UNIVERSITY OF ALBERTA

Cosmic Rays and Muons

Dark Matter Week – Friday

William Woodley

Cosmic Rays

- Cosmic rays are highly-energetic charged particles that come from outer space and are continuously bombarding the Earth.
- We don't know where they come from. Because they're charged, they get deflected by magnetic fields in space, so we can't trace their origins.
- They span a wide energy range (reaching energies of macroscopic objects).

Major Questions:

1. Where do cosmic rays come from?
2. How are they accelerated to such high energies?

Discovery of Cosmic Rays

- Cosmic rays were discovered by Victor Hess in 1912.

- At the time, physicists knew of a constant source of radiation, but thought that source was the Earth. They expected the level of radiation to decrease at higher altitudes.

- Hess took an ionisation chamber up into the atmosphere in a balloon. He found that radiation levels increased at higher altitudes.

- He concluded the source was space, and won the Nobel Prize for this discovery in 1936.

Victor Hess (1883 – 1964)

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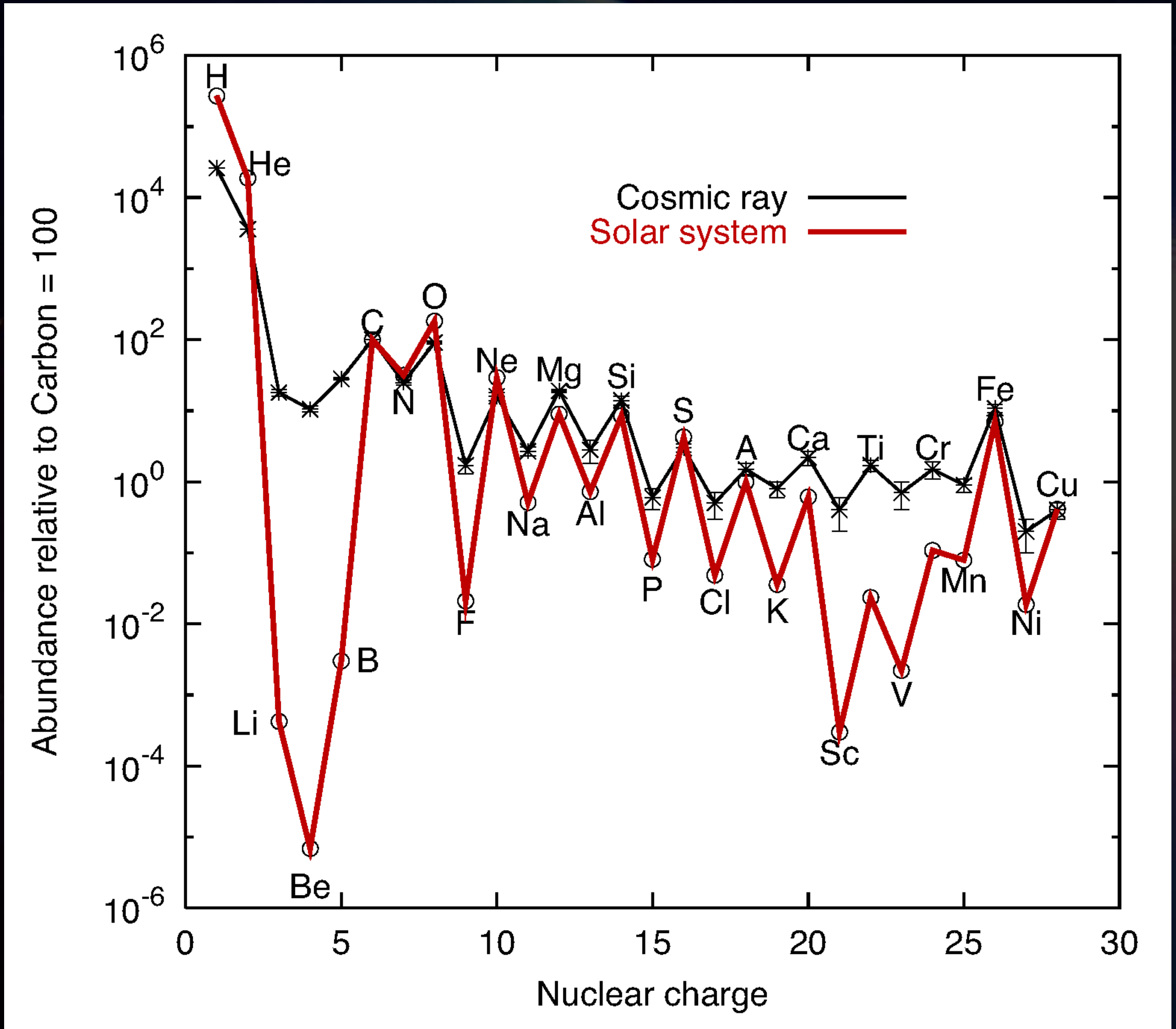
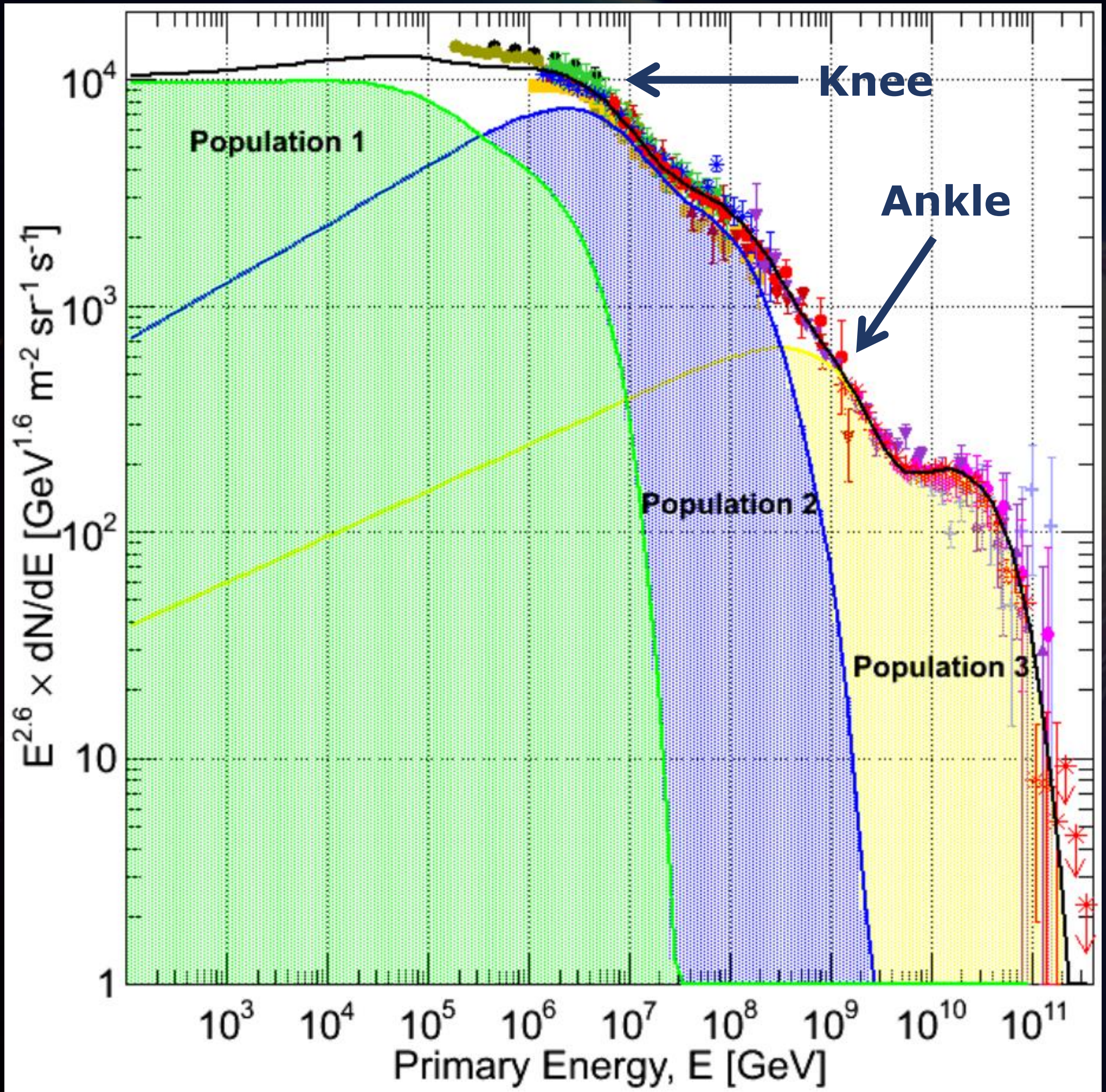
Composition



- 90% of CRs are protons.
- 9% are α particles (He nuclei).
- 1% are heavier elements.
- Low-energy CRs have similar abundances of elements that we observed in the solar system.
- This suggests CRs in this energy range come from the sun.

1 GeV = 1.602×10^{-10} J

Energy Spectrum

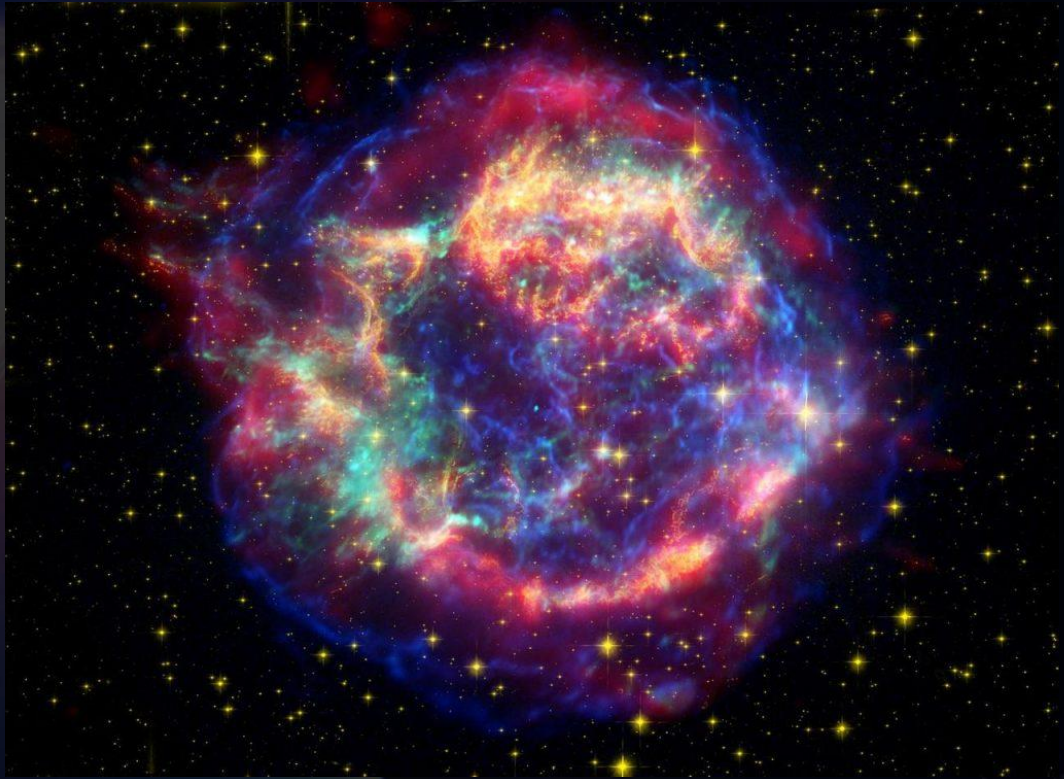


- We usually talk about CRs in terms of their energy spectrum.
- **Features:**
  1. Knee at 10^6 GeV = 1 PeV
  2. Ankle at 10^9 GeV = 1 EeV
- **Sources:**
  - Population 1: The sun and supernovae
  - Population 2: Outside the solar system but within the galaxy
  - Population 3: Outside the galaxy

Acceleration by Supernovae

- Supernovae are massive explosions some stars undergo at the end of their lifetimes.

Crab Nebula SNR (1054)



Casseopeia A SNR (1667)

Acceleration by Supernovae

- Supernovae are massive explosions some stars undergo at the end of their lifetimes.

- In the explosions, supernovae eject huge amounts of matter. The outer edge of the explosion is called the shock wave, which expands into the interstellar medium.

- Charged particles get caught up in the magnetic fields of the interstellar medium and bounce around. With each bounce, they gain more and more energy, until their energies are so high they escape the shock wave and travel through space, reaching Earth.

- This process is known as Fermi Acceleration.

High-Energy Cosmic Rays

- Supernovae can only explain CRs with energies up to about 10^6 GeV. However, we have observed CRs with (much) higher energies:
  - **UHECRs:** Ultra-High-Energy Cosmic Rays (> 10^9 GeV).
  - **EECRs:** Extreme-Energy Cosmic Rays (> 5×10^{10} GeV).
- The most energetic CR ever observed had an energy of 3.12×10^{11} GeV.
- According to what we know, this is physically impossible. The highest energy a CR should be able to reach is 5×10^{10} GeV.
- This is given by the GZK limit. Beyond this energy, CRs should interact with the Cosmic Microwave Background Radiation (CMBR), which should slow them down.

Pfotzer Maximum

- Radiation in the atmosphere reaches a maximum dose rate of about 400 μGyh^{-1} at 20 km.

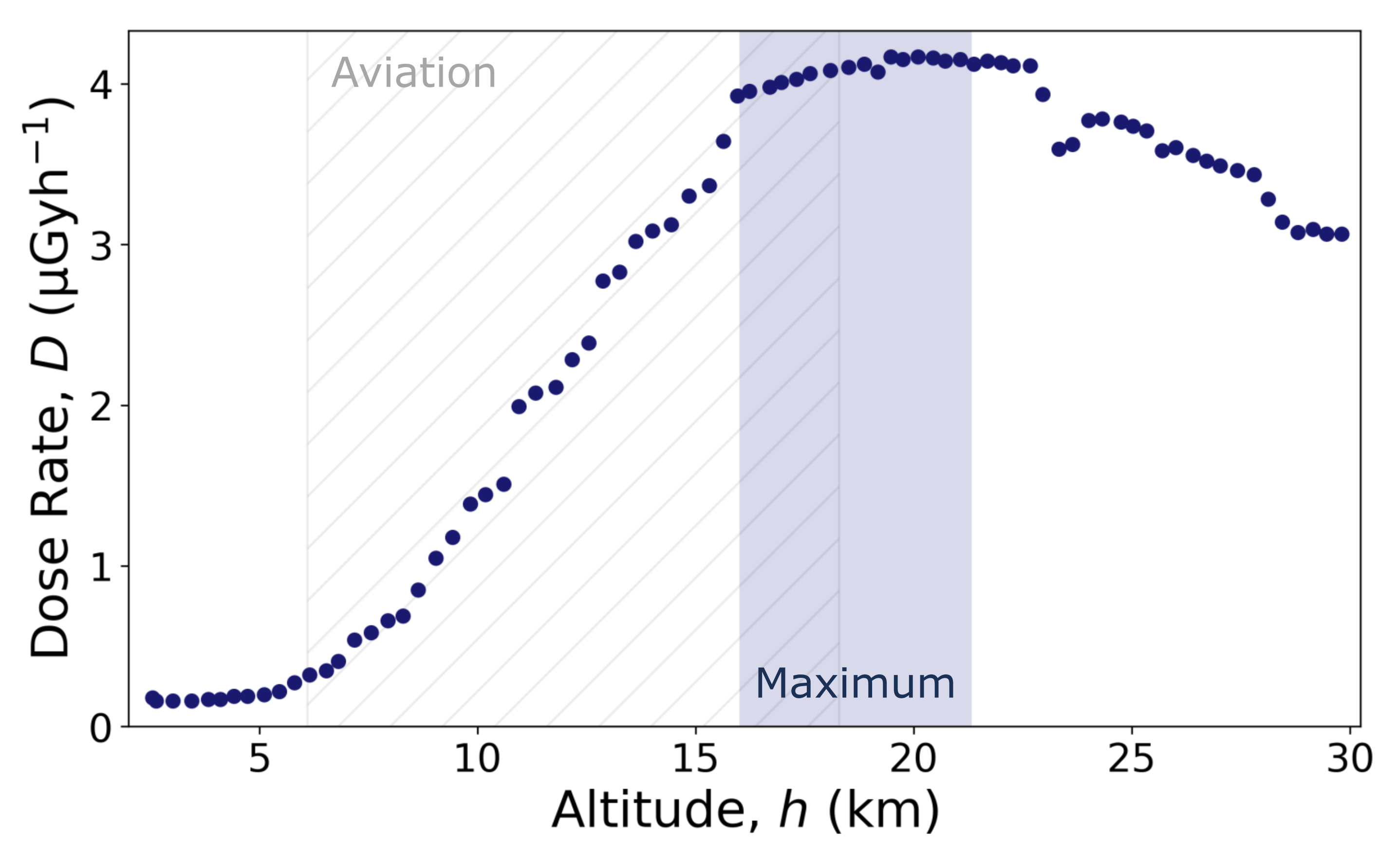
- This is called the Pfotzer maximum. It is caused by two competing effects:

  1. **Higher Primary Flux at Higher Altitudes:** Most CRs do not survive to low altitudes, so the flux is highest at high altitudes.
  2. **Lower Secondary Flux at High Altitudes:** The atmosphere is thicker at lower altitudes, meaning more CRs interact and produce air showers of many particles.

