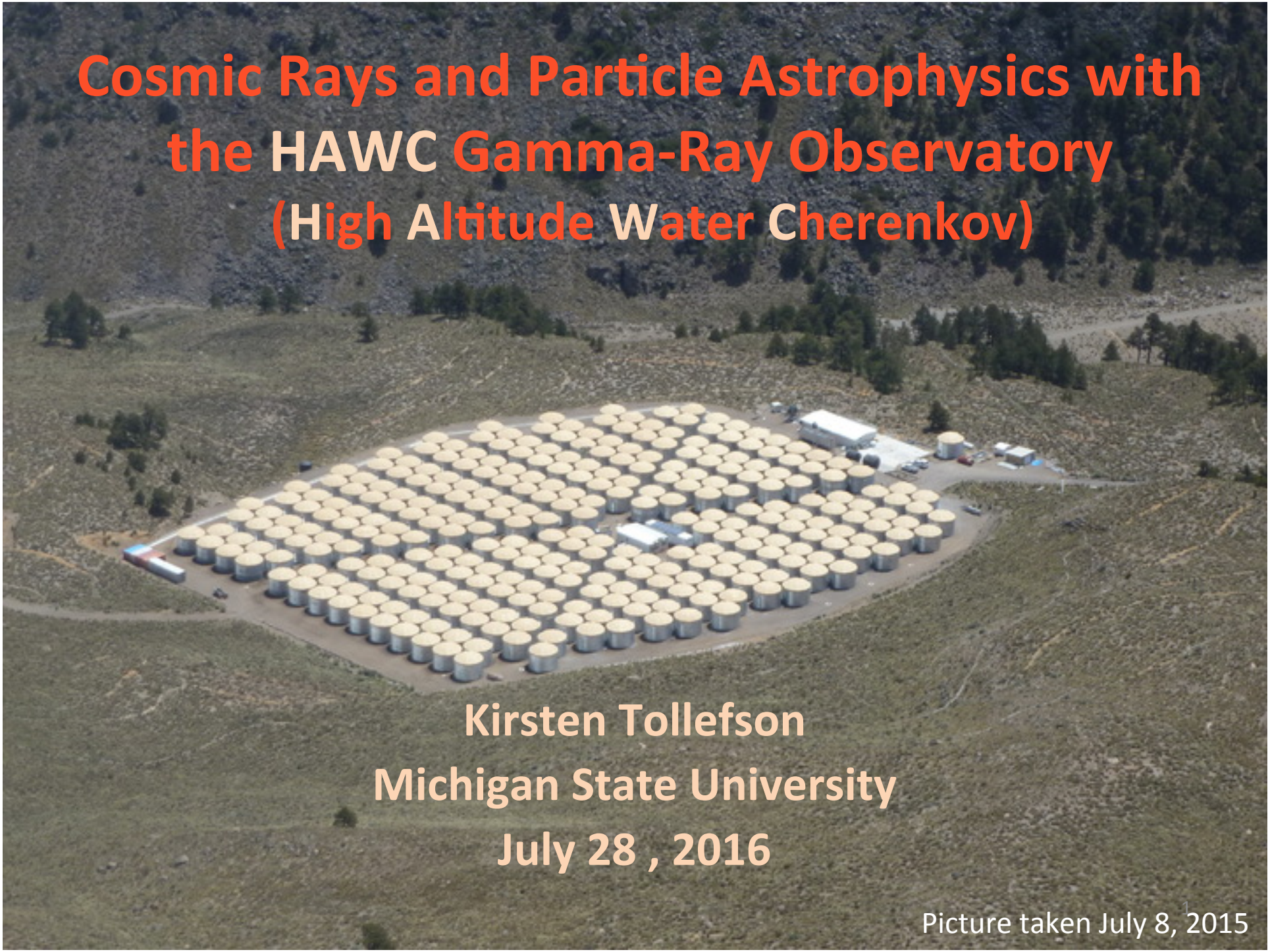


Cosmic Rays and Particle Astrophysics with the HAWC Gamma-Ray Observatory (High Altitude Water Cherenkov)

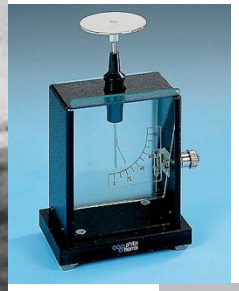
Kirsten Tollefson
Michigan State University

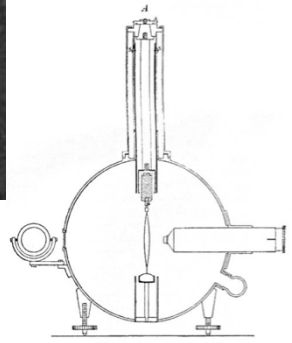
July 28 , 2016

Picture taken July 8, 2015

A Century Old Question: Where do cosmic rays come from?

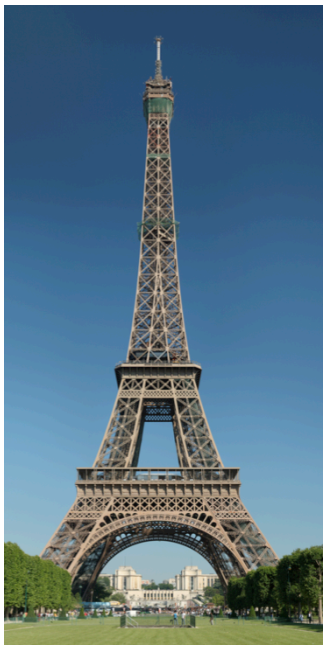
Electroscopes



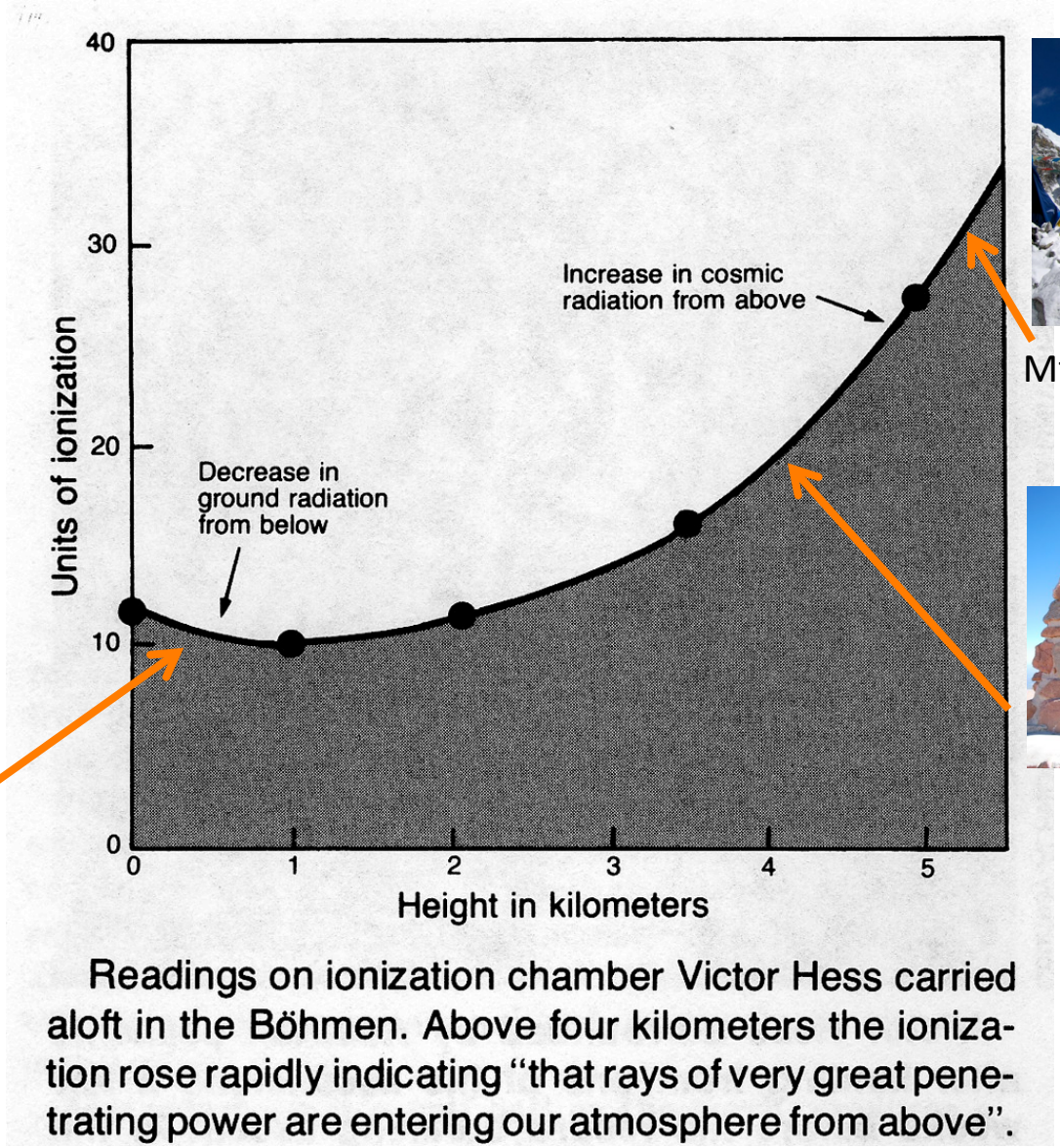


Hess was awarded the Nobel Prize in 1936 for the discovery of cosmic rays.

A Century Old Question: Where do cosmic rays come from?



Eiffel Tower
0.3 km

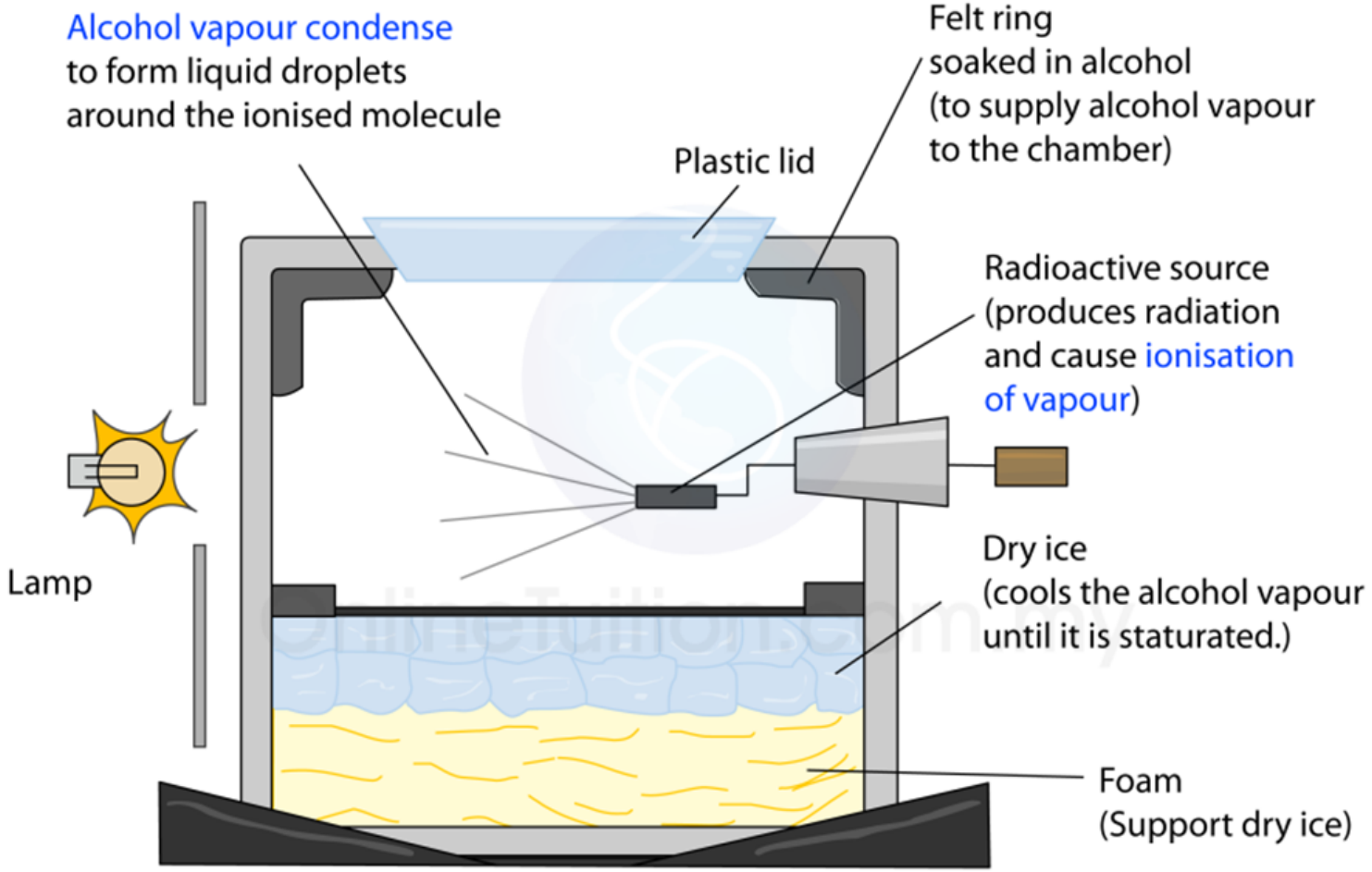


Readings on ionization chamber Victor Hess carried aloft in the Böhmen. Above four kilometers the ionization rose rapidly indicating "that rays of very great penetrating power are entering our atmosphere from above".

Mt. Everest Base Camp
5.3 km

Pikes Peak
4.3 km

Cloud Chamber

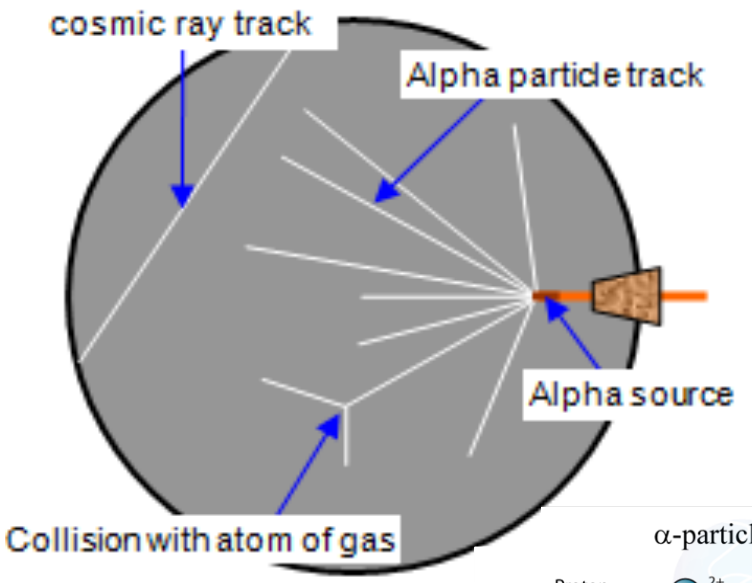


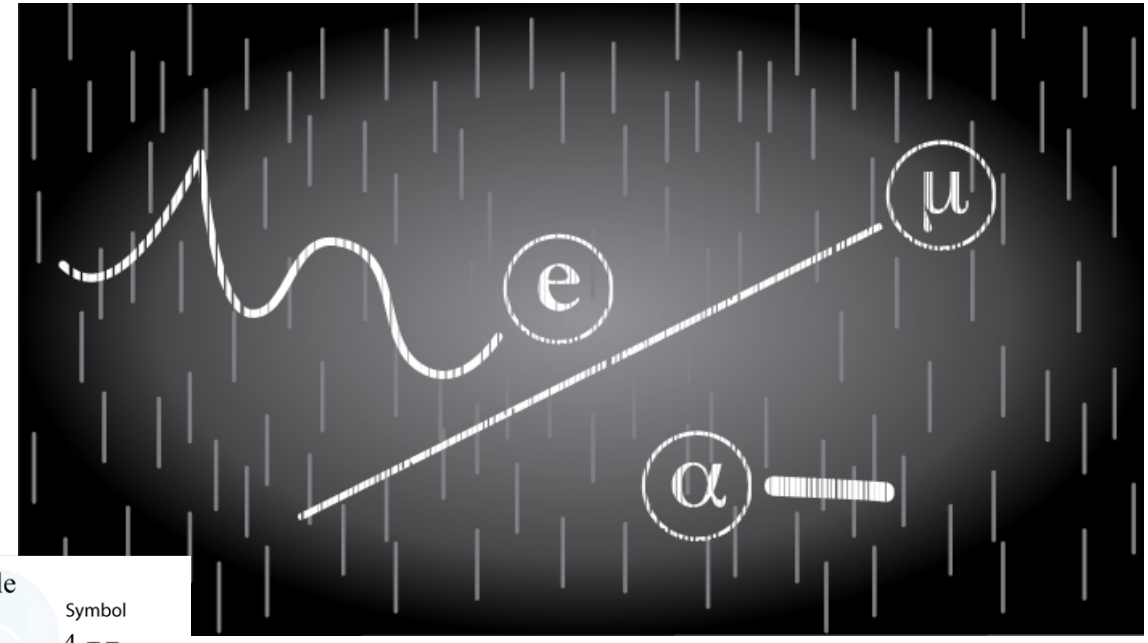
Try to Answer these Questions While Looking at the Cloud Chamber

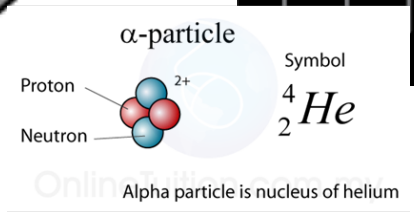
- Are there different types of tracks?
  - Characterize the types of tracks you see
  - E.g. short, long, wide, narrow, straight, squiggly?

- How many tracks pass through the chamber in 30 seconds or 1 minute?
  - Don't count the ones originating from the alpha source in the side of the chamber.
  - Remember your #, we'll use it later.

Tracks in Cloud Chamber







Video of tracks in a cloud chamber at MIT:

http://video.mit.edu/watch/cloud-chamber-4058/

First 20 seconds are of cosmic rays at ~3000 meters:

https://www.youtube.com/watch?v=SnKvtazt5So

Make Your Own Cloud Chamber

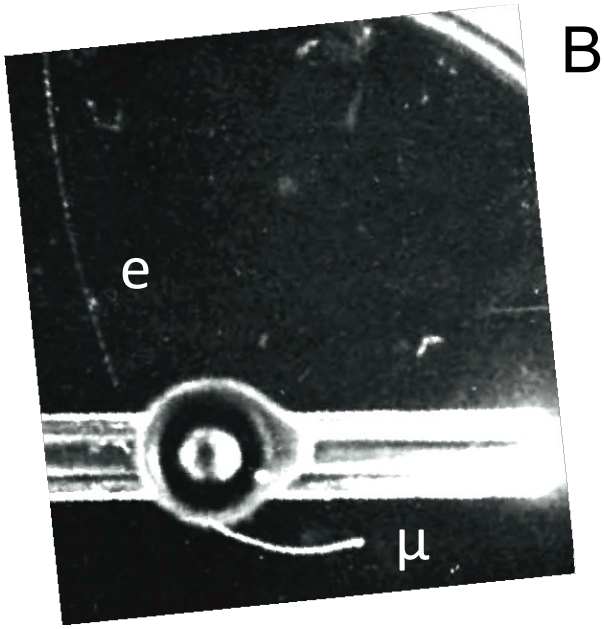
- Article explaining how to make your own cloud chamber and what you are seeing: http://www.symmetrymagazine.org/article/january-2015/how-to-build-your-own-particle-detector

- Version using a plastic cup (so easy a 6-year old shows you how to do it): https://www.youtube.com/watch?v=_qbYvZ-Op4M

Investigating Cosmic Rays

- The West Hill Biological website has several high-school level physics and bio lab activities, including teacher's guides, that can be downloaded for free from http://www.westhillbio.com/
- There is one on "Investigating Cosmic Rays" http://www.westhillbio.com/investigating-cosmic-rays
- You can purchase their cloud chamber kit for ~$40 which works better than most of the do-it-yourself ones

