# Introduction to Particle Physics

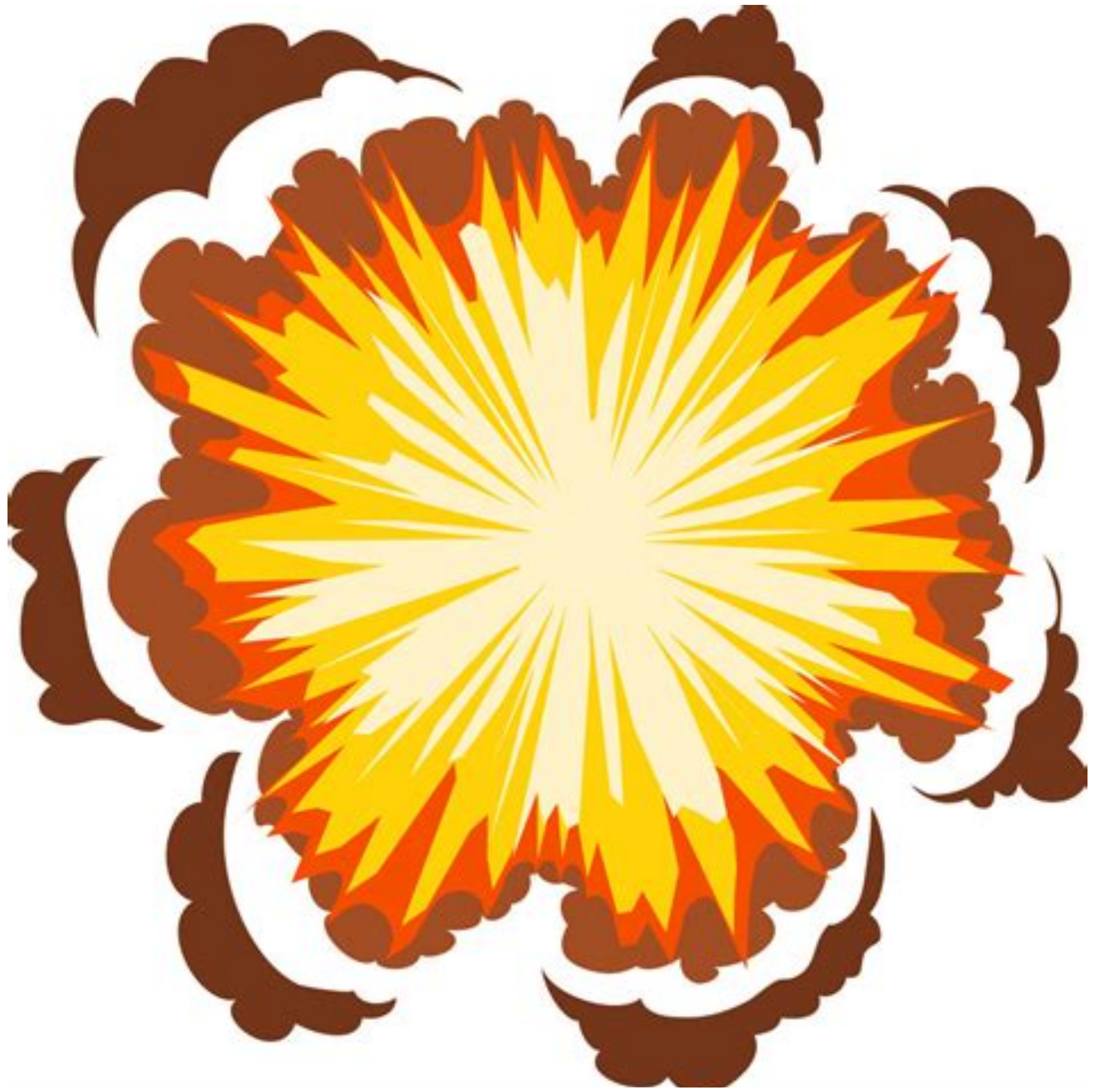
Nina Nathanson

ALICE Masterclass, February 2025

UNIVERSITY OF COPENHAGEN

# The Standard Model

# Fundamental Questions



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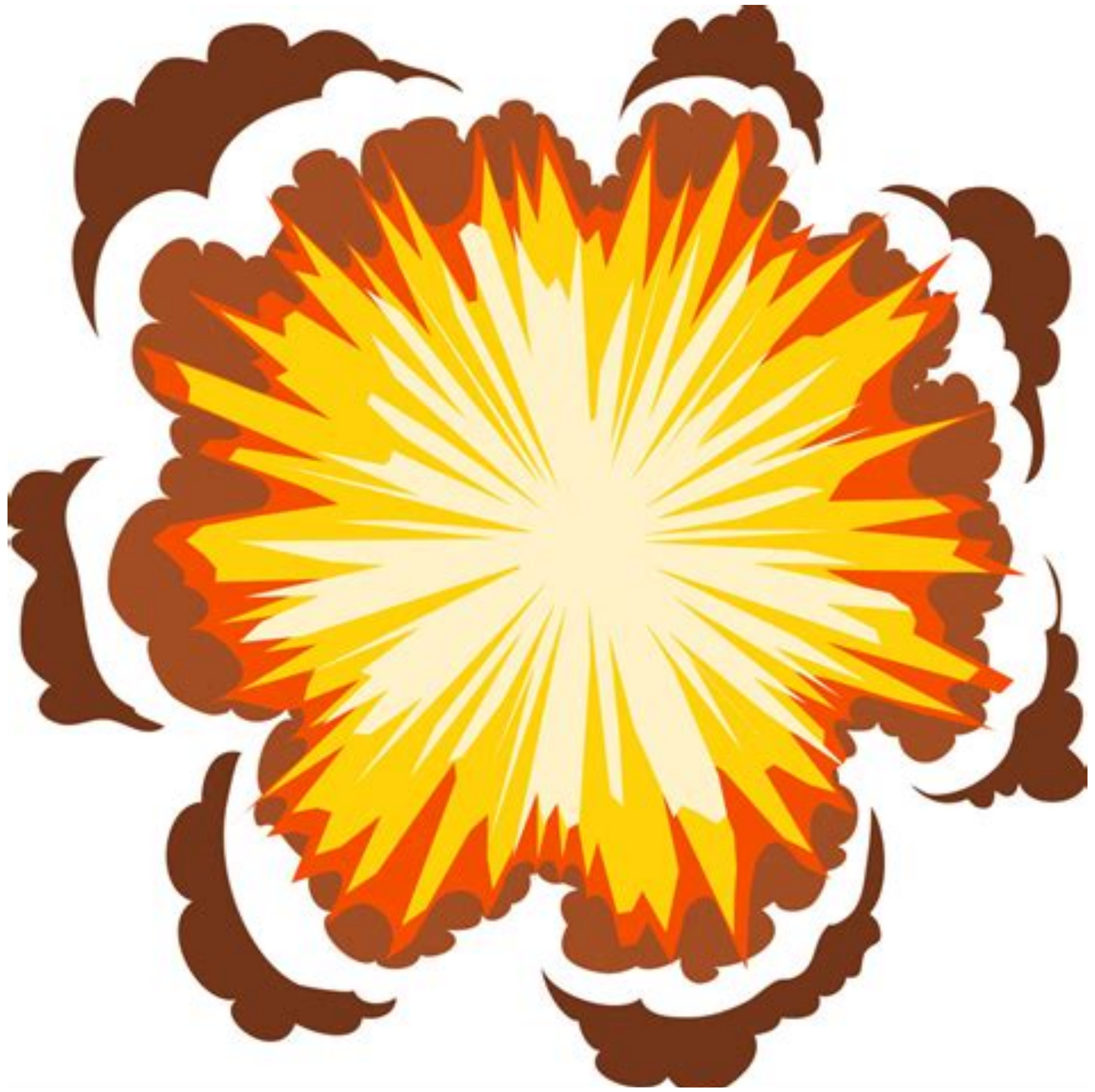
# Fundamental Questions

How did the universe start?



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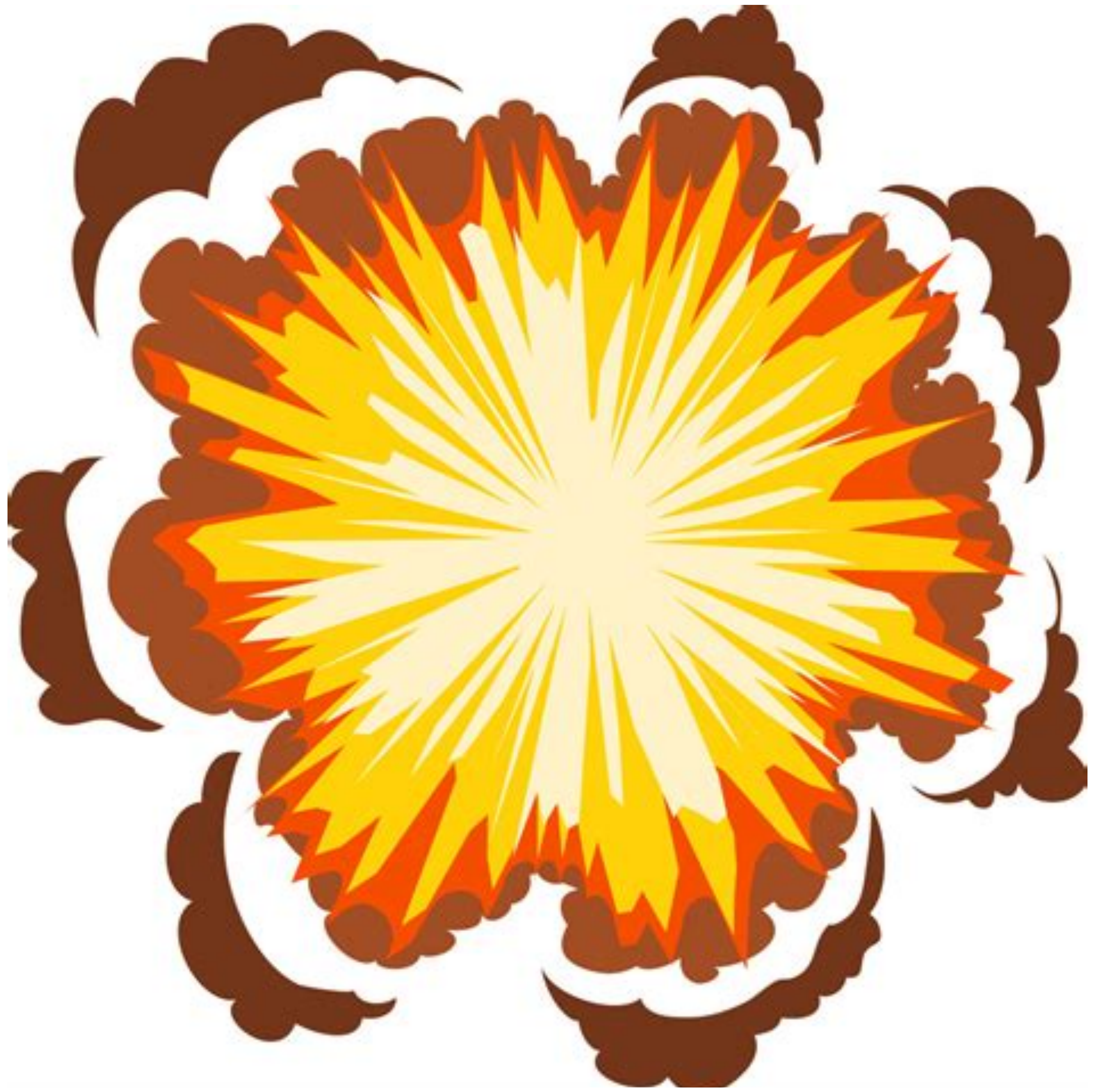
How did the universe start?

↓

How did it become what we see today?



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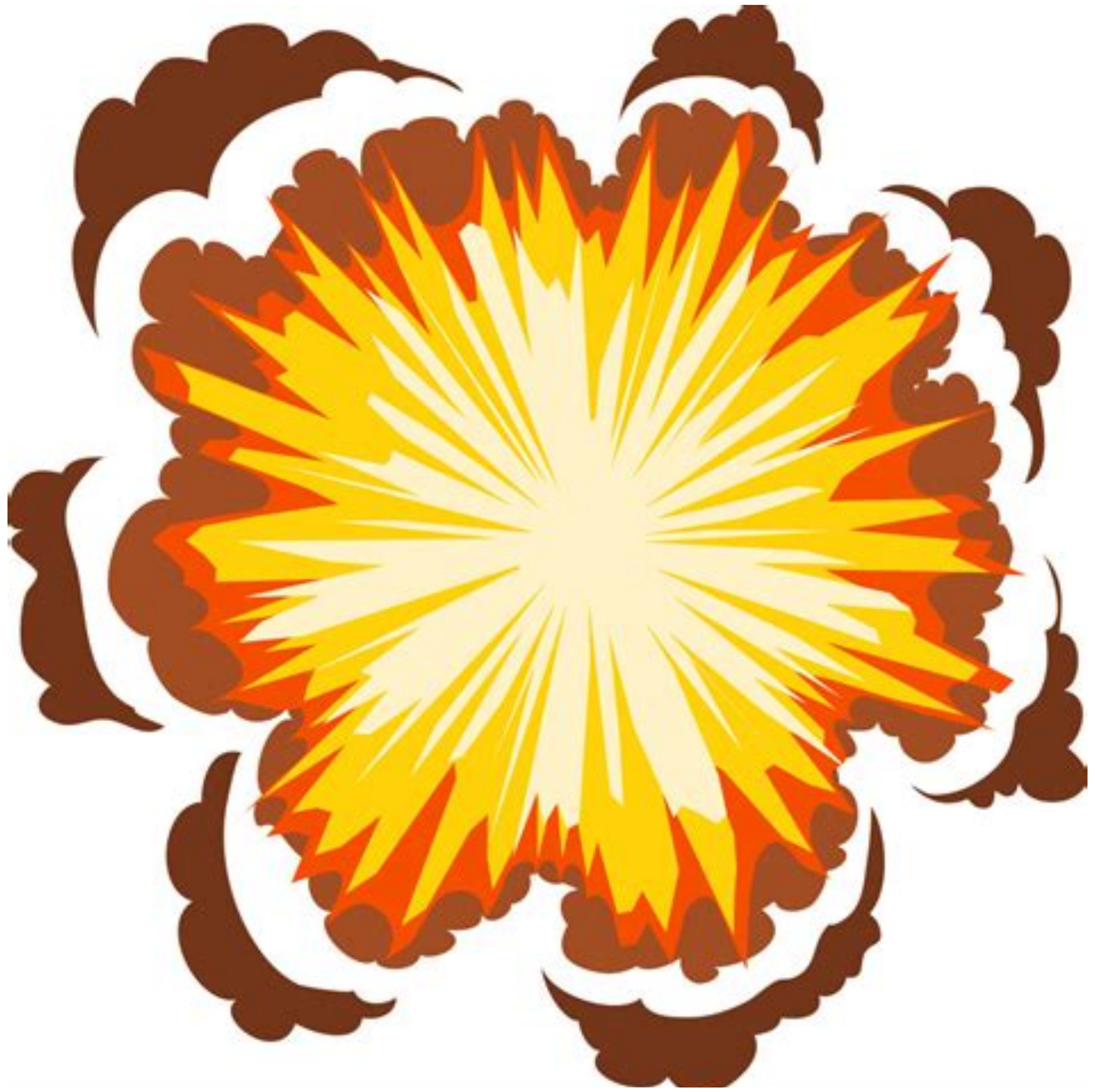

What is matter?

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# Fundamental Questions

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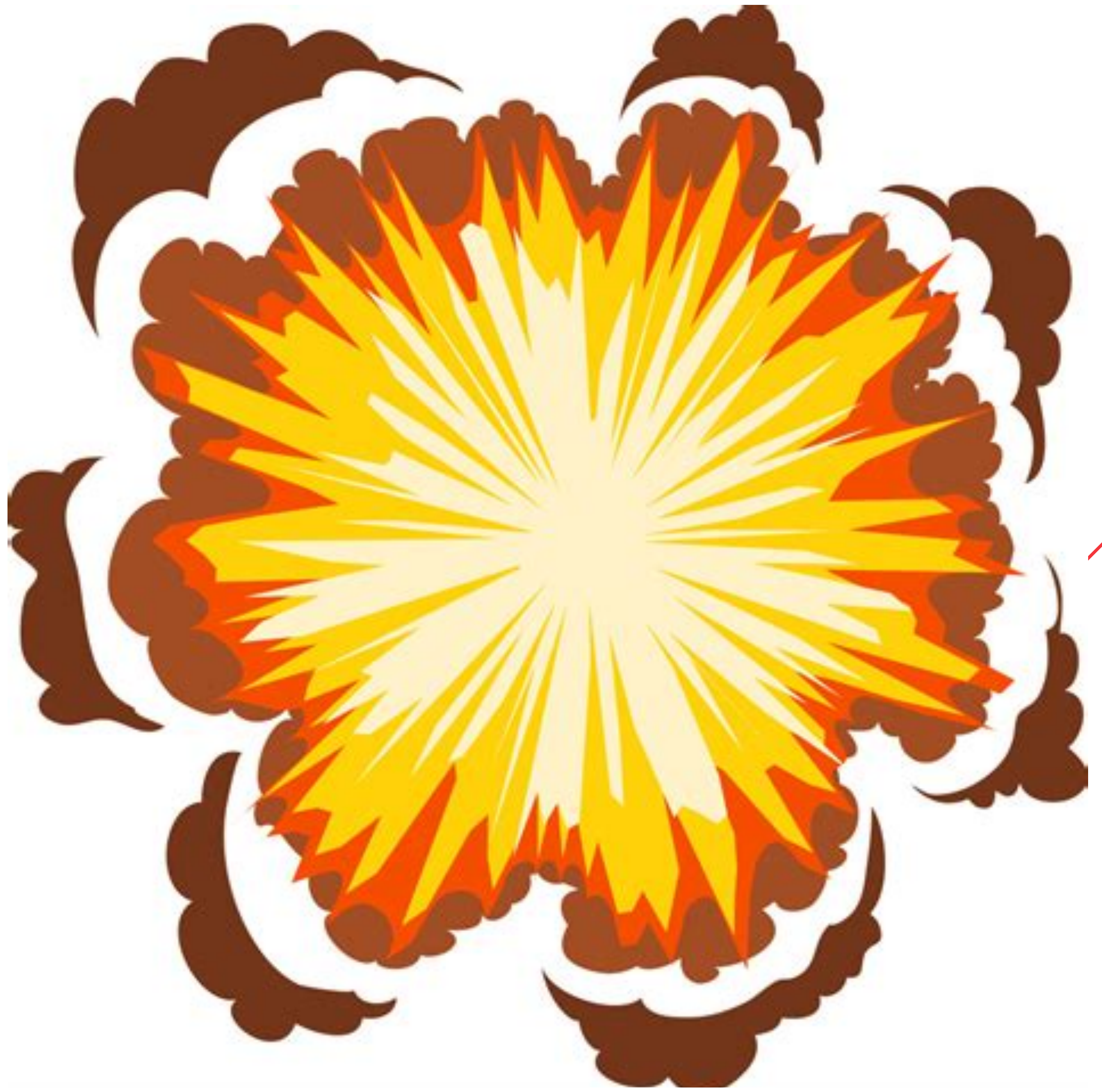

What is matter?

How does matter interact, down to the smallest scale?

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# The Standard Model

The most fundamental theory in modern physics is called the **Standard Model**, and it can be summarized in the following formula:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\,\psi + \text{h.c.} + \psi_i y_{ij}\psi_j\phi + \text{h.c.} + |D_\mu\phi|^2 - V(\phi)$$

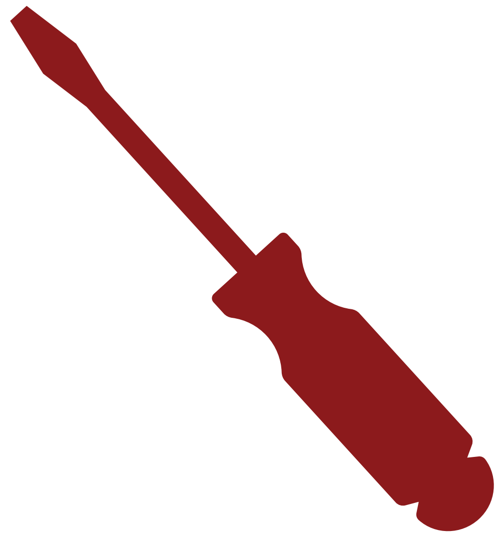
Simple… right?

Let's break it down anyway!

