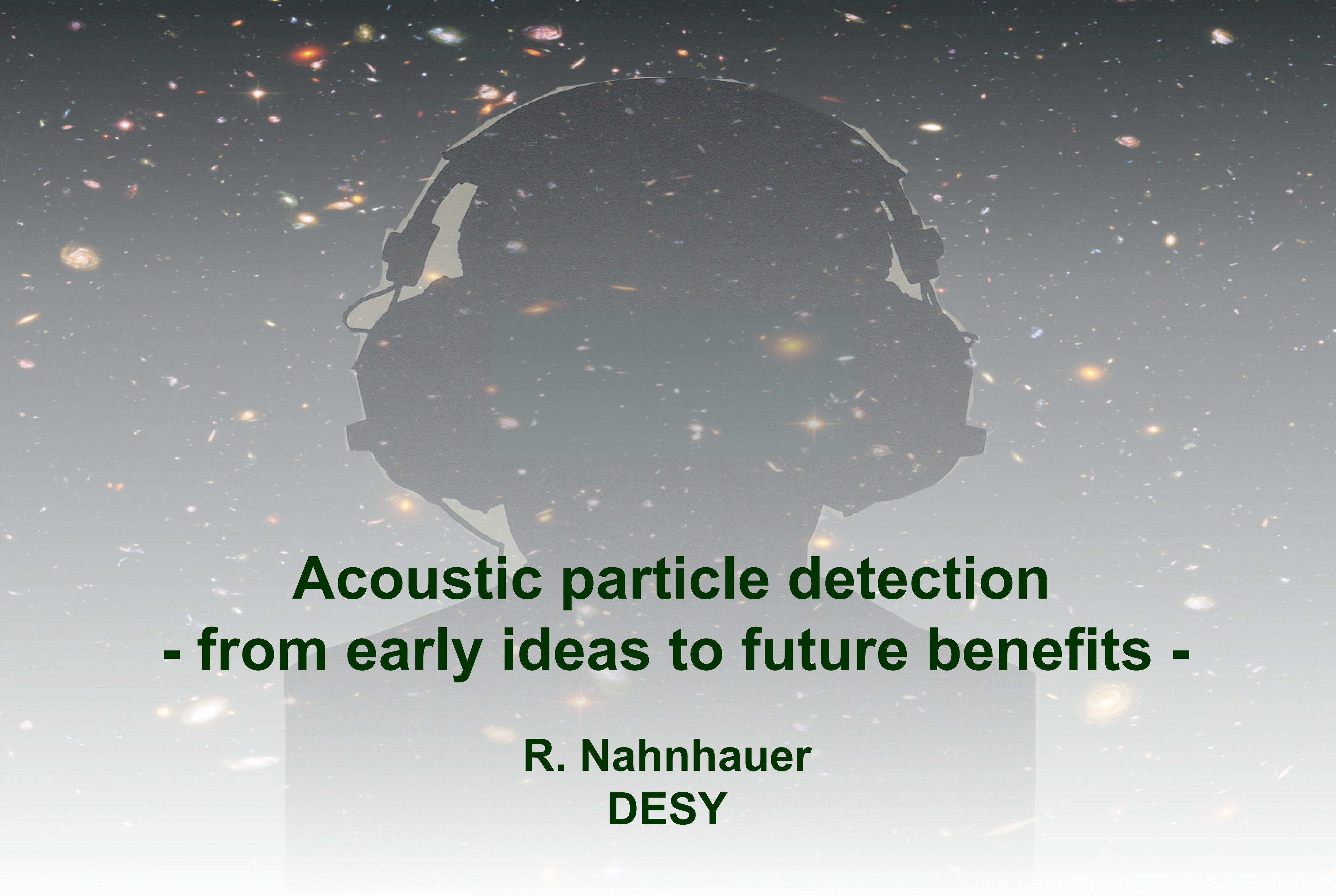


Acoustic particle detection
- from early ideas to future benefits -

R. Nahnhauer
DESY

Once upon a time, 50 years ago…

neutrino detected only ~4 years ago

neutrino cross section measured ~ E^2 at low energies

different types of neutrinos not established

first accelerator neutrino experiments at ~GeV energies still in preparation at BNL and CERN

weak interaction theory → V-A

cosmic microwave background radiation not known

But first suggestions to do neutrino astrophysics:

→ to measure the cross section with atmospheric neutrinos
→ to do physics with neutrinos from cosmic (point) sources

Proc. 1960 ICHEP, Rochester, p. 578.

In the papers by Zheleznykh and myself (1958, 1960) possibilities of experiments with cosmic ray neutrinos are analyzed. We have considered those neutrinos produced in the earth's atmosphere from pion decay. ~~From the known μ spectrum the neutrino~~

NEUTRINO INTERACTIONS[1]

BY FREDERICK REINES[2]

Physics Department, Case Institute of Technology, Cleveland, Ohio

Ann.Rev.Nucl.Sci. 10 (1960) 1

the neutrinos produced extraterrestrially (cosmic) and in the earth's atmosphere (cosmic ray) can be detected and studied. Interest in these possibilities stems from the weak interaction of neutrinos with matter, which means that they propagate essentially unchanged in direction and energy from their point of origin (except for the gravitational interaction with bulk matter, as in the case of light passing by a star) and so carry information which may be unique in character. For example, cosmic neutrinos can reach us from other galaxies ~~whereas the charged cosmic ray primaries reaching us may be~~

COSMIC RAY SHOWERS[1]

BY KENNETH GREISEN

Laboratory of Nuclear Studies, Cornell University, Ithaca, N. Y.

Ann.Rev.Nucl.Sci 10 (1960) 63

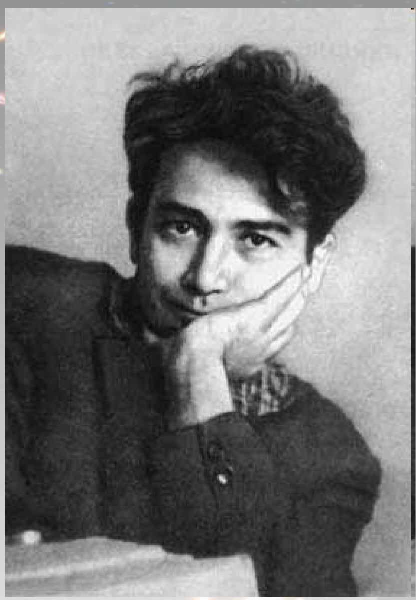
Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. ~~The counter should be surrounded with~~

Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

Some Effects of Ionizing Radiation on the Formation of Bubbles in Liquids*

DONALD A. GLASER
University of Michigan, Ann Arbor, Michigan
(Received June 12, 1952)

Nobel price 1960:
"for the invention of the bubble chamber"[



Atomnaja Energija V3(1957)152

Гидродинамическое излучение от треков ионизирующих частиц в стабильных жидкостях

G. A. Askaryan

Hydrodynamic radiation from tracks of ionizing particles in stable liquids

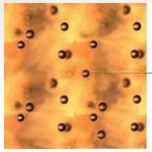
Прохождение ионизирующих частиц в жидкостях сопровождается увлечением молекул среды расталкивающимися скоплениями одноименно заряженных ионов и микровзрывами при локальных нагревах, создаваемых вблизи треков частиц. Эти

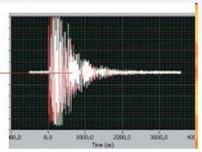
The passage of ionizing particles in liquids is accompanied by entrainment of molecules of the medium by mutually repelling accumulations of like-charge ions and microexplosions upon local heating near the particle tracks. These processes

First mentioning of an acoustic particle detection possibility

A modern application:
PICASSO - searching for Dark Matter

If a dark matter particle hits a nucleus in a tiny superheated droplet, the atom recoils and deposits its energy in a heat spike, which in turn triggers a phase transition.





First experimental detection of acoustic particle signals?

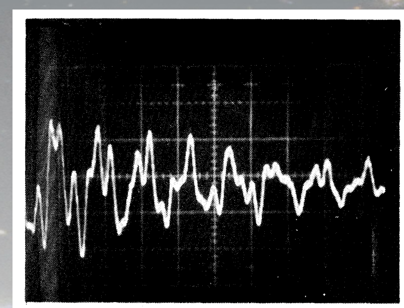
GENERATION OF MECHANICAL VIBRATIONS BY PENETRATING PARTICLES*

B. L. Beron and R. Hofstadter
Department of Physics and High Energy Physics Laboratory, Stanford University, Stanford, California 94305
(Received 11 June 1969)
Phys. Rev. Lett. 23, V4 (1969)184

Mechanical oscillations of lead-zirconate-titanate piezoelectric disks have been observed when penetrating high-energy (1.0-BeV) beams of electrons impinge on the disks. Radial and compressional modes of vibration have been observed in the frequency range 40-158 kHz. Possible applications of this observation to particle detection at very high energies are discussed. The observed phenomenon also has a possible connection with measurements of gravitational waves.

We have recently observed mechanical, or sound, vibrations in ceramic piezoelectric disks of lead-zirconate-titanate (PZT) struck by high-energy electrons. ~~Four ½-in.-thick disks of PZT~~

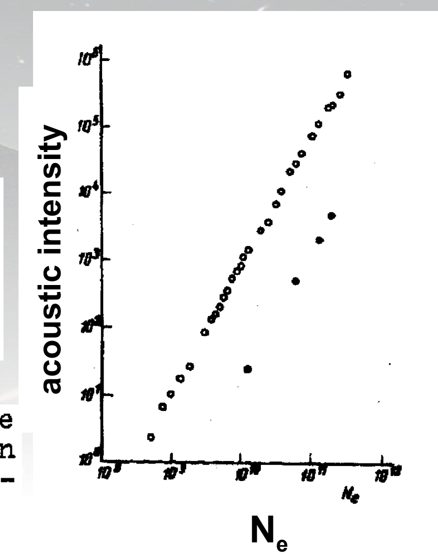
~~modes~~. Electrons of energy 1.00 and 0.20 BeV were used in pulses, each lasting about 1.0 μsec and containing 10^4-10^6 electrons. The cross section of the incident 1.00-BeV beam was about 9 mm²



EXCITATION OF ULTRASONIC WAVES BY PASSAGE OF FAST ELECTRONS THROUGH A METAL

I.A. Borshkovskii, V.D. Volovik, I.A. Grishaev, G.P. Dubovik, I.I. Zalyubovskii, and V.V. Petrenko
Khar'kov State University
Submitted 15 April 1971
ZhETF Pis. Red. 13, No. 10, 546 - 549 (20 May 1971)
V. D. Volovik et al., Sov. JETP Lett. 13 (1971) 390

Using the electron accelerator of the Physico-technical Institute of the Ukrainian Academy of Sciences, with E_0 = 300 MeV, experiments were undertaken aimed at observing ultrasonic oscillations in solids excited by passing elec-



The first blossom of acoustic ideas

strongly connected to the early DUMAND project:

DEEP UNDERWATER MUON AND NEUTRINO DETECTOR

1973: Cosmic Ray Conference in Denver → DUMAND steering committee
1975: First DUMAND workshop, (Washington), start of the project
1976: DUMAND Workshop (Honolulu), Thermo-acoustic model, acoustic detector
1977: DUMAND acoustic workshop (La Jolla)
1978: several DUMAND workhops
1979: DUMAND workshop (Khabarovsk+Baikal)
1980: several DUMAND symposia and workshops

} experimental test of Thermo-acoustic model
explanation of signal shape and origin
study of background conditions in the ocean

until 1980 close collaboration of scientists from US and Russia, particularly in acoustic technology development
after Soviet occupation of Afghanistan most links lost

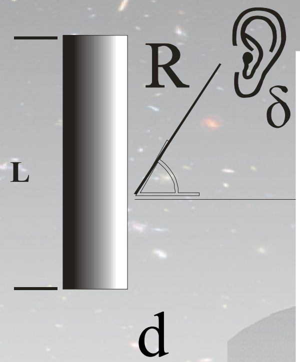
A. Roberts(1992): Russian participation in DUMAND was strong at this time, and continued strong until it was abruptly cut off by the Reagan administration.[2] Even after their connection with DUMAND had

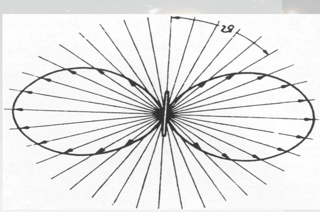
[2]The severing of the Russian link was done with elegance and taste. We were told, confidentially, that while we were perfectly free to choose our collaborators as we liked, if perchance they included Russians it would be found that no funding was available for us.

The Thermo-acoustic Model

First ideas presented at the 1976 DUMAND workshop independently by T. Bowen and B.A. Dolgoshein,
Proceedings not accessible (to me) but see:

G. A. Askaryan and B.Dolgoshein, JETP Lett. 25 (1977) 213
T.Bowen, Proc. 15th ICRC, Plovdiv, 1977, V6, p. 277





G.A. Askaryan et al.
NIM 164(1979) 267

In frequency domain :

$$P = (k/c_p)\,(E/R)\,M$$

$$M = (f^2/2)\,(\sin x/x)$$

$$f = v_s/(2d), \qquad x = (\pi L/2d)\sin\delta$$

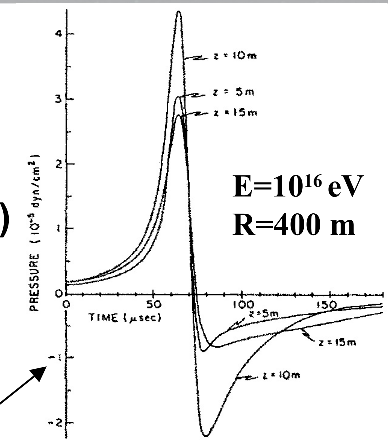
k : vol. expans. coefficient
c_p: specific heat

signal shape:
flat disk, width ~L

Bowen:

In time domain :

$$P = (1/4\pi)(k/c_p)\,(E/R)$$



J. Learned,
Phys.Rew. D 19
(1979) 3293

$$P = (1/\sqrt{(5.4\pi)}\,(1/4\pi)(k/c_p)\,(E/R)\,(v_s/\sigma)^2$$

σ: Gaussian width of ionization distr.

