

# Ultra-high Energy Cosmic Rays

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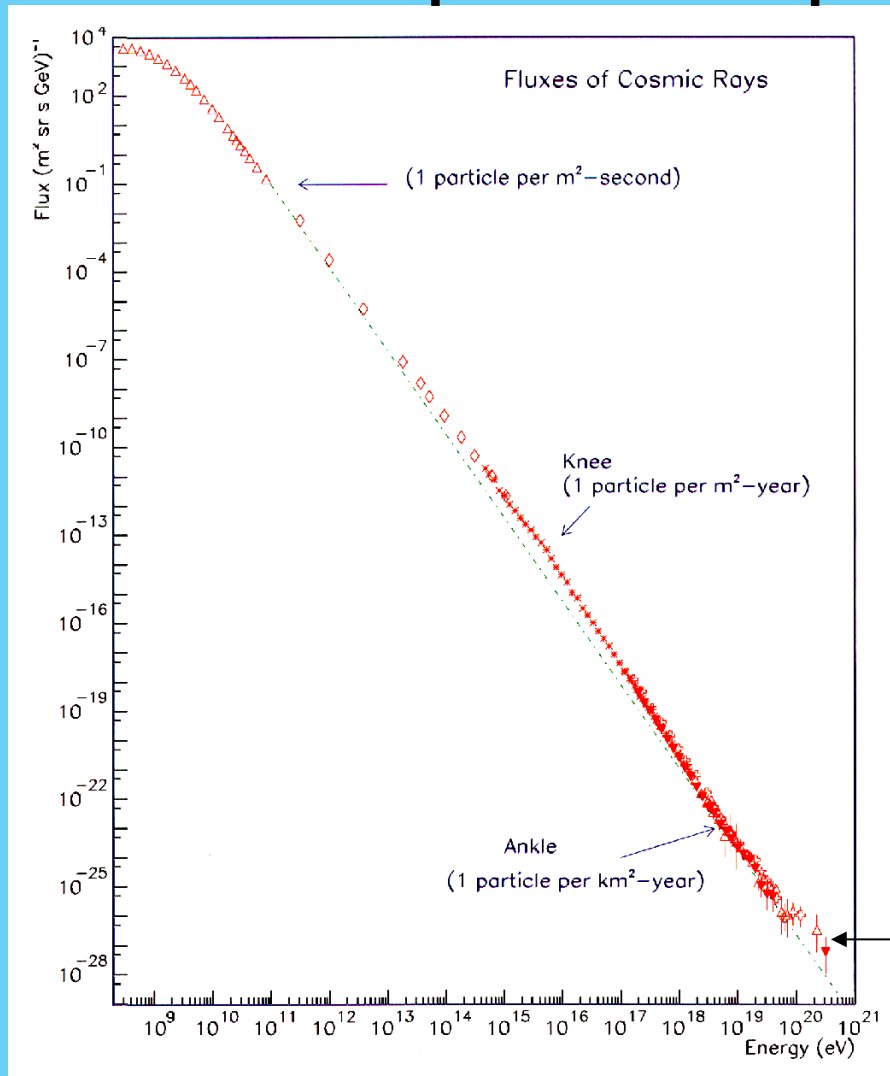
Winter, 2019

Wind Crest Learners  
Academy for Lifelong Learning

# What other eyes do we have?

- UltraHighEnergyCosmicRays (UHECR)
- GAMMA RAYS
- X-rays
- ACE, stereo
- Parker probe
- Other
- Gravitational waves
- CALET

