Particle Physics

Columbia Science Honors Program

Week 1: Introduction

January 28th, 2017

Inês Ochoa, Nevis Labs, Columbia University

Welcome!

José Crespo-Anadón

- Postdoc on Neutrino group, MicroBooNE experiment at Fermilab

Inês Ochoa

- Postdoc on ATLAS experiment at CERN

Cris Vilela

- Postdoc on T2K and Super-K experiments in Japan

Course Policies

- Attendance:
  - Up to four excused absences

    (two with notes from parent/guardian)
- Valid excuses:
  - Illness, family emergency, tests or athletic/academic competitions, mass transit breakdowns
- Invalid excuses:
  - Sleeping in, missing the train
- I will take attendance during class.
- Please no cell phones.
- Ask questions :)

Schedule

1. Introduction
2. History of Particle Physics
3. Special Relativity
4. Quantum Mechanics
5. Experimental Methods
6. The Standard Model - Overview
7. The Standard Model - Limitations
8. Neutrino Theory
9. Neutrino Experiment
10. LHC and Experiments
11. The Higgs Boson and Beyond
12. Particle Cosmology

Schedule

Inês	✻
José	▼
Cris	■

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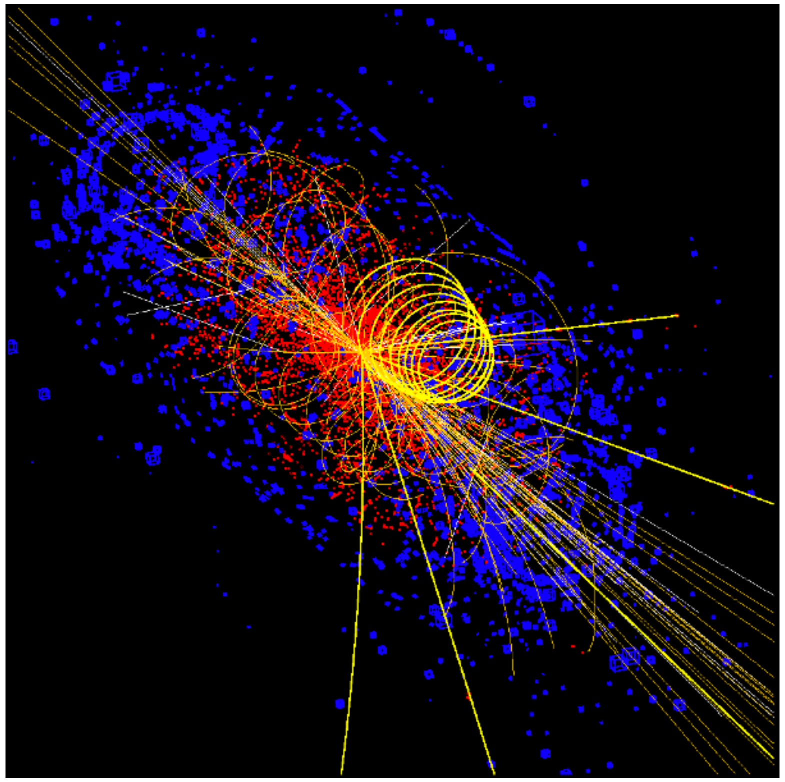
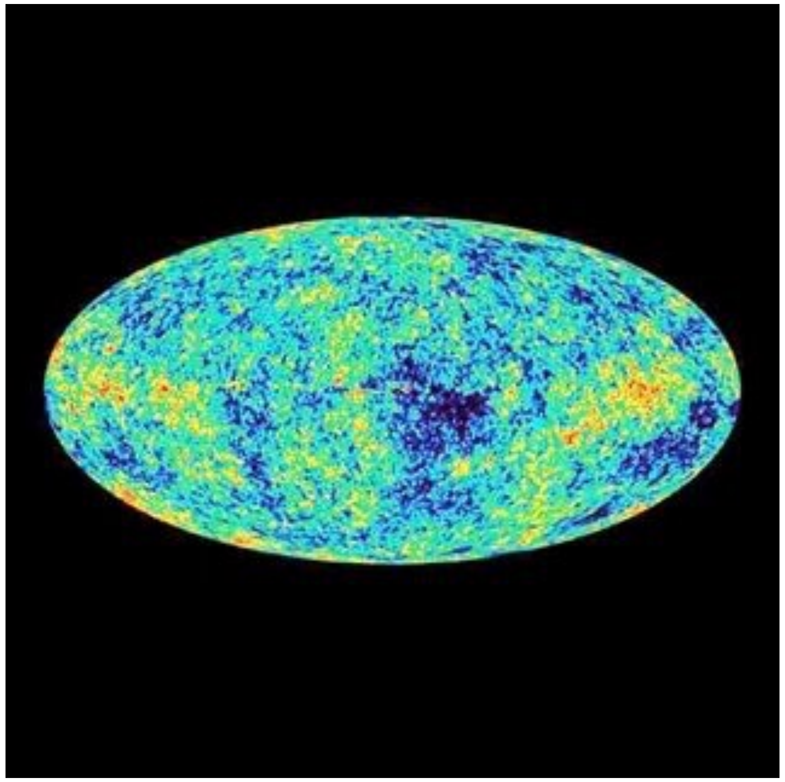
Let's start from the beginning…

What is Particle Physics?

- Particle physicists explore the most basic components of our natural world:
  - Particles!
- Not just particles though, also their interactions, and how they become the things we see around us.
- This leads us from the littlest things to the the biggest things: from the Big Bang and the basic constituents of our universe, to its large scale structure, the interiors of stars and even extra dimensions of space.





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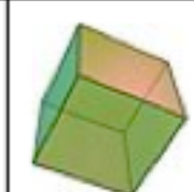
Particle physics is a highly developed field:
Physicists now want to know more than just what the Universe is made of.
The real interesting questions relate to **why** the Universe is what it is.

Where did it begin?

Today, particle physics is the study of matter, energy, space and time.

- The Greeks already considered space and time to be important concepts in their natural philosophy.
- Since the early 20th century, our understanding of space and time has undergone some profound shifts, becoming ever more closely connected to particle physics.
- It is likely that further dramatic advances will occur in our lifetime!

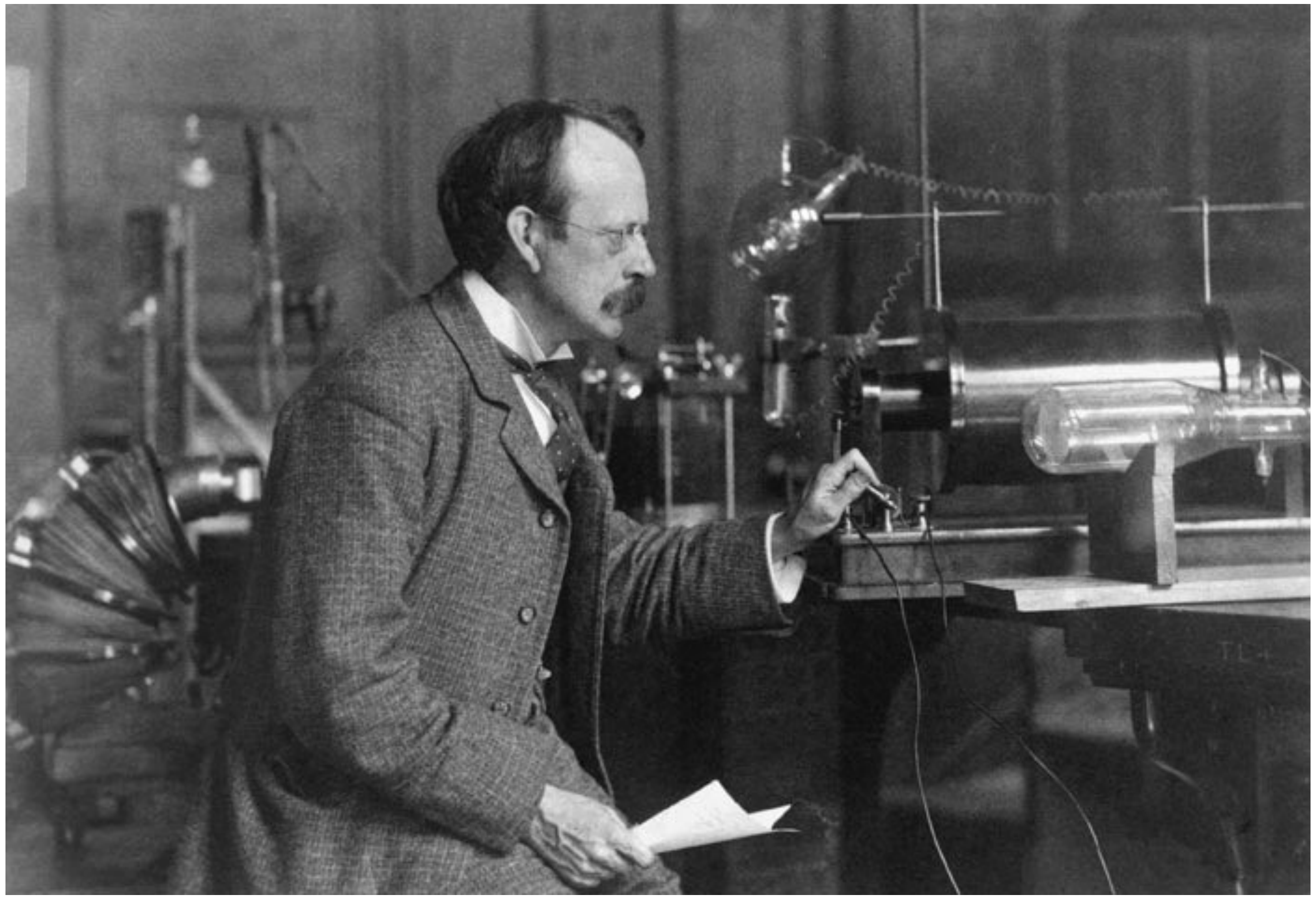
What is matter made of: 500-300 BCE

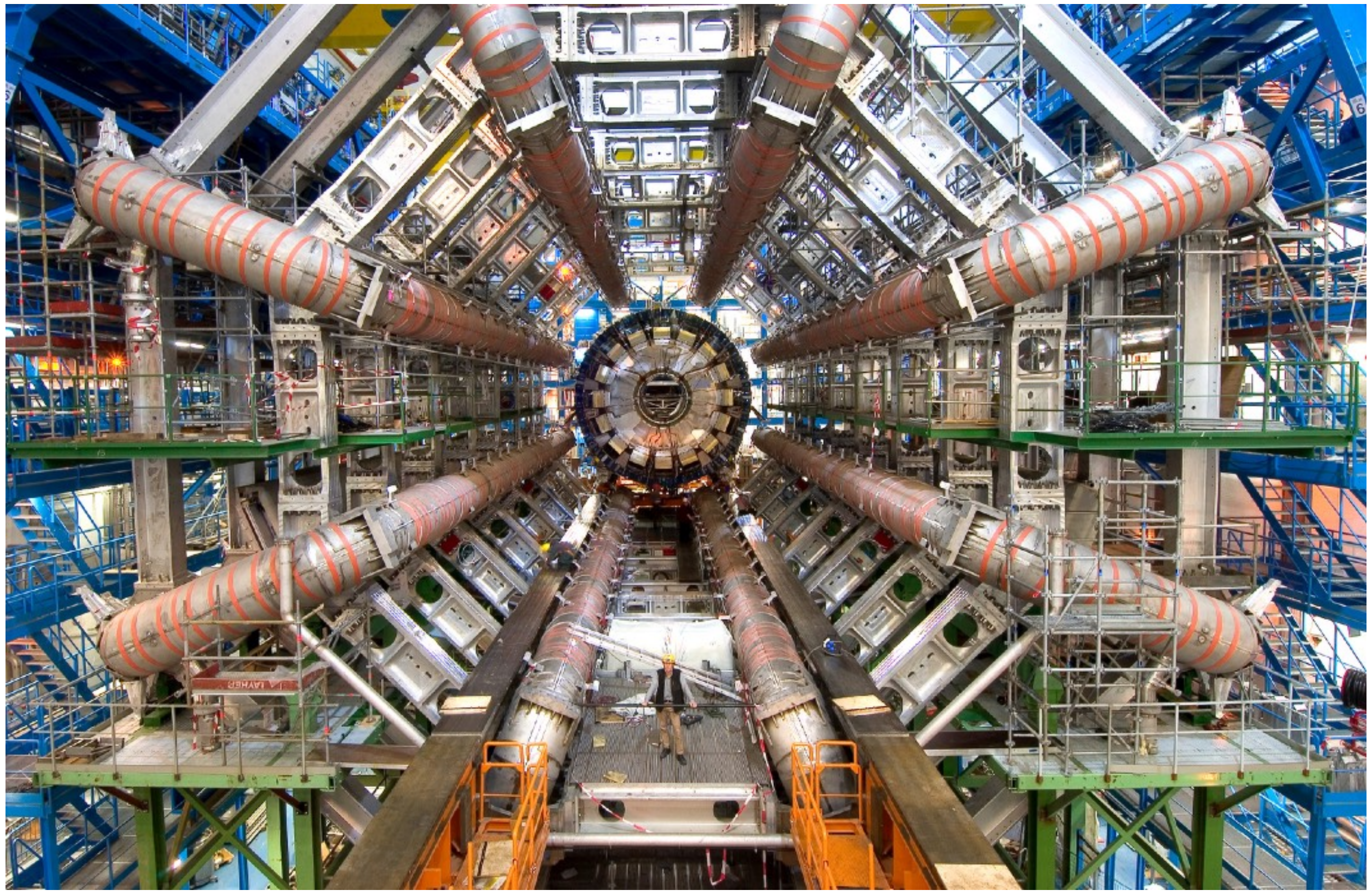
Element	Polyhedron		Number of Faces	Number of Triangles
Fire	Tetrahedron (Animation)		4	24
Air	Octahedron (Animation)		8	48
Water	Icosahedron (Animation)		20	120
Earth	Cube (Animation)		6	24

Geometrical Simple Bodies According to Plato

This picture of indivisible, solid atoms remained essentially unchanged until ~1900!

