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

Giorgio Riccobene
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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: throughgoing muon from CC $\nu_\mu$ interaction.
But also showers from NC, $\nu_e$, $\nu_{\tau}$

Array of Optical sensors

Cherenkov photons ($\sim 42^\circ$ in water)

Cable to shore

A bullet at Mach = 2.5

Look at upgoing muons: use the Earth as a filter
Only atmospheric and astrophysical neutrinos can cross the Earth
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 $4\pi$.
‘Good’ energy resolution, worse directional resolution

Lollypops et al.:
taus (HE)
Unambiguous topology at $E_{\tau} > \text{PeV}$
Optical Cherenkov neutrino telescopes

**IceCube**

- no point sources (so far) BUT
- 1) extra-terrestrial 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

**Optical Detection** (IceCube-KM3NeT)

- Medium: Seawater, Polar Ice
- $\nu_\mu$ (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
- $\nu$ (cascades)
- Carrier: Cherenkov Radio
- Attenuation length: 1 km
- Sensors: Antennas
- Instrumented Volume: >1 km$^3$

**Acoustic Detection** (prototypes)

- Medium: Seawater, Polar Ice
- $\nu$ (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

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:

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

Neutrino interaction with Earth: downgoing or horizontal neutrinos

Extremely low fluxes:

- need large exposure $\rightarrow$ $O(100) \text{km}^3 \text{ year}$
- very sparse arrays $\rightarrow$ reduce cost per unit and installation cost
- hybrid/complementary detectors $\rightarrow$ exploit/share infrastructure with “mature” experiments

Reduce detection threshold!
Originated by gammas, CR or neutrinos

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

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

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

Geomagnetic radiation
Shower axis
Dielectric medium

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

Askarian radiation
Shower axis

Geomagnetic effect dominates ($\approx 80\%$)
large $B$ $\rightarrow$ intense radio emission
Linear polarisation (direction of $F_{\text{Lorenz}}$)
Radio absorption negligible
Dense media:
narrow shower front, confined core
$R_{\text{Moliere}} \approx 10 \text{ cm} \rightarrow f \approx 100 \text{ MHz: } 1\text{GHz}$
$L \approx O(10 \text{ m}), \text{LPM at extreme energies}$
Cherenkov angle $\approx 57^\circ$ in ice

Askaryan effect dominates
Radial polarisation (towards shower axis)
Radio absorption $O(1 \text{ km in ice})$
# Neutrino detection with radio arrays

<table>
<thead>
<tr>
<th>Ground-based air shower detectors</th>
<th>Direct (CR,ν) or reflected* Inclined young showers (v) Direct (ντ) from ground</th>
</tr>
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<tbody>
<tr>
<td>AERA@PAO, Lofar, GRAND, Taroge*</td>
<td>O(&gt;10^3 km^2) instrumented, Observed volume 10^3 km^3, E^{th}≈10^{16:17} eV</td>
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<th>Ice surface-based detectors</th>
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<th>Balloon and Satellites detectors</th>
<th>Refracted (ν) and reflected (CR,ν) signal, upgoing (ντ)</th>
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<tr>
<td>Anita, Forte, EVA</td>
<td>O(m^3, 1000 m^3) instrumented areas, Observed Volume 10^6 km^3, E^{th}≈10^{18} eV</td>
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<th>Ground-based lunar observatories</th>
<th>Refracted signal in lunar regolith (ν) Skimming events (CR)</th>
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<td>GLUE, NuMoon, SKA,LOFAR</td>
<td>O(&gt;10^2 m^2: 10 km^2) instrumented, Observed volume 10^6 km^3, E^{th}≈10^{20} eV</td>
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- Production and detection of Askaryan radiation in salt and ice.
- Testbed for ANITA

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

10 ps bunch. Coherent (P_{\alpha}E^2) radio emission

END STATION A side view

approximately to scale

13.4m

10.7m

beamline

4.8m

4m

1.2m

2.4m

10m

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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
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ARIANNA

脉冲（模拟）
$5 \times 10^{18} \text{ eV p}$

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

Total power trigger

5x10^{18} \text{ eV p}

Pulse (simulation)
Polarization: X, Y, Z

Single antenna response
10 mV

Raw digitizer beam-forming

Track and energy reconstruction
Ray Tracing!

