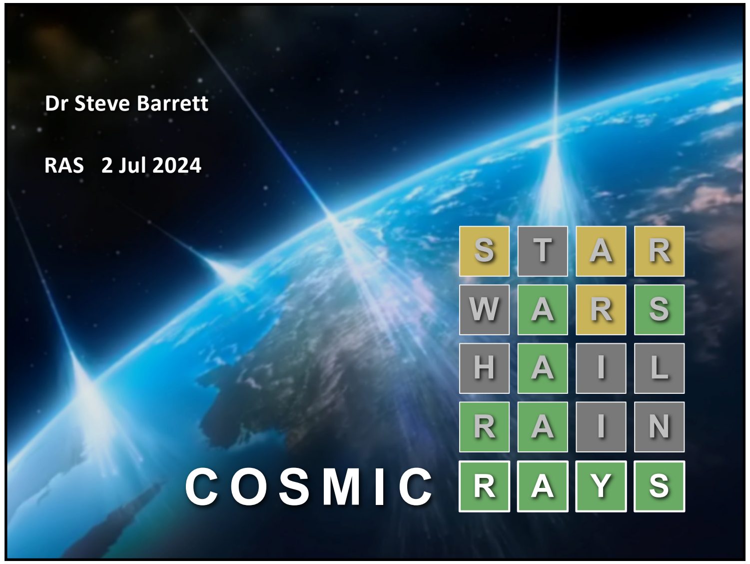

Contents

UNIVERSITY OF LIVERPOOL 2

Background Radiation

Terrestrial radioactivity and isotopes

UNIVERSITY OF LIVERPOOL 3

Background Radiation

Radiation is all around us ... all the time.

You have lived with it all your life and it is not something to fear.

Before dealing with cosmic rays, let's get some context by considering radiation from the Earth itself.

The Earth is radioactive.

It was radioactive when it was made 4.54 billion years ago and it still is today. This is a natural consequence of the properties of some elements.

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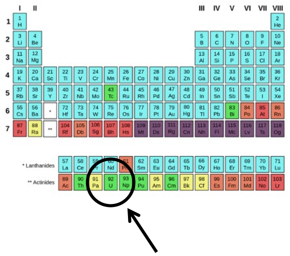
Radioactivity

The periodic table contains many elements that are **stable** – once an atom has been made it remains essentially unchanged … forever.

Some elements are **unstable**. They decay (change) into other elements and in the process the atomic nuclei emit sub-atomic particles.



We can visualise the particles emitted by radioactive uranium…

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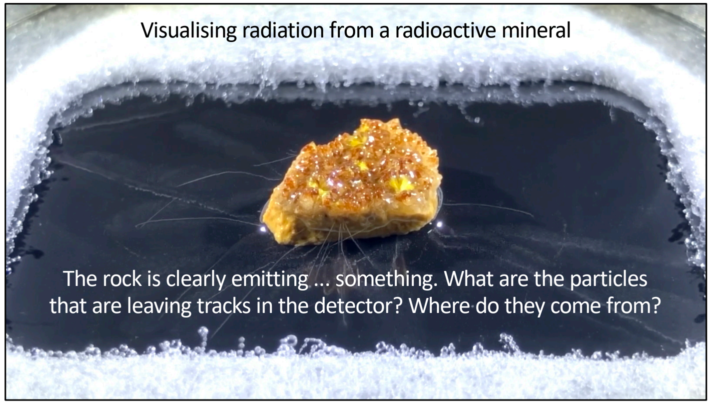
Demonstration



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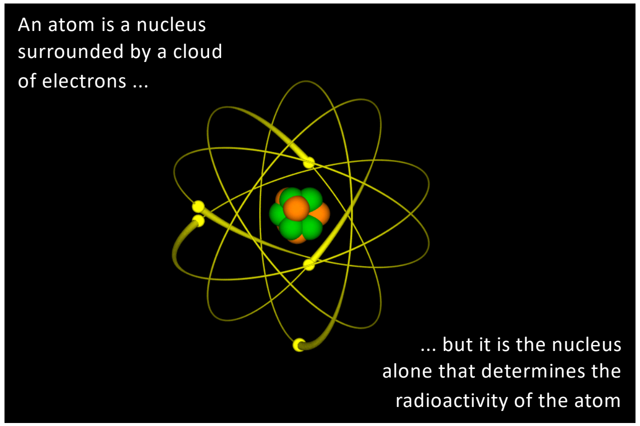
Atomic Nucleus



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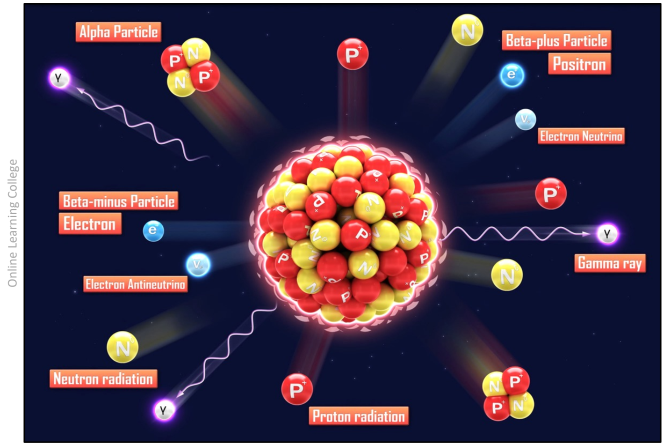
Atomic Nucleus



