Fisica Nucleare e Subnucleare

Lezioni n. 44 e 45

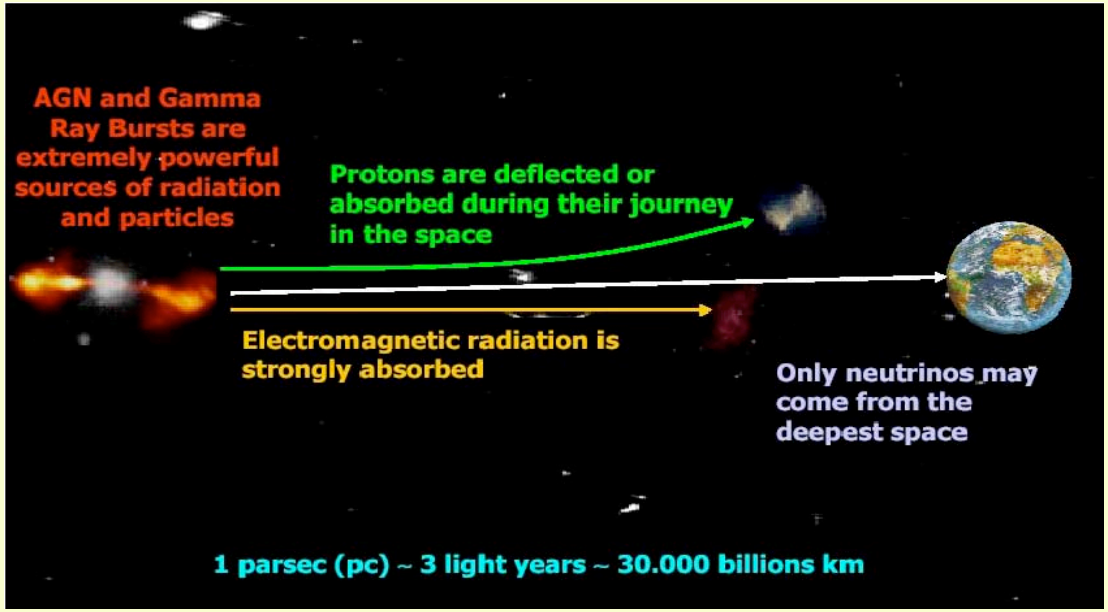
- Rivelazione di neutrini astrofisici di energia estrema: $E_\nu > 10^{17}$ eV
  - rivelazione "acustica" (in acqua e/o in ghiaccio)
  - rivelazione "radio" (per sciami atmosferici, nel ghiaccio, in miniere di sale)

Outline

- **Cosmic Neutrinos Astrophysics**
  - Neutrino Astronomy
  - Neutrino Production
  - GZKν
  - Flux Limits
- **Detection Techniques**
  - [Optical Cherenkov]
  - Radio Cherenkov
  - Radio (EAS)
  - Acoustical

- **Detection principles**
- **Tests & Experiments**
- **Future Developments**

Neutrino - Astronomy



- **Astrophysics**

EHECν's as a diagnostic of astrophysical processes

(sources, acceleration engines, propagation…)

- **Particle Physics**

beyond the Standard Model

($\sigma_{\nu N}$, strongly interacting ν's…)

- **Cosmology**

EHEC absorption on the CνB

(resonant annihilation of EHECν with relic $\underline{\nu}$ into Z-bosons)

UHEν's Production

- Acceleration (*bottom-up* model)
- X-particles Annihilation (*top-down* model)

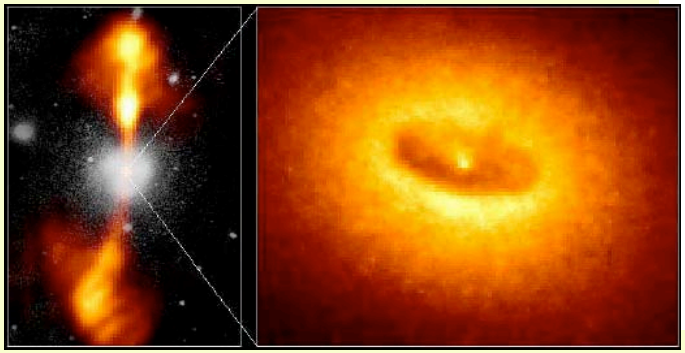
BUT

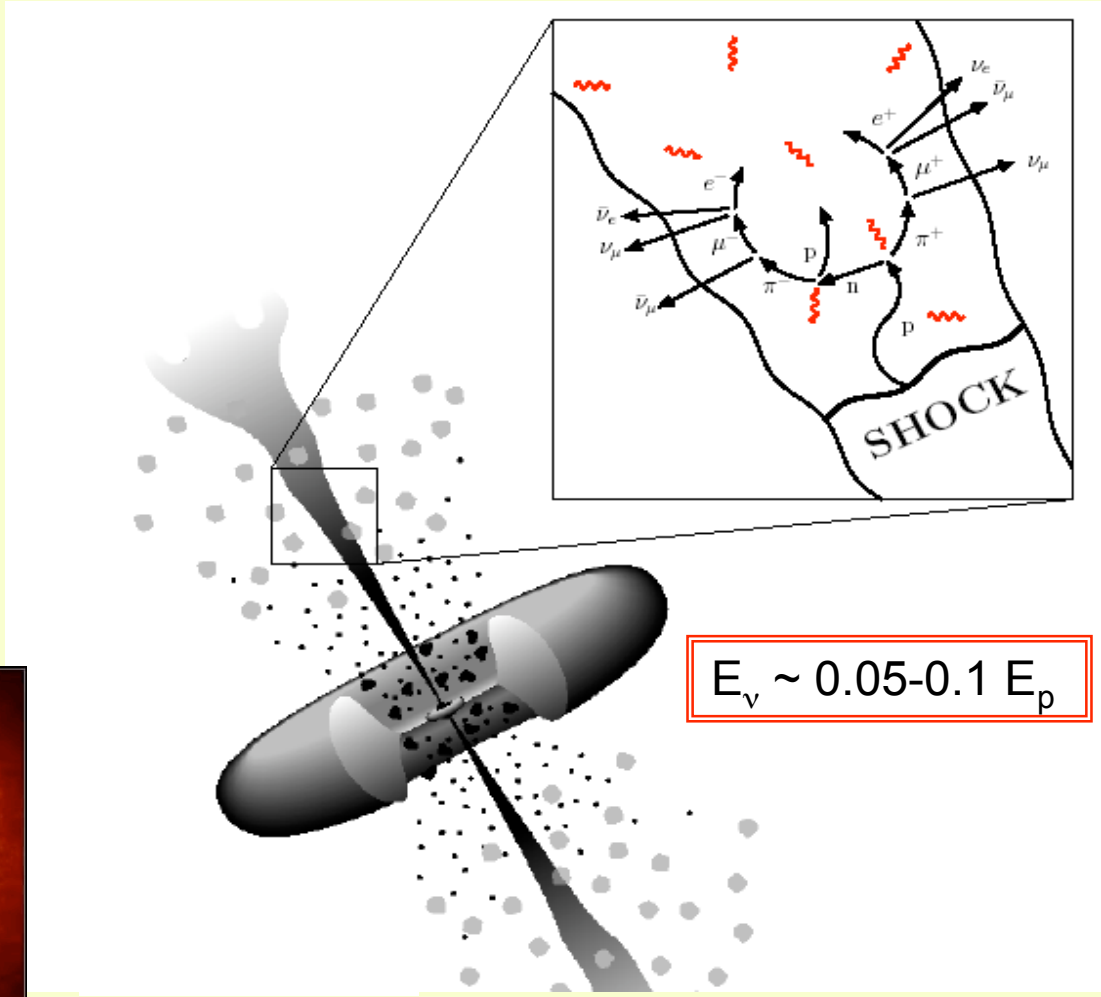
- **A huge target volume is needed (~ km3)**
- **Signal to noise should be optimized**

UHEν's production: Acceleration
(*bottom-up* model)

Fermi Engine

- *p*'s, confined by magnetic fields, accelerated through repeated scattering by plasma shock fronts
- production of π's and *n*'s through collisions of the trapped *p*'s with ambient plasma produces γ's, ν's and CR's

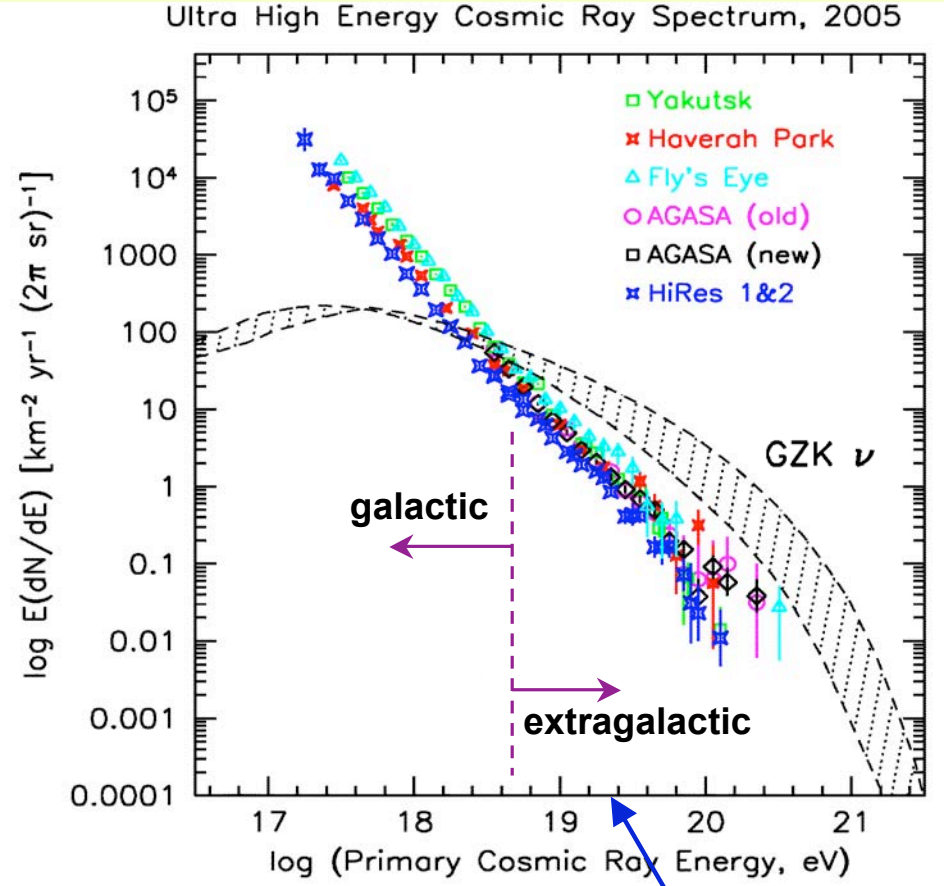




GZK Neutrinos

- Neither origin nor acceleration mechanism known for cosmic rays above 10^{19} eV
- A paradox:
  - No *nearby* sources observed
  - distant sources *excluded* due to GZK process
- **Neutrinos** at $10^{17\text{-}19}$ eV **required** by standard-model physics through the GZK process:

  observing them is crucial to **resolving the GZK paradox**



10^7 times Tevatron

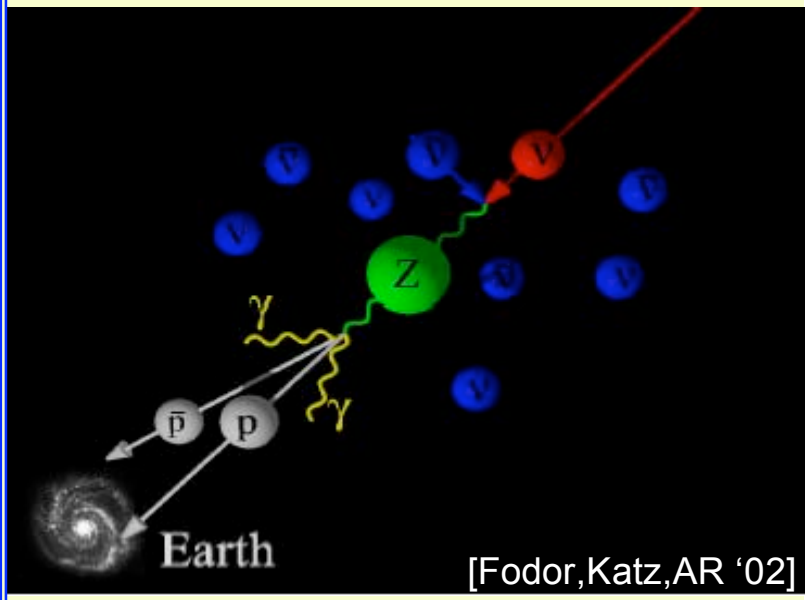
The Z-burst model

- Original idea, proposed as a method of Big-bang relic neutrino detection via **resonant annihilation** (T. Weiler, D. Fargion):

  10^{23} eV ν + 1.9K $\underline{\nu}$ → Z_0

  produces a dip in a cosmic neutrino source spectrum, *IF one has a source of 10^{23} eV neutrinos*

- More recently: Z_0 decay into hadron secondaries gives 10^{20+} eV protons to explain any super-GZK particles, again *IF there is an appropriate source of neutrinos at super-mega-GZK energies*



[Fodor,Katz,AR '02]

The Z-burst proposal has the virtue of solving two completely unrelated (and very difficult) problems at once: **relic neutrino detection** AND **super-GZK cosmic rays**

Event Rates & Detection Techniques

- Predicted neutrino fluxes are very **LOW** →
  Cubic kilometer scale detectors required
  → NATURAL TARGET (ice, water, rock …)

→ **Optical neutrino detectors**

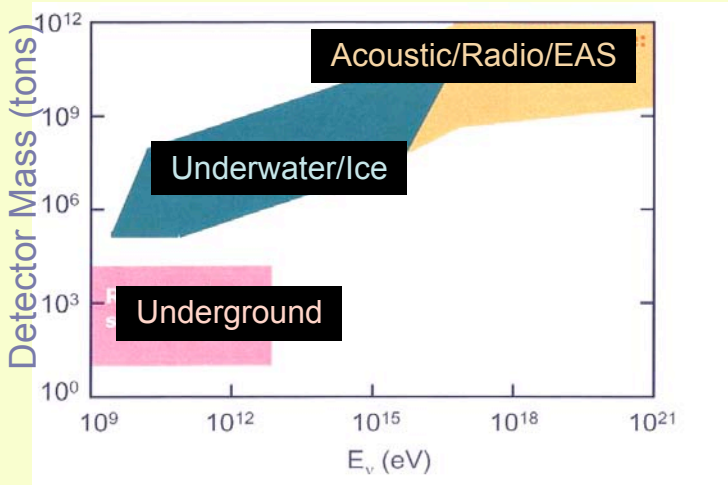
– Light attenuation (60m) limits the effective volume

⇓

- Need a detector with a100% duty cycle.
- Need attenuation lengths of scale O(1km)

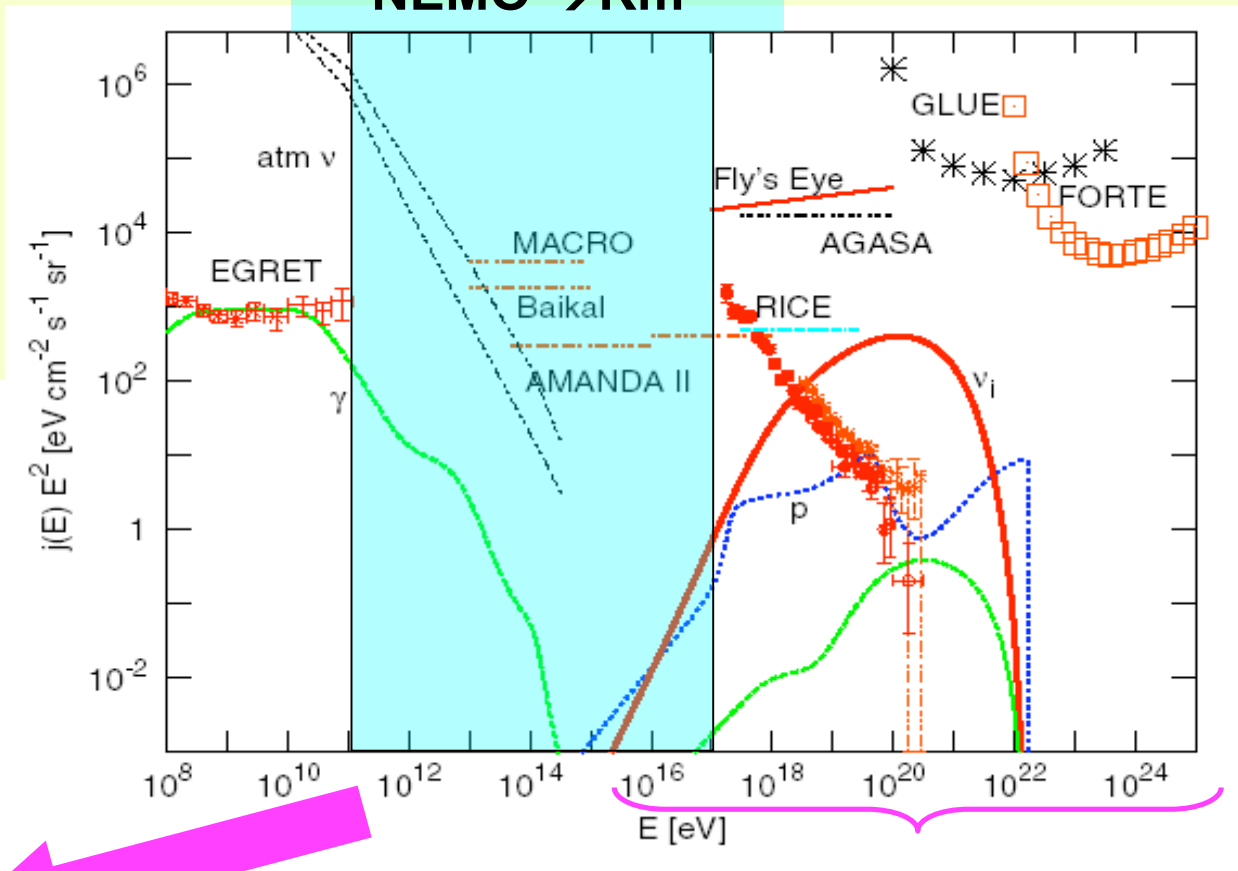
→ **Radio & Acoustic Detection Tecniques**

