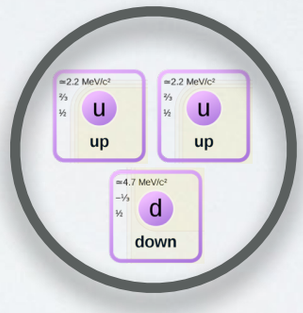
- Matter that can create numerous, stable connections
  - i.e., atoms and chemistry
- Fundamental forces that facilitate the necessary processes
- Energy (from stars)
- Planets or other dense, solid structures
  - Gas is transient in its structure; life cannot emerge in stars or gas planets
  - Compact objects (white dwarfs, neutron stars) allow no chemistry
- Time
  - Human life took 3 billion years to develop; a Universe that recollapses after a short time probably won't do
  - Stable environment for prolonged period of time

# Part 2: Fine-tuning the Universe

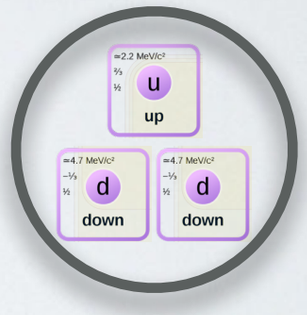
# Fundamental particles

- At least 18 free parameters in the standard model that could be different
- Some of these parameters are the particle masses, e.g., $m_{\mathrm{up}} = 4.5 m_{\mathrm{e}}$ and $m_{\mathrm{down}} = 9.4 m_{\mathrm{e}}$
- Proton is stable because lightest baryon (three-quark particle)
- Make **down-quark 70+ times heavier**:
  - decays into up-quarks
  - only $\Delta^{++}$ baryons
  - only one element ($\Delta^{++}$ + 2 electrons, like $\Delta^{++}$ -Helium), with no chemical reactions
- Make **up-quark 130+ times heavier:**
  - decays into down-quarks
  - only $\Delta^{-}$ baryons
  - one atom ($\Delta^{-}$-hydrogen) and one molecule ($\Delta^{-}$-$\Delta^{-}$ molecular hydrogen)

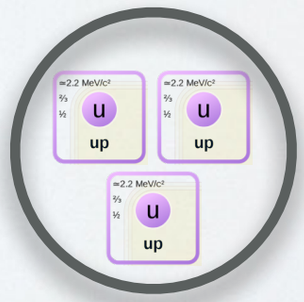


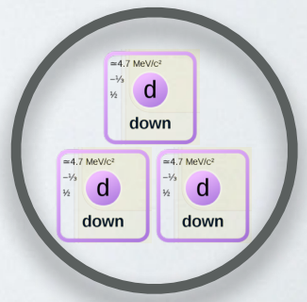

proton




neutron




$\Delta^{++}$

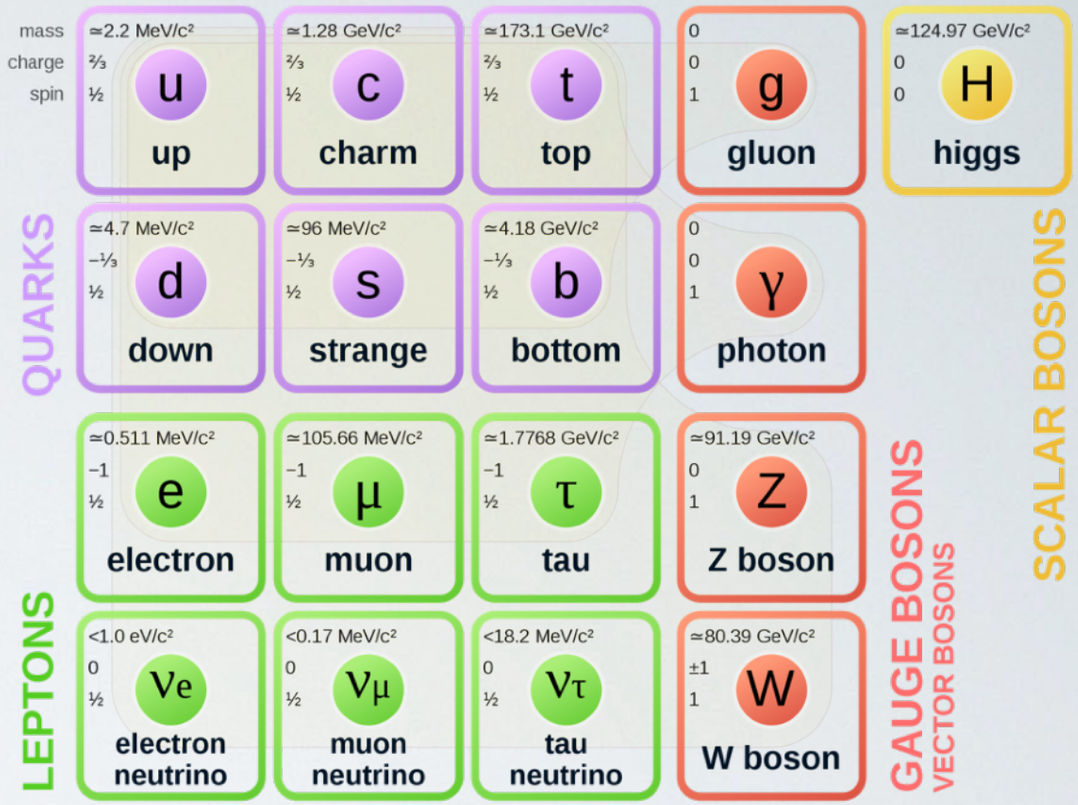


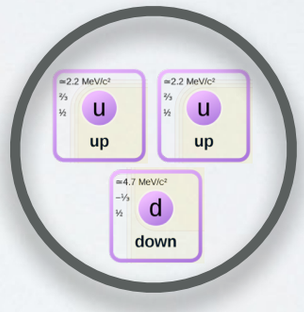

$\Delta^{-}$

Lewin & Barnes, A fortunate Universe

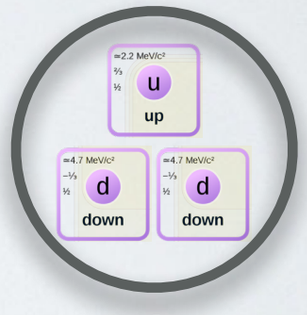
# Fundamental particles

- What about less dramatic changes?
- Make **down-quark heavier by a factor of 3**:
  - all neutrons decay into protons, even in nuclei
  - only hydrogen atoms
- Make **up-quark heavier by factor of 6:**
  - protons decay into neutrons
  - no atoms at all, only neutrons
- Make **electron heavier by factor of 2.5:**
  - again, only neutrons
- And so on…



