IceCube, IceCube Upgrade, and IceCube-Gen2



Chiba University Aya Ishihara

The extreme Universe viewed in very-high-energy gamma rays

2023.2.6

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Detection Principle of the Neutrino Telescopes

An array of photo sensors + dark and transparent material (ice and water)



IceCube Detector



dor 8

LED

Flavor Identifications



IceCube Construction and Runs



First important multi-messenger result



• Results based on the first (40strings and 59strings) 2 years of data



First observations of cosmic neutrinos





A big question on the background/diffuse neutrino flux Neutrino energy density matches gamma rays and cosmic rays

Neutrinos in all directions (isotropic). What is producing them?



IceCube Realtime Alert System to trigger multimessager observations





IceCube-170922A event

Science 361, eaat1378 (2018)

I c e C u b e

- 2017/9/22 20:54:30.43 UTC
- 5th and the most cosmic neutrino signal like EHE alert
- automated alert was distributed to observers just 43 seconds later



Multiwavelength Campaign with $\boldsymbol{\nu}$





2014/2015 Neutrino Flare





SCIENCE • 13 Jul 2018 • Vol 361, Issue 6398 • pp. 147-151 • DOI: 10.1126/science.aat2890



neutrino only time dependent search around the blazar TXS 0506-056
→Inconsistent with bkg-only hypothesis at the 3.5σ level
 (In addition and independently of the previous 3σ when looking in this specific direction)

However, stacking blazer search limits total contribution from Blazar and limited

After 10 yrs: Neutrino Source Searches



Science — Nov.4, 2022

RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068 global significance





Neutrinos from Obscured Cores of AGN



Not jets, but cores?



IceCube Collab. "A search for neutrino emission from cores of Active Galactic Nuclei," arXiv:2111.10169 Consistent with a contribution of AGN core neutrinos of more than 27% to the total observed extragalactic neutrino flux at 100 TeV

Ultra hot gas

Accretion disk

Supermassive Black Hole

IceCube Collab. "Analysis of the cumulative neutrino flux from Fermi-LAT blazar populations using 3 years of IceCube data," arxiv:1502.03104.

A comparison of the neutrinos with a catalog of γ-ray blazars does not produce evidence of a correlation Upper bounds ~30% as the maximum contribution from these blazars to the diffuse astrophysical neutrino flux below 100 TeV Credit: NASA/JPL-Caltech

What can we do for the neutrino astronomy after the first 10 years of the full operation?



- High energy events for the high energy (>10¹⁸ eV) CR production mechanism
- Low threshold sample for the understanding of soft sources
- Better reconstruction, better calibration

More and better in all the energy regions!





Designs of the Deep-ice Optical Sensor Array for IceCube-Gen2



IceCube-Gen2 array (1.34km~2.69km depth)

3km

IceCube-Upgrade Optical Modules

dia 36cm dia 30cm



3" x 24 ch 8" x 2 ch



1km

IceCube array (145km~2.45km depth)



DeepCore IceCube-Upgrade array

How large Gen2 must be?

arxiv.org/2107.08527





Event rates

Table 5: Rate of upgoing tracks in the IceCube-Gen2 optical array [yr⁻¹]

	astro	ophysical- ν	atmospheric-v		
Deposited energy	IceCube	IceCube-Gen2	IceCube	IceCube-Gen2	
>1 TeV	1.2×10^{2}	4.0×10^{2}	2.9×10^{5}	3.4×10^{5}	
>10 TeV	16	59	2.4×10^{2}	5.3×10^{2}	
>100 TeV	1.4	3.8	0.67	0.99	

Table 6: Rate of astrophysical neutrinos of various event categories (optical array only) [yr⁻¹]

	shower-type events		double cascades		starting tracks	
Deposited energy	IceCube	IC-Gen2	IceCube	IC-Gen2	IceCube	IC-Gen2
> 10 TeV	6.0	50	0.36	2.4	1.4	21
> 100 TeV	3.6	32	0.3	1.9	0.81	13

A factor of \sim 3.5 event rate increase for track events A factor of \sim 8.5 event rate increase for cascade events



20

Angular resolution improvement with larger detector









Anisotropy of ice

Recent improvements!

Insitu estimation of ice crystal properties at the South Pole using LED cali bration data from the IceCube Neutrino Observatory

In-situ estimation of ice crystal properties at the South Pole using LED calibration data from the IceCube Neutrino Observatory

data from the

pacial ice using \$160.

