

Deciphering the secret code of Nature: From the Higgs particle to gravity waves

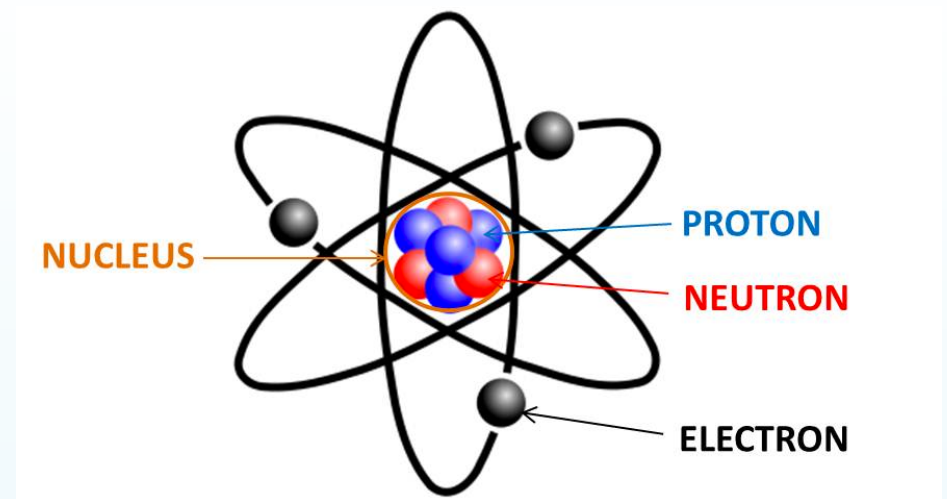
Juan Rojo

VU Amsterdam & Theory group, Nikhef

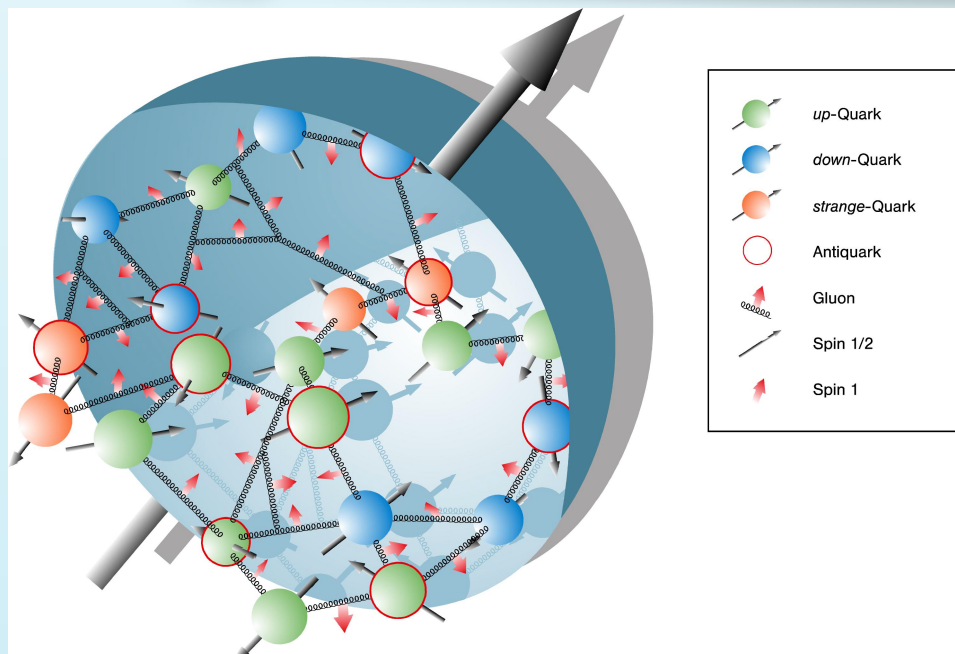
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Visit to Nikhef of the Rotterdam International Secondary School (RISS)

Nikhef, Amsterdam, 15/02/2018



Deep into the mysteries of matter



Juan Rojo

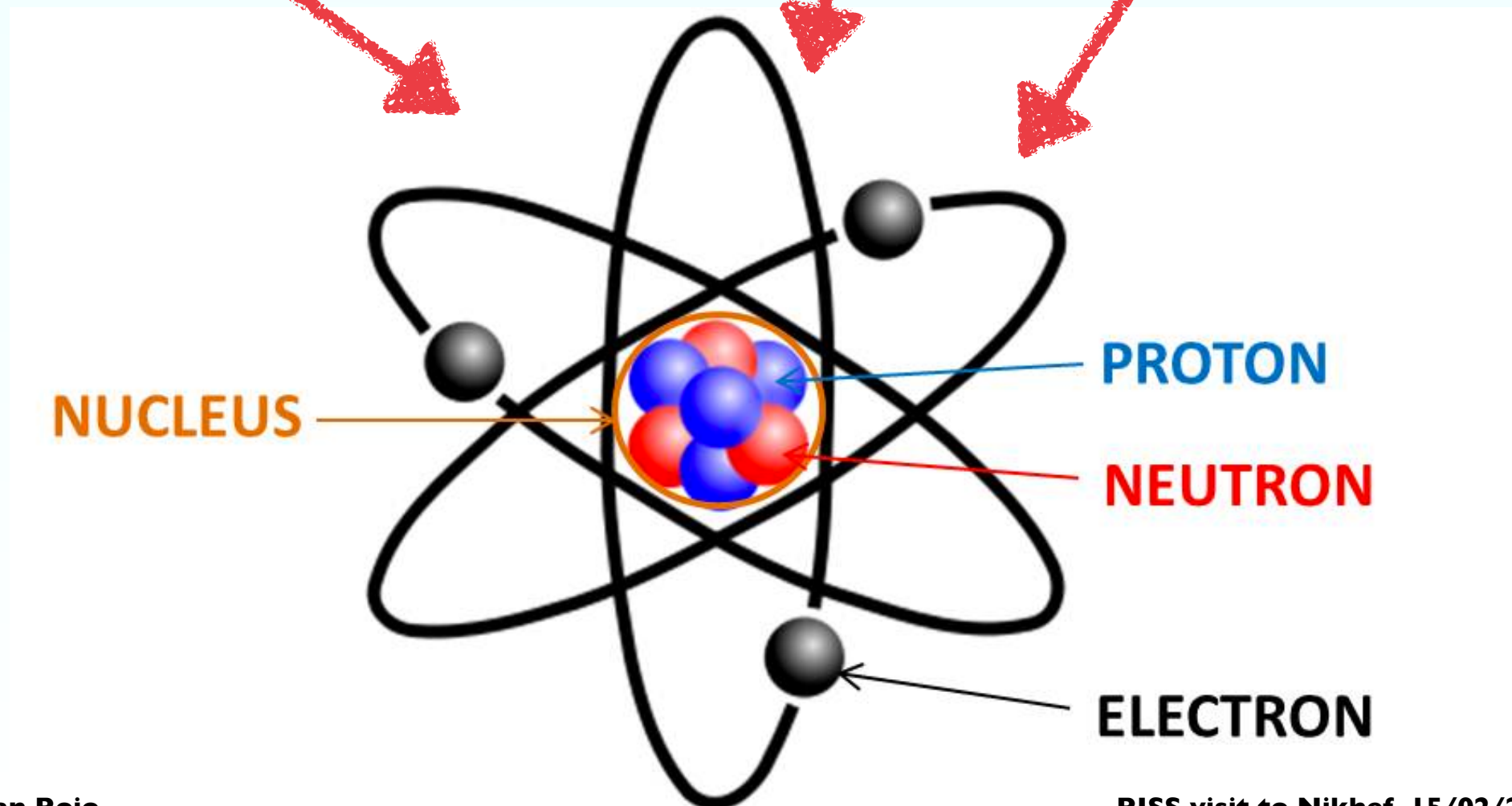
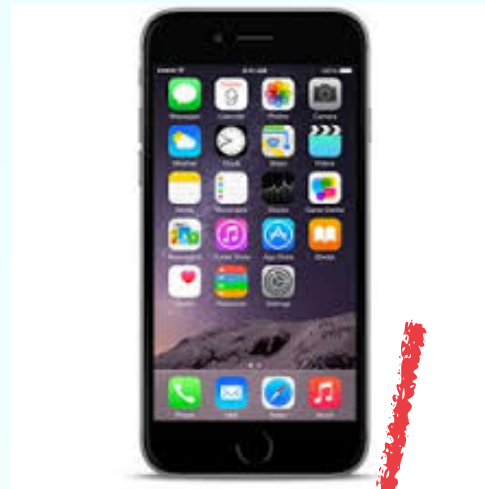
The Stuff of Matter

- ☑ A **table**, a **cell phone** and a **squirrel** look very different ... but ultimately, they are composed by the **same kind of building blocks**: we call them **atoms**



The Stuff of Matter

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How small are atoms?



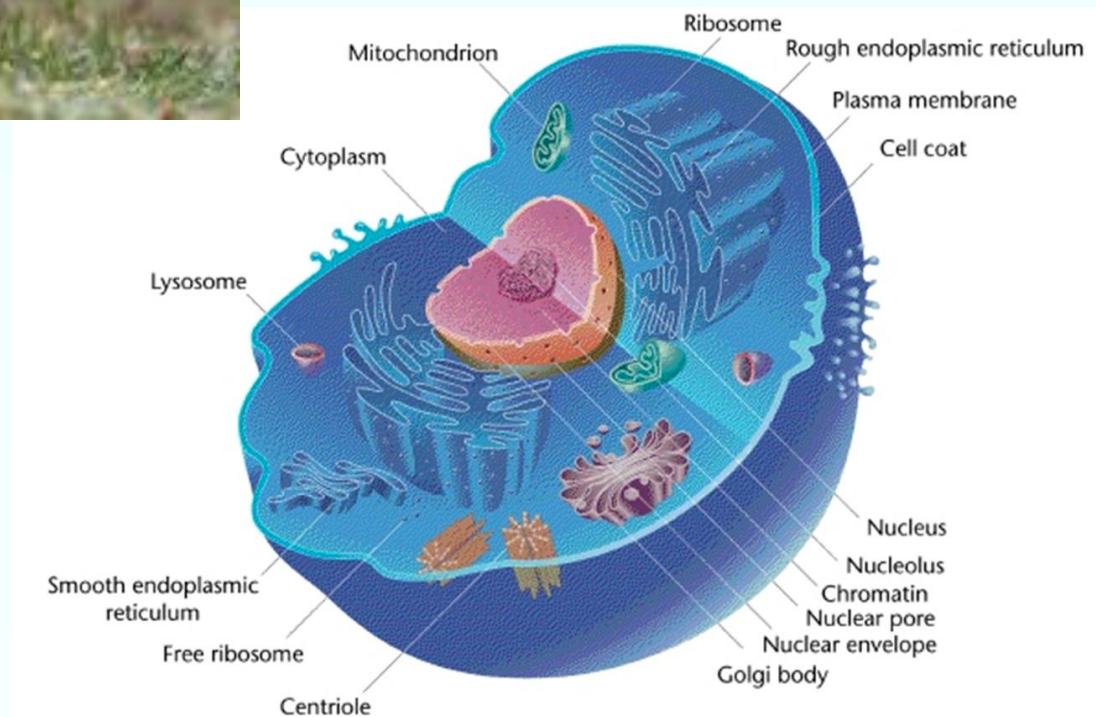
A squirrel has a length of **10 centimeters**

How small are atoms?



A squirrel has a length of **10 centimeters**

All animals are composed by **cells**, of size **10 micrometers: 10000 times smaller**

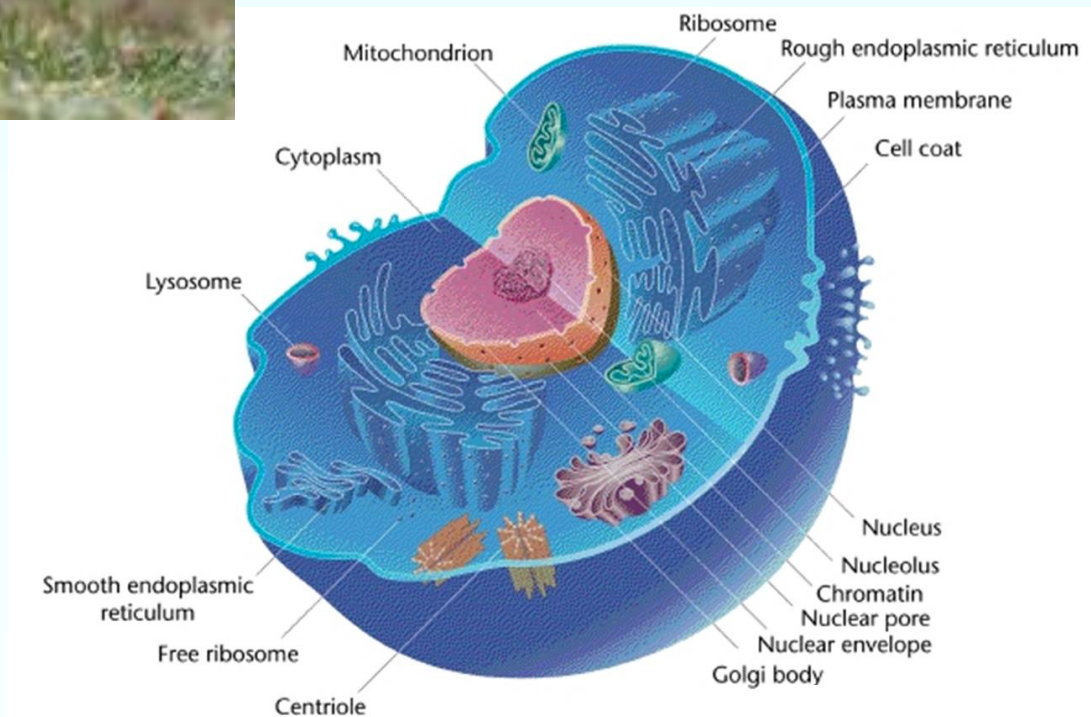


How small are atoms?

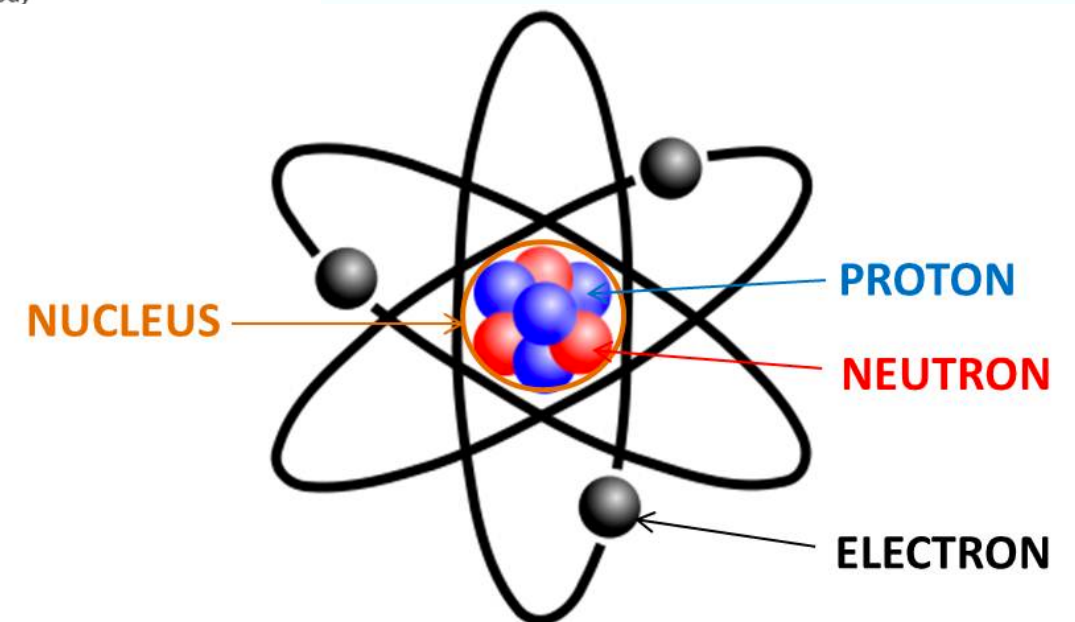


A squirrel has a length of **10 centimeters**

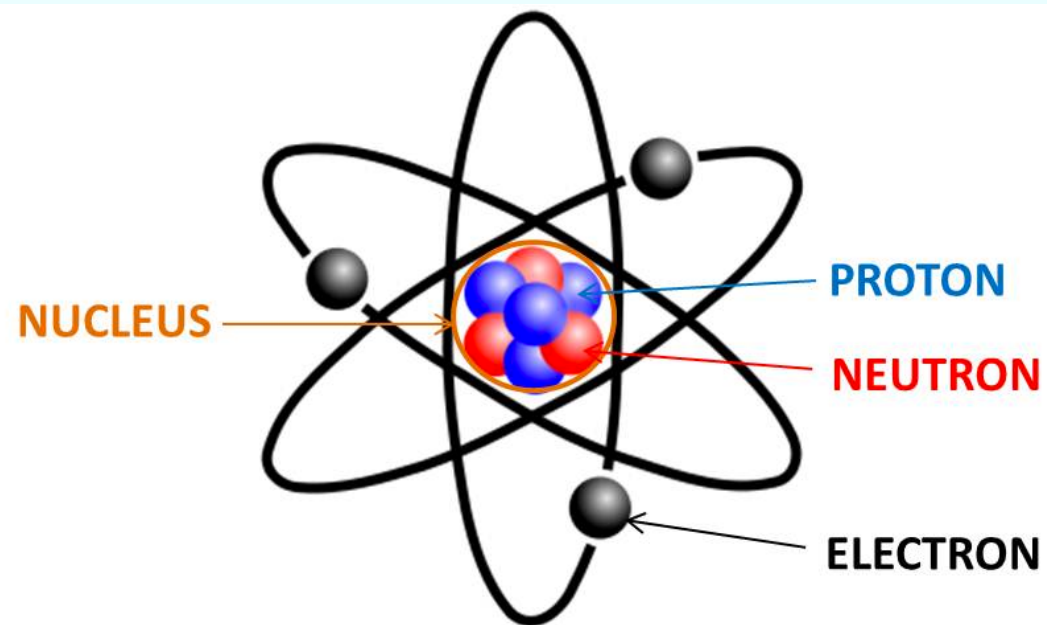
All animals are composed by **cells**, of size **10 micrometers: 10000 times smaller**



The size of an atom is **0.1 nanometers, 1000 million times smaller!** Atoms are very small!