Rapid progress…





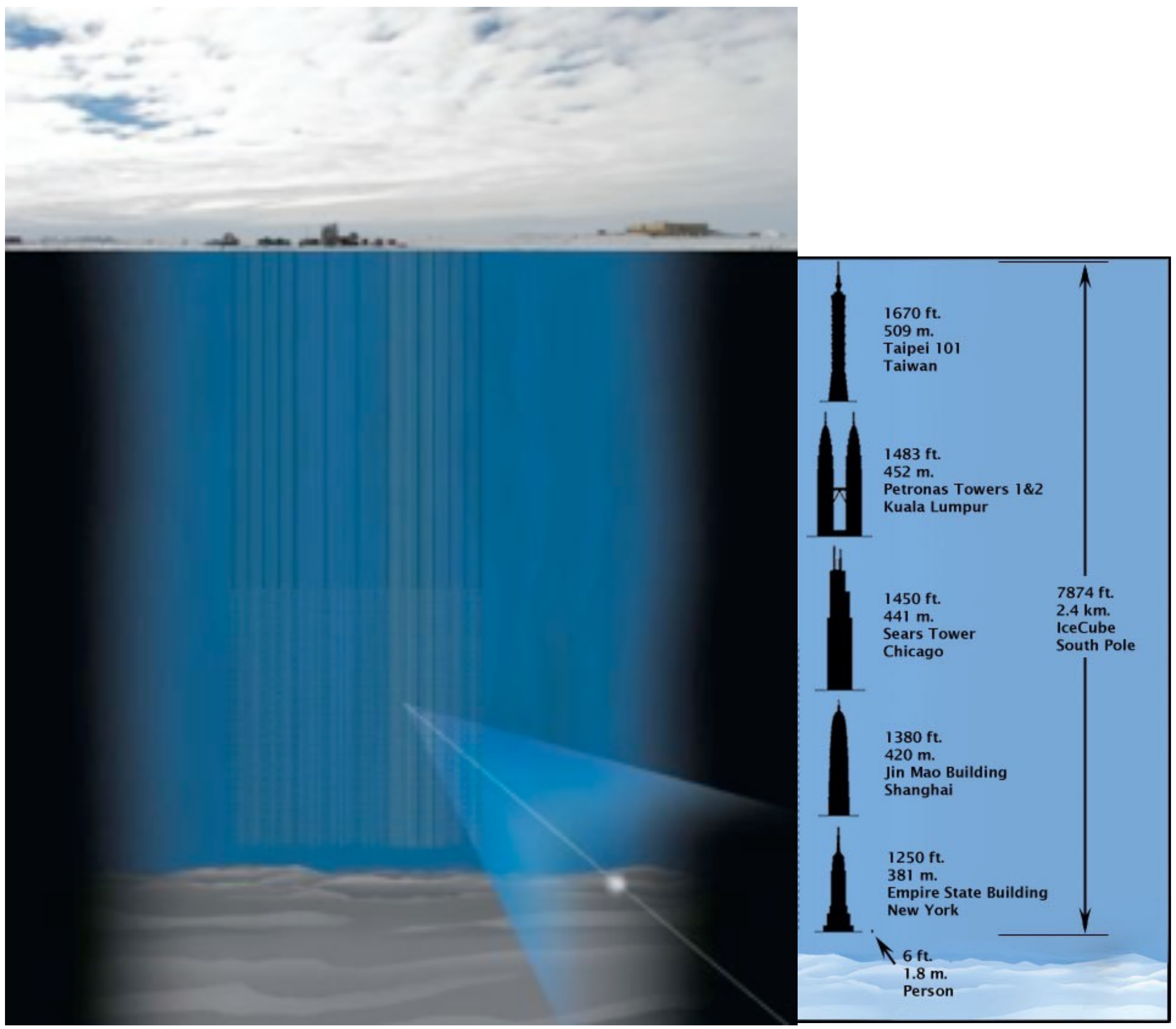
J.J. Thompson

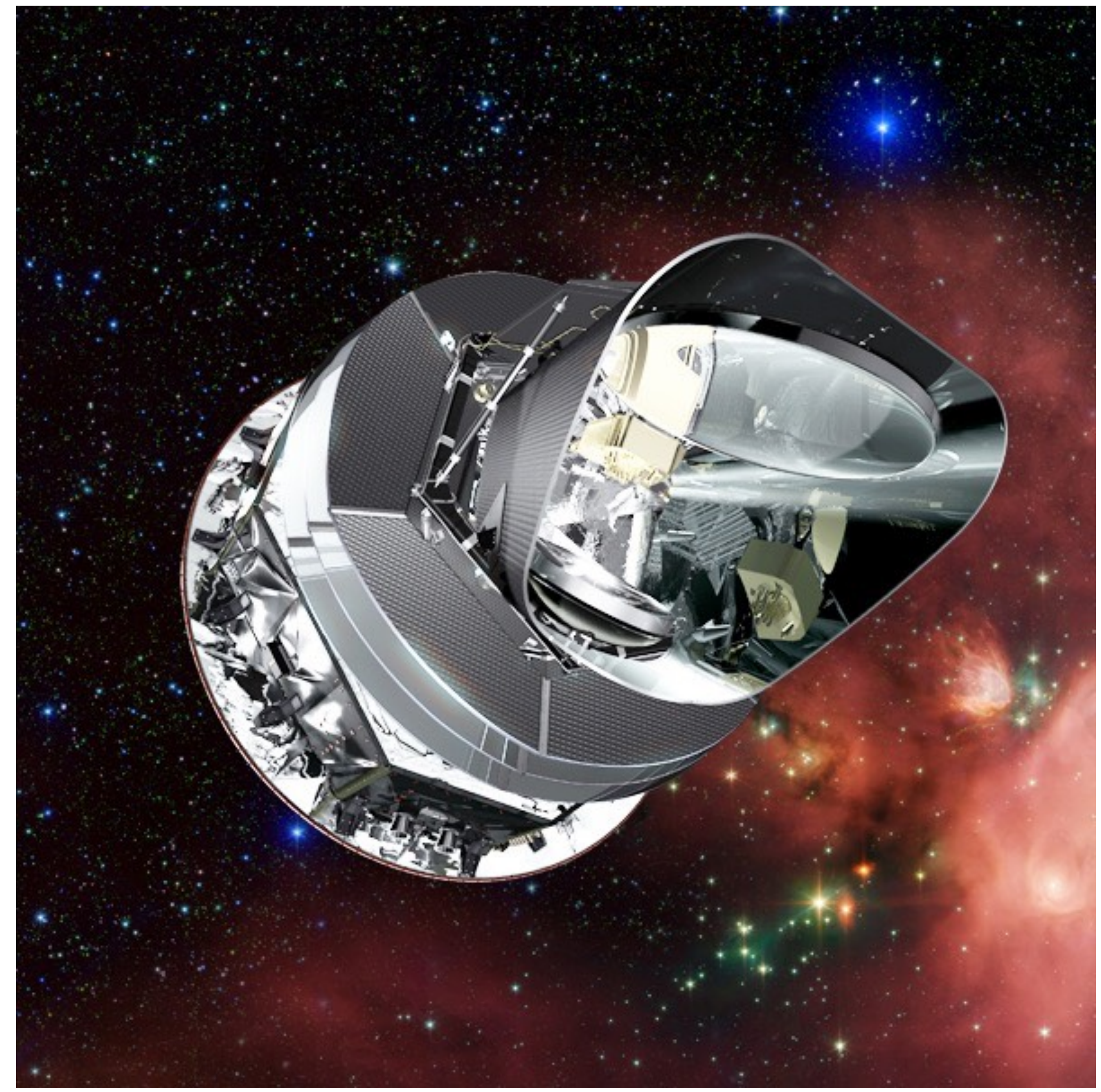
Discovering the electron (1897)

ATLAS

Discovering the Higgs (2012)

Many experiments





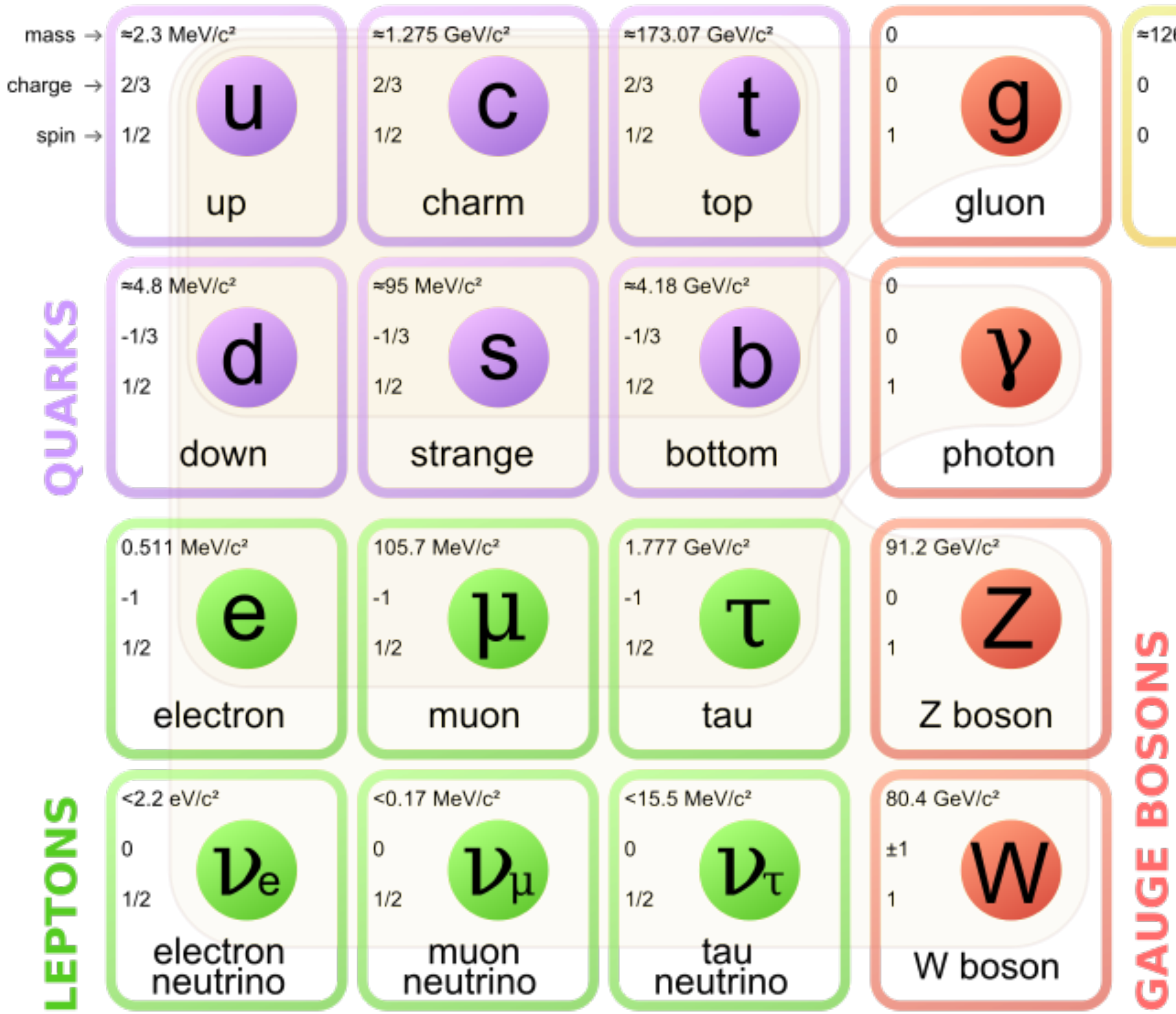
IceCube Neutrino Observatory

Studying cosmic neutrinos (2010)

Planck Satellite

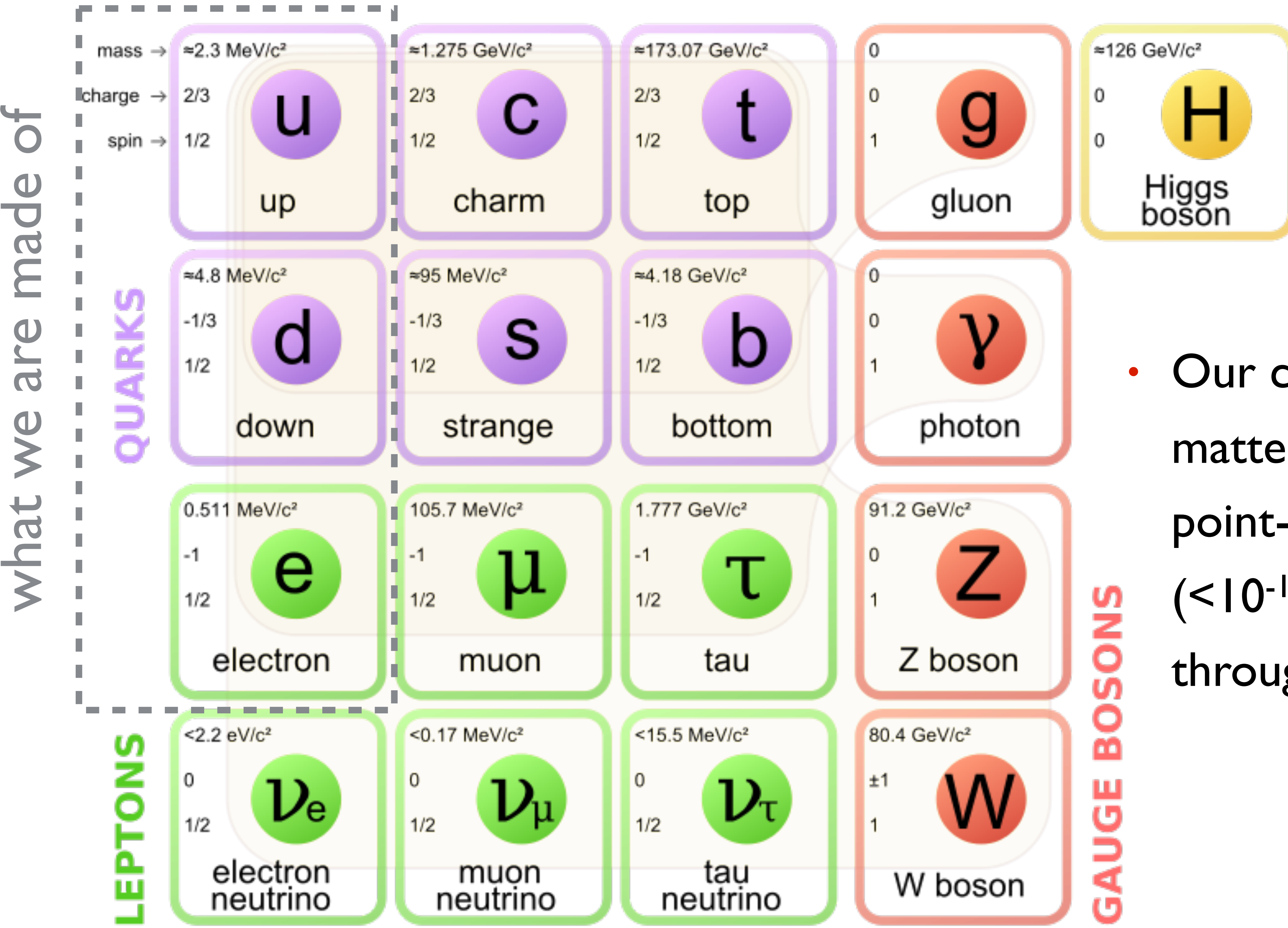
Mapping the CMB (2010)

What is matter made of?



- Our current model of matter consists of point-like particles (<10^{-18} m), interacting through four forces.

What is matter made of?



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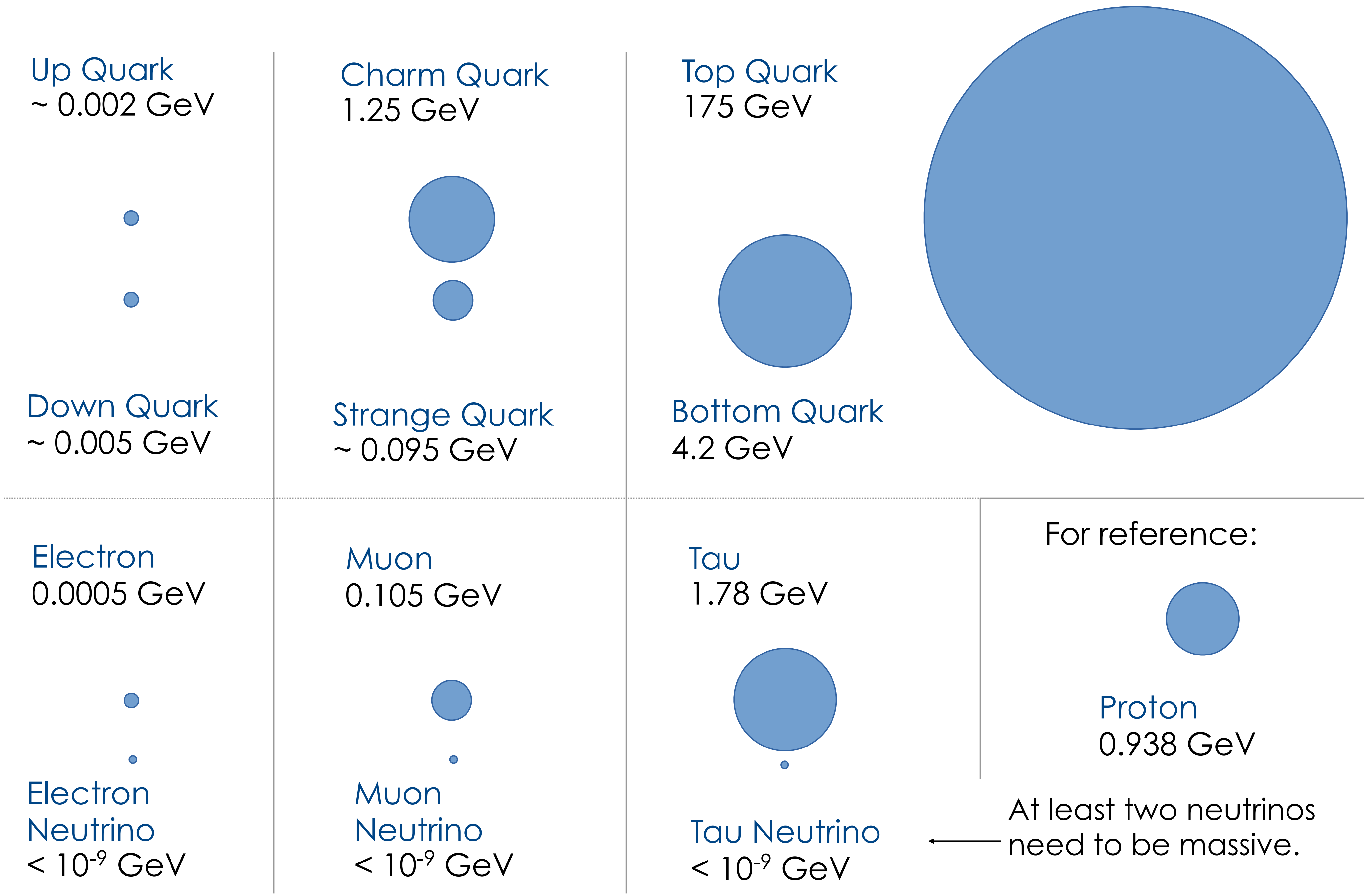
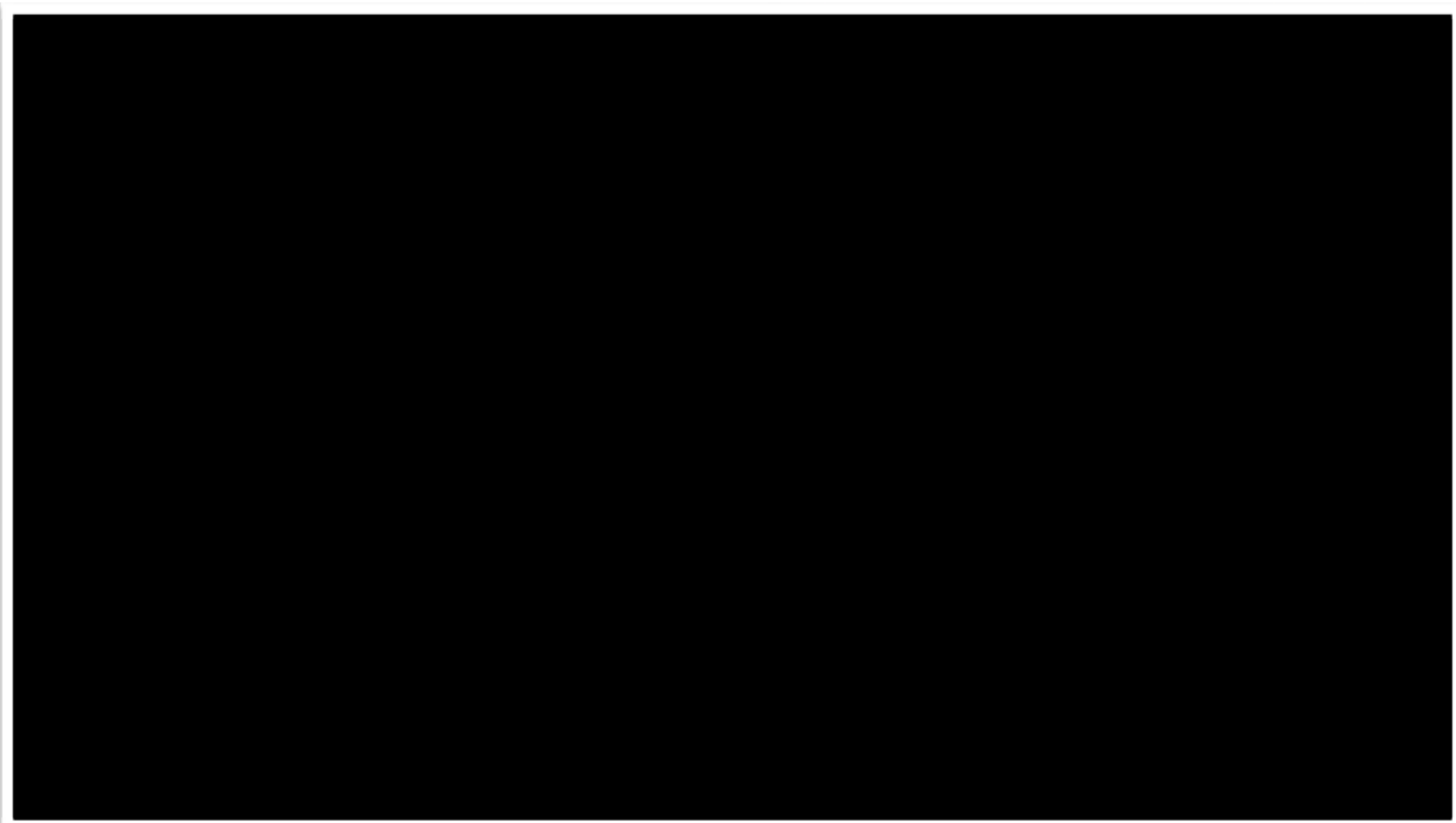


Adding forces…

Interaction	Description	Mediator	Strength
Strong	binds quarks in protons and neutrons, protons and neutrons in nuclei	gluon	1
Electromagnetic	all extra-nuclear physics (atoms, molecules, chemistry, etc.)	photon	10^{-2}
Weak	nuclear β decay	$W^{\pm}$, Z^0	10^{-7}
Gravity	all types of particles	graviton (?)	10^{-39}

- This picture (excluding gravity) summarizes the **Standard Model** of particle physics.