# All particle spectrum

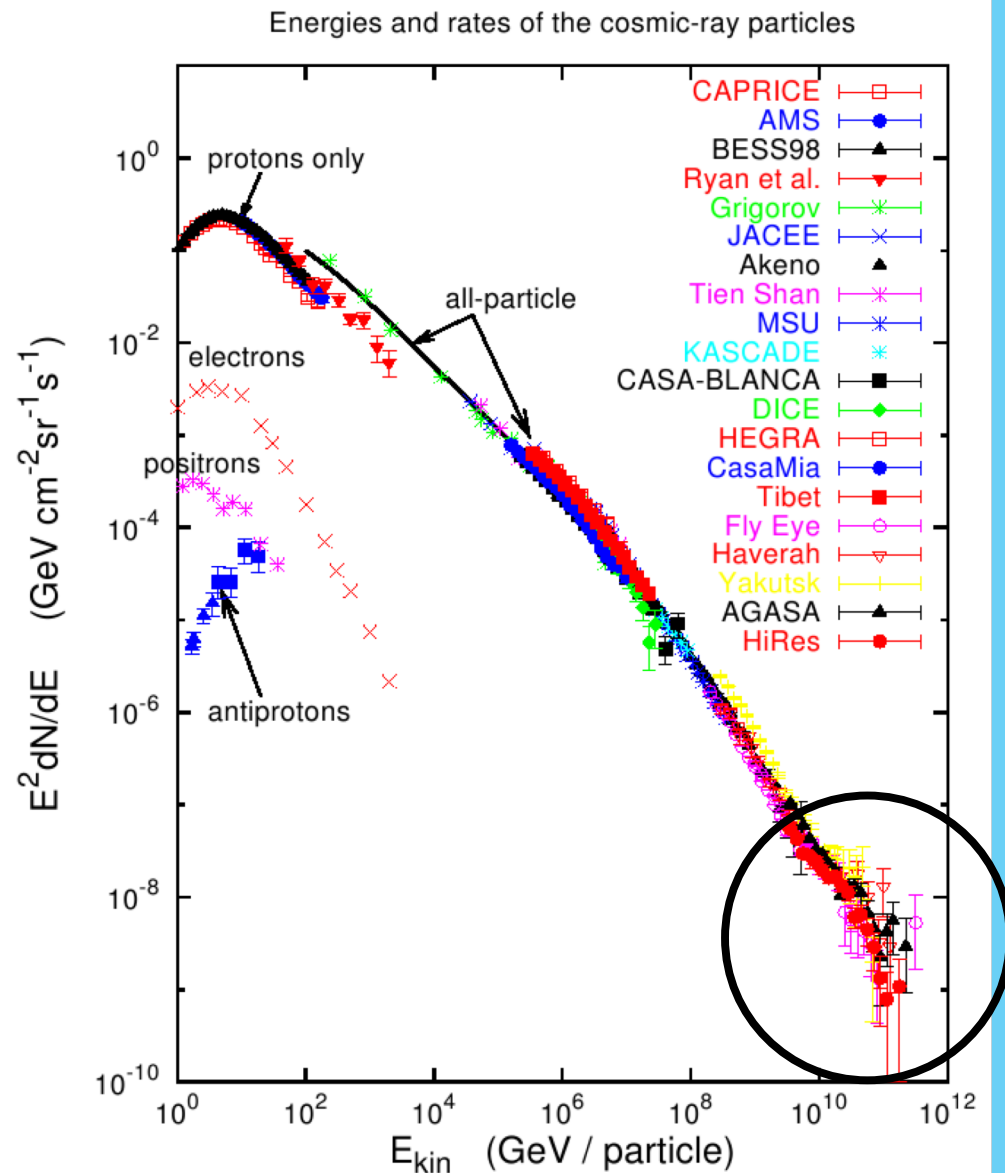


Remember  
this slide?

1 particle  
per  $\text{km}^2$  per millennium

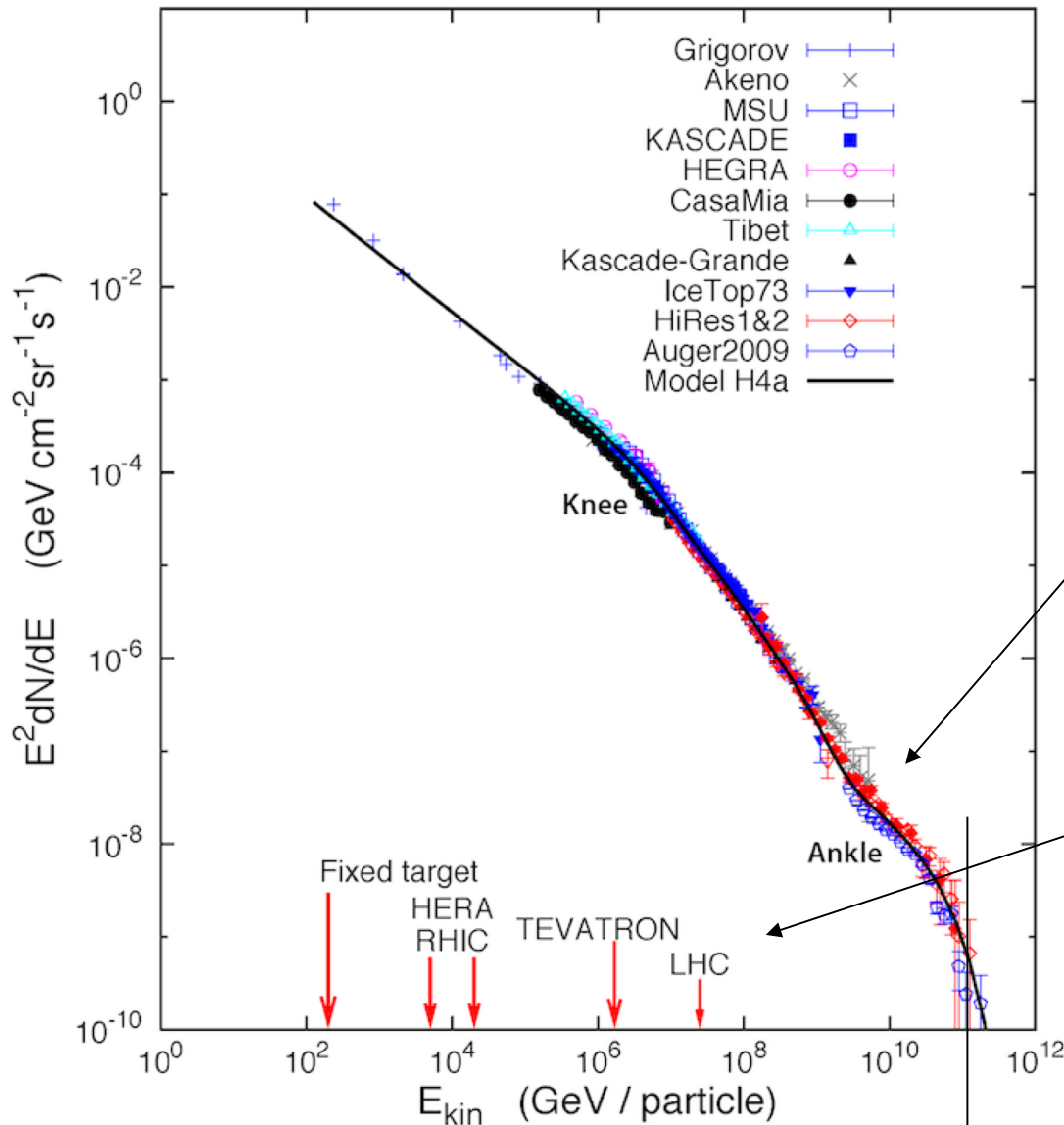


By the time of my retirement, the plot has been filled in considerably and lots of work was being done at the extreme energy end of the spectrum.





