The Particle World

CERN Summer School Lectures 2021

Lecture 3: What We Don't Know

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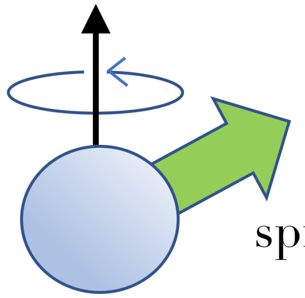
What We Don't Know

- Things that the Standard Model gets wrong
- Questions that the Standard Model raises
- Things that the Standard Model doesn't explain

Does the Standard Model Get Anything Wrong?

Muon g-2



For the electron:

$$g_{\text{expt}} = 2.0023193043617 \pm 3$$

$$g_{\text{theory}} = 2.00231930436\ldots$$

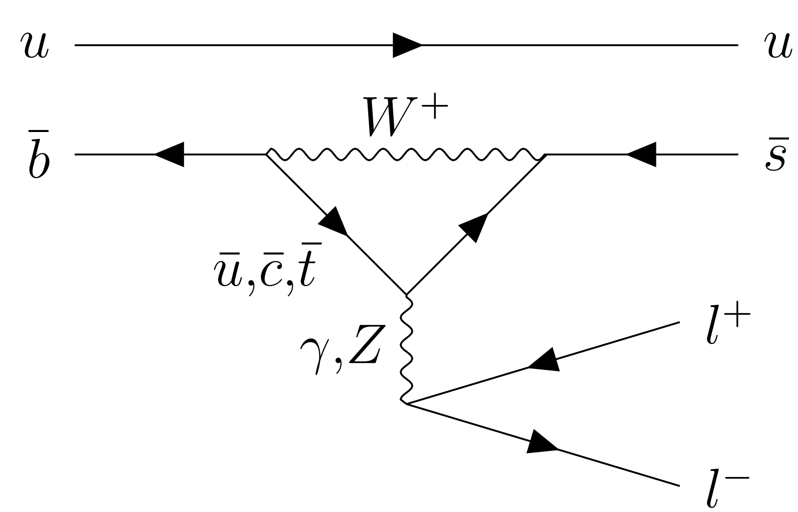
For the muon:

$$g_{\text{expt}} = 2.00233184122$$

$$g_{\text{theory}} = 2.00233183602$$

But...

