IceCube: Dark Matter Searches and Future Perspectives

CARSTEN ROTT
DEPARTMENT OF PHYSICS, SUNGKYUNKWAN UNIVERSITY

ABSTRACT

Dark matter could be detected through the observation of neutrinos originating from dark matter annihilations or decays. The world's largest neutrino telescope, IceCube, is at the forefront of such indirect searches for evidence of beyond the standard model physics. Analyses of IceCube data have resulted in some of the most stringent constraints on dark matter annihilations, interactions with nucleons, and have spurred imaginations on the yet to be determined origin of the recently discovered high-energy astrophysical neutrino flux. In the future, improved analyses methods combined with high statistics samples of multiple years of IceCube data and later from detector expansions will provide significant potential for discovery of dark matter.

INTRODUCTION

While the presence of dark matter (DM) in the universe has been inferred from imprints on the cosmic microwave background, structure formation, and rotational curves of galaxies, its nature remains a mystery [1]. Weakly Interacting Massive Particles (WIMPs) are one of the most promising and experimentally accessible DM candidates, which are predicted in extensions of the Standard Model (SM) of particle physics. WIMPs may be captured in large celestial bodies like the Sun, where self-annihilation to SM particles could produce neutrino fluxes accessible by terrestrial neutrino detectors. Further dark matter annihilations in the Galactic dark matter halo, or from other dense accumulations, such as dwarf spheriodals or the Galactic center, are excellent targets for searches.

The cubic-kilometer-volume neutrino telescope, IceCube, has produced some of the strongest bounds to date on WIMP properties, constraining the spin-dependent scattering cross section with protons to 1.3×10^{-40} cm^2 for WIMP masses of 250 GeV [2]. The dark matter self-annihilation cross section averaged over the velocity distribution can be constrained to about 10^{-23} cm^{3}s^{-1} for masses above 1 TeV [3, 4]. Based on these neutrino searches, some scenarios motivated by the rise of the positron-to-electron fraction in cosmic rays observed by PAMELA and AMS-02 and the claims of anomalous annual modulation signals in direct detection experiments, have already been excluded [5, 6]. Striking neutrino signatures, such as a high-energy neutrino flux from the Sun with a spectrum as expected from annihilations would leave little doubt about the observation.

THE ICECUBE NEUTRINO OBSERVATORY

The IceCube detector [7] shown in Figure 1 is a neutrino detector of one cubic kilometer volume. It is located at the geographic South Pole and was completed at the end of 2010 after seven years of construction. IceCube exploits ice as a natural detector medium with excellent optical properties that have been extensively studied [8, 9]. This multipurpose detector consists of 5160 optical

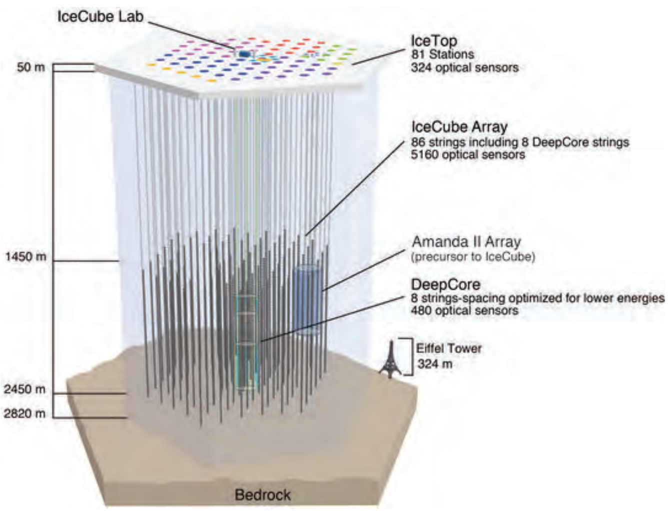

Fig. 1: The IceCube Neutrino Observatory instruments roughly one cubic kilometer of clear Antarctic ice with 86 strings anchored at depth of about 2450m and each containing 60 digital optical modules (DOMs).

