High-Energy Neutrino Observations by IceCube

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Unique abilities of **cosmic neutrinos**:

- **no deflection** in magnetic fields  
  (unlike cosmic rays)

- **coincident** with photons and gravitational waves

- **no absorption** in cosmic backgrounds  
  (unlike gamma-rays)

- **smoking-gun** of unknown sources of cosmic rays

**BUT, very difficult to detect!**
IceCube Observatory

- Giga-ton optical Cherenkov telescope at the South Pole
- Collaboration of about 300 scientists at more than 50 international institutions
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings instrumenting 1 km$^3$ of clear glacial ice
- 81 IceTop stations for cosmic ray shower detections
High-Energy Neutrinos

First observation of high-energy astrophysical neutrinos by IceCube in 2013.

"track event" (e.g. $\nu_\mu$ CC interactions)

"cascade event" (e.g. NC interactions)

(colours indicate arrival time of Cherenkov photons from early to late)
Diffuse TeV-PeV Neutrinos

![Graph showing energy scales and neutrino observations](image)

- **isotropic γ-ray background** (Fermi)
- **high-energy neutrinos** (IceCube)
- **ultra-high energy cosmic rays** (Auger)

**Energy Scale**

$E^2 \phi [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$10^{-6}$ to $10^{-9}$

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

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

$10^{-9}$ to $10^{-10}$

$10^{-10}$ to $10^{-11}$

**Energy $E$ [GeV]**

$10$ to $100$

$10^3$ to $10^4$

$10^5$ to $10^6$

$10^6$ to $10^7$

$10^7$ to $10^8$

$10^8$ to $10^9$

$10^9$ to $10^{10}$

$10^{10}$ to $10^{11}$

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• **Tau neutrino** charged current interactions can produce delayed hadronic cascades from tau decays.

• Arrival time of Cherenkov photons is visible in individual DOMs.

This constitutes the first non-zero measurement of the test statistic $T_{S}$ for $\nu_{\tau}$ at a value on the astrophysical $\nu_{\tau}$ spectrum. The full one-dimensional scan shows previously published results. The first event, "Big Bird," has a short double cascade topology with all other components of the fit profiled over. The test statistic $T_{S}$ is well described with a double cascade hypothesis, which translates to a significance of 6.0% at source and 95% on Earth. The result being only weakly dependent on Earth. No firm conclusion can be drawn about the nature of the $T_{S}$ pattern, which is well described with a double cascade hypothesis.

The shaded regions show previously published results. The observed test statistic $T_{S}$ at source is 0.05. The one-dimensional scan of the astrophysical $\nu_{\tau}$ spectrum can be disfavored. The observed test statistic $T_{S}$ at source is 0.05. The one-dimensional scan of the astrophysical $\nu_{\tau}$ spectrum can be disfavored.

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MOTIVATION TO DEVELOP NEW TECHNIQUES

A gift from nature – Glashow resonance at 6.3 PeV.

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

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

At \(~68\%\) in hadronic cascade channel.

Resonant interaction of electron antineutrinos with electrons at 6.3 PeV:

\[ \bar{\nu}_e + e^- \rightarrow W^- \rightarrow X \]

[IceCube, Nature 591 (2021) 220-224]
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.

Southern Hemisphere | Northern Hemisphere

[Image of skymap with pre-trial p-values]

- **No significant** time-integrated point sources emission in all-sky search.
- **No significant** time-integrated emission from known Galactic and extragalactic high-energy sources, but interesting candidates, e.g. NGC 1068.

[Image of sensitivity flux]

[Image of spectra]

[Image of skymap with coordinates]

[Image of discovery analysis]

[Image of source catalog searches]

[Image of gamma-ray sources from TeVCat and gammaray emission]
Populations of extragalactic neutrino sources can be visible individual sources or by the combined isotropic emission.

The relative contribution can be parametrized (to first order) by the average local source density and source luminosity.
Rare sources, like blazars or gamma-ray bursts, can not be the dominant sources of TeV-PeV neutrino emission (magenta band).
• IceCube routinely follows up on γ-ray bursts.  

• Search is most sensitive to “prompt” (<100s) neutrino emission.

