Neutrinos as Messengers

Markus Ahlers, NBI Copenhagen
European Neutrino Town Meeting
October 22-24, 2018
Multi-Messenger Astronomy

- **Cosmic ray** acceleration – especially in the aftermath of cataclysmic events, sometimes seen in gravitational waves.

→ Inelastic collisions with radiation or gas produce \(\gamma\)-rays and **neutrinos**, e.g.

\[
\pi^0 \rightarrow \gamma + \gamma \\
\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu
\]

- **Unique aspects of neutrino messengers:**
  - *identify* cosmic ray sources
  - *qualifies* \(\gamma\)-ray emission
  - *covers blind spot* of astronomy to the very-high-energy Universe
# Cherenkov Observatories

<table>
<thead>
<tr>
<th>Mediterranean</th>
<th>South Pole</th>
<th>Lake Baikal</th>
<th>Mediterranean</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008–2019</td>
<td>fully instrumented since 2011</td>
<td>under construction (3 out of 8 clusters)</td>
<td>under construction (3 out of 230 DUs)</td>
</tr>
<tr>
<td>~0.01 km³</td>
<td>~1 km³</td>
<td>~0.4 km³ (Phase 1)</td>
<td>~0.1 km³ (Phase 1)</td>
</tr>
<tr>
<td>885 OMs (10’’)</td>
<td>5160 OMs (10’’)</td>
<td>2304 OMs (10’’)</td>
<td>4140 OMs (31x3’’)</td>
</tr>
</tbody>
</table>
Detection Methods

Up-going Muon-Neutrino Tracks

- 10,000,000,000 atmospheric muons
- 100,000 atmospheric neutrinos
- 10 cosmic neutrinos (per year and km$^3$)

High-Energy Starting Events (HESE)

- Virtual veto region triggered by atmospheric muons
- Self-veto of coincident atmospheric neutrinos
- Cosmic neutrino events are required to start inside

[Schoenert et al. PRD79 (2009) 043009]
Breakthrough in 2013

First observation of high-energy astrophysical neutrinos by IceCube!

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

$E_{\text{dep}} \sim 71$ TeV  
$E_{\text{dep}} \sim 1.0$ PeV

[“Breakthrough of the Year” (Physics World), Science 2013]  
(neutrino event signature: early to late light detection)
Diffuse TeV-PeV Neutrinos

- **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

![Graph of energy distribution](image-url)

- **Isotropic \(\gamma\)-ray background (Fermi)**
- **HESE (7yr)**
- **Work in progress**
- **\(\nu_\mu + \overline{\nu}_\mu\) (8yr)**
- **Ultra-high energy cosmic rays (Auger)**

[Science 342 (2013); work in progress]

[Astrophys.J. 833 (2016); update ICRC 2017]
Diffuse TeV-PeV Neutrinos

- **High-Energy Starting Events (HESE) (7yrs):**
  - bright events \(E_{\text{th}} \gtrsim 30\) TeV starting inside IceCube
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![Graph showing energy vs. flux with various events and backgrounds](image)

- **HESE** (7yr)
- **cosmic rays** (Auger)
- **GZK mechanism**
- **cosmogenic \(\nu + \bar{\nu}\)**
- **calorimetric limit**
- **production \(\pi^\pm / \pi^0\)**
- **work in progress**
- **isotropic \(\gamma\)-ray background (Fermi)**

**[Science 342 (2013); work in progress]**

**[Astrophys.J. 833 (2016); update ICRC 2017]**
Astrophysical Flavors

- Energy resolution of detectors is limited and neutrino source is distant.

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

- oscillation-averaged probability:

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

- 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 Flavors

early muons from hadronic cascade

energy reconstruction

Glashow resonance candidate

fit of flavor composition

tau neutrino candidate

two distinct energy depositions seen

6.3 PeV

MOTIVATION TO DEVELOP NEW TECHNIQUES

A gift from nature – Glashow resonance at 6.3 PeV

\[ E = \frac{M^2}{2m_e} = 6.3 \text{ PeV} \]

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

At ~68% in hadronic cascade channel

\[ \text{energy reconstruction} \]

HESE with ternary topology ID

Best fit: 0.29 : 0.50 : 0.21

Sensitivity, \( E^{-2.9} \) spectrum

1 : 1 : 1 flavor composition

\[ \text{tau neutrino candidate} \]

\[ \text{two distinct energy depositions seen} \]

\[ >60 \text{TeV} \]
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

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

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

- **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)
- **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

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[Blaufuss et al., Proceedings of ICRC 2017]

[PoS(ICRC2017)982]

[Stefan et al., Proceedings of ICRC 2017]
Realtime Neutrino Alerts

IceCube EHE ("extremely-high energy") alert IC-170922A
Up-going muon track (5.7° below horizon) observed on September 22, 2017.
The best-fit neutrino energy for an $E^{-2}$-spectrum is 311 TeV.
IC-170922A observed in coincident with flaring blazar TXS 0506+056.

