HE neutrino detection with acoustic and radio techniques: a state of the art summary

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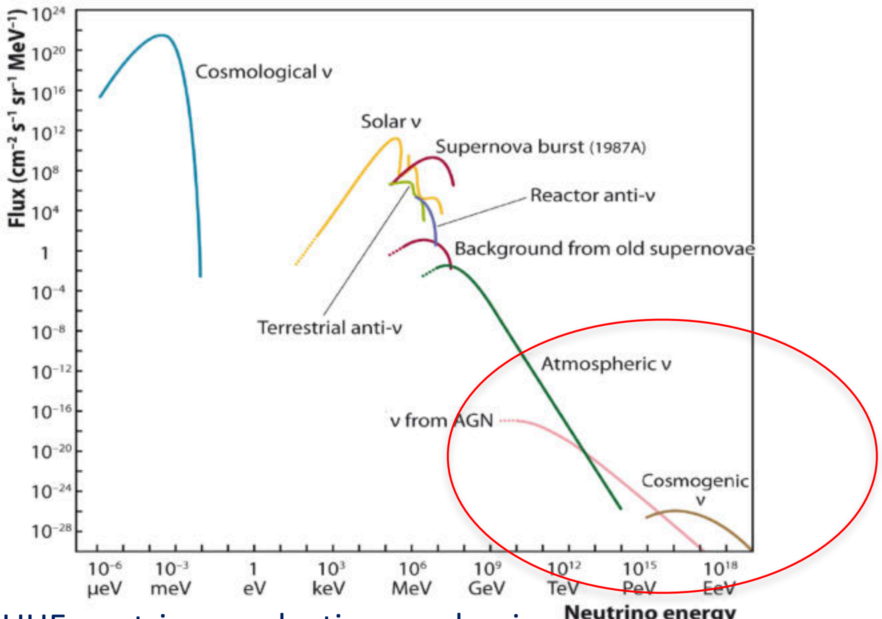
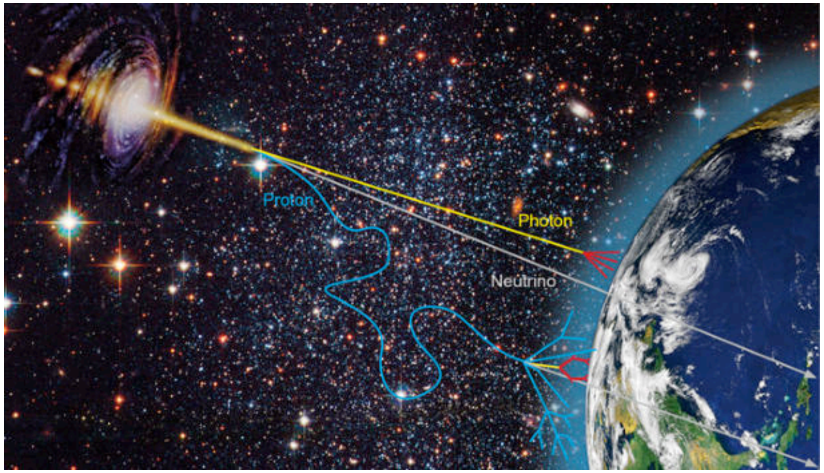
Overview

- The Physics Case
- Radio Detection
- Acoustic Detection
- Conclusions

Cosmic neutrinos: production



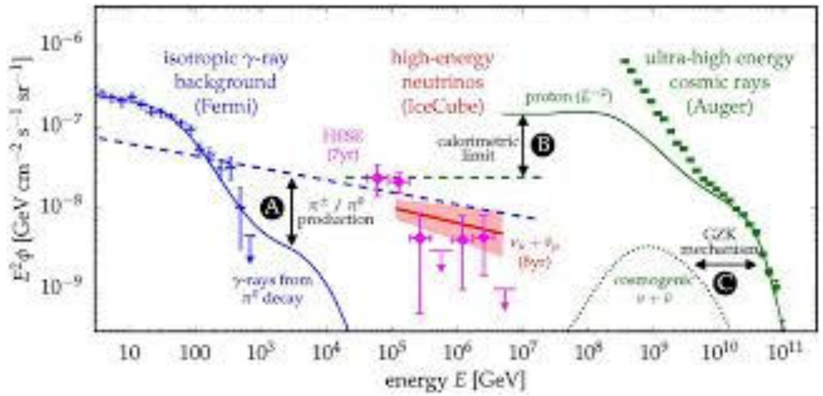


Sources: AGNs, SNR,…

UHE neutrino production mechanisms:

1) “Fermi” proton acceleration

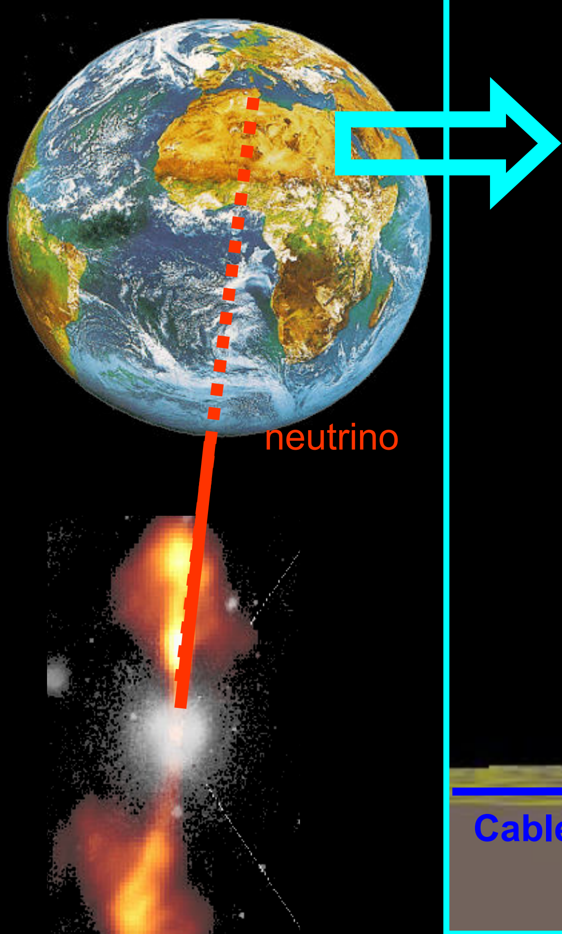
2) proton-proton, proton-gamma interaction in ambient source or during journey to Earth (BZ neutrinos)

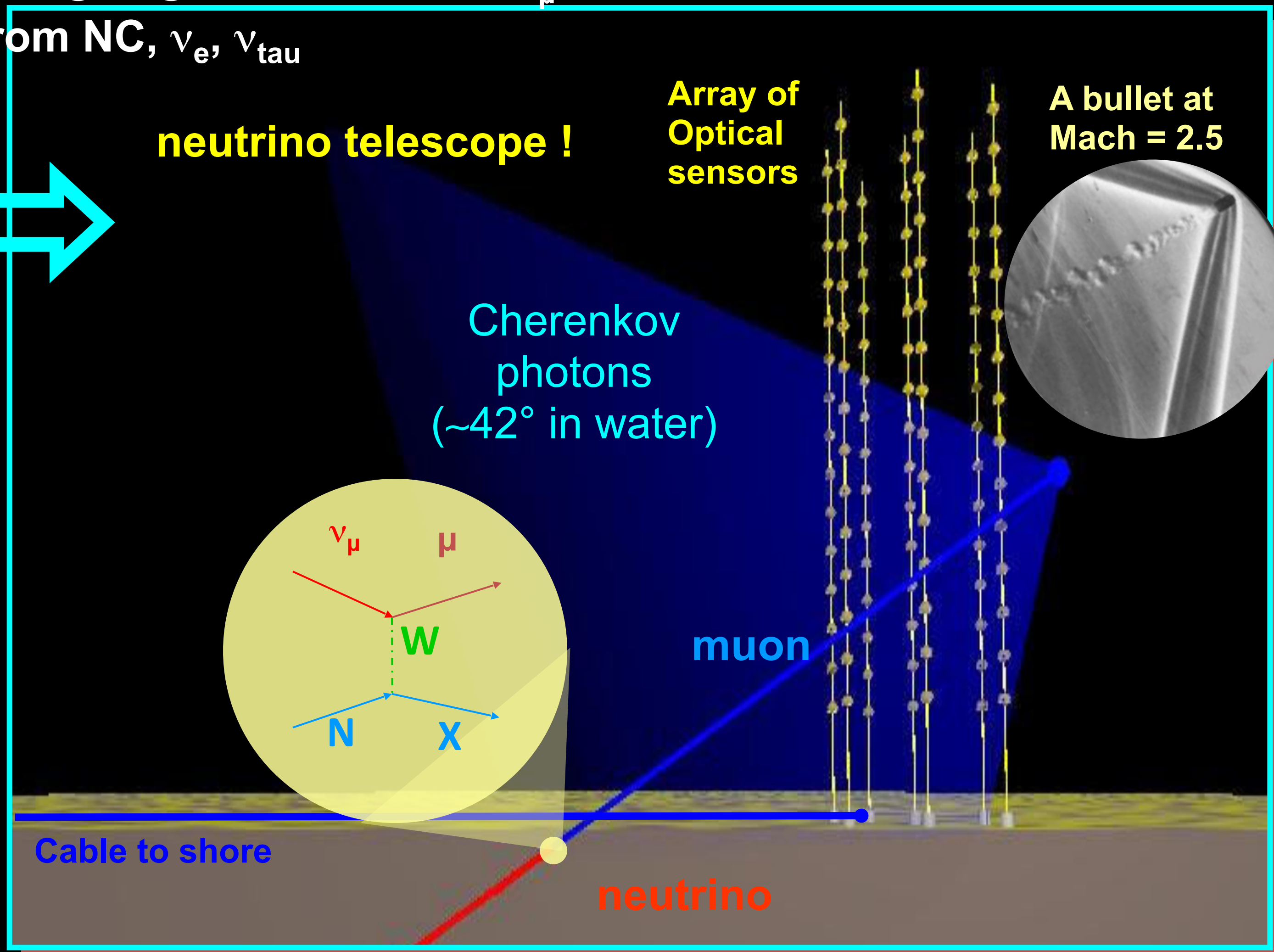


Detection

Golden channel: througoing muon from CC ν_μ interaction.

But also showers from NC, ν_e, ν_{tau}

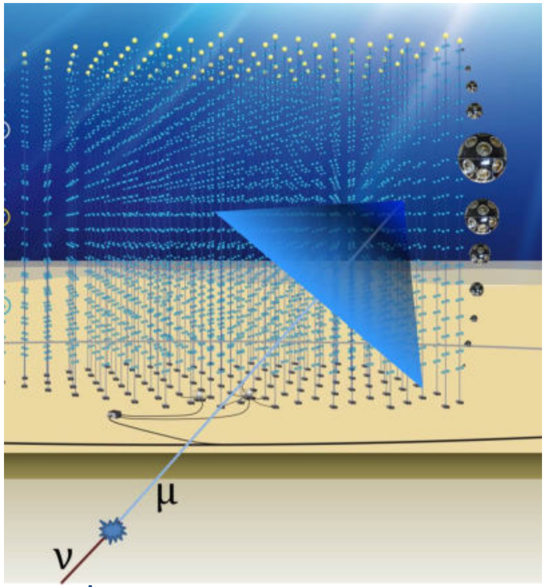




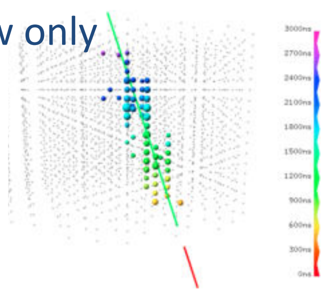
Look at upgoing muons: use the Earth as a filter

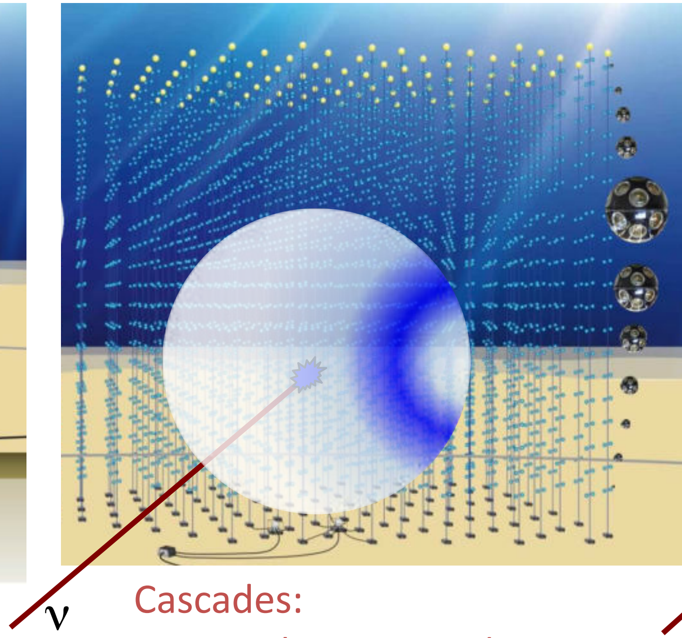
Only atmopheric and astrophysical neutrinos can cross the Earth

Detection

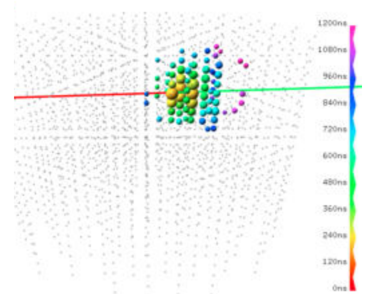


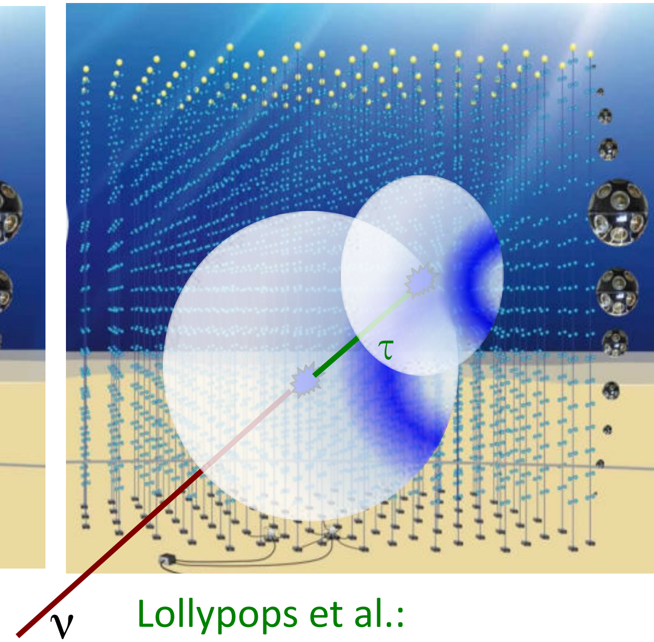
Tracks:
CC muons (and taus)
highest effective area, good angular resolution
High atmospheric muon background: look at events from below only



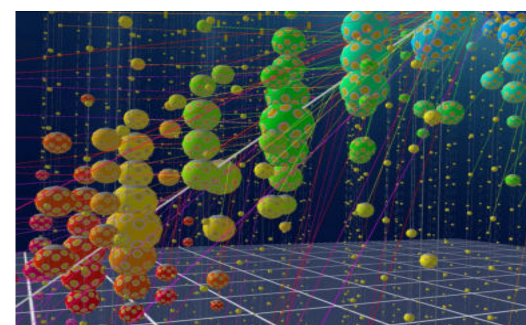


Cascades:
NC, CC electrons and taus
remove atmospheric muon background: studies over 4π.
'Good' energy resolution, worse directional resolution





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



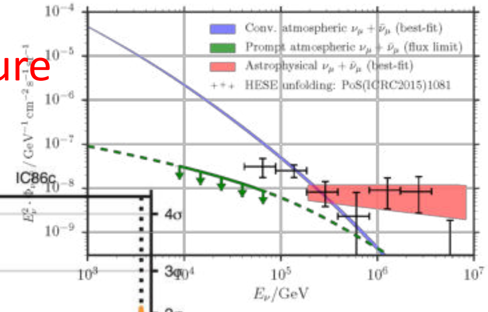
Optical Cherenkov neutrino telescopes

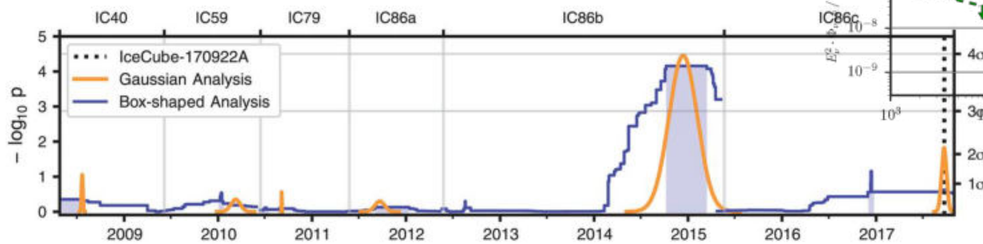
IceCube

no point sources (so far) BUT

1) extra-terrestiral neutrino flux signature

2) "multimessenger" time coincidence



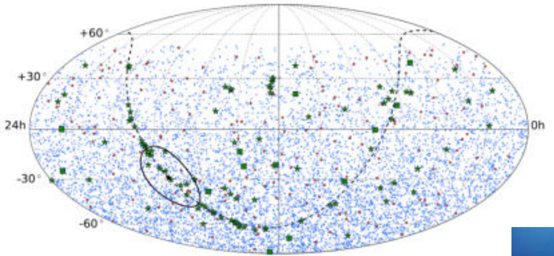


Use sea water, better angular resolution and expected improved sensitivity

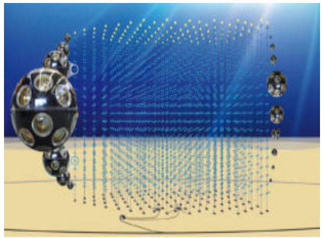
ANTARES (Med Sea)

