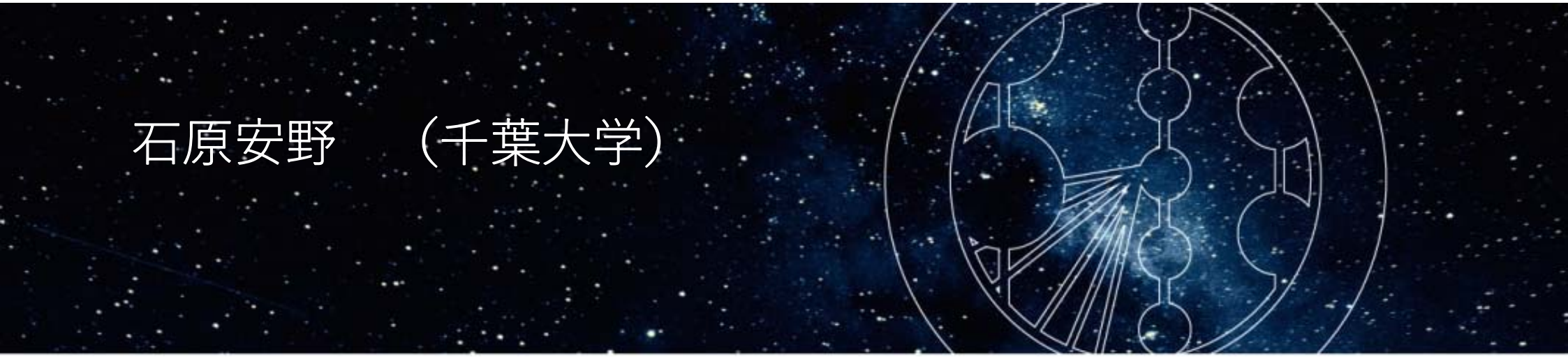
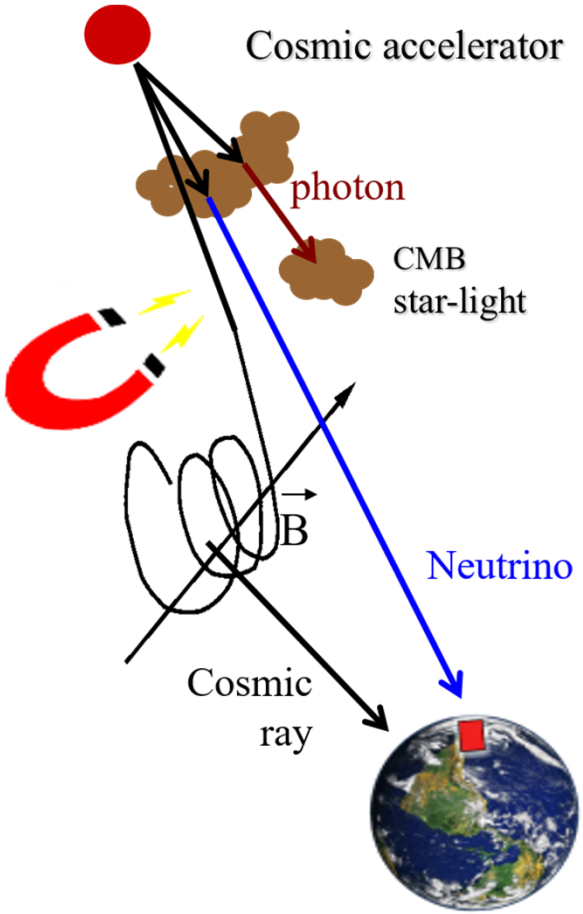
日本物理学会秋季大会2021シンポジウム
ニュートリノ・重力波時代のマルチメッセンジャー天文学の展望

高エネルギー宇宙ニュートリノ観測: これまでの進展と将来展望

石原安野　（千葉大学）



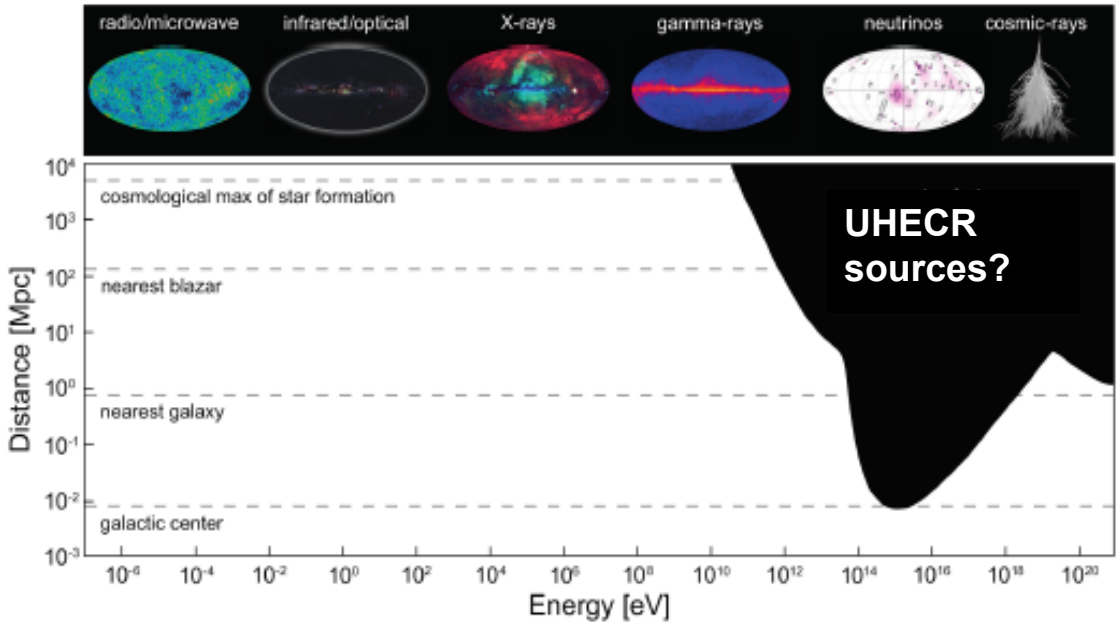
High Energy Neutrino as a Cosmic Messenger



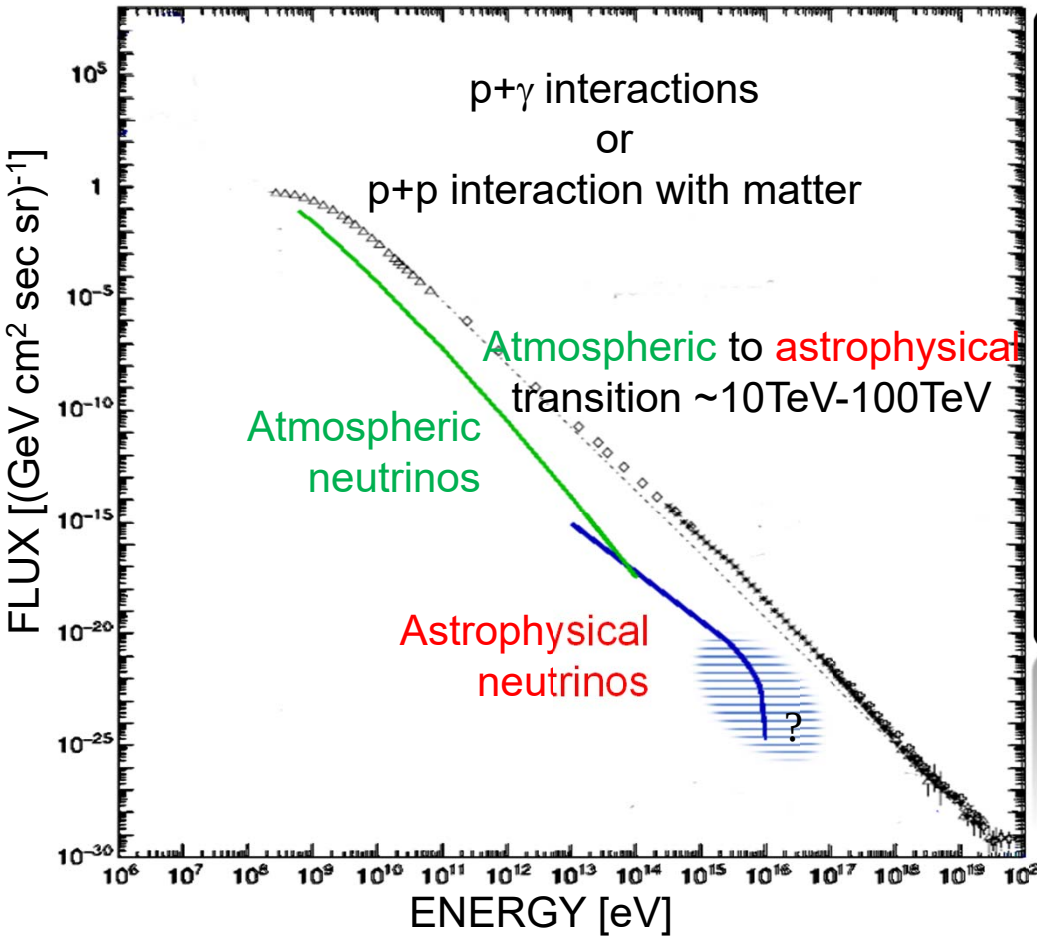
Weak interaction during "propagation"

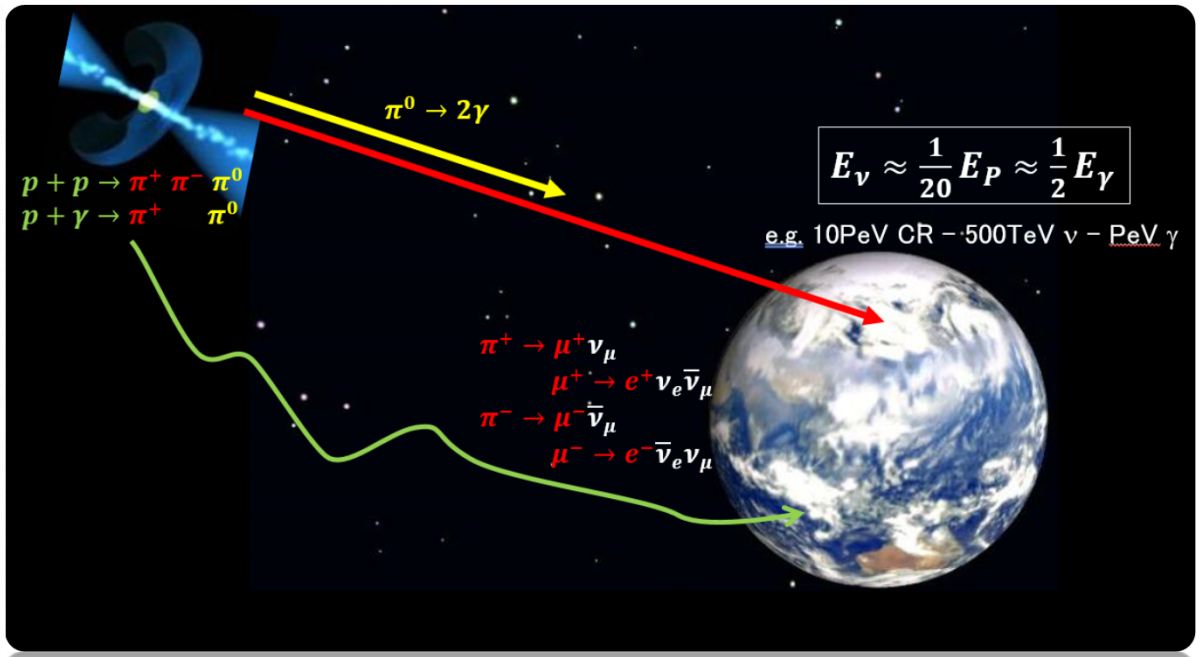
- **Penetration power**
- **Pointing capability**

even at extreme energies

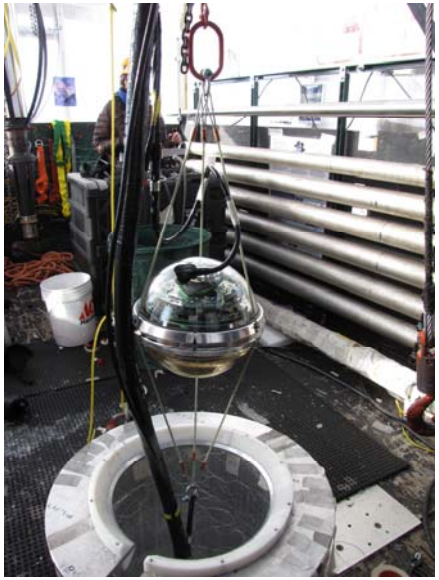


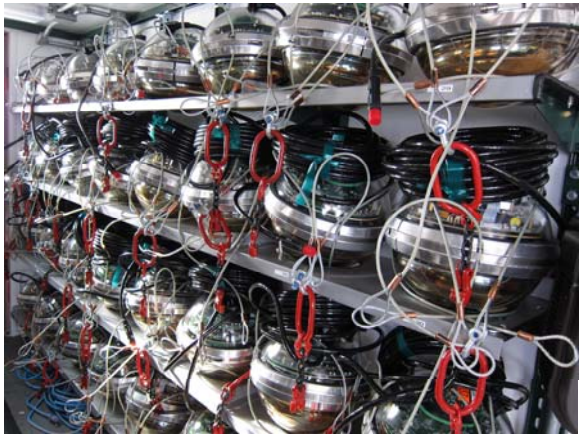
Ultra-high Energy Neutrinos in the Universe