Energies and rates of the cosmic-ray particles



Beyond ankle,  
particles were  
probably  
extragalactic in  
origin

LHC – 8-10 Tesla  
Diameter 8.5 km  
 $E_{\text{max}} = 7 \times 10^3 \text{ GeV}$   
 $v = 0.9999999991 \text{ c}$

Predicted  
extragalactic cutoff

# High energy cutoff (aka GZK cutoff)

- We surmise that UHECR are coming from extragalactic sources
  - No objects in the galaxy are large enough to boost the energy to such an extreme,
- Imagine yourself sitting on a proton with  $10^{20}$  eV
  - You are moving at the speed of light minus a smidge
  - The low energy photons that fill the cosmos appear to you as if they had  $10^{20}$  eV.
  - If one of these plentiful guys should hit you it can do some damage – in fact you won't survive the collision.
  - The effect is real and prevents these extreme from coming too far across the universe to us.

# Remember this slide?

collision

$$p + p \rightarrow \pi^+ + \pi^- + \pi^0$$

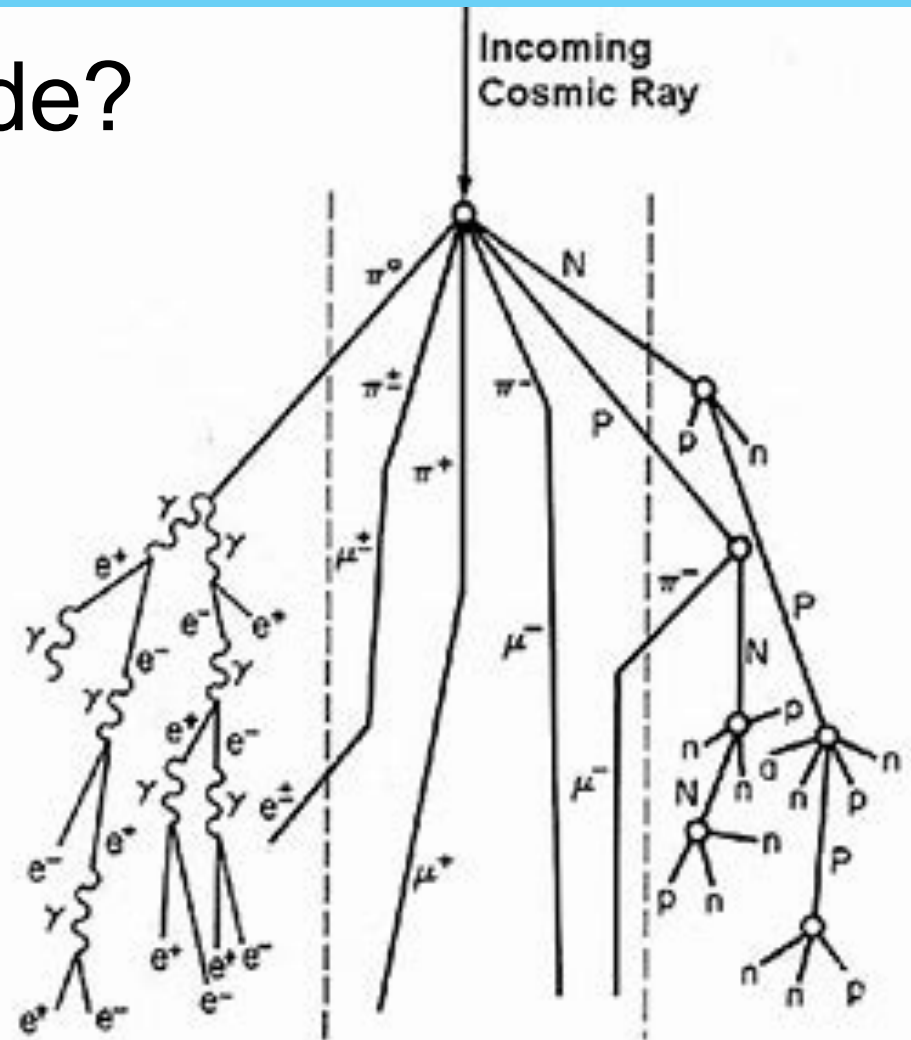
unstable particles decay

$$\pi^+ \rightarrow \mu^+ \text{ and } \pi^- \rightarrow \mu^-$$

$$\pi^0 \rightarrow 2\gamma$$

This shower stimulates fluorescence of nitrogen in the atmosphere. The pulse of light can be seen by photomultipliers

The muons proceed through the atmosphere and to the ground where they can be counted.



