Galactic and extra-galactic cosmic rays: ultra-high-energy particles

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Some slides have been swiped (with many thanks) from talks by colleagues...

Cosmic rays

- Charged particles from the cosmos
  - Protons, atomic nuclei
  - Originate in supernovae (exploding stars) or other astrophysical sites
  - Energies from few million to 10^{20} electron volts
    - Old-fashioned CRT TV set uses a 10000 eV electron beam
  - Number of particles/sec/area drops rapidly with increasing energy:

Energy	**Rate of arrival**
10^{10} eV	1000 per m^2 per sec
10^{12} eV	1 per m^2 per sec
10^{15} eV	1000 per m^2 per year
10^{19} eV	1 per kilometer^2 per year

- Highest energy seen is ~10^{20} eV, about 50 joules = KE of thrown baseball!

First: Relative energy scales

- Here are some connections between energies in eV and the kinds of processes in that energy range:

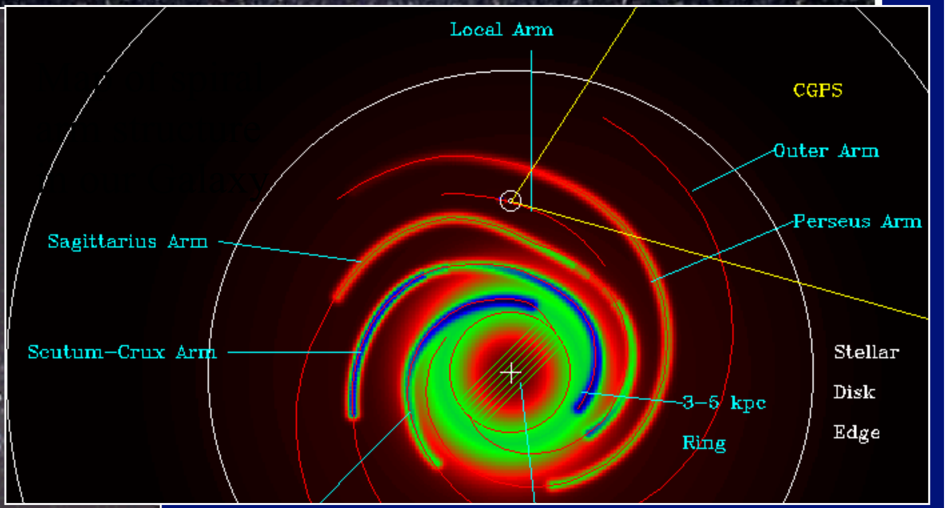
eV	Typical energy for processes in atoms and molecules: • energy released in chemical reactions • energy involved in emission or absorption of visible light
MeV (10^6 eV)	Typical energy for processes in nuclei: • energy released in radioactive decays • energy released in nuclear fission or fusion
GeV (10^9 eV)	Typical energy for elementary particle interactions: • 1 GeV is the mass (rest energy) of a proton
EeV (10^{18} eV) 0.16 J	Low end of cosmic ray energy range of interest in experiments to be discussed • Kinetic energy of a golf ball dropped from a height of 50 cm

Varieties of "cosmic rays"

- Cosmic rays = particles (with mass>>0) reaching Earth from space
  - Usually we do not include gamma rays and neutrinos
- Solar cosmic rays = particles from the Sun
  - Typically low (MeV) energies (nuclear physics processes !)
  - Strongly affected by magnetic fields of Earth and Sun
    - ...which are linked in many ways
- Galactic cosmic rays = particles from our Galaxy
  - Energies > 1 GeV or so, to penetrate Earth's magnetic field
  - Produced in supernova explosions up to 10^{15} eV energies
- Extra-galactic cosmic rays
  - Energies over 10^{18} eV (due to Galaxy's magnetic field)
  - "Highest energy cosmic rays" – up to ^{21} eV – sources unknown!
- Puzzles:
  - How are cosmic rays over ^{15} eV accelerated?
  - Is there a cutoff of all cosmic rays around 10^{19} eV, as predicted?

Home sweet home: our Galaxy

- Our Galaxy = the Milky Way
  - Flat, spiral cloud of about 10^{11} stars, with bulge at center
  - 20,000 light years to center from here
  - 100,000 light years in diameter
  - disk is a few hundred light years thick in our neighborhood



Galactic and extra-galactic CRs

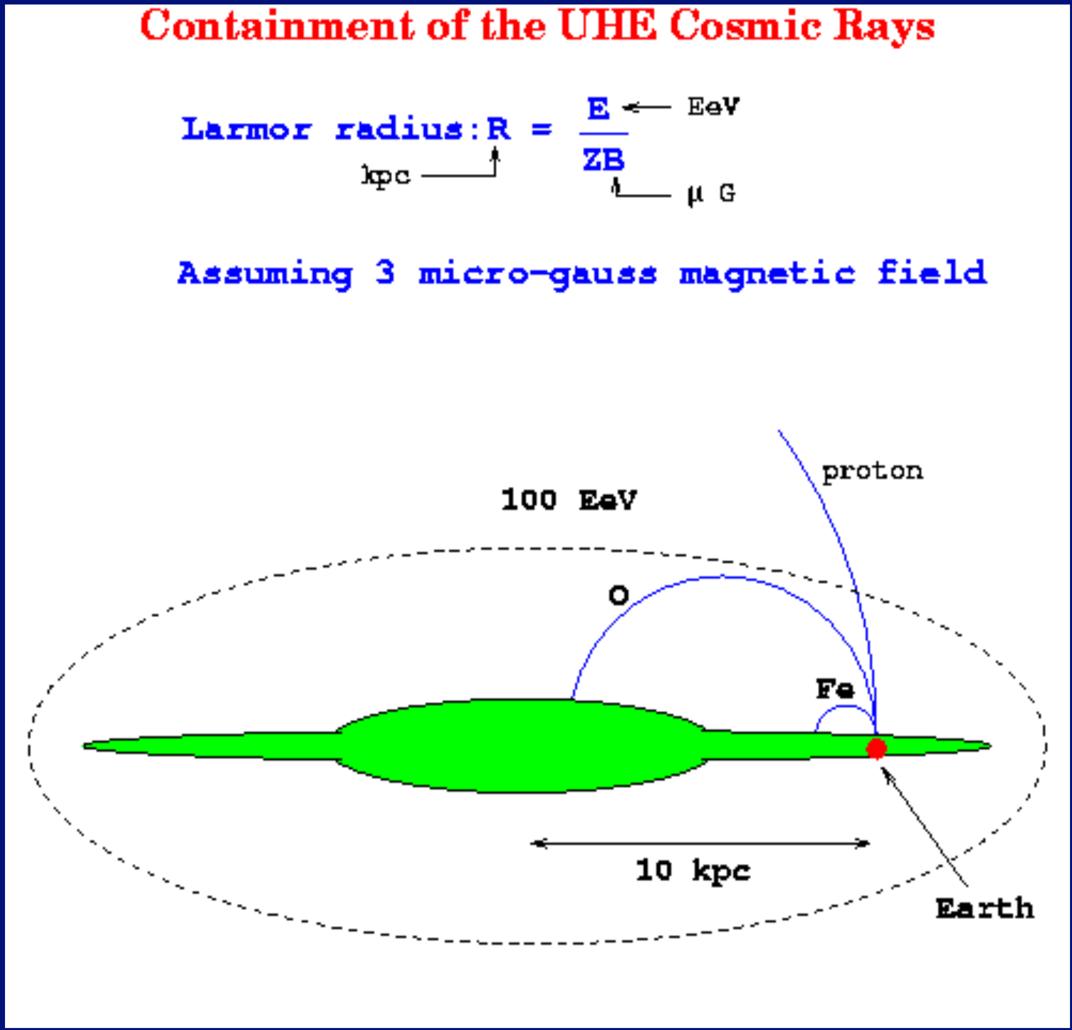
Our Galaxy's magnetic field cannot trap protons with

$E > 10^{18}$ eV, so

- Galactic EHE cosmic rays escape
- Observed EHE cosmic rays are mainly from other galaxies

Q: Is there a significant intergalactic B?

Probably very weak

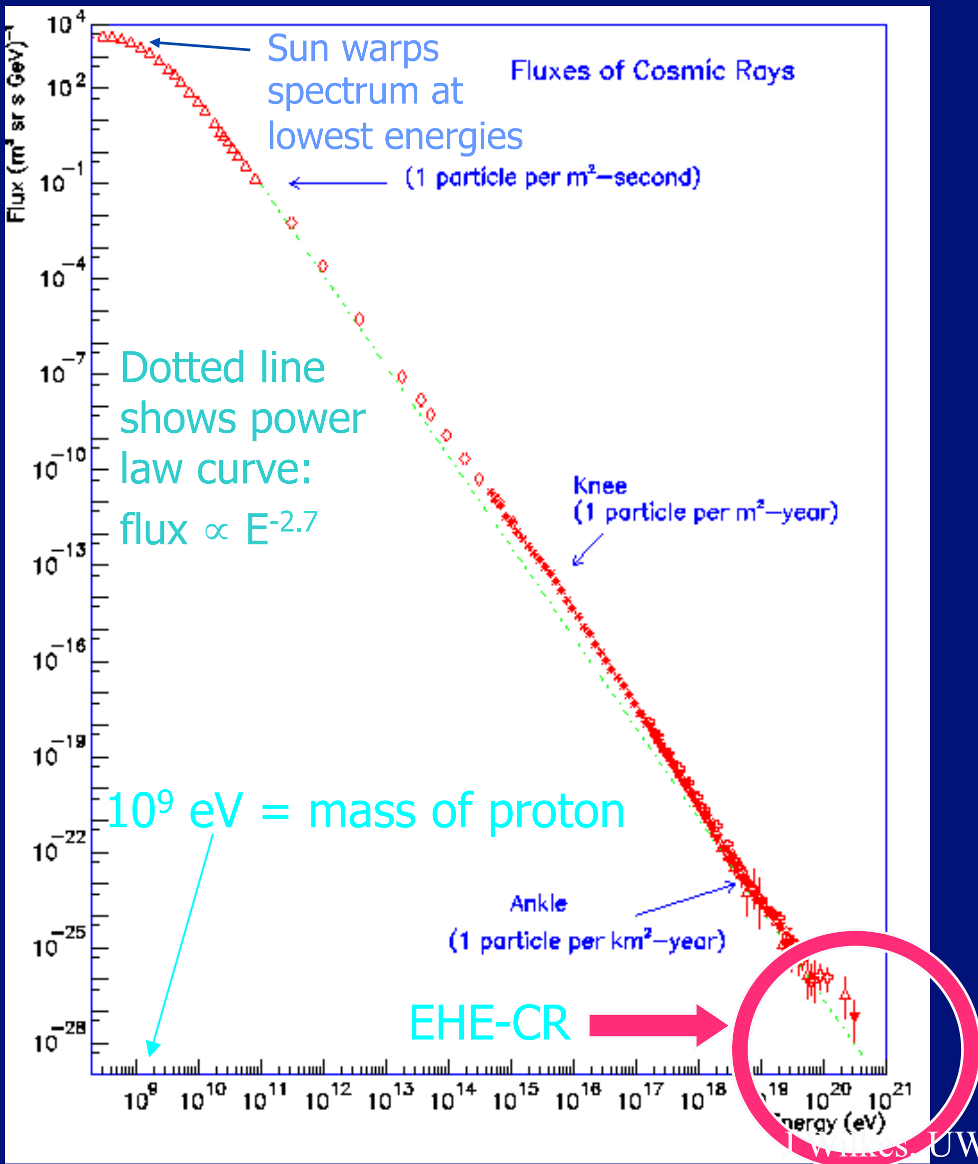


Extragalactic - our neighborhood in the Universe

- Virgo Supercluster of galaxies (several thousand)
  - Cluster is about 50 million light years across
  - Dinosaurs ruled Earth when light recorded here left these galaxies …

