Ultra-high energy cosmic ray 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
    - An old 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 we'll discuss • Kinetic energy of a golf ball dropped from a height of 50 cm

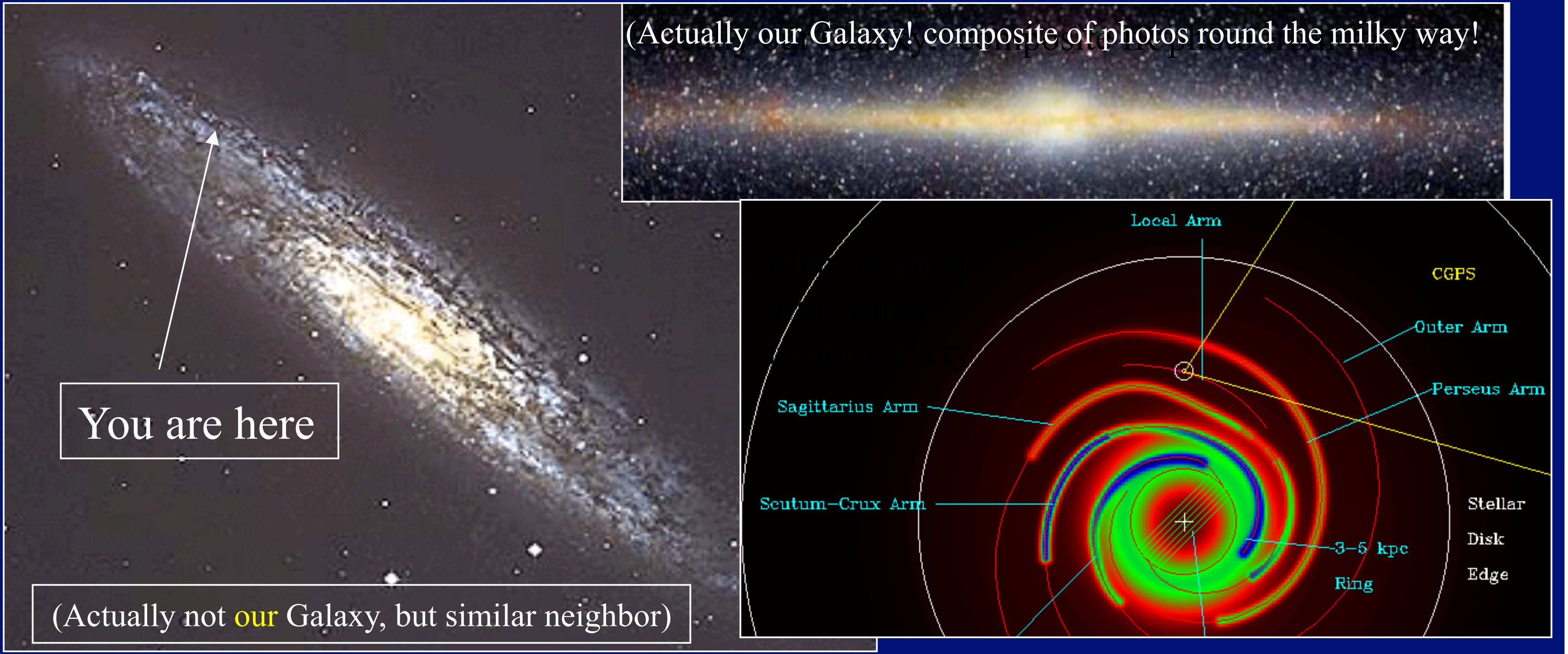
Varieties of "cosmic rays"

- Cosmic rays = particles (with mass>>0) reaching Earth from space
  - Usually we do not call gamma rays and neutrinos cosmic rays
- 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

* Astronomers use *parsecs*
1 pc =3.25 ly



You are here

(Actually not our Galaxy, but similar neighbor)

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

Galactic and extra-galactic CRs

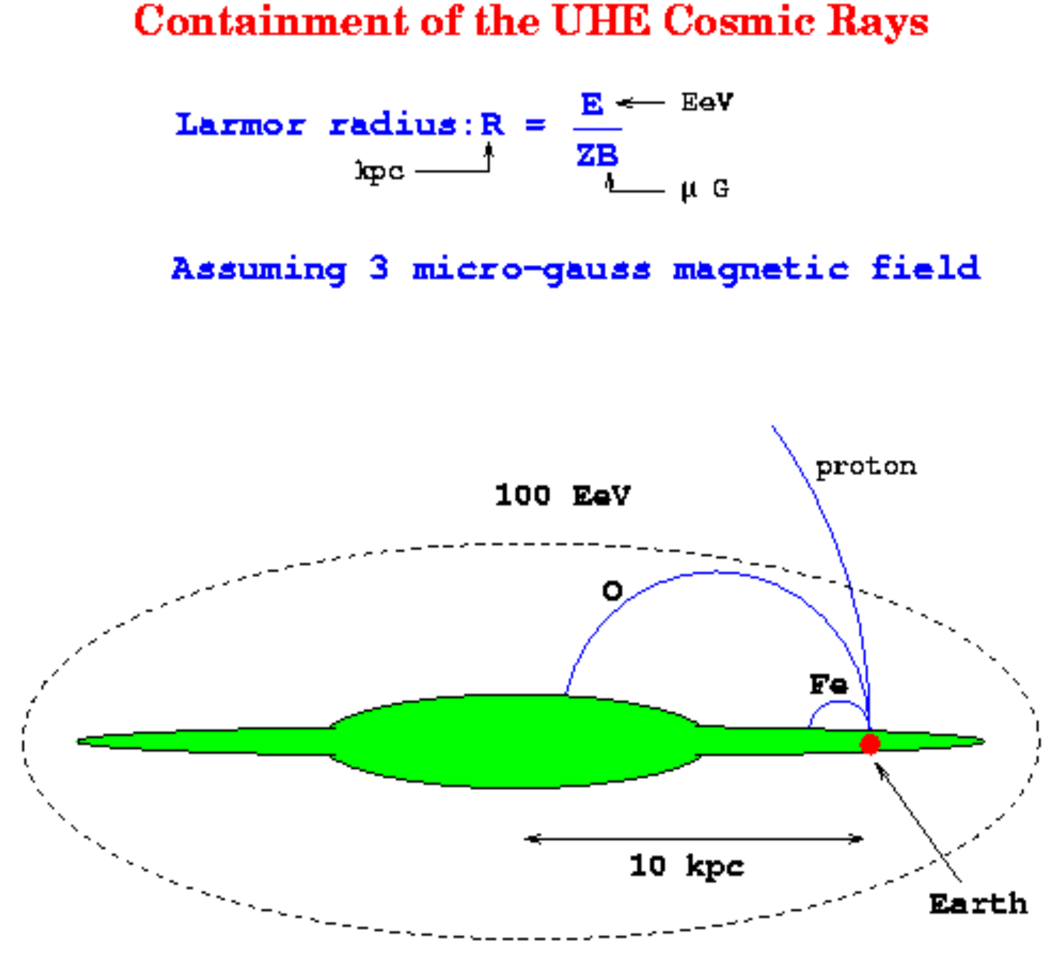
Our Galaxy’s magnetic field cannot trap protons with

E > 10^{18} eV, so above that energy

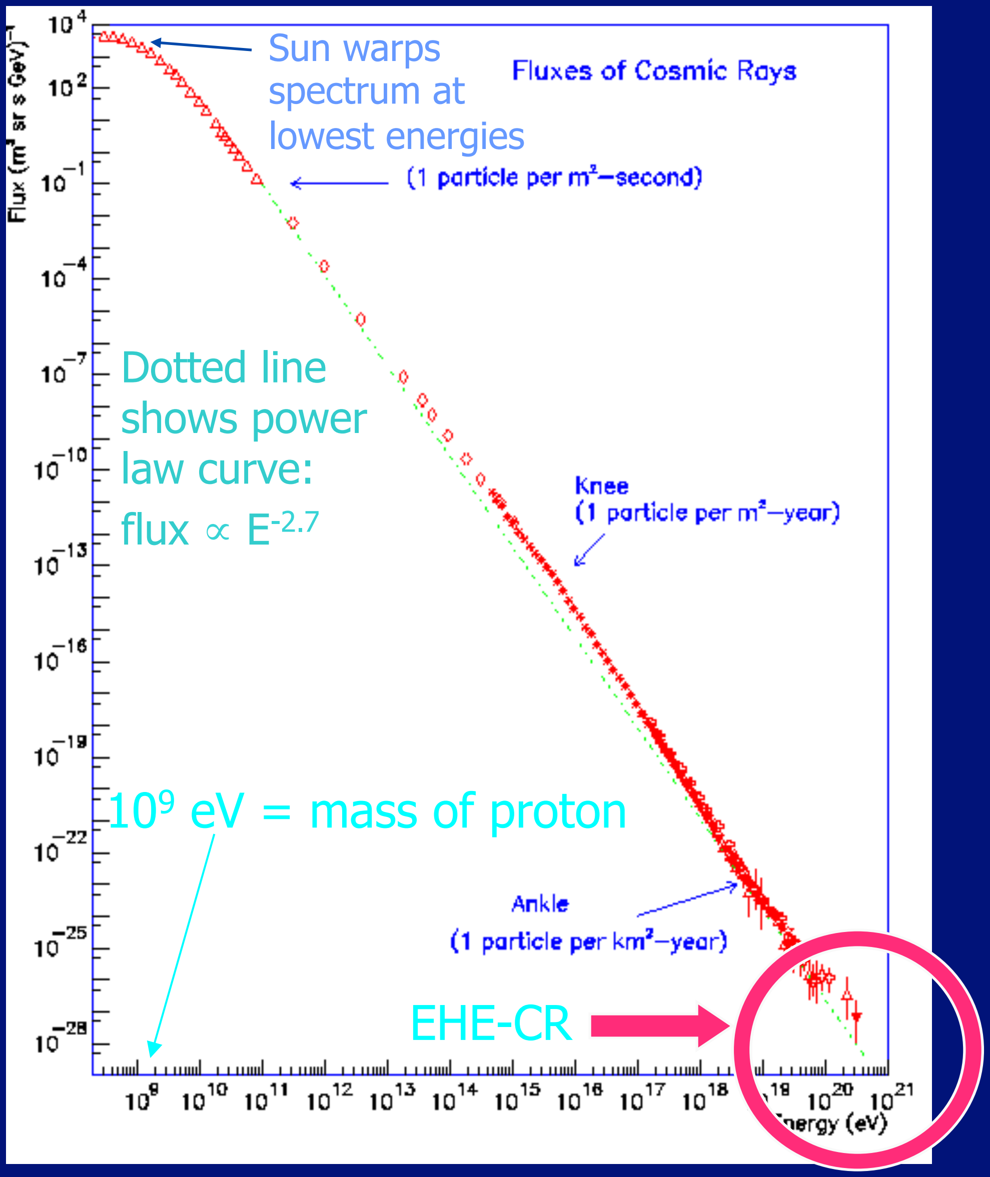
- Our galaxy’s cosmic rays escape
- Observed cosmic rays are mainly from other galaxies

Q: Is there a significant intergalactic B?

…Probably very weak



The galactic cosmic ray spectrum



Sun warps spectrum at lowest energies

Dotted line shows power law curve:

flux ∝ $E^{-2.7}$

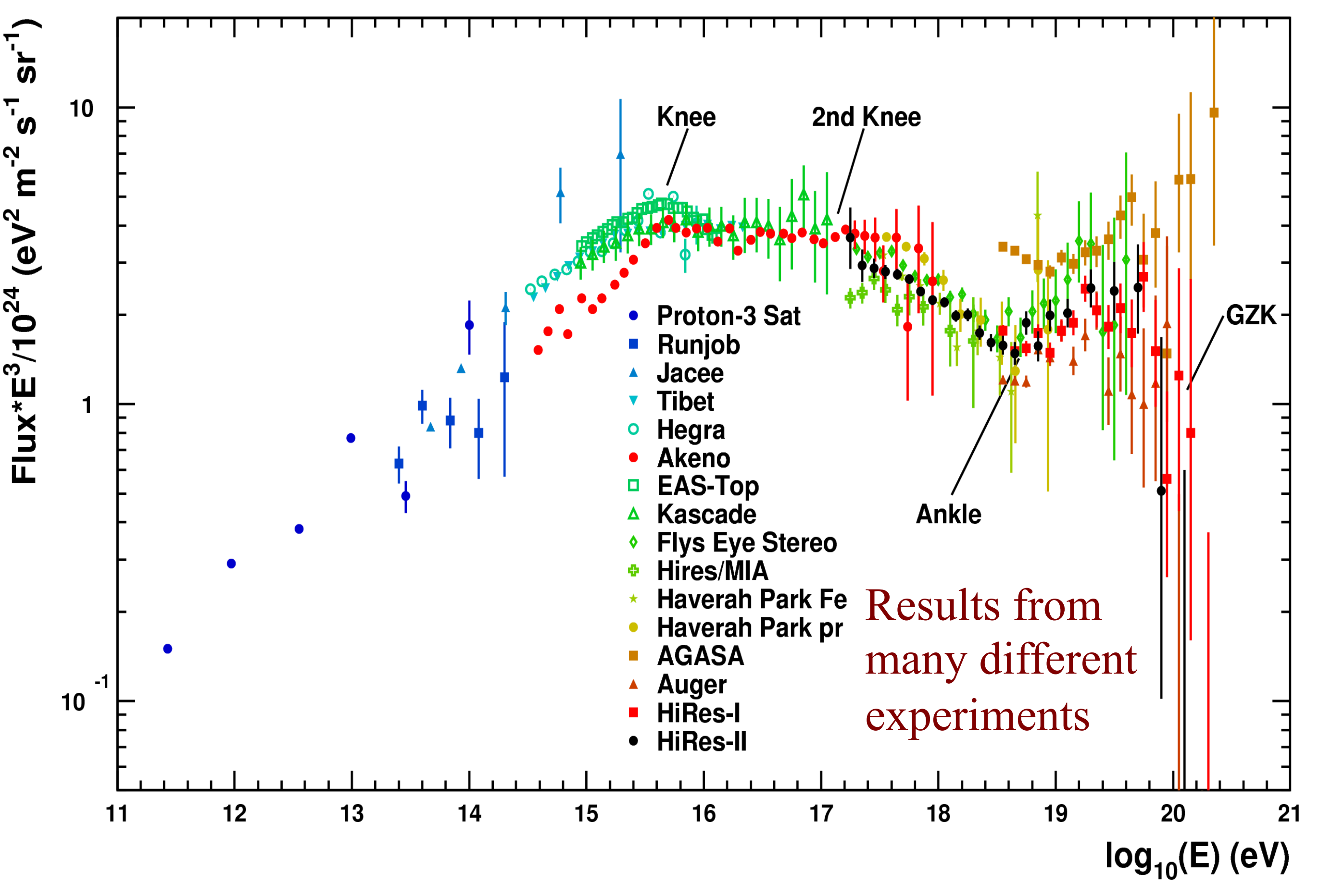
10^9 eV = mass of proton

EHE-CR

- 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 (>10^{20} eV):
  - Rare and puzzling
  - Only a few detected worldwide
  - Should be none!

