Outline

- Cherenov detectors in APP:

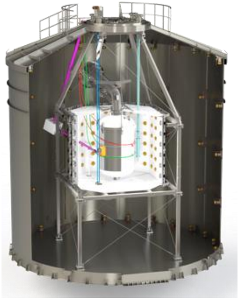
  Xenon Muon veto

RICH:	Super/Hyper – Kamiokande HAWC, LHAASO, SWGO, PAO
(S)IACT:	Hegra, Veritas, Cangaroo, Magic, Hess, CTA
Neutrino Telescopes:	Bakal GVD, Antares, IceCube, KM3NeT

  Radio Cherenkov

- Medical physics

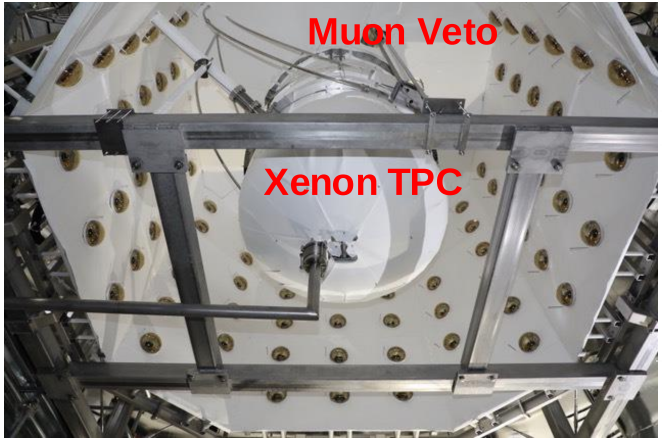
Dark Matter detectors: XENON muon veto

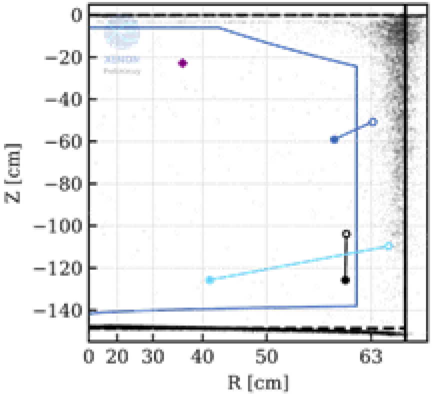


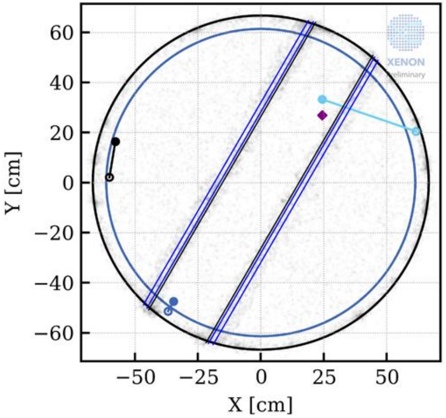
- Dual phase TPC to Search for Nuclear Recoil (NR) events generated by DM interaction on LXe
- nVeto used to tag multiple and single scatter NR events in the TPC
- data-driven estimation of the neutron background

120 x 8” high-QE low-radioactivity PMTs installed in water 1m away from the cryostat

High-reflectivity ePTFE panels confine nVeto region (33 m^3) with large light-collection efficiency







LED calibrations for PMT gain check
Laser calibrations for transparency monitor

RICH deep underground

Early 1980's Kamiokande and IMB

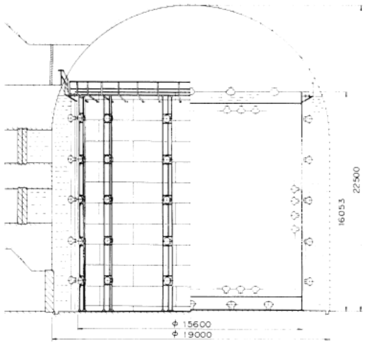
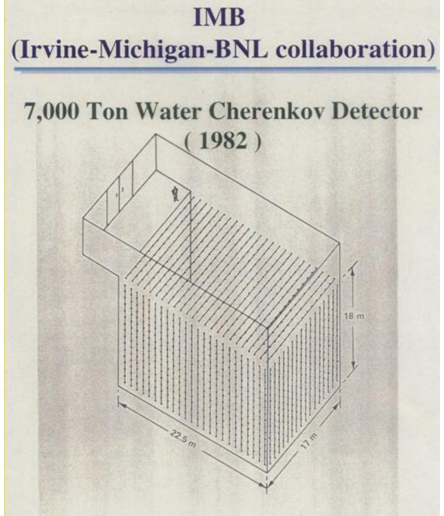
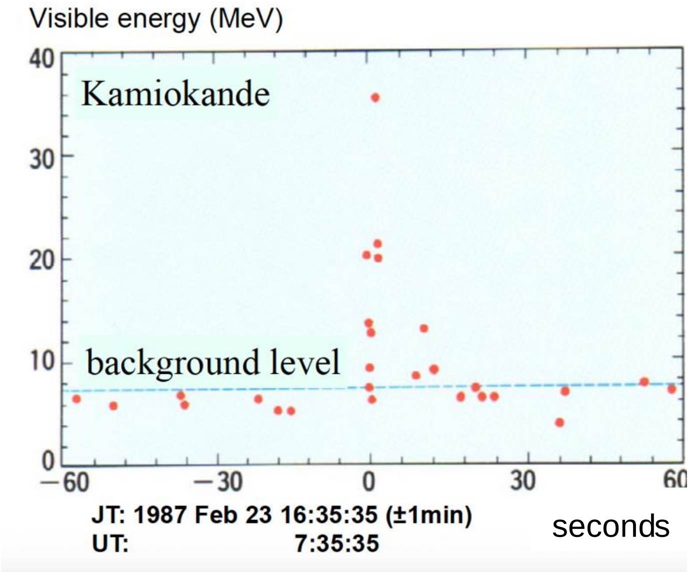


FIG. 1. Schematic view of the Kamiokande II detector. The inner detector contains 3000 tons of water of which 2140 tons are fiducial volume. It is viewed by 948 20-in.-diameter PMT's mounted on a 1-m grid on the inner surface. The outer (veto) counter surrounds the inner detector and is viewed by 123 PMT's. Dimensions in the figure are in millimeters.





Proton decay (NDE) and neutrinos →SN1987A (Nobel prize!)
Main detection channel $\nu_e + p \rightarrow e^+ + n$

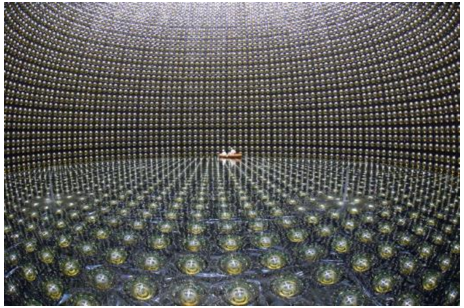
RICH deep underground

RICH ideal technique for detecting ν and PID (μ, e)

large mass (target and transparent radiator)
large active volume
low background

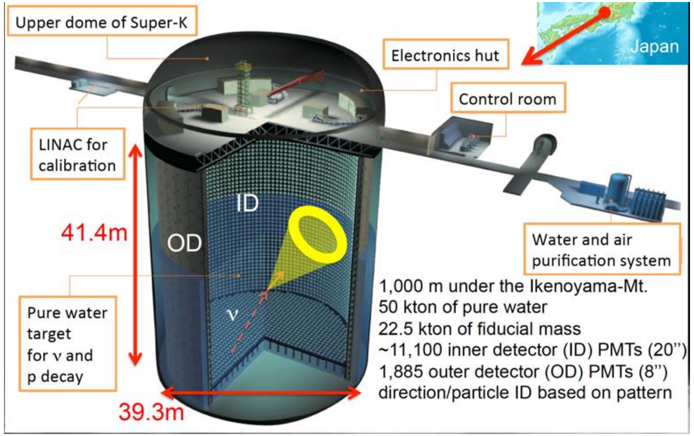
Use ultra pure water (water purification system)
Use very large area PMTs

Good timing resolution for vertex and direction reconstruction
Good imaging resolution for PID and particle counting
Good energy resolution



Super-Kamiokande
- 50k tonnes H_20
- 1 km underground
- 11000 large area PMTs

Detection of atmospheric neutrino oscillaltion (Nobel prize)



RICH deep underground

Event Reconstruction (for high energy events)

Momentum → Amount of light-yield inside a ring
Vertex →Timing of the PMT at the ring edge
Particle ID → Cherenkov ring edge and the opening angle.

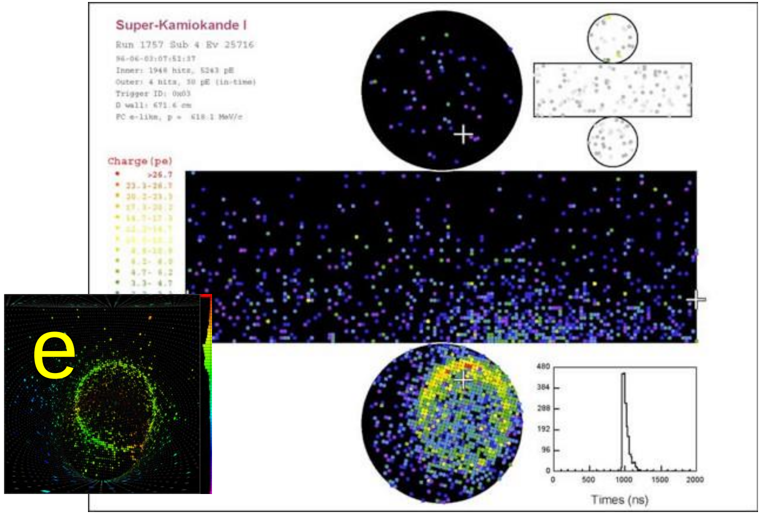
Energy response (SK detector: ~50 m path length)

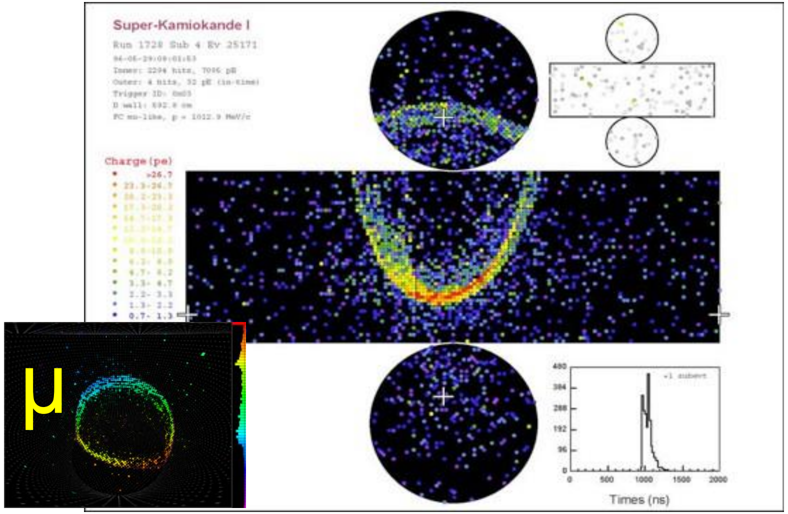
Muon energy loss in water = ~2 MeV / cm @~GeV
Maximum energy loss = ~10 GeV / particle

Low-energy response in SK: ~6 hit PMT / MeV
Rough estimation for 10 MeV electron
5 cm path length → ~1700 photon

RICH deep underground

Ring Imaging Water Cherenkov pixel detector





No momentum charge sign measurement

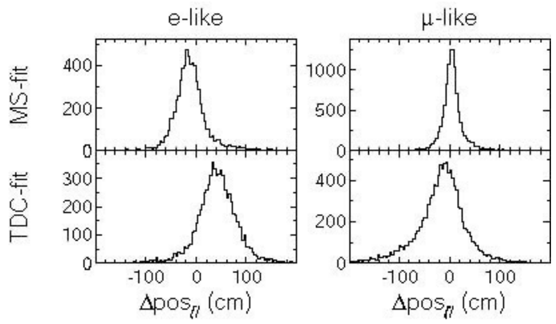
PID from sharpness of ring: muon sharper edges; electron showers: fuzzy edges

Timing response of PMTs used to determine particle direction

The number of hit PMTs is a better energy scale than total charge of hit PMTs

RICH deep underground

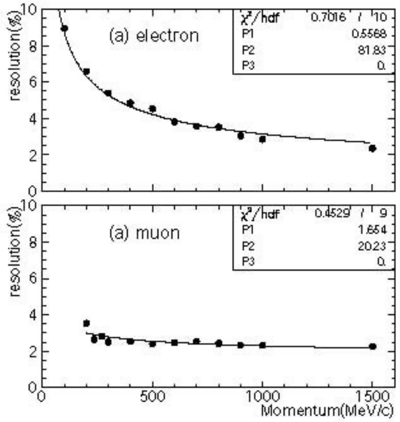
Vertex resolution
Timing calibration using laser
accuracy 0.5 ns (10 cm)



c_{water} ~23 cm/ns in water

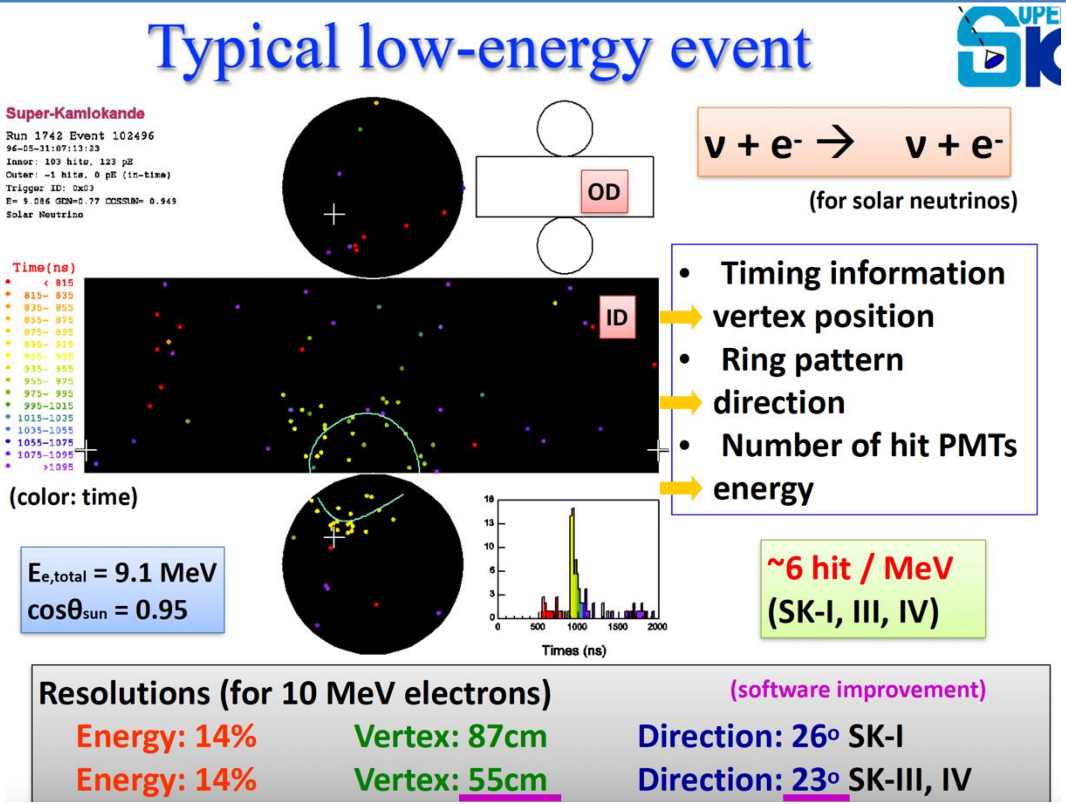
Energy resolution

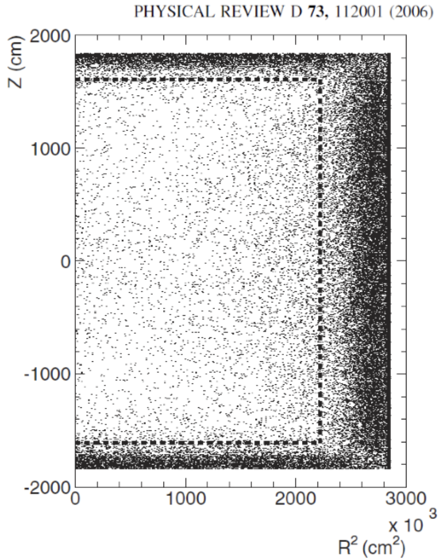
Mainly depends on the number of photo-electrons (p.e.) detected.
Rough figure from 6 p.e. / MeV:
10 MeV → 60 hit PMT → σ(E)/E = ~13%
1 GeV → 6000 p.e. → σ(E)/E = ~1.3%