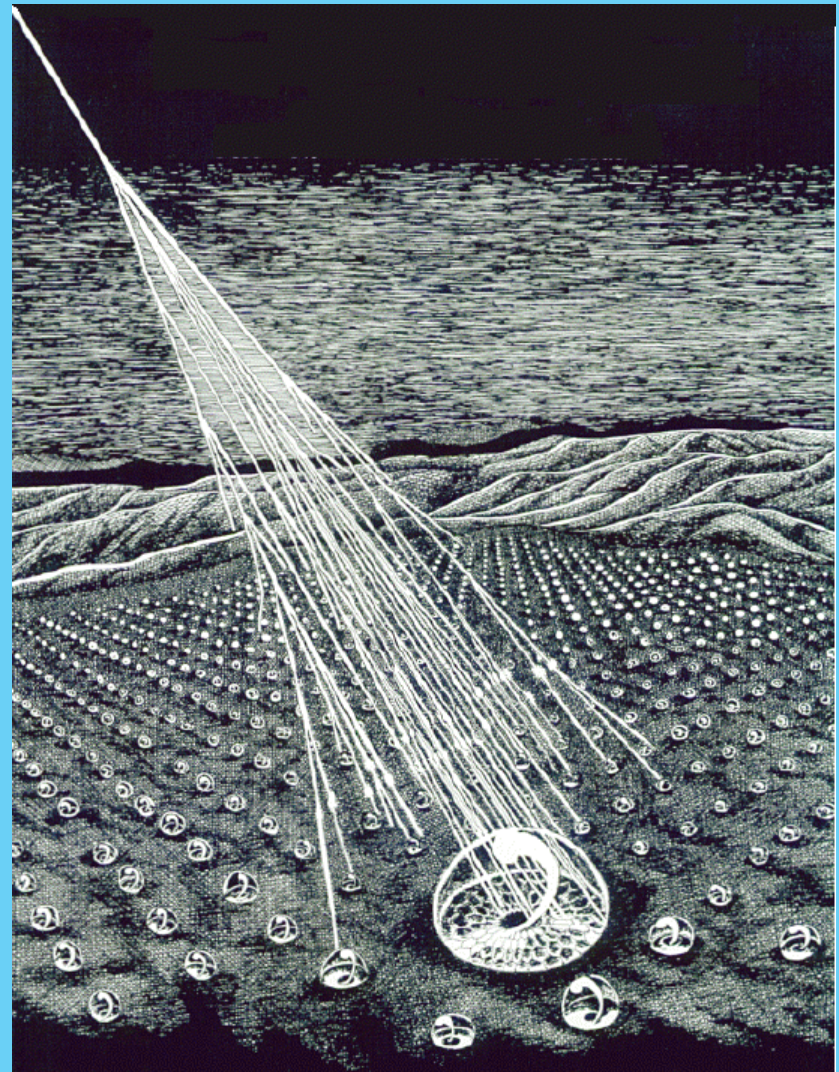
## KEY

$p$	Proton	$e$	Electron
$n$	Neutron	$\mu$	Muon
$\pi$	Pion	$\gamma$	Photon

## The Highest Energy Cosmic Rays

- $>10^{20}$  eV  $\sim$  100 Joules: Energy of a well-thrown baseball in a single nucleus

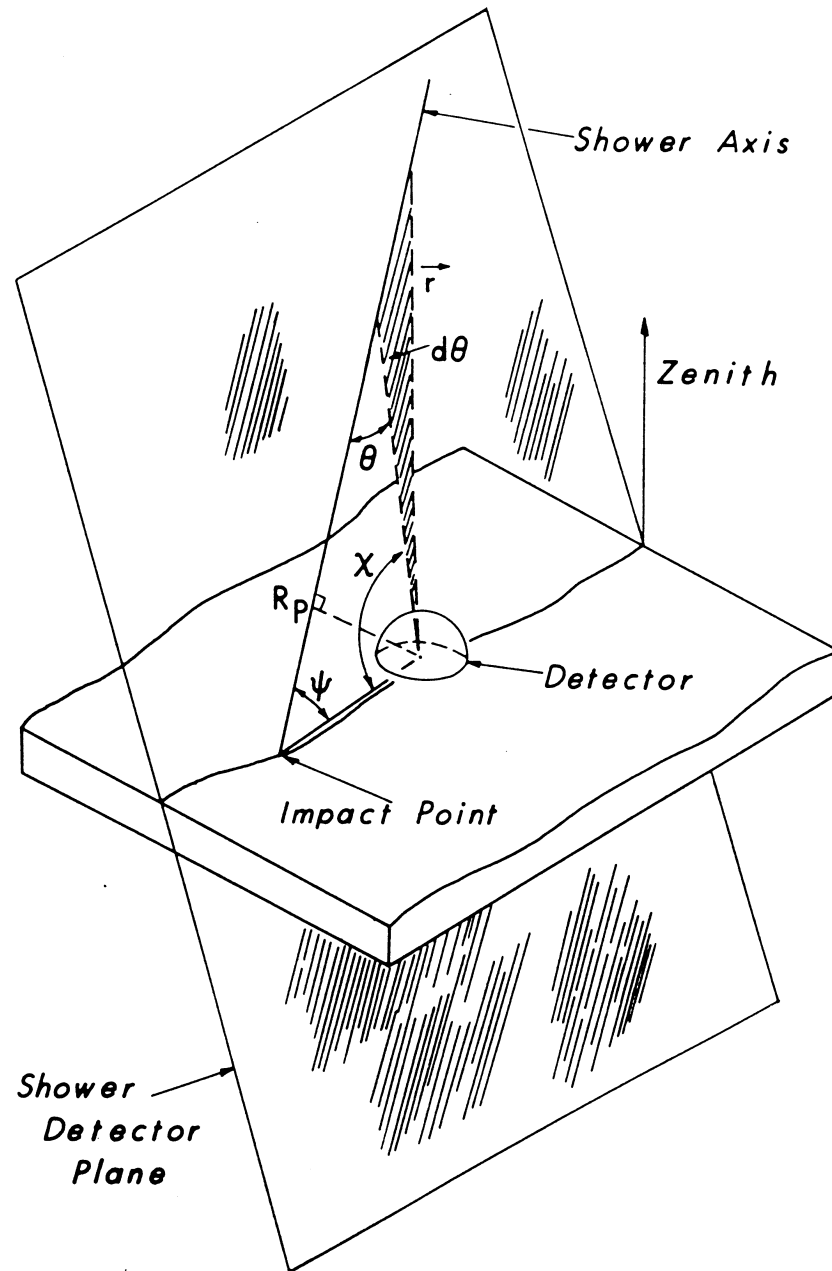
Predicted cutoff above  $10^{20}$  eV  
due to interactions with  
Cosmic Microwave  
Background radiation (Greisen,  
Zatsepin, Kuzmin, or GZK effect)



