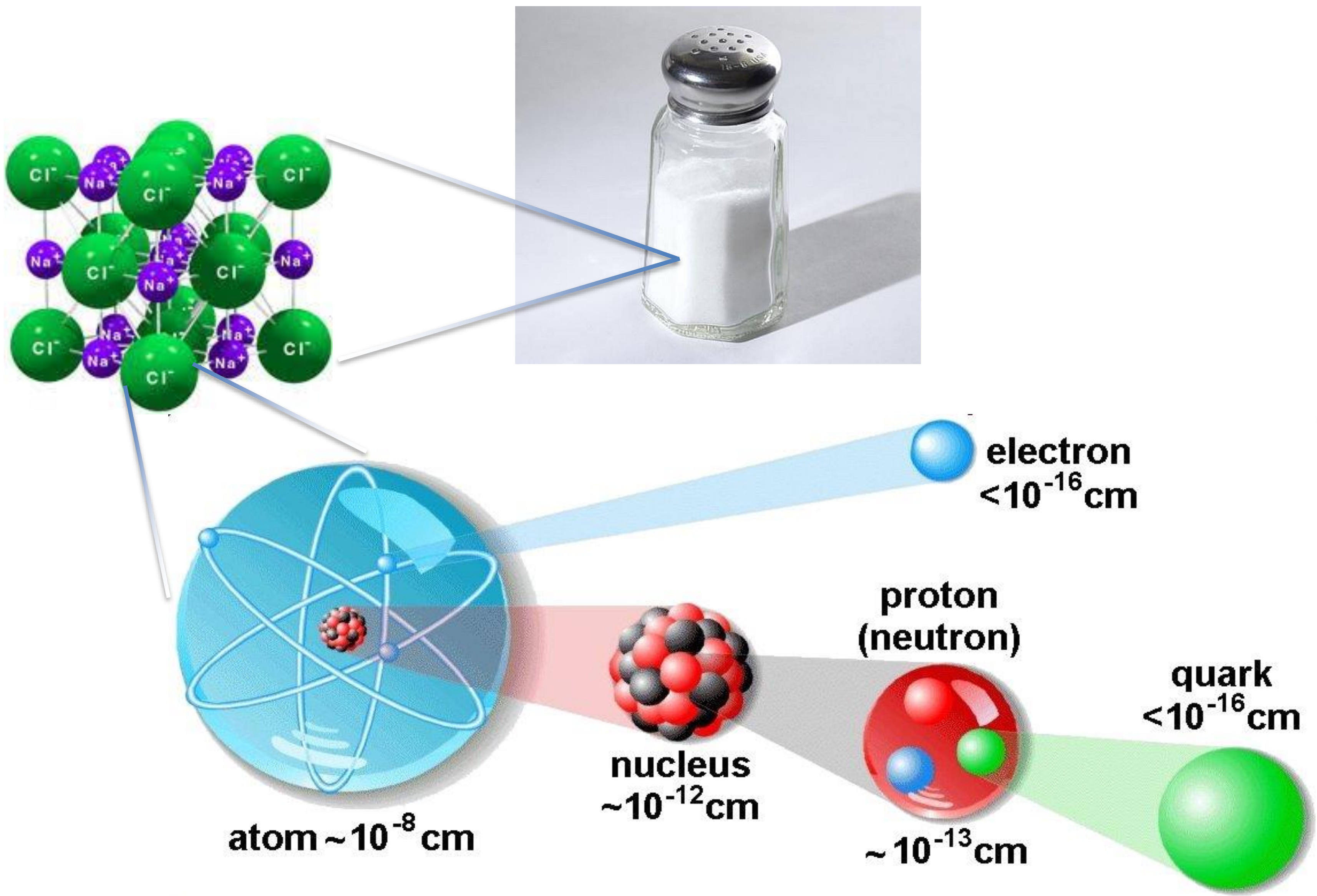
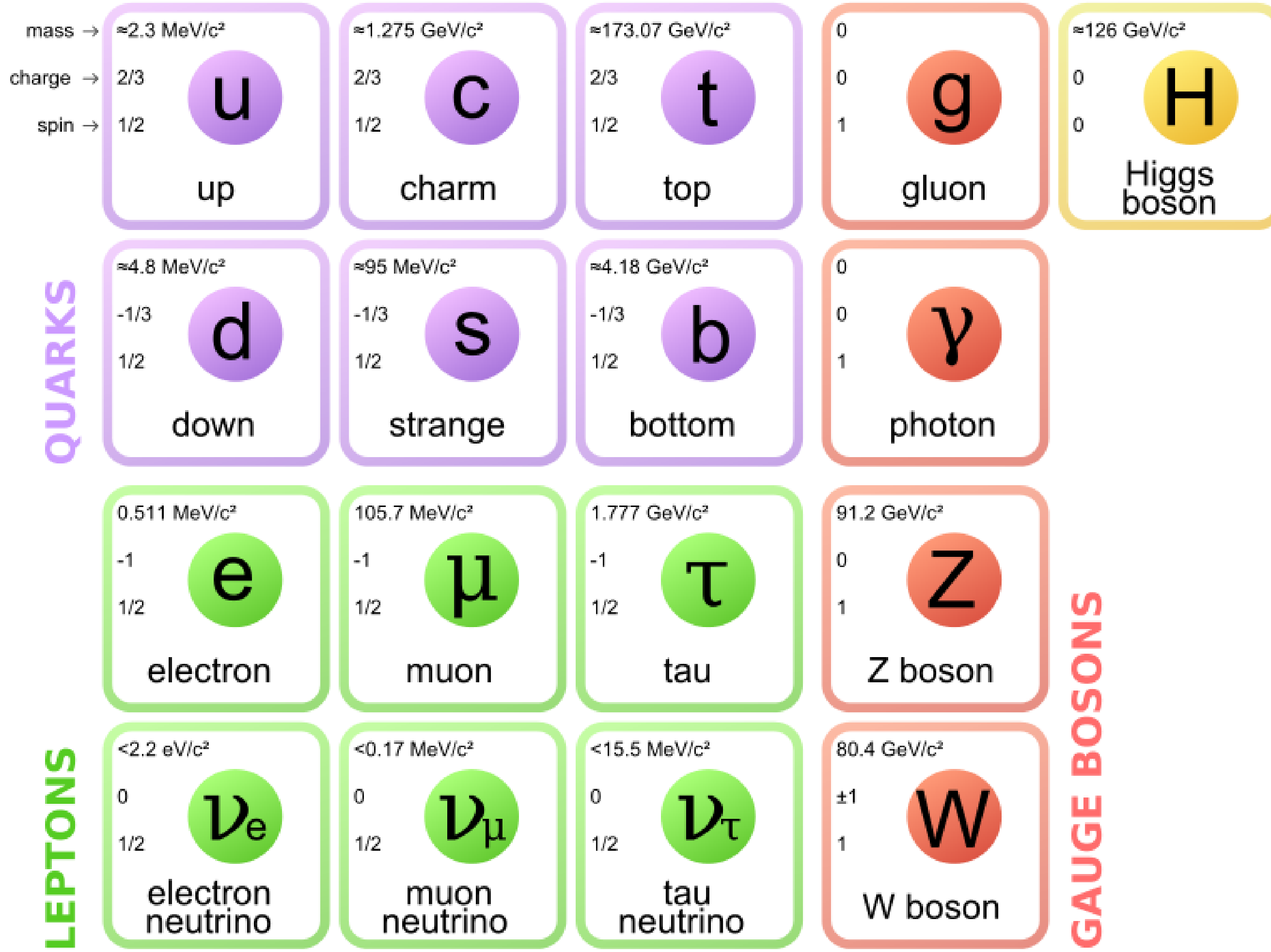
INTRODUCTION TO PARTICLE PHYSICS

Joe Haley

QuarkNet 2025


electron
<10^{-16}cm
proton
(neutron)
quark
<10^{-16}cm
nucleus
~10^{-12}cm
atom ~ 10^{-8} cm
~ 10^{-13}cm

The Fundamental Particles



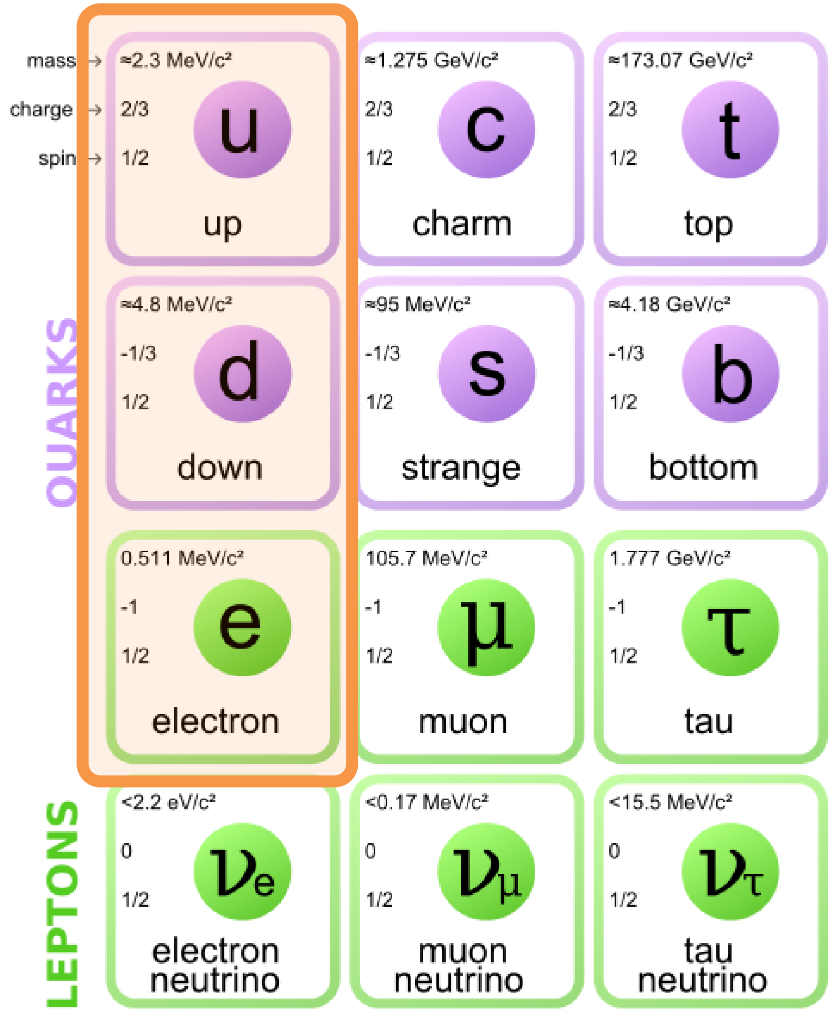
This is all of them! (As far as we know…)

