Ultra-High-Energy Neutrinos

Carsten Rott

Sunkyunkwan University
• Motivation
• Anomalous ANITA events
• Astrophysical Neutrinos
• Multi-messenger Neutrino Astroparticle physics
• Search for Physics Beyond the Standard Model
• Outlook and Conclusions
Motivation
• Identify the origin of the high-energy cosmic rays
• Open a new window to the Universe
**Sources of High Energy Neutrinos**

### Astrophysical Neutrinos

**Greisen-Zatsepin-Kuzmin (GZK) - neutrinos**

At energies above $4 \times 10^{19} \text{eV}$, protons interact with CMB to produce delta resonance and in sequential decays ($p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ \pi^- \rightarrow \nu_\mu$, $\mu^- \rightarrow e^- \nu_e \nu_e \nu_e$) neutrinos of $10^{17} - 10^{20} \text{eV}$.

### Atmospheric Neutrinos

Cosmic rays interact in the upper atmosphere:

$p + A \rightarrow \pi^\pm (K^\pm) + \text{other hadrons} \ldots$

$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^- \nu_e \nu_e \nu_e \nu_\mu$

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Neutrino detection via water/ice Cherenkov light

Neutrino detection via Askaryan effect:
Coherent radio emission from excess negative charge in an electromagnetic shower (positron annihilation and Compton scattering)
Threshold $\sim 10\text{PeV}$

Askaryan effect confirmed in beam dump experiment:
SLAC data: D. Saltzberg et al., PRL 86, 2802 (2001)
Angles: O. Scholten et al.
ANITA - ANtarctic Impulsive Transient Antenna
- ANtarctic Impulsive Transient Antenna
- NASA ultralong duration balloon experiment
- Seeking radio signals from earth-skimming UHE neutrinos
- To this date, 4 flights

<table>
<thead>
<tr>
<th>ANITA-Lite</th>
<th>ANITA-I</th>
<th>ANITA-II</th>
<th>ANITA-III</th>
<th>ANITA-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 days, 2 antennas</td>
<td>35 days, 32 antennas</td>
<td>30 days, 40 antennas</td>
<td>22 days, 48 antennas</td>
<td>29 days, 48 antennas</td>
</tr>
<tr>
<td>Analyzed</td>
<td>Analyzed</td>
<td>Analyzed</td>
<td>Recently analyzed</td>
<td>Analysis Ongoing</td>
</tr>
</tbody>
</table>
I) Neutrino-Induced Askaryan Emission in Ice

Signals are vertically polarized

Not to scale, angles don't reflect reality

Askaryan effect confirmed in beam dump experiment:
SLAC data: D. Saltzberg et al., PRL 86, 2802 (2001)
2) Radio Emission from Tau-Neutrino-Induced EAS

- Signals are horizontally polarized
- Comes from below the horizon

Not to scale, angles don't reflect reality

ARENA 2018
3/4) Radio Emission from Cosmic-Ray-Induced EAS

- Signals are horizontally polarized
- Polarity of reflected (below-horizon) signal is inverted compared to direct (above-horizon) signal and tau neutrino (below-horizon) signal
- Two anomalous events observed
- Mostly H-pol
- Consistent with UHECR signature but clearly up-going (emerging from ice)

### ANITA Anomalous Events

**Fox et al (2019)**

<table>
<thead>
<tr>
<th>Property</th>
<th>AAE 061228</th>
<th>AAE 141220</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight &amp; Event</td>
<td>ANITA-I #3085267</td>
<td>ANITA-III #15717147</td>
</tr>
<tr>
<td>Date &amp; Time (UTC)</td>
<td>2006-12-28 00:33:20</td>
<td>2014-12-20 08:33:22.5</td>
</tr>
<tr>
<td>Energy $\varepsilon_{cr}$</td>
<td>$0.6 \pm 0.4$ EeV</td>
<td>$0.56 \pm 0.03$ EeV</td>
</tr>
<tr>
<td>Zenith angle $z'/z$</td>
<td>$117°$4 / $116°.8 \pm 0.3°$</td>
<td>$125°.0 / 124°.5 \pm 0.3°$</td>
</tr>
<tr>
<td>Earth chord length $\ell$</td>
<td>$5740 \pm 60$ km</td>
<td>$7210 \pm 55$ km</td>
</tr>
<tr>
<td>Mean interaction length for $\varepsilon_{\nu} = 1$ EeV</td>
<td>$290$ km</td>
<td>$265$ km</td>
</tr>
<tr>
<td>$p_{SM}(\varepsilon_{\tau} &gt; 0.1$ EeV for $\varepsilon_{\nu} = 1$ EeV</td>
<td>$4.4 \times 10^{-7}$</td>
<td>$3.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>$p_{SM}(z &gt; z_{obs})$ for $\varepsilon_{\nu} = 1$ EeV, $\varepsilon_{\tau} &gt; 0.1$ EeV</td>
<td>$6.7 \times 10^{-5}$</td>
<td>$3.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$n_{\tau}(1-10$ PeV) : $n_{\tau}(10-100$ PeV) : $n_{\tau}(&gt; 0.1$ EeV)</td>
<td>$34 : 35 : 1$</td>
<td>$270 : 120 : 1$</td>
</tr>
</tbody>
</table>