Early experimental checks and problems

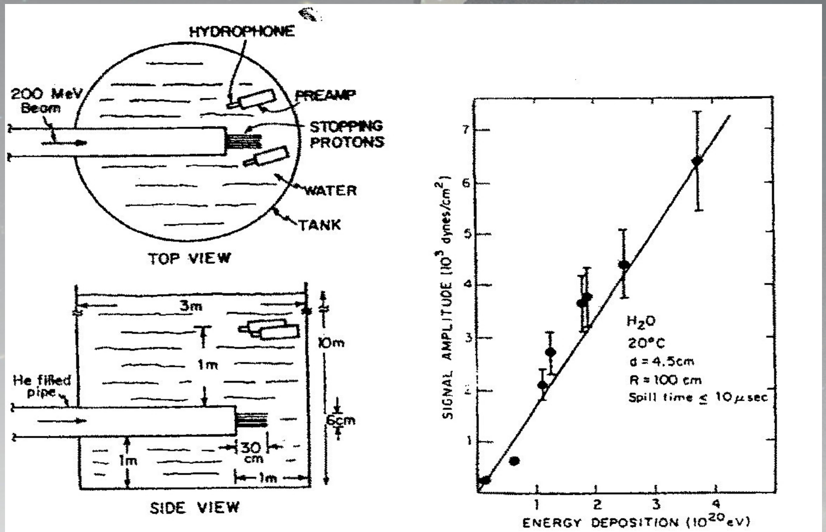
Sulak et al. NIM 161(1979) 203

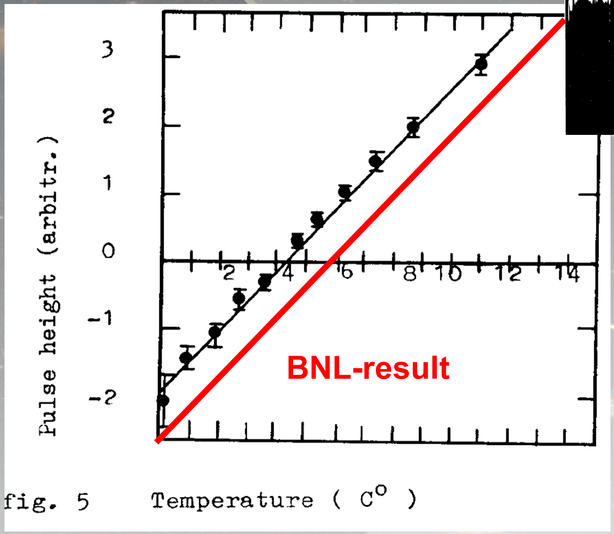
BNL: 200 MeV and 28 GeV protons, E_{min} = 10^{20} eV

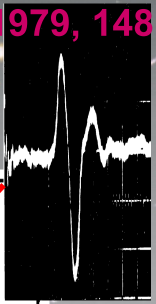
Harvard: 158 MeV Protons, E_{min} = 10^{15}eV

P.I. Golubnichy et al. Proc. DUMAND-1979, 148

Laser , λ= 1060 μm







Conclusions from these and several other studies:

→ many Thermo-acoustic Model predictions confirmed

→ dominant mechanism is thermal expansion

→ other contributions (microbubbles, ???) can not be excluded

Other questions studied

A= f(d), varying beam diameter

A= f(K/c_p), varying liquids

A=f(R), varying distance

A=f(p), varying static pressure

Think big … - the early DUMAND design

A. Roberts, Rev. Mod. Phys. V64 1 (1992) 259

The optical detector design

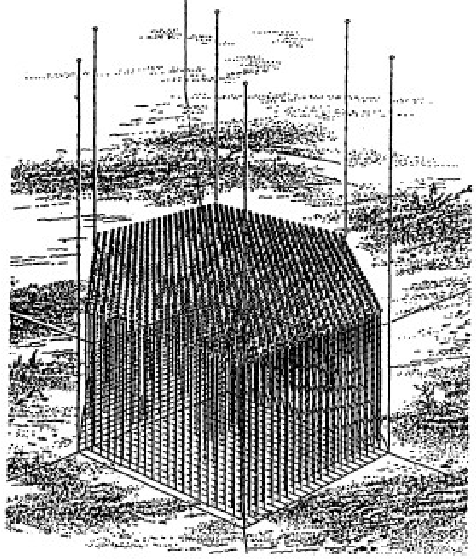


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

volume:	1.26 km³
#strings:	1261
Δs_{xy}:	40 m
depth:	3900 m - 4400 m
# OMs/string;	18
# OMs:	22,698

!

The acoustic detector design

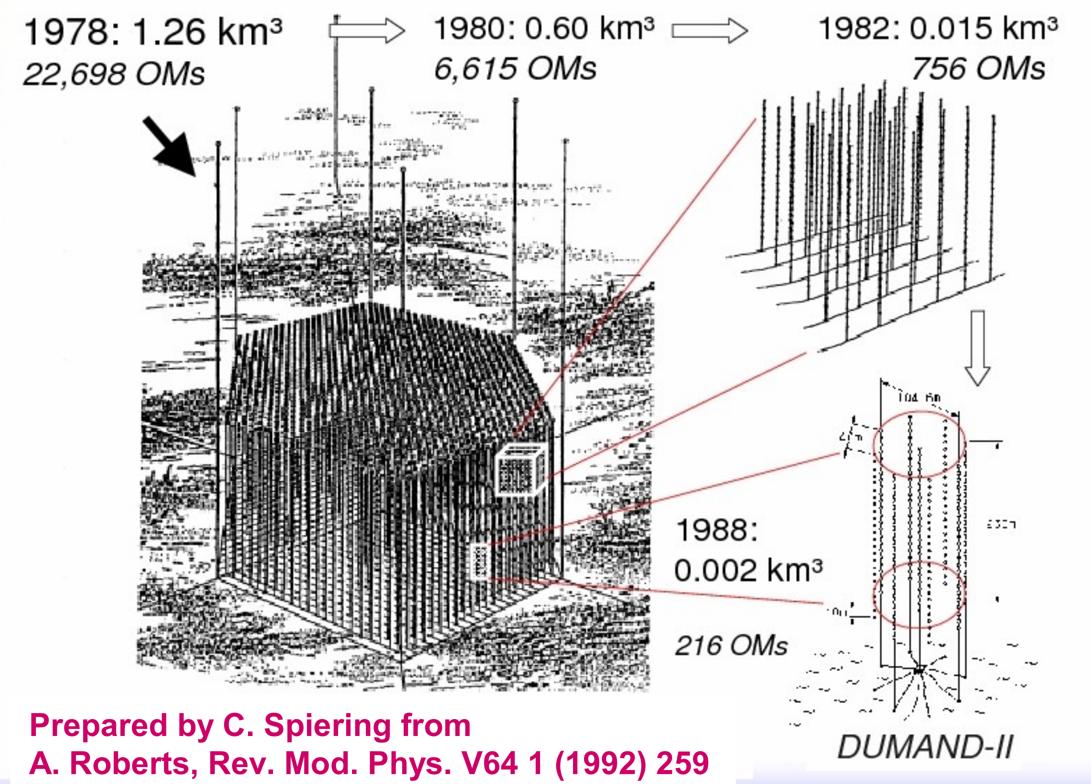
See e.g.

G. A. Askaryan and B.Dolgoshein, JETP Lett. 25 (1977) 213

V. S Berezinskii and G. T. Zatsepin Sov. Phys. Usp. V20 5 (1977) 361

volume:	100 km³
#strings:	10000
Δs_{xy}:	100 m
depth:	3400 m - 4400 m
# hp/string:	100
# hydrophones:	100000

Budding hopes go to the bottom



Prepared by C. Spiering from
A. Roberts, Rev. Mod. Phys. V64 1 (1992) 259

DUMAND II:
acoustic positioning system
5 hydrophones at each string
will monitor the actual position

In addition, the hydrophones will be monitored to look for the possibility of very-high-energy neutrino interactions — 10^{16} eV or more — which should produce acoustically detectable signals. Possible sources for such neutrinos can be imagined; but in any case, if the data are there, we will record them.

A. Roberts

1989: HEPAP supports DUMAND-II
1990: DOE allocates funds for DUMAND-II
Further financial cuts → TRIAD (3 strings)
1993: shore cable laid, inDecember 1993:
deployment of first string and
connection to junction box.
Failure after several hours
1995: DUMAND project is terminated

although DUMAND was not successfully finished, it had a big impact
on future ideas for other optical and acoustic high energy neutrino telescopes

Science Fiction 1983

A. De Rujula, S. L. Glashow, R. R. Wilson, G. Charpak

PHYSICS REPORTS (Review Section of Physics Letters) 99, No. 6 (1983) 341–396.

THE GENIUS PROJECT

Geological Exploration by Neutrino Induced Underground Sound

use the „geotron“ to send a neurino beam pulse
location and time of pulse are known
measure $V_s = f(\rho_i, \Delta d_i)$

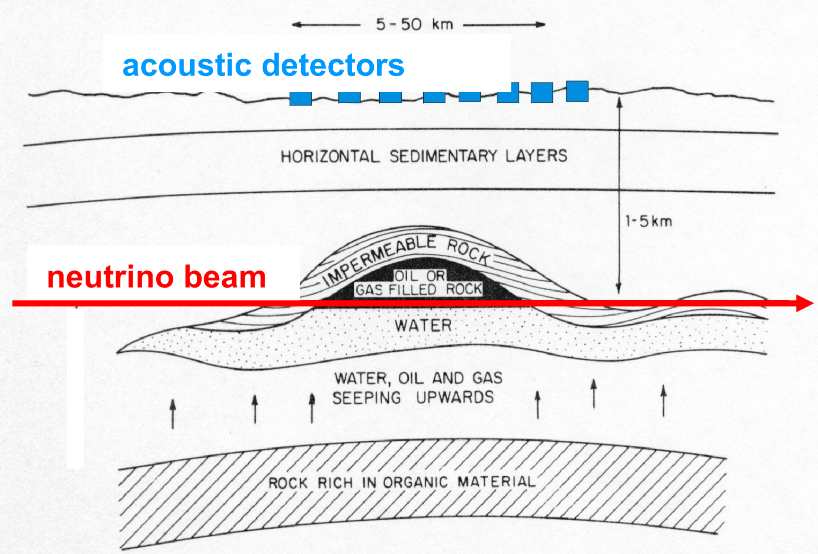


Fig. 6.1. Typical oil or gas deposit.

The acoustic dessert, 1985 – 2000 ?

B. Price, Astropart. Phys. 5 (1996) 43
studies situation for ice

Comparison of optical, radio, and acoustical detectors for ultrahigh-energy neutrinos

Signal: S(ice) ~ 10 S(water)
but : high energy threshold
expensive sensors ~1000$/piece

The acoustical technique is least sensitive, the mechanism of energy conversion from a cascade to an acoustic signal is very inefficient, and no tests have been carried out with particle beams in ice.

A comparison of the three techniques shows that the optical technique is most effective for energies below ~ 0.5 PeV, that the radio technique shows promise of being the most effective for higher energies, and that the acoustic method is not competitive. ~~Due to the great transparency of ice, the event rate of AGN ν_e-induced cascades may be~~

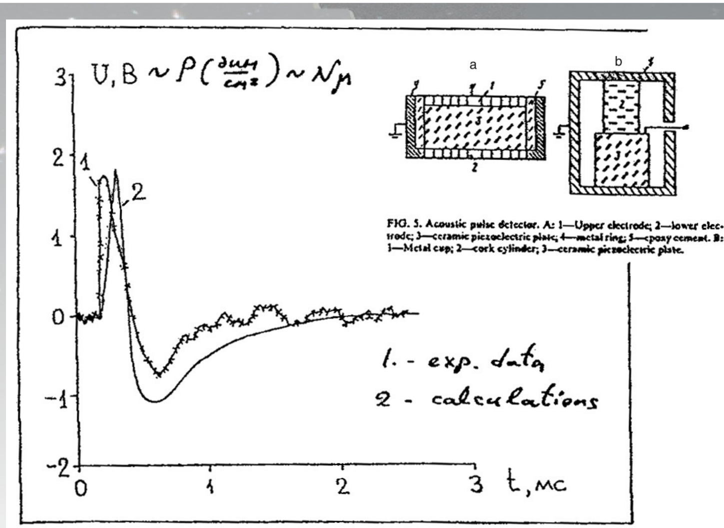
Exotic exceptions

A.Borisov et al.
Zh. Eksp. Teor. Fiz. 100 (1991) 1121

Detection of acoustic signal from the muon flux in the U70 neutrino channel

A.Borisov et al. Saratov Preprint (1992)

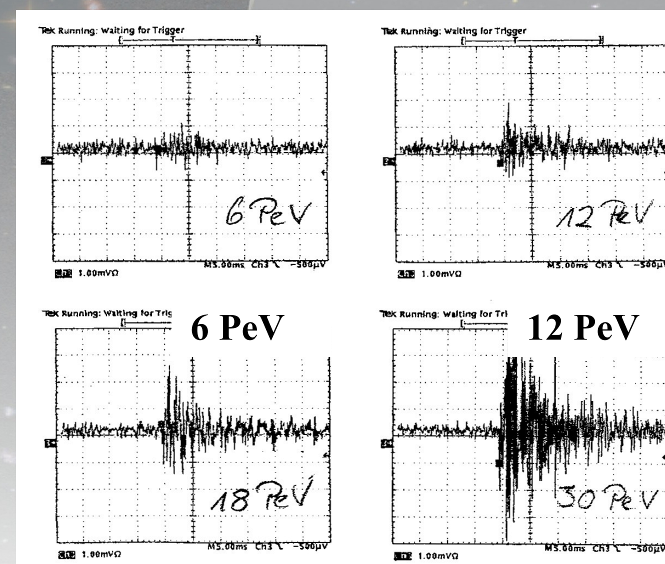
Acoustic calorimetry of high energy muons



J.Bähr,R.N.,M.Pohl
DESY Zeuthen (1996) unpulished

$$E_{pot} = mgh$$

m=1g, h=10cm, E=6 PeV



18 PeV **30 PeV**

Detectors: own production using piezo-elements → cheap

The revival of acoustics, 2000 - 2010

GZK-cutoff and corresponding cosmogenic neutrino detection at ultra-high energies (> 10^{17} eV) comes in the focus of physicists

e.g. A. V. Butkevich et al. "Prospects for radiowave and acoustic detection of ultra- and superhigh energy cosmic neutrinos(cross sections, signals, thresholds)"

«ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА»
1998, ТОМ 29, ВЫП.3

or G. Sigl, "Probing Physics and Astrophysics at extreme energies with ultra high energy cosmic radiation" in Proc. RADHEP , AIP Conf. Proc V579, p. 32

Needs new detection techniques,
a series of corresponding workshops happens:

time	name	location	countries	particip.	ac. talks
2000	RADHEP	Los Angeles	6?	50	1
2003	Acoustic mini-ws.	Stanford	5	20	16
2005	ARENA2005	Zeuthen	10	90	26
2006	ARENA2006	Newcastle	9	50	13
2008	ARENA2008	Rom	12	80	22
2010	ARENA2010	Nantes	18!	80	12

Activities at many sites

Table from ARENA2006 — [green] with contr. 2006 — [light blue] connect. to military proj.

