PHYS 575A/B/C

Autumn 2015

Radiation and Radiation Detectors

Course home page:

http://depts.washington.edu/physcert/radcert/575website/

8: Case studies: cosmic ray experiments; Cherenkov detectors

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Course calendar (revised)

week	date	day	topic	text
1	10/1/15	Thurs	Introduction, review of basics, radioactivity, units for radiation and dosimetry	Ch. 1, notes
2	10/6/15	Tues	Radioactive sources; decay processes;	Ch. 1, notes
3	10/13/15	Tues	Photomultiplier tubes and scintillation counters; Counting statistics	Chs. 3, 8, 9 (I-V)
3	10/15/15	Thurs	**LAB: Room B248** Scopes, fast pulses; PMTs and scintillation counters; standard electronics modules	Chs. 4, 9, 16, 17
4	10/20/15	Tues	Overview of charged particle detectors	Ch. 4
4	10/22/15	Thurs	**LAB: Room B248** Coincidence techniques; nanosec time measurement, energy from pulse area	Chs. 17, 18
5	10/27/15	Tues	Interaction of charged particles and photons with matter; counting statistics; gas detectors; Proposal for term paper must be emailed to JW by today	Chs. 2, 3; Chs. 5, 6, 7
6	11/3/15	Tues	ionization chambers; solid-state detectors	Chs. 11, 12, 13
Tonight → 7	11/10/15	Tues	Statistics for data analysis; Case studies: classic visual detectors (cloud and bubble chambers, nuclear emulsion, spark chambers)	Ch. 19, notes
8	11/17/15	Tues	Case studies: Cosmic ray detectors (Auger, Fermi gamma ray observatory); Cherenkov detectors: atmospheric Cherenkov, triggering Cherenkov	Ch. 19, notes
9	11/24/15	Tues	Case studies: neutrino detectors (IceCube, Daya Bay, Majorana), Detecting neutrons; high energy accelerators;	Ch. 19, notes Ch. 14, 15, 18
10	12/1/15	Tues	Finish case studies; begin student presentations	Notes
11	12/8/15	Tues	Student presentations	-
11	12/10/15	Thurs	Student presentations	

Announcements

- Presentation dates: Tues Dec 1, Tues Dec 8, and Thurs Dec 10
  - See class web page for link to signup sheet

- NEW Schedule and signup table for term project presentations. This is a Google spreadsheet in the UW Google Docs filespace; log in with your UW NetID username and password (NOT your personal Google username) for access. Sign in to the slot you want, then exit, and let me know you did so by email.

I will arbitrarily assign slots for those not signed up by November 29

As of today:

PHYS 575 Au-15: Report Presentations

Please send me your presentation ppt/pdf (or URL) at least 1 hour before class on your date

Day	Time	Name	Topic
12/1/2015	7:00 PM	Per Provencher	Low Background Laboratories
	7:20 PM	Rick McGann	Neutron Generation and Effects on Materials and Electronics
	7:40 PM	Chris Provencher	Bremsstrahlung
	8:00 PM	Charles Ko	Radiometric Dating
	8:20 PM	Padmaja Vrudhula	Dosimetry
12/8/2015	6:40 PM	Diana Thompson	NORM
	7:00 PM	Shawn Apodaca	Fast Neutron Time of Flight and Spectroscopy
	7:20 PM	Erin Board	Cosmic Radiation and Shielding
	7:40 PM	Louie Cueva	Thermal Neutron Detection
	8:00 PM		
	8:20 PM		
12/10/2015	6:40 PM	Nathan Hicks	Methods of Radionuclide Production for Medical Isotope Usability: Meeting the Demand
	7:00 PM	Farrah Tan	QCD
	7:20 PM	Nicolas Michel-Hart	microXRF
	7:40 PM	Michael Esuabana	proton-Boron11 fusion
	8:00 PM	Kaifu Lam	Synchrotrons
	8:20 PM		

Varieties of "cosmic rays"

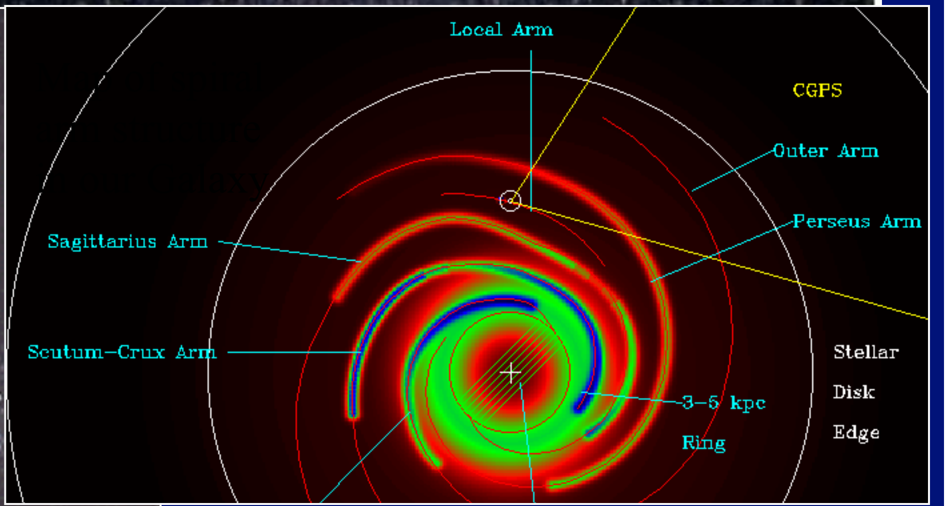
- Cosmic rays = particles (with mass>>0) reaching Earth from space
  - Usually we do not include gamma rays and neutrinos
- Solar cosmic rays = particles from the Sun
  - Typically low (MeV) energies (nuclear physics processes !)
  - Strongly affected by magnetic fields of Earth and Sun
    - ...which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

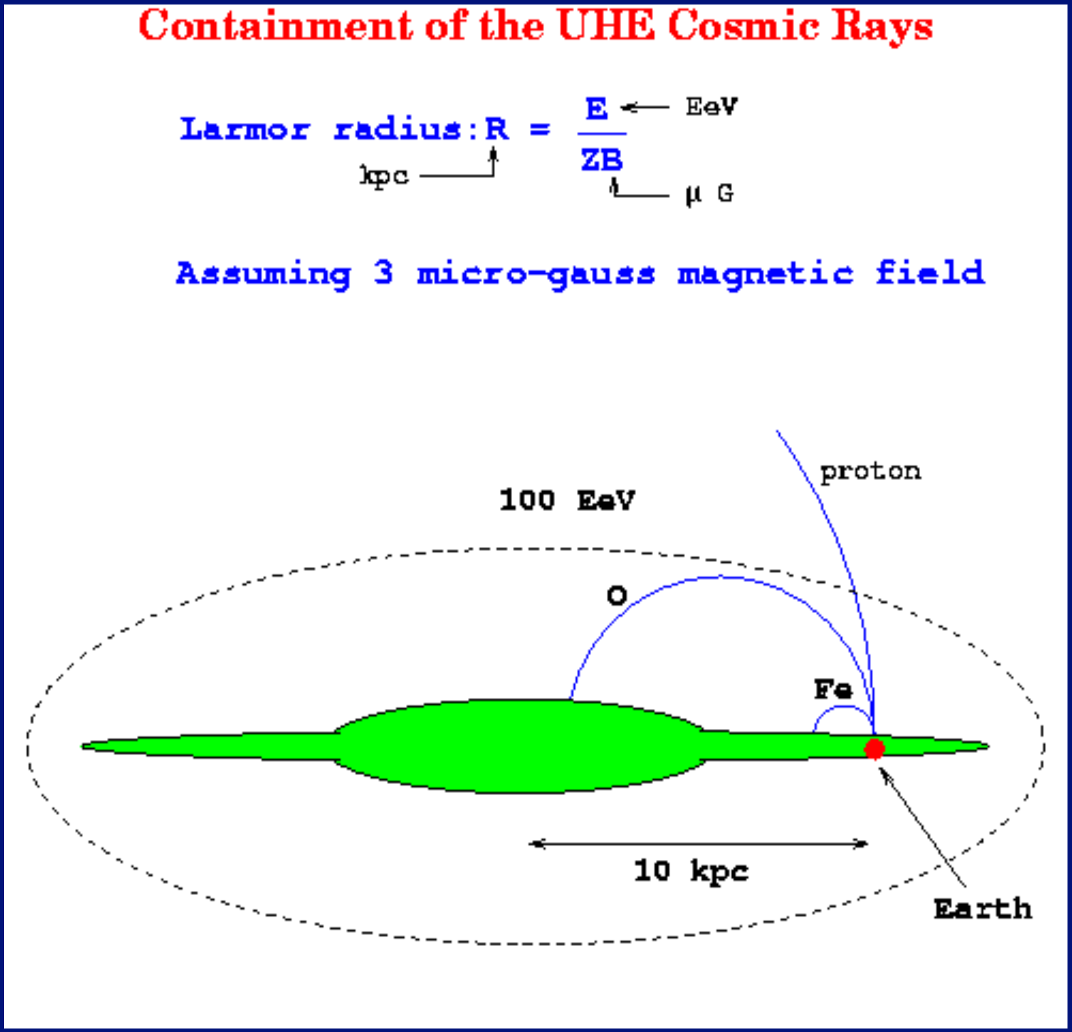
Our Galaxy's magnetic field cannot trap protons with E > 10^{18} eV, so

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

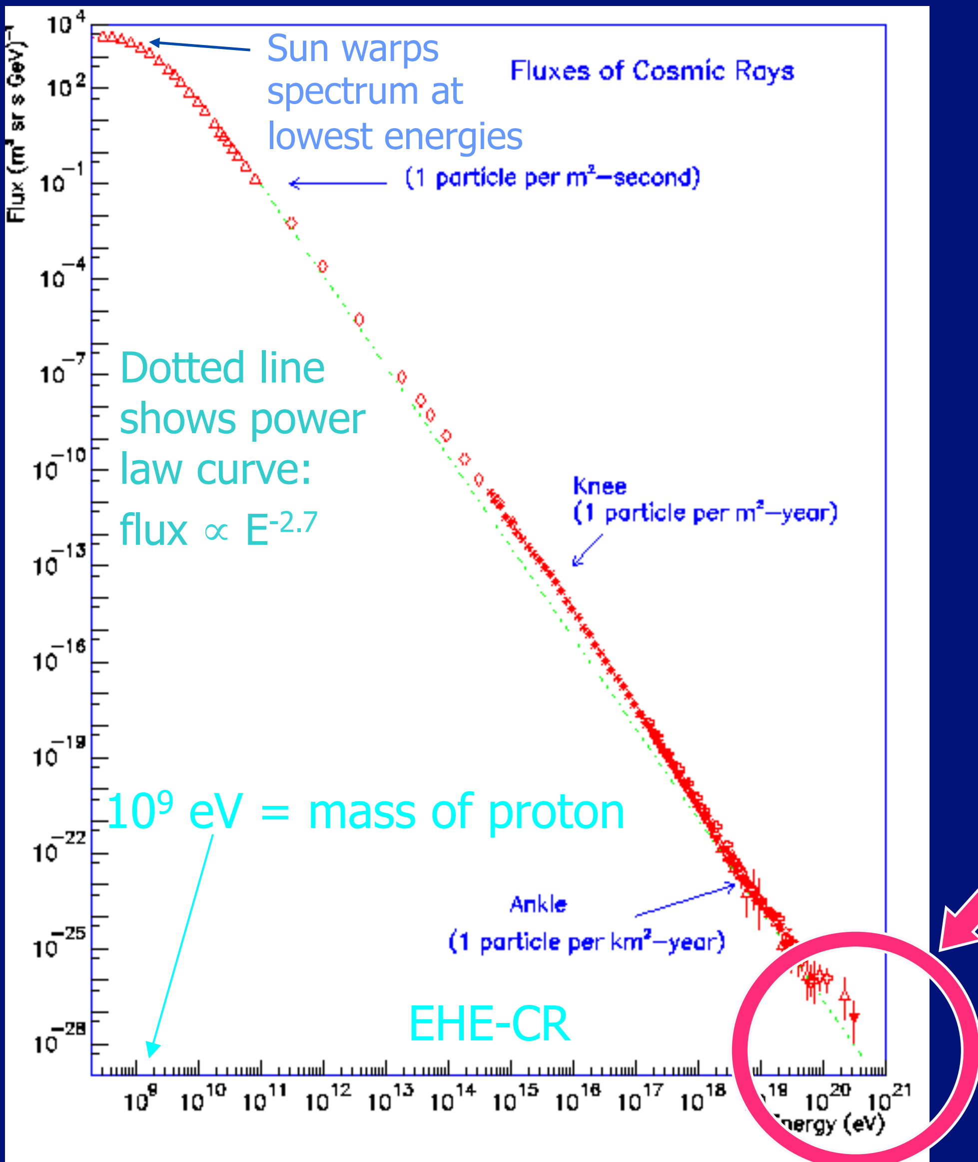
Q: Is there a significant intergalactic B?

Probably very weak

Fermi Gamma Observatory data sets limit B < 10^{-19} T (Earth field ~ 10^{-4} T)



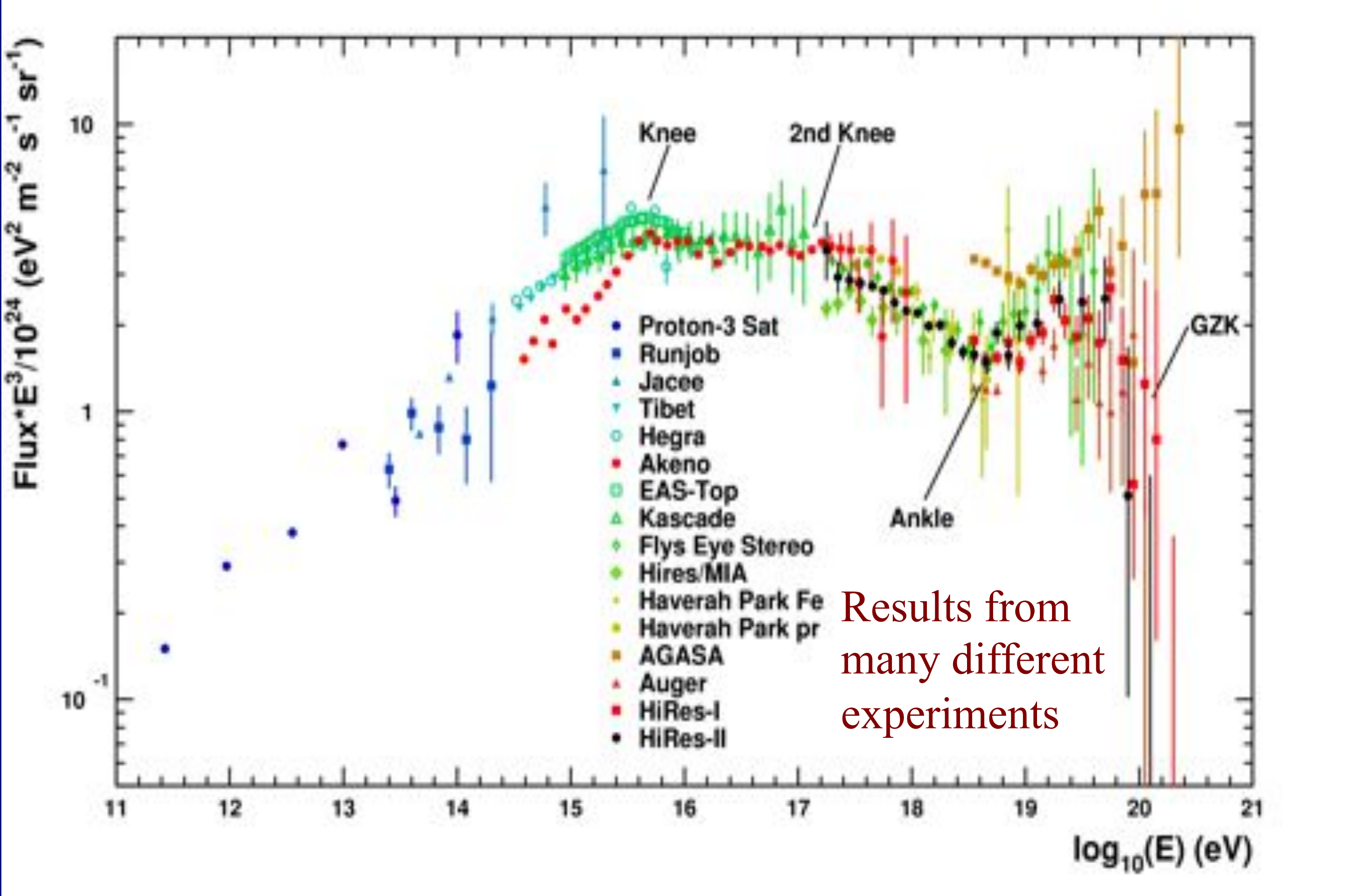
The galactic cosmic ray spectrum



- Cosmic ray *spectrum:* intensity vs energy for cosmic rays
  - protons and all 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!

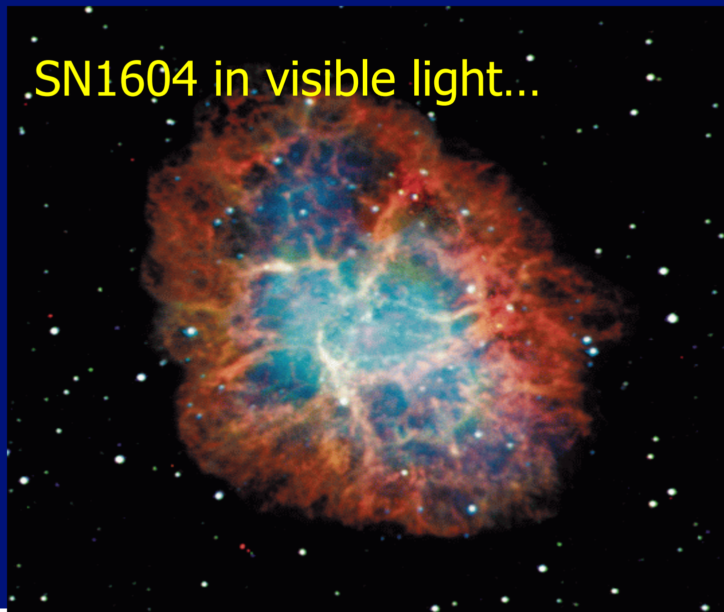
Spectrum is not boringly smooth, if you look closely

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



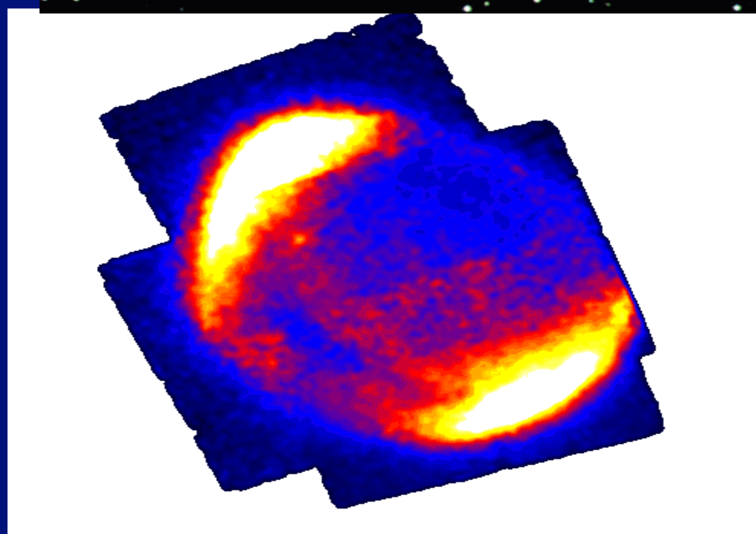
Most cosmic rays come from Supernovae
Example of remnant: SN1604 = Kepler's

- SN1604 in visible light…

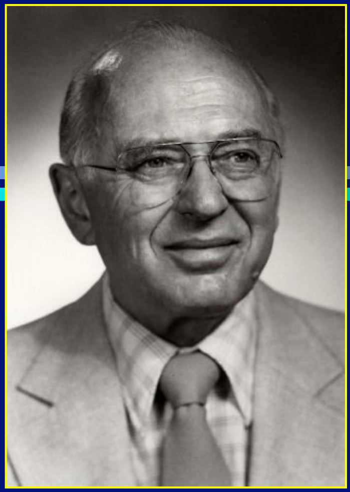


When large stars run out of nuclear fuel, they collapse and sometimes explode, becoming a "super-nova".

