High-Energy Messengers: Present & Future

Markus Ahlers
WIN2019, Bari
June 6, 2019
Acceleration of charged nuclei (cosmic rays) - especially in the aftermath of cataclysmic events, sometimes visible in gravitational waves.

Inelastic cosmic ray collisions with gas or radiation create a flux of secondary pions/kaons.

Secondary neutrinos and gamma-rays from pion decays:

\[
\begin{align*}
\pi^+ & \rightarrow \mu^+ + \nu_\mu \\
\pi^0 & \rightarrow \gamma + \gamma \\
\downarrow & e^+ + \nu_e + \nu_\mu
\end{align*}
\]
Unique abilities of cosmic neutrinos:

- no deflection in magnetic fields (unlike cosmic rays)
- no absorption in cosmic backgrounds (unlike gamma-rays)

smoking-gun of unknown sources of cosmic rays

coincident with photons and gravitational waves

...but difficult to detect...
High-Energy Neutrino Interaction

- Low-energy (<10GeV) neutrino interaction with matter in quasi-elastic or resonant interactions.
- High-energy neutrinos interact with nuclei via deep inelastic scattering.

[Diagram showing lepton scattering, interaction with individual quarks, and hadronic cascade]

[Graphs showing charged and neutral current cross-sections as a function of neutrino energy]

[Cooper-Sarkar, Mertsch & Sarkar’11]
Secondary charged particle are visible via optical Cherenkov emission in **transparent media**.

*back-of-the-envelope* \( (E_{\nu} \sim 1\text{PeV} = 10^{15}\text{ eV}) : \)

- **flux of neutrinos** : \( \frac{d^2N_{\nu}}{dt\ dA} \sim \frac{1}{\text{cm}^2 \times 10^5\text{yr}} \)
- **cross section** : \( \sigma_{vN} \sim 10^{-8} \sigma_{pp} \sim 10^{-33}\text{cm}^2 \)
- **targets** : \( N_N \sim N_A \times V/\text{cm}^3 \)
- **rate of events** :

\[
\dot{N}_\nu \sim N_N \times \sigma_{vN} \times \frac{d^2N_{\nu}}{dt\ dA} \sim \frac{1}{\text{year}} \times \frac{V}{1\text{km}^3}
\]

**minimum detector size : 1\text{km}^3**
Cherenkov Observatories

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**Notes:**
- ANTARES/KM3NeT talk by Pasquale Migliozzi (Tuesday)
The IceCube Observatory

- Giga-ton Cherenkov telescope at the South Pole
- Collaboration of about 300 scientists at 47 international institutions
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings instrumenting 1 km³ of clear glacial ice
- 81 IceTop stations for cosmic ray shower detections
- 7-year construction phase (2004–2011)
- Price: $0.3 per ton
→ Selecting **up-going muon tracks** reduces atmospheric muon background:

\[
\begin{align*}
\text{atmospheric muons (from above)} & \quad : \quad 10,000,000,000 \\
\text{atmospheric neutrinos} & \quad : \quad 100,000 \\
\text{cosmic neutrinos} & \quad : \quad 10
\end{align*}
\]
• Outer layer of optical modules used as virtual **veto region** (gray area)

• **Atmospheric muons** pass through veto from above.

• **Atmospheric neutrinos** coincidence with atmospheric muons.

• **Cosmic neutrino** events can start inside the fiducial volume.

• **High-Energy Starting Event (HESE)** analysis
First observation of high-energy astrophysical neutrinos by IceCube.

“track event” (from $\nu_\mu$ scattering)

“cascade event” (from all flavours)

$E_{\text{dep}} \approx 71$ TeV

$E_{\text{dep}} \approx 1.0$ PeV

[“Breakthrough of the Year” (Physics World), Science 2013]
(neutrino event signature: early to late light detection)
**High-Energy Starting Events (HESE) (7yrs):**  
- bright events ($E_{th} \gtrsim 30\text{TeV}$) starting inside IceCube  
- efficient removal of atmospheric backgrounds by veto layer  

**Up-going muon-neutrino tracks (8yrs):**  
- large effective volume due to ranging in tracks  
- efficient removal of atmospheric muon backgrounds by Earth-absorption
Similar intensity, but mild tension between power-law fits

Indications for spectral breaks?
Energy resolution of detectors is limited and neutrino source is distant.