High Energy Neutrino Detection

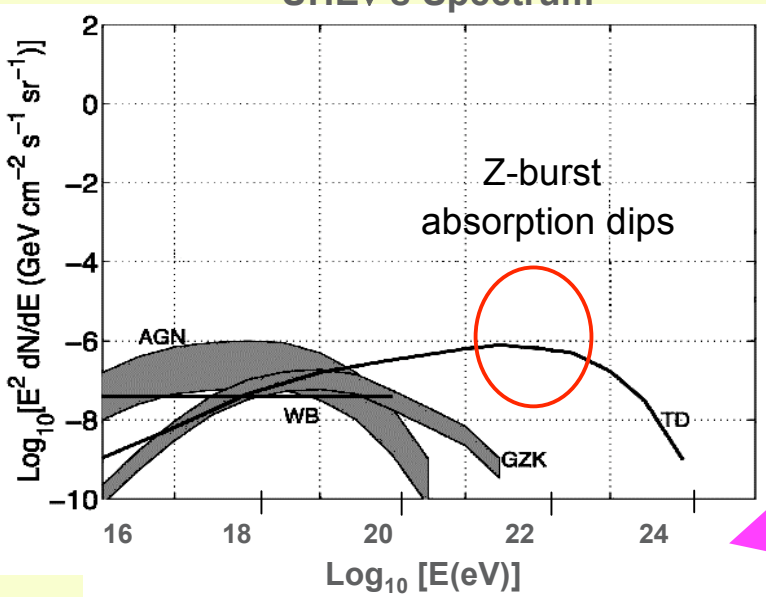


Optical Cherenkov
Underwater/Ice Telescopes

NEMO →Km³



UHEν's Spectrum



Detection Techniques
&
Target Media

- Optical Cherenkov (water, ice)
- Radio Cherenkov (ice, salt, sand)
- Radio – Geosynchr. Effect (EAS → atmosphere)
- Acoustical (water, ice, salt)

Neutrino Interactions → Simulation

Neutrino Interactions

$$\nu + N \rightarrow l^{\pm} + X \quad (CC)$$

$$\nu + N \rightarrow \nu + X \quad (NC)$$

& Neutrino Detection

- Lepton Track (μ, [τ]) → Cherenkov Light Emission
- Hadronic (X) + E.M ($e^{\pm}$) Cascade → Acoust. Signal
- E.M. Cascade → Charge Excess → Radio Signal

The Askaryan Effect

- Proposed by G. Askaryan, 1962
  - High-energy neutrino interacts in a solid dielectric
  - Net charge excess develops in e-γ shower
  - Charge excess moving at speed of light in vacuum

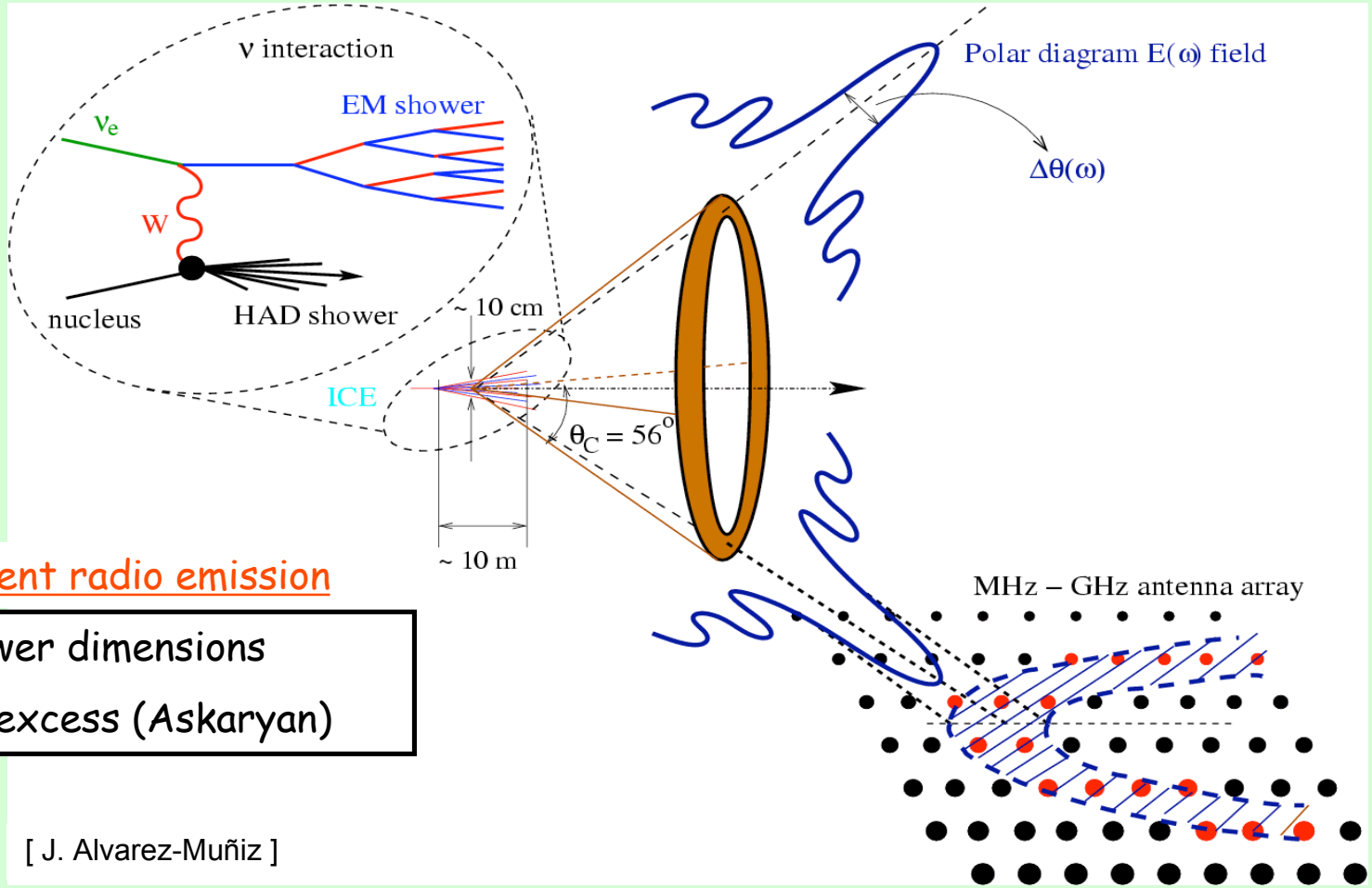
    → Cherenkov radiation results

- The key: Cherenkov radiation is **coherent** for wavelengths larger than shower bunch size:

  λ >> shower dimensions

  - For sand, salt and ice, coherent at frequency f < 1-10 GHz

The Askaryan Effect



Coherent radio emission

- λ >> shower dimensions
- Charge excess (Askaryan)

[J. Alvarez-Muñiz]

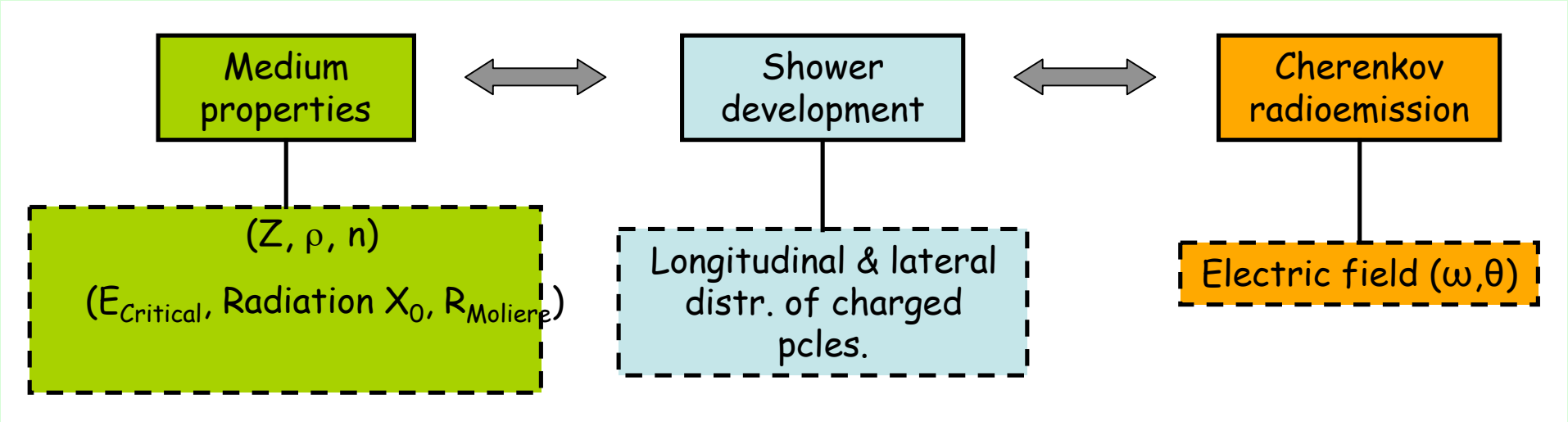
Radio Cherenkov Detection

The Target

- **ICE** → Antarctic icecap (RICE, ANITA);
  - Possible co-detection with IceCube
  - Large volume seen with ANITA
- **SAND** → Lunar regolith (GLUE, others)
  - Showers visible from radio telescopes at E>10 EeV
- **SALT** → Salt domes (SALSA, ZESANA, SND …)
  - Easily accessible
  - No terrestrial radio interference

Simulation & Development

A simple model that relates medium properties with Cherenkov radio-emission is needed



Lab Test

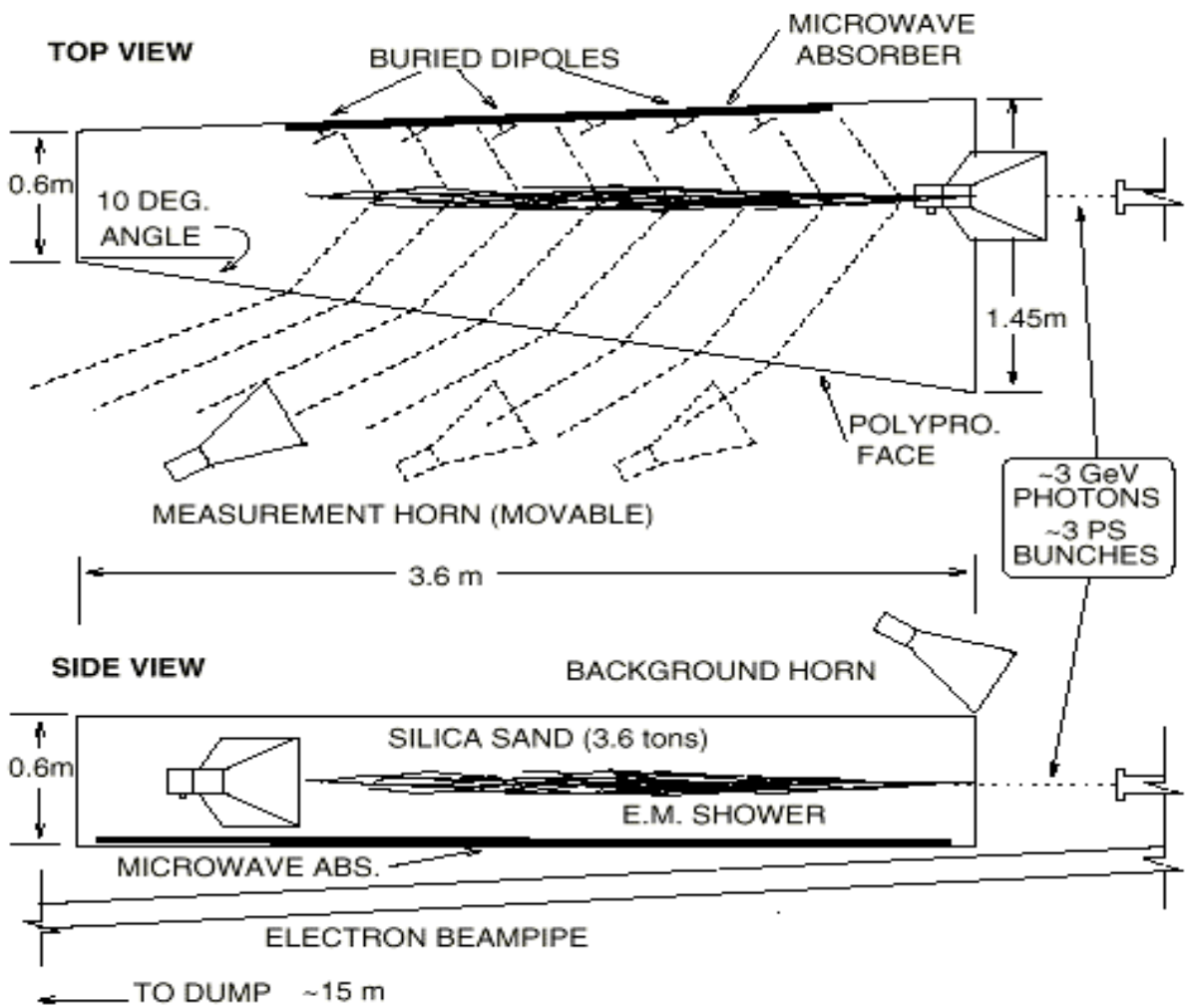
Radio Signals from Photon Beams in Sand and Salt

- Equivalent bunch energy from 10^{15} to 10^{19} eV
- Coherence observed over many decades in energy, frequencies from ~0.5 to 14 GHz

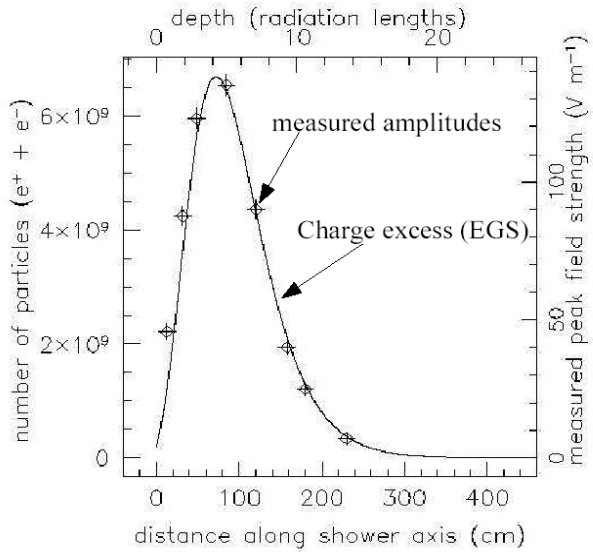
(SLAC, 2000-2002)

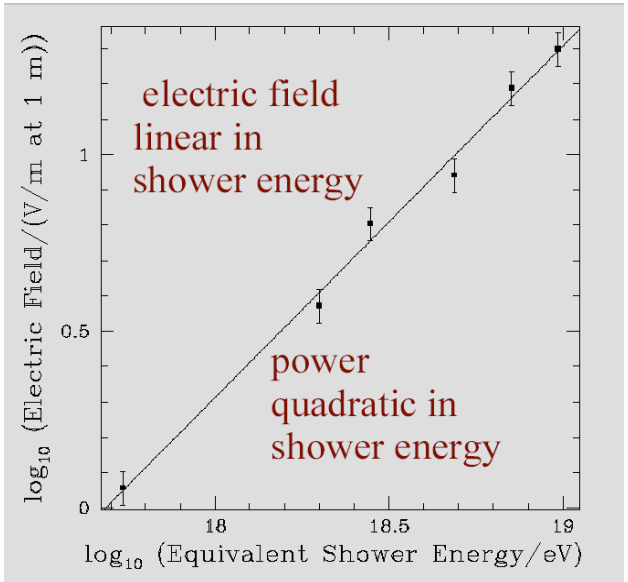
- **Askaryan effect has been observed directly in sand a**

Experimental Set-up



Results





Radio Signals from Photon Beams in Sand and Salt **(SLAC, 2000-2002)**

Radio Cherenkov Detection

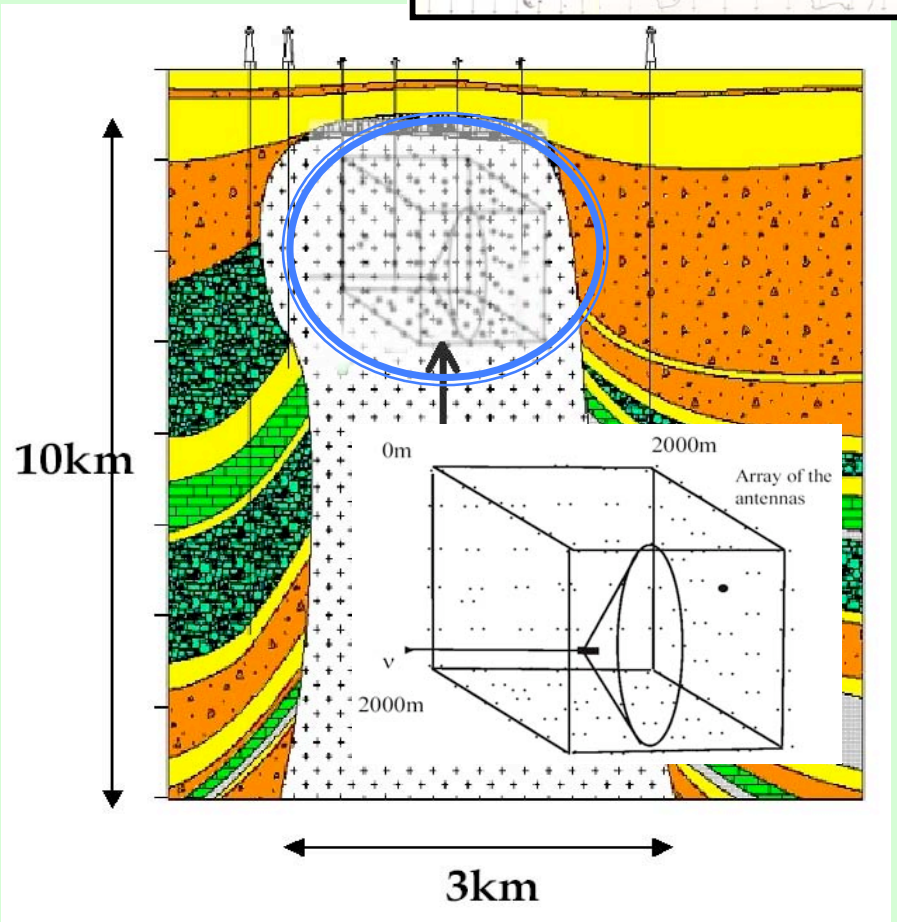
SALT Domes

- Rock salt is free from liquid and gas permeation
  - → **Homogeneity**
  - → **Good radio wave transparency**

  (Evaporate beds have high impurity content: water inclusions, beds of clay, silt, anhydrite,…)

- Covered soil prevents surface radio waves to penetrate

  (Penetrating CRs underground are too spatially disperse to generate coherent Cherenkov emission)



SALSA → **Sal**t-dome **S**hower **A**rray

SND → **S**alt **N**eutrino **D**etector

Measurement of Attenuation Length for Radio Wave in Salt

Tests have been performed using synthetic and natural rock salt samples.