Beginnings of Particle Physics



Before there were man-made particle accelerators there were **cosmic rays…**

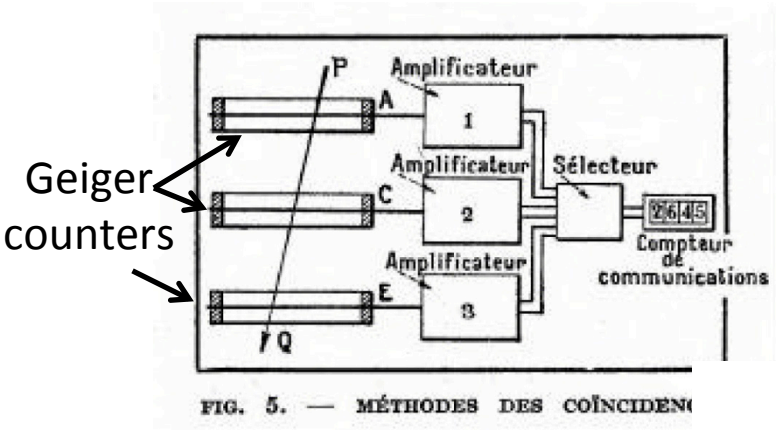
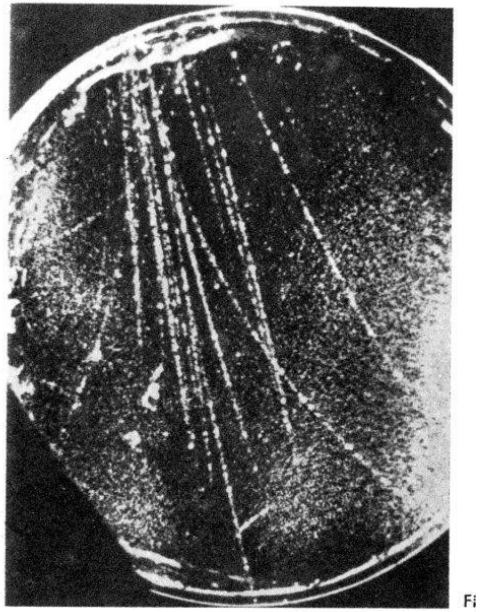
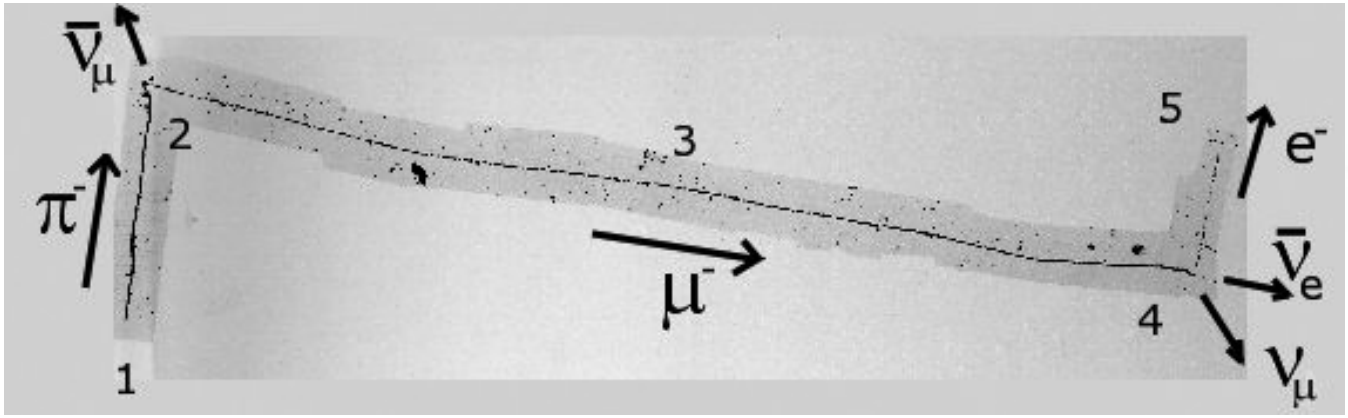
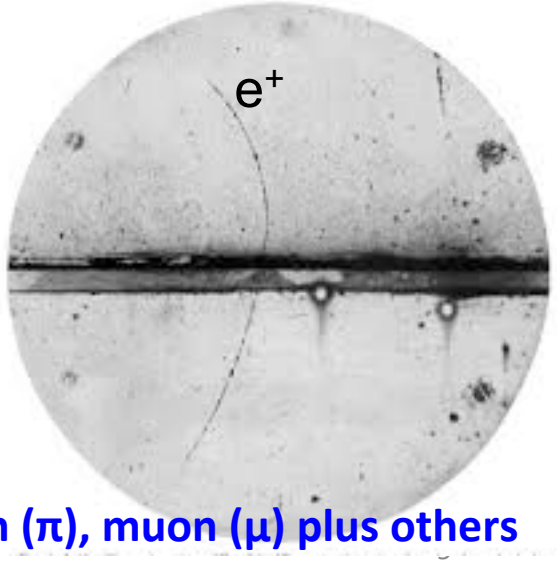


FIG. 5. — MÉTHODES DES COÏNCIDEN

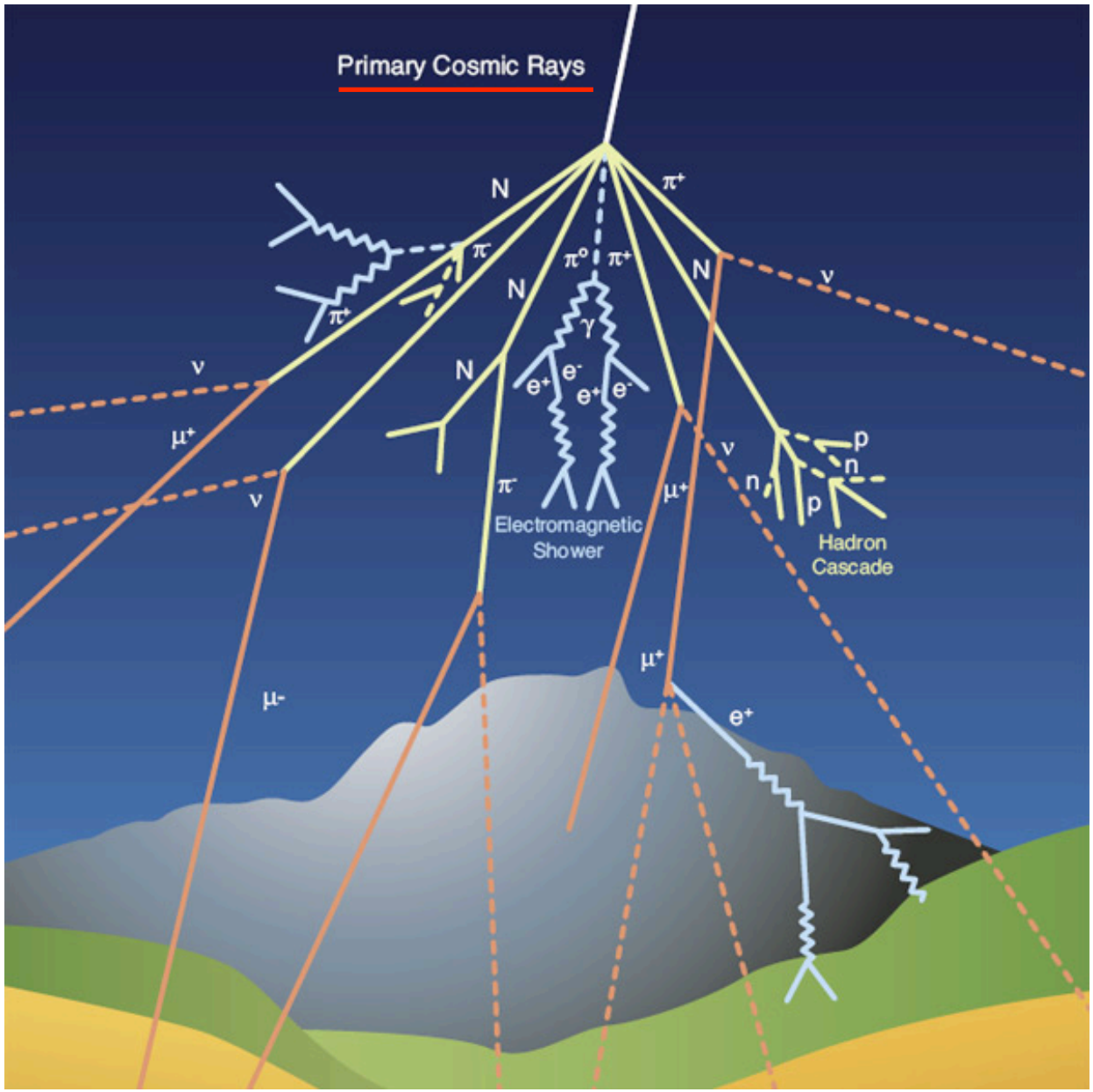






Studying cosmic rays led to the discovery of the positron (e^+), pion (π), muon (μ) plus others

Cosmic Ray Air Shower

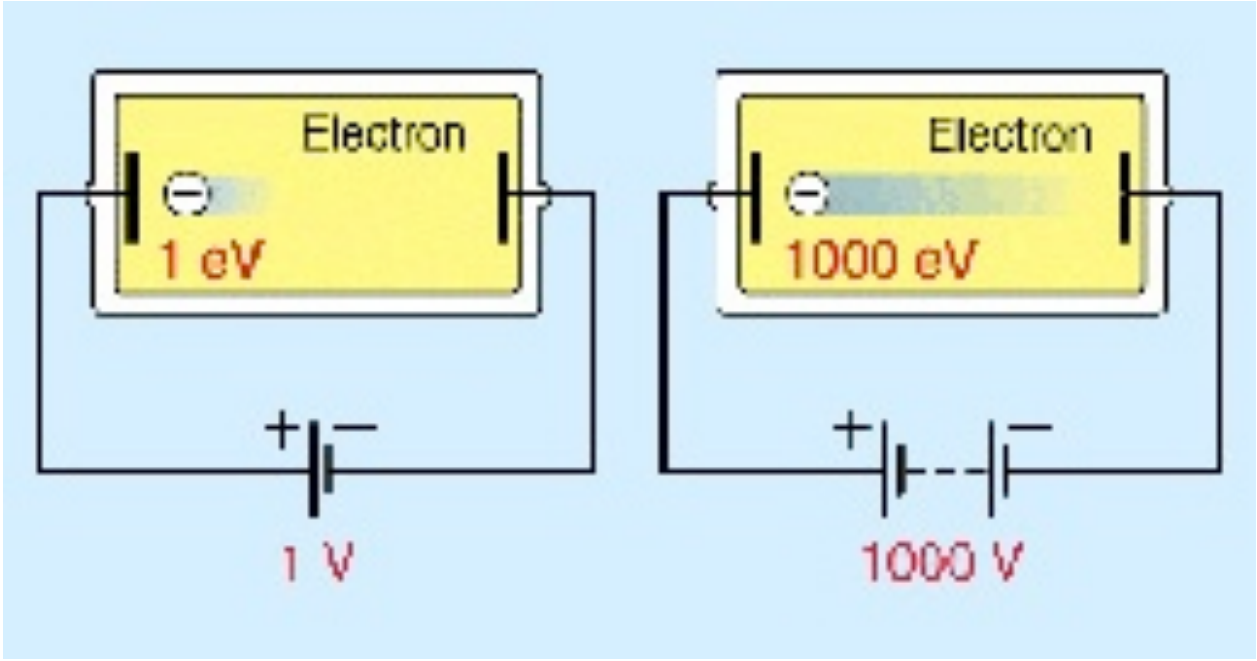


What are Cosmic Rays?

Cosmic rays are charged particles:

- 87% are protons (hydrogen nuclei)
- 12% are alpha particles (helium nuclei)
- 1% are electrons plus a small amount of nuclei from heavier elements (such as iron)

A Unit of Energy called the Electron Volt (eV)



$$E = qV$$

$$1\ \text{eV} = 1.6\text{x}10^{-19}\ \text{J}$$

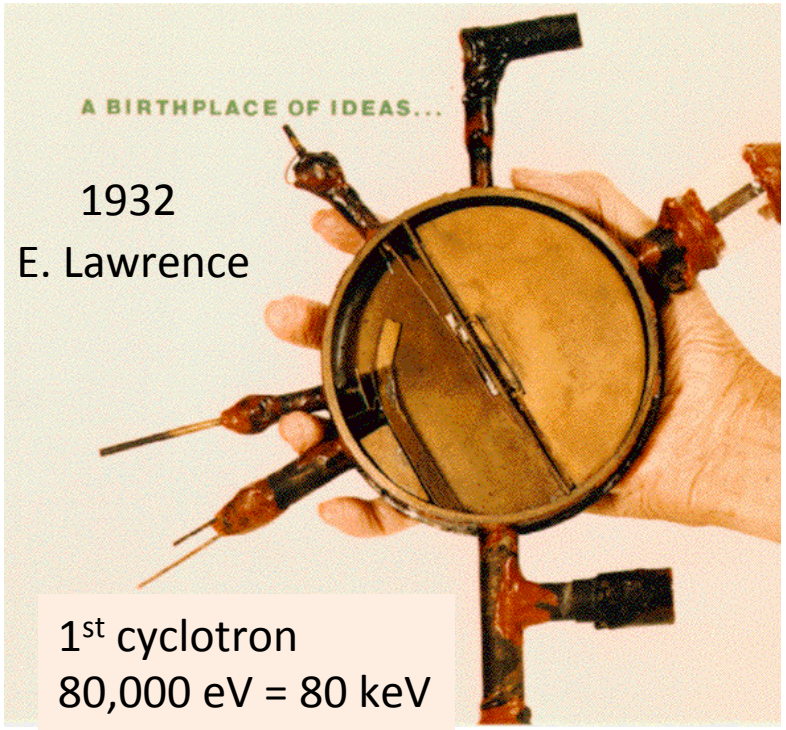
$$1\ \text{keV} = 1000\ \text{eV} = 10^{3}\ \text{eV}$$

$$1\ \text{GeV} = 10^{9}\ \text{eV}$$

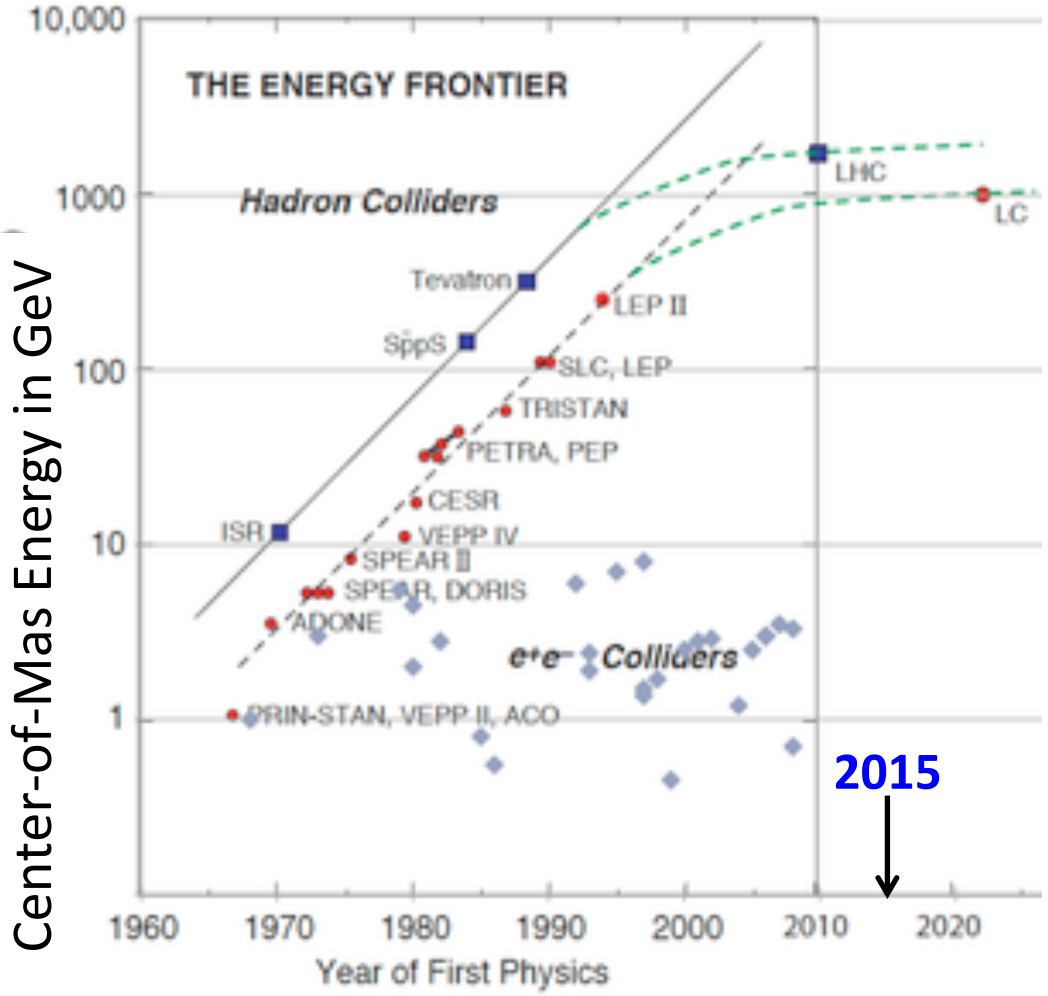
$$1\ \text{TeV} = 10^{12}\ \text{eV}$$

$$1\ \text{ZeV} = 10^{21}\ \text{eV}$$

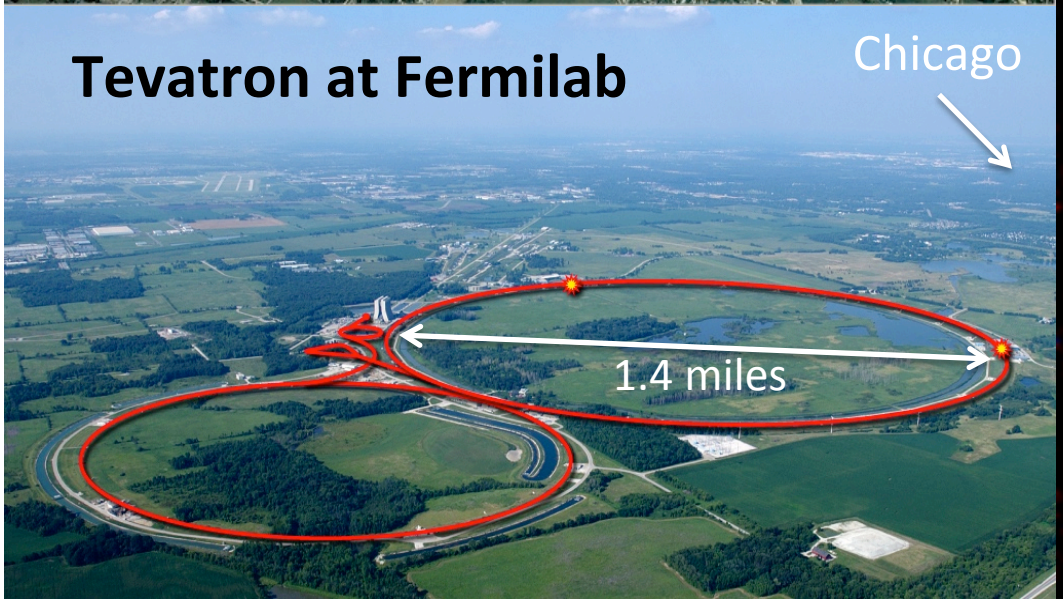
Man-made Accelerators



1 keV = 10^3 eV
1 MeV = 10^6 eV
1 GeV = 10^9 eV
1 TeV = 10^{12} eV



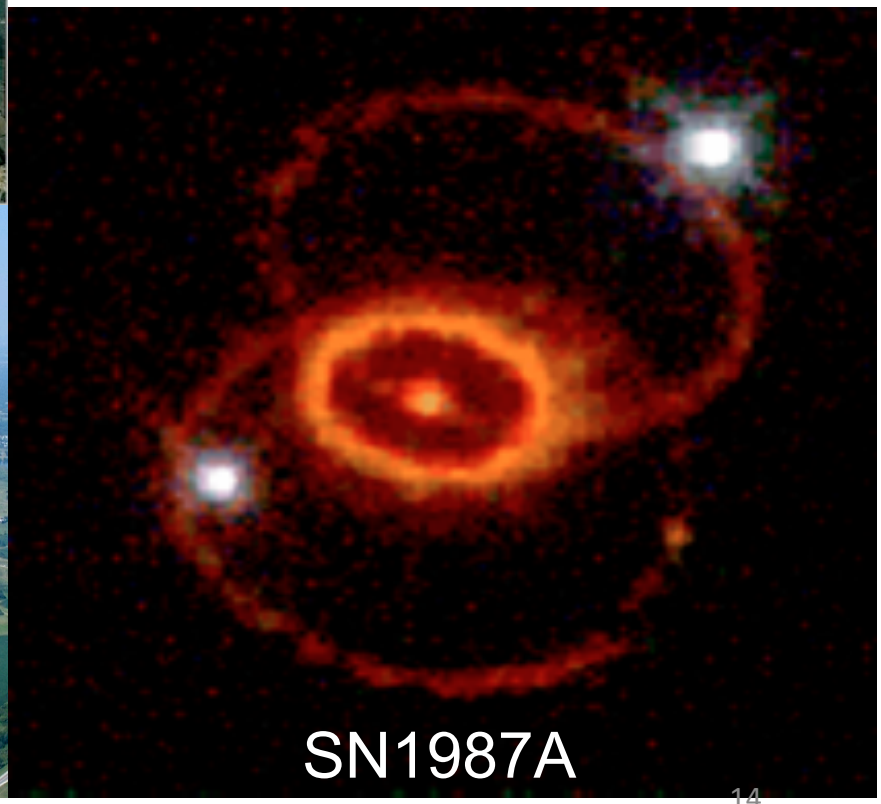
Particle Accelerators



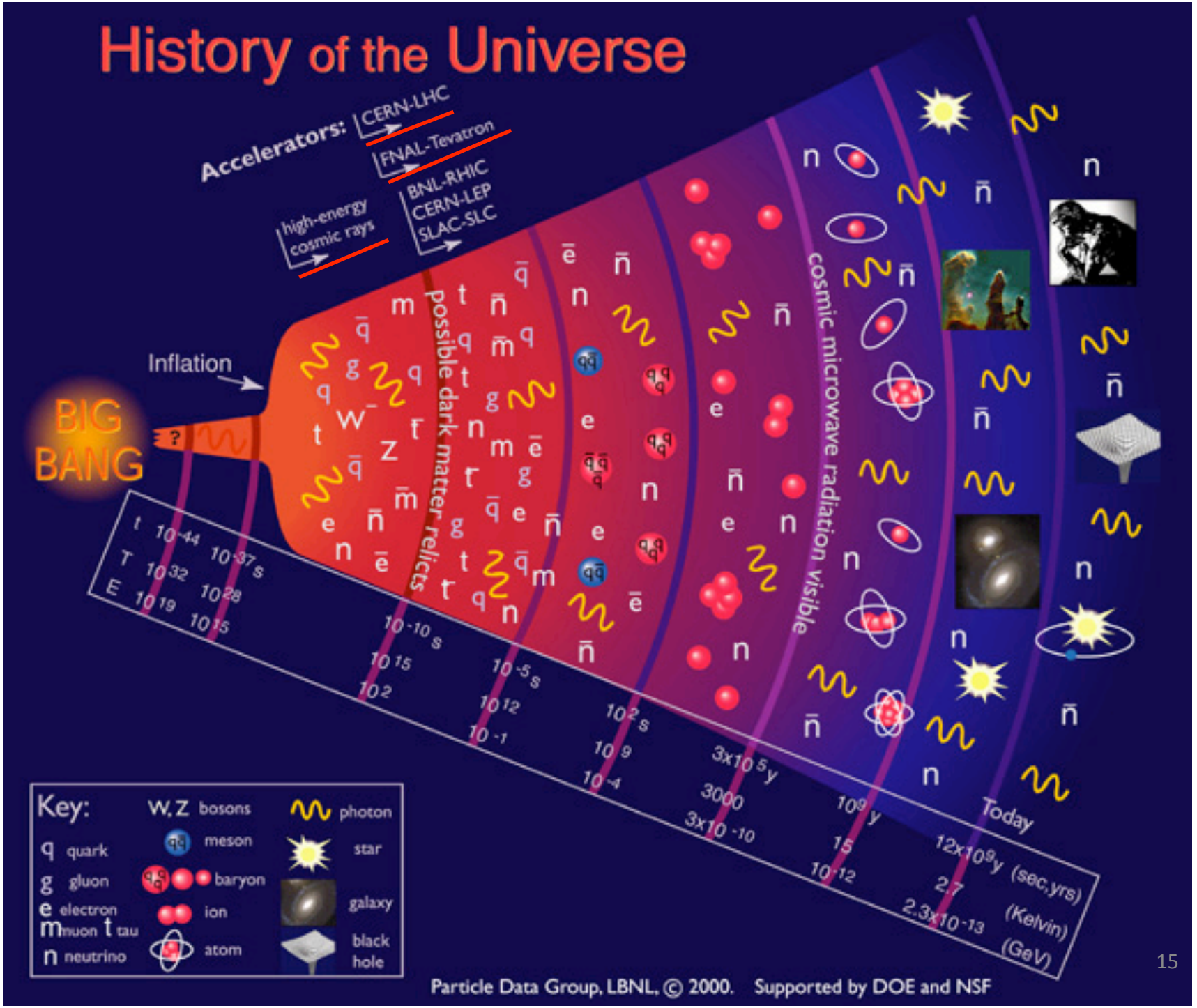
Fermilab $\sqrt{s} \approx 2$ TeV = 2×10^{12} eV