10 MeV electron 14 %
1 GeV electron 3 %
1 GeV muon 2 %

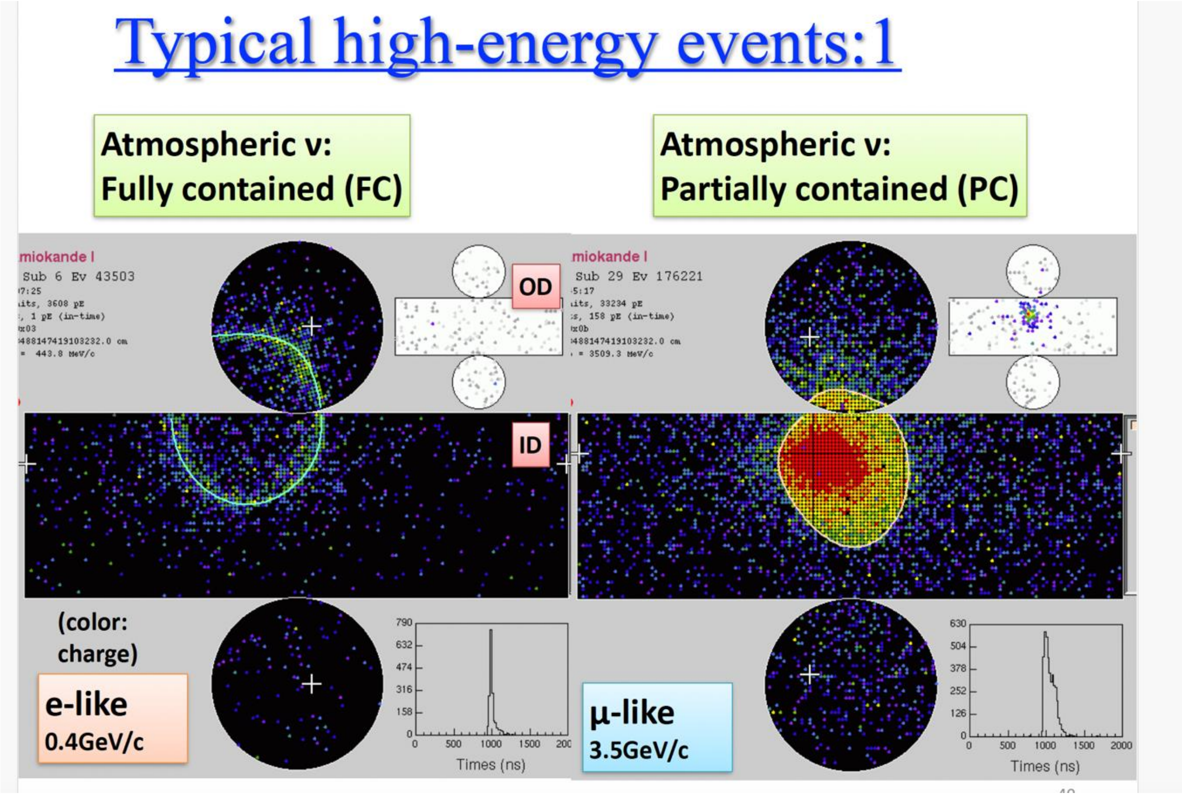
RICH deep underground



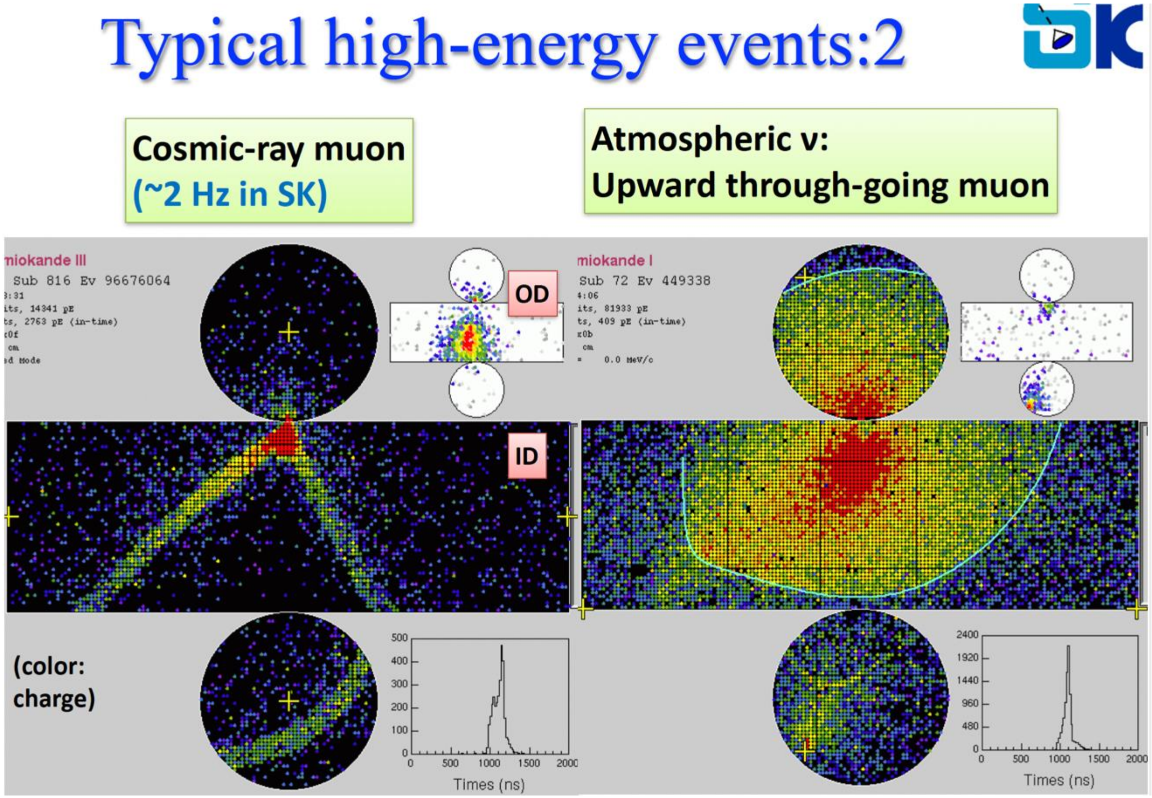


Low-energy vertex distribution fiducial volume &bkg suppression

RICH deep underground



RICH deep underground



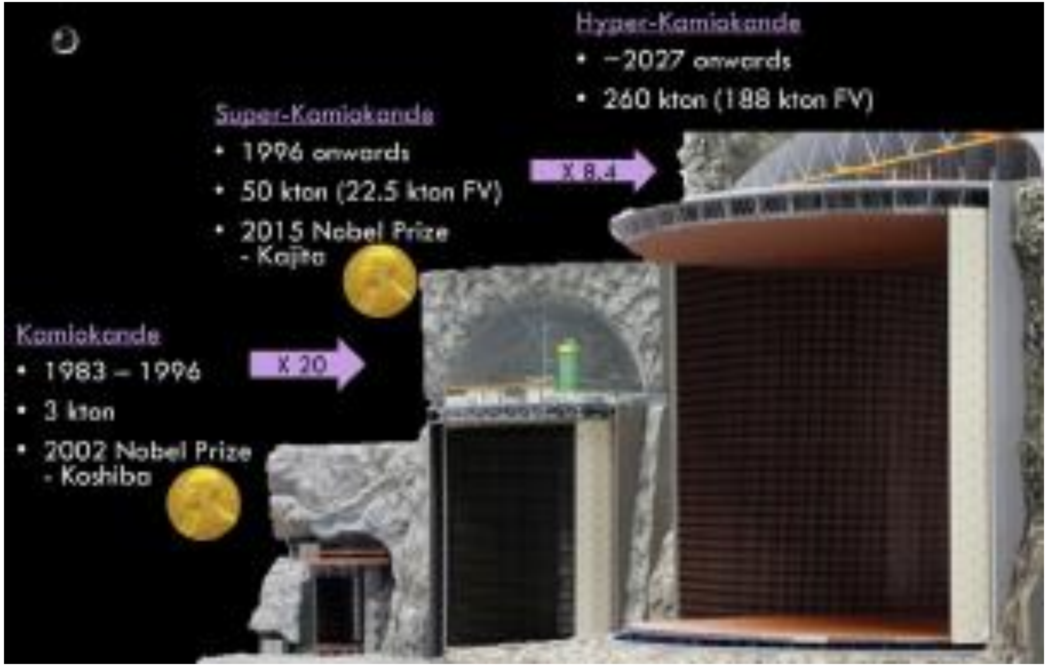
RICH deep underground

Next Step

Hyper Kamiokande (2027):

260 kT (190 kT fiducial)
40.000 PMTs
8.4 x SK

E_{th} ~ 6.5 MeV

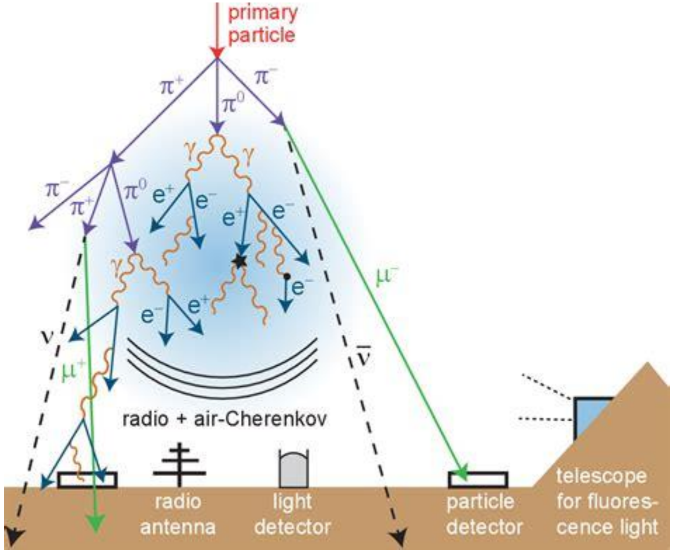


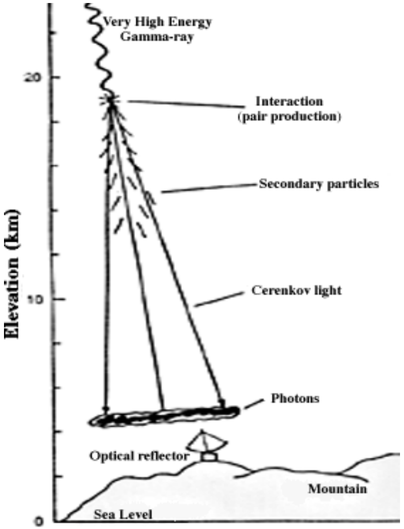
Cherenkov on ground: Shower detection

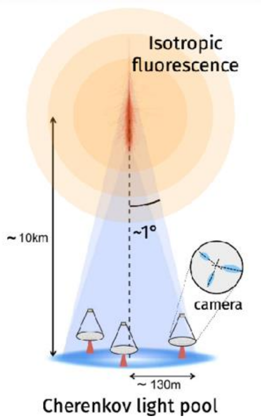
Use atmosphere as calorimeter $\rho_{\text{atm}}(h) \approx \rho_0 e^{-h/h_0}$ $\rho_0 \approx 1.225\ \text{kg/m}^3$

> TeV CR Showers:
Cherenkov counters/RICH over ground

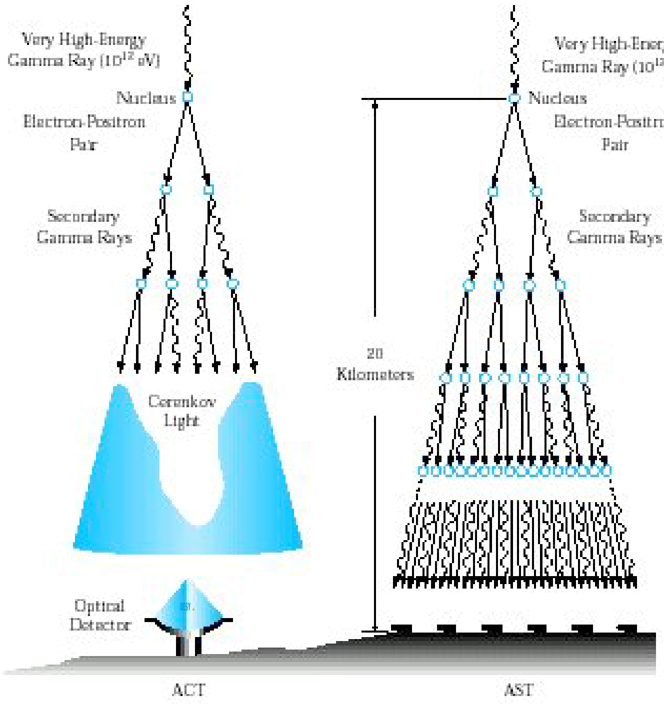
GeV-TeV Gamma showers
Imaging Air Cherenkov Telescopes







Cherenkov on ground: Shower detection



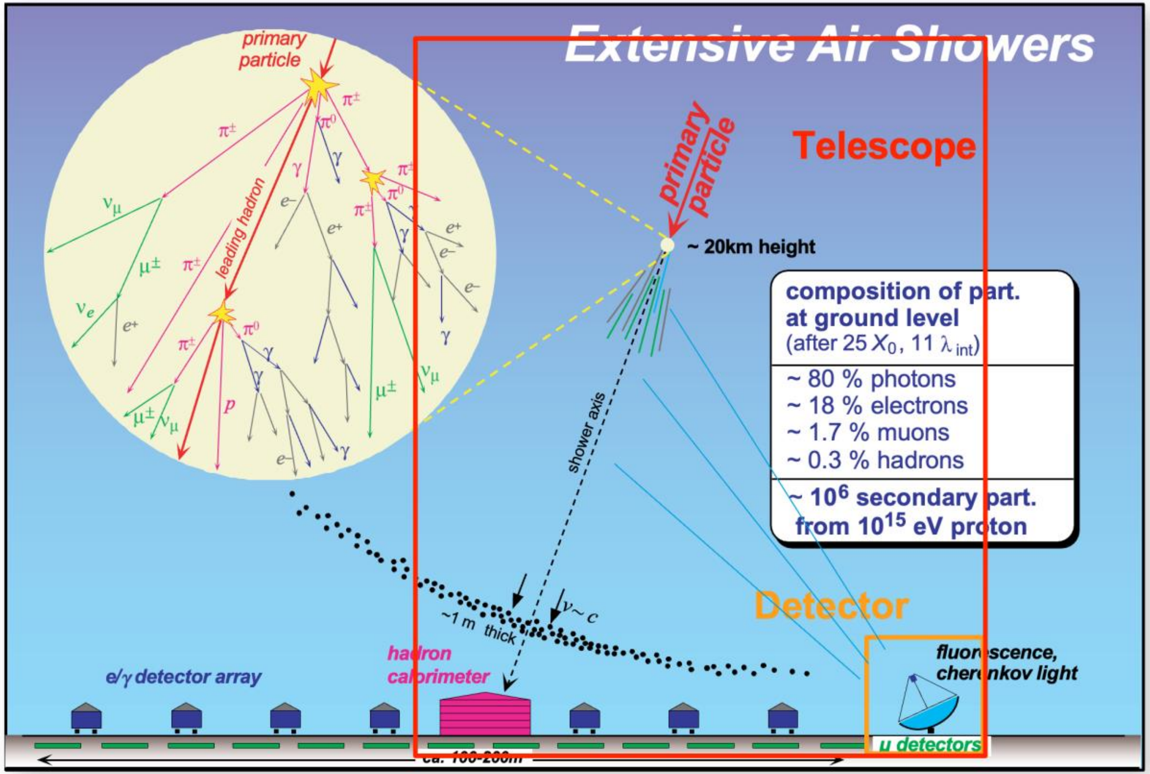
Atmospheric Cerenkov Detectors (ACTs)

Limited field of view instrument (few degrees)
Dish must follow the source displacement in the sky
→ only work at clear sky moonless nights
→need γ-hadron discriminating power

Surface detectors
(charged particles and γ secondaries at ground level)

Large field of view (≈ steradian) instrument
High duty cycle
→need γ-hadron discriminating power