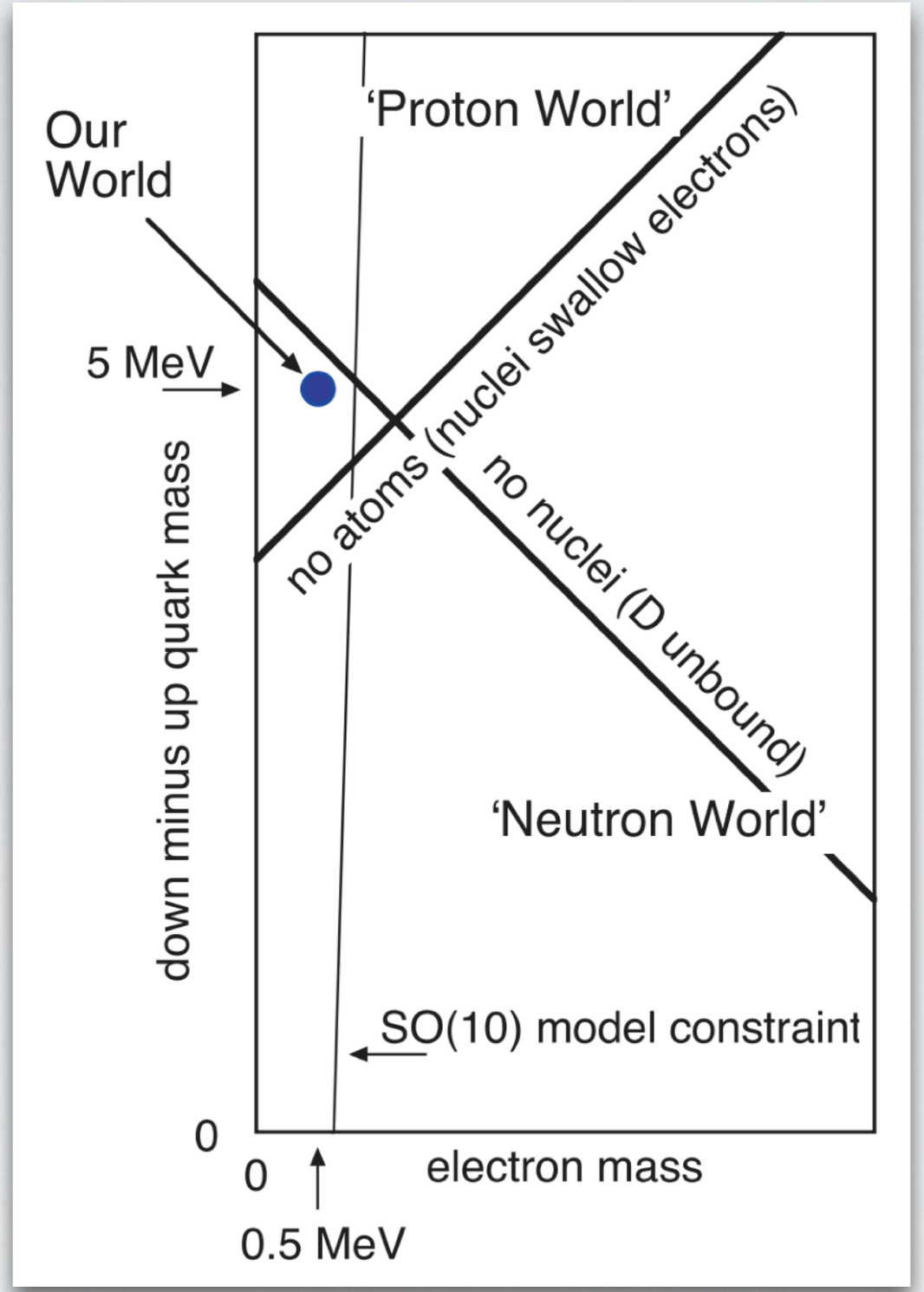

proton




neutron

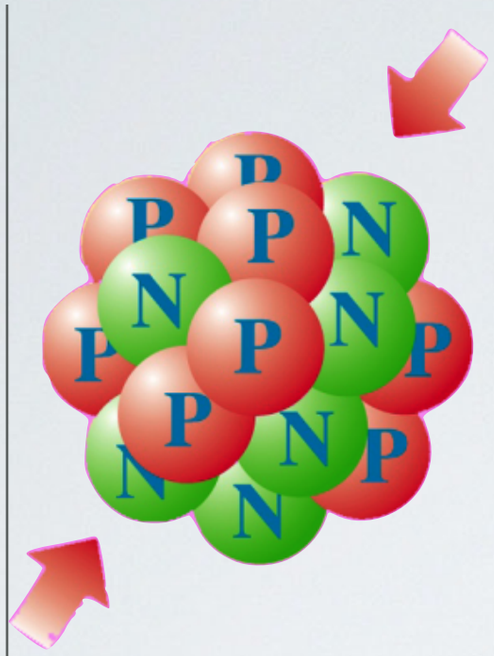
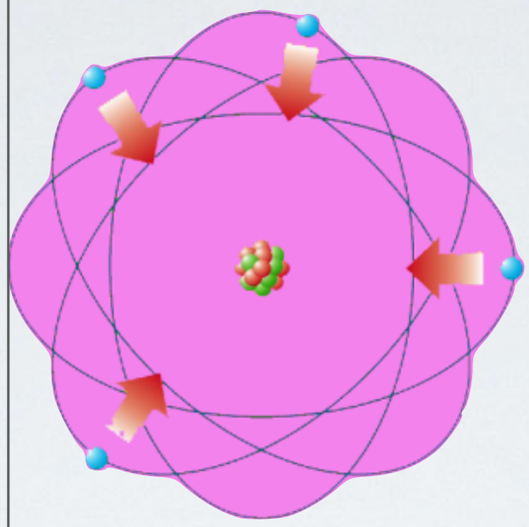
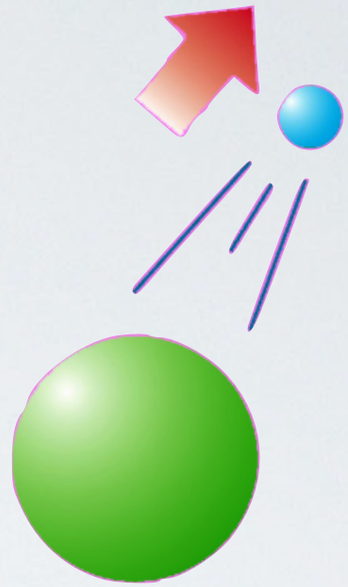
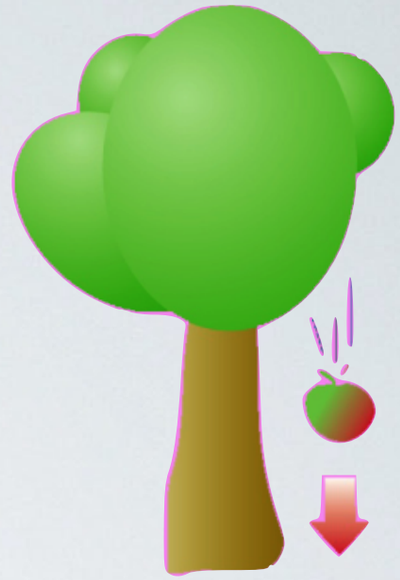
Lewin & Barnes, A fortunate Universe

