Galactic and extra-galactic cosmic rays: air shower experiments

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

Discovery of cosmic rays: 1911-12

Austrian physicist Victor Hess on a 1912 balloon Flight

- Studied radioactivity in the Earth
- Carried “electroscope” (ionization measurement device) in a balloon, to measure total radiation rates vs altitude
- Expected to show that radiation drops off with increasing altitude
- Instead: radiation increases!

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
    - CRT TV set produces 10^3 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 released in emission of 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: • Mass (rest energy) of proton
TeV (10^{12} eV)	Energy per proton reached by Fermilab's Tevatron particle accelerator
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"

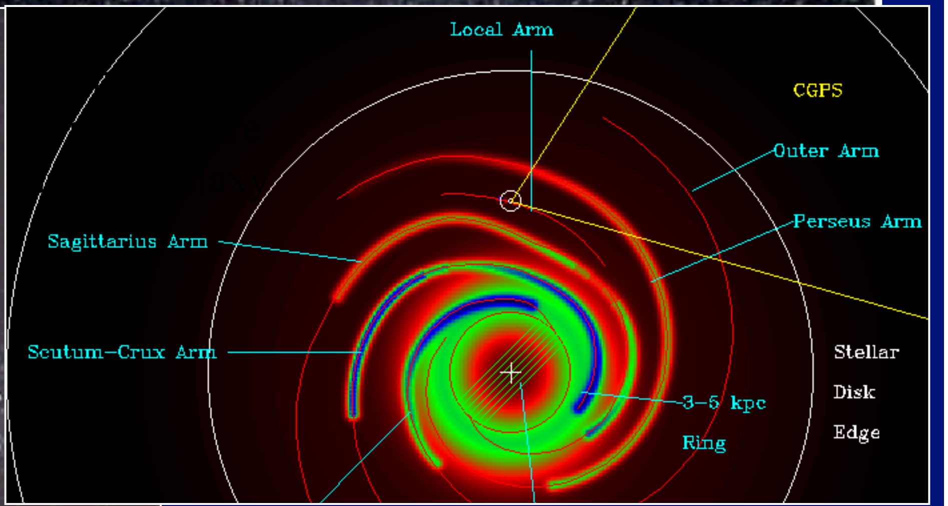
- Cosmic rays = particles (with mass>>0) reaching Earth from space
  - Usually we do not include gamma rays and neutrinos
- Solar cosmic rays = particles from the Sun
  - Typically low (MeV) energies (nuclear physics processes !)
  - Strongly affected by magnetic fields of Earth and Sun
    - ...which 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

(Actually not our Galaxy, but similar neighbor)

(Actually our Galaxy! composite of photos round the milky way!

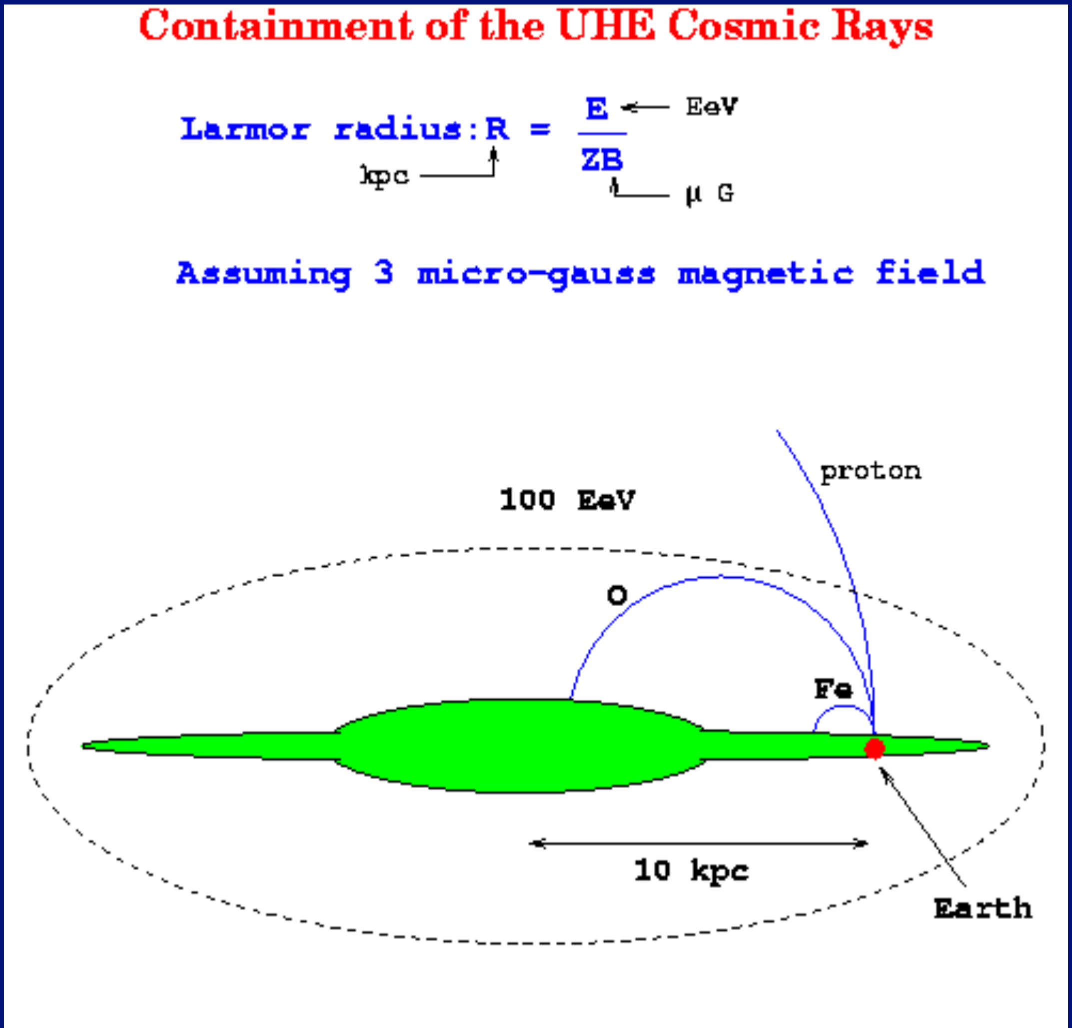


Galactic and extra-galactic CRs

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?

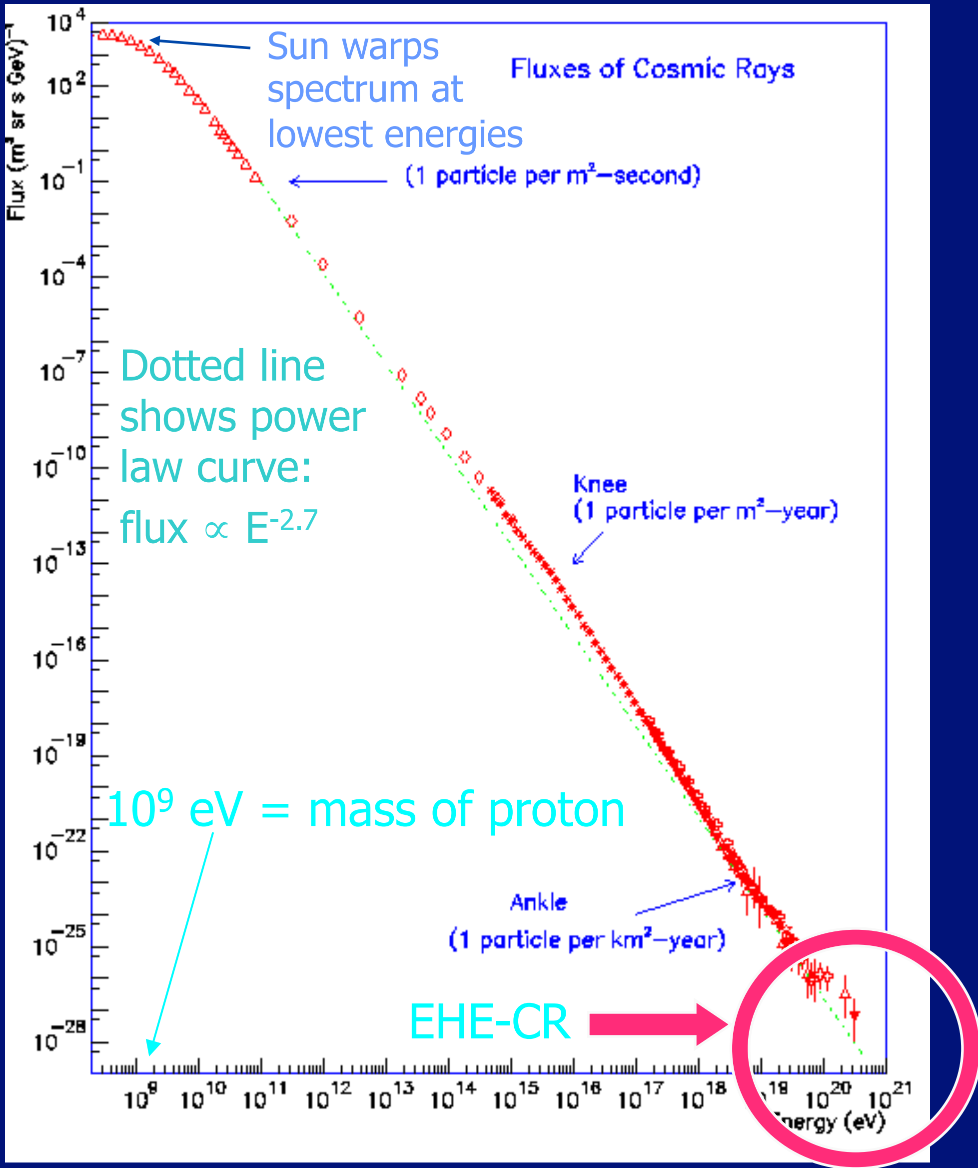
Probably very weak

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

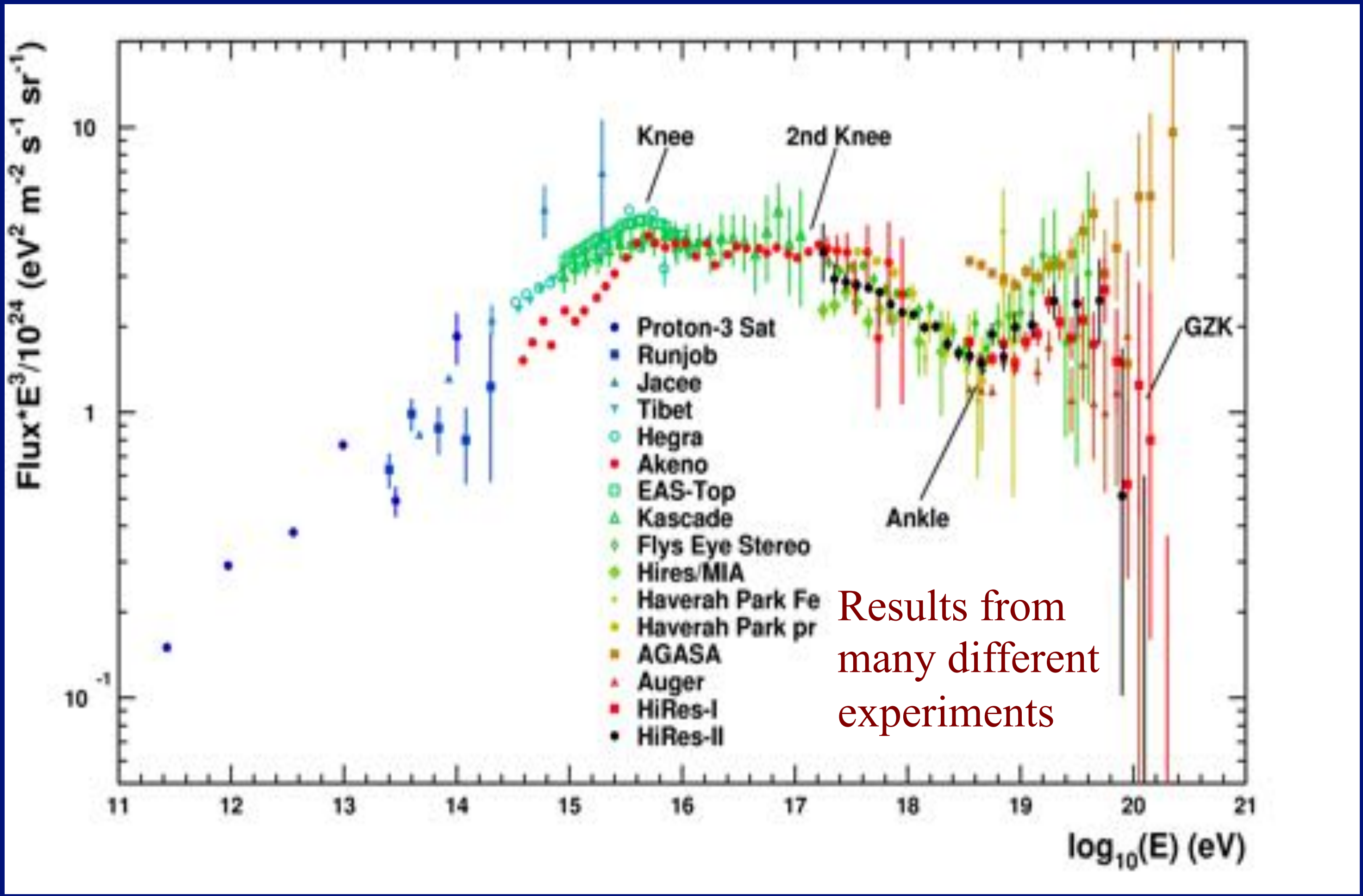
The galactic cosmic ray spectrum

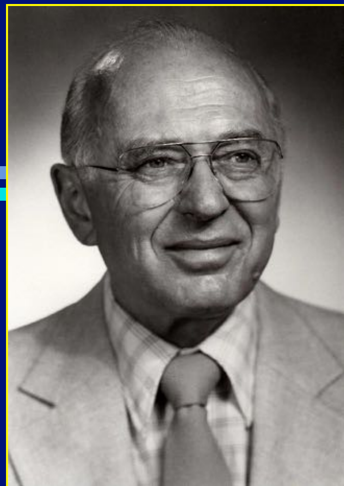


- Cosmic ray *spectrum:* intensity vs energy for cosmic rays
  - All: protons and nuclei
  - At "top of atmosphere"
  - Notice: scales' steps are factors of 10!
- The very highest energy cosmic rays:
  - Rare and puzzling
  - Only a few detected worldwide
  - Should be none!