group	experiment	activities
Stanford	SAUND	data taking, signal processing, calibration , simulation
INR1	AGAM, MP10	signal processing, calibration , simulation
INR2, Irkutsk	Baikal	signal processing, noise studies, in-situ tests at Baikal
ITEP	Baikal,Antares	detector R&D, accel. tests, in-situ tests at Baikal, signal proc., noise st.
Marseille	Antares	detector and installation R&D, calibration, noise studies, simulation,
Erlangen	Antares, KM3NET	detector R&D, accel. tests, calibration, simulation, noise studies, in-situ test measurements
Pisa, Firenze, Genua	KM3NET	detector R&D
Rom, Catania	NEMO	installation R&D, noise studies, simulation
Sheffield, Newcastle	Rona, KM3NET	simulation, signal processing , calibration
U. Texas	Salt Dome	detector R&D, attenuation studies, material studies
Berkeley, DESY, Stockholm, Uppsala	IceCube	detector R&D, accel. tests, material studies, simulation, noise studies, in- situ test measurements (SPATS)

A few selected examples

parasitic arrays to military projects

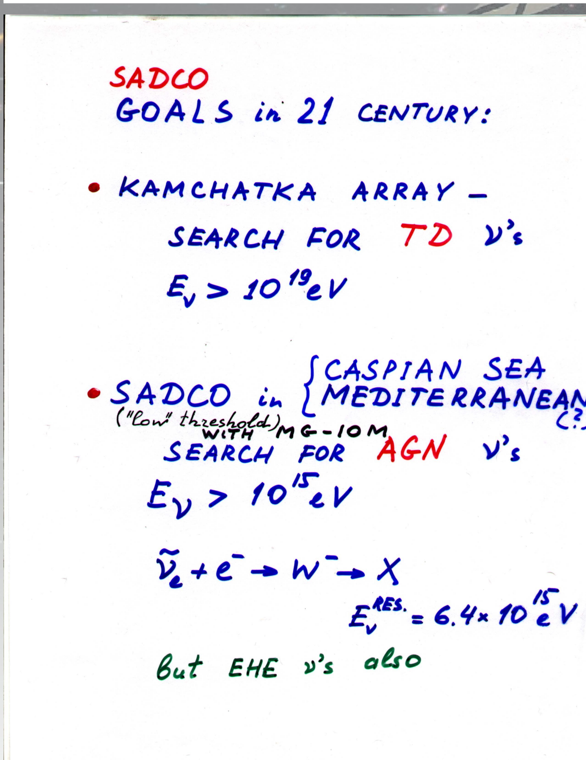
arrays for in-situ R&D studies

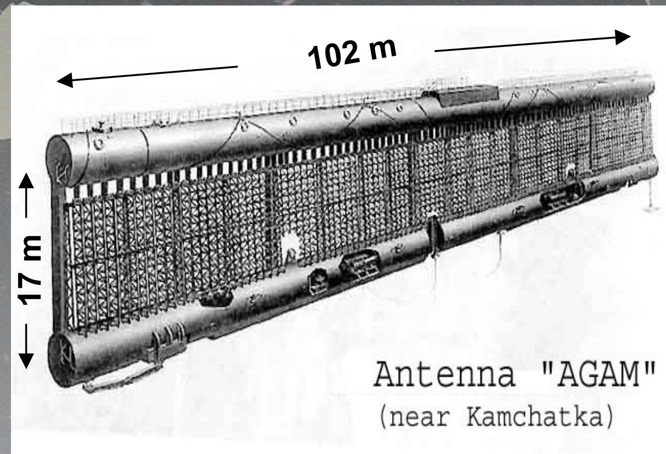
Not discussed:

- sensor develop.
- beam tests
- calibration
- data processing
- target materials
- simulation
- …

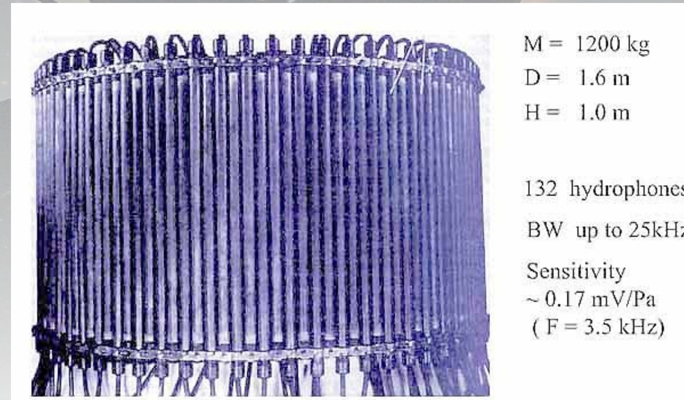
Military: AGAM - MP10 - SADCO

From a talk of I. Zelesnykh
given by J. Learned
at Stanford-2003





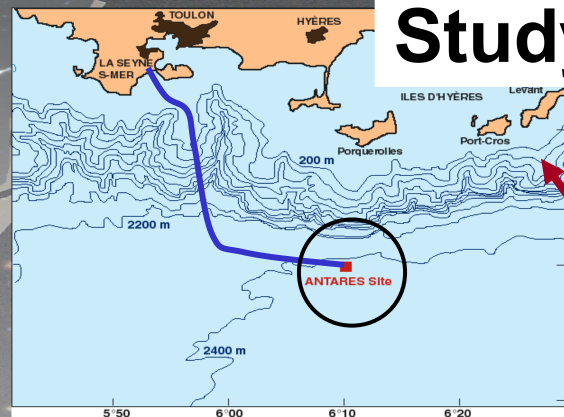
2400 hydrophones
f < 2 kHz
V_{eff} > 100 km^3 for
$E_\nu > 10^{20}$ eV



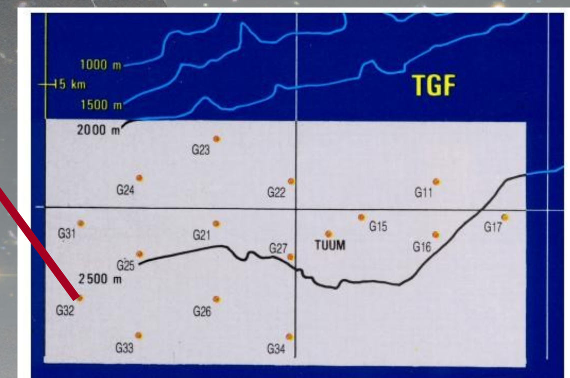
Portable Submarine
Antenna MG-10M
as a basic module
of the deep-water
Neutrino Telescope
Test from oil platforms
in Caspian Sea

Present status of project not known (to me)

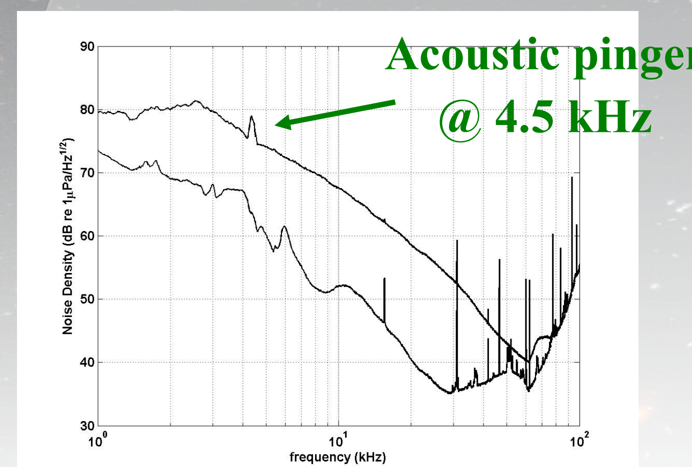
Military: TREMAIL - Marseille



Study of ambient noise



Use French navy tracking array
Data taking campaign in June 2001:
8 hydrophones @ 1500 and 2500 m
sampling frequencies 250 kHz
filters window 10-100 kHz
3Gbytes of data
but many uncertainties
should be redone soon

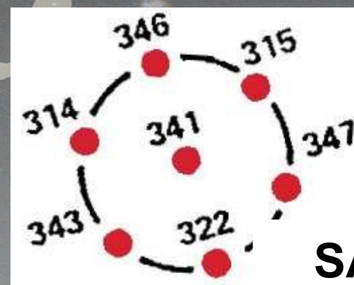


From V.Bertin, talk Stanford 09/2003

Military: AUTEC - SAUND

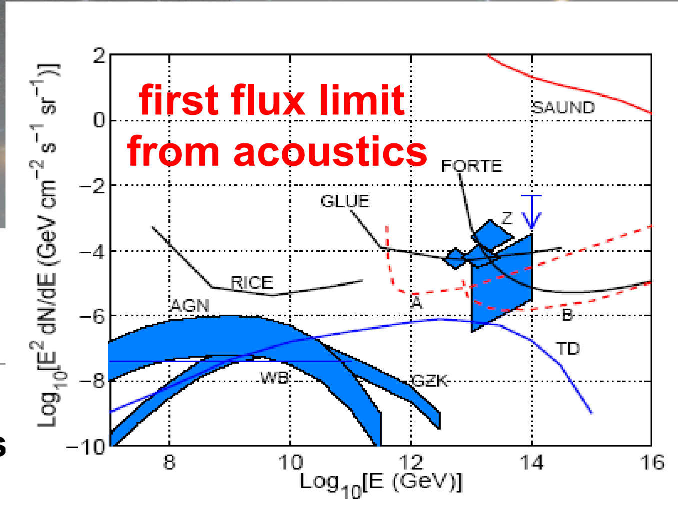
Study of Acoustic
Ultrahigh-energy Neutrino Detection

J. Vandenbroucke et al.,
Astrophys.J. 621 (2005) 301

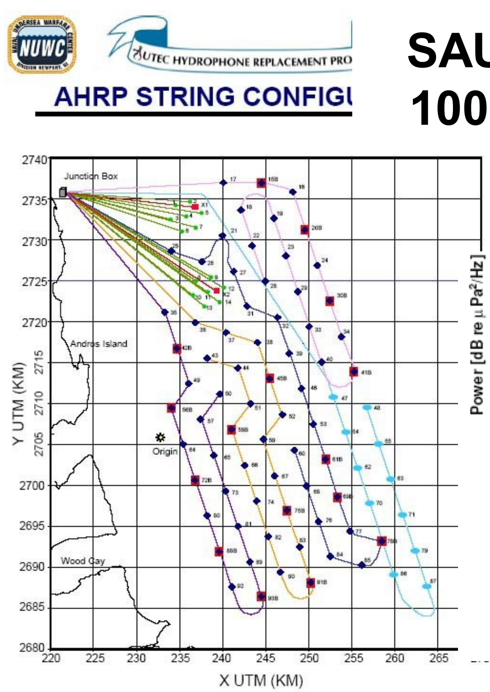


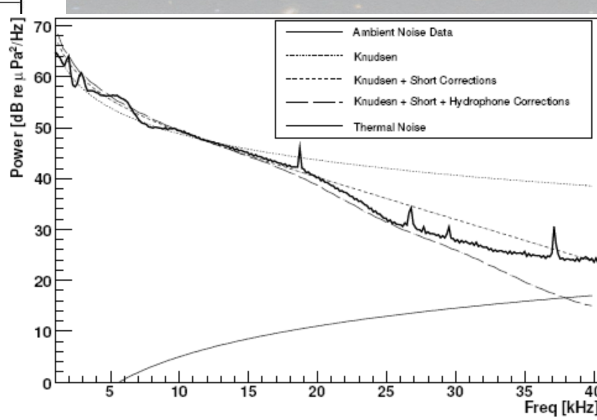
SAUND I
7 km²

Data taking:
65 *10⁶ events
in 195 days



SAUND II
1000 km²





From: N. Kurahashi,
talk at ARENA2008N
See also: N. Kurahashi, G. Gratta
Phys. Rev. D 78, 092001 (2008)

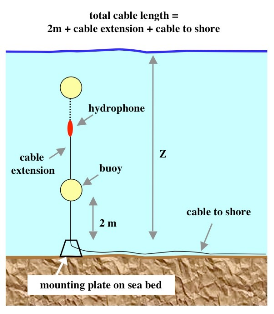
New information
at this conference

Military: RONA - ACoRNE

Rona hydrophone array

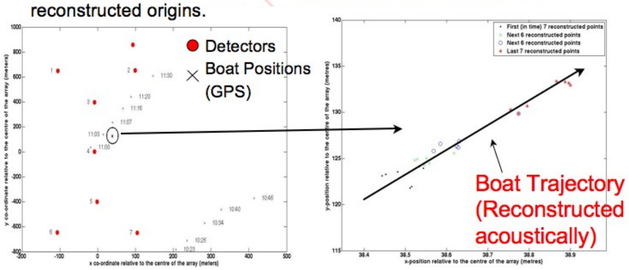
- North-West Scotland (ranging hydrophones)
- Good test bed for future deep sea experiments

- Existing infrastructure √
- Wideband hydrophones √
- Omnidirectionality √
- Unfiltered data √
- All data to shore √
- Control over DAQ √
- No remote access X

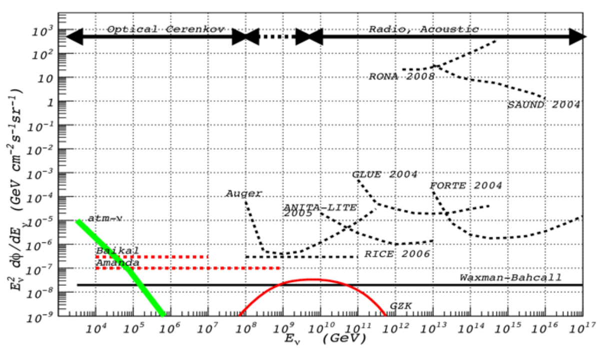


Boat Reconstruction

- Using the known detector positions and the time of arrival of the pulse on each hydrophone, each detected pulses' origin (if detected on > 4 detected) could be calculated.
- The boat, and drift, was successfully reconstructed
- Plots show the detector positions, the boat positions, and the reconstructed origins.