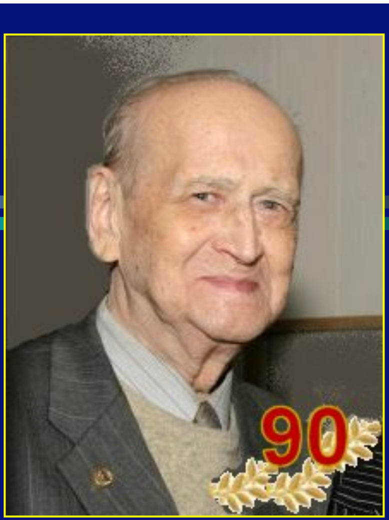
Spectrum is not boringly smooth, if you look closely

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



Results from many different experiments

Ken Greisen (Cornell)



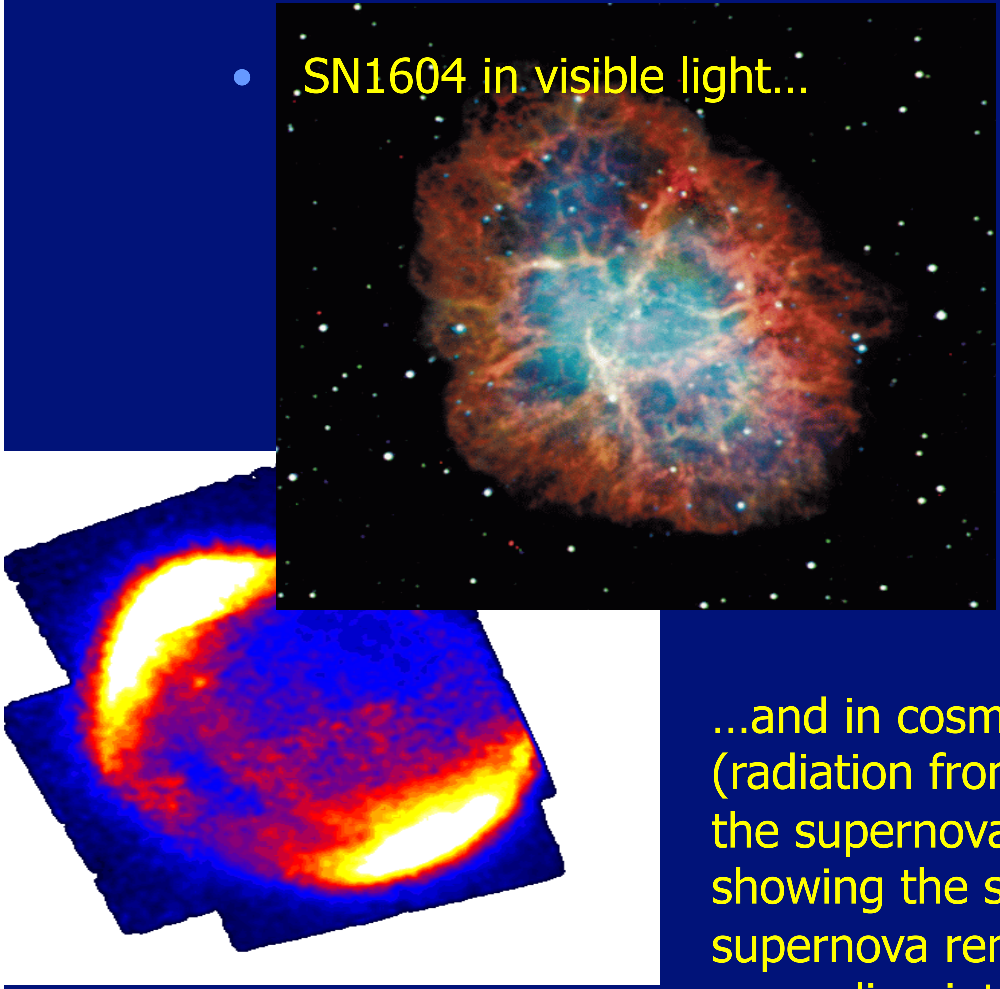
G. Zatsepin (Moscow State Univ.)

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
    - To UHE proton, a low-E photon seems like a high-E gamma ray!

  ➔ 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: SN1604 = Kepler's



- SN1604 in visible light…

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

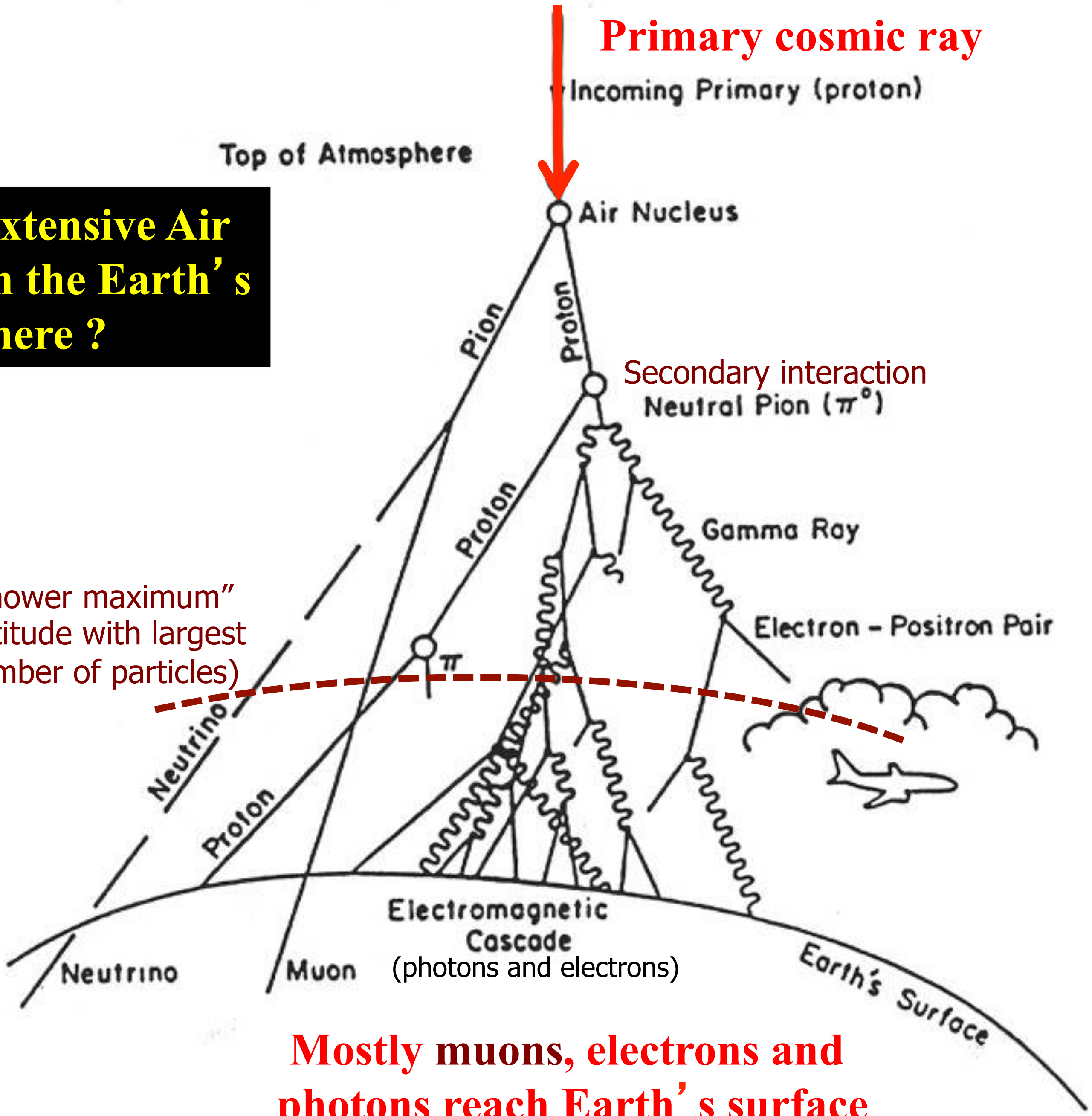
SN's can emit as much energy as a galaxy-full of normal stars, for a few days…

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

SN-1604 was described by Johannes Kepler (who provided Newton with crucial data on the motion of planets)

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

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



Primary cosmic ray

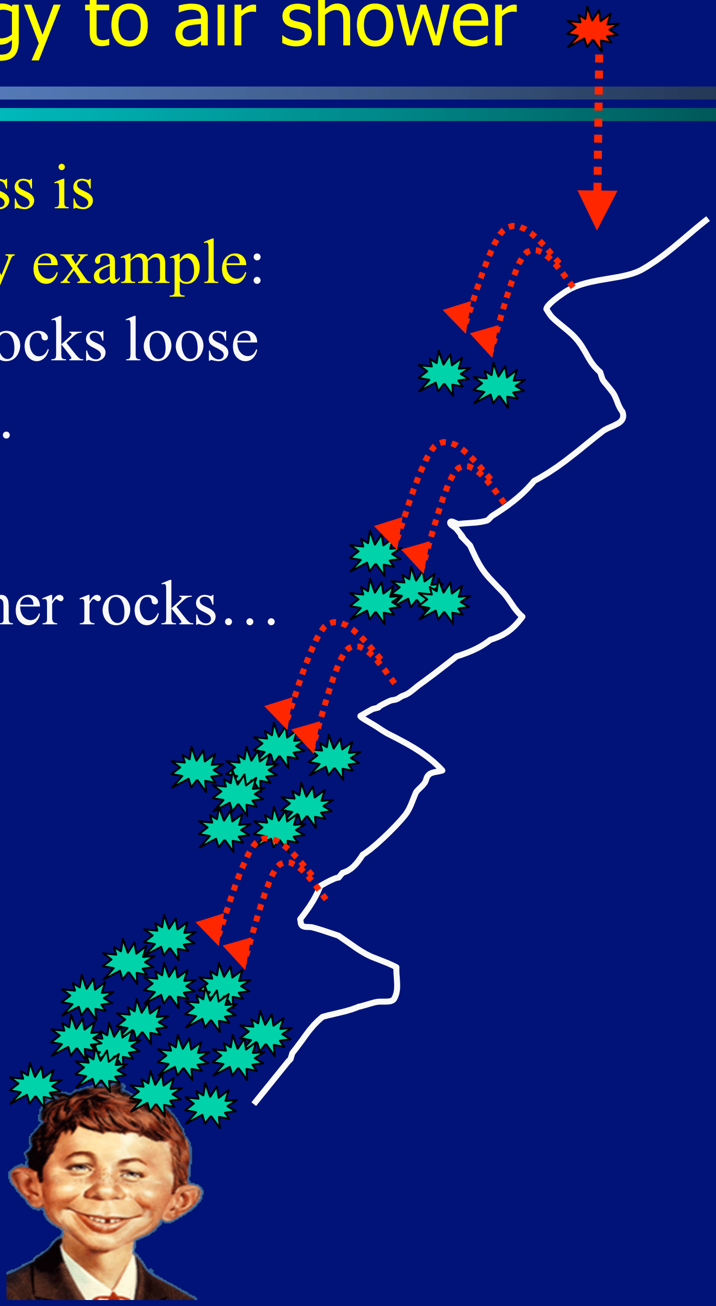
Secondary interaction

"Shower maximum"
(altitude with largest number of particles)

(photons and electrons)

Mostly muons, electrons and photons reach Earth's surface

Gravitational analogy to air shower



The cascade process is familiar – everyday example: Mountain hiker knocks loose a rock above you…

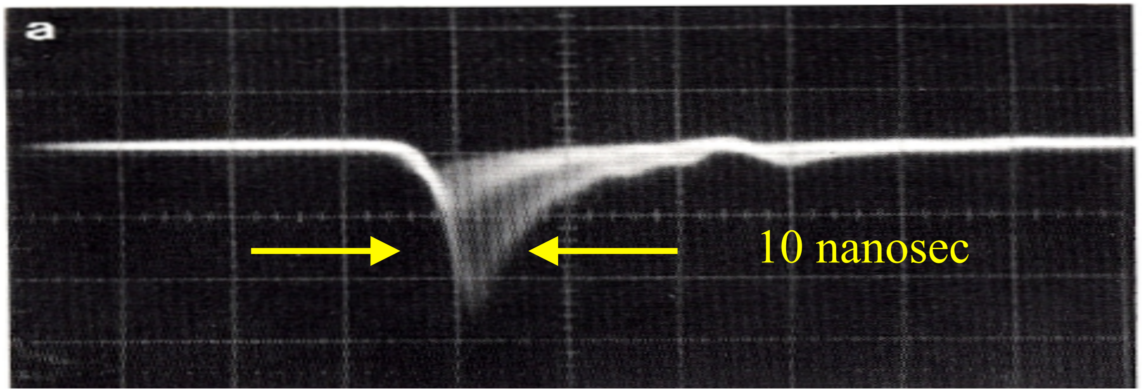
That knocks loose other rocks…

…and so on

Cascade process

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:

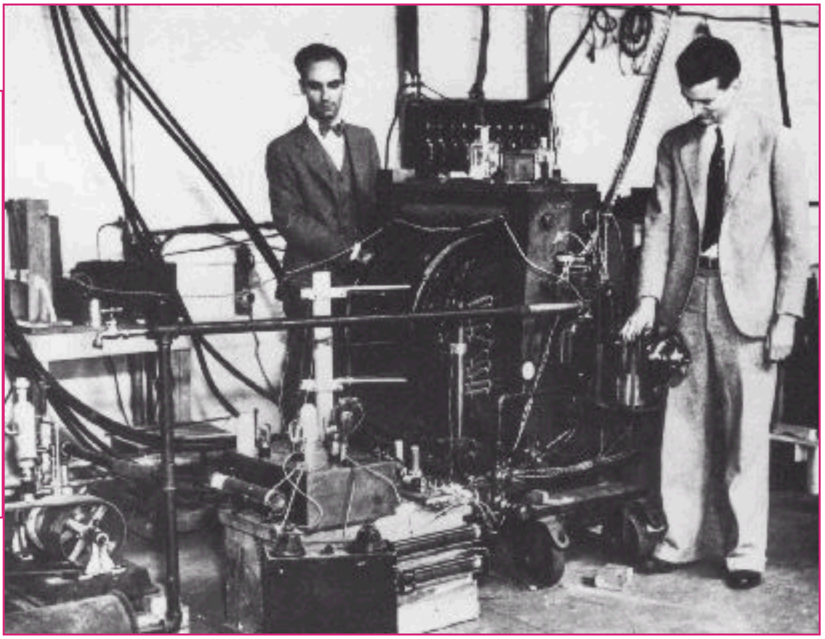
Arrival times of electrons at PMT anode ←→ arrival times of particles in shower

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

Cosmic Rays, Muons and UW Physics Dept

UW Prof. Seth Neddermeyer (1907-1988) was first to observe a muon (his PhD thesis project

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

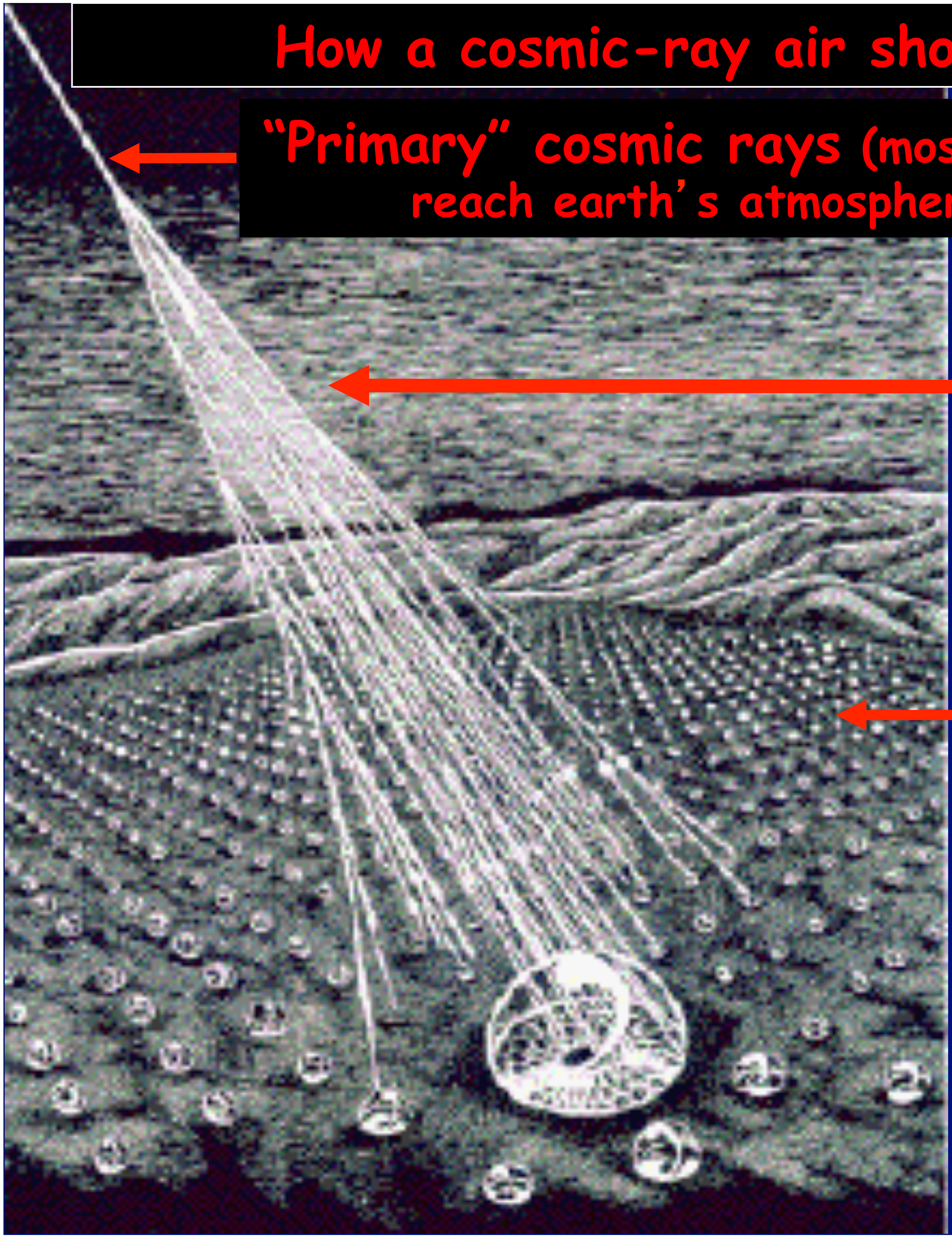


Muon was the first "new" elementary particle (protons and electrons were known)

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

8/16/18

How a cosmic-ray air shower is detected



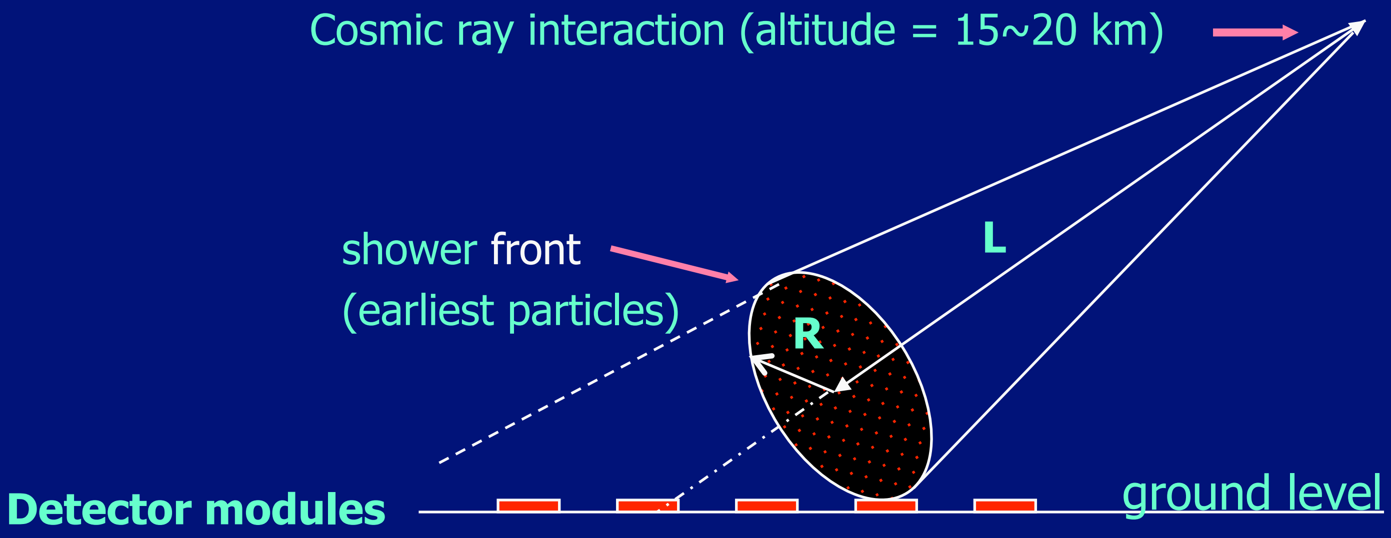
"Primary" cosmic rays (mostly protons or light nuclei) reach earth's atmosphere from outer space

"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

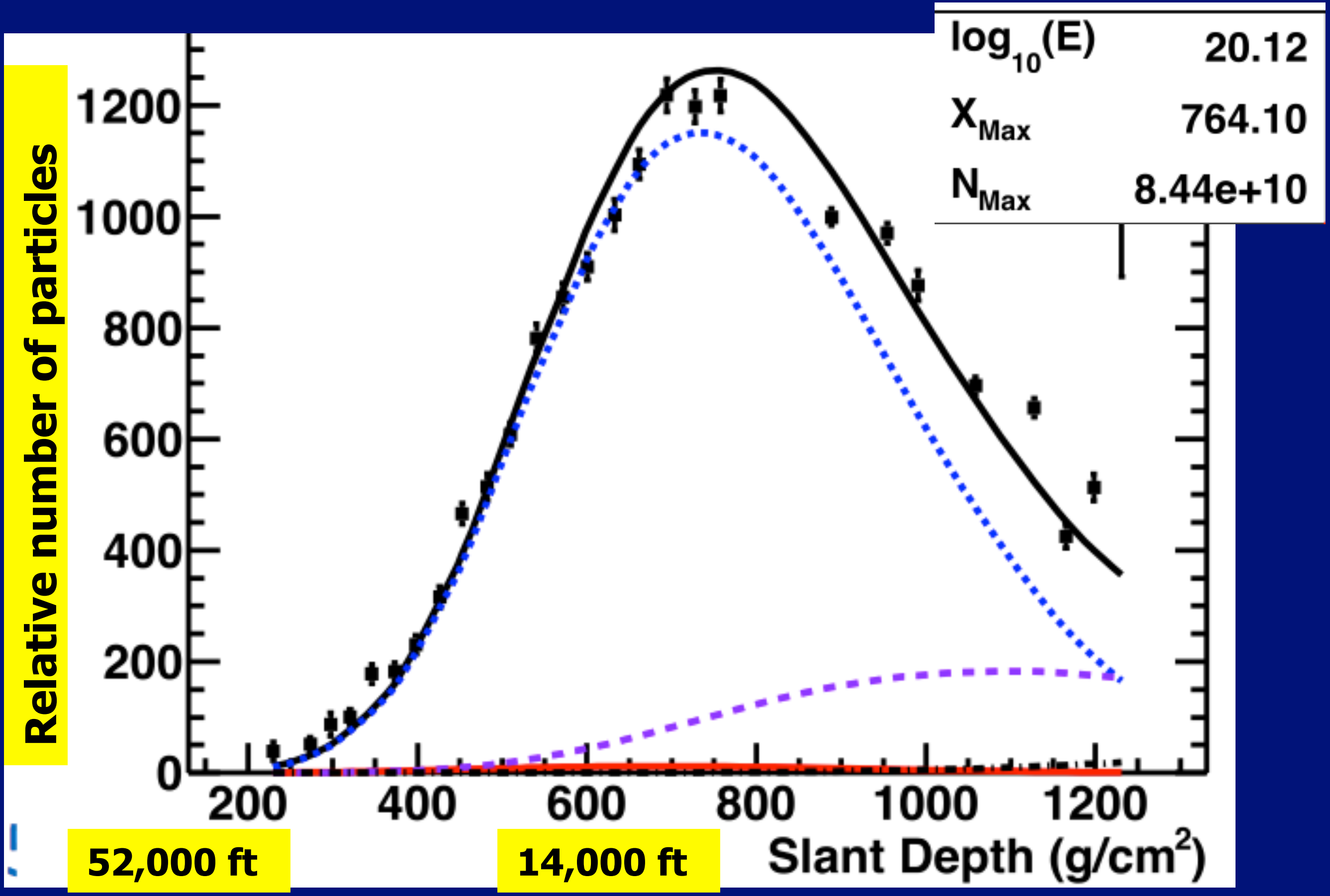


- Each detector module reports:
    - Time of hit (better than μsec accuracy)
    - Number of particles hitting detector module
- Time sequence of hit detectors → shower direction
- Total number of particles → shower energy
- Distribution of particles → distance L to shower origin

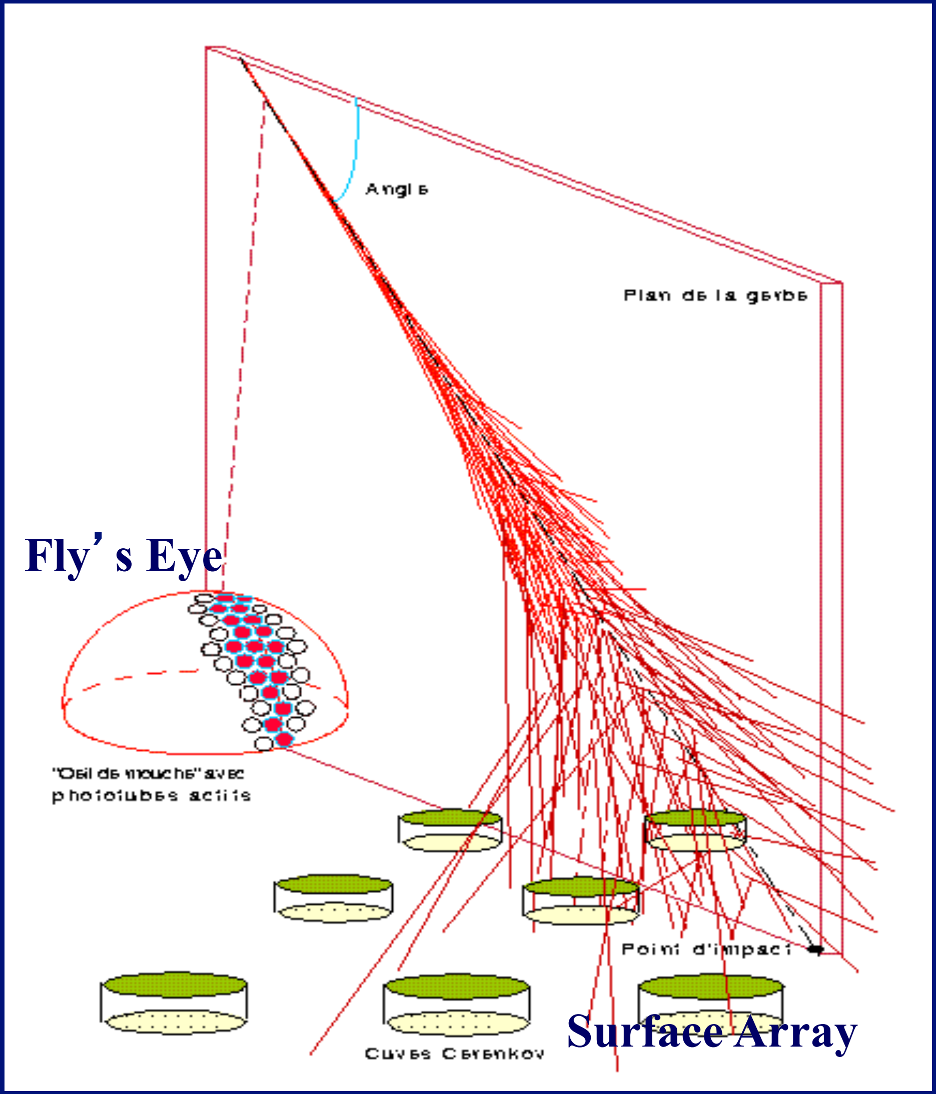
Shower profile: number of particles vs depth