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





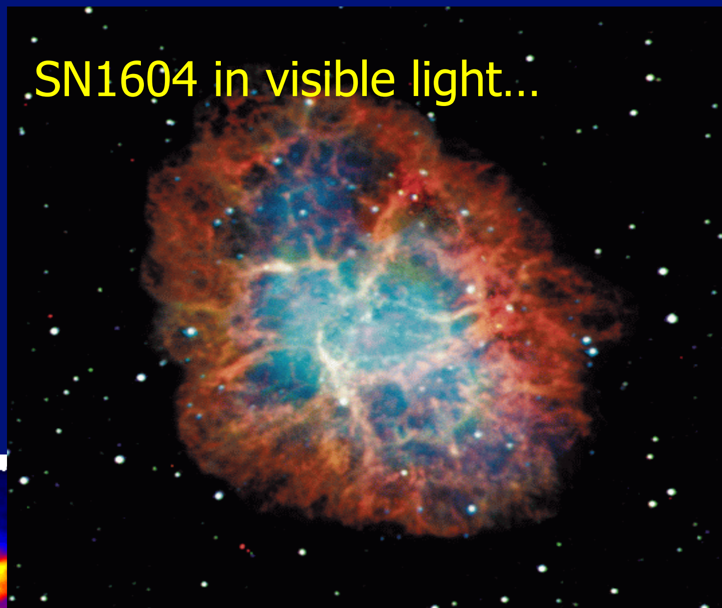
Ken Greisen (Cornell) **G. Zatsepin (Moscow State Univ.)**

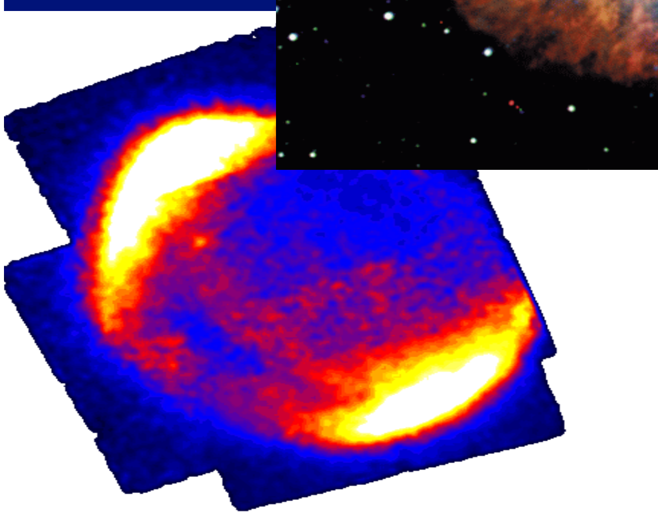
The "GZK cutoff"?

- 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

Most cosmic rays come from Supernovae
Example of remnant: SN1606 = Kepler's

- SN1604 in visible light…





When large stars run out of nuclear fuel, they collapse and sometimes explode, becoming a "super-nova".

SN's can emit as much energy as a galaxy-full of normal stars, for a few days…

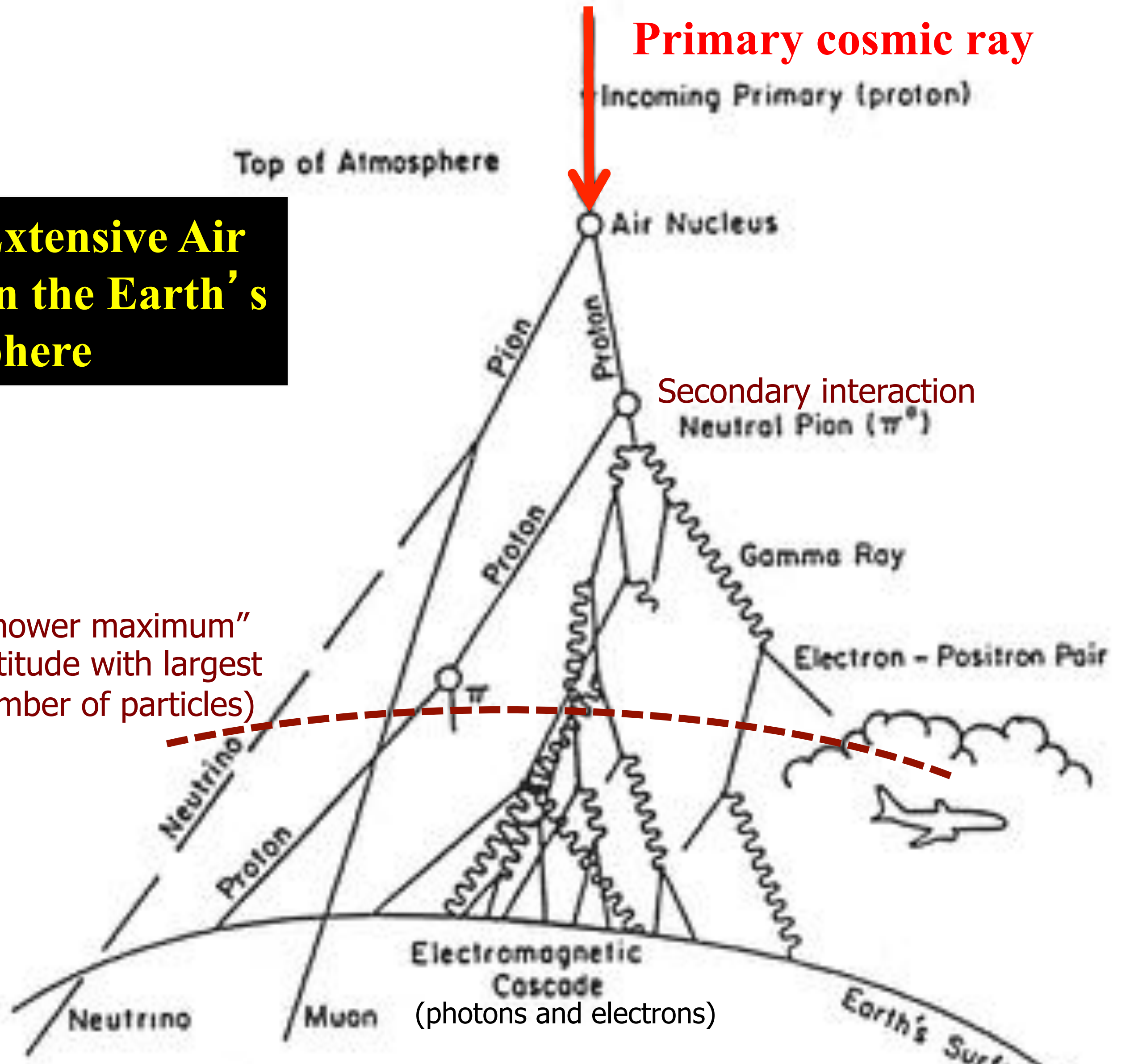
…and in cosmic rays (radiation from electrons in the supernova remnant), showing the shell of the supernova remnant still expanding into space

SN-1006 was recorded by scholars in China, Europe and Central Asia: a "visiting star", visible in the daytime for weeks in 1006.

SN-1604 was described by Johannes Kepler (who provided Newton with basic info on the solar system)

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

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



Mostly muons, electrons and photons reach Earth's surface

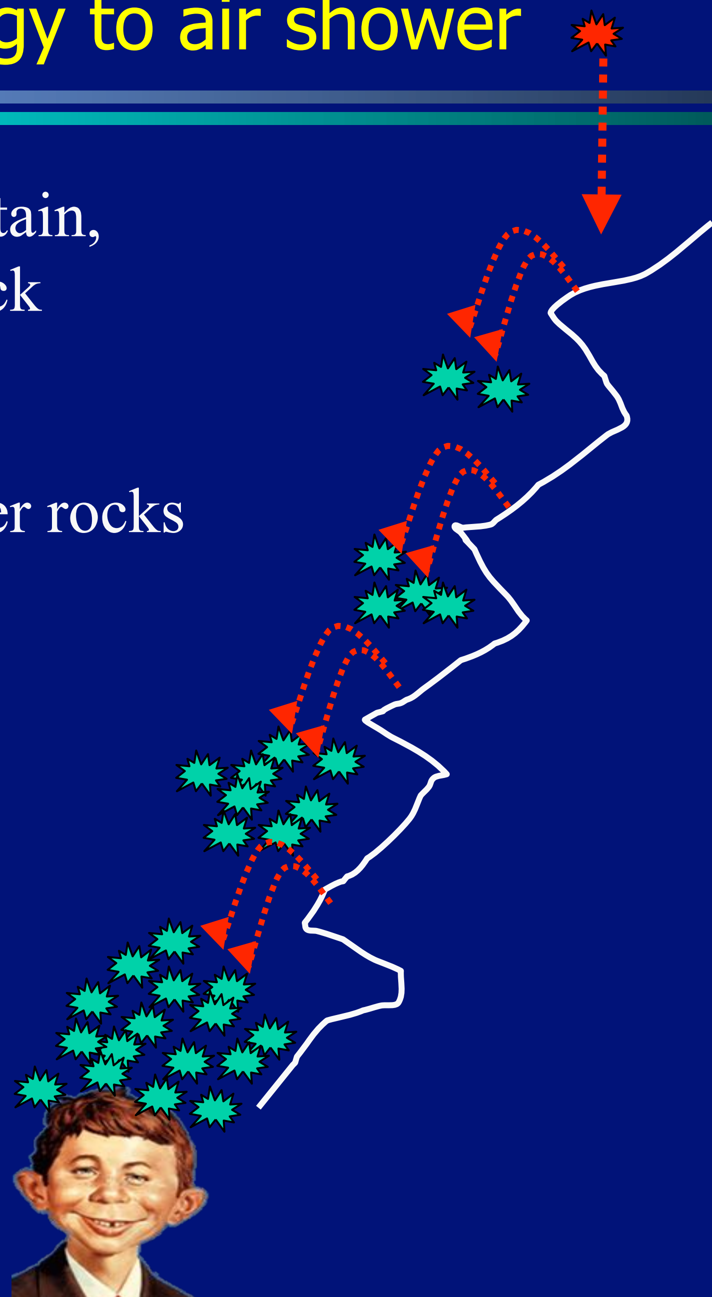
Gravitational analogy to air shower

Meteor hits mountain,
knocks loose a rock

knocks loose other rocks

…and so on

Cascade process



Brief digression: more about muons
Clocks “really do” slow down

- Famous demonstration: fly a super-accurate clock at high speeds

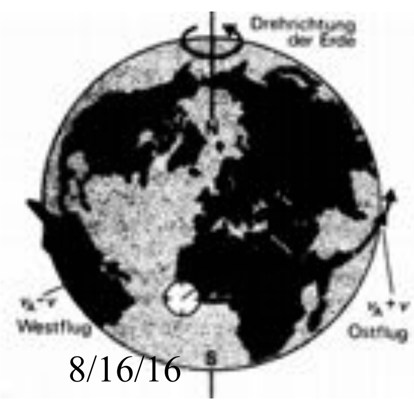
Airborne Atomic Clocks to Test Einstein Time Theory

New York Times, Oct 2, 1971

Atomic clocks use very stable oscillations of cesium atoms – 1970s models had nanosecond accuracy.

Hafele-Keating 1971 experiment: Synchronized 2 cesium clocks, flew one around the world in jet, compared again.

Difference*: predicted 40 $\pm$ 23 ns,
Observed 59 $\pm$ 10 ns



Cesium clocks at NIST
Similar to ones used in 1971

Clocks in different reference frames really **do** measure time intervals differently

*we have much more precise measurements since then...

Everyday proof: cosmic ray muons*

***Discovery of muons was PhD thesis of UW Prof. Seth Neddermeyer**

- Cosmic rays = protons or nuclei from dying stars (supernova explosions)
  - Constant rain of high energy particles onto earth from all directions
    - More on cosmic rays later
  - CRs smash atoms in upper atmosphere, make a cascade of elementary particles in atmosphere = "cosmic ray air shower"
  - Muon particles are produced at 15~20 km altitude, with speeds ~ 0.95c

- In lab, muons have radioactive lifetime **2.2 microsec**

  So, average distance they can travel ought to be

  d = $(3\times10^{8}$ m/s$)$ $(2.2\times 10^{-6}$ s$)$ = **660m** (less than 1 km)

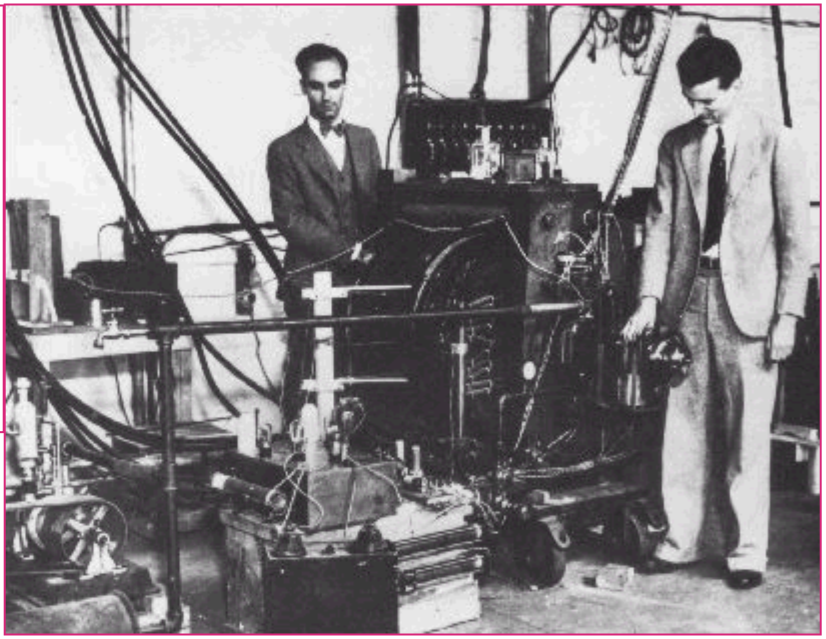
  - But muons are **abundant** at sea level
    - they travel 20X farther – live 20X longer!