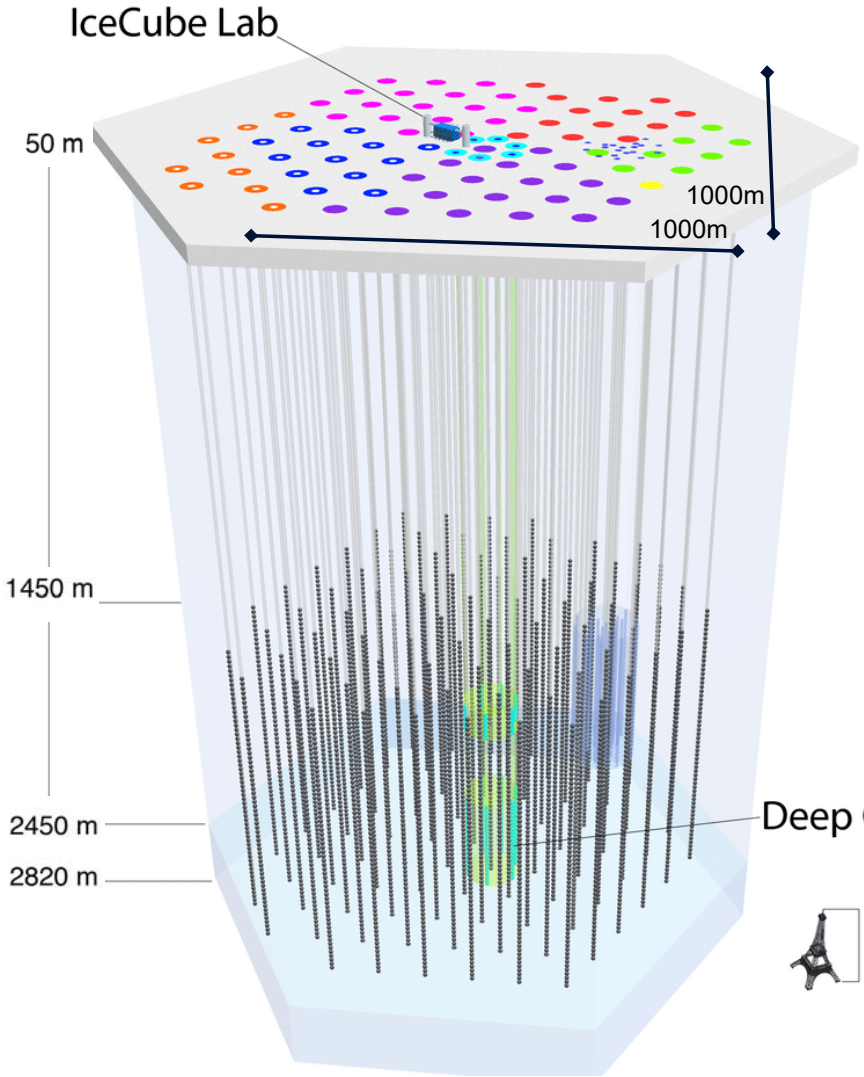




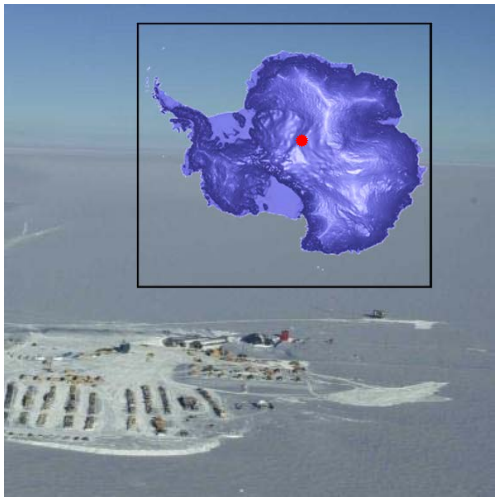
The IceCube Detector



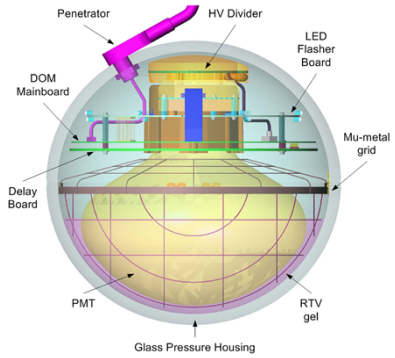


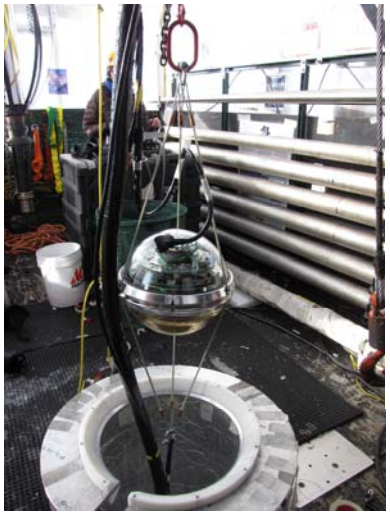


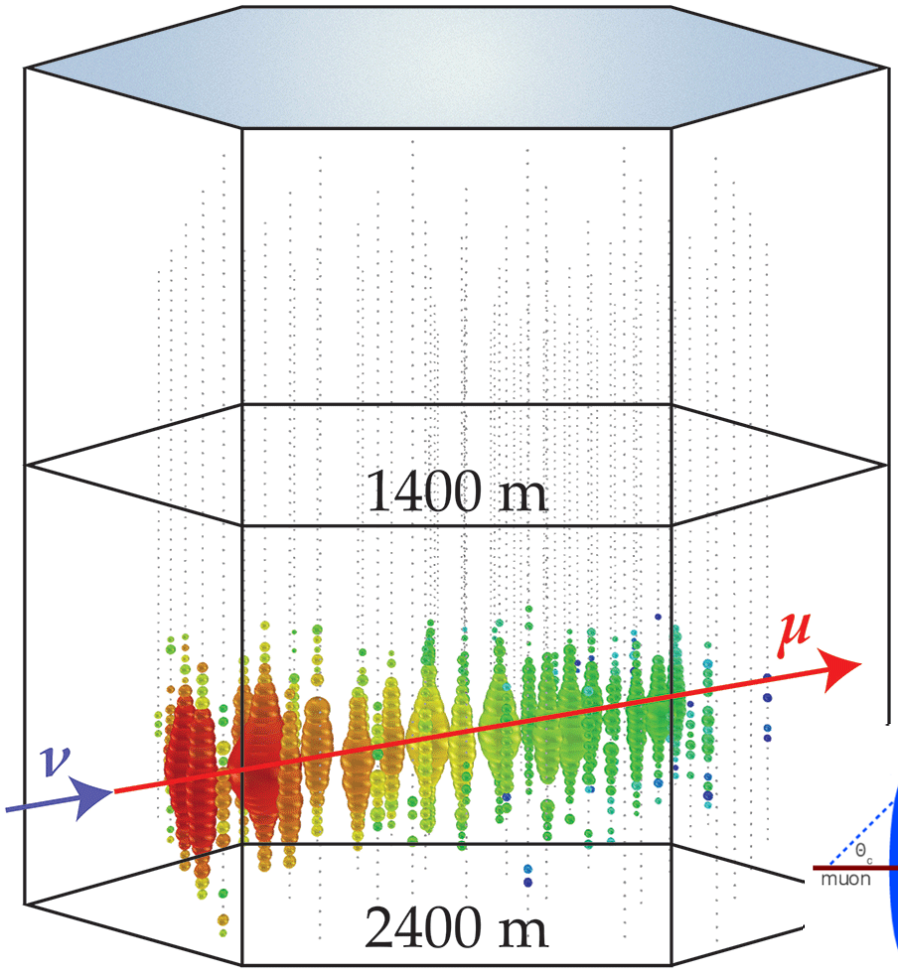
@ Amundsen-Scott South Pole station

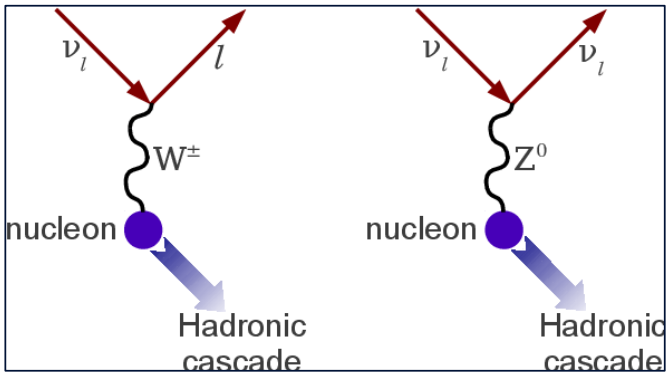


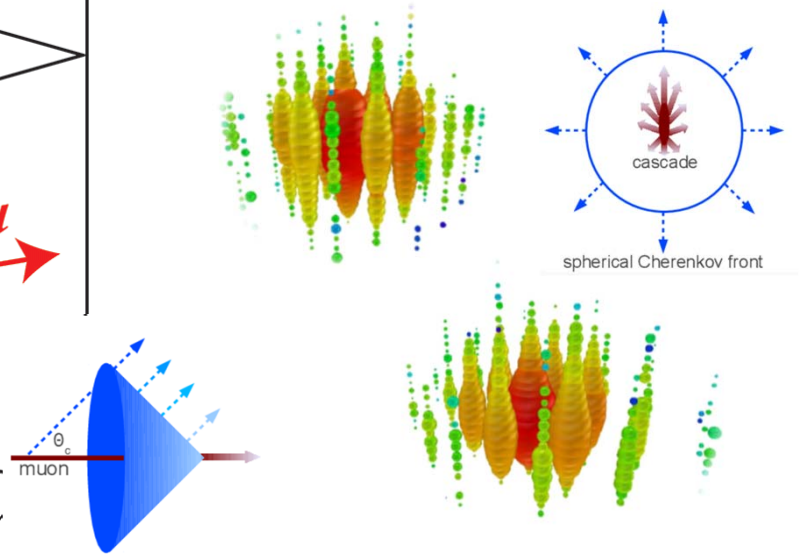
IceCube Neutrino Events





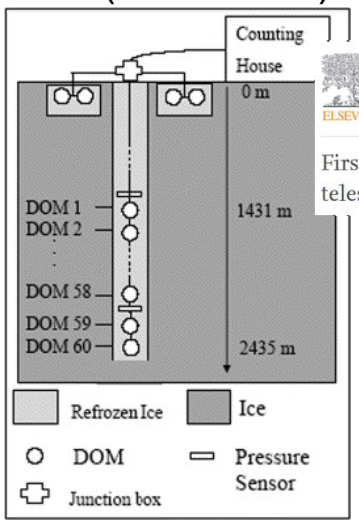


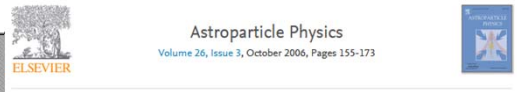




IceCube Construction and Runs

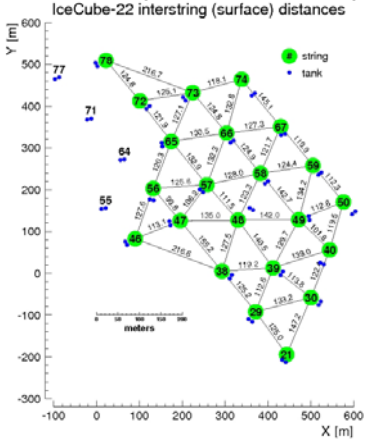
IC1(2005-2006)



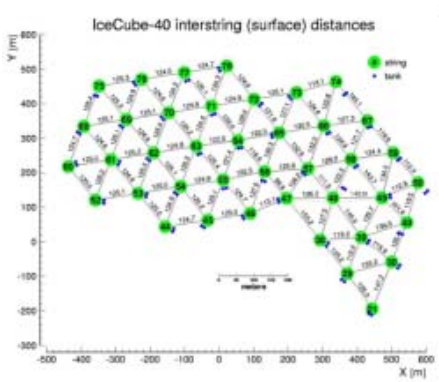


IC9 (2006-2007)

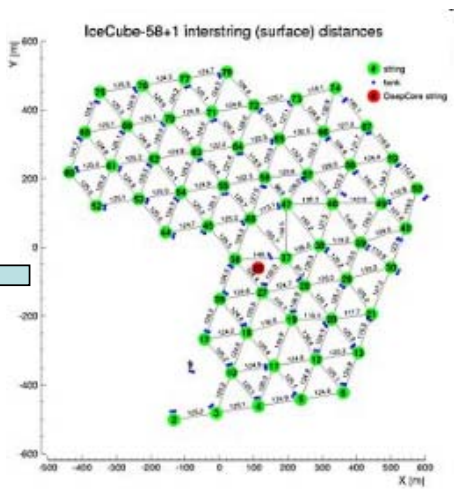
IC22 (2007-2008)



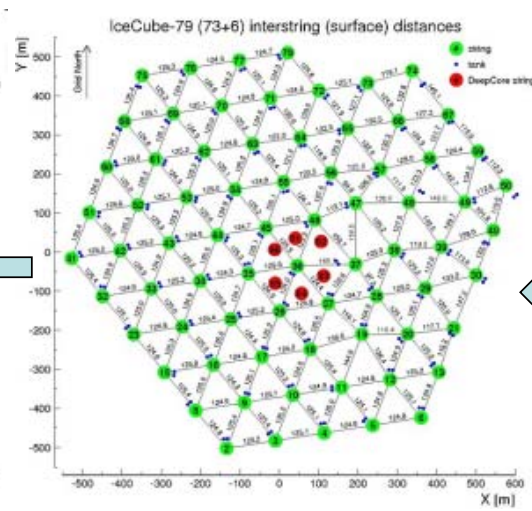
IC40 (2008-2009)



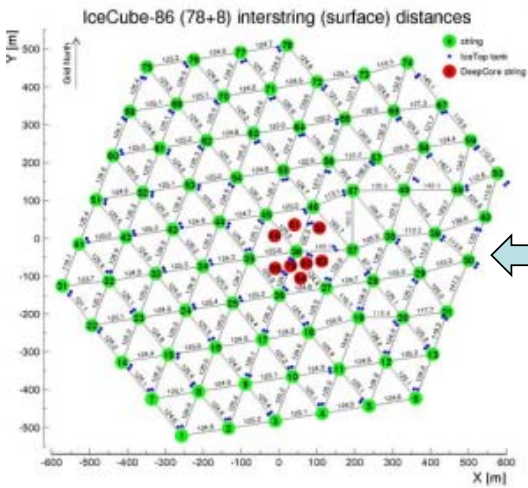
IC59 (2009-2010)



IC79 (2010-2011)



IC86 = full IceCube (2011~)



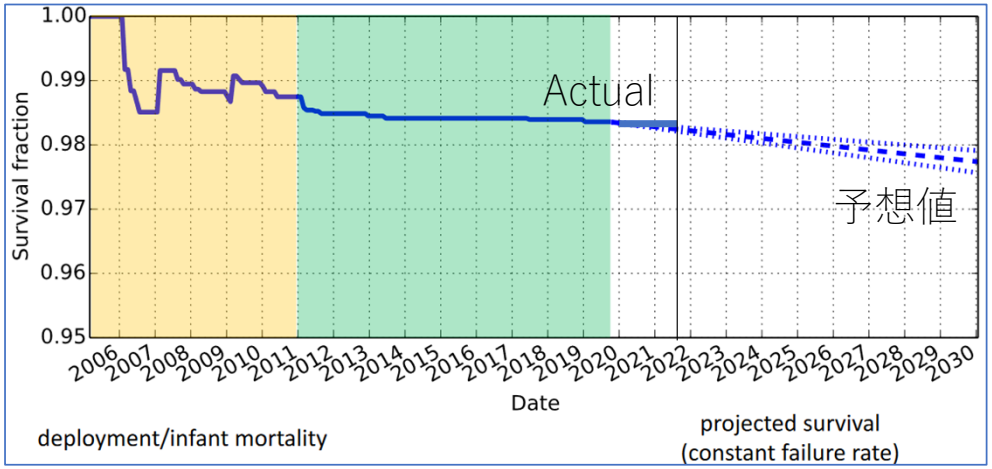
CELEBRATING THE
FIRST DECADE OF
DISCOVERY

10

IceCube Operation

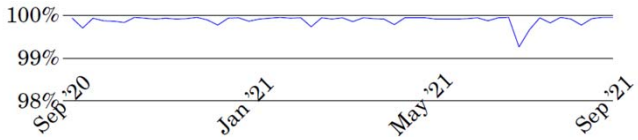
Partial operation has started since 2005, full operation since 2011

DOMの生存率 (ここ10年は) 98.5%をキープしている

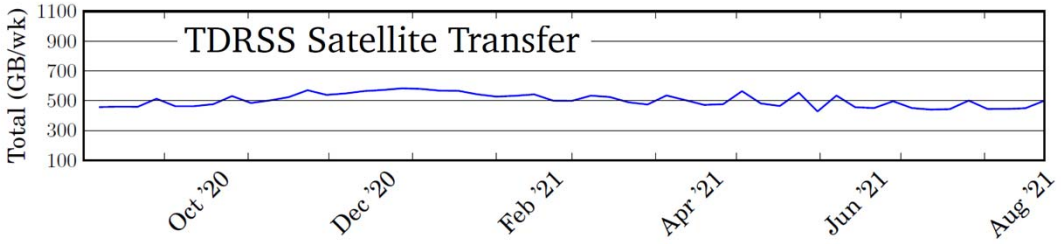


>99.5% uptime for 8 years !!

Uptime



99.95%



First important multi-messenger result

- IceCube建設中の40stringsと59strings コンフィギュレーションによる2年分のデータからの結果

2012

nature

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nature > letters > article

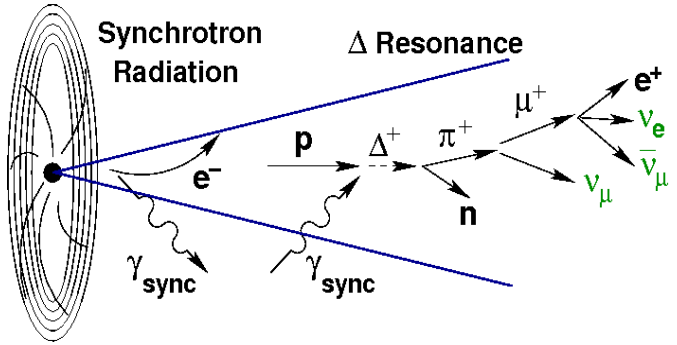
Published: 18 April 2012

An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts

IceCube Collaboration

Nature **484**, 351–354 (2012) | Cite this article

This implies that GRBs are not the only sources of cosmic rays with energies $> 10^{18}$ eV or that the efficiency of neutrino production is much lower than has been predicted.



First observations of cosmic neutrinos

Energetic Neutrinos on Ice

2013

July 8, 2013 • *Physics* 6, s93

The IceCube detector at the South Pole has observed two of the highest energy neutrinos ever recorded.

First Observation of PeV-Energy Neutrinos with IceCube

M. G. Aartsen *et al.* (IceCube Collaboration)

Phys. Rev. Lett. 111, 021103 (2013)

Published July 8, 2013

Science

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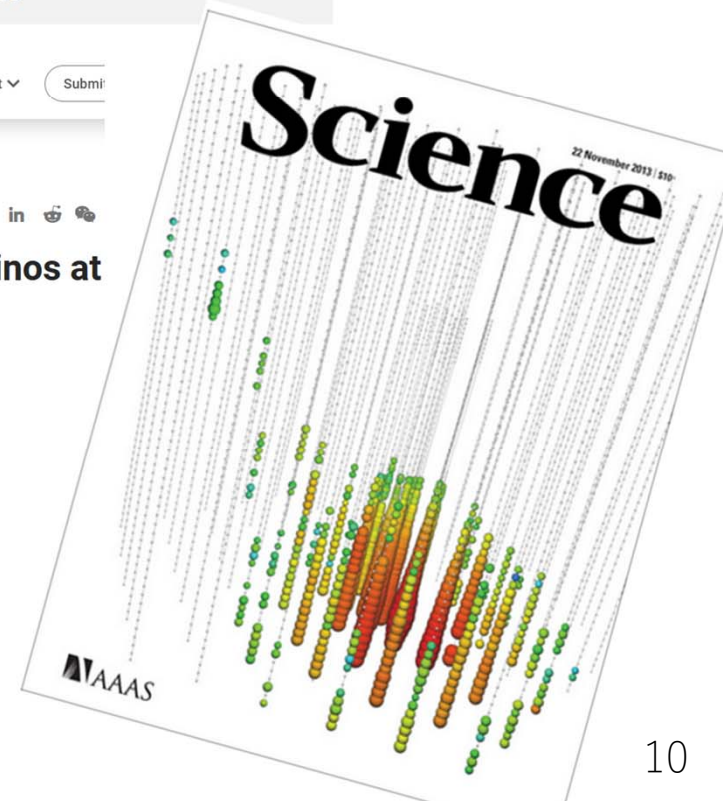
HOME > SCIENCE > VOL. 342, NO. 6161 > EVIDENCE FOR HIGH-ENERGY EXTRATERRESTRIAL NEUTRINOS AT THE ICECUBE DETECTOR

RESEARCH ARTICLE

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

ICECUBE COLLABORATION*

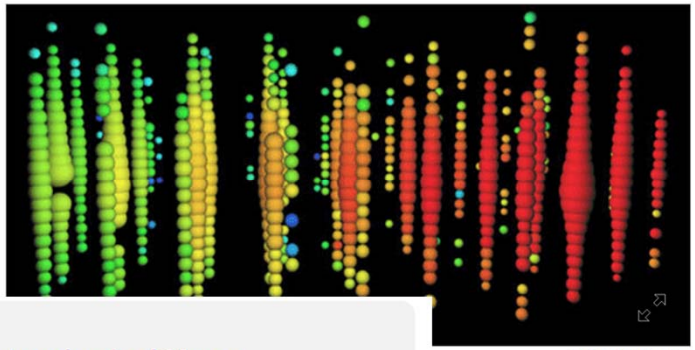


Astrophysical Diffuse Neutrino Spectra

Neutrinos from the North 2015

August 20, 2015 • *Physics* 8, s98

Using Earth as a neutrino filter, the IceCube neutrino experiment strengthens its claim that it has detected neutrinos from powerful astrophysical accelerators outside our Galaxy.



