Detectors of Cosmic Rays Gamma-Rays and Neutrinos

(III)

G. Navarra
University – INFN
Torino – Italy

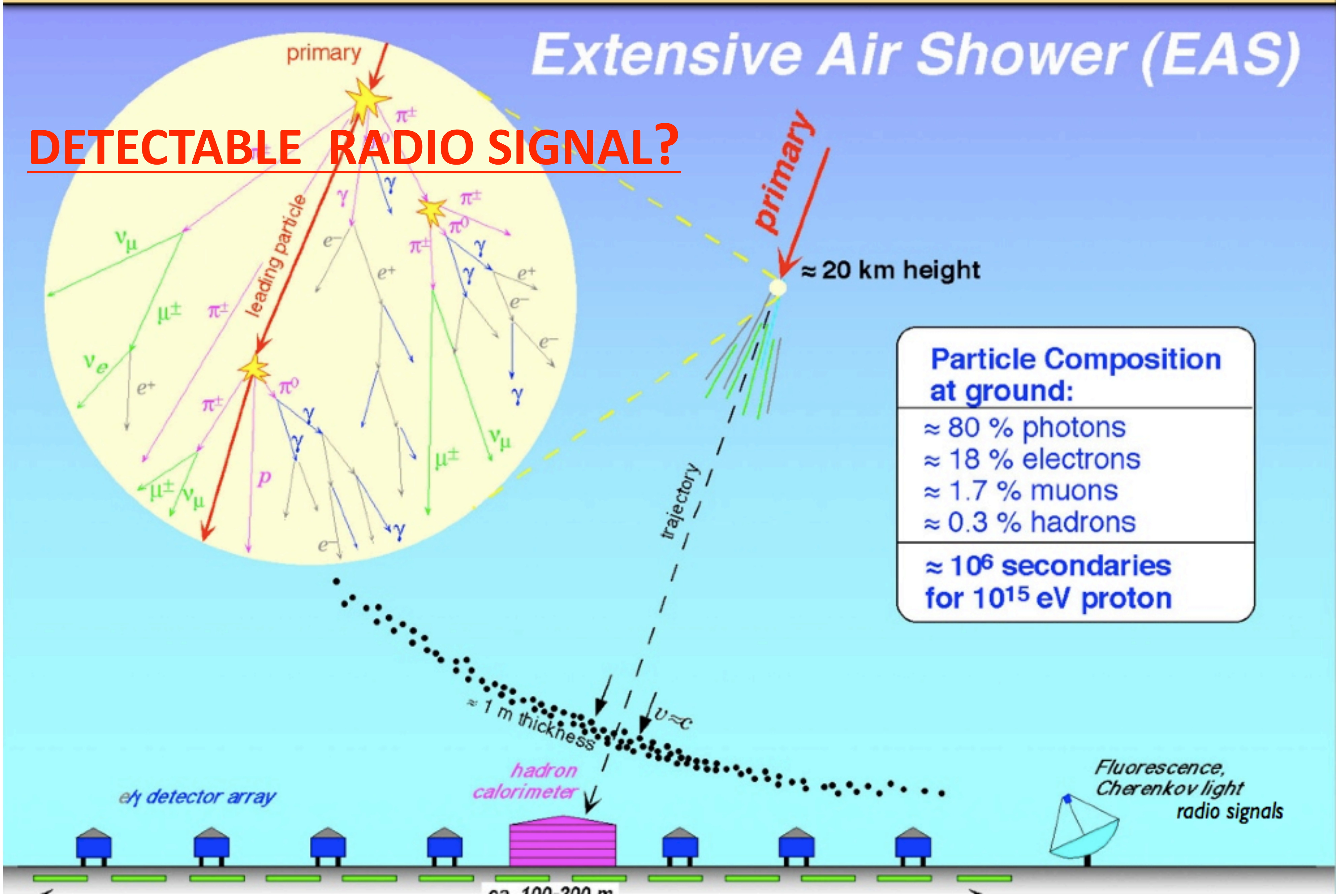
Third School on Cosmic Rays and Astrophysics
August 25 to September 5, 2008
Arequipa - Perú

(III)

EAS Radio technique
and
Neutrino & gamma-ray detectors
(introduction)

Measuring high energy CRs

DETECTABLE RADIO SIGNAL?



EAS RADIO DETECTION:

SYNCHROTRON RADIATION

Synchrotron radiation is the electro-magnetic radiation emitted by charged particles that are moving (in circular orbits) at extremely high speeds (close to the speed of light) in a magnetic field.

From Cyclotron to Synchrotron radiation

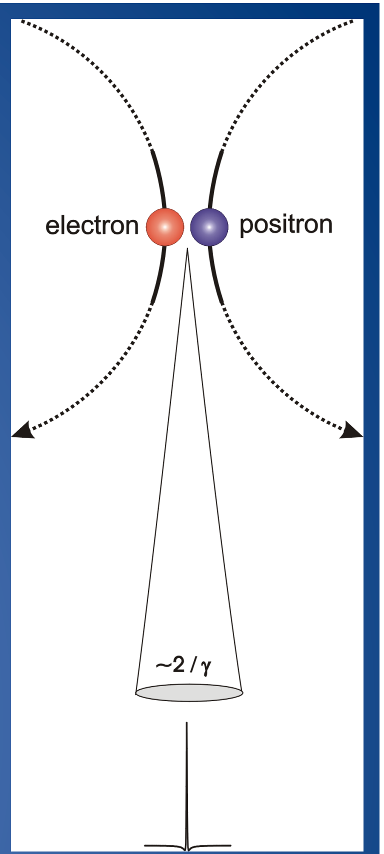
- $F = e\,(v_\perp\, B) = \gamma\, m\, v_\perp^{\,2} / r_g$ modules & $|\underline{v}| = v_\perp$
- $r_g = \gamma\, m\, v_\perp / e\, B = v_\perp / \omega_g$
- $\omega_g = e\, B / \gamma\, m$
- $T = 2\,\pi\,\gamma\, m / e\, B$

- If ϕ' isotropic in rest-frame ϕ in lab:
- $\sin(\phi) = [\sin(\phi') / (1+\beta\cos(\phi'))] / \gamma$

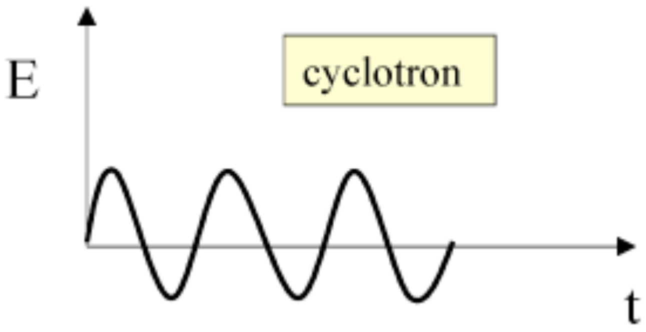
  => beamed inside cone opening $\alpha \sim / \gamma$
- $\Delta t_{obs} = (T\,\alpha / 2\,\pi)\,(1-v/c) =$ [(1-v/c) Doppler term]

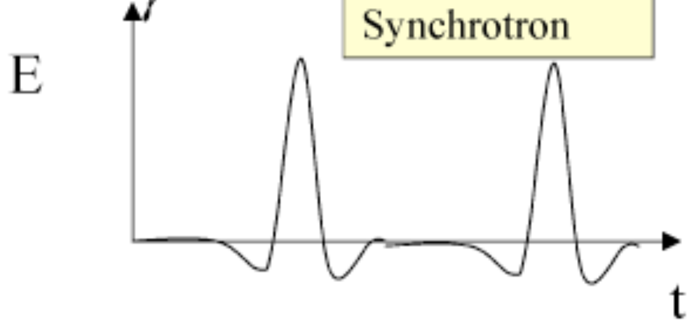
  $= 2\,\pi\,\gamma\, m / (e\, B)\; 1/\gamma / (2\,\pi)\,(1/2\gamma^2)$

➔ $\nu_{sync} \sim 1/\Delta t_{obs} \sim (e\, B/m)\,.\,\gamma^2$

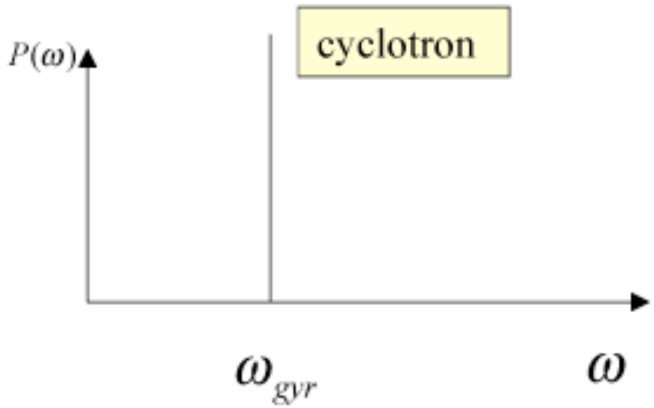


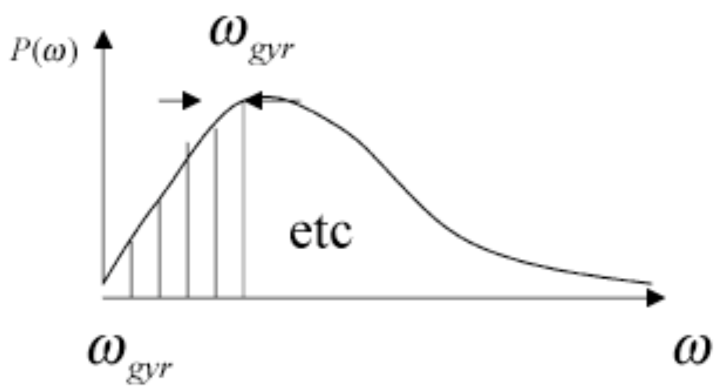
For comparison, the observed field from a cyclotron radiation is a sinusoidal function, vs. the synchrotron is spikes due to the $\sim\frac{1}{\gamma}$ beaming.





This leads to many frequency components necessary to describe the energy distribution shape.





- $\nu_{sync} \sim 1/\Delta t_{obs} \sim (e B/m) . \gamma^2$
- $\nu_{sync}^{corr} = (3 e B/ 4 \pi m) . \gamma^2$

$(3 \times 1.6\ 10^{-19} \times 0.3\ 10^{-4} / 4 \pi \times 9\ 10^{-31})\ 10^{+4} \sim 10$ GHz

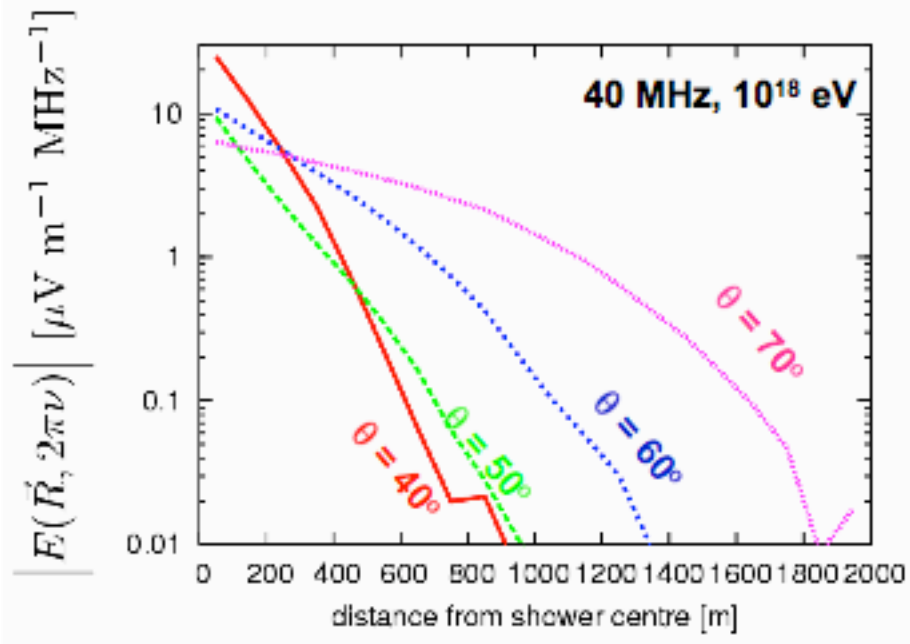
Ee ~ 50 MeV

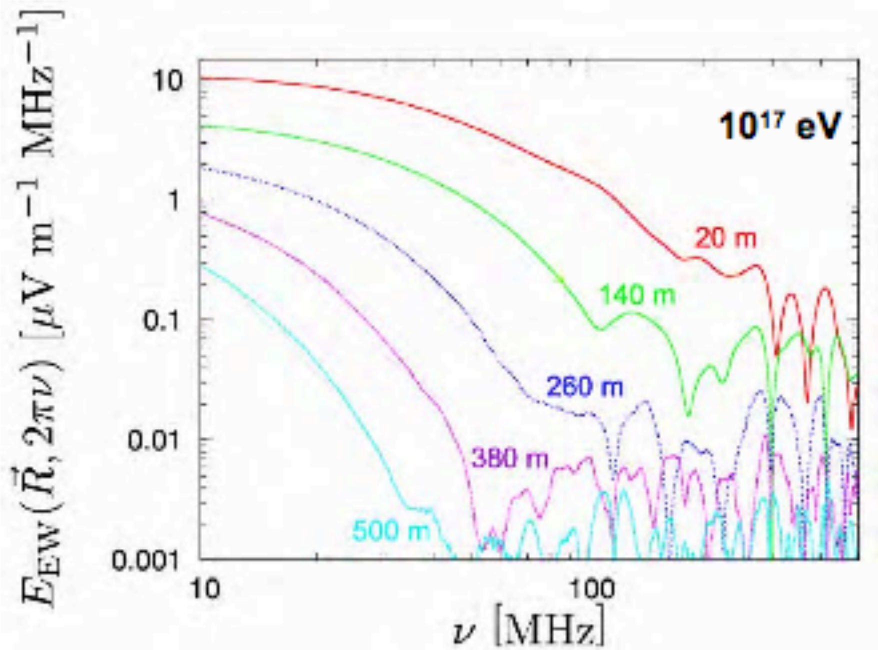
coherence

- $\lambda > d_{electron\ disk} \sim (1\text{-}10\ m)$
- $\nu = c / \lambda < c / 3\ [m] = 3.10^8 / 3 = 10^8\ s^{-1}$
- $\nu < 100$ MHz

Theory and Simulations

1. analytical calculation of emission processes
2. Monte Carlo simulations of radio signals with input of parameterized air showers
3. Monte Carlo simulations of radio signals with input of CORSIKA simulated air showers



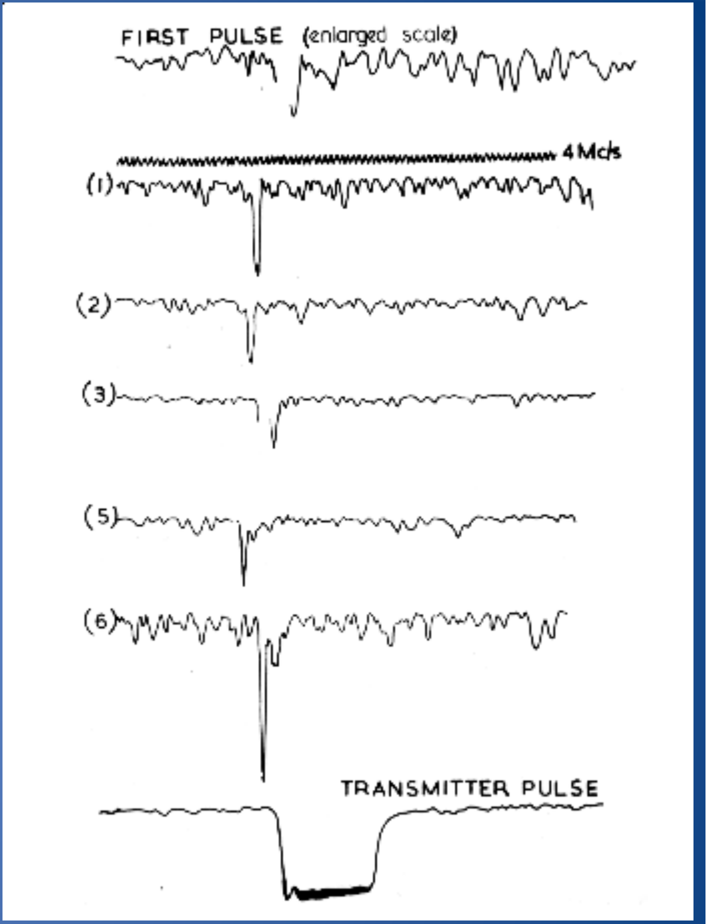


- expectations on
  - → frequency spectrum
  - → lateral distribution
  - → polarization
  - → …

T. Huege & H. Falcke
Astrop. Phys. 24 (2005) 116

Radio Emission Processes

- First discovery: Jelley et al. (1965), Jodrell Bank at 44 MHz.
- Theory papers by Kahn & Lerche (1968) and Colgate (1967)



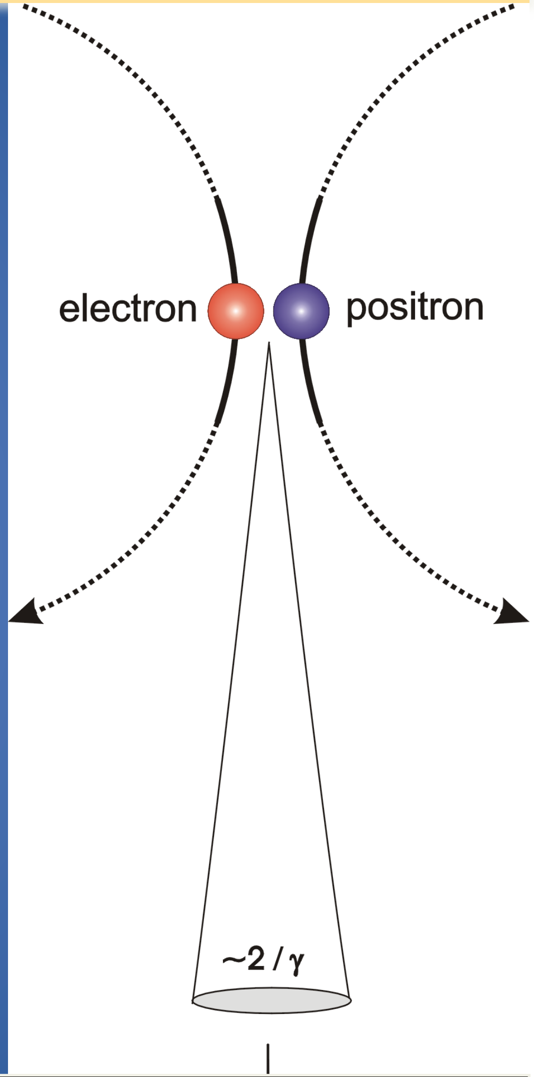
Radio Emission Processes

- First discovery: Jelley et al. (1965), Jodrell Bank at 44 MHz.
- Theory papers by Kahn & Lerche (1968) and Colgate (1967)
- coherence if λ_{rad} < thickness of shower disk (some 10 MHz)
- e^+e^- separation in geomagnetic field?
- or geosynchrotron radiation? (Gorham/Falcke)

Allan formula (1971) from his review:

$$\varepsilon_\nu = 20\left(\frac{E_p}{10^{17}\,\mathrm{eV}}\right)\sin\alpha\cdot\cos\theta\cdot\exp\left(-\frac{R}{R_0(\nu,\theta)}\right)\left[\frac{\mu V}{\mathrm{m}\cdot\mathrm{MHz}}\right]$$

ε_ν: field strength; α: angle to B-field; θ: zenith angle;
R distance from core; R_0=110 m at 55 MHz



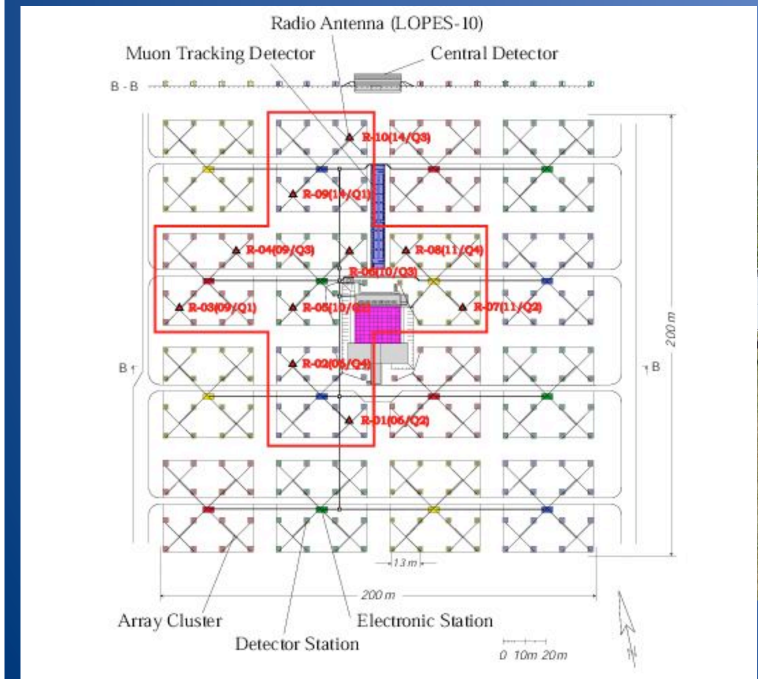
A 10^{17} eV airshower produces a 1 GJy radio flare in 25 ns (40 MHz bandwidth)!

(The brightest radio source, the sun has 1MJy.)

LOPES @ KASCADE

Goal: Answer long standing question:
Are EAS observable by their radio signals ? (30-80 MHz)
➲ **observe EAS at their maximum, 24 hrs a day!**

KASCADE-Grande used as a reference and trigger

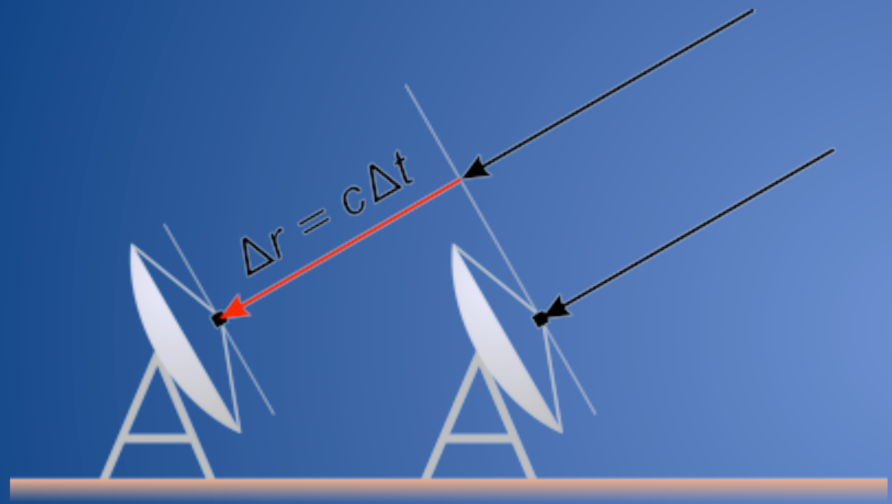


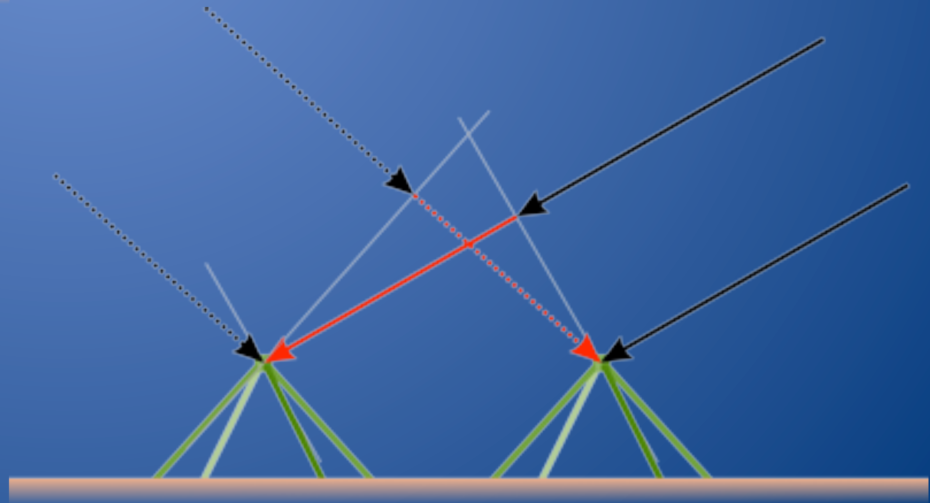
10 antennae in field, triggered by KASCADE (now 30 antennae)

Beam-forming

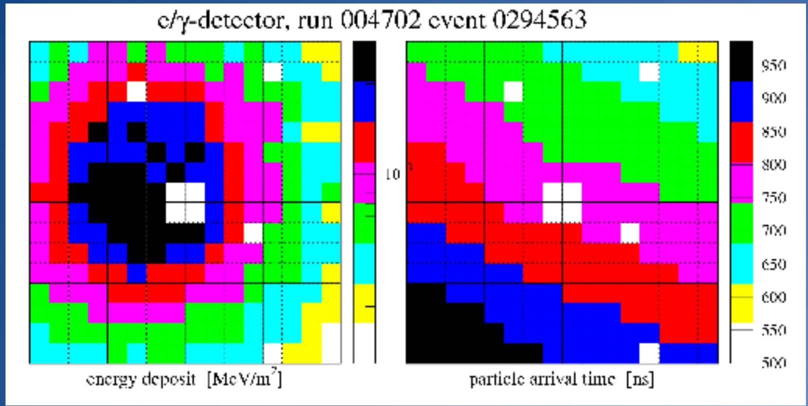
Interconnection of several telescopes

- telescopes observe same source (beamed)
- sums up field of views
- suppression of (uncorrelated) noise
- resolution scales with baseline (~λ/b instead of ~λ/d)