• Neutrino predictions based on the assumption of cosmic ray acceleration in internal shocks.  
  [Waxman & Bahcall ’97]

Gamma-Ray Burst Burst Limits

- Model-dependent limits based on 1172 GRBs
- Model-independent limits

- Internal Shock Fireball Prediction
- Photospheric Fireball Prediction
- ICMART Prediction

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Markus Ahlers (NBI)  High-Energy Neutrino Observations by IceCube
Fermi-LAT Blazar Limits

Combined contribution of Fermi-LAT blazars (2LAC) **below 30%** of the isotropic TeV-PeV neutrino observation.
Realtime Neutrino Alerts

Low-latency (<1 min) public neutrino alert system established in April 2016.

- **Gold alerts:** ~10 per year >50% signalness
- **Bronze alerts:** ~20 per year 30-50% signalness
• 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.
Neutrino Flare in 2014/15

- Independent $3.5\sigma$ evidence for a neutrino flare (13±5 events) in 2014/15.

- Neutrino luminosity over 158 days is about four times that of Fermi-LAT $\gamma$-rays.

neutrino “morphology” of 2014/15 flare
The high intensity of the neutrino flux compared to that of $\gamma$-rays and cosmic rays offers many interesting multi-messenger interfaces.
Hadronic Gamma-Rays

Hadronic Gamma-Ray Emission

Inelastic collisions of cosmic rays (CR) with radiation or gas produce $\gamma$-rays and neutrinos via pion decay:

\[
p^0 \rightarrow \gamma + \gamma \quad p^+ \rightarrow \mu^+ + n \quad \mu^- \rightarrow e^- + \bar{\nu}_e + n
\]

• relative production rates comparable

8 TeV $\gamma$-rays scatter in cosmic microwave background (CMB) and initiate electromagnetic cascades:

\[
\gamma + \gamma_{bg} \rightarrow e^+ + e^- \quad \text{(PP)}
\]

\[
e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma \quad \text{(ICS)}
\]

EM cascades from interactions in cosmic radiation backgrounds:

\[
\begin{align*}
\gamma + \gamma_{bg} & \rightarrow e^+ + e^- \quad \text{(PP)} \\
e^\pm + \gamma_{bg} & \rightarrow e^\pm + \gamma \quad \text{(ICS)}
\end{align*}
\]

interaction length [Mpc]

\[
E [\text{GeV}] \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5
\]

pair production

inverse-Compton

CMB

EBL

Galactic Center

Cen A
Neutrino production via cosmic ray interactions with gas (pp) or radiation (pγ) saturate the isotropic diffuse gamma-ray background.

Cascaded and direct gamma-rays saturate IGRB.

Fermi

IceCube

[see also Murase, MA & Lacki’13; Tamborra, Ando & Murase’14; Ando, Tamborra & Zandanel’15]
[Bechtol, MA, Ajello, Di Mauro & Vandenbrouke’15; Palladino, Fedynitch, Rasmussen & Taylor’19]
[Ambrosone, Chianese, Fiorillo, Marinelli, Miele & Pisanti’20]
Efficient production of 10 TeV neutrinos in pγ scenarios require sources with **strong X-ray backgrounds** (e.g. AGN core models).

Hidden Sources?

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

\[ \tau_{\gamma\gamma} \approx 1000 f_{p\gamma} \]
Outlook: IceCube Upgrade

- **7 new strings** in the DeepCore region (~20m inter-string spacing)
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts
- Midscale NSF project with an estimated total cost of $23M
- Additional $9M in capital equipment alone from partners
- **Aim: deployment in 2023/24**
Outlook: IceCube Upgrade

- **Precision measurement** of atmospheric neutrino oscillations and tau neutrino appearance

- **Improved energy and angular reconstructions** of IceCube data

![Graph showing deposition energy vs. median angular error for HESE cascades](image)

![Graph showing sensitivity to neutrino parameters](image)

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Markus Ahlers (NBI)  
High-Energy Neutrino Observations by IceCube
**Vision: IceCube-Gen2**

- **Multi-component facility** (low- and high-energy & multi-messenger)
- **In-ice optical Cherenkov array** with 120 strings and 240m spacing
- **Surface array** (scintillator panels & radio antennas) for cosmic ray veto
- **Askaryan radio array** for >10PeV neutrino detection

Summary

• Neutrino astronomy has reached an important milestone by the discovery of an isotropic flux of high-energy (TeV-PeV) neutrinos.

• So far, no significant point sources, but many interesting candidates.

• Intensity of cosmic neutrinos is comparable to that of ultra-high energy cosmic-rays (Auger/TA) and γ-rays (Fermi-LAT).

• Many interesting options for joint multi-messenger studies.

