Beyond ANTARES: the future of neutrino telescopes, a short review.

Vincent Cecchini

Instituto de Física Corpuscular (CSIC - Universitat de València)

17th Marcel Grossmann meeting, Pescara
11/07/2024

VEGA Valencia Experimental Group of Astroparticles

IFIC INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

CSIC

MINISTERIO DE CIENCIA E INNOVACIÓN

UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
"Una manera de hacer Europa"

AGENCIA ESTATAL DE INVESTIGACIÓN

Foreword

"Describe the continuation of neutrino astronomy in the Mediterranean Sea with *[...]* the prospects of incoming neutrino telescopes in the following years."

→ A talk about the future of High Energies (HE) Neutrinos searches

- The potential of High Energies Neutrinos for astrophysics
- A focus on the future experiments

→ A talk NOT about < TeV searches, nor past experiments.

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Contents

Neutrinos production mechanisms

Thermal mechanisms

- Beta decays & EC
  $n \to p + e^- + \overline{\nu_e}$
  $p \to n + e^+ + \nu_e$
  $p + e^- \to n + \nu_e$
- Nuclear fusion
  $p + p \to D + e^+ + \nu_e$

→ Low energies: keV to ~MeV

Hadronic acceleration processes

Particle acceleration and collisions

- $pp \to \pi^{+/-/0}$ mechanism
- $p + \gamma \to (\Delta^+ \to)\ \pi^+ + n$ or $\to \pi^0 + p$ mechanism

Meson production → Pion decay:

$$\pi^\pm \to \mu^\pm + \nu_\mu(\overline{\nu_\mu})$$
$$\mu^\pm \to \overline{\nu_\mu}(\nu_\mu) + \nu_e(\overline{\nu_e}) + e^\pm$$

Energy transfer from primary p to final states:
$E_\nu \sim E_p/20$. Palladino *et al.* Universe 2020.
$\nu_\mu : \nu_e : \nu_\tau$ flavor ratio 2:1:0 $\xrightarrow{\text{oscillation}}$ 1:1:1 (TBD)
$\pi^0 \to \gamma + \gamma \implies \nu$ and γ produced together.

→ HE neutrinos requires acceleration mechanisms from violent events in universe.

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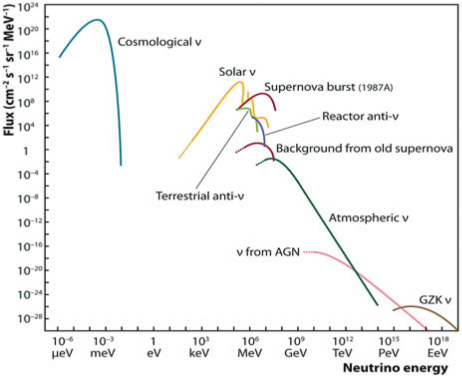
Neutrinos at earth, where are they coming from?

Spiering, C. (2020): Fabjan, Schopper (Ch17 Springer).



Right part of spectra ⇔ Low flux

- Thermal mechanisms from astrophysical object (keV-~MeV, dominated by the sun)
- Supernova neutrinos (MeV-GeV)
- pp/pγ acceleration at astrophysical sources (TeV-10s PeV): ν_{astro}
- UHE CRs interaction with CMB: "cosmogenic"
- CRs interactions with atmosphere: ν_{atmos} → no pointing = **background** for NTs

∗ **High Energy** (HE) > 100 TeV;
∗ **Ultra-High Energy** (UHE) > 100 PeV.

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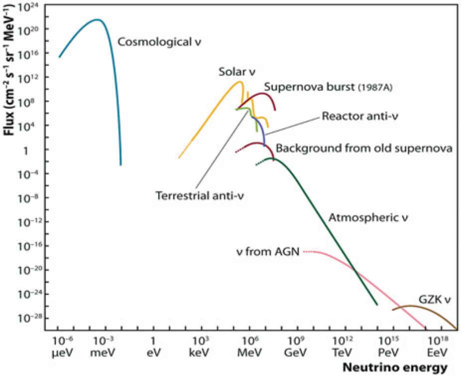

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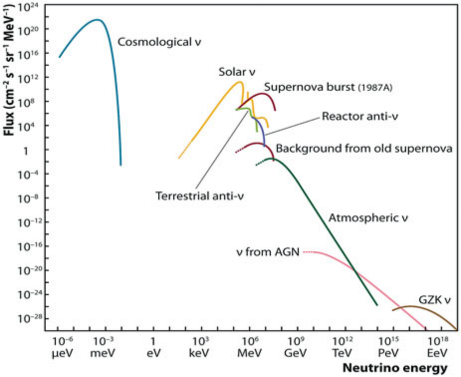

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Neutrinos at earth, interaction manifestation

HE ν interactions:

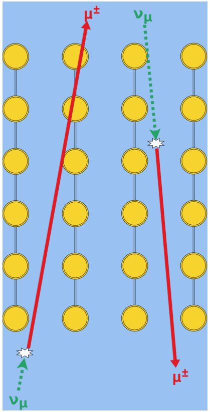
Charged and Neutral Current (CC:NC ratio 2:1)

- ν_μ CC $\rightarrow$ Muon track (kinematic deviation $\phi_{\nu l} \approx (E_\nu/\text{TeV})^{-0.55}$ (see PDG, Phys. Rev. D 110, 030001 (2024))
- ν_e CC, ν_τ CC, all NC $\rightarrow$ Particles cascades

  NB: Double-bang separation (interaction and decay vertex distance): $\approx (E_\tau \times 50\ m/\text{PeV})$ (see IC-Gen2 TDR (2023))

Neutrinos at earth, interaction manifestation

$\nu_\mu CC$ tracks $\Longrightarrow$ **Good pointing**



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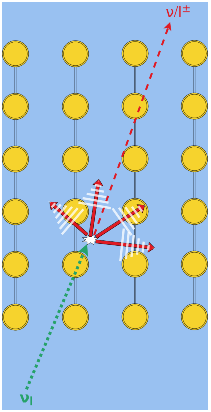
Neutrinos at earth, interaction manifestation

$\nu_{e,\tau}\,CC+$ all NC Cascades/Shower

$\Longrightarrow$ **Good energy resol.**



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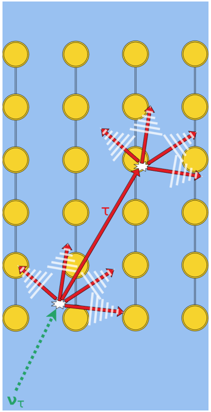
Double-Bang: ν_τ CC + EM cascades



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Interaction outcomes:

Cherenkov light production from relativistic particles.

→ Cherenkov light: Firsts parts of this talk. (1) in water, (2) in air.

The **particles them-self** (in part 2).

Radio emission from cascades movement in ice and air.

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The HE neutrino science cases

→ Identify neutrino **point sources** (detection of several neutrinos from a single source).

→ $\nu \Leftrightarrow$ undeflected signature of hadronic interactions.
Probe models of particle acceleration in extreme environments (*eg:* coincidence $\gamma + \nu$ would prove the hadronic process, unveiling the CR acceleration mechanism)
Multi-Messenger astrophysics: Access the universe without deflection and (low) absorption ; trigger fast/early alerts.

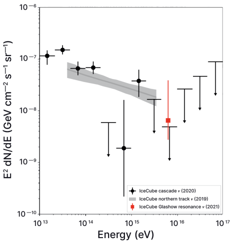
→ Where are the highest energy cosmic rays sources?
$E_{CR} > 100$ EeV $\implies$ EeV ν should exist.

1. Are UHE ν really there?
2. Measure UHE neutrino spectrum → Constrain UHECRs propagation & source properties.

Where are we? [addressed in C. Raab talk (Jul. 11)]

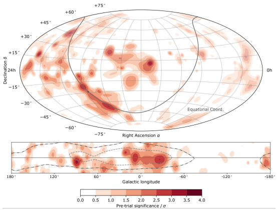
- 2013: diffuse HE astrophysical neutrinos flux IceCube, Science 342 (2013), IceCube, Phys. Rev. Lett. 113 (2014)

2021: Glashow resonance IceCube, Nature 591



Max(E_ν) ≈ 7 PeV

2023: Galactic plane IceCube, Science 380



Galactic plane contribution of ~10% of ν flux, consistent with γ-rays

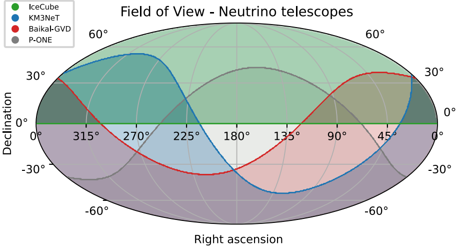
More PS & Multi-messenger astrophysics:

- 2018: Neutrino coincidence with EM radiation from the blazar TXS0506+056 Science 361 (2018)
- 2022: 4.2σ evidence for PS emission from the AGN NGC1068 IceCube, Science 378 (2022)

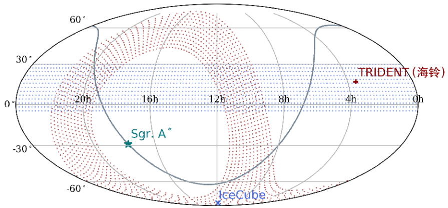
Contents

A global network of NTs?