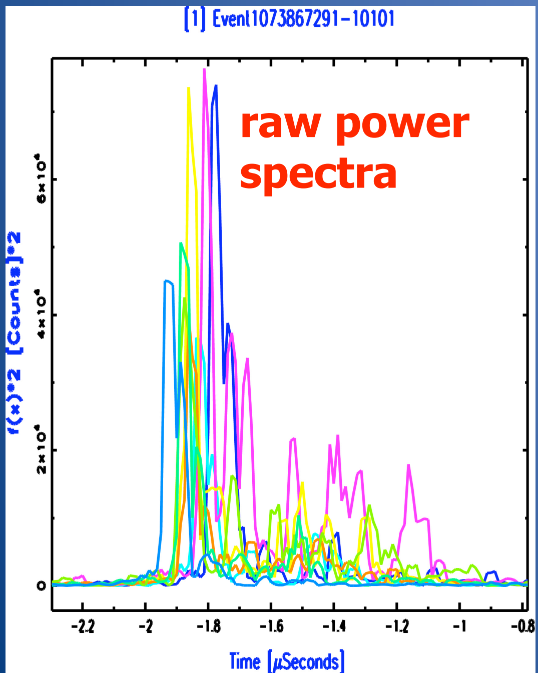


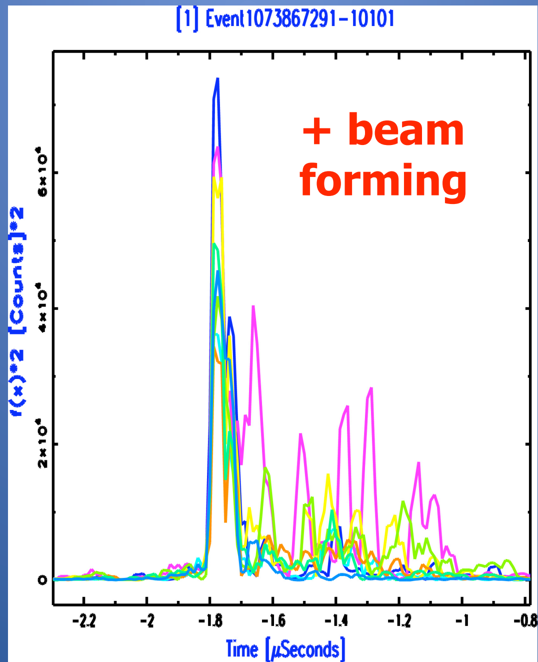
A bright Radio Event in LOPES

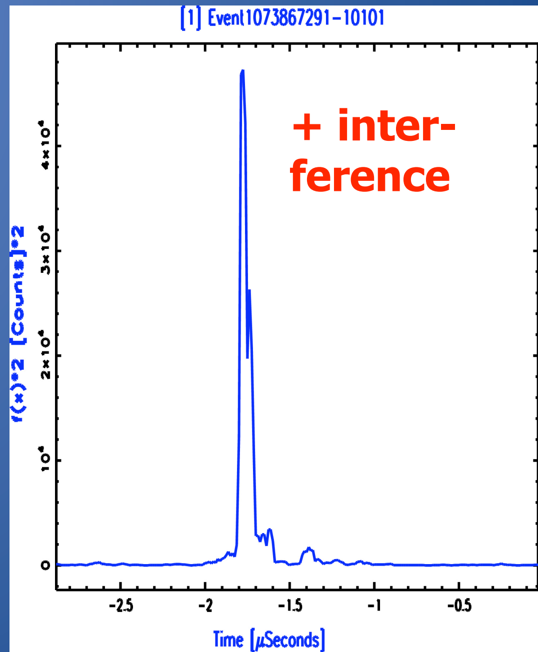


event in KASCADE

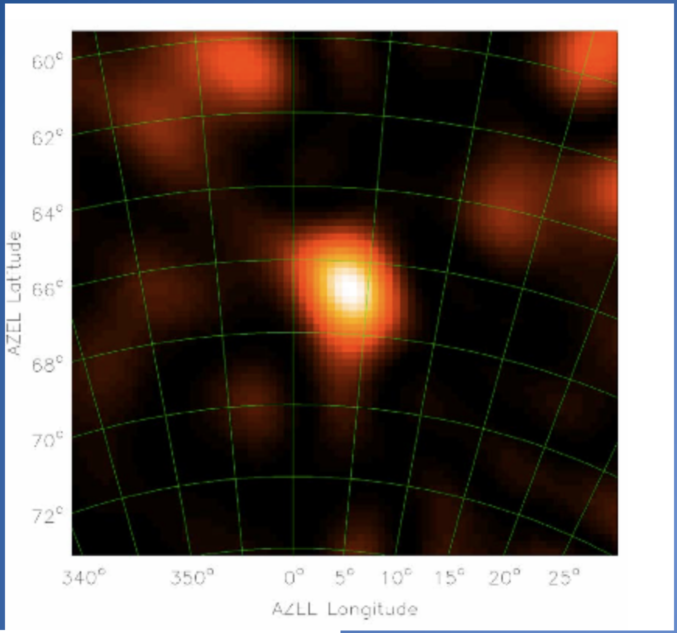
- energy ≈ 10^{17} eV
- EAS core inside antennas
- Θ = 25.5°, Φ = 42.5°
- 8 antennas were working and show signals
- signal is coherent





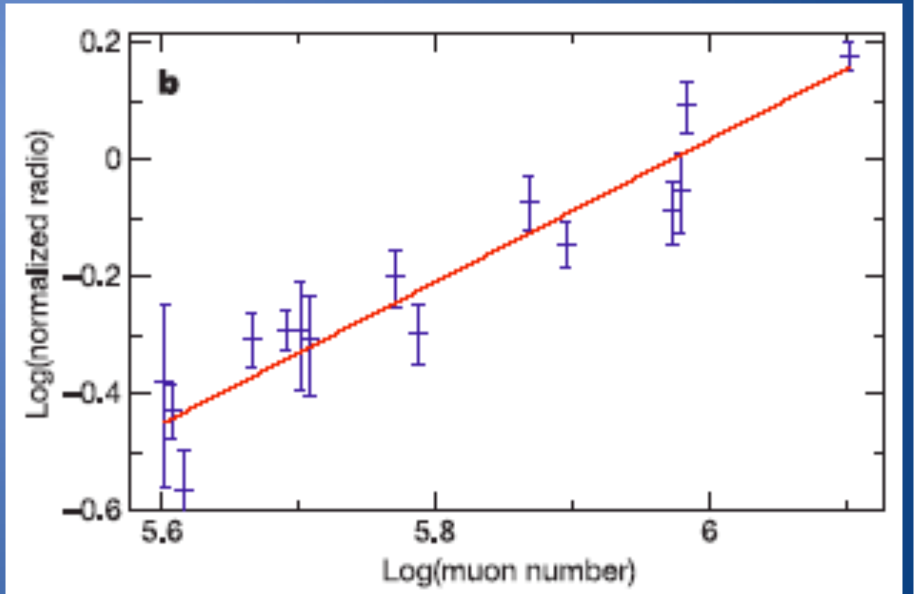


LOPES Experiment: Proof of principle

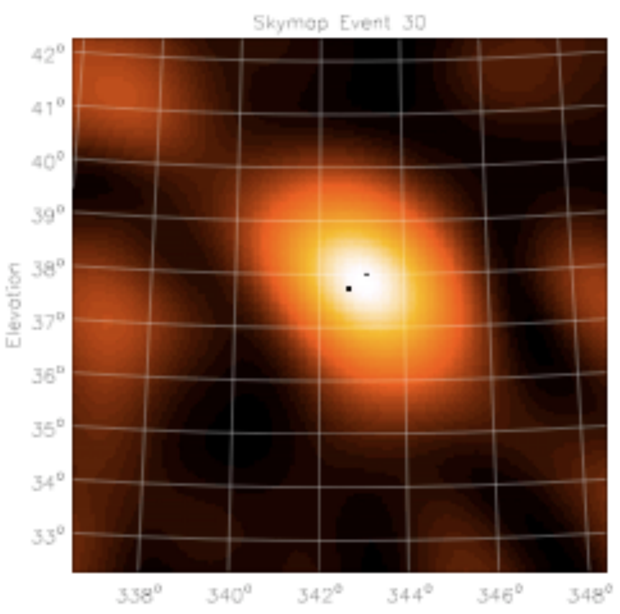


Measured EAS;
Falcke et al. Nature 435 (2005)

Radio signal vs muon number



Log (Energy)

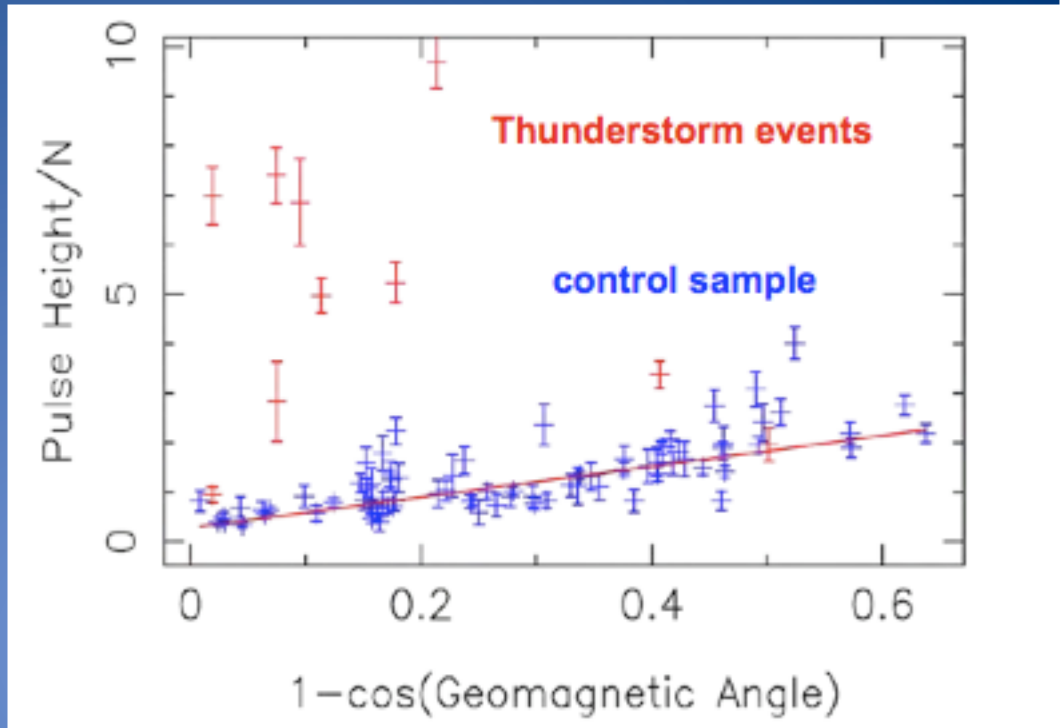


Radio Maps
after beam forming

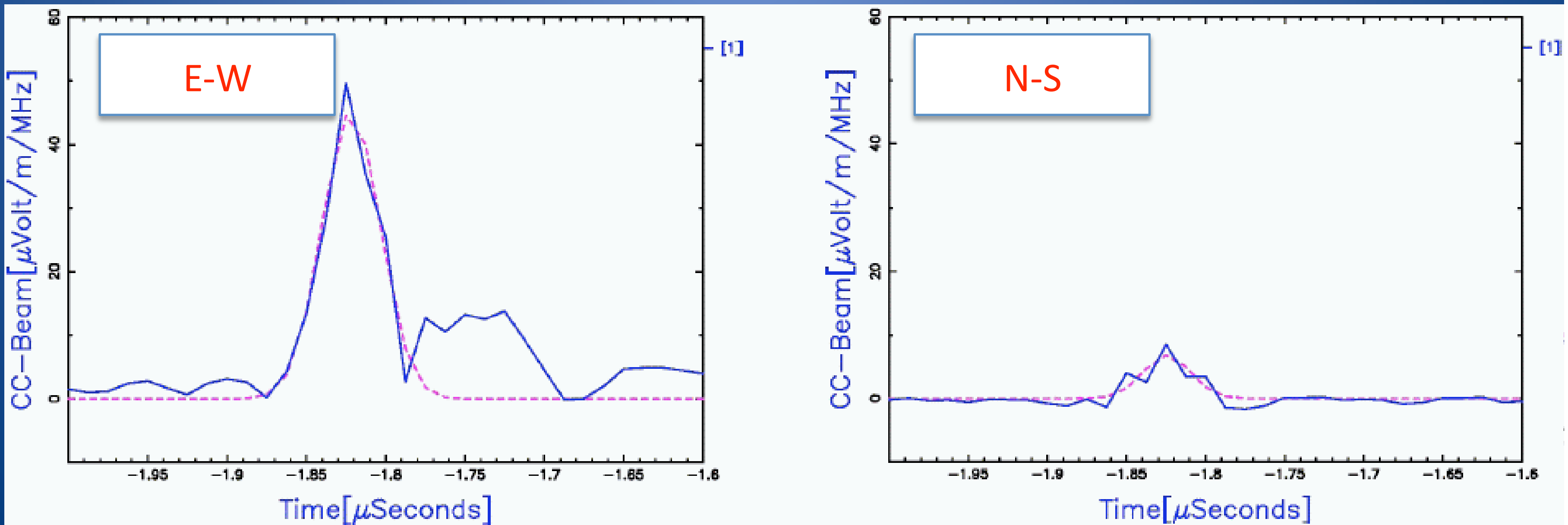
Similar initiative:
Codalema; Ardouin et al.

Buitink et al. (LOPES coll.) A&A 467(2007)385

Synchrotron?



Isar et al. (LOPES coll.) ICRC(2007) Merida



LOPES result (so far):

$$\varepsilon_\nu = 20 \cdot (E / 10^{17} \mathrm{eV}) \cdot \sin\alpha \cdot \cos\theta \cdot \exp(- R / R_0(\nu,\theta))$$

[μV / m MHz]

ε_ν	– radio pulse amplitude per unit bandwith
E	– primary energy
α	– angle to geomagnetic field
θ	– zenith angle
R	– distance to shower axis
R_0	– scaling radius (110 m at 55 MHz)

H.R. Allan, review 1971, p.269

$$\varepsilon_{est\text{-}EW} = (11 \pm 1) \cdot ((1.16 \pm 0.025) - \cos\alpha) \cdot \cos\theta \cdot \exp(- R / (236 \pm 81)\mathrm{m}) \cdot (E / 10^{17}\mathrm{eV})^{(0.95 \pm 0.04)}$$

[μV / m MHz]

LOPES coll, ICRC 2007

Moreover.. work in progress:

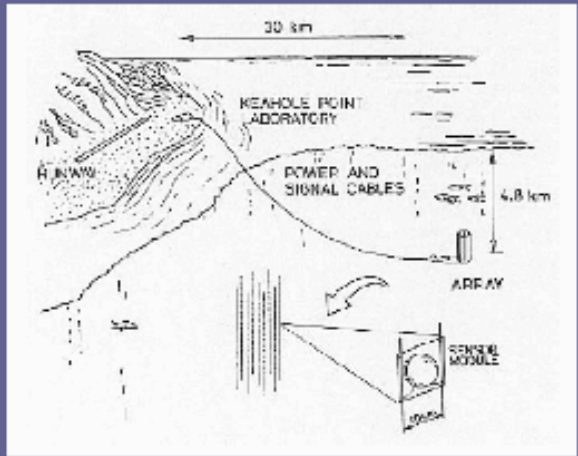
- Inclined events (…neutrinos)
- Depth of maximum
- Thunderstorm identification
- Angular resolution
- Energy threshold
- Ultra High Energies (…Auger)
- Auto-trigger

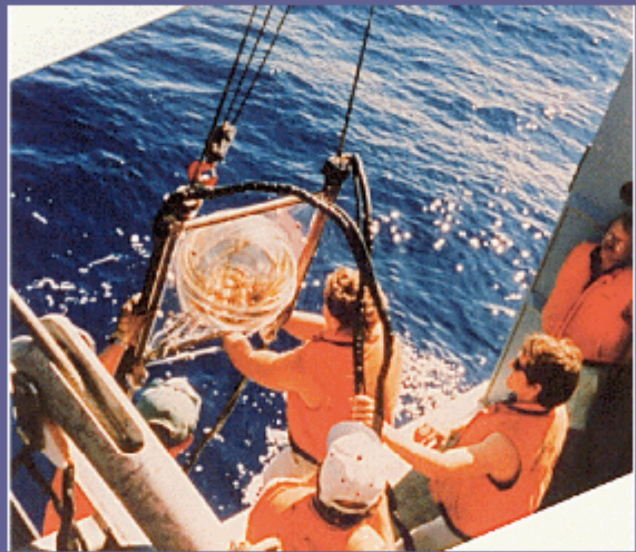
HIGH ENERGY NEUTRINO (C.L.)

P
R
O
G
E
N
I
T
O
R

Dumand

- 1976 conceptual design
- 1987 prototypes 7-15" PMTs in 17" glass vessels
- Deployment to 4.5 km depth
- 1993 funding stopped





Neutrino detectors

- Small cross section:

Interaction cross section

$$\sigma(\nu_\mu N) \approx 6.7 \bullet 10^{-36} \bullet E[TeV] /cm^2/ n$$

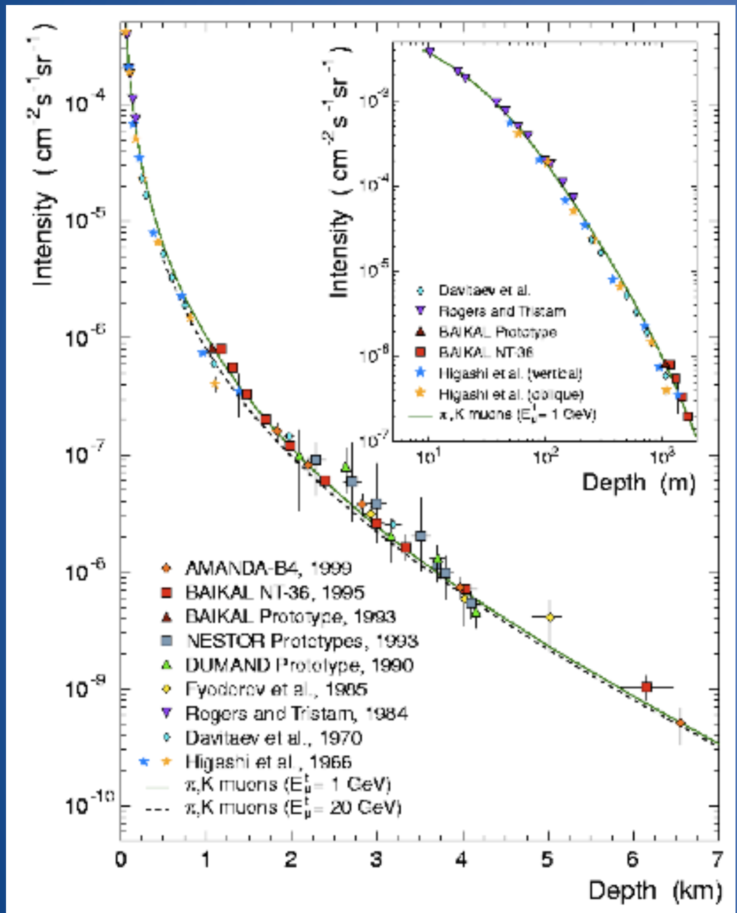
Interaction probability [H_2O, d=1km]:

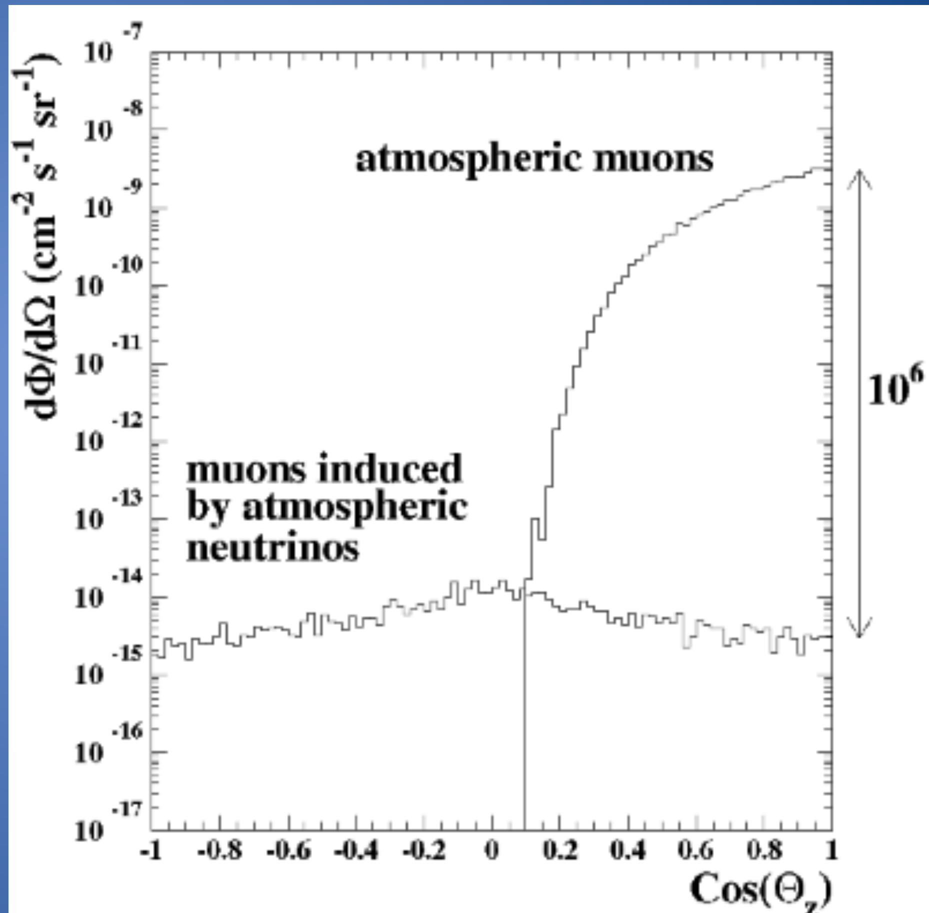
$$W=N_A\sigma d\rho \approx 4 \bullet 10^{-7} \bullet E [TeV]$$

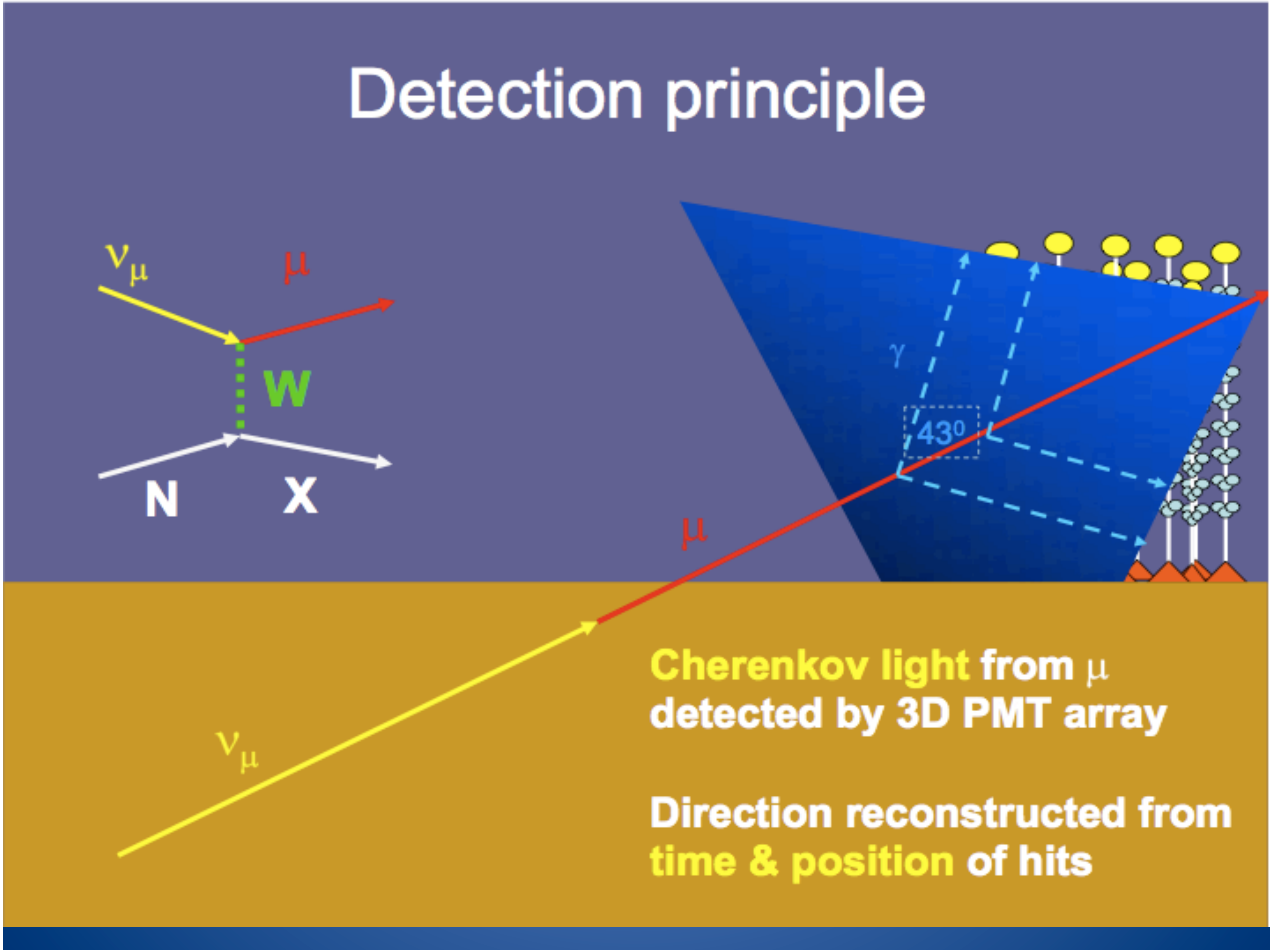
around TeV, than ~ $E^{0.4}$

Relevant $\nu_\mu + N \rightarrow N + X + \mu$

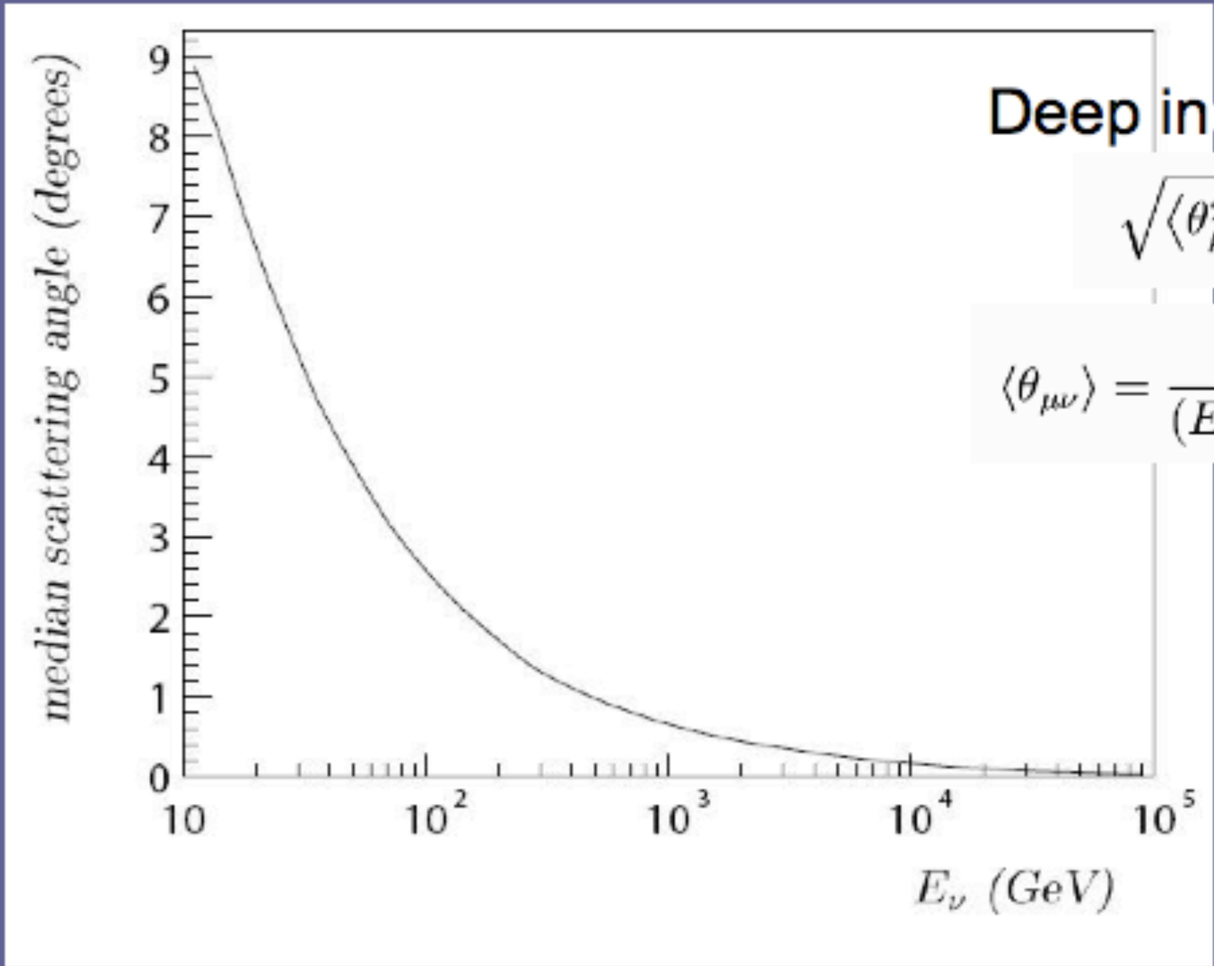
And large background:






Detection principle
ν_μ
μ
W
N
X
γ
43^0
μ
ν_μ
Cherenkov light from μ
detected by 3D PMT array
Direction reconstructed from
time & position of hits

