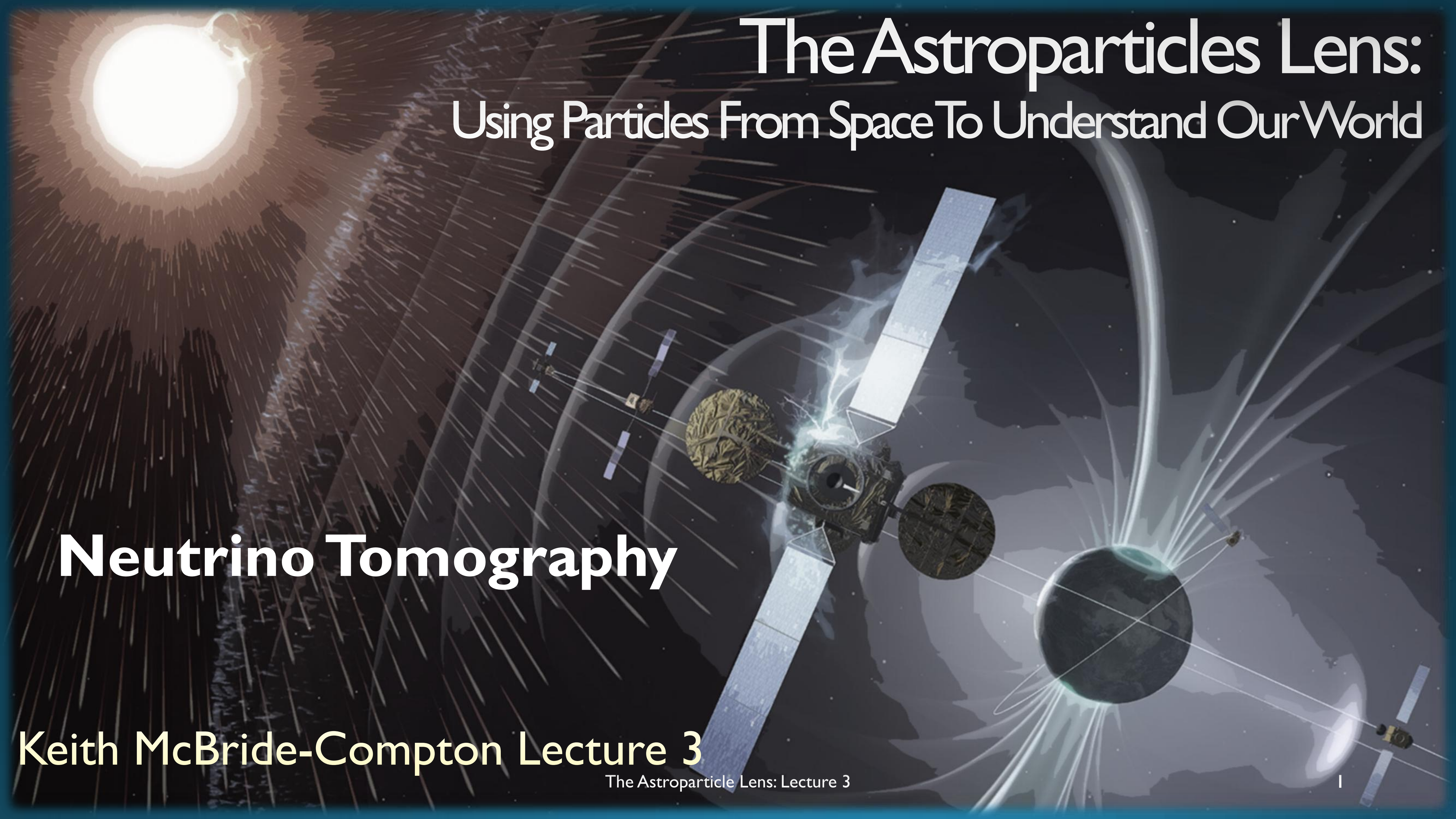
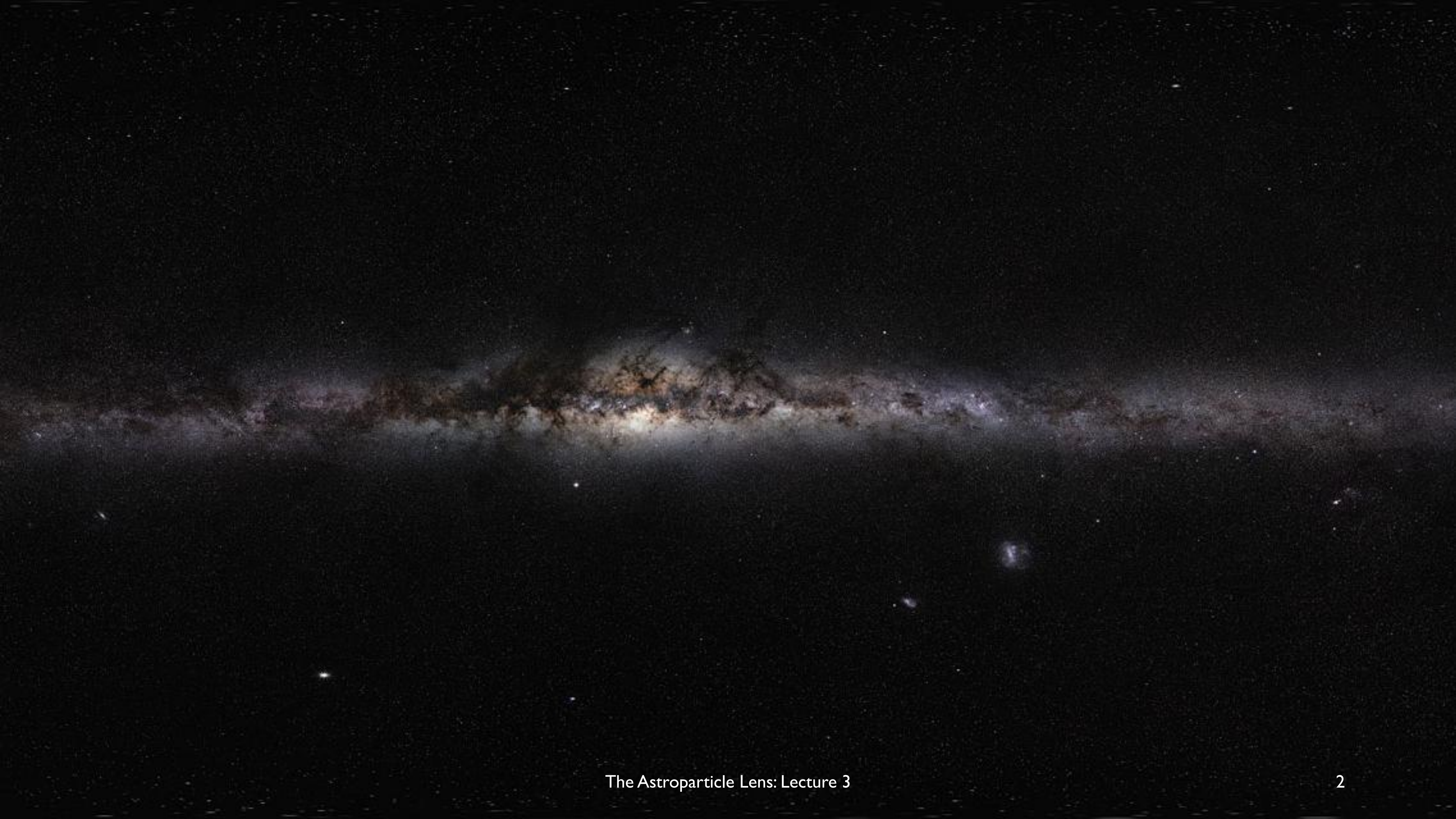


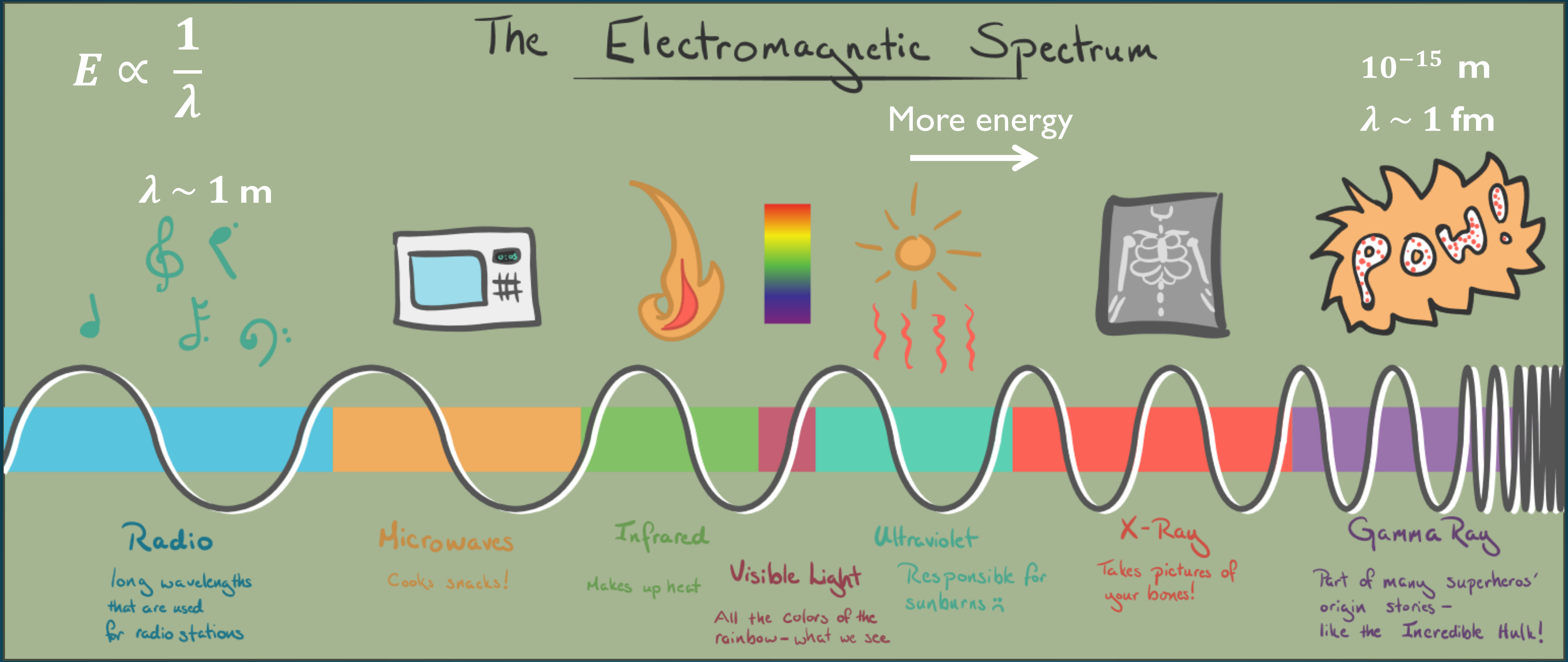
The Astroparticles Lens:

Using Particles From Space To Understand Our World

Neutrino Tomography

Keith McBride-Compton Lecture 3





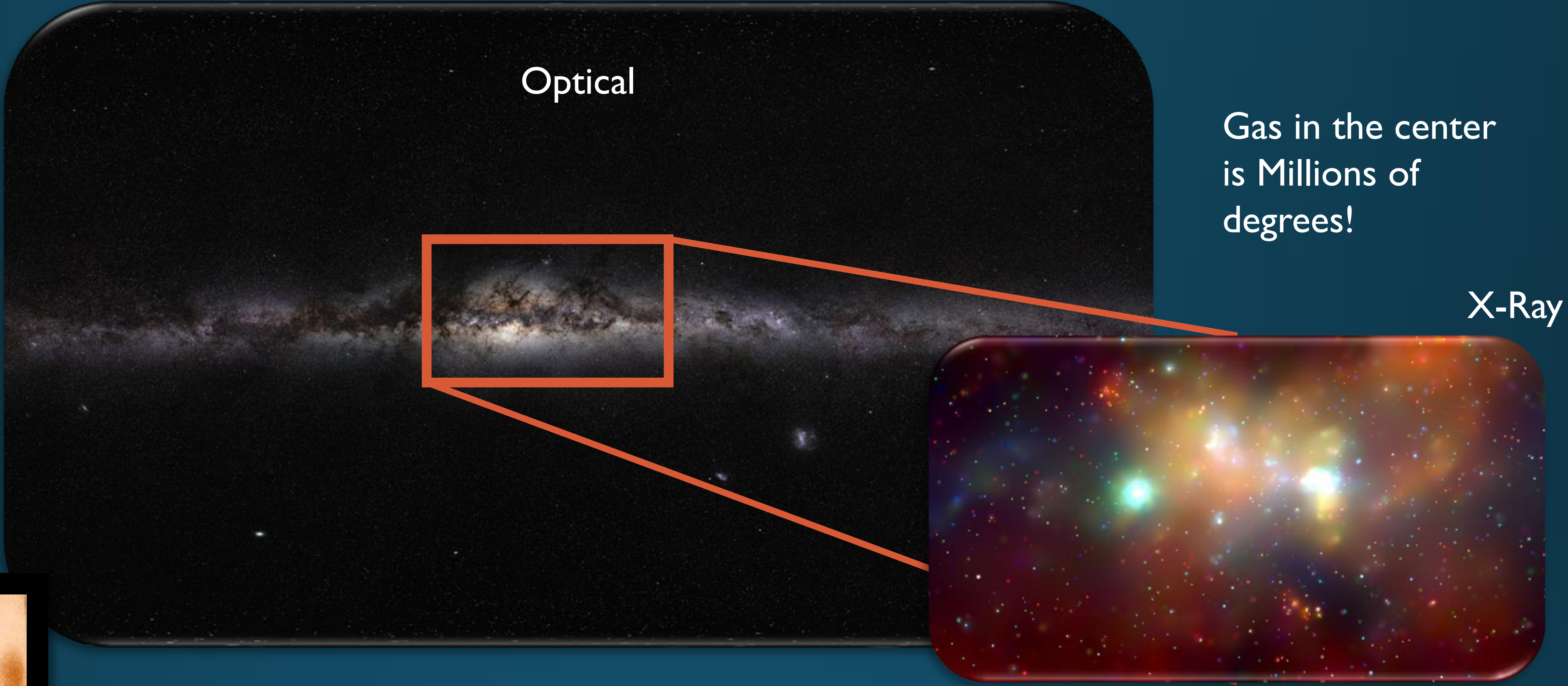
$$E \propto \frac{1}{\lambda}$$

$\lambda \sim 1$ m

More energy →

10^{-15} m

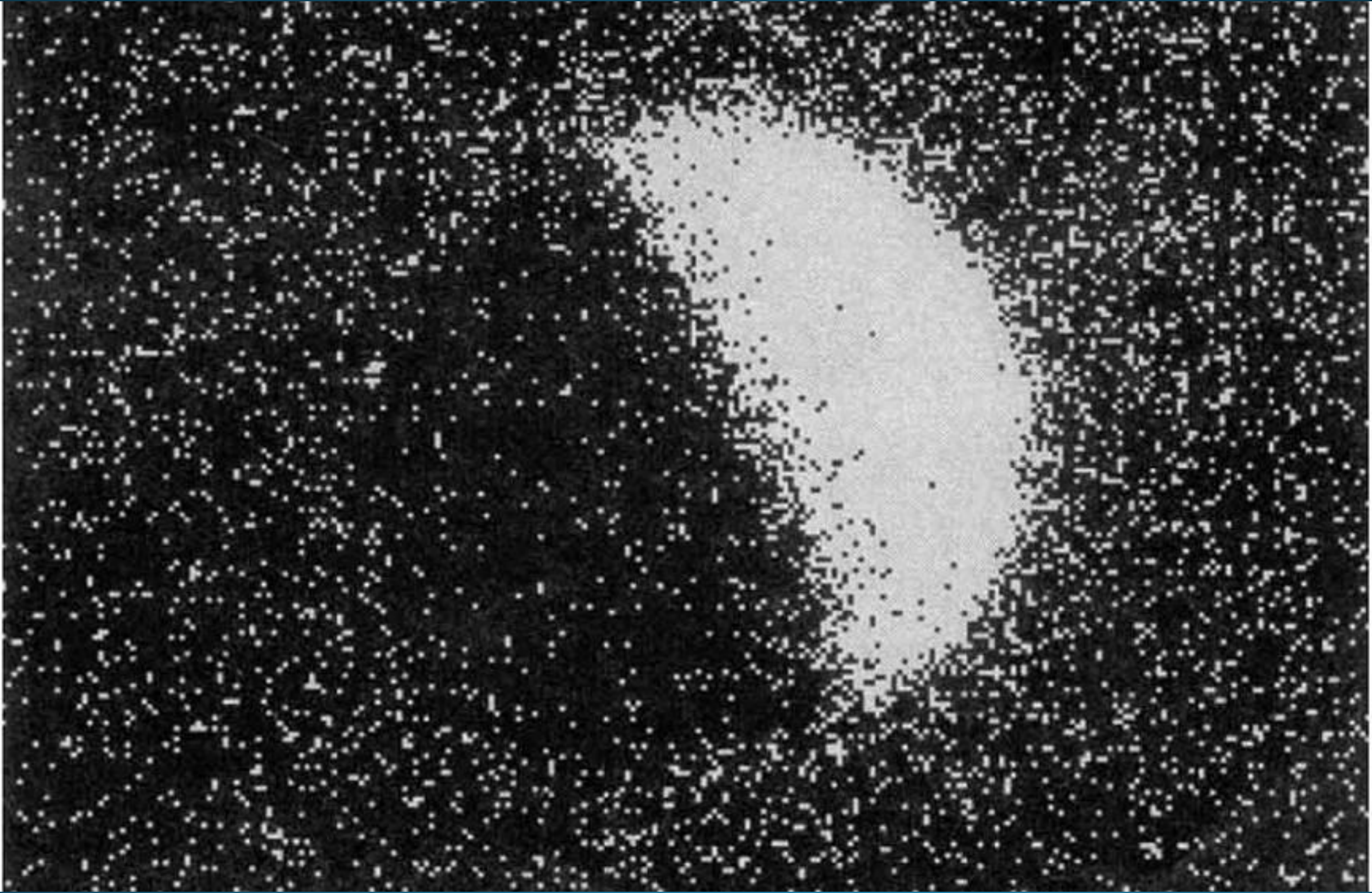
$\lambda \sim 1$ fm



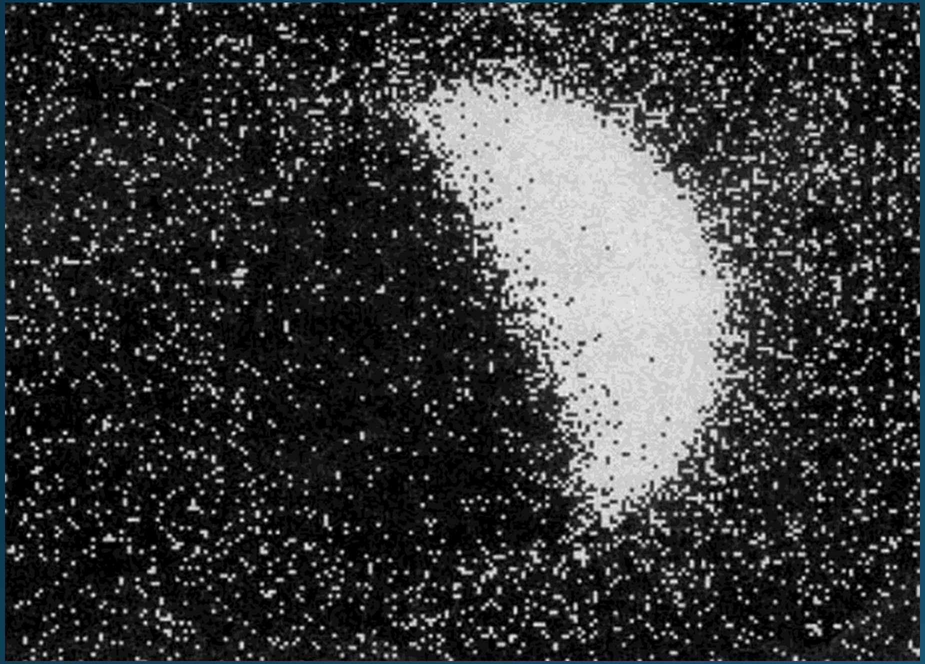
Gas in the center
is Millions of
degrees!