From atoms to protons to quarks

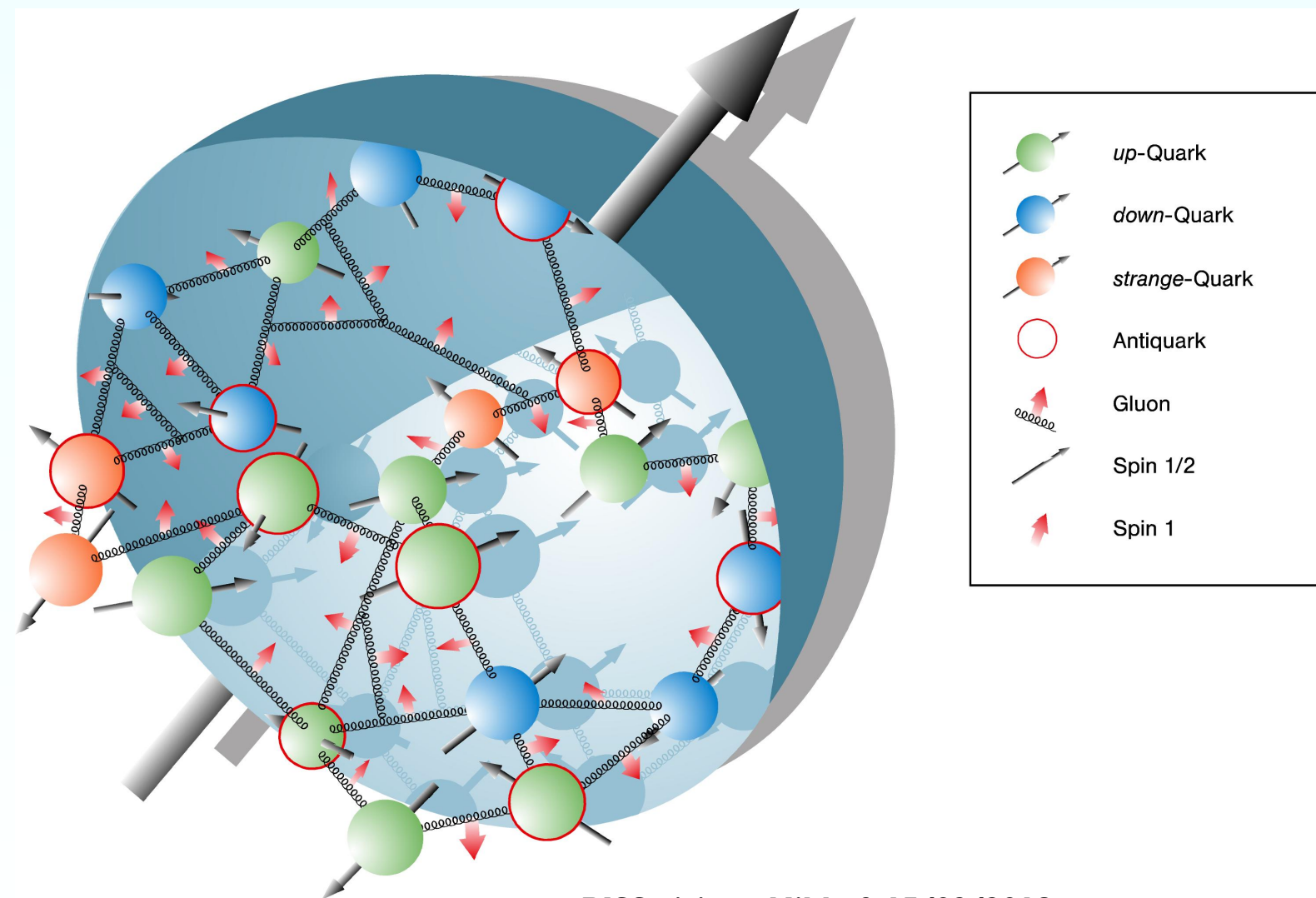


Atoms themselves have even smaller constituents: **protons, neutrons and electrons**

Protons are 10000 times smaller than atoms!

Even the tiny protons have **smaller constituents**: we call them **quarks and gluons**

Are there **more, even smaller, particles** that we can find? We need to **build gigantic experiments** to answer this!

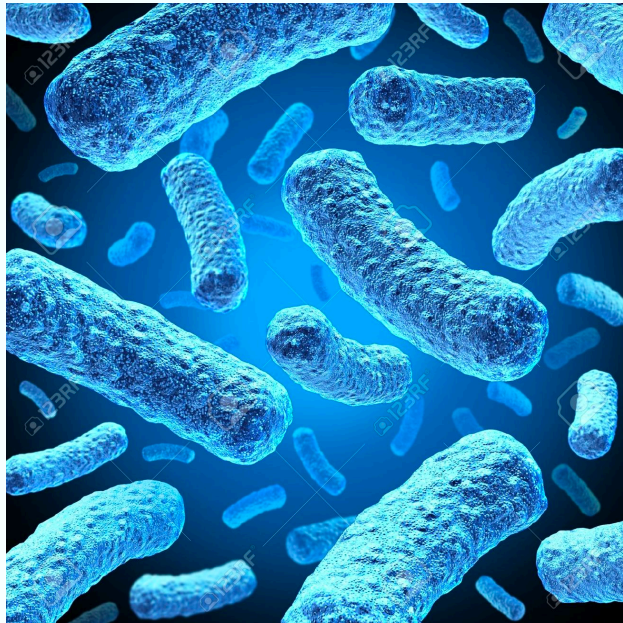


From galaxies to quarks

To grasp the immensity and smallness of the length scales involved, it is useful to work with orders of magnitudes and exponential notation

$$L \approx 10^M \text{ meters}$$

bacterium $L = 0.00001$ meters



bacterium $M = -5$

Lamborghini $L = 3$ meters



Lamborghini $M = 0$

The size of a bacterium is smaller by 5 orders of magnitude as compared a typical car

Ourselves, a table and a car all have lengths of the same order of magnitude

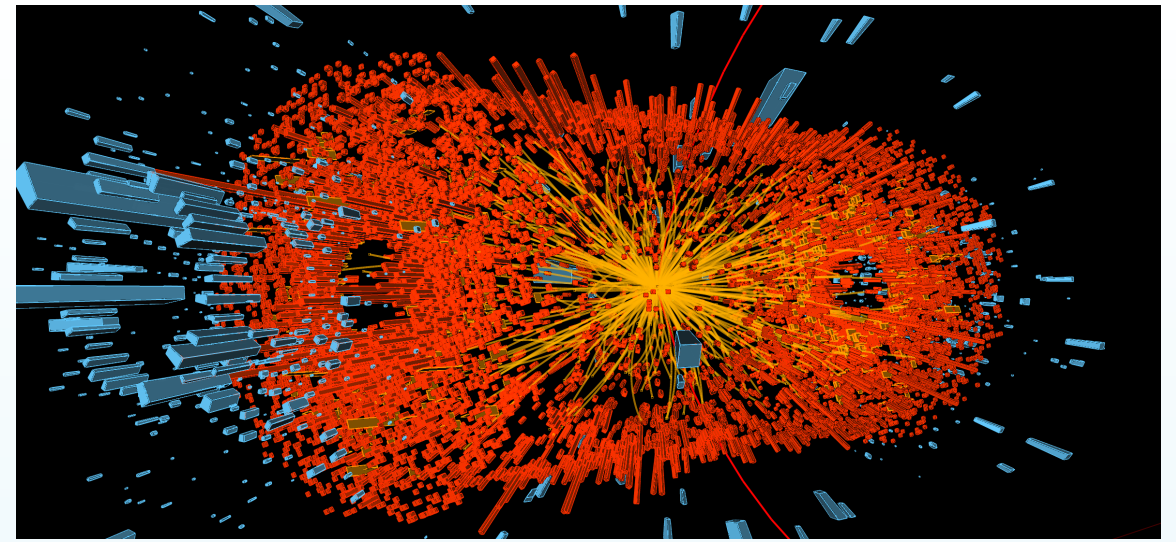
Structure within the Atom

The diagram illustrates the hierarchical structure of an atom, showing the relative sizes of its components. At the center is the **Nucleus**, with a size of approximately 10^{-14} m. It contains **Neutrons and Protons**, which have a size of approximately 10^{-15} m. These nucleons are composed of **Quarks**, which are smaller than 10^{-19} m. Surrounding the nucleus are **Electrons** (e^-), which are smaller than 10^{-18} m. The entire **Atom** has a size of approximately 10^{-10} m.

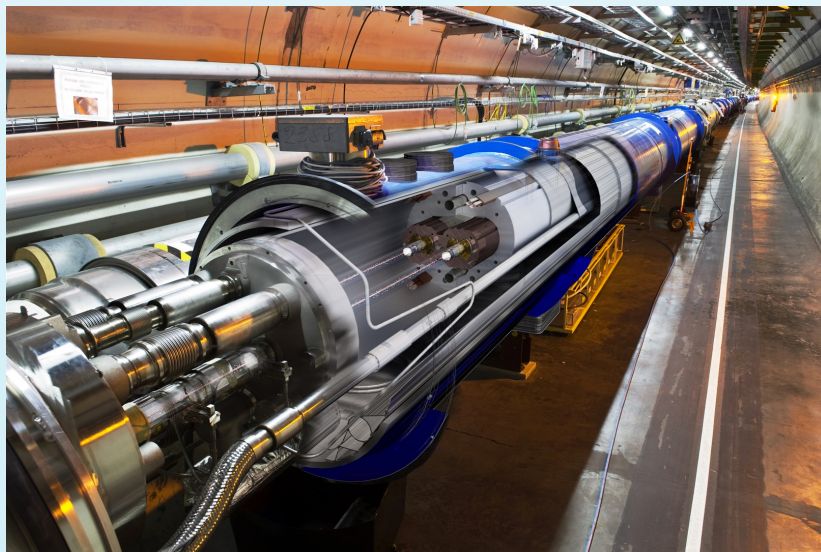
If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

A high-magnification scanning electron micrograph (SEM) showing numerous rod-shaped bacteria, likely Bacillus anthracis spores. The spores are elongated, cylindrical, and have a textured, slightly irregular surface. They are scattered across the field of view, with some appearing in clusters and others individually. The background is dark, and the lighting highlights the three-dimensional structure of the spores.

Juan Rojo



Exploring the secret code of Nature at the Large Hadron Collider

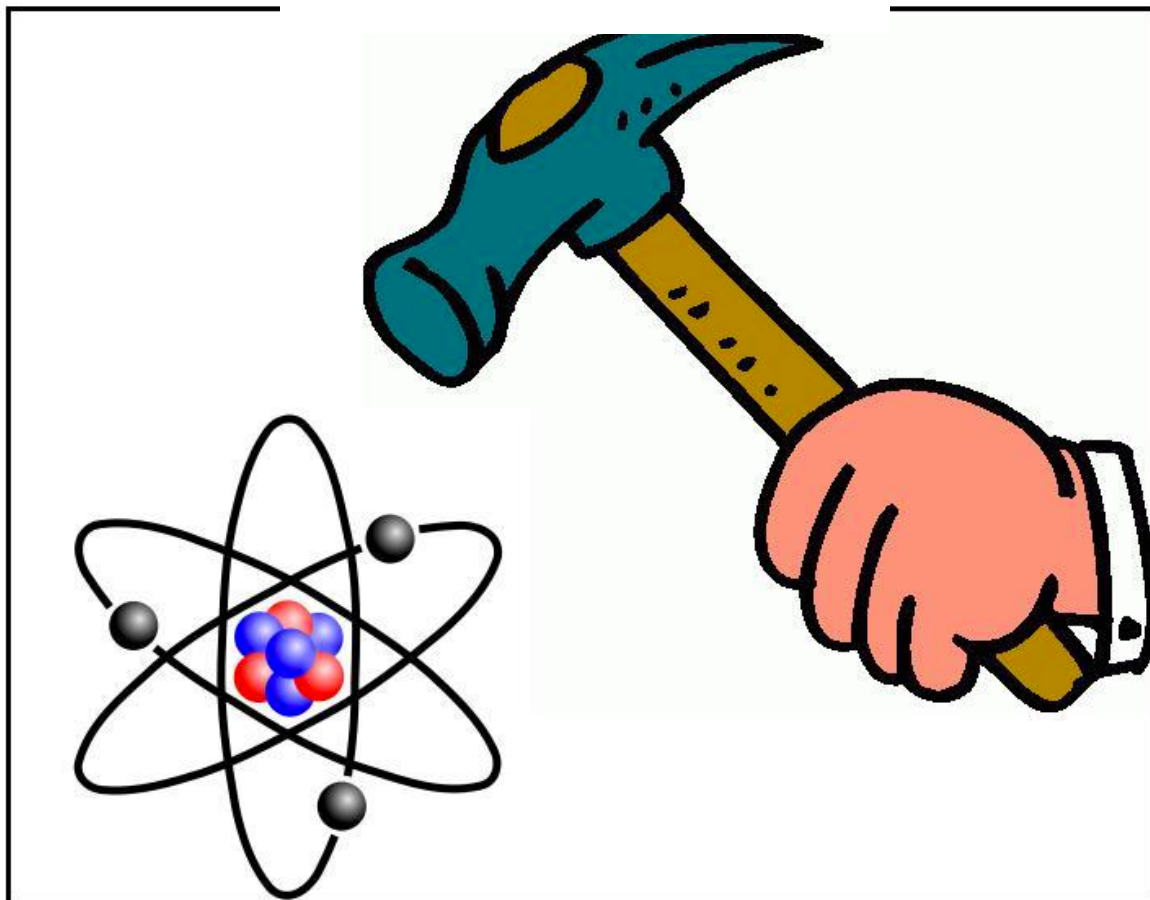


High energy colliders

The idea behind **high-energy colliders** is very simple!

📌 We want to see **what is inside protons**: we need to **break them**. How we do this?