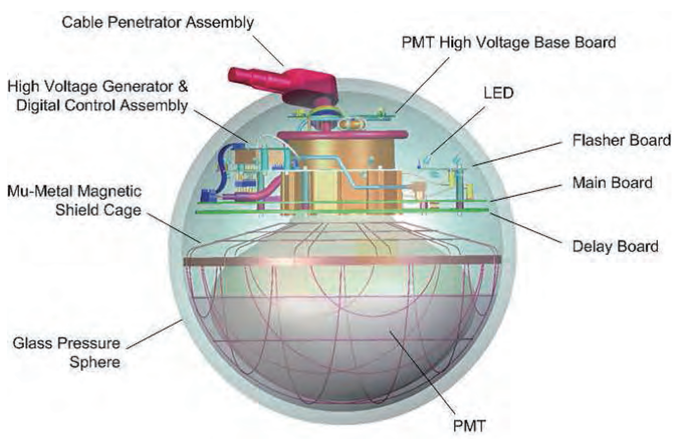

Fig. 2: Digital optical modules (DOMs) are pressure resistant glass spheres, each containing a Hamamatsu photomultiplier tube (PMT) of 25 cm diameter and the associated electronics necessary for waveform digitization [12, 13].

sensors buried between 1450 and 2450 meters below the surface of the Antarctic ice sheet. There are 86 vertical strings each having 60 optical sensors (see Figure 2) connected together. Each of the strings was lowered into 60 cm diameter holes drilled using up to 85 °C heated water.

IceCube was optimized and designed to detect interactions of neutrinos of astrophysical origin, but is also sensitive to downward-going highly energetic muons and atmospheric neutrinos produced in cosmic-ray-induced air showers. The observatory includes a densely instrumented subdetector, DeepCore [10], capable to detect neutrinos with energies above 10 GeV. A surface tank array, IceTop, complements the in-ice detector with sensitivity to cosmic-ray induced extended air showers with primary energies above 1 PeV [11].

IceCube detects neutrinos by observing Cherenkov radiation from the charged particles produced in neutrino interactions. Event topologies allow for easy identification of charge-current muon neutrino interactions. An energetic muon will be produced that creates a track-like pattern in the detector (see right plot on Figure 3). The muon carries on average 80% of the energy of an energetic neutrino or 50% for a neutrino of 10 GeV. Electron and tau neutrino interactions show similar spherical topologies (cascade) that are generally indistinguishable with exception of yet to be observed double bang events caused by the boosted lifetime of taus in the PeV range [14, 15, 16, 17]. In neutral-current interactions a small fraction of the neutrino energy is transferred to a nuclear target, resulting in a cascade produced by the hadronic shower.

IceCube operates at a 99% uptime and records about 10^{11} events per year. The vast majority of these are downward-going atmospheric muons from cosmic ray air showers, out of which about 10^5 atmospheric neutrinos can be extracted. Recently a high-energy astrophysical neutrino component was identified at 5.7σ [18, 19].

SCIENTIFIC OBJECTIVES AND DISCOVERIES

IceCube results have surpassed all expectations and with the observation of high-energy neutrinos of astrophysical origin, IceCube has revolutionized astroparticle physics

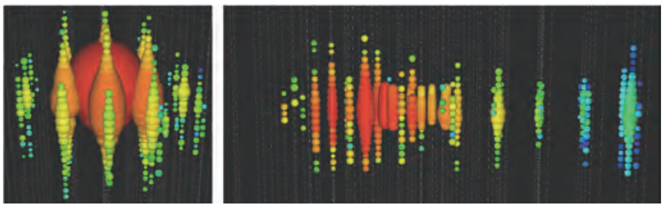

Fig. 3: Left: The most energetic neutrino event observed with energy of about 2 PeV [18]. This event, nicknamed "Big Bird", shows a spherical topology as expected from an electron neutrino interaction. Right: A track-like event, the typical signature of a detected muon neutrino. Colors indicate the time and the diameter of each sphere represents the number of photons detected by the corresponding DOM.