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.
This plot was presented in ICRC-2015



Cosmic Ray Air Shower – detector types



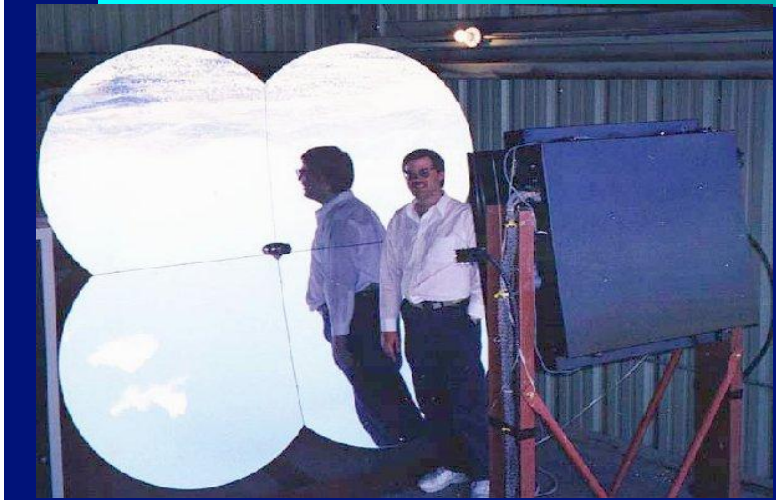
UHE air shower measurements are made by two techniques

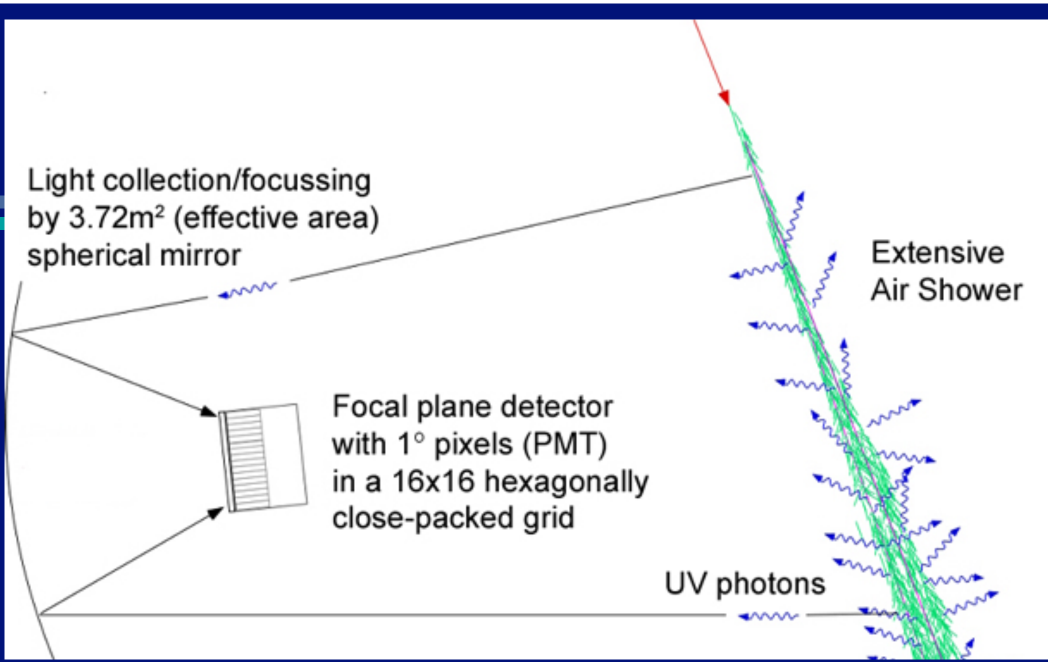
1) Surface Arrays

Scintillator counters or Cherenkov detectors

2) Fluorescence Telescopes
Arrays of photodetectors ("Fly's Eyes")

Air fluorescence detectors





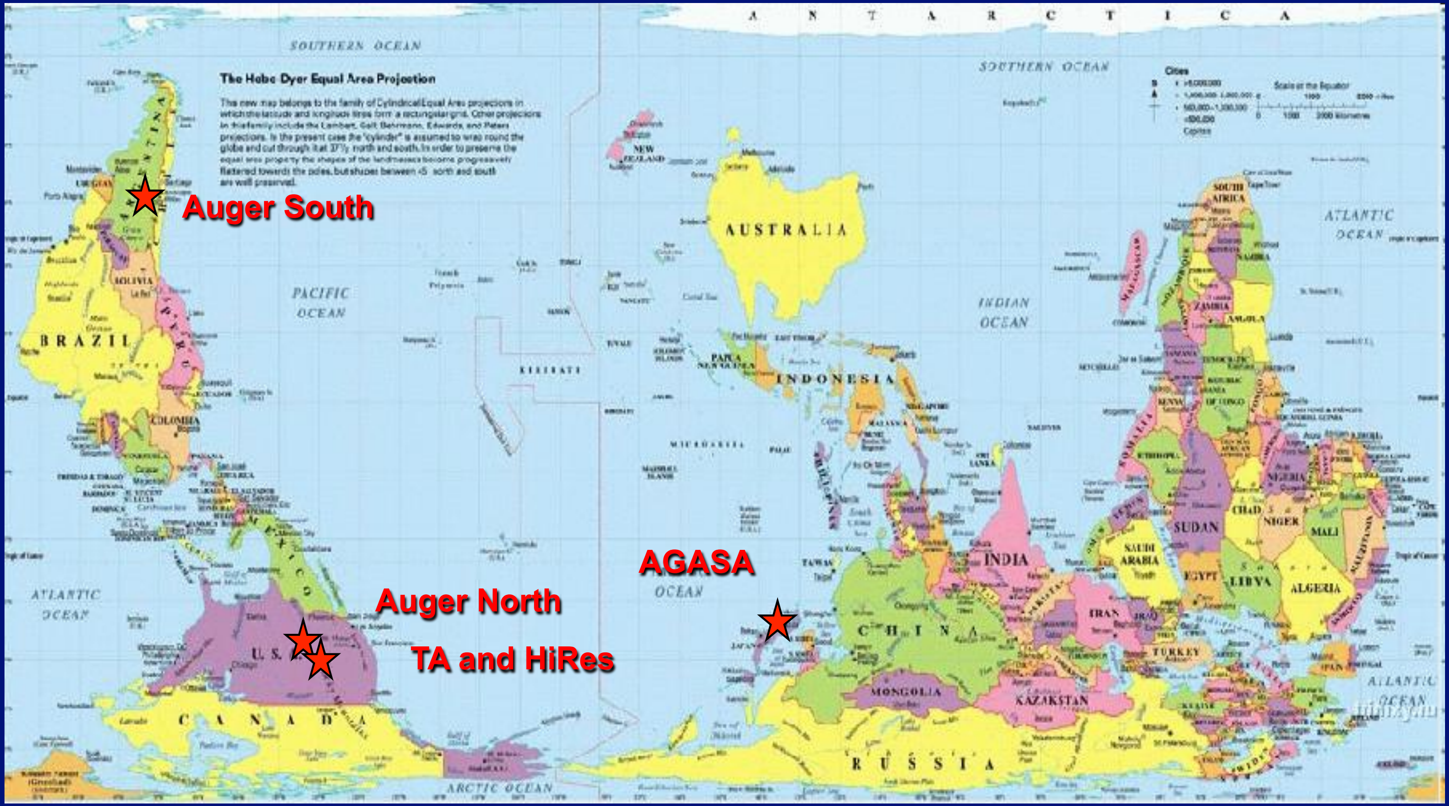
Drawback: only works on **moonless, clear nights!**

- See the shower as it develops in the atmosphere
- Shower particles excite nitrogen molecules in air
  - They emit light
- Detect 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

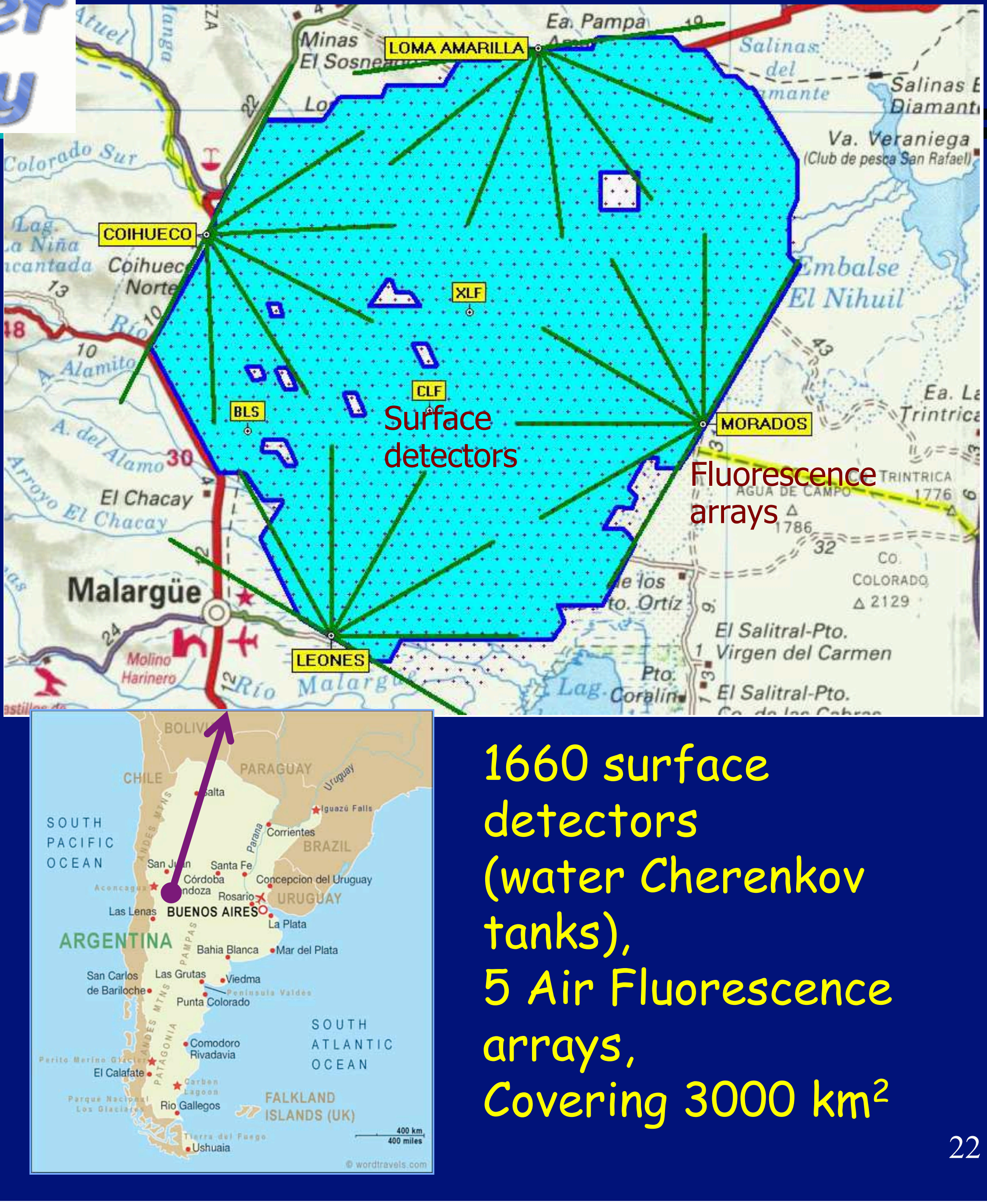
World map, Australian style



Pierre Auger Observatory

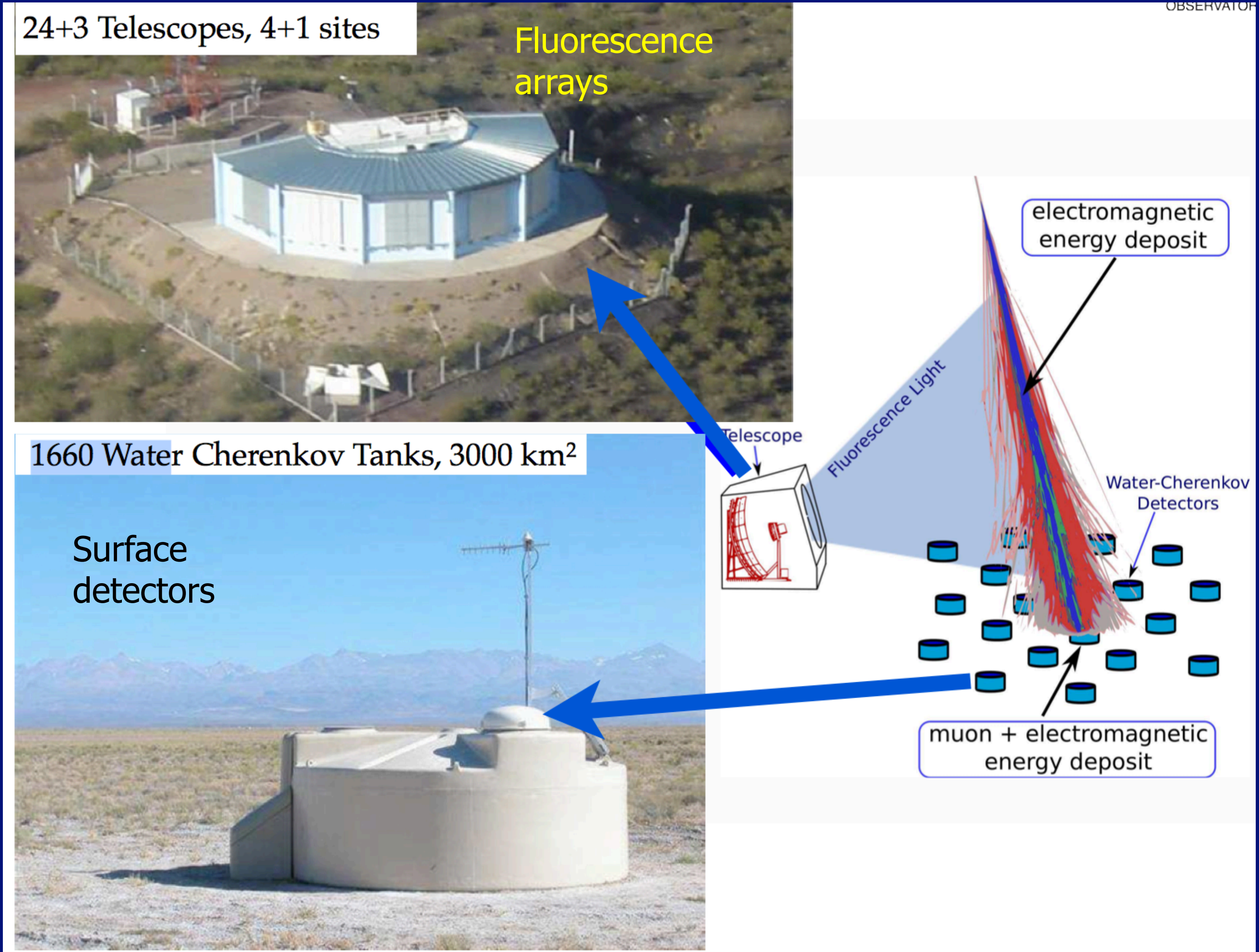
Southern hemisphere:
Mendoza Province,
Argentina