IceCube Collaboration

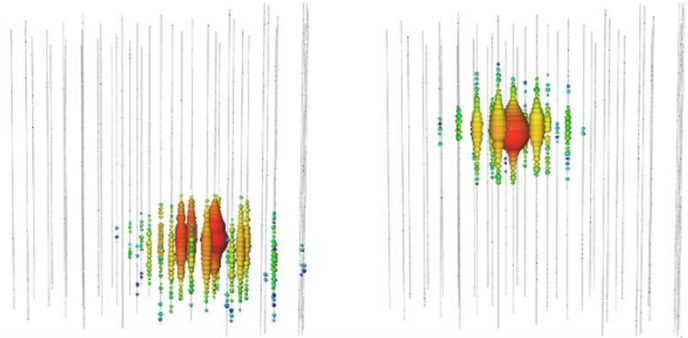
Evidence for Astrophysical Muon Neutrinos from the Northern Sky with IceCube

M. G. Aartsen *et al.* (IceCube Collaboration)

Phys. Rev. Lett. 115, 081102 (2015)

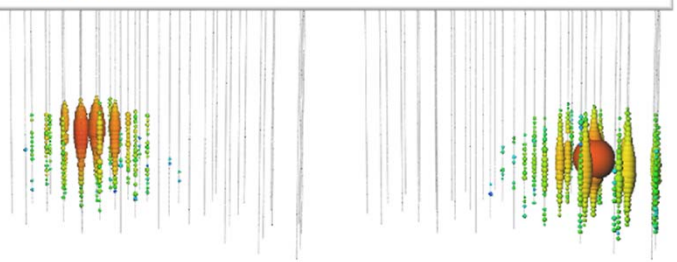
Published August 20, 2015

2014

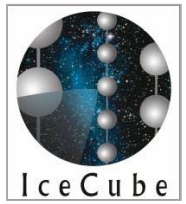


Search for neutrino-induced particle showers with IceCube-40

M. G. Aartsen *et al.* (IceCube Collaboration)
Phys. Rev. D **89**, 102001 – Published 1 May 2014



Ultra-high Energy ν Interactions



nature

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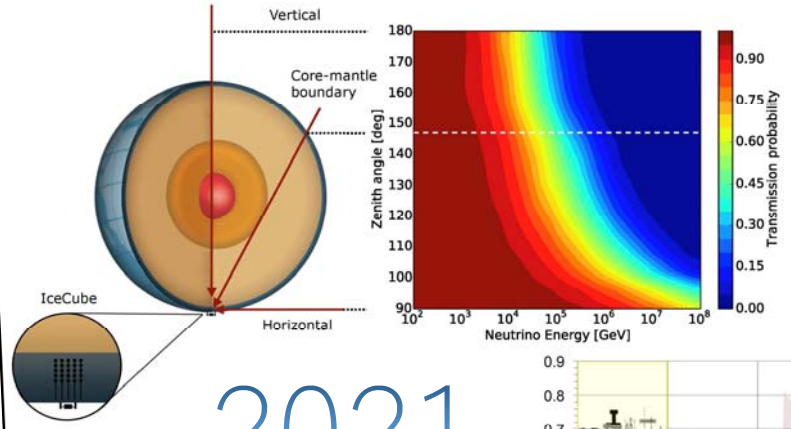
nature › letters › article

2017

Published: 22 November 2017

Measurement of the multi-TeV neutrino interaction cross-section with IceCube using Earth absorption

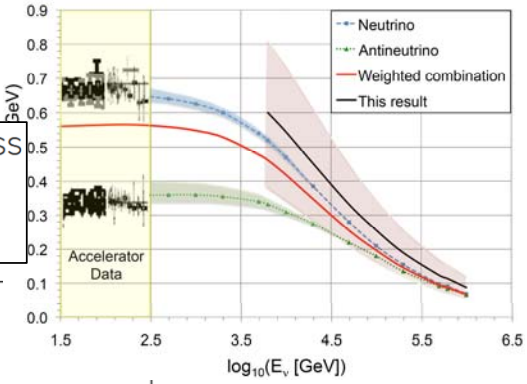
The IceCube Collaboration



2021

Measurement of the high-energy all-flavor neutrino-nucleon cross section with IceCube

R. Abbasi *et al.* (IceCube Collaboration)
Phys. Rev. D **104**, 022001 – Published 8 July 2021

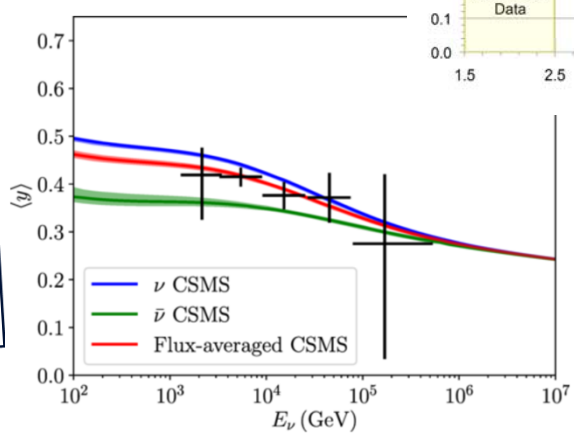


Editors' Suggestion Open Access

Measurements using the inelasticity distribution of multi-TeV neutrino interactions in IceCube

2019

M. G. Aartsen *et al.* (IceCube Collaboration)
Phys. Rev. D **99**, 032004 – Published 13 February 2019



IceCube Realtime Alert System

High energy starting track (HESE) and Extremely high energy (EHE) alert channels has started since 2016

ELSEVIER

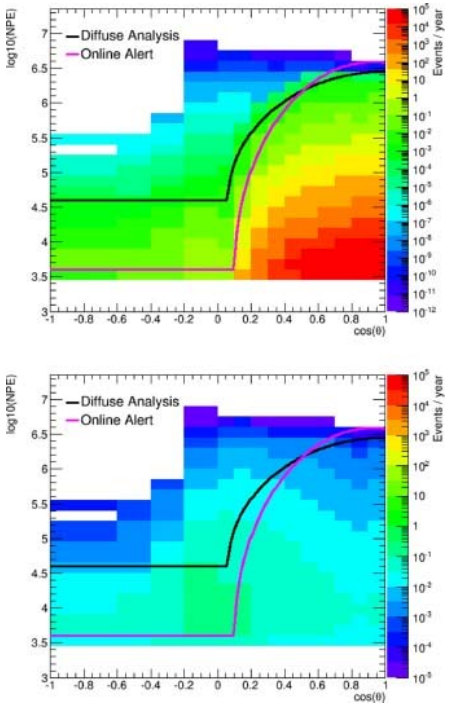
Astroparticle Physics
Volume 92, June 2017, Pages 30-41

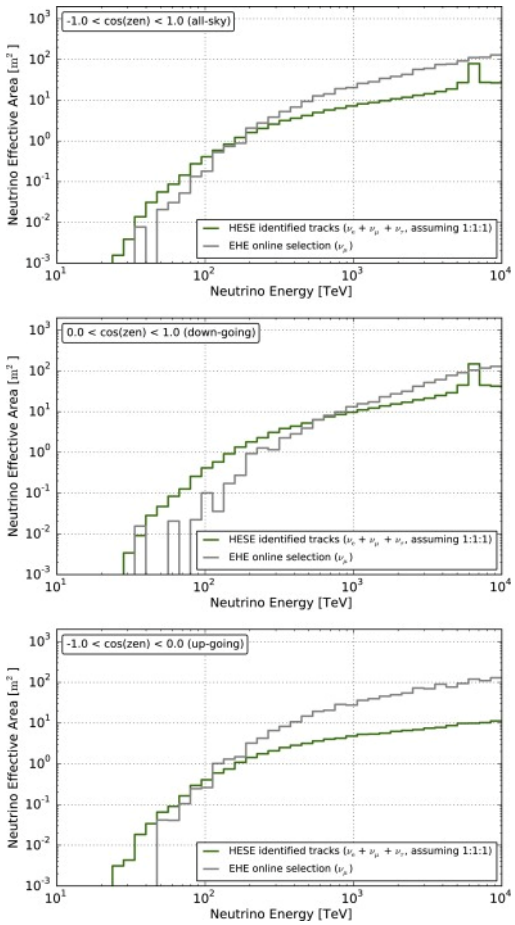
The IceCube realtime alert system

M.G. Aartsen [b], M. Ackermann [az], J. Adams [p], J.A. Aguilar [l], M. Ahlers [ad], M. Ahrens [ap], D. Altmann [x], K. Andeen [af], T. Anderson [av], I. Ansseau [l], G. Anton [x], M. Archinger [ae], C. Argüelles [n], J. Auffenberg [a], S. Axani [n], X. Bai [an], S.W. Barwick [aa], V. Baum [ae] ... M. Zoll [ap]

Show more

2017



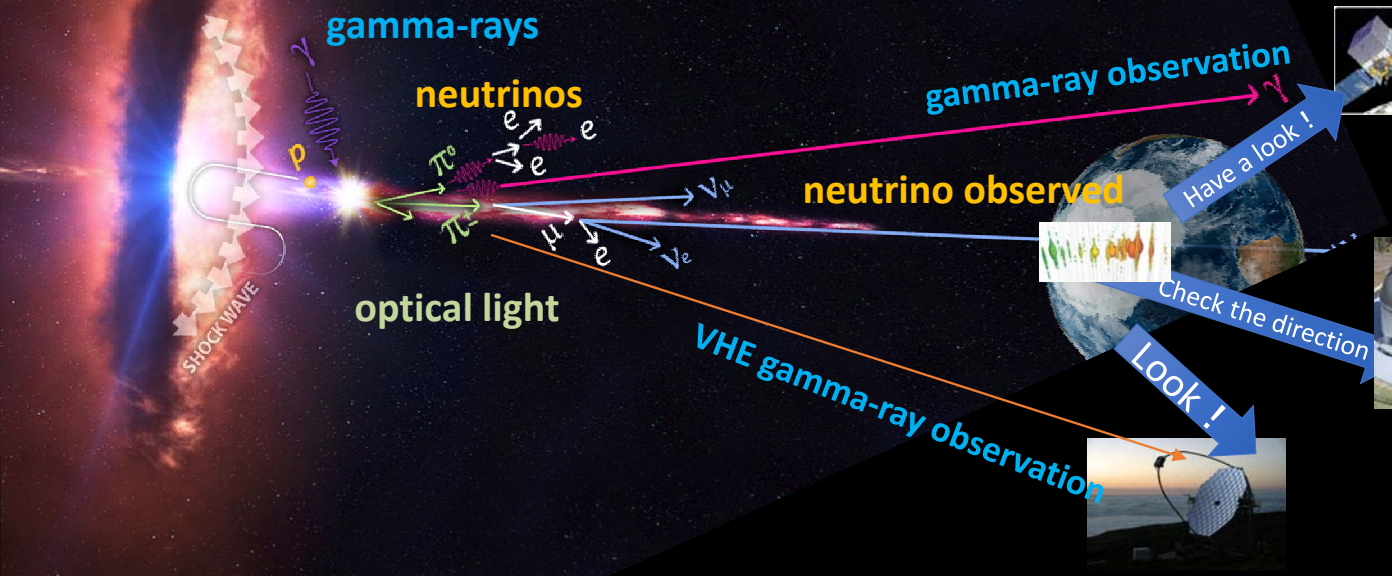


IceCube-170922A event

Science 361, eaat1378 (2018)

2018

- 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

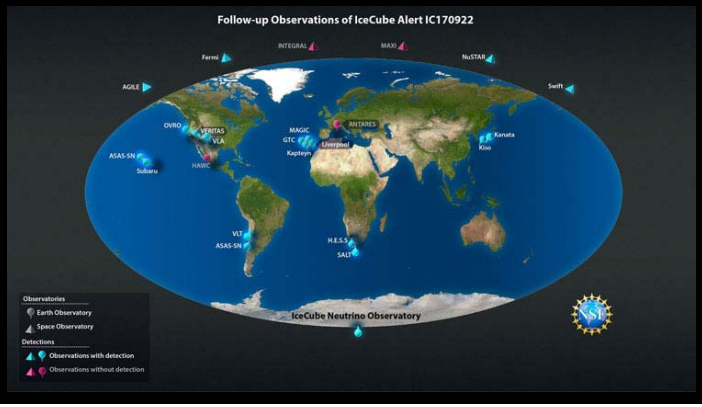


Fermi Telescope

Optical telescopes

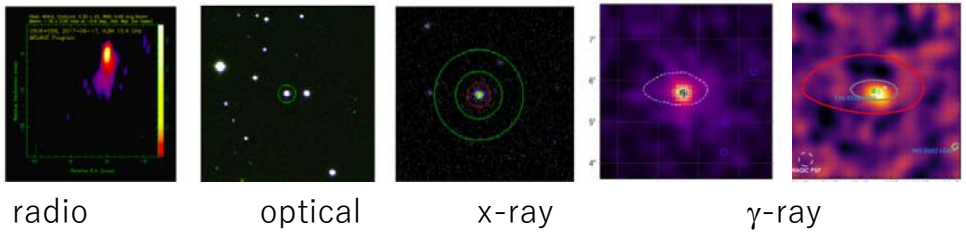
Kanata telescope

...and many more telescope

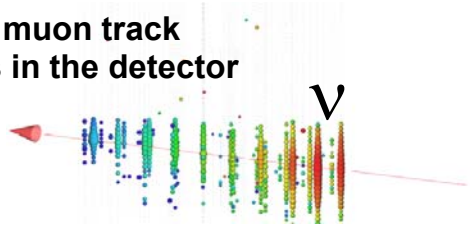


Magic telescope

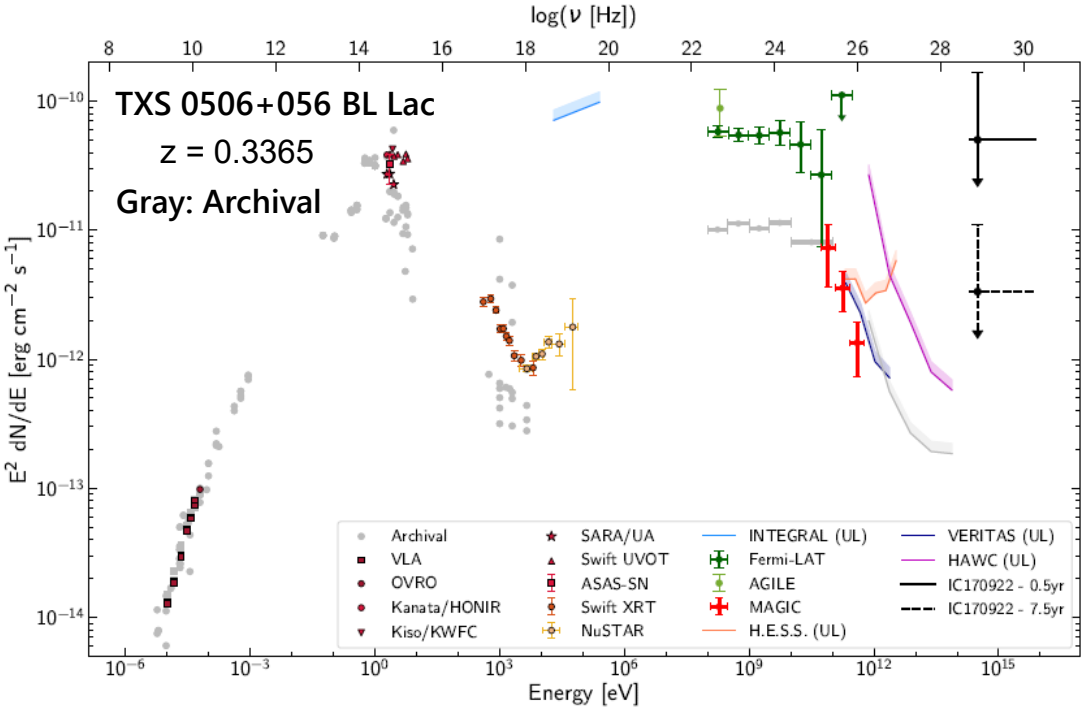
Multiwavelength Campaign with ν



upward going neutrino induced muon track
23.7 ± 2.8 TeV muon energy loss in the detector

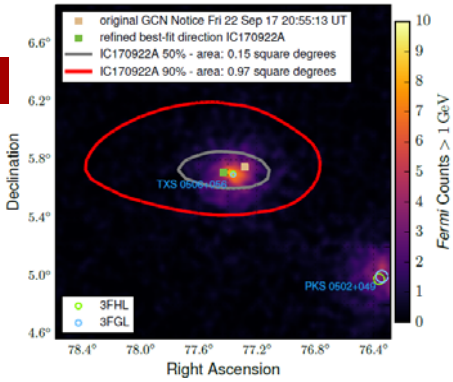


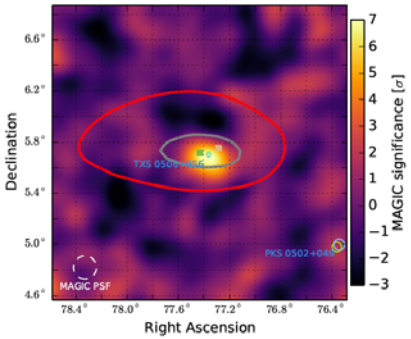
2018



HE gamma-ray observations

- Fermi-LAT(20MeV - 300 GeV) reported gamma-ray flaring blazer TXS 0506+056 (ATel#10791)





VHE gamma-ray observations

- Furthermore TXS 0506+056 was observed VHE gamma-ray Magic telescope (E > 100GeV) with >6.2σ (ATel#10817)