# Fundamental Forces

Before we learn about the building blocks of the universe, let's review the tools that dictate how matter interacts:

| | |
|---|---|
| ? | ? |
| ? | ? |



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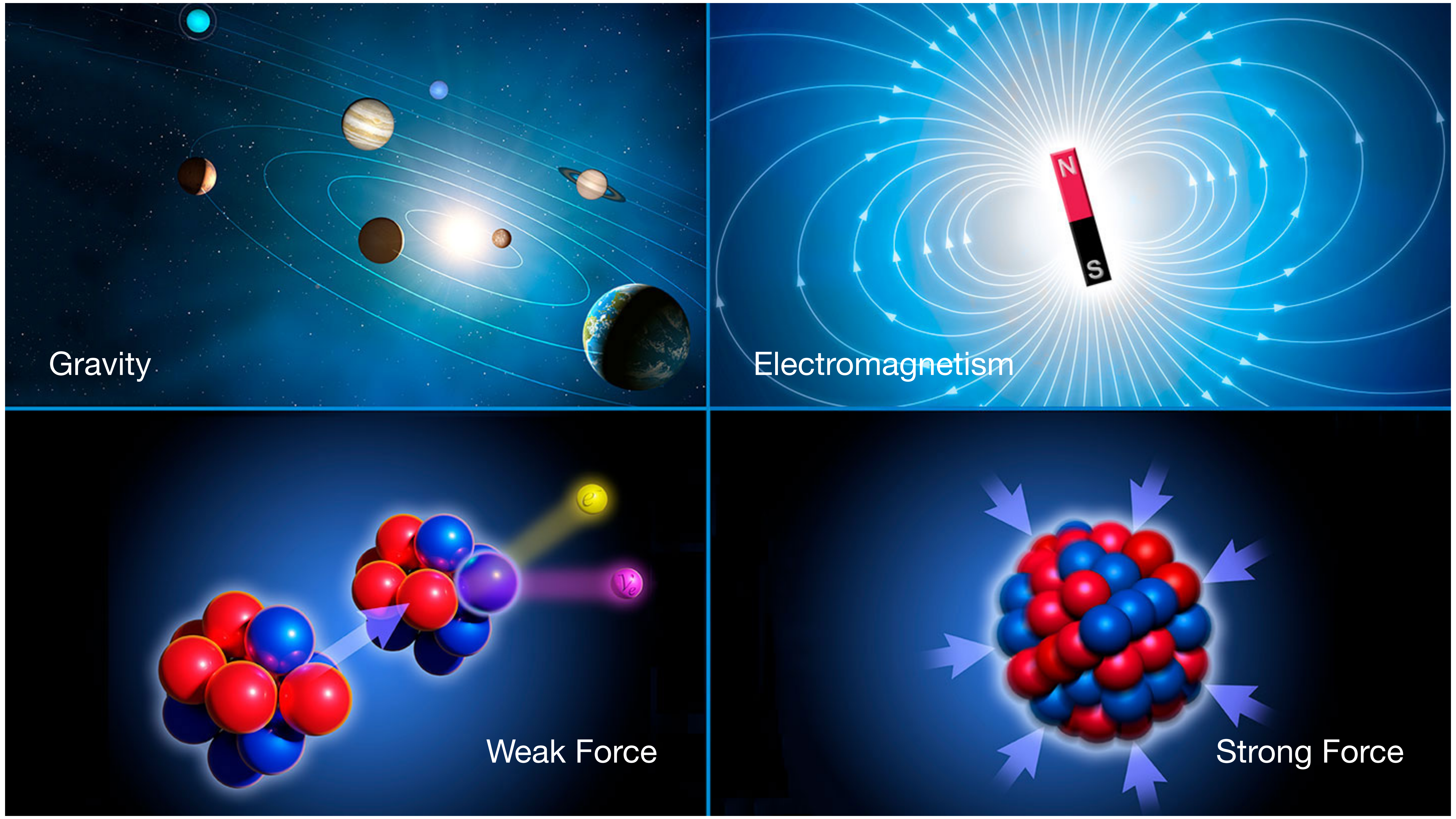
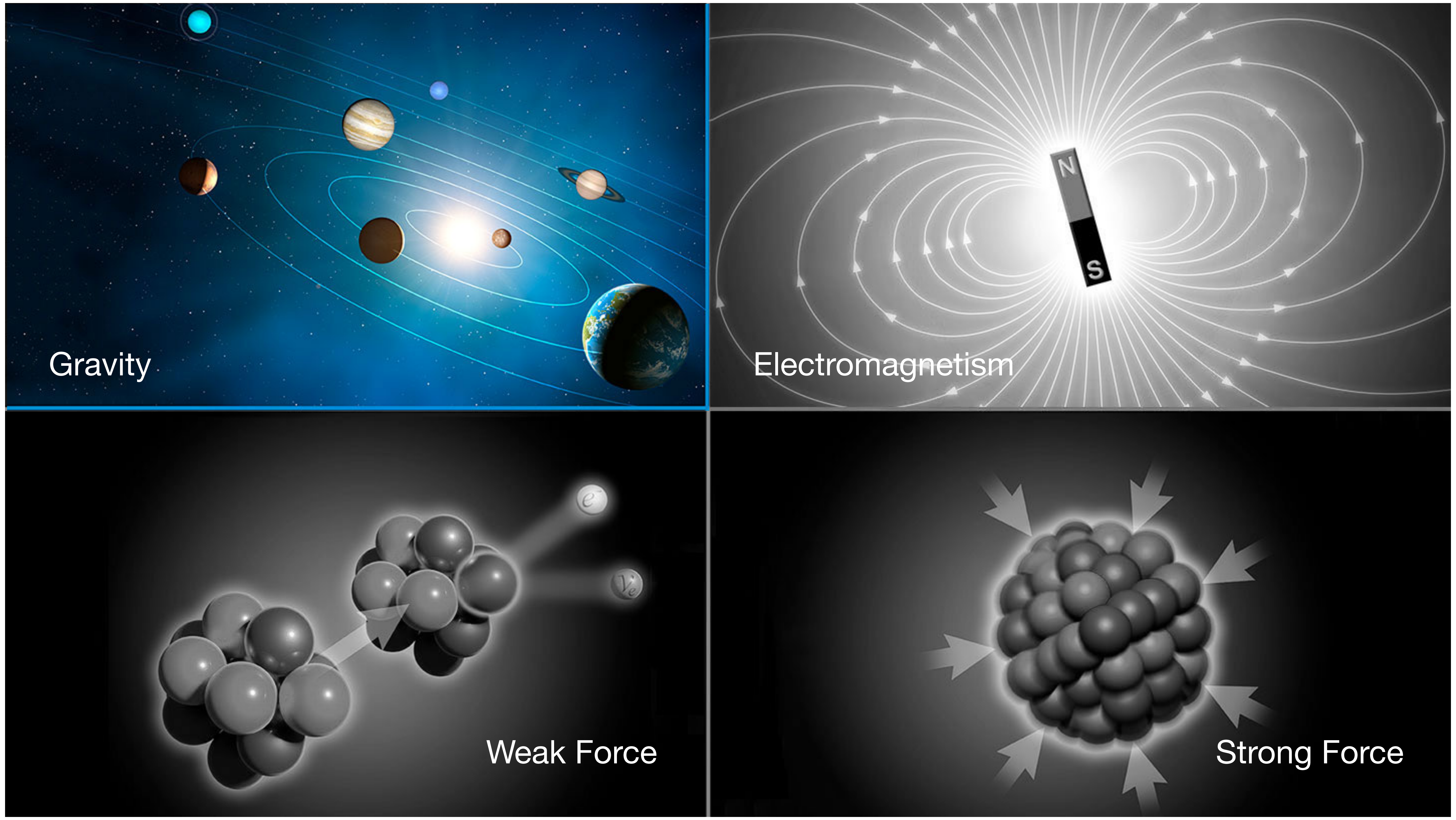



*Mark Garlick/Science Photo Library/Getty Images Plus; adapted by L. Steenblik Hwang*

# Gravity

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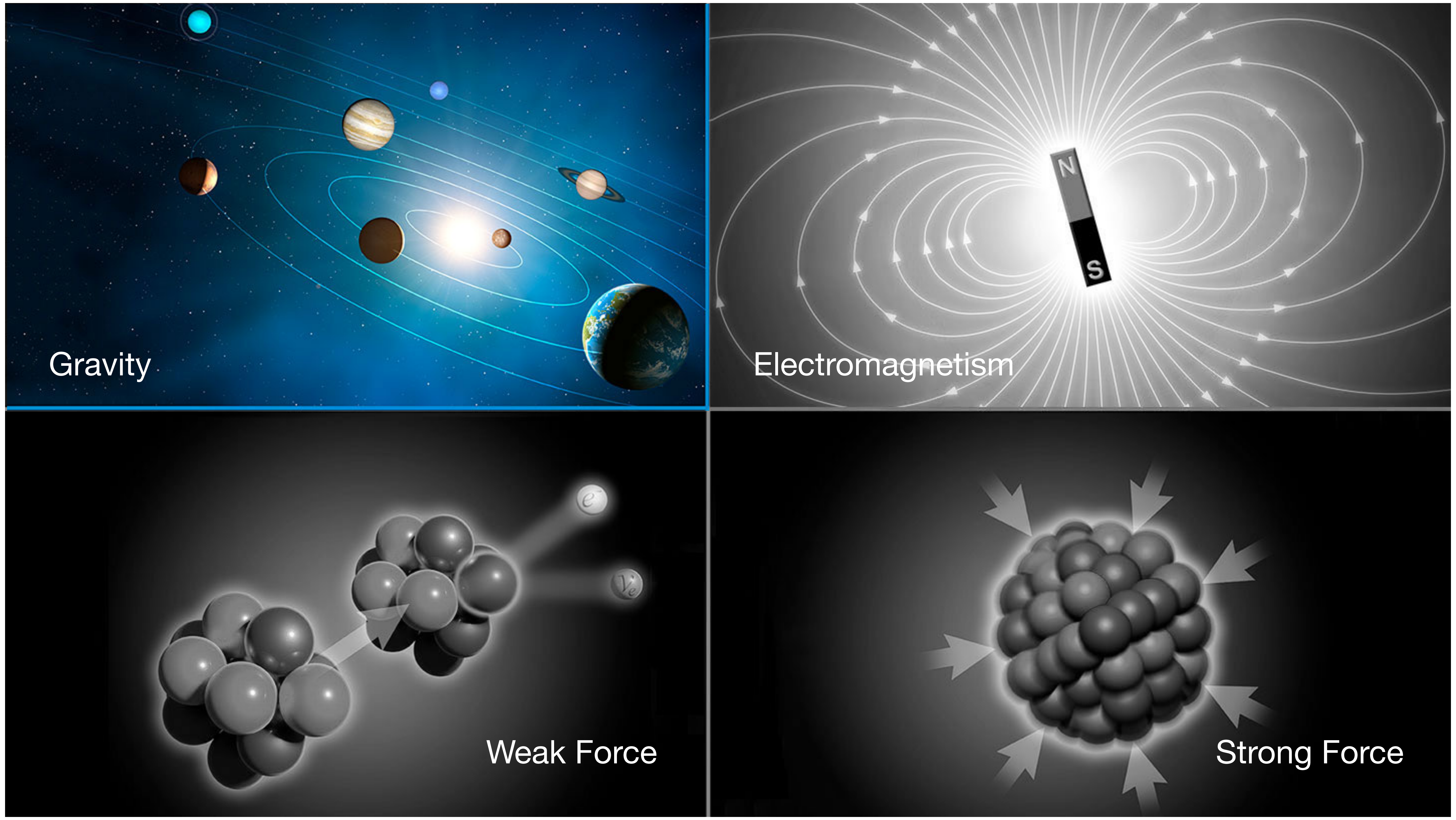


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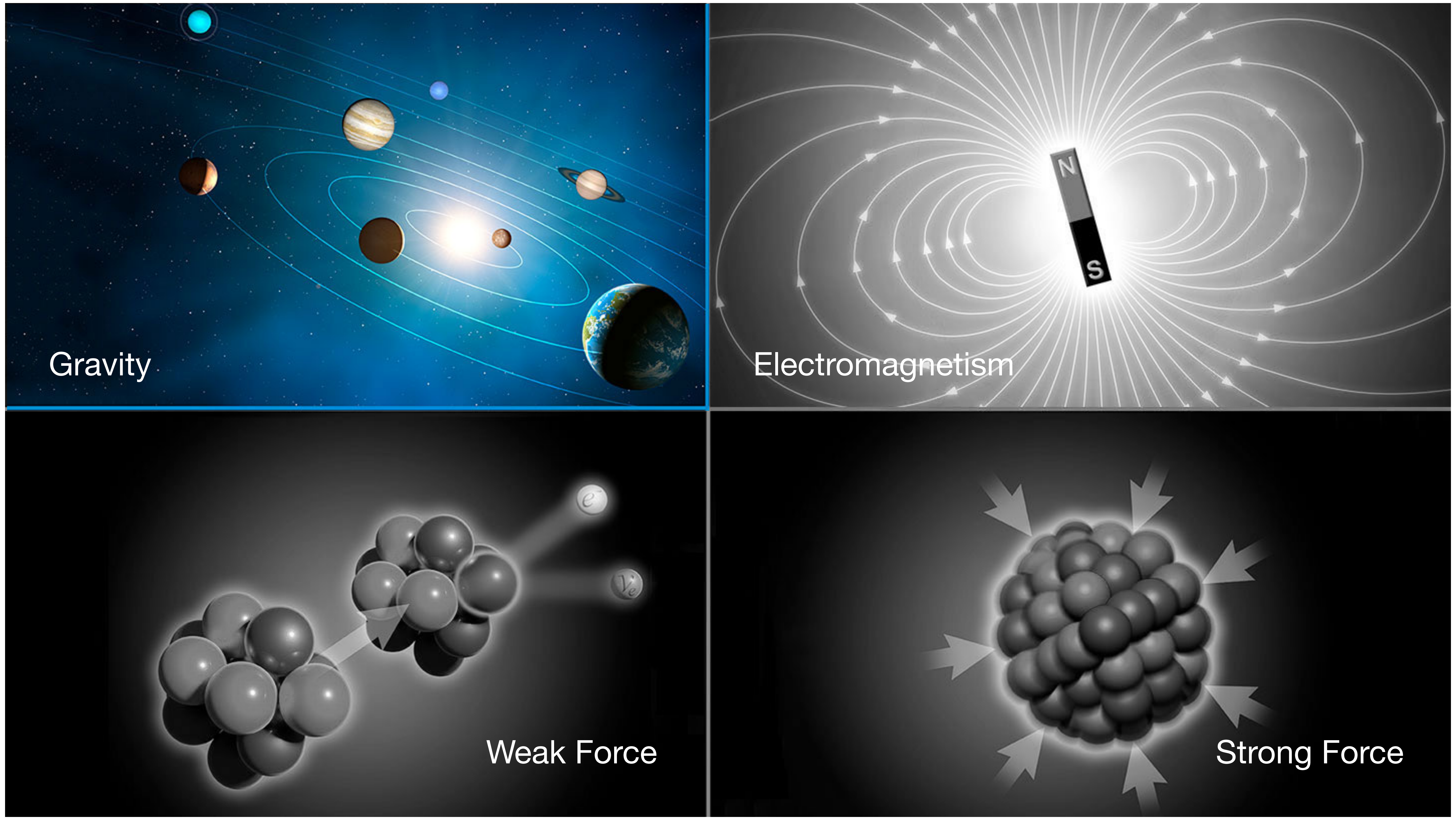


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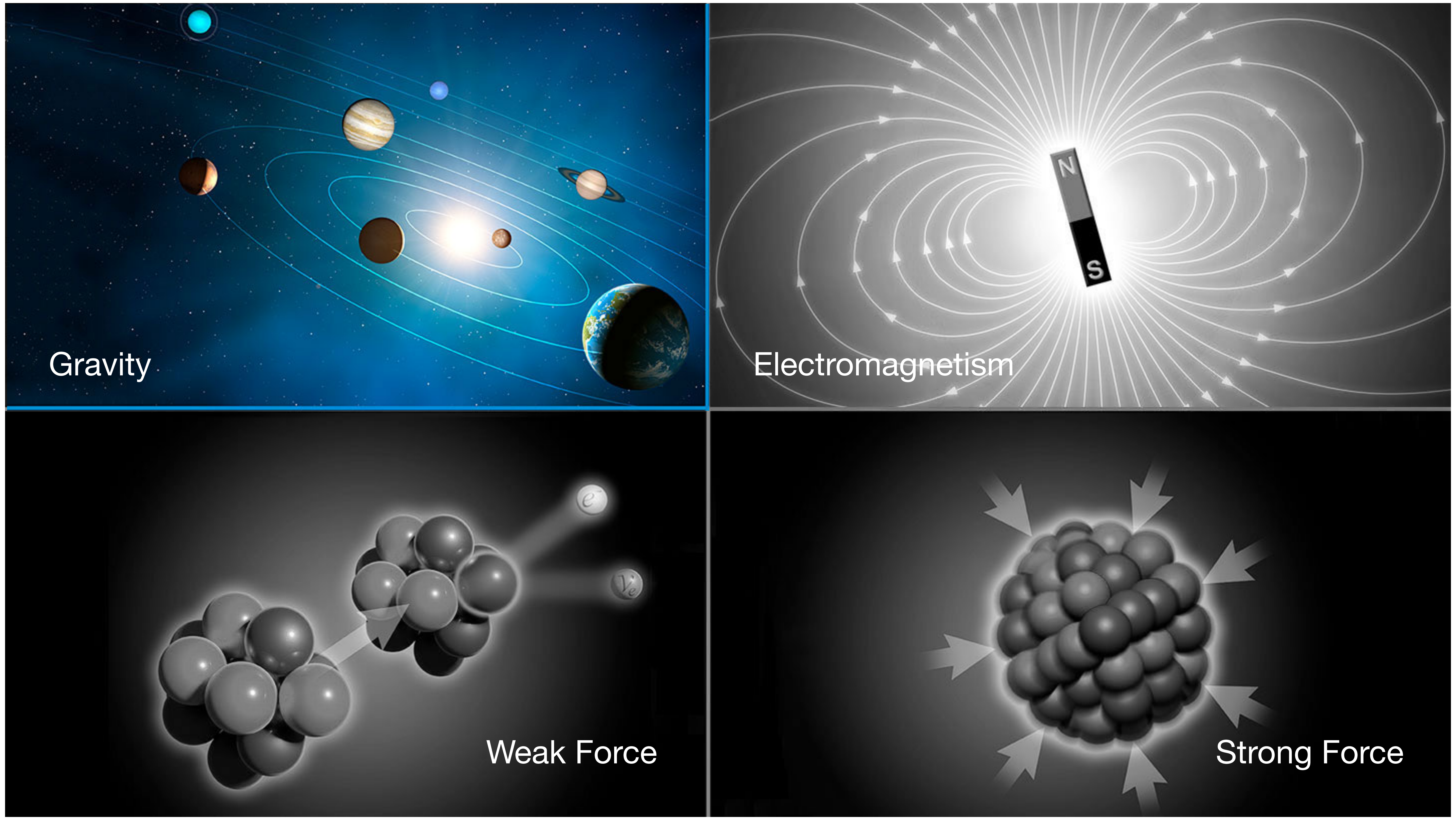


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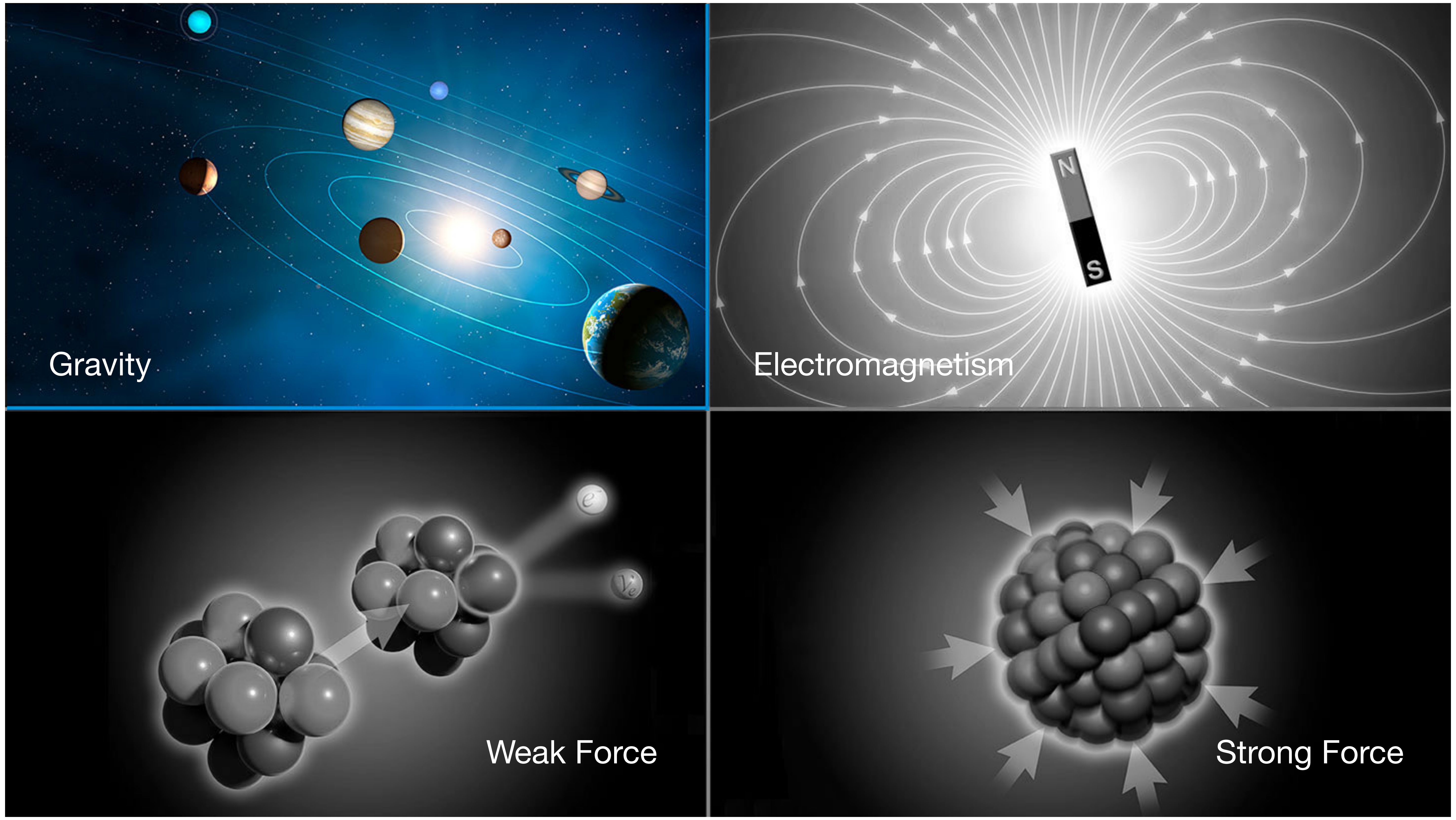