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



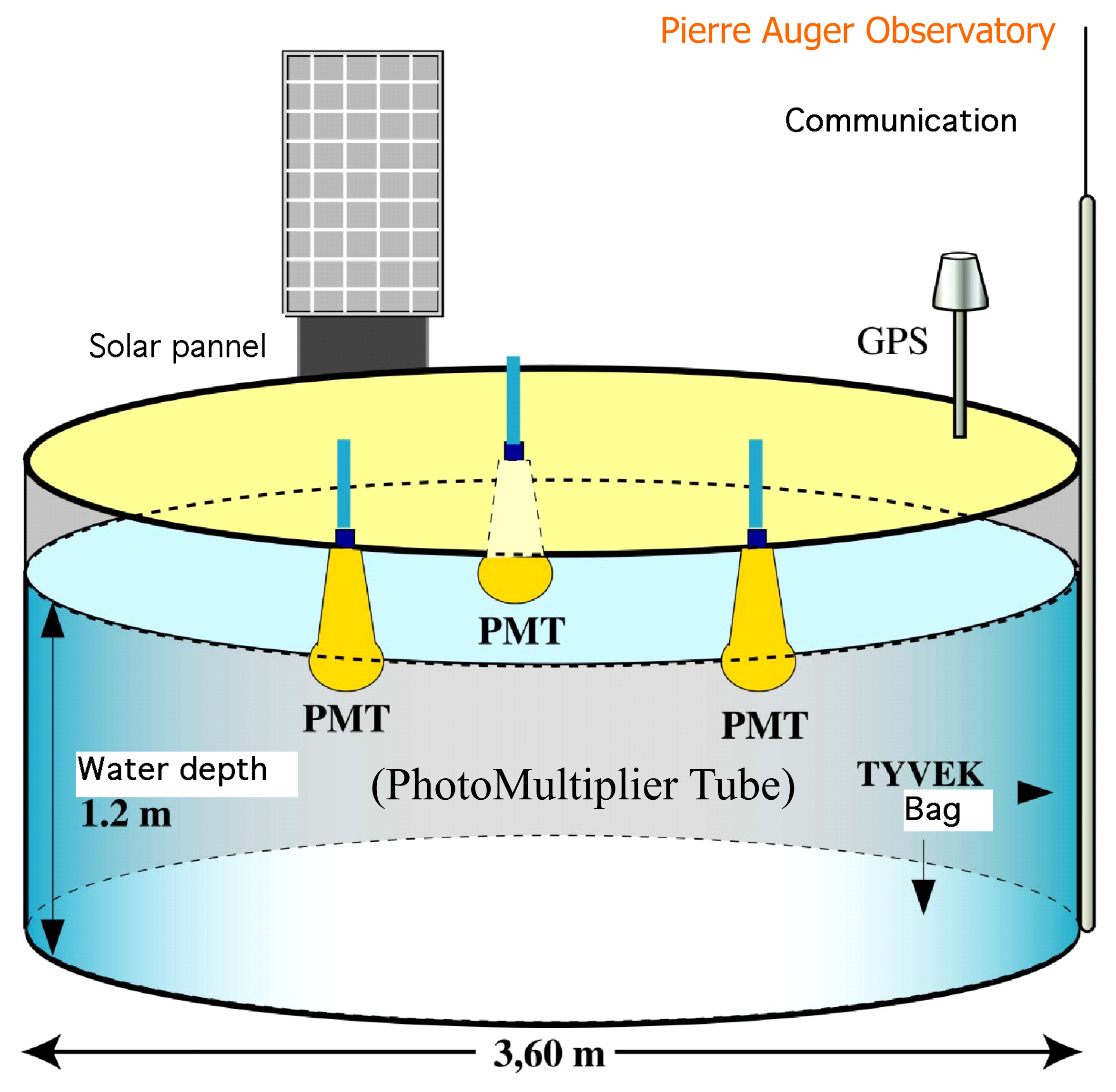
24+3 Telescopes, 4+1 sites

Fluorescence arrays

1660 Water Cherenkov Tanks, 3000 km^2

Surface detectors

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:

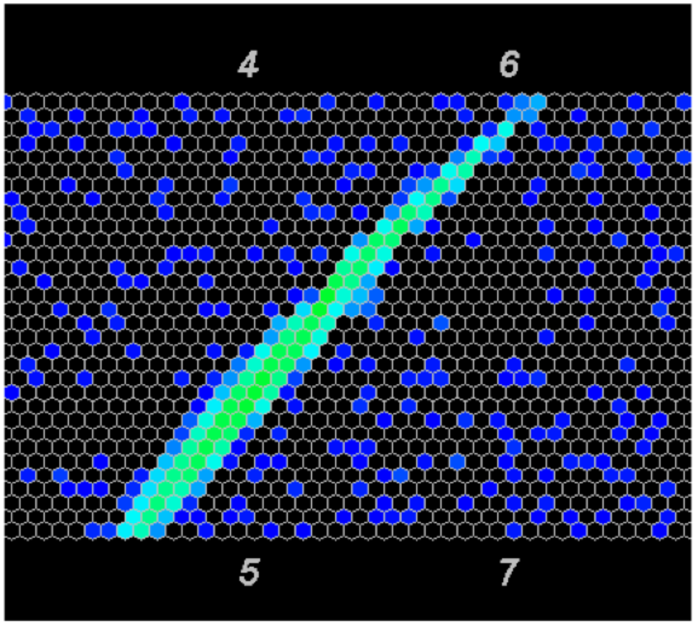
❑ Charged particles move at ~ c (speed of light in vacuum)

❑ but light can propagate in water at only 0.75c

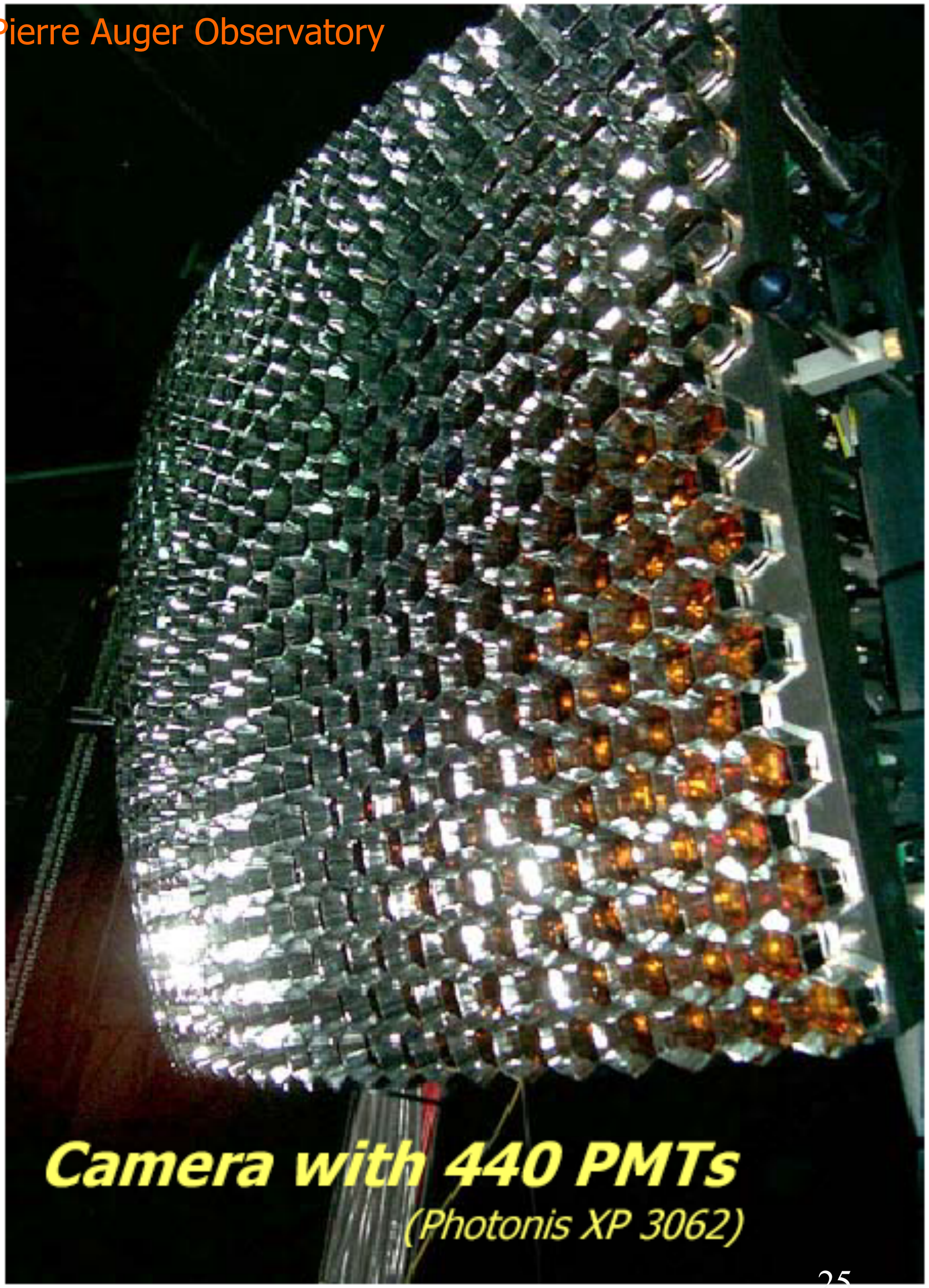
❑ Electromagnetic fields get "backed up" = Cherenkov radiation, detected by PMTs

❑ Cheap and low-maintenance detectors!