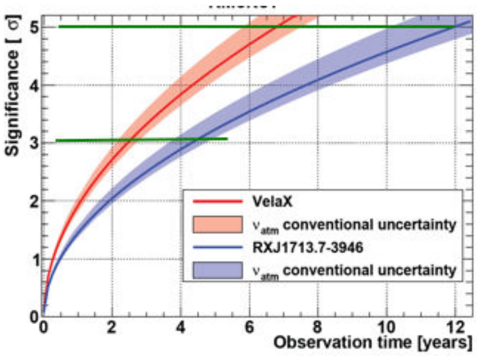
KM3NeT – ARCA (Med Sea)

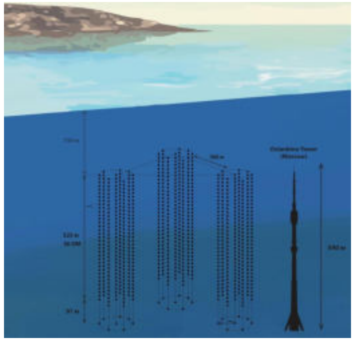
Baikal GVD



size limited





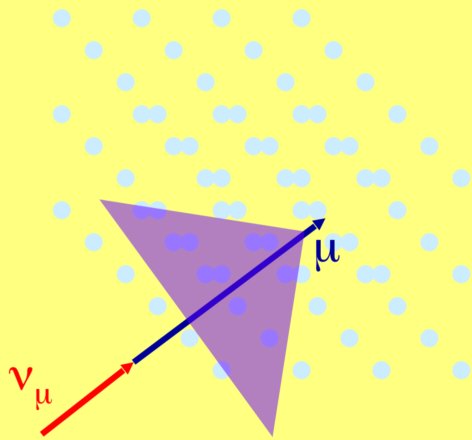


mainly UHE events

Cosmic neutrinos above PeV

1 TeV — 100 PeV — 1000 ZeV

Optical Detection (IceCube-KM3NeT)



Medium: Seawater, Polar Ice

ν_μ (throughgoing and contained)

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

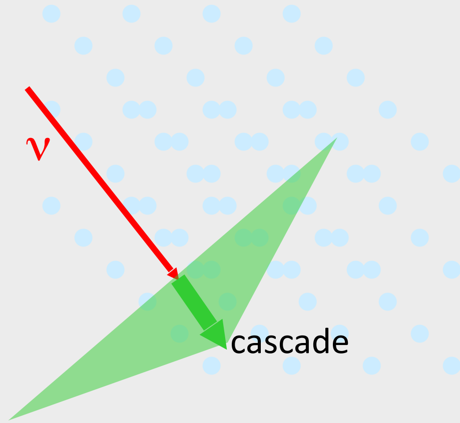
Carrier: Cherenkov Light (UV-visible)

Attenuation length: 100 m

Sensor: PMTs

Instrumented Volume: 1 km^3

Radio Detection (Anita, Arianna, Ara, …)



Medium: Polar ice, Salt domes

ν (cascades)

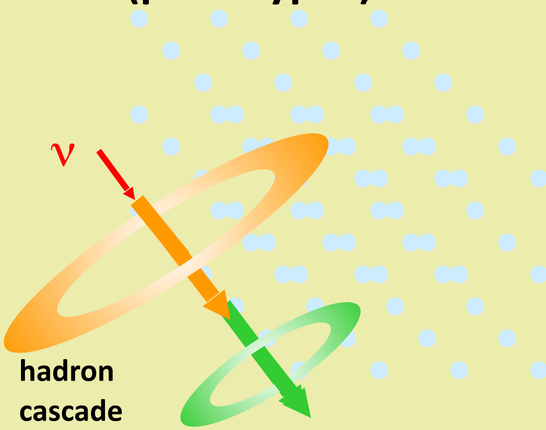
Carrier: Cherenkov Radio

Attenuation length: 1 km

Sensors: Antennas

Instrumented Volume: >1 km^3

Acoustic Detection (prototypes)



Medium: Seawater, Polar Ice

ν (cascades)

Carrier: Sound waves (tens kHz)

Attenuation length: few km

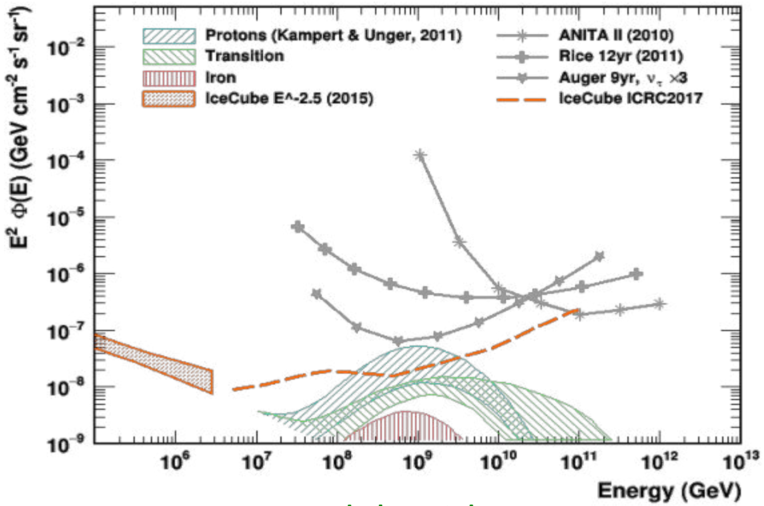
Hydro-phones

Instrumented Volume: >10 km^3

Cosmic neutrinos above PeV

IceCube:
Flux cutoff at very high energies ?

UHECR experiments (e.g. PAO):
Neutrino events/signatures not (yet?) identified



Pure proton models with a strong source evolution already constrained by IceCube and Fermi LAT measurement

CR at extreme energies:
Composition (Auger – TA)
if protons
interaction with CMBR → GZK →BZ ν (10^{18} eV)
if heavy nuclei
via interaction with CMBR → pion decay (10^{18} eV), beta decay of n, relic (10^{16} eV)

lower thresholds but also lower fluxes for interactions with the EBL

Super Heavy Dark matter decay scenario ? (10^{20} eV)

Cosmic neutrinos detection above PeV

Threshold (actual estimate) for large radio and acoustic arrays:

$E_\nu > 10^{17}$ eV (radio) $E_\nu > 10^{19}$ eV (acoustic)

Neutrino interaction with Earth: downgoing or horizontal neutrinos

Extremely low fluxes:

need large exposure → O(100)km^3 y

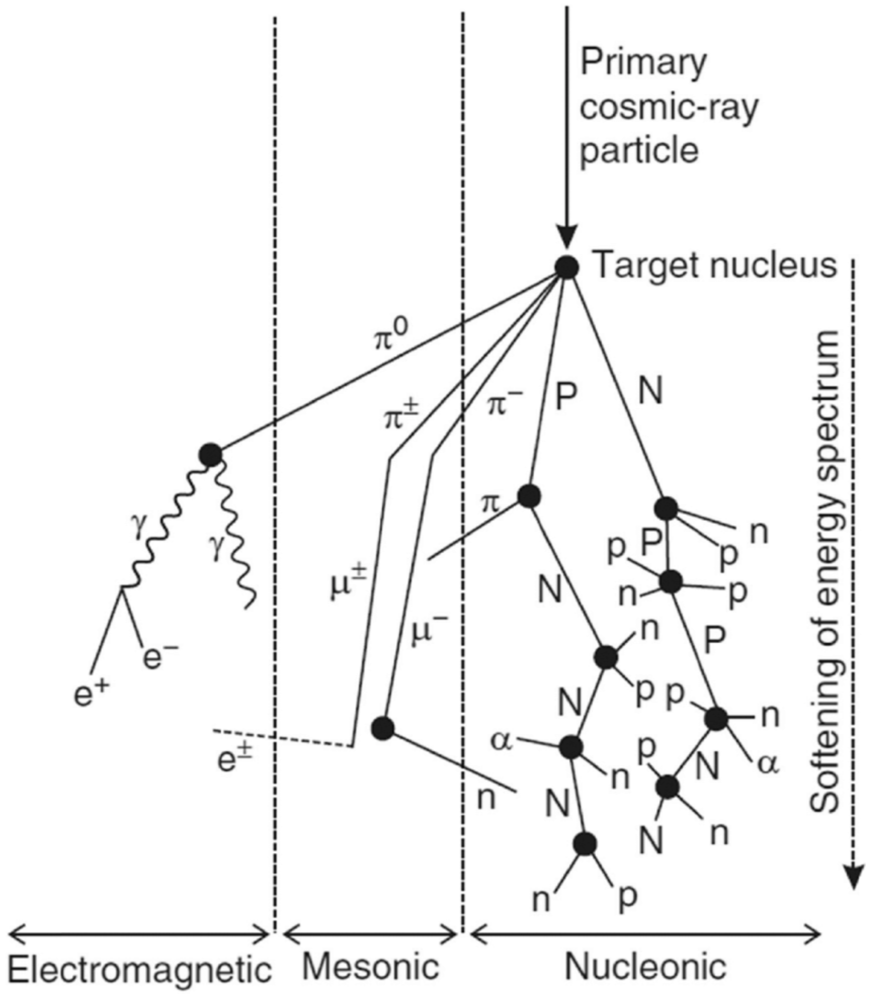
very sparse arrays → reduce cost per unit and installation cost

hybrid/complementary detectors → exploit/share infrastructure with “mature” experiments

Reduce detection threshold !

UHE Shower development

Originated by gammas, CR or neutrinos



Propagation in
- atmosphere
- ice
- water
- (salt)

induces characteristic radio and/or acoustic signatures that propagates for >km distance

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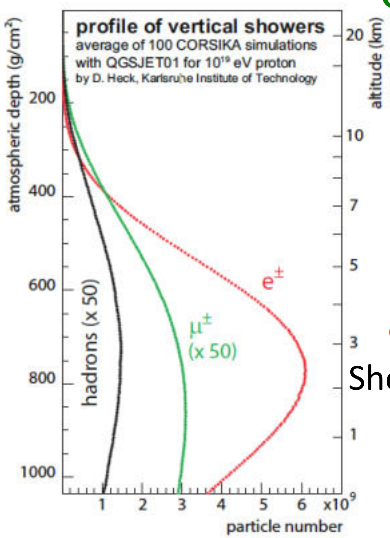
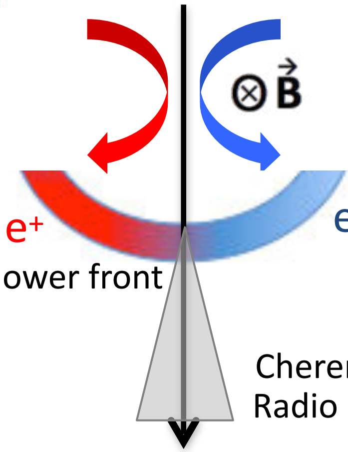
Choerent dipole radio emission



Geomagnetic radiation

Shower axis



Shower front

Cherenkov angle
Radio pulse

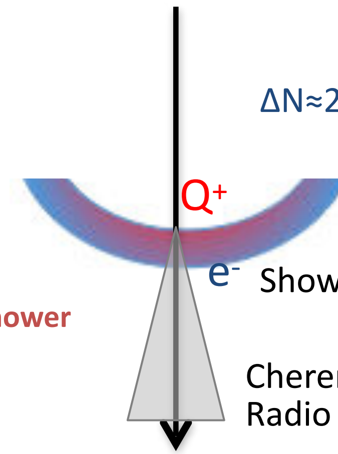
Dielectric medium

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

Askarian radiation

Shower axis

ΔN≈20% e- excess
Compton scattering
positron annihilation

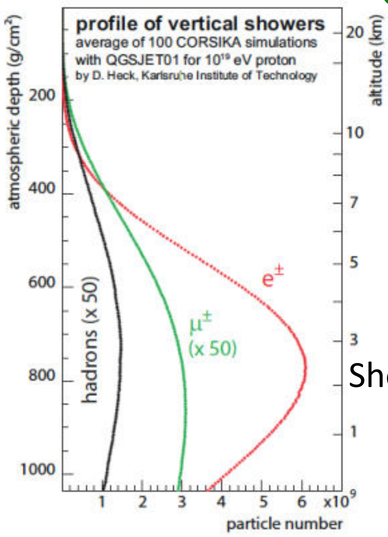


Shower front

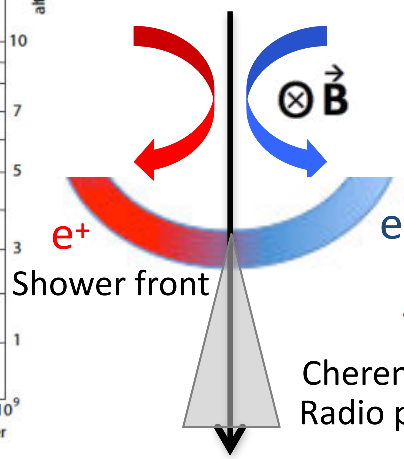
Cherenkov angle
Radio pulse

Other effects (under study): molecular bremsstrahlung, transition radiation (air/ice, ground/air)

Choerent dipole radio emission



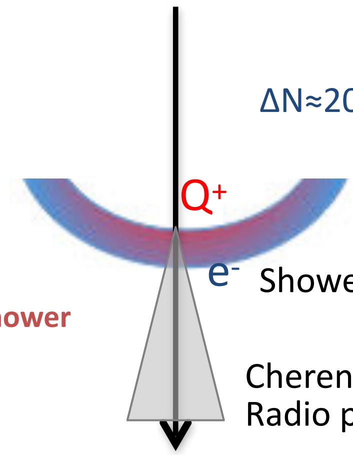
Geomagnetic radiation



Dielectric medium

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

Askarian radiation



Air

extended cascades, large shower front

$R_{Moliere}$ ≈O(100 m), R_{core}≈O(10 m) →f ≈10 MHz: 100 MHz

L ≈ O(km)

Cherenkov angle≈ 1°

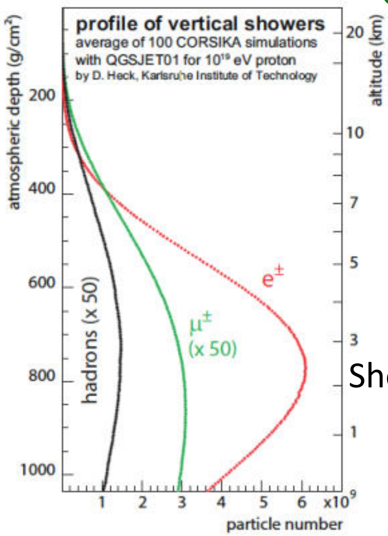
Geomagnetic effect dominates (≈80%)

large B → intense radio emission

Linear polarisation (direction of F_{Lorenz})

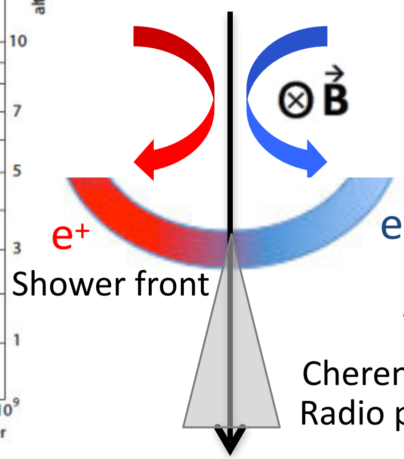
Radio absorption negligible

Choerent dipole radio emission



Geomagnetic radiation

Shower axis



Dielectric medium

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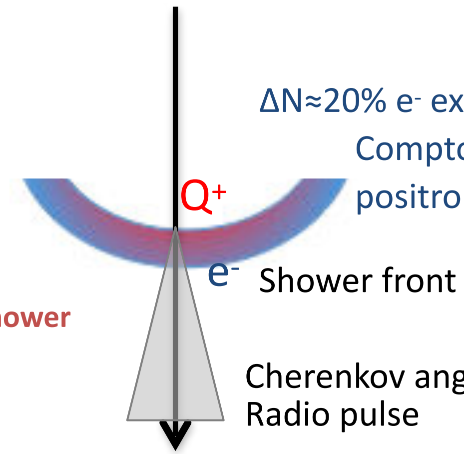
Askarian radiation

Shower axis



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

Askaryan effect dominates
Radial polarisation (towards shower axis)

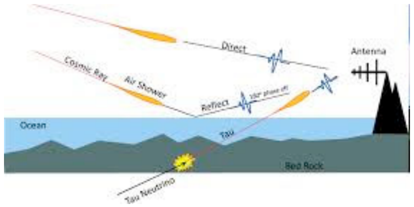
Radio absorption O(1 km in ice)

Neutrino detection with radio arrays

Ground-based air shower detectors

AERA@PAO, Lofar, GRAND, Taroge*

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

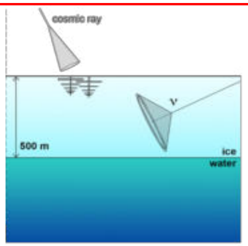


O(>10^3 km^2) instrumented, Observed volume 10^3 km^3, $E^{th} \approx 10^{16:17}$ eV

Ice surface-based detectors

ARIANNA, GNO

Direct and reflected signal (ν)

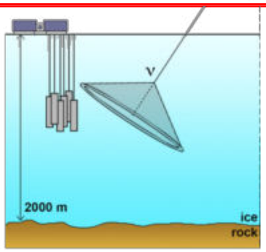


O(>10^2 km^2) instrumented, Observed volume 10^2 km^3, $E^{th} \approx 10^{16:17}$ eV

In ice detectors

ARA (RICE)

Direct and reflected signal (ν)

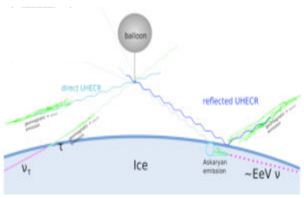


O(>10^2 km^3) instrumented volumes, Observed volume 10^2 km^3, $E^{th} \approx 10^{17}$ eV