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- It is only attractive, with **no repulsive component**
- It is **much weaker** than the other forces
- We have yet to find a specific particle that is associated with it (more on this later…)

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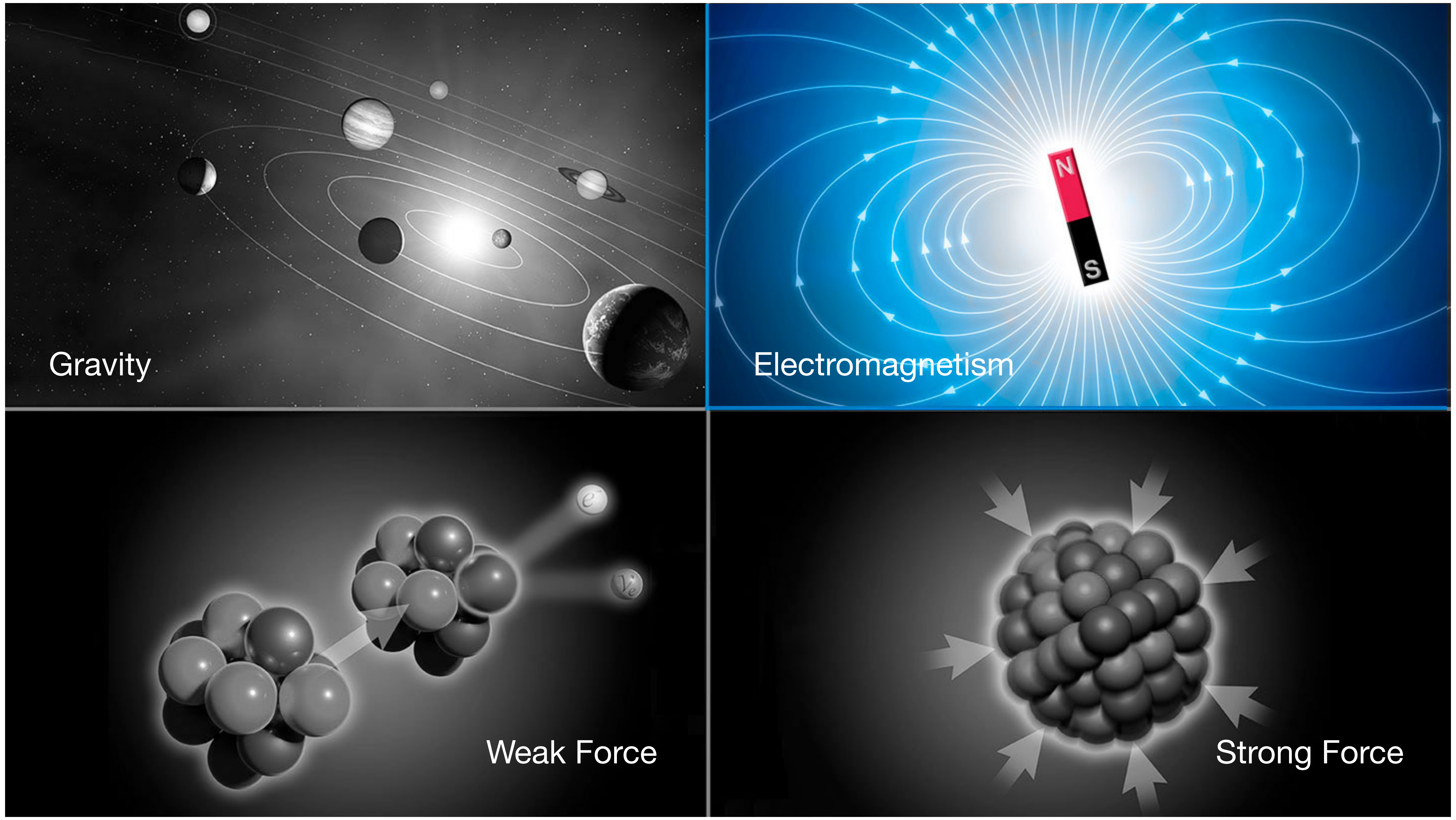
# Electromagnetism

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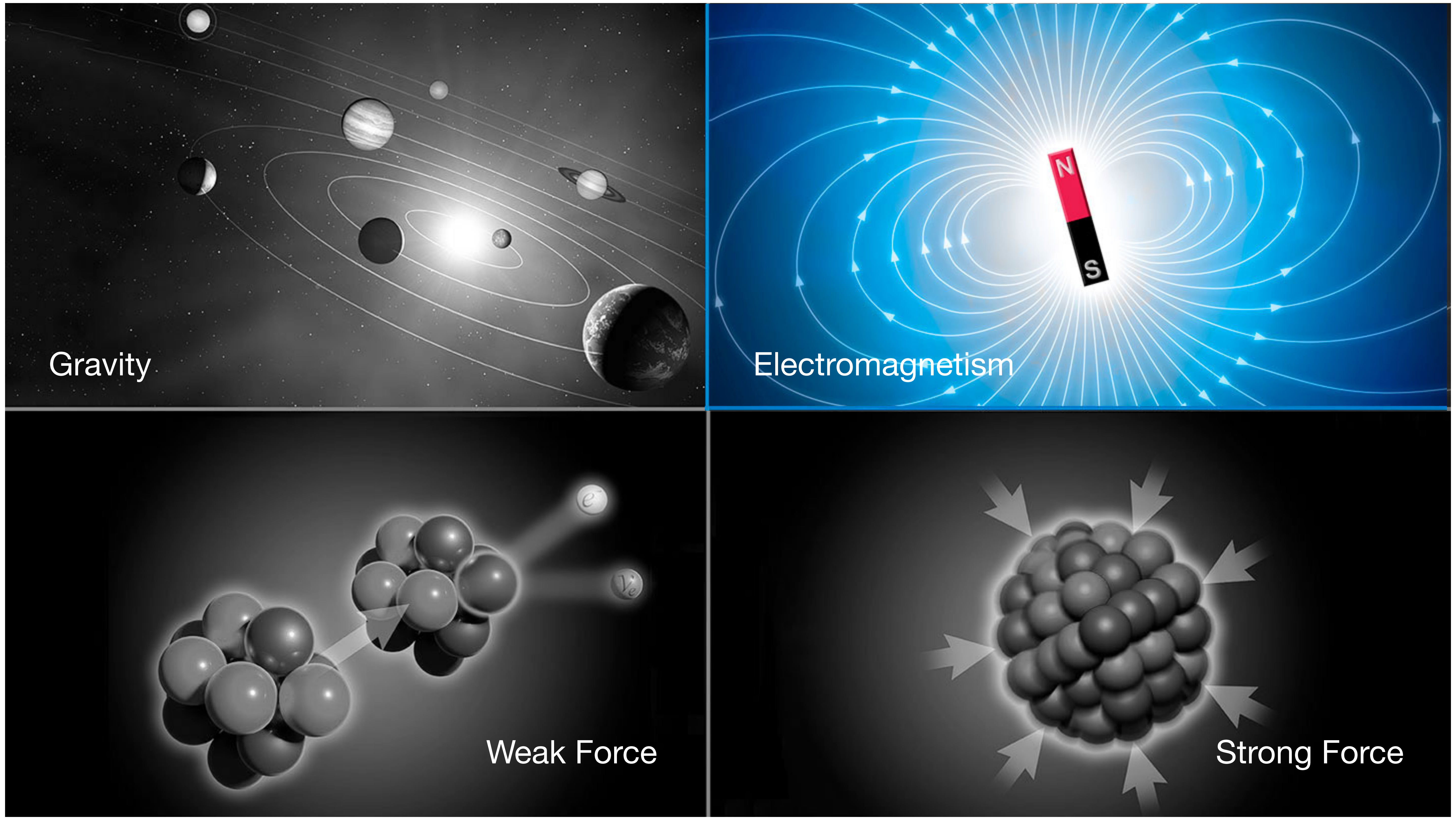


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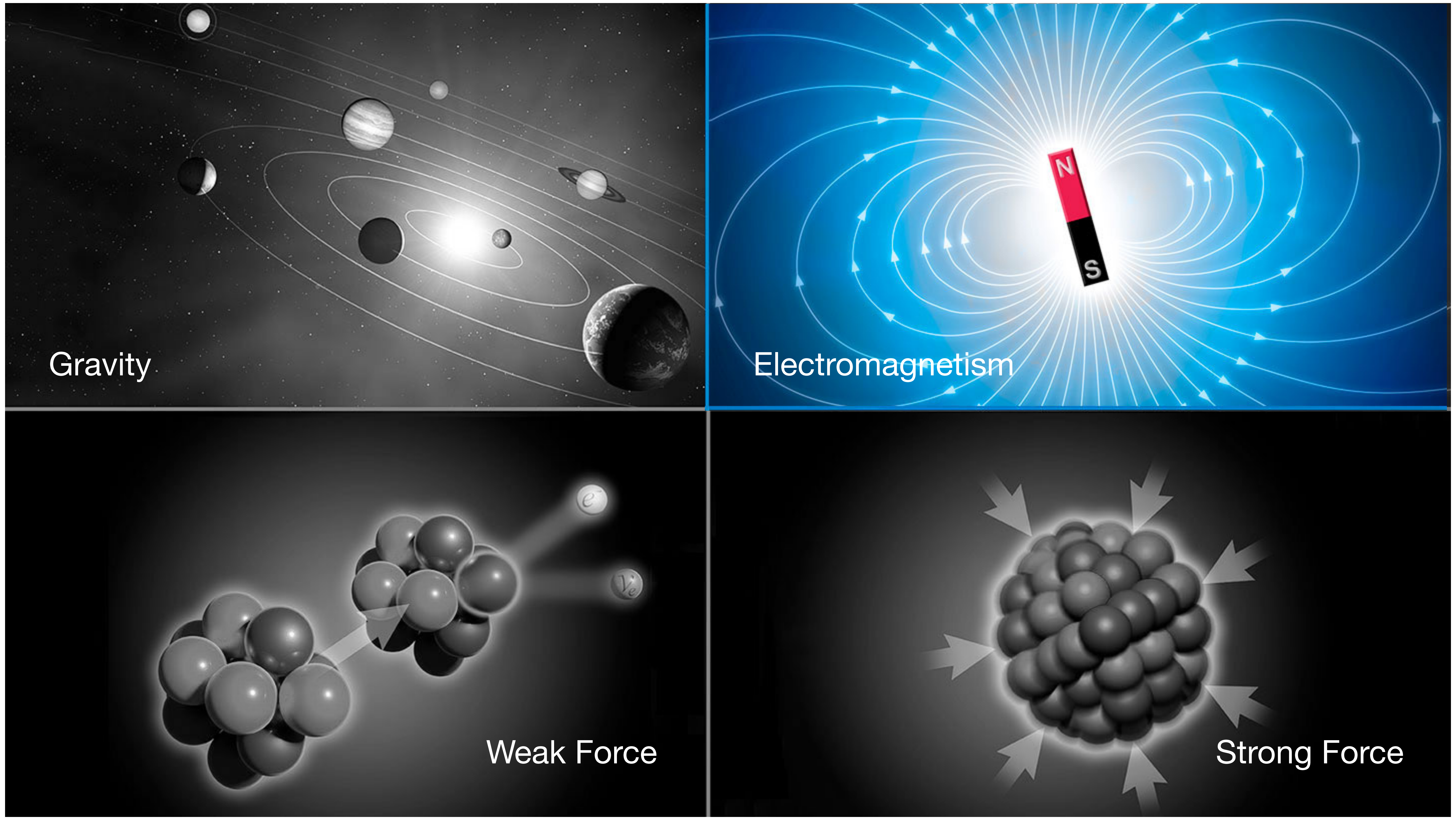


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Electromagnetism is responsible for many effects we see in day to day life: **light, electricity and magnetism**

- It affects all particles which carry **electric charge**

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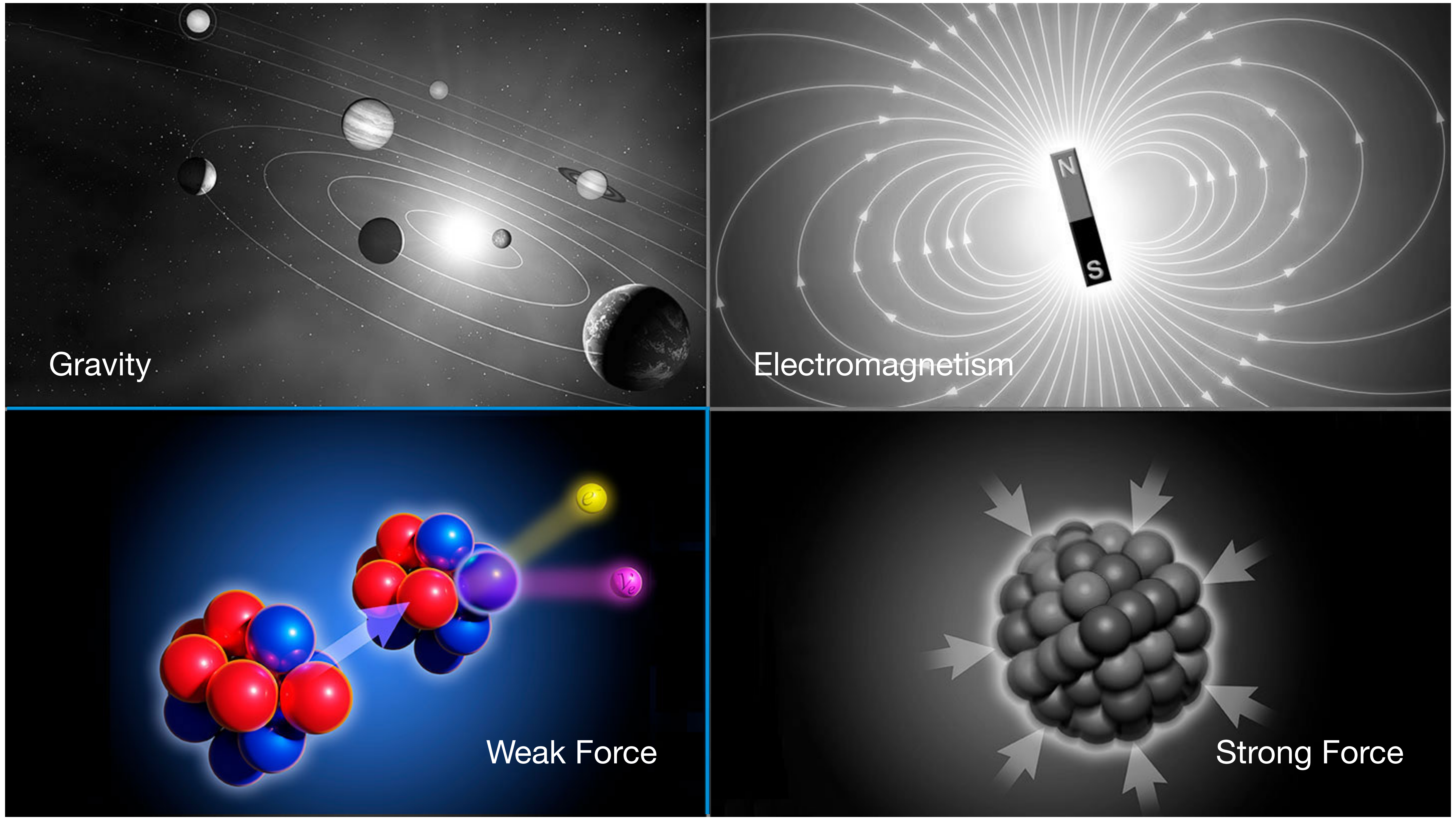
# The Weak Force

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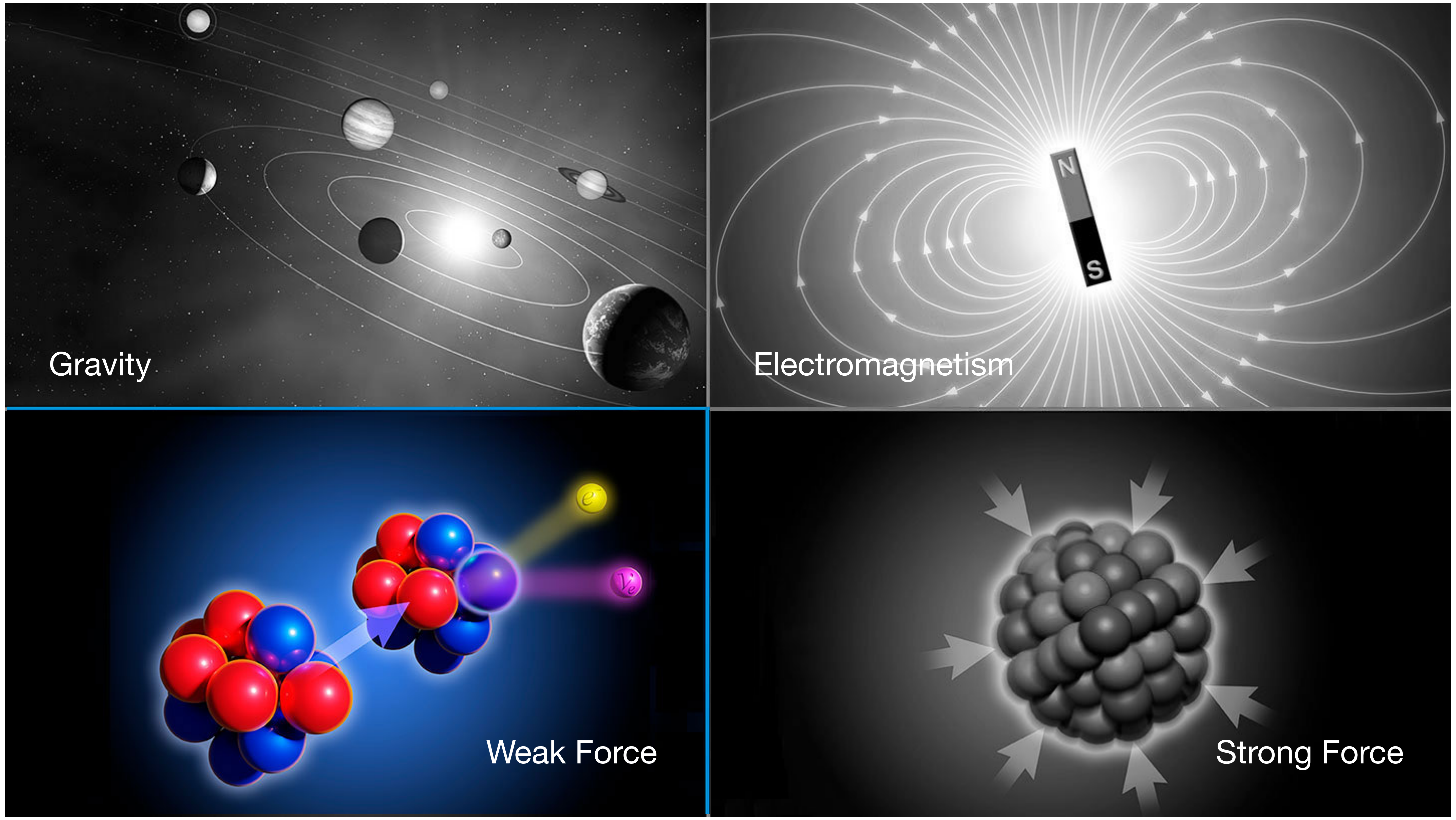


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The weak force is the mechanism behind **radioactive decay**