LHC $\sqrt{s} = 13$ TeV (soon 14 TeV)

Supernova ≈ 300,000,000 TeV



Not to scale

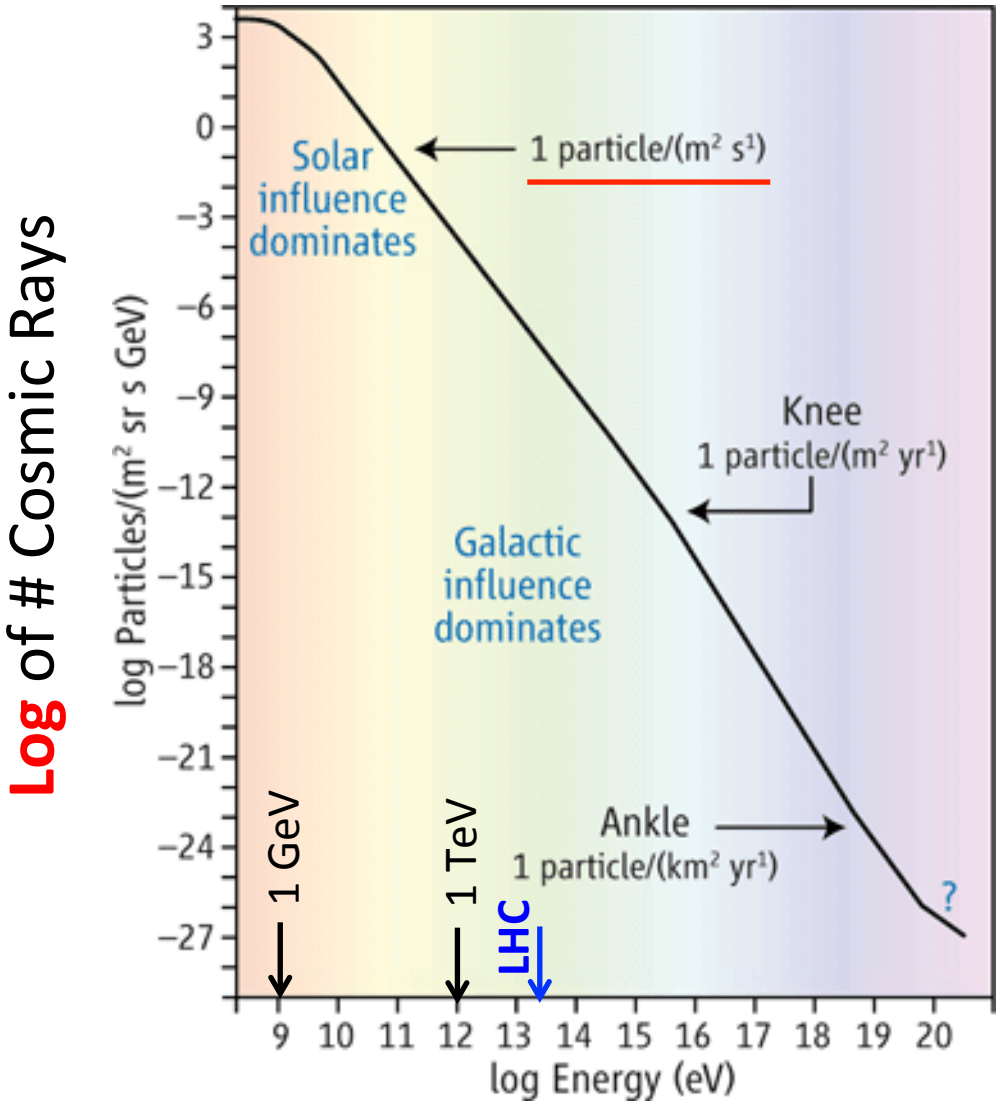

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Exercise: # of cosmic rays going through your body every minute/second

- Using the # of tracks/minute you counted passing through the cloud chamber earlier, estimate how many cosmic rays are going through your body.

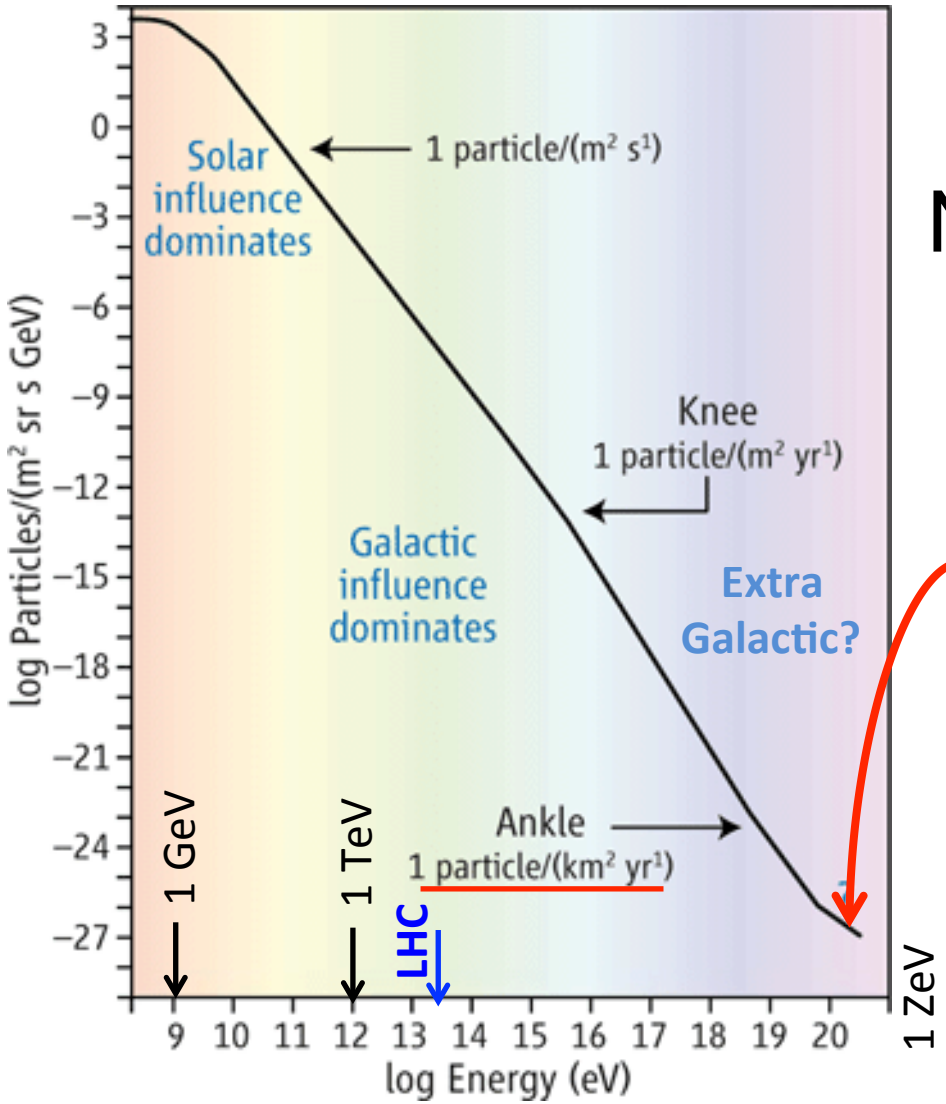
Hint: Estimate how many cloud chambers it would take to equal the area of your body.

of Cosmic Rays vs. Their Energy



- Notice log scales on graph
- Most cosmic rays are low energy (<1 GeV) coming from the sun
- **~30 cosmic rays fly through your body every second**

Highest Energy Cosmic Rays



Log of # Cosmic Rays

Log of Cosmic Ray Energy (eV)

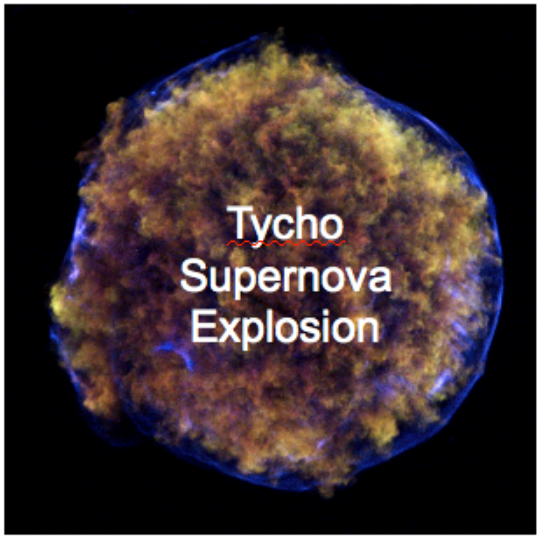
Nature accelerates cosmic rays to 3×10^{20} eV

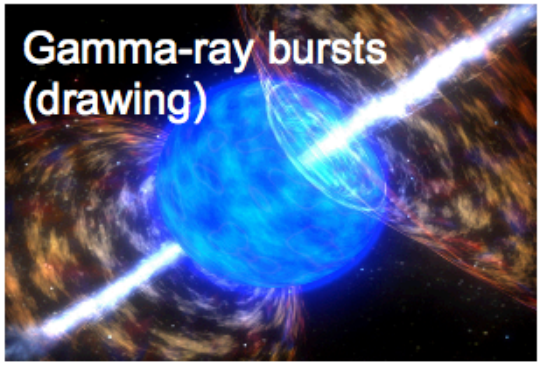
= 50 Joules

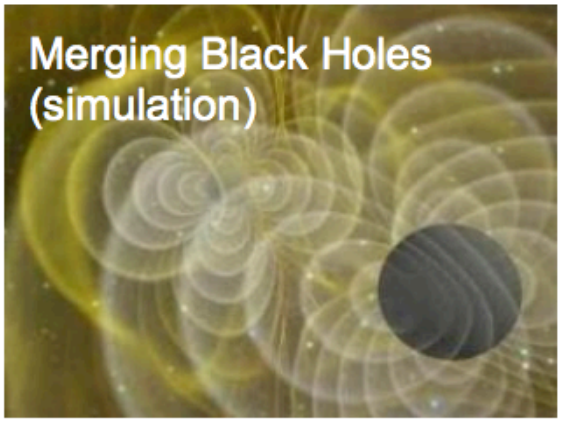
= a baseball thrown at 58 mph

but what process can do that?!

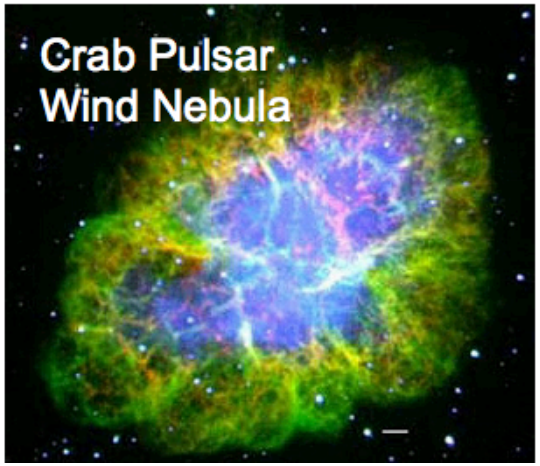
Astrophysical Particle Accelerators

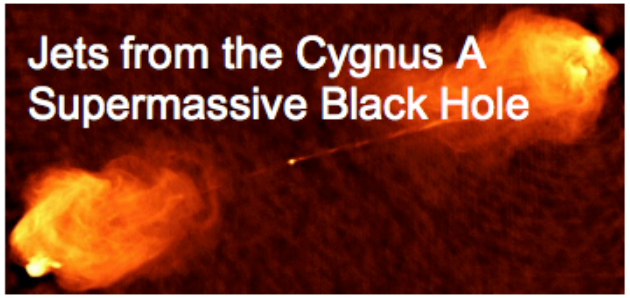




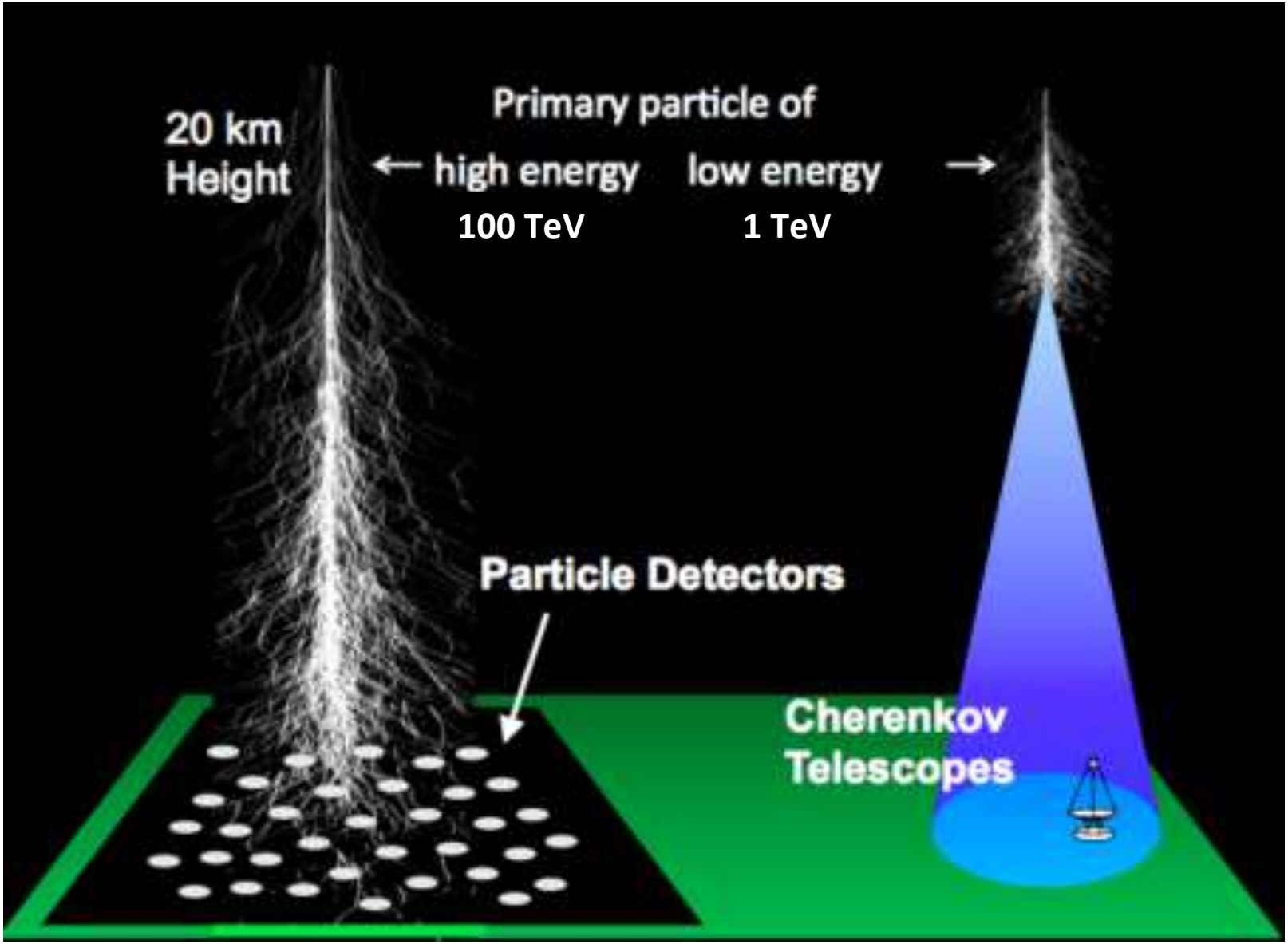


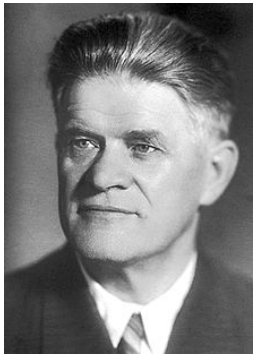
The Most Violent Processes in the Universe