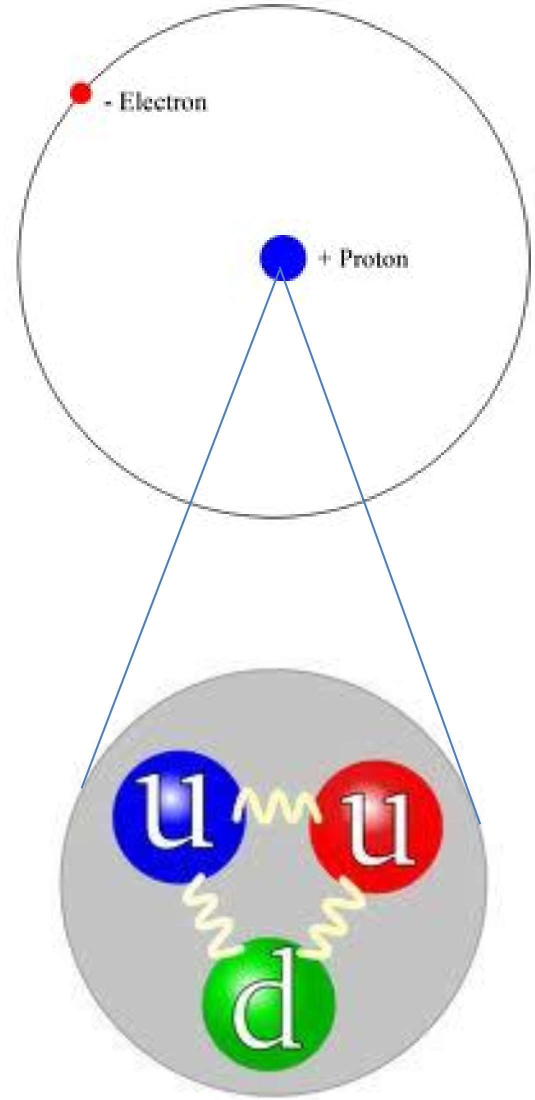
The Birth of the Standard Model

Matter

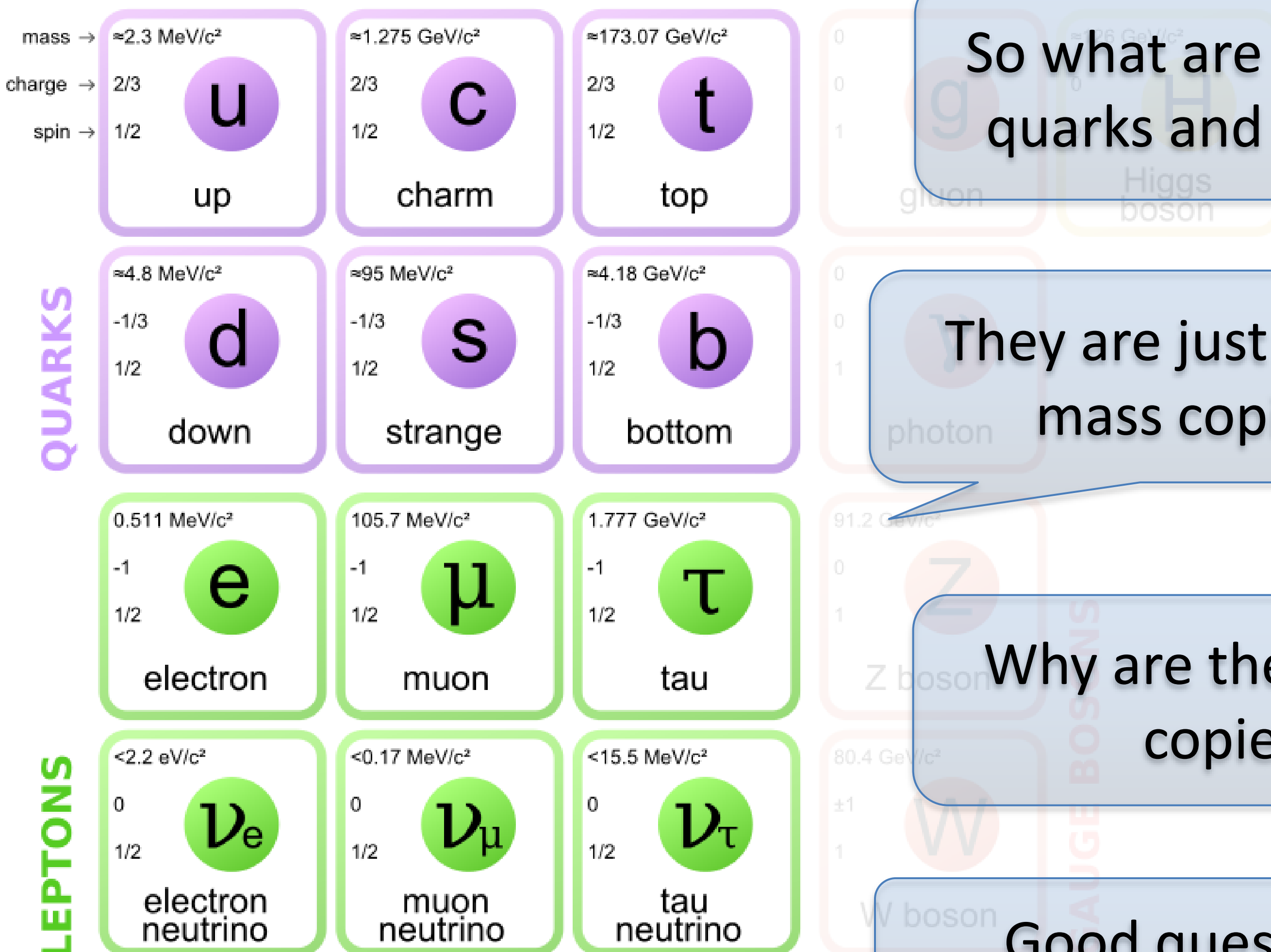
Matter Particles

Ordinary matter





Matter Particles



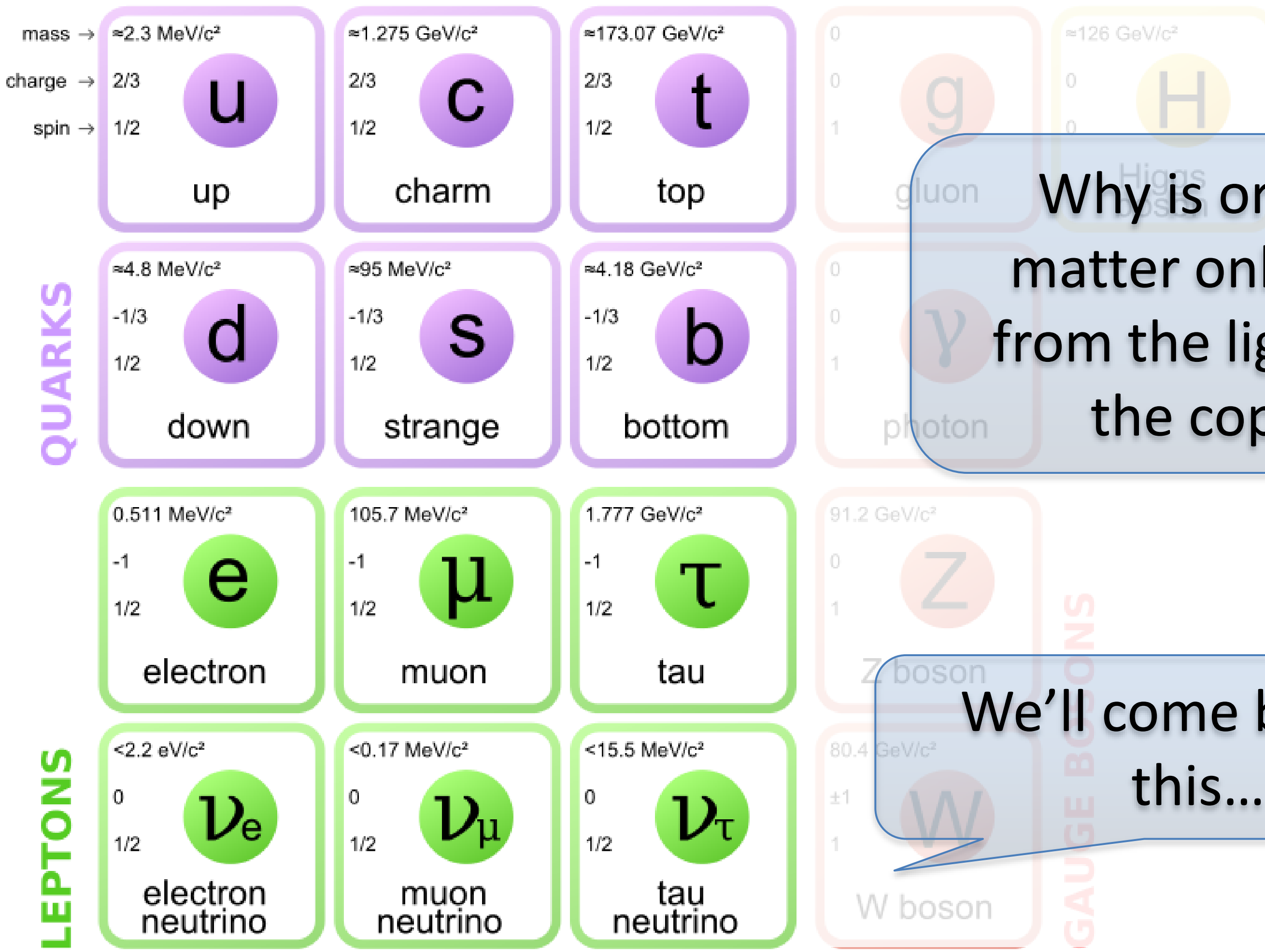
So what are the other quarks and leptons?

They are just higher mass copies.

Why are there *three* copies?

Good question!