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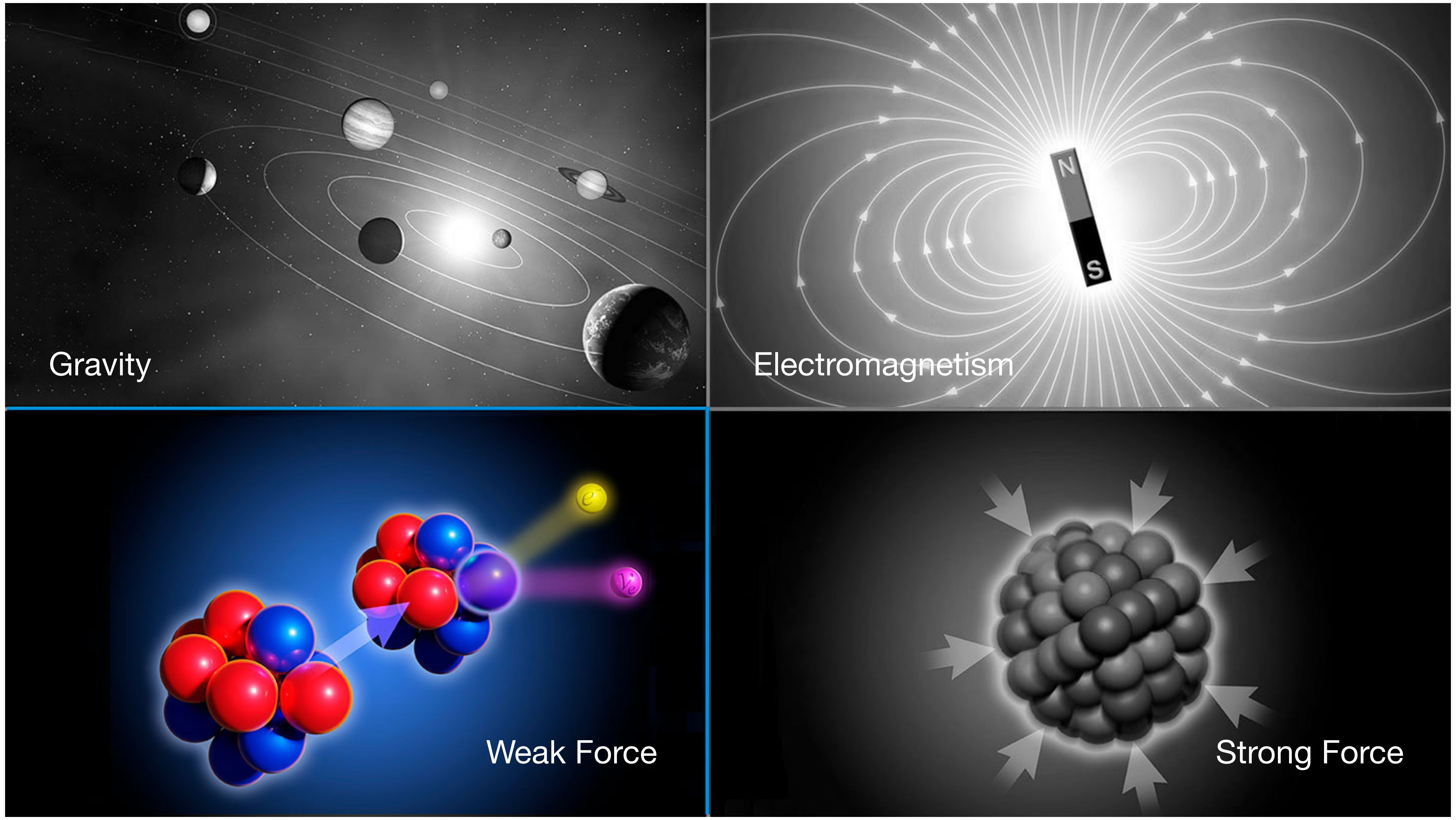


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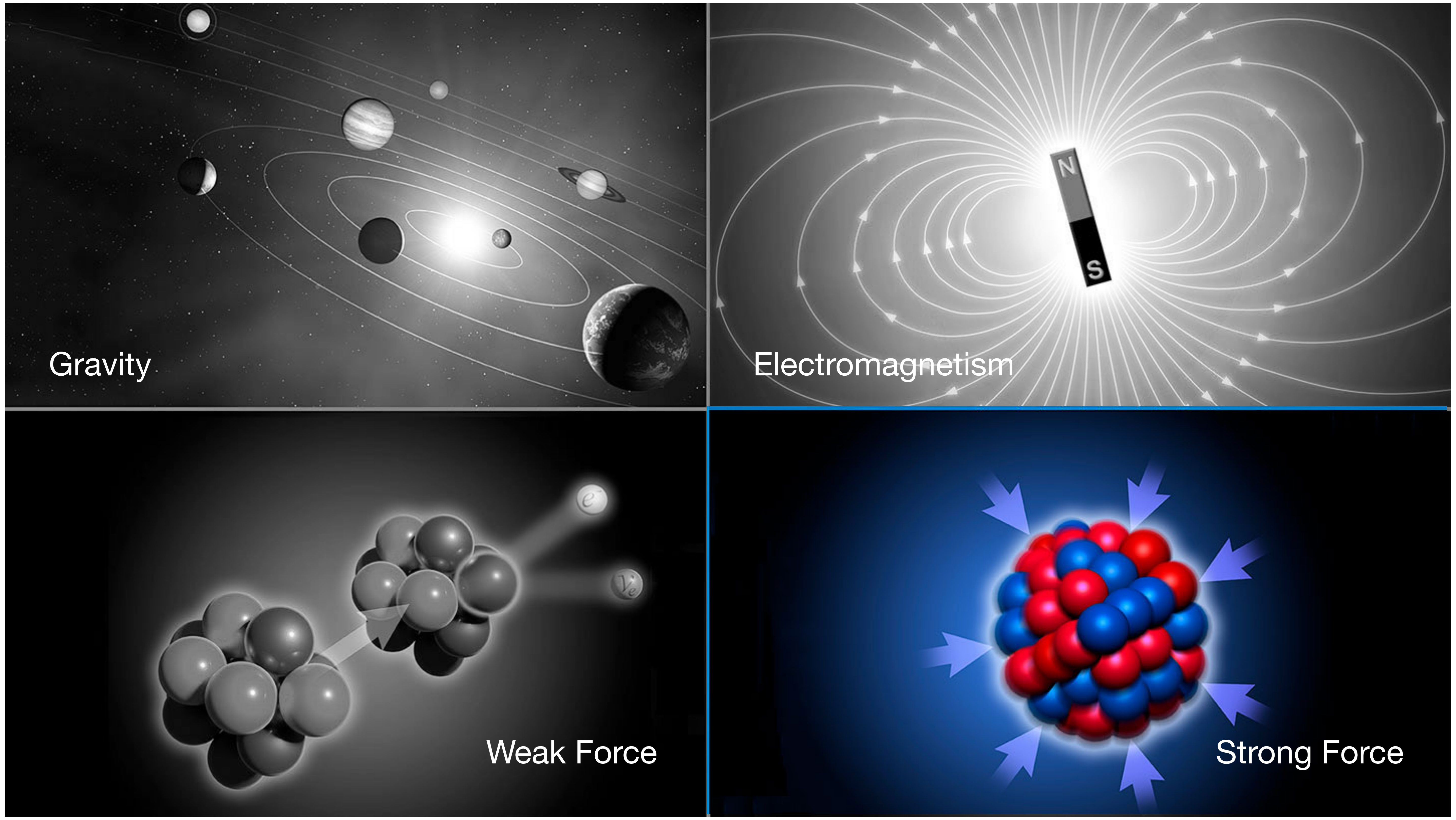
The weak force is the mechanism behind **radioactive decay**

- It is able to turn **neutrons into protons**, and vice-versa

# The Strong Force

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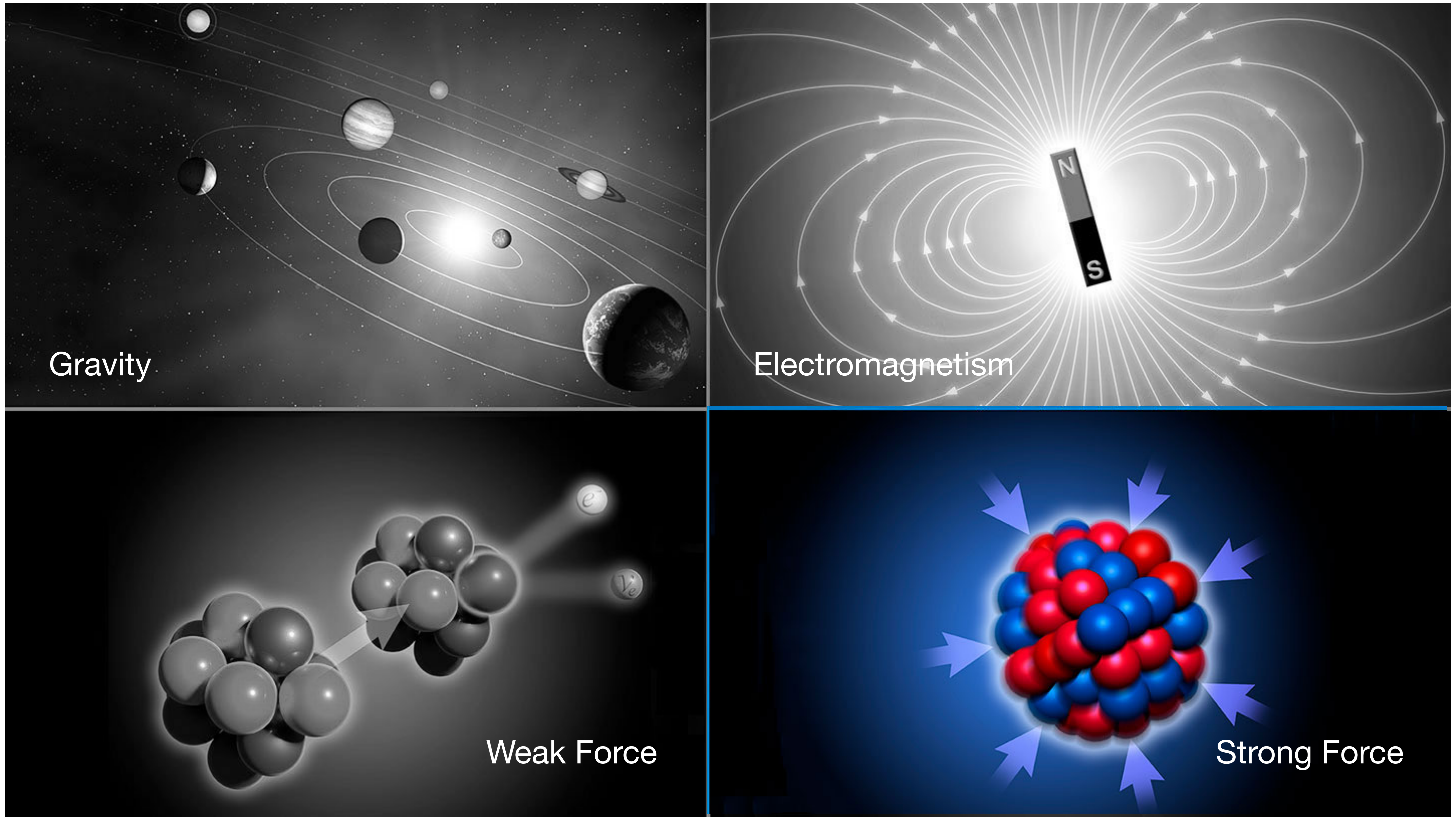


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The strong force is responsible for holding together the particles **within protons and neutrons**

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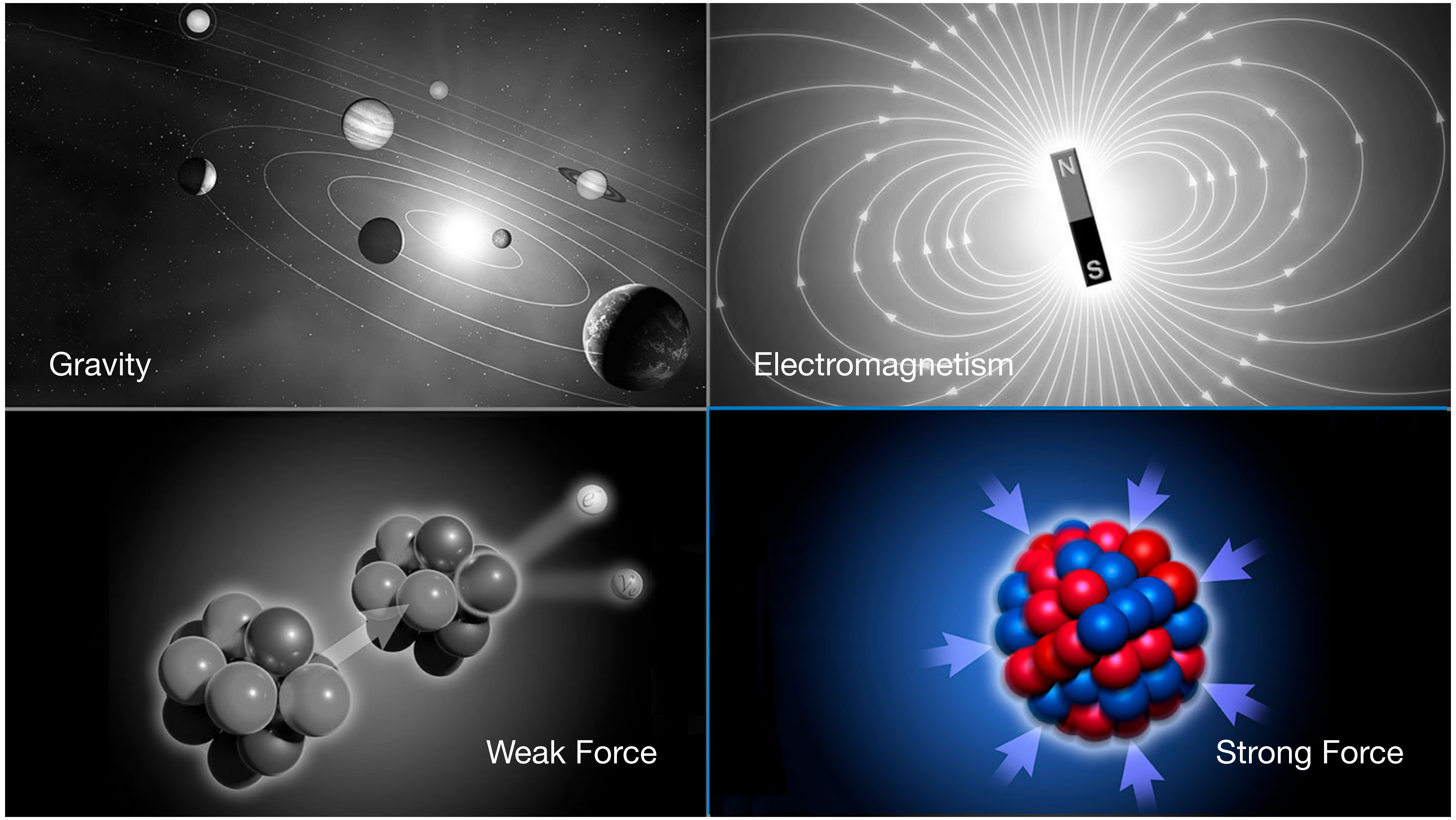


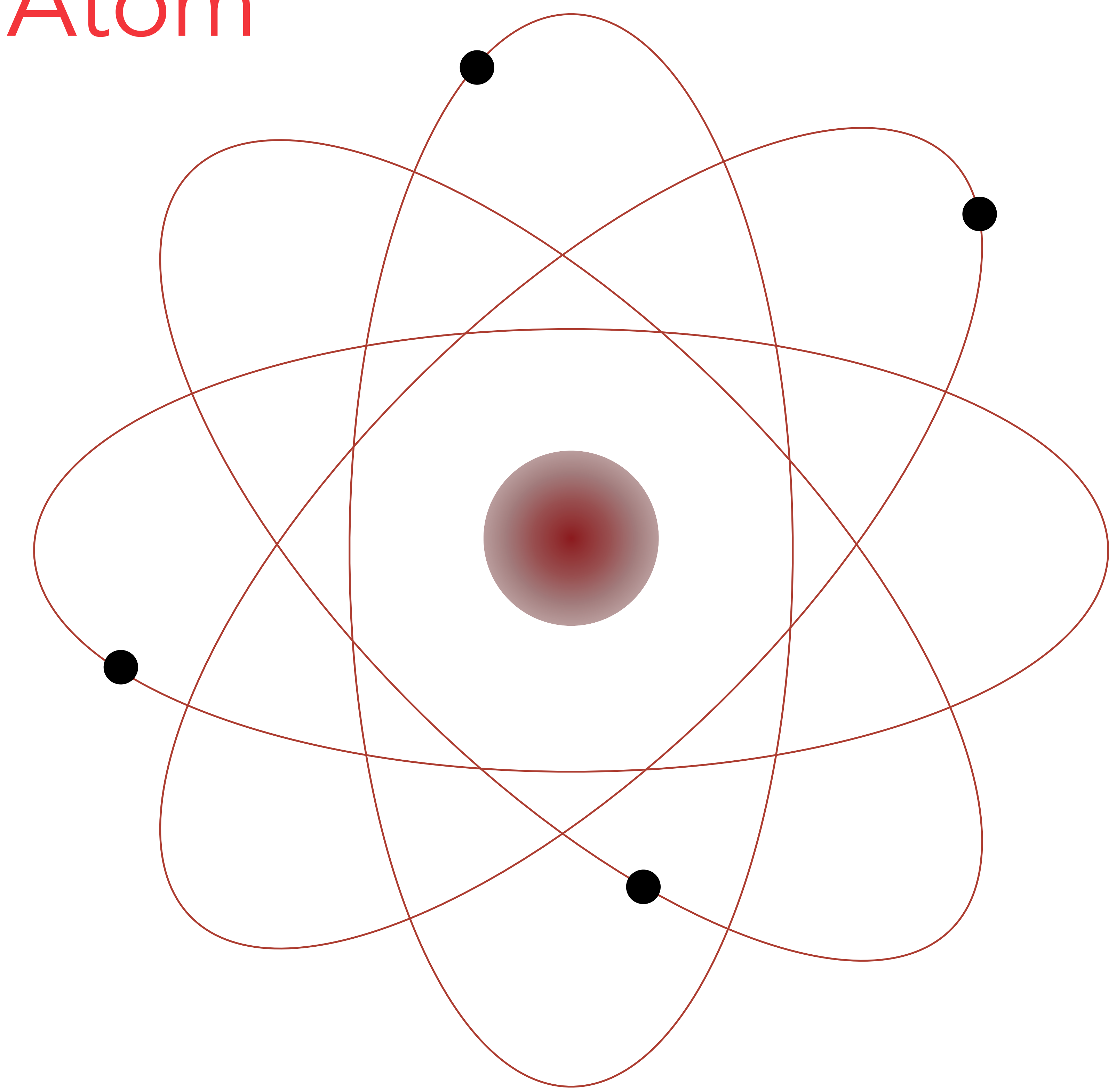

*Mark Garlick/Science Photo Library/Getty Images Plus; adapted by L. Steenblik Hwang*

The strong force is responsible for holding together the particles **within protons and neutrons**

- It affects all particles that carry **color charge**
- We will return to this in more depth soon!

# Inside the Atom

## Atom



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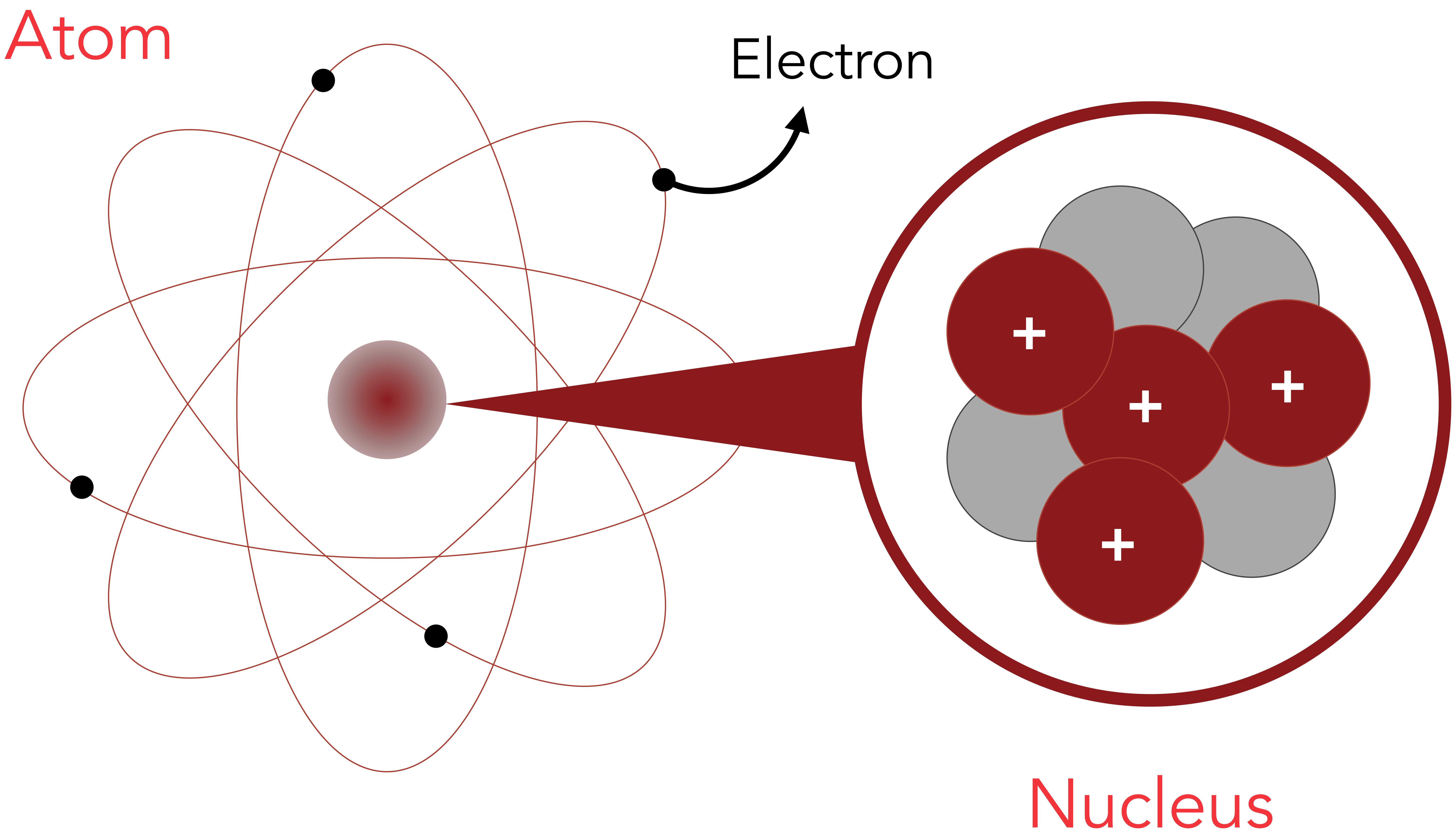


