Cosmic Rays

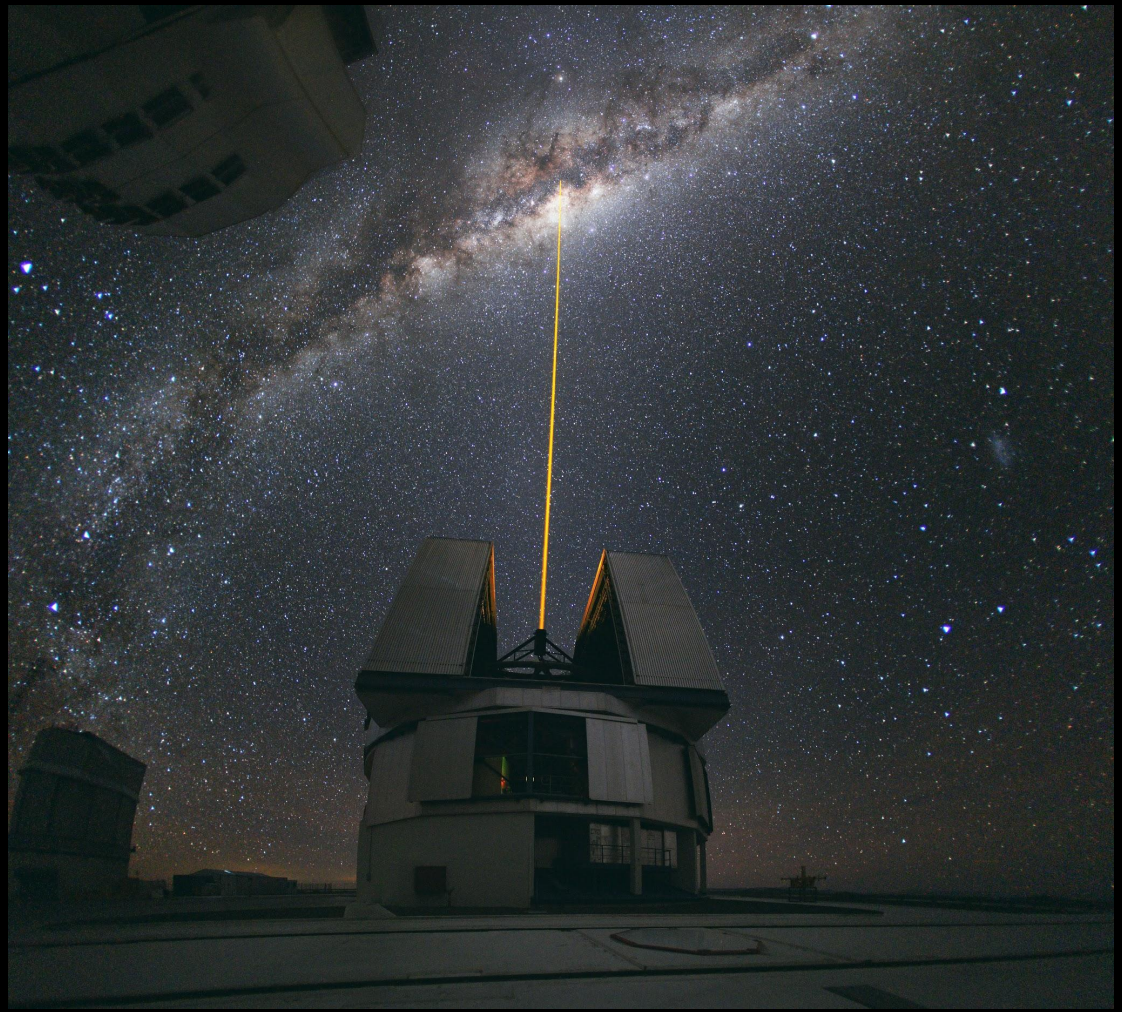
& other particles from outer space



05.05.2025

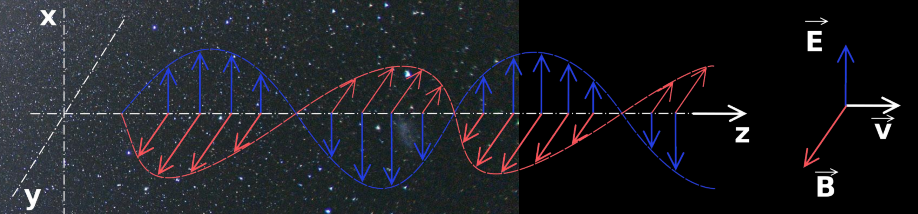
Lorenzo Ramella

What is astroparticle Physics?



Paranal Observatory (part of the European Southern Observatory) in the Atacama Desert, Chile

Astrophysicists look at visible light



Which is electromagnetic radiation / photons coming from space

Paranal Observatory (part of the European Southern Observatory) in the Atacama Desert, Chile

Is there anything else coming from space?

Yes

Neutrinos

Gravitational Waves

Dark Matter (maybe)



Protons (and other charged particles)

Nuclei

And also asteroids, cosmic dust …

Yes

Neutrinos

Gravitational Waves

Dark Matter (maybe)



Protons (and other charged particles)

+

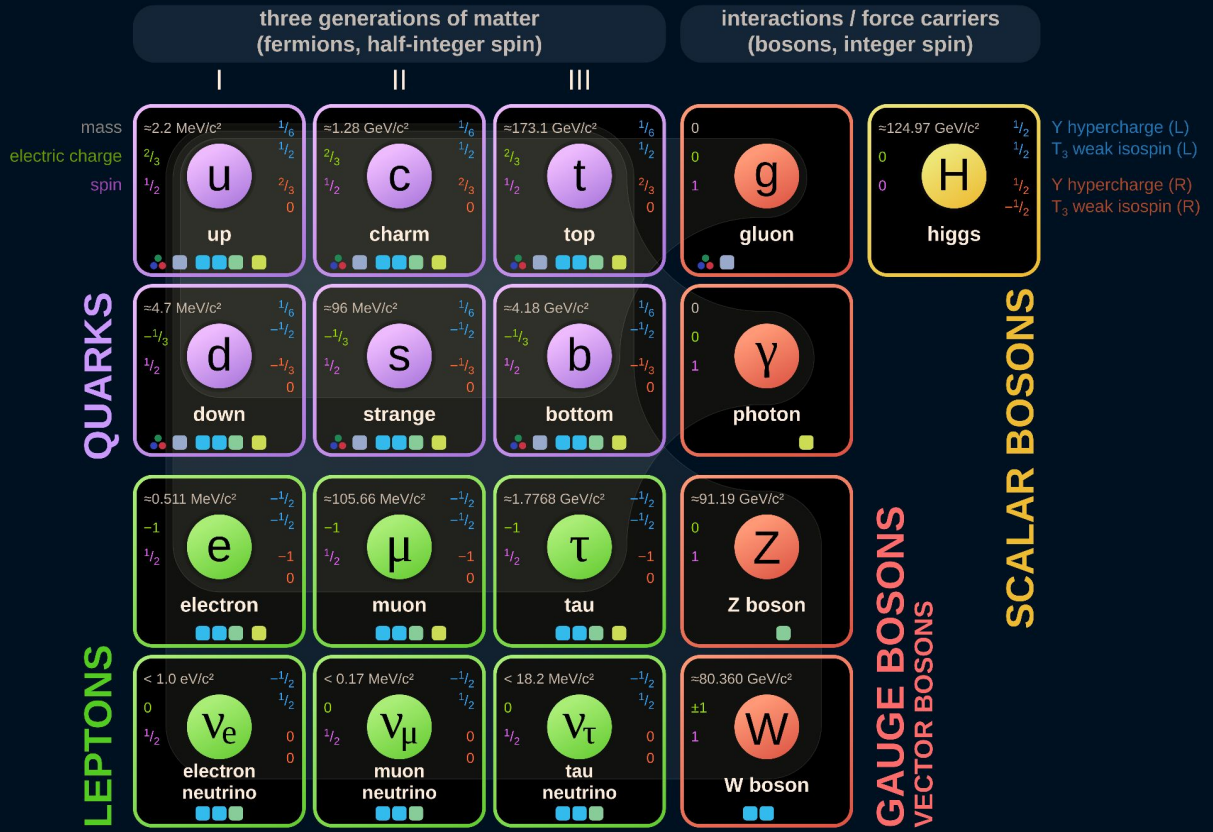
Nuclei

Cosmic Rays

And also asteroids, cosmic dust …

What is a particle?