	Freq.	Synthetic Rock Salt Samples (diameter/mm)	Attenuation Length/m
Synt.	300MHz	OHYO KOKEN KOGYO CO.25, 30φ	1000±640
	1GHz	OHYO KOKEN KOGYO CO.5, 6, 7, 8, 9φ	538±171
	Freq.	Natural Rock Salts Samples (diameter/mm)	Attenuation Length/m
U.S.A	300MHz	Hockley 10.4×10.9, 28, 29φ (USA)	156±112
	1GHz	Hockley6×6:monocrystalline form, 8φ, 9φ, 9φ (USA)	275±234
NL	300MHz	Zuidwending 28φ(Netherlands)	22±2
	1GHz	Zuidwending 8φ(Netherlands)	77±11
D	300MHz	Asse 25φ, 28φ (Germany)	405±166
	1GHz	Asse 9φ, 10φ(Germany)	60±25
	300MHz	Heilbronn 29φ (Germany)	41±3
UA	1GHz	Lugansk 9φ, 9φ: monocrystalline form (Ukraine)	517±339

Attenuation Length depends on grain diameter & homogeneity (scattering)

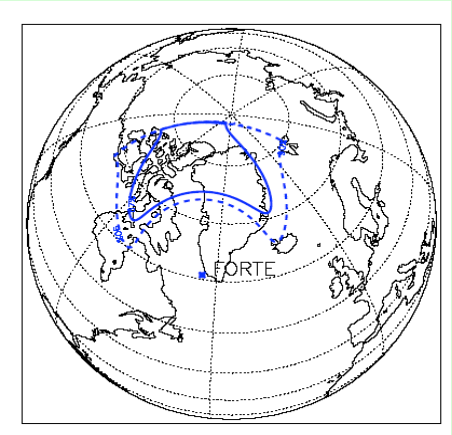
Attenuation Length is Frequency-Dependant

Selecting a suitable site, economical antenna spacing (~ 300 m) could detect GZK neutrinos.

Radio Cherenkov Detection

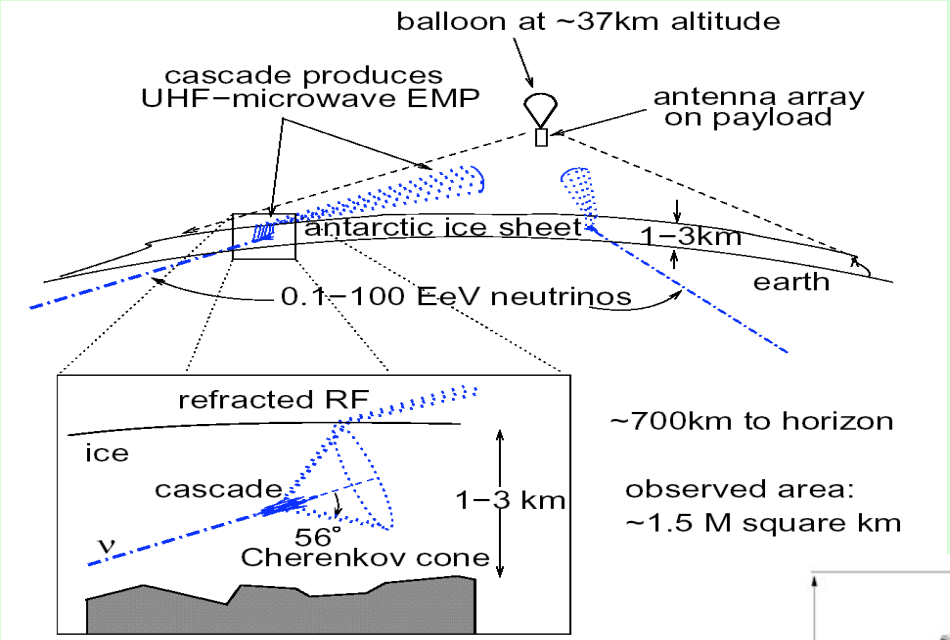
ICE

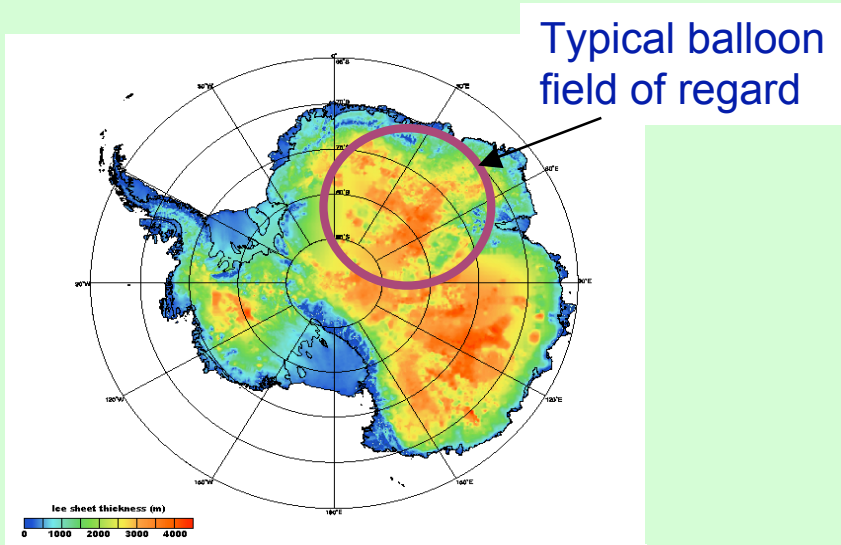
- **FORTE** → **F**ast **O**n-orbit **R**ecording of **T**ransient **E**vents (satellite)



- **RICE** → **R**adio **I**ce **C**herenkov **E**xperiment (ice)
- **ANITA** → **A**ntarctic **I**mpulsive **T**ransient **A**ntenna (balloon)

ANITA

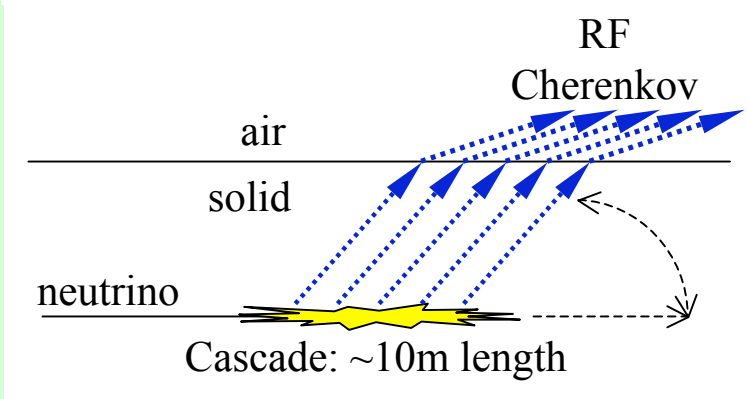


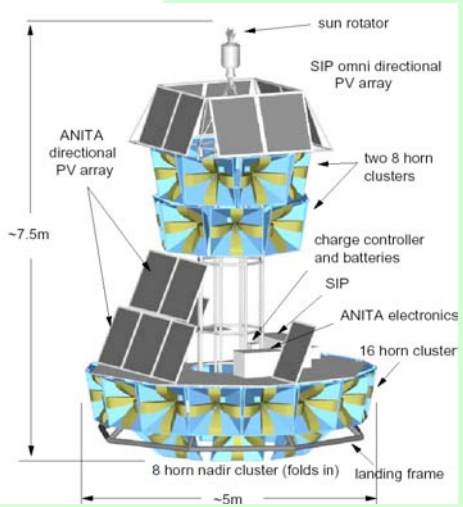


Effective "telescope" aperture:

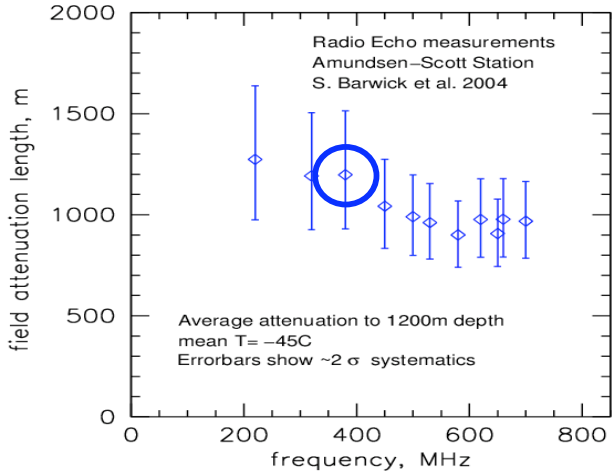
- ~ 250 km^3 sr @ 10^{18} eV
- ~ 10^4 km^3 sr @ 10^{19} eV

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

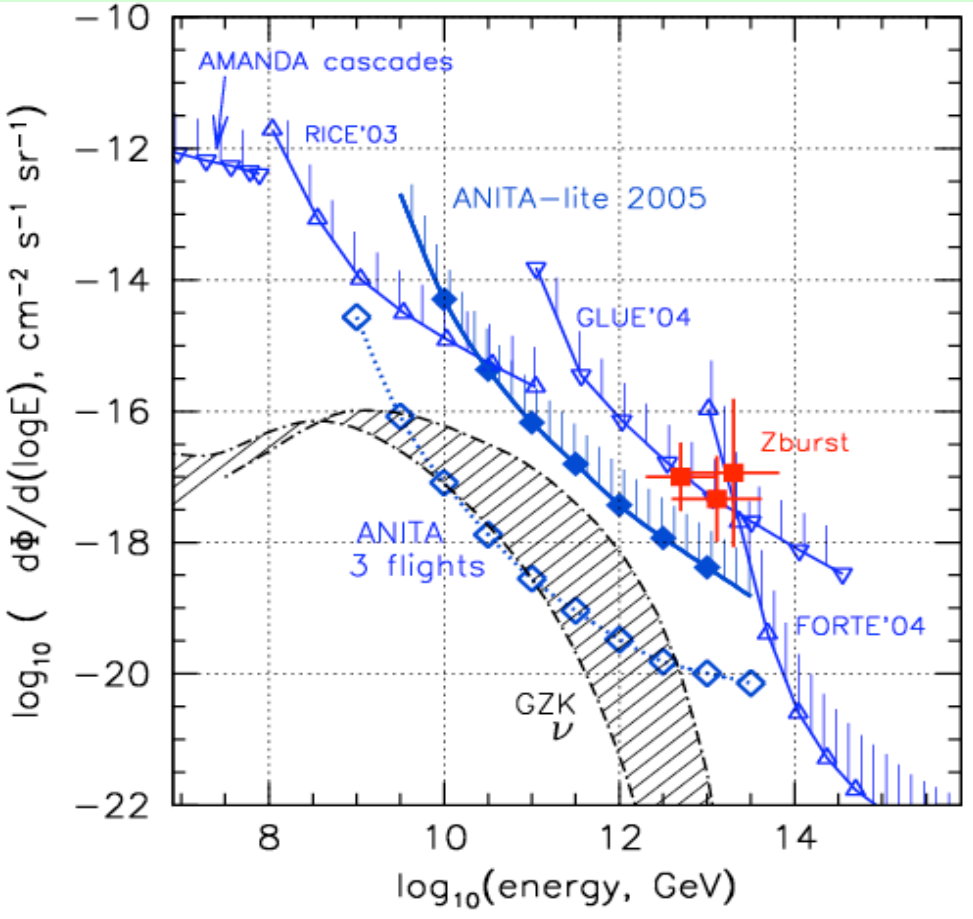




Ice RF clarity:
~1.2km attenuation length



Experiments Flux Limits

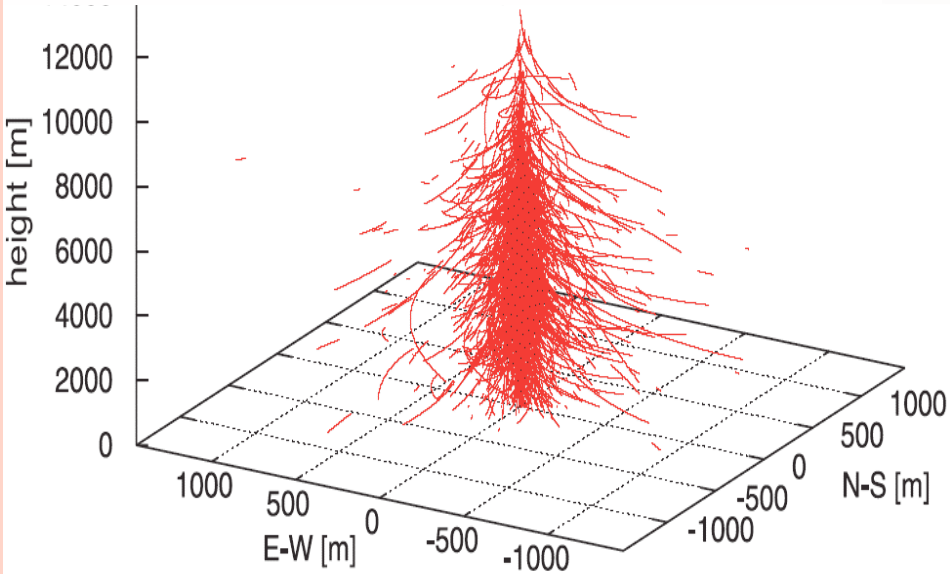


- **RICE** limits for 3500 hours livetime in embedded South Pole array
- **GLUE** limits ~120 hours livetime, Lunar regolith observations
- **FORTE** limits on 3 days of satellite observations of Greenland ice sheet
- **ANITA-lite** limits on 18.4 days of data, net 40% livetime with 60% analysis efficiency for detection

The Geosynchrotron Effect

MC Simulation takes into account:

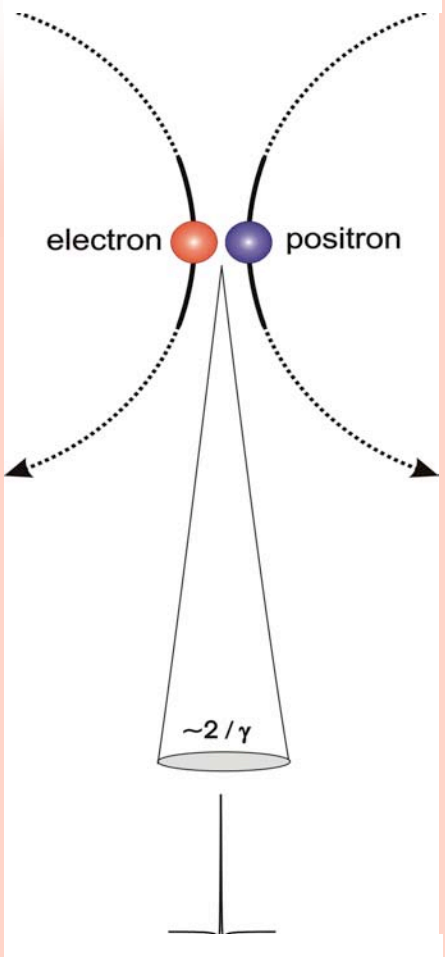
- longitudinal & lateral particle distribution
- particle track length & energy distributions
- air shower and magnetic field geometry
- shower evolution as a whole