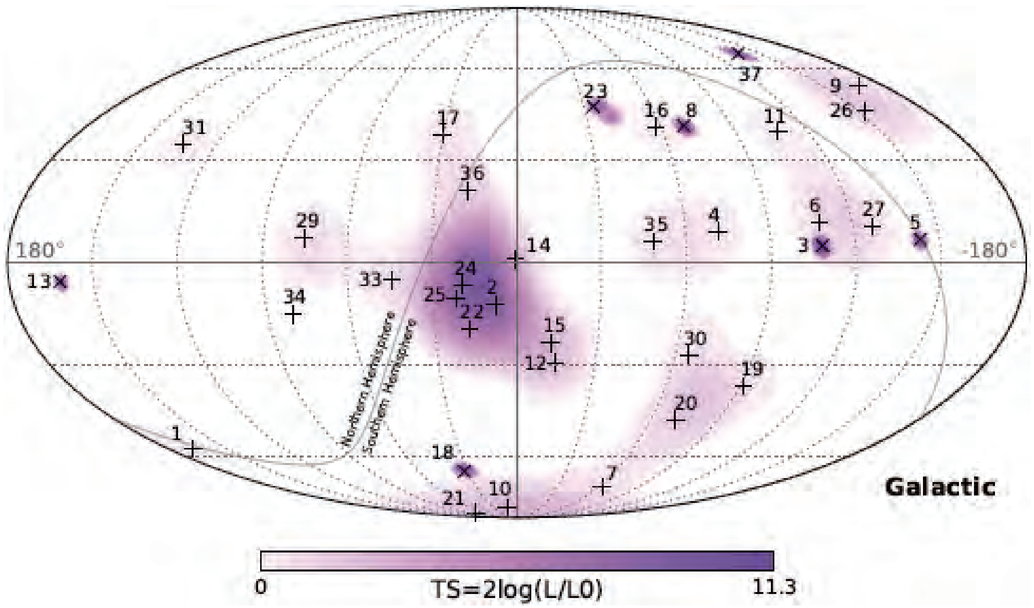

Fig. 4: Skymap in Galactic coordinates of the astrophysical neutrino candidate events. Shower-like events (median angular resolution <15°) are denoted by +, while those containing a tracks (<1°) by x. The purity fraction of the astrophysical sample is about 60%, with the remaining events expected from atmospheric backgrounds. No significant clustering is present, as derived from the test statistic of a point source clustering test shown in color [18].

and opened up a new window to the Universe. The ability to detect individual neutrinos from a few GeV to beyond EeV (10^{18} eV) as well as MeV neutrino supernova burst signals, give IceCube neutrino energy coverage of more than 12 orders of magnitude. The sub-degree angular resolution for muon-neutrino-induced muons above TeV, as well as the excellent energy resolution on cascades from electron- and tau-neutrinos, allow for a large diversity of analyses. Recent results from IceCube include a measurement of atmospheric neutrino fluxes [20], observation of a cosmic-ray anisotropy [21], constraints on slow moving monopoles [22], and a measurement of atmospheric neutrino mixing parameters which is compatible, and comparable in precision, to those of dedicated oscillation experiments [23].

First Discoveries

IceCube's astrophysical neutrino analysis observed 37 candidate events with deposited energies ranging from 30 to 2000 TeV in three years of data [18, 19]. The event rate far exceeds expected atmospheric backgrounds. The most outstanding component of the astrophysical flux originates from cascade events, like the one shown in Figure 3, which are more detectable due to lower atmospheric backgrounds [24] and were the first ones to be observed [25].

With every new high-energy neutrino event detected, IceCube moves closer to solving the century-old mystery about the origin of the high-energy cosmic rays, which has been left open since Victor Hess's discovery in 1912. Energetic neutrinos are produced in the dense environments of the cosmic accelerators through decays of pions. The observed high-energy neutrino events, shown in Figure 4, are consistent with an isotropic distribution and no source correlations have been established, yet. Primary source candidates are massive blackholes in the center of large active galaxies, starburst galaxies, gamma-ray bursts, although already tightly constrained [26]. Active discussions are on-going about the origin of the PeV events, including numerous scenarios involving exotic physics or dark matter.