  = Direct demonstration of "reality" of time dilation:
    - » decay lifetime is measured in muon's clock
    - » Muon's clock runs slow according our clock

Muon "telescope" in a local school classroom: each black square is a particle detector. If all 4 fire at once, a muon particle has passed through them.
For details see http://neutrino.phys.washington.edu/~walta/

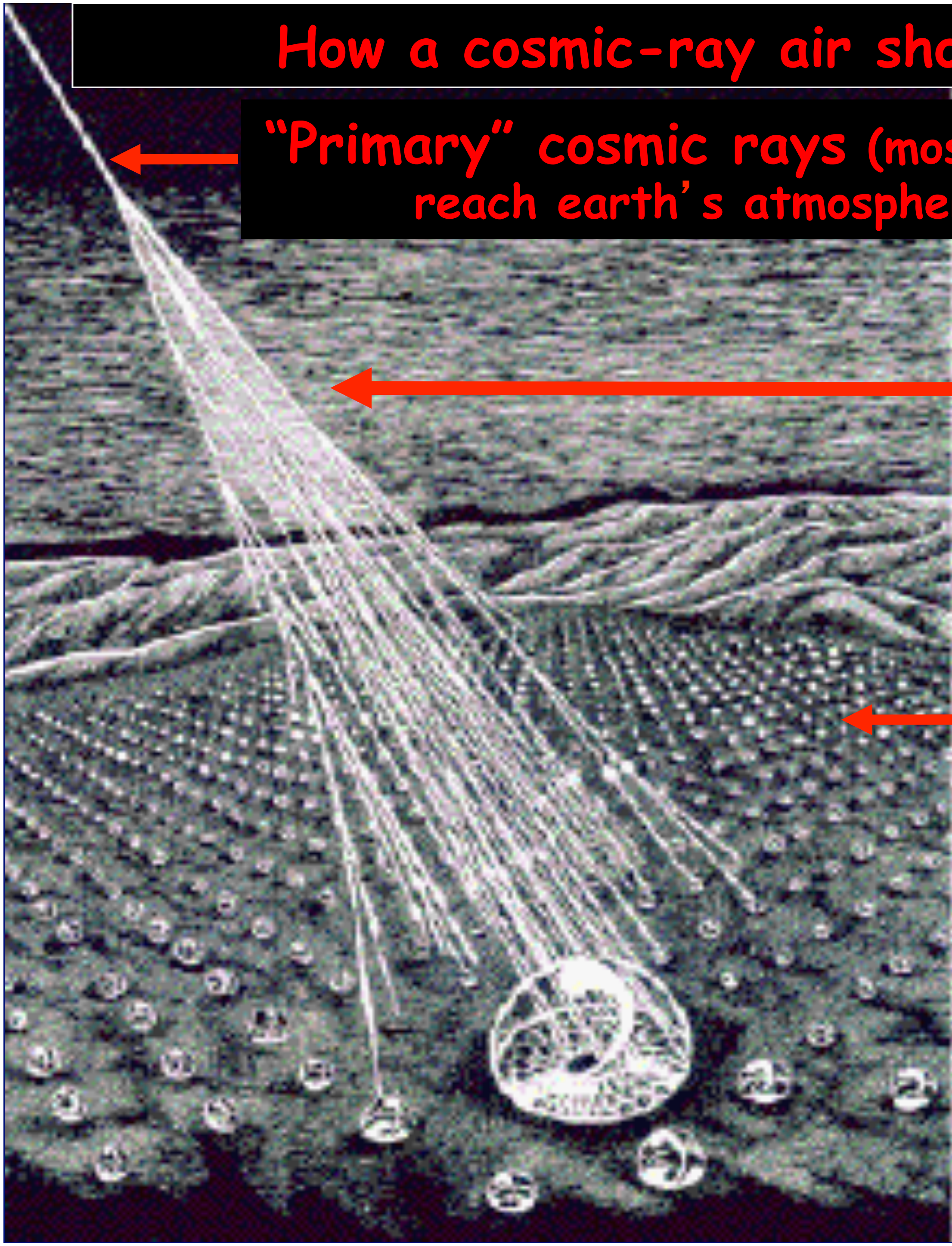
Cosmic Rays, Muons and UW Physics Dept

Grad student Seth Neddermeyer (r.) and Prof. Carl Anderson at CalTech in 1937, with cloud chamber they used to discover the muon.



Neddermeyer (1907-1988) later came to UW where he founded our cosmic ray and particle physics research group.
He received US Medal of Science from President Ronald Reagan in 1983.

How a cosmic-ray air shower is detected



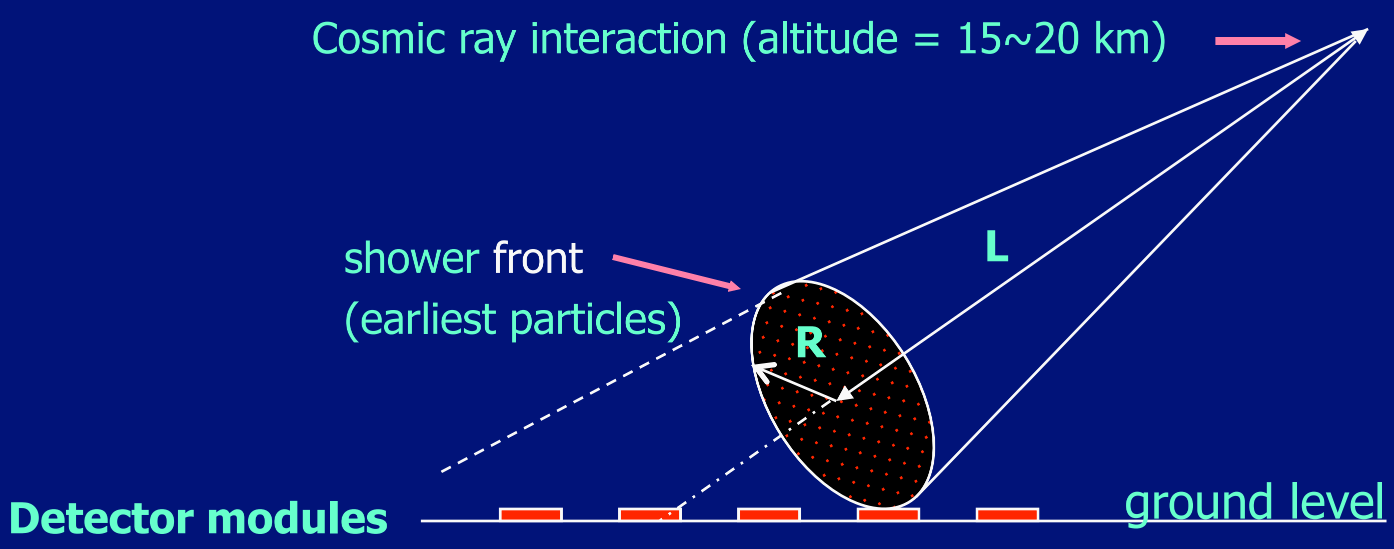
"Primary" cosmic rays (mostly protons or light nuclei) reach earth's atmosphere from outer space

"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

Howe we estimate CR direction and energy from EAS

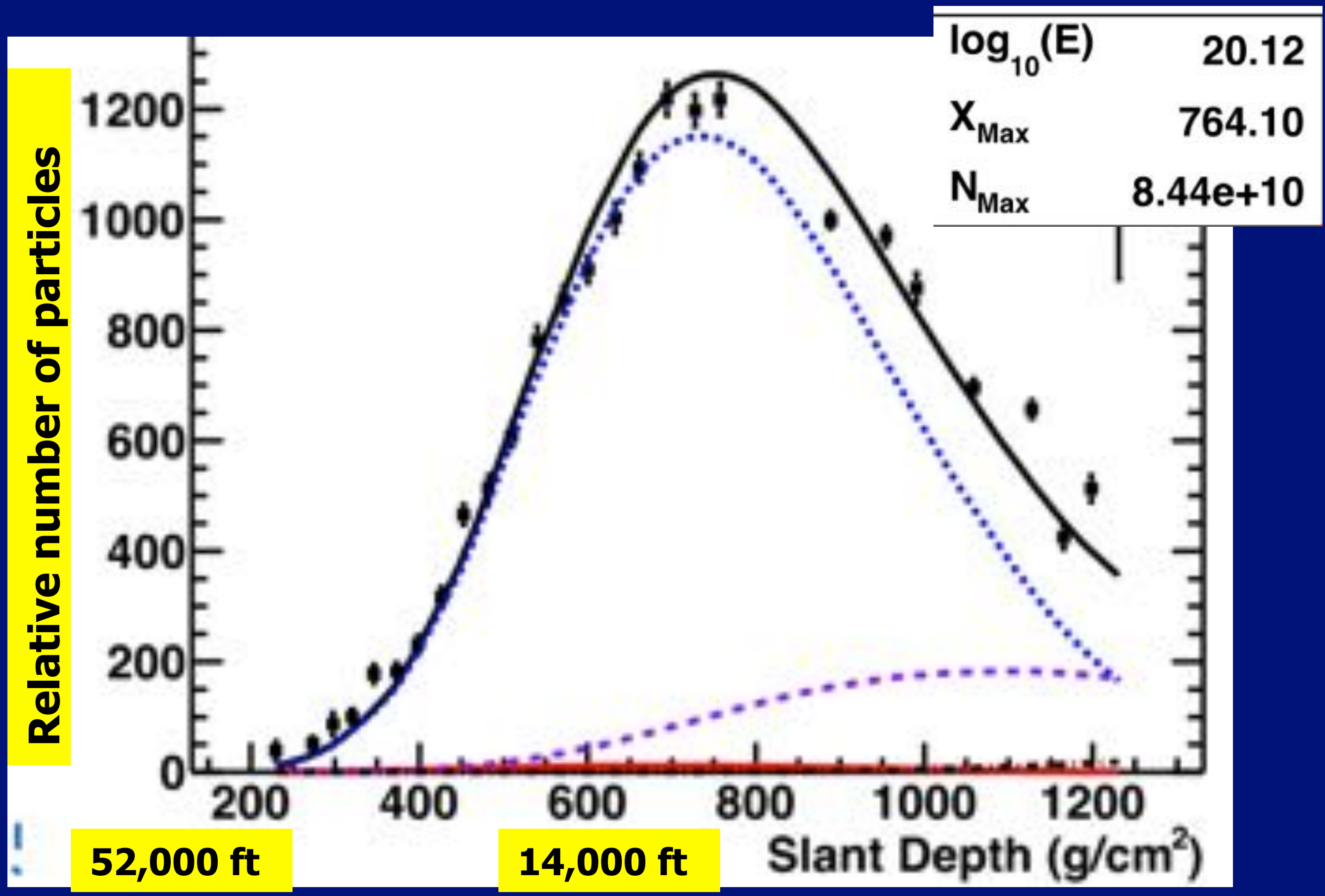


- Each detector module reports:
  - Time of hit (better than μsec accuracy)
  - Number of particles hitting detector module
- Time sequence of hit detectors → shower direction
- Total number of particles → shower energy
- Distribution of particles → distance L to shower origin

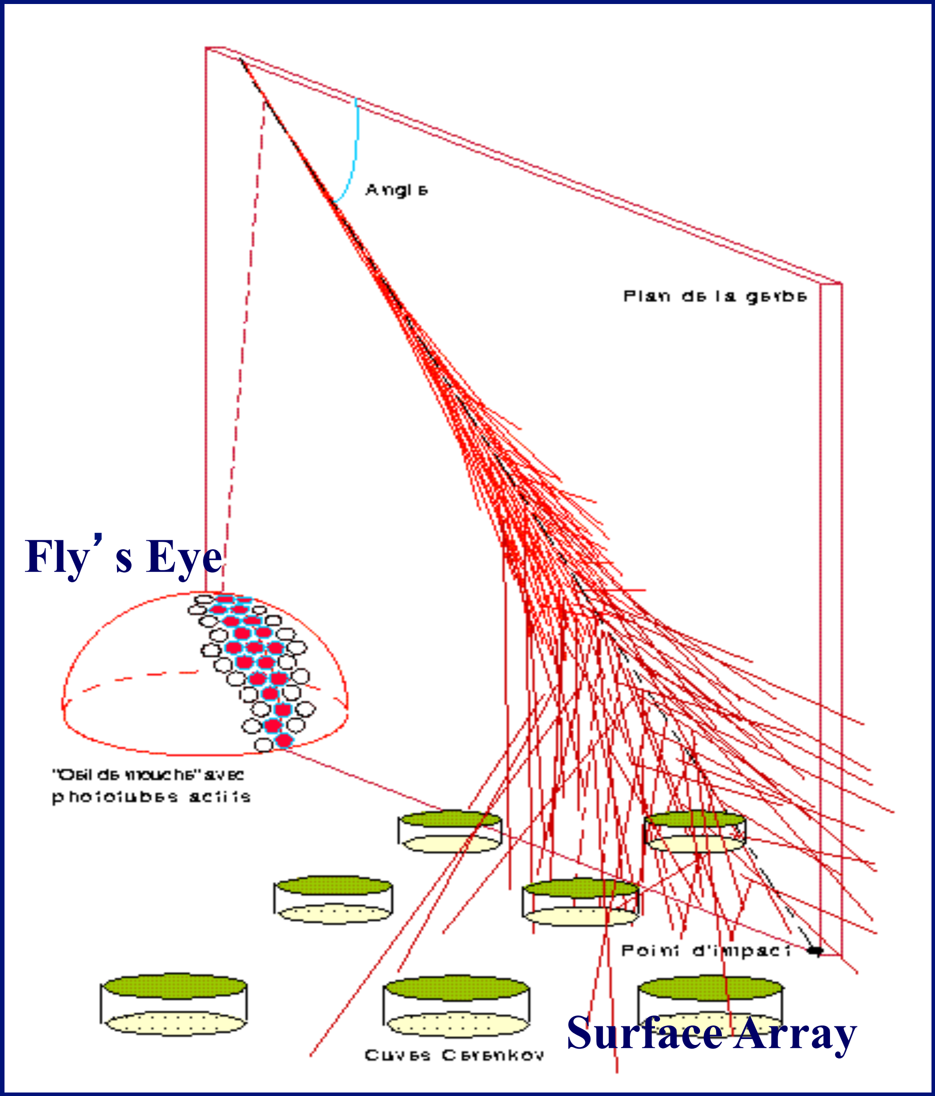
Shower profile: number of particles vs depth

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 other year since 1947. CR physicists present their latest results at ICRCs. ICRC-2015 was held in late July in the Netherlands.