• Essential for future discoveries are multi-messenger partners facilitating low-latency studies.
  ✦ Fermi-LAT, Magic, H.E.S.S., HAWC, Swift-XRT, VERITAS, LIGO/Virgo,…

• In parallel, development of future neutrino telescopes with complementary FoV and/or increased sensitivity and energy coverage.
  ✦ Baikal-GVD, KM3NeT, P-ONE, RNO-G, IceCube-Gen2, ARA, ARIANNA, GRAND,…
Backup Slides
The high intensity of the neutrino flux compared to that of $\gamma$-rays and cosmic rays offers many interesting multi-messenger interfaces.
• **UHE CR proton emission rate** density:

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

• Neutrino flux can be estimated as (\(\xi_z\) : redshift evolution factor): \[E_\nu^2 \phi_\nu(E_\nu) \approx f_\pi \frac{\xi_z K_\pi}{1 + K_\pi} 1.5 \times 10^{-8}\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\]

\[\mathcal{O}(1)\] IceCube diffuse level

• Limited by **pion production efficiency**: \(f_\pi \lesssim 1\)

• Similar UHE **nucleon emission rate** density (local minimum at \(\Gamma \approx 2.04\)): \[ [E_N^2 Q_N(E_N)]_{10^{19.5\text{eV}}} \approx 2.2 \times 10^{43}\text{erg Mpc}^{-3}\text{yr}^{-1}\]

• **Competition** between pion production efficiency (*dense target*) and CR acceleration efficiency (*thin target*).
**Starburst Galaxies**

- High rate of **star formation** and SN explosions enhances (UHE) CR production.

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

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

- Power-law neutrino spectra with high-energy softening from CR leakage and/or acceleration.

[Romero & Torres'03; Liu, Wang, Inoue, Crocker & Aharonian'14; Tamborra, Ando & Murase'14]

[Palladino, Fedynitch, Rasmussen & Taylor'19; Peretti, Blasi, Aharonian, Morlino & Cristofari'19]

[Ambrosone, Chianese, Fiorillo, Marinelli, Miele & Pisanti'20]
Cosmogenic Neutrinos

- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range.
- 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.
- Absolute flux level serves as independent measure of UHE CR 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 [71] and the Pierre Auger Observatory [72]. Sensitivities are for POEMMA [400] (assuming full-sky coverage), GRAND in its 10 000-antenna (GRAND10k) and 200 000-antenna configurations (GRAND200k) [392], ARA-37 [401] (trigger level), ARIANNA [402] (“optimal wind” sensitivity), and Trinity [403] (10 m$^2$ mirror).

M. Bustamante for this review.

Will detect air showers induced by taus or tau neutrinos by observing the Cherenkov or fluorescence light produced by the EAS.

5 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

[Alves Batista et al.’19]
**Improved sensitivity** for neutrino sources to find the origin of the isotropic TeV-PeV flux

100s $\nu$ bursts $E_{\text{iso}} = 10^{50}$ erg

**Vision: IceCube-Gen2**

**Precision measurement of PeV-EeV neutrino fluxes** with extended in-ice optical and surface radio array

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[$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$]

**Figure 19:** Sensitivity of the IceCube-Gen2 radio array at the highest energies in comparison to models [41, 80, 81], existing upper limits [40, 235–238], and the 10 year sensitivity of the proposed GRAND array of 200,000 antennas [239]. The uncertainties on the IceCube-Gen2 radio array sensitivity are $\pm 20\%$, which are uncertainties in the estimated sensitivity of the array, e.g. due to remaining design decisions.

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Disintegration or photo-pion production of CR, can produce neutrinos when decaying. All of these neutrinos are referred to as cosmogenic neutrinos. So while this secondary flux of neutrinos is extremely well motivated, its level depends strongly on the composition of the CR [241, 242], the cosmic evolution of the sources, the spectral index of the sources, and their maximum acceleration energy [71, 72]. IceCube can already exclude scenarios with a very strong evolution of the CR sources with cosmic redshift [39, 40], but to draw firm conclusions much larger exposures are needed.

The sweet spot for cosmogenic neutrino detection is at $10^{18}$ eV, since the flux at these energies depends less strongly on the maximum acceleration energy and spectral index than at the highest energies [73]. The flux at this energy is primarily a function of the proton fraction and even the most conservative flux estimates peak here [80]. Conveniently, this is the energy region where in-ice neutrino detectors, and the radio array of IceCube-Gen2 will be most sensitive to the energy flux of neutrinos (see Fig. 19).