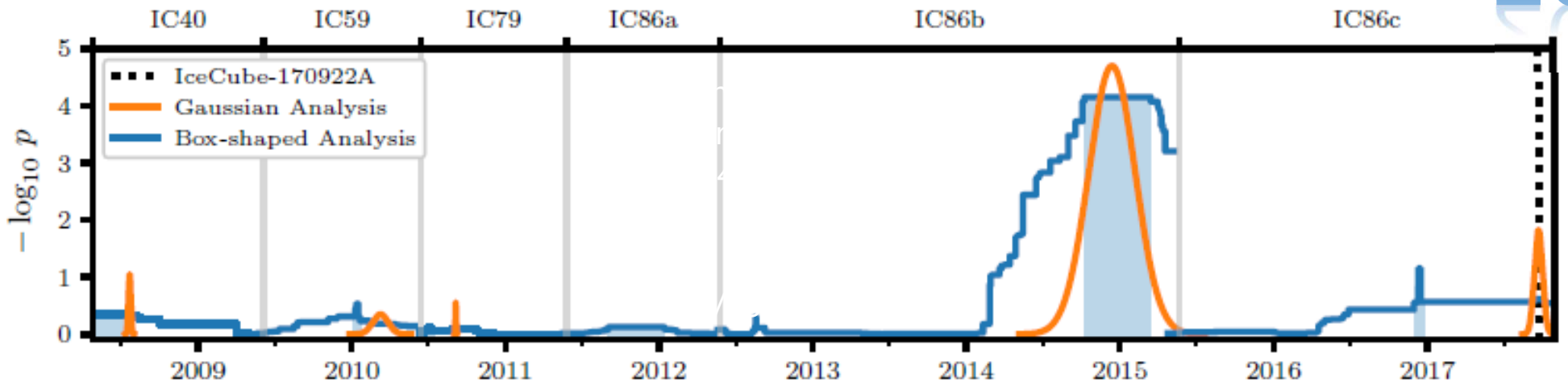
2014/2015 Neutrino Flare

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

IceCube

2018

IceCube evaluated 9.5 years of archival data in the direction of TXS 0506+056

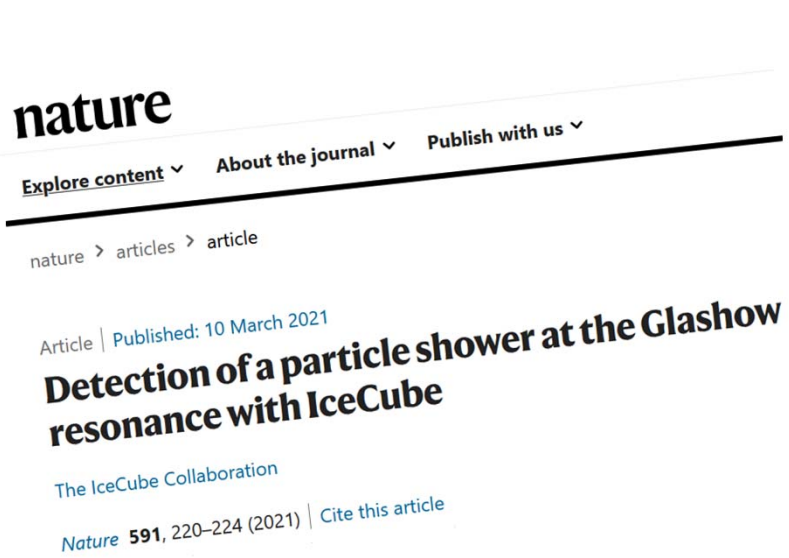


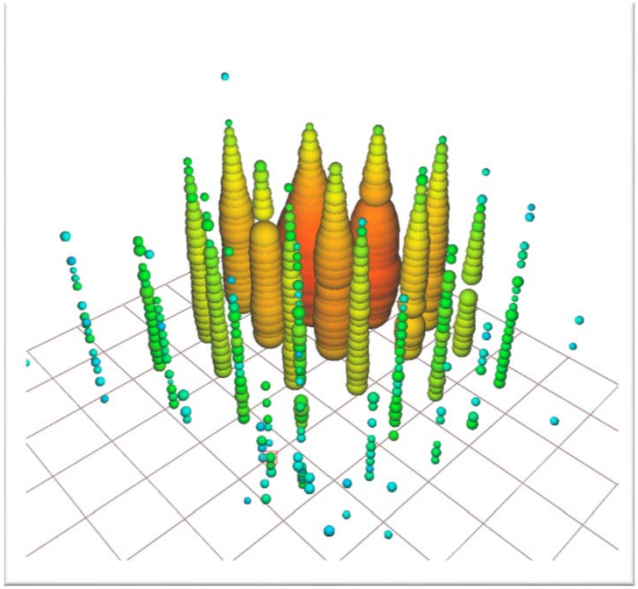
- neutrino only time dependent search around the blazar TXS 0506−056

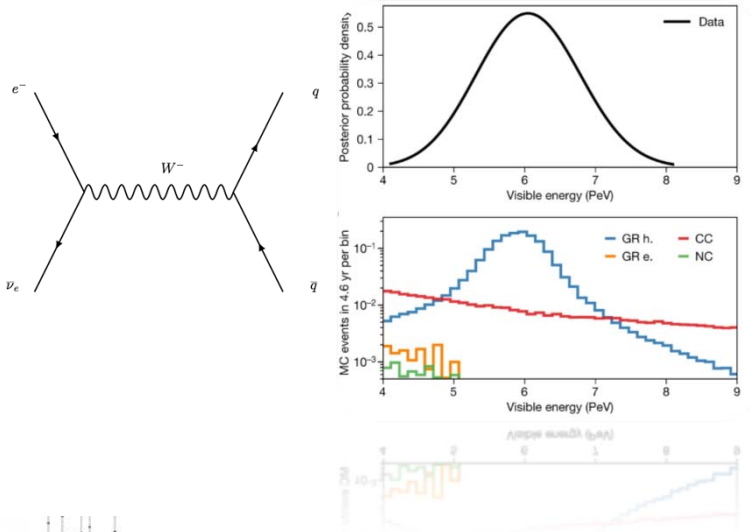
→Inconsistent with bkg-only hypothesis at the 3.5σ level

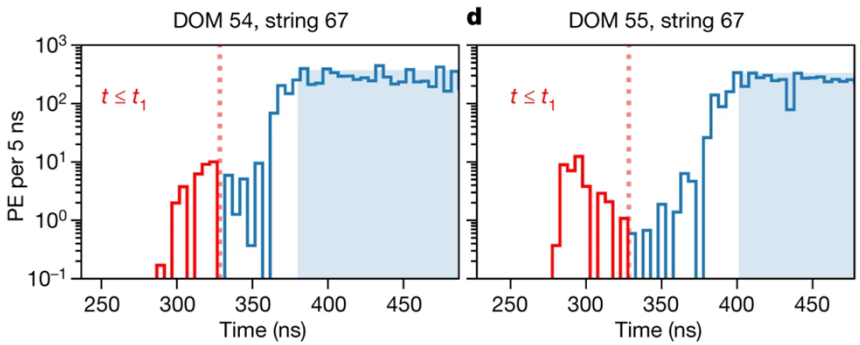
(In addition and independently of the previous 3σ when looking in this specific direction)

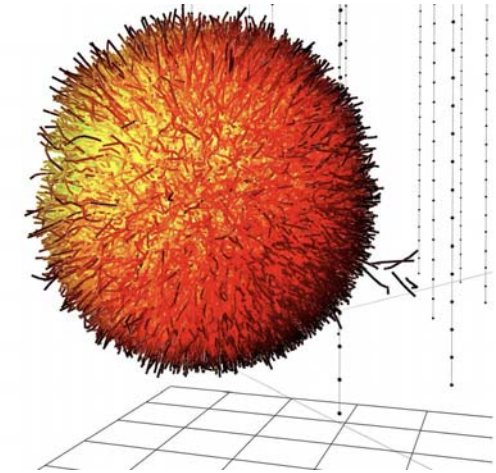
Cascade events at Glashow resonance









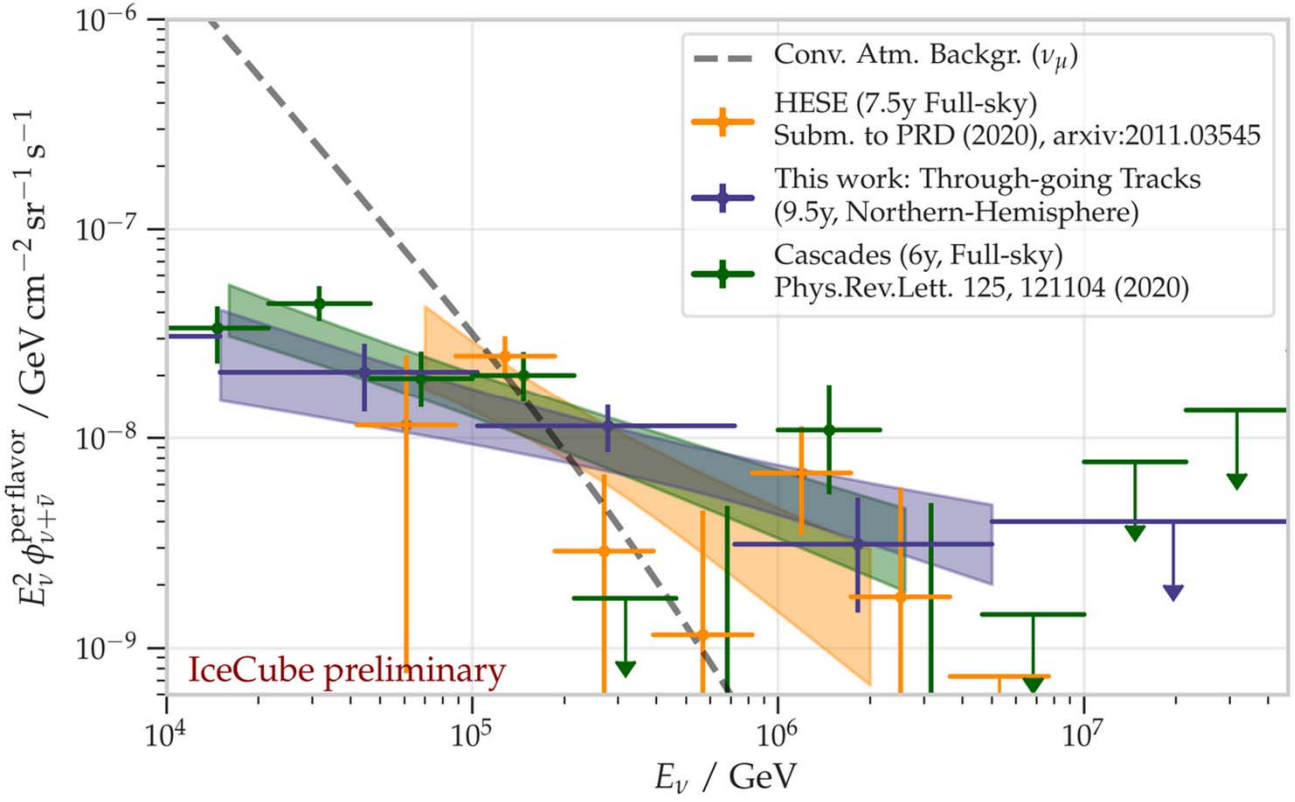


2021

After 10 yrs: Diffuse Neutrino Spectra

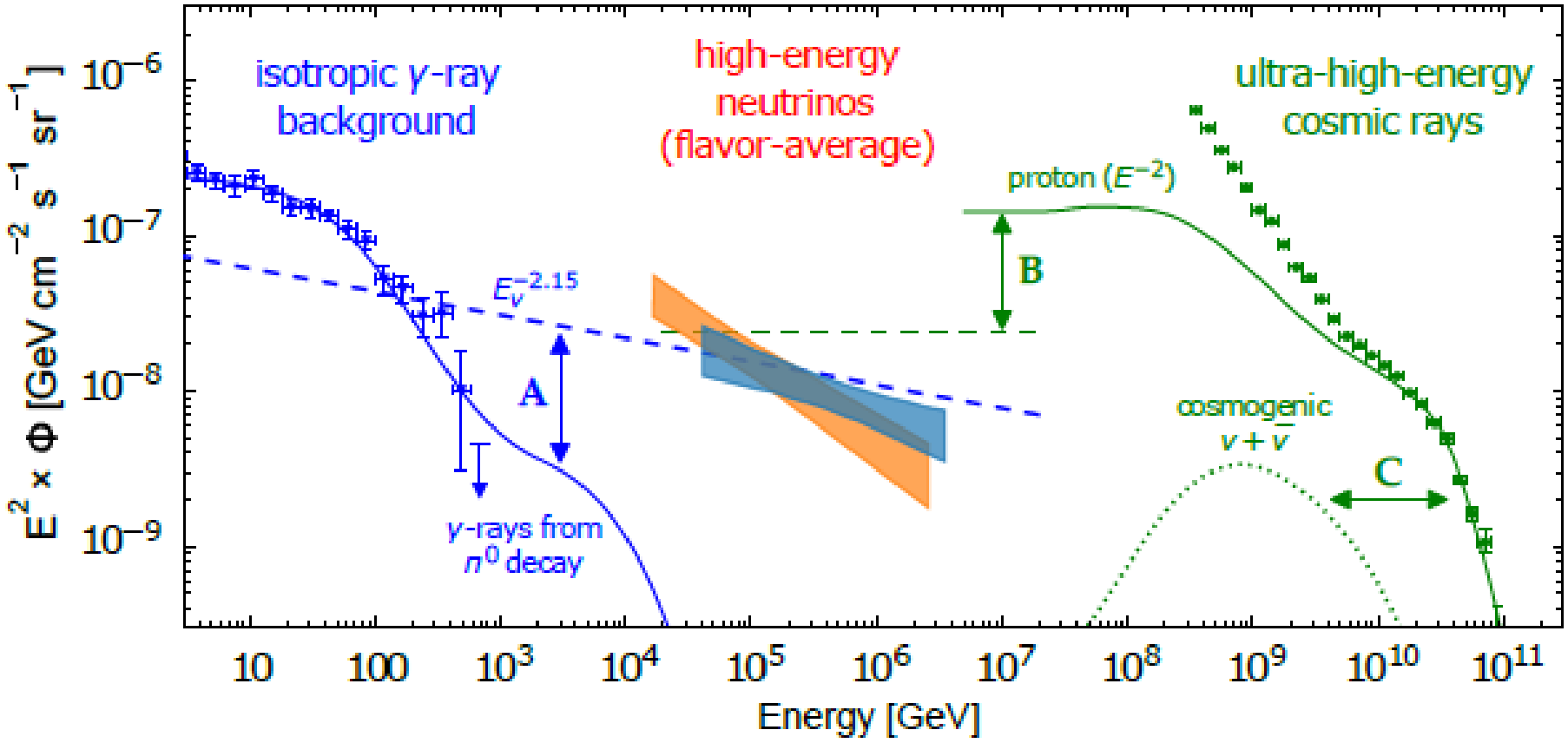
Published and almost to be published samples

- Upgoing muon neutrino sample 9.5 years
- High energy starting event sample 7.5 years
- Cascade sample 6 years



Deviation from power law as well as spectral cut off still not conclusive…

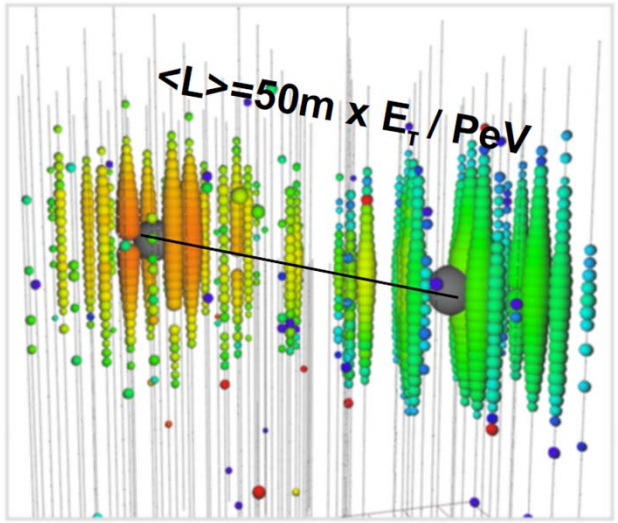
After 10 yrs: Diffuse gamma-rays, UHE cosmic rays and neutrino connection



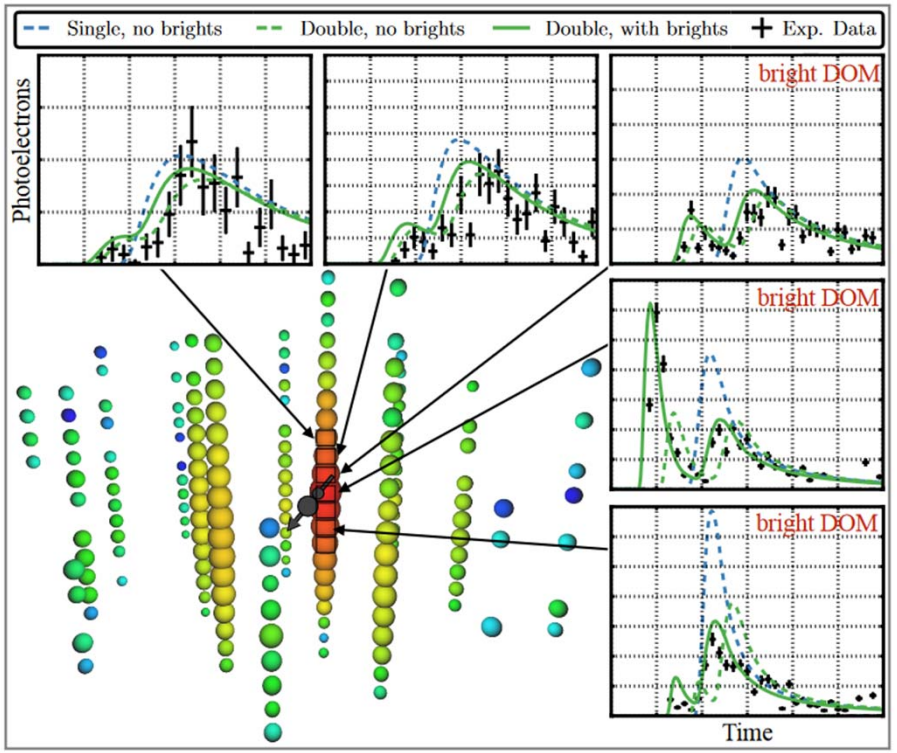
https://arxiv.org/abs/2008.04323

After 10 yrs: High Energy Tau Neutrinos

2 candidate events observed over expected 1.5 ν_τ signal and 0.8 ν_e, ν_μ background



Tau neutrinos:
"double bang"