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

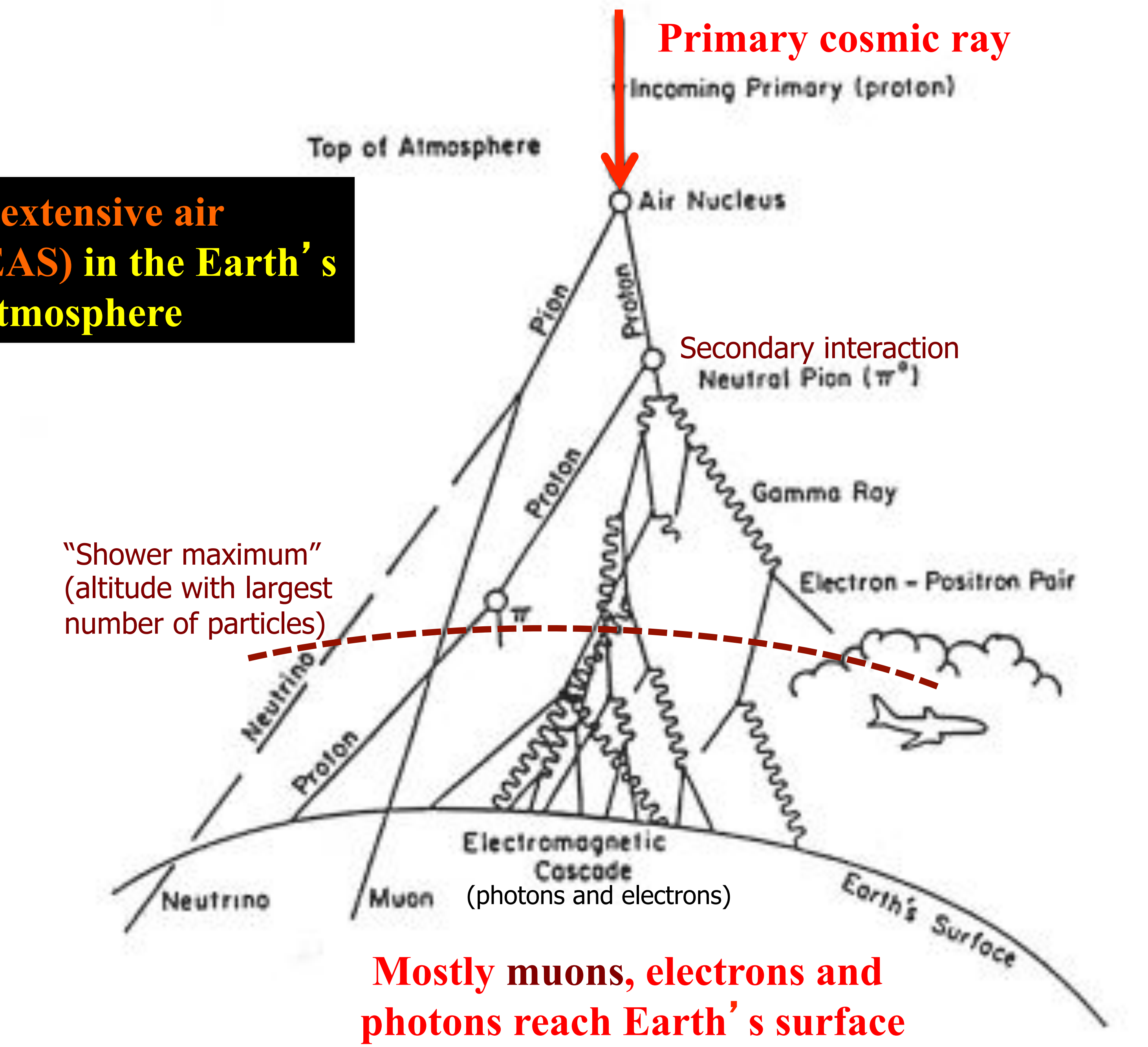


Ken Greisen (Cornell)

G. Zatsepin (Moscow State Univ.)

Why no ultra-HE CRs? The "GZK cutoff"

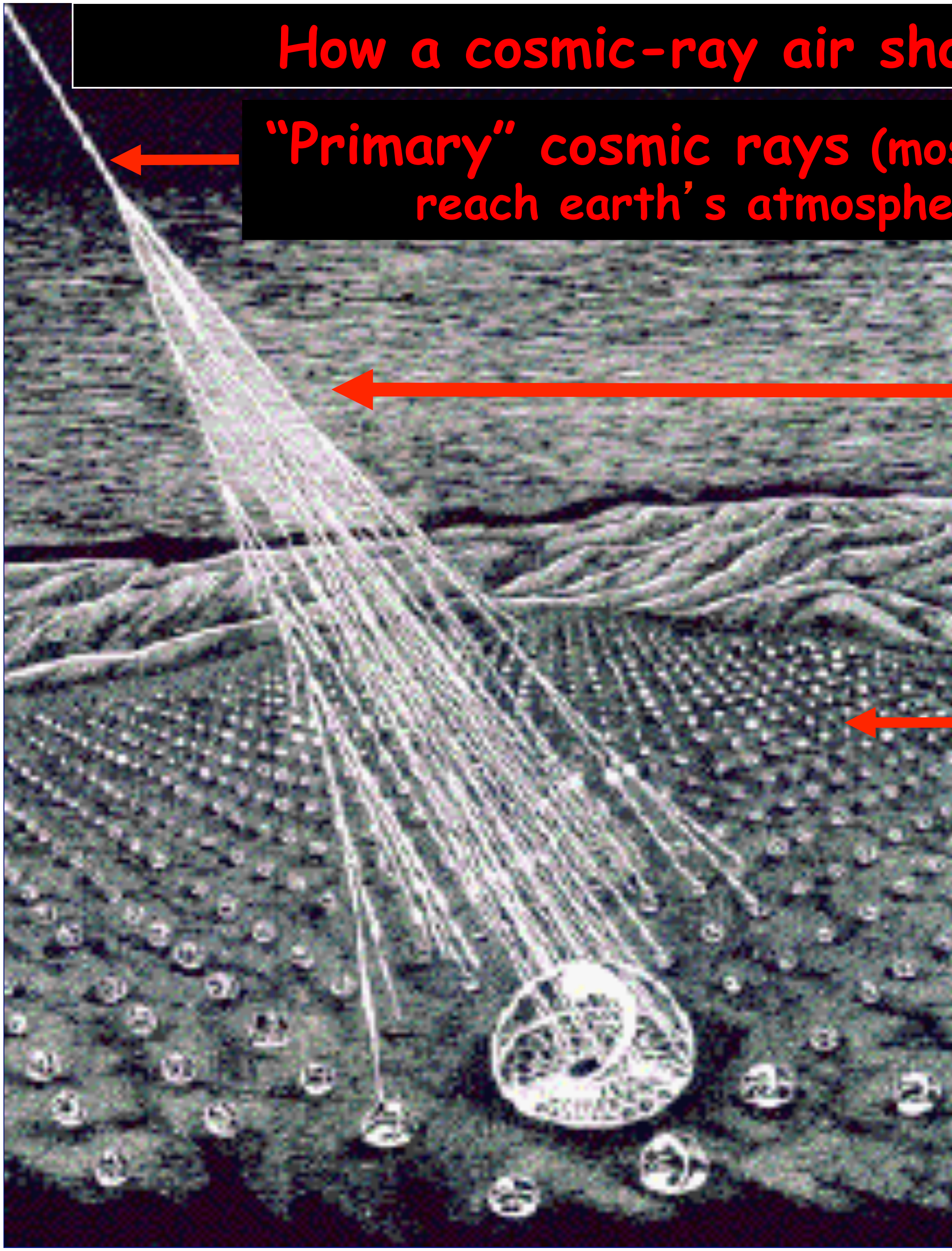
- GZK= Ken Greisen, and Grigor Zatsepin + V. Kuzmin: in 1966 predicted cosmic ray spectrum would cut off above 10^{19} eV
  - Intergalactic space is filled with microwave radiation (big bang!)
  - Microwave photons interact with UHE protons with large cross-section
    - In proton's rest frame, milli-eV photons look like GeV gammas
  - ➔ 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



An extensive air Shower (EAS) in the Earth's atmosphere

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

How a cosmic-ray air shower is detected



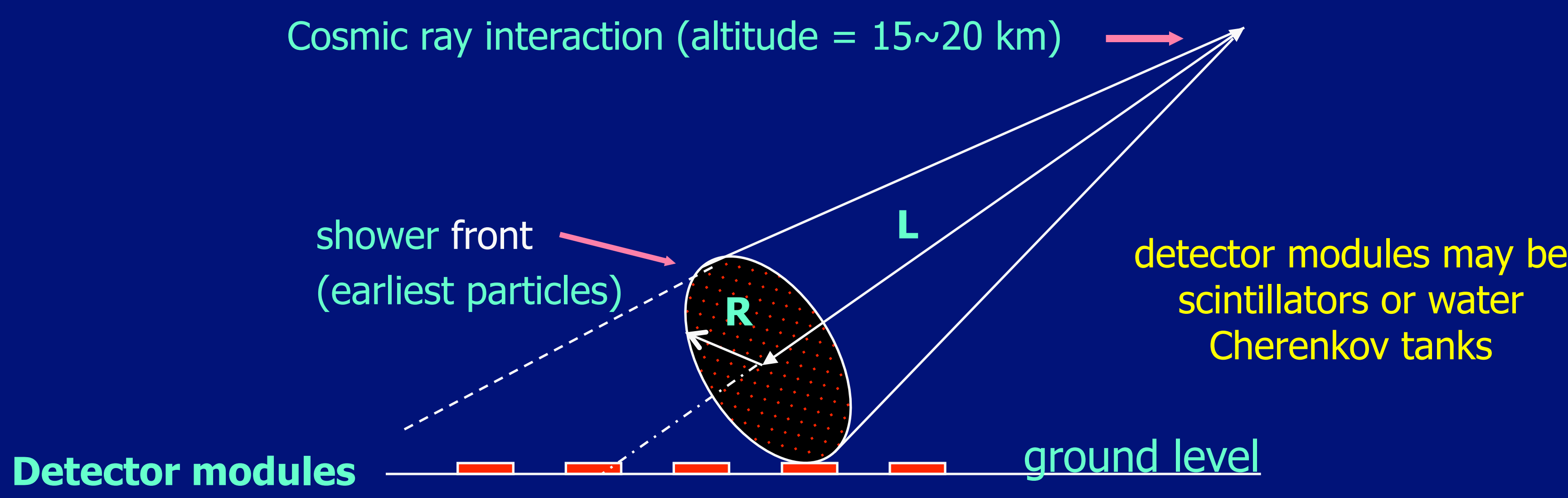
"Primary" cosmic rays (mostly protons or light nuclei) reach earth's atmosphere from outer space

"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

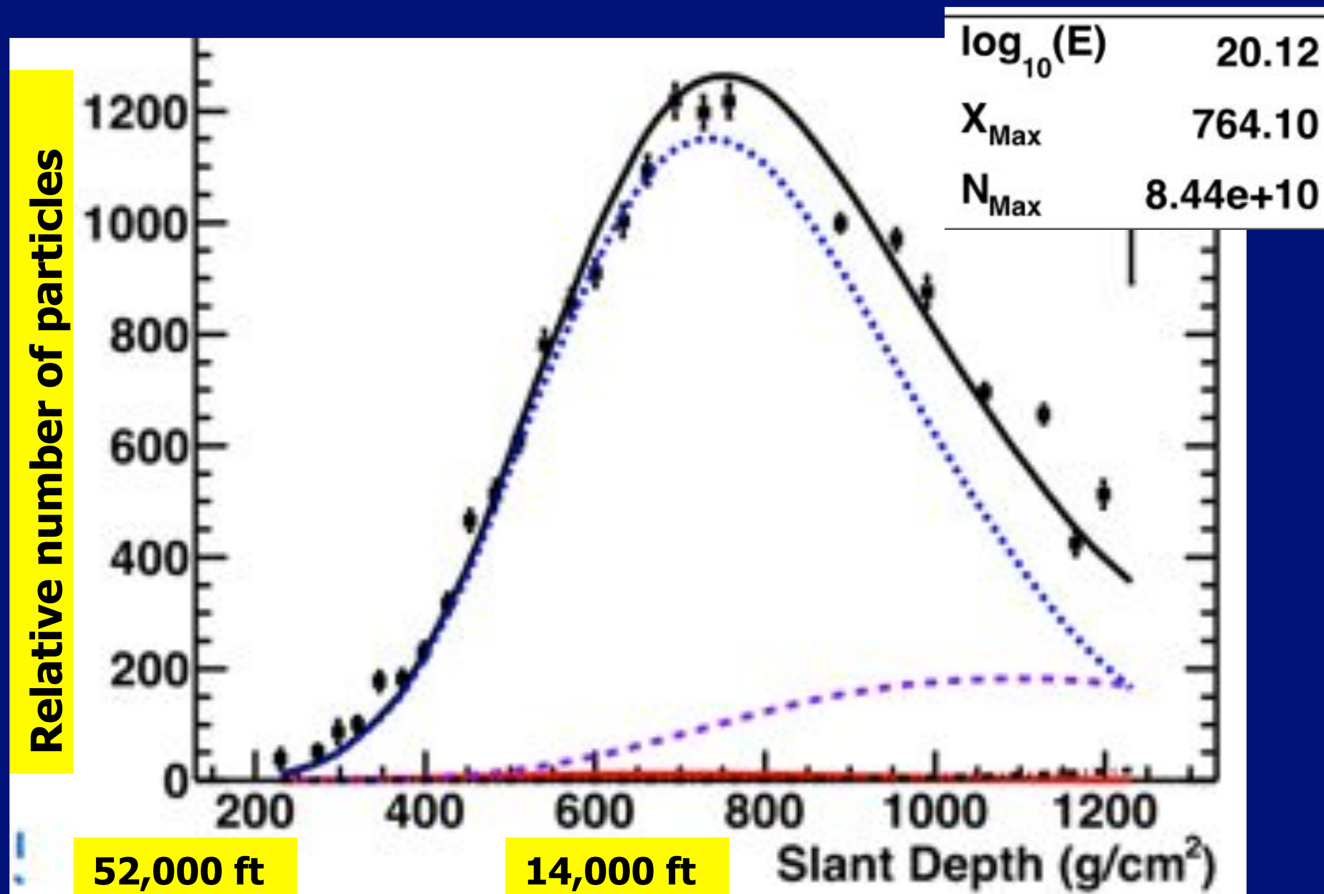


- Each detector module reports:
  - Time of hit (better than μsec accuracy)
  - Number of particles hitting detector module
- Time sequence of hit detectors → shower direction
- Total number of particles → shower energy
- Distribution of particles → distance L to shower origin

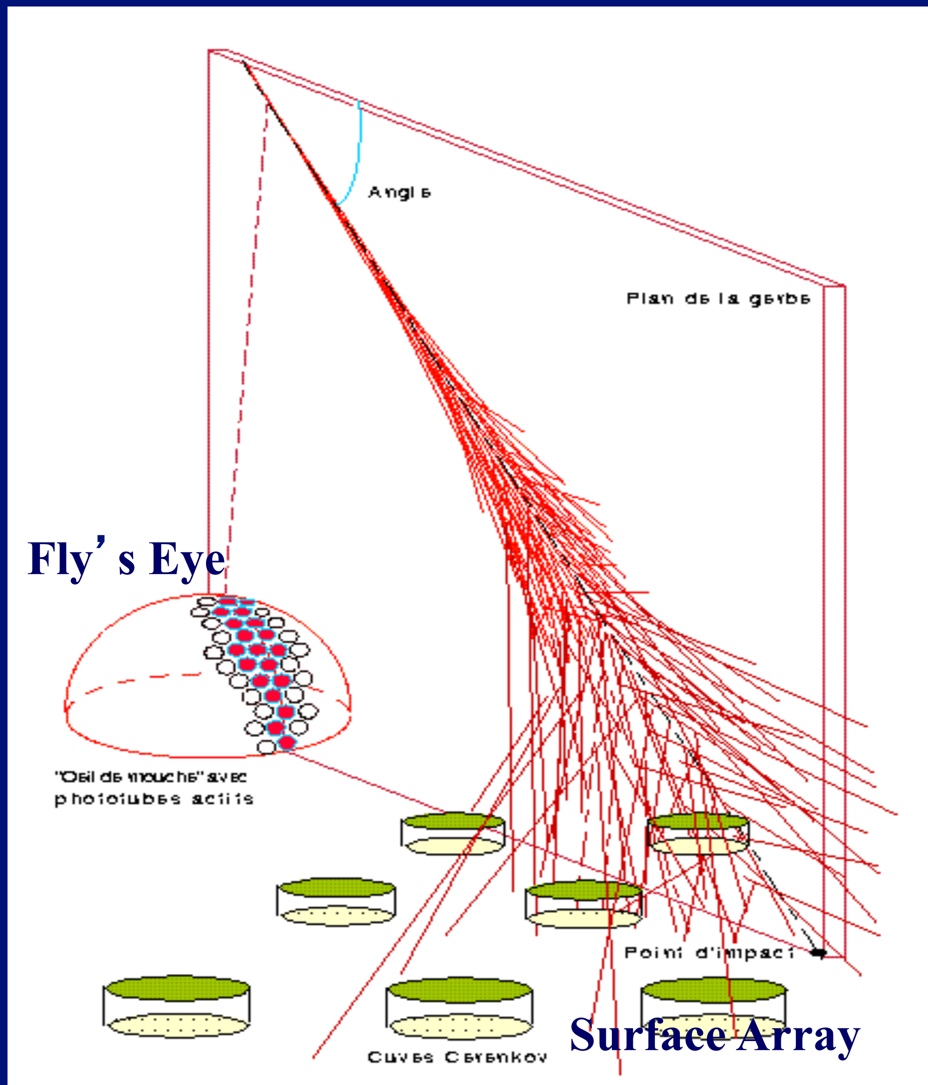
Shower profile: number of particles vs depth

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



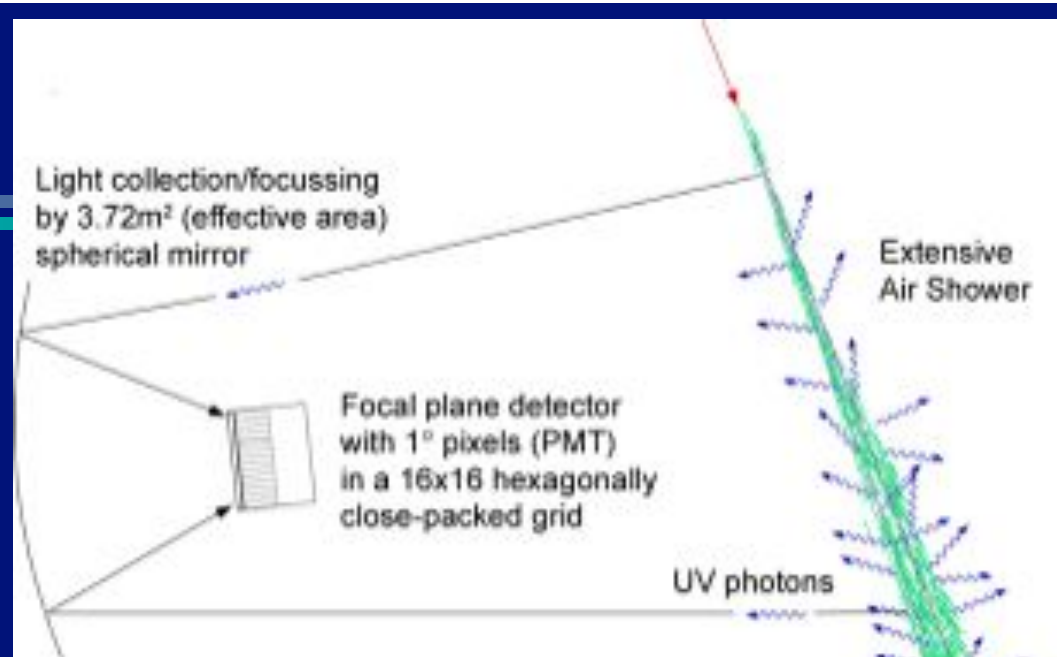
UHE air shower measurements are made by two techniques

1) Surface Arrays

   Scintillator counters or Cherenkov detectors

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

Air fluorescence detectors



Drawback: only usable 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

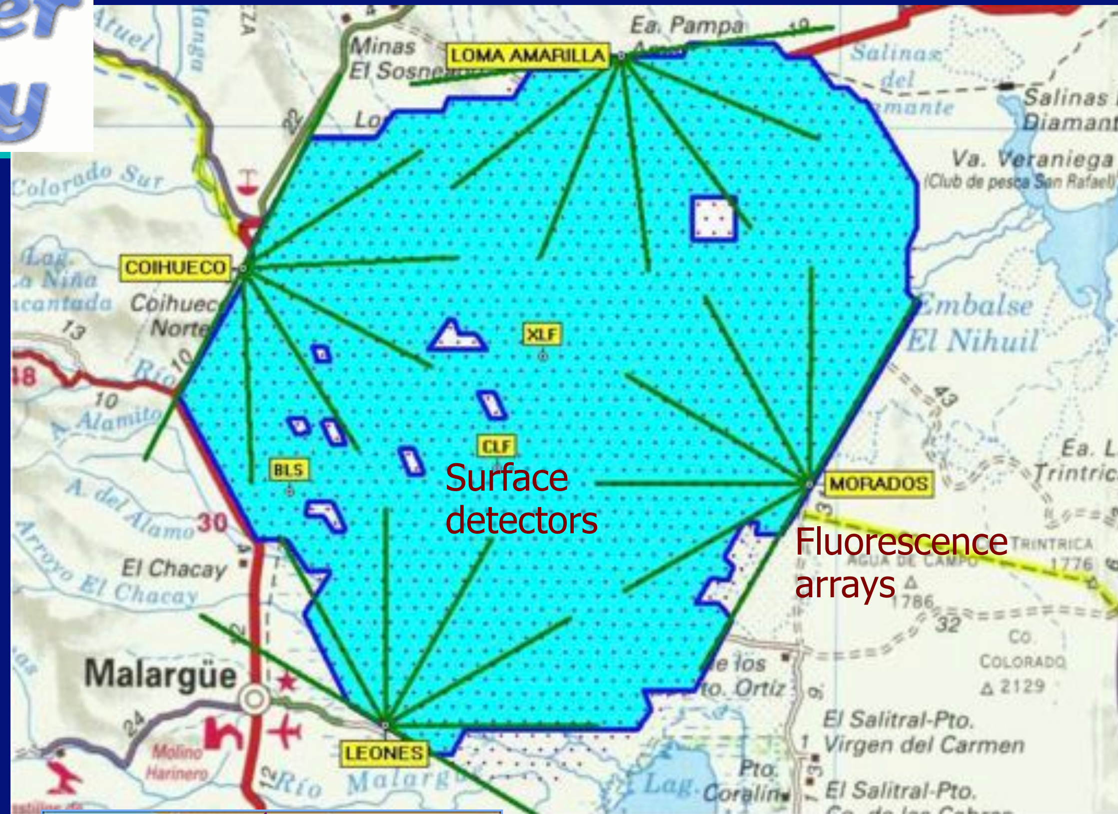
- Pierre Auger Observatory – Argentina, 2005--. Air-fluorescence and ground array (water tanks instead of plastic scintillator).
- Telescope Array (TA) – Utah, 2008--. Scintillator and air-fluorescence detectors