EAS (Extensive Air Shower)

Emission of geosynchrotron radiation (electric field) due to Earth's magnetic field

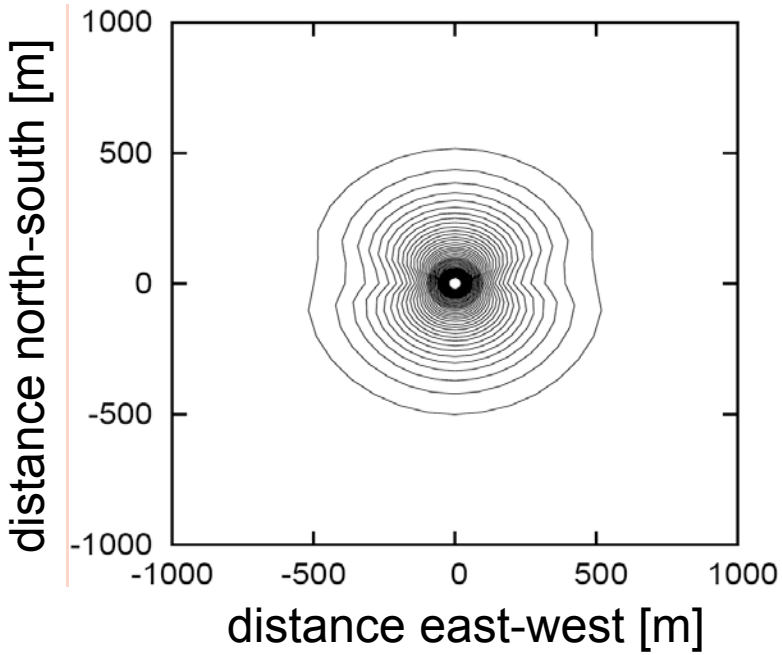
	velocity
	geomagnetic field
q	charge
γ	Lorentz factor
m	mass



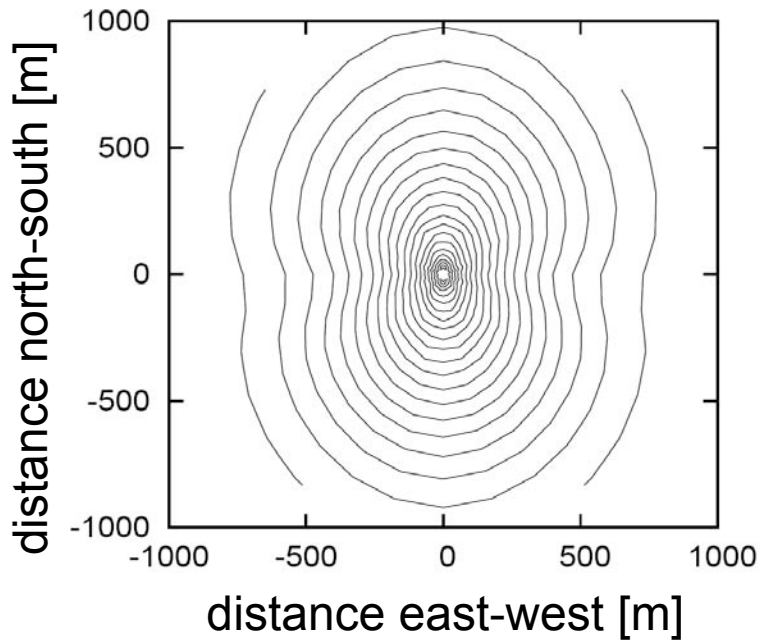
Simulation

Emission pattern for EAS at 10 MHz

Vertical 10^{17} eV shower



45° inclined 10^{17} eV shower



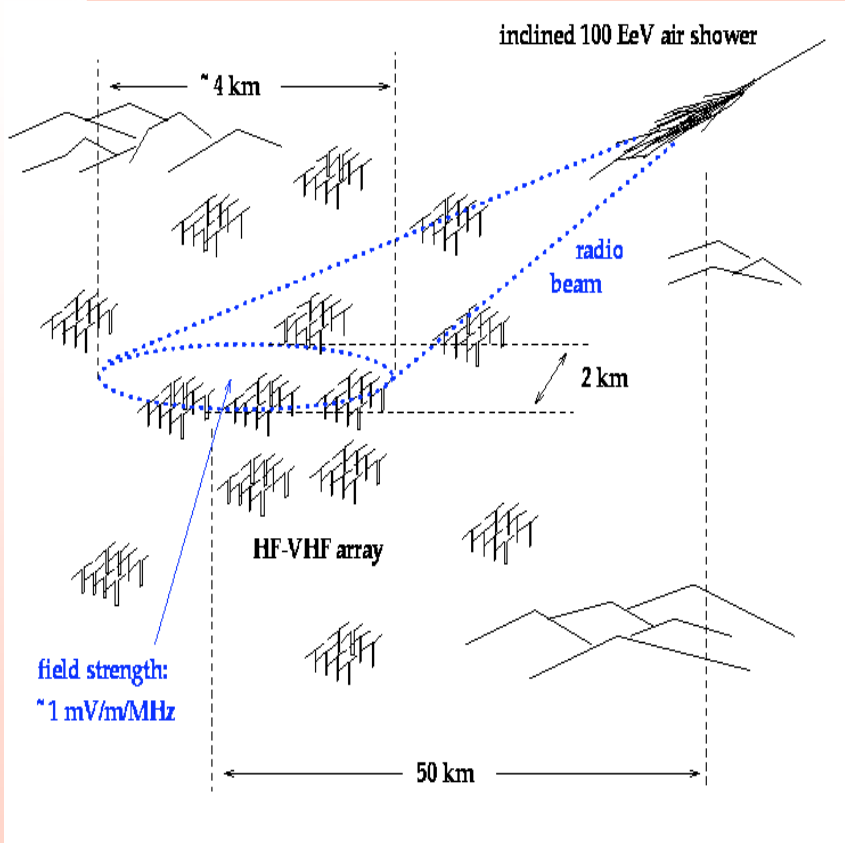
Radio Emission from CR Air Showers

ADVANTAGES

- Cheap detectors, easy to deploy
- High duty cycle (24 hours/day minus thunderstorms)
- Low attenuation (can see also distant and inclined showers)
- Also interesting for neutrinos

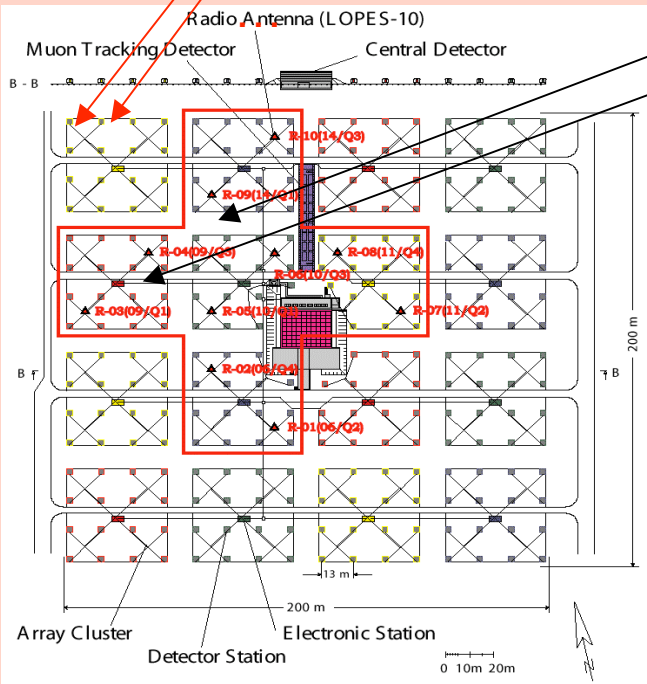
Potential problems

- Radio freq. interference (RFI)
- correlation with other parameters unclear
- only practical above ~10^{17} eV.



LOPES@KASCADE-Grande

KASCADE: ~250 electron & muon scintillator detector **LOPES10**: 10 radio antennas
KASCADE Grande: expansion of KASCADE



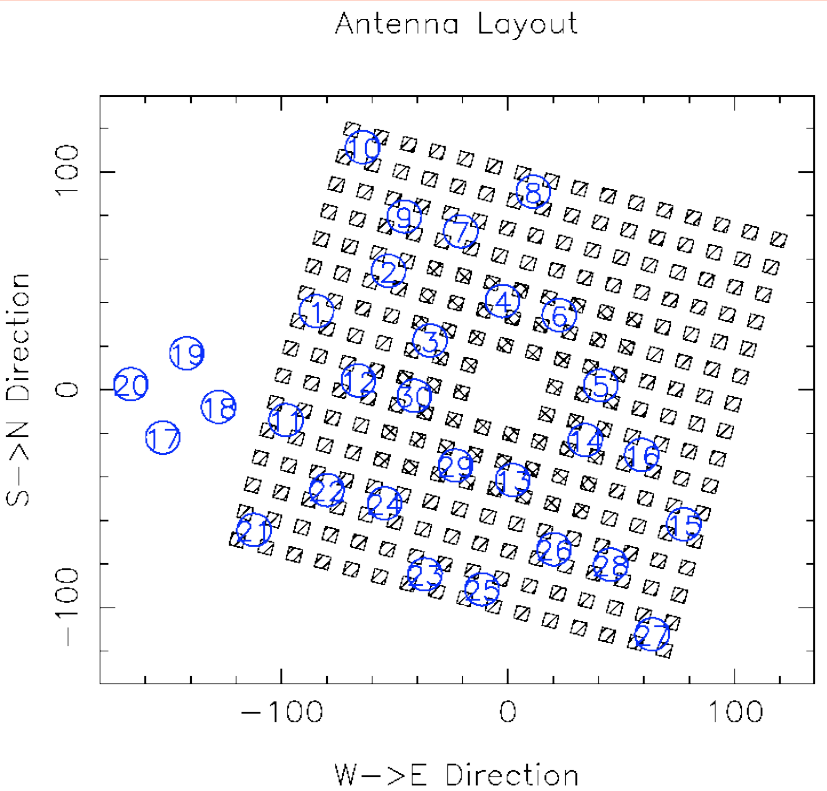
KASCADE

KASCADE Grande

Karlsruhe **S**hower **C**ore and **A**rray **De**tector

LOPES: Current Status

- 10 antenna prototype at KASCADE
- triggered by large event (KASCADE) trigger
- offline correlation of KASCADE & LOPES
  (not integrated yet into the KASCADE DAQ)
- KASCADE can provide starting points for LOPES air shower reconstruction
  - core position of the air shower
  - direction of the air shower
  - size of the air shower
- Now: 30 antennas have been installed and will take data soon



89 KASCADE events in first 6 months

→ 33 detected by LOPES

LOPES
Summary & Conclusions

- LOPES works, the geosynchrotron effect is real
- Radio is a faithful tracer of air showers
- Radio gives very good energy information and arrival directions.
- Inclined showers: Excellent prospects for composition studies and neutrino hunting
- Next steps:

  - detailed comparison of simulated events with events measured by LOPES

  - Argentina (AUGER) [better radio BG], Moon

→ LOFAR

Low **F**requency **Ar**ray

Acoustical Detection

Particles Interaction in Water - the Acoustic Signal

" instantaneous "
& localized
energy deposition

↓

local heating of the medium

↓

Local density variation

↓

PRESSURE WAVE

Thermo-Acoustic (Hydrodynamic) Mechanism of Energy Dissipation

(Askaryan)

Wave Equation

$$\nabla^2 p(\vec{r},t) - \frac{1}{c_s^{\,2}}\frac{\partial^2 p(\vec{r},t)}{\partial t^2} = -\frac{\beta}{C_p}\frac{\partial^2 q(\vec{r},t)}{\partial t^2}$$

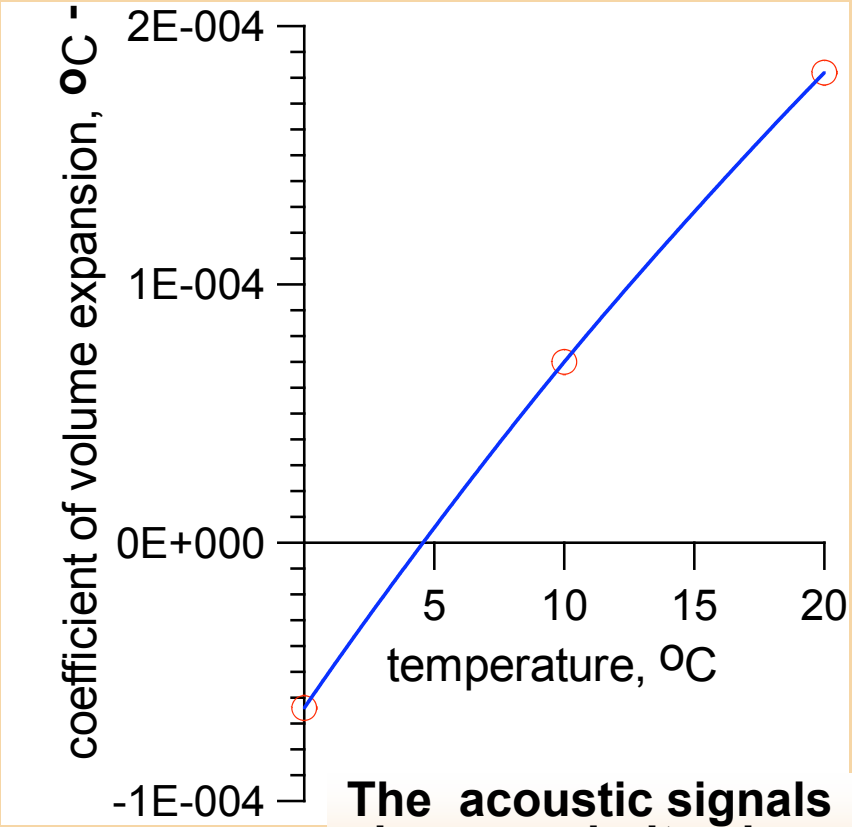
p(**r**, t)	pressure
q(r, t)	energy deposition density
c_s	speed of sound
β	volume expansion coeff.
C_p	heat capacity

Solution (Kirchoff Integral)

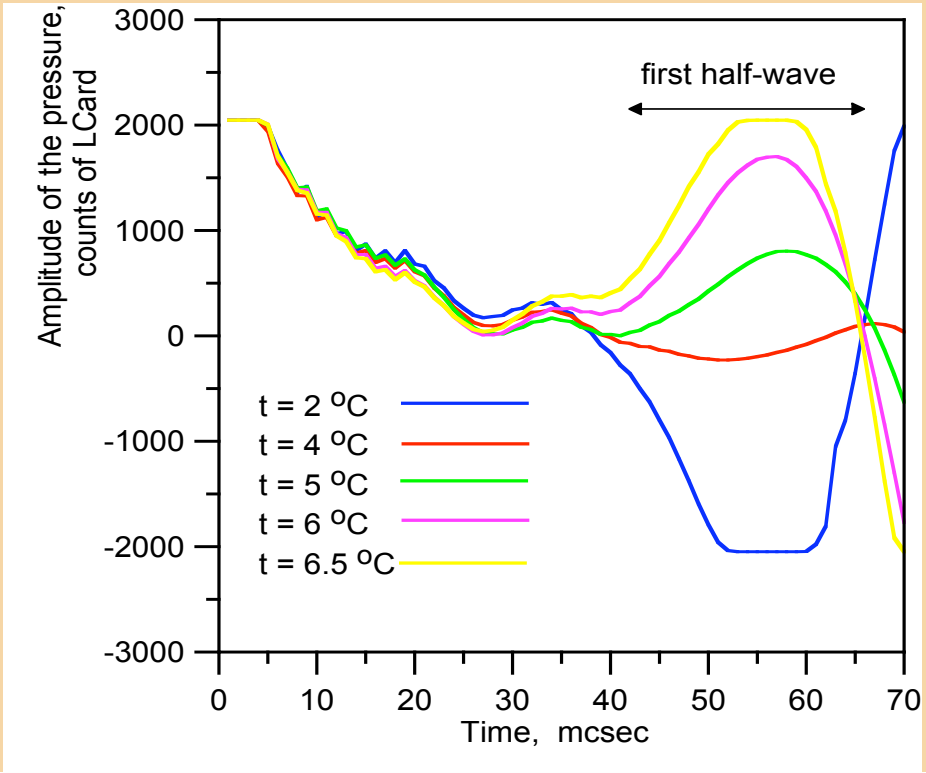
$$p(\vec{r},t) = \frac{\beta}{4\cdot\pi\cdot C_p}\int \frac{dV'}{\left|\vec{r}-\vec{r}\right|}\cdot\frac{\partial^2}{\partial t^2} q\left(\vec{r}, t - \frac{\vec{r}-\vec{r}}{c_s}\right)$$

Acoustical Detection

β depends on temperature (data in water)