Balloon and Satellites detectors

Anita, Forte, EVA

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



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

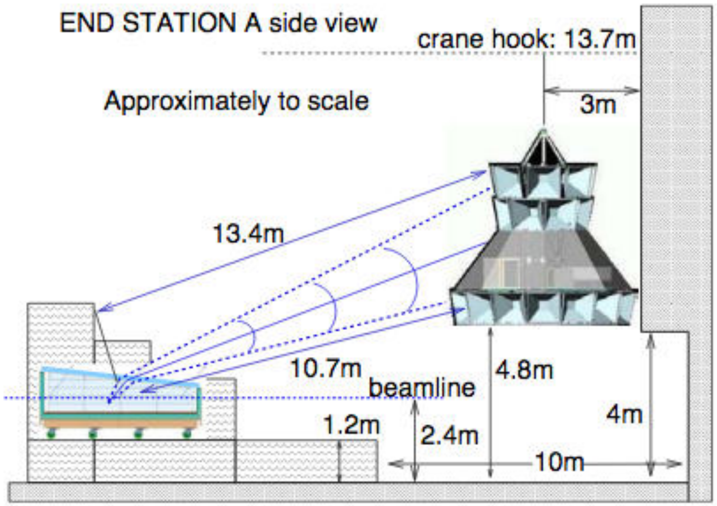
Ground-based lunar observatories

GLUE, NuMoon, SKA,LOFAR

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

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

The SLAC experiment (2001,2004,2006)

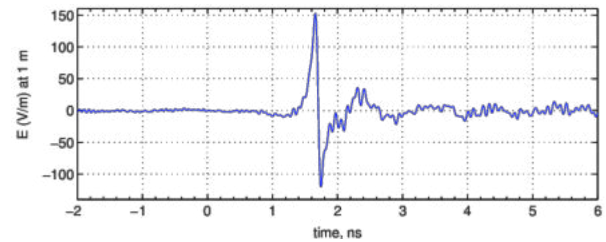


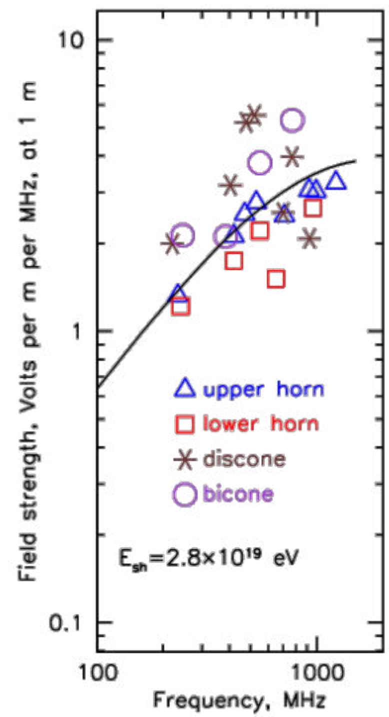
28.5 GeV x 10^9 particles/shower ($4x10^6$ e^- excess)

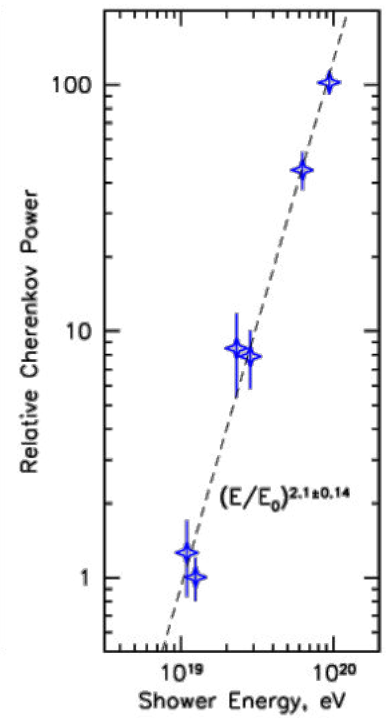
10 ps bunch. Coherent ($P \propto E^2$) radio emission

Production and detection of Askaryan radiation in salt and ice.

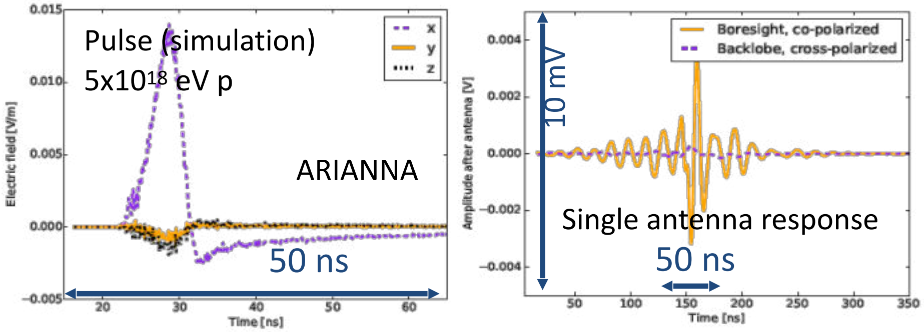
Testbed for ANITA







Detection and simulation chain



Simulation (Coreas,ZHS,…)
- CR interaction
- Maxwell Equations, Coherence

Propagation in medium (n vs depth)

Antenna+amplifier+digitizer response

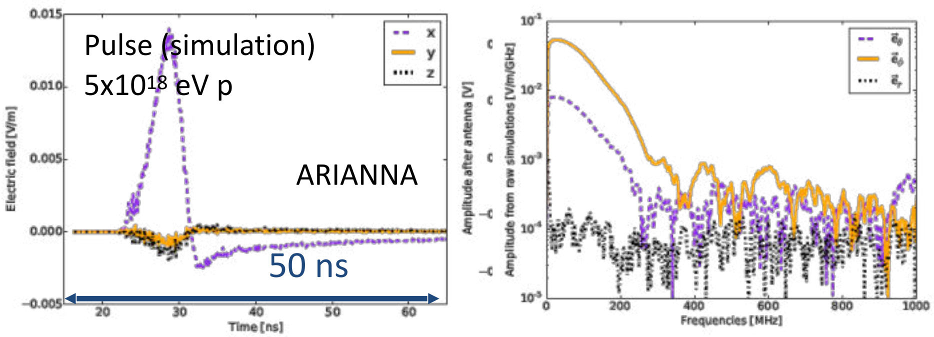
Antenna Thermal noise

Correlation, beam forming, trigger
- Digitally phased arrays

Background cuts:
- Galactic radiation
- Anthropogenic noise
- Air showers (calibration, training)

Track and energy reconstruction

Detection and simulation chain



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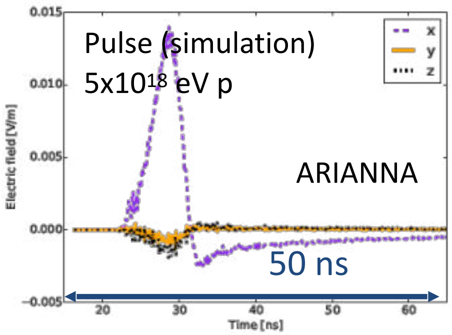

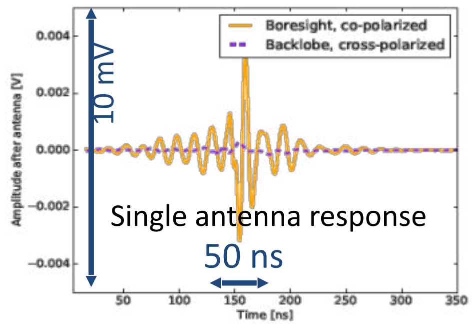

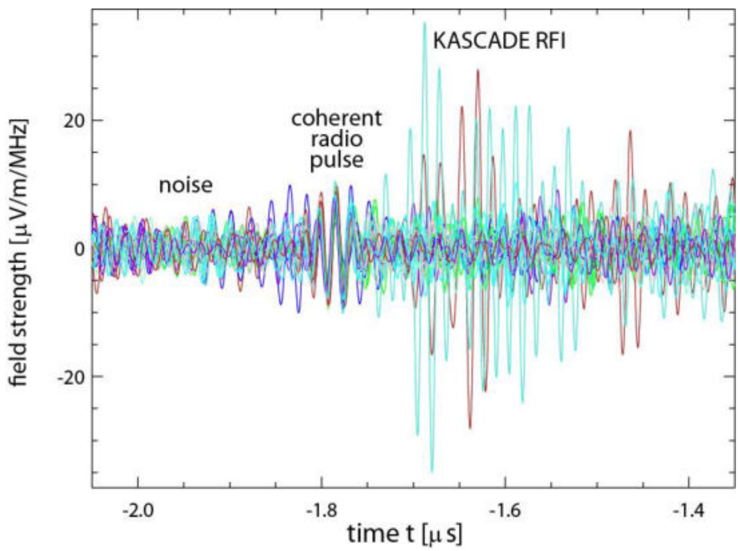

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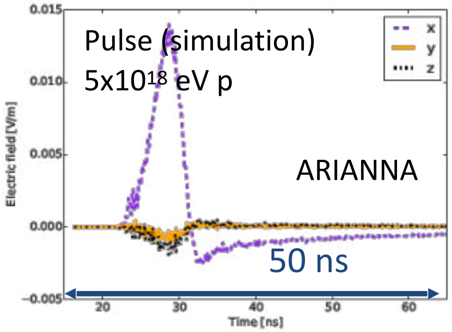

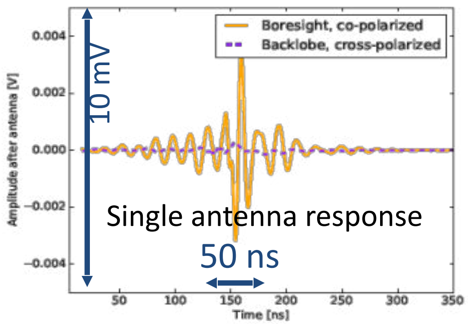

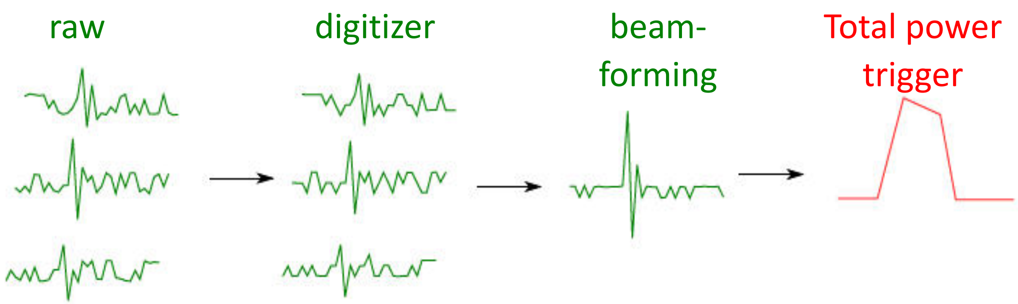

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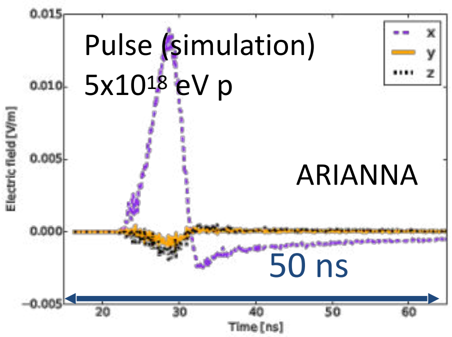

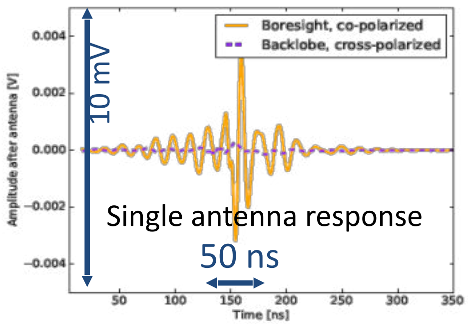

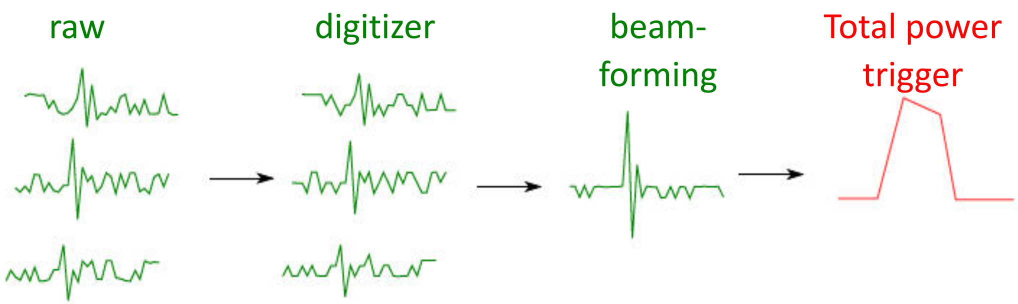

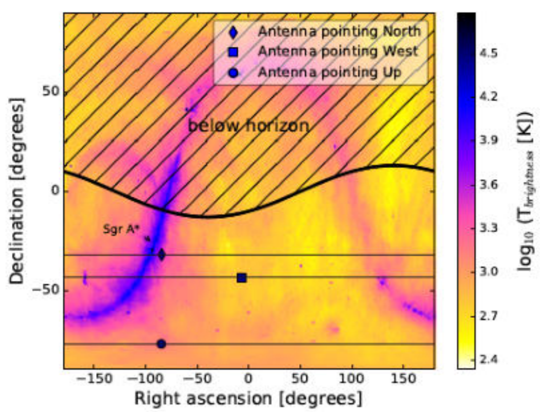

ARIANNA

Simulation (Coreas,ZHS,…)

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Galactic radiation

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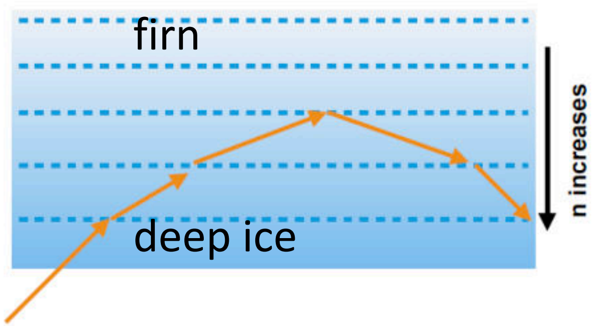
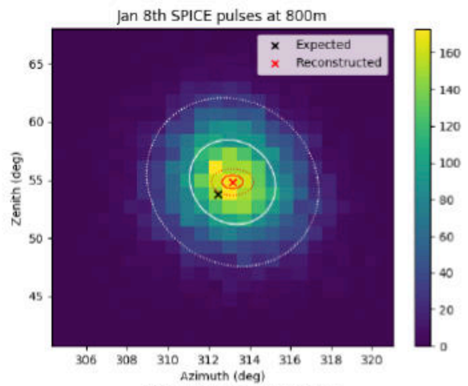
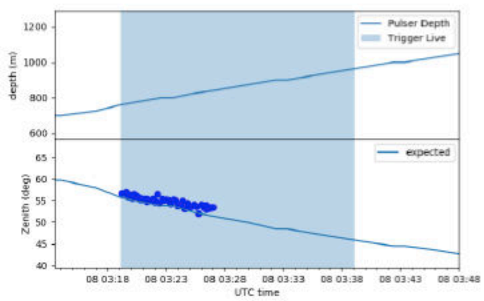
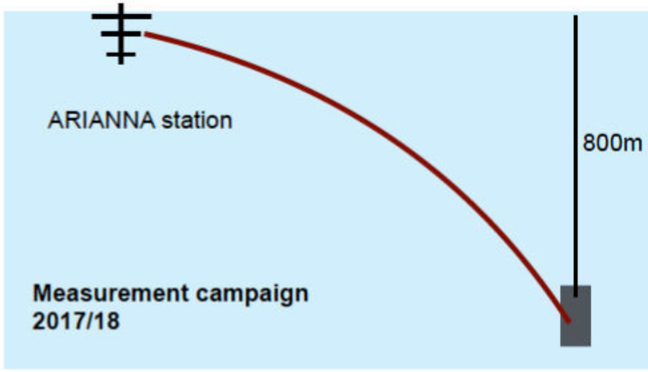
Track and energy reconstruction

Ray Tracing!