Cosmic Ray Air Shower – detector types



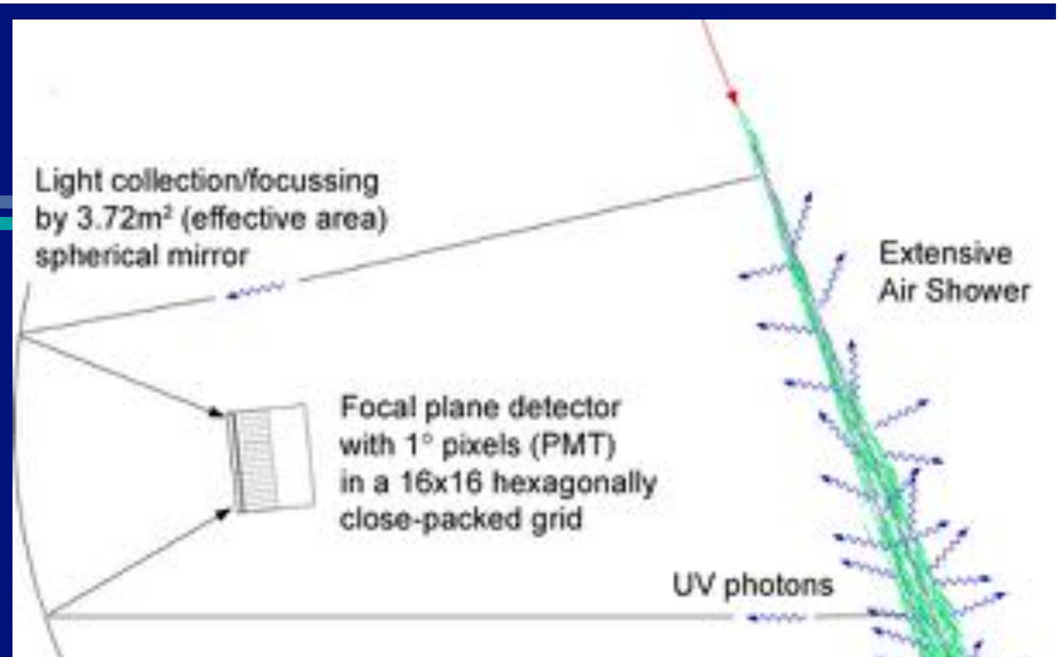
EHE air shower measurements are made by two techniques

1) Surface Arrays

   Scintillator counters or Cherenkov detectors

2) Fluorescence Telescopes
   Arrays of photodetectors (“Fly’s Eyes”)

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

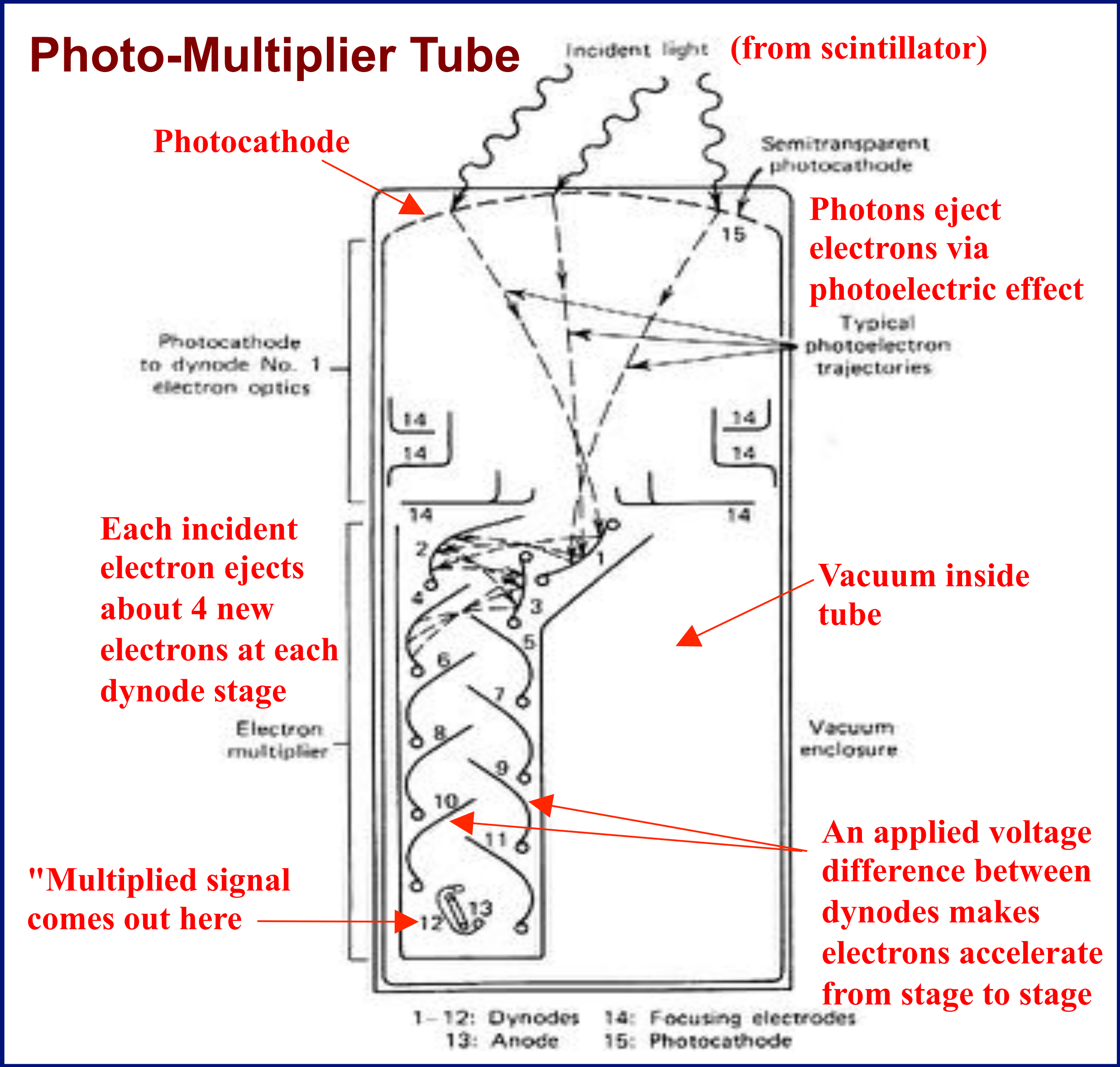
Experiments exploring UHE air showers

- 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

Another digression: PMTs

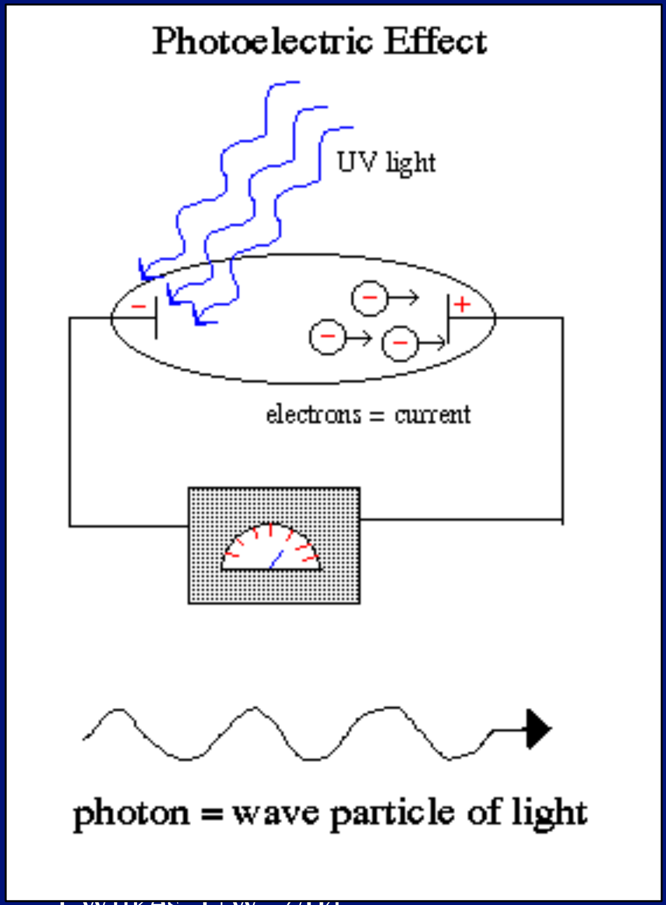
Photomultiplier Schematic



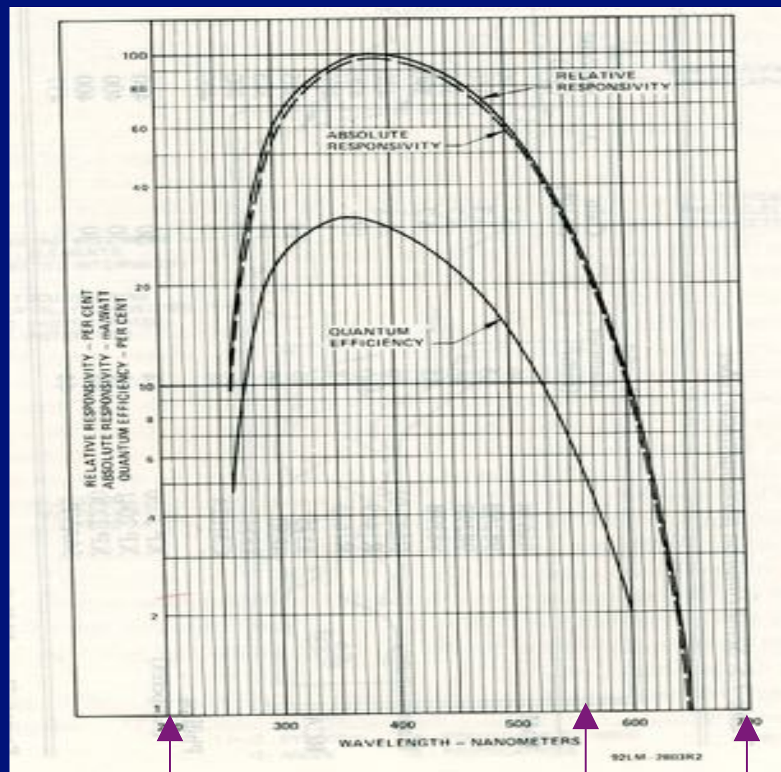
The Photoelectric Effect

- **Incoming photons expel electrons from the metallic surface of the photocathode via the** photoelectric effect.

The effect was discovered by Heinrich Hertz in 1887 and explained by Albert Einstein in 1905.



Typical Photocathode Response Curve



200 nm (UV) **Green** **700 nm (red)**

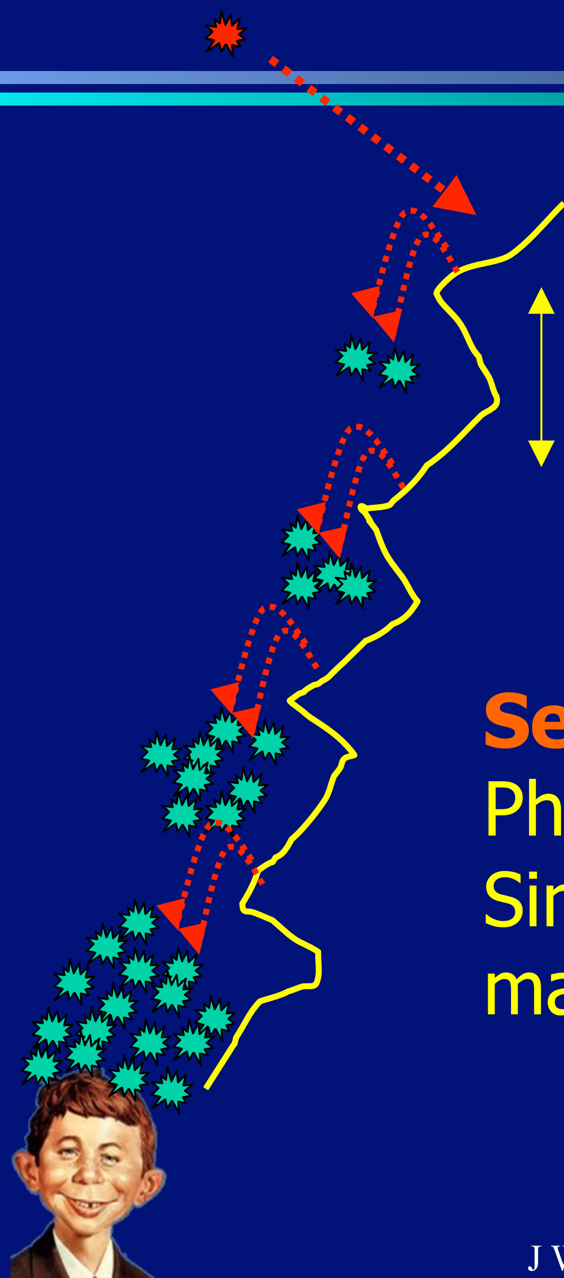
Wavelength of light

1 nm = 1 nanometer = 1×10^{-9} meter

Note: Quantum efficiency > 20% in range 300 - 475 nm

Peak response for light wavelengths near 400 nm

Gravitational Analog to PMT



Meteor hits cliff, knocks loose rocks

$\Delta V_{GRAV} = g\Delta h$

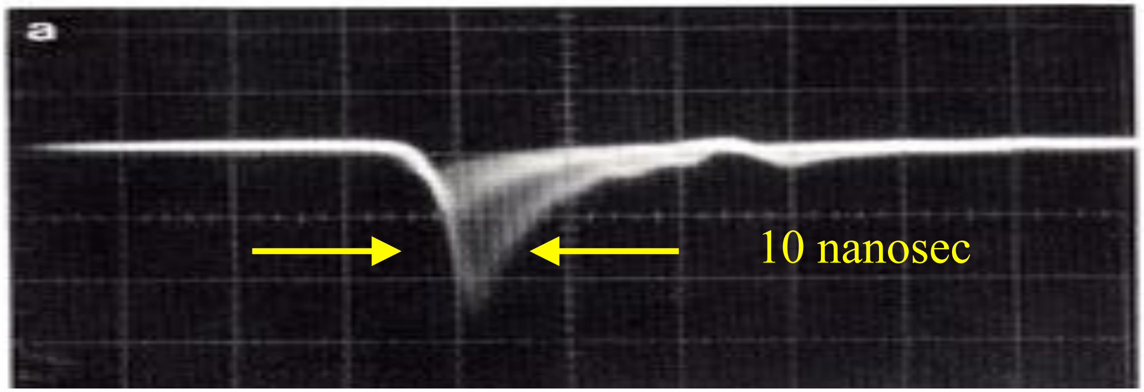
Seen this picture before?

Physics point:

Similar processes appear in many different phenomena

RJW, 7/01

Oscilloscope Traces from Scintillation Counters



Plastic scintillator

Plastic
Vert. scale : 0.2 V/cm
Hor. scale : 10 ns/cm
Source : ^{207}Bi 10μCi

10 nsec / division

Another case of similar processes in different phenomena:

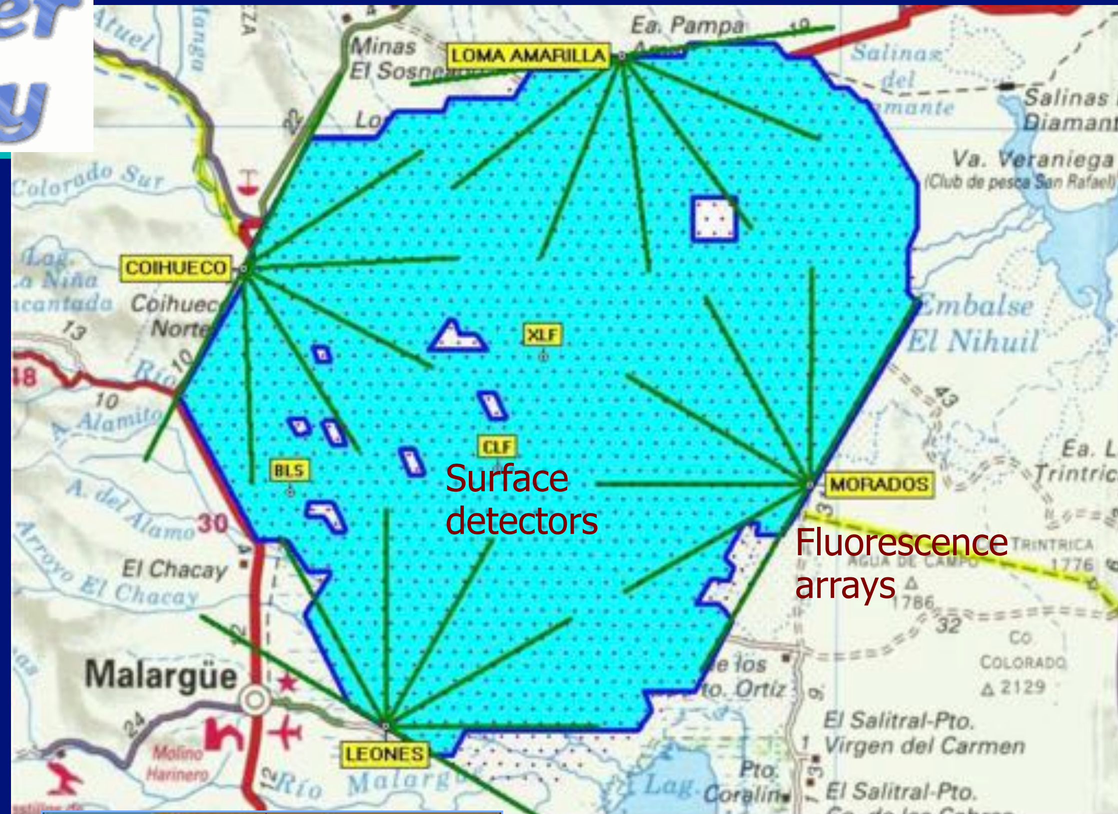
Arrival times of electrons in PMT ←→ arrival times of particles in air shower