A sense of scale…



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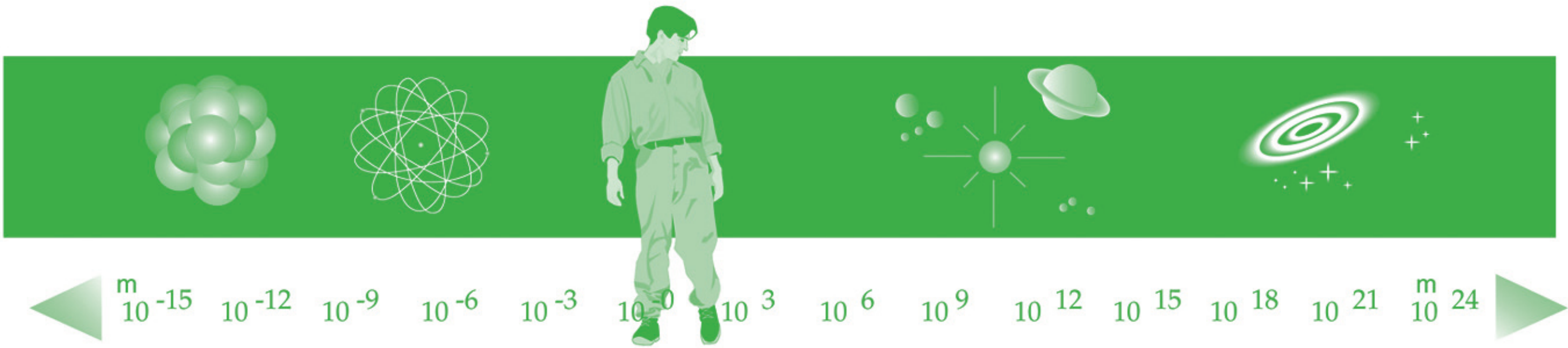
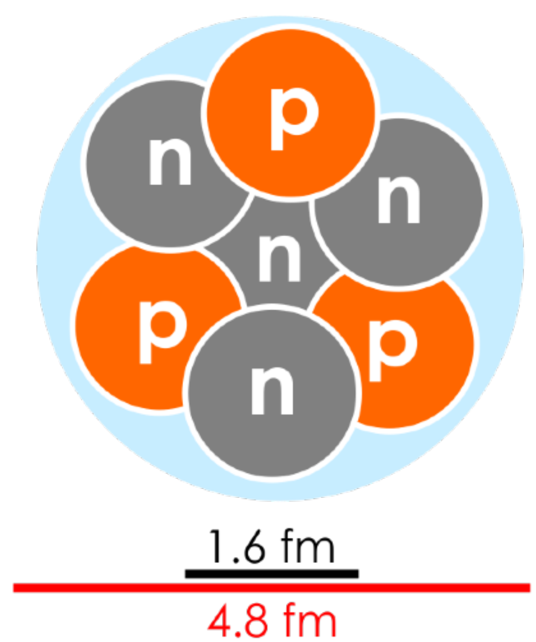
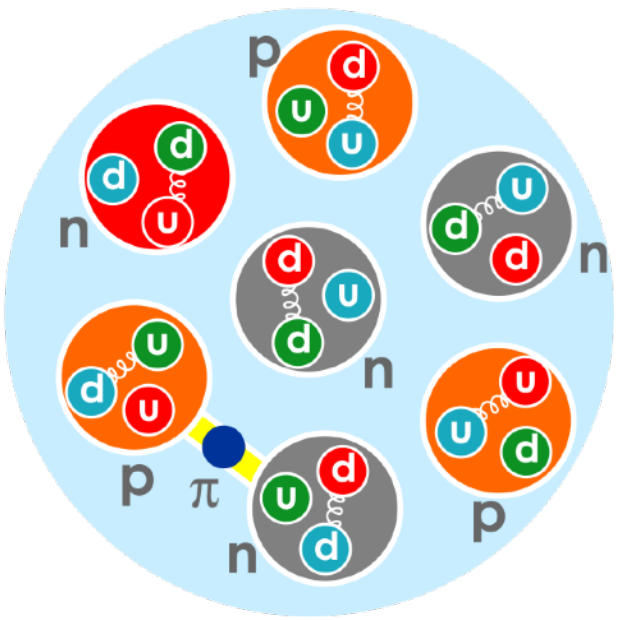
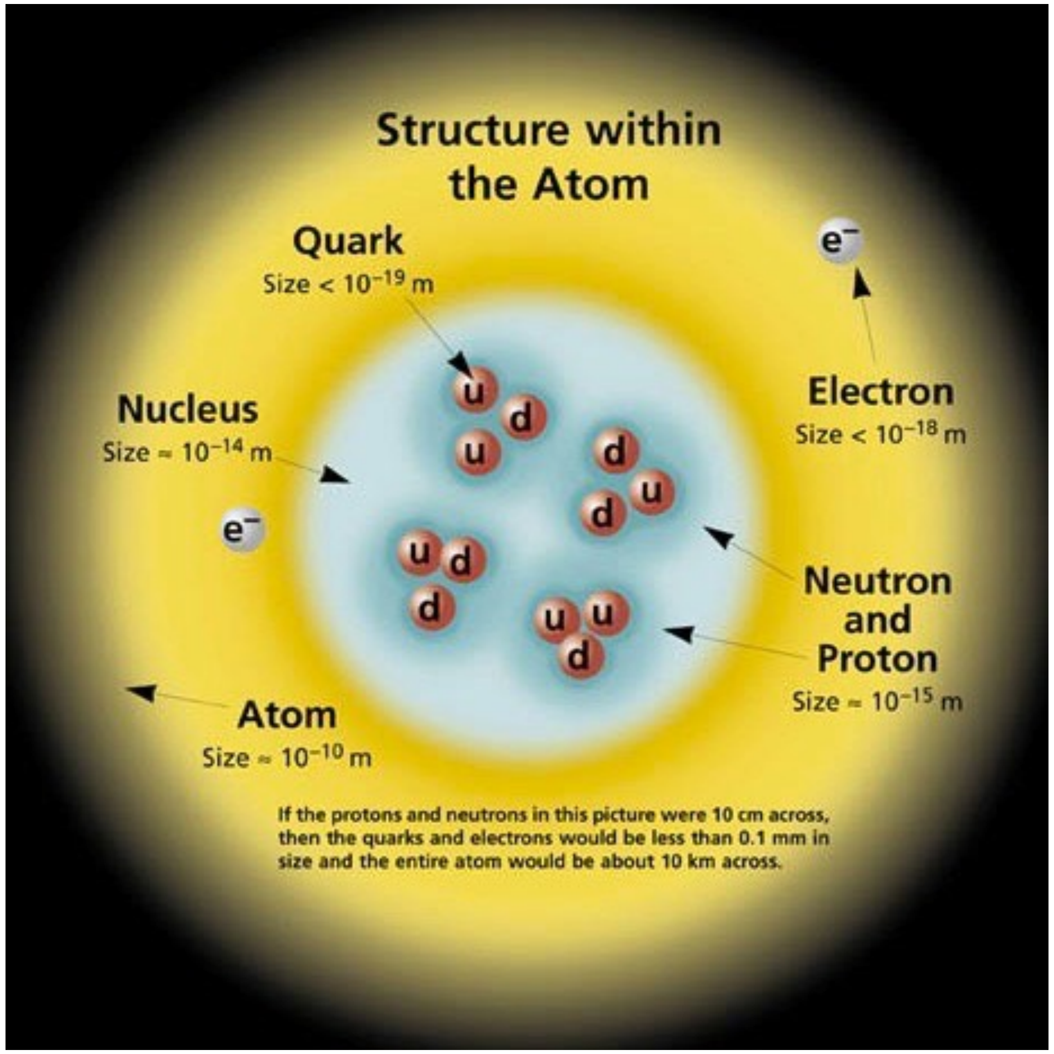


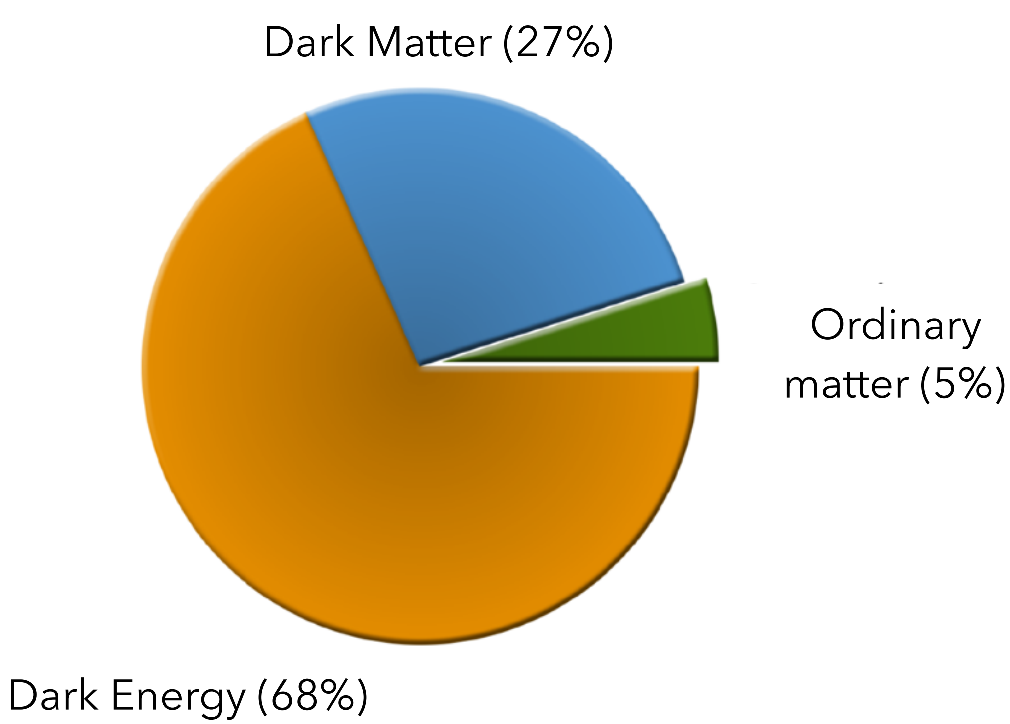


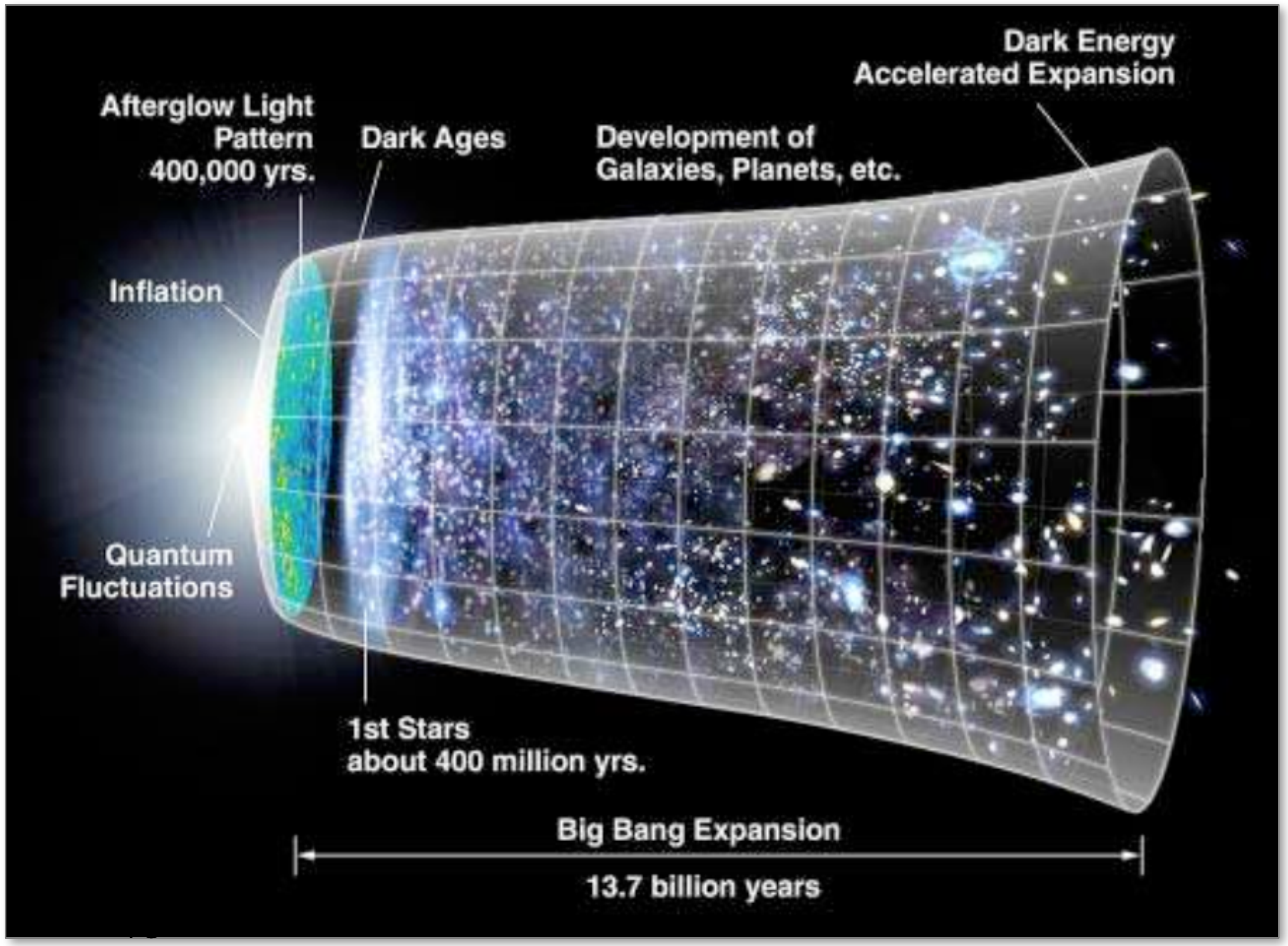




But this isn't even half the story…

- The matter described by the Standard Model makes up only 4% of the total matter/energy in the Universe.
- We know almost nothing about the other 96%…
  - …more on this later.