**Bad
idea!**

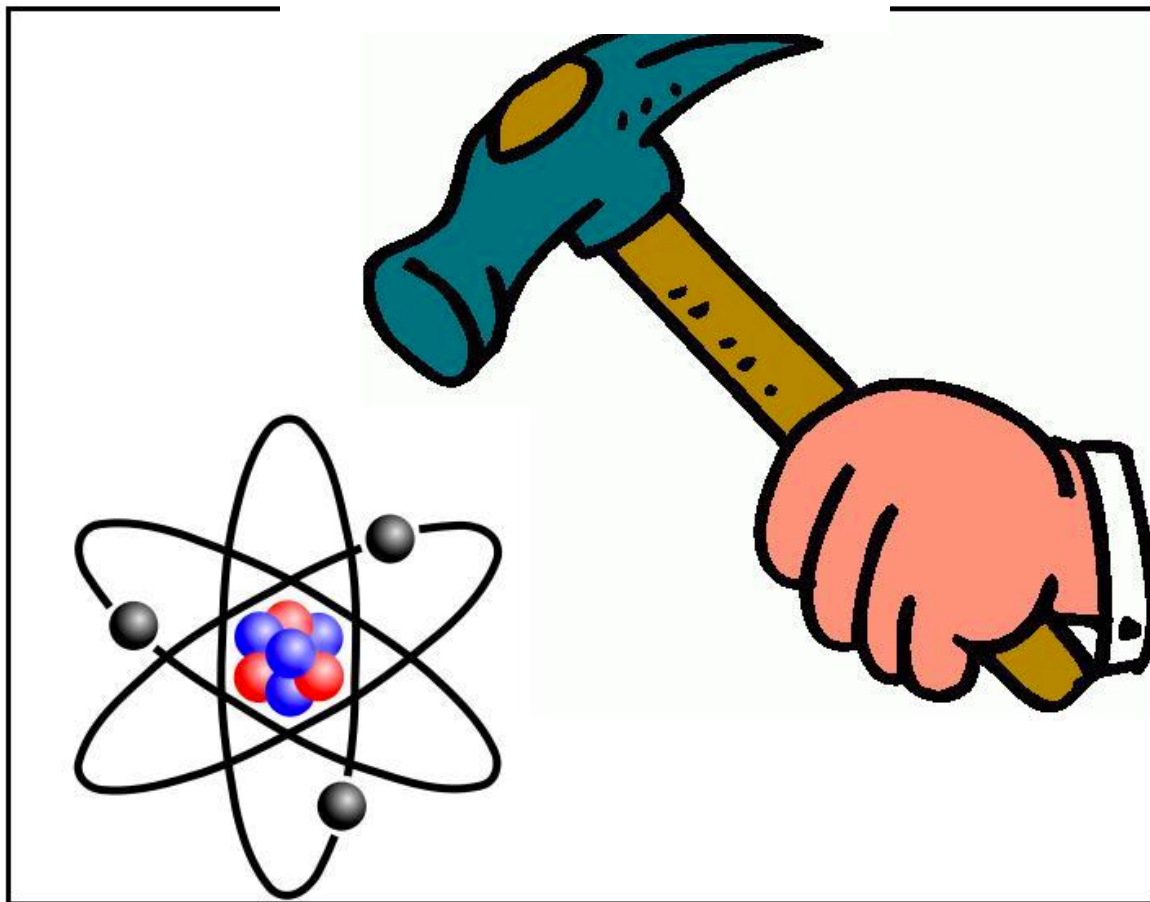


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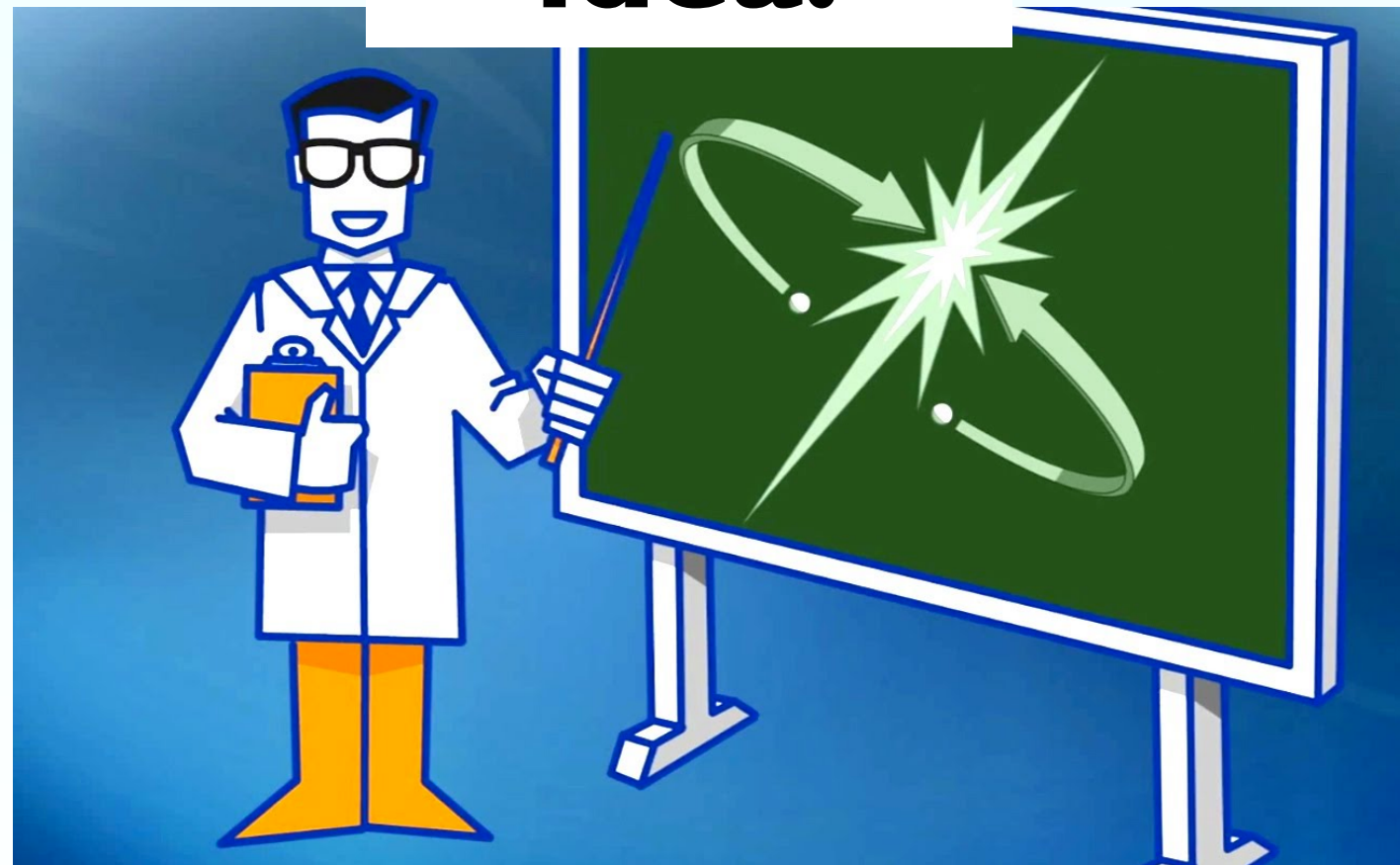
- 📌 We want to see **what is inside protons**: we need to **break them**. How we do this?
- 📌 We make protons **go very fast**, and then collide them: by looking at the **results of the collision**, we can understand the stuff protons are made of, if there are new particles or forces
- 📌 Since protons are very small, we need **extremely high energies to see inside them**: modern colliders are **gigantic machines**!

**Bad
idea!**



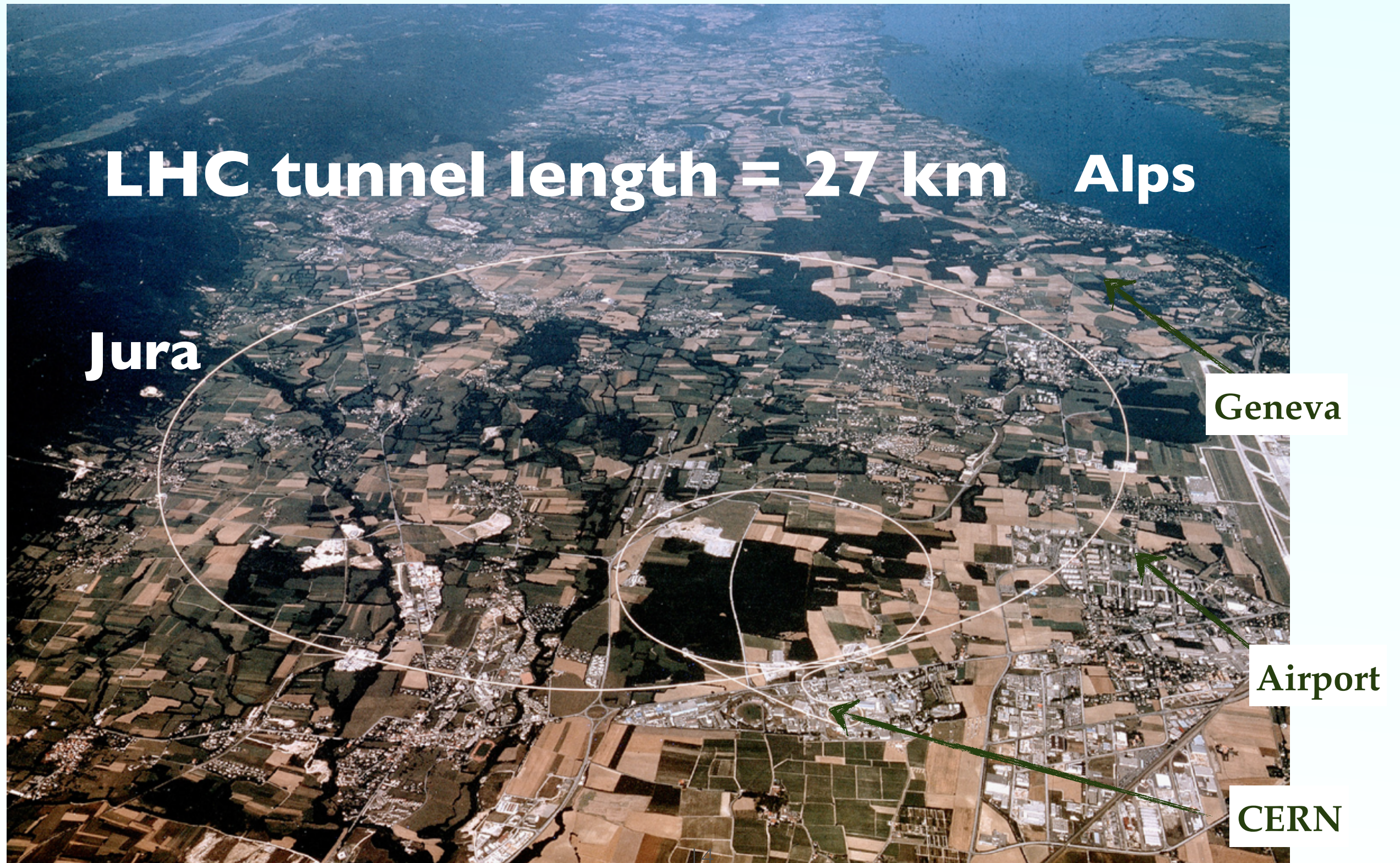
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**Good
idea!**



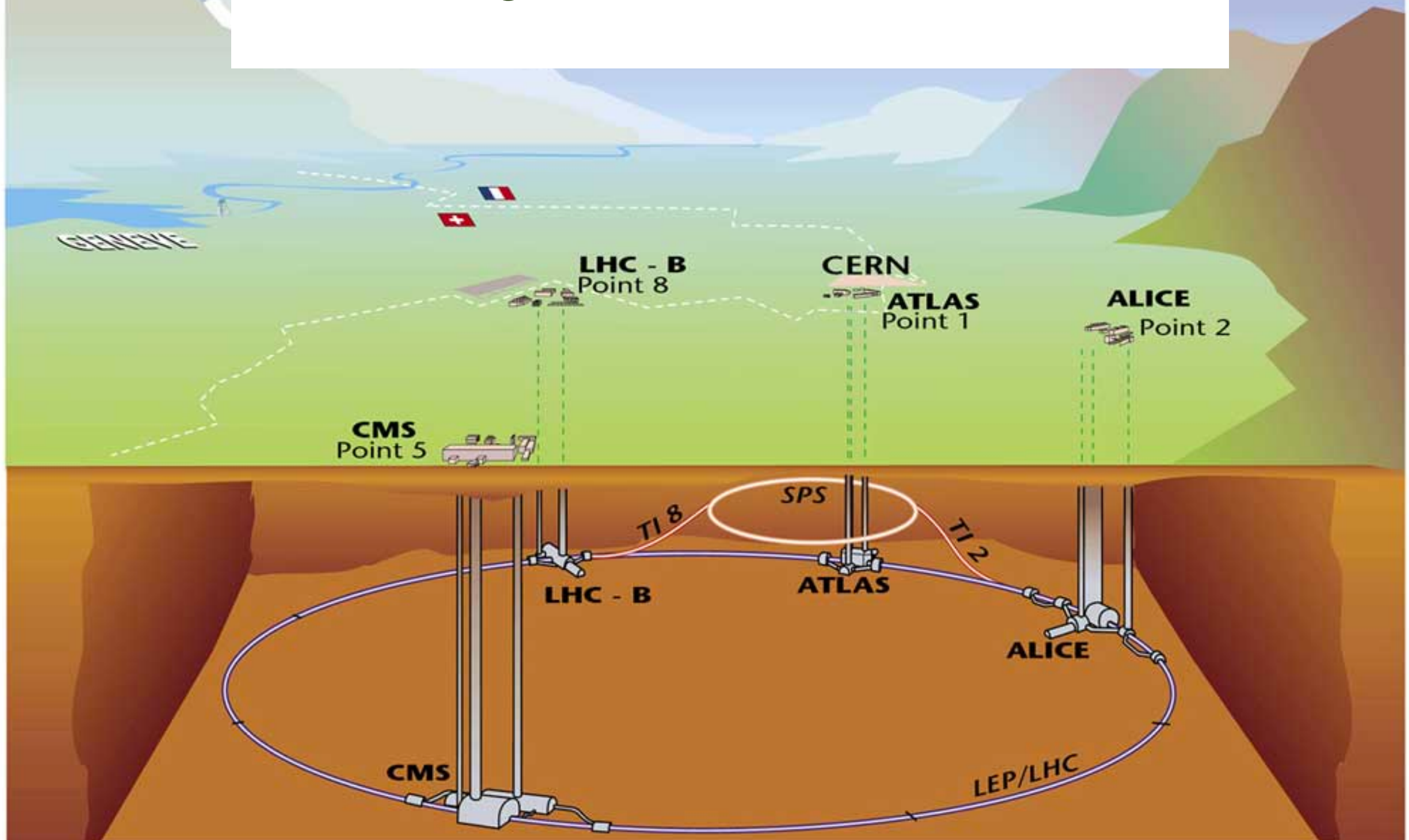
The Large Hadron Collider

- ✓ The LHC is the most powerful particle accelerator ever build by mankind
- ✓ Hosted by CERN in Geneva, the LHC is composed by a massive 27 km long tunnel with four gigantic detectors



Overall view of the LHC experiments.

Length of LHC tunnel: 27 km!

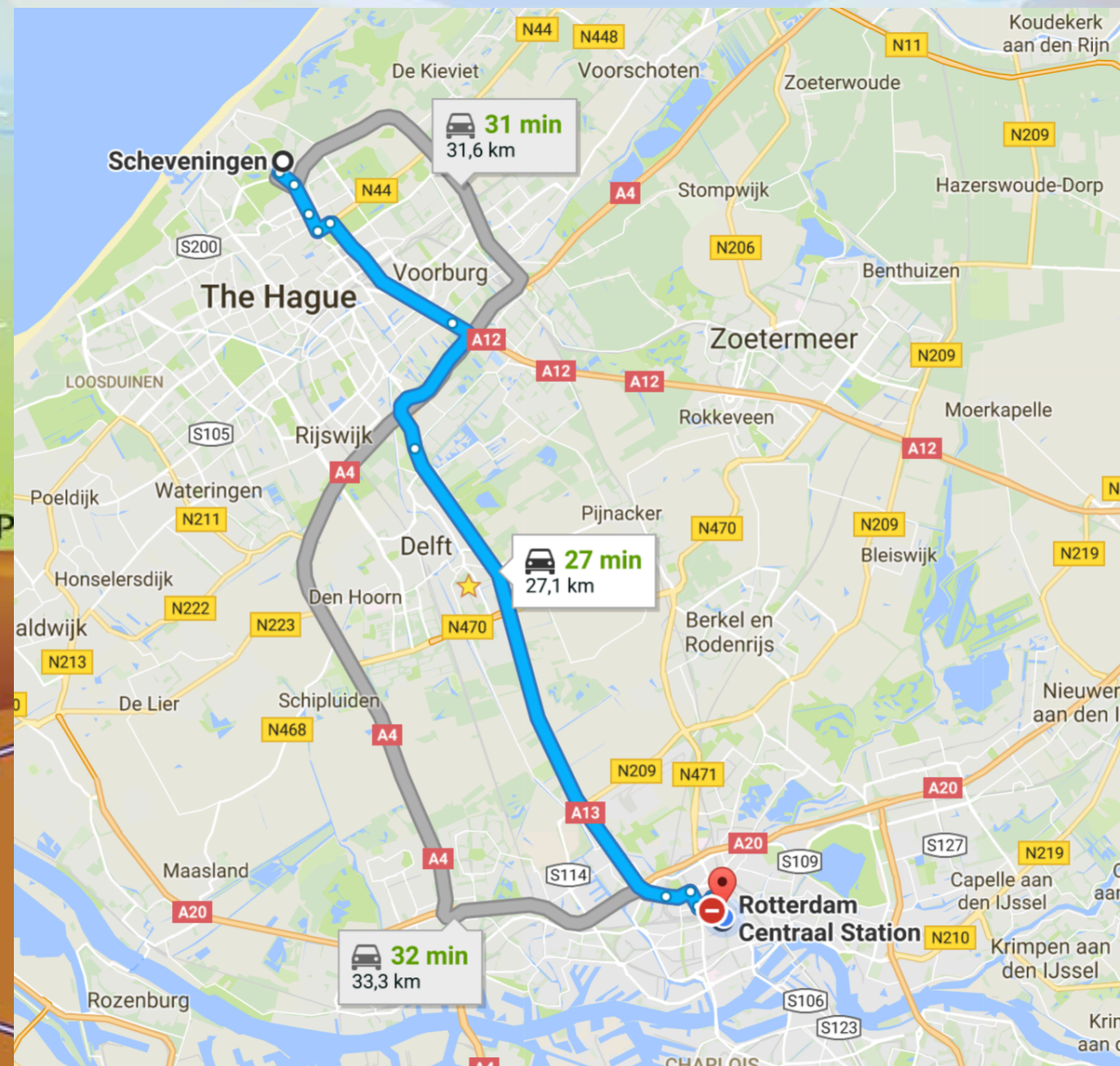


Experiments are hosted in underground tunnel to minimise disruption (+ reduce real state costs!)

