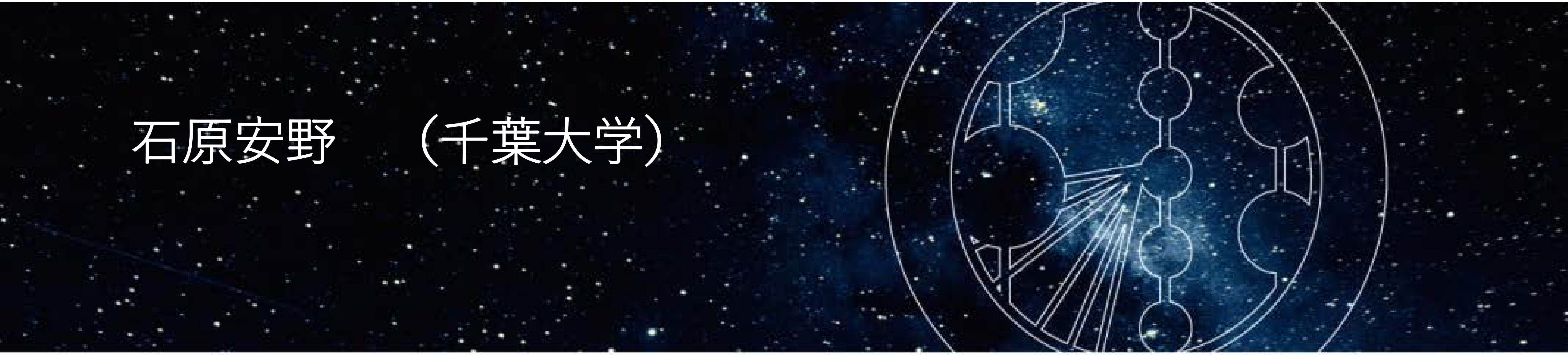
第12回光赤外線天文学大学間連携ワークショップ

マルチメッセンジャー観測時代における高エネルギー宇宙ニュートリノ観測

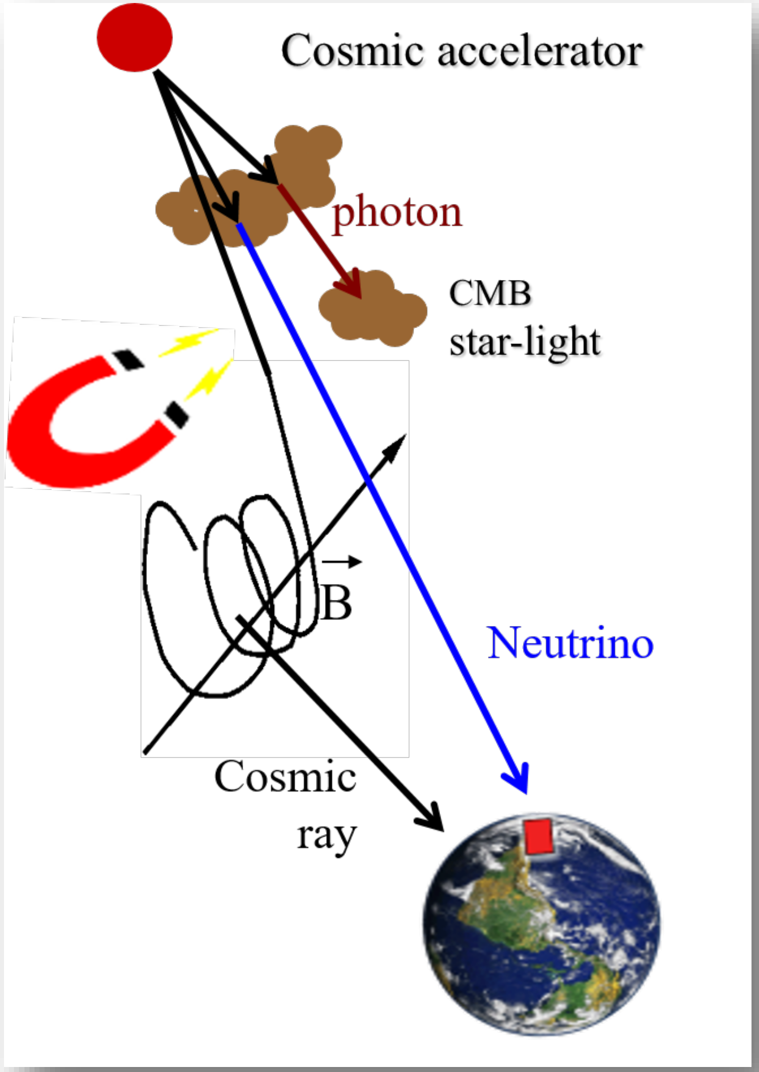


石原安野　（千葉大学）

CELEBRATING THE FIRST DECADE OF DISCOVERY

ICECUBE'S 10TH ANNIVERSARY | 2011-2021

High Energy Neutrino as a Cosmic Messenger



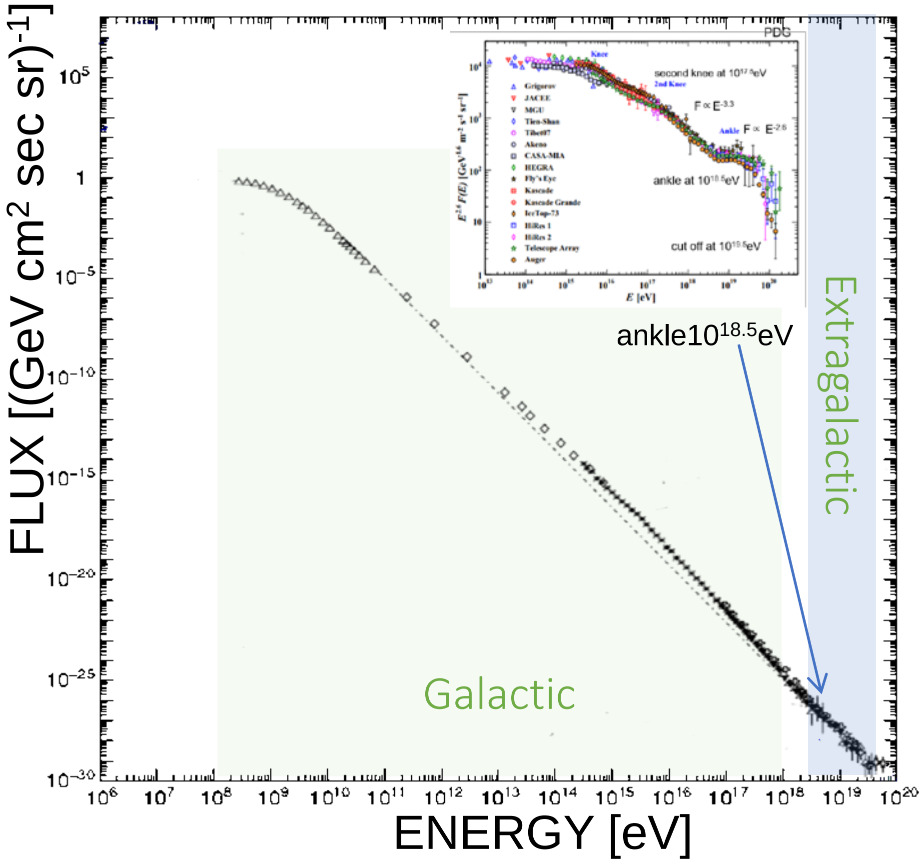
Weak interaction during "propagation"

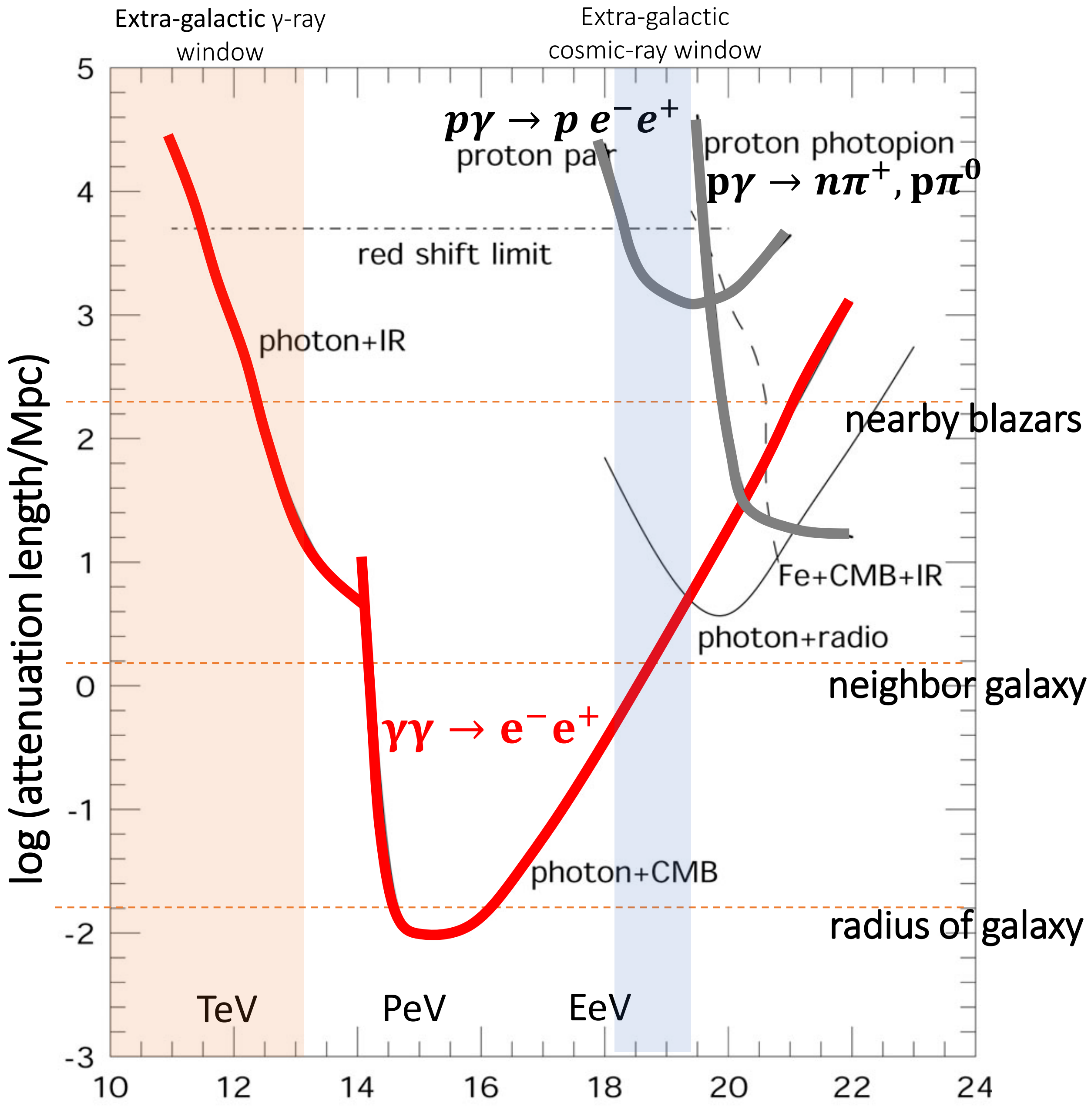
- **Penetration power**
- **Pointing capability**