Matter Particles

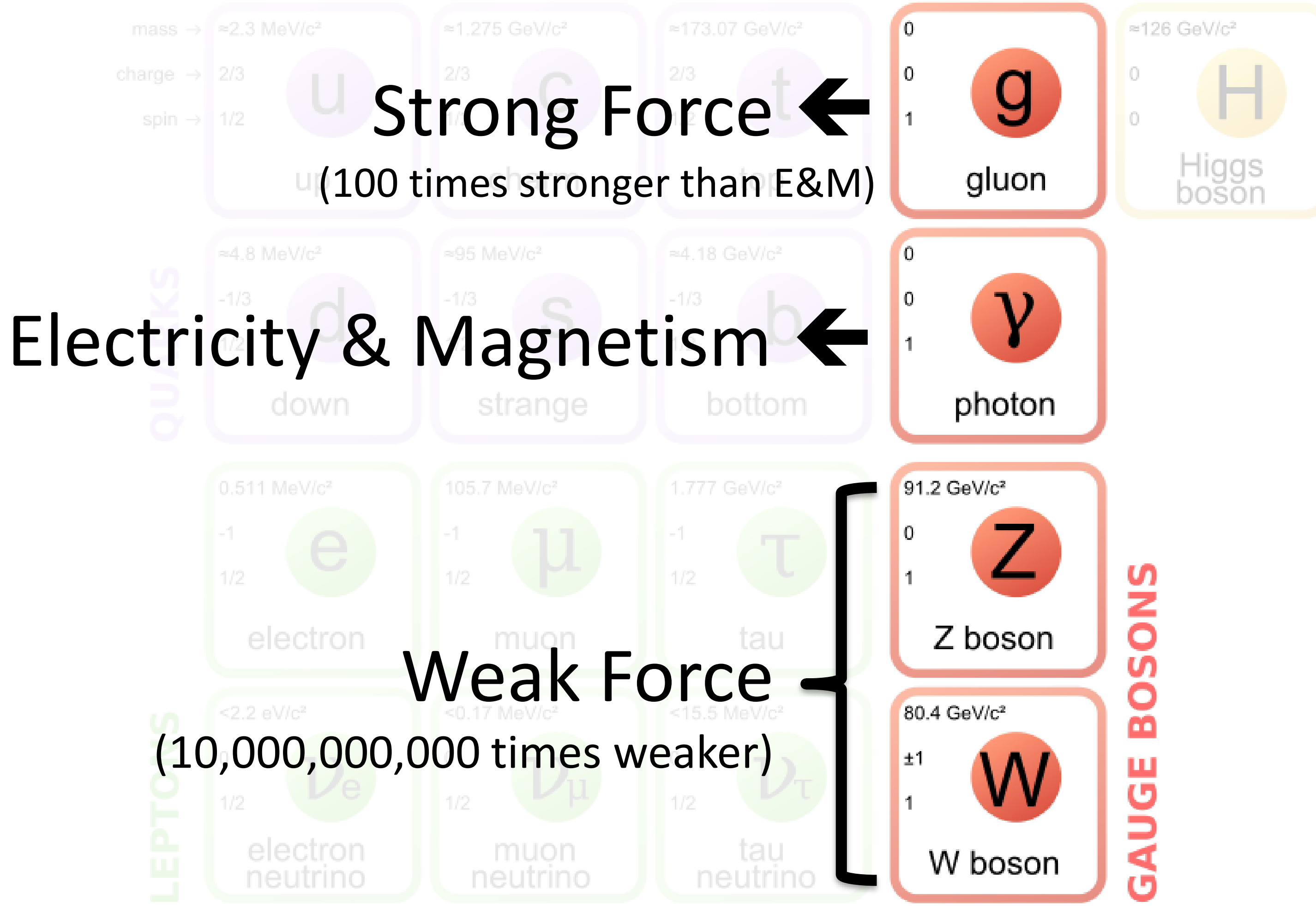


Why is ordinary matter only made from the lightest of the copies?

We'll come back to this…

Forces

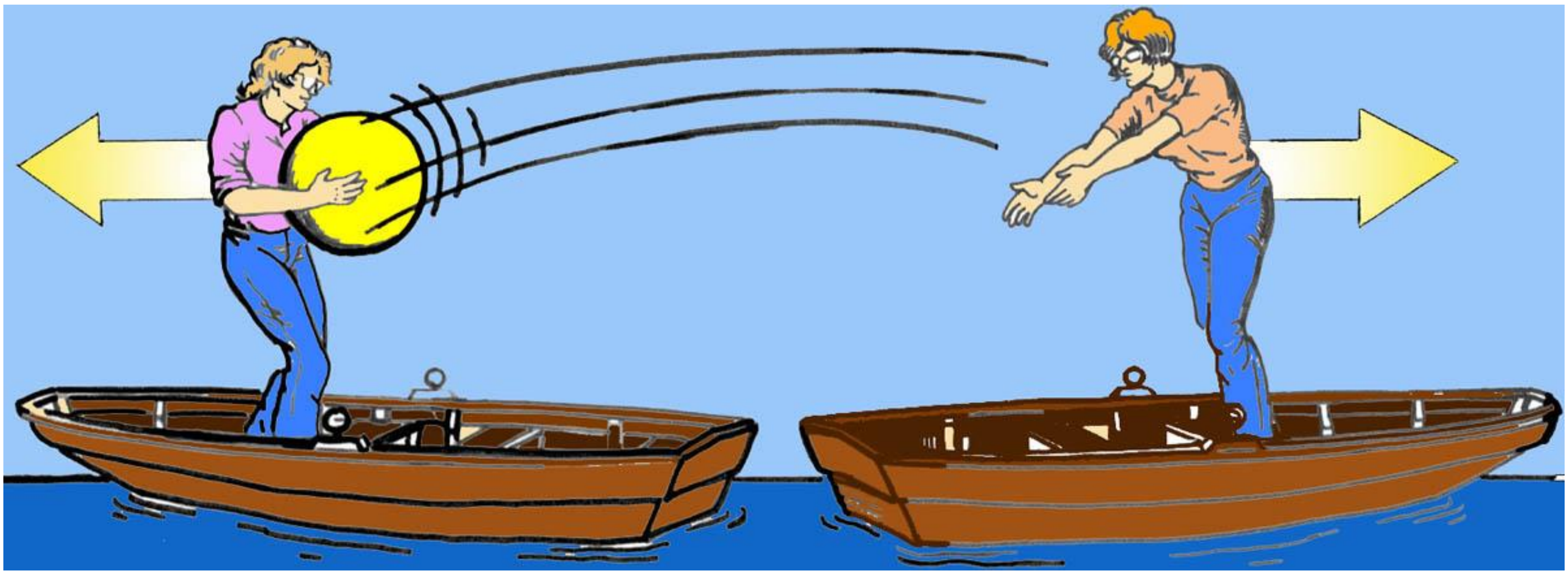
Forces and Interactions



Gravity is not included because it’s 10^{36} times weaker!

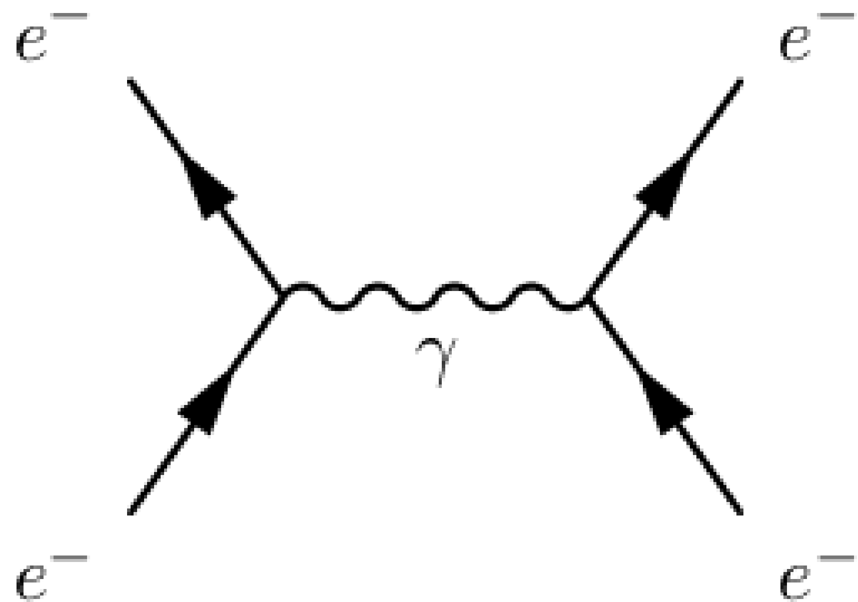
versity

How do particles cause forces?