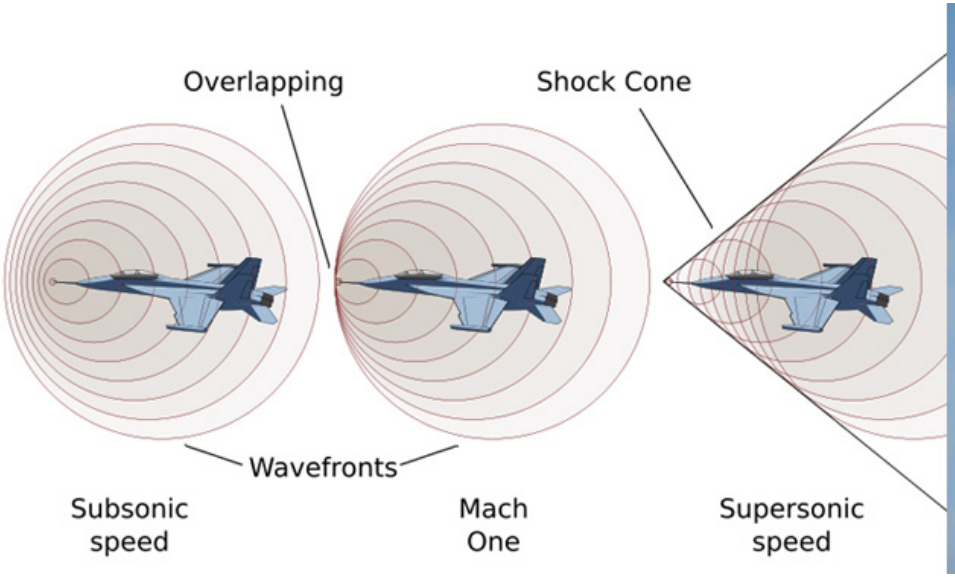
Detecting High Energy Cosmic Rays

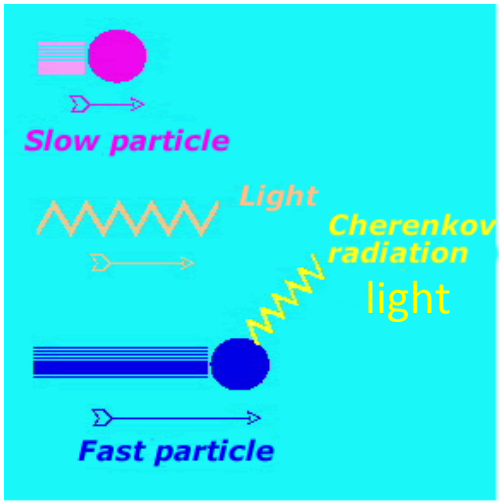




Pavel Cherenkov

Cherenkov Radiation: A Sonic Boom of Light

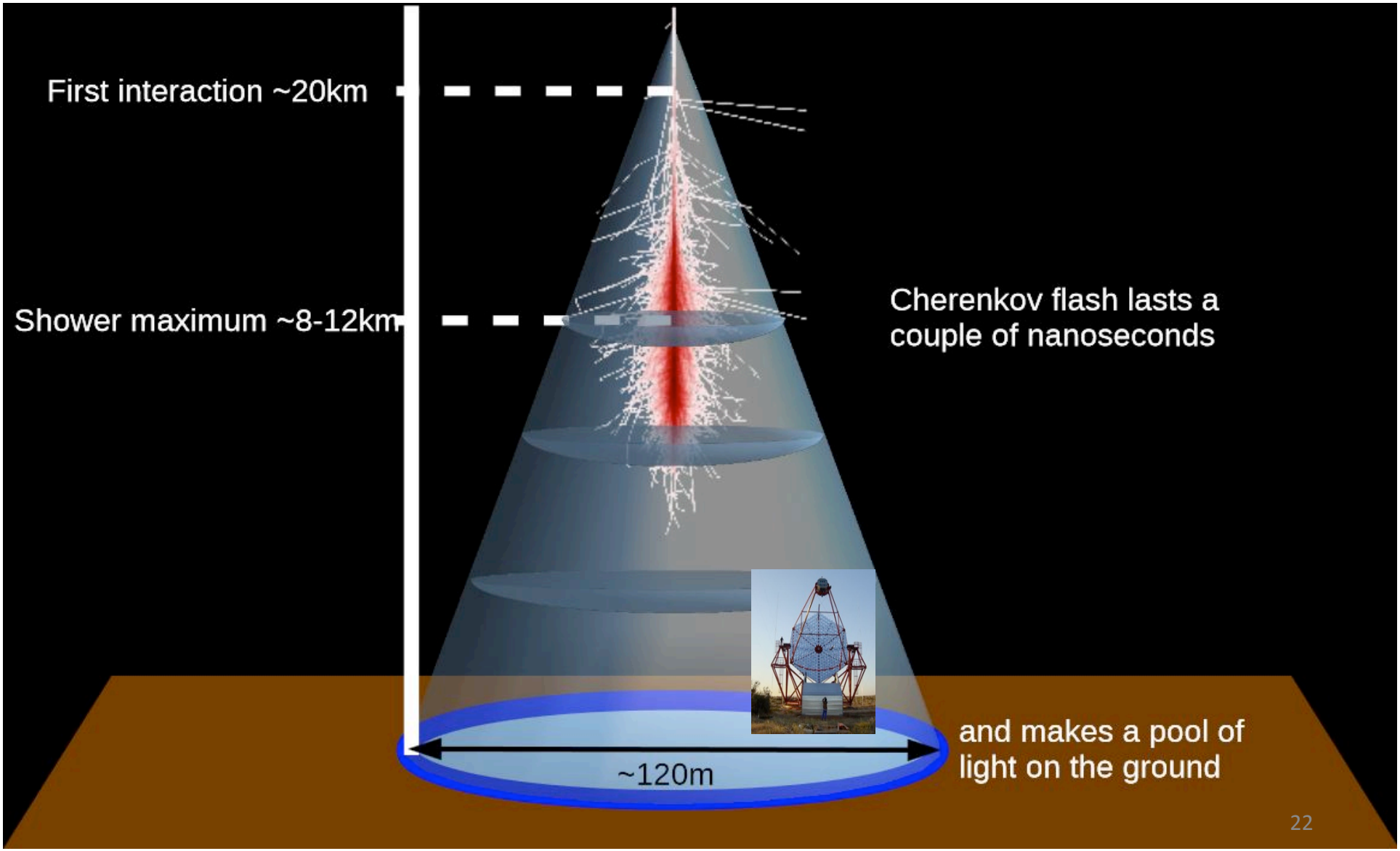




Medium	Index of Refraction, n	Speed of light, c (in m/s)
Vacuum	1.00 exactly	3.00×10^8
Air	1.0003	2.999×10^8
Water	1.33	2.256×10^8

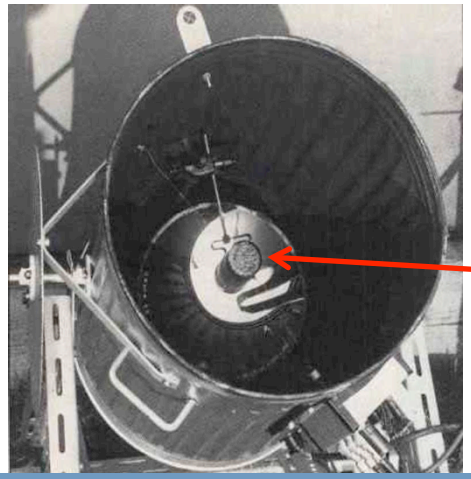
$$n = c / v$$

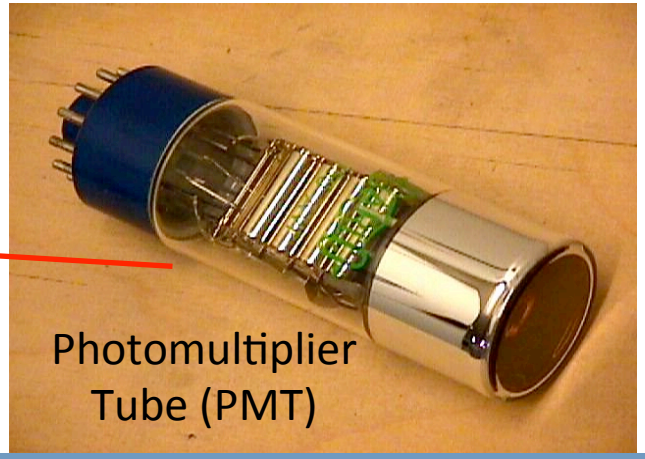
Cherenkov Light in Air

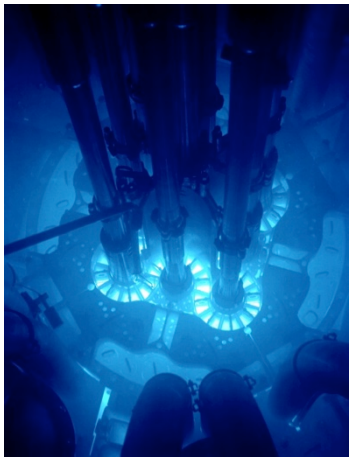


Imaging Atmospheric Cherenkov Telescopes (IACTs)

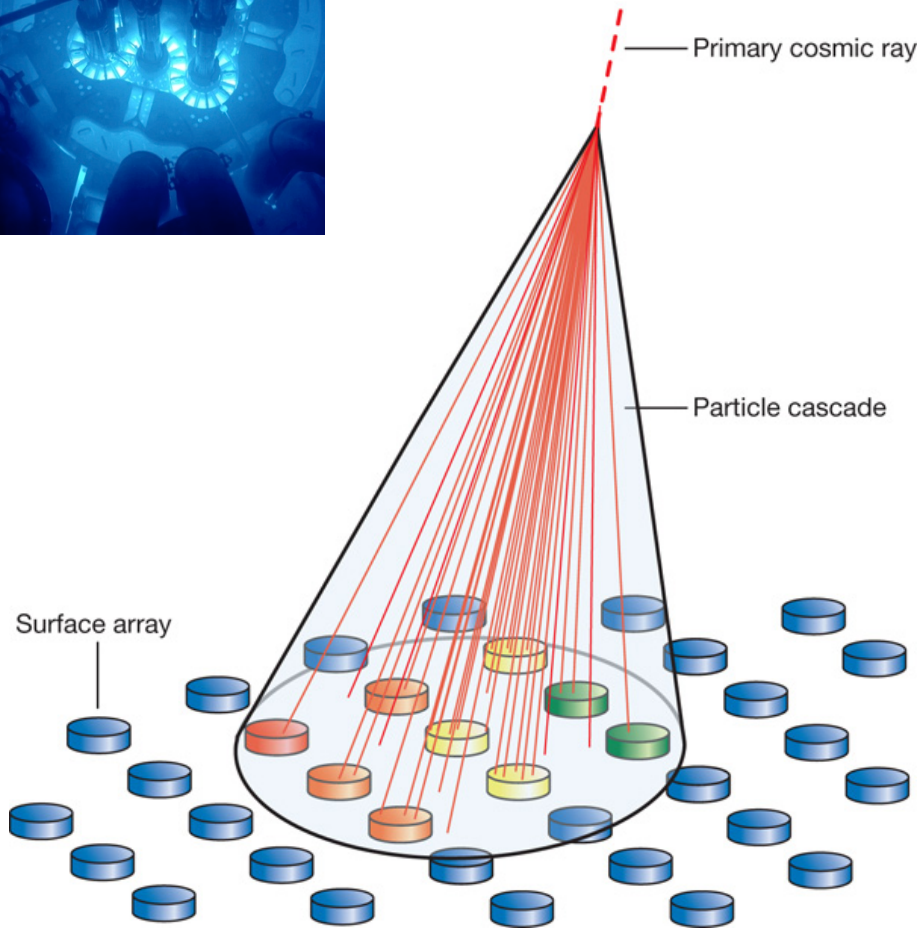
First IACT built in 1953 using a garbage can and PMT

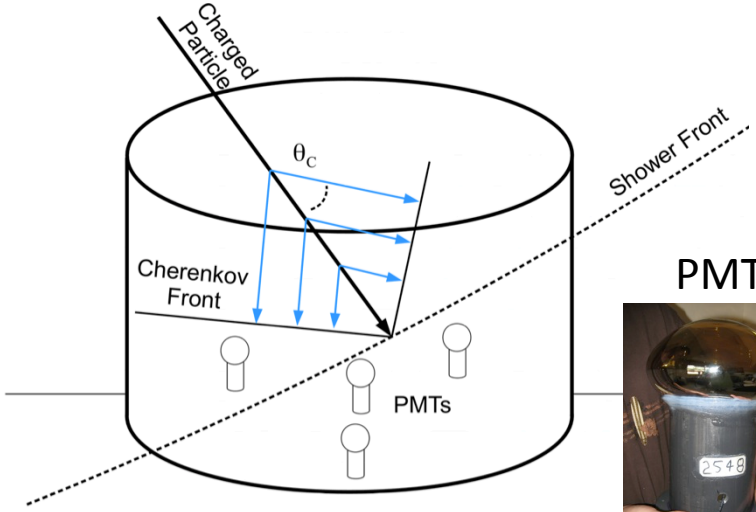






Cherenkov Light in Water





PMT

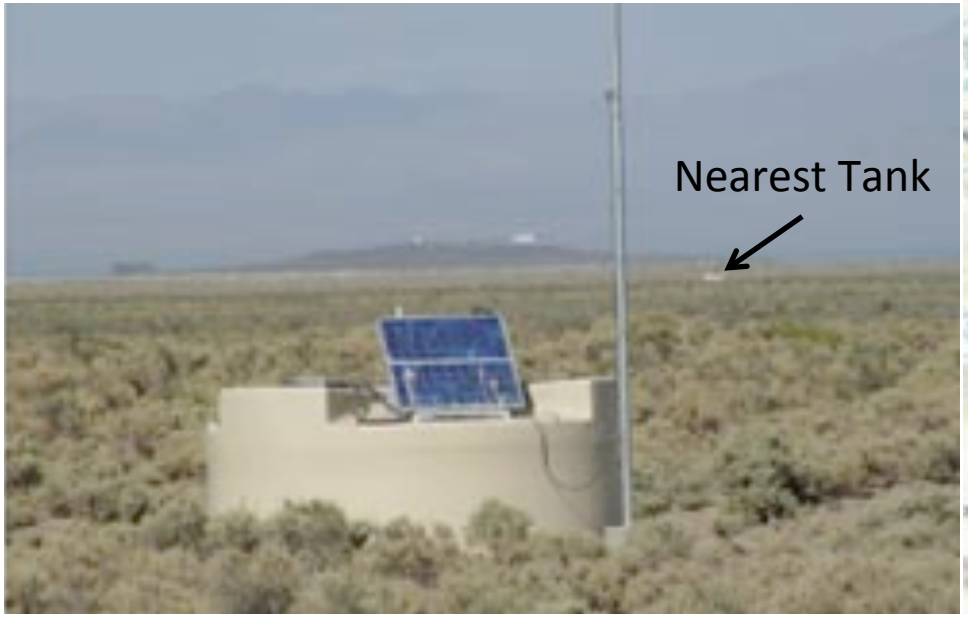
Pierre Auger Observatory

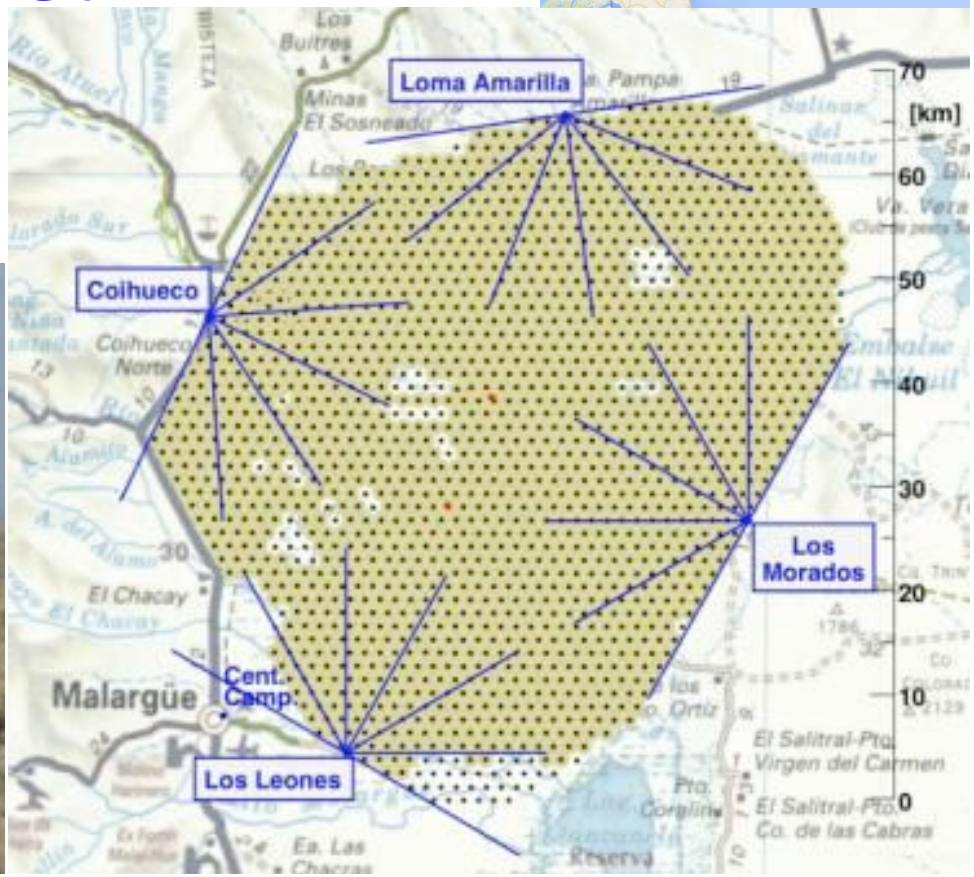
Mendoza province, Argentina

Looking for highest energy cosmic rays which happen at the rate of < 1 particle/(km^2 year)

so make it BIG!

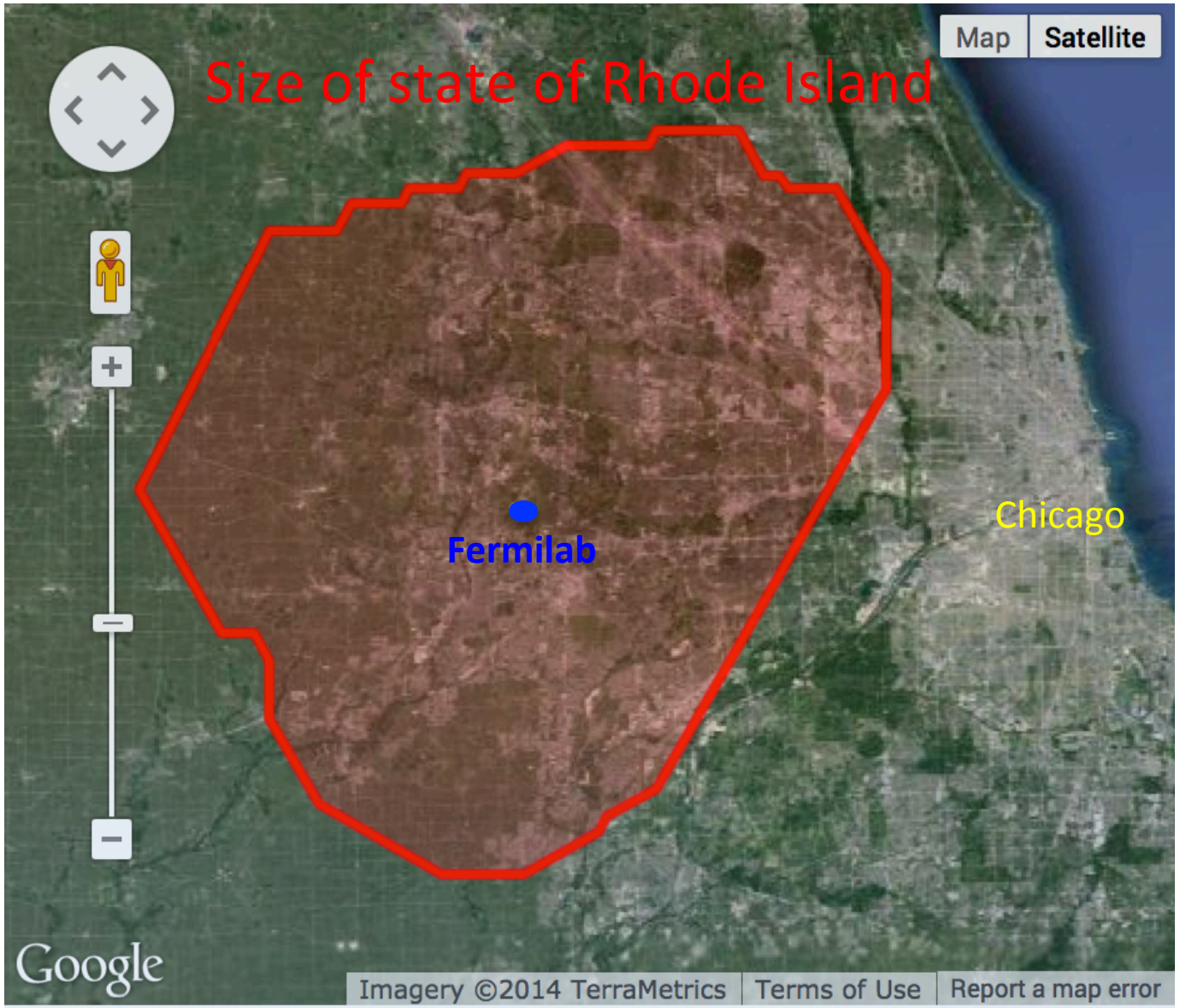
1600 tanks spaced 1.5 km apart





PIERRE AUGER OBSERVATORY

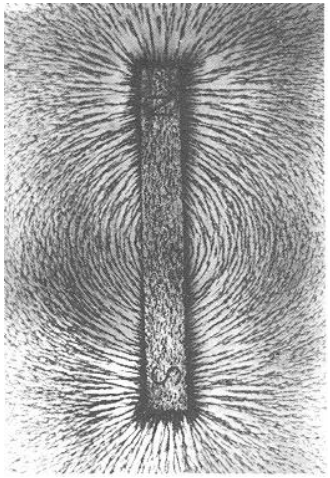
Size of Pierre Auger vs. Chicago



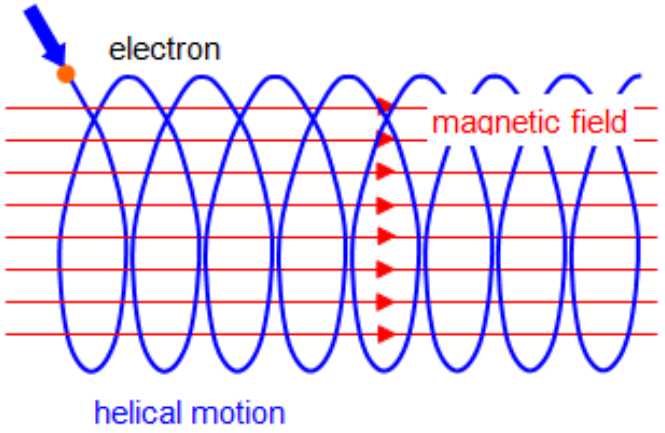
World's Largest Cosmic Ray Detector

- Become an astrophysicist with your cell phone
- App turns your smartphone into a cosmic ray detector
- Combine data from phones around the globe
- CRAYFIS: http://crayfis.io/
  - Sorry doesn't work on iPhones yet.

