What happens when you smash a proton?

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SITN @ BHS October 26th 2026

How small is the smallest thing you can imagine?

Hint: the real things I study are way smaller than that!

Let’s zoom in



~10 cm

Look at your hand

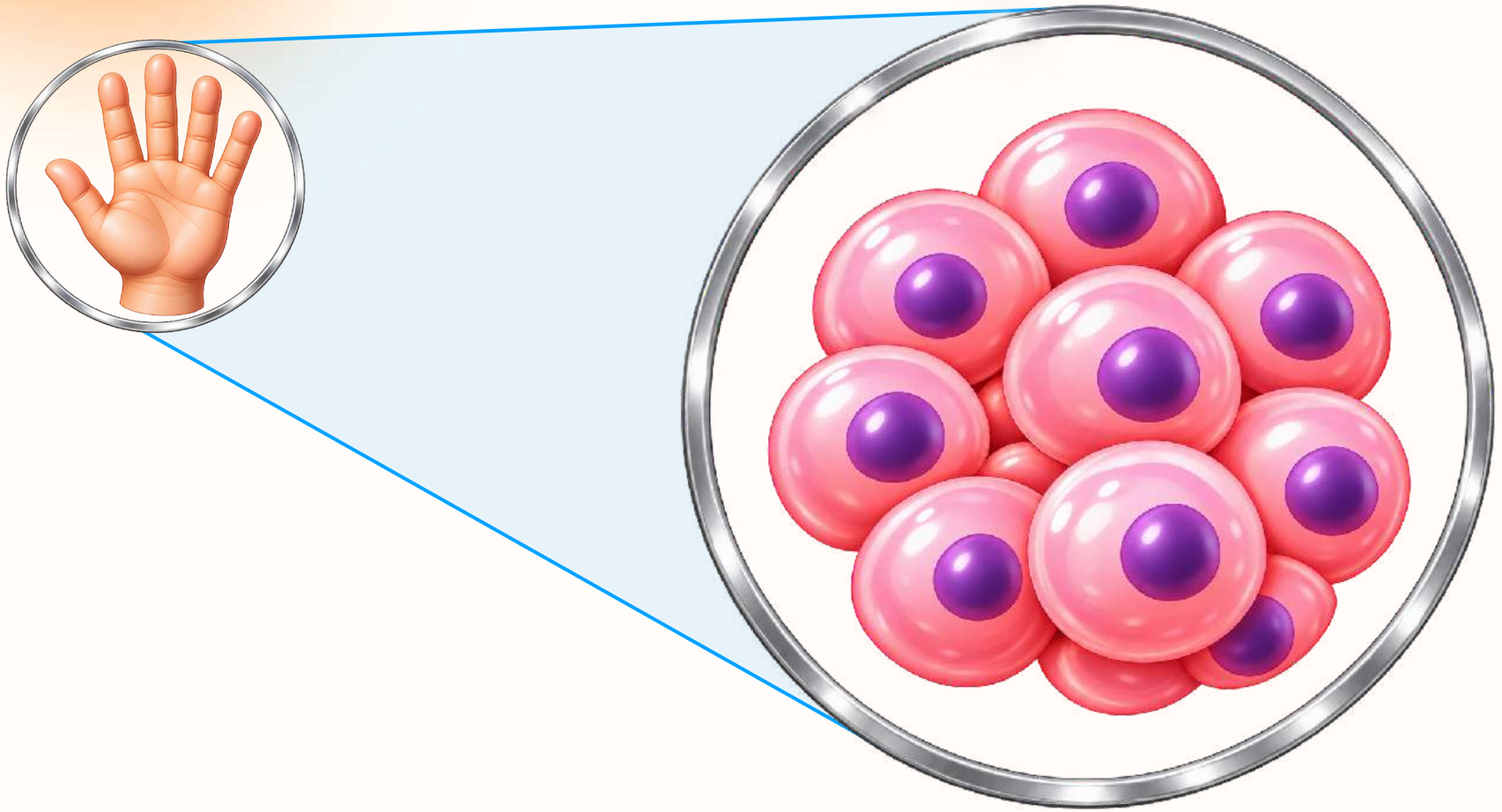
Let’s zoom in



~10 cm

Look at your hand

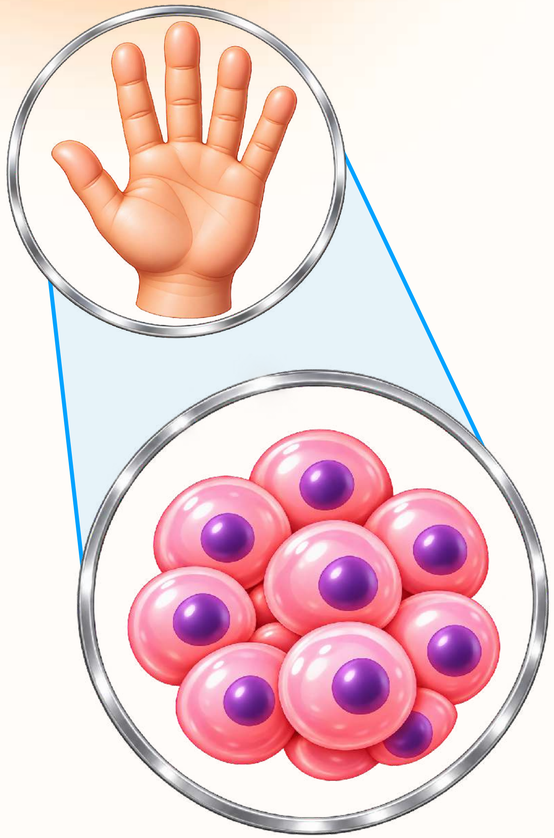
Let’s zoom in



~10 µm
(10^{-5} m)

It is made out of cells

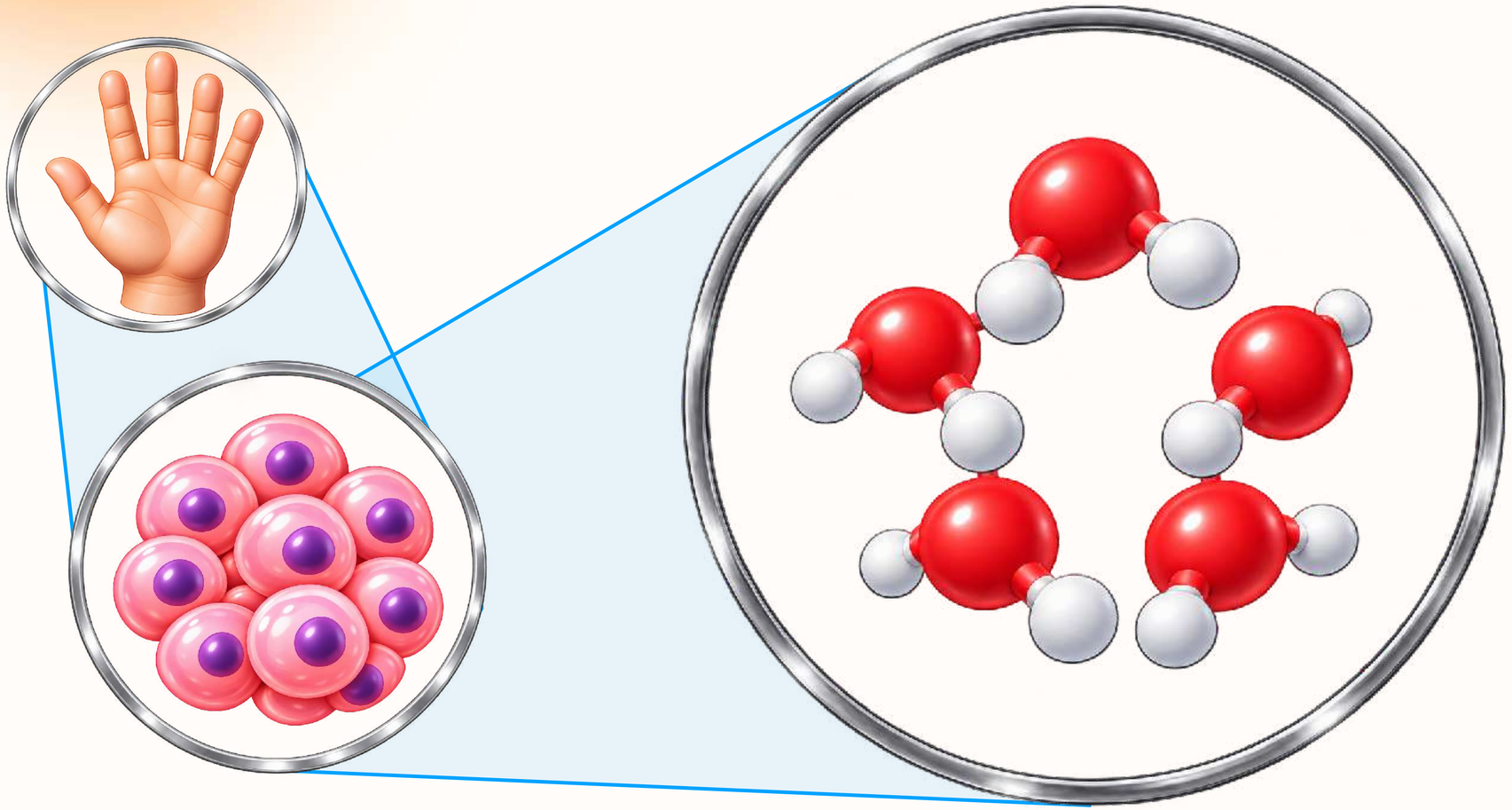
Let’s zoom in



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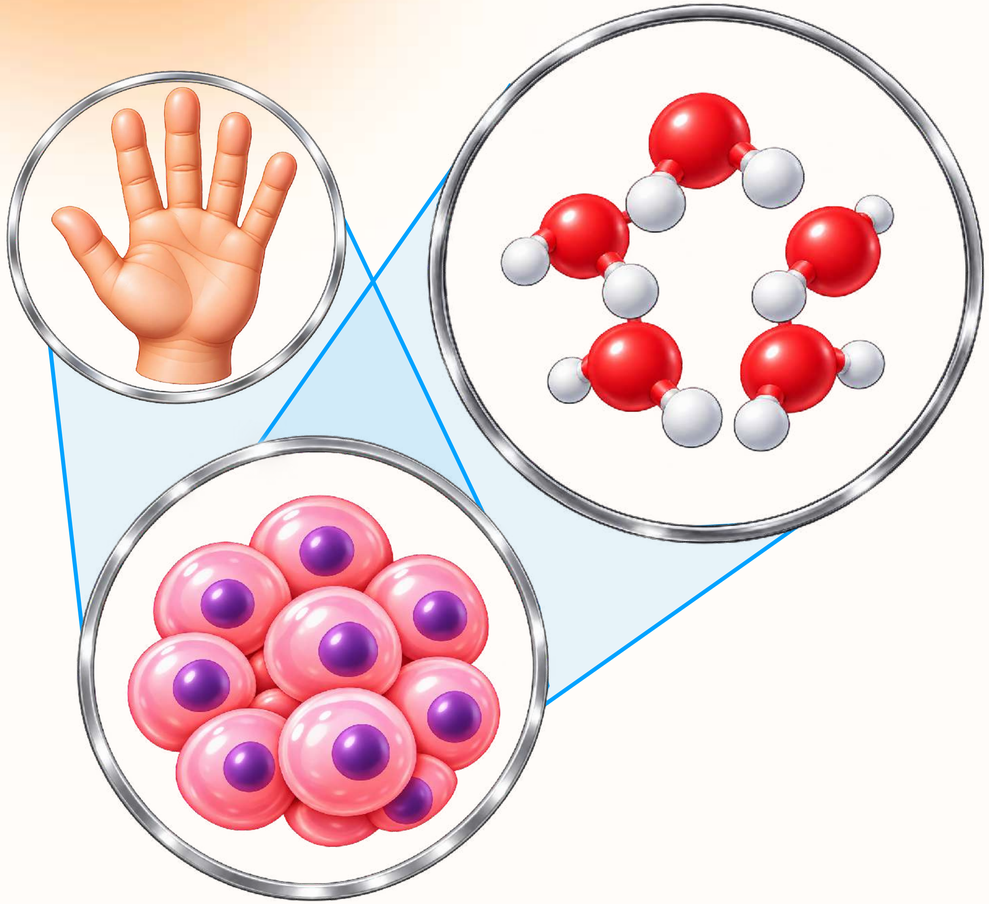
Let’s zoom in



~0.3 nm
(3×10^{-10} m)

The cells are made up of molecules

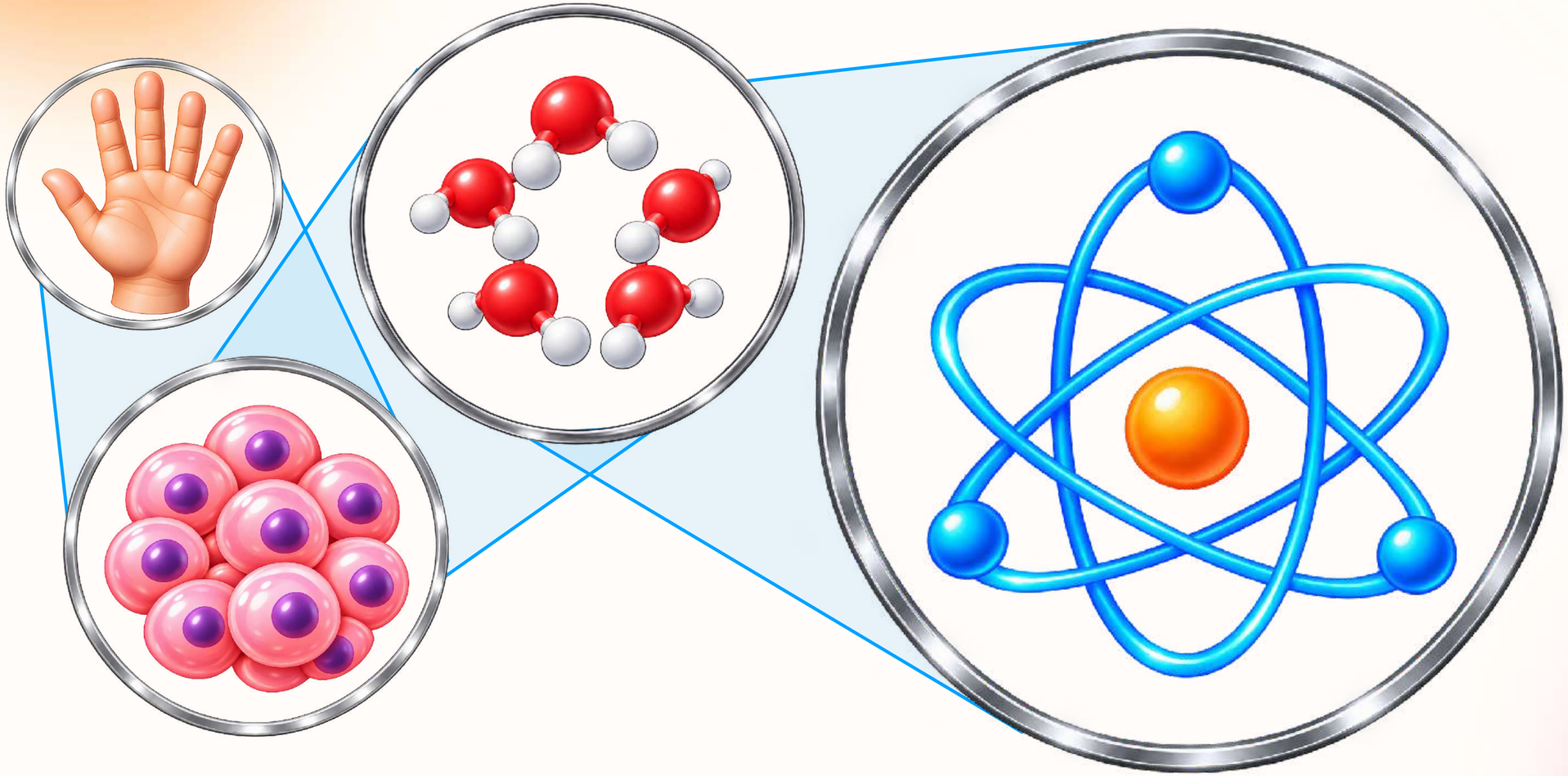
Let’s zoom in



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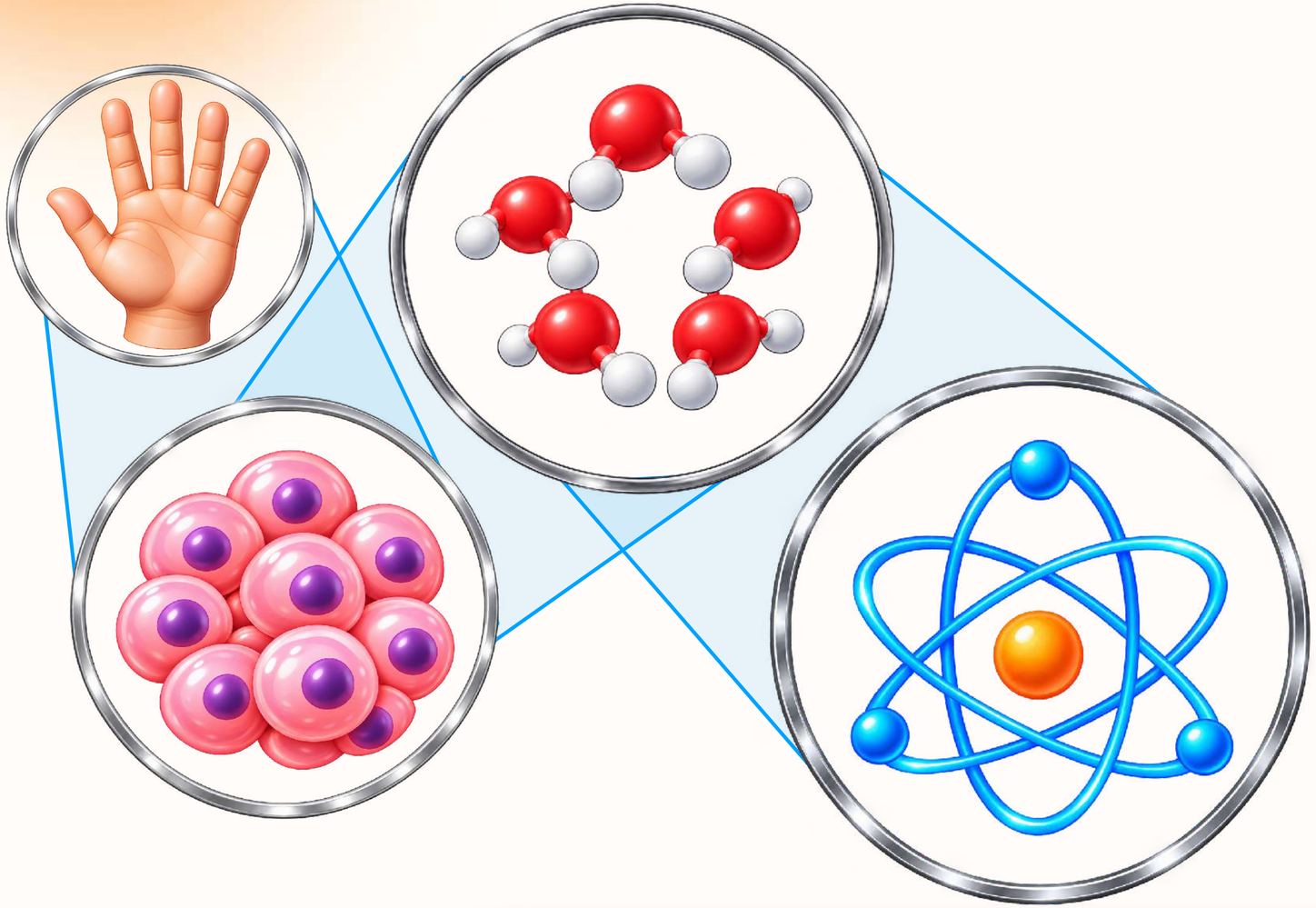
Let’s zoom in