B-anomalies and Lepton Universality

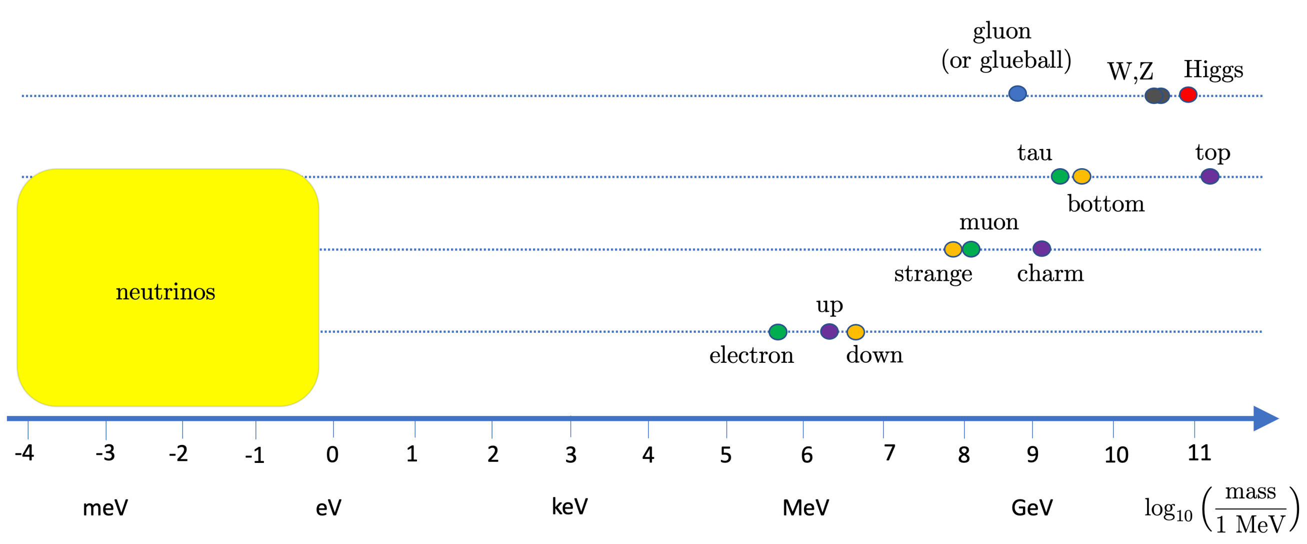


$l = e$ vs $l = \mu$

Questions Raised by the Standard Model

Why do parameters take certain values?

- 3 force strengths
- 2 parameters in the Higgs potential
- Loads of parameters in flavour physics



$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.97 & 0.22 & 0.004 \\ 0.22 & 0.97 & 0.04 \\ 0.009 & 0.04 & 0.999 \end{pmatrix}$$

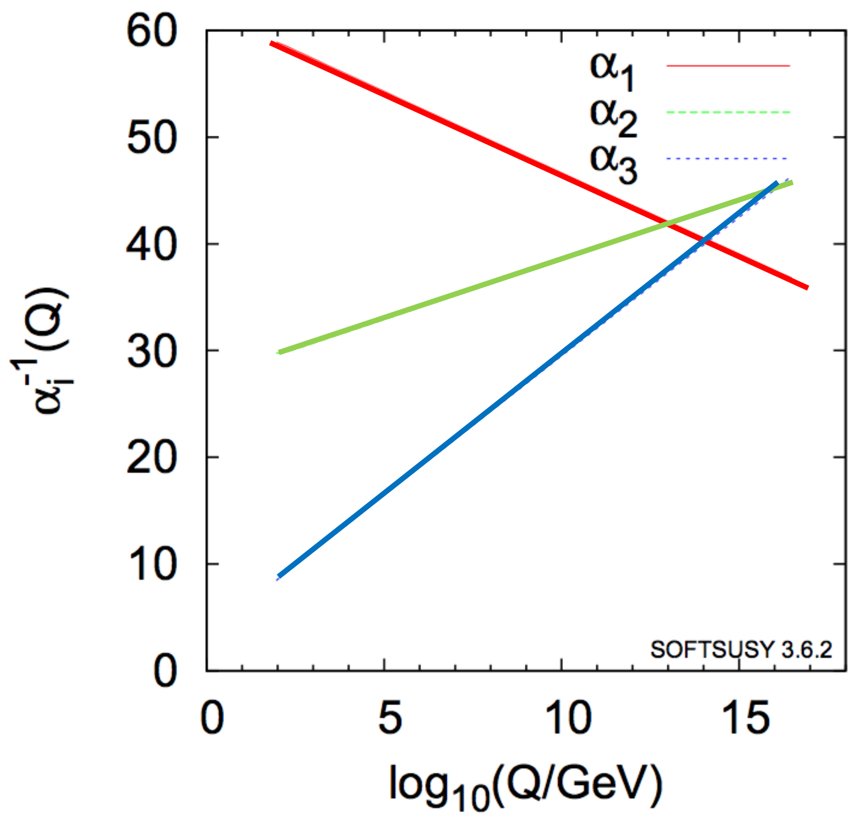
$$\begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} \approx \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.3 & 0.5 & 0.7 \\ 0.4 & 0.6 & 0.6 \end{pmatrix}$$

Strengths of Forces

At an energy of 100 GeV, we have

$$\alpha_{\text{QED}} \approx \frac{1}{127} \qquad \alpha_{\text{strong}} \approx \frac{1}{10} \qquad \alpha_{\text{weak}} \approx \frac{1}{30}$$

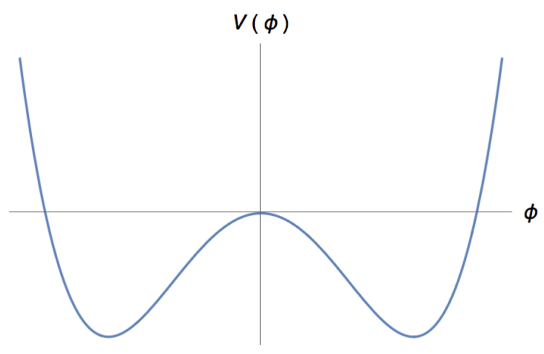
But each of these is a function of scale



Unification or coincidence?