- The altitude that this maximum occurs at changes depending on the solar cycle.

Pfotzer Maximum

- This region of altitude overlaps with heights airplanes fly at. Pilots experience more radiation than normal in their lifetimes because of this.



Detecting Cosmic Rays Directly

Satellite Experiments

Balloon Experiments

Single-Event Upsets

- Cosmic rays passing through computers can sometimes cause bits to flip (changing a 0 to a 1 or vice versa). These events are known as single-event upsets.

- **Example:** In 2003, a candidate in a federal election in Belgium received 4096 more electronic votes than paper votes.

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0	0	0	0	0	1	0	0	1	0	0	1	0	1	0	0	0
2^{16}	2^{15}	2^{14}	2^{13}	2^{12}	2^{11}	2^{10}	2^{9}	2^{8}	2^{7}	2^{6}	2^{5}	2^{4}	2^{3}	2^{2}	2^{1}	2^{0}

2344 votes

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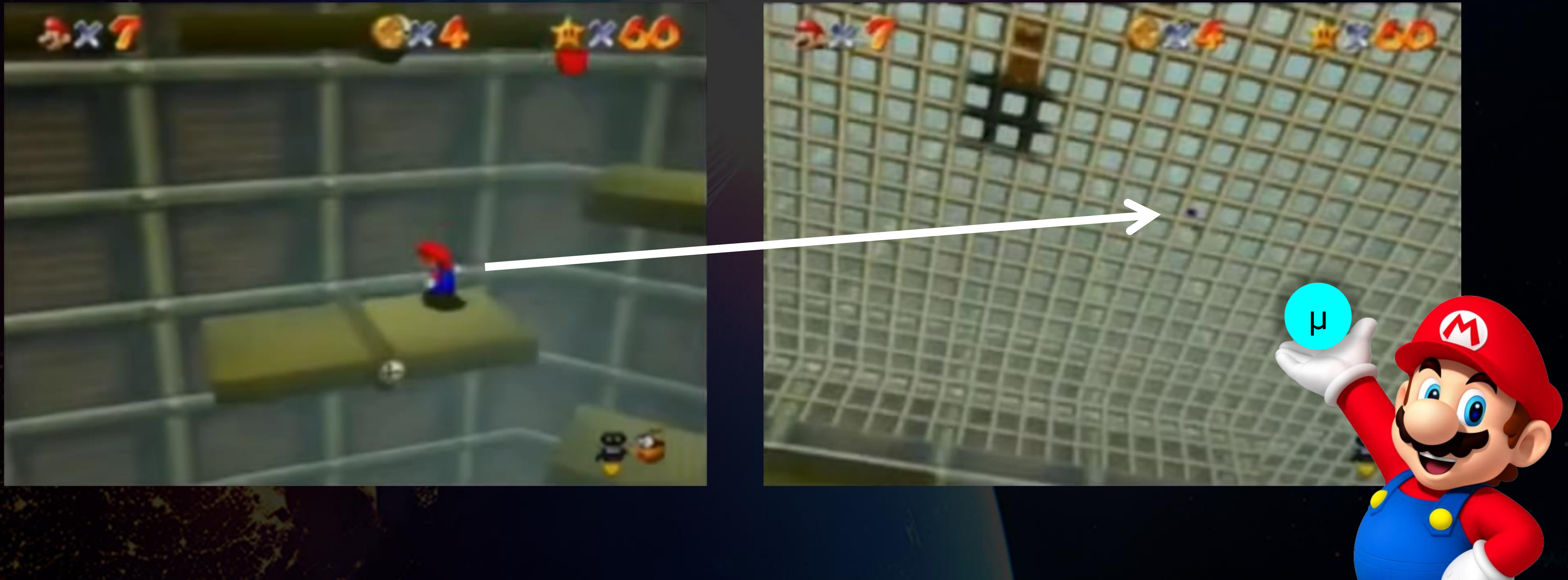
6440 votes

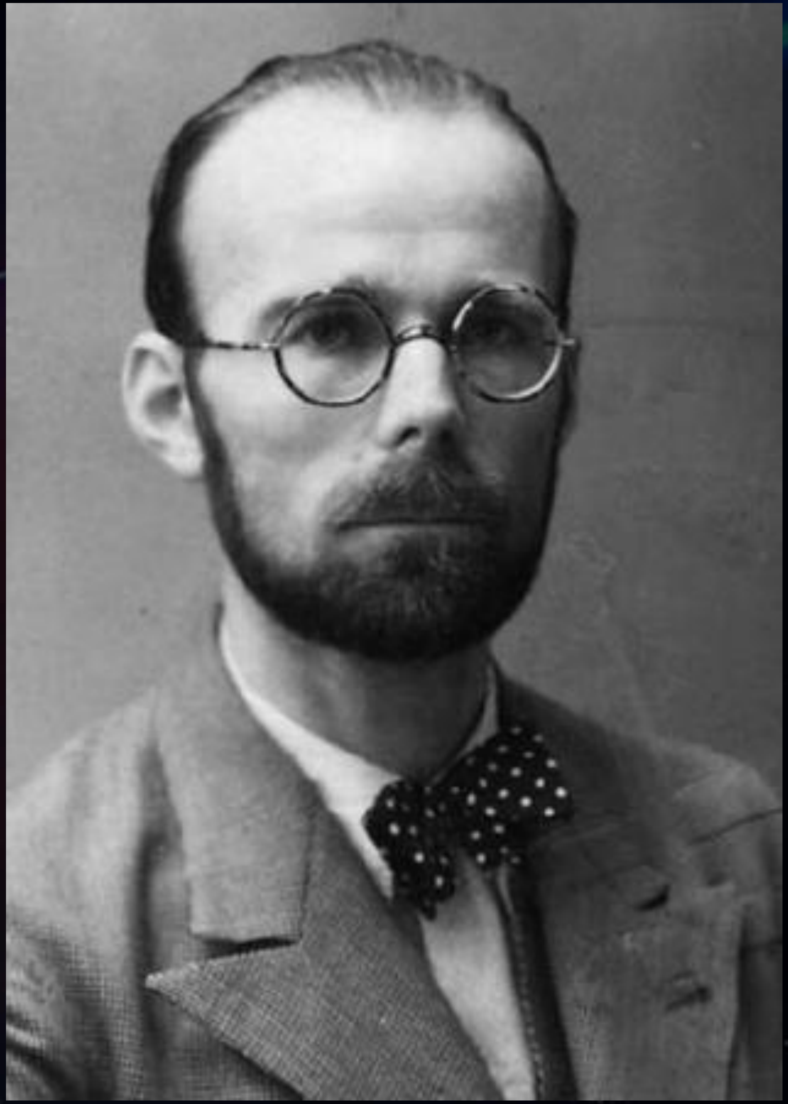
Single-Event Upsets

- **Example:** In 2013, a Super Mario 64 speedrunner was instantly teleported up to a higher height in the level. Changing a single bit in the value that specifies Mario’s height reproduces this glitch exactly.



Discovery of Air Showers

- Air showers were first discovered by Pierre Auger in 1939.
- He spread a number of particle detectors out on the ground, and noticed coincident spikes in particles between them.
- He concluded the particles must have come from a single CR of high energy.
- The Pierre Auger Observatory in Argentina is the world's largest CR detector, and was named after him when design began in 1995.



Pierre Auger (1899 – 1993)

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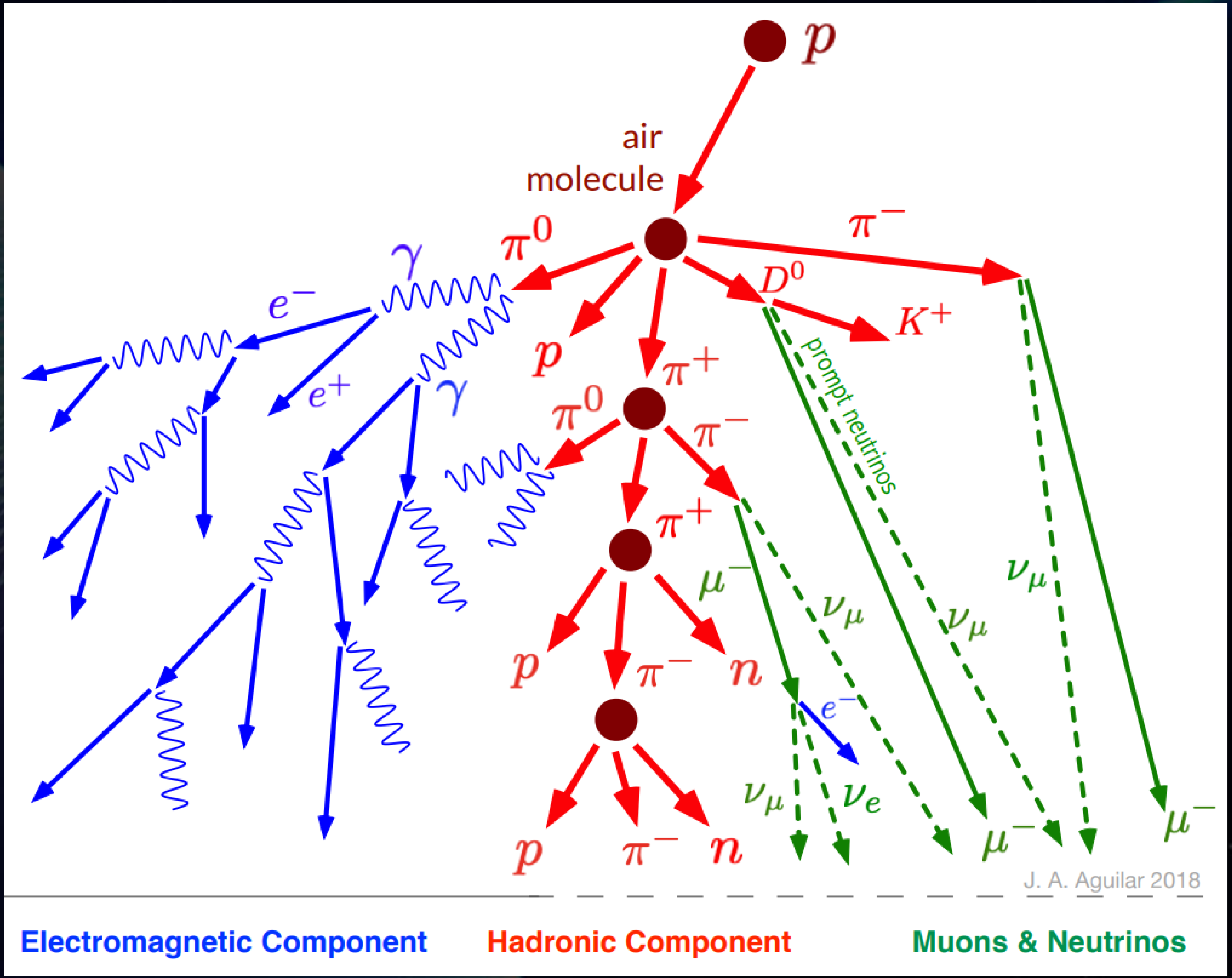
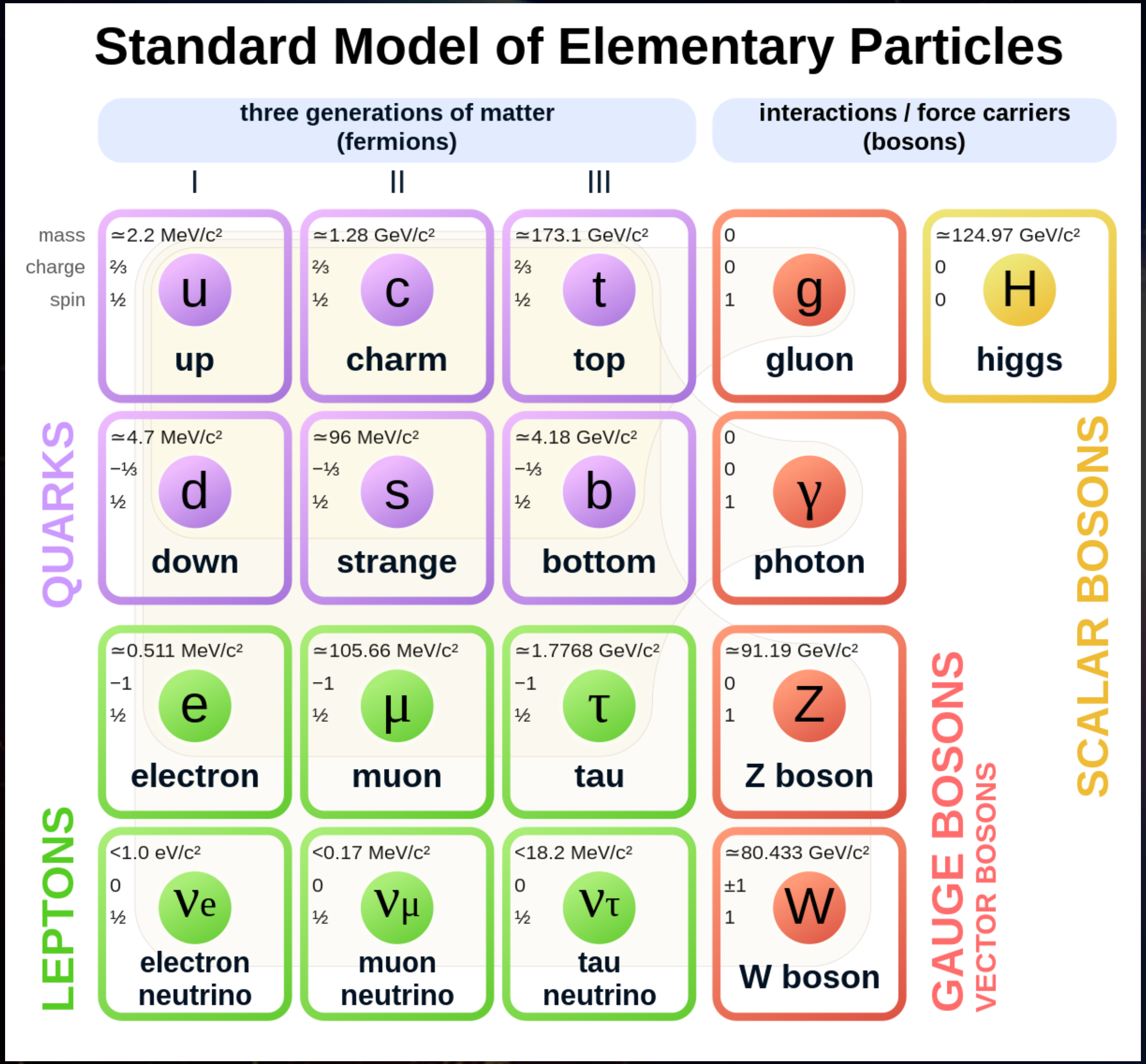
Pierre Auger Observatory

Air Showers and Atmospheric Muons

- Protons interact with atoms in the Earth's atmosphere.
- This leads to the production of air showers.
- Air showers contain pions.
- The main decay mode of charged pions is into a muon. These muons are called atmospheric muons.