Sky coverage complementarity



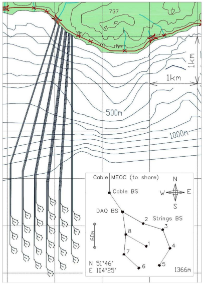
FoV for up-going sky of IceCube (green), Baikal (Red), KM3NeT (Blue), P-ONE (grey). *Courtesy* Juan Palacios-Gonzalez (IFIC, KM3NeT)



Horizontal (VHE) ν visibility of IceCube (Blue) and TRIDENT (red, TRIDENT (CGTN news))

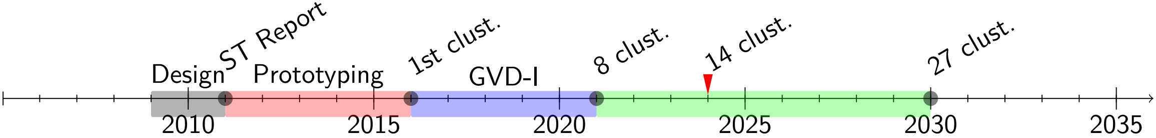
Baikal-GVD: Gigaton Volume Detector

Location	Baikal Lake (51°46N, 104°24E)
Max. Depth	1275 m
Nb. Strings [OM]	214 [7776]
Dist. inter- Str [OM]	60 m [15 m]
Strings height	525 m
Instrumented Vol.	1 km^3
Energy range	TeV-100 PeV
Trk angular resol.	0.2°



27 cluster of 8 lines.
3×12 OMs (1PMT) / line.
Central distance between cluster: 300 m

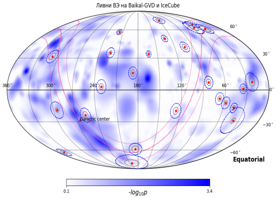
Frozen lake $\Longrightarrow$ cost-efficient deployment.



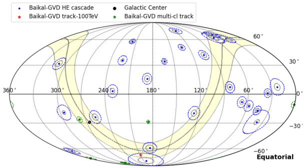
PoS (ICRC2023) 976 | Baikal Scientific-Technical Report | Dvornicky, Neutrino2024

Some Baikal-GVD results

Shower-like (25 evt 4/18-3/22):

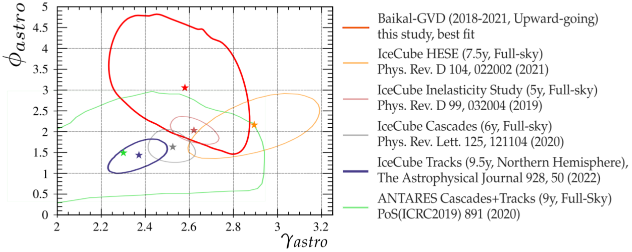


Track-like (Baikal-GVD preliminary):



green: multi-clust (ν_{atm} dominated);
red: >100 TeV single clust.

$>3\sigma$ evidence of astrophysical ν flux (agreement with IceCube and ANTARES).



$$\Phi^{\nu+\bar{\nu}}_{\text{astro}} = 3 \times 10^{-18} \phi_{\text{astro}} \left(\frac{E_\nu}{E_0}\right)^{-\gamma_{\text{astro}}}$$

Phys.Rev. D 107, 042005 (2023)

Dvornicky, Neutrino2024

KM3NeT: Kilometer^3 Neutrino Telescope

One collaboration, one (OM) technology, two telescopes, two energy ranges:

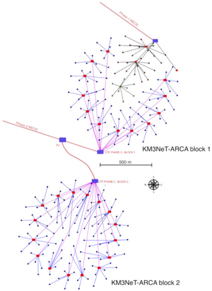
- ARCA (Astroparticle Research with Cosmics in the Abyss):
  Offshore of Sicily.
  Optimized for E > TeV.
- ORCA (Oscillation Research with Cosmics in the Abyss)
  Offshore of Toulon.
  Optimized for E in [GeV - TeV].

→ (Main) Difference: ARCA volume, inter-strings and inter-OM distances ≫ ORCA

KM3NeT: Wide energy range and physics cases, under construction but already taking data.

KM3NeT/ARCA: Astroparticle Research with Cosmics in the Abyss

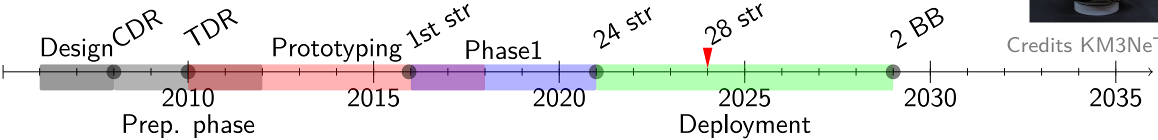
Location	100km S.E. Sicily (26°16N, 16°06E)
Max. Depth	3450 m
Nb. Strings [OM]	230 [4140]
Dist. inter- Str [OM]	90 m [36 m]
Strings height	700 m
Instrumented Vol.	1 km^3
Energy range	0.2 TeV - PeV
Trk angular resol.	0.1°



2 Building Blocks (BB) of 115 lines (18 DOMs). Central distance: ~1000 m

Multi-PMT DOMs (31PMT) → coverage, directionality, single DOM triggering.

