Particle Physics in a Nutshell

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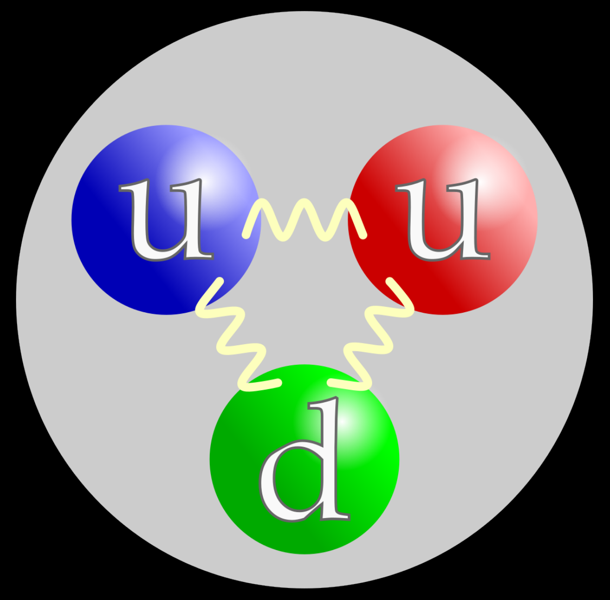
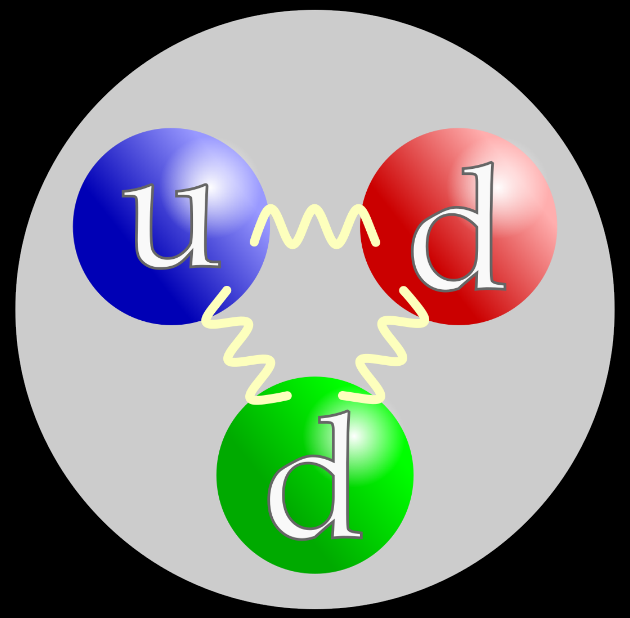
QuarkNet

What are particles?

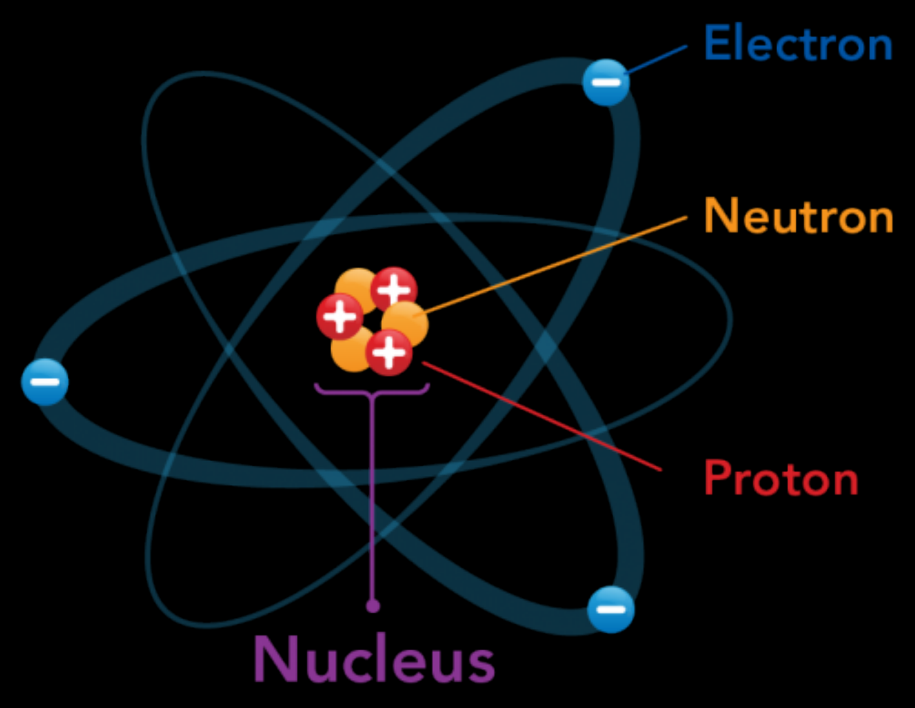
- All the matter around us today is made of three type of particles:
  - “up” quark, $Q = +\frac{2}{3}$
  - “down” quark, $Q = -\frac{1}{3}$
  - electron, $Q = -1$
- They are fundamental, cannot be divided



Proton



Neutron



Atom

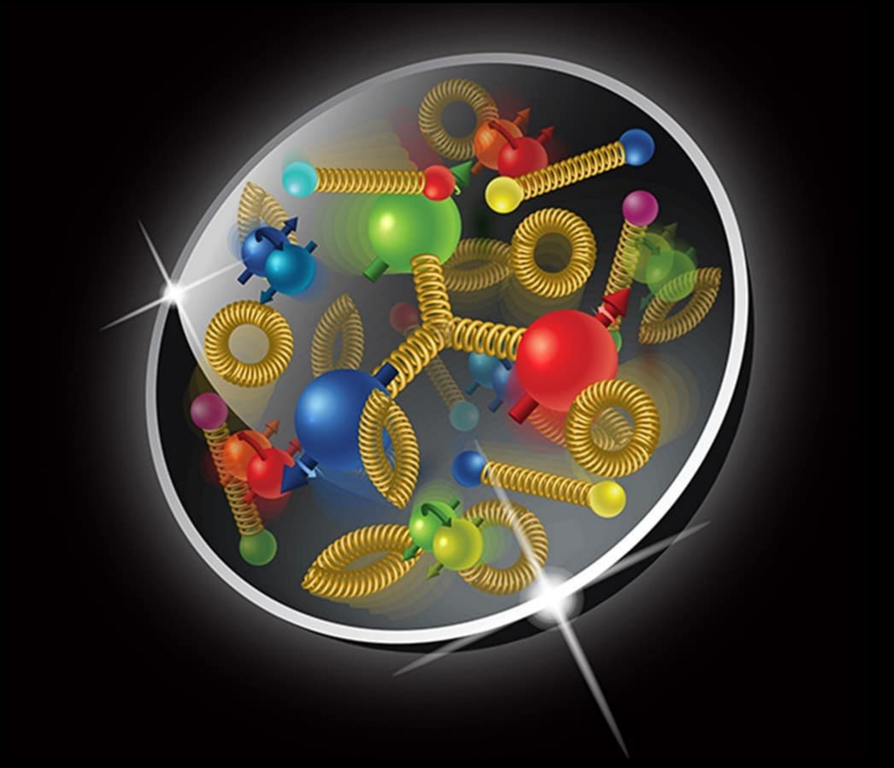
What is particle physics?

a reductionist perspective

Particle physics is the branch of physics that studies the fundamental particles that constitute the universe and the forces through which they interact.

Fundamental Forces

- **Strong force**: binding force for the formation of proton and neutron



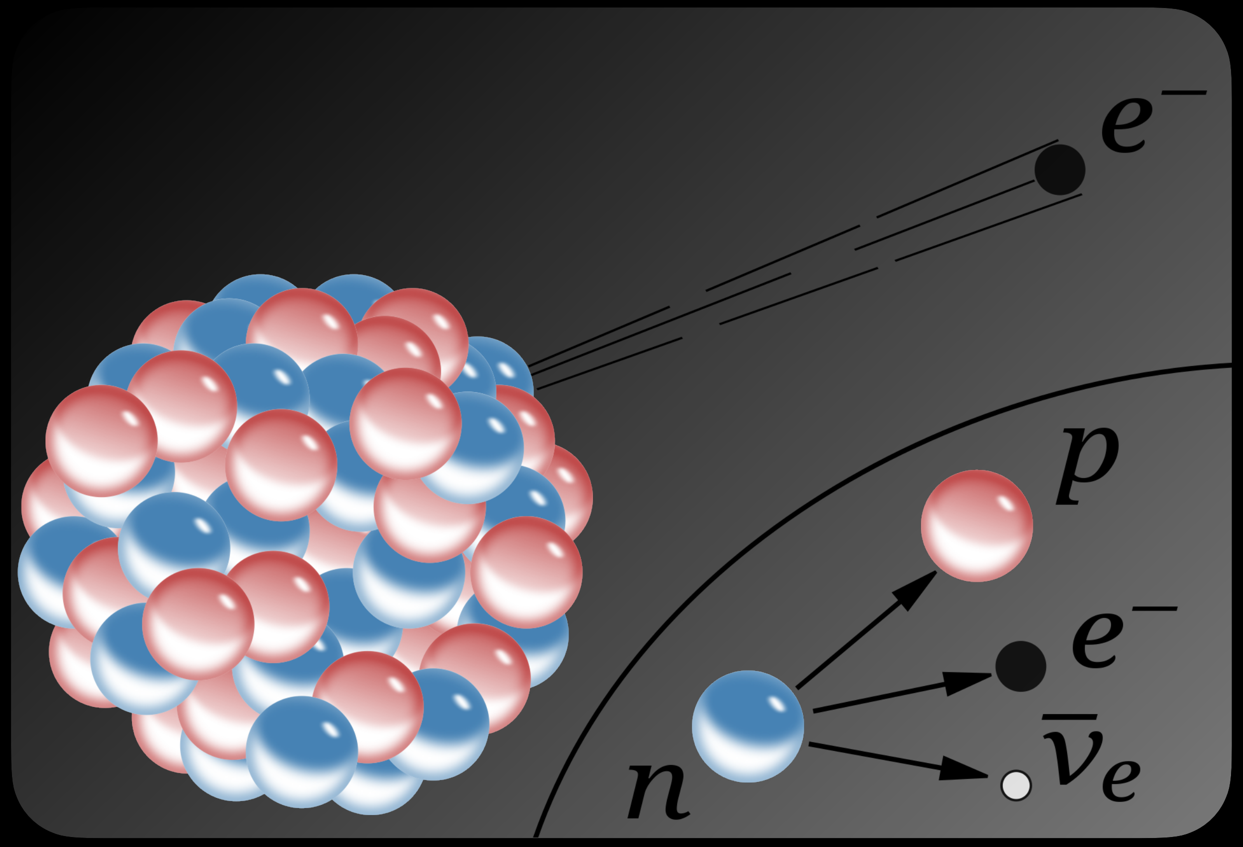
- **Electromagnetic force**:
  - Electric force between charges
  - Magnetic force between magnets and charge currents

Decreasing strength

Image: BNL

Fundamental Forces

- **Weak force**: responsive for the radiative decay of particles
  - Example: the neutron decay into proton



- **Gravitational force**: attractive force between massive objects

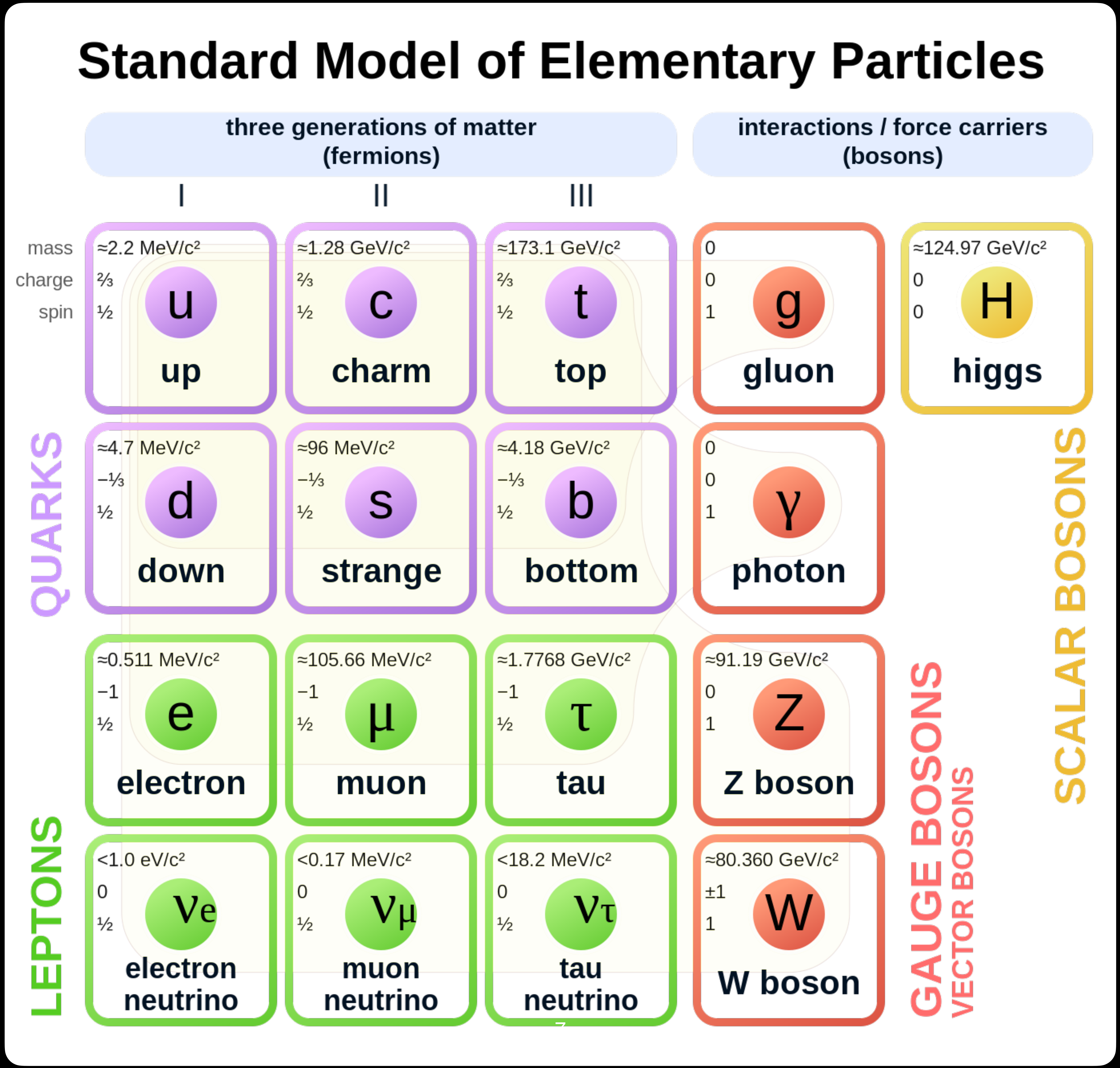
Decreasing strength

Fundamental Forces

- **Strong force**: binding force for the formation of proton and neutron
- **Electromagnetic force**:
    - Electric force between charges
    - Magnetic force between magnets and charge currents
- **Weak force**: responsive for the radiative decay of particles
- **Gravitational force**: attractive force between massive objects