\[ P_{\nu_\alpha \rightarrow \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathcal{R}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \Delta_{ij} + 2 \sum_{i>j} \mathcal{R}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin 2\Delta_{ij} \rightarrow 1/2 \]

\[ \rightarrow 0 \]

\[ P_{\nu_\alpha \rightarrow \nu_\beta} \approx \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 \]

oscillation-averaged probability:

- initial composition: \( \nu_e : \nu_\mu : \nu_\tau \)
  - pion & muon decay: 1 : 2 : 0
  - muon-damped decay: 0 : 1 : 0
  - neutron decay: 1 : 0 : 0

Astrophysical Flavours

Resimulation shows good data - MC agreement on time delays if assuming hadronic cascades with leading muon ~40 GeV

Early muons from hadronic cascade

Glashow resonance candidate

6.3 PeV

W-resonance

MOTIVATION TO DEVELOP NEW TECHNIQUES

A gift from nature – Glashow resonance at 6.3 PeV

E= M^2 W/(2 m_e) = 6.3 PeV

A boost of cross-section by a factor of 300!

At ~68% in hadronic cascade channel

6.3 PeV reconstructed energy

Glashow resonance candidate

Astrophysical Flavours

IceCube Preliminary

Expected events in 4.6 yrs per bin

E^{-2.13} no cut off

reconstructed energy
- Tau neutrino charged current interactions can produce second hadronic cascades from tau decays (“double-bangs”).

- Arrival time of delayed Cherenkov photons is visible in individual DOMs.

**tau neutrino candidate**
1 PeV neutrinos require collisions of 20-30 PeV cosmic ray nucleons.
Figure 29.8: The all-particle spectrum as a function of $E$ (energy-per-nucleus) from air shower measurements [91–106].

Energy. Some types of expanding supernova remnants, for example, are estimated not to be able to accelerate protons above energies in the range of $10^{15}$ eV. Effects of propagation and confinement in the Galaxy [111] also need to be considered. A discussion of models of the knee may be found in Ref. 112. The KASCADE-Grande experiment [101] has reported observation of a second steepening of the spectrum near $8 \times 10^{16}$ eV, with evidence that this structure is accompanied a transition to heavy primaries.

Concerning the ankle, one possibility is that it is the result of a high energy population of particles overtaking a lower energy population, for example an extragalactic flux beginning to dominate over the galactic flux (e.g. Ref. 107). Another possibility is that the dip structure in the region of the ankle is due to $p\gamma \rightarrow e^+ + e^-$ energy losses of extragalactic protons on the 2.7 K cosmic microwave radiation (CMB) [114]. This dip structure has been cited as a robust signature of both the protonic and extragalactic nature of the highest energy cosmic rays [113]. If this interpretation is correct, then the galactic cosmic rays do not contribute significantly to the flux above $10^{18}$ eV.
No significant steady or transient emission from known Galactic and extragalactic high-energy sources (except for one candidate).
Status of Neutrino Astronomy

1967

Orbiting Solar Observatory (OSO-3) (Clark & Kraushaar’67)
between the two axes of the error ellipses was 1.20, so most Gaussian distribution, not the full TS map and an ellipse as good enough to constrain the absolute precision well 3FGL, but the statistical precision on localization was not were not calibrated on 3FHL itself, but on the larger ratio was even smaller, 1.12. 

provides only a symmetric brightest sources. This ensures that the surrounding sources were correctly represented. The main drawback is that the main iterative procedure at large off-axis angles function of its event type and off-axis angle were treated just as point sources, except (see the Appendix) for their spatial templates. Whenever possible, we applied the new RadialDisk and RadialGaussian analytic spatial templates. Whenever possible, we applied the alt-ergo with 4 degrees of freedom minimized. The global best rejected because of this limit, and only two have been systematically tested, and adopted when threshold to 3.

We ended up with 1556 sources with TS\_ndsrc > 25 with the PL model, corresponding to a significance of 4\_{\text{ab}} \sigma \text{ evidence in favor of the curved model. At the end of the iteration, we reduced the number of sources to 1490. Of these, 623 were discarded, 42 of which were rejected because of the curvature limit. Among the remaining 1303 sources, 348 were considered extended sources.}

The alternative curved LogParabola model-predicted events for the likelihood calculation. They are not pixelized and hence including sources in the outer parts of the RoI from the neighboring RoIs at the previous step. Above 10 GeV the PSF broadens rapidly. The diffuse emission model had exactly one free normalization parameter per RoI. The threshold was 4. The systematic uncertainties associated with localization was systematically tested, and adopted when threshold to 3. It was systematically tested, and adopted when threshold to 3. It was systematically tested, and adopted when threshold to 3. It was systematically tested, and adopted when threshold to 3.
Contribution of Galactic diffuse emission at 10TeV-PeV is subdominant.
Extragalactic Source Candidates