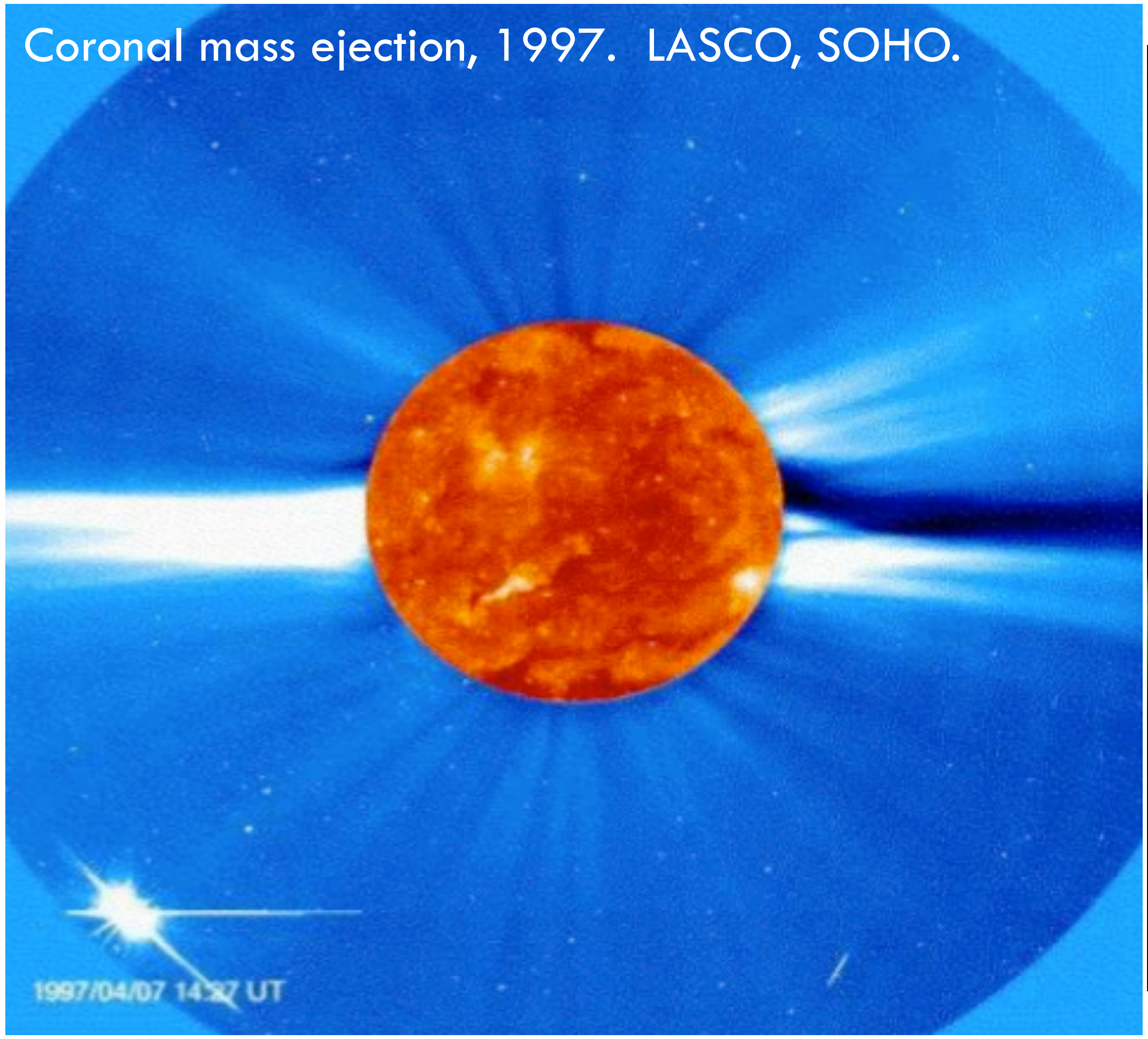
Many mysteries…

- What is the "dark matter" that makes up a quarter of the universe?
- What is the "dark energy" that is causing the universe to expand at an increasing rate?
- Why was there slightly more matter than antimatter in the very early universe?
- Why do particles have the masses that they have?
- Why is gravity much weaker than the other forces?
- How do neutrinos fit into the picture?
- And more…

Sources of particles

How can particles be produced?

- Historically, most elementary particles were discovered by observation of natural sources:
  - Decays of radioactive elements.
  - Astrophysical sources: coronal mass ejections, extensive air showers, etc.



Coronal mass ejection, 1997. LASCO, SOHO.

Northern Lights

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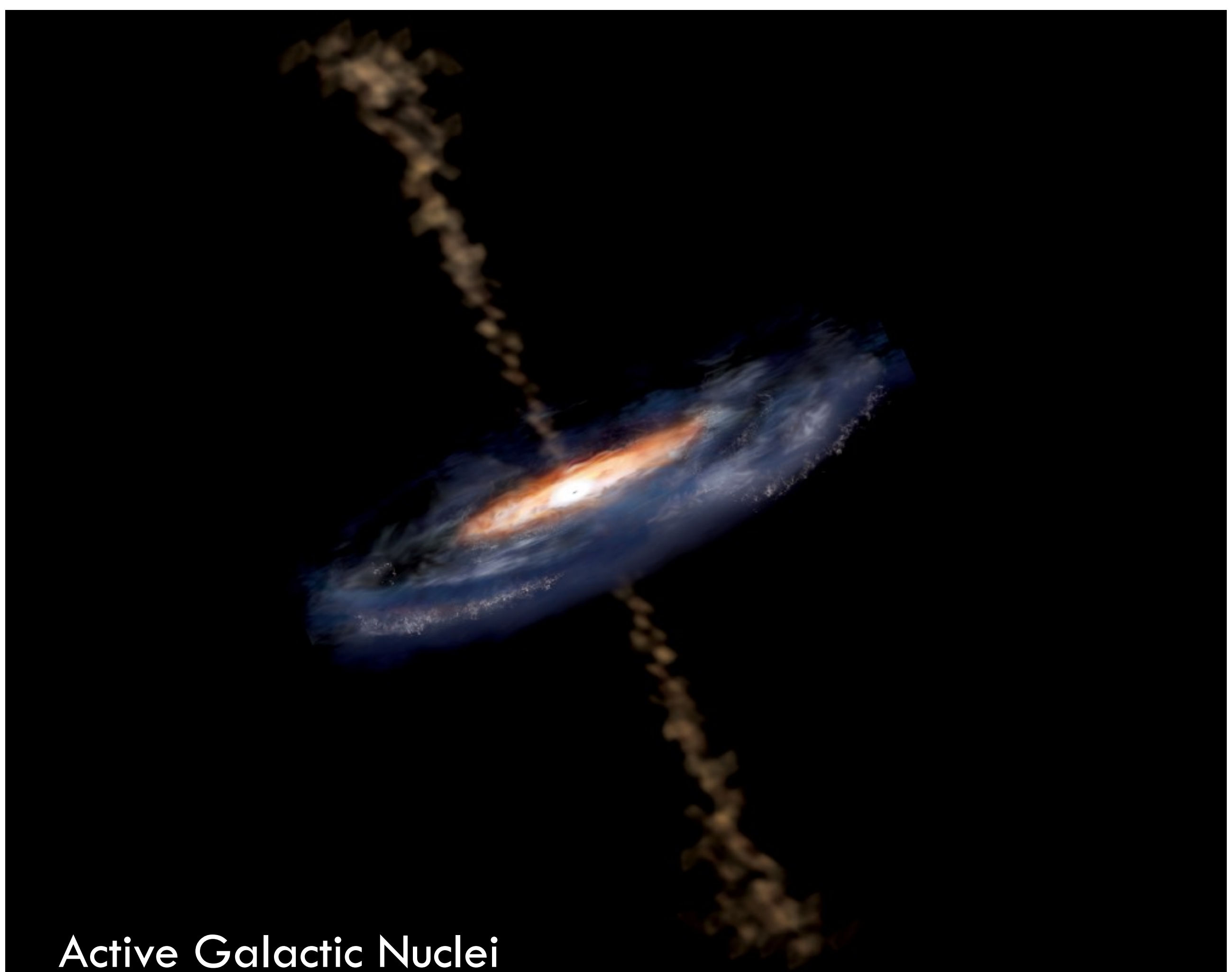

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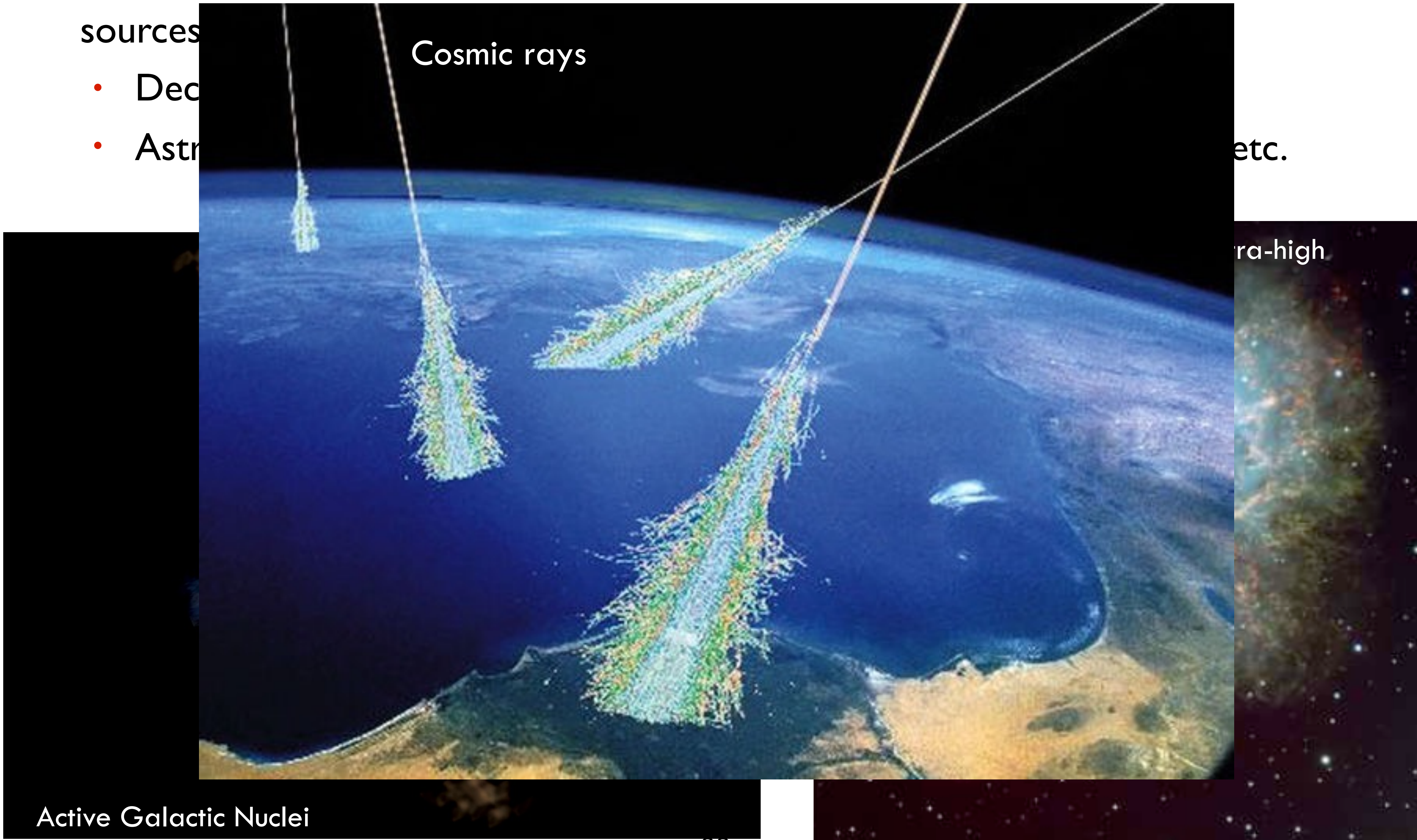
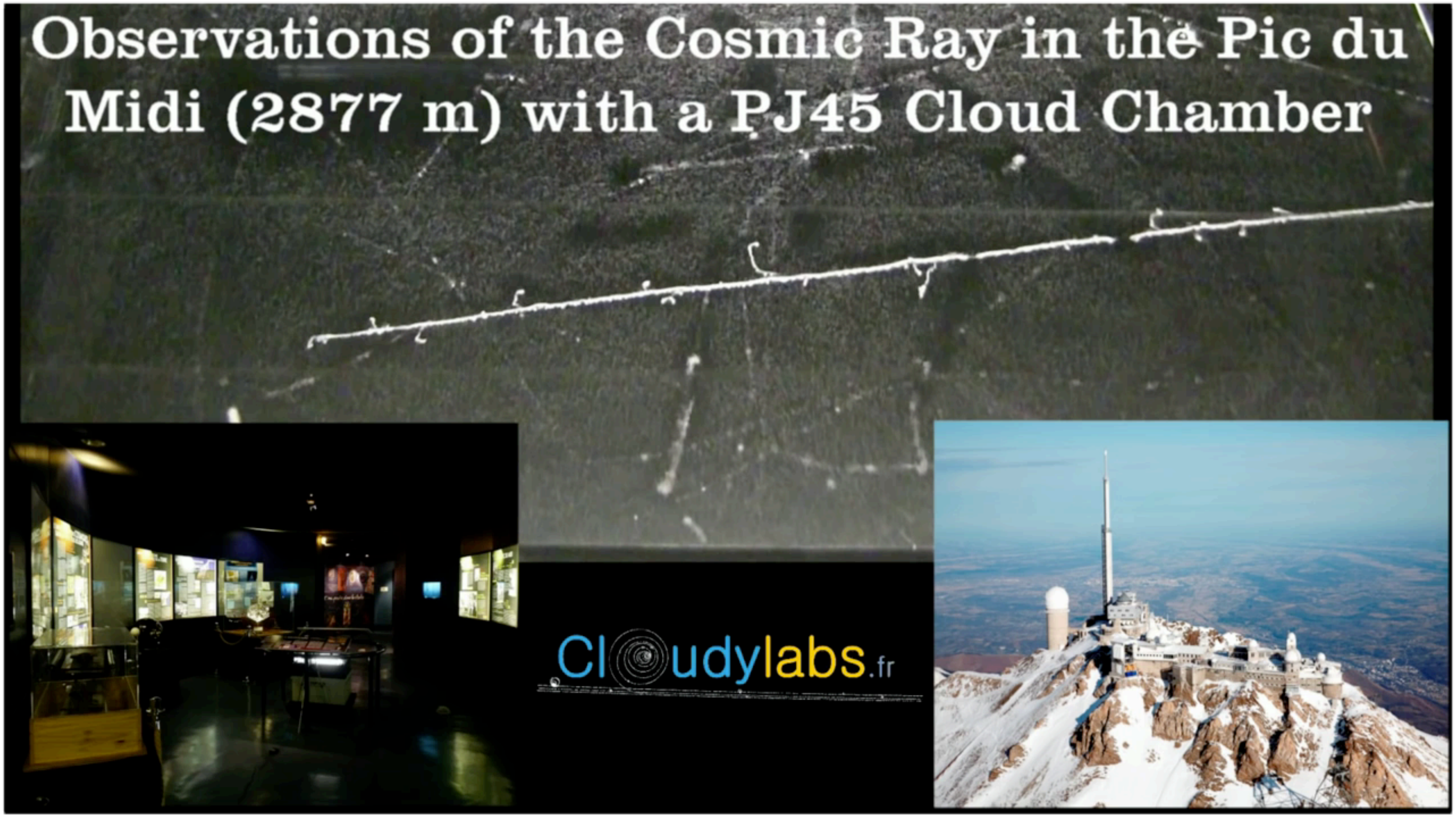


Cosmic rays


Observations of the Cosmic Ray in the Pic du Midi (2877 m) with a PJ45 Cloud Chamber
Cloudylabs.fr

How can particles be produced?

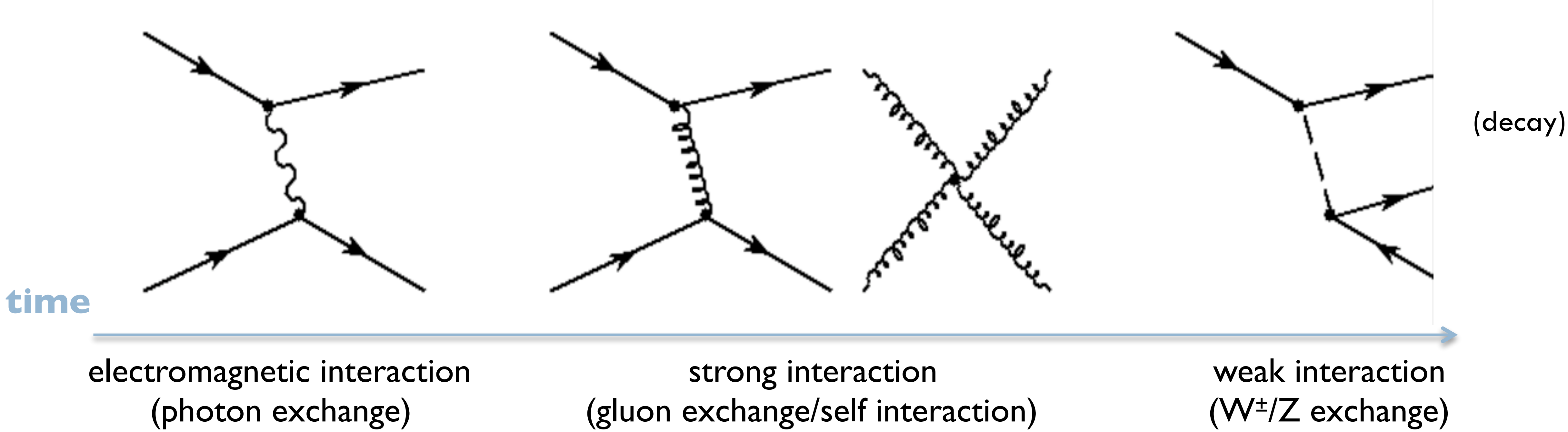
- Today, we have sophisticated multi-billion dollar machines that accelerate and collide particles in finely-tuned beams.
- Accelerators are expensive, but unlike nature, they provide a precise, controlled testing environment.

More on this on a later lecture.