# Fundamental particles



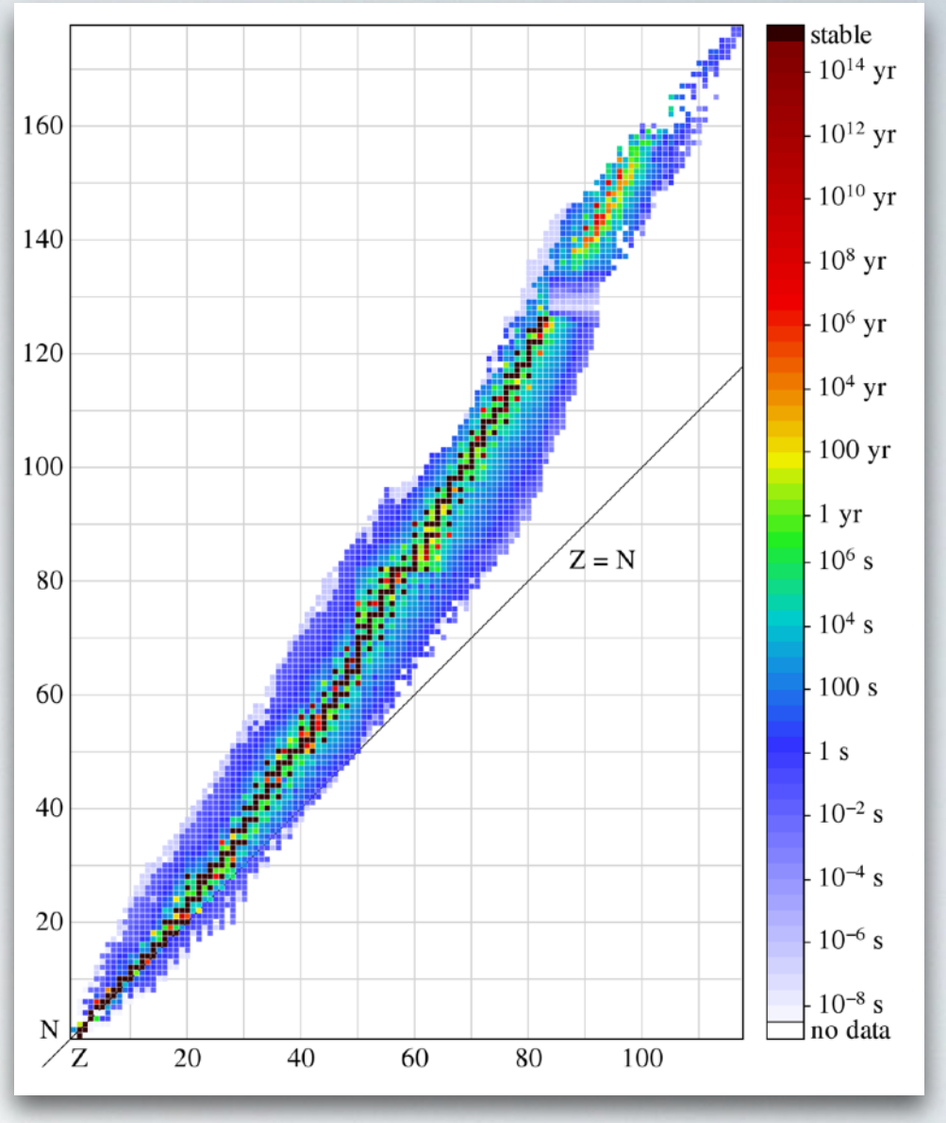

Barnes 2012

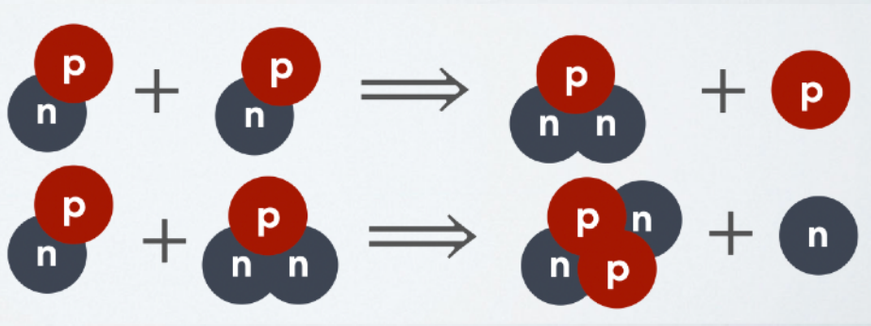
# Fundamental forces

| Force | Strong Interaction | Electro-magnetism | Weak Interaction | Gravitation |
|---|---|---|---|---|
| |  |  |  |  |
| **Strength** | $1$ | $\approx 10^{-2}$ | $\approx 10^{-6}$ | $\approx 10^{-38}$ |
| **Mediator particle** | gluon | photon | W/Z bosons | graviton? |
| **Examples** | • Binds quarks into protons, neutrons etc<br>• Holds nuclei together | • Electric and magnetic fields<br>• Light | • Neutron decay | • Gravity<br>• Graviton has not yet been detected |