even at extreme energies

なぜニュートリノ天文学なのか

- 宇宙の超高エネルギー放射の起源とその発生機構を知りたい

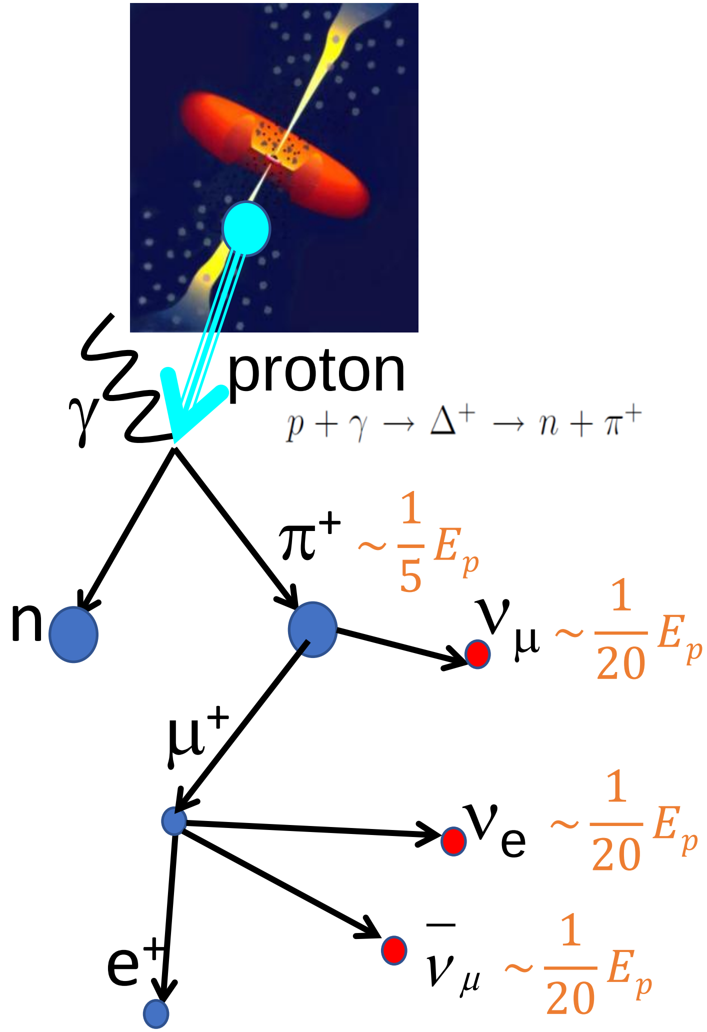




Anchordoqui+
hep-ph/0206072v3

なぜ、ニュートリノ天文学なのか

- ニュートリノの特徴：　非常に軽く、弱い相互作用のみ働く（相互作用をせずに、長距離を走る・生成機構がシンプル）



①宇宙線陽子がパイオンをつくる

$$p+\gamma \rightarrow n+\pi^{+}$$
$$p+\gamma \rightarrow p+\pi^{0}$$

$$p+p \rightarrow p+p+\pi^{0}$$
$$p+p \rightarrow p+n+\pi^{+}$$
$$p+p \rightarrow p+p+\pi^{+}+\pi^{-}\ldots$$

②パイオンがニュートリノとミューオンに崩壊

$$\pi^{0} \rightarrow \gamma+\gamma$$
$$\pi^{+} \rightarrow \mu^{+}+\nu_{\mu}$$

（中性パイオンがガンマ線に崩壊）

↓

ニュートリノ発生領域からくるガンマ線との相関が有力手段

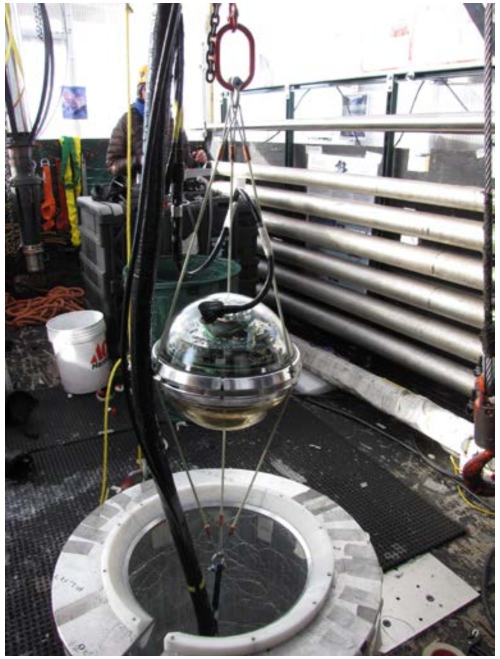
↓

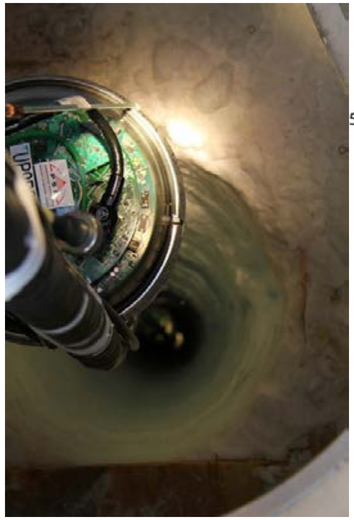
③ミューオンがニュートリノと(陽)電子に崩壊

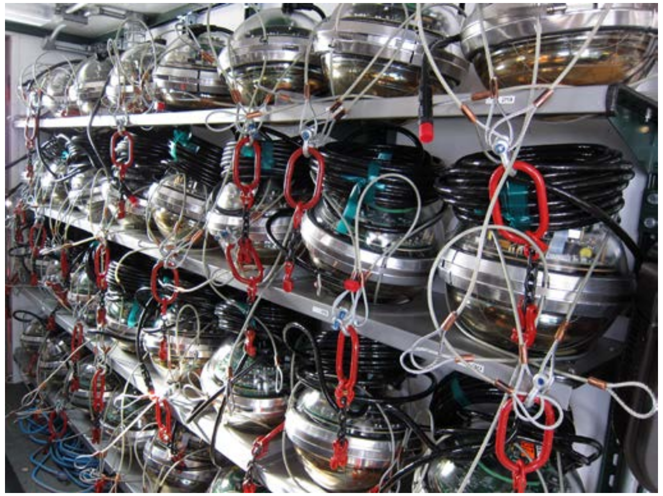
$$\mu^{+} \rightarrow e^{+}+\bar{\nu}_{\mu}+\nu_{e}$$

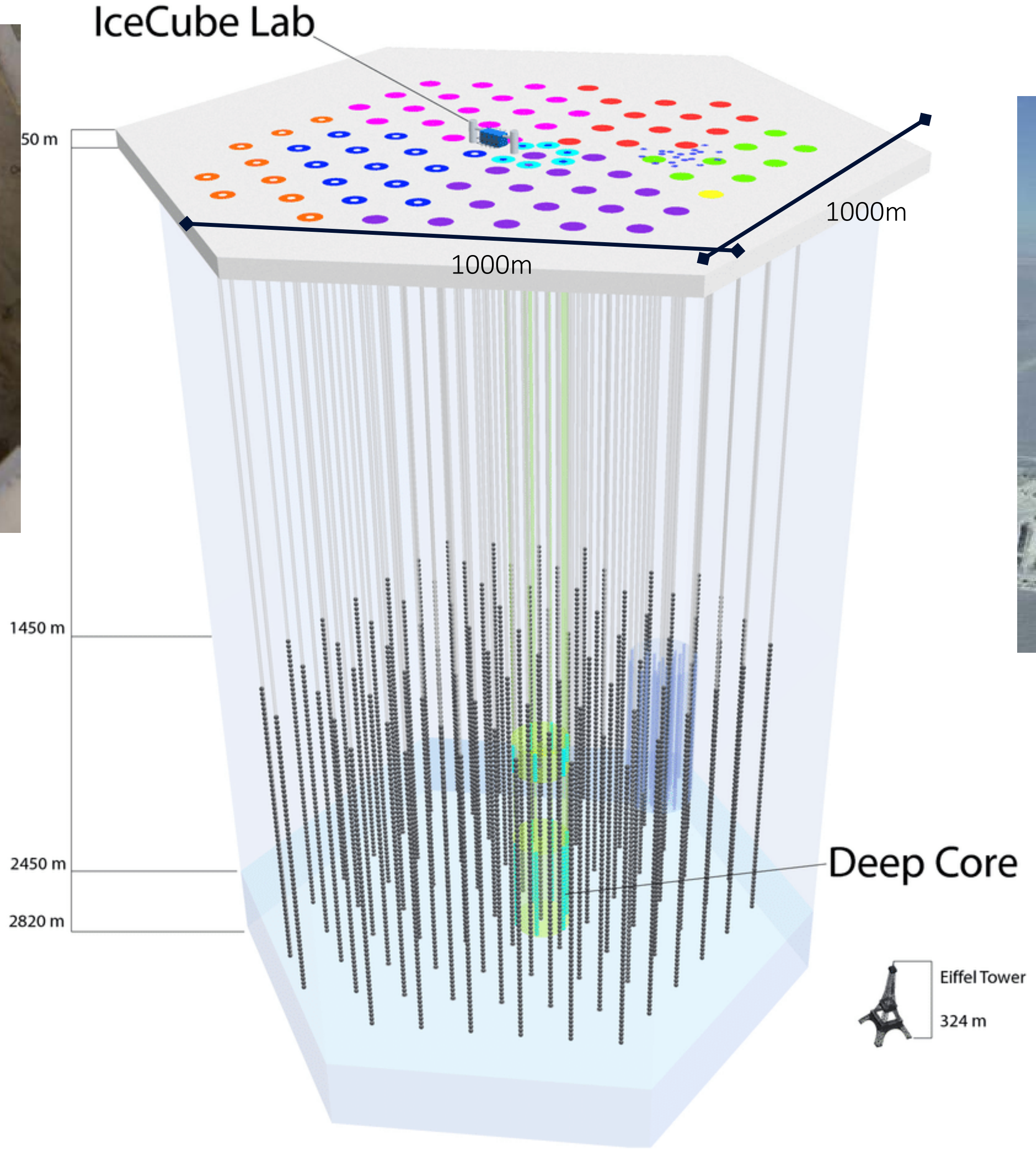
ニュートリノ発生天体はRadio,可視光からX線、さらに重力波も

The IceCube Detector

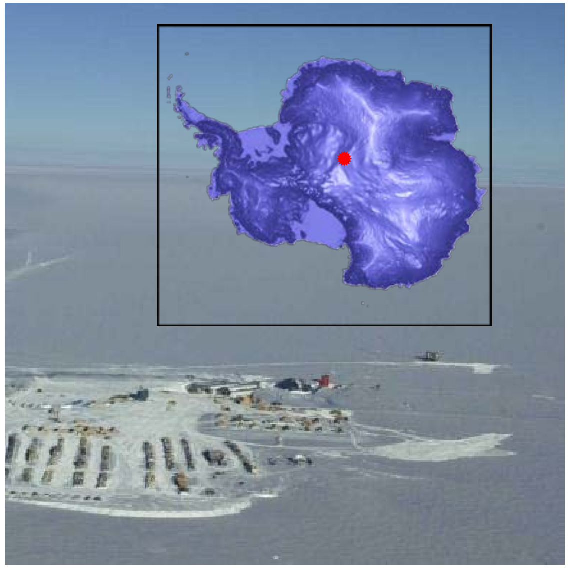






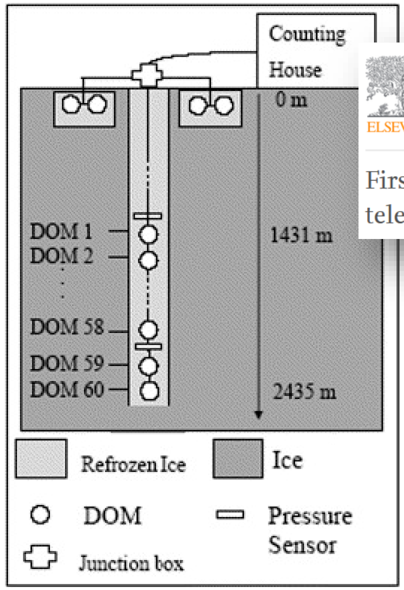


@ Amundsen-Scott South Pole station



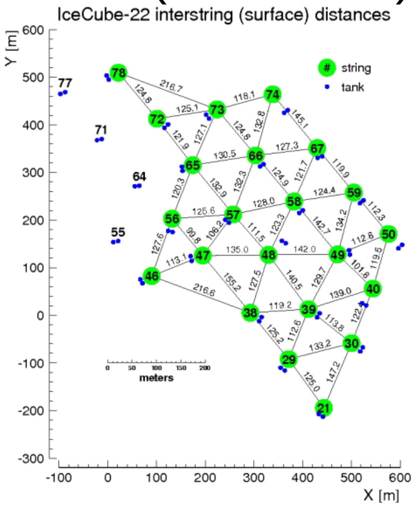
IceCube Construction and Runs

IC1(2005-2006)