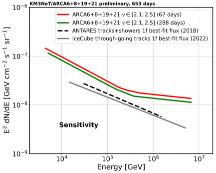
Credits KM3NeT

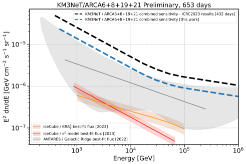


J. Phys. G: Nucl. Part. Phys. 43 08400 | Neutrino2024

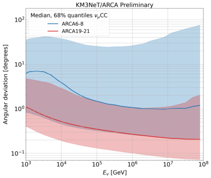
Some KM3NeT results [reported in S. Biagi talk (Jul. 9)]

Diffuse Flux - All Sky & Galatic plane

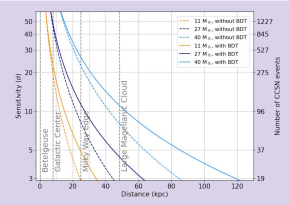




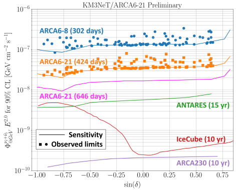
KM3NeT/ARCA Angular Resolution



CCSN sensitivity of ARCA28+ORCA24

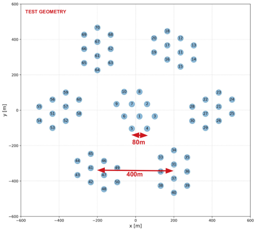


KM3NeT/ARCA6-21 PS sensitivity

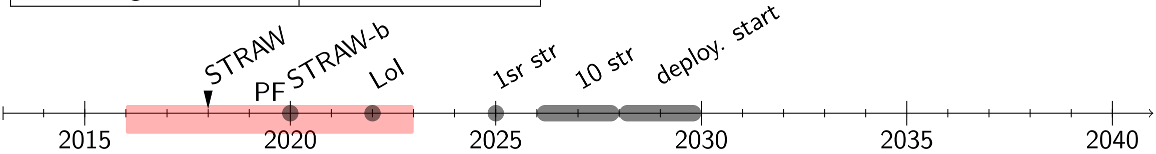


P-ONE: Pacific Ocean Neutrino Experiment

Location	Cascadia Basin (∼ 48°N, 129°W)
Max. Depth	2660 m
Nb. Strings [OM]	70 [1400]
Dist. inter- Str [OM]	80 m [50 m]
Strings height	1000 m
Instrumented Vol.	∼1 km^3
Energy range	TeV-PeV
Trk angular resol.	∼ 0.1°



Particularities:
- Multi-PMT DOMs (16 PMT/OM)
- Cluster Geometry (Intercluster 400 m).



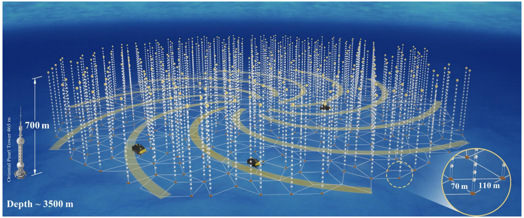
Agostini, Nat. Astron., s41550-023-02087-6 (2023)

Malecki, *Universe* 2024, 10(2), 53

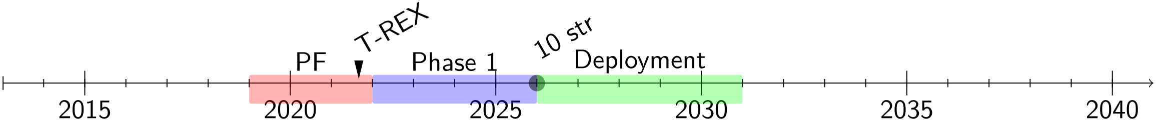
PoS (ICRC2023) 1175

TRIDENT: Tropical Deep-sea Neutrino Telescope

Location	S. China Sea (17.4°N, 114.0°E)
Max. Depth	3500 m
Nb. Strings [OM]	1211 [24220]
Dist. inter- Str [OM]	70/110m [30m]
Strings height	700 m
Instrumented Vol.	8 km^3
Energy range	>TeV
Trk angular resol.	0.1°