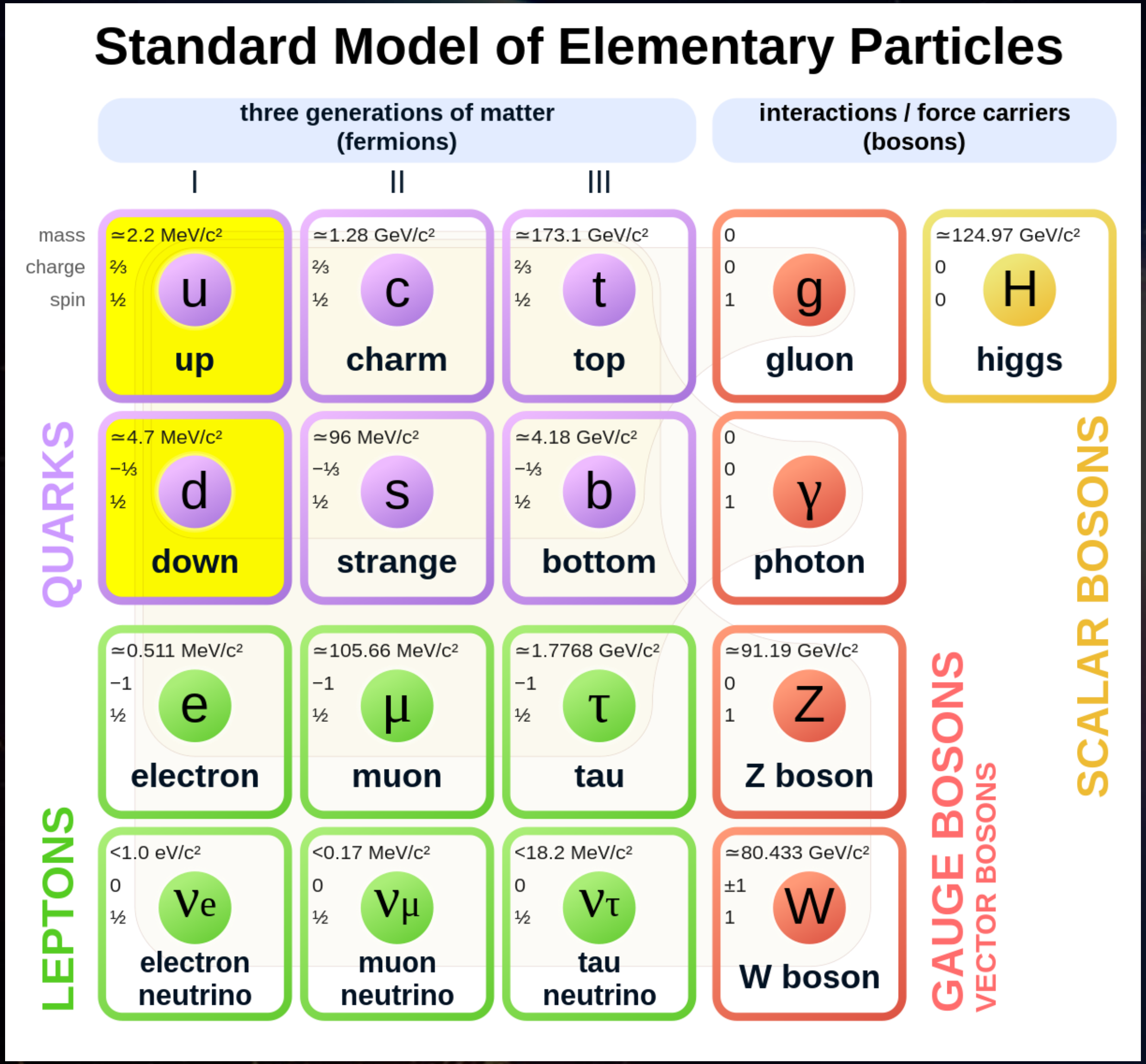


Particles



Proton

Particles



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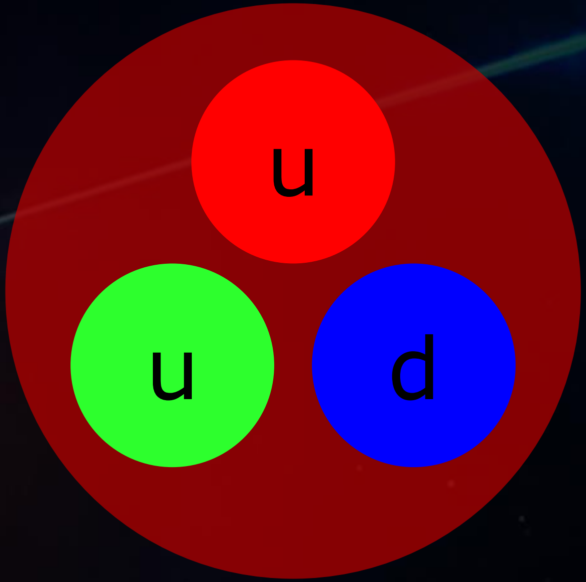

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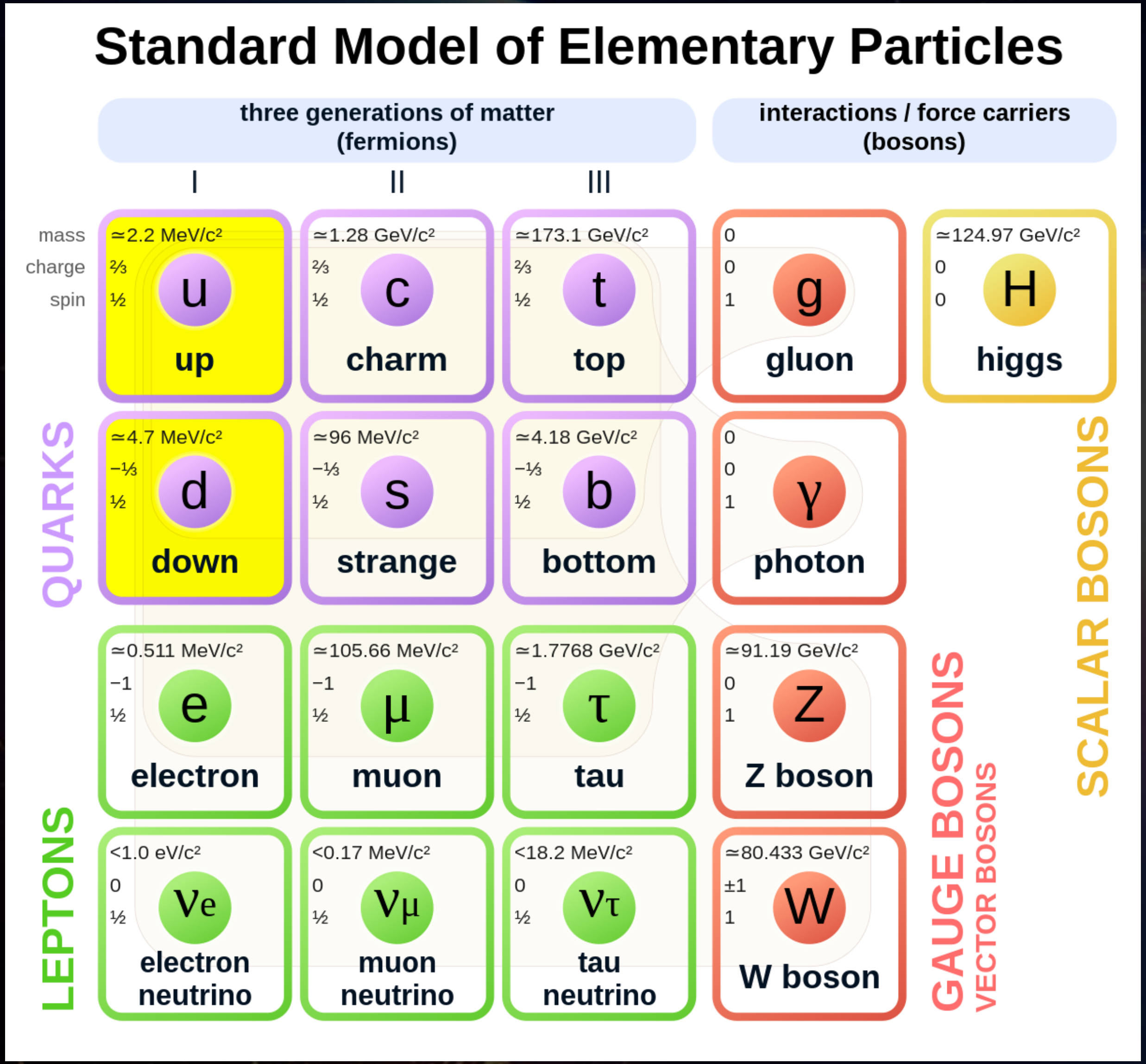
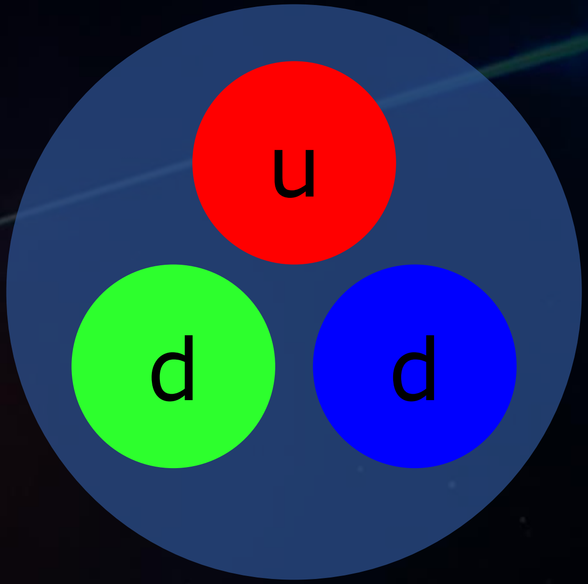


Neutron



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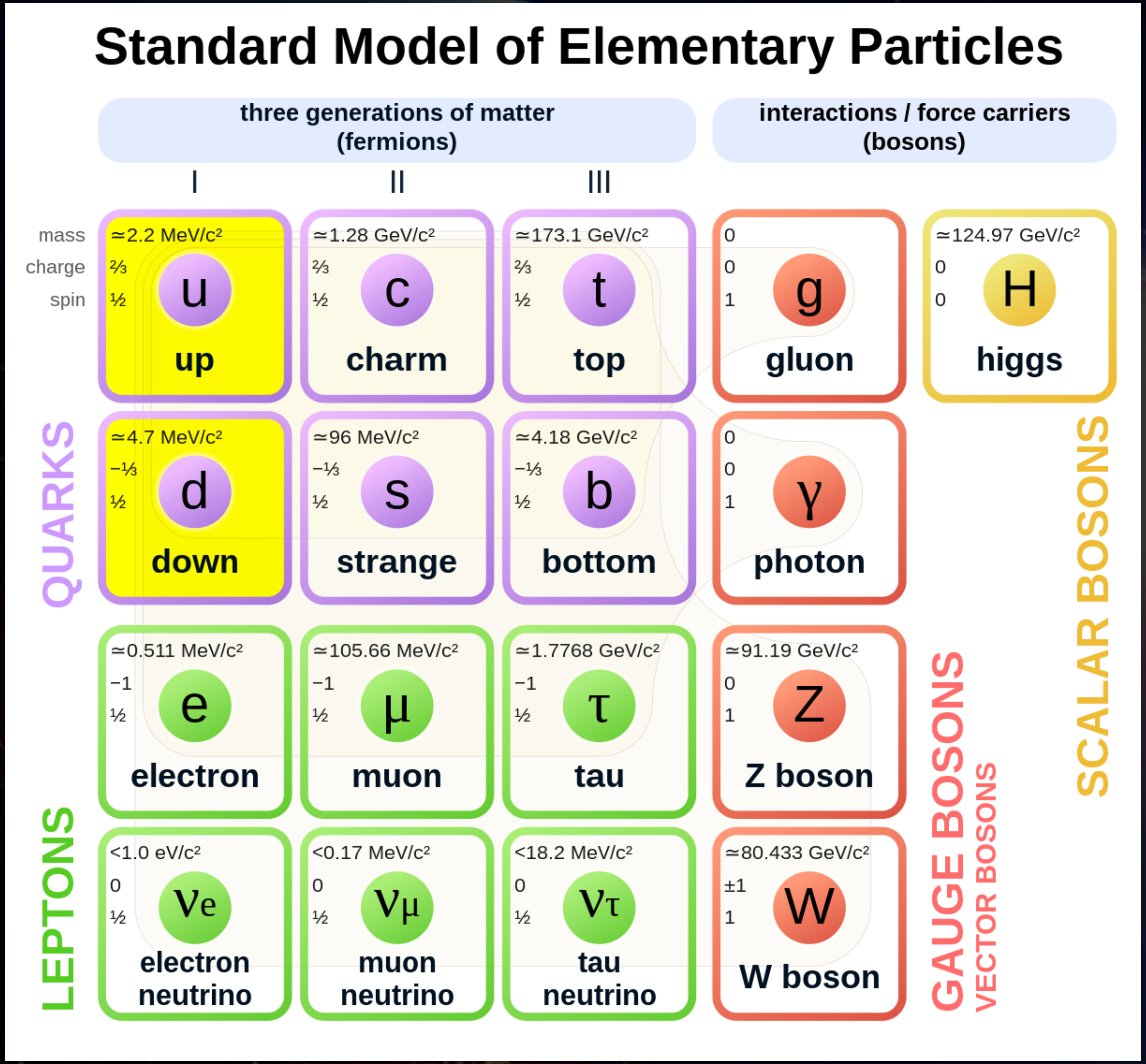