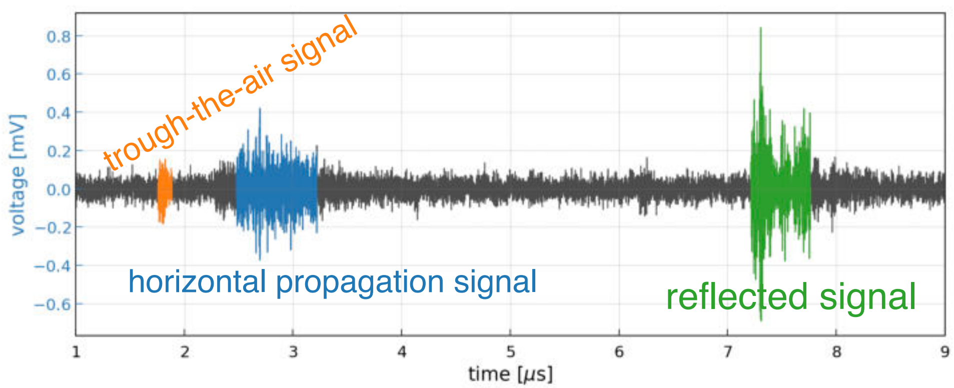








- Excellent angular reconstruction of pulse in deep ice, with the assumption of bend rays



Anna Nelles

ANITA

NASA Long Duration Balloon ≈30 days flight above Antarctica

4 flights from 2006

- horn antennas, 200-1200 MHz: 32 (ANITA I) → 48 (ANITA IV)
- 8 M events (ANITA I) → 100 M events (ANITA IV)

In-flight calibration from ground

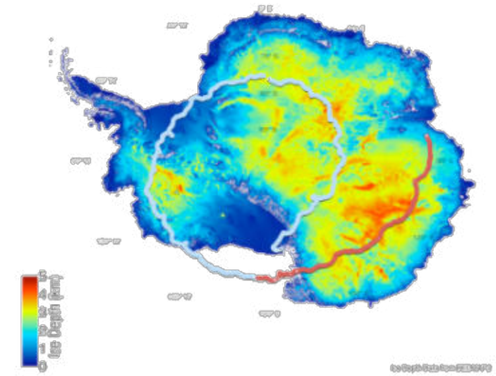
Threshold limited by thermal noise

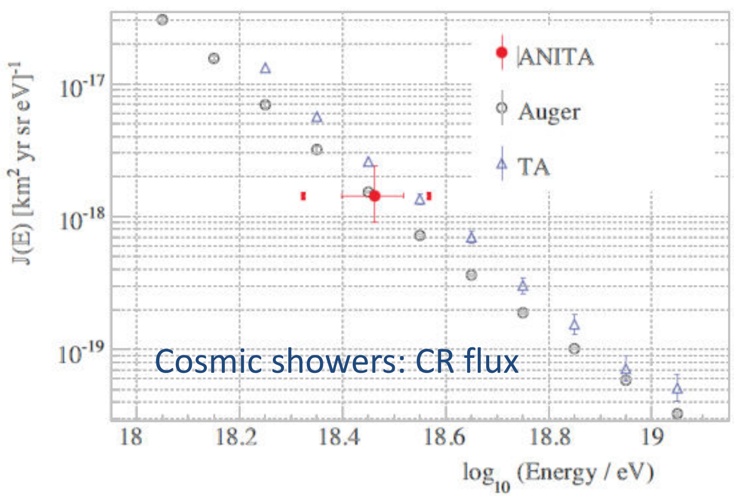
Cosmic Ray showers (reflected)

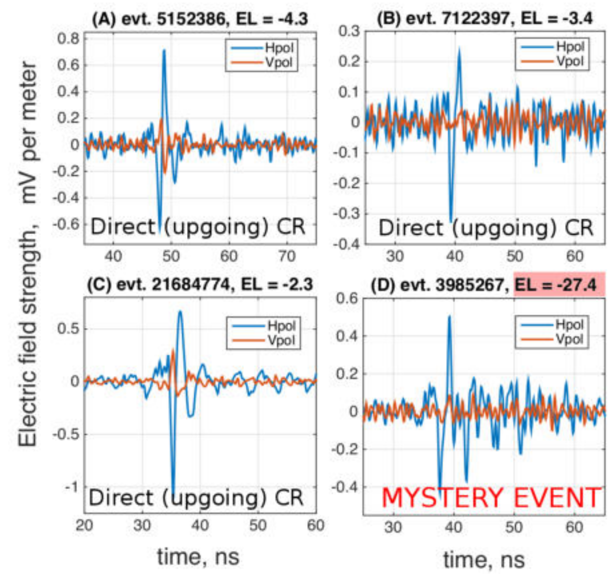
phase inversion, H-polairisation

ice-skimming neutrinos:

V-Polarisation due to geometry of emission cone







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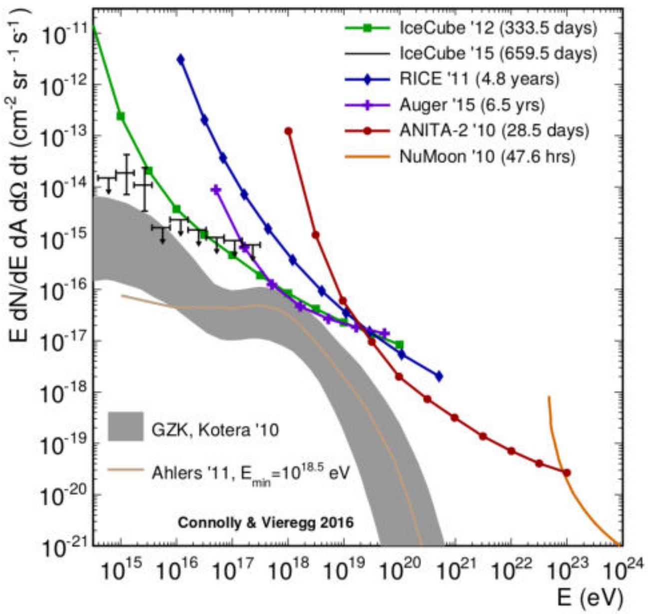


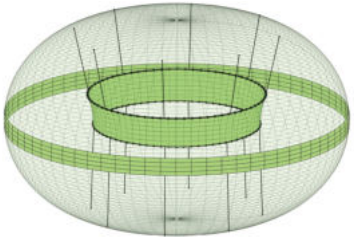
1 candidate event in ANITA 1

1 candidate event in ANITA 2

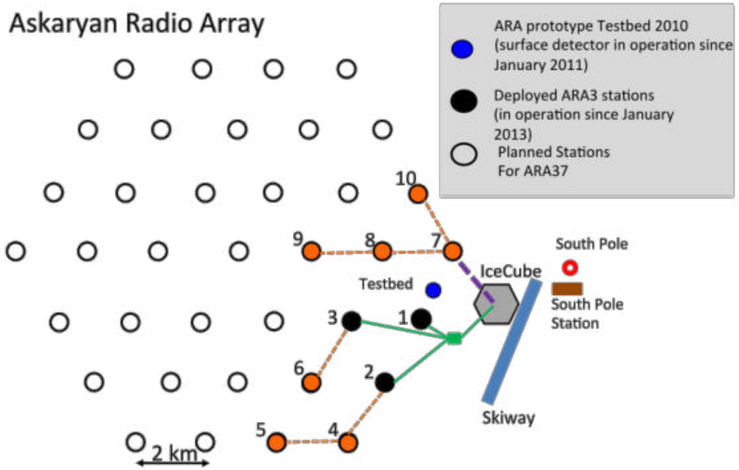
Consistent with background

EVA - Full Balloon

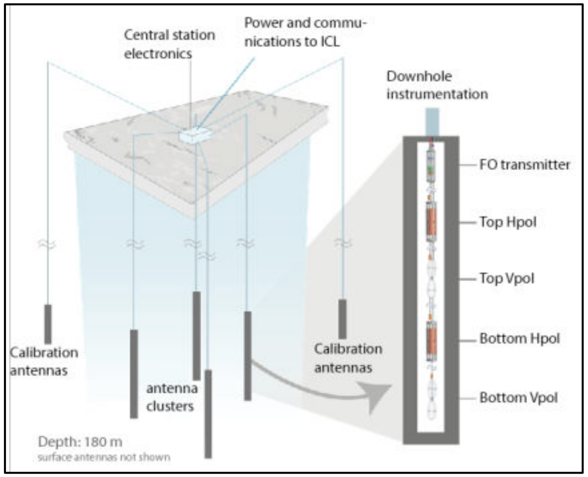
similar sensitivity to 3-year of ground-based array



ARA

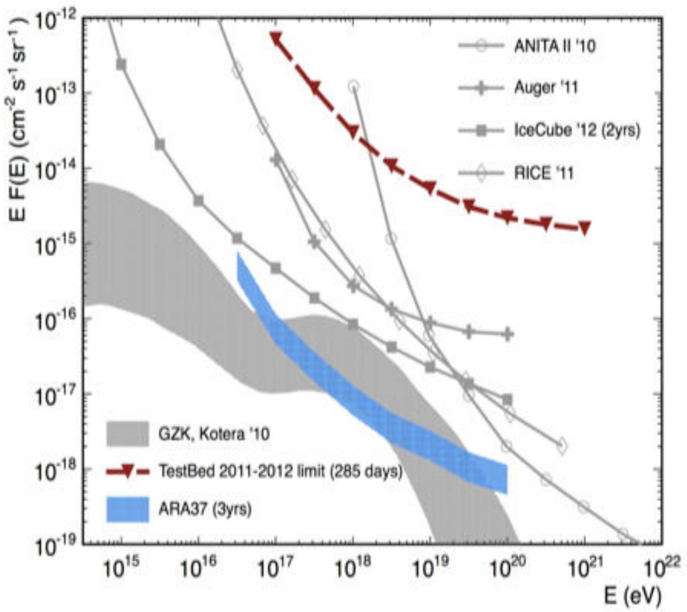


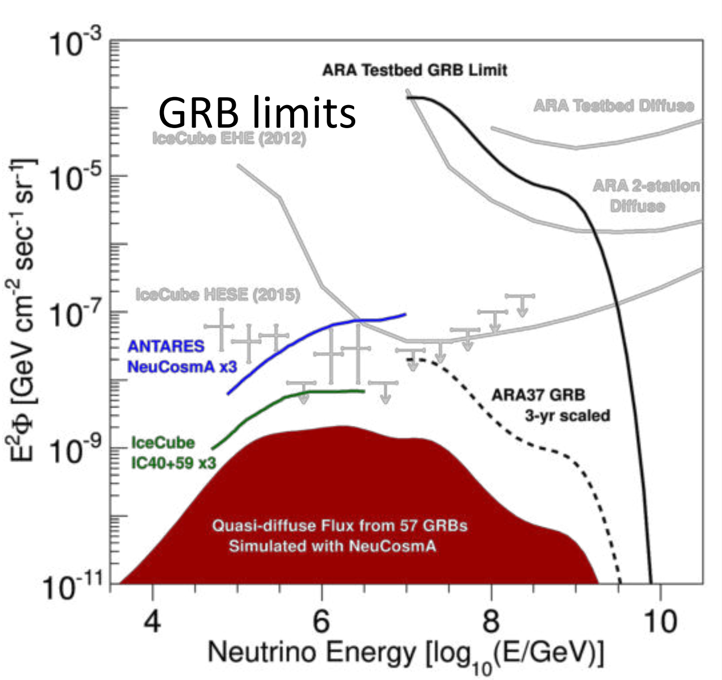
37 stations. Now 3 stations + testbed



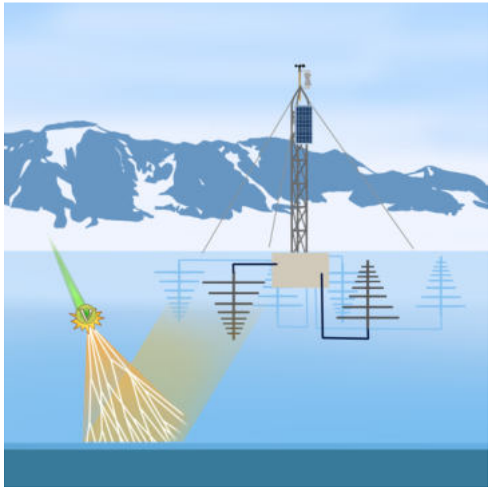
Station:
2 V-pol and 2 H-pol antennas in a 200 m buried string

RF signal transport via fiber-optic





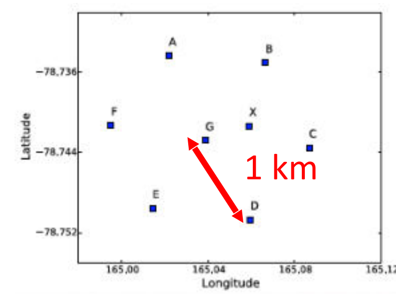
ARIANNA



1000 antennas (LPDA High Gain 50-1000 Hz, low power)

HRA 7 stations

Now 12 stations



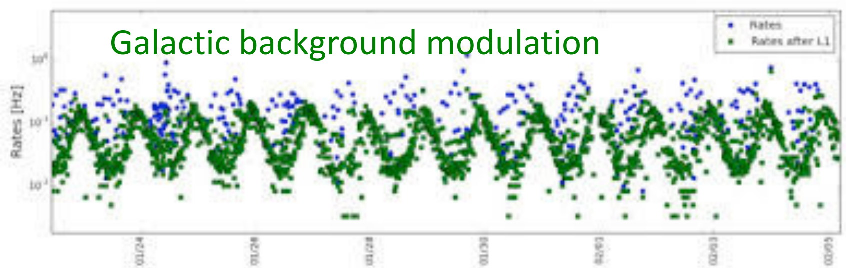
Wide bandwidth measurement

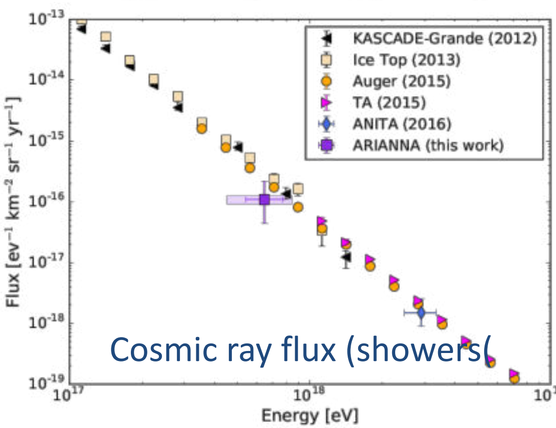
→ better energy reconstruction

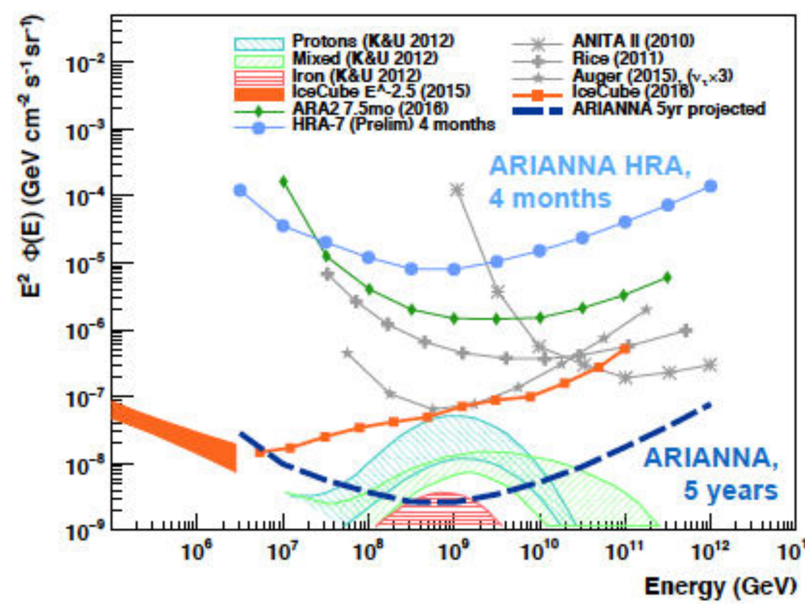
Radio-quiet environment

Now only austral summer, wind powered ?

Data transmission bandwidth limited

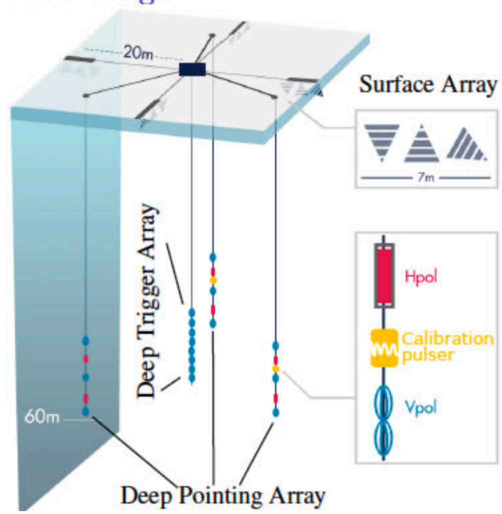




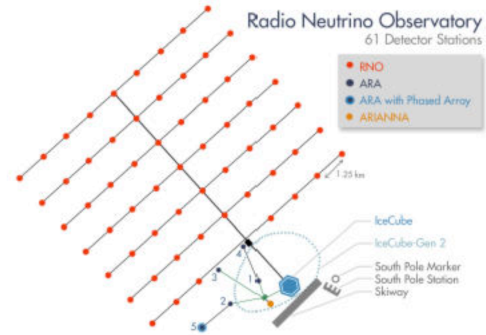


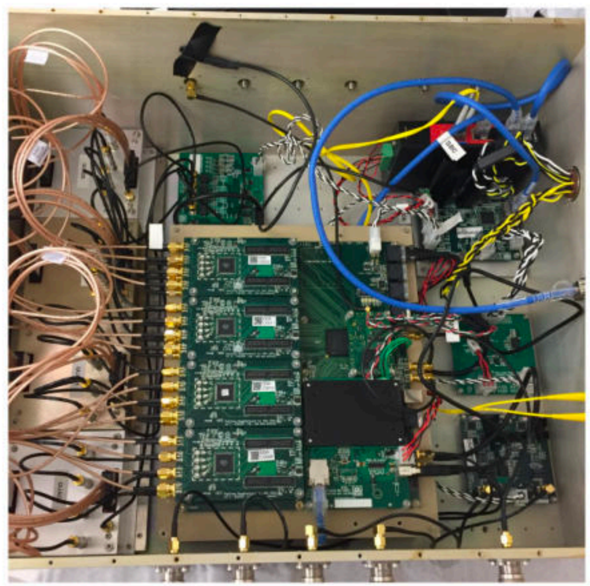
Radio Neutrino Observatory

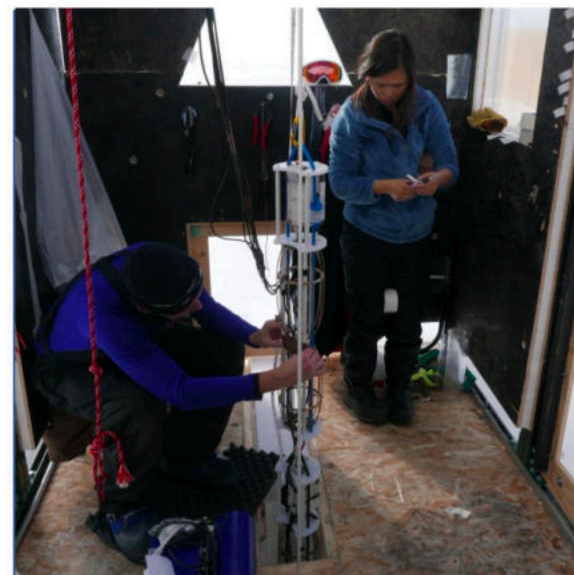
RNO design



61 Stations, each with a surface (LPDA) and deep (VPol bicone + HPol slot) component, combining elements of both ARA and ARIANNA stations.