~0.1 nm
(10^{-10} m)

The molecules are made up of atoms

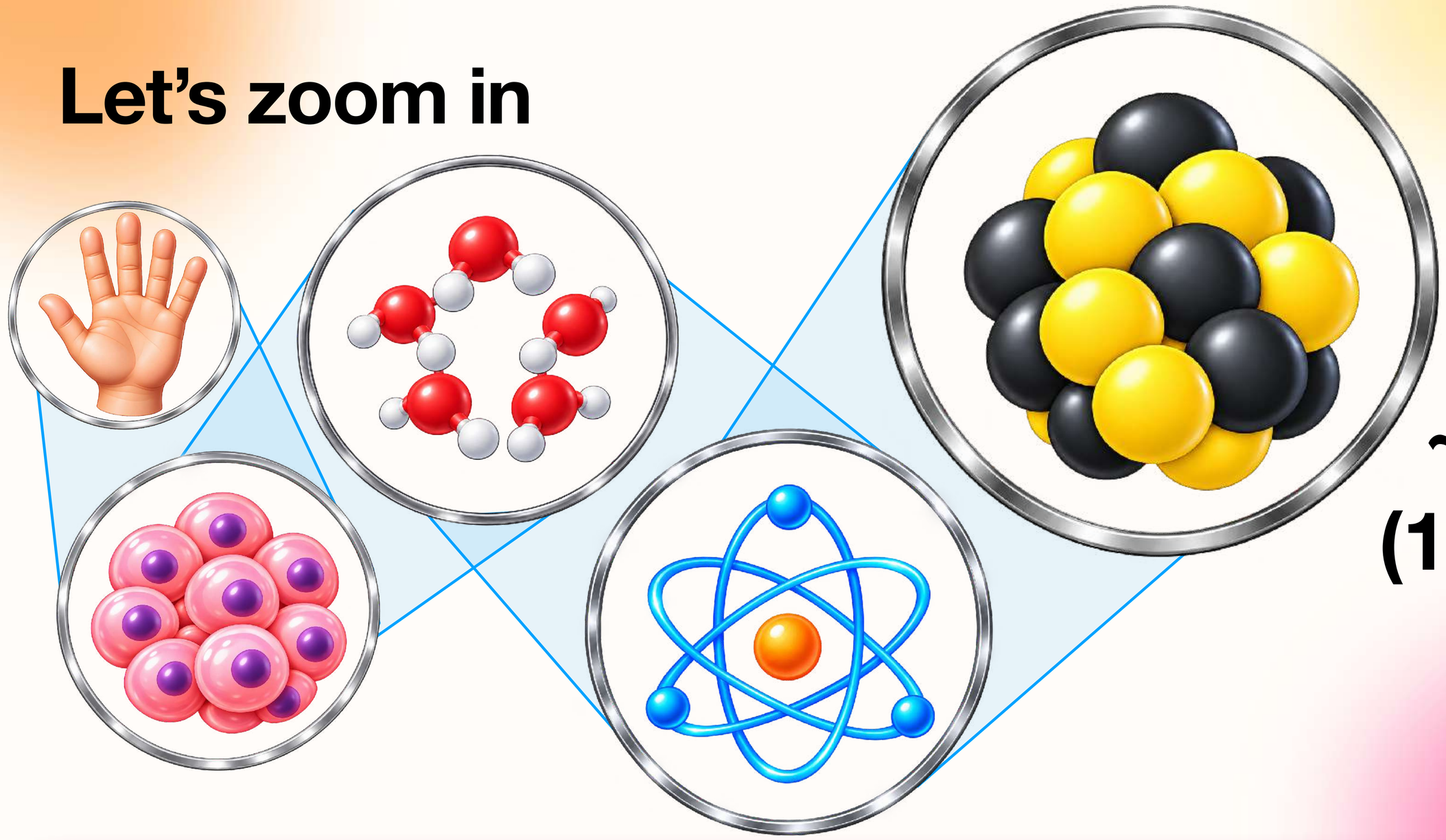
Let’s zoom in



~0.1 nm
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The molecules are made up of atoms

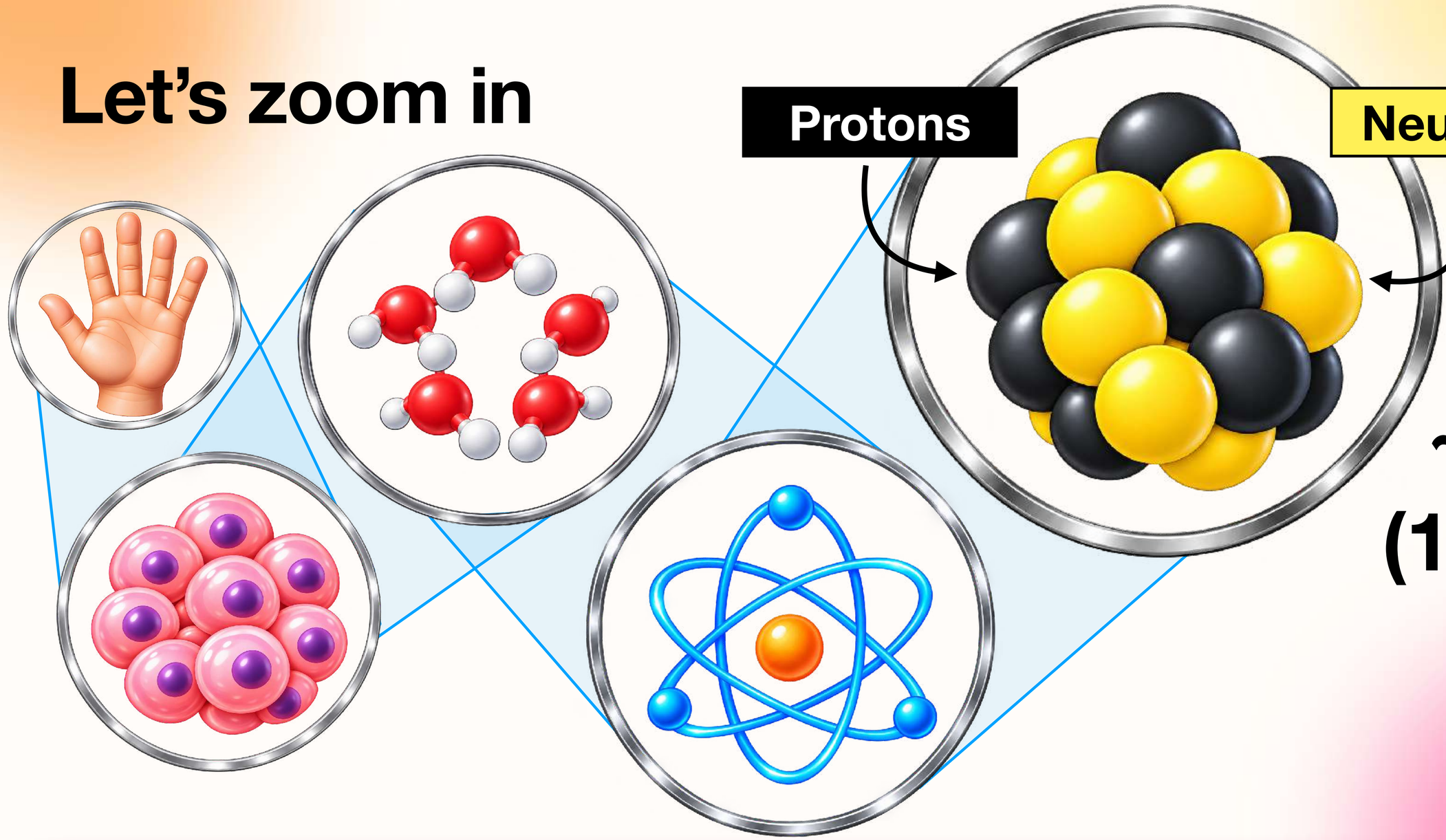
Let’s zoom in



~1 fm
(10^{-15} m)

The atoms have nuclei inside of them, comprised of protons and neutrons

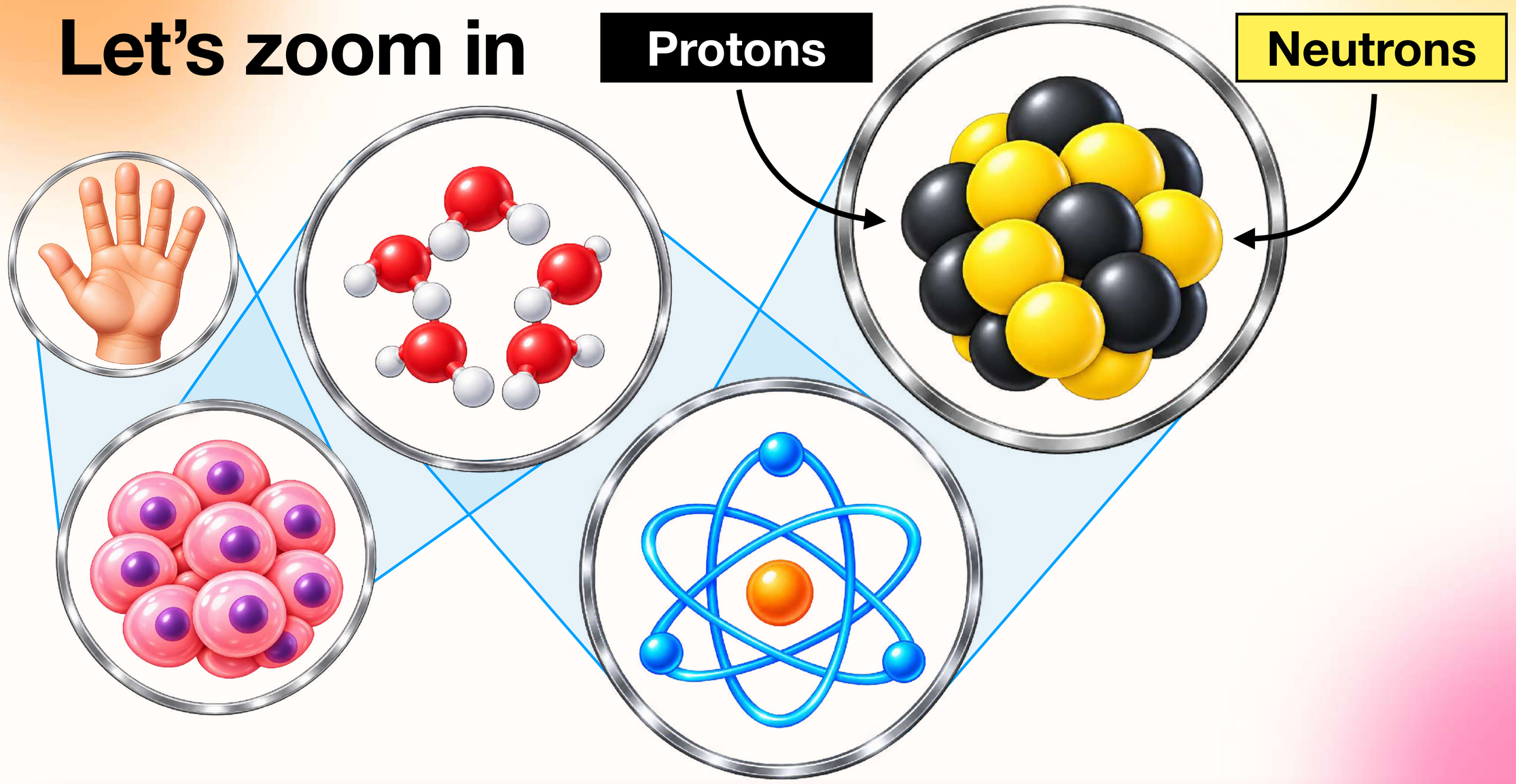
Let’s zoom in



~1 fm
(10^{-15} m)

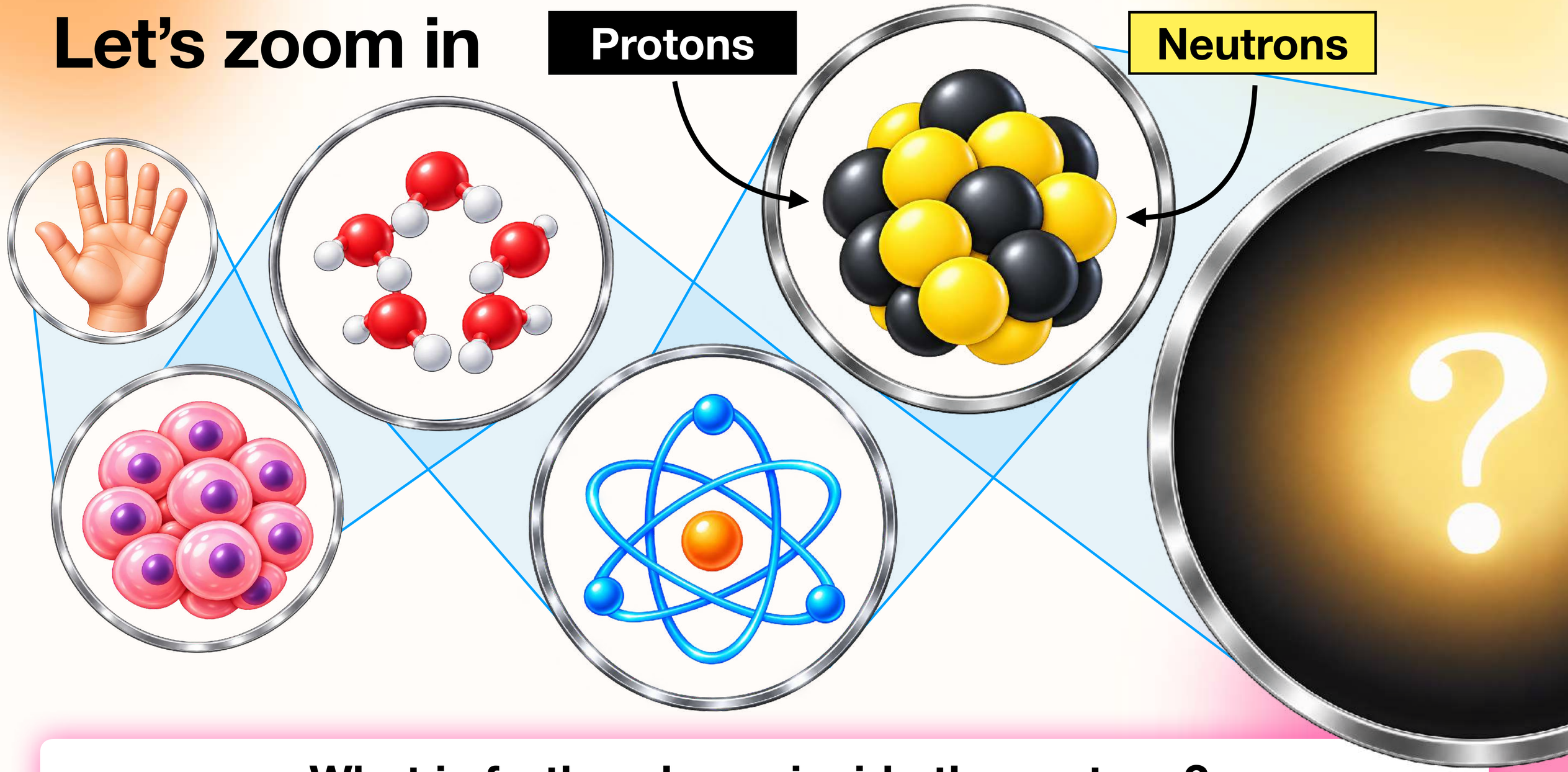
The atoms have nuclei inside of them, comprised of protons and neutrons

Let’s zoom in



The atoms have nuclei inside of them, comprised of protons and neutrons

Let’s zoom in



What is further down, inside the protons?

Today

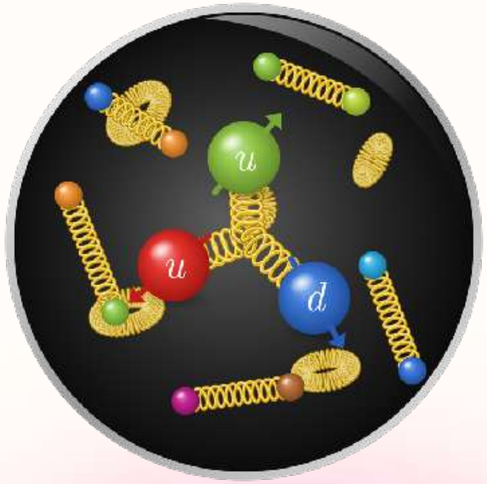
1 **What's in the proton?** and how had a peek inside

2 **Colliders** one collision, step by step

3 **What I do** a theorist

4 **Open questions** what we still don't know

5 **Why do we care?** things nobody planned



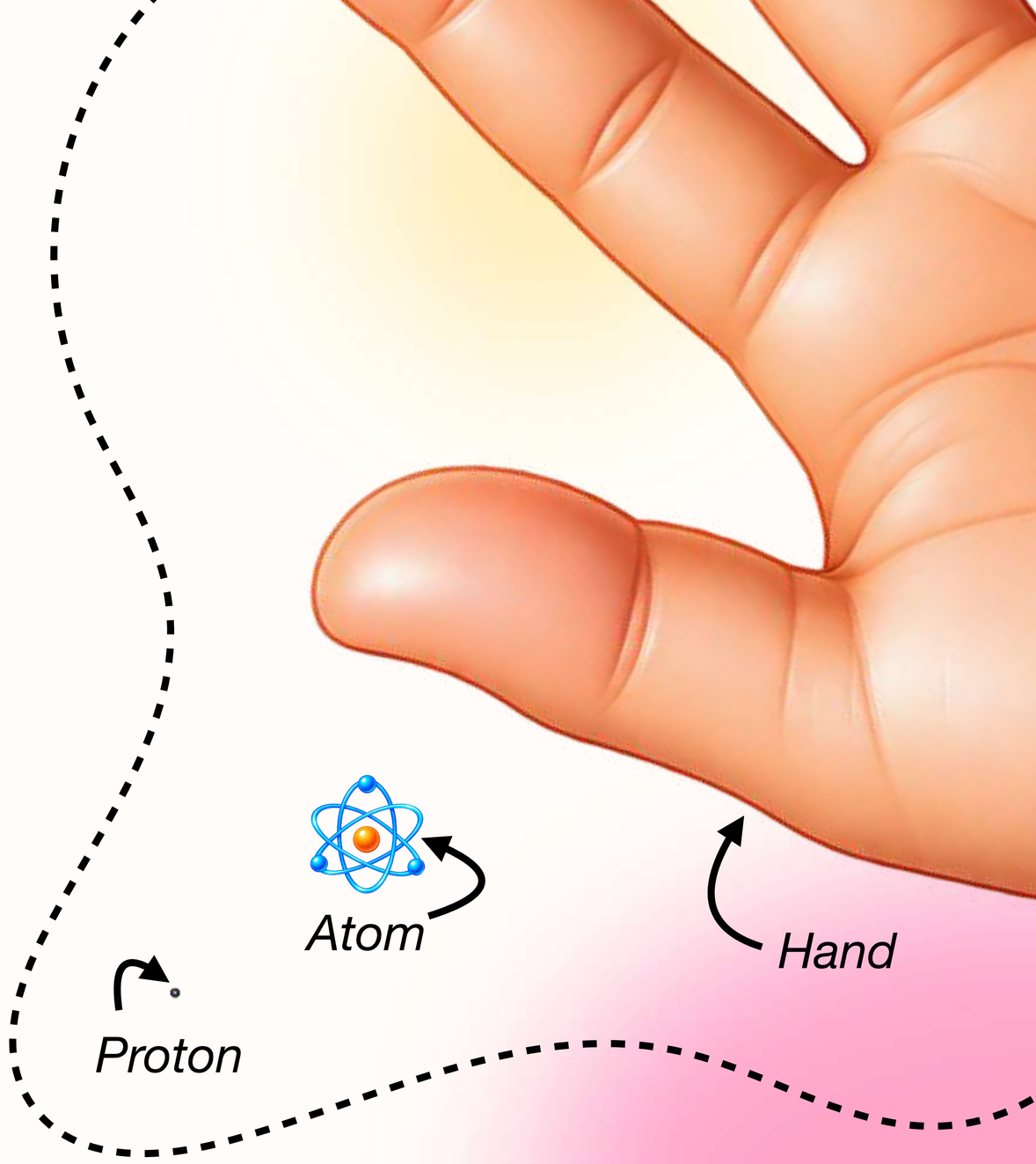
1 What's in the proton?