Cherenkov on ground

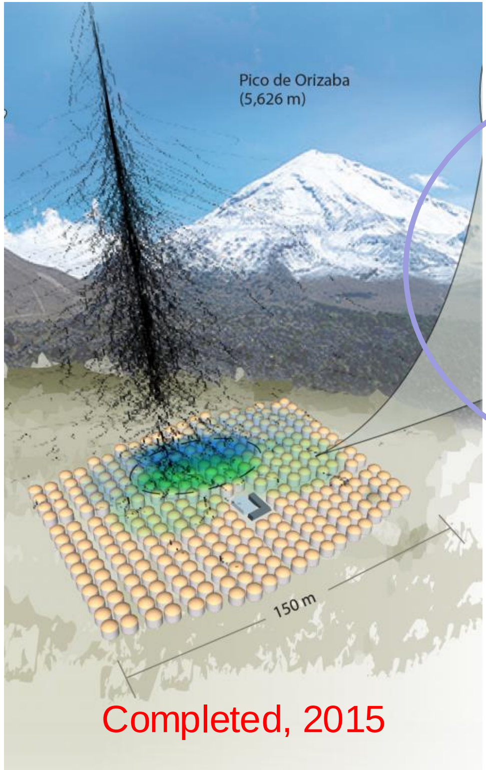


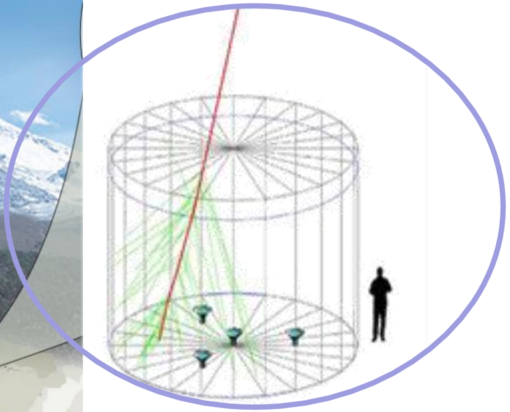
overground Cherenkov particle counting:

LHAASO
Pierre Auger
HAWC
SWGO

Cherenkov on ground: HAWC

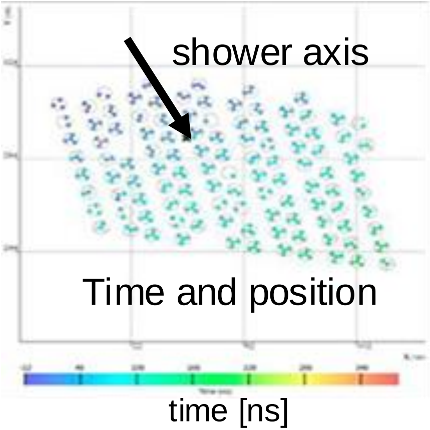
High Altitude Water Cherenkov (HAWC): CR/gamma Air Shower Detector





22,000 m^2 air shower array
300 Water Cherenkov detectors (WCD)
200,000 liters of purified water per WCD
4 sensors (photo-multiplier tubes) per WCD

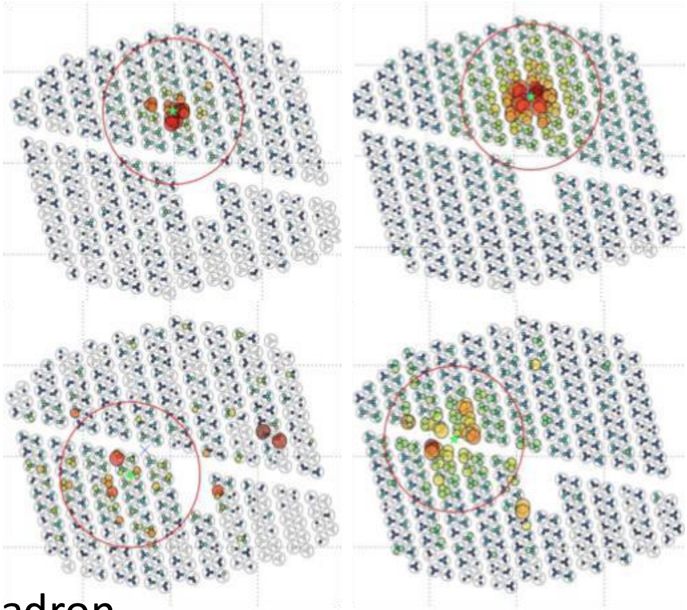
Cherenkov light recorded by 4 PMTs at the bottom of each WCD



Cherenkov on ground: HAWC

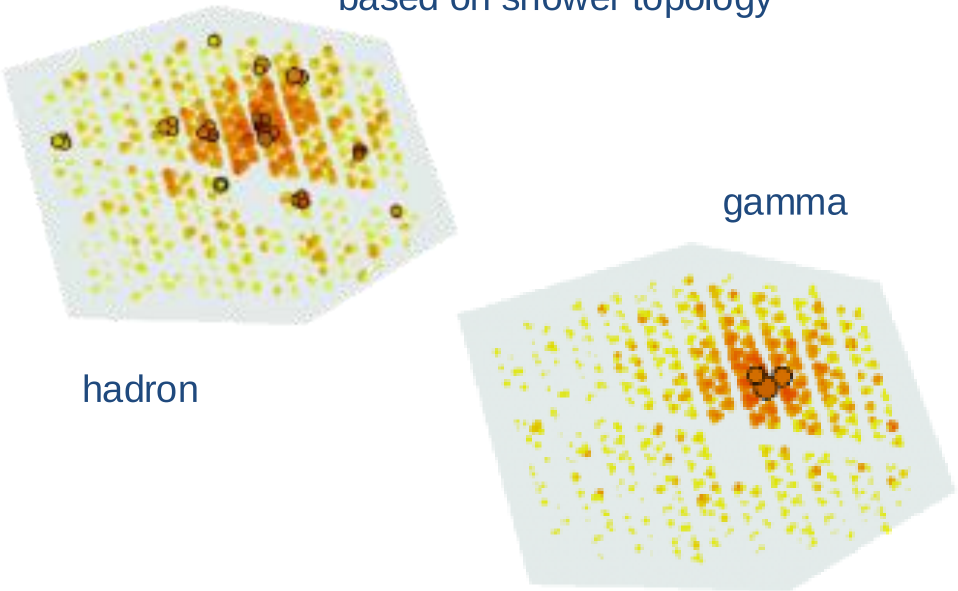
HAWC detects a few thousand γ rays per day and 20,000 hadronic cosmic rays per second (~2 billion/day)

γ



hadron

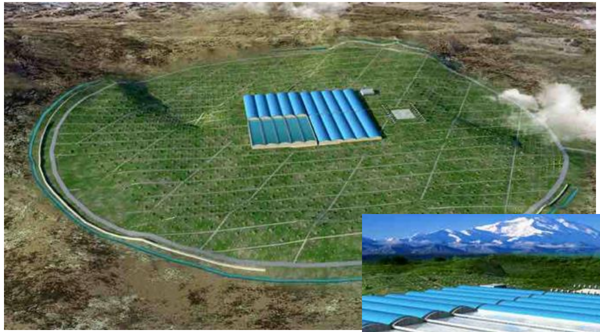
hadron/gamma separation based on shower topology

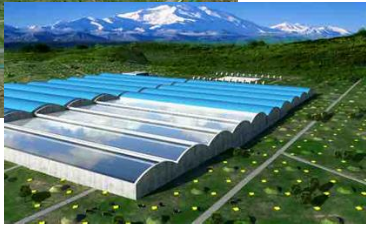


hadron

gamma

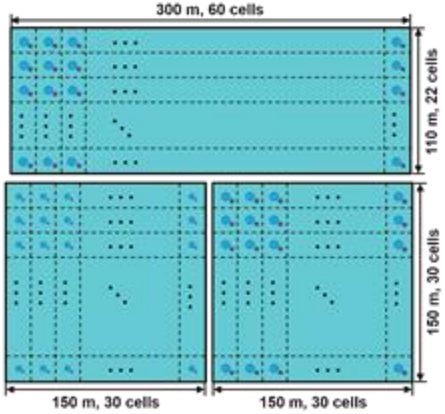
Cherenkov on ground: LHAASO

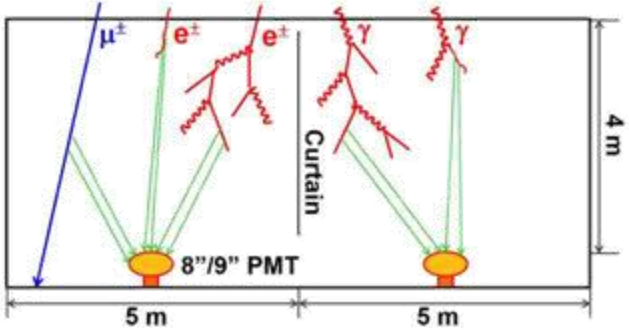


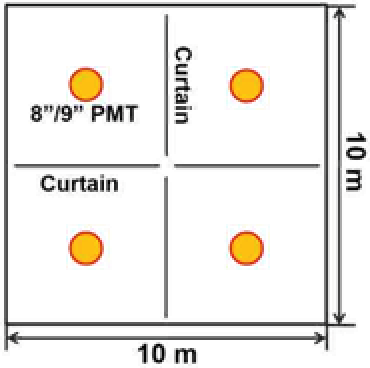


4500 m altitude, Sichuan
Total area: 1.3 km^2

Water Cherenkov Detector Array (WCDA)
3600 cells 90,000 m^2



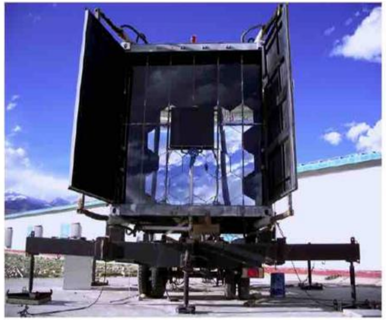




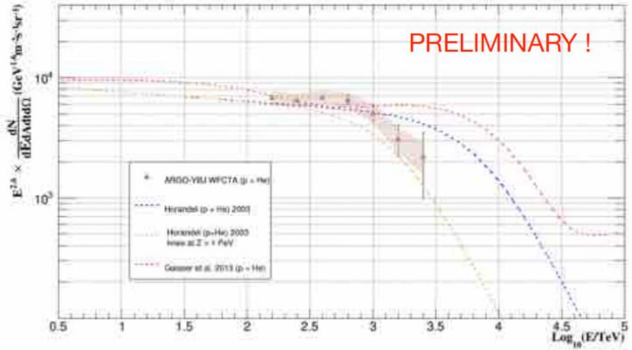
Cherenkov Telescope Array: LHAASO

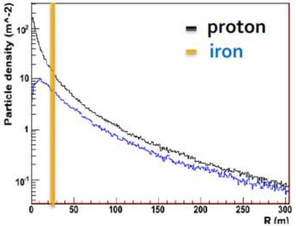
24 telescopes (Cherenkov/Fluorescence)

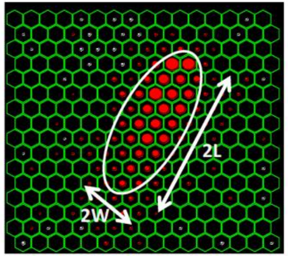
- 5 m^2 spherical mirror
- 16 × 16 PMT array
- pixel size 1°
- FOV: 14° × 14°
- Elevation angle: 60°

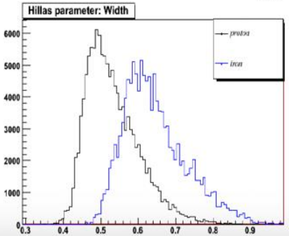


ARGO-YBJ / WFCTA







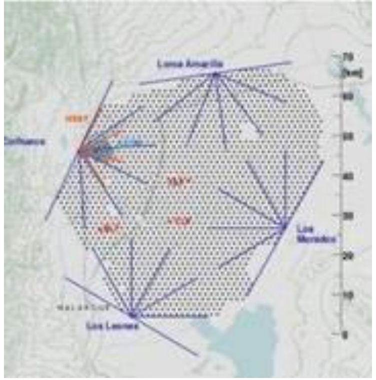


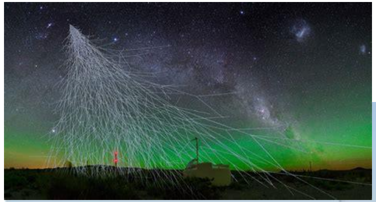
G. Di Sciascio, Roma Tor Vergata, July 13, 2015

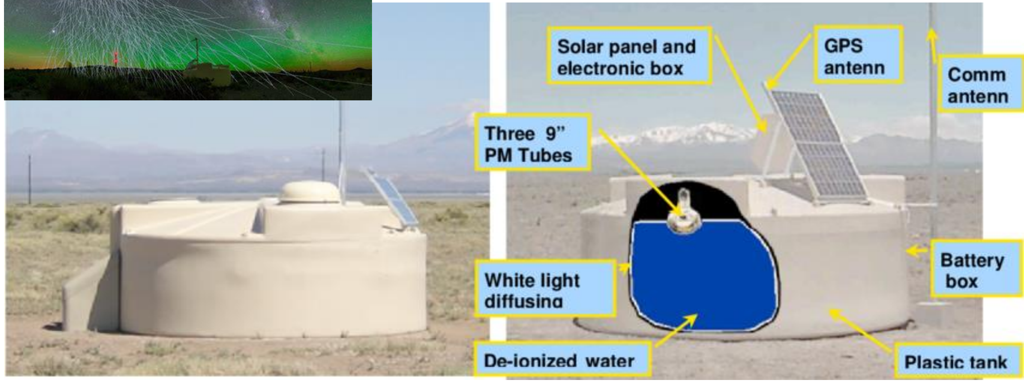
22

Cherenkov on ground: Pierre Auger

designed to detect UHE CR > 10^{18} eV





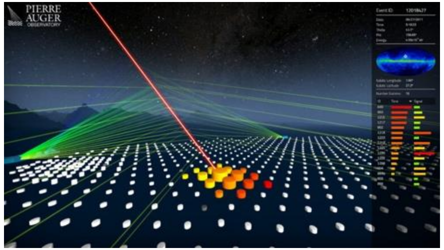


PAO, Combination of:

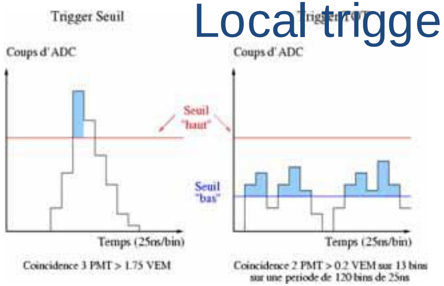
Surface detector (1600 water Cherenkov tanks 1.2 km^2)

Array of Fluorescence Detectors

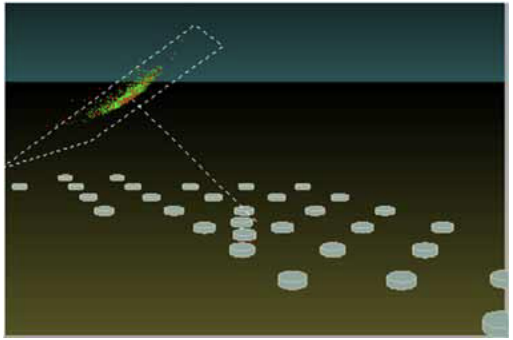
Hybrid detection



Local trigger

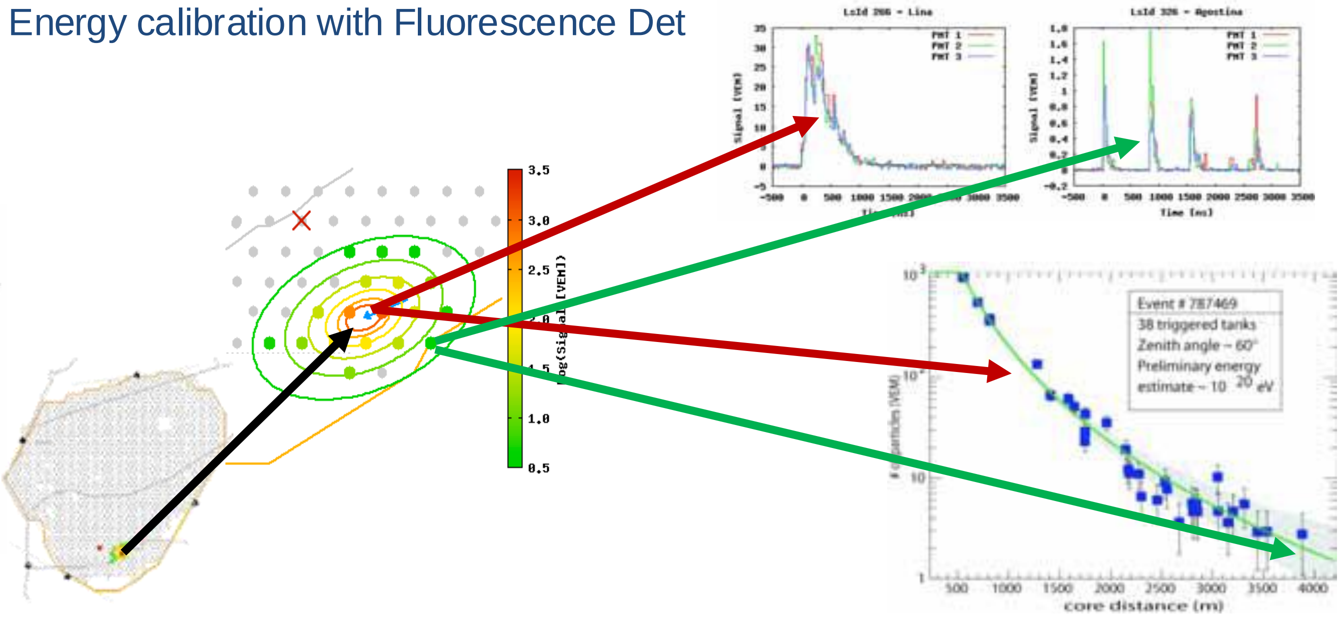


Cherenkov on ground: Pierre Auger

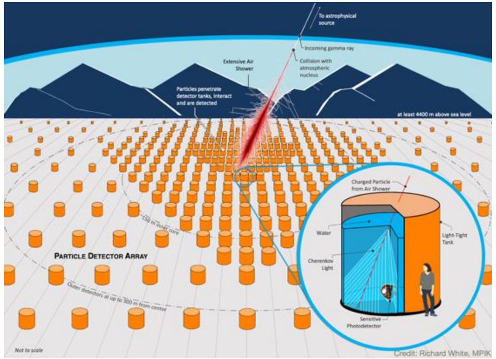


EAS footprint estimator of primary CR energy
→ Hillas relation as energy estimator: signal at fixed (>100m) core distance
→ particle density at a given radius from the reconstructured axis S(R)
→ small shower-to-shower fluctuations
Energy calibration with Fluorescence Det

	Hybrid	SD only	FD only
Angular resolution	0.2°	1-2°	3-5° (0.5° stereo)
Aperture	Independent on E, mass, models.	Independent on E, mass, models.	Dependent on E, mass, models, spectral shape.
Energy	Independent on mass, models.	Dependent on mass, models.	Independent on mass, models.