Described by the Standard Model of particle physics

The Standard Model

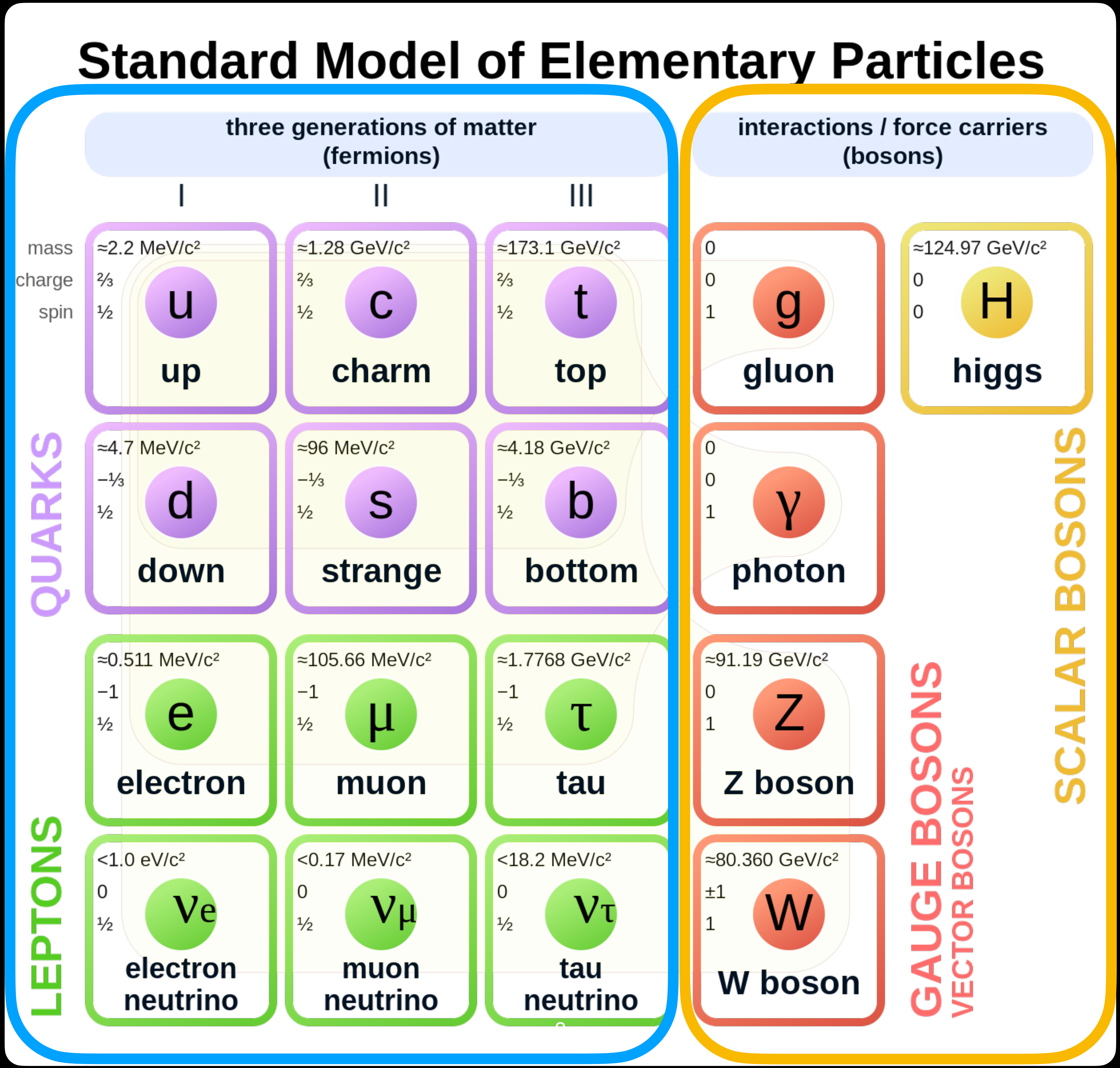


particles are light

$$1\ \mathrm{eV} \simeq 2 \times 10^{-33}\ \mathrm{gram}$$

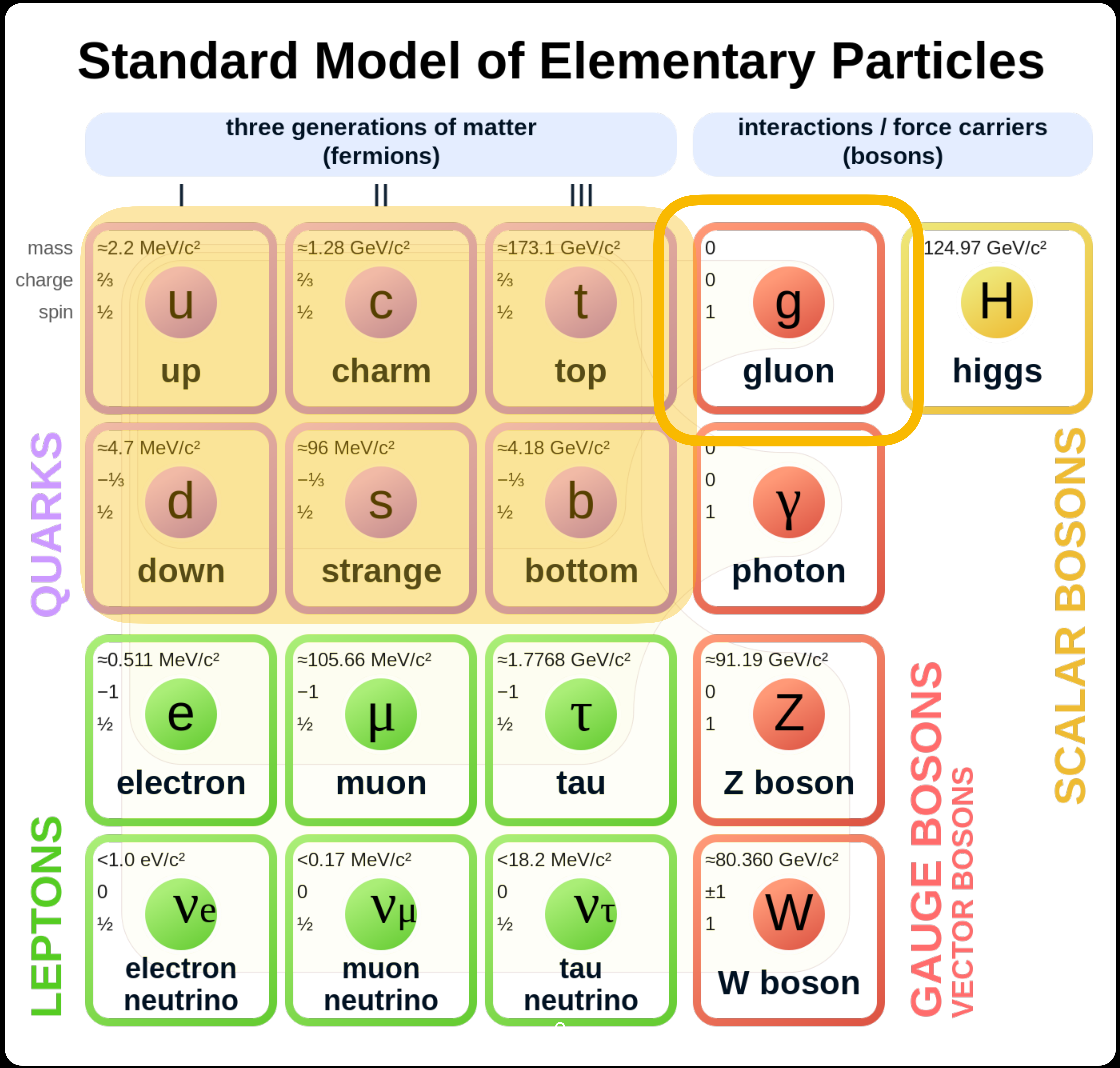
The Standard Model

Fermions in the table are matter particles



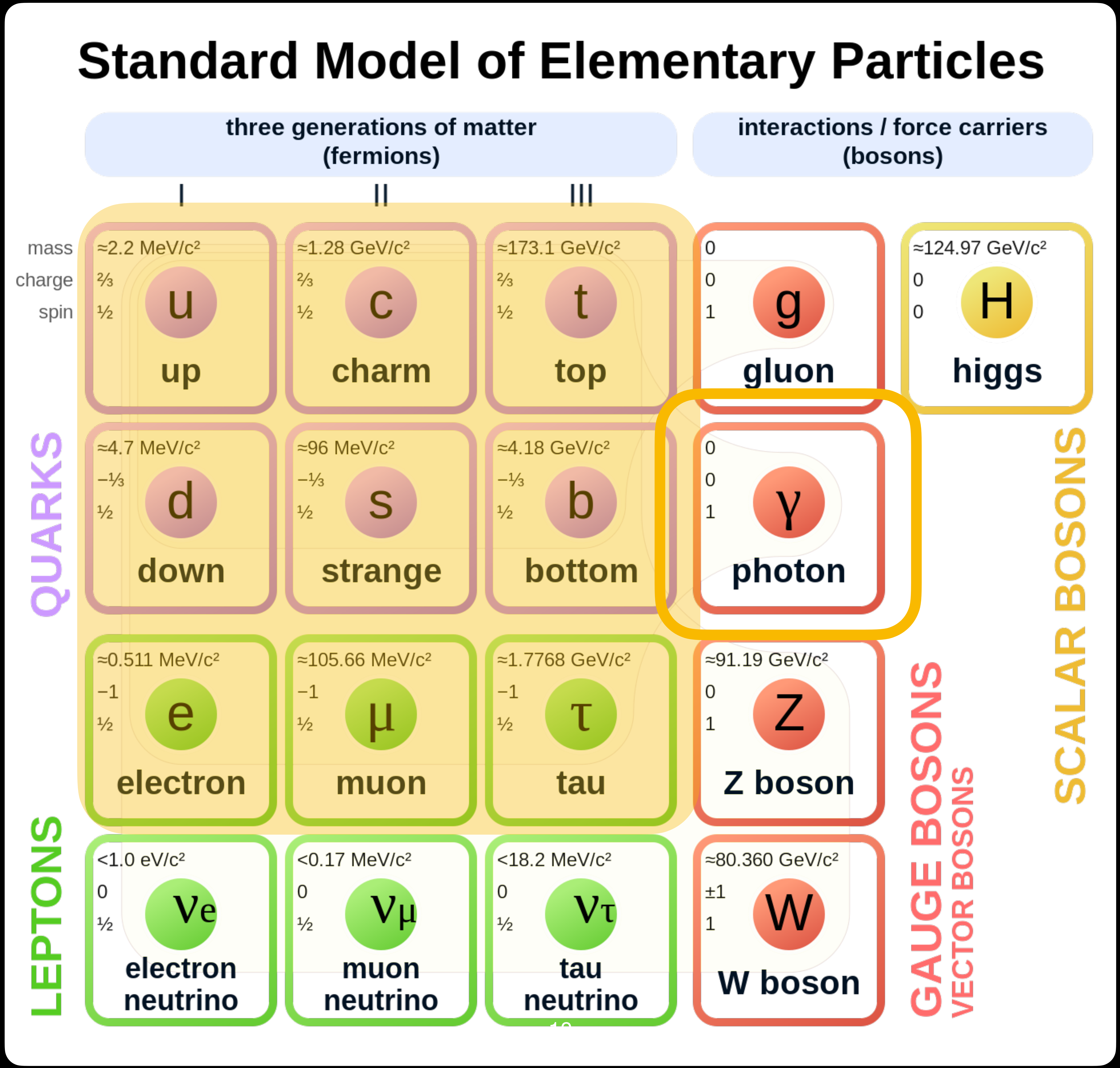
Bosons in the table are exchanged to mediate the force

The Standard Model



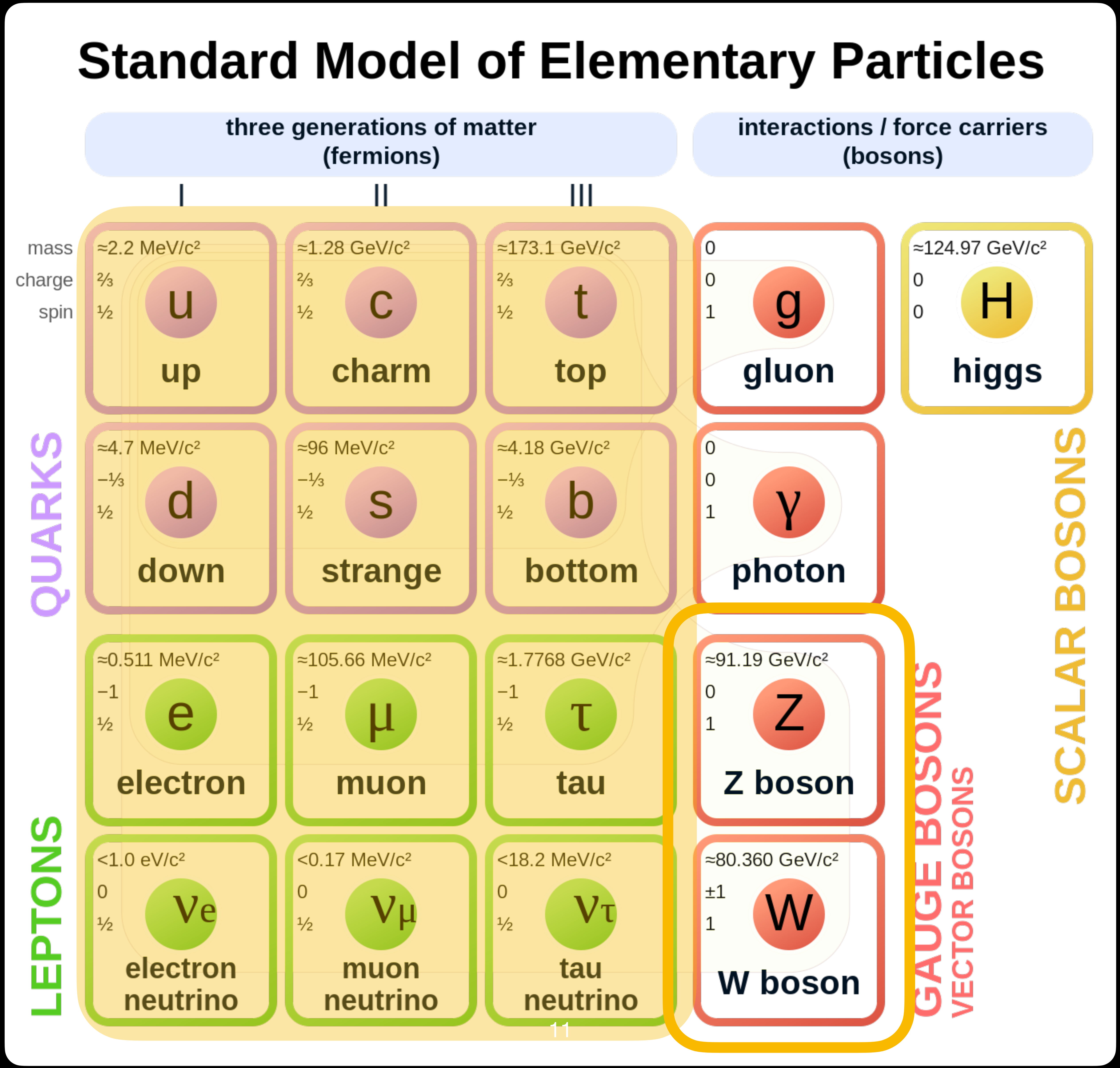
Gluon mediates the strong force.

The Standard Model



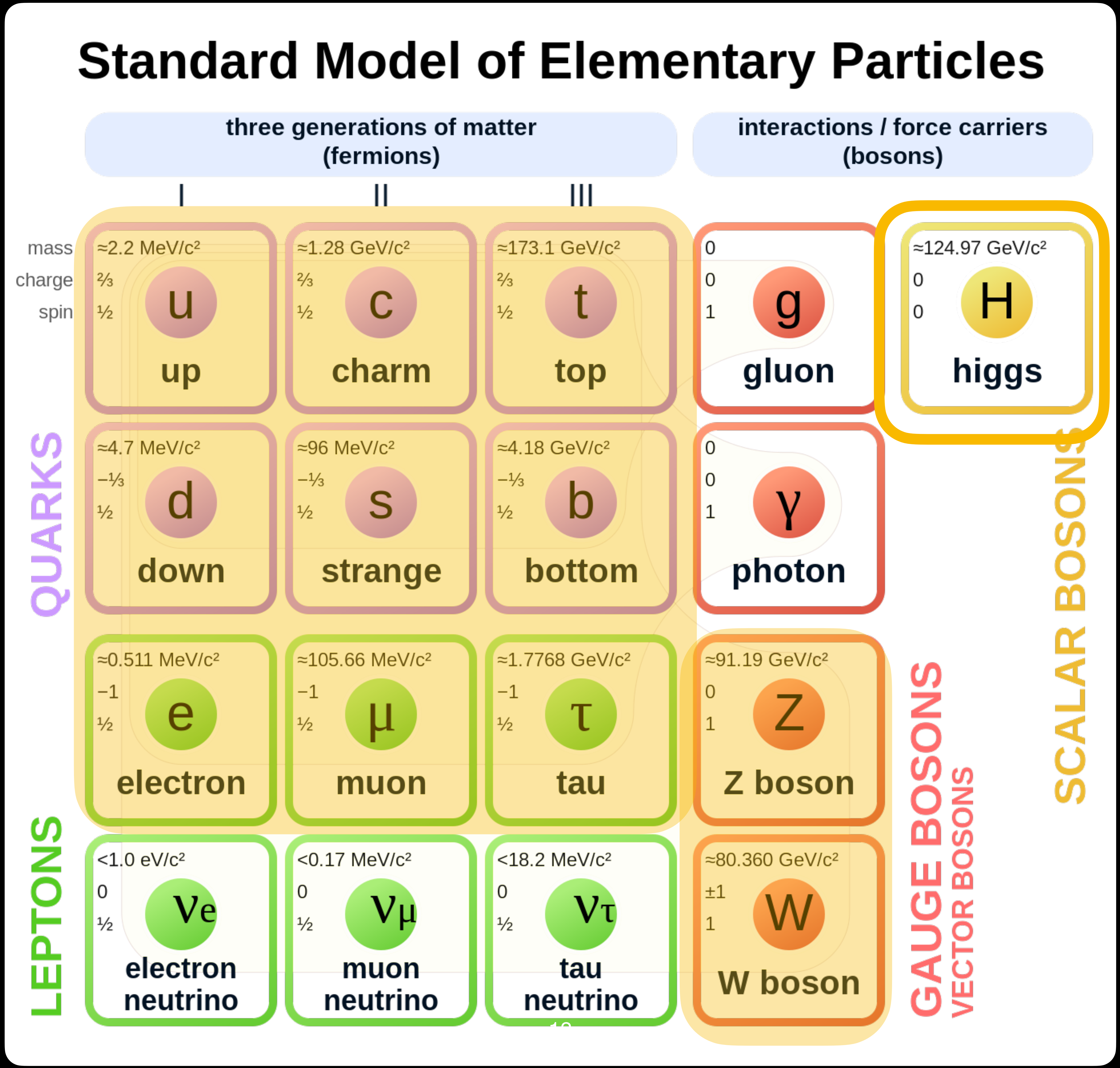
Photon mediates the electromagnetic force.