With the predicted sensitivity, IceCube-Gen2 will also be able to provide independent evidence for whether the observed cut-off in the flux of UHE cosmic rays is due to the GZK suppression or just due to reaching the limit of acceleration in the sources [243]. The neutrino flux at energies above $10^{-2}$ EeV depends primarily on the maximum energy of CR protons and the spectral index of their power-law spectrum rather than the source evolution parameters [72]. Detecting the corresponding neutrino flux will be a measurement independent of the uncertainties in the modelling of the hadronic interactions in extensive air showers and, thus, complementary to results from air shower arrays.

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**Figure 9:** Observable volume of IceCube and IceCube-Gen2 for a generic 100 s burst with equivalent isotropic emission of $10^{50}$ erg in neutrinos. The observable volumes are calculated separately for each decade in energy, assuming a neutrino spectrum of $dN/dE \propto E^2$ in that decade only and an equal flux of neutrinos in all flavors.

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In the sources and the intergalactic medium the photons are reprocessed to the GeV and TeV bands (or absorbed, in which case the neutrino energy flux could be even higher than the $\gamma$-ray energy flux). Consequently, IceCube-Gen2 will be able to measure or constrain CR acceleration processes for thousands of known $\gamma$-ray sources, as well as searching for cosmic accelerators opaque to high-energy electromagnetic radiation.

Short, second-to-day-scale transients like GRBs, compact object mergers, or core-collapse supernovae (CCSN) explosions are different from persistent sources. Backgrounds from diffuse neutrinos, air showers, thermal and anthropogenic noise are usually negligible when searching for a short burst of neutrinos; therefore, the sensitivity scales differently with effective area, volume, and angular resolution than for persistent sources.

An important performance measure for transient events is the volume within the universe in which they can be observed. Figure 9 shows the observable volume of the universe for IceCube-Gen2 in comparison to IceCube for a generic 100 s burst with equivalent isotropic emission of $10^{50}$ erg in neutrinos as a function of energy. An order-of-magnitude increase in observable volume is expected for energies up to $10^{19}$ PeV compared to IceCube, while at energies above $10^{20}$ PeV the radio array will allow for the first time the observation of a relevant portion of the universe. The observable volume of up to few times $10^7$ Mpc$^3$ for such a burst is similar to the one that gravitational wave detectors will reach in the next decade for the detection of binary neutron star mergers [110].

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### Outlook: Baikal-GVD

- **GVD Phase 1**: 8 clusters with 8 strings expected to be completed by end of 2021 (~0.4 km³)

- Cluster depth: 735–1260 m

- **Status March 2021**: 7 clusters

- **Final goal**: 27 clusters (~1.4 km³)

### Cumulative Number of Clusters vs. Year

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<th>Number of Clusters</th>
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<td>2020</td>
<td>7</td>
</tr>
<tr>
<td>2021</td>
<td>9</td>
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### Detector Outline in 2019

- Map and schematic of detector outline in 2019

### Search for Cascade Events

<table>
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<tr>
<th>Date</th>
<th>E (TeV)</th>
<th>Zenith °</th>
<th>Azimuth °</th>
<th>RA</th>
<th>Dec</th>
<th>T UNIX</th>
<th>x (m)</th>
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<td>4.3</td>
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</table>

- Approximately 157 TeV cascade event observed in 2016/7 data

- Project scope is cubic-km-scale detector deployed in Lake Baikal
- Phase 1 (GVD-1) is 8 clusters instrumenting 0.4 km³
- 3 clusters operational with 1-2 deployed per season
- Final goal: 27 clusters (~1.4 km³)

### Work in Progress

- 3 events passed the final cut ($N_{\text{hit}} > 20$ & $E_{\text{sh}} > 100$ TeV)
- If assume that all passed events are from background, upper limit is:
  - $F_{90\%} = 5.4 \times 10^{-10}$ (TeV cm² sr⁻¹)
  - 3 times higher than IC flux
- Work is in progress
Outlook: KM3NeT/ARCA

- **ARCA**: 2 building blocks of 115 detection units (DUs)
- **status March 2021**: 1 DU
- April 2021: +5 DUs
- September 2021: +12 DUs

- **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.
Tests of fundamental physics accessible with neutrinos of different energies.