Neutrino-Muon angle



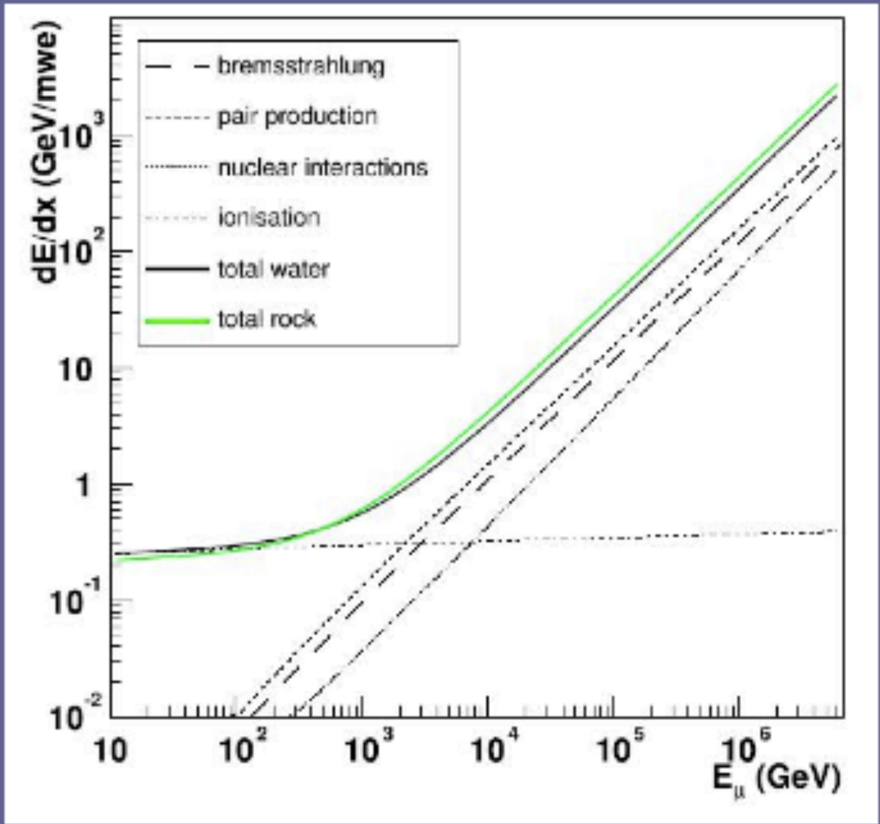
Deep inelastic scattering :

$$\sqrt{\langle \theta_{\mu\nu}^2 \rangle} \approx \sqrt{\frac{m_N}{E_\nu}}$$

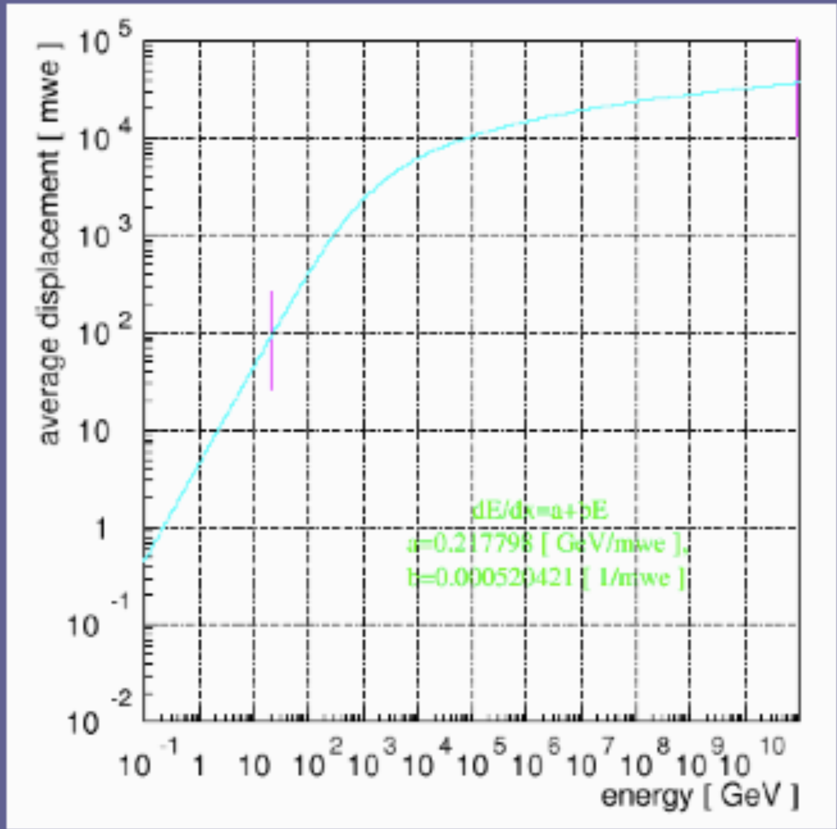
$$\langle \theta_{\mu\nu} \rangle = \frac{0,64^\circ}{(E_\nu/TeV)^{0,56}} \qquad E_\nu > 10\,\mathrm{TeV}$$

$$\theta \le \frac{1.5\,\mathrm{deg.}}{\sqrt{E_\nu[\mathrm{TeV}]}}$$

For muon neutrinos



Muon energy loss

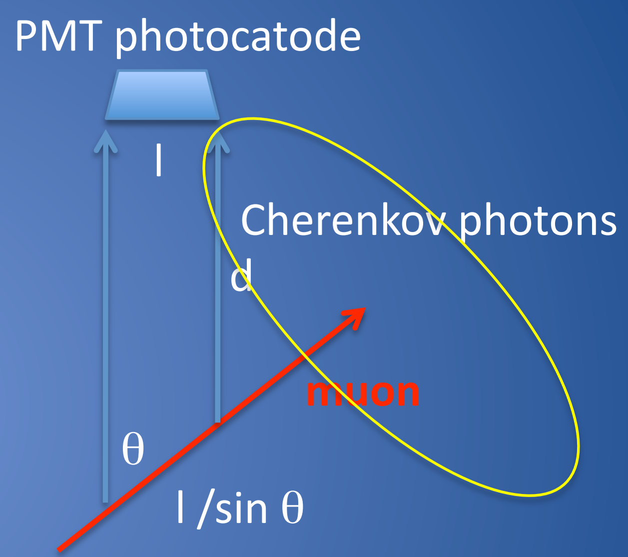


Muon range in water

Neutrino can be detected outside detection volume

Scale of the array grid

medium	n	θ_{max} (β=1)	N_{ph} (eV^{-1} cm^{-1})
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4



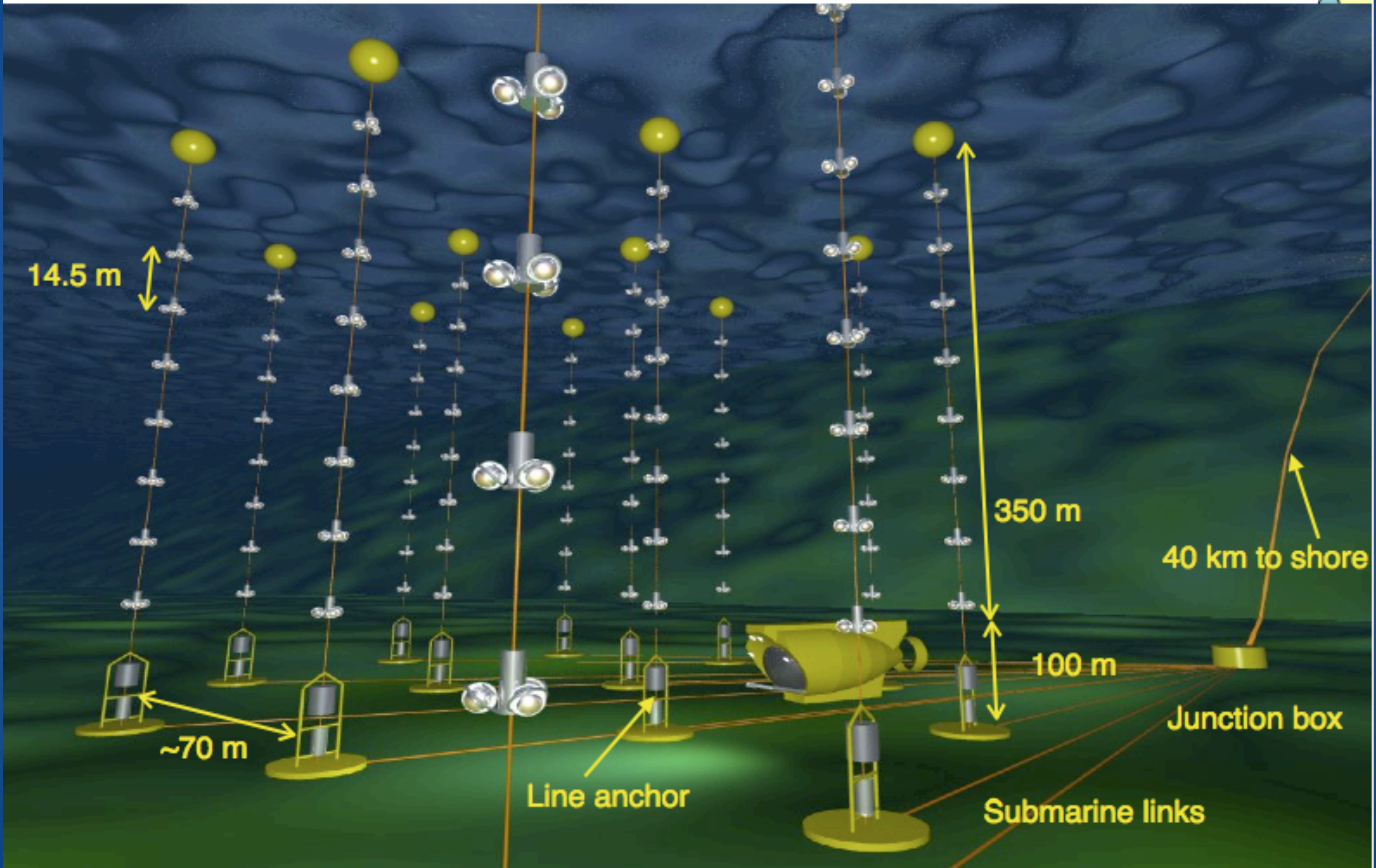
$$N_{pe} \sim N_{ph} \,.\, (l/\sin\theta) \,.\, l/(2\pi d \cos\theta) \,.\, \varepsilon_q > 1$$

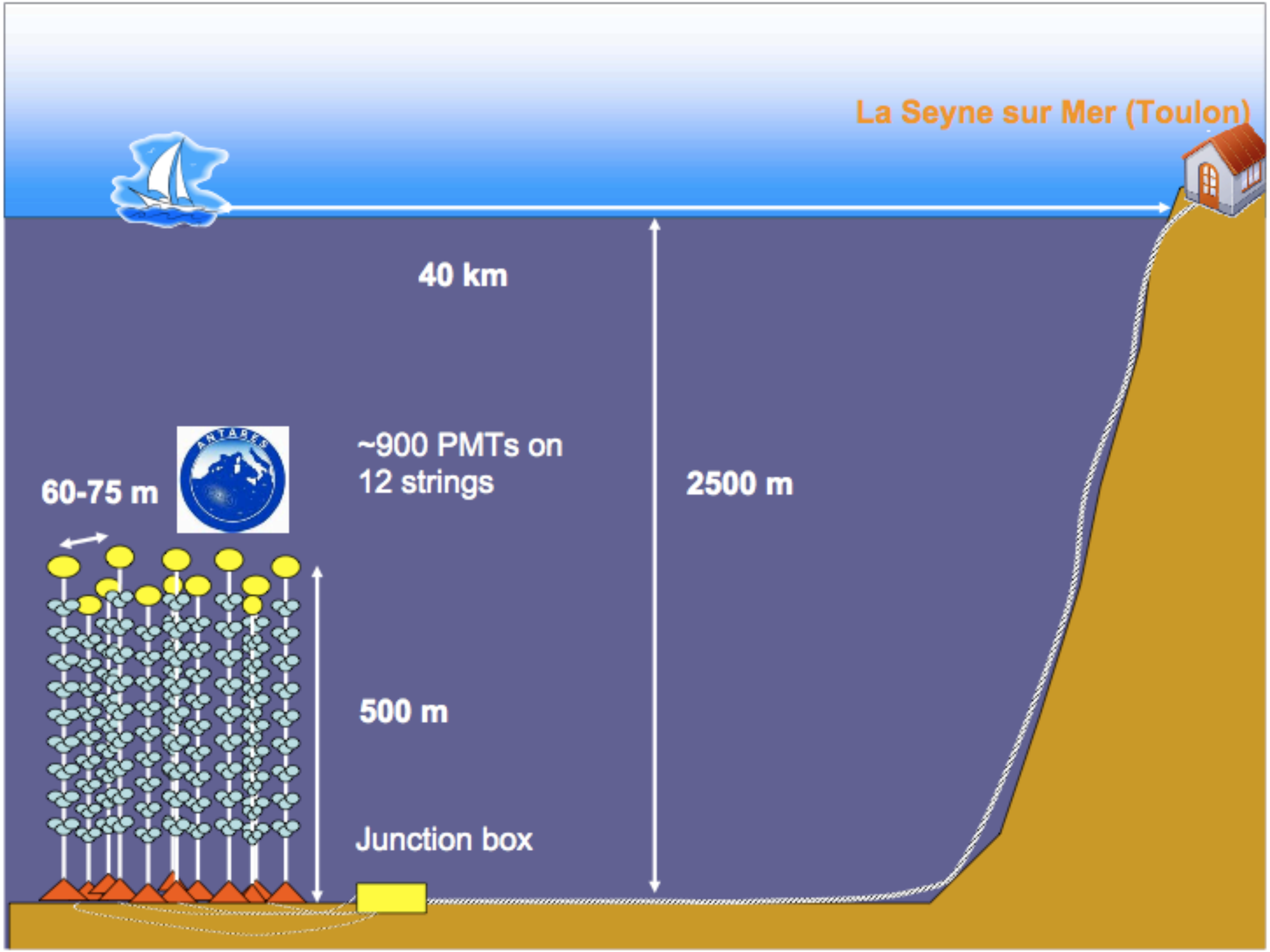
$$d < N_{ph} \,.\, (l/\sin\theta) \,.\, l/(2\pi \cos\theta) \,.\, \varepsilon_q$$

$\sim 160\ 30^2\ 0.2 / \pi \sim 100$ m ← scale of array (no absorption)

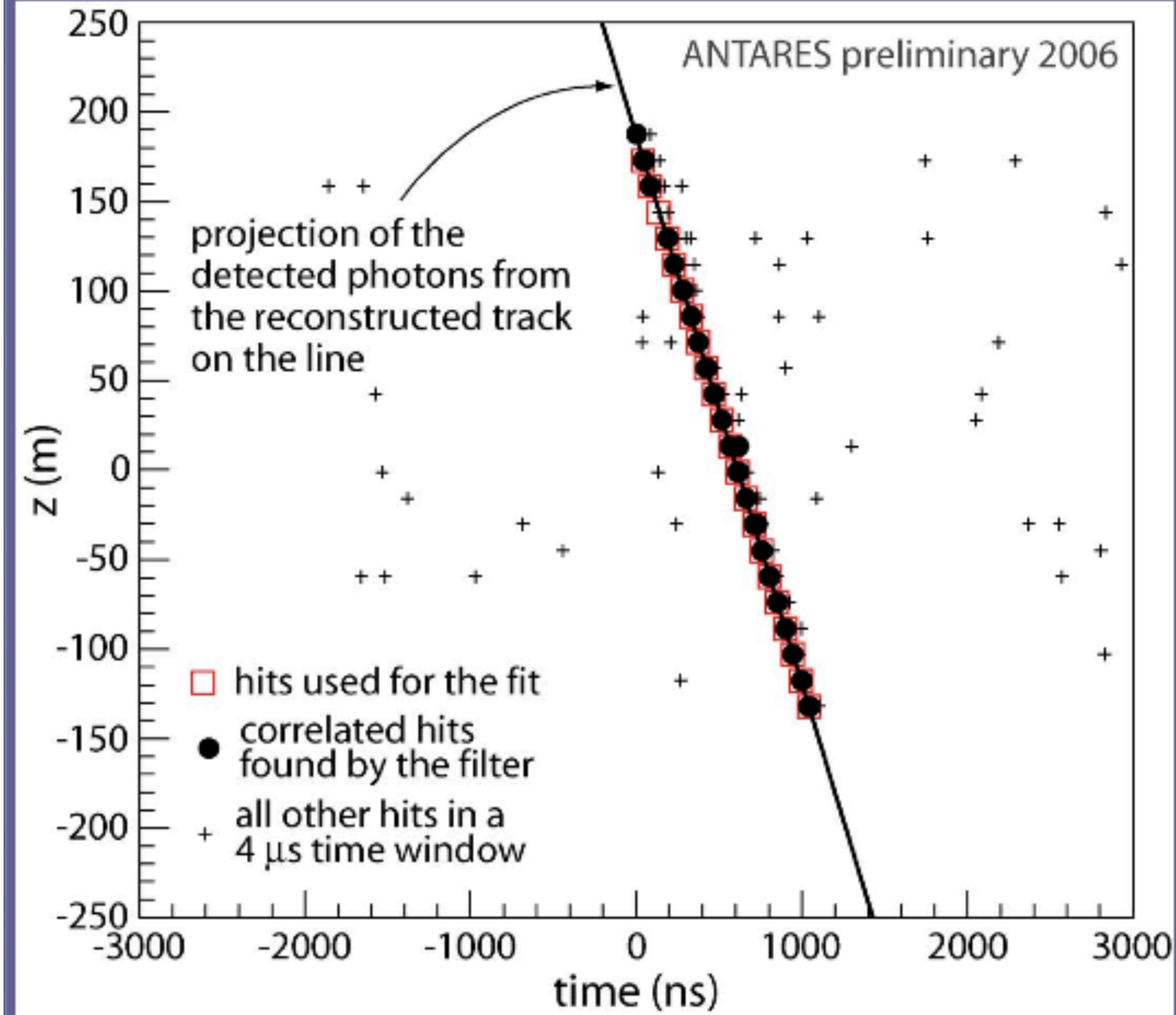
Antares detector layout

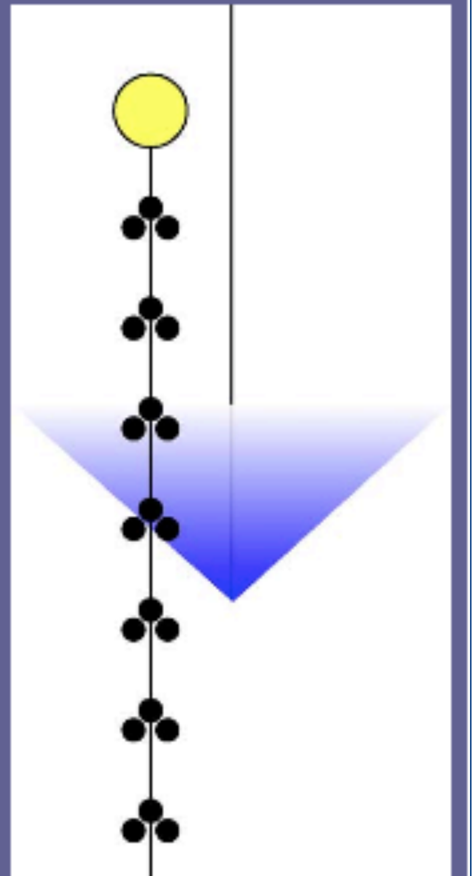
planned are 900 PMT, 12 lines, 25 stories/ line, 3 PMT/ story




La Seyne sur Mer (Toulon)
40 km
60-75 m
~900 PMTs on
12 strings
2500 m
500 m
Junction box

Display of a downgoing muon in Line 1





Nestor

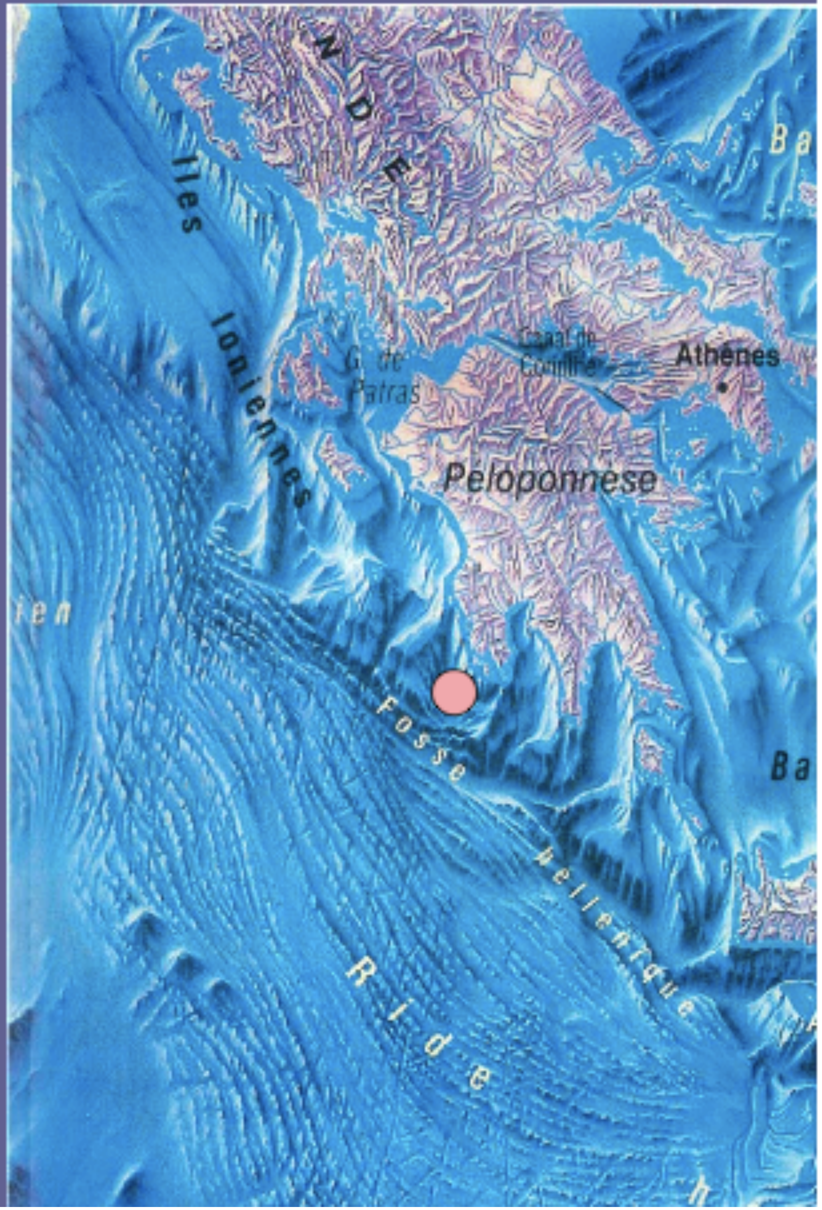
depth: ~4000m

transmission length:
55 $\pm$ 10m at λ=460 nm

underwater currents:
<10 cm/sec
(measured over the last 10 years)

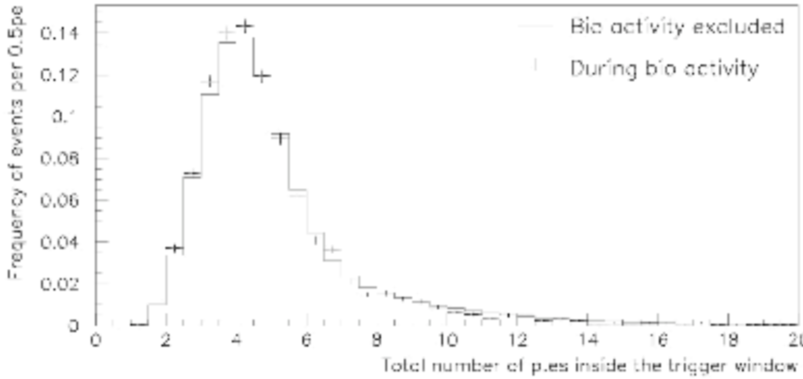
optical background:
~50 kHz/OM due to K40 decay,
bioluminescence activity
(1% of the experiment live time)

sedimentology tests:
flat clay surface on sea floor
good anchoring ground.

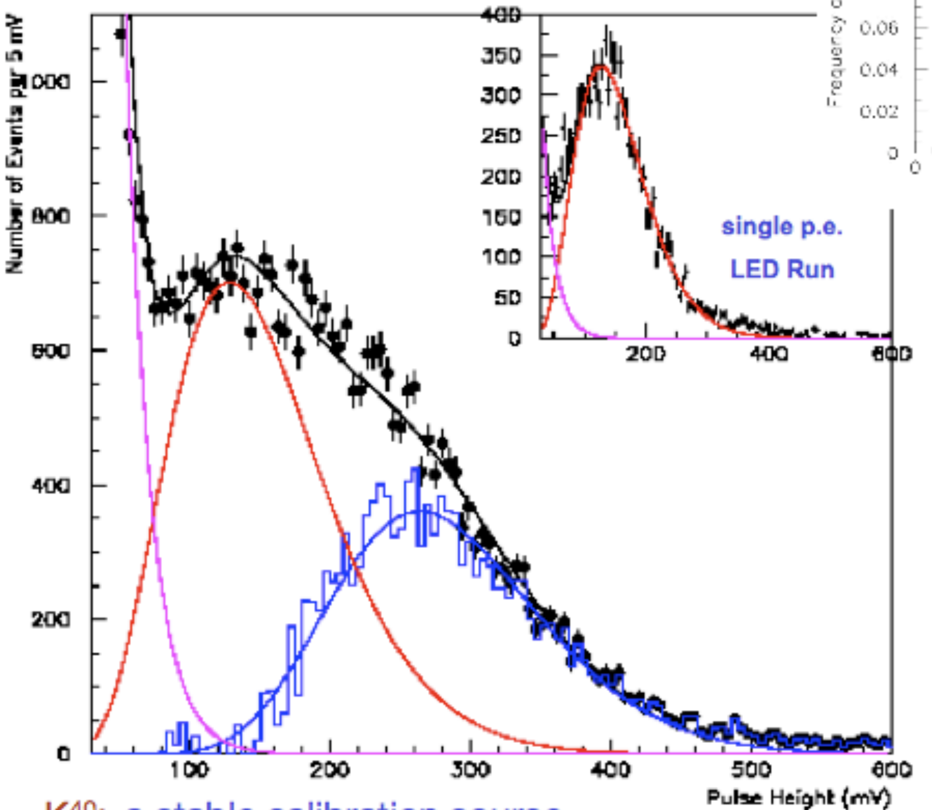


Backgrounds

Data from a depth of 3800 m: PMT Pulse Height Distribution



Bioluminescence Occurs
for the 1.1% ± 0.1%
of the Active Experimental
Time



single p.e. pulse height distribution

two p.e.s pulse height distribution

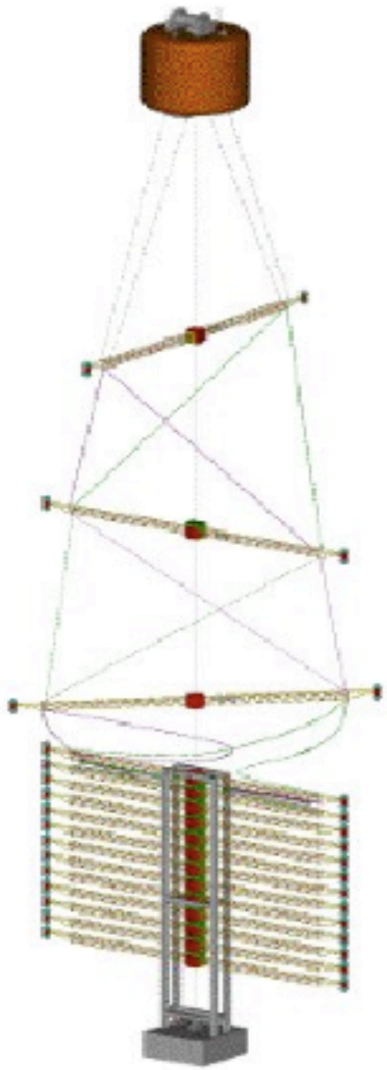
dark current pulse height distribution

sum of the above

K^{40}: a stable calibration source

THE NEMO PROJECT

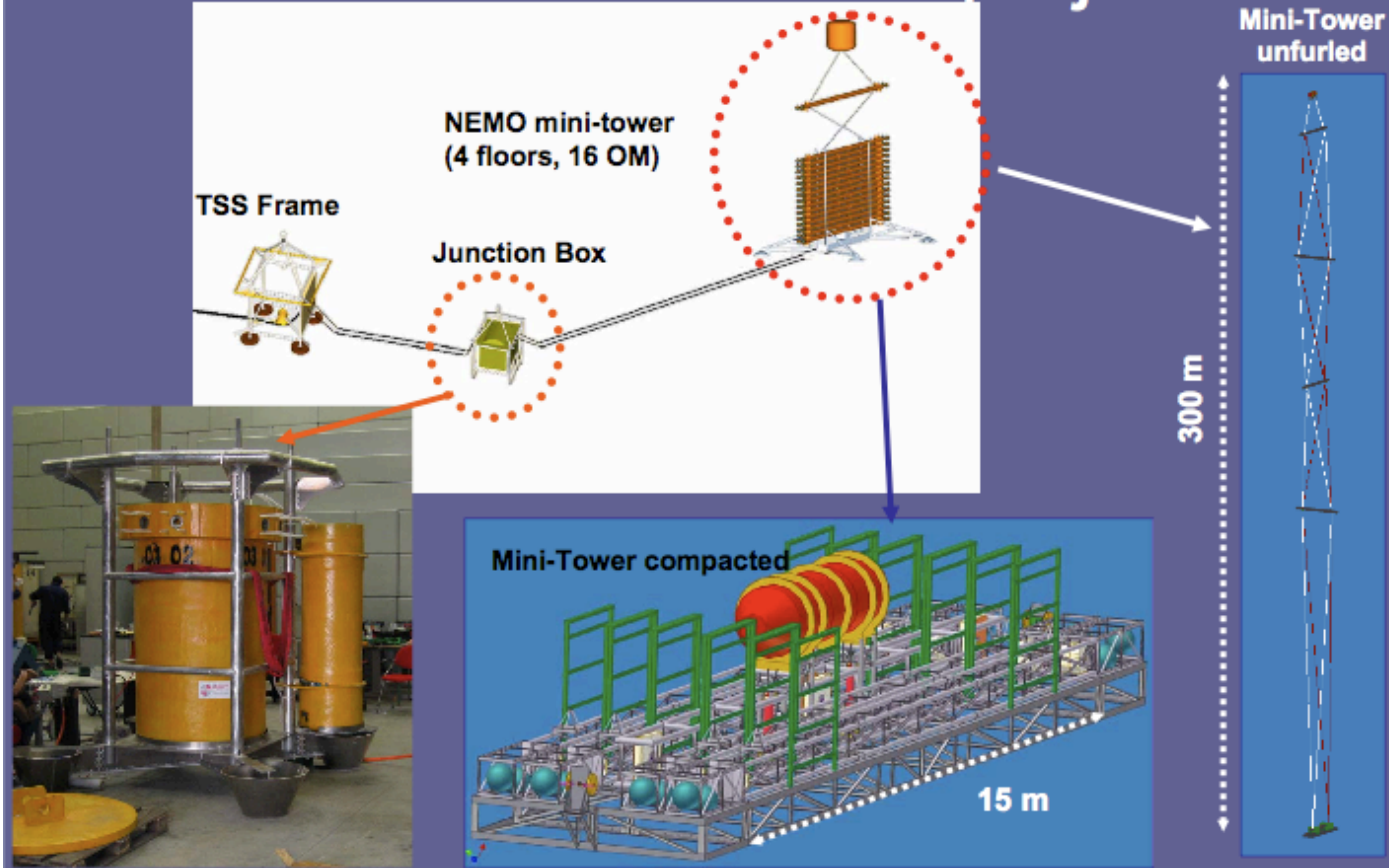
- Extensive exploration of a site close (80 km) to Capo Passero near Catania, depth 3340 m
- More than 20 sea campaigns on the site to measure and monitor water optical properties, optical background, deep sea currents, nature and quantity of sedimenting material
- R&D towards km^3: architecture, mechanical structures, readout, electronics, cables ...