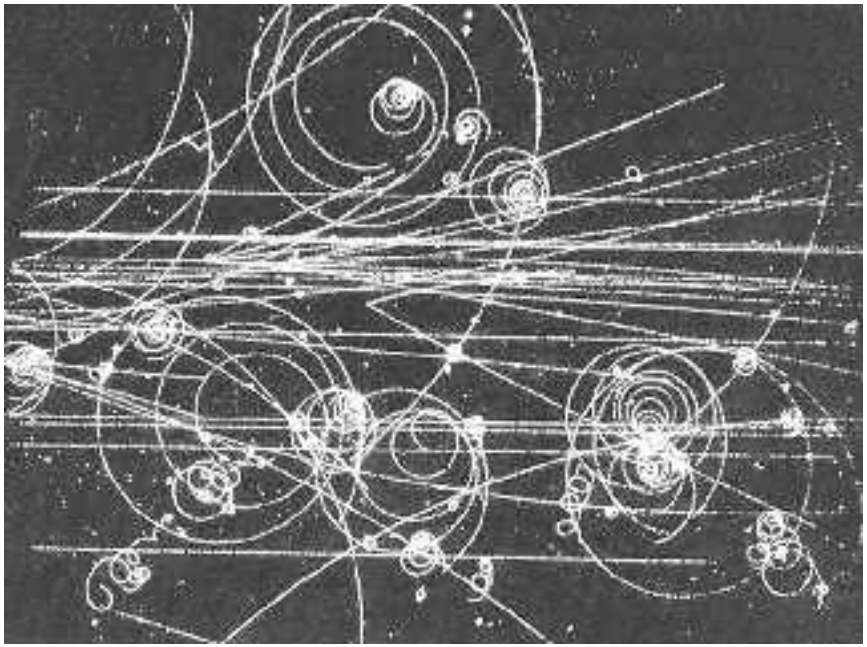
The Problem with Cosmic Rays



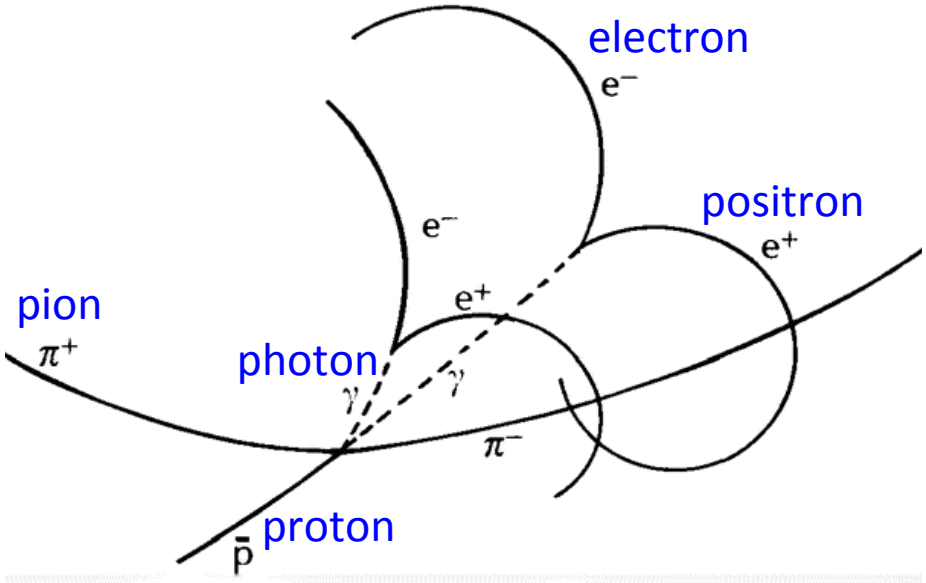
The path of a charged particle bends when moving through a magnetic field.



A hydrogen bubble chamber picture.



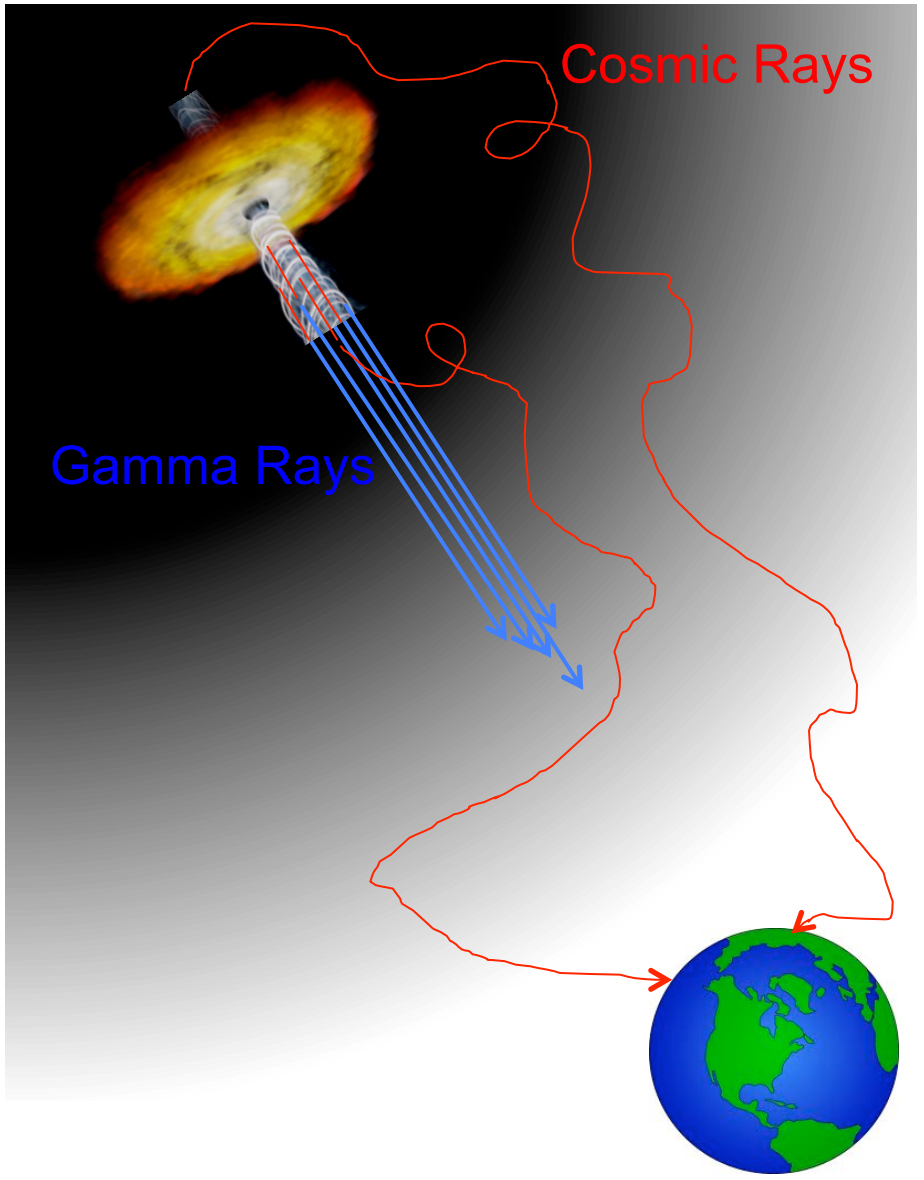
Schematic of a proton colliding with a pion.



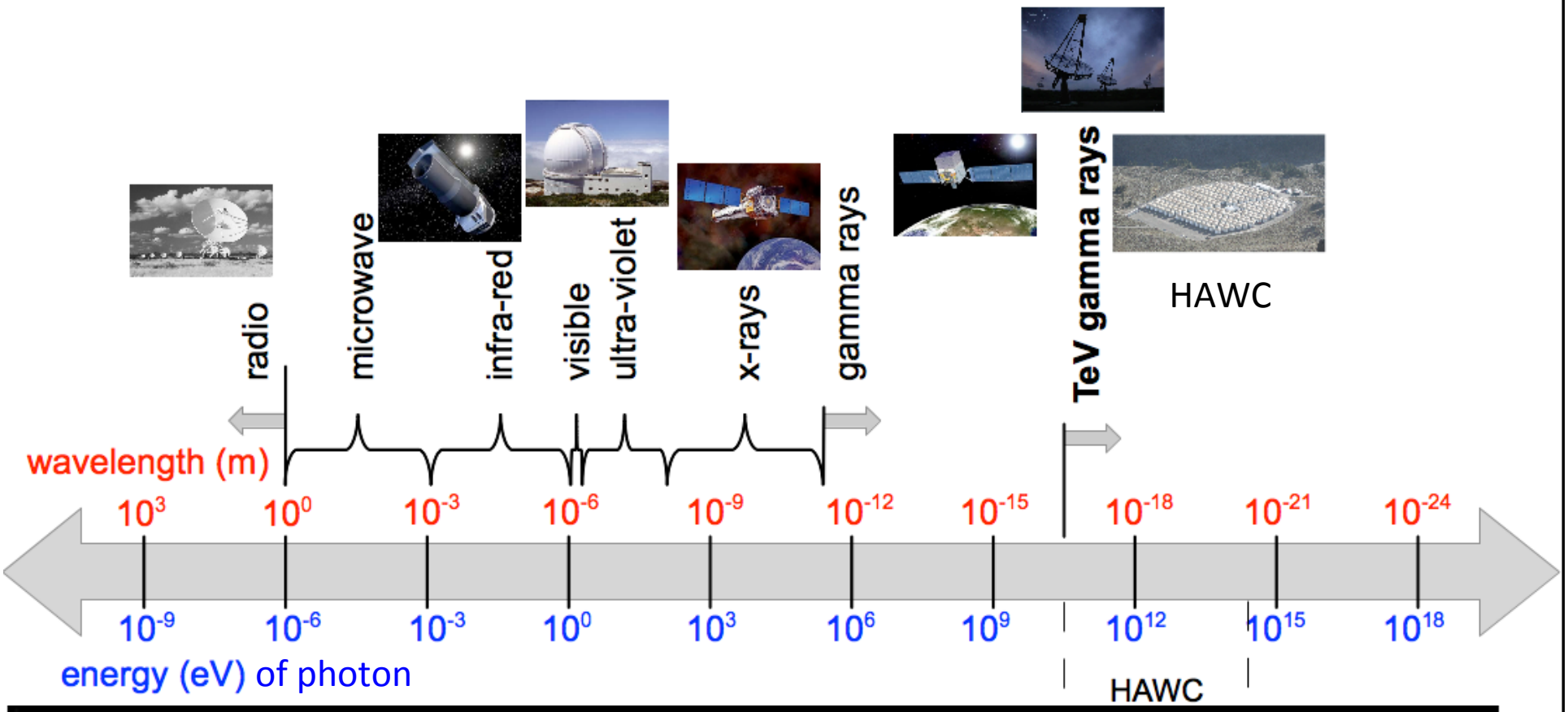
Gamma Rays to the Rescue

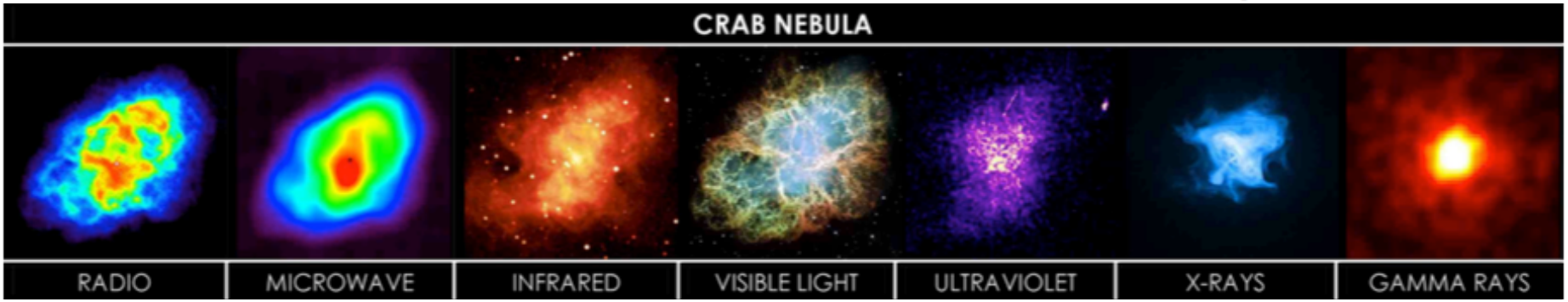
- **Gamma rays** are the highest energy photons (particles of light).
- They are electrically neutral (not charged).
- Their energy (E) is inversely proportional to their wavelength (λ).

$$E = \frac{hc}{\lambda}$$

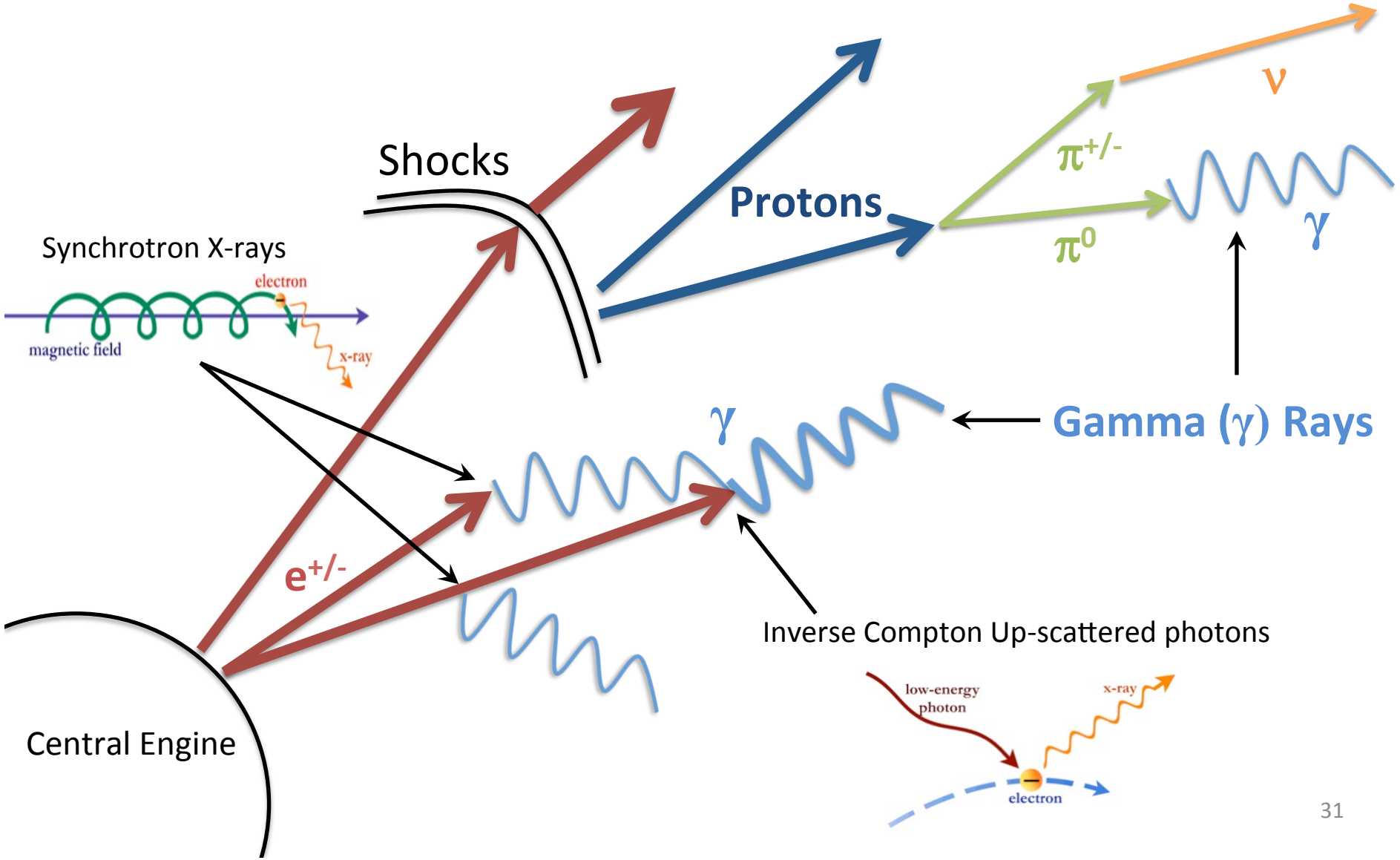


The Electromagnetic Spectrum

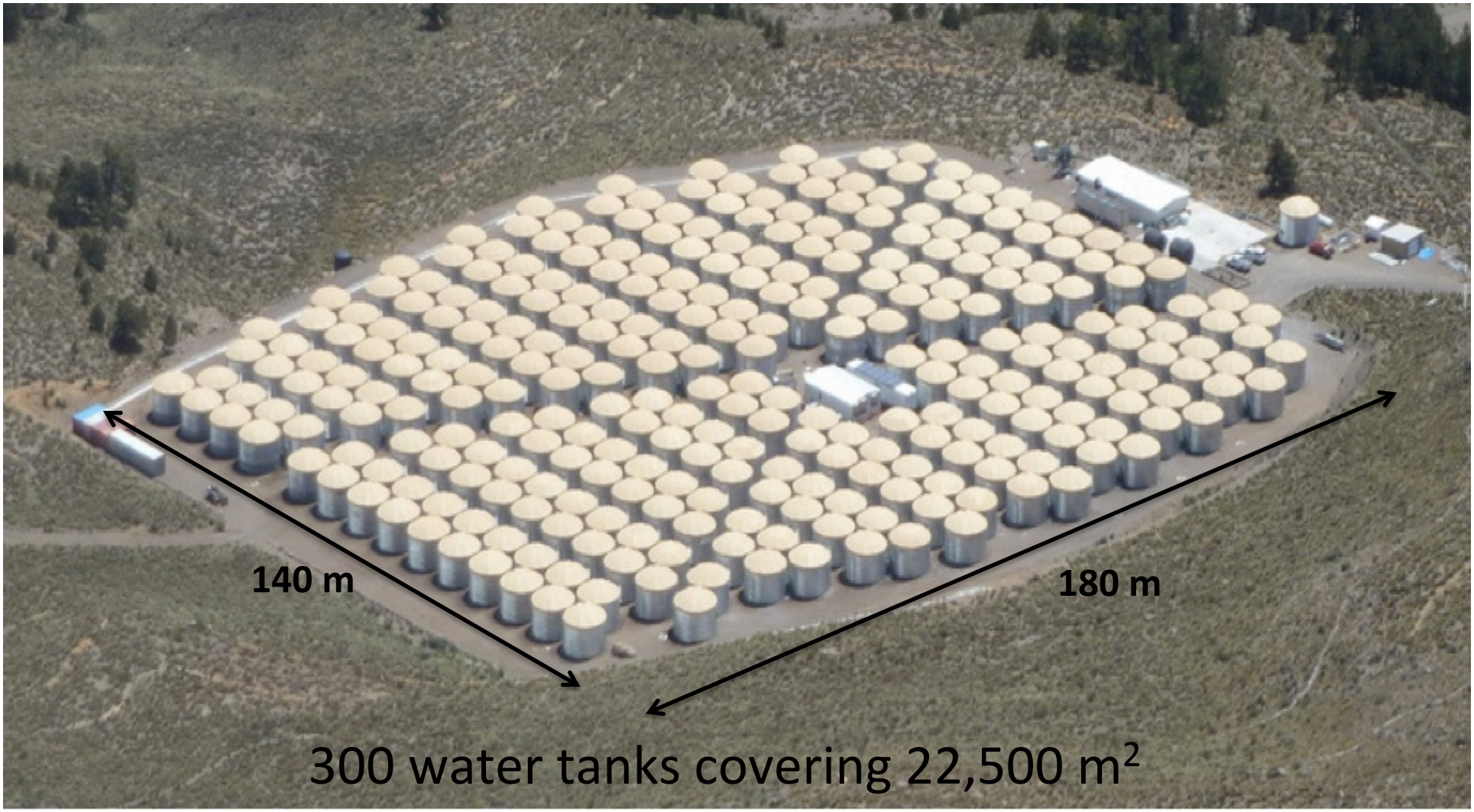




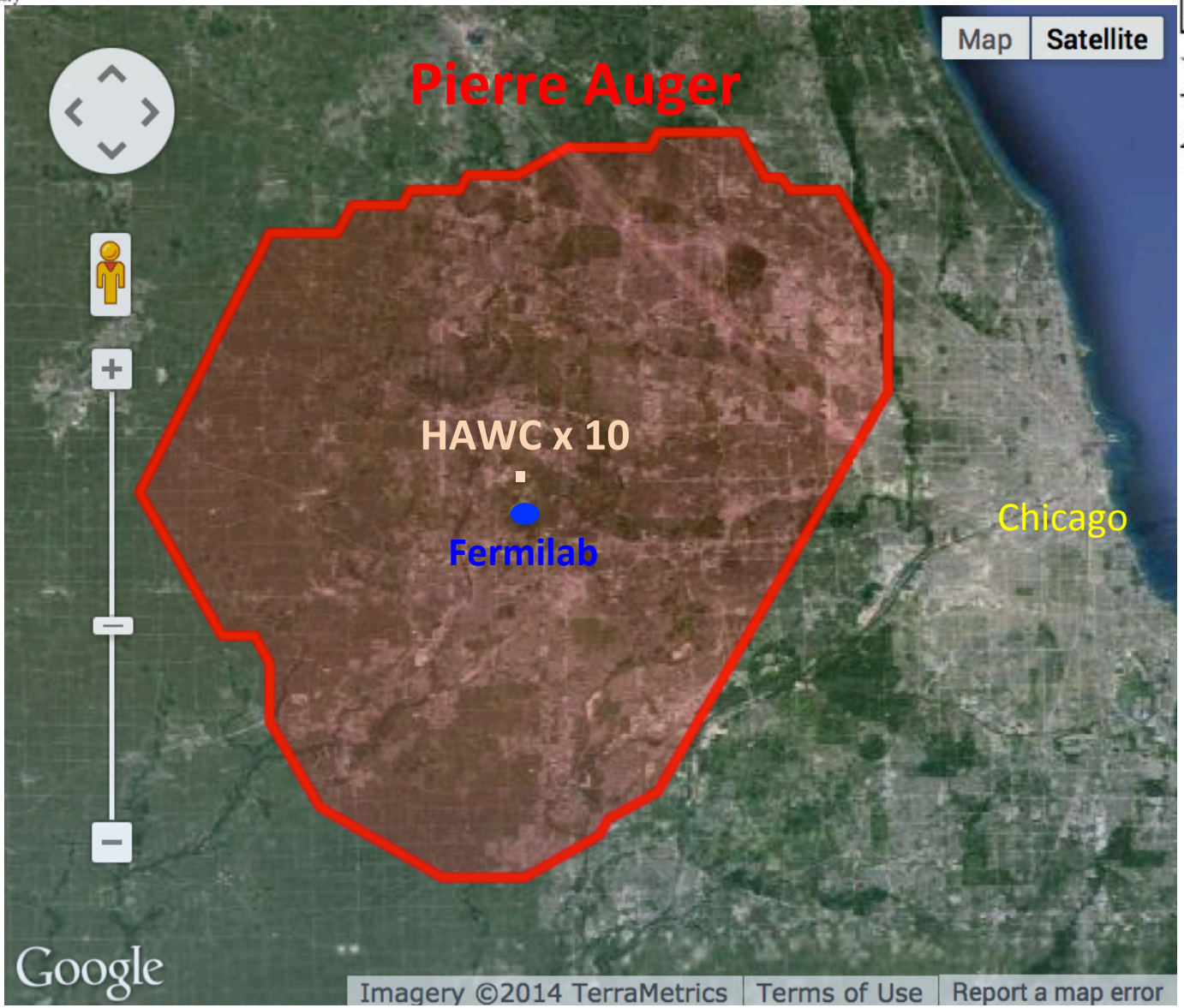
Cosmic Rays and Gamma Rays come from the Same Sources