Central Part of Virgo Cluster

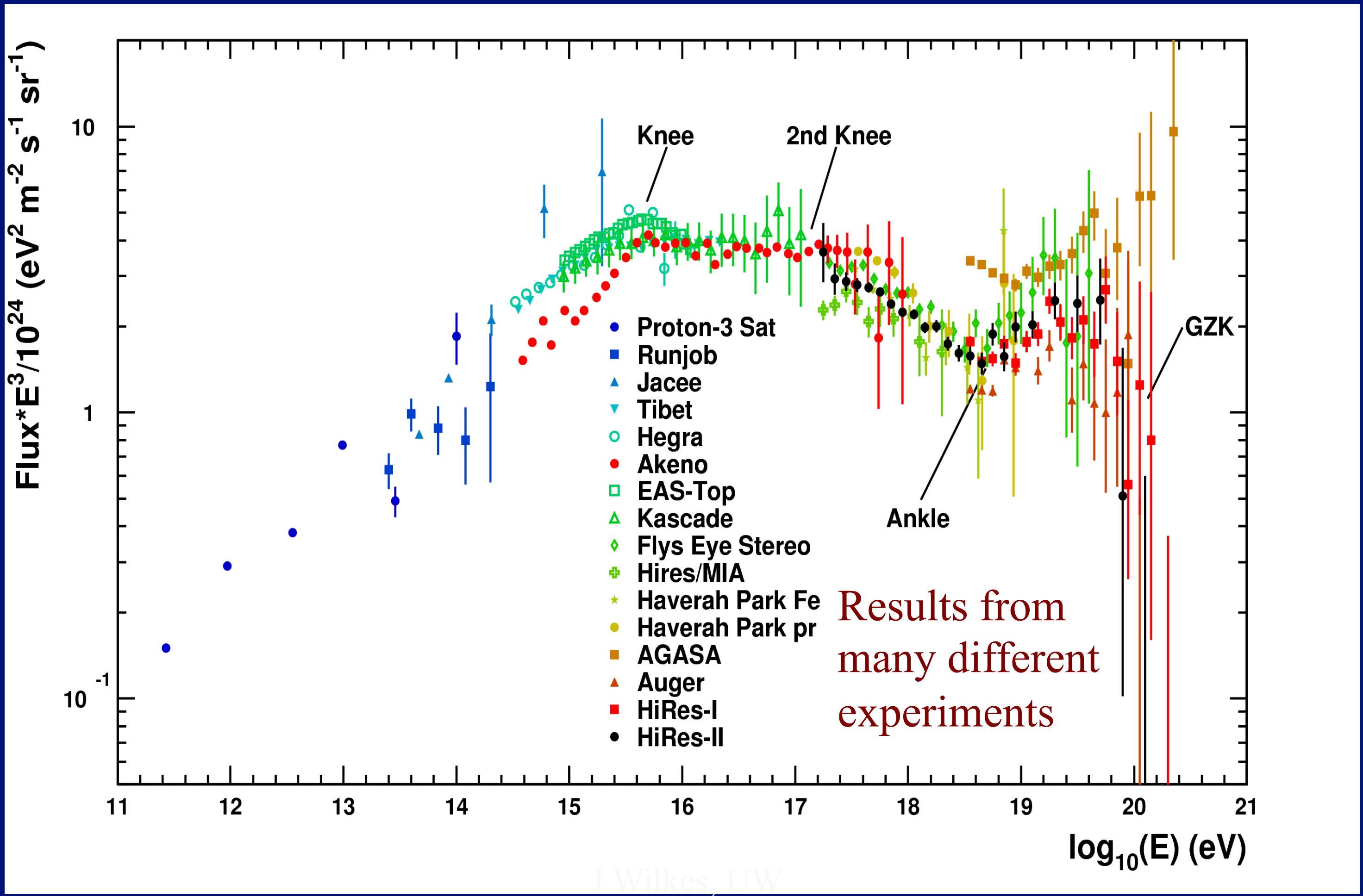
The galactic cosmic ray spectrum

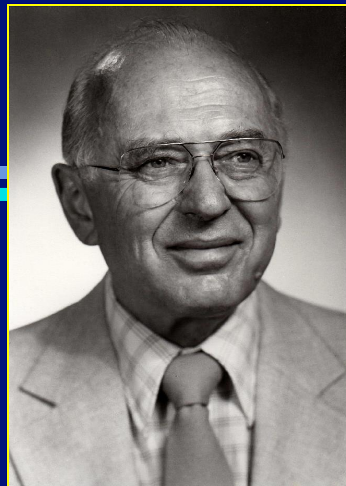


- Cosmic ray *spectrum:* intensity vs energy for cosmic rays
  - All: protons and nuclei
  - At "top of atmosphere"
  - Notice: scales' steps are factors of 10!
- The very highest energy cosmic rays:
  - Rare and puzzling
  - Only a few detected worldwide
  - Should be none!

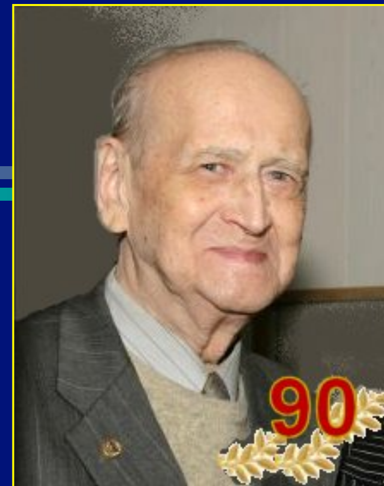
Spectrum is not boringly smooth, if you look closely

- This graph has data multiplied by E^3
  - If the spectrum falls like $1/E^3$, it would be a horizontal line





Ken Greisen (Cornell)

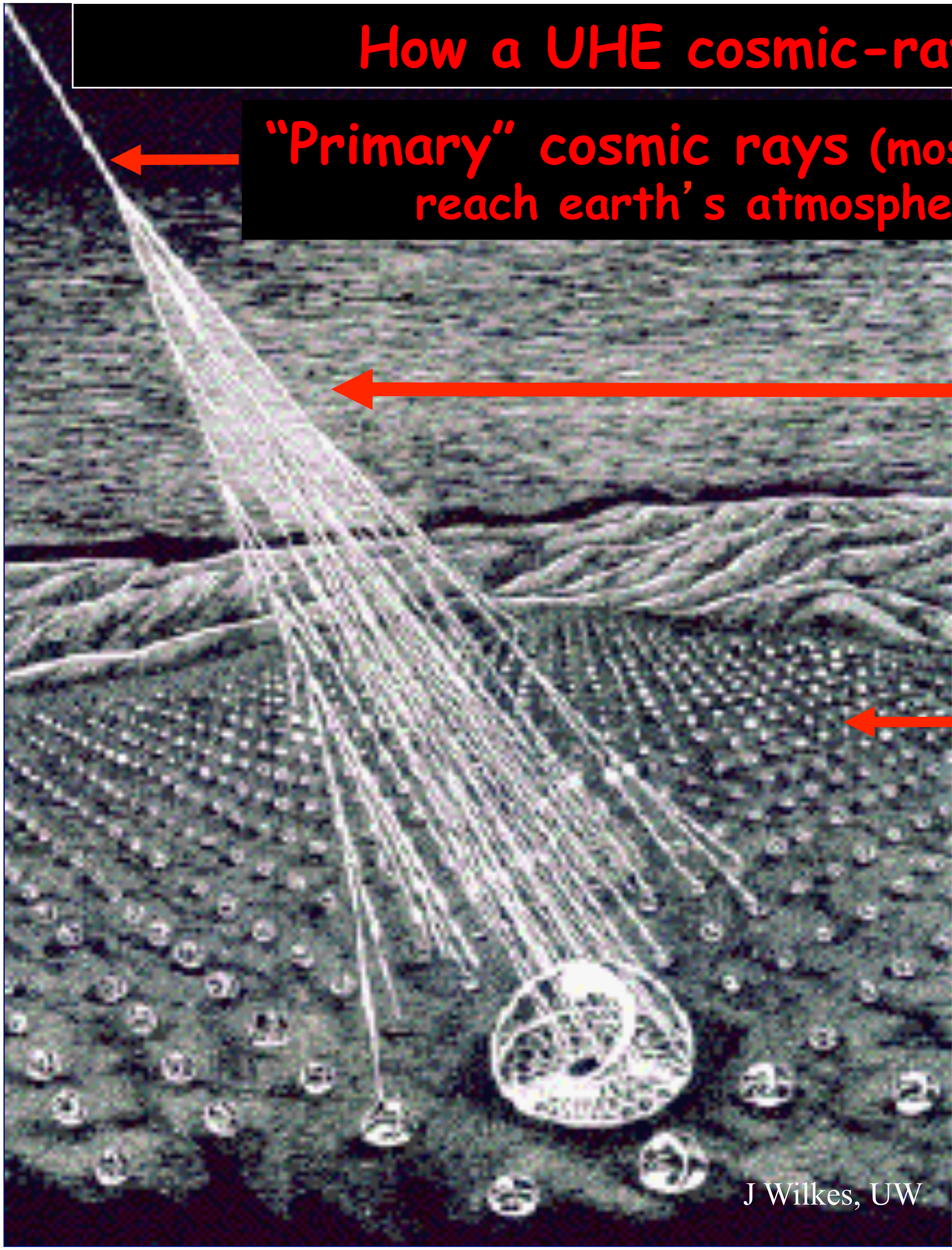


G. Zatsepin (Moscow State Univ.)

The "GZK cutoff"?

- GZK= Ken Greisen, and Grigor Zatsepin + V. Kuzmin: in 1966 predicted cosmic ray spectrum would cut off above 10^{19} eV
  - Intergalactic space is filled with microwave radiation (big bang!)
  - Microwave photons interact with cosmic ray protons
  - ➔ big energy-loss for protons that travel farther than from nearby galaxies
- GZK predicts a sharp break in the CR spectrum
- Cutoff in spectrum should occur around 10^{19} eV if sources are more or less equally distributed around the universe

How a UHE cosmic-ray is detected



"Primary" cosmic rays (mostly protons or light nuclei) reach earth's atmosphere from outer space

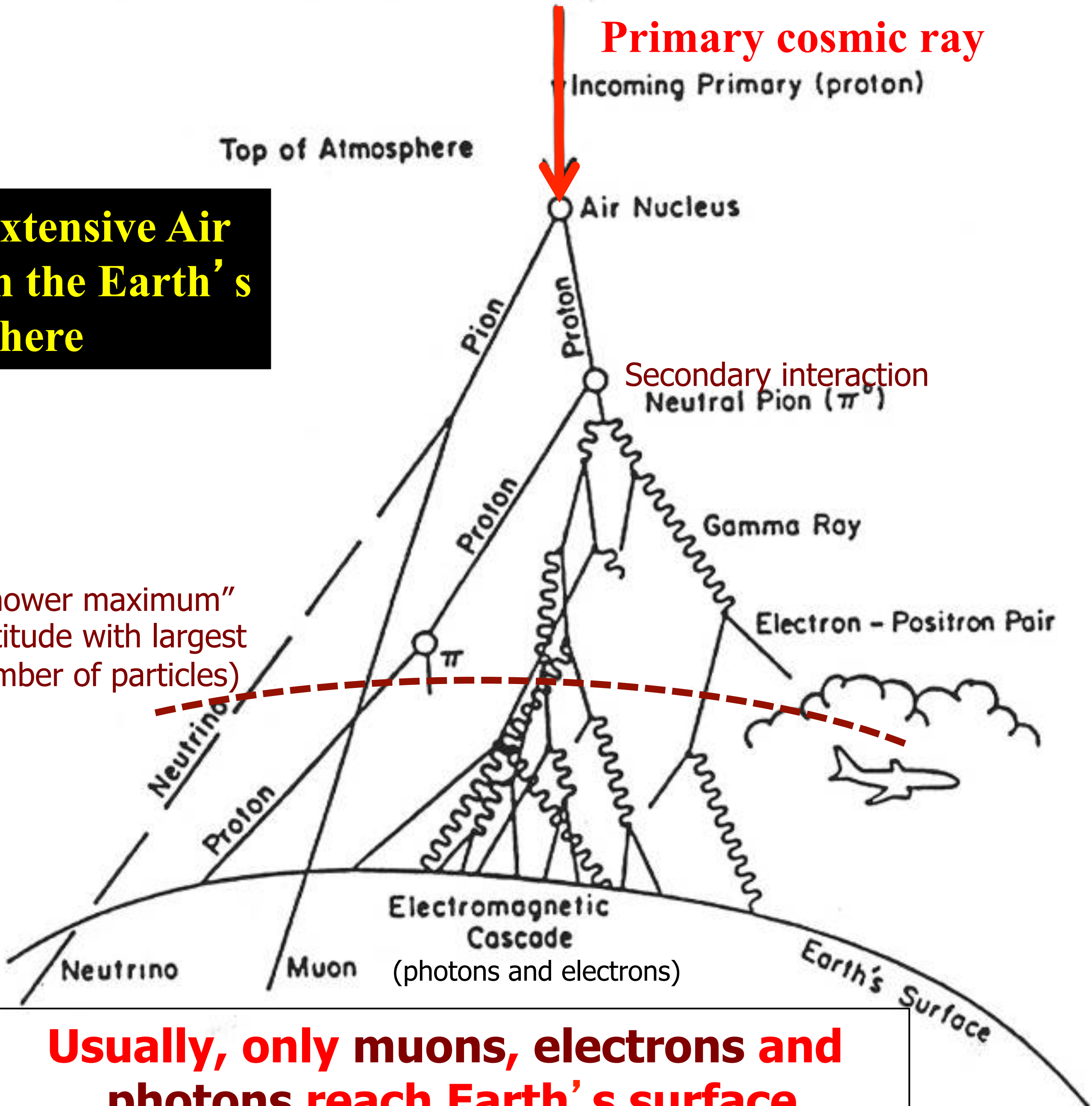
"Air shower" of secondary particles formed by collisions with air atoms

Grid of particle detectors to intercept and sample portion of secondaries

1. Number of secondaries related to energy of primary
2. Relative arrival times tell us the incident direction
3. Depth of shower maximum related to primary particle type