World map, Australian style

Pierre Auger Observatory

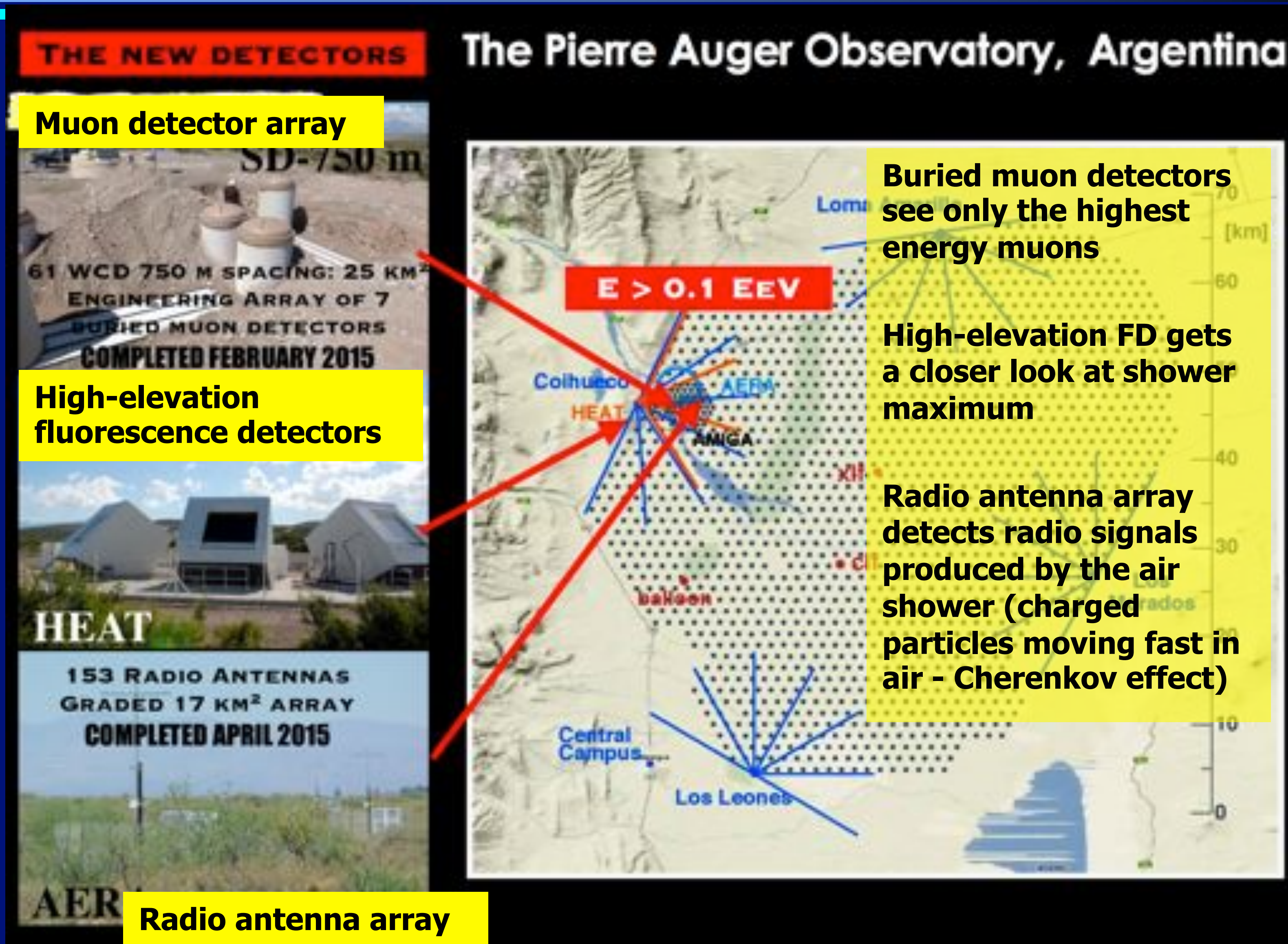
Southern hemisphere:
Mendoza Province,
Argentina

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

Recent upgrades/additions to Auger



Muon detector array

High-elevation fluorescence detectors

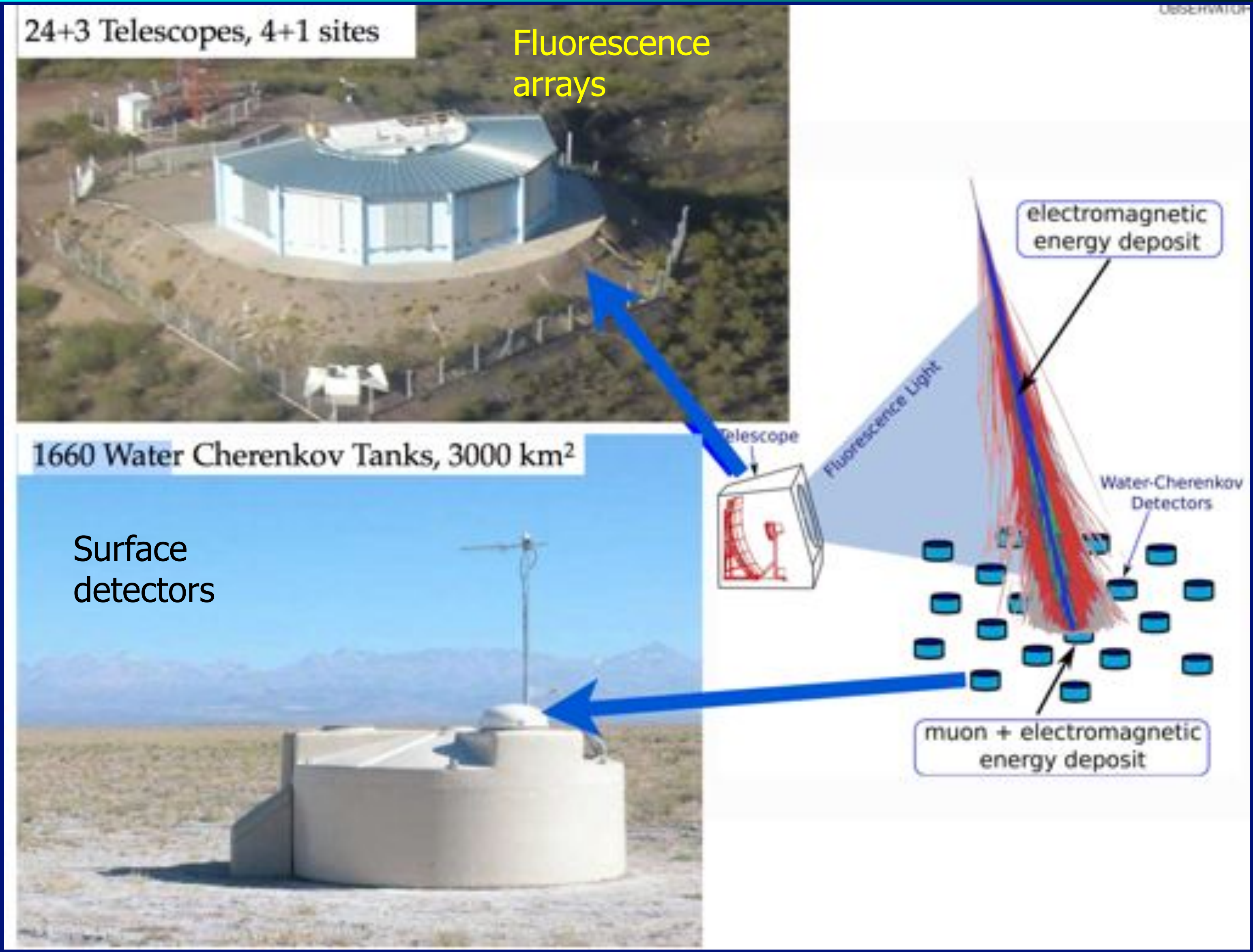
Radio antenna array

Buried muon detectors see only the highest energy muons

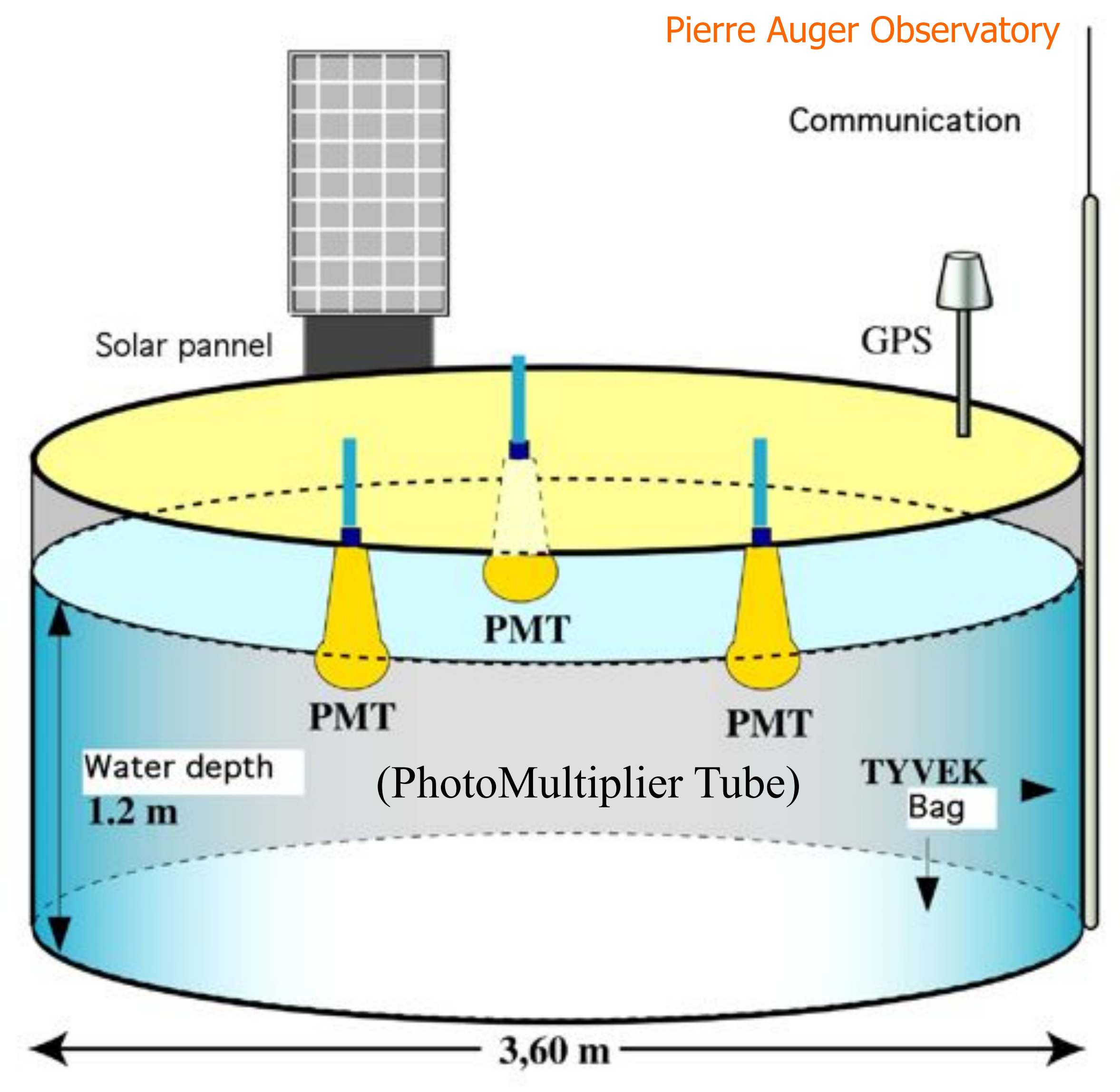
High-elevation FD gets a closer look at shower maximum

Radio antenna array detects radio signals produced by the air shower (charged particles moving fast in air - Cherenkov effect)

Pierre Auger Observatory

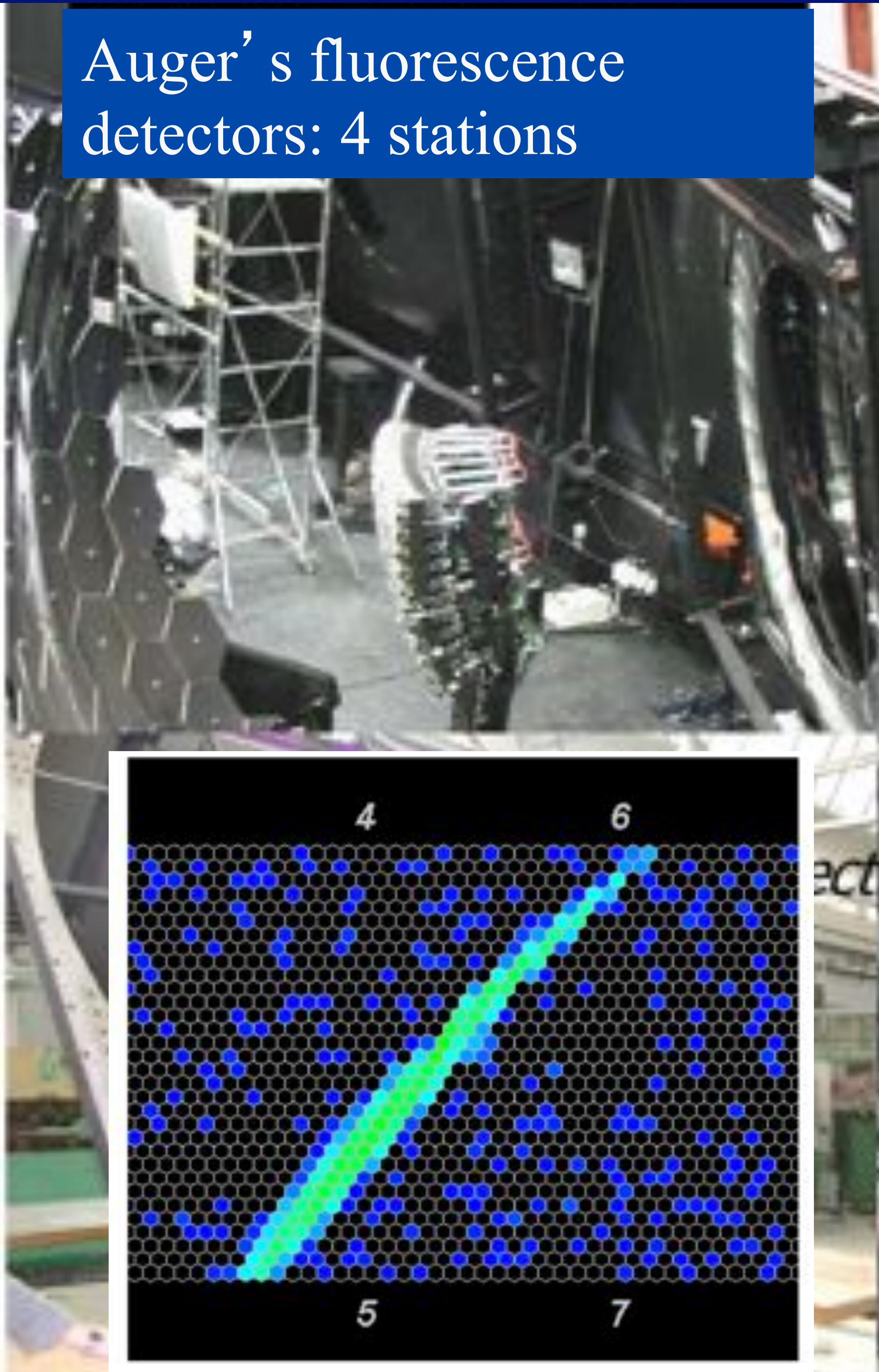


Surface detectors (SD): water Cherenkov detectors

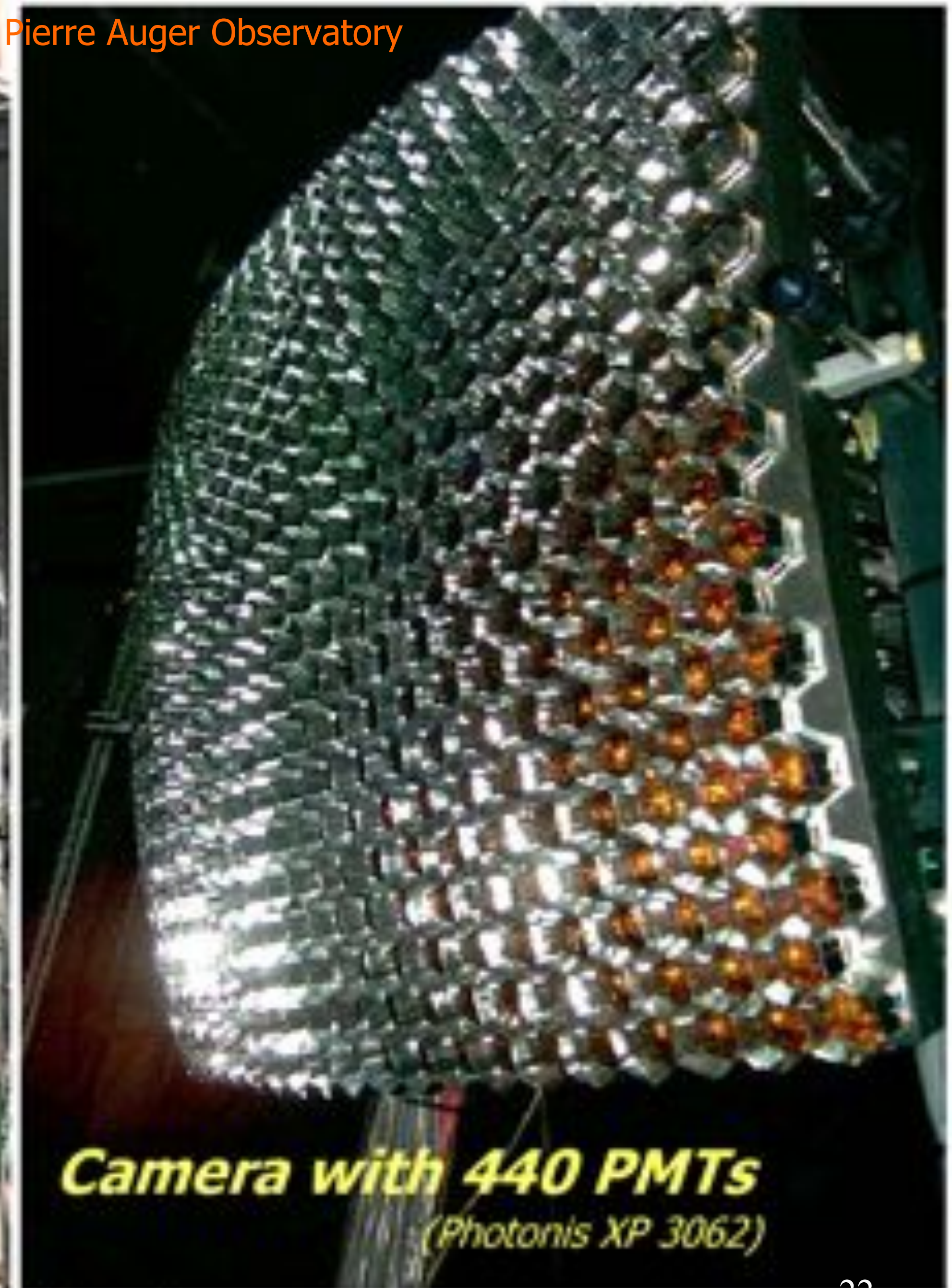


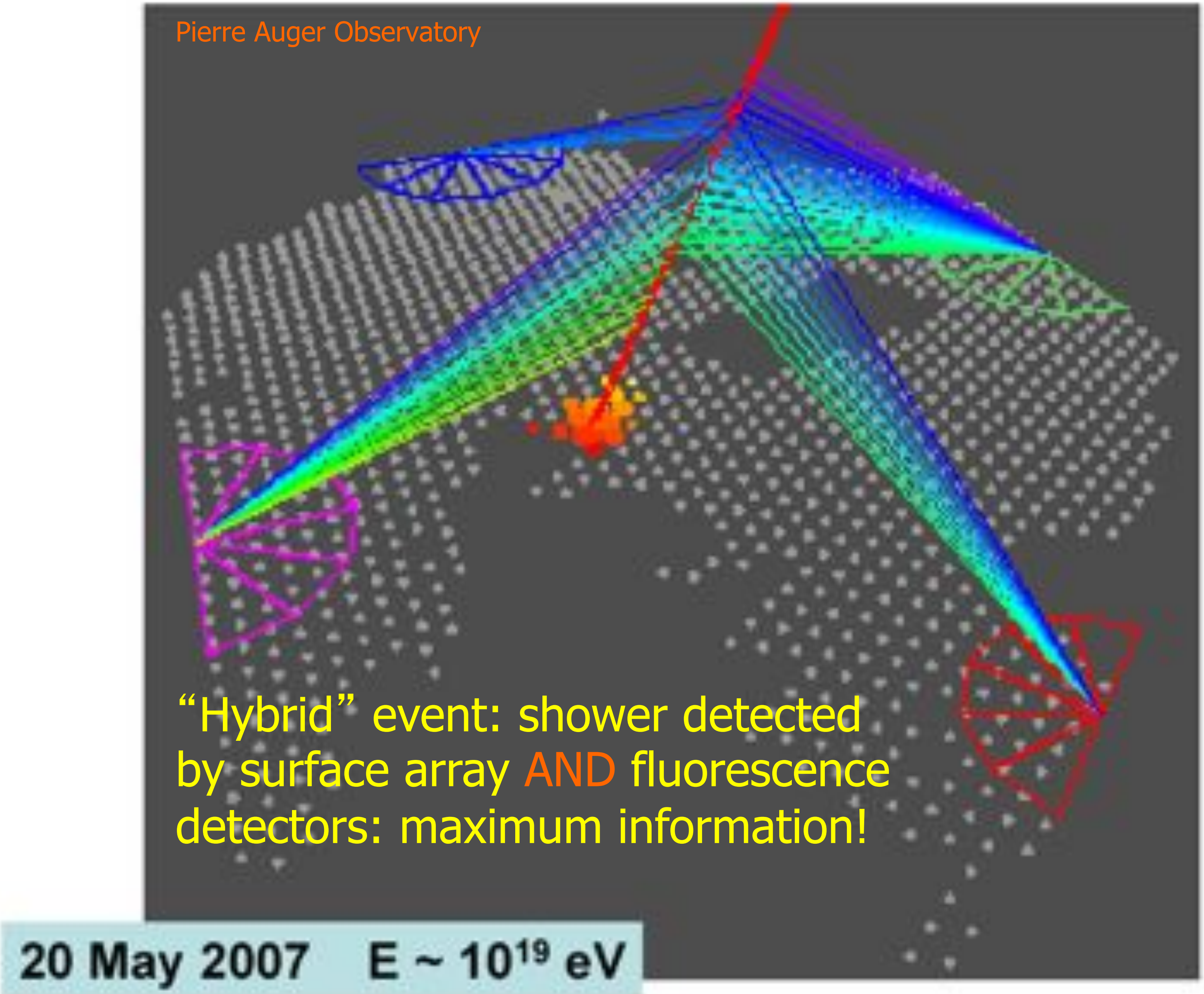
- Each unit is self-contained: solar panels, batteries, GPS
- Communication with cell-phone technology
- Three 8" PMTs detect **Cherenkov light** produced in water:
  - Charged particles move at ~ c (speed of light in vacuum)
  - but light can propagate in water at only 0.75c
  - Electromagnetic fields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