20 DOMs per line; Penrose tiling shape; **Hybrid OM**: PMT+SiPM → timing, waveform analysis (ν_τ)



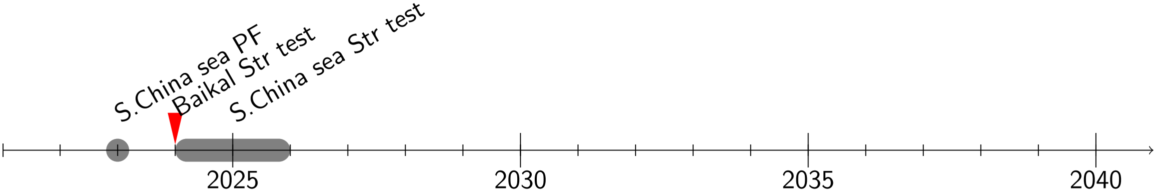
Nat. Astro. 10.1038/s41550-023-02087-6 (2023)
10.1016/j.nima.2023.168588(2023)
Neutrino2024

HUNT (Huge Underwater high-energy Neutrino Telescope)

Location	Baikal / S. China Sea
Max. Depth	1300 / 2500-3400
Nb. Strings [OM]	2304 [55300]
Dist. inter- Str [OM]	130 m [30 m]
Strings height	860 m
Instrumented Vol.	$\sim$30 km^3
Energy range	>100 TeV
Trk angular resol.	0.1°

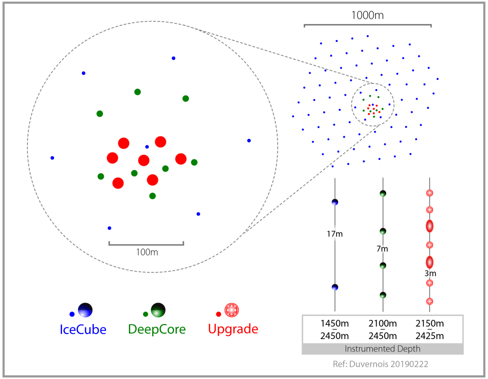
Single PMT OMs (24 OMs/line)
$\sim$30 km^3 $\rightarrow$ huge size detector.
PathFinders ongoing, CDR soon?

Huang, PoS (ICRC2023) 1080



IceCube Upgrades, Phase-1 [see C. Raab talk (Jul. 11)]

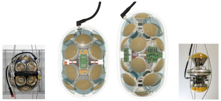
IC(86) + 7 strings in 2025-2026, 2150-2425 m depth, 22 m interstring space.



IceCube, PoS (ICRC2019) 1031

Purposes:

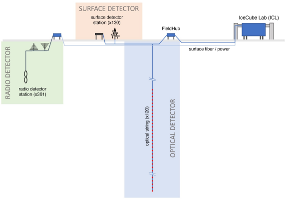
- Improve angular error reco. (**retroactive** to IC datas)
- Enhances sensitivity to
  - HE cosmic neutrino fluxes
  - oscillation: ν_τ appearance (PMNS matrix test)
  - dark matter
- R&D for Gen2



New OMs: mDOM and D-Egg (Gen2 TDR (2023))

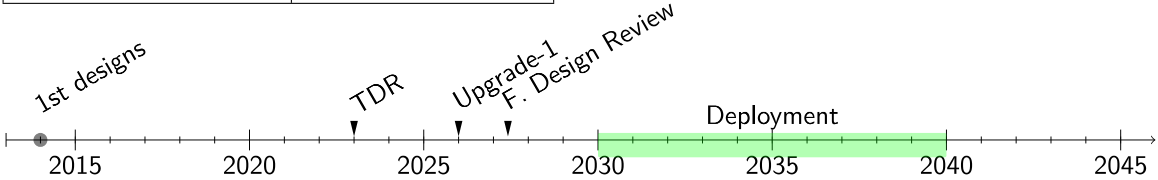
IceCube-Gen2, a multi instrument experiment: The optical detector

Location	Amundsen-Scott (90°S, 0°E)
Max. Depth	2689 m
Nb. Strings [OM]	93IC+120 [+9600]
Dist. inter- Str [OM]	120/240m [17m]
Strings height	1345 m
Instrumented Vol.	7.9 km^3
Energy range	5 TeV - >10 PeV
Trk angular resol.	0.3°



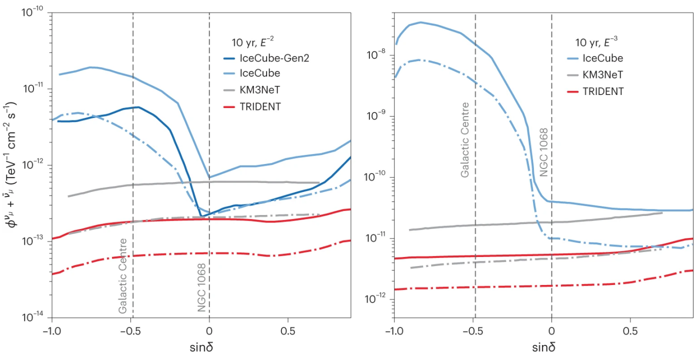
Multi-instrument: Optical + surface array + ice shower radio det.