Standard Model of Elementary Particles

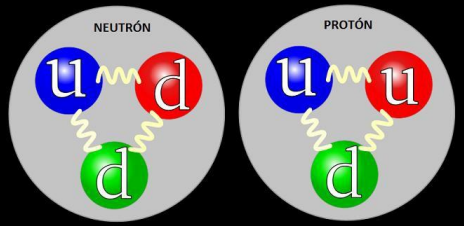


The building blocks of matter

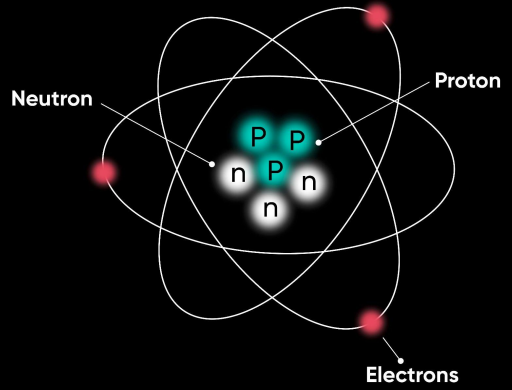
Quarks



Hadrons



Atoms



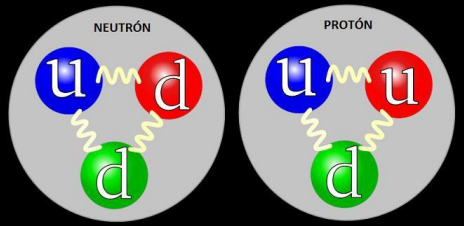
The building blocks of matter

Quarks



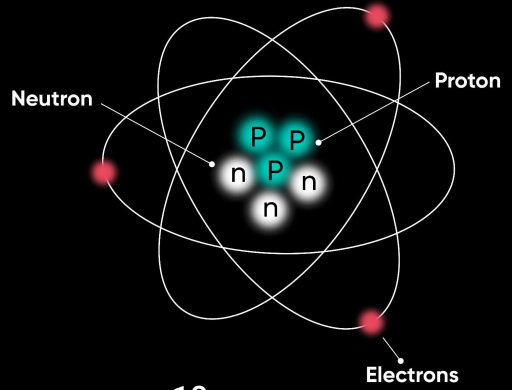
Immeasurable

Hadrons



~ 10^{-15} m
= 0.000000000000001 m

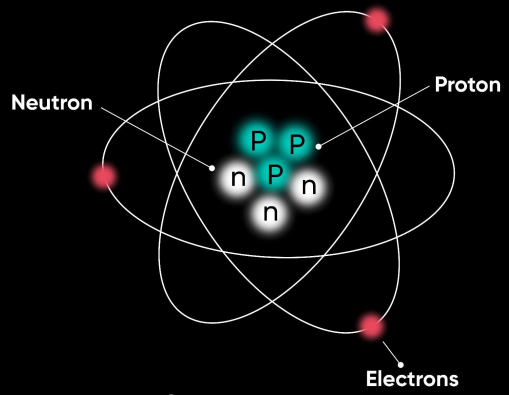
Atoms



~ 10^{-10} m
= 0.0000000001 m

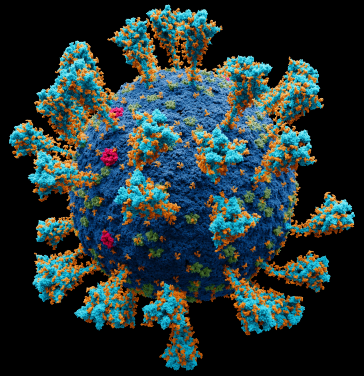
For comparison

Atom



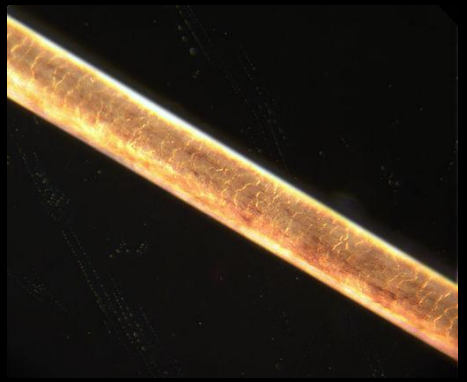
~ 10^{-10} m
= 0.0000000001 m

SARS-CoV-2



~ 10^{-7} m = 100 nm
= 0.0000001 m

Hair



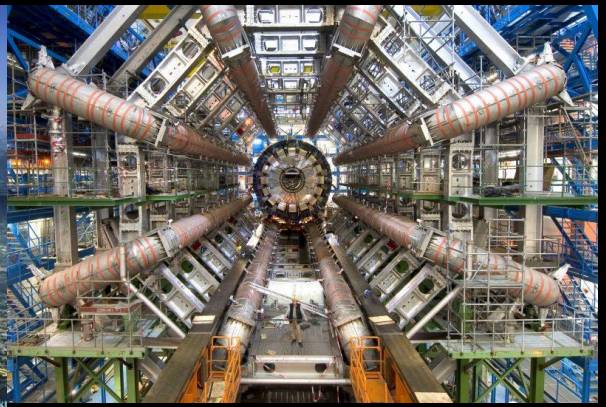
~ 10^{-4} m = 0.1 mm

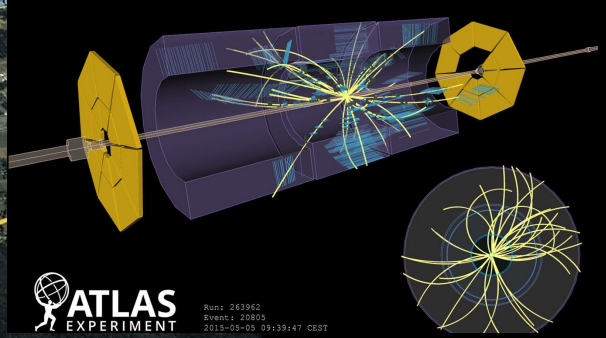
Particle physics research



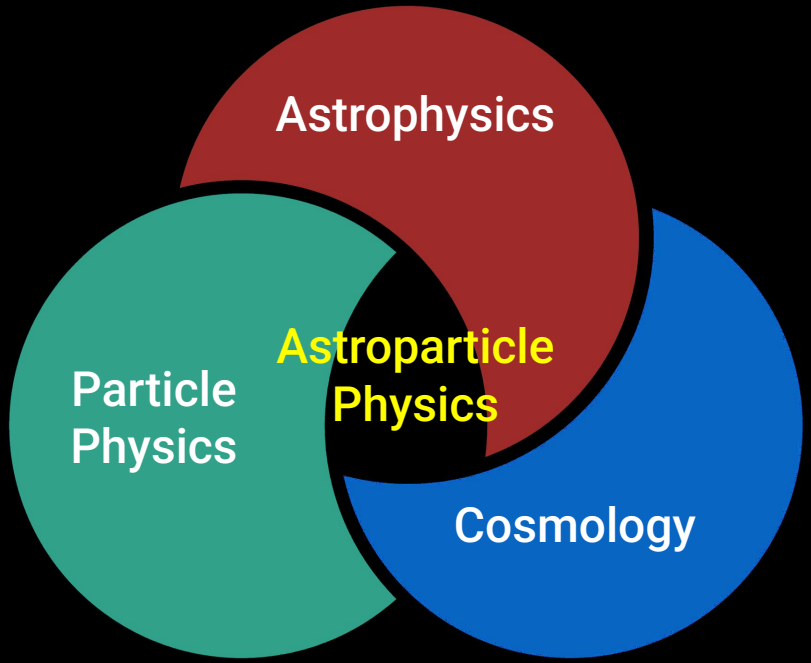
Particle physics research



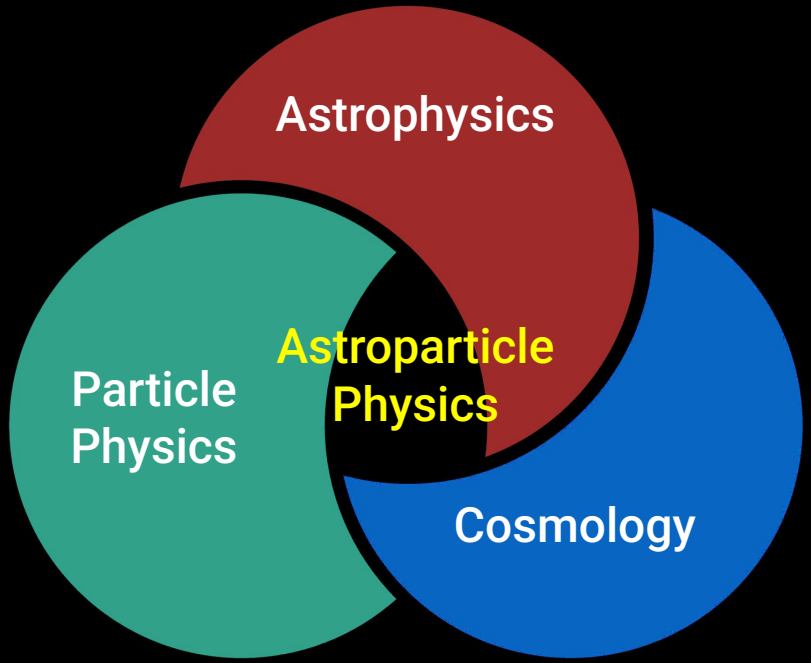




Astroparticle physics research



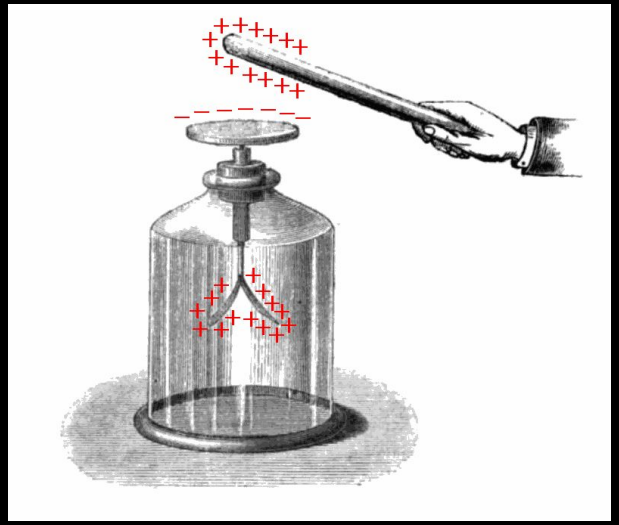
Astroparticle physics research



- Astrophysics:
  We look at particles to understand the universe
- Particle Physics:
  We look at the universe to understand particles
- Cosmology:
  We investigate the nature and the history of the universe

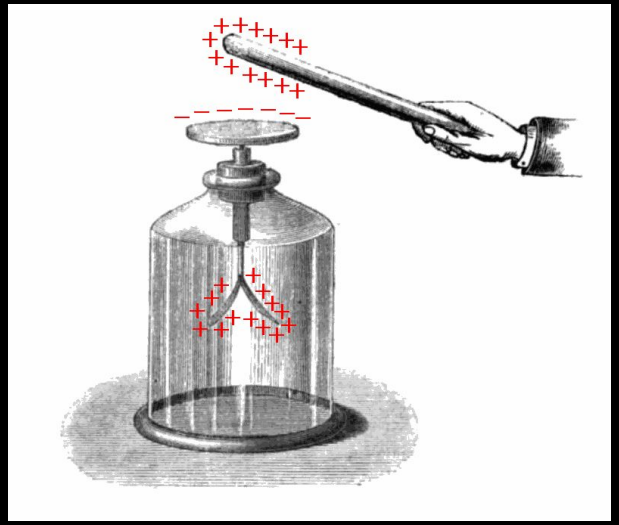
A brief history

The electroscope

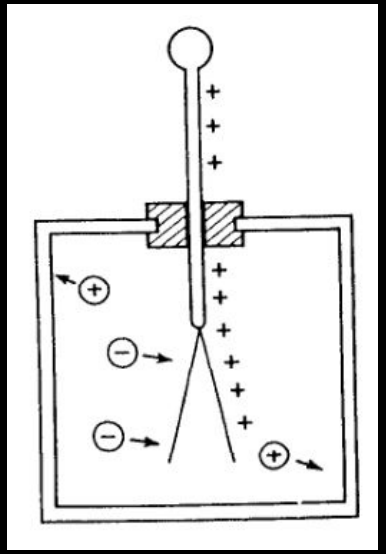


A gold-leaf electroscope

The electroscope

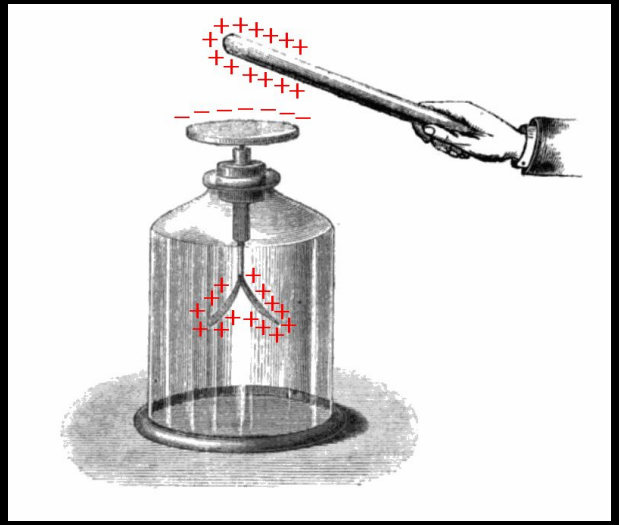


A gold-leaf electroscope

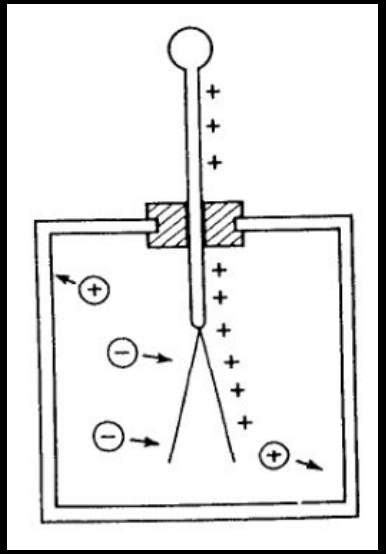


Electroscopes discharge naturally due to the ionization of the air

The electroscope



A gold-leaf electroscope



Electroscopes discharge naturally due to the ionization of the air

What is the reason for the ionization of the air?

Radiation causes ionization

- We know that radiation causes ionization
- There MUST be some kind of natural, “background” radiation present at all times in the air
- Where does this radiation comes from?

Radiation causes ionization

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From the ground



A sample of Uraninite, a radioactive mineral

Radiation causes ionization

- We know that radiation causes ionization
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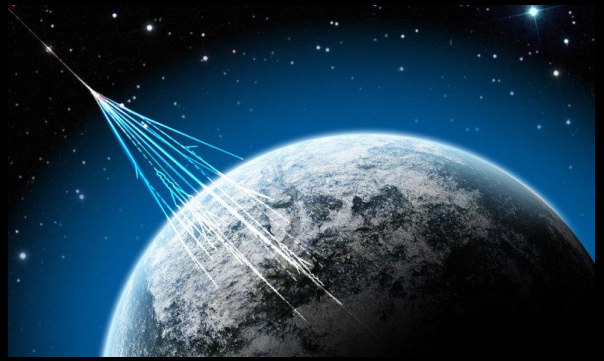
From the ground



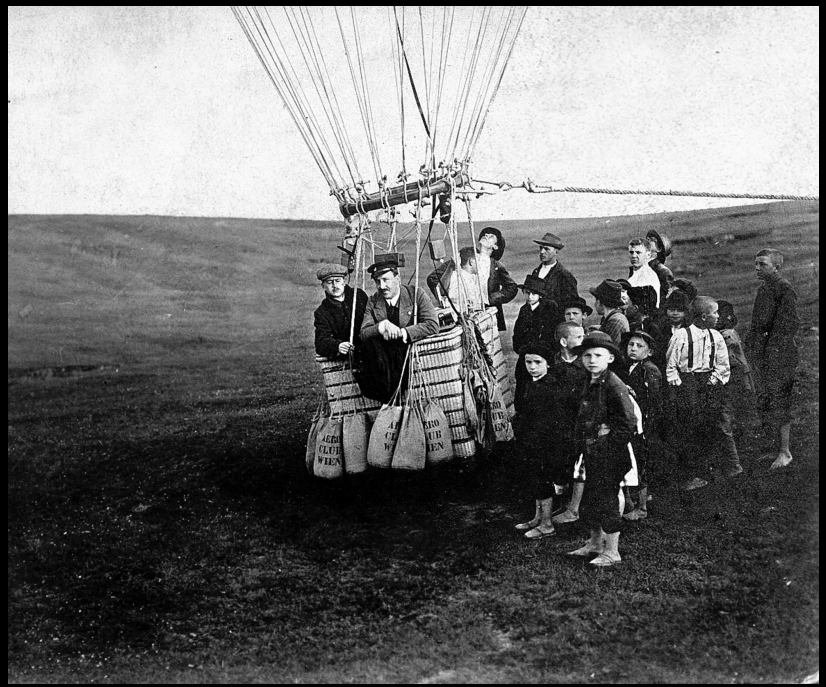
A sample of Uraninite, a radioactive mineral

or

From above



The discovery of Cosmic Rays



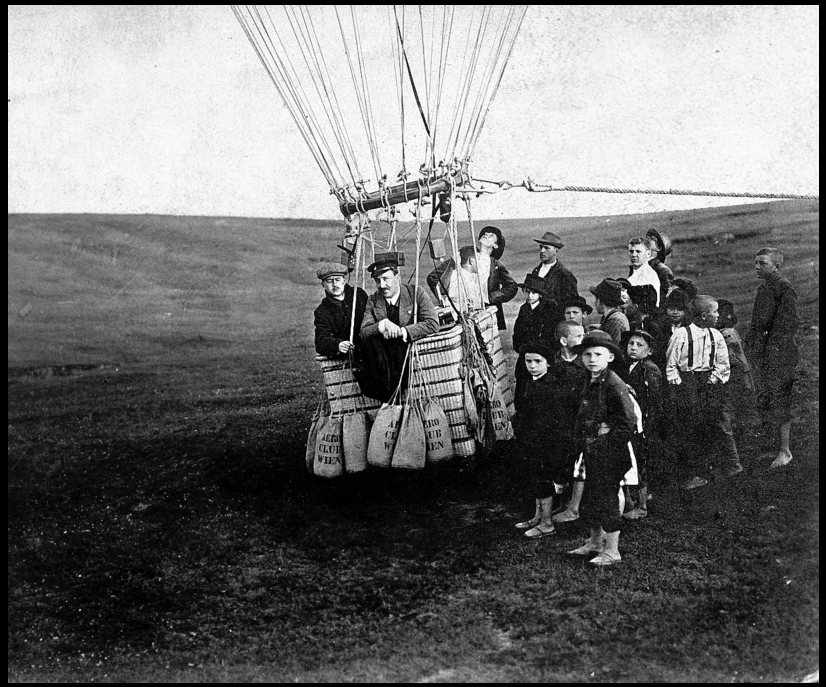
Victor Hess, center, departing from Vienna on a hot-air balloon, about 1911

- The decisive experiment was performed using hot-air balloons

Victor Hess



The discovery of Cosmic Rays



Victor Hess, center, departing from Vienna on a hot-air balloon, about 1911

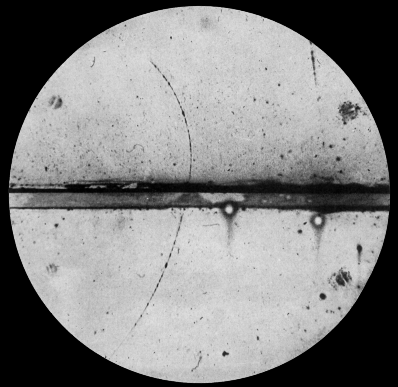
- The decisive experiment was performed using hot-air balloons
- The amount of natural radiation INCREASES at high altitude
- There is radiation coming from space

Victor Hess



Nobel Prize in Physics in 1936

History of Cosmic Rays

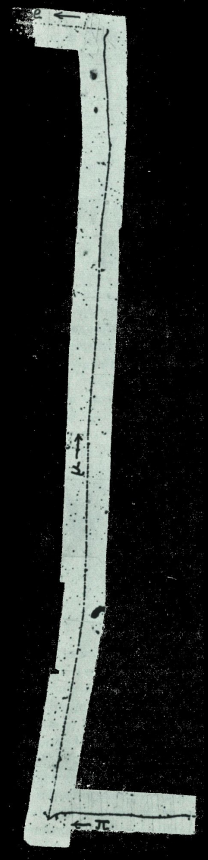


Discovery of the positron, the first antimatter particle, by Anderson in 1932

Cosmic rays are a natural source of high energy particles

- Discovery of new particles:
  - Muon (1936)
  - Pion (1947)
- Discovery of antimatter (1932)

Ever more refined experiments showed that this radiation is mostly composed of protons and nuclei



Today

Open questions:

- **Where do Cosmic Rays come from?**
  - How do these particle accelerate to high energies?
- **What exactly is their composition?**
  - How many protons
  - How many irons
  - etc…
- **What happens along the way?**

Today

Open questions:

- **Where do Cosmic Rays come from?**
  - How do these particle accelerate to high energies?
- **What exactly is their composition?**
  - How many protons
  - How many irons
  - etc…
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Experiments in space:

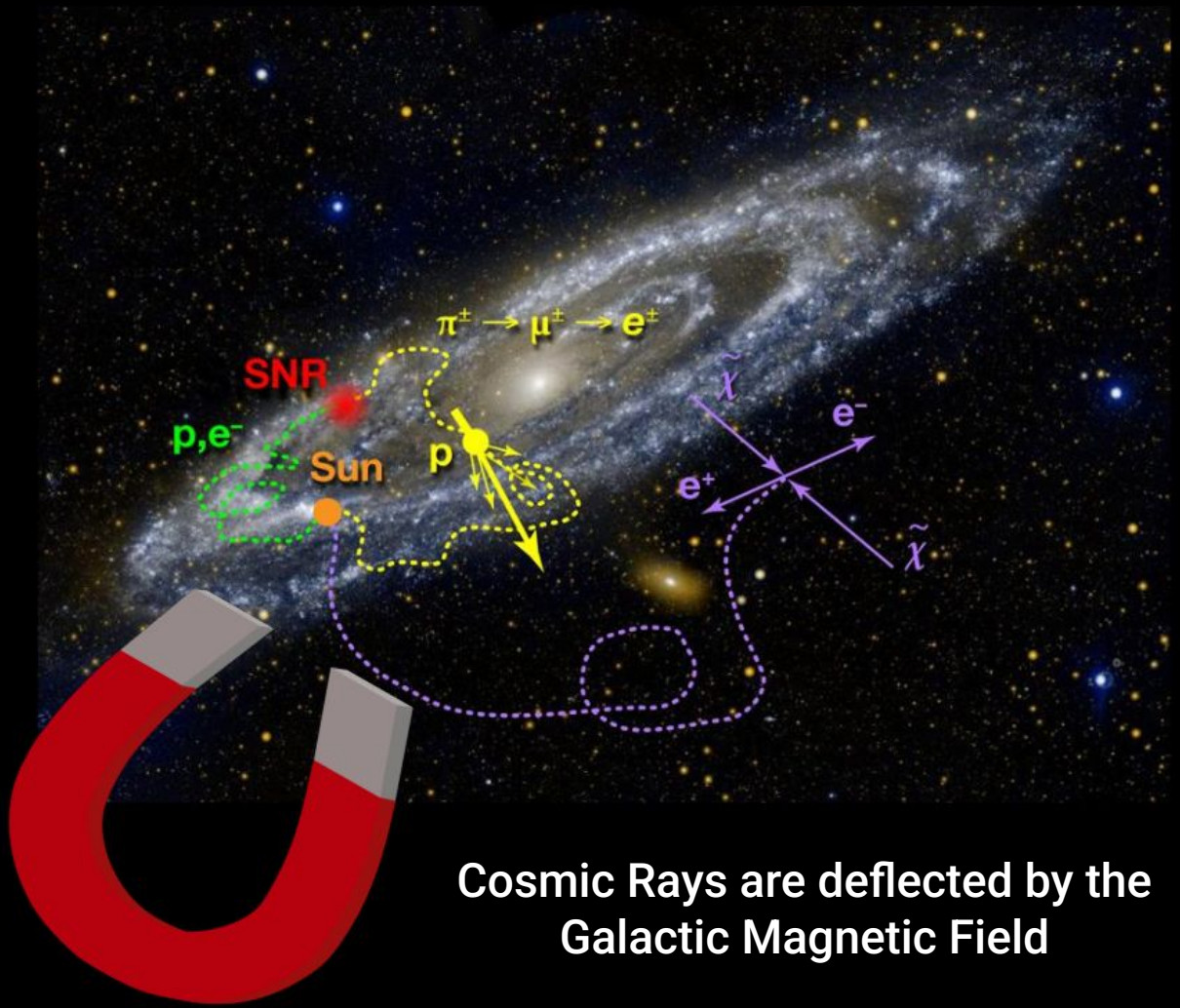


And on the ground:

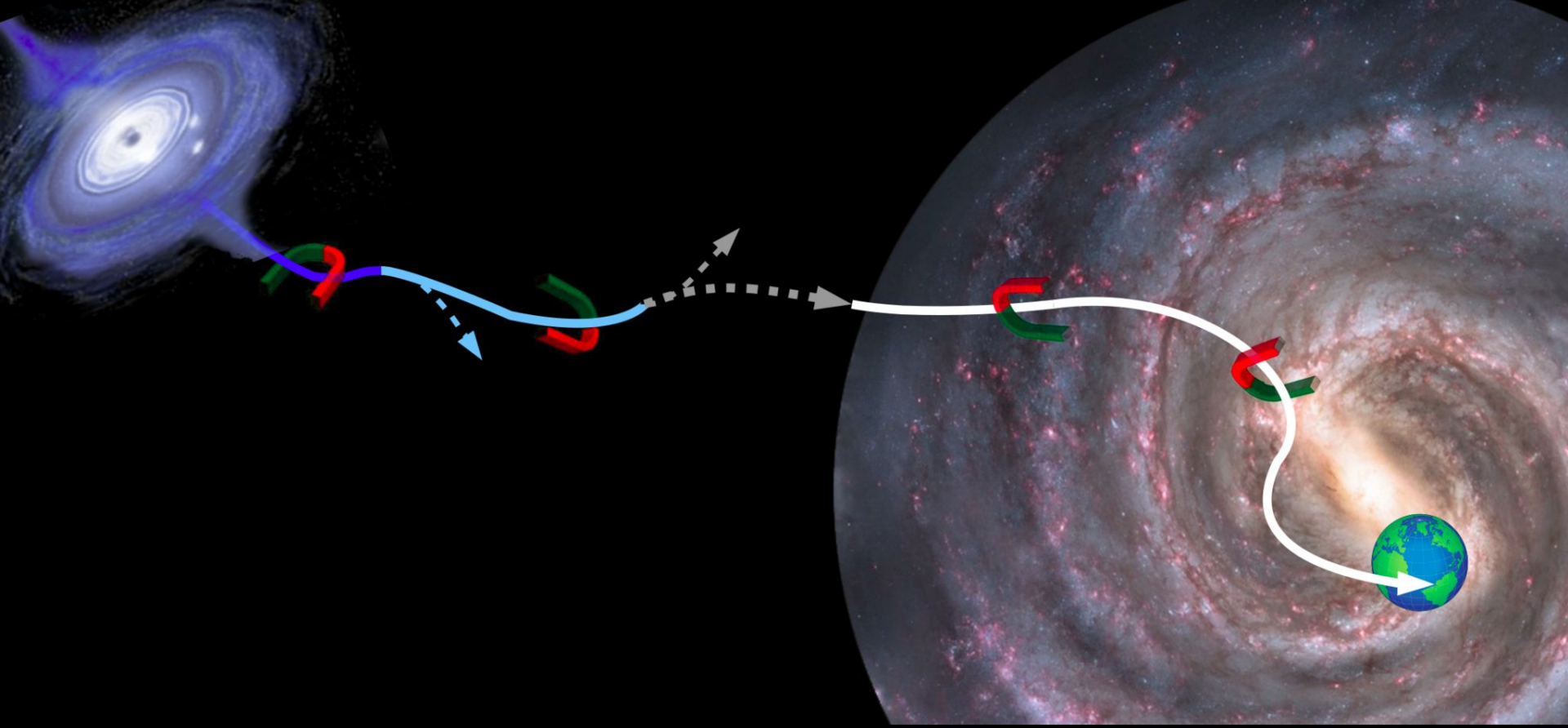


Let’s have a break

Arrival directions

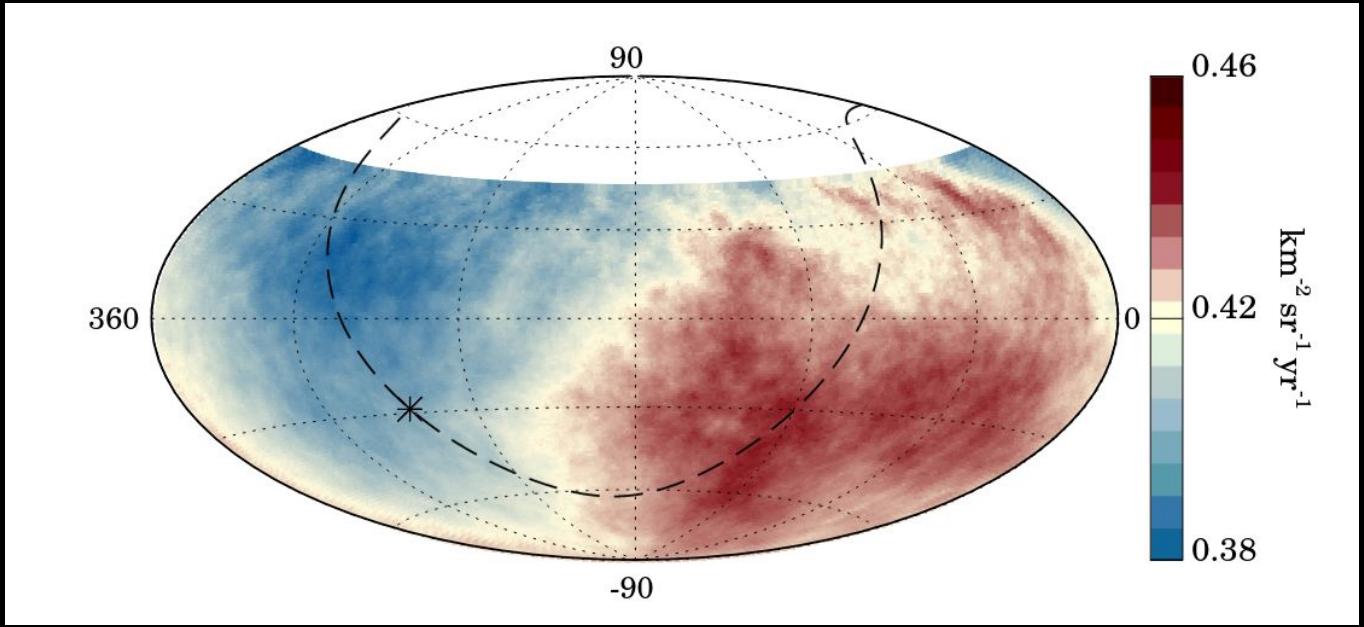


Cosmic Rays are deflected by the Galactic Magnetic Field



The arrival direction does not correspond to the position of the source

More Energy -> Less Deflection

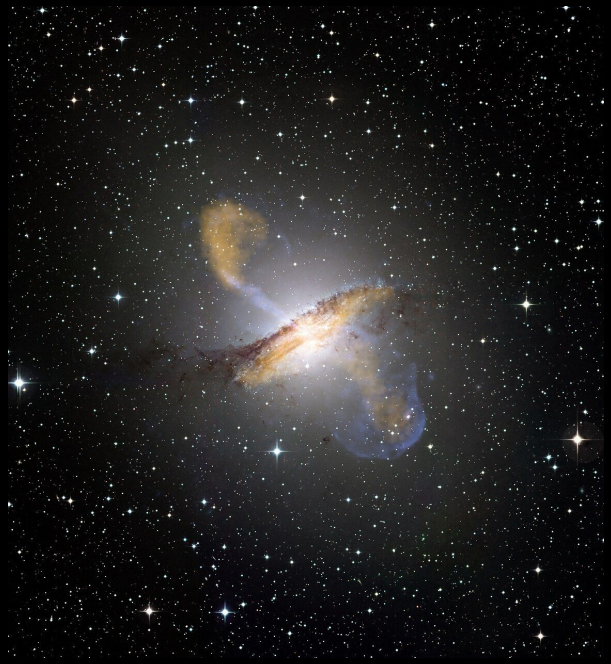


Anisotropy at high energies: extragalactic sources

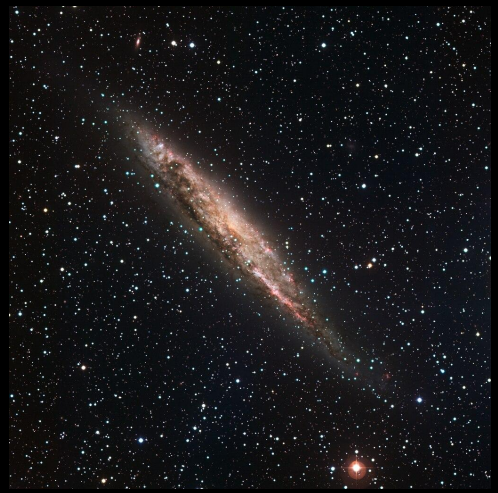
Candidate Sources



Neutron Stars



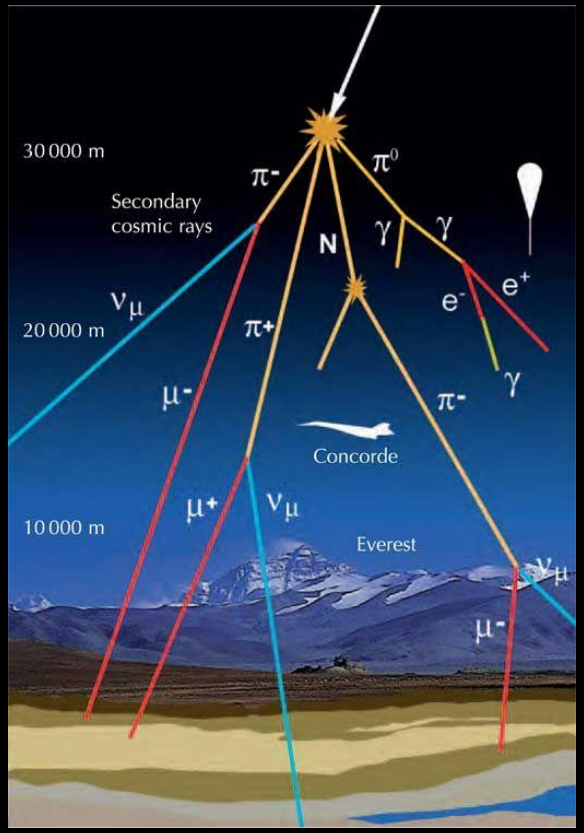
Active Galactic Nuclei



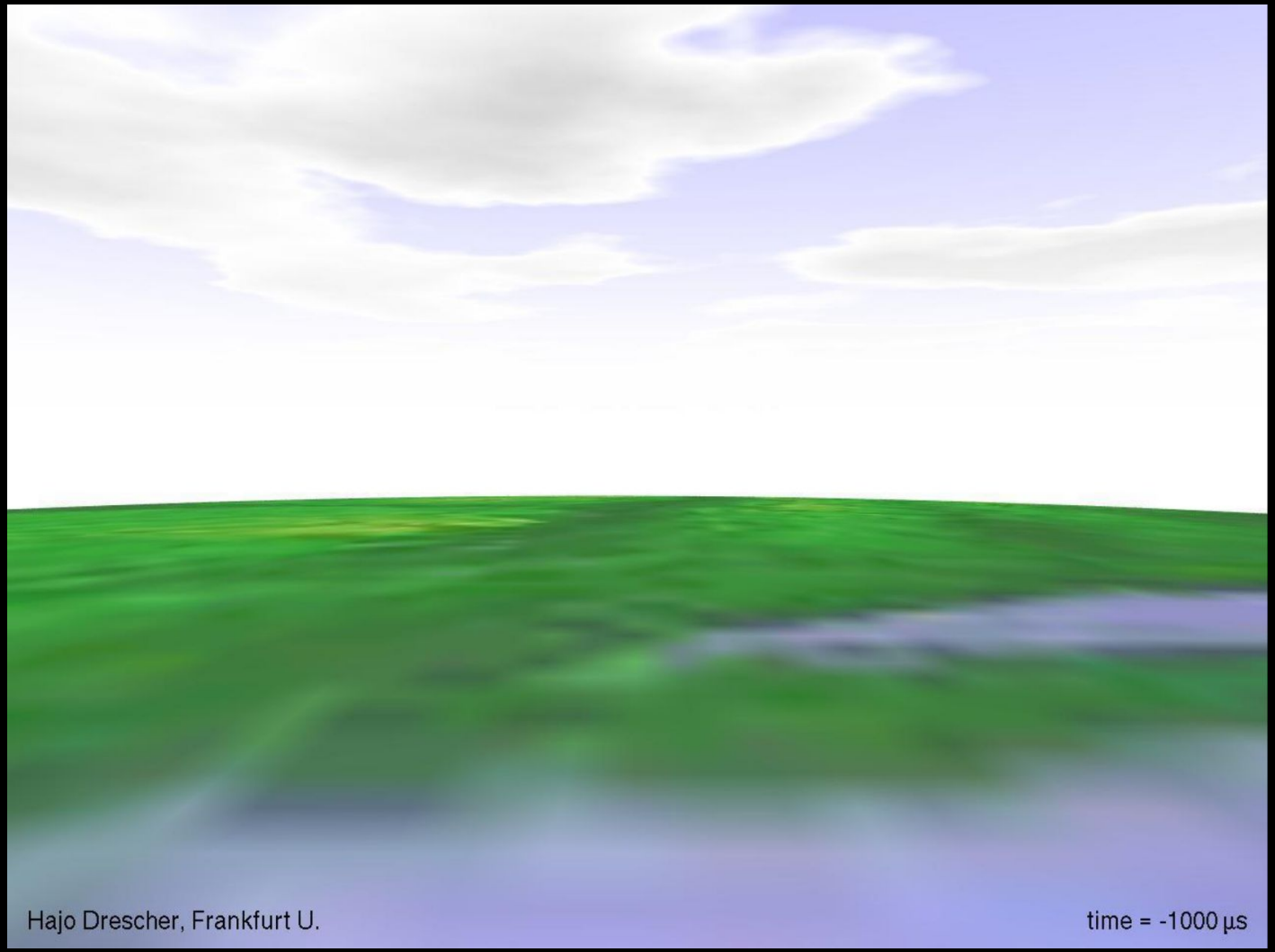
Starburst Galaxies

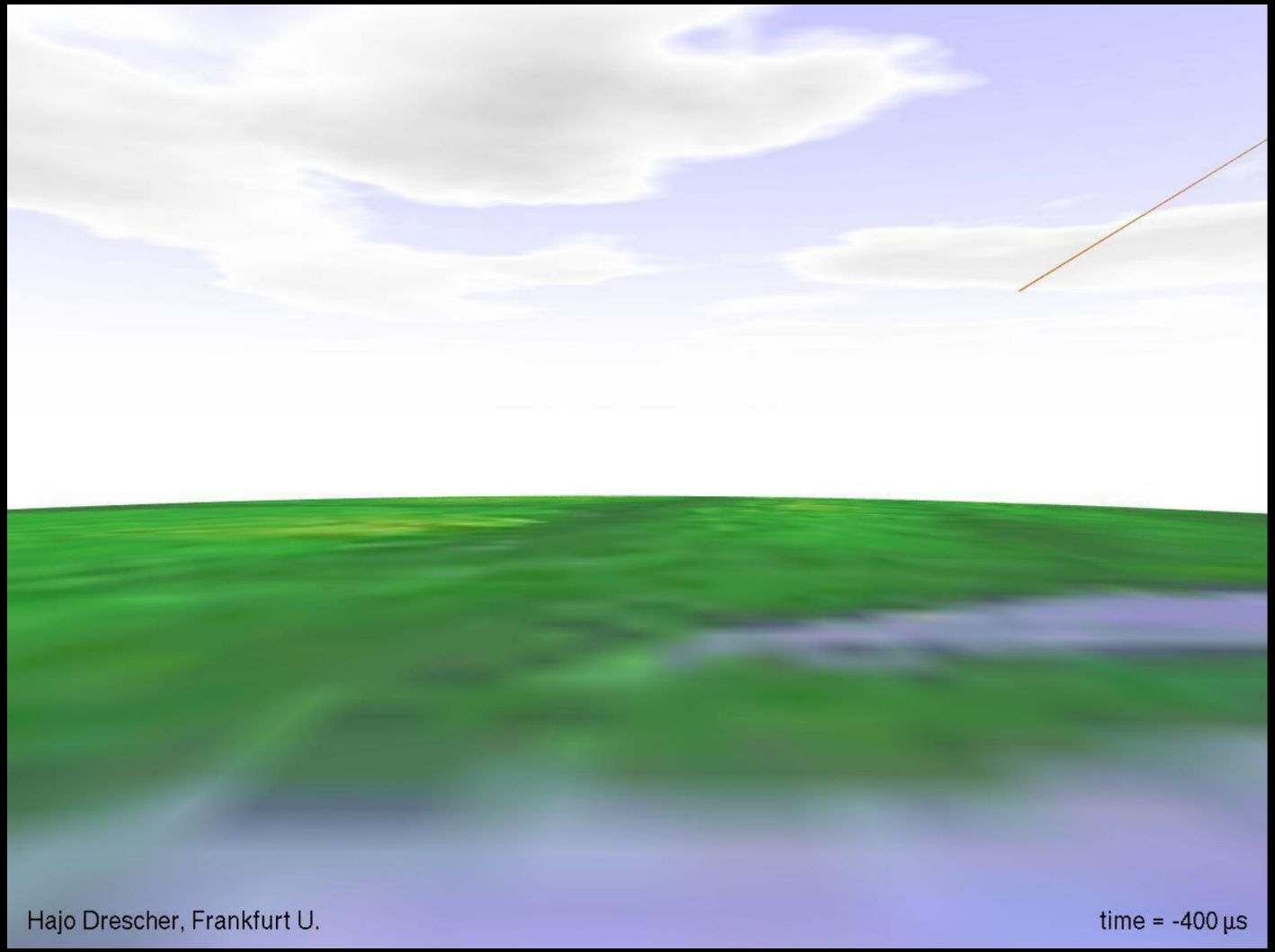
How do we detect Cosmic Rays?