With a different type of lens, you can:

1. See through opaque objects

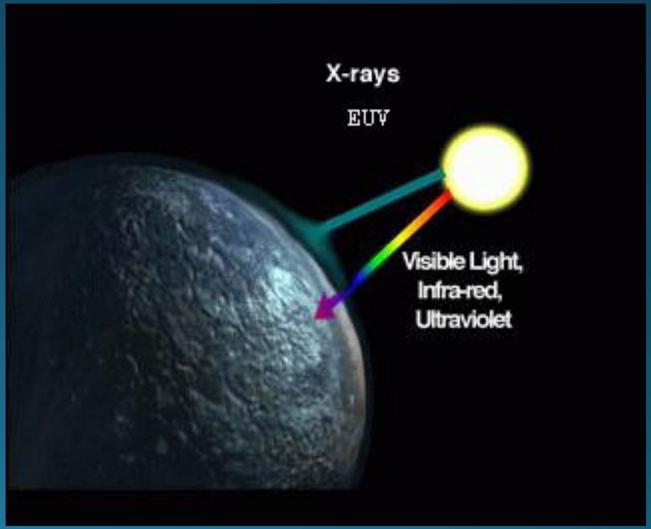


X-rays don't make it to the ground



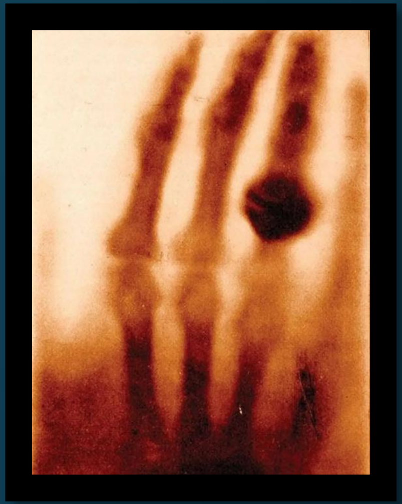
X-Ray telescopes have to be in space

- The universe's X-rays are absorbed in the atmosphere

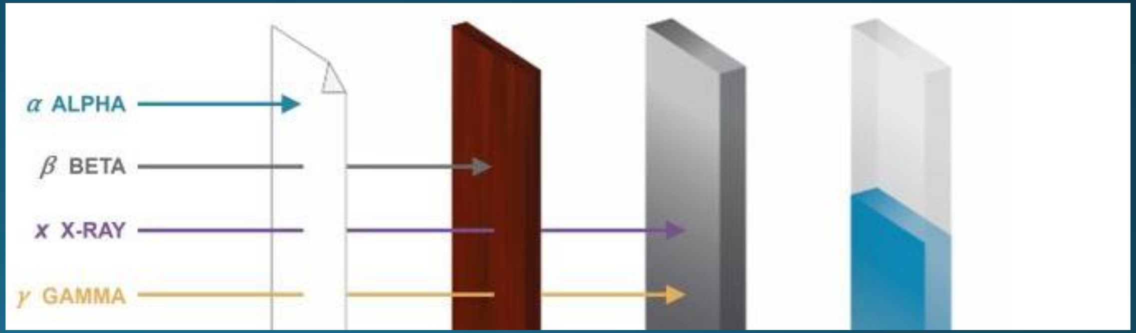


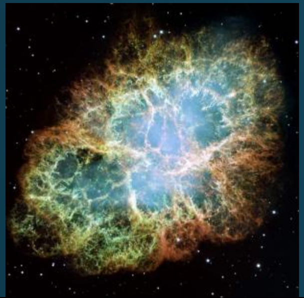
Line of sight – The atmosphere is in our way

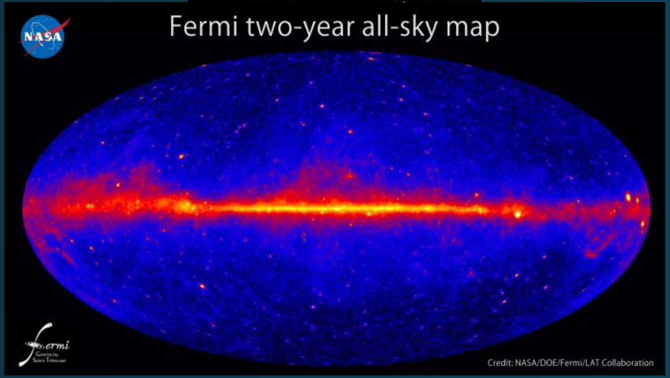
X-rays can’t probe everything



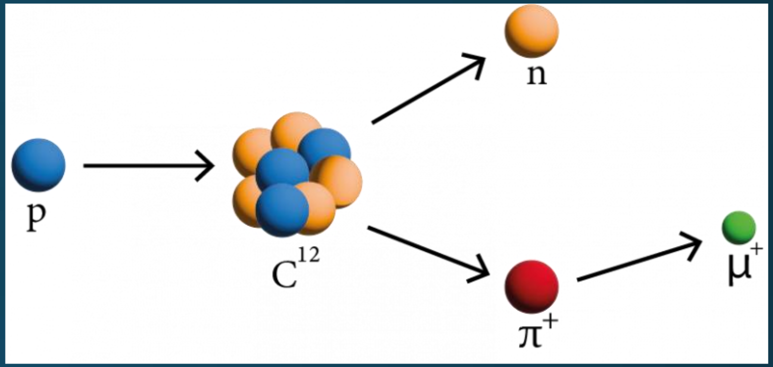
- X-Rays can go through the skin
  - But not the metal ring
- The moon is dense
- Other kinds of radiation might help?

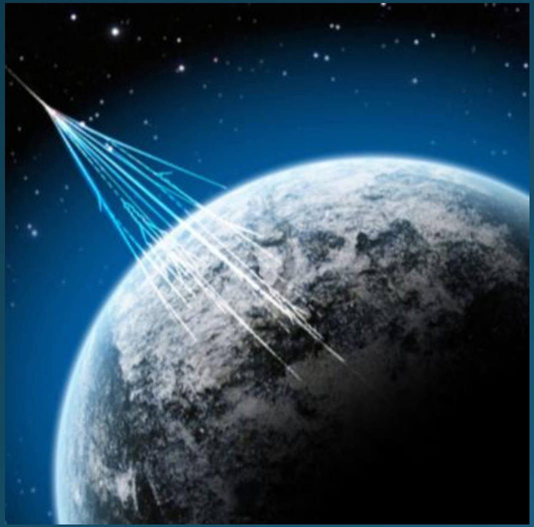


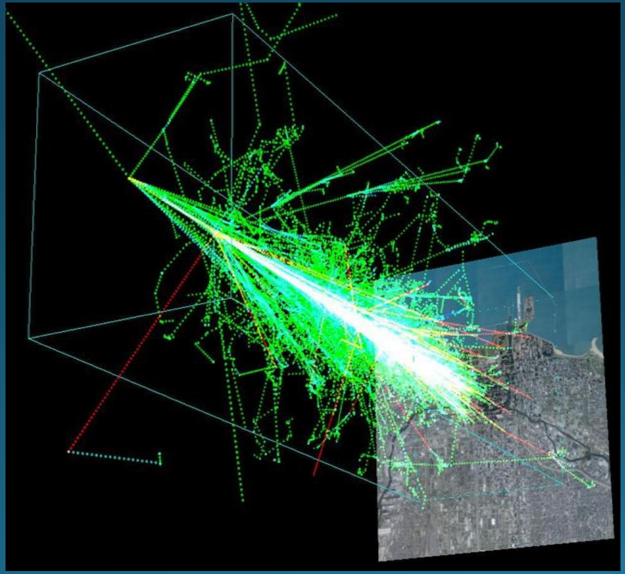




We live in a sea of cosmic rays



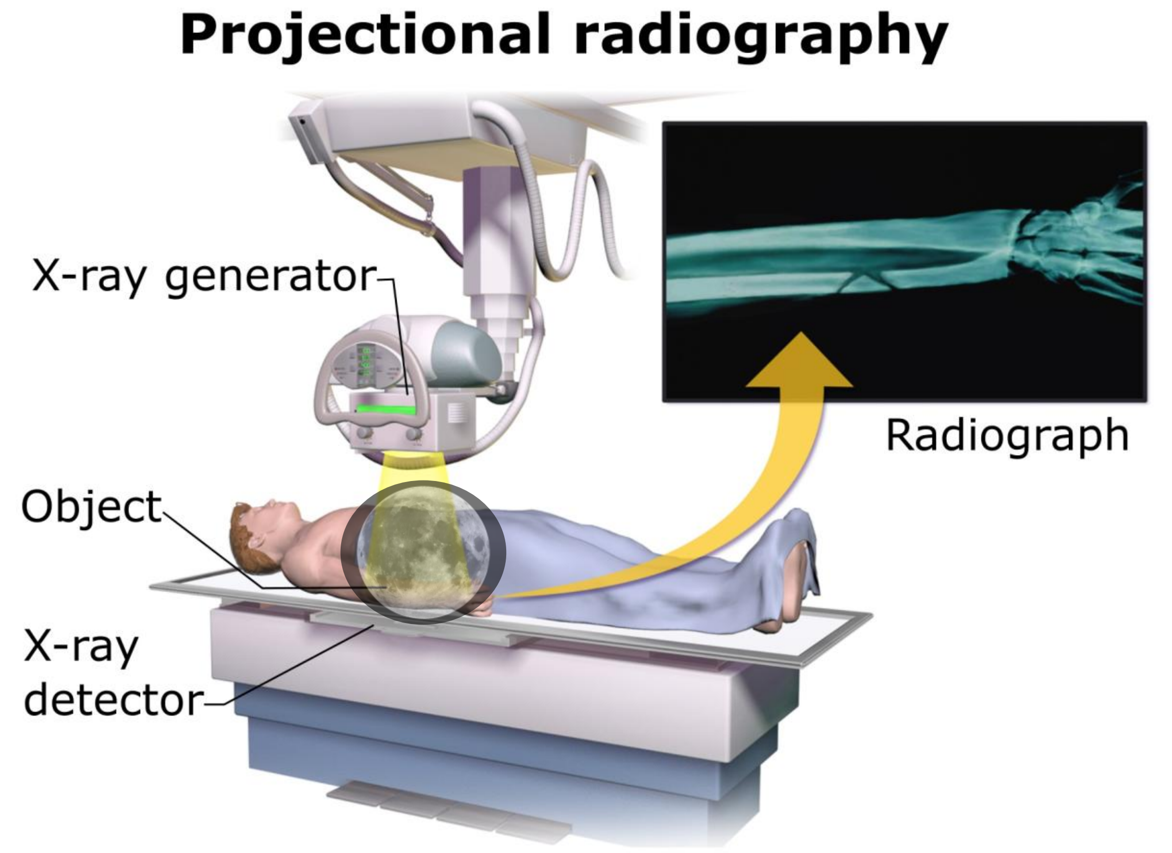




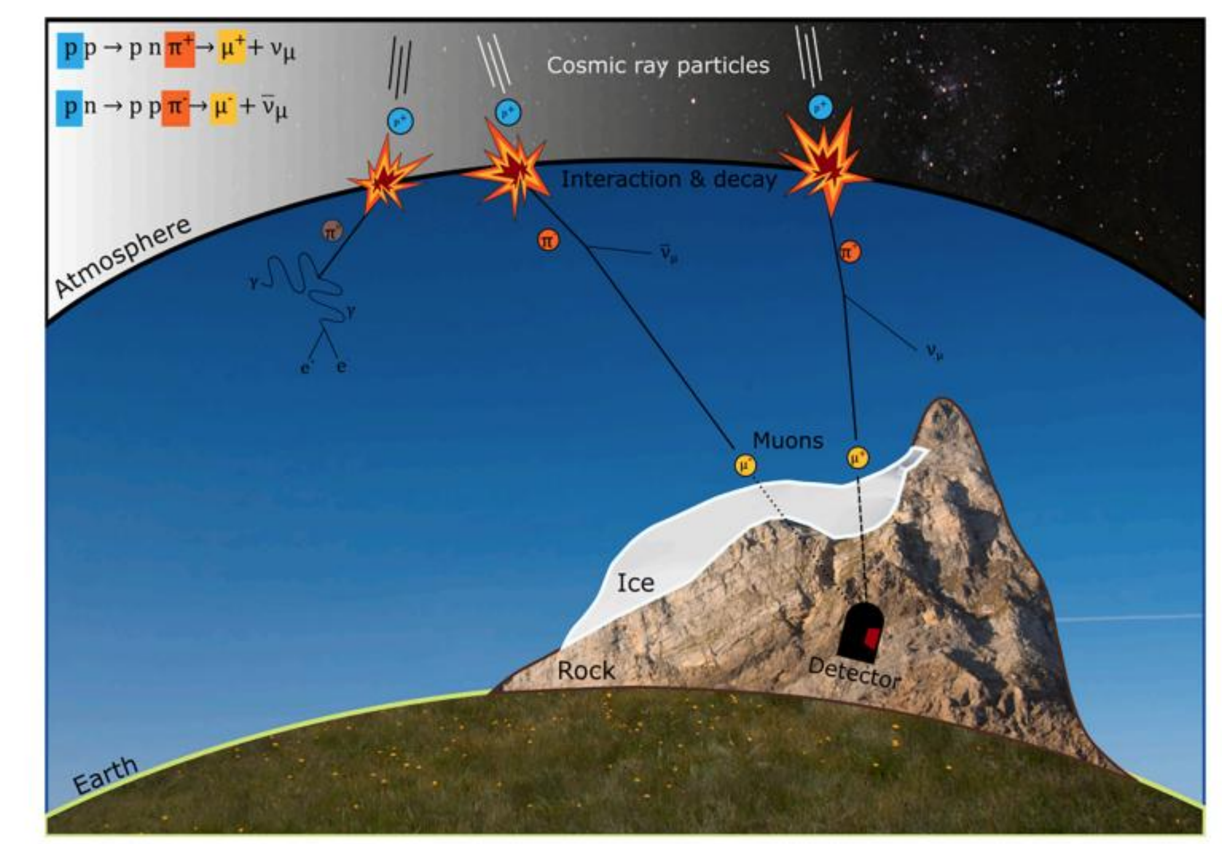
1. The cosmic ray protons interact with gas in the atmosphere

2. The muons make it to the surface → Penetrating radiation

Last time- muon tomography



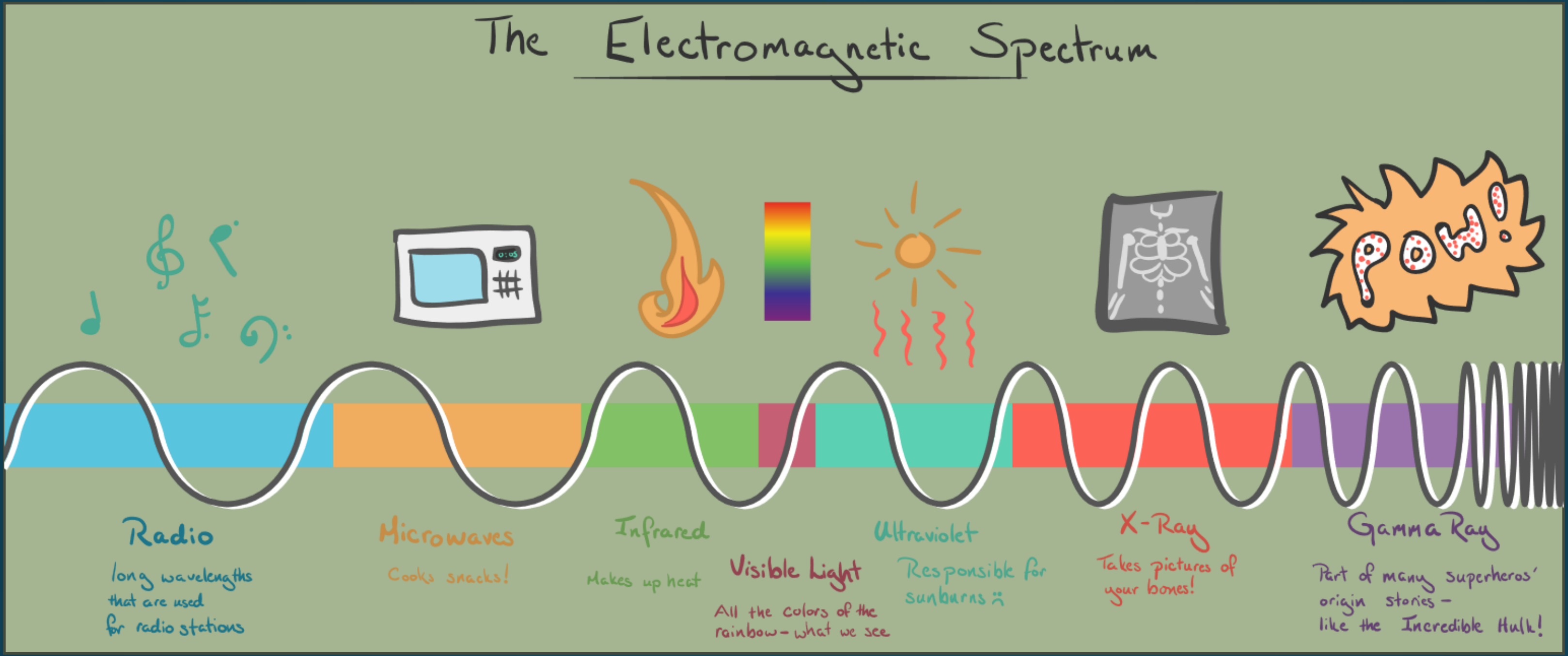
Muography

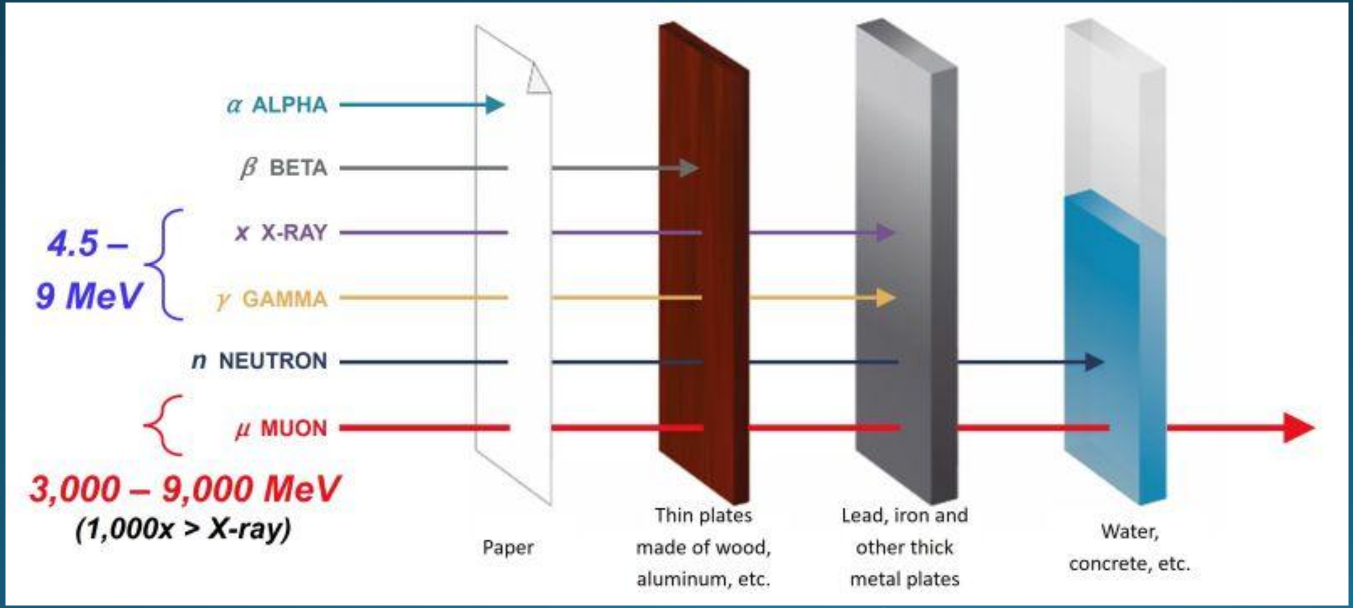


“Sit there for 100 days”

Line of sight with the cosmic ray muon lens

Radiation

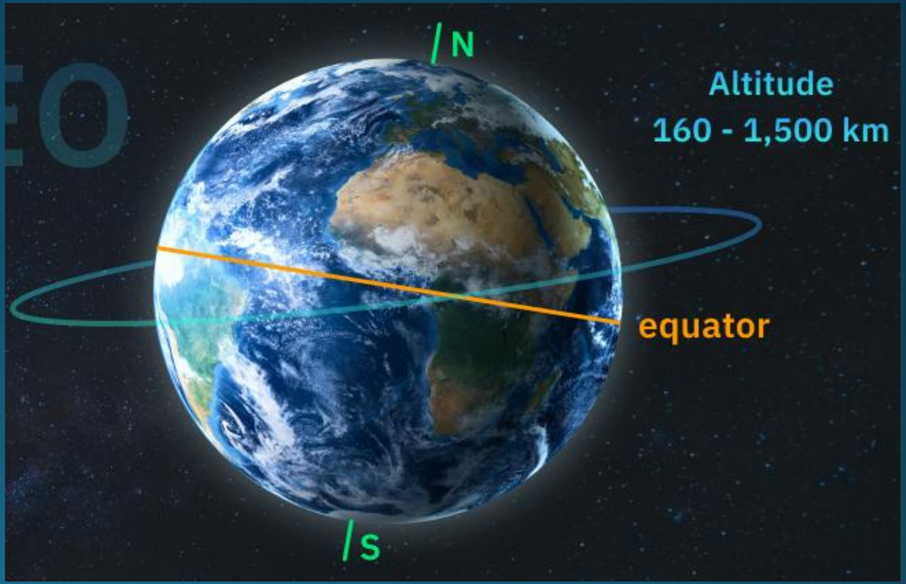

The Electromagnetic Spectrum
Radio
long wavelengths that are used for radio stations
Microwaves
Cooks snacks!
Infrared
Makes up heat
Visible Light
All the colors of the rainbow - what we see
Ultraviolet
Responsible for sunburns
X-Ray
Takes pictures of your bones!
Gamma Ray
Part of many superheros' origin stories - like the Incredible Hulk!
POW!


