Example 5: astro-particle physics experiments

Motivation

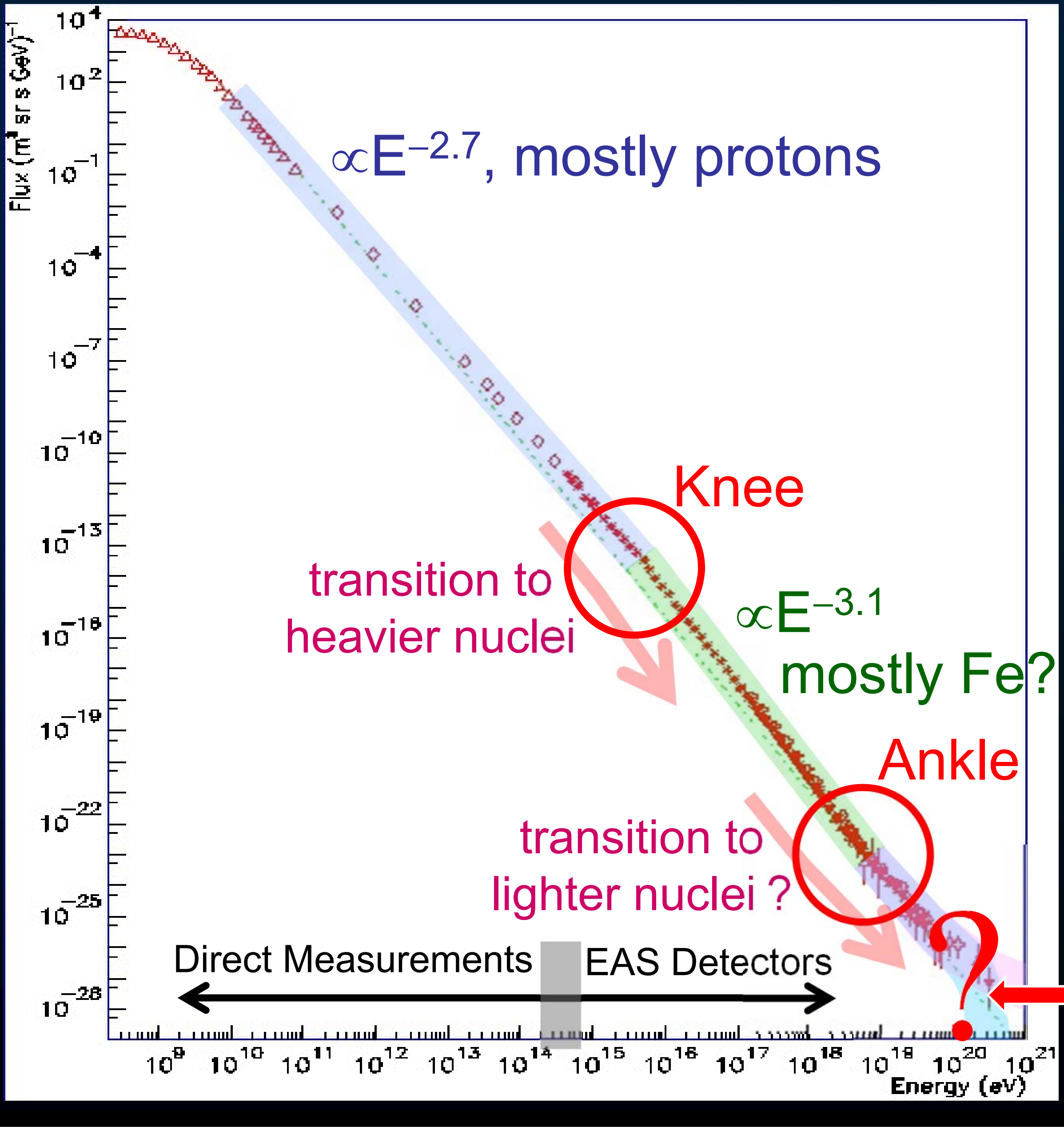
High energy gamma detection

High energy cosmic ray detection

Detectors for cosmic neutrinos

Peter Križan, Advanced particle detectors and data analysis

The Cosmic Ray Spectrum



$\propto E^{-2.7}$, mostly protons

Knee

transition to
heavier nuclei

$\propto E^{-3.1}$
mostly Fe?

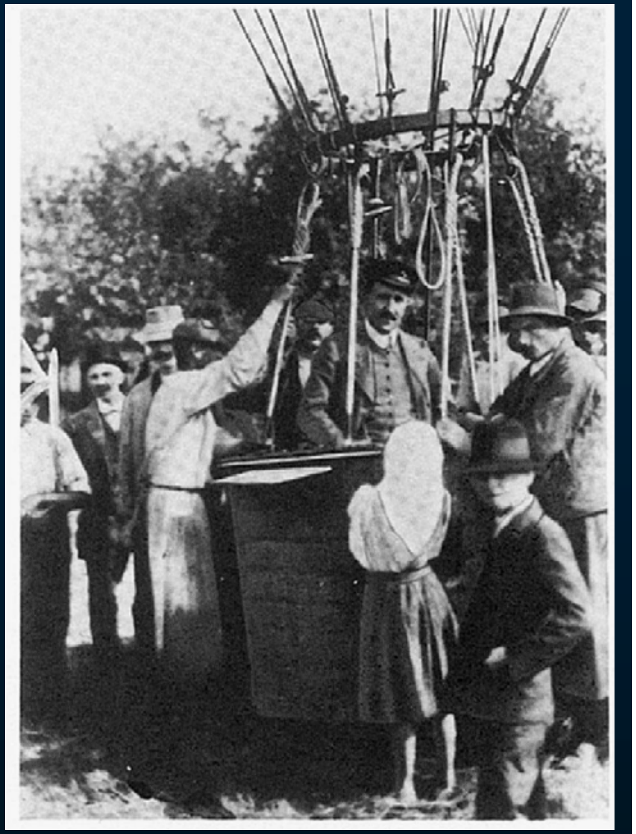
Ankle

transition to
lighter nuclei ?

Direct Measurements

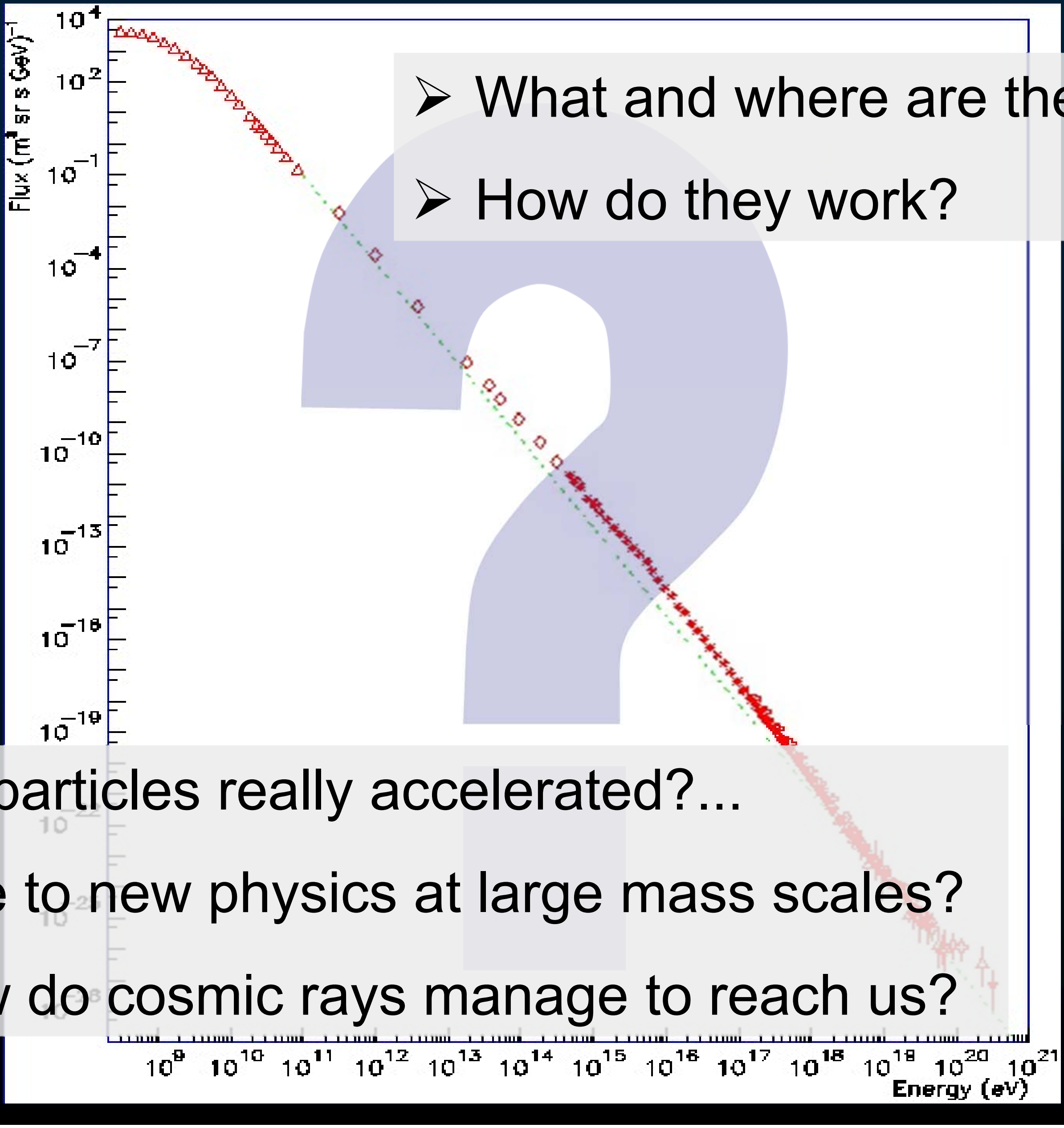
EAS Detectors

< 1 particle/km²/century!



Discovery Balloon Flight
Victor Hess, 1912

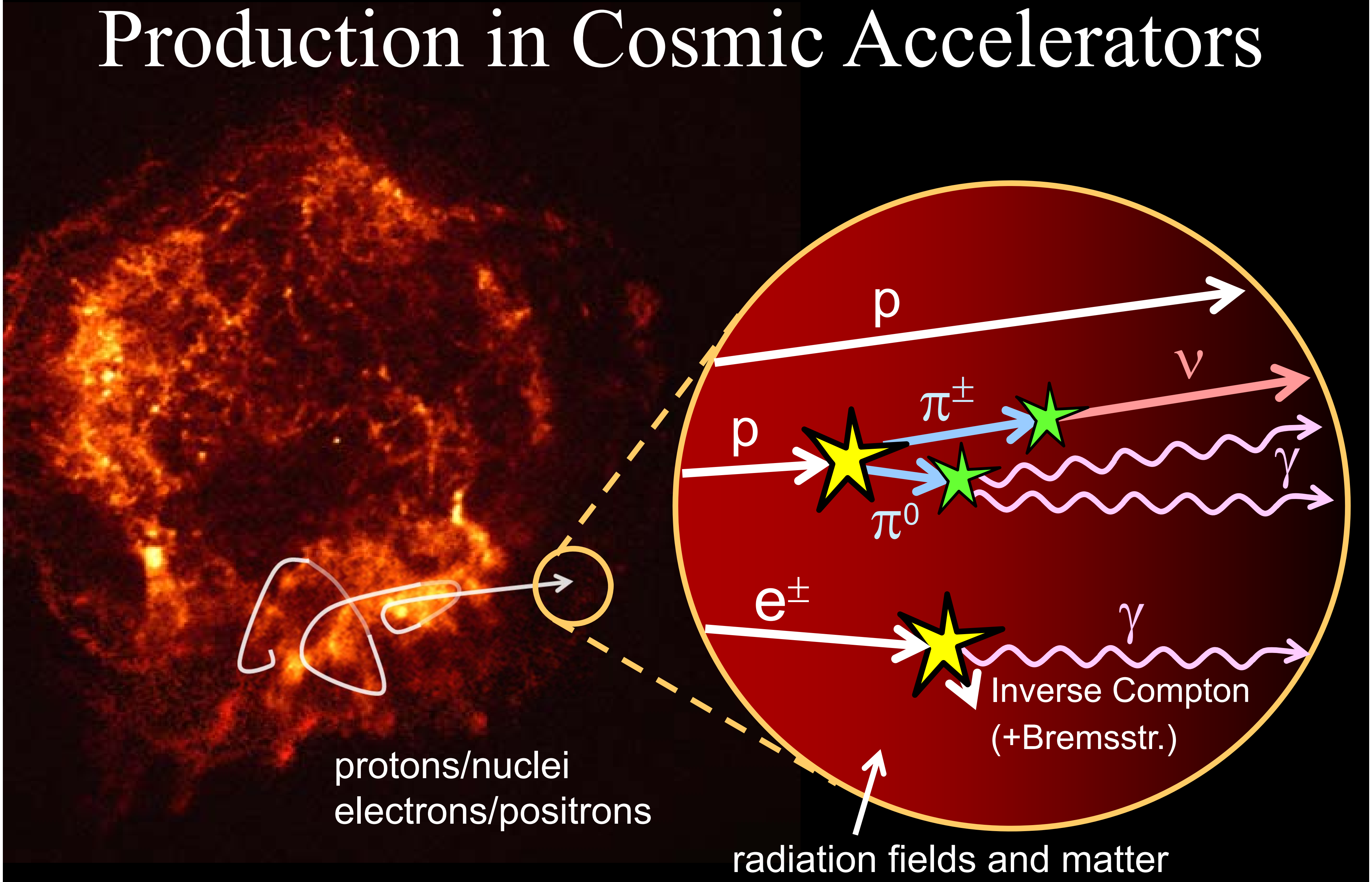
Open questions after >90 years



- ➢ What and where are the sources?
- ➢ How do they work?

- ➢ Are the particles really accelerated?...
- ➢ …or due to new physics at large mass scales?
- ➢ And how do cosmic rays manage to reach us?

Production in Cosmic Accelerators

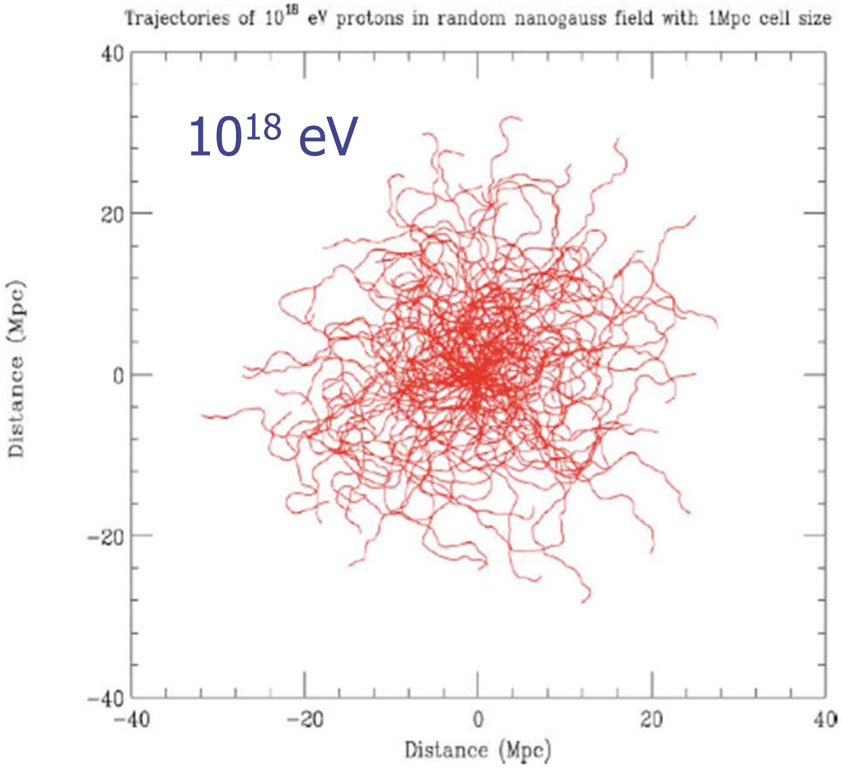


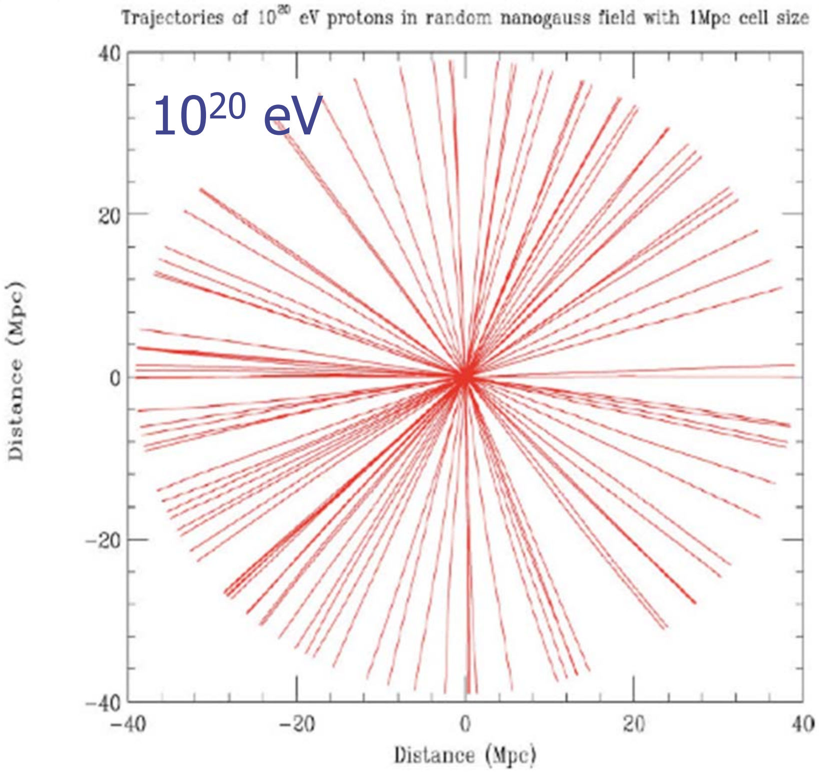
protons/nuclei
electrons/positrons

radiation fields and matter

MAGNETIC FIELD DEFLECTION

Deflection of charged particles


Trajectories of 10^{18} eV protons in random nanogauss field with 1Mpc cell size


Trajectories of 10^{20} eV protons in random nanogauss field with 1Mpc cell size

Gammas and neutrinos are not deflected.