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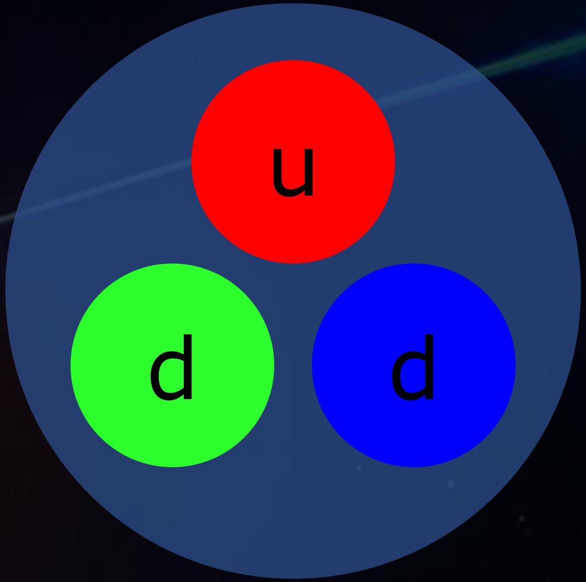
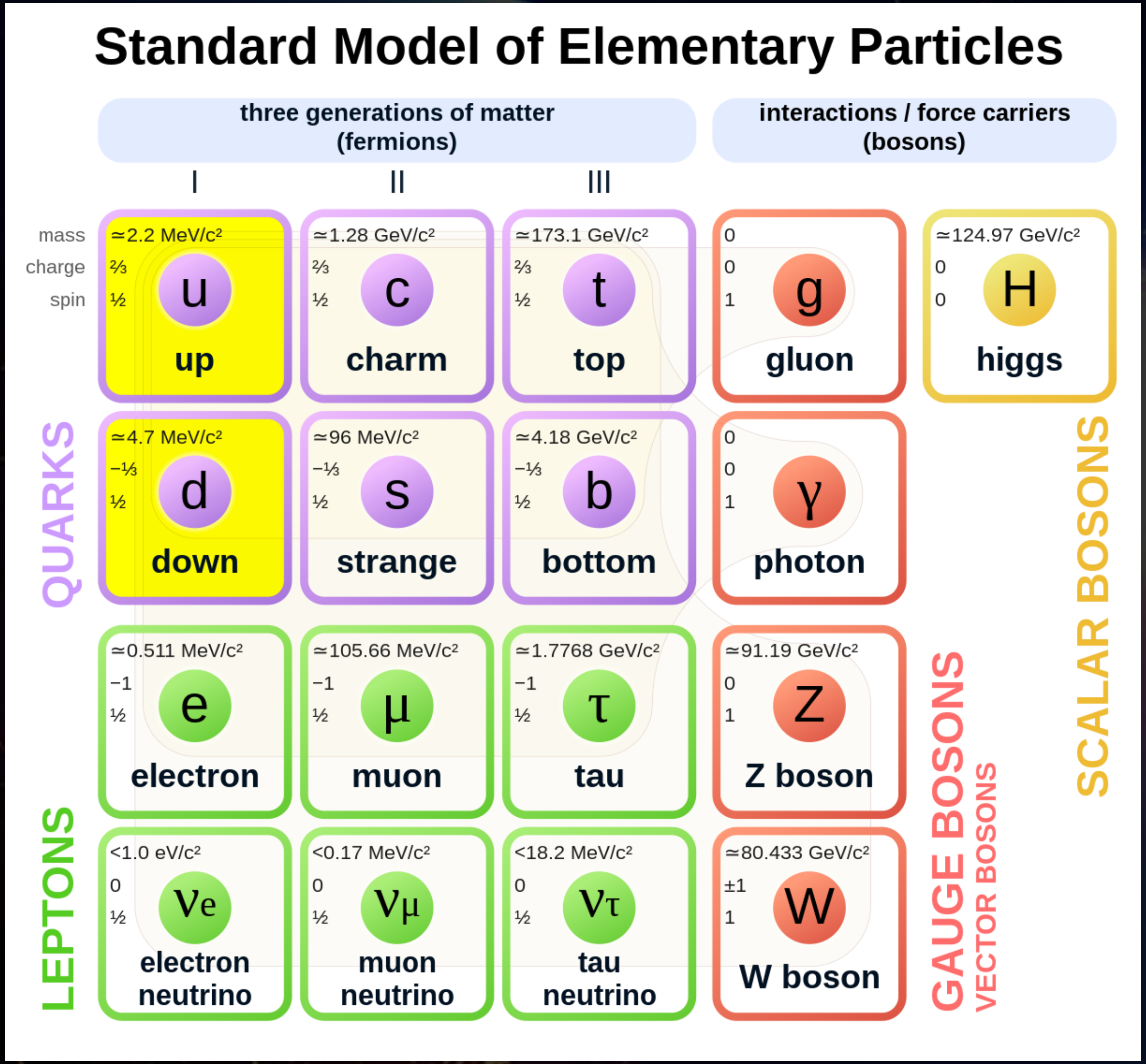
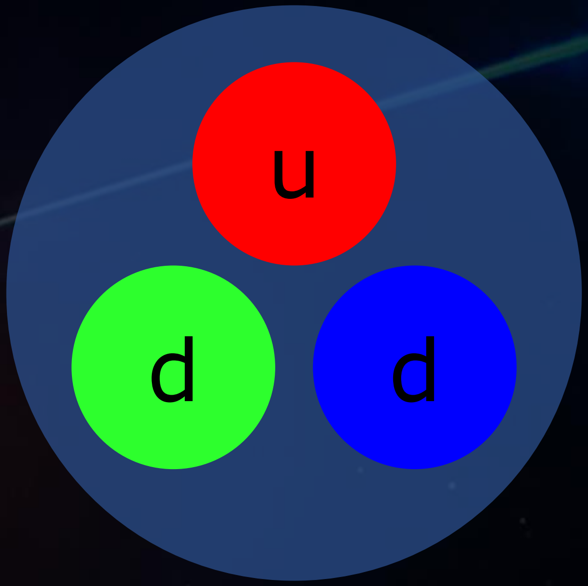


Pion

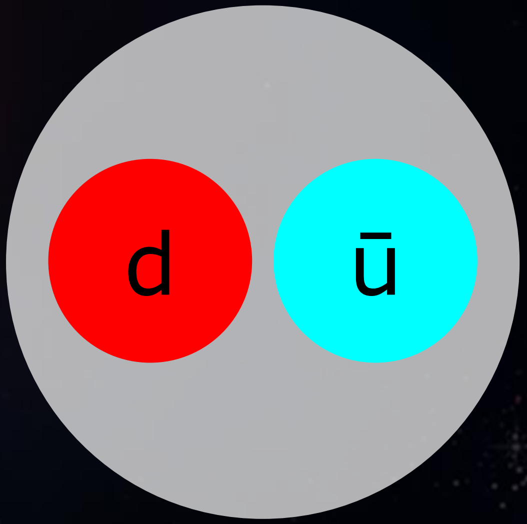
Particles



Neutron



Pion



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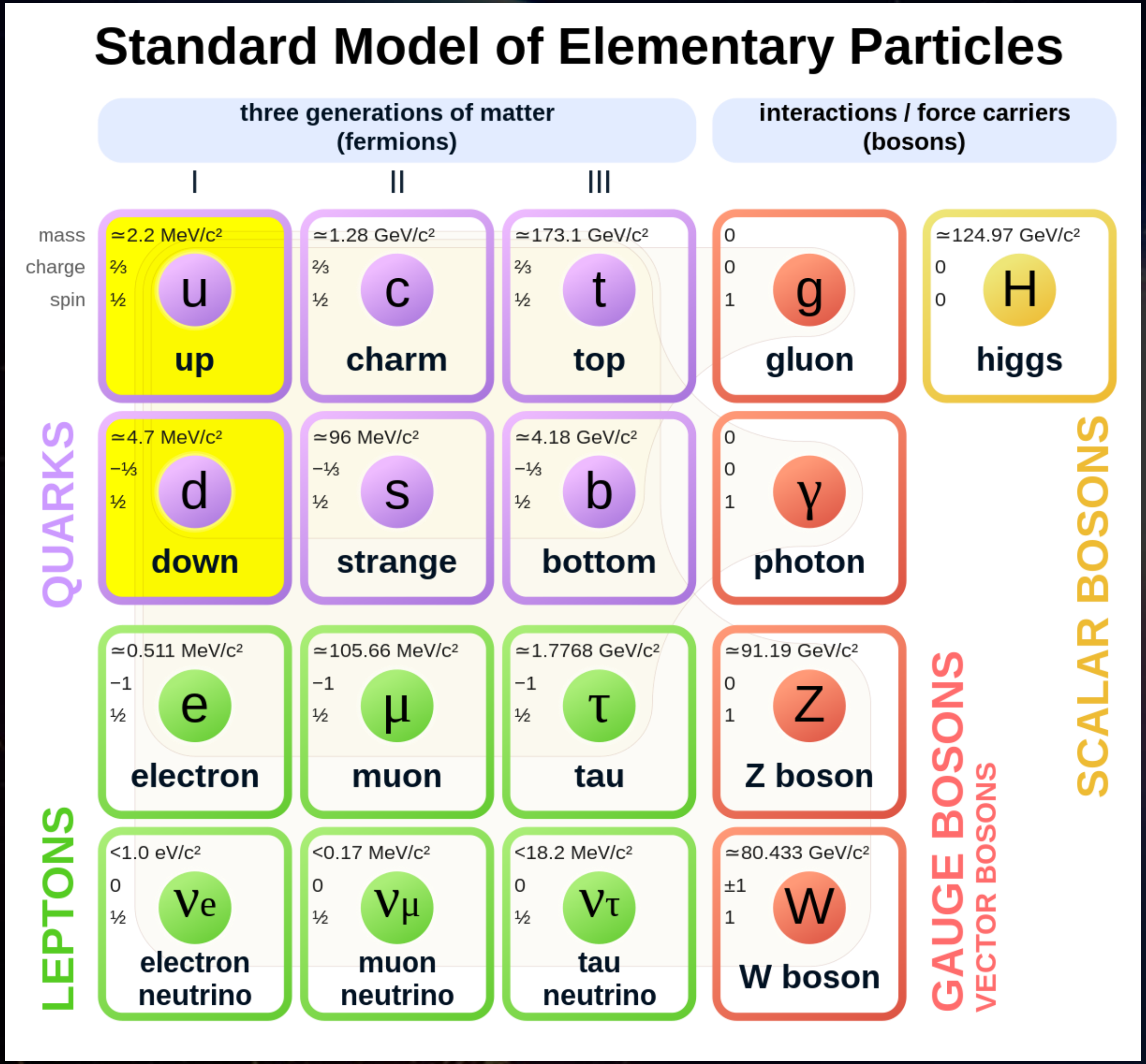

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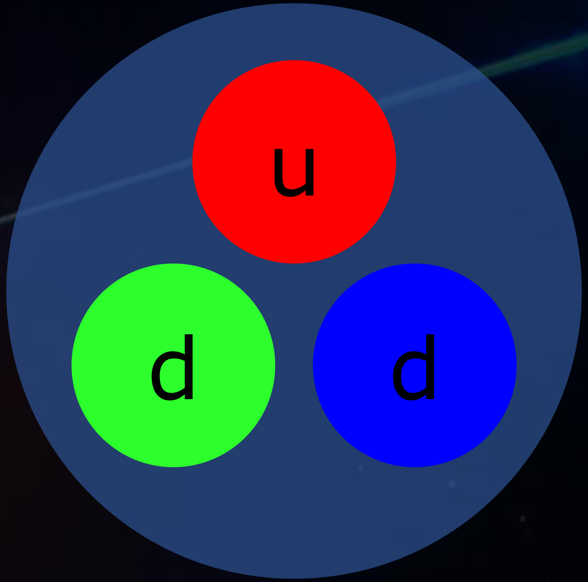
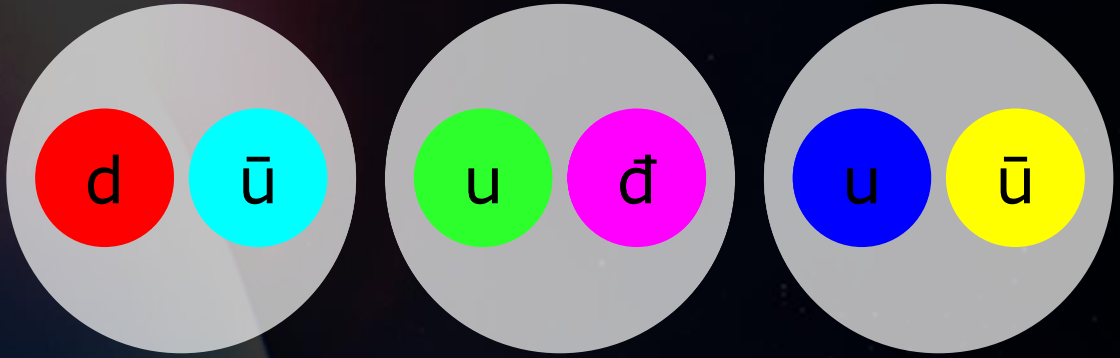
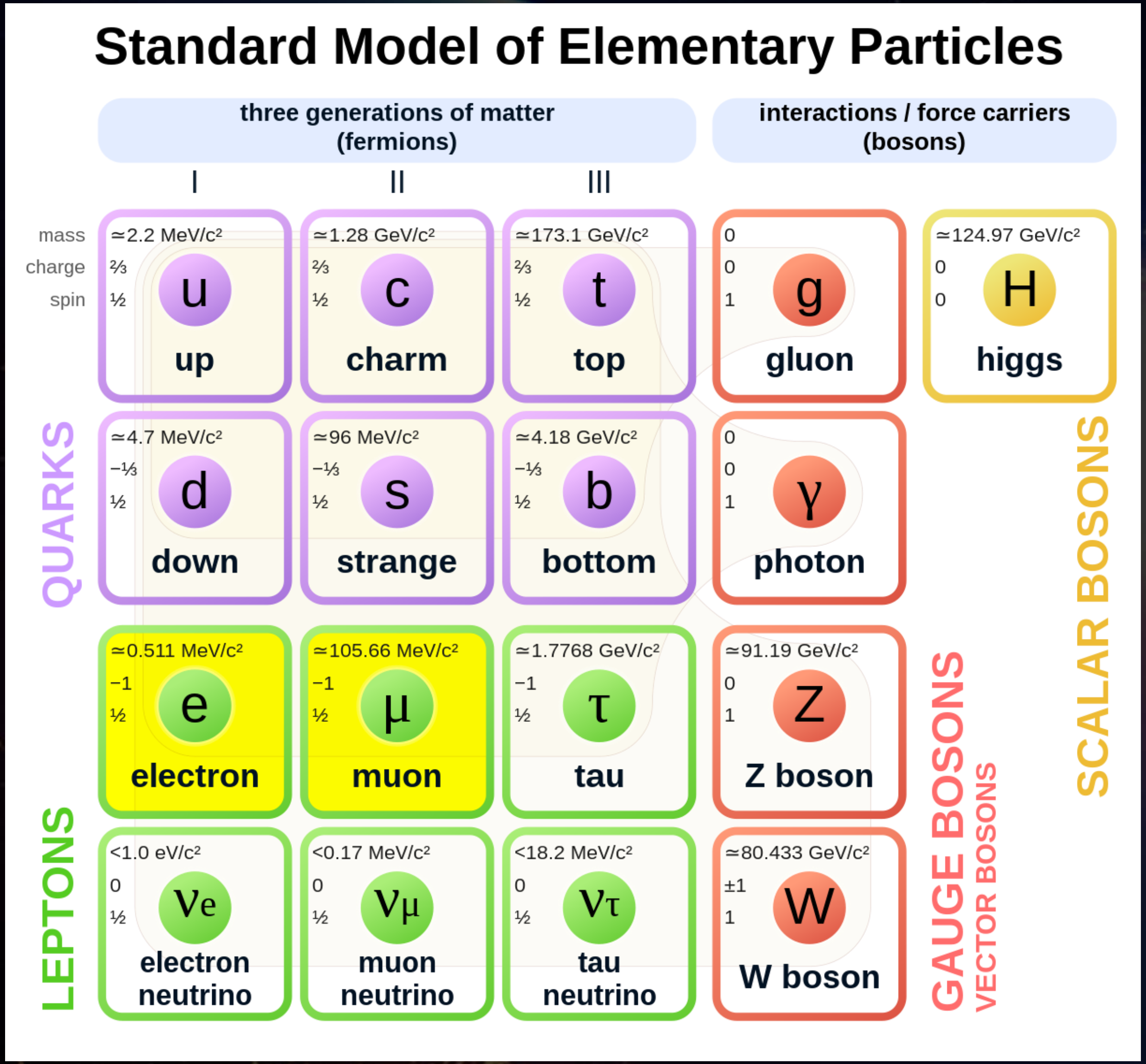