Overall view of the LHC experiments.

Length of LHC tunnel: 27 km!

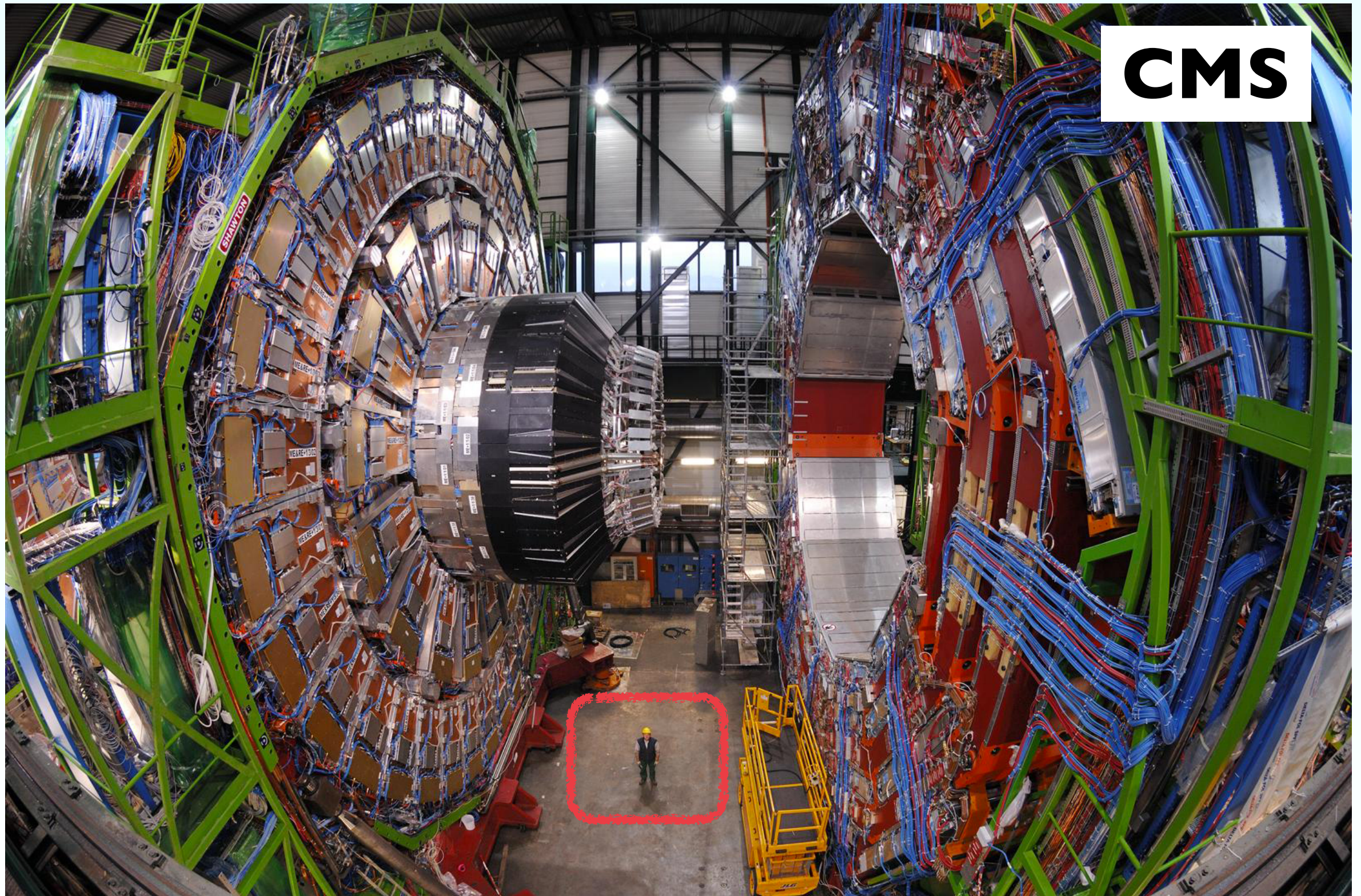
Same distance as from Rotterdam to Scheveningen

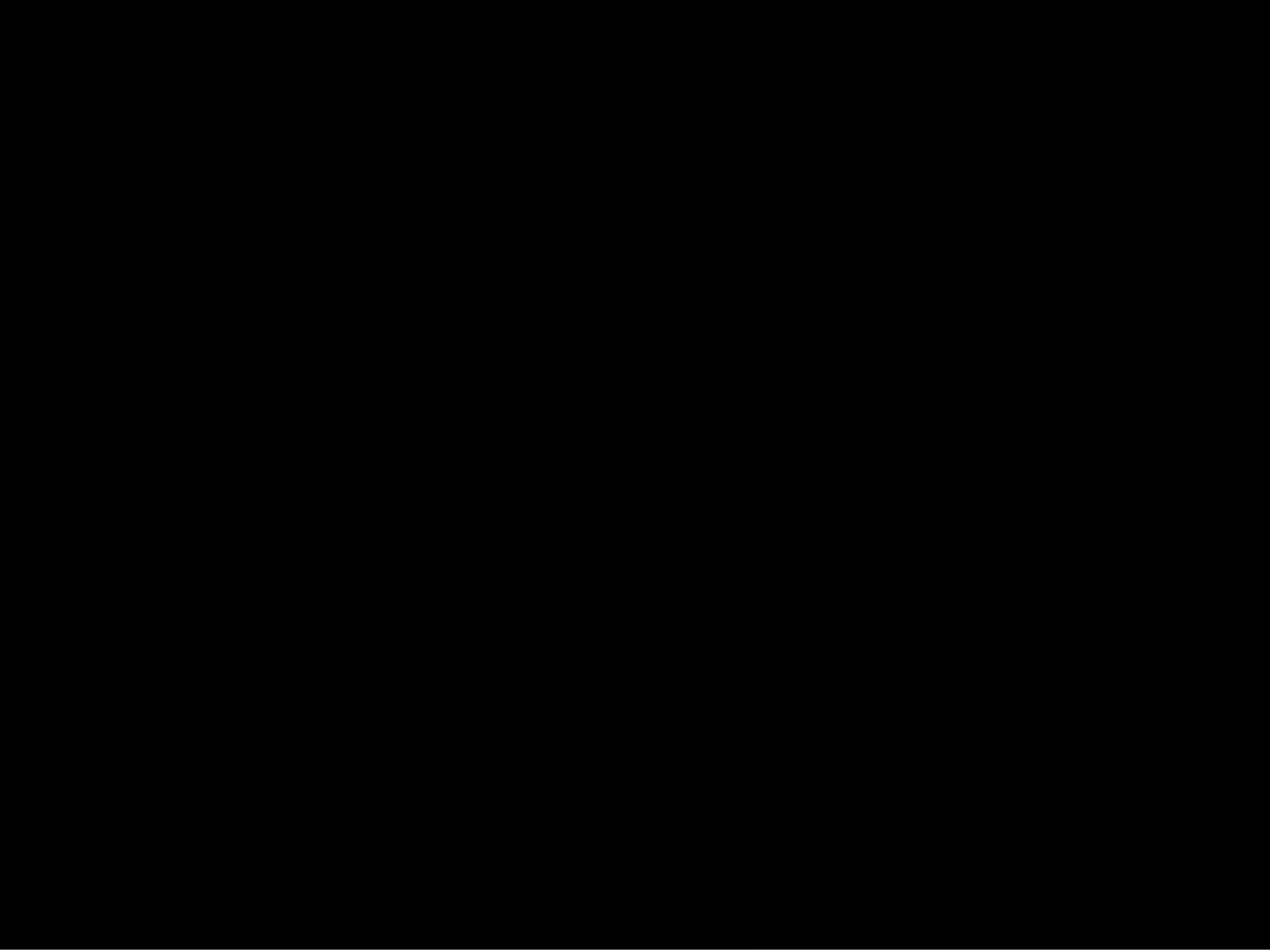


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The LHC detectors

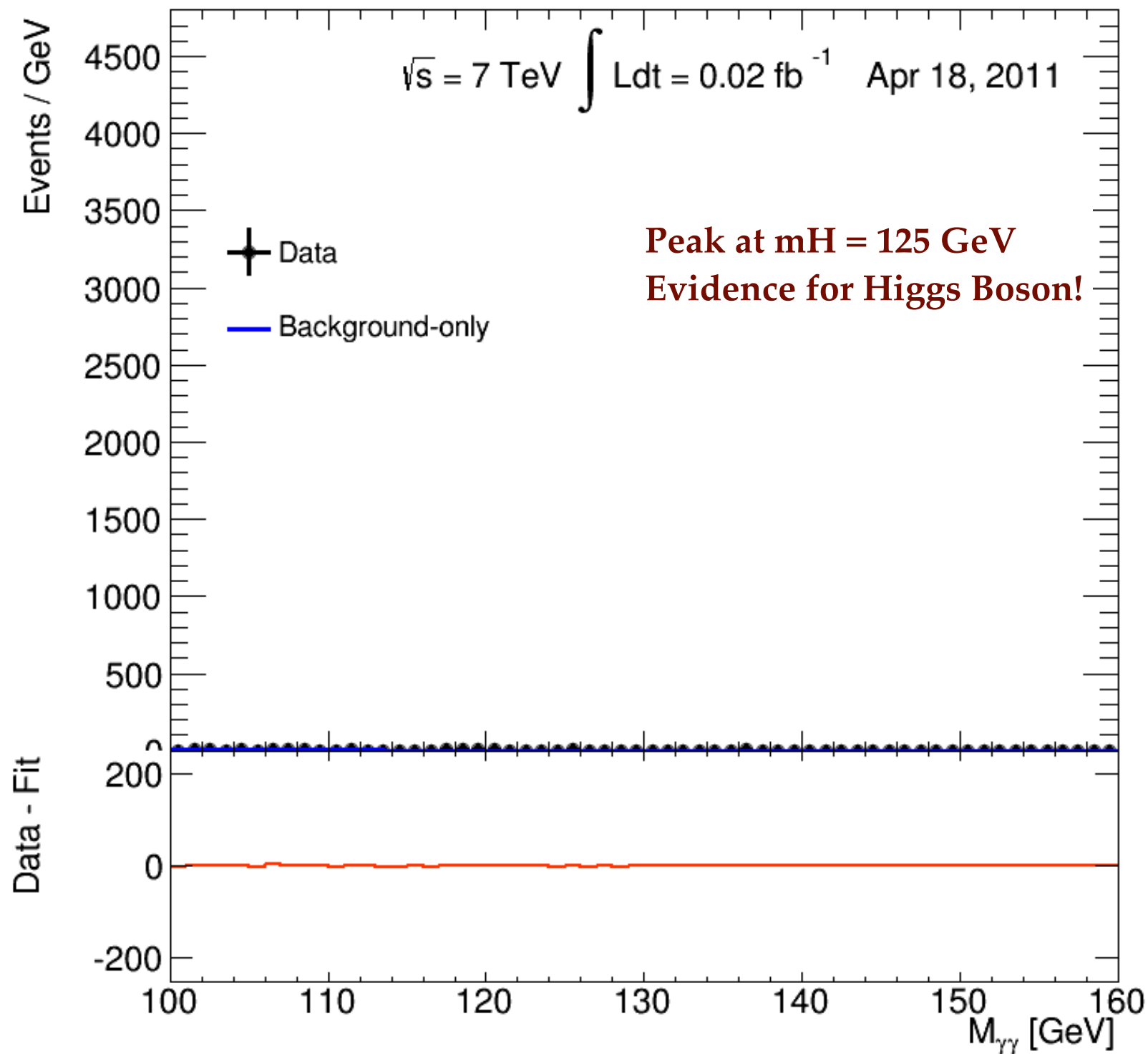
Where proton beams cross and **collisions** take place, huge detectors measure the products of the collision in an attempt to understand **the laws of Nature at the smallest distances**





Discovering New Particles

- ✓ At the LHC, we search for new **Fundamental Particles**, like the recently discovered **Higgs Boson**, by **looking for deviations** with respect known processes



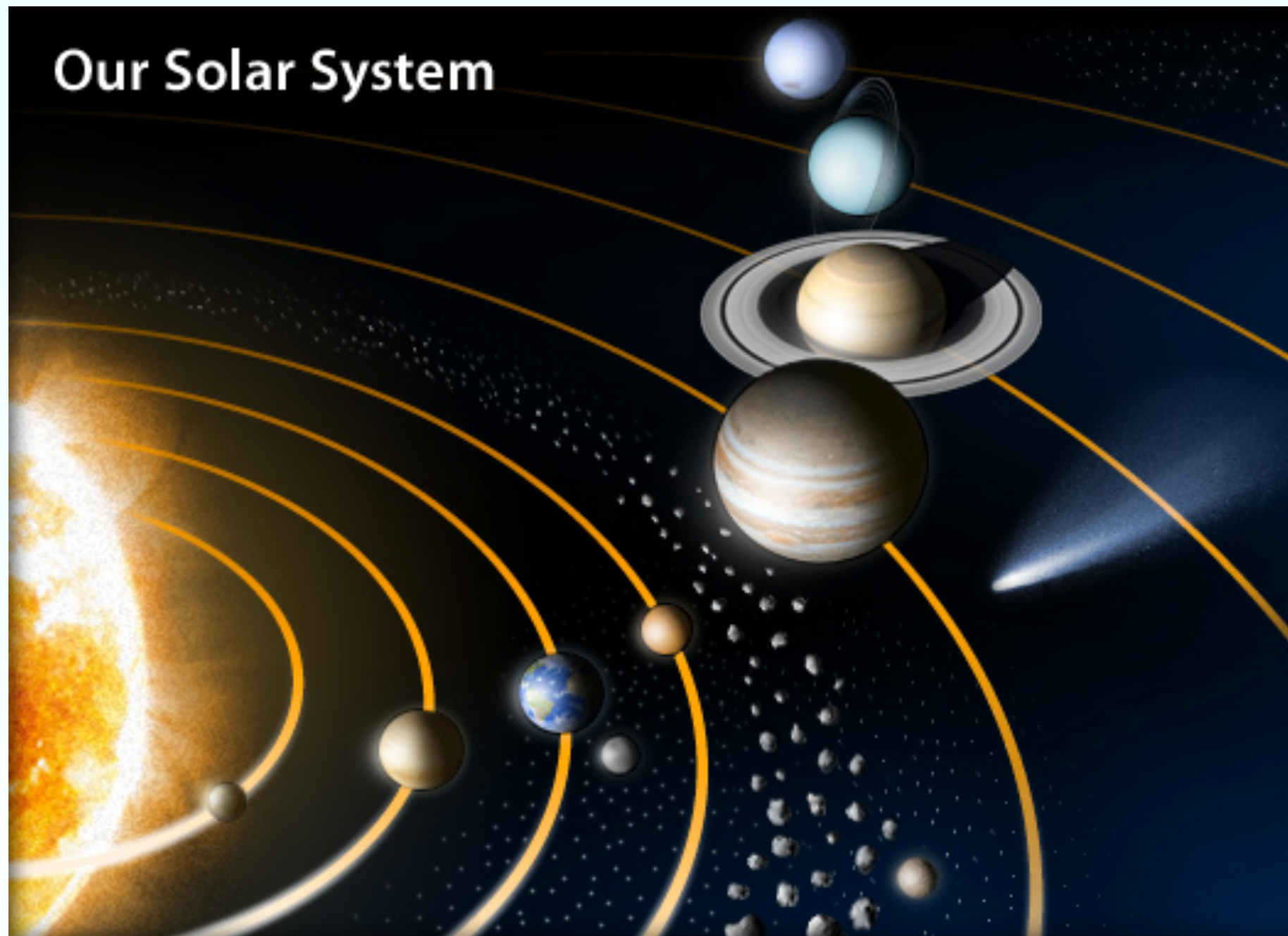
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Remarkable facts about the LHC

- ☑ The emptiest place in the Solar System: vacuum in the beam pipe similar to interplanetary space



Remarkable facts about the LHC

- ☑ One of coldest places in the Universe: the LHC magnets are kept at only 1.9 degrees above absolute zero, colder than interstellar space!