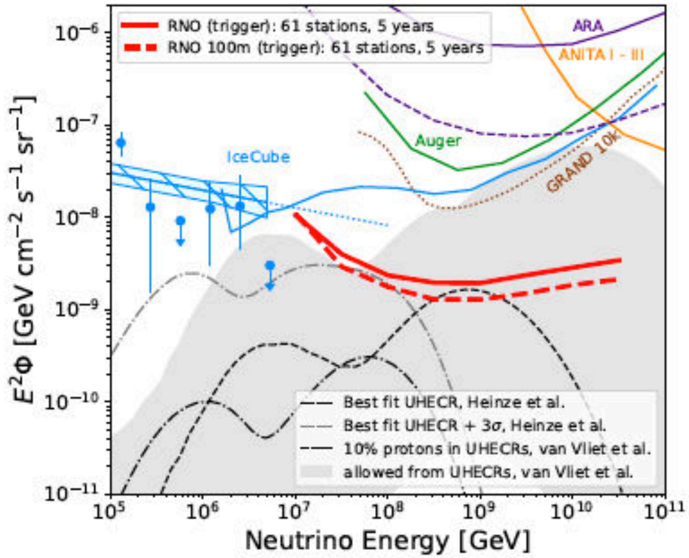




Cosmin Deaconu (UChicago/KICP)

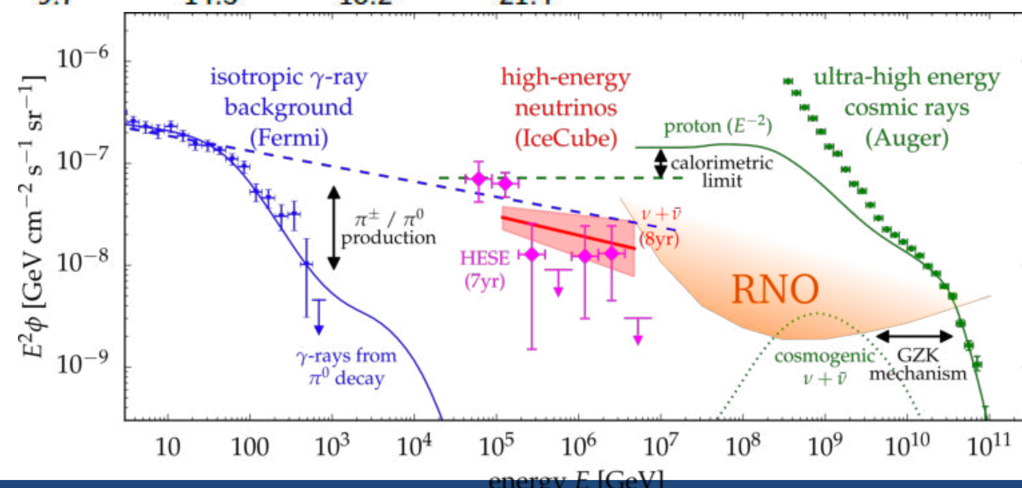
Radio Neutrino Observatory

RNO projected sensitivity



- Trigger-level sensitivity shown. With ample reco antennas, expect analysis level to be close.
- Backgrounds expected to be low ($<$ 0.01 / station / year).
  - Thermal fluctuations negligible (no correlation between trigger and pointing arrays)
  - RFI will reconstruct to surface; can be cut with small sensitivity loss
  - Any background from cosmic ray signals entering ice likely vetoable by surface antennas

Cutoff Energy on IceCube Flux	10^8 GeV	$10^{8.5}$ GeV	10^9 GeV	$10^{9.5}$ GeV	10^{10} GeV
Expected Number of Neutrinos	5.1	9.7	14.3	18.2	21.4



Cosmin Deaconu (UChicago/KICP)

Overview

- The Physics Case
- Radio Detection
- Acoustic Detection (R&D)
- Conclusions

Acoustic detection of HE neutrinos

Hadronic shower formation at interaction vertex

(if ν_e also an e.m. shower)

Hadronic shower carries≈ ¼ E_ν

Shower Development (LPM must be taken into account)

Sudden deposition of heat through ionization (10^{-8} sec)

Thermo-acoustic process dominant (10^{-5} sec):

Increase of temperature (C_p), Volume Expansion (β)

Bipolar pulses

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

$$p_{max} \approx 6\cdot 10^{-21}\left[\frac{Pa}{eV}\right]\cdot E_\nu$$

site dependent parameters

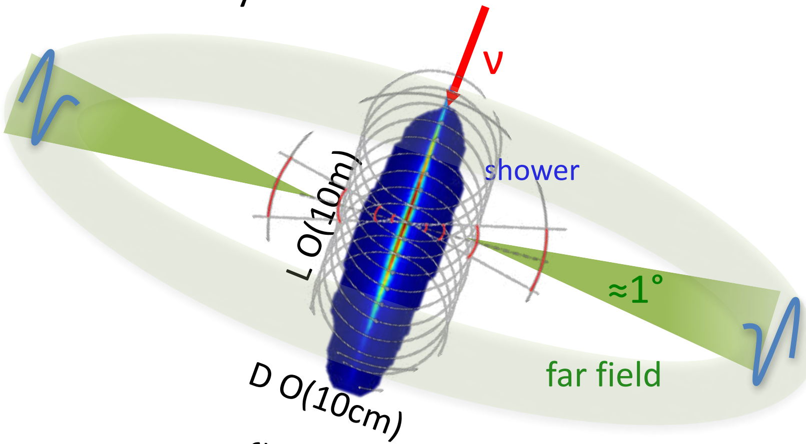
"Pen shaped" energy deposition region (20 m depth, 10 cm diameter)

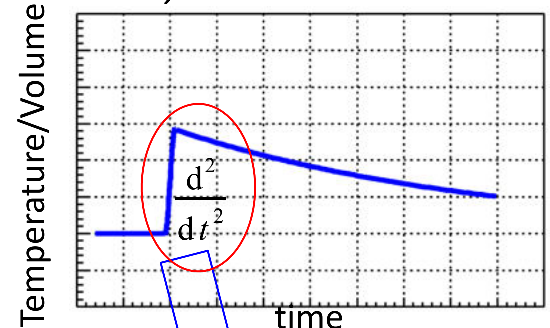
Coherence:

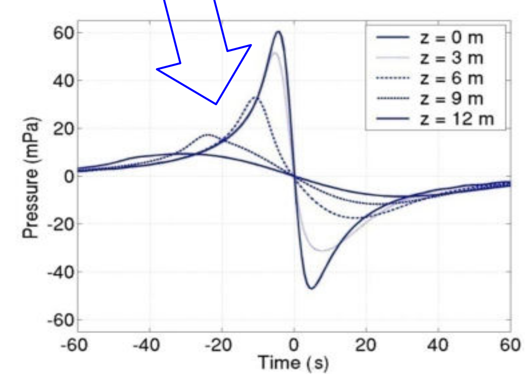
$f \approx c_s/d \approx O(10\ kHz)$

"pancake" waveform (≈1° aperture) $p(r) \propto 1/r$

Askaryan 1957







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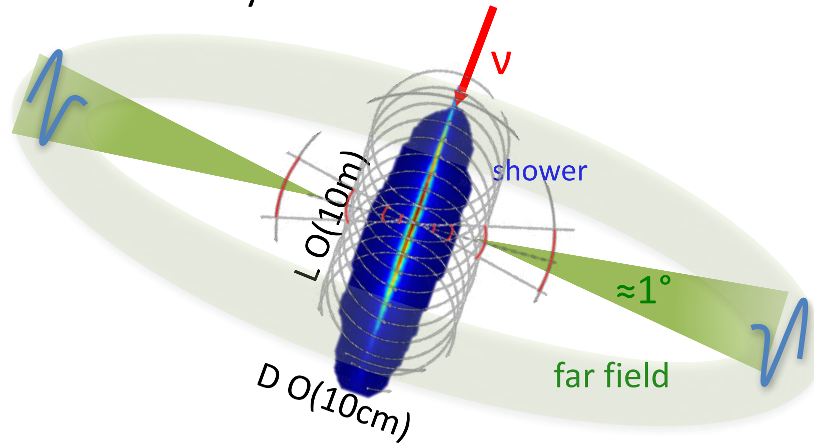

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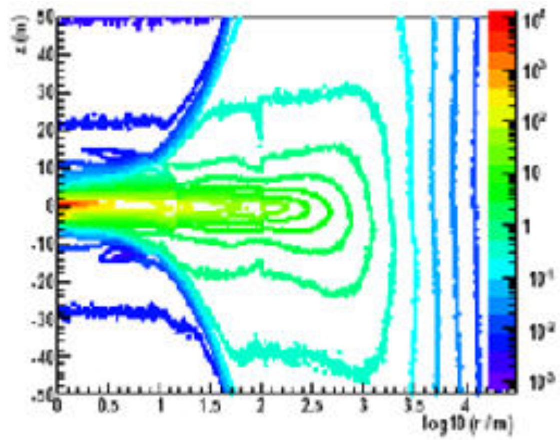

Propagation in seawater

Acoustic detection of HE neutrinos

Hadronic shower formation at interaction vertex
(if ν_e also an e.m. shower)

Hadronic shower carries≈ ¼ E_ν

Shower Development (LPM must be taken into account)

Sudden deposition of heat through ionization (10^{-8} sec)

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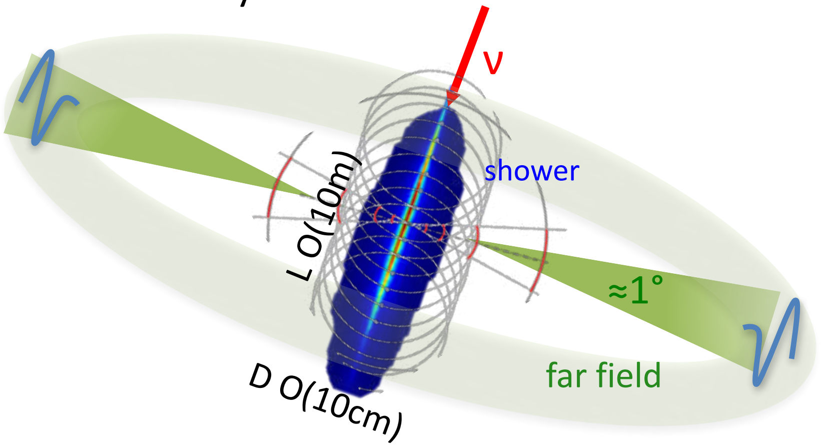
Bipolar pulses



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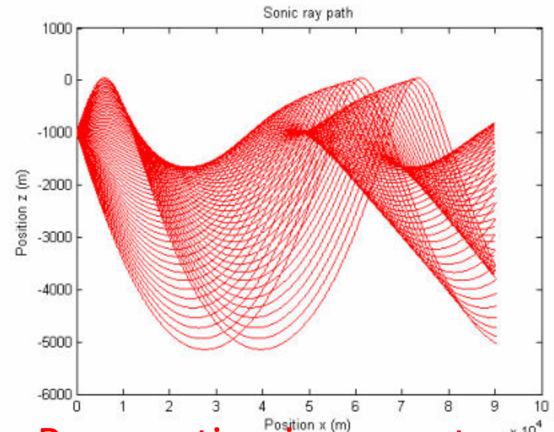


Propagation in seawater

Proton beam experiments

History: BNL 1979

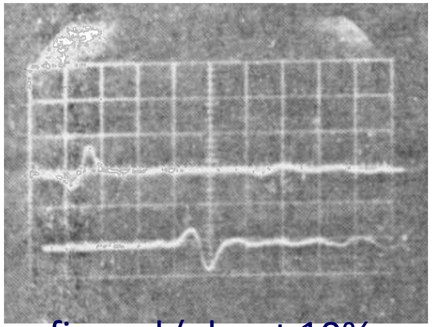
200 MeV proton beam

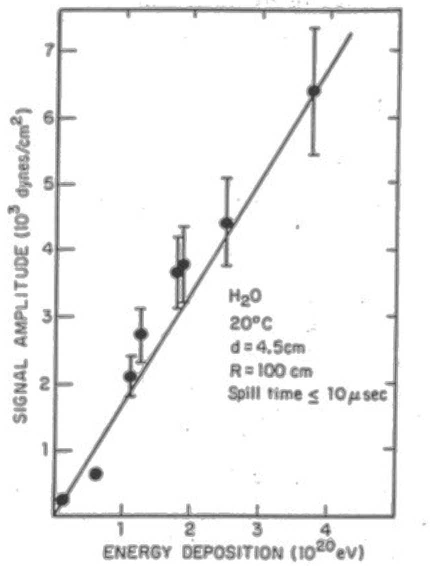
Beam diameter 4.5 cm

Energy deposited in water $10^{19} \rightarrow 10^{21}$ eV

Bipolar pulses observed

Dependency on C_p, T and on beam diameter confirmed (about 10% uncertainty)

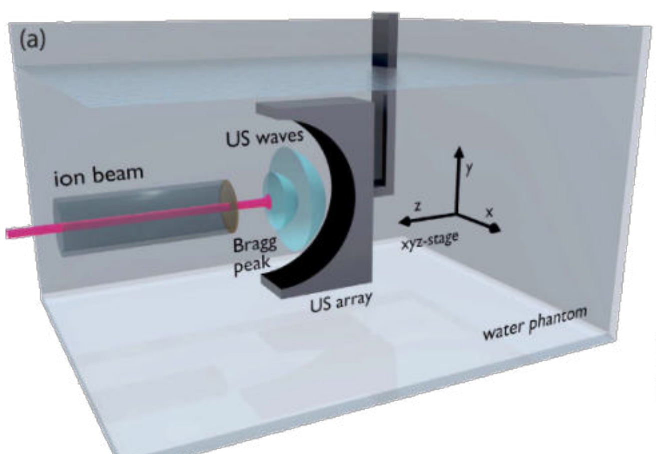


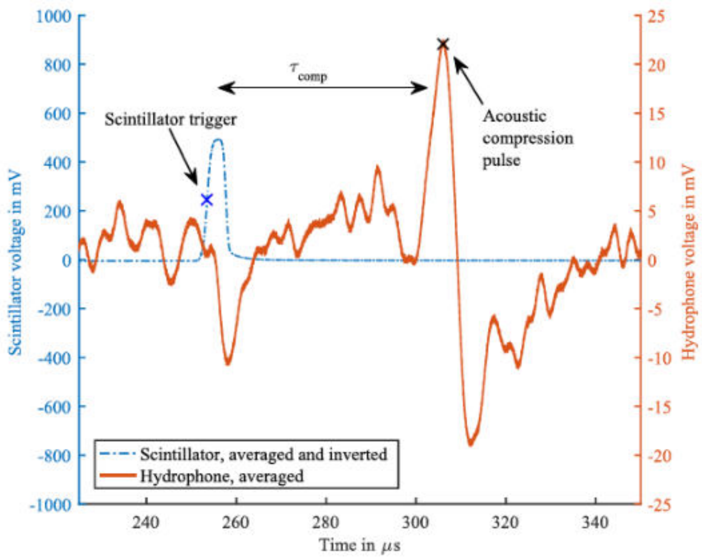


Quasi-spherical wavefront ($p \propto 1/r^2$). Not a pancake!

New: LMU 2016

Iono-acosutic methods for Bragg peak tomography of medical beams: 220 MeV protons





0.1:1 MHz signals (mm scale Bragg peak region)

Challenges in acoustic detection

Subsea network

needed to connect the sensors: use exising infrastructures

Piezoelectric transducers

reliable , linear response

noise: can be improved with new premps, ADCs, power noise filters

New transducers:

MEMS-AVS: cheap, wave direction, but still high noise

fiber-optic hydrophones need laser and interferometer. need dedicated fibres?