Rona Limit

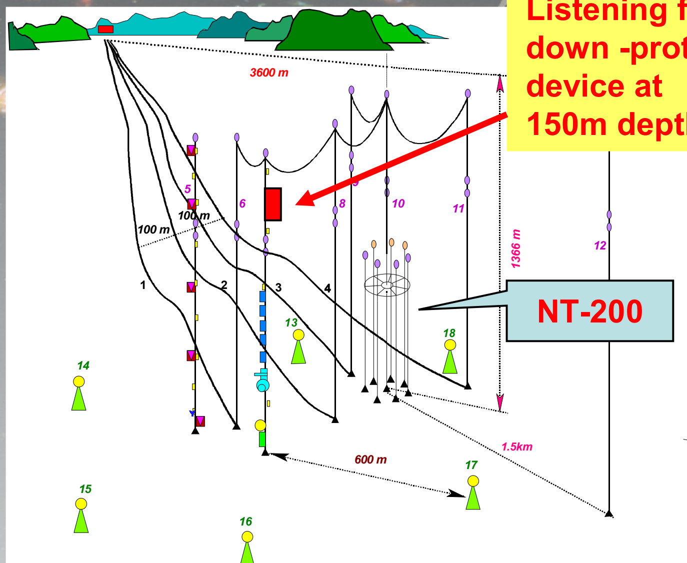


26/06/2008 ARENA 2008 - Rome 26

From L. Thompson, ARENA2008 and S. Bevan, Theses

New information at this conference

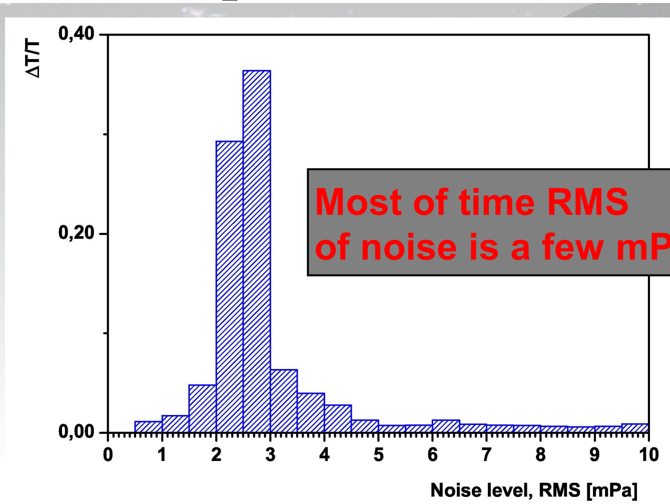
R&D-arrays: BAIKAL



Listening from top to down -prototype device at 150m depth

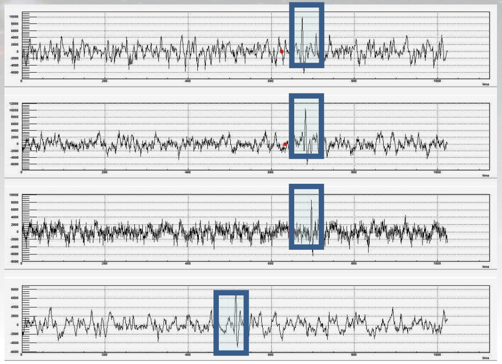
An acoustic detector for background studies

- Tetrahedral antenna 1.5m
- 4 hydrophones H2020C
- 4-ch, 195kHz, 16-bit ADC
- One-plate computer
- 2 Mbit DSL modem



Most of time RMS of noise is a few mPa

One signal from the deep layer of the Lake

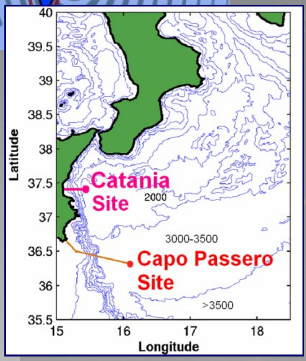


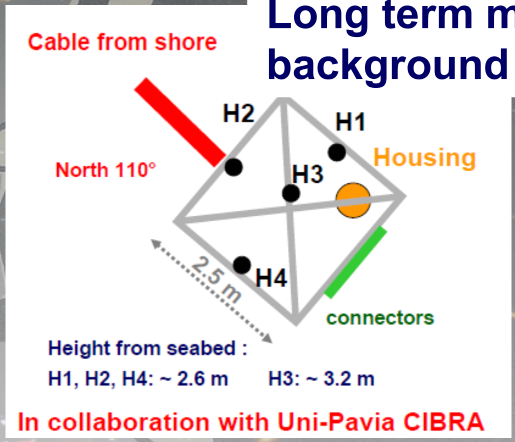
Next step: Prototype acoustic string

New information at this conference

From N. Budnev, VCI 2010

R&D-arrays: ONDE



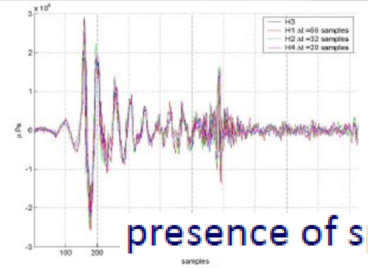


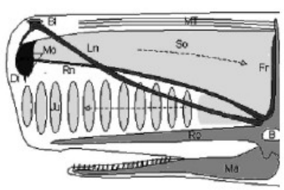
Long term measurements of acoustic background noise in very deep sea

4 hydrophones (10 Hz-40 kHz bandwidth) synchronized.
Acoustic signal digitization (24bit@96 kHz) at 2000m depth.
Data transmission on optical fibers over 28 km.
On-line monitoring and data recording on shore.
Recording 5' every hour.
Data taking from Jan. 2005 to Nov. 2006 (NEMO Phase 1 deployed).

The average noise in the [20:43] kHz band is $5.4 \pm 2.2_{stat} \pm 0.3_{syst}$ mPa

From G. Riccobene: ARENA2008, VLVNT2009





Depth = 560 ± 5 m
L = 3.41 ± 0.05 m
Size = 9.72 - 10.50 m
Young male or female

presence of sperm whales

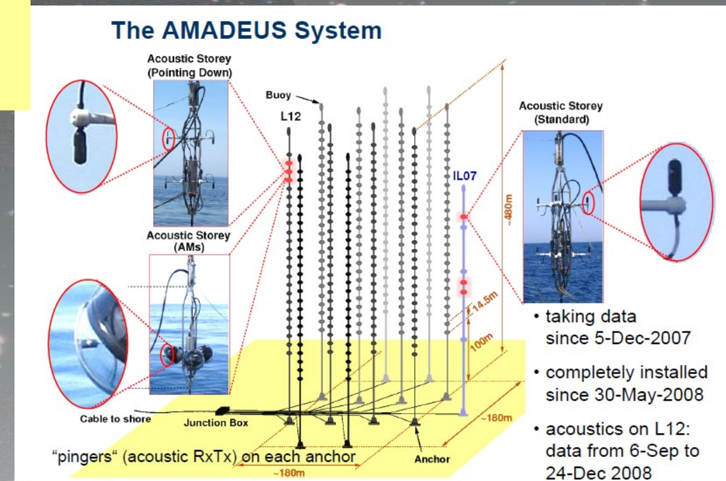
Next step:

R&D for an innovative acoustic positioning system for the KM3NeT neutrino telescope

New information at this conference

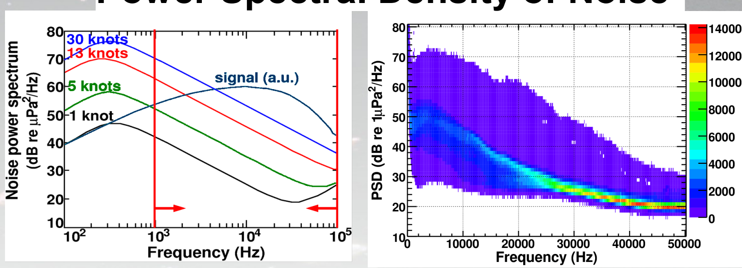
R&D-arrays: AMADEUS

New information at this conference

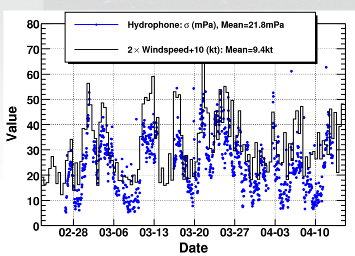


36 sensors at 6 storeys
(1 – 350m distance, 34 active)
16bit @ 250kSps sampling
~ -125dB re 1V/µPa sensitivity
~85-90% uptime

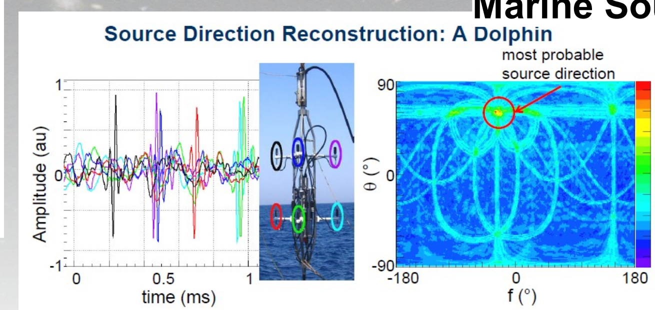
Power Spectral Density of Noise

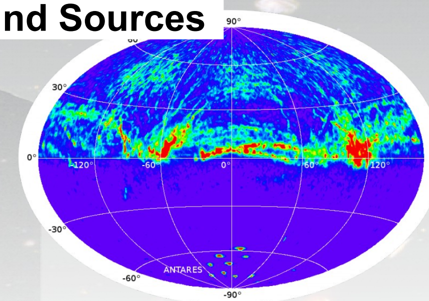


Noise strongly correlated with weather conditions



Angular Distribution of Marine Sound Sources

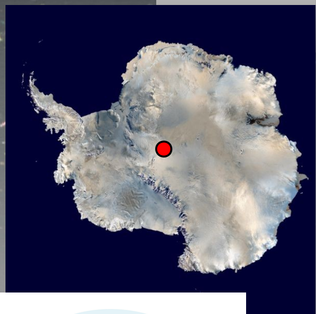




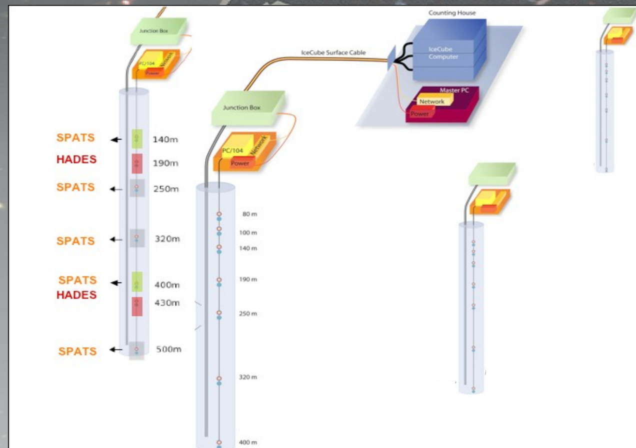
Beam forming or time difference algorithms used,
uncertainty < 1 degree

From R.Lahmann VLVNT 2008,
K. Graf, VLVNT 2009

R&D-arrays: SPATS



SPATS 2007
South Pole Acoustic Test Setup



4 strings in IceCube holes

instrumented depth:
80 m - 500 m

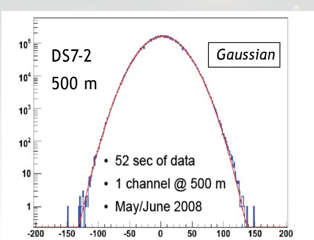
per string:
7 stations with sensors + transmitters

pinger

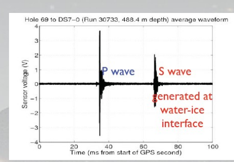
Noise conditions:

~ 2 years monitoring

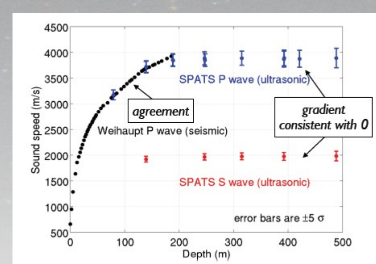
Gaussian,
Stable
≤ 25 mPa



Sound speed:



From pinger data 2007/08

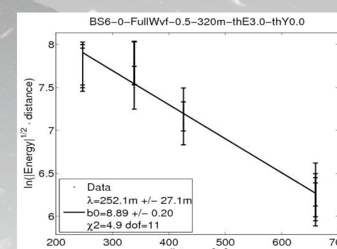


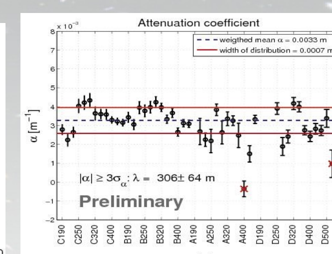
- two combinations at 125 m distance
- accuracy < 1%
- first in situ measurements for P and S waves at SP

$$v_P(375m) = 3878 \pm 12 \ \ m/s$$

$$v_S(375m) = 1975.8 \pm 8.0 \ \ m/s$$

Attenuation length: From pinger data 2008/09





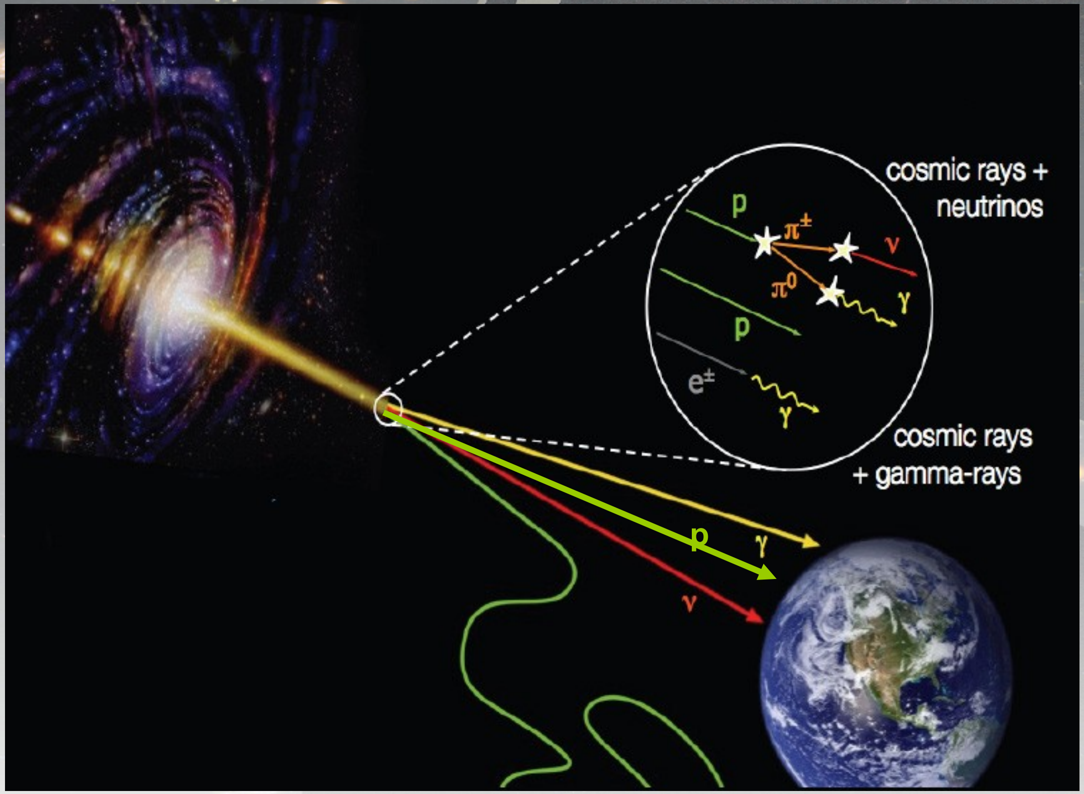
No significant evidence for depth or frequency dependence, but not excluded

New information at this conference

From D.Tosi, TEVPA 2009

Why all these efforts?