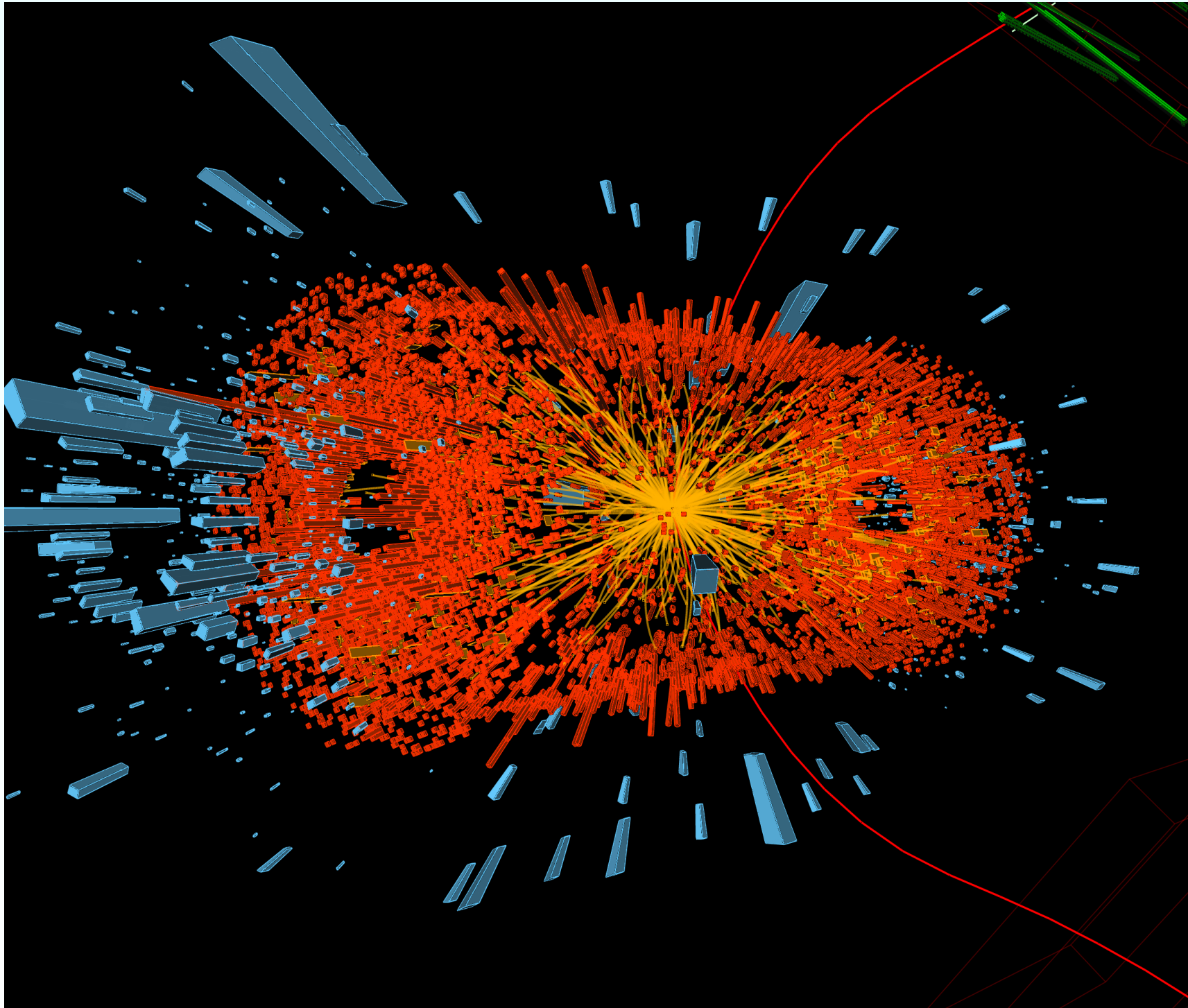
Remarkable facts about the LHC

- ✓ The data volume recorded is like reading 10,000 times the full Encyclopedia Britannica - each second!



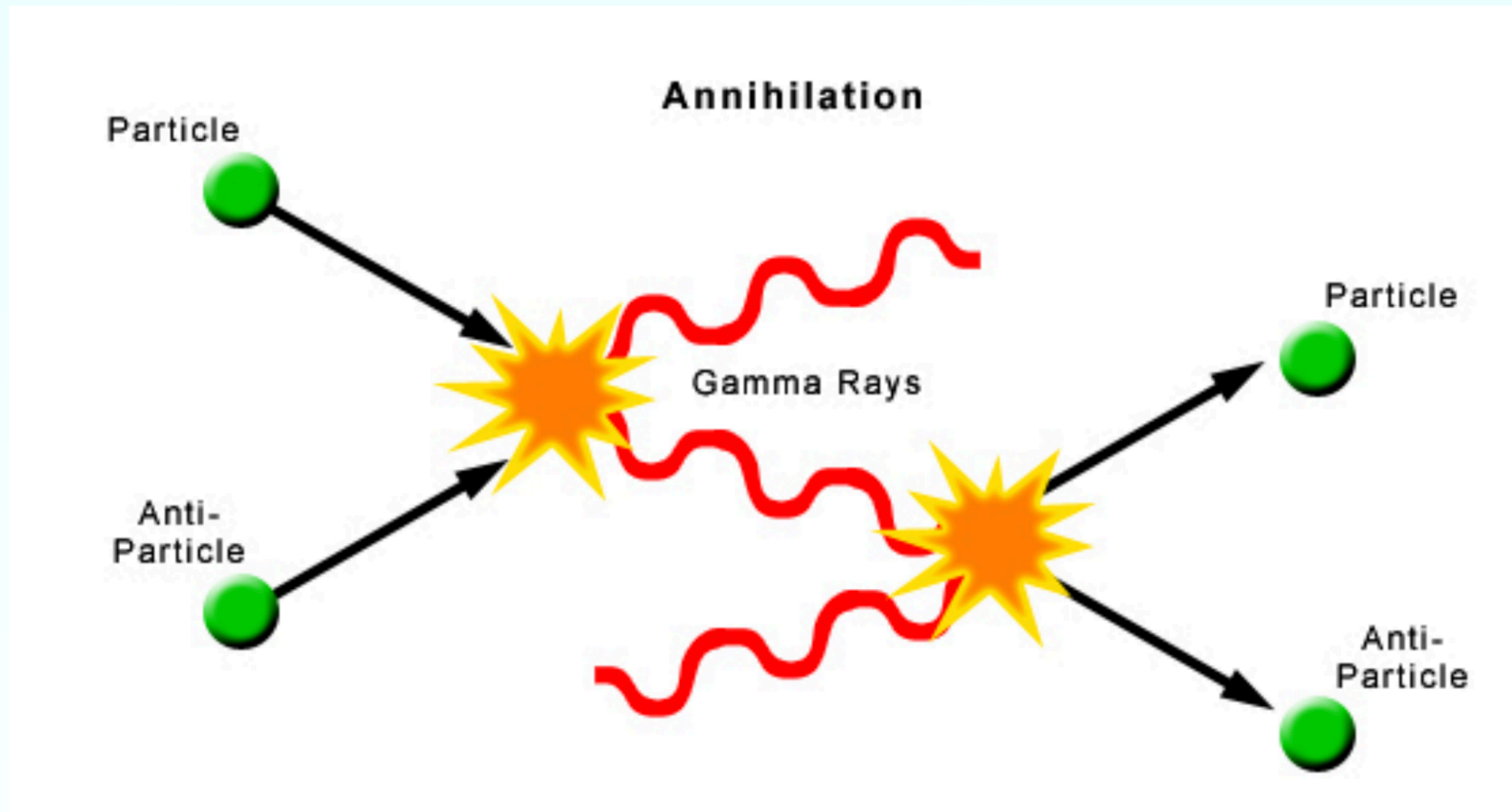
Remarkable facts about the LHC

- ☑ One of hottest places in the Galaxy: collisions generate a temperature **billions of times larger than the Sun**, reproducing conditions of **early Universe**



Antimatter matters

☑ CERN is also the world's leading producer of antimatter



Antimatter particles are just like regular particles, but with opposite charge

For example, the electron has an antiparticle called the **positron** with positive charge

When particles and anti-particles meet, they **annihilate into energy**

Antimatter matters



Antimatter matters



Antimatter matters

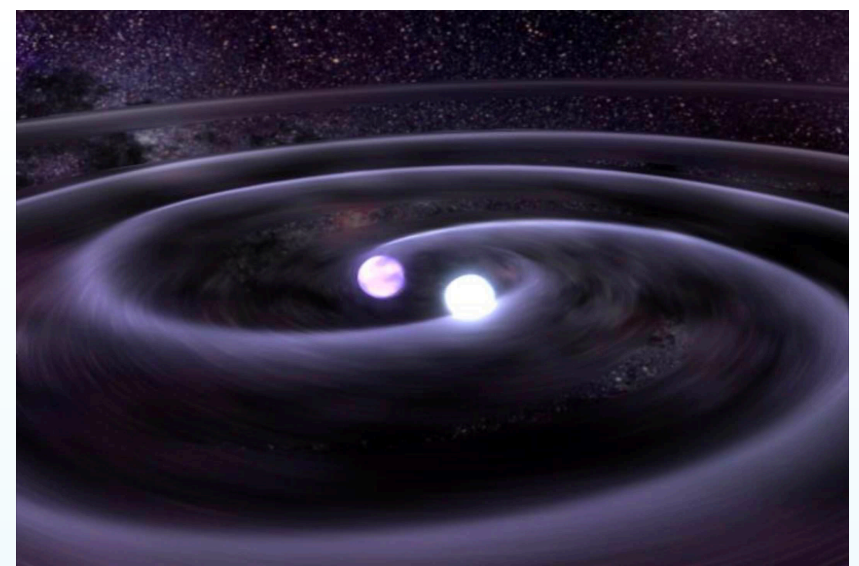
In Dan Brown's bestseller *Angels and Demons*, the perverse *Illuminati* want to steal antimatter from CERN to build a bomb to blow up the Vatican. This bomb is supposed to carry 0.25 grams of antimatter. How much energy will be released when all this antimatter is annihilated in the contact with normal matter? We can easily compute it using special relativity:

$$E = mc^2 = (2 \times 2.5 \times 10^{-4} \text{ kg}) \times (3 \times 10^8 \text{ m/s})^2 \simeq 5 \times 10^{13} \text{ J} = 50 \text{ TJ}, \quad (2.36)$$

where the factor 2 arises from the contribution of the 0.25 g of normal matter which annihilate with the antimatter in the bomb. This is about the same energy released by the atomic bomb dropped on Hiroshima ($\simeq 63 \text{ TJ}$). So indeed antimatter seems to be a very powerful weapon!

The only downside of this malicious program is that producing antimatter is *very slow*. Even using all the accelerator complex from CERN^a, at most one can produce 10^{-12} grams of antimatter per year, meaning that it would take around *one billion years* to produce that much antimatter as required by the *Illuminati* dark master-plan. Of course, the same limitation affect proposals to power interstellar spaceships with antimatter engines.

^a<http://angelsanddemons.web.cern.ch/antimatter/making-antimatter>

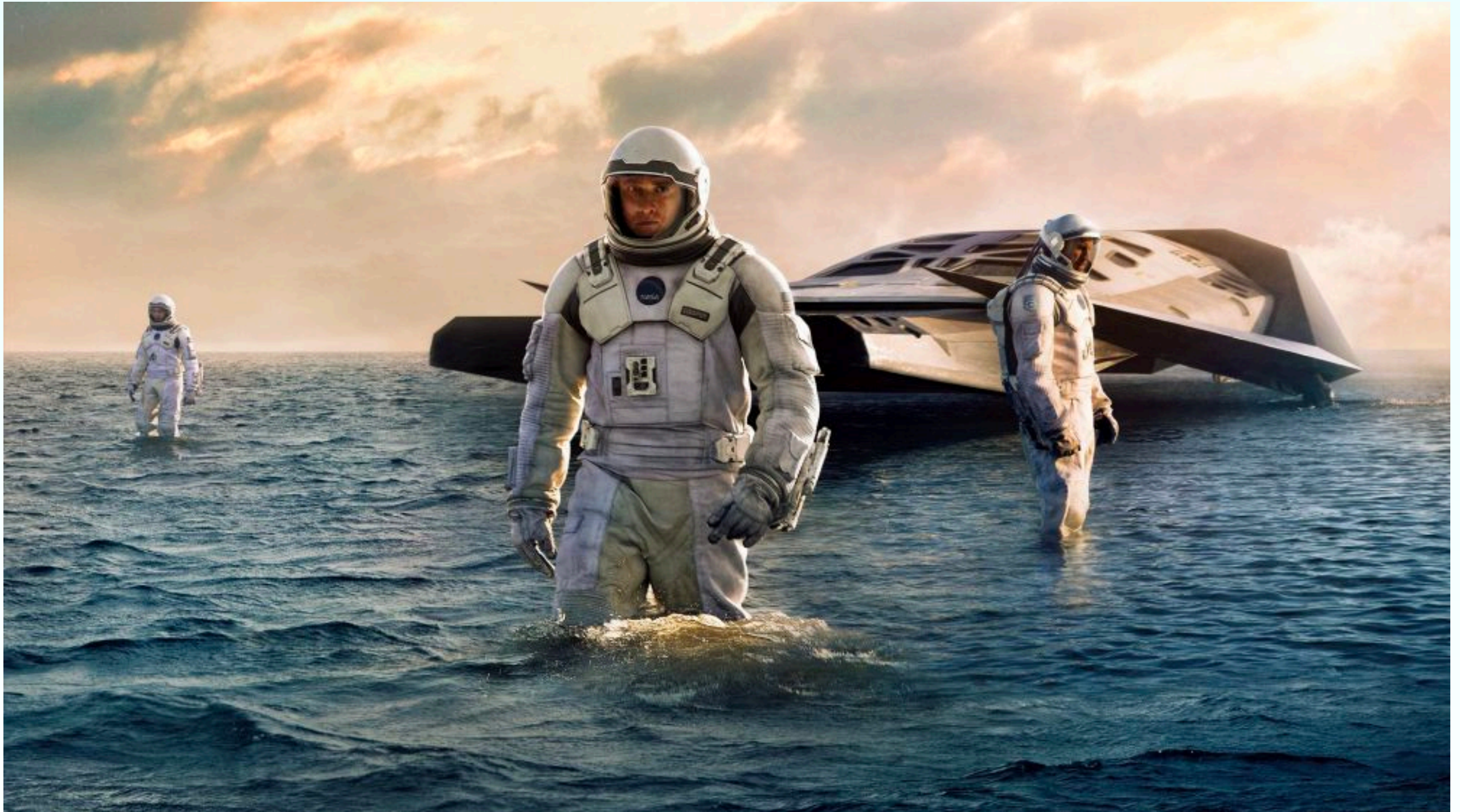


Gravitational waves: The symphony of space-time



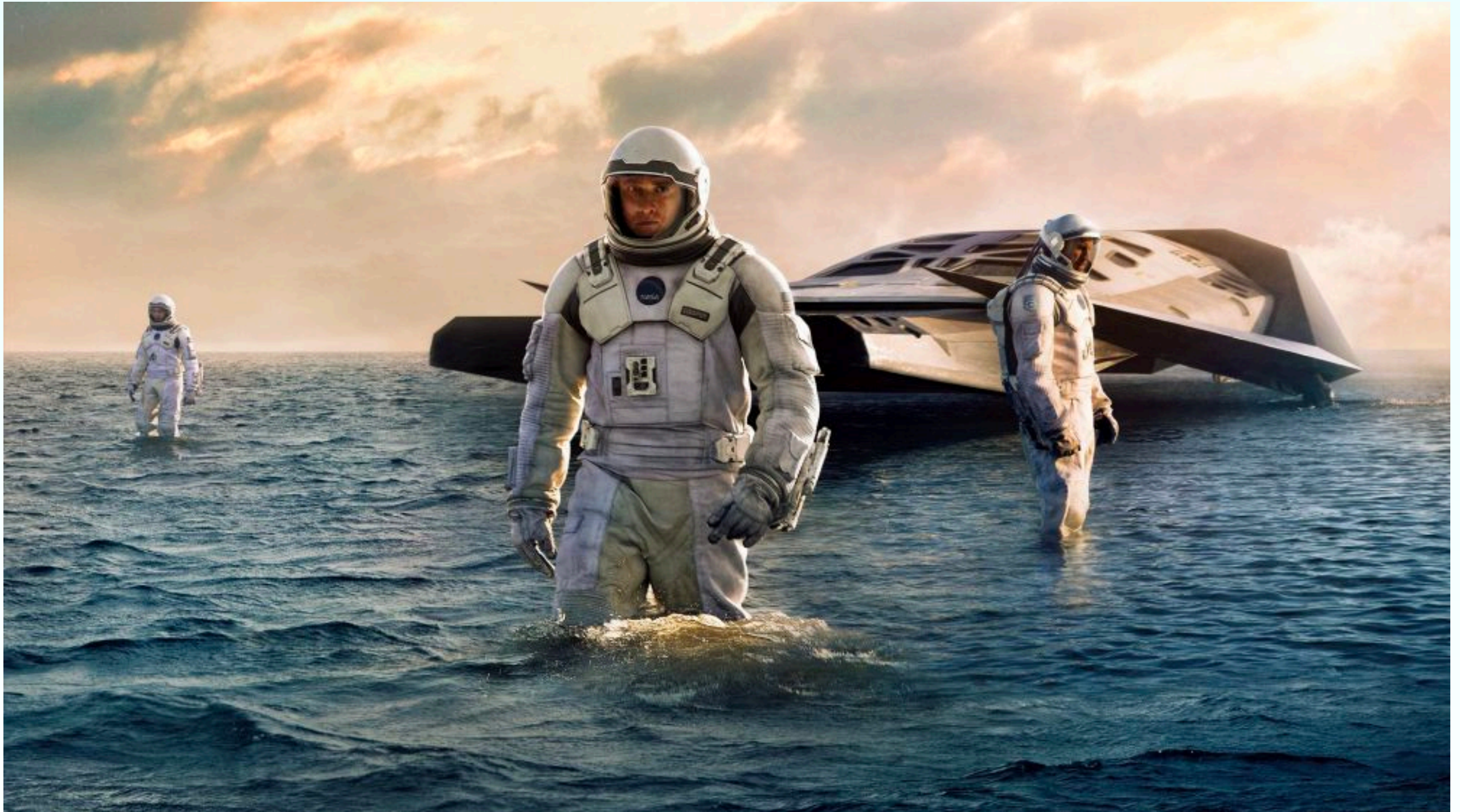
This is not science fiction!