- Emerged from the Earth at ~27 degrees below the horizon
- Earth chord length 5740 km (~15 interaction lengths for incoming EeV neutrino)
- Emerged from the Earth at ~35 degrees below the horizon
- Earth chord length 7210 km (~27 interaction lengths for incoming EeV neutrino)

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K. Murase LHC-Results Forum 2019

$\sigma_{\nu N} = 10^{-32}$ cm$^2$ @ EeV

$\rho_{\text{Earth}} = 5.5$ g cm$^{-3}$

chord length ~7300 km

$\tau_{\nu N} \approx 60 \gg 1$

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$\tau$ regeneration

**NuTauSim**

Alvarez-Muniz + 08
Standard model explanation can be excluded (if we consider the ANITA signals as real)

- Inconsistency with energy and zenith angle of events
- Inconsistency with observed astrophysical neutrino flux by IceCube

• SUSY (Long-lived particles) - NLSP stau / NLSP bino / CHAMPS / sphaleron configurations

• Leptoquarks
  • Chauhan & Mohanty 2018

• Dark matter related models
  • Heurtier et al 2019, Anchordoqui et al. 2018

• Sterile neutrinos
  • Cherry & Shoemaker 2018, Huang 2018

Figure 2: Sketch of the signature being considered here. Although the figure shows one stau being produced in the $\nu N$ interaction, a stau pair could be produced instead, doubling the probability of detection.
Under the framework of RPV-SUSY, ANITA anomaly has quite large parameter space, which is in the similar range demanded by RD and RK.

- Rk Rk* and RD RD* anomalies could be explained simultaneously after a “fourth term” is included in the traditional RPV-SUSY Rk Rk* expression.

- Under the simplified parameter setup, we find that there exist parameter spaces that could satisfy RK-RD-ANITA altogether.
Many more events in IceCube & Auger data expected for $E<10^{19.5}$ eV
… but not reported
(Kistler & Laha PRL 120 (2018) no.24, 241105 - very high-energy tau tracks)
Unexpected Backgrounds

- Double reflection by crevasses?
- Anthropogenic backgrounds
- Other unknown backgrounds?
- Coherent transition radiation (de Vries & Prohira 2019)
Astro-physical Neutrino Search
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Detector completed in December 2010 after 7 years construction
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

$$\nu_\mu$$

$$E_{\text{Thr}} \sim 100 \text{ GeV}$$

$$E_{\text{Thr}} \sim 10 \text{ GeV}$$
Event topologies in IceCube

**Track**
- Muon tracks (CC $\nu_\mu$)
- Resolution $< 1^\circ$
- Large energy uncertainties

**Cascade**
- NC or $\nu_e/\nu_\tau$
- Resolution $\approx 15^\circ - 20^\circ$
- Energy resolution $\delta E/E \approx 15\%$

**Double-bang**
- High energy $\nu_\tau (>100$ TeV)
- Not observed yet

amount of light in detector $\propto$ $\nu$ energy
Arrival directions (highest energy events)

High-Energy Starting Events (HESE) – 7.5 yr

Isotropic distributed

No evidence for point sources, nor a correlation with the galactic plane

$E < 300\, \text{TeV}$

$300\, \text{TeV} < E < 1\, \text{PeV}$

$1\, \text{PeV} < E$

HESE 7.5 year
103 events
(60 events > 60 TeV)
Best-fit: $\gamma=2.87\pm0.3$

8-yr upgoing $\nu_\mu$ “track”
36 events at $>200$ TeV ($6.7\sigma$)
- Best-fit: $\gamma=2.19\pm0.1$
- $\nu_\mu$ flux above 100 TeV:
  $E_\nu^2\Phi_\nu=(1.01^{+0.26}_{-0.23}) \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$
Two double cascades candidate events have been identified