Double pulse signatures

After 10 yrs: GZK Neutrino Constraints

Upper limit on neutrinos 10 PeV and above with 9 years of data

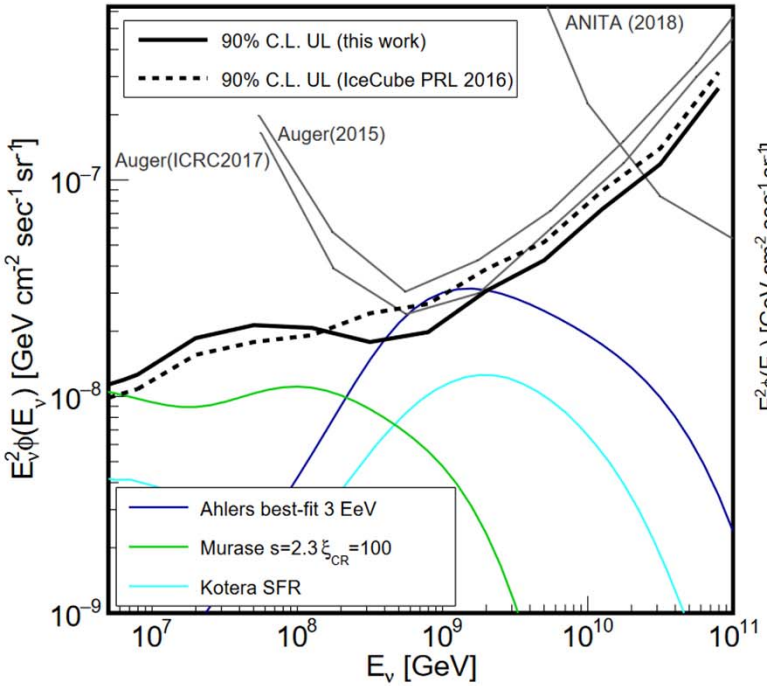
Differential limit on the extremely-high-energy cosmic neutrino flux in the presence of astrophysical background from nine years of IceCube data

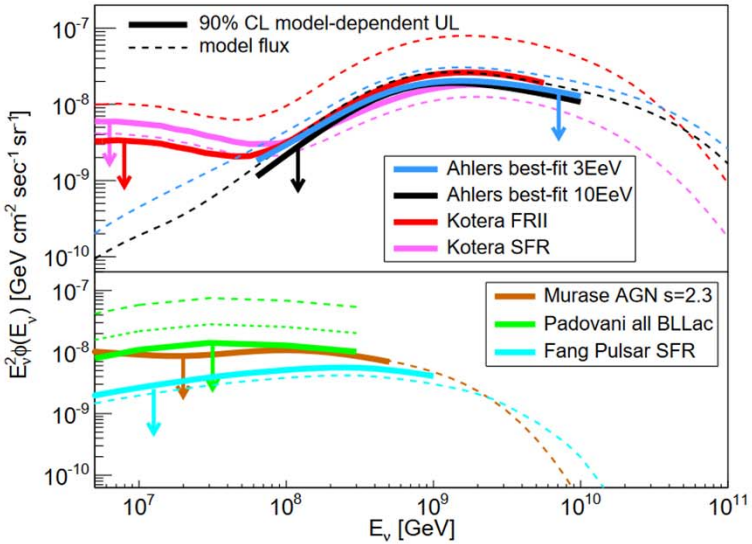
M. G. Aartsen *et al.* (IceCube Collaboration)
Phys. Rev. D **98**, 062003 – Published 12 September 2018

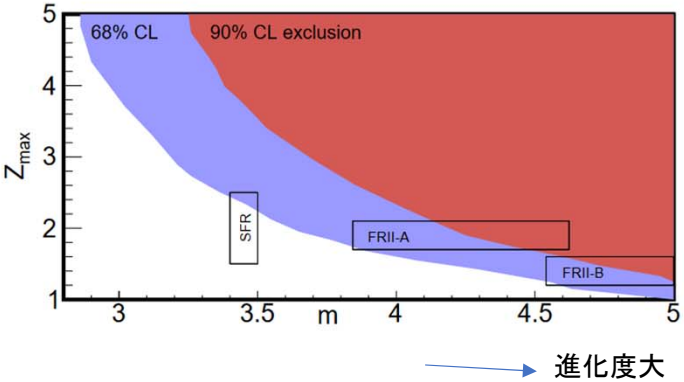
Editors' Suggestion

Constraints on Ultrahigh-Energy Cosmic-Ray Sources from a Search for Neutrinos above 10 PeV with IceCube

M. G. Aartsen *et al.* (IceCube Collaboration)
Phys. Rev. Lett. **117**, 241101 – Published 7 December 2016; Erratum Phys. Rev. Lett. **119**, 259902 (2017)







進化度大

After 10 yrs: Neutrino Source Searches

Featured in Physics | Editors' Suggestion

Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data

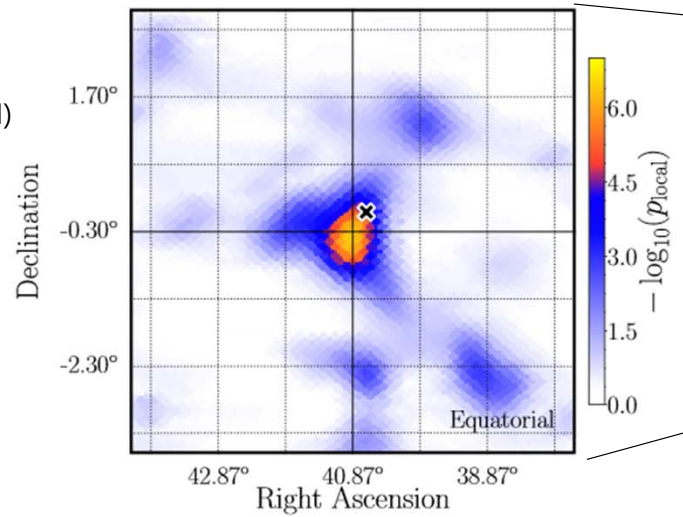
M. G. Aartsen *et al.*
Phys. Rev. Lett. **124**, 051103 – Published 6 February 2020

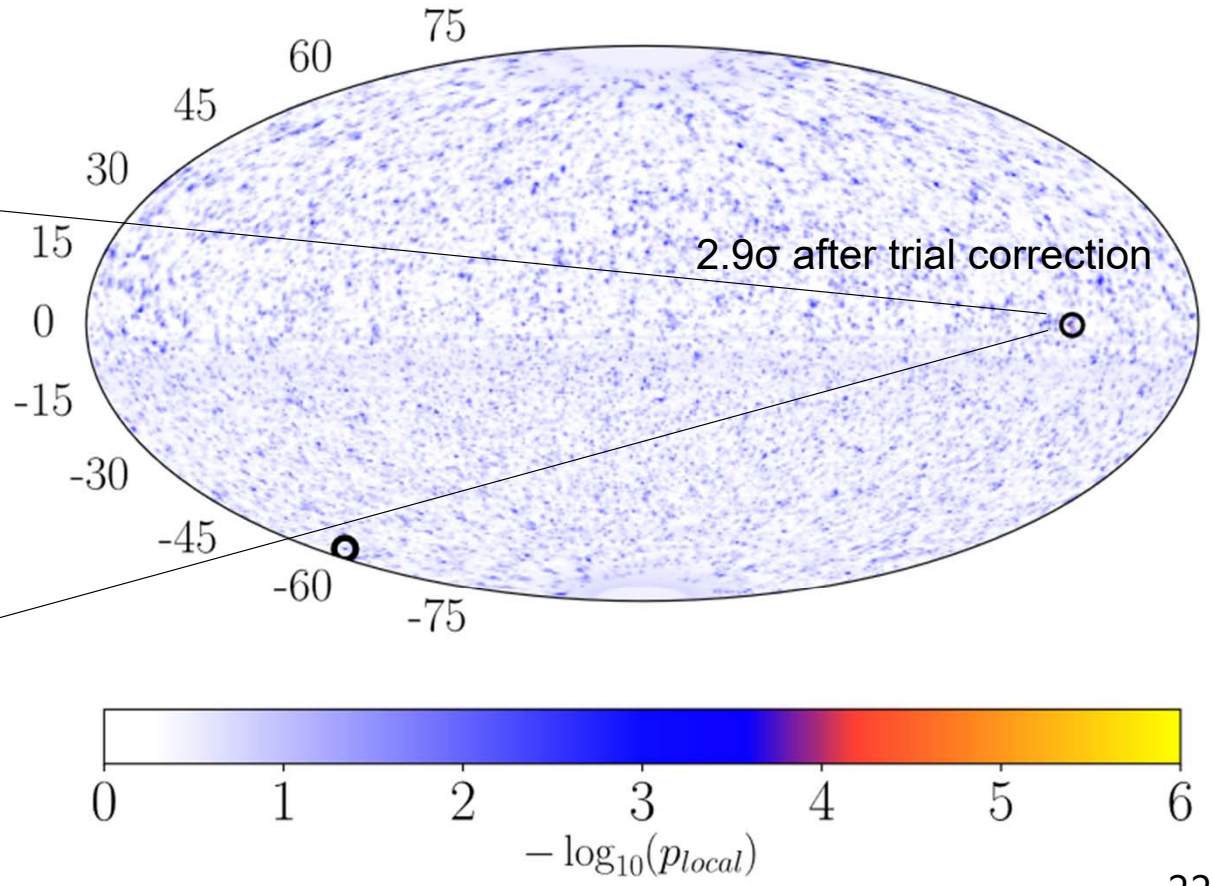
Physics See Synopsis: Possible Neutrino Sources Peek out of IceCube Data

IceCube South Pole Neutrino Observatory — About Us | Science | Collaboration

10 years of IceCube data now publicly available at NASA's HEASARC archive

x: NGC 1068
(star burst AGN)





Neutrino Source Searches with 10 years of IceCube Data

Featured in Physics | Editors' Suggestion

Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data

M. G. Aartsen *et al.*
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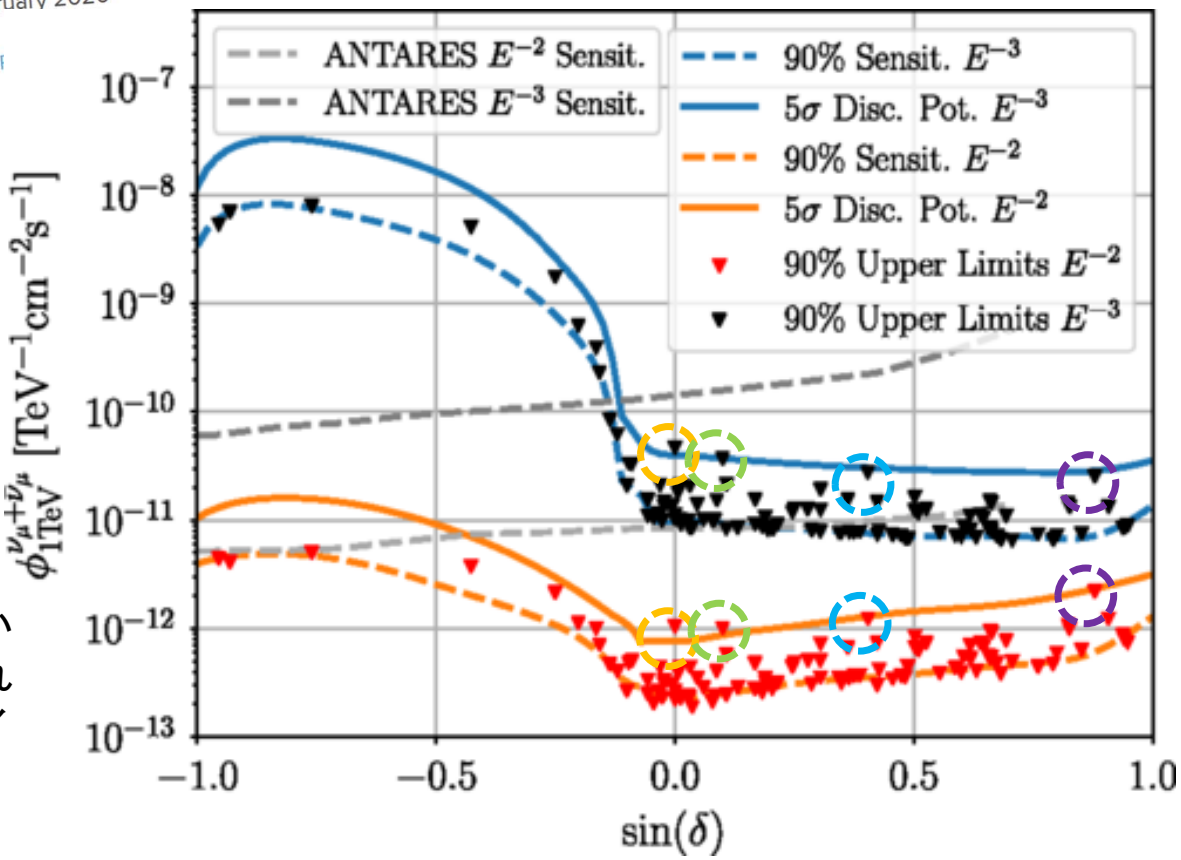
Physics See Synopsis: Possible Neutrino Sources f

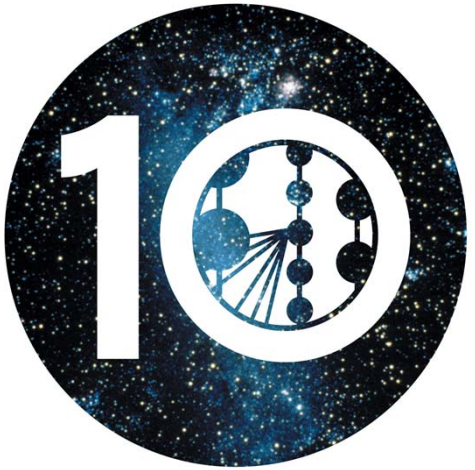


上限値が感度を卓越し有意な信号が見え始めている天体

- NGC 1068 (star burst AGN)
- TXS 0506+056 (blazer AGN)
- PKS 1424+240 (BL Lac Blazer AGN)
- GB6 J1542+6129 (BL Lac Blazer AGN)

近くて明るいブレーザーから見え始めているが、それが宇宙ニュートリノのメインの起源天体種ではない

A Short Summary of 10 yrs



- 初めての一立方キロメートルニュートリノ検出器の完成！

- 10TeVから10PeVの宇宙ニュートリノ流量
  - 超高エネルギー宇宙線エネルギー密度と近い値
  - 拡散ガンマ線放射エネルギー密度とも近い

- EHE流量上限値からはUHECR陽子起源天体の宇宙進化度に制限が得られている

- Real Timeアラートによる宇宙ニュートリノ起源天体TXS 0506+056(blazer AGN)のマルチメッセンジャー観測
- TXS 0506+056は2014-2015にもニュートリノをバースト的にだしていた
- 時間相関のないニュートリノ放出天体NGC 1068(star burst AGN)が見え始めている
- 他にもデータ量が増えるにつれ有意度が上がっている天体がある

- 高エネルギー素粒子物理への示唆(Glashow共鳴事象、超高エネルギーニュートリノ反応断面積)
- 宇宙論的距離の伝搬によるフレーバー物理(タウニュートリノ事象候補観測)

- 他にも多くのユニークな物理：標準理論を超える物理への制限、WIMP探査、重いダークマター、モノポール探査、…

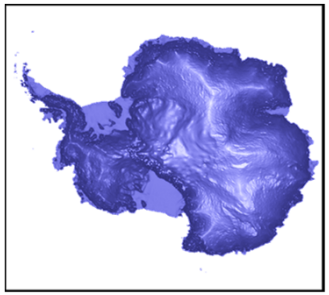
しかし多くの興味深い信号が、10年で数事象レベル、もしくは3σレベルの有意度で見え始めているところである！