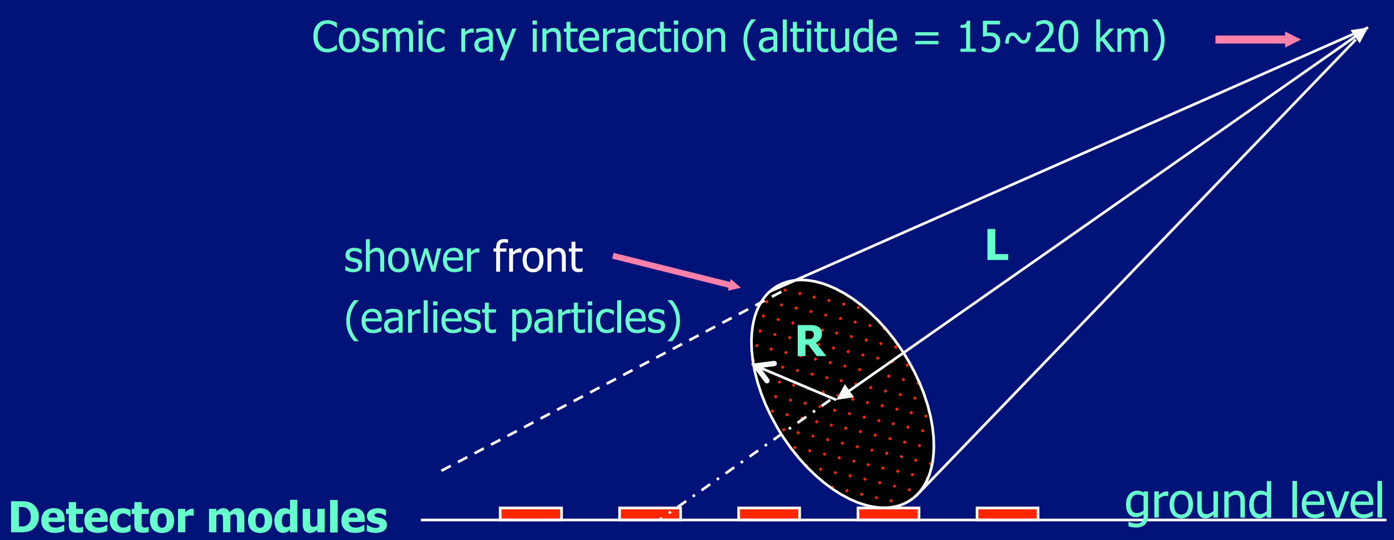
What's in an Extensive Air Shower (EAS) in the Earth's atmosphere

(We can only directly detect **charged** particles)



Usually, only muons, electrons and photons reach Earth's surface

Howe we estimate CR direction and energy



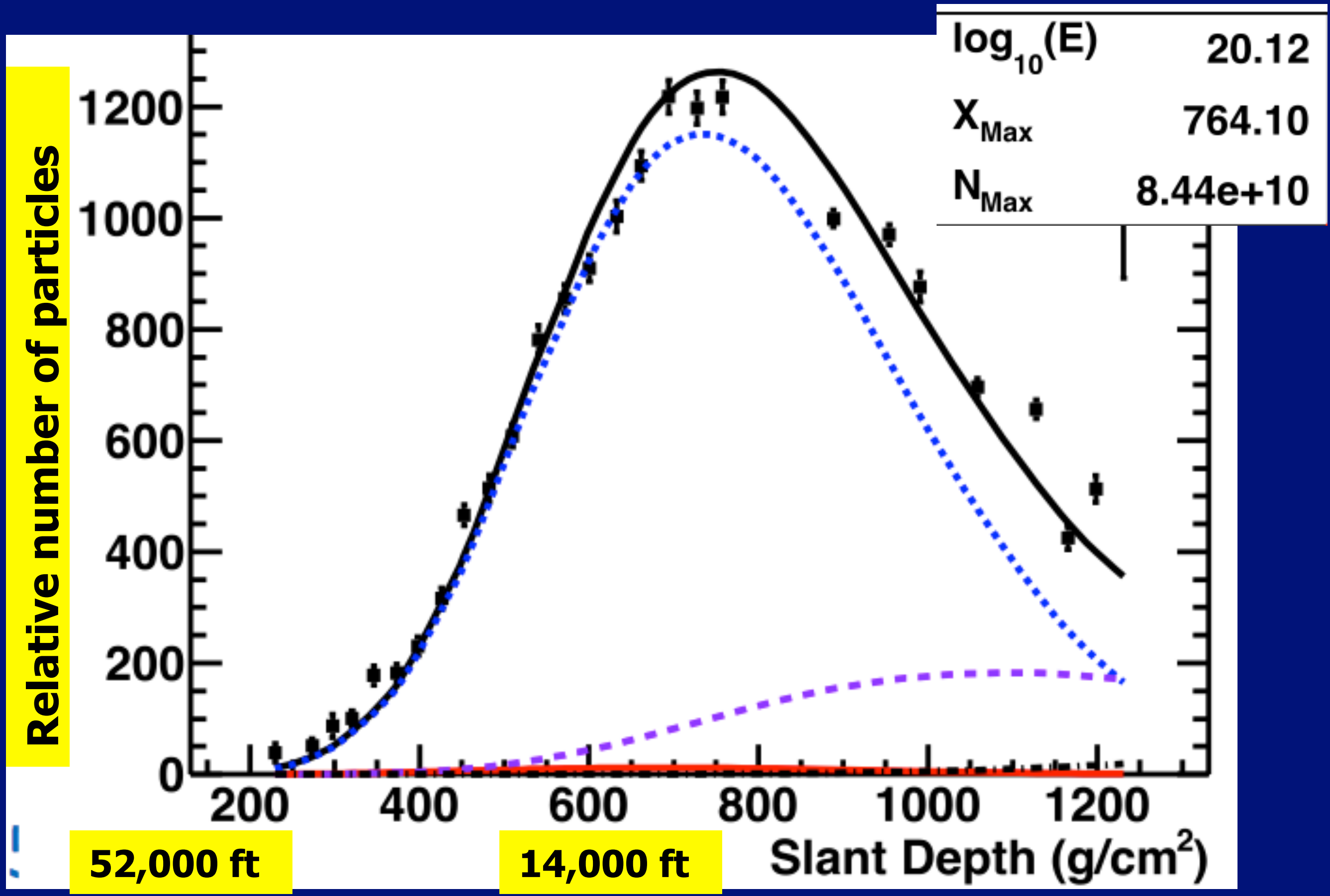
- Each detector module reports:
  - Time of hit (better than μsec accuracy)
  - Number of particles hitting detector module
- Time sequence of hit detectors → shower direction
- Total number of particles → shower energy
- Distribution of particles → distance L to shower origin

Shower profile: number of particles vs depth

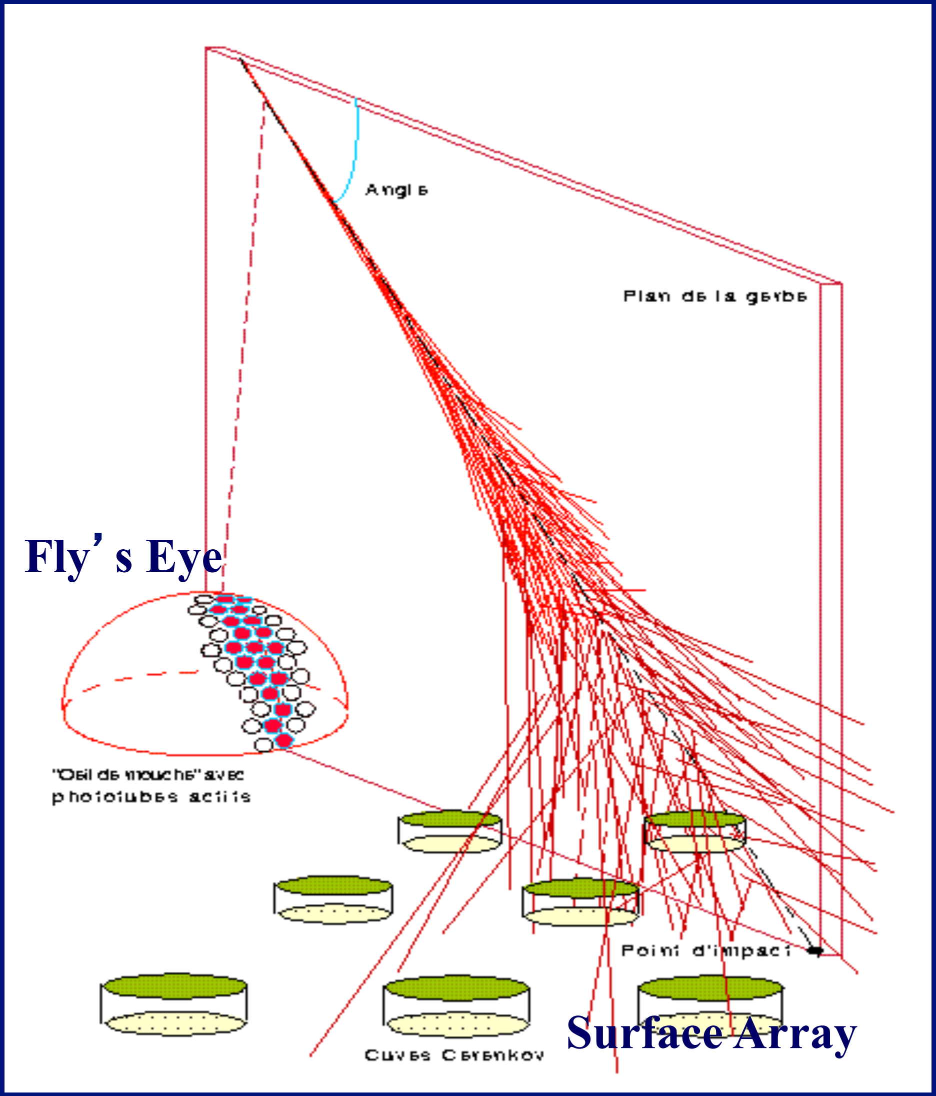
This example is for a 10^{20} ev shower, with 80 billion particles at max (from TA experiment paper, at ICRC-2015*)

* ICRC = the International Cosmic Ray Conference, held every 2nd year since 1947. CR physicists present their latest results at ICRCs.

35th ICRC-2017 was held in late July in Korea.



Cosmic Ray Air Shower – detector types



UHE air shower measurements are made by two techniques

1) Surface Arrays

   Scintillator counters or Cherenkov detectors

2) Fluorescence Telescopes

   Arrays of photodetectors ("Fly's Eyes")

Experiments exploring UHE air showers

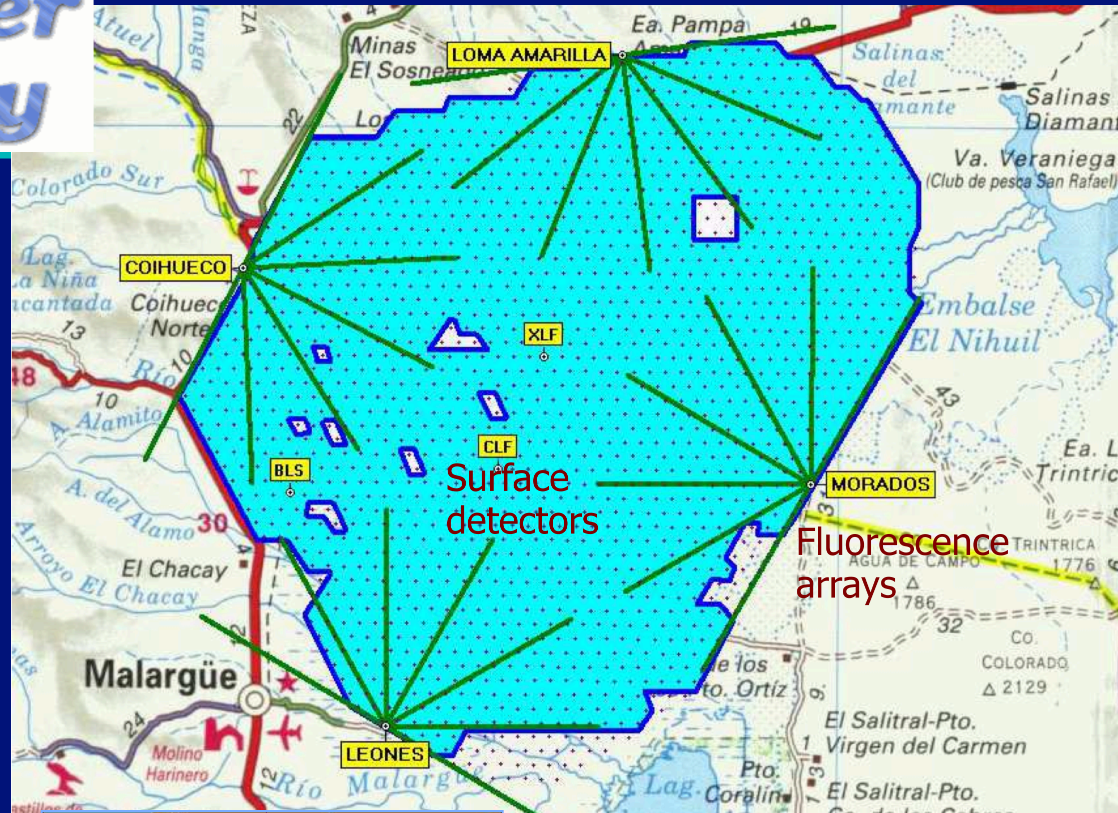
- Pierre Auger Observatory – Argentina, 2005--. Air-fluorescence AND ground array (water tanks instead of plastic scintillator).
- Telescope Array (TA) – Utah, 2008--. HiRes and AGASA scientists joined together - similar to Auger in N. hemisphere