Two boats are pushed apart by
exchanging a medicine ball

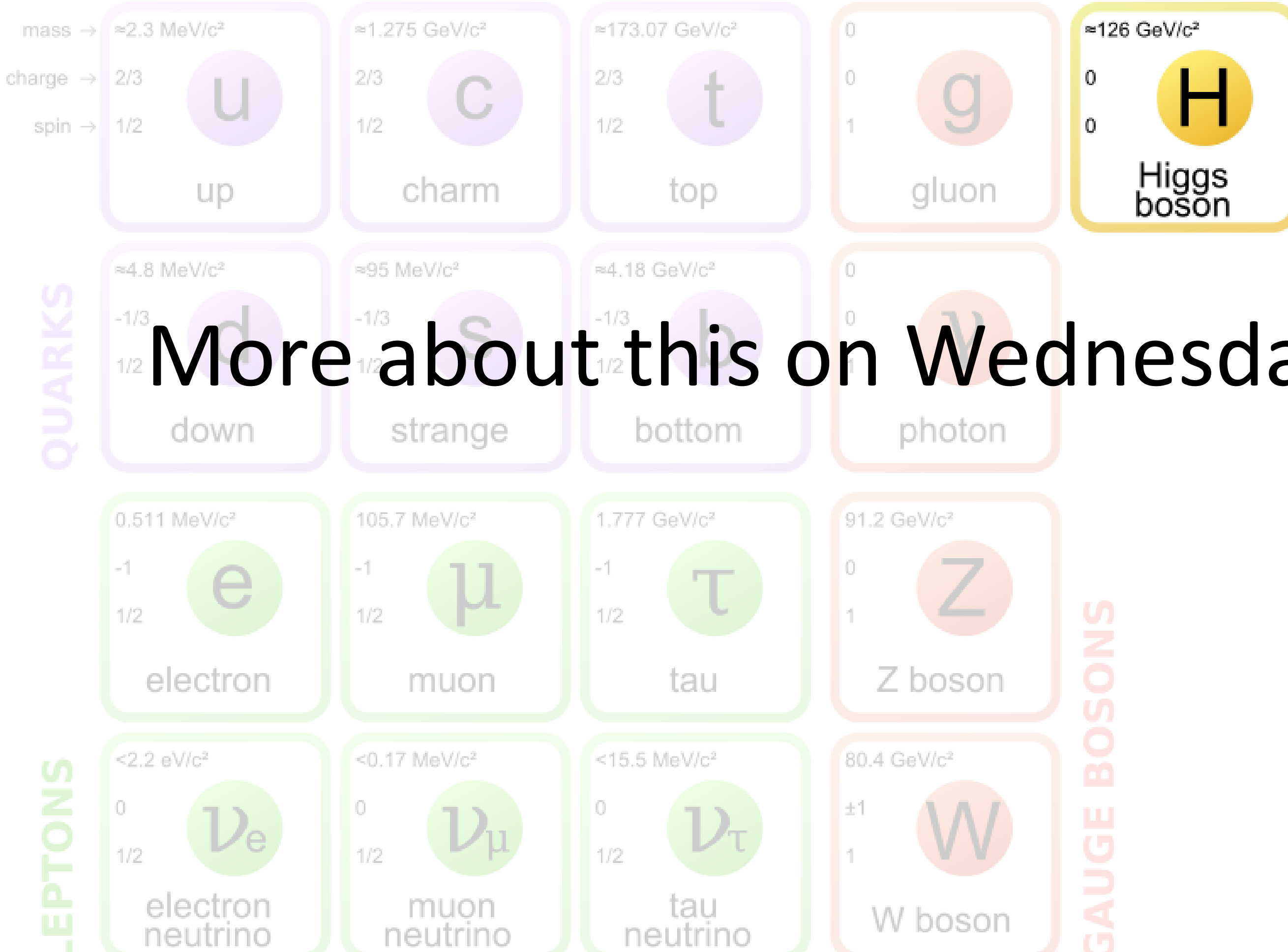
How do particles cause forces?



Two matter particles are pushed apart by exchanging a force particle

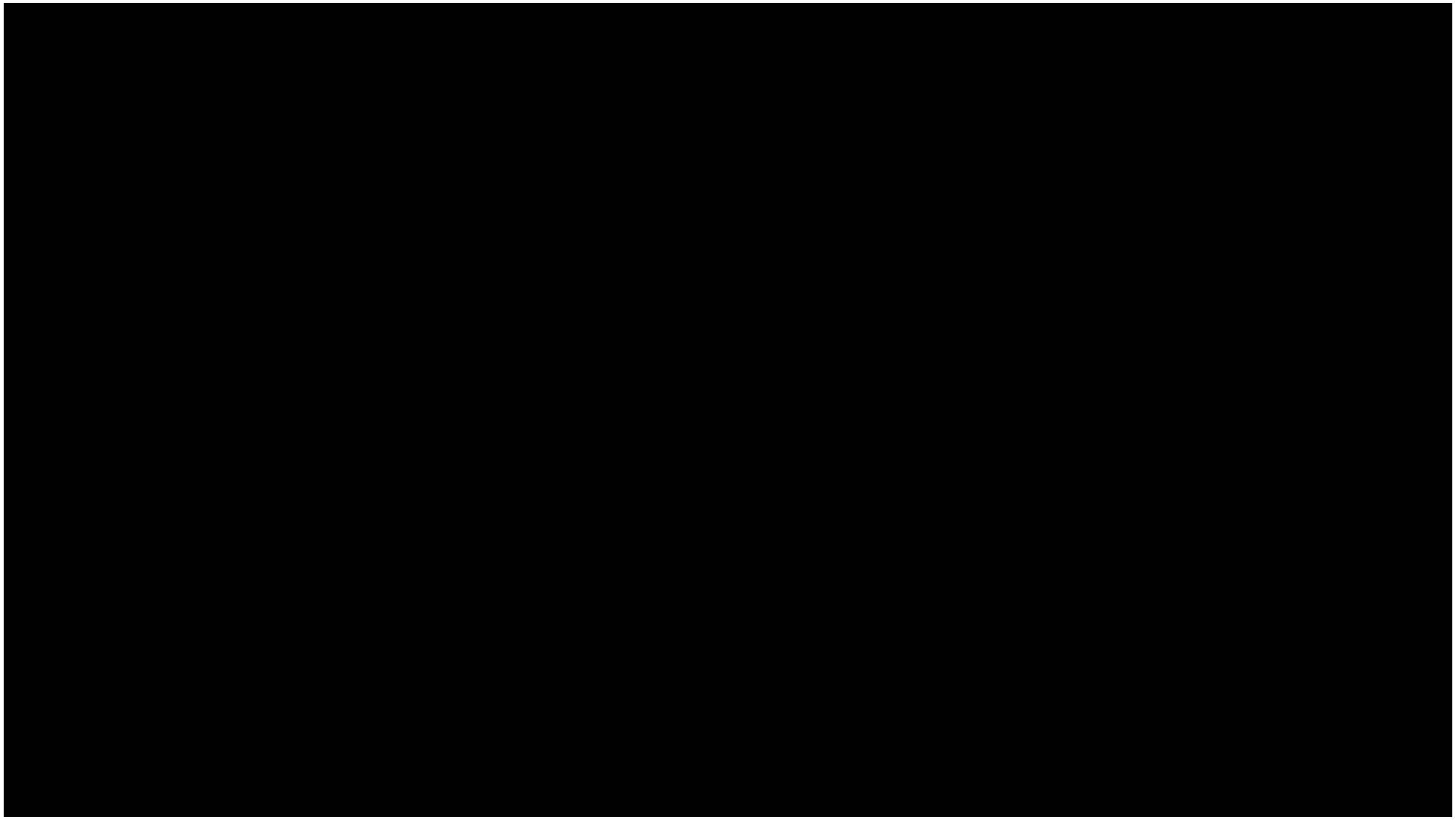
Mass

Mass



More about this on Wednesday!

The Higgs Boson



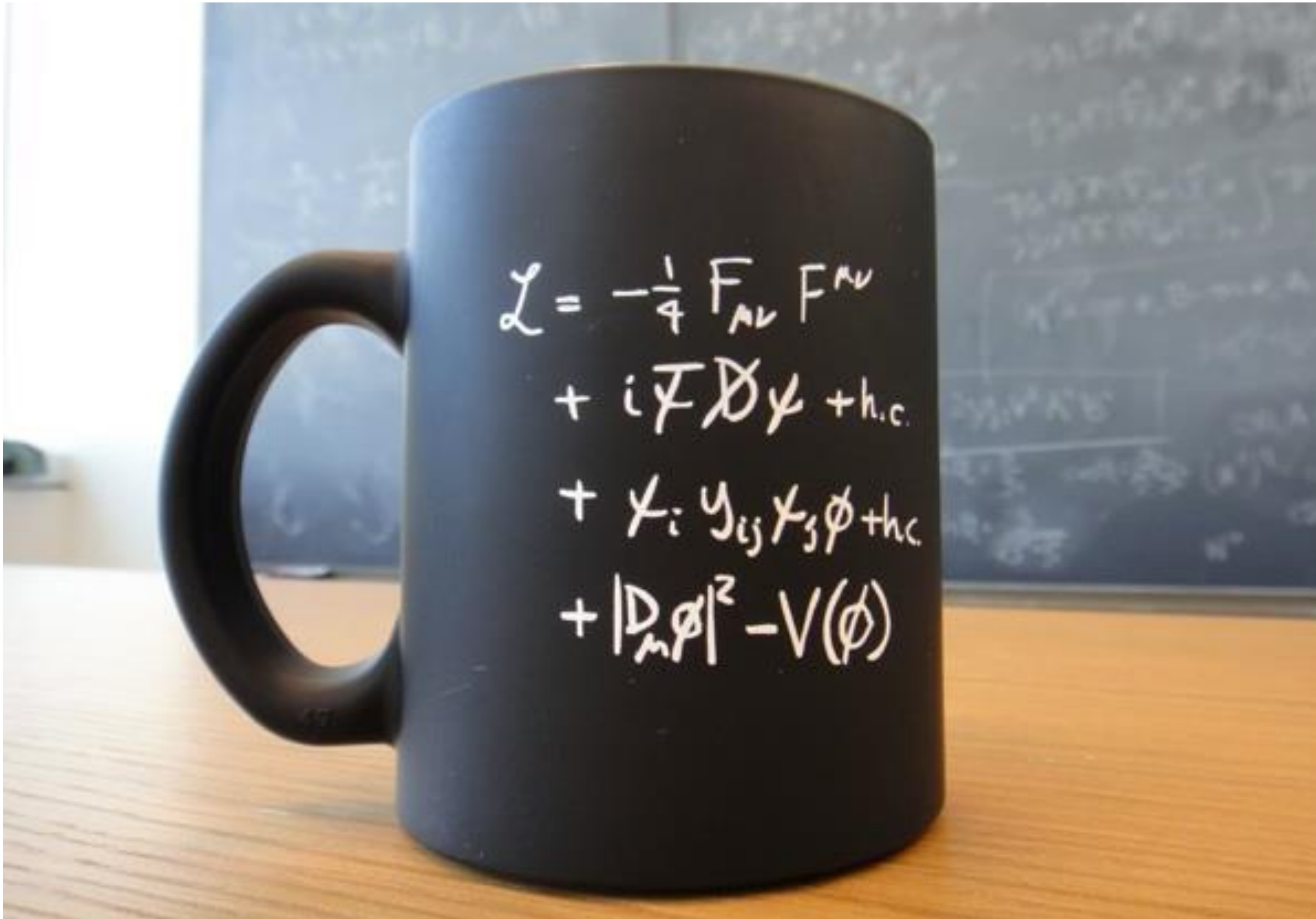
Higgs field and Higgs boson

- The theory predicts the existence of a field, known as a Higgs field, that permeates the universe and can be thought of as being like syrup.
- Particles are affected by the field as if they are wading through sticky syrup, making them sluggish.
- Mass varies depending on how easily a particle can interact with the field.
- Messenger of this field is a Higgs boson
  ➔ We must find the Higgs boson to prove the theory!