Has anyone seen this movie? What happened in this particular part?



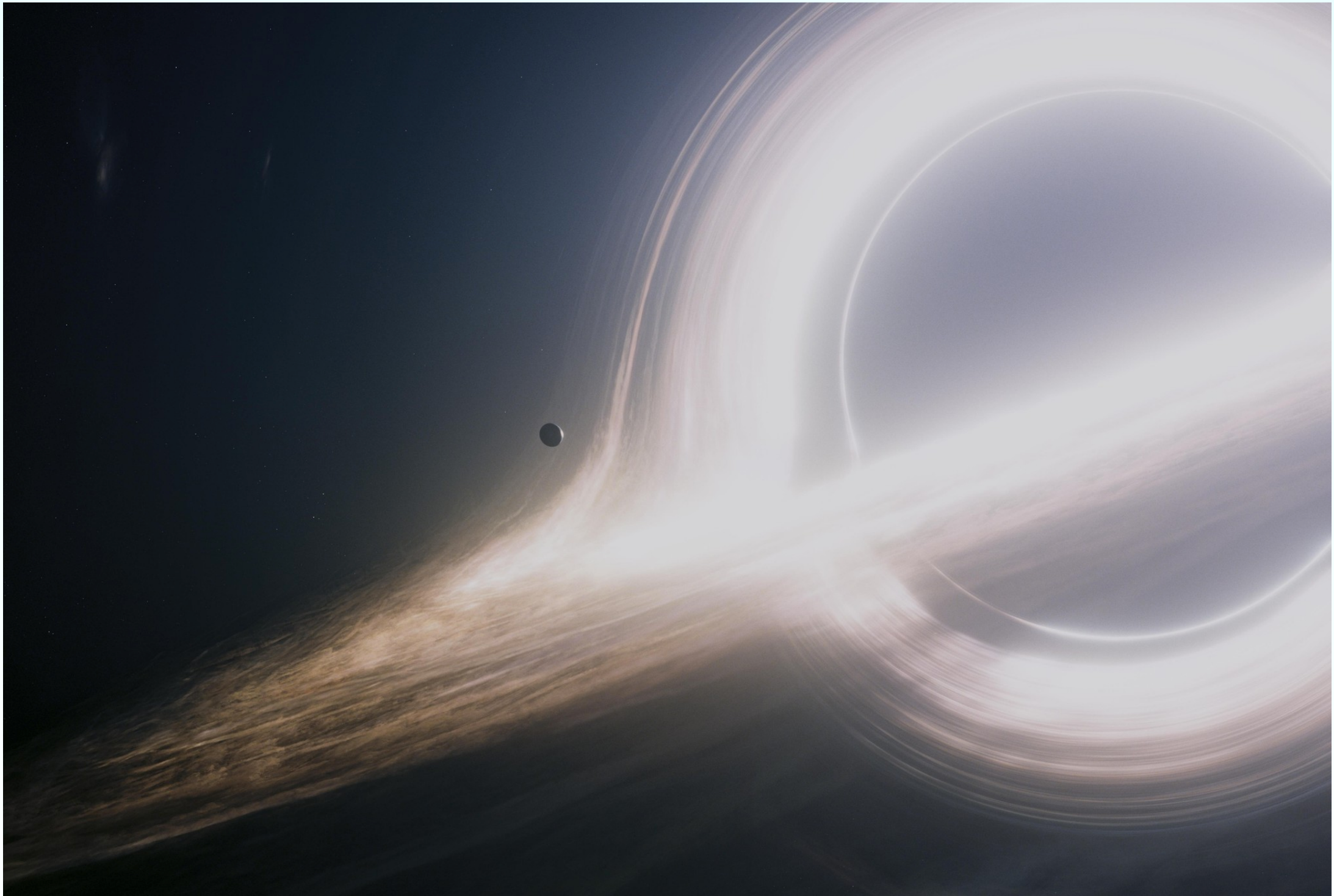
This is not science fiction!

Einstein's theory of General Relativity describes *gravity* as **deformations of space-time**
Massive enough bodies, such as black holes, deform space-time and **slow the local time**



This is not science fiction!

Black holes are one of the most fascinating objects in the Universe:
nothing can escape from their attraction, not even light!

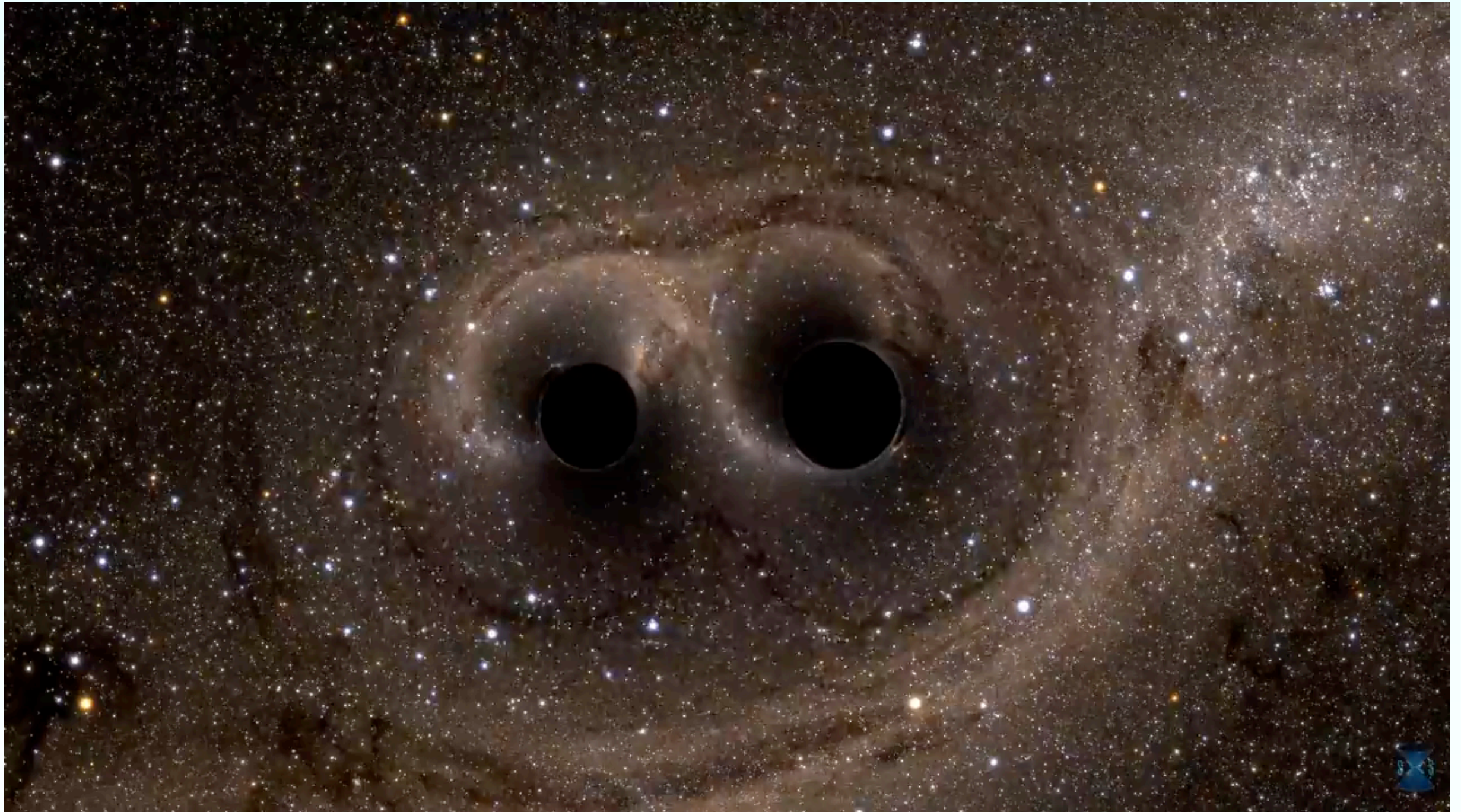


Remarkably, the gargantuan black hole from “Interstellar” is physically realistic

When worlds collide

Black holes can be found in **pairs**, remnants from binary star systems

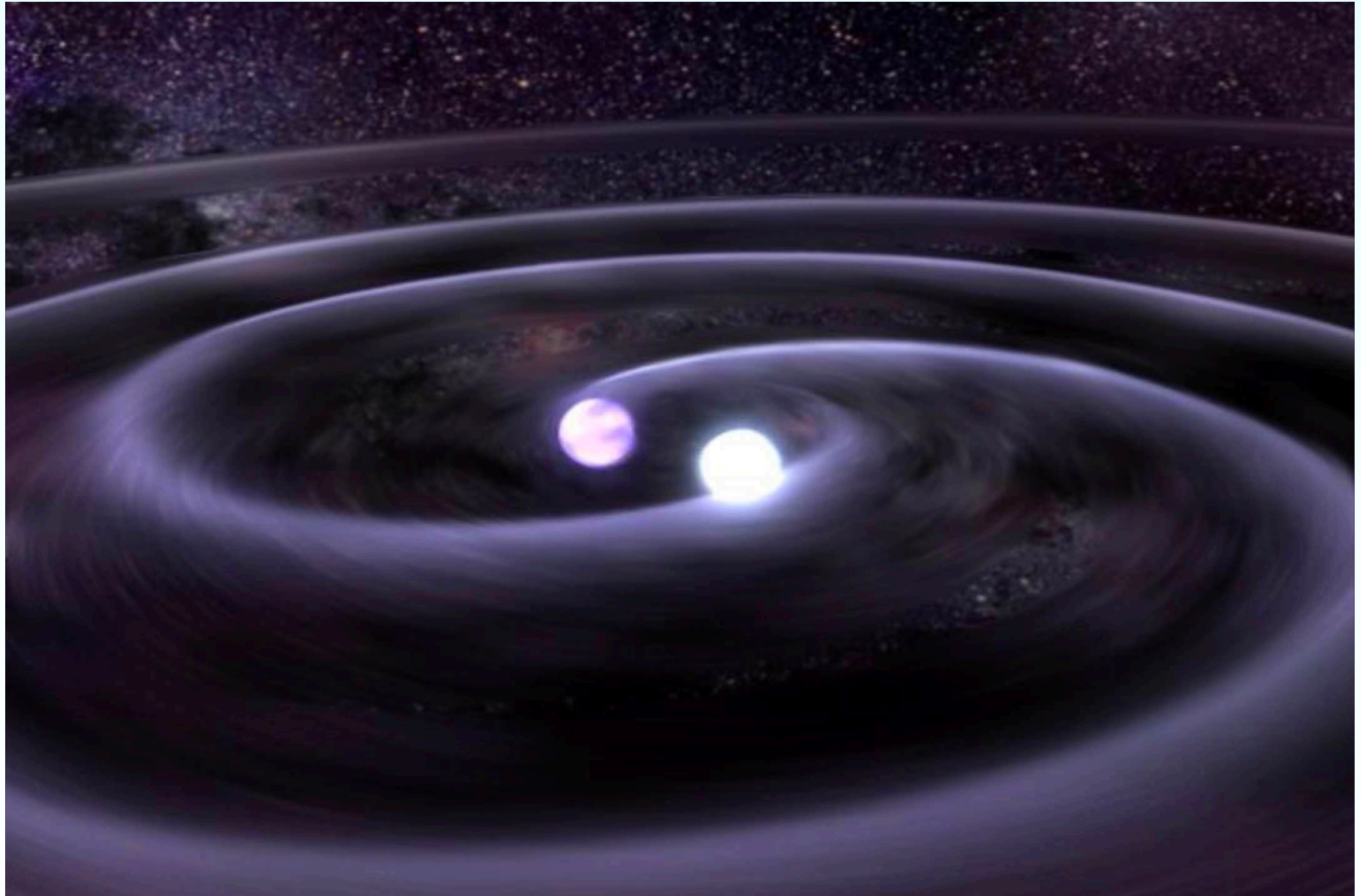
Black hole mergers are some of the most cataclysmic events that take place in the Universe



*If a black hole is, well, black, then how is all this energy released?
In terms of gravitational waves, ripples of space-time itself!*

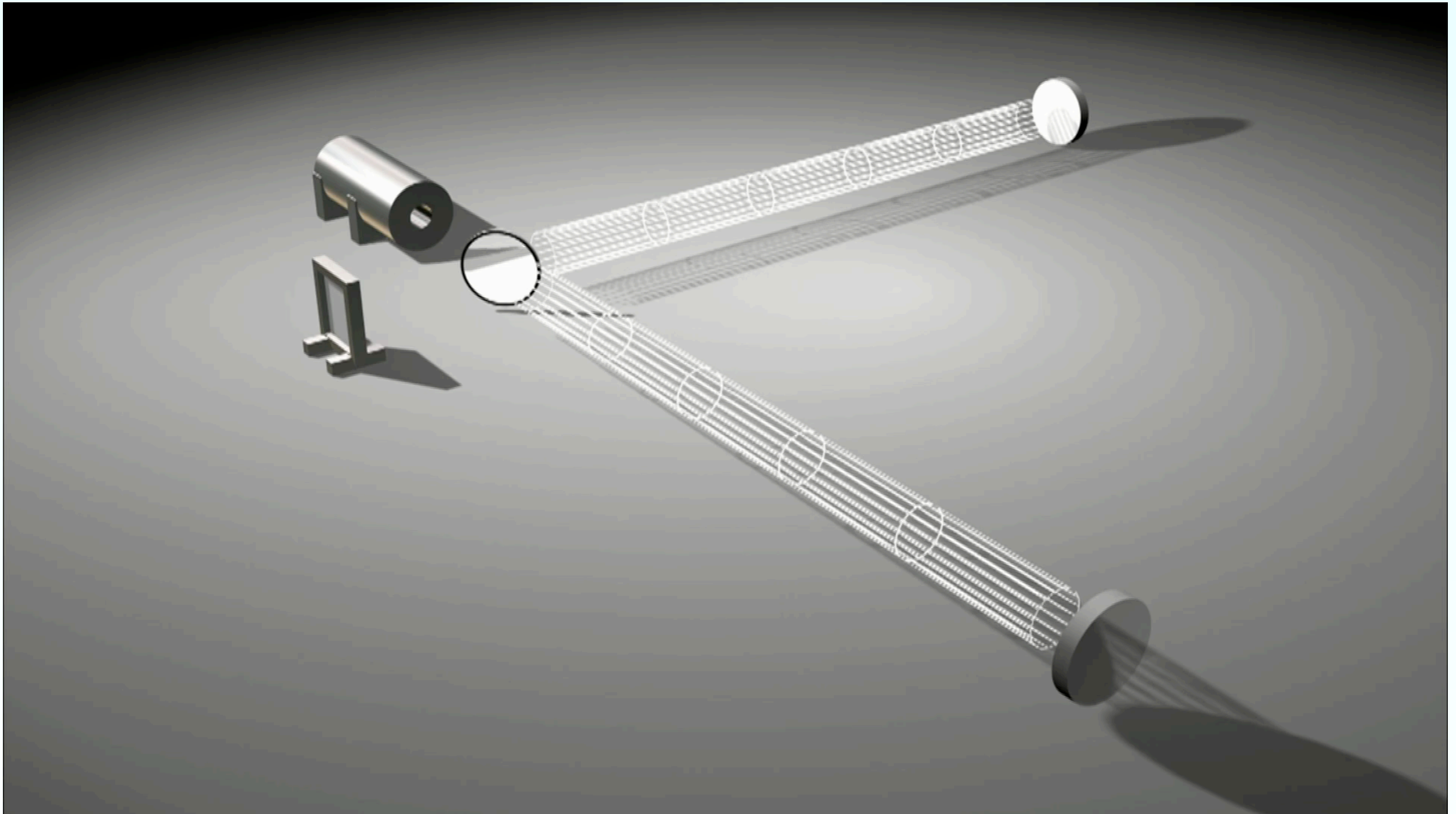
When worlds collide

*Gravitational waves, unlike matter waves, do not propagate on top of something
space-time itself oscillates, propagating energy across the universe*