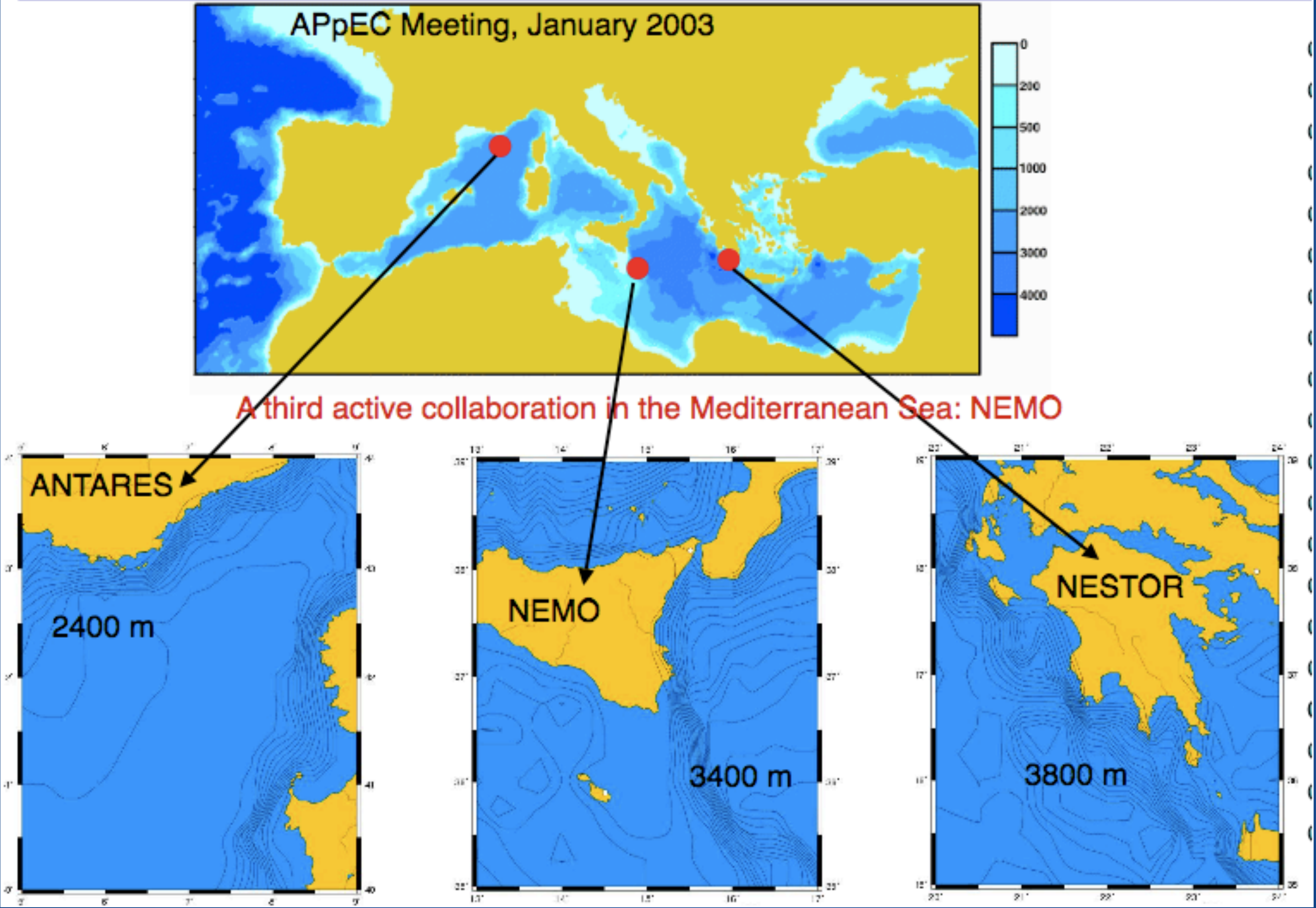
<u>Example: Flexible tower</u>

- 16 arms / tower, 20 m arm length, arms 40 m apart
- 64 PMs per tower
- Underwater connections
- Up- and down-looking PMTs

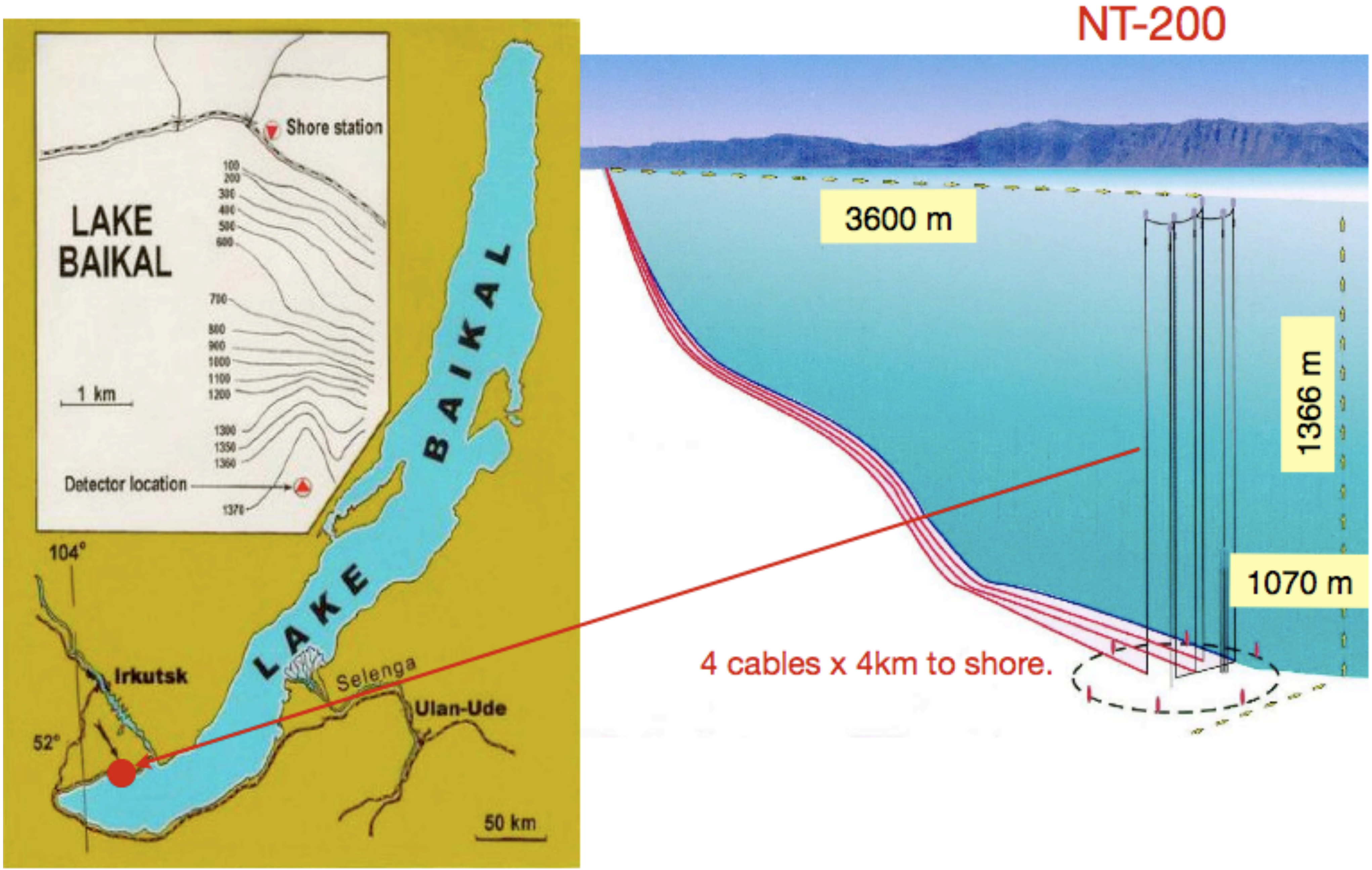
The NEMO Phase-1 project



The Mediterranean KM3



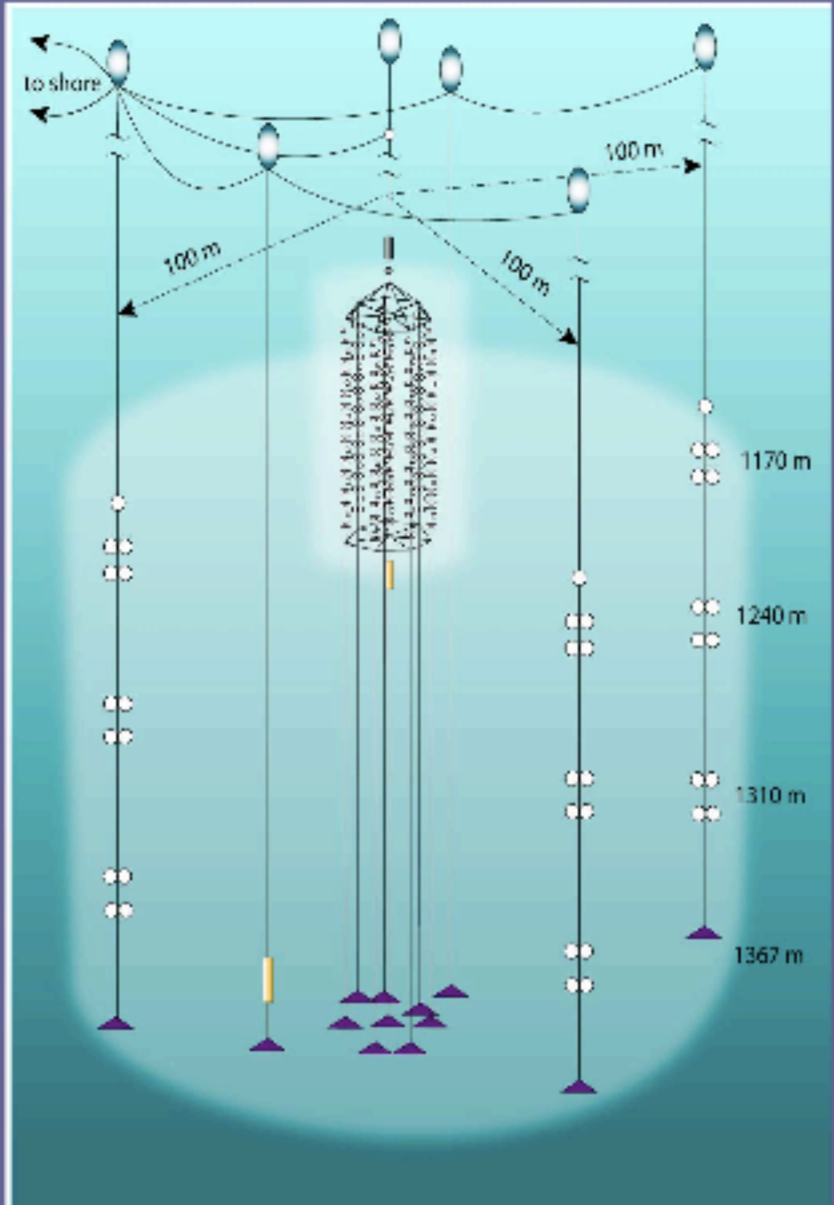
The Baikal detector site



Deployment

Ice – a natural deployment platform, stable for 6-8 weeks/year:
- Maintenance & upgrades
- Test & installation of new equipment
- Operation of surface detectors (EAS, acoustics,…)
- Electrical winches used for deployment operations

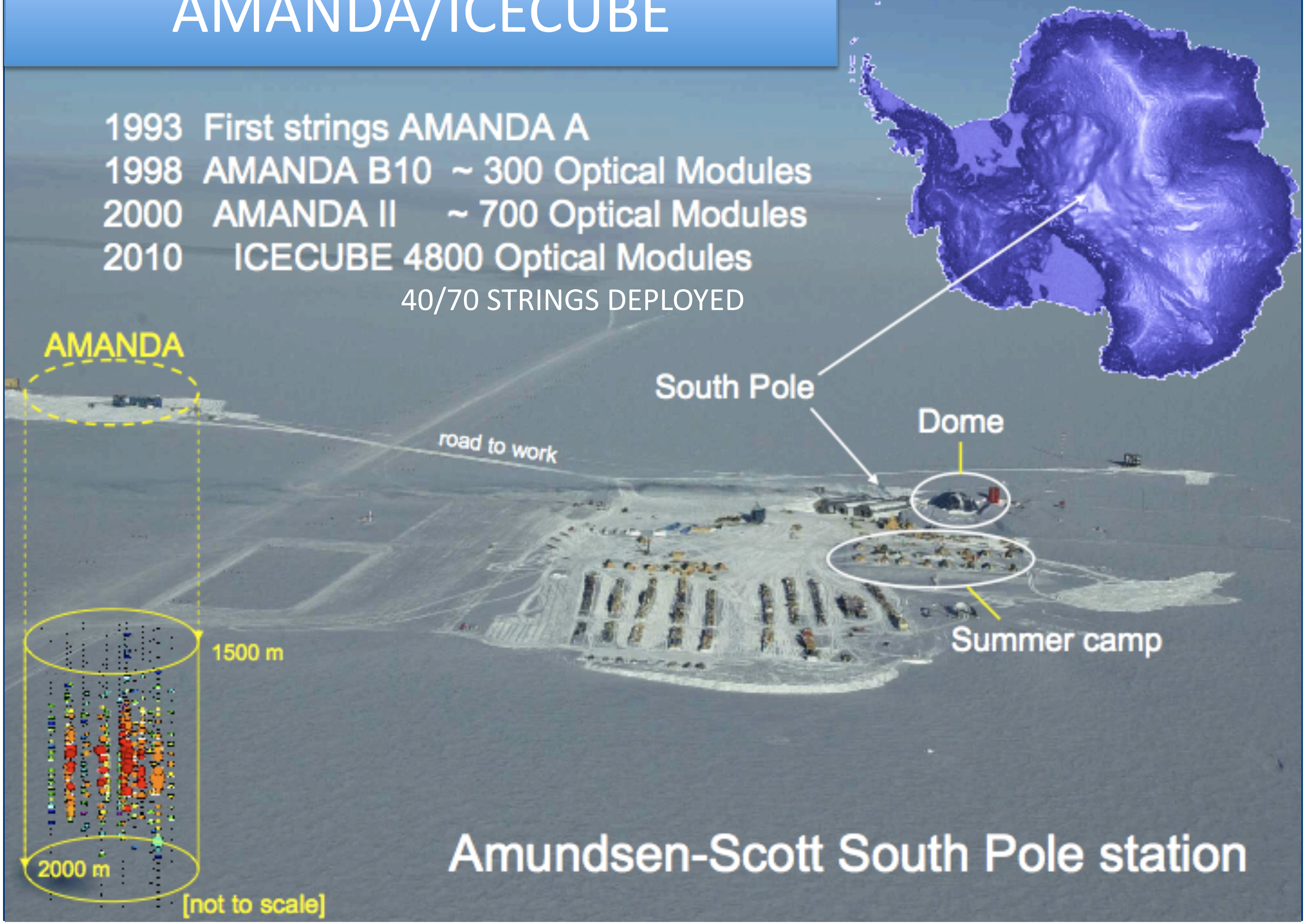
Baikal NT200+



- NT200 + 3 new strings, 200 m height, 36 OMs
- Goal: improvement of sensitivity to neutrino induced cascades (EM+Hadronic showers)

AMANDA/ICECUBE

1993 First strings AMANDA A
1998 AMANDA B10 ~ 300 Optical Modules
2000 AMANDA II ~ 700 Optical Modules
2010 ICECUBE 4800 Optical Modules
40/70 STRINGS DEPLOYED



IceCube installation on South Pole

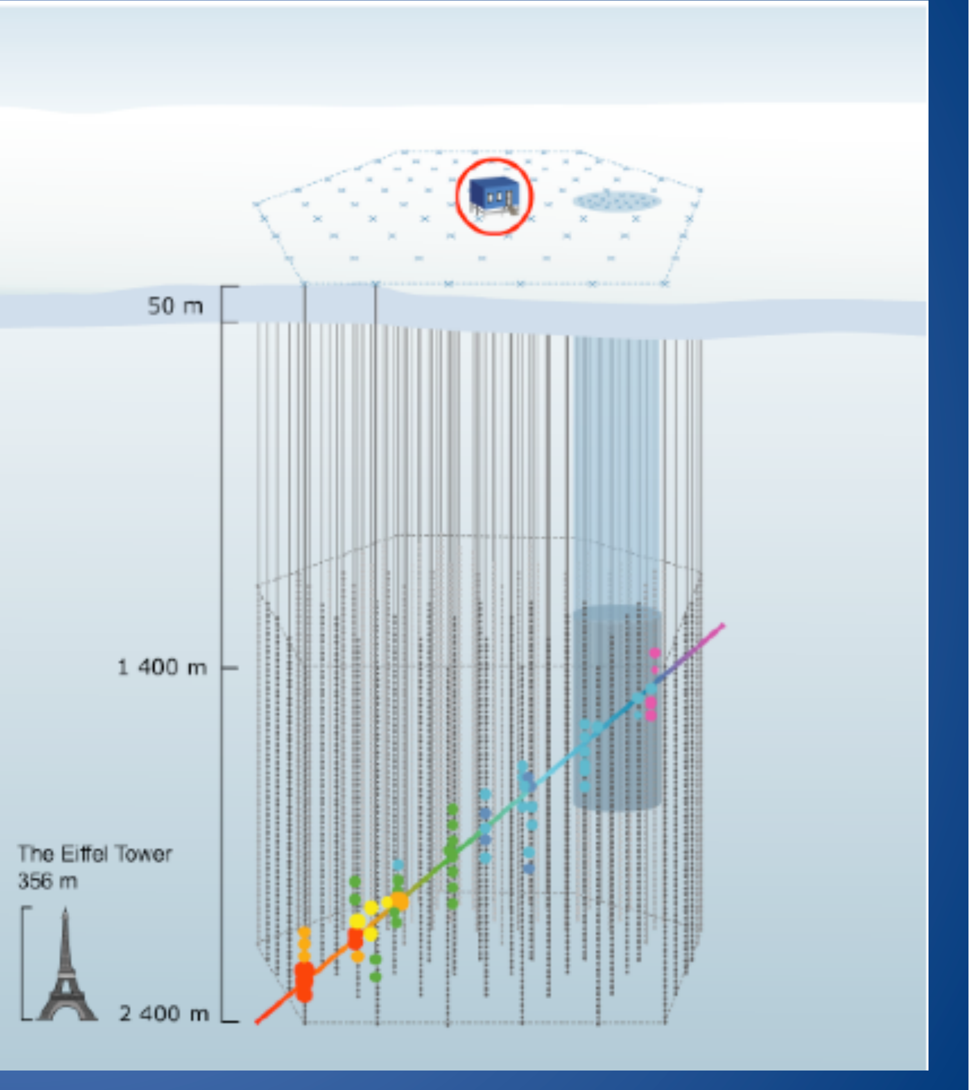
January 2005:

60 optical modules

Deepest module at 2450 m

An up-going neutrino induced muon in IceCube

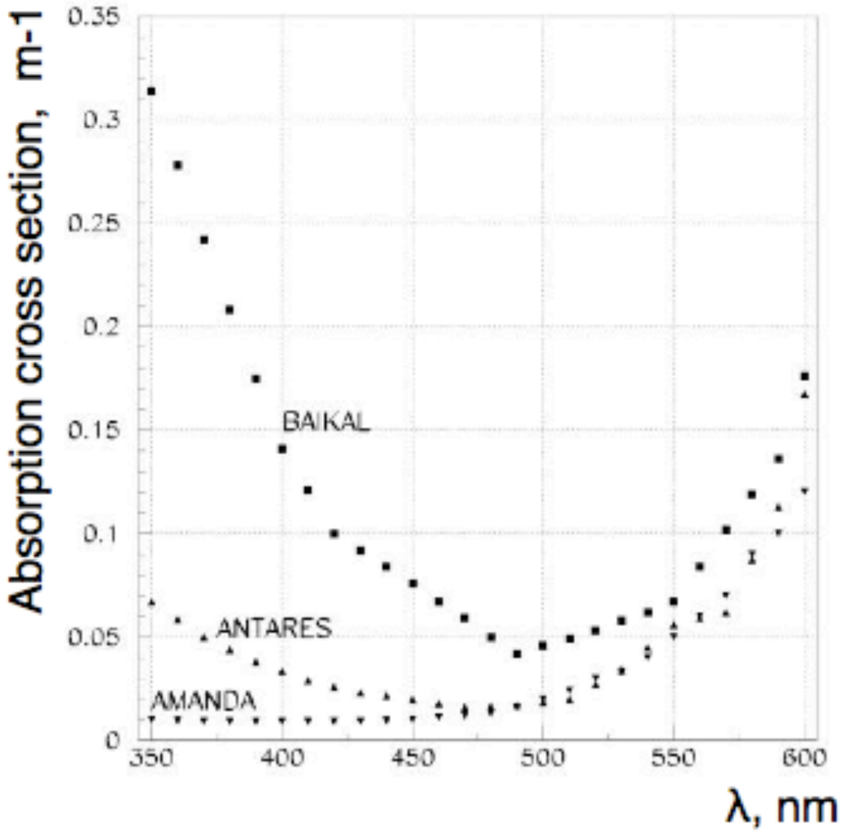
T. Gaisser



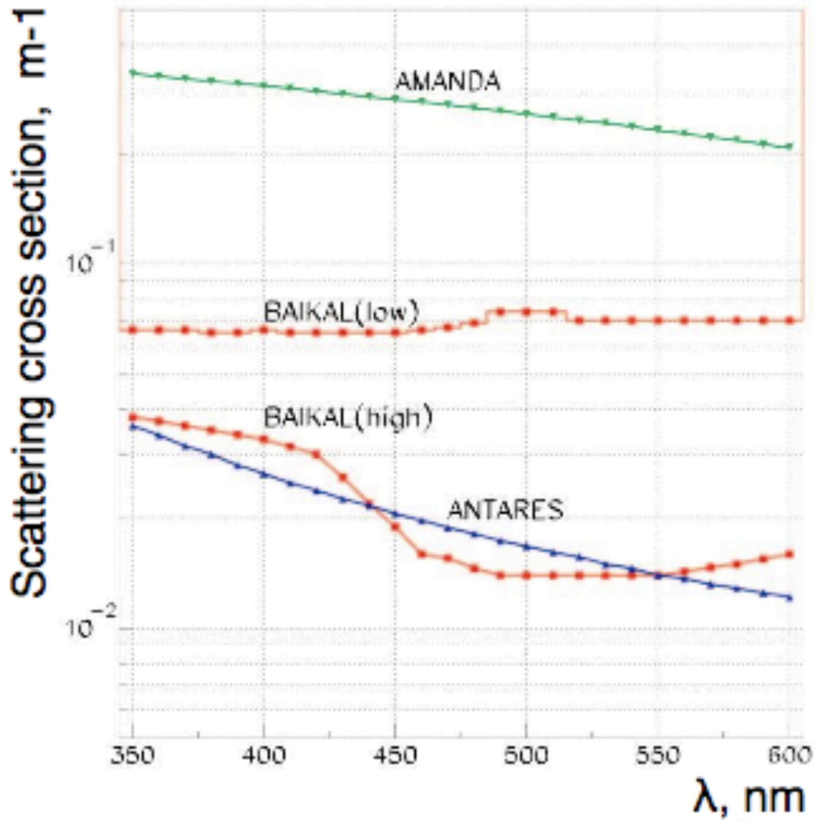
Media Comparison

Ice (AMANDA, ICECUBE)	Sea Water (ANTARES, NEMO, NESTOR, KM3NeT)	Fresh Water (Baikal)
Long absorption length (fewer PMTs required)	Short absorption length (more expensive)	Unlike ice the absorption length is short: (22±2m)
Short scattering length - poor angular resolution	Very long scattering length (>~200m)	Scattering length is (16 ÷ 70)m at 490nm
No Potassium-40 present - low noise environment	Potassium-40 present	Little Potassium-40 present - low noise environment
No bioluminescence	Bioluminescent burst activity observed and understood	No bioluminescence
No repair of detector components possible	Surfacing, repair and re-deployment of strings possible	As for sea water during summer months