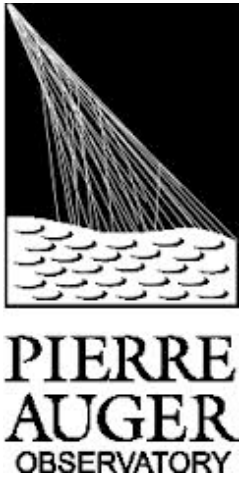
The **H**igh **A**ltitude **W**ater **C**herenkov (**HAWC**) Gamma-Ray Observatory



Relative Size of HAWC



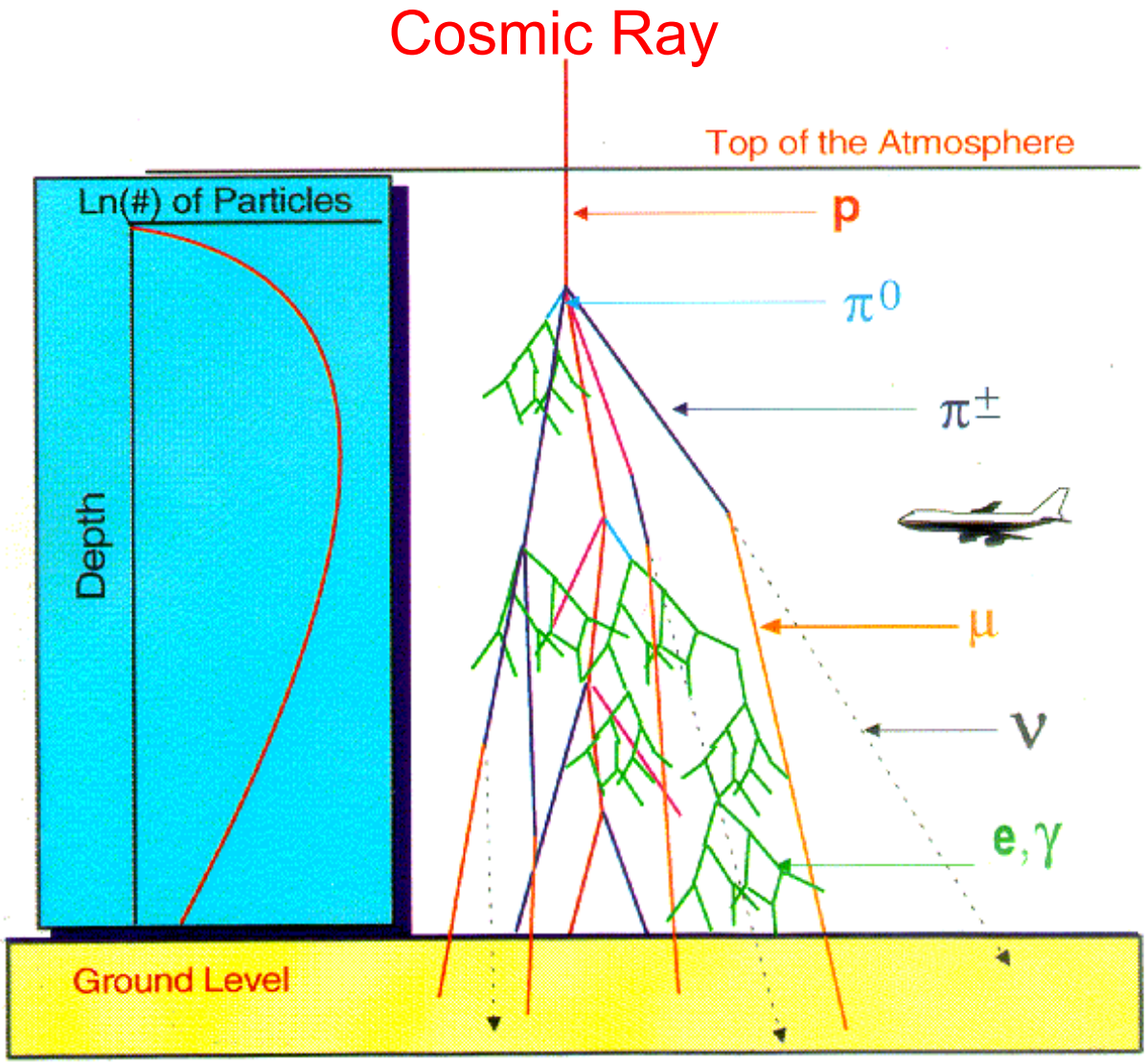
HAWC vs. Pierre Auger



- **Studies gamma rays from 0.1 to 100 TeV**
- Looking for gamma rays coming from the cosmic rays
- Can point back to source directly without worrying about magnetic fields
- Looking for lower energy particles so can have smaller detector

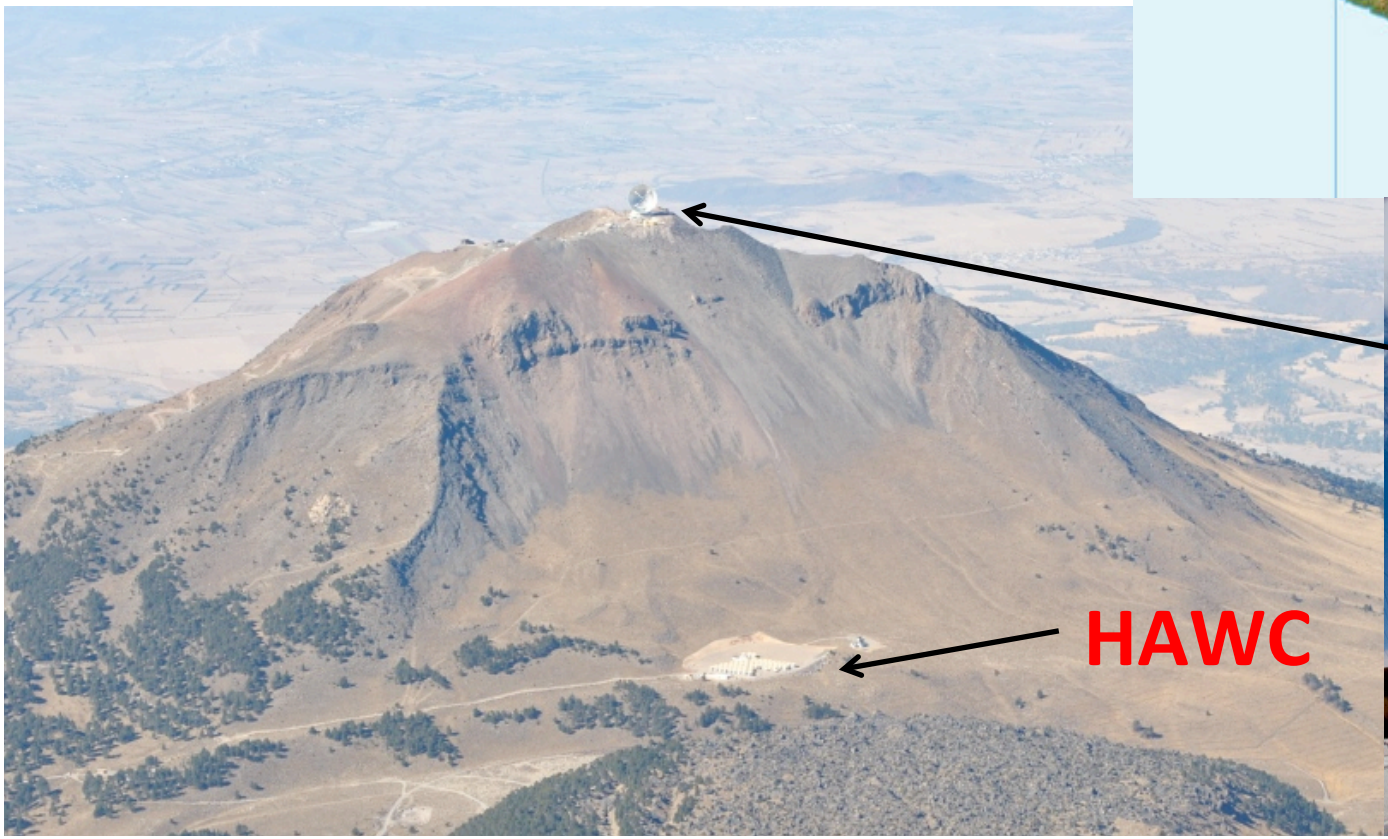
- **Studies cosmic rays $>10^{18}$ eV = 10^{6} TeV**
- Looking for Ultra High Energy Cosmic Rays (UHECR) which are extremely rare
- UHECR showers cover a large area (several km^2)
- Need huge detector to see events which happen once per km^2 per year (or decade)

Higher Altitude = More Particles



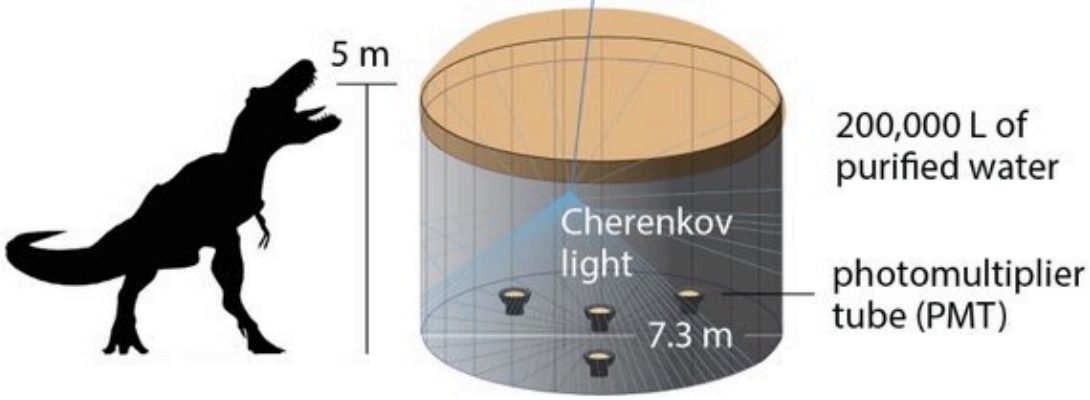
Site Location

- Sierra Negra volcano near Puebla, Mexico
- HAWC altitude is 4100 m (13,500 feet or 2.55 miles)
- LMT altitude is 4500 m




Pico de Orizaba
5610 meters
Climbing Hut
Taken March 18, 2015

Inside the Tanks



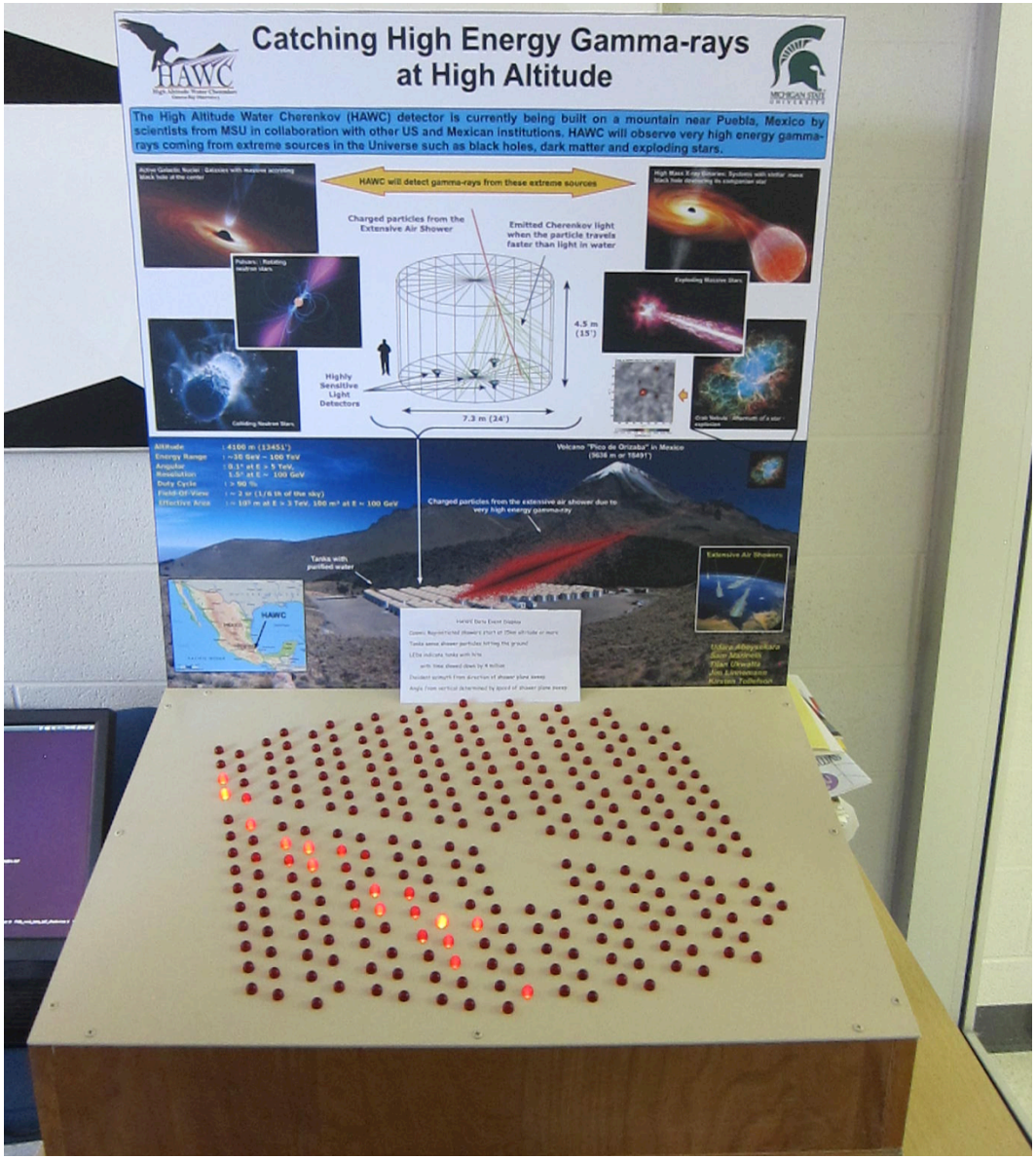
Three 8” PMTs

Center 10” PMT

Filling the Tanks with Water

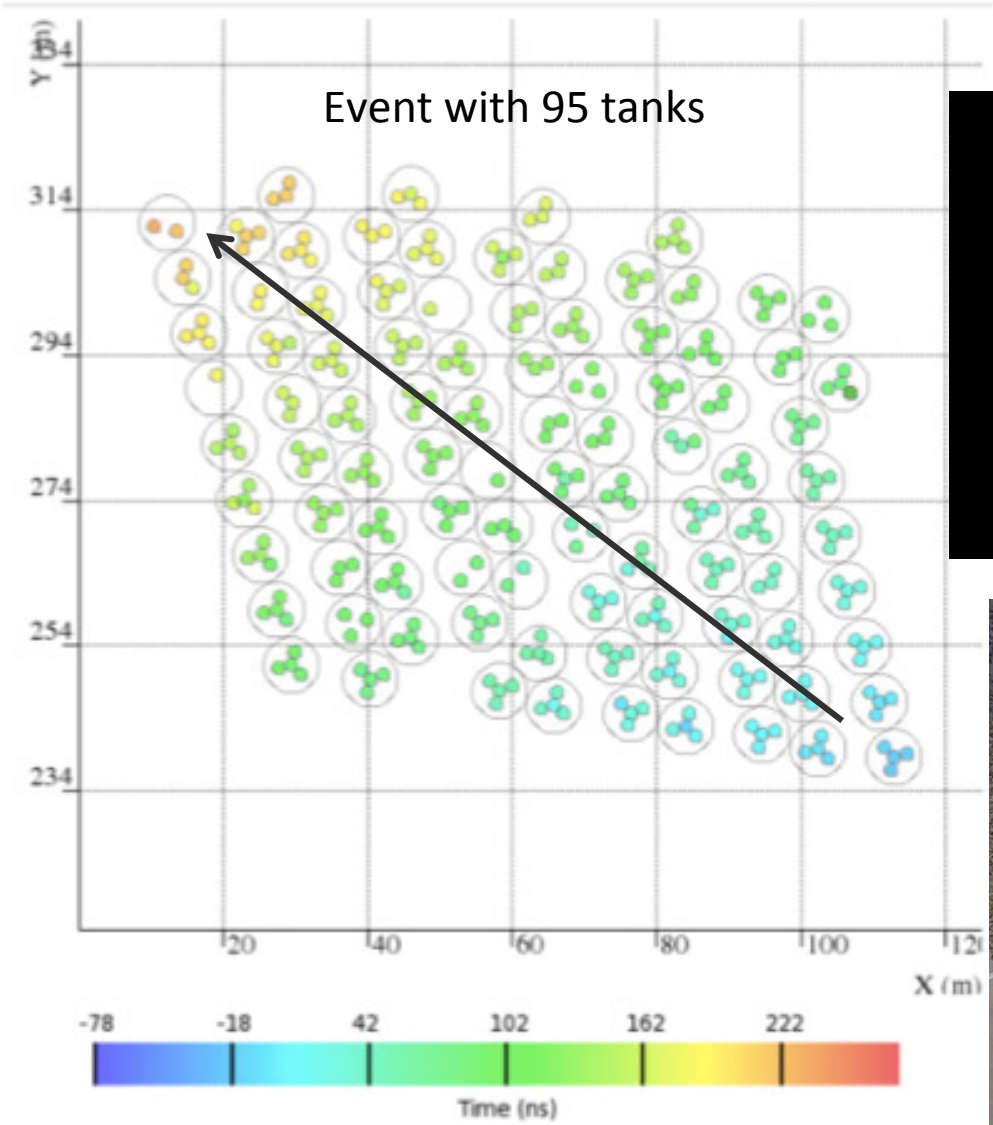
- One tank requires 14 truck loads of water (200,000 L)
- ~3,900 tanker truck trips
- Filtration system takes 5 hours to fill one tank.
- PMTs are installed wet in batches later, independent of water filling

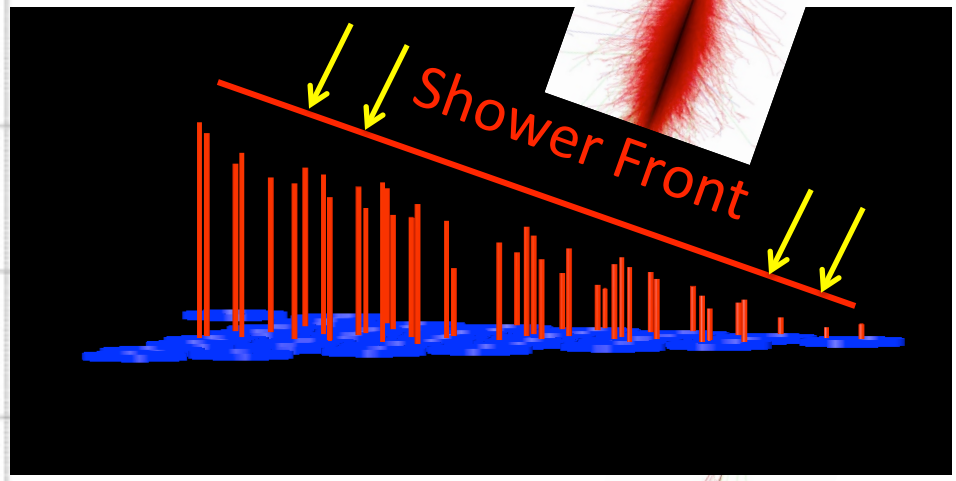
Event Display

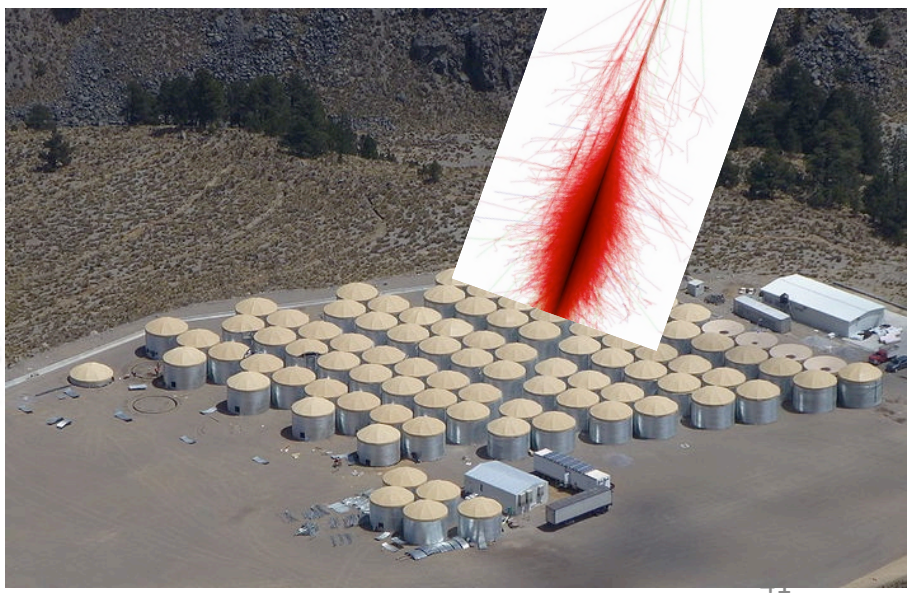


- Lit LEDs show which tanks detected particles by seeing light in its PMTs.
- In order to see the flash of the LEDs, time is slowed down by a factor of 4 million.
- The direction and speed the shower sweeps across the tanks indicates where the shower came from.