How matter interacts

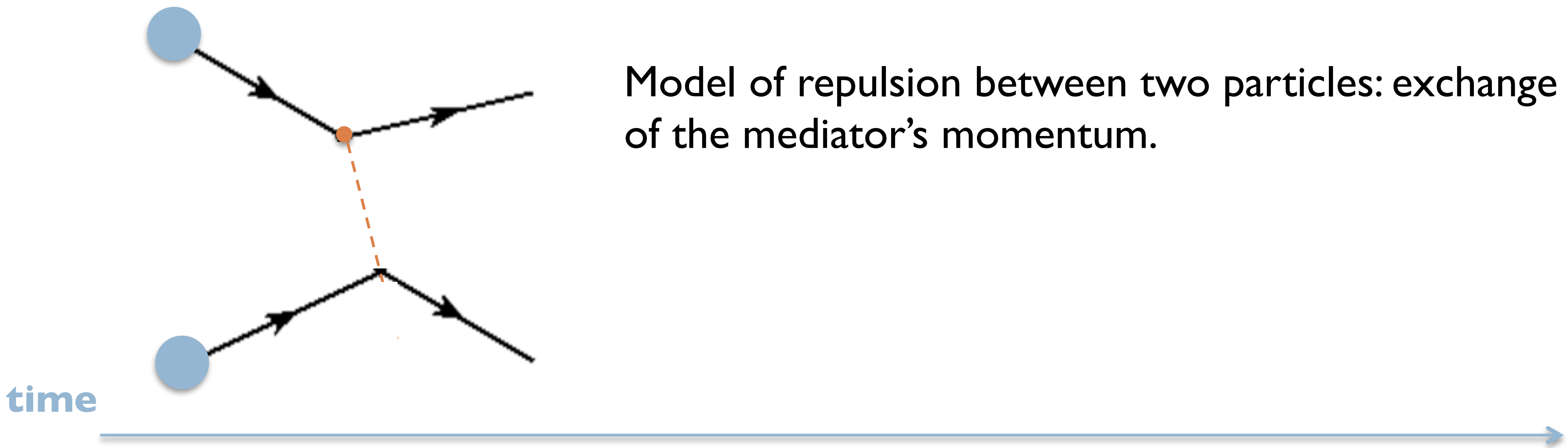
How matter interacts

- Elementary particles interact by exerting forces on each other.
- The mechanism: quarks and leptons exchange “mediator" particles, like photons, W or Z bosons, and gluons.
- We depict particle interactions using space-time cartoons called Feynman Diagrams.
    - Each diagram encodes quantitative physical information about the interaction.



How matter interacts

- The mediators carry momentum (energy) between two interacting particles, thereby transmitting the force between them.



Model of repulsion between two particles: exchange of the mediator's momentum.

electromagnetic interaction
(photon exchange)

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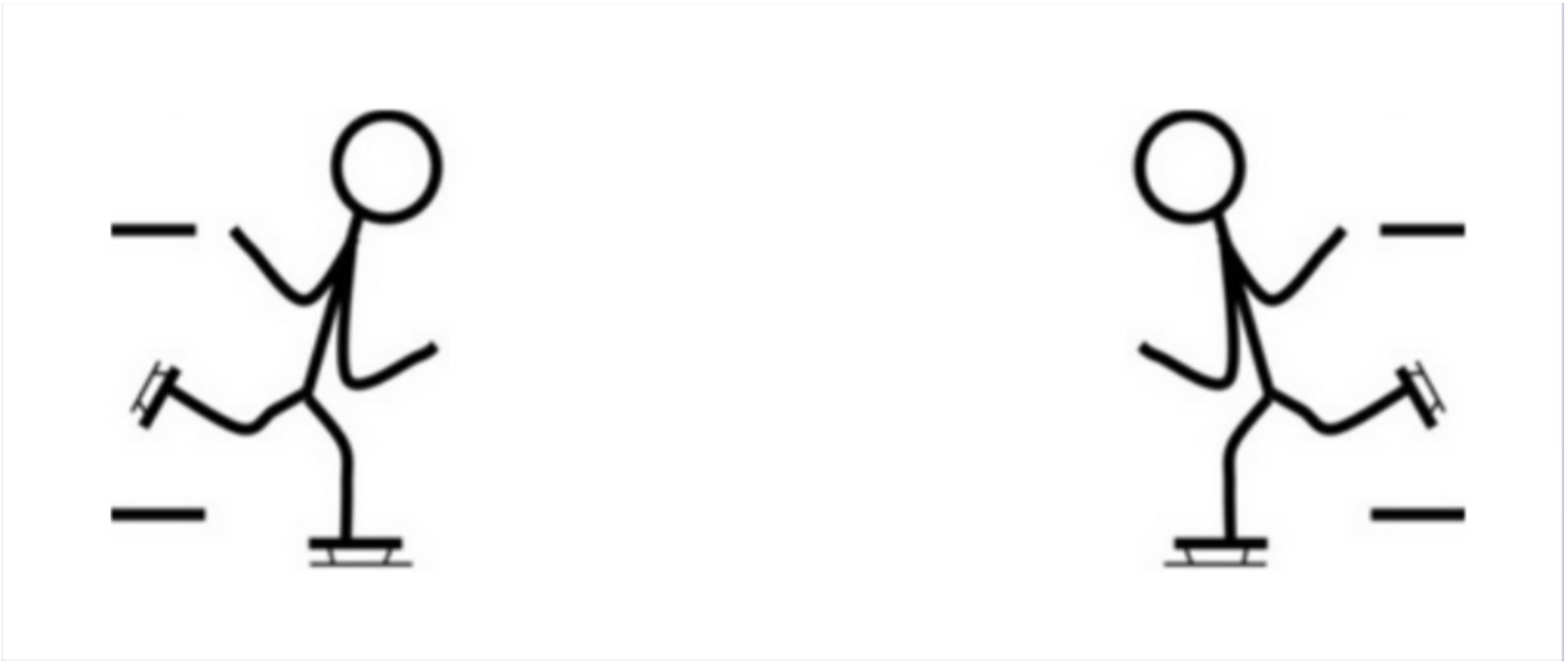

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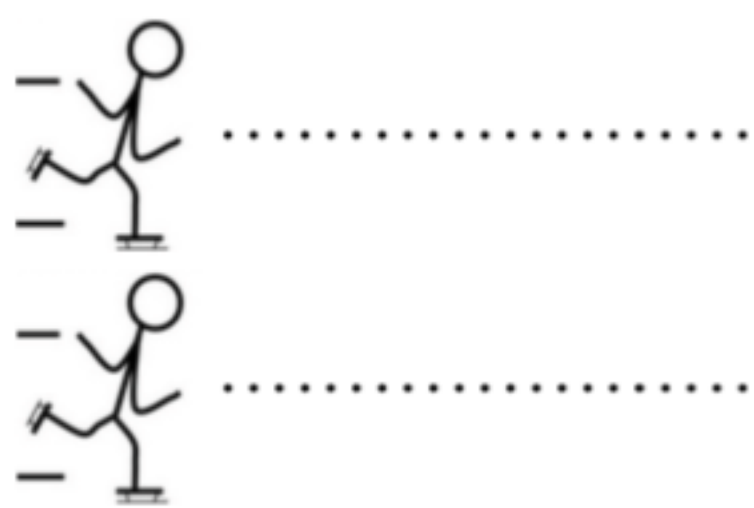

- Matter particle (electron)
- Force particle (photon)

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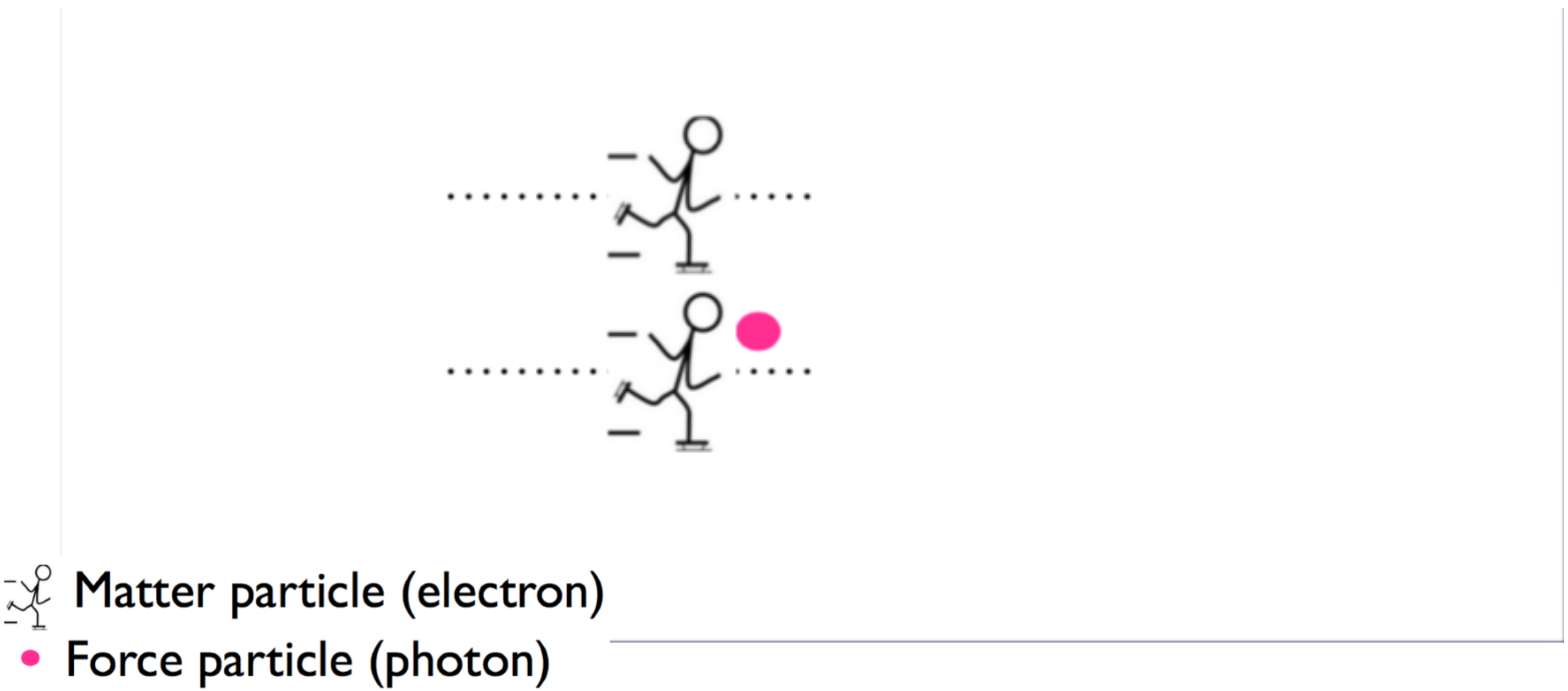

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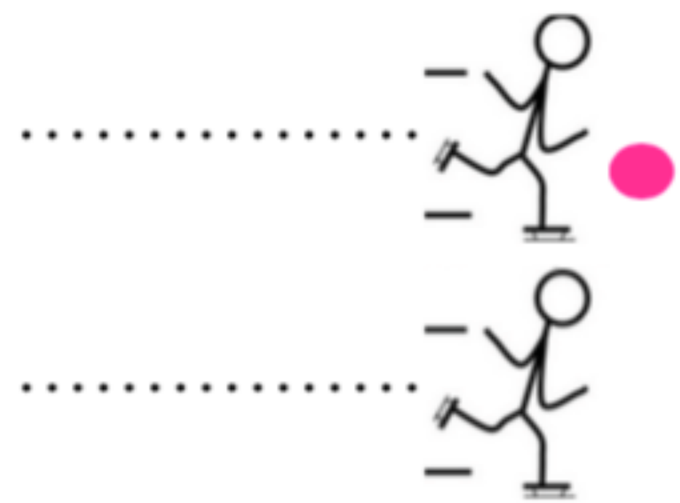

Matter particle (electron)

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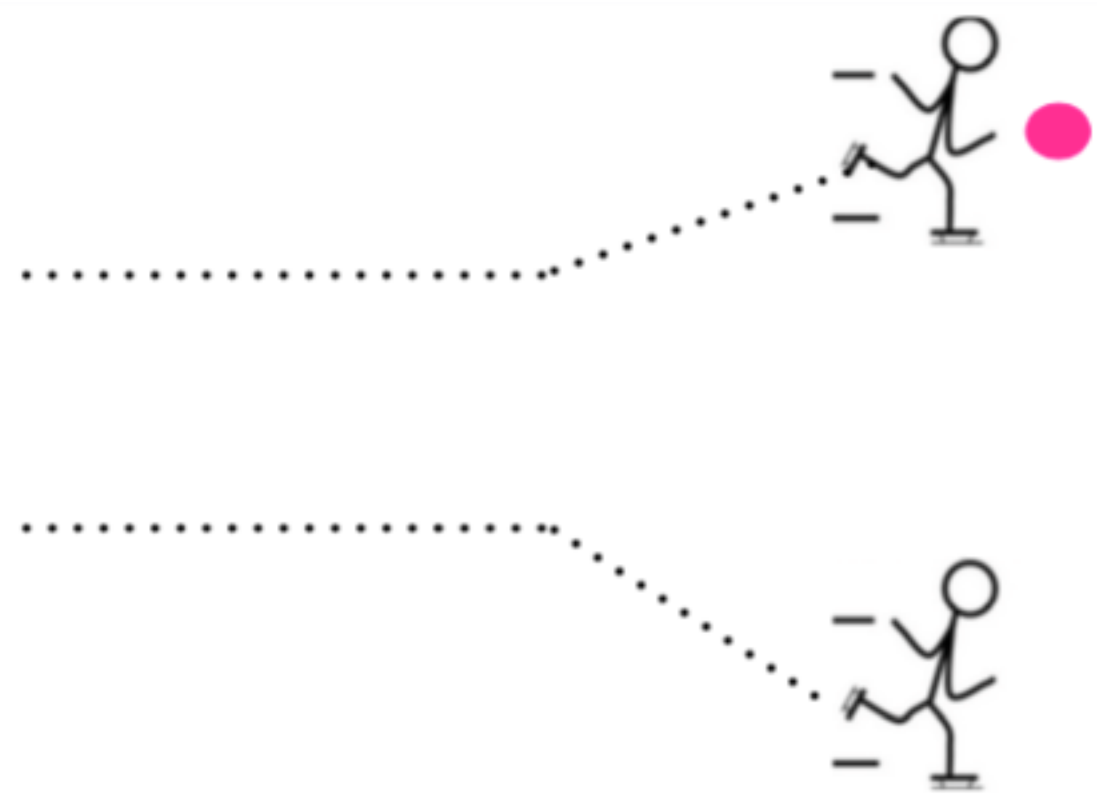


Matter particle (electron)

• Force particle (photon)

How matter interacts: the four forces

- Evidence suggests that all interactions in our universe can be understood in terms of four fundamental forces:
  - Electromagnetism (photon exchange)
  - Weak interactions (W, Z exchange)
  - Strong interactions (gluon exchange)
  - Gravity ("graviton" exchange? Not yet observed.)

  } The Standard Model
- This model is phenomenological: we know there are four forces, but we don't know why.
- Current thinking: the four forces are actually different manifestations of a single field. This field is unified at sufficiently high energies (e.g., right after the Big Bang).

Foundations of Particle Theory

- Particle physics is the study of the smallest constituents of matter.
- At these size scales, matter behaves quite differently than in the macroscopic world.
  - Here, particles obey the rules of quantum mechanics.
  - Moreover, to observe the smallest size scales, we must accelerate particles to very high energies, near the speed of light, **c**. At these speeds, Newtonian mechanics is superseded by special relativity.
- Elementary particle physics describes objects that are both *very small and very fast*.
- Physicists developed a theoretical framework that incorporates relativistic and quantum principles: **Quantum Field Theory**.

Field Theory and the Standard Model

- Quantum field theory (QFT) is the sophisticated mathematical infrastructure of particle physics. It tells us the dynamics of elementary particles - that is, how to use force laws to describe subatomic behavior.
- While QFT is itself quite challenging, its main product - the Standard Model of particle physics - is conceptually straightforward.
- Some parts of the Standard Model perform incredibly well, for example, Quantum Electrodynamics. Its predictions match experiment with stunning accuracy!
  - Actually, these are the most precise predictions and measurements in Science.

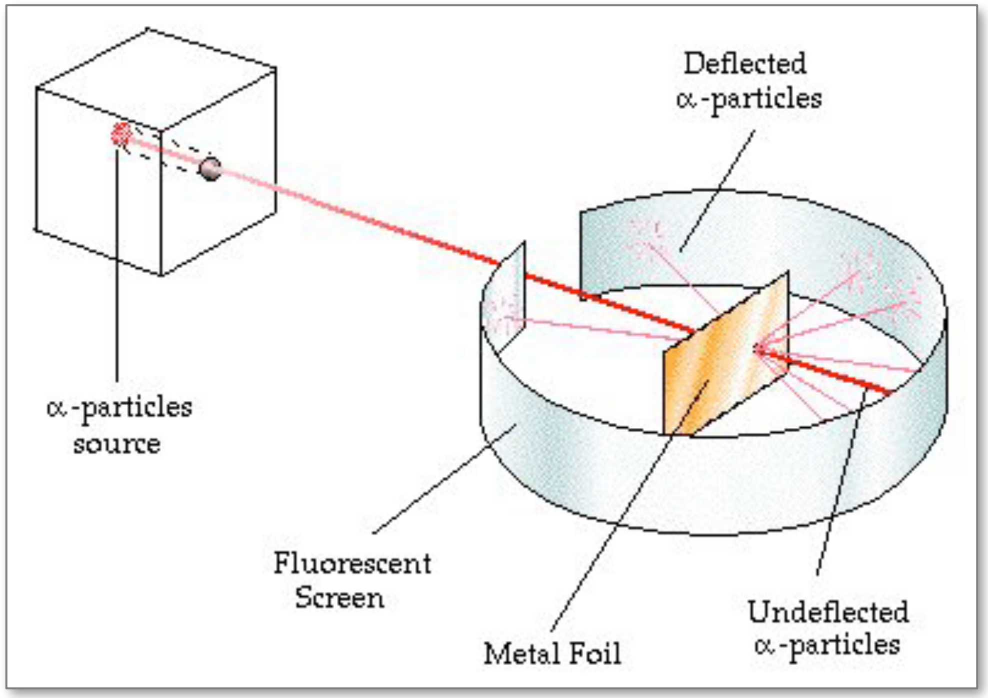
$\mu_{electron}$= 1.00115965219 ±0.00000000001 μ_B (measured)
$\mu_{electron}$= 1.00115965217 ±0.00000000003 μ_B (QED prediction)
(PDG, 2002)

Measurement

Measurement

- Because elementary particles are microscopic - or more correctly, at most *femtoscopic* - we must usually resort to indirect observations to see the fundamental forces at work.