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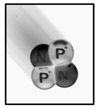
Alpha – Beta – Gamma

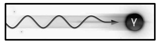
The most common types of radiation are labelled α, β and γ:

α Alpha rays (or alpha particles)
α = nuclei of helium atoms = 2 protons + 2 neutrons
Heavy particles that cannot travel far through matter

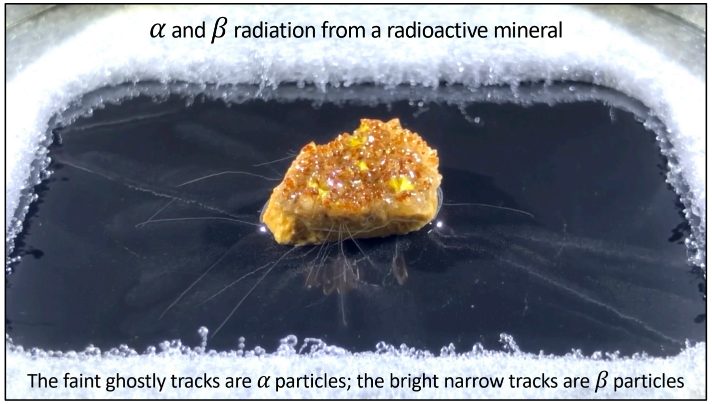


β Beta rays (or beta particles)
β = electrons
Lightweight particles that can penetrate further than alphas

γ Gamma radiation is rather different from α and β rays because it is a high-energy electromagnetic wave.



Demonstration



α and β radiation from a radioactive mineral

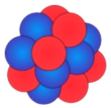
The faint ghostly tracks are α particles; the bright narrow tracks are β particles

Radioactive Isotopes

Isotopes are 'cousins' of the same type of atom. For instance ...

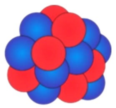
All carbon atoms have 6 protons in the nucleus (by definition).

Carbon atoms that have 6 **neutrons** are the **stable** isotope C-12



6 + 6 = 12

Carbon atoms that have 8 **neutrons** are the **radioactive** isotope C-14

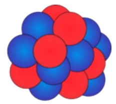


6 + 8 = 14

Aside: Radioactive Carbon-14

Because C-14 atoms decay (change) into nitrogen atoms over 1000s of years they can be used in carbon dating organic material.

If they don't last long, where do the C-14 atoms come from in the first place?



They are being continuously replenished by cosmic rays hitting nuclei of nitrogen, kicking out protons and changing N-14 into C-14.

Radioactive Elements

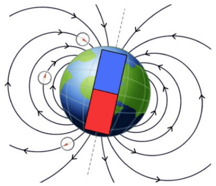
Potassium (K) is the most abundant of the radioactive elements
In your body, potassium atoms decay at the rate of 4000/sec
It is one of largest contributions to natural radiation

Thorium (Th) is more abundant than uranium, and…

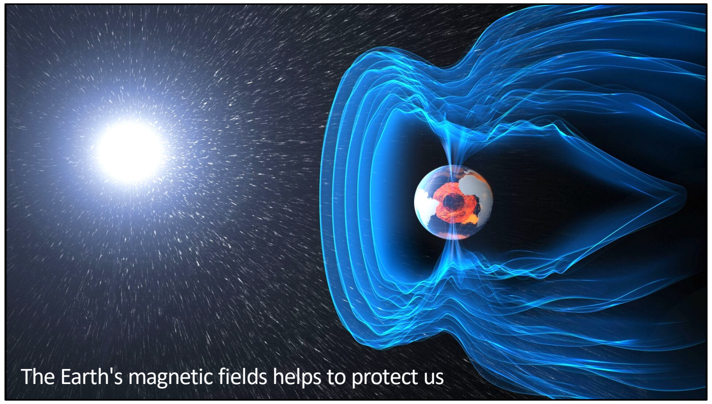
Uranium (U) is more abundant than you think
At 3 ppm there is 500x more uranium than gold in the Earth's crust

In the Earth's core, these radioactive elements have been emitting radiation for billions of years, heating the core and keeping it molten.

A rotating molten core is the dynamo that creates the Earth's magnetic field.



Earth's Magnetic Field



Aside: Anti-Matter

0.01% of potassium is K-40, an isotope that emits β+ radiation.

β+ particles are like electrons, but with the *opposite* electrical charge. They are particles of **anti-matter**.

Hence, foods rich in potassium emit anti-matter radiation.

This gave rise to the unit of "banana equivalent dose" (BED) that compares any dose of radiation to the dose a person would be exposed to by eating one average-sized banana.

Banana Equivalent Dose

Eating 1 banana =

Dose of cosmic rays that everybody is exposed to every day =

(double it if you fly a lot)

Radon

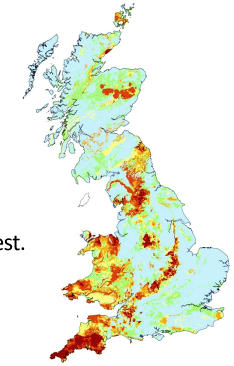
Not all radioactive elements are found in solid form.