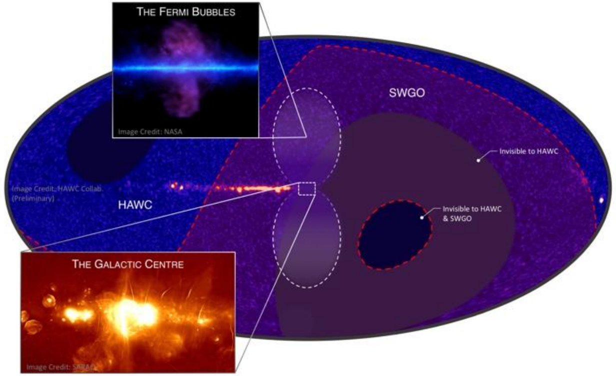
Cherenkov on ground: SWGO



Located in Atacama Astronomical Park, Chile.
altitude of 4770 m.
Gamma-ray observatory based on ground-level particle detection
close to 100% duty cycle
1 steradian field of view.
100 GeV : PeV

Water Cherenkov detector units
high fill-factor core
area considerably larger than HAWC
low density outer array

Use of multi PMT



Cherenkov on ground: Air Cherenkov

Cherenkov light flash emitted by shower particles
- directional
- faint O(30) photons/m^2)
- short O(ns)
- 300-550nm

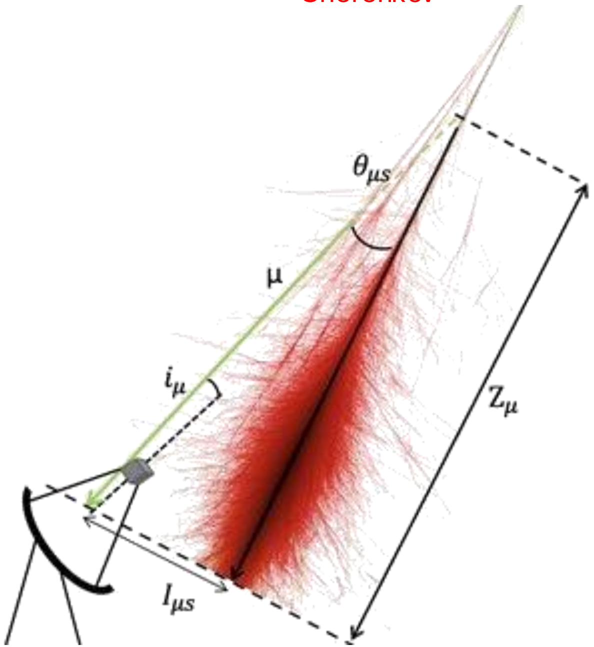
Photon energy (total collected light)
larger area == lower threshold

Photon direction (Cherenkov track)
need:
good timing
good granularity
hadron/gamma separation

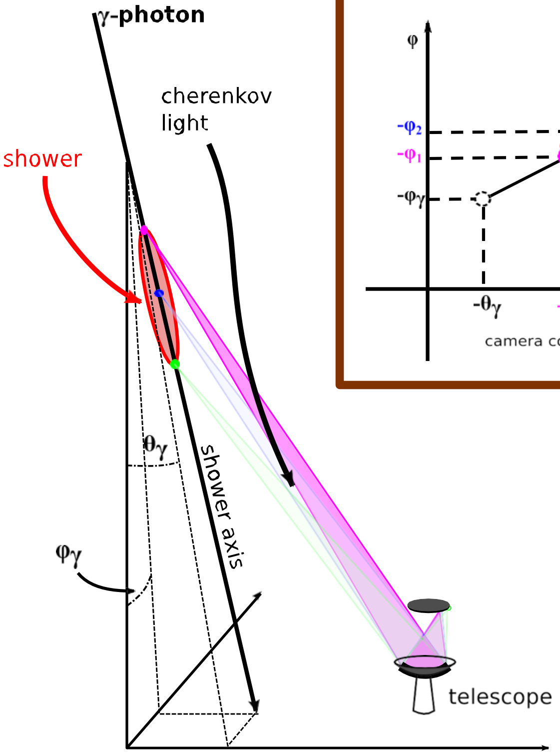
optimal site conditions
(air quality, altitude, optical bkg)

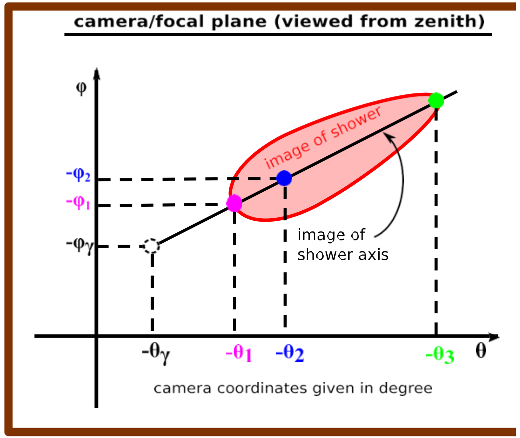
n_{air} =1.00029

$\theta_{Cherenkov}$ ~23 mrad ~ 1.3°



Cherenkov on ground: Air Cherenkov



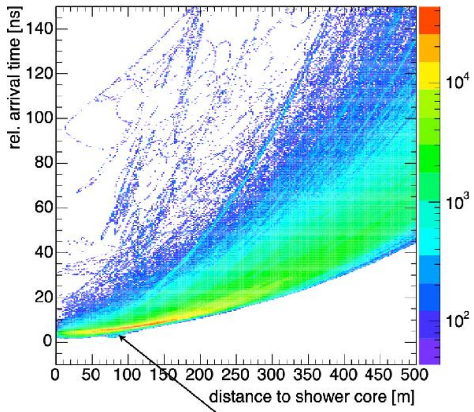


Thresholds for Cherenkov emission:

e: 20 MeV at sea level
35 MeV at 10 km

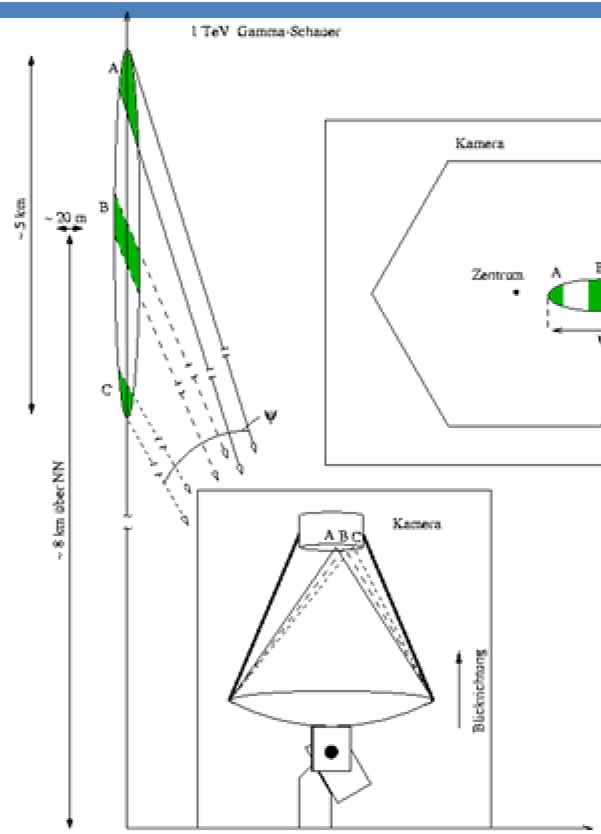
μ: 4.5 GeV at sea level
8 GeV at 10 km

Shower max at about 10 km from s.l.
radius = 10^4* 0.023 = 2 10^2 m
illuminated area on ground *1.6 * 10^5 m^2*



most light arrives within few ns

Cherenkov on ground: Air Cherenkov



Shower develops in the atmosphere

charged relativistic particles emit Cherenkov radiation

Photons get reflected by a mirror to a camera

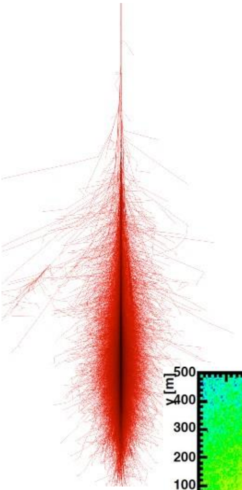
High reflectivity mirrors

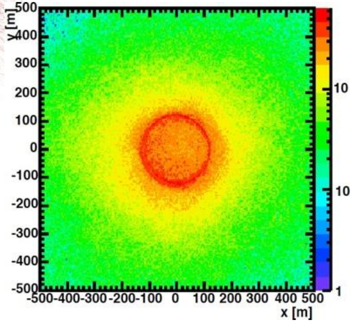
High sensitivity light detectors

good time resolution

Cherenkov on ground: Air Cherenkov

Shower lateral distribution gamma



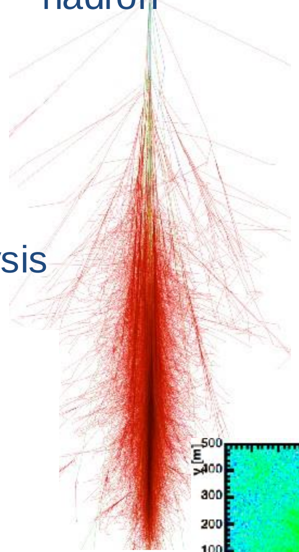


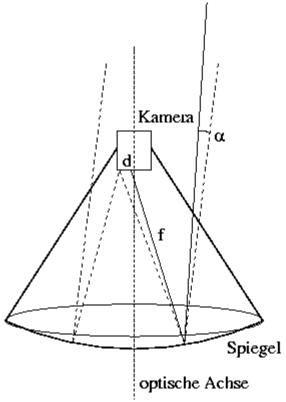
hadron showers (cosmics) dominate the trigger

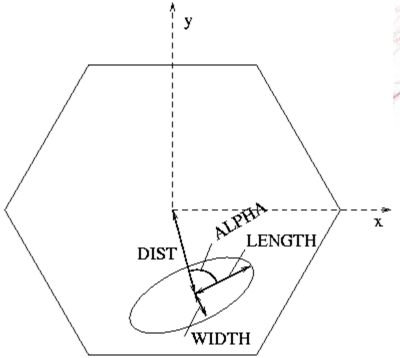
→ image analysis must discriminate gammas from hadrons

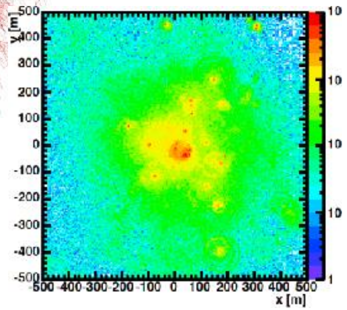
→ showers feature extraction using principal component analysis

Shower lateral distribution hadron

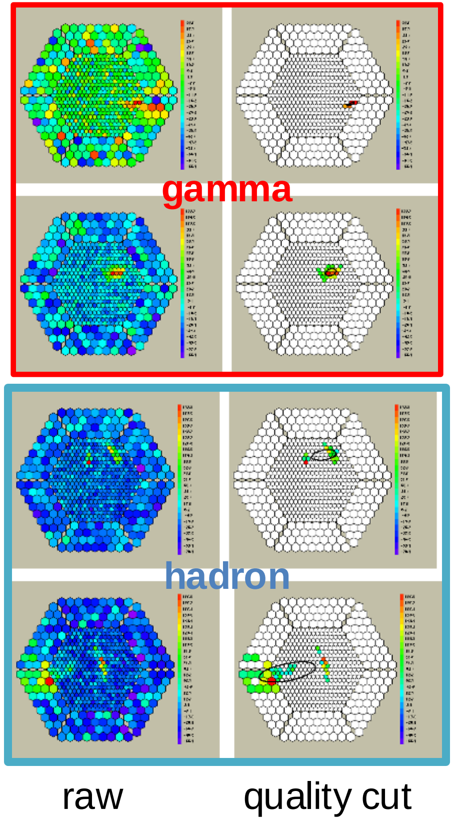


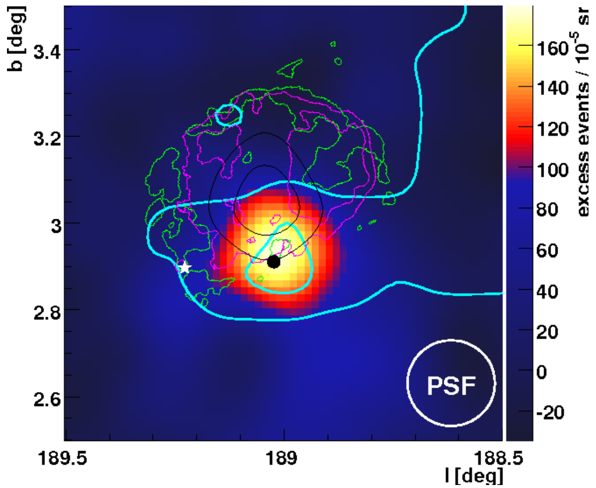






Cherenkov on ground: Air Cherenkov

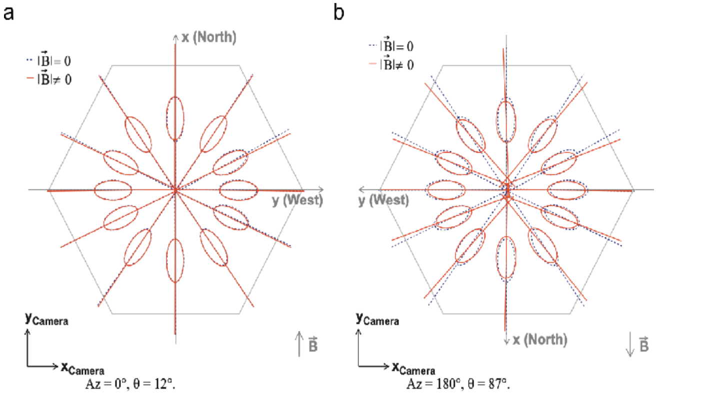




Detection of IC433 (MAGIC)

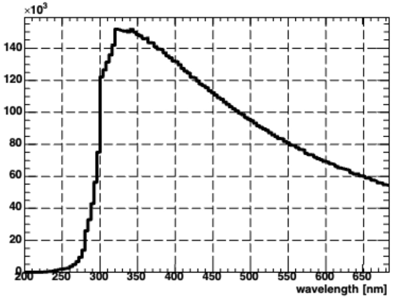
Air Cherenkov: backgrounds

Atmosphere: Natural medium as radiator
molecular absorption bands
molecular (Rayleigh) scattering
aerosol (Mie) scattering & absorption
clouds
moon, star-light background