Sound propagation

ray-tracing (water depth 3500 m, reflected signal)

Background

sea state (wind, rain)

geophysics and bioacoustic signals

anthropogenic noise

Use geometry cut:

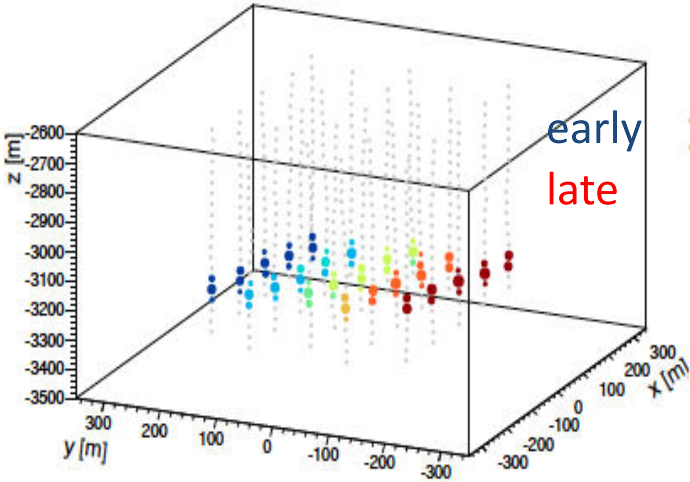
unique pancacke shape, vertex direction/position

Singnal processing

matched filters → wavelet

beamforming

Acoustic pancake in KM3NeT



Working in situ

Working in situ

Saund (ended): AUTEC military infrastructure. 49 hydrophones 20x50 km^2

Large calibrated array available (analogic and digital) but subject to military duties

First limit of the EHE neutrino flux via acoustic detection

Acorne (ended): RONA military infrastructure. 8 sensors, few 100 m spacing

shallow water (noise, sound channelling)

Amadeus (ended): ANTARES infrastructure. 36 sensors in 6 clusters (2 lines, ≈100 m apart)

Commercial ITC hydrophones, analogic readout, data transmission via Antares DAQ

check of acoustic positioning, detection of anthropogenic and biological source

test of piezo sensors in glass spheres: towards KM3NeT

Baikal: GVD infrastructure: 32 sensors, 8 clusters in 4 lines, few 100 m apart

Low noise: 2 mPa in average but Low water temperature wrt Med Sea (smaller pulses)

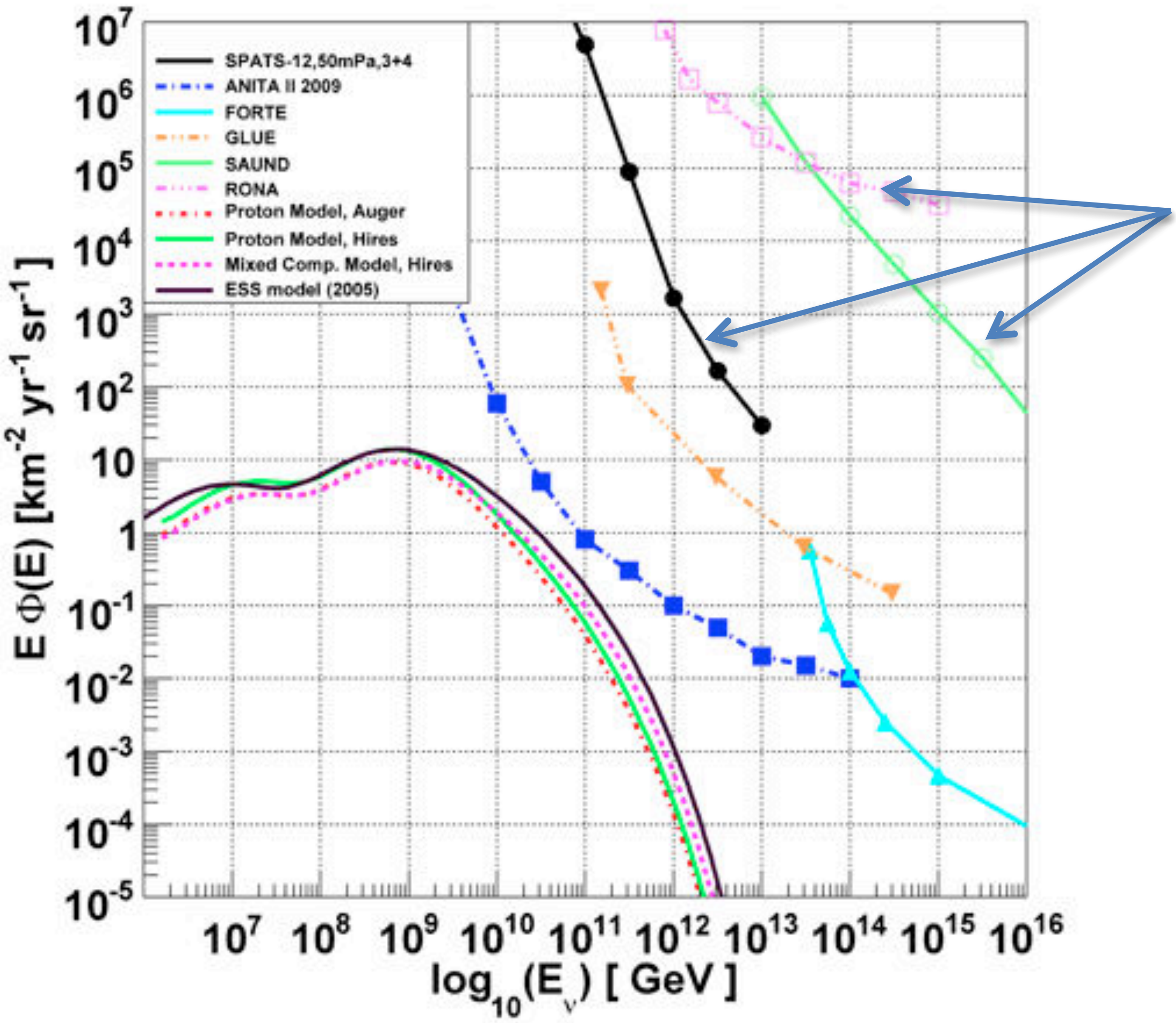
R&D on directional hydrophones

Spats: IceCube infrastructure, 28 sensors on 4 strings

technology for good glaciophones is not cheap

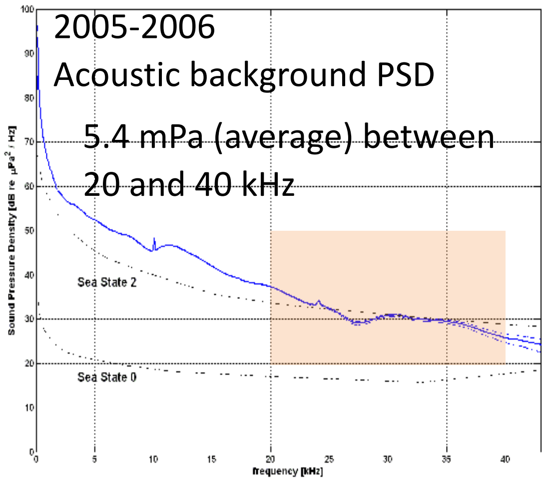
attenuation length less that in water

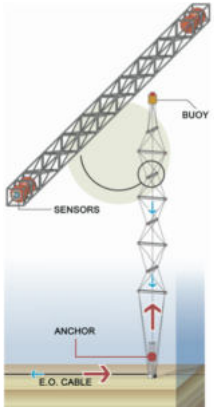
Flux limits with acoustic detectors

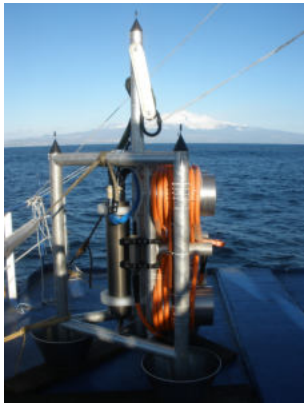


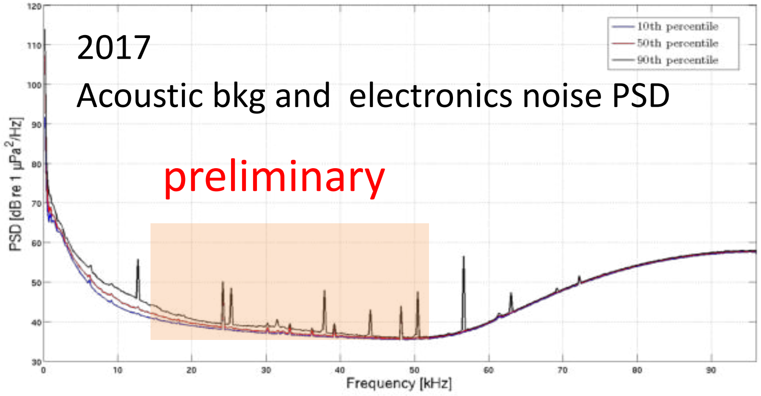
The OνDE and SMO expereince

OνDE (2005-2006), SMO (running): 2100m depth. SMO@CP (2012-2013): 3500 m depth
Tetrahedral antenna cluster (1m size). Low self noise, pressure independent calibration
R&D for KM3Net: Digitization (192 kHz) in-situ, interface to KM3NeT DOM electronics
Available sound library (raw data saved, 5' per hour ≈20 TB)

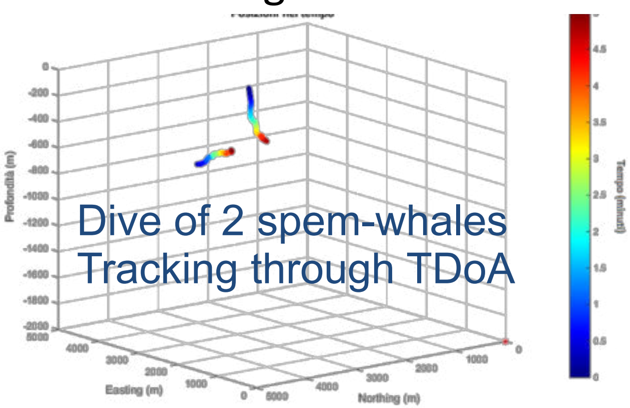








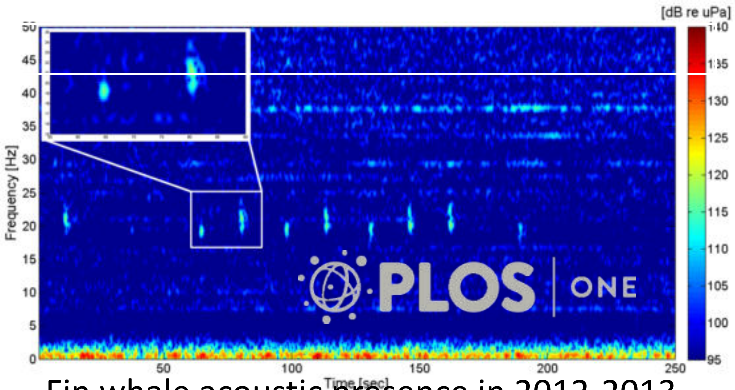
Algorithm training and calibration



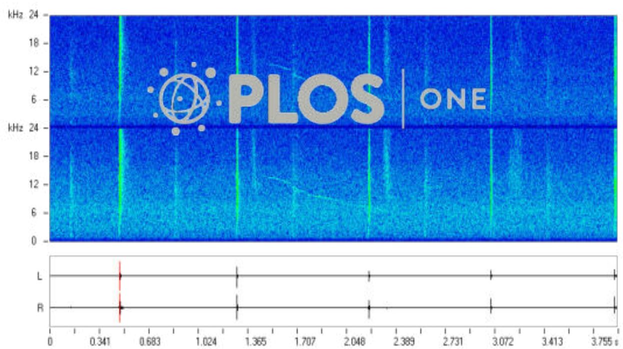
Bioacoustics and noise monitoring

Developing technology and models using natural and man-made acoustic sources
First on-line node in the Mediterranean Sea capable to provide real-time data for the EU Marine Strategy Framework Directive

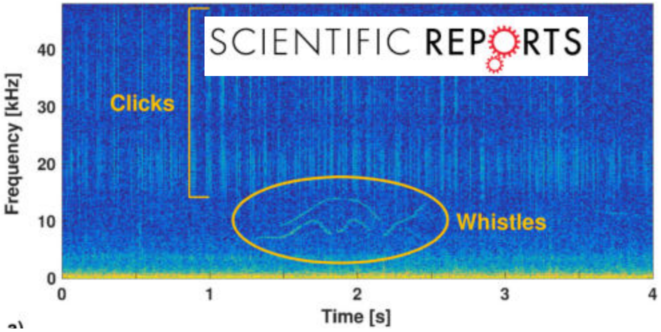
european multidisciplinary seafloor observatory emso



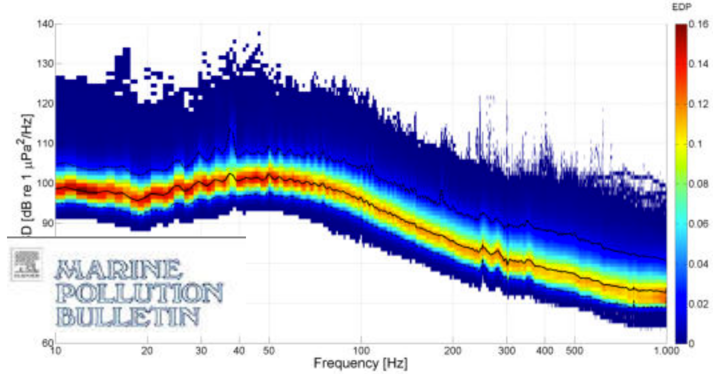
Fin whale acoustic presence in 2012-2013



Sperm-whale dimensions and population (2005-2006)



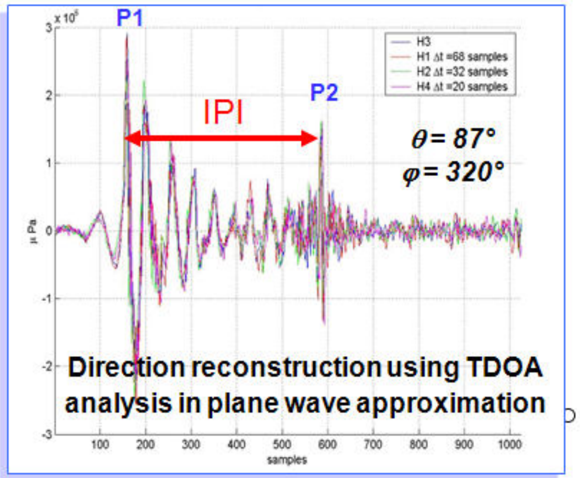
Day-night predatory pattern of dolphins (2005-2006)

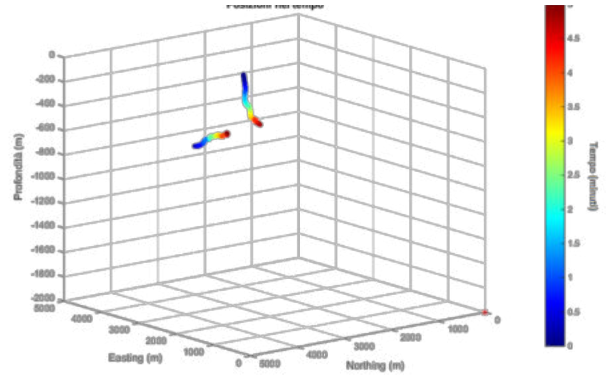


Shipping noise monitoring and modelling (2012-2013)

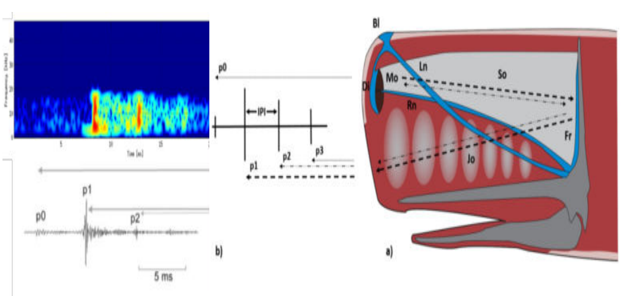
Sperm Whale identification and Tracking

On-line monitoring of acoustic signals with OnDE allowed identification of sperm whales, determination of the population, size and tracking

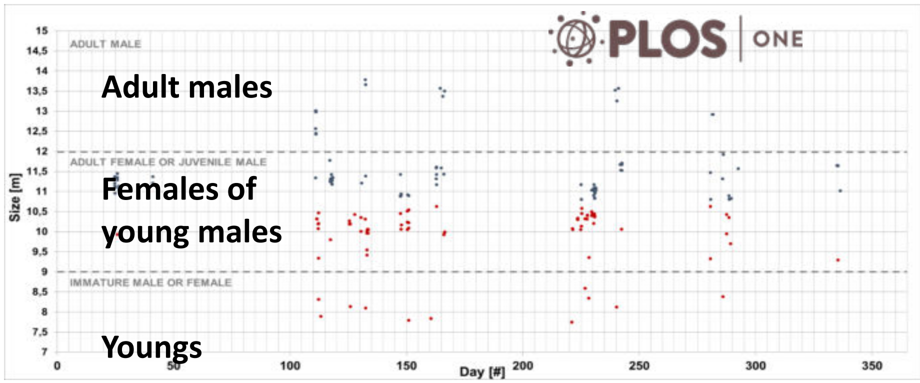




Dive of 2 spem-whales

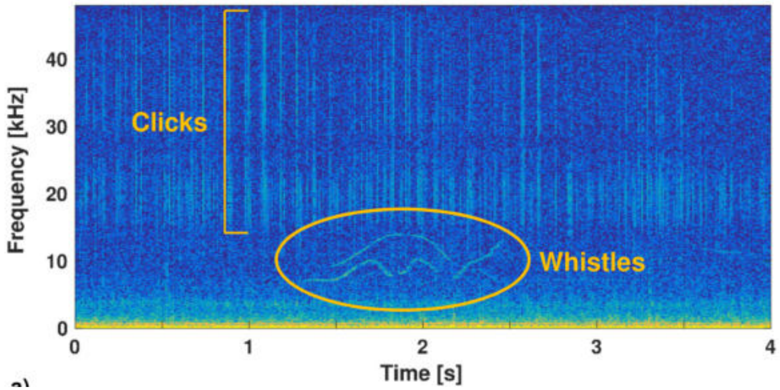


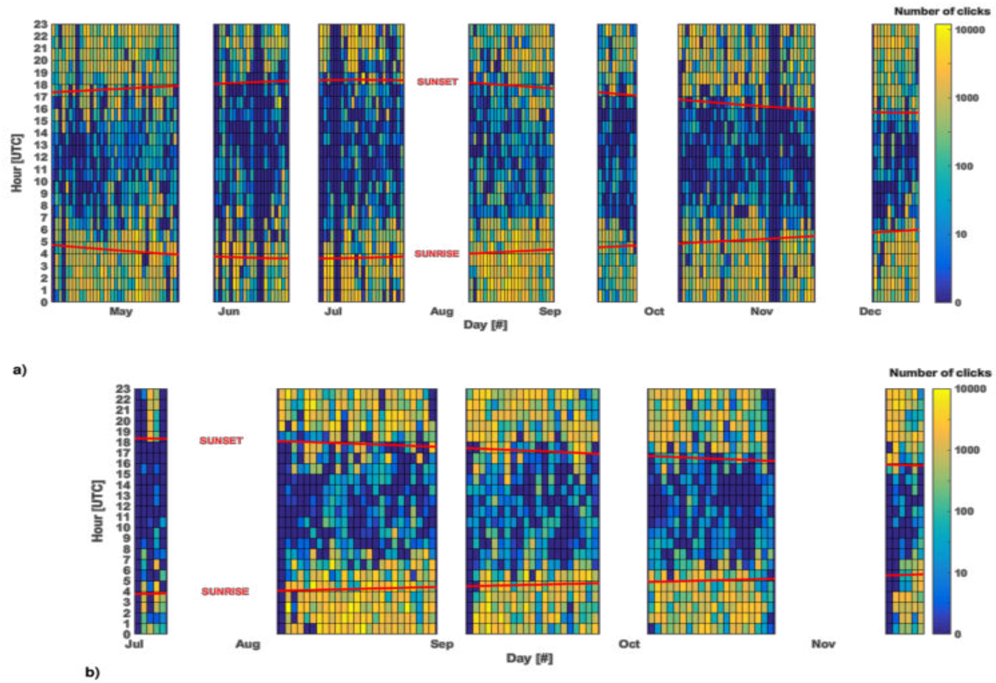
F. Caruso et al, 2016



Dolphin click analysis

Automatic identification of dolphins’ echolocation clicks (hunting)
day/night cycle assessed with 2 years of data