Three carrier of information: protons, gamma-rays, neutrinos

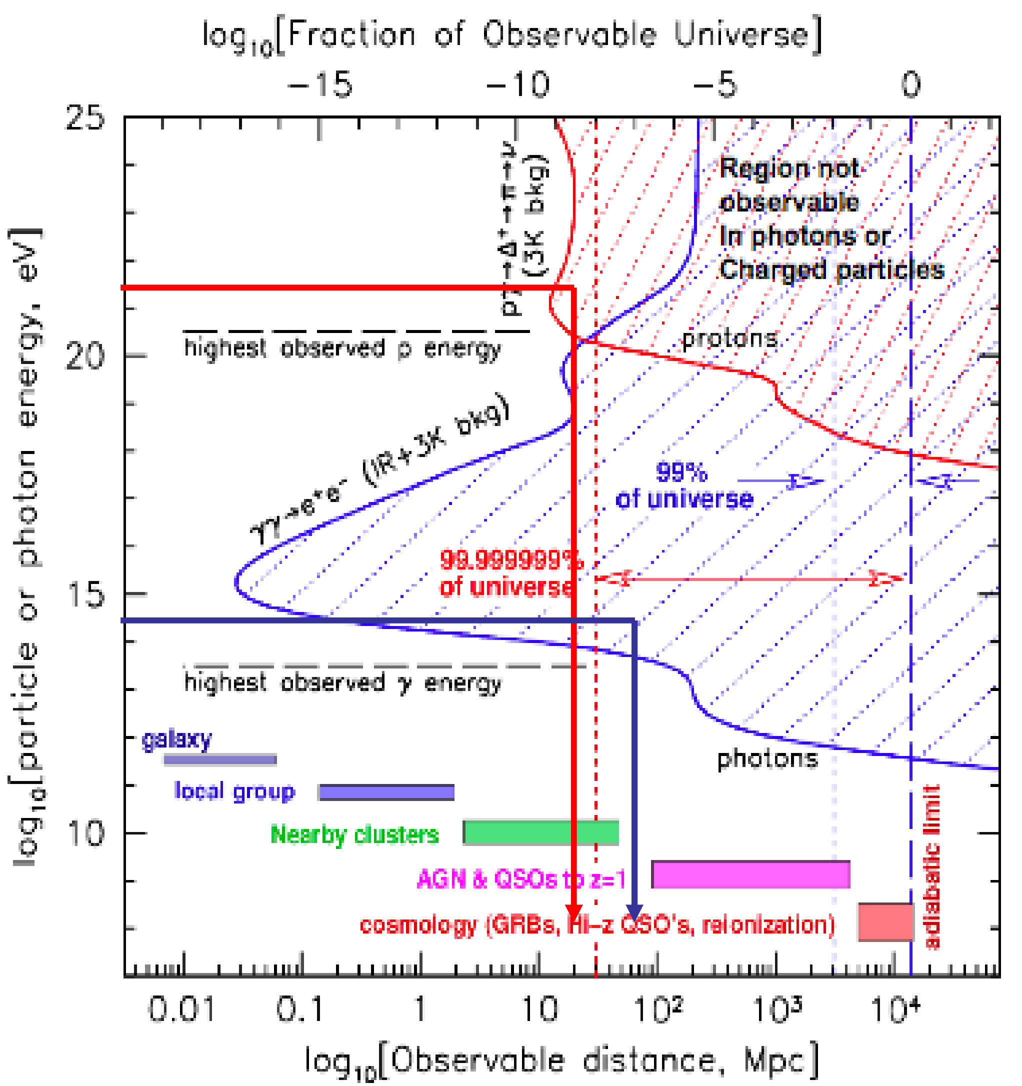


p: TeV – 100 EeV
- point back to sources only at highest energies
- observable range limited
- signals observed
- sources still unidentified

γ: GeV – 10 TeV
- point always back to sources
- observable range limited
- signals observed
- many sources identified

ν: 1TeV – 100 EeV
- **point always back to sources**
- **observable range "unlimited"** → **no signals observed yet**

Limits from particle propagation through the universe



100 EeV Protons travel ~20 Mpc

10 TeV photons travel ~100 Mpc

Neutrinos:

- travel uneffected by dust and B-fields
- interact only weakly
- can escape from thick dense sources

At high energies only neutrinos can give information about most of the universe

Get new insights from the study of ultra-high energy neutrinos above ~10^{17} eV about:

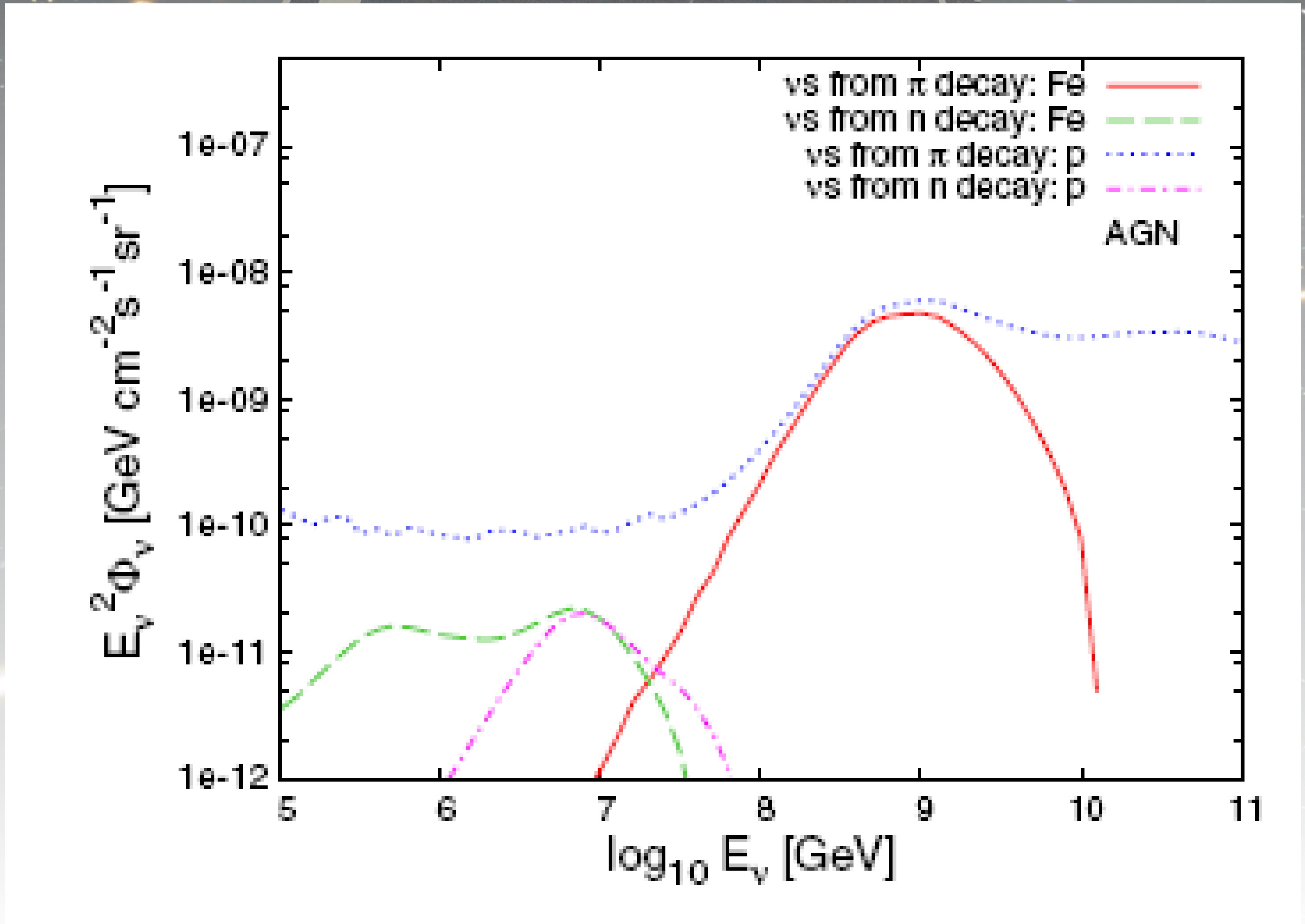
- Astrophysics
- Particle Physics
- Cosmology
- Basic symmetries

Considered sources:

- AGN's
- neutrinos from GZK-effect
- topological defects

AGN:

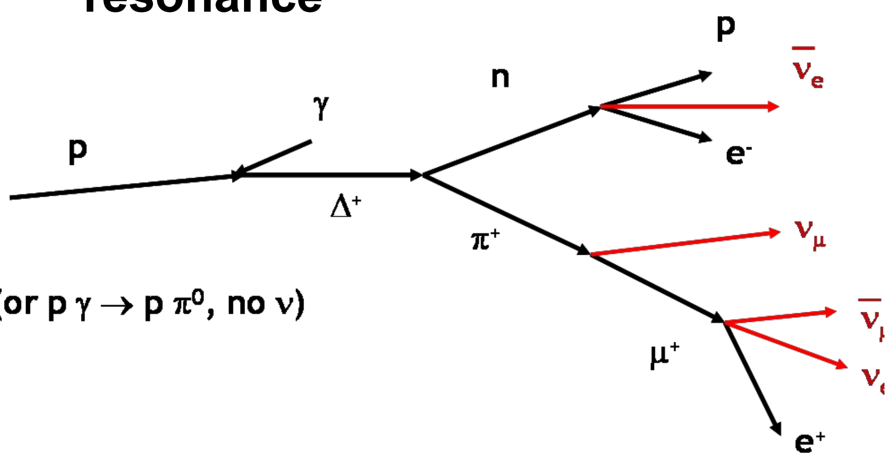
e.g. L. A. Anchordoqui et al. Astropart. Phys. 29(2008)1



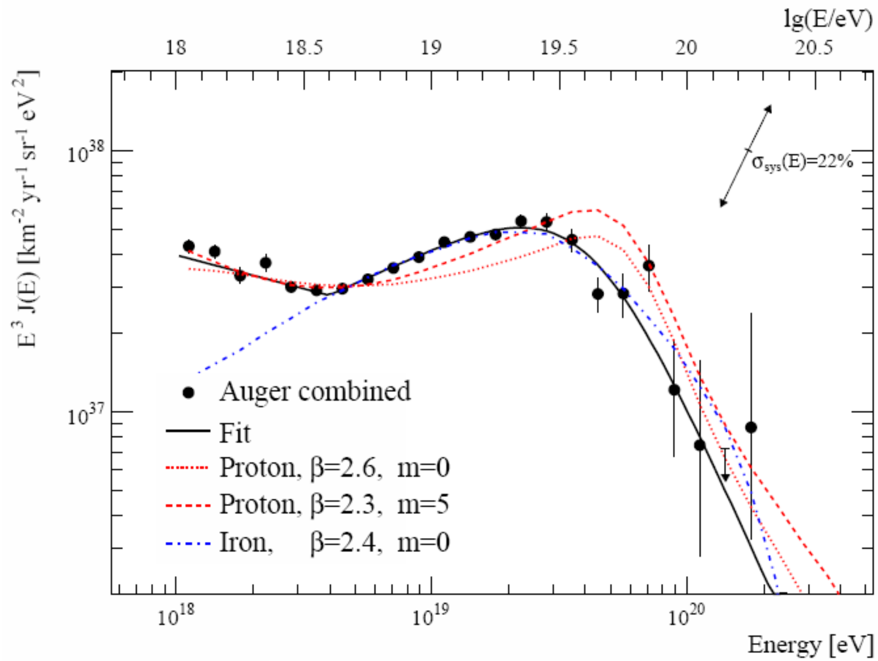
GZK mechanism:

a guaranteed source of neutrinos

Cosmic rays interact with CMB photons and produce π through Δ^+ resonance



$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4 \cdot 10^{19}\,\mathrm{eV}$$



If UHE-CR exist they should undergo GZK mechanism

If GZK happens a neutrino flux is guaranteed

GZK neutrinos → BZ neutrinos

V. S. Berezinsky, G.T. Zatsepin, Phys Lett B 28 (1969)423

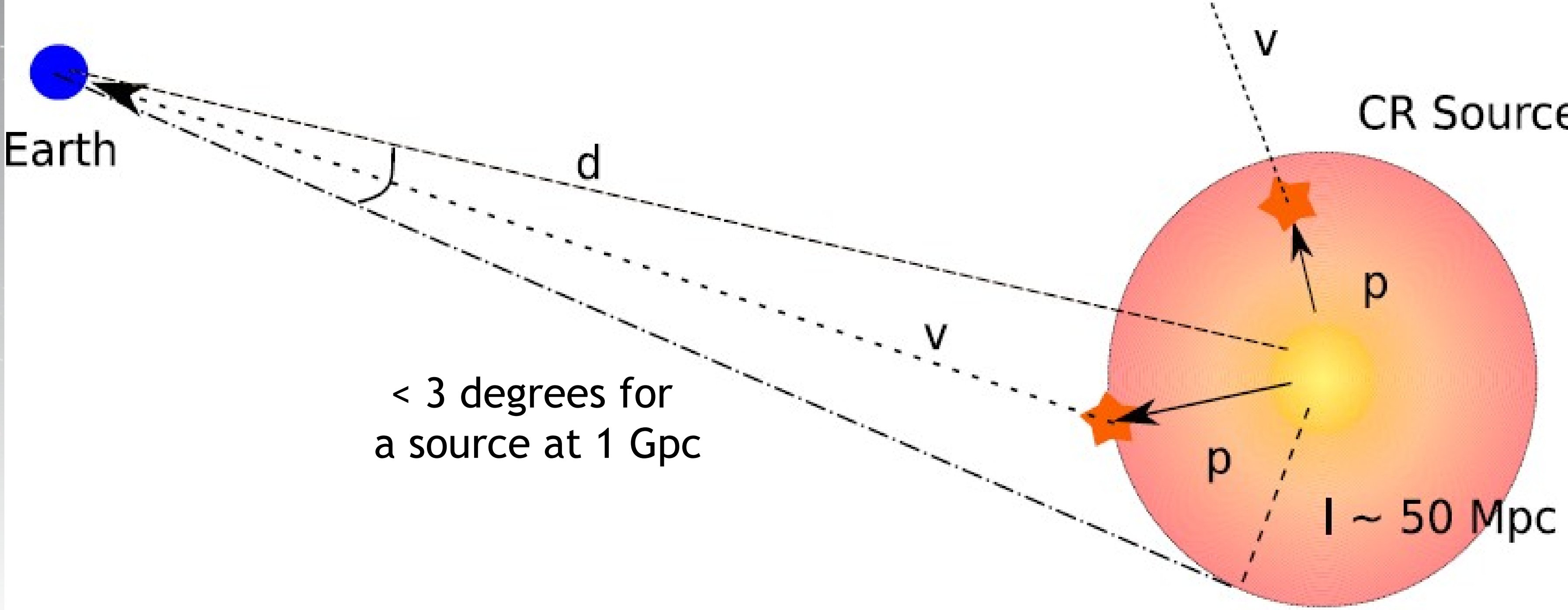
- Missing statistics?
- No more sources?
- No more power?
- or real GZK?