World map, Australian style

Pierre Auger Observatory

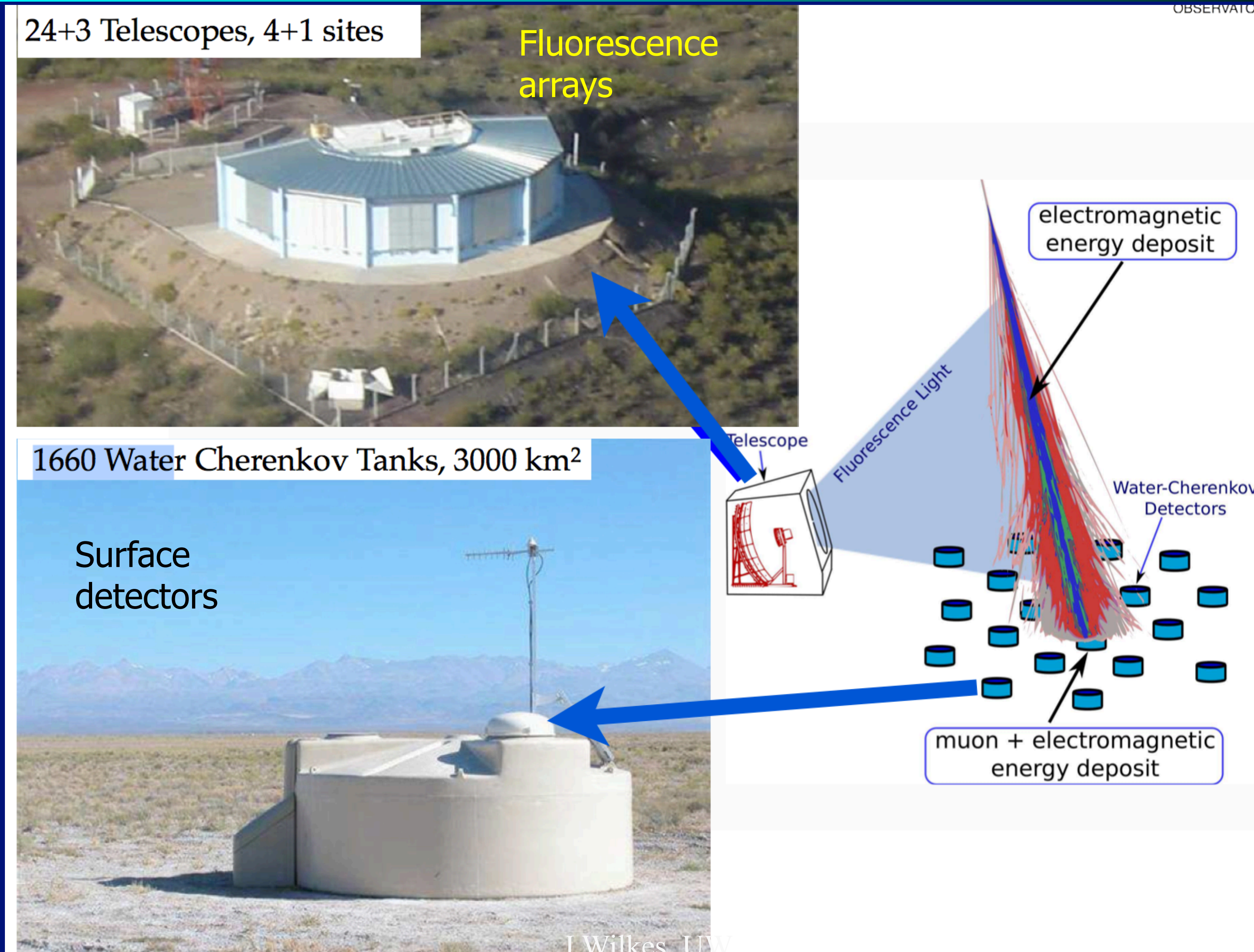
Southern hemisphere:
Mendoza Province,
Argentina

International Collaboration:
over 250 researchers
from 54 institutions and 19 countries:
Argentina, Australia, Bolivia, Brazil, Chile, China, Czech Republic, France, Germany, Greece, Italy, Japan, Mexico, Poland, Russia, Slovenia, United Kingdom, United States of America, Vietnam

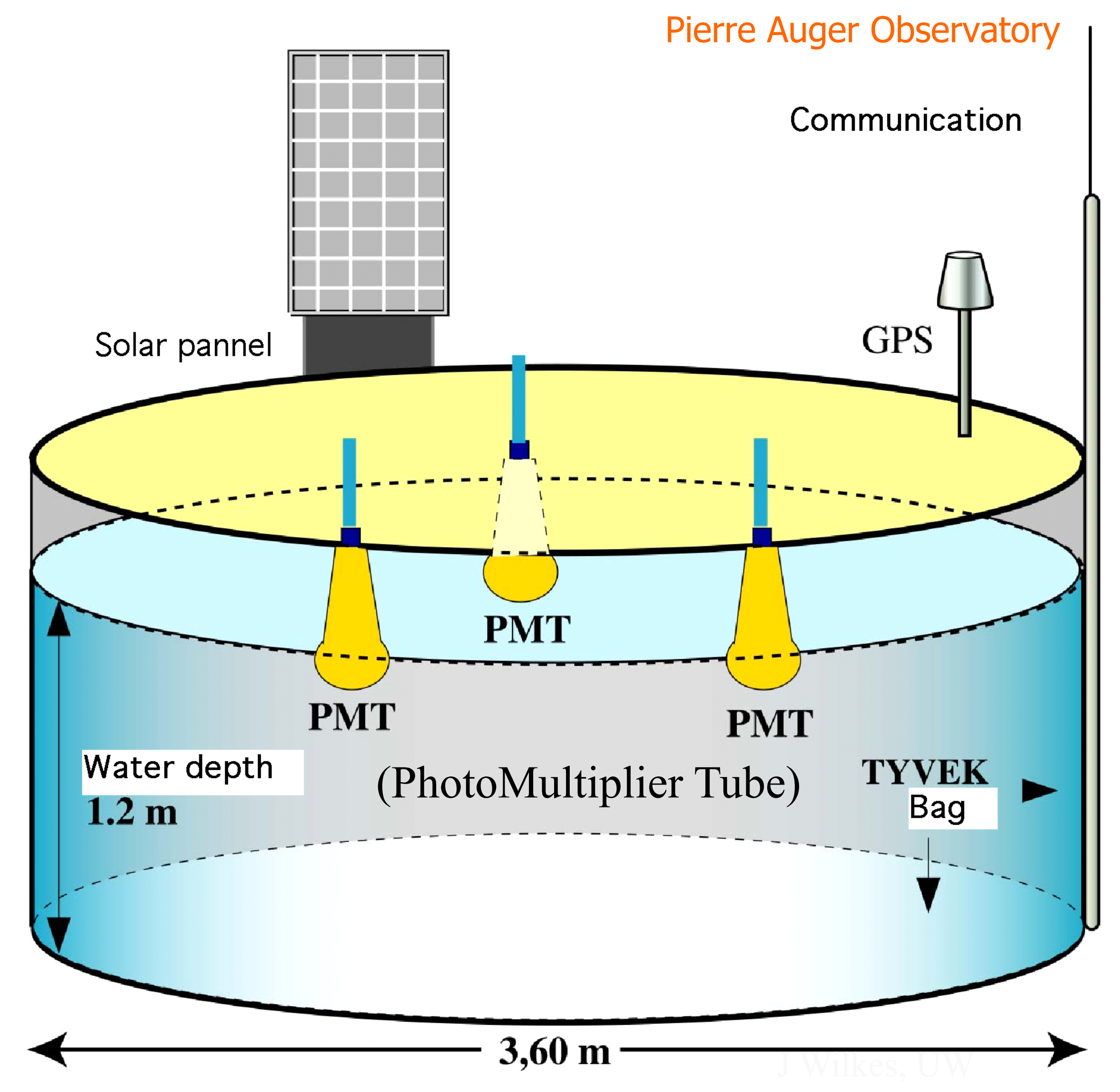


1660 surface detectors
(water Cherenkov tanks),
5 Air Fluorescence arrays,
Covering 3000 km^2

Pierre Auger Observatory



Surface detectors (SD): water Cherenkov detectors

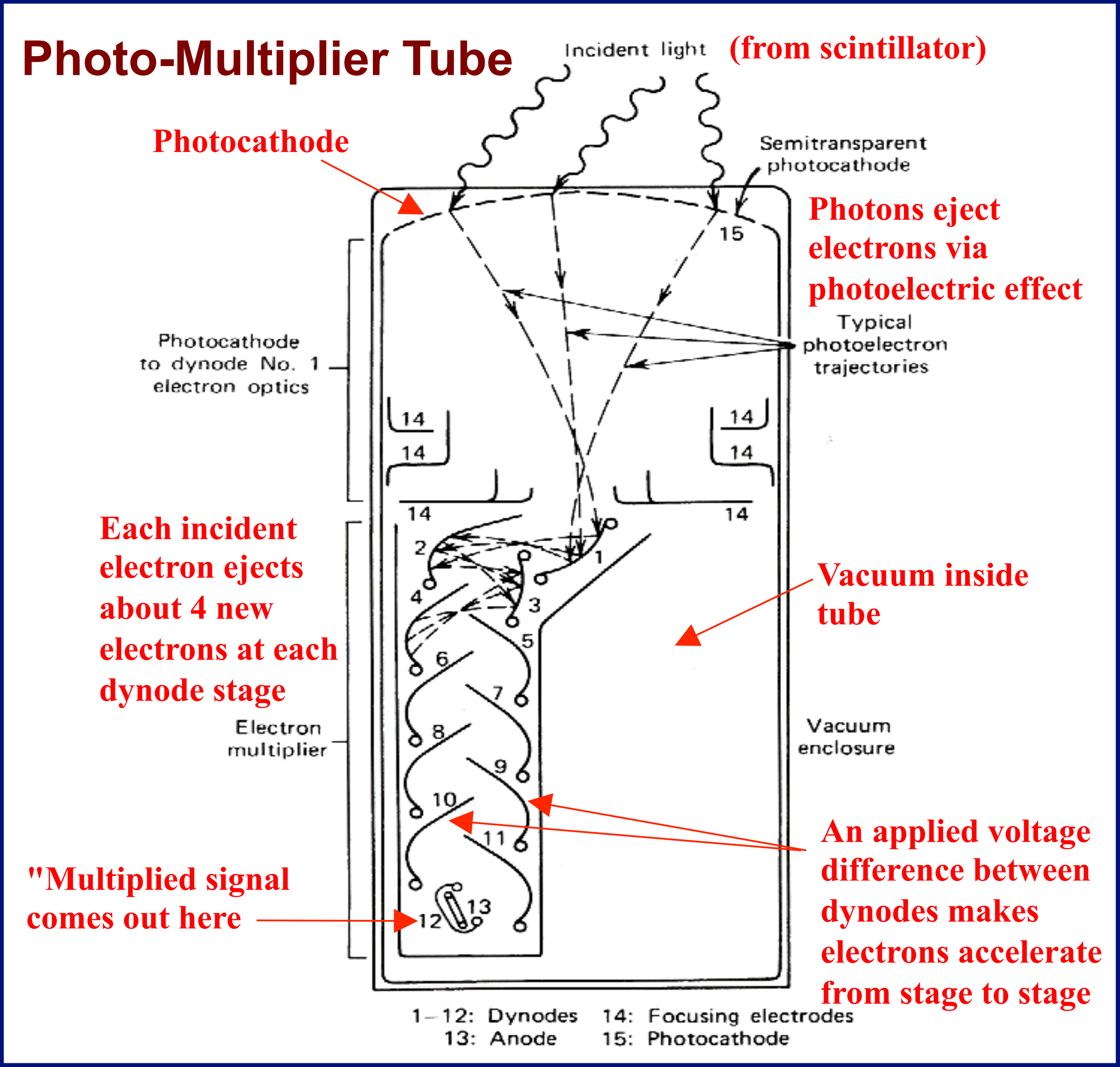


- Each unit is self-contained: solar panels, batteries, GPS
- Communication with cell-phone technology
- Three 8" PMTs detect **Cherenkov light** produced in water:
  - ❑ Charged particles move at ~ c (speed of light in vacuum)
  - ❑ but light can propagate in water at only 0.75c
  - ❑ Electromagnetic fields get "backed up" = Cherenkov radiation, detected by PMTs
  - ❑ Cheap and low-maintenance detectors!