And how do we have a peek inside?

A proton is 100,000 times smaller than an atom and a hundred trillion times smaller than your hand.

No microscope reaches that far:

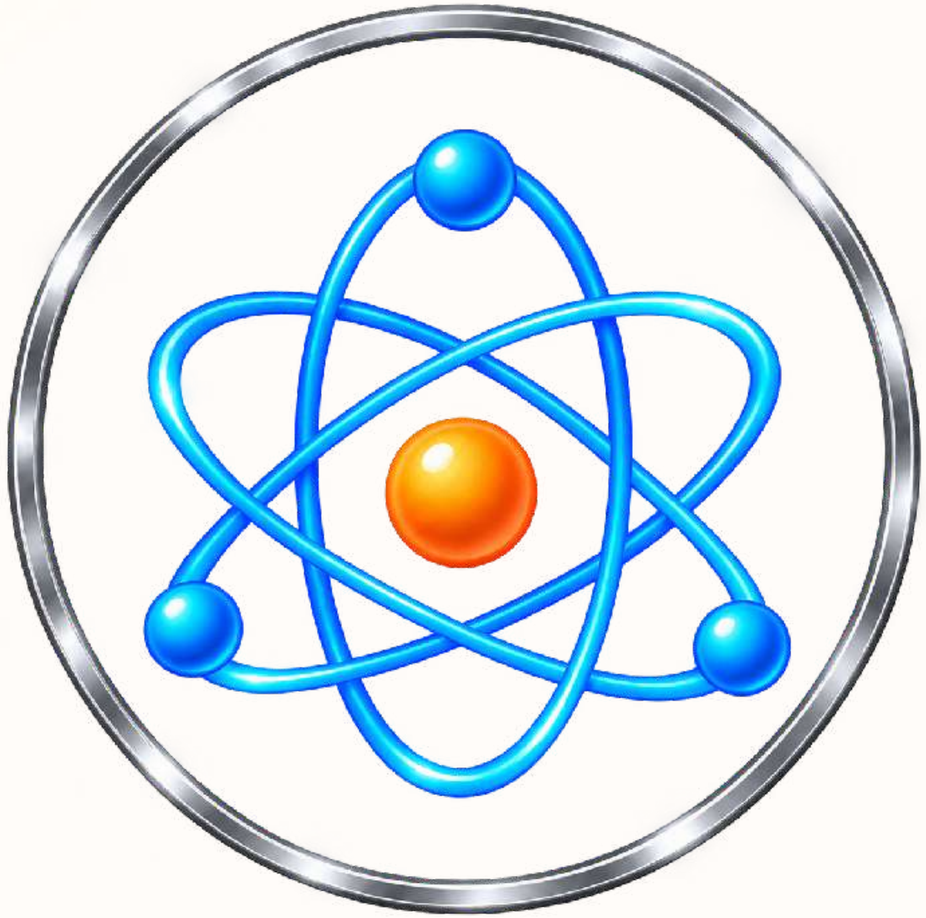
the best microscope stops 50,000 times short



So how did we ever find that is inside the atoms in the first place?

How did we do it historically?

Start of 20th century



We knew about molecules, atoms and electrons inside the atoms, but that's it.

Had no idea if there is anything else inside the atoms.

How did we do it historically?

Rutherford gold foil experiment (1911) — discovery of atom nucleus



Ernest Rutherford

With Hans Geiger
(yes, that Geiger)
and Ernest Marsden, a 20-year-old student,
counting flashes by eye in a dark

most fly straight through, a few bounce back scattering off a tiny, dense core.

1 in 8,000

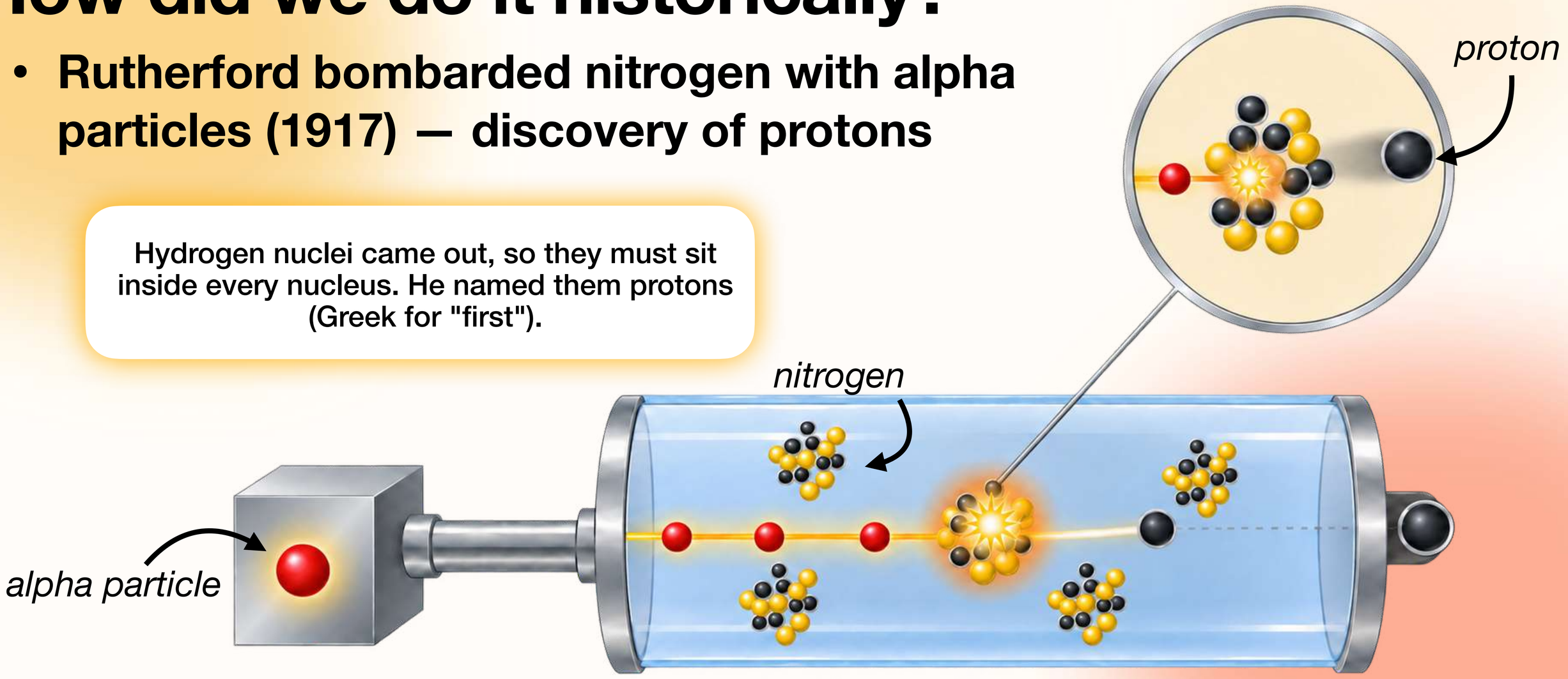
alpha particles bounced back.

"as if you fired a 15-inch shell at tissue paper and it came back and hit you."

How did we do it historically?

- **Rutherford bombarded nitrogen with alpha particles (1917) — discovery of protons**

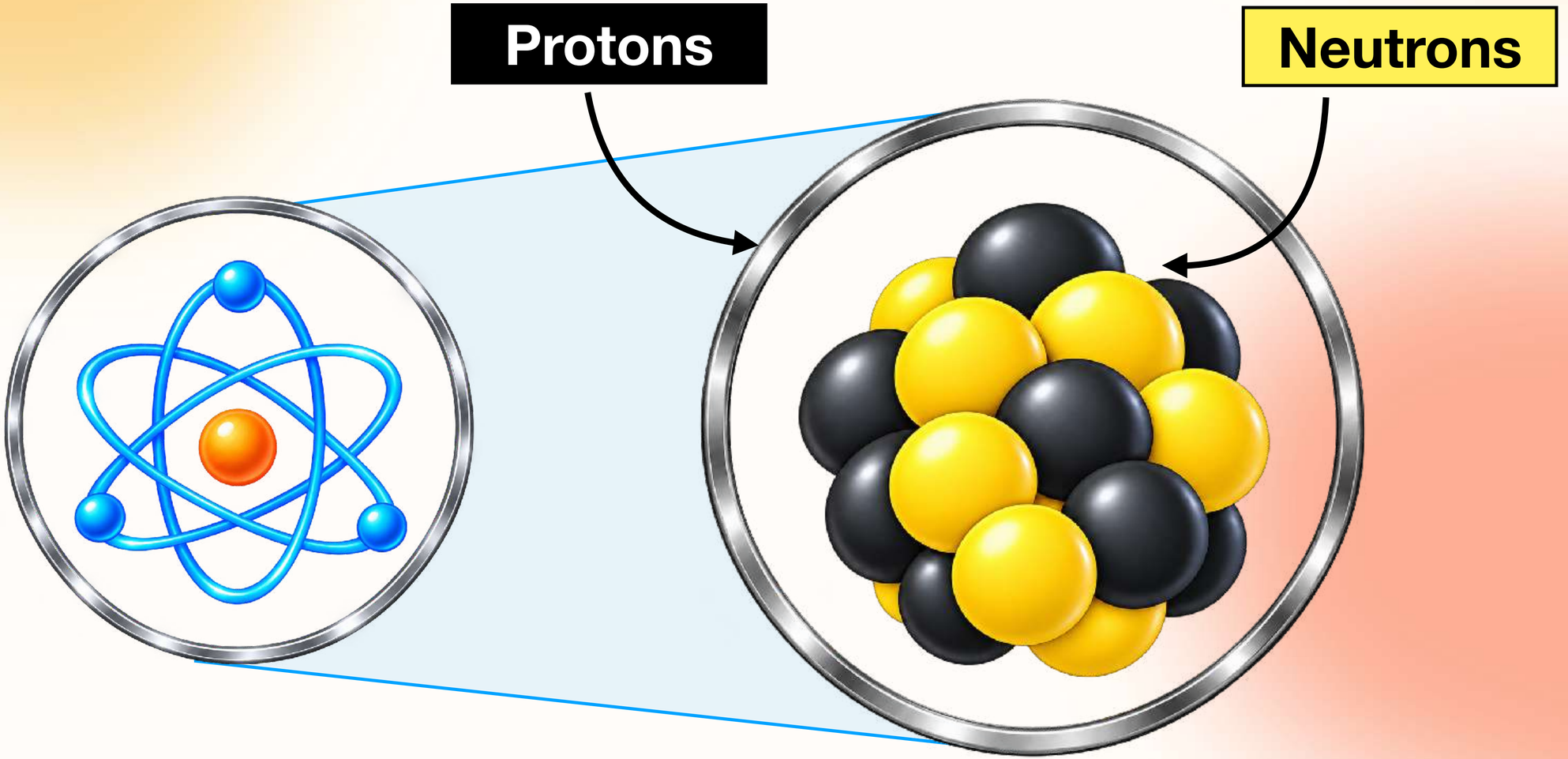
Hydrogen nuclei came out, so they must sit inside every nucleus. He named them protons (Greek for "first").



- **Chadwick bombarded beryllium with alpha particles (1932) — discovery of neutrons**

How did we do it historically?

End of 1930s: atoms have nuclei and nuclei have two types of particles — protons and neutrons



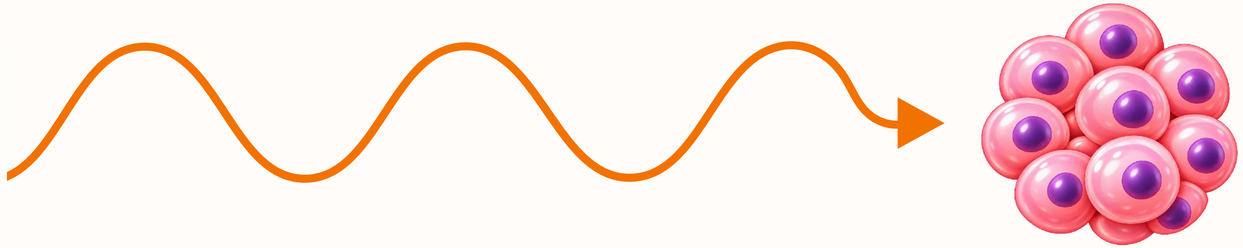
All of the experiments are just microscopes!

Shoot some stuff at other stuff — measure the outcome!

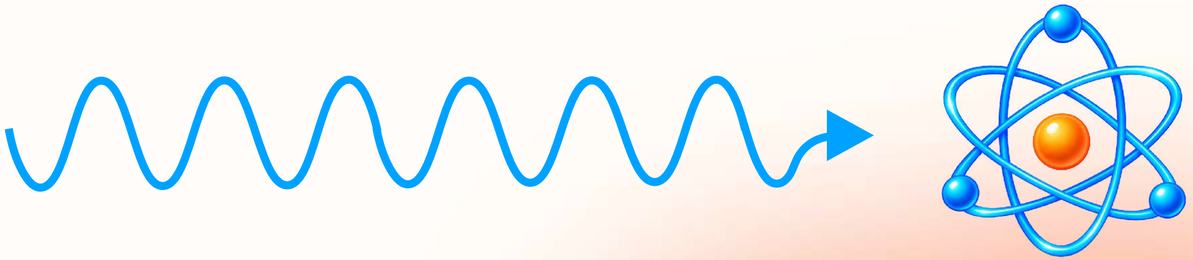
Higher energy → *Shorter wavelength* → *Finer resolution*



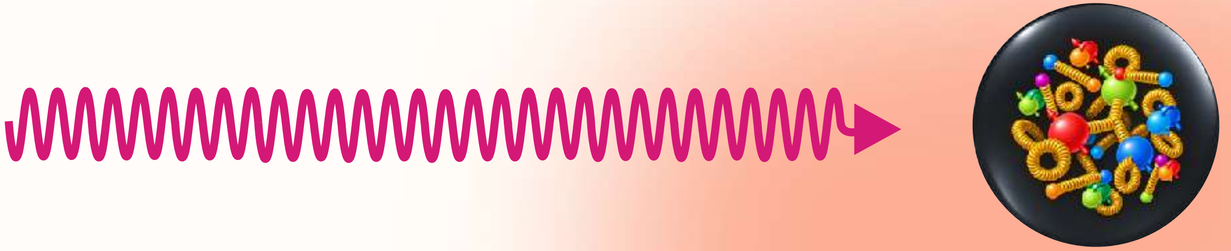
Photons



Electrons



Other particles



The insides of the proton

- **Quarks proposed**

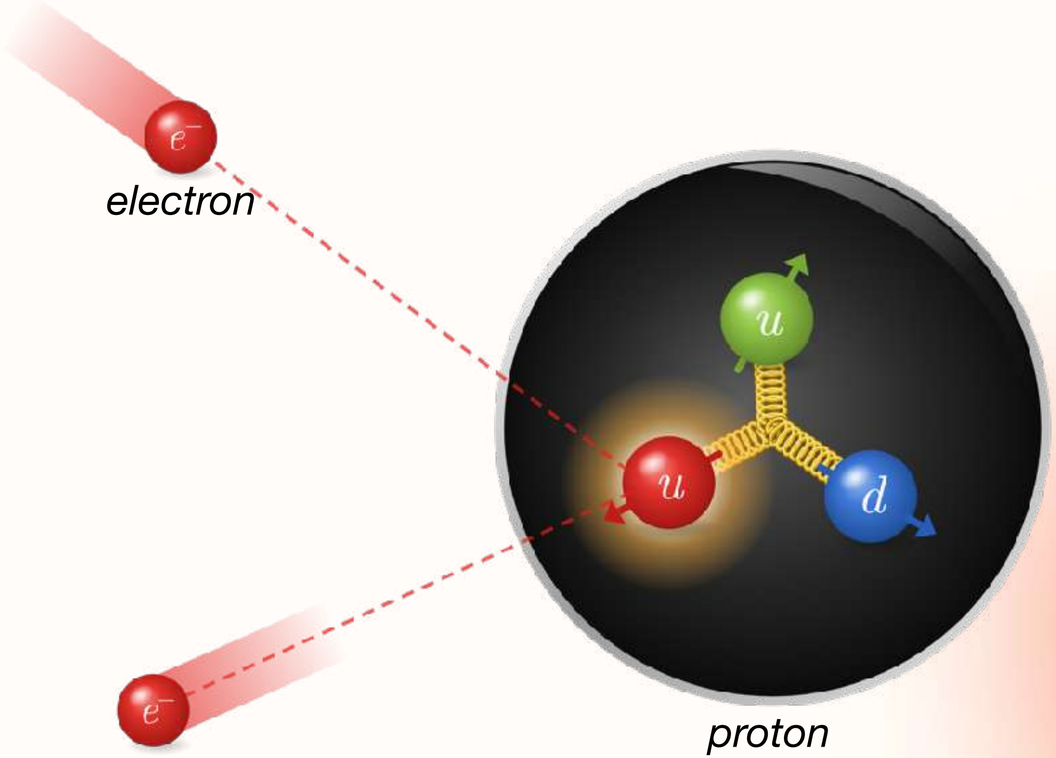
  Gell-Mann and Zweig in 1964

- **Experimental proof**

  Shoot high-energy electrons at protons: 1967-1973



Stanford Linear Accelerator (SLAC)



Electrons bounced back sharply, as if hitting hard little points.