Double cascades arise from $\nu_\tau$ or mis-identified backgrounds (astrophysical neutrinos / atmospheric backgrounds)

Separate study of taus of the double cascade events on-going
The global high-energy picture

**PeV Energy Partially-contained Events: PEPE**

- HESE $\nu_e$
- PEPE $\nu_e$
- EHE-PeV $\nu_e$

**Effective Area [m$^2$]**

- Contained cascades
- Partially-contained
- Through-going tracks

4.6 years (2012-2016) of data. **One event is at Glashow bin**

**Brightest of all IceCube PeV events** in the dataset even though only partially-contained
The global high-energy picture

![Graph showing energy vs. probability density for different experimental data sets including IceCube diffuse, IceCube EHE, Auger, Anita, and Auger cosmic-rays.]

- IceCube diffuse numu (ICRC 2017)
- IceCube EHE cosmogenic nu (2018)
- Auger cosmogenic nu (2017)
- Anita cosmogenic nu (2018)
- Auger cosmic-rays (ICRC 2015)
- IceCube HESE nu (ICRC 2017)
- The new event

IceCube Preliminary

All flavours
nuebar:nue=1:1

Energy [GeV]

$E^2 \cdot \phi$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
Multi-messenger Neutrino Astronomy and IceCube-170922A
• September 22, 2017: a neutrino alert issued by IceCube
• Fermi-LAT and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
• Very active multi-messenger follow-up from radio to γ-rays
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, KappTev, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams*

- Chance probability of a Fermi-IceCube coincident observation: \( \sim 3\sigma \) (determined based on the historical IceCube sample and known Fermi-LAT blazars)

- Time-integrated neutrino spectrum is approximately \( E^{-2.1} \)

- **TXS 0506+056 redshift determined to be** \( z=0.3365 \) (S. Paiano et al. ApJL 854.L32(2018))

- Time-average luminosity about an order of magnitude higher than Mkn 421, Mkn 501, or 1ES 1959+605
• 9.5 years of archival data was evaluated in direction of TXS 0506+056

• An excess of $13 \pm 5$ events above background was observed during Sep 2014 - March 2016

• Inconsistent with background only hypothesis at $3.5 \sigma$ level (independently of the $3 \sigma$ associated with IceCube-170922A alert)
Search for Physics Beyond the Standard Model
**Heavy Dark Matter Decay**

Decay process might produce mono-energetic neutrinos

Two flux contributions:
Galactic and Extra galactic

\[ \frac{d\Phi_{DM,\nu_\alpha}}{dE_\nu} = \frac{d\Phi_G,\nu_\alpha}{dE_\nu} + \frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu} \]

- Characteristics of the signal components:
  - (1) Dark Matter decay in the Galactic Halo (Anisotropic flux + decay spectrum)
    \[ \frac{d\Phi_G}{dE_\nu} = \frac{1}{4\pi m_{DM} \tau_{DM}} \frac{dN_\nu}{dE_\nu} \int_0^\infty \rho(r(s,l,b)) \, ds \]
  - Dark Matter decay at cosmological distances (Isotropic flux + red-shifted spectrum)
    \[ \frac{d\Phi_{EG}}{dE} = \frac{\Omega_{DM} \rho_c}{4\pi m_{DM} \tau_{DM}} \int_0^\infty \frac{1}{H(z) \, dE_\nu} \left[ (1 + z)E_\nu \right] \, dz \]
**Dark Matter Decay with IceCube**

- Two IceCube analyses have been performed on independent data samples:
  - Track-like with 6 years of data
  - Cascade-like with 2 years of data

<table>
<thead>
<tr>
<th></th>
<th>Track-like</th>
<th>Cascade-like</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events</td>
<td>352,294</td>
<td>278</td>
</tr>
<tr>
<td>Livetime</td>
<td>2060 days</td>
<td>641 days</td>
</tr>
<tr>
<td>Sky coverage</td>
<td>North (zenith &gt; 85°)</td>
<td>Full Sky</td>
</tr>
<tr>
<td>Atm. muon background</td>
<td>0.3%</td>
<td>10%</td>
</tr>
<tr>
<td>Median reconstr. error</td>
<td>&lt; 0.5° (Eν &gt; 100 TeV)</td>
<td>~ 10°</td>
</tr>
<tr>
<td>Energy uncertainty</td>
<td>~ 100%</td>
<td>~ 10%</td>
</tr>
</tbody>
</table>