The Standard Model



W and Z bosons mediate the weak force.

The Standard Model

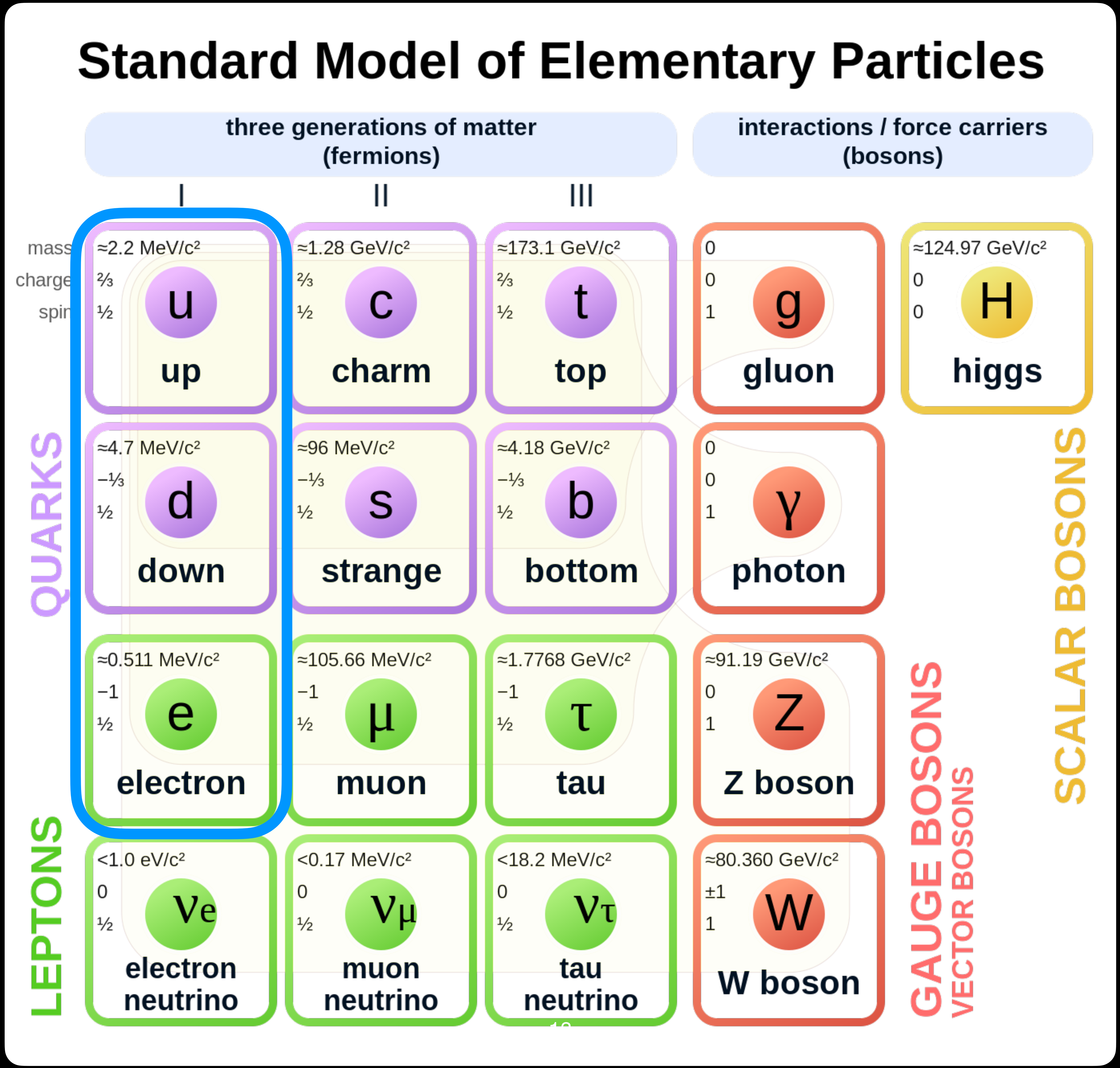


Higgs boson is responsible for generating masses in the Standard Model.

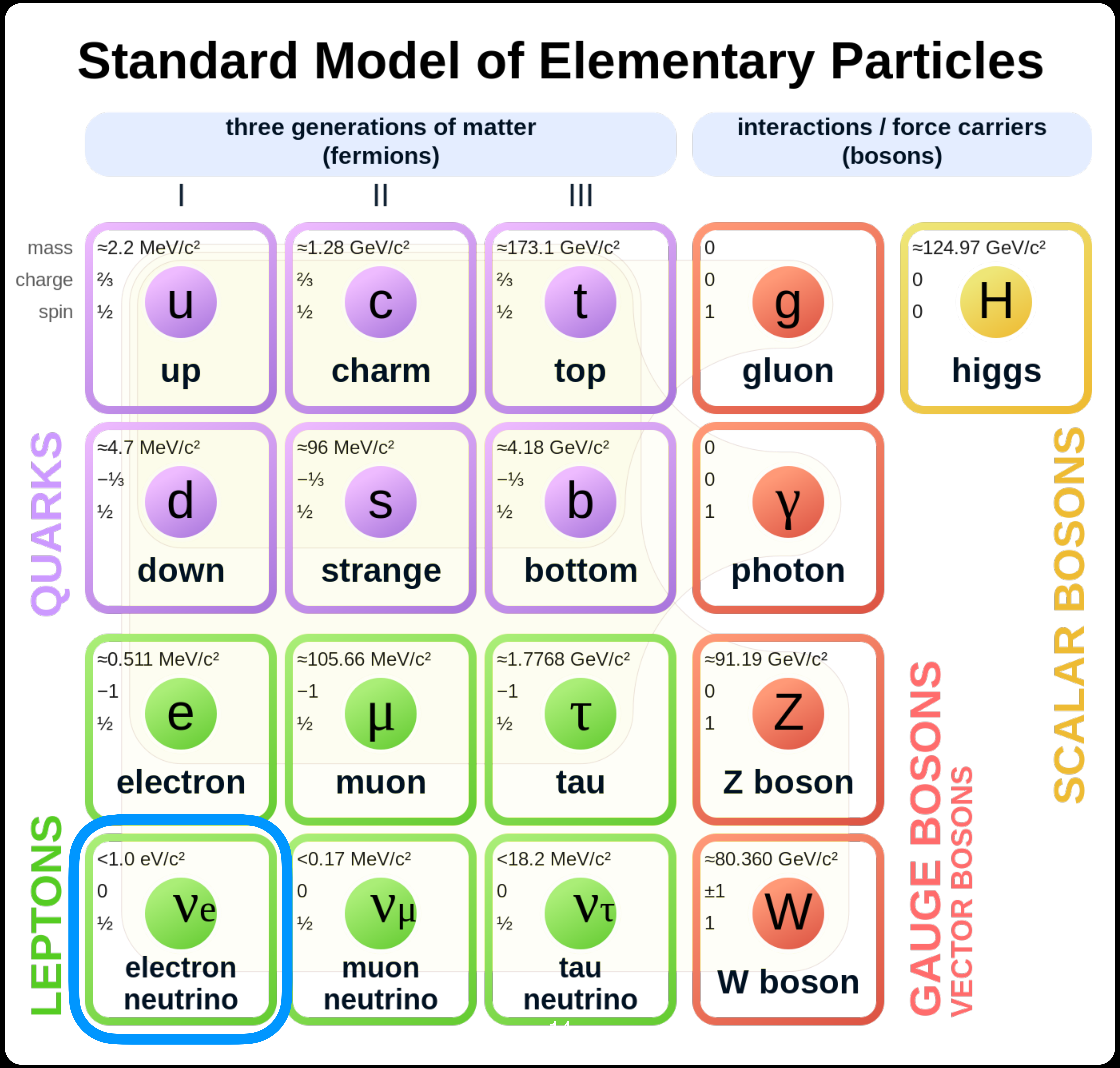
“Higgs Mechanism”

The Standard Model

Stable particles making up ordinary matter



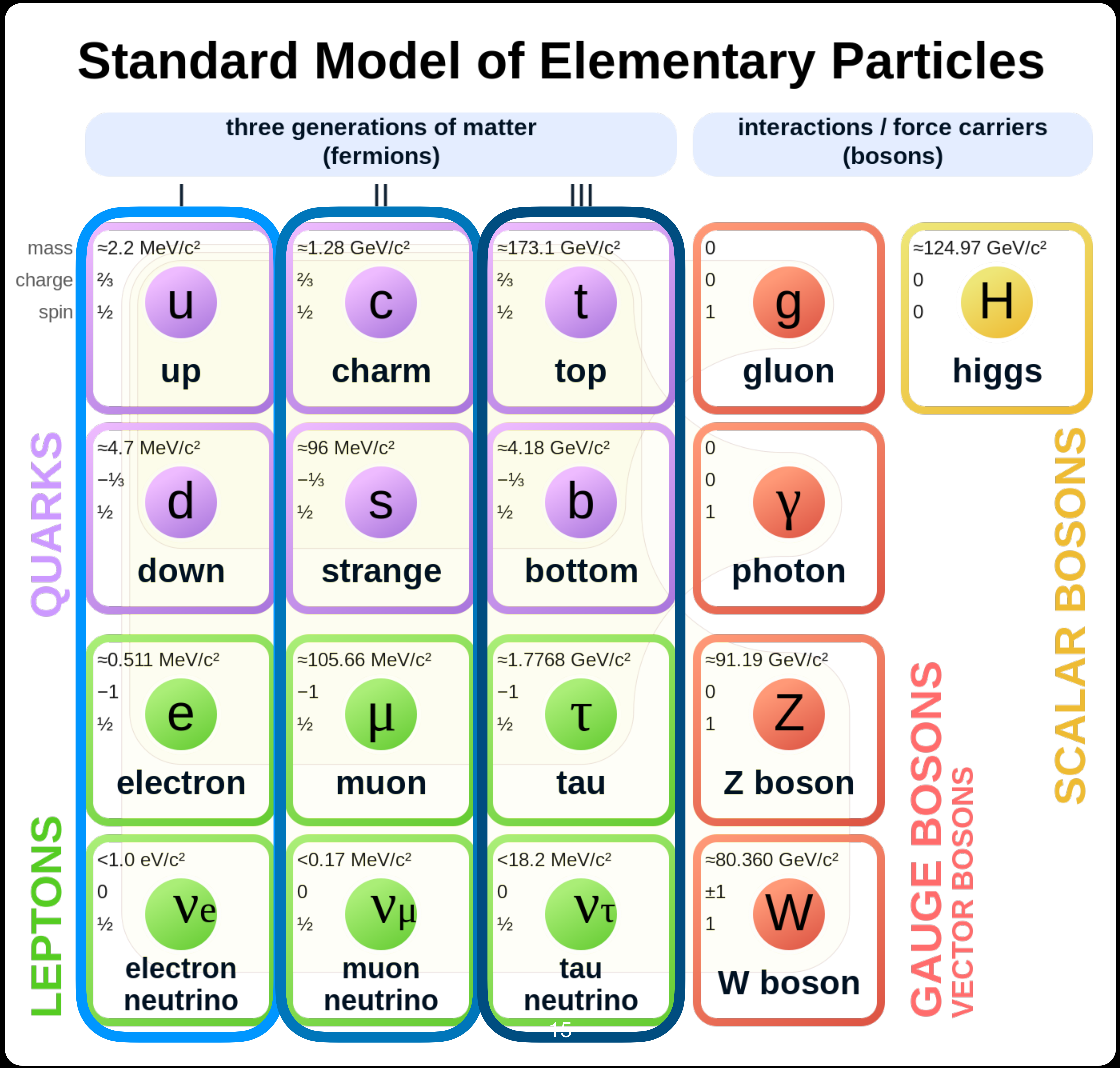
The Standard Model



There is also a neutrino which interacts very weakly.

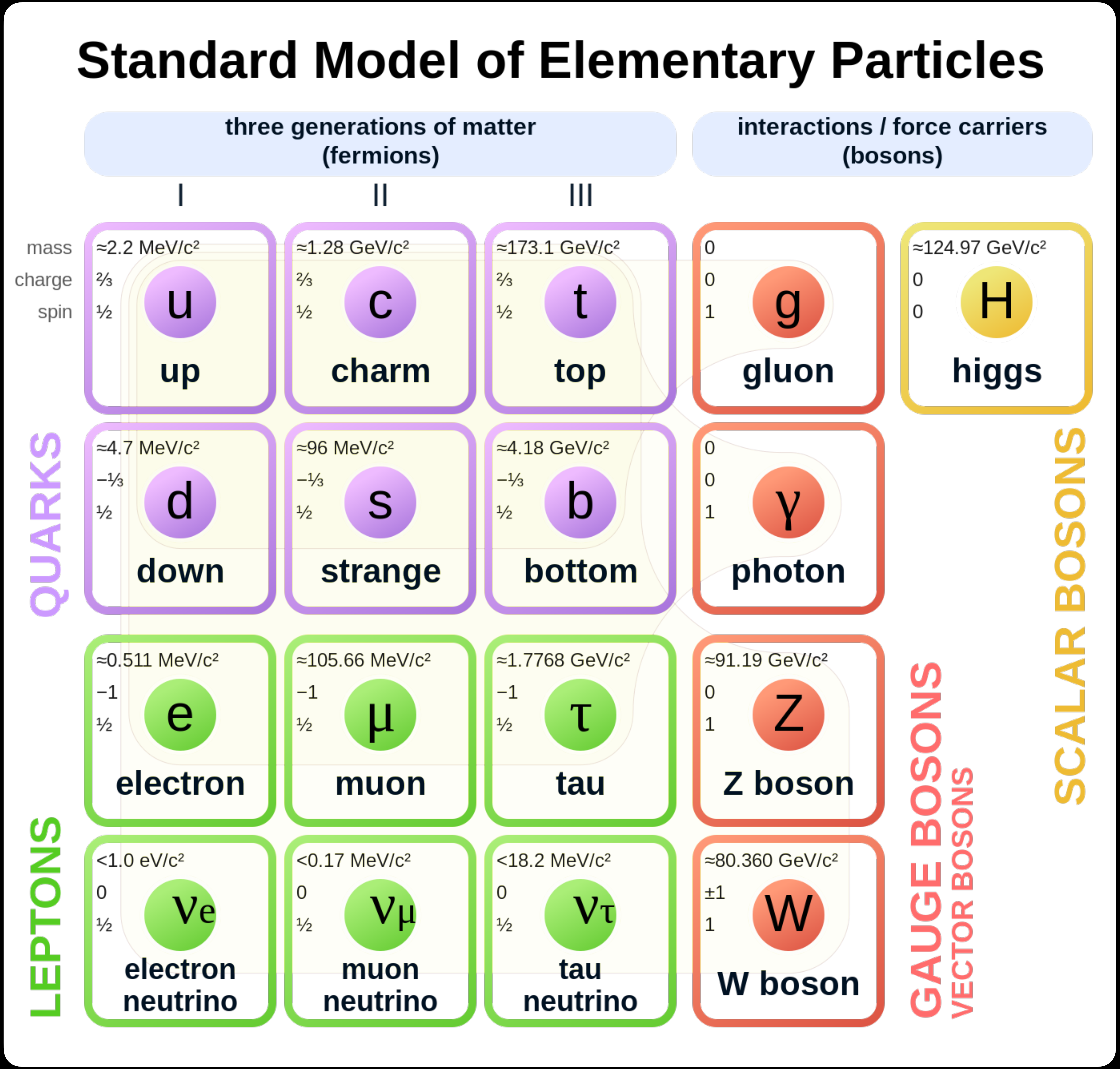
The Standard Model

Two more copies of the first generation with difference in their masses.



The Standard Model

- We have Quantum Field Theory as a successful theoretical tool to describe the Quantum mechanics of relativistic particles
    - accuracy to 0.0000000001 for quantum electrodynamics.
- For unstable particles, we find a way to produce them in particle colliders and study their decay.