1969

Murray Gell-Mann



1990

Jerome Friedman



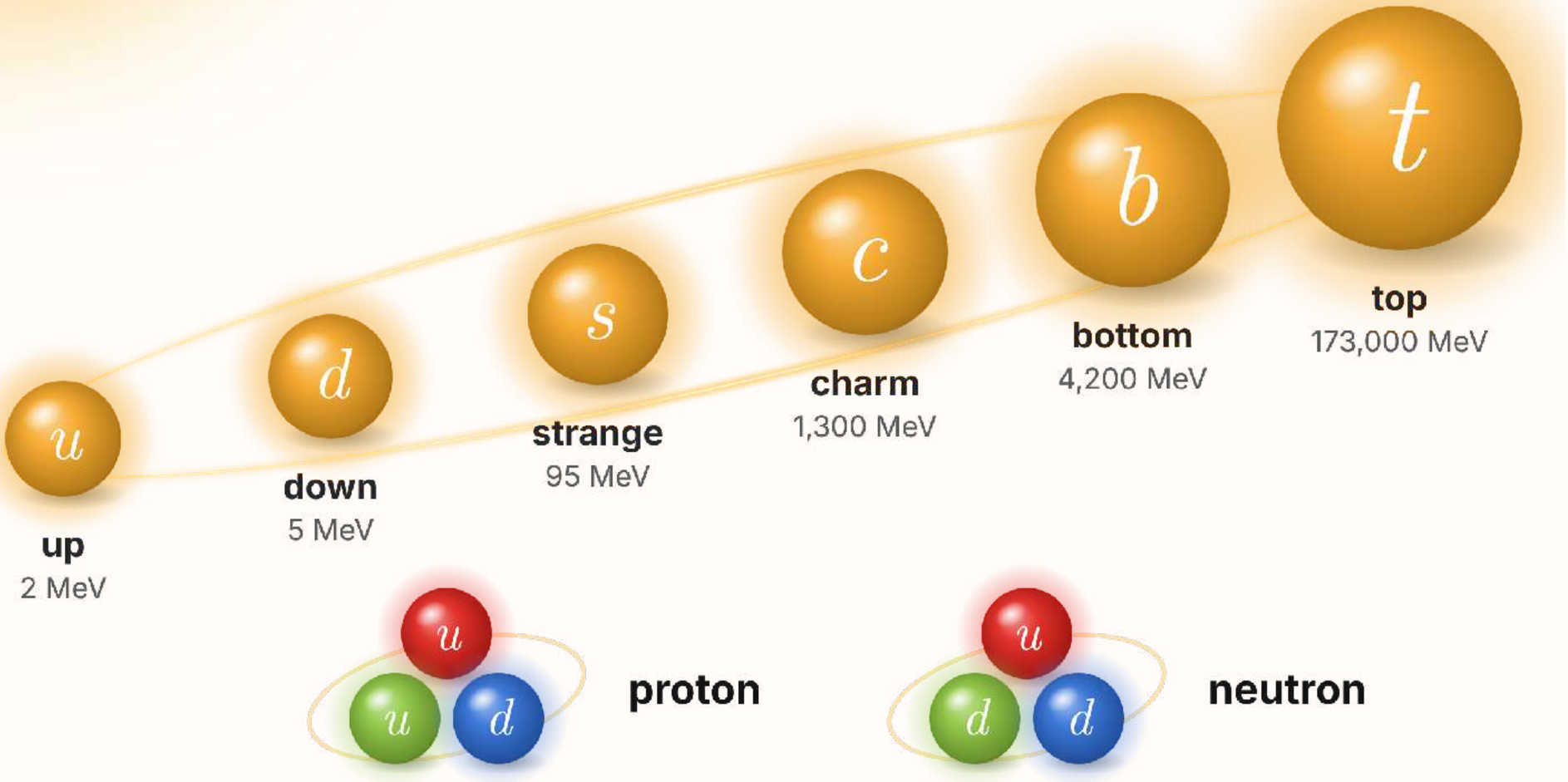
Richard Taylor

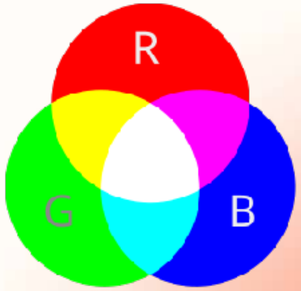


Henry Kendall

Quarks

The smallest pieces of matter. Six kinds, called flavors.





A kind of charge with three values, named **red**, **green**, **blue**. Only "white" combinations can exist on their own.

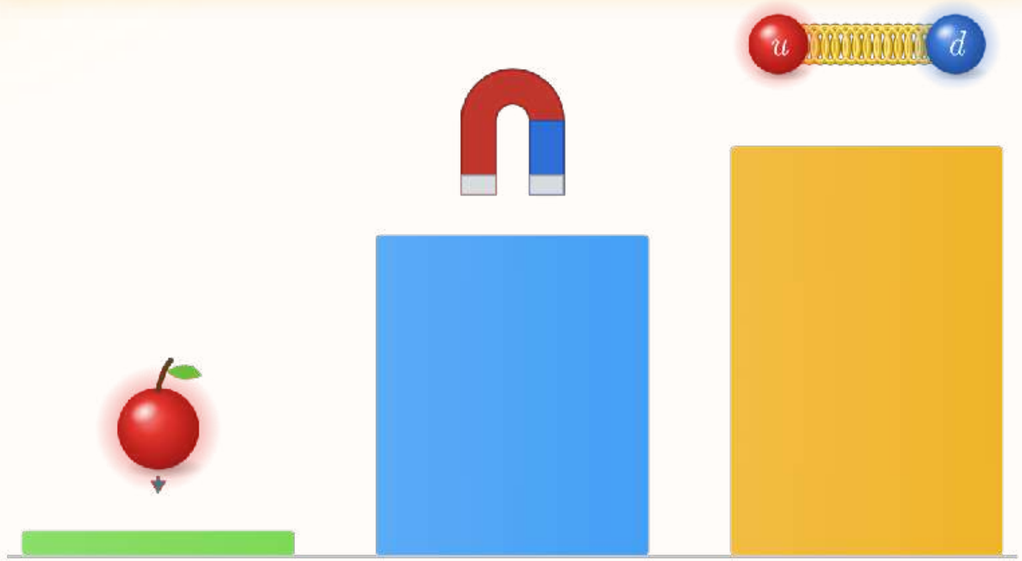
Only up and down live in everyday matter; the other four appear in collisions and vanish within a trillionth of a second.

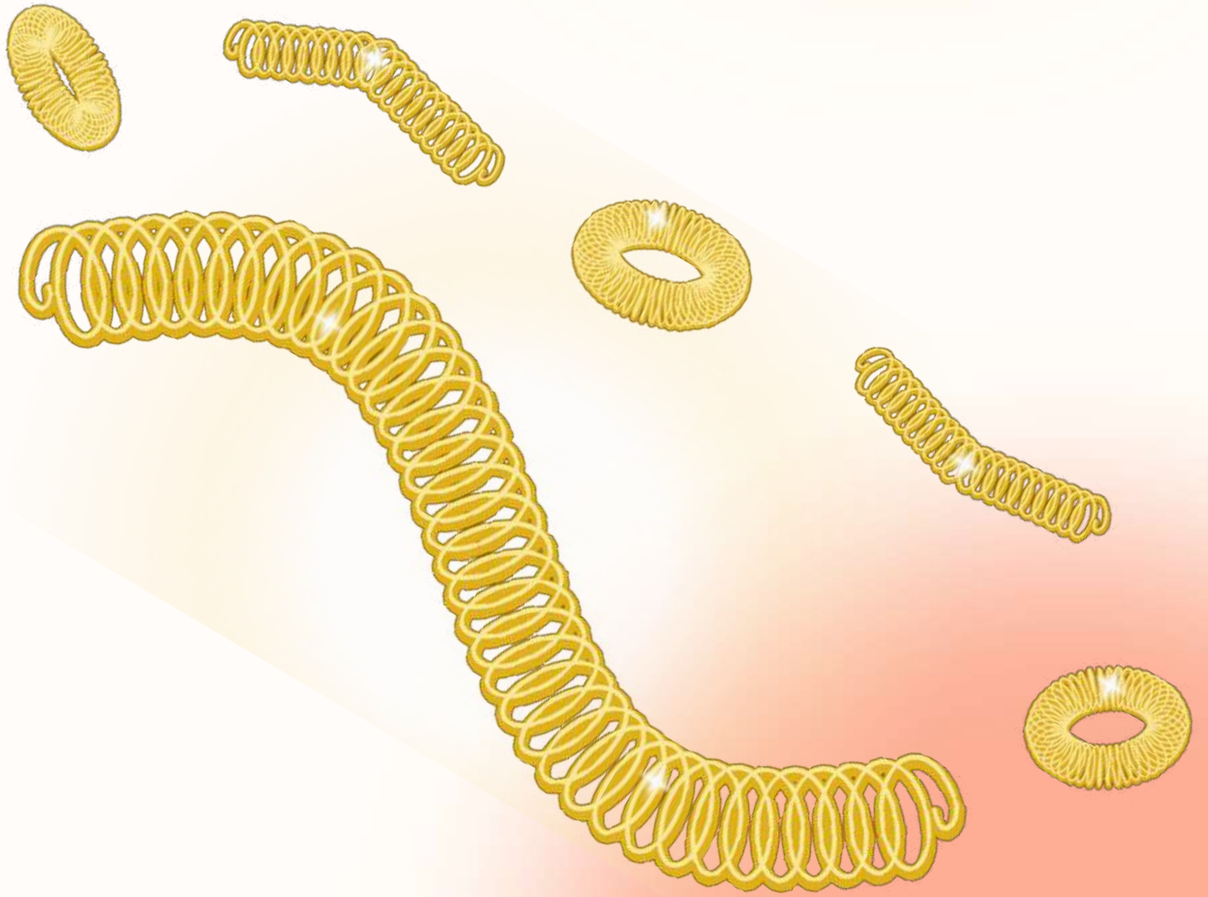
Gluons

“Glue” that keeps the quarks together

Strongest force in nature

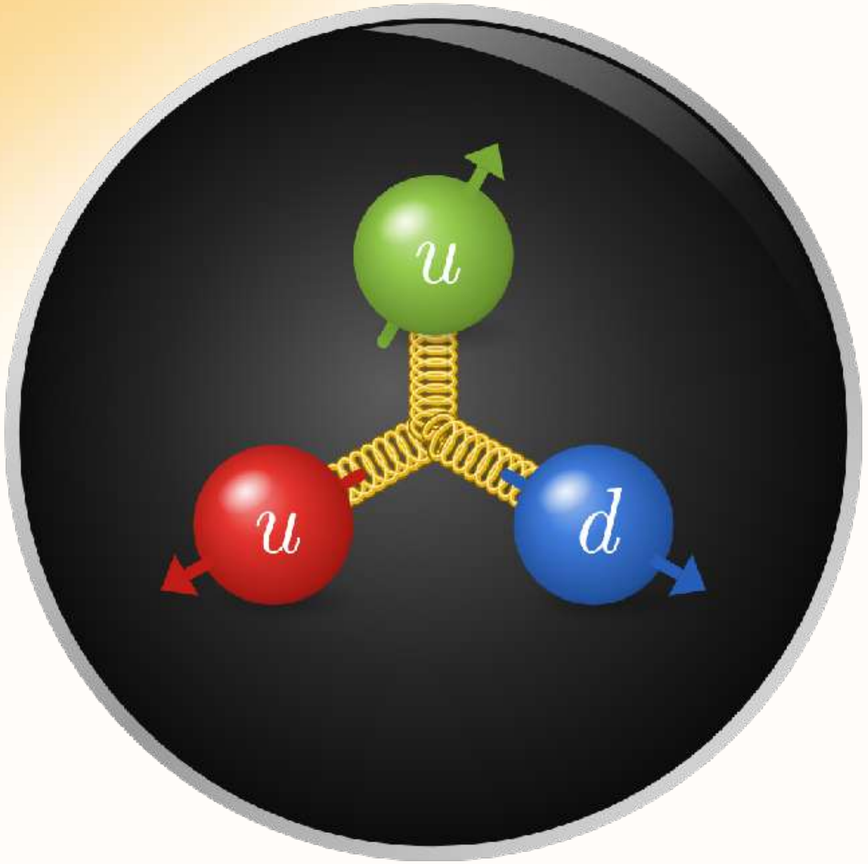
Gravity holds you on Earth. The force gluons carry is a trillion trillion times stronger.



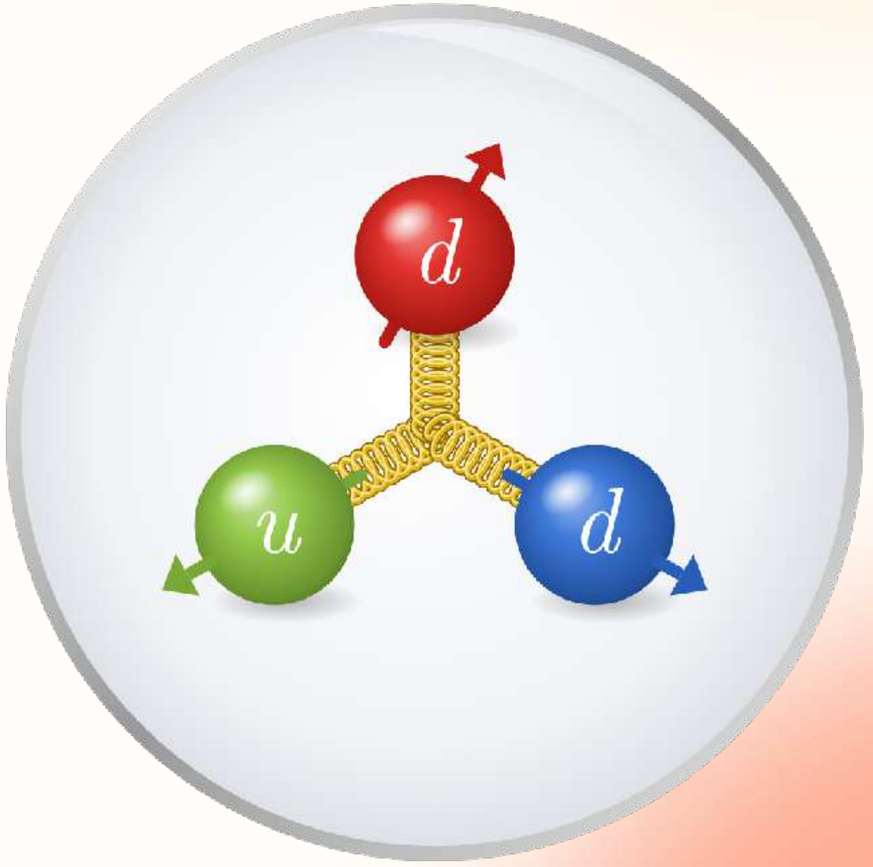


Quarks keep tossing gluons back and forth. That exchange is the force, and it carries most of the proton's mass

Quarks + gluons = protons and neutrons!

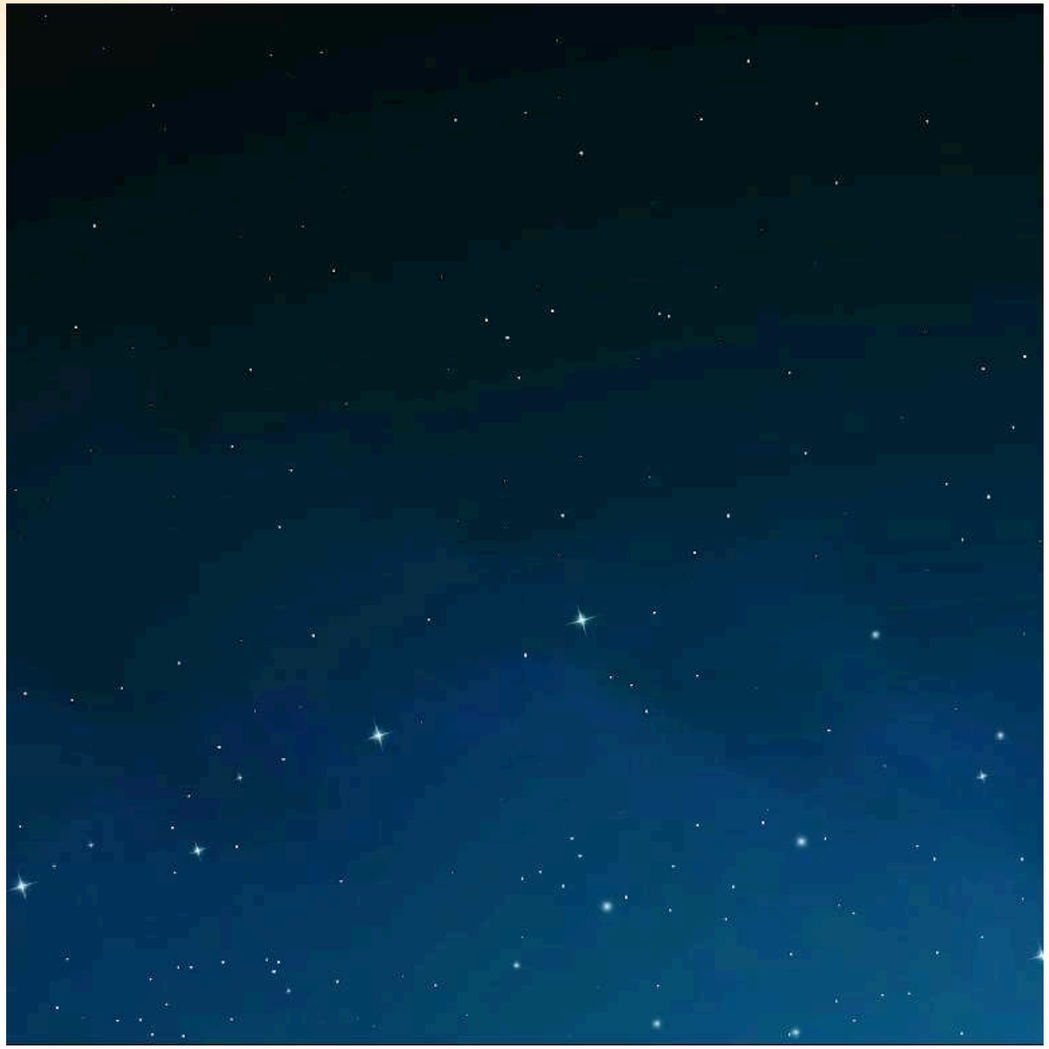


proton



neutron

Proton is a fizzling soup!



Nothing stands still

Three quarks, a swarm of gluons, and pairs of quark + antiquark that pop out of nothing and vanish again



And we just kept on pushing the energy up



7 trillion
electron-volts

Modern experiments

20 billion
electron-volts

SLAC

5 million
electron-volts

Rutherford

1.5
electron-volts

Battery

every day

1911

1968

today

And we just kept on pushing the energy up



7 trillion
electron-volts

Modern experiments

× 1,000,000

from Rutherford's alphas to today's protons.