Air Showers

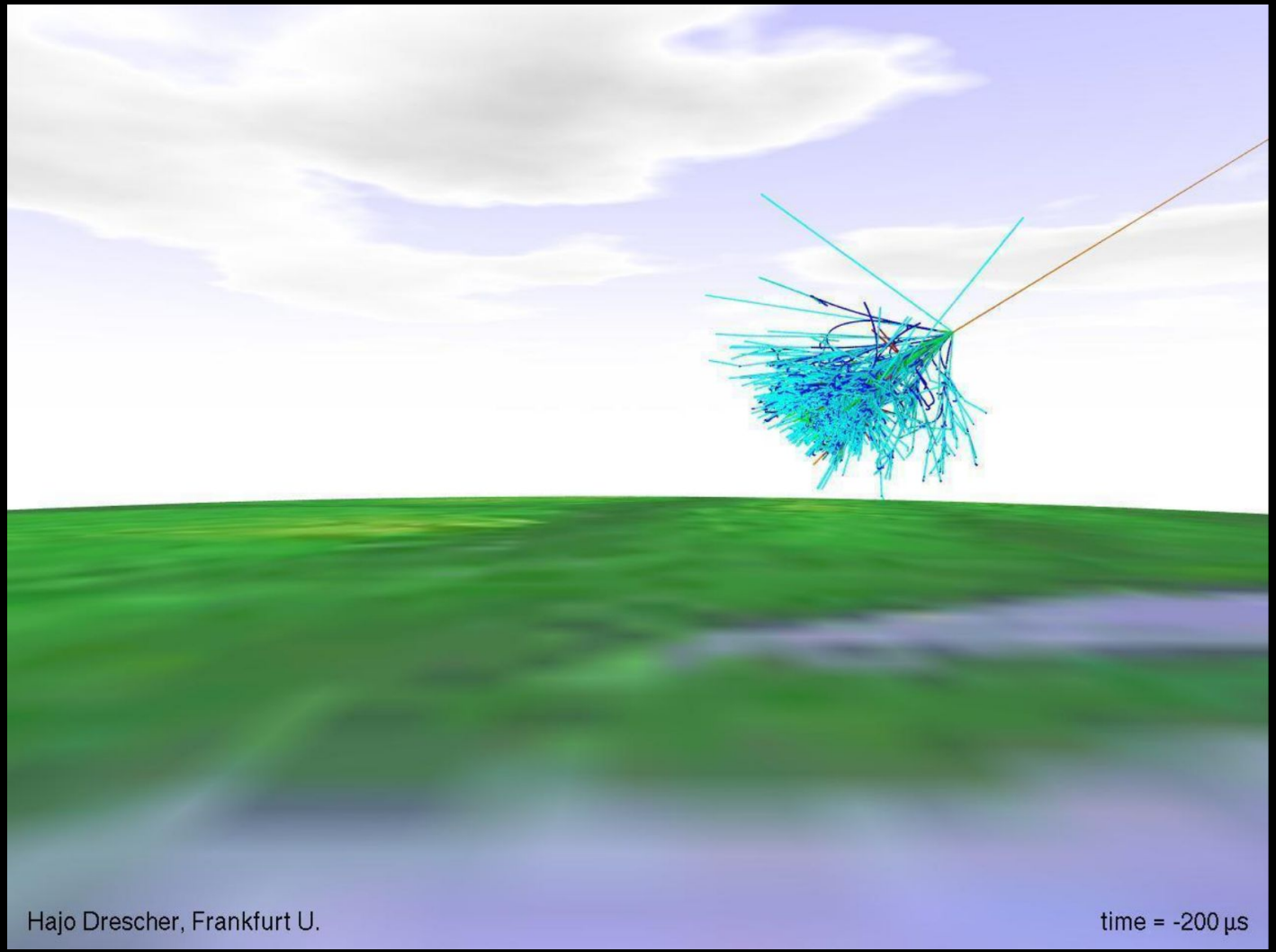


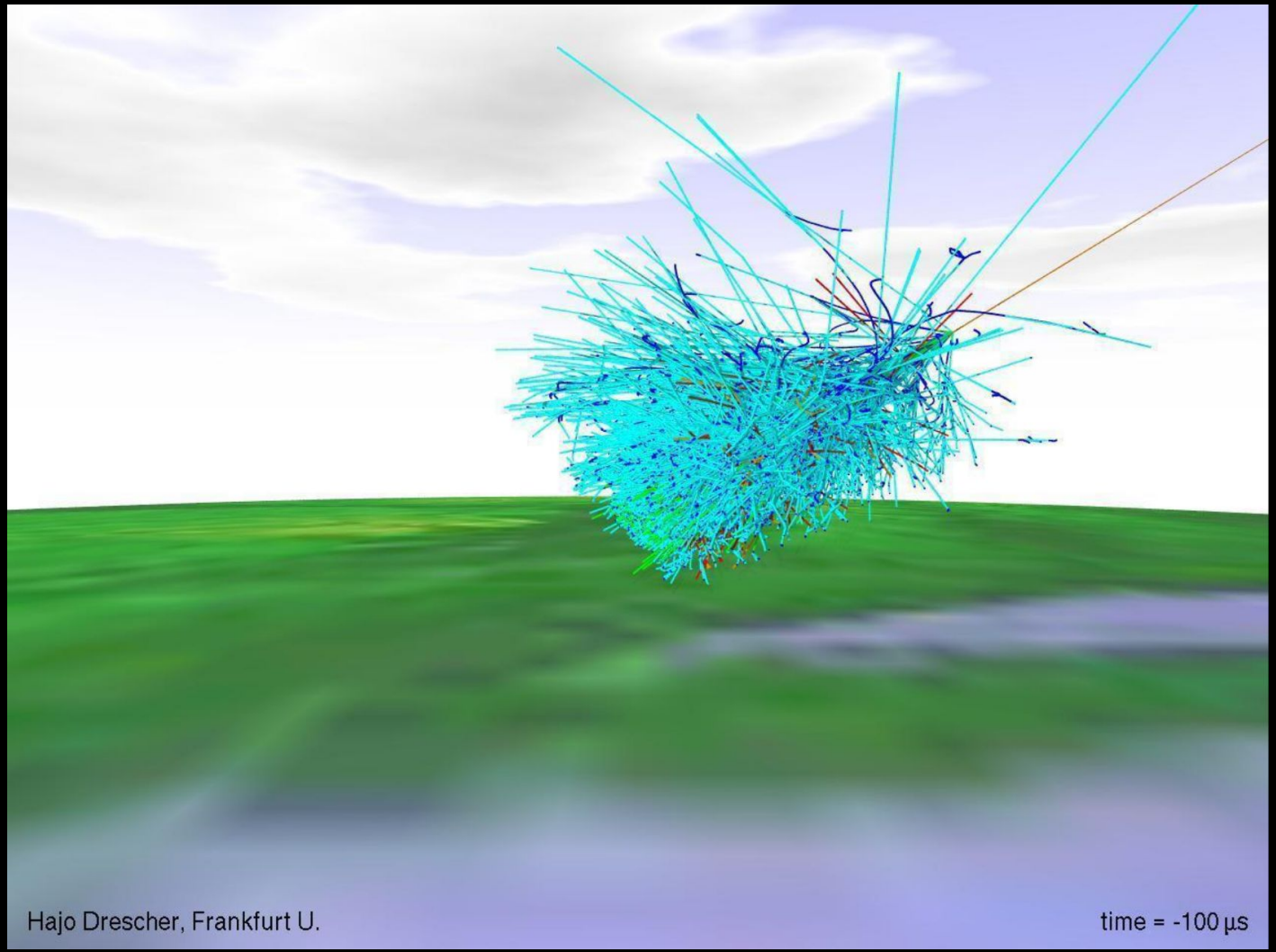
$E = mc^2$

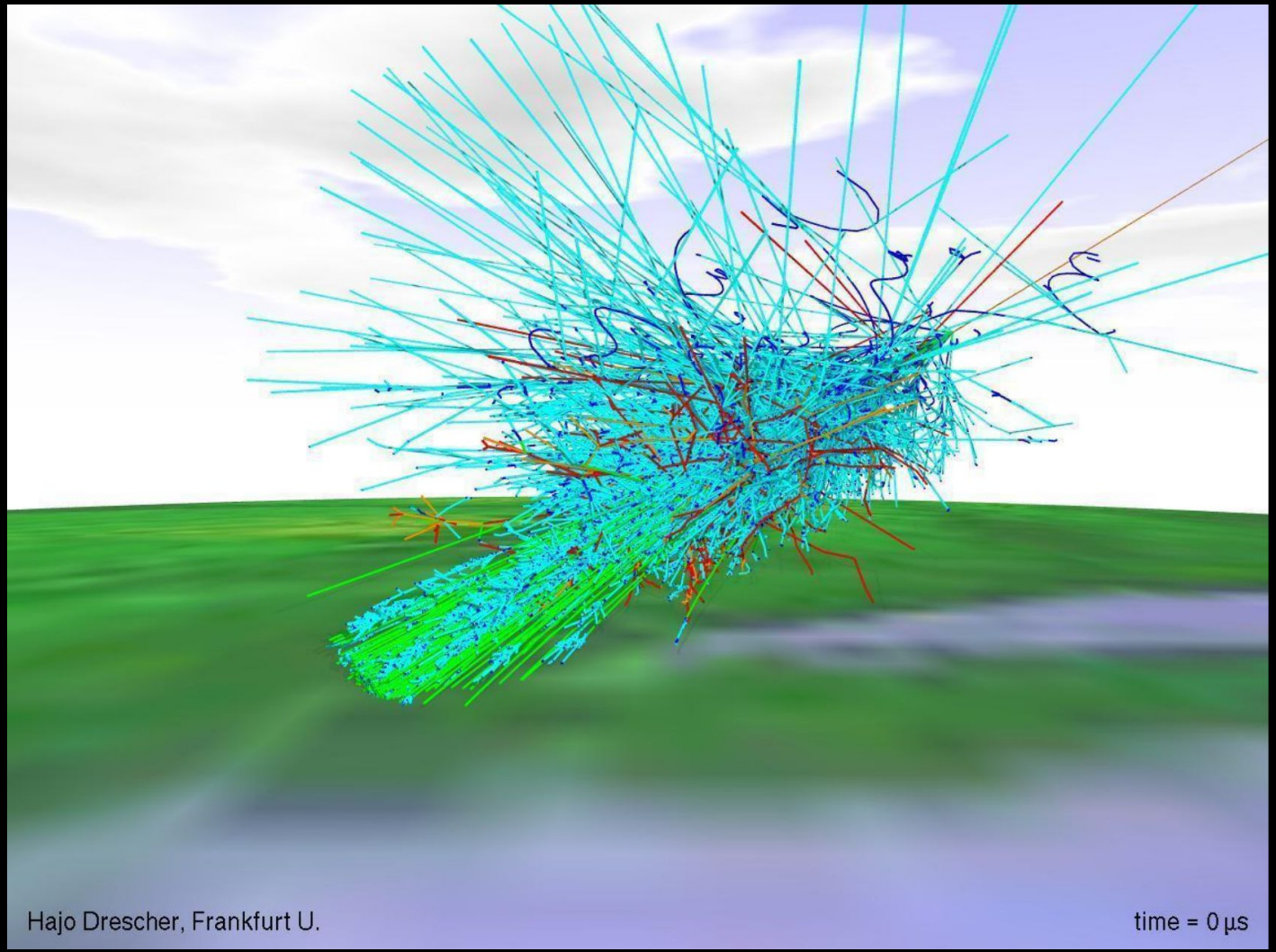

Hajo Drescher, Frankfurt U.
time = -1000 µs

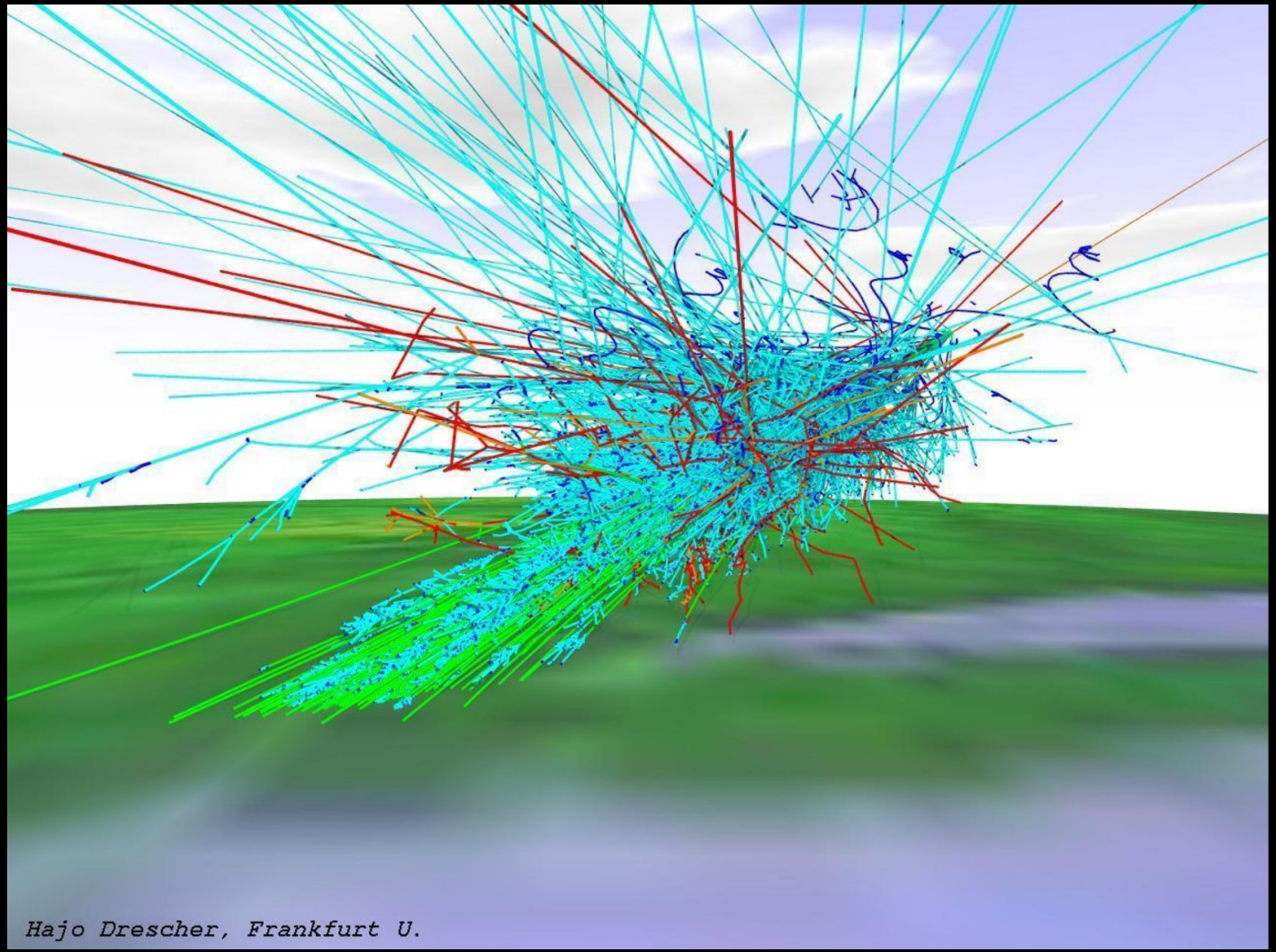

Hajo Drescher, Frankfurt U.
time = -400 µs


Hajo Drescher, Frankfurt U.
time = -300 µs


Hajo Drescher, Frankfurt U.
time = -200 µs


Hajo Drescher, Frankfurt U.
time = -100 µs


Hajo Drescher, Frankfurt U.
time = 0 µs

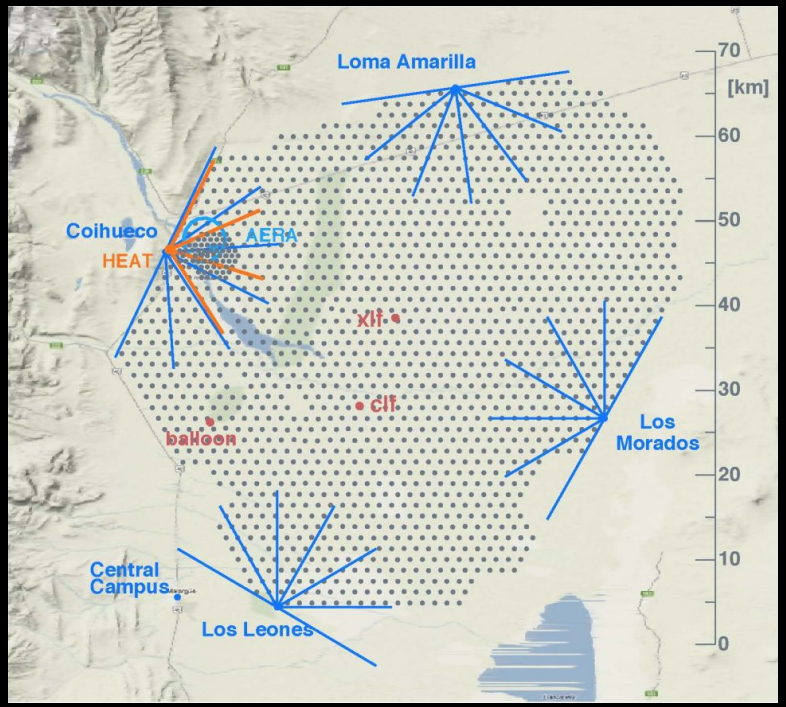

Hajo Drescher, Frankfurt U.

How do we measure a particle shower?

KASCADE



Pierre Auger Observatory

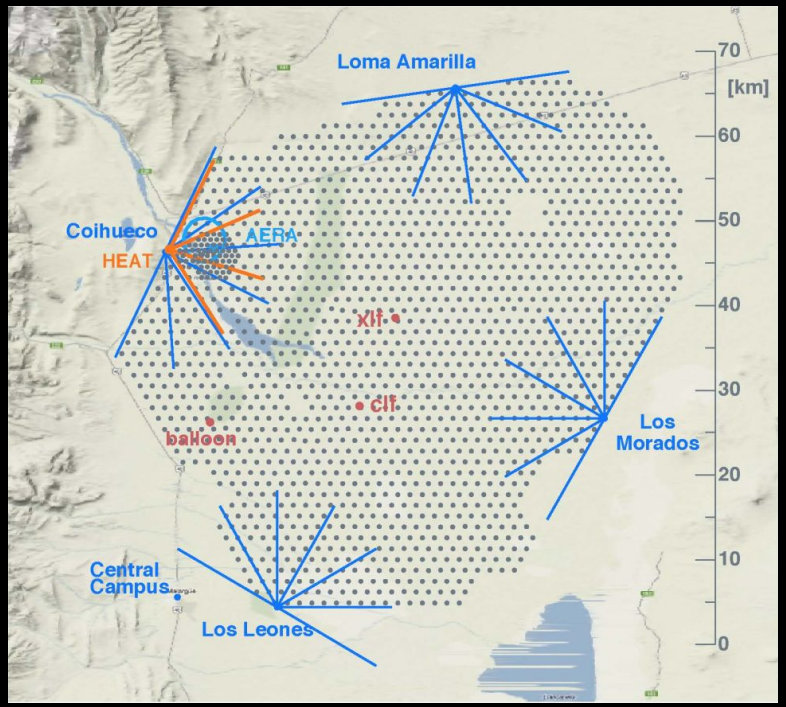


In Argentina 🇦🇷

- ~ 3000 km^2
- ~ 1500 m a.s.l.
- 1660 stations on the ground

The largest Cosmic Rays Observatory in the world!

Pierre Auger Observatory



In Argentina 🇦🇷

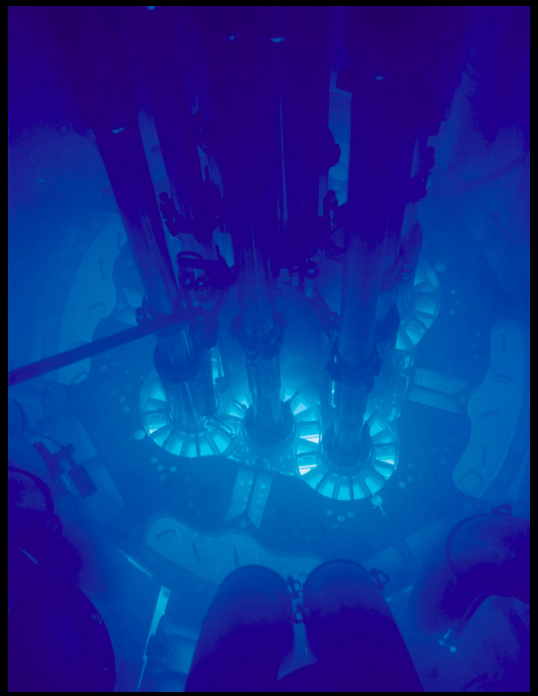
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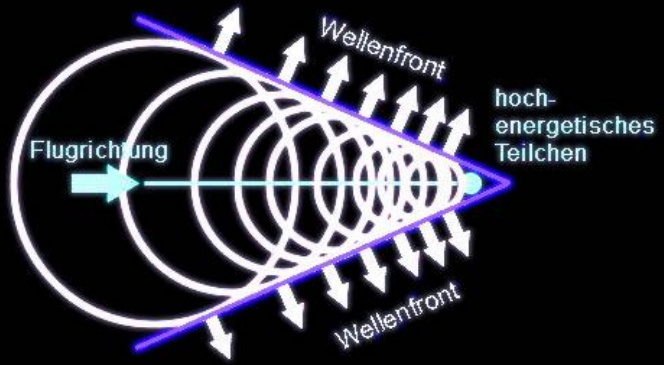
Each station is a tank full of water
Particle detection with Cherenkov light

Cherenkov light

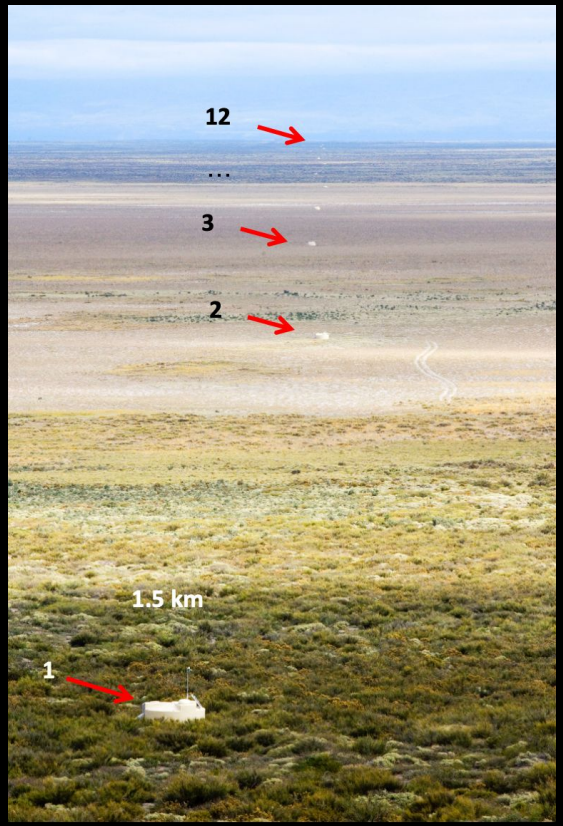


Cherenkov light in a nuclear reactor

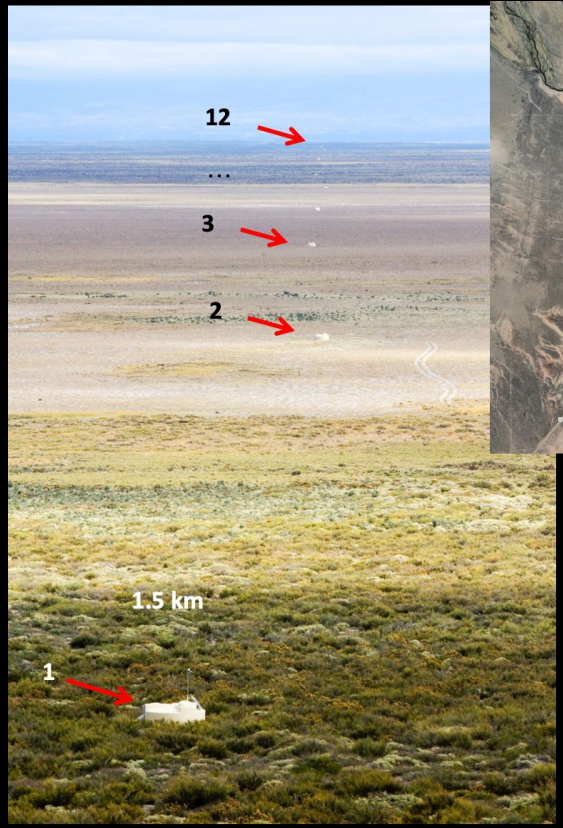
- Speed of light in water ~ 75% of speed of light in air/vacuum
- When a charged particle is faster than the speed of light -> “sonic boom”
- But with light
- This phenomenon emits a blue light called “Cherenkov light”