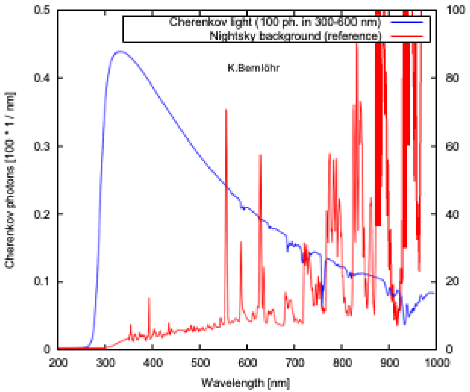


geomagnetic field impact

450 GeV γ-rays, 100 m impact parameter, ZA = 40°, Az = 0° and 180°,

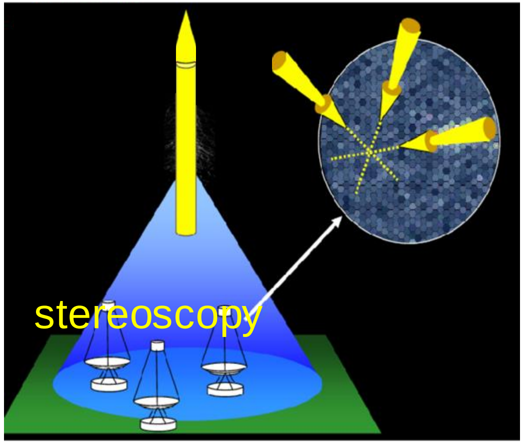


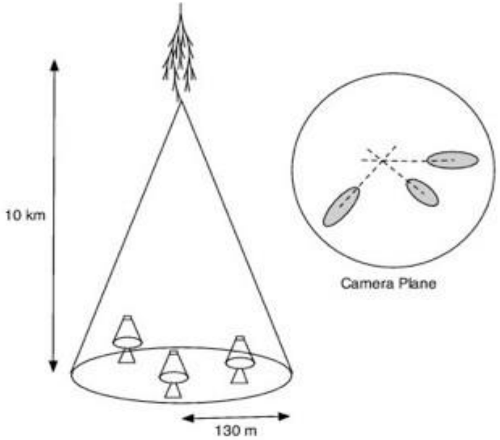
Cherenkov spectrum
after extinction
in atmosphere



night sky background

Cherenkov on ground: Stereo Air Cherenkov





Each showers seen by several telescopes

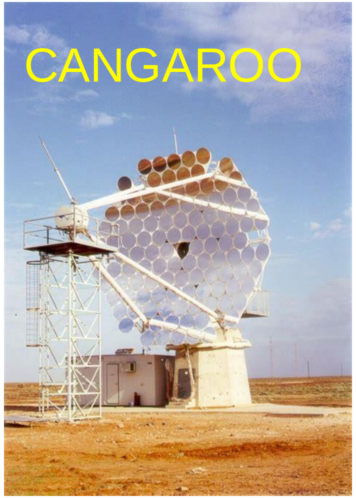
improved hadron shower rejection factor
axial symmetry + narrow 3D width + punctual source pointing

Improved angular resolution wrt 1 telescope (≈ 4' with 4 telescopes)

Energy resolution (≈15%)

Cherenkov on ground: Air Cherenkov

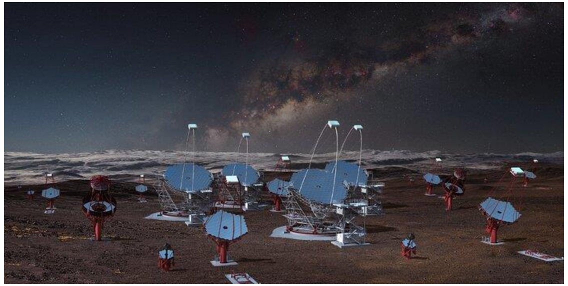
Experiment	# pixels	Pixels size	Field of view
CANGAROO III	552	0.115°	3°
HESS I	960	0.16°	5°
MAGIC	396+180	0.08°-0.12°	4°
VERITAS	499	0.15°	3.5°



Cherenkov on ground: Air Cherenkov

CTAO: Cherenkov Telescope Array Observatory

North (Canaria) and South (ESO) sites

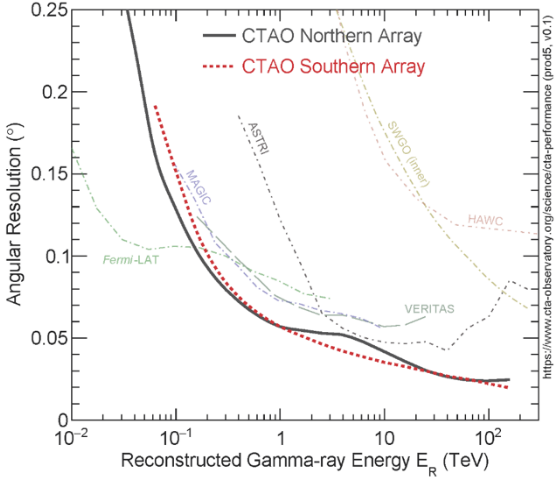


Three types of telescopes: 20 GeV : 300 eV.

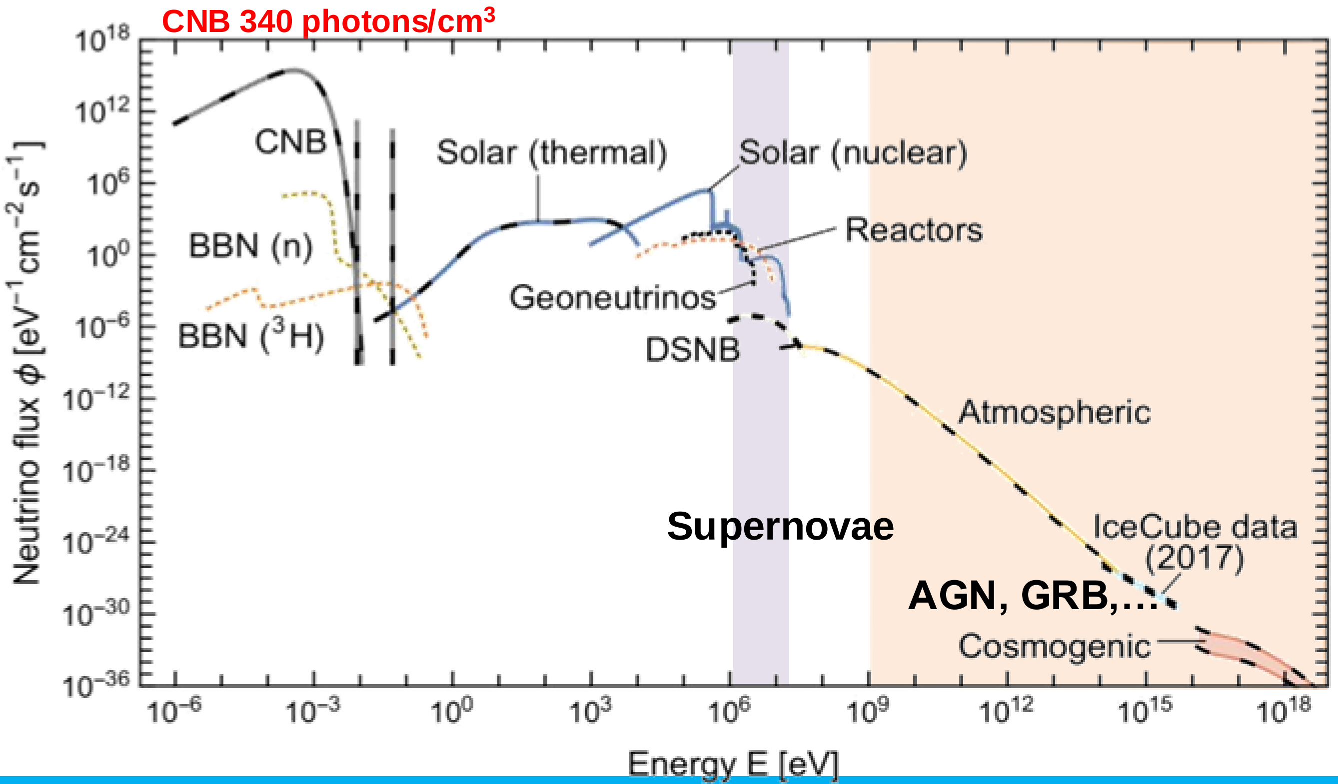
23 Medium-Sized Telescopes

4 Large-Sized Telescopes in the Northern hemisphere (Threshold 150 GeV)
37 Small-Sized Telescopes in the southern array (threshold 5 TeV)

Energies below 150 GeV and above 5 TeV, respectively.



…And neutrino telescopes

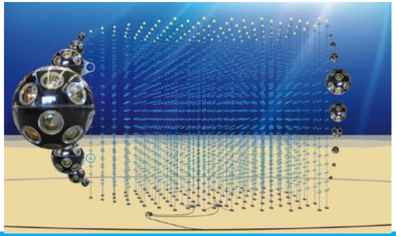


…And neutrino telescopes

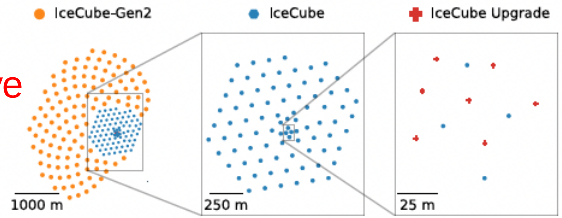
P-ONE
2500 m w.d. Victoria (Canada)
Ocean Network Canada Infrastructure
multi km3 for UHE event
Prototyping phase
(technology in definition)
possible limitation:
seawater depth
and background

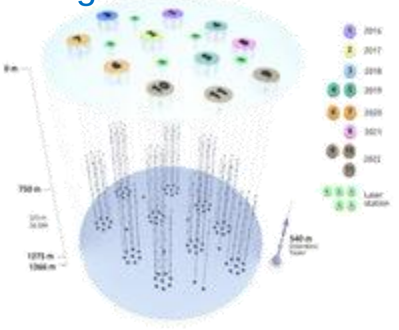
Baikal
Lake Baikal 1250 m w.d.
1km^3 with 18 clusters in 2026
Water quality limits TeV data
Quality for mass production
improved wrt the past.
Detector behaviour not fully
understood.
“Heroic effort” in the past
international situation limiting
collaboration growth

ANTARES
Toulon 2500 m w.d.
KM3NeT (ARCA)
Capo Passero 3500 m

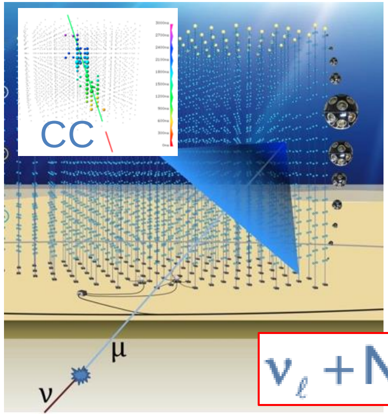


IceCube xtension to
IceCube Gen 2: x8 Active
Volume wrt IceCube

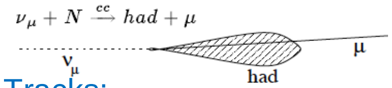




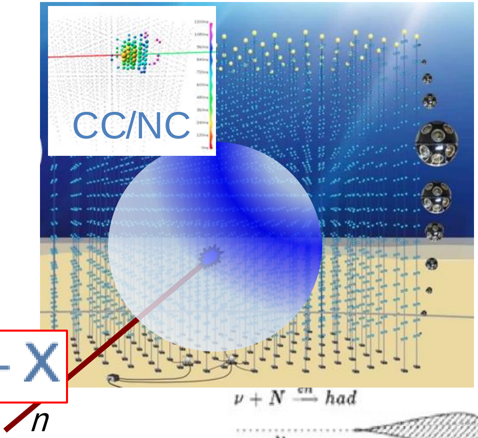
…And neutrino telescopes

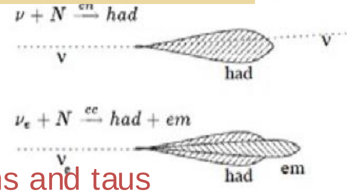


$\nu_\ell + N \rightarrow \ell + X$



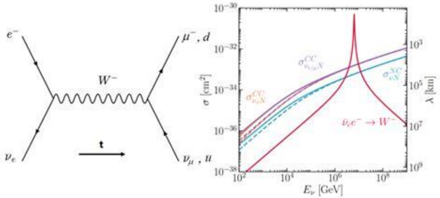
Tracks:
CC muons (and HE taus)
highest effective area, good angular resolution (<1°).
$E_{res} \approx 50\%$
High atmospheric muon background:
look at events from below only



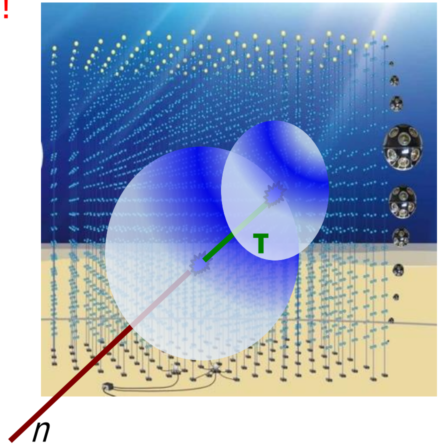


Cascades:
NC, CC electrons and taus
remove atmospheric muon background: studies over 4π.
Good' energy resolution ($E_{res} \approx 15\%$' at 100 TeV), worse directional resolution (<10°)

$\boxed{\nu_e + e^- \rightarrow \nu_e + e^-}$



6.3 PeV: Glashow resonance !



Lollypops et al.:
taus (HE)
Unambiguous topology at $E_{tau} \approx$ PeV

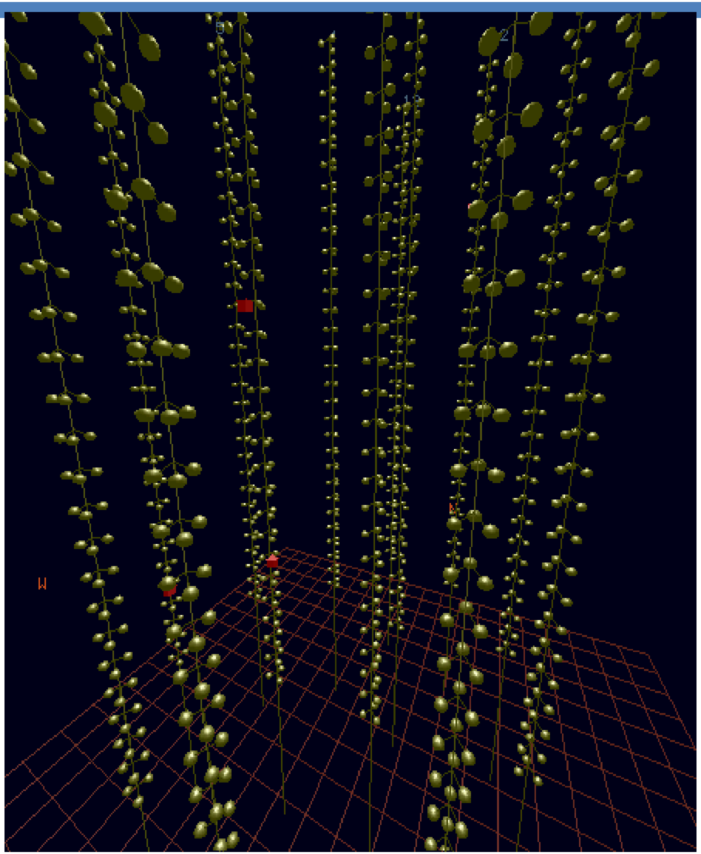
…And neutrino telescopes

Cherenkov photons emitted by the muon track are correlated by the causality relation:

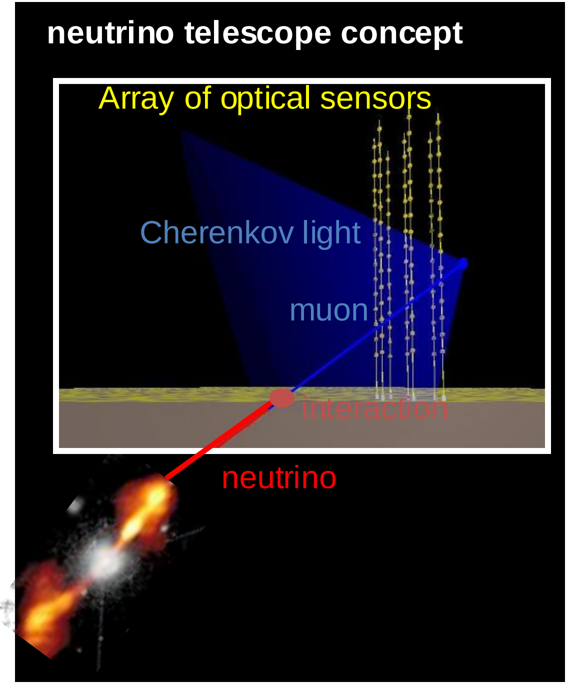
$$c(t_j - t_0) = l_j + d_j\ tg(\vartheta_c)$$

The track can be reconstructed during offline analysis of space-time correlated PMT signals (hits).
Main indetermination is the size of PMT
(≈ 20 cm → ≈ 1 ns)