Detect particles from distant sources

- Charged particles
- High energy gamma rays (photons)
- Neutrinos

Measure their:

- Direction
- Energy

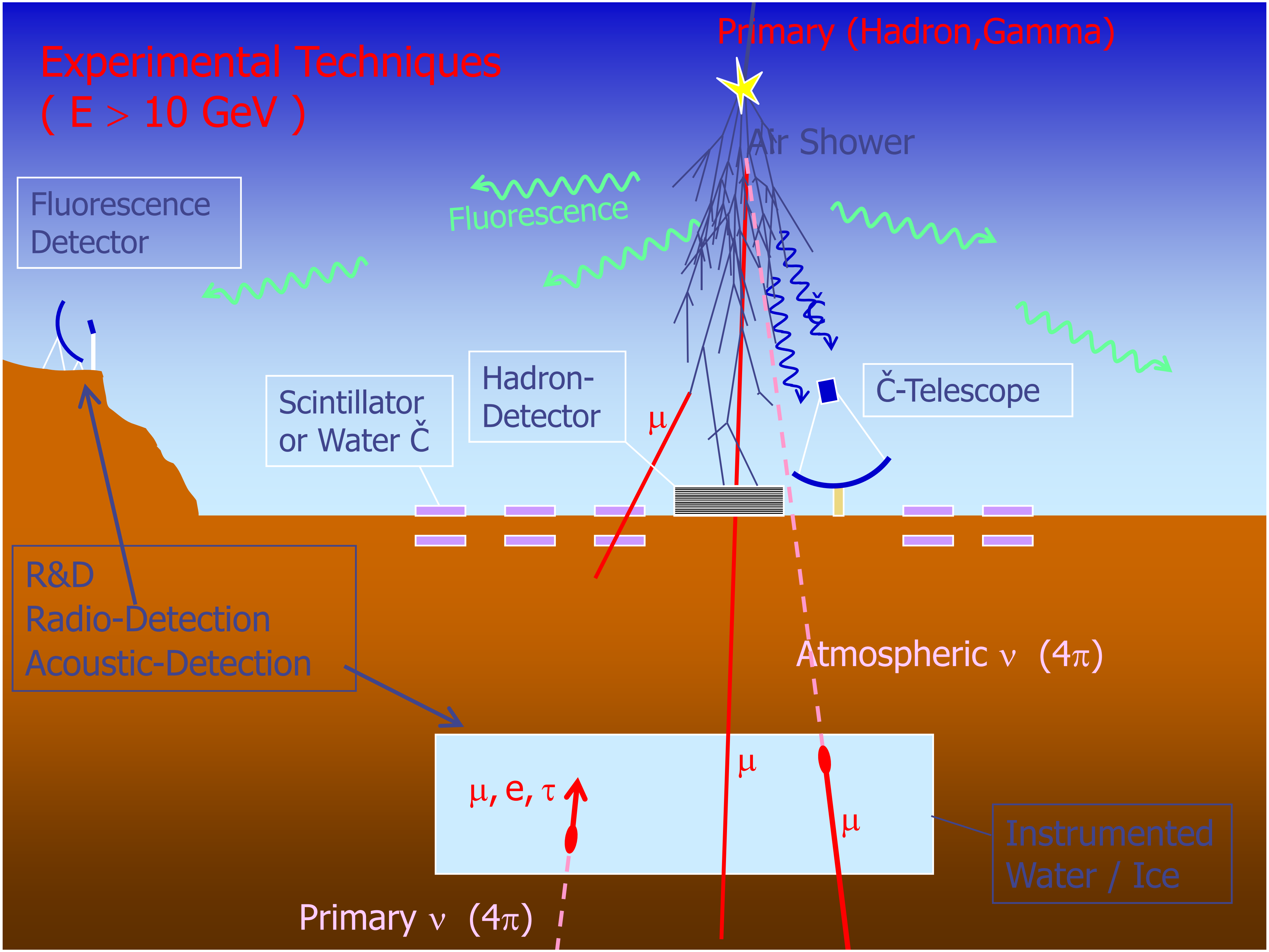
Detection of high energy particles from distant sources

Challenge:

- Very low fluxes

→need huge detectors

Experimental Techniques
(E > 10 GeV)



Primary (Hadron,Gamma)

Air Shower

Fluorescence Detector

Fluorescence

Scintillator or Water Č

Hadron-Detector

Č-Telescope

Č

μ

R&D
Radio-Detection
Acoustic-Detection

Atmospheric ν (4π)

μ, e, τ

μ

μ

Instrumented Water / Ice

Primary ν (4π)

Atmosphere as a calorimeter

Need:

- Detect high energy cosmic rays
- Measure their energy
- Determine the identity (gamma or hadron, which hadron)

Idea: use atmosphere as a detector + calorimeter

Virtues:

- A lot of material
- Transparent

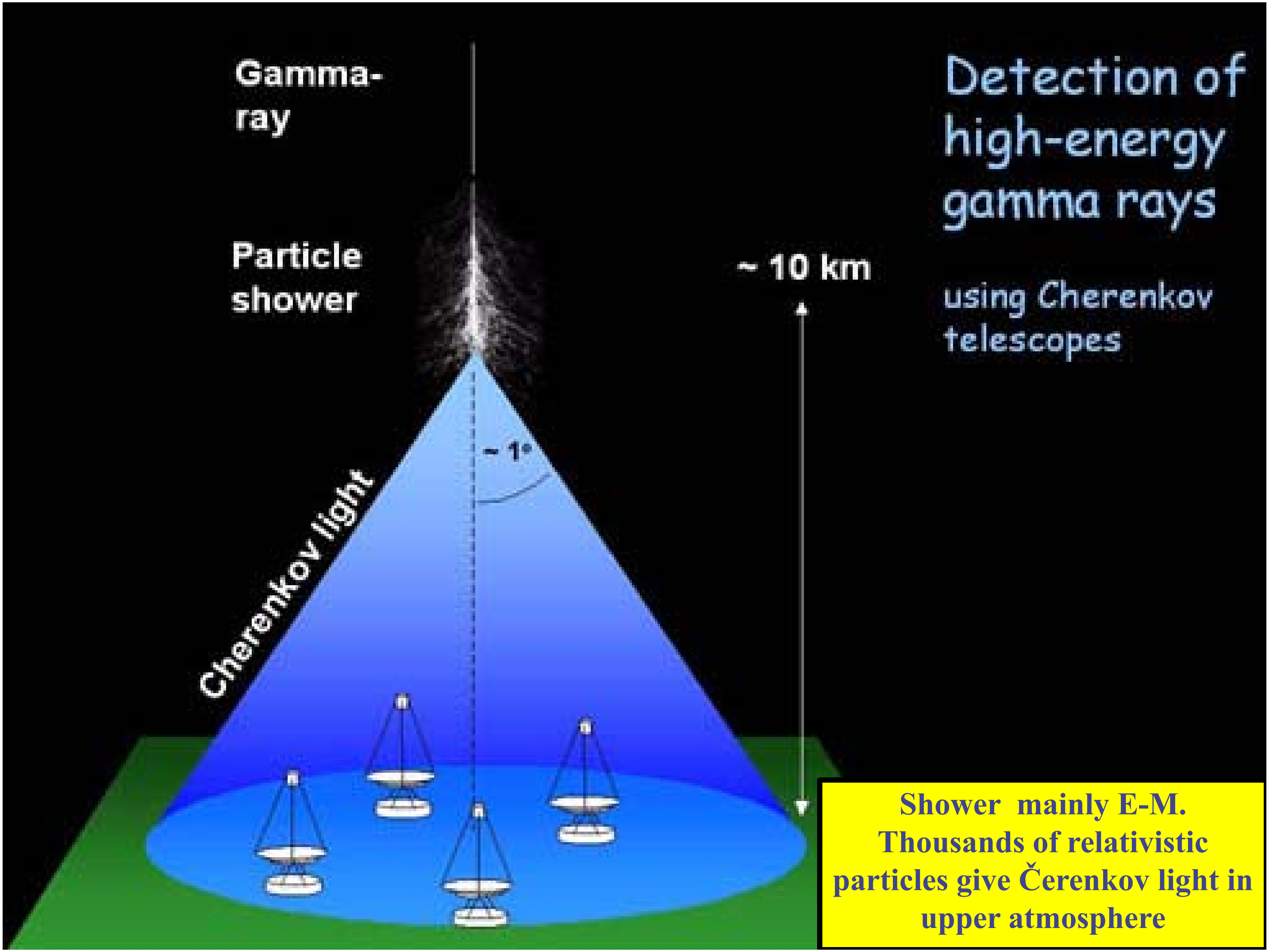
Use Cherenkov light or fluorescence emitted by charged particles to determine the energy of the incoming cosmic ray.

Atmosphere as a calorimeter: gamma rays

Detect high energy cosmic gamma rays

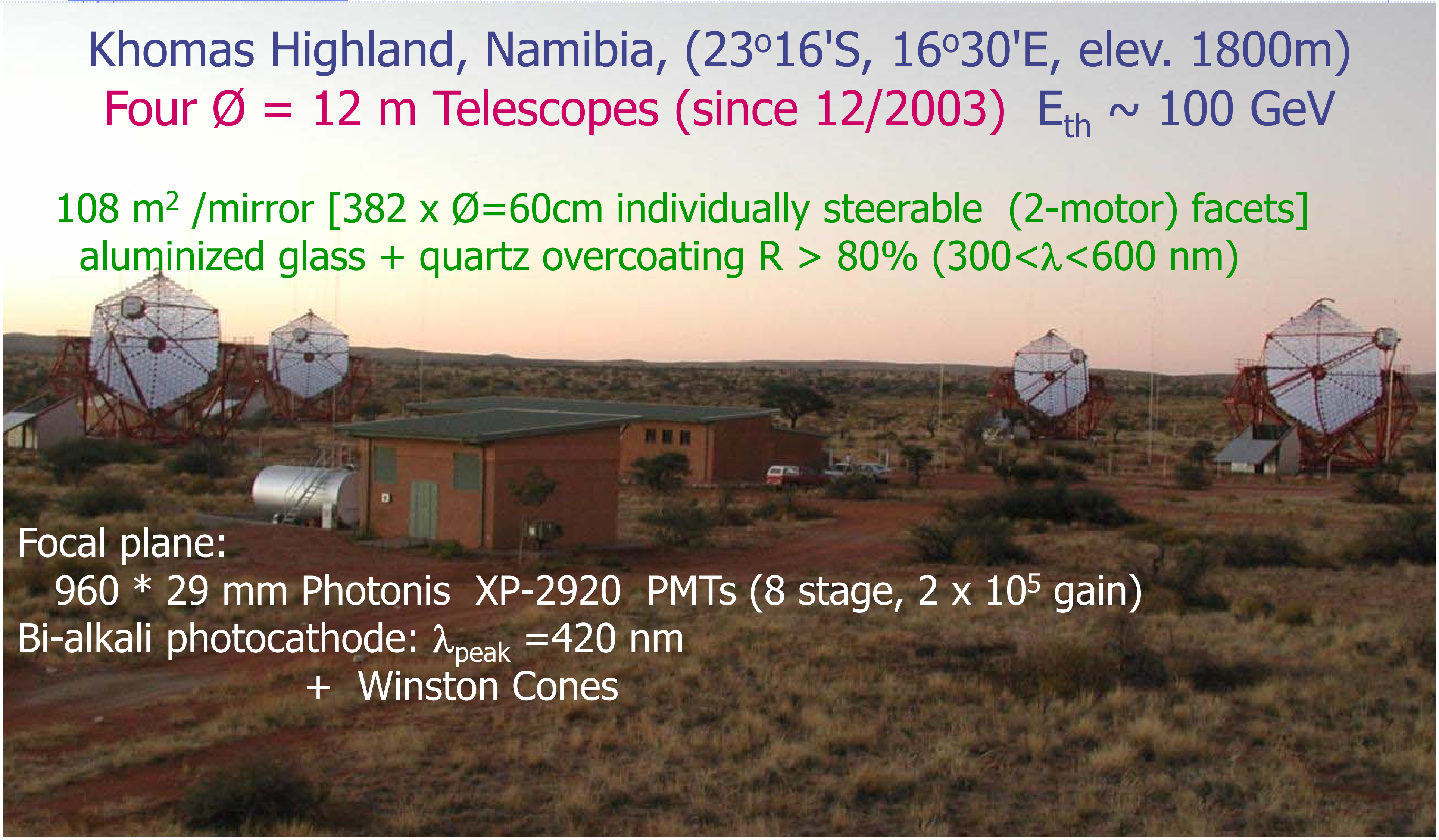
- Measure their energy
- Measure their direction

Use Cherenkov light emitted by electrons and positrons from a electromagnetic shower to determine the energy of the incoming cosmic gamma ray.



**Shower mainly E-M.
Thousands of relativistic particles give Čerenkov light in upper atmosphere**

HESS 1 UHE Gamma Ray Telescope Stereoscopic Quartet



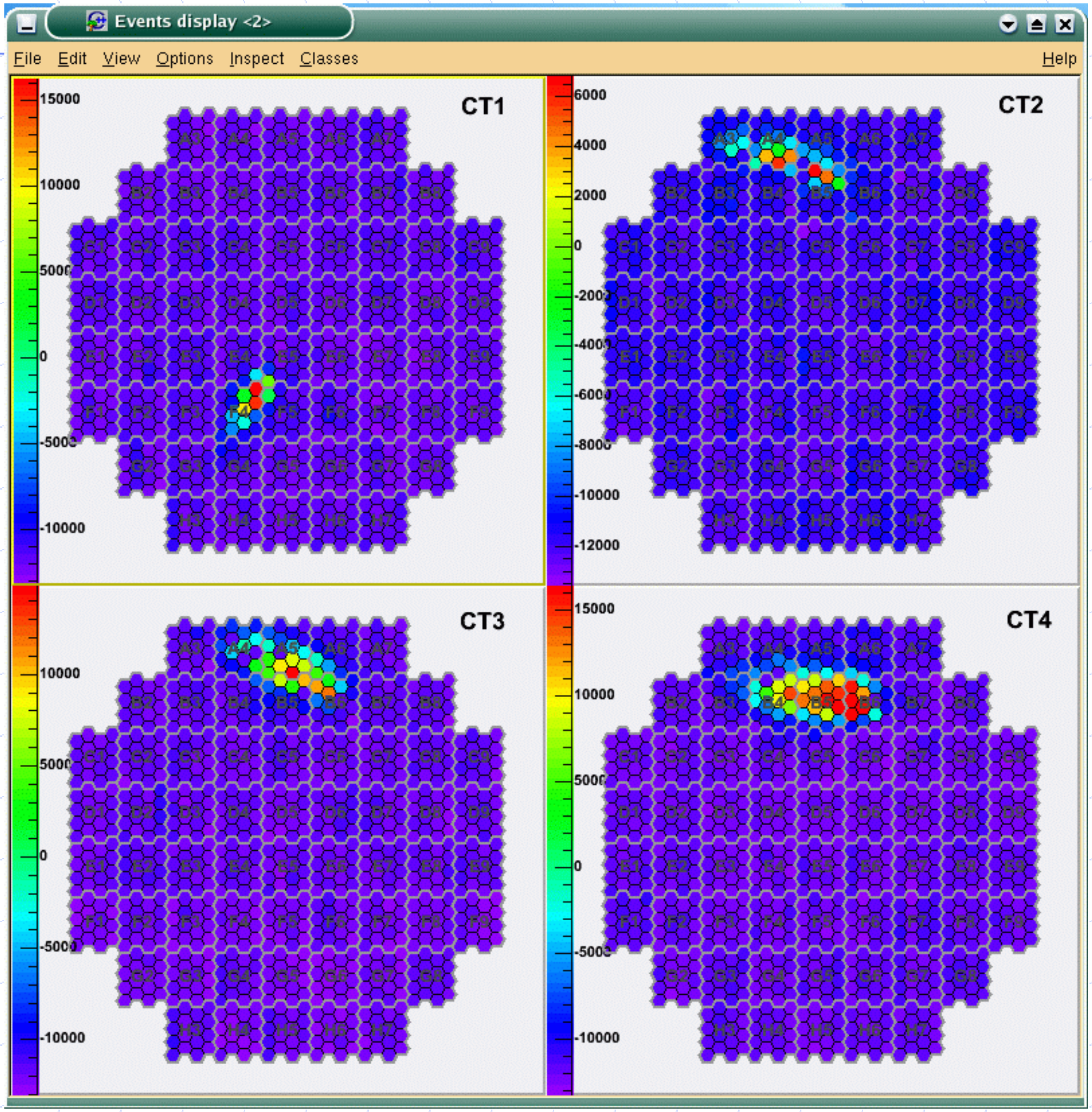
Khomas Highland, Namibia, (23°16'S, 16°30'E, elev. 1800m)

Four Ø = 12 m Telescopes (since 12/2003) $E_{th} \sim 100$ GeV

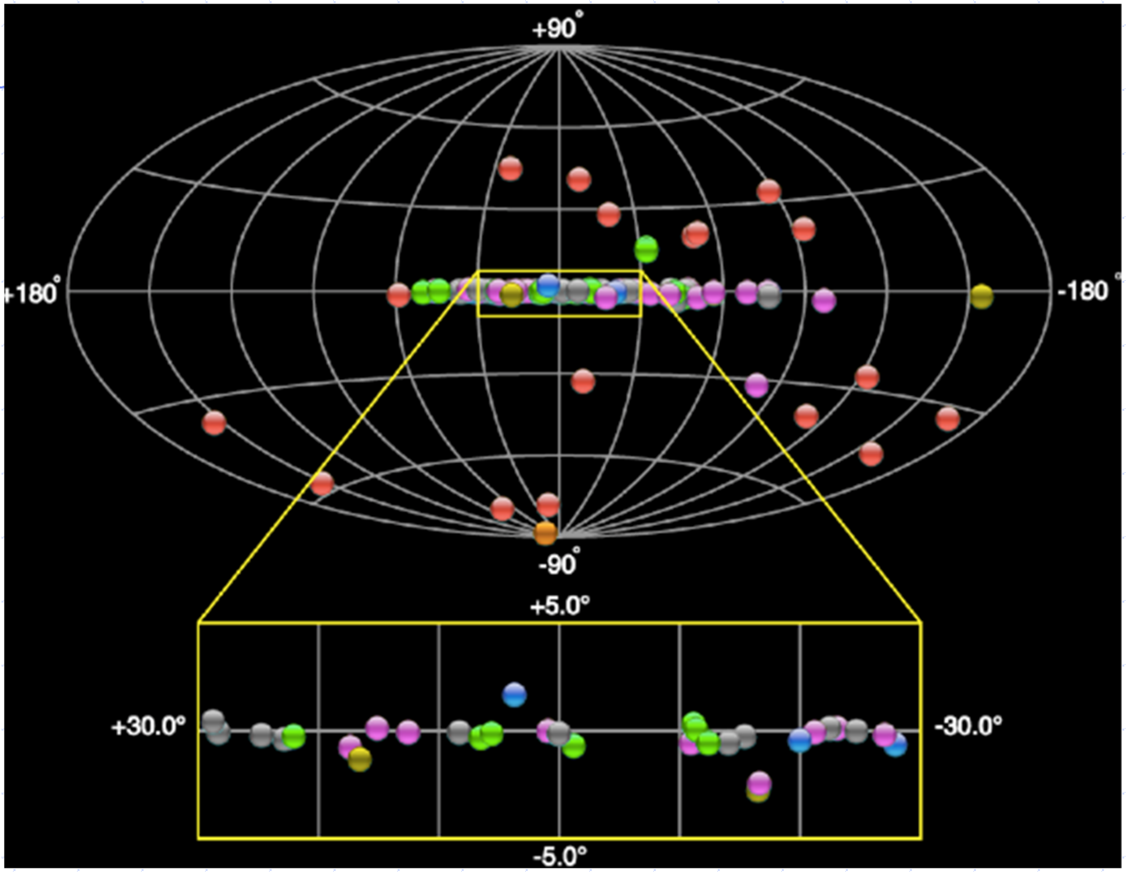
108 m^2 /mirror [382 x Ø=60cm individually steerable (2-motor) facets]
aluminized glass + quartz overcoating $R > 80\%$ ($300<\lambda<600$ nm)

Focal plane:
960 * 29 mm Photonis XP-2920 PMTs (8 stage, 2 x 10^5 gain)
Bi-alkali photocathode: λ_{peak} =420 nm
+ Winston Cones

More than one telescope: combine 2 or more 2D images → → 3D reconstruction of the shower is possible → → determine the direction of the gamma ray