# Fundamental forces

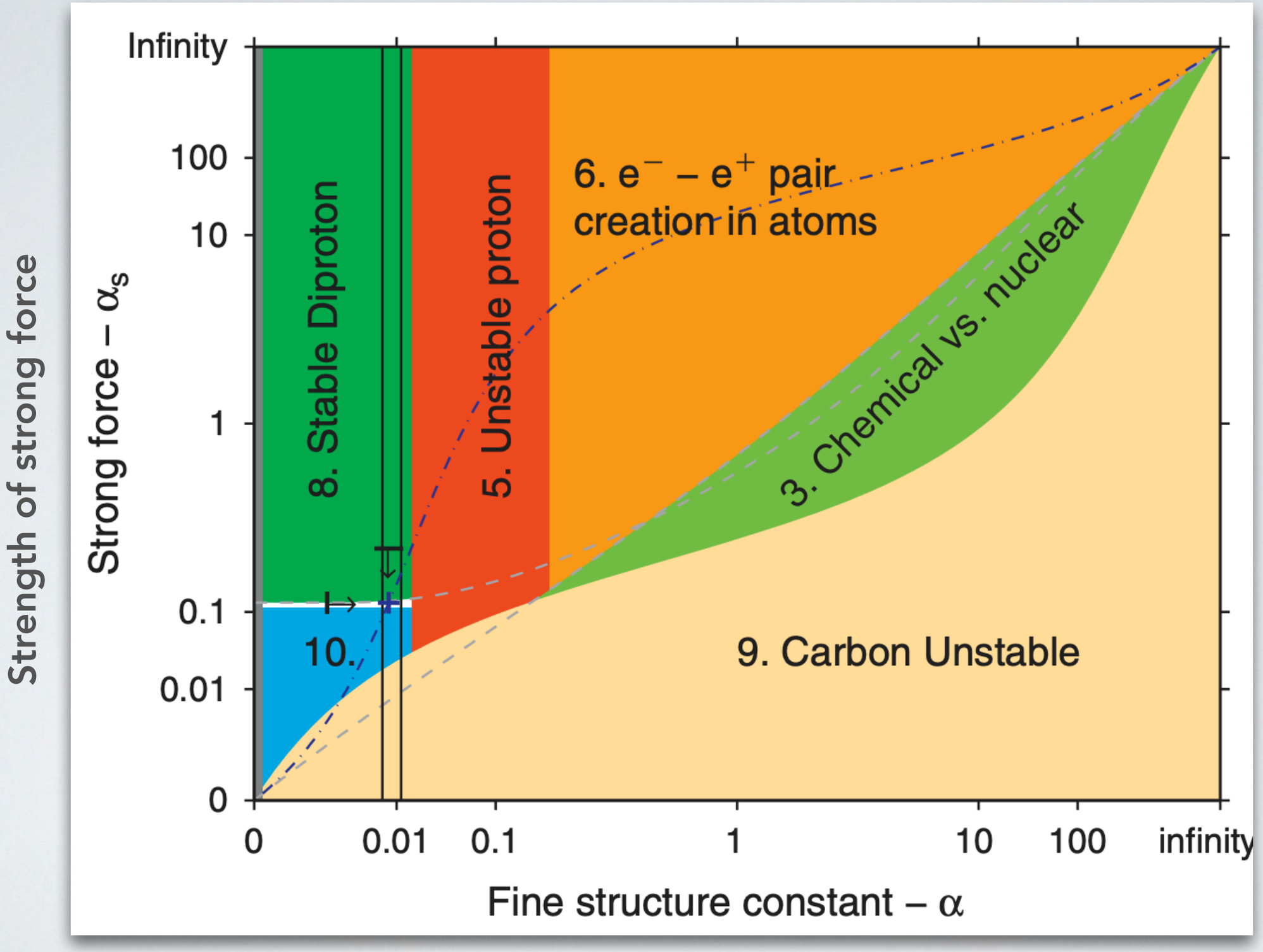
- Strength given by "coupling constants"
- E&M is responsible for **chemical** reactions, strong & weak forces for **nuclear** reactions
- Strong force is about 20,000 times stronger than electromagnetic
- Thus, chemical reactions consume / produce way less energy than nuclear reactions
  - e.g., a fire can chemically burn C to $CO_2$ but not convert one element into another
- Imagine making **E&M much stronger:**
  - Elements would change all the time!
  - Overbaking your cake could turn carbon into iron…
  - This universe could still allow life, but it seems chaotic
- Make **strong force twice stronger:**
  - Helium forms at higher temperature (earlier) in the Universe
  - More neutrons (because they have not decayed yet)
  - 90% of hydrogen "burns" to Helium! Less fuel for stars