π^- π^+ π^0

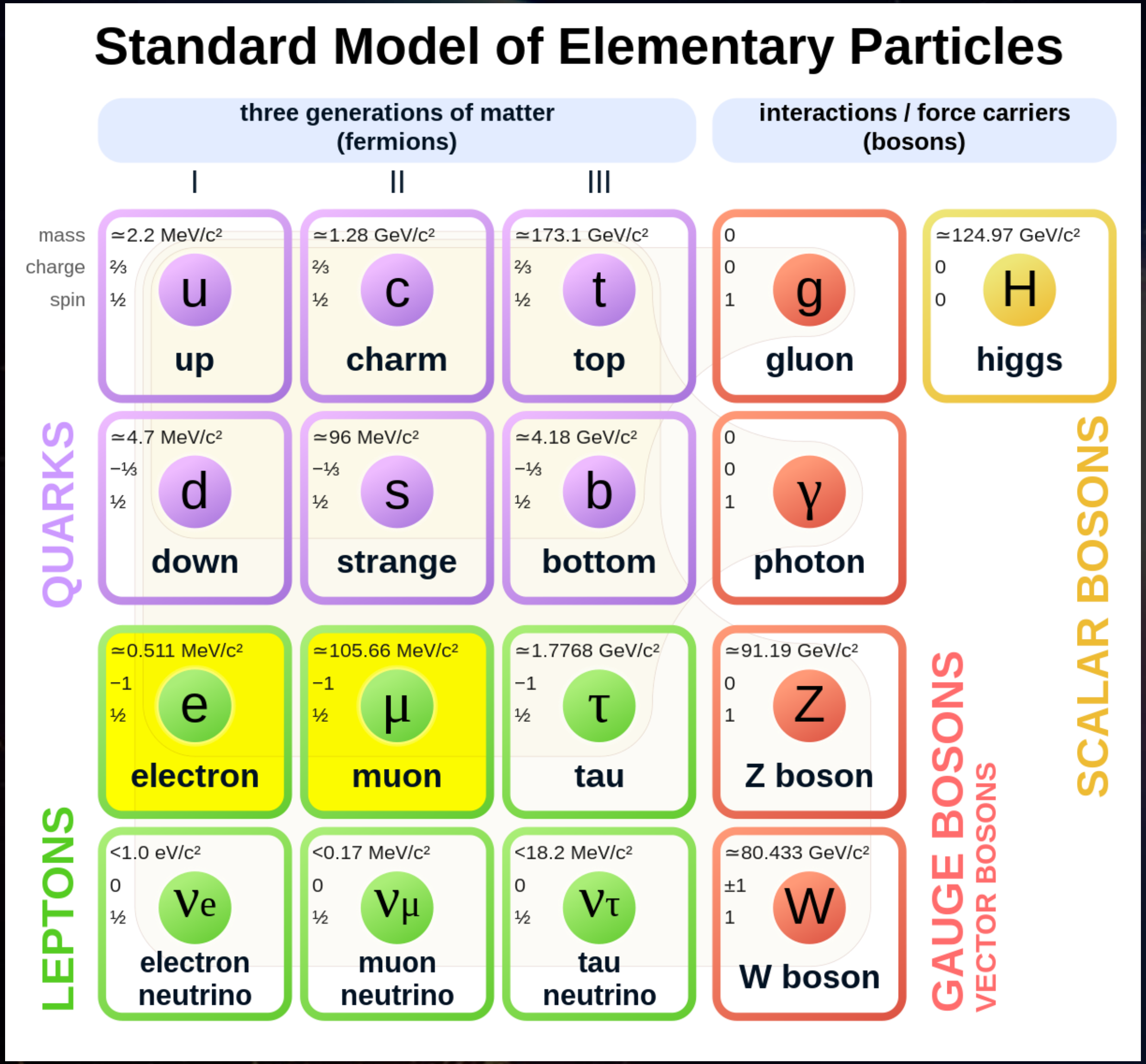
Particles

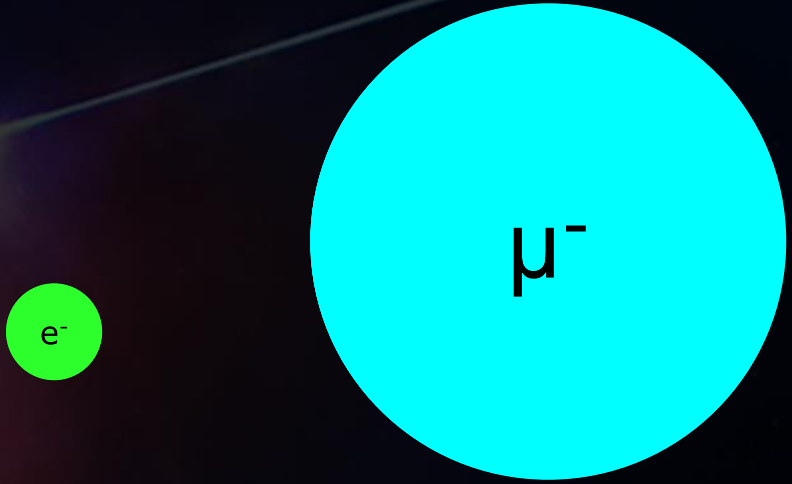


Electron

Muon

Particles

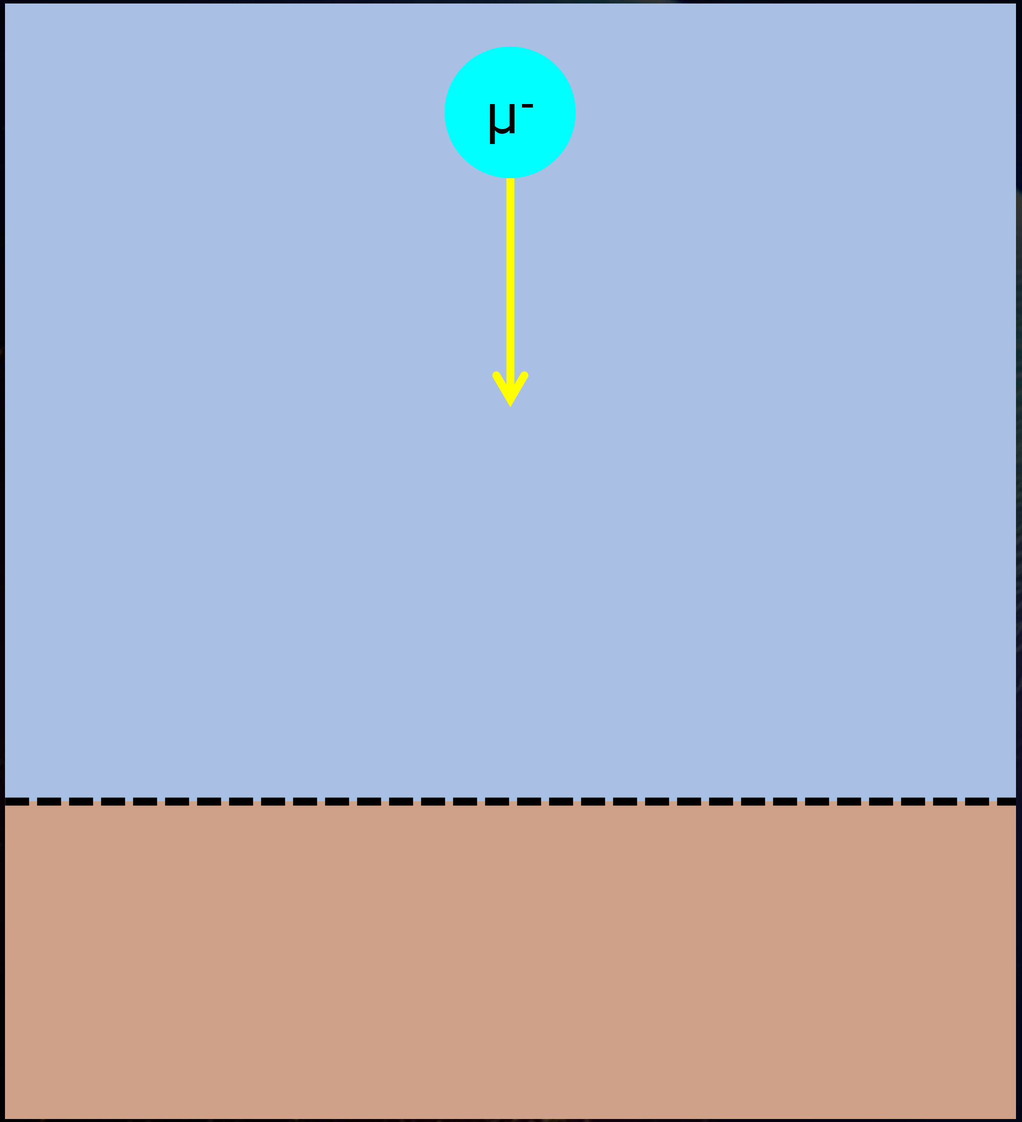




Electron

Muon
$200m_e$

Muon Lifetime



- Muons are produced around ~15 km above sea level.
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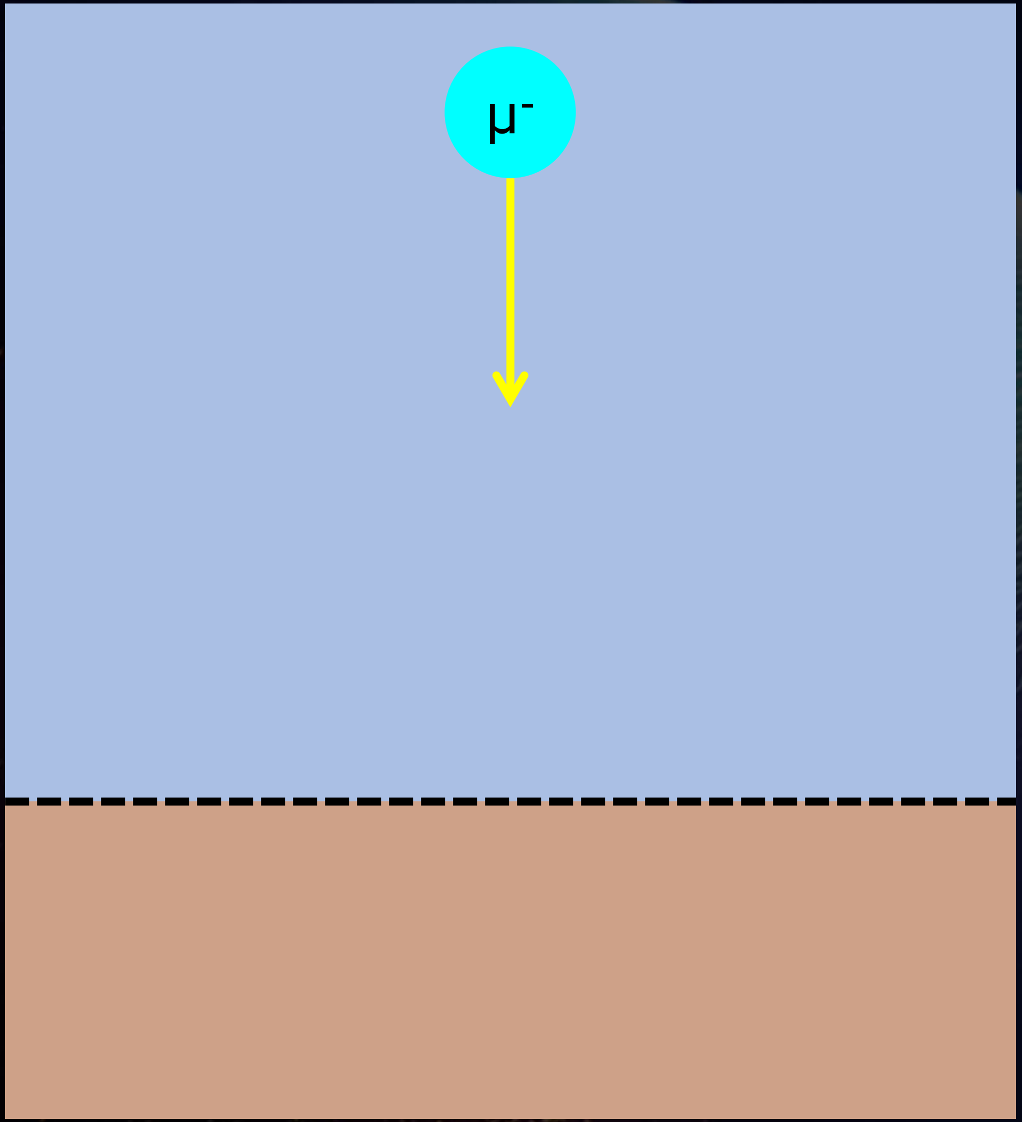
Muon Lifetime



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- In special relativity, objects moving near *c* experience length contraction.
- From the muon's perspective, the journey to the Earth is <1 cm.