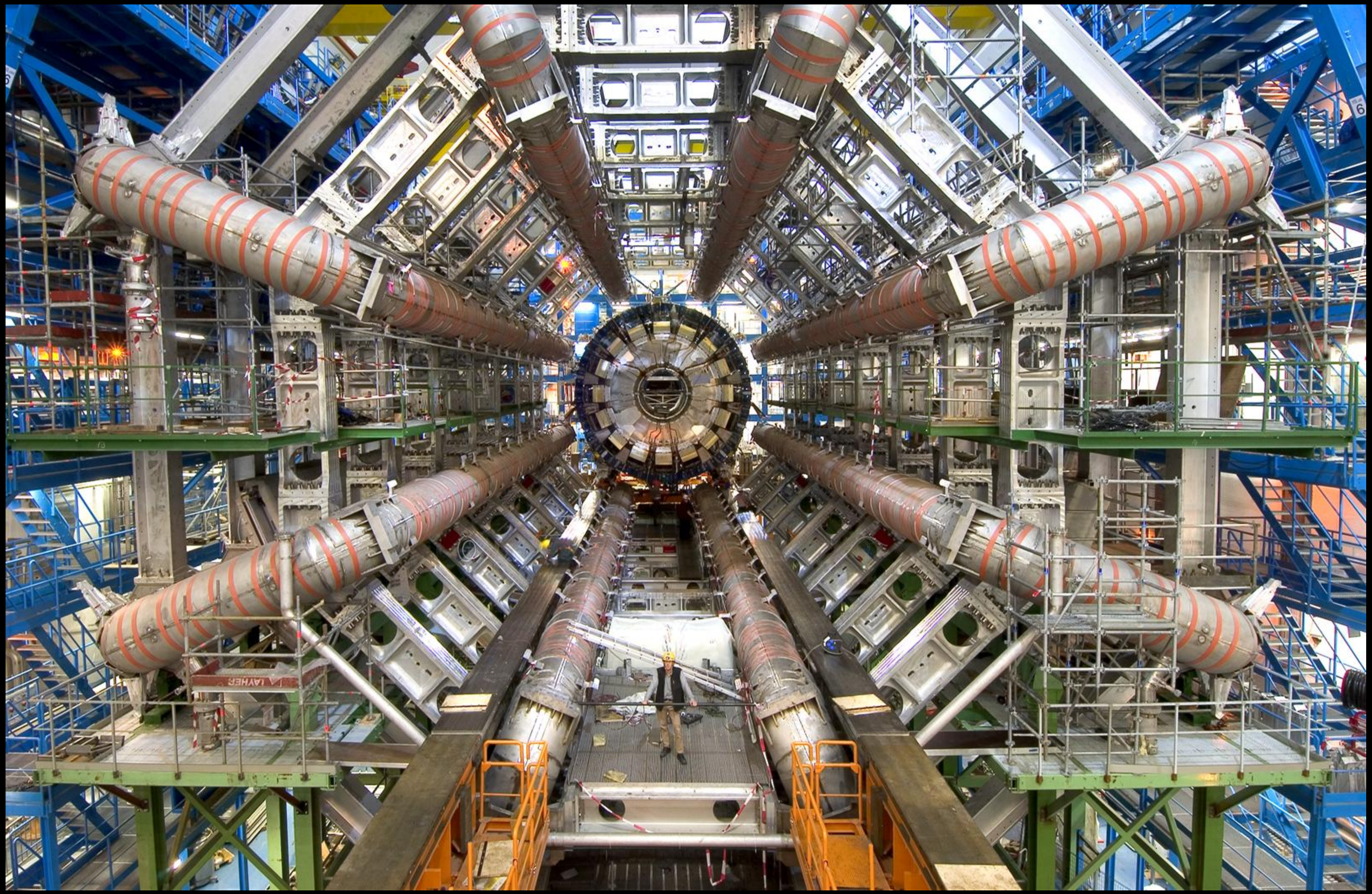


Large Hardron Collider

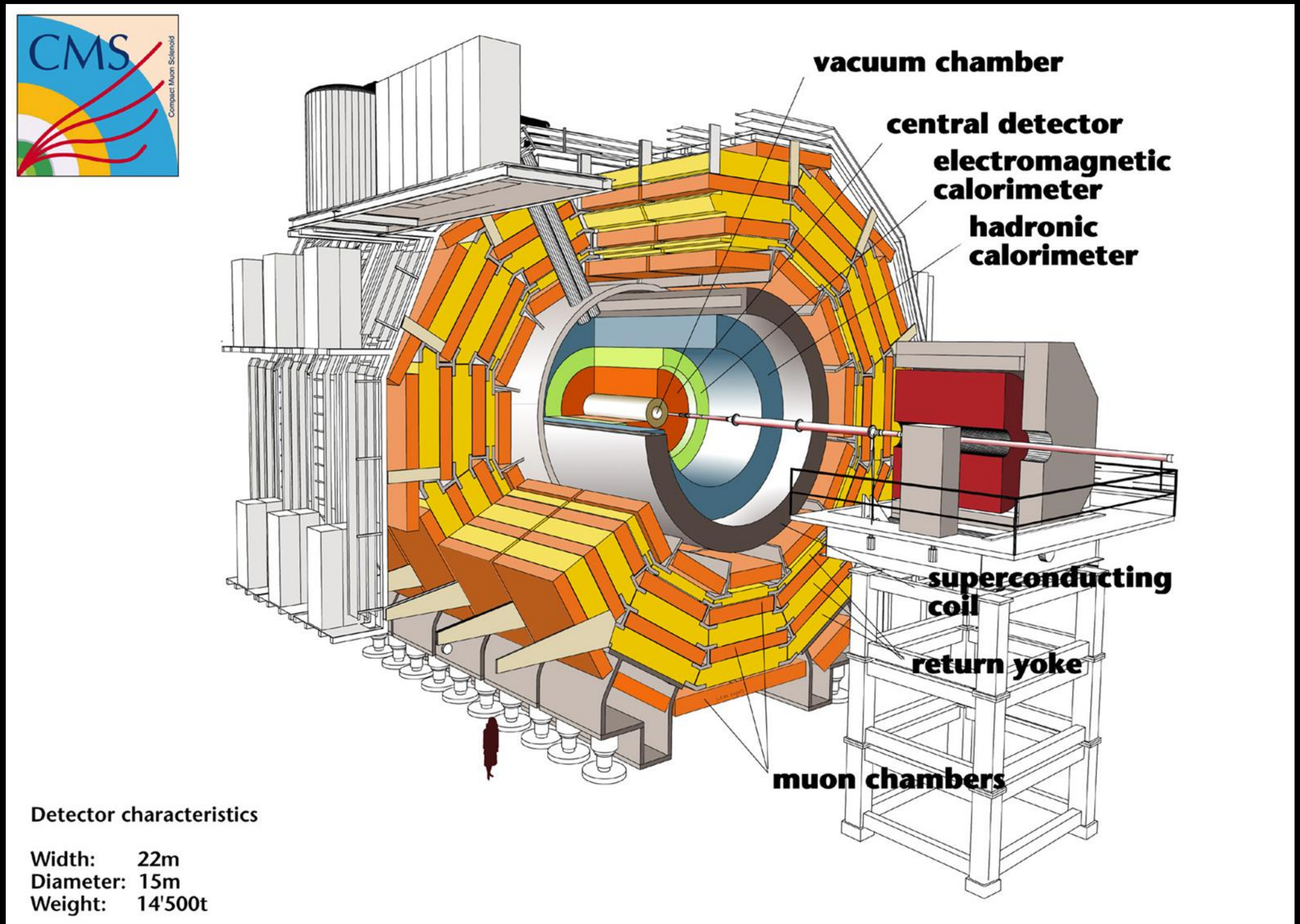
- Colliding Proton and Ion beams
- LHC circumference of 26.7 km
- Four experiments
    - ATLAS
    - CMS
    - ALICE
    - LHCb

Image: CERN

ATLAS and CMS experiments



Picture of ATLAS detector



Structure of CMS detector

Image: CERN

Higgs boson decay into two photons

a particle scattering event contains a lot of particles

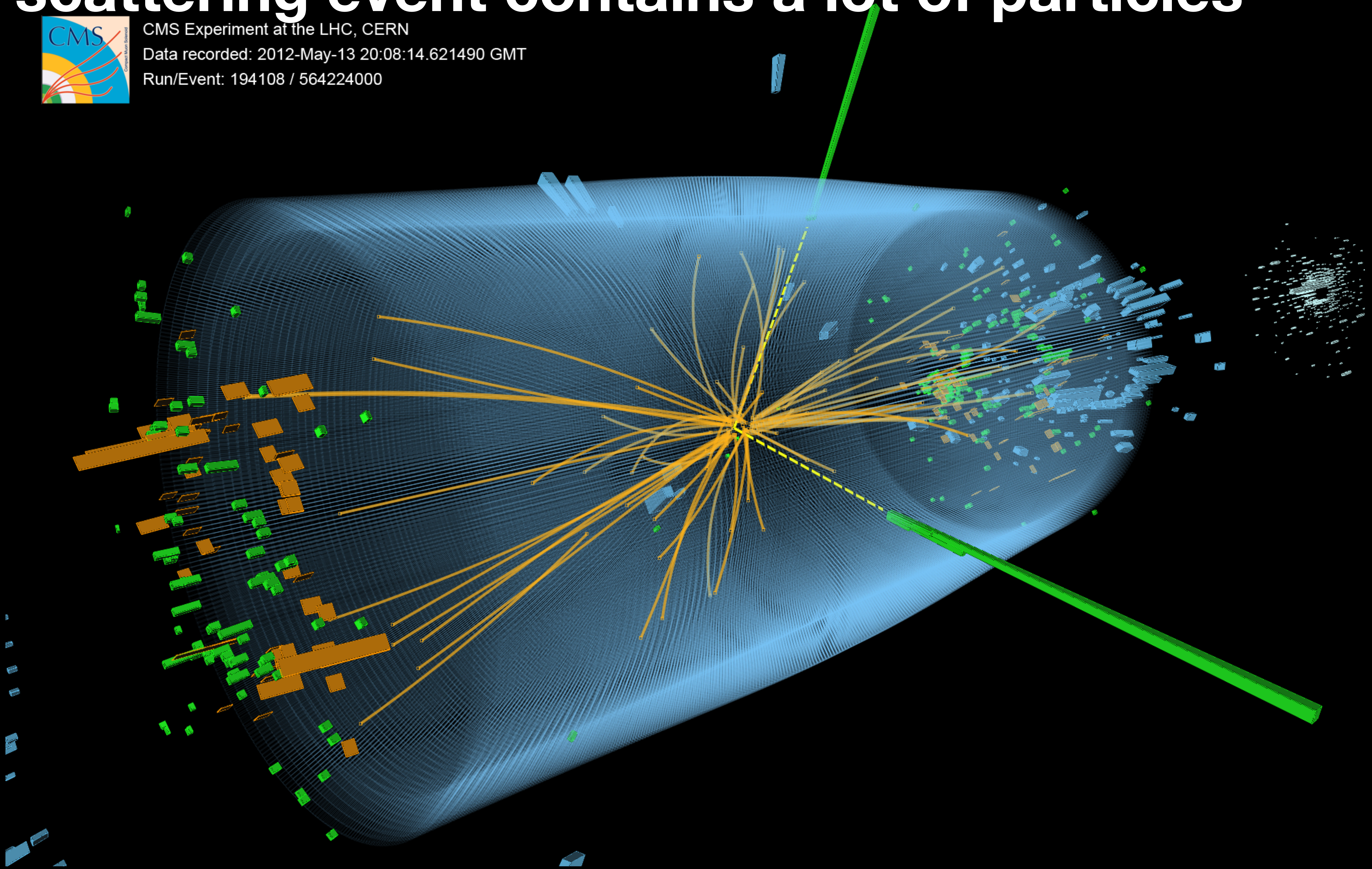
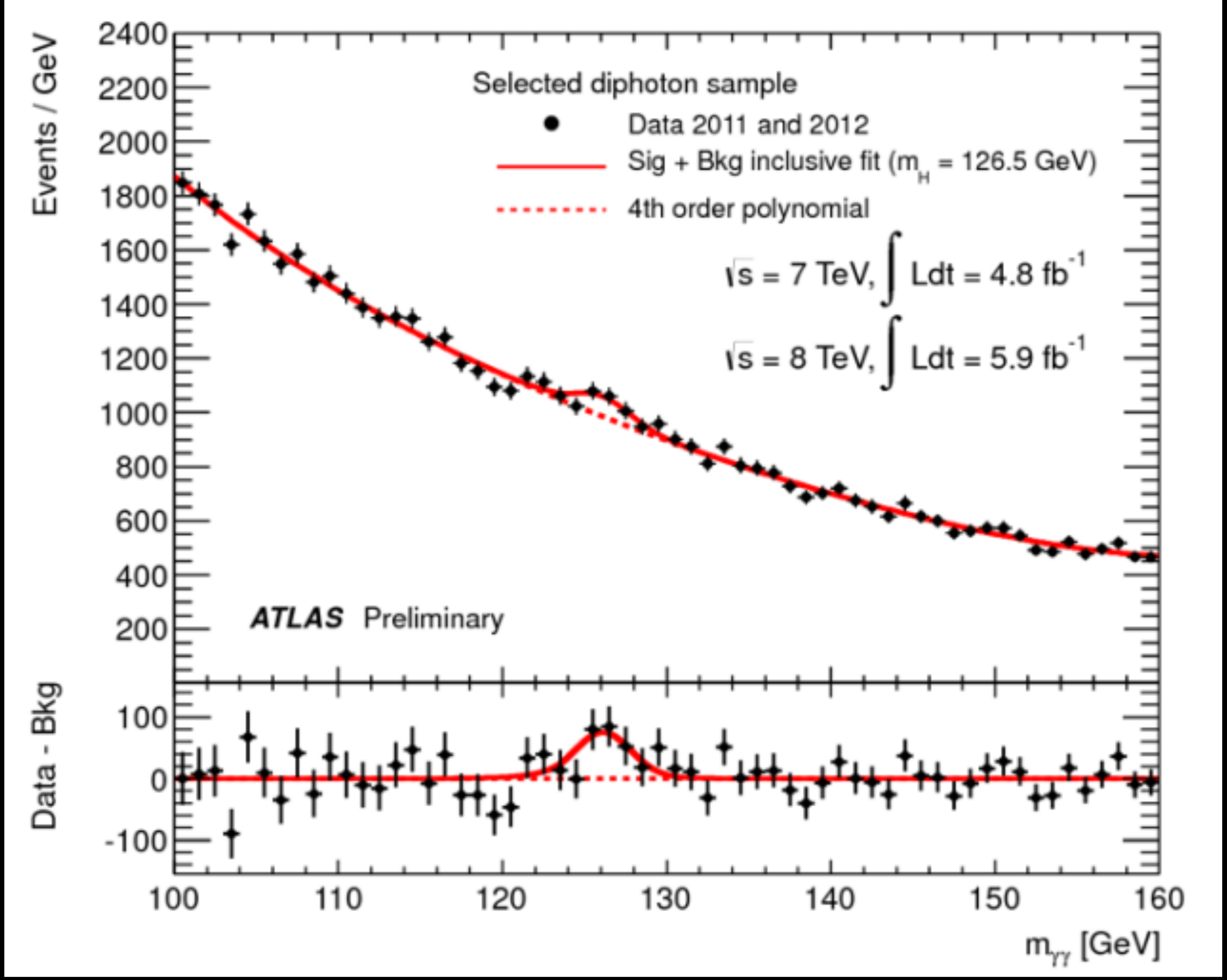