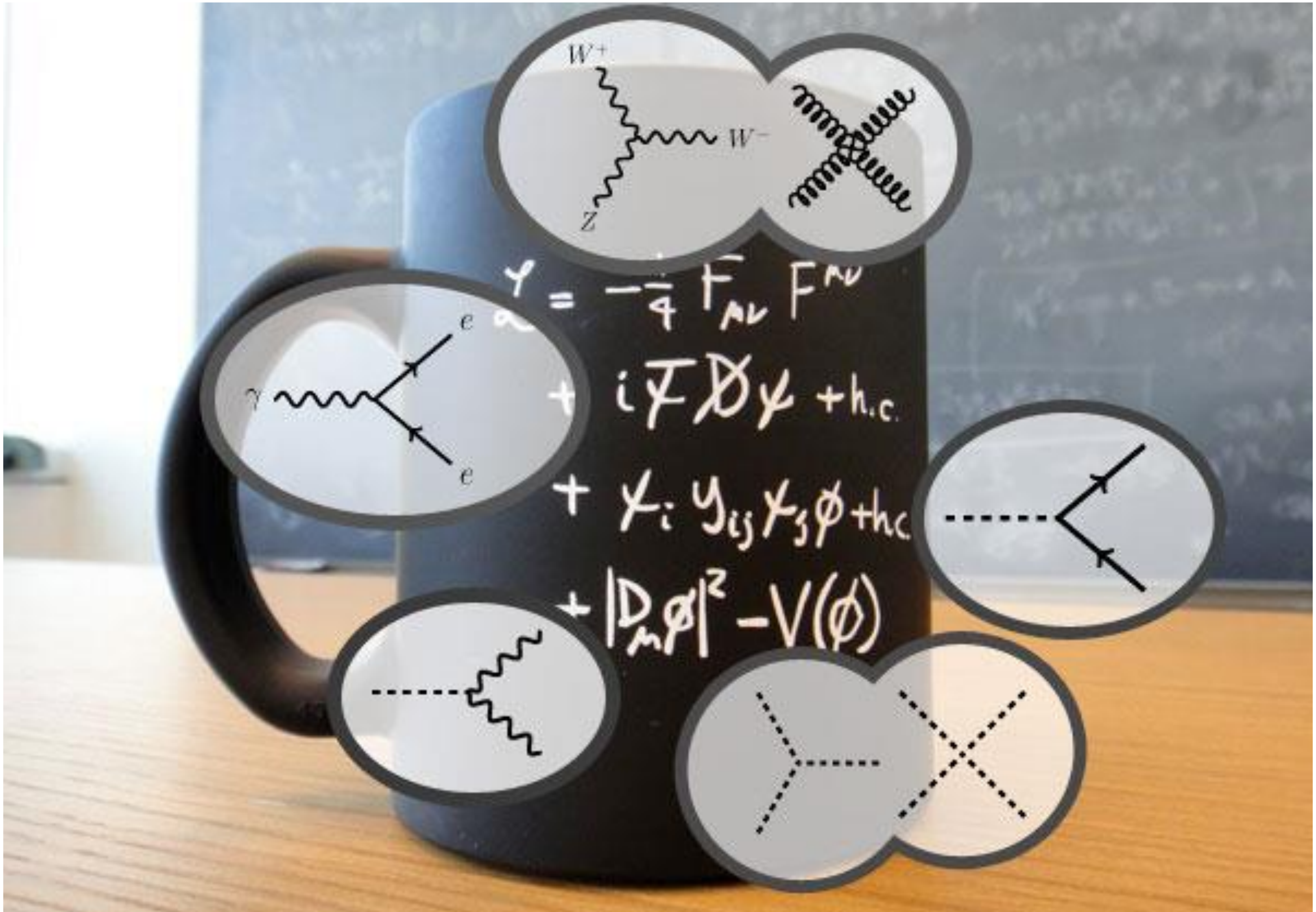
… how do we do we find it?

The Theory

Standard Model Lagrangian



Standard Model Lagrangian



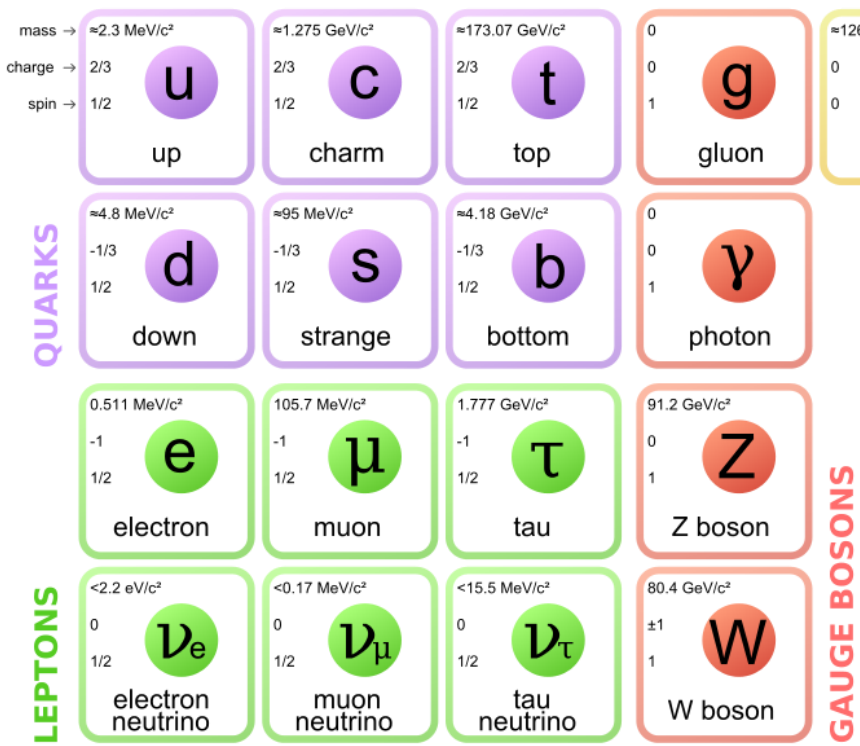
Standard Model Lagrangian

$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)} && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)}
\end{aligned}
$$

Testing the Theory

Search for New Physics

- The Standard Model has been *extremely* successful at describing the sub-atomic world.
- But many questions still remain....



Why are there three copies of matter?

Why these masses?

Why is there more matter than anti-matter?

What is dark matter?

How do we include gravity?

...

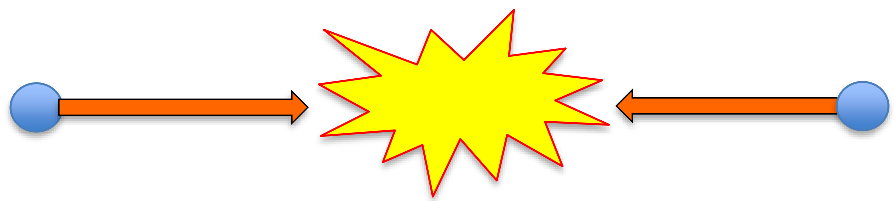
Testing the Standard Model

- We need to **create** these particles and test if they interact as we predict
  - Deviations from the prediction = new physics
  - New physics will provide the clues to answer our burning questions

- How do we create these particles? $\Rightarrow E = mc^2$
  - To create a particle with mass m, we need an energy of $E = mc^2$ (and c is a big number!)

Particle creation

- $E = mc^2$
  - With enough energy, we can create new heavy particles



Particle creation

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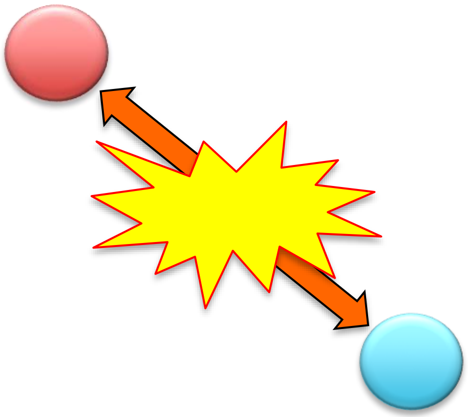
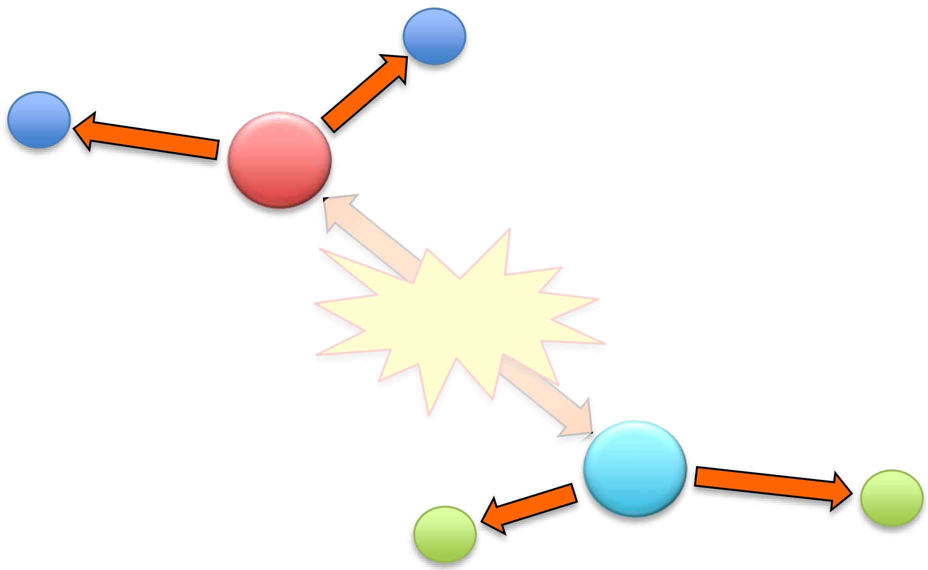