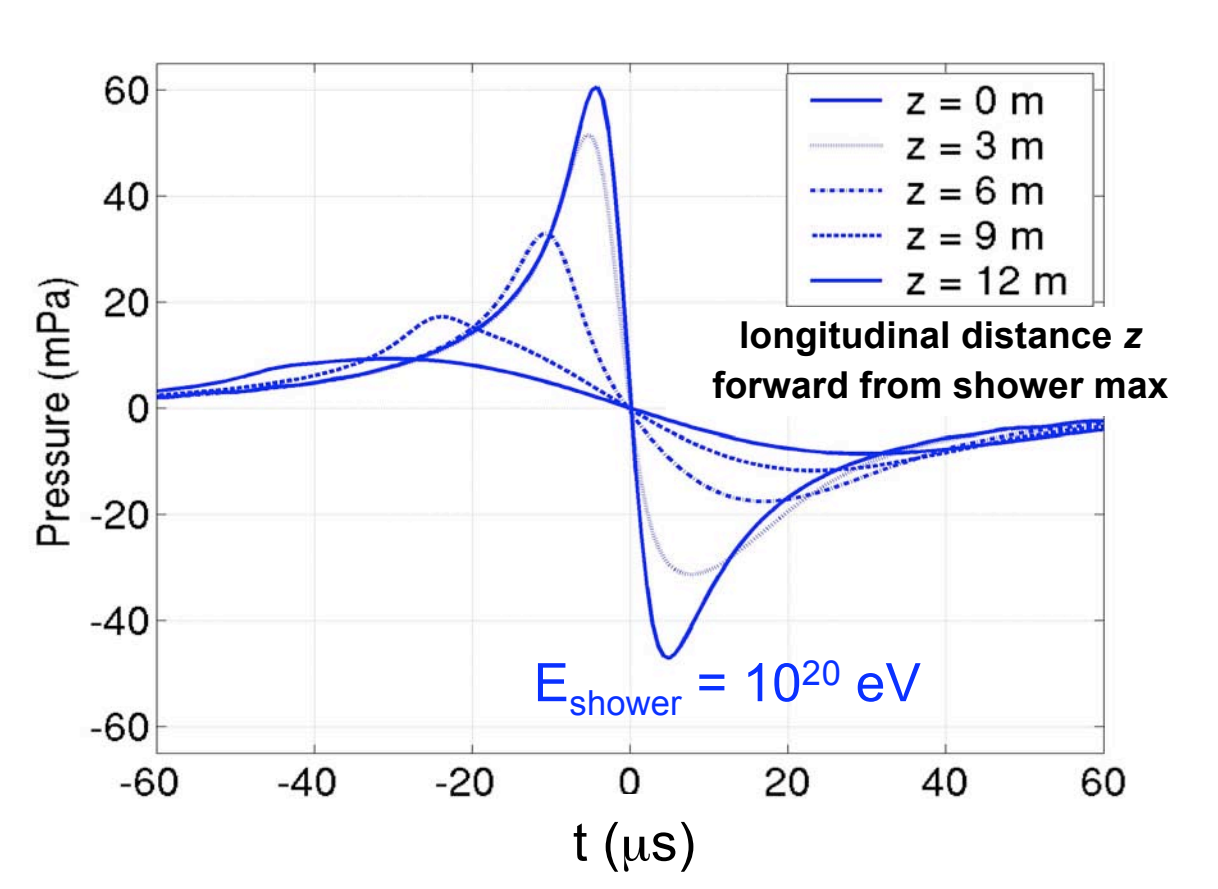
The acoustic signals change polarity close to t ~ 4 °C

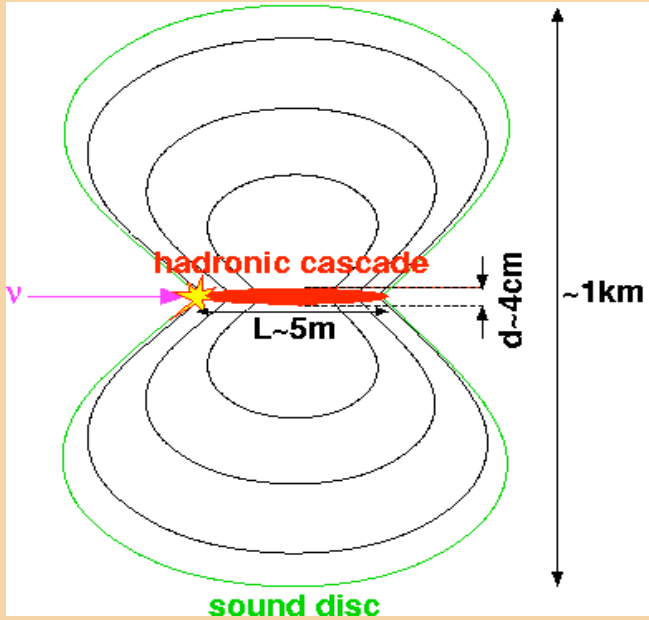


Largest Signal in Mediterranean (~14 °C)

Acoustical Detection

Acoustic Signal from Neutrinos





Simulated Neutrino Pulse

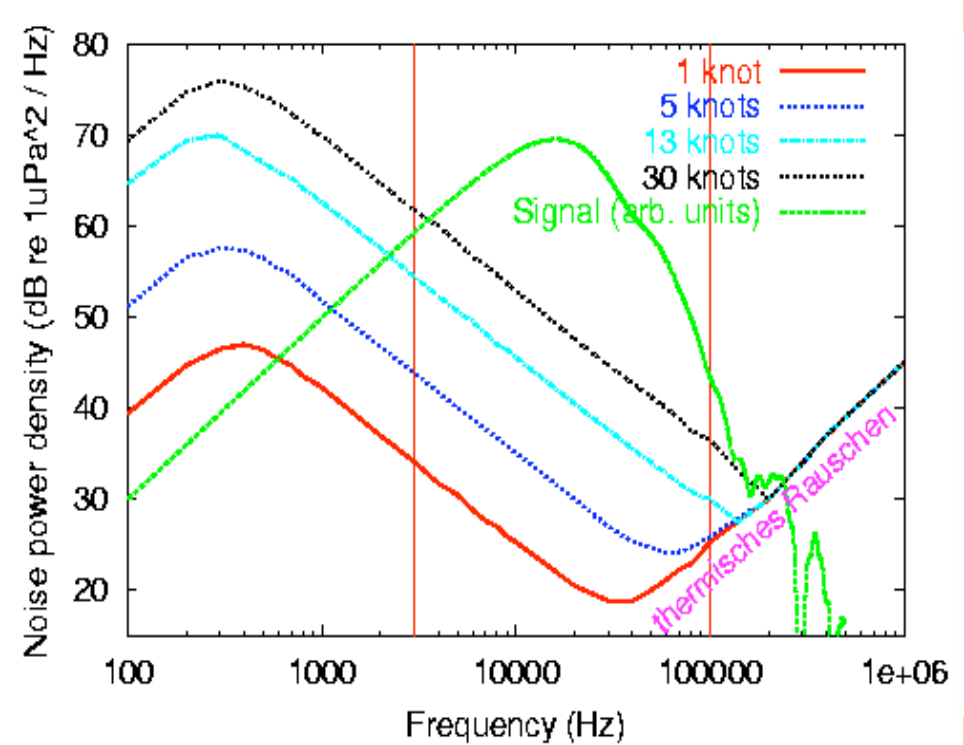
1050 m transverse distance from shower

Acoustical Detection

other marine sources of sound:
wind, waves, ships, animals

Underwater Noise

Signal and Noise Spectrum in the Sea
Signal – to – Noise Ratio



- noise depends on wind speed
- at *high frequencies* dominated by *thermal noise*
- Expected signal maximum between 10 and 50kHz, where noise is minimal (at sea state zero)

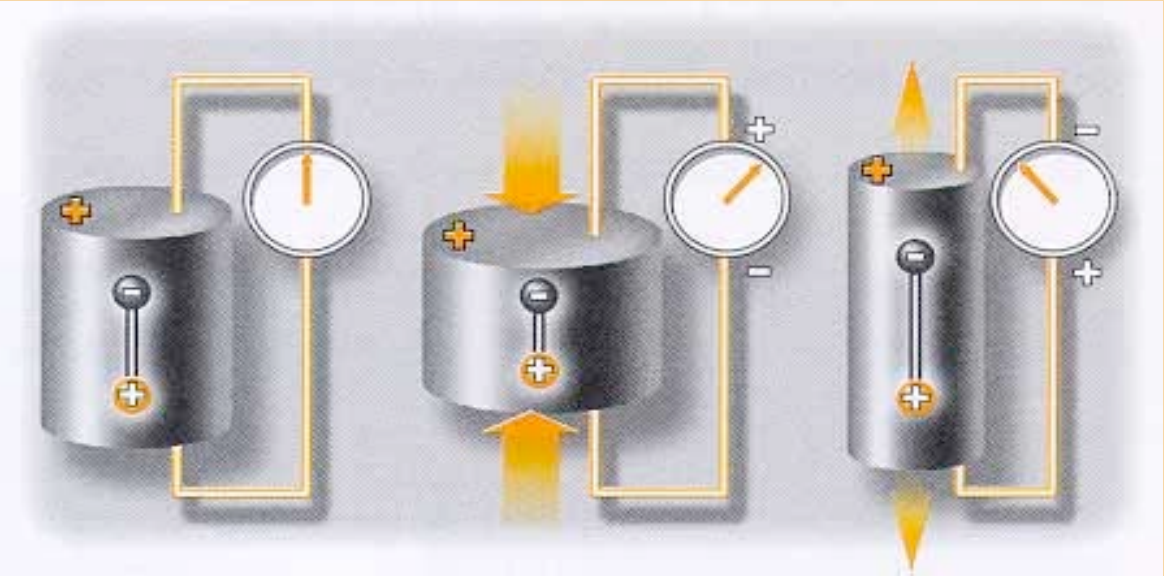
⇒ look for signal in frequency band ~10 to ~50kHz

Acoustical Detection

Acoustic Sensors Development

The Piezoelectric Effect

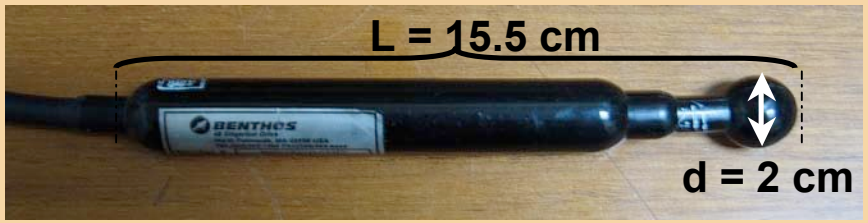
Piezoelectric effect consists on voltage produced between surfaces of a solid dielectric (non - conducting substance) when a mechanical stress is applied to it



Acoustical Detection

Acoustic Sensors Development

Hydrophones
- Commercial hydrophones
- Self-made hydrophones



Requirements

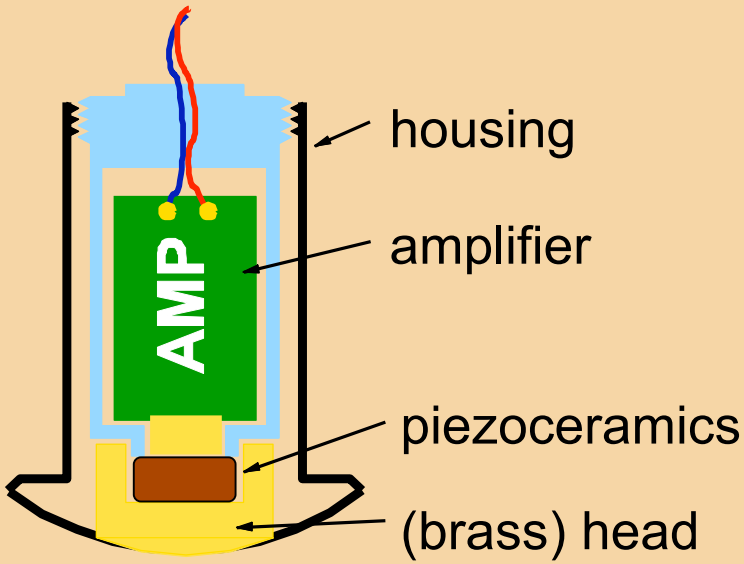
Hydrophones to be used in an underwater neutrino telescope must be:

- *pressure resistant* (very deep ocean sites)
- *very sensitive* (expected pressure signals from neutrino events ~10mPa peak-to-peak for 10^{18} eV in 400m distance)
- *low cost* (large number of sensors)

Acoustical Detection

Acoustic Sensors Development 

Glaciophones



Acoustical Detection

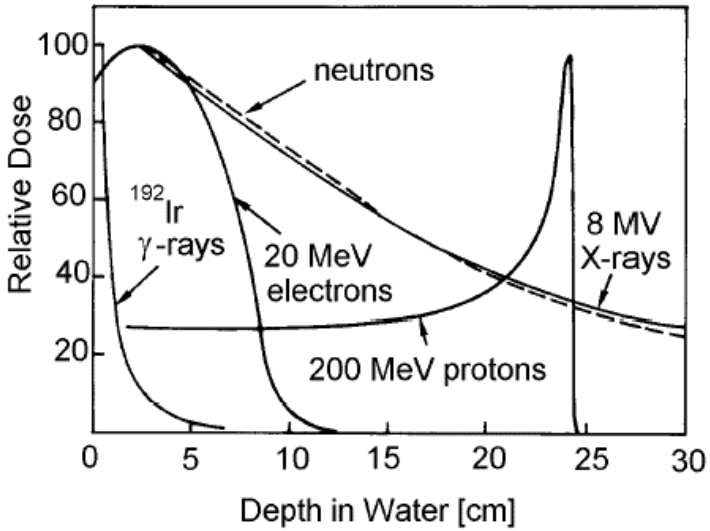
Electric bulbs

Acoustic Sensors Calibration

Calibration Sources

- Sensitivity Response
- Energy Calibration

Proton beam: the Bragg Peak

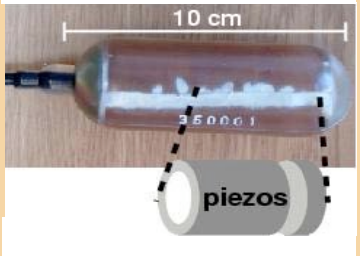


If the proton energy is in the range 100-200 MeV,the most of the primary proton energy is deposited at the Bragg Peak.

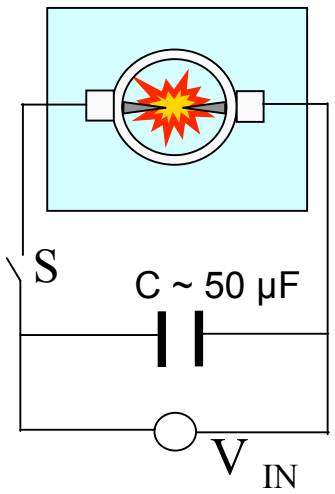
Heated wires

Laser beam

Piezos

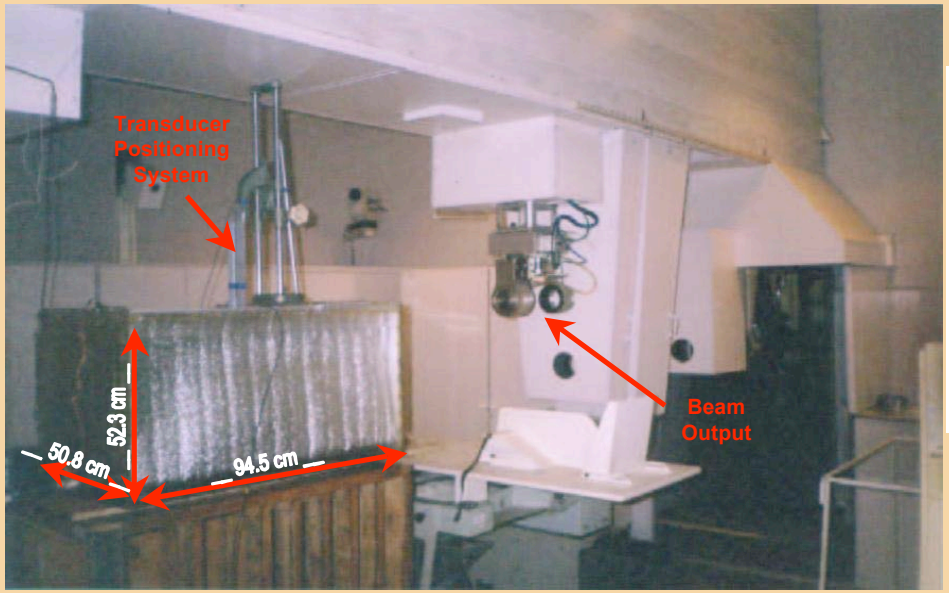


Sparker



Test at ITEP (Moscow) Proton Beam

June 2004

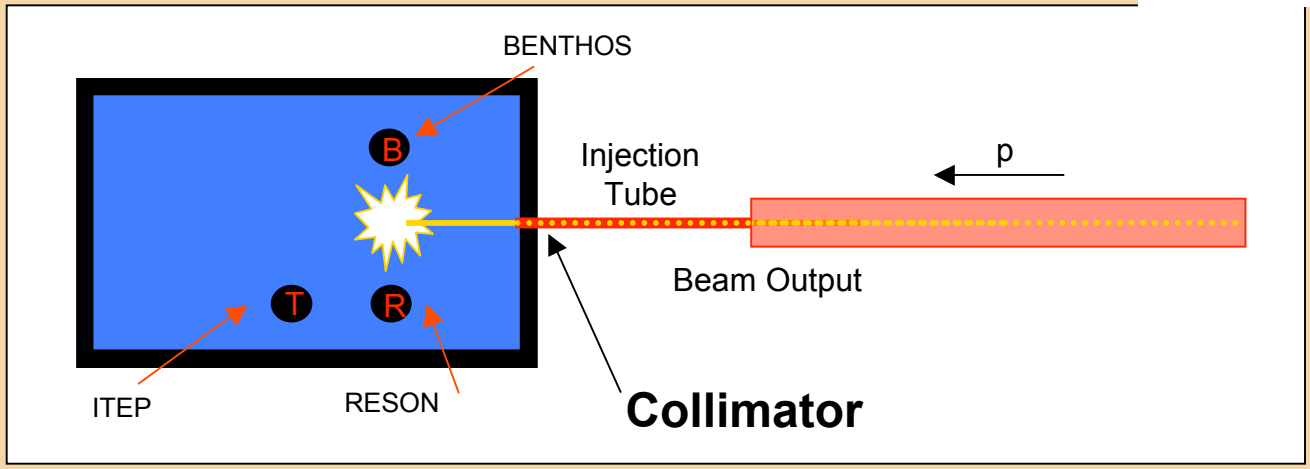


Dimensions

50.8 cm × 52.3 cm × 94.5 cm

The 90% of the basin's volume is filled with fresh water.
NO control on temperature.