How do PMTs work?

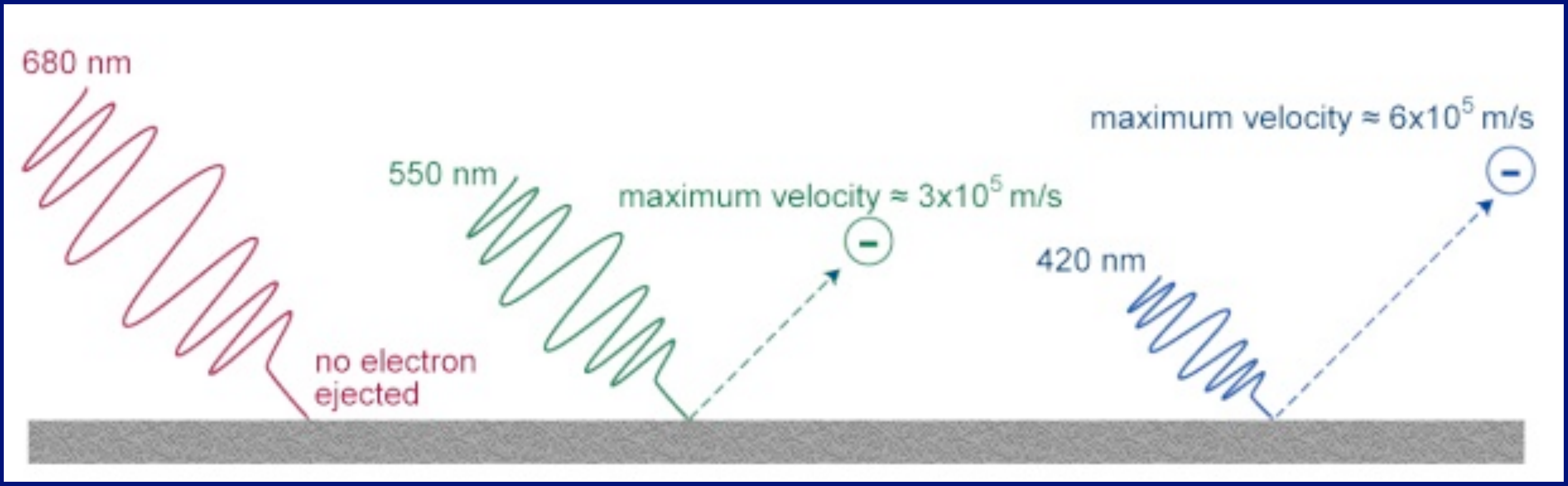
cross section of a PhotoMultiplier Tube

PMTs are used in both scintillator and fluorescence detectors



The Photoelectric Effect

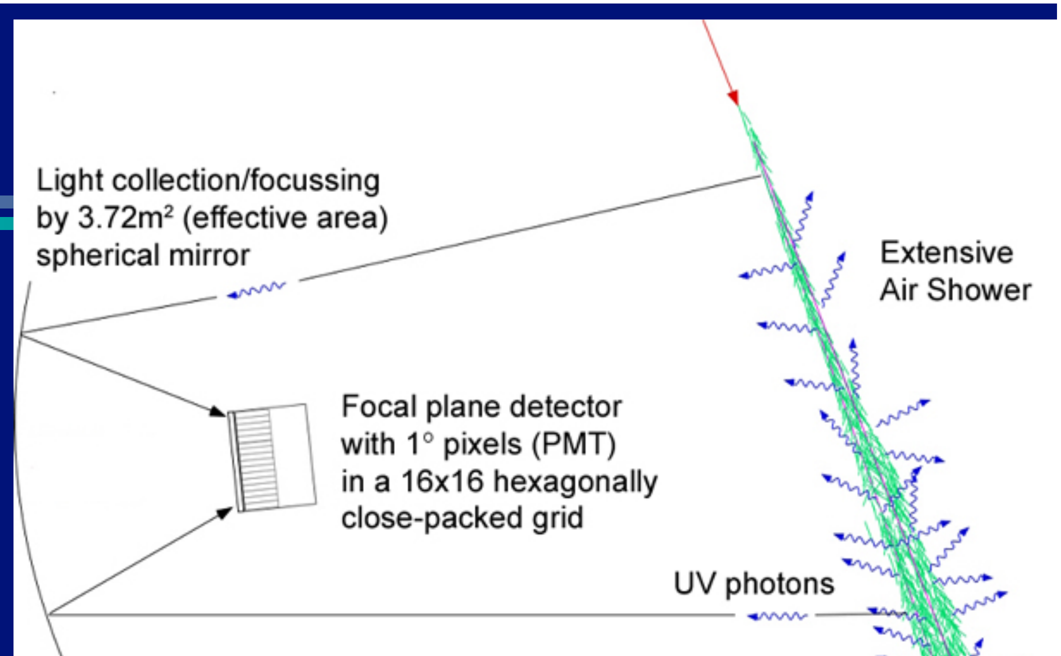
- Incoming photons kick electrons out of the metallic surface of photocathode via the photoelectric effect.



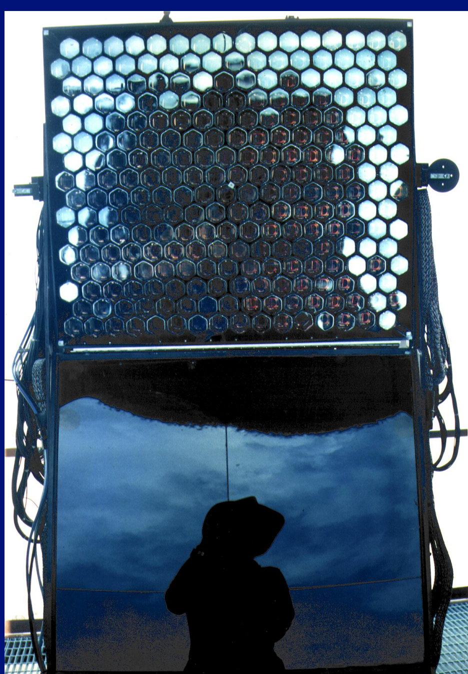
Discovered by Heinrich Hertz in 1887, and explained by Albert Einstein in 1905, using the new idea of quantum theory

- Red light cannot kick electrons loose no matter how intense
- Shorter wavelengths do, even at very low intensity
    - Electrons don't *soak up* light energy, they absorb a *quantum* of light all at once, as if hit by a particle

Air fluorescence detectors

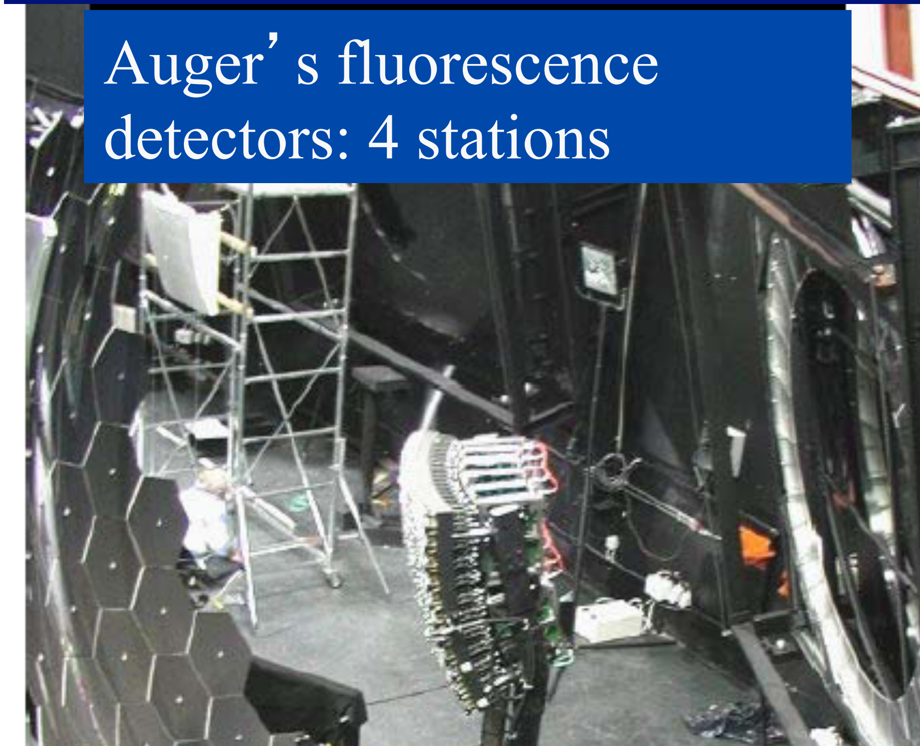


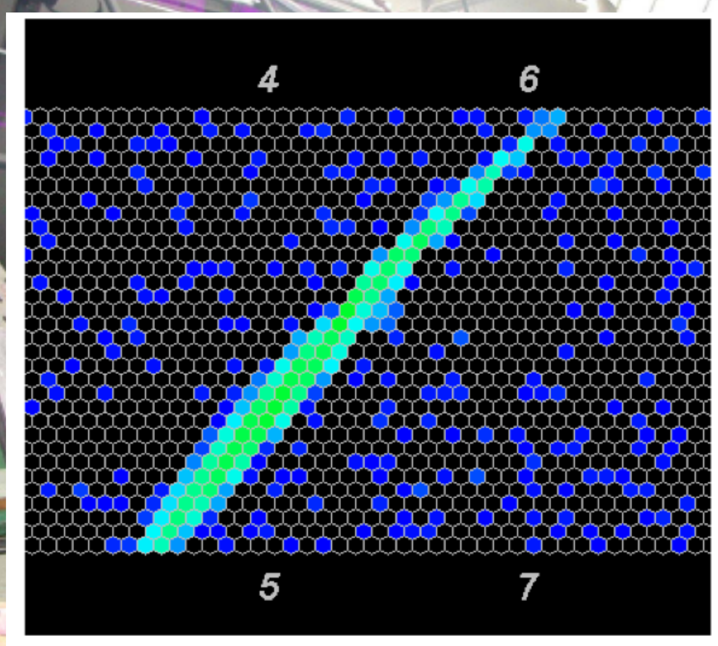
Drawback: only works on **moonless, clear nights!**