→ Many arrive at ~ same time (those moving at high speed), followed by a diminishing number of 'stragglers'

Pierre Auger Observatory

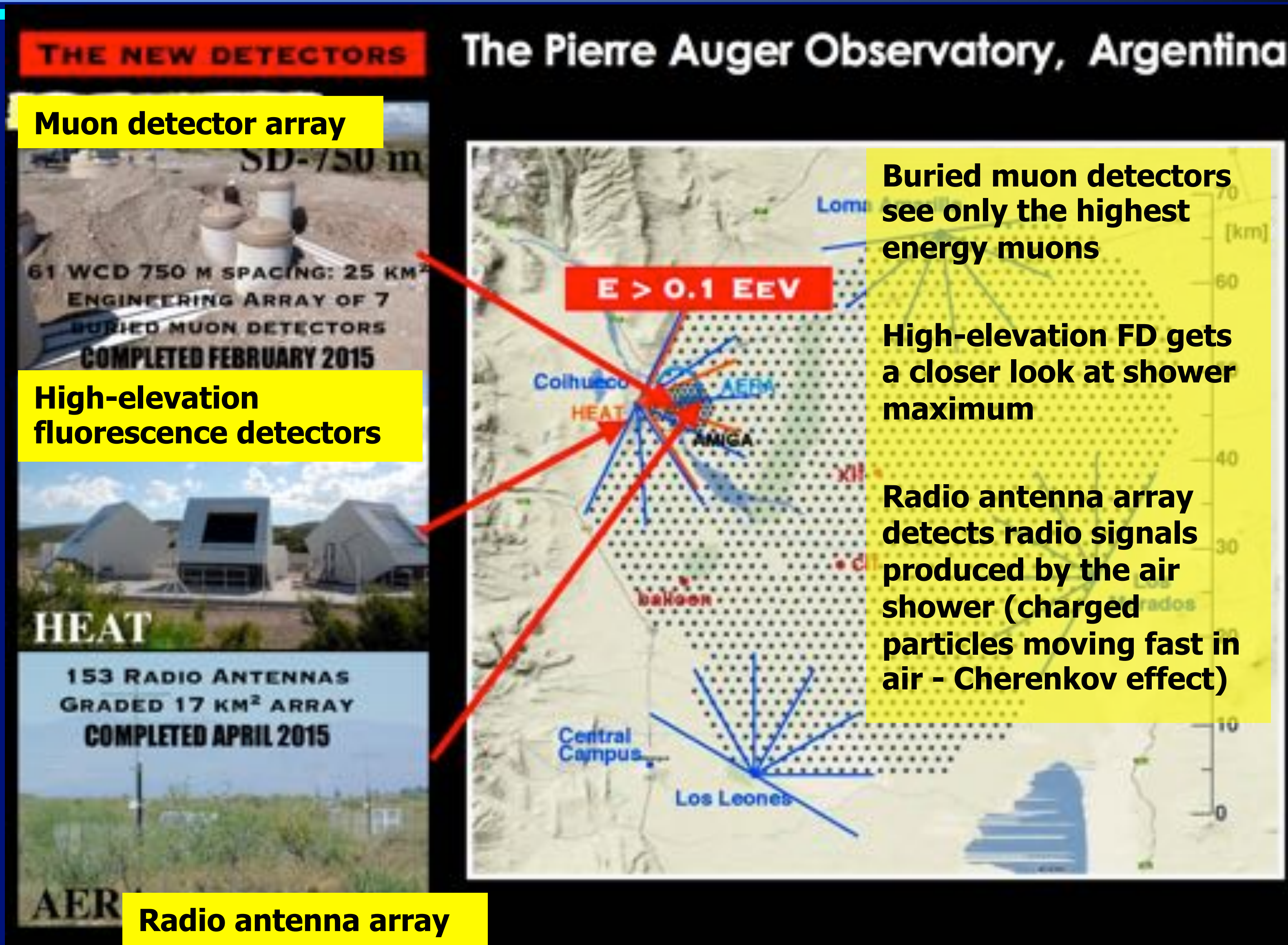
Southern hemisphere:
Mendoza Province,
Argentina

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

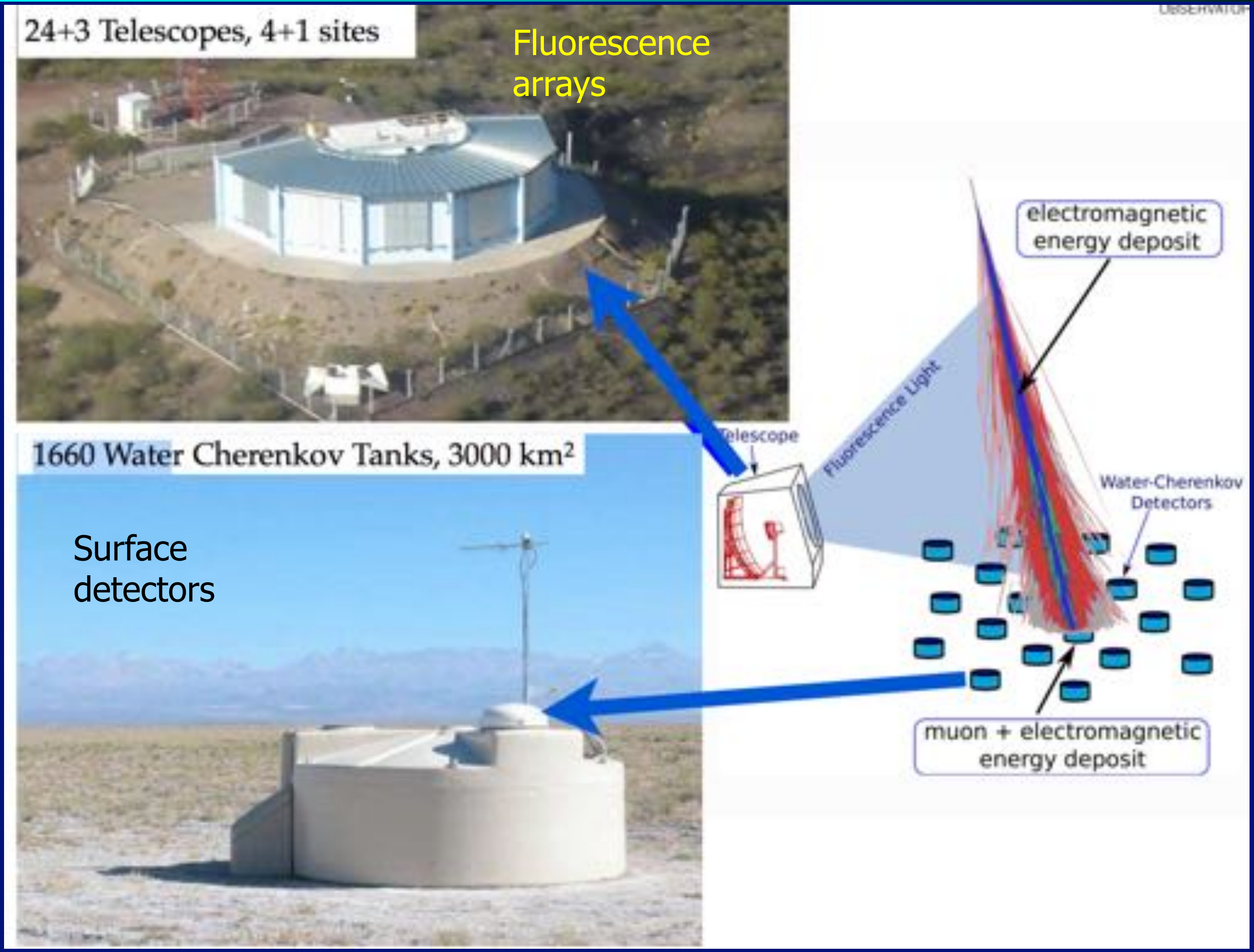


1660 surface detectors
(water Cherenkov tanks),
5 Air Fluorescence arrays,
Covering 3000 km^2