1.5
electron-volts
Battery
every day



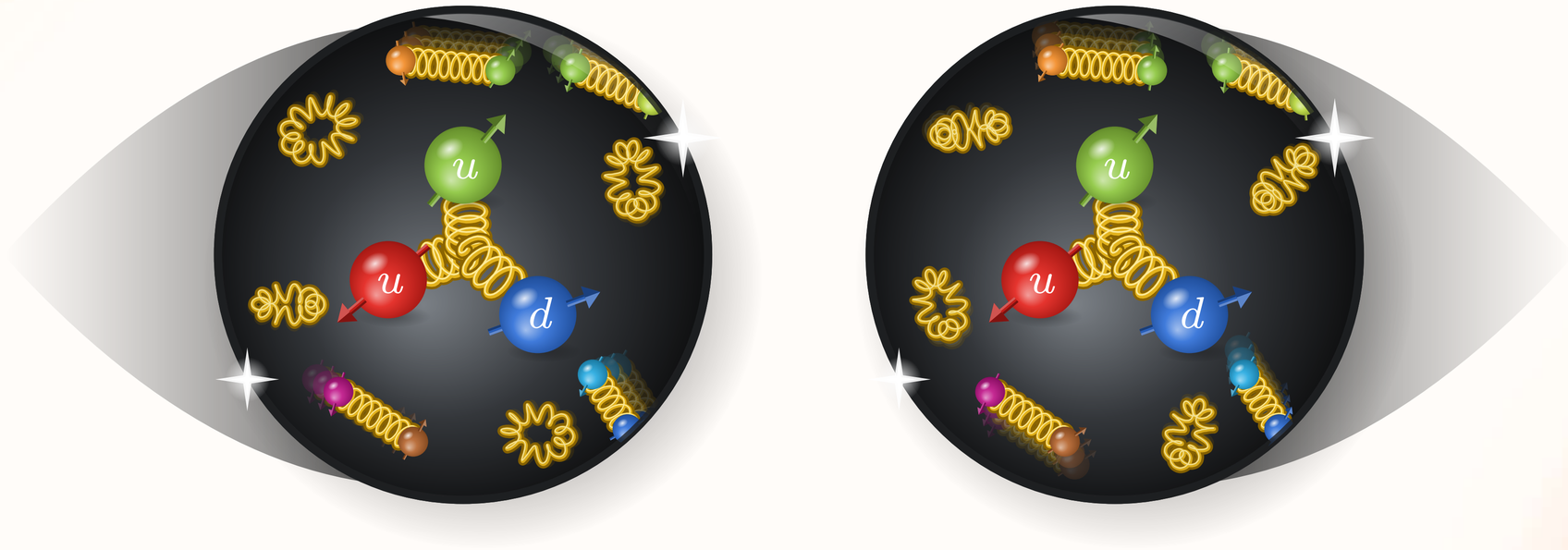
5 million
electron-volts
Rutherford
1911



20 billion
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SLAC
1968

today

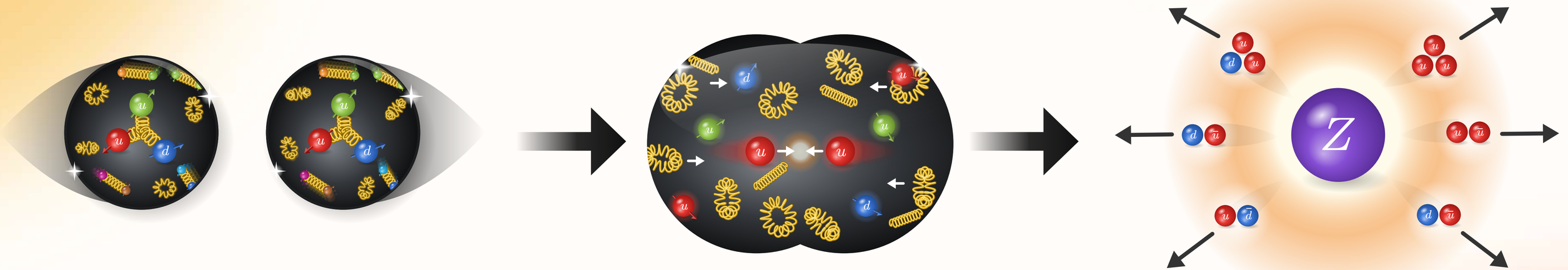
Now we have graduated to shooting protons at protons!



More energy!

More energy in, more particles out

Incoming particles ***Collision*** ***New particles***

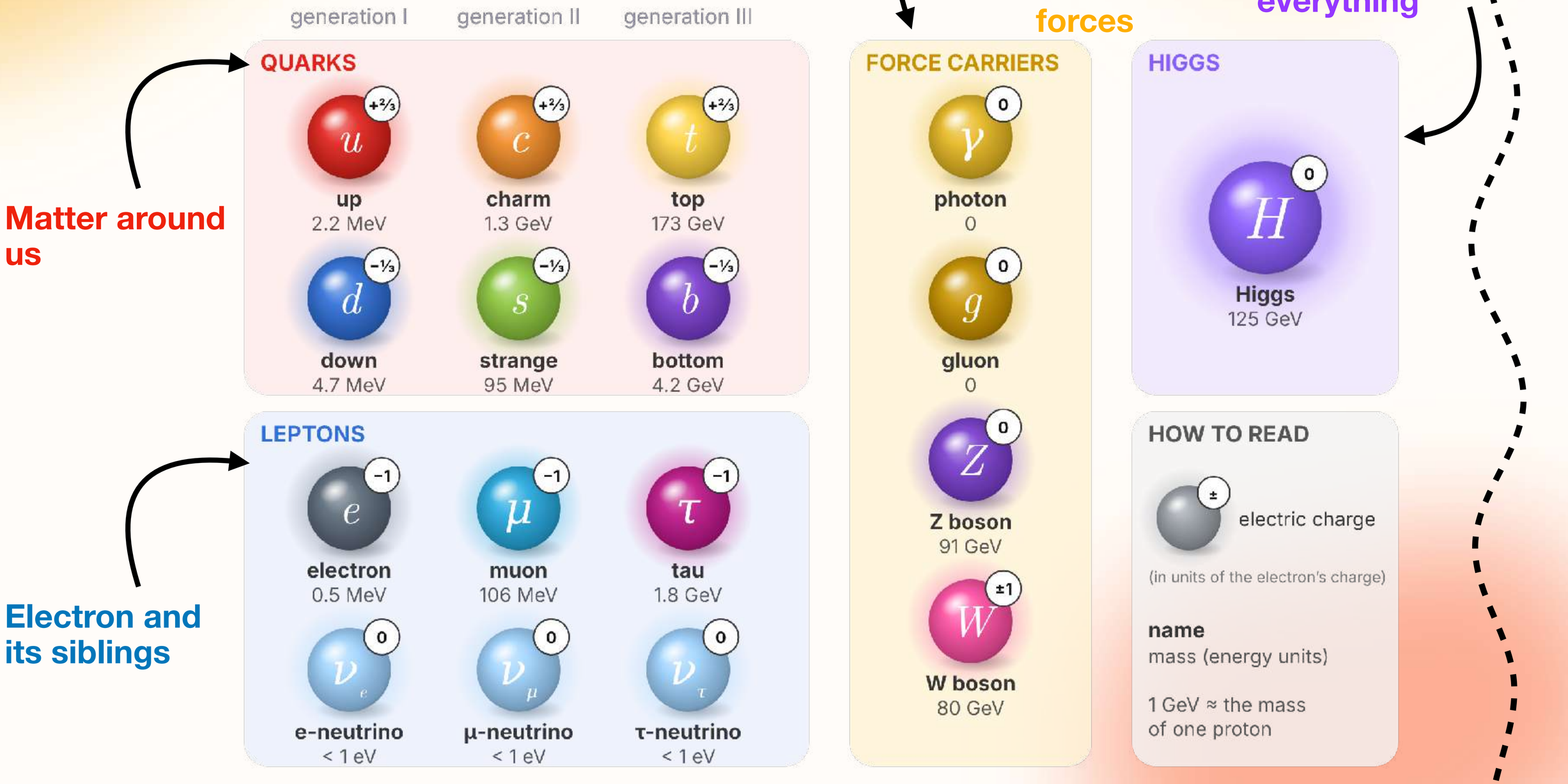


$$E = mc^2$$

energy *mass*

During a collision all of the energy is in one point.
It can turn into any particle, not only the ones we had at the start.

The Standard Model



Matter around us

Electron and its siblings

Four fundamental forces

"God" particle giving mass to everything

The Standard M



generation I generation I

QUARKS

+⅔ *u* **up** 2.2 MeV

+⅔ *c* **charm** 1.3 GeV

−⅓ *d* **down** 4.7 MeV

−⅓ *s* **strange** 95 MeV

LEPTONS

−1 *e* **electron** 0.5 MeV

−1 *μ* **muon** 106 MeV

0 ν_e **e-neutrino** < 1 eV

0 ν_μ **μ-neutrino** < 1 eV

τ-neutrino < 1 eV

HIGGS

0 *H*

HOW TO READ

± electric charge

(in units of the electron's charge)

name
mass (energy units)

1 GeV ≈ the mass of one proton

Matter around us

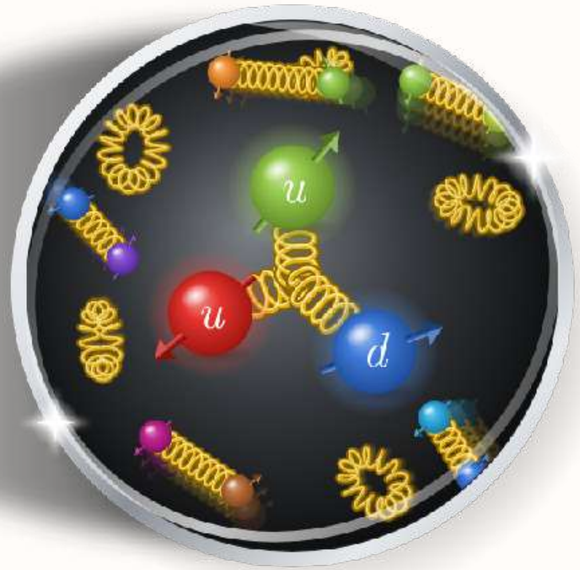
Electron and its siblings

"God" particle giving mass to everything

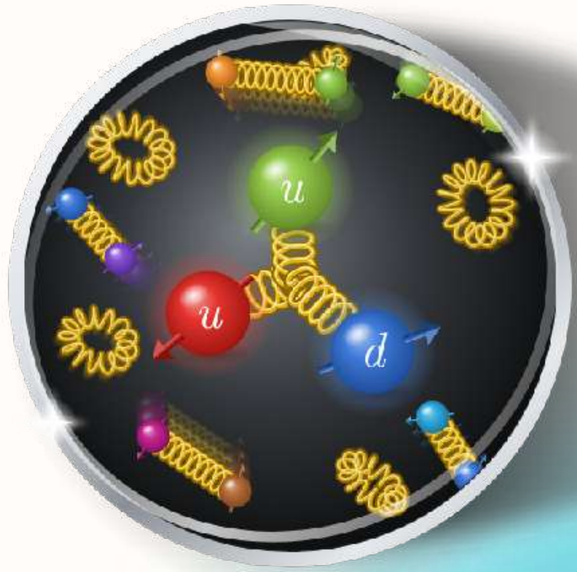
So popular — can even buy plush toys of your favorite particle!

2 Modern Colliders

Step by step of the collision, from the moment the collider turns on to the moment we learn something new



proton



proton

accelerate collide create fly out measure interpret

Large Hadron Collider (LHC)

at CERN, near Geneva

27 km around

100 m underground

2008 switched on



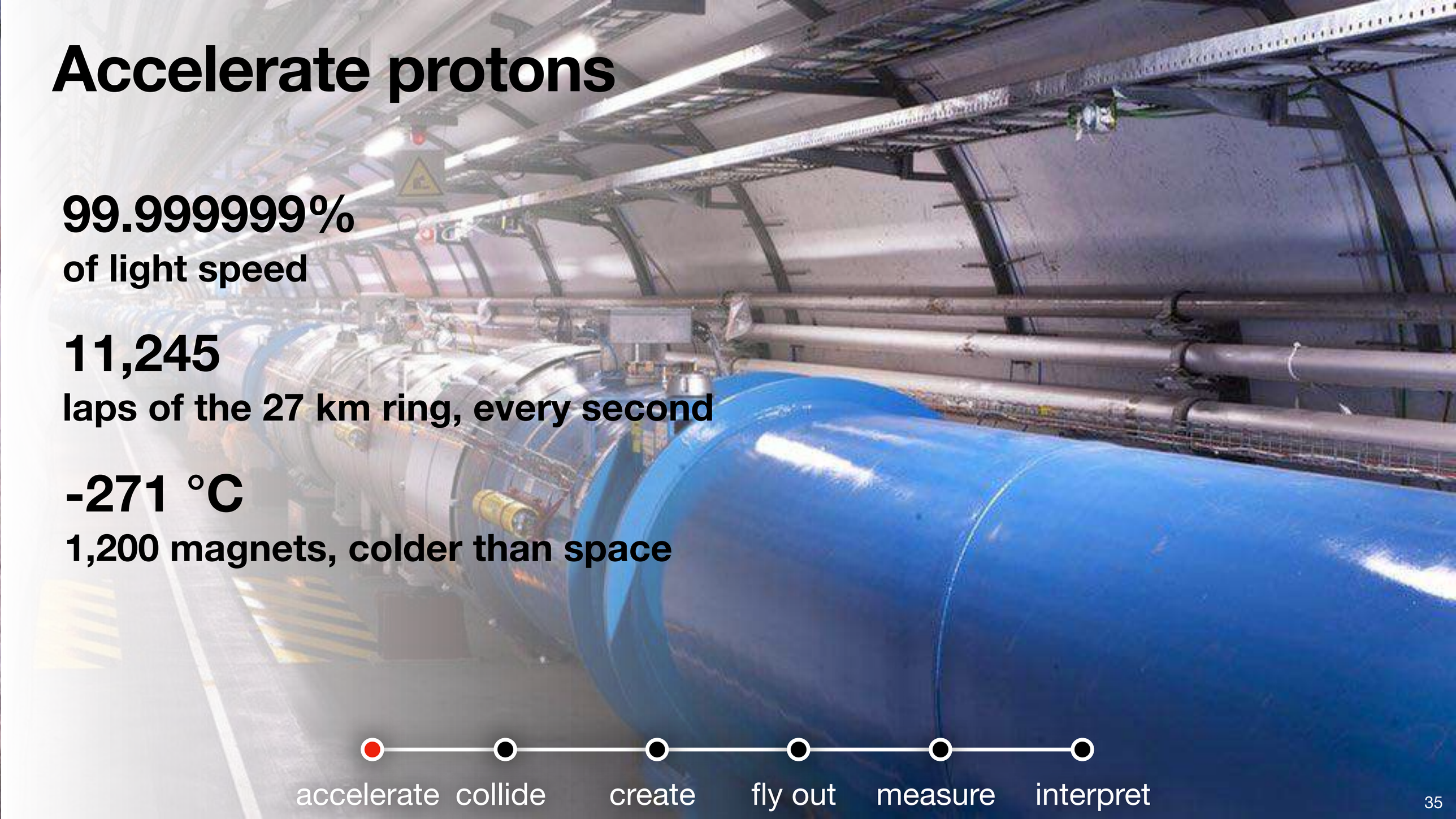
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Accelerate protons

99.999999%
of light speed

11,245
laps of the 27 km ring, every second

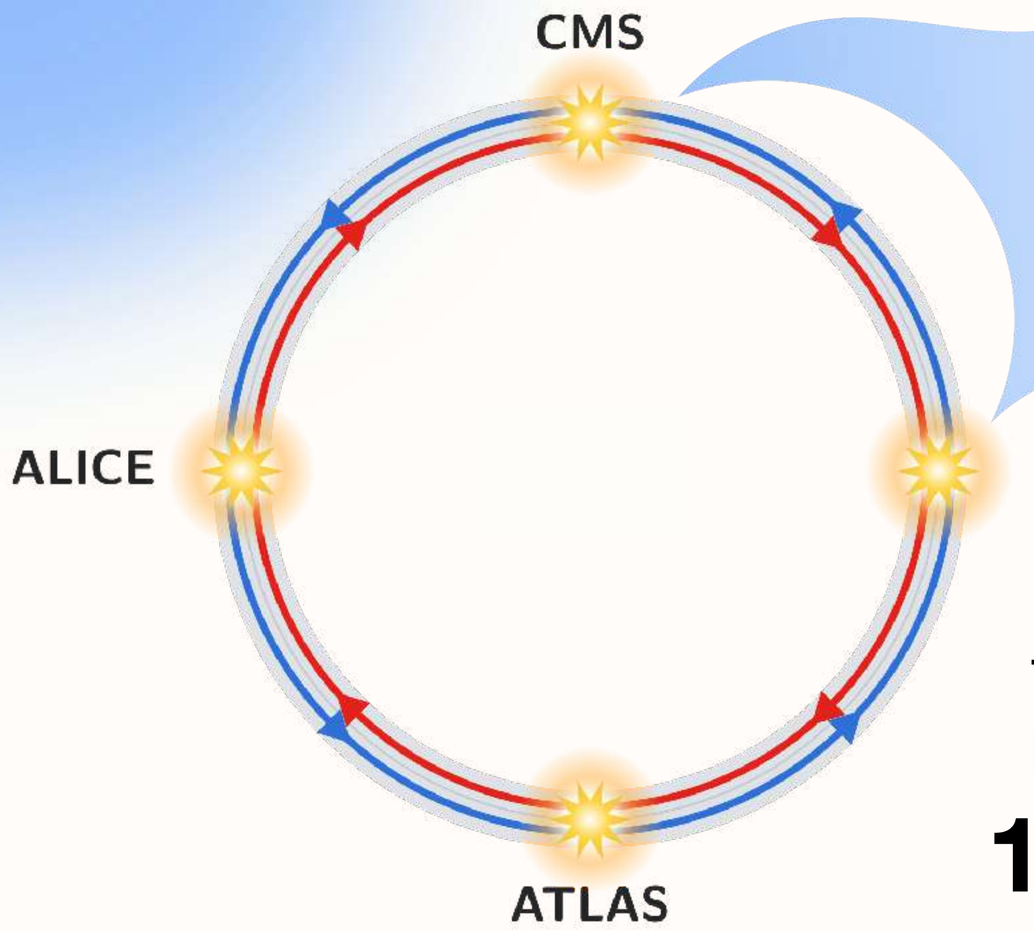
-271 °C
1,200 magnets, colder than space

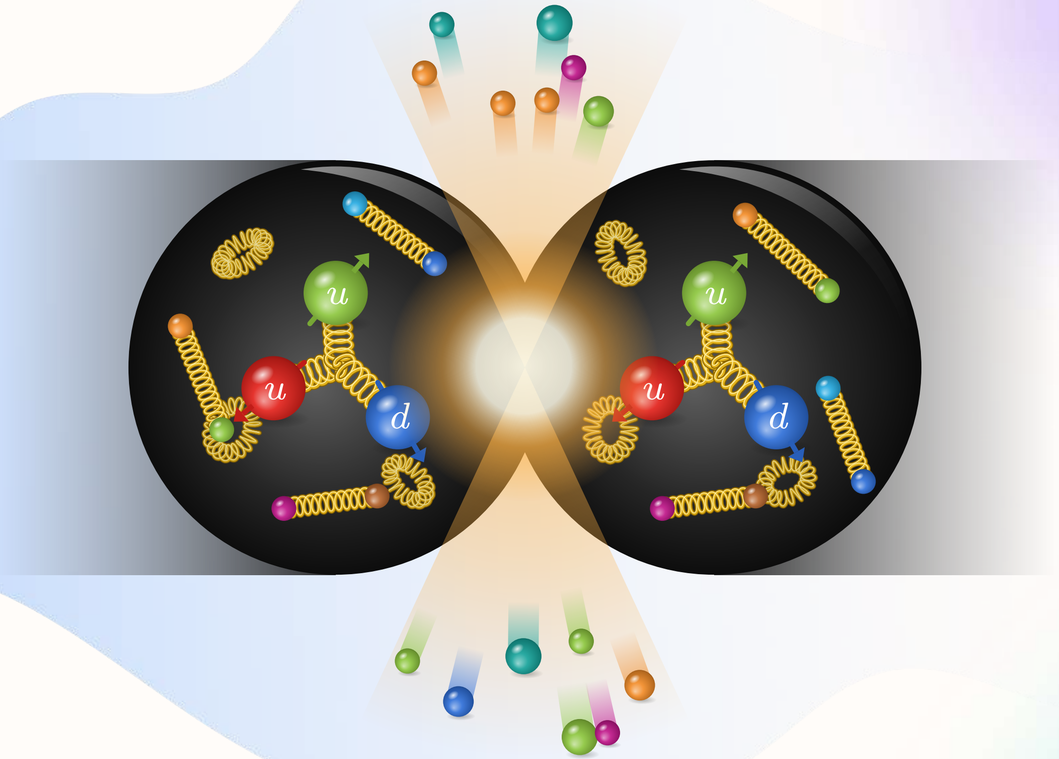


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Collide

Four crossing points at LHC.