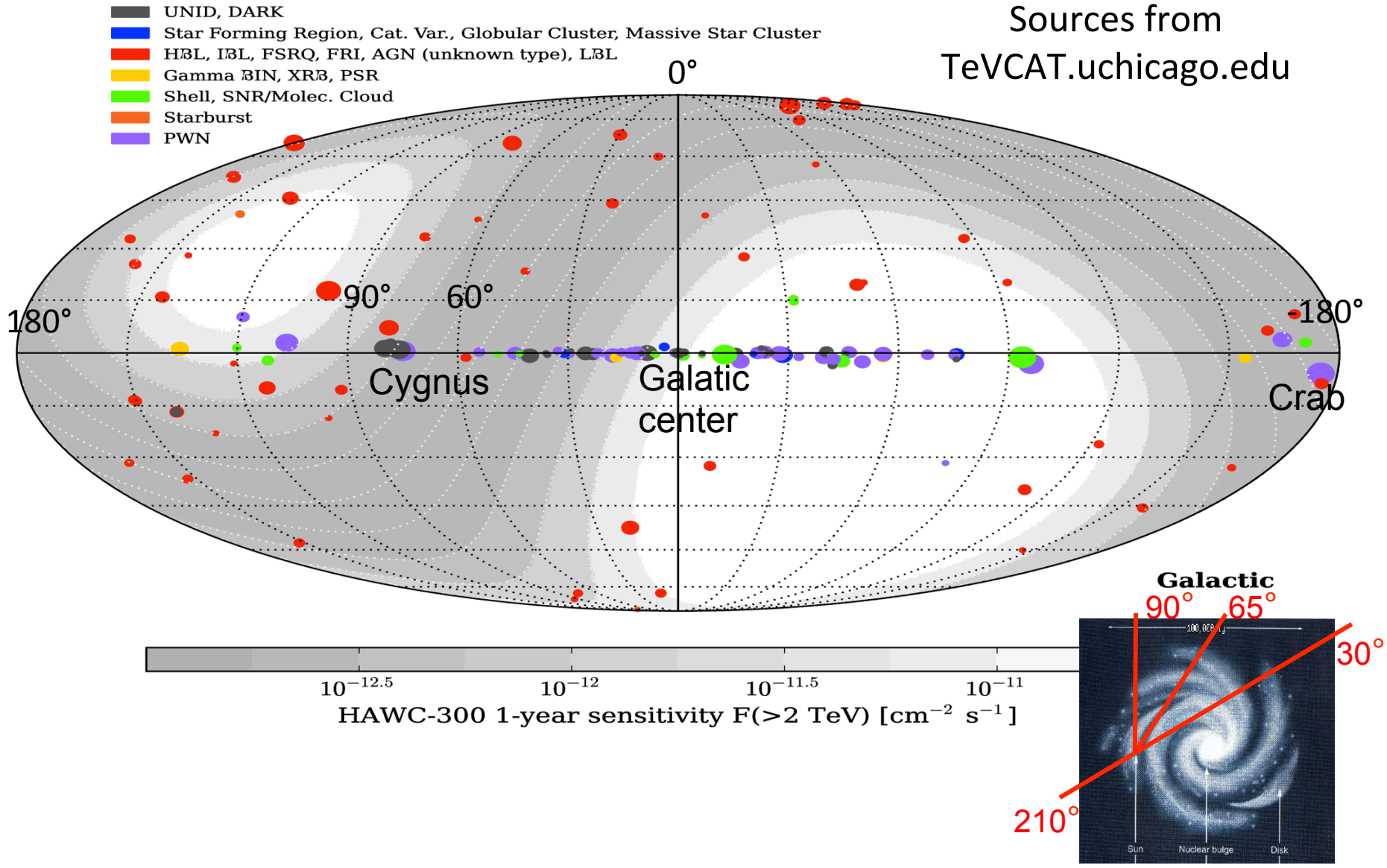
Pointing Back to a Source



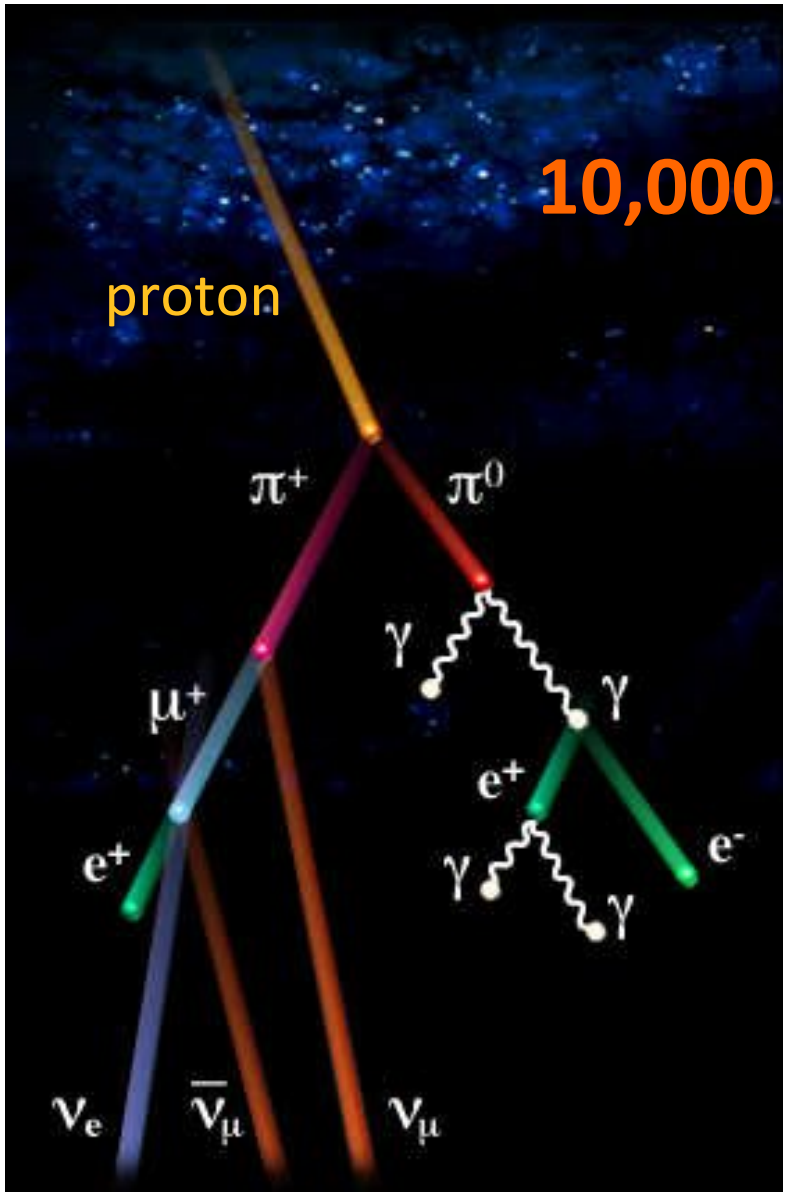




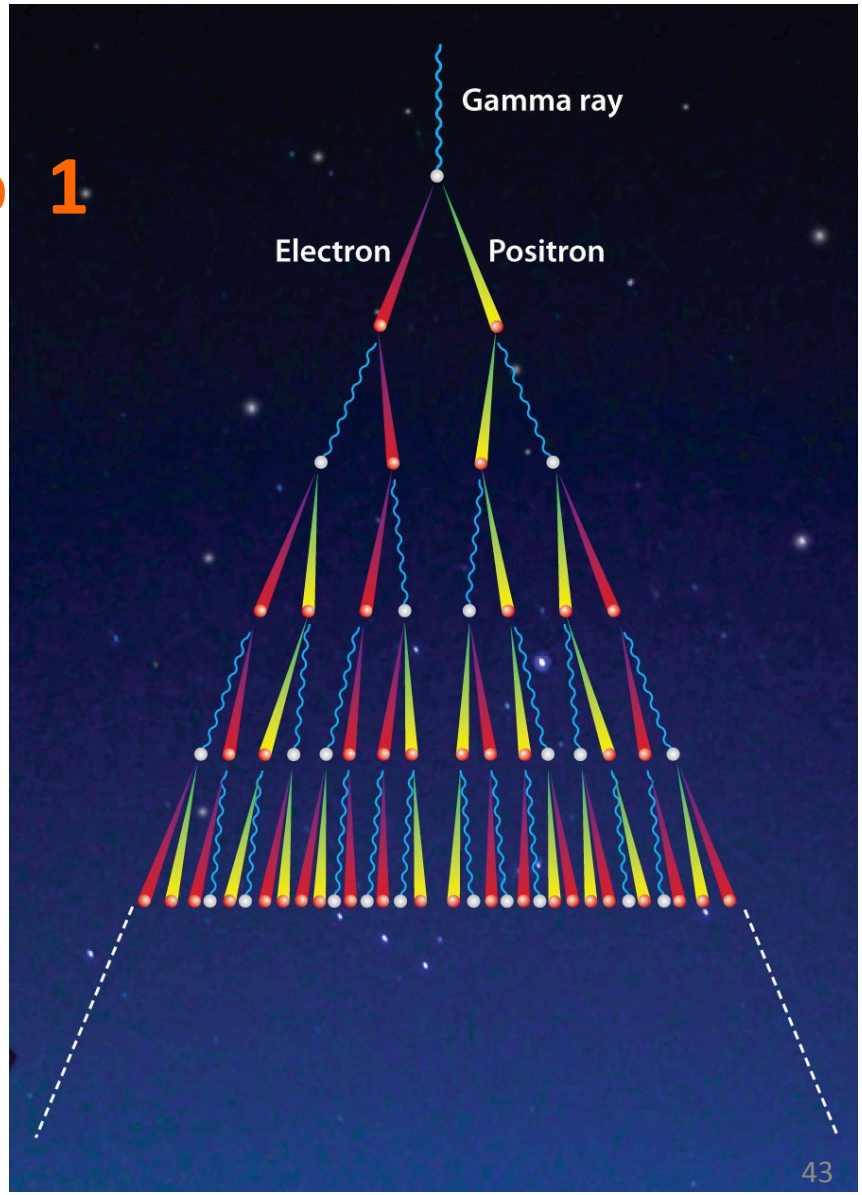
HAWC Field Of View



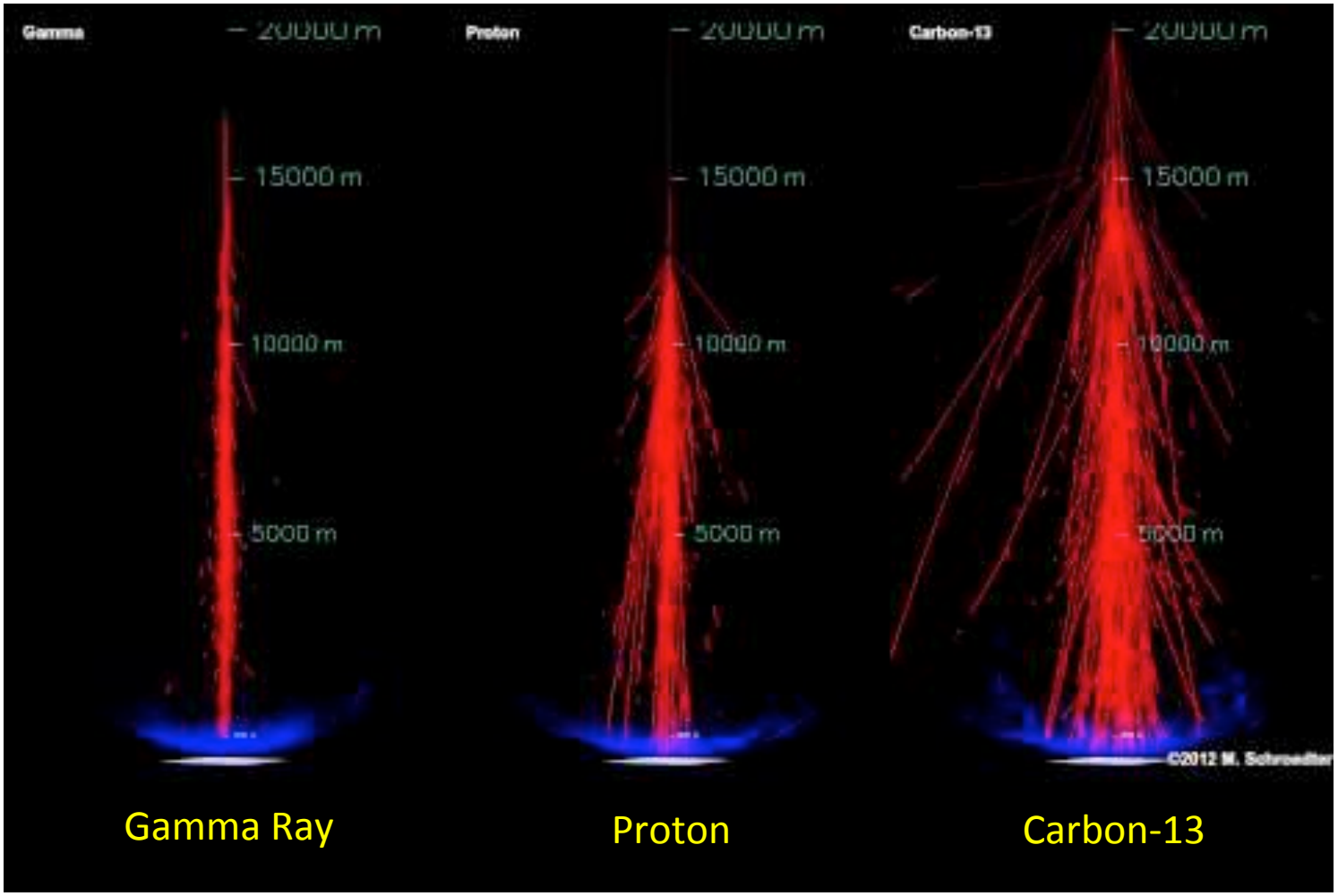
Cosmic Rays vs. Gamma Rays



10,000 to 1

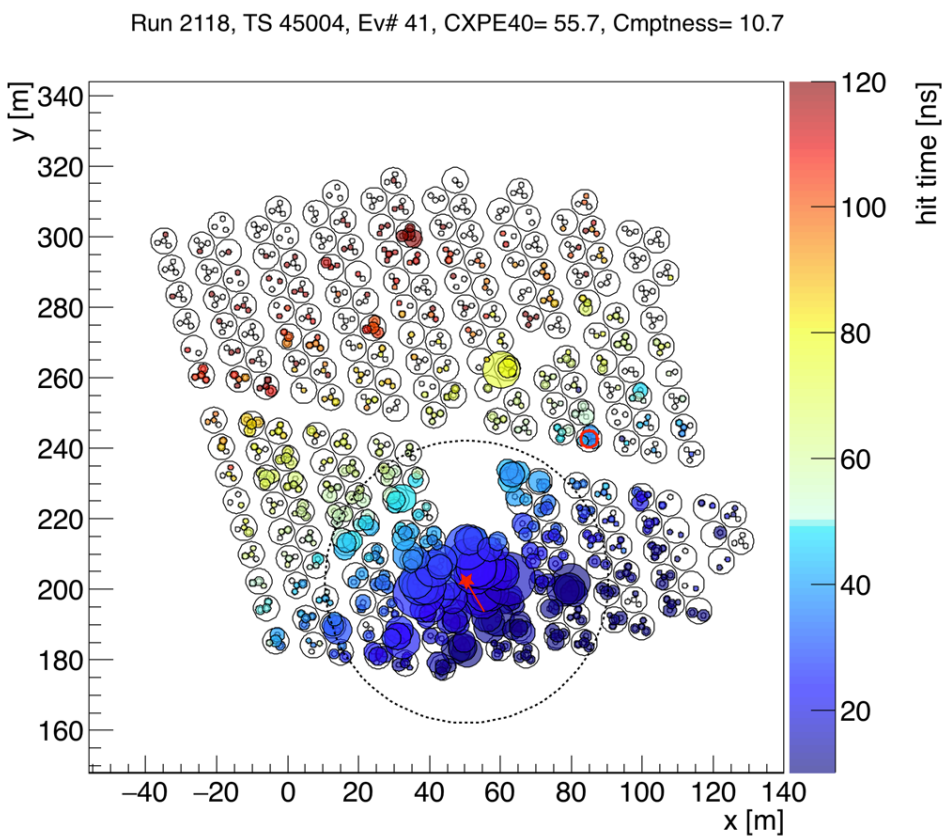


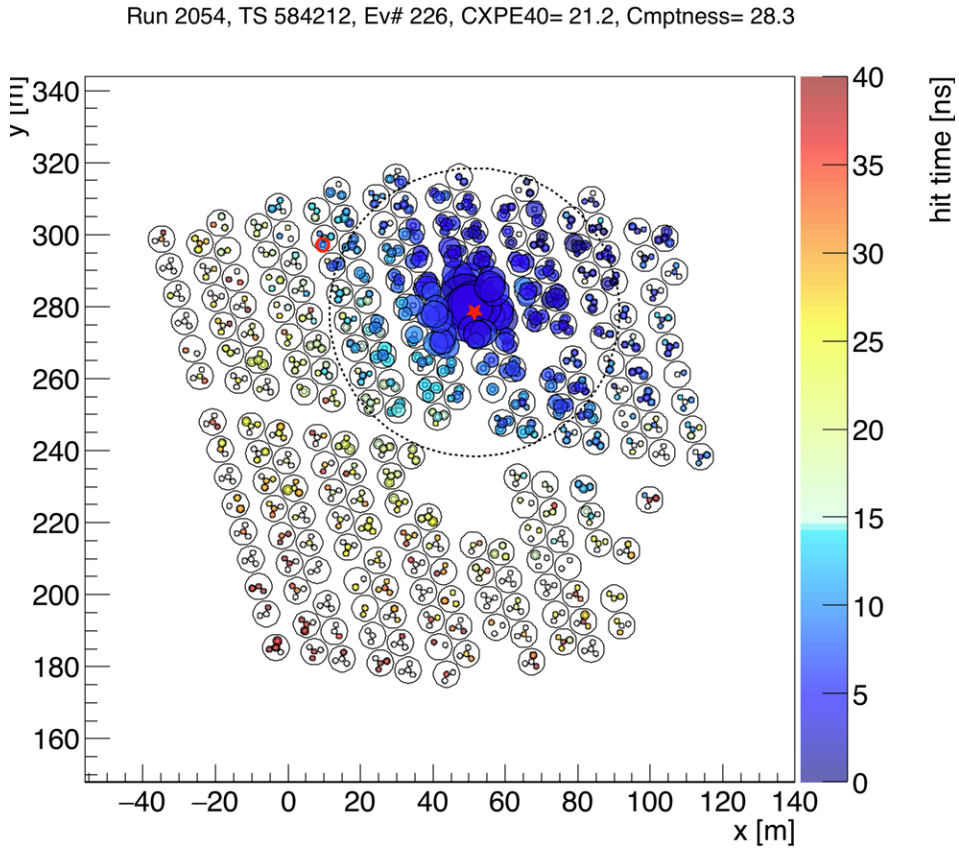
Air Showers Look Different for Different Particle Types