Required resolution:
≈ 1 ns PMT TTS
≈ 10 cm in position of the PMT



…And neutrino telescopes

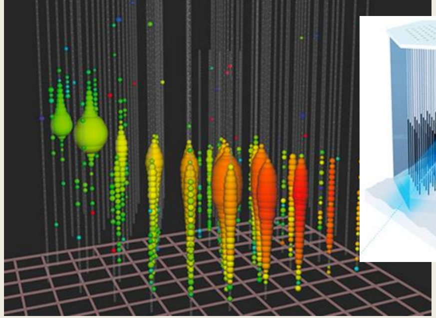


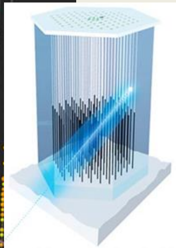
IceCube: 2500 m depth, ice, Antarctica

ice cap

https://icecube.wisc.edu/

astrophysical neutrino event





1 km

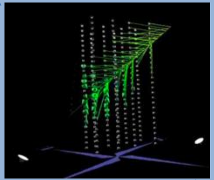
Antares: 2500 m, sea, offshore Toulon

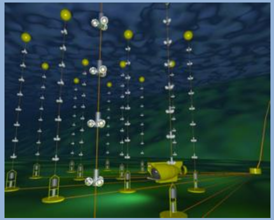
seawater

https://antares.in2p3.fr/

electro-optical marine cable 40 km

atmospheric muon event

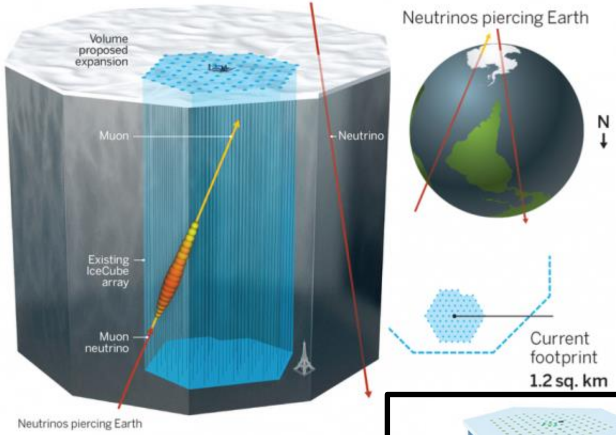


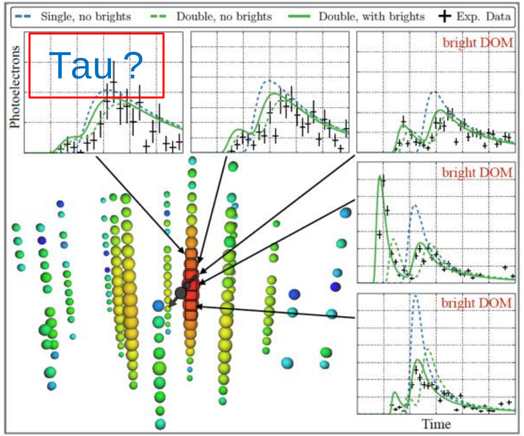


300 m

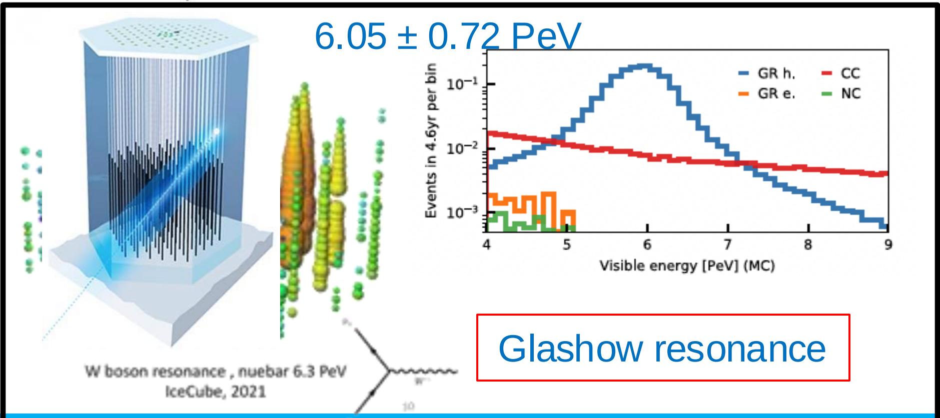
…Icecube in Antarctica

5160 PMTs in Optical Modules
1 km^3 volume
86 strings
17 m vertical spacing
125 m string spacing
Completed in 2010
Fully operational since 2011

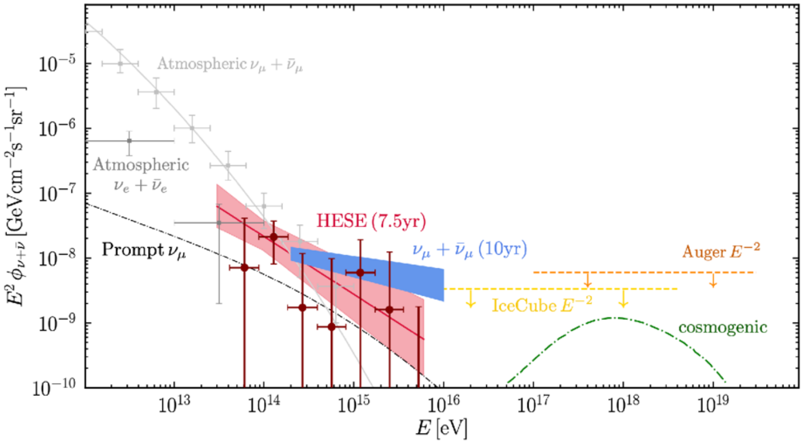


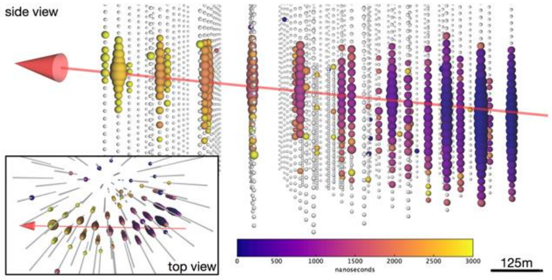


no ^{40}K background, fixed strings
"standard" data transport and time calibration
light scattering in ice



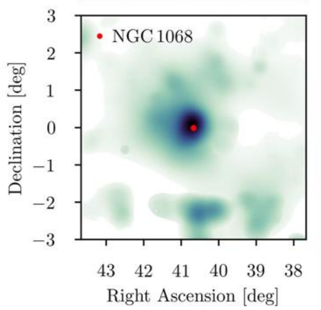
…Icecube in Antarctica





TXS
Multimessenger detection during a source flare
IceCube-170922 (~290 TeV)

NGC1068



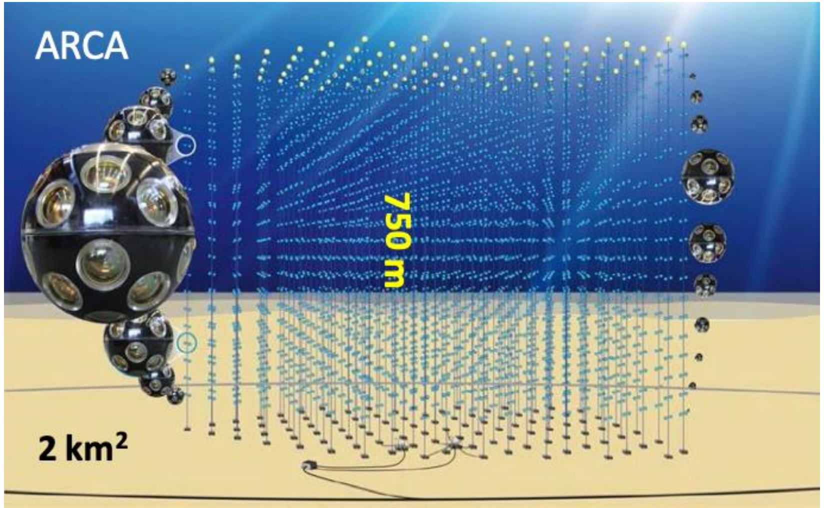
Neutrino flux Consistent with an isotropic distribution
Galactic plane emission < 14%
no signal from GRBs
but 4 interesting candidate sources (2 in particular)

Special AGN: not jetted, neutrinos prodcued in the AGN corona, gamma «hidden» source

KM3NeT

ARCA @ Capo Passero
Astronomy Research with Cosmic Rays in the Abysses
3500 m water depth, 100 km from shore

2 building blocks (few km among the blocks)
115 Detection Units(DU) / block
18 DOMs (36 m inter-DOM)
90 m inter-DU distance
>1 km^3 volume



ORCA @ Toulon
Oscillation Research with Cosmic Rays in the Abysses
2500 m water depth, 40 km from shore

1 building block
115 detection Units
18 DOMs (9 m inter-DOM)
0.01 km^3 volume

Network of cabled observatories located in deep waters of the Mediterranean Sea.

Centrally managed: common hardware, software, data handling and control

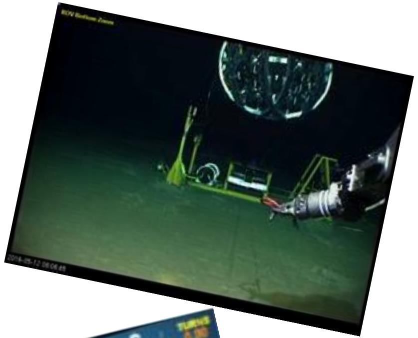
KM3NeT: detector elements

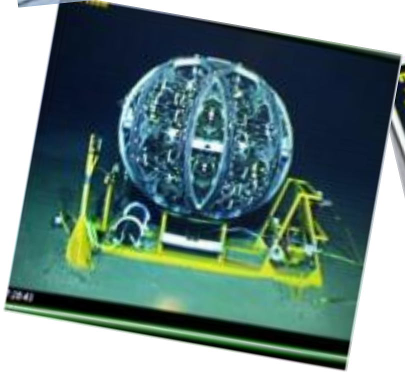
Digital Optical Module (DOM)
A fly's eye light detector
Inside a 17'' glass sphere

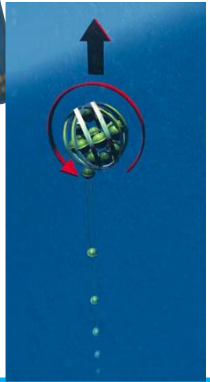
Plus:
compass, acoustic sensor, front-end and data transmission electronics

1 hydrophone at each Detection Unit base

Detection Unit
a vertical string
with 18 DOMs

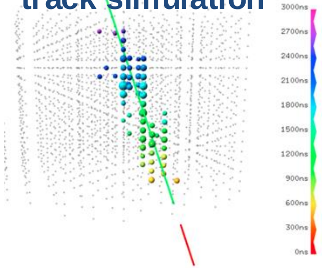




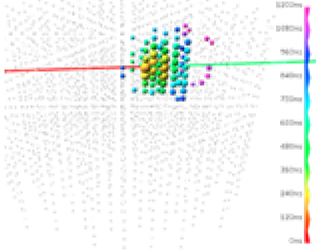


Angular resolution

track simulation

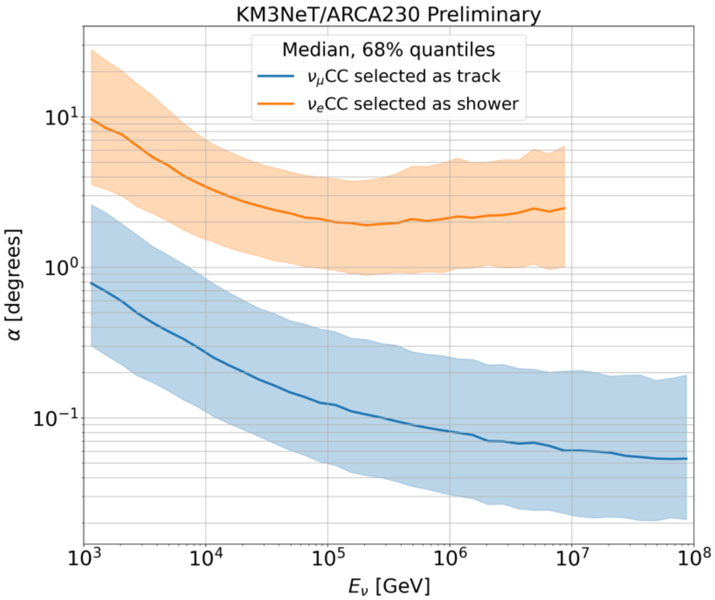


shower simulation

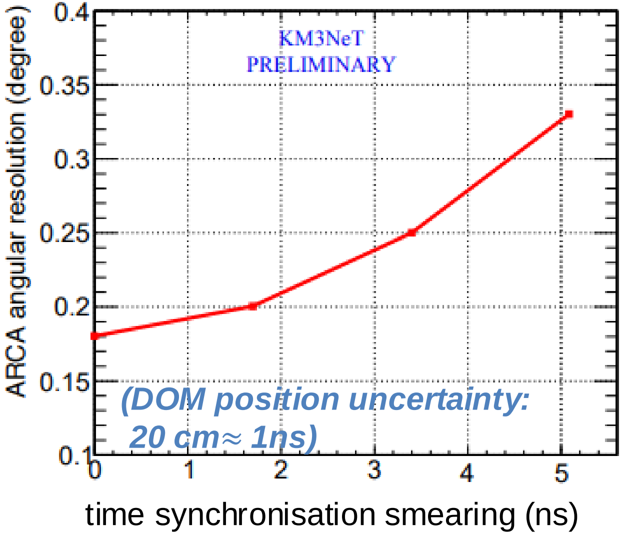


Photon hit information:
Hit Time (T0)
Hit Charge (Q → ToT, Time over threshold)

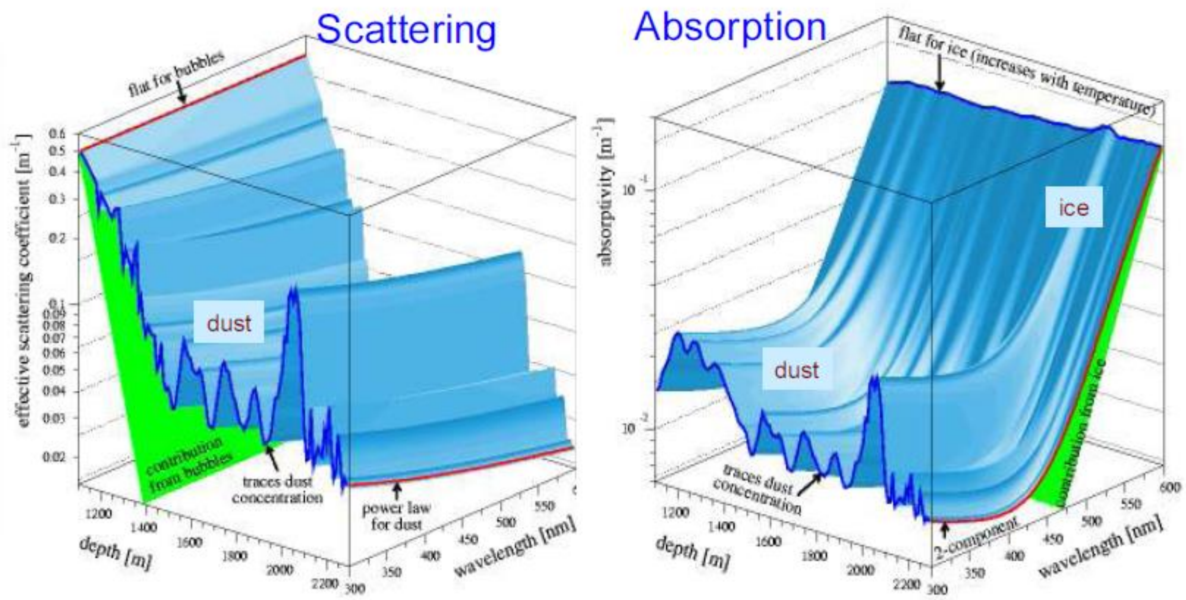
Angular resolution (in ARCA):
- Rejection of atmospheric muons
- Source identification



Time Synchronisation and DOM position calibration is the key parameter to optimise angular resolution