α ALPHA
β BETA
x X-RAY
γ GAMMA
n NEUTRON
μ MUON
4.5 – 9 MeV
3,000 – 9,000 MeV
(1,000x > X-ray)
Paper
Thin plates made of wood, aluminum, etc.
Lead, iron and other thick metal plates
Water, concrete, etc.

Muon tomography of the moon?

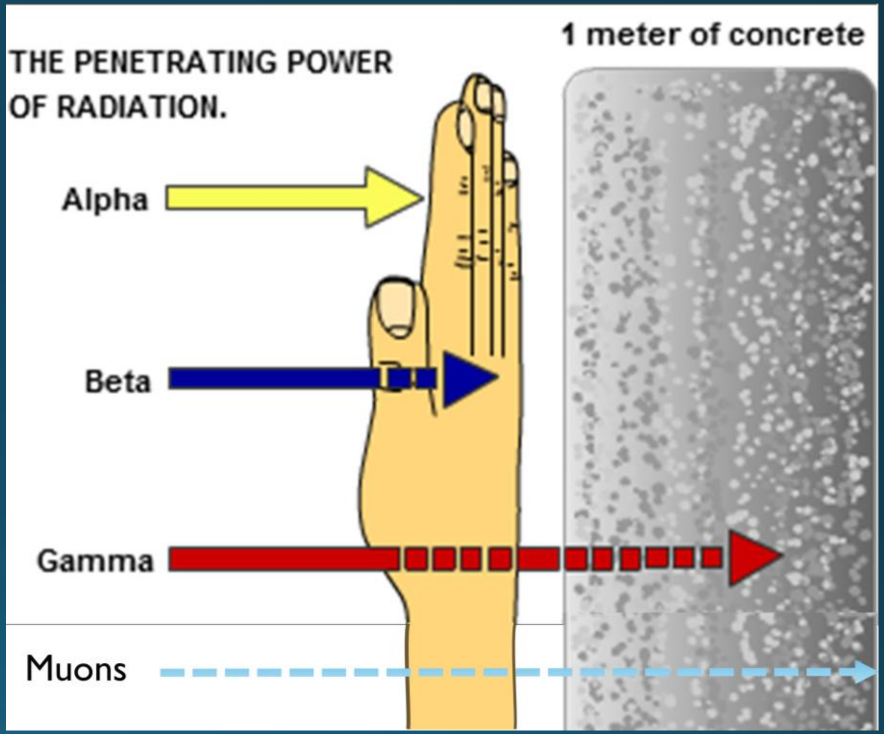
- Muons can travel through hundreds of meters of rock
- But cosmic ray muons produced at Earth b/c of atmosphere
- What about muons from outer space?
  - Muons decay
    - 2.2us (even with time dilation)
  - They can travel ~60km or so
- And even then, the moon is too thick and dense (~3,400km)
  - Same with the Earth (~12,000km)

Not really feasible



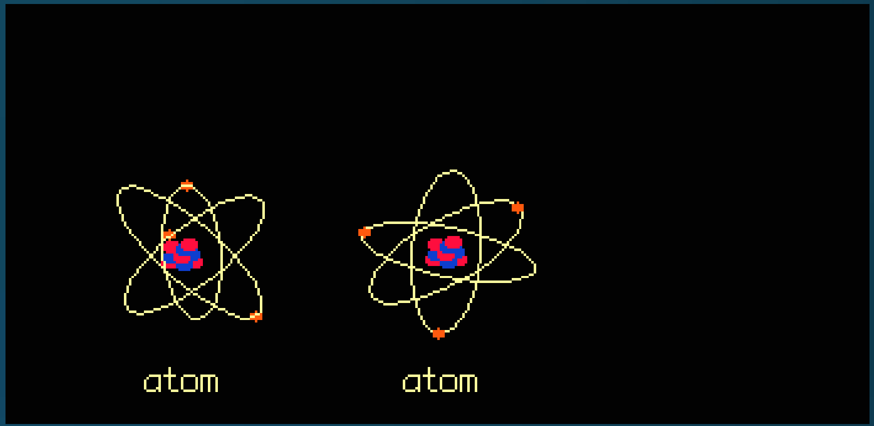
Different kinds of radiation

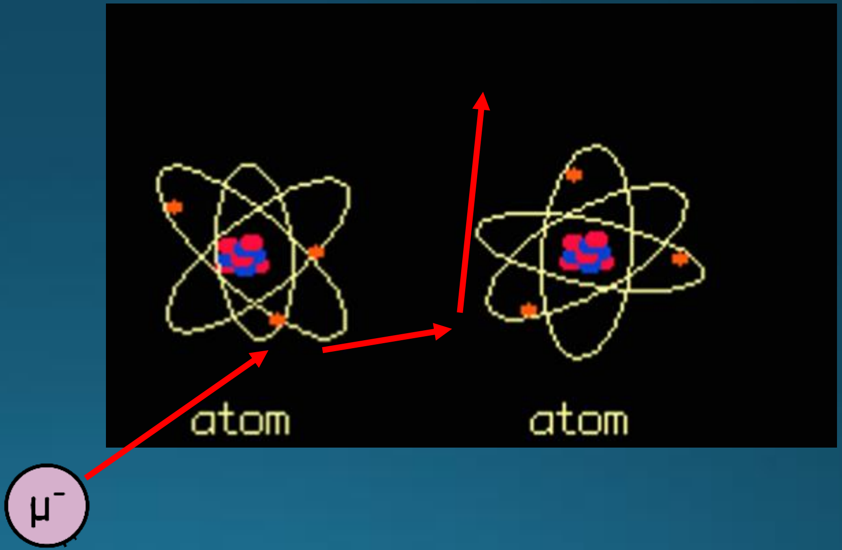
- Alpha
  - Nucleus of Helium atoms
- Beta
  - Electrons
- Gamma
  - Photons
- Muons are more penetrating



Energy loss of radiation

- It was determined how electrons/beta rays were losing energy
  - Ionization of the electrons of atoms in the material
- Muon is 200 times more massive than electron
  - So travels through much more material
- Coulomb scattering
- Alpha, beta, and muons are charged particles

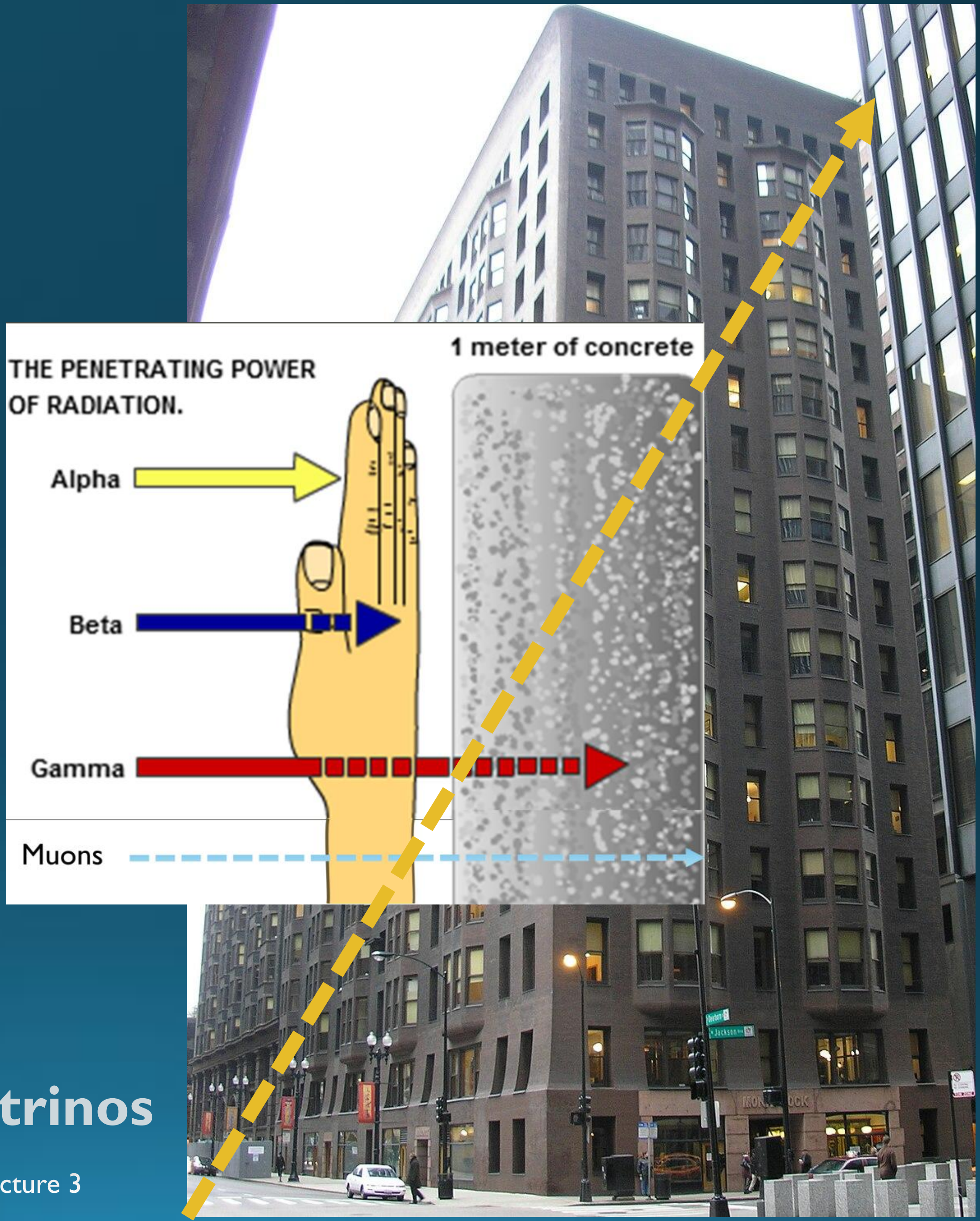




Electromagnetic force

- Get rid of the electromagnetic force from the muon
  - Just have the weak force left!
- It goes through all the lead!
  - Well not all, but most of it.
- This is why it’s called the weak force

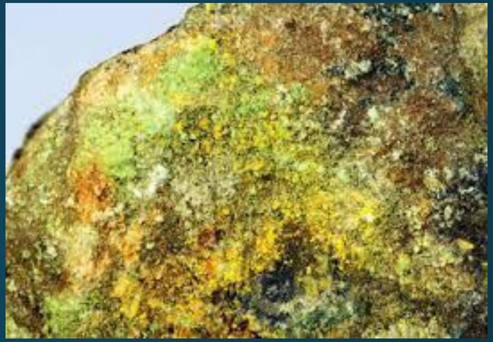
Monadnock Building, built in 1890’s

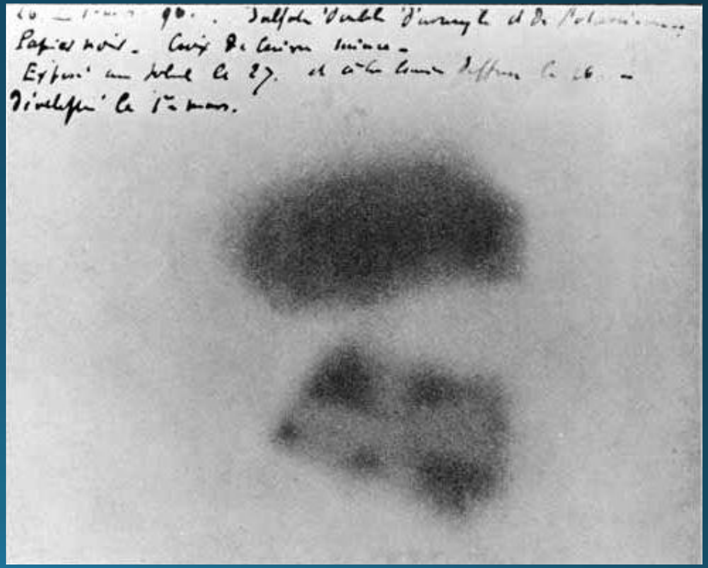


Neutrinos

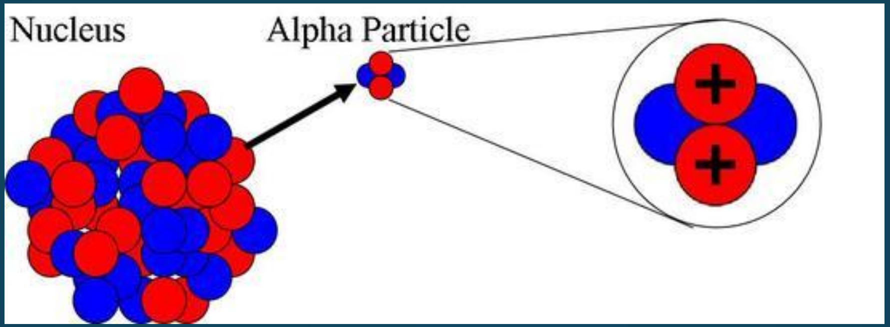
It all started in 1896

- Becquerel discovered radioactivity with Uranium
  - At the time, he thought that it had to do with sunlight
- Was looking for the X-rays reported by Roentgen
  - He wrapped photographic plates in black paper
- Shared Nobel prize in 1903 with Marie Curie

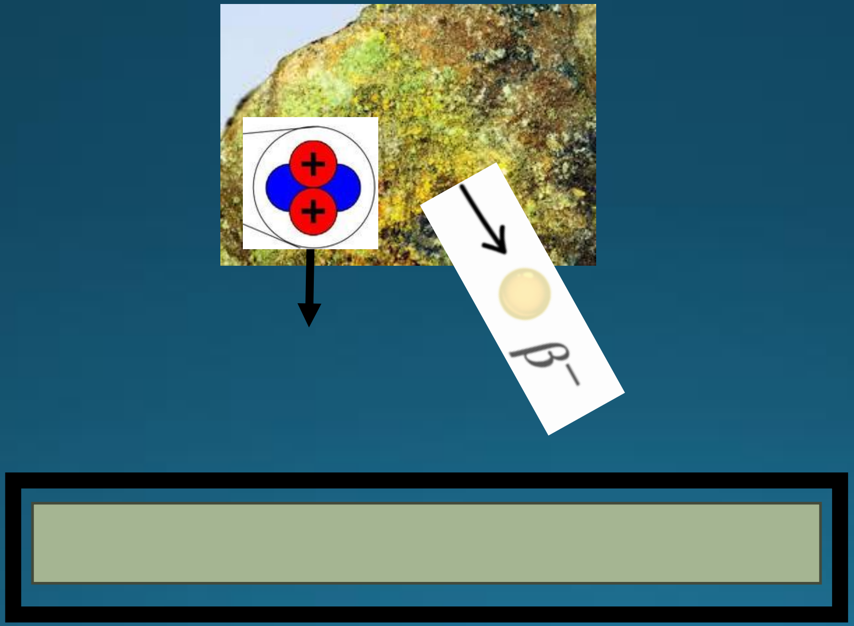




The radiation from the salt



1. Uranium-238 in salts
2. Photographic plates
3. Paper (sunlight)



Alpha

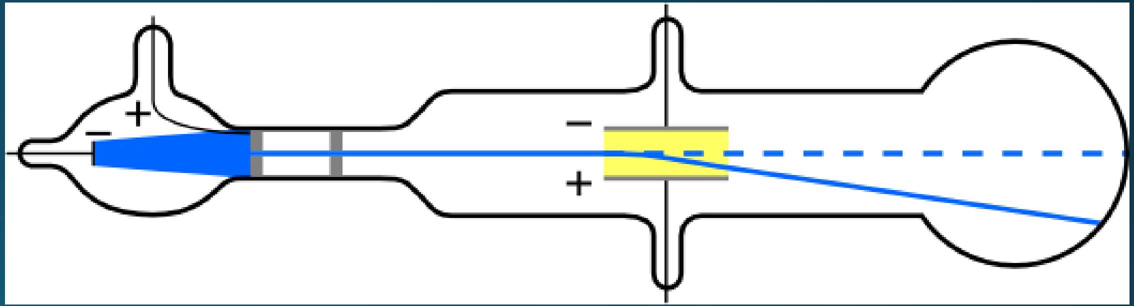
Nucleus of Helium atoms

Beta

Electrons

Electrons were just being discovered

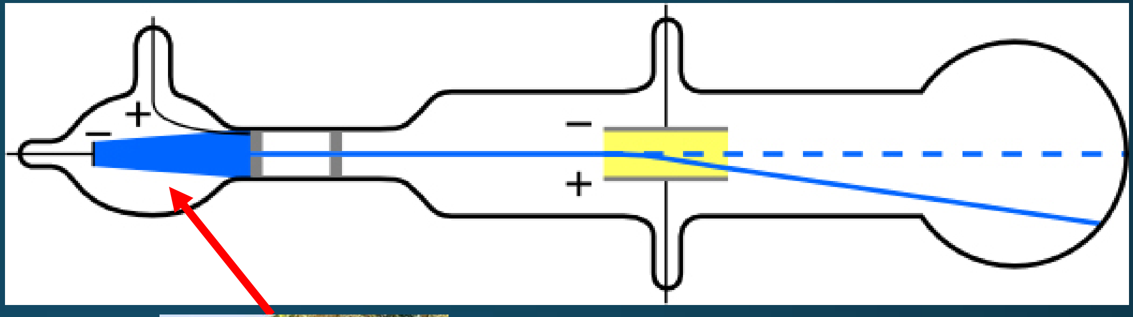
- J.J. Thompson bent cathode rays in fields
  - calculated the charge to mass ratio
    - e/m
  - Used both electric and magnetic fields
- Discovery of electrons
  - Fundamental particle
  - 1906 Nobel Prize

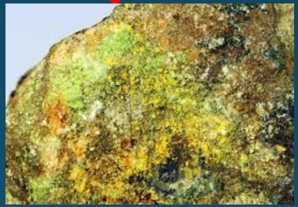


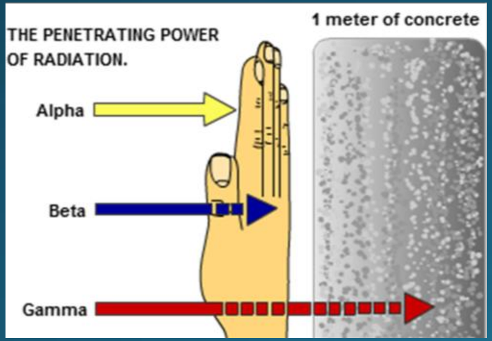
Rutherford and Becquerel do a "J.J. Thompson"

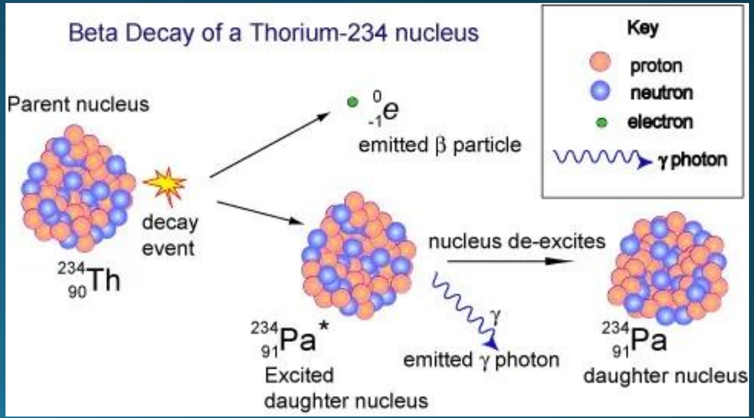
- Determined that:
  - Alphas are positively charged (+2)
  - Betas are negatively charged (-1)
    - The electrons!
- Unstable materials

Becquerel's uranium salts actually produced all 3 of these radiation









- Elements are identified by number of protons in the nucleus
  - Helium has 2 protons
  - Alphas are +2 charge
- Isotopes – identified by the number of neutrons and protons together
  - Some combinations are not stable
  - Will revisit in another lecture in a few weeks

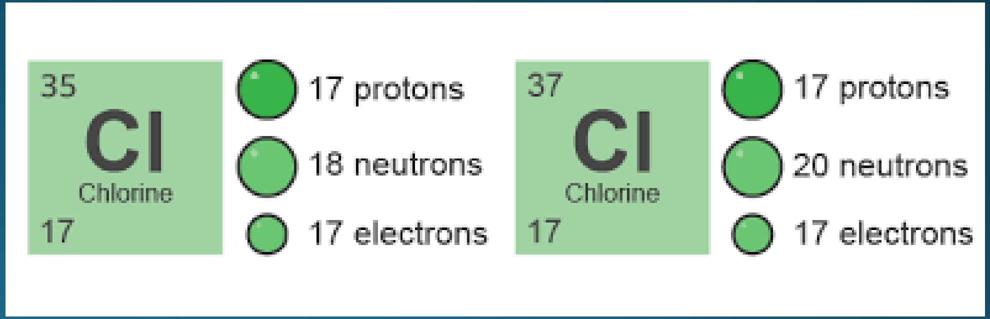
Remember:

Protons don’t decay

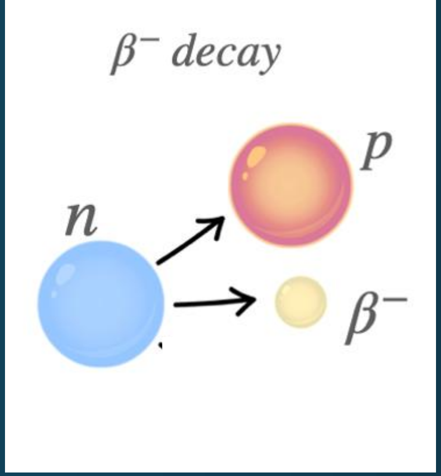
Proton lifetime is longer than 10^{34} years

Neutrons and some nuclei decay!