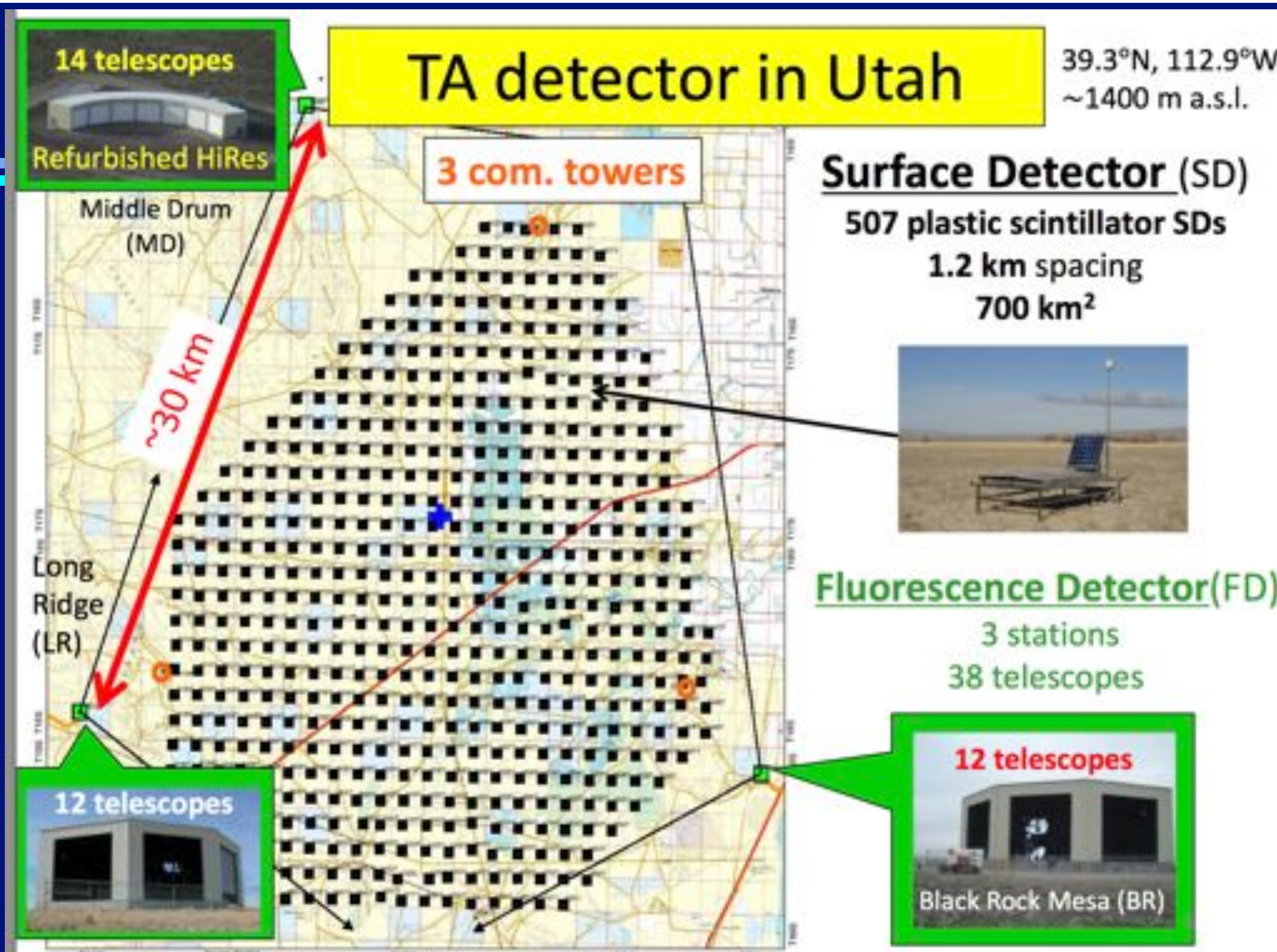
Auger’ s fluorescence detectors: 4 stations



Pierre Auger Observatory

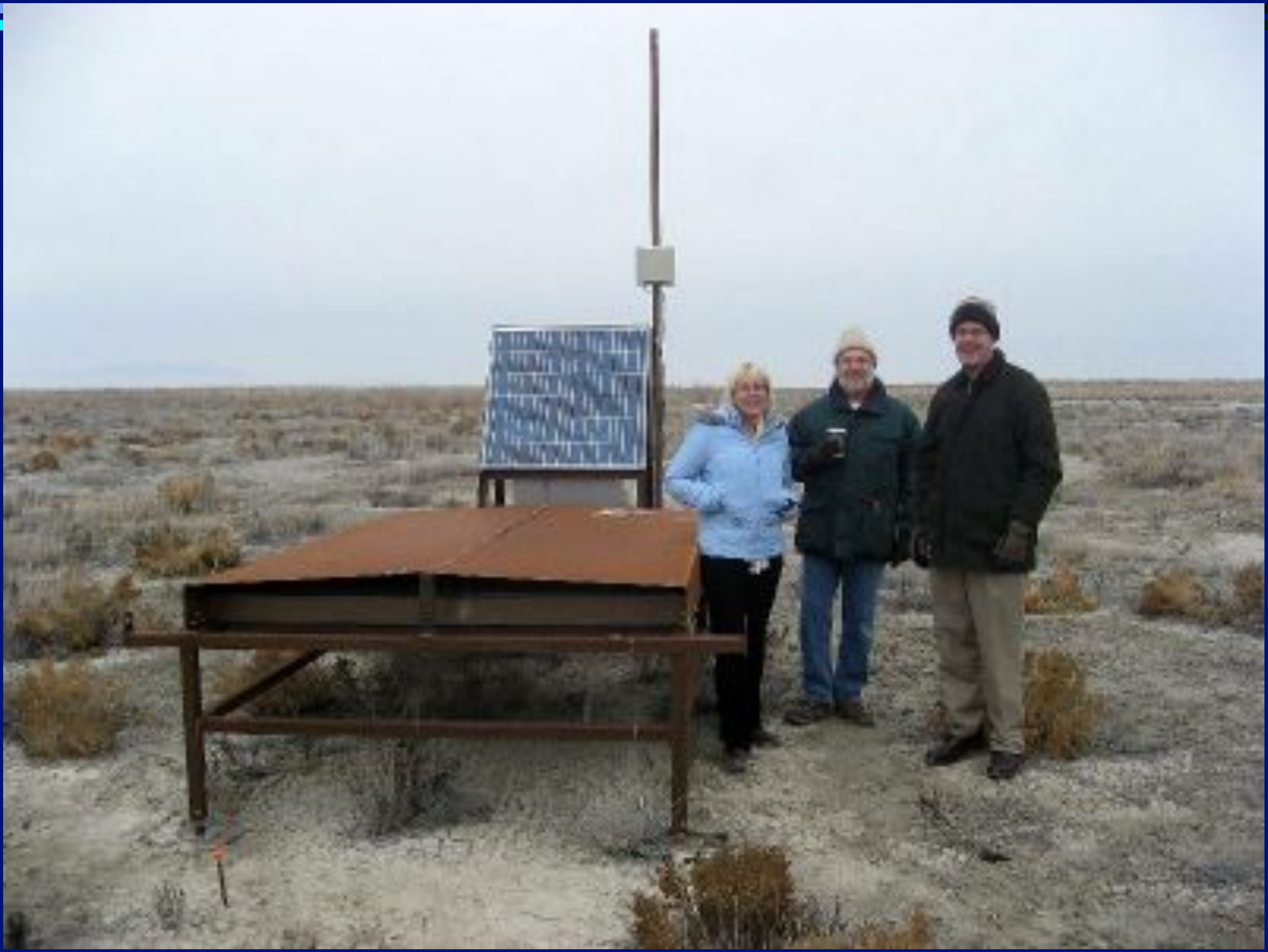



Pierre Auger Observatory
"Hybrid" event: shower detected by surface array AND fluorescence detectors: maximum information!
20 May 2007 E ~ 10^{19} eV

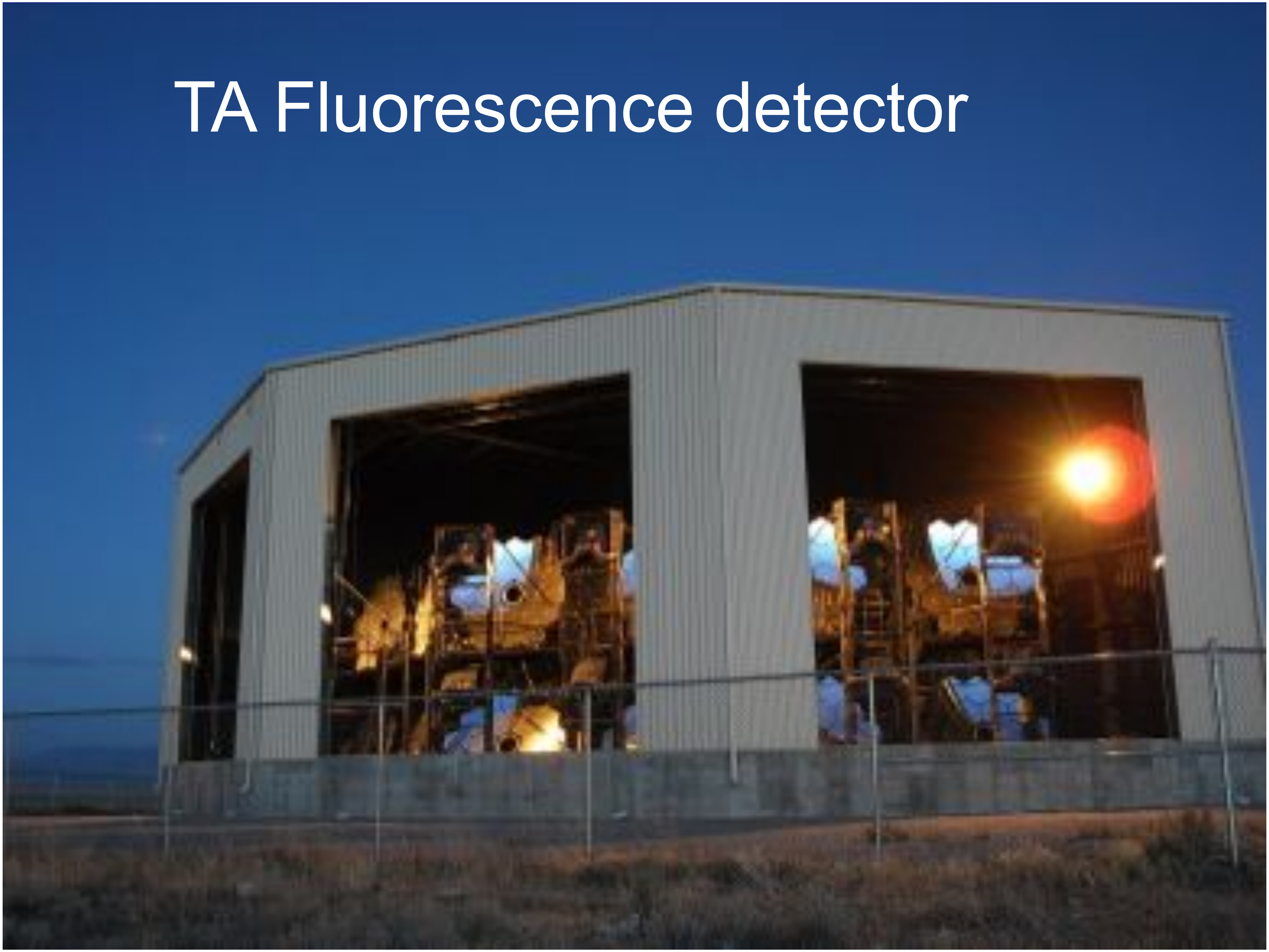


- Japan-US collaboration: AGASA and Fly's Eye/Hi-Res veterans
- Location : Millard County, Utah - ~ 100 mi SW of Salt Lake City

One TA scintillator detector, with size references



TA Fluorescence detector



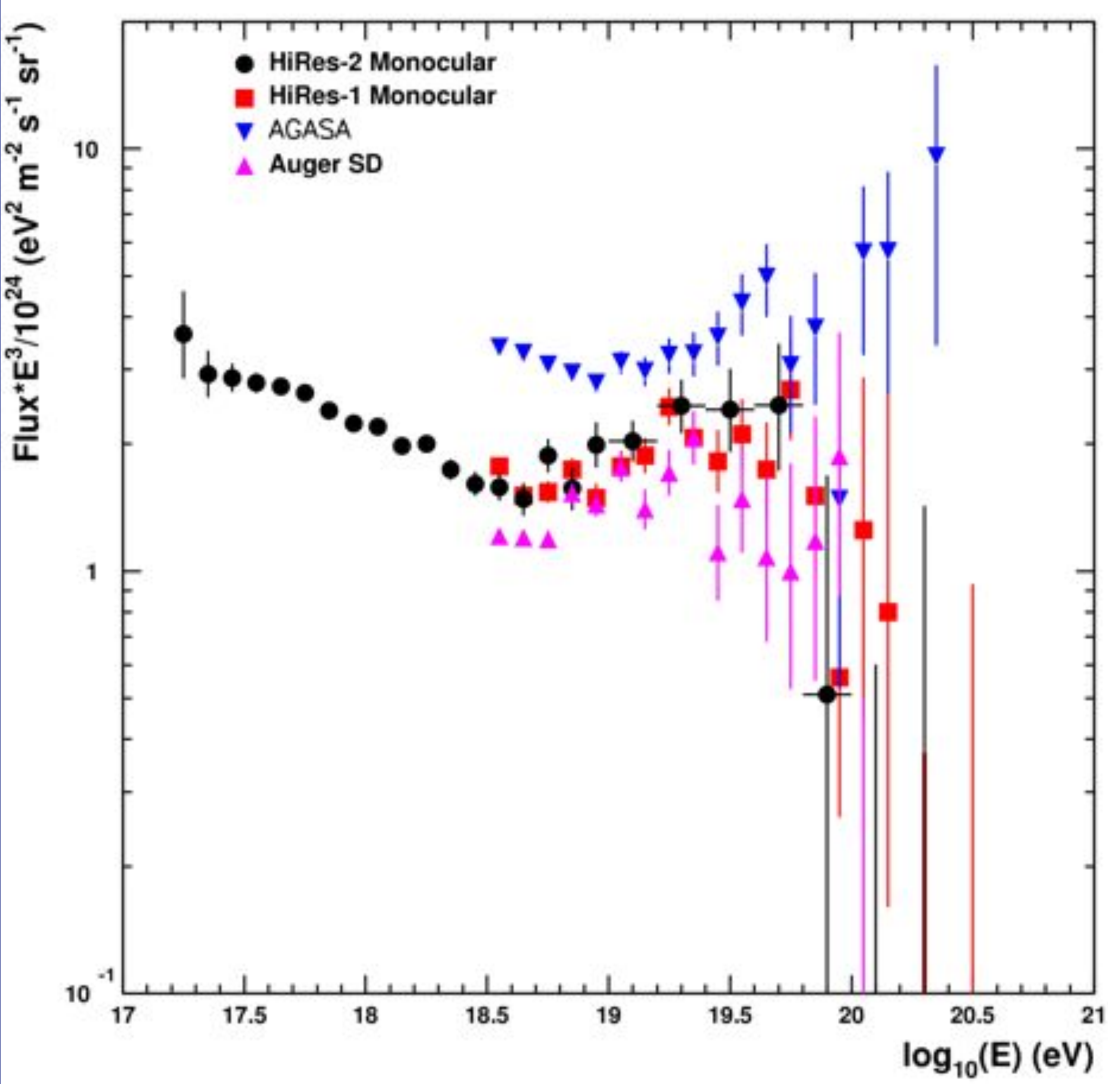
Top end of the CR spectrum: some time ago...