Optical properties

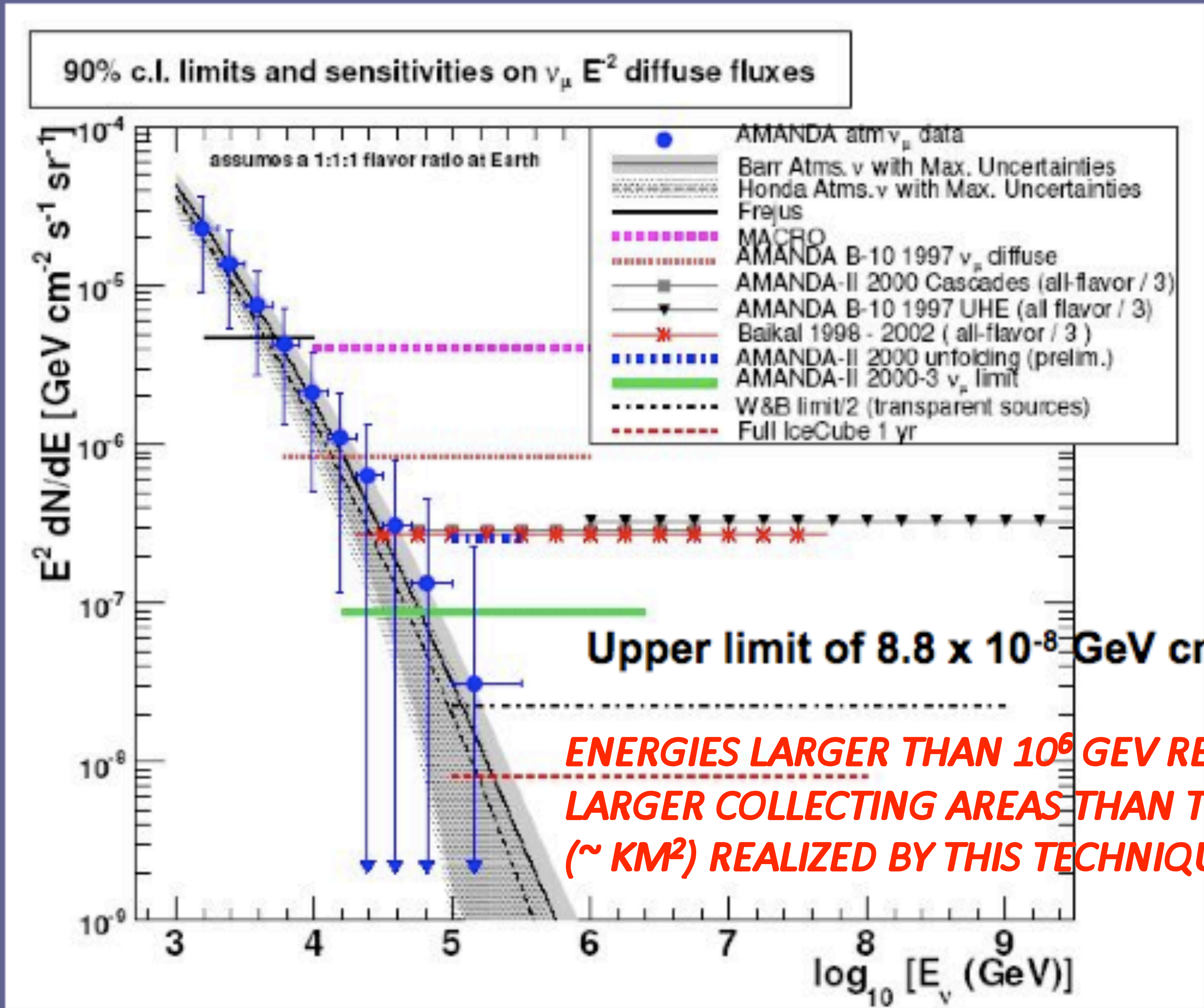


Abs. Length Baikal 22 ± 2 m



Scatt. Length Baikal ~ 30-50 m

Diffuse flux (AMANDA II)



Upper limit of 8.8 x 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

ENERGIES LARGER THAN 10^6 GEV REQUIRE LARGER COLLECTING AREAS THAN THE ONES (~ KM^2) REALIZED BY THIS TECHNIQUE

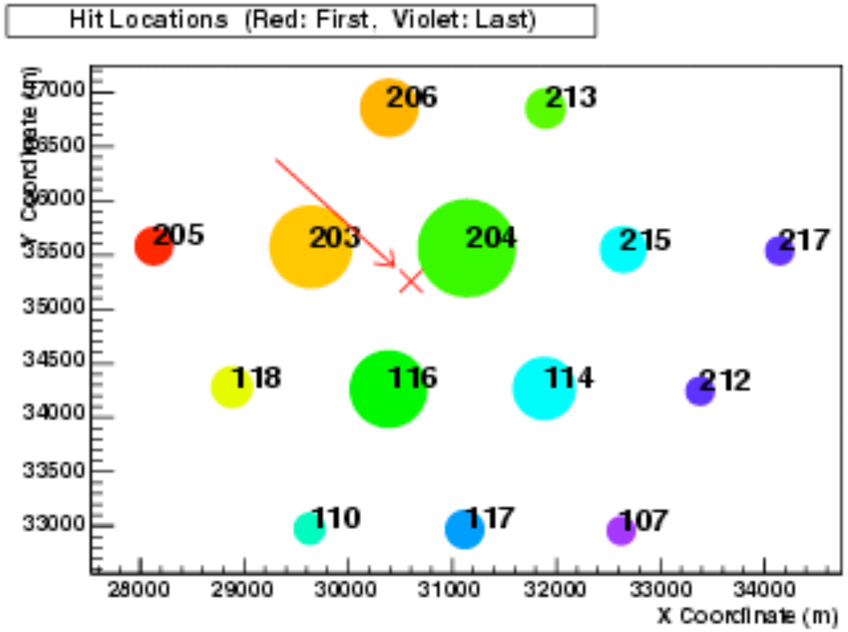
UHE energy neutrinos

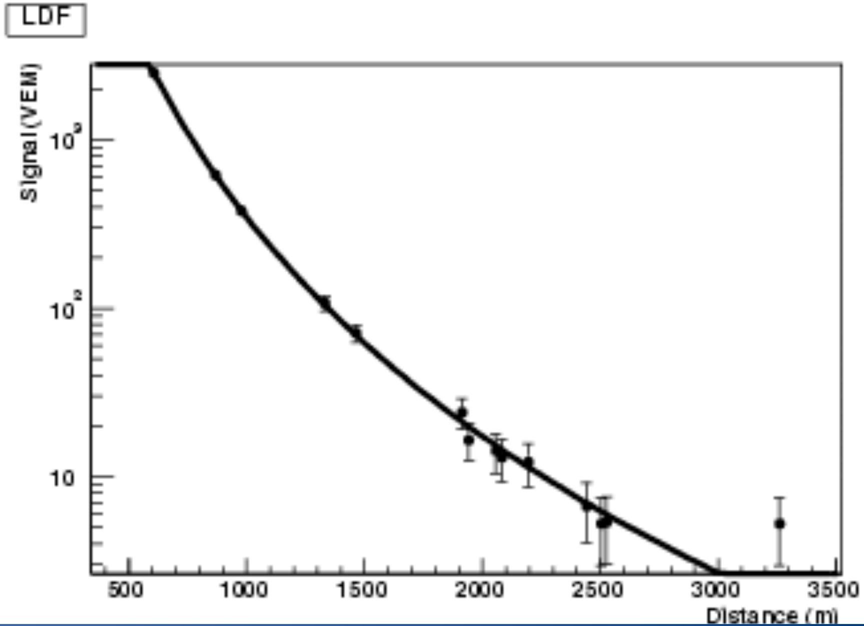
Radio, Acoustic detection, Auger

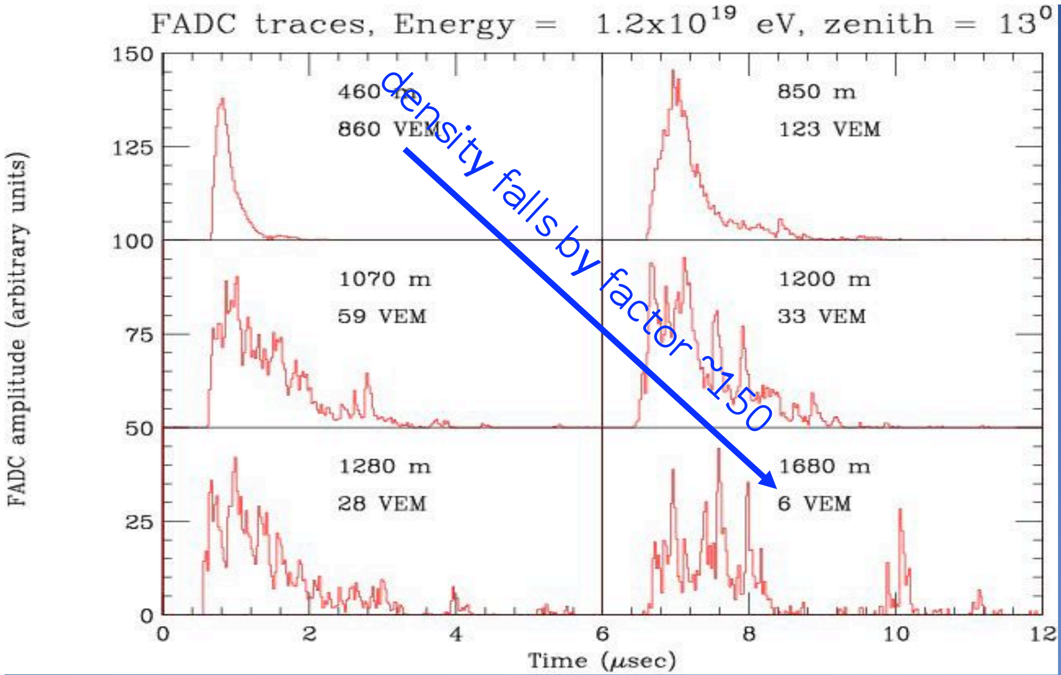
Neutrino detection require low background (e.g. deep underground/underwater arrays). At sea level it can be realized by “looking” in very inclined directions, i.e. selecting very inclined events (~ 90 degrees).

How select neutrino candidates?

AUGER

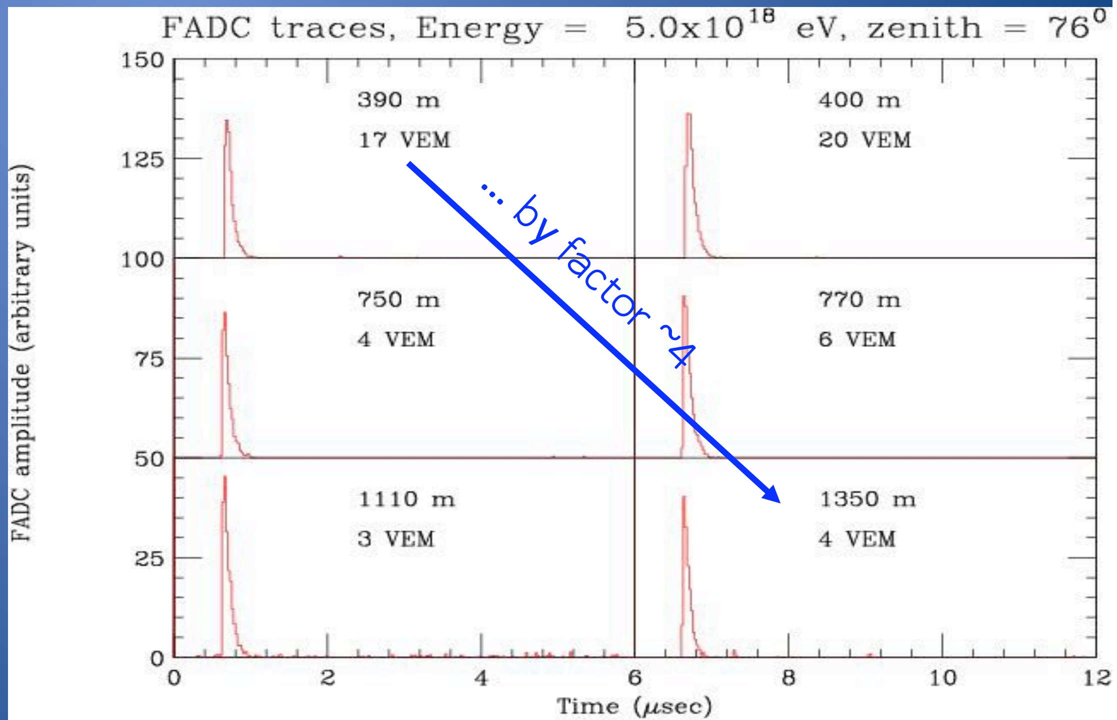




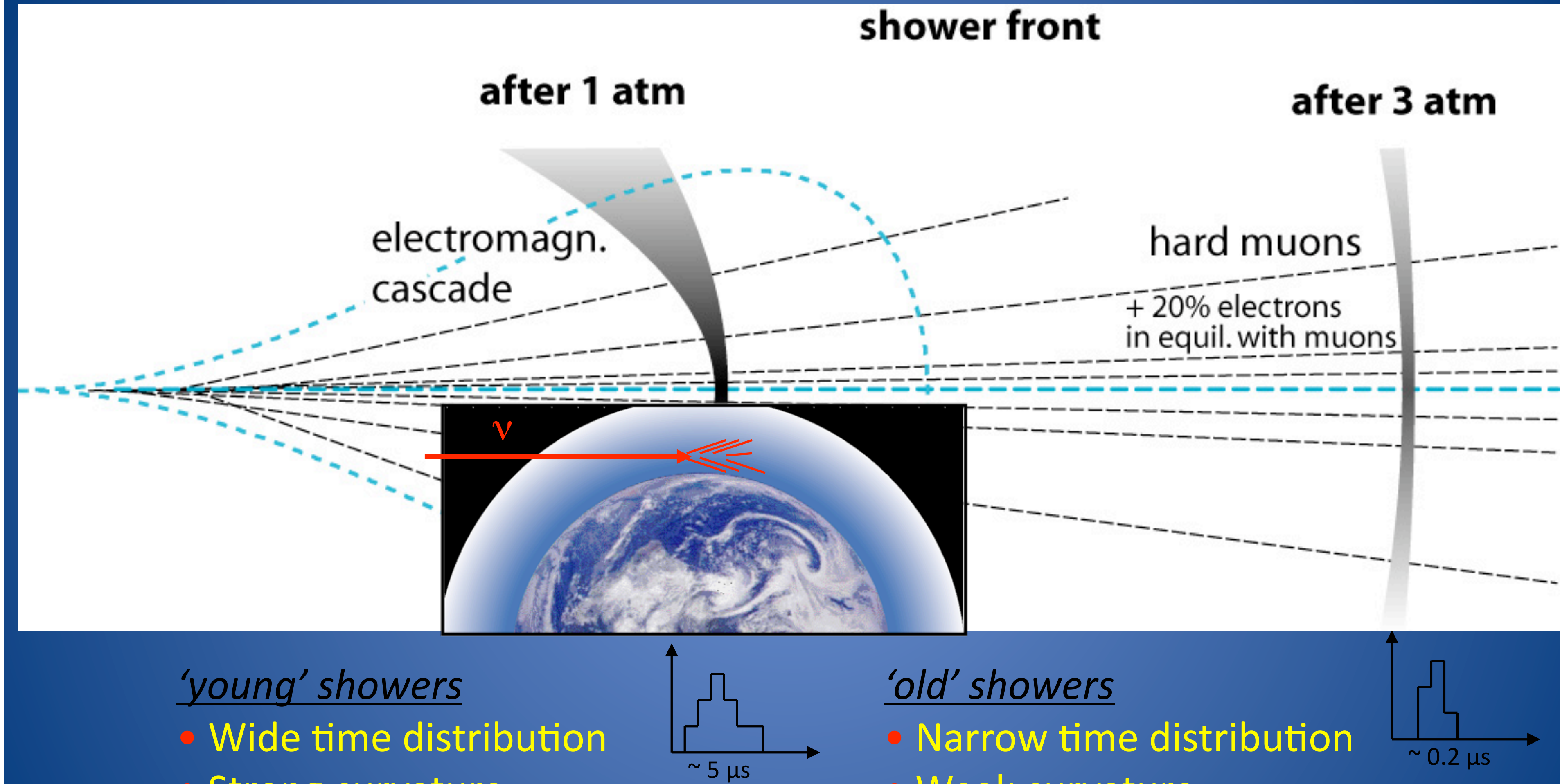


'young' shower

'old' shower



Vertical vs Horizontal Showers



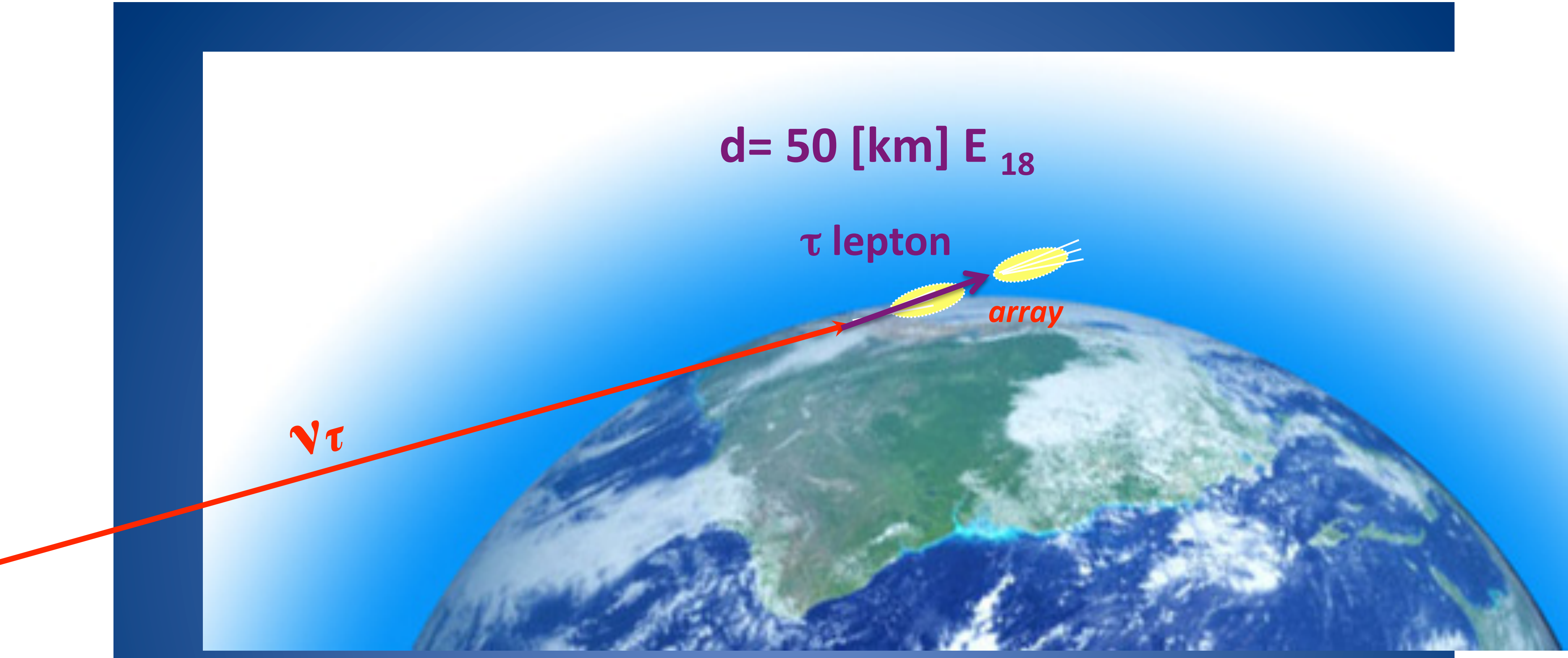
'young' showers

- Wide time distribution
- Strong curvature
- Steep lateral distribution

'old' showers

- Narrow time distribution
- Weak curvature
- Flat lateral distribution

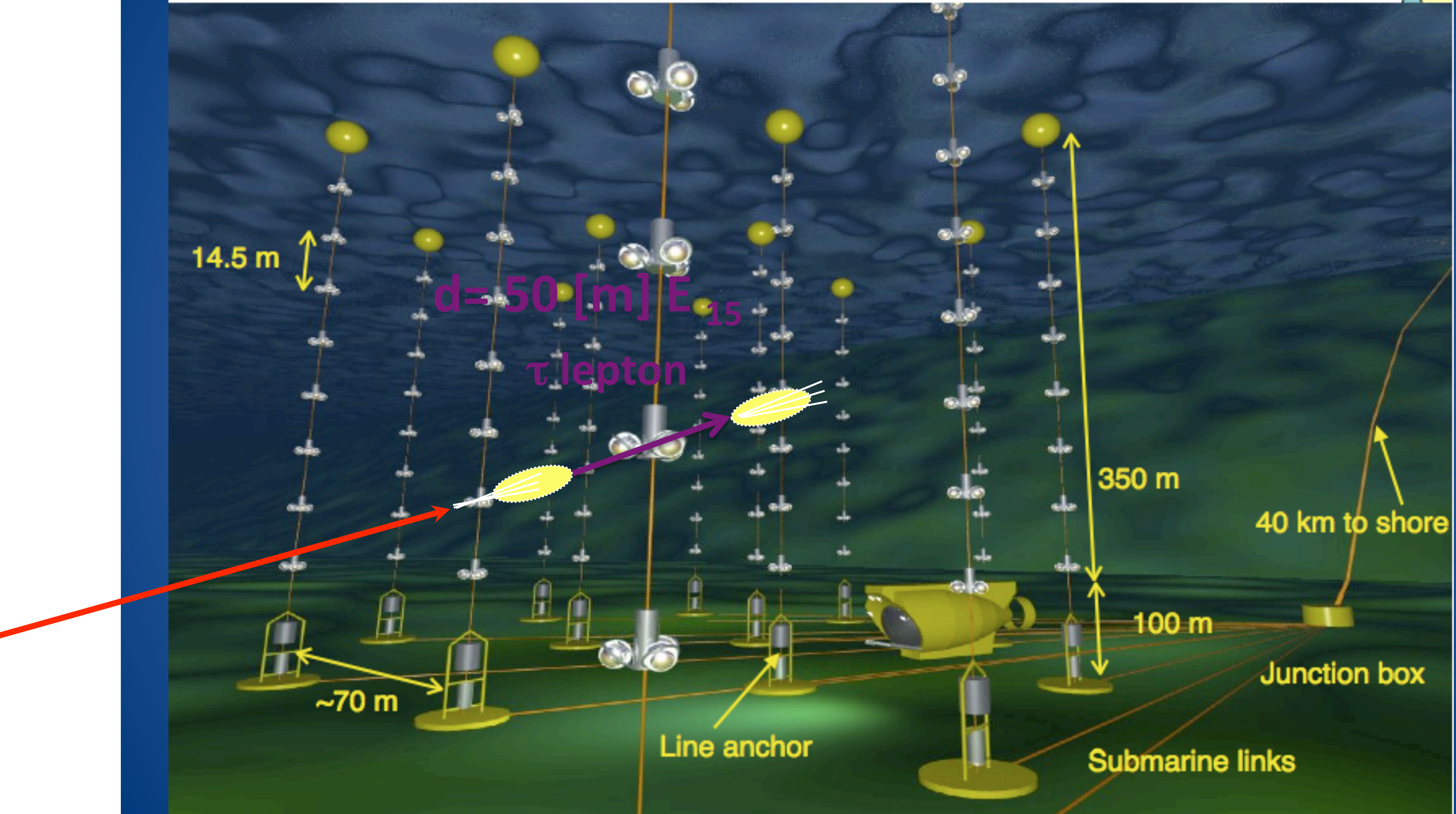
Only a neutrino can induce a young horizontal shower !



d= 50 [km] E 18
τ lepton
array
ντ

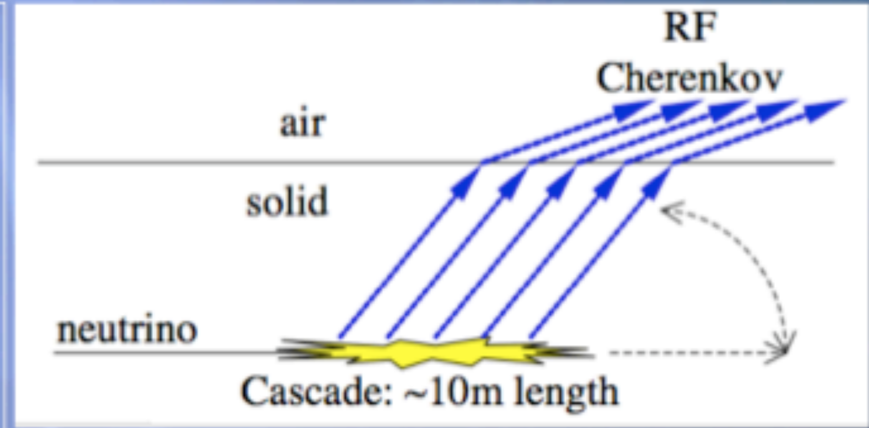
Antares detector layout

planned are 900 PMT, 12 lines, 25 stories/ line, 3 PMT/ story



Radio Askaryan Effect

- Proposed in 1961
- In a neutrino-induced cascade there is a net moving negative charge ~20% of overall charge
- Predominantly due to positron annihilation and $A \rightarrow A_{z+1} + e^-$
- This relativistically moving charge will produced Cerenkov radiation



- This time in the radio spectrum - typically 0.1 to few GHz
- Should be coherent ($P_{RF} \propto E^2$ at radio frequencies
- Should be above thermal noise at high E
- Detectable at a distance
- Radiation polarised

Target requirements:

- radio quiet
- instrumentable
- radio transparent

Radio Askaryan Effect

- Proposed in 1961
- In a neutrino-induced cascade there is a net moving negative charge ~20% of overall charge
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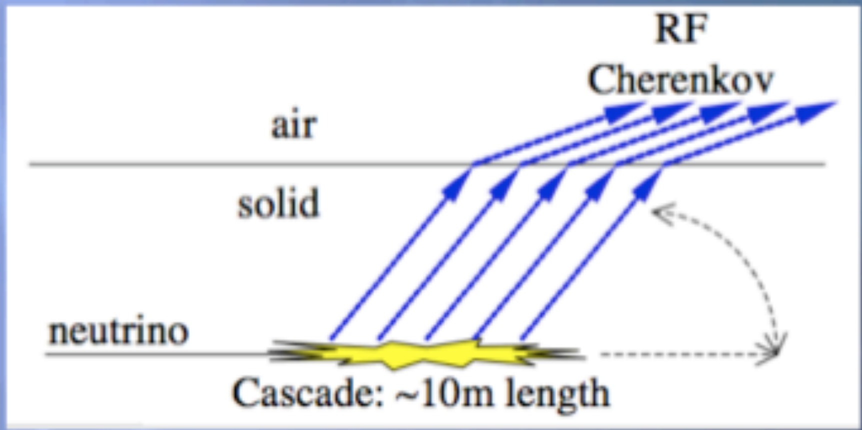
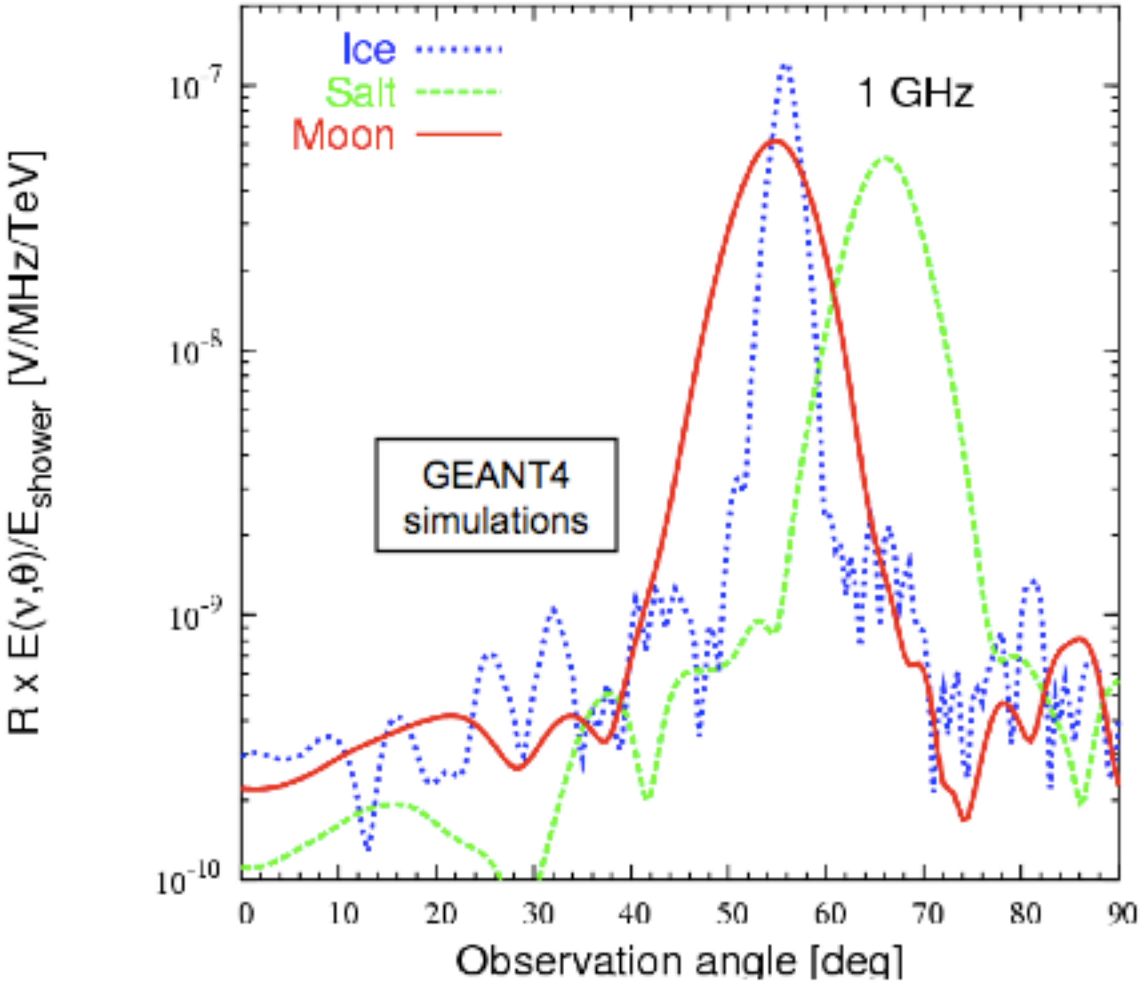


A typical shower initiated by a 100 PeV neutrino creates a total number of charged particles at shower maximum of ~ $2\ 10^7$.
The net charge is thus ~ $4\ 10^6$ e
Since the radiated power for Cherenkov emission grows quadratically with the charge of the emitter, the coherent power in the cm-to-m wavelength regime is ~10^{13} times greater than the single-charge emission.
(Gorham et al Phys. Rev. Lett.)