IceCube-Gen2 検出器

IceCubeコントロールルーム

南極点傍に立つ
居住建屋

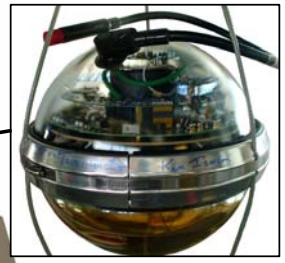
アムンゼンスコット南極点基地



IceCube-Gen2

IceCube
&
Gen2 Phase1

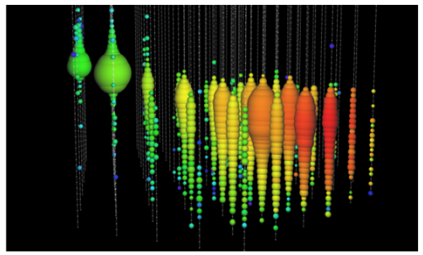
IceCube光検出器DOM



Gen2 Phase1長球型光検出器D-Egg
- 縦長で掘削費用および時間を大幅に削減

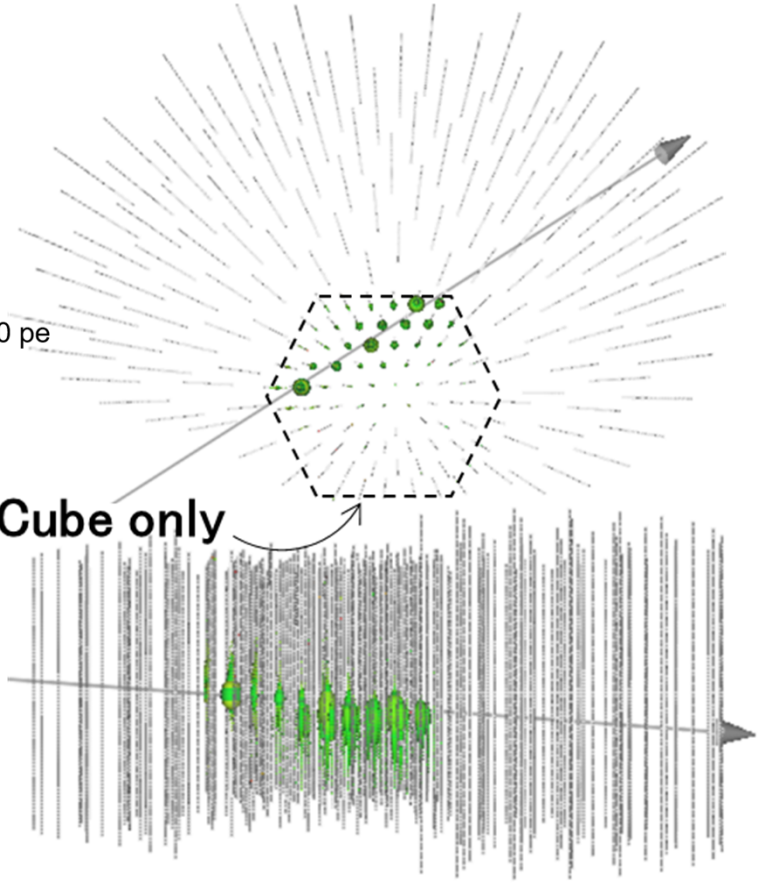
- Gen2に向けさらなる改良
  - 実効感度の向上
  - 消費電力の低減

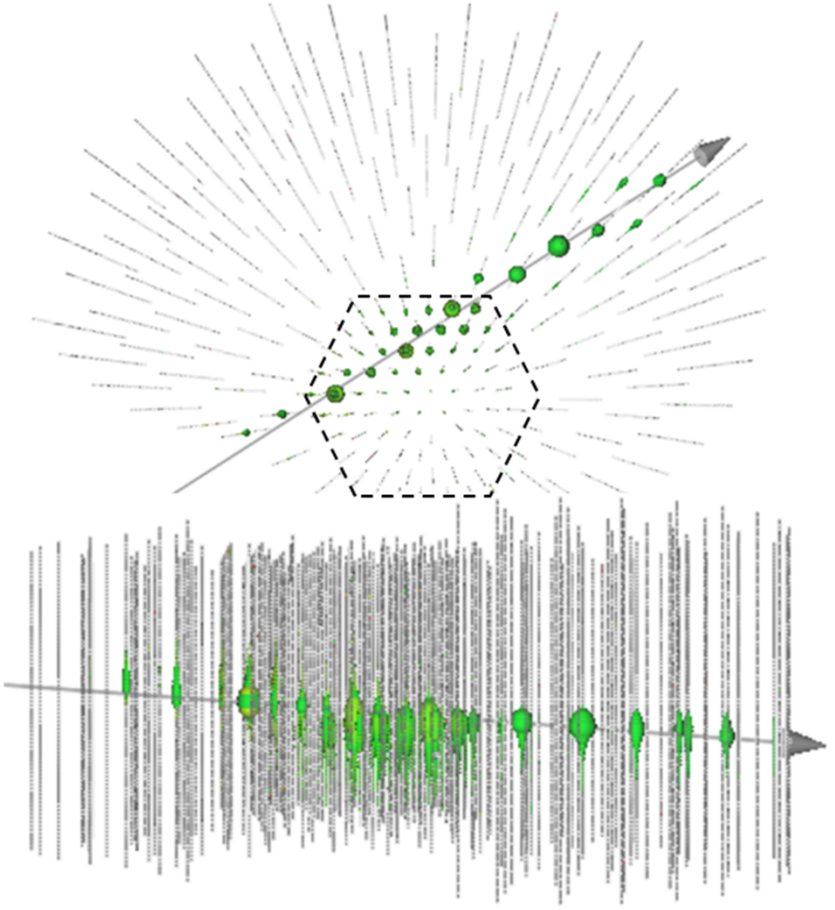
Angular resolution improvement with larger detector



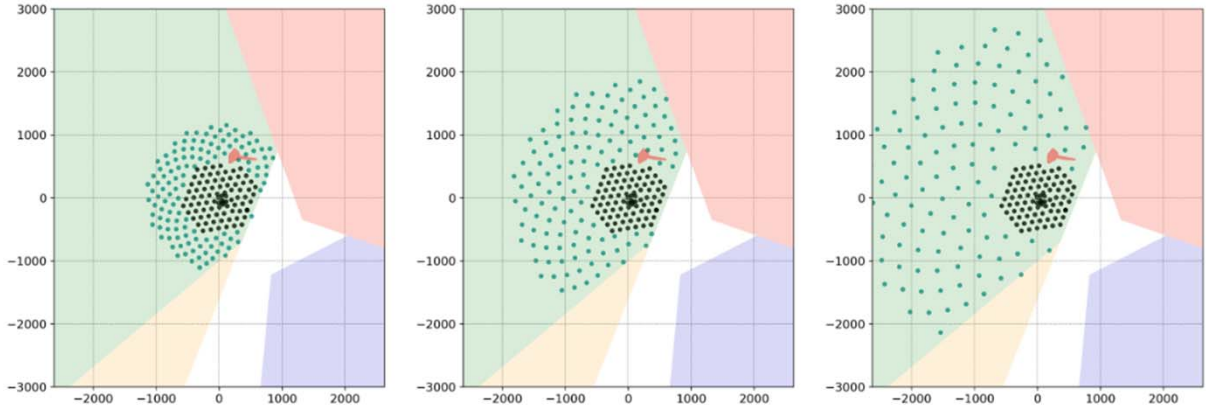
Highest energy event to date,
an upward-going track.

- Deposited energy 2.6±0.3 PeV
- Median neutrino energy 8.7 PeV
- Observed photoelectrons 130,000 pe



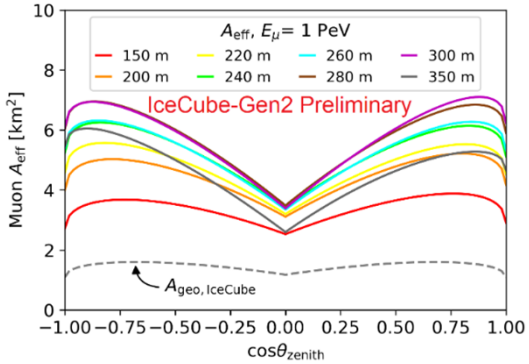


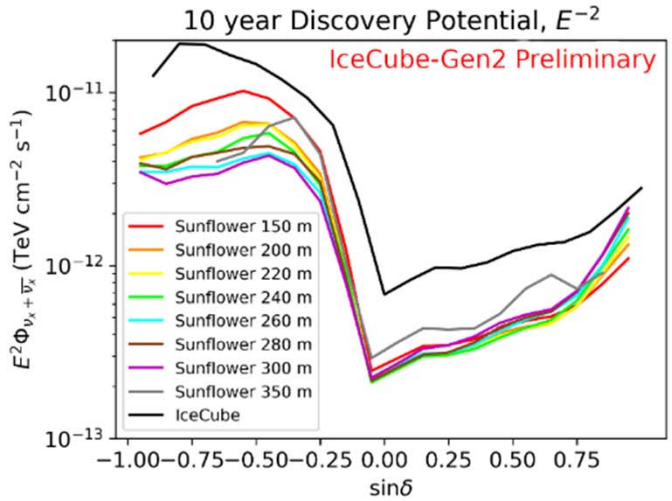
How large Gen2 must be?



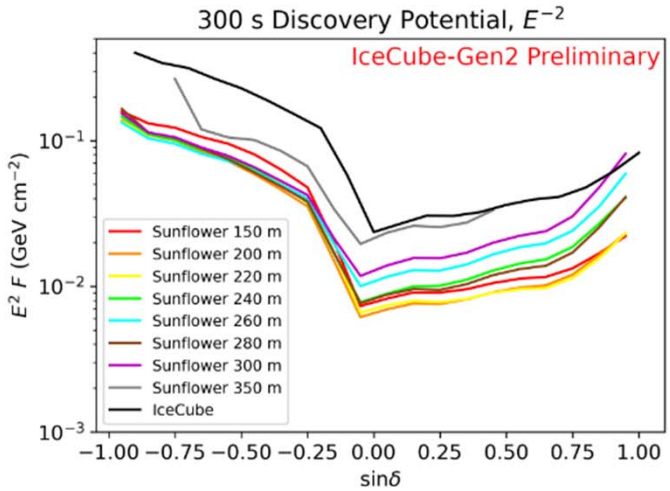
(a) s=150 m **(b)** s = 240 m **(c)** s = 350 m

….For given number of strings (or cost)



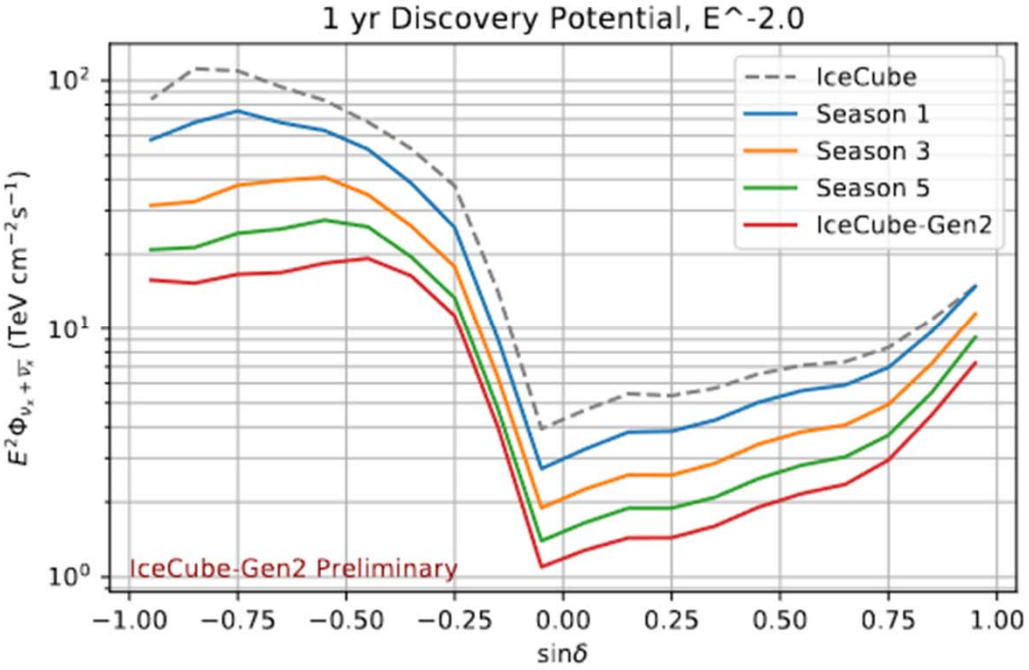


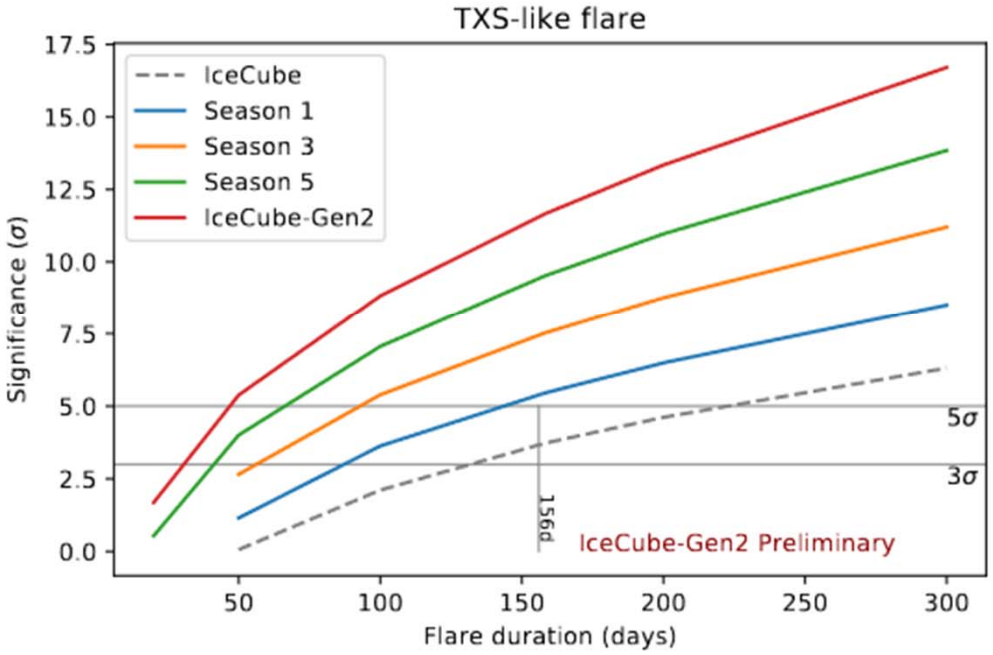
(a) HE cuts set for event selection >100TeV



(b) LE cuts set event selection >50TeV

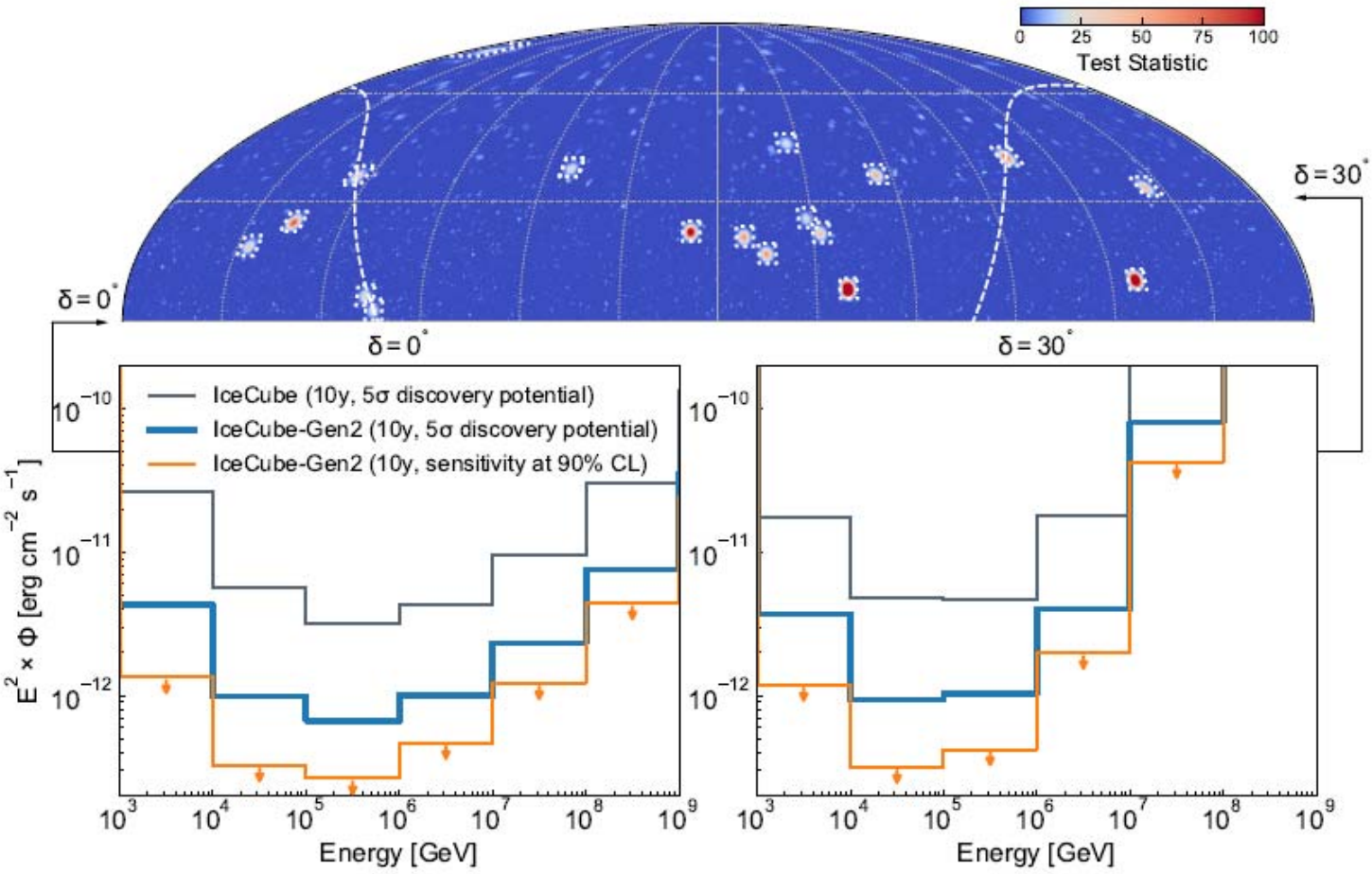
Intermediate sensitivities



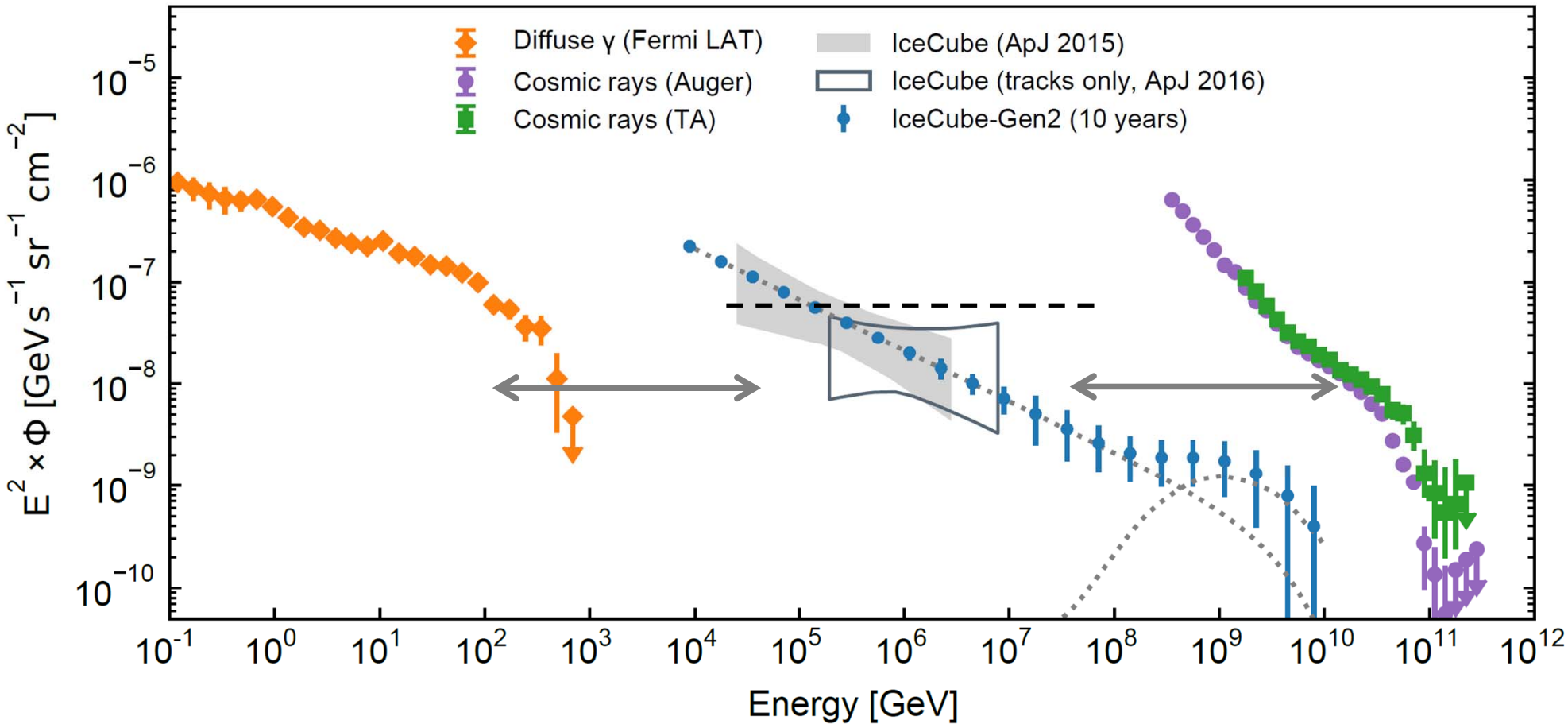


- Full sensitivity and good exposure is required for the detection of dimmer neutrino sources
- However for time-dependent flares such as TXS-like flare, deployment of first year or two, Gen2 becomes large enough to achieve 5σ $level$ of observation
  - Partial construction is still valuable for time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