OM: Multi-PMT, narrower (D-Egg). 240 m str spacing.
Core: IC historic (86 str, 120 m spacing) + IC upgrade (7 str, 22 m spacing)

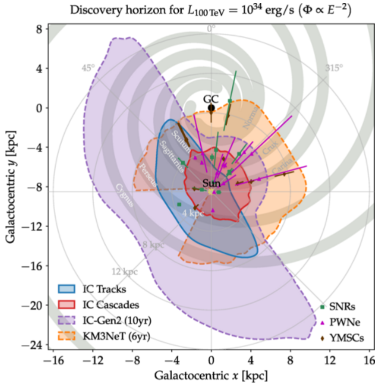


IC-Gen2 TDR (2023)

Projected sensitivities



Projected 90% CL Upper Limit sensitivity (Full-line) and Discovery Potential (Dashed) to ν Point Sources for TRIDENT, compared with IceCube, IceCube-Gen2 and KM3NeT/ARCA.
Assumed fluxes are, Left: E^{-2}, E>10 TeV; Right: E^{-3}, E>1 TeV (Wenlian, NIM-A 1056 (2023))

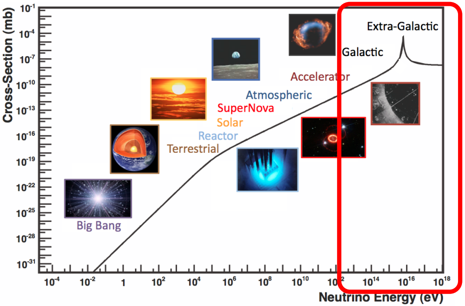


Projected P.S. Detection Horizon (assumed E^{-2} flux) of IceCube-Gen2 and KM3NeT/ARCA (Ambrosone, Phys. Rev. D 109 (2024))

Contents

Detection above the PeV: Neutrino induced shower

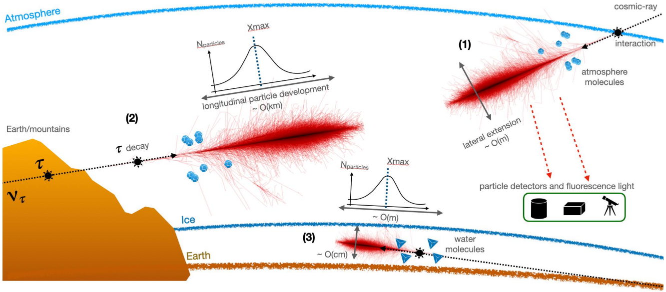
ν Cross-section increase with energy



Formaggio-Zeller, Rev. Mod. Phys. (2012)

VHE → earth opaque to ν (*i.e.*: transmission <2% @ 1 PeV): highest energies are horizontal

UHE cascades from eart-skimming neutrinos



Chiche & Decoene, Moriond 2022

Cherenkov and Fluorescence Air shower imaging detectors

Cherenkov detectors

Particles moving at relativistic speed in the air
$\Longrightarrow$ Cherenkov light

Technology from gamma-ray astronomy (like HESS / CTA)

Fluorescence detectors

Charged particles moving in a gas
$\Longrightarrow$ Ionisation and Excitation
$\rightarrow$ fluorescence lights (U.V., visible) along the track.
Efficient energy and direction reco.

Technology used in CRs experiments (like Auger)

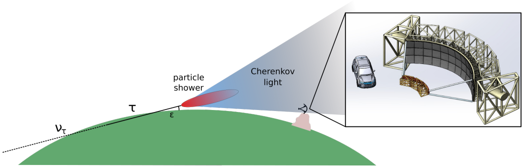
Some pros and cons:

+ Effective volume
- Require obscurity: duty cycle limited (*e.g.* moonless night);
- Light yield depends on atmospheric conditions.

Project of Cherenkov and Fluorescence detectors

Ground based experiments

- Ashra-NTA (PoS(ICRC2021)970)
  E_{ν_τ} PeV - EeV, Hawai
  2002 Proposal, 2008 Ashra-1, 2013 LoI
- Trinity (PoS(ICRC2023)1170): E_{ν_τ} PeV - 10 EeV
  2023: Demonstrator (Utah, US);
  2025: construction of 1st telescope.



Space based experiments

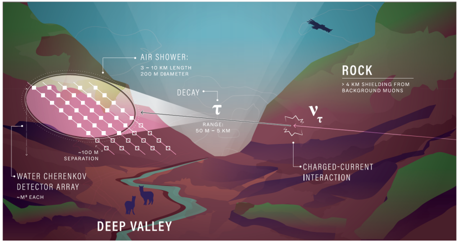
- POEMMA (PoS(ICRC2023)1159, CL+FL):
  E_{ν_τ} >20 PeV. 2 spacecraft, 5y mission.
  2026: Balloon mission
- JEM-EUSO (PoS(ICRC2023)208). 2013: ground det., 2019: ISS det., 2023: EUSO-SPB2 Balloon.
- NUSES (PoS(ICRC2023)391, CL):
  Spacecraft launch: end 2025

Surface Detector for particles detection

Principle: Detect particles of a cascade induced by earth skimming ν_τ, like in CRs searches (*e.g.* Auger). NB: Can be combined with Fluorescence imaging too.