Image: CERN

Discovery of the Higgs boson at 125 GeV



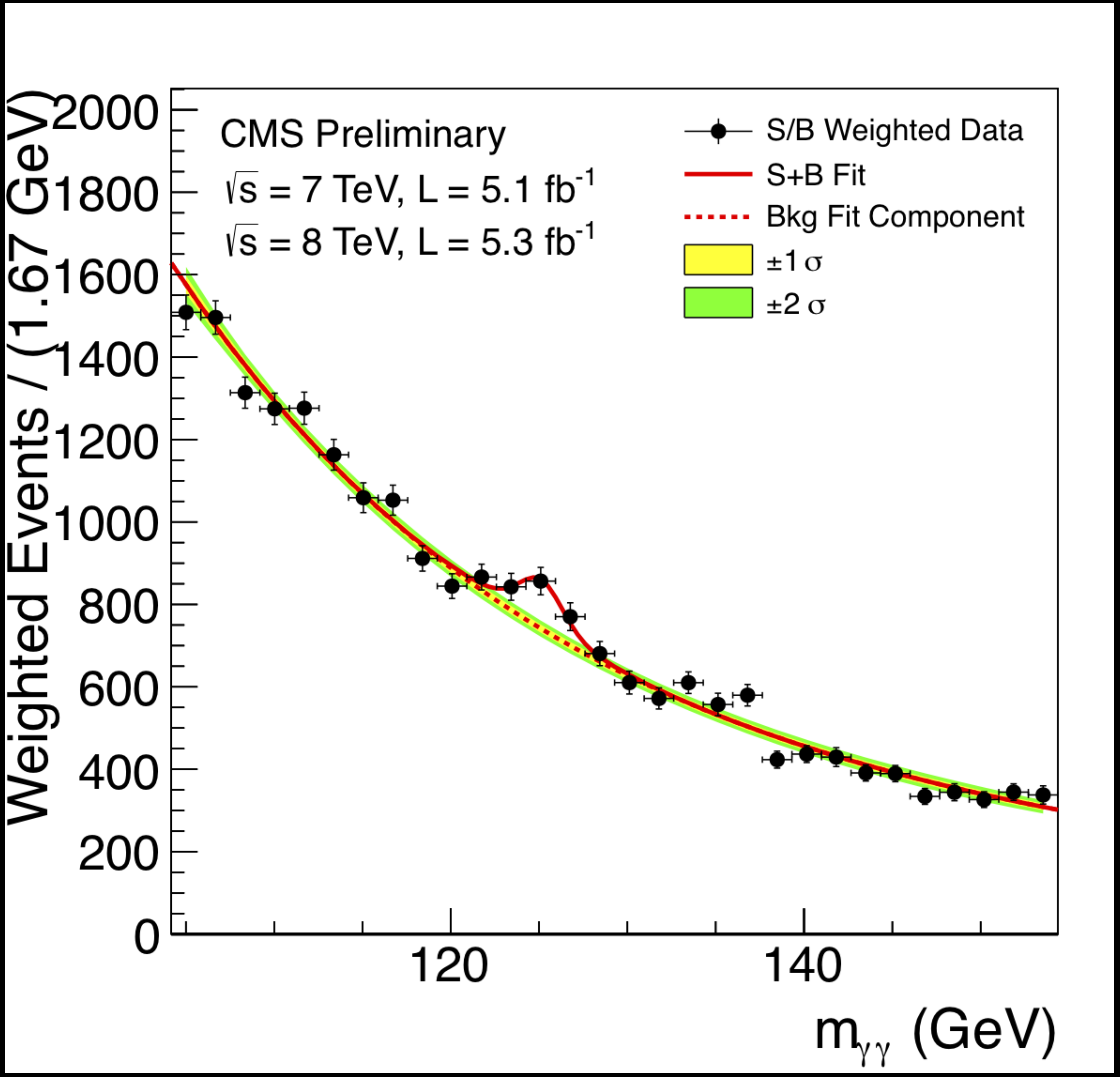


Image: ATLAS, CMS

Roadmap of Particle Discoveries

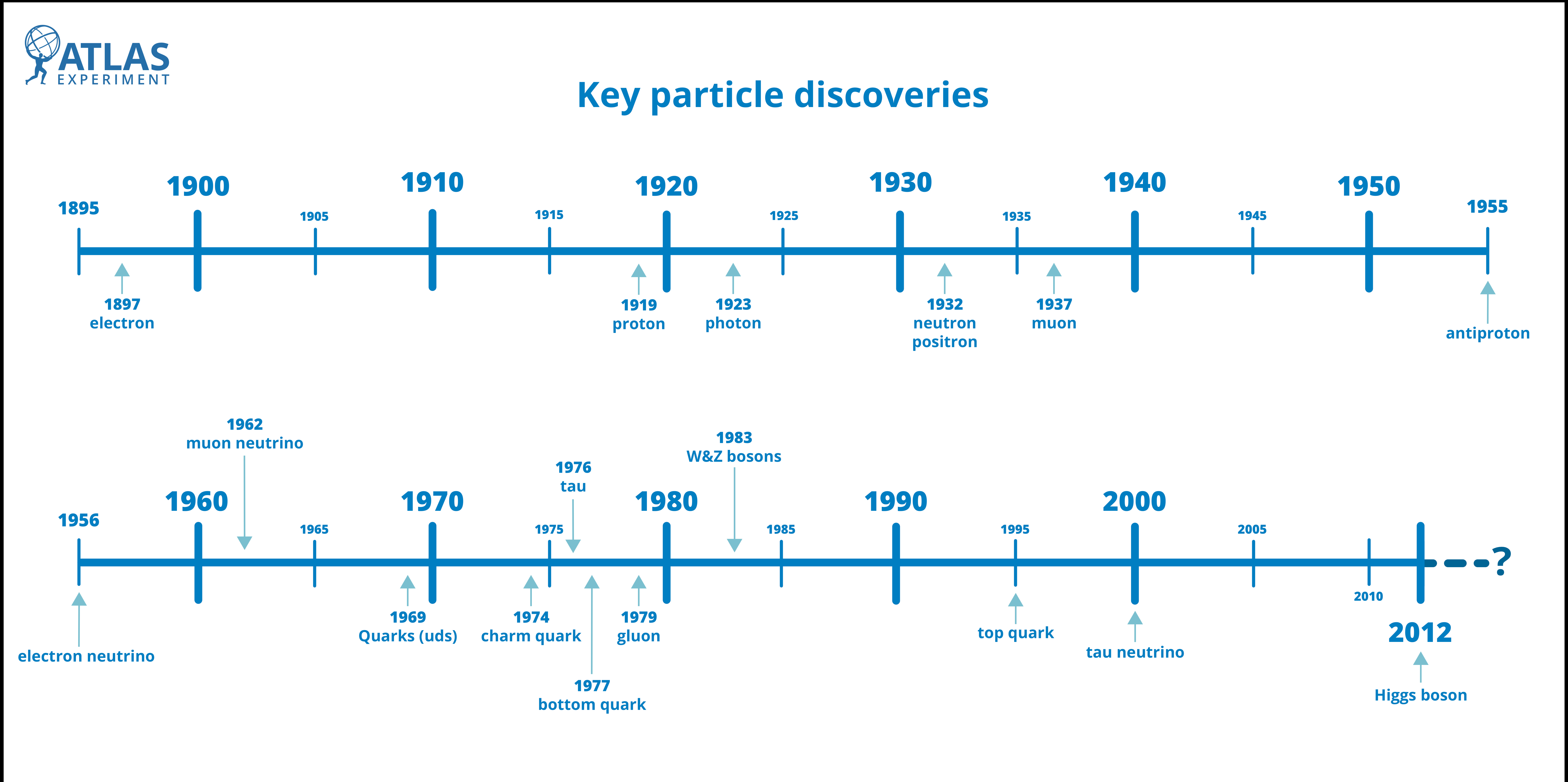


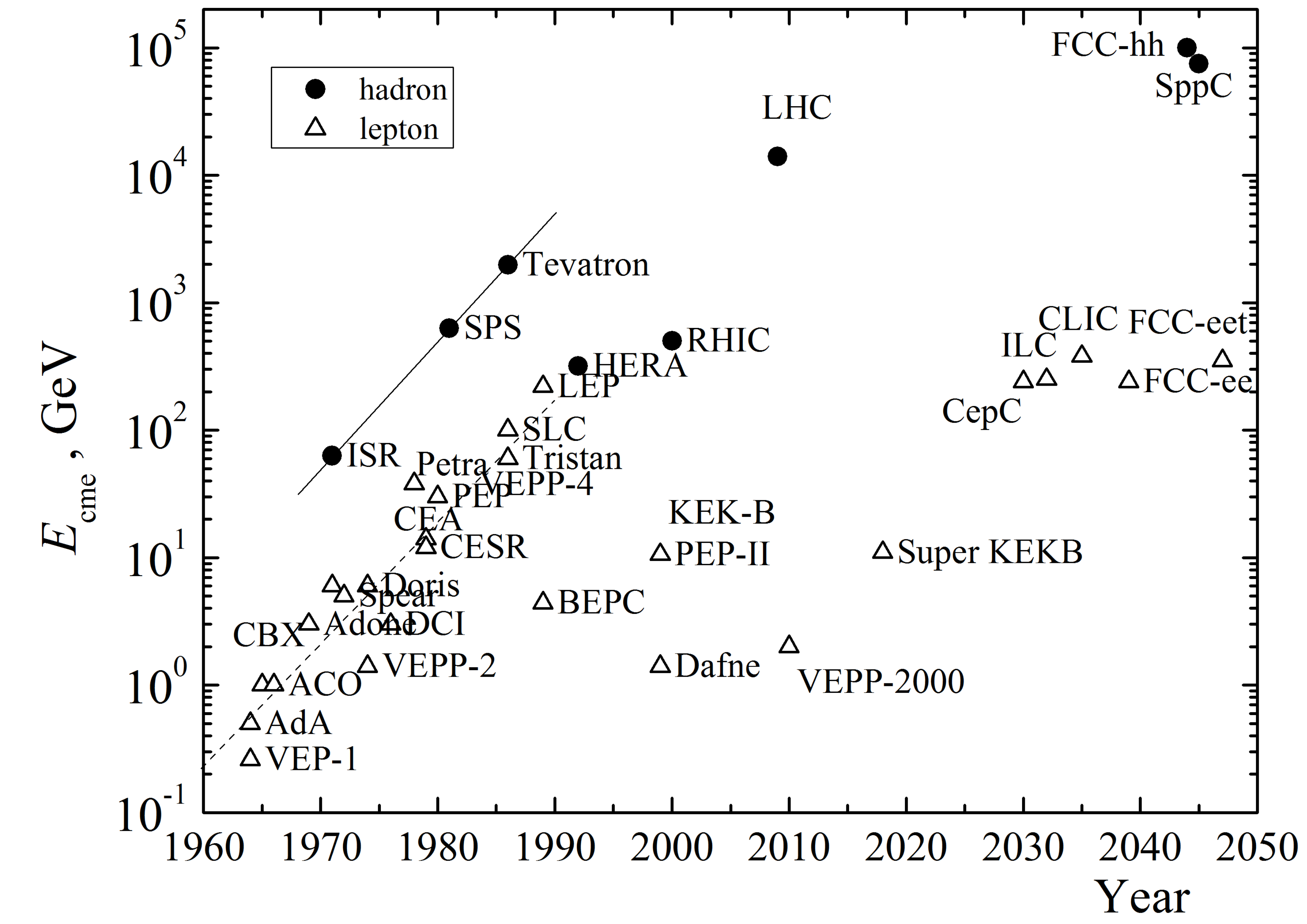
Image: ATLAS

What's next?

- Build a more powerful collider to produce unknown constituents of matter. Look for heavier particles and higher energy scales. "Energy Frontier"

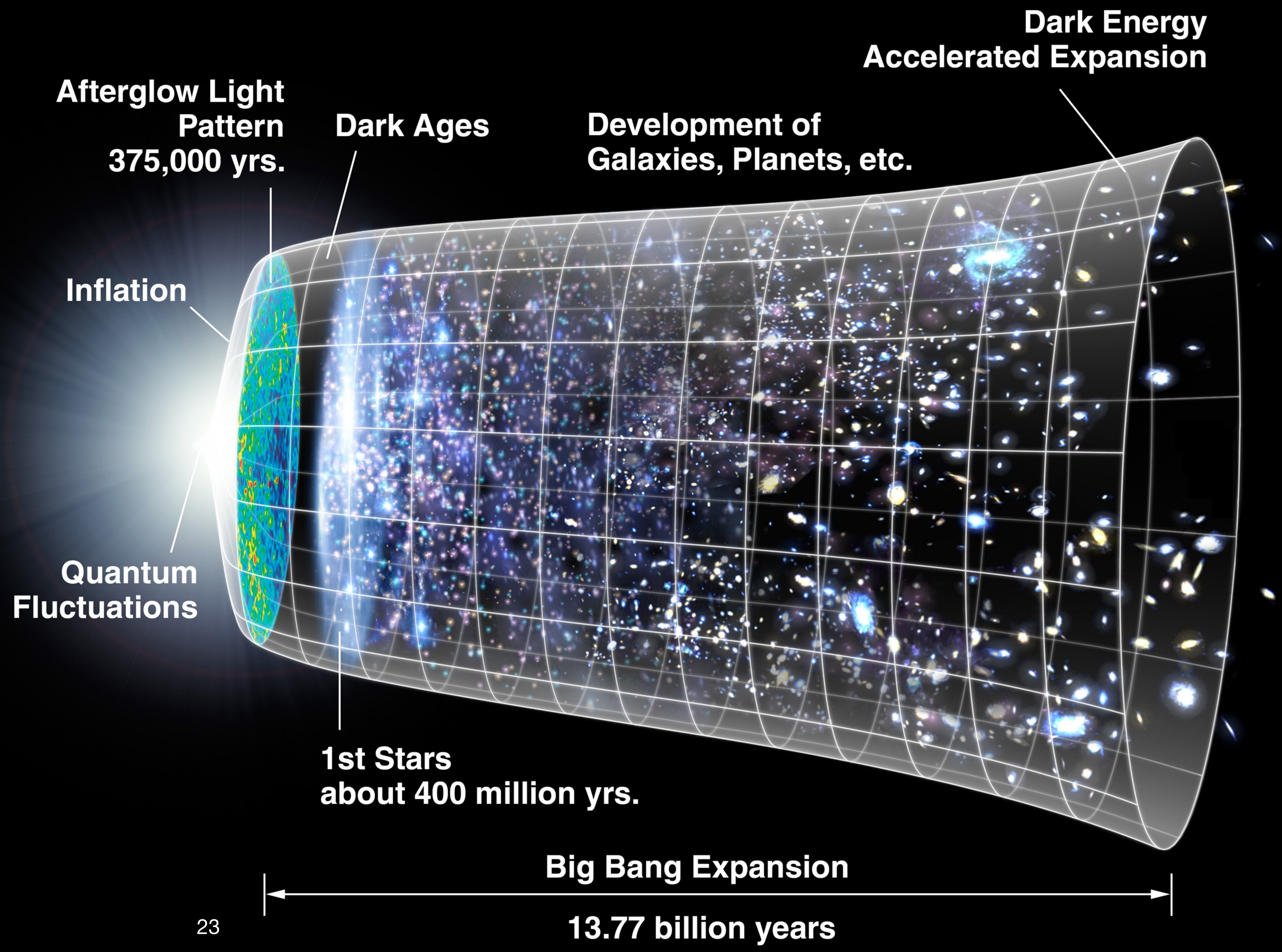
- Perform precise measurements using more data and higher detector sensitivity. Study rare processes and possible modification from new physics beyond the Standard Model. "Intensity Frontier"

- Observe particles from space to understand the source and the propagation of particles. Explore particle physics in the current and early universe. "Cosmic Frontier"