Particle decay

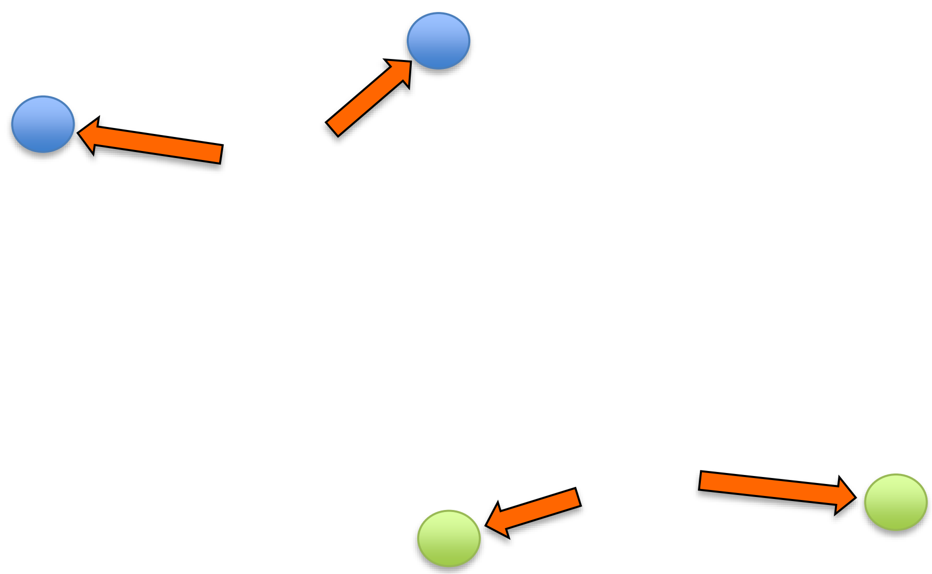
- Conversely, particles with a lot of mass have a lot of energy, so they can decay to lighter particles



- This is why ordinary matter is only made from the lightest copy of the quarks and leptons
- We can create heavy particles in high energy collisions, but they quickly decay to lighter particles

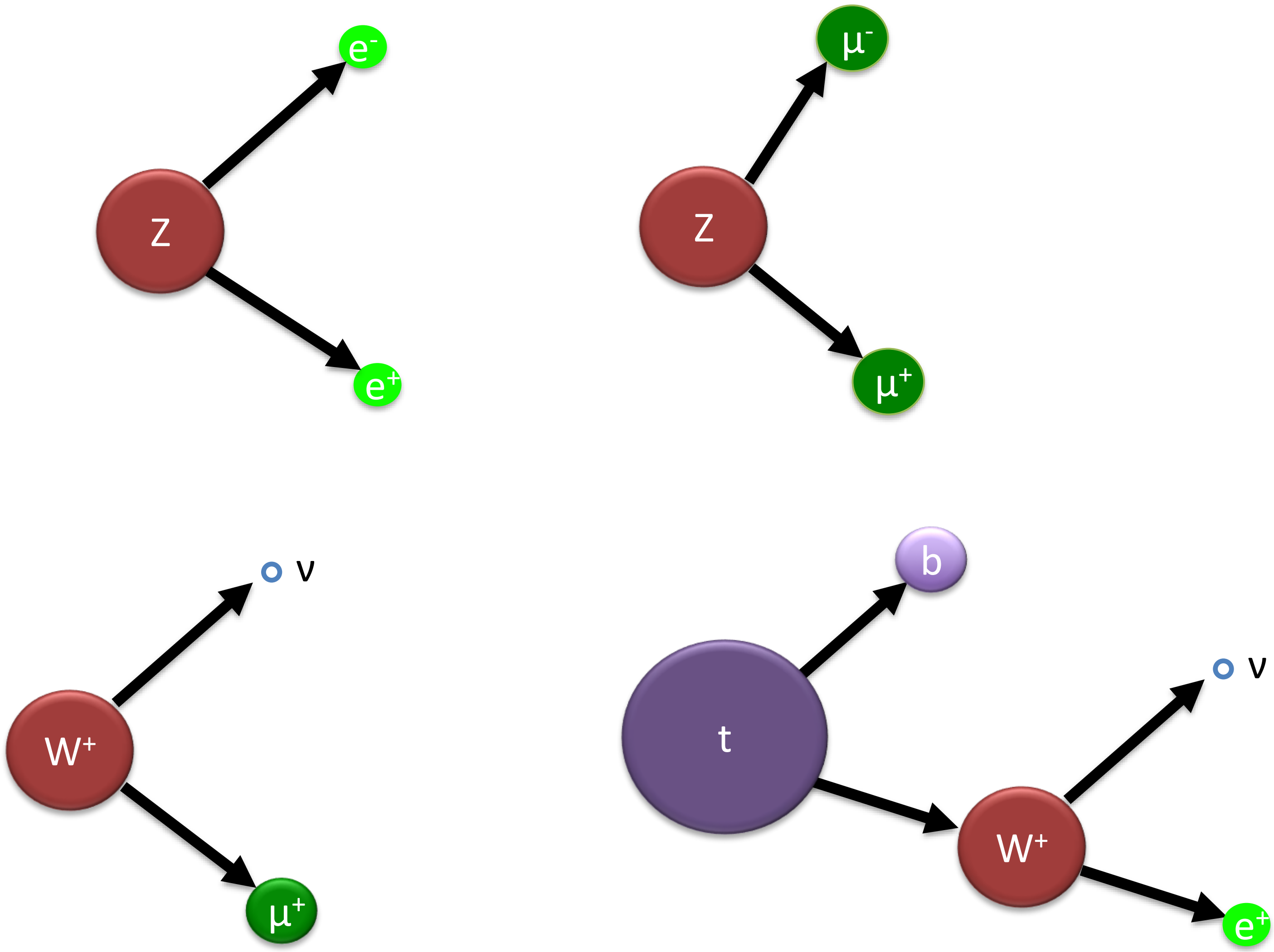
Decay products

- We only **detect** the **decay products** of the heavy particles



- But the **mass** of the heavy particles was converted into the **energy** of the decay products
- Thus, if we find the decay products and measure their energy, **we can determine the mass of the parent particle**!

Decay Examples

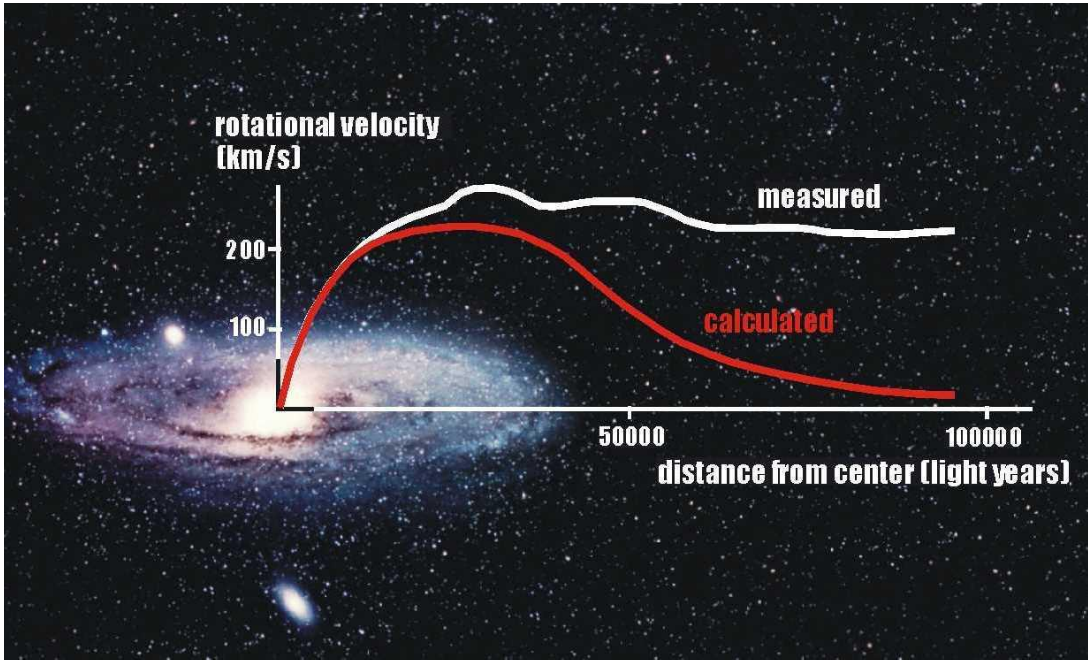


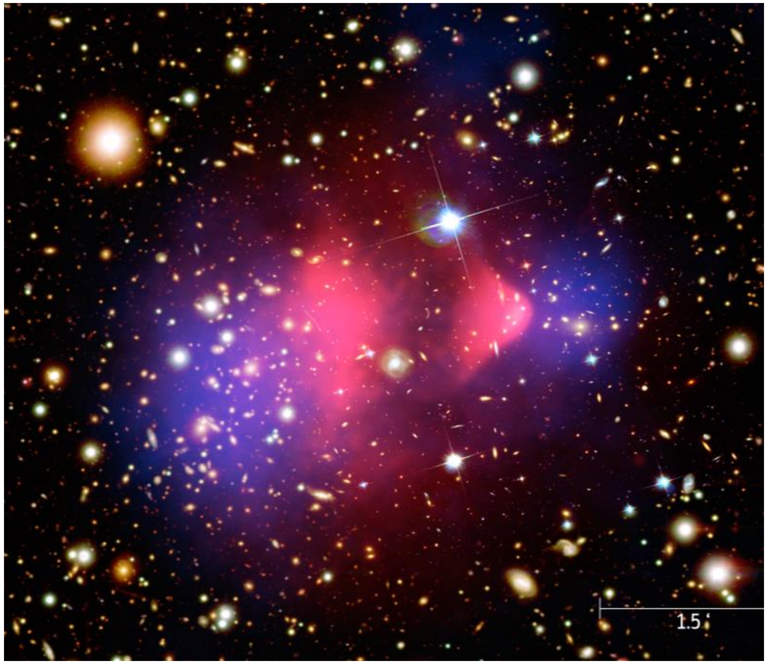
Why do we need the LHC?