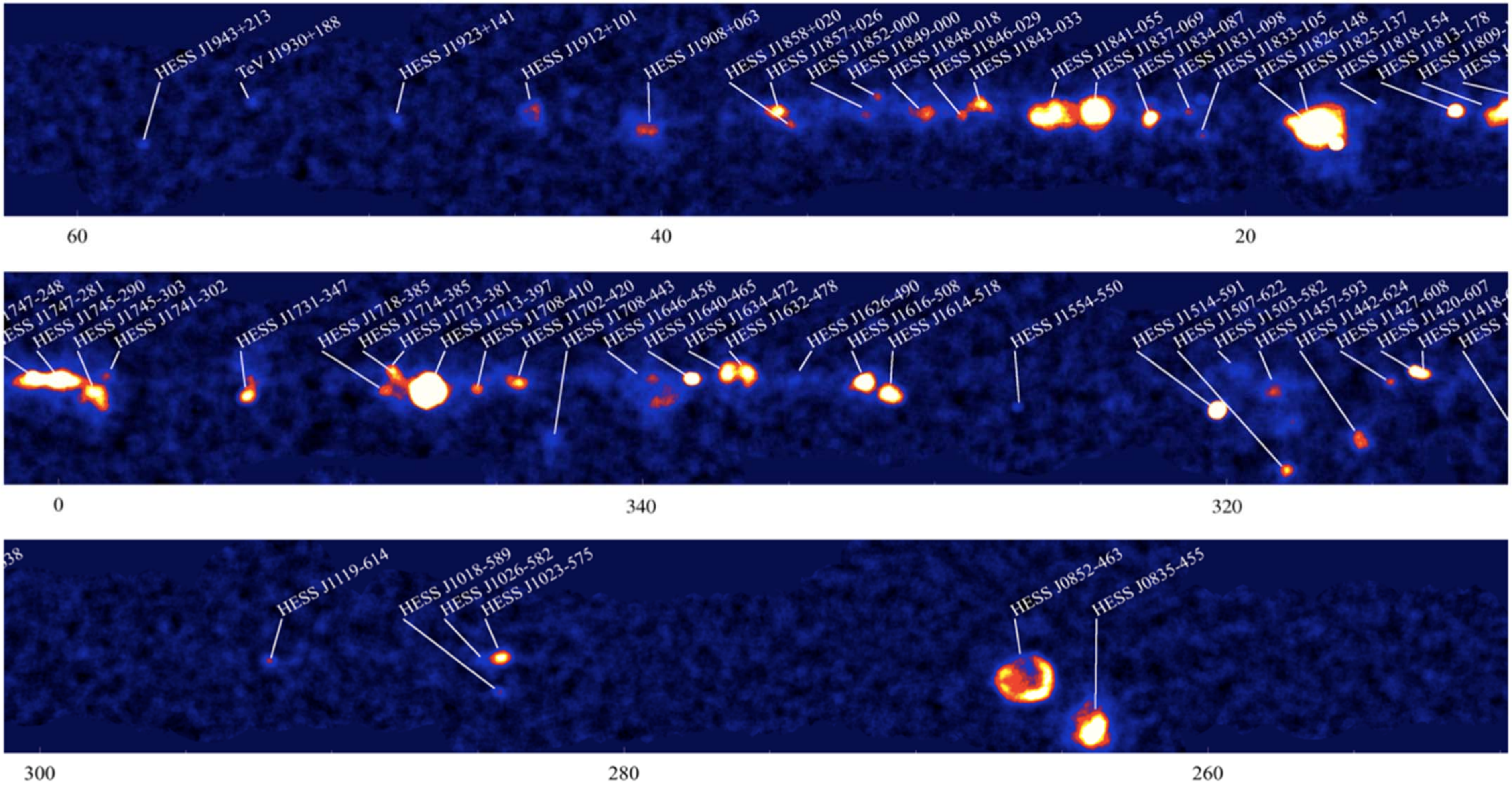


HESS gamma ray sources



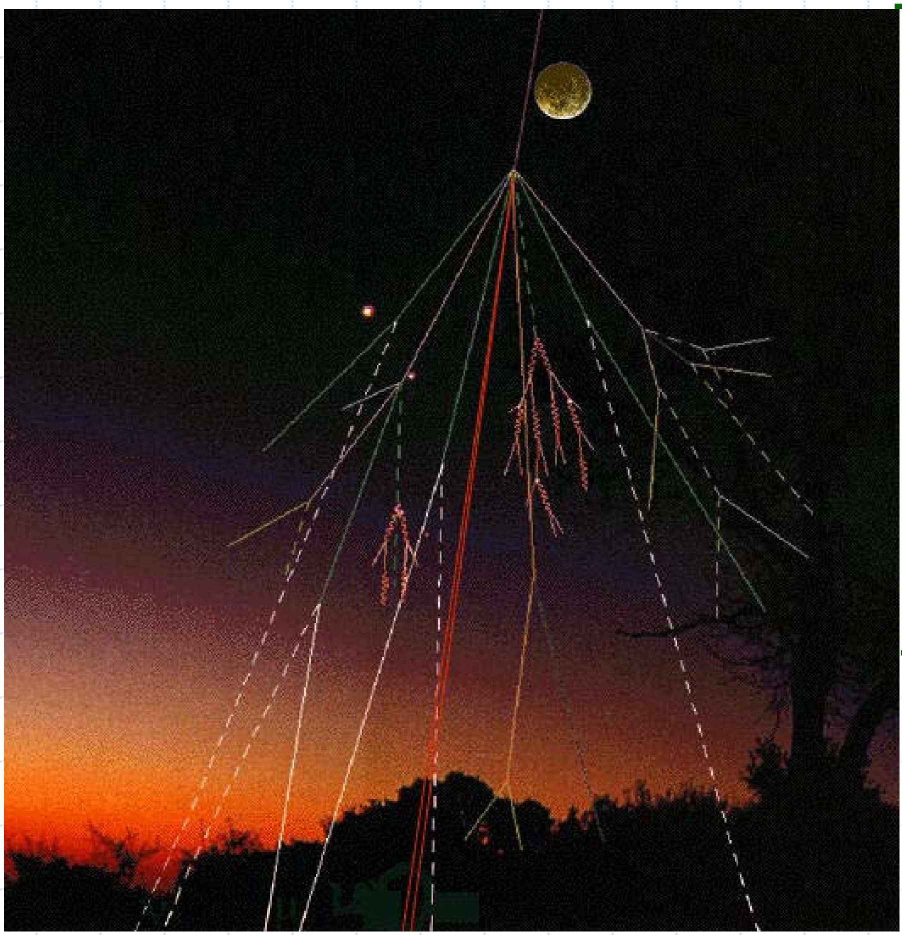
Map of H.E.S.S.-discovered gamma ray sources. The colors indicates the likely nature of sources: Supernova remnants (green), pulsar wind nebulae (violet), binaries (yellow), star cluster/star forming regions (blue), unidentified (grey), starburst galaxy (orange), active galactic nucleus (red).

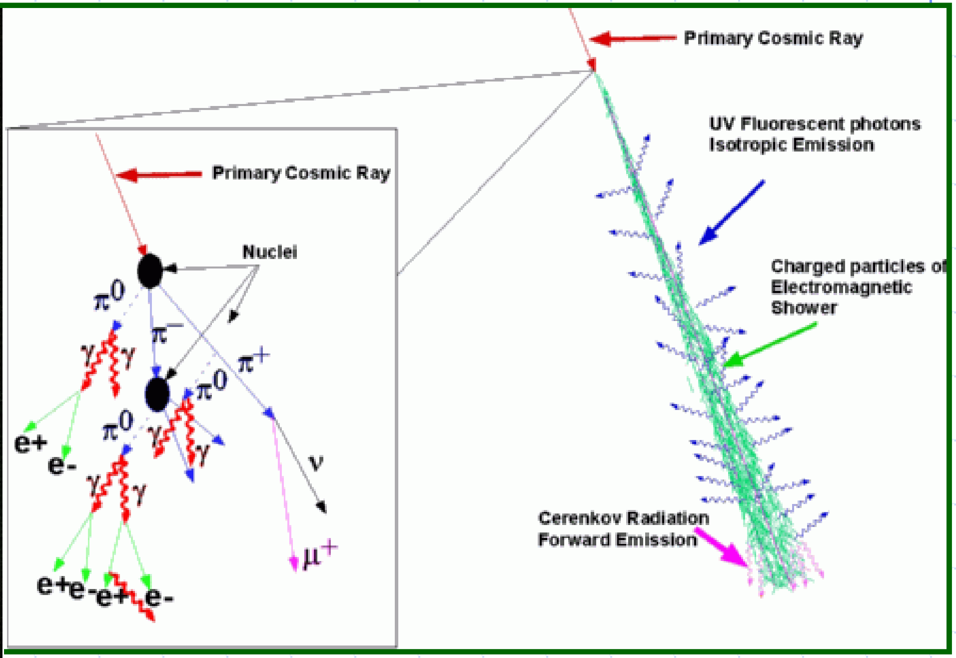
HESS gamma ray sources: Galactic plane



Charged particle detection

Measurement of extensive air showers

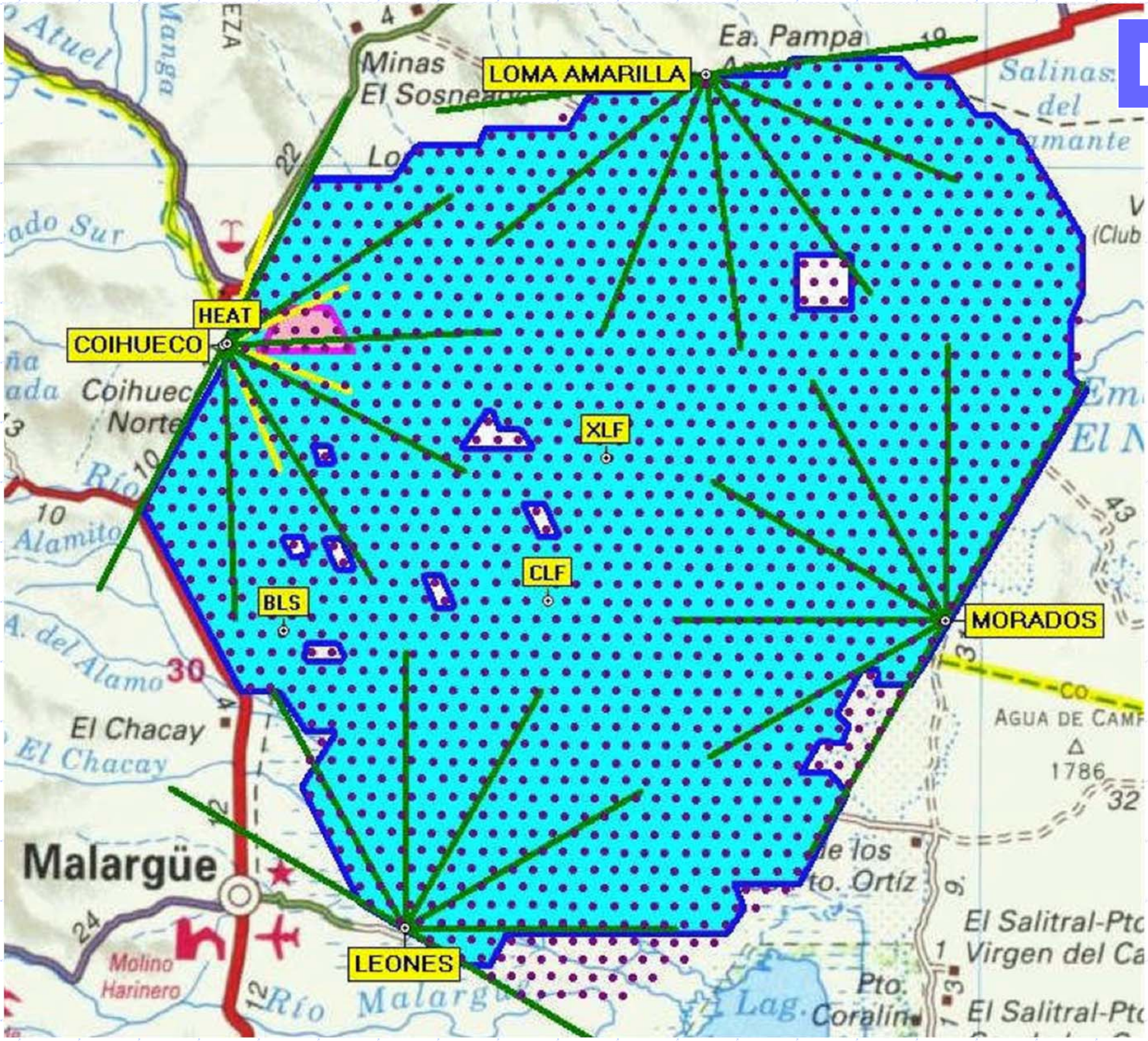




Calorimetry

- Calorimeter
  - ~ 50.000 km^3 of atmosphere
- Read out
  - Fluorescence detectors
  - Particle detector array

PIERRE AUGER OBSERVATORY



HYBRID DETECTOR

Surface Detector

- ~ 1.600 surface detectors with 1.5 km spacing

Fluorescence Detector

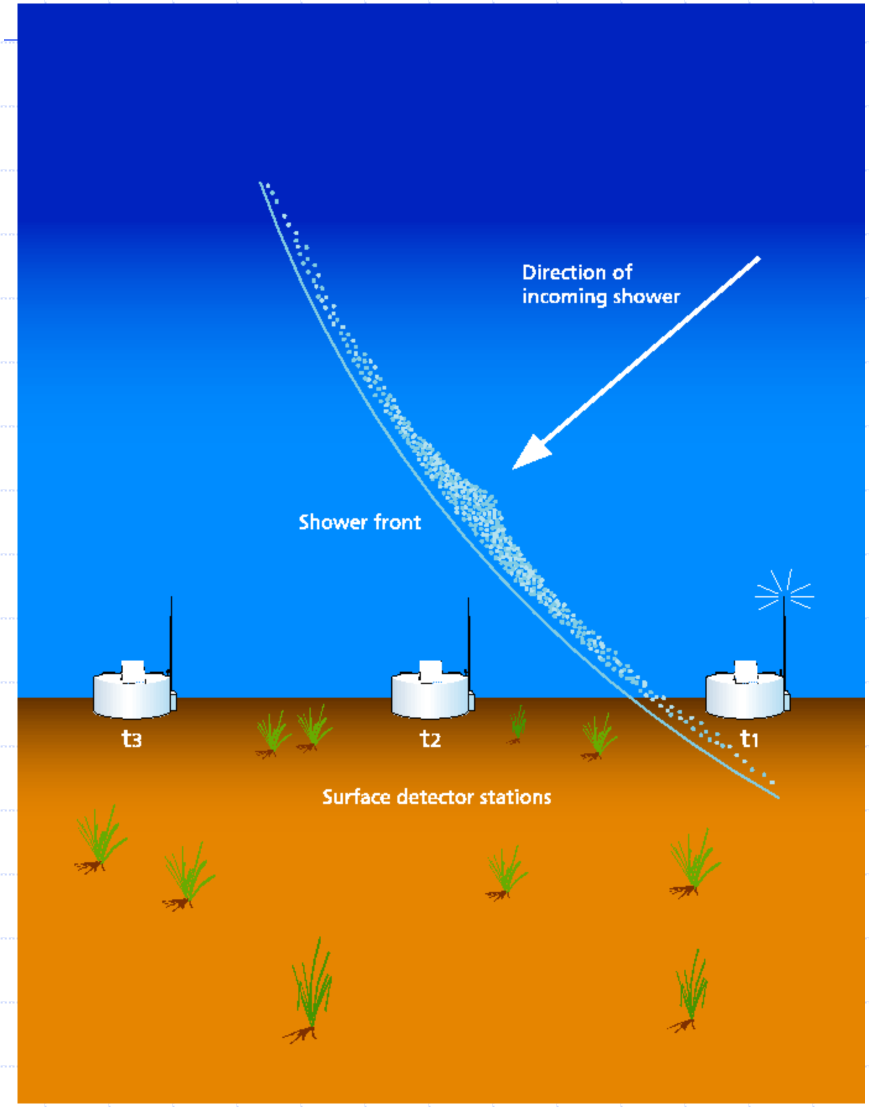
- 4 fluorescence buildings with 6 telescopes each

World largest array

- 3.000 km^2 area

SURFACE DETECTOR ARRAY

SURFACE DETECTOR ARRAY

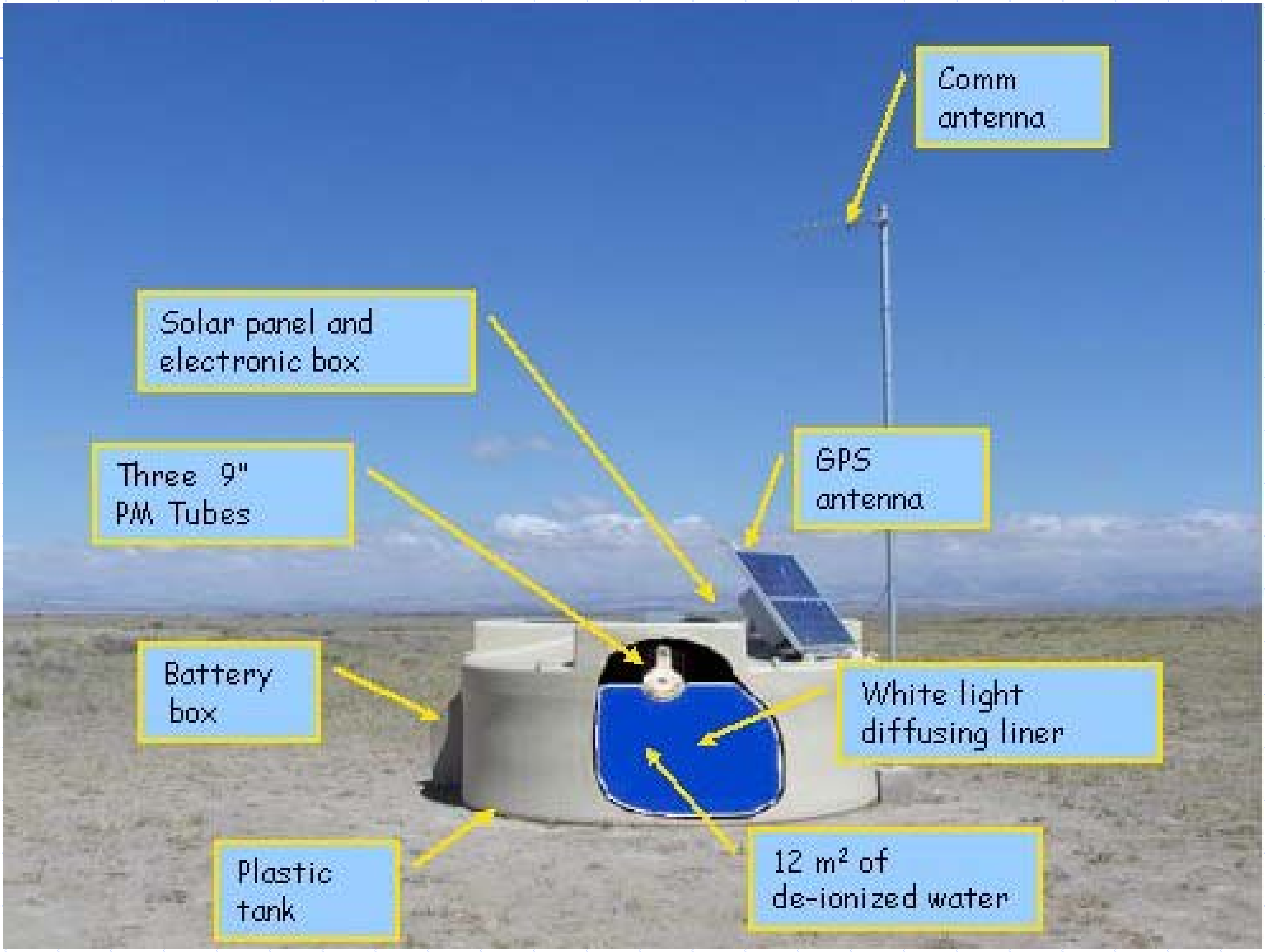


Event timing and direction determination

- Shower timing → Shower angle
- Particle density → Shower energy
- Muon number
- Muon Xmax
- Pulse rise time