The Higgs Potential

$$V(\phi) = a|\phi|^2 + b|\phi|^4$$



<u>Naively</u>

$$m_H^2 = |a| \qquad \text{and} \qquad \langle\phi\rangle^2 = \frac{a}{2b}$$

This then sets the scale for the masses of all other particles

$$m_H \approx 125 \text{ GeV} \quad \text{and} \quad \langle\phi\rangle \approx 246 \text{ GeV} \quad \Longrightarrow \quad a \approx -(125)^2 \text{ GeV}^2 \quad \text{and} \quad b \approx 0.13$$

Remarkably, the coefficient a is the only dimensionful parameter in the Standard Model!

The Hierarchy Problem

The equation $m_H^2 = |a|$ is sadly too naive. There are quantum corrections that give

$$m_H^2 \approx \left| a + \mathcal{O}(\Lambda_{\mathrm{UV}}^2) \right|$$

This should be thought of as the biggest scale in the game...maybe the Planck scale?

Why should the coefficient a be so finely tuned to the higher energy scale? This is the problem of naturalness.

Things Still to Explain

- (Gravity)
- Dark Matter
- Dark Energy
- Early Universe

Gravity

Standard Model + General Relativity = Job Done. (Almost)

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

In contrast to the other forces, gravity has a dimensionful coupling constant

$$G = \frac{\hbar c}{8\pi M_{\rm pl}^2} \qquad \text{with} \qquad M_{\rm pl} \approx 10^{18}\ \text{GeV}$$