- The LHC is our tool to create new particles so that we can answer our many questions
  - Why do particles have mass? ➔ Higgs boson found in 2012!
  - Why are there three copies of the quarks and leptons?
  - Are there more copies?
  - Are the quarks and leptons actually made of smaller pieces?
  - What is dark matter made of?
  - Even more exotic possibilities (extra dimensions, Supersymmetry,…)

Dark matter

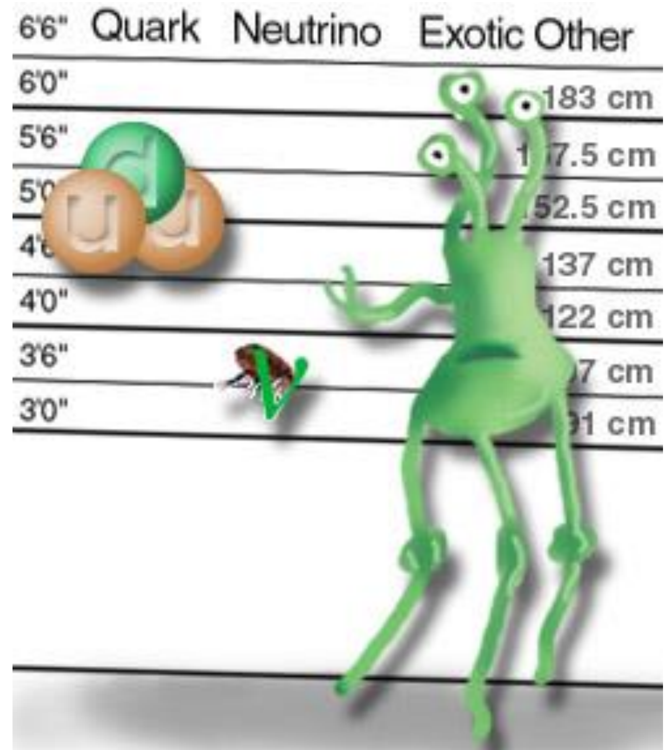
- All planets and stars that we see in the sky are made of the same type of quarks and leptons as our Earth
- But the majority of our Universe may not be made of the same type of matter as our Earth – something else is there that holds all stars and their systems together – dark matter





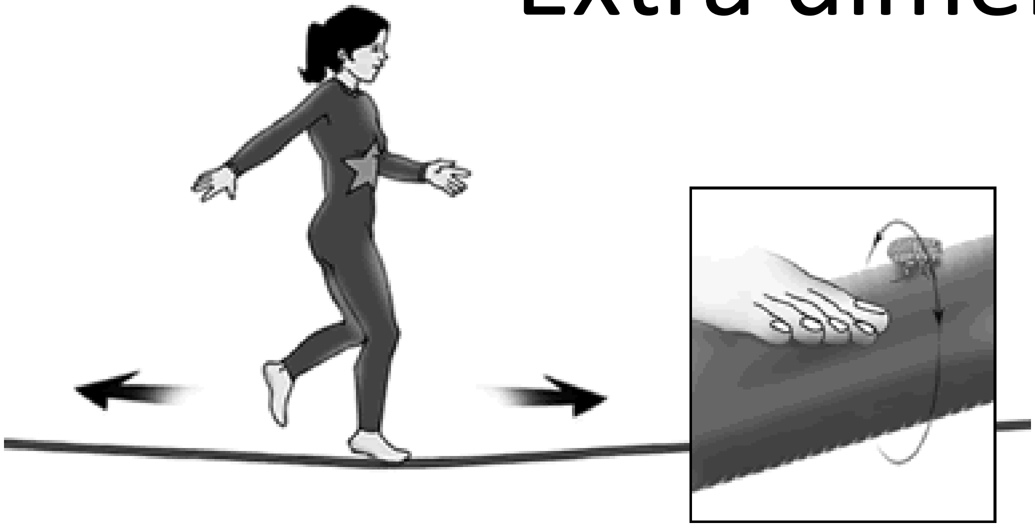
The search for Dark Matter

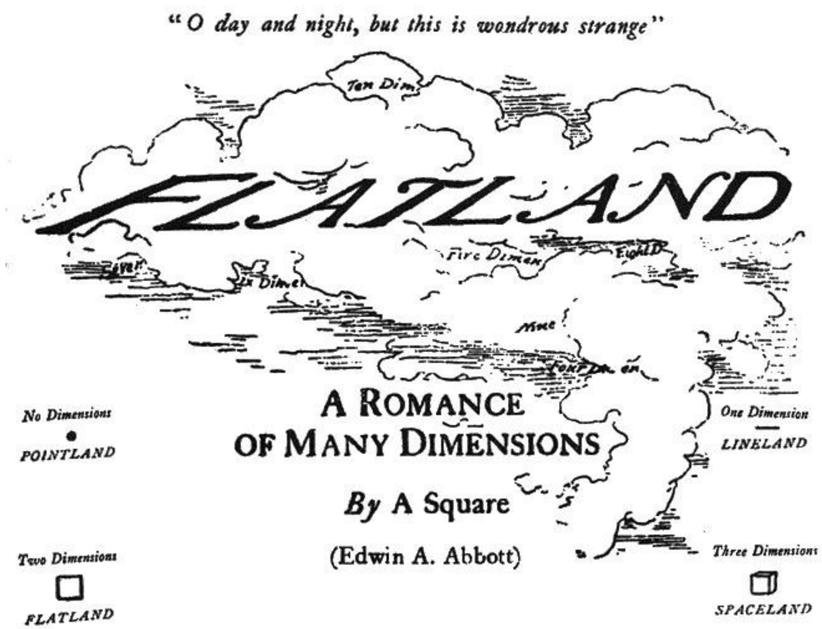
- We know it's there
  - Galactic rotation curves
  - Collision of cluster galaxies
  - Cosmic microwave background temperature fluctuations
- But what is it?
  - Probably **a new particle** that we can find at LHC!
  - The simplest Dark Matter
  - Must be stable
  - Density of ~one particle per "hand"

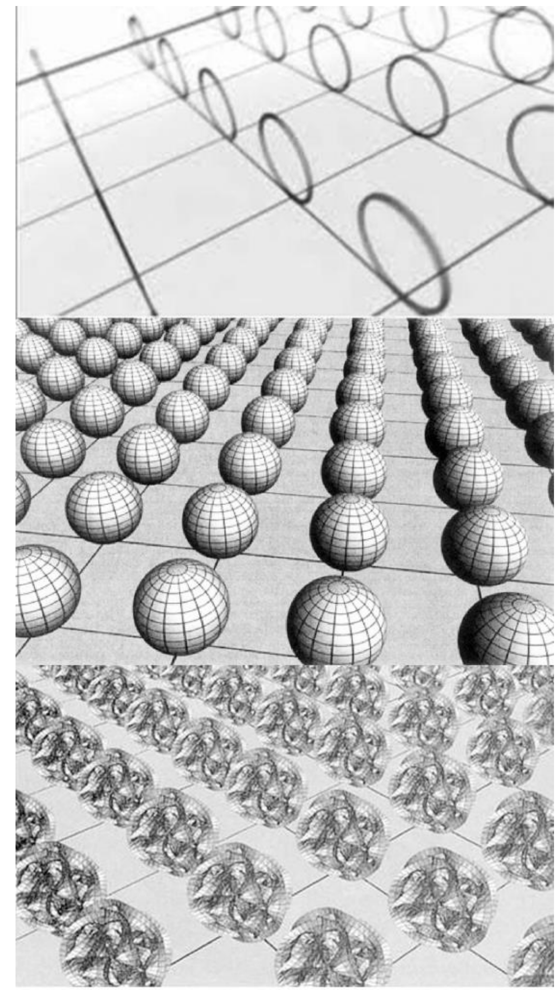


"All right... which of you punks is responsible for dark matter?"