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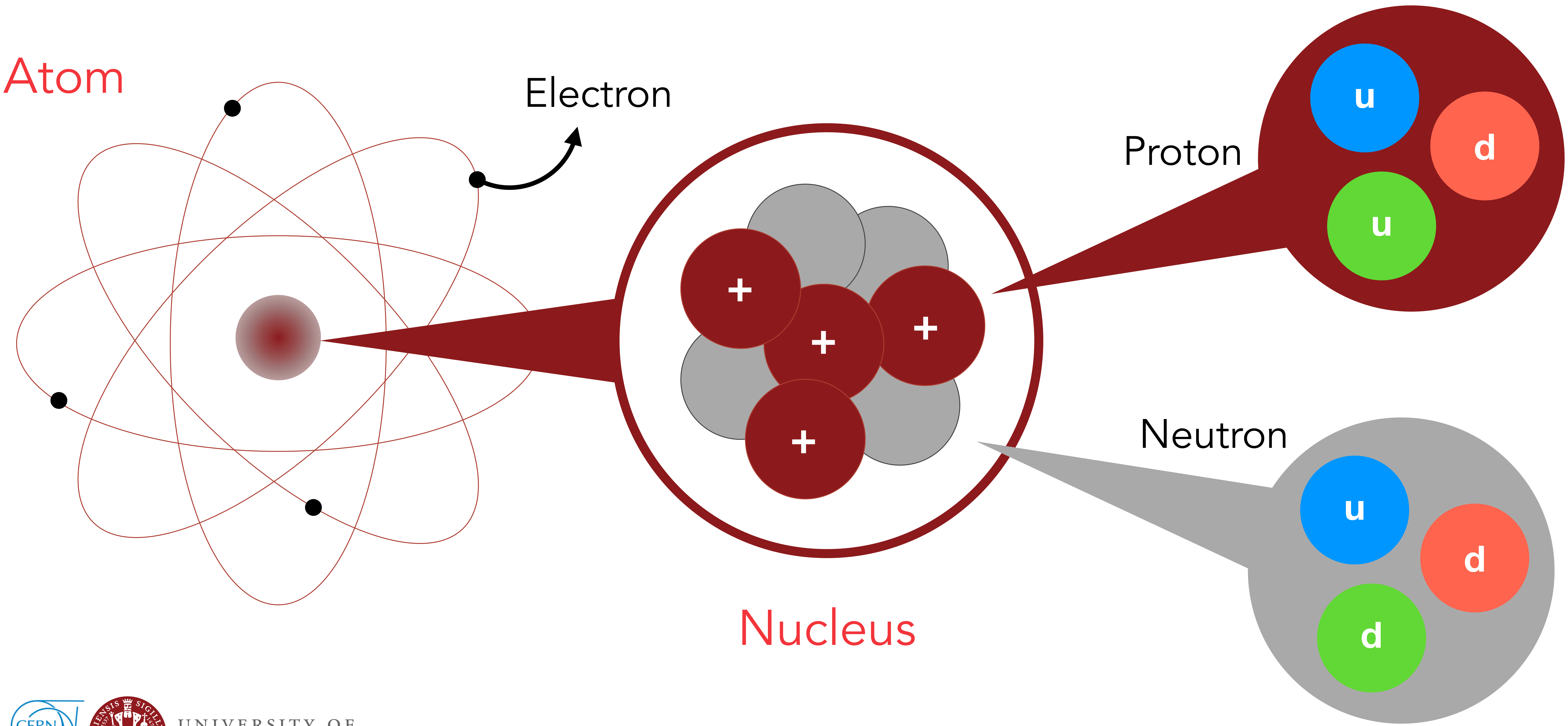


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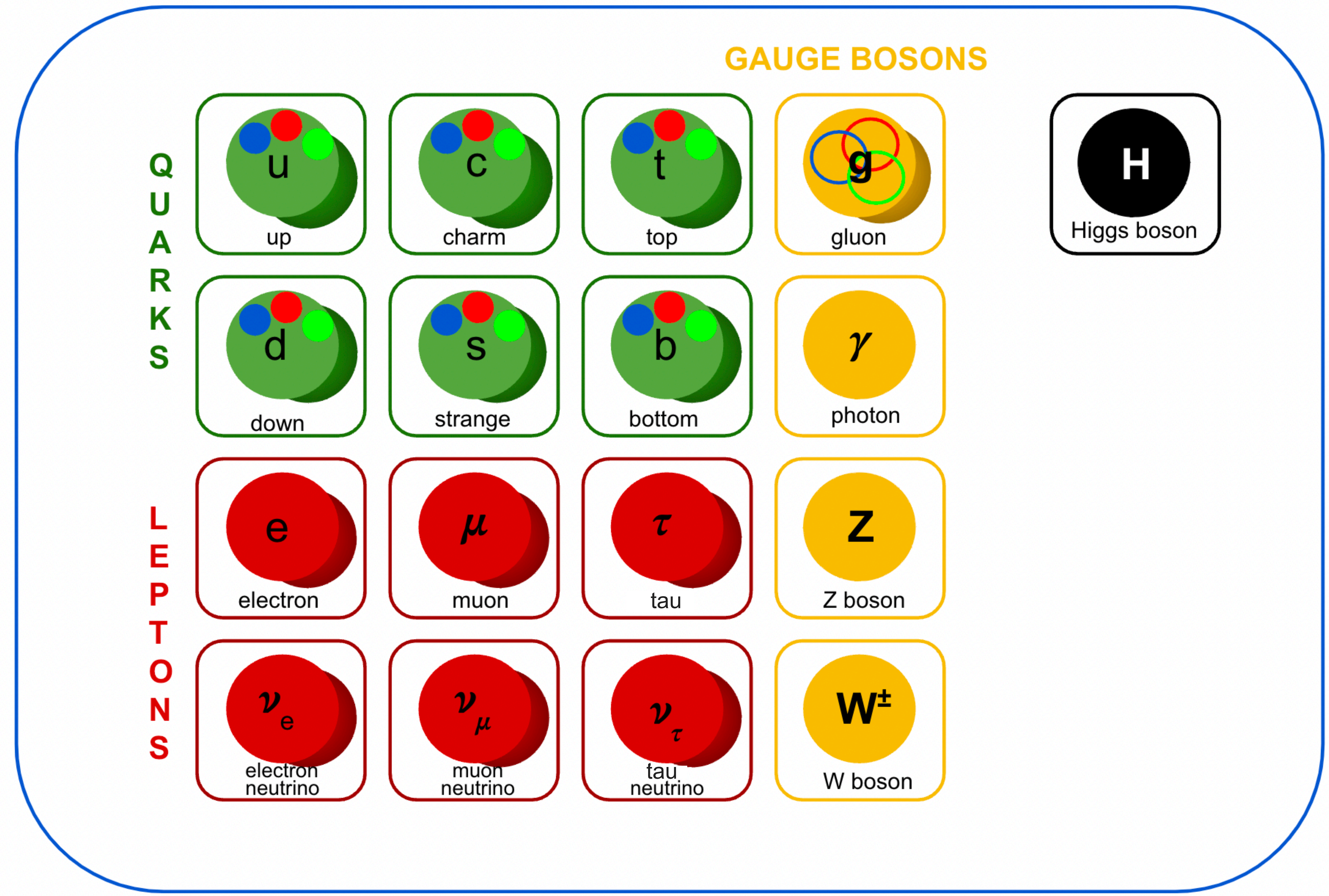
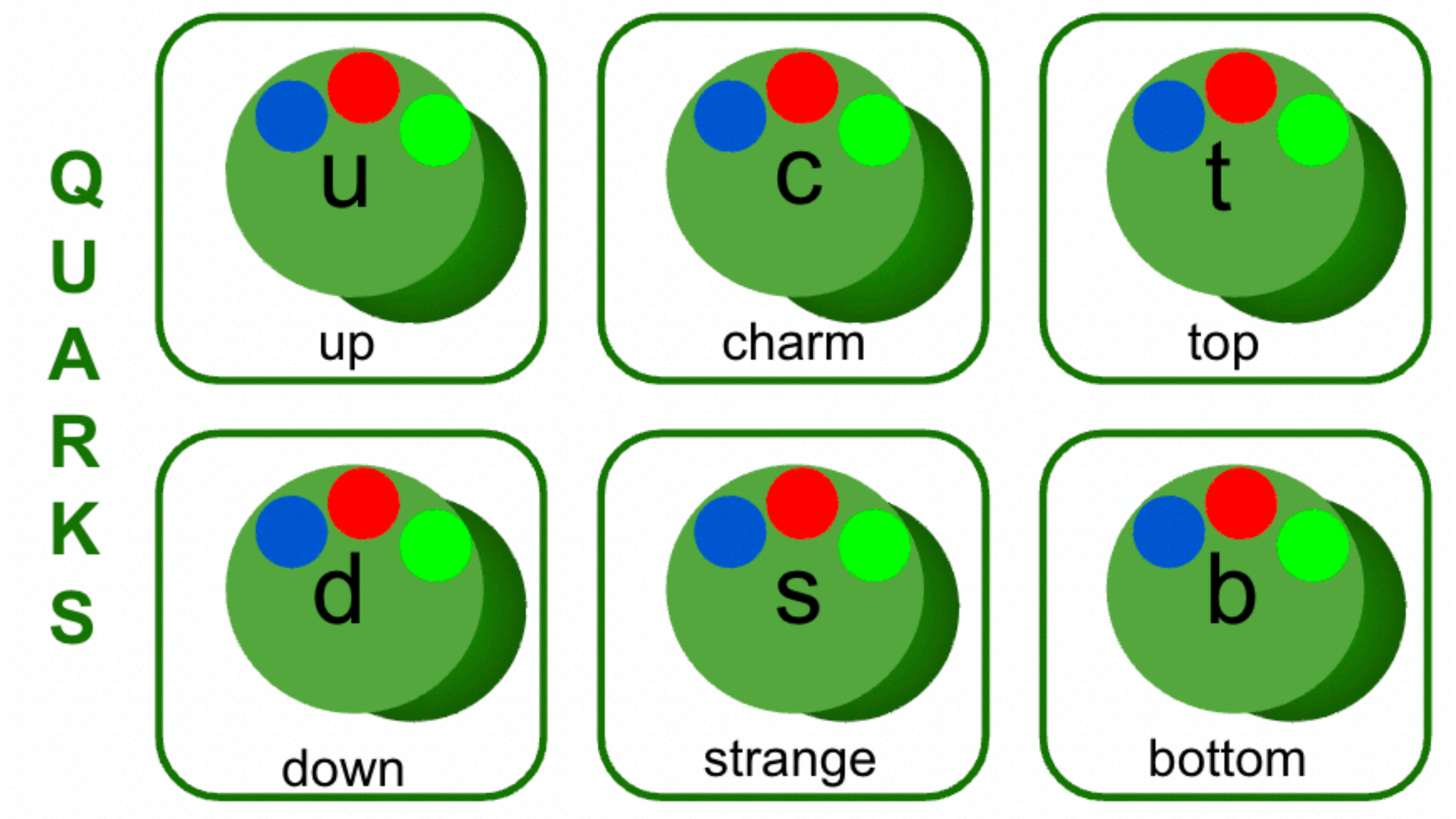
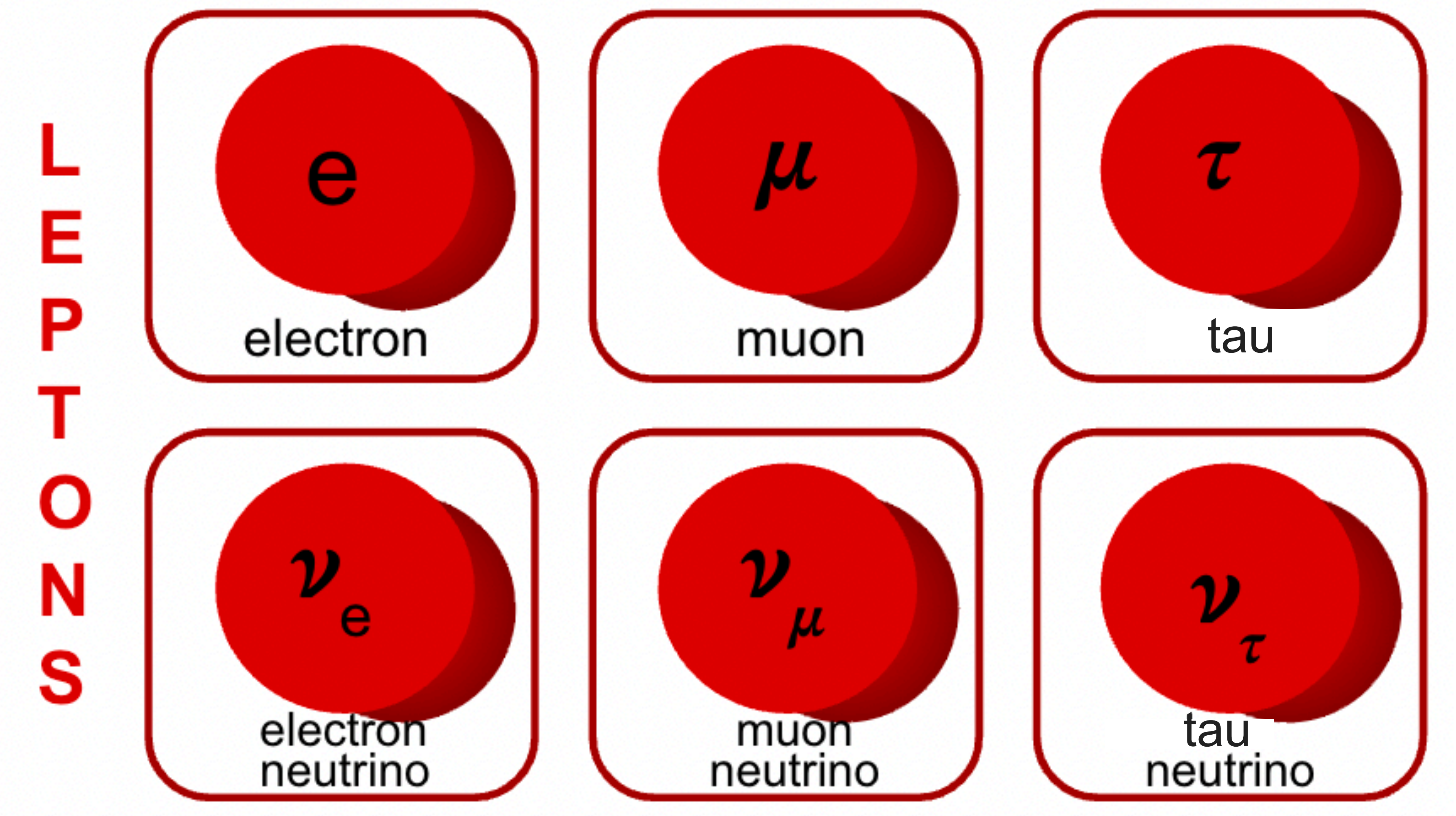
# Fundamental Building Blocks



# Fermions

The particles making up physical matter are called **fermions**, and they can be split into two distinct categories:

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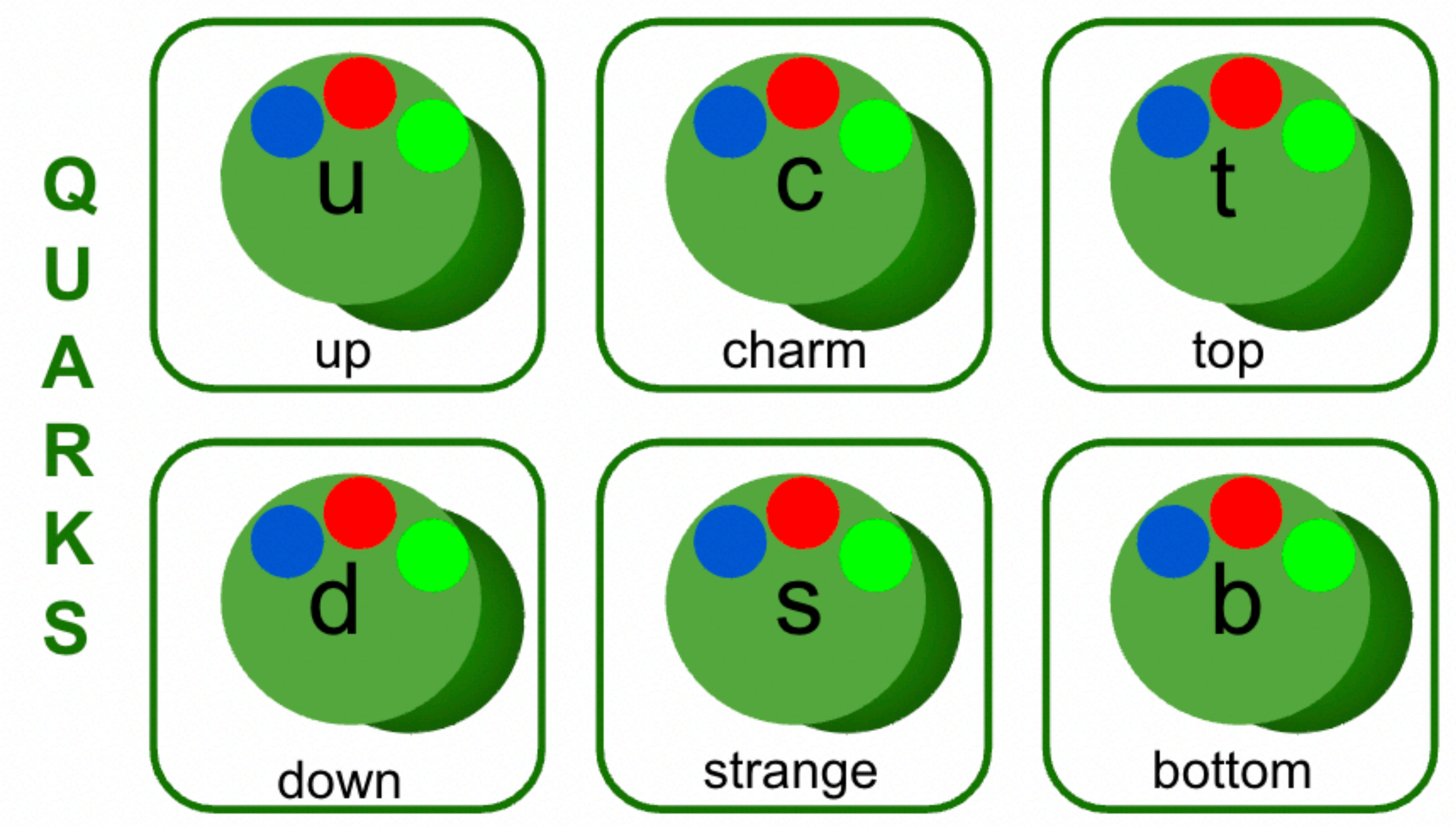
# Quarks

**Quarks** come in six "flavors" and are found within the atomic nucleus, <u>always grouped into bound states called hadrons</u>

More on this later…

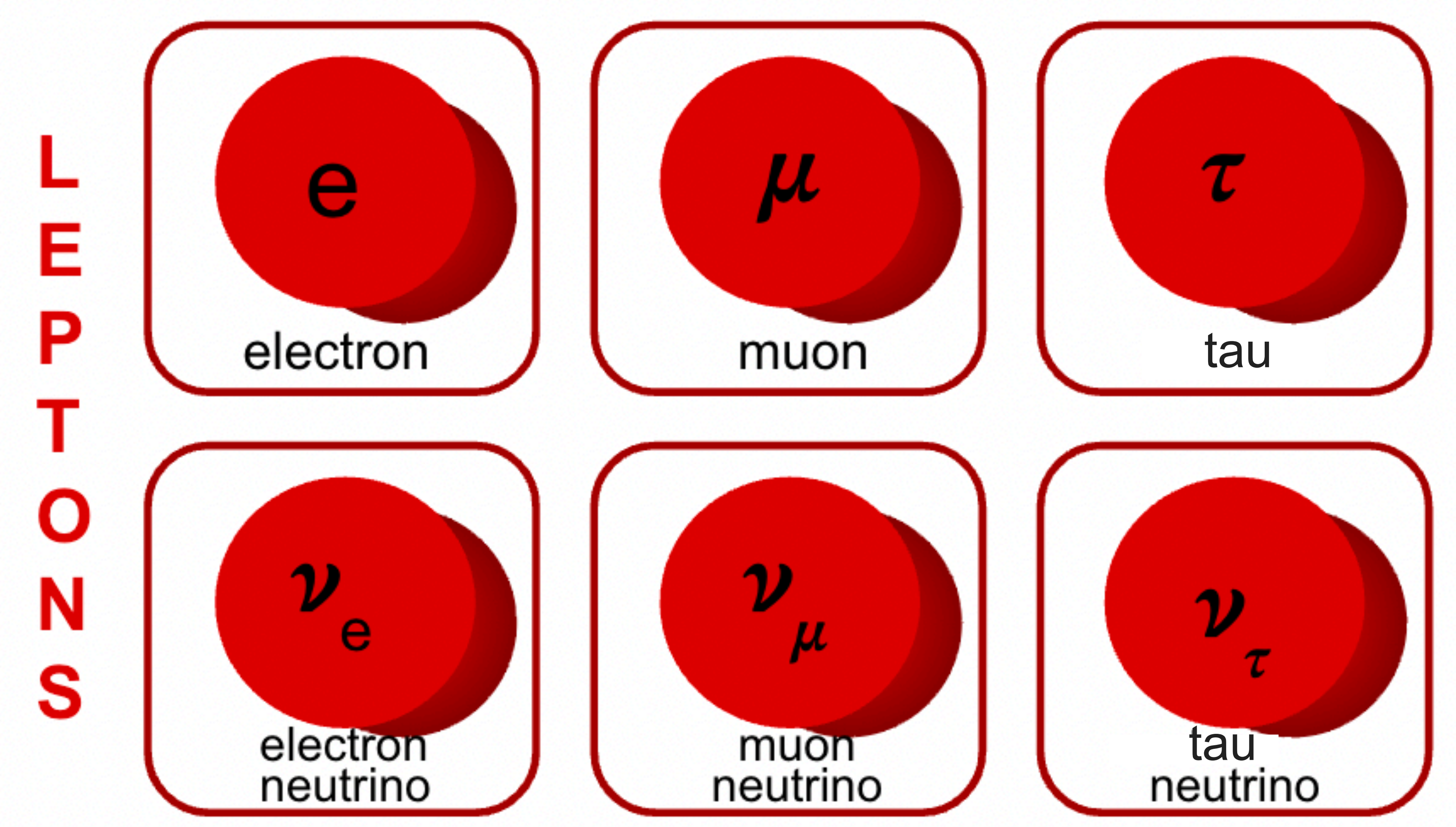



Hadrons can be made up of two quarks **(mesons)** or three quarks **(baryons)**

*Different combinations of quarks make different hadrons: for instance two ups and a down make a proton, while two downs and and up make a neutron!*

# Leptons

**Leptons,** however, can exist freely - you are likely familiar with the most common particle of this type: the electron!