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

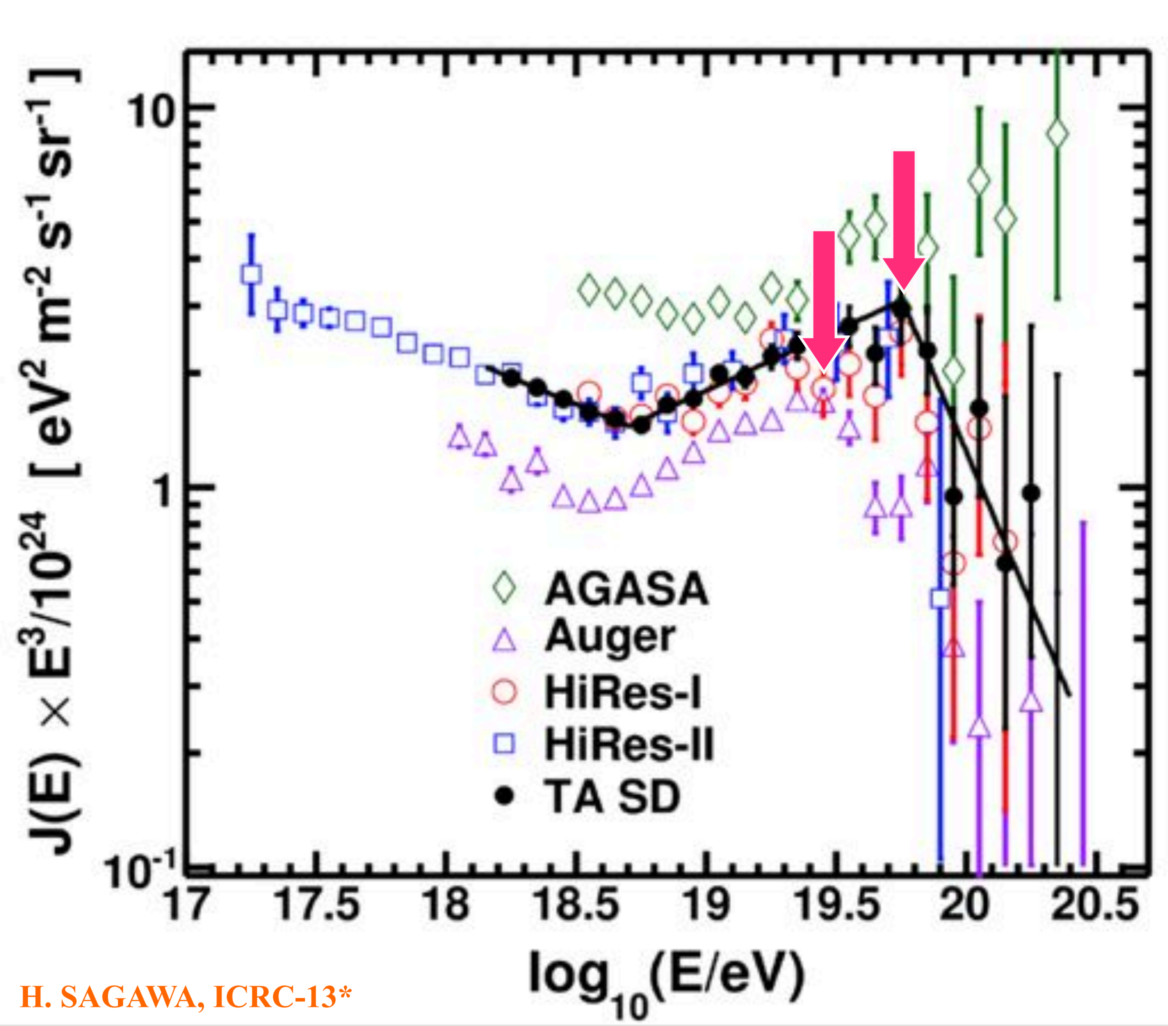
New York Times, Dec. 30, 1934

...and 2 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

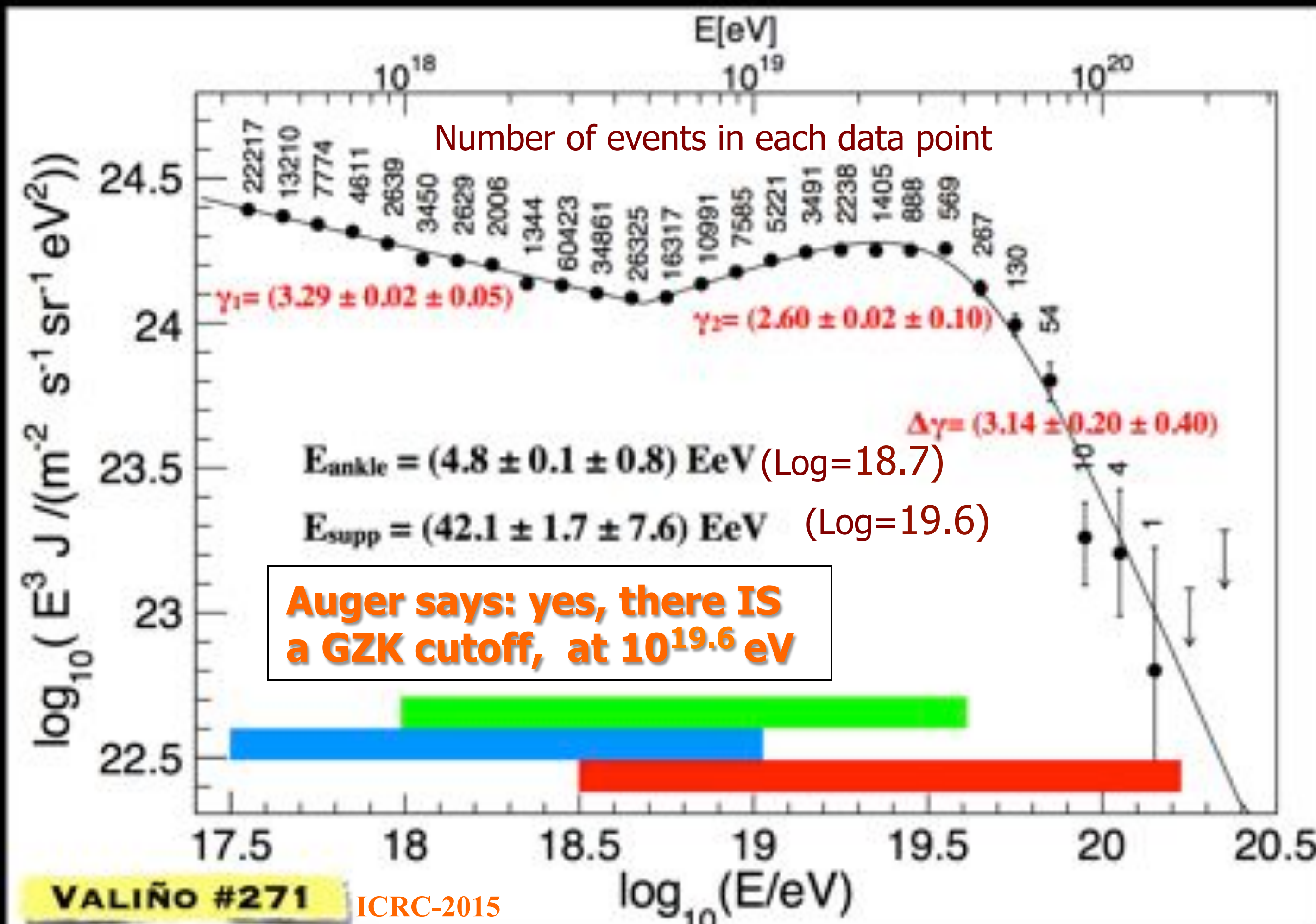


*2013 Int. Cosmic Ray Conf. http://143.107.180.38/indico/conferenceTimeTable.py?confId=0#20130702

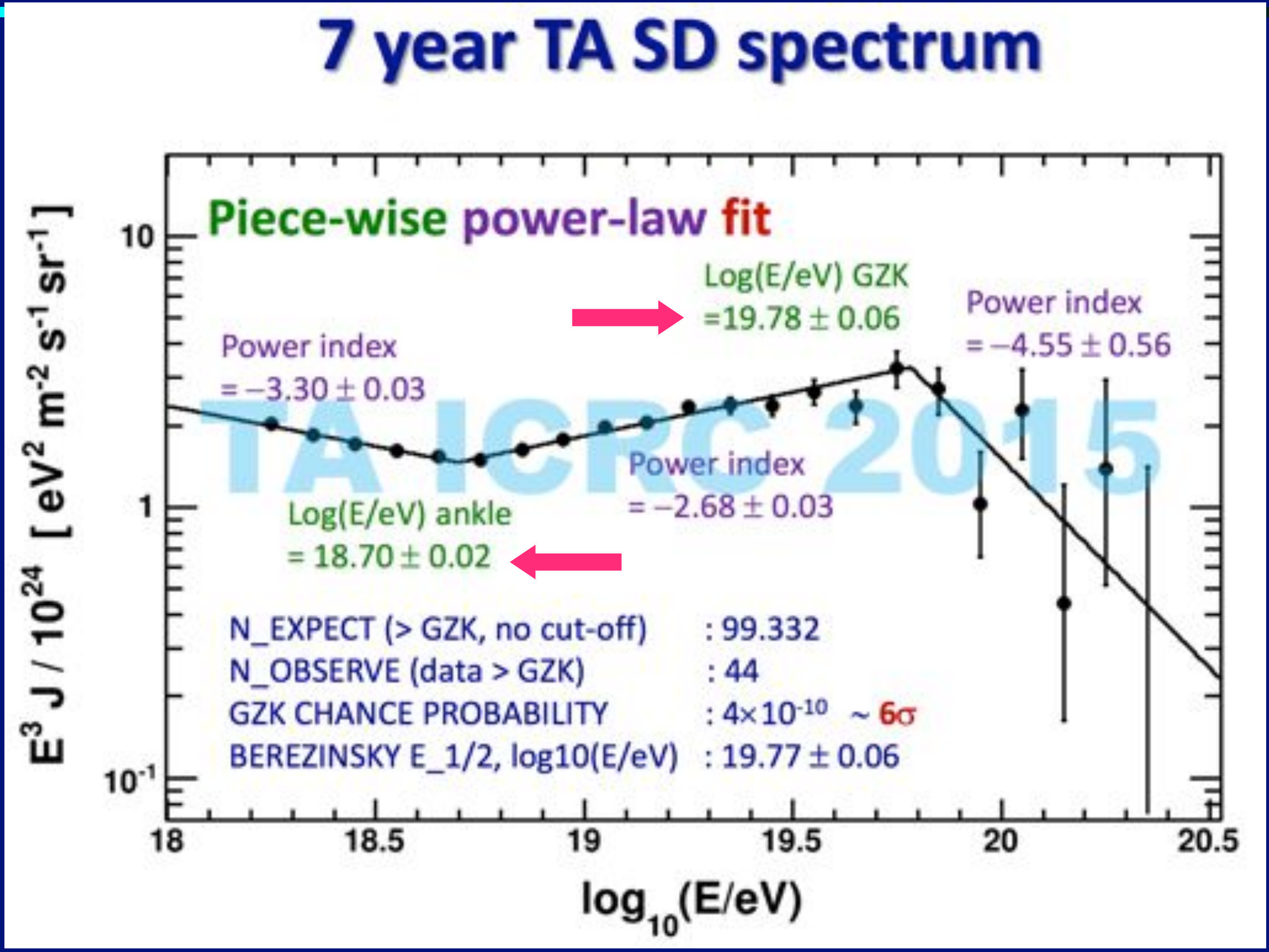
2015 results: fits to slope, numbers of events

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

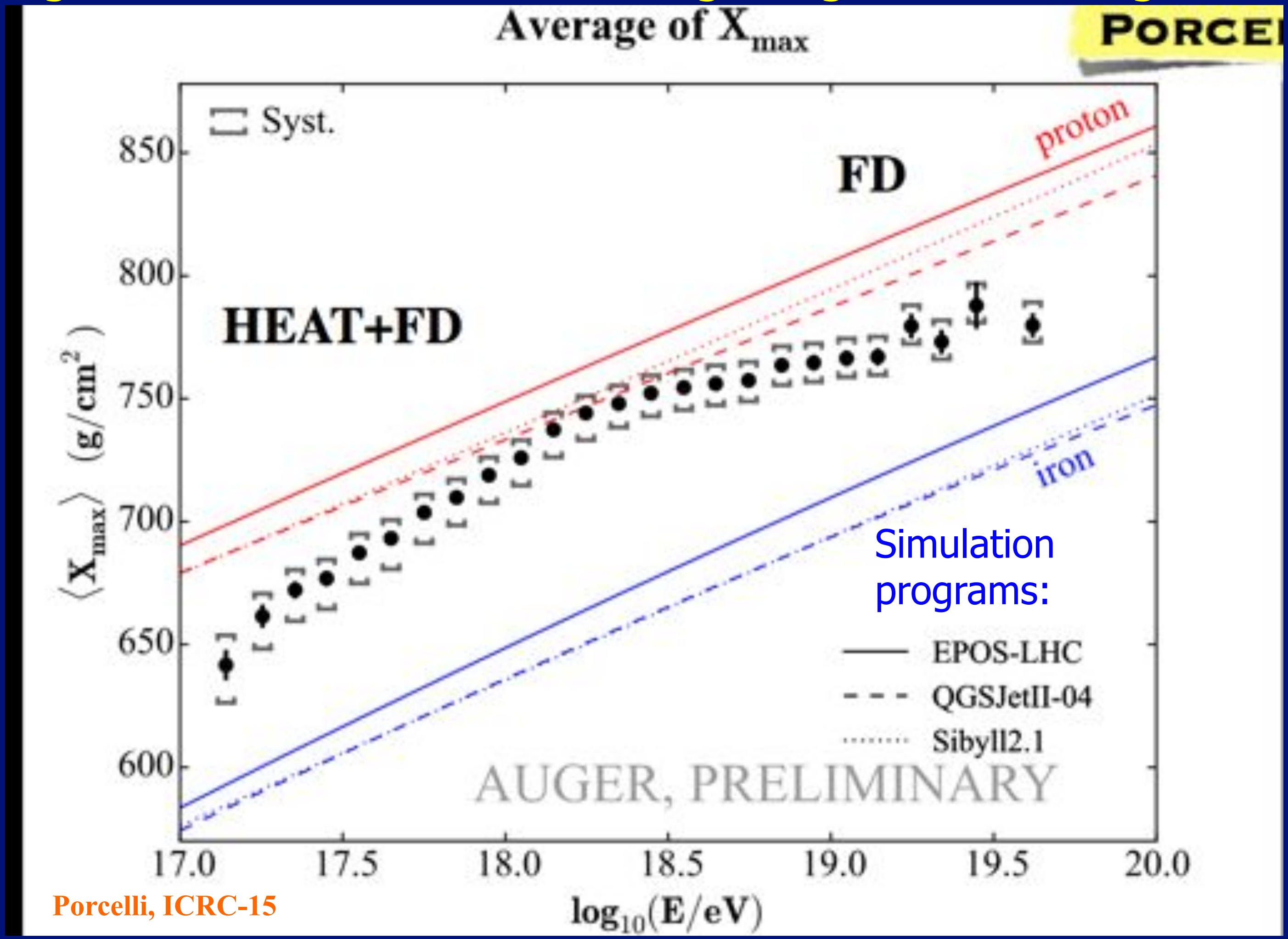


2015 TA results: GZK is closer to Auger's



Are EHE CRs protons, or nuclei ?

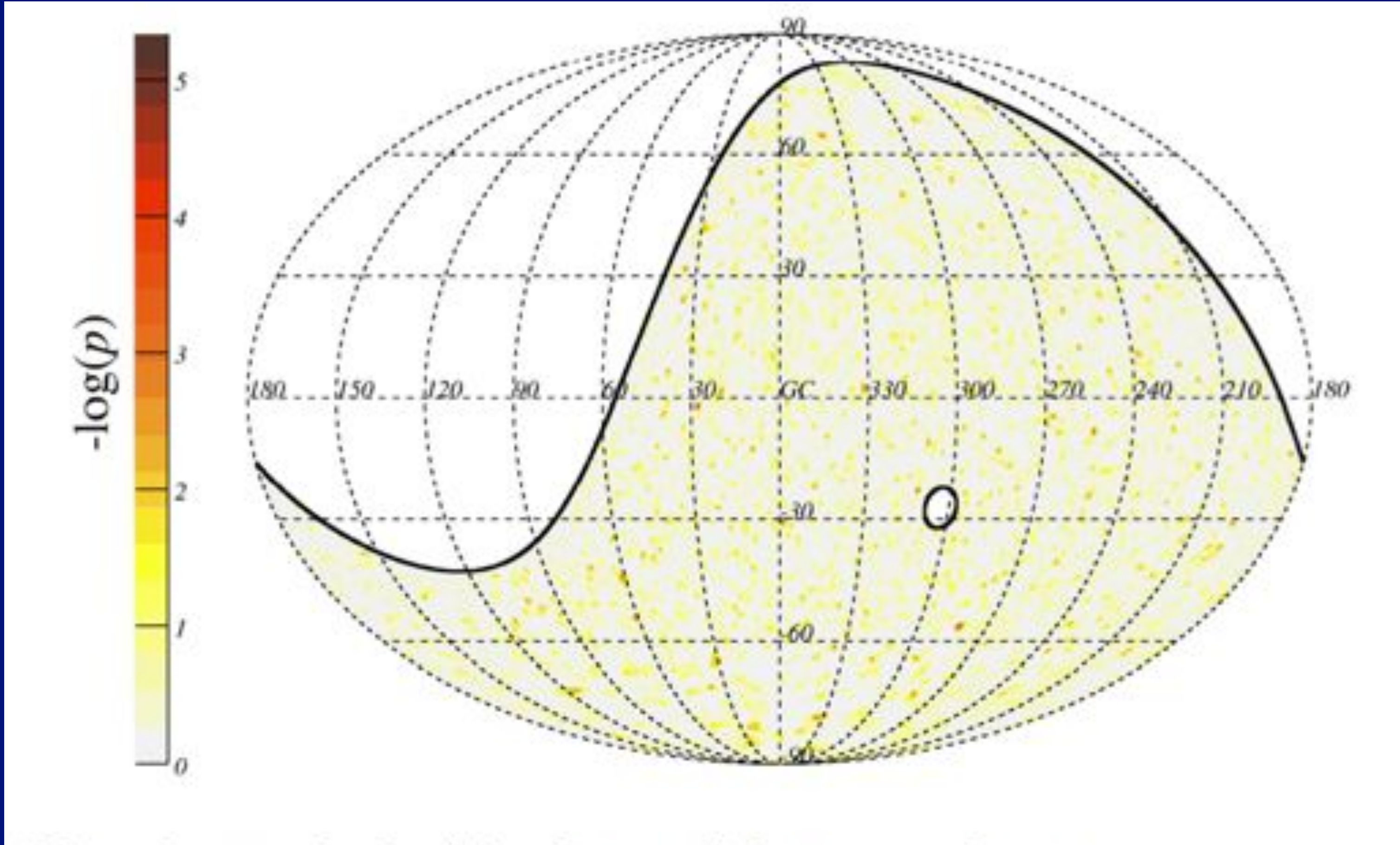
- Depth of “shower maximum” is smaller if CR= lighter nuclei
- Augerdata: the mix seems to be getting heavier at highest E’s



Search for point sources of EeV photons

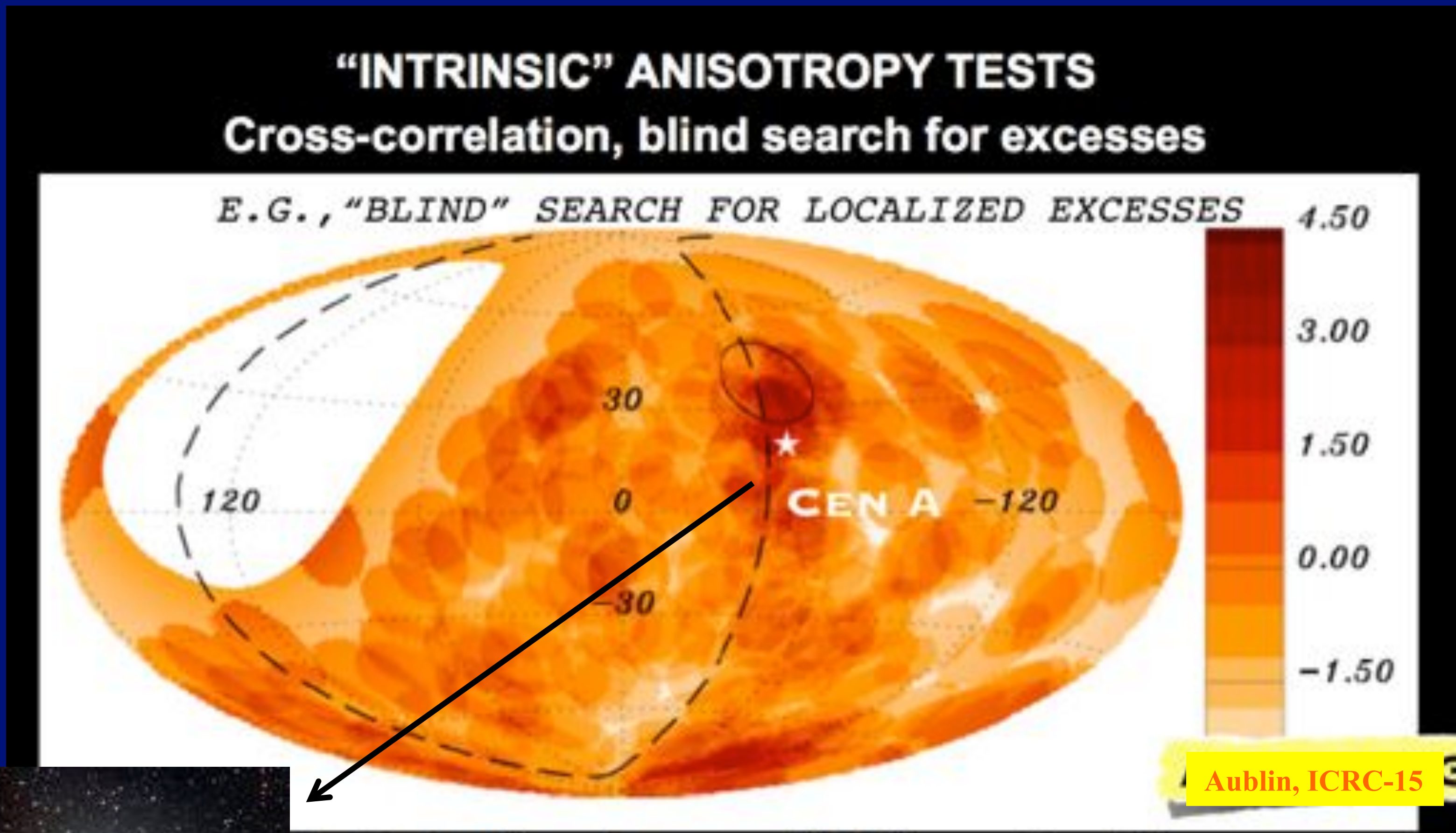
- No evidence for point sources of gamma-ray showers

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 spots (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 average UHE sources?