Pierre Auger Observatory

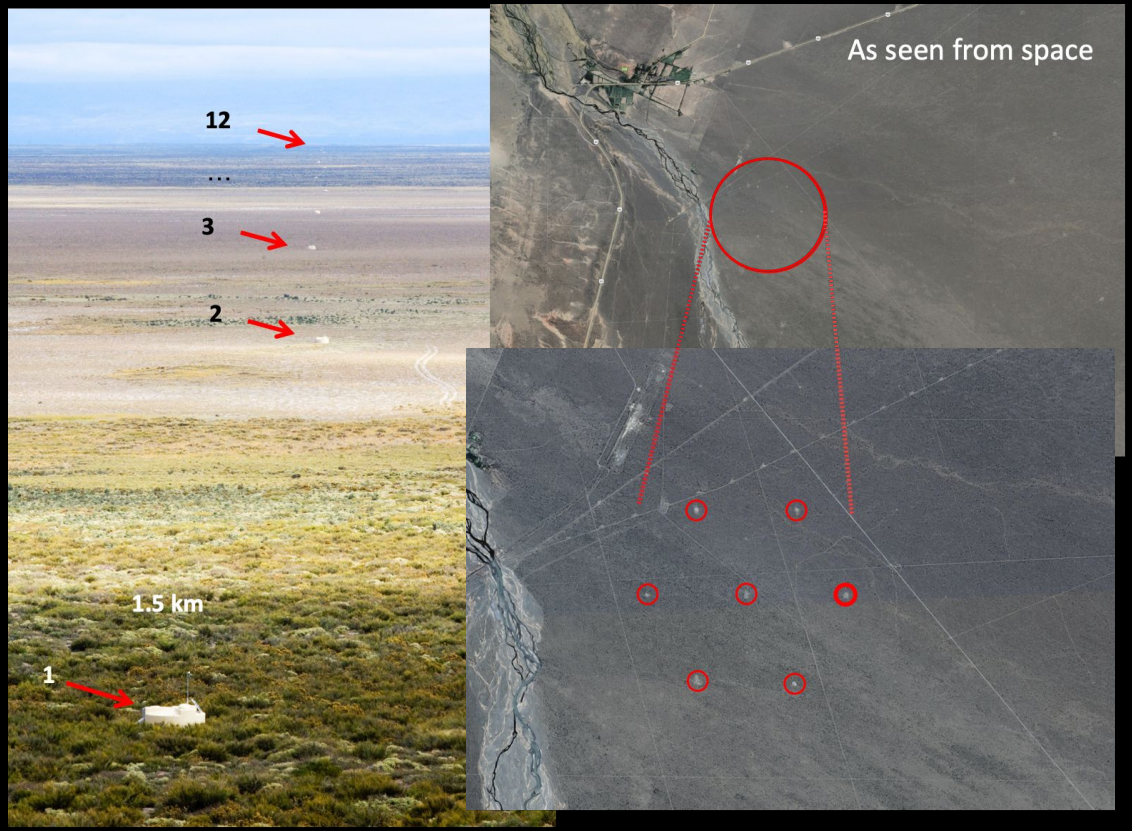


Pierre Auger Observatory

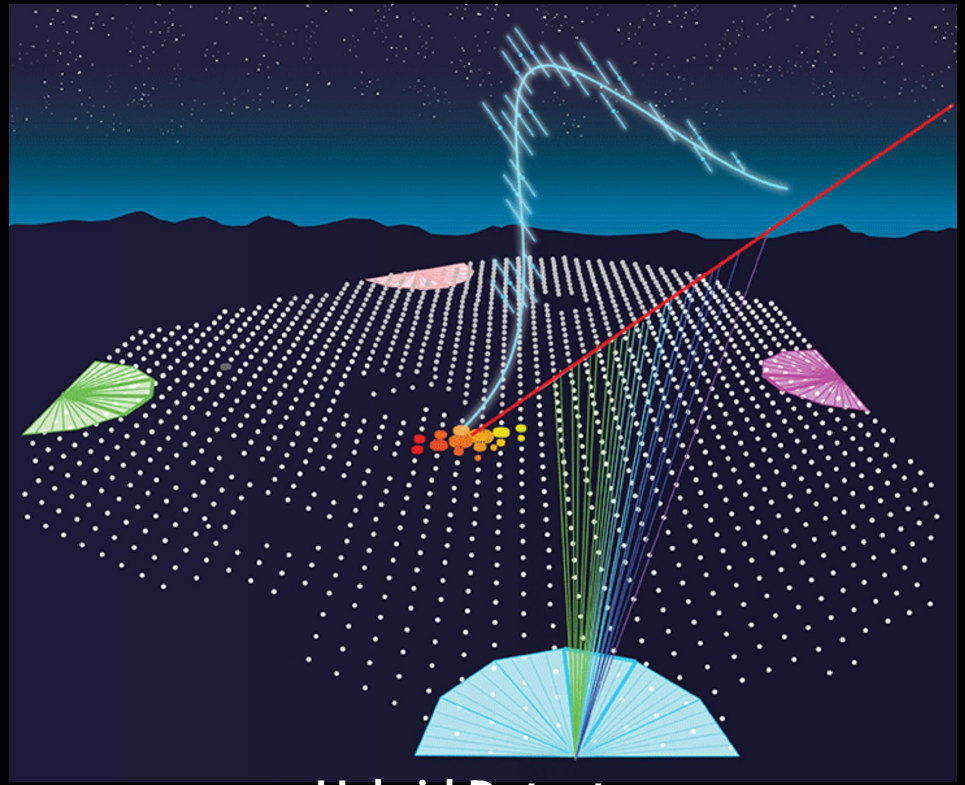




Pierre Auger Observatory



Pierre Auger Observatory



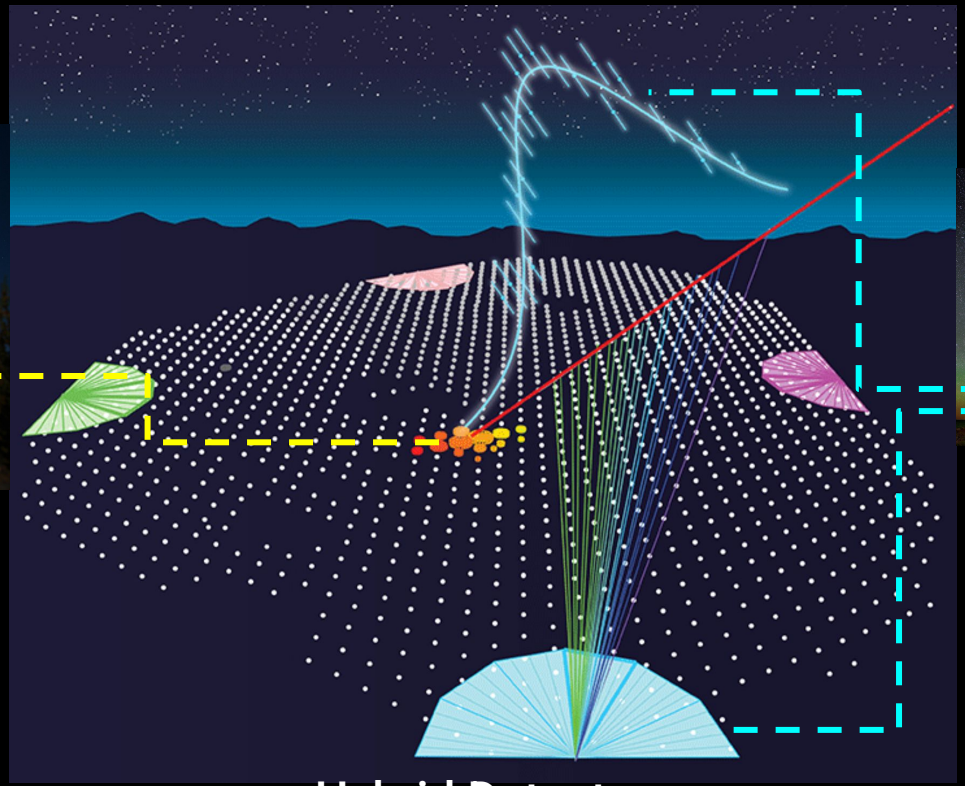
Hybrid Detector

Pierre Auger Observatory

Surface Detector



Samples shower on the ground



Hybrid Detector

Fluorescence Detector



Observes shower in the atmosphere

Pierre Auger Observatory

Surface Detector



Samples shower on the ground

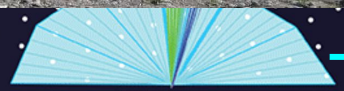
And also:



Radio Antennas



Underground Muon Detector



Hybrid Detector

Fluorescence Detector

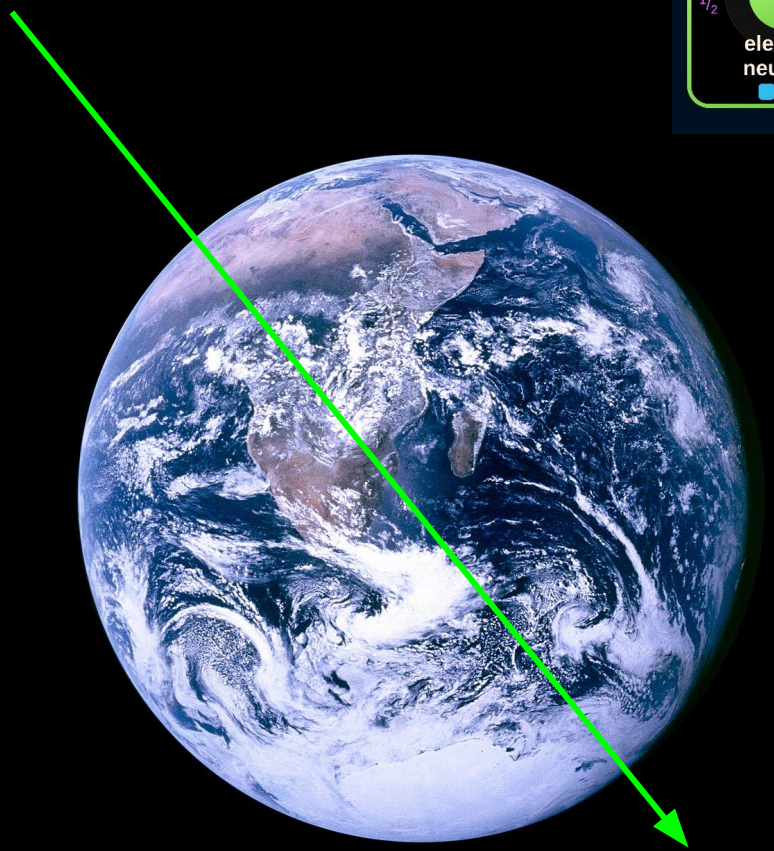


Observes shower in the atmosphere

and more ...

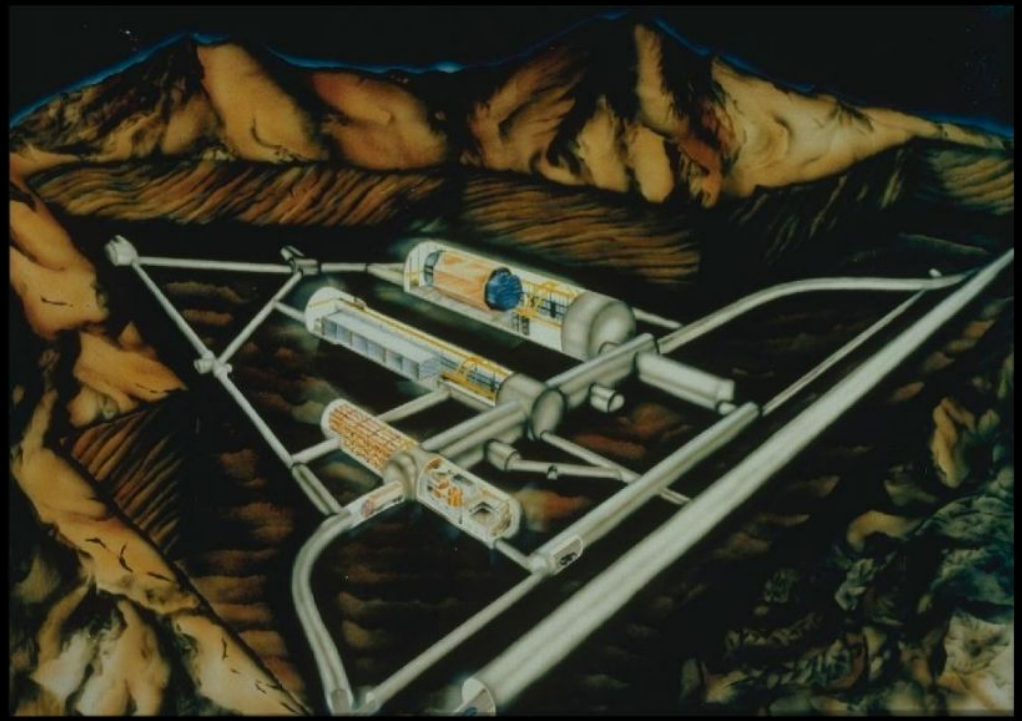
What about neutrinos?