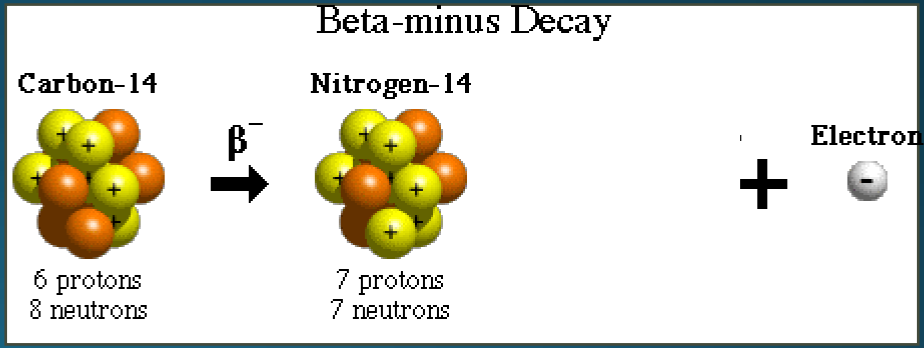
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Ce	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuo
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb		
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No		



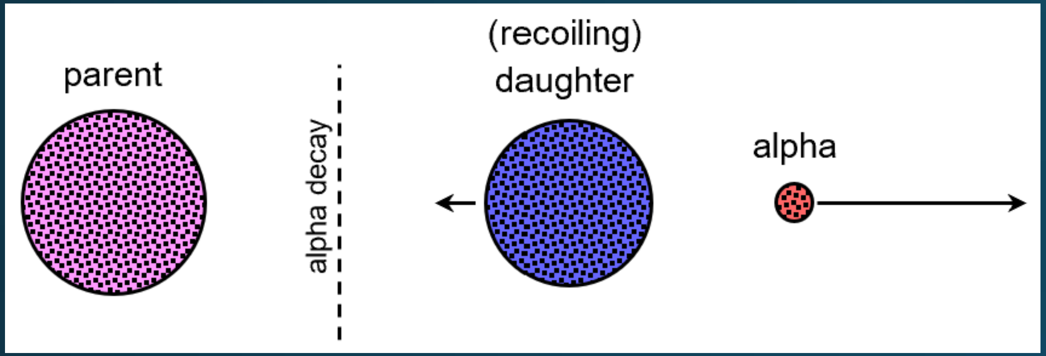
Developed an understanding

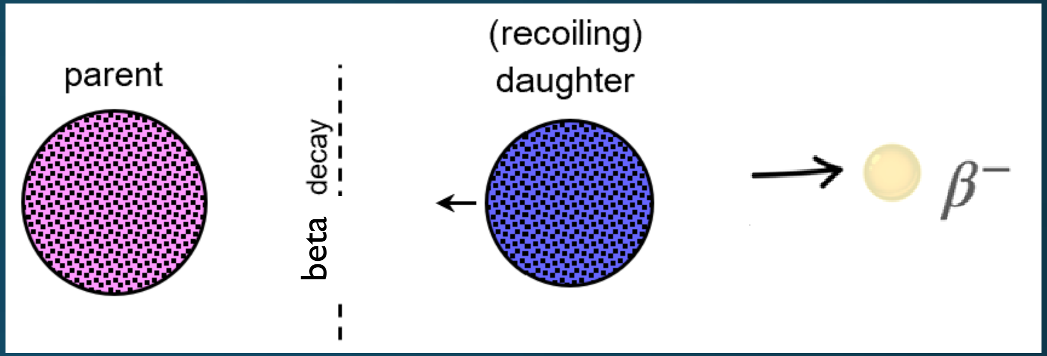


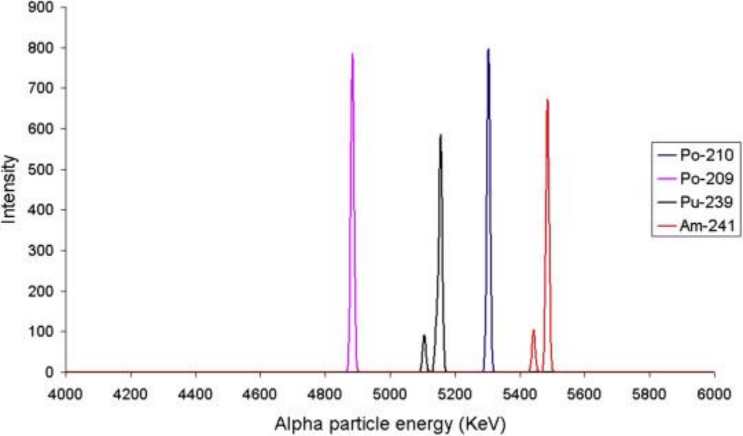
- Neutrons in a nucleus can decay
- Elements of one kind can “transform” to other elements
- Good example is carbon
    - Useful for carbon dating
    - Amount of Carbon-14 can be used to radioactively date organic material



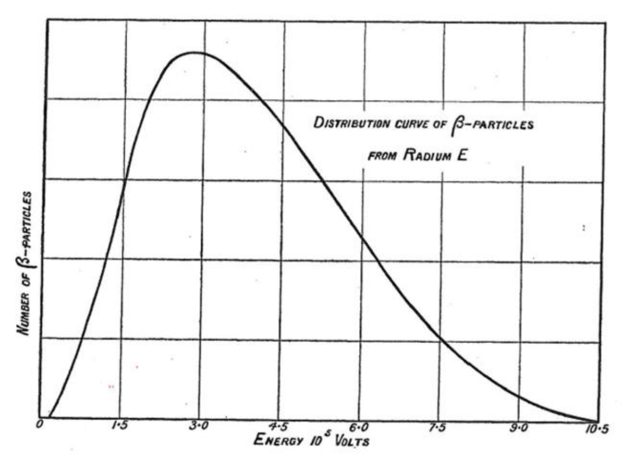
Alpha decay vs Beta decay





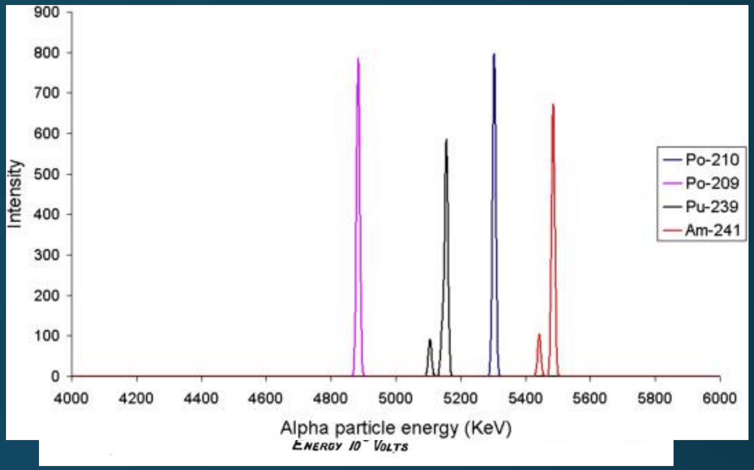


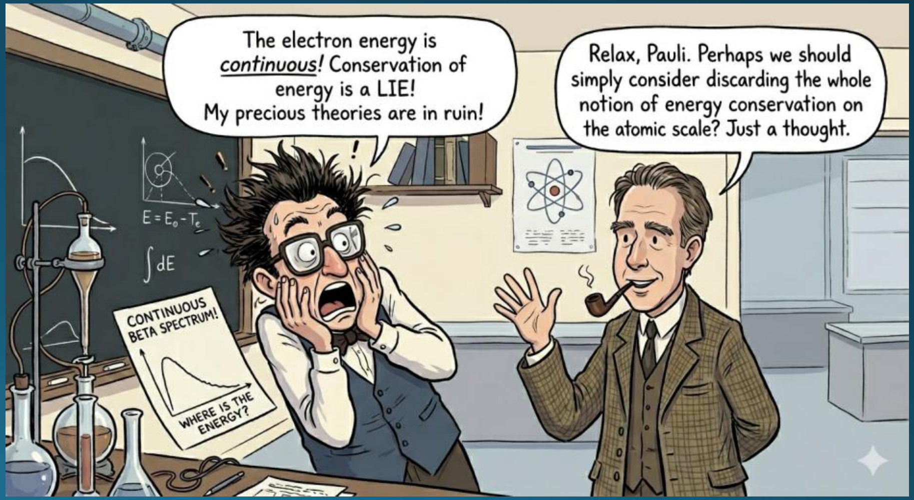
Measure the energy



Everyone is shocked

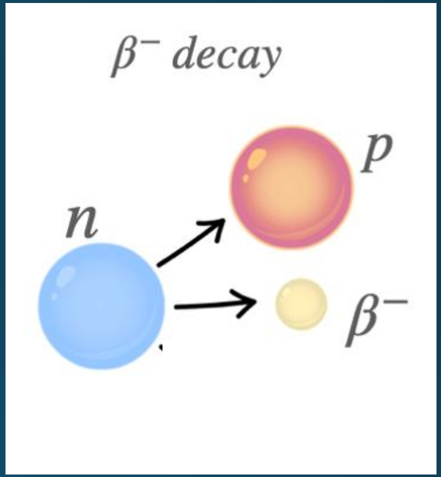
- In both decays, momentum and energy conservation predicted very specific energies
- In alpha decay
  - This determined the spectrum accurately
  - And only measured the new nucleus and the alpha particle
- Chadwick’s 1914 measurement of beta decay showed something extremely wrong
- Another particle?
  - Bohr was fine with just losing conservation of energy

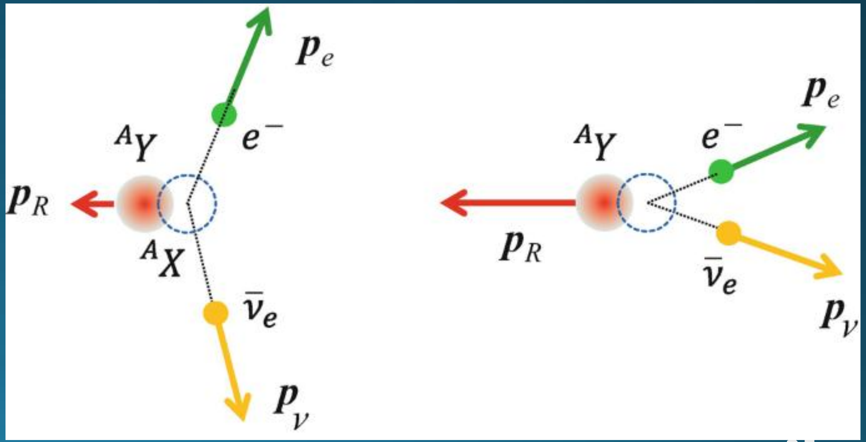




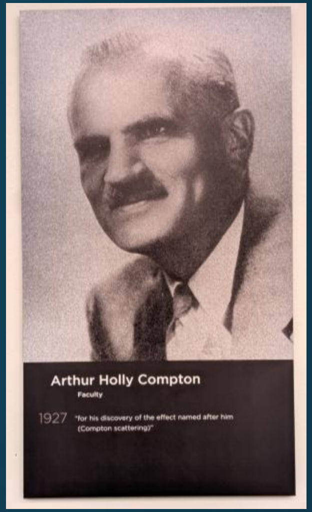
Around 1930

- Wolfgang Pauli and Enrico Fermi had an idea
- Propose a third, undetectable particle
    - Solves the issue, because the electron energy changes each time
    - Keeps energy conserved!
- Undetectable? What is this new particle?



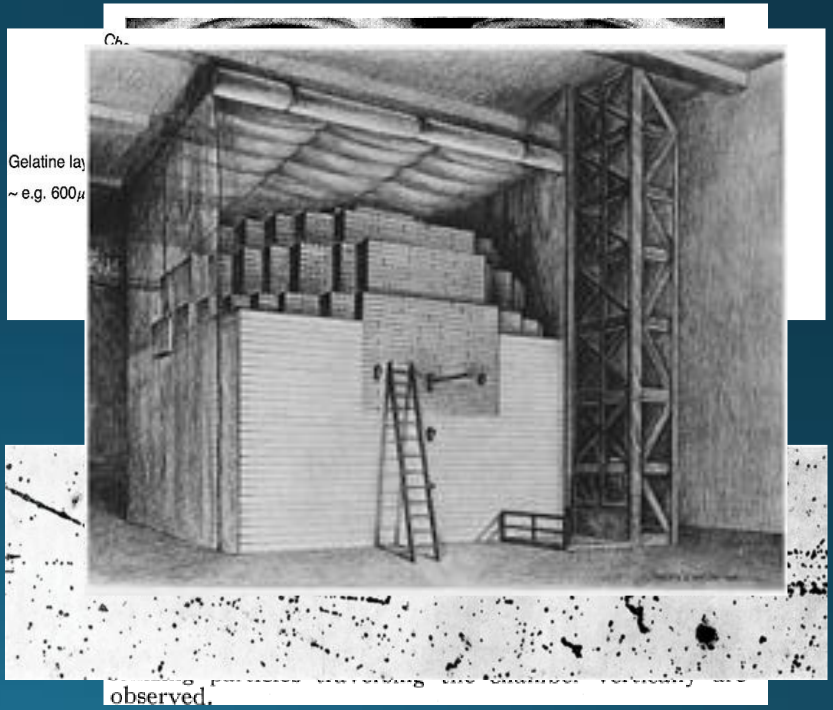


From 1930s to the 1950s



Cosmic rays played an important role in this period!

1. Put cloud chambers at high altitude to investigate the cosmic radiation
   - ➢ Discovered muons
2. World War 2 and the atomic bomb
   - ➢ Fermi and Compton at the University of Chicago
3. More cosmic ray measurements on ballons
   - ➢ Discovered pions



We figured out what was happening with cosmic rays and the particle cascades

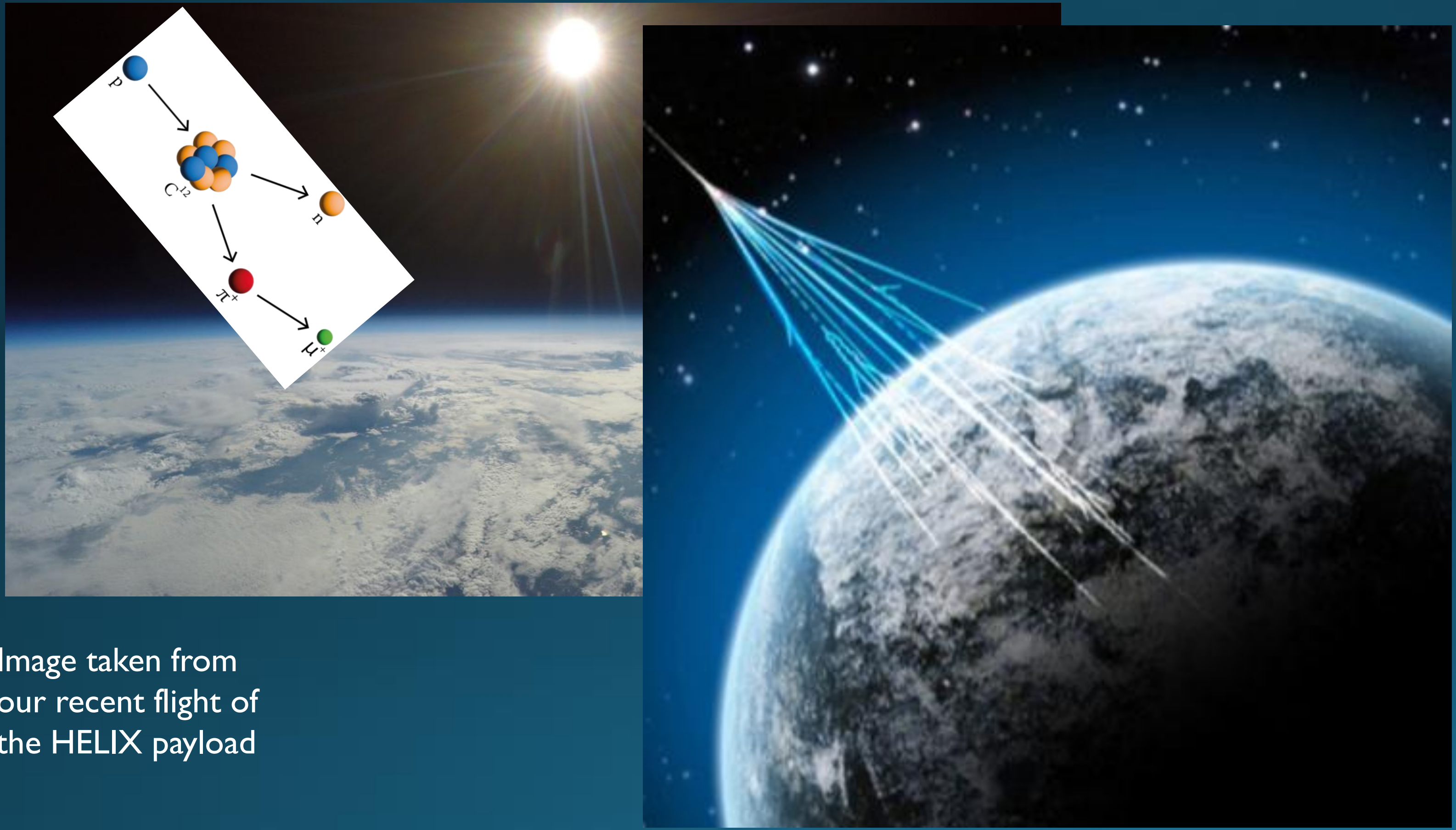
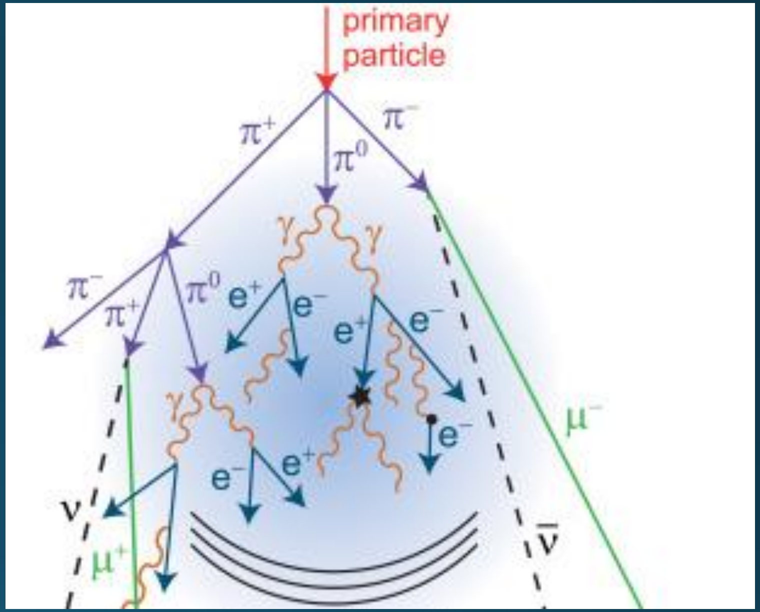


Image taken from
our recent flight of
the HELIX payload



- Muons decay to neutrinos
- Pions decay to neutrinos
- Cosmic ray particles hit the atmosphere and produce pions and muons

Neutrinos should be everywhere

- So how do you detect this new particle?
  - You can’t!
    - Well not directly
- Remember: ionization, tracking charged particles
  - Neutrinos wouldn’t leave trails
- Traces of their interactions, instead
  - Indirect detection

“Needle in a haystack”

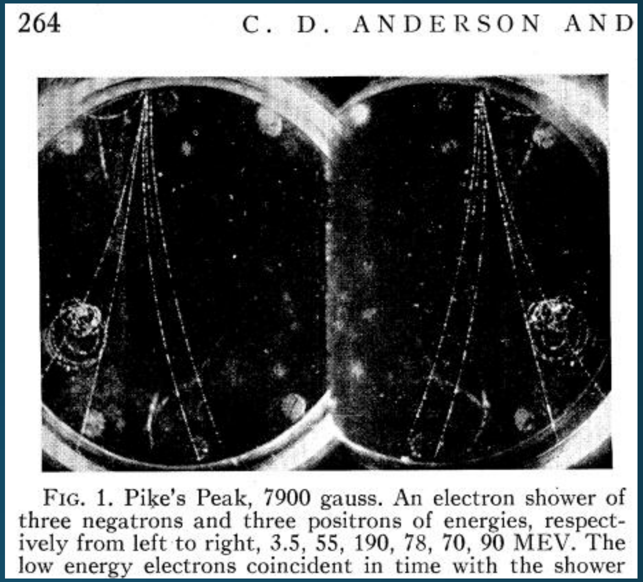
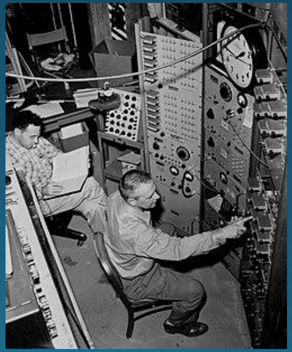