→ Measure of primary mass or interaction

WATER ČERENKOV DETECTOR



FLUORESCENCE DETECTOR

- Shower ~ 90% electromagnetic
- Ionization of nitrogen measured directly

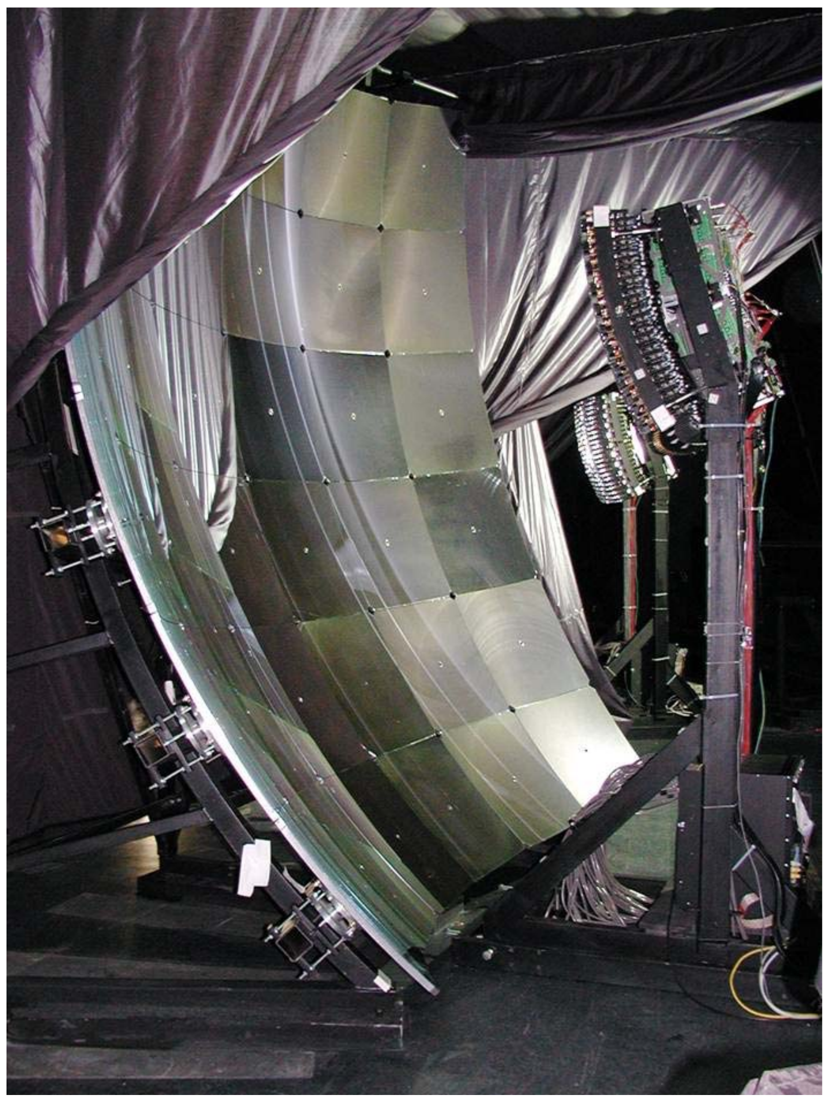
↓

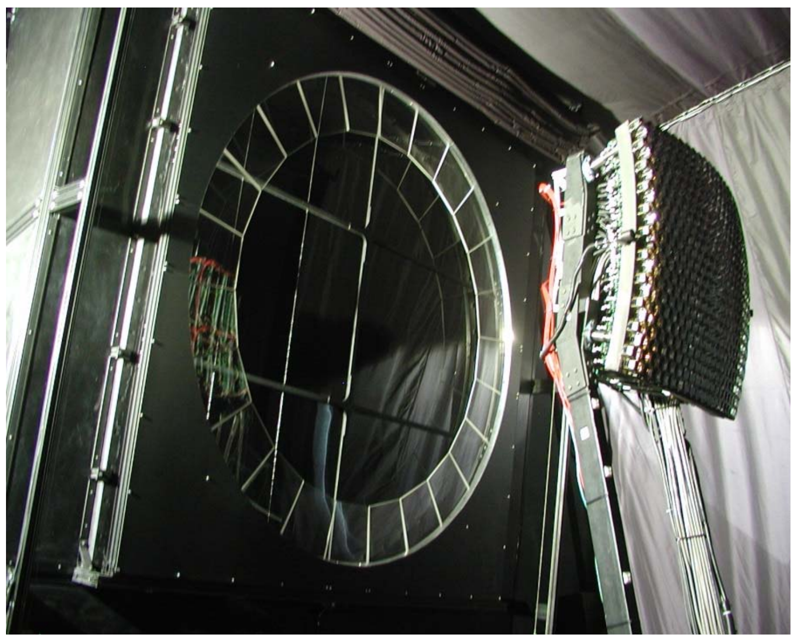
- Fast UV camera (~100 MHz)

↓

- Calorimetric energy measurement
- Measurement of shower development

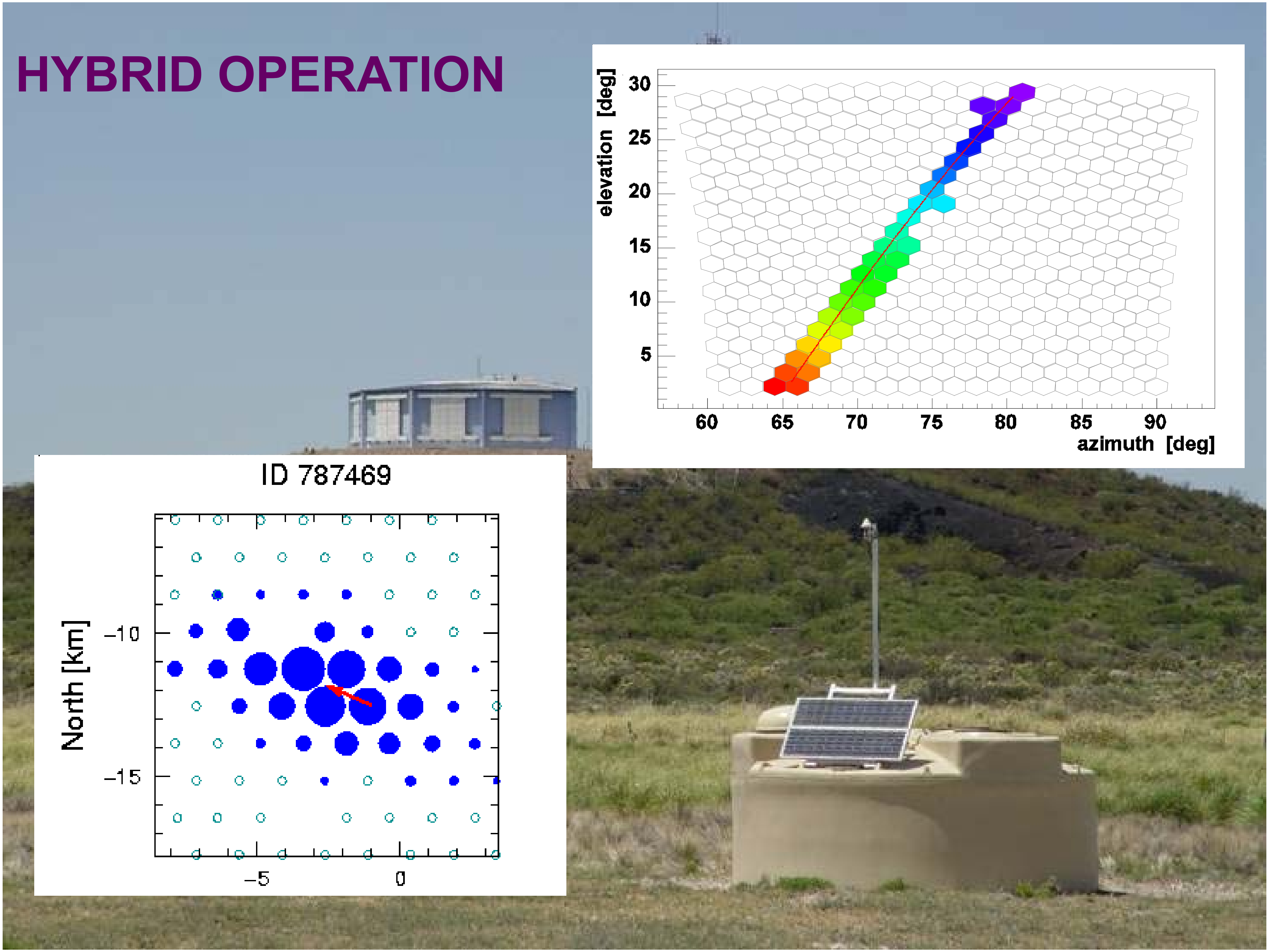
FLUORESCENCE DETECTOR



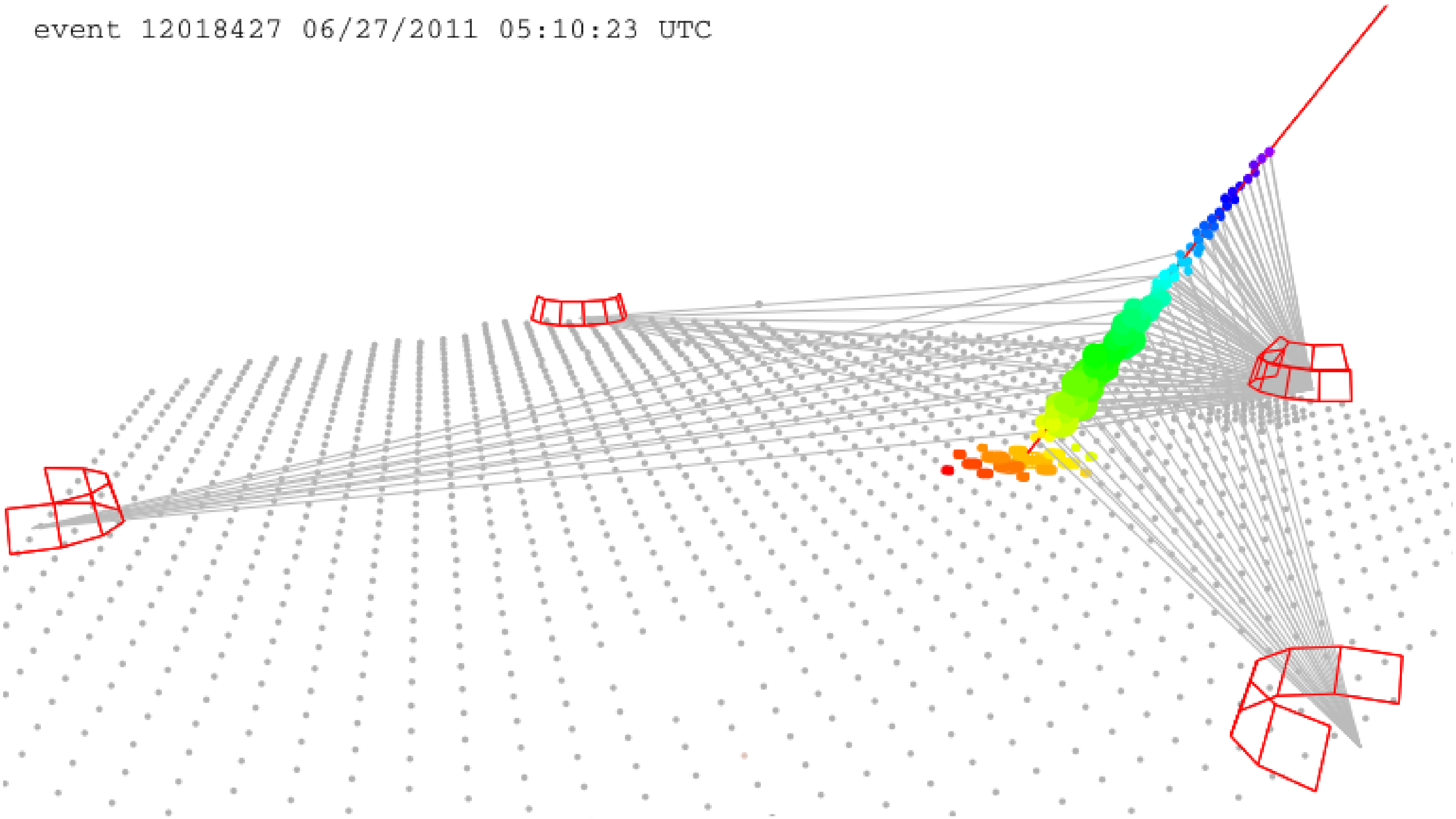


Fluorescence telescopes:
Number of telescopes: **24**
Mirrors: **3.6 m x 3.6 m with field of view 30º x 30º, each telescope is equipped with 440 photomultipliers.**

HYBRID OPERATION



HYBRID STEREO EVENT



event 12018427 06/27/2011 05:10:23 UTC

Short flight small area detectors (Balloons)
Examples of Balloon-flown RICH detectors

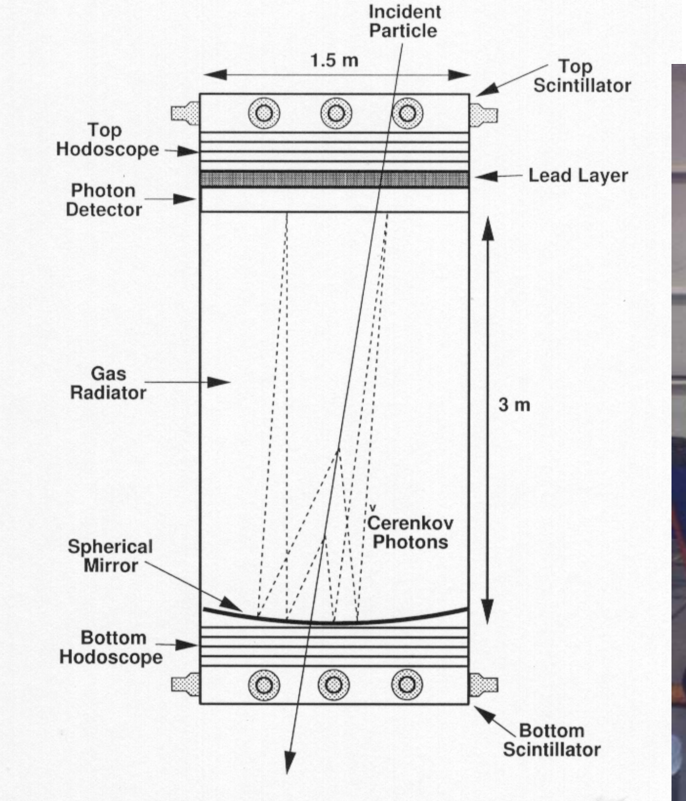
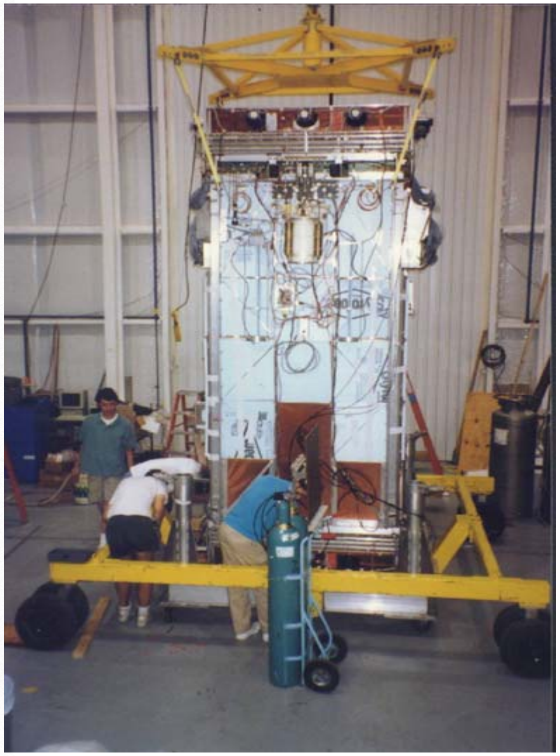
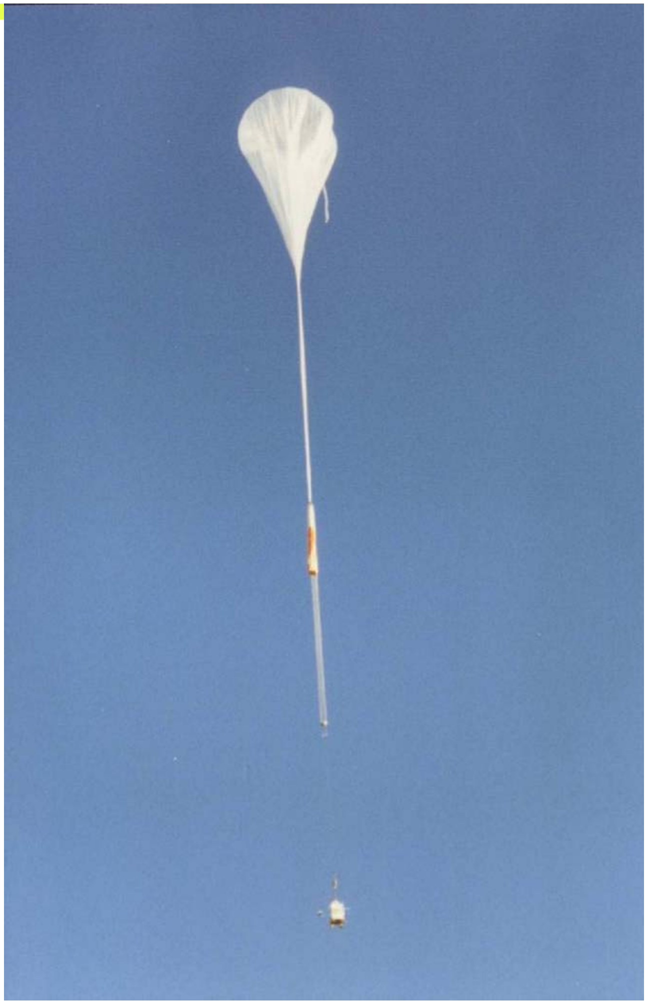
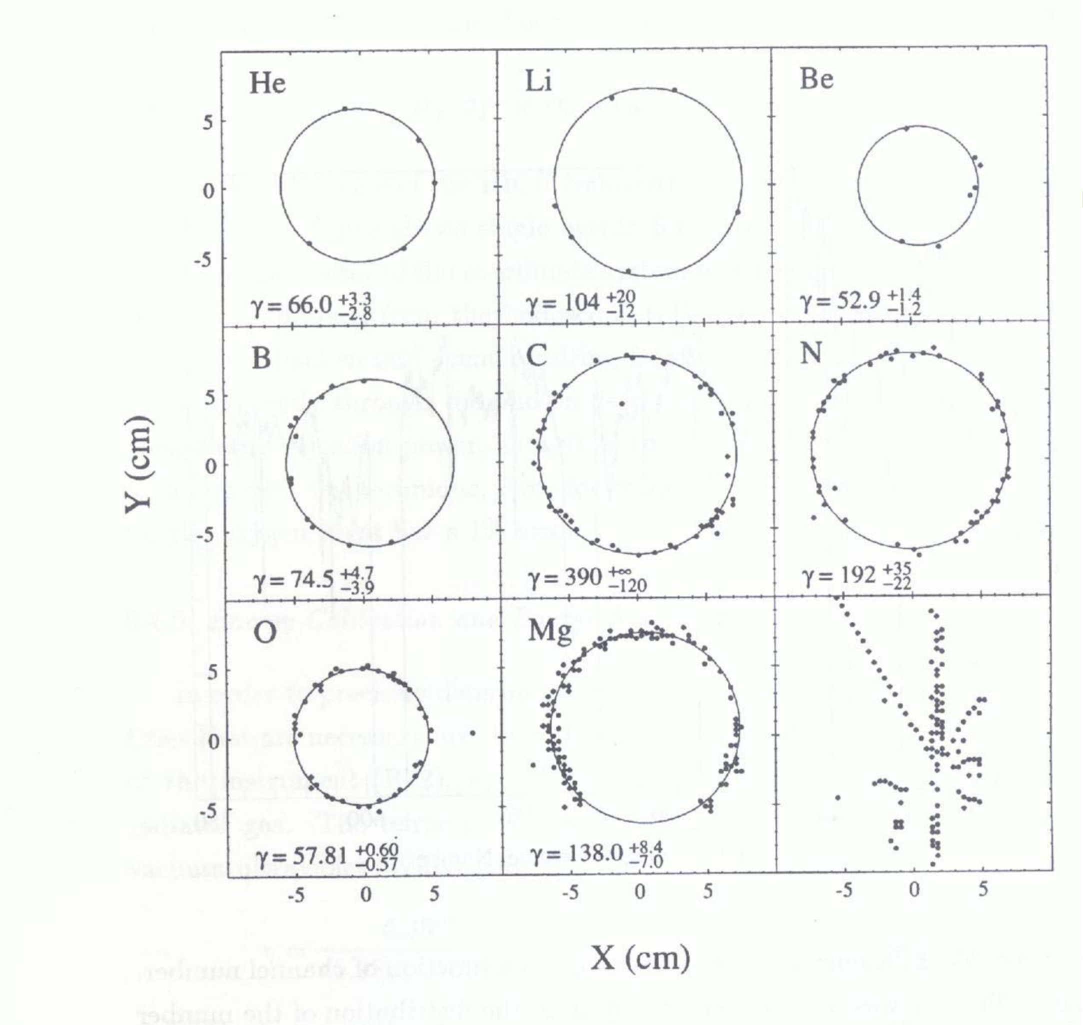