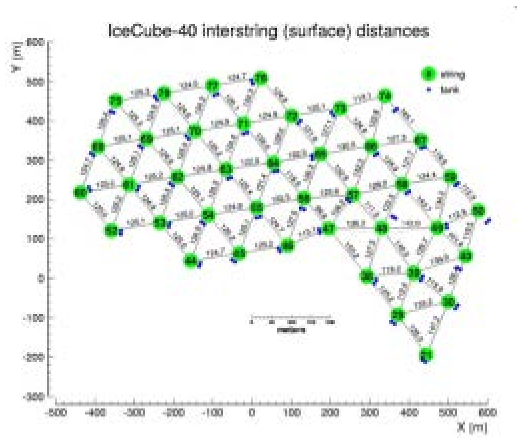


IC9 (2006-2007)

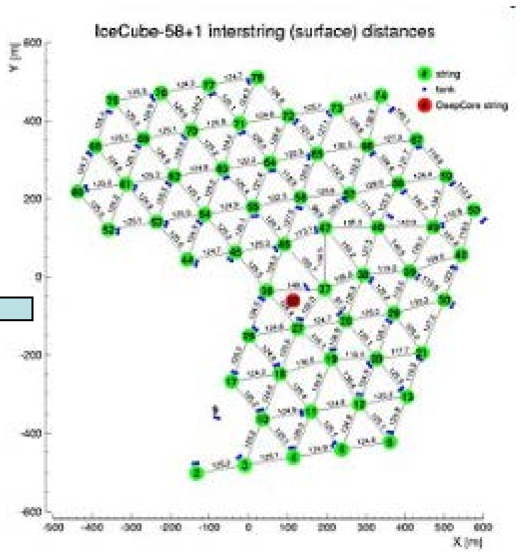
IC22 (2007-2008)



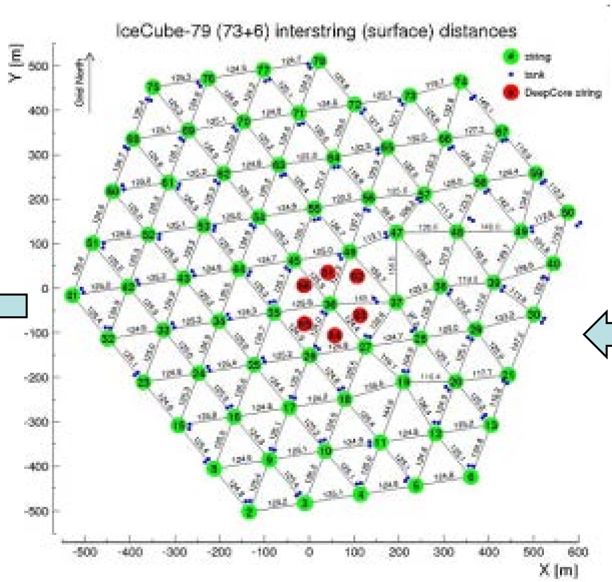
IC40 (2008-2009)



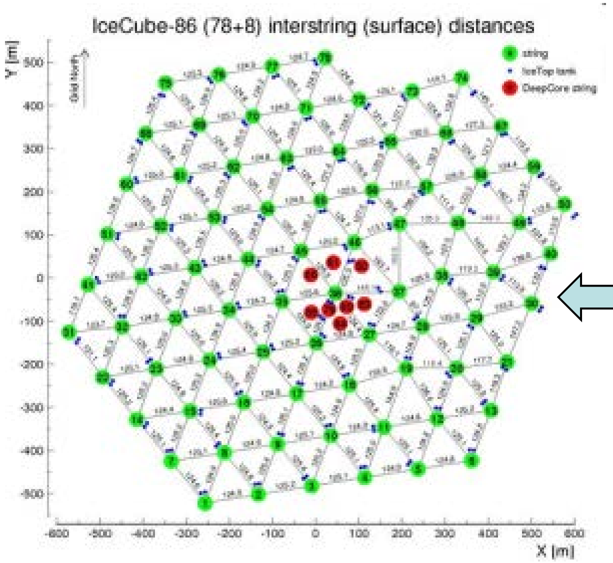
IC59 (2009-2010)



IC79 (2010-2011)

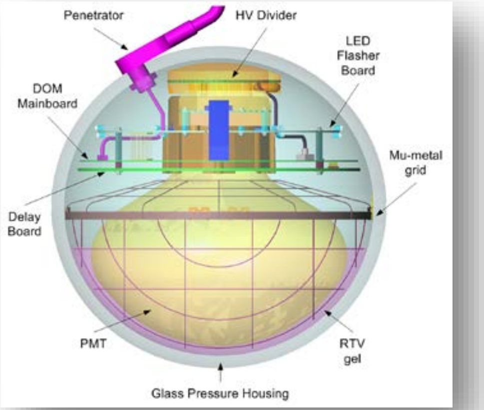


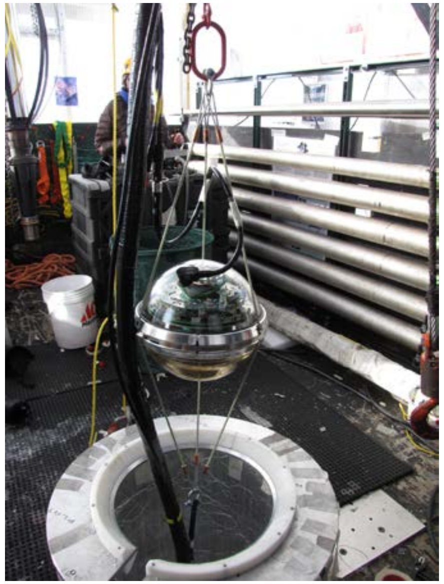
IC86 = full IceCube (2011~)

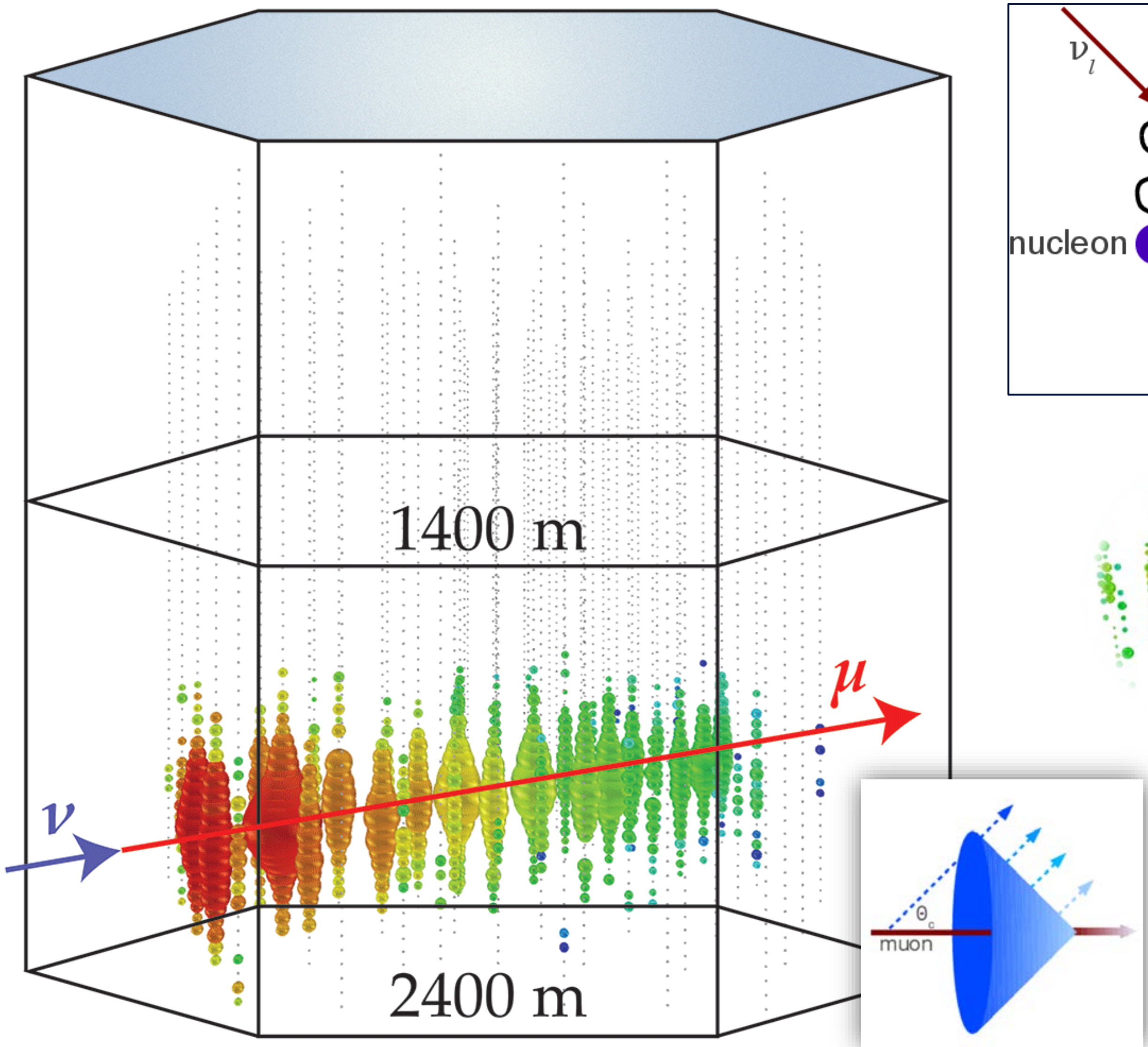


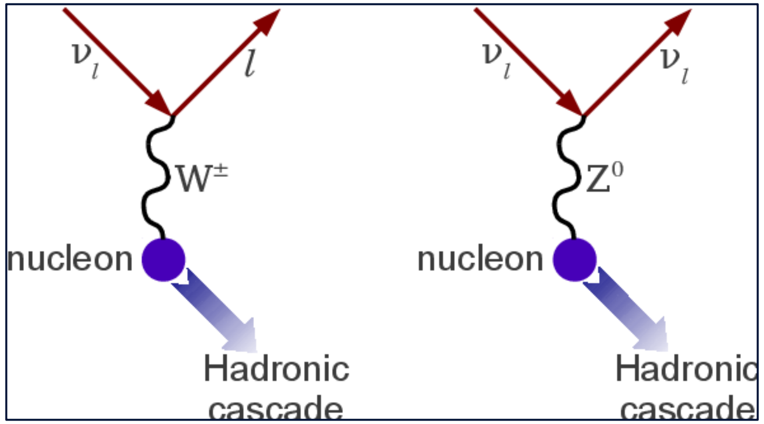
CELEBRATING THE FIRST DECADE OF DISCOVERY