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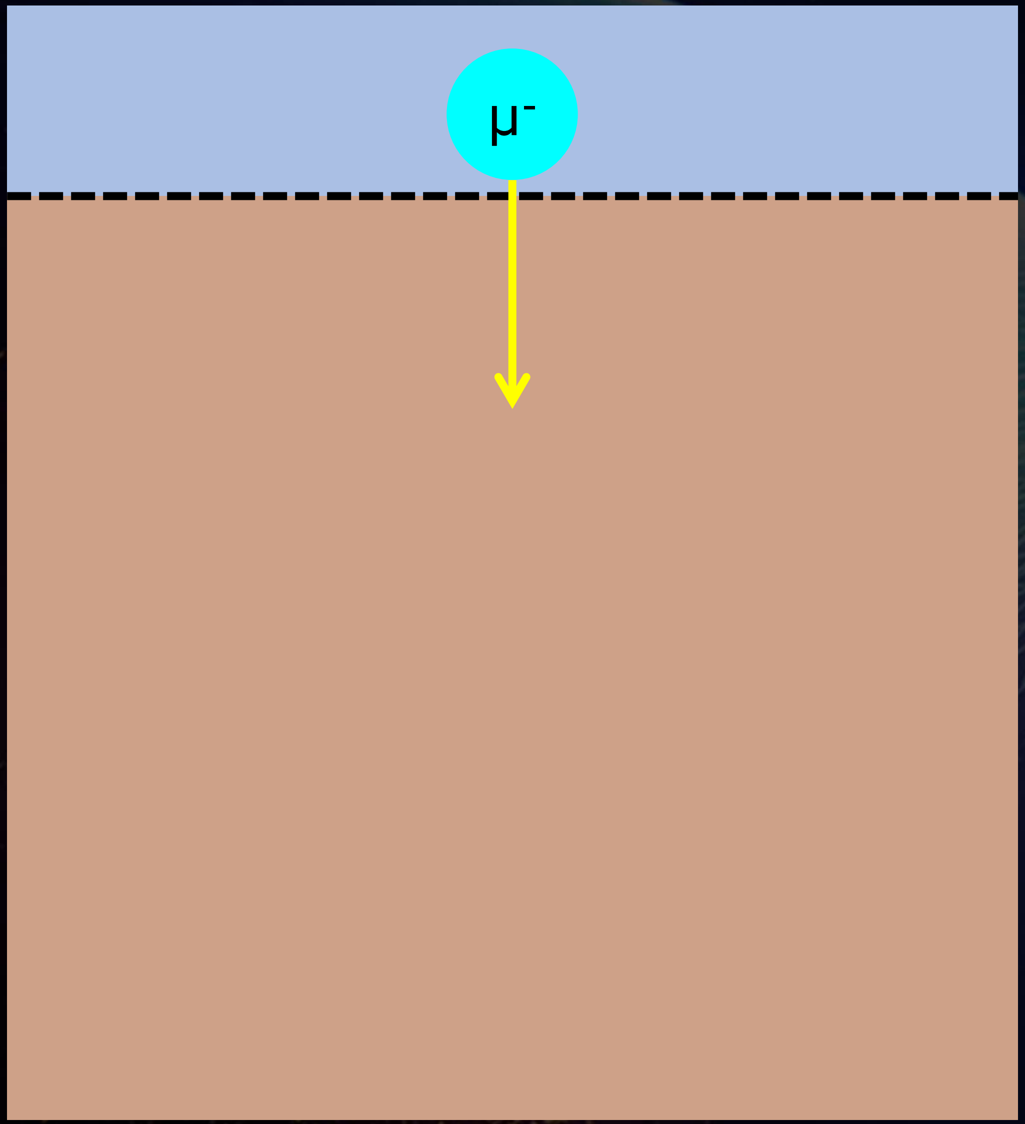

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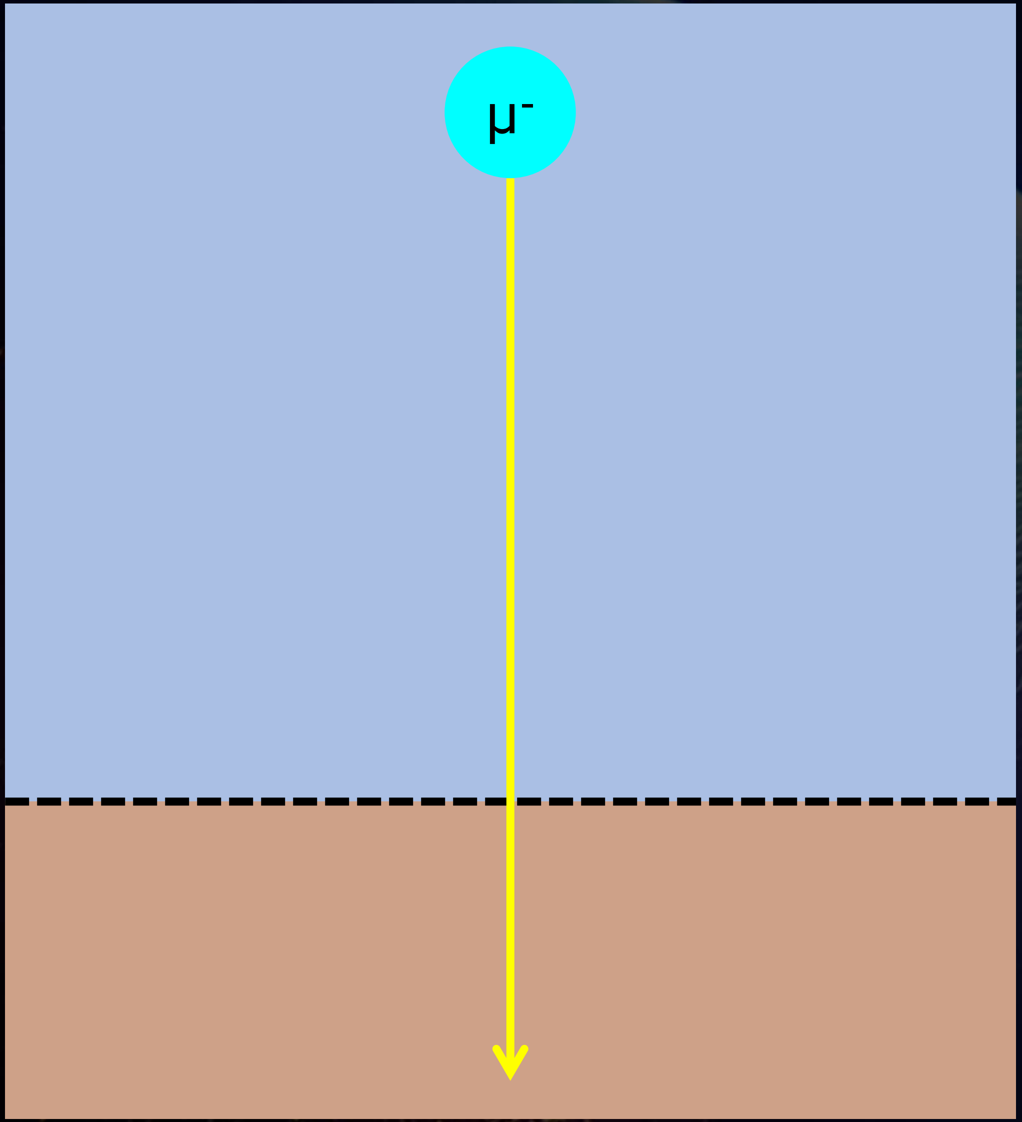

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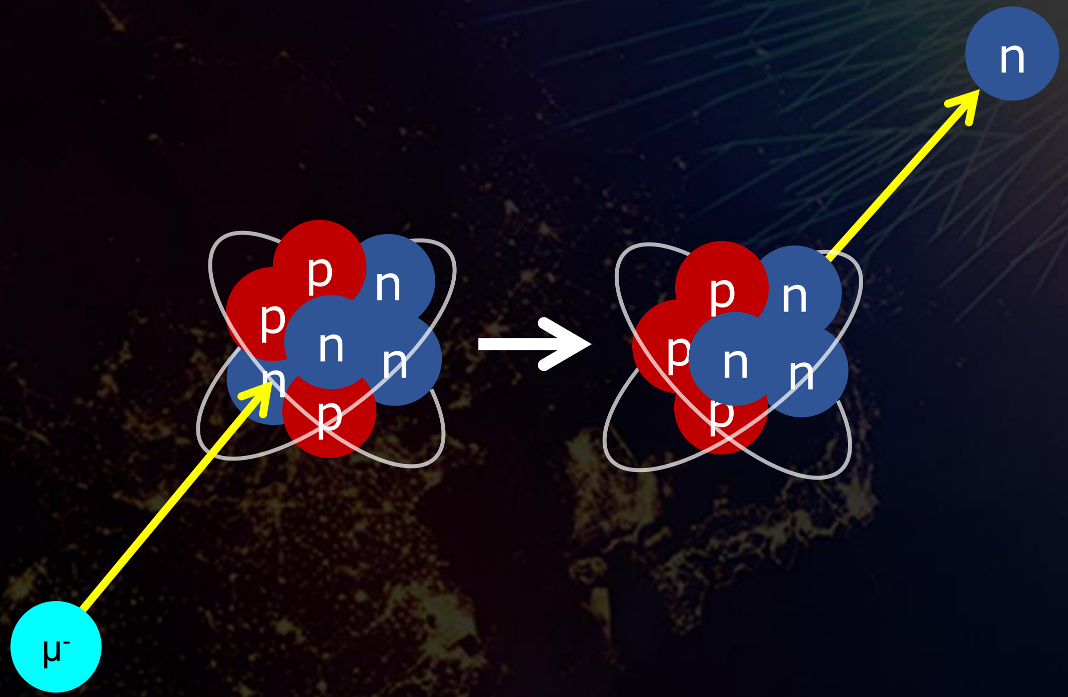
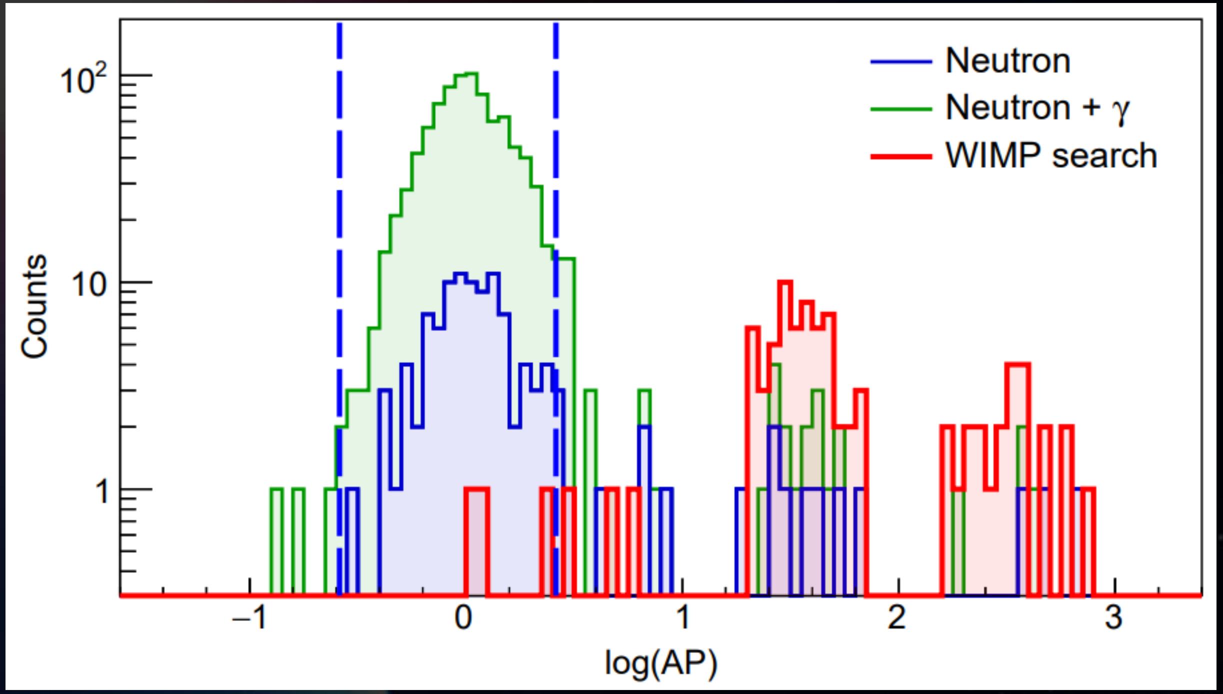
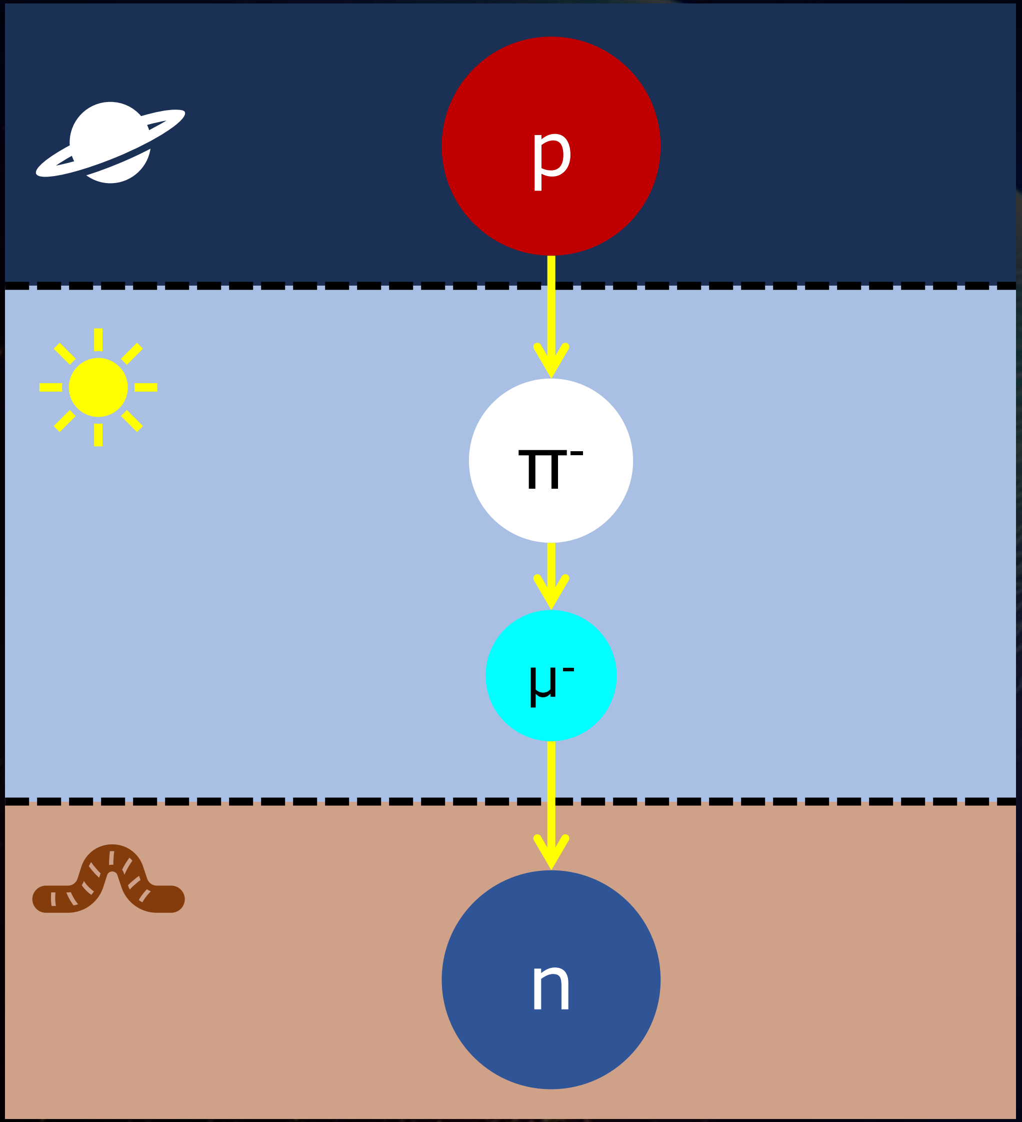
Muon-Induced Neutrons

- While travelling underground, muons interact in the rock to produce neutrons via spallation.
- Neutrons are a big problem for Dark Matter detectors because they can mimic WIMP signatures in the data.