Piezo-Electric Hydrophones

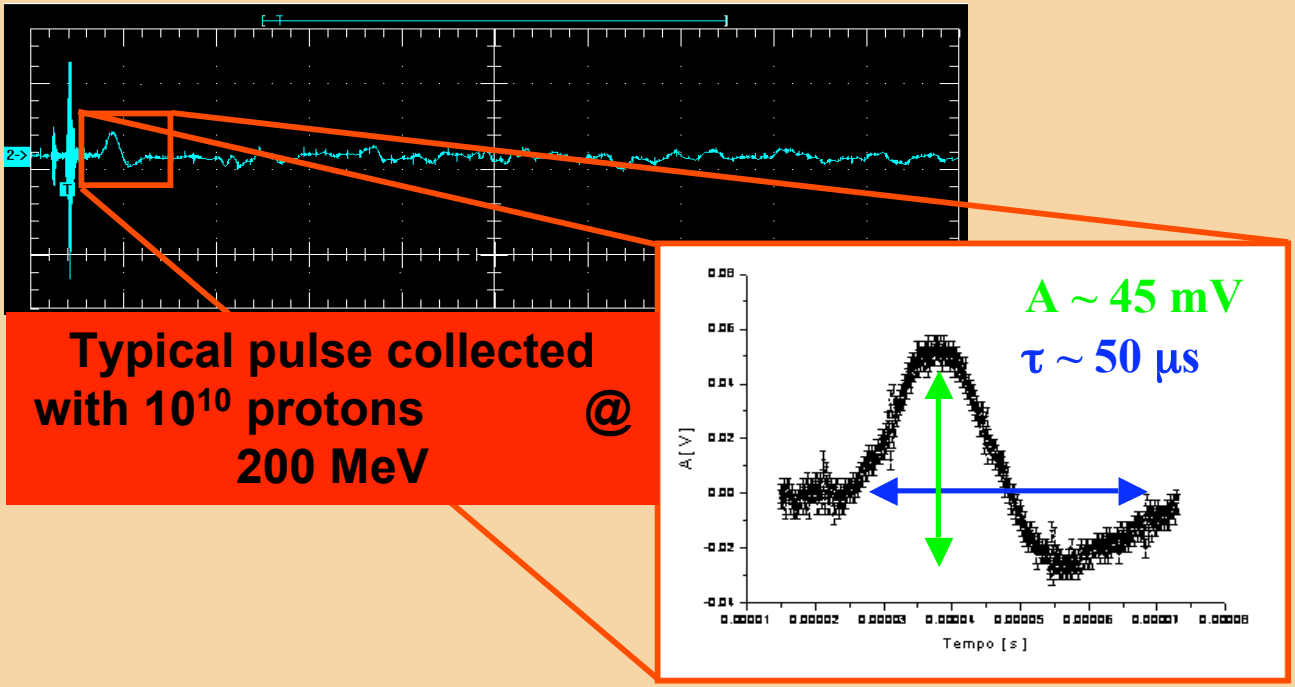


$N_{protons}$/spill ~ 10^{10}
$E_{protons}$ = 100 MeV, 200 MeV

up to 10^{18} eV deposited per spill

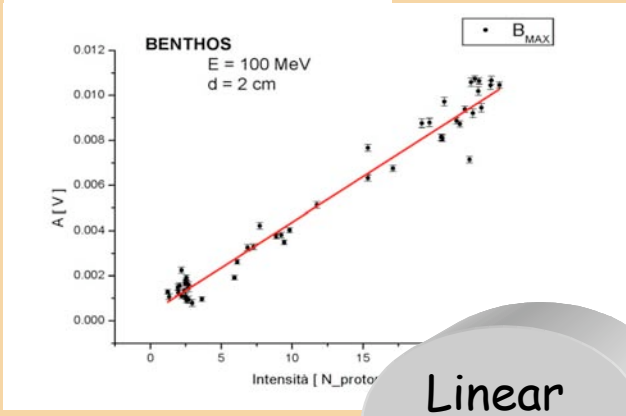
Test at ITEP (Moscow) Proton Beam

June 2004



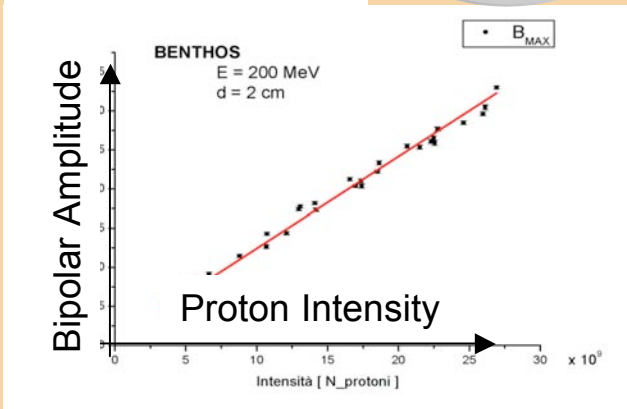
Typical pulse collected with 10^{10} protons @ 200 MeV

E_{beam} = 100 MeV



Linear Fit

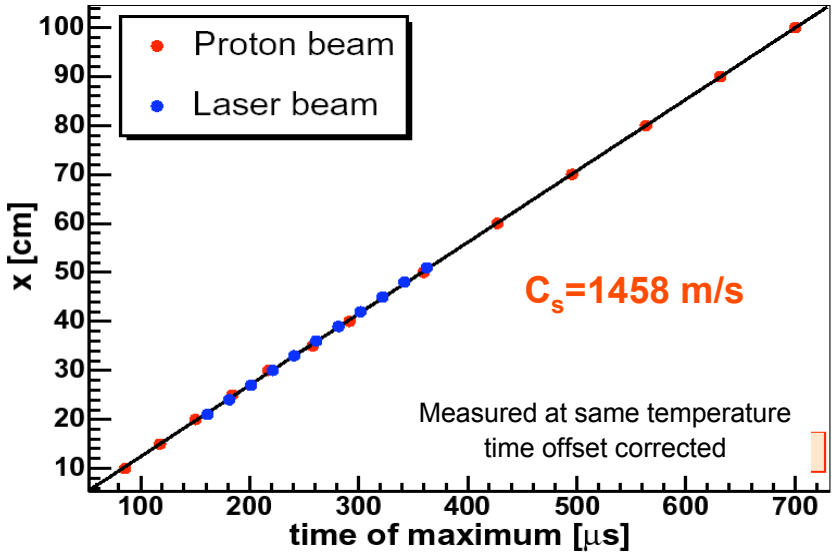
E_{beam} = 200 MeV



Calibration with Proton and Laser Beams

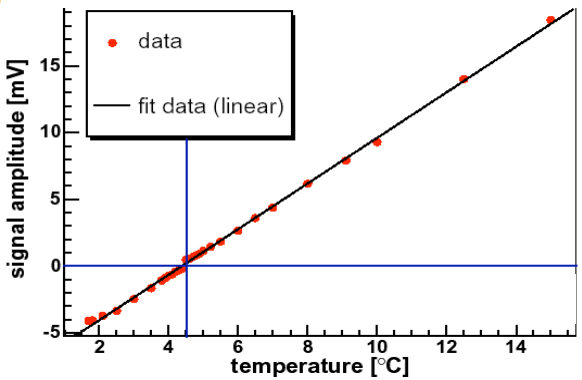
[K. Graf]

Signal is Acoustic

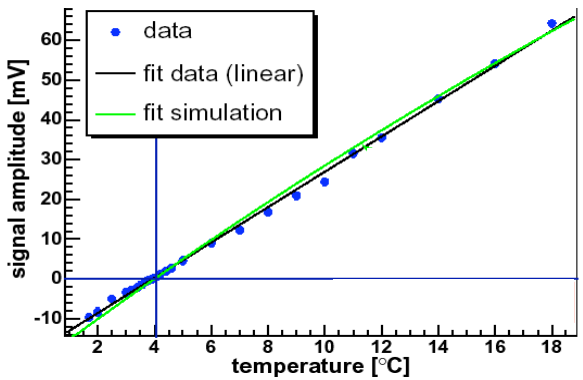


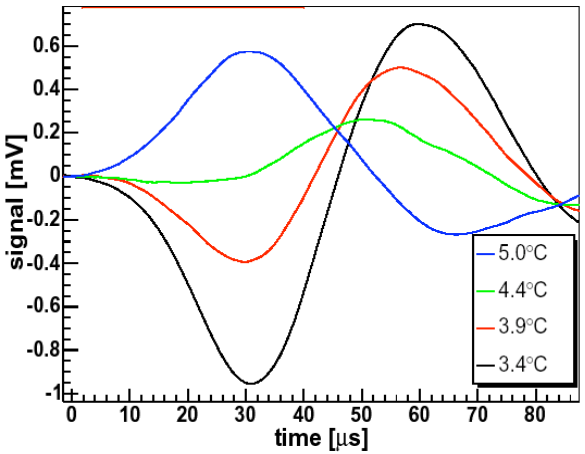
Temperature Dependance

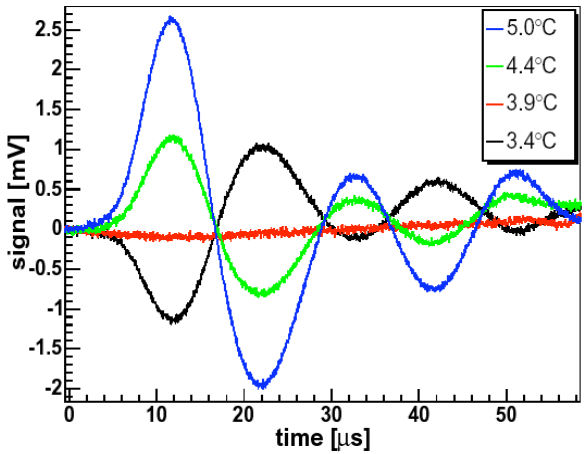
Proton Beam



Laser Beam



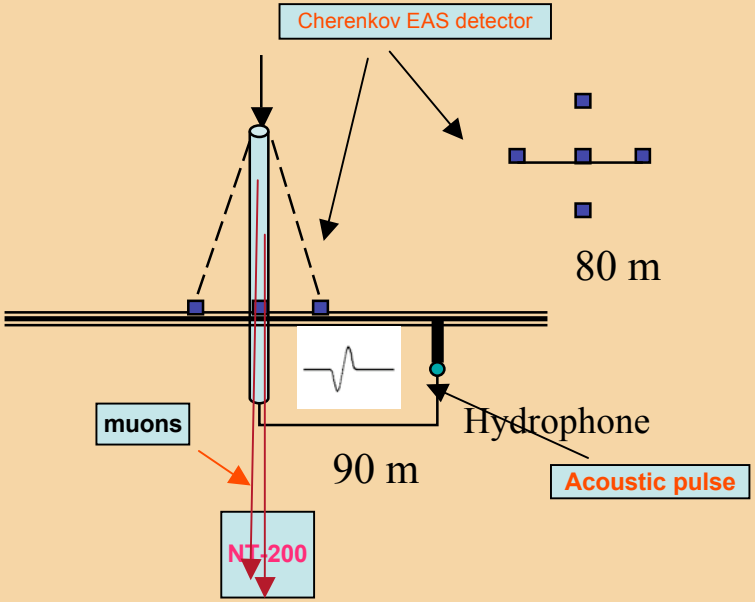


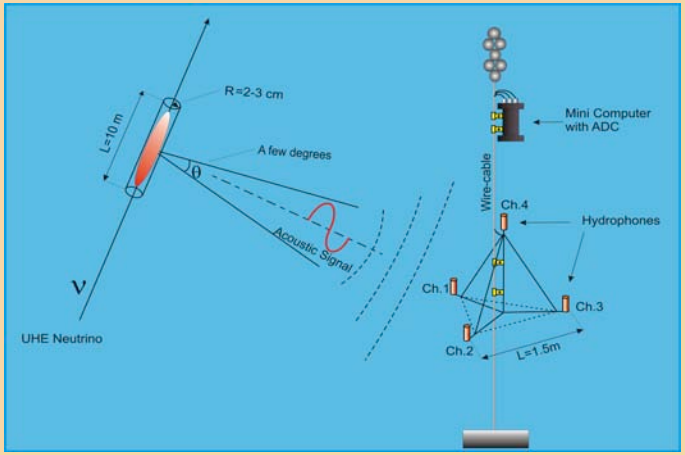


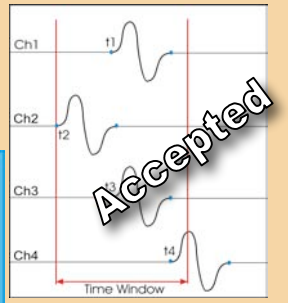
Proton & laser beam experiments confirm thermo – acoustic sound generation is primary effect

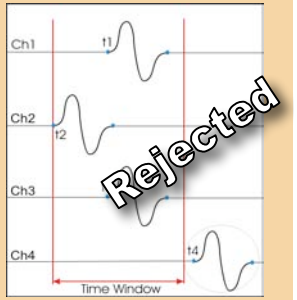
- Simulation and model predictions in good agreement with measured signals
- Some minor effect (around 4 °C) need to be clarified

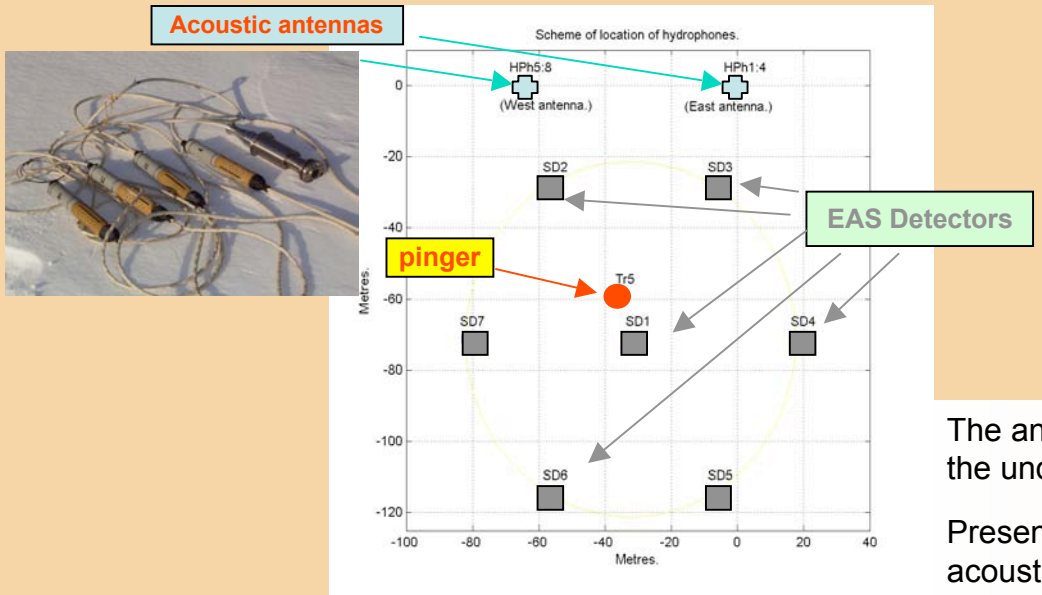
Lake Baikal

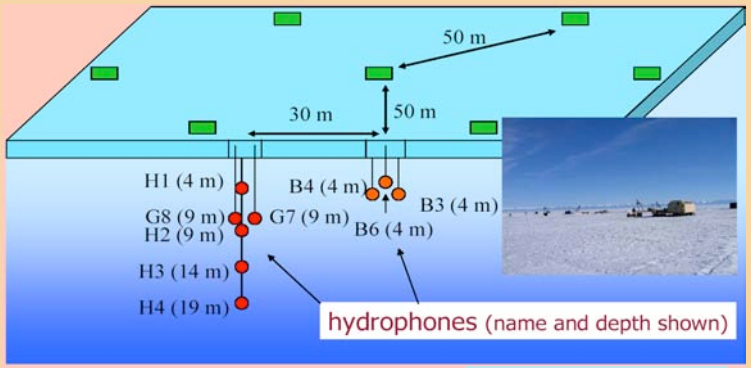












The analysis reveals many interesting features of the under-ice acoustic noise.

Present straightforward method does not allow to find acoustic signal from EAS.