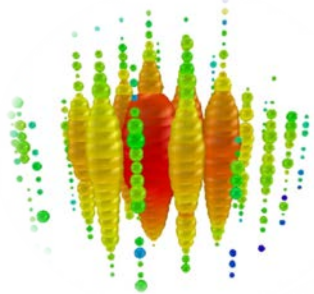
IceCube Neutrino Events

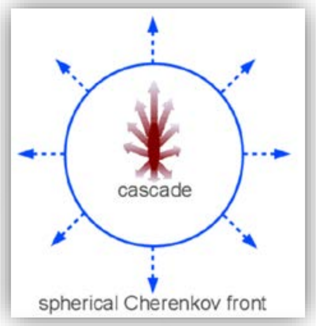


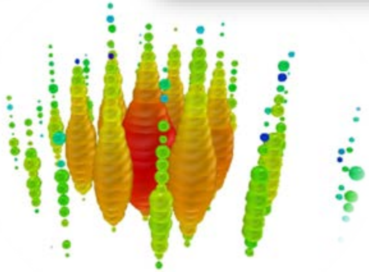








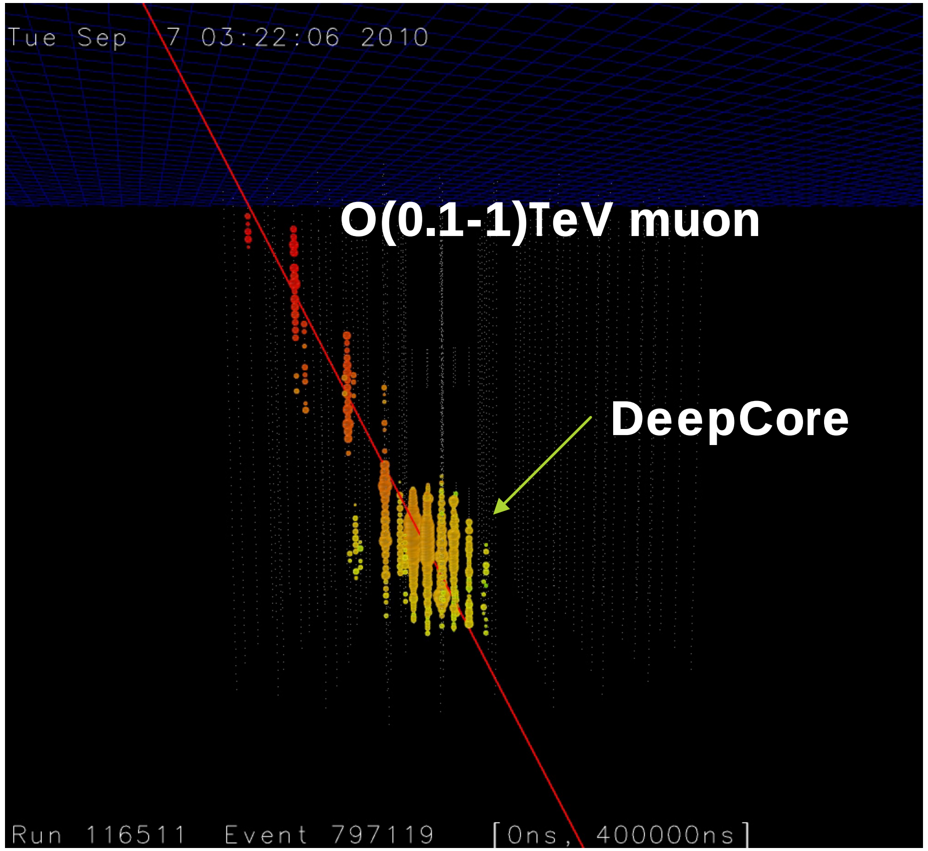


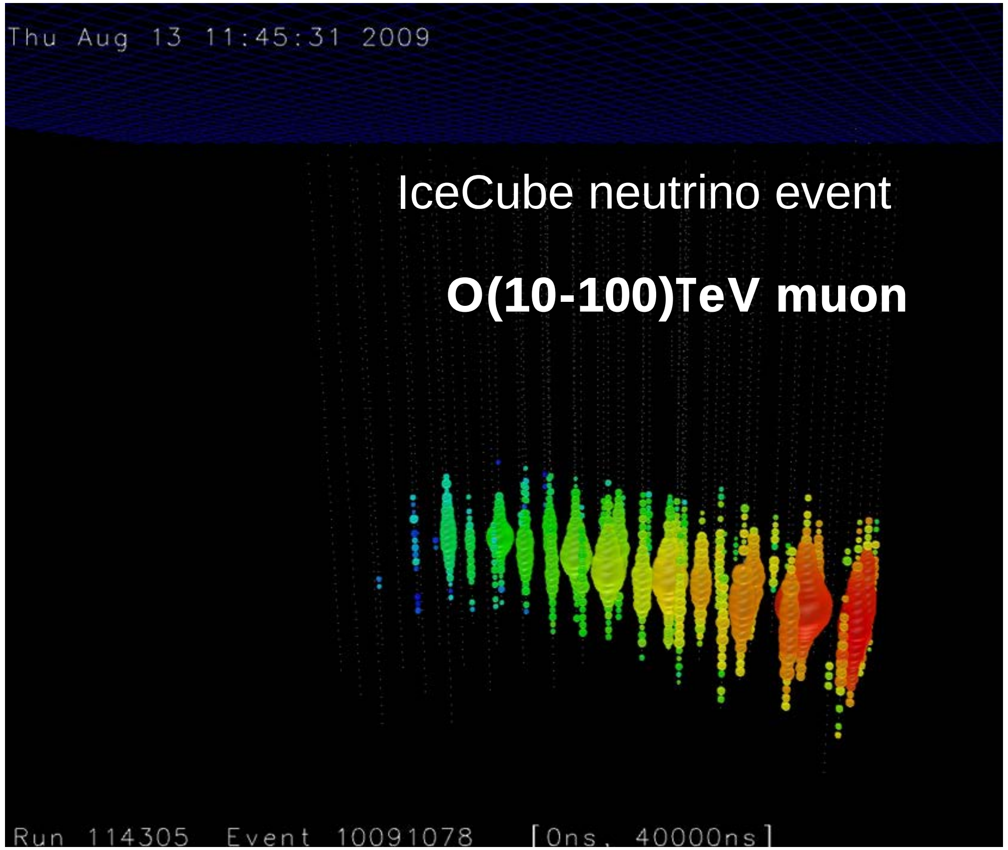


Energy Range for IceCube/DeepCore

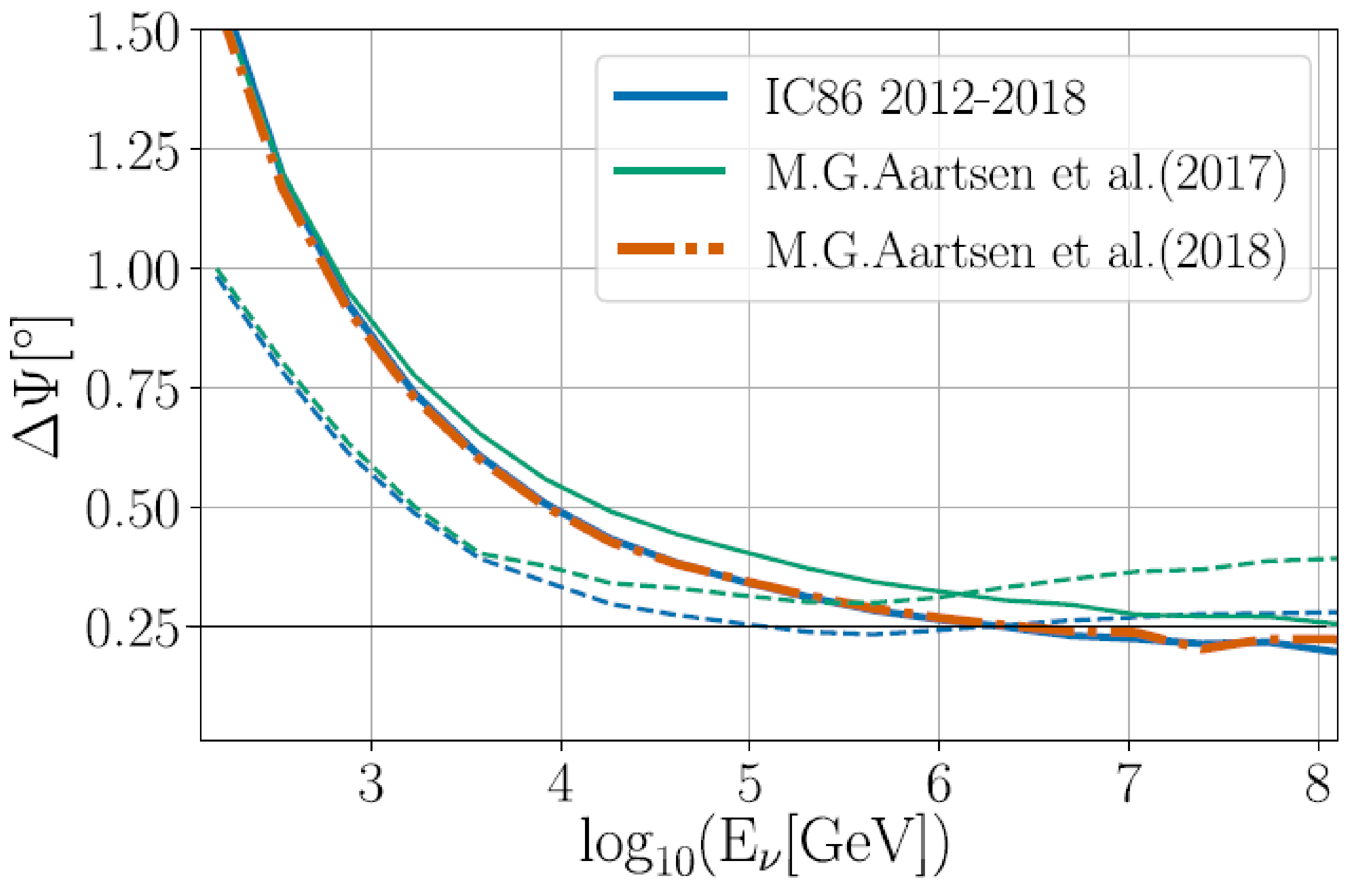
Icecube can measure 10GeV – 10^{11}GeV neutrinos !