DARK MATTER SEARCHES WITH NEUTRINOS

Dark Matter Annihilation

The Milky Way is engulfed in a large dark matter halo, which is peaked toward the Galactic center. If dark matter annihilates, neutrinos are expected to be produced through sequential decays of annihilation products. As neutrinos are weakly interacting and uncharged, they travel unimpeded to us. Self-annihilations could be detected with IceCube, through the observation of an

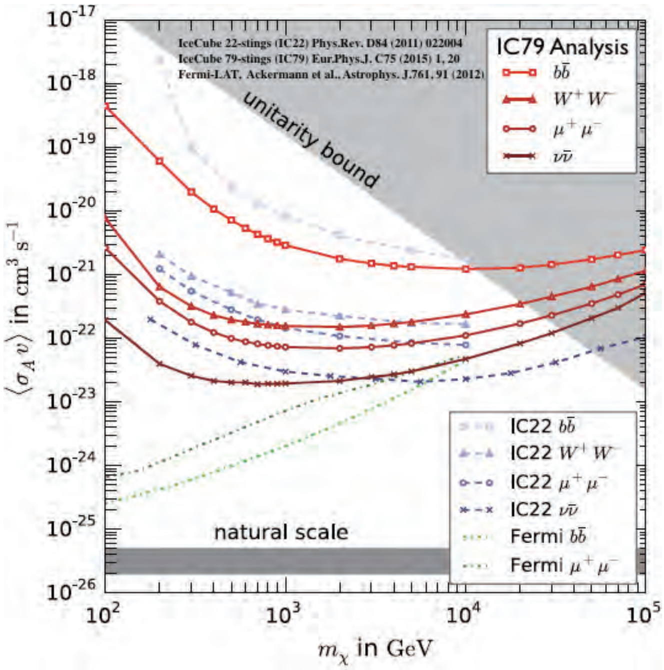

Fig. 5: Limit on the dark matter self-annihilation cross section are shown [3, 4]. The natural scale assumes dark matter is a thermal relic of the early Universe [27]. Also shown is the unitarity bound [28] and limits from observations of Dwarf galaxies by Fermi-LAT [29].

anisotropy in the neutrino arrival distribution. Figure 5 shows the result of a search using one year of IceCube data. A high purity neutrino sample was obtained, by selecting upwards going muons, which can only originate from neutrinos traversing the Earth and interacting near the detector. The sample is dominated by nearly isotropically distributed atmospheric neutrinos, from which a dark matter signal could be distinguished by its anisotropy. No anisotropy was observed and limits on the dark matter self-annihilation cross section computed.

IceCube's limits on dark matter annihilations are rather insensitive against assumptions on the dark matter distribution as an extended area is surveyed. This distinguishes IceCube's results from most searches with gamma-rays, which often focus on small dense objects. To compliment targeted gamma-ray searches, IceCube has also looked at the Galactic center and dwarf spheriodal galaxies and placed constraints on the dark matter self-annihilation cross-section [41]. Results have already largely excluded scenarios that tried to explain the observed rise in positron fraction by PAMELA and AMS-02, by dark matter annihilations into taus. IceCube is unique in placing bounds on the annihilation into neutrinos which is of high theoretical interest [42, 43].

Dark Matter Captured in the Sun

WIMPs from the Milky Way dark matter halo could accumulate in the Sun and give rise to detectable neutrino signals. A WIMP scattering off a nucleon in the Sun could result in a large enough energy loss for the WIMP to fall below the escape velocity of the Sun and to be gravitationally captured. The probability of such an interaction, which is the same underlying physics process as being searched for in direct detection experiments, depends on the WIMP-proton scattering cross section. As WIMPs accumulate in the Sun they will start to annihilate at an increasing rate. The rate increases steadily with the number of thermalized WIMPs near the center of the Sun up to a point where it becomes equal to half the capture rate. At this point as many WIMPs will be captured as annihilate away; once this equilibrium is established the annihilation rate is independent of the self-annihilation cross section and as such the neutrino flux from the Sun only depends on the WIMP-proton scattering cross section. Equilibrium is typically established on time scales less than the age of the Sun. WIMP capture is rather intensive to assumptions on the dark matter halo model [44, 45]. Capture is in particular sensitive to the spin-dependent WIMP-proton scattering cross section, as the Sun is primarily a proton target, making indirect bounds strongest compared to direct searches.