→ detect neutrinos

BZ neutrinos:

astronomy for UHE proton sources throughout the universe

BZ neutrinos from cosmological distances point back to the UHECR sources (within a GZK length precision)



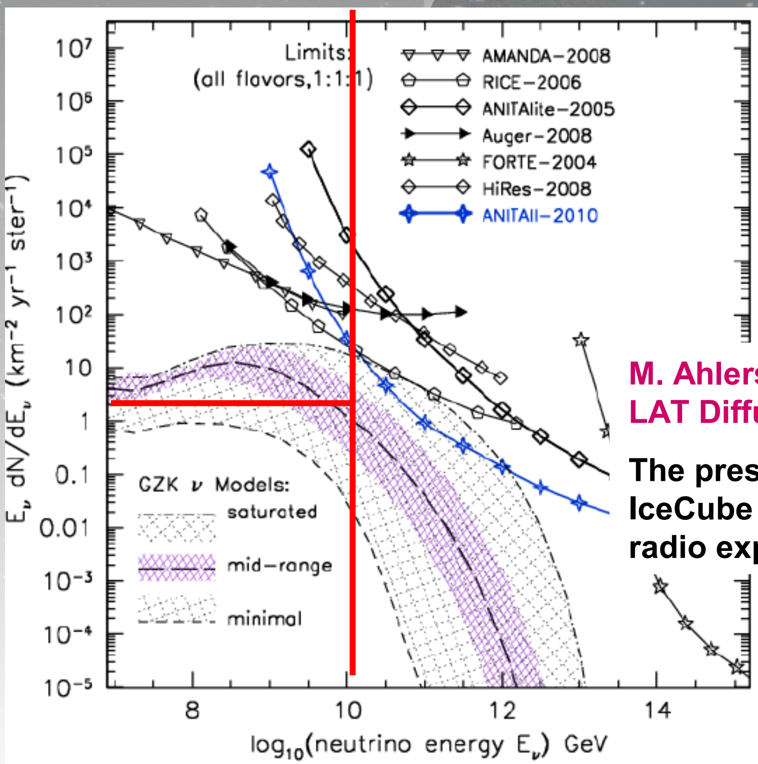
“GZK sphere”

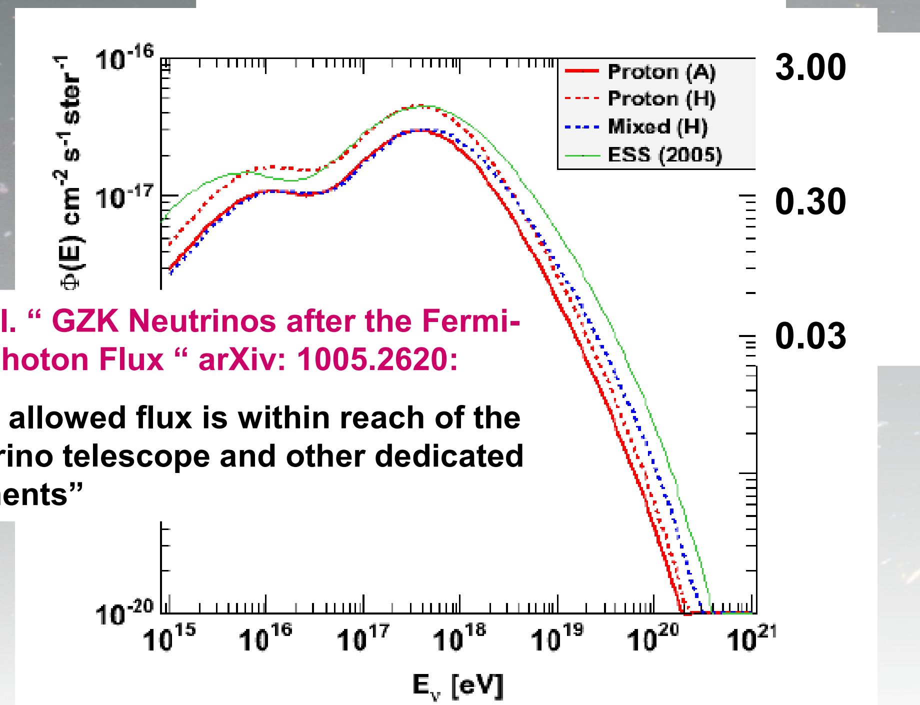
BZ neutrino flux:
prediction and detection

The expected flux is very low and uncertain (0.01-10 events/km^2 year @ $E_\nu = 10^{19}$ eV)

The standard case:

D. Seckel and T. Stanev, 2008





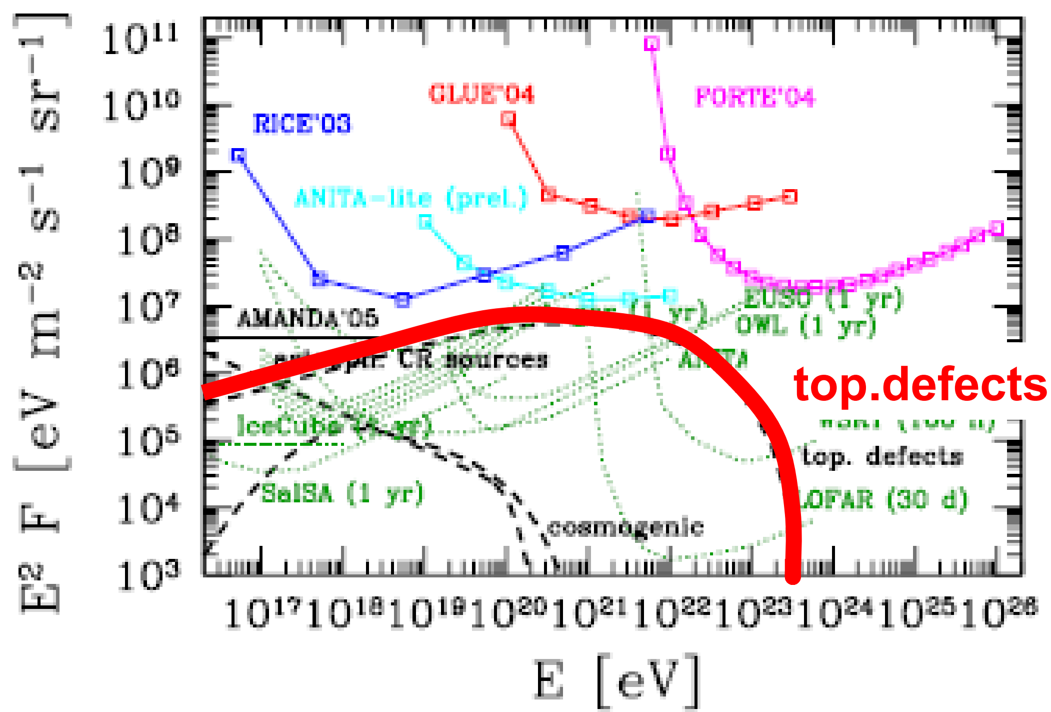
M. Ahlers et al. " GZK Neutrinos after the Fermi-LAT Diffuse Photon Flux " arXiv: 1005.2620:

The presently allowed flux is within reach of the IceCube neutrino telescope and other dedicated radio experiments"

from P. Gorham, March 2010 Madison

Topological Defects:

from A. Ringwald, 2005



Neutrinos from decay of super-heavy relic particles from big bang

$m_X = 10^{21} – 10^{25}$ eV

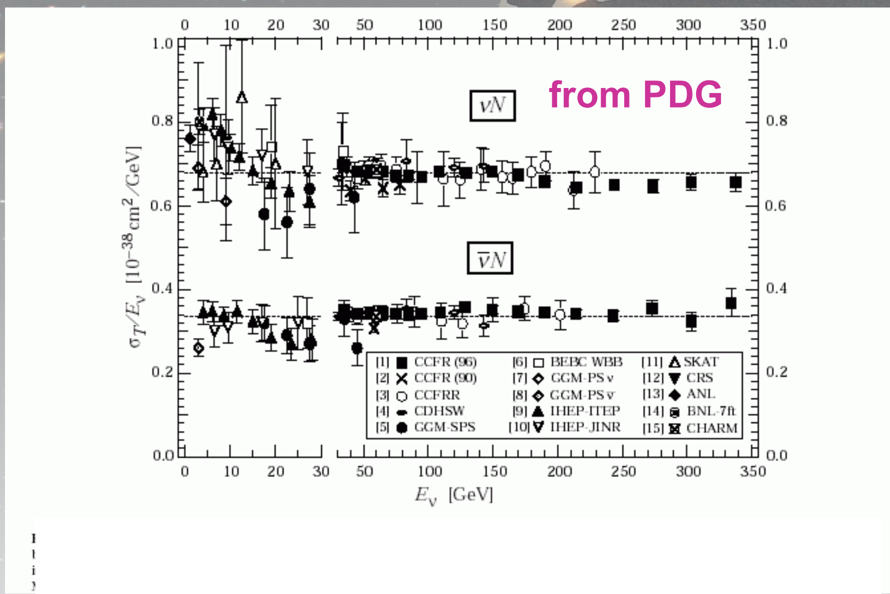
$E_\nu \sim 0.05\ m_X$

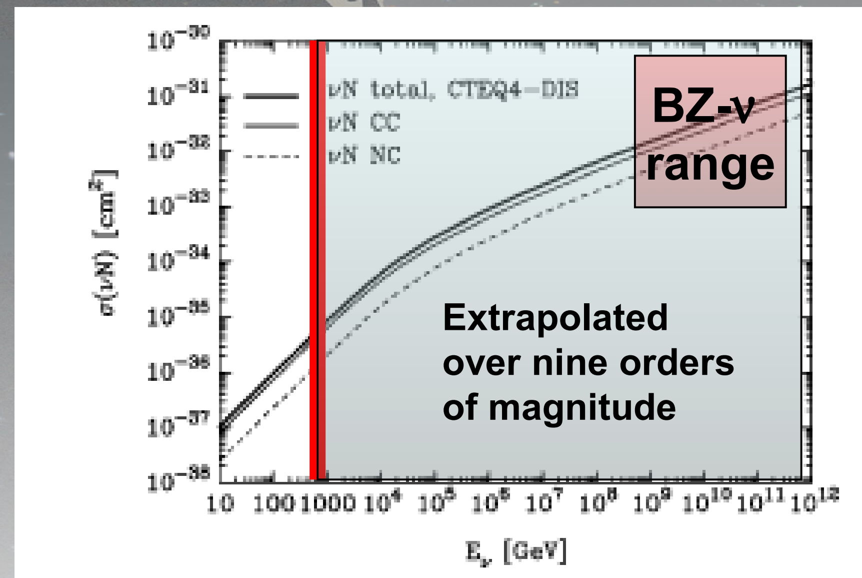
Very high neutrino energies possible

Such high fluxes probably ruled out today by ANITA flux limit, but model in general still interesting

Particle Physics with UHE neutrinos I:
cross section measurements

R.Gandhi et al. Phys.Rev. D58 (1998)093009



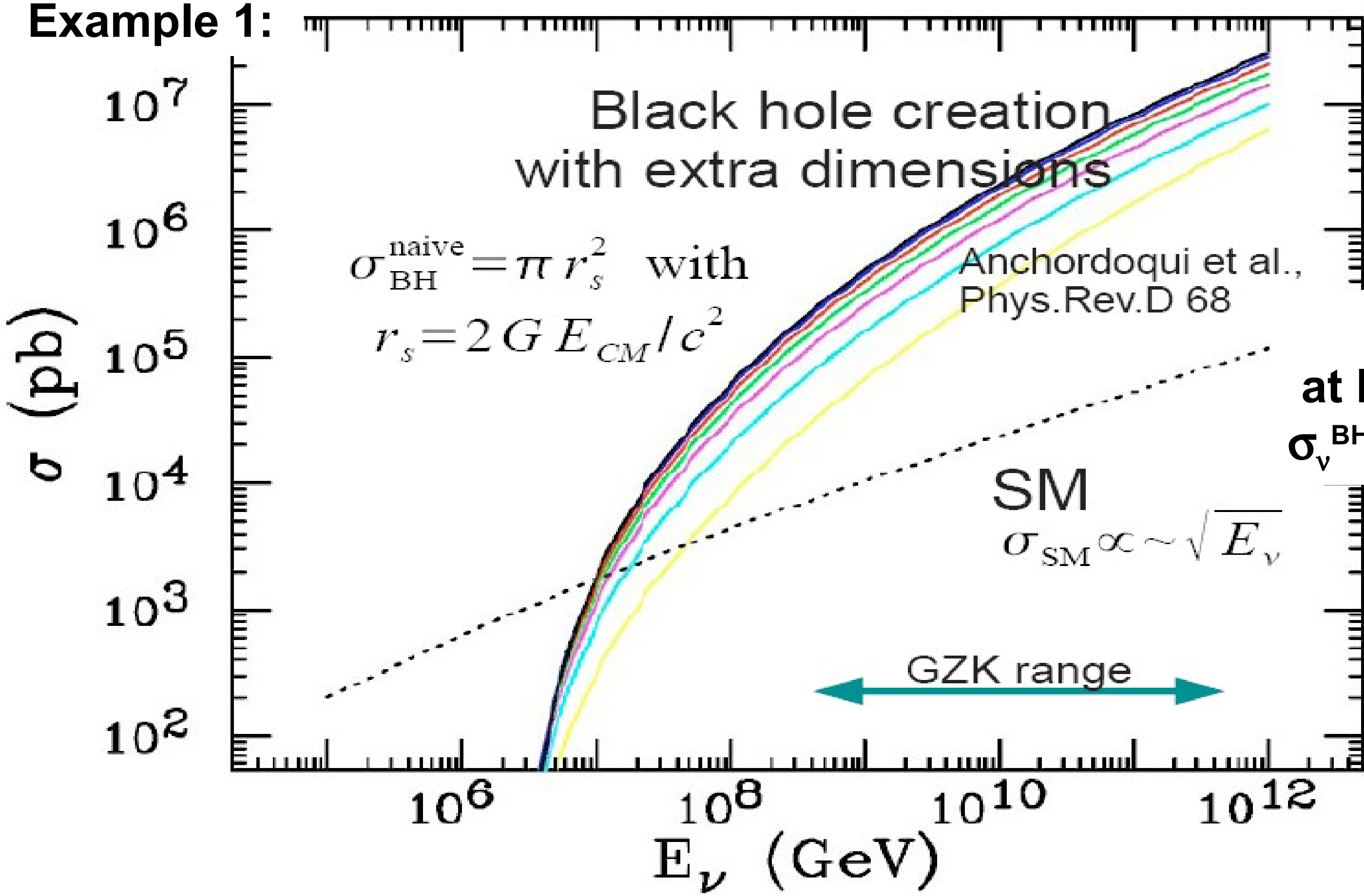


Measure reasonable number (O(100)) of BZ-neutrinos at different zenith angles → get access to σ_ν in the $10^{17} – 10^{20}$ eV range