Expectation with more than 5 times better sensitivity



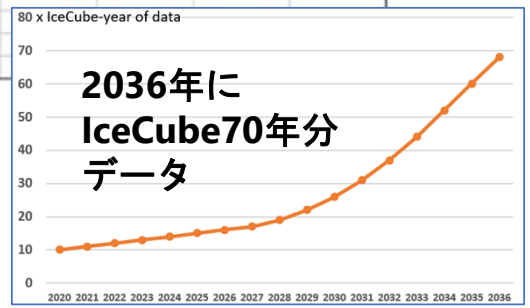
Better link between gamma-ray and UHECR



Timeline

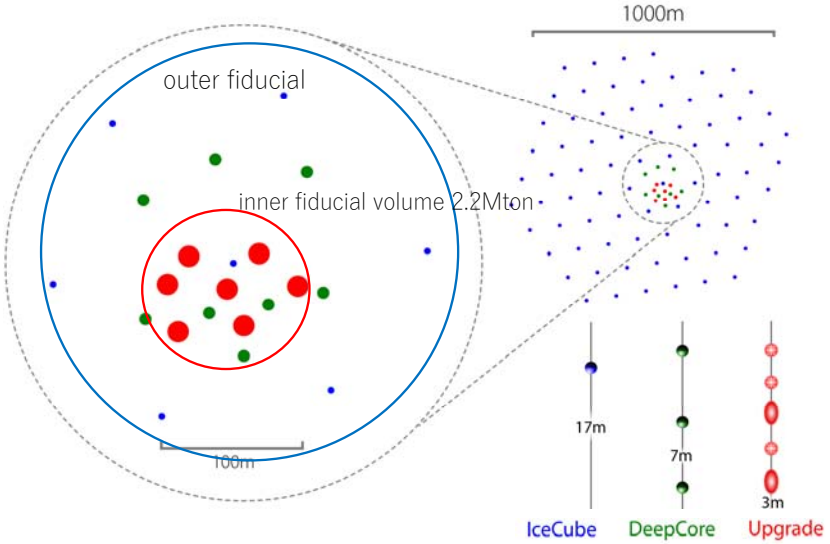
YEAR (calendar year)	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
IceCube Upgrade															
Scintillators/Field Hubs															
Radio development			Radio development in Greenland												
			Development at Pole												
IceCube-Gen2															
Project year						PY1	PY2	PY3	PY4	PY5	PY6	PY7	PY8	PY9	PY10
Conceptual design phase	since 2016														
Preliminary design phase															
Final design phase															
MREFC funding (construction)															
DOM production (12000)						500	1000	1500	2000	2200	2200	2000	600		
On ice construction: 120 Strings								4	8	8	20	21	21	21	17
On ice construction: Radio stations								5	10	30	36	36	36	36	11
						Major field activity									
						Hot water drilling operations									

New drill ($12M/3yr) is ready for upgrade and Gen2

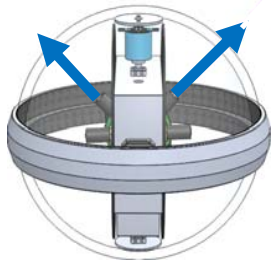


IceCube-Gen2 Phase1

- Calibration of the IceCube and Gen2 detector
- Deep survey for Gen2

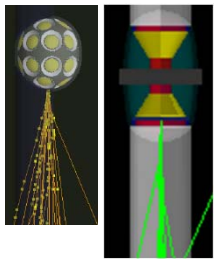


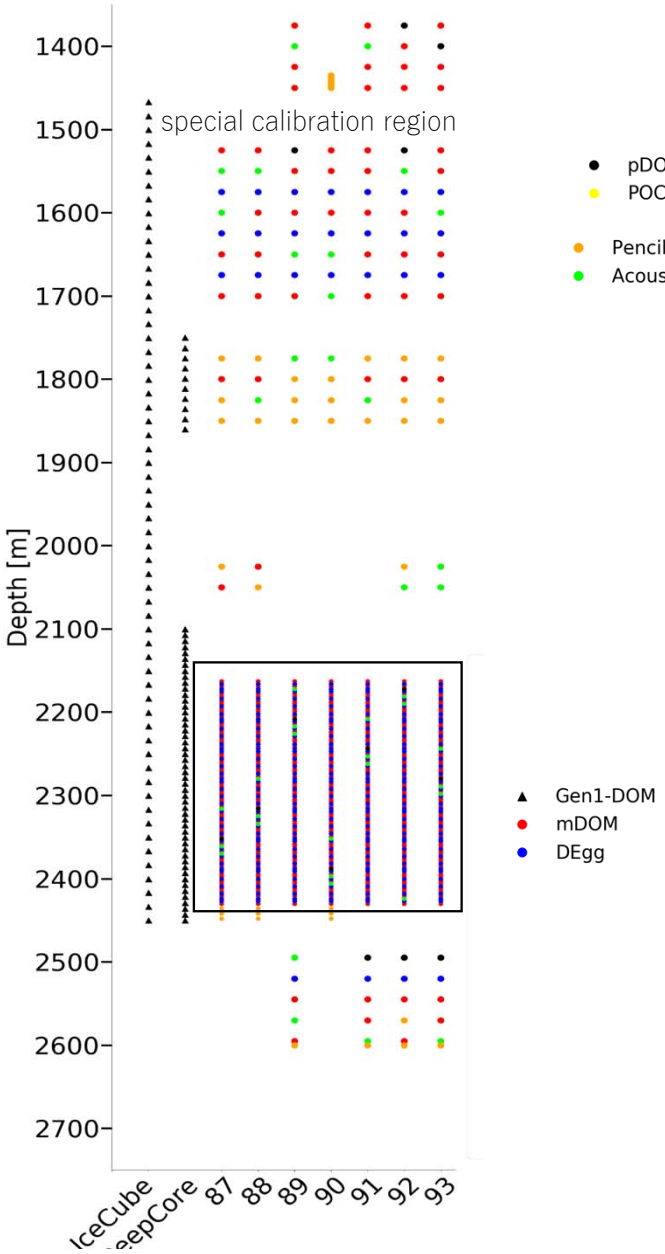
Pencil beam
(beaming light source)



POCAM
(isotropic light source)

LEDs in modules





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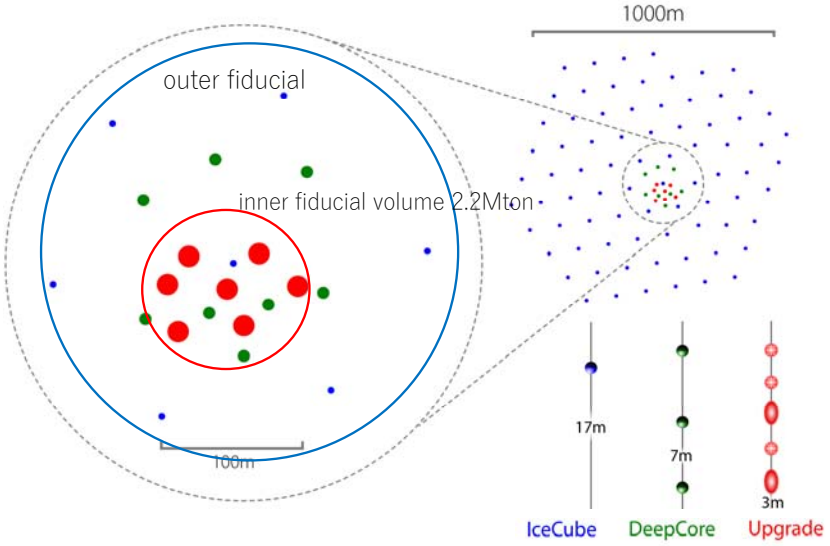
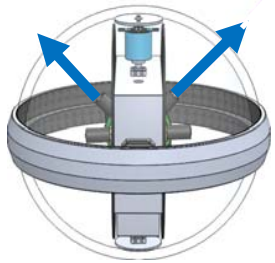
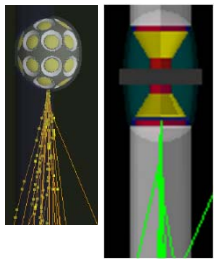


Pencil beam
(beaming light source)

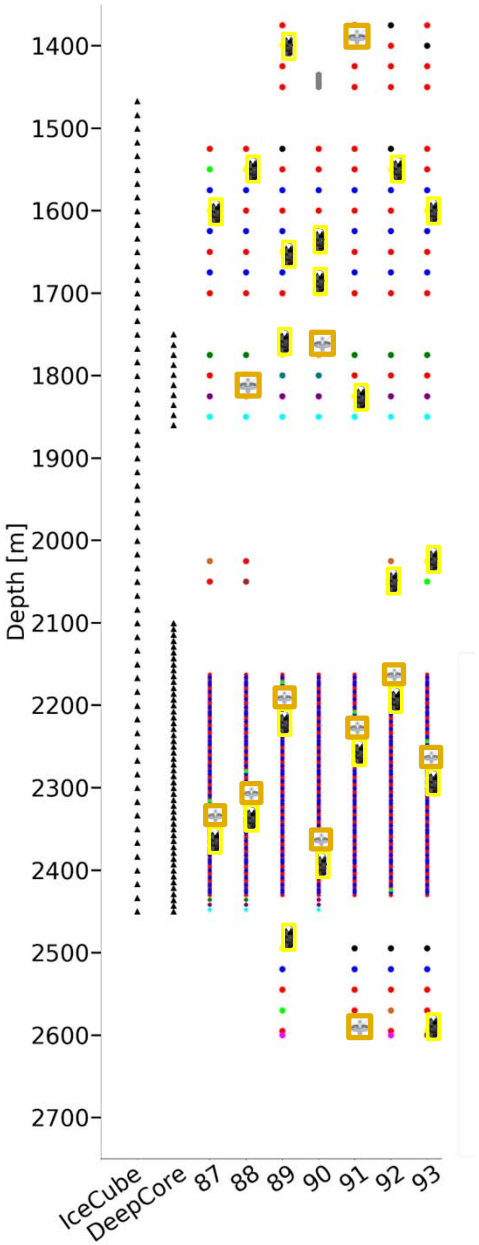


POCAM
(isotropic light source)

LEDs in modules



clear ice



Information

IceCube-Gen2 Technical paper is upcoming the next!

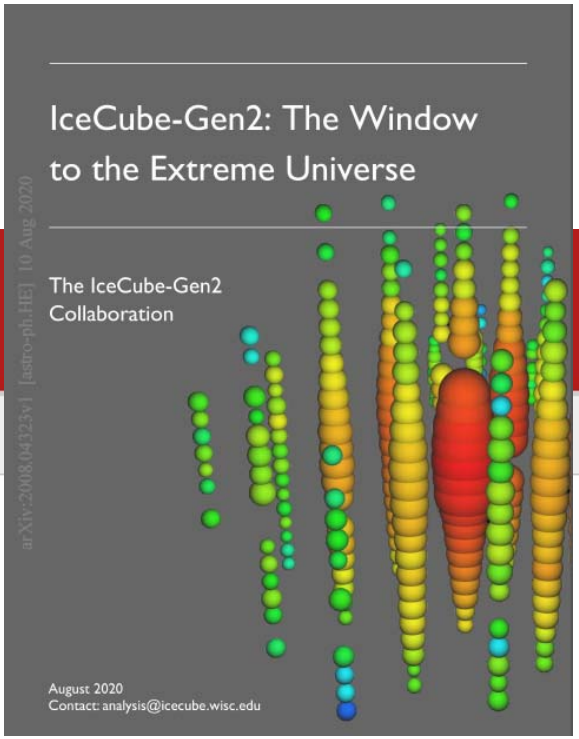
arXiv.org > astro-ph > arXiv:2008.04323

Gen2 White Paper

Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 10 Aug 2020]

IceCube-Gen2: The Window to the Extreme Universe



arXiv.org > astro-ph > arXiv:1911.02561

Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 6 Nov 2019]

Decadal Survey on Astronomy and Astrophysics 2020

Neutrino astronomy with the next generation IceCube Neutrino Observatory

Summary

- **2011**年の***IceCube****検出器*はその完成以来、世界唯一の一立方キロメートルニュートリノ望遠鏡として、安定した運転をしている
- 観測においても部分的な検出器の頃より解析をすすめ、宇宙線起源に重要な制限を与え、世界初となる高エネルギー宇宙ニュートリノの観測を行っている
- 拡散宇宙ニュートリノのエネルギー分布、３**σ**レベルのニュートリノ起源天体の同定が**2**天体、**”**面白い**”**事象、**GR**事象やタウニュートリノ事象など、が**10**年で**1-2**事象見つかっている**(PeV**を超える事象頻度は**2**年に一度**)**
- **10**年分のデータはすでにパブリックになっている
- 角度分解能、検出率を高め、観測の高性能化を可能とする***IceCuge-Gen2***計画を進めている。
- 粒子シャワー事象の有効検出体積が約８倍、トラック事象の有効検出体積が約５倍。宇宙ニュートリノ事象やさらに稀な事象の観測頻度は検出体積増える
- さらに、体積の拡大からのトラック事象の角度分解能の向上が期待。ニュートリノ起源天体の同定で約５倍の感度向上
- **2023**年に**IceCube-Gen2 Phase-1**の建設が行われる。**2025**年からの**IceCube-Gen2** メイン配列の建設にむけた準備をすすめている


THE ICECUBE COLLABORATION
AUSTRALIA
University of Adelaide
BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
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Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
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The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
IceCube
South Pole Neutrino Observatory
icecube.wisc.edu