When worlds collide

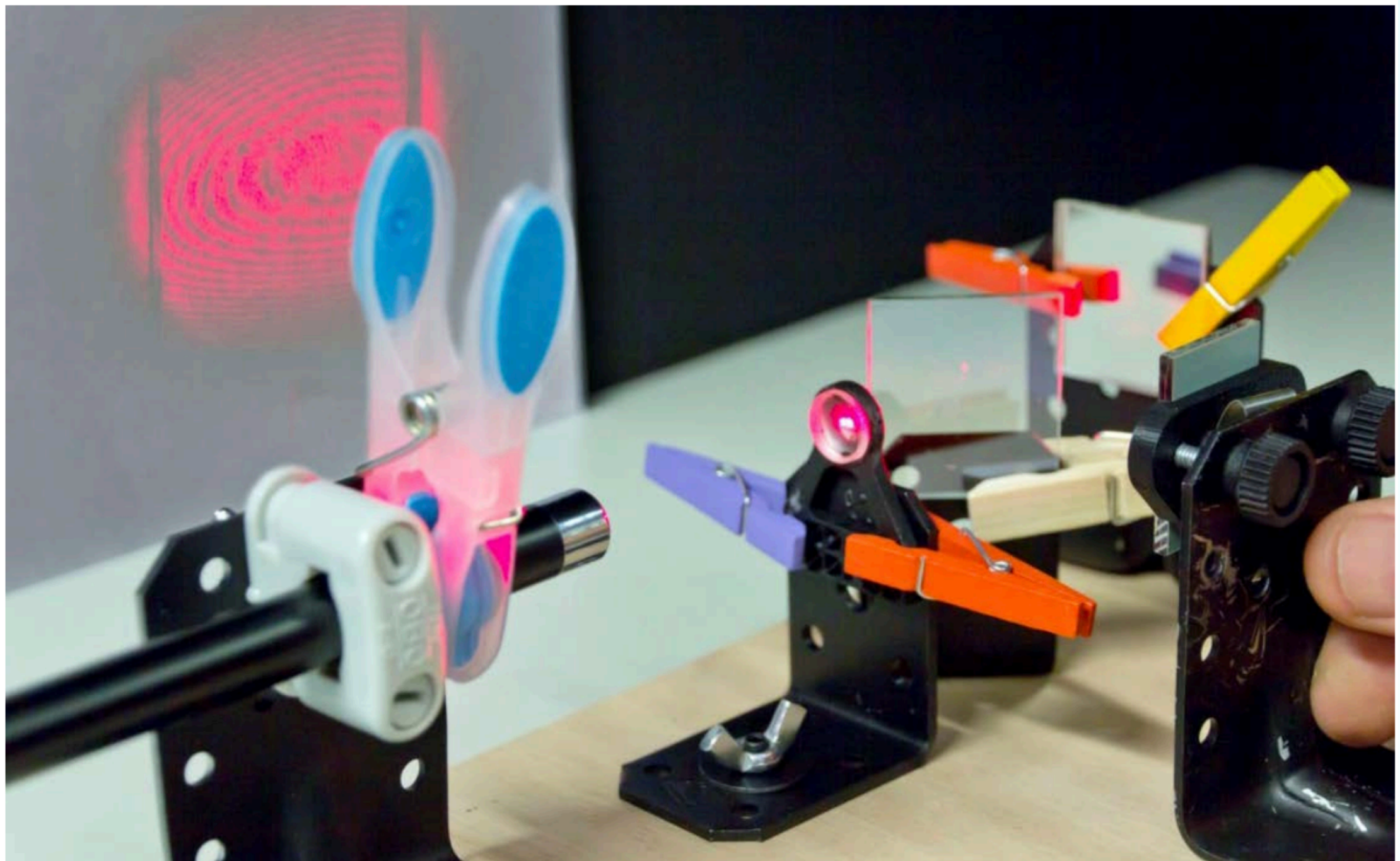
Gravitational waves can be detected with **ultra-precise laser interferometers**



Need to measure length variations of less than $1/1000$ of a proton size in the interferometer arms of 4 km each!

Measuring gravitational waves

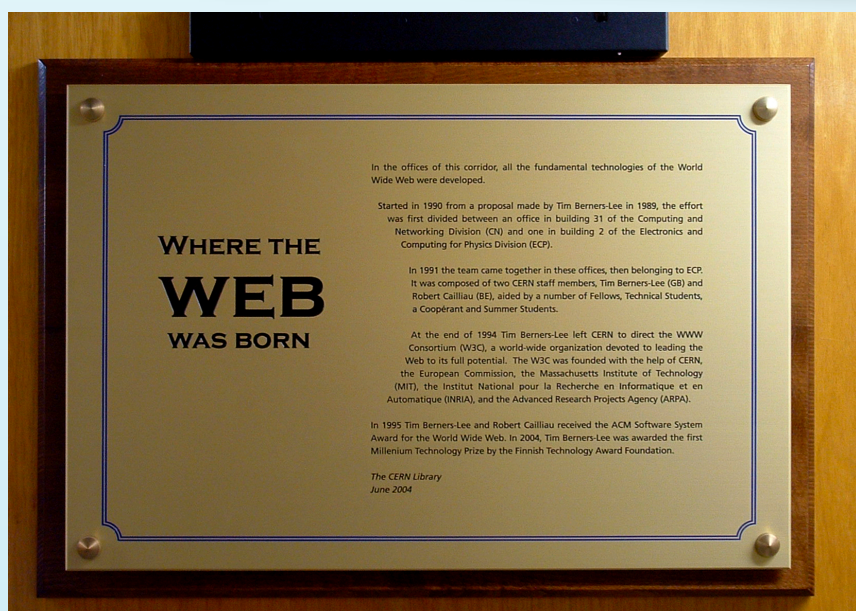
After the lecture, you will carry out your own measurements of gravity waves using a **table-top laser interferometer**: exactly the same physical principle as that used to discover gravitational waves!



We want to give you a snapshot of how a **real scientific experiment works!**



Useless science?



Useless science?

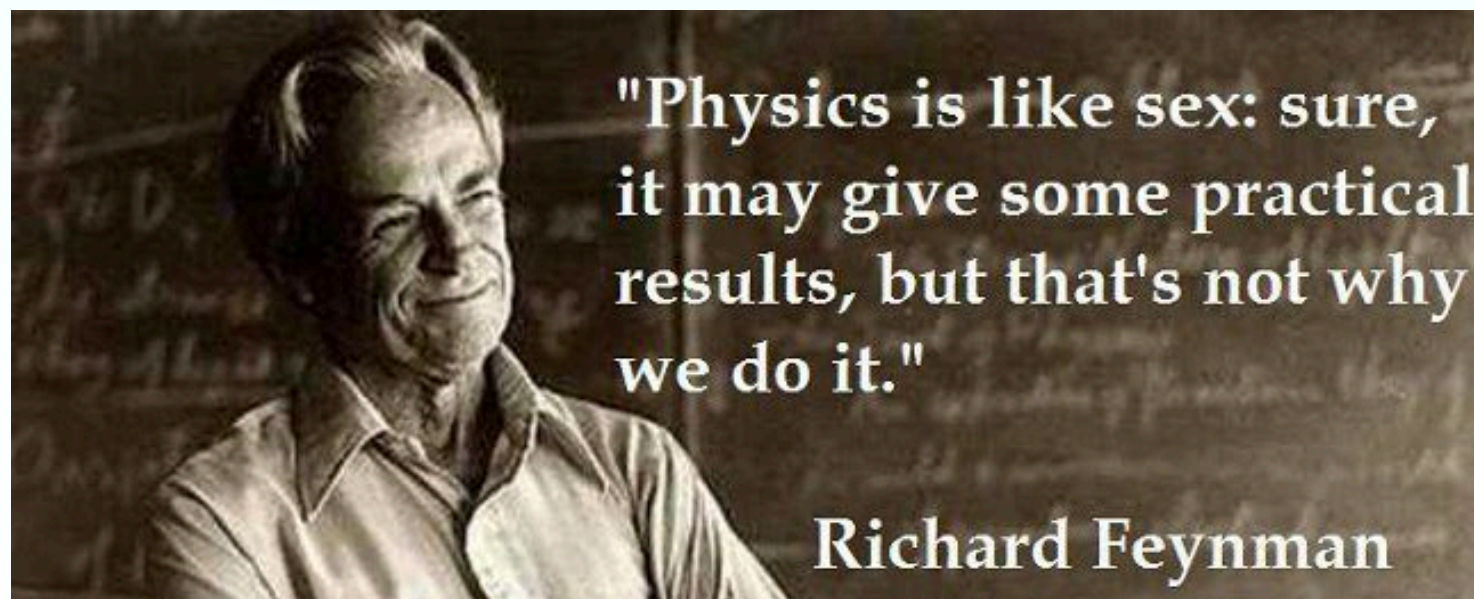
The main driver beyond fundamental science is **sheer curiosity**, our **intrinsic fascination to understand what we are made of**, where we come from, where are we going



In that sense, this new knowledge has all to do with honour and country but it has nothing to do directly with defending our country except to help make it worth defending

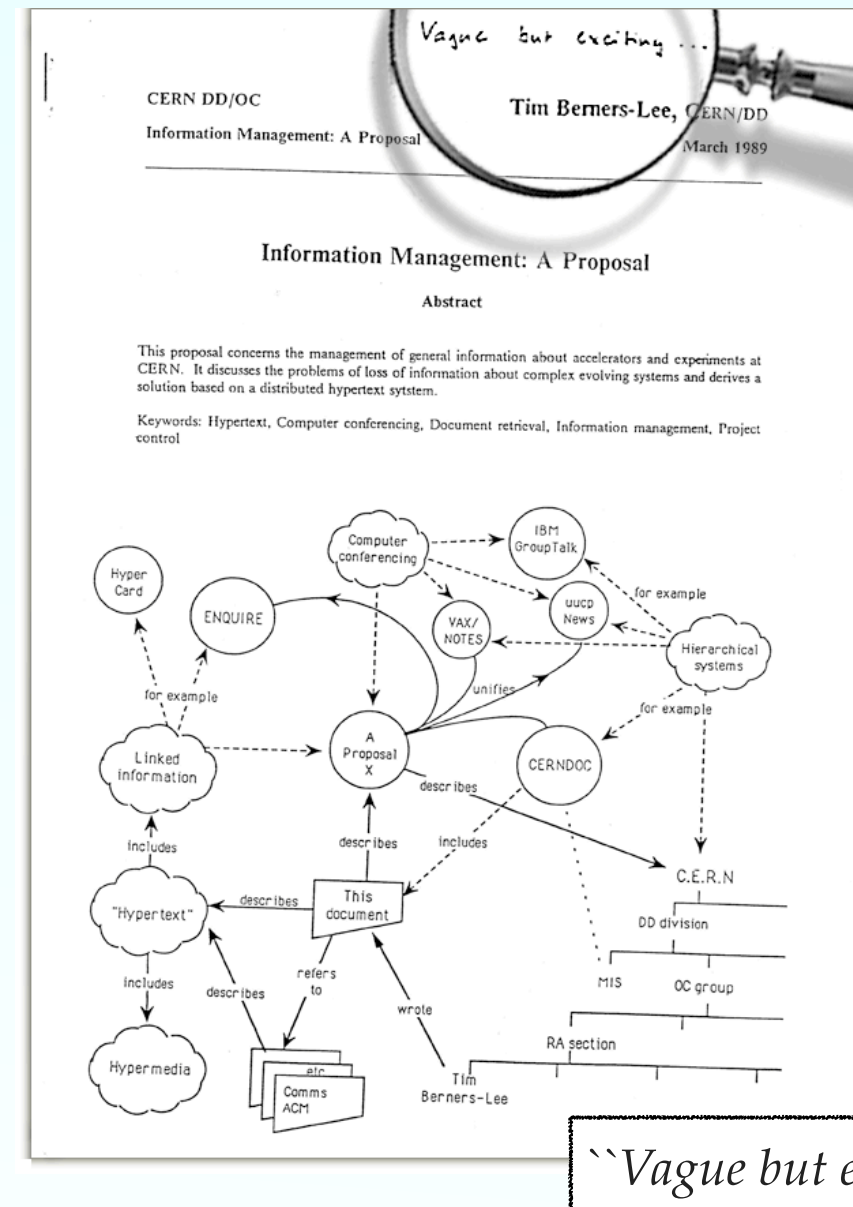
The physicist Robert Wilson, when asked by the U.S. Congress about practical applications of particle physics

This said, basic research has lead to a large number of **crucial practical applications**, many of them shaping the modern world - from **Internet** to the **GPS**



Where the web was born!

I am old enough to remember a **world without Internet!** (or even without smartphones)



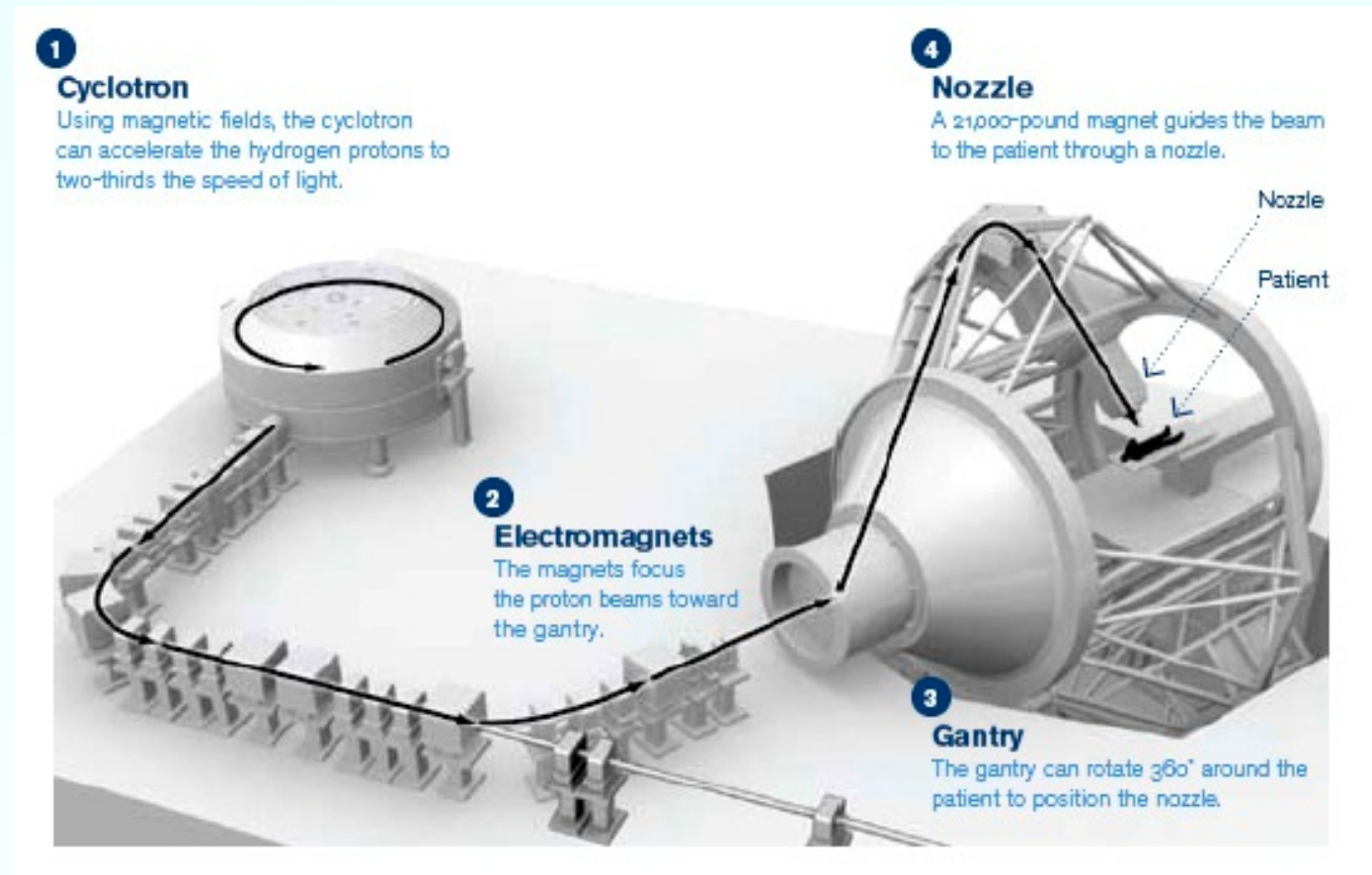
“Vague but exciting...”