Target requirements:
- radio quiet
- instrumentable
- radio transparent

Askaryan mechanism

- Coherent up to GHz frequencies (small, but dense showers)
- Different geometry and polarization than geomagnetic mechanism



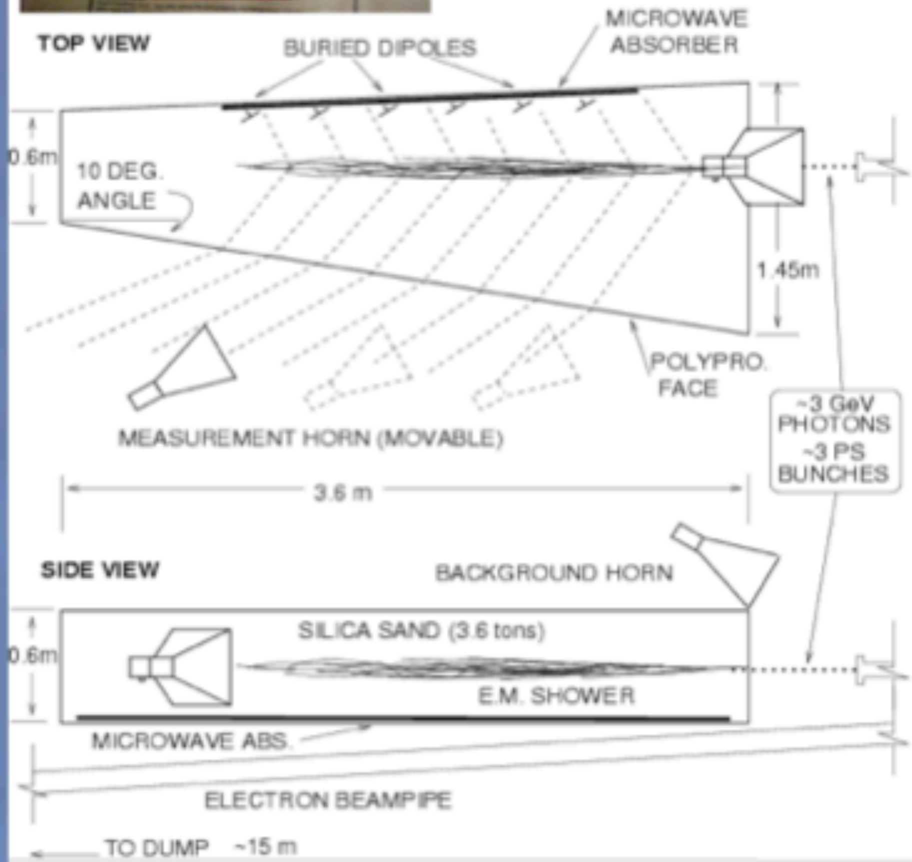
J. Alvarez-Muñiz, E. Marqués, R.A. Vázquez, E. Zas

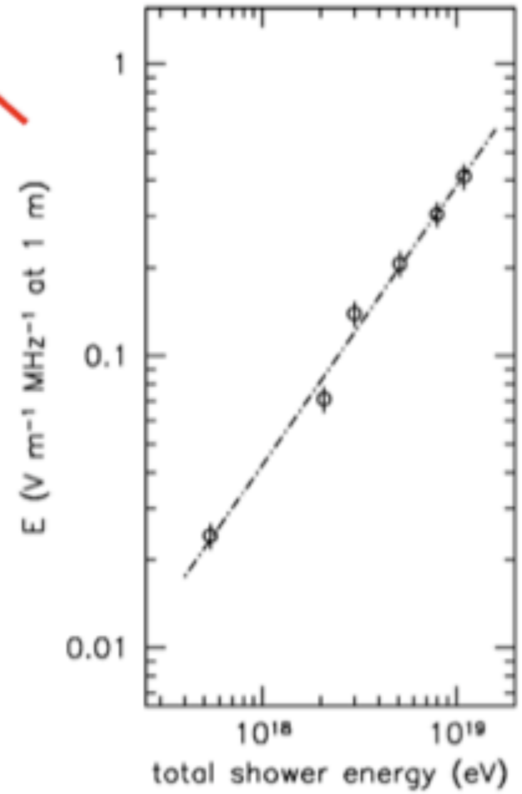
Test Beam (Silica)

Saltzberg et al. (2000)

Power $\propto (E_{shower})^2$

COHERENCE DEMONSTRATED





Radio Askaryan - Test beam

Gorham et al. (2004)

Target : SALT

- Radiation properties
  - polarisation ✔
  - speed ✔
  - long. profile ✔

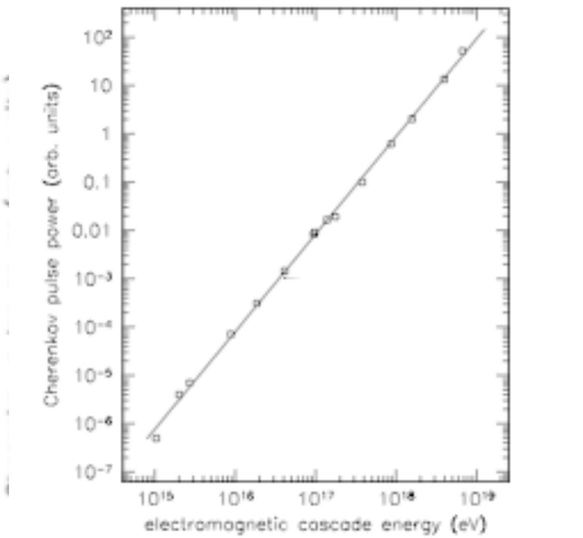
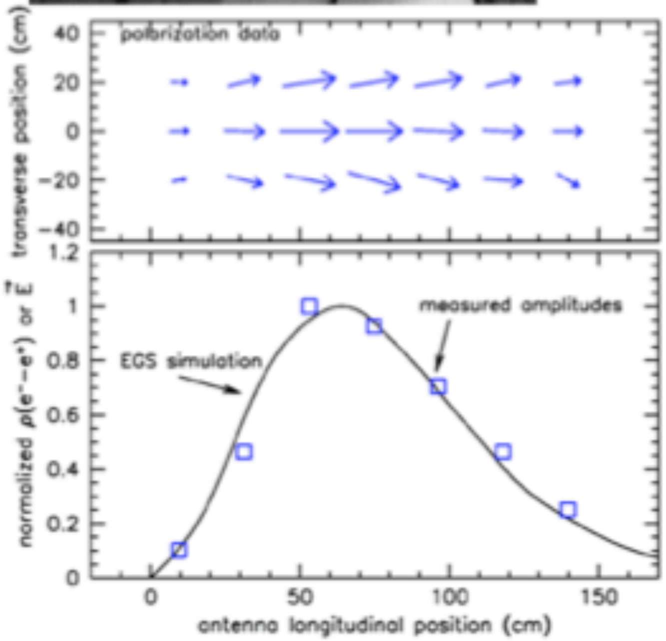
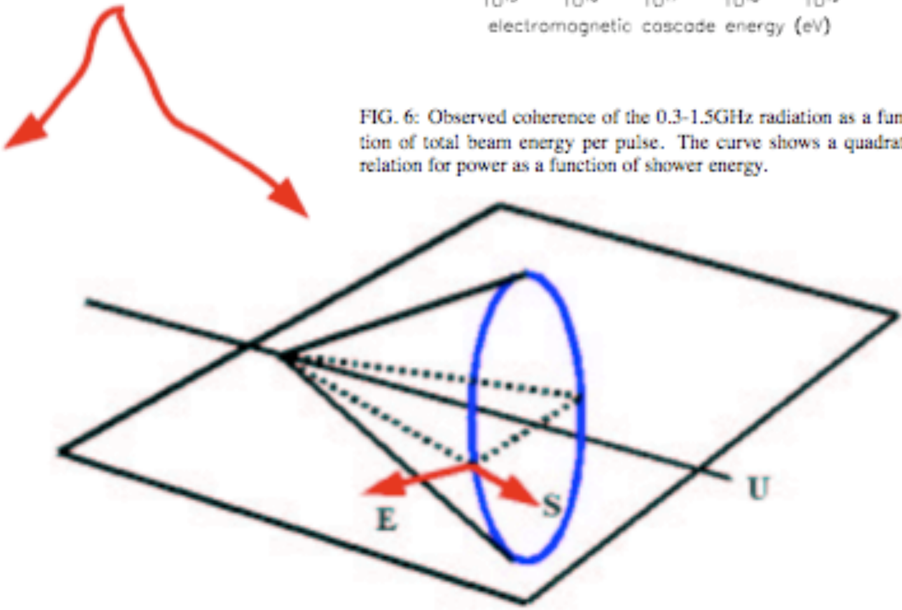
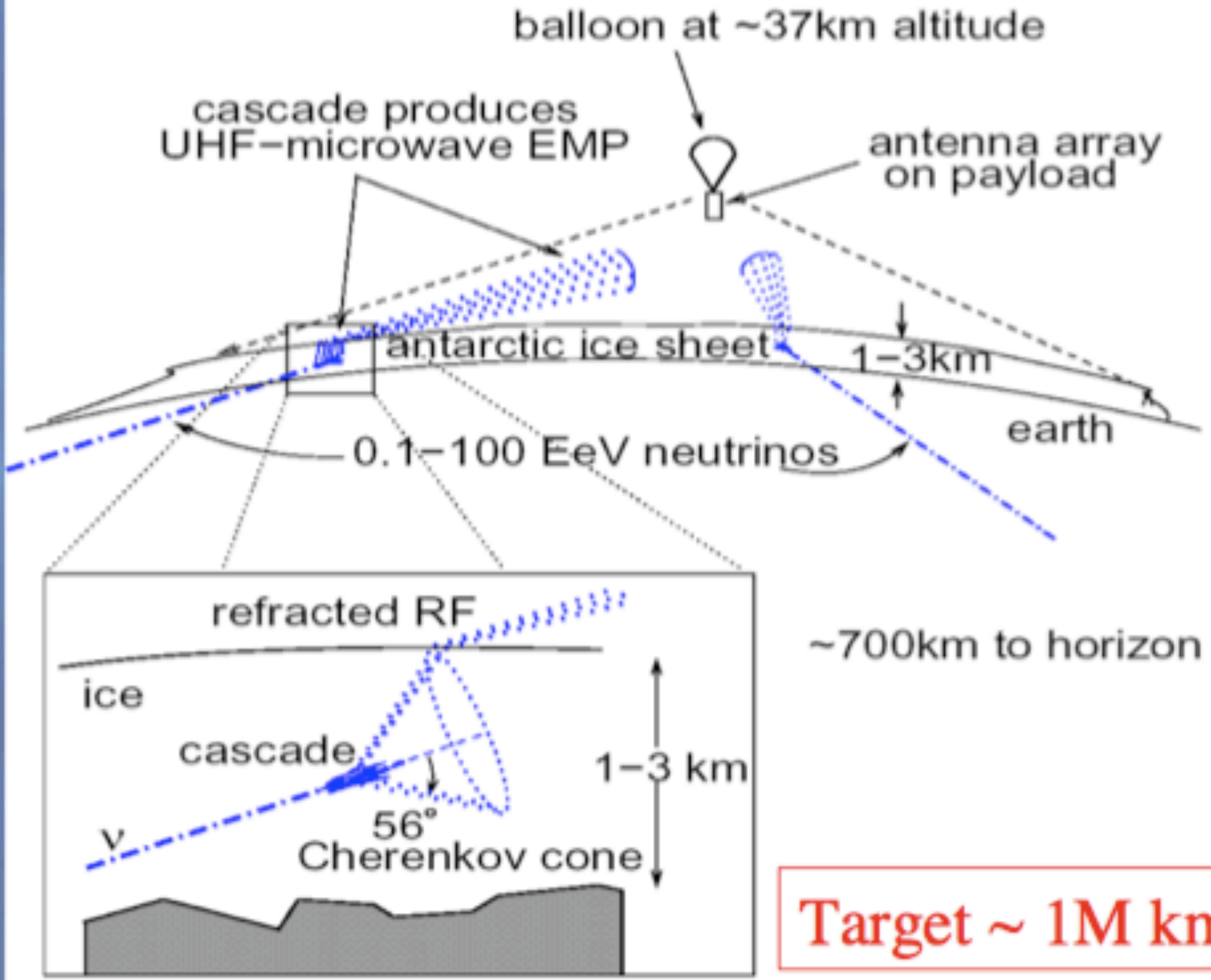


FIG. 6: Observed coherence of the 0.3-1.5GHz radiation as a function of total beam energy per pulse. The curve shows a quadratic relation for power as a function of shower energy.





ANITA concept



~700km to horizon

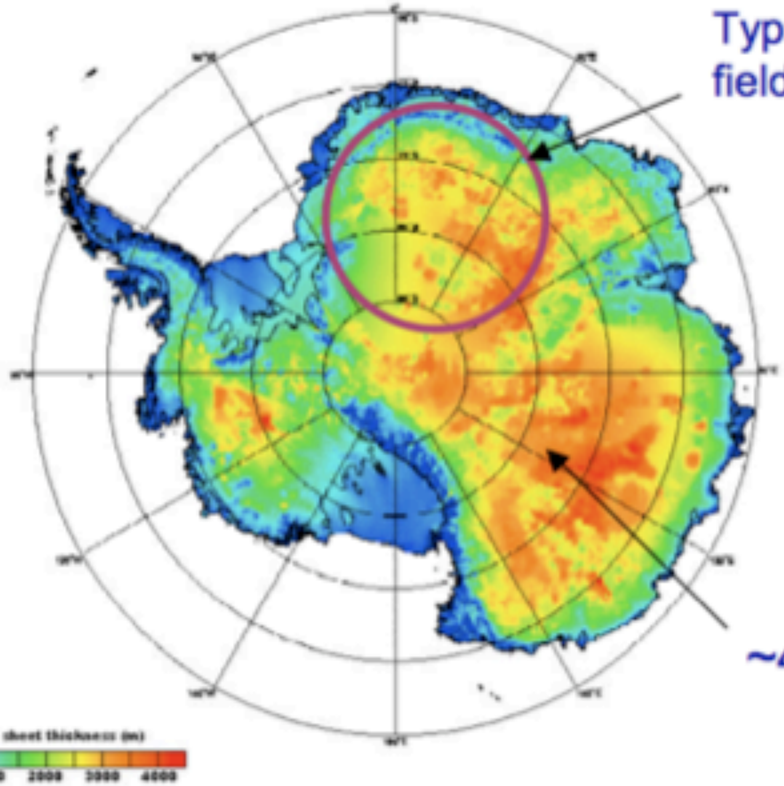
Target ~ 1M km^3

Antarctic Ice at f<1GHz, T<-20C :

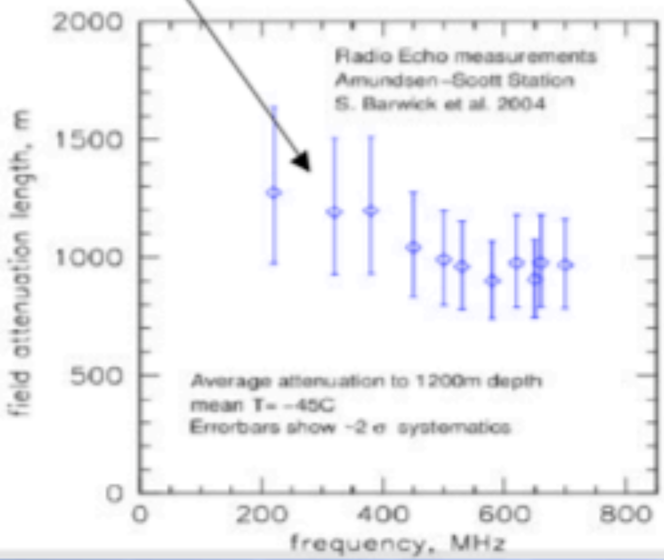
- ~Lossless RF transmission
- Minimal scattering
- largest homogenous, RF-transmissive solid mass in the world
- RF quiet!

Typical balloon field of view

Ice RF clarity: ~1km(!) attenuation length



~4km deep ice!



Effective "telescope" aperture:

- ~250 km^3 sr @ 10^{18} eV
- ~10^4 @ km^3 sr 10^{19} eV

(compare to ~1 km^3 at lower E)

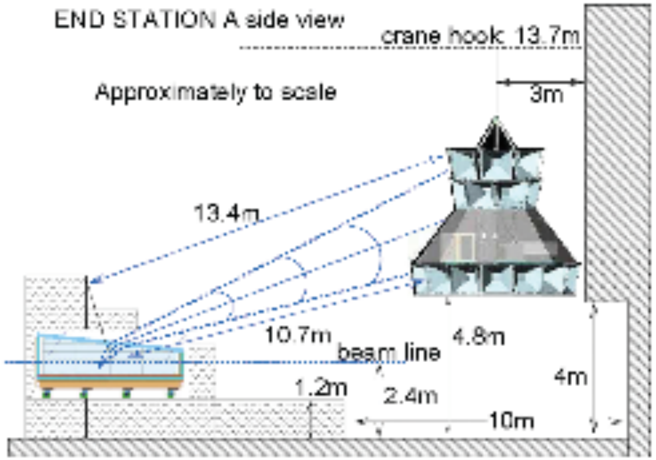
PRL 99, 171101 (2007) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2007

Observations of the Askaryan Effect in Ice

P. W. Gorham,[1] S. W. Barwick,[2] J. J. Beatty,[3] D. Z. Besson,[4] W. R. Binns,[5] C. Chen,[6] P. Chen,[6] J. M. Clem,[7] A. Connolly,[8] P. F. Dowkontt,[5] M. A. DuVernois,[9] R. C. Field,[6] D. Goldstein,[2] A. Goodhue,[8] C. Hast,[6] C. L. Hebert,[1] S. Hoover,[8] M. H. Israel,[5] J. Kowalski,[1] J. G. Learned,[1] K. M. Liewer,[10] J. T. Link,[1,11] E. Lusczek,[9] S. Matsuno,[1] B. Mercurio,[3] C. Miki,[1] P. Miočinović,[1] J. Nam,[2] C. J. Naudet,[10] J. Ng,[6] R. Nichol,[3] K. Palladino,[3] K. Reil,[6] A. Romero-Wolf,[1] M. Rosen,[1] L. Ruckman,[1] D. Saltzberg,[8] D. Seckel,[7] G. S. Varner,[1] D. Walz,[6] and F. Wu[2]

(ANITA Collaboration)

T-486 [Ice!]



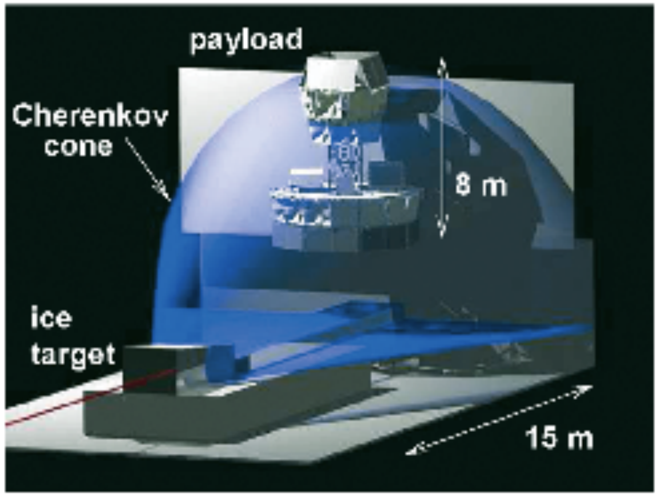
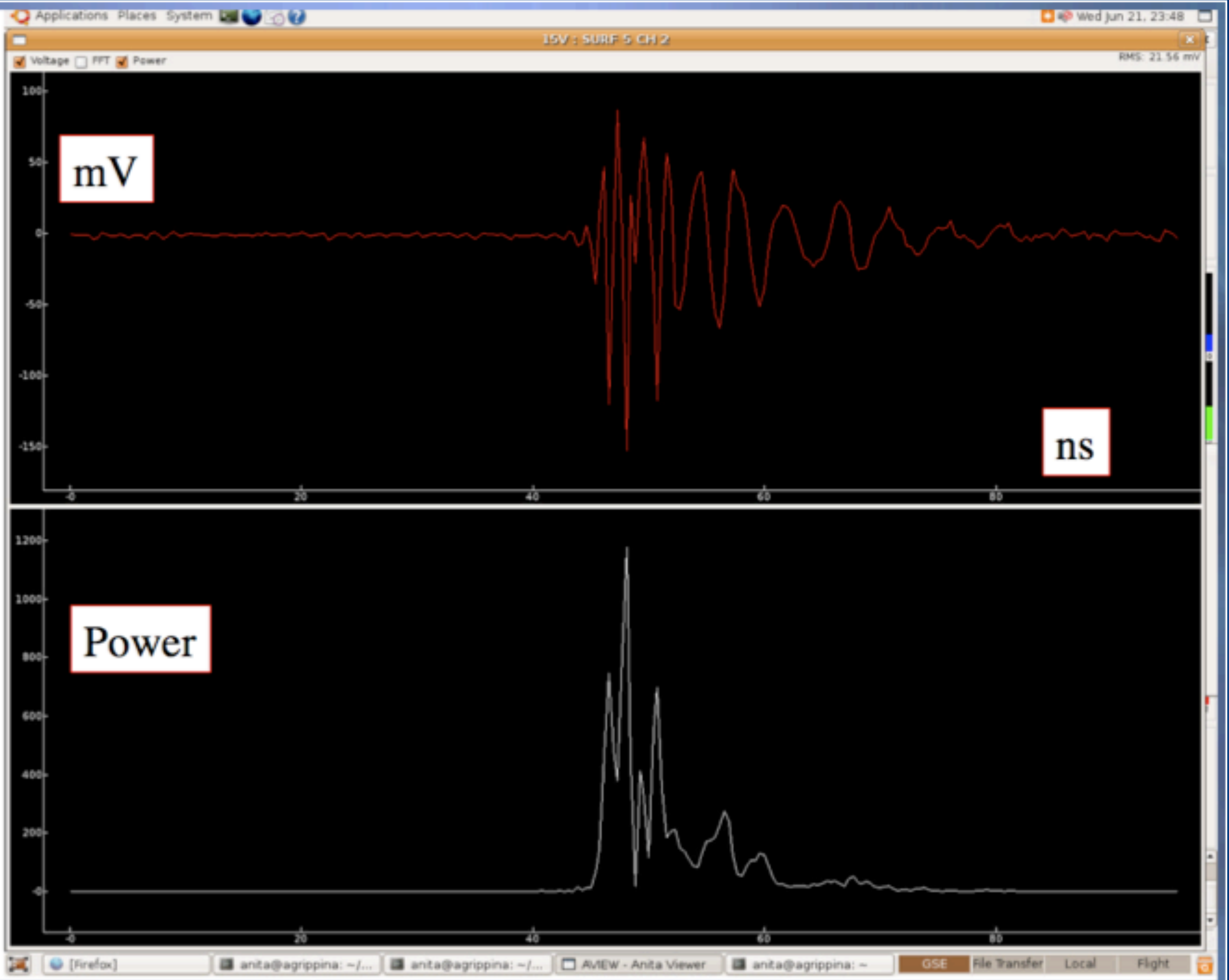


FIG. 1 (color). Top: Side view schematic of the target and receiver arrangement in ESA. Bottom: Perspective view of the setup, showing the key elements.

Impulse response



SLAC T486 RESULTS

- The showers were produced by 28.5 GeV electrons in 10^{-11} s bunches of typically 10^{9} particles. The total composite energy of $3 \cdot 10^{19}$ eV, with a total of ~ $2 \cdot 10^{10}$ el. at max dev.

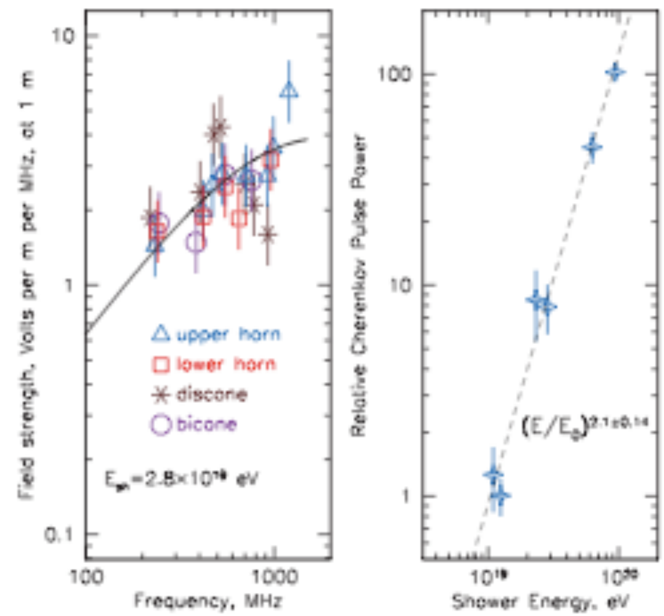


FIG. 3 (color). Left: Field strength vs frequency of radio Cherenkov radiation in the T486 experiment, for several different antennas used, including a theoretical curve [9]. Right: Pulse power vs total shower energy (number of particles × mean energy/particle), curve is for completely coherent radio Cherenkov emission.

Acoustic detection

Why acoustic detection ?

•High energy neutrinos interact with matter (1% probability in 1 km of water at 10^{20}eV).

•Energy is shared between a quark ad a lepton; on the average 80% to the lepton and 20% to the hadronic shower ($\approx$ Joule for 10^{20}eV neutrinos) .