TAMBO: Tau Air-Shower Mountain-Based Observatory (TAMBO, 2002.06475 (2023))

- $E(\nu_\tau)$: 1-100 PeV
- Location: Colca Canyon (Peruvian Andes)
- Dates: 2020: White Paper; 2023: Prototype construction
- Technology: array of water Cherenkov and/or plastic scintillator detectors



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) • COLCA VALLEY, PERU

Credits TAMBO

NB: AugerPrime (~2030) sensible to earth-skimming ν_τ > EeV Ackermann, J. HE Astrophy (2022).

Contents

Radio detection of shower

Geomagnetic Radiation

Magnetic field deflect $e^{\pm}$ in opposites directions + particle number vary $\Longrightarrow$ current varying in time → radio signal

→ Dominant in the air

Askaryan Radiation

Negative charge excess at shower front + positively charged plasma behind $\Longrightarrow$ moving dipole → radio signal

→ Dominant in dense medium (ice)

Air shower properties

Longitudinal dev.: $\mathcal{O}(km)$
Lateral extension: $\mathcal{O}(m)$
Radio attenuation length: ~1000km
Coherence band: [MHz : GHz]

Large attenuation lengths $\Longrightarrow$ Large effective volumes.

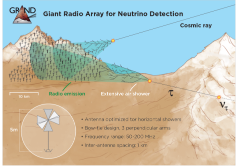
Ice shower properties

Longitudinal dev.: $\mathcal{O}(m)$
Lateral extension: $\mathcal{O}(cm)$
Radio attenuation length: ~1km
Coherence band: [100 MHz : GHz]
⚠Radio coherent cone aperture $[40° : 60°]$

Air shower radio detection with ground array

GRAND s11433-018-9385-7 (2019)
Giant Radio Array for Neutrino Detection

E_ν >50 PeV, Autonomous radio detection
Proto: GP300 (Gobi desert), Nançay, @Auger
Future steps: GRAND10k (2028)
Target: GRAND200k (= 20 sites of 10k).

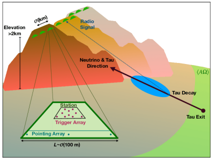


Credits GRAND

BEACON 2022.167889, NIM-A (2022)
Beam forming Elevated Array for COsmic Neutrinos

E_ν >30 PeV, Interferometry @30-80 MHz from top of mountain (increased FoV)
Now: 8 antenna prototype in California
Target: 100 antennas

Credits BEACON



TAROGE PoS(ICRC2023)1126

Self-triggered antenna array, E_ν >100 PeV, Mt. Melbourne, Antartica. Prototypes in 2020, 2023

∃ Proposal to use a forest as antenna Prohira, 2401.14454 (2024)

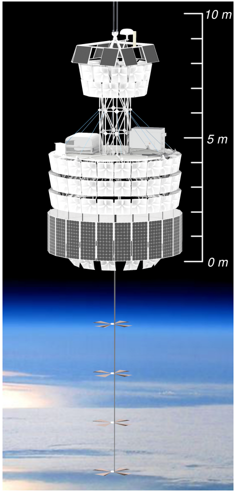
Radio detection from air and space

PUEO: Payload for Ultrahigh Energy Observations (PUEO, J.Inst 16 (2021)).

Long-duration balloon experiment over Antarctic
2 instruments: [300-1200] MHz (main); [50-300] MHz (larger eff. area).
→ 30 days flight planned for 2025-2026 austral summer.

100 PeV energy threshold, ×100 ANITA I-IV integrated sensitivity.
Sensible to:

- Earth-skimming tau neutrinos;
- Neutrinos interacting in the ice;
- Geomagnetic radio emission from UHECRs (stratosphere included).



Credits PUEO

NB: ∃ also project to detect ν interaction in moon regolith.

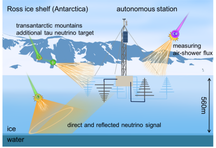
Radio detection in the ice

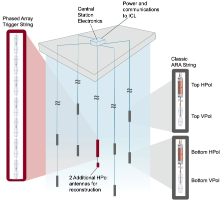
RNO-G: Radio Neutrino Astronomy in Greenland (PoS(EPS-HEP2023)076).
Energy threshold 50 PeV.

Design based on ARIANNA and ARA:

- Sub surface antenna (-3 m)
- Deep antenna (-100 m)
- 7 stations deployed before summer 2024.
- Target: 35 stations (1.25 km spread) by 2027 → 40 km^2.