- association with sources of UHE CRs
  - [Kistler, Stanev & Yuksel’13]
  - [Katz, Waxman, Thompson & Loeb’13; Fang, Fujii, Linden & Olinto’14; Moharana & Razzaque’15]

- association with diffuse $\gamma$-ray background
  - [Murase, MA & Lacki’13]
  - [Chang & Wang’14; Ando, Tamborra & Zandanel’15]

- active galactic nuclei (AGN)
  - [Stecker’13; Kalashev, Kusenko & Essey’13]
  - [Murase, Inoue & Dermer’14; Kimura, Murase & Toma’14; Kalashev, Semikoz & Tkachev’14]
  - [Padovani & Resconi’14; Petropoulou et al.’15; Padovani et al.’16; Kadler et al.’16; Wang & Loeb’16]

- gamma-ray bursts (GRB)
  - [Murase & Ioka’13; Dado & Dar’14; Tamborra & Ando’15]
  - [Senno, Murase & Meszaros’16; Denton & Tamborra’18; Boncioli, Biehl & Winter’18]

- galaxies with intense star-formation (e.g. starbursts)
  - [He, Wang, Fan, Liu & Wei’13; Yoast-Hull, Gallagher, Zweibel & Everett’13; Murase, MA & Lacki’13]
  - [Anchordoqui, Paul, da Silva, Torres & Vlcek’14; Tamborra, Ando & Murase’14; Chang & Wang’14]
  - [Liu, Wang, Inoue, Crocker & Aharonian’14; Senno, Meszaros, Murase, Baerwald & Rees’15]
  - [Chakraborty & Izaguirre’15; Emig, Lunardini & Windhorst’15; Bechtol et al.’15]

- galaxy clusters/groups
  - [Murase, MA & Lacki’13; Zandanel, Tamborra, Gabici & Ando’14]

- tidal disruption events (TDE)
  - [Wang, Liu, Dai & Cheng’11; Senno, Murase & Més’aros’17]
  - [Guépin, Kotera, Barausse, Fang & Murase’17; Biehl, Boncioli, Lunardini & Winter’17]
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.

Southern Hemisphere | Northern Hemisphere

- No significant time-independent point sources emission in all-sky search.
- No significant time-independent emission from known Galactic and extragalactic high-energy sources.
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.

Southern Hemisphere | Northern Hemisphere

KM3NeT

- KM3NeT/ARCA, 6 y
- IceCube, 7 y
- ANTARES, 9 y

$E^2 \Phi_{90} [\text{GeV s}^{-1} \text{cm}^{-2}]$

- $10^{-10}$
- $10^{-9}$
- $10^{-8}$
- $10^{-7}$

$\sin(\delta)$

- $-1$
- $-0.5$
- $0$
- $0.5$
- $1$


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Where are the Sources?

Rare objects, like blazars or gamma-ray bursts, can not be the dominant sources of TeV-PeV neutrino emission (magenta band).
The 90% credible intervals (Veitch et al. 2015; Abbott et al. 2017) for the component masses (in the $m_{\text{m}}^{12}$ convention) are $m_{\text{m}1} = 1.36, 2.26 \pm 0.86, 1.36 \pm 0.89$ for total mass $M = 2.82_{-0.09}^{+0.47}$. Considering dimensionless spin with magnitudes up to 0.89 (high-spin prior, hereafter), when the dimensionless spin prior is restricted to 0.05 (low-spin prior, hereafter), the measured component masses are $m_{\text{m}1} = 1.36, 1.17, 1.36$ and $m_{\text{m}2} = 1.60$. With a high energy limit of least 80 MeV, the total mass is $M = 2.82_{-0.09}^{+0.47}$.