Fig. 1. Schematic cross-section of the instrument



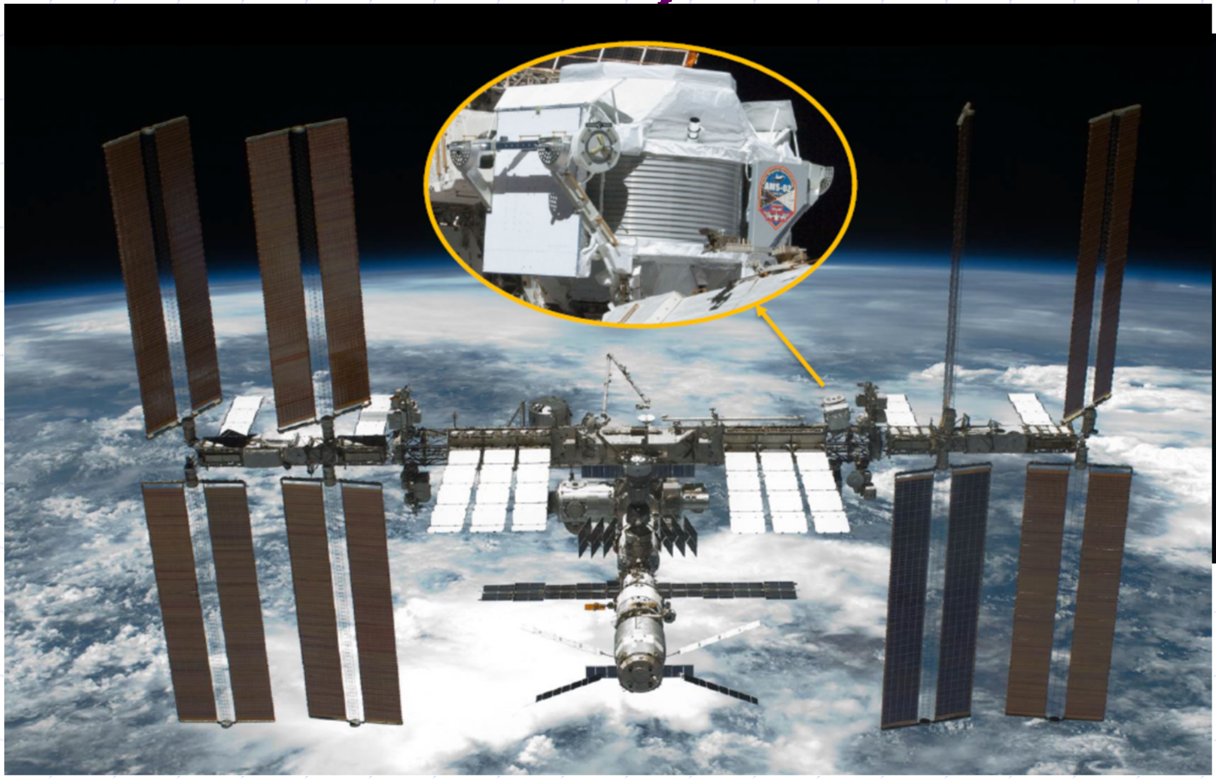




Number of Chrenkov photons: proportional to Z^2

Heavy nucleus rings from 1991 flight – Note that carbon here has total energy ~ 12*390 GeV = 4.6TeV

Cosmic ray detector at the ISS

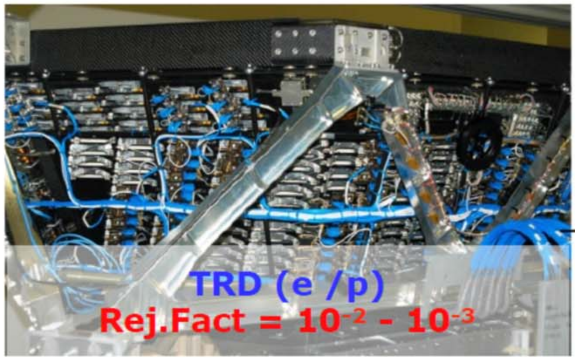


Measure:

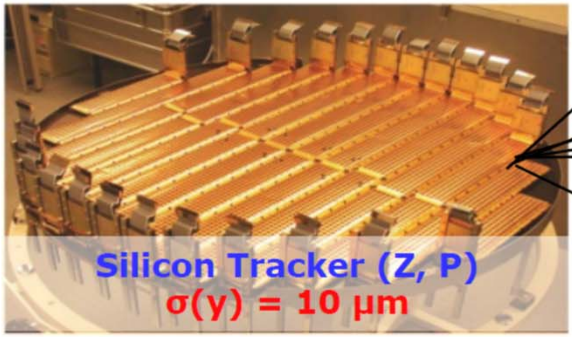
- Antimatter fluxes (antiprotons, antideuterons) – searches for new sources (e.g., dark matter annihilation)
- Isotope composition

AMS: A TeV precision, multi-purpose spectrometer

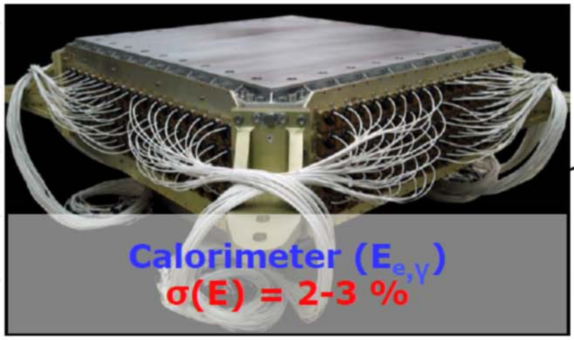
Separates hadrons from leptons, matter from antimatter and able to do CRs chemical and isotopic composition in GeV to TeV range



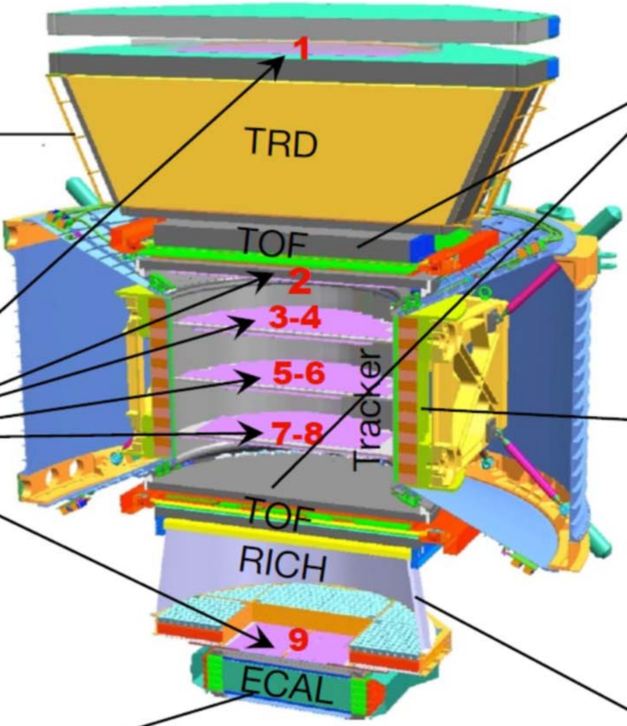
TRD (e / p)
Rej.Fact = 10^{-2} - 10^{-3}

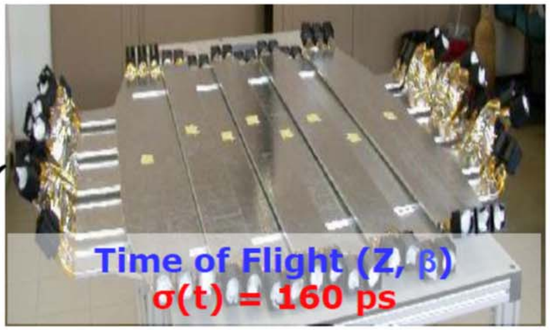


Silicon Tracker (Z, P)
$\sigma(y)$ = 10 μm

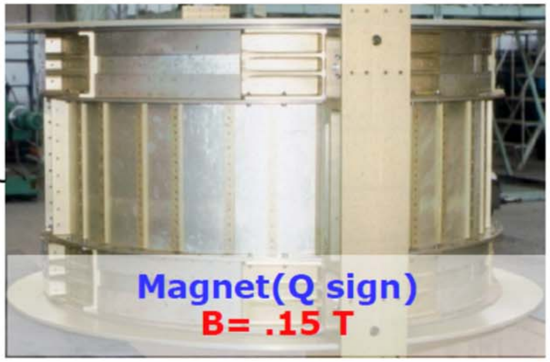


Calorimeter ($E_{e,\gamma}$)
$\sigma(E)$ = 2-3 %

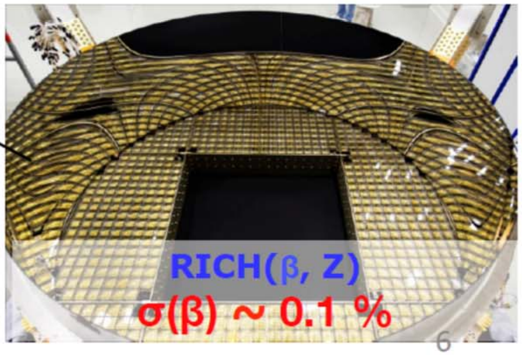




Time of Flight (Z, β)
$\sigma(t)$ = 160 ps



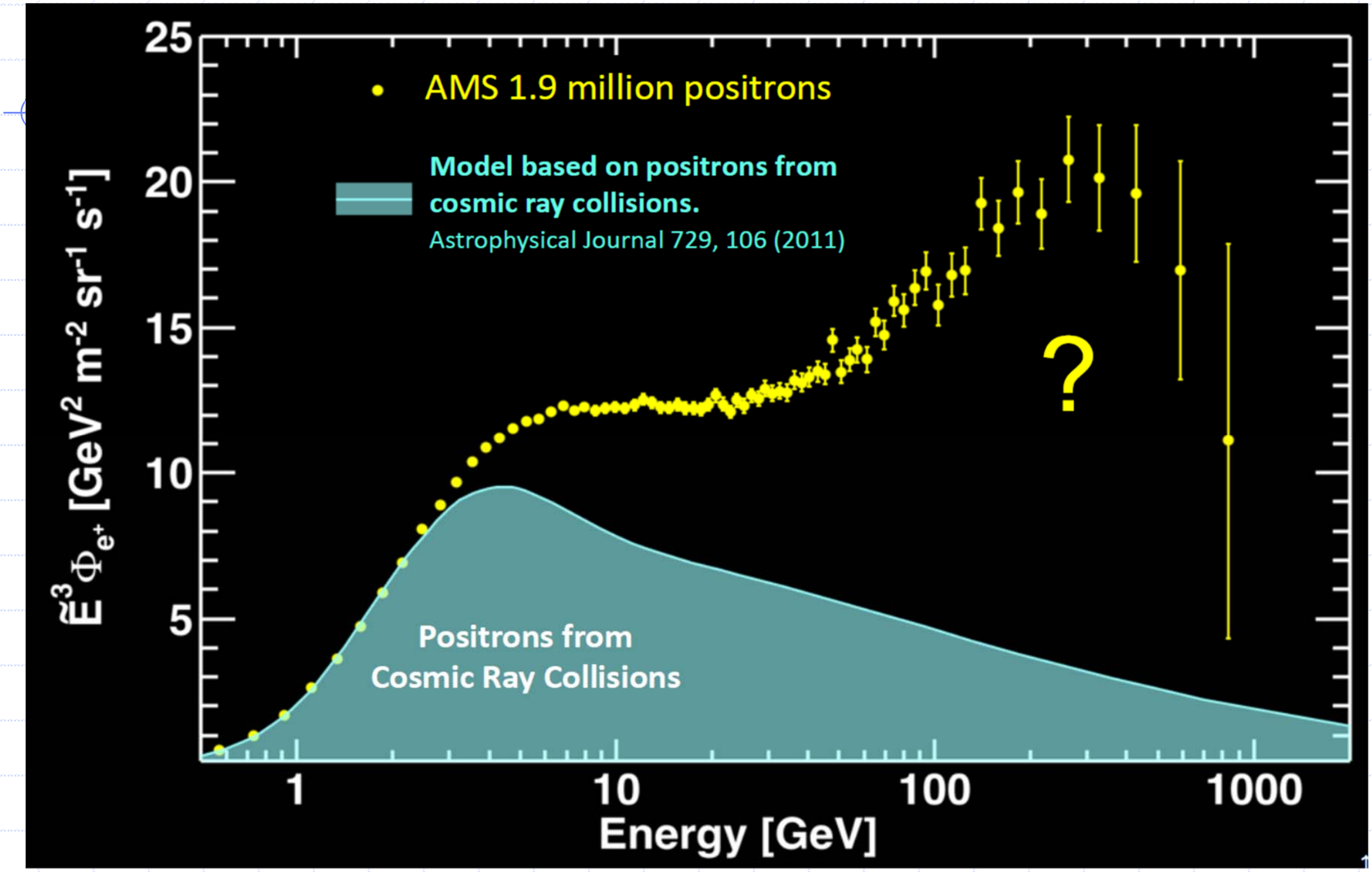
Magnet(Q sign)
B= .15 T



RICH(β, Z)
$\sigma(\beta) \sim 0.1$ %

Multiple and independent measurement of Charge (Z), Energy (β,p,E) and Q sign (±).

AMS: studies of antimatter in cosmic rays



Intriguing result: surplus of positrons at high energies up to 1T

→ Source still to be understood. Dark matter annihilation?

Neutrino detection

Use inverse beta decay

$\nu_e + n \rightarrow p + e^-$

$\bar{\nu}_e + p \rightarrow n + e^+$

$\nu_\mu + n \rightarrow p + \mu^-$

$\bar{\nu}_\mu + p \rightarrow n + \mu^+$

$\nu_\tau + n \rightarrow p + \tau^-$

$\bar{\nu}_\tau + p \rightarrow n + \tau^+$

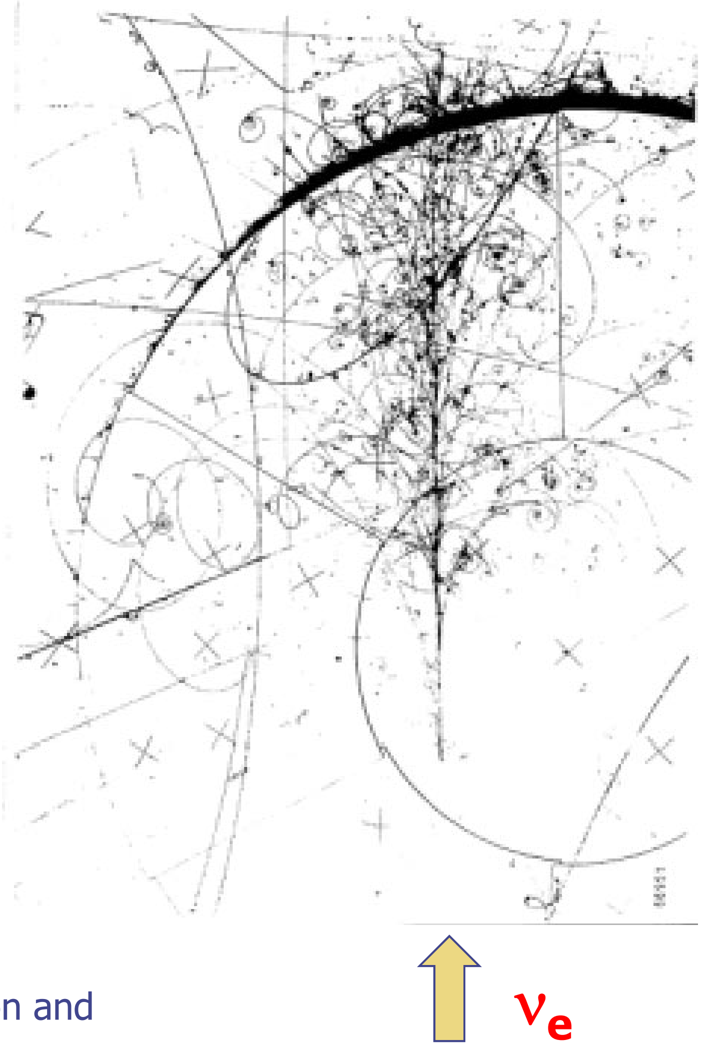
However: cross section is very small!

$6.4\ 10^{-44}\ \mathrm{cm}^2$ at 1MeV

Probability for interaction in 100m of water = $4\ 10^{-16}$

Electron neutrino detected in a bubble chamber

Electron neutrino produces an electron, which then starts a shower. Tracks of the shower are curved in the magnetic field.



Which type of neutrino?

Identify the reaction product, e,μ,τ, and its charge.