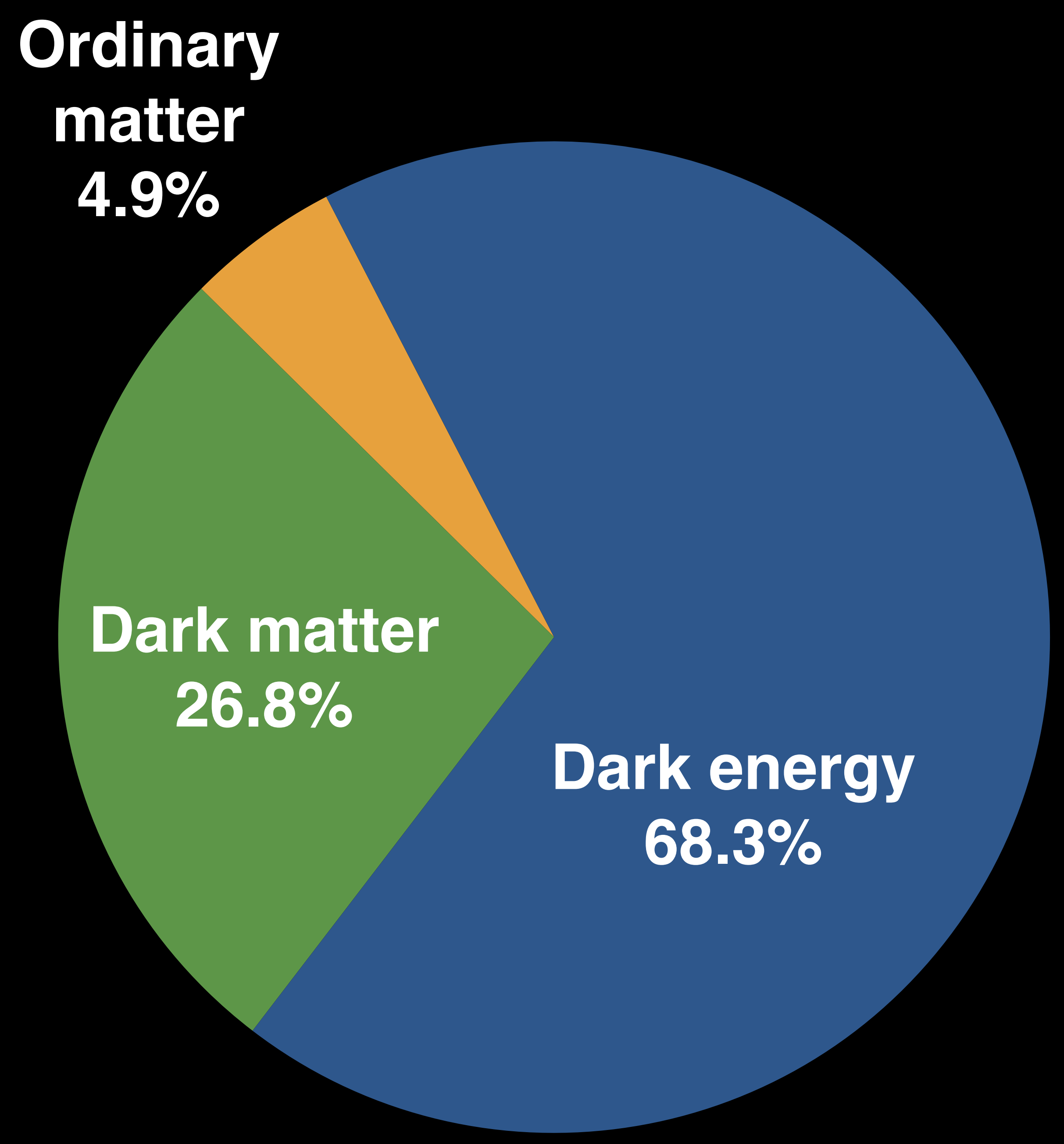


Modern and Future Colliders, V. Shiltsev, F. Zimmermann

The universe as a Particle Lab



The content of the universe

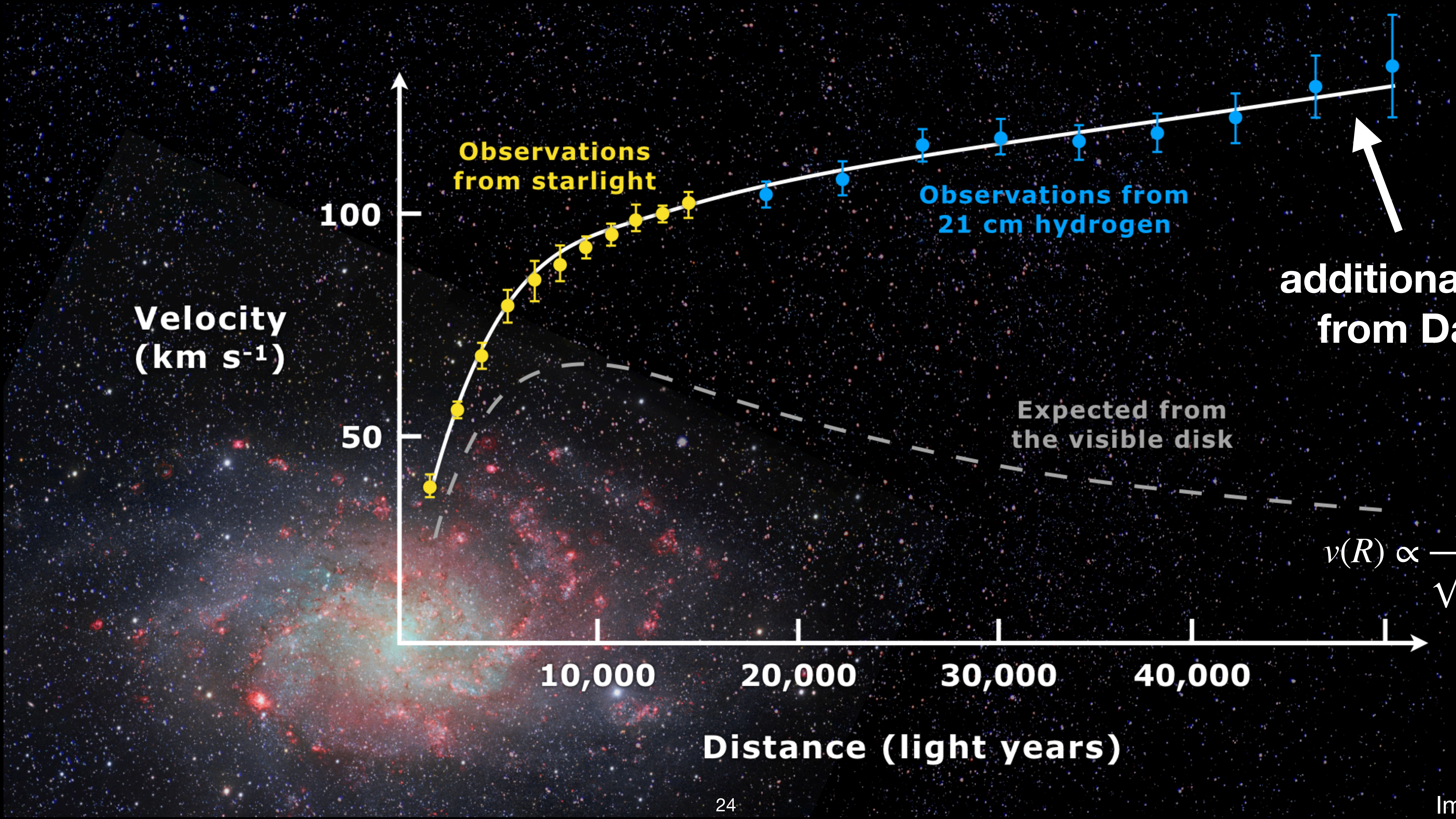


What is Dark Matter?

Image: NASA/WMAP

The Rotational Curve

stars rotating faster than expected



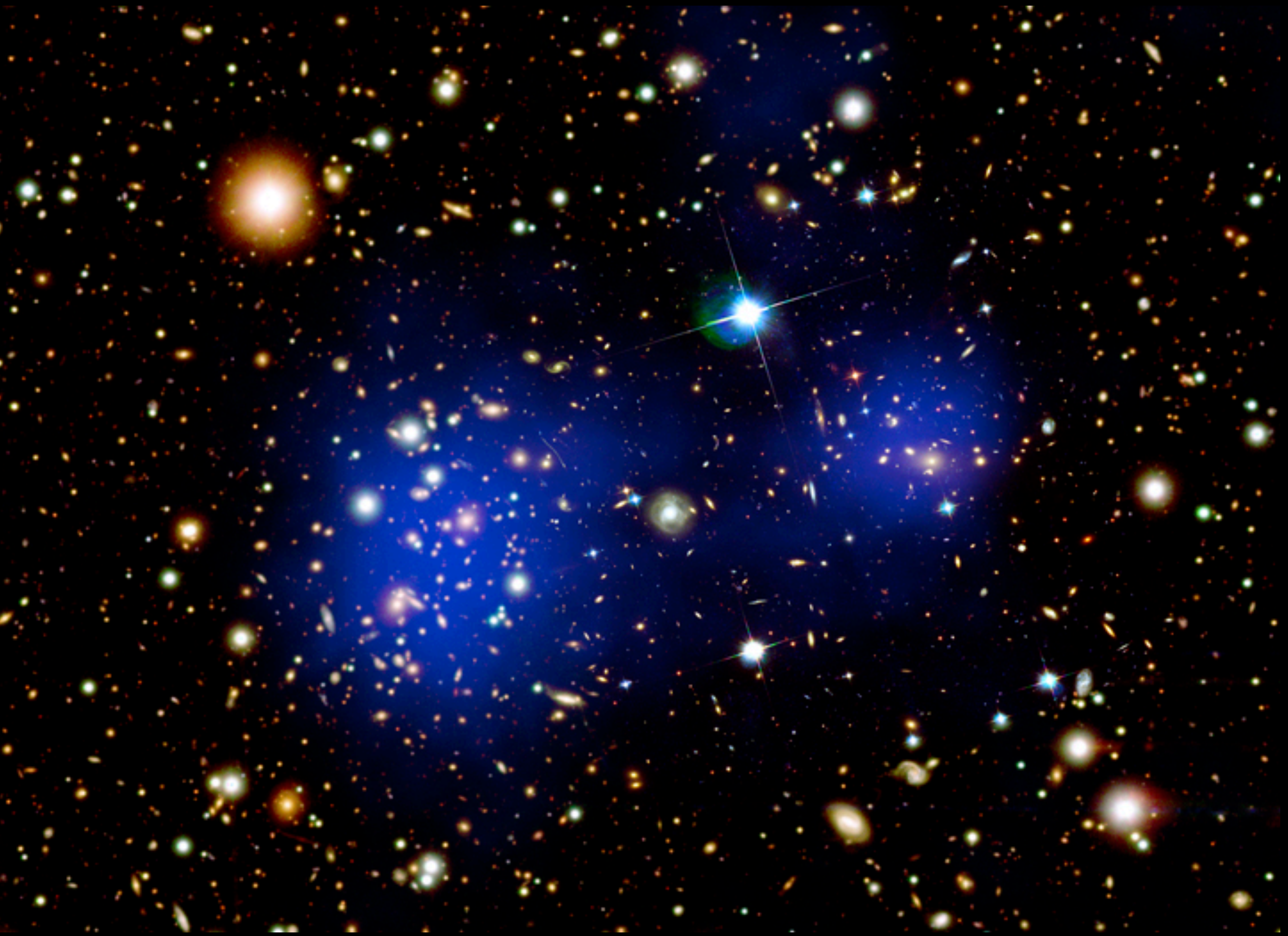
additional gravitation from Dark Matter

$$v(R) \propto \frac{1}{\sqrt{R}}$$

Image: Mario De Leo

Bullet Cluster

Distribution of mass



Distribution of gas (only luminous mass)

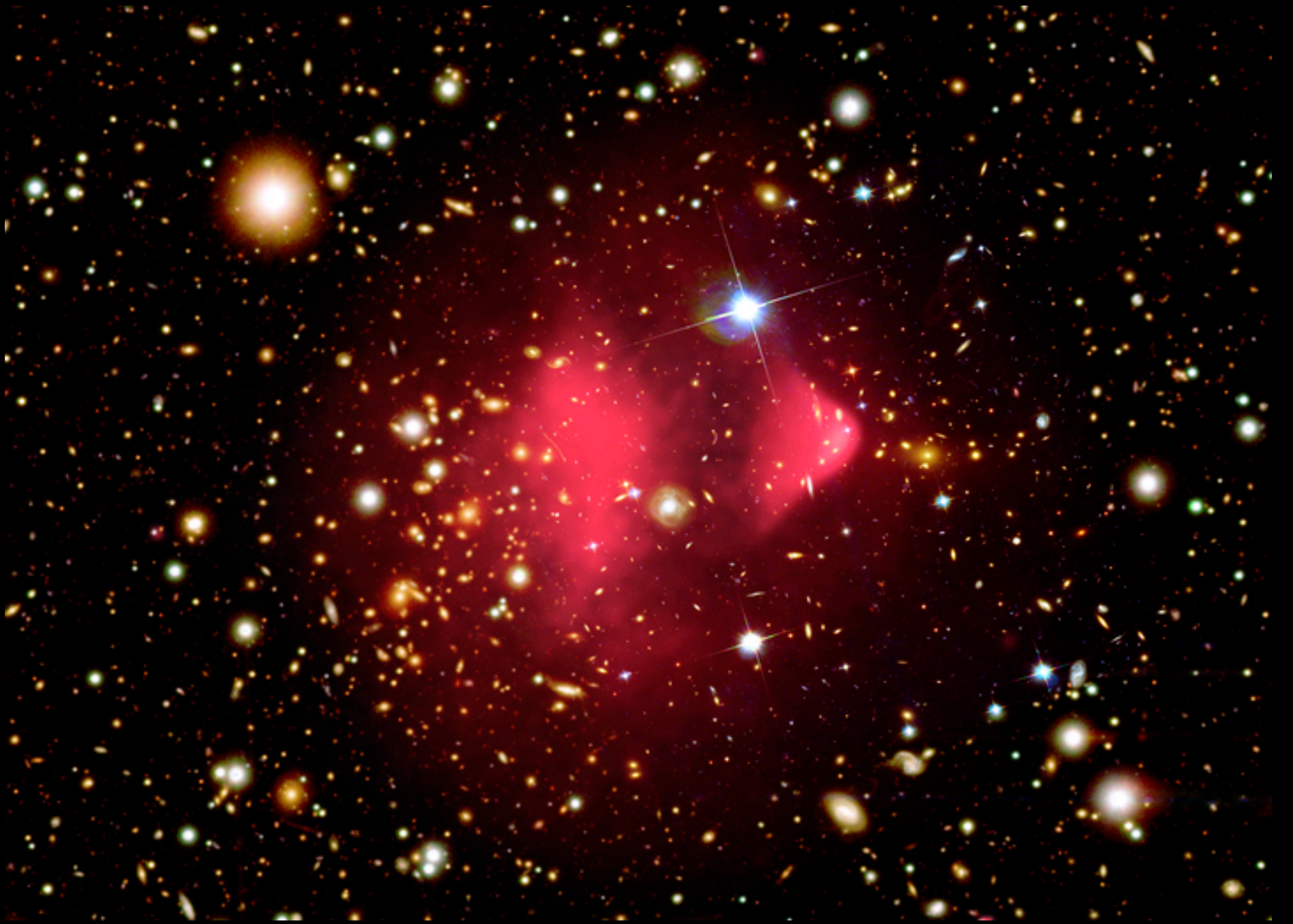
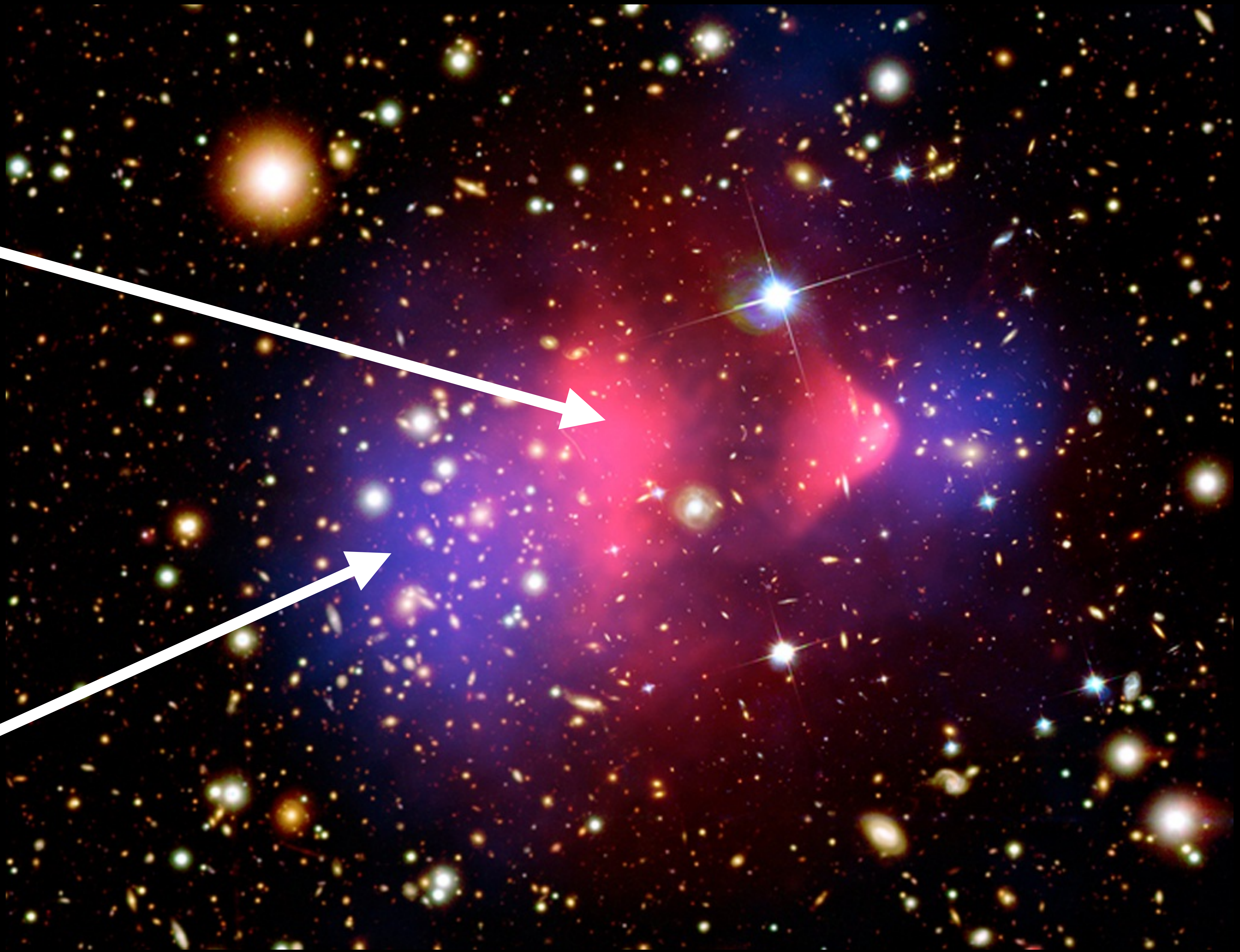


Image:
X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Bullet Cluster

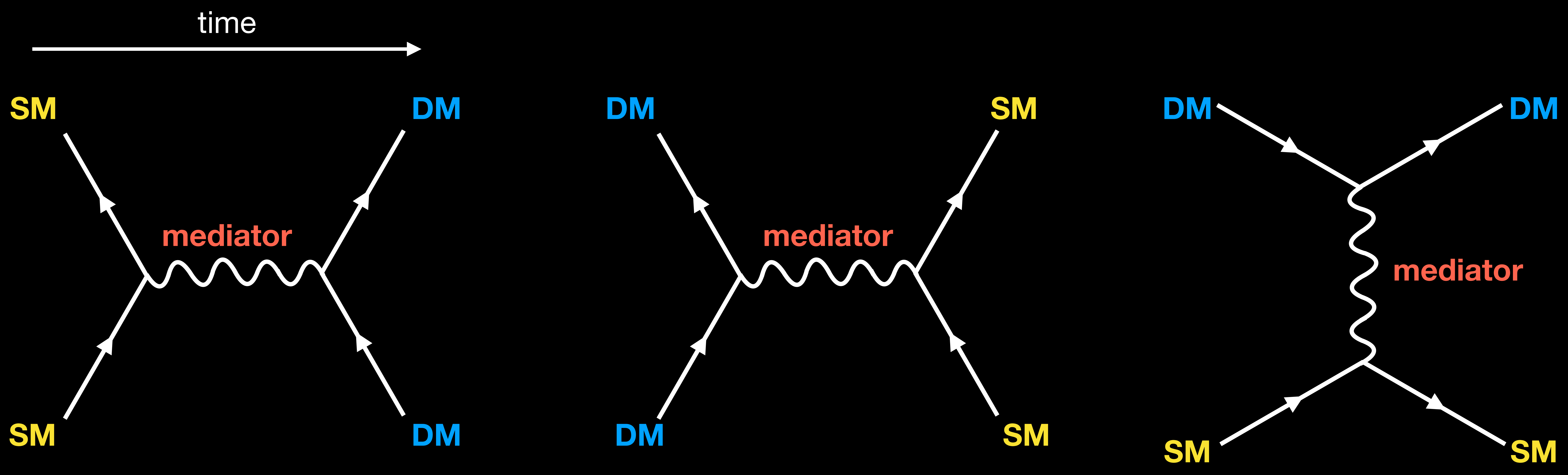
Distributions don’t match. They are from different components of galaxies.