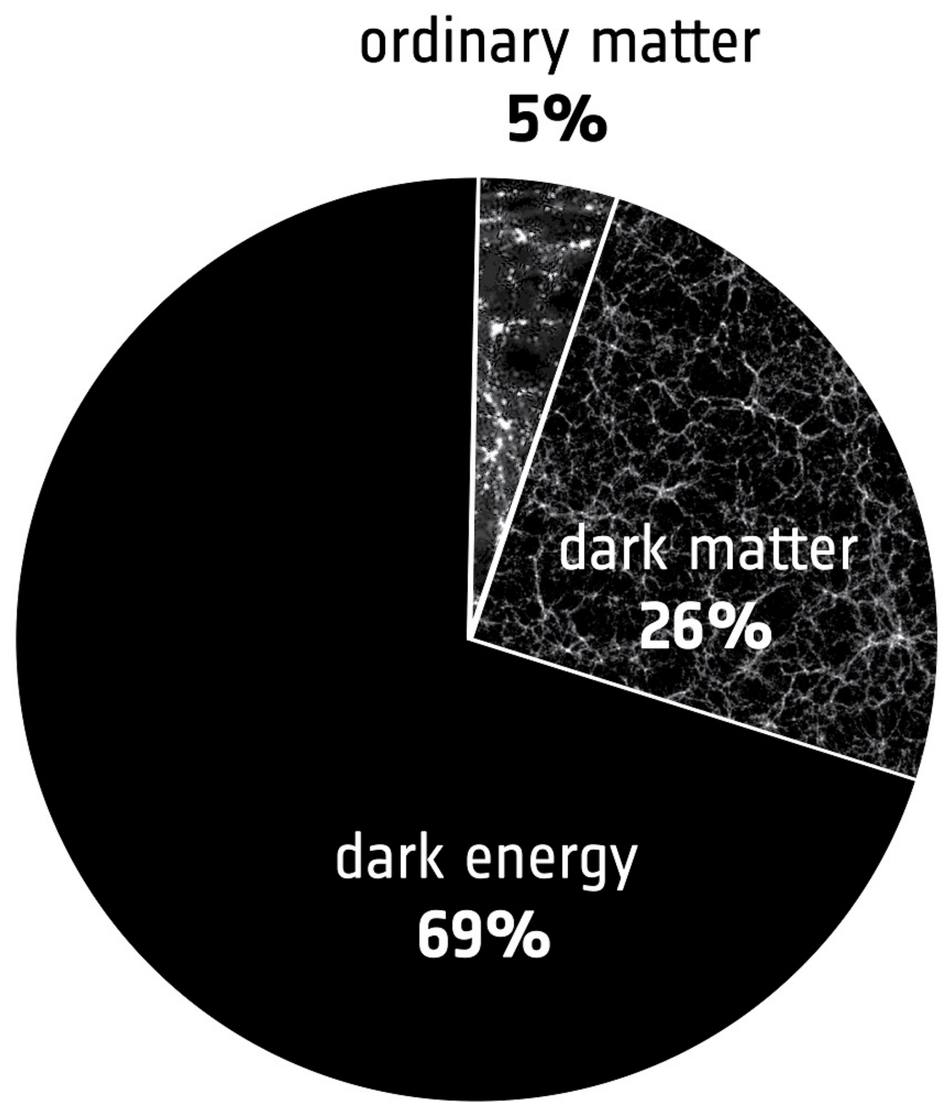
This means that

$$\text{Strength of Gravity} \sim \left(\frac{E}{M_{\rm pl}}\right)^2 \sim GE^2$$

This is perfectly fine for any experiments that we can currently perform. But...

- Black holes
- Big Bang

The Dark Universe



The Cosmological Constant

The energy density of the vacuum – or cosmological constant – acts as dark energy

Observed: $\rho_\Lambda \approx (10^{-3}\ \text{eV})^4$

Value of Standard Model: $\rho_{\text{SM}} = (10^{12}\ \text{eV})^4$

A solution (of sorts!):

$$\boxed{\rho_\Lambda = \rho_{\text{SM}} + \text{something else}}$$

This is the second, much more acute, hierarchy problem in physics.