Water detectors (e.g. Superkamiokande)

muon: a sharp Cherenkov ring

electron: Cherenkov ring is blurred (e.m. shower development)

tau: decays almost immediately – after a few hundred microns to one or three charged particles

High energy neutrinos

Interaction cross section:

Neutrinos:

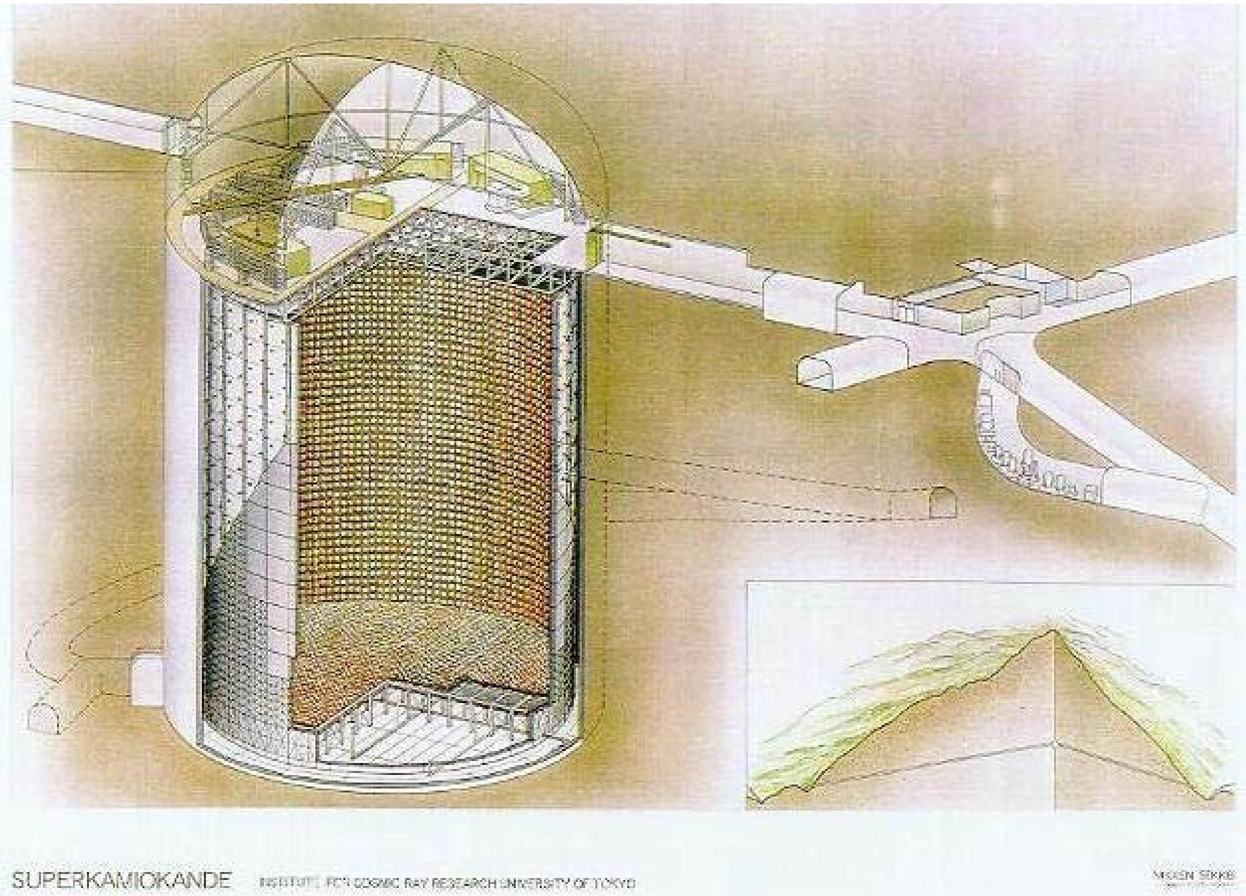
$0.67\ 10^{-38}$ E/1GeV cm^2 per nucleon

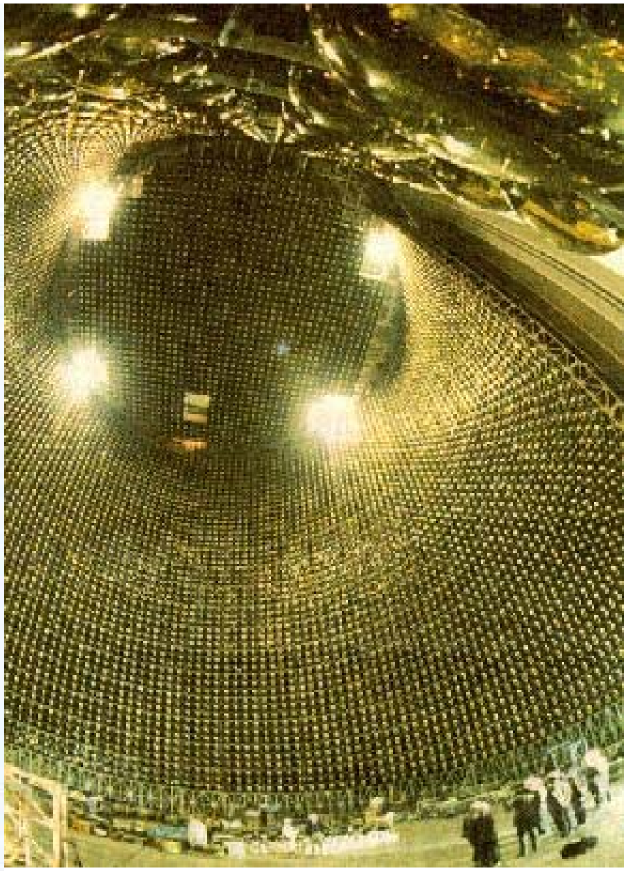
Antineutrinos:

$0.34\ 10^{-38}$ E/1GeV cm^2 per nucleon

At 100 GeV, still 11 orders below the proton-proton cross section

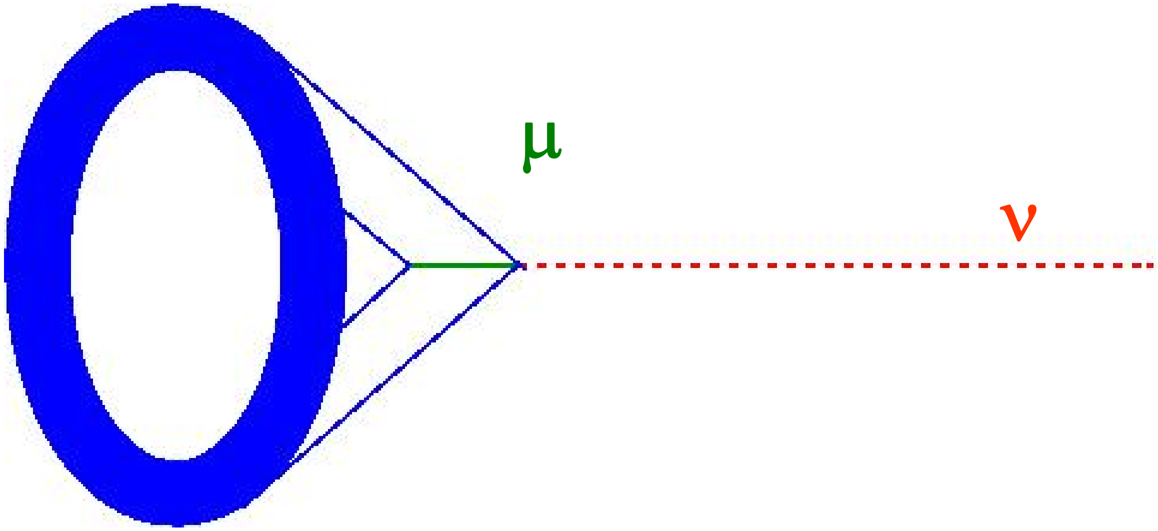
Superkamiokande: an example of a neutrino detector





Superkamiokande: detection of electrons and muons

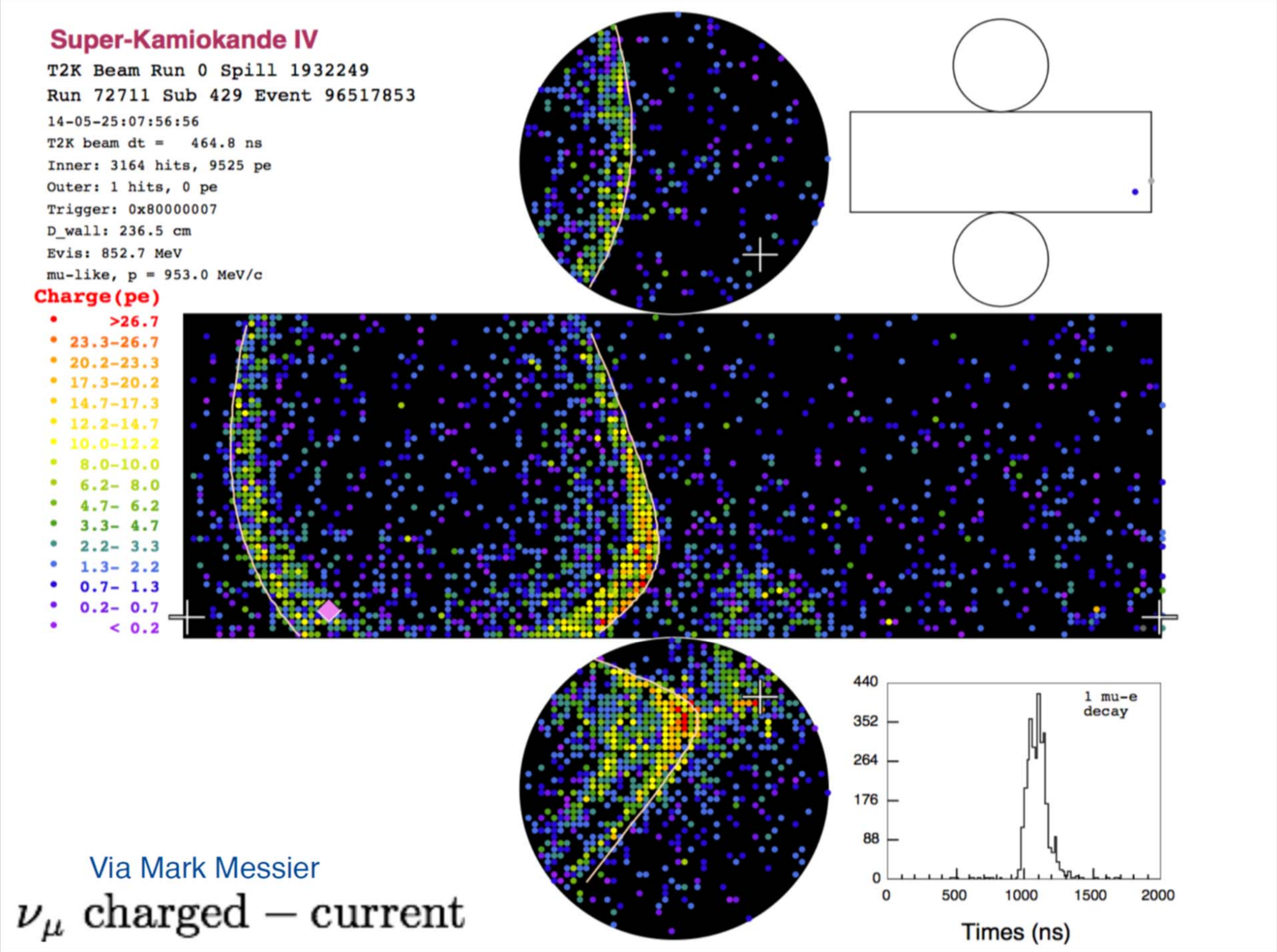
How to detect muons or electrons? Again through Cherenkov radiation, this time in the water container. Neutrino turns into an electron or muon.



Muons and electrons emit Cherekov photons
→ ring at the container wals

- Muon ring: sharp edges
- Electron ring: blurred image (bremstrahlung)

Muon event: photon detector, cillinder walls



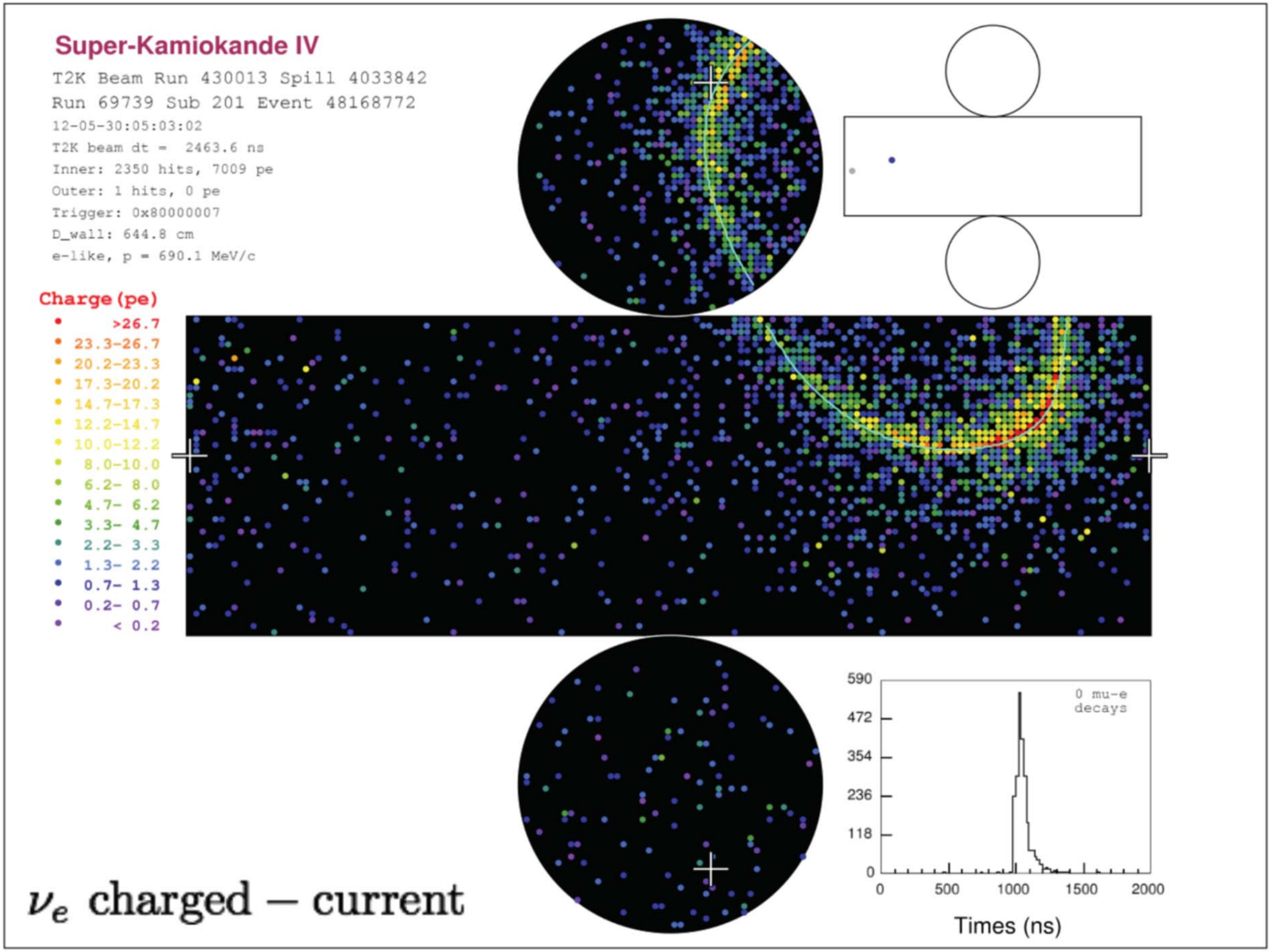
Super-Kamiokande IV

T2K Beam Run 0 Spill 1932249
Run 72711 Sub 429 Event 96517853
14-05-25:07:56:56
T2K beam dt = 464.8 ns
Inner: 3164 hits, 9525 pe
Outer: 1 hits, 0 pe
Trigger: 0x80000007
D_wall: 236.5 cm
Evis: 852.7 MeV
mu-like, p = 953.0 MeV/c

Via Mark Messier

ν_μ charged − current

Electron event: blurred ring



ν_e charged – current

Detection of very high energy neutrinos (from galactic sources)

The expected fluxes are very low:

Need really huge volumes of detector medium!

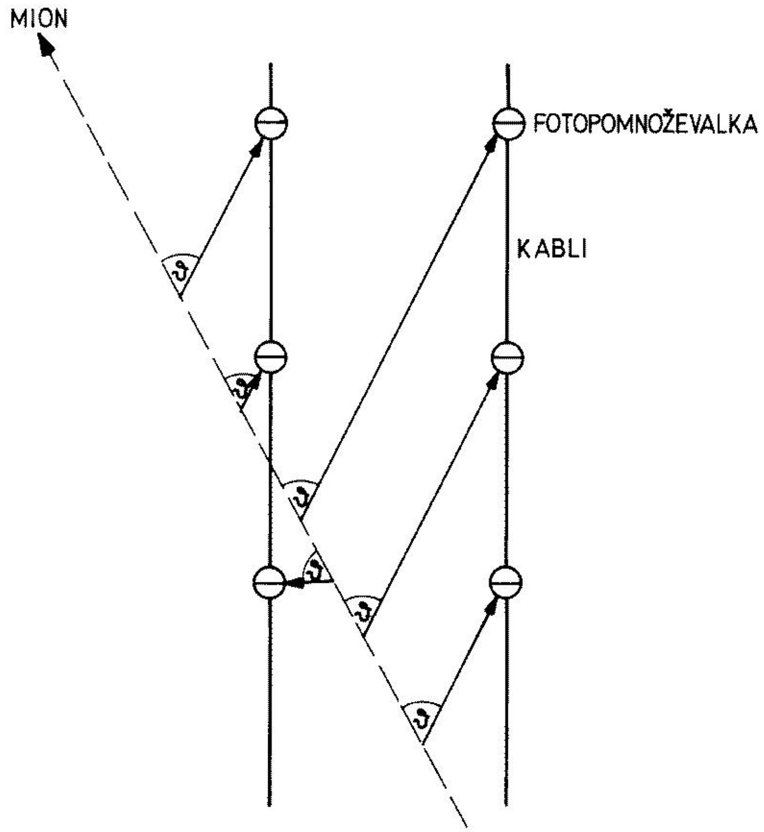
What is huge? From $(100\mathrm{m})^3$ to $(1\mathrm{km})^3$

Also needed: directional information.

Again use: $\nu_\mu + n \rightarrow p + \mu^-$; μ direction coincides with the direction of the high energy neutrino.