# History of UHECR

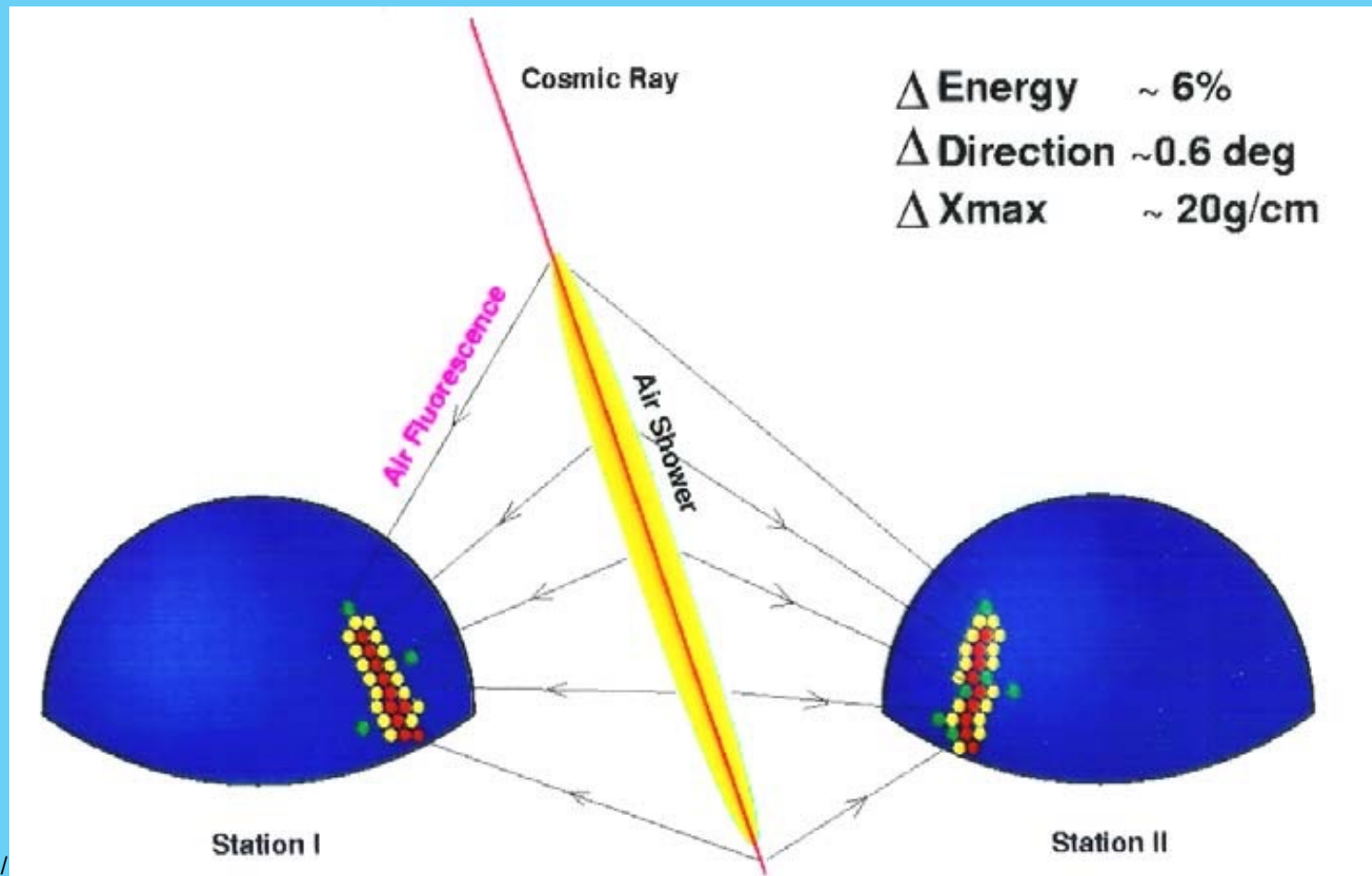
- Volcano Ranch, New Mexico
  - Observed for UHECR using ground based array
- Air fluorescence by Cornell and U of Utah
  - Fly's Eye array, Utah
- Auger array in Argentina
  - Planned Northern array near Lamar and Springfield in Southeast Colorado
- HiRes, Utah