Radon is a radioactive gas formed by the radioactive decay of the small amounts of uranium that occur naturally in all rocks.

Radon concentrations vary across the UK depending on the type of ground.

For instance, radon levels are high in parts of the UK rich in granite, such as in the South West.

Radon gas atoms emit α particles.



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Cosmic Rays

Having considered terrestrial sources of radiation we can now return to the main topic of this talk

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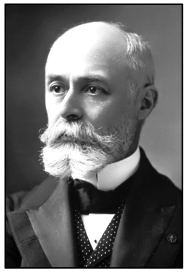
Pioneers

The pioneers studying radiation in the period 1895 – 1915 were ...



Henri Becquerel
1852 – 1908

Marie Curie
1867 – 1934

Victor Hess
1883 – 1964

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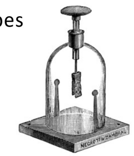
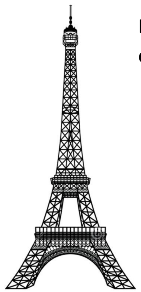
Above or Below?

In the late 1800s it was known that gold leaf electroscopes lost their charge due to background radiation ...



... but was it coming from **above** or from **below**?



In 1910 Theodore Wulf took an electroscope to the top of the Eiffel Tower.

The radiation levels decreased by far less than would be expected if the radiation was coming ***only*** from the ground.

Is the tower radioactive?

Is the atmosphere radioactive?

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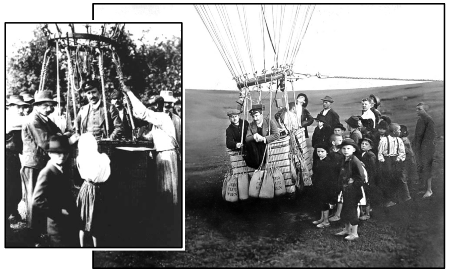
Above or Below?

To resolve the question of '... from above or from below?' Hess figured that the Eiffel Tower was not high enough.

He designed detectors that would work at high altitudes and in 1911 and 1912 he took them on a series of balloon flights.



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Cosmic Radiation

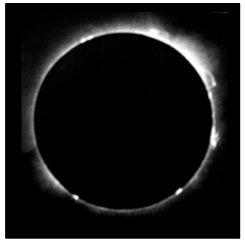
1911 – Ascent to 1000 m – radiation levels essentially unchanged

1912 – Ascent to 5000 m – radiation levels **increased** dramatically

Was the increase due to radiation from the Sun, or from beyond?

Measurements during a **solar eclipse** effectively ruled out the Sun as the source of cosmic rays.

In 1936 Hess was awarded the Nobel Prize in Physics for his "discovery of cosmic radiation".



17 Apr 1912

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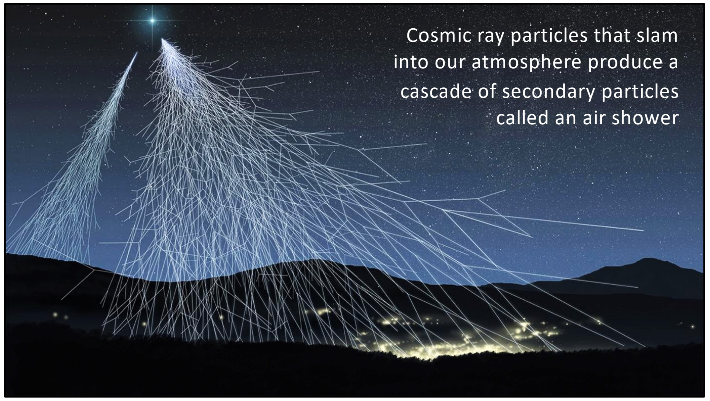
Air Showers



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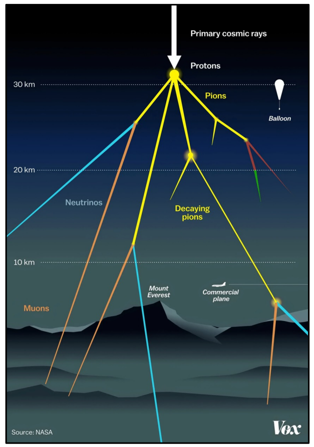
Air Showers

High-energy **primary** cosmic ray particles collide with atoms in the upper atmosphere, starting a cascade of **secondary** particles.

At each level of the cascade, new particles are created, each sharing the energy of the particle that created them.

A cascade from one primary cosmic ray particle might result in millions of secondary cosmic ray particles at sea level.



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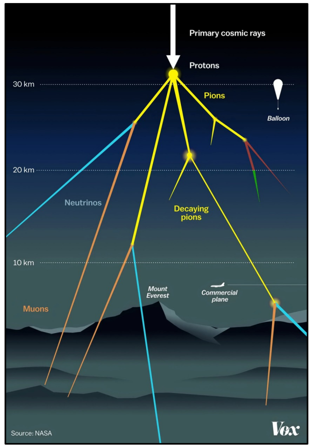
Cosmic Rays

Air Showers

Many of these new particles are unstable and do not live more than a tiny fraction of a second.