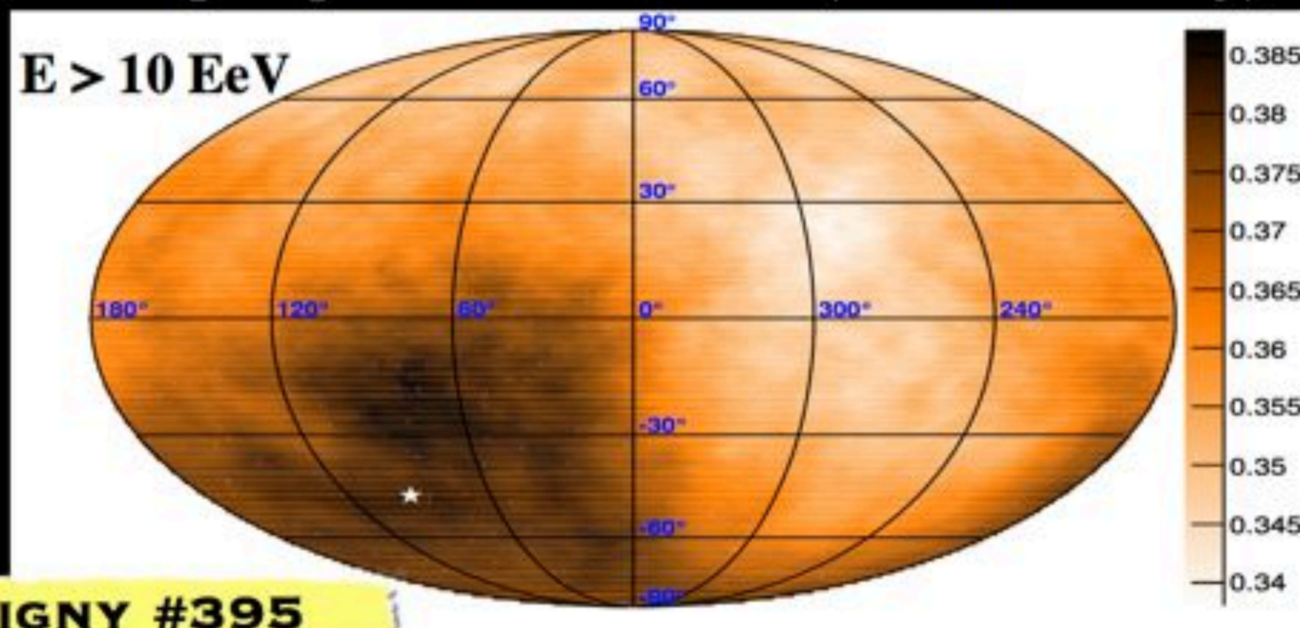
AUGER and TA: Spherical harmonic analysis

≈ 17000 Auger events and ≈ 2500 TA events with E>10 EeV

Full sky coverage

(Combined analysis)

Sky map of the CR flux (60° smoothing)

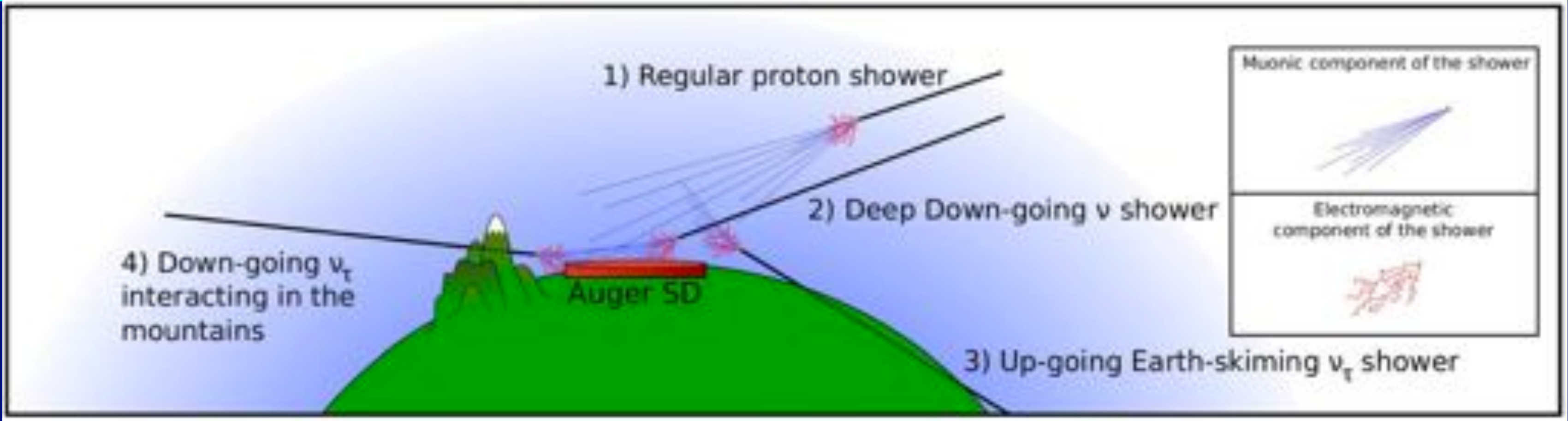


DELIGNY #395

Dipole Amplitude: 6.5 ± 1.9% (p=5x10^{-3})

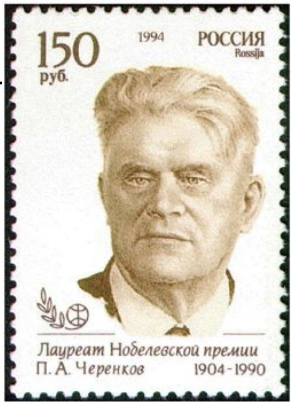
Pointing to (a, d) = (93°±24°, -46°±18°)

Other GZK products: cosmic UHE neutrinos



- Neutrinos = Products of intergalactic collisions of above-GZK protons + CMB
    - Neutral – should point back to origin of above-GZK cosmic ray
  - Weakly interacting – most do not interact, can penetrate 100km of Earth
  - Tau neutrino decays to τ particle
    - Tau particle decays into e → we see a shower starting at decay point
- Auger can detect and identify neutrinos
  - Any flavor ν downgoing (showers start much deeper in atmosphere than p or Fe)
    - Not likely to see many
  - ντ if it interacts near surface of Earth (skims surface, or interacts in Andes mountains)

Cherenkov detectors



Cherenkov effect (often misspelled “Čerenkov”)

- charged particle with speed v > c/n (or $\beta = v/c > 1/n$)
- radiation is emitted at the *Cherenkov angle*:
  - $\theta = \cos^{-1}(c/vn) = \cos^{-1}(1/\beta n) = \tan^{-1} [(\beta^2 n^2 - 1)^{1/2}]$
- Number of photons emitted per unit length of track is

$$dN(\nu)/d\nu = 2\pi Z^2 (\alpha/hc) \sin^2\theta \, d\nu = 370 \sin^2\theta \text{ per eV per cm}$$

  - ν = frequency, θ = Cherenkov angle, $\alpha = 1/137$ (E-M interaction strength constant)
  - Short wavelengths dominate
  - Transparency of media cuts off above blue / UV

Threshold Cherenkov detector

- Used for particle ID and selective triggering

Examples

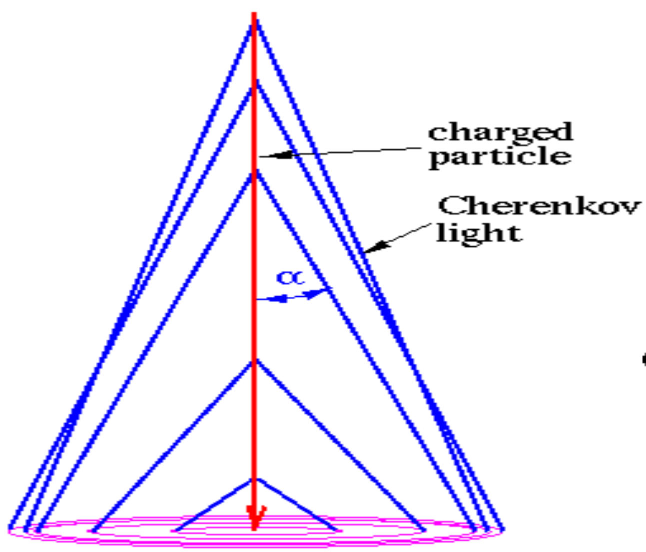
- in water, momentum threshold for electrons is 570 keV/c, for muons it is 120 MeV/c, for protons it is 1 GeV/c
- in aerogel, momentum threshold for electrons is 2.3 MeV/c, for muons it is 438 MeV/c, for protons it is 4.2 GeV/c

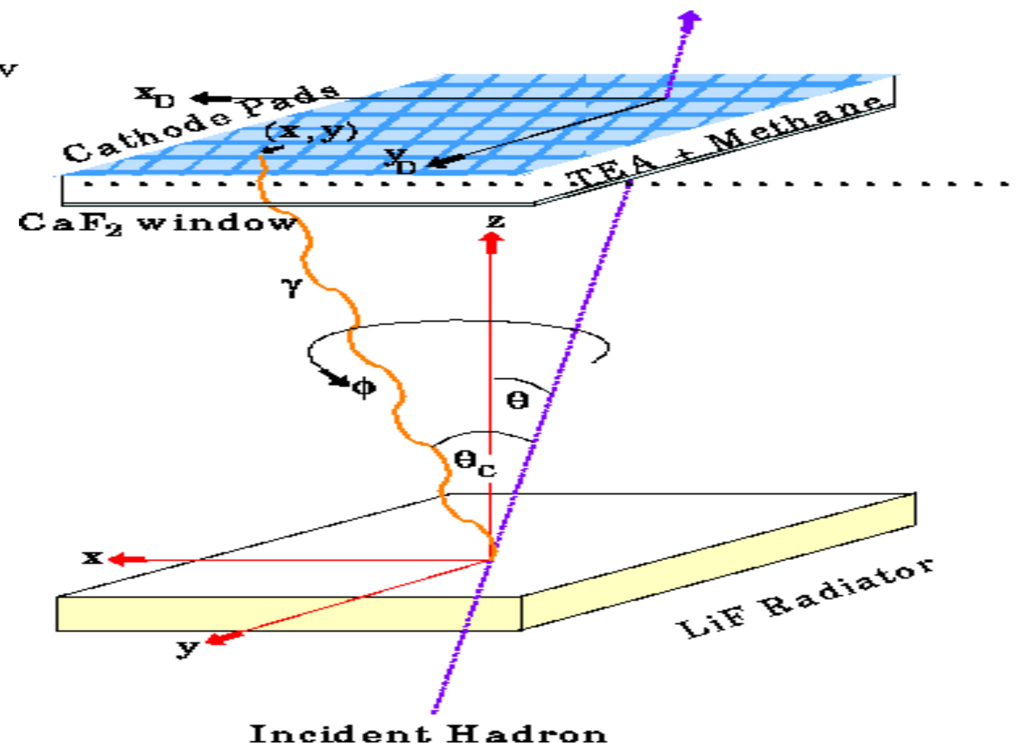
Material	n	Threshold β	θ, degrees
Glass	1.5	0.67	48.19
water	1.33	0.75	41.25
Aerogel	1.025	0.976	12.68
Xe	1.00070	0.99930	2.14
CO2	1.00041	0.99959	1.64
Air (STP)	1.00029	0.99971	1.39
H2	1.00014	0.99986	0.96

Another example:
emitter velocity > velocity of propagation

Ring-imaging Cherenkov (RICH) detectors

- Use pixel detector to observe rings of light
  - Ring = short track; if particle exits, image is a disk
  - Note that particle moves faster than light, so first light detected is last emitted
  - Detector can be proportional chamber, image intensifier/CCD, or array of PMTs



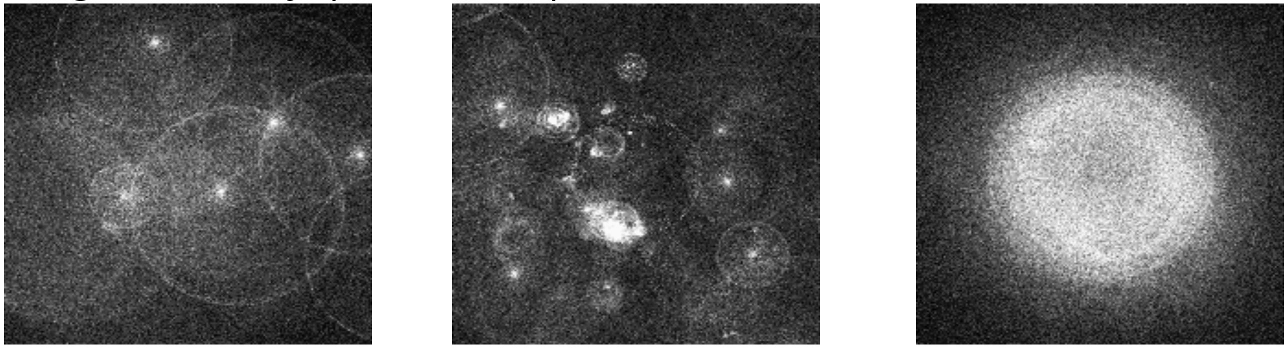


Air Cherenkov UHE CR / gamma ray detectors

- Similar to fluorescence detectors, but use Cherenkov light from EAS
  - Due to narrow cone of light (θ_C ~ 1 deg), must face source direction
  - Good for measuring gamma fluxes / variations from known sources
  - Can also distinguish proton/nucleus showers

Whipple observatory (Arizona):
First major air Cherenkov UHE gamma detector (1980s)
10m array of mirrors, with PMT array at focus

images from proton, Fe nucleus and gamma ray (all ~1 TeV)



VERITAS air cherenkov telescope (ACT) array

Newer ACT detectors use multiple mirror arrays to reconstruct shower development in same way as air fluorescence arrays:

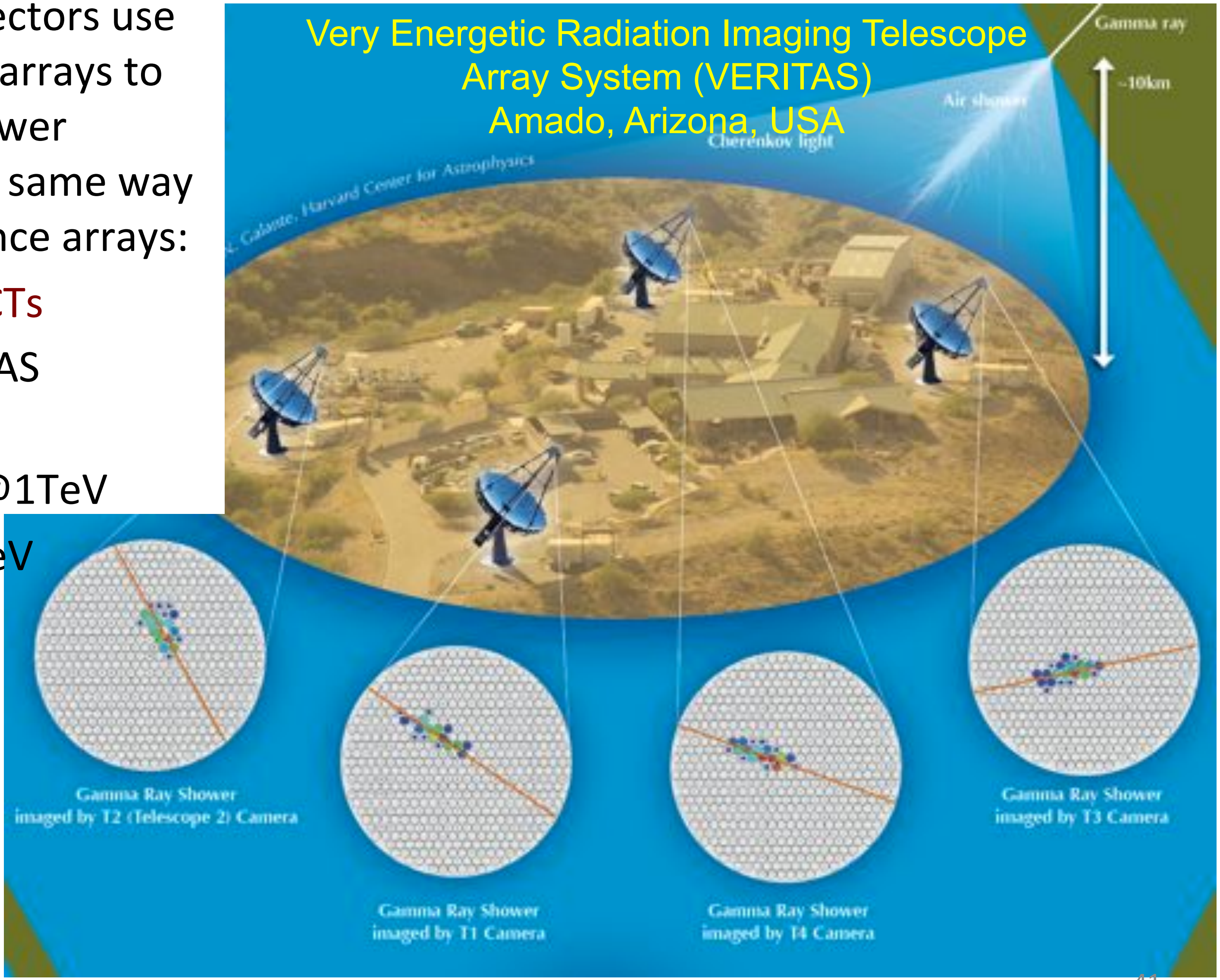
Stereoscopic ACTs

Example: VERITAS

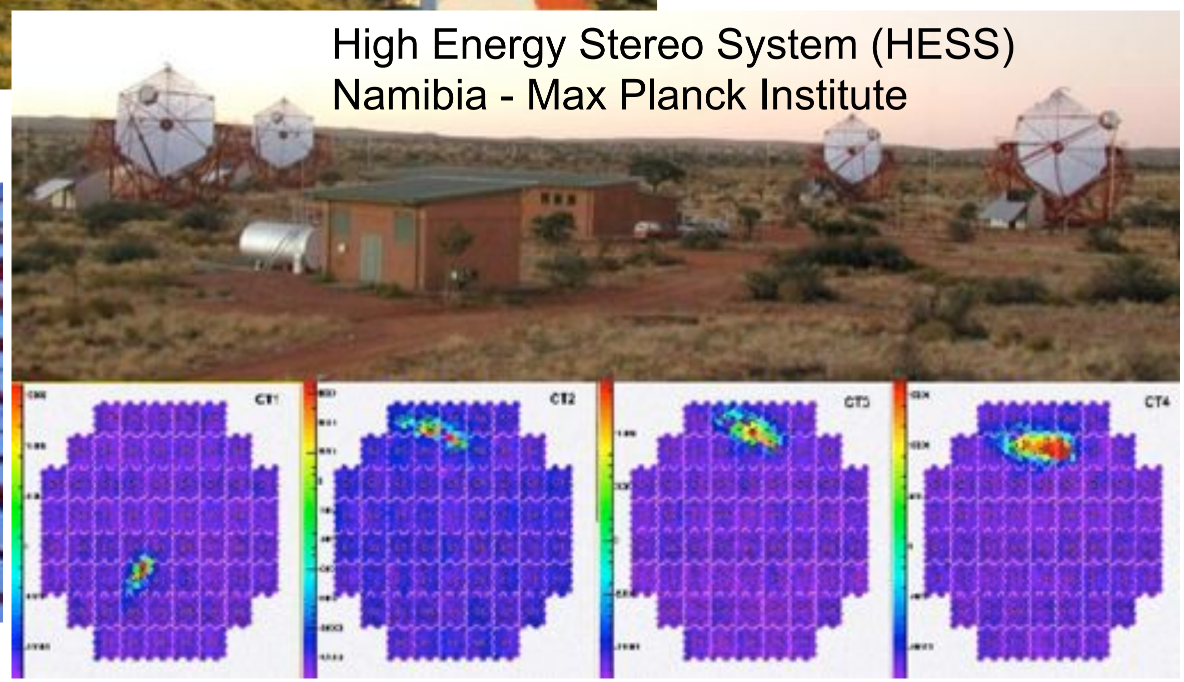
50GeV – 50TeV

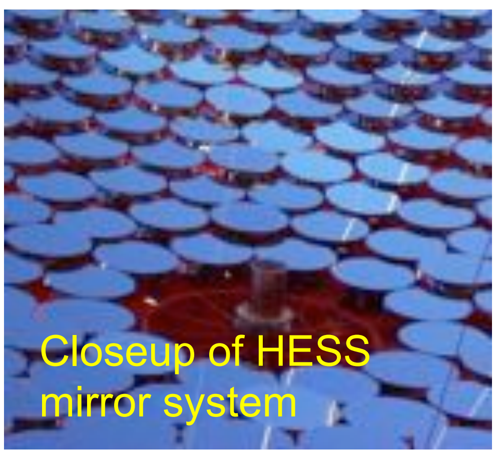
- $\Delta\theta/\theta \sim 0.03^o$ @1TeV

$\sim 0.09^o$ @100GeV



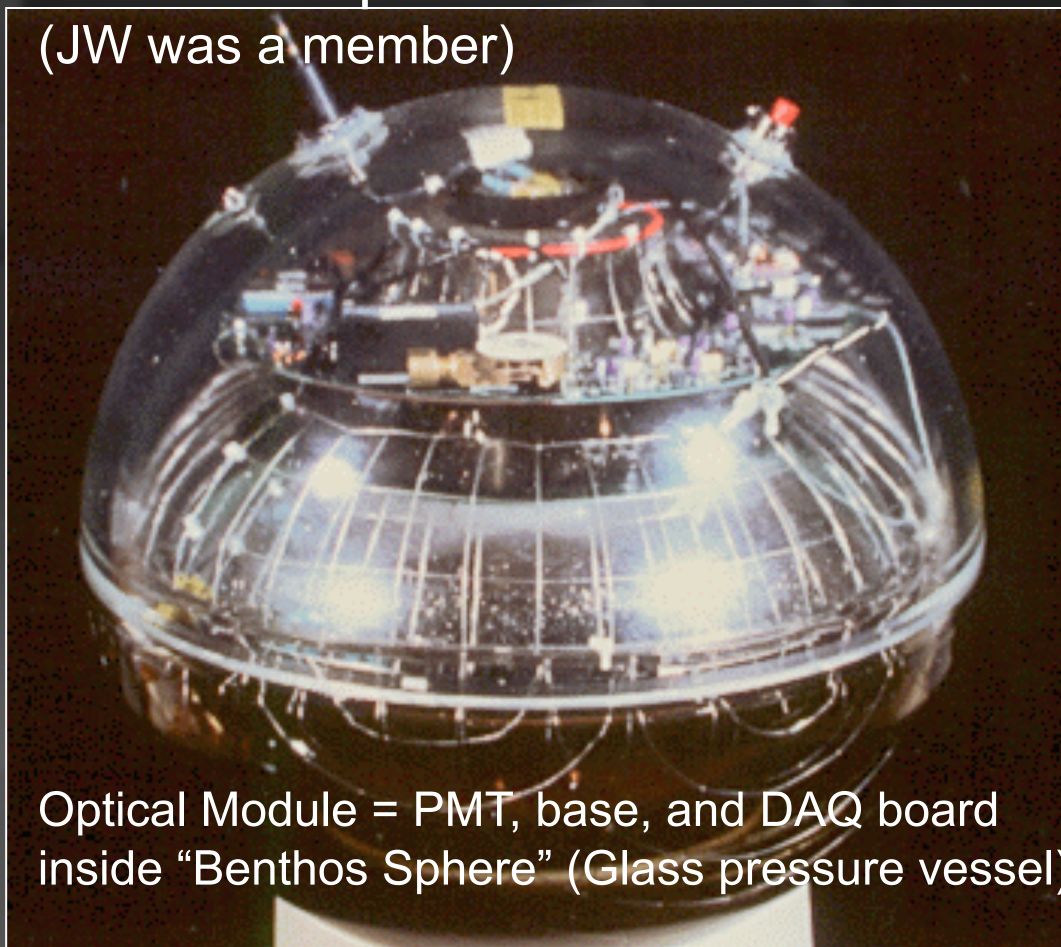
Other Air Ch detectors



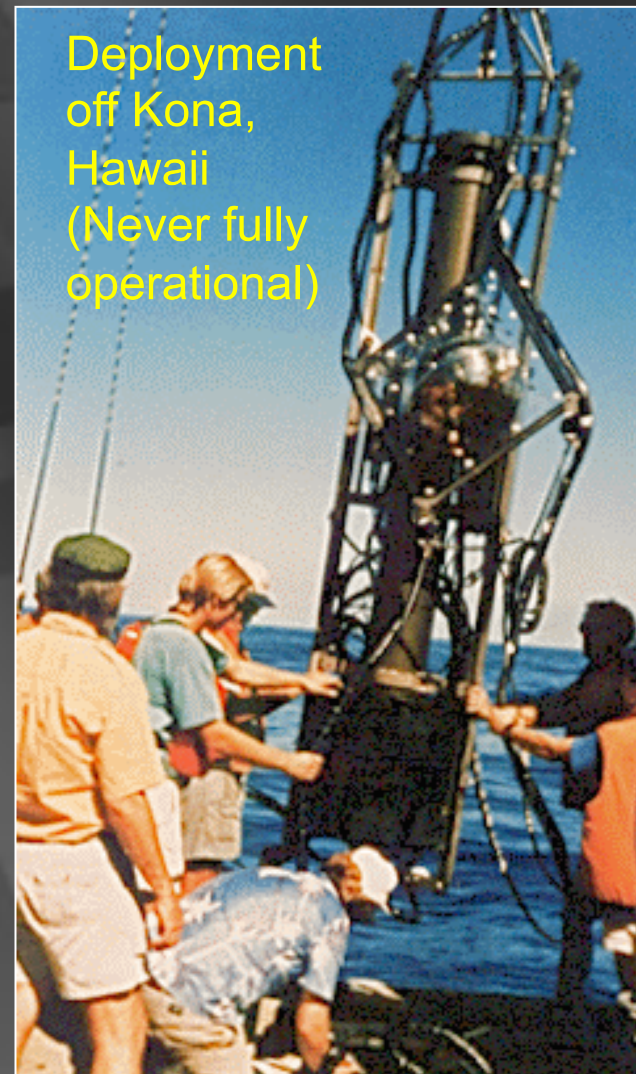


Water Cherenkov arrays for neutrinos

1987: DUMAND Deep Undersea
Muon and Neutrino Detector
5000m deep in seawater
(JW was a member)