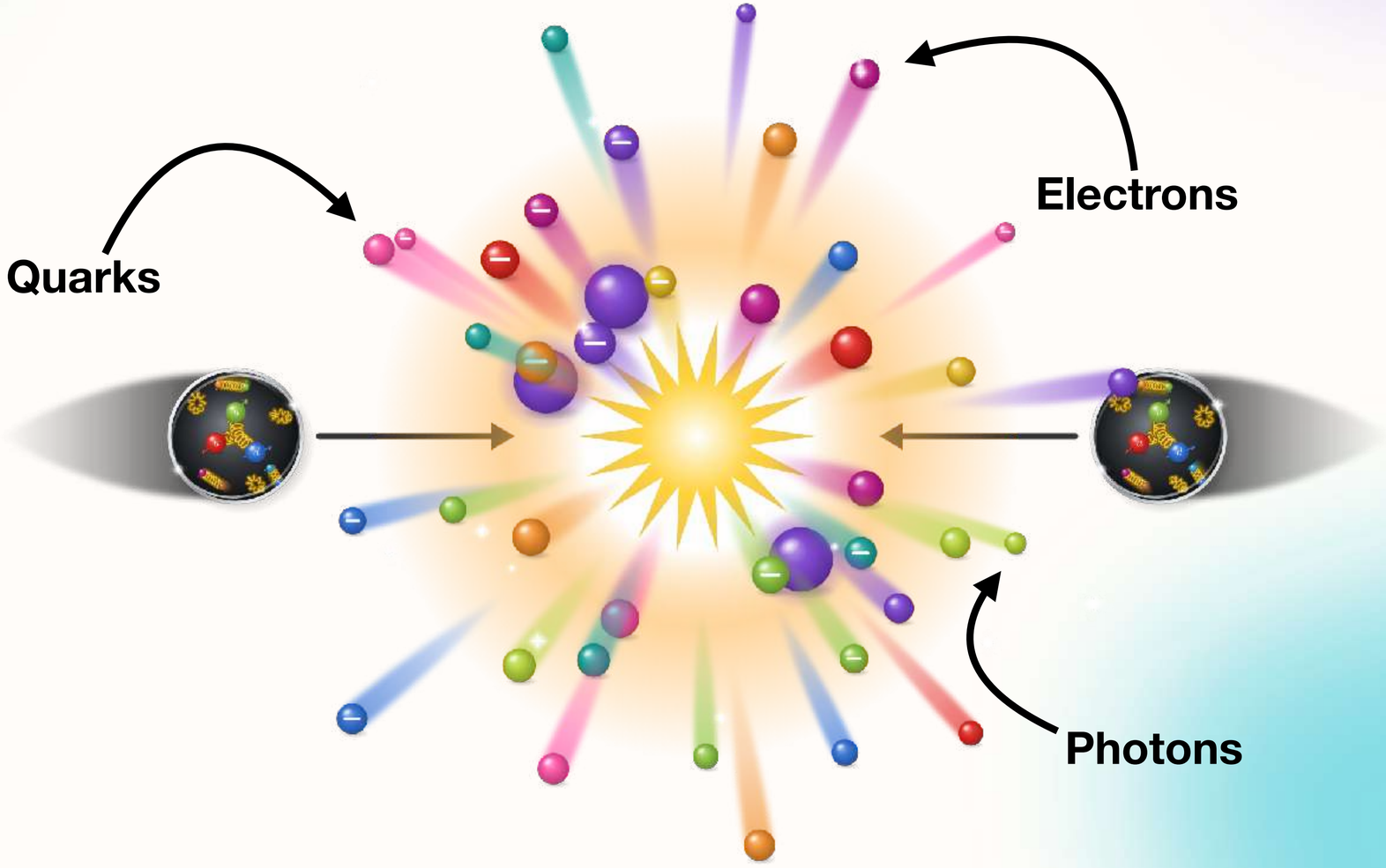
The beams are focused to a tine spot of the width of human hair at each crossing point producing

1 billion collisions per second

accelerate — collide — create — fly out — measure — interpret

Create

Collisions can produce many different particles

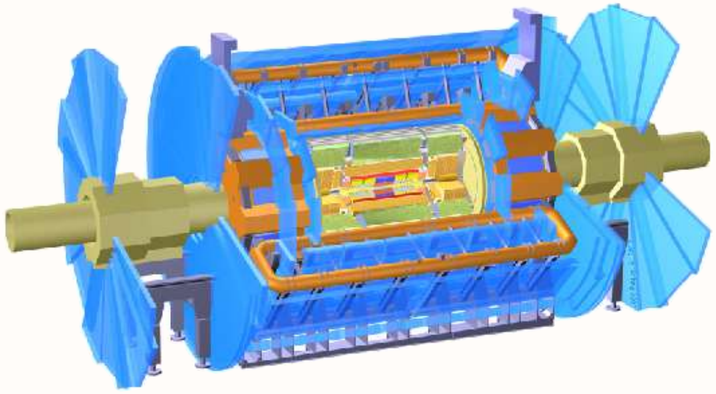


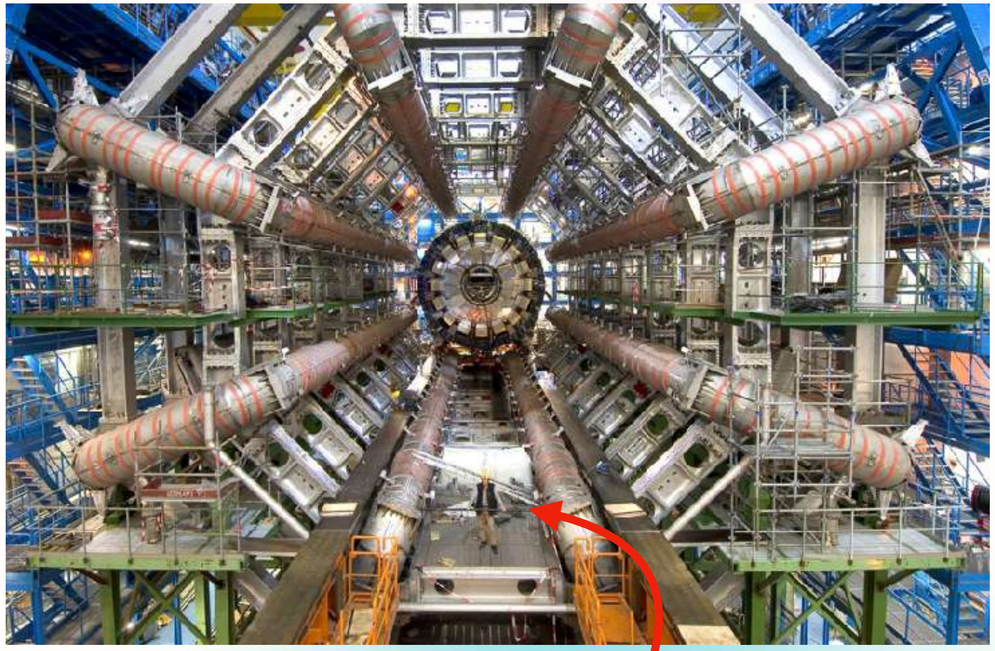
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Measure

ATLAS: a camera the size of a cathedral!







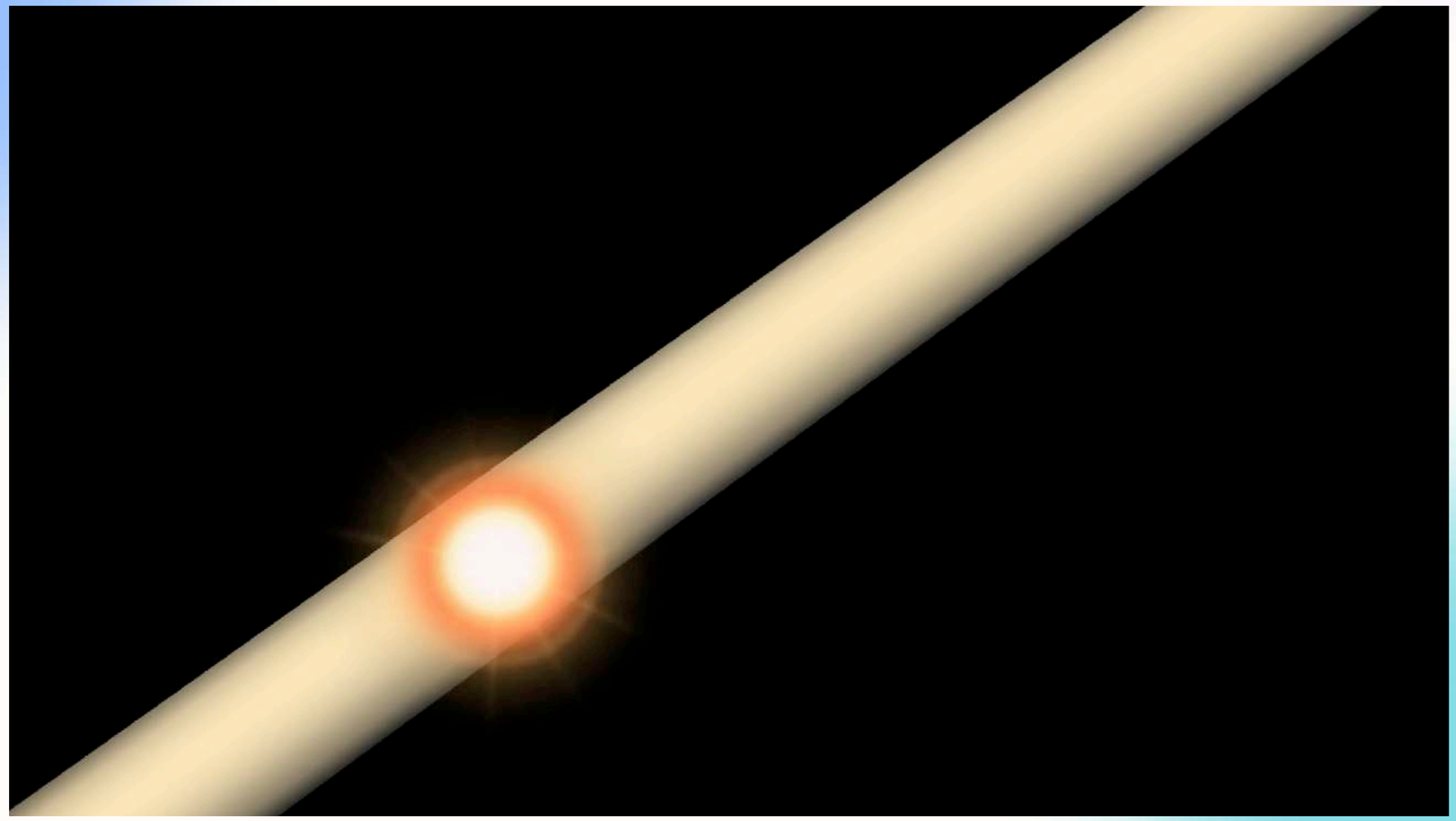
Person!



Notre-Dame — 69 m *ATLAS — 46 m x 25 m* *you — 1.7 m* *bus — 12 m*

accelerate collide create fly out measure interpret

Measure

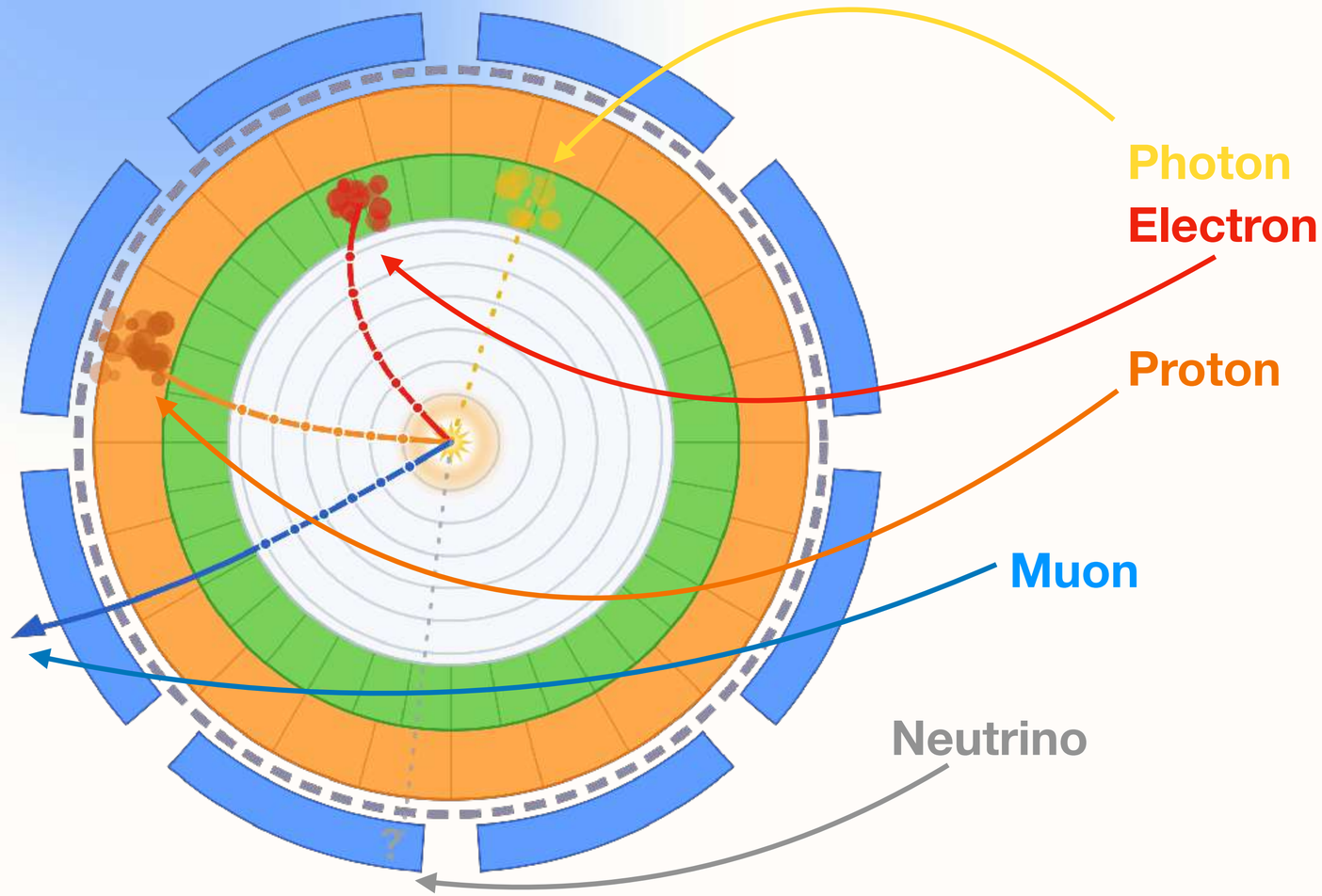


https://www.youtube.com/watch?v=NhXMXiXOWAA

accelerate collide create fly out measure interpret

Interpret

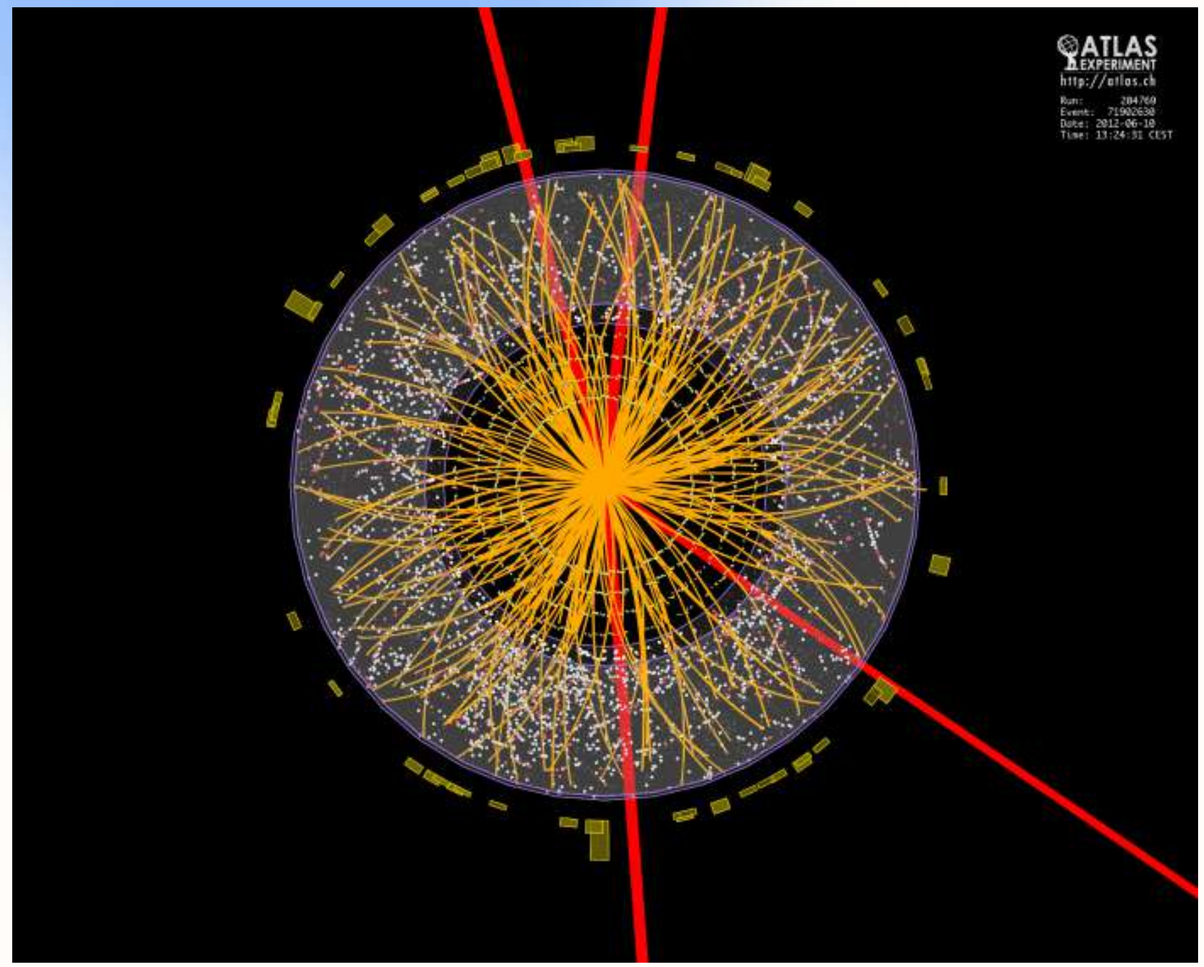
Every kind of particle leaves its own signature and we track it down to its origin



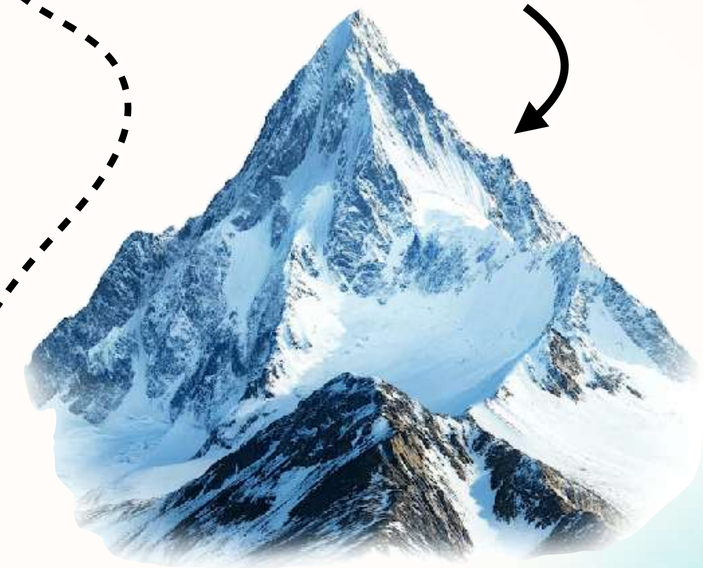
accelerate collide create fly out measure interpret

Interpret

Every kind of particle leaves its own signature and we track it down to its origin



Mount Everest — 8.8 km



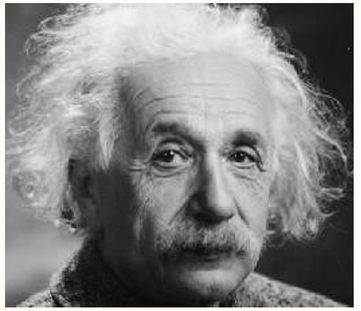


One year of LHC data
6 million DVDs — 7.7 km

accelerate collide create fly out measure interpret

3 My job is to interpret

I am a theorist.