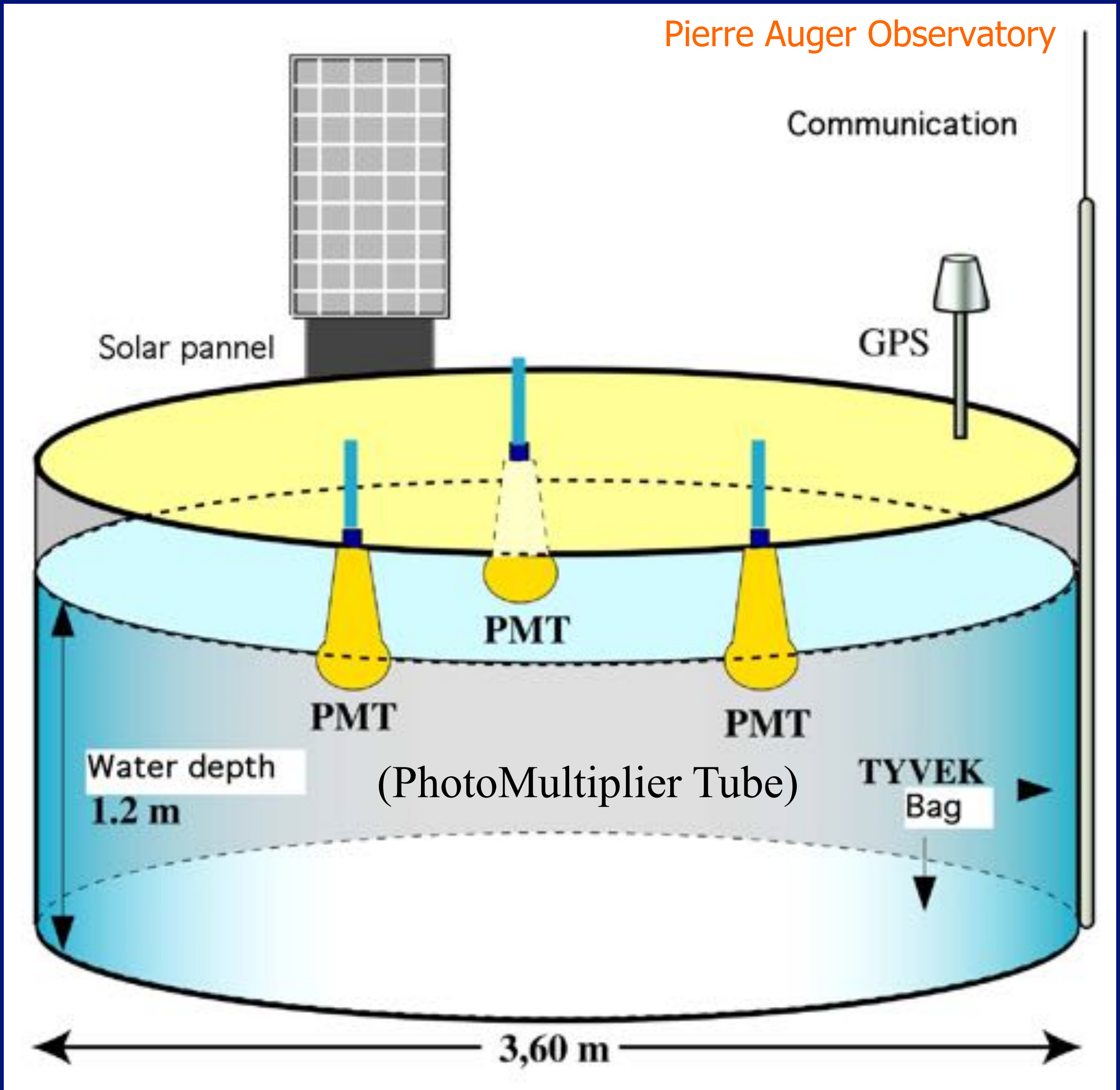
Recent upgrades/additions to Auger



Pierre Auger Observatory

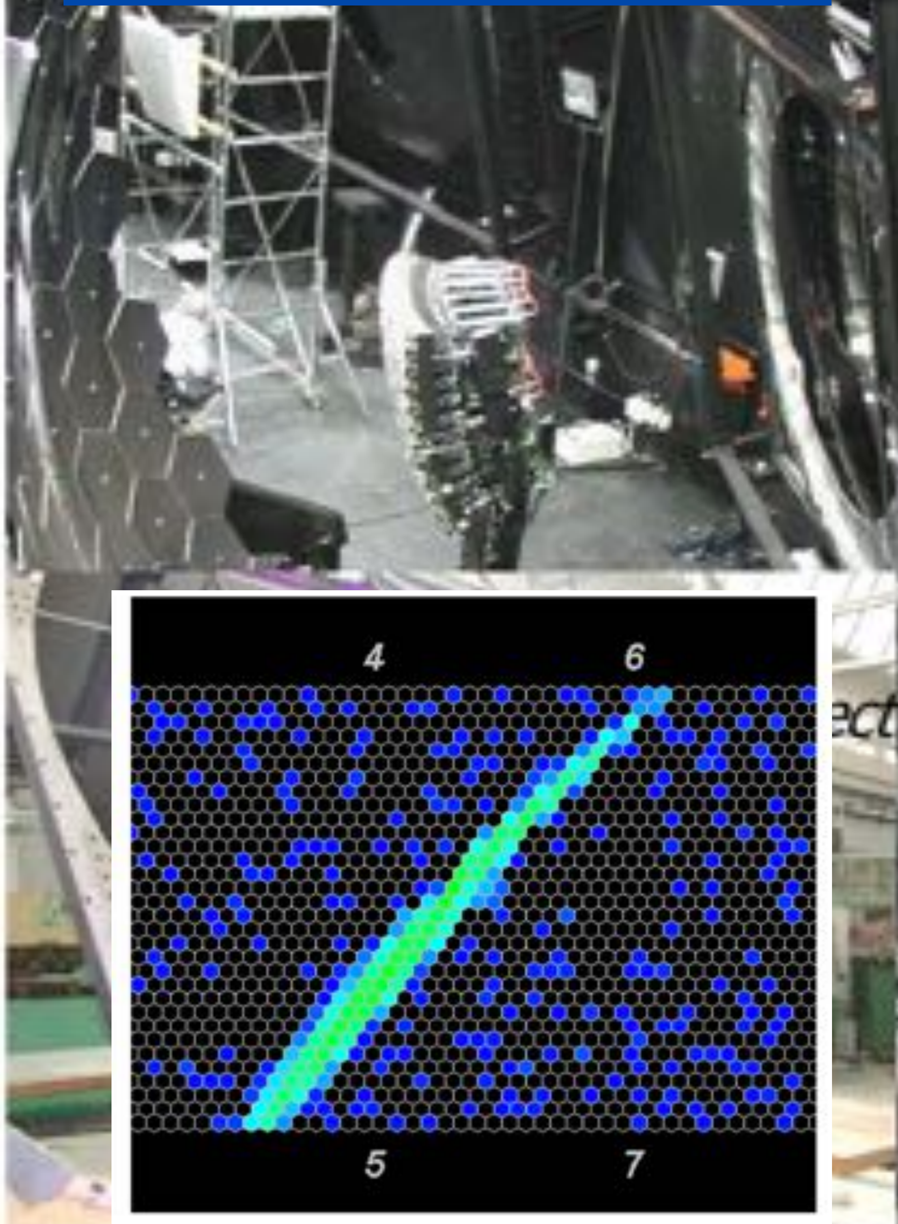


Surface detectors (SD): water Cherenkov detectors

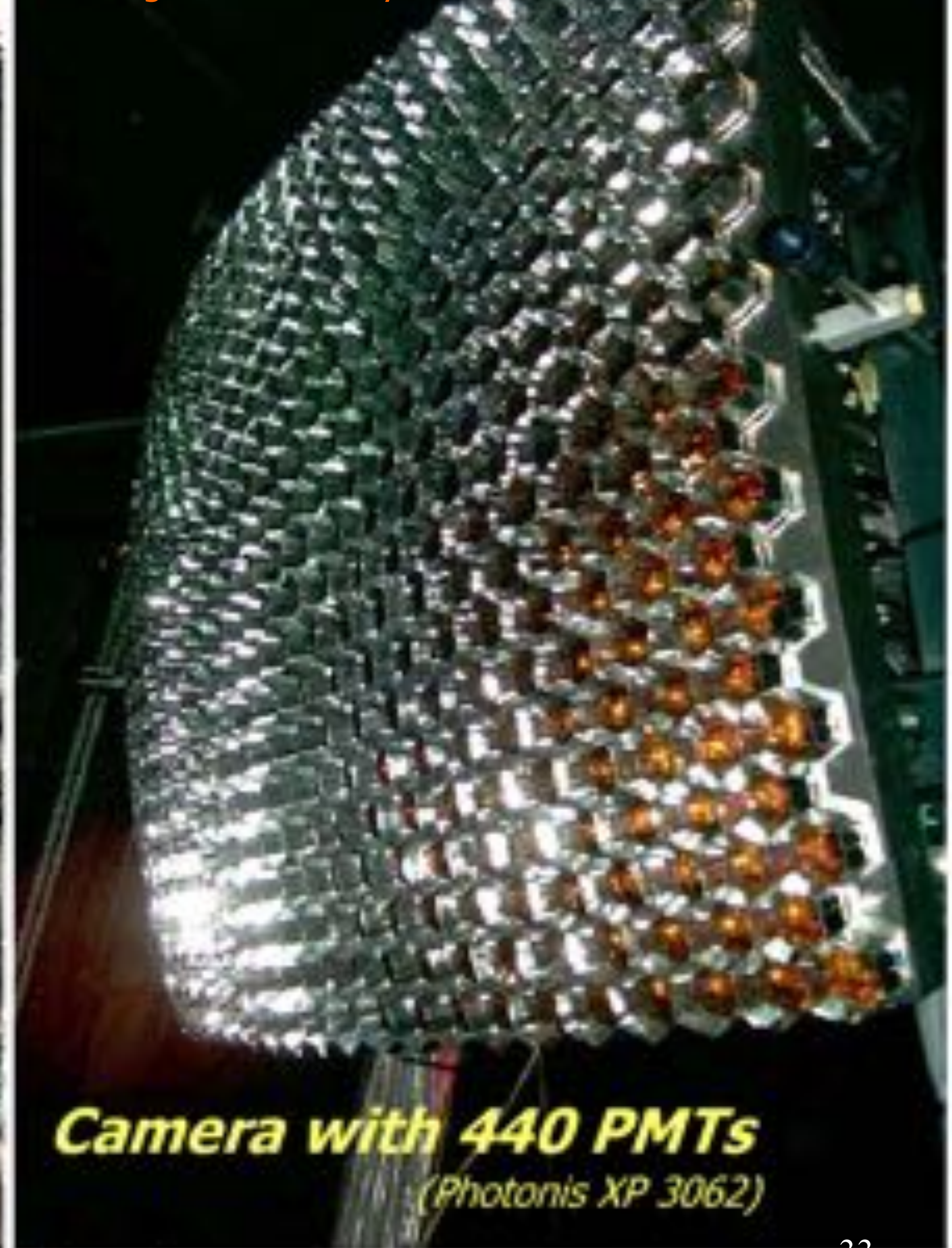


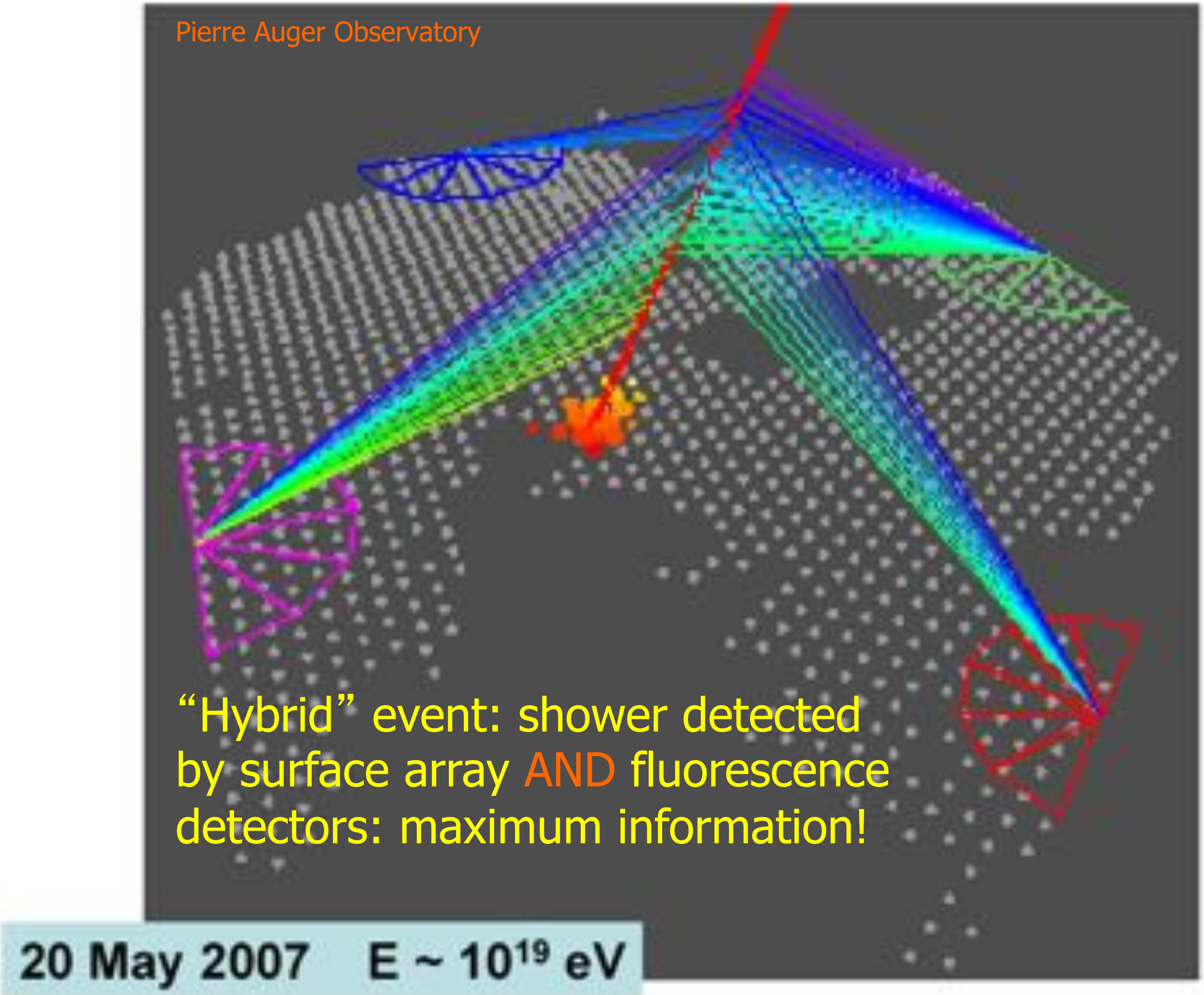
- Each unit is self-contained: solar panels, batteries, GPS
- Communication with cell-phone technology
- Three 8" PMTs detect **Cherenkov light** produced in water:
  - ❑ Charged particles move at ~ c (speed of light in vacuum)
  - ❑ but light can propagate in water at only 0.75c
  - ❑ Electromagnetic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

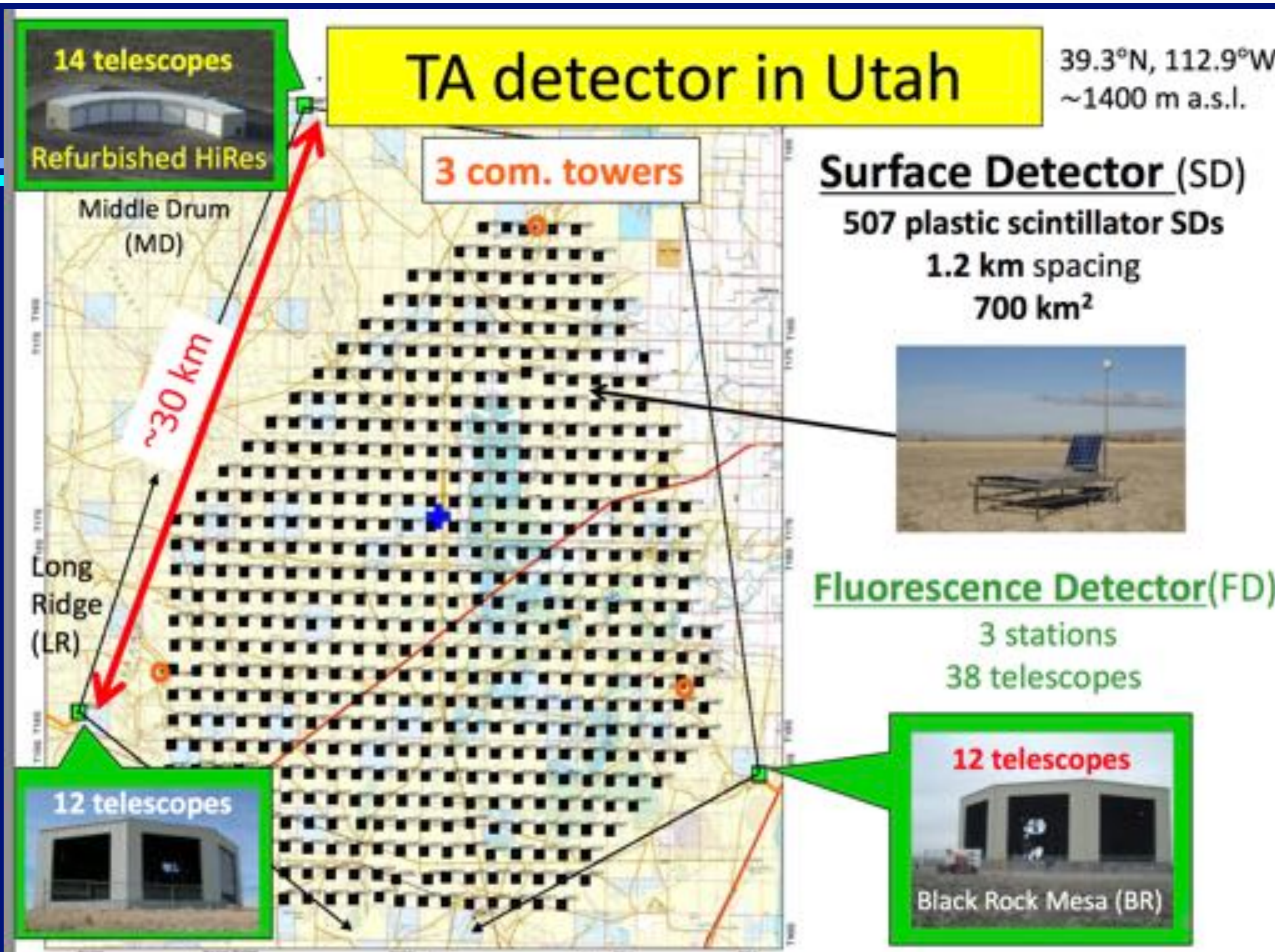
Auger’ s fluorescence detectors: 4 stations



Pierre Auger Observatory




Pierre Auger Observatory
“Hybrid” event: shower detected by surface array AND fluorescence detectors: maximum information!
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

TA Fluorescence detector

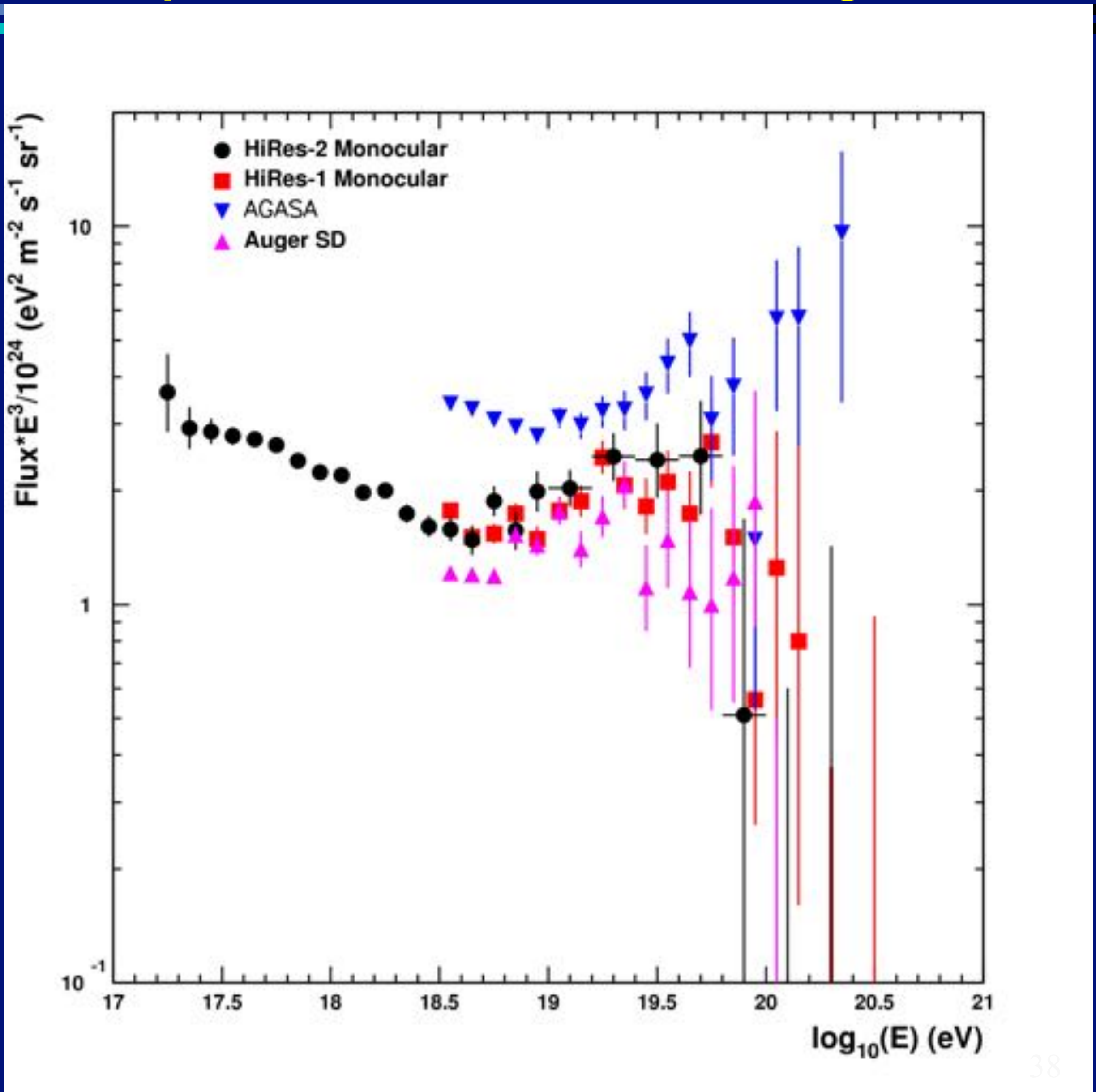
Top end of the CR spectrum: some time ago...