Reconstruction of neutrino direction and energy

- Reconstruction of direction and energy of an incident high energy muon neutrino:
- Measure time of arrival on each of the tubes
- Cherenkov angle is known: $\cos\theta = 1/n$
- Reconstruct muon track
- Track direction -> neutrino direction
- Track length -> neutrino energy



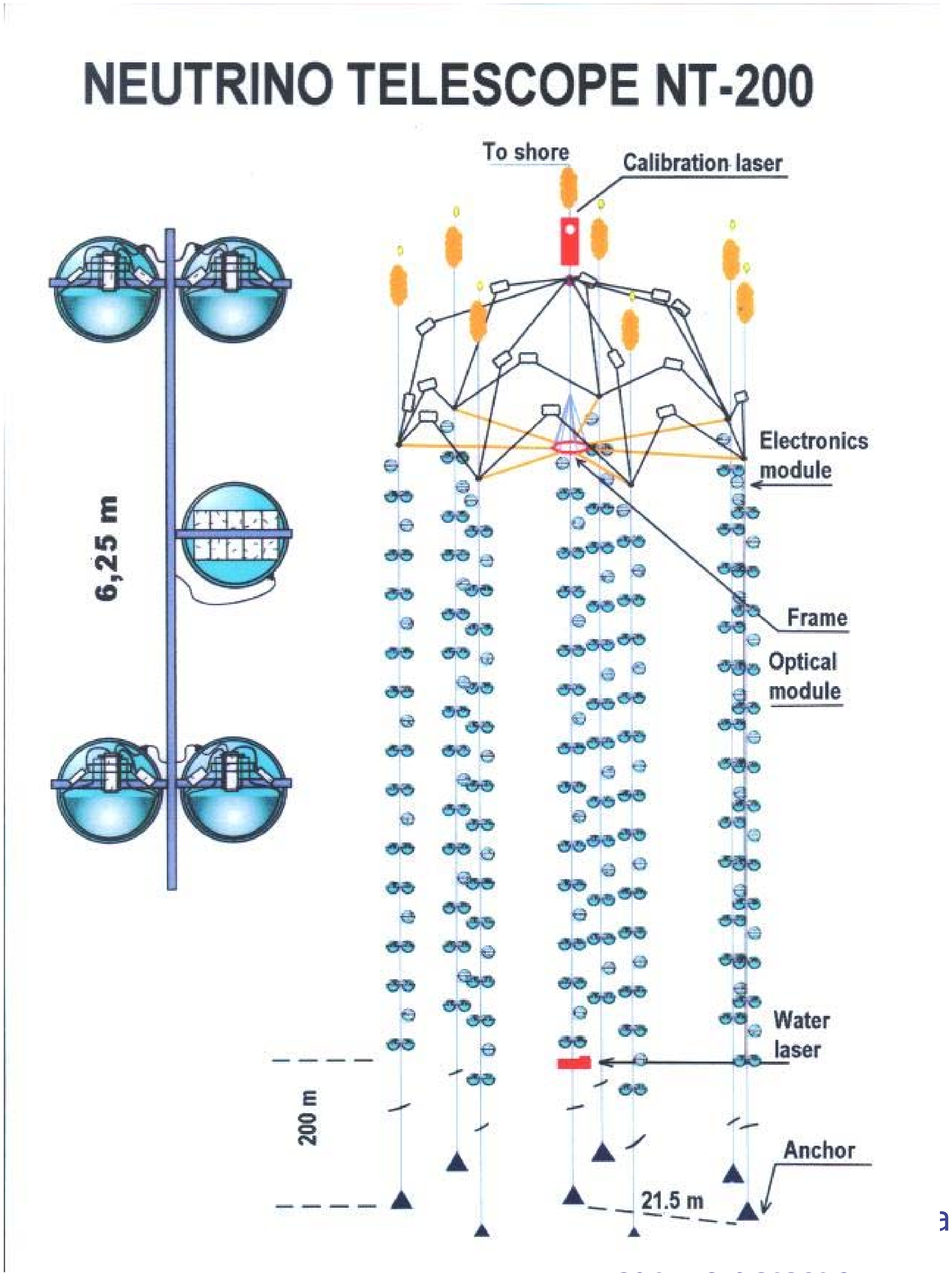
Neutrino detection arrays in water

Similar geometry can be used in a water based detector deep below the sea surface (say around 4000m)

- ANTARES (Marseille)
- Nestor (Pylos, SW Pelophonysos)
- Lake Baikal
- DUMAND (Hawaii) - stoped

Problems: bioluminescence, currents, waves (during repair works)

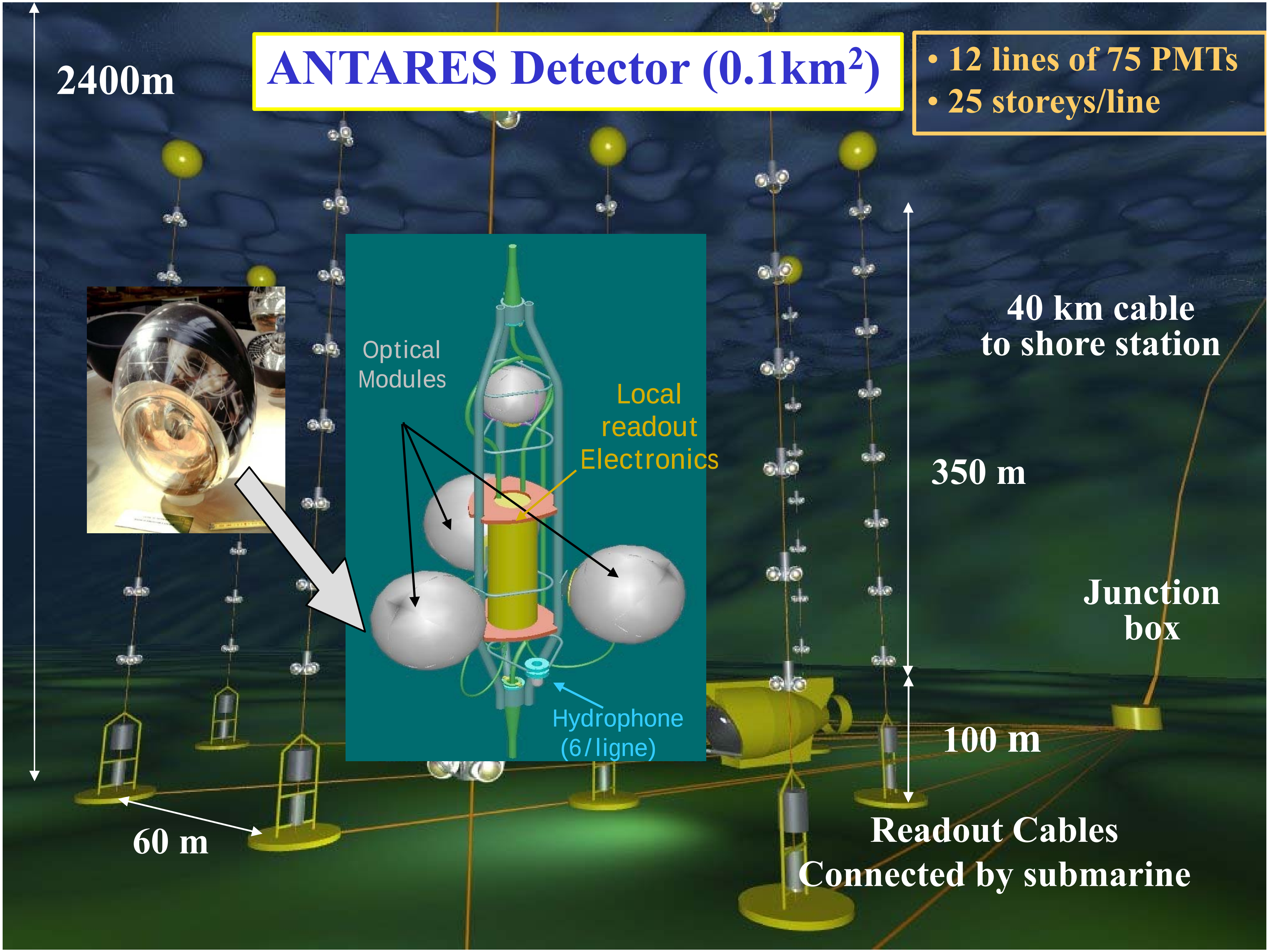
Lake Baikal: deployment, repair works: in winter, from the ice cover


NEUTRINO TELESCOPE NT-200
To shore
Calibration laser
6,25 m
Electronics module
Frame
Optical module
Water laser
200 m
Anchor
21.5 m

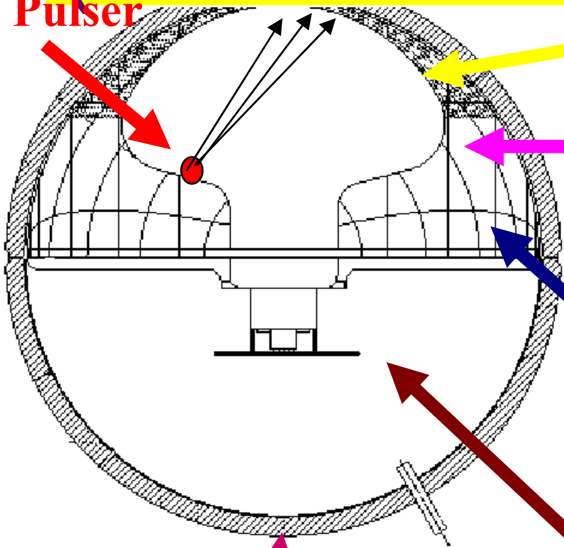
and

ANTARES Detector (0.1km^2)

- 12 lines of 75 PMTs
- 25 storeys/line

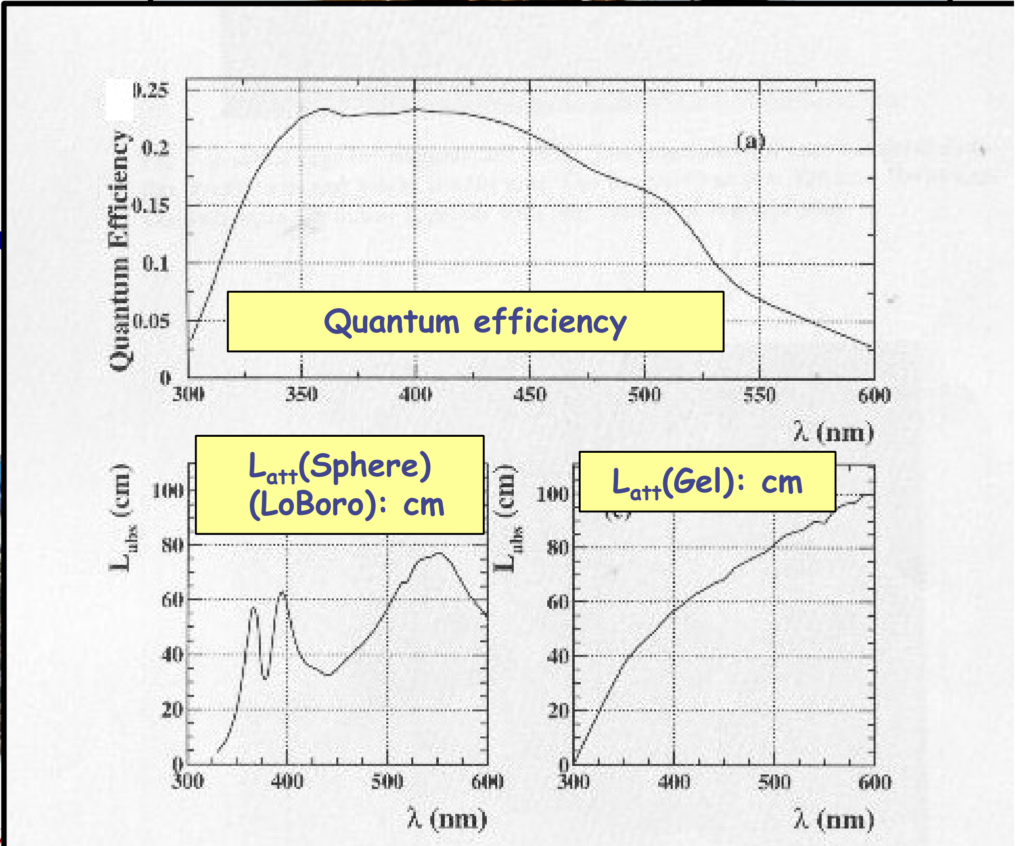


Generic Optical Module Components (from ANTARES)



LED Pulser

Optical coupling & (almost) index-matching gel



Quantum efficiency

L_{att}(Sphere) (LoBoro): cm

L_{att}(Gel): cm

Efficiency:(quantum ⊕ collection)>16%;

Glass Pressure Sphere

Activ

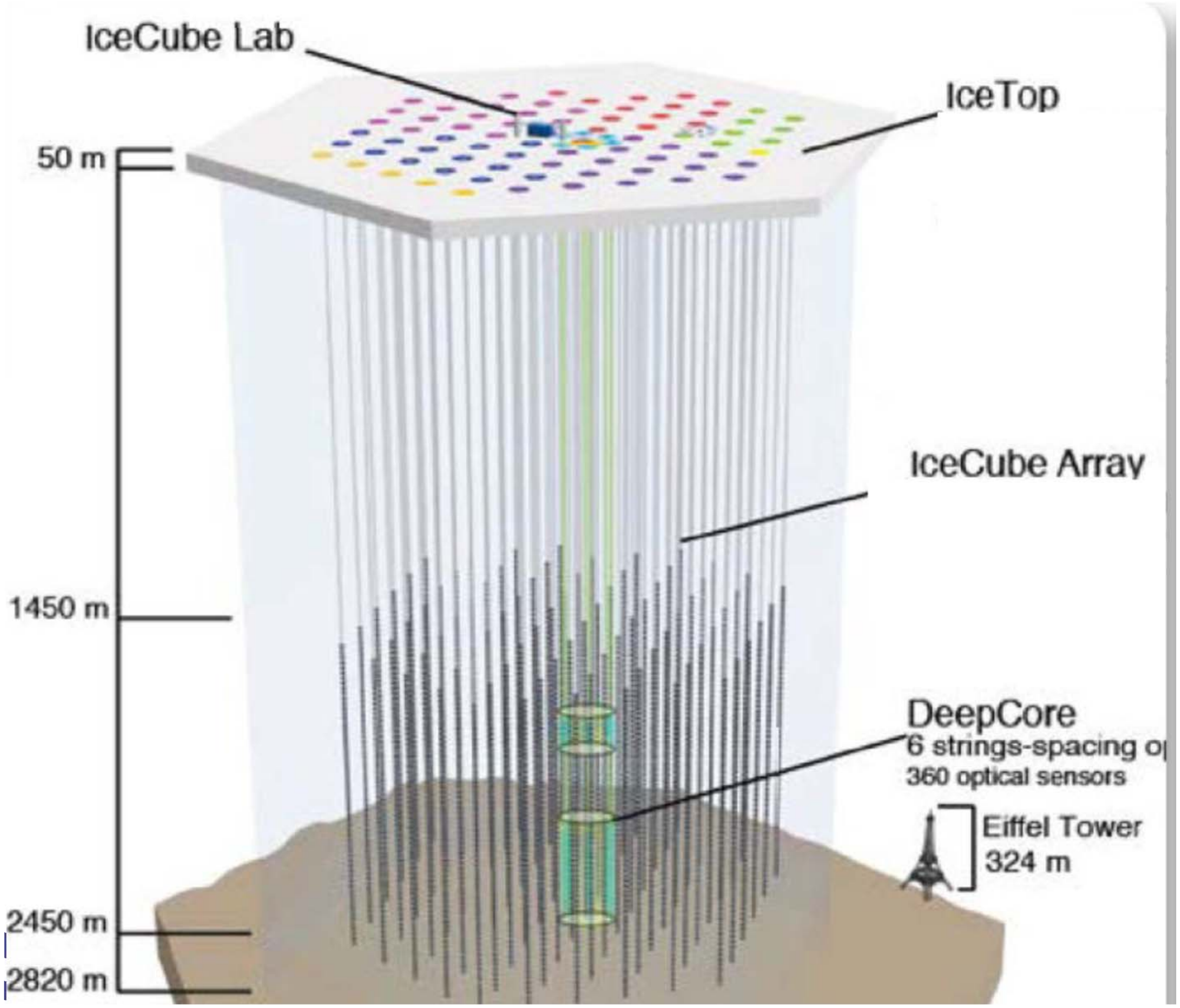
(Cock

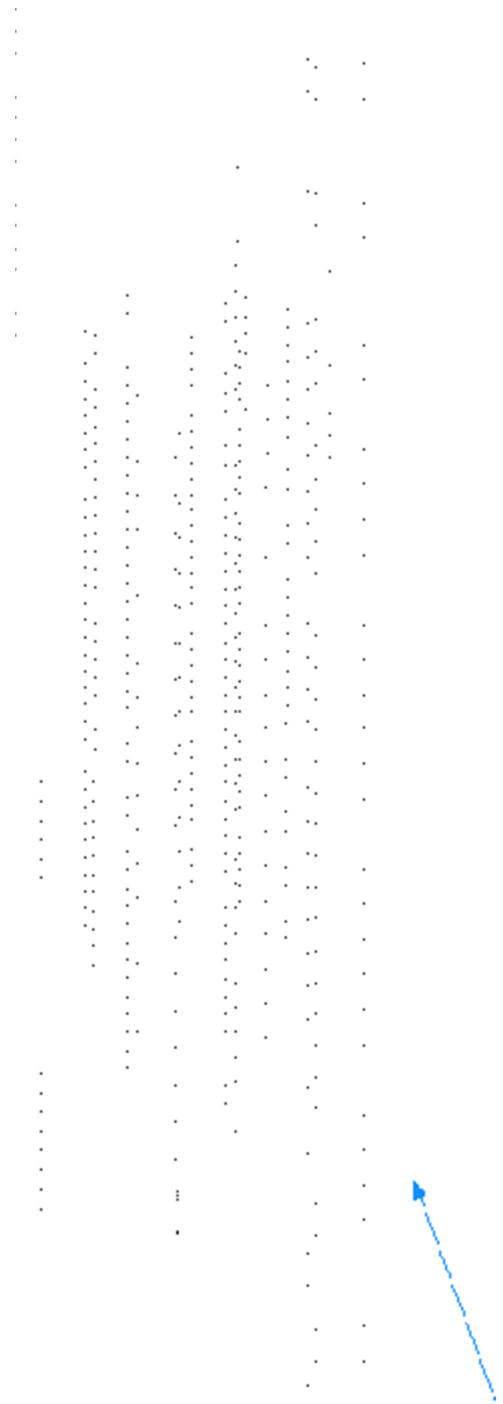
neutr

Use the Antarctic ice instead of water

Normal ice is not transparent due to Rayleigh scattering on inhomogenuities (air bubbles)

At high pressures (large depth) there is a phase transition, bubbles get partly filled with water → transparent!