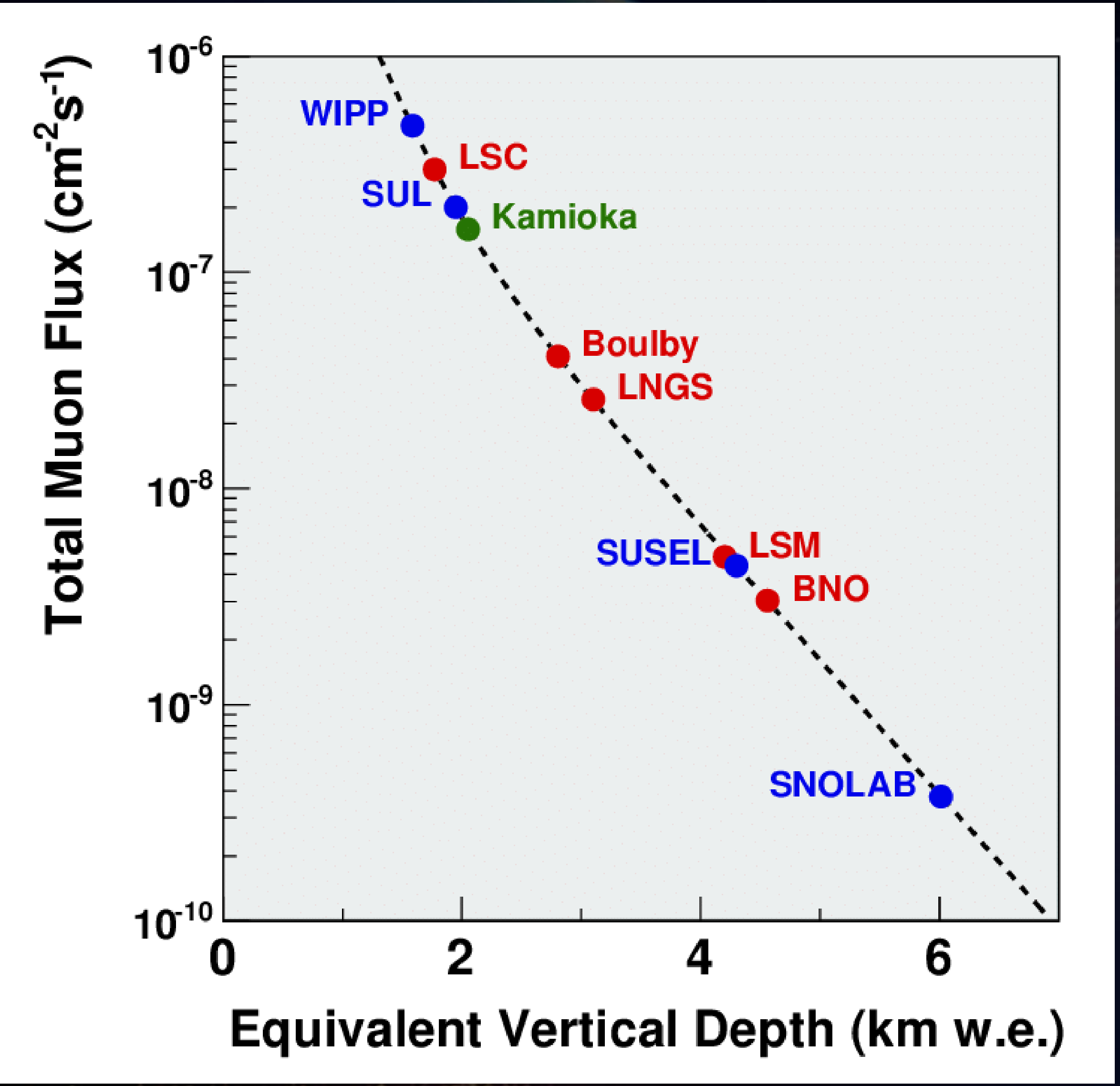


Summary of Processes



1. Protons are accelerated in outer space.
2. Protons produce pions in the atmosphere.
3. Pions decay into muons.
4. Muons produce neutrons underground.

Underground Labs



- **Goal:** Have the lowest muon flux possible.
- The deeper you go underground, the lower the muon flux.
- For this reason, Dark Matter experiments are done in mines or in tunnels under mountains.
- SNOLAB is one of the deepest labs in the world.

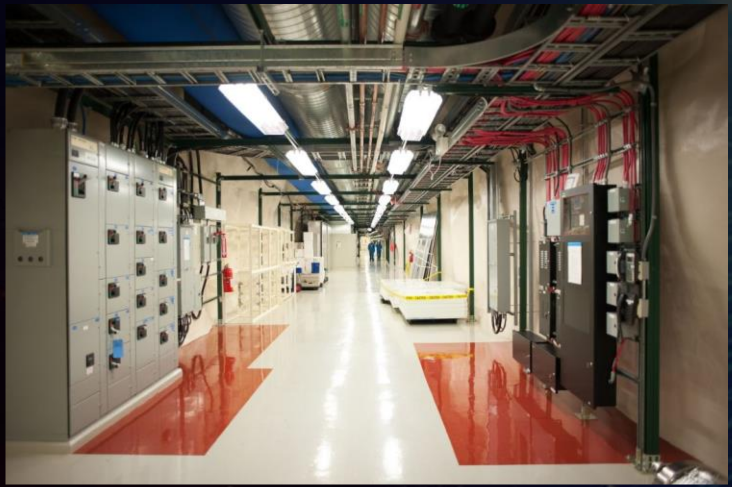
* km.w.e. = Kilometres Water Equivalent

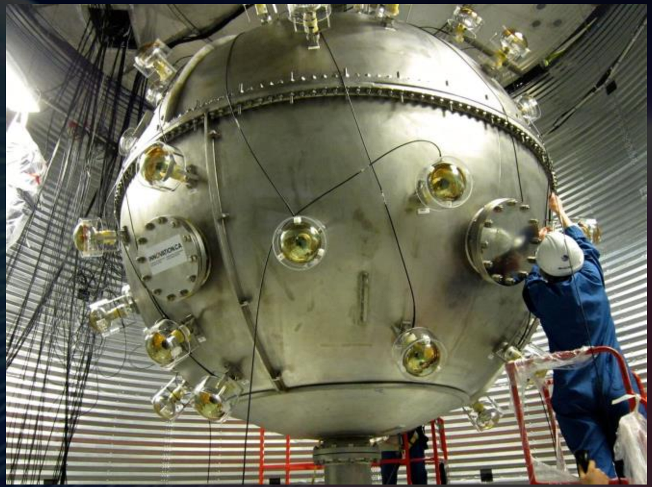
SNOLAB

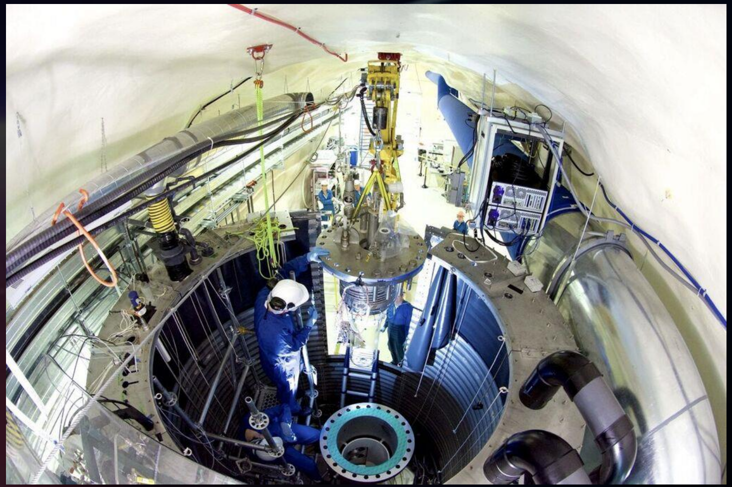
- DM research is done all over Canada, but experiments are held 2 km underground in Sudbury, Ontario at SNOLAB, located inside an active nickle mine.

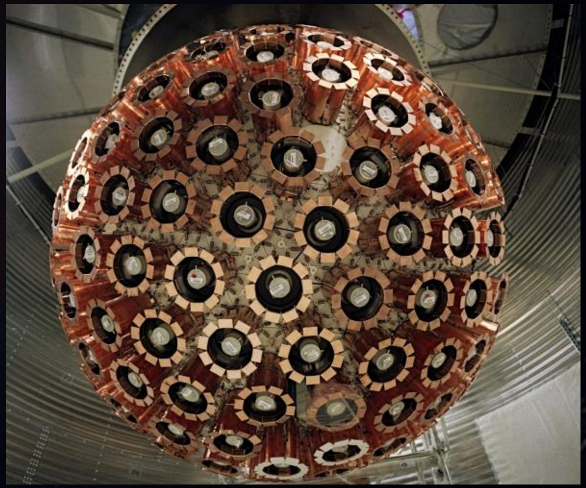
SNOLAB

- SNOLAB hosts 11 experiments, including DEAP, NEWS-G, and SBC.







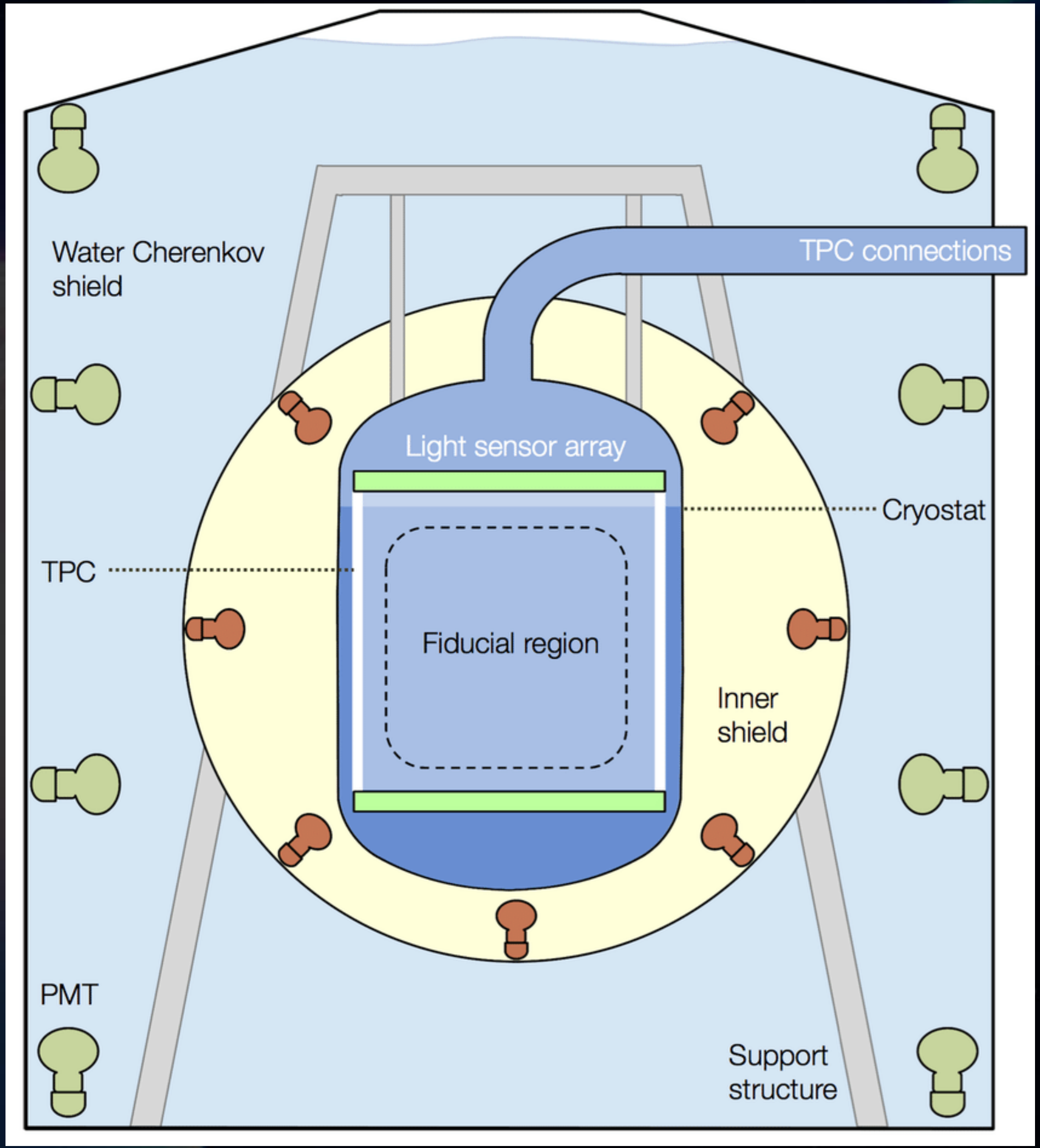


Muon Vetoes

- What happens if a neutron enters a detector and the detector thinks it's seen a DM particle?

- A lot of experiments wrap their detectors in smaller detectors that look specifically for muons, called muon vetoes.

1. Muons pass through the water and emit light.
2. The light is captured by the PMTs.
3. The PMTs tell the DAQ to discard the event just recorded.



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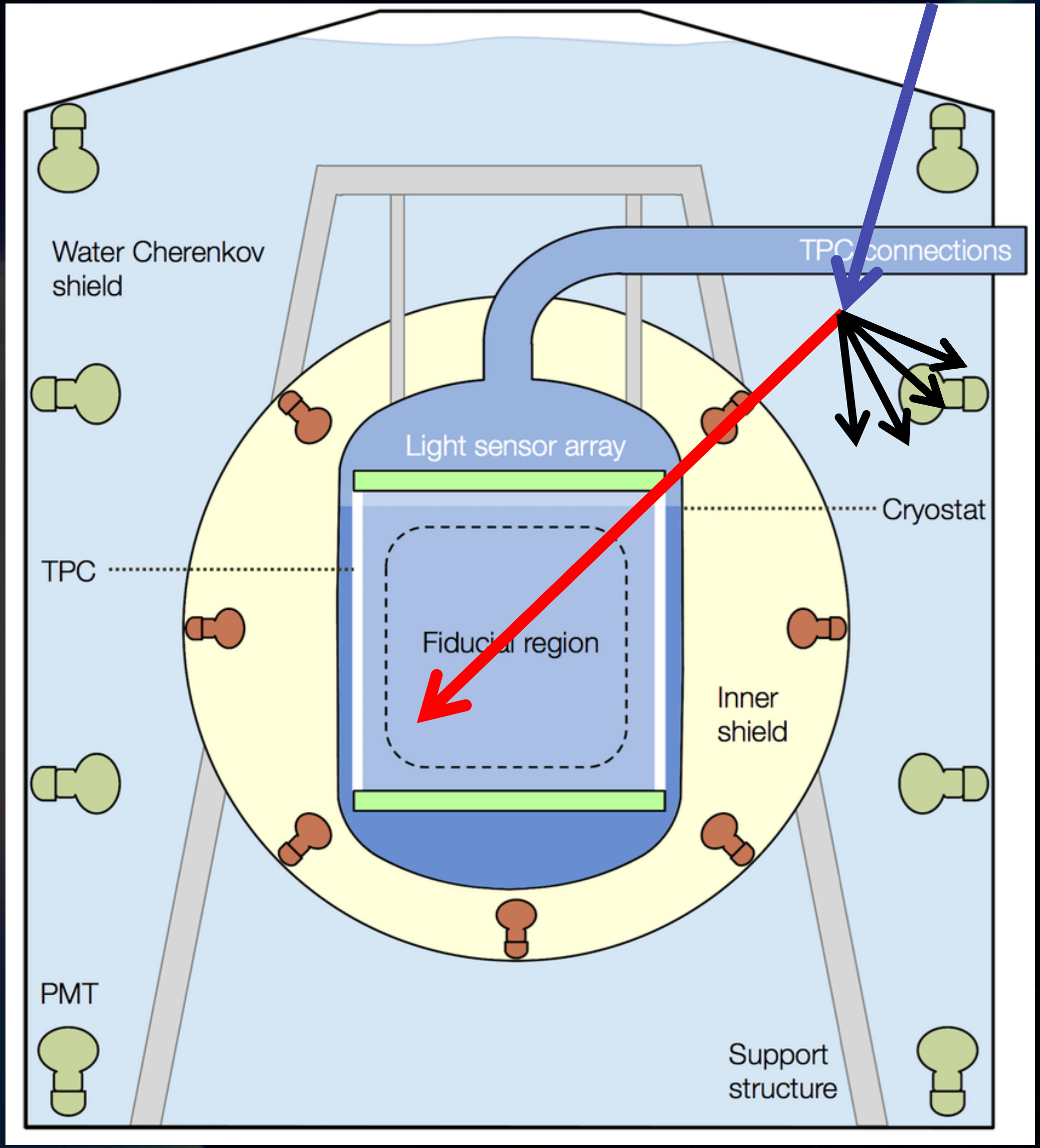


Simulating Expected Backgrounds

- In order to design effect muon veto systems, experiments need a good idea of how many neutrons to expect in their detector.
- General particle transport simulation codes like Geant4 and FLUKA are written specifically for this type of thing.