Auger’ s fluorescence detectors: 4 stations

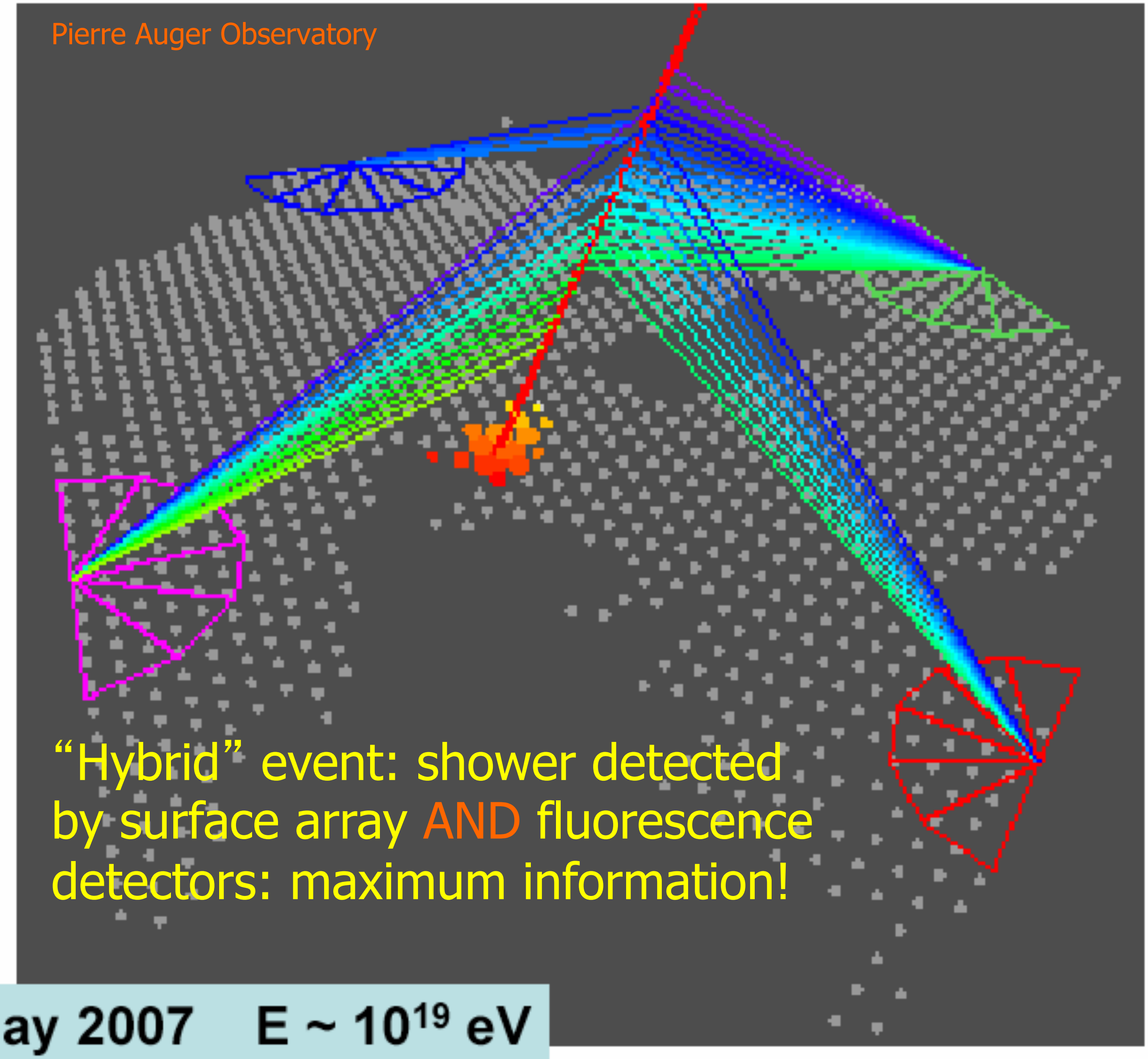


Pierre Auger Observatory



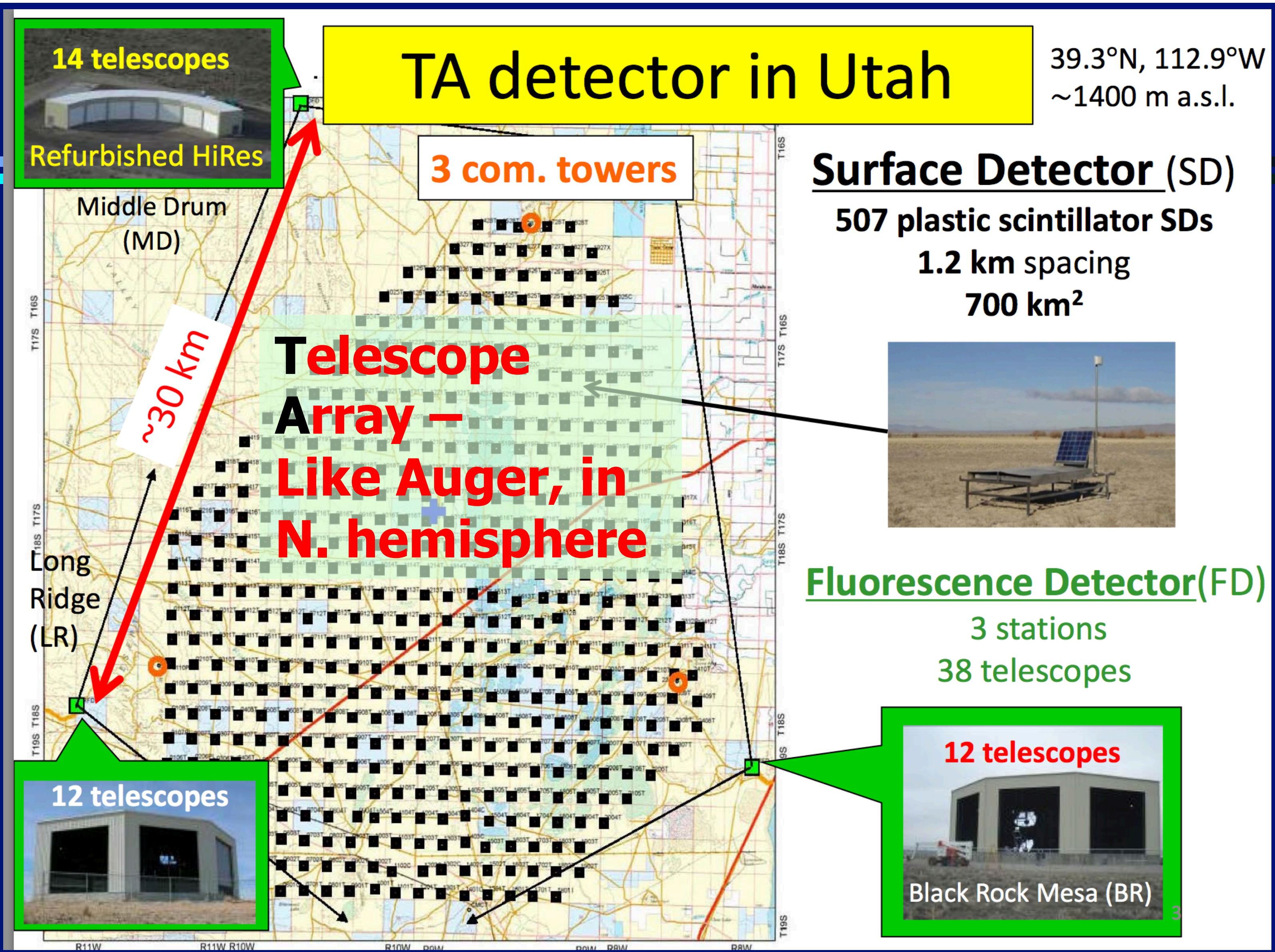
Camera with 440 PMTs

(Photonis XP 3062)



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

20 May 2007 E ~ 10^{19} eV



TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.

Surface Detector (SD)

507 plastic scintillator SDs
1.2 km spacing
700 km^2

Fluorescence Detector(FD)

3 stations
38 telescopes

Telescope Array – Like Auger, in N. hemisphere

- 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 human size references

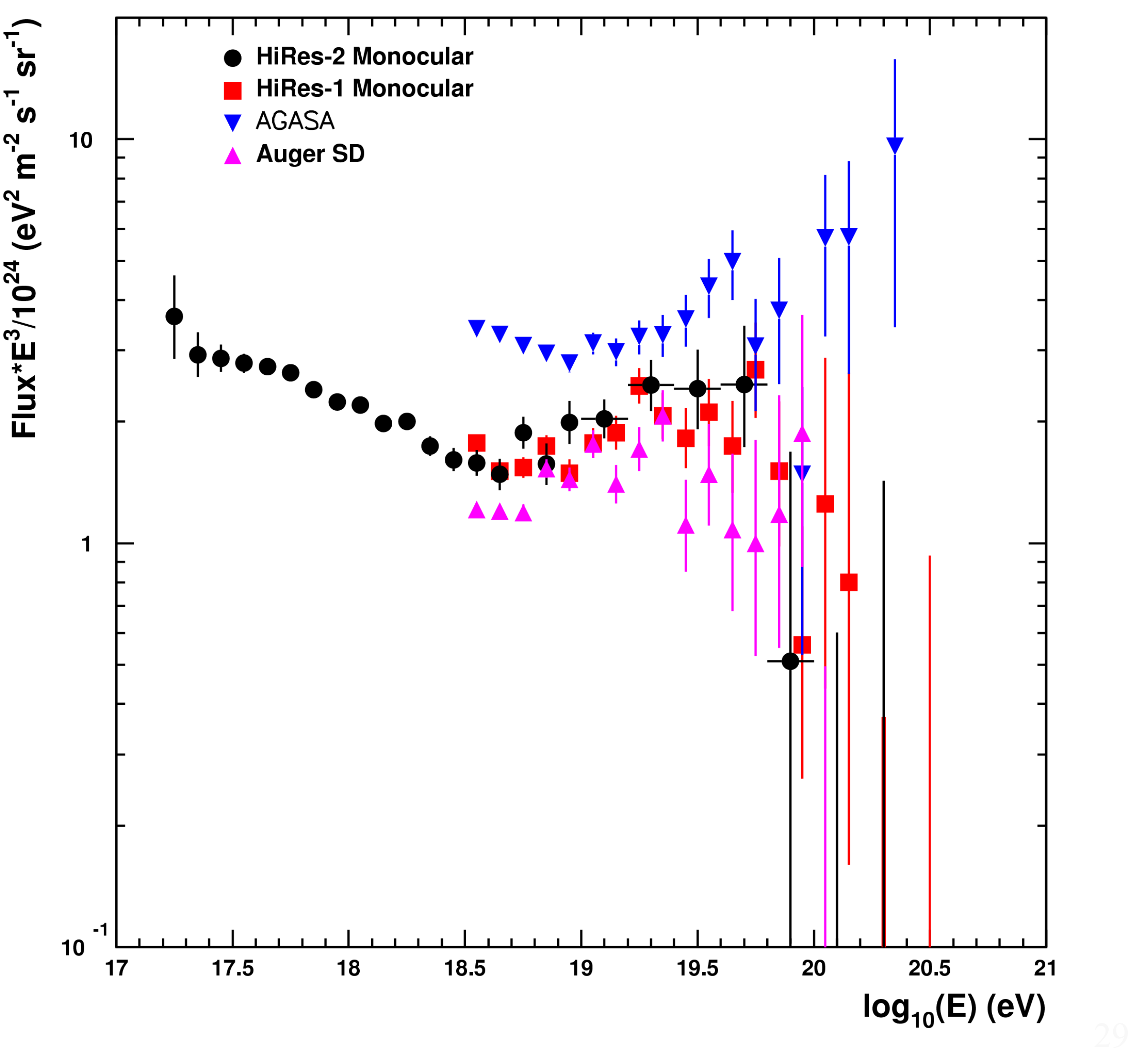
Why build TA?

- 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?

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

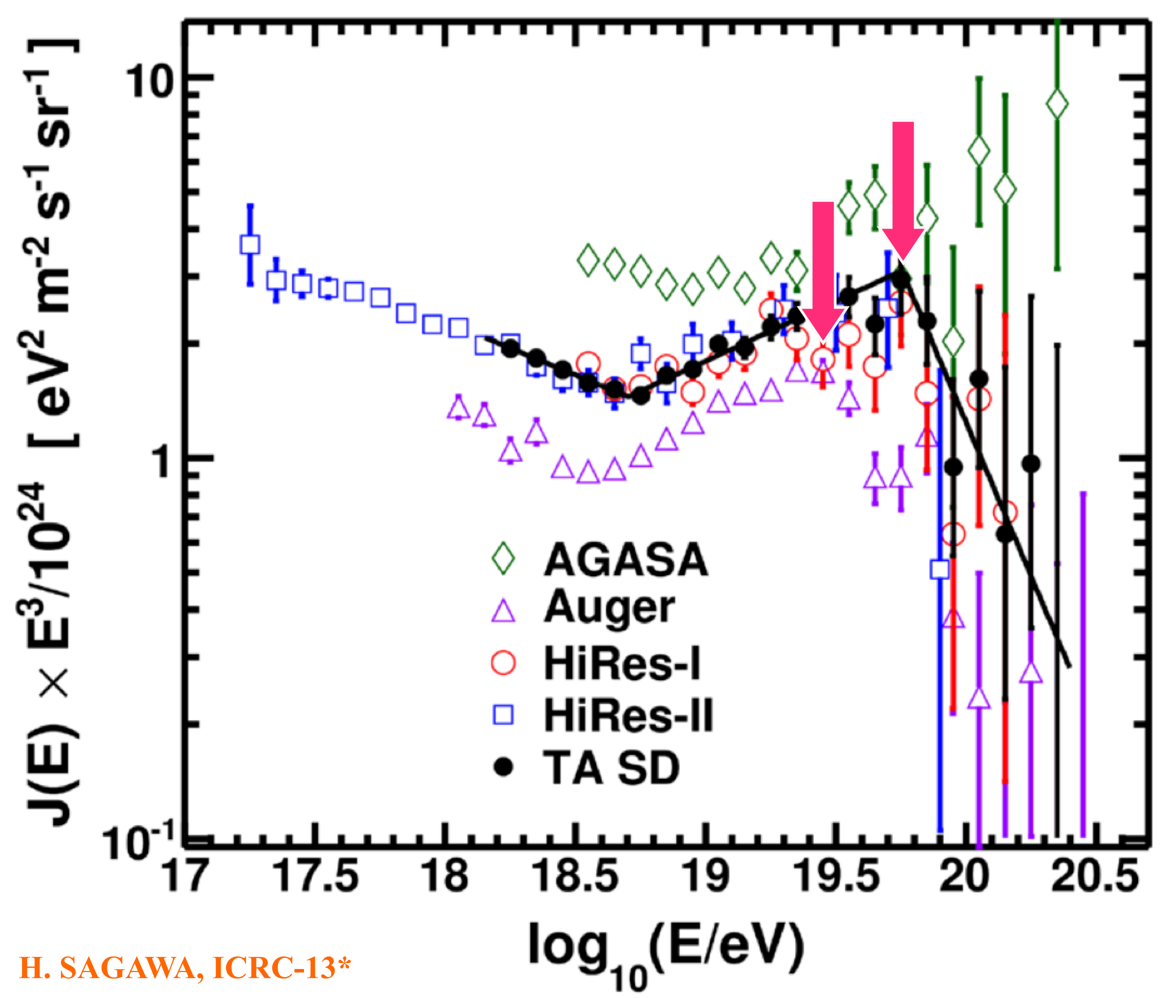
New York Times, Dec. 30, 1934

...then, in 2013...