Lewin & Barnes, A fortunate Universe

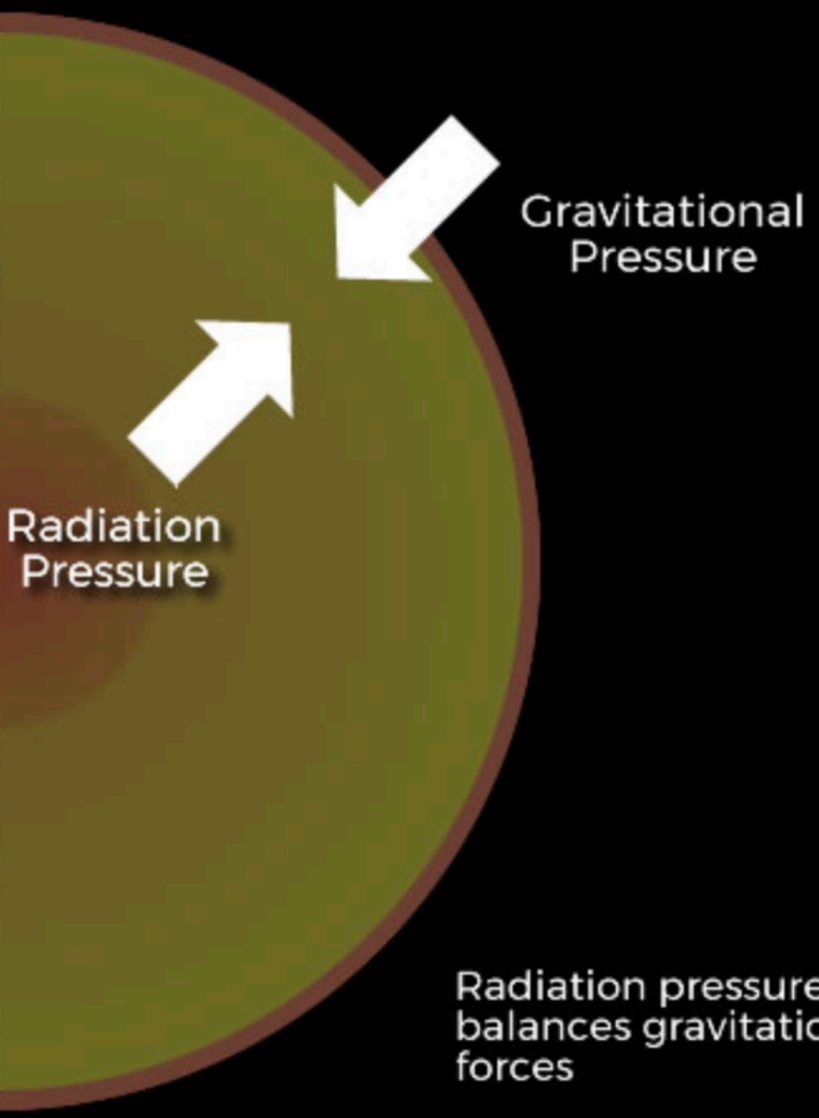
# Fundamental forces




Strength of electromagnetism

Barnes 2012

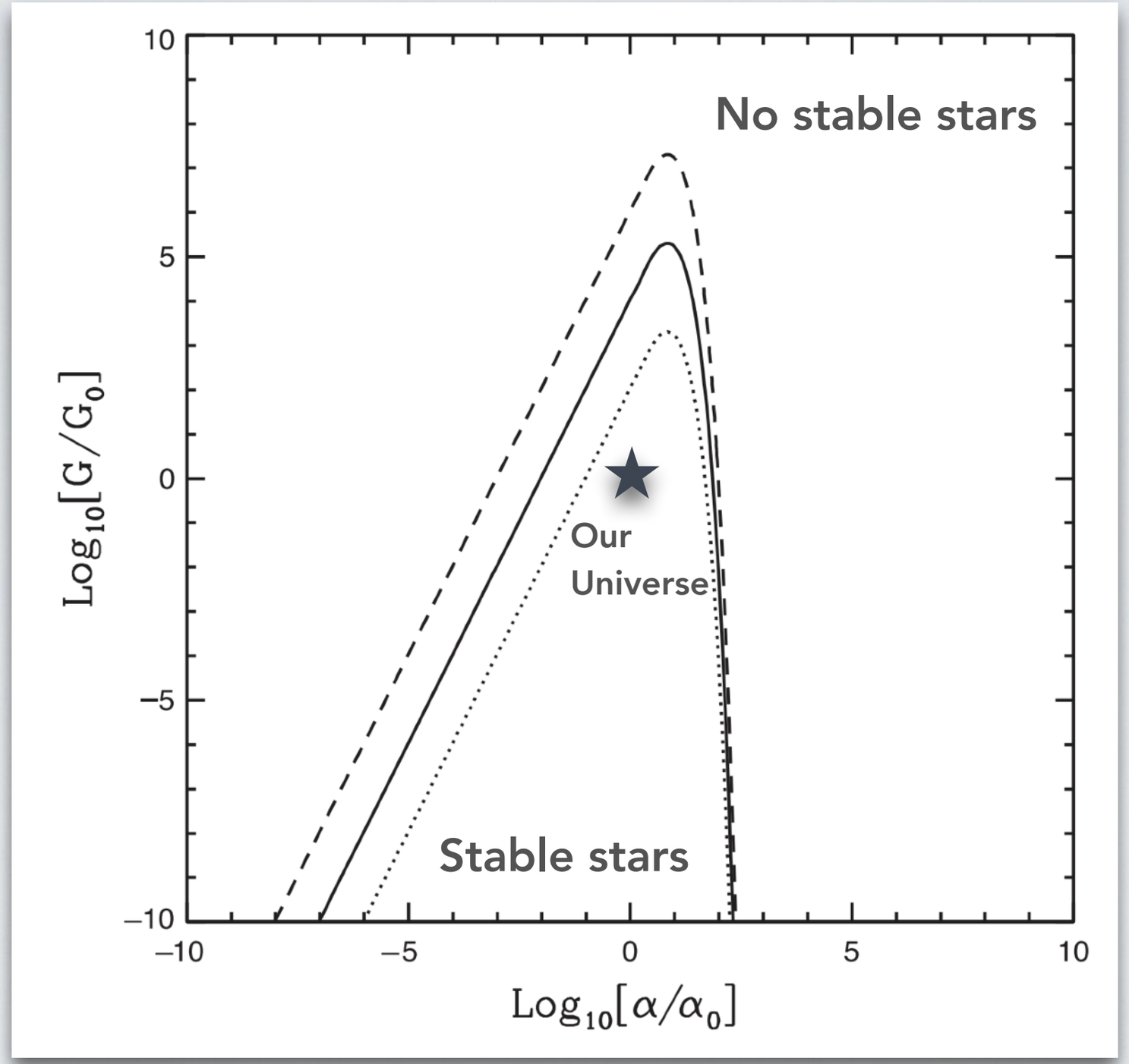
# Making Stars




Radiation pressure balances gravitational forces

- Balance between **gravity** and pressure from **nuclear** burning
- Gravity is about $10^{40}$ times weaker than strong force
- Make gravity weaker
  - Uniform “soup” universe:
    no structure, no stars, no life
- Make gravity much stronger (say only $10^{30}$ times weaker than strong force)
  - Stars have to burn faster and hotter to resist gravitational collapse (like large, blue stars)
  - They use their fuel quickly and die off soon