Chance correlation can be rejected at the 3\(\sigma\)-level.

TXS 0506+056 is among the 3% brightest Fermi-LAT blazars and one of the most luminous BL Lacs \((2.8 \times 10^{46} \text{ erg/s})\).

[Science 361 (2018) no.6398, eaat1378]
Independent 3.5σ evidence for neutrino flare (13 ± 5 events) in 2014/15.

Implies neutrino luminosity of $1.2 \times 10^{47}$ erg/s over 158 days ($\simeq 4 \times L_{\text{Fermi}}$).
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
- 3 clusters deployed 2016–18
- **final goal**: 27 clusters (~1.4 km³)

**BAIKAL-GVD** present detector outline (2018)

**first physics results**: cascade spectrum / cascade event in 2015 data

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Neutrinos as Messengers
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.

- deployment in 2022/23

- **October 1st: first $1M increment**

- additional $9M in capital equipment alone from partners
Vision: IceCube-Gen2

- **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 Askarayn and cosmic ray veto (air Cherenkov and/or scintillator panels).

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**Surface Array**

**High-Energy Array**

**IceCube**

**DeepCore**

**PINGU**

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[Aartsen et al., Proceedings of ICRC 2017]
Summary

- The future of neutrino astronomy is bright:
  - Diffuse TeV-PeV neutrino flux of unknown origin.
  - Intensity comparable to cosmic-ray and gamma-ray observations.
  - First compelling evidence of neutrino emission from blazars.
- With next-generation telescopes we will go from discovery to astronomy!
- Many more avenues, that could not be covered in this talk:
  
  * supernova neutrinos, GZK neutrinos, BSM physics, neutrino-nucleon cross-section measurements, dark matter indirect signals, …

Thank you for your attention!
Backup Slides
Neutrino Physics

neutrino-nucleon cross section

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

spin-dependent DM-nucleon cross section

[Aartsen et al. EPJ C77 146]

sterile neutrino search

[Aartsen et al. PRL 117, 071801]

atmospheric neutrino oscillations

[Aartsen et al. PRL 120, 071801]
Detection Principles
**Blazars as Neutrino Factories**

- **Active galaxies** powered by accretion onto a supermassive black hole expel **relativistic jets pointing into our line of sight**.

- **Cosmic ray acceleration** and p-gamma interaction in blazar zone leads to neutrino beam.

- Predicted neutrino spectra have a **strong energy dependence** following photon target spectra.

[Stecker et al.’91; Mannheim'96; Halzen & Zas'97]
The IceCube-Gen2 Facility

Preliminary timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>IceCube Upgrade</th>
<th>R&amp;D</th>
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<tr>
<td>2032</td>
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Today

Surface Array

Radio Array

High-Energy Array

IceCube

DeepCore

PINGU

Surface air shower

Deployment

MeV- to EeV-scale physics

Surface air shower

Construction

R&D

Design & Approval

IceCube Upgrade

Today

Find (more) neutrino point sources

Characterise spectrum, flux, and flavour composition of astrophysical neutrinos with higher precision

GZK neutrinos

Continue search for BSM physics

Precision measurements of atmospheric neutrino oscillations: \( \nu_\mu \rightarrow \nu_\tau \)

Neutrino mass ordering

Characterise atmospheric flux (hadronic interactions)

Also continue search for BSM physics

A vision for the future of neutrino astroparticle physics at the South Pole

IceCube

DeepCore

PINGU

High-Energy Array

Surface Array

Radio Array
## Supernova Forecast


<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass (kt)</th>
<th>Location</th>
<th>Events [10 kpc]</th>
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<tbody>
<tr>
<td>IceCube</td>
<td>long string</td>
<td>600</td>
<td>South Pole</td>
<td>1,000,000</td>
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<tr>
<td>Hyper-K*</td>
<td>H$_2$O</td>
<td>374</td>
<td>Japan</td>
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<td>DUNE*</td>
<td>Ar</td>
<td>40</td>
<td>USA</td>
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<td>Super-K</td>
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<td>Japan</td>
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<tr>
<td>JUNO*</td>
<td>C$<em>n$H$</em>{2n}$</td>
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<td>China</td>
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