A **muon** is a particle similar to an electron, except that it is much more massive and has no part to play in making atoms.

A muon will not live for much more than a few microseconds, but that is long enough for it to reach sea level.



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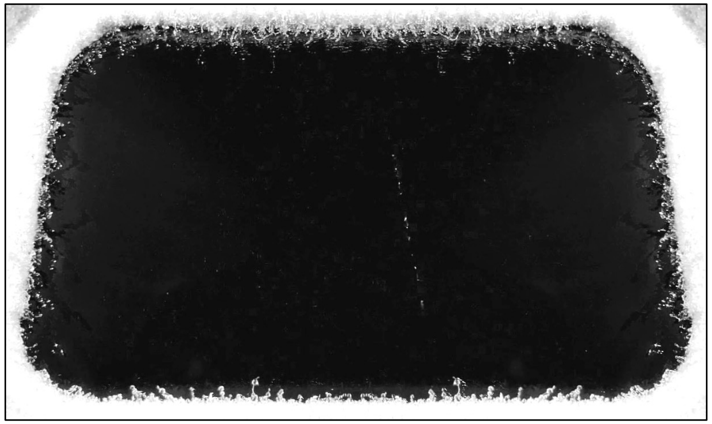
Muon Track in Cloud Chamber



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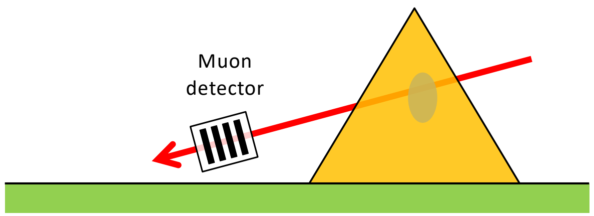
Applications of Cosmic Ray Muons



If there is any variation in density (of the rock or stone) inside the structure, that will affect the absorption of muons. The process is analogous to using the absorption of x-rays to see inside matter.

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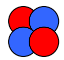
What Are the Primary Particles?

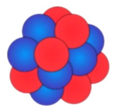
So far we have been looking at **secondary** cosmic ray particles.

What about the **primary** particles – the ones that *create* the showers?

Decades of research has told us about the primary cosmic rays ...

90% are protons  (nuclei of H atoms)

9% are α particles  (nuclei of He atoms)

1% are nuclei of heavy atoms  (the same atoms as found here within the solar system)

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Detecting Cosmic Rays

How can we detect cosmic rays either before or after they hit our atmosphere?

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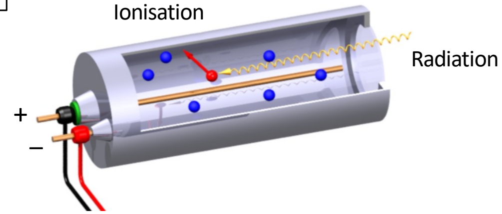
Radiation Detectors

What's going on inside the detector?



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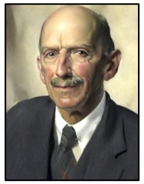
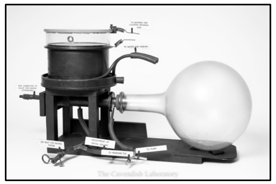
Cloud Chambers

Inspired by sightings of the Brocken spectre from the top of Ben Nevis in 1894, Charles Wilson developed chambers for studying cloud formation and optical phenomena in moist air.



In 1911 he perfected the first cloud chamber.



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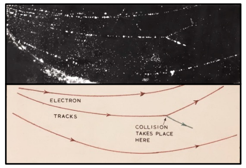
Cloud Chambers

Wilson realised that when charged particles passed through the cloud chamber water droplets condensed to form visible tracks.

As a result, his cloud chambers had an important role in experimental particle physics for decades.



In 1927 he was awarded the Nobel Prize in Physics for the "most original and wonderful instrument in scientific history".

1911

⟶

2024

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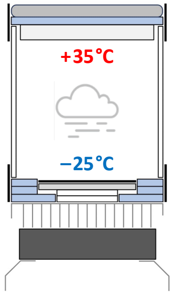
Cloud Chambers

My cloud chamber is a distant cousin of Wilson's original invention. Details of its design and construction will be left for another day.