- Just about all particle physics measurements come from the following sources:
  - **Scattering:** fire particles at each other and measure the deflection (e.g. Rutherford experiment)
  - **Decays:** a particle spontaneously disintegrates, and we observe the debris (e.g. neutron decay, muon decay)
  - **Bound states:** two or more particles (oppositely charged) form composite objects, whose properties we observe (e.g. atom, nucleus)



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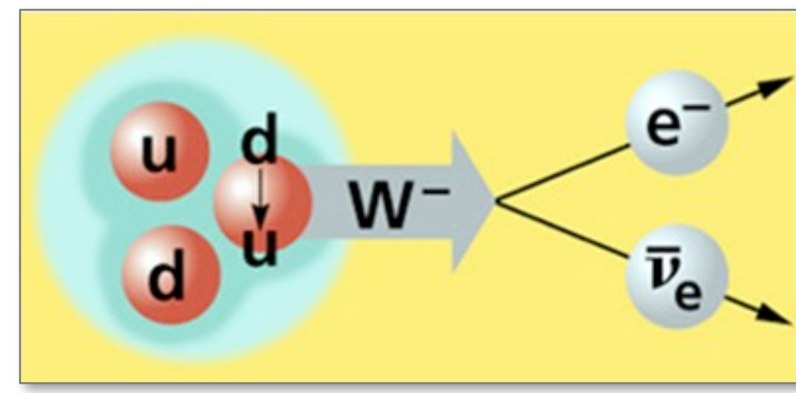

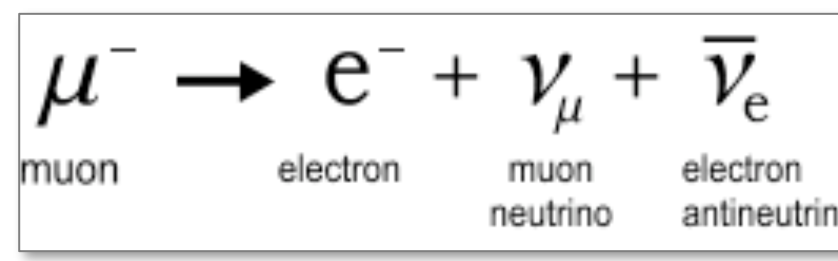

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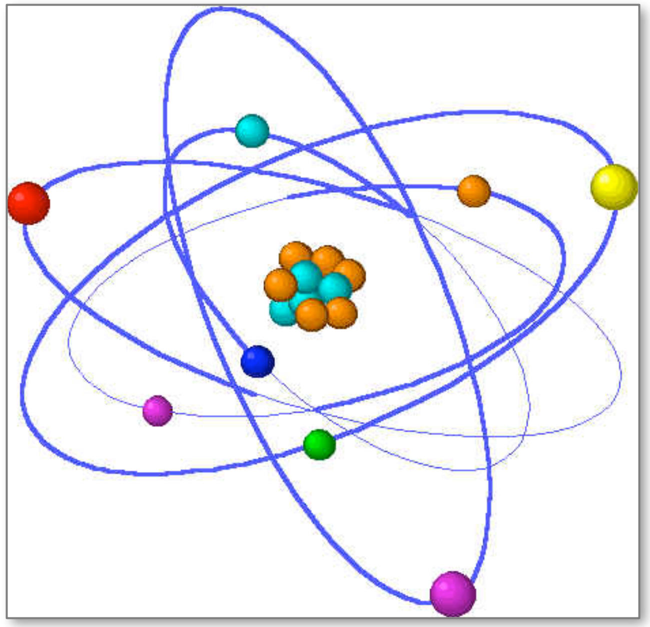

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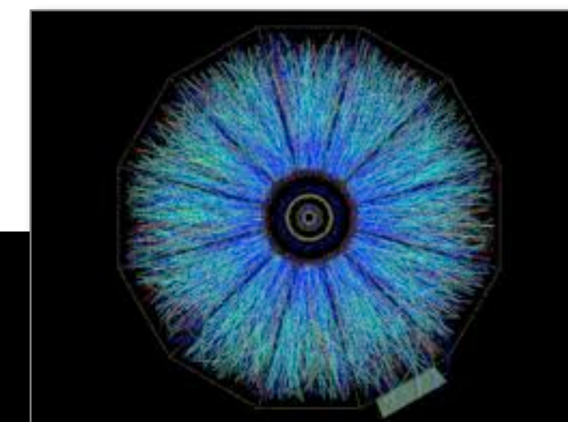
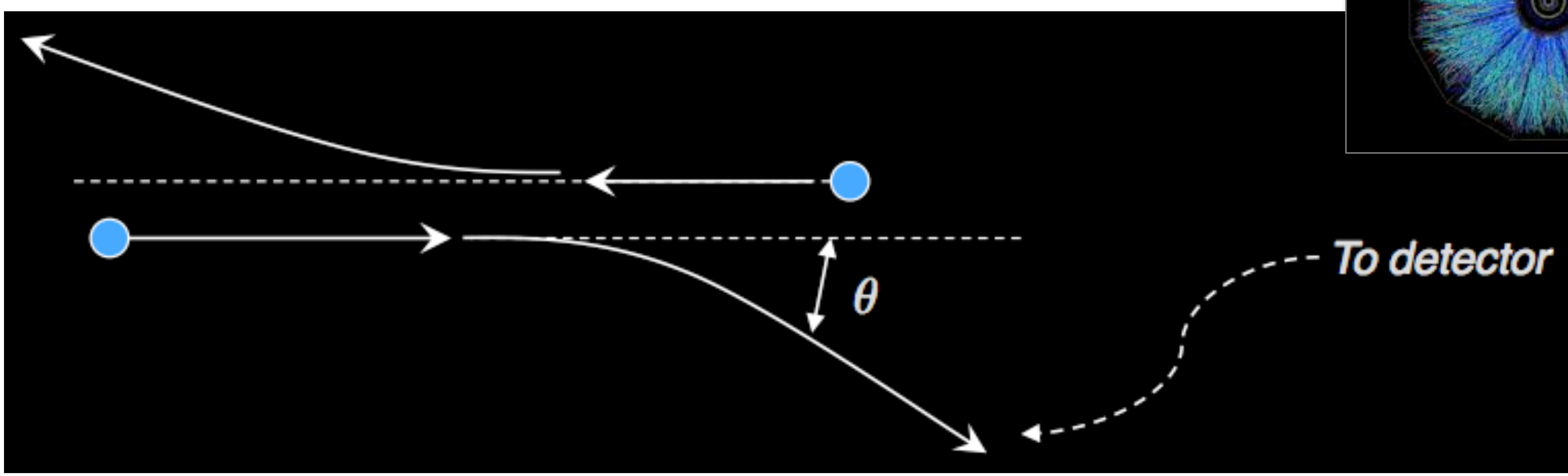
Scattering example

- In a scattering experiment, we fire particles at each other and see what happens.
  - Sometimes the particles collide and form new particles according to $E = mc^2$ (e.g., LHC, Tevatron).
  - Other times, they just deflect (e.g. Rutherford experiment)





The amount of deflection can be predicted from a force law.

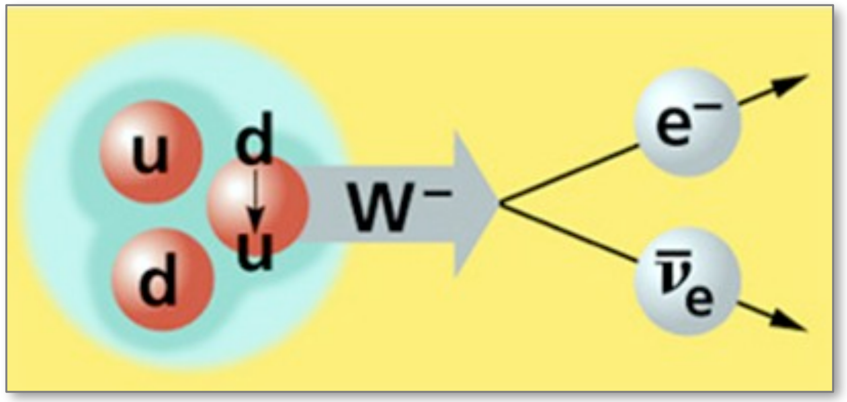
Hence, we can test whether or not we know the force law's correct form:

$$F = \frac{q_1 q_2}{4\pi r^2} \quad \Rightarrow \quad N(\theta) \propto \sin^{-4}(\theta/2)$$

Decay example

- Inside most nuclei, neutrons are very stable particles.
- However, free neutrons are unstable; on average, a newly created neutron will last about 15 minutes before it breaks into three pieces: a proton, an electron and an electron anti-neutrino:

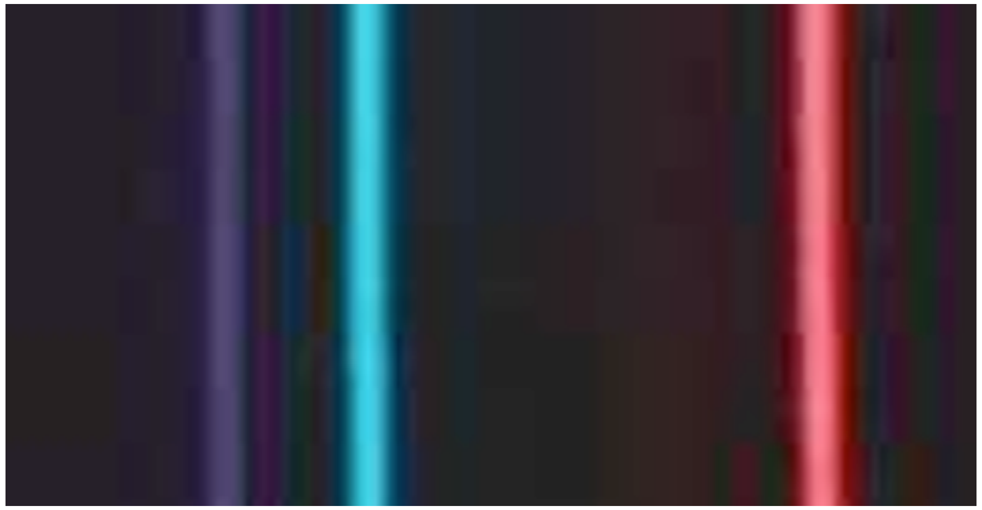
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



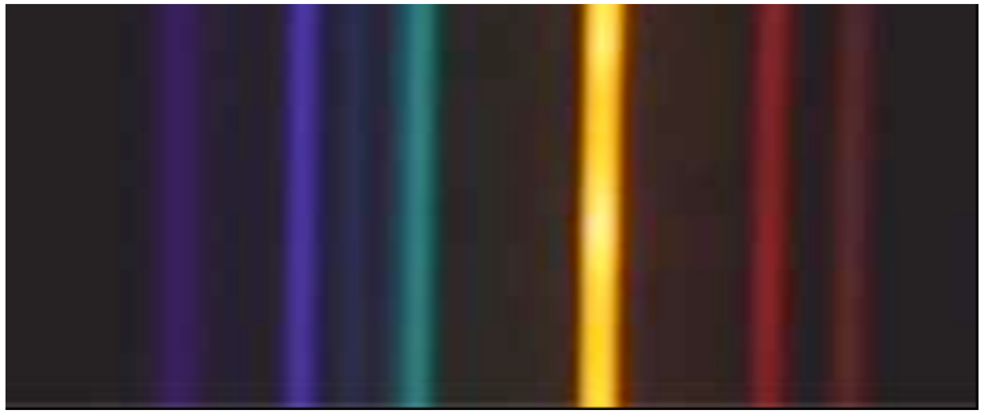
- The weak force is causing the neutron to spontaneously break apart.
- The nature of the weak force can then be determined by studying the decay products and their energies.

Bound states

- You are very familiar with bound states: all of the familiar chemical elements are just bound states of nuclei and electrons.
- When we excite bound states, they emit radiation in particular wavelength bands.
- This radiation contains a wealth of information about the structure of the bound state and the governing force law.



Excitation spectrum of hydrogen, a bound state of one proton and one electron.



Helium, a bound state of two protons, two neutrons, and two electrons, has a different excitation spectrum, but is governed by the same force law.

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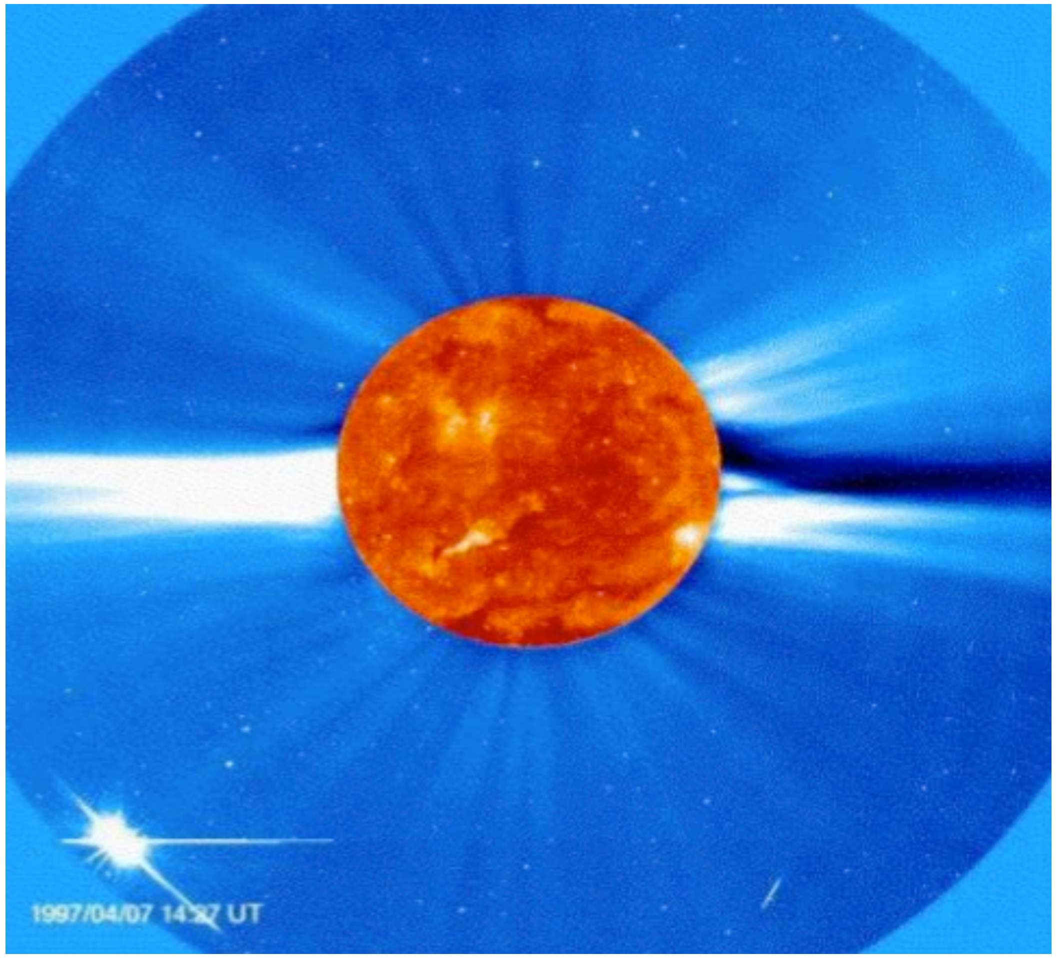
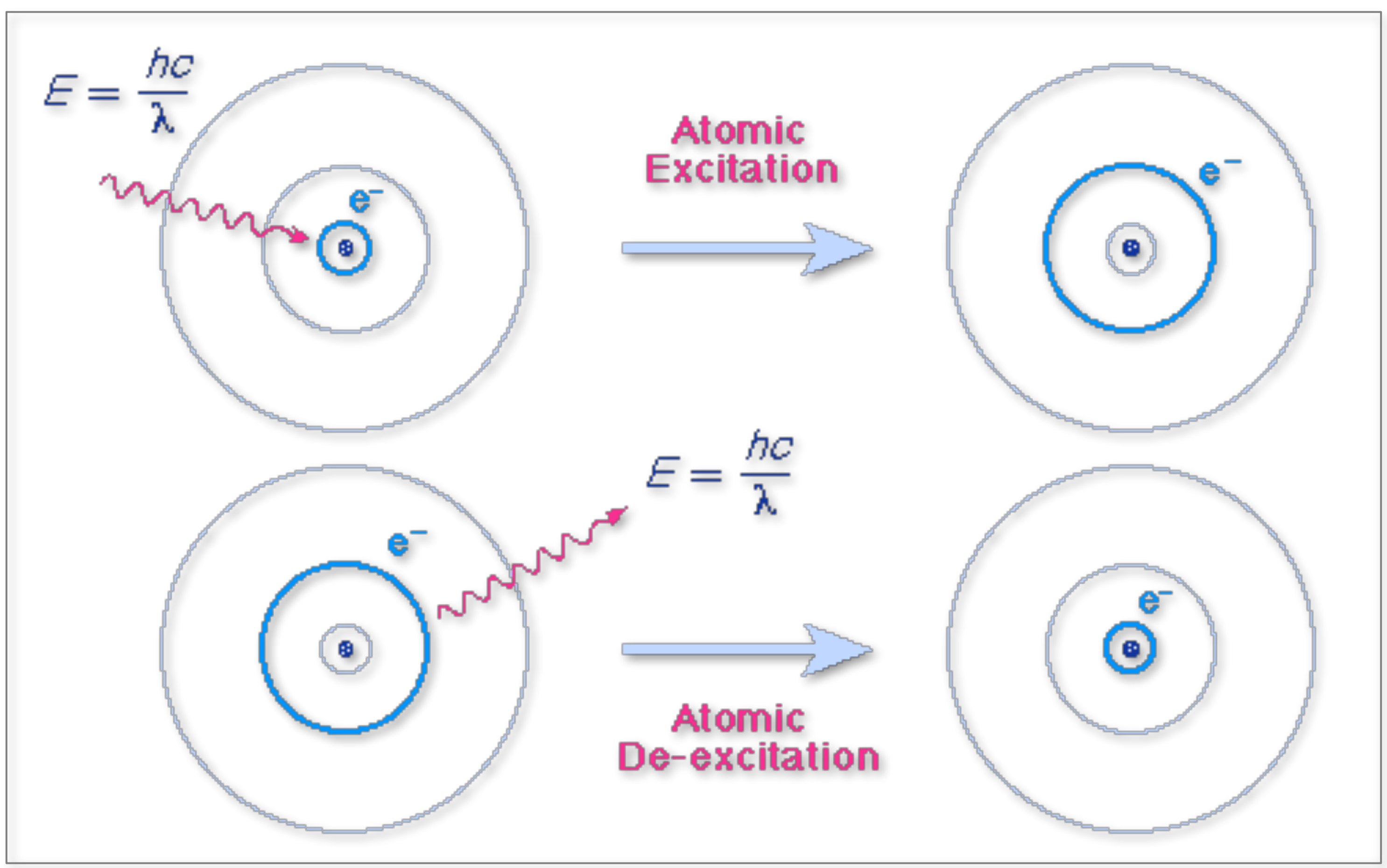