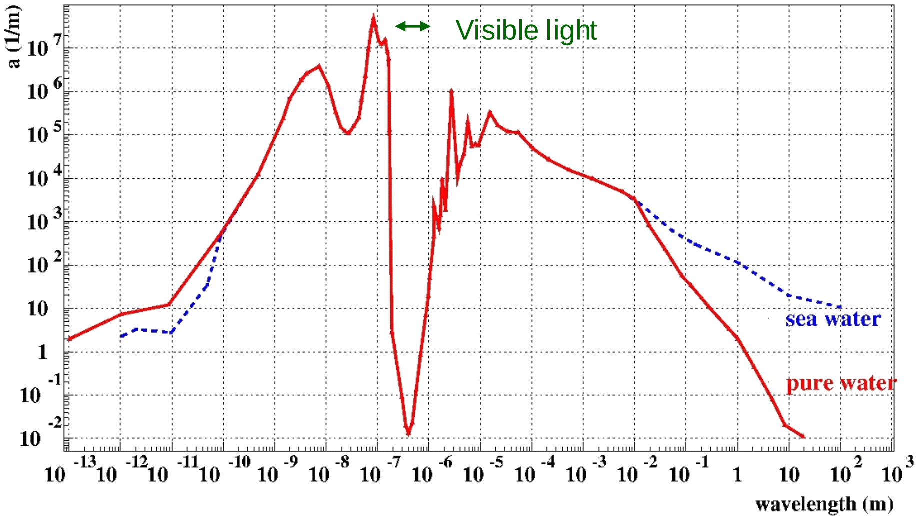
Ice optical properties



Absorption length is about 100 m
Scattering length is few cm (effective is few metres)

Light propagation in water

Spacing of optical sensors inside the instrumented volume must be of the order of the light absorption lenght in seawater (≈70 m for blue light)



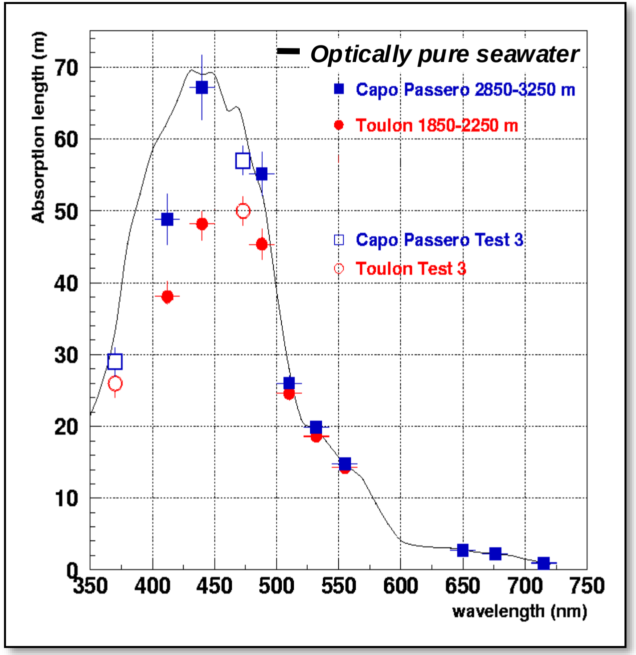
$$I = I_0 e^{-\frac{a(\lambda)}{D}}$$

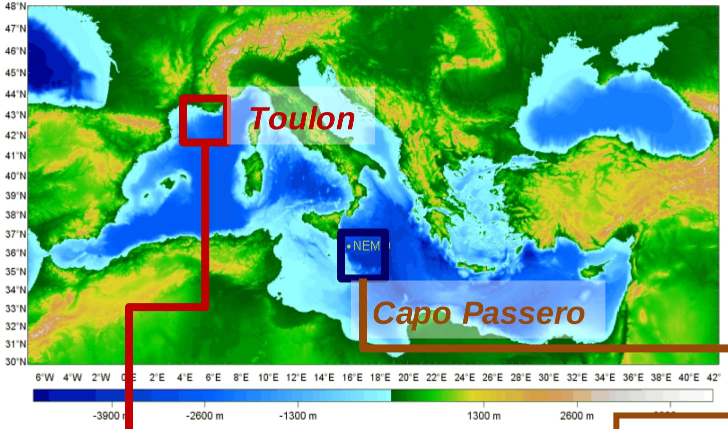
$$L_a(\lambda) = \frac{1}{a(\lambda)}$$

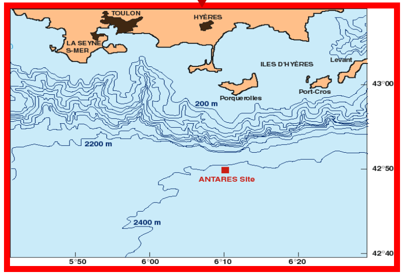
$$L_a(\text{blue}) \approx 70\text{m}$$

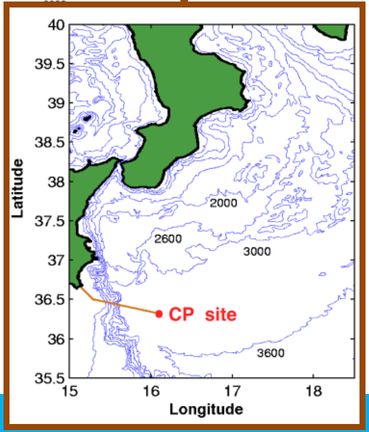
About 5000 optical modules are needed to fill up one km³

Water Optical properties









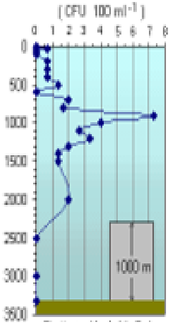
Backgound Light in water

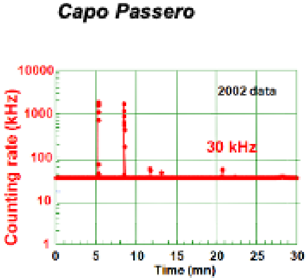
$^{40}K \rightarrow {}^{40}Ca + e^- + \nu_e$ (B.R. = 89.28%)

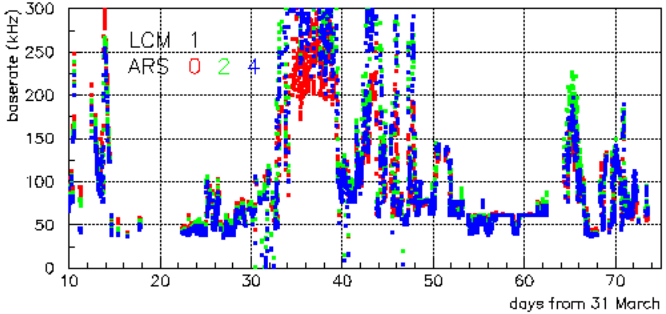
$^{40}K + e^- \rightarrow {}^{40}Ar + \nu_e + \gamma$ (B.R. =10.72%)

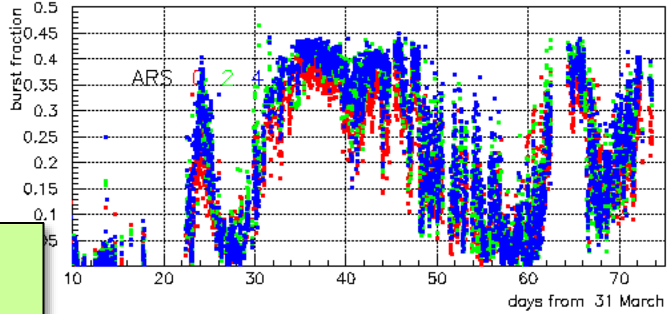
Induces a Constant rate 30 kHz (10'' PMT @ 0.5 spe)

Bioluminescence Increases average rate and produces bursts...









Both sources are not present in polar ice

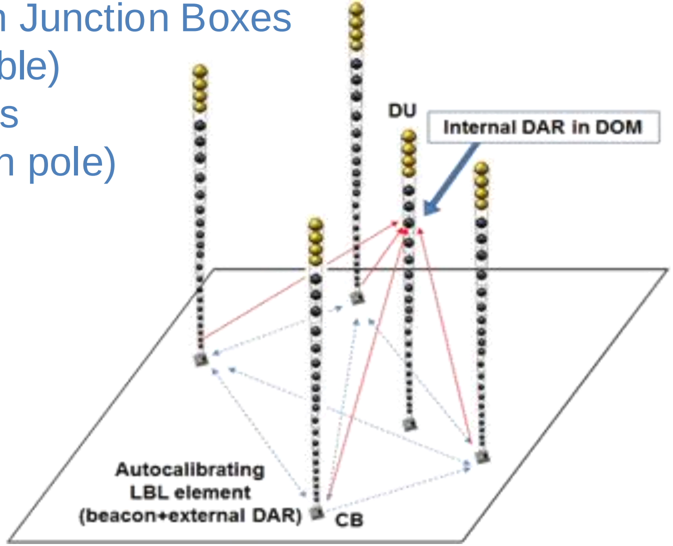
Underwater Positioning system

Digital acoustic receivers (192 kHz/24 bits) synchronised with detector master clock (<1 μs)
All data to shore in real time

→ the largest (scientific) phased array of acoustic receivers subsea

Long baseline of acoustic emitters and receivers

- reconfigurable beacons on selected DU bases and (in ARCA) on Junction Boxes
- autonomous beacons on tripods at the subsea field rim (retrievable)
- hydrophones on each DU base and (in ARCA) on Junction boxes
- acoustic sensors glued to the inside of each DOM (close to south pole)



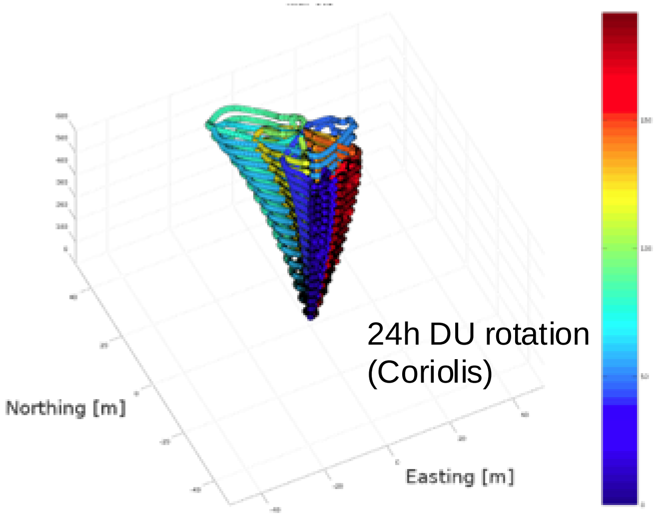
KM3NeT: Acoustic positioning system

Goal 20 cm accuracy (1ns / DOM radius)

Two reconstruction methods in action:

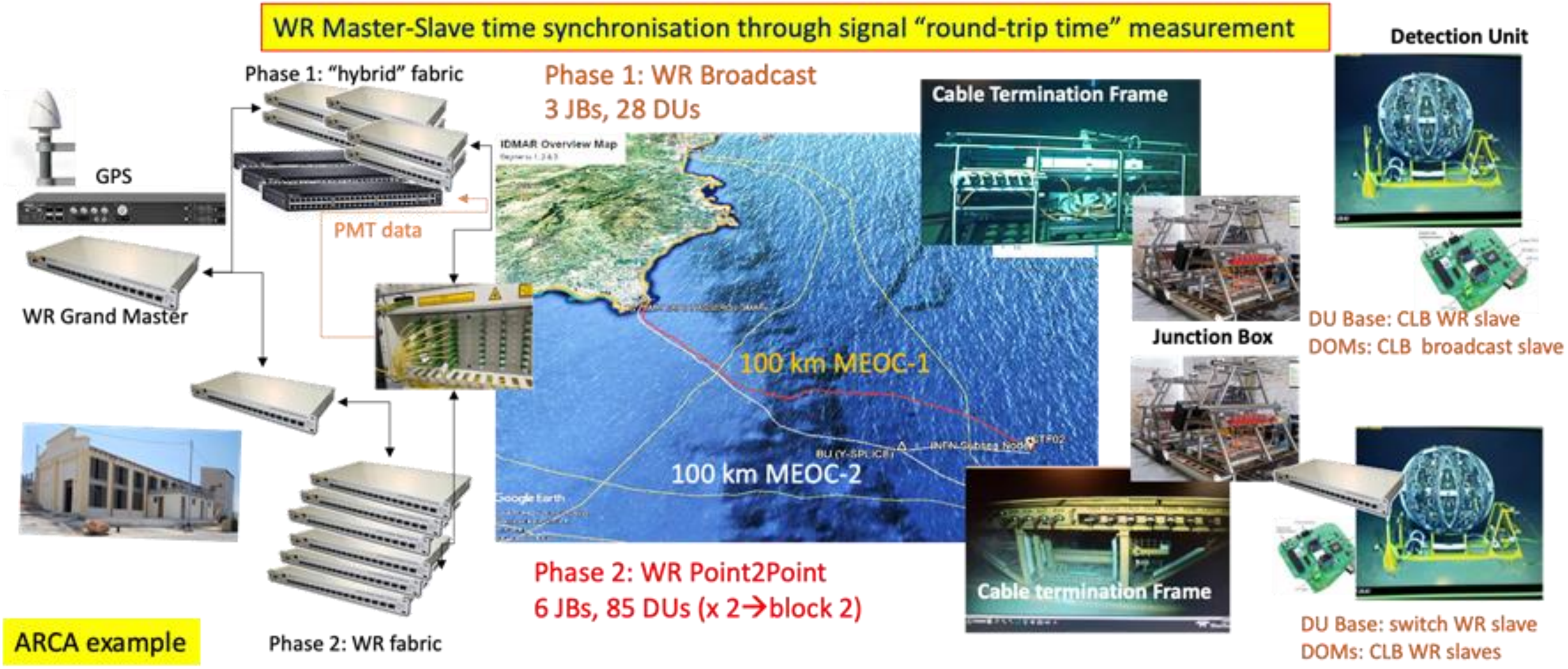
1) Measurement of time of emission (ToE, beacon/hydro) and Time of arrival (ToA, beacon/piezo) plus multi-lateration; independent measurement of DOM position

2) Global fit of ToAs (only DOM receivers) [used at present for data analysis for ARCA and ORCA]

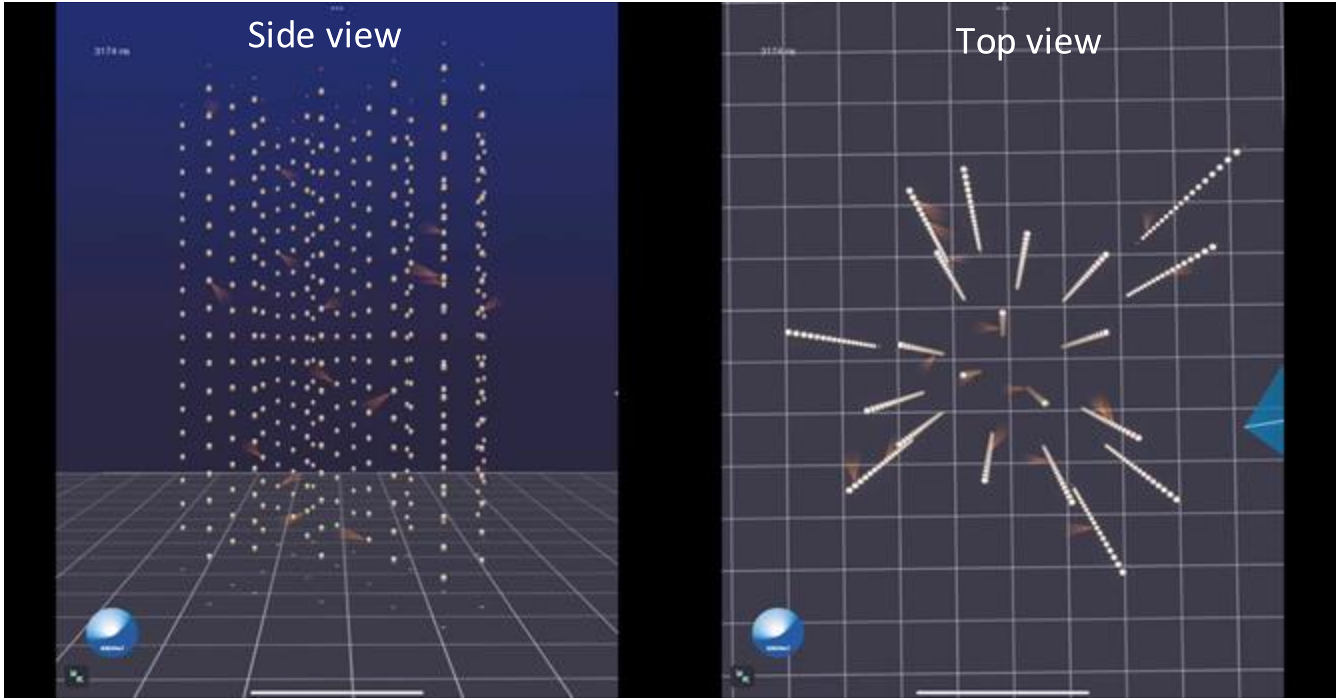


10 minutes integration

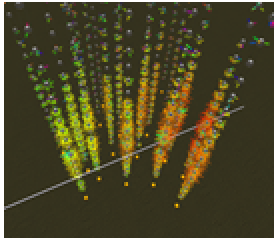
KM3NeT Time distribution underwater: White Rabbit network