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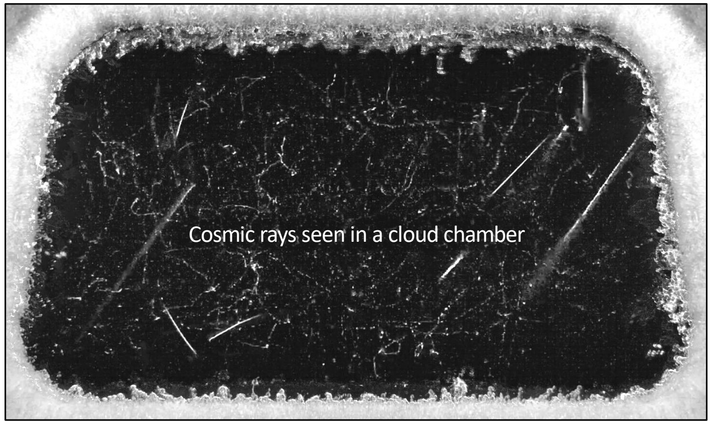
Demonstration



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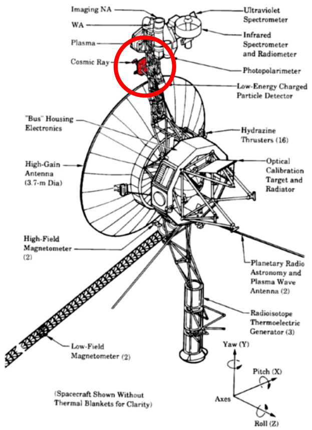
Cosmic Ray Experiments

Voyager 1 and Voyager 2 carried instruments to measure cosmic rays as they flew through the interplanetary medium.

In 2012 Voyager 1 measured a significant increase in galactic cosmic rays, indicating that it had entered interstellar space.

Travelling about 10% slower, Voyager 2 measured a similar increase in cosmic rays in 2018.



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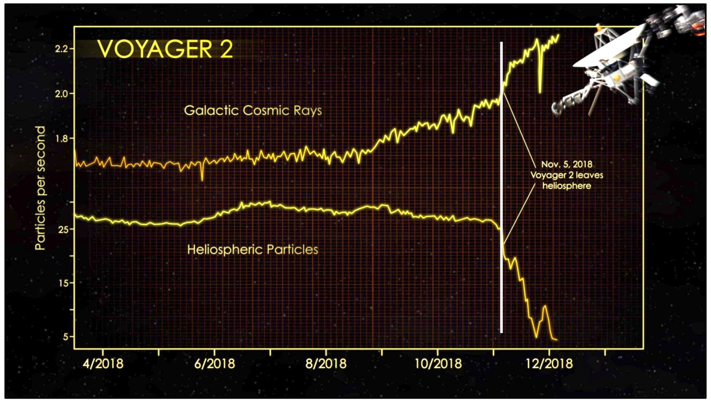
Cosmic Ray Experiments



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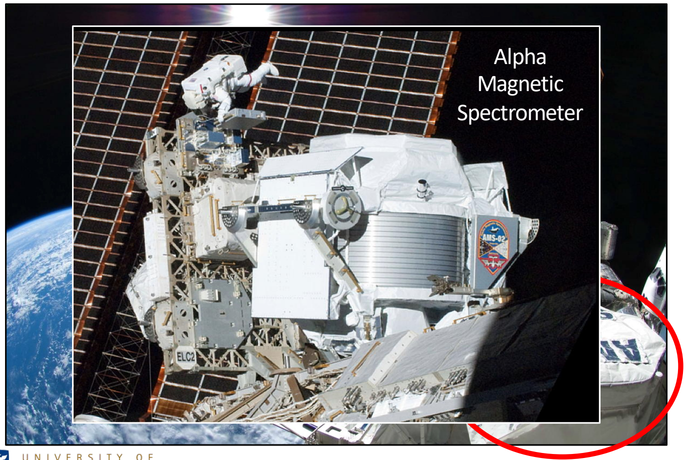
Cosmic Ray Experiment on the ISS



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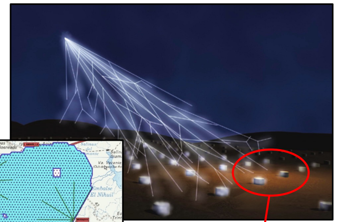
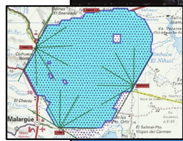
Cosmic Ray Observatory

There are a number of ground-based cosmic ray observatories. One of the biggest is the Pierre Auger Observatory in Argentina.

To catch a reasonable fraction of the particles created in an air shower the detectors have to be spread over a large area.





For the PAO, this is the area of … Luxembourg.

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Cherenkov Radiation

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Cherenkov Radiation

Development of an air shower

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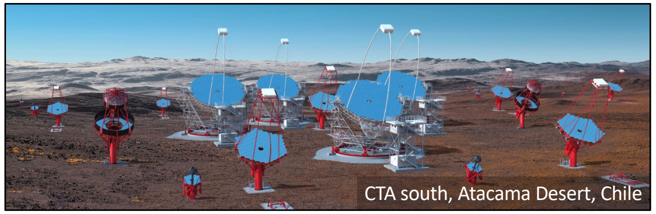
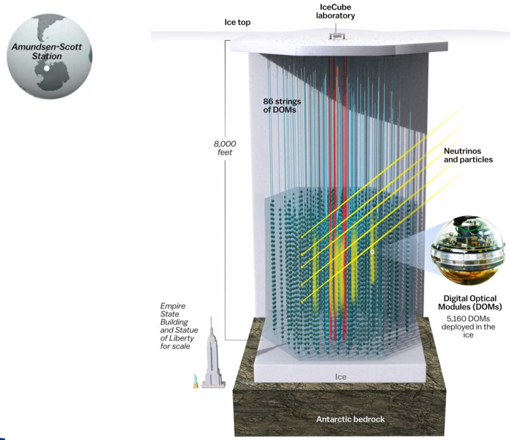
Cherenkov Telescope Array