DeepCore atmospheric muon event





Angular resolution of muon track reconstruction

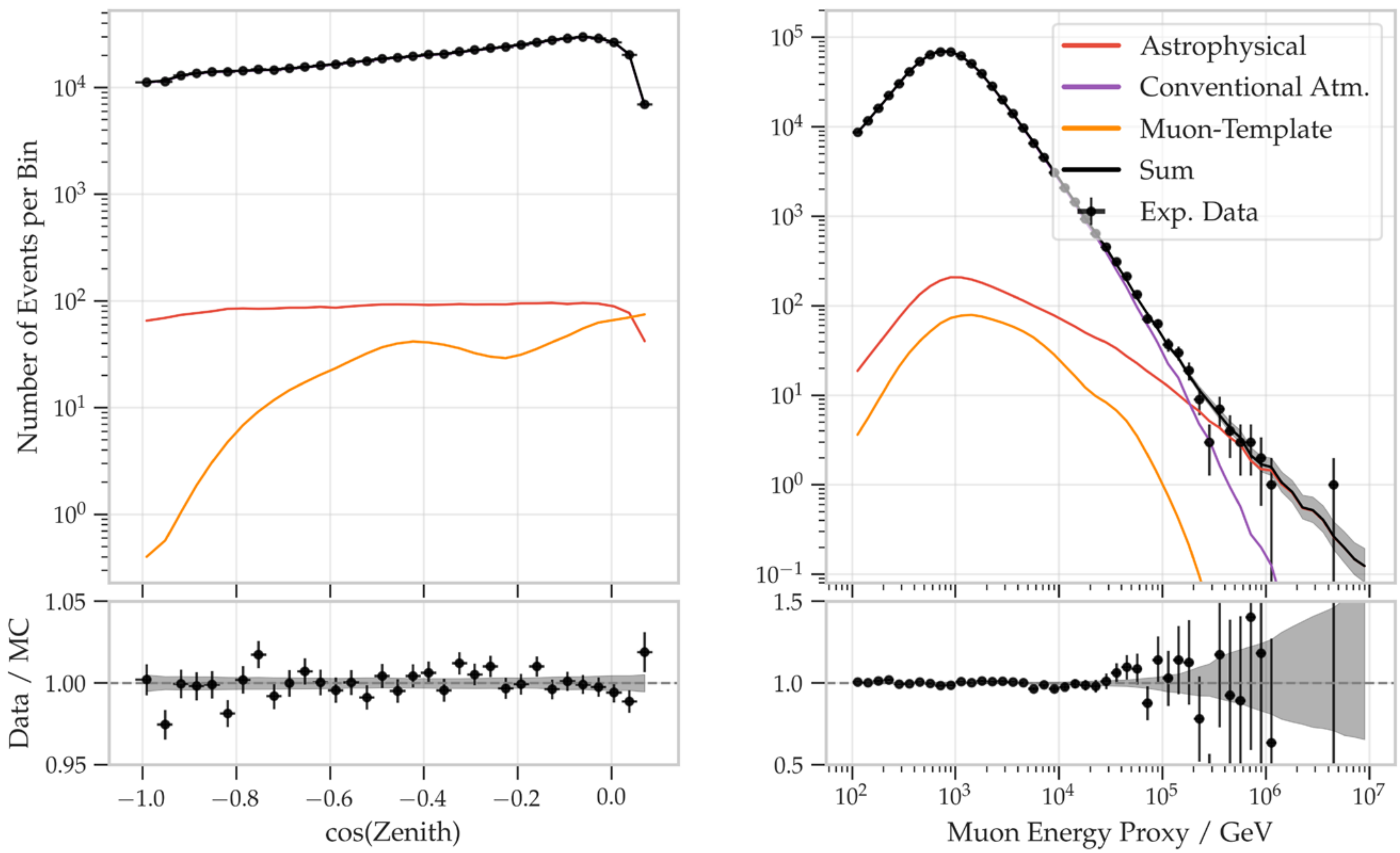


Background dependent on the directions in the sky

- Southern sky: High energy atm muon BG (signal PeV-EeV)
- Northern sky: Atm neutrino BG (signal TeV-PeV)

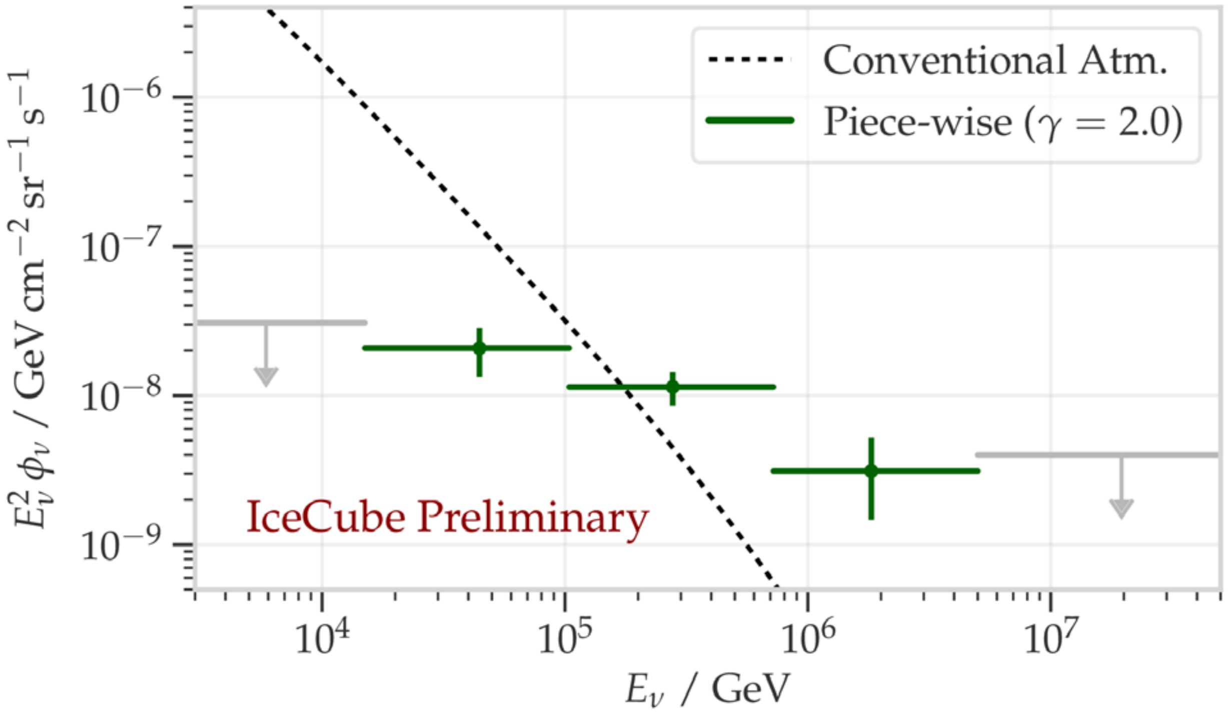
- solid lines are for Northern hemispheres (upward-going)
- dashed lines are for Southern hemispheres (downward-going)

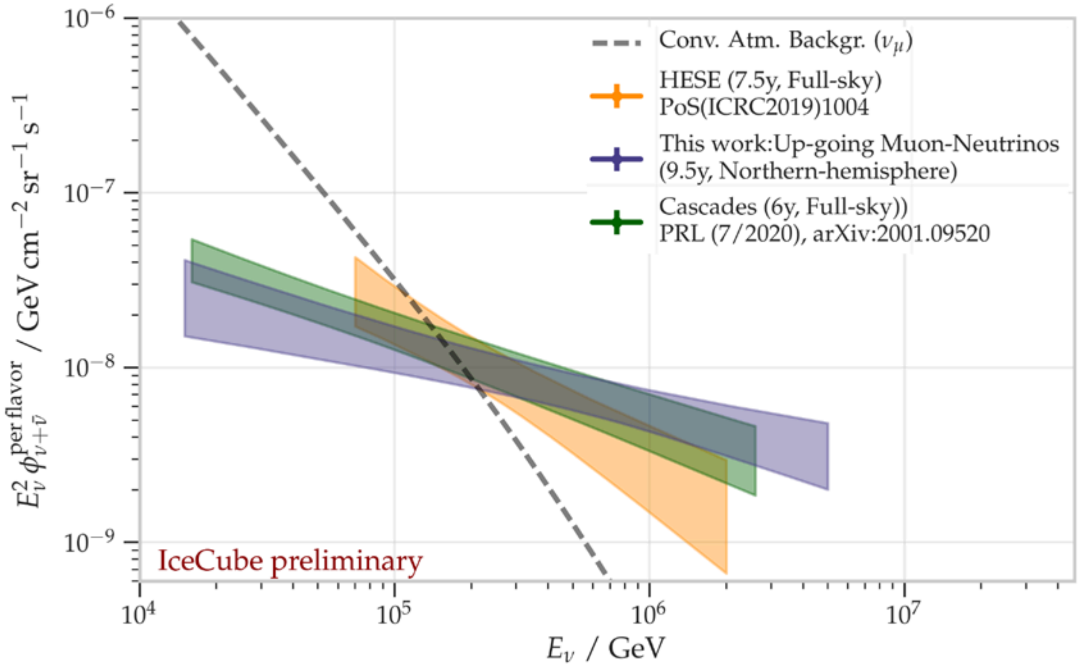
ニュートリノの流量の測定 (9.5 Years)



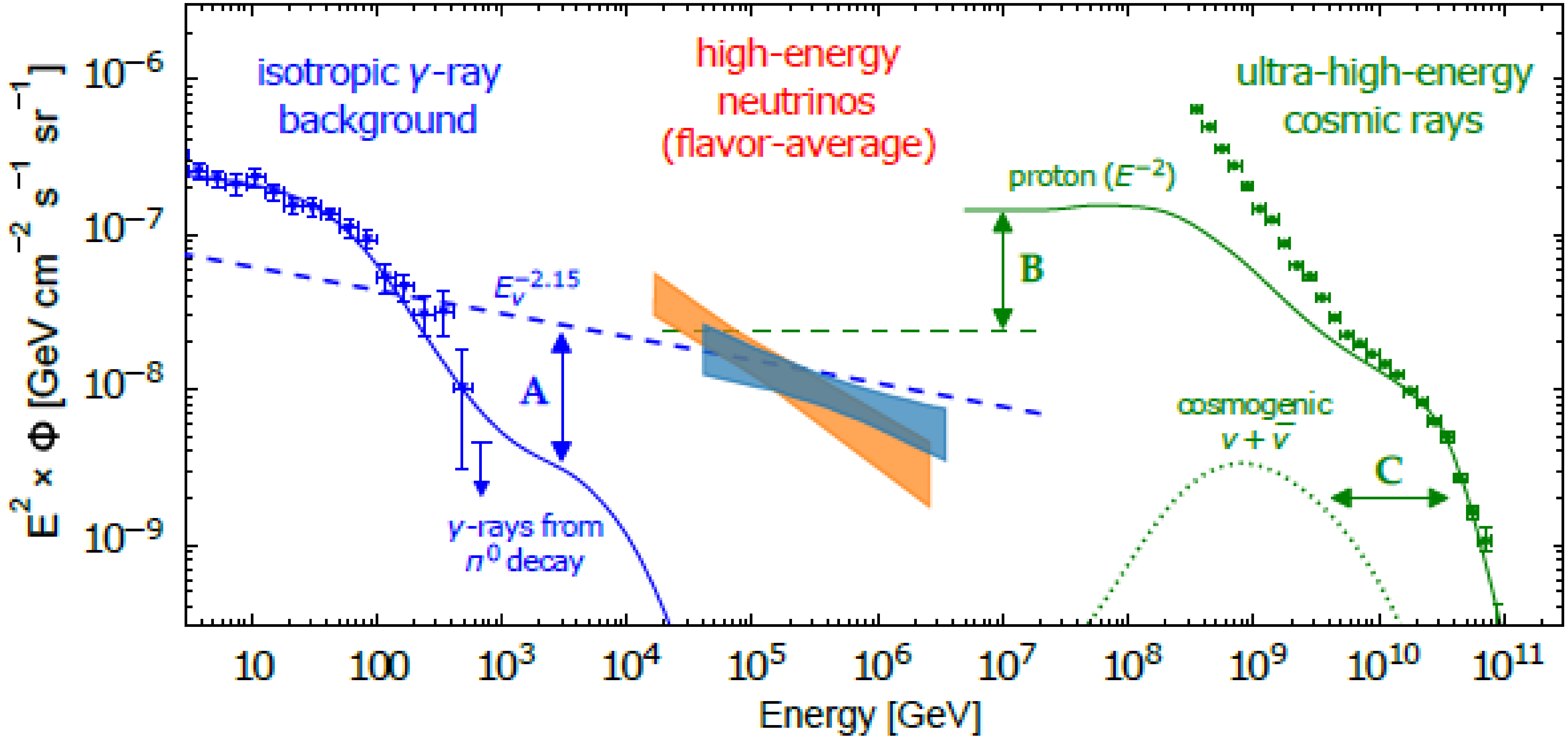
ニュートリノの流量の測定 (9.5 Years)

$$\frac{d\phi_{\nu+\bar{\nu}}}{dE} = \left(1.44^{+0.25}_{-0.26}\right)\left(\frac{E}{100\mathrm{TeV}}\right)^{-2.37\pm0.09} \times 10^{-18}\mathrm{GeV}^{-1}cm^{2}s^{-1}sr^{-1}$$





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



https://arxiv.org/abs/2008.04323

観測された$\frac{d\phi_{\nu+\bar{\nu}}}{dE} = 1.44 \times 10^{-18}\mathrm{GeV}^{-1}cm^{2}s^{-1}sr^{-1}$という
ニュートリノ放射はどこからきているのか？