IceCube data has been searched for excess neutrinos from the direction of the Sun. The observed flux was consistent with the background expectations and limits on the WIMP-proton scattering were derived. The latest results compared with direct detection constraints and other indirect searches are shown in Figure 6. The expected neutrino flux and spectrum depends on the annihilation channels. We show a few representative cases for annihilation into b-quarks and W bosons (or tau, if below the W mass), denoted by soft and hard channel, respectively. Interactions in the solar medium lead to a large number of pions for nearly all annihilation final states, which can also result in interesting neutrino signals [46, 47].

Decaying Dark Matter

Decaying dark matter can be constrained by searching for neutrino signals from the Galactic dark matter halo. IceCube has ruled out dark matter decaying into neutrinos falling short of lifetimes of 10^{10} times the age of the universe for mass above 10 TeV [4].

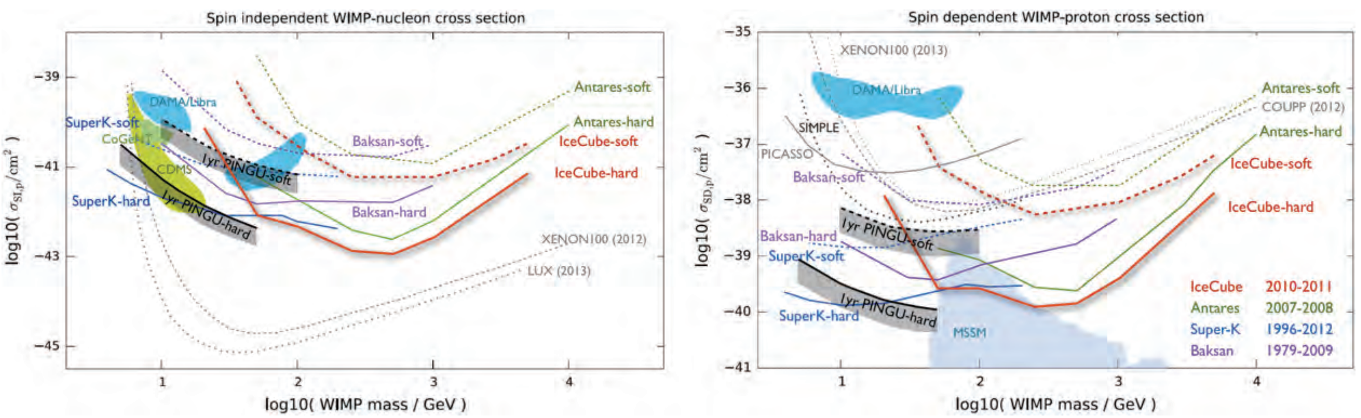

Fig. 6: Upper limits at 90% CL on spin independent (left plot) and spin dependent (right plot) scattering of WIMPs with nucleons are shown for hard and soft annihilation channels over a range of WIMP masses from IceCube [2], Super-K [30], ANTARES [31], and Baksan [32]. Direct search results from COUPP [33], XENON100 [34, 35], LUX [36], and tentative signal regions [37, 38, 39] are shown for comparison. Sensitivities for the IceCube upgrade (PINGU) assuming one year of data are shown [40], the grey shaded region represents the potential improvements over a conservative analysis. The blue shaded region refers to supersymmetric models [2].

FUTURE PERSPECTIVE

Following the success of IceCube, a low energy infill array and a high-energy extension are currently envisioned as upgrades to IceCube. The Precision IceCube Next Generation Upgrade (PINGU) [40], forsees the creation of a high-precision neutrino detector with a threshold of about one GeV, through the deployment of 40 densely instrumented strings. IceCube-Gen2 [48] would increase the effective area by roughly a factor of ten for neutrinos about 10 TeV through the deployment of about 100 widely spaced strings.

Precision IceCube Next Generation Upgrade

The main physics objective of the Precision IceCube Next Generation Upgrade (PINGU) is determining the hierarchy of the neutrino mass states and search for dark matter in the experimentally interesting mass range of a few to 100 GeV. PINGU is designed to distinguish between the normal and inverted neutrino mass hierarchy at 3σ significance with less than four years of data. PINGU would significantly improve sensitivity to WIMP masses below 100 GeV in searches for dark matter captured in the Sun or from annihilations in the Galactic center and Milky Way halo. As such PINGU can extend solar WIMP searches into the region currently favored by some dark matter direct detection experiments. Figure 7 shows PINGU's sensitivities using a 40 strings benchmark geometry.