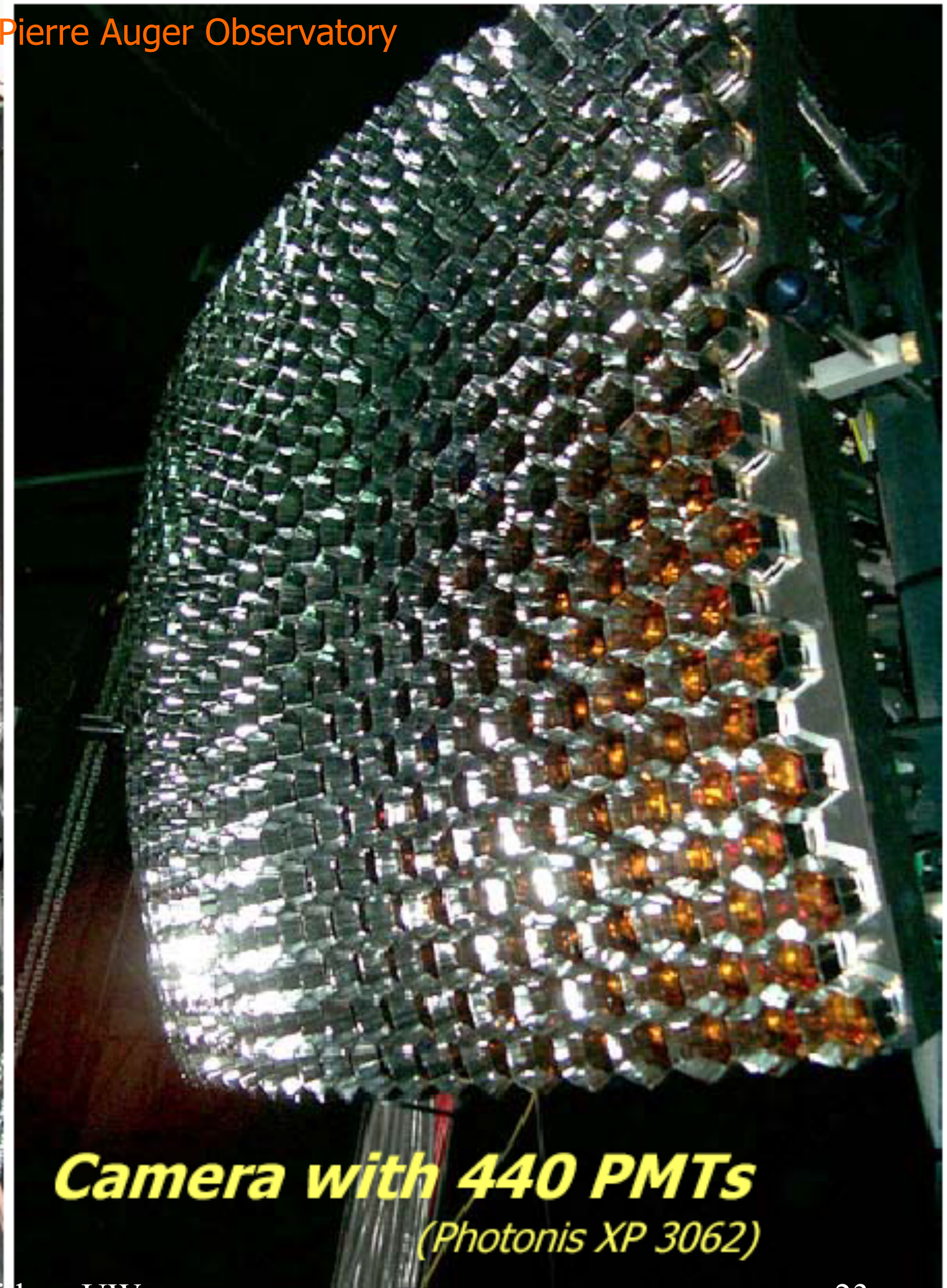


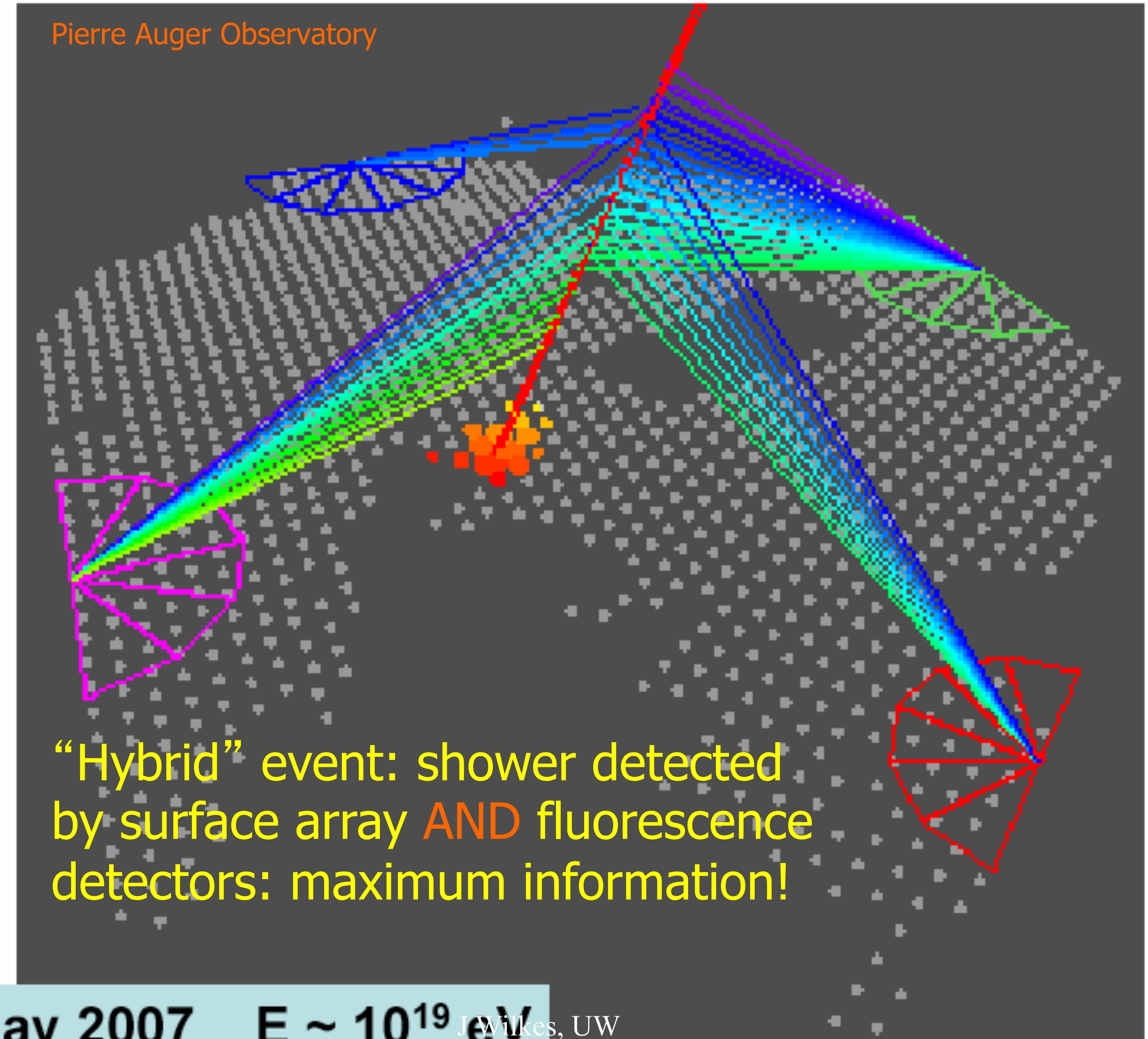
- See the shower as it develops in the atmosphere
- Shower particles excite nitrogen molecules in air
  - They emit UV light
- Detect UV light with "Fly's Eye" on the ground
  - Each small patch of sky is imaged onto one photomultiplier tube

Auger’ s fluorescence detectors: 4 stations

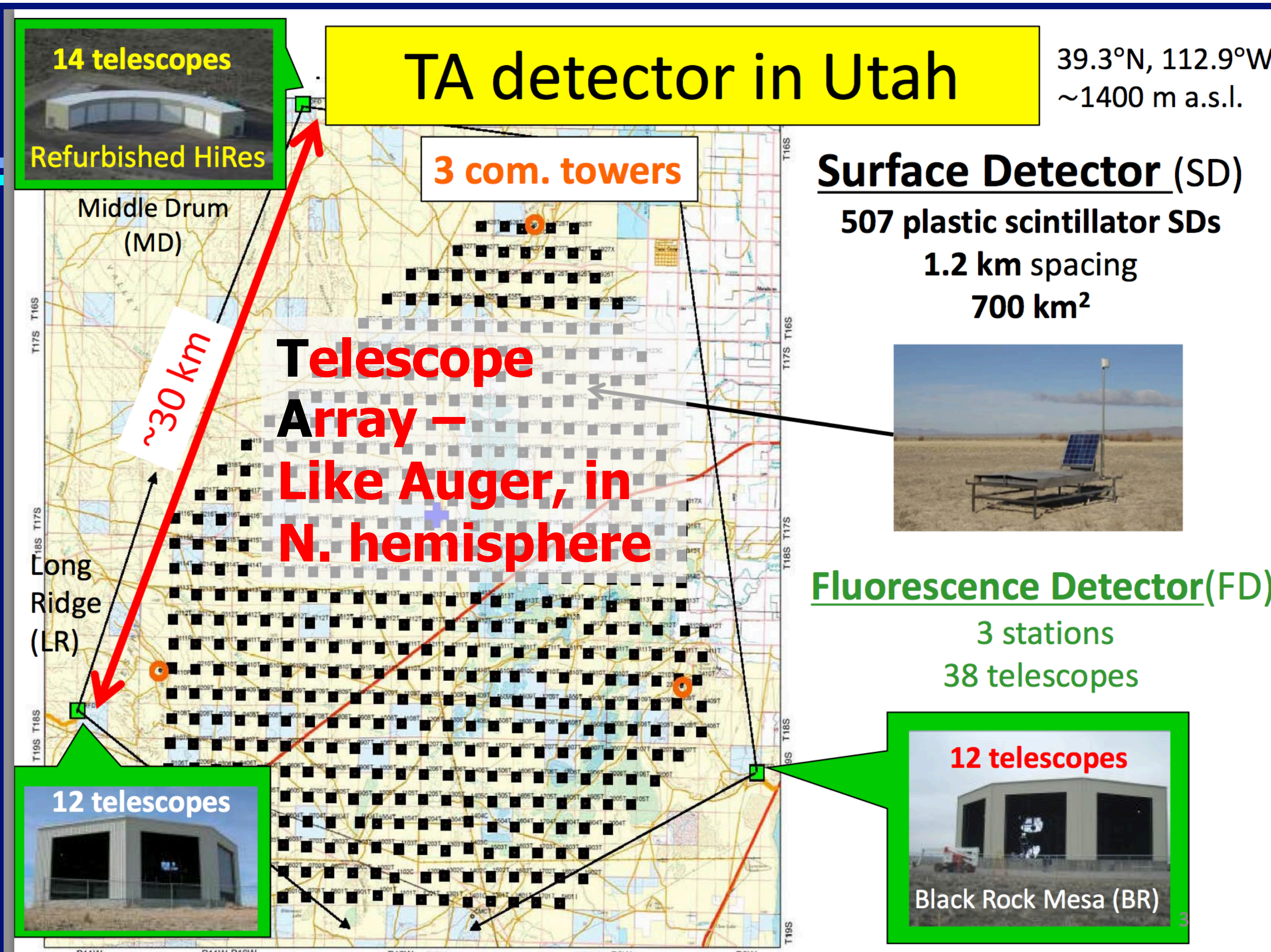








20 May 2007 E ~ 10^{19} eV



- Japan-US collaboration: AGASA and Fly's Eye/Hi-Res veterans
- Location : Millard County, Utah - ~ 100 mi SW of Salt Lake City

One TA scintillator detector, with size references

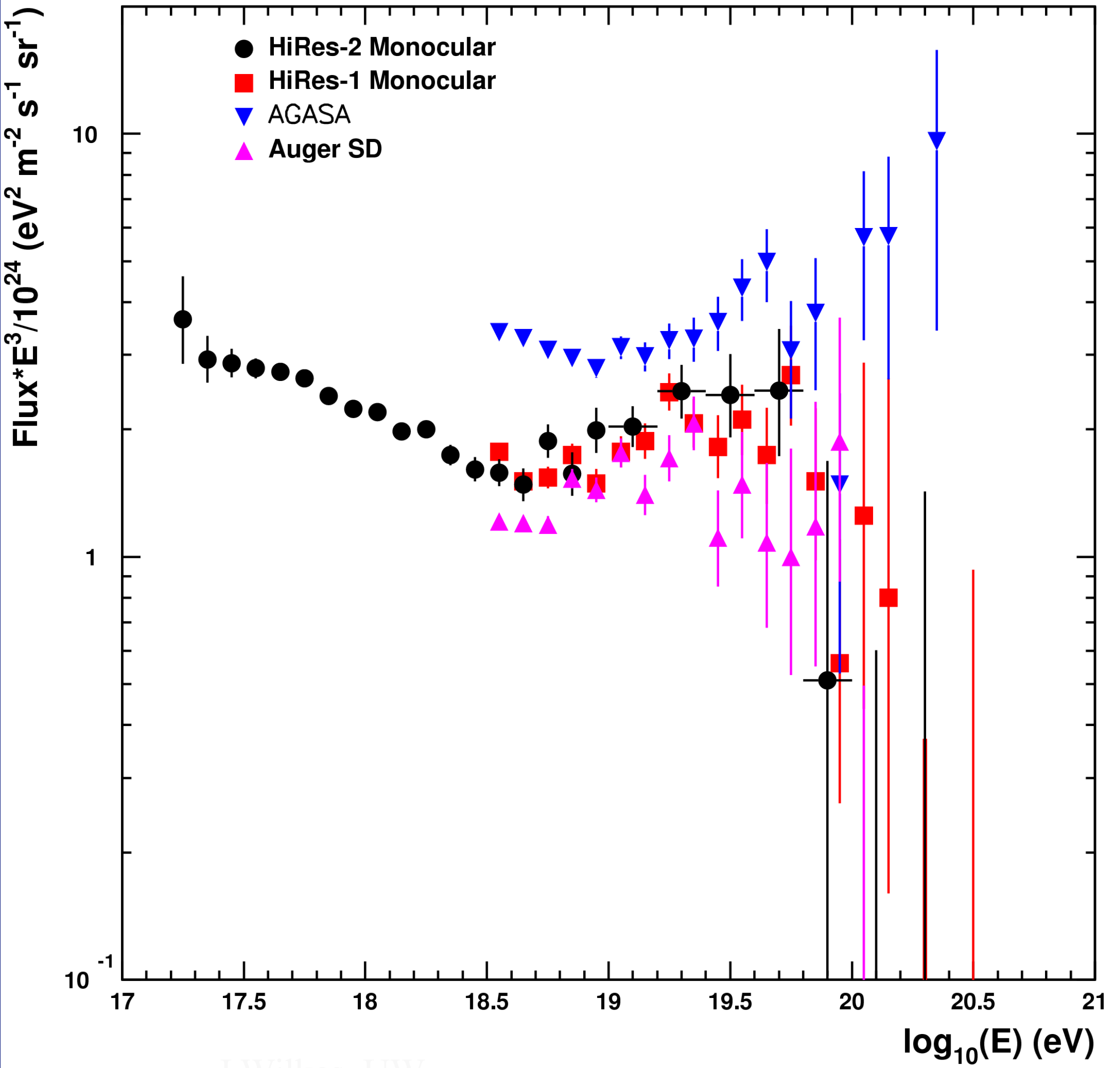
Why build TA?