$\mathrm{sqrt}(s_{\nu N}) = \mathrm{sqrt}(2m_\nu E_\nu) = 14\ \mathrm{TeV}(E_\nu/10^{17}\mathrm{eV})^{1/2}$

Several effects at energies > 10^{17} eV may change the cross section by orders of magnitude

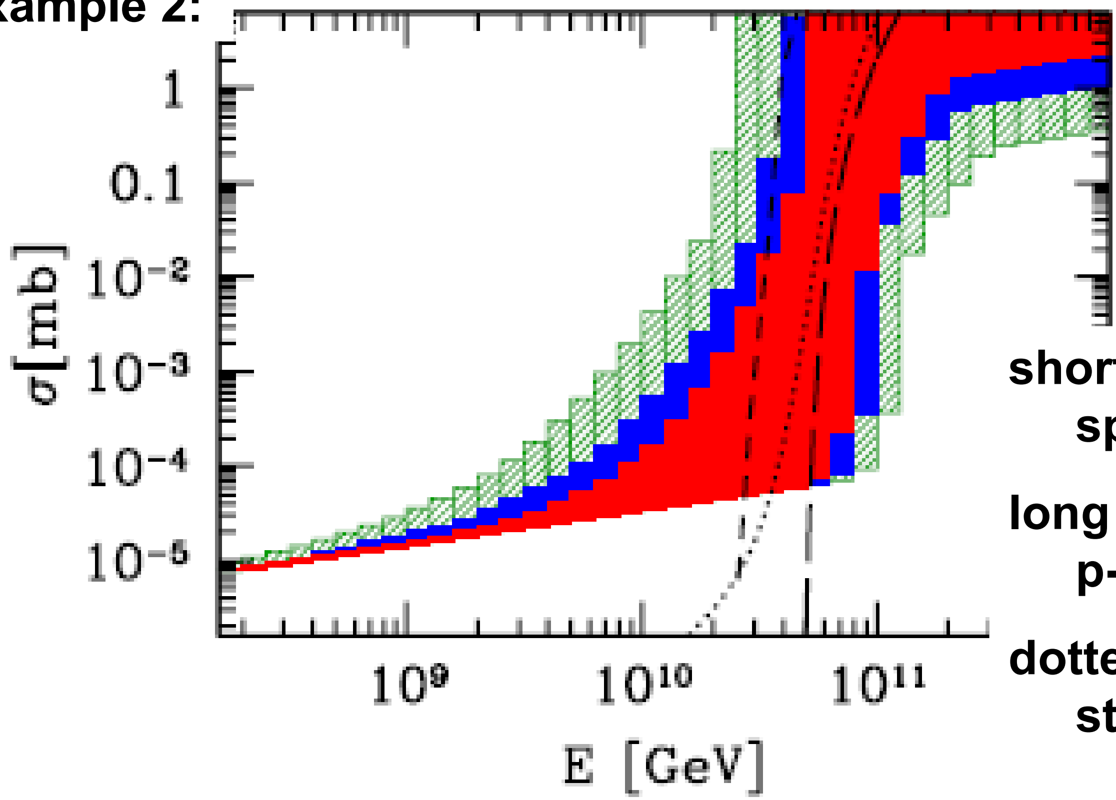
Example 1:



at E = 10^{19} eV
$\sigma_\nu^{BH} / \sigma_\nu^{SM} \sim 100$

L. Anchordoqui et al. Astropart. Phys. V25(2006)14

Example 2:



short dashed:
sphalerons [43,44]

long dashed:
p-branes [45]

dotted:
string excitations [46]

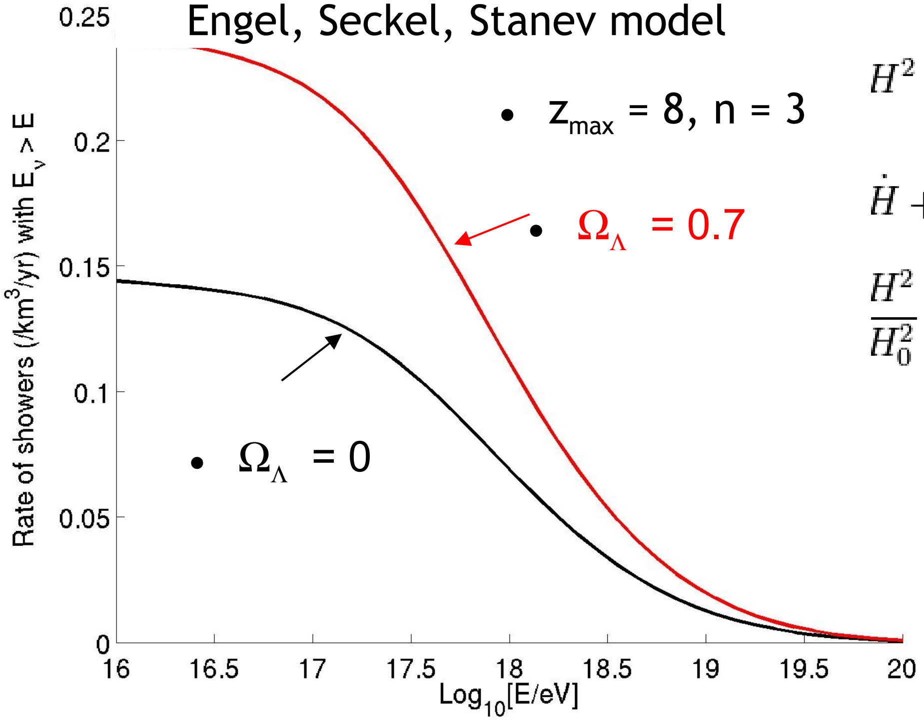
43. A. Ringwald, JHEP **0310** (2003) 008.
44. T. Han and D. Hooper, Phys. Lett. B **582** (2004) 21.
45. L. A. Anchordoqui, J. L. Feng and H. Goldberg, Phys. Lett. B **535** (2002) 302.
46. W. S. Burgett, G. Domokos and S. Kovesi-Domokos, Nucl. Phys. Proc. Suppl. **136** (2004) 327.

from A.Ringwald, ARENA 2005

Cosmology and UHE neutrinos
the cosmological constant

number of GKZ neutrinos predicted depends on sources distribution vs. redshift and on the source evolution model (z_{max}, n, Ω_Λ)

- GZK ν event rates following Engel, Seckel, Stanev model



$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} + \Lambda\,g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$ **Einstein**

$$ds^2 = a(t)^2 ds_3^2 - dt^2$$ a(t): scale factor

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$ **Friedman**

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

$$\Lambda = 8\pi\rho_{vac},$$

ρ_{vac}: intrinsic energy density of the vacuum

$$\Omega_\Lambda = \rho_{vac}/\rho_{cri}$$

present observations:

$$\Omega_\Lambda = 0.7$$

Cosmology and UHE neutrinos
relic neutrino detection

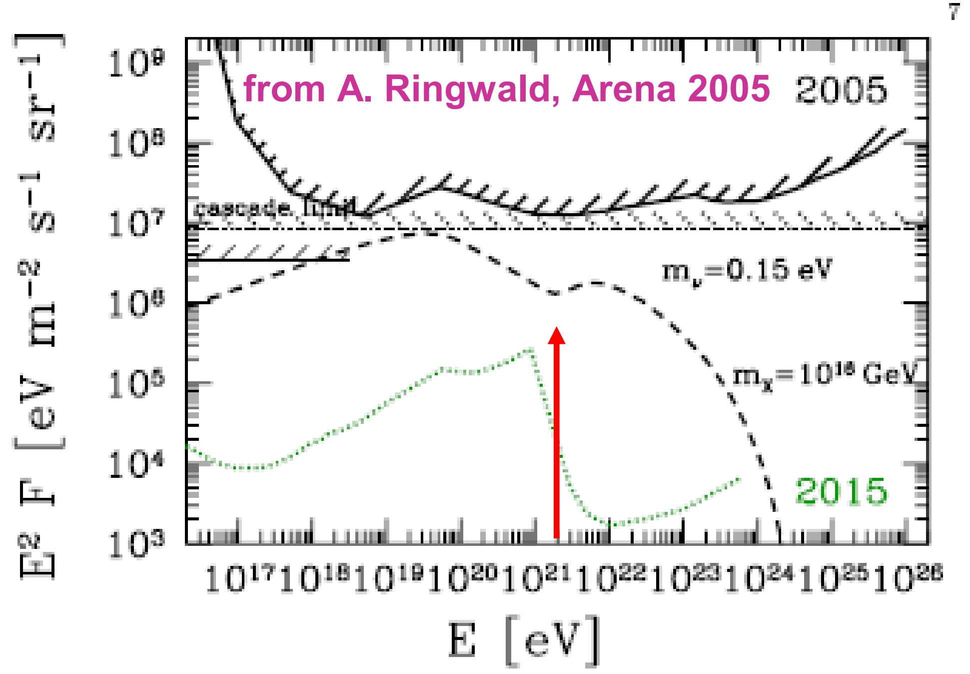
resonant annihilation of UHE neutrinos with relic neutrino background particles

UHE neutrinos from topological defects

For early ideas see e.g.:

T. Weiler, Phys.Rev. Lett. 49(1982)234

S. Yoshida, G. Sigl, S. Lee, Phys Rev. Lett. 81(1998)5505



CMB: T_γ = 2.752 K

$$T_{\nu 0} = \left(\frac{4}{11}\right)^{1/3} = 1.945\ \mathrm{K}$$

$$\rightsquigarrow 1.697 \times 10^{-4}\ \mathrm{eV}$$

$$n_{\nu_i}(T_{\nu 0}) \approx 56\ \mathrm{cm}^{-3}$$

$$E_\nu^{\mathrm{Zres}} \simeq \frac{4 \cdot 10^{21}}{m_\nu}\ \mathrm{eV}$$

dip in neutrino flux spectrum

Particle Physics with UHE neutrinos II: neutrino mass spectroscopy

Use information the other way around:

→ **absorption lines in neutrino spectrum point to neutrino mass(es)**

$$m_\nu = M_Z^2 / 2E_\nu^{Z\mathrm{res}}$$

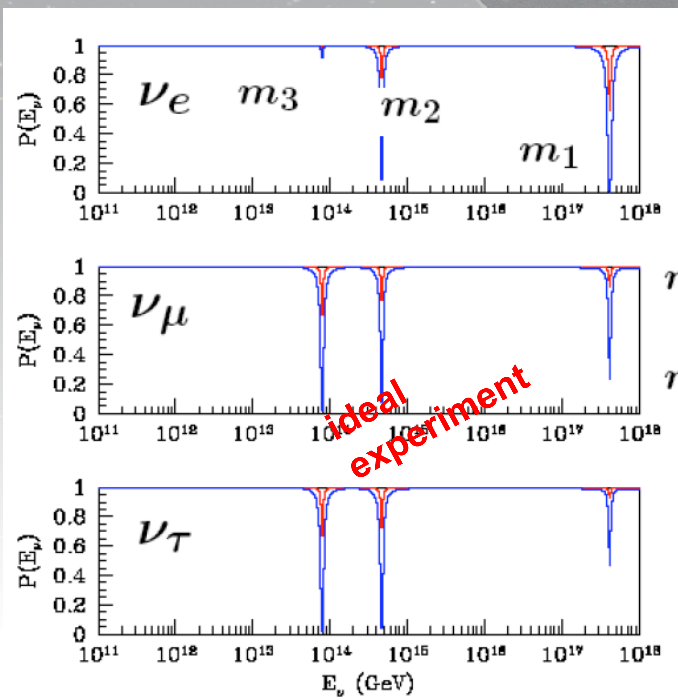
$$m_\ell = 10^{-5} \ \ \mathrm{eV}$$

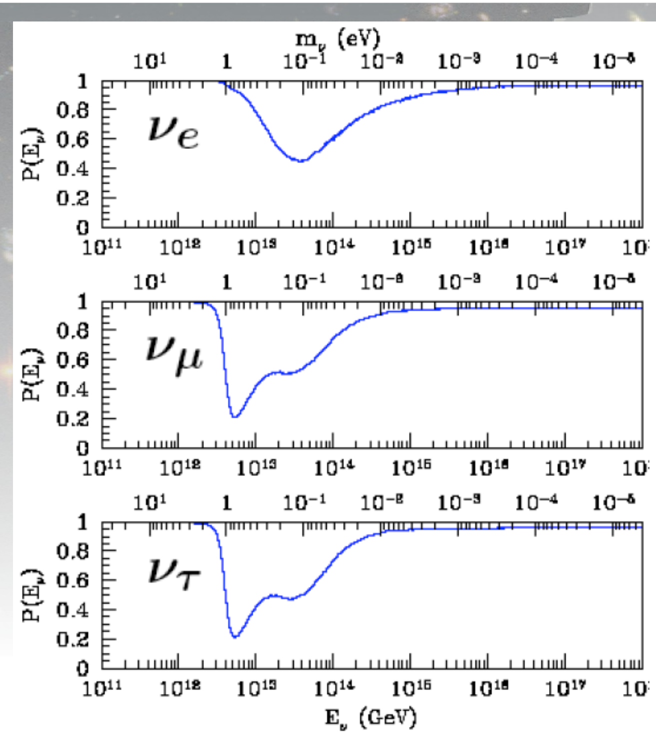
$$m_2 = \sqrt{m_\ell^2 + \delta m^2_{solar}} \sim 0.01 \ \mathrm{eV}$$

$$m_3 = \sqrt{m_2^2 + \delta m^2_{atmos}} \sim 0.05 \ \mathrm{eV}$$

But time evolution of universe: $E_{\nu 0}^{Z\mathrm{res:z}} = \dfrac{M_Z^2}{2m_{\nu_i}(1+z)}$