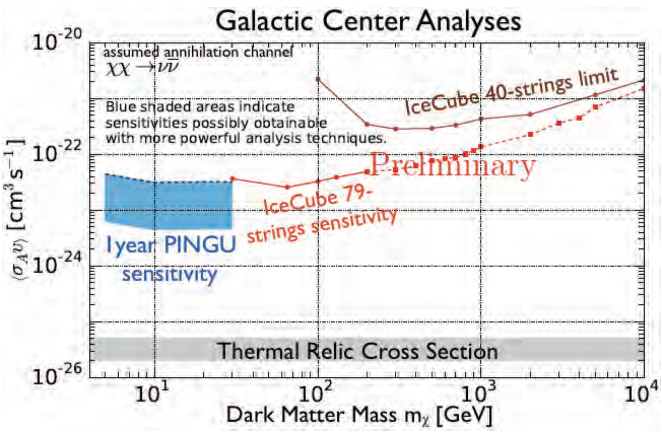

Fig. 7: Sensitivity with one year of PINGU data to dark matter annihilating in the Galactic center [40].

IceCube-Gen2

IceCube-Gen2 would deliver substantial increases in the astrophysical neutrino sample for all flavors to determine the origin and sources of the high-energy astrophysical neutrino flux. It will precisely measure the neutrino spectrum, flavor ratios, and arrival distributions. The sensitivity to heavy decaying dark matter will be improved significantly.

CONCLUSIONS

With the discovery of high-energy astrophysical neutrinos, IceCube has reigned in a new era in astroparticle physics. This new vibrant field that provides copious connections between particle physics and astrophysics continues to grow rapidly. Indirect searches for neutrinos from dark matter annihilations provide a high discovery potential and striking signatures, like the one expected from dark matter captured in the Sun, would leave little doubt about its origin. The IceCube constraints on spin-dependent scattering of dark matter on proton are the world's strongest for masses above 50 GeV. The limits have already excluded some of the dark matter direct detection anomalies and with PINGU the majority of these scenarios become testable.

Acknowledgement: I would like to thank my collaborators at IceCube, John Beacom, Shinsuke Kawai, Ranjan Laha, and Kenny Ng for fruitful discussions.