264 C. D. ANDERSON AND

FIG. 1. Pike's Peak, 7900 gauss. An electron shower of three negatrons and three positrons of energies, respectively from left to right, 3.5, 55, 190, 78, 70, 90 MEV. The low energy electrons coincident in time with the shower

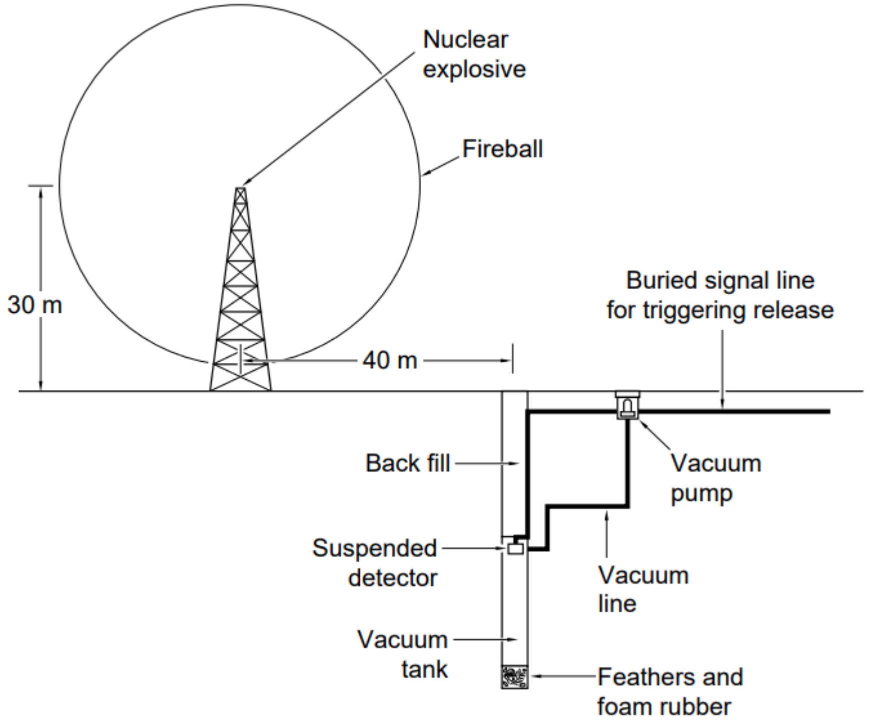


$$\bar{\nu}_e + p \rightarrow n + e^+$$

Frederick Reines and Clyde Cowan

Crazy idea…

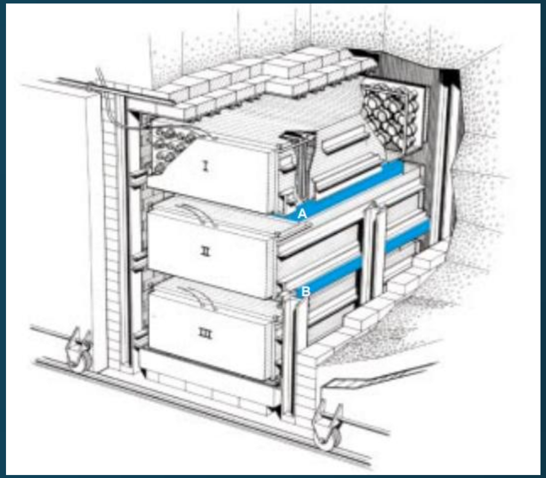
- We need a lot of neutrinos and a big detector
  - Cosmic ray neutrinos (from muons) are too low in number
  - How do you get a lot of neutrinos?
- Set off a nuclear bomb?
  - Proposal: 20 kilo-ton in Nevada
- Detector developed called "El Monstro"
  - Drop the detector down a vacuum shaft at the same moment the bomb goes off
- Project "Mad Scientist"
  - Actually, called Project Poltergeist
  - And was approved

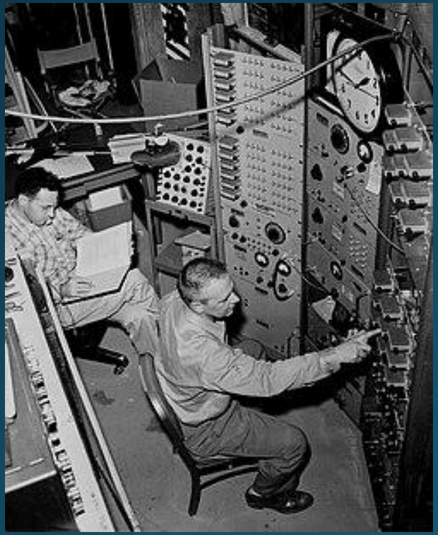


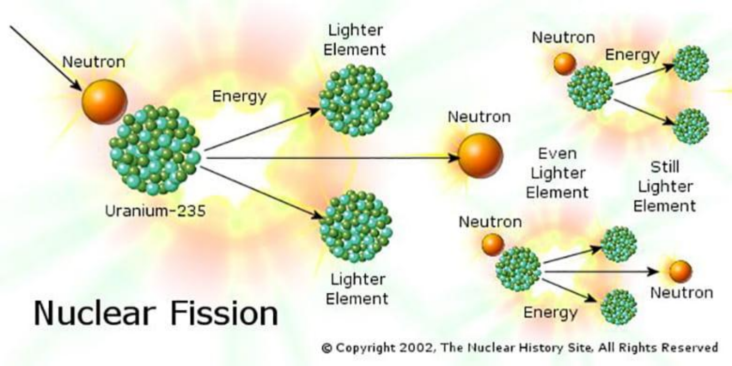
ure 1. Detecting Neutrinos from a Nuclear Explosion
ineutrinos from the fireball of a nuclear device would impinge on a liquid scinti
detector suspended in the hole dug below ground at a distance of about
meters from the 30-meter-high tower. In the original scheme of Reines and Cow
antineutrinos would induce inverse beta decay, and the detector would record

The real Project Poltergeist

- Savannah River Plant in South Carolina
  - Second site choice







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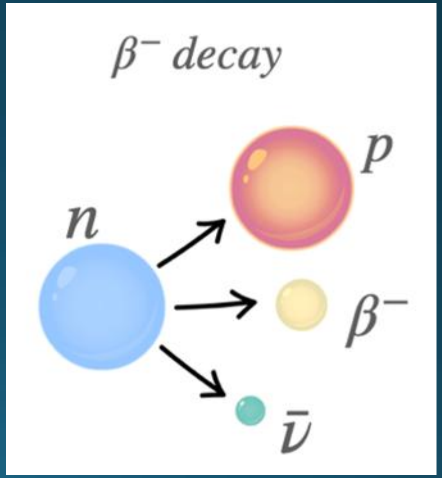


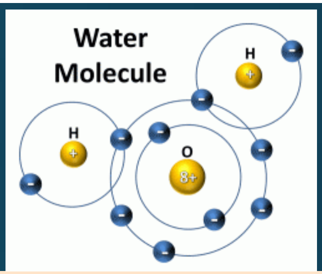
First neutrino measurements

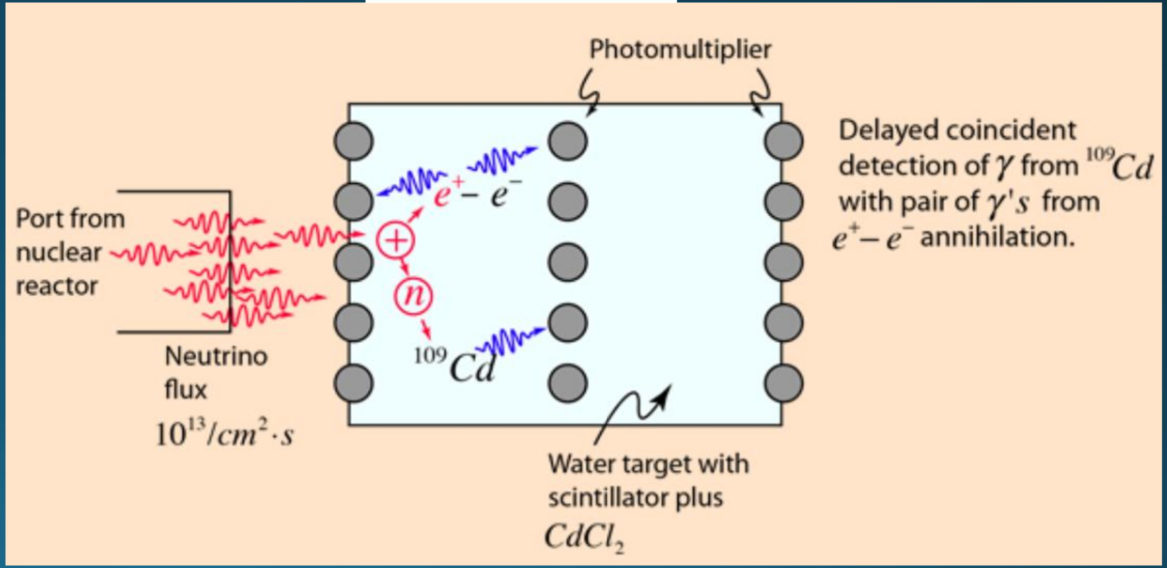
- Indirect measurements near a reactor
  - Need material to absorb neutrinos
- Theory predicts a neutron and a positron from proton interactions
  - Water (protons)
  - Detect those neutrons and positrons together
- Designed a coincident experiment

Turned off reactor and see events go away

Won the Nobel prize in 1995

$$\bar{\nu}_e + p \rightarrow n + e^+$$

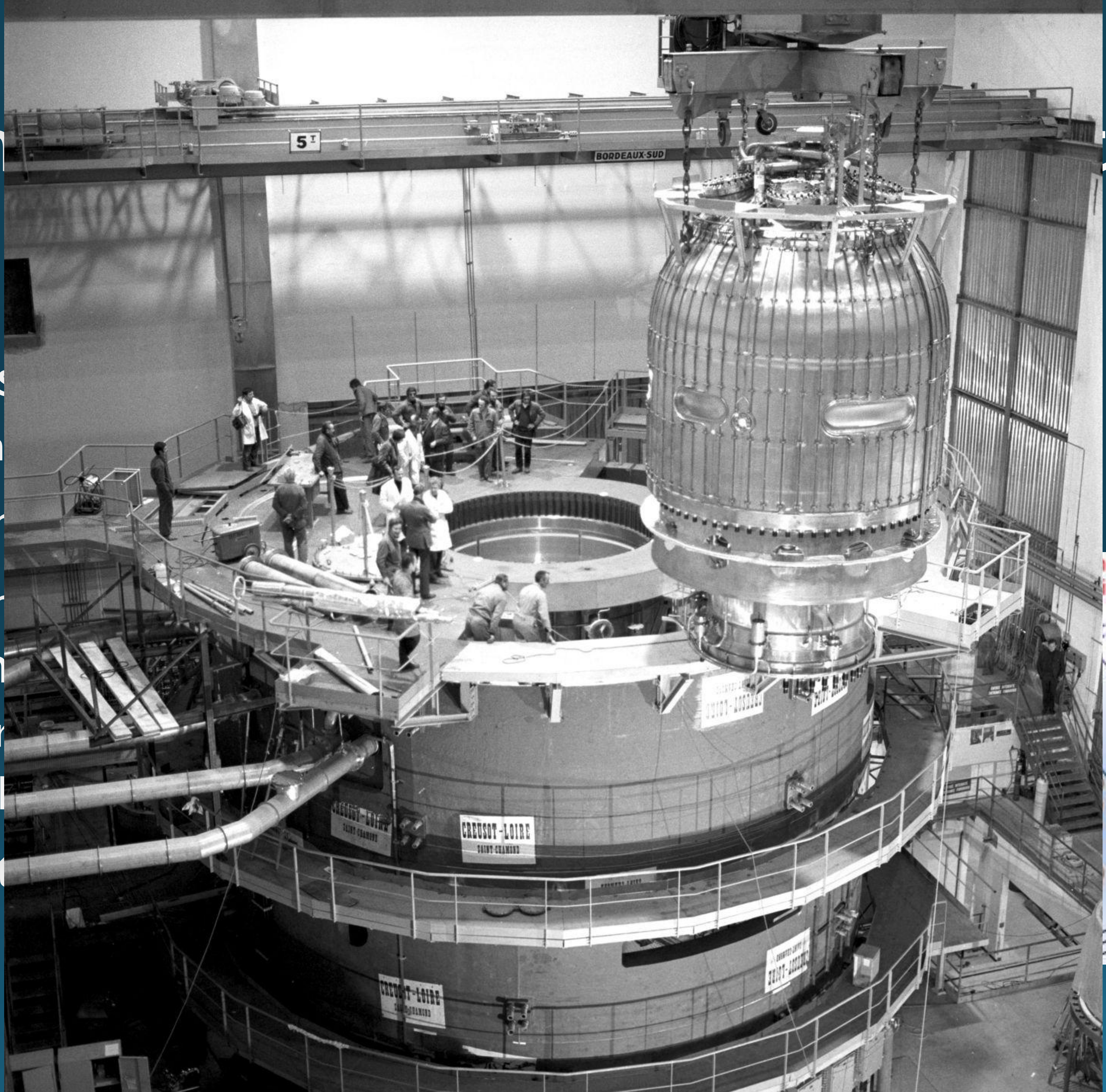


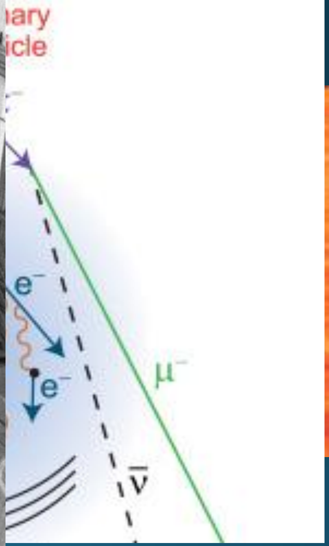


Neutrin more?

- Reactors
  - And n
- But we r
- There sh atmosph
  - And fr
  - And th

→We start

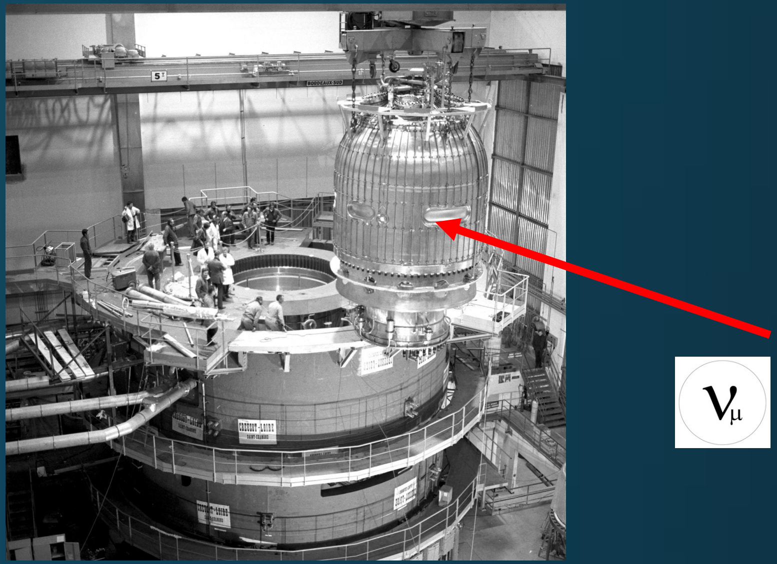


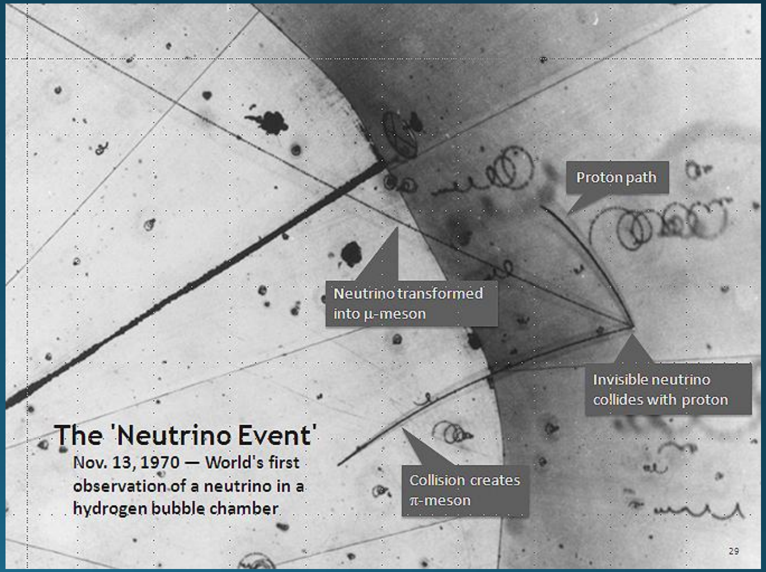


Tracks of the interactions

- First bubble chamber image of a neutrino
  - ~1970
- Neutrino comes in undetected
  - Experiment just watching nothing
- Then bam, nucleus changes!
  - And nothing happened before

→Neutrinos!




The 'Neutrino Event'
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

Valuable, but this is beamline neutrinos. What about the atmospheric and astrophysical neutrinos?
→New detectors

Neutrino interactions

- Neutrinos have a lot of energy
  - Basically travelling the speed of light
    - ~massless
    - Topic for another lecture (and previous series have covered this!)
- The particles produced are also moving pretty fast (usually)
- New detection mechanism
  - Cherenkov light
  - “light-equivalent of a sonic boom”