The World Wide Web was first started by **Tim Berners-Lee**, a **CERN software engineer** aiming to streamline the communication between CERN scientists and researchers

In the U.S.A. alone, Internet-related economic sectors amount to **\$966 billion** (6% of total economy)

Proton therapy

A collimated beam of high energy protons is used to irradiate diseased tissue

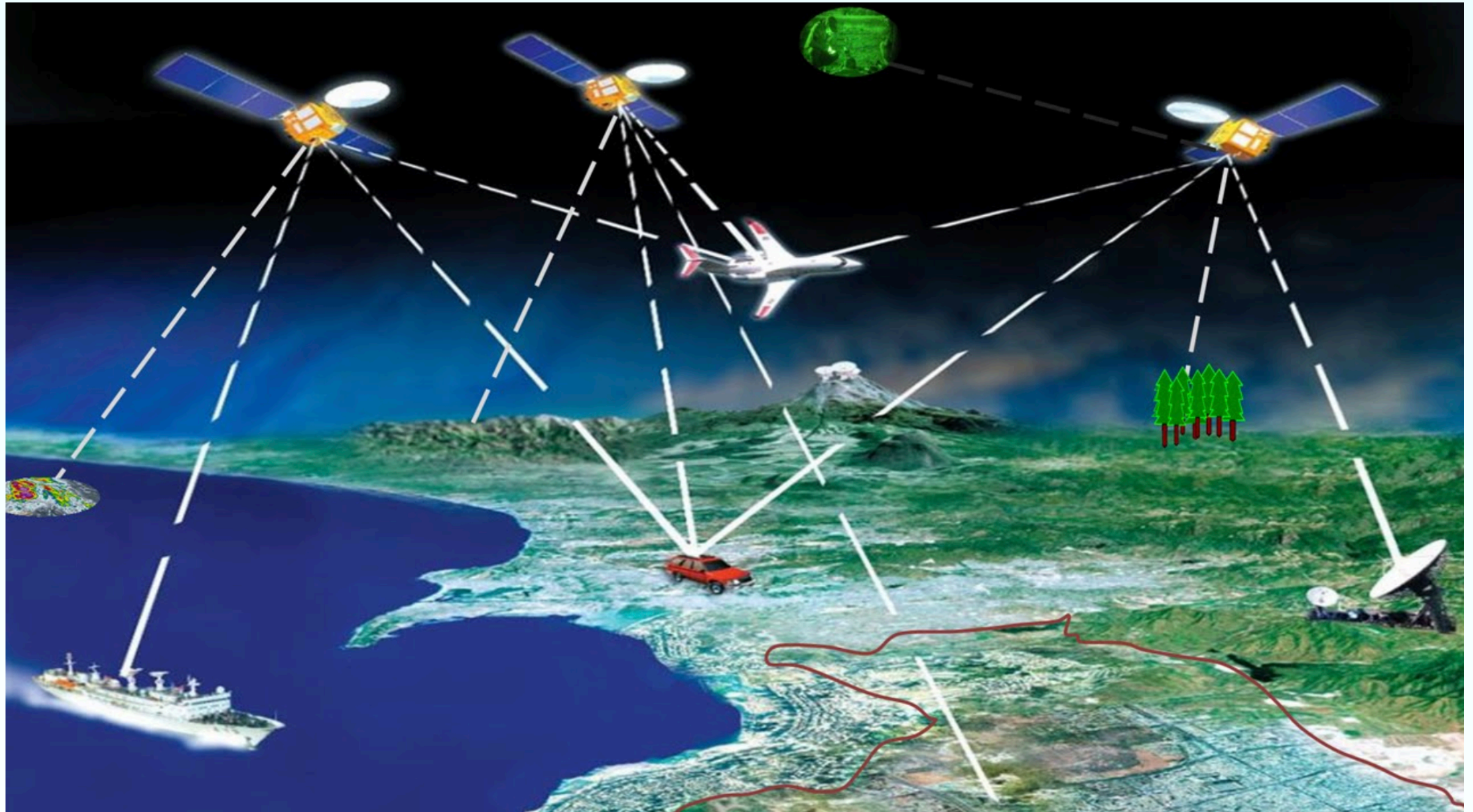


Uses **particle accelerators** to deliver precise doses, well-focused on diseased tissues like tumors and with minimal spill over to healthy tissues

Around **100 facilities of proton therapy** spread all over the world

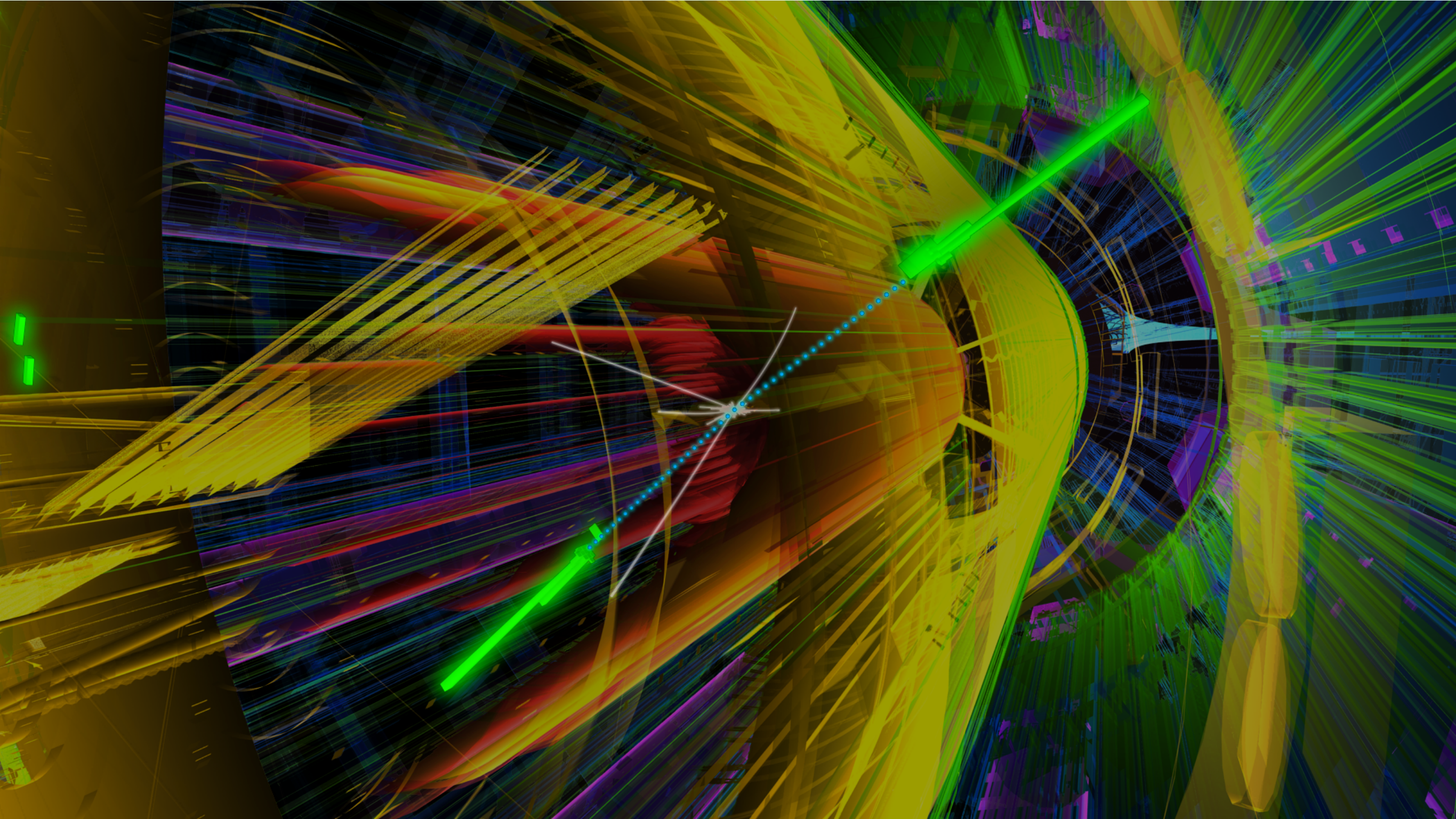
Global Positioning System

A system of connected satellites that, once accounted for the effects of **Einstein's Special and General Relativity**, allow determining our position with an accuracy of a few meters



Remember to **thank Einstein** next time you find your way using Google Maps!

Fascinating times for high-energy physics!



Stay tuned for new discoveries!

Fascinating times for high-energy physics!

An abstract visualization of particle tracks, likely from a particle detector. The image features a dense network of colorful lines (yellow, green, blue, red) representing particle paths. A prominent green line runs diagonally across the center. A dark grey banner with white text is overlaid on the image.

Thanks for your attention!

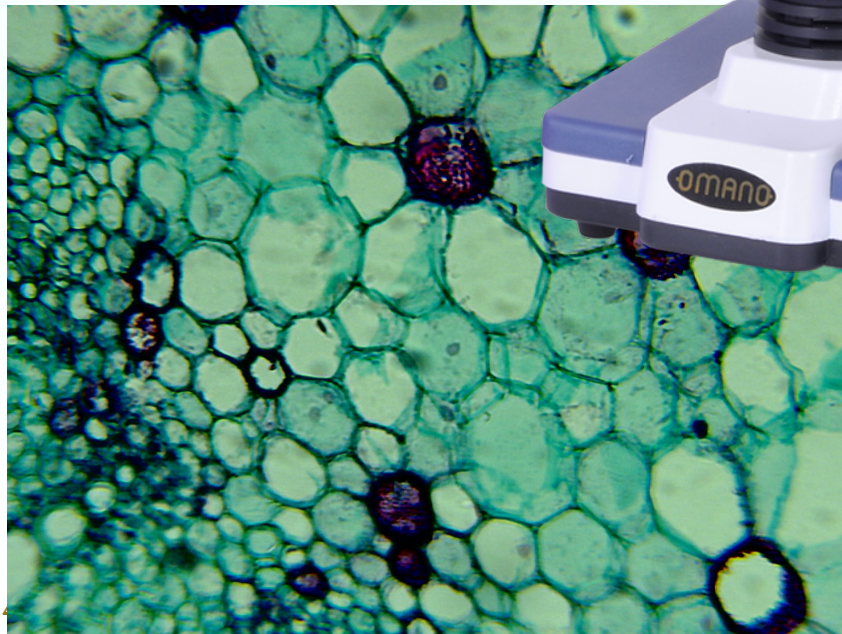
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Extra material

Remarkable facts about the LHC

- ☑ The LHC is the **most powerful microscope ever constructed**, able to see the smallest things ever seen by mankind!

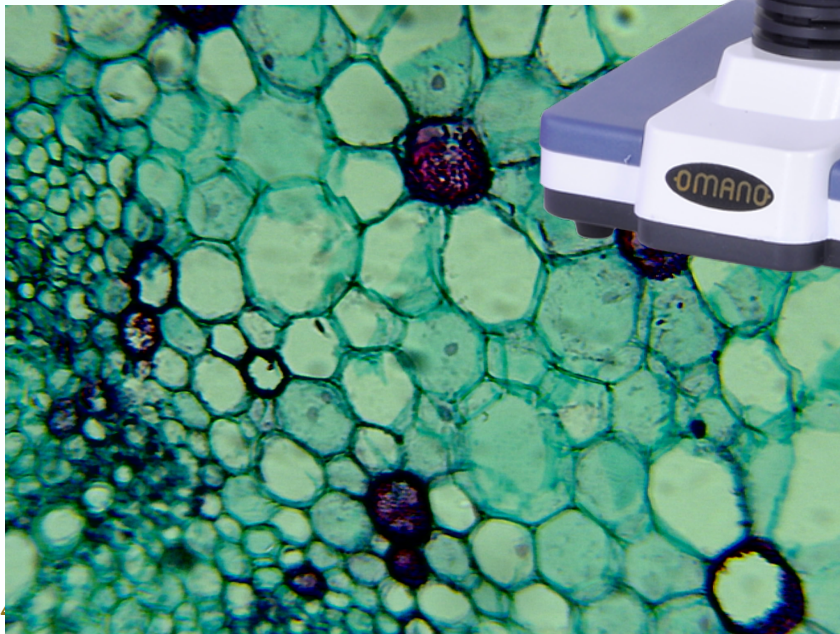
Just as I can use
a **microscope** to
see cells



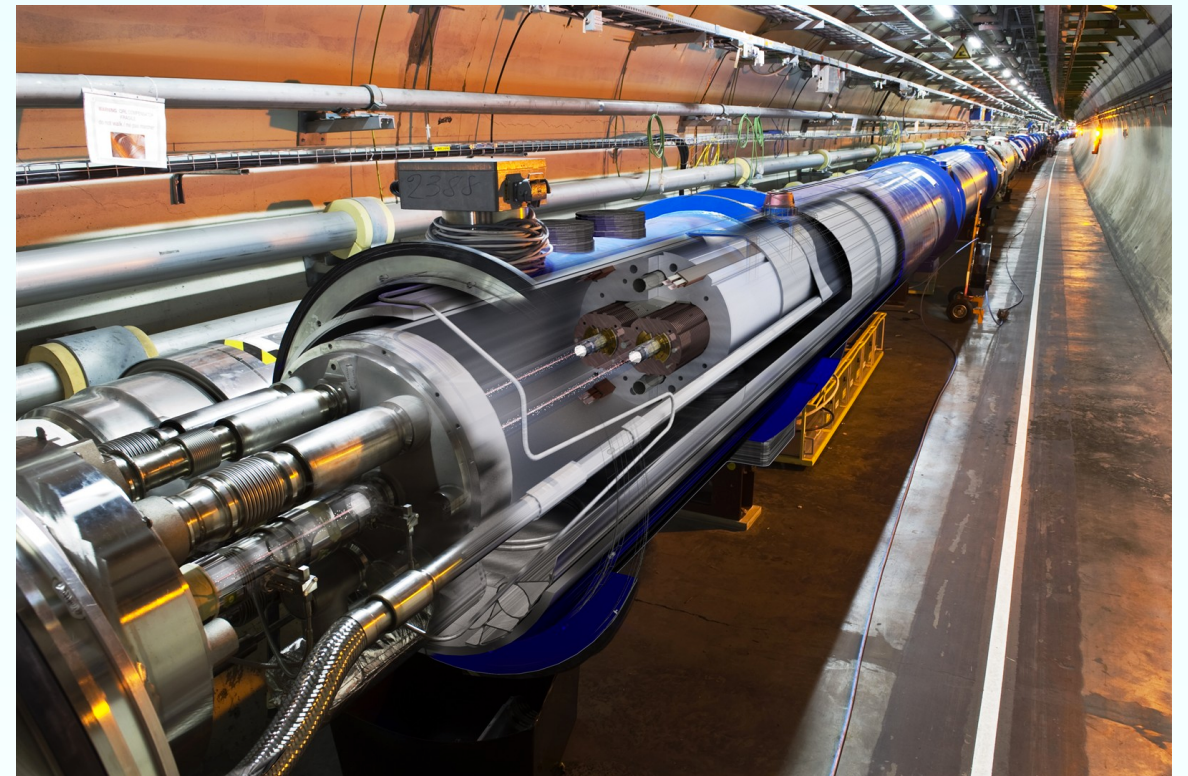
Remarkable facts about the LHC

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Just as I can use
a **microscope** to
see cells



... I can use the LHC to see **new
fundamental particles**



ONE OF THE THINGS PEOPLE
PREDICT WILL COME OUT IS

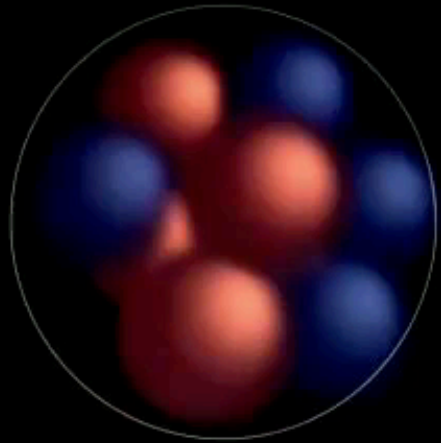
THE
HIGGS
BOSON



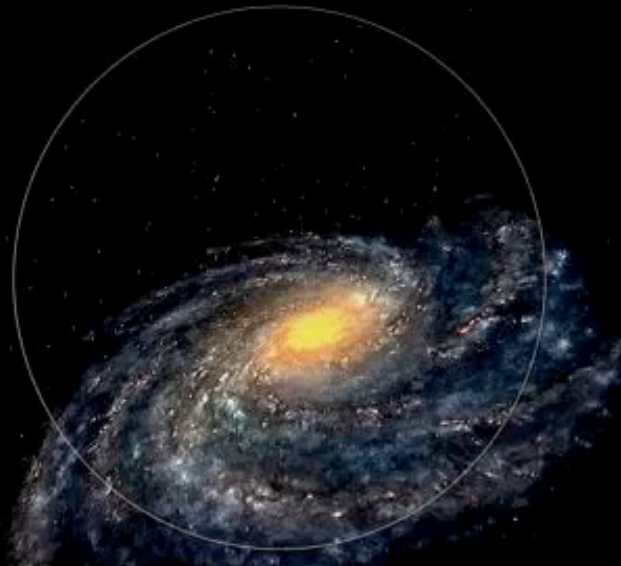
THE HIGGS IS THE
PARTICLE RESPONSIBLE
FOR GIVING MASS TO
OTHER PARTICLES.



From galaxies to quarks



Powers of Ten (-18/+26)



<https://www.youtube.com/watch?v=bhofN1xX6u0>