Optical Module = PMT, base, and DAQ board
inside “Benthos Sphere” (Glass pressure vessel)



Deployment
off Kona,
Hawaii
(Never fully
operational)

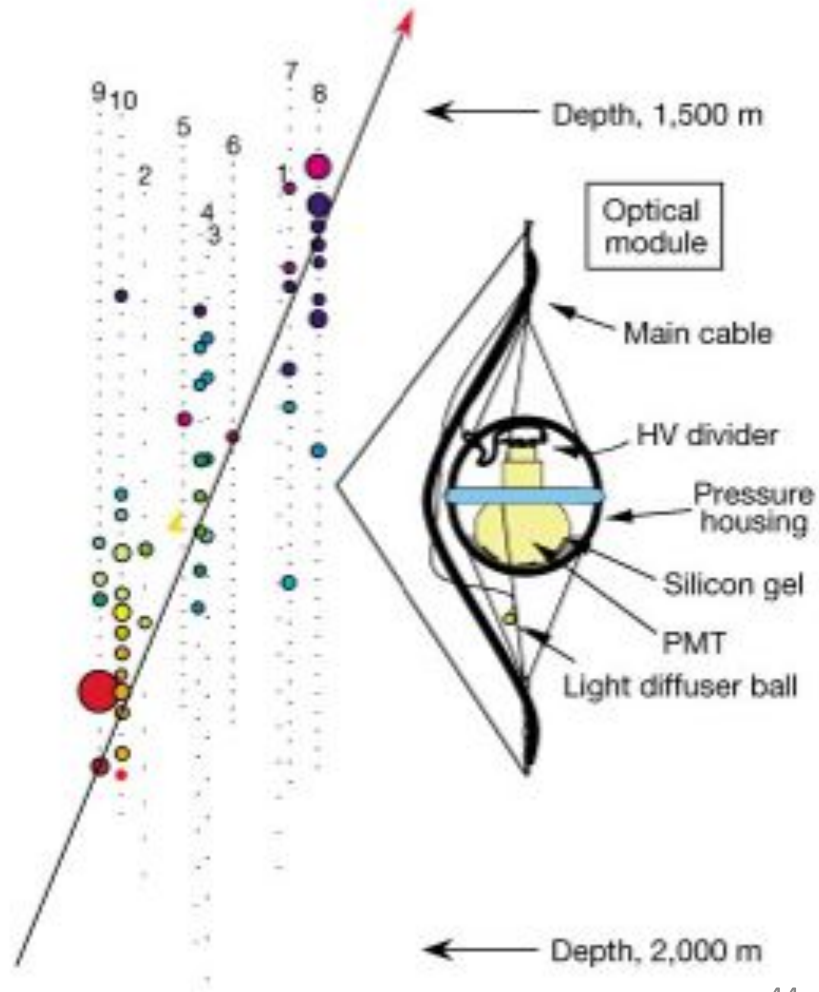
IceCube

- South Polar icecap = transparent pure-water ice, 5000 m deep
- Transpose DUMAND to S. Pole station
- Predecessor/Development project

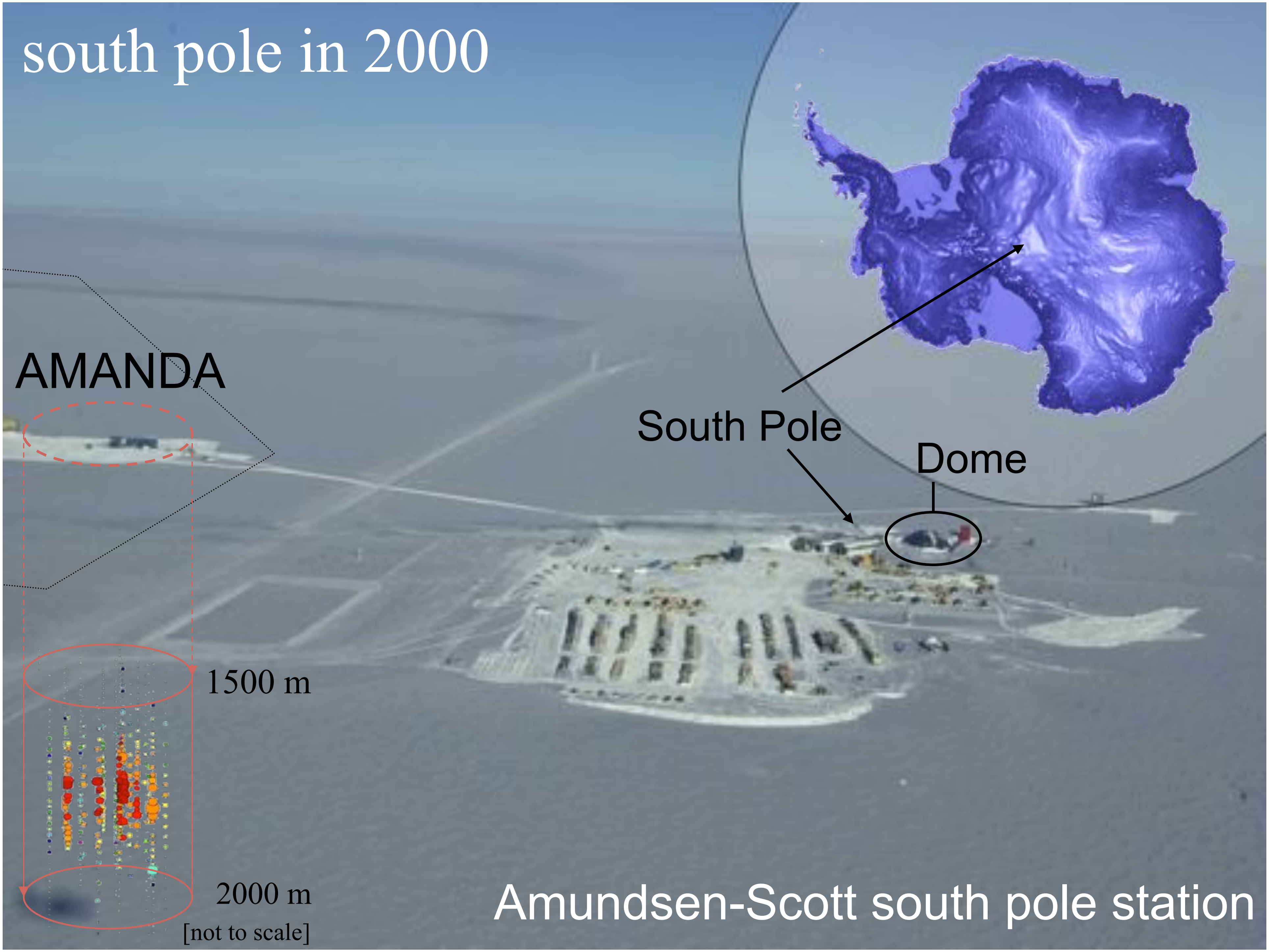
AMANDA (Antarctic ...etc) (1990s)

AMANDA's Problems:
shallower (< 2km deep) ice not optically uniform
Layers of dust from volcanic eras

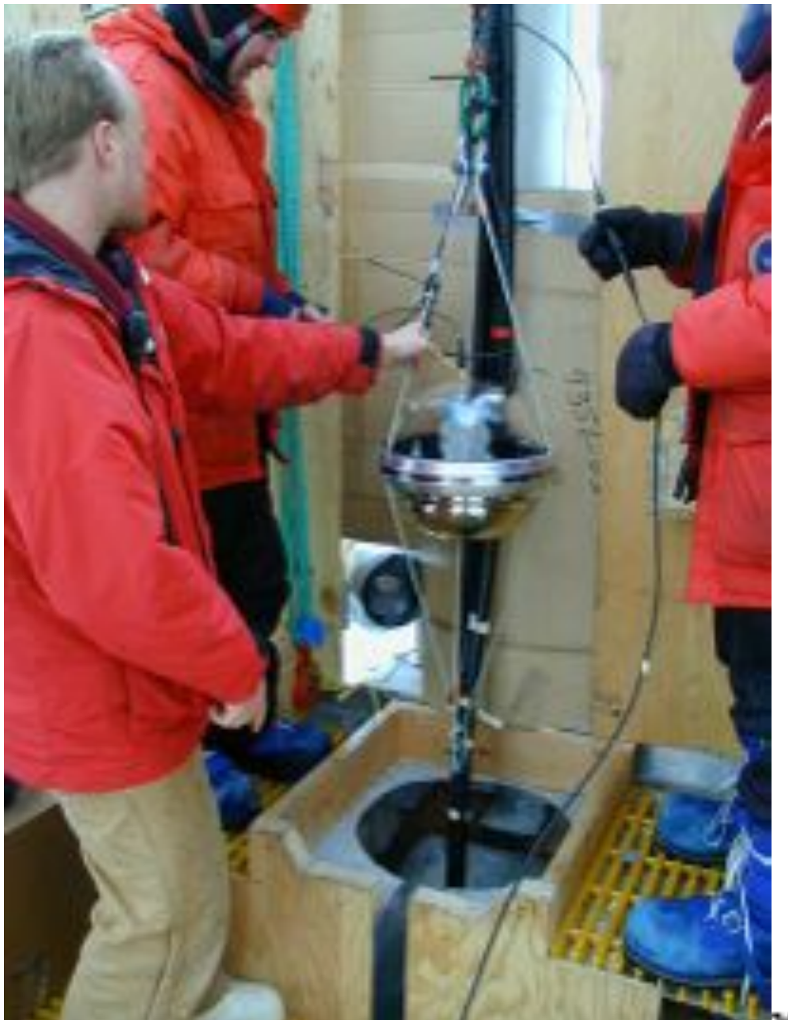
IceCube:
Improved optical modules
Deeper – below dust layers, greater pressure makes ice more isotropic
Success of AMANDA made support by NSF possible
(Antarctic program helps!)