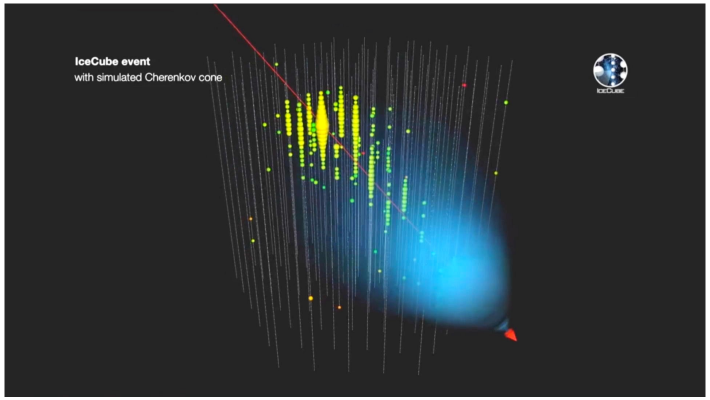

CTA north, La Palma, Canary Islands


CTA south, Atacama Desert, Chile

IceCube Laboratory



IceCube Event



Sources of Cosmic Rays

Where do cosmic rays come from?
How do they gain so much energy?

Aside: Spiral Nebulae are Galaxies

100 years ago Edwin Hubble reported that …

… thirty-six [Cepheid] variable stars were discovered in the two spirals, Andromeda and M33. The study of the periods of these stars at once provided the means of determining the distances of these objects. The results are striking in their confirmation of the view that these spiral nebulae are distant stellar systems. They are found to be at a distance of the order of 1,000,000 light years.

New York Times, 23 Nov 1924

This was the nail in the coffin of the Great Debate that took place in the early 1920s – "*spiral nebulae*" are galaxies in their own right.

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Cosmic Origins

Hess showed that (most) cosmic rays do ***not*** come from the Sun.

So where ***do*** they come from?

Sources in the Milky Way? … or beyond?

Hubble's observations made in the 1920s led to a paradigm shift in our understanding of the Universe … it is a ***lot*** bigger than was thought, and is full of billions of galaxies like our own.

So are the sources of cosmic rays galactic, or extra-galactic?

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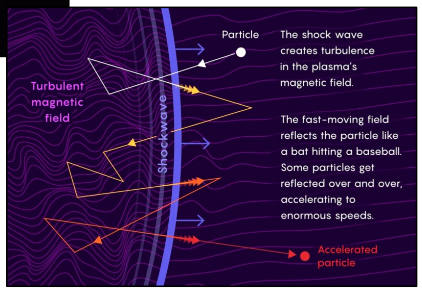
Supernovae and SMBH

Violent events like supernovae or jets from supermassive black holes produce shock waves in the gas around them.



These shock waves can result in the acceleration of charged particles to **very** high energies.

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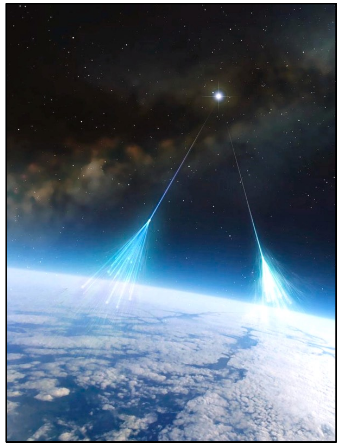
Cosmic Sources

Pinning down the sources of cosmic rays?

Shouldn't that be easy?

Measure the direction of incoming cosmic rays and trace their direction back to the source.

Simples!



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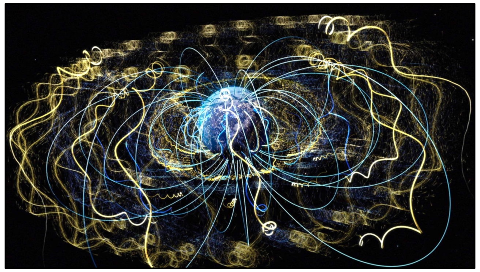
Magnetic Fields

No, not so simple.
The paths of charged particles are **deflected** in a magnetic field…
… and magnetic fields are everywhere.



Charged particles spiralling along Earth's magnetic field lines

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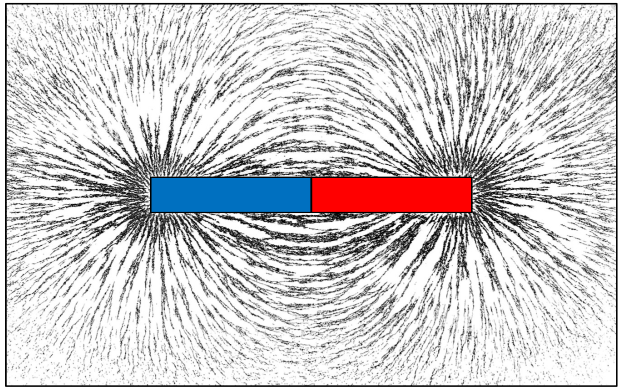
Magnetic Fields