$\gamma \rightarrow \nu$

- ニュートリノを放出し得る既知の天体の方向から来るニュートリノを探す

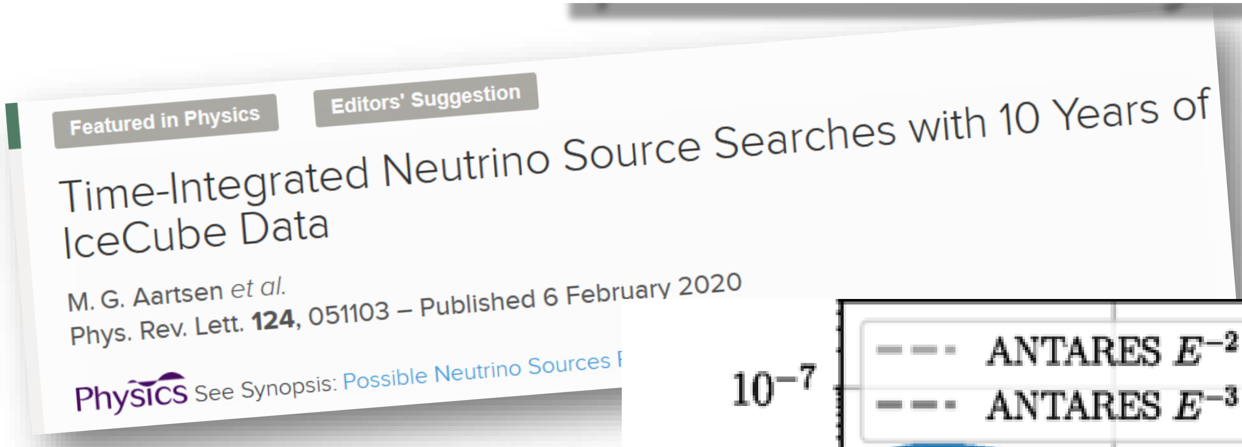
$\nu \otimes \nu$

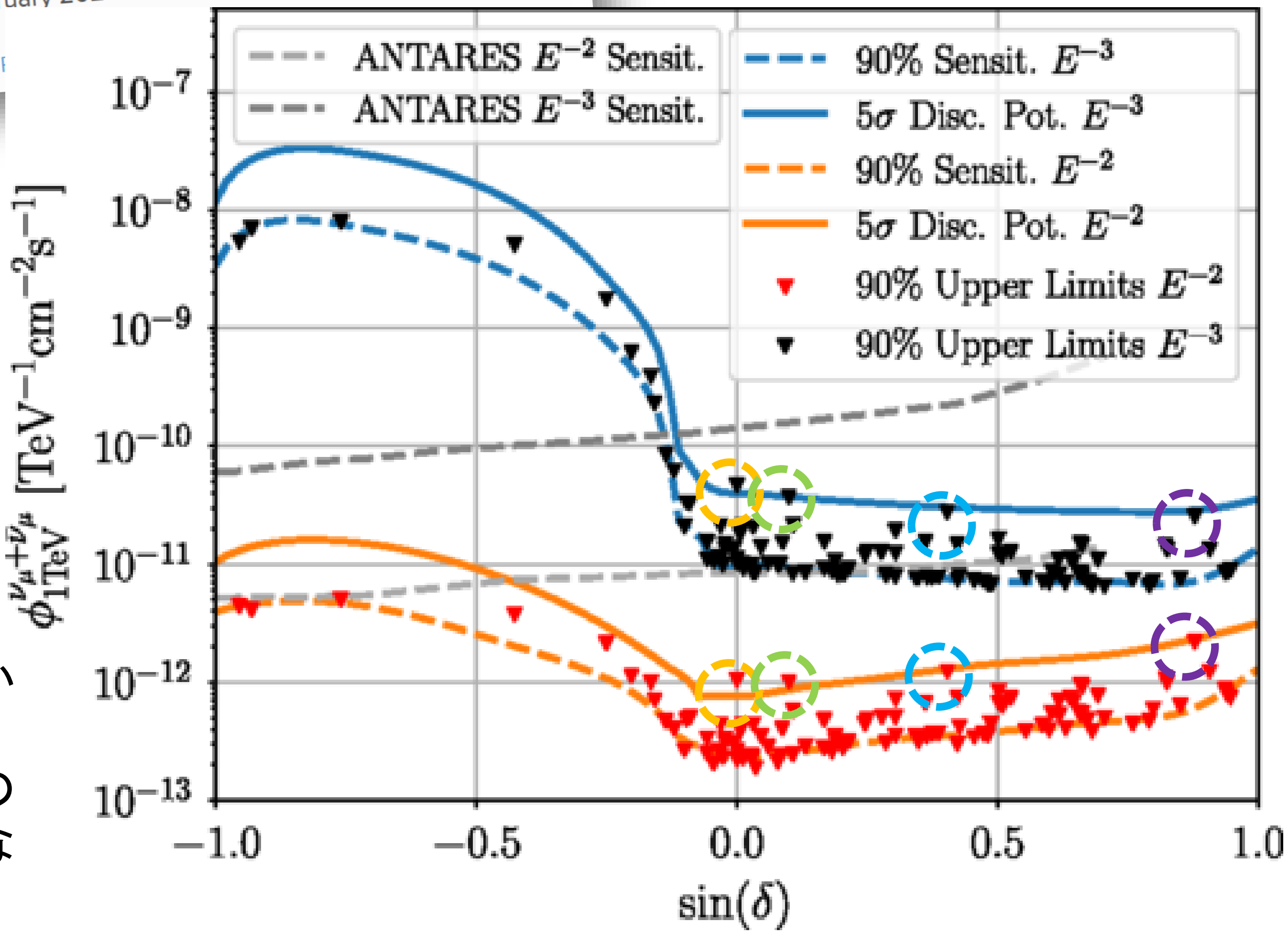
- ニュートリノのみで点源を探す

$\nu \rightarrow \gamma$

- ニュートリノが来た方向にある、最もニュートリノを放出し得る既知の天体を探す

$\gamma \rightarrow \nu$ with10 years of IceCube


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 F

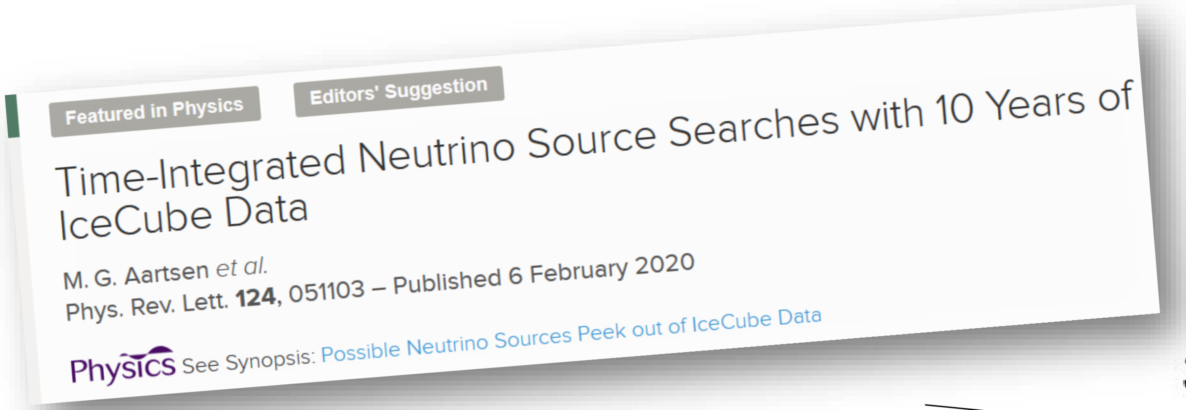


上限値が感度を卓越し有意な信号が見え始めている天体

- 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
しかし宇宙ニュートリノのメインの起源天体種ではない

$\nu \otimes \nu$ with10 years of IceCube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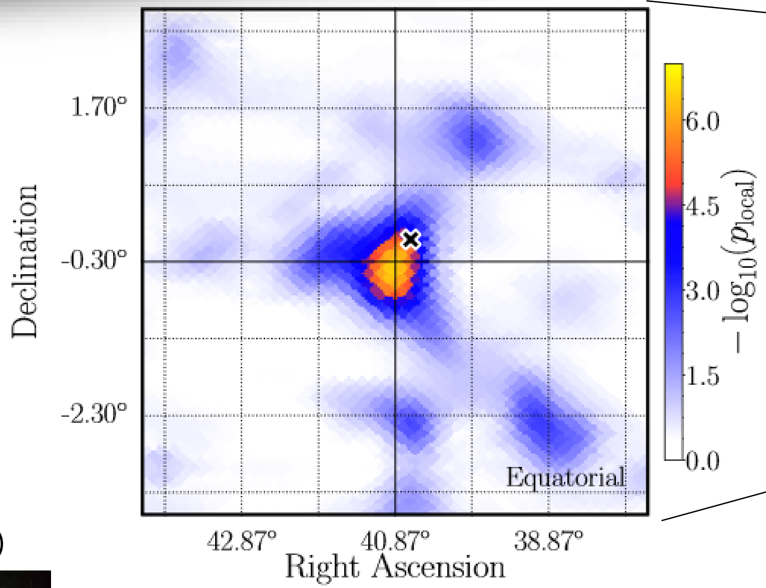
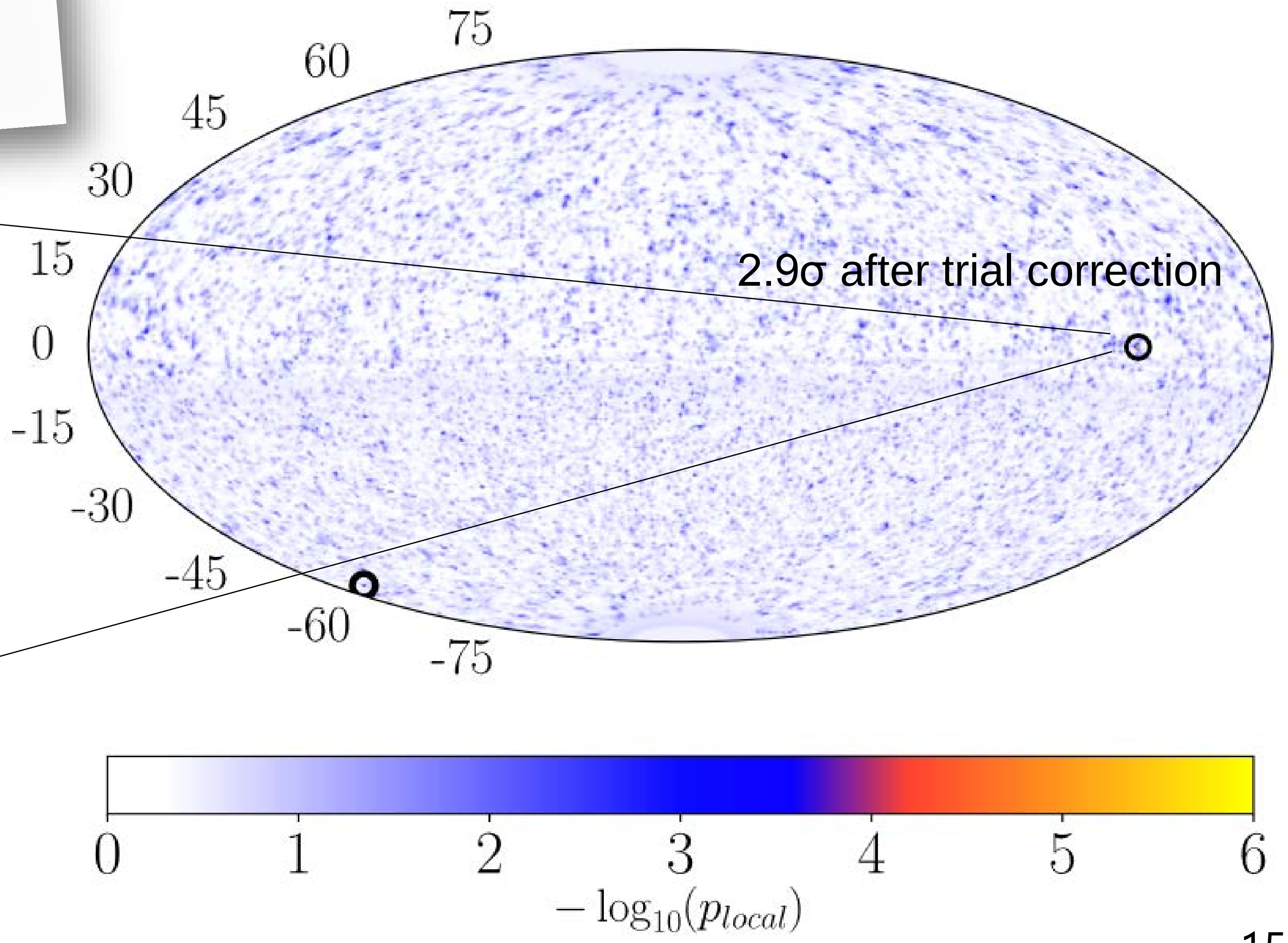
Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data
M. G. Aartsen *et al.*
Phys. Rev. Lett. **124**, 051103 – Published 6 February 2020
Physics See Synopsis: Possible Neutrino Sources Peek out of IceCube Data