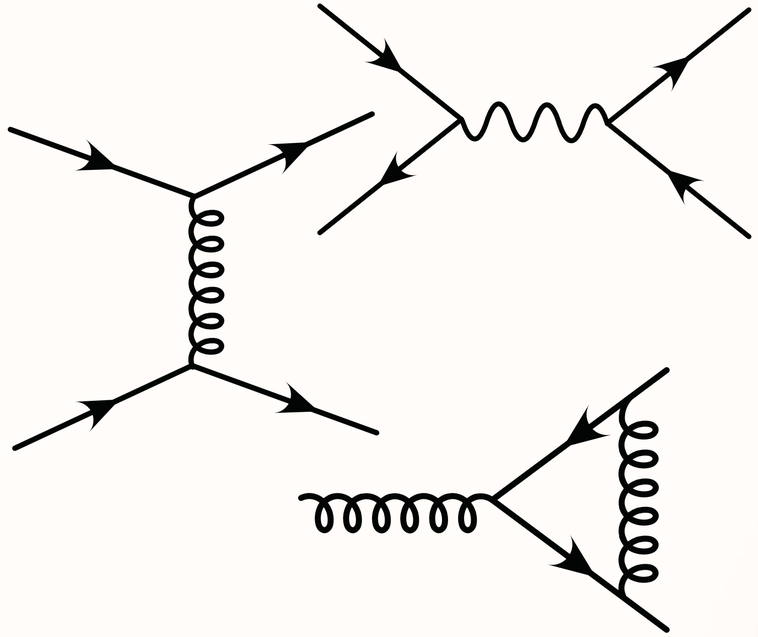


I write equations and use them to predict what the detector should see

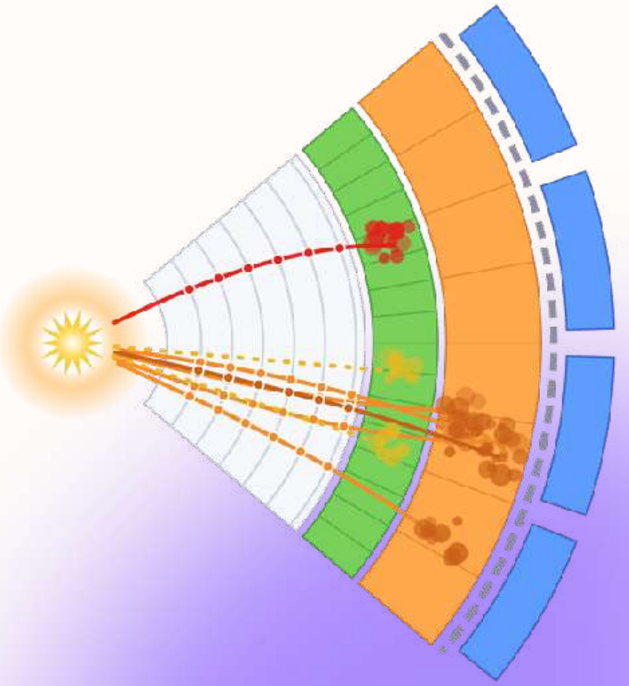
Theory

$$\mathcal{L}_{SM} = -\tfrac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$+\ \bar{Q}\,i\gamma^\mu D_\mu Q + \bar{L}\,i\gamma^\mu D_\mu L$$
$$+\ (D_\mu H)^\dagger (D^\mu H) - V(H)$$
$$-\ (\bar{Q}\,Y_u\,\tilde{H}\,u + \bar{Q}\,Y_d\,H\,d$$
$$+\ \bar{L}\,Y_e\,H\,e + \text{h. c.}\,)$$

Calculate processes



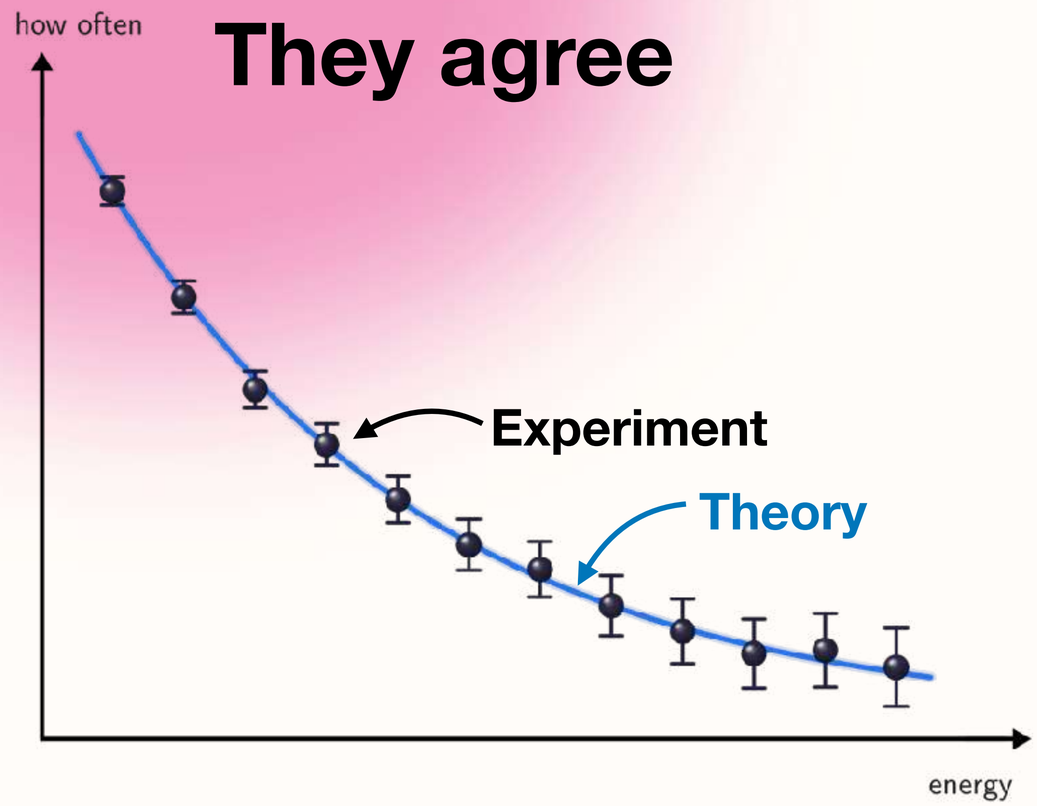
Predict detector results



accelerate — collide — create — fly out — measure — interpret

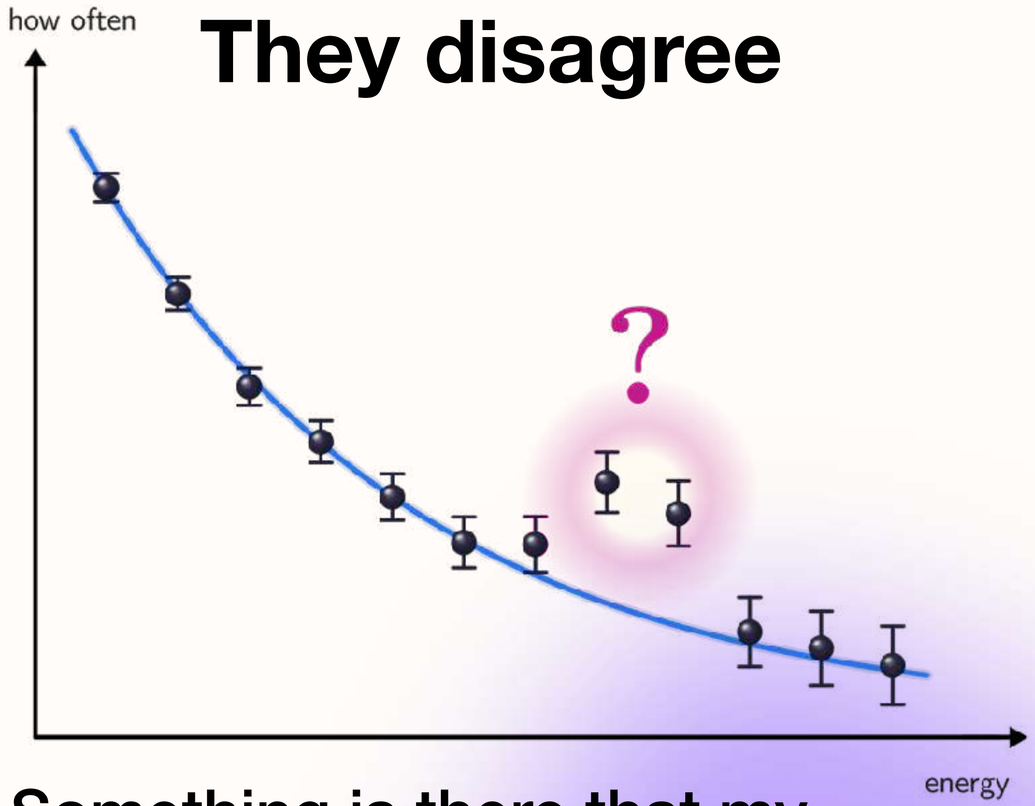
When predictions and experiment disagree

They agree



The Standard Model wins again.
Useful but boring.

They disagree



Something is there that my equations don't know about!
That is physics beyond the Standard Model.

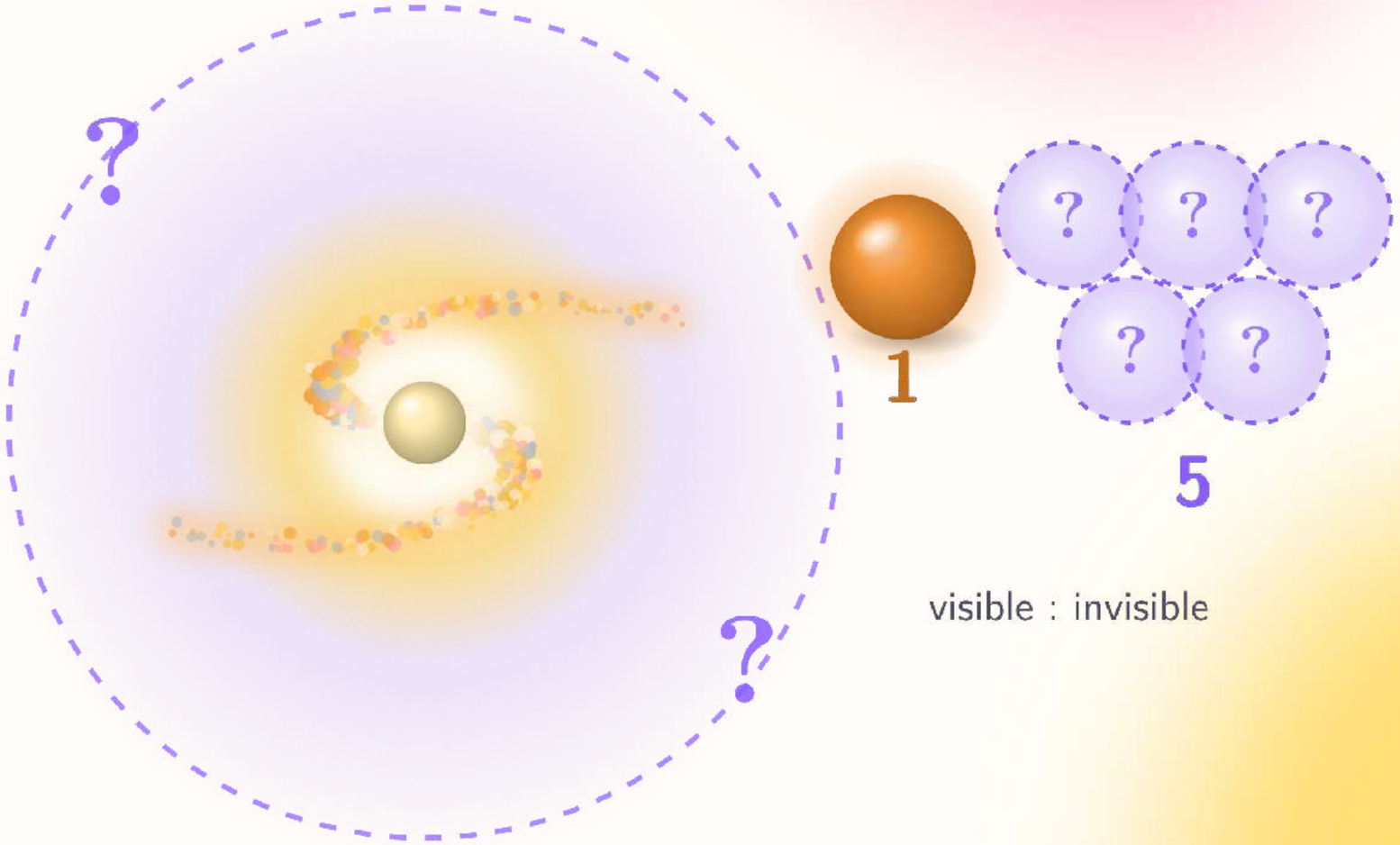
4 Open questions in particle physics

What is dark matter?

Galaxies spin too fast

The stars we see can not hold them together.

Something invisible supplies five times more gravity.



27% of the universe is dark matter, 5% is Standard Model

Open questions in particle physics

Why can’t quarks escape?



$1,000,000 Clay Millennium Prize

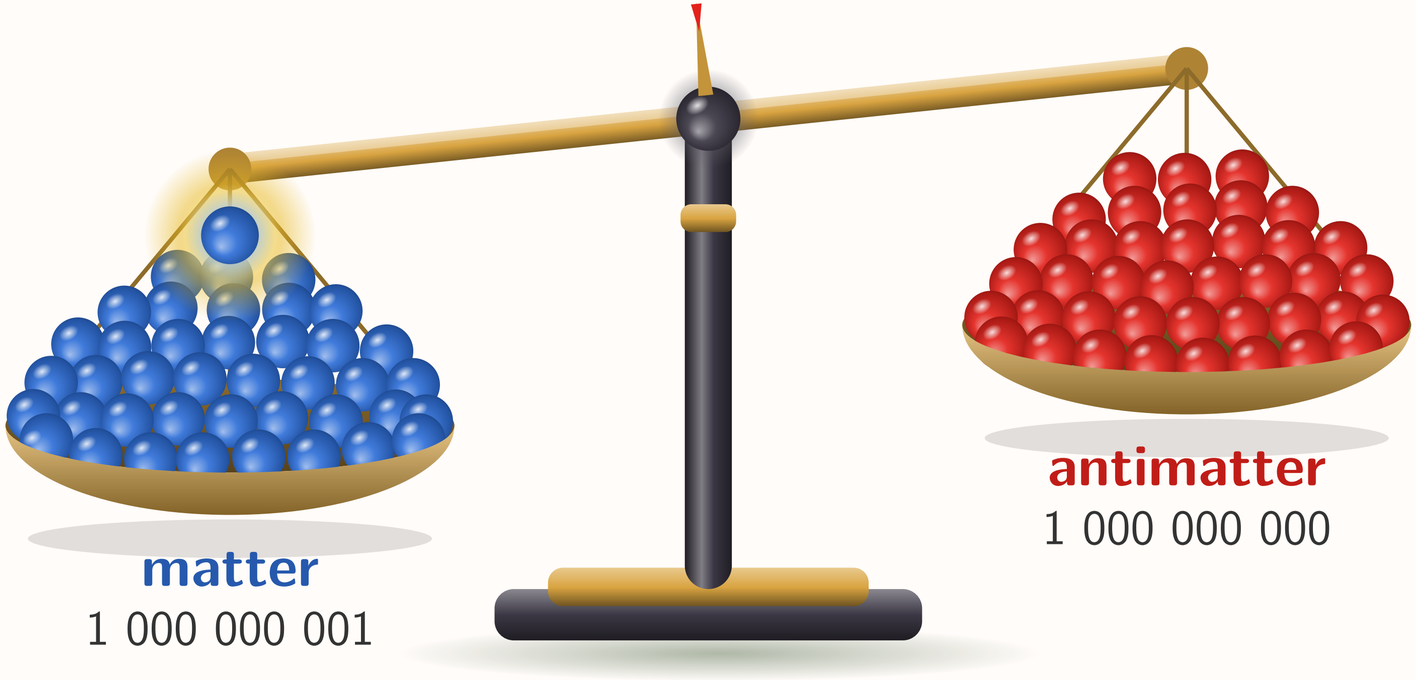
Prove it from the equations

Open questions in particle physics

Why is there anything at all?

The Big Bang should have made equal amounts of matter and antimatter.

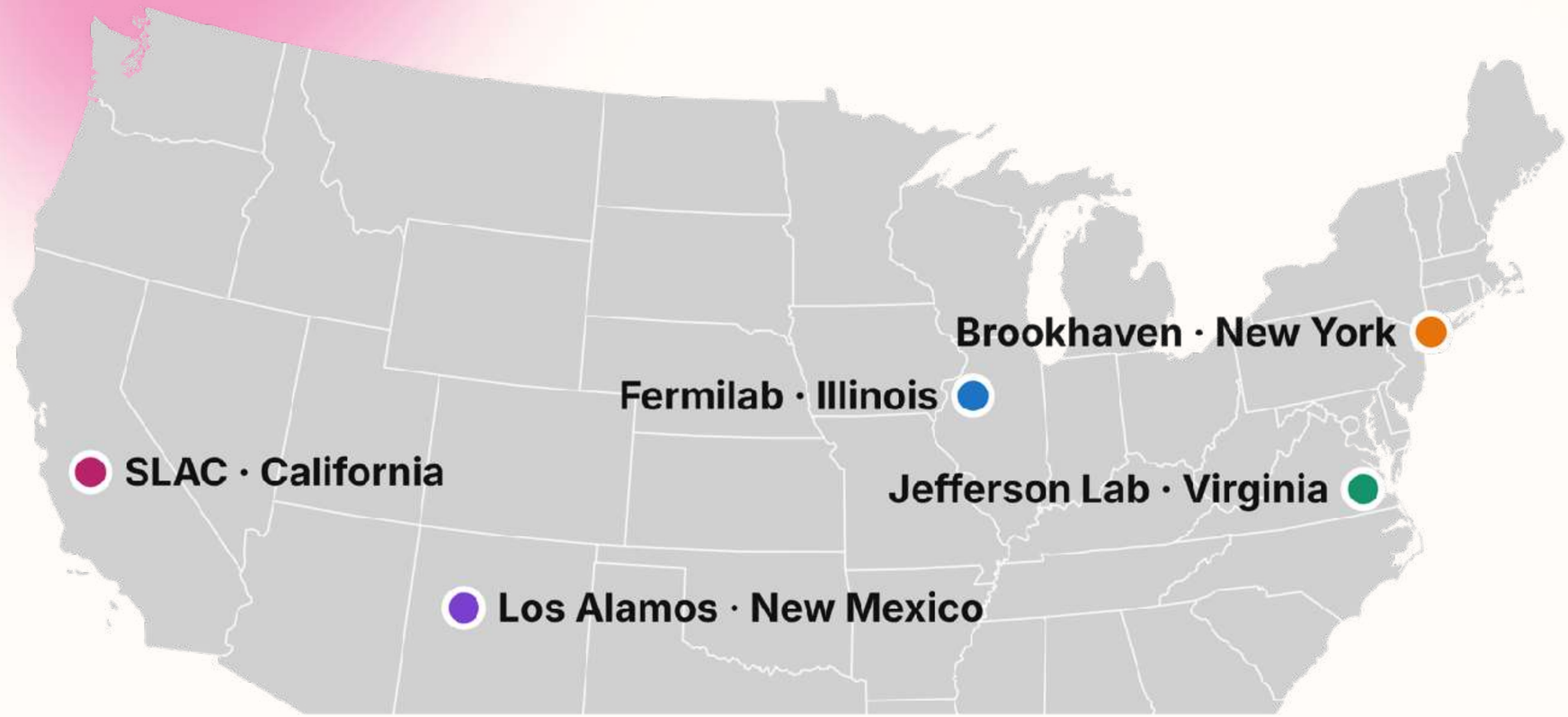
1 in a billion survived: every atom in the universe, including you.