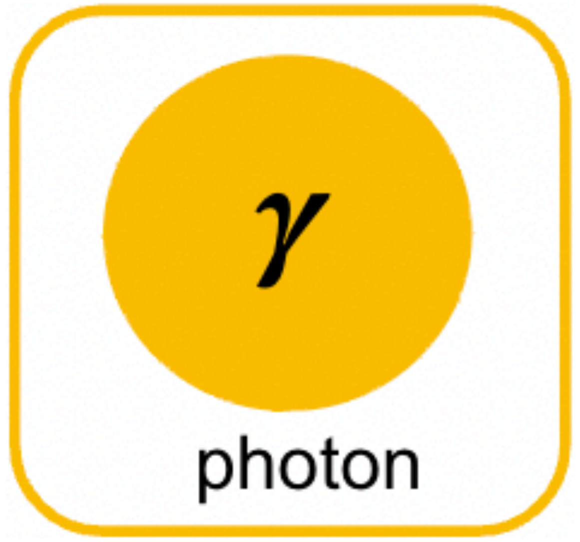



**Electrons, muons and taus** all act similarly (though they have different masses), and each have an associated **neutrino**

# Bosons

**Gauge Bosons** are "force carrying" particles - they mediate the fundamental forces of nature which dictate how the fermions interact


Strong Force




Electromagnetism



Weak Force


The **Higgs Boson** is a special case.
Though it is a boson, it doesn't carry a specific fundamental force - instead it's responsible for giving the other particles mass!

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# Zooming Out

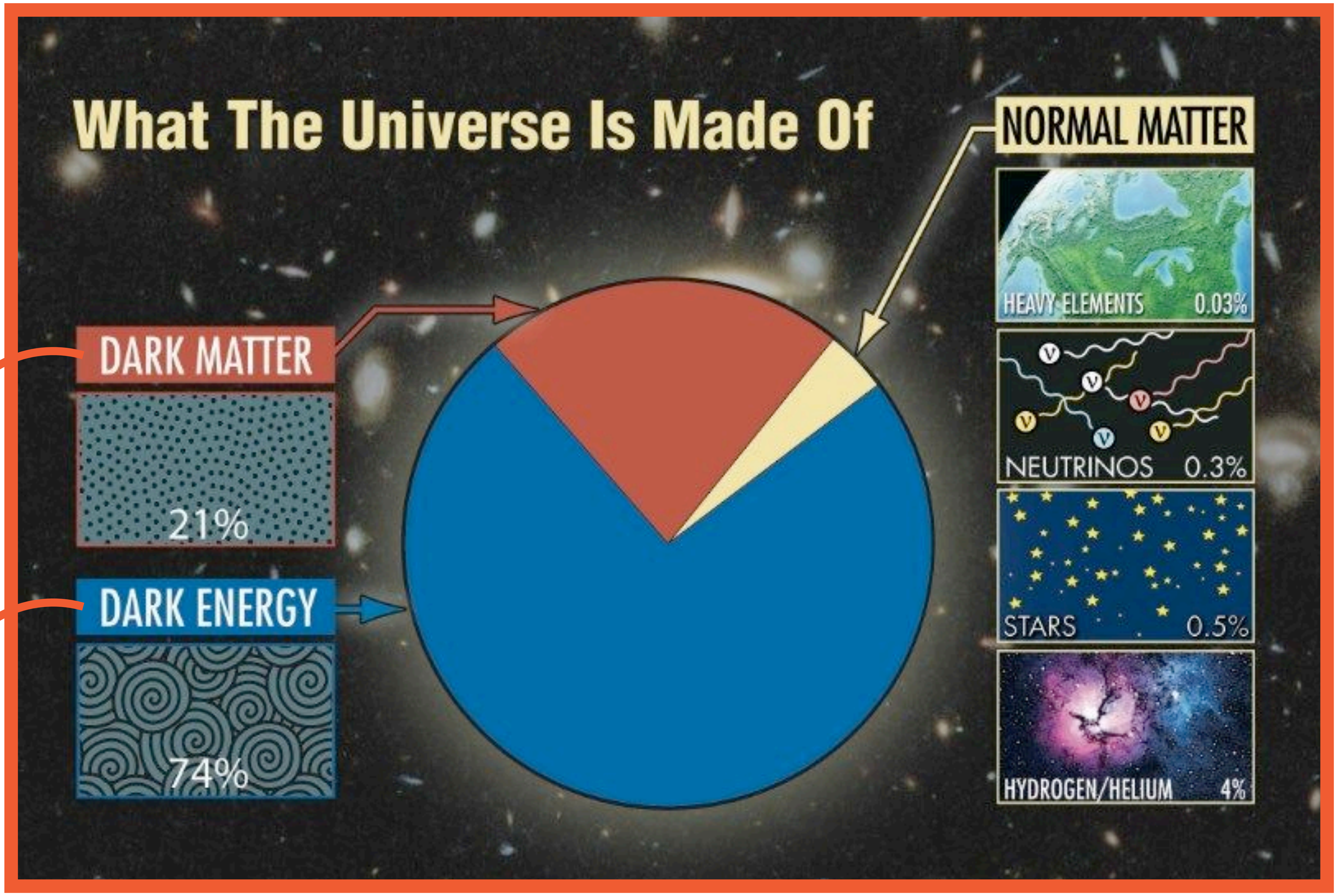
# The Fabric of the Universe

How do our building blocks and tools come together?

A large part of the universe is made up of components we can construct from their effects, but **have not observed directly**

Matter (?) that only interacts via gravity

The explanation for the universe expanding




The fundamental particles we have covered come together to form recognizable elements and astronomical objects, but this is just **~5%** of the universe!

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# Unanswered Questions

The Standard Model does a good job of describing a lot of physical effects, but there are still phenomena it cannot explain:

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The Standard Model does a good job of describing a lot of physical effects, but there are still phenomena it cannot explain:

- **The Hierarchy Problem:** Why is gravity so much weaker than the other forces?
- **Matter-Antimatter Imbalance:** Why is there so much more matter than antimatter?
- **Unknowns in the Universe:** What are dark matter and dark energy, and what exactly are they?
- **And more…**

**How do we go about searching for the answers?**

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# Particle Experiments

# CERN

The **European Organization for Nuclear Research** (CERN) is one of the largest scientific collaborations in the world and is a major center for experimental particle physics

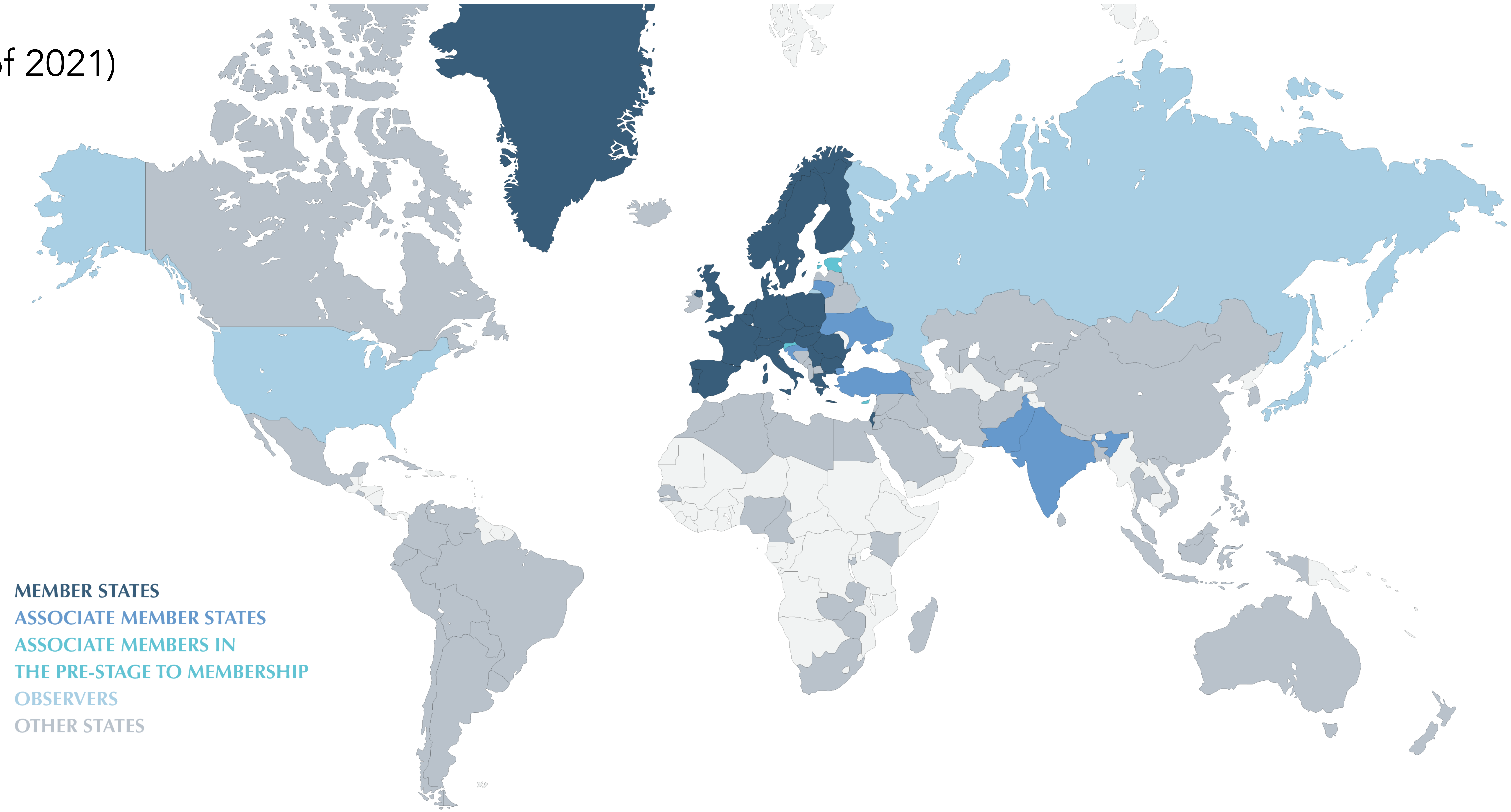
**1949** — A proposal is made for a collaborative European lab in the wake of WWII

**1952** — CERN is officially established, with Denmark signing on as a founding state

**2008** — The LHC is turned on for the first time

# An International Effort!

(Map as of 2021)




Even though CERN is a European laboratory, it collaborates with countries across the world!

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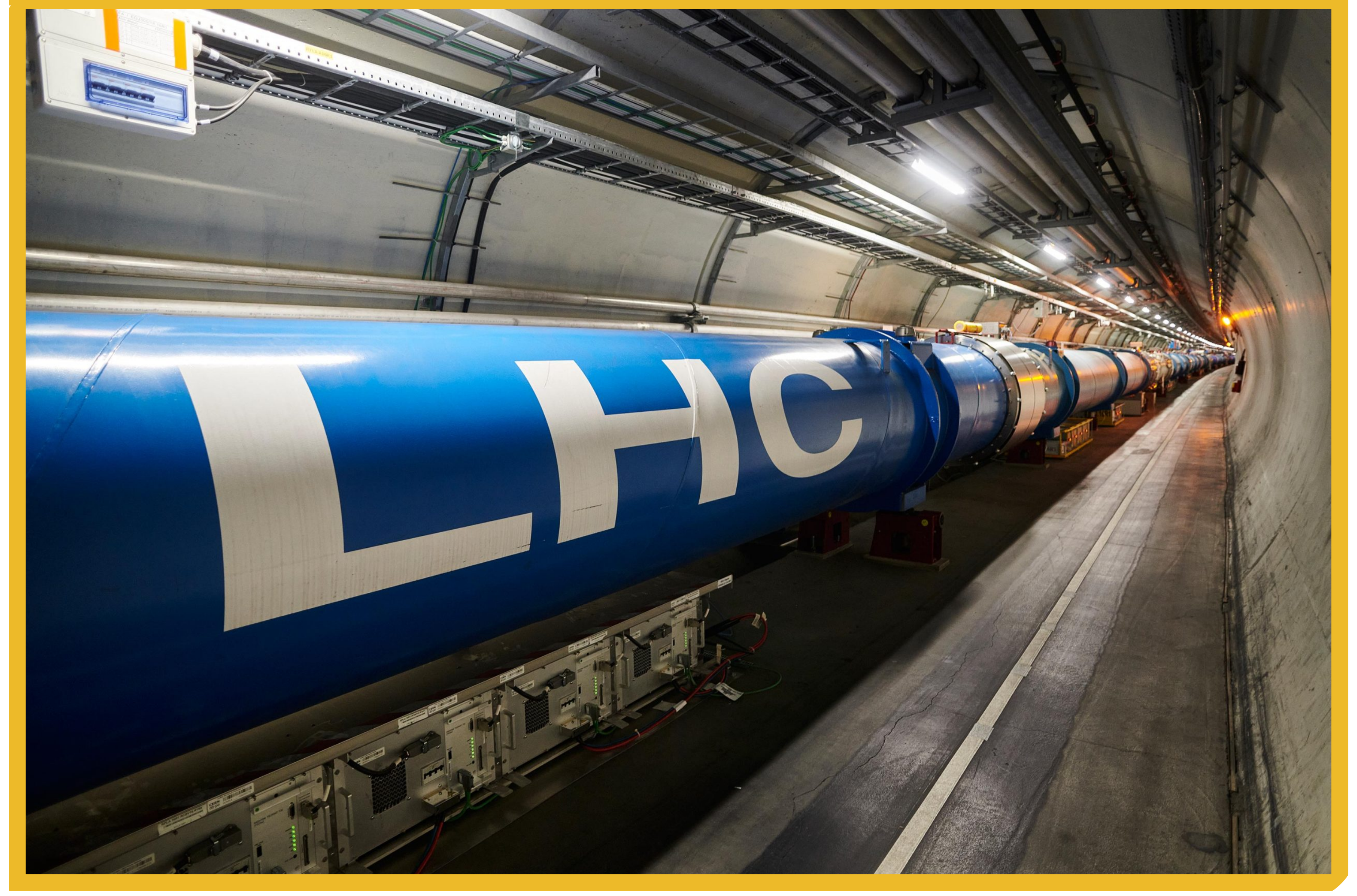
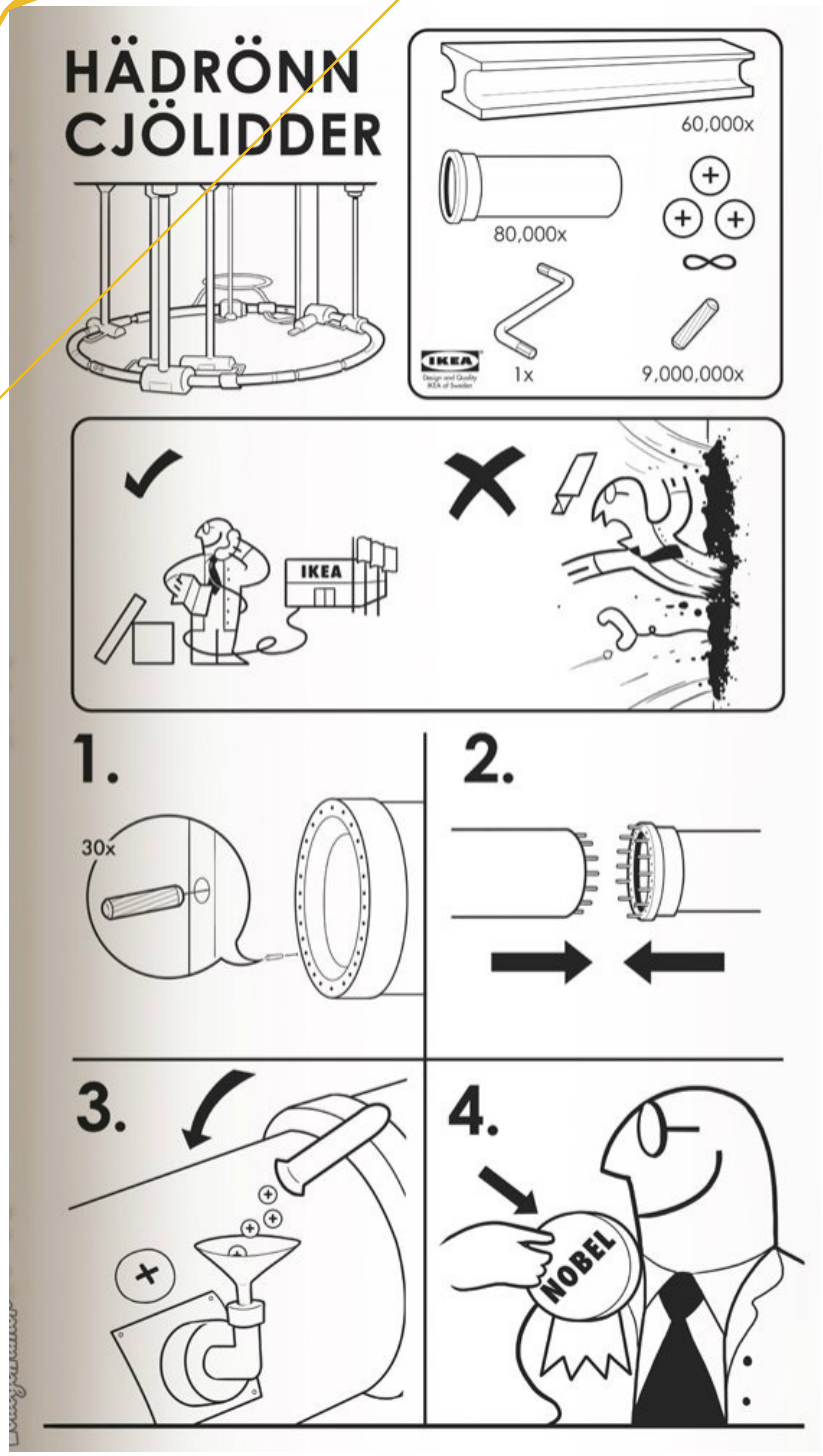
# The LHC

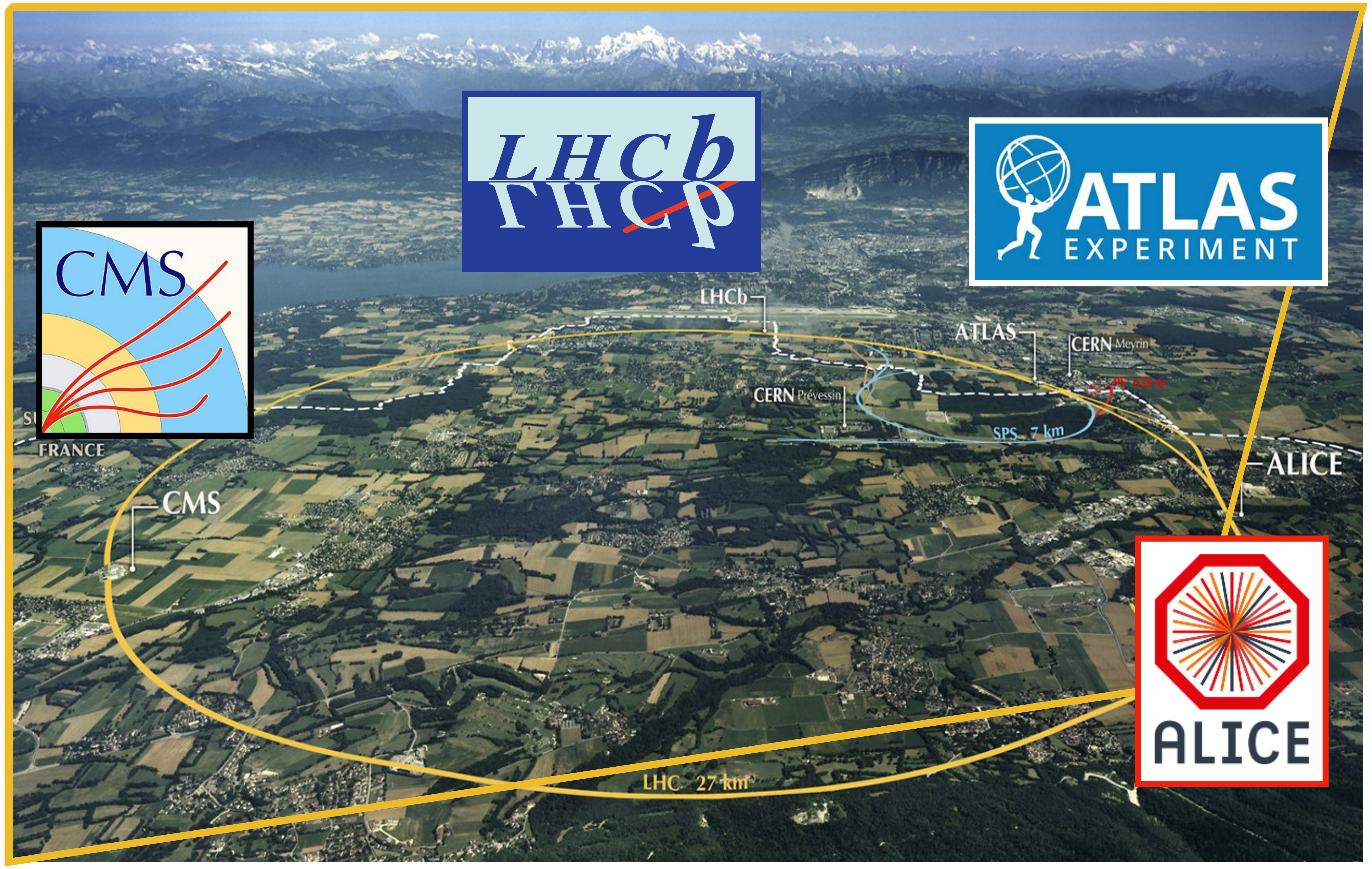

The **Large Hadron Collider** is CERN's current flagship experiment

It is located in a **27km** long tunnel, buried beneath France and Switzerland

In the LHC, particles are accelerated to **almost the speed of light** and then collided at dedicated locations - billions of collisions take place every second!