Test Statistic: \( TS = 2 \times \log \left( \frac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM} = \infty, \Phi^{Astro}, \gamma^{astro})} \right) \)

- Dark matter alone cannot explain the observed astrophysical neutrino flux in IceCube
- Scenarios with a PeV neutrino line became less attractive with IceCube’s observation of neutrino events well above this energy

Bound on DM lifetime at \( \sim 10^{27}\) s obtained with IceCube data for \( m_{DM} > 10 \text{ TeV} \)
7 years of IceCube's HESE (High Energy Starting Events) Sample

- Events with energies above $>60$ TeV
- Binned likelihood analysis
- Most competitive limits above 100 TeV for a large number of channel
Probing dark matter neutrino interactions with HESE 7.5yrs and based on TXS0506

Dark Matter - Neutrino Interaction

- Scattering of high energy astrophysical neutrinos on DM in the Galactic halo can lead to a deficit of high energy neutrinos
  - Neutrino-DM interactions mediated by a scalar or vector mediator \( f \).
  - Limits on coupling constant, \( g \), possible by measuring the isotropy of the HE neutrino flux

Assume:

\[
\sigma_{DM-\nu} \propto E_{\nu}^2
\]

vector mediator

scalar mediator

[1] Fermionic DM, vector mediator
[2] Scalar DM, fermionic mediator

Solar Dark Matter Summary

Spin-dependent scattering

Spin-independent scattering

Dark Matter Mass (log(m\(_{DM}/\text{GeV})\))

Dark Matter Mass (m\(_{DM}/\text{GeV}\))

Spin-dependent scattering

Spin-independent scattering


Baksan JCAP 1309 (2013) 019


Dark Matter Mass (log(m\(_{DM}/\text{GeV})\))

Dark Matter Mass (m\(_{DM}/\text{GeV}\))
Next generation neutrino telescopes
Neutrino telescope landscape expanding quickly

The neutrino telescope timeline

- ANTARES
- KM3Net/ARCA
- ? KM3Net/Phase 3
- KM3Net/Neutrino astronomy
- KM3Net/ORCA
- KM3Net/Neutrino oscillations
- ? IceCube
- IC Upgrade
- ? IceCube Gen2
- IceCube Gen2
- Baikal/GVD-1
- Baikal/GVD (next steps)
- Baikal GVD

- 2015
- now
- 2020
- 2025
- 2030

Height: ~160m ORCA (600m ARCA)
Radius: ~120m ORCA (500m ARCA)

2018: Data taken with three Baikal-GVD clusters

Status in 2018
- Cluster 1 since 2016
- Cluster 2 since 2017
- Cluster 3 since 2018
- Powerful isotropic laser source
IceCube-Gen2

- IceCube has provided an amazing sample of events, but is still statistics limited
- Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors

Gen2 objectives
- High precision flavor composition studies
- Detailed measurement of features / cut-off in neutrino spectrum
- Transients sources and multi-messenger astrophysics
- Identify astrophysical neutrino sources
- GZK neutrinos
- New physics or something unexpected
Science goals

- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Recalibration campaign - Retroactively apply improved ice-model to archival data ( )

<table>
<thead>
<tr>
<th>Array</th>
<th>String Spacing</th>
<th>Module Spacing</th>
<th>Modules / String</th>
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<tbody>
<tr>
<td>IceCube</td>
<td>125 m</td>
<td>17 m</td>
<td>60</td>
</tr>
<tr>
<td>DeepCore</td>
<td>75 m</td>
<td>7 m</td>
<td>60</td>
</tr>
<tr>
<td>Upgrade</td>
<td>20 m</td>
<td>2 m</td>
<td>125</td>
</tr>
</tbody>
</table>
• Anomalous ANITA events imply new physics (clarity from ANITA-IV and PUEO)

• High-energy astrophysical neutrinos have opened up a new window to the Universe
  - What’s the origin of the high-energy neutrinos?