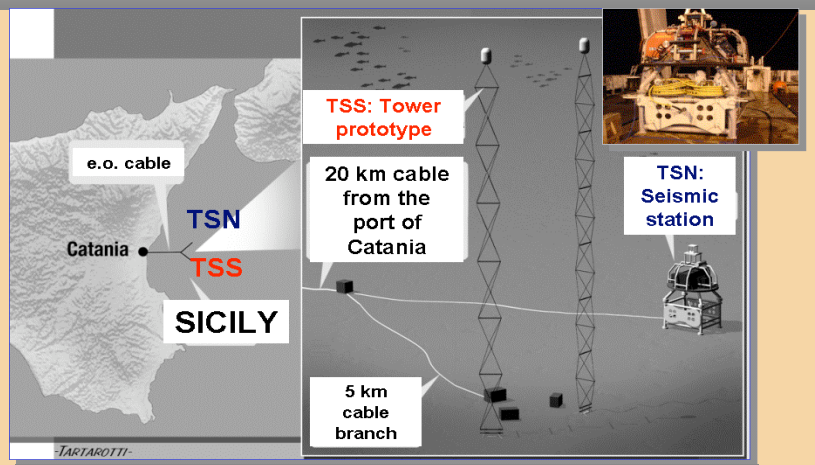
Energy up to ~ 10^{17} eV

NEMO

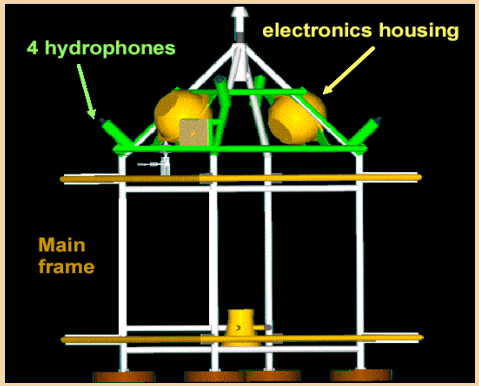
Neutrino Mediterrean Observatory

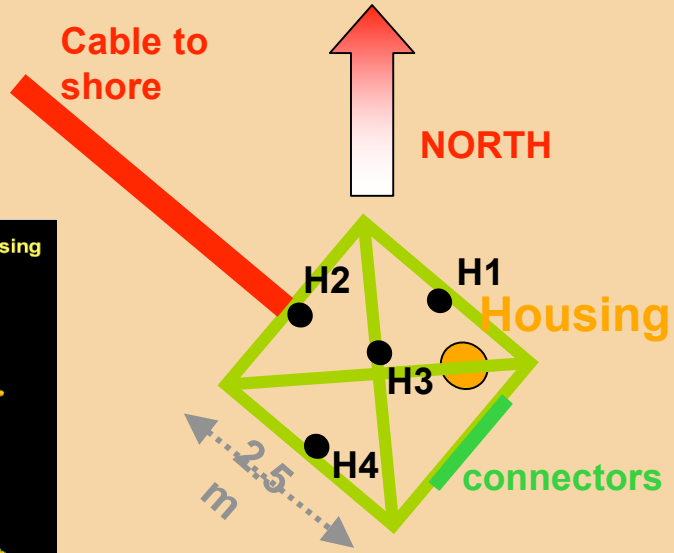
ONDE – Ocean Noise Detection Experiment

NEMO Test Site (Catania)



Lat: 37° 32.681' N
Long: 015° 23.773' E
Depth: 2050 m





Height from seabed :

H1, H2, H4: ~ 2.6 m

H3: ~ 3.2 m

First noise spectra

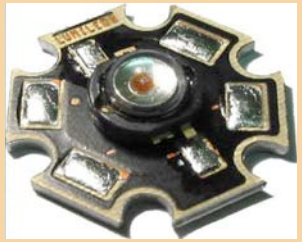
Whales&Dolphins signals

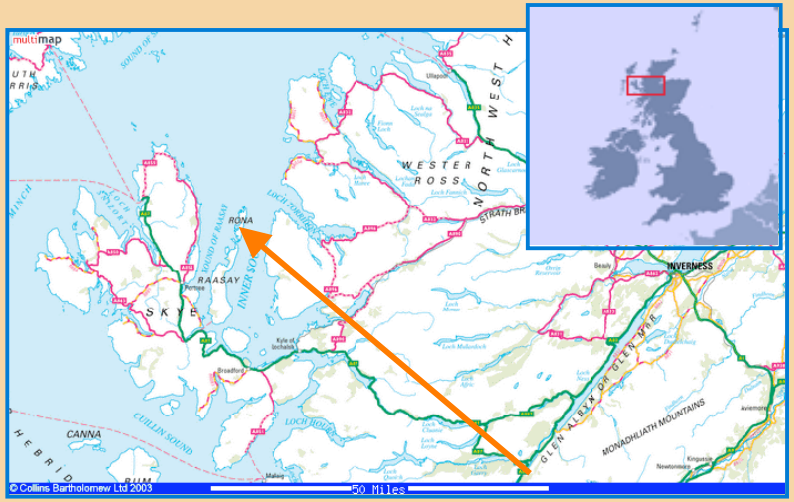
ACORNE

Acoustic Cosmic Ray Neutrino Experiment

Calibration – Light Deposition Simulator

- Laser
- High Power Leds
- Xenon Flash Guns



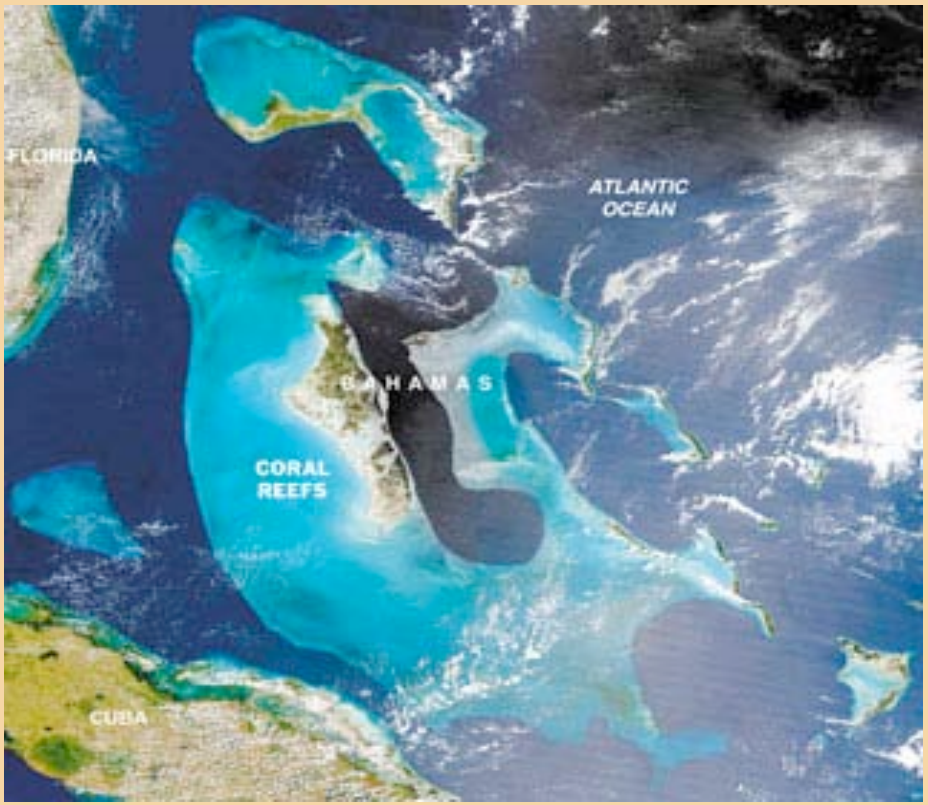


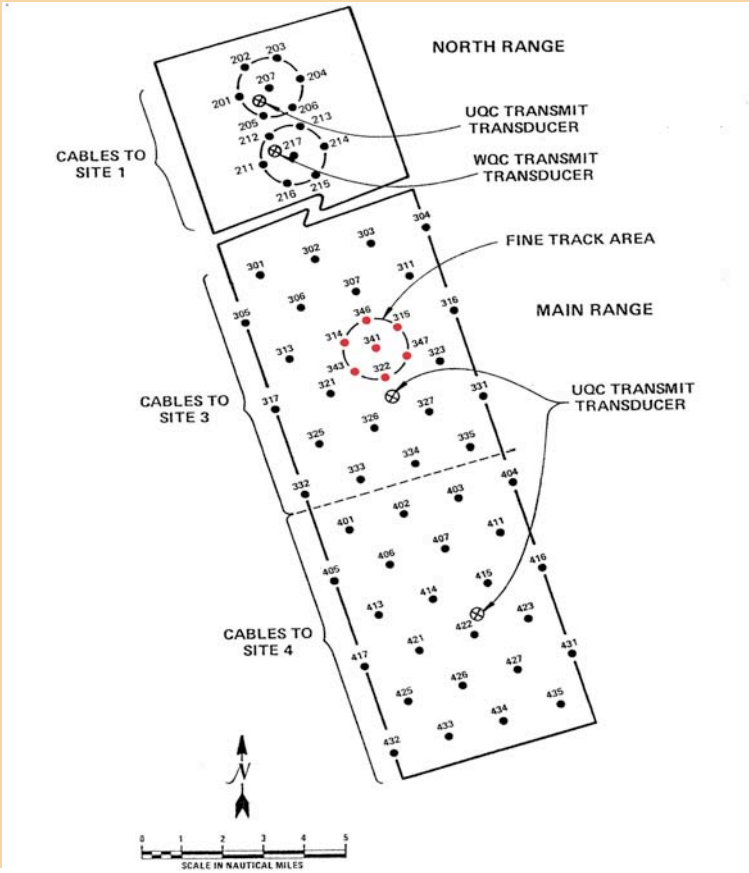
Rona Hydrophone Array

- An array of high sensitivity hydrophones with a frequency response appropriate to acoustic detection studies
- Existing large-scale infrastructure including DAQ, data transmission, buildings, anchorage
- Provides an excellent test-bed for the “simulator”

SAUND

Study of Acoustic Ultra-high-energy Neutrino Detection

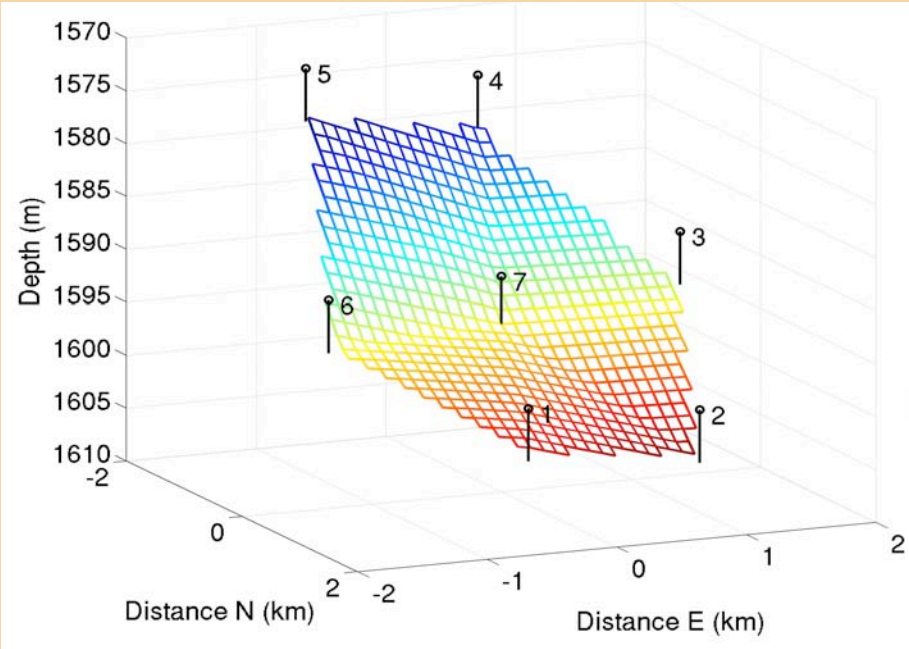




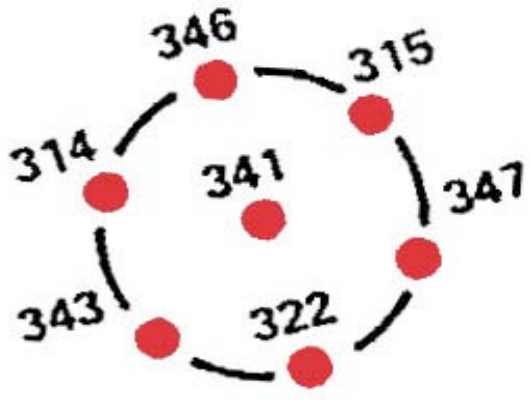
The Atlantic Undersea Test and Evaluation Center (AUTEC) hydrophones

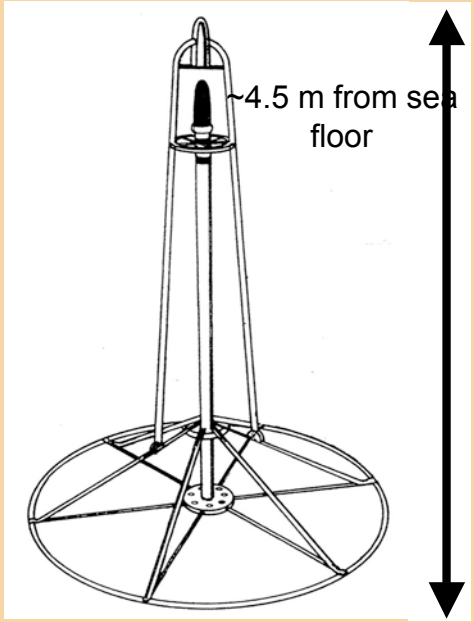
SAUND – 1

7 km^2



7 hydrophones on sea floor, spacing ~1.5 km

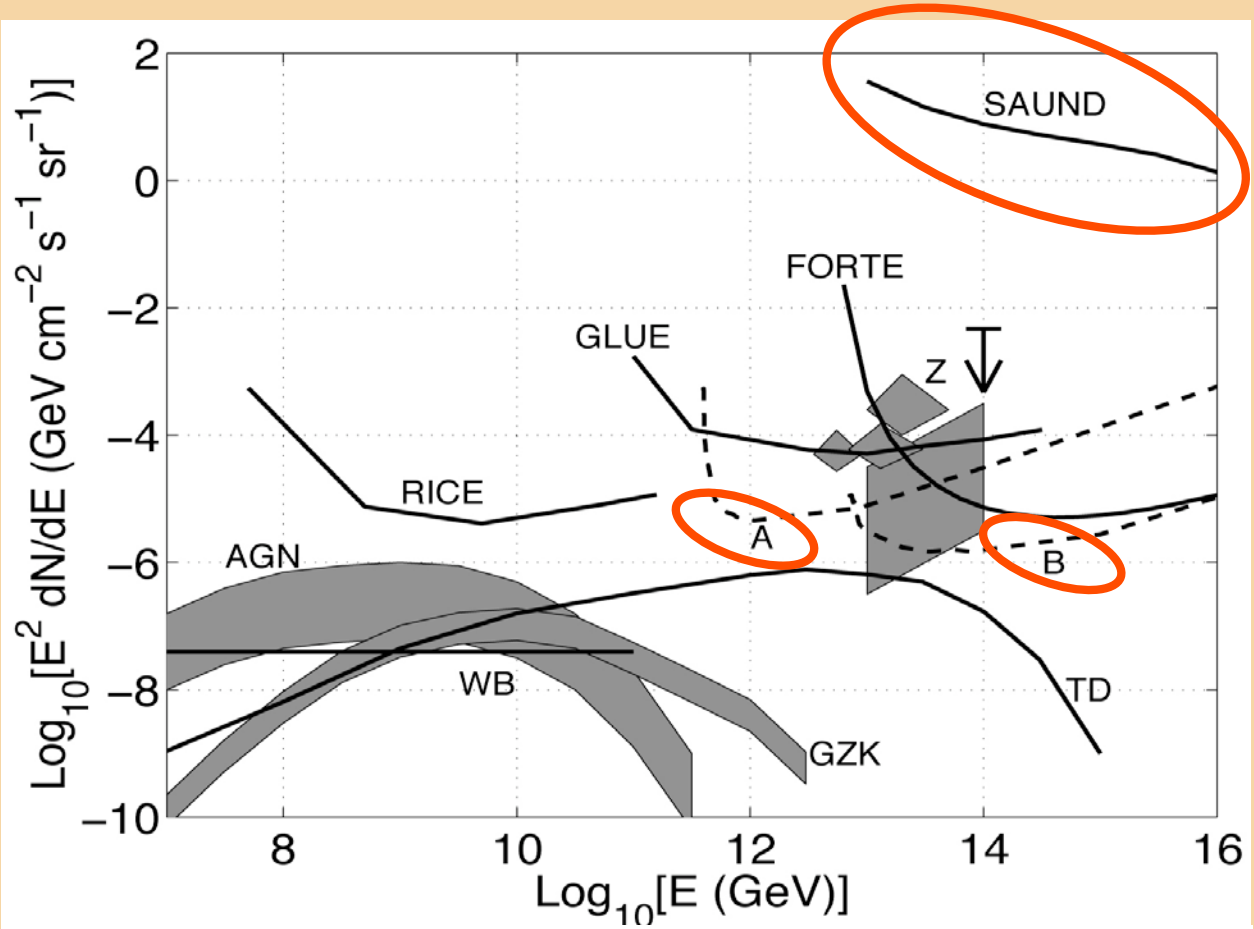




→SAUND – 2 **AUTEC array improvment**

increased BW, gain, stability

SAUND - Flux Limits



A/B represent 1-year limits from hypothetical large arrays (367 1.5-km strings, spaced 0.5/5 km apart)

Acoustical Detection

Comparison Water – Ice – Salt

Conversion of Ionization Energy into Acoustic Energy

	Ocean	Ice	NaCl
T [°C]	15	-51	30
c_s [m s^{-1}]	1530	3920	4560
β [K^{-1}]	25.5×10^{-5}	12.5×10^{-5}	11.6×10^{-5}
C_p [J Kg^{-1} K^{-1}]	3900	1720	839
γ	0.153	1.12	2.87

$$\gamma = c_s^{\,2} \cdot \frac{\beta}{C_P}$$

Grüneisen constant

figure of merit of the medium

	λscatt		λabs	
	10^4 Hz	3×10^4 Hz	10^4 Hz	3×10^4 Hz
Ice (d=0.2 cm)	1650 km	20 Km	8-12 Km	8-12 Km
NaCl (d=0.75 cm)	120 Km	1.4 Km	3×10^4 Km	3300 Km