Iron filings can reveal the magnet field around a simple bar magnet



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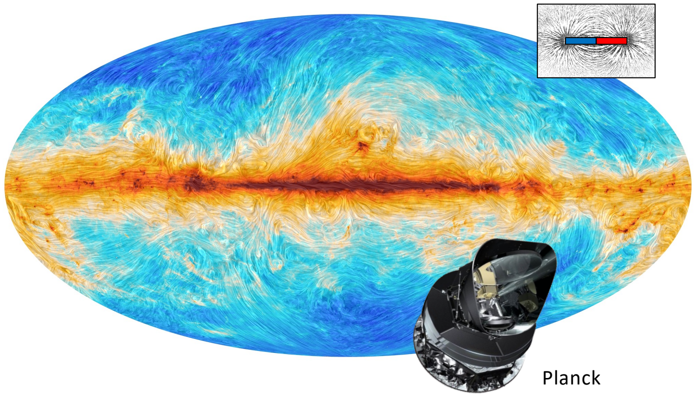
Galactic Magnetic Fields

Dust particles floating around the Milky Way behave like iron filings



Planck

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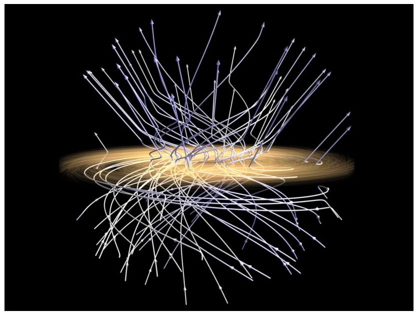
Galactic Magnetic Fields

Magnetic fields embedded in the Milky Way have a complex structure. The fields deflect charged particles and so scramble the direction from which cosmic rays appear to originate.



T. Sandstrom, NASA

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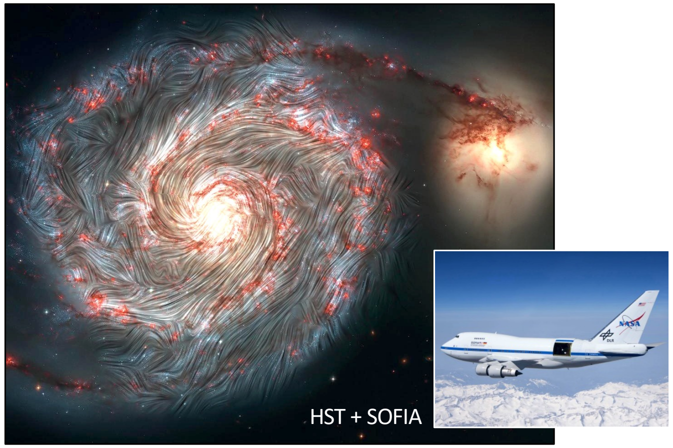
Magnetic Fields in M51



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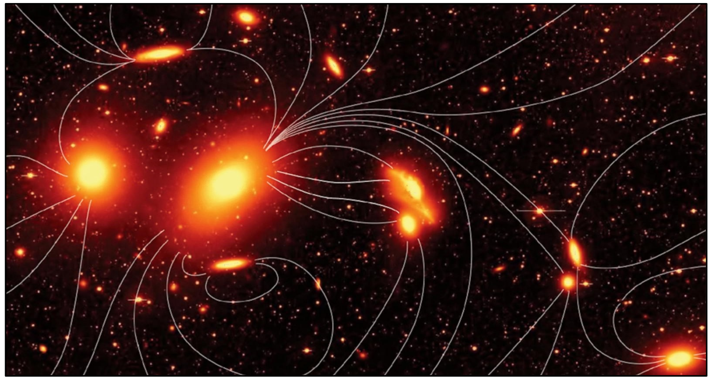
Inter-Galactic Magnetic Fields



Galactic magnetic fields make it difficult to trace cosmic rays to their source

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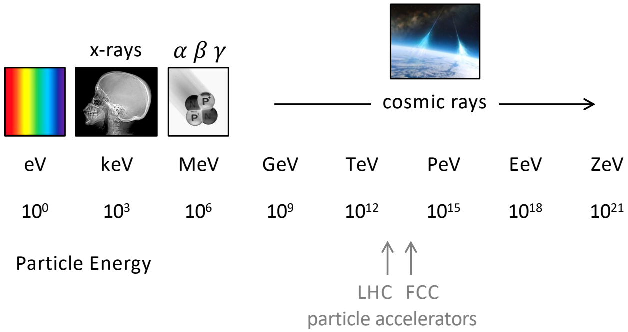
Energy Distribution



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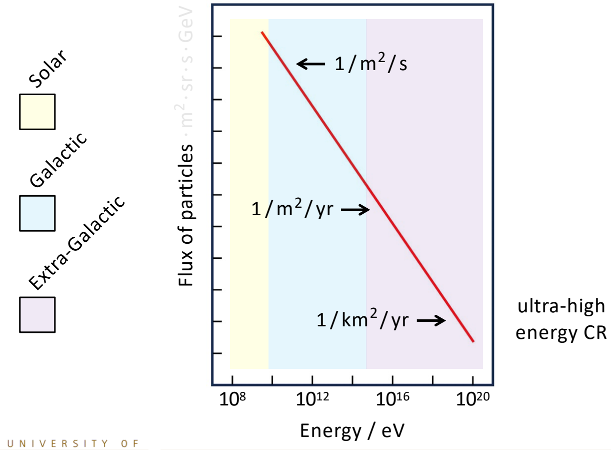
Energy Distribution