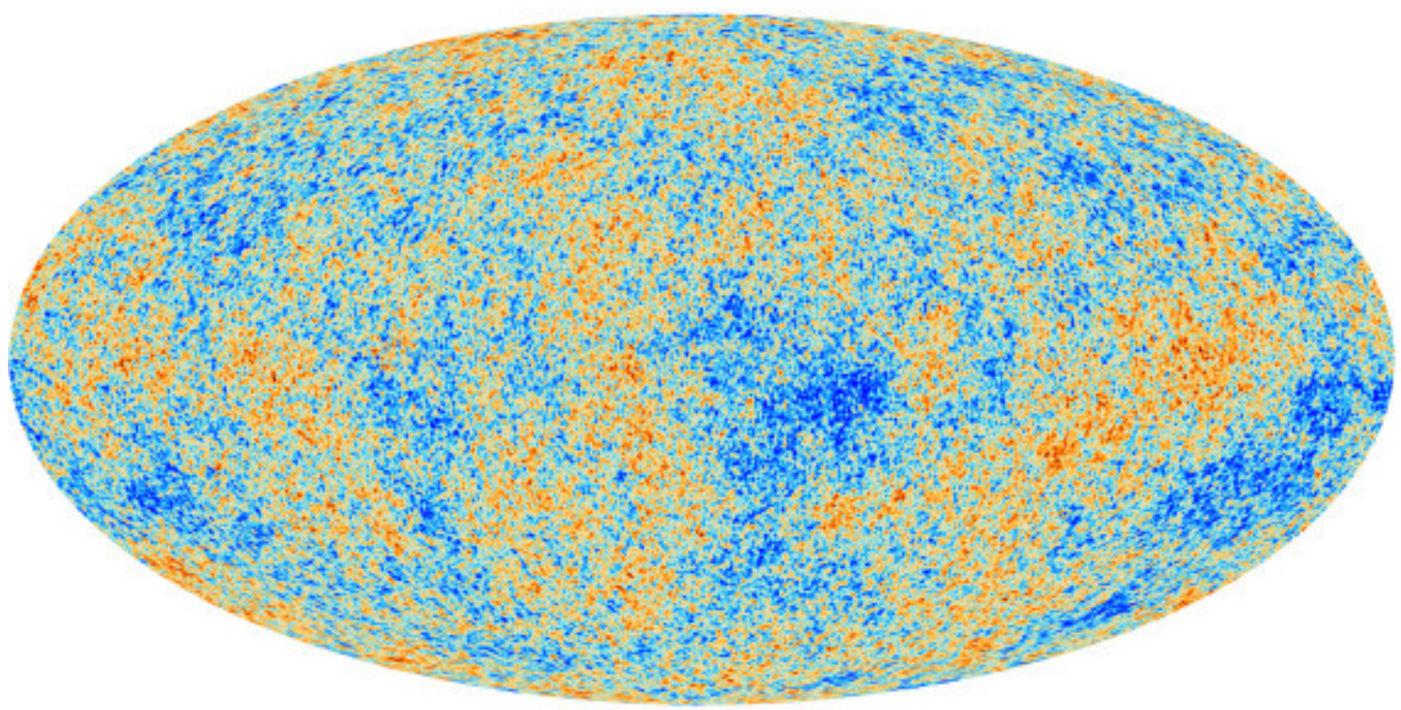
Dark Matter

Whenever we weigh galaxies, or galaxy clusters, they always have more matter than we can see.

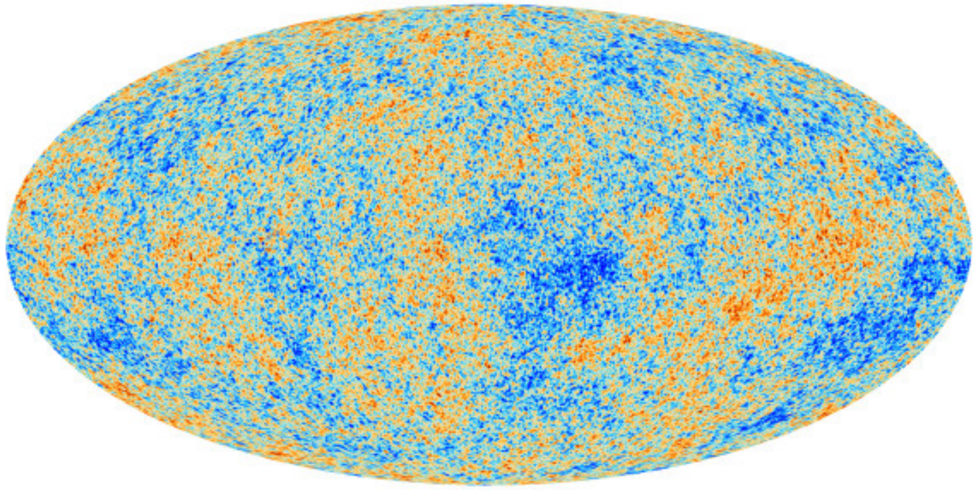
Further evidence comes from early universe cosmology.

Big question: does it interact with Standard Model other than through gravity?