• First compelling evidence of high-energy neutrinos with electromagnetic counterparts (TXS 0506+056)

• Neutrino astronomy is a central part of the multi messenger astroparticle physics field

• First hint of a Glashow resonance event

• Very strong bounds on dark matter scattering with nucleons and decaying dark matter

• Funding for IceCube Upgrade approved
**New Window to the Universe!**

**Following the observation of supernova burst neutrinos in 1987,** neutrino astronomy is becoming a reality quickly now …

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**Discovery of diffuse astrophysical neutrino flux**

**2013**

**2018 Neutrino multi-messenger astroparticle physics**

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**Data**
- Yellow: Astro.
- Blue: Atmo. Muons
- Purple: Atmo. Prompt 90% U.L.

**Deposited Energy [GeV]**

**Events per 2635 days**

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**First confirmed source of high-energy neutrinos and extra-galactic cosmic rays**

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**Progress**

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Carsten Rott
More sources in the future?

10 years of IceCube data which recently have been unblinded, unifying the muon diffuse and point source streams. Most significant excess was found 0.3° away from M77 (NGC1068) (RA 40.667°, Dec -0.0069°) with a significance of 2.9σ (post-trial).
Solar Atmospheric neutrinos give a new background to solar dark matter searches

- However, energy spectrum expected to be different
- In DM annihilation neutrinos significantly attenuated above a few 100 GeV
ORCA will consist of one dense KM3NeT Building Block

115 detection lines

**Total:** 64K * 3” PMTs

ARCA/ORCA construction on-going

<table>
<thead>
<tr>
<th></th>
<th>ORCA</th>
<th>ARCA</th>
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</thead>
<tbody>
<tr>
<td>String spacing</td>
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<td>90 m</td>
</tr>
<tr>
<td>Vertical spacing</td>
<td>9 m</td>
<td>36 m</td>
</tr>
<tr>
<td>Depth</td>
<td>2470 m</td>
<td>3500 m</td>
</tr>
<tr>
<td>Instrumented mass</td>
<td>1x 8 Mton</td>
<td>2x 0.6 Gton</td>
</tr>
</tbody>
</table>
GVD detector construction underway in Lake Baikal

Currently clusters #2 and #3 are in operation while cluster #1 is subject to maintenance works

Baikal-GVD expedition on-going (deployments until April 11th) Plan was to deploy and commission two new GVD-clusters (clusters 4 and 5), well underway (and **completed on April 7**)

Now reached 0.25 km$^3$ effective volume

### 2018: 24 strings (864 OMs) – largest NT in the northern latitudes

<table>
<thead>
<tr>
<th>Configuration</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tbody>
<tr>
<td>The number of OMs</td>
<td>192</td>
<td>288</td>
<td>576</td>
<td>864</td>
</tr>
<tr>
<td>Geometric sizes, m</td>
<td>$\varnothing 80 \times 345$</td>
<td>$\varnothing 120 \times 525$</td>
<td>$2 \times \varnothing 120 \times 525$</td>
<td>$3 \times \varnothing 120 \times 525$</td>
</tr>
<tr>
<td>Eff. Vol</td>
<td>0.03 km$^3$</td>
<td>0.05 km$^3$</td>
<td>0.1 km$^3$</td>
<td>0.15 km$^3$</td>
</tr>
</tbody>
</table>

### 2018: Data taken with three Baikal-GVD clusters

Status in 2018
- Cluster 1 since 2016
- Cluster 2 since 2017
- Cluster 3 since 2018
- Powerful isotropic laser source

Details see Olga Suvorova @ XVIII International Workshop on Neutrino Telescopes - Venezia - 18-22 of March, 2019

Optical module
PMT: R7081-100
• Real-time alerts. Since 04/2016, ≈6-8/yr

• Improved selection summer 2018

• Good angular resolution (0.5° - 2° 90% of events)

• 50% astrophysical fraction
The IceCube Upgrade

Recalibration campaign

- Improved ice model
- Retroactively apply improved ice-model to archival data
- Precision neutrino physics
- Multi-messenger science with improve pointing

3σ discovery of cosmic tau neutrinos in 12 years of IceCube data, using the new calibration devices
Dark Matter Signals

- Identify overdense regions of dark matter
  \[ \Rightarrow \text{self-annihilation can occur at significant rates} \]
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds

\[ \begin{align*}
\tilde{\chi} & \rightarrow W^+ , Z , \tau^+ , b , \ldots \Rightarrow e^\pm , \nu , \gamma , p , D , \ldots \\
\tilde{\chi} & \rightarrow W^- , Z , \tau^- , \bar{b} , \ldots \Rightarrow e^\mp , \nu , \gamma , \bar{p} , D , \ldots
\end{align*} \]
BSM Physics Searches
• Anomalies in short baseline experiments have been interpreted as evidence for additional neutrino mass states with large mass splittings

• No evidence for sterile neutrinos observed. Data consistent with 3 active neutrinos
Absorption of neutrinos in the Earth can be a powerful tool to measure neutrino-nucleus cross section.