•The hadronic shower is confined (typically a 2 cm. Radiux x 20 m length cylinder) and produces detectable pressure waves.

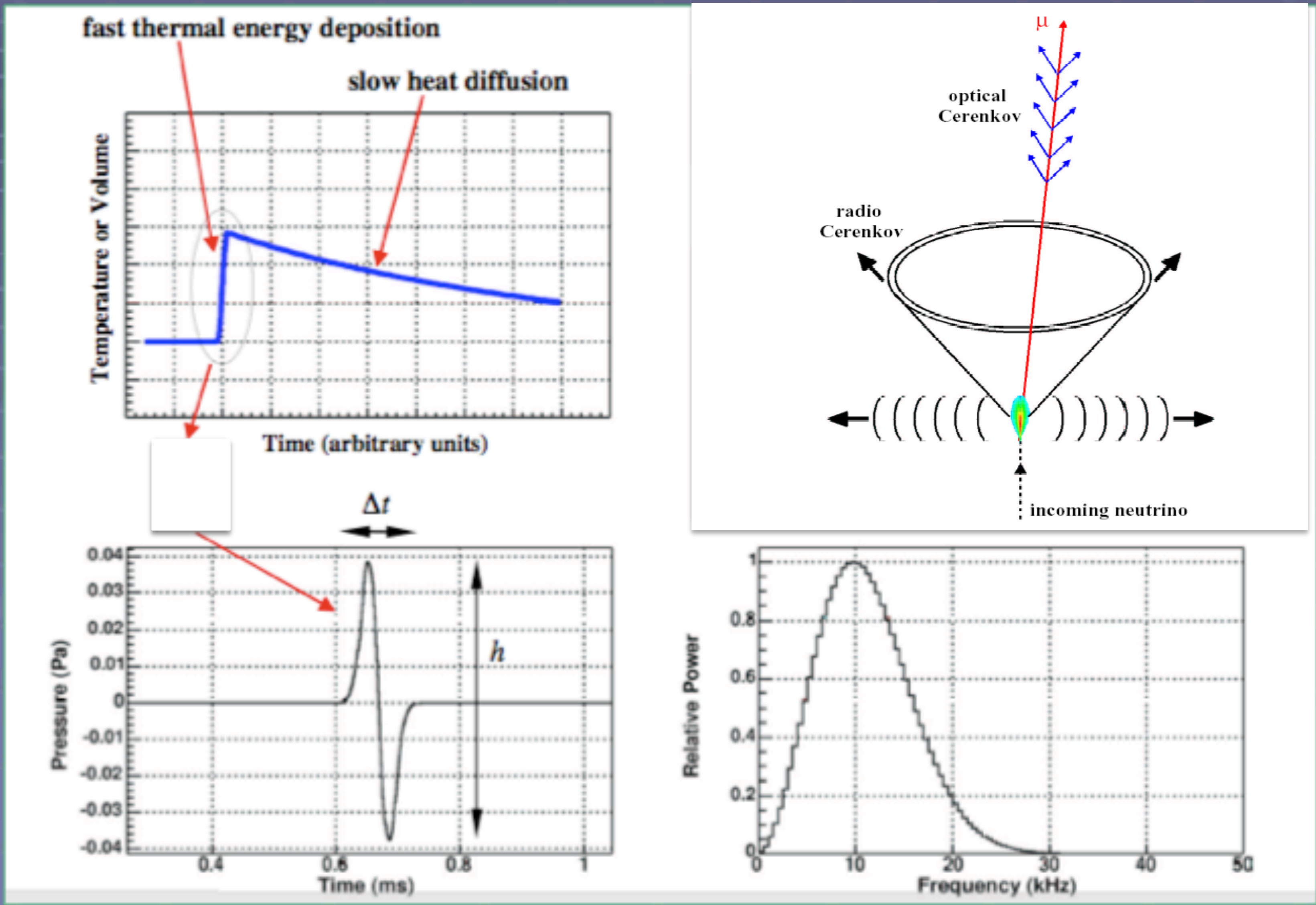
• the acoustic front has a typical disk shape('pancake'), the pressure wave is bipolar, $\approx$ 50 μs period, amplitude $\cong$ mPa or higher depending on the initial energy and distance

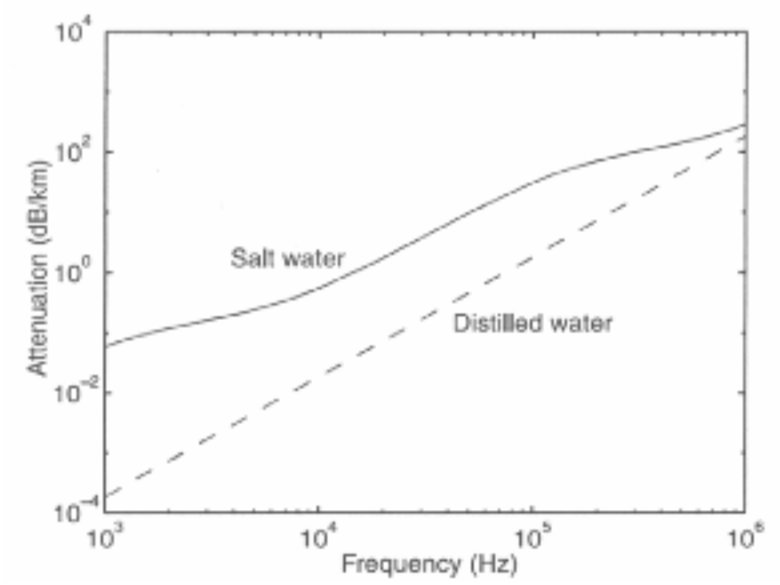
•The signal propagates for several km (attenuation lenght of 1km at 20 kHz)

→

at high energies ($\geq 10^{18}$eV) the acoustic detection may be an alternative to Cerenkov light detection (attenuation lenght $\cong$ 50 m)

Acoustic Detection Principle

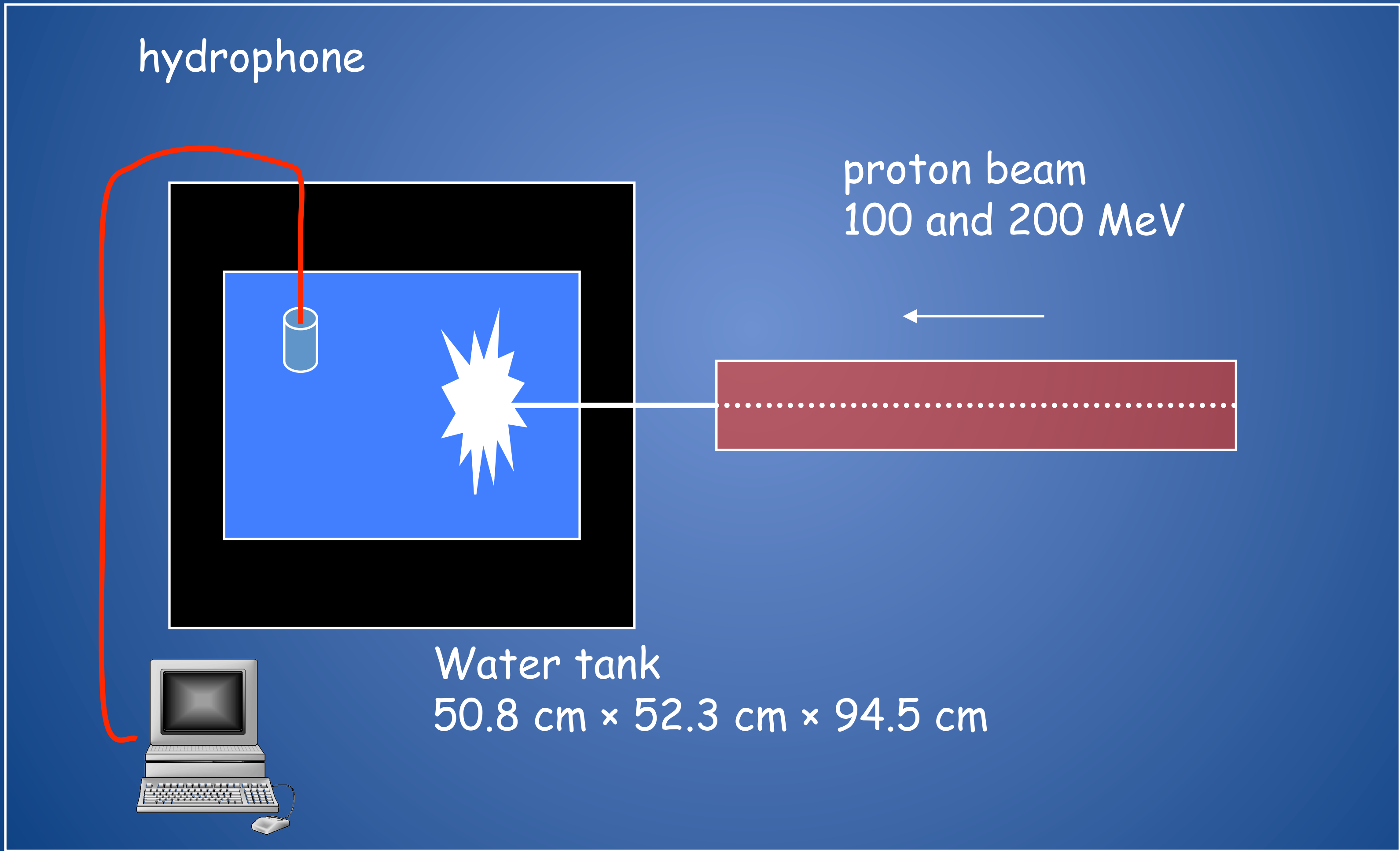




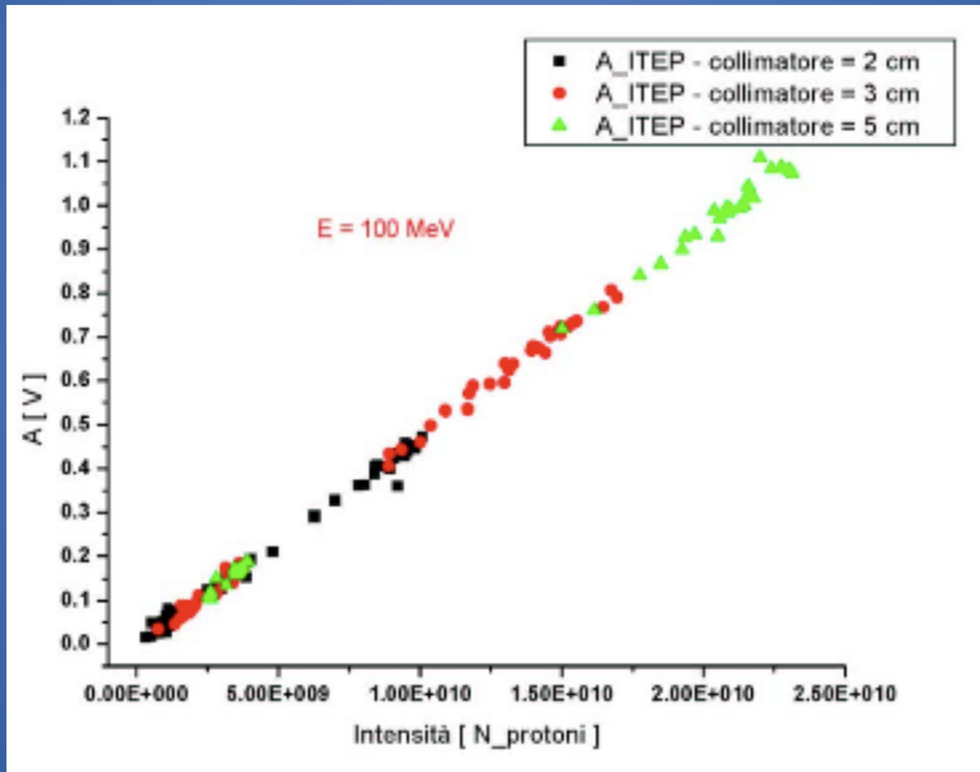
ACOUSTIC ATTENUATION

Hydrophone Calibration at ITEP

ITEP & ROMA (University)



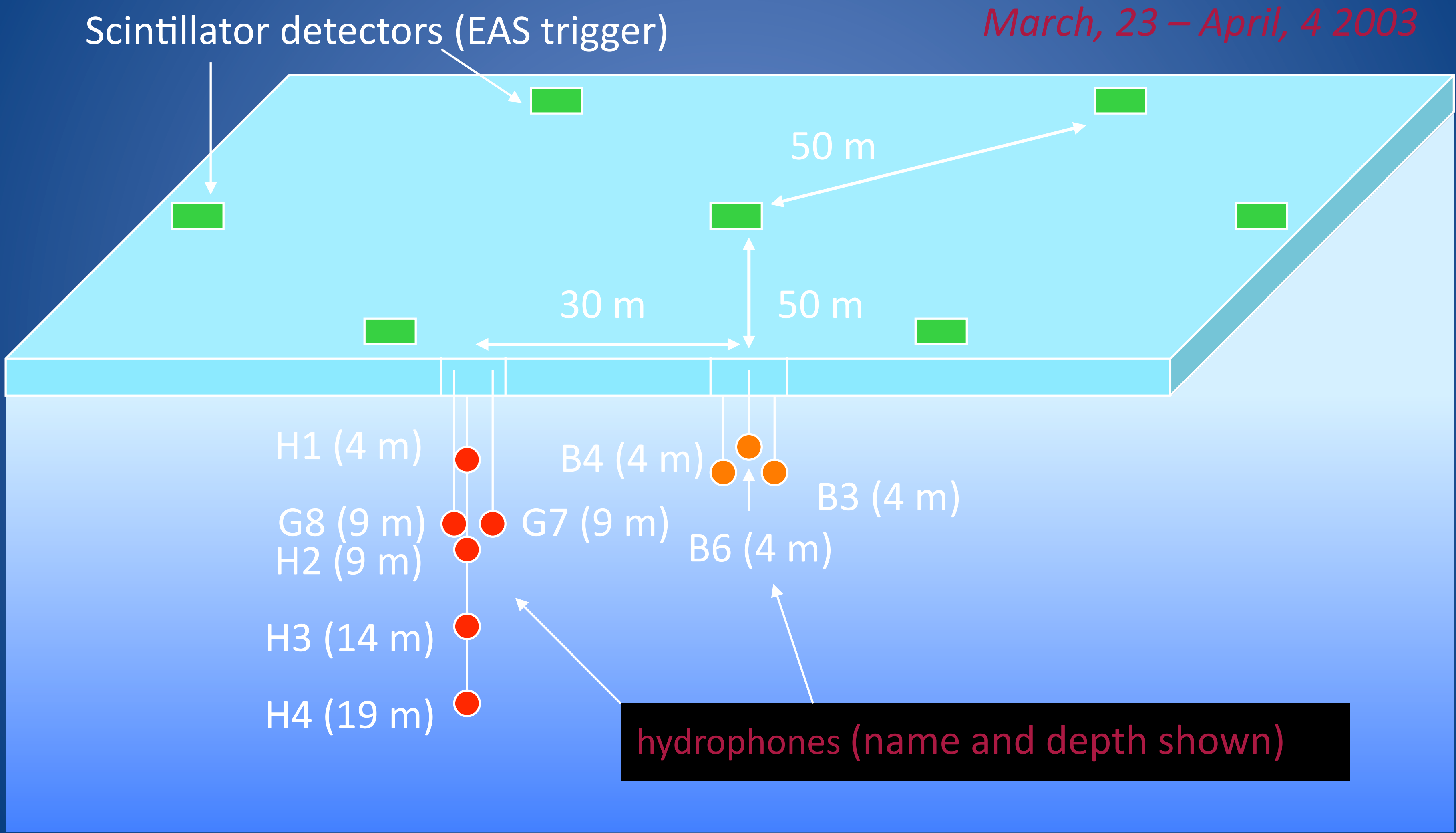
ACOUSTIC TEST ON P-BEAM



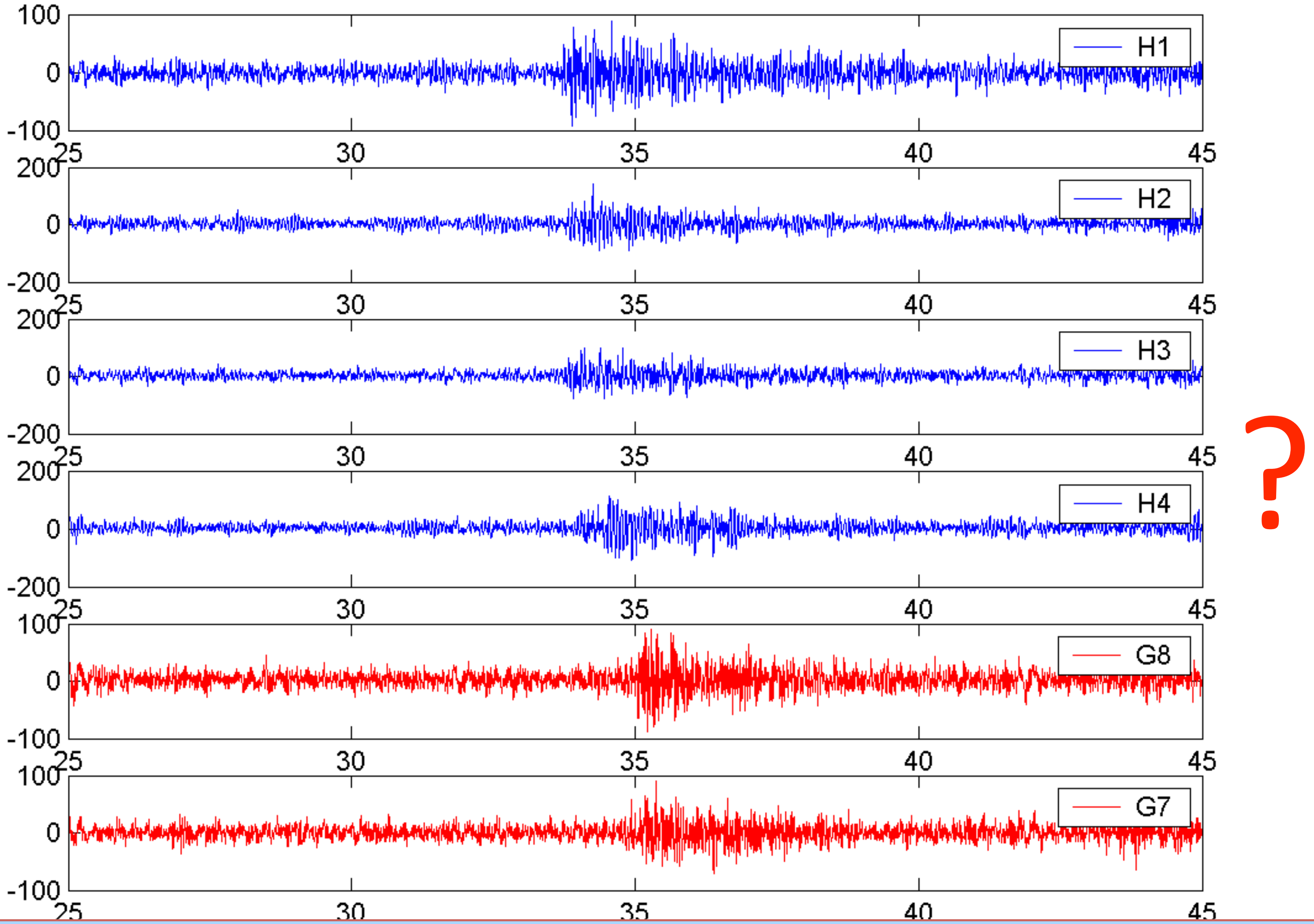
Scheme of the acoustic experiment

lake Baikal

March, 23 – April, 4 2003



An example of detected sound (hydrophones H1-H4,G7,G8)



energy deposition in water E = 3.2 E+17ev, distance 0.32m (compared to the model of G.A.Askarian)

Neutrino detectors

- Cherenkov in ice/water $10^{13} – 10^{15}$ eV
  - Towards km^3
- Horizontal showers
- Radio inclined showers / geo-synchrotron
- Radio Askaryan / Cherenkov
  - Ice/space, ice/ground, moon, salt….
- Acoustic
- ………

GAMMA RAY PRIMARIES

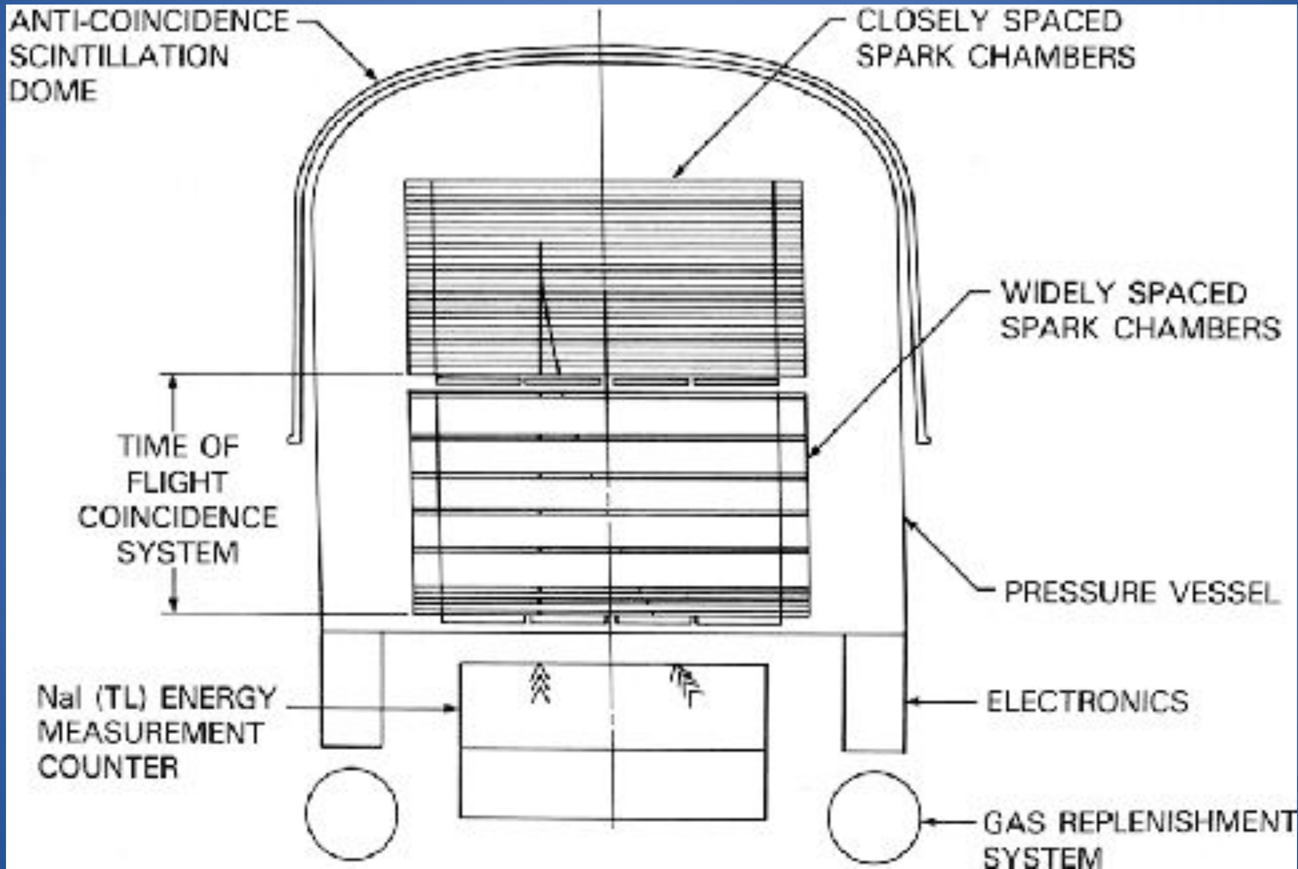
DIRECT (E $_{\gamma}$ < 50 GeV)

&

GROUND BASED (E $_{\gamma}$ > 50 GeV)

EGRET

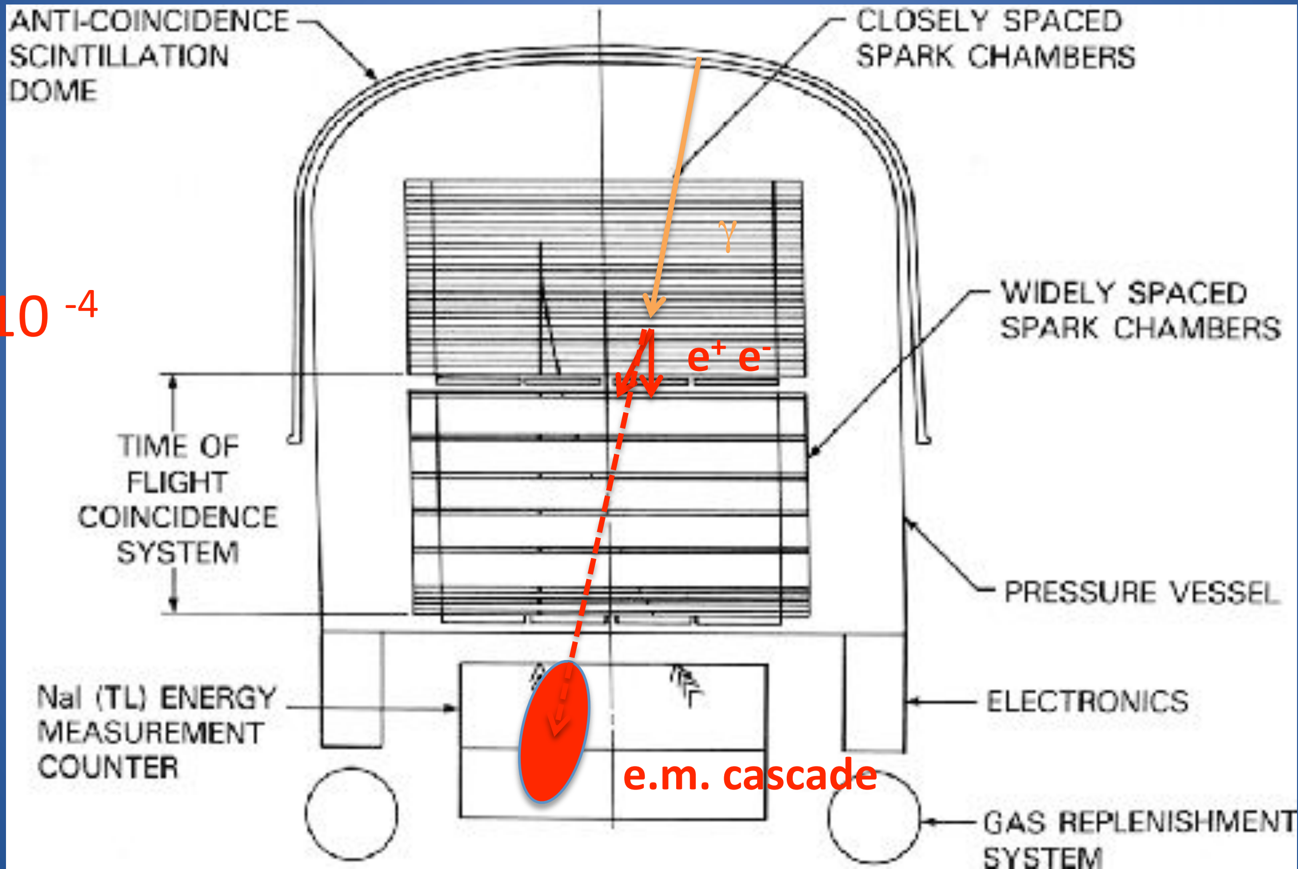
Energetic Gamma-Ray Experiment Telescope