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?



Wise words...

"But beyond that, do not report to your pupil any conclusions as even probable until two or three independent observers get into agreement on them.

It is just too bad to drag an interested public through all our mistakes, as we cosmic ray experimenters have done during the past four years."

Robert A. Millikan

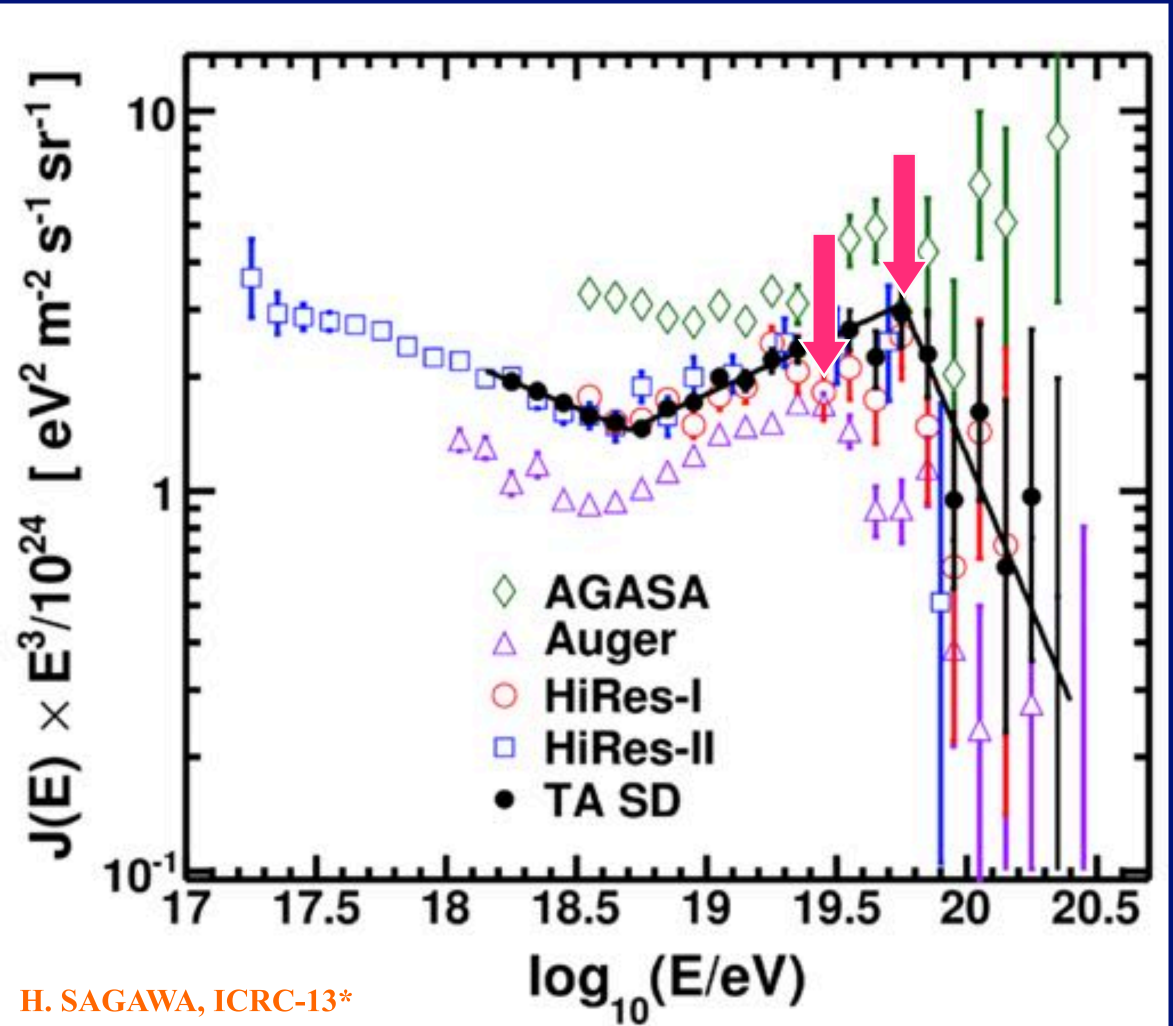
New York Times, Dec. 30, 1934

...and 3 years ago...

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

TA, and Auger (2013 ICRC)

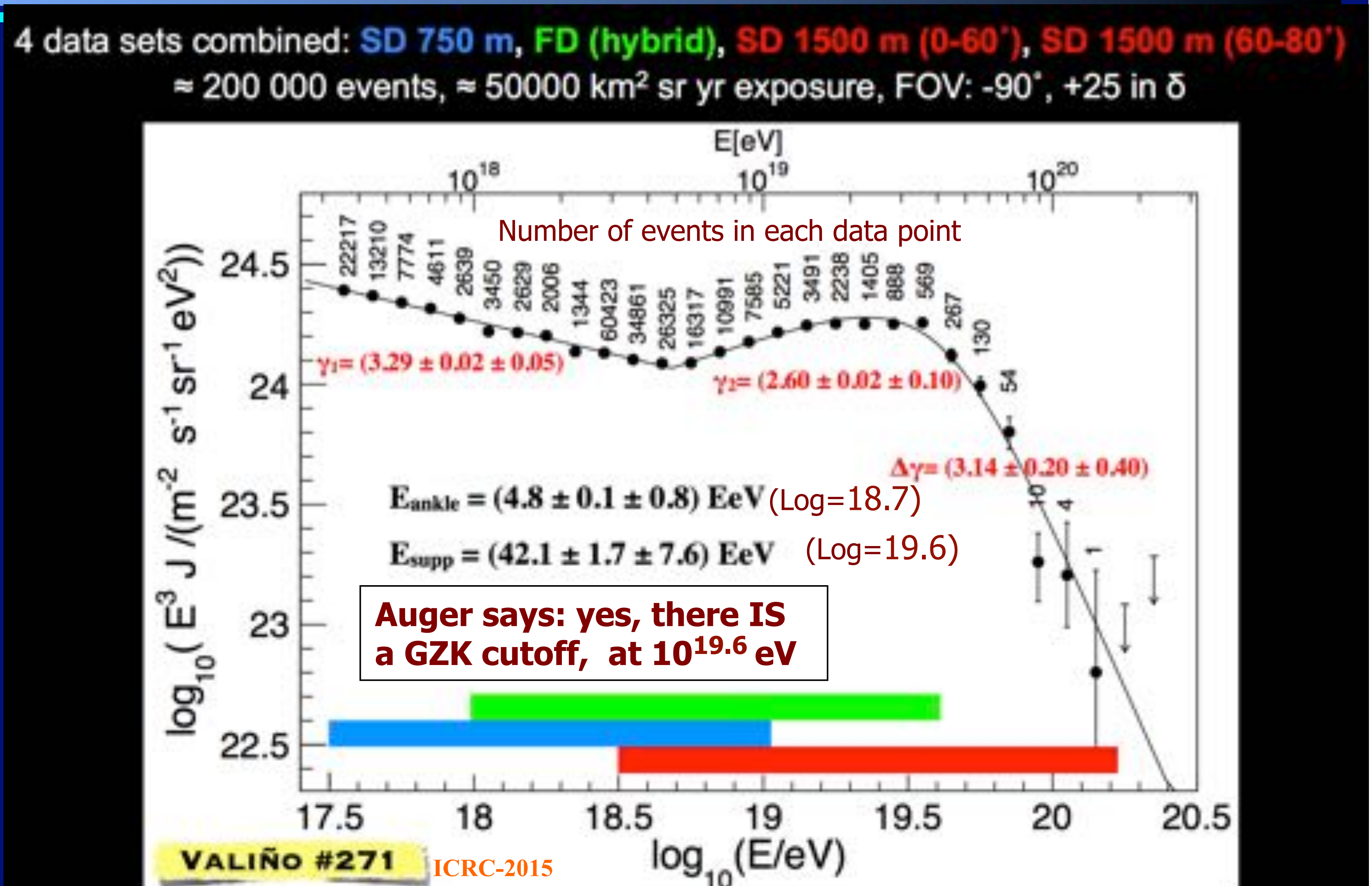
Notice difference between the two – Auger's GZK cutoff at lower E