# Making Stars




Barnes 2012

# Interlude: Murkiest points

# Participation: Discussion #26

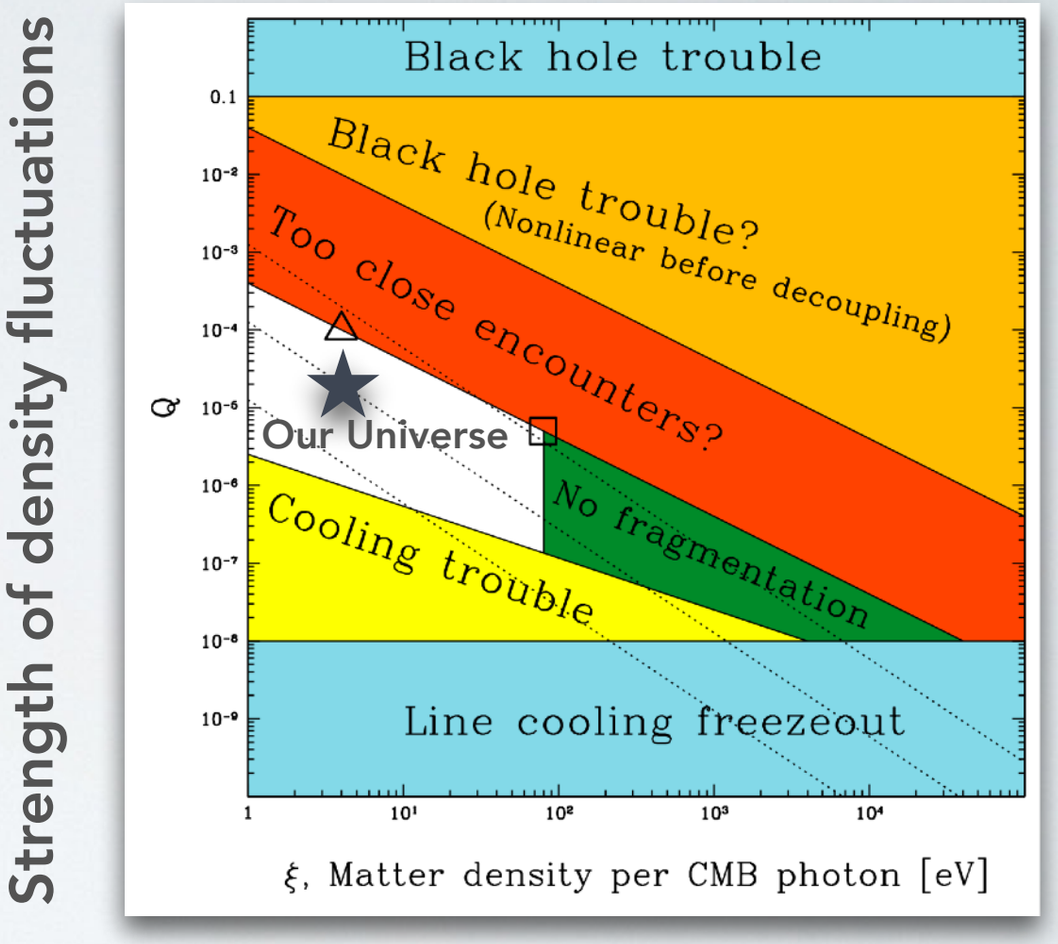
**Murkiest point**

Are there any questions that you feel confused about, and that you would like me to discuss during the review lecture?

 8 minutes

# Cosmology

- The **strength of CMB fluctuations** (about $10^{-5}$) is not fundamentally predicted by inflation or early Universe theory
- If fluctuations are **too strong** (greater than $10^{-4}$ or so), halos collapse into massive **black holes!**
- If fluctuations are **too weak** (smaller than $10^{-6}$ or so), we cannot form dense galaxies that make stars

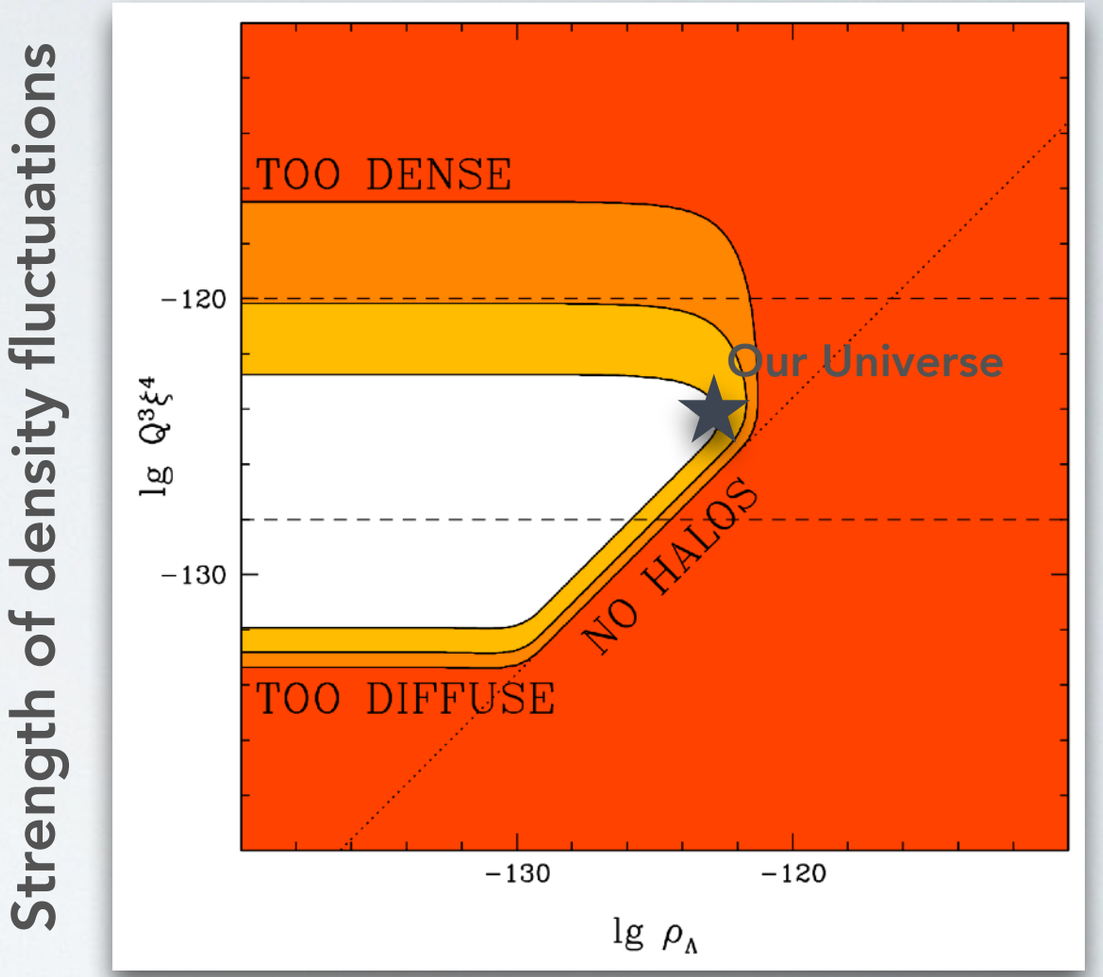



**Matter-photon ratio**

Tegmark et al. 2006 • Lewis & Barnes

# Cosmological Constant

- We have no fundamental prediction for the strength of the cosmological constant, $\Omega_\Lambda$
  - If assuming that it is vacuum energy, can predict it from sum of vacuum energies of all particle fields (electron, quarks, neutrinos…)
  - That is **$10^{120}$ too large!**
- Making **cosmological constant larger** -> universe expands exponentially -> no structure -> no life
- No cosmological constant ($\Omega_\Lambda = 0$) would be OK