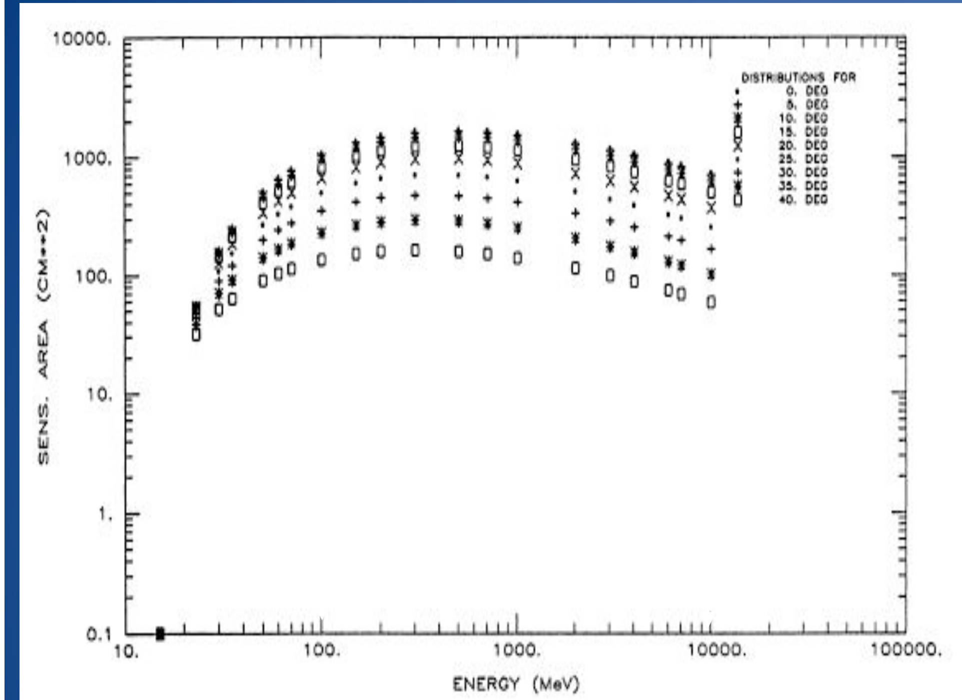
EGRET

Energetic Gamma-Ray Experiment Telescope

$I_{\gamma} / I_{cr} \sim 10^{-4}$



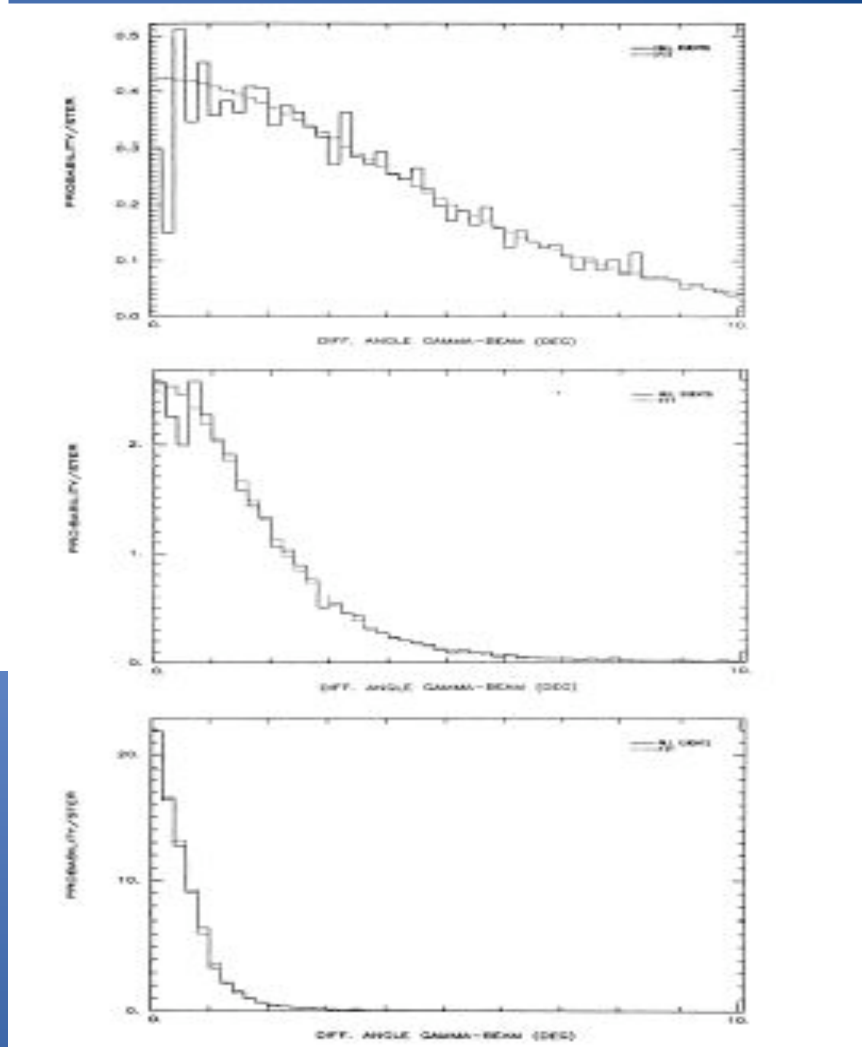
EGRET



Effective detection area = f(E)

Point-spread function

(angular resolution)



High energy region (30 MeV-100 GeV)

- γ-ray conversion into e^+e^- pair
- Tracker

  Converting material +

  detection planes

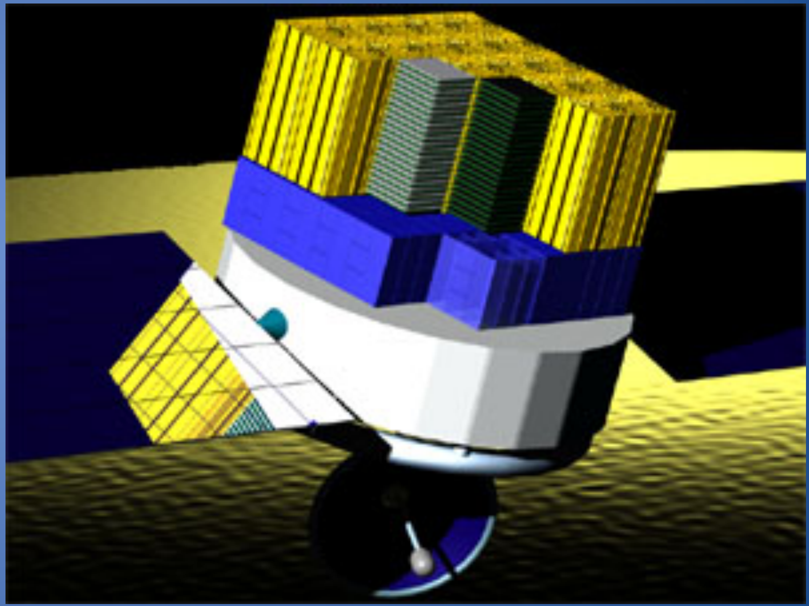
→ direction measurement

- Calorimeter

→ energy measurement

- Anticoincidence dome

→ remove charged particles



The GLAST Large Area Telescope

(launched in 2008)

High energy region (30 MeV-100 GeV)

- γ-ray conversion into e^+e^- pair
- Tracker

  Converting material +

  detection planes

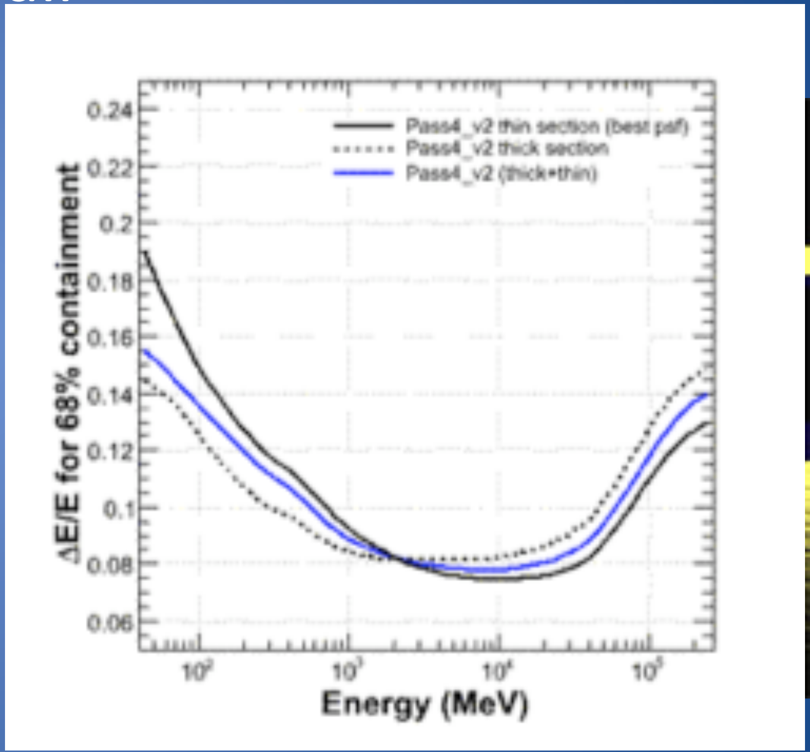
→ direction measurement

- Calorimeter

→ energy measurement

- Anticoincidence dome

→ remove charged particles



The GLAST Large Area Telescope

(launched in 2008)

Old and new detectors

Instrument	EGRET	AGILE	GLAST
Energy range	2 MeV-30 GeV	30 MeV-50 GeV	10 MeV-300 GeV
Field of view	0.20 sterad.	2 sterad.	2.4 sterad.
Angular resolution	1.5° @ 1 GeV	0.6°	0.12° @ 10 GeV 4° @ 100 MeV
Source location	5' to 10 '	30 ' @300 MeV	0.4 '
$\Delta E/E$	10 %	100 %	10 %
Dead time	0.1 s	< 100 μs	< 100 μs

γ-ray astronomy above 100 GeV: Cherenkov light technique

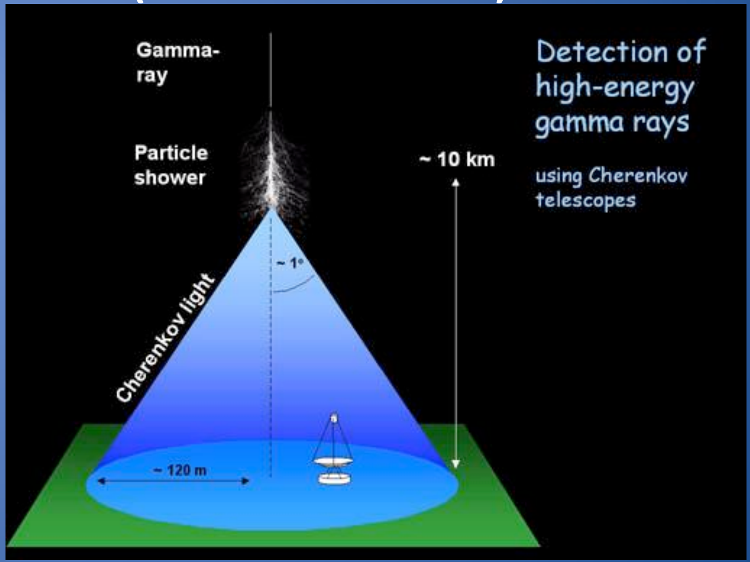
- Very low fluxes:

  e.g. Crab nebula: flux(E > 1 TeV) = 2 × 10^{-11} cm^{-2} s^{-1}

  Large effective detection areas (>30 000 m^2) needed

  → Back to the ground

- Use the atmosphere as a huge calorimeter and detect γ-ray-induced atmospheric showers through Cherenkov light:



Light pool on the ground: 300 m diameter

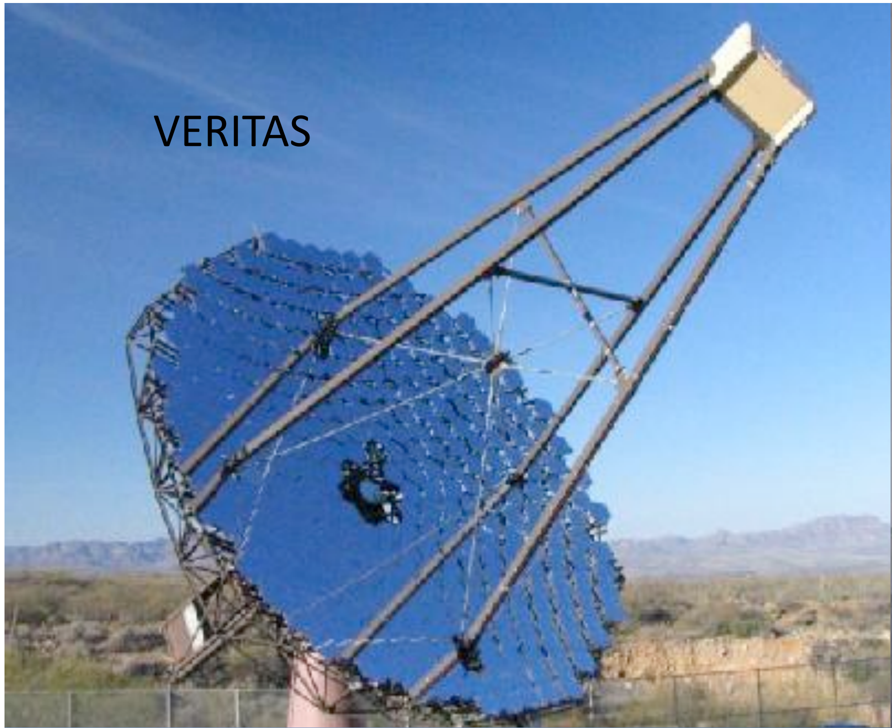
Atmospheric Cherenkov techniques

- Only working by clear moonless nights
  → Duty cycle ≈ 10 % or less
- Detection area ≈ size of the Cherenkov light pool on the ground
  - *Cherenkov angle ≈ 1° at ground level*
  - *Light pool diameter ≈ 300 m at 2000 m a.s.l.*
- Very brief flash of Cherenkov light (a few nanoseconds) → need fast photodetectors
- $E_o f(r) A qe > k\sqrt{B\,\Omega\,\Delta t\,A\,qe}$ ➔ $E_o^{th} \sim k\sqrt{B\,\Omega\,\Delta t\,/\,A\,qe}$

  ➔ need large light collectors

Numerically:

- $E_o f(r)\ A\ qe > k \sqrt{B\ \Omega\ \Delta t\ A\ qe}$
- $A > k^2\ B\ \Omega\ \Delta t\ /\ (qe\ E_o^{\,2} f(r)^{\,2})$
- $B = 10^{12}$ ph $m^{-2} s^{-1} sr^{-1}$
- $\Omega = \pi\ \theta^2 \sim 10^{-3}$ sr (1 degree)
- $\Delta t = 10^{-8}$ s
- $qe = 0.2$
- $K = 3$
- $E_o f(0) \sim 1$ ph m^{-2} @ 100 GeV
- A (100 GeV) $> 10\ 10^{12}\ 10^{-3}\ 10^{-8}\ /\ 0.2\ m^2 \sim 500\ m^2$
- $=> R \sim 10$ m


VERITAS

CANGAROO III

MAGIC

HESS I

Present imaging atmospheric telescopes

Experiment	Number of telescopes	Reflector diameter (m)	Site
CANGAROO III	4	10	Australia
HESS I	4	12	Namibia
MAGIC	1	17	Canaries
VERITAS	4	12	Arizona

A gamma-ray induced electromagnetic shower

On average

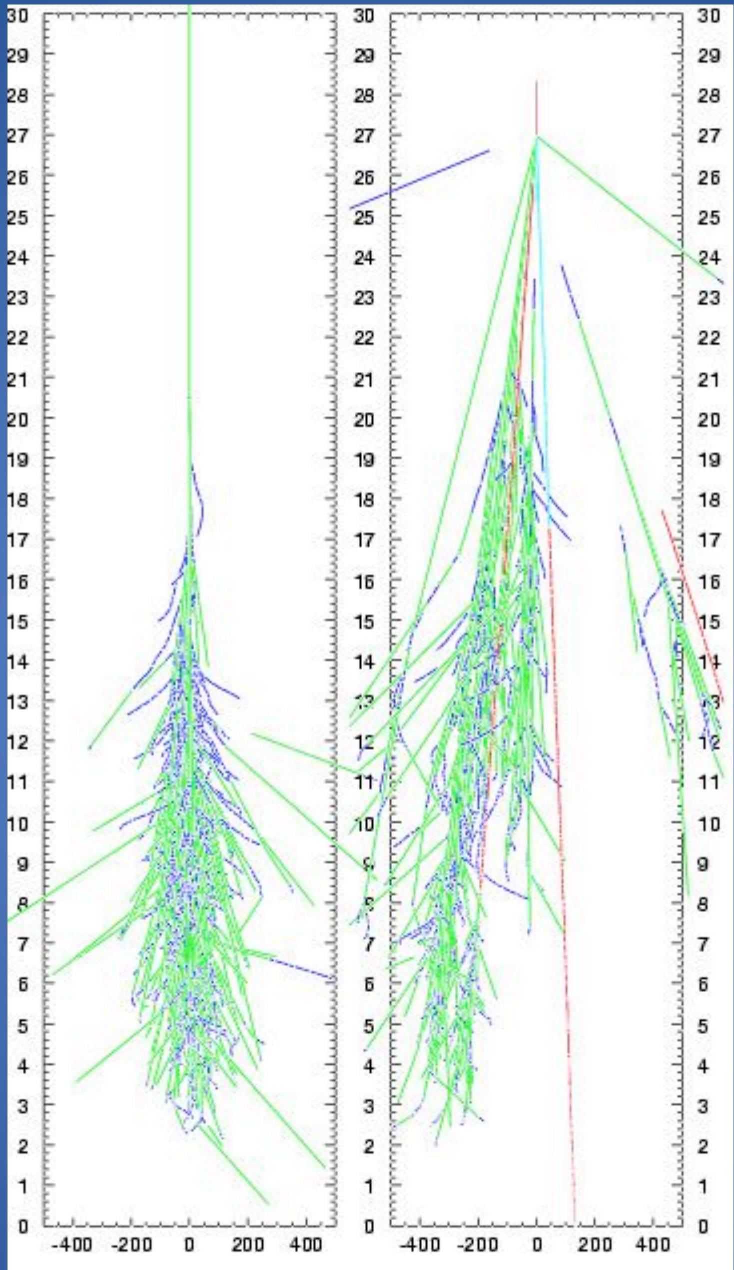
rotational symmetry

Small transverse momenta

(Almost) no muons

Essentially

e+ e- and secondary γ-rays



A proton-induced hadronic shower

Larger tranverse momenta

Presence of muons from meson decays

(in red on the figure)

=> HIGH ANGULAR RESOLUTION => SMALL FIELD OF VIEW => TRACKING DETECTORS

Imaging telescopes: the cameras

Experiment	Number of pixels	Pixel size	Field of view Ø
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°

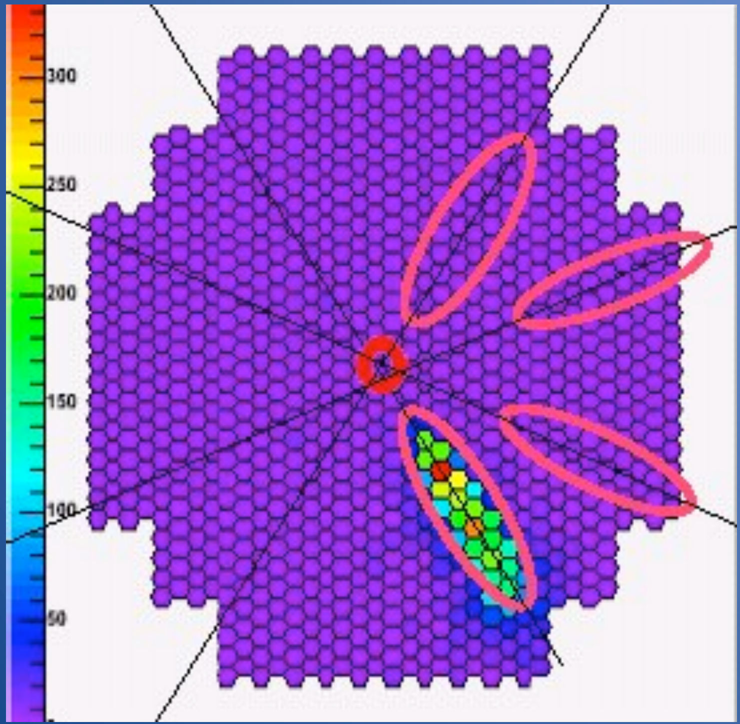
Goodbye!

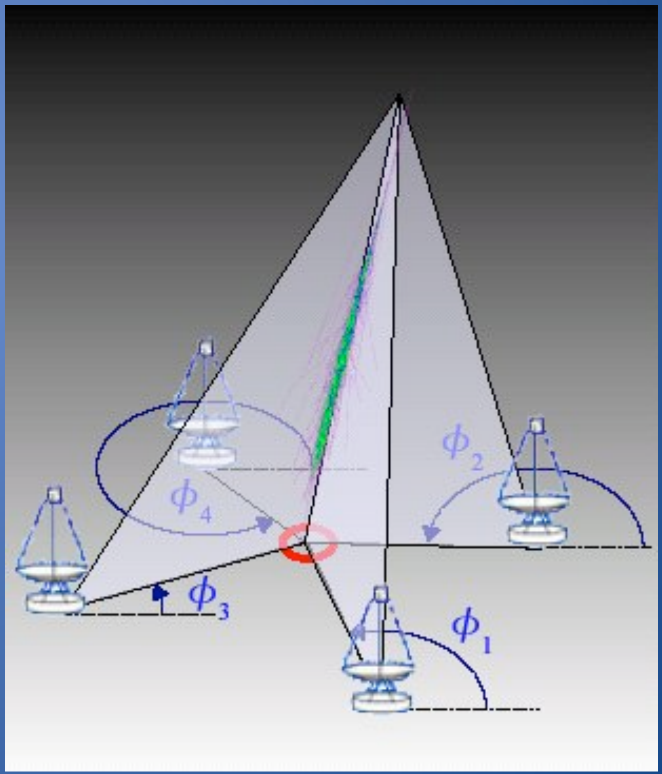
High-definition cameras (H.E.S.S.)

- 960 phototubes …
- … equipped with light collectors (Winston cones).
- Trigger electronics within the camera (overlapping sectors; majority logic).
- Readout from analogue memories (1 GHz sampling) within the camera.
- Analogue signal integrated over 12 ns → ADC

Stereoscopic analysis (e.g. HEGRA, H.E.S.S.)

- Direct measurement of the **γ-ray origin** in the field of view (important for extended sources)
- Direct measurement of the **impact on the ground** (important for energy measurement)

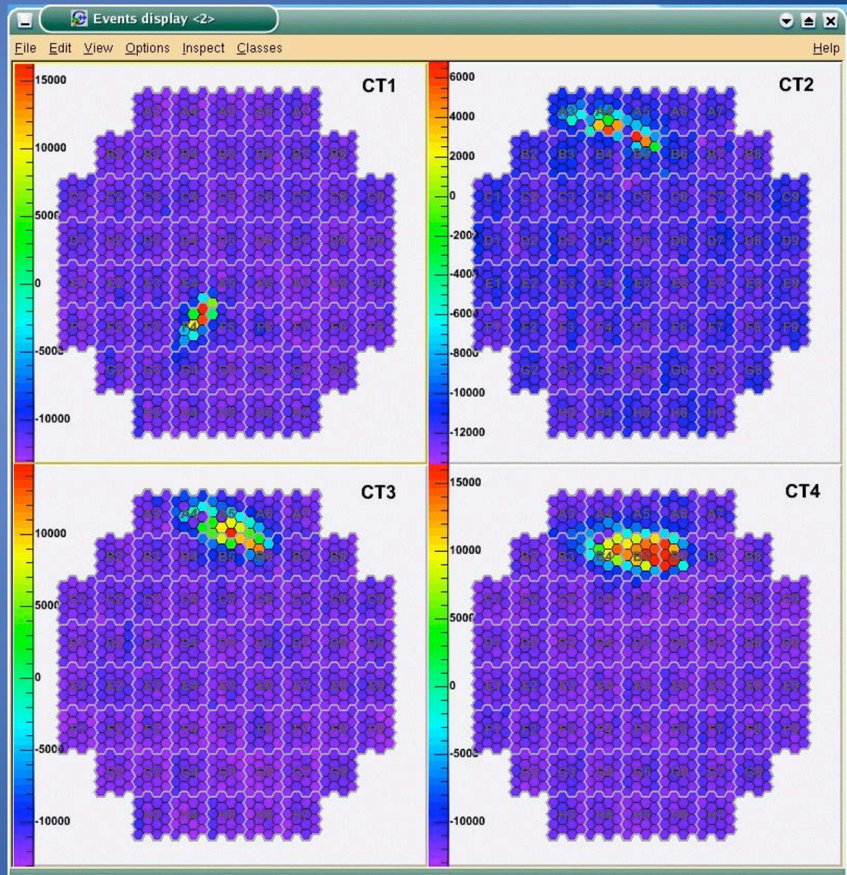




Stereoscopic analysis (e.g. HEGRA, H.E.S.S.)

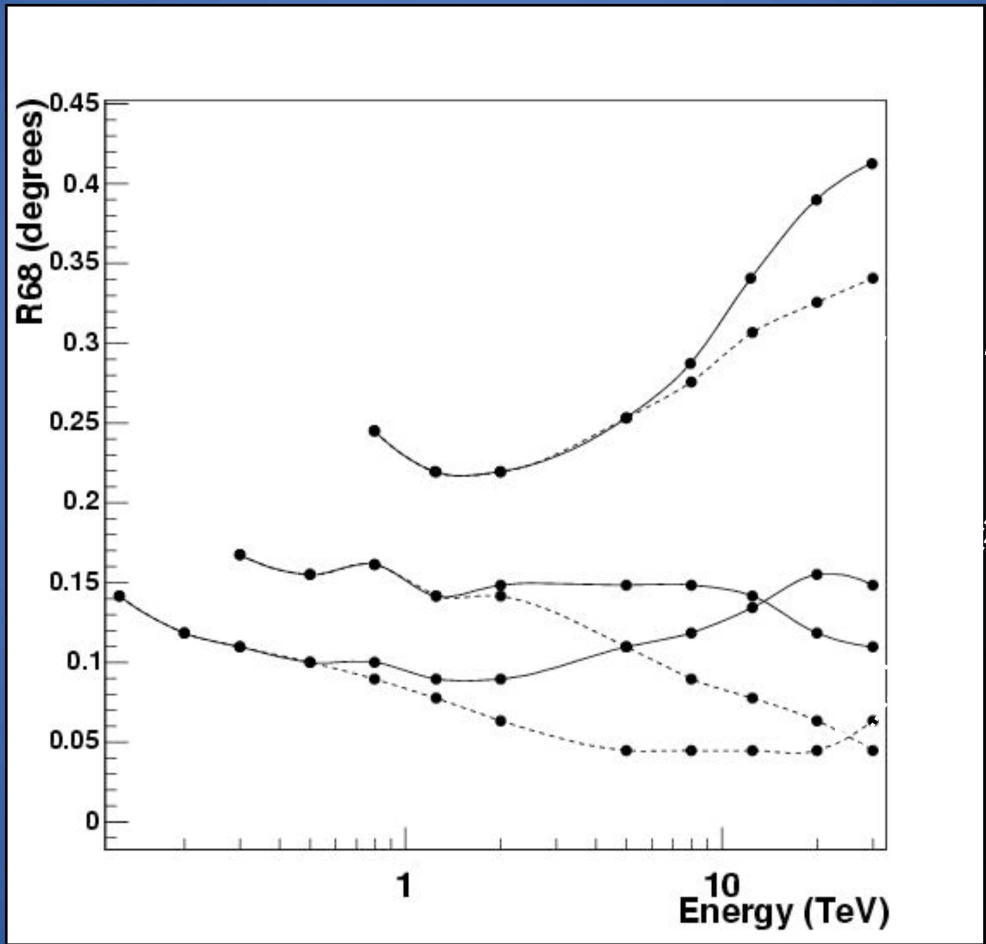
- Showers viewed by several telescopes
- Considerable hadronic rejection (> 1000)

  Use constraint of rotational symmetry
- Much better angular resolution
- Better energy resolution



H.E.S.S. angular resolution

Angular radius around the source containing 68% of reconstructed origins vs. energy and zenith angle ζ



With cutoff on angular distance from the centre of the field of view