- **To see galaxies in northern sky**
- **Need to check/ confirm Auger results!**

Top end of the CR spectrum: some time ago...

Why we need TA:
Earlier experiments disagreed!

HiRes, AGASA, and Auger (as of 2005)



If AGASA was right, where is the GZK cutoff?

New physics at EHE?

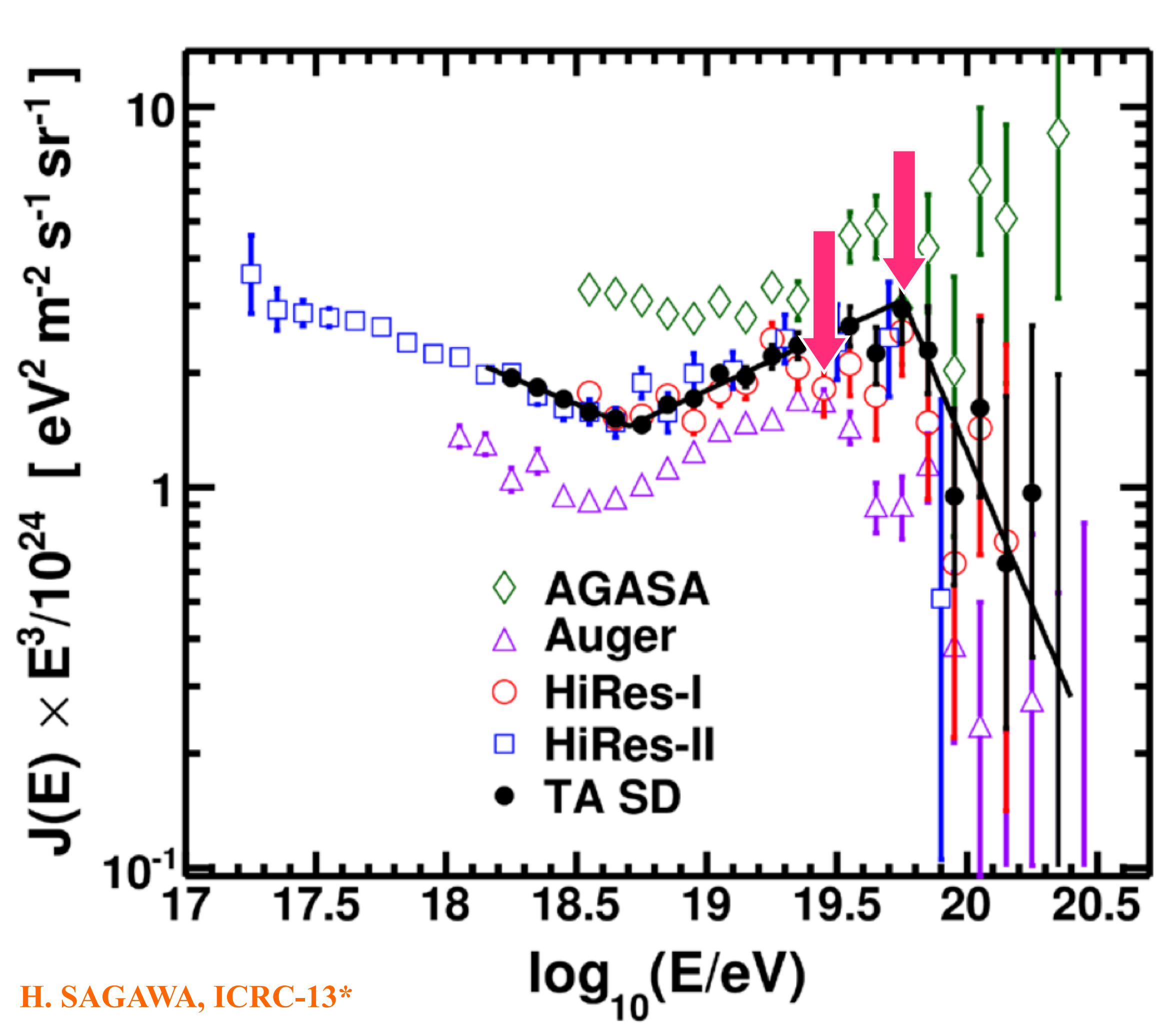
Or just the E axis, shifted due to error?

...and 3 years ago...

Old data from HiRes and AGASA, compared to new data from

TA, and Auger (2013 ICRC)

Notice difference between the two – Auger's GZK cutoff at lower E

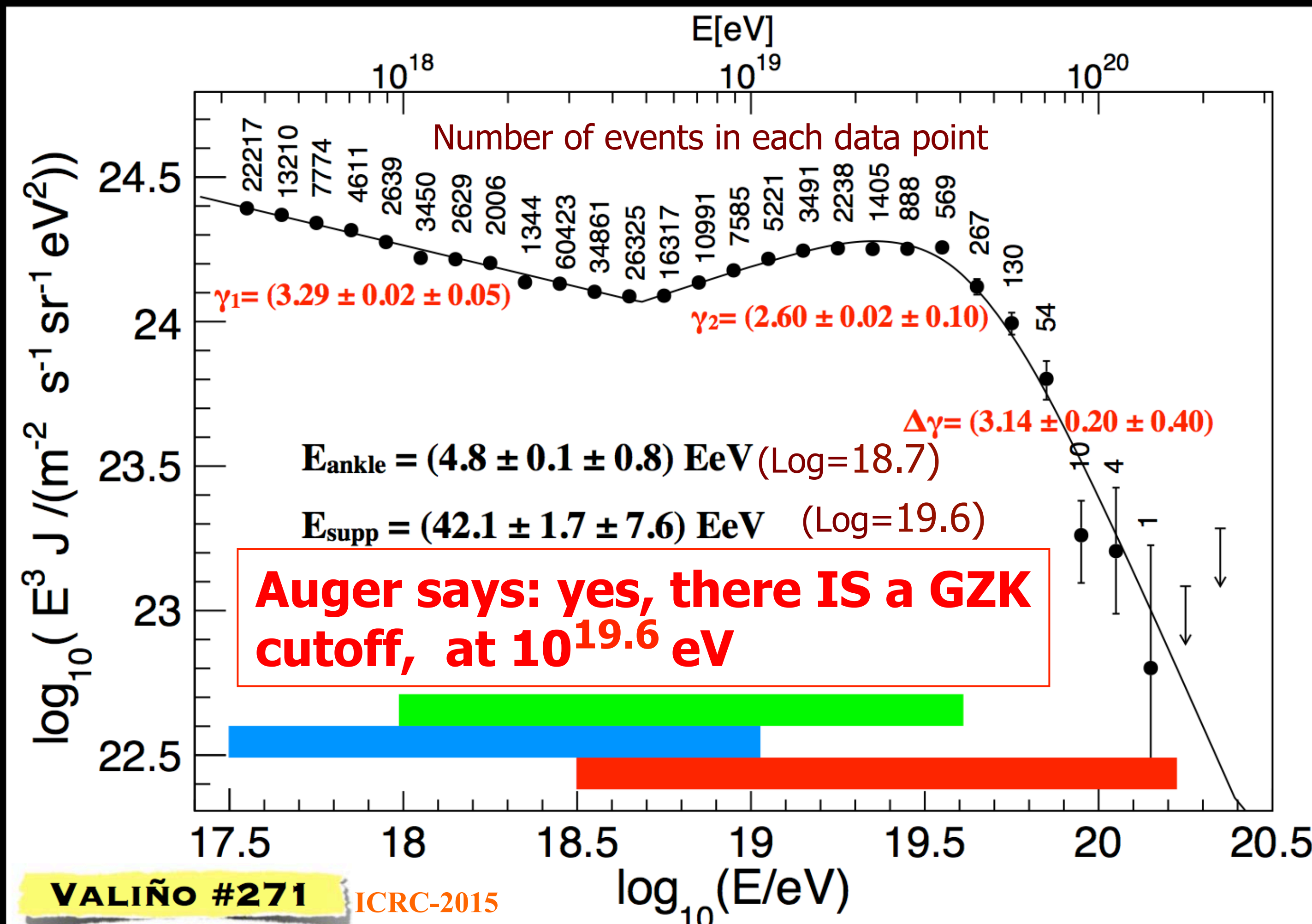


*2013 Int. Cosmic Ray Conf. http://143.107.180.38/indico/conferenceTimeTable.py?confId=0#20130702

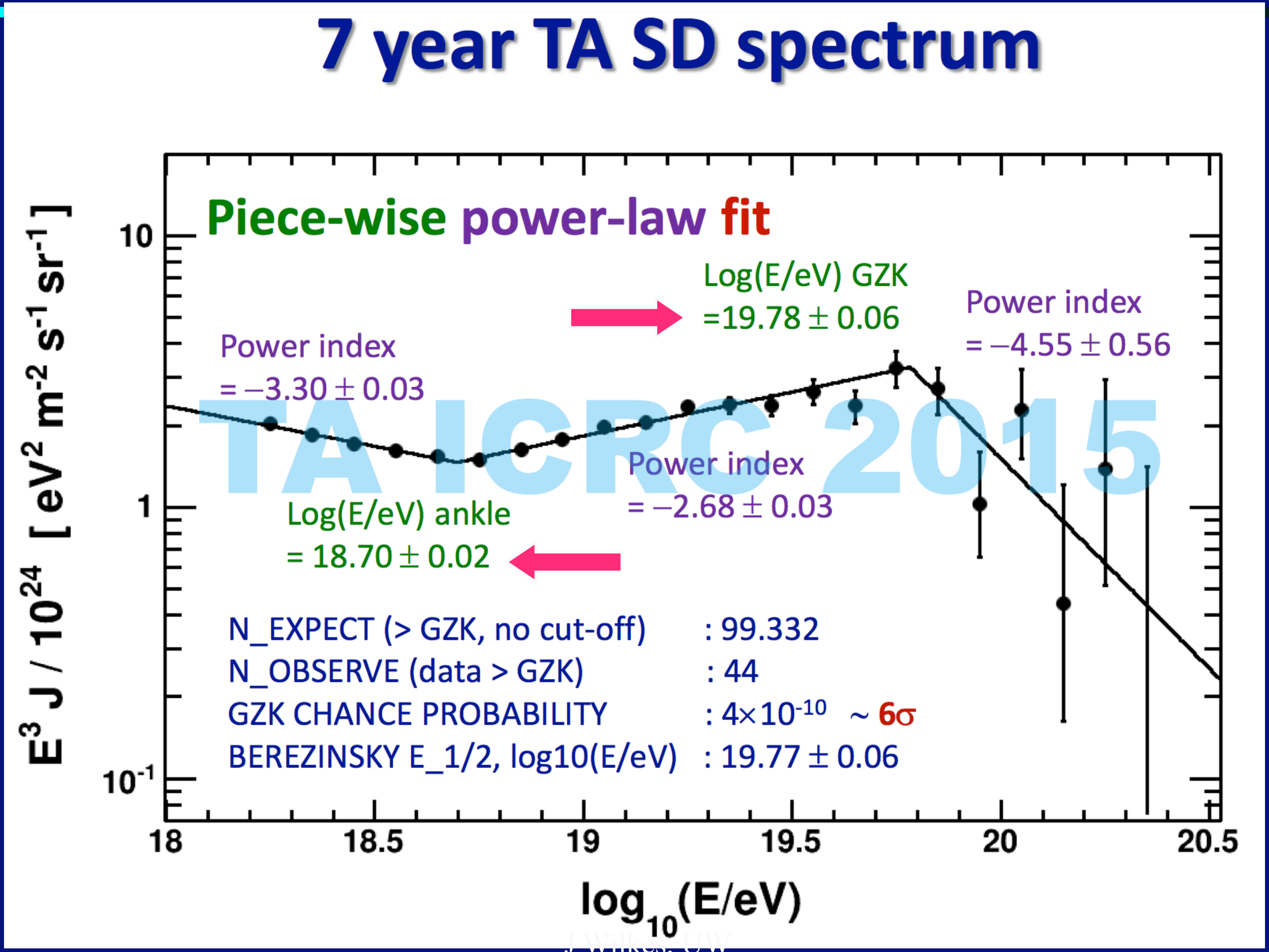
2015 results: fits to slope, numbers of events

4 data sets combined: SD 750 m, FD (hybrid), SD 1500 m (0-60˚), SD 1500 m (60-80˚)