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

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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

Galactic background modulation

Cosmic ray flux (showers)
Radio Neutrino Observatory

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)
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

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<th>Cutoff Energy on IceCube Flux</th>
<th>$10^9$ GeV</th>
<th>$10^{8.5}$ GeV</th>
<th>$10^9$ GeV</th>
<th>$10^{9.5}$ GeV</th>
<th>$10^{10}$ GeV</th>
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<td>Expected Number of Neutrinos</td>
<td>5.1</td>
<td>9.7</td>
<td>14.3</td>
<td>18.2</td>
<td>21.4</td>
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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 $\nu_e$ also an e.m. shower)

Hadronic shower carries $\approx \frac{1}{4} E_{\nu}$

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 ($\beta$)

Bipolar pulses

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

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

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

Coherence:

$$f \approx c_s / d \approx \mathcal{O}(10 \text{ kHz})$$

“pancake” waveform ($\approx 1^\circ$ aperture)

$$p(r) \propto \frac{1}{r}$$
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“Pen shaped” energy deposition region (20 m depth, 10 cm diameter)

Coherence:

\[f \approx \frac{c_s}{d} \approx O(10 \text{ kHz})\]

“pancake” waveform ($\approx 1^\circ$ aperture) $p(r) \propto 1/r$

Propagation in seawater
Acoustic detection of HE neutrinos

Hadronic shower formation at interaction vertex
(if $\nu_e$ also an e.m. shower)

Hadronic shower carries $\approx \frac{1}{4} E_\nu$

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Proton beam experiments

History: BNL 1979
200 MeV proton beam
Beam diameter 4.5 cm
Energy deposited in water $10^{19}$–$10^{21}$ 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-acoustic 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 existing infrastructures

Piezoelectric transducers
- reliable, linear response
- noise: can be improved with new preamps, 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 pancake shape, vertex direction/position

Signal processing
- matched filters → wavelet beamforming
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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, \(\approx\)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 experience

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)

2005-2006
Acoustic background PSD
5.4 mPa (average) between
20 and 40 kHz

2017
Acoustic bkg and electronics noise PSD
preliminary

Algorithm training and calibration

Dive of 2 sperm-whales
Tracking through TDoA
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

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

Dive of 2 sperm-whales

F. Caruso et al, 2016

Adult males

Females of young males

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

F. Caruso et al., 2017
Earthquake detection

Etna Earthquake 4.8 (Catania, October 2018)
Real-time identification of “airguns” (compressed-air cannons)– 2012-2013 used for geophysics studies and oil/gas search

Noise level increase: 10 dB

Identified source, offshore Greece!

Anticoincidence between airgun shoots and fin whale presence

In 2019 Identified Airguns offshore Cyprus

EMSO-SMO (INFN,INGV, CNR)
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

Work in progress

Contemporary detection of Etna Eruption May 6, 2020

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SMO Analysis: Lockdown silence
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 $\approx \sqrt{N_{\text{sensors}}}$
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
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

Long Baseline beacons

DU base digital hydrophone
Colmar DG330

Piezo in DOM

Hydrophone digital acoustic receiver in all DU Bases

LBL acoustic beacons in few DU Bases
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 interferometer on shore
Vertical Dus subject to currents
Ground array for horizontal neutrinos?

MEMS hydrophones:
cheap sensor, commercial
wave pressure and direction (integrated gyroscope)
easy to build large matrices 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?
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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 front end chain noise
  - Use digitally phased arrays

A plethora of Earth and Sea Science cases and technological applications is available
Thanks!
Relative strength of Askaryan effect

LOFAR \textit{JCAP} 10(2014)014
\begin{itemize}
  \item $\theta = [0^\circ, 20^\circ]$
  \item $\theta = [20^\circ, 40^\circ]$
  \item $\theta = [40^\circ, 60^\circ]$
\end{itemize}

AERA (scaled to LOFAR mag. field)
\begin{itemize}
  \item polarization \textit{PRD} 89(2014)052002
  \item LDF asym. \textit{PRD} (2016) accepted
\end{itemize}

CoREAS sims. for \textbf{Tunka-Rex}
(scaled to LOFAR mag. field)
\begin{itemize}
  \item proton
  \item iron \textit{Astropart. Phys.} 74 (2016) 79
\end{itemize}
• At ~100 EeV energies, neutrino interaction length in lunar material is ~60km

• $R_{\text{moon}} \sim 1740$ 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 $\rightarrow$ 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