Ordinary Matter described by the Standard Model



Dark Matter

Dark Matter Particle Searches



Produce DM
at particle collider

Observe DM annihilate
into visible matter

Detect DM scattering
in Lab

Collider Searches

This is the distribution in the perpendicular direction to the beams. The total momentum on this plane from all particles is zero.

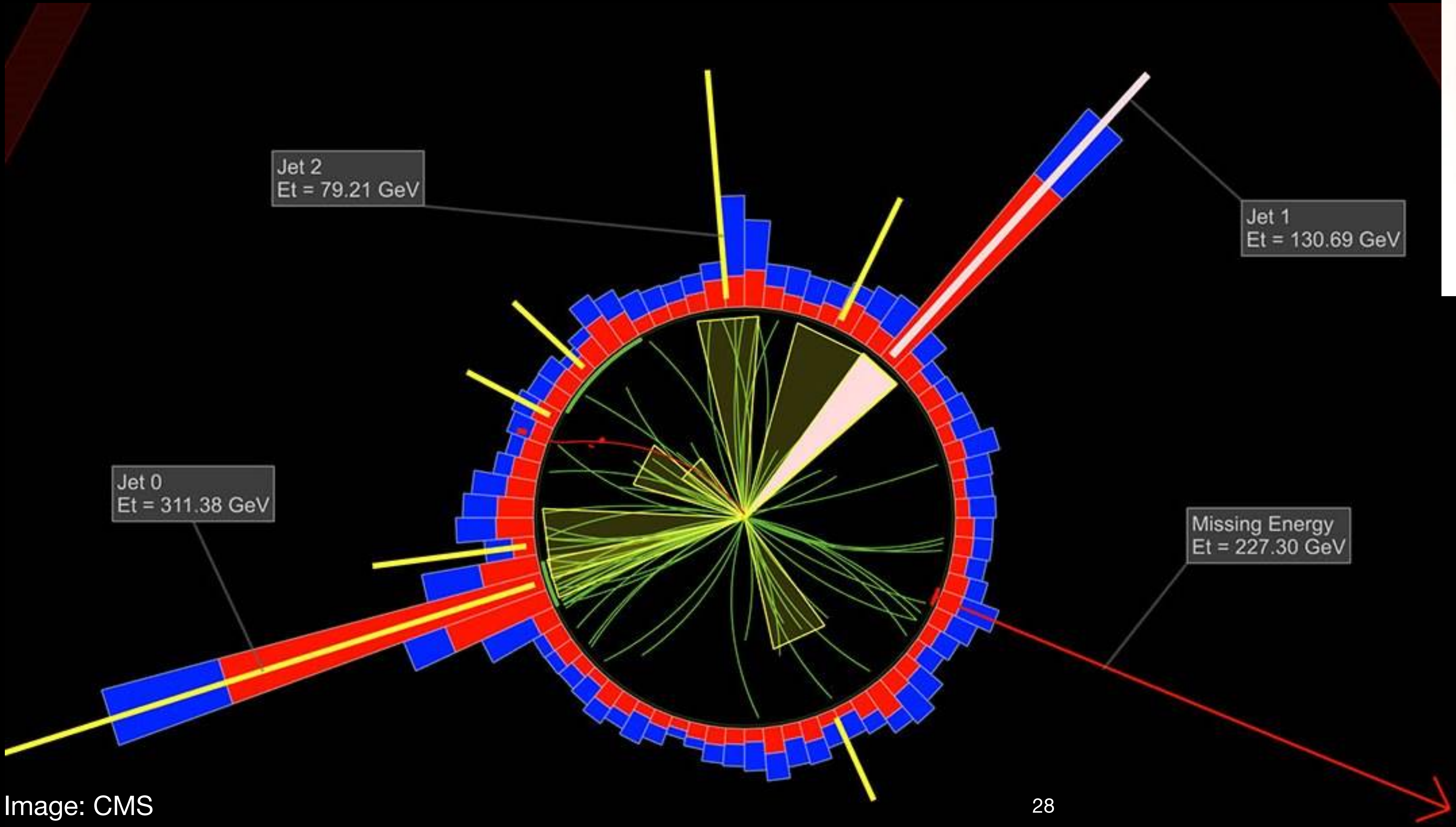
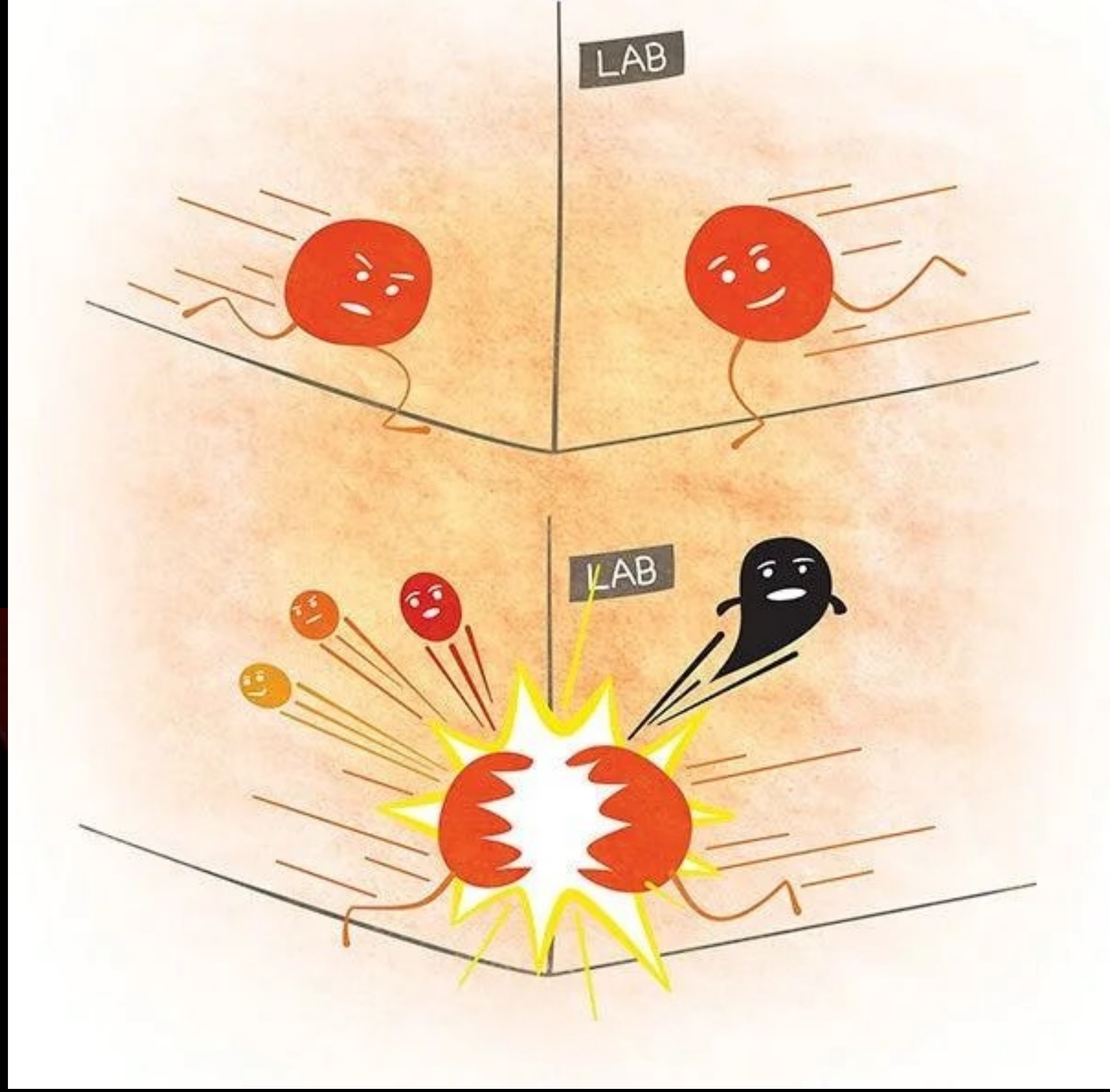


Image: CMS



Momentum conservation predicts Dark Matter signal in the form of invisible (missing) energy momentum.

Image: SLAC

Indirect Detection

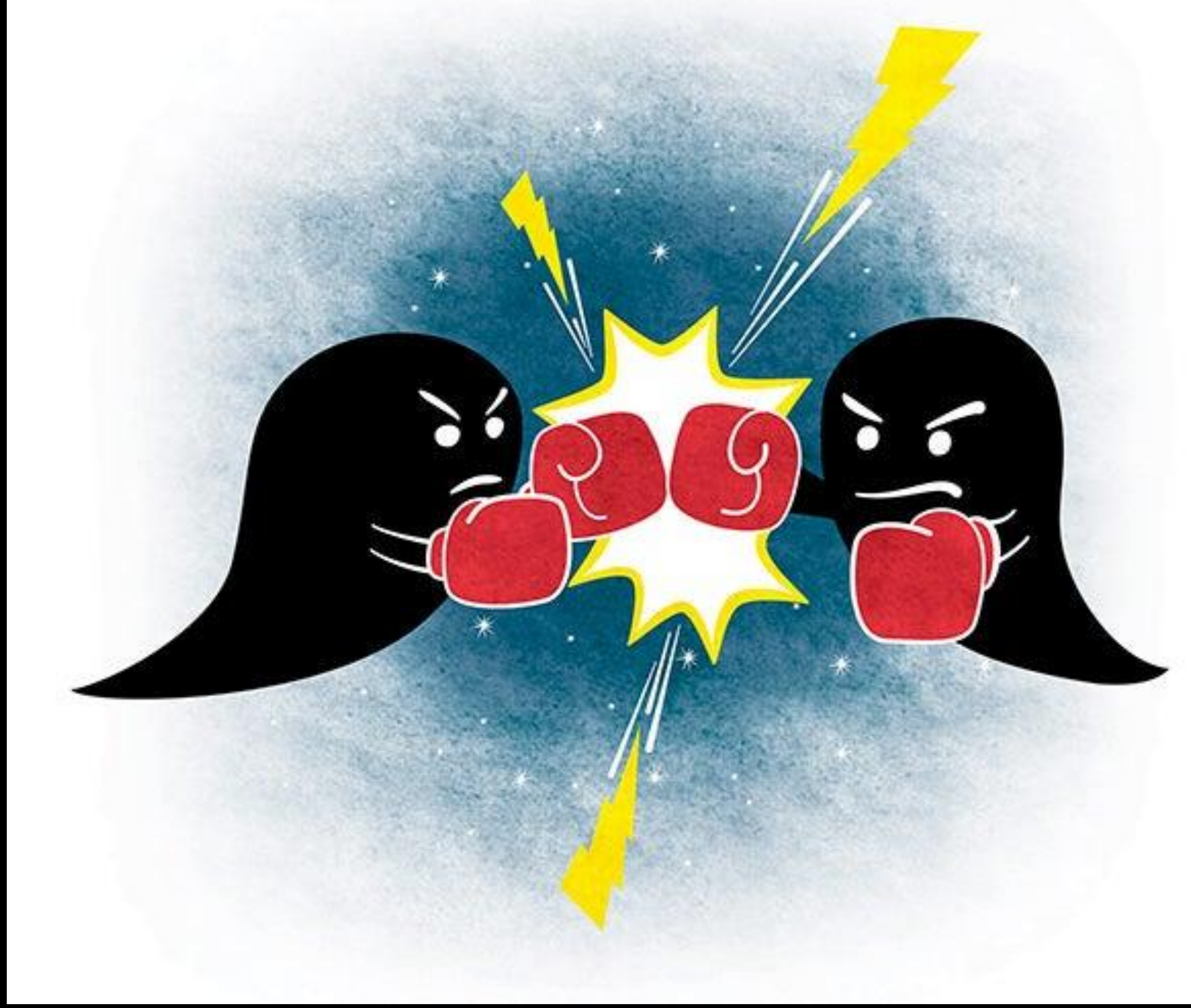


Image: SLAC

Dark Matter generate visible particles from locations with large abundance, for example the center of the Milky Way.

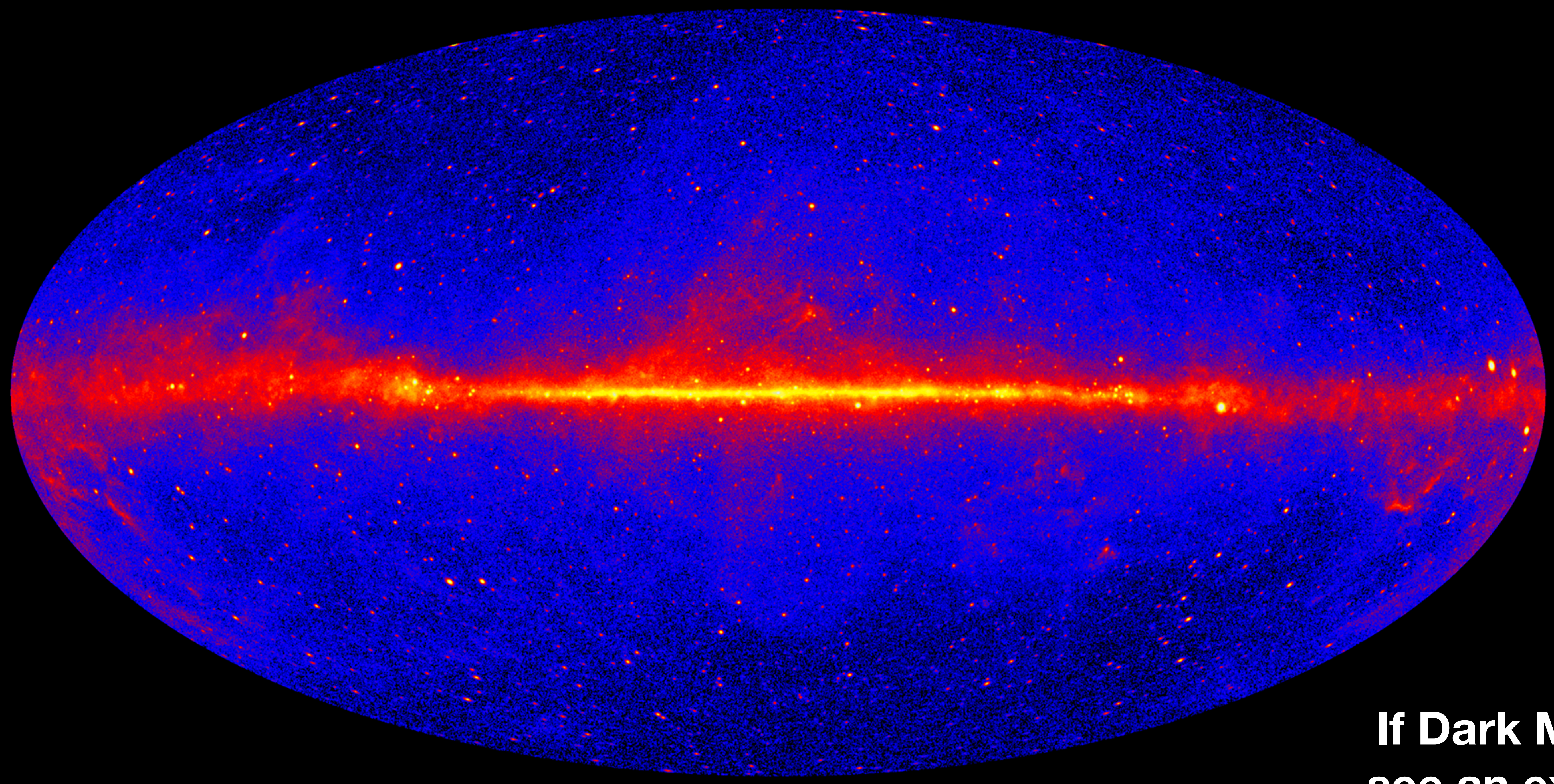


Image: NASA

If Dark Matter annihilation produces photons, we expect to see an excess of gamma-rays from the center of the galaxy.