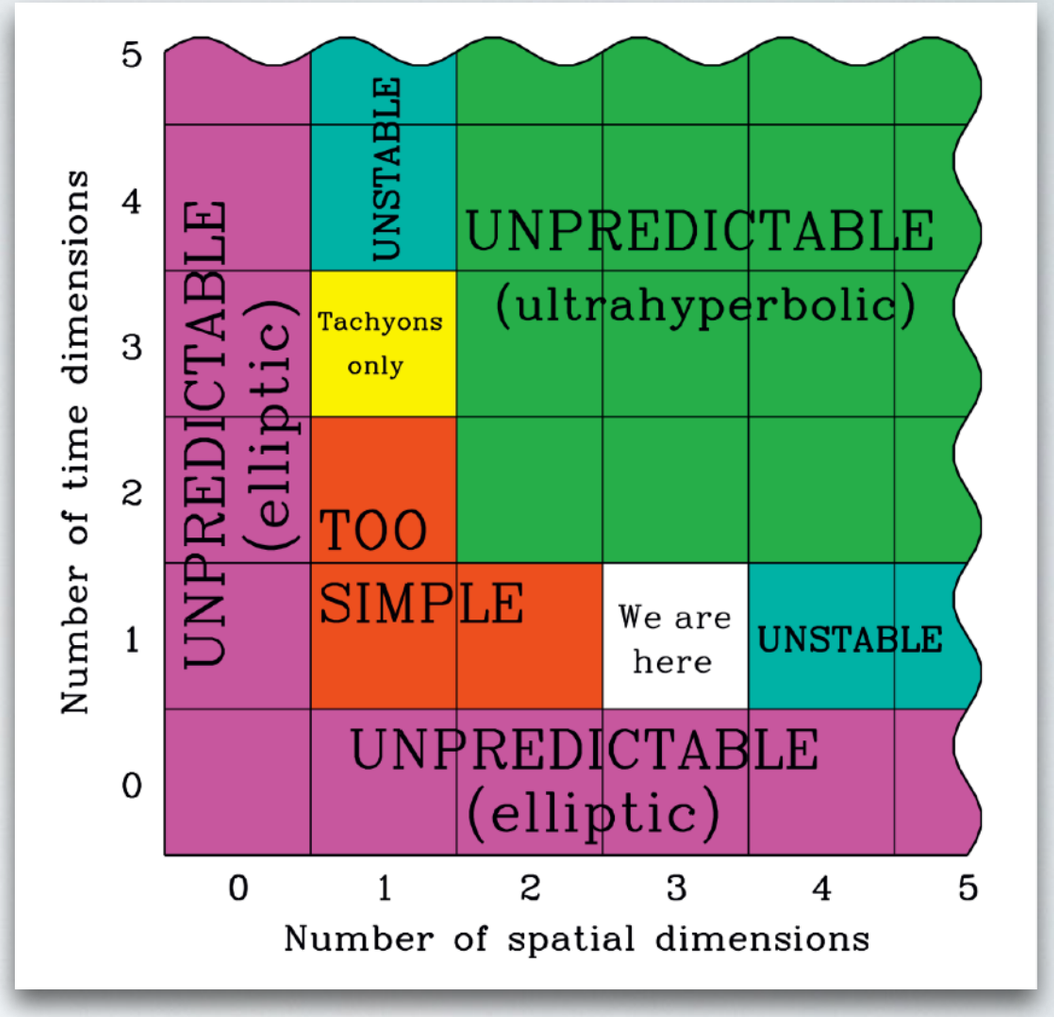



Cosmological Constant

Tegmark et al. 2006 • Lewis & Barnes

# Dimensionality of the Universe

- Our Universe has 3+1 space and time dimensions
- What happens if we had **extra dimensions?**
- **2 space dimensions**
  - No gravitational fields in empty space
- **4 space dimensions**
  - Gravity and electrostatic force scale as $1/r^3$ instead of $1/r^2$
    - **No stable orbits!** Earth would fall into Sun
    - Electrons would fall into nuclei -> **no atoms!**
- **2 time dimensions**
  - Physics follows laws, but they would be very hard to predict because we'd need to know the state of a system over a large range of the "other" time dimension!
- Compactified dimensions from String Theory could be a way out of this conundrum




Tegmark 1997 • Lewin & Barnes, A fortunate Universe

# Part 3: Possible solutions to fine-tuning

# Solution 1: Coincidence

- Unlikely outcomes sometimes happen — so what?
- Basically equivalent to saying “I don’t care about fine-tuning”
- Not really a solution
- Depends on your attitude