Ratha Abadu¹¹⁷, Markua Akermanol¹⁰⁴, Jenni Adamu¹¹⁶, Nakia Aggama¹¹⁷, Januan Agular¹¹⁷, Markua Akers¹¹², Maryon Ahren¹¹⁶, Jean Marco Akamedone¹¹⁷, Antonio Auguto Akees Junio¹¹⁶, Najai Kondersen Bine Amm¹¹, Karen Andeem¹¹, Jenni Marco, Gasta Anton¹¹⁶, Carlo Argobers¹¹⁴, Youka Antol¹¹⁶, Sahamashadu¹¹⁶, Sepreter Anton¹¹⁷, Xahuna Balaya¹¹, Assemb Balagoga J. ¹¹⁶, ¹¹⁶ Marco Barice¹¹⁶, Store Barole¹¹⁶, Vedant Basu¹¹⁷, Vedant Basu¹¹⁶, ¹¹⁶ Sepreter Anton¹¹⁷, Xahuna Balaya¹¹⁶, Assemb Balagoga J. ¹¹⁶, ¹¹⁶ Marco Barice¹¹⁶, ¹¹⁷, Store Barole¹¹⁷, ¹¹⁶, ¹¹⁶

The Cryosphere (European Geosciences Union)



- Rivers over the Antarctica! Anisotropy along the ice flow
 - Reconstruction bias likely due to the anisotropy
- Explanation based on birefringence of ice
 - Depth dependence of anisotropy factor
 - Flasher data strongly favors an absorption only anisotropy (timing is well matched)









Refrozen ice calibration in IceCube



What we want to with Upgrade?

- Concrete understanding of glacial ice below 1300m
 - Do we really know 3000m deep ice?
 - Yes. we know quite well
 - but we are the first experiment reaches and uses that depth of ice. Can not be perfect
 - Ice is still the largest systematic in high energy astrophysical neutrino analyses and in low energy neutrino physics
 - New understanding of ice is applicable to >10 years worth of archived IceCube data
- Physics with 5-100 GeV neutrinos
 - Low energy / small volume compared to IceCube but high energy + high statistics (large volume) opportunity compared to the many other
- Prove new techniques and improvements from the hardware side
 - 3 types of new optical sensors (plus two R&D designs for Gen2)
 - Technical challenges: New drill, cleaner ice, controlling various calibration modules...



Densely Instrumented and Improved Optical Sensors







Precision ice calibration with >10 times more effective photocathode area per volume compared to DeepCore

Upward-going 20 GeV tau neutrino











High energy cascade reconstruction

- Cascade reconstruction (incl. tau neutrinos) is systematic sensitive
- Good understanding of ice allows angular error of 5 degrees
- Re-analysis of >12 years of IceCube data





Reminder: Drill





34

The IceCube-Upgrade Schedule

• The IceCube Upgrade Rebaseline has been officially confirmed by NSF





IceCube-Gen2 @Astro2020 Decadal

Upgrade rebaseline set and updating Gen2 schedule/proposal



Gen2 Schedule



Intermediate sensitivities



- Full sensitivity and good exposure is required for the detection of dimmer neutrino sources
- However for time-dependent flares such as TXS-like flare, deployment of first year or two, Gen2 becomes large enough to achieve 5σ level of observation
 - Partial construction is still valuable for time dependent neutrino emissions!



Optical Module Production Sites

As soon as positive indication from NSF (PDR approval), need to start…





Summary



- IceCube opened the field of the high energy neutrino astronomy
- Extension is anticipated
 - Statistical, calibration, reconstruction, and systematic improvements
- Based on the IceCube's designs with many improvements, IceCube Upgrade and IceCube-Gen2 have been designed
- Upgrade had some impact due to COVID 3 years delay in projects, rebaseline schedule/cost successfully approved in 2022, secured logistics at the South Pole in 23/24, 24/25, 25/26 seasons
- Astro2020 in 2021 and the Upgrade re-baseline review in 2022, Gen2 official review is now ramping up with TDR submission within a month to NSF! Meetings with International financial agencies and NSF soon
- The IceCube-Gen2 surface/radio array not covered in this talk





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IceCube-Gen2 Working group structure





Figure 104: IceCube-Gen2 Project Organization Structure