References

[1] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267, 195 (1996); G. Bertone, D. Hooper and J. Silk, Phys. Rept. 405, 279 (2005); J. L. Feng, Ann. Rev. As-tron. AstroPhys. 48, 495 (2010).
[2] M. G. Aartsen (IceCube Coll.), Phys. Rev.Lett. 110, 131302 (2013).
[3] M. G. Aartsen (IceCube Coll.), Eur.Phys. J. C75 (2015) 1, 20.
[4] R. Abbasi et al. (IceCube Coll.), Phys. Rev. D84 (2011) 022004.
[5] P. Meade, M. Papucci, A. Strumia, and T. Volansky, Nucl.Phys. B831, 178 (2010).
[6] L. Accardo et al. (AMS Collaboration), Phys. Rev. Lett. 113, 121101 (2014).
[7] J. Ahrens et al. (IceCube Coll.), Astropart. Phys. 20, 507 (2004).
[8] M. G. Aartsen et al. (IceCube Coll.), Journal of Glaciology, Vol. 59, No. 218, 2013.
[9] R. Abbasi et al. (IceCube Coll.), Nucl. Instrum. Meth. A618, 139 (2010).
[10] R. Abbasi et al. (IceCube Coll.), Astropart. Phys. 35 (2012) 615-624.
[11] M. G. Aartsen et al. (IceCube Coll.), Phys. Rev. D.88.042004 (2013).
[12] R. Abbasi et al. (IceCube Coll.), Nucl. Instr. Meth. A, 618 (2010) 139.
[13] R. Abbasi et al. (IceCube Coll.), Nucl. Instr. Meth. A, 601(2009) 294.
[14] F. Halzen and S. Klein Phys. Today 61N5 (2008) 29-35.
[15] J. G. Learned and S. Pakvasa, Astropart. Phys. 3, 267(1995).
[16] J. F. Beacom et al. Phys. Rev. D68 (2003) 093005.
[17] M. G. Aartsen et al. (IceCube Coll.) JINST 9 (2014) P03009.
[18] M. G. Aartsen et al. (IceCube Coll.) Phys. Rev.Lett. 113 (2014) 101101.
[19] M. G. Aartsen et al. (IceCube Coll.) Science 342 (2013) 1242856.
[20] M. G. Aartsen et al. (IceCube Coll.) Phys. Rev.Lett. 110 (2013) 15, 151105.
[21] R. Abbasi et al. (IceCube Coll.) AstroPhys. J. 746 (2012) 33.
[22] M. G. Aartsen et al., (IceCube Coll.) Eur. Phys. J. C (2014) 74:2938.
[23] M. G. Aartsen et al. (IceCube Coll.) Phys. Rev. D91 (2015) 7, 072004.
[24] J. F. Beacom and J. Candia, JCAP 0411, 009 (2004).
[25] M. G. Aartsen et al. (IceCube Coll.) Phys. Rev.Lett. 111 (2013) 021103.
[26] R. Abbasi et al. (IceCube Coll.) Nature 484 (2012) 351-353.
[27] G. Steigman, Annu. Rev. Nucl. Part. Sci. 29, 313 (1979).
[28] K. Griest and M. Kamionkowski, Phys. Rev. Lett. 64, 615 (1990).
[29] M. Ackermann et al. (Fermi-LAT Coll.), AstroPhys. J. 761, 91 (2012).
[30] K. Choi et al. (Super-Kamiokande Coll.) Phys. Rev. Lett. 114, 141301 (2015).
[31] S. Adrian-Martinez, et al., (ANTARES Coll.), JCAP 1311 (2013) 032.
[32] M. Boliev, S. Demidov, S. Mikheyev, O. Suvorova, JCAP 1309 (2013) 019.
[33] E. Behnke, et al., (COUPP Coll.), Phys. Rev.D 86 (2012) 052001.
[34] E. Aprile, et al., (XENON100 Coll.), Phys. Rev. Lett. 109 (2012) 181301.
[35] E. Aprile, et al., (XENON100 Coll.), Phys. Rev. Lett. 111 (2013) 021301.
[36] D. Akerib, et al., (LUX Coll.), Phys. Rev.Lett.112 (2014) 091303.
[37] C. Savage, G. Gelmini, P. Gondolo, K. Freese, JCAP 04 (2009) 010.
[38] C. Aalseth, et al., (CoGeNT Coll.), Phys. Rev. Lett. 107 (2011) 141301.
[39] R. Agnese, et al., (CDMS Coll.), Phys. Rev. Lett. 111 (2013) 251301.
[40] M.G. Aartsen et al. (IceCube-PINGU Coll.), Letter of Intent: The Precision IceCube Next Generation Upgrade (PINGU) arXiv:1401.2046 [physics. ins-det].
[41] M.G. Aartsen et al. (IceCube Coll.), Phys. Rev. D 88,122001 (2013).
[42] J. F. Beacom, N. F. Bell, and G. D. Mack, Phys. Rev. Lett. 99, 231301 (2007).
[43] M. Lindner, A. Merle, V. Niro Phys. Rev.D82 (2010) 123529.
[44] K. Choi, C. Rott, Y. Itow JCAP 1405 (2014) 049.
[45] M. Danninger and C. Rott Phys. Dark.Univ. 5–6 (2014) 35–44.
[46] C. Rott, J. M. Siegal-Gaskins, and J. F. Beacom Phys. Rev. D 88, 055005.
[47] N. Bernal, J. Martín-Albo, and S. Palomares-Ruiz, J. Cosmol. Astropart. Phys. 08 (2013) 011.
[48] M. G. Aartsen et al., (IceCube Coll.) "IceCube-Gen2: A Vision for the Future of Neutrino Astronomy in Antarctica," arXiv:1412.5106 [astro-ph. HE].

Carsten Rott is an assistant professor at Sungkyunkwan University and a co-convener of the beyond standard model working group of the IceCube Experiment. After receiving a Ph.D. from Purdue University in 2004 for supersymmetry searches at the Collider Detector at Fermilab, he worked at the Pennsylvania State University and was a senior fellow of the Center for Cosmology and Astroparticle Physics at the Ohio State University. He has been a member of the IceCube Collaboration since 2005.