GEANT4
A SIMULATION TOOLKIT

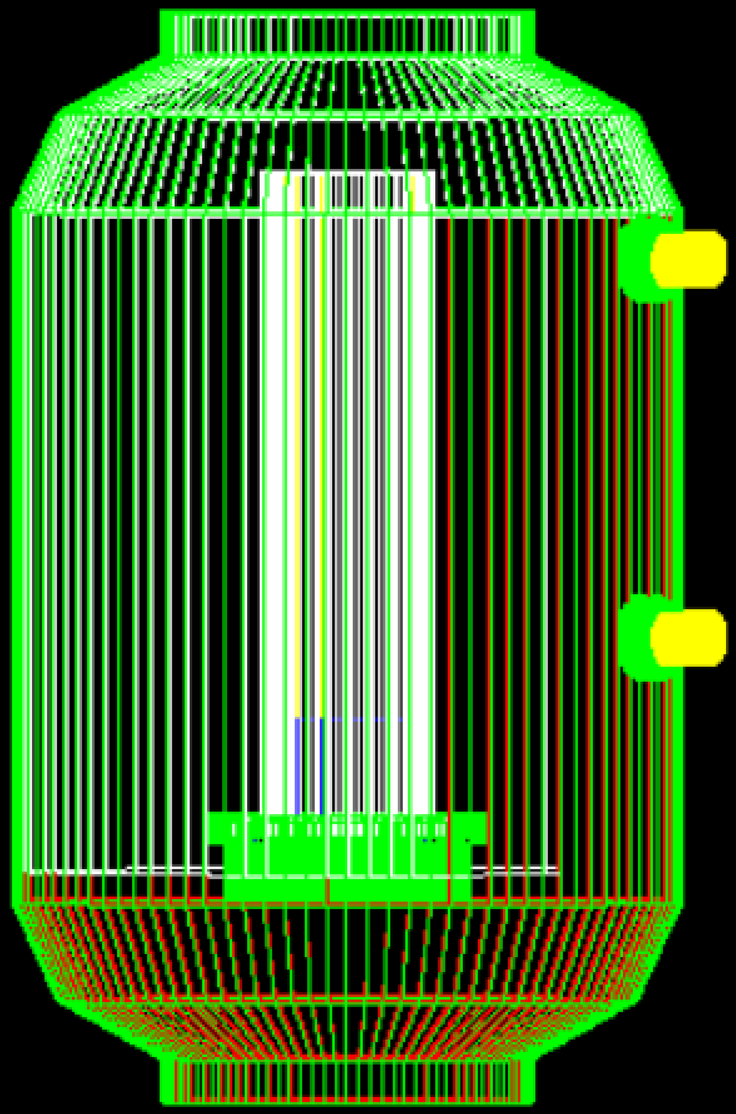
FLUKA

Simulating Expected Backgrounds

- **Basic Steps:**
  1. Construct your detector geometry.
  2. Simulate a bunch of muons.
  3. See how many turn into neutrons.
  4. See how many of those neutrons reach your detector.

- But how do you know how many muons to simulate?

- And what energies and directions do you give them?



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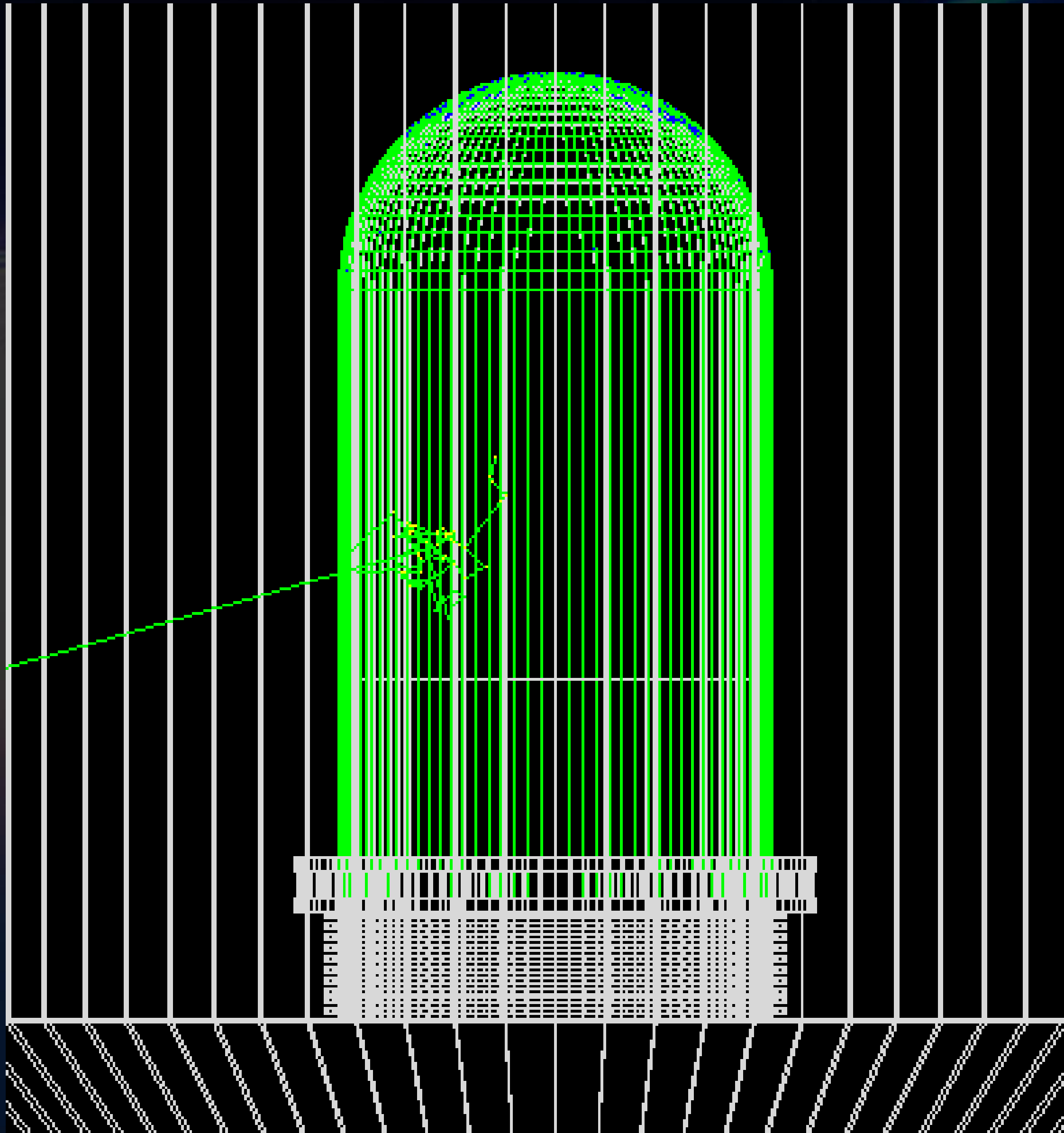

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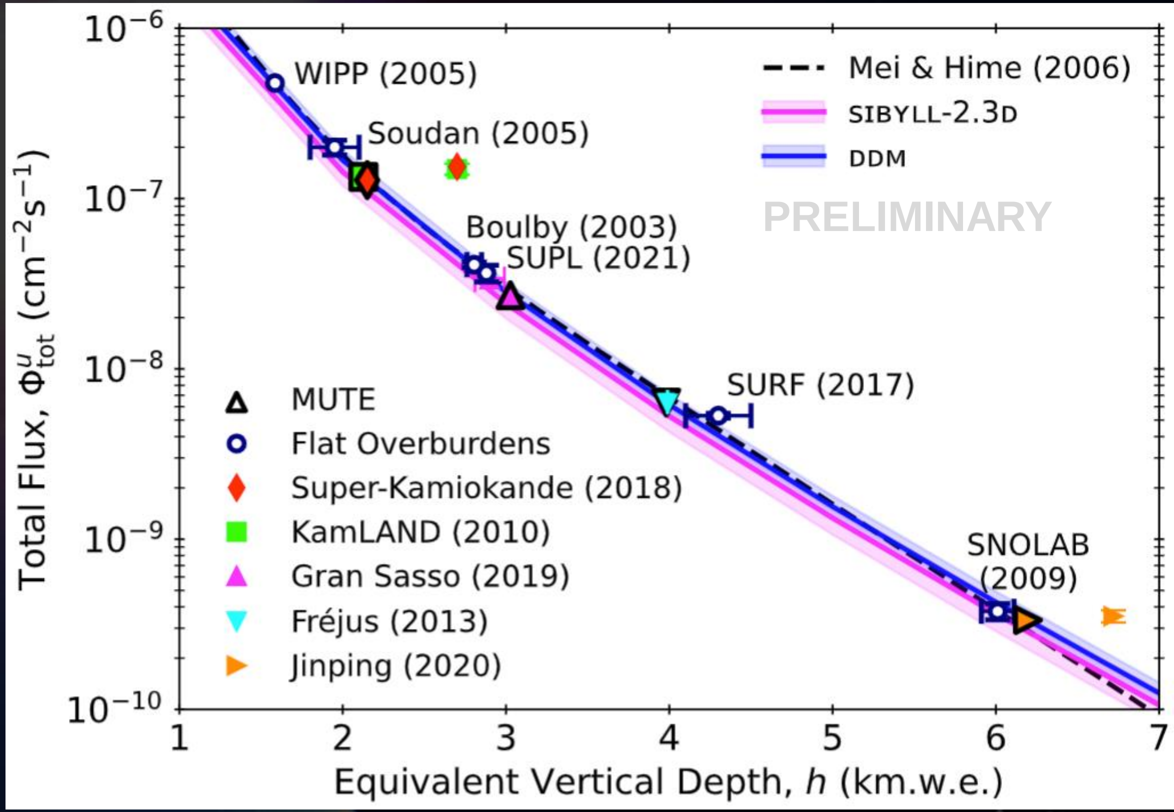
MUTE

How many muons do we expect at different depths underground, and at what energies and angles?

- **MU**on in**T**ensity cod**E:** Open-source Python code.
- Calculates muon intensities, fluxes, and energy and angular distributions underground and underwater.
- Calculations can be done for labs in mines and under mountains.



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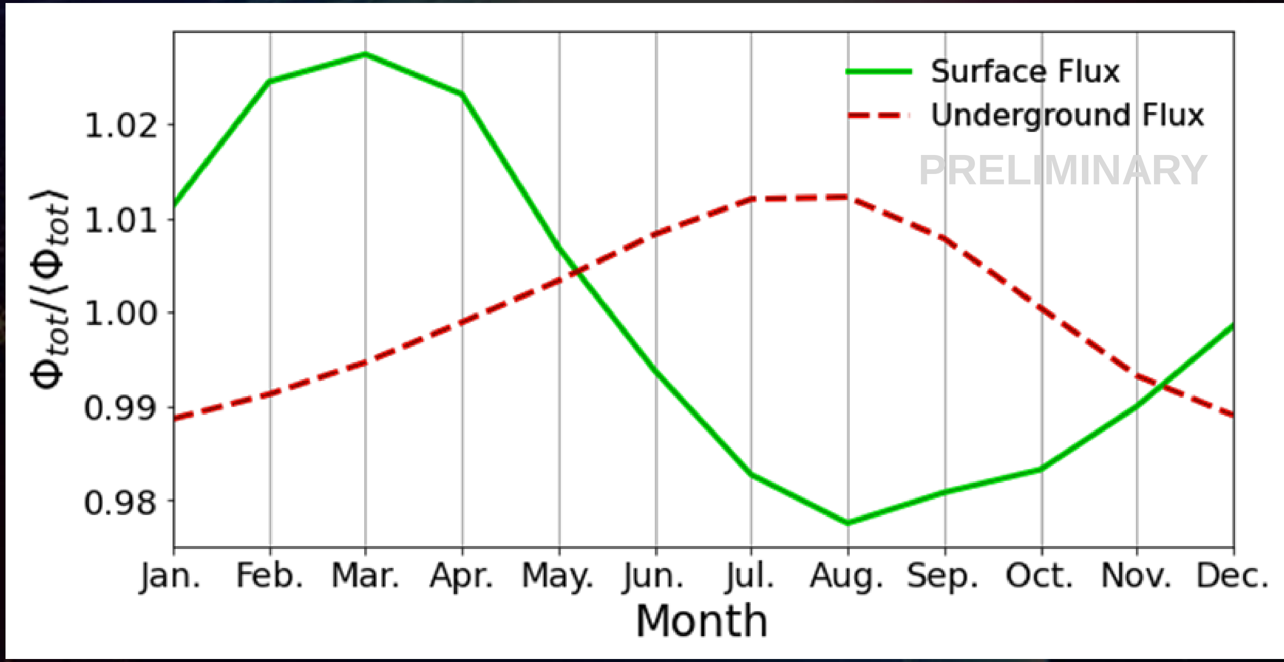
MUTE

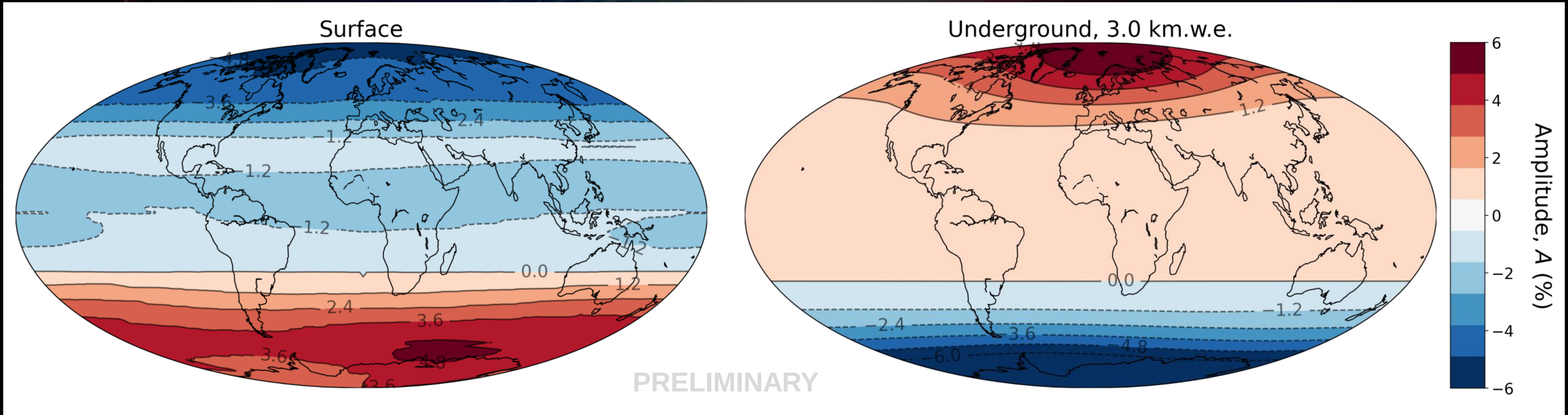
- MUTE can calculate seasonal variations in the muon flux.

- During summer, the atmosphere is gets warmer, causing it to expand and become less dense. Muons decay more often before reaching the surface of the Earth, causing the surface flux to decrease in summer.



MUTE

- The amplitude of the variations can be plotted around the world.
- Two inversions are seen:
  1. Northern vs southern hemisphere
  2. Surface vs underground



Muon Tomography

- Muon tomography is the use of muon flux measurements to create 3D images of structures.

- Measurements of CR muons have been used to discover a previously unknown inside the Great Pyramid of Giza.

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