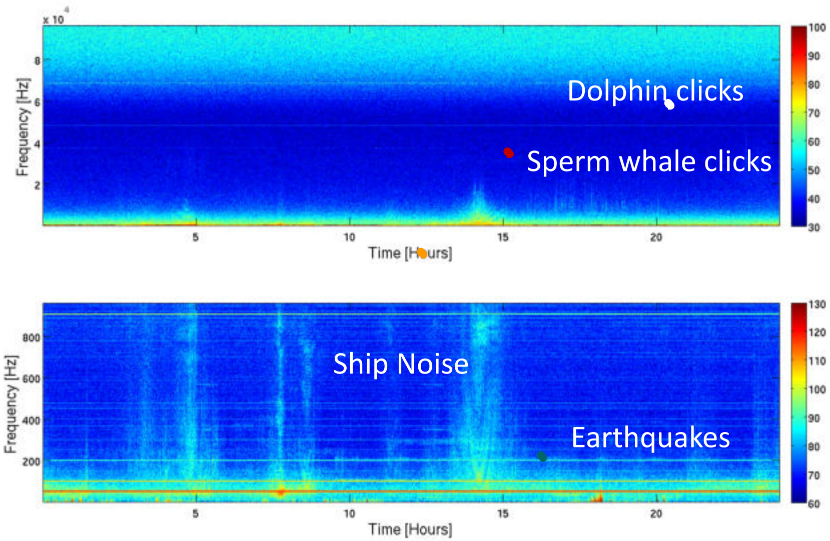


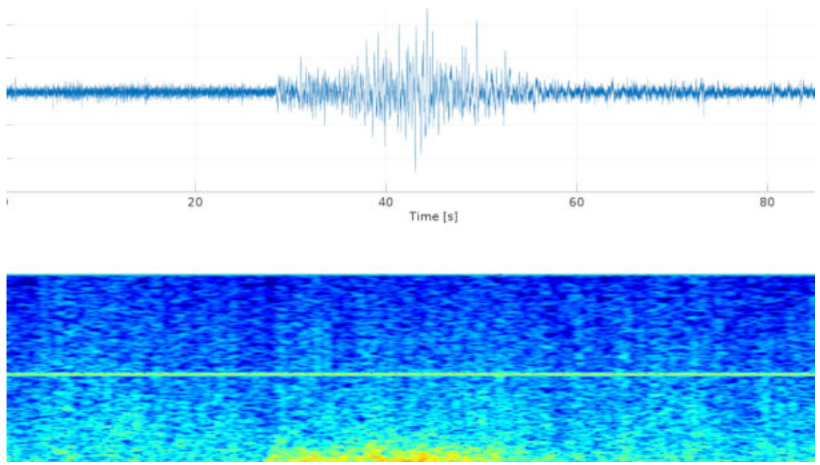


SCIENTIFIC REPORTS

F. Caruso et al., 2017

Earthquake detection

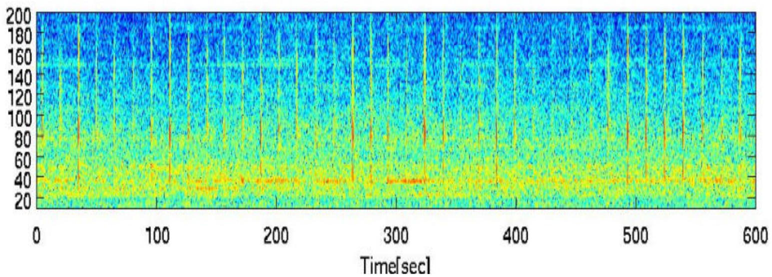




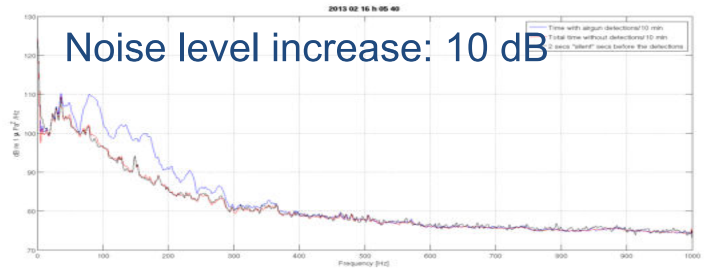
Etna Earthquake 4.8 (Catania, October 2018)

Airguns

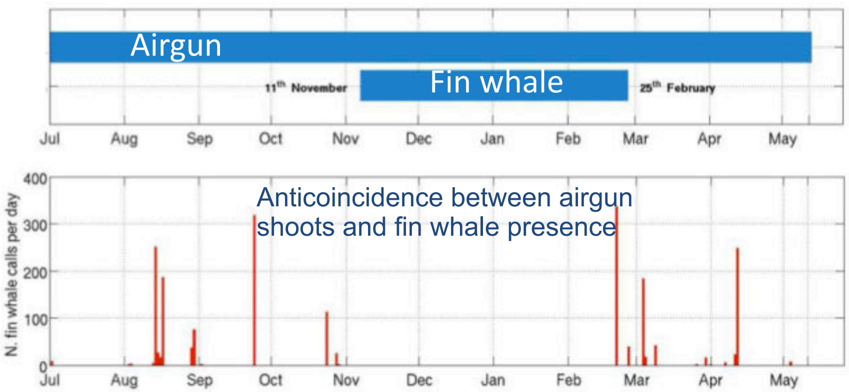
Real-time identification of “airguns” (compressed-air cannons)– 2012-2013 used for geophysics studies and oil/gas search

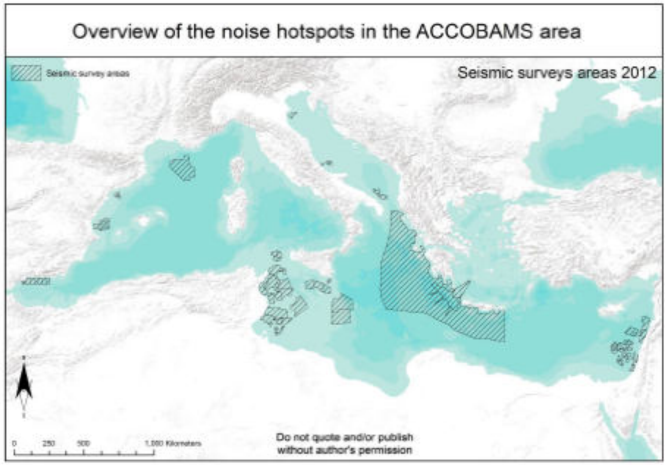


Italian Ministry of the environment



Identified source, offshore Greece !





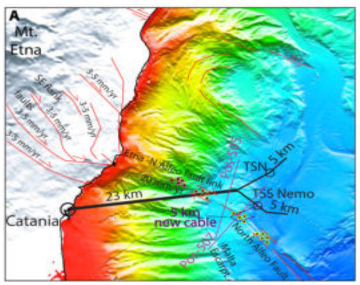
EMSO-SMO (INFN,INGV, CNR)

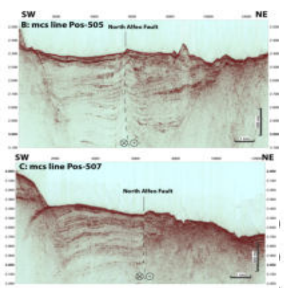
In 2019 Identified Airguns offshore Cyprus

Etna Eruption Detection

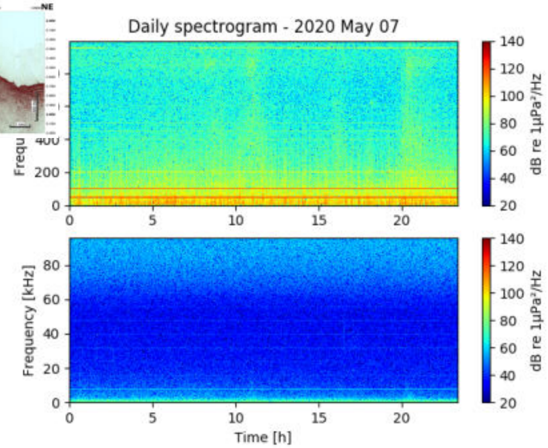
Deployment of OBS and dedicated optical fiber (attached to TSS) to monitor:

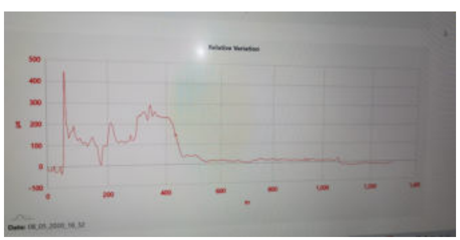
- Slow geophysical events (e.g. slip along North Alfeo Fault / sliding of submarine flank of Mount Etna) via BOTDR analysis
- Fast geophysical events detection with IDAS





Univ. Brest,INFN,CNRS,,IDIL IFREMER,INGV, GFZ, INGV

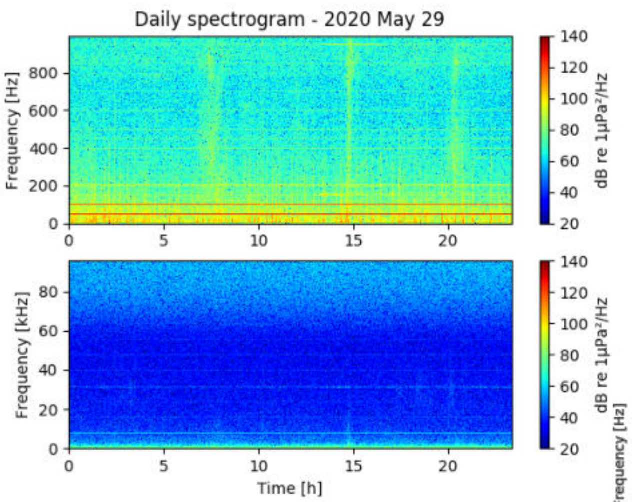


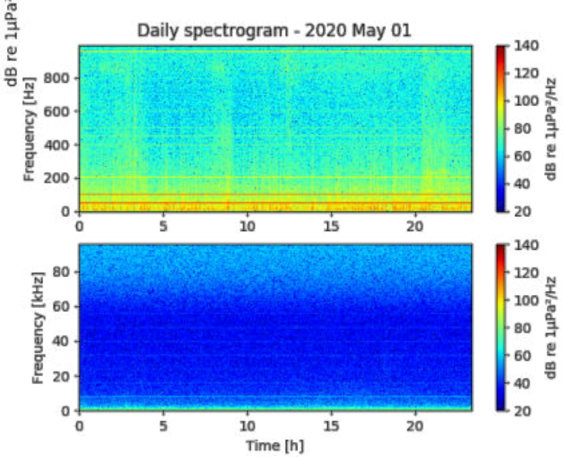


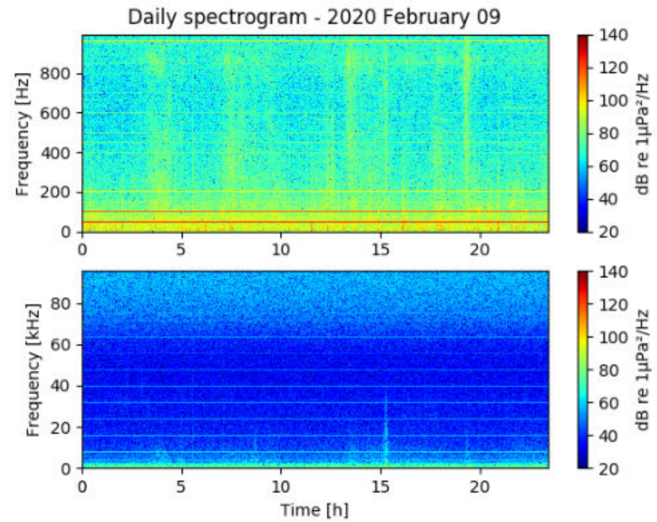
Work in progress

Contemporary detection of Etna Eruption May 6, 2020

SMO Analysis: Lockdown silence





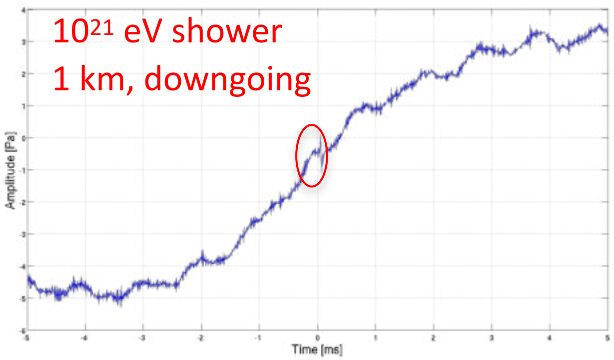


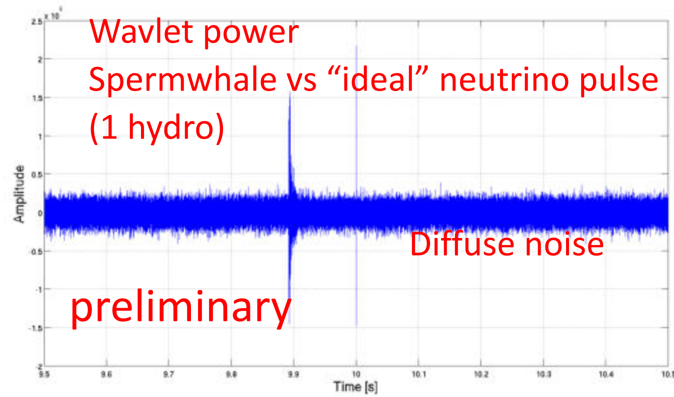
Event trigger and reconstruction

Typical approach: matched filters to identify the signal over background

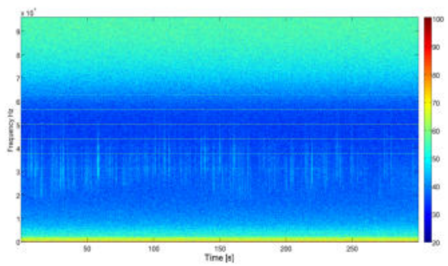
Neutrino signals changes shape with angle and shower parameters!

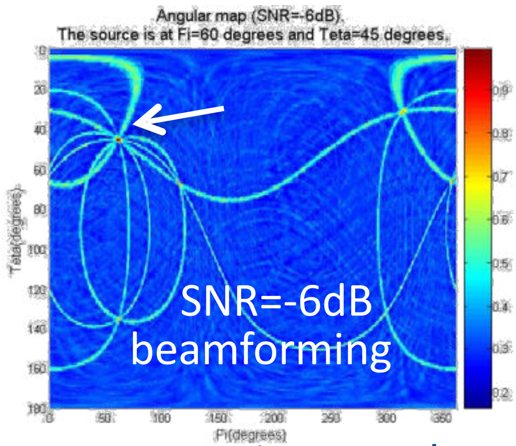
Use wavelet (work in progress): no pre-filtering, real time, 10x SNR increase

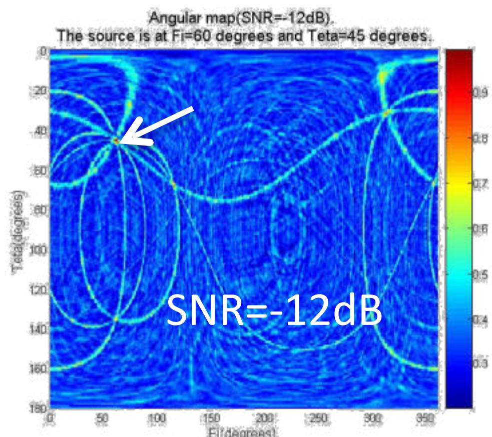




(Quasi) Real-time beam-forming would increase SNR by a factor ≈ √ $N_{sensors}$







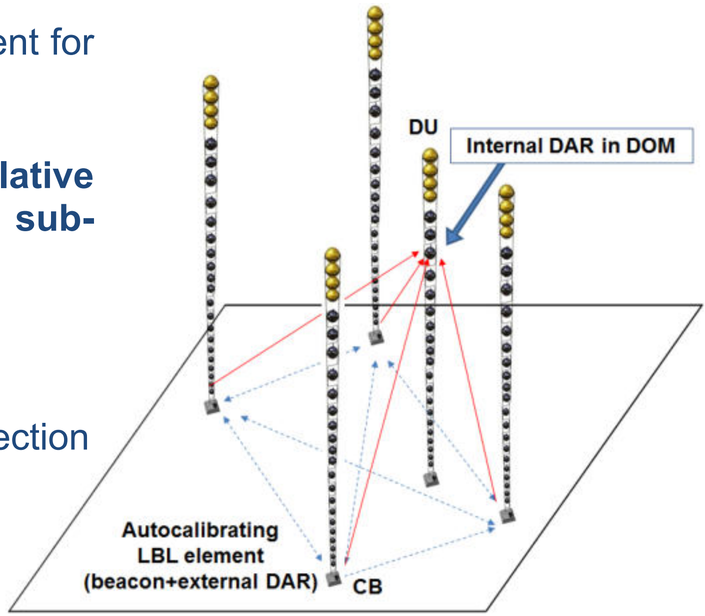
neutrino search anlysis ongoing

Acoustic sensors on KM3NeT

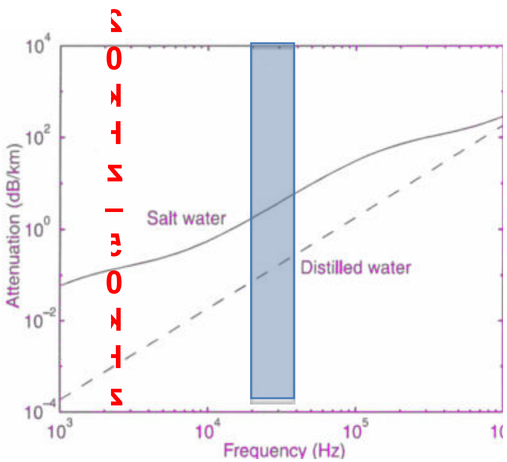
Continuous monitoring of the DOMs positions is a mandatory requirement for an accurate direction reconstruction of neutrino events