Neutrinos
are elusive





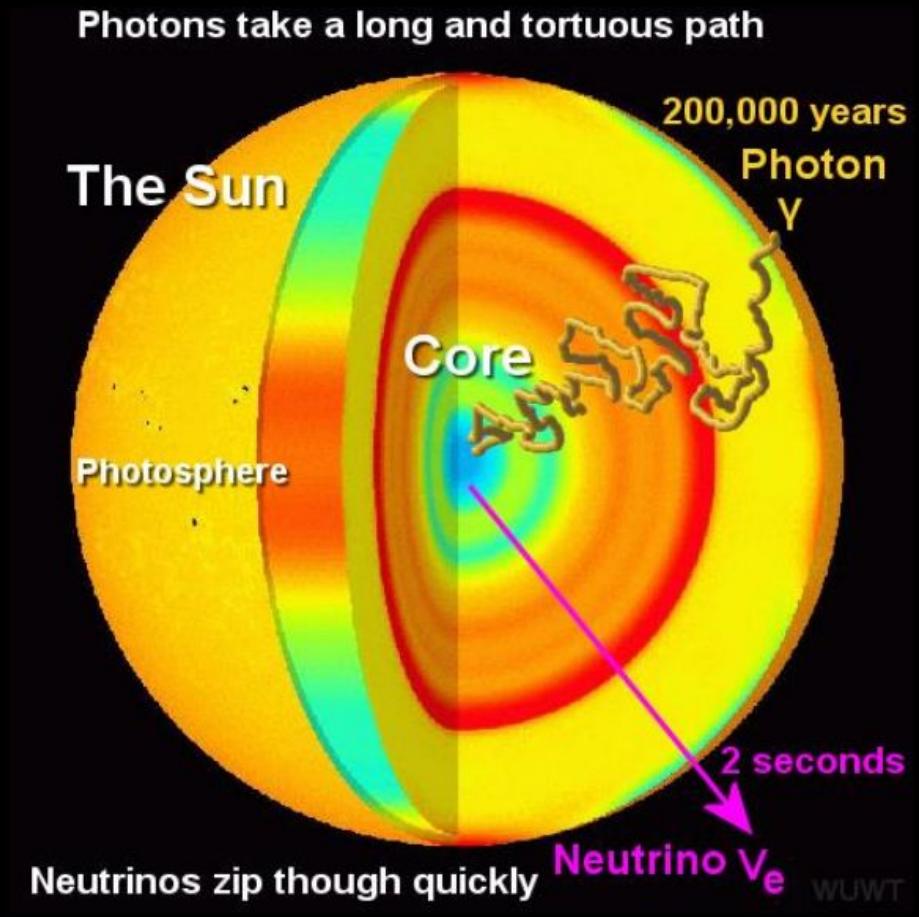
This is annoying…



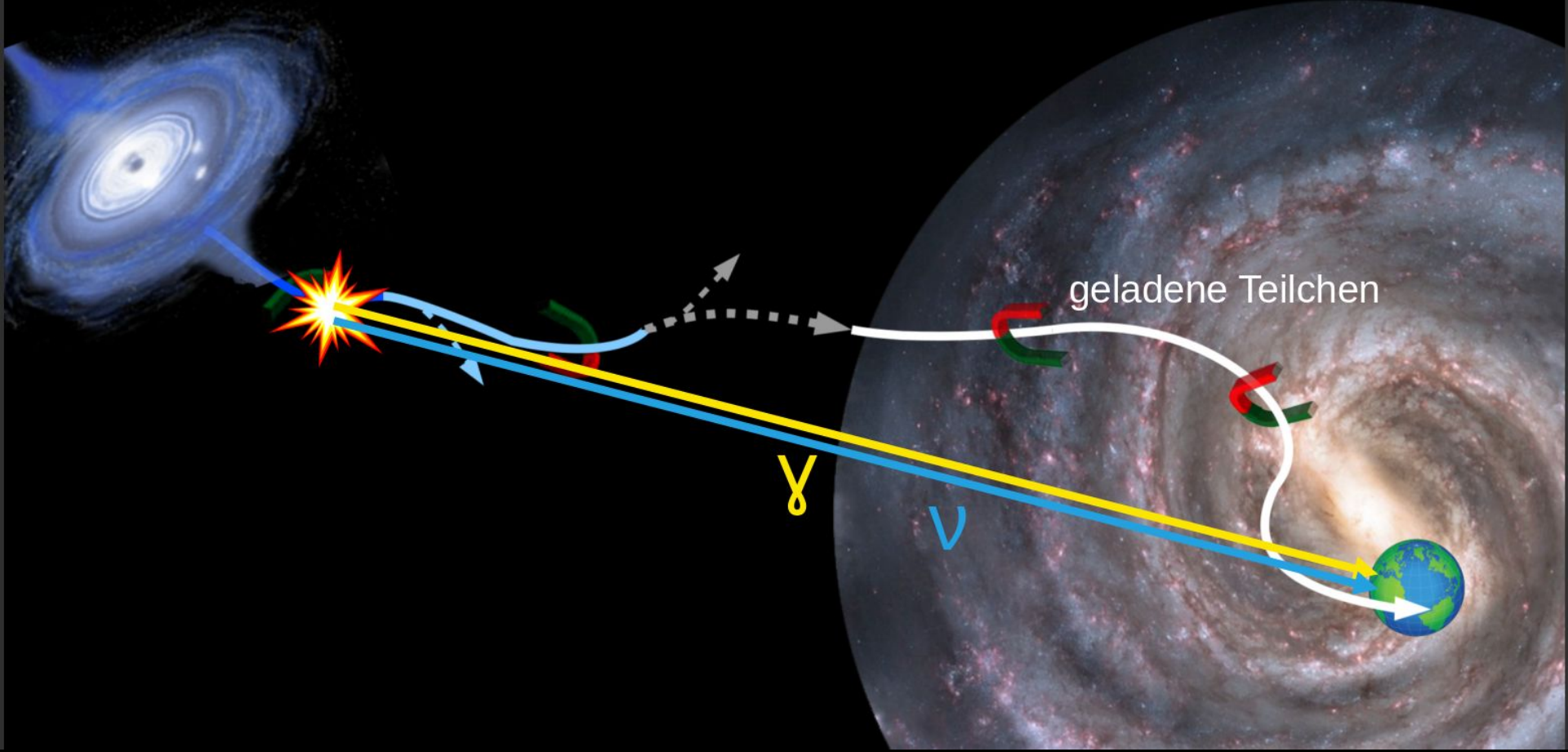
We need

- Large detectors
- Underground laboratories

But:

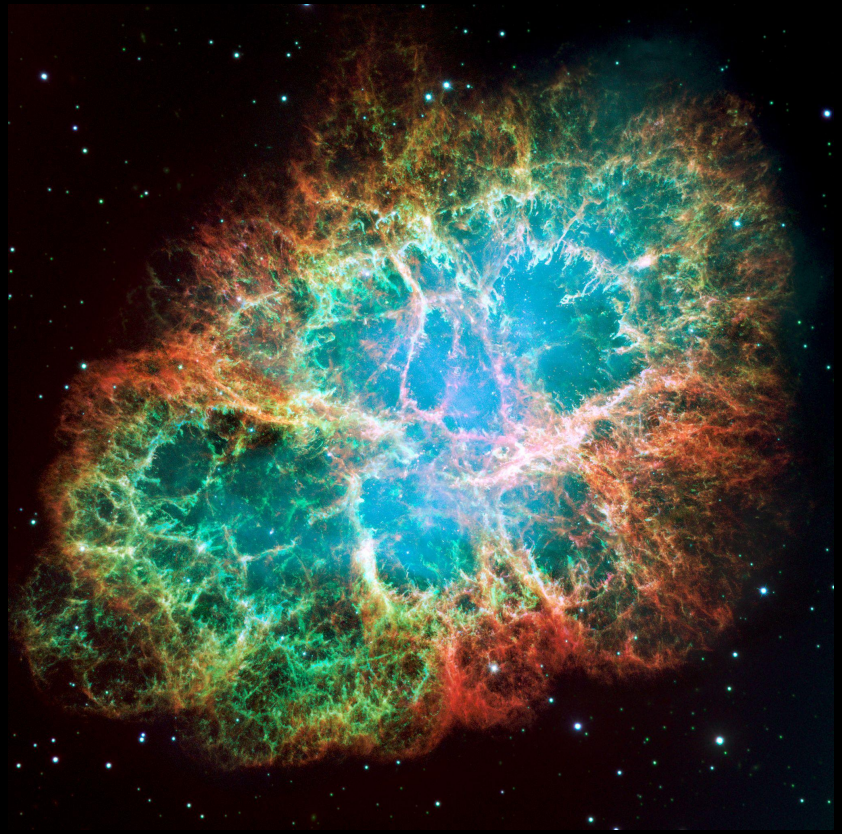


Neutrinos give us real time information about the core of the Sun



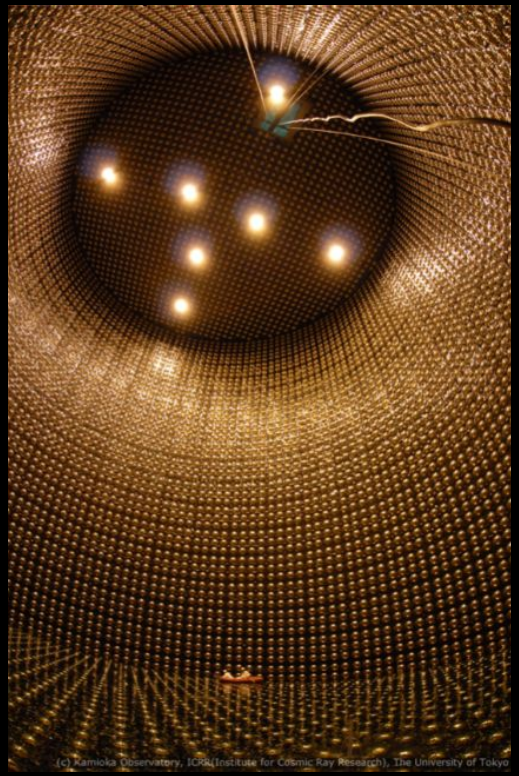
Neutrinos travel in a straight line from their source
(just like photons)