How do flavors mix at high energies? Experiments with neutrinos of up to TeV energies have confirmed that the different neutrino flavors, $n_e$, $n_\mu$, and $n_\tau$, mix and oscillate into each other as they propagate [33]. Figure 3 shows that, if high-energy cosmic neutrinos en route to Earth oscillate as expected, the predicted allowed region of the ratios of each flavor to the total flux is small, even after accounting for uncertainties in the parameters that drive the oscillations and in the neutrino production process [57]. However, at these energies and over cosmological propagation baselines [58], mixing is untested; BSM effects could affect oscillations, vastly expanding the allowed region of flavor ratios and making them sensitive probes of BSM [57, 59–68].

What are the fundamental symmetries of Nature? Beyond the TeV scale, the symmetries of the SM may break or new ones may appear. The effects of breaking lepton-number conservation, or CPT and Lorentz invariance [69], cornerstones of the SM, are expected to grow with neutrino energy and affect multiple neutrino observables [70–81]. Currently, the strongest constraints in neutrinos come from high-energy atmospheric neutrinos [82]; cosmic neutrinos could provide unprecedented sensitivity [62,71,73,76,78,83–90]. Further, detection of ZeV neutrinos, well beyond astrophysical expectations, would probe GrandUnified Theories [43, 91–94].

Are neutrinos stable? Neutrinos are essentially stable in the SM [95–97], but BSM physics could introduce new channels for the heavier neutrinos to decay into the lighter ones [98–100], with shorter lifetimes. During propagation over cosmological baselines, neutrino decay could leave imprints on the energy spectrum and flavor composition [65, 101–104]. The associated sensitivity outperforms existing limits obtained using neutrinos with shorter baselines [103]. Comparable sensitivities are expected for similar BSM models, like pseudo-Dirac neutrinos [65, 105, 106].

What is dark matter? Cosmic neutrinos can probe the nature of dark matter. Dark matter may decay or self-annihilate into neutrinos [107–110], leaving imprints on the neutrino energy spectrum, e.g., line-like features. Searches for these features have yielded strong constraints on dark matter in the Milky Way [111–113] and nearby galaxies [114]. High-energy cosmic neutrinos...
Neutrino Selection I

- IceCube
- atmospheric neutrinos
- cosmic neutrinos
- 10 per year (above 100 TeV)

Up-going and down-going neutrinos detected by IceCube.
Neutrino Selection I

IceCube

atmosphere

10 per year (above 100TeV)

60,000,000,000 per year

atmospheric muon

cosmic neutrino

cosmic ray

down-going

up-going
Neutrino Selection I

Neutrino Selection I

- **cosmic ray**: 10 per year (above 100 TeV)
- **atmospheric neutrino**: 10,000 per year
- **atmospheric muon**: 60,000,000,000 per year
- **IceCube**: up-going and down-going cosmic rays

Markus Ahlers (NBI)  High-Energy Neutrino Observations by IceCube
• Outer layer of optical modules used as virtual veto region.

• 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
• Outer layer of optical modules used as virtual veto region.

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

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• High-Energy Starting Event (HESE) analysis
Astrophysical Neutrino Fluxes

![Graph showing non-anthropogenic neutrino fluxes](image)

- **CvB**
- Core-collapse SNe
- Avg. atm. $\nu_\mu + \bar{\nu}_\mu$
- Avg. Galactic diffuse
- IC cascade (6yr)
- Cosmogenic (p)

**Non-anthropogenic neutrino fluxes** ($\nu + \bar{\nu}$ per flavour)

- SN 1987A
- The Sun
- Cosmic neutrino background
- Cosmic neutrinos

**Neutrino energy $E$ [eV]**

- $10^{-3}$
- $10^3$
- $10^6$
- $10^9$
- $10^{12}$
- $10^{15}$
- $10^{18}$
Gamma-Ray Bursts

High-energy neutrino emission is predicted by cosmic ray interactions with radiation at various stages of the GRB evolution.
The 90% credible intervals for the component masses (in the $m_{12}$ convention) are $m_1 = 1.36, 2.26$ and $m_2 = 0.86, 1.36$, with total mass $M = 2.82^{+0.47}_{-0.09}$. When considering dimensionless spin with magnitudes up to 0.89 (high-spin prior, hereafter), the measured component masses are $m_1 = 1.36, 1.60$ and $m_2 = 1.17, 1.36$, and the total mass is $M = 2.86$. When the dimensionless spin prior is restricted to 0.05 (low-spin prior, hereafter), the measured component masses are $m_1 = 1.36, 1.17$ and $m_2 = 1.17, 1.36$, and the total mass is $M = 2.86$. 