Moving target ν's → energy smearing





Compromises individual mass determination

First peak could determine mass hierarchy

C. Barenboim, O. Mena Requero, C. Quigg, Phys. Rev. D71 (2005)083002

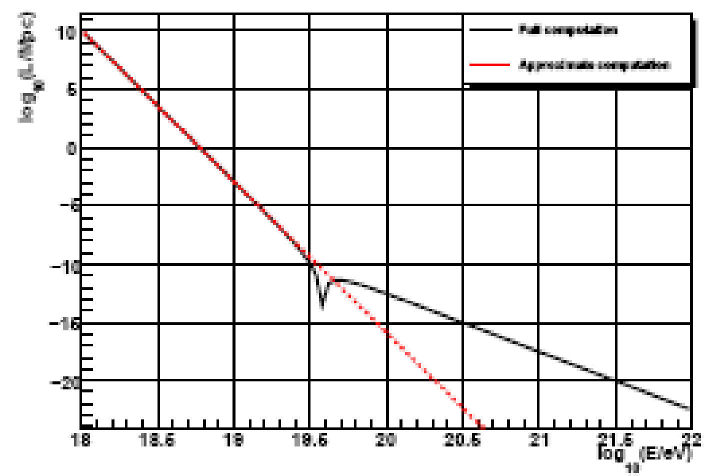
Basic symmetries and UHE neutrinos
Planck scale Lorentz invarianz violation

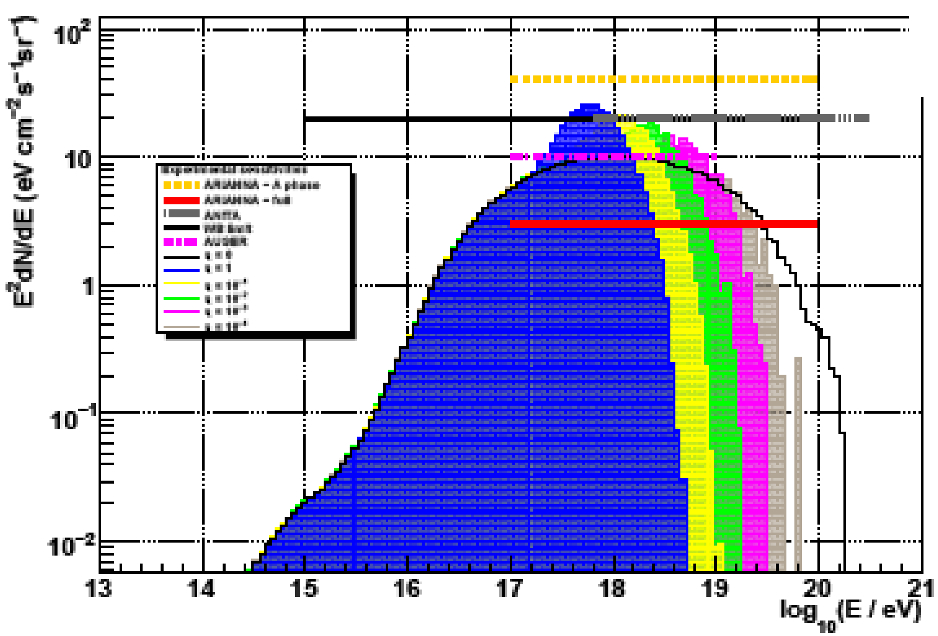
$$E_\nu^2 = p^2 + m_\nu^2 + \eta_{\nu I}\frac{p^4}{M_{\rm Pl}^2} ,$$

offers possibility for neutrino splitting:

$$\nu_A(p) \to \nu_A(p')\nu_B(q)\bar{\nu}_B(q'),$$

D. M. Mattingly et al., JCAP1002:007,2010





leads to cut-off of spectrum corresponding to η-scale parameter

$$\eta_\nu^{(4)} \lesssim \left(\frac{E_{\rm obs}}{6\times 10^{18}\ {\rm eV}}\right)^{-13/4}$$

and enhancement at lower energies

Necessary detector size ?

assume: (E ~10^{19} eV)

σ= 0.5 10^{-31} cm^2
Φ = 2π 10 km^{-2} y^{-1} !
N_{av} = 6 10^{23}/$mol_{(H2O)}$
ρ = 1g/cm^3
t = 1y

$N_{obs} = \sigma\, \Phi\, N_t\, t = \sigma\, \Phi\, N_{av}\, \rho\, V_{eff}\, t$

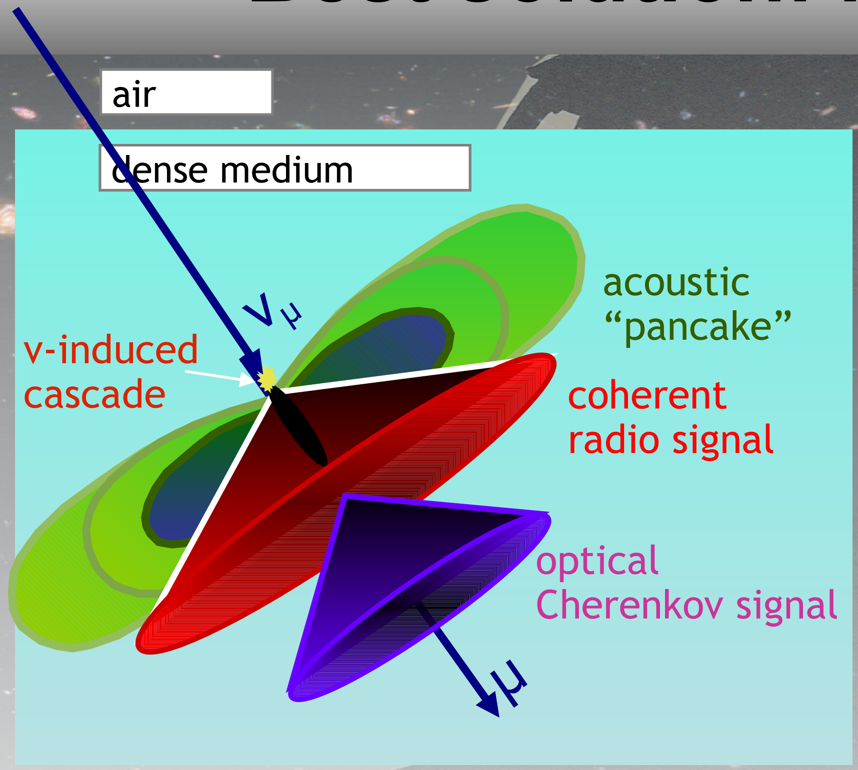
$V_{eff} = N_{obs} / \sigma\, \Phi\, N_{av}\, \rho\, t$

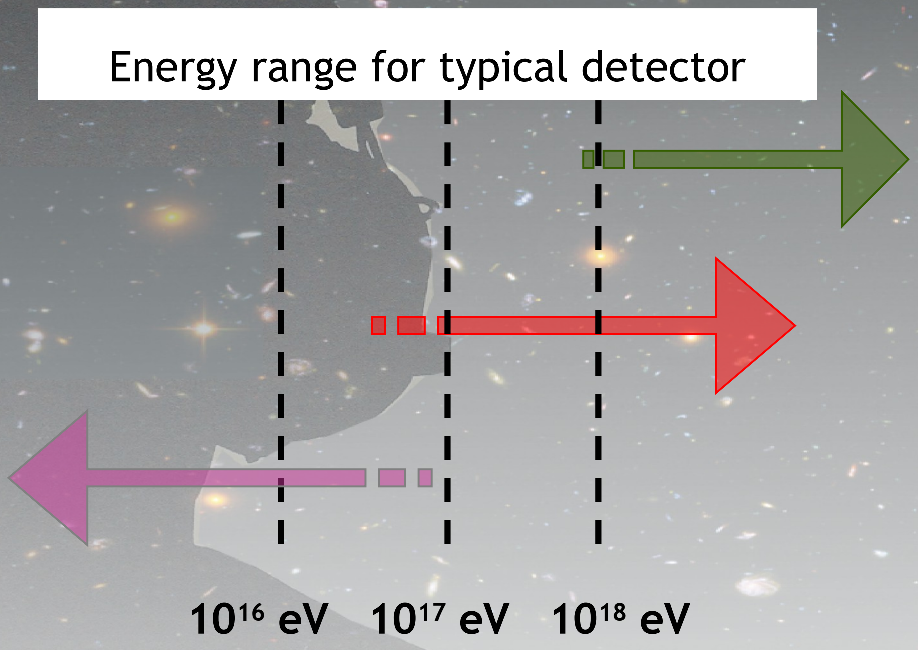
					number of strings		
					optical	acoustic	radio(?)
N_{obs}/1y	V_{eff}/km^3	D/km	A/km^2	L/km	N^{200}	N^{500}	N^{1000}
10	50	1	50	7.1	1296	225	64
100	500	1	500	22.3	12544	2025	529

D: Depth, A: horizontal area, L: side length
N^{xxx} : Number of strings necessary to fill a grid of xxx m grid constant

caution: these numbers are given without taking into account any detector effciency

Best solution: hybrid detector





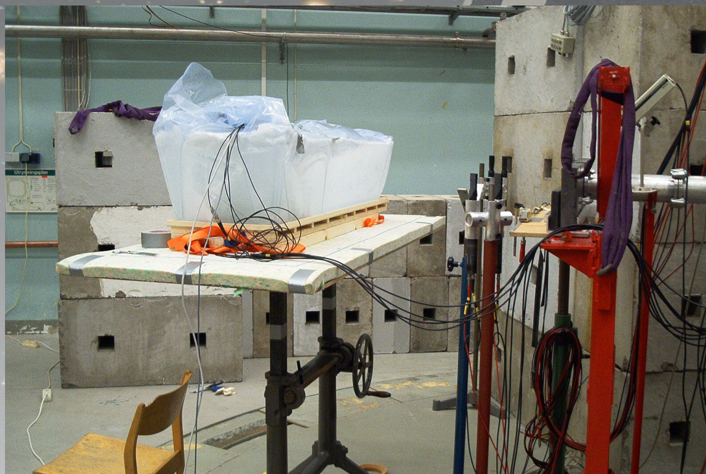
Multiple detection of same signal possible in several materials (best in ice)

- **Extend energy range of sensitivity and enlarge volume (bigger spacing?)**
- **Calibrate R with O and cross-calibrate A & R**
- **Improve energy and direction reconstruction**
- **More efficient background rejection**

Trust your signal !

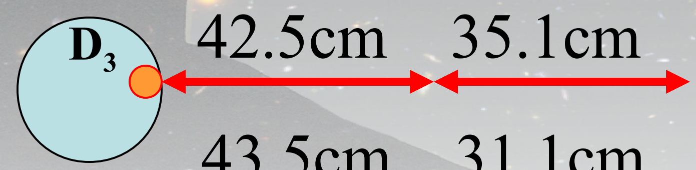
The End

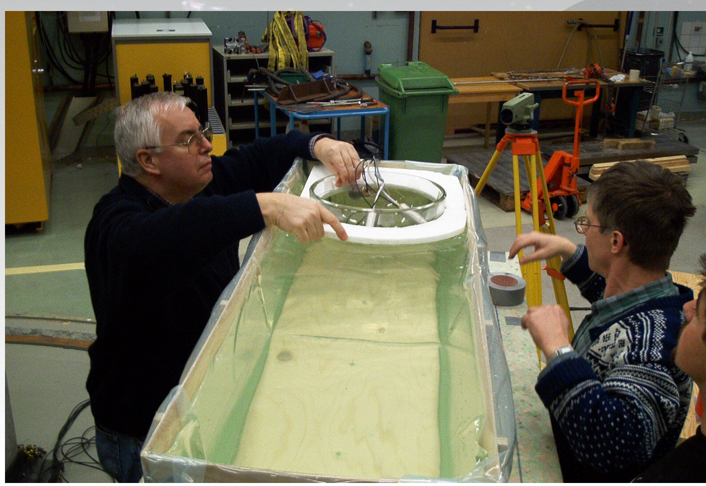
Target - Configurations



Ice

LxBxH = 130x40x27 cm^3



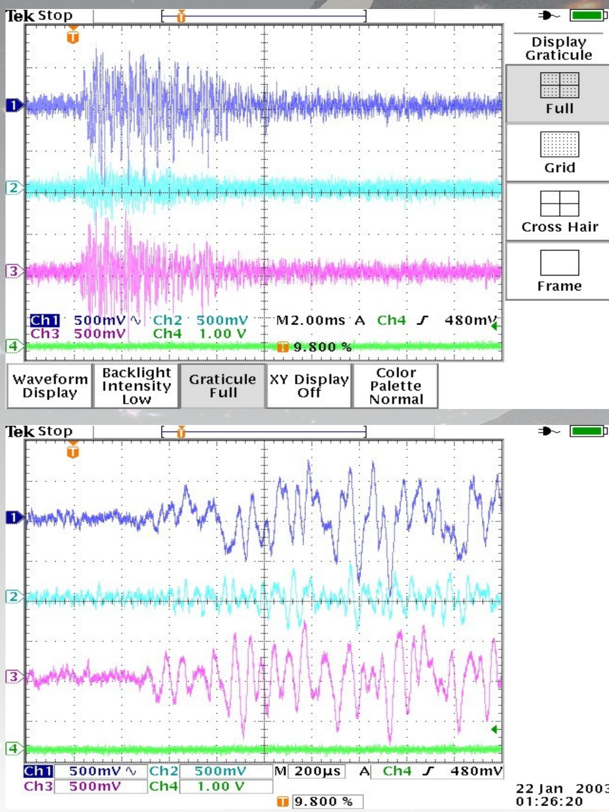


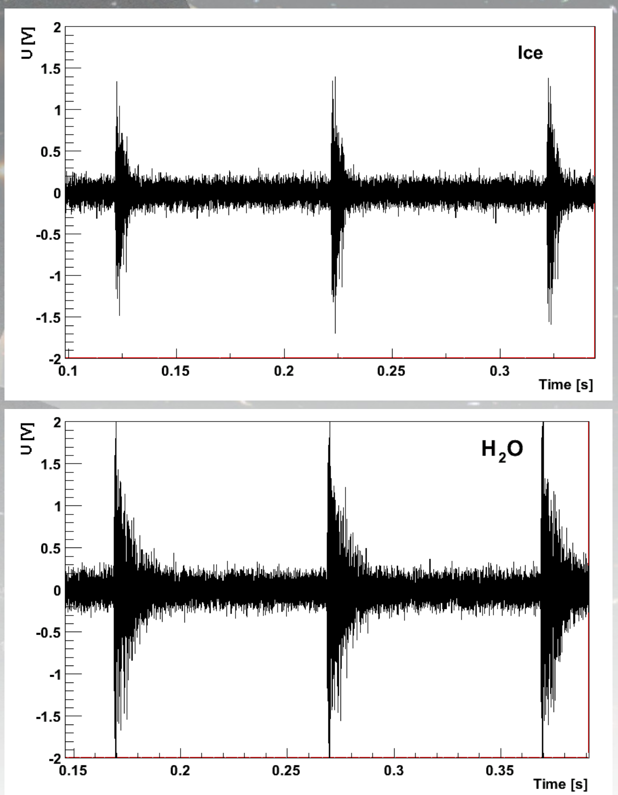
H_2O

LxBxH = 135x45x27 cm^3

Signal Shapes

ϕ = 2cm, E = 110 PeV R = 40cm






The End
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The End


Ultra Deep Space — NASA, Hubble