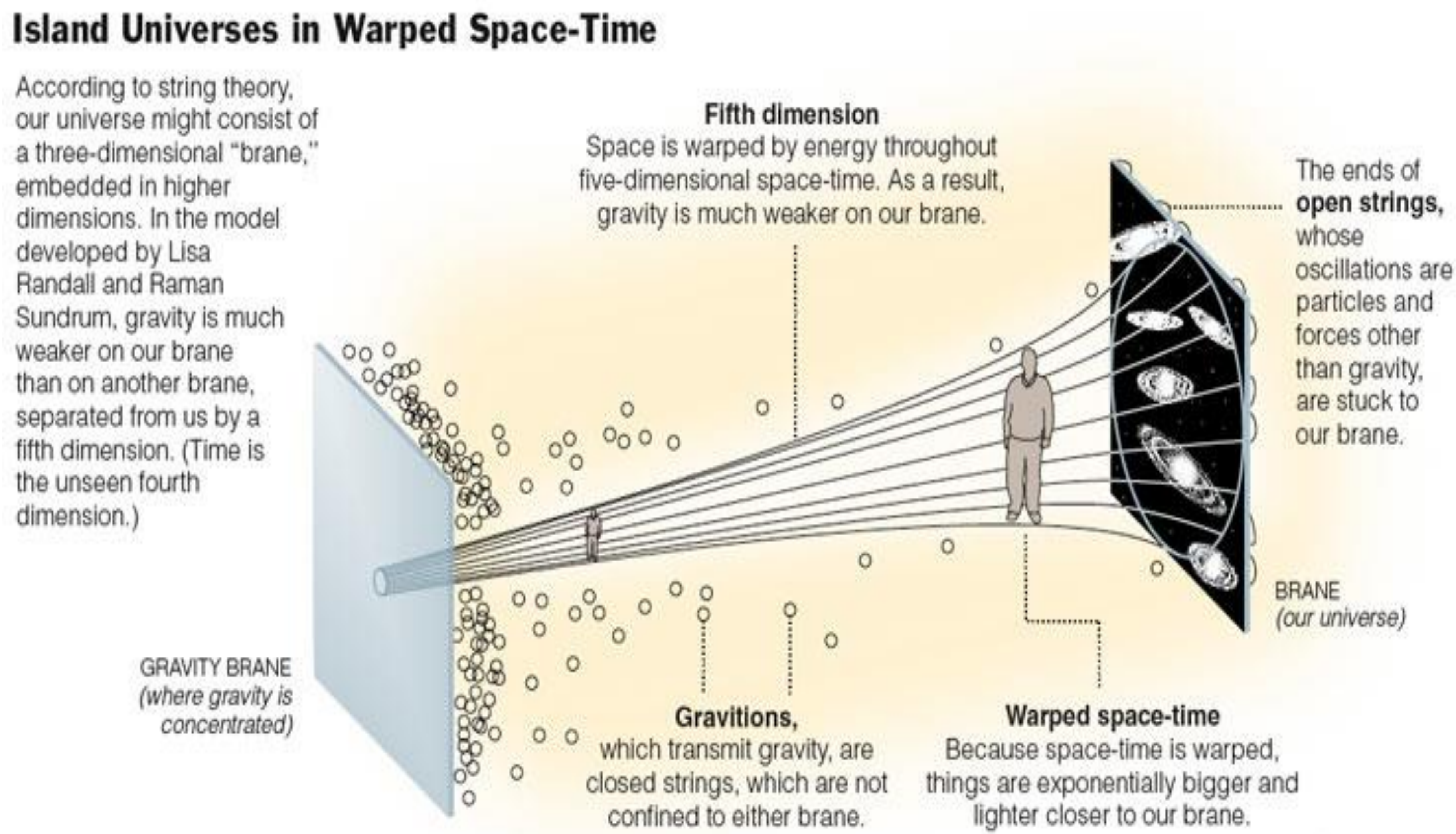
Extra dimensions





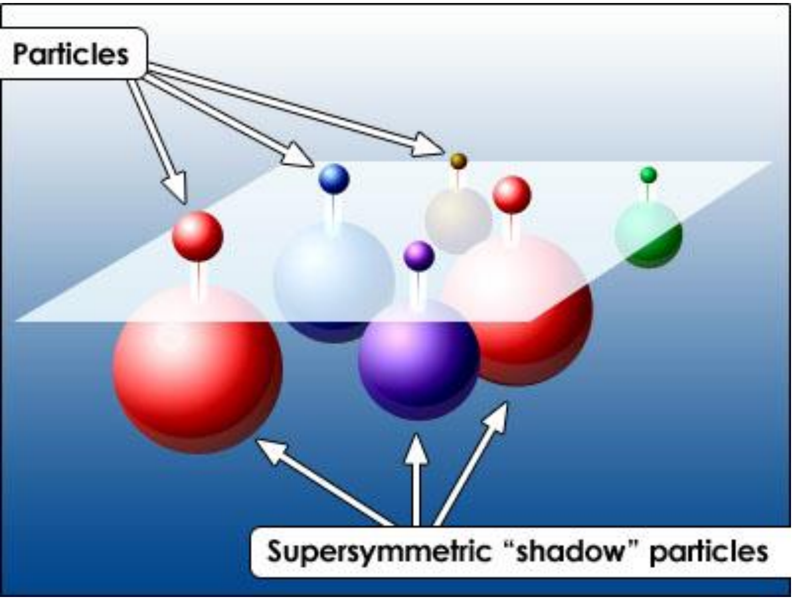


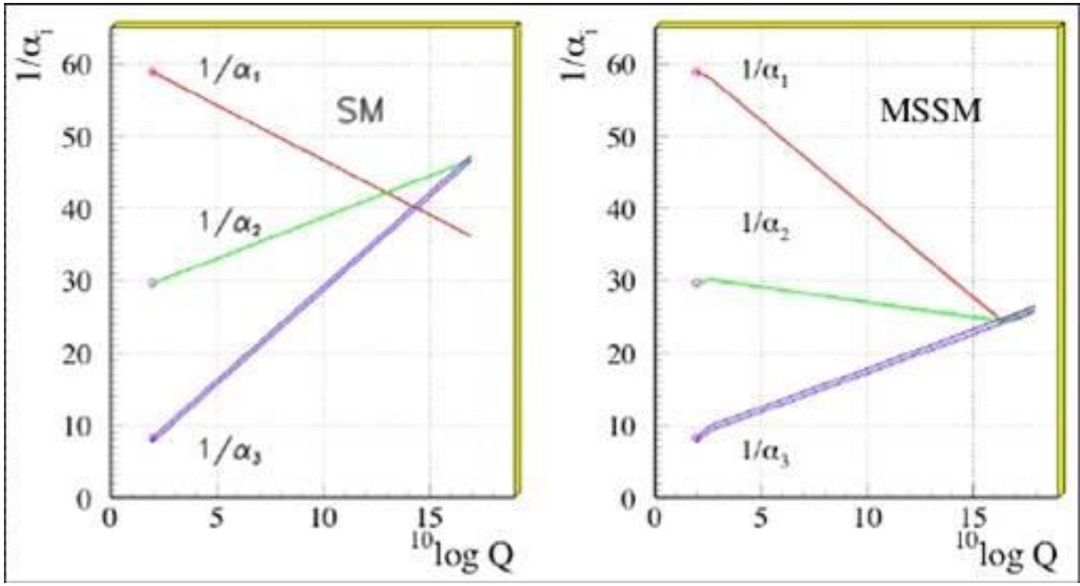
One extra dimension theory



Heavy cousins

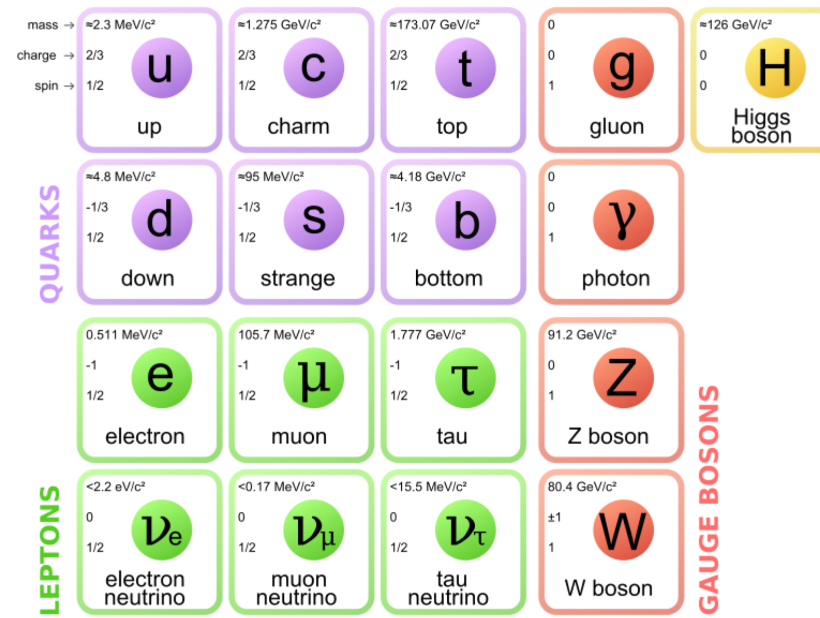
- Some theories beyond the Standard Model introduce more symmetries
  - Quark-Lepton symmetry, Supersymmetry, Mirror symmetry, …
  - New symmetries could unify the electromagnetic, weak, and strong forces
  - Could explain other phenomena
    - Dark matter, multiple generations of quarks and leptons, the Higgs boson…

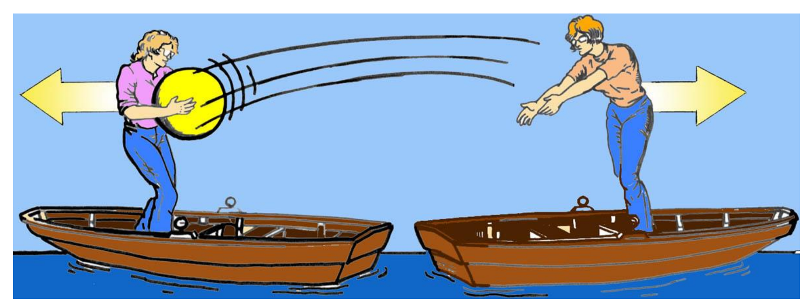




Conclusions

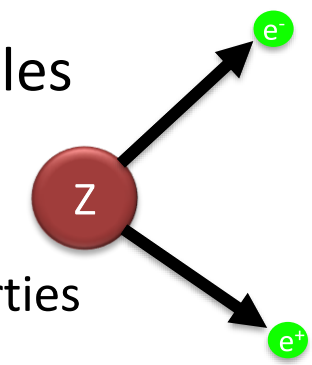
- The Standard Model describes the fundamental particles and three of the four forces
- Matter is made from quarks and leptons, which come in three copies of increasing mass
  - Ordinary matter is made from the lightest copies
- Forces are caused by exchanging force carrier particles



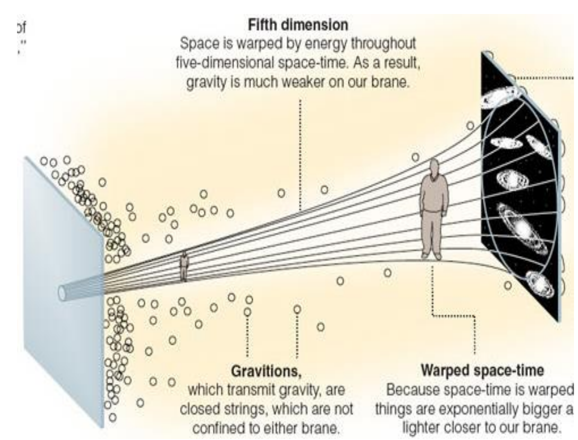


Conclusions

- We can create new, heavier particles in high energy collisions
- Heavy particles will quickly decay to light particles
  - Photons, electrons, muons, neutrinos,
  - By measuring the decays products, we can "reconstruct" the heavy particle and study its properties



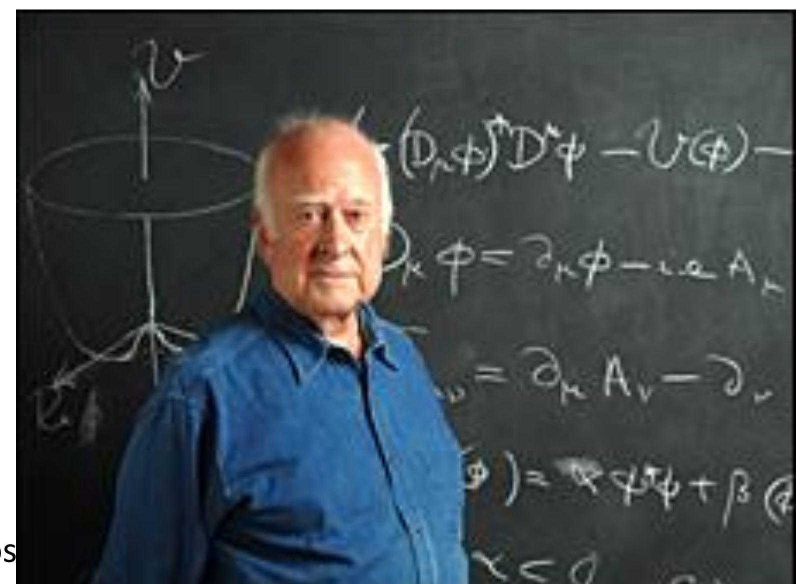
- The Standard Model works well, but it must not be complete
  - Dark matter, gravity, …
  - Many possible extensions
  - Need experiments to figure out which theories are correct!



Thank You

Origin of mass

- Initially in theory, all fundamental particles are massless. From experiment we know that this is not true – elementary particles have mass.
- The first physicist who was able to propose a theory to explain how particles acquire mass, was Prof. Peter Higgs.



Born in 1929, Prof. Higgs is an English theoretical physicist and Emeritus professor at the University of Edinburg. His fundamental work on the origin of mass was published in 1964.