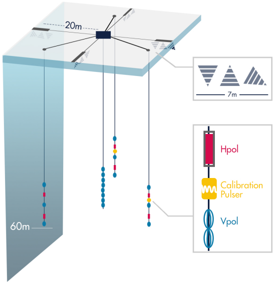
ARIANNA, ~15 m





ARA, ~150-200 m

=



ICGen2-Radio. E_ν[10 PeV : EeV]. ~400 km^2, ~200 sub-surface + ~150 hybrid (RNO-G like)

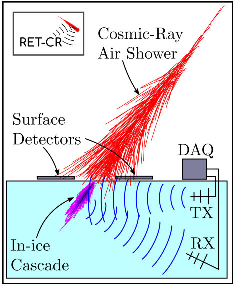
Radar echoes detection

Principles: Radio wave are reflected on the ionization trail left by ice showers.
Send radio signal with transmitter, detect echoes with receiver → **Active method** for detecting UHE neutrinos.

RET-N: Radar Echo Telescope (PoS(ICRC2023)1135), E ∈ [PeV : EeV]

2018: Concept validation by T-576 experiment.
2023: RET-CR (Cosmic Ray) pathfinder deployed in Greenland: Tiggered on CRs by scintillator panels

Target: Self-triggered station, comprising
(a) a central phased-array radio transmitter;
(b) an array of receivers (hundreds meters baseline), buried ∼1.5 km deep.



Credits RET-CR

Contents

Takes away messages and conclusion

Various kind of detectors coming, some oncoming, other in project:

- Order of magnitude increased sensitivity.
- Diverse Neutrino Astronomy Targets $\Longrightarrow$ different (but complementary) detectors.
- Various techniques: reduce holds in the racket.
- Wider energy range (and potential sources) covered.
- Powerful astronomy capabilities by combining results (minimize background hypothesis)

→ **Needs of collaboration** and tools for real-time data combination.

- Universe opaque at PeV/EeV: **Only NTs can do astronomy at UHE**.

Low to medium energies not addressed here, but a lot of physics can be done there too, *e.g*: SN detection, mass hierarchy, dark matter, NSI, ...

New era begins, bright future is ahead of us: STAY TUNED!

GRAZIE A LEI!

Some references used to prepare this presentation:

Decoene, PoS (ICRC2023) 026

Palladino, Spurio and Vissani, *Universe* (2020).

Ackermann *et al.*, J. High Energy Astrophysics (2022).

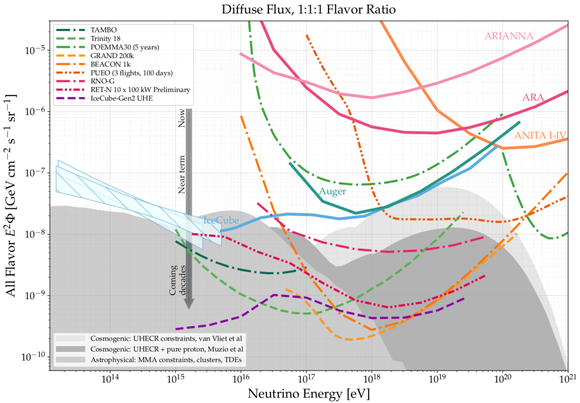
S. Navas *et al.* (PDG), Phys. Rev. D 110, 030001 (2024).

Guepin, Kotera and Oikonomou, Nat. Rev. Phys. (2022).

Note: Pictures without close-by credits comes from paper referenced in each slide.

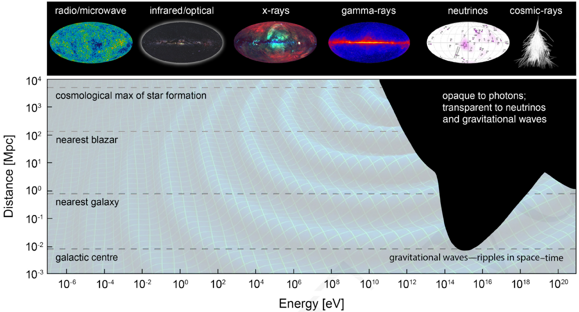
BACKUP

What to expect for the highest energies?



Expected differential 90% C.L. sensitivities for a variety of experiments to an all-flavor diffuse neutrino flux computed in decade-wide energy bins and assuming a ten-year integration. From Ackermann (2022).

Opaque Universe



From Multimessenger Astronomy, Bartos and Kowalski
Radio/microwave image, credit: ESA/DLR/Ducris, CC BY-SA 3.0 IGO. Infrared/optical image, credit: Axel Mellinger, www.milkywaysky.com. X-rays image, credit: X-Ray Group at the Max-Planck-Institut fur extraterrestrische Physik (MPE). Gamma-rays image, credit: NASA/DOE/Fermi LAT Collaboration. Neutrinos and cosmic-rays images, credit: IceCube.