# LHC Experiments




There are **4 large experiments** at the LHC, each with a specific physics goal

The experiments each have a **particle detector** located at one of the collision points along the ring

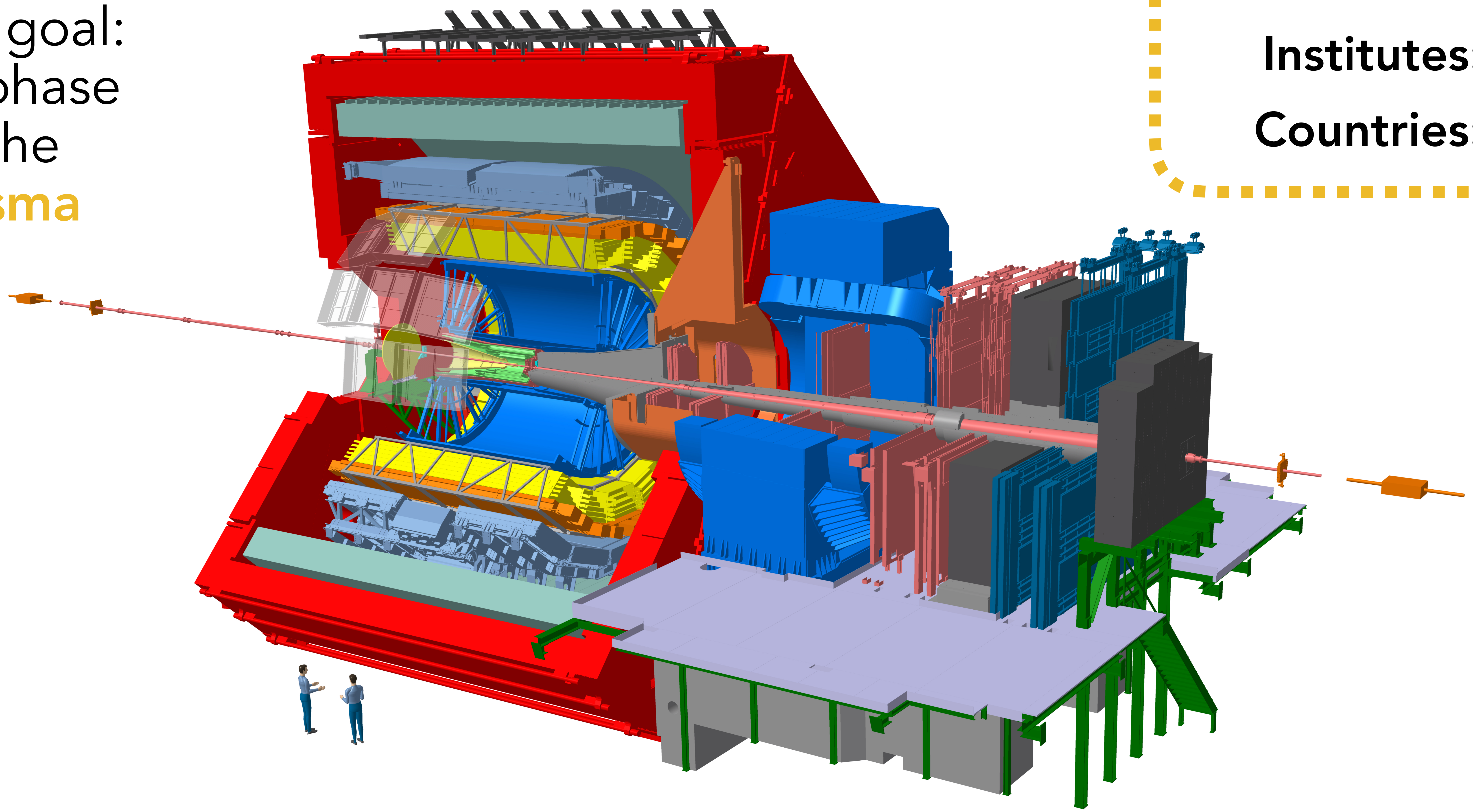
These detectors can be thought of as **cameras** which capture an image of what is produced in every collision

# ALICE

## A Large Ion Collider Experiment

ALICE has a unique goal:
To study an exotic phase
of matter called the
**Quark Gluon Plasma**

| | |
|---|---|
| Researchers: | ~2100 |
| Institutes: | 169 |
| Countries: | 40 |



ALICE Experiment (https://alice.cern/), 2024

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# QCD and Heavy Ion Physics

# Color Charge

The field of physics relating to the strong force is called **Quantum Chromodynamics**, named after the "color charges" carried by quarks and gluons

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## Electric Charge

| | |
|---|---|
| + | (Positive) |
| - | (Negative) |

There is only one type of electric charge, but there are **three** types of color charge - **red, green and blue**

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## Electric Charge

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|---|---|
| + | (Positive) |
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## Color Charges

| | | | | | |
|---|---|---|---|---|---|
| r | (Red) | g | (Green) | b | (Blue) |
| $\bar{r}$ | (Anti-red) | $\bar{g}$ | (Anti-green) | $\bar{b}$ | (Anti-blue) |

There is only one type of electric charge, but there are **three** types of color charge - **red, green and blue**

Similarly to how a particle carrying electric charge can be either positively or negatively charged, each of the three color charge states have an **equivalent, opposite anticolor charge**

# Quark Confinement

The strong force is well named - not only is it much stronger than the other forces, it is felt **more strongly** over larger distances and at lower temperatures!

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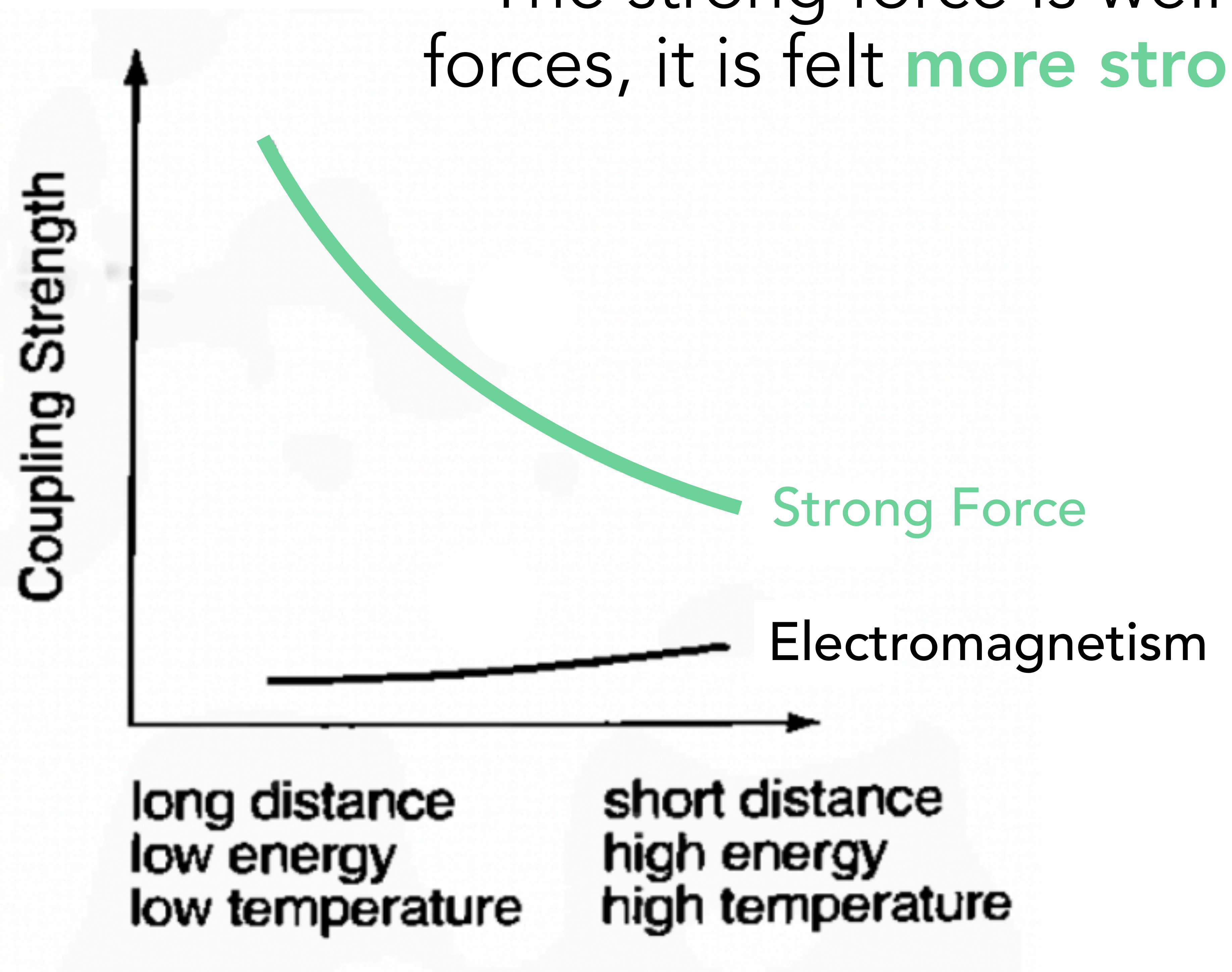

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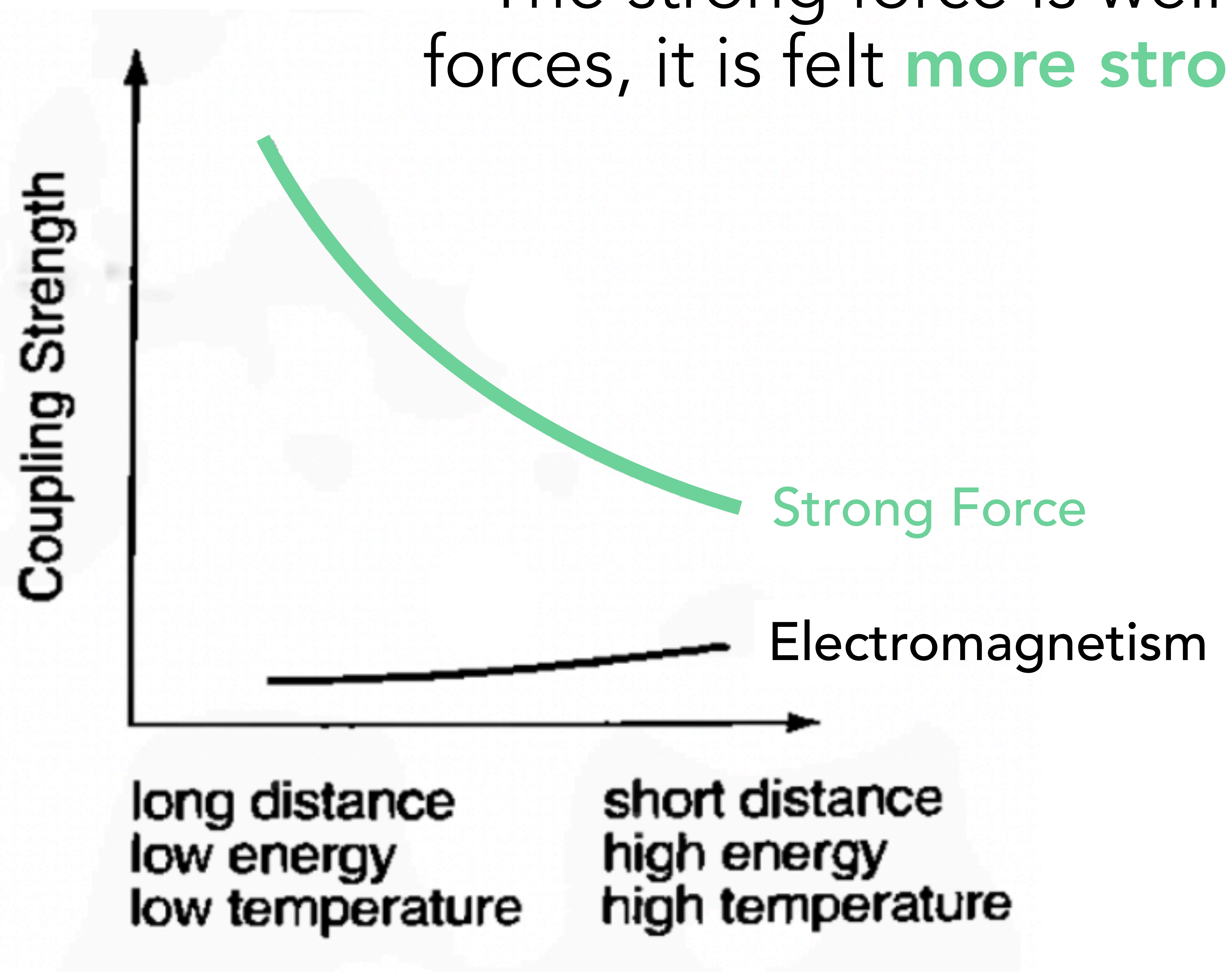