**First binary neutron star merger observed in gravitational waves (GW170817) coincident with a short gamma-ray burst (GRB 170817A).**

**Gravitational Wave Follow-Up**

![Gravitational wave light curves and time-frequency map](image)

**Figure 2.** Joint, multi-messenger detection of GW170817 and GRB 170817A. Top: the summed GBM lightcurve for sodium iodide (NaI) detectors 1, 2, and 5 for GRB 170817A between 10 and 50 keV, matching the 100 ms time bins of the SPI-ACS data. The background estimate from Goldstein et al. (2016) is overlaid in red. Second: the same as the top panel but in the 50–300 keV energy range. Third: the SPI-ACS lightcurve with the energy range starting approximately at 100 keV and an high energy limit of least 80 MeV. Bottom: the time-frequency map of GW170817 was obtained by coherently combining LIGO-Hanford and LIGO-Livingston data. All times here are referenced to the GW170817 trigger time $T_{\text{GW}}$. The Astrophysical Journal Letters, 848:L13 (27pp), 2017 October 20 Abbott et al.
Search for neutrino emission from GRB 170817A by ANTARES, IceCube & Pierre Auger.

No neutrino candidates found within +/-500s and the GW 90% angular uncertainty region.

LVC O3 science run (since April 1): near real-time follow-up by IceCube
Cosmic ray acceleration expected in internal shocks of short duration gamma-ray burst.

- Short-term neutrino production in scattering off photons (top panel).
- Non-observation consistent with off-axis emission:
  \[ F_{\text{off}}(E_{\nu}) = \frac{\delta(\theta)}{\delta(0^\circ)} F_{\text{on}} \left( \frac{\delta(0^\circ)}{\delta(\theta)} E_{\nu} \right) \]
- Doppler factor:
  \[ \delta(\theta) = \frac{1}{\Gamma(1 - \beta \cos \theta)} \]
- Long-term neutrino emission from remnant pulsar wind (bottom panel).

**Figure 2.** GW170817 Neutrino limits (fluence per flavor: \(\nu_x + \bar{\nu}_x\))

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IceCube and ANTARES issue realtime neutrino alerts to multi-messenger partners for rapid follow-up.

- time to issue alert: 5s
- median angular resolution 0.5deg
- **neutrino doublets**
  - 0.04 alerts/year
- **neutrinos from local galaxies (>1TeV)**
  - 10 alerts/year
- **high-energy neutrinos (>5TeV)**
  - 20 alerts/year
- **very high-energy neutrinos (>30TeV)**
  - 3-4 alerts/year

- 50% astrophysical neutrino fraction
- angular resolution 0.5-2deg
- **high-energy starting tracks (>60TeV)**
  - 4.8 alerts/year (1.1 signal/year)
- **through-going muons (>100TeV)**
  - 4-5 alerts/year (2.5-4 signal/year)

[Blaufuss et al., Proceedings of ICRC 2017] [Dornic et al., Proceedings of ICRC 2017]
The vast majority of neutrinos detected by IceCube arise from cosmic-ray interactions within Earth’s atmosphere. Although atmospheric neutrinos are dominant at energies below 100 TeV, their spectrum falls steeply with energy, allowing astrophysical neutrinos to be more easily identified at higher energies. The muon-neutrino astrophysical spectrum, together with simulated data, was used to calculate the probability that a neutrino at the observed track energy and zenith angle in IceCube is of astrophysical origin. This probability, the so-called signalness of the event, was reported to be 56.5%. Although IceCube can robustly identify astrophysical neutrinos at PeV energies, for individual neutrinos at several hundred TeV, an atmospheric origin cannot be excluded. Electromagnetic observations are valuable to assess the possible association of a single neutrino to an astrophysical source. Following the alert, IceCube performed a complete analysis of relevant data prior to 31 October 2017. Although no additional excess of neutrinos was found from the direction of TXS 0506+056 near the time of the alert, there are indications at the 3σ level of high-energy neutrino Fig. 1. Event display for neutrino event IceCube-170922A. The time at which a DOM observed a signal is reflected in the color of the hit, with dark blues for earliest hits and yellow for latest. Times shown are relative to the first DOM hit according to the track reconstruction, and earlier and later times are shown with the same colors as the first and last times, respectively. The total time the event took to cross the detector is ~3000 ns. The size of a colored sphere is proportional to the logarithm of the amount of light observed at the DOM, with larger spheres corresponding to larger signals. The total charge recorded is ~5800 photoelectrons. Inset is an overhead perspective view of the event. The best-fitting track direction is shown as an arrow, consistent with a zenith angle 5°±0°:50/C0°±30° below the horizon.