Figure 2. Joint, multi-messenger detection of GW170817 and GRB170817A. Top: the summed GBM lightcurve for sodium iodide (NaI) detectors 1, 2, and 5 for GRB170817A 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 with a 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 $T_{GW}$. 


Markus Ahlers (NBI) 

High-Energy Neutrino Observations by IceCube
• No coincident neutrinos observed by IceCube, ANTARES or Auger.

• Consistent with predicted neutrino flux from internal shocks and off-axis viewing angle.
Formalism can be extended to off-axis emission of structured jets as in the case of GRB 170817A.

Figure 1.

Note that the angular distributions in Fig. 10 correspond to the velocity vector of the specific volume element in the GRB’s rest frame and reflects the strong angular distribution in the GRB. The relative distribution of GRB 170817A compared to an exact calculation is shown in Fig. 32. Solid lines represent the on-axis prediction and dotted lines represent the off-axis prediction. The relative distribution of the neutrino fluence at different energies is shown in Fig. 32.

The general relation of the energy fluence is motivated by the specific emissivity of the non-thermal baryonic loading factor, which depends on jet angle. The relative distribution of the neutrino fluence at different energies is shown in Fig. 32.

We will study the on-axis and off-axis neutrino emission based on the on-axis top-hat jet calculation with Lorentz approximation (thin green lines) of the off-axis prediction has only a weak dependence on the viewing angle. The relative distribution of the neutrino fluence at different energies is shown in Fig. 32.

The uncertainties in the off-axis neutrino fluence are determined via the specific emissivity of neutrino emissivity from cosmic ray interactions in the frame of the central colliding sub-shells. The general relation of the energy fluence is also determined via the specific emissivity of neutrino emissivity from cosmic ray interactions in the frame of the central colliding sub-shells.

The uncertainties in the off-axis neutrino fluence are determined via the specific emissivity of neutrino emissivity from cosmic ray interactions in the frame of the central colliding sub-shells. The general relation of the energy fluence is also determined via the specific emissivity of neutrino emissivity from cosmic ray interactions in the frame of the central colliding sub-shells.
Active galaxy powered by accretion onto a supermassive black hole with relativistic jets pointing into our line of sight.
Neutrino Flux Predictions are fairly insensitive to the exact parameter values included here. Photon attenuation at other set to twice this maximal value (dashed gray line). Figure 5. Photon SED can be modelled by lepto-hadronic or proton-synchrotron models.

- 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]
Non-Blazar Limit

- Photon fluctuation analyses of Fermi-LAT data allow to constrain the source count distribution of blazars below the source detection threshold.

- Inferred blazar contribution to EGB above 50 GeV:
  - Fermi Collaboration'15: 86^{+16}_{-14} \%
  - Lisanti et al.'16: 68^{+9}_{-8}(\pm 10)_{\text{sys}} \%
  - Zechlin et al.'16: 81^{+52}_{-19} \%
Neutrino production via cosmic ray interactions with gas (pp) in general overproduce \( \gamma \)-rays in the Fermi-LAT range.

\[ \Gamma \leq 2.15 \]

hadronic \( \gamma \)-ray emission normalized to best-fit non-blazar EGB

\[ \text{pp scenario} \]

\[ \text{combined fit range} \]

[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke’15]

[see also Murase, MA & Lacki’13; Tamborra, Ando & Murase’14; Ando, Tamborra & Zandanel’15]

[Guetta, MA & Murase’16; Palladino, Fedynitch, Rasmussen & Taylor’19]

[Ambrosone, Chianese, Fiorillo, Marinelli, Miele & Pisanti’20]
Tidal Disruption Events

Stars are pulled apart by tidal forces in the vicinity of supermassive black holes. Accretion of stellar remnants powers plasma outflows.
Tidal Disruption Events

• Association of alert IC-191001A with radio-emitting TDE AT2019dsg
• Plot shows data from Zwicky-Transient Facility and SWIFT-UVOT.
• Chance for random correlation of TDEs and IceCube alerts is 0.5%.

Astrophysical Flavours

3-flavor oscillation
($\nu$-fit v5.0 / NO)

 ternary graph

Superposition of flavour and mass states induces oscillations.

flavour ratios on production

$\nu_e$ fraction ($f_{\nu_e,\oplus}$)

$\nu_\tau$ fraction ($f_{\nu_\tau,\oplus}$)

$\nu_\mu$ fraction ($f_{\nu_\mu,\oplus}$)
No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but several interesting candidates.