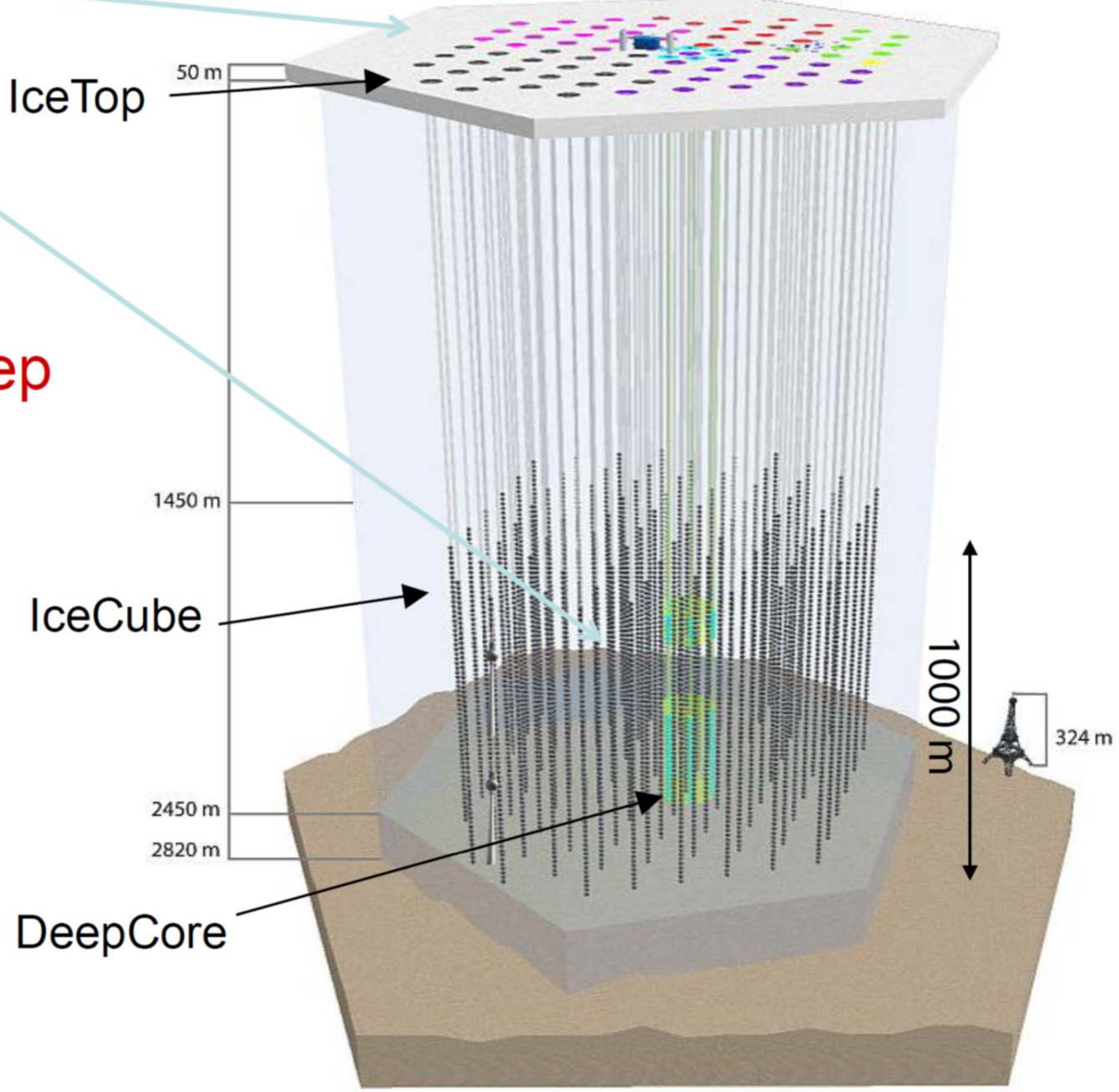


Example of a detected event, a muon entering the PMT array from below

IceCube

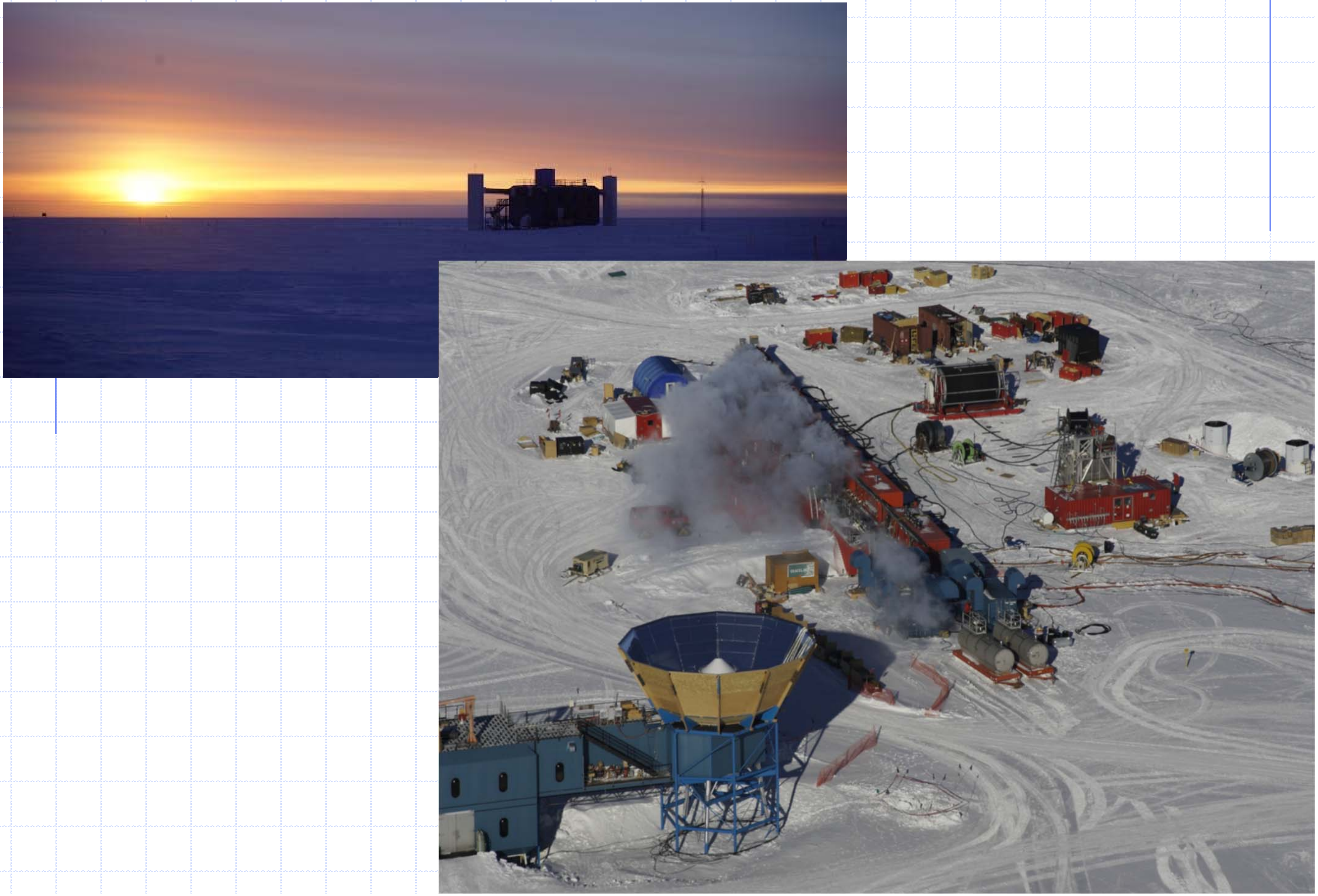
air shower array

gigaton-scale neutrino telescope

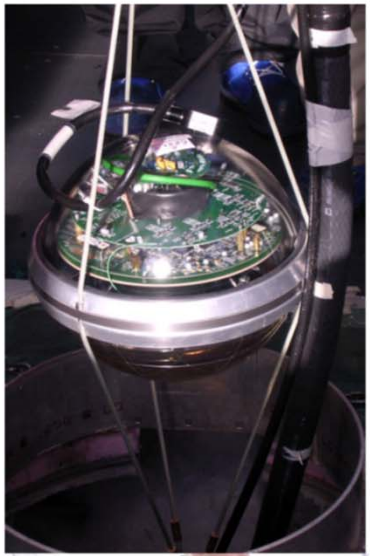


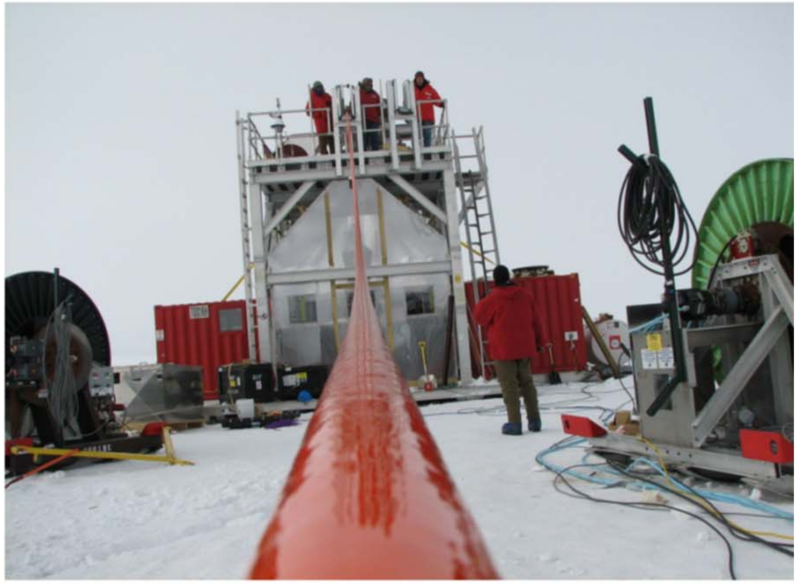
- 86 Strings, 2450 m deep
- 5160 Optical Modules
- Instrumented: 1 km^3
- IceTop: 1 km^2
- Installation: 2005-2011

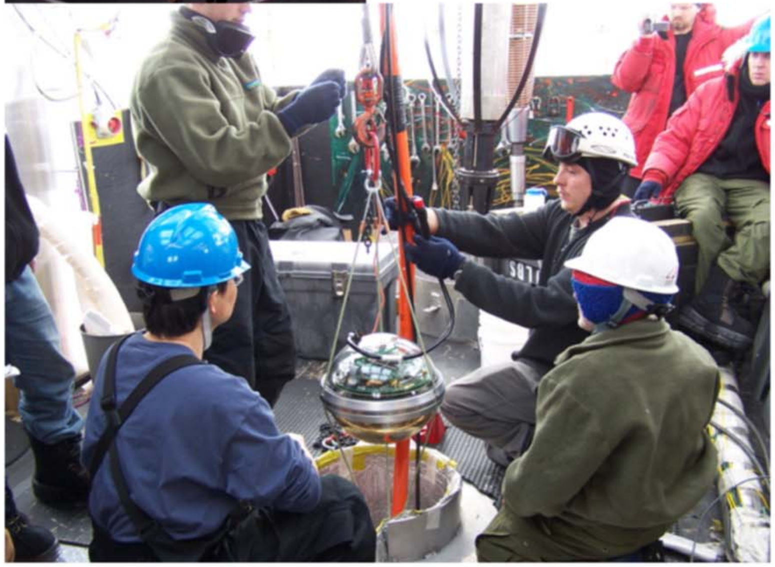
Ice Cube Neutrino Observatory

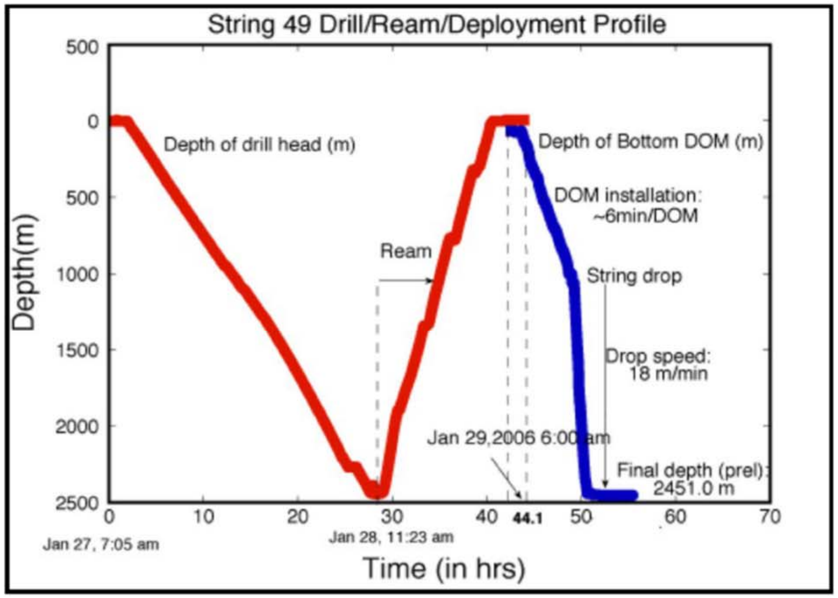


Deployment



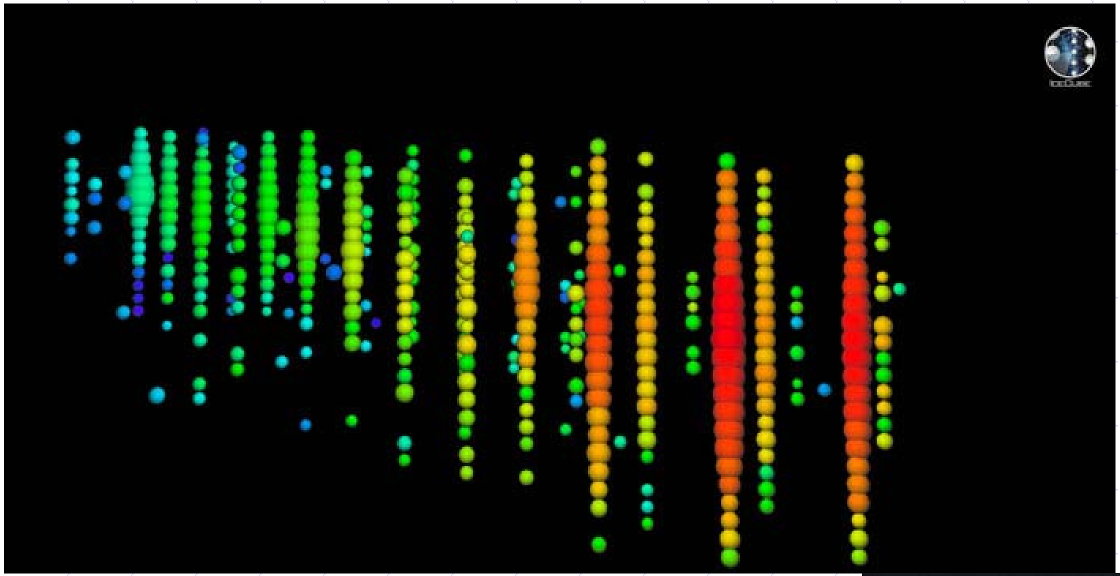






99% of DOMs survive deployment and freeze-in

A very-high energy neutrino detected in the Ice Cube

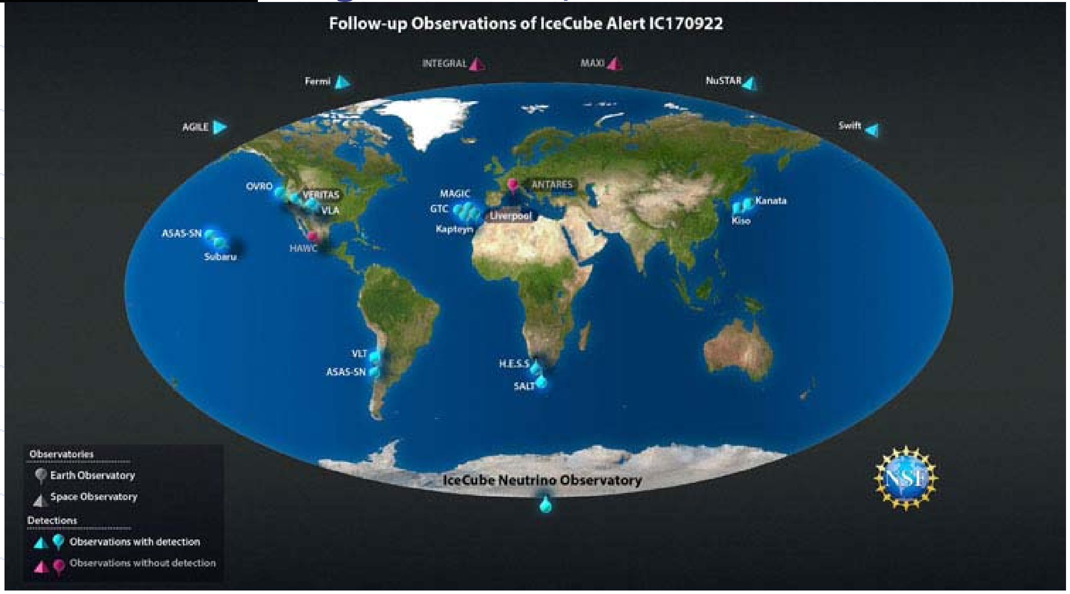


High-energy neutrino detected by IceCube on Sept. 22, 2017, shows a muon, created by the interaction of a neutrino with the ice very close to IceCube, which leaves a track of light while crossing the detector. In this display, the light collected by each sensor is shown with a colored sphere. The color gradient, from red to green/blue, show the time

Follow up observations with gamma ray detectors, optical and radi-telescopes

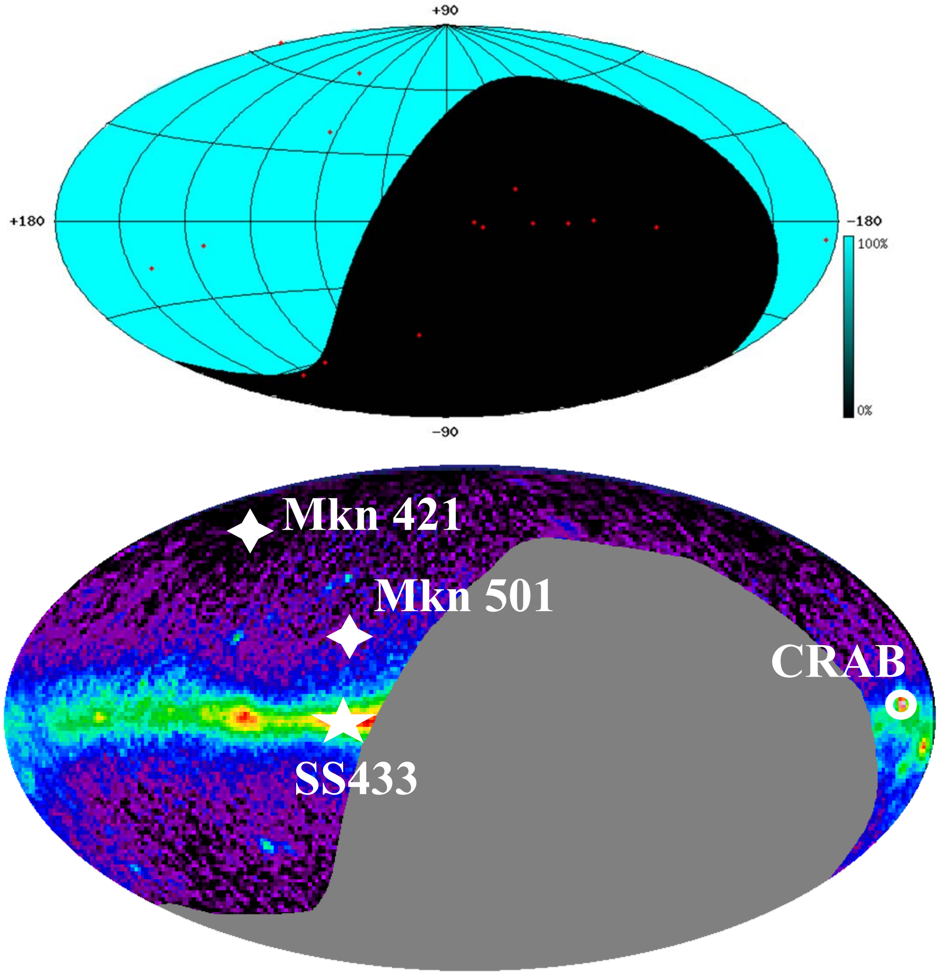
→

Source: Blazar TXS 0506+056, a powerfull cosmic accelerator

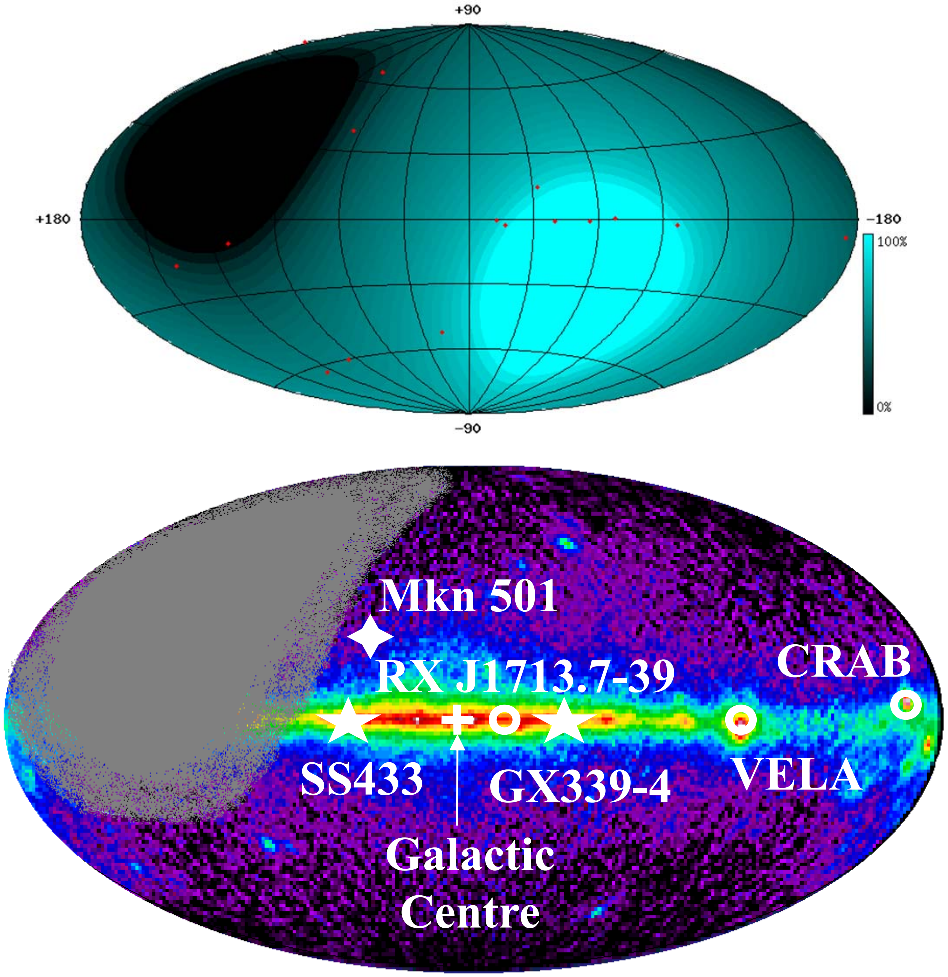


Region of sky observable by Neutrino Telescopes

Ice Cube (South Pole)



ANTARES (43° North)



Backup slides