Fig. 2. Fermi-LAT and MAGIC observations of IceCube-170922A’s location. Sky position of IceCube-170922A in J2000 equatorial coordinates overlaying the γ-ray counts from Fermi-LAT above 1 GeV (A) and the signal significance as observed by MAGIC (B) in this region. The tan square indicates the position reported in the initial alert, and the green square indicates the final best-fitting position from follow-up reconstructions (18). Gray and red curves show the 50% and 90% neutrino containment regions, respectively, including statistical and systematic errors. Fermi-LAT data are shown as a photon counts map in 9.5 years of data in units of counts per pixel, using detected photons with energy of 1 to 300 GeV in a 2° by 2° region around TXS0506+056. The map has a pixel size of 0.02° and was smoothed with a 0.02°-wide Gaussian kernel. MAGIC data are shown as signal significance for γ-rays above 90 GeV. Also shown are the locations of a γ-ray source observed by Fermi-LAT as given in the Fermi-LAT Third Source Catalog (3FGL) (23) and the Third Catalog of Hard Fermi-LAT Sources (3FHL) (24) source catalogs, including the identified positionally coincident 3FGL object TXS 0506+056. For Fermi-LAT catalog objects, marker sizes indicate the 95% CL positional uncertainty of the source.
TXS 0506+056

- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.
Active galaxy powered by accretion onto a supermassive black hole with relativistic jets pointing into our line of sight.
Neutrino Flare in 2017

- Photon SED can be modelled by lepto-hadronic or proton-synchrotron models.
  
  "[Keivani et al.'18,; Gao et al.'18; Cerruti et al.'18; Zhang, Fang & Li'18; Gokus et al.'18; Sahakyan'18]

- Neutrino flux limited to **less than one event** by theoretically feasible cosmic ray luminosity and X-ray data.
  
  "[Murase, Oikonomo & Petropoulou’18]

- **Eddington bias**: expected number of events expected from BL Lacs observed by one event in the range **0.006 - 0.03**
  
  "[Strotjohann, Kowalski & Franckowiak’18]"
Neutrino Flare in 2014/15

- Independent 3.5σ evidence for a **neutrino flare** (13±5 events) in 2014/15.
- Neutrino luminosity over 158 days is about **four times brighter than gamma-ray emission** (Fermi-LAT).
- On average, **1000 times brighter** than 2017 neutrino flux

neutrino “morphology” of 2014/15 flare
Are Blazars the TeV-PeV Sources?

- Blazar stacking limits derived from Fermi-LAT AGN catalogue (2LAC).
- Upper limit on the diffuse flux at the level of 30% assuming all blazar classes contribute.
- Energy of IC-170922A in the region of strongest differential upper limit.
Further progress on diffuse emission via multi-messenger relations:

(A) **Joint production** of gamma-rays and neutrinos in CR interactions.

(B) Low-rigidity CRs trapped in **calorimetric environments** (e.g. starburst galaxies).

(C) **GZK neutrinos** from UHE CR propagation in cosmic backgrounds.
Hadronic Gamma-Rays

- Joint production of gamma-rays and neutrinos from cosmic ray collisions.

- TeV gamma-rays initiate electromagnetic cascades in collisions with cosmic microwave background.
Hadronic Gamma-Rays

• Gamma-ray emission from EM cascades ends up in the sub-TeV range observed with Fermi-LAT.

• In addition, CR interactions with gas (pp) predict extended power-law spectra of neutrinos and gamma-rays.

• Cosmic ray spectral index strongly constrained by the isotropic diffuse gamma-ray background (IGRB):
  \[ \Gamma \leq 2.15 \]

• IceCube best-fit (HESE 7.5yr):
  \[ \Gamma \approx 2.87 \pm 0.3 \]

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Isotropic Diffuse Gamma-Ray BGR

- **Isotropc diffuse gamma-ray background (IGRB)** consists of unidentified point-like sources and diffuse contributions.
- Extrapolation of identified (bright) gamma-ray sources allows to model the emission.
- Large contribution (>50%) from unidentified blazars (BL Lac) at E>50 GeV
Hidden Sources?

Efficient production of 10 TeV neutrinos requires strong X-ray backgrounds.