WISCONSIN

Backup

Gen2 Optical Module

Gen2 Phase-1

24 ch x 3'' PMT

dia 36cm

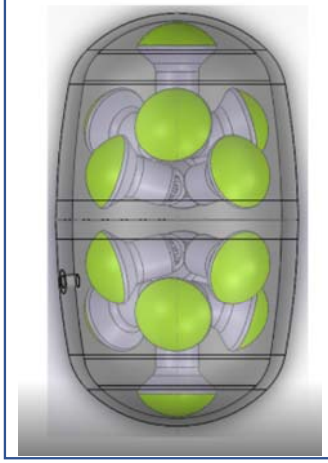
\+

2ch x 8'' PMT

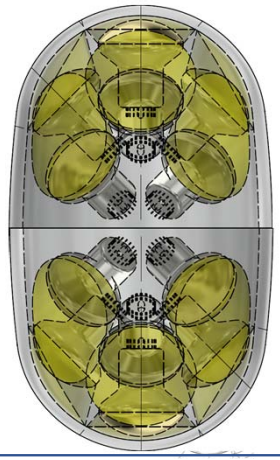
dia 30cm

dia 30cm

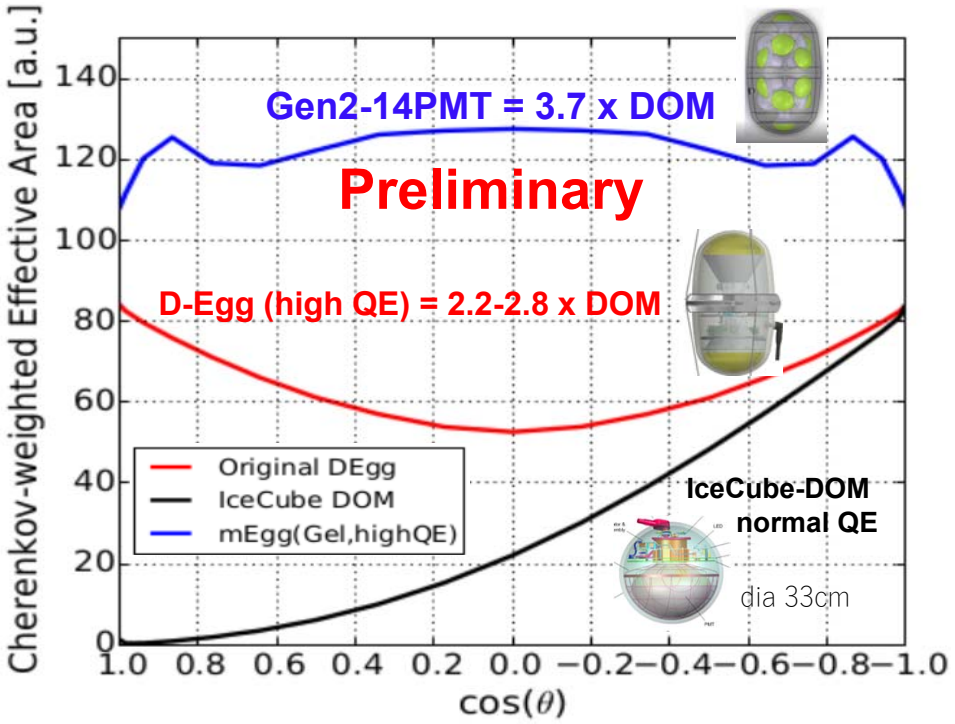
dia 30cm
14ch x 4'' PMT



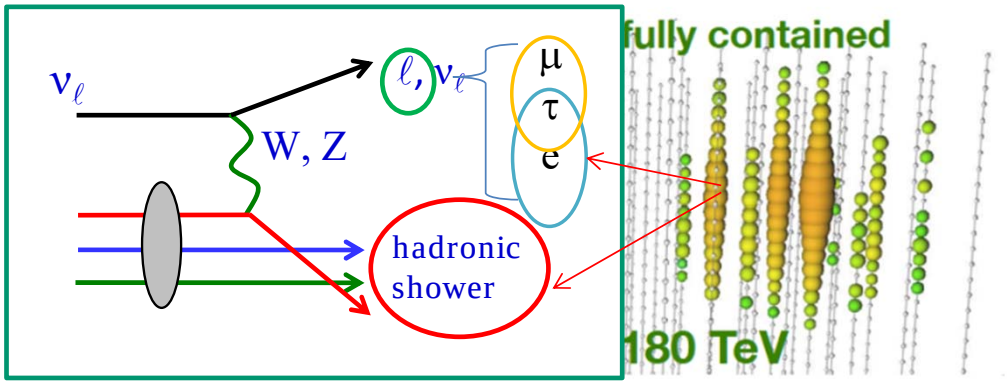
dia 31.8cm
18ch x 4'' PMT



GEANT4 calculation of preliminary Gen2 OM sensitivity



Additional Improvements with Cascade Events



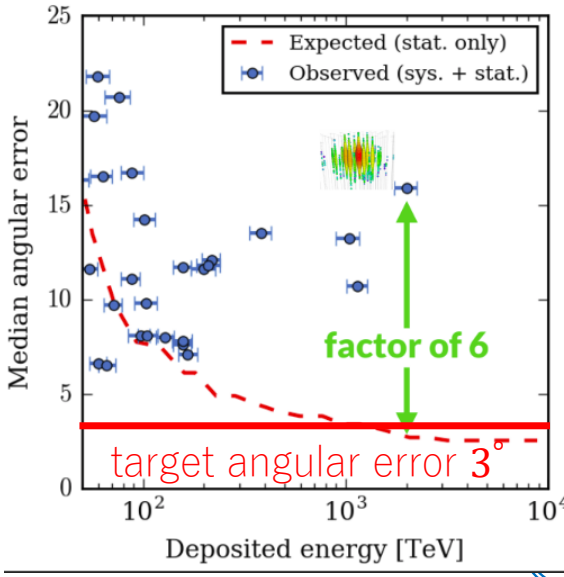
Cascade channel is complementary to upward muon track channel

- Good energy resolution of ~10%
- Sensitive to full sky
- Less atmospheric neutrino background
  - lower energy threshold (10TeV – 100TeV)
- Cascade event rates proportional to volume
  ⇒ a factor of 8 in Gen2

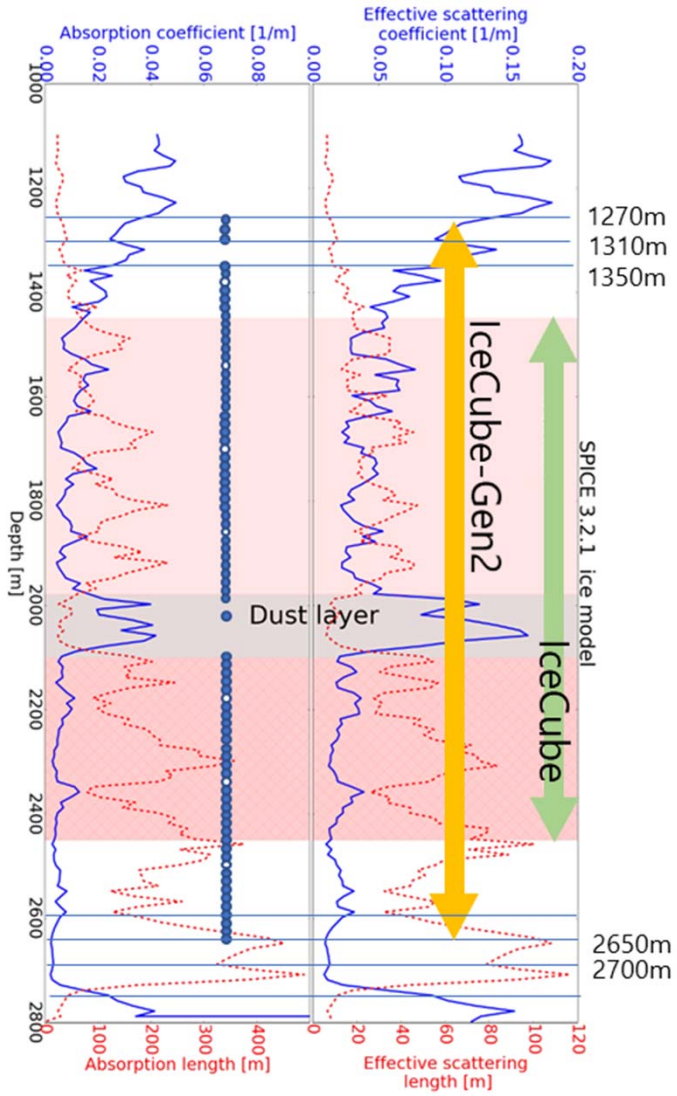
However, currently directional resolution is ~10° dominated by uncertainty associated with optical properties of ice

- Improvements on the reconstruction of cascade *prior to Gen2* construction give us significant benefit
- Reduce ice induced systematics with 800 densely (3m) instrumented optical modules

☞ Calibration of ice with Gen2-Phase1

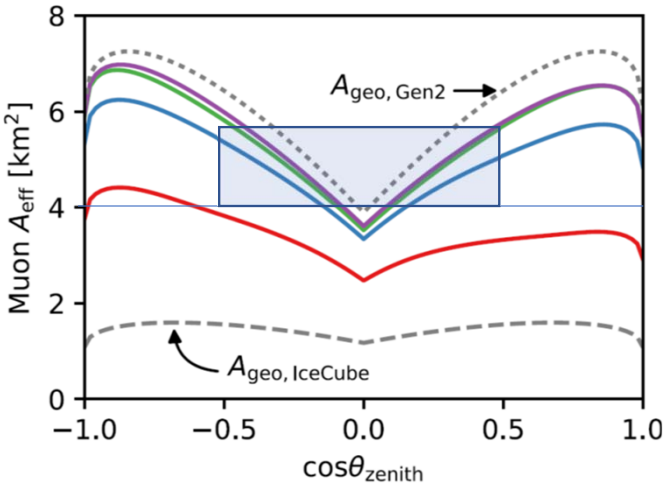


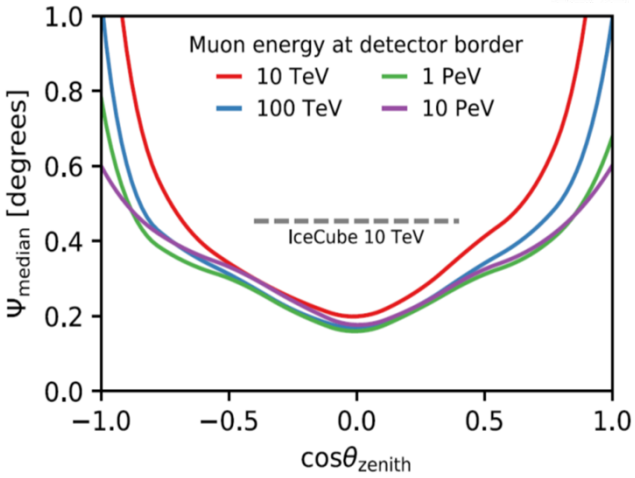
an example – less dust layer
+ more shallow option



Design Principle

- ∝sqrt(x): Livetime, Detector size
- ∝1/x: Angular resolution
- Signal selection efficiency
- BG rejection efficiency





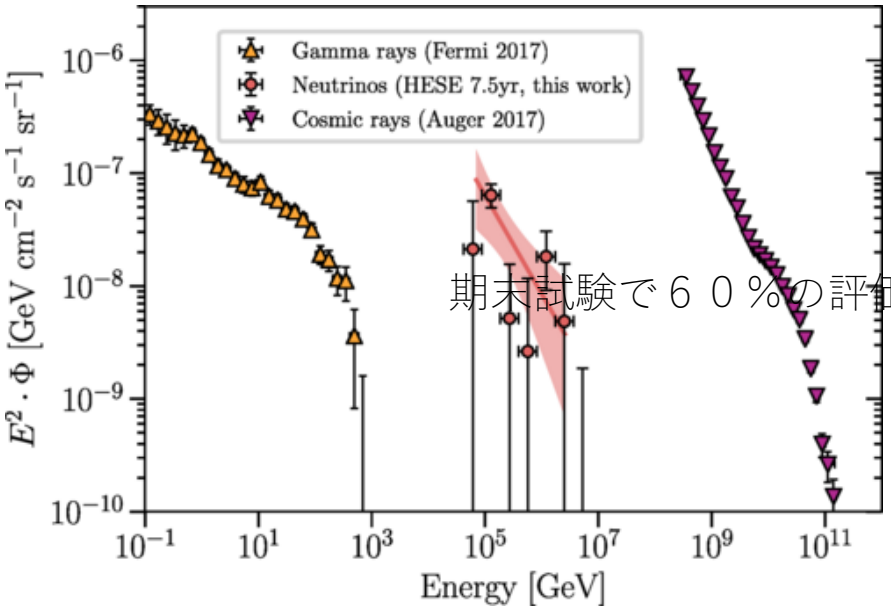
- **Detector effective muon area — x 4～5 (horizontal)**
- **Angular resolution — x ～ 0.45 (horizontal)**

default factor gives a factor of 5 better sensitivity

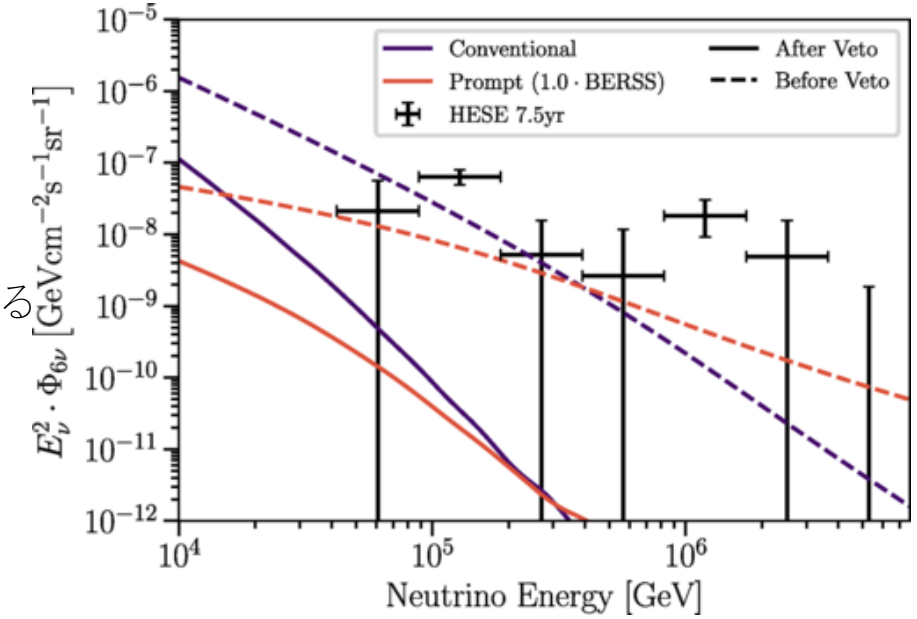
- **improvement with new optical sensors**
- **improvement with new calibration**

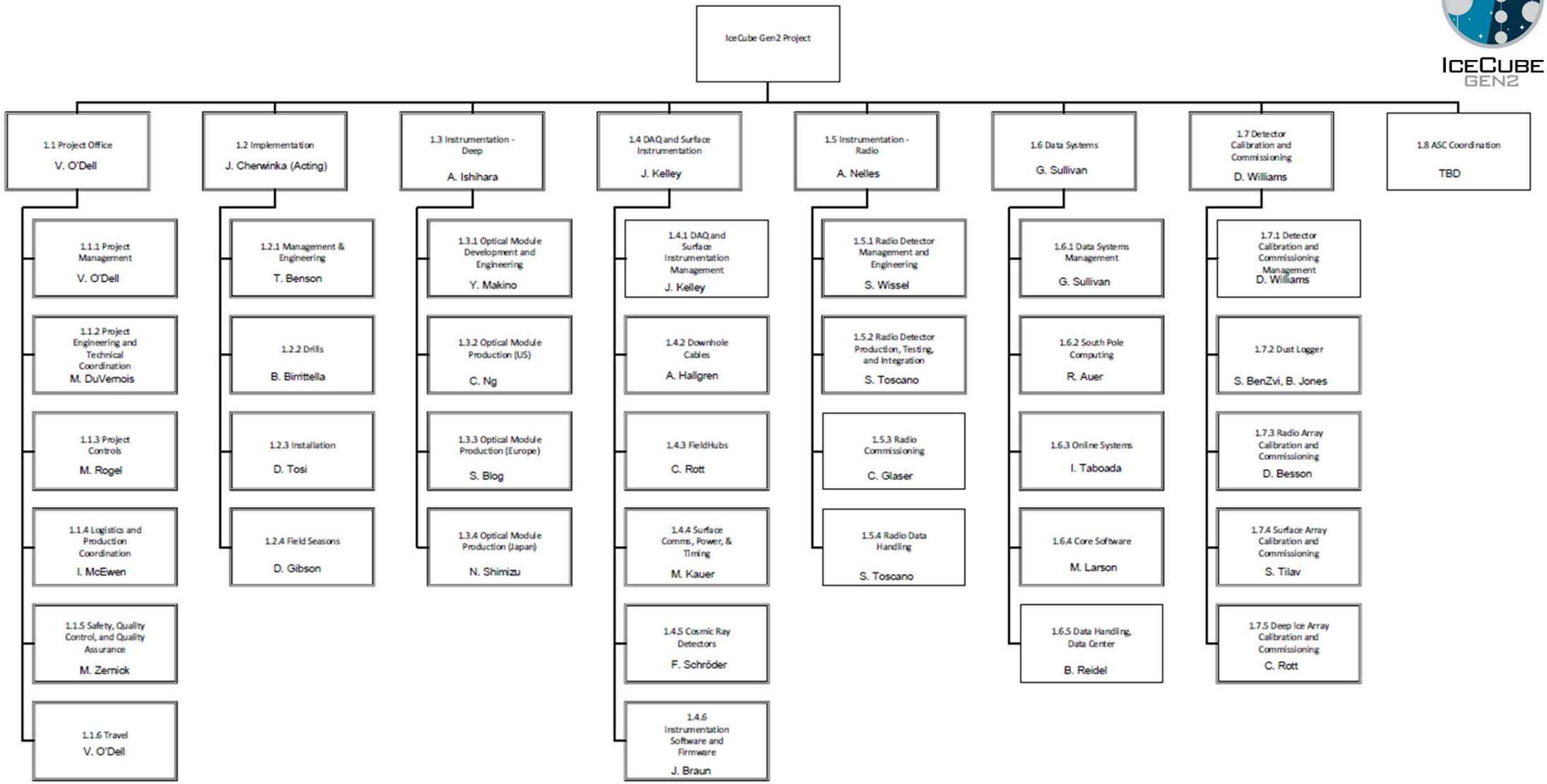
Additional improvements

HESE 7.5yrs



期末試験で６０％の評価をする




IceCube Gen2 Project
1.1 Project Office
V. O'Dell
1.1.1 Project Management
V. O'Dell
1.1.2 Project Engineering and Technical Coordination
M. DuVernois
1.1.3 Project Controls
M. Rogel
1.1.4 Logistics and Production Coordination
I. McEwen
1.1.5 Safety, Quality Control, and Quality Assurance
M. Zernick
1.1.6 Travel
V. O'Dell
1.2 Implementation
J. Cherwinka (Acting)
1.2.1 Management & Engineering
T. Benson
1.2.2 Drills
B. Birrittella
1.2.3 Installation
D. Tosi
1.2.4 Field Seasons
D. Gibson
1.3 Instrumentation - Deep
A. Ishihara
1.3.1 Optical Module Development and Engineering
Y. Makino
1.3.2 Optical Module Production (US)
C. Ng
1.3.3 Optical Module Production (Europe)
S. Blog
1.3.4 Optical Module Production (Japan)
N. Shimizu
1.4 DAQ and Surface Instrumentation
J. Kelley
1.4.1 DAQ and Surface Instrumentation Management
J. Kelley
1.4.2 Downhole Cables
A. Hallgren
1.4.3 FieldHubs
C. Rott
1.4.4 Surface Comms, Power, & Timing
M. Kauer
1.4.5 Cosmic Ray Detectors
F. Schröder
1.4.6 Instrumentation Software and Firmware
J. Braun
1.5 Instrumentation - Radio
A. Nelles
1.5.1 Radio Detector Management and Engineering
S. Wissel
1.5.2 Radio Detector Production, Testing, and Integration
S. Toscano
1.5.3 Radio Commissioning
C. Glaser
1.5.4 Radio Data Handling
S. Toscano
1.6 Data Systems
G. Sullivan
1.6.1 Data Systems Management
G. Sullivan
1.6.2 South Pole Computing
R. Auer
1.6.3 Online Systems
I. Taboada
1.6.4 Core Software
M. Larson
1.6.5 Data Handling, Data Center
B. Reidel
1.7 Detector Calibration and Commissioning
D. Williams
1.7.1 Detector Calibration and Commissioning Management
D. Williams
1.7.2 Dust Logger
S. BenZvi, B. Jones
1.7.3 Radio Array Calibration and Commissioning
D. Besson
1.7.4 Surface Array Calibration and Commissioning
S. Tilav
1.7.5 Deep Ice Array Calibration and Commissioning
C. Rott
1.8 ASC Coordination
TBD