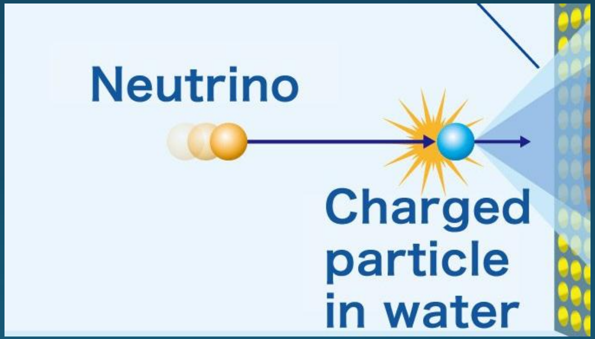
*Light slows down in denser materials

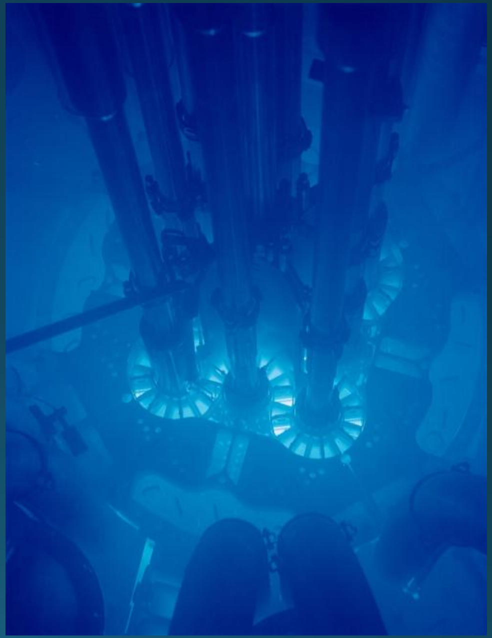
A lot of energy

$$\bar{\nu}_e + p \rightarrow n + e^+$$

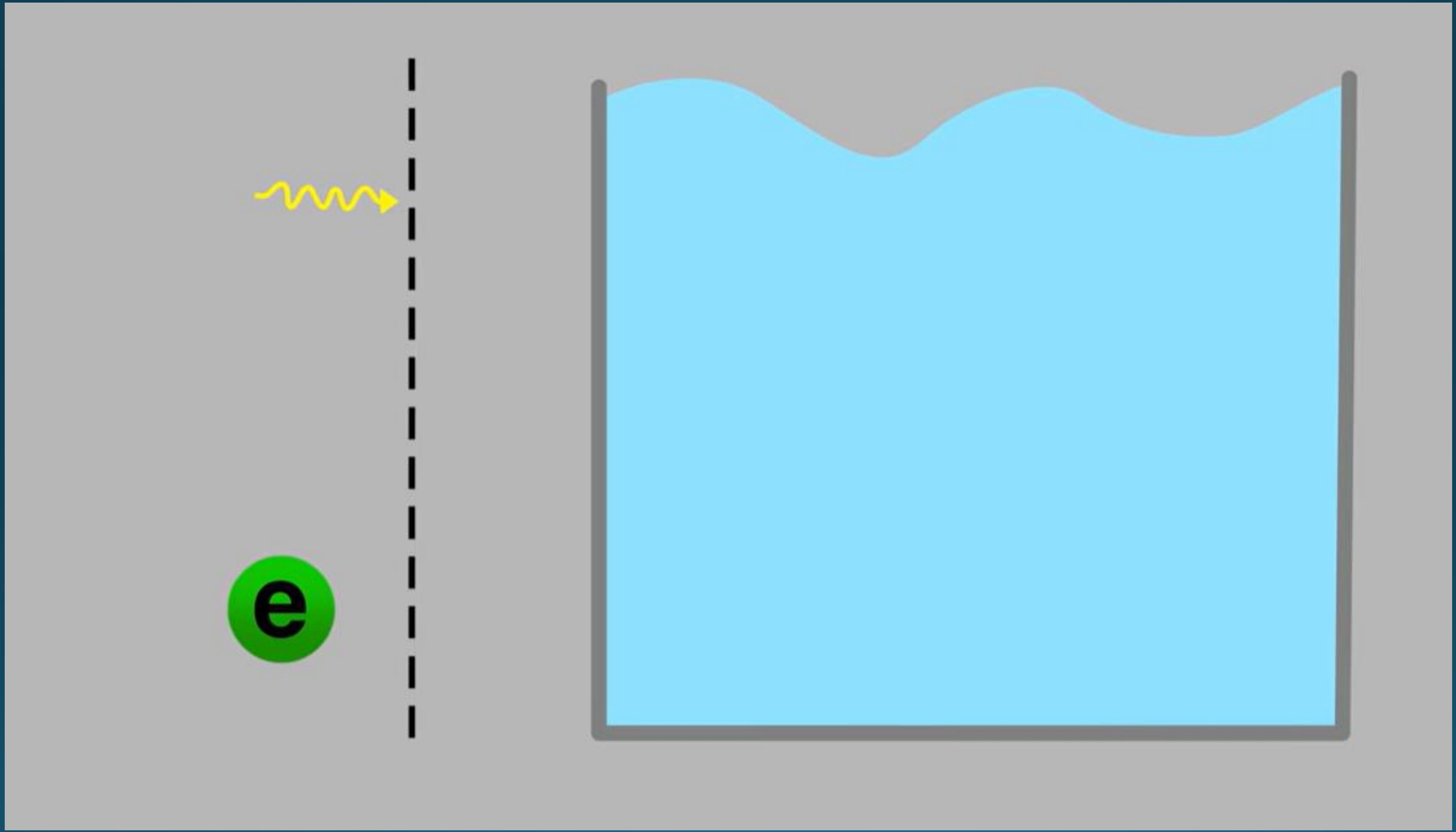
A lot of energy

Not moving





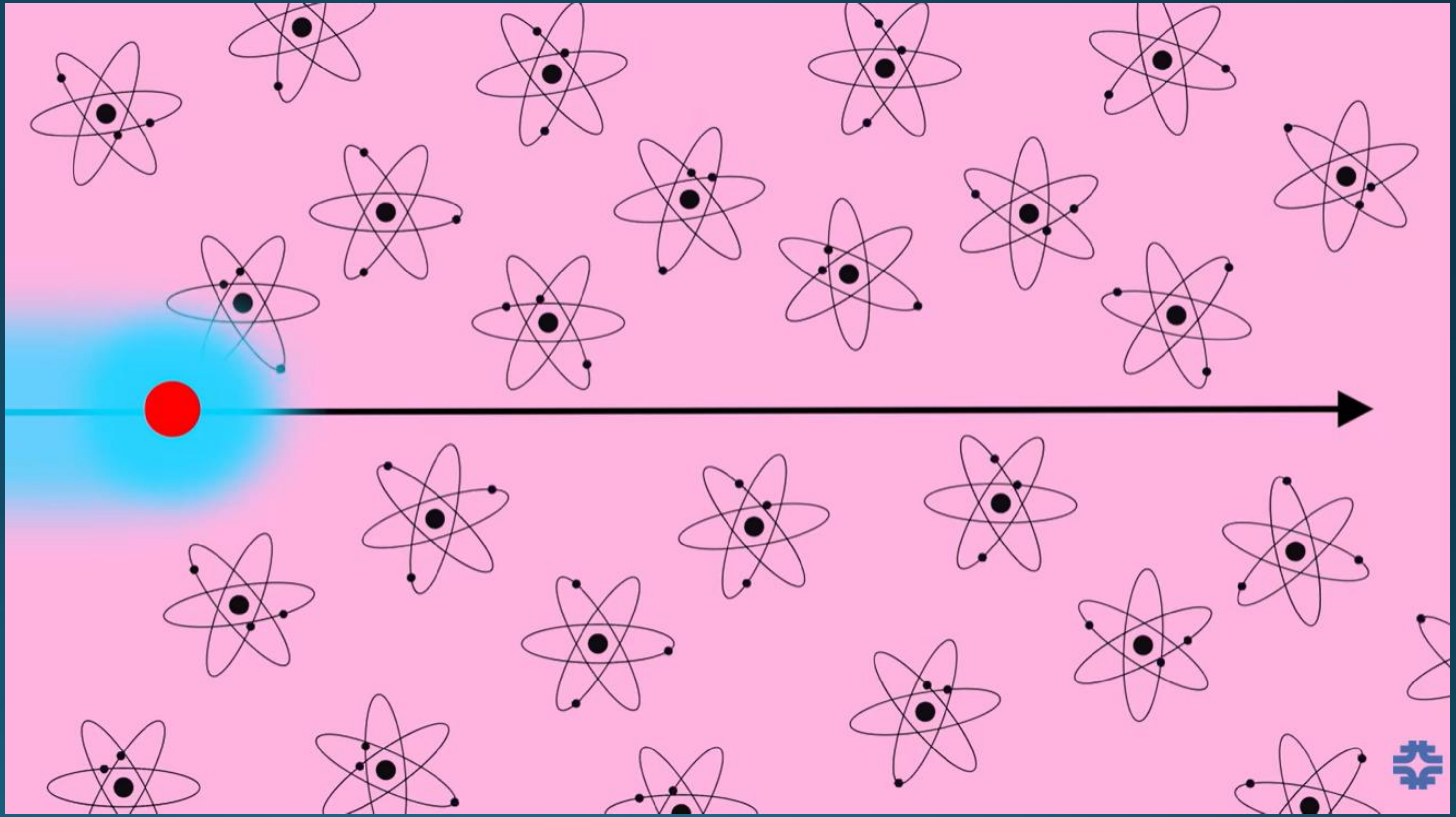
A particle traveling near the speed of light



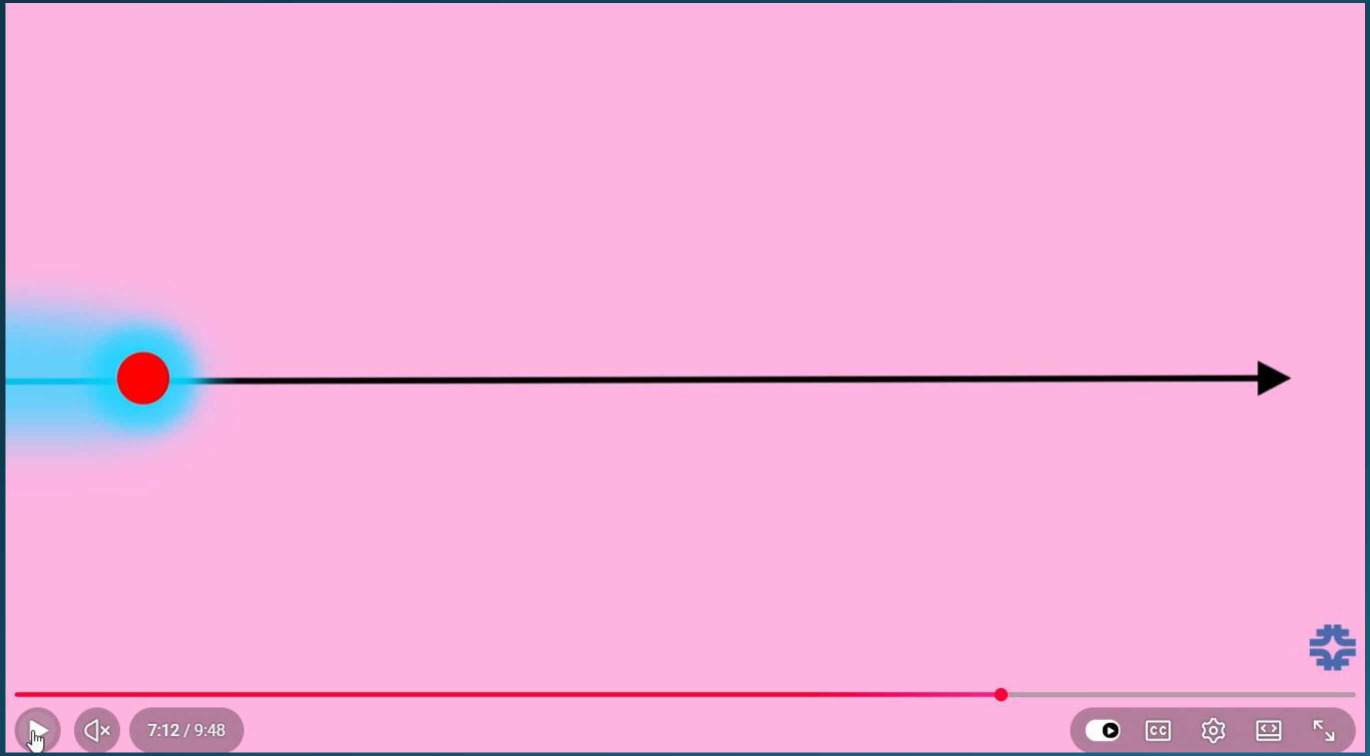
Cherenkov radiation 101

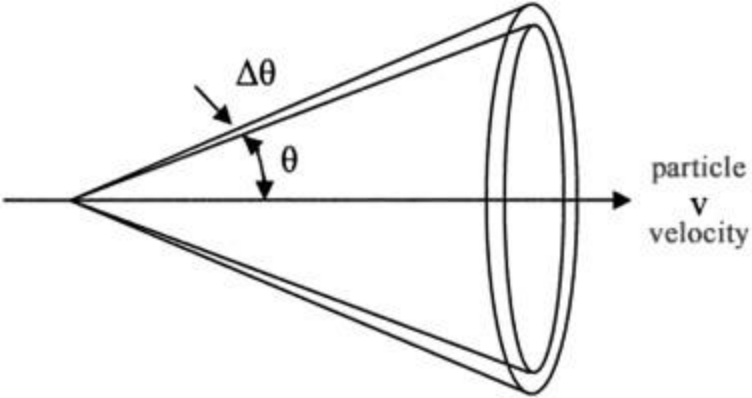
- Since light slows down in the medium, particles can travel "faster than light does in the medium"
- In the water, blue light emission
  - As was found in the discovery

*Only if the particle is charged



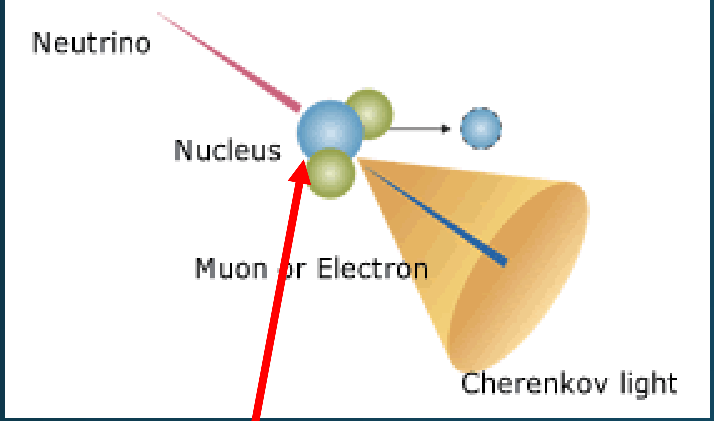
Cherenkov light tells you the direction of the fast, charged particle

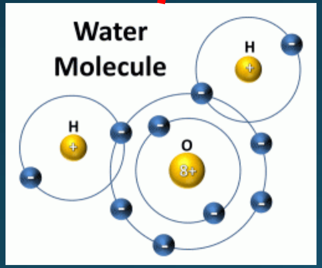


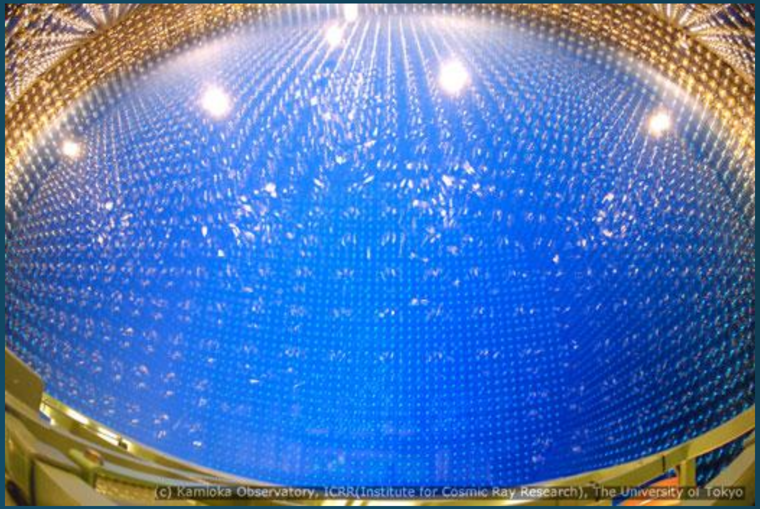


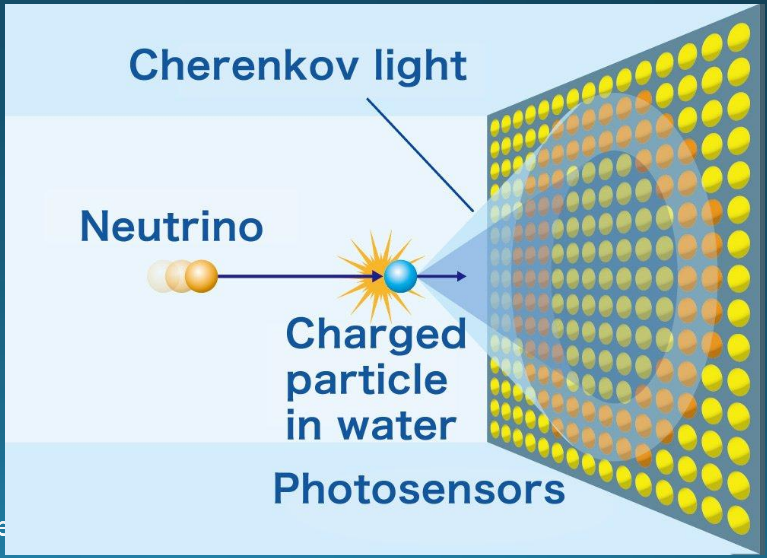
1. Cherenkov light will be emitted at an angle
2. That angle is related to the speed of the particle and the speed of light in the medium

“New” neutrino detection mechanism






(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



Cherenkov light can be seen great in water

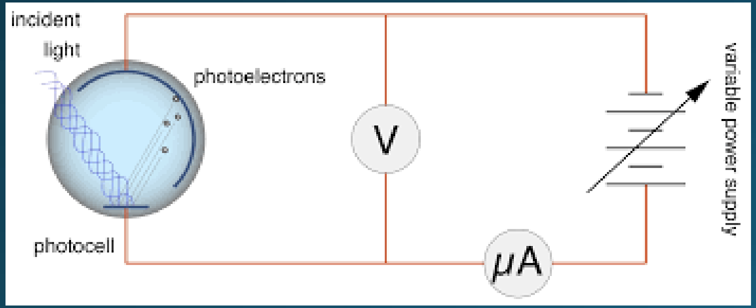
Direction of the neutrino is determined

Neutrino detection in water-Cherenkov

Optical/Cherenkov light sensors

- Photomultiplier tubes (PMT)

Count the light and flashes with photoelectric effect, measure voltage

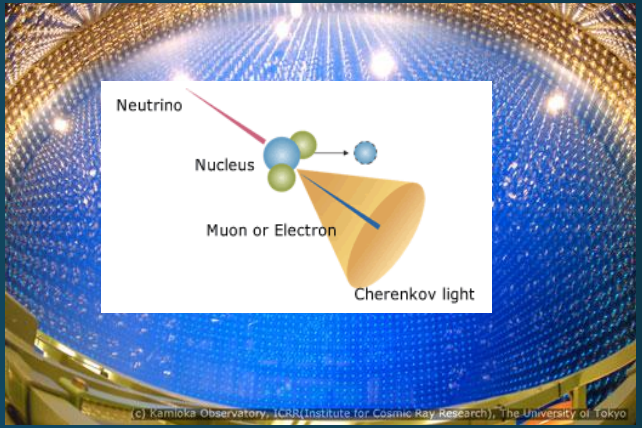


Photomultiplier Tube (PMT)

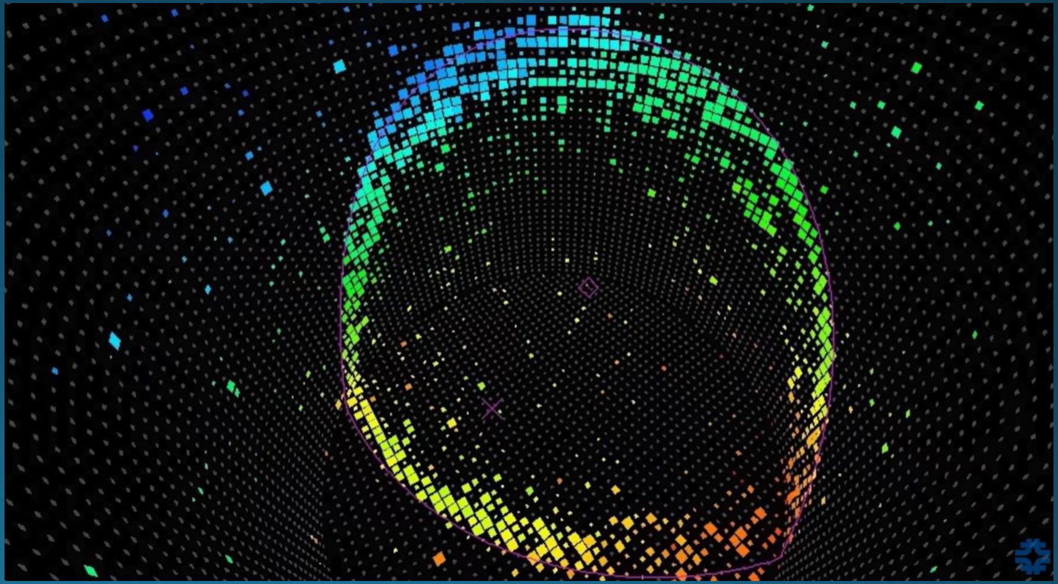
11,000 PMTs

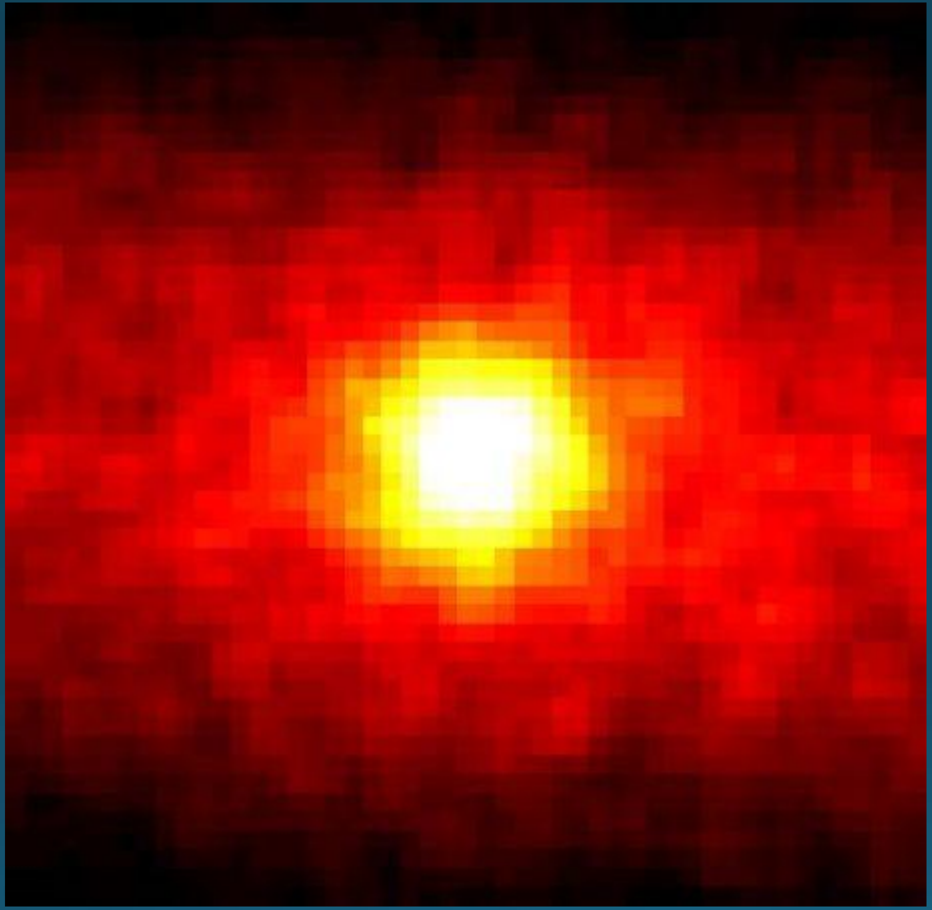
50,000 tons of water
~11 million cats

Super-Kamiokande



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



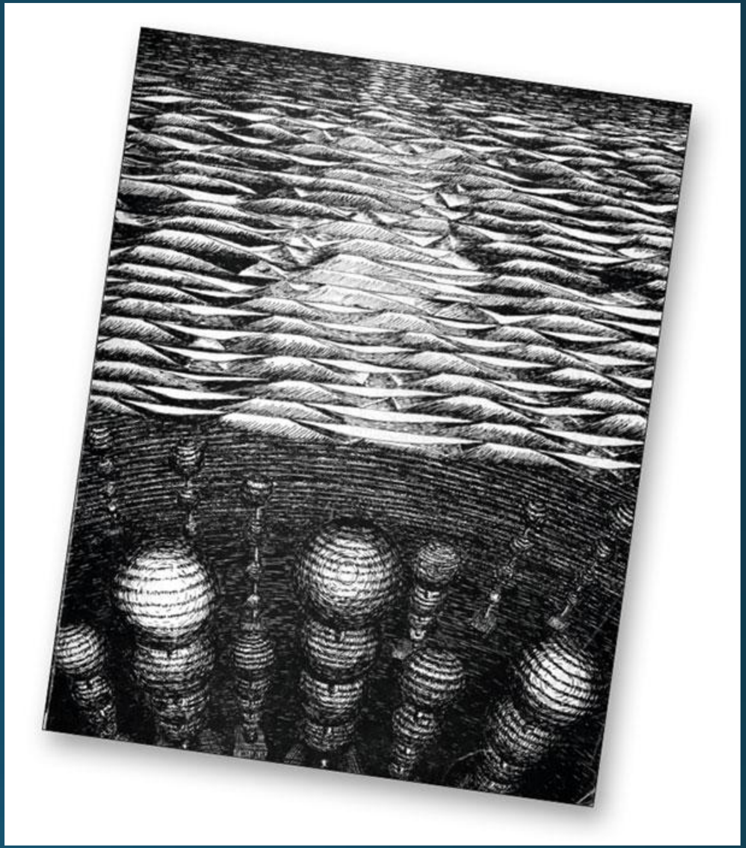


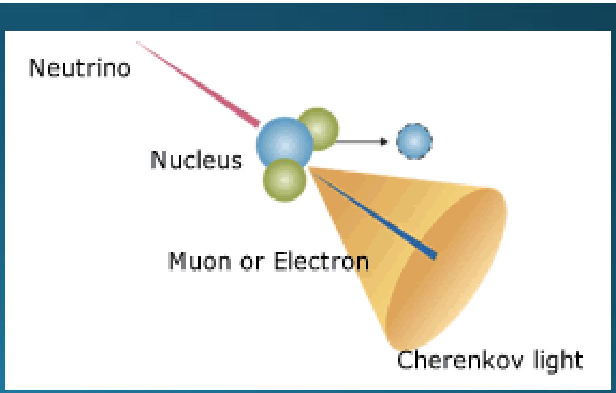
The sun in neutrinos (1998)