High pion production efficiency implies strong internal gamma-ray absorption in Fermi-LAT energy range:

\[ \tau_{\gamma\gamma} \approx 1000 f_{p\gamma} \]

[Guetta, MA & Murase’16]

Fermi-LAT

\[ p\gamma/\gamma\gamma \text{ optical depth correspondence} \]

\[ \text{power law } (\alpha=2.5) \]

\[ \text{power law } (\alpha=2/3) \]

\[ \text{gray body} \]

\[ \tau_{\gamma\gamma} \]

\[ v \ & \ CR \ bound \ on \ \gamma\gamma \ annihilation \]

\[ f_{p\gamma} \]

\[ v \ & \ CR \ bound \ on \ p\gamma \ interaction \]

\[ \log(\tau_{\gamma\gamma}) \text{ or } \log(f_{p\gamma}) \]

\[ \text{opaque} \]

\[ \text{transparent} \]

\[ \log(\epsilon) \ [\text{GeV}] \]

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• **Ultra-High Energy (UHE) CR** spectrum (>EeV) expected to show suppression due to resonant interactions with cosmic microwave background beyond ~40EeV (GZK-cutoff).

  [Greisen & Zatsepin’66;Kuzmin’66]

• UHE CRs above 40EeV limited to local Universe (~200Mpc).

• **Window for UHE CR astronomy** for light composition (high rigidity).

  ![Graph](image)

  - Suppression feature observed in spectra with high significance.

  - However, could also be related to **intrinsic cutoff** of UHE CR sources.

  - **Testable by GZK neutrinos.**

  [Berezinsky & Zatsepin’70]
UHE CR Composition

- **Composition of UHE CR** determined by fits of shower maxima ($X_{\text{max}}$) distribution.
- **Large systematic uncertainties in hadronic interaction models**
- **Auger**: significant contribution of heavy nuclei above the ankle.

![Graph showing species fractions and fitted fraction and quality for the scenario of a complex mixture of protons, helium nuclei, nitrogen nuclei, and iron nuclei. The upper panels show the species fractions and the lower panel shows the $p$-values.](image-url)

- [Auger’17]
GZK Neutrinos

- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range. [Berezinsky&Zatsepin’70]

- Target of proposed in-ice Askaryan (ARA & ARIANNA), air shower Cherenkov (GRAND) or fluorescence (POEMMA & Trinity) detectors.

- Optimistic predictions based on high proton fraction and high maximal energies. [e.g. MA et al.’10; MA & Halzen’12]

- Absolute flux level serves as independent measure of UHE CR composition beyond 40EeV. [Alves Batista et al.’19]
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  \[ \text{[e.g. MA et al.'10; MA \& Halzen'12]} \]

- Absolute flux level serves as independent measure of UHE composition beyond 40EeV.

**Figure 17.** Predicted fluxes of cosmogenic neutrinos and expected sensitivities of current, upcoming and proposed UHECR and UHE neutrino experiments. Upper limits are from IceCube \[ \text{[71]} \] and the Pierre Auger Observatory \[ \text{[72]} \]. Sensitivities are for POEMMA \[ \text{[400]} \] (assuming full-sky coverage), GRAND in its 10 000-antenna (GRAND10k) and 200 000-antenna configurations (GRAND200k) \[ \text{[392]} \], ARA-37 \[ \text{[401]} \] (trigger level), ARIANNA \[ \text{[402]} \] ("optimal wind" sensitivity), and Trinity \[ \text{[403]} \] (10 m\(^2\)) mirror.

**OUTLOOK**

Despite revolutionary progress, some critical, long-standing questions in the field of UHECRs remain unanswered, or only answered partially: What are the sources of UHECRs? What is the mass composition of UHECRs at the highest energies? What mechanism accelerates CRs beyond PeV energies? What is the flux of secondary messengers — neutrinos, gamma rays — associated with UHECRs, and what can we infer from them about UHECR sources?

Observations performed by current and planned ultrahigh-energy facilities have an opportunity to give definite answers to these questions. Yet, to fulfill this potential, it is necessary to undertake a number of essential steps towards experimental and theoretical progress. Below, we list what we believe are the most important of these. This list is, of course, non-exhaustive and only expresses our views.

- **UHECR composition:** Precise measurement of the UHECR mass composition near the end of the spectrum is hindered by uncertainties in models of hadronic interaction, uncertainties in measuring \( X_{\text{max}} \), and small statistics. The latter issue will be addressed by upgraded configurations of current...  
  \[ \text{[Alves Batista \textit{et al.}'19]} \]

- **Cosmogenic (GZK) neutrinos** produced in UHE CR interactions peak in the EeV energy range.  
  \[ \text{[Berezinsky\&Zatsepin'70]} \]

- **Target of proposed in-ice Askaryan (ARA \& ARIANNA), air shower Cherenkov (GRAND) or fluorescence (POEMMA \& Trinity) detectors.**

- **Optimistic predictions based on high proton fraction and high maximal energies.**  
  \[ \text{[e.g. MA \textit{et al.}'10; MA \& Halzen'12]} \]