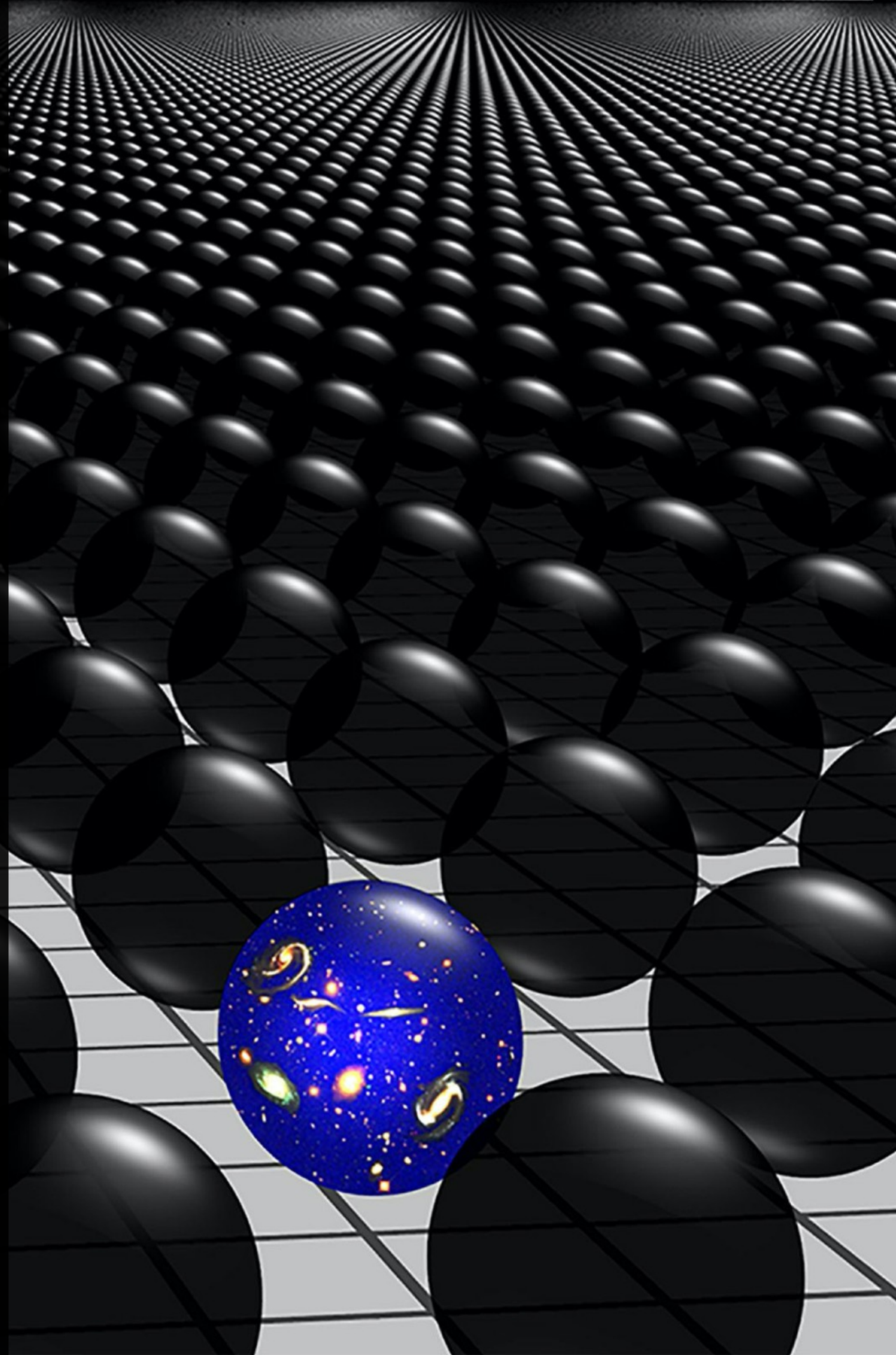
# Solution 2: Divine creation

- Fine-tuning can be used as an argument against physics and for **creationism**
- Two quite different flavors
  - An **omnipotent entity** is managing everything (which arguably makes the explanation more complex than the question)
  - An entity **designed** the laws of the Universe so that they allowed for life
- Variant of creationism: we live in a **computer simulation** like The Matrix
  - Could look for glitches or rounding errors

Lewis & Barnes • The Good Place

# Solution 3: Multiverses

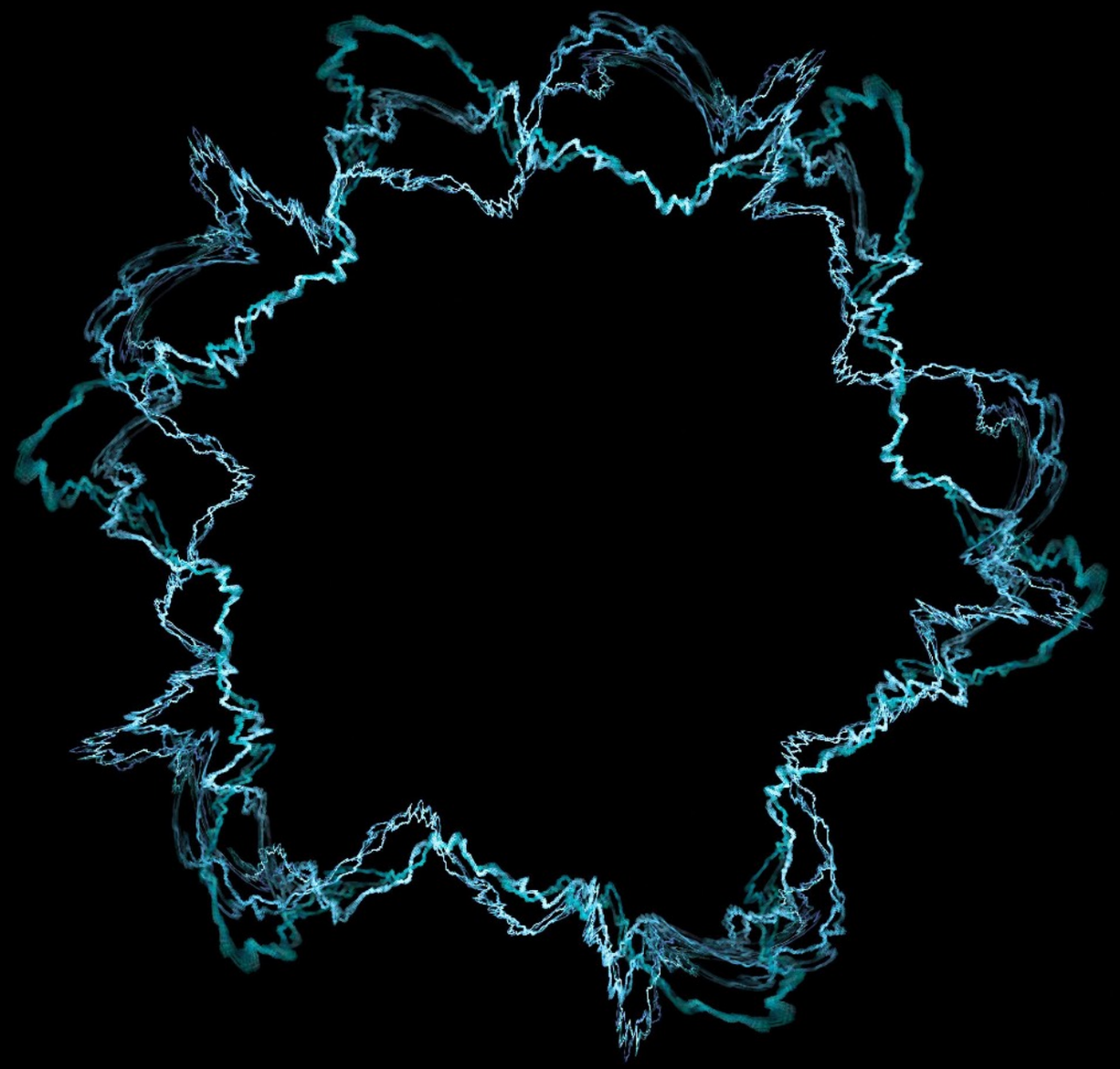
- A super-universe spawns a large (infinite?) number of **sub-universes with different physics and/or constants**
  - For example, due to inflation happening in different patches of the super-universe
  - **Fine-tuning is explained by the anthropic principle**: we can only observe our Universe because it provided for our existence
- Problem #1: we probably can never see the other sub-universes, making it hard to understand the underlying physical laws
- Problem #2: we do not know how to quantify how likely a given Universe is, and how to compare that probability to all others (“measure problem”)



Lewis & Barnes

# Solution 4: Find more fundamental theory

- Fine **theory of everything** (TOE) which would ideally have **no fine-tuned parameters**
- This is the big goal!
- We cannot say with certainty that it is possible to find such a theory, but we certainly shouldn't give up yet!
- The progress of fundamental physics theories will likely rely on **astrophysics** to deliver some of the key data



# Take-aways

- Our existence means that our Universe must provide the conditions for life to form (the **anthropic principle**)

- The laws of physics appear to be **fine-tuned** in many ways to produce an interesting, life-supporting Universe

- Possible **solutions** to this conundrum include creationism, multiverses, and that we have not yet discovered the true, underlying theory of physics

# Next time…

**We'll talk about:**

- Review of the course

**Assignments**

- Homework #6 (by 12/9)