## SHOWER GEOMETRY





# Ground based stereo observatory



# Auger, near Mendoza, Argentina

Detector tanks



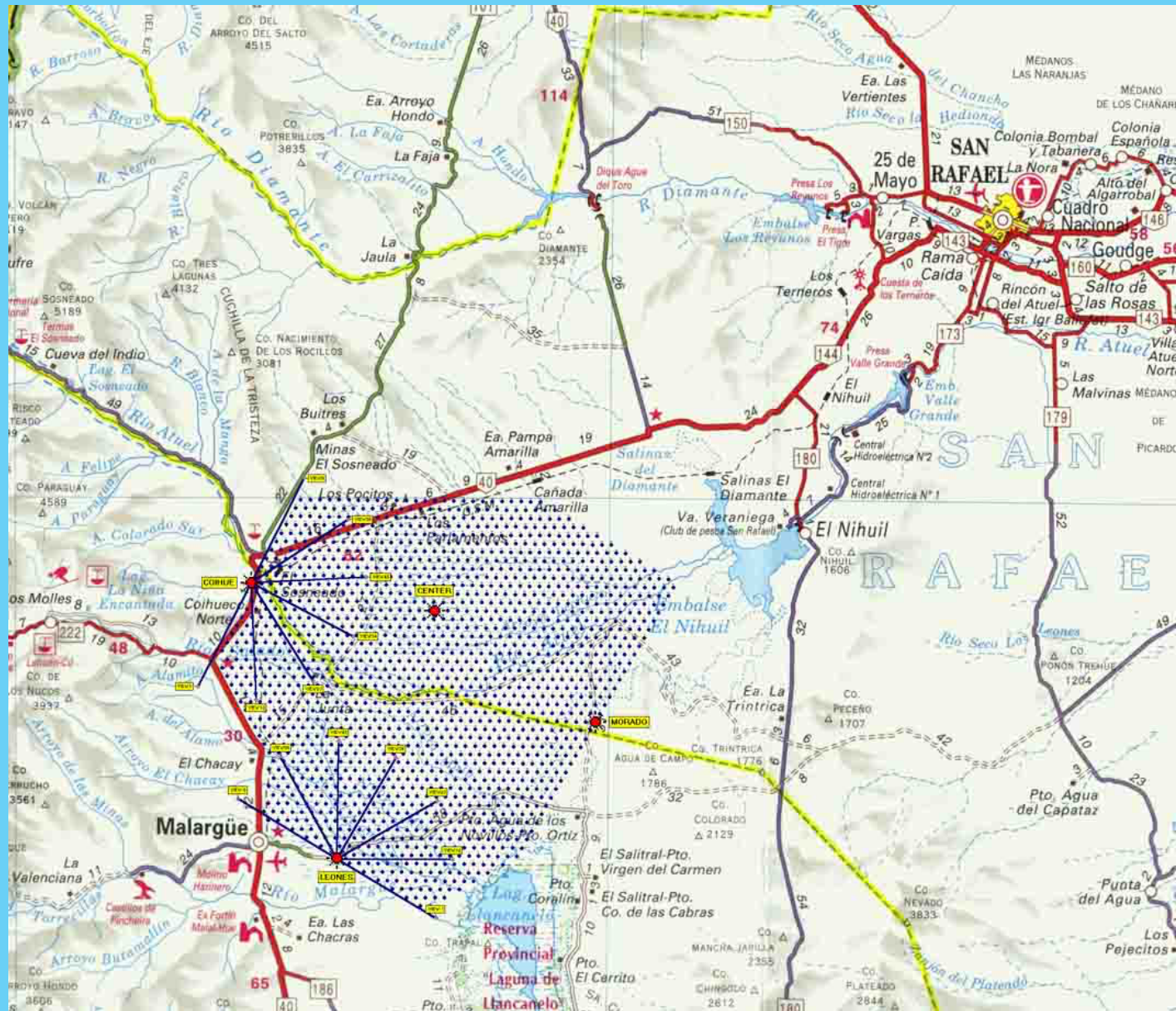
Mendoza



Buenos Aires

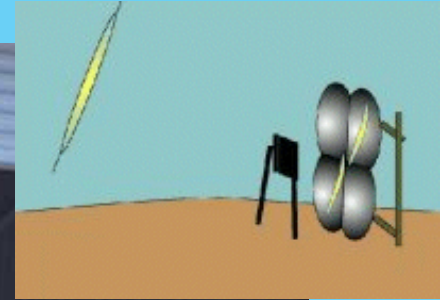


# Auger in Argentina



3/19/19

# HiRes Fly's Eye mirror and detector



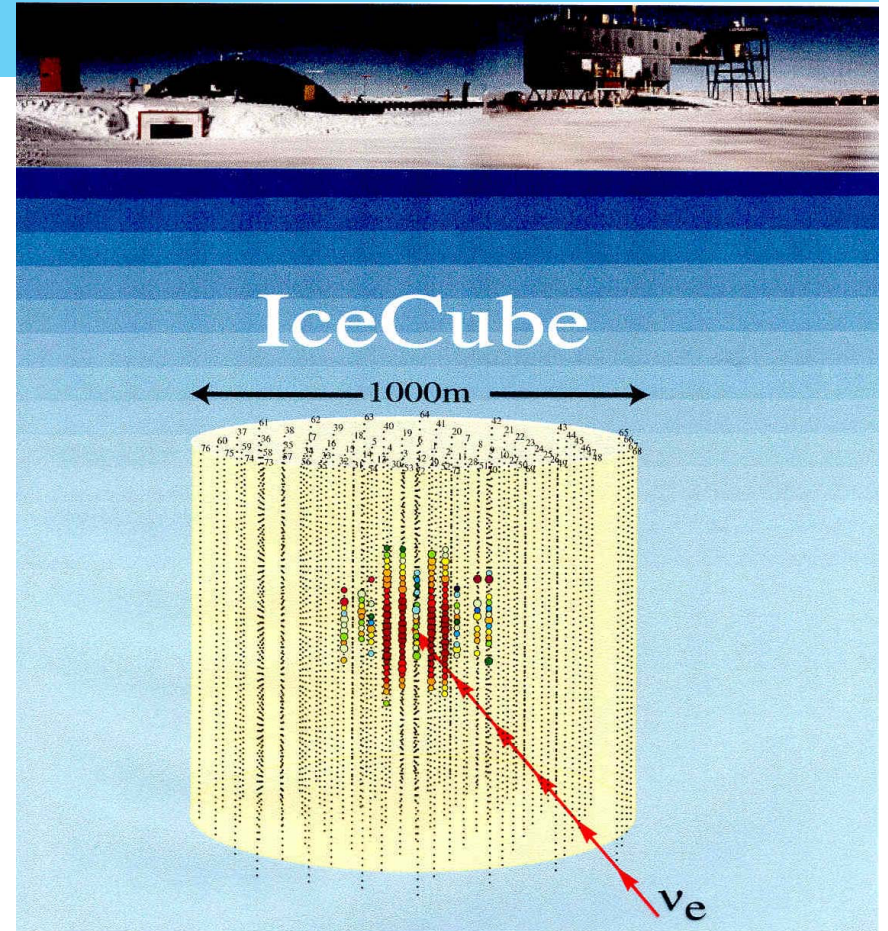
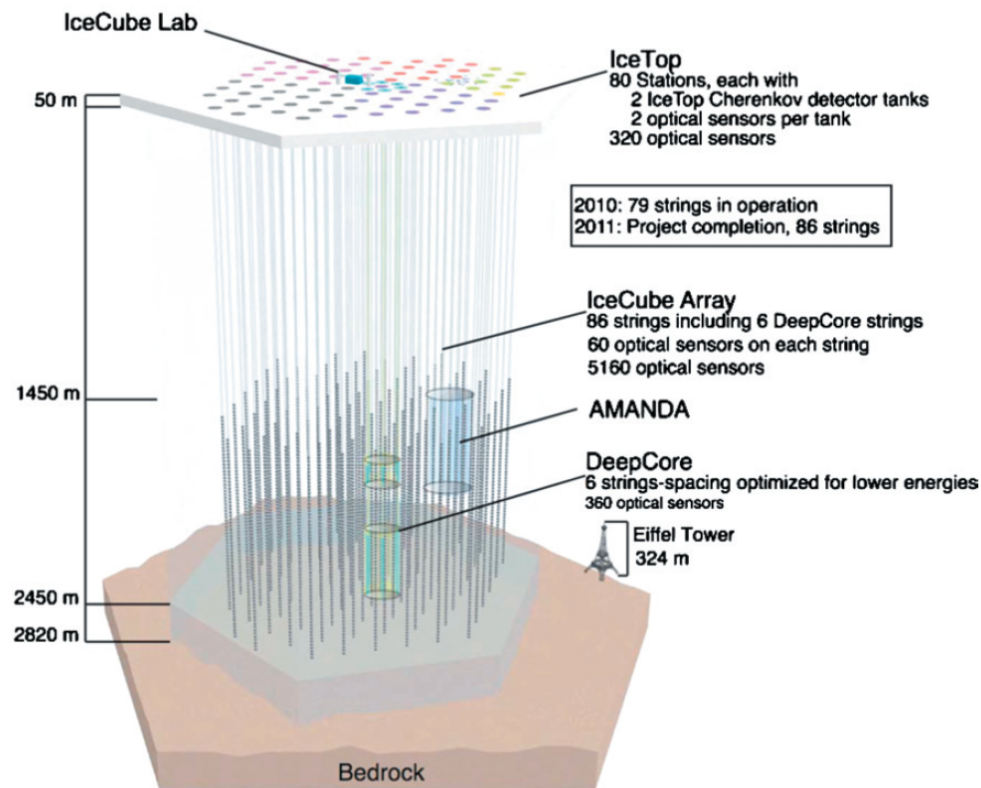
# Findings and Origin

- Many years of back and forth between the two experiments Utah and Argentina
  - Calibration issues
  - Shower simulation issues
- Cutoff at  $10^{20}$  eV established
- Extragalactic nature established



# IceCube

## South Pole Neutrino Observatory



# IceCube

## South Pole Neutrino Observatory

The beginnings of neutrino astronomy  
Neutrino eyes, not “above the skies” but “below the ice”

Jim Madsen Ted Talk

<https://www.youtube.com/watch?v=JzXuvowtZ6A>

July 12, 2018

[https://www.youtube.com/watch?v=xUit5\\_B9k-U](https://www.youtube.com/watch?v=xUit5_B9k-U)

July 12, 2018

<https://www.youtube.com/watch?v=vTya9hoKsfM>

# blazar TXS 0506+056

A blazar is an Active Galactic Nucleus (AGN)  
powered by a black hole with a jet pointed at Earth.