- **Absolute flux level serves as independent measure of UHE composition beyond 40EeV.**  
  \[ \text{[Alves Batista \textit{et al.}'19]} \]
• UHE CR arrival direction above 8 EeV show strong (6.5%) dipole anisotropy (5.2σ). [Auger’17]

• Arrival directions of UHE CRs above 40 EeV show correlation with local starburst galaxies (4σ). [Auger’18]

• Indications for medium-scale anisotropy above 16 EeV in Northern Hemisphere (3.7σ) [TA’18]
**UHE CR Anisotropy**

- UHE CR arrival direction above 8EeV show **strong** (6.5%) dipole **anisotropy** (5.2σ).
  - [Auger’17]
- Arrival directions of UHE CRs above 40 EeV show **correlation with local starburst galaxies** (4σ).
  - [Auger’18]
- **Indications for medium-scale anisotropy** above 16 EeV in Northern Hemisphere (3.7σ) [TA’18]

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![Auger talk by Roberta Colalillo (Tuesday)](auger_talk.png)

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• UHE CR proton emission rate density:

\[ [E_p^2 Q_p(E_p)]_{10^{19.5}\text{eV}} \simeq 8 \times 10^{43} \text{erg Mpc}^{-3} \text{yr}^{-1} \]

• neutrino flux can be estimated as (\(\zeta_z\) : factor accounting for redshift evolution):

\[
E_{\nu}^2 \phi_{\nu}(E_{\nu}) \simeq f_\pi \frac{\zeta_z K_\pi}{1 + K_\pi} \underbrace{1.5 \times 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}}_{\mathcal{O}(1)} \sim \text{IceCube diffuse}
\]

\(\Rightarrow\) limited by pion production efficiency: \(f_\pi \leq 1\)  

• similar UHE nucleon emission rate density (local minimum at \(\Gamma \simeq 2.04\))  

\[ [E_N^2 Q_N(E_N)]_{10^{19.5}\text{eV}} \simeq 2.2 \times 10^{43} \text{erg Mpc}^{-3} \text{yr}^{-1} \]

• Sources of UHECRs could be embedded in “calorimetric” environments (\(f_\pi = 1\)), producing a large flux of neutrinos, e.g., starburst galaxies or galaxy clusters.
Observed neutrino flux close to Waxman-Bahcall (WB) limit:

Common origin of TeV-PeV neutrinos and UHE CRs?
• Intense star formation enhances UHE CR production, e.g. by gamma-ray bursts.

• Low-energy cosmic rays remain magnetically confined and eventually collide in dense environment.

• In time, efficient conversion of CR energy density into gamma-rays and neutrinos. [Loeb & Waxman ’06]

• Expect power-law neutrino spectra with high-energy break from CR leakage.

[Loeb & Waxman ’06]
• **No significant cross-correlation** found between UHE CRs and HE neutrinos.

• Galactic and extragalactic magnetic fields can introduce **significant angular deflections and time delays**: \( \Delta t \approx d(\Delta \psi)^2 \)

• Maximal cross-correlation **limited by GZK horizon**: \( \lambda_{\text{GZK}}/\lambda_{\text{Hubble}} \approx 5\% \)
Outlook: Baikal-GVD

- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by 2020/21 (~0.4 km³)
- Cluster depth: 735–1260 m
- 5 clusters deployed 2016–19
- **final goal:** 27 clusters (~1.4 km³)

First physics results: cascade spectrum / cascade event in 2015 data
KM3NeT 2.0: Letter of Intent for ARCA and ORCA

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Outlook: KM3NeT/ARCA

- **ARCA**: 2 building blocks of 115 detection units (DUs)
- 24 DU funded (**Phase-1**, ~0.1 km³)
- 3 DU deployed off the coast of Italy (1 DU recovered after shortage)
- 2 DUs operated until March 2017

- **Improved angular resolution** for water Cherenkov emission.
- **5σ** discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.
Outlook: IceCube Upgrade

- **7 new strings** in the DeepCore region (~20m inter-string spacing) with improved optical modules.

- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts.

- **Precision measurement** of atmospheric neutrino oscillation.

- Midscale NSF project with an estimated total cost of $23M.

- Additional $9M in capital equipment alone from partners

- **Aim: deployment in 2022/23**
• **Multi-component facility** (low- and high-energy & multi-messenger).

• **In-ice high-energy Cherenkov array** with 6-10 km$^3$ volume.