The Standard Model does not allow the imbalance

Next machines

America's accelerator laboratories





Fermilab



Brookhaven

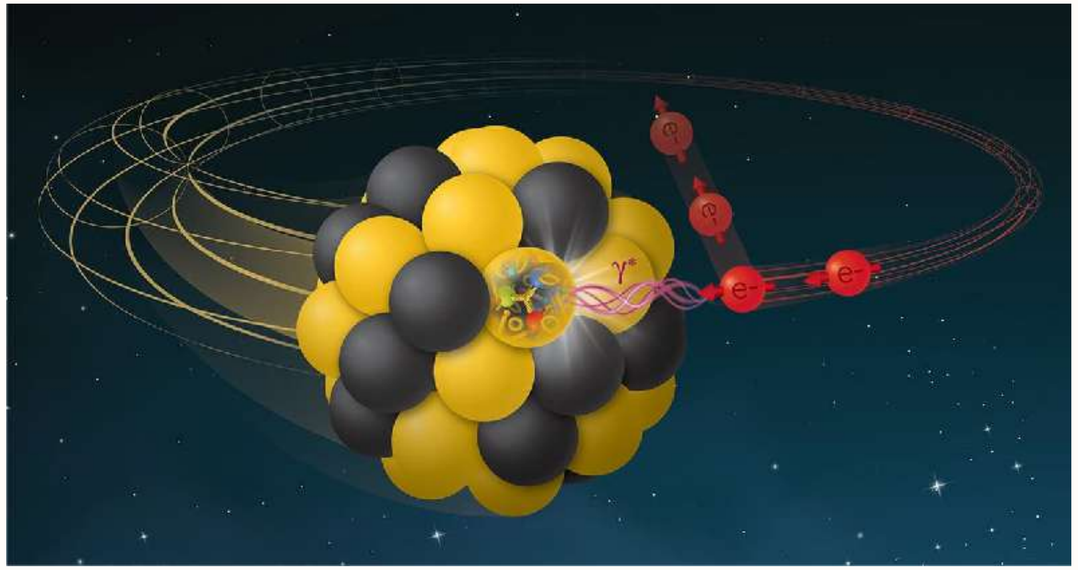


Jefferson Lab

The Electron-Ion Collider

Brookhaven, Long Island — under construction — first collisions early 2030s



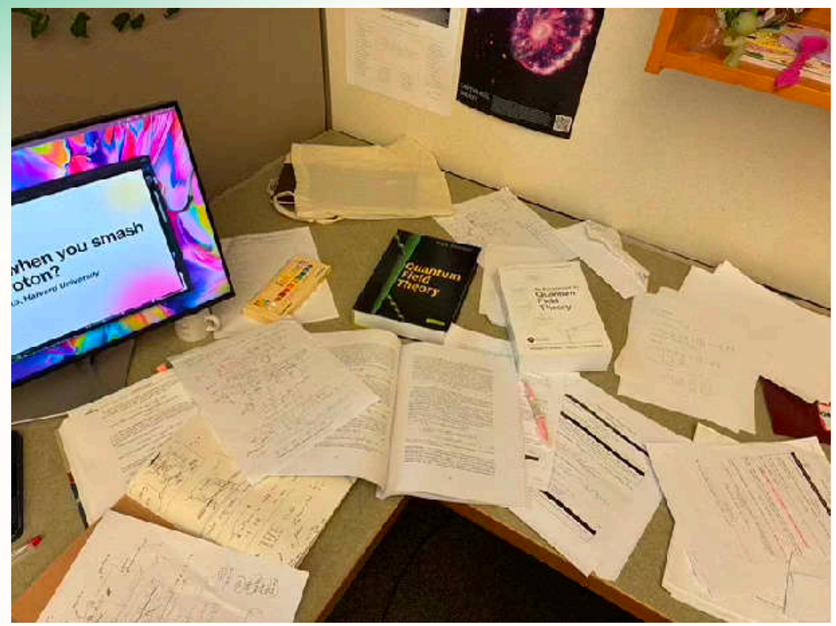


Electrons on protons

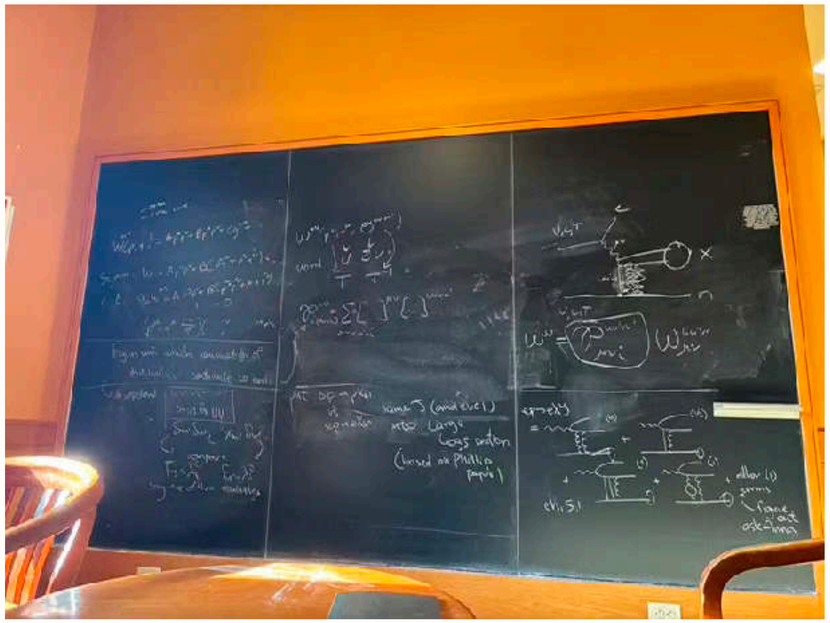
- $2.8 billion
- 1,500 scientists from 40 countries
- The first 3D images of the inside a proton

A day in my life as a particle physicist

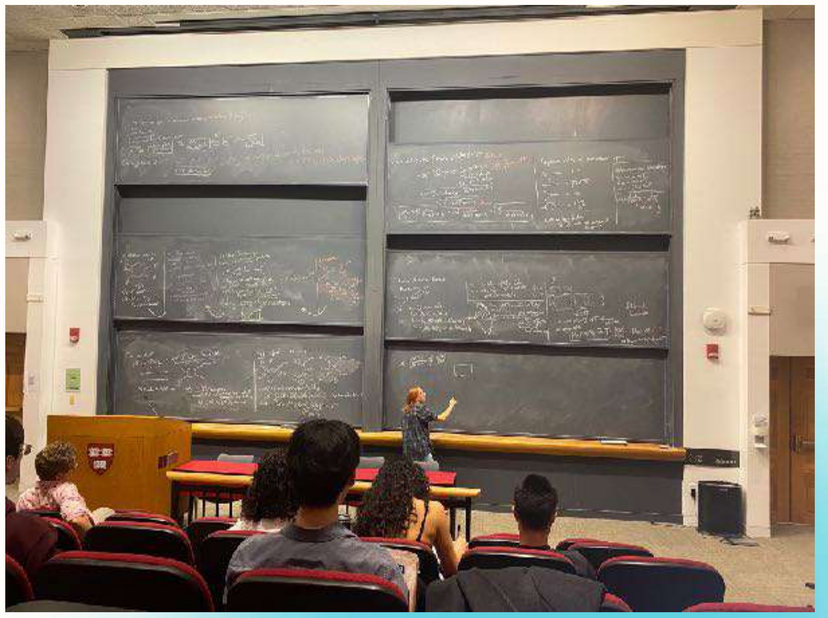
Morning — **Noon** — **Afternoon**



Coffee, prepare the section I am teaching: quantum field theory.



Research project meeting



Teach my section, then return to research

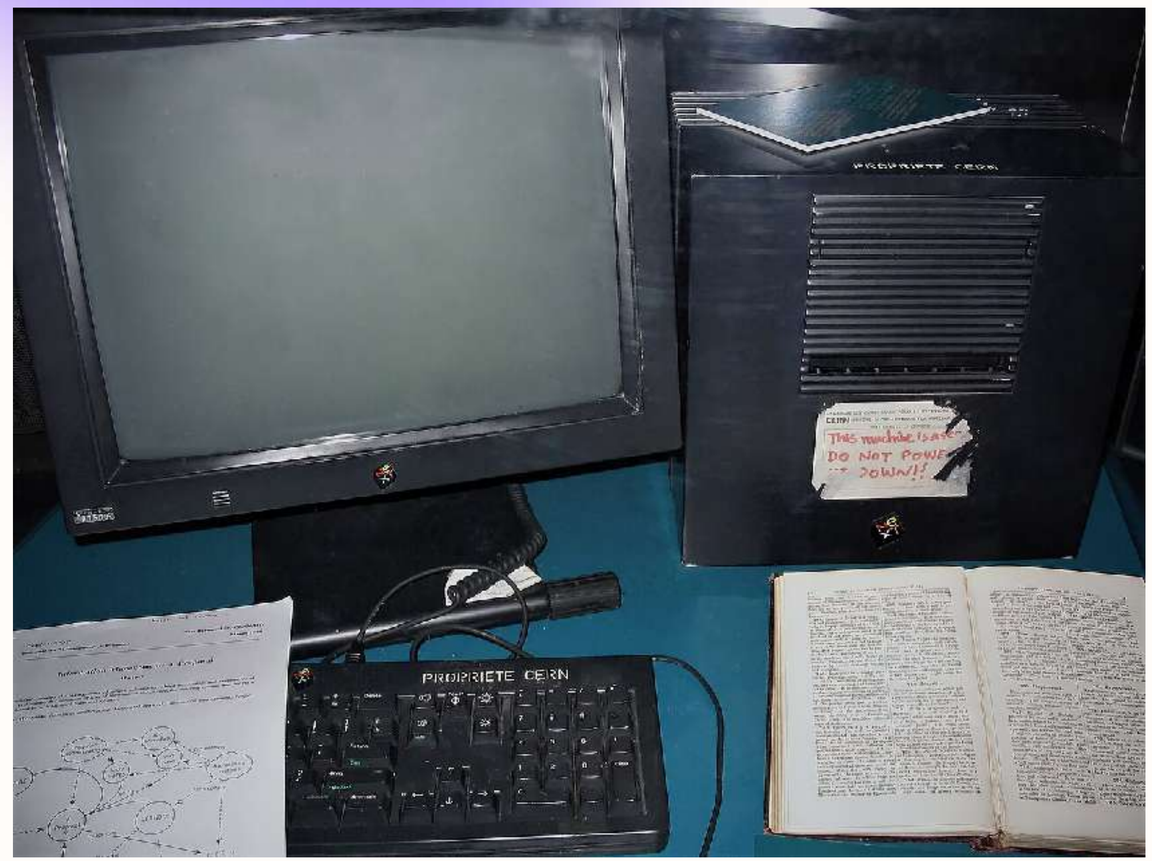
Evening: relax (sometimes work)

Where physics has taken me so far



5 Why do we care?

The World Wide Web was invented as CERN



The sticker on the computer reads: "This machine is a server. DO NOT POWER IT DOWN!!"

1989 A CERN physicist proposes a system for sharing information among scientists

1993 CERN releases the Web to the public domain

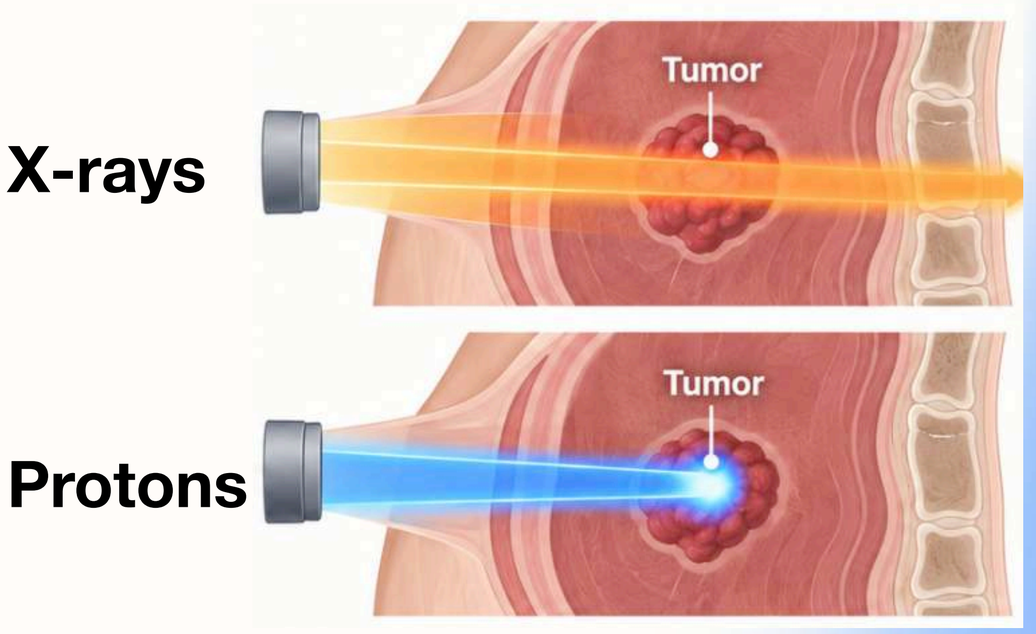
Today Billions of people use the Web

Why do we care?

Proton therapy: the accelerator as a scalpel



Harvard Cyclotron Laboratory



Protons deposit most of their energy at a chosen depth, limiting dose beyond the tumor

300,000

patients treated worldwide

Why do we care?

MRI: the magnets came from particle physics



An MRI scanner needs a magnetic field 30,000 times Earth's.

Magnets like that were developed in the 1960s and 70s for accelerators at Fermilab and CERN.

Why do we care?

Muons from space found a hidden room in the Great Pyramid



Protons from space hit the atmosphere and make muons. They go through metres of stone and accumulate in the pyramid voids.

2017

ScanPyramids finds a 30 m void above the Grand Gallery, the first new room in 200 years

Thank you!

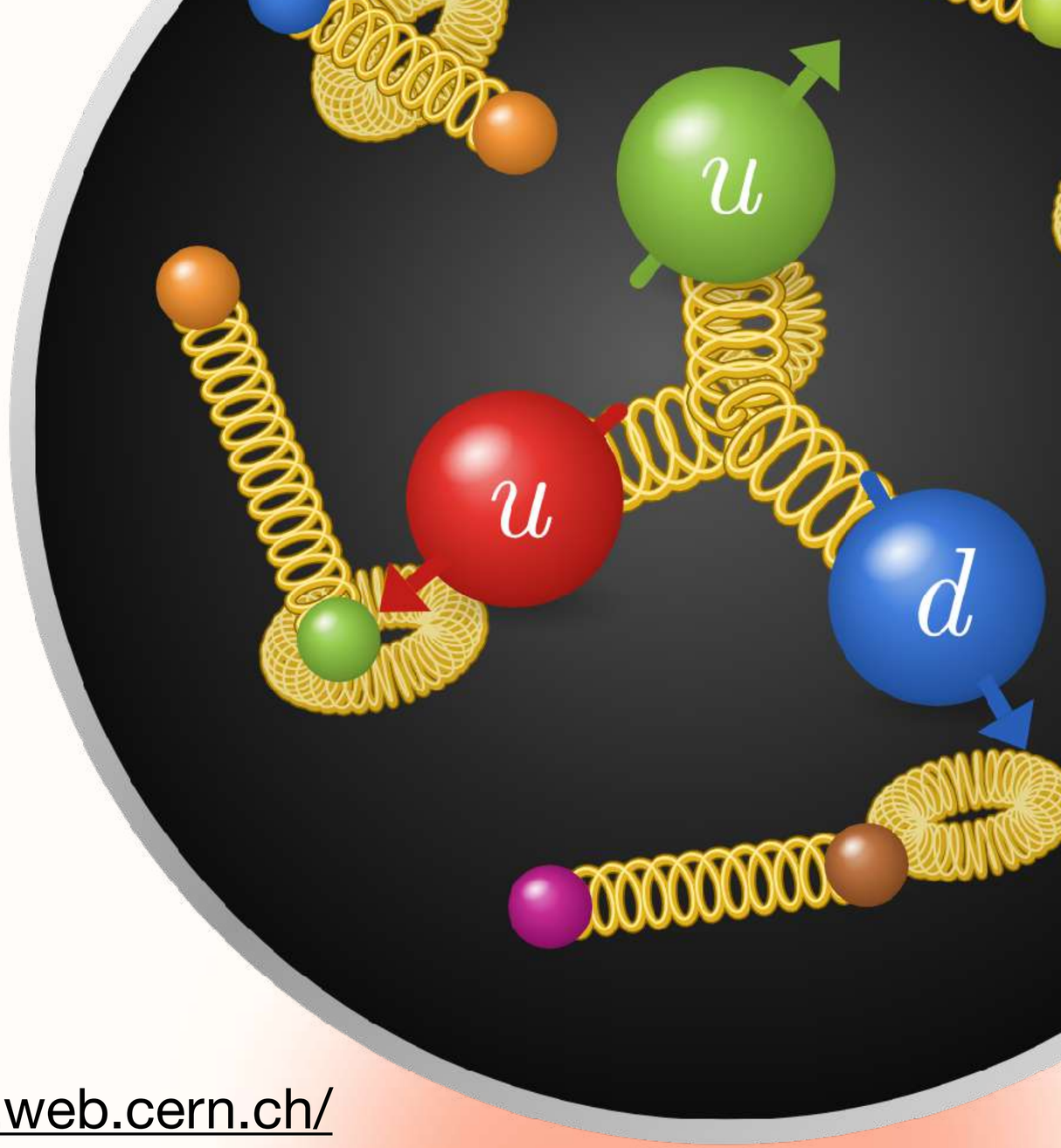
Let’s talk!

What surprised you most?

Which particle are you?

CERN's 2-minute quiz:

https://resources-particle-identities-game.web.cern.ch/



Reach out to me: dtrotsenko@g.harvard.edu