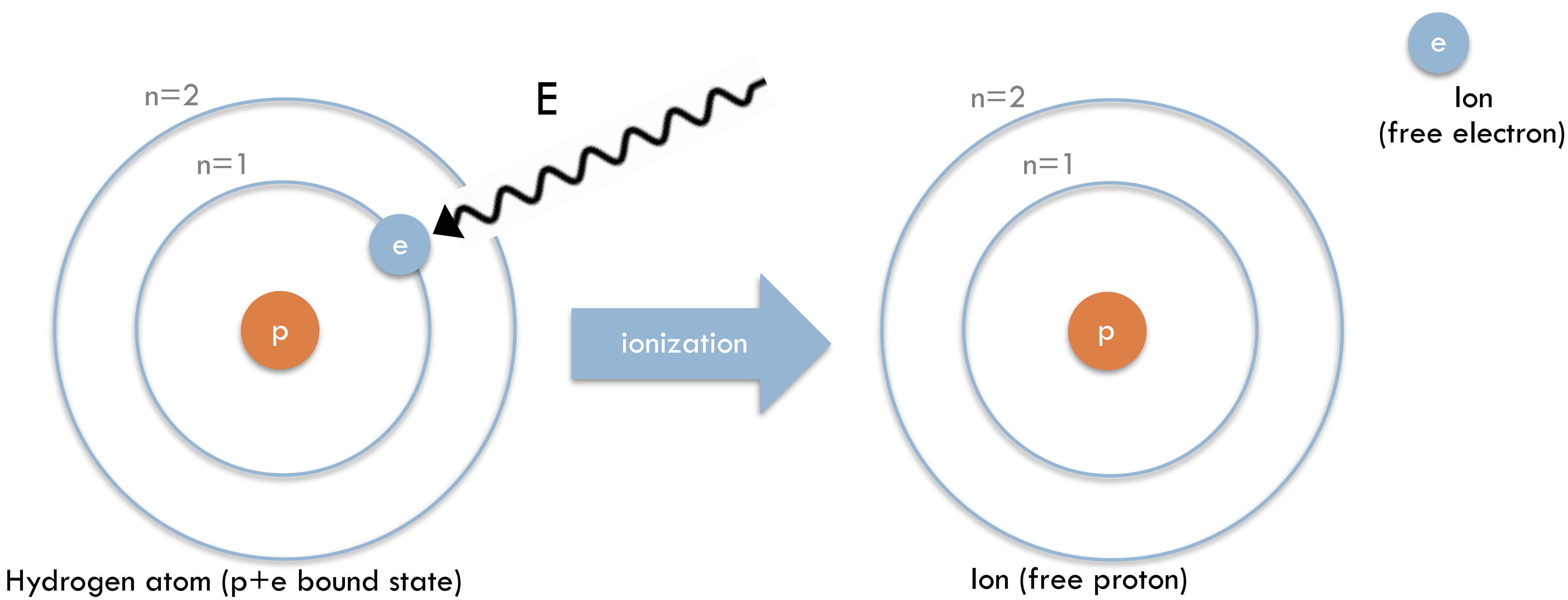
Atomic excitation

- An atom is excited when it has the potential to spontaneously produce energy.
  - This happens when one or more of the electrons occupy a higher-energy state.
  - When the electron returns to a lower energy state, the energy difference is given off in the form of radiation.
- The lowest energy state is the ground state.



Ionization

- **Ion:** positively or negatively charged particle (or part of atom)
- Ions can be produced when enough energy is given to remove one or more electrons from an atom:



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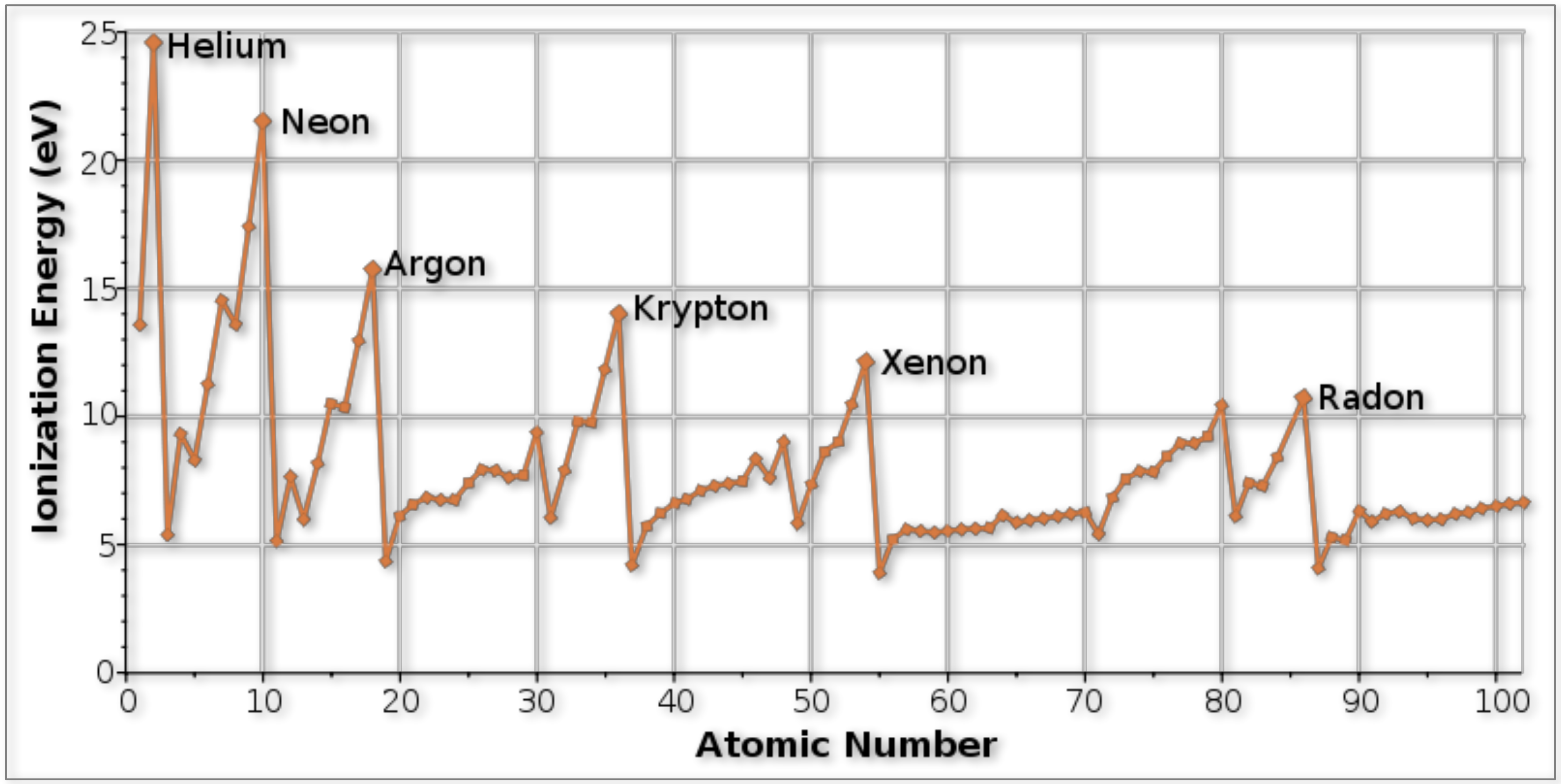
- **Ionization energy** is the energy necessary to strip an atom of its most loosely bound electron (valence electron).



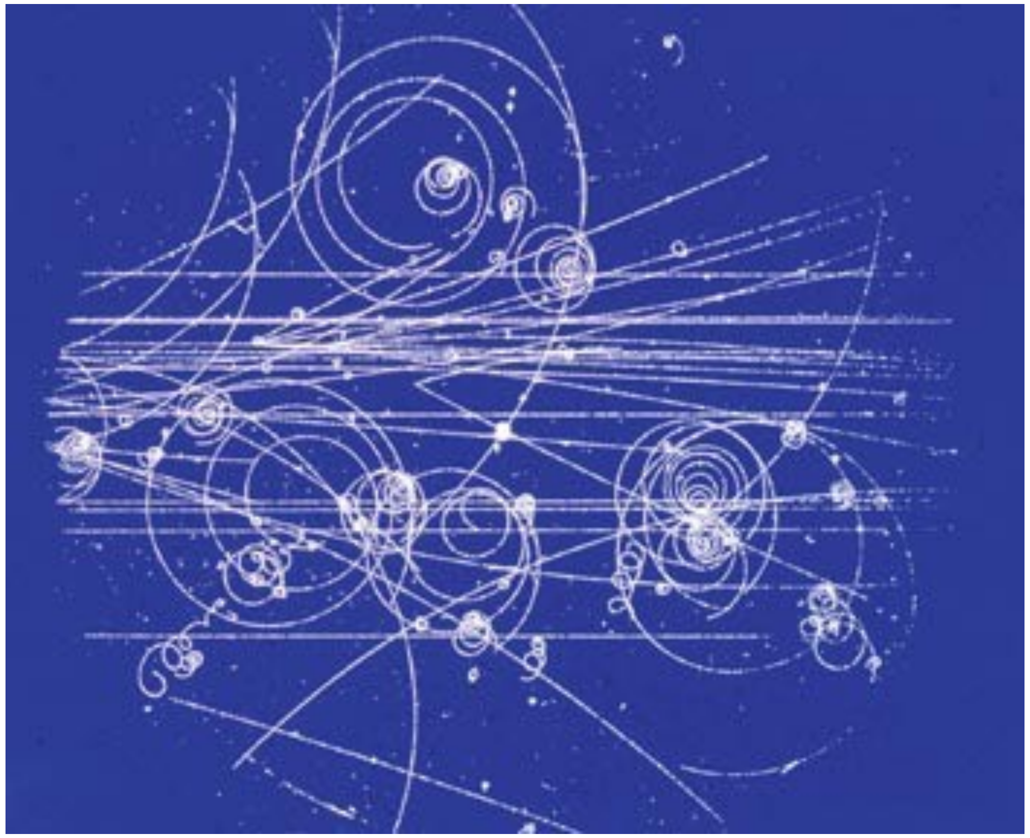
Detecting particles

Detecting particles

When charged particles pass through matter, they ionize atoms in their path, liberating charges, and causing the emission of detectable light (scintillators) or the formation of tracks of droplets (cloud/bubble chambers).
This is how we "see" them.

Experimental physicists use many kinds of particle detectors, including:

- Geiger counters
- Cloud chambers *
- Bubble chambers *
- Spark chambers *
- Photographic emulsions *
- Wire chambers
- Cherenkov counters
- Scintillators
- Photomultipliers
- Calorimeters

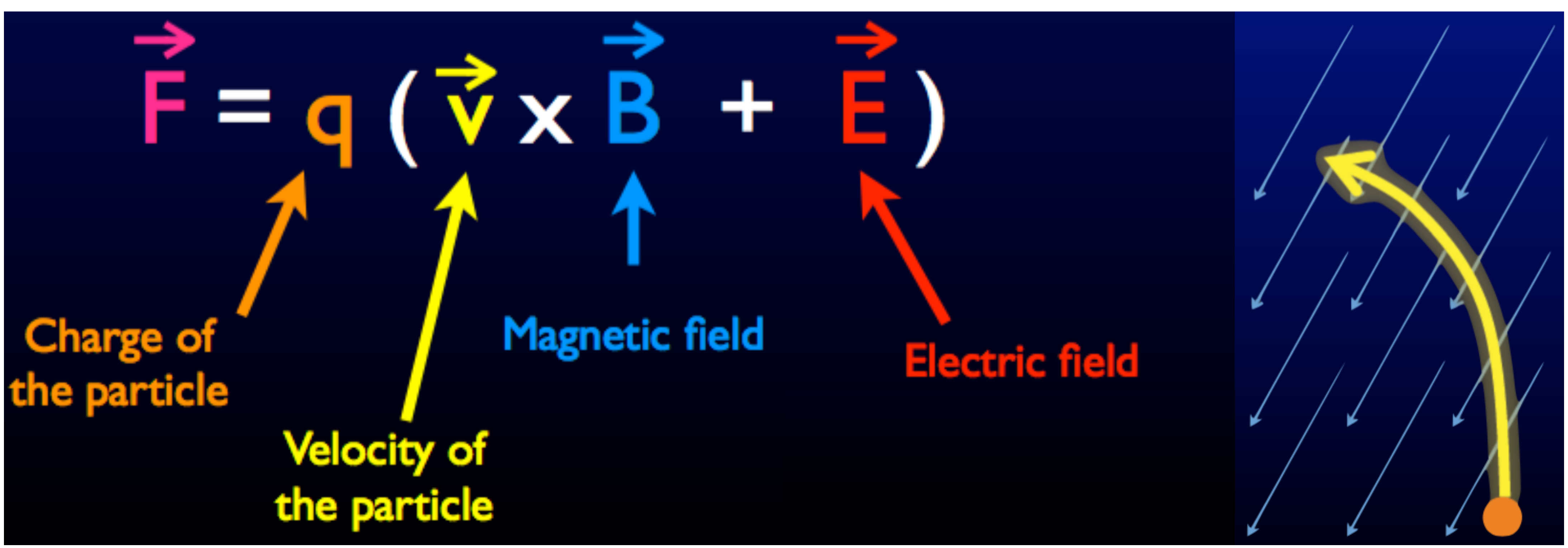


➡ Note: most are sensitive to electrically charged particles only!

* Less common these days…

Measuring particle properties

- Particle physics tries to identify elementary particles and deduce the quantitative force laws that most simply describe their behavior.
- A vital force law: Lorentz Force Law, the **force** on an electric charge **q** placed in an electromagnetic field (electric field **E** and magnetic field **B**):



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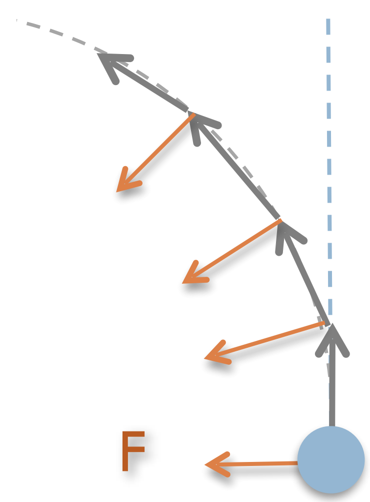


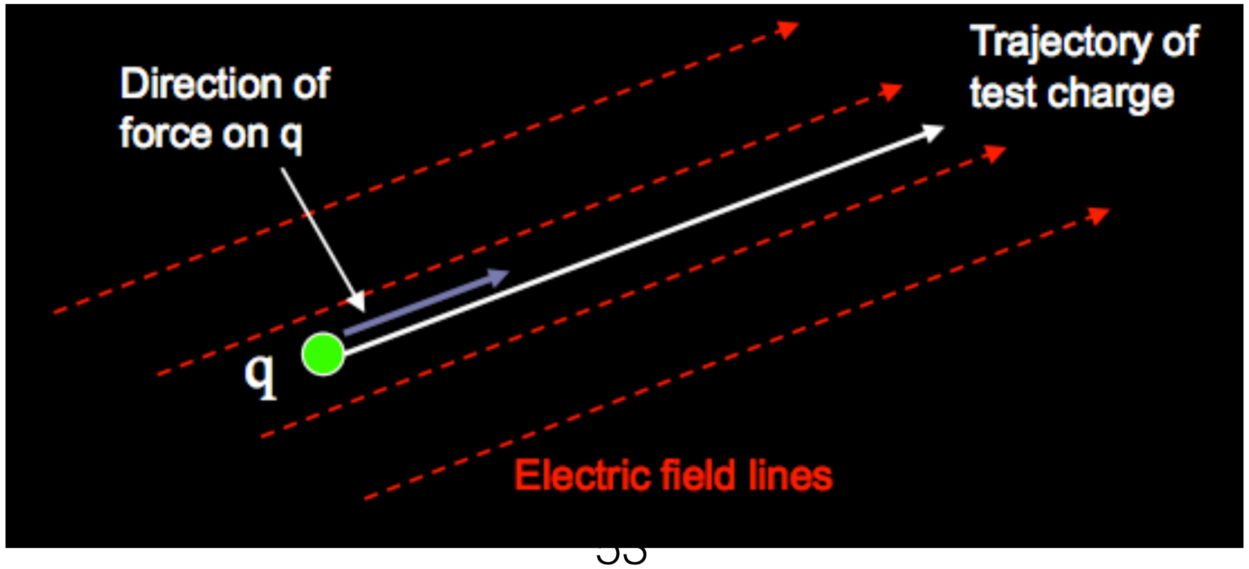
RECALL: A body under the influence of a force will be deflected from its original path.