• **Under investigation:** Surface arrays for in-ice radio (Askaryan) and cosmic ray veto (air Cherenkov and/or scintillator panels).
Summary

• The future of high-energy multi-messenger astronomy is bright:
  
  • TeV-PeV neutrino emission (of unknown origin) with intensity comparable to ultra-high energy cosmic-rays and gamma-rays.
  
  • First observation of binary neutron star merger in gravitational waves and photons.
  
  • First compelling evidence of neutrino emission from gamma-ray blazars.
  
• Real-time multi-messenger campaigns involving photons, gravitational waves and neutrinos are becoming routine.

• With next-generation telescopes we will go from discovery to astronomy.

Thank you for your attention!
Backup Slides
The IceCube-Gen2 Facility

Preliminary timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>2016</td>
<td>Surface air shower</td>
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<td>2017</td>
<td>R&amp;D</td>
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<tr>
<td>2018</td>
<td>Design &amp; Approval</td>
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<td>2019</td>
<td>Construction</td>
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<td>2020</td>
<td>IceCube Upgrade</td>
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<td>2021</td>
<td>Deployment</td>
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A vision for the future of neutrino astroparticle physics at the South Pole

- Find (more) neutrino point sources
- Characterise spectrum, flux, and flavour composition of astrophysical neutrinos with higher precision
- GZK neutrinos
- Continue search for BSM physics

Low energy

- Precision measurements of atmospheric neutrino oscillations: \( \nu_\mu \rightarrow \nu_\tau \)
- Neutrino mass ordering
- Characterise atmospheric flux
- Also continue search for BSM physics

High energy

- Precision measurements of ultra-high energy astrophysical neutrinos
Outlook: UHE CR Observatories

Figure 16. Evolution of the exposure of past, current, and upcoming (solid lines) UHECR experiments as a function of time for ground-based and space experiments. Proposed experiments are also shown (dashed lines).

The project concept of OWL, based on the simultaneous detection of UHECRs by UV telescopes placed on two satellites, was recently developed in the POEMMA project [404]. This project, based on the use of Schmidt optics with 45° FOV and a large photodetector camera, can become a space instrument of record characteristics and surpass in terms of exposure the ground-based Auger and TA installations (see Figure 16).

4.3 The Current Status and Perspectives of UHE Neutrino Experiments

Currently the UHE neutrino flux is best confined by the IceCube Observatory [71] and the Auger Observatory [72] at the level of \( \sim 3 \times 10^8 \) GeV cm\(^2\) sr\(^{-1}\) around EeV (all-flavor). Figure 17 summarizes the sensitivity of current and proposed experiments that target EeV neutrinos.

The Askaryan Radio Array (ARA) [401, 405] and ARIANNA [406, 407] are in-ice radio arrays which detect UHE neutrinos via the Askaryan effect. As an alternative to the expensive ice-Cherenkov technique the three experiments equipped with radio antennas are located in Antarctica and optimized for UHE neutrino detection, namely two in-ice arrays, the Askaryan Radio Array (ARA) [401, 405] and ARIANNA [406, 407], and a balloon-borne interferometer ANITA [73, 408]. The propose GRAND [392] will use large arrays of cost-effective radio antennas to detect particle cascades produced in media and air by UHE tau neutrinos. POEMMA [404] will also detect tau neutrinos, by observing the Cherenkov radiation produced by upward-going tau decays [409].

Frontiers 35 [Alves Batista et al.’19]
Future Multi-Messenger Landscape

Future Multi-Messenger Landscape

LIGO/VIRGO + KAGRA (2021) + IndIGO (2025)

[Buson et al. Astro2020]
Neutrino Physics

**neutrino-nucleon cross section**

[Aartsen et al. Nature 551, 596-600]

| [Aartsen et al. EPJ C77 146] | spin-dependent DM-nucleon cross section |

| [Aartsen et al. PRL 117, 071801] | sterile neutrino search |

| [Aartsen et al. PRL 120, 071801] | atmospheric neutrino oscillations |

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HESE Alert IC-190331A

- HESE alert on March 31, 2019
- deposited energy: 5.3 PeV
- brightest HESE event, so far
- down-going muon neutrino
- RA 337.785° ± 2.240°
- DEC -21.075° ± 3.064°
- Follow-up by Fermi-LAT / AGILE (gamma-ray), NuSTAR (X-ray), MASTER / SARA (optical)
- No obvious EM counterpart.