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

TA, and Auger (2013 ICRC)

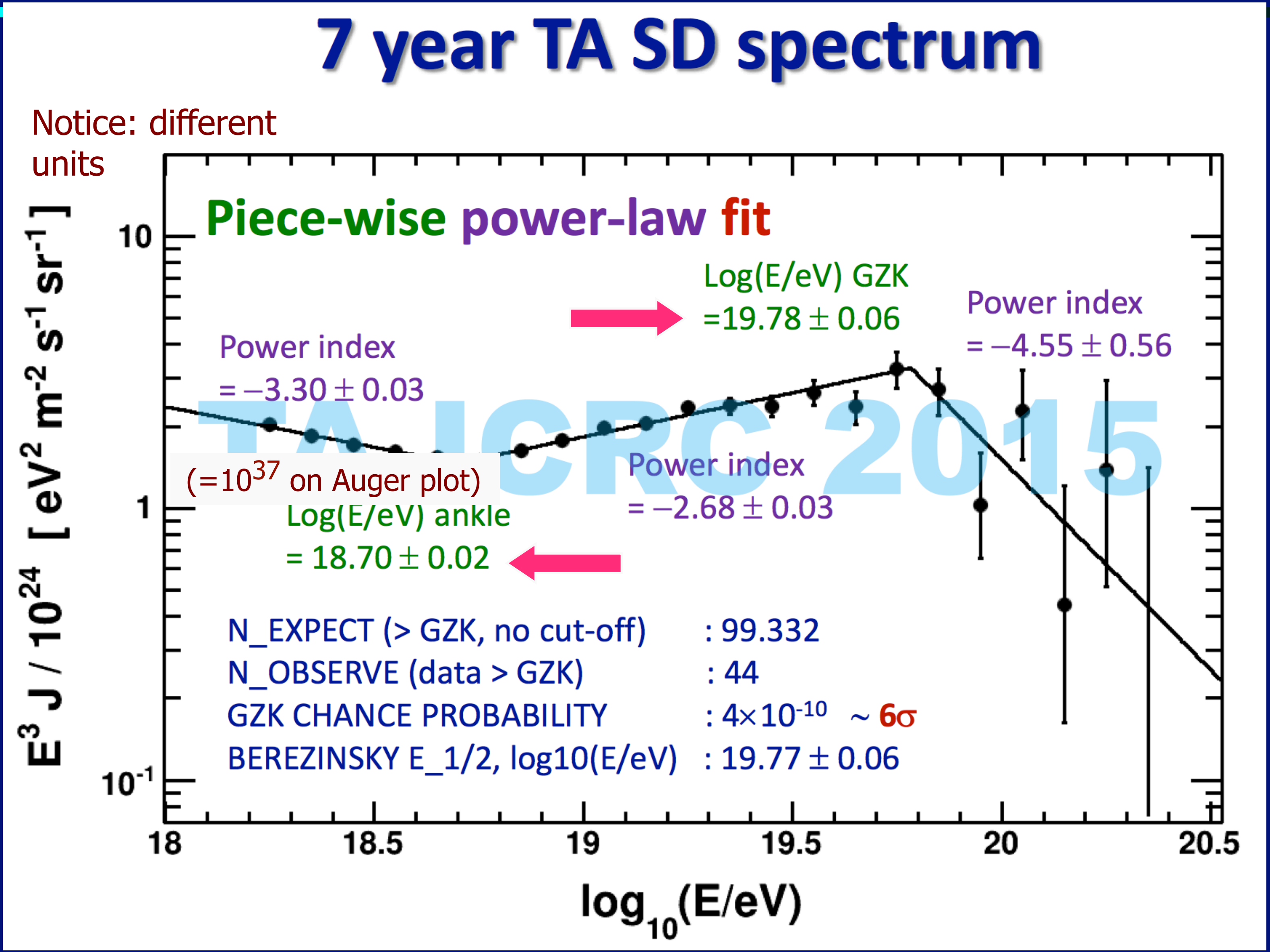
Notice difference between the two – Auger's GZK cutoff is at lower E



H. SAGAWA, ICRC-13*

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

TA 2015: now their E_{GZK} is closer to Auger's



7 year TA SD spectrum

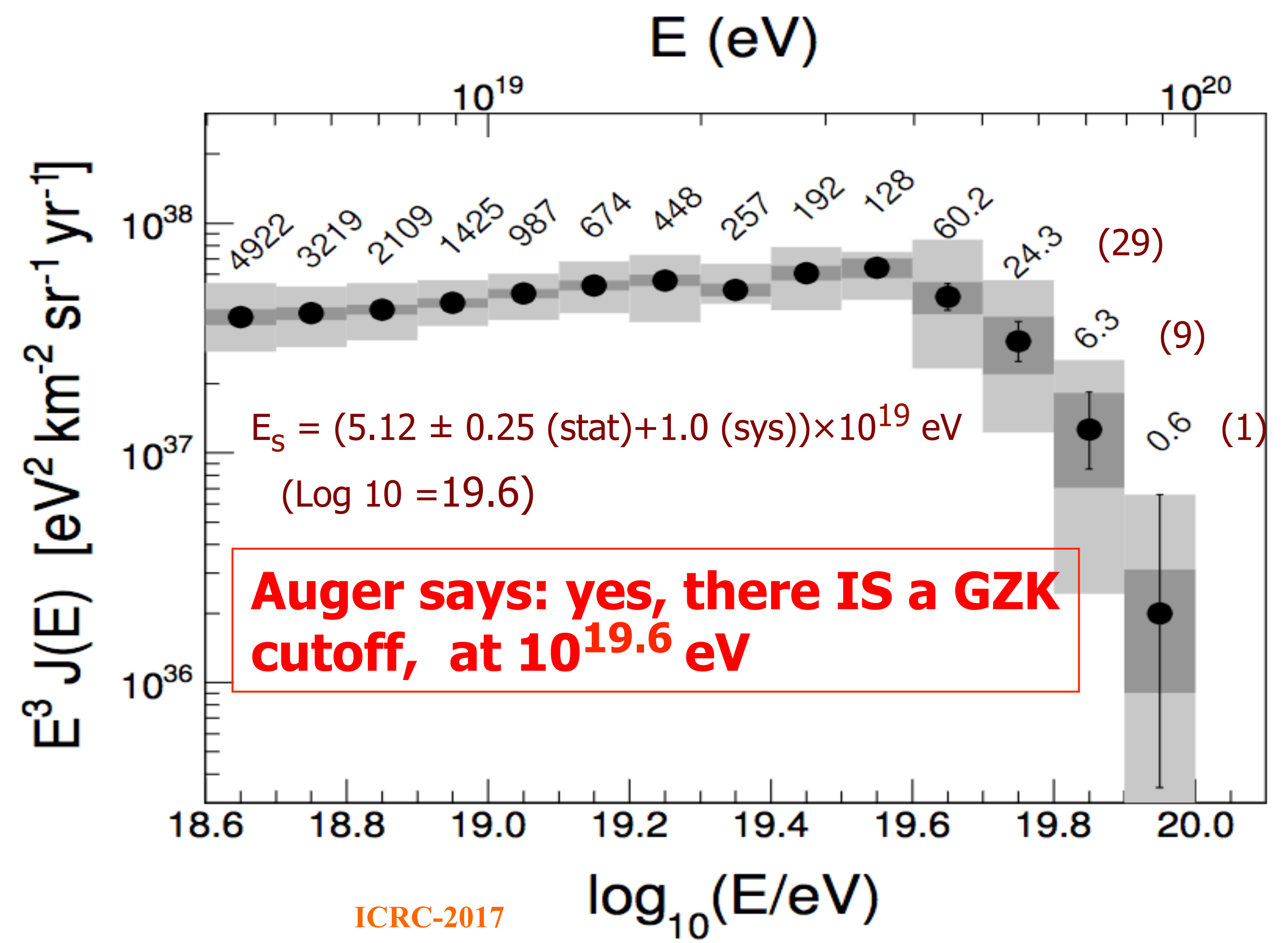
Notice: different units

(=10^{37} on Auger plot)

N_EXPECT (> GZK, no cut-off) : 99.332
N_OBSERVE (data > GZK) : 44
GZK CHANCE PROBABILITY : 4×10^{-10} ~ 6σ
BEREZINSKY E_1/2, log10(E/eV) : 19.77 ± 0.06

Latest: ICRC 2017 – Auger: numbers of events vs energy

Number of events in each data point *after* / (before) corrections

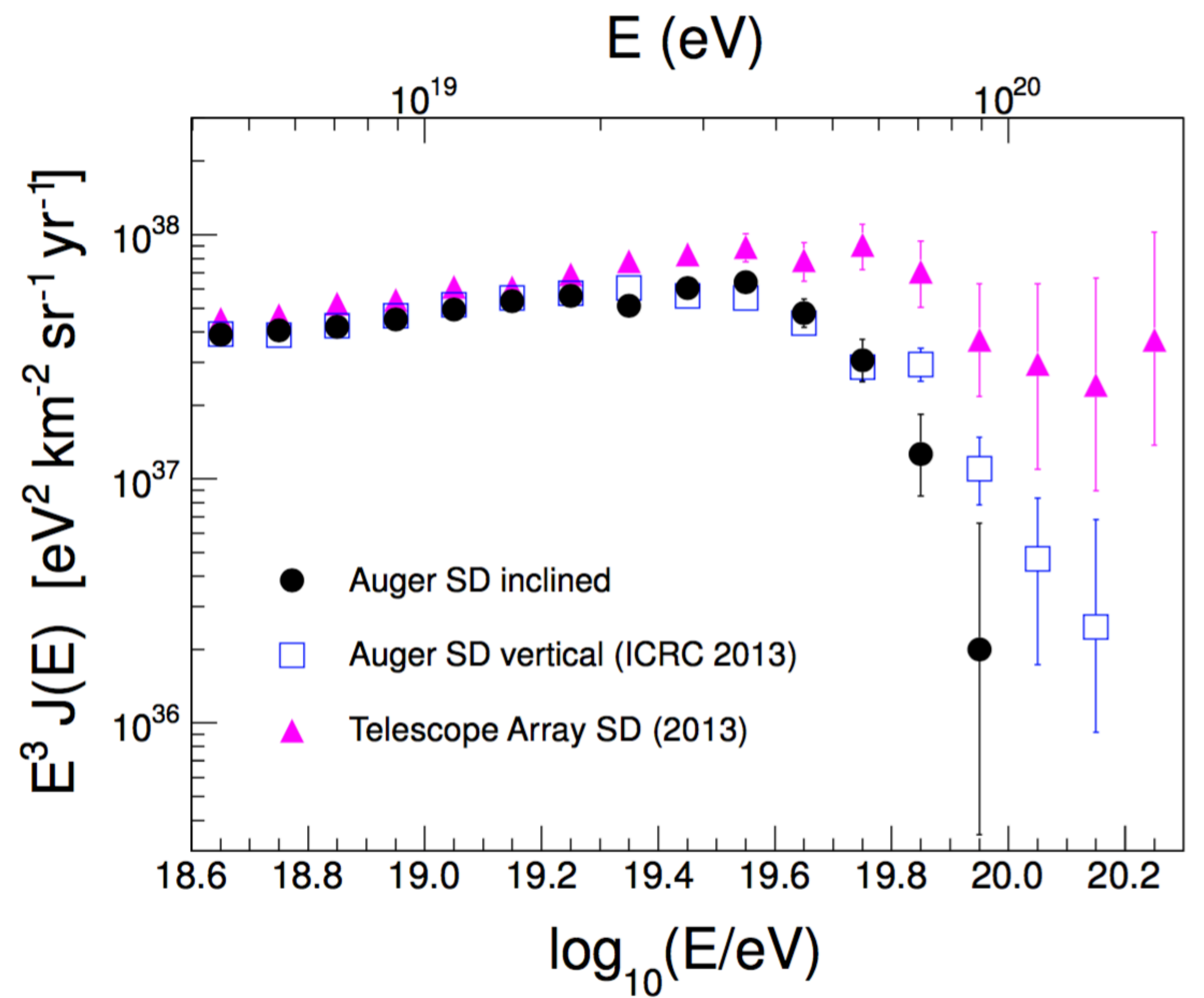


E_s = (5.12 ± 0.25 (stat)+1.0 (sys))×10^{19} eV

(Log 10 =19.6)

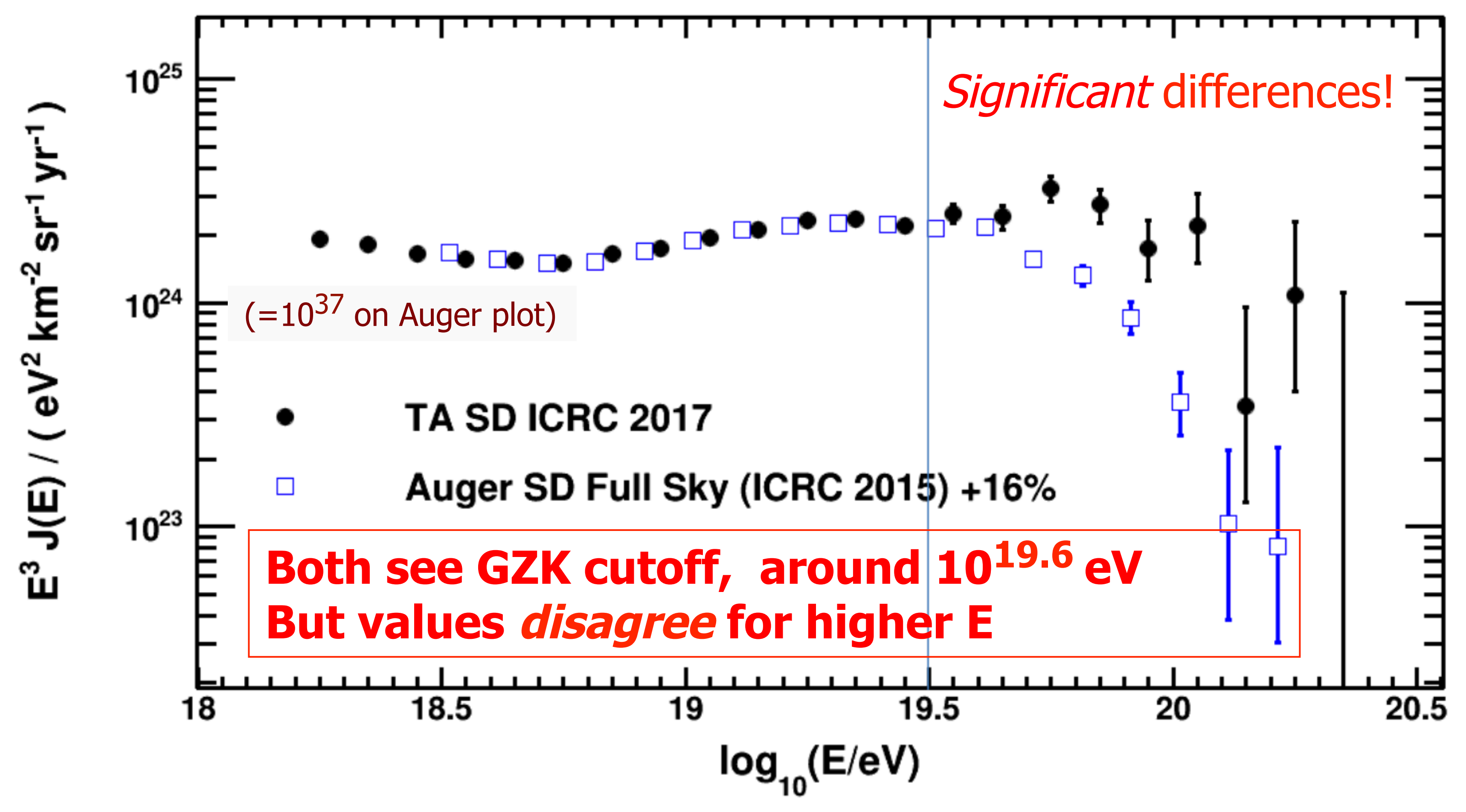
Auger says: yes, there IS a GZK cutoff, at $10^{19.6}$ eV

2017 TA results: *more* conflict with Auger!



Easier to see differences in this comparison

TA and Auger spectra *match* below $10^{19.4}$ eV, but only if Auger energy values are increased by 16% (“within Auger’s uncertainties”)



Significant differences!