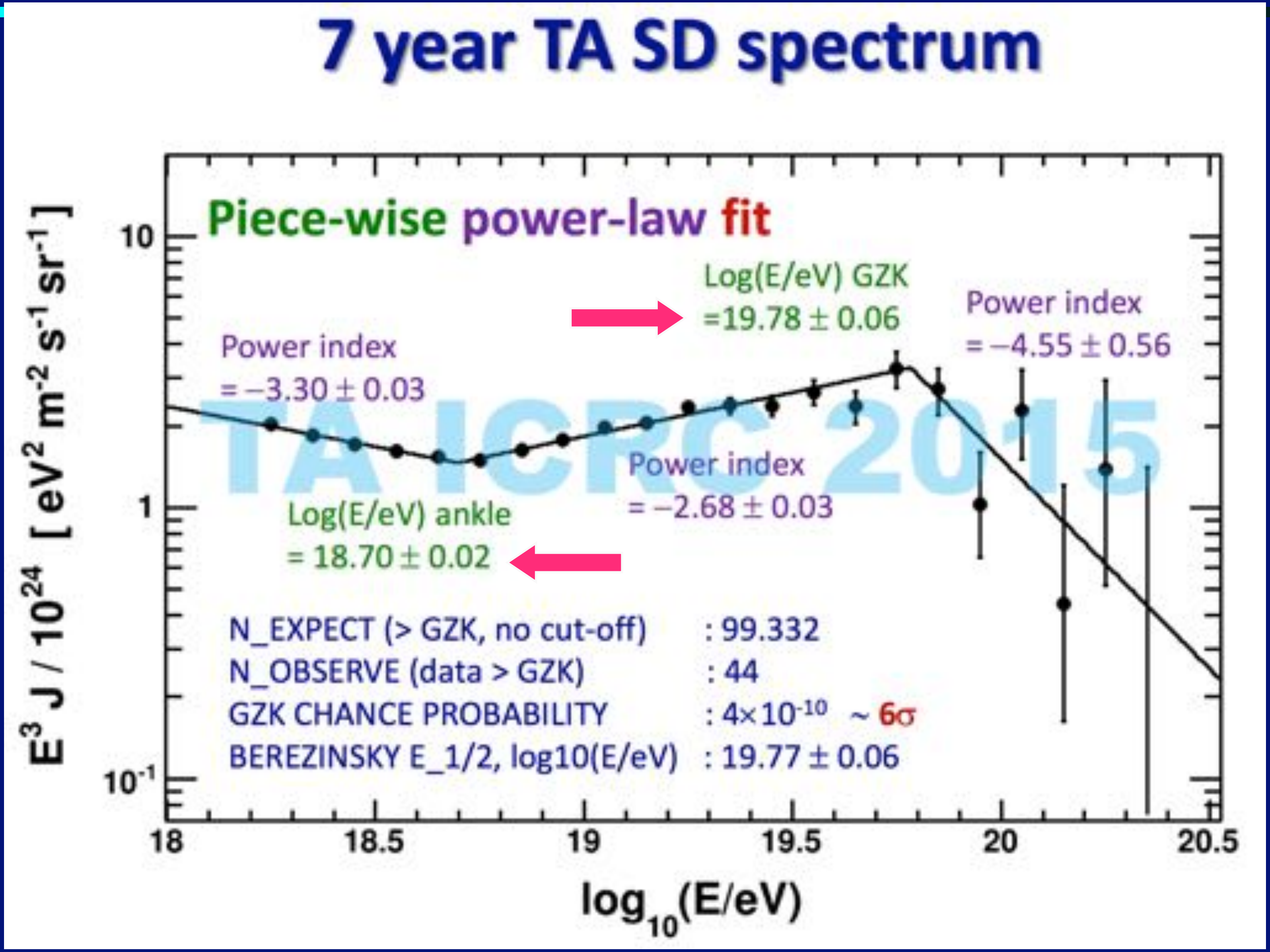
H. SAGAWA, ICRC-13*

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

2015 results: fits to slope, numbers of events

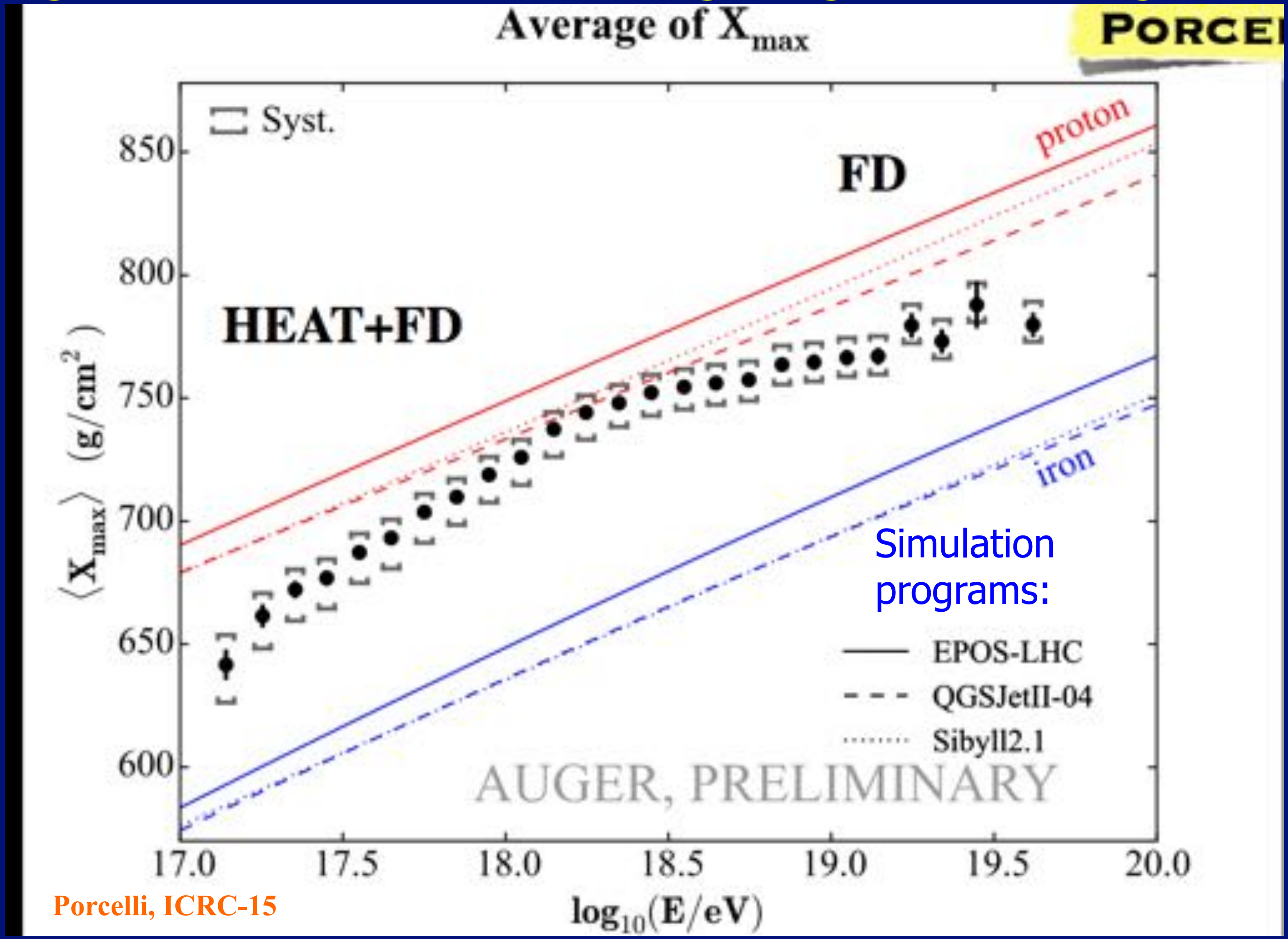


2015 TA results: GZK is closer to Auger's



Are EHE CRs protons, or nuclei ?

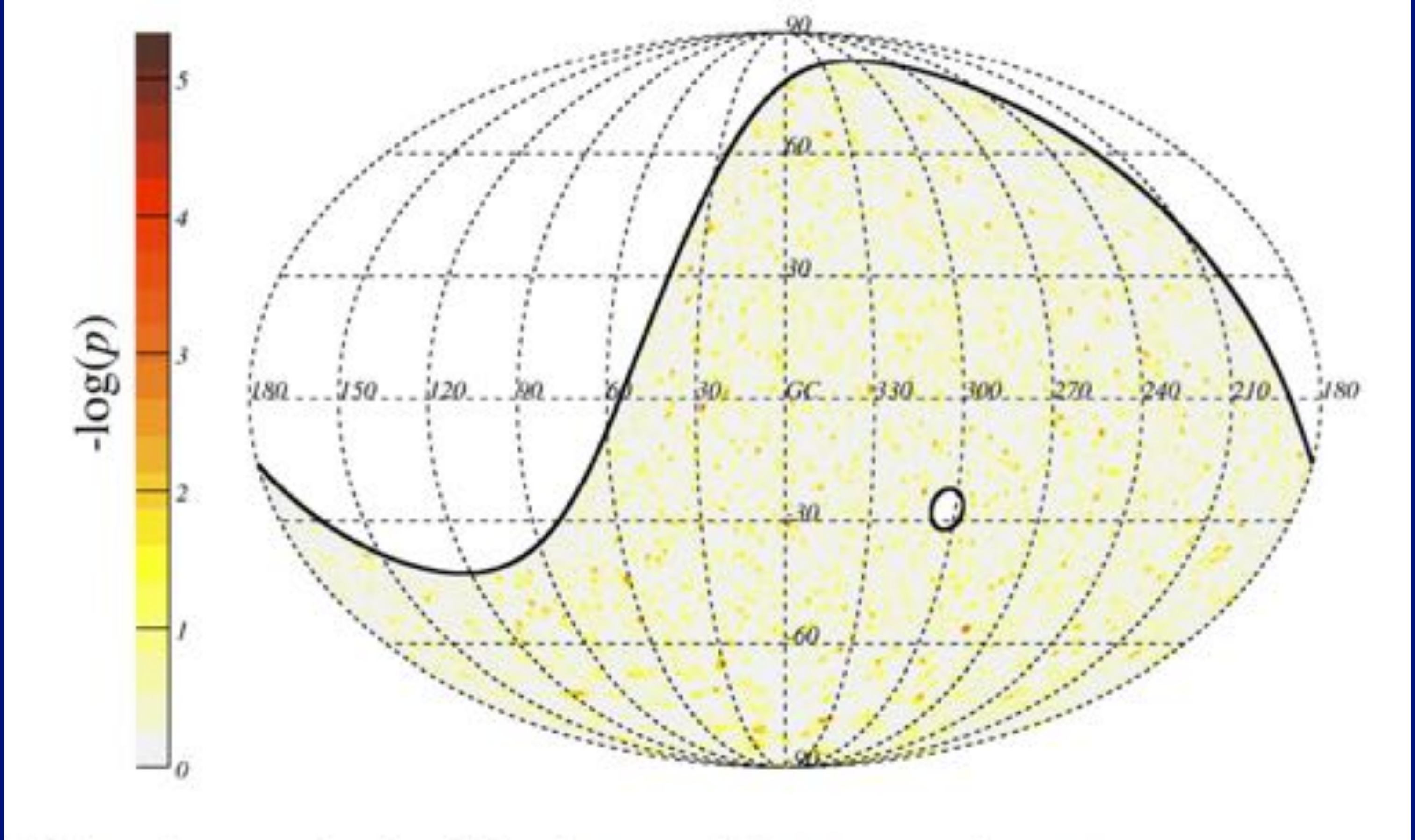
- Depth of “shower maximum” is smaller if CR= lighter nuclei
- Augerdata: the mix seems to be getting heavier at highest E’s



Search for point sources of EeV photons

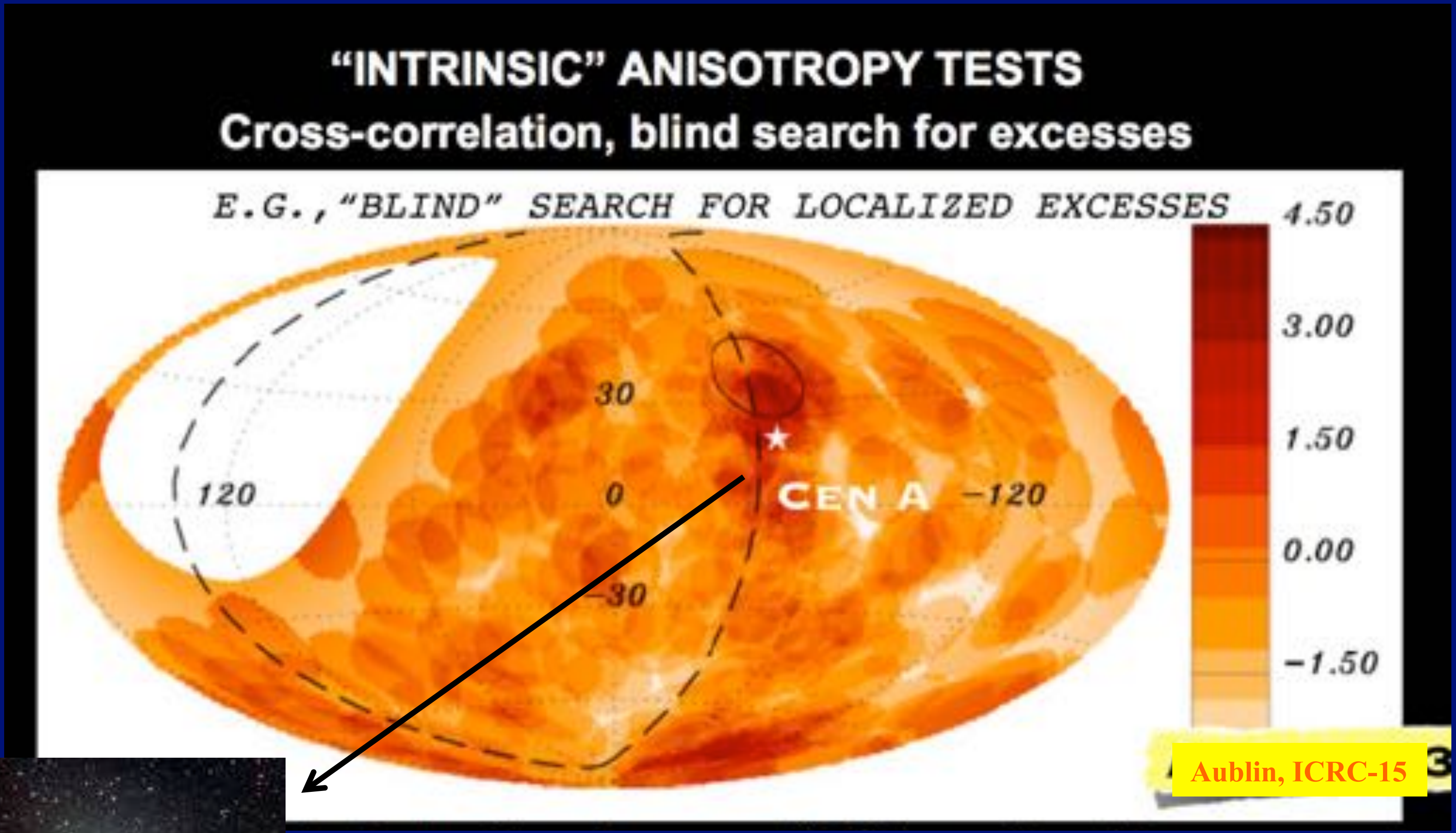
- No evidence for point sources of gamma-ray showers

p = local probability that the data is in agreement with a uniform distribution.



Celestial map of $-\log(p)$ values in Galactic coordinates.

No evidence for small hot areas (under 30 deg)



FYI: Cen (Centaurus) A is a galaxy 10 million light years away.
It is a bright source of light and radio waves.
It contains a supermassive black hole with M~ 55 million solar masses, and emits jets of ultra-relativistic particles.

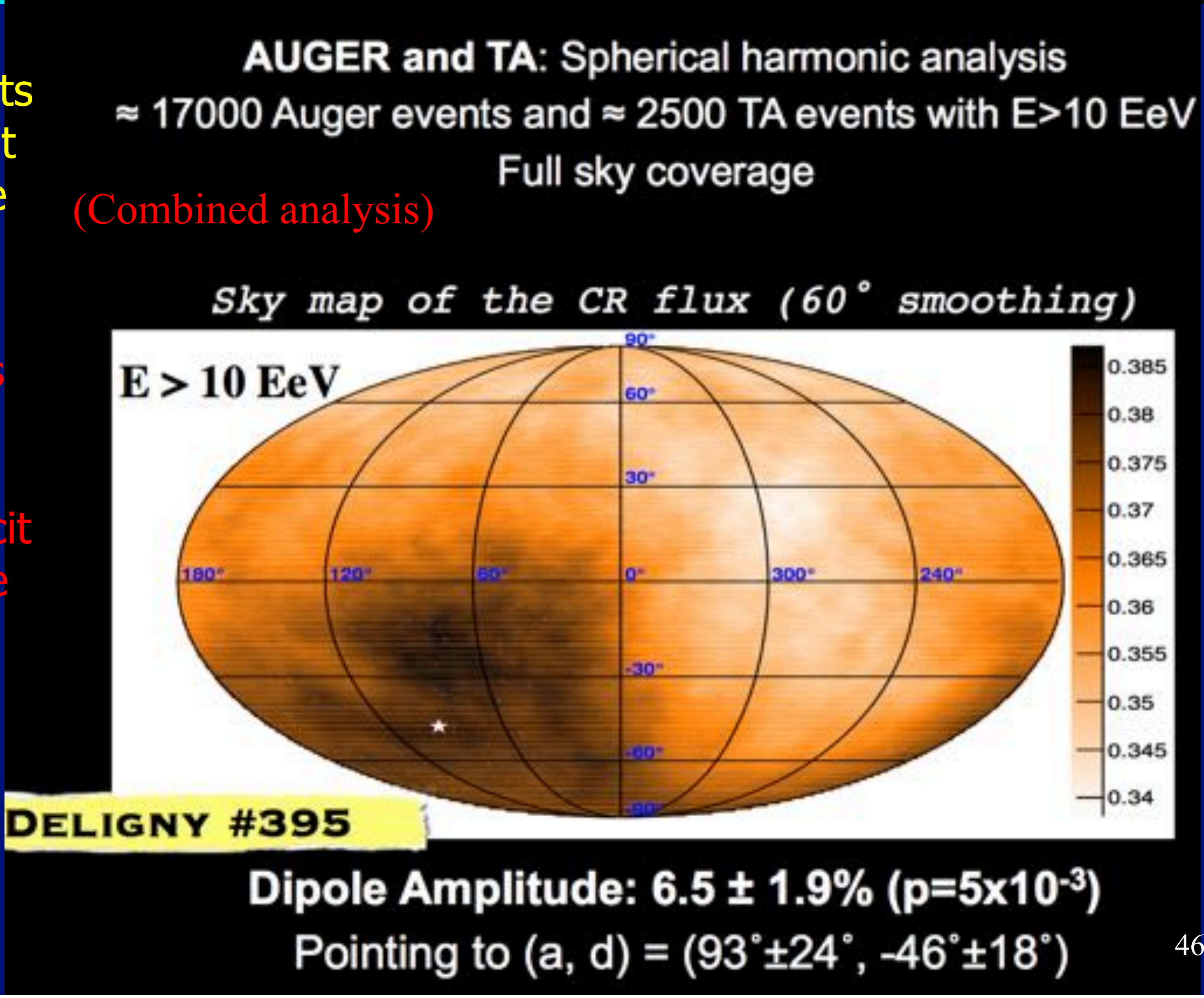
Expect UHE CR to be isotropic (uniform arrival)

But... both experiments see a slight bias in one direction

"Dipole":

6% excess in one sky direction, equal deficit in opposite direction

Are we moving relative to UHE sources?



What's the message?

- Physics is not a closed book!
  - We have 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
    - Takes lots of effort by lots of people over a long time
    - Plenty of (friendly) arguments to decide who is right !
    - Rarely a clear black-and-white separation between true and false – in science, or in general