DUMAND

Deep Underwater Muon and Neutrino Detector

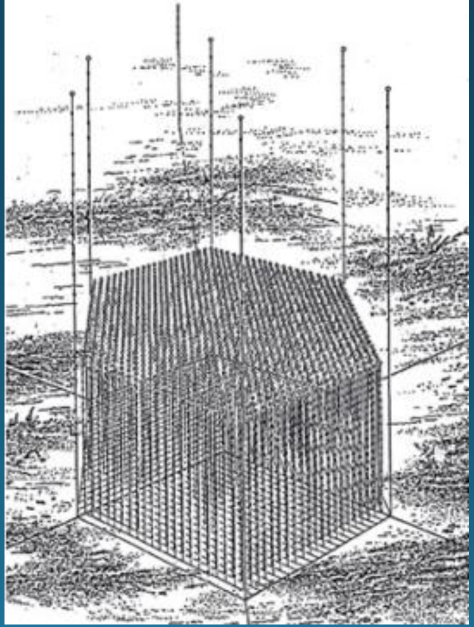
- Soviet and US collaboration
  - ~1976
- Actually laid the ground work for Kamiokande (and later Super-K)
- Naturally occurring medium transparent to Cherenkov light
  - The ocean?
- We knew to detect the "showers" or secondary particles
  - Only real way to measure neutrinos and their interactions is with large detectors





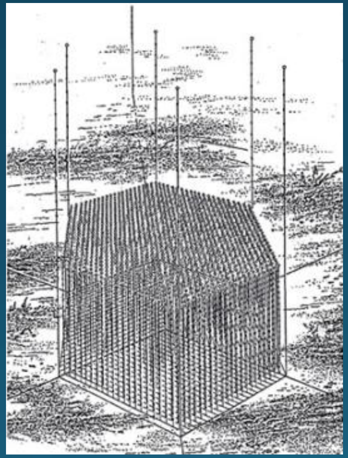
DUMAND proposal

- Off the coast of Hawaii
  - Confusing choice, right?
- Detect atmospheric and astrophysical neutrinos
  - Cherenkov and Acoustic
- String a bunch sensors underwater (~20k)
- In a few years, Soviet and US collaboration ended



From salt to ice

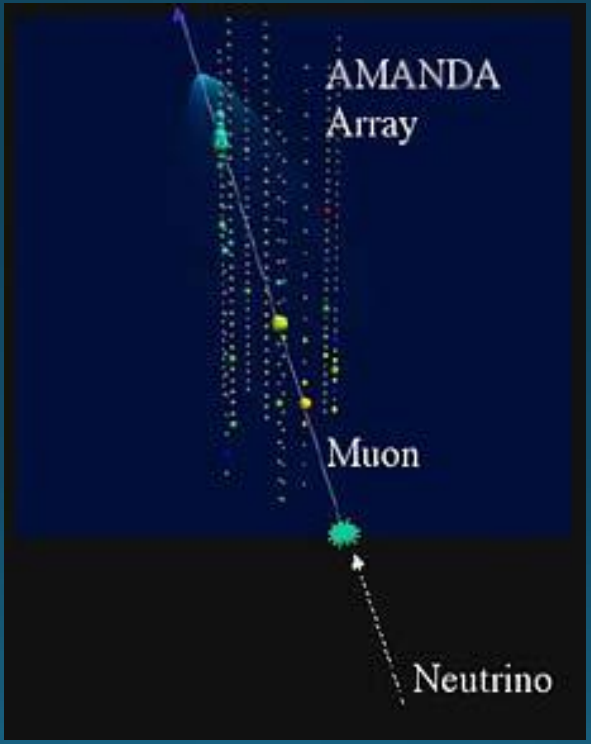
Challenges: salt-water corrosion, pressure at large depths, deep currents with ~1km long cables



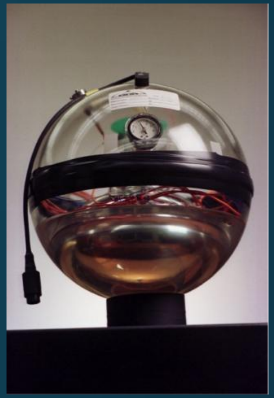
Antarctic Muon And Neutrino Detector Array

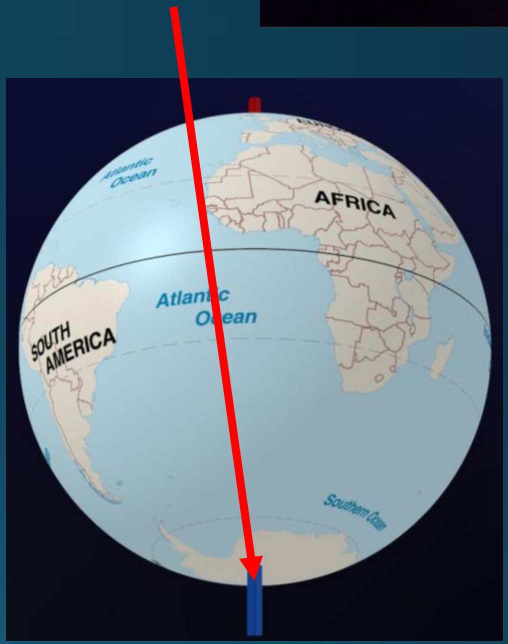
AMANDA

- Drill holes in Antarctic ice
  - At South Pole
  - ~2km deep (1.25 miles)
- Install optical/PMT devices
  - Measure Cherenkov light from neutrino interactions
- The sensors are stuck there forever
- First atmospheric neutrino in 1997



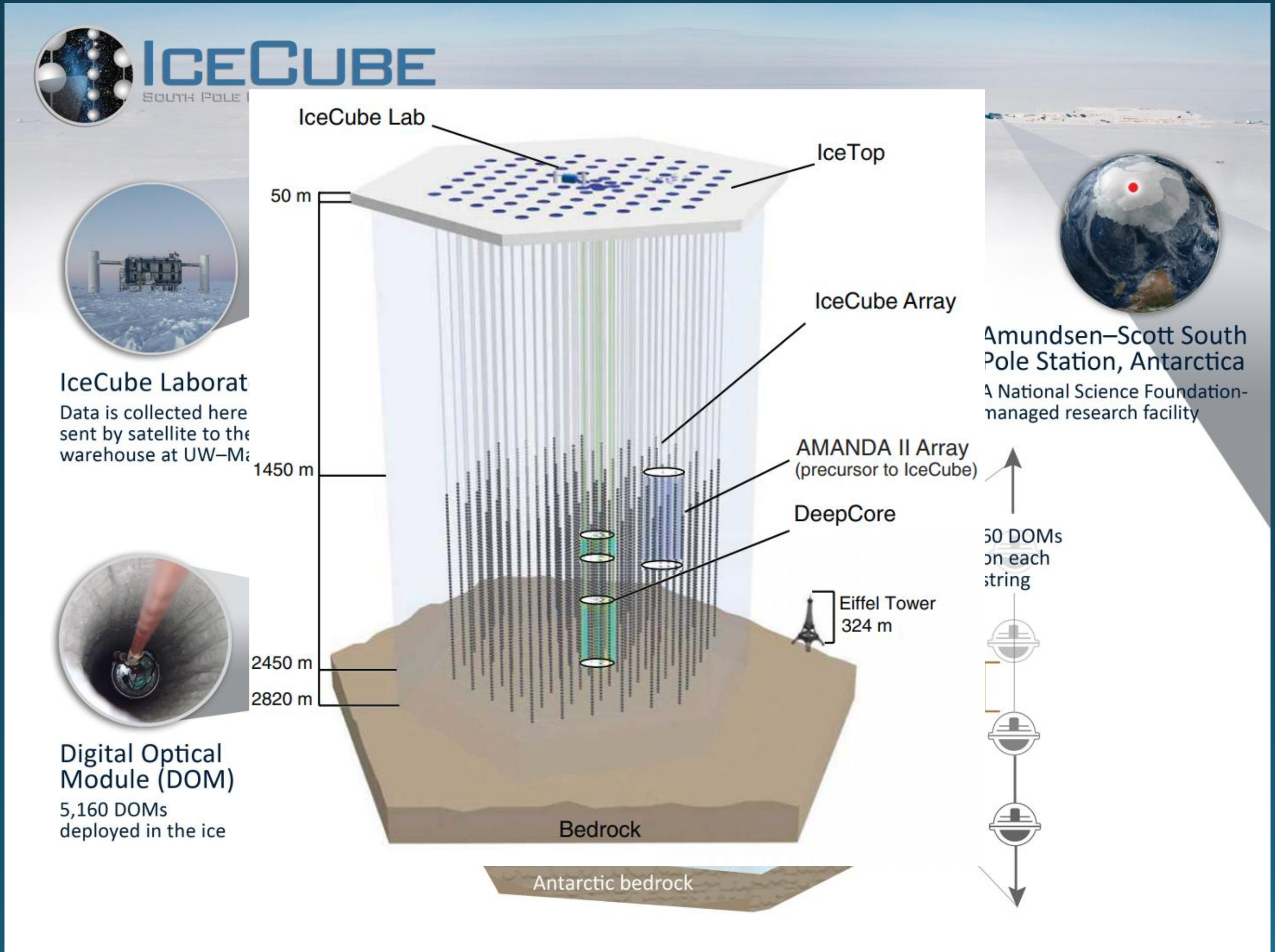
ν_μ





Neutrino telescopes in the ice works!

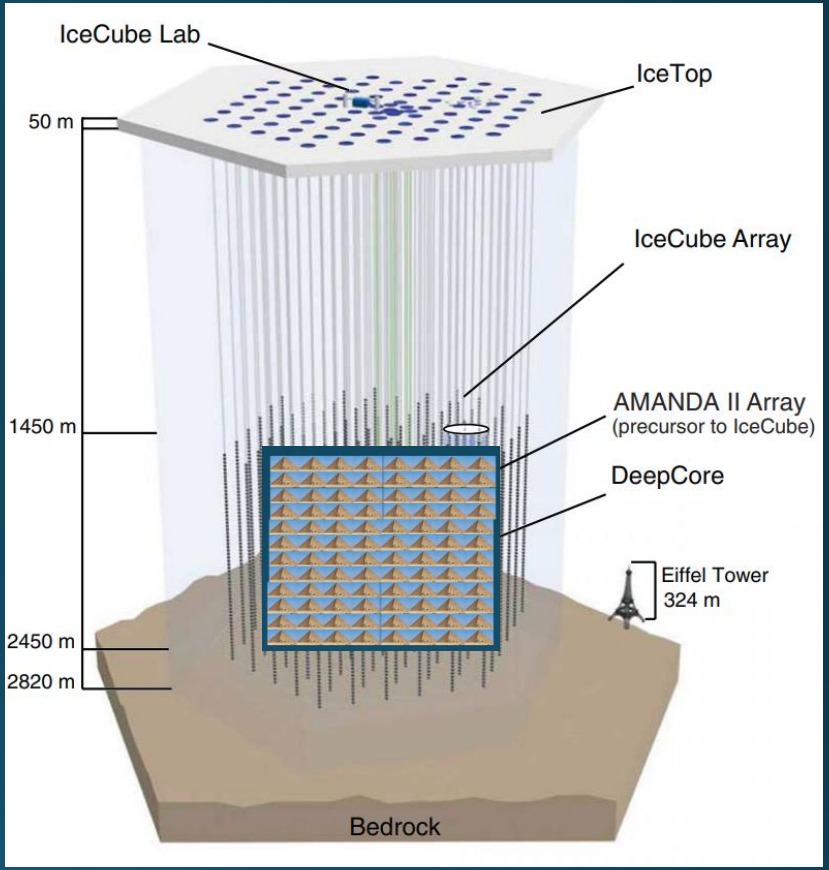
AMANDA to IceCube

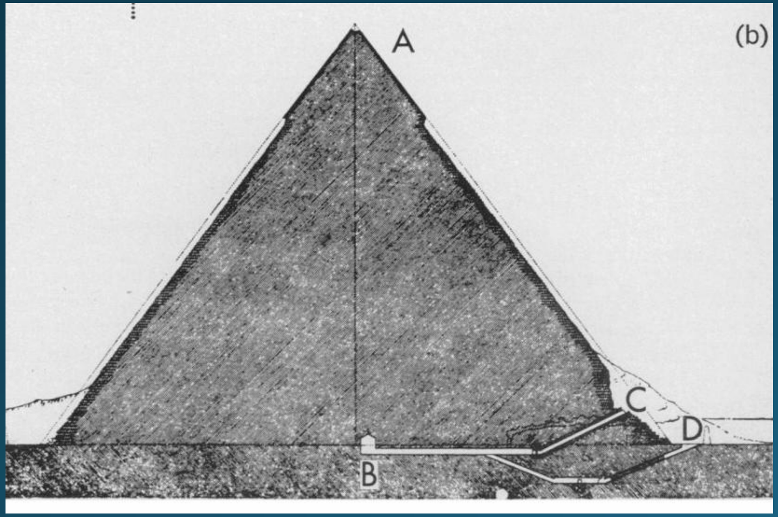


IceCube

Need large detectors to catch neutrinos

- Well, this is a cubic kilometer

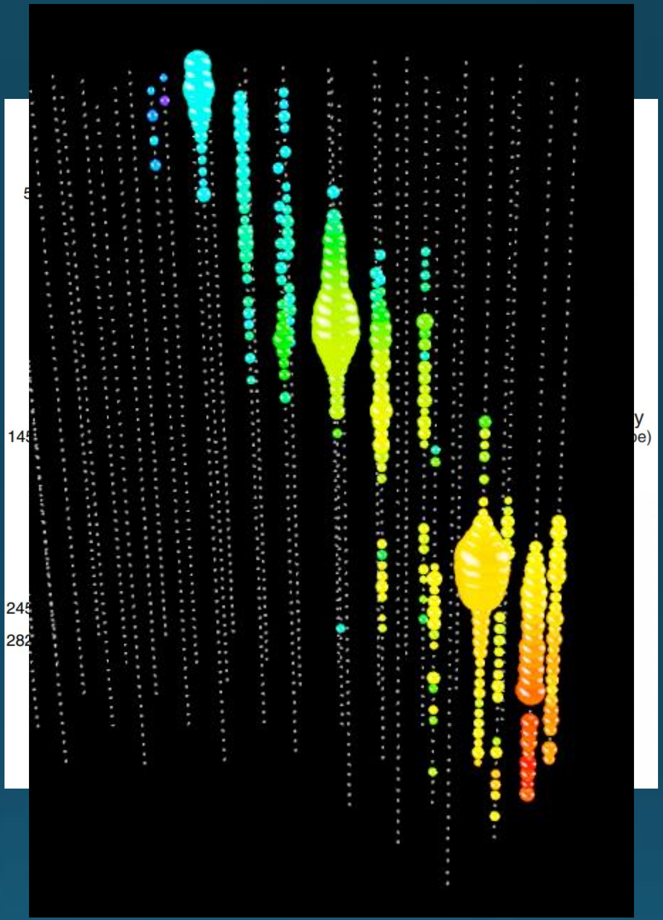




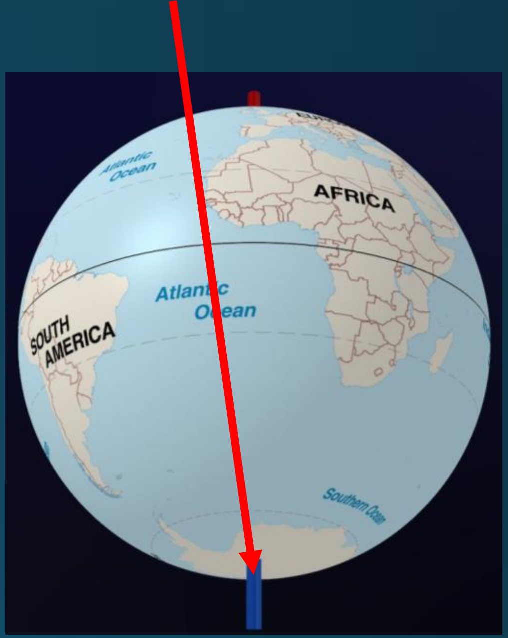
Need 400 of these

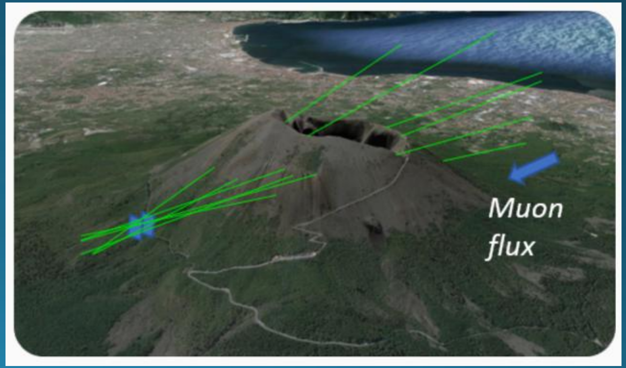
IceCube

- Finished in 2010
- By 2013, observed neutrinos of very high energies
    - Peta electron volts
        - One thousand - trillion
- Remember: muons from last week were giga (billion) electron volt
    - These neutrinos are 1 million times the energy of the muons