≈ 200 000 events, ≈ 50000 km² sr yr exposure, FOV: -90˚, +25 in δ



2015 TA results: confirm Auger's

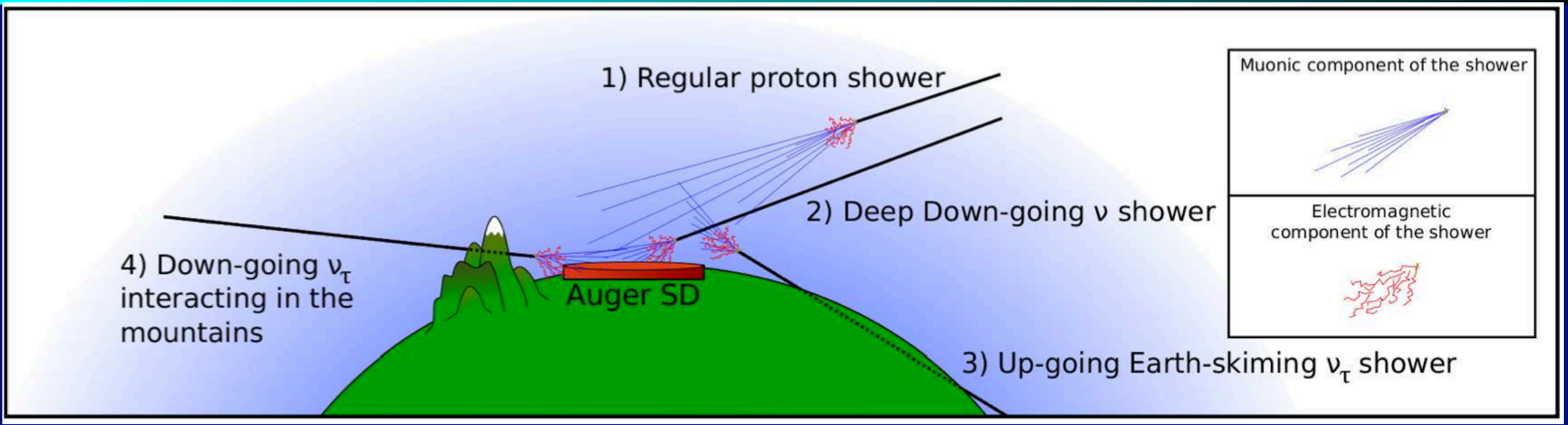


So there *IS* a GZK effect: can we find 'lost' CRs?

- CRs above 10^{20} eVinteract long before reaching Earth
  - About half of CR's original energy is lost in each interaction
    - Energy lost becomes *secondary particles*
    - All kinds of particles produced – energy available is enormous
- BUT: only stable particles can reach us!
  - Millions of years to travel from intergalactic space to Earth
  - All radioactive secondary particles decay
- The only stable particles we know of are
  - Protons
  - Electrons / photons
  - Neutrinos: (GZK-produced neutrinos are called "cosmogenic")

  Everything else decays, eventually becoming these
- So: We should see neutrinos instead of >20 EeV CRs

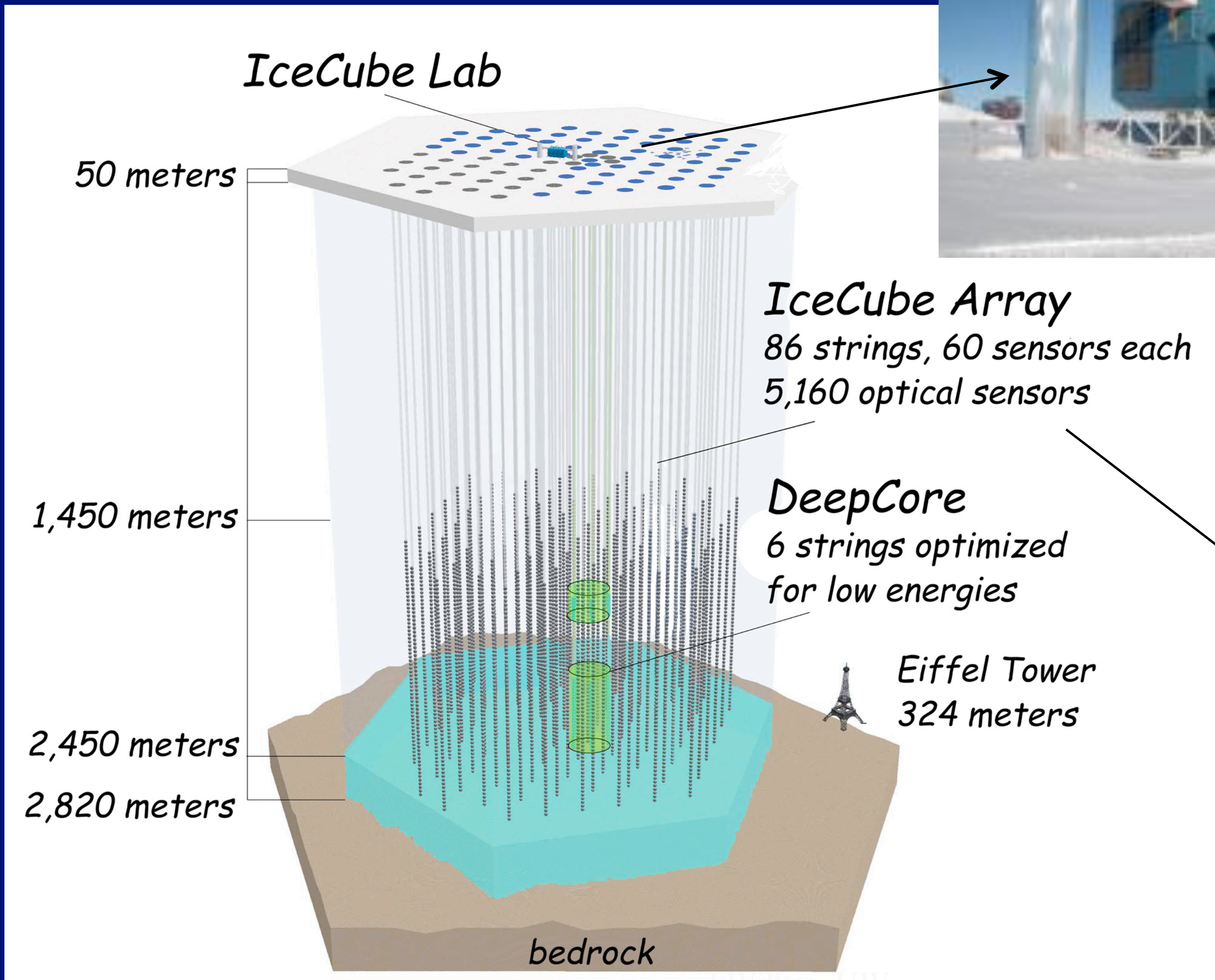
GZK products: Detecting cosmic UHE neutrinos

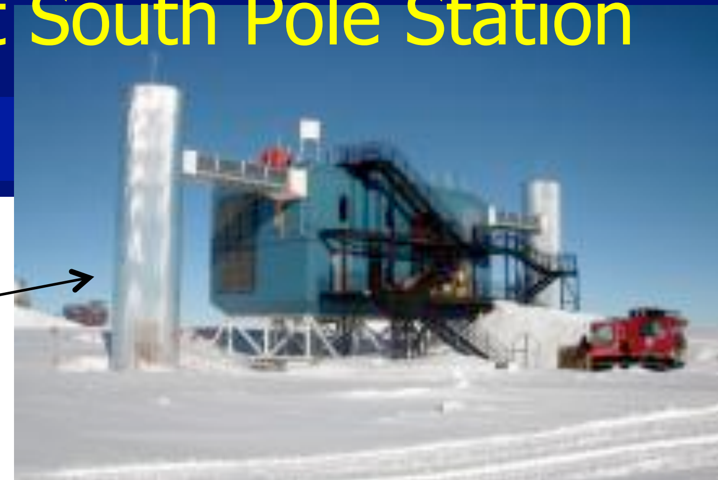


- Neutrinos = neutral particles produced in decays of mesons
  - They can point back to sources of trans-GZK cosmic rays
  - Weakly interacting – most do not interact, can penetrate 100km of Earth
- Auger can detect and identify neutrinos
  - Downgoing if it interacts in the atmosphere
  - Upward going if it interacts near surface of Earth (skims surface, or interacts in Andes mountains → shower reaches Auger)
- Other experiments specialize in neutrinos

IceCube neutrino detector at South Pole Station

South pole icecap is 3000 m thick



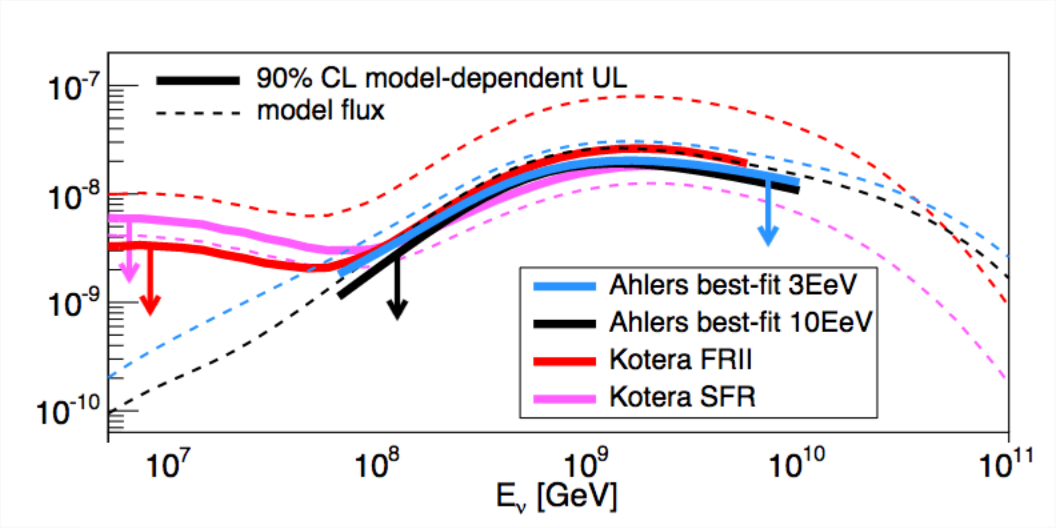


IceCube's Optical Sensors (PMTs)

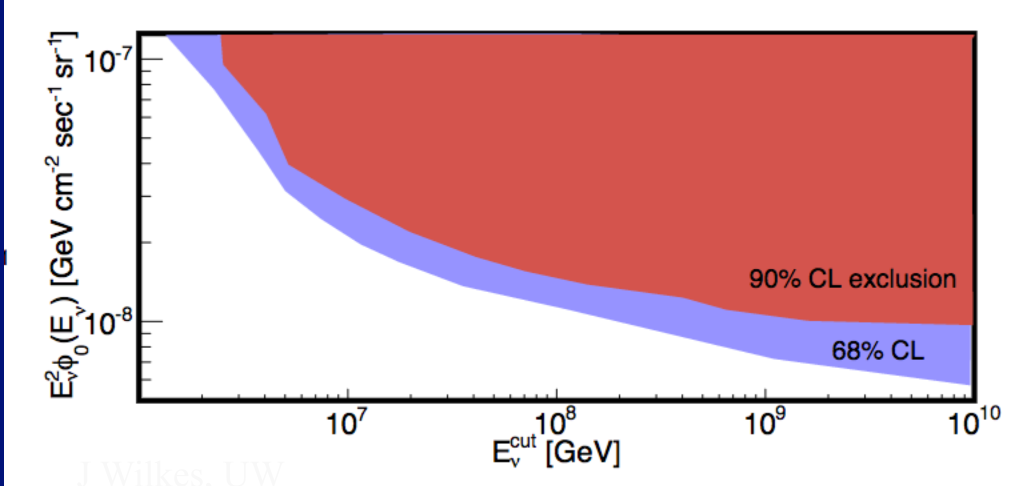
Does IceCube see cosmogenic neutrinos?

- Not yet: no UHE neutrinos found in 7 years of IceCube data
  - Highest energy neutrinos observed so far: ~10^{15} eV

Predictions by theorists for cosmogenic neutrino flux versus energy: expect an excess around 10^{18} eV



How do you describe a non-observation?
You give an upper limit:
Zero events seen means fluxes in red area can be ruled out with 90% confidence



What's my message?

- Physics is not a big book of "answers"!
  - We have lots of open questions, lots more to learn
    - YOU can help
      - Students: come to UW and study physics (or another science, or engineering)
      - Teachers: send us your best students!
  - The process of learning about the universe is not easy
    - Everybody finds physics hard!
    - Takes lots of effort by lots of people all over the world, over a long time
    - Constant (friendly) arguments to decide who is right !
    - Rarely a simple black-and-white separation between true and false – in science, or in the world in general

References: Websites to visit

- https://www.auger.org
- http://www.telescopearray.org
- http://icecube.wisc.edu/outreach
- https://helios.gsfc.nasa.gov/cosmic.html

New website prepared by UW student:

Building a Thermoelectric Cloud Chamber

Instructions, Science, and Resources for Educators and Hobbyists

- http://students.washington.edu/jlslack/wordpress/science/

- These slides will be posted on the UW Quarknet web