Direct Detection

Dark Matter interact with target detectors placed in extremely silent environments underground.

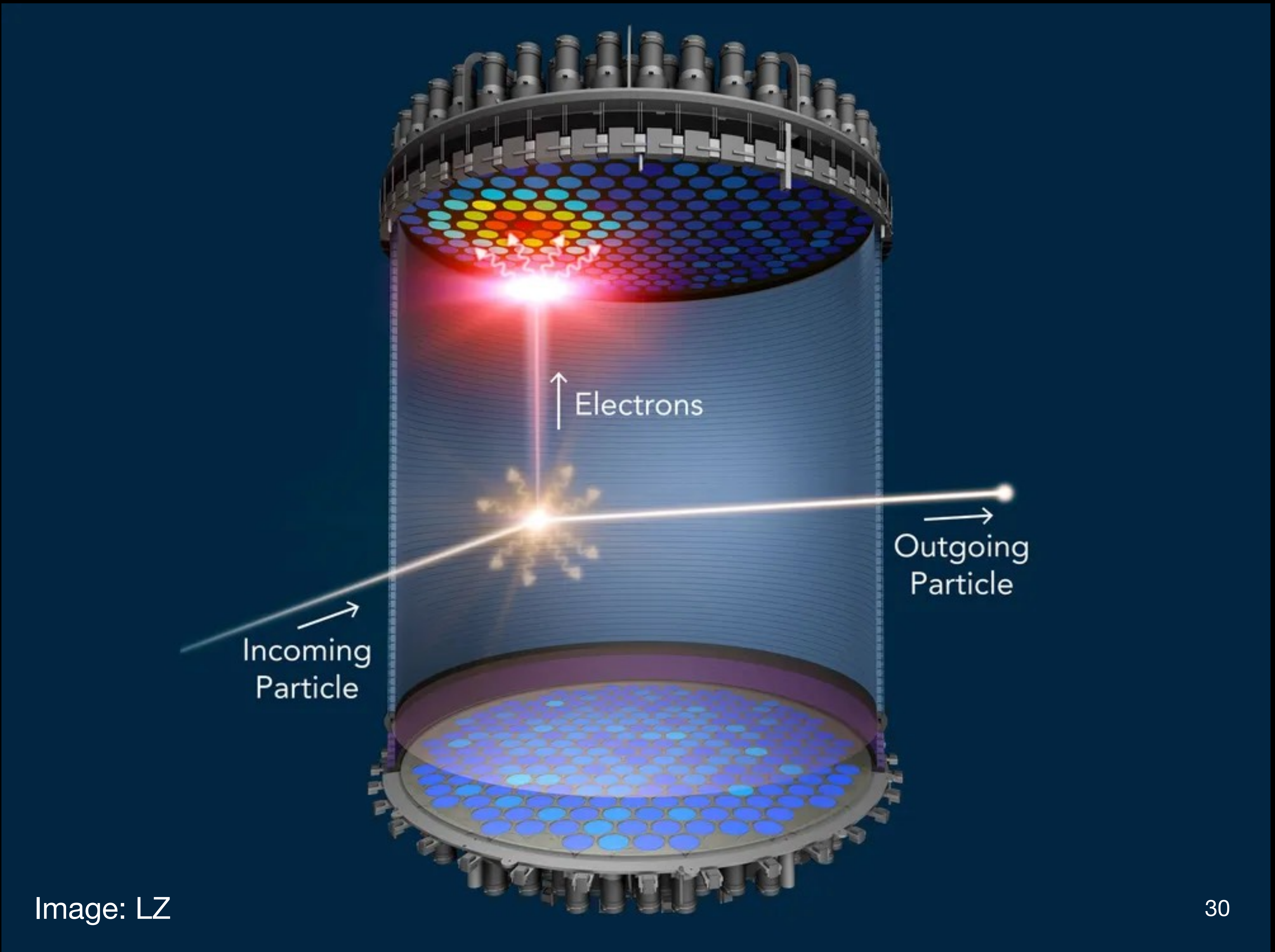
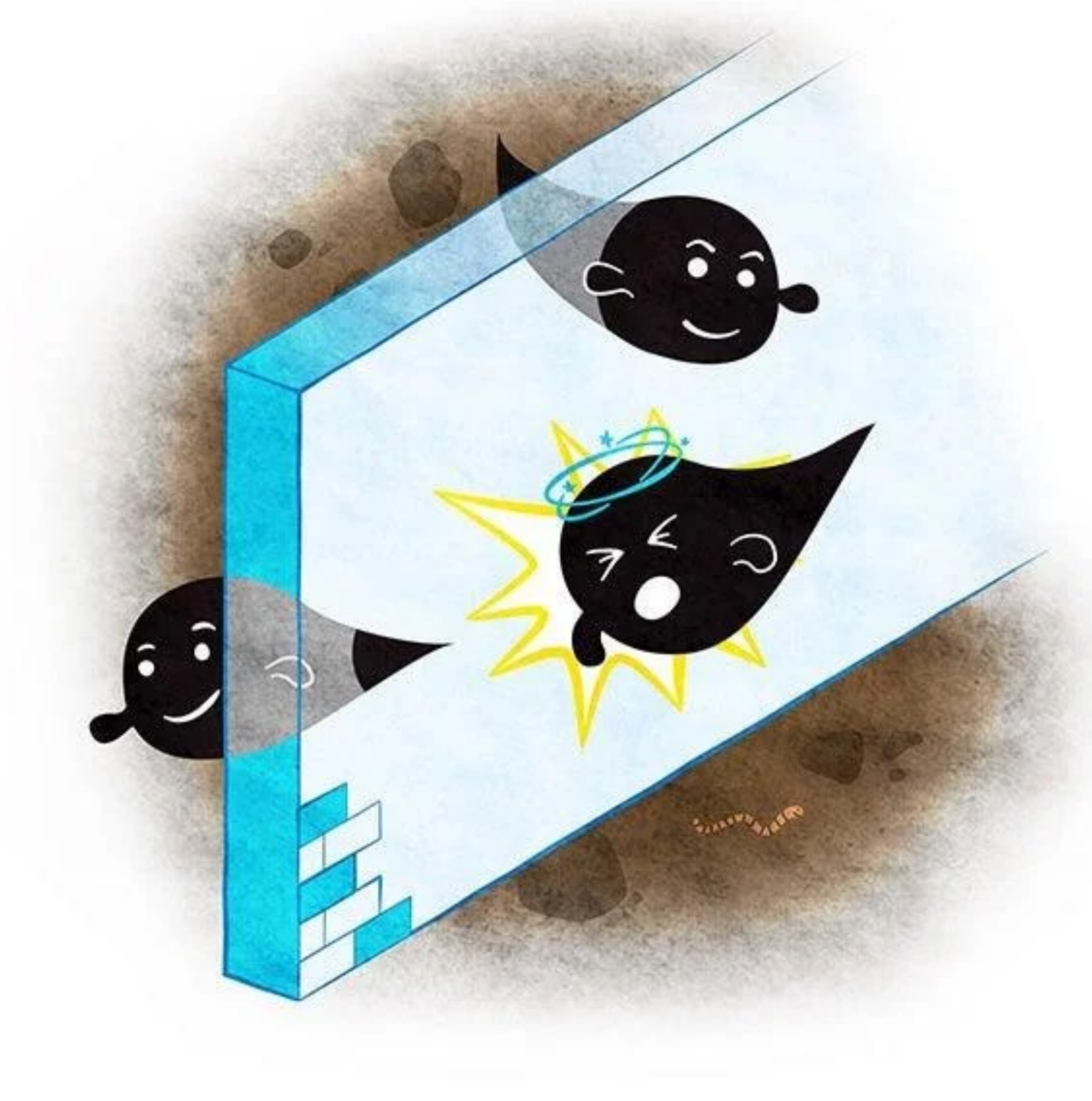


Image: LZ



We know the local Dark Matter abundance near earth. If Dark Matter is Weakly-Interacting Massive Particle, about one Dark Matter particle in a coffee mug.

Image: SLAC

The Particle Soup

- The expanding universe used to be denser and hotter,
  - At the highest temperature, all particles are produced as massless relativistic particles
  - The universe was like a soup of particles in thermal equilibrium
- Particle interactions determine the very beginning of the cosmic expansion. We infer the early universe with relic particles today.

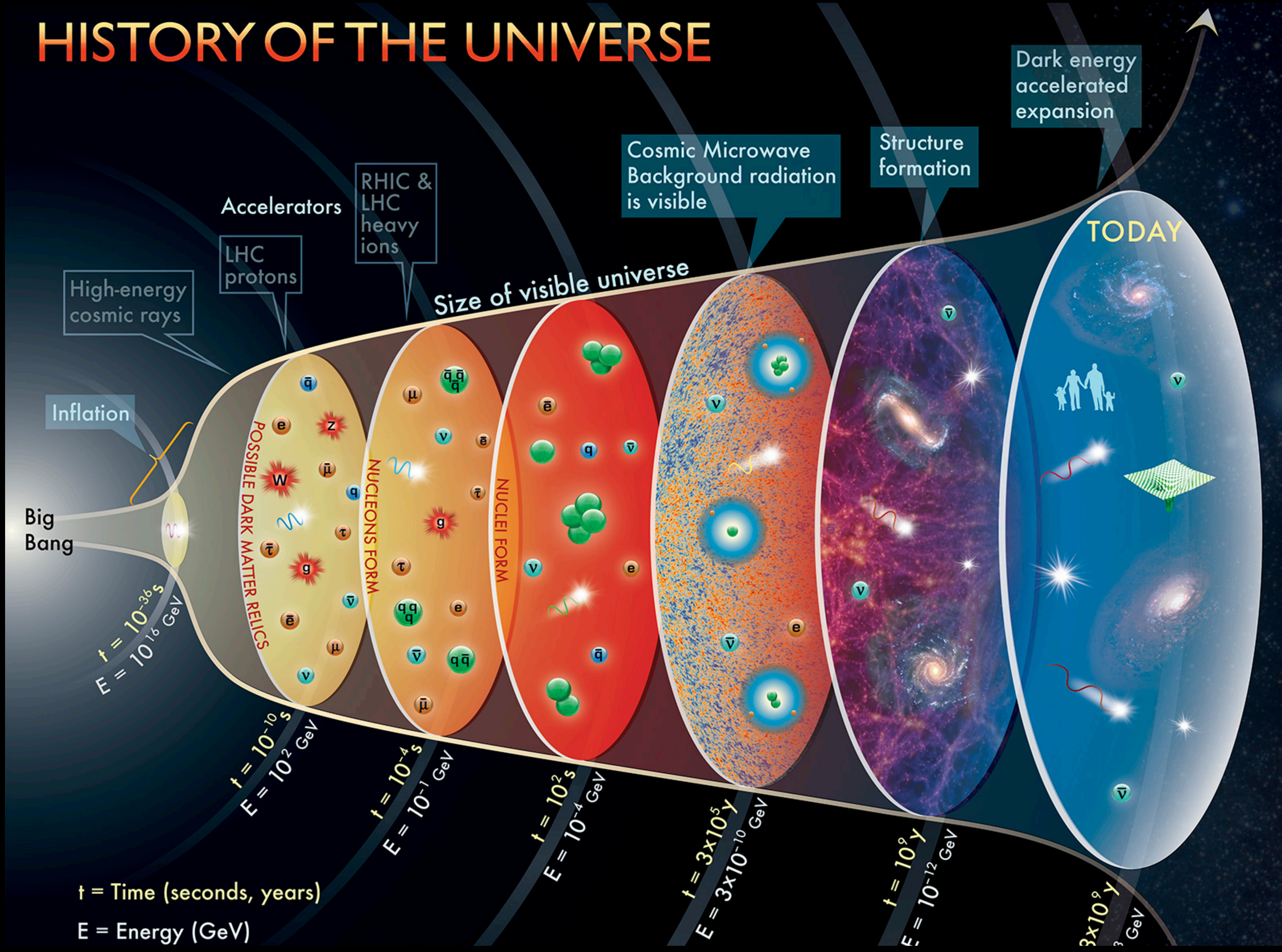


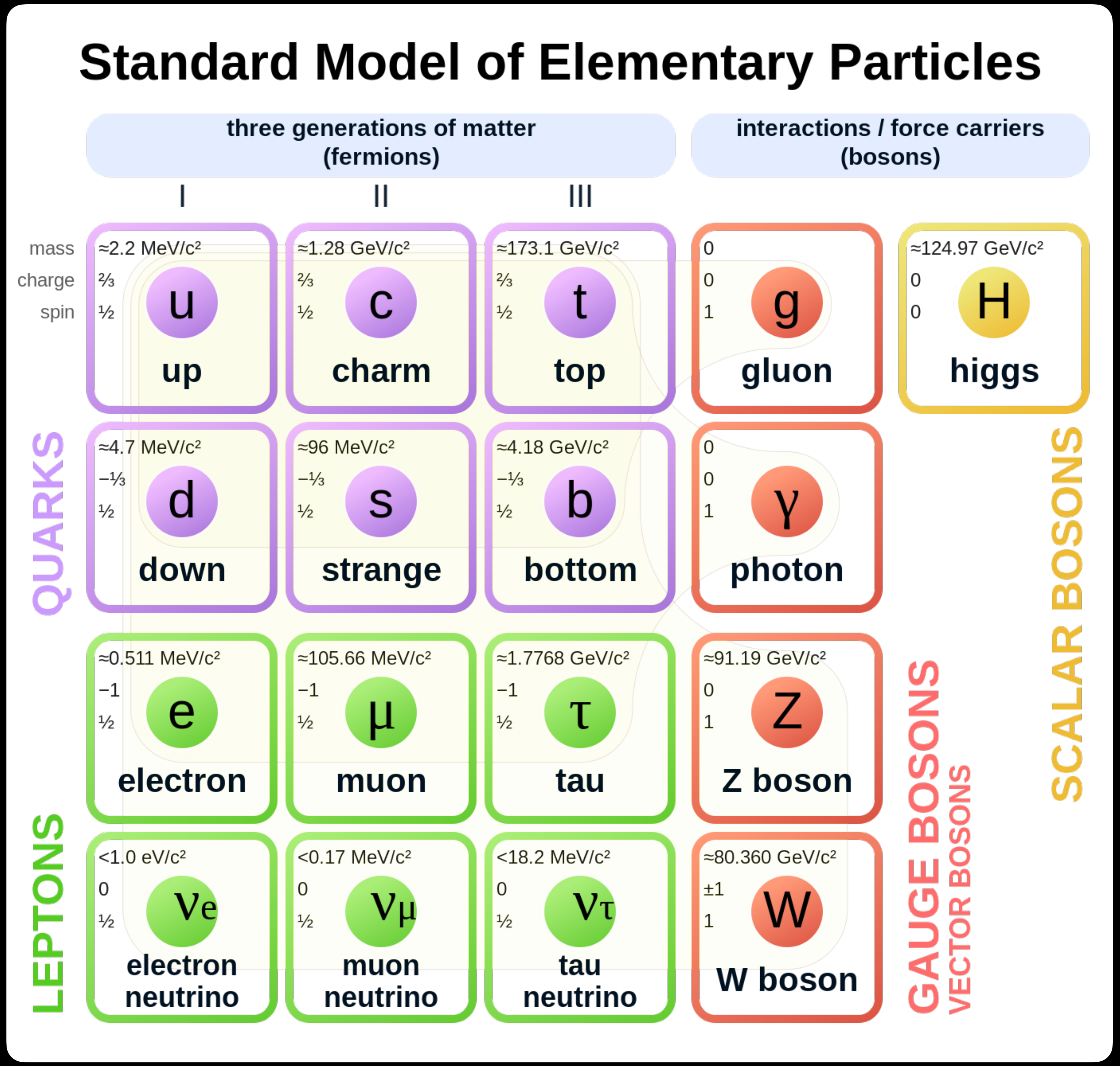
Image: Particle Data Group

Open Questions in Particle Physics

an incomplete list

- What stabilizes the mass of the Higgs boson?
- What is the origin of neutrino mass?
- What is the next energy scale beyond the Standard Model?
- Why is there a matter-antimatter asymmetry in the universe?
- What is the nature of Dark Matter?

Beyond the Standard Model



+ χ **Dark Matter** + **?**

both challenges and opportunities ahead for us

Thank you!