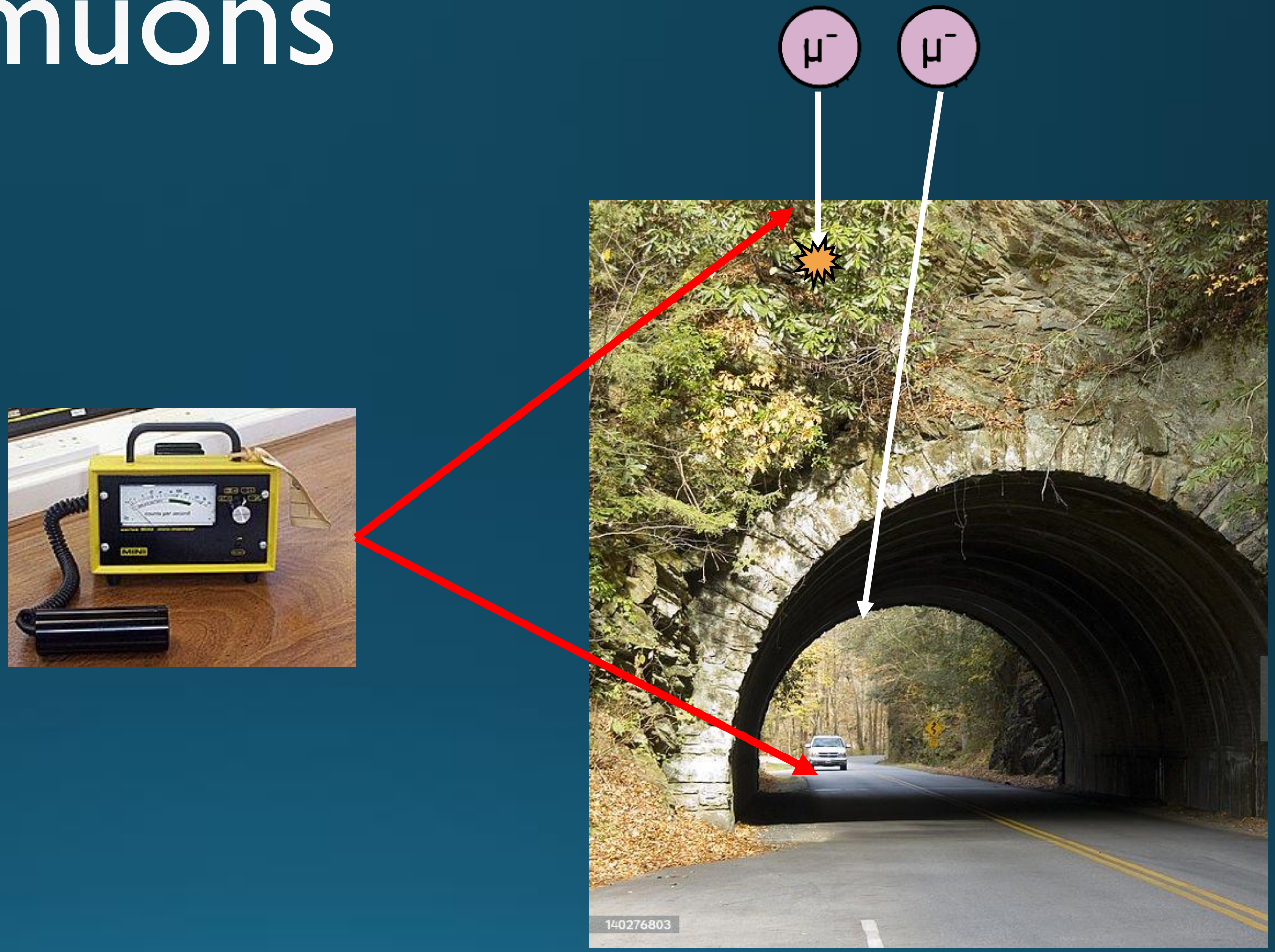
ν_μ



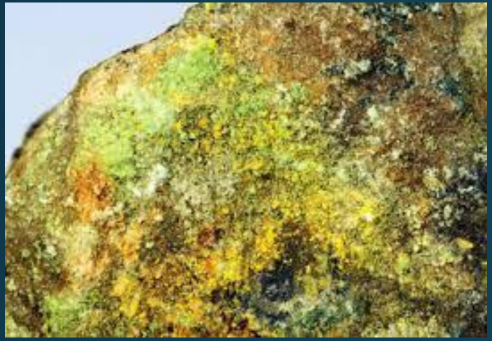


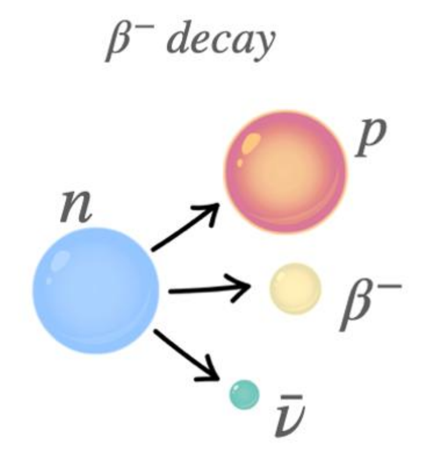
Last week with muons

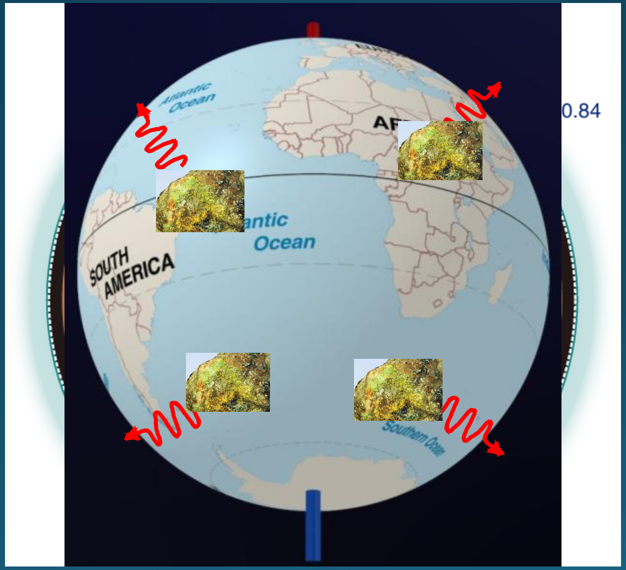
1. We know how many muons are above the tunnel
2. We measure the number of muons above and below
3. We can find the density of rock above



Back to Uranium



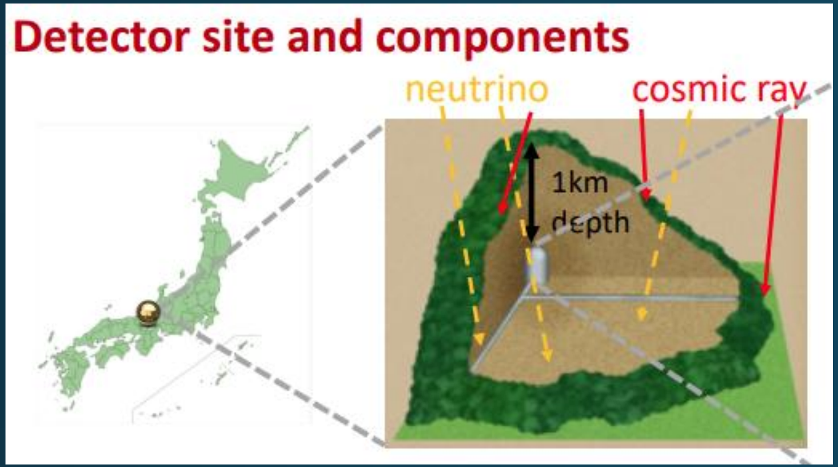


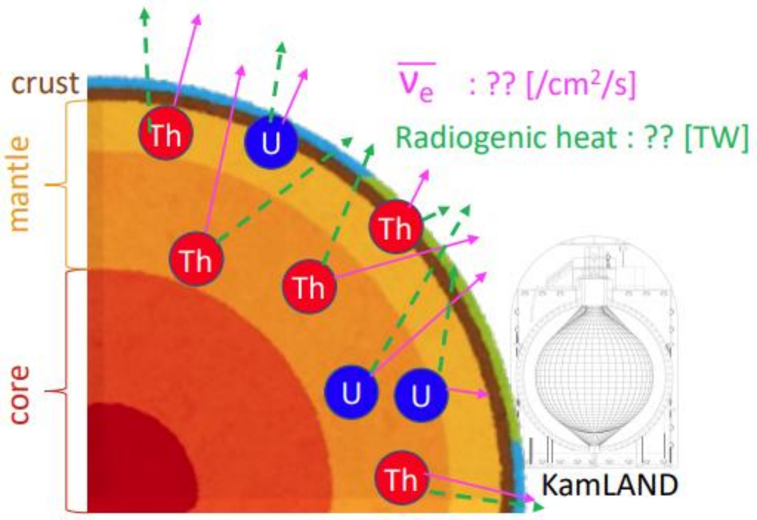


$$\bar{\nu}_e + p \rightarrow n + e^+$$

Detect Geoneutrinos

KamLAND





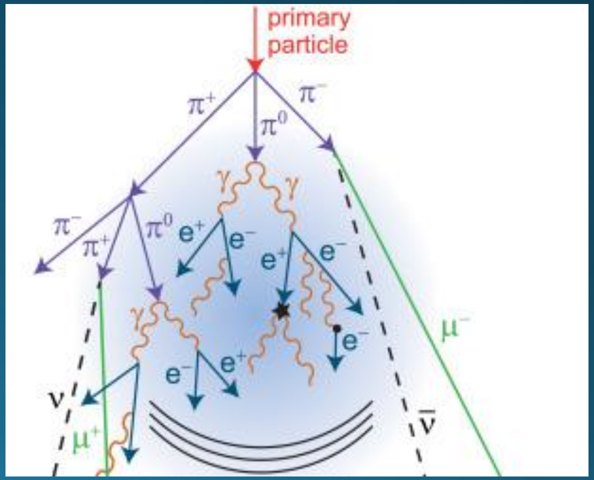
Kamioka Liquid Scintillator Antineutrino Detector (KamLAND)

Geophysics
How much heat is generated in different layers

A sea of neutrinos

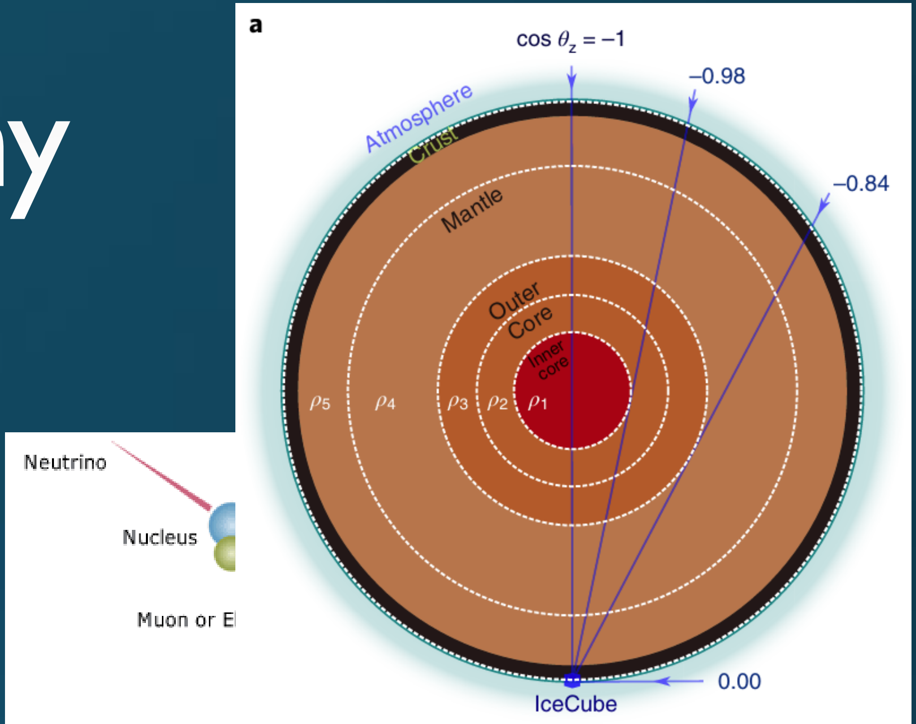
Cosmic rays are constantly bombarding our atmosphere

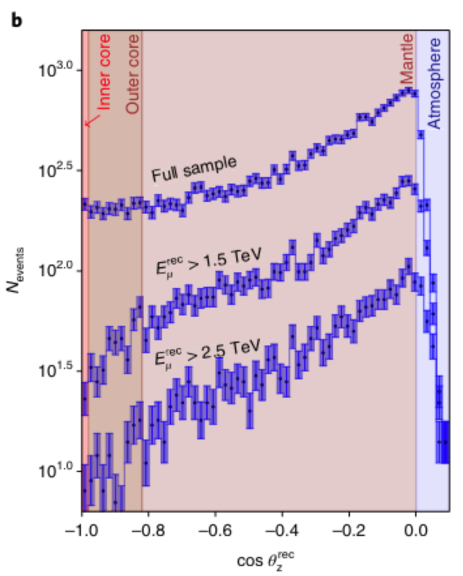
And their interactions are producing neutrinos (and muons)



Neutrino Tomography

- We know the size of the Earth
- IceCube measured 20k upward going muons from neutrinos
    - Range of crossing angles through the Earth
- The core of the Earth is more dense, so less neutrinos will come from directions that go through the core

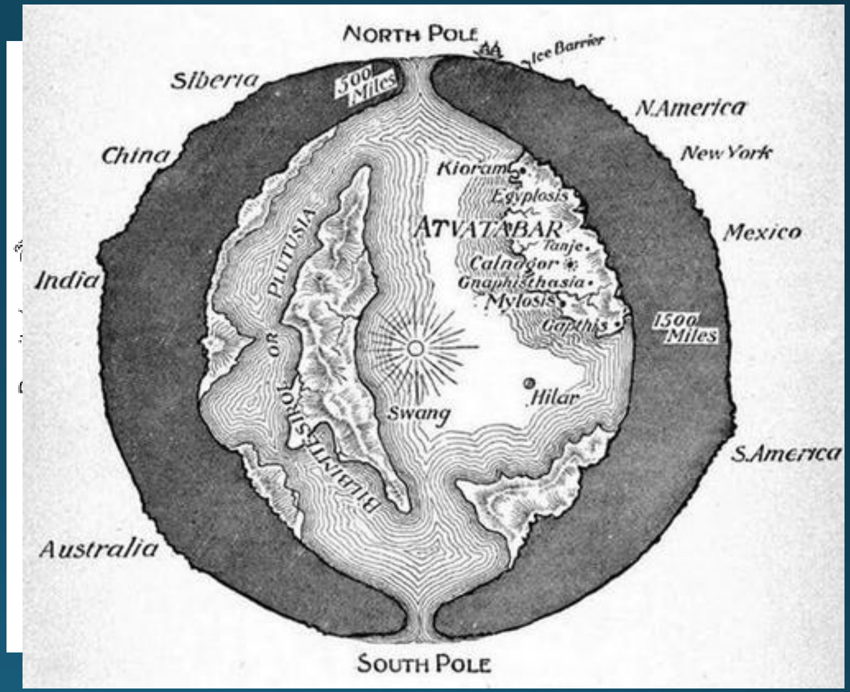




Line of sight with neutrino vision

(ongoing)Neutrino tomography of the Earth

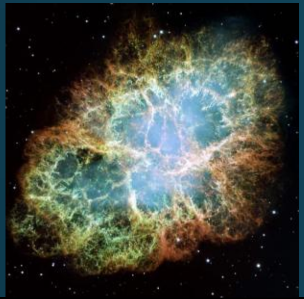
- Density determined by the neutrino measurements with IceCube
- Estimate that the mass of the Earth with neutrinos is
  - 6.0 * 10^{24} kg (Good agreement)
- The first measurement of Earth's mass not using gravitational force
  - Cavendish's measurement in 1798 was more precise than this

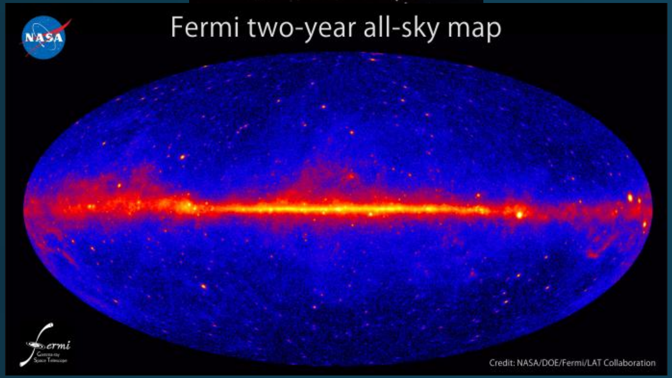


More importantly: the Earth isn't hollow

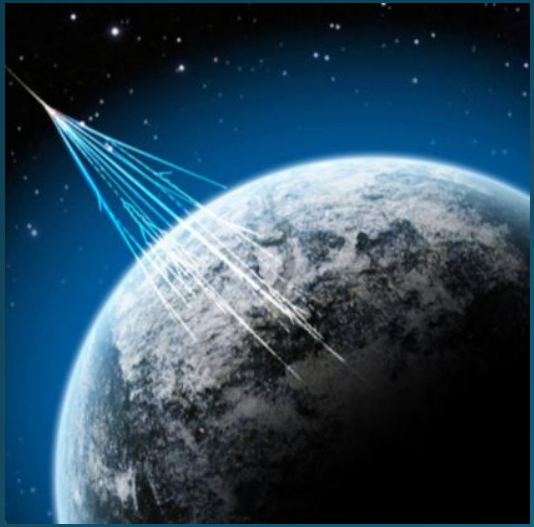
We live in a sea of cosmic rays

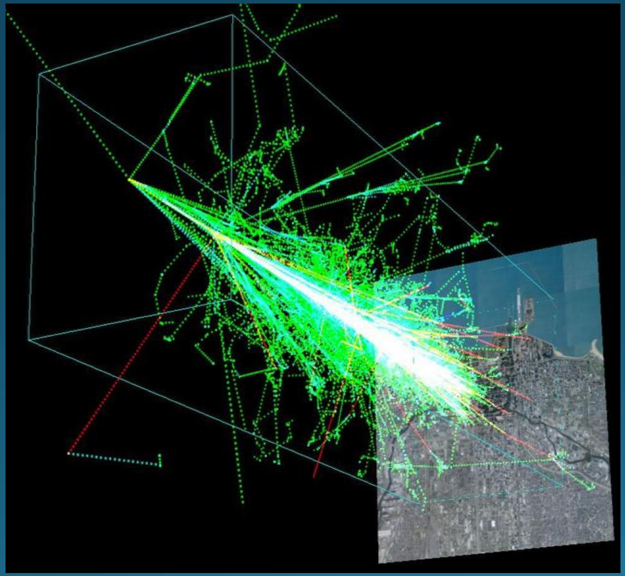
We just have to put on the astroparticle lens.

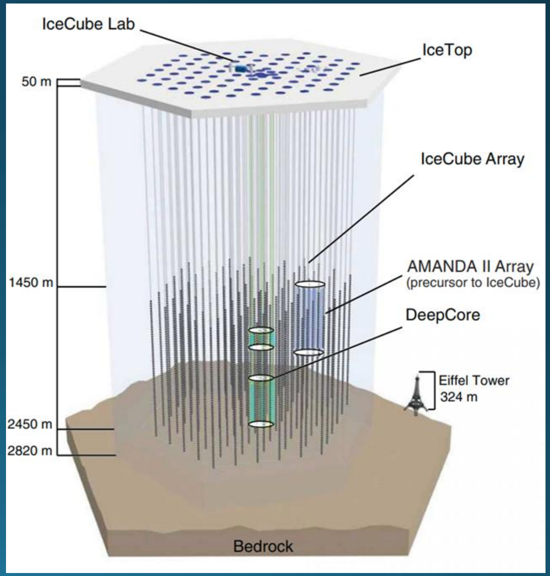


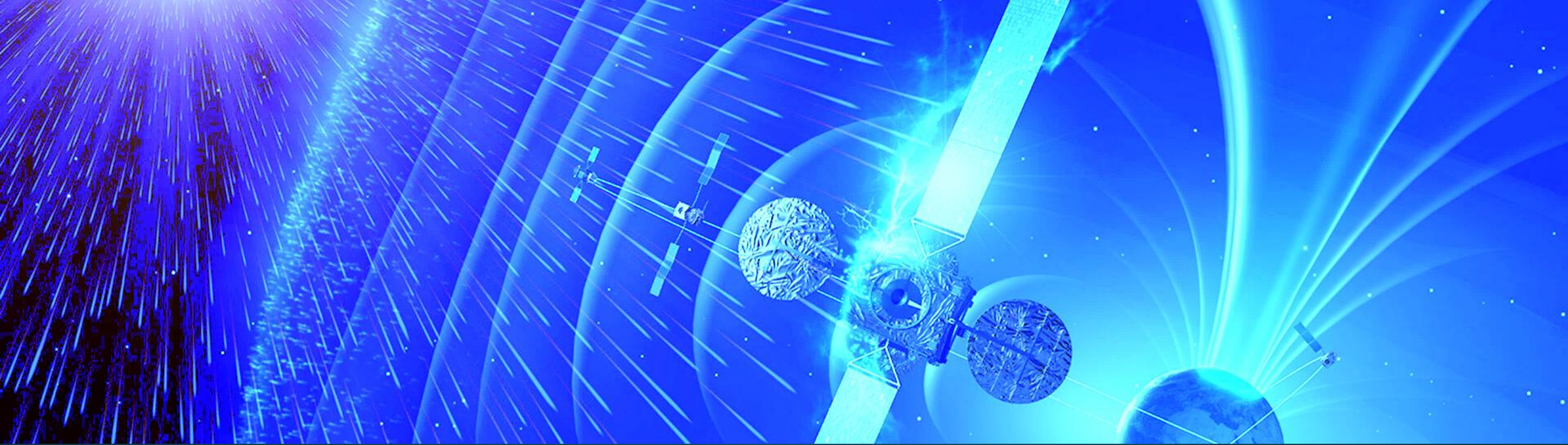


Credit: NASA/DOE/Fermi/LAT Collaboration









Next week, cosmic ray air showers and how they may play a role in lightning

Thank you!