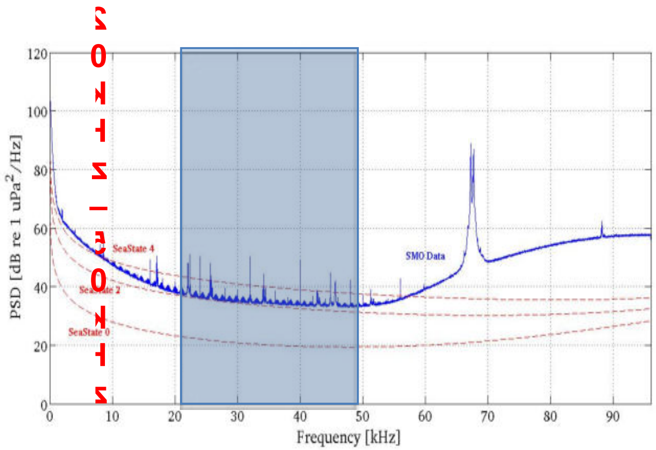
In KM3NeT the positions of the DOMs are recovered through a relative acoustic positioning system (RAPS) composed of three main sub-systems:

1. A Long Base-Line (LBL) of acoustic transmitters (beacons) and receivers, located at known positions
2. An array of digital acoustic receivers (DARs) installed along the detection units (DUs) of the telescope
3. A farm of PCs for the analysis of acoustic data



Acoustic emitter signals must be detected up to distances of 1 km





- **Suitable frequency range: 20 kHz-50 kHz**
- **Lowest level of PSD: ~40 dB re 1 uPa²/Hz**
- **Attenuation: 1-10 dB/km**

Acoustic Sensors in KM3NeT

1 hydrophone per DU base and on Junction Boxes, 18 piezo acoustic receivers per DU

All acoustic sensors are digital receivers (192 kHz/24 bits) synchronized and in phase with GPS (<1 us)

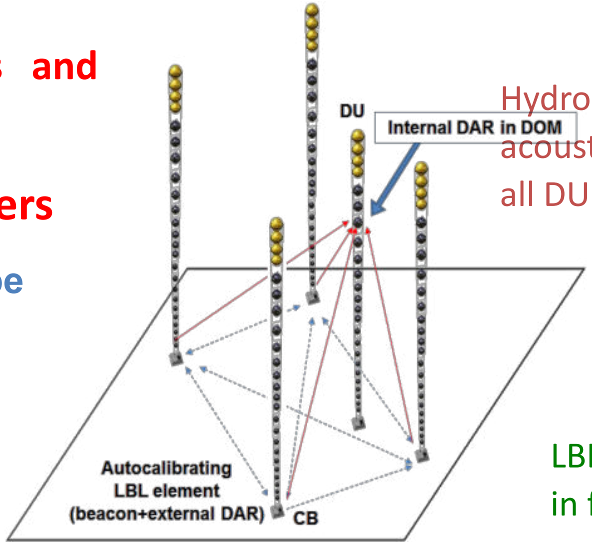
Auto-calibrating Long Baseline of acoustic emitters and hydrophones

Synchronized array of acoustic emitters and receivers

Main Goal: acoustic positioning system for the telescope
- Long Baseline of acoustic emitters

All data to shore:
- Access to Earth and Sea Science

Add-on:
- Instrumentation line with CTDs, SVs and CMs



Hydrophone digital acoustic receiver in all DU Bases

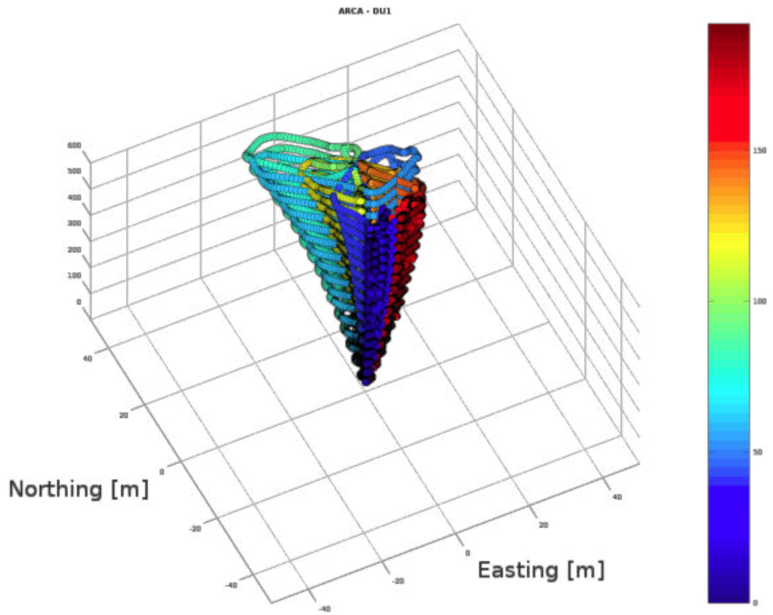
LBL acoustic beacons in few DU Bases

Long Baseline beacons

DU base digital hydrophone Colmar DG330

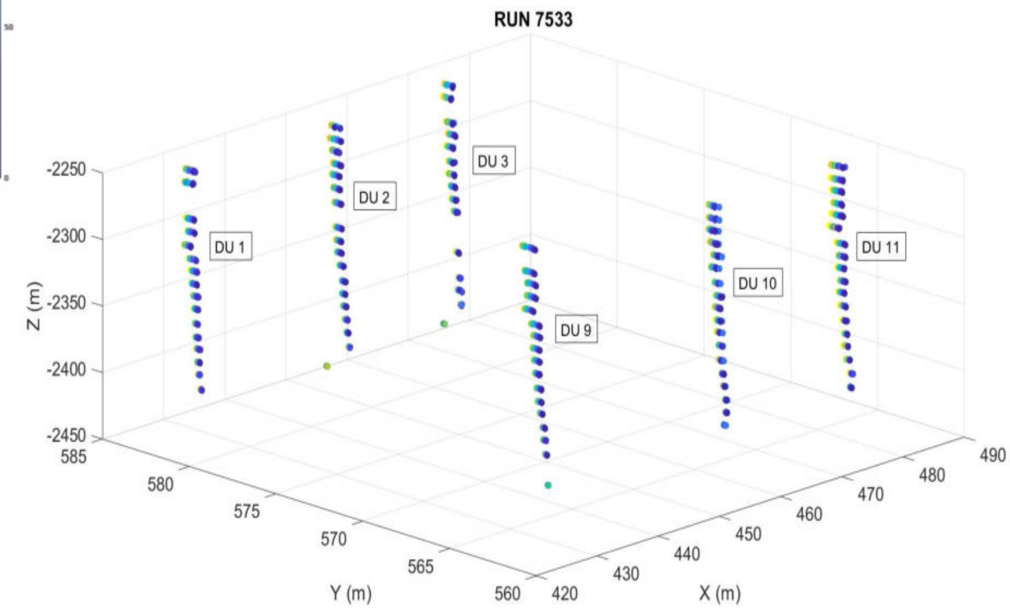
Piezo in DOM

Acoustic Positioning in KM3NeT



DOM by DOM data analysis (no fit):
30 cm resolution (work in progress)

Time evolution of positions of a 750 m long DU under strong current (KM3NeT-ARCA)



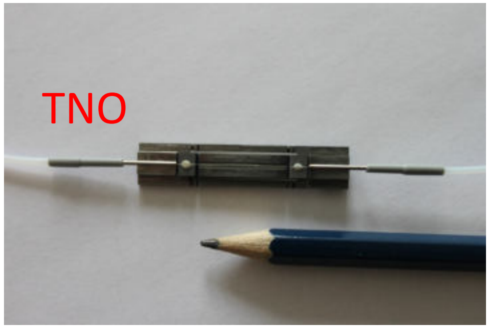
Time evolution of positions of 6 DUs, 6 hours (KM3NeT ORCA)

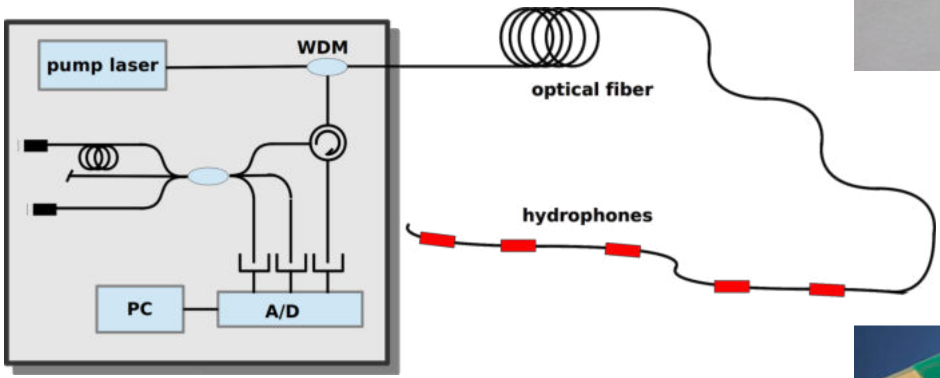
R&D: New transducers

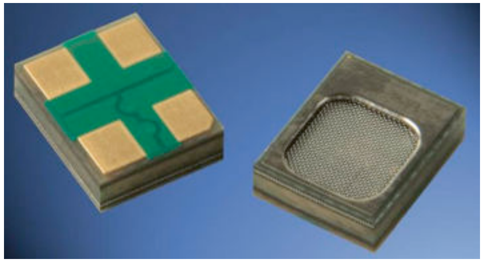
Fiber Optic hydrophones:

Strain on the fiber converts into peculiar interferometric pattern

- lab tests show SNR ratio factor 10 better than hydrophones
- cheap sensor but requires a dedicated fiber
- laser pump and inteferometer on shore
- Verical Dus subject to currents
- Ground array for horizontal neutrinos ?







MEMS hydrophones:

- cheap sensor,commercial
- wave pressure and direction (integrated gyroscope)
- easy to build large matixes with readout and digitisation electronics (System on Chip)
- actual limits: noise, frequency band (≈10 kHz)

Maturity of Acoustic detectors

Technology: Well established piezoelectric sensors, new MEMS, fiber-optic

Costs: high (1 good sensor plus connectors amounts to 2500€)

BUT great opportunity to share technology/infrastructure for positioning and multidisciplinary science

Background noise: well characterised

Neutrino Signal Identification:

Faint bipolar pulse (several) BUT cylindrical sound emission: Topology (almost) unique. At extreme energies down-going and (some) horizontal

Energy Reconstruction: need more simulation work (heat/sound conversion)

Direction Reconstruction: ray tracing, beamforming

Threshold reduction: large arrays, direction pre-guess, opto/acoustic coincidences?

Overview

- The Physics Case
- Radio Detection
- Acoustic Detection
- Conclusions

Conclusions

- Radio detection technique is rapidly reaching maturity to allow neutrino detection* at extreme energies

- Acoustic detection is still in its infancy (few groups, limited resources) but is exploiting the needs of KM3NeT and Baikal GVD of acoustic sensors for positioning

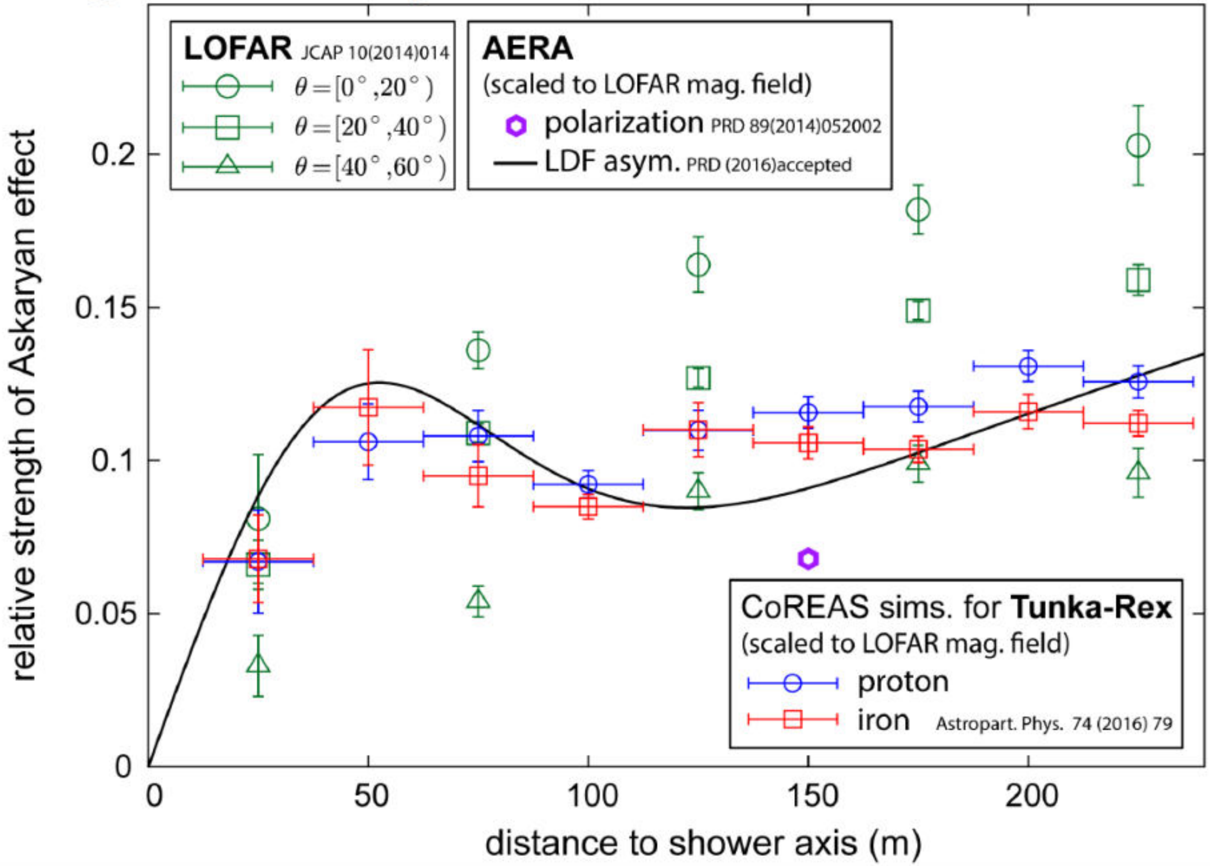
- The need of huge detectors can be partially compensated by lowering the energy threshold:
  - Reduce sensors and frond end chain noise
  - Use digitally phased arrays

A plethora of Earth and Sea Science cases and technological applications is available

Thanks!

Radio emission in air and dense media

Relative strength of Askaryan effect



12 08 June 2016
ARENA 2016, Groningen

Overview on Radio Detection of Air Shower

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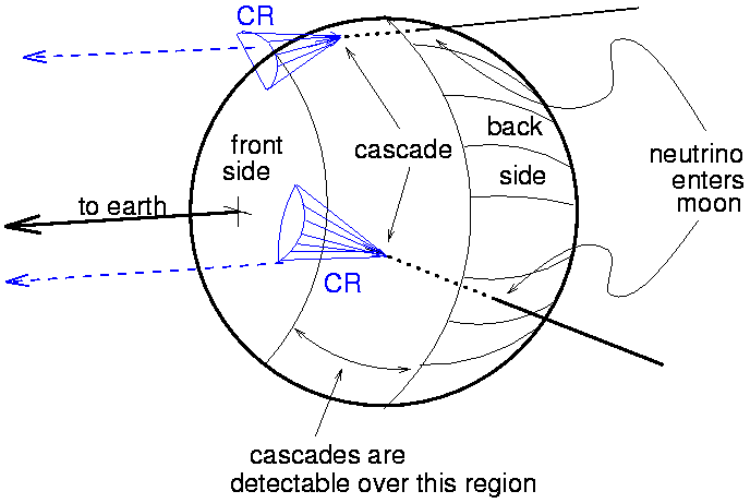
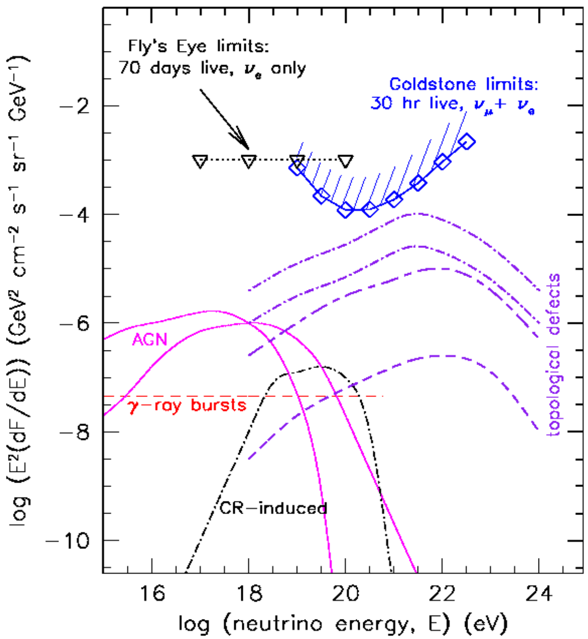
Institut für Kernphysik

Lunar Regolith Interactions & RF Cherenkov radiation





- At ~100 EeV energies, neutrino interaction length in lunar material is ~60km
- R_{moon} ~ 1740 km, so most detectable interactions are grazing rays, but detection not limited to just limb
- Refraction of Cherenkov cone at regolith surface "fills in" the pattern, so acceptance solid angle is ~50 times larger than apparent solid angle of moon

- GLUE-type experiments have huge effective volume ➔ can set useful limits in short time
- Large VHF array may have lower energy threshold, also higher duty cycle if phasing allows multiple source tracking

Ice considerations: Surface vs. deep antennas

- Near-surface antennas are easier to deploy, and more flexible (can use higher gain antennas, same antenna for all polarizations.)
- But top layer of ice ("firn") has density gradient → index of refraction gradient so not all signals reach surface
- Deep antennas see more volume, but drilling adds to cost and antenna options limited by borehole size
- Another consequence of firn is existence of with multiple paths ("direct" and "refracted") which allow for more precise vertexing