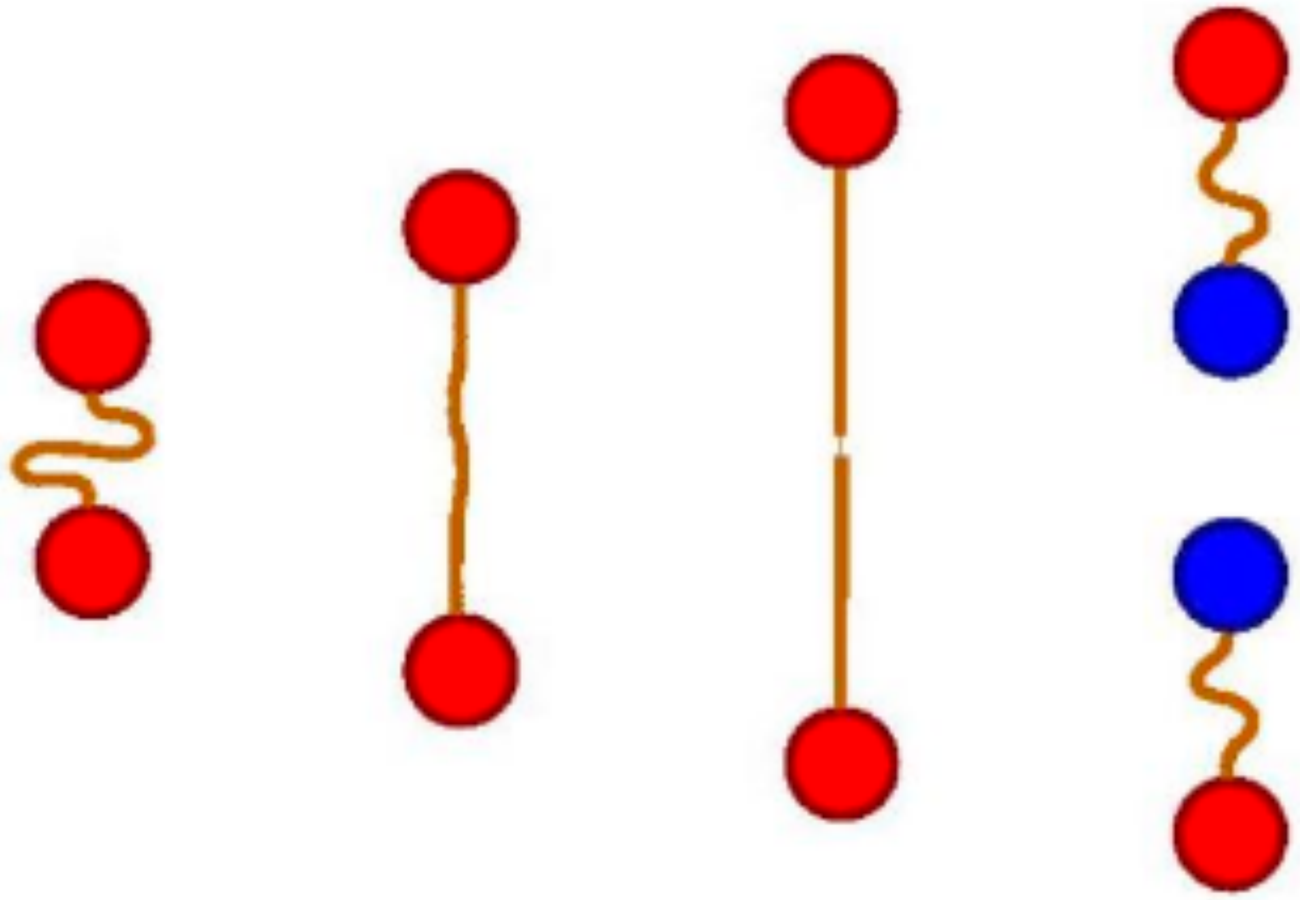

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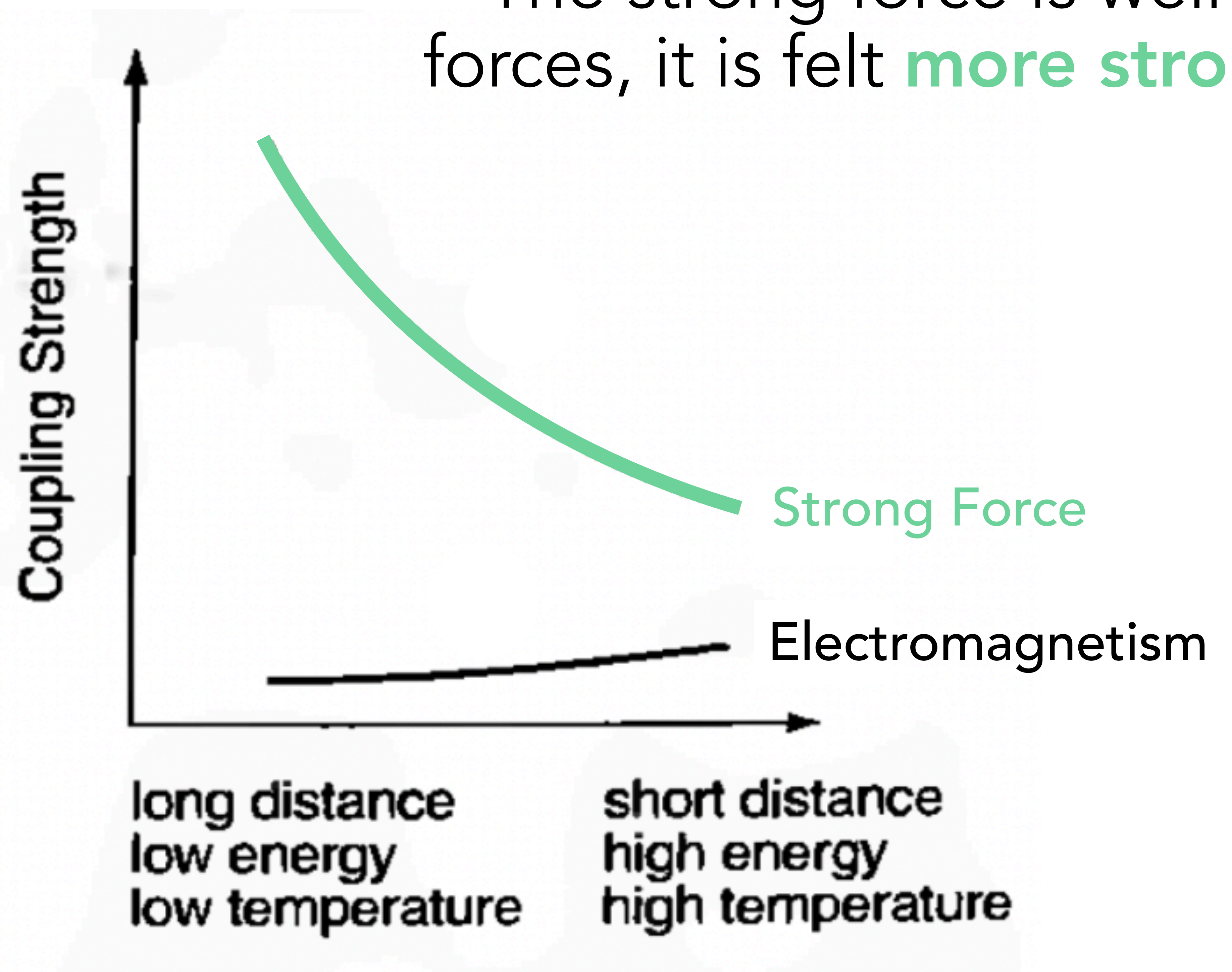
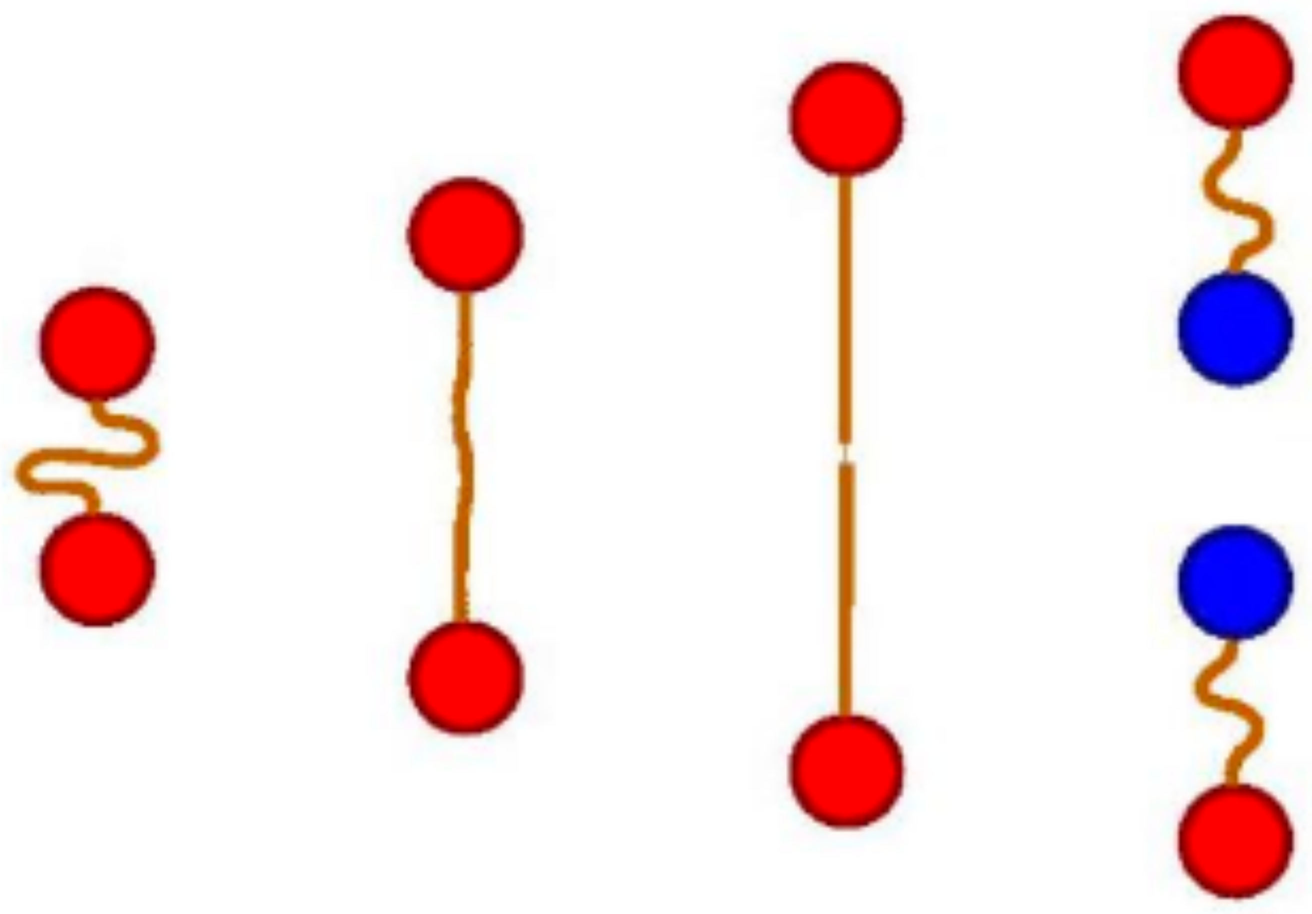



This leads to an effect called **confinement** - trying to separate two quarks leads to two new pairs of quarks, so they usually can't be observed except when they are grouped up as hadrons



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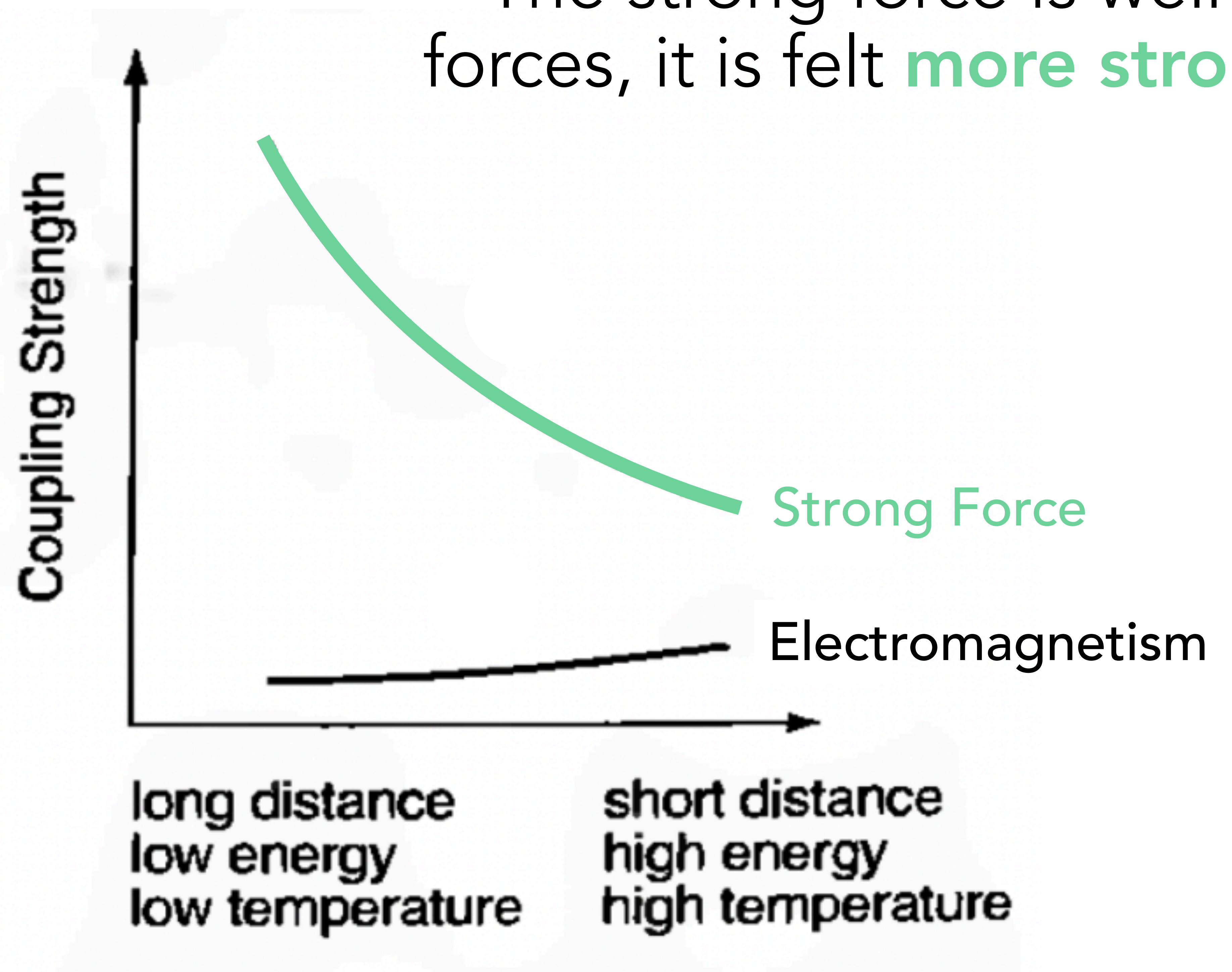


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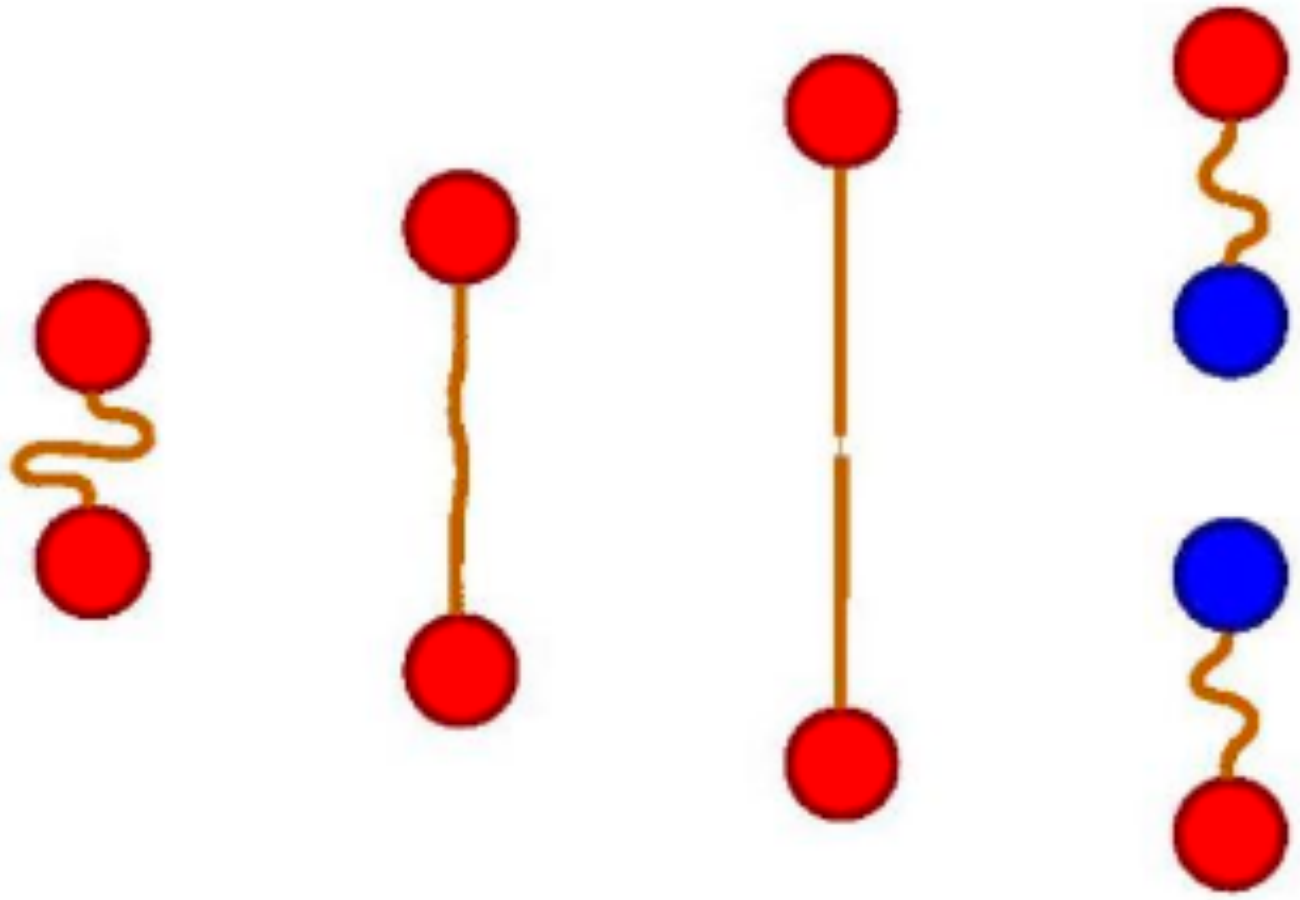

So if we want to study quarks and gluons and learn more about the strong force, how do we go about it?

# The First Microsecond of the Universe

To find the solution, we need to travel back in time - right to the very beginning!

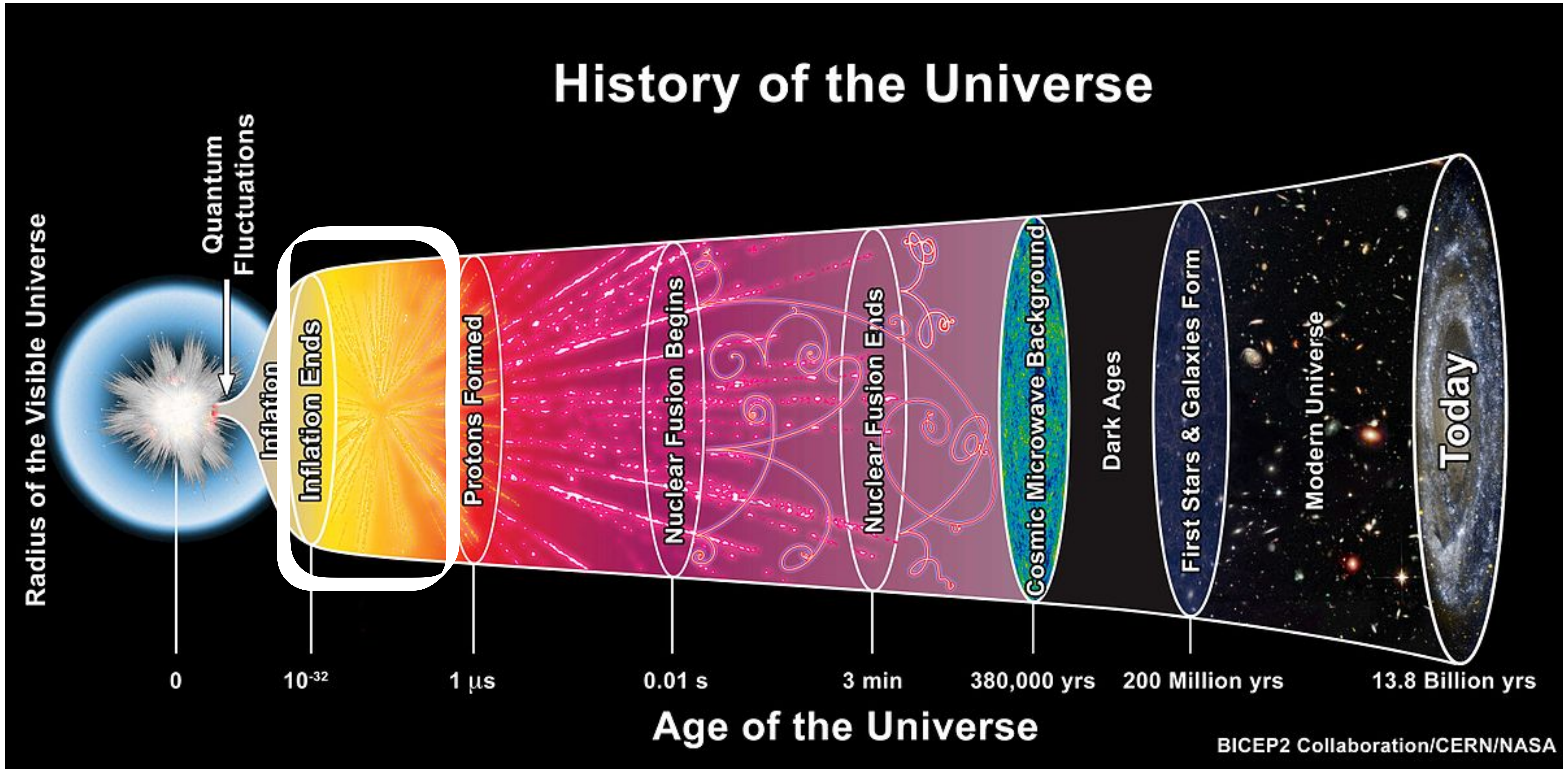


*Image taken from https://simonsobservatory.org/primordial-particles/, but originally credited to BICEP2//CERN/NASA*

The universe was once in a state hot and dense enough that quarks and gluons could exist as a deconfined "soup" of particles

This soup is called the **Quark Gluon Plasma**

QGP is a **phase of matter**, like a solid, liquid or gas, but it can only exist under extreme conditions

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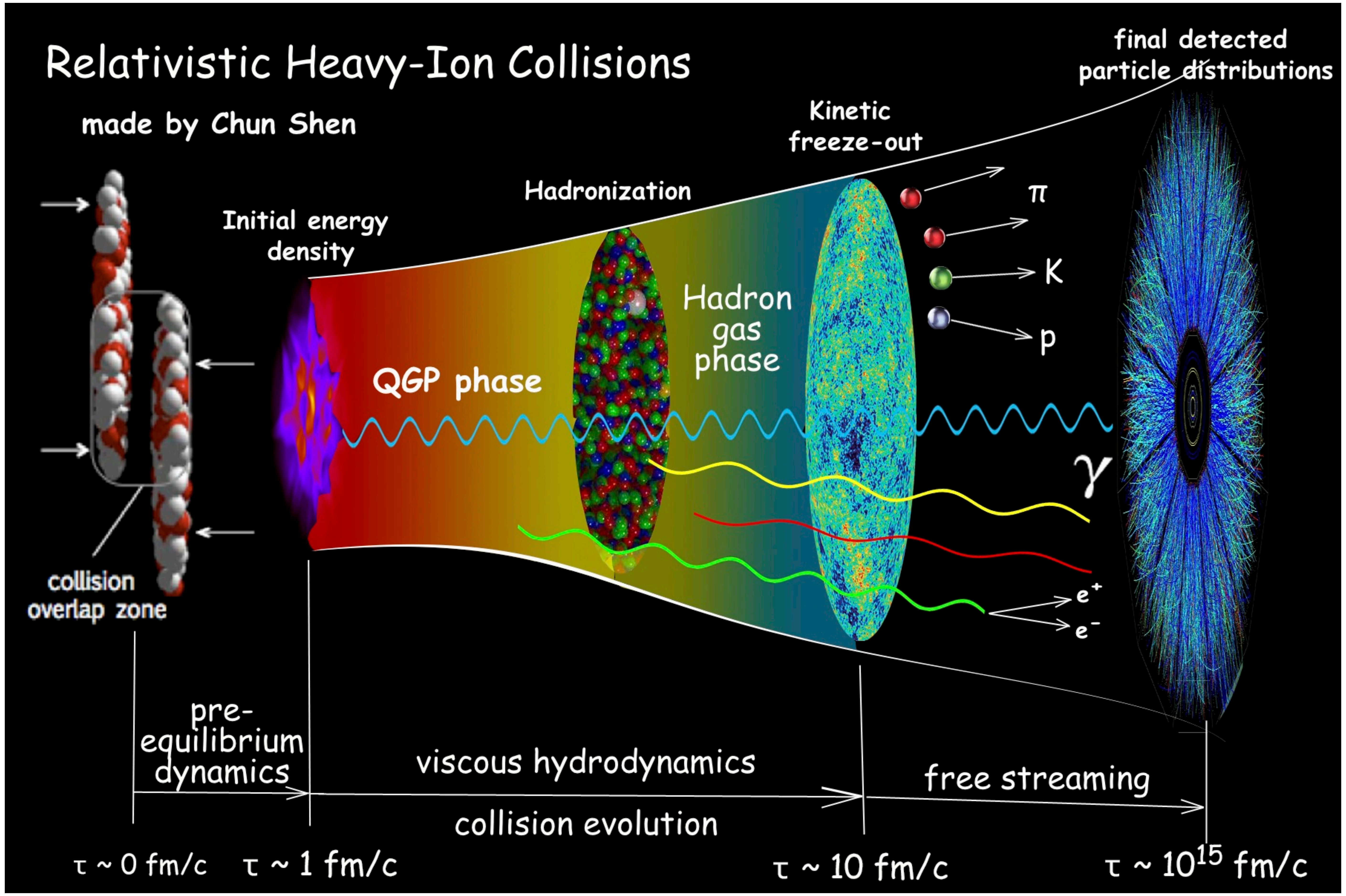
# Heavy Ion Collisions




Luckily, we don't have to create new universes to study the QGP!

Instead, we can simulate the Big Bang (on a much smaller scale) in the lab by **colliding heavy particles** such as lead nuclei

However, the QGP doesn't survive long enough to reach our detectors - so some detective work is needed…

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# Review/Conclusion

# Where Are We?

**Forces**

We have defined the fundamental forces of nature and know what effects they are responsible for

**Particles**

We have built a framework to define the particles which underlie matter and interactions in the universe

**QGP**

We have learnt about QGP, the primordial quark soup, and the strategy to study it in the lab

# Where to Next?

As you can see, there's still a lot to learn!

- **Unanswered Questions:** The holes in the Standard Model that we've discussed
- **Improving our Understanding:** Even in the defined theory of the Standard Model, there is plenty to test to refine our understanding
- **Quark Gluon Plasma:** There are still many questions to be asked and answered about this exotic state of matter
- **And more!**


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# Questions?