The CMB



Structure Formation



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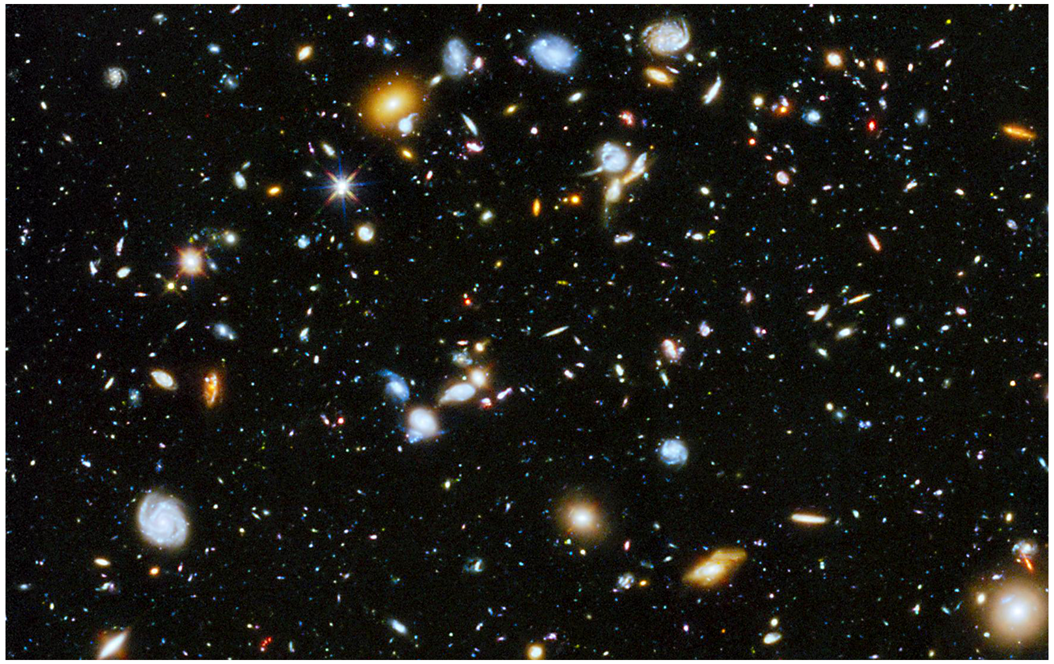
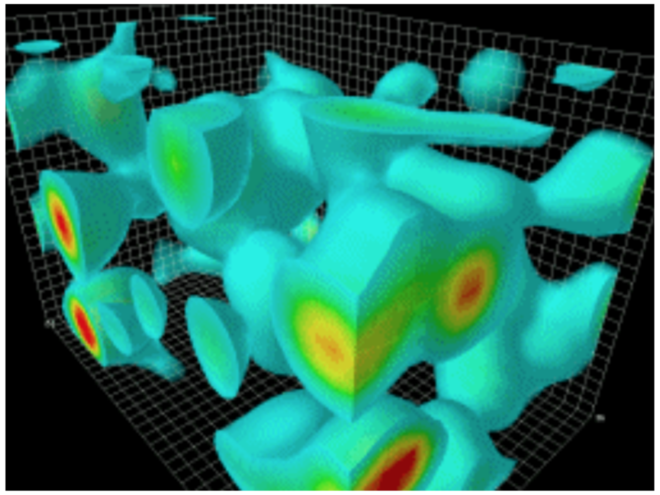


Inflation



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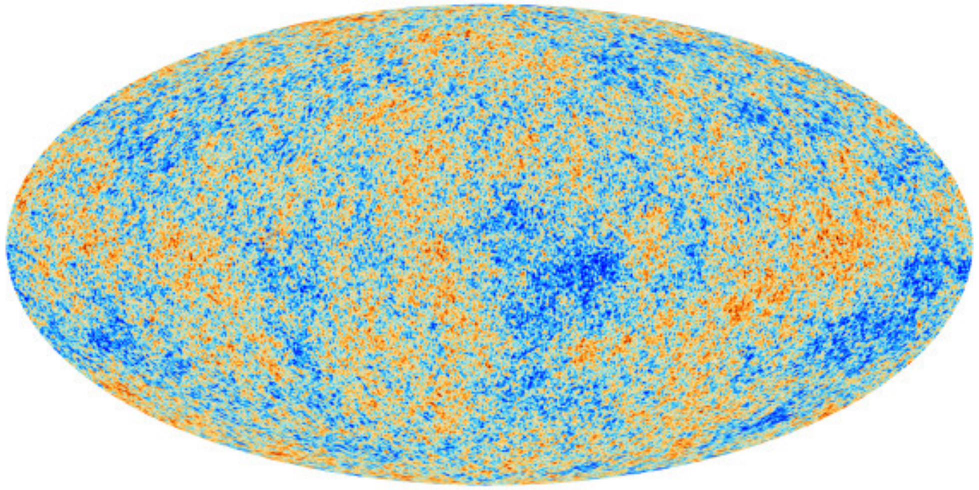

Big Question: What quantum field are we looking at? And how can we see it now?

Summary

Still lots of work to be done!