September 22, 2017 IceCube saw 290 TeV neutrino

September 28, 2017 Fermi-LAT saw gamma ray flaring

from blazar TXS 0506+056

4 Billion light years away

Archival data found many events – flare in 2015 – 13 neutrinos

We now know **original particles are protons**

# Fermi-LAT sees blazar TXS 0506+056

<https://www.youtube.com/watch?v=cbWATaQx33s>

Source visualized accumulating

<https://www.youtube.com/watch?v=pCA47Fo5Yvk>



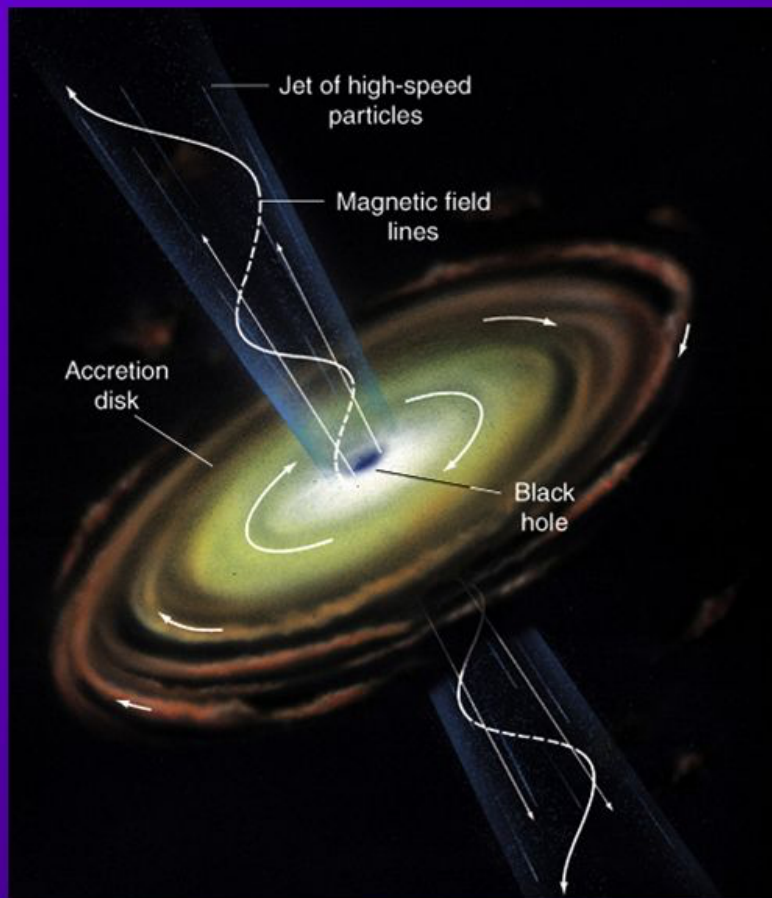
# Blazar physics





# Black holes power AGN jets

## Powering Active Galactic Nuclei



- (1) A compact central source – *blackhole* - produces intense gravitational field.  
 $M_{\text{BH}} = 10^6 - 10^9 M_{\text{sun}}$
- (2) Infalling gas forms an accretion disk around the black hole.
- (3) As the gas spirals inward, friction heats it to extremely high temperatures; emission from the accretion disk at different radii ( $T > 10^4 \text{ K}$ ) accounts for optical thru soft X-ray continuum.
- (4) Some of the gas is driven out into jets focused by magnetic fields.

# The Most Energetic Particles Known!

***The highest energy cosmic rays have an energy of over  $10^{20}$  eV, equivalent to that of universe  $\sim 10^{-27}$  s after the big bang!***

**These are very rare events with only 1 particle per sq kilometer per century, detected as air showers by ground based *fly's eye* telescopes**

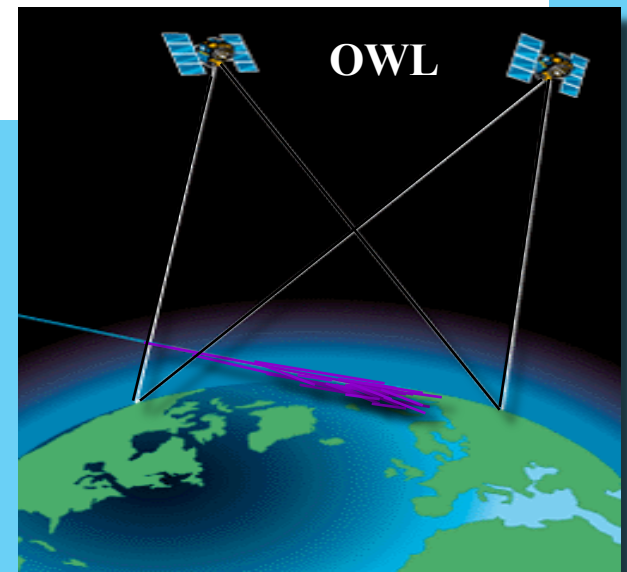
Their origin is a mystery, models include:

- ♦ Acceleration by spinning super-massive black holes in nearby galaxies?
- ♦ Decay products from the early universe?

**We designed OWL to use the Earth as a gigantic detector to observe thousands of UHECR events to determine their directions and energies.**

**OWL could also detect neutrinos**

3/19/19



# Fly's Eye mirror and detector