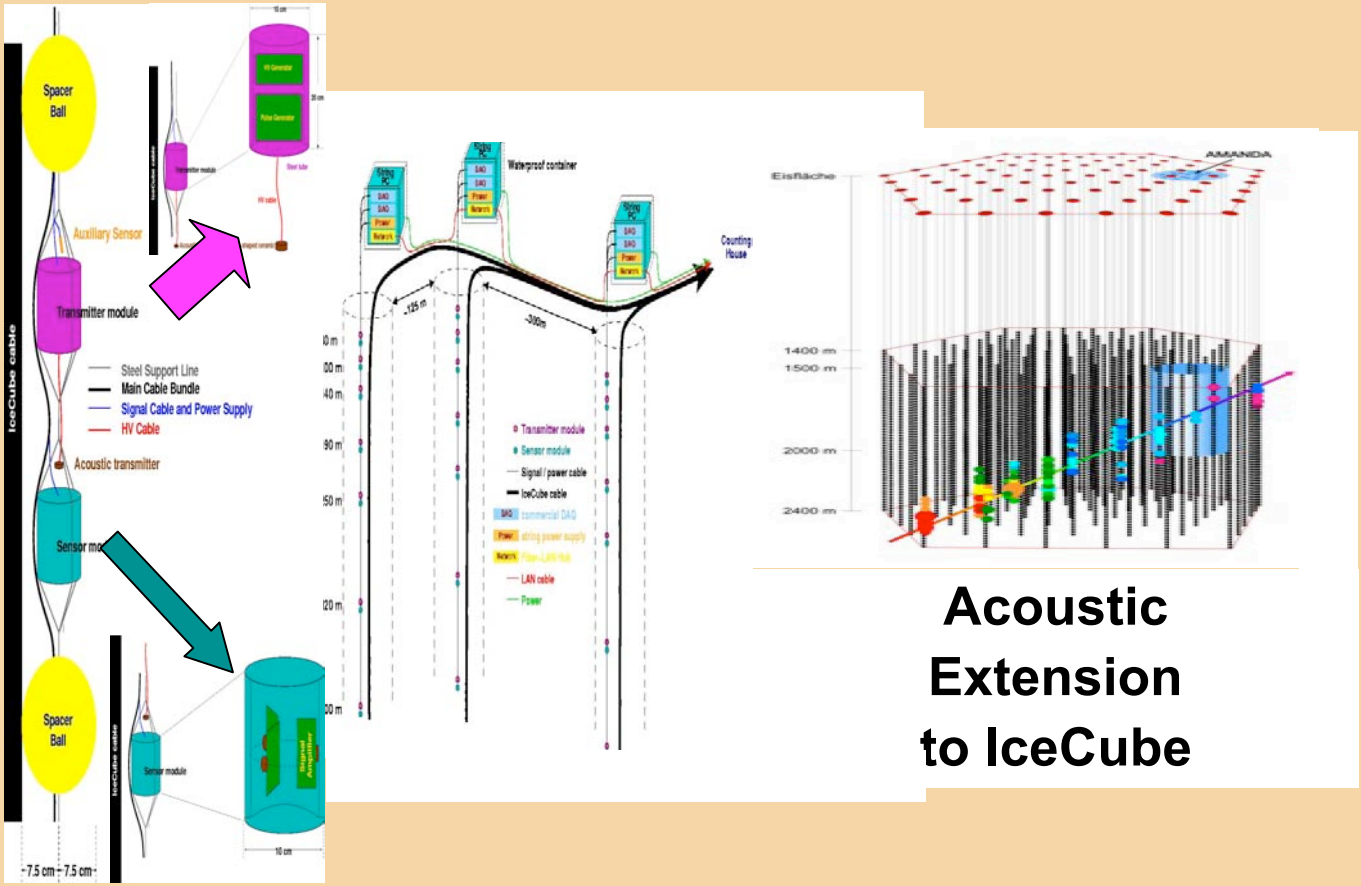
Speed of a pressure wave in a crystalline solid depends on angle with respect to symmetry axis.

This leads to **scattering at grain boundaries**.

***in situ* measurements are needed**

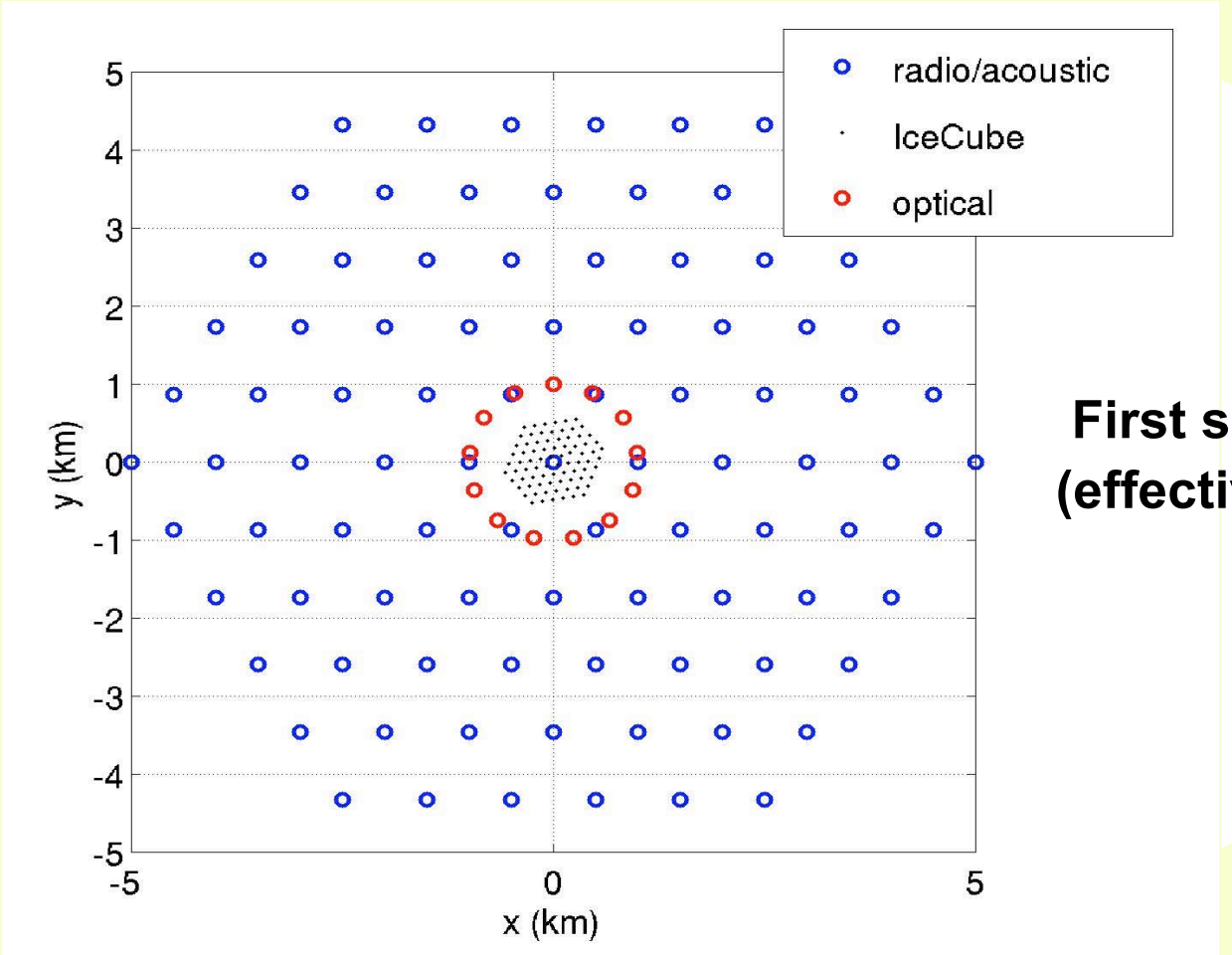
SPATS

a South Pole Acoustic Test Setup



IceCube + Acoustic + Radio EeV Neutrino Array

- hybrid extension to *IceCube*



Optical Cherenkov
Radio Cherenkov
&
Acoustical Detection
ALL IN ONE

First simulations in progress (effective volumes, event rate)

Large Area Detectors for HE neutrinos

1 TeV — 100 PeV — 1000 ZeV

Optical Detection (ICECUBE-KM3NeT)

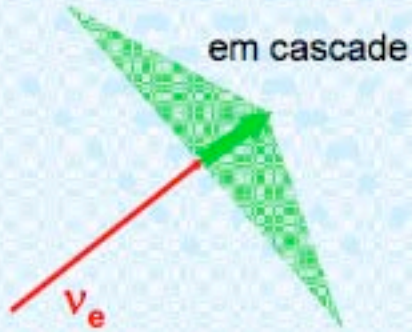
Medium: Seawater, Polar Ice

ν_μ (throughgoing and contained)
$\nu_{e,\tau}$ (contained cascades)

Carrier: Cherenkov Light (UV-visible)
Attenuation length: 100 m

Sensor: PMTs
Instrumented Volume: 1 km^3

Radio Detection (RICE, SALSA)



Medium: Salt domes, Polar Ice

ν (cascades)

Carrier: Cherenkov Radio
Attenuation length: 1 km

Sensors: Antennas
Instrumented Volume: >1 km^3

Acoustic Detection (Prototypes)

Medium: Seawater, Polar Ice, Salt Domes

ν (cascades)

Carrier: Sound waves (tens kHz)
Attenuation length: ~ 10 km

Hydro(glacio)-phones
Instrumented Volume: >100 km^3

Basics of thermo-acoustics mechanism

A pressure wave is generated instantaneous following a sudden deposition of energy in the medium (neglecting absorption: O(10 km) at 10 kHz)

Istantaneous deposition of heat through ionization

$$t_{deposition} \approx D/c \approx 10^{-7} : 10^{-8} \text{ sec}$$

Thermo-acoustic process:

increase of temperature (specific heat capacity C_p), expansion (expansion coeff β)

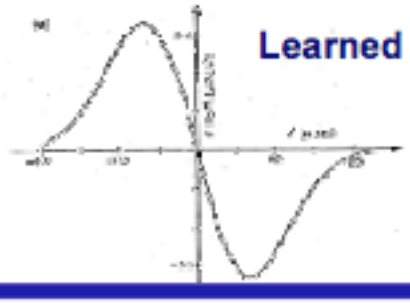
$$t_{expansion} \approx 10^{-5} \text{ sec} \gg t_{deposition}$$

$$\nabla^2 p - \frac{1}{c_s^2}\ddot{p} = -\frac{\beta}{c_p}\cdot\frac{\partial\varepsilon(r,t)}{\partial t}$$

For a point like source (micropulse):

$$p(r,t) \propto \frac{E_0\beta}{4\pi c_p}\frac{\partial}{\partial t}\frac{\delta\left(t-\frac{r}{c_s}\right)}{r}$$

Bipolar pulse
spherical expansion



For a shower heating a volume of matter (macropulse):

$$p(r,t) \propto \frac{\beta}{4\pi c_p}\frac{\partial}{\partial t}\int\frac{1}{r}\varepsilon\, dV$$

Sum of pointlike sources: wavefront and signal shape depend on the energy density distribution

The Size of Neutrino Acoustic Detectors

$E_\nu = 10^{20}$ eV

in water: p = 0.6 Pa @ 1 km → 20 mPa (neglecting attenuation)

in Ice : p = 6 Pa @ 1 km → 200 mPa (neglecting attenuation)

Underwater Cherenkov detectors
Upgoing events – 100 TeV

$$P_{\nu\mu}\left(E_\nu, E_\mu^{min}\right) = R_\mu^{eff}\sigma_{CC}N_A \approx 10^{-4}$$

$$\frac{N}{A_{eff}\cdot T} = \Phi_\nu P_{\nu\mu} 2\pi e^{-D(N_A\sigma_{Tot}\rho_{Earth})} \approx 100 \ \frac{events}{km^2 y}$$

WB flux

Underwater Acoustic detectors
Downgoing events – 10^{20} eV

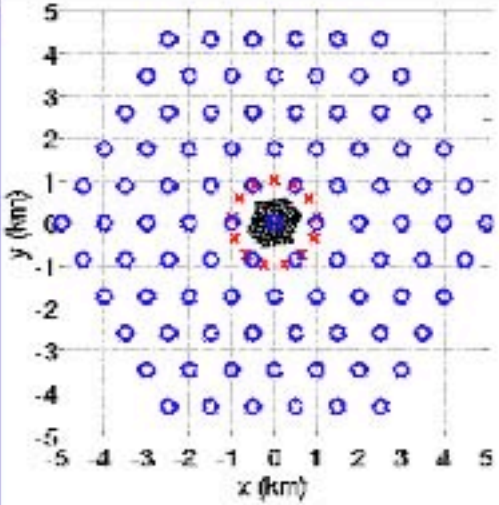
$$P_{det}(E_\nu, p_{min}) = H_{det}^{eff}\sigma_{Tot}N_A \approx 10^{-3}$$

$$\frac{N}{A_{eff}\cdot T} \approx 10^{-3} \ \frac{events}{km^2 y}$$

Sound absorption length in ocean O(10 km), noise O(10 mPa)

Several groups developing and improving simulation codes for large acoustic detectors
What we can do with 1 km^3 filled with hydrophones ?

Hybrid detector in Ice



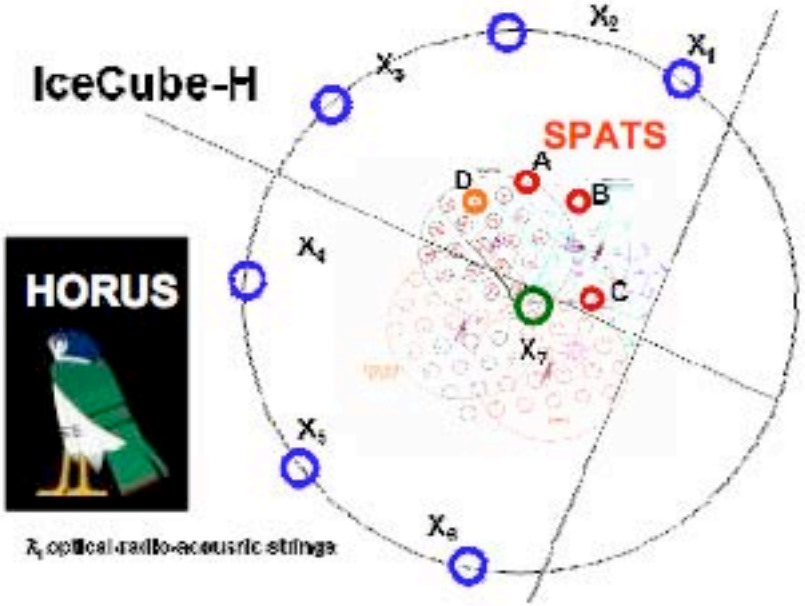
Optical:

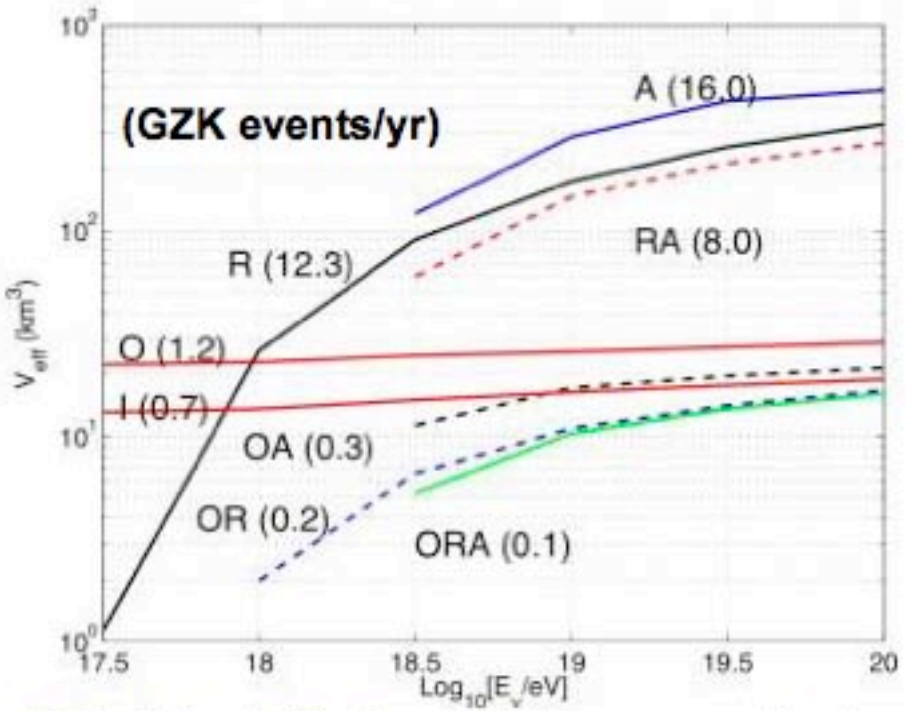
■ - 80 IceCube

X - 13 IceCube-Plus holes at 1 km radius (2.5 km deep)

Radio/Acoustic:

O - 91 holes, 1 km spacing, 1.5 km deep





Coincident effective volumes + event rates for IceCube (I), an optical extension (O), and combinations with surrounding A + R arrays