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Amaterasu Event

Osaka Metropolitan U / Kyoto U / Ryuunosuke Takeshige

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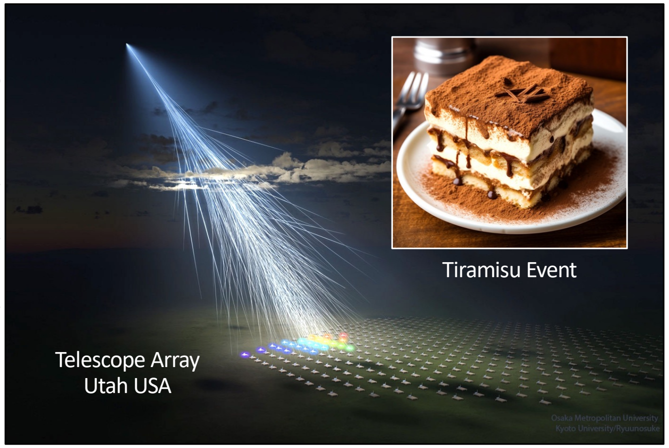
Amaterasu Event

Osaka Metropolitan U / Kyoto U / Ryuunosuke Takeshige



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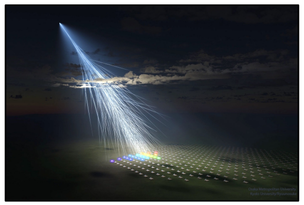
Ultra-High Energies

Ultra-high-energy cosmic rays should be deflected very little by the magnetic fields that permeate the Milky Way and inter-galactic space.

Hence, tracing back the direction of the Amaterasu event should reveal the source in the sky.



The direction points to ... nothing. No supernova, no SMBH could be identified as the source.

More observations are needed to resolve the mystery of cosmic ray origins.

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Close To the Speed of Light

Just how close to the speed of light are these ultra-high-energy cosmic ray particles travelling?

Expressed as a percentage of the speed of light, the most energetic particle yet observed (the "Oh-My-God particle") was travelling at

99.99999999999999999999995 % *c*

We can attempt to visualise this speed by imagining a race ...

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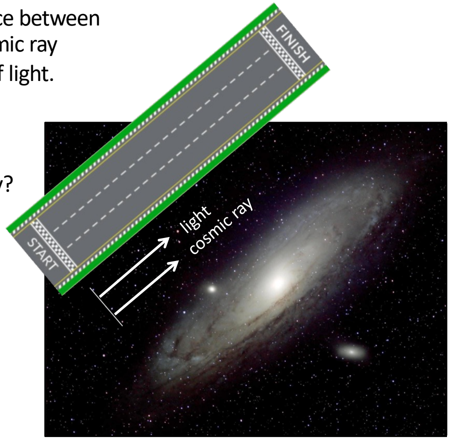
Race With Light

Imagine a 100,000 ly race between the most energetic cosmic ray particle and a photon of light.



When the light crosses the finish line, how far behind is the cosmic ray?

After 100,000 ly the cosmic ray would be about **5 mm** behind.

The time difference would be less than a nanosecond.

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Summary

- Cosmic ray particles are accelerated … somewhere, somehow
- **Supernovae** and **SuperMassive Black Holes** are probably sources
- Cosmic rays are **deflected** by magnetic fields
  - Lower energy particles get their paths scrambled
  - Higher energy particles travel in straighter lines
- Some particles make it past Earth's protective **magnetic field**
- Hitting the atmosphere creates an **air shower** of secondary particles
- Some of the **secondary** cosmic ray particles make it to sea level
  - These include muons, electrons and protons
  - They make clicks in Geiger counters and tracks in cloud chambers

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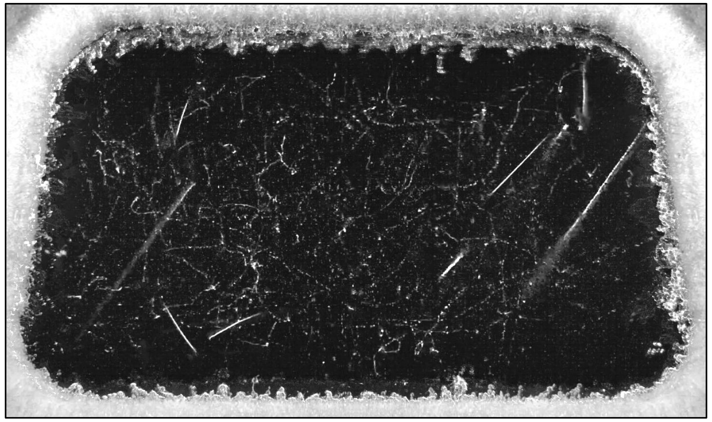
Cosmic Rays



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