- Data sample more than 10,000 muon neutrino in one year of data.
- Measured cross section between 6.3-980 TeV (extends previous measurements by more than an order of magnitude).
See also tomography:

- Rott, Taketa, Bose, 2015; Winter, 2016; Bourret, Coelho, van Elewyck, 2017
Atm. neutrino

Down-going high-energy neutrinos can be nearly background free identified as astro-physical neutrinos

• Recently unblinded 1.5 additional years of data (new calibration)

• Ternary topology ID added (Cascades, Tracks, Double Cascades)

• Above 60 TeV: 60 events
  • 12 new events in 2016 season
  • 5 new events in 2017 season

• All energies: 102 events
  • 22 new events in 2016 season
  • 9 new events in 2017 season
Search DM Annihilation with IceCube’s 7 years HESE Sample

- 7 years of IceCube’s HESE (High Energy Starting Events) Sample
  - Events with energies above >60 TeV
- Binned likelihood analysis
- Improve neutrino bounds above 100 TeV and extend to high masses
Solar Atmospheric Neutrinos
• Cosmic ray interactions in the Solar atmosphere produce gamma-rays and neutrinos

• Background to dark matter searches from the Sun, that soon will be relevant (and could result in the first high-energy neutrino point source)

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**Leptonic**
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

**Hadronic**
- Seckel, Stanev, Gaisser (1991)
- Moskalenko, Karakula (1993)
- Ingelman & Thunman (1996)
Gamma-ray flux extends to 100 GeV and beyond
Gamma-rays below 10 GeV anti-correlations with solar activity
Observed flux factor 5 larger compared to central prediction of SSG1991
Spectrum could be fit by single power law ($\gamma \sim 2.3$)

- Six gamma rays above 100 GeV are observed during the 1.4 years of solar minimum, none are observed during the next 7.8 year
- From morphology: Evidence that emission is produced by two separate mechanisms
- To understand the underlying physics, gamma-ray (HAWC, Fermi, ...) and neutrino (IceCube) observation of the imminent Cycle 25 solar minimum are crucial
The analysis utilizes data collected over a 7 year period (May 31, 2010 - May 18, 2017)

- Up-going muon neutrino candidate events are selected using the well established IceCube point source analysis selection procedure
- We only consider events from the winter season when the Sun is below the horizon ($\delta=[-5^\circ,23^\circ]$). This results in a total analysis livetime of 1420.73 days.

Energy proxy distribution

Zenith angle distribution
• Maximum log likelihood method is used to calculate significance with a test statistic (TS) distribution
  • Observation in data consistent with background only hypothesis

Feldman-Cousins Upper limit at 90% C.L.
- preliminary systematic uncertainties are included by worsening the limit by 13%
Galactic Neutrino Searches

- Combined ANTARES and IceCube search for diffuse $\nu$ emission from Galactic plane

Diffuse astrophysical neutrino flux cannot be attributed to Galactic sources / Galactic plane

IceCube tested HAWC sources … no significant excess observed
Two double cascades have been identified

Double cascades arise from $\nu_\tau$ or mis-identified backgrounds (astrophysical neutrinos / atmospheric backgrounds)

Separate study of taunts of the double cascade events on-going
Tests of Lorentz Symmetry

Neutrino Interferometry for High-Precision Tests of Lorentz Symmetry with IceCube

- Most precise test of space-time symmetry in the neutrino sector to date
- Search for anomalous neutrino oscillations in IceCube’s high energy neutrino sample
  - No evidence for such phenomena
Neutrino Oscillations

- 3 years of IceCube Deep Core data
- Measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

Normal ordering best fits

$$\Delta m_{32}^2 = 2.31^{+0.11}_{-0.13} \times 10^{-3} \text{eV}^2$$

$$\sin^2 \theta_{23} = 0.51^{+0.07}_{-0.09}$$