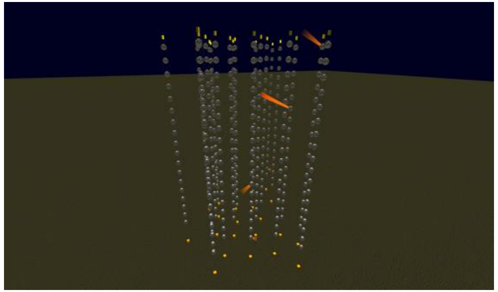


…And the super-HE neutrino event



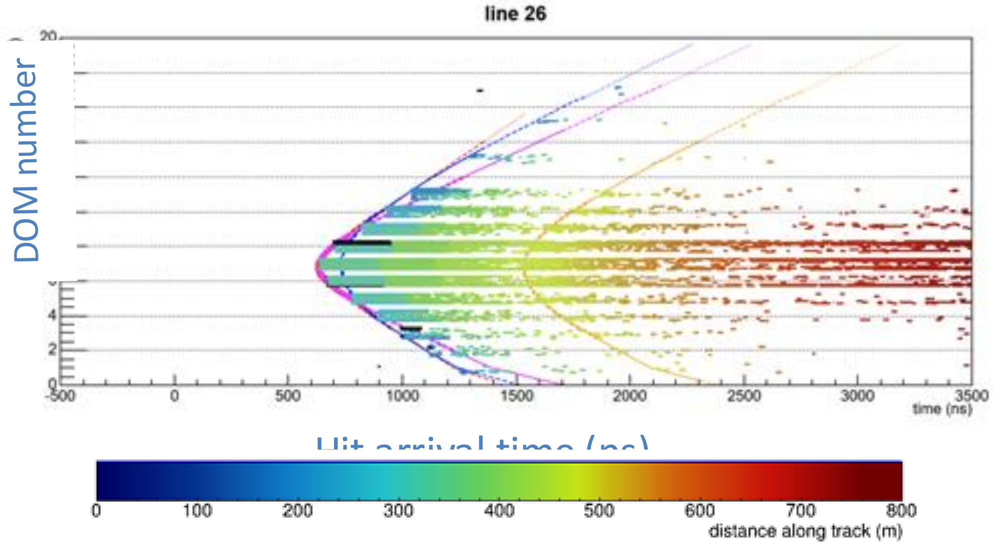
Almost all DUs hit during the event



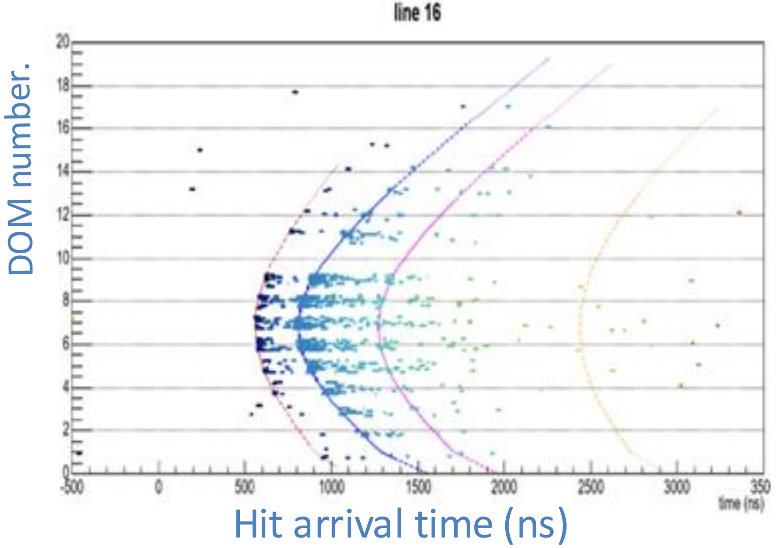


The event is horizontal (about 1° above the horizon)

ARCA: the highest energy neutrino event

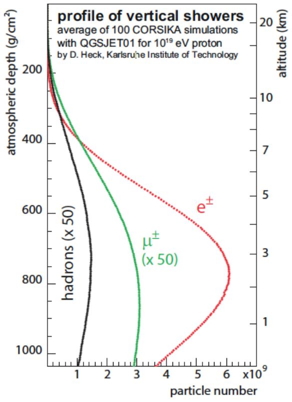


The event is reconstructed as a muon track and three showers

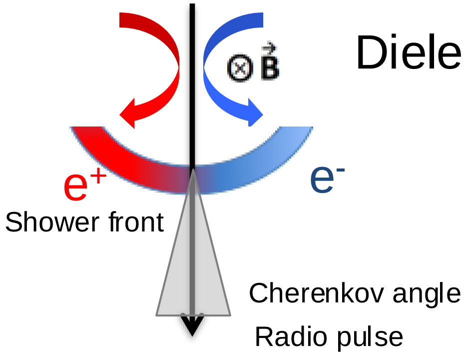


Hit times fully consistent with photons from Cherenkov emission

Radio Cherenkov: Choerent dipole radio emission

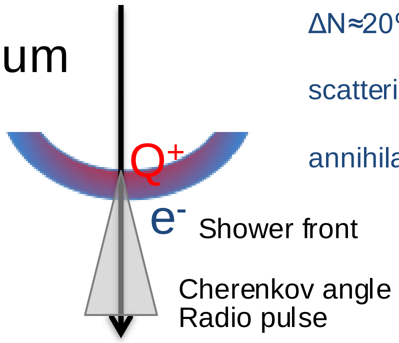


Geomagnetic radiation



Dielectric medium

Askarian radiation



$\Delta N \approx 20\%$ e^- excess
Compton scattering
positron annihilation

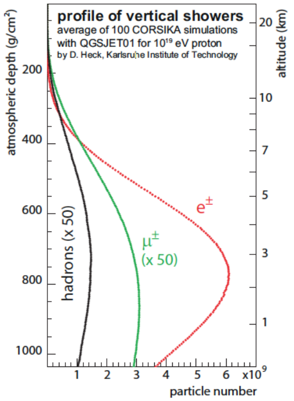
$$A_{\text{radio pulse}} \propto \Delta N \propto E_{\text{shower}}$$

Air
extended cascades, large shower front
$R_{Moliere} \approx O(100\text{ m})$, $R_{core} \approx O(10\text{ m})$
→f ≈10 MHz: 100 MHz
L ≈ O(km)
Cherenkov angle≈ 1°

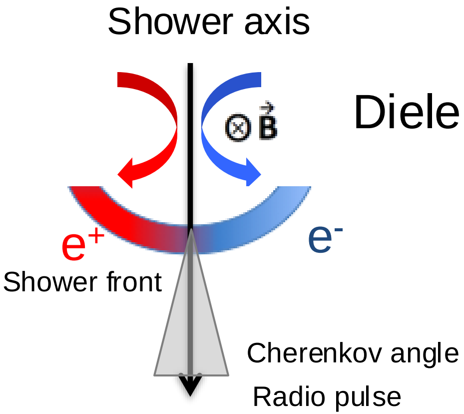
Geomagnetic effect dominates (≈80%)
large B → intense radio emission
Linear polarisation (direction of F_{Lorenz})

Radio absorption negligible

Radio Cherenkov: Choerent dipole radio emission

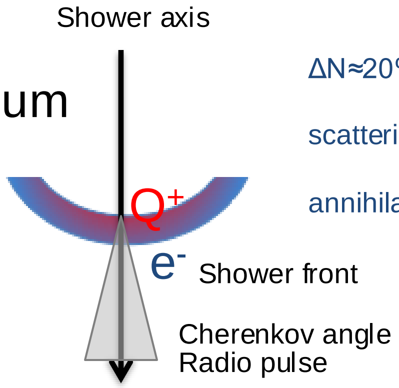


Geomagnetic radiation



Dielectric medium

Askarian radiation



$\Delta N \approx 20\%$ e^- excess
Compton scattering
positron annihilation

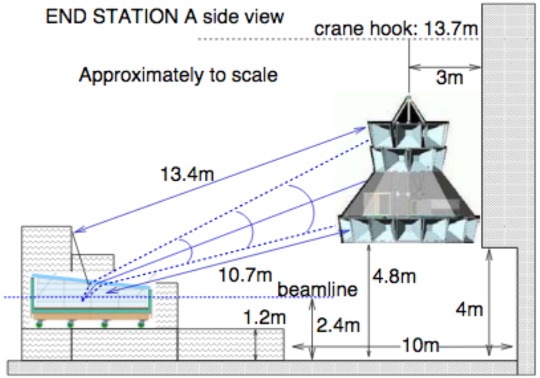
$$A_{\text{radio pulse}} \propto \Delta N \propto E_{\text{shower}}$$

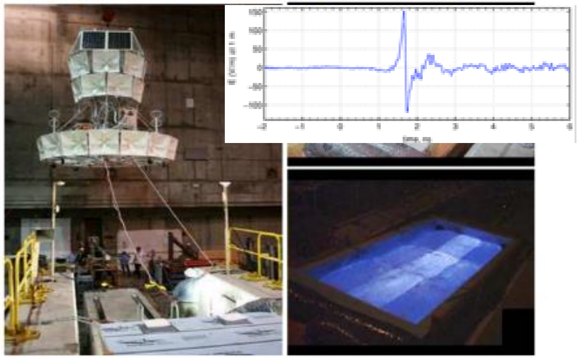
Dense media:
narrow shower front, confined core
$R_{Moliere} \approx 10$ cm → f ≈100 MHz: 1GHz
L ≈ O(10 m), LPM at extreme energies
Cherenkov angle ≈57° in ice

Askaryan effect dominates
Radial polarisation (towards shower axis)

Radio absorption O(1 km in ice)

ANITA: The SLAC experiment (2001,2004,2006)



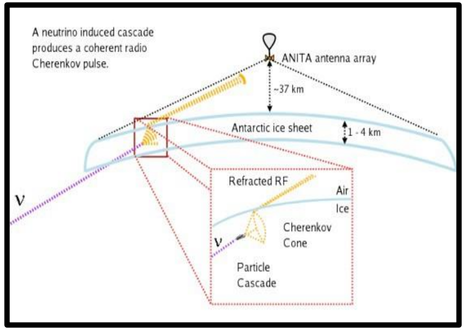


Coherent radio emission $P \propto E^2$

Production and detection of Askaryan radiation in salt and ice.

balloon borne

- 32 dual polarization antennas
- Altitude of 37km (120,000 ft)
- Horizon at 700km
- Over 1 million km^3 of ice visible



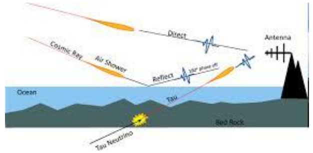
Cosmic Ray showers (reflected)
phase inversion, H-polarisation
ice-skimming neutrinos:
V-Polarisation (geometry of emission cone)

Neutrino detection with radio arrays

Ground-based air shower detectors

AERA@PAO, Lofar, GRAND, Taroge*

Direct (CR,ν) or reflected*
Inclined young showers (ν)
Direct (ν_τ) from ground

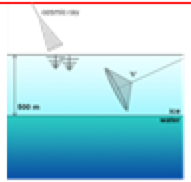


O(>10^3 km^2) instrumented, Observed volume 10^3 km^3, $E^{th} \approx 10^{16:17}$ eV

Ice surface-based detectors

ARIANNA, GNO

Direct and reflected signal (ν)

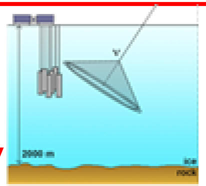


O(>10^2 km^2) instrumented, Observed volume 10^2 km^3, $E^{th} \approx 10^{16:17}$ eV

In ice detectors

ARA (RICE)

Direct and reflected signal (ν)

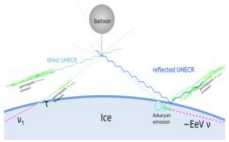


O(>10^2 km^3) instrumented volumes, Observed volume 10^2 km^3, $E^{th} \approx 10^{17}$ eV

Balloon and Satellites detectors

Anita, Forte, EVA

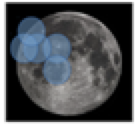
Refracted (ν) and reflected (CR,ν) signal, upgoing (ν_τ)



O(m^3, 1000 m^3) instrumented areas, Observed Volume 10^6 km^3, $E^{th} \approx 10^{18}$ eV

Ground-based lunar observatories
GLUE, NuMoon, SKA,LOFAR

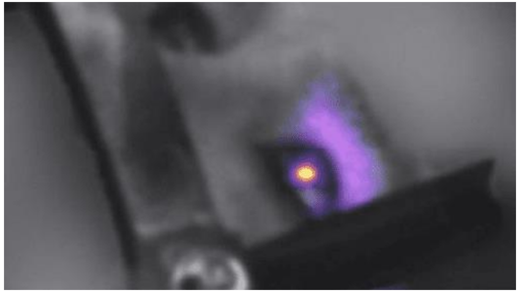
Refracted signal in lunar regolith (ν)
Skimming events (CR)



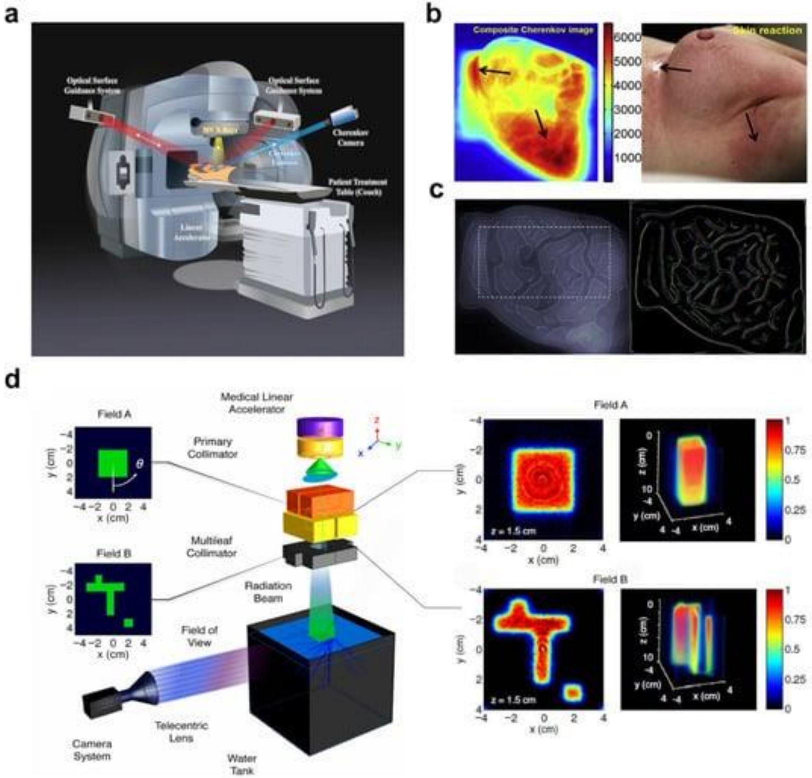
O(>10^2 m^2: 10 km^2) instrumented, Observed volume 10^6 km^3, $E^{th} \approx 10^{20}$ eV

Medical Physics imaging with Cherenkov light

Cherenkov light generated inside patient’s eyeball



Real Time Imaging Cherenkov during radiotherapy allows the visualization and recording of frame-by-frame relative maps of the dose being delivered to the tissue



Conclusion

almost 90 years from discovery

simple and cheap application

widely used in particle and astroparticle physics experiments

(and many Nobel prizes)

Brigth future ahead, also in technological applications!

…polarisation still not exploited

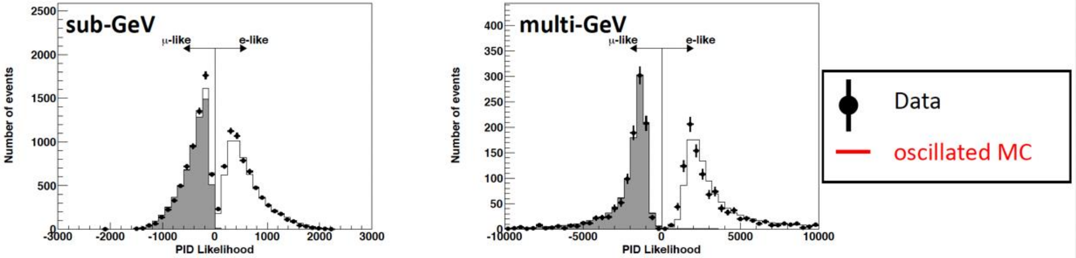
RICH deep underground

Particle ID (electron vs muon)

- Need separate measurements between ν_e and ν_μ
- Electron-like / Muon-like separation is possible from event pattern
- SK: use likelihood function
  → Good agreement

	SK-III	SK-IV w/ fiTQun
ν_e mis-ID as ν_μ	1.5%	0.05%
ν_μ mis-ID as ν_e	0.5%	0.02%

Single Ring FC events



SK-IV w/ fiTQun PID performance

42