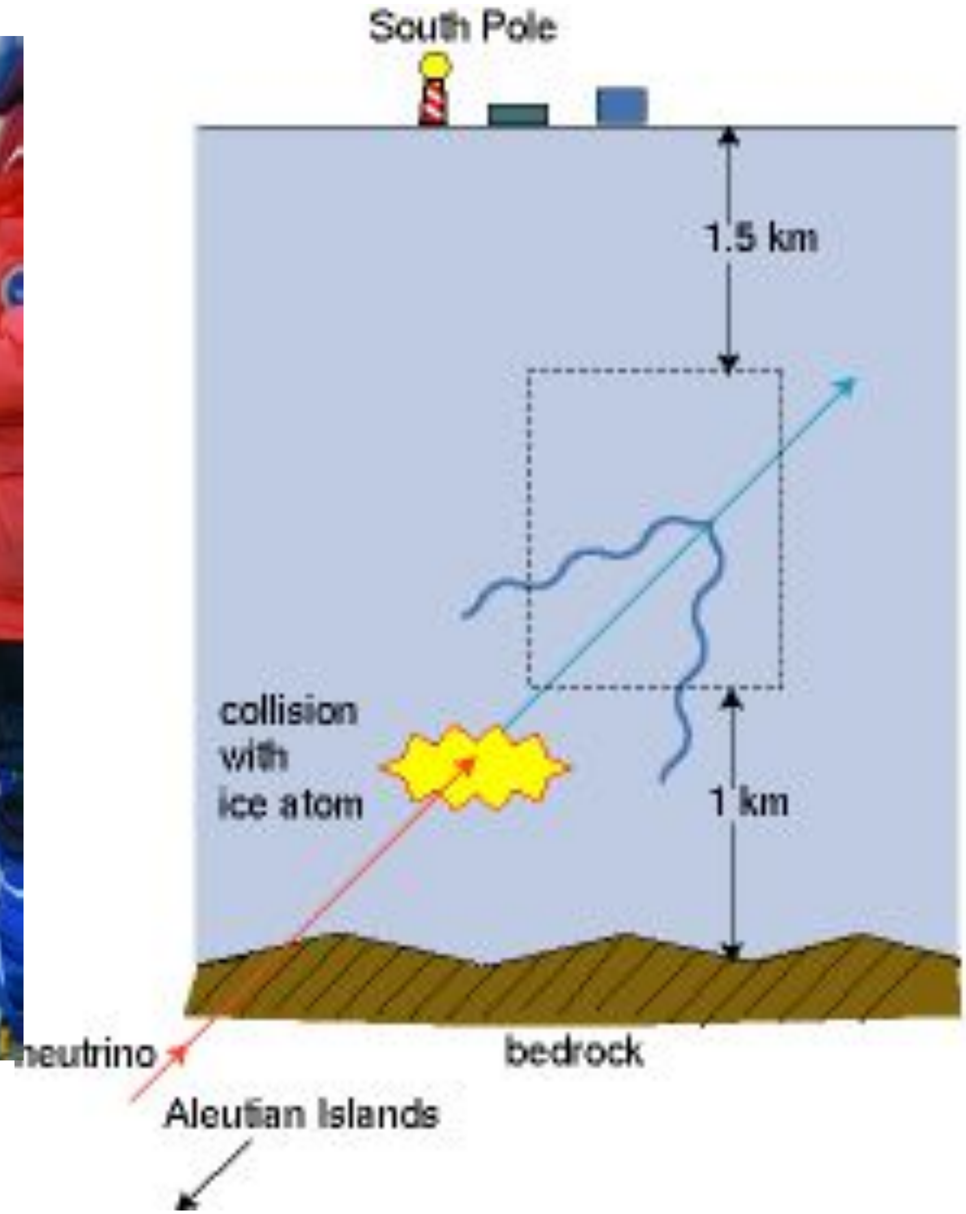


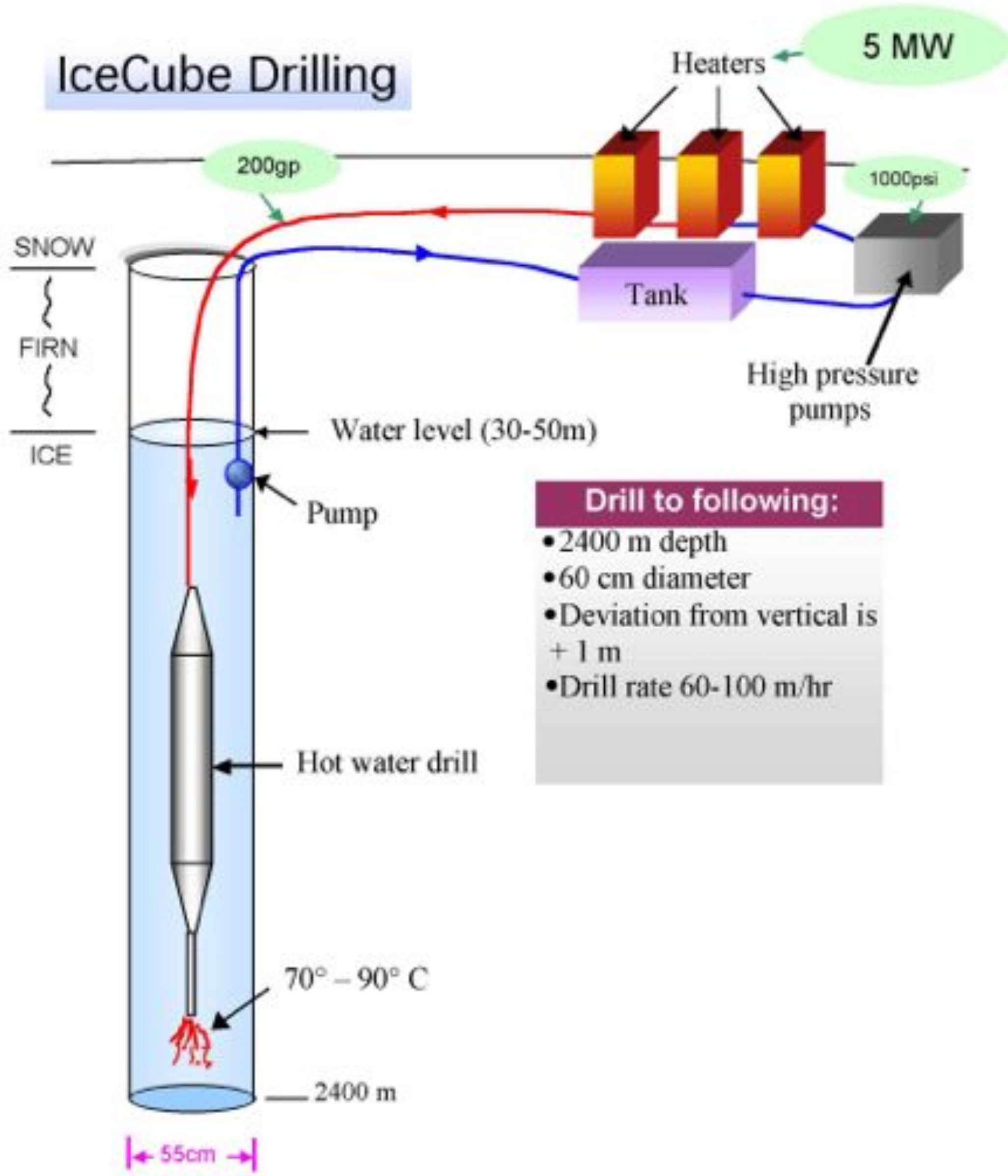
south pole in 2000



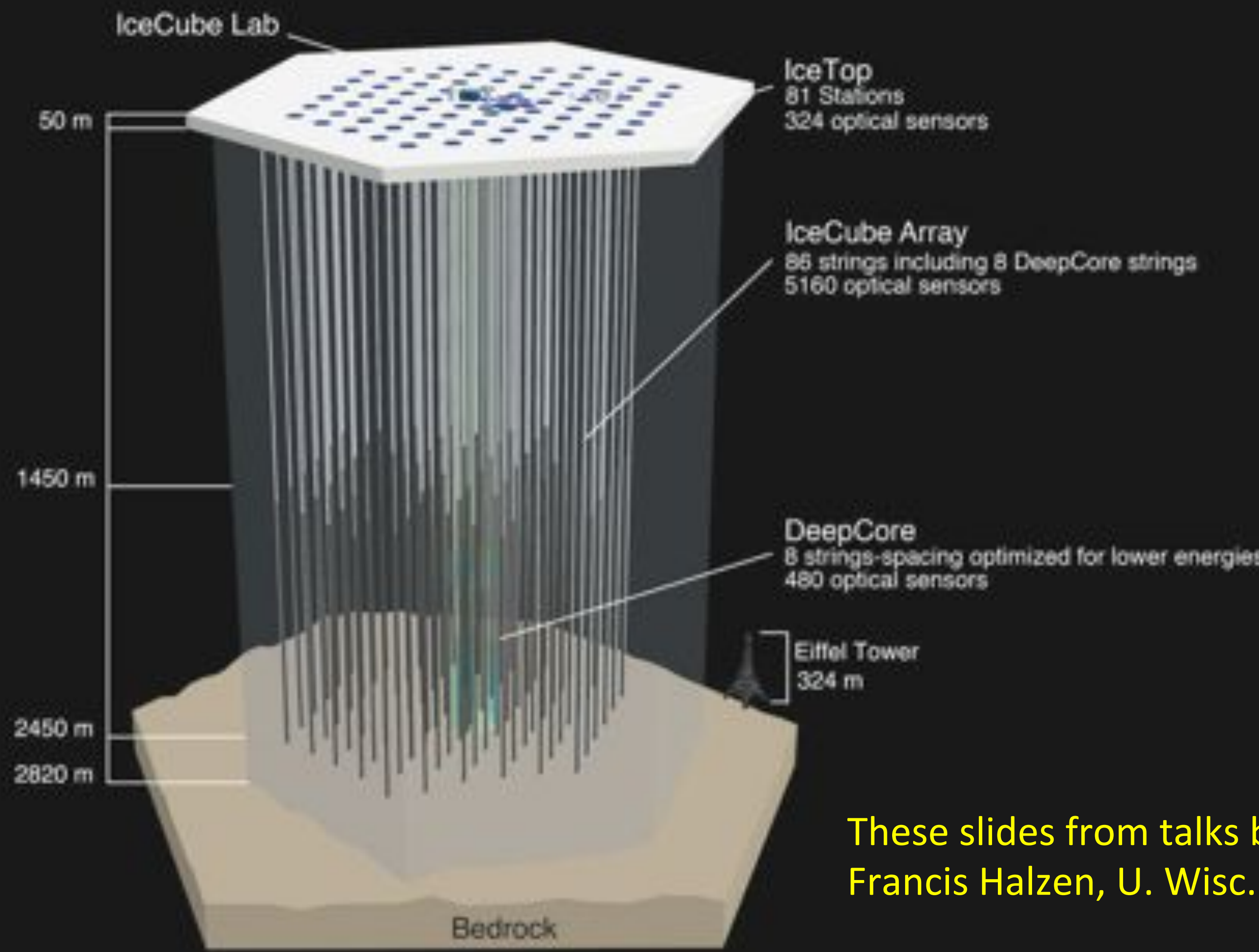
AMANDA/IceCube





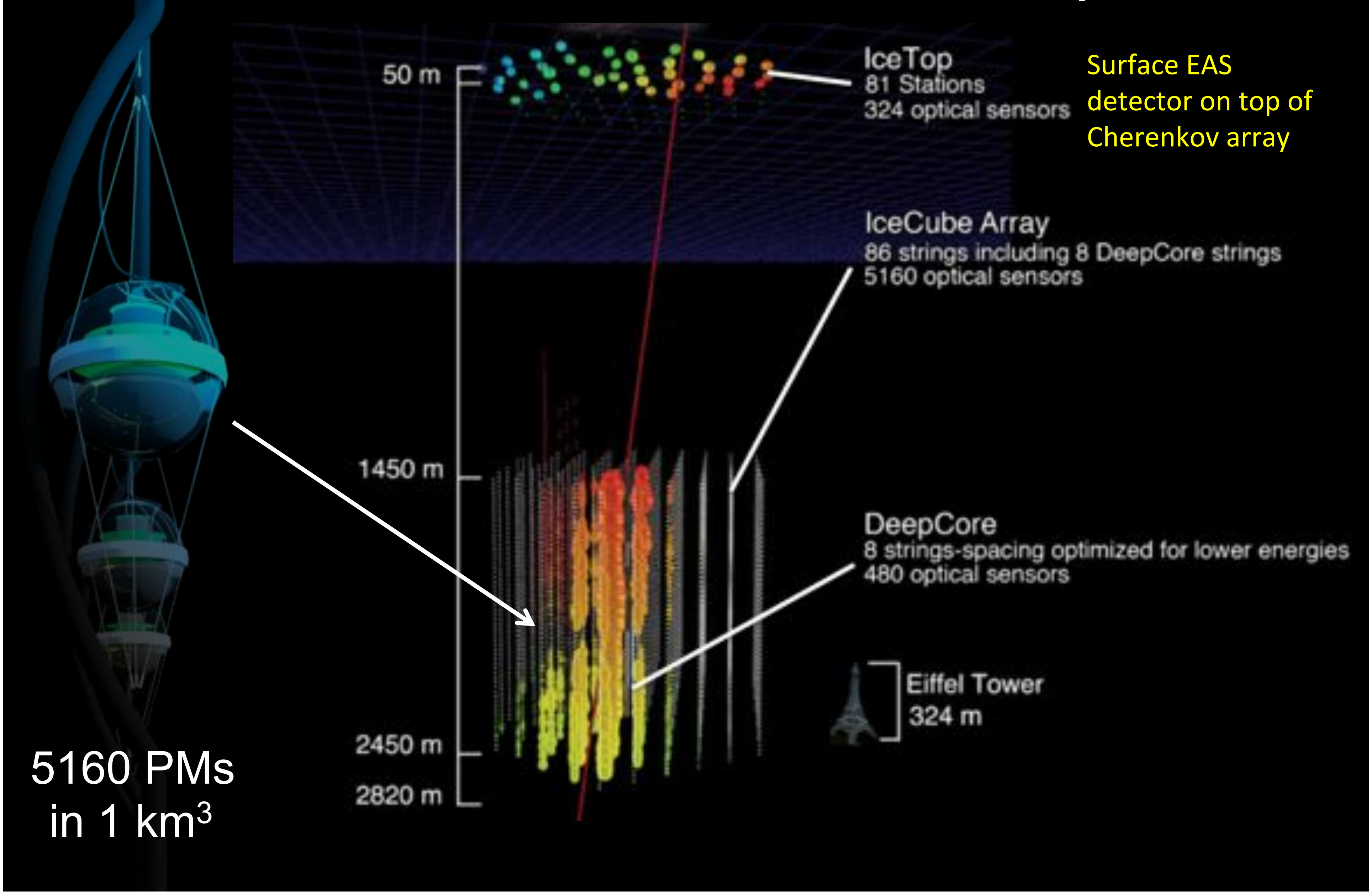

IceCube Drilling
Heaters
5 MW
200gp
1000psi
SNOW
FIRN
ICE
Tank
High pressure pumps
Water level (30-50m)
Pump
Drill to following:
•2400 m depth
•60 cm diameter
•Deviation from vertical is + 1 m
•Drill rate 60-100 m/hr
Hot water drill
70° – 90° C
2400 m
55cm

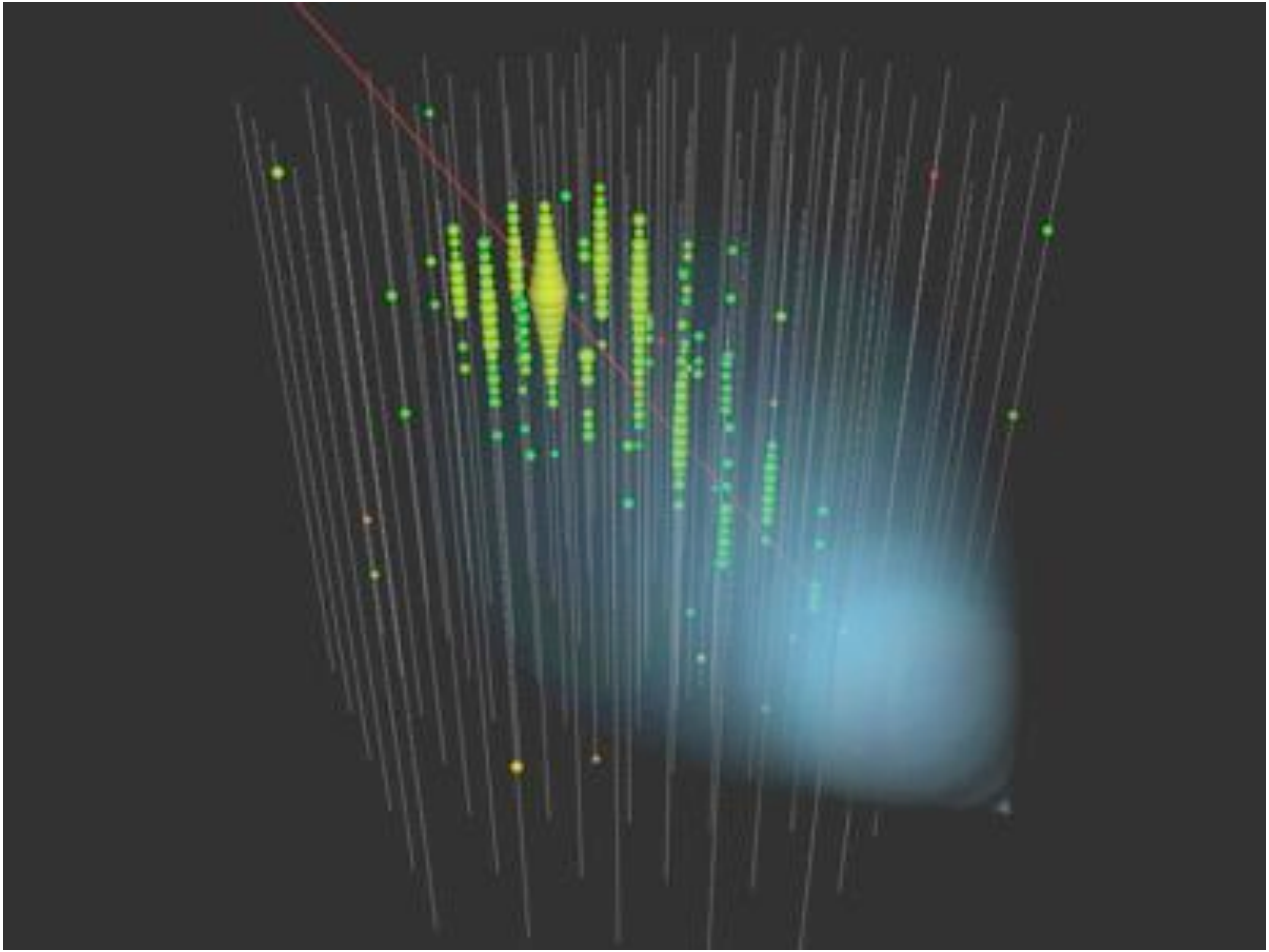
IceCube: transforms 1 km^3 of natural Antarctic ice into a Cherenkov detector

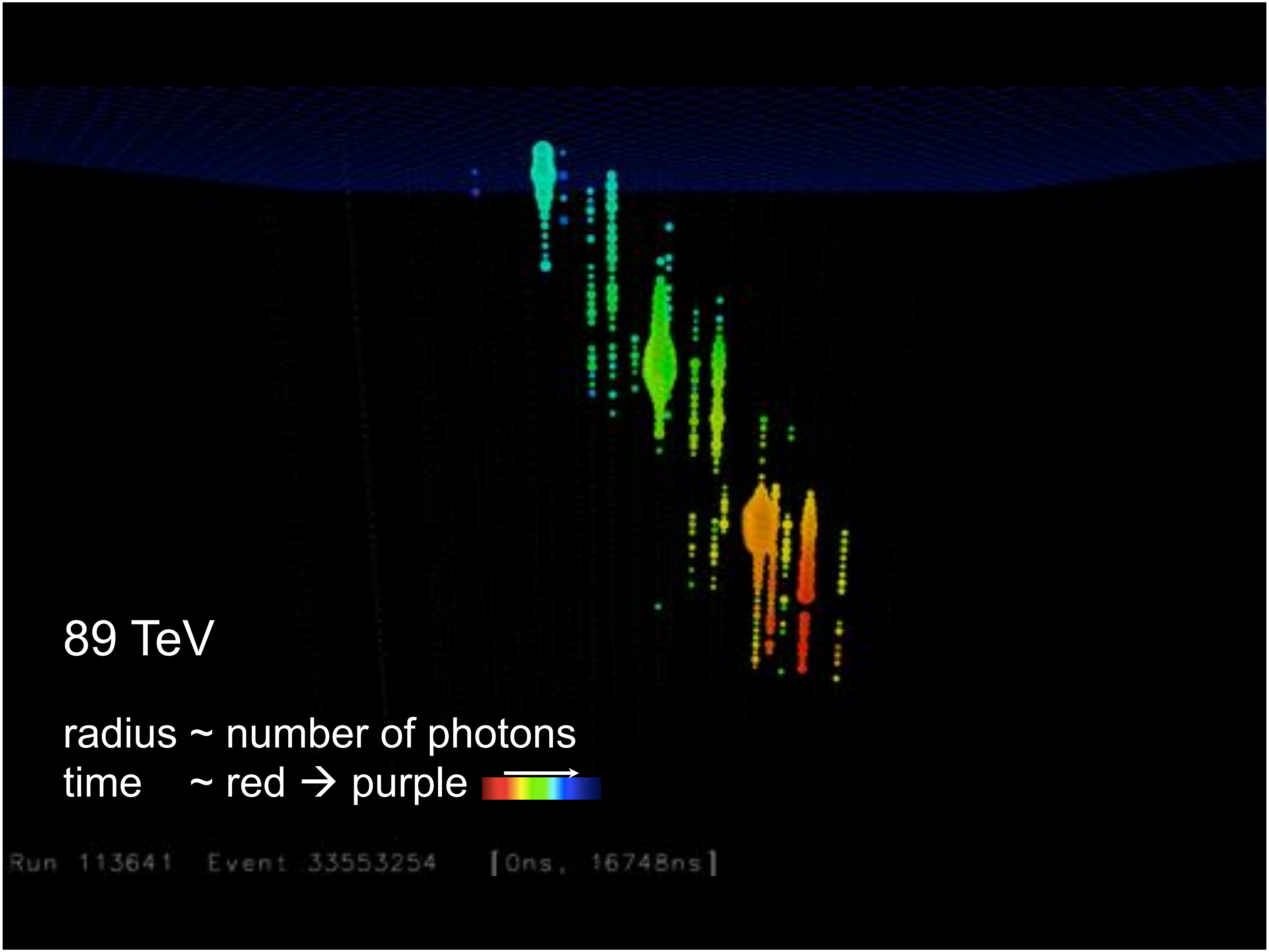


These slides from talks by Francis Halzen, U. Wisc.

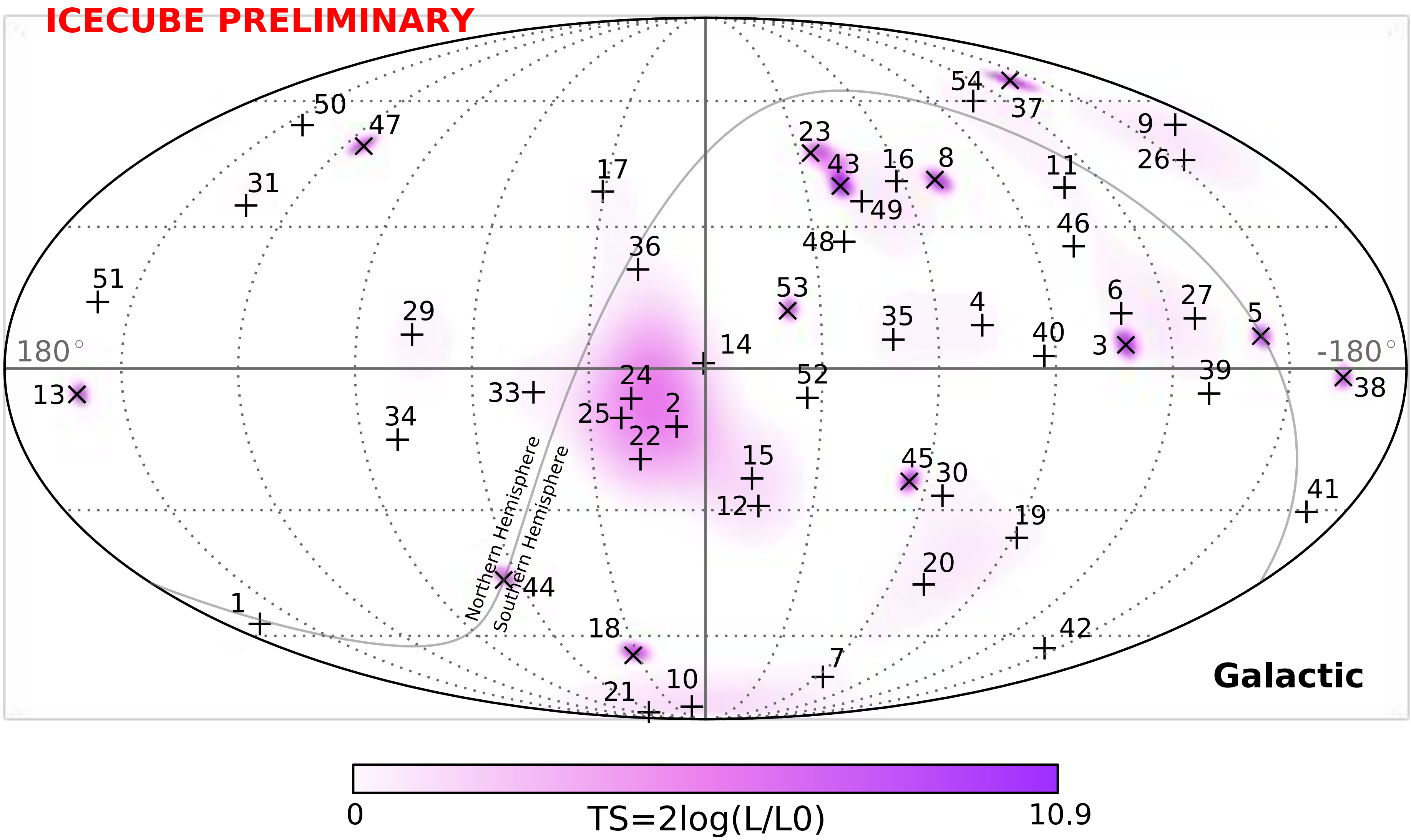
IceCube Today






89 TeV
radius ~ number of photons
time ~ red → purple
Run 113641 Event 33553254 [0ns, 16748ns]

4 year HESE



where do they come from?

RESEARCH

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

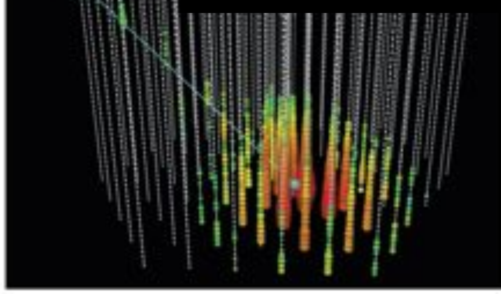
IceCube Collaboration*

Introduction: Neutrino observations are a unique probe of the universe's highest-ene
nomena: Neutrinos are able to escape from dense astrophysical environments that photo
and are unambiguous tracers of cosmic ray acceleration. As protons and nuclei are acc
they interact with gas and background light near the source to produce subatomic particle
charged pions and kaons, which then decay, emitting neutrinos. We report on results of
search for these neutrinos at energies above 30 TeV in the cubic kilometer Antarctic IceCu
vatory between May 2010 and May 2012.

Methods: We have isolated a sample of neutrinos by rejecting background muons from c
showers in the atmosphere, selecting only those neutrino candidates that are first observ
detector interior rather than on the detector boundary. This search is primarily sensitive
nos from all directions above 60 TeV, at which the lower-energy background atmospheric
become rare, with some sensitivity down to energies of 30 TeV. Penetrating muon backgro
evaluated using an in-data control sample, with atmospheric neutrino predictions based
retical modeling and extrapolation from previous lower-energy measurements.

Results: We observed 28 neutrino candidate events (two previously reported), substanti
than the 10.6 expected from atmospheric backgrounds, and ranging in energy from 3
TeV. With the current level of statistics, we did not observe significant clustering of these
time or space, preventing the identification of their sources at this time.

Discussion: The data contain a mixture of neutrino flavors compatible with flavor equi
originate primarily from the Southern Hemisphere where high-energy neutrinos are not
by Earth, and have a hard energy spectrum compatible with that expected from cosmic ray accelerators. Within our present knowledge, the directions, energies, and topologies of these events are not compatible with expectations for terrestrial processes, deviating at the 4σ level from standard assumptions for the atmospheric background. These properties, in particular the north-south asymmetry, generically disfavor any purely atmospheric explanation for the data. Although not compatible with an atmospheric explanation, the data do match expectations for an origin in unidentified high-energy galactic or extragalactic neutrino accelerators.



A 250 TeV neutrino interaction in IceCube. At the neutrino interaction point (bottom), a large particle shower is visible, with a muon produced in the interaction leaving up and to the left. The direction of the muon indicates the direction of the original neutrino.

*The list of author affiliations is available in the full article online.
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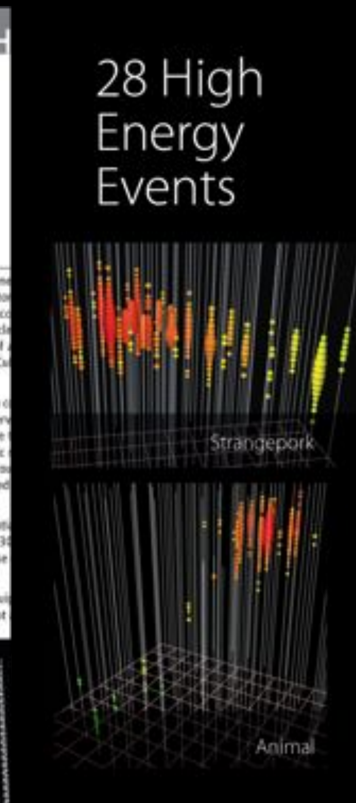
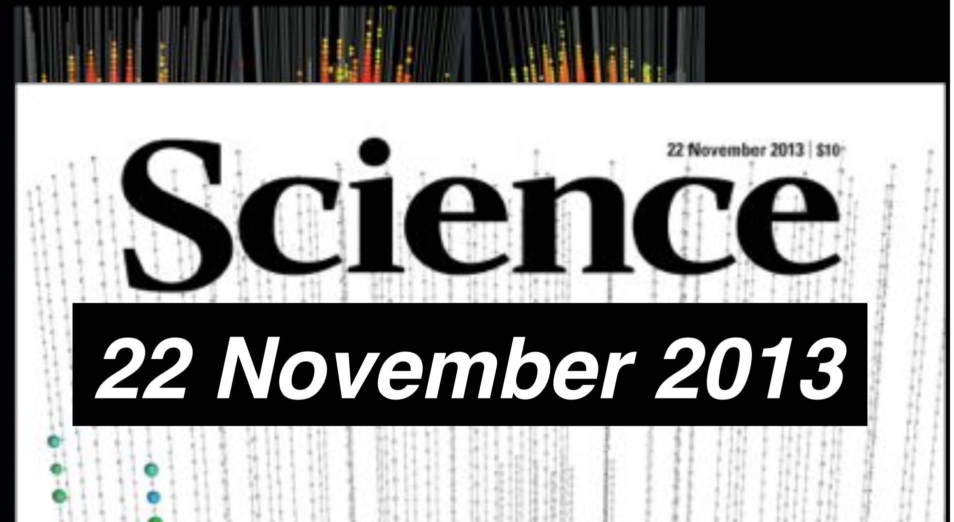
www.sciencemag.org SCIENCE VOL 342 22 NOVEMBER 2013

Published by AAAS





22 November 2013