Aside: the electric field E

- You can define the electric field according to what it does to test (electric) charges.
- The electric field **E** in a region of space in which a test charge **q** gets accelerated by a force **F**, is given by:

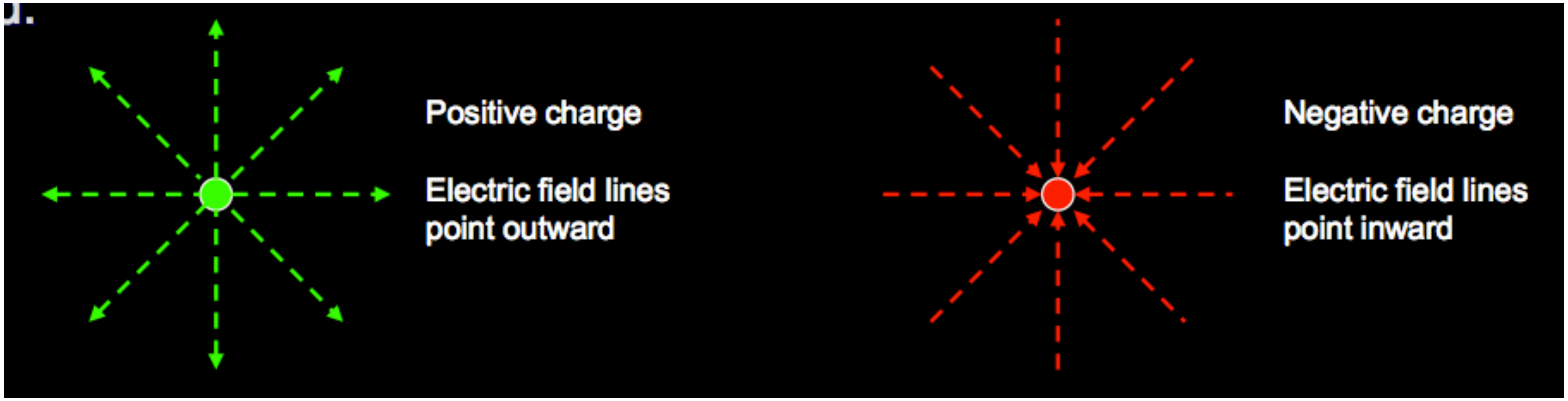
$$\vec{F}_{\text{electric}} = q\vec{E}$$

- In other words, if you put a charge **q** in an electric field **E**, that charge will experience a force proportional to **q** along the direction of **E**.



Aside: the electric field E

- Every electric charge is also the source of an electric field.



- According to classical physics, this is how charges attract and repel each other: each charge detects *the field of the other*, and then responds according to the force law: $\vec{F}_{\text{electric}} = q\vec{E}$

- At the quantum level, this view has been replaced by the model of mediator exchange, which we flesh out later in the course…

Measuring particle properties

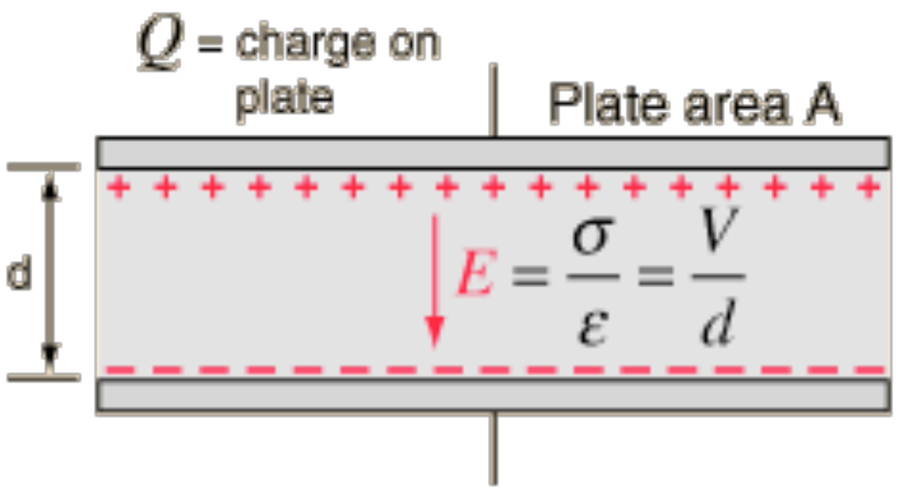
A basic particle accelerator:

- Consider the parallel-plate capacitor…

  Two metal plates are given equal but opposite charges +Q and -Q, creating a potential difference V, or drop in voltage, between them.

  The charges set up a uniform electric field E between the plates.

  A test charge in this region gets accelerated.



- This is the principle behind every particle accelerator: pass charges through an electric field to increase their kinetic energy.

Energy units: electron-Volts (eV)

- **Basic unit of energy in particle physics: electron-Volt (eV)**
- The eV is the energy acquired by one electron accelerated (in vacuum) through a potential difference of one Volt.
- Comparison with more familiar units: 1 eV = 1.602×10^{-19} Joule

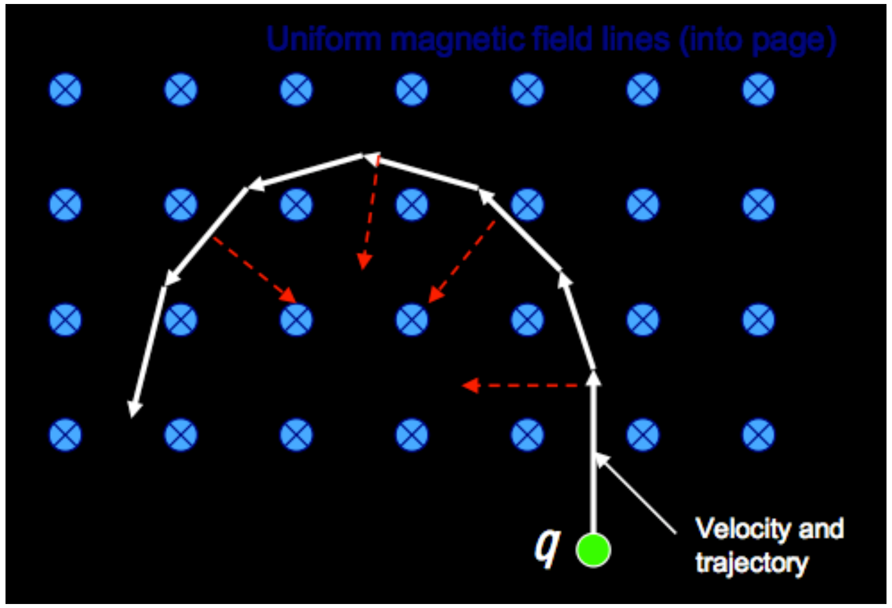
- **Also unit of mass:** $E = mc^2$ ➡ in natural units ($c = 1$): $E = m$
- **And momentum:** $E = pc$ ➡ in natural units ($c = 1$): $E = p$

Note: 1 Joule is roughly the energy it takes to lift a 1kg object 10 cm off the ground.

The magnetic field B

- According to the Lorentz Force Law, the magnetic force on a charge q is:

$$\vec{F}_{\text{magnetic}} = \frac{q}{c}\vec{v} \times \vec{B}$$



- Note: the magnetic force is perpendicular to both the direction of the field and the velocity of the (positive) test charge (right-hand rule). If v and B are perpendicular to each other, the charge's trajectory will bend into a circle.
- Note: if the charge is stationary (v=0), the magnetic force on it is zero. Magnetic fields only affect moving charges (currents).
- **Note: the direction of the particle's path depends on the sign of its charge!**

Measuring particle properties

- Electric charges moving in uniform magnetic fields travel in circular paths. The path's radius of curvature yields important information:

$$F_{\text{magnetic}} = F_{\text{centripetal}}$$

$$\frac{q}{c}\left\|\vec{v}\times\vec{B}\right\| = m\frac{v^2}{r}$$

Measuring particle properties

- Electric charges moving in uniform magnetic fields travel in circular paths. The path's radius of curvature yields important information:

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$$\frac{qvB}{c} = m\frac{v^2}{r}, \quad \vec{v}\times\vec{B} = vB, \text{ if } \vec{v} \text{ is perpendicular to } \vec{B}$$

$$r = \frac{mvc}{qB}, \quad r \text{ is radius of curvature}$$

$$r = \frac{pc}{qB}, \quad p = mv = \text{ momentum of particle}$$

- By measuring the radius of curvature of a charge's path, physicists can determine both the momentum and the sign of the charge.
- **This is the primary means of particle identification in experiments!**

Recap

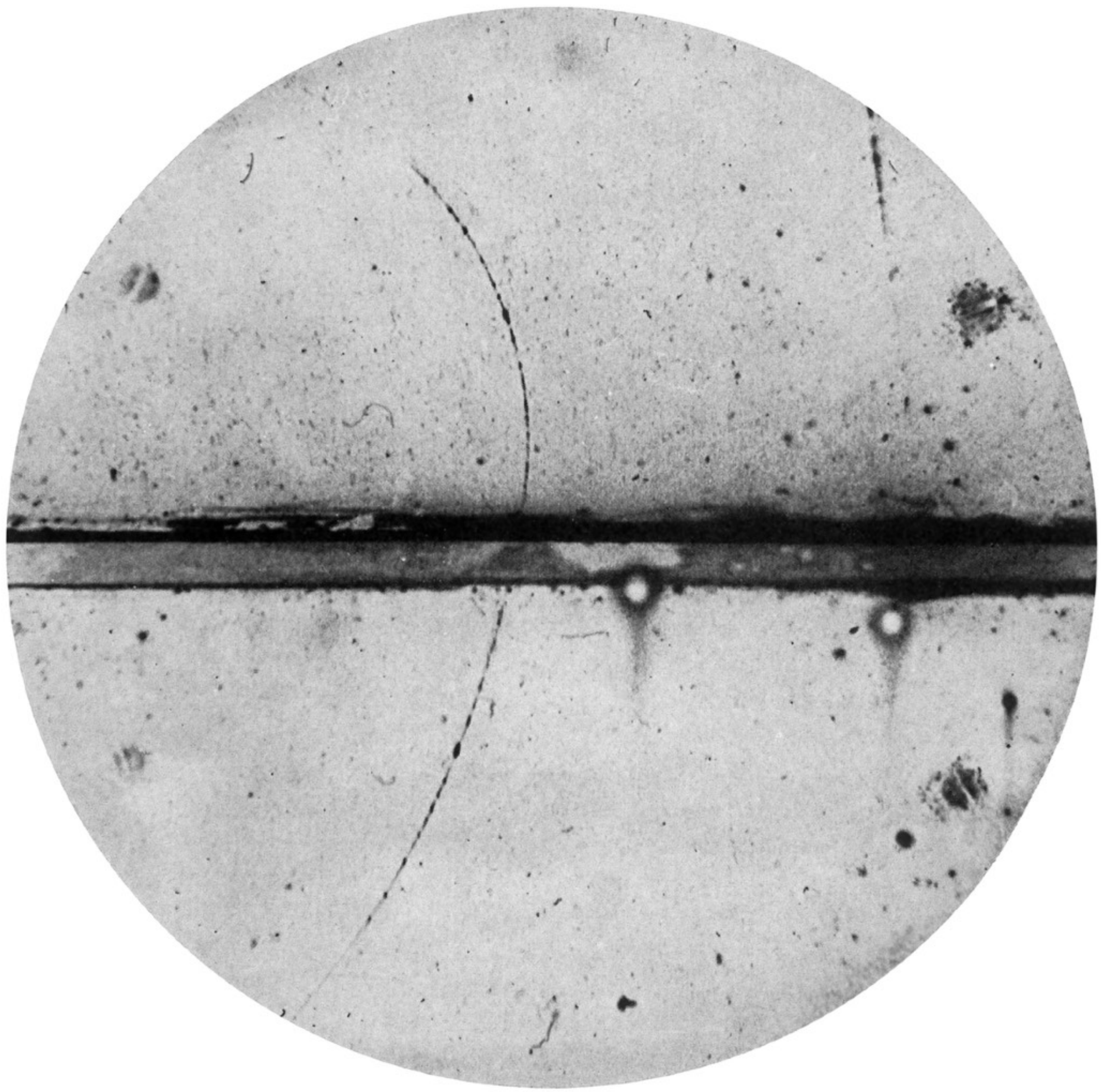
- Particle physics studies the fundamental constituents of the Universe.
- The Standard Model is the theory that describes the electromagnetic, weak and strong interactions.
    - It has shown incredible prediction power!
    - But leaves some phenomena unexplained…

- **Next week: History of Particle Physics**

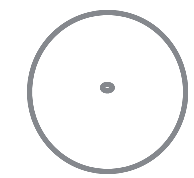
Material

- Material covered in classes will be available here:
  - https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram

Bonus

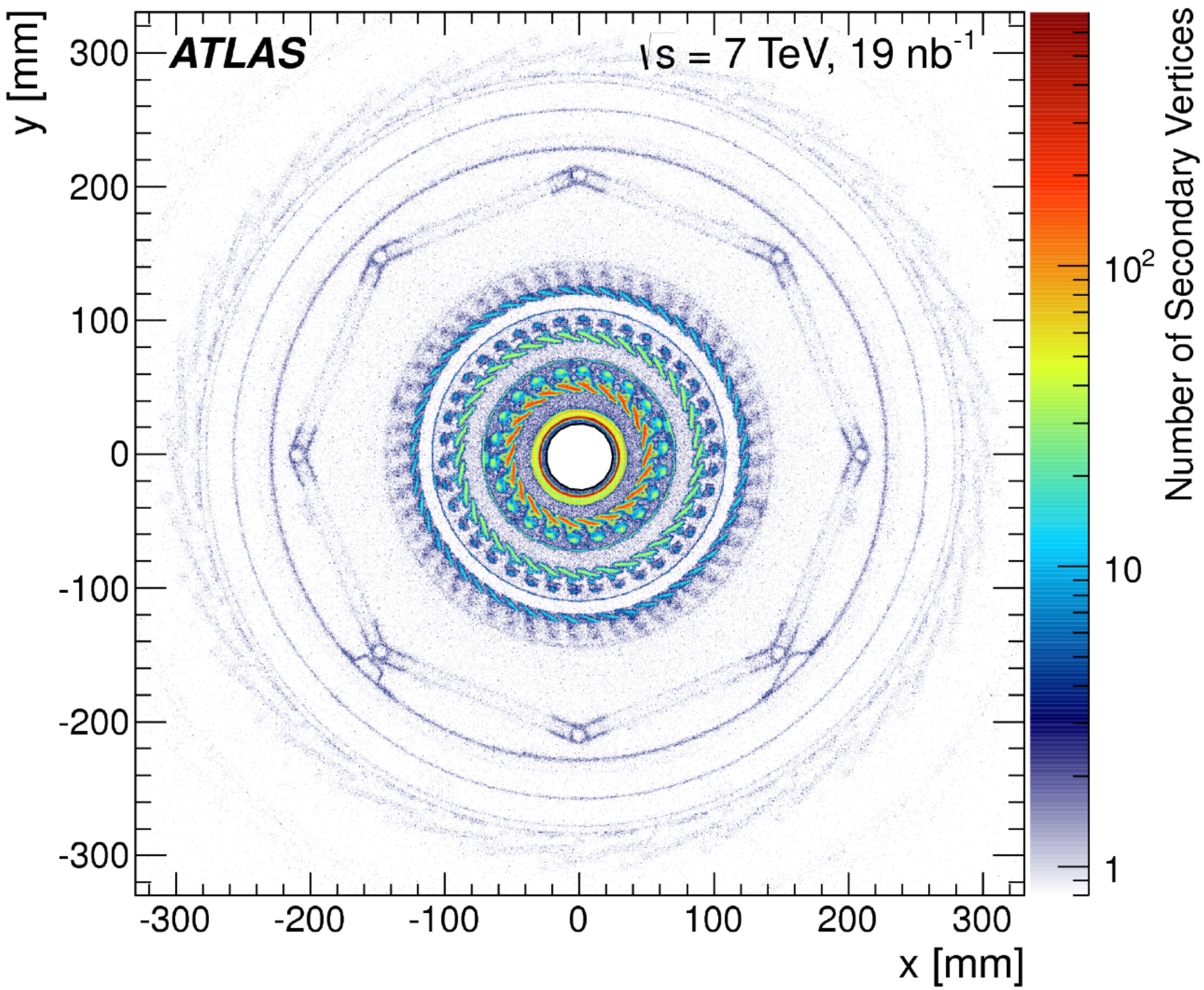


Magnetic field



Carl D. Anderson (1932)

Bonus



ATLAS
√s = 7 TeV, 19 nb-1
y [mm]
300
200
100
0
-100
-200
-300
-300
-200
-100
0
100
200
300
x [mm]
Number of Secondary Vertices
10^2
10
1