(=10^{37} on Auger plot)

Both see GZK cutoff, around $10^{19.6}$ eV
But values *disagree* for higher E

So there *IS* a GZK effect: where are 'lost' CRs?

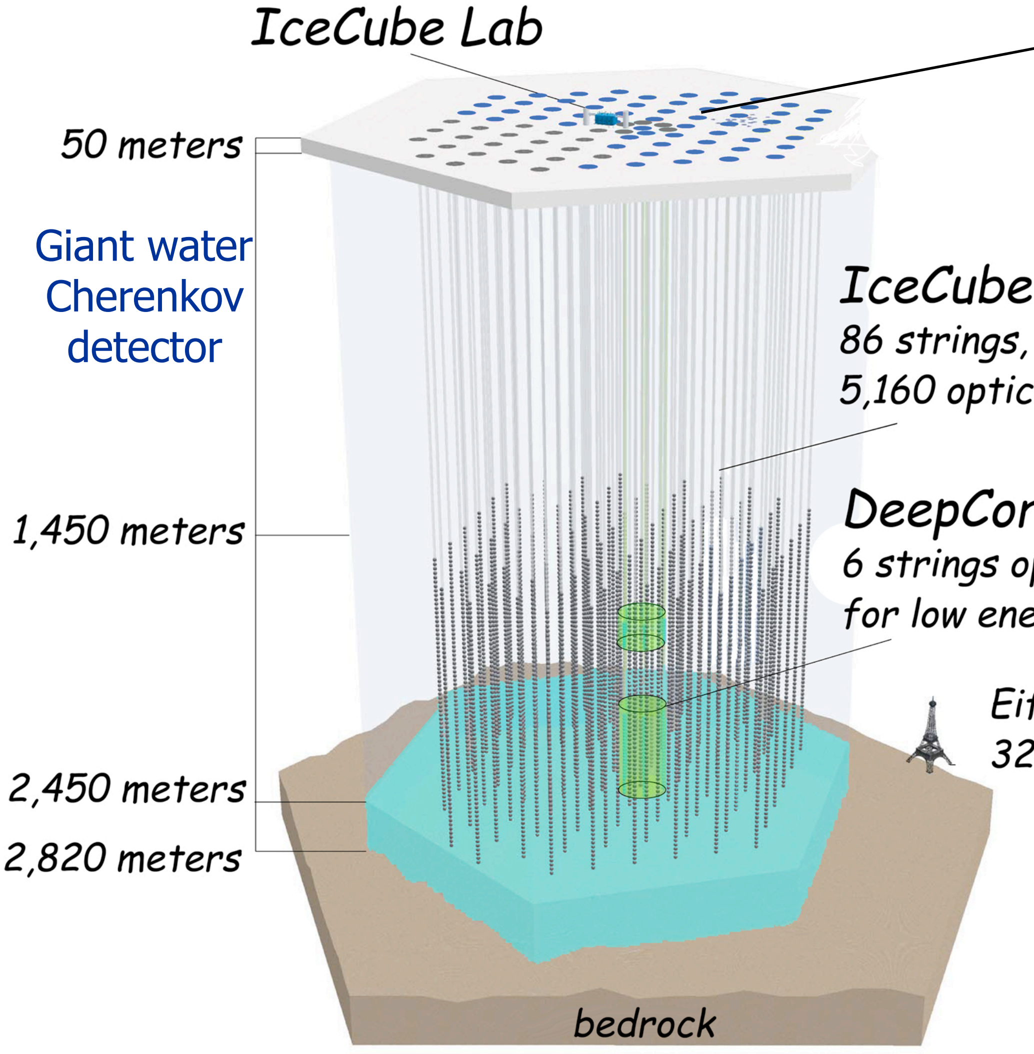
- CRs above 10^{20} eV interact long before reaching Earth
  - About half of CR's original energy is lost in each interaction
    - Energy lost becomes *secondary particles*
    - All kinds of particles produced – energy available is enormous
- BUT: only stable particles can reach us!
  - Millions of 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

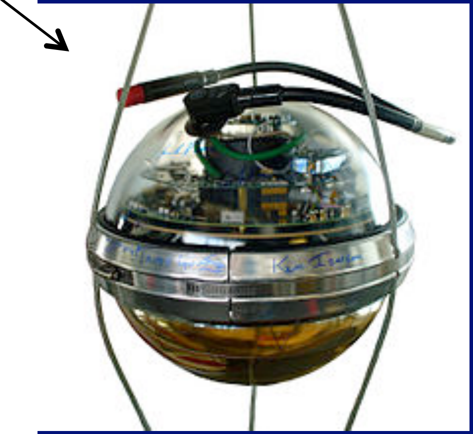
IceCube neutrino detector at South Pole Station

South pole icecap is 3000 m thick

Ice works like water in Auger tanks



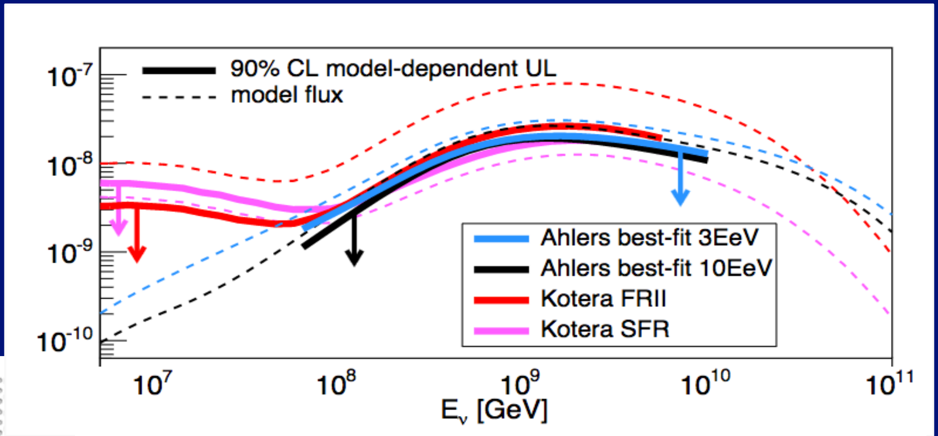
IceCube's Optical Sensors (PMTs)

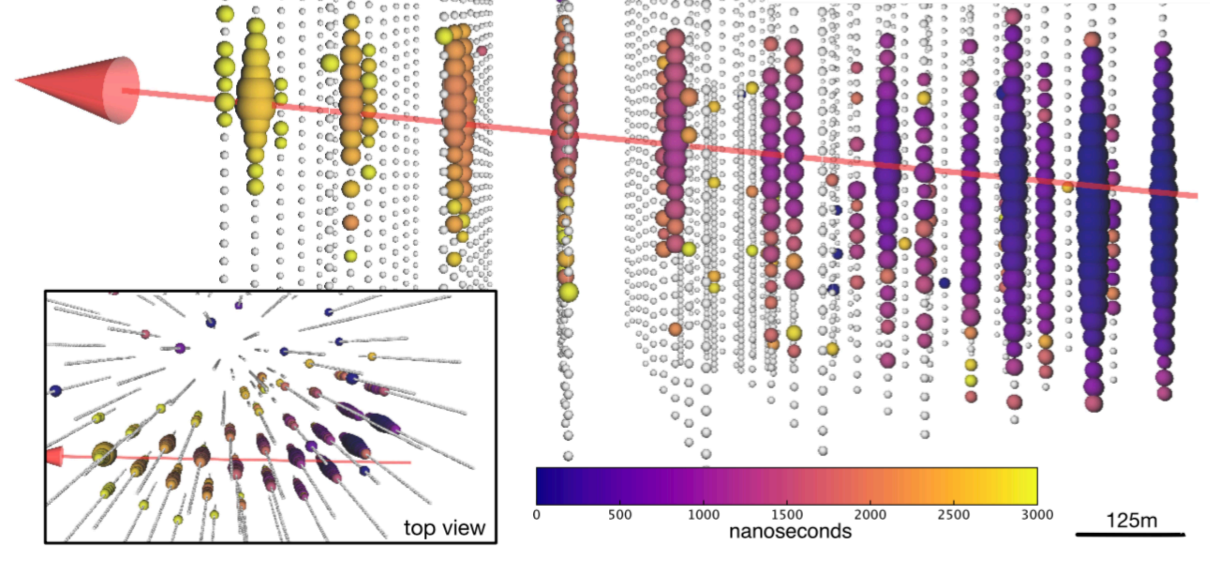


Does IceCube see cosmogenic neutrinos?

- ONE: no UHE neutrinos found in 7 years of IceCube data,
  - until 9/22/2017: Highest energy neutrino observed so far: ~10^{15} eV

Predictions by theorists for cosmogenic neutrino flux versus energy: expect an excess around 10^{18} eV due to "GZK pile-up" ⟶





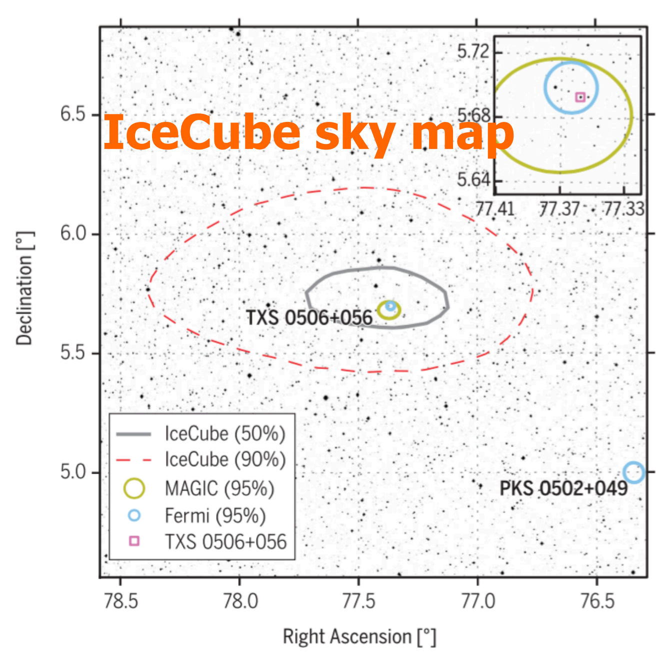
IceCube event display:

Blob size → number of photons in PMT

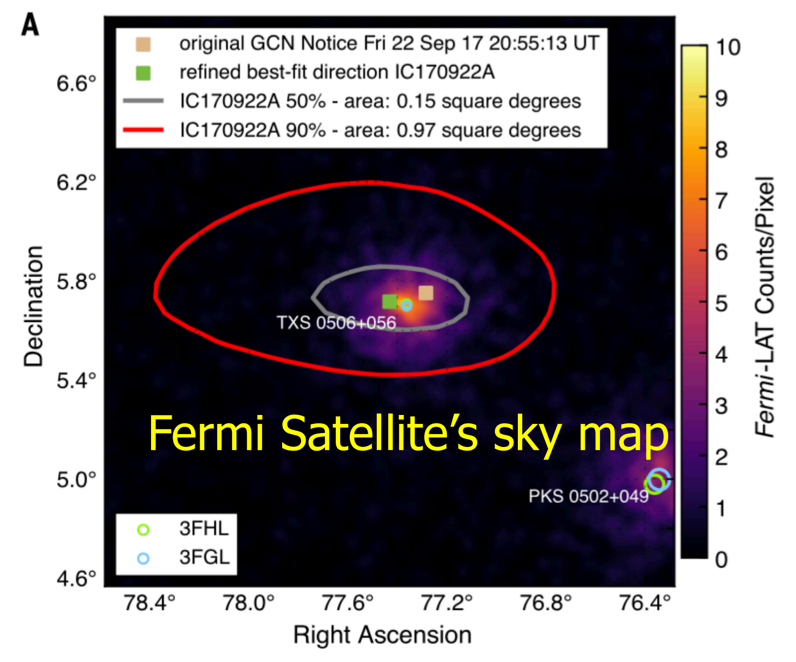
Color → relative time of arrival at PMT

"Multimessenger Astrophysics"

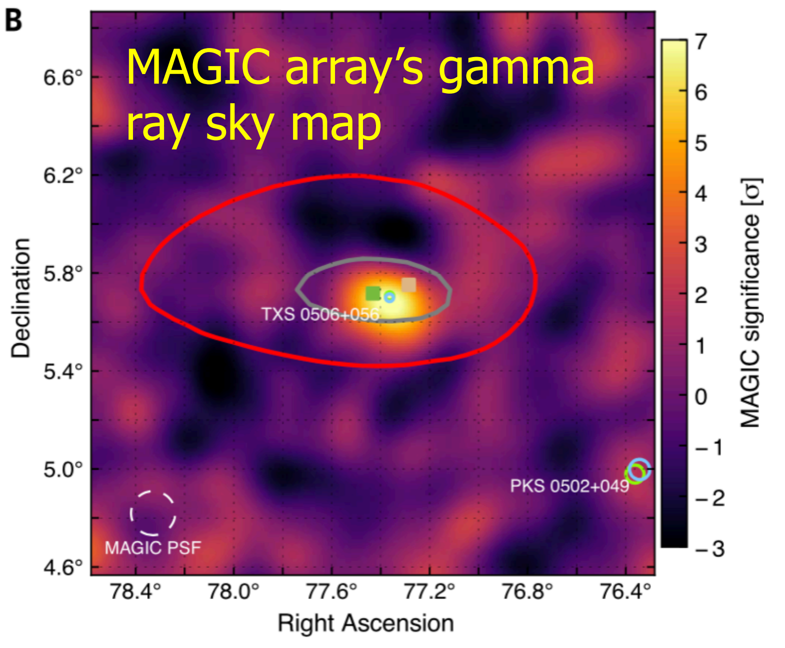
- Now we have *multiple ways* to "see" astrophysical events: neutrinos as well as photons!
- IceCube's neutrino came from the direction of a known, powerful gamma-ray source: TXS 0506+056



IceCube sky map



Fermi Satellite's sky map



MAGIC array's gamma ray sky map

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 learning physics is 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