Video from VERITAS simulating different air showers

Data from HAWC with 250 tanks



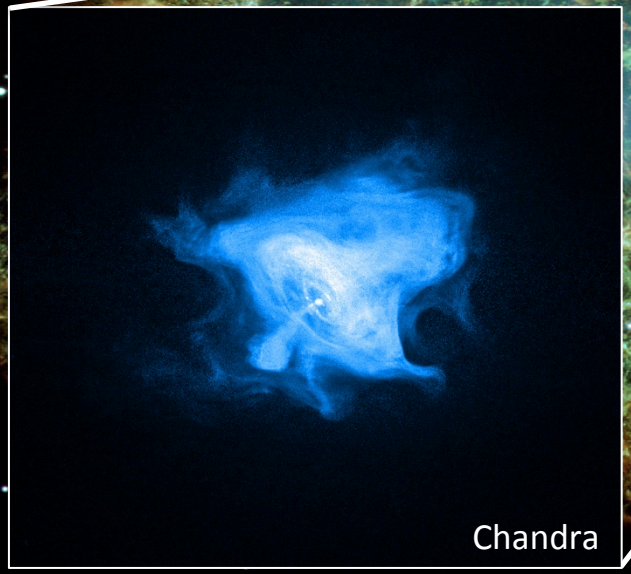


Likely **Cosmic Ray** Shower

Data

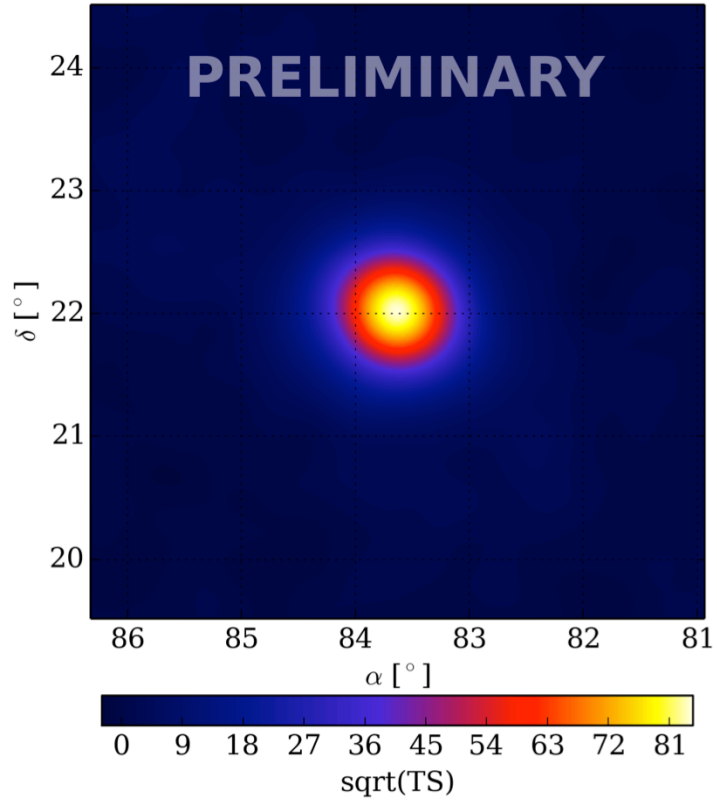
Likely **Gamma Ray** Shower (from the Crab)

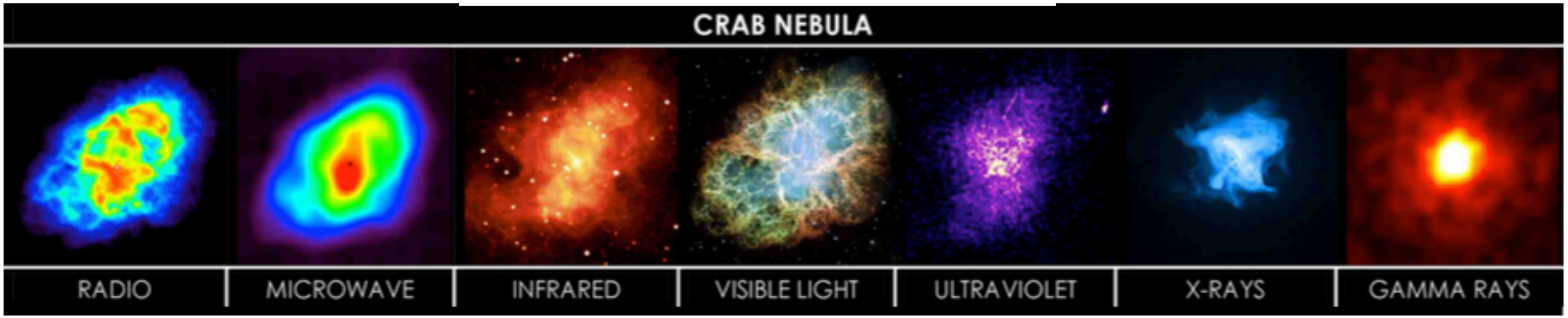
The Crab Nebula
(Pulsar Wind Nebulae)



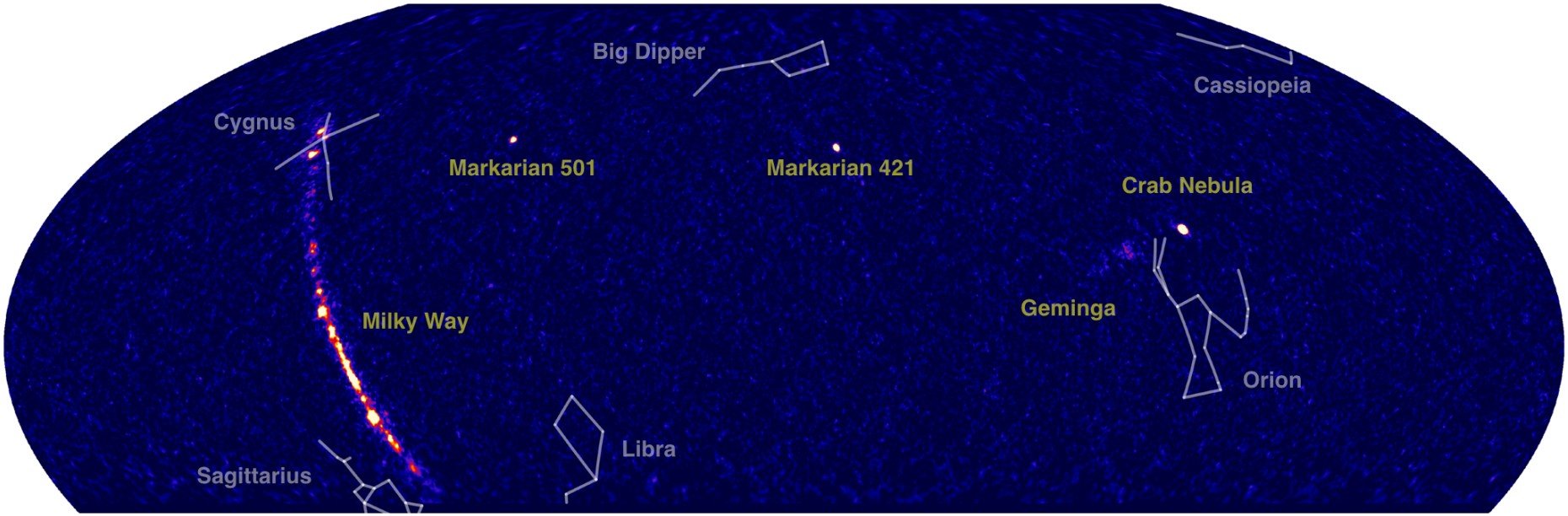
HST Image

HAWC Sees the Crab Nebula





Sky Map from HAWC



Particle Astrophysics

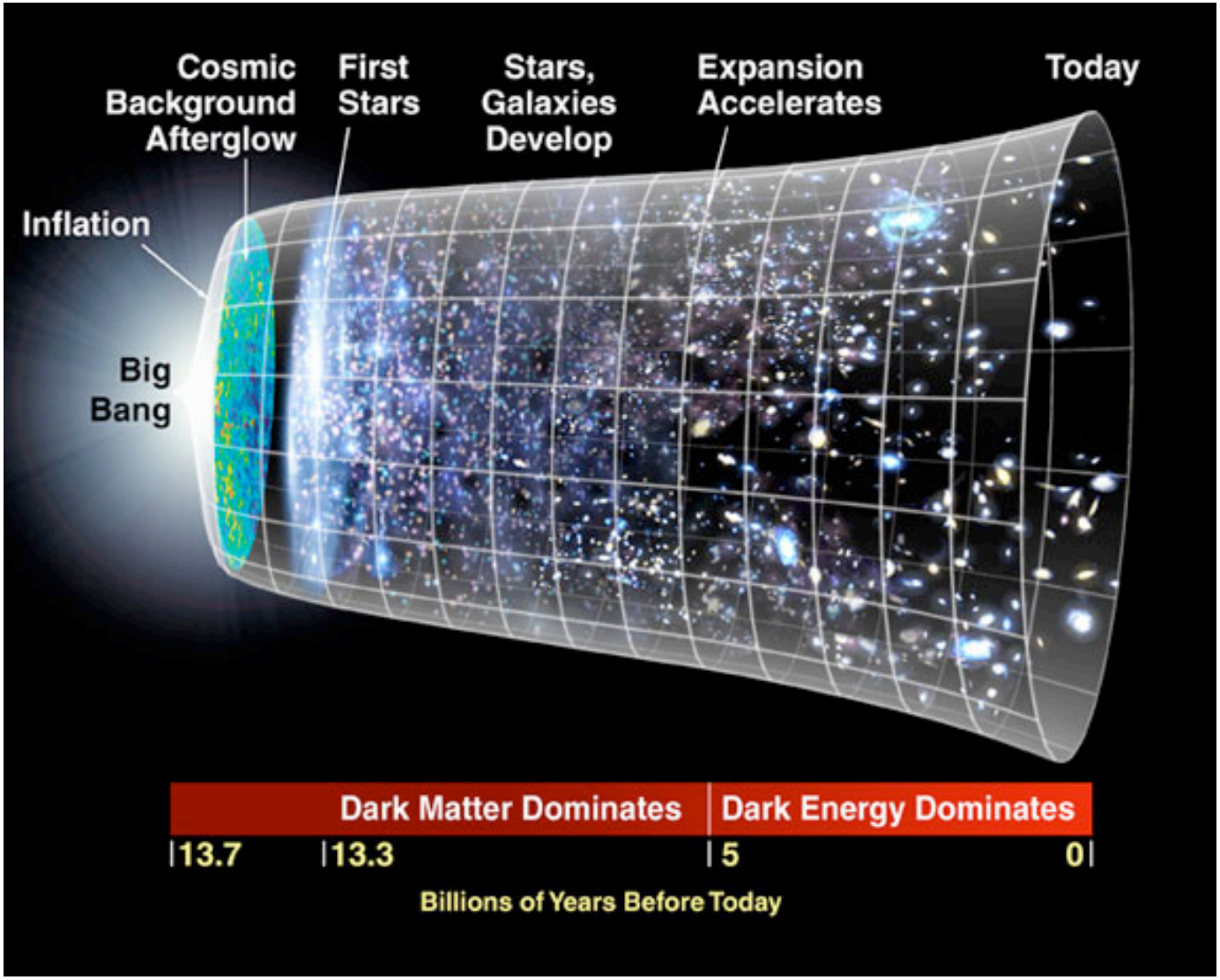
What we know:

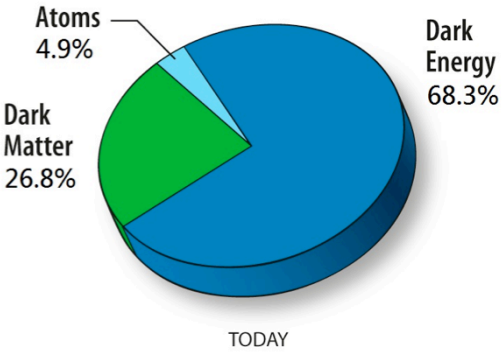
- Nature accelerates cosmic rays to $>10^{20}$ eV
- Gamma-ray sources accelerate particles to $>10^{14}$ eV

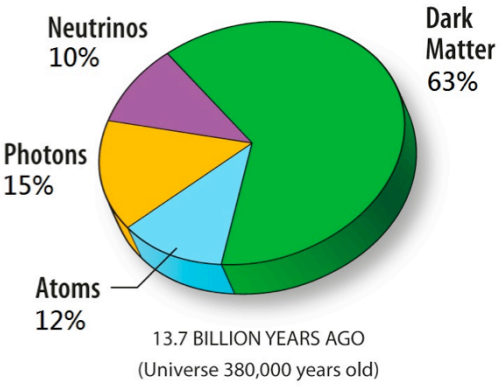
What we want to know:

- What astrophysical sources accelerate particles?
- How do they accelerate the particles?
- What new high-energy physics can we learn from astrophysics?

Evolution of the Universe

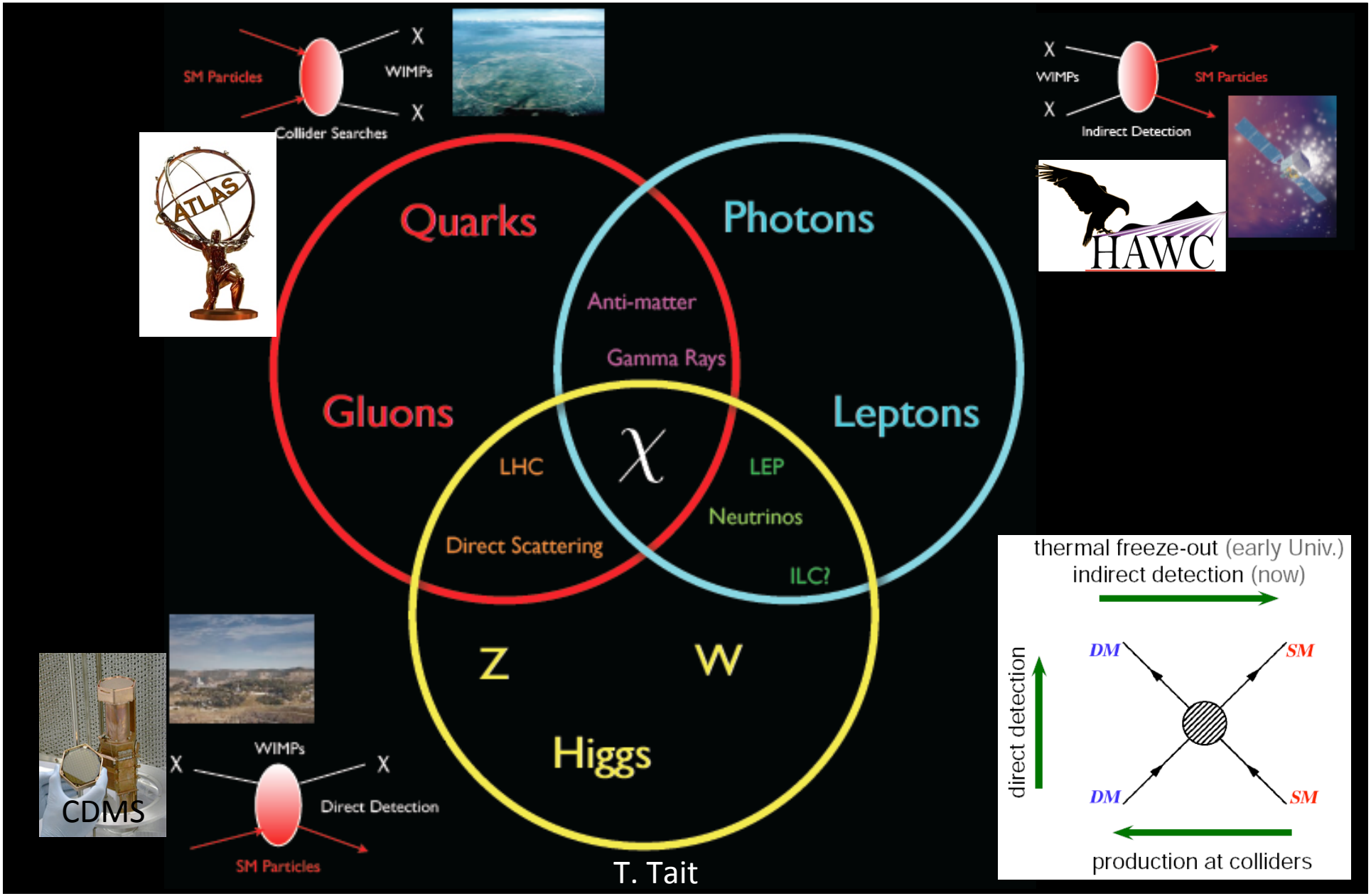




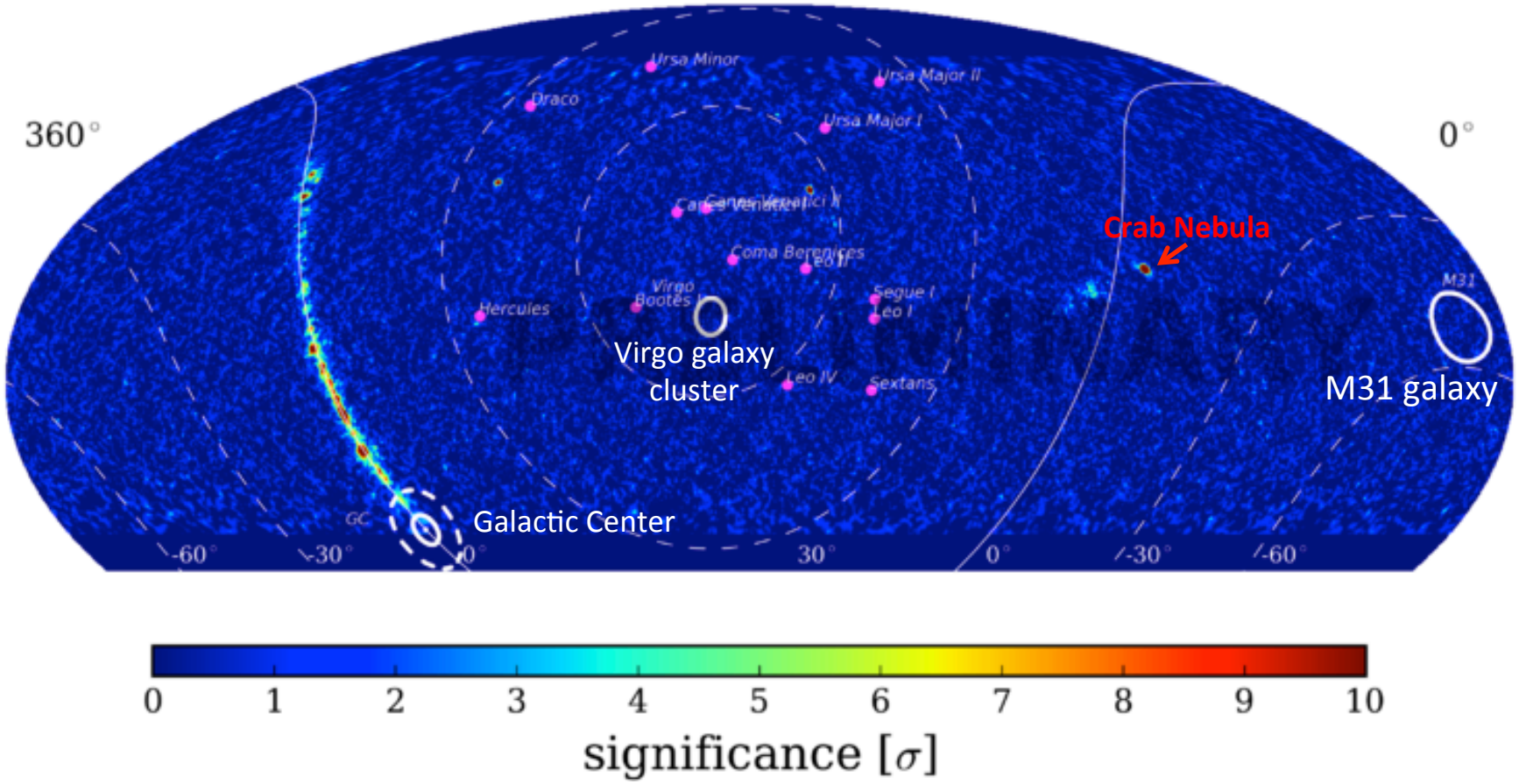


The Cosmic Cocktail: Three Parts Dark Matter by Katherine Freese

Looking for Dark Matter, χ



Dark Matter Rich Objects that HAWC can Observe



Pink Dots – Dwarf Spheroidal galaxies

Summary

- Particle astrophysics makes use of nature's accelerators to probe the highest energies (shortest times after the Big Bang) to answer fundamental questions about the universe.
- HAWC uses a Water Cherenkov technique to detect TeV gamma-rays that will answer questions about:
  - The origin of cosmic rays
  - Particle acceleration in extreme environments
  - New physics beyond the Standard Model (e.g. dark matter)
- The full HAWC detector was inaugurated in March 2015 and will collect data for at least 5 years.

Inauguration on March 19, 2015