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





x: NGC 1068
(star burst AGN)

$\nu \rightarrow \gamma$ operational since 2016

Science 361, eaat1378 (2018)

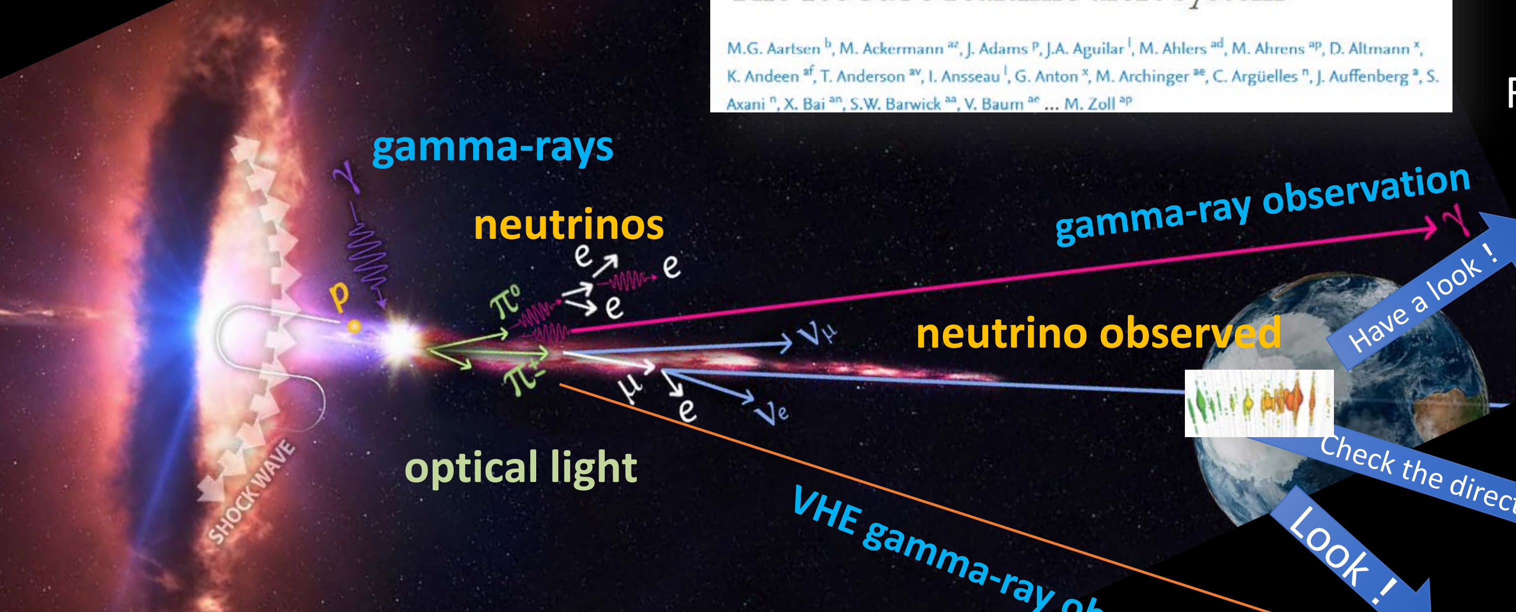
2018

ELSEVIER

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

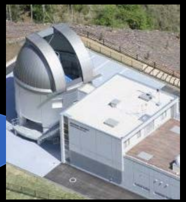
The IceCube realtime alert system

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]



Fermi Telescope

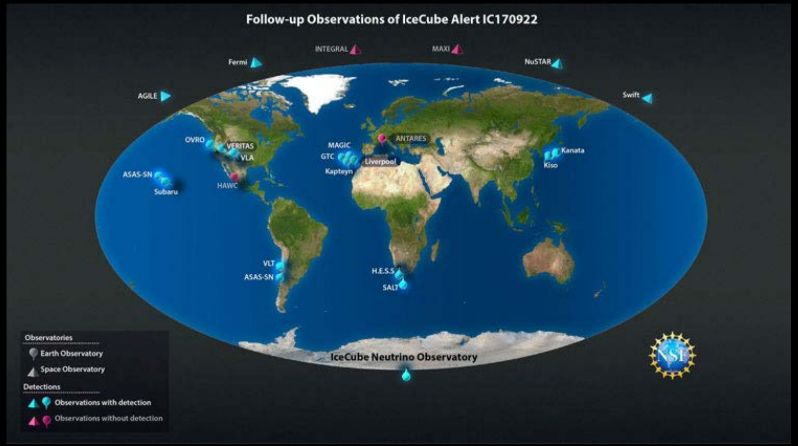
Optical telescopes



Kanata telescope

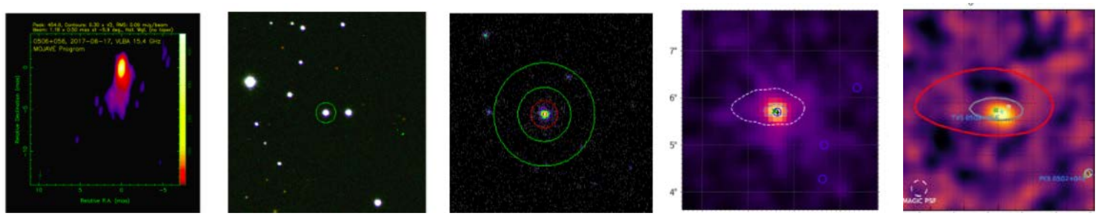
Magic telescope

...and many more telescope



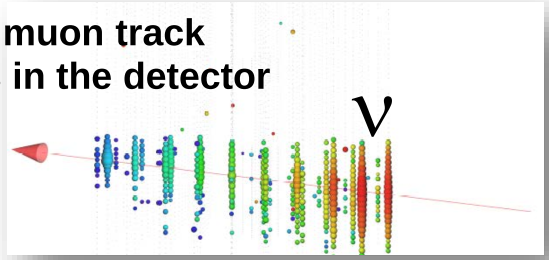
- **IceCube-170922A event**
- 2017/9/22 20:54:30.43 UTC
- 5th and the most cosmic neutrino signal like EHE alert
- automated alert was distributed to observers just 43 seconds later