Supernovae also produce neutrinos

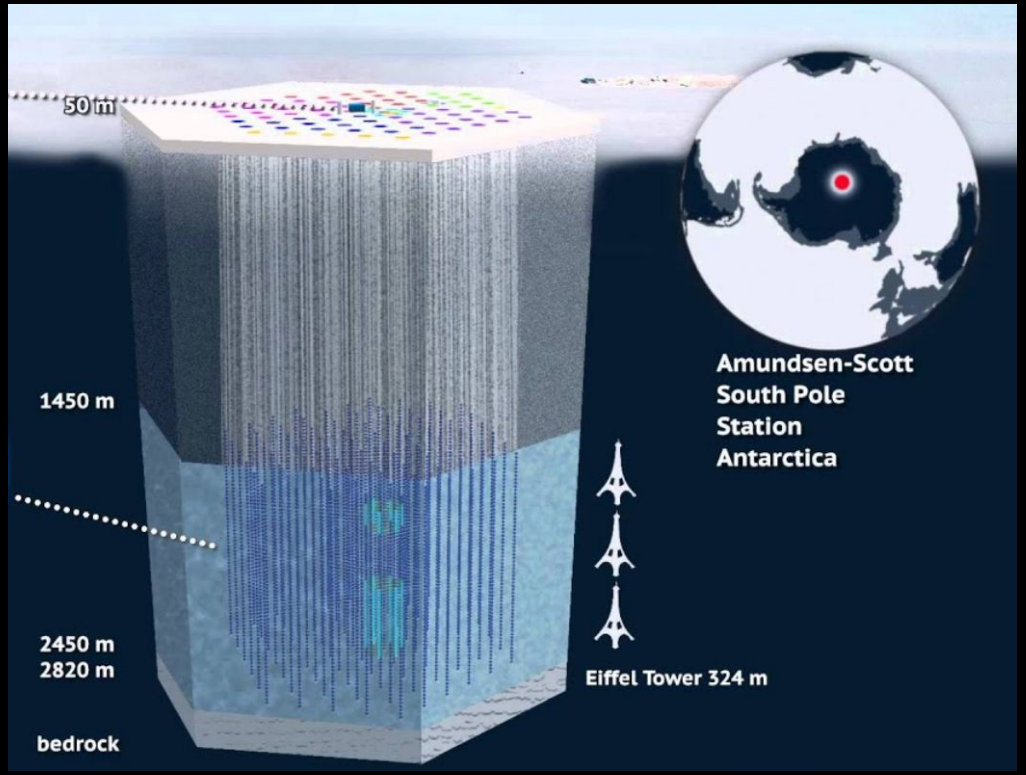


99% of the energy of a Supernova explosion goes to neutrinos

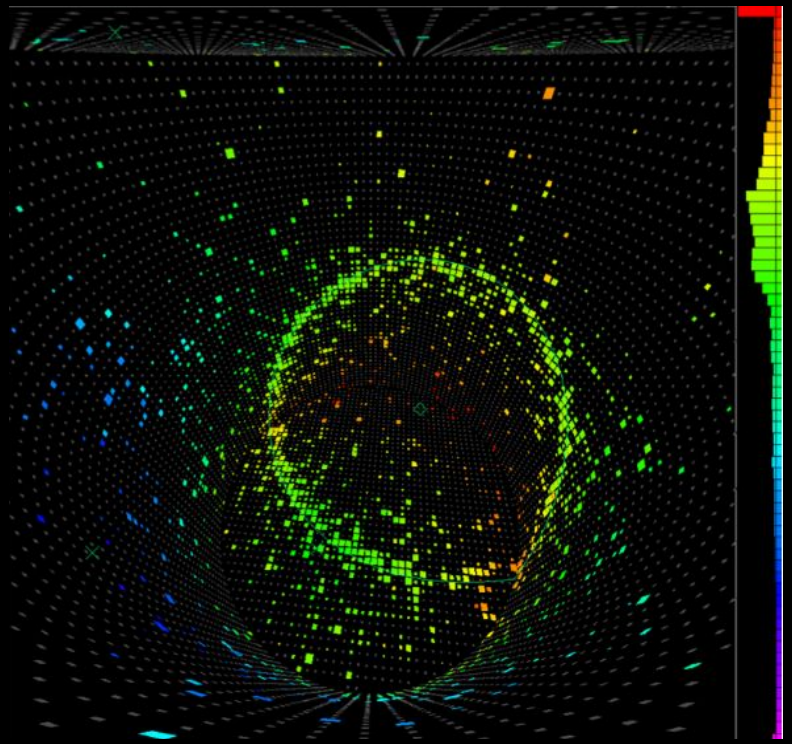
Super-Kamiokande



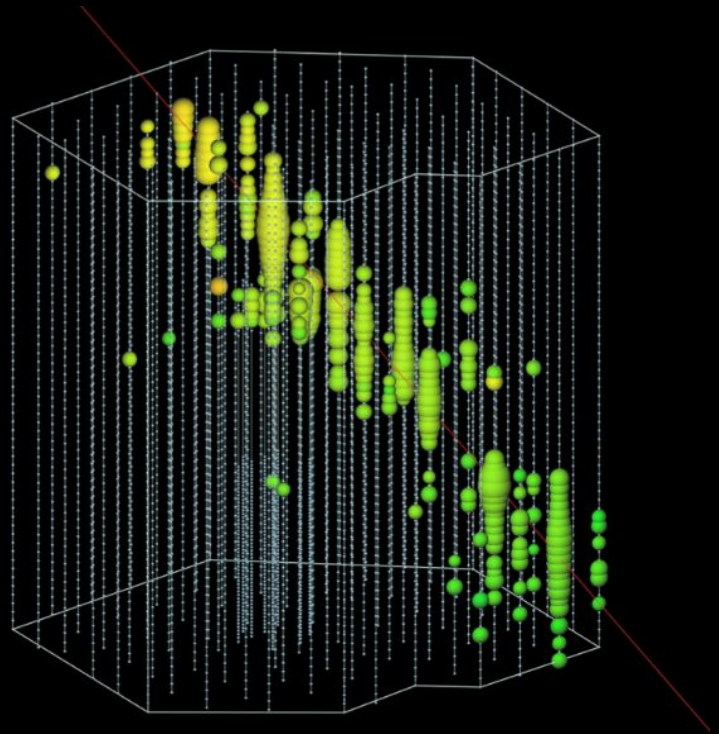
IceCube



Super-Kamiokande



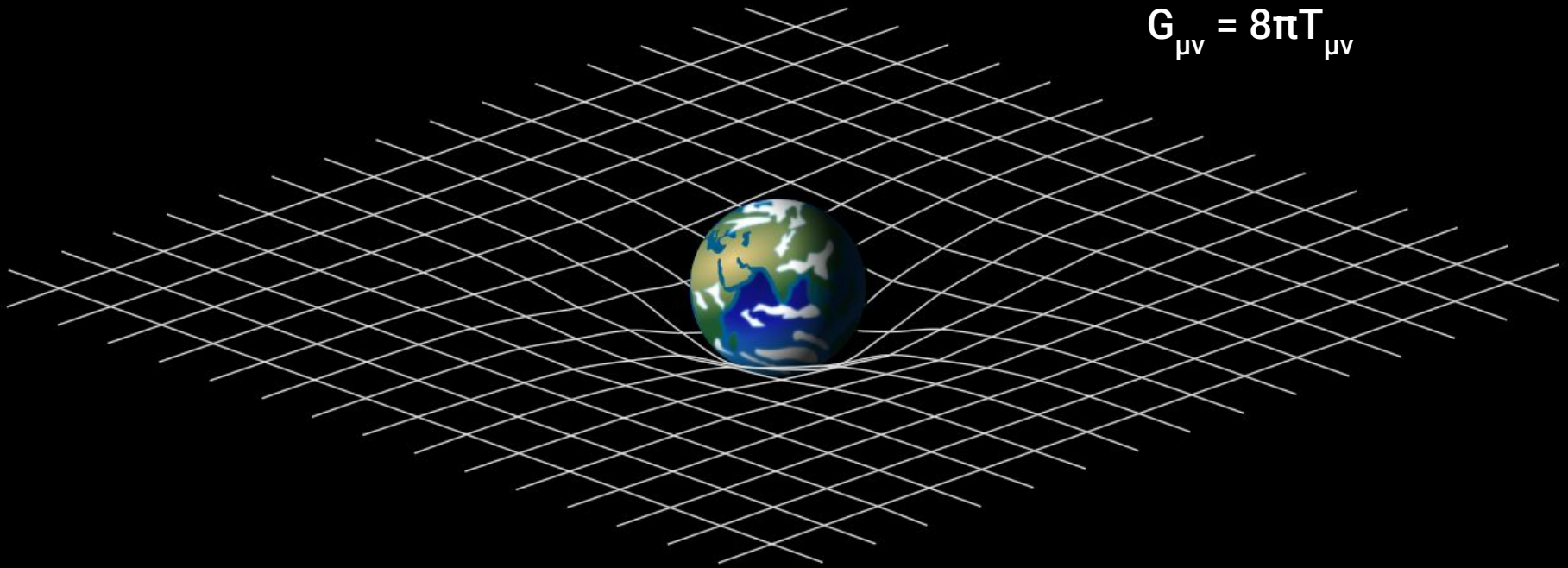
IceCube



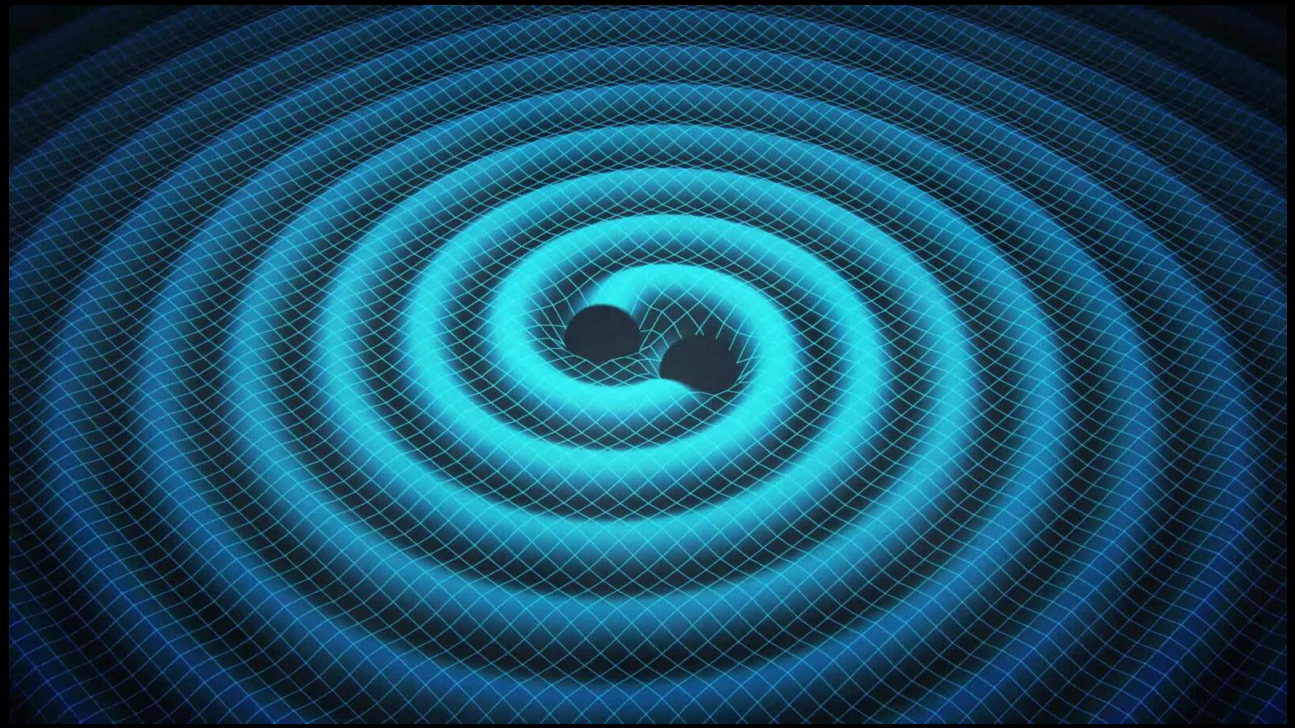
Gravitational Waves

Spacetime is bendy…

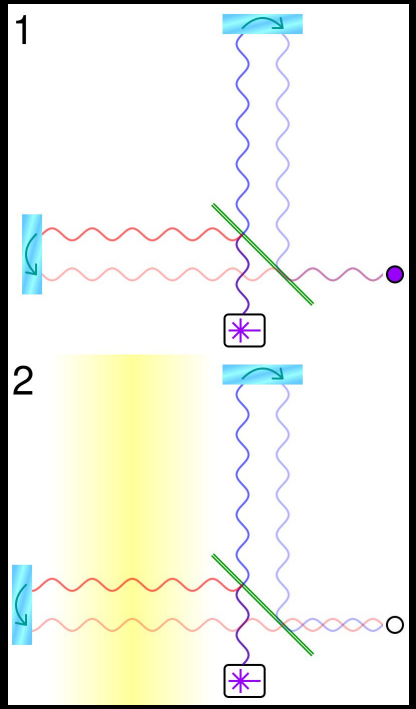
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



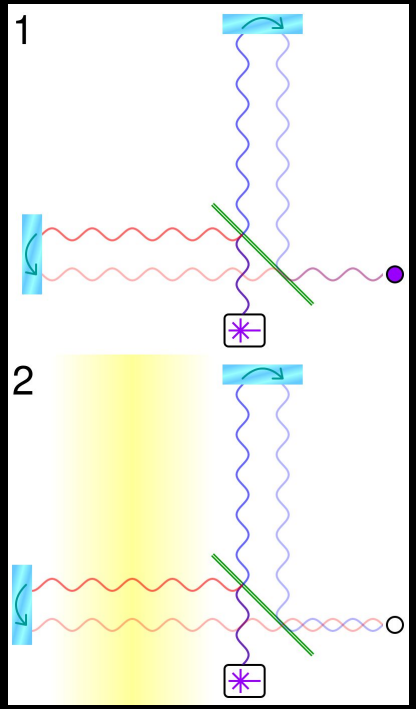
… which means you can have waves of spacetime

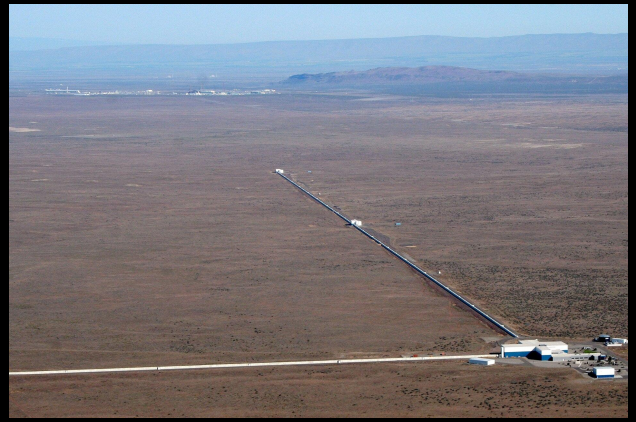


How to observe GWs



How to observe GWs



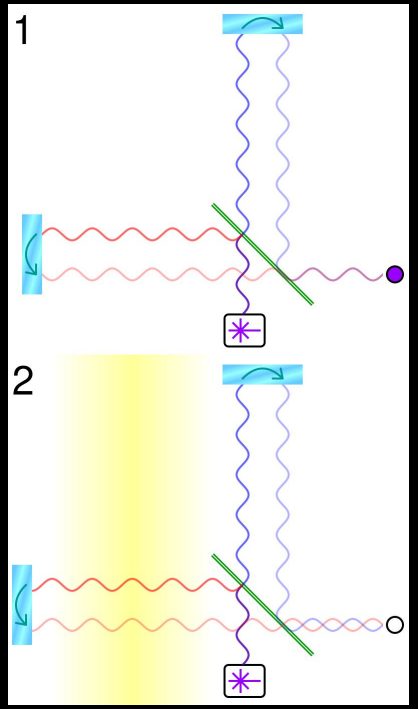


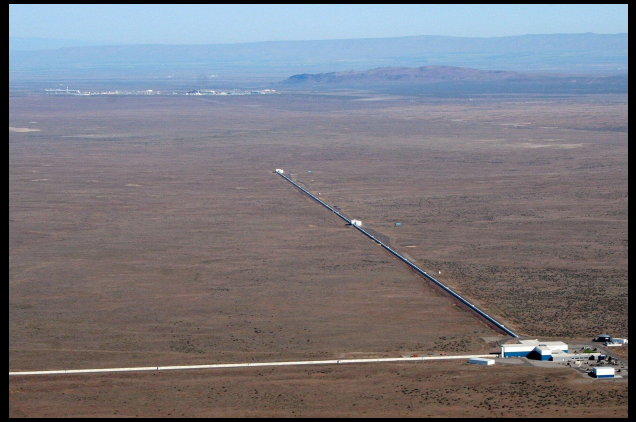
LIGO Hanford



LIGO Livingston

How to observe GWs





LIGO Hanford



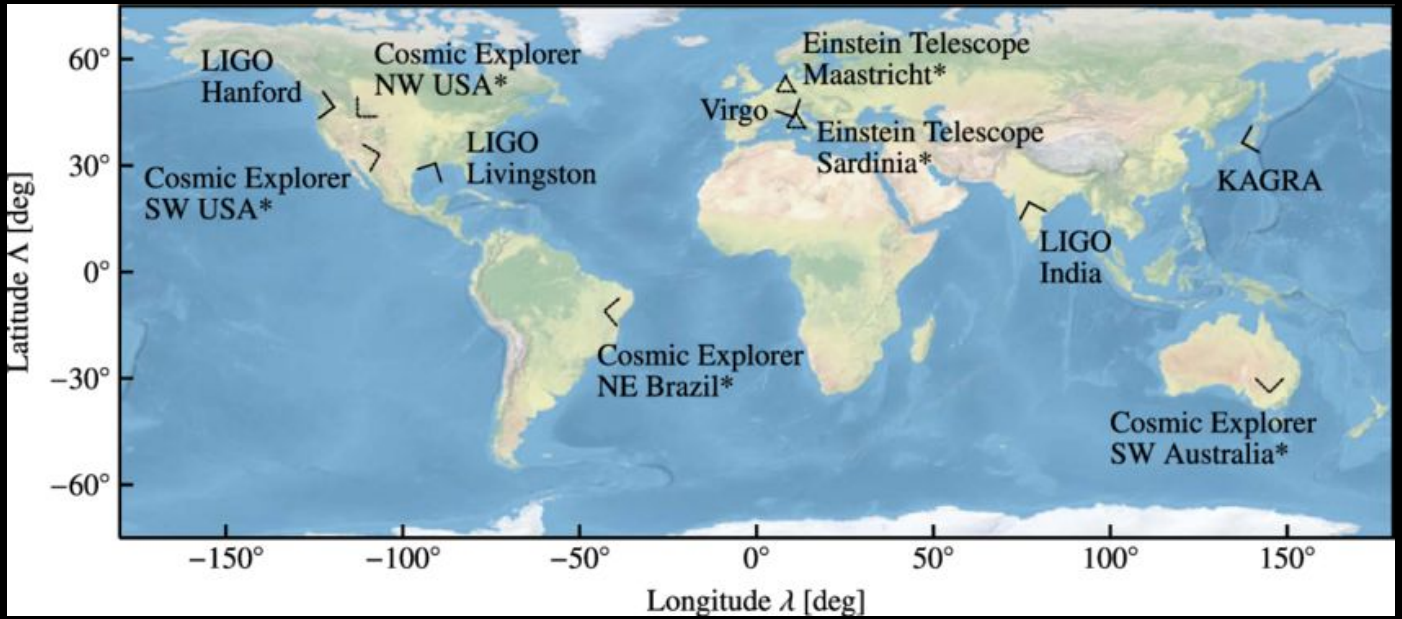
LIGO Livingston

Discovery of Gravitational Waves in 2016 by LIGO



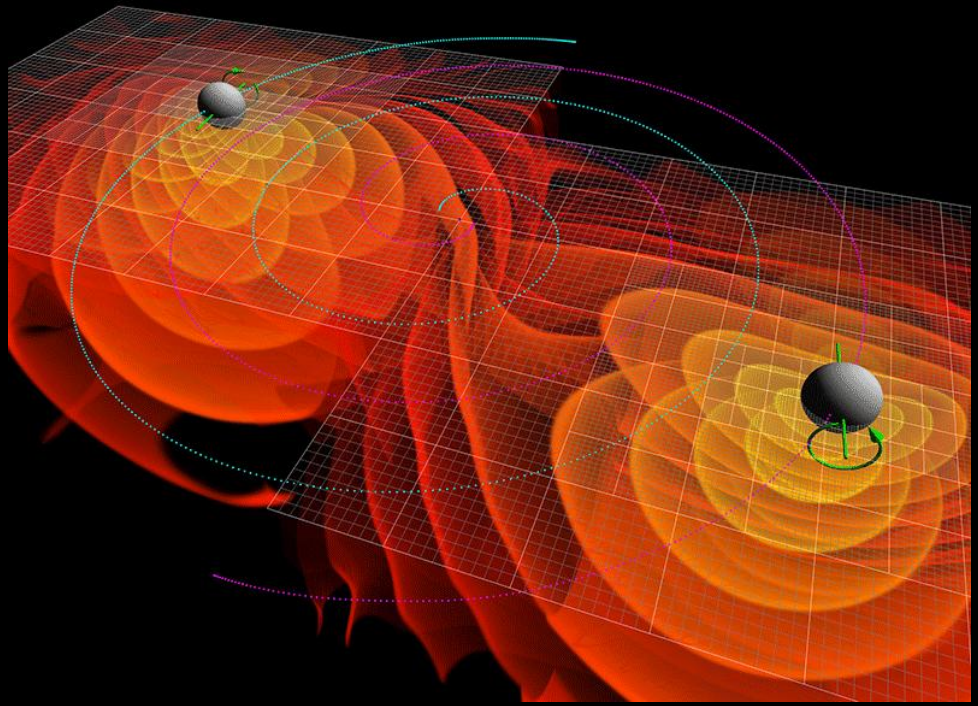
Nobel Prize in Physics in 2017

Current Observatories



Proposed Observatories marked with a *

Sources of GWs

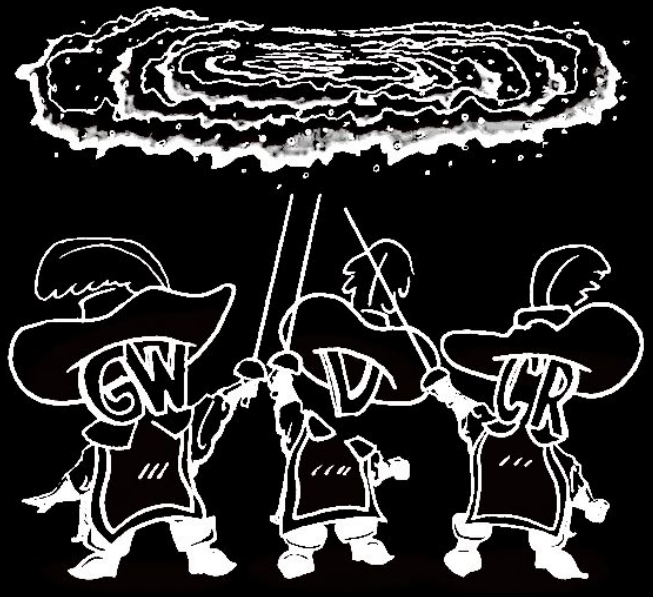


Simulation of merging black holes

Massive astrophysical events

- Two black holes merging
- Spinning Neutron Stars
- Supernovae

Multi-messenger Astronomy



The three messengers
All for one, and one for all

Thank you