Multiwavelength Campaign with ν

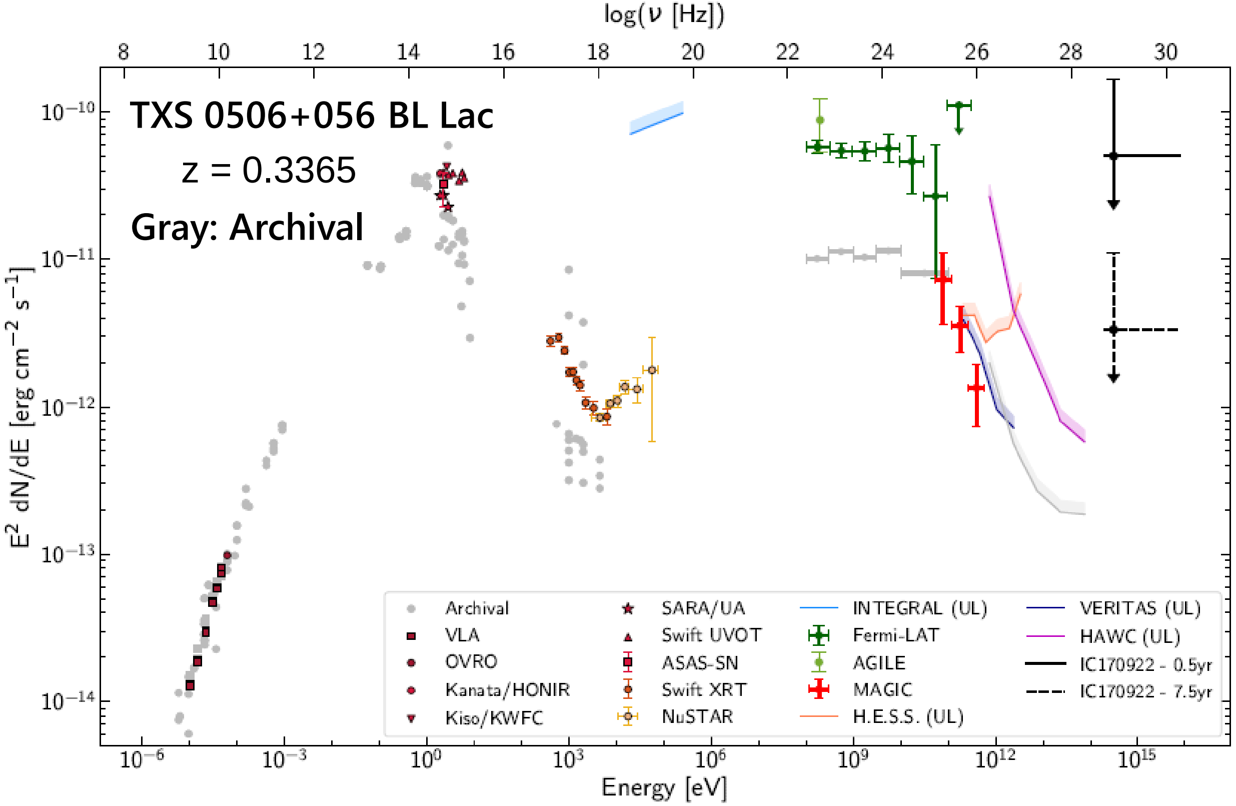


radio optical x-ray γ-ray

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

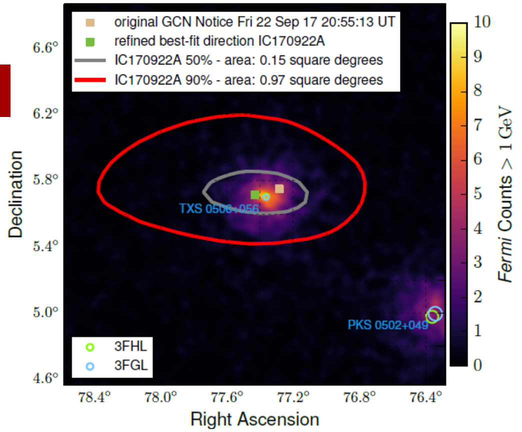


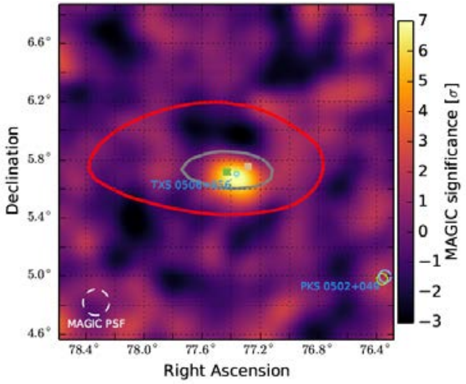
2018



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

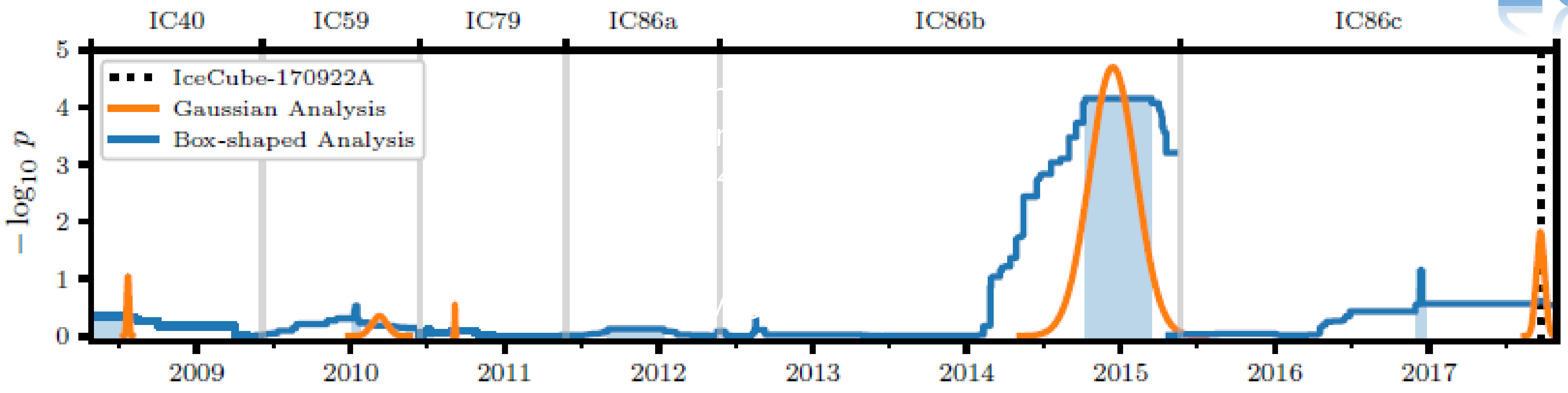
Science

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

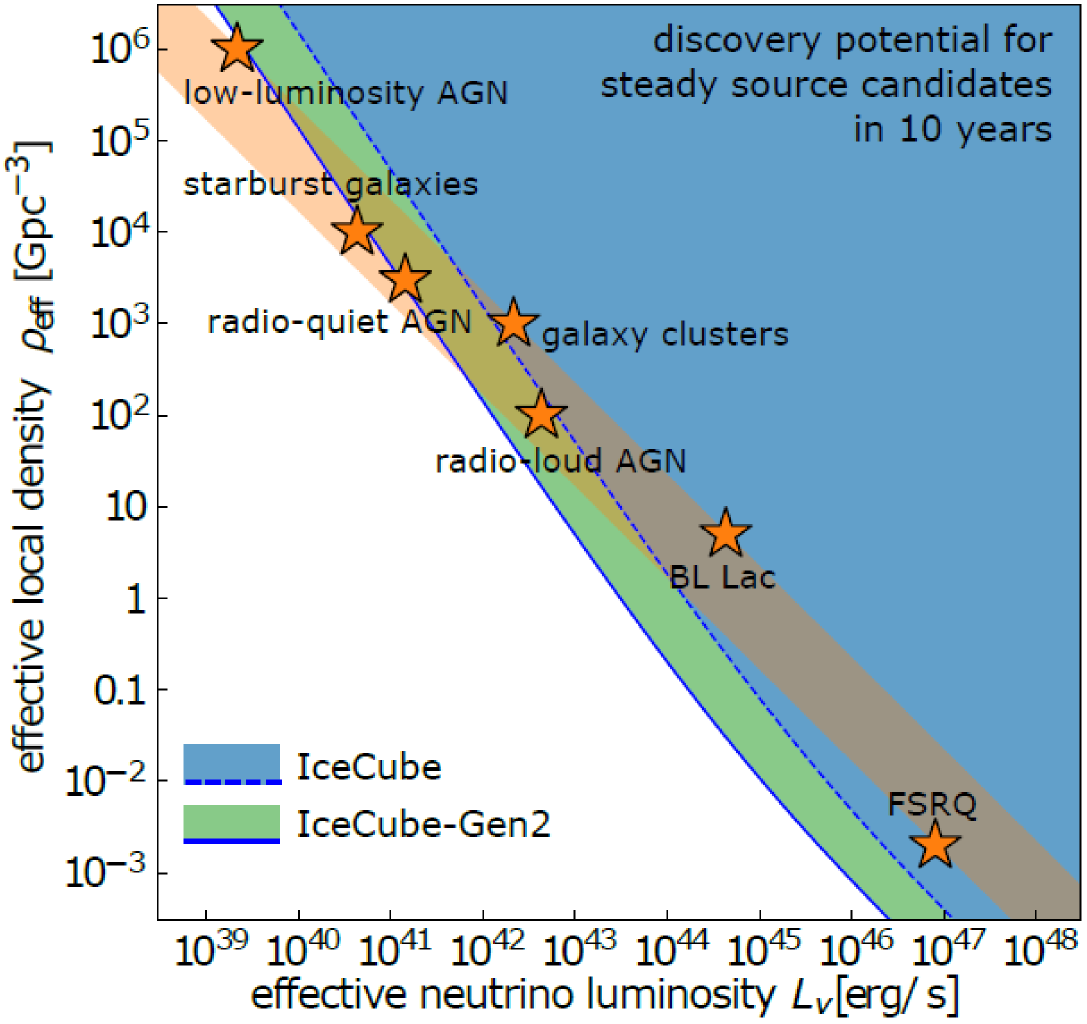


- neutrino only time dependent search around the blazar TXS 0506−056

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

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

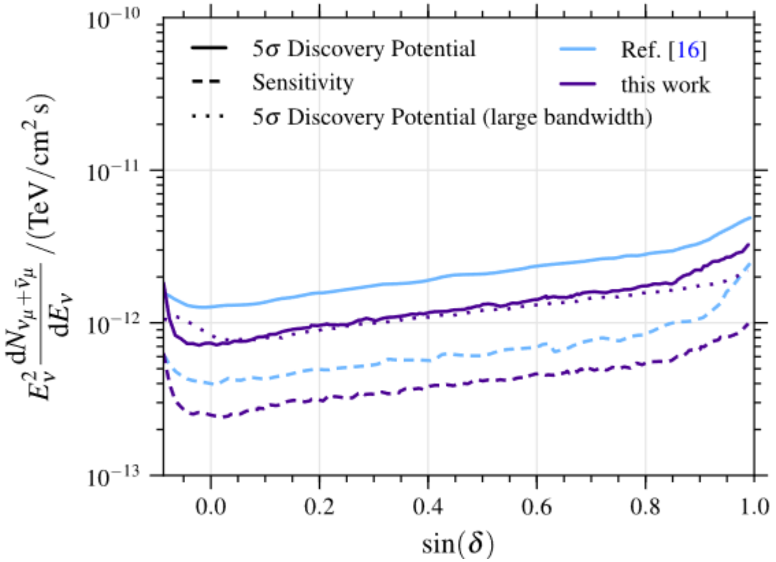
Neutrino emitting steady source candidates



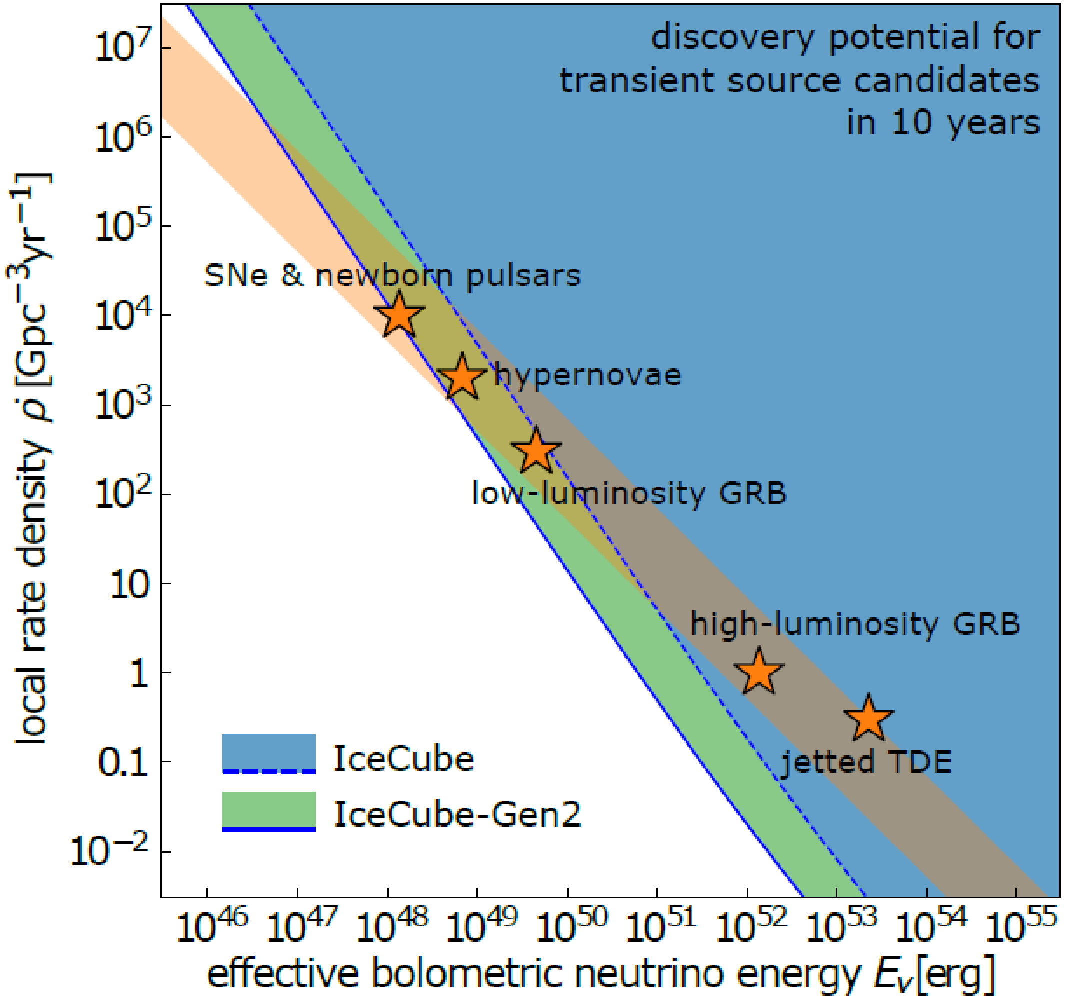
$$\phi_{diff} = \frac{\Delta\Omega}{4\pi}\int dV \left(\frac{L_\nu^{PS}}{4\pi d_z^2}\right)\rho_{eff}(1+z)^3\Psi(z)$$

一方、各天体から期待できるニュートリノの数

$$N_{PS} = T_{observation}\int d\Omega_{PS}\int dE\, A_{eff}\left(\frac{L_\nu^{PS}}{4\pi d_z^2}\right)$$



Neutrino emitting transient source candidates



$$\phi_{diff} = \frac{\Delta\Omega}{4\pi}\int dV \left(\frac{E_\nu^{PS}/\Delta T_{emission}}{4\pi d_z^2}\right)\dot{\rho}_{eff}\Delta T_{emission}(1+z)^3\Psi(z)$$

一方、各突発天体から期待できるニュートリノの数

$$N_{PS} = \Delta T_{emission}\int d\Omega_{PS}\int dE\, A_{eff}\left(\frac{E_\nu^{PS}/\Delta T_{emission}}{4\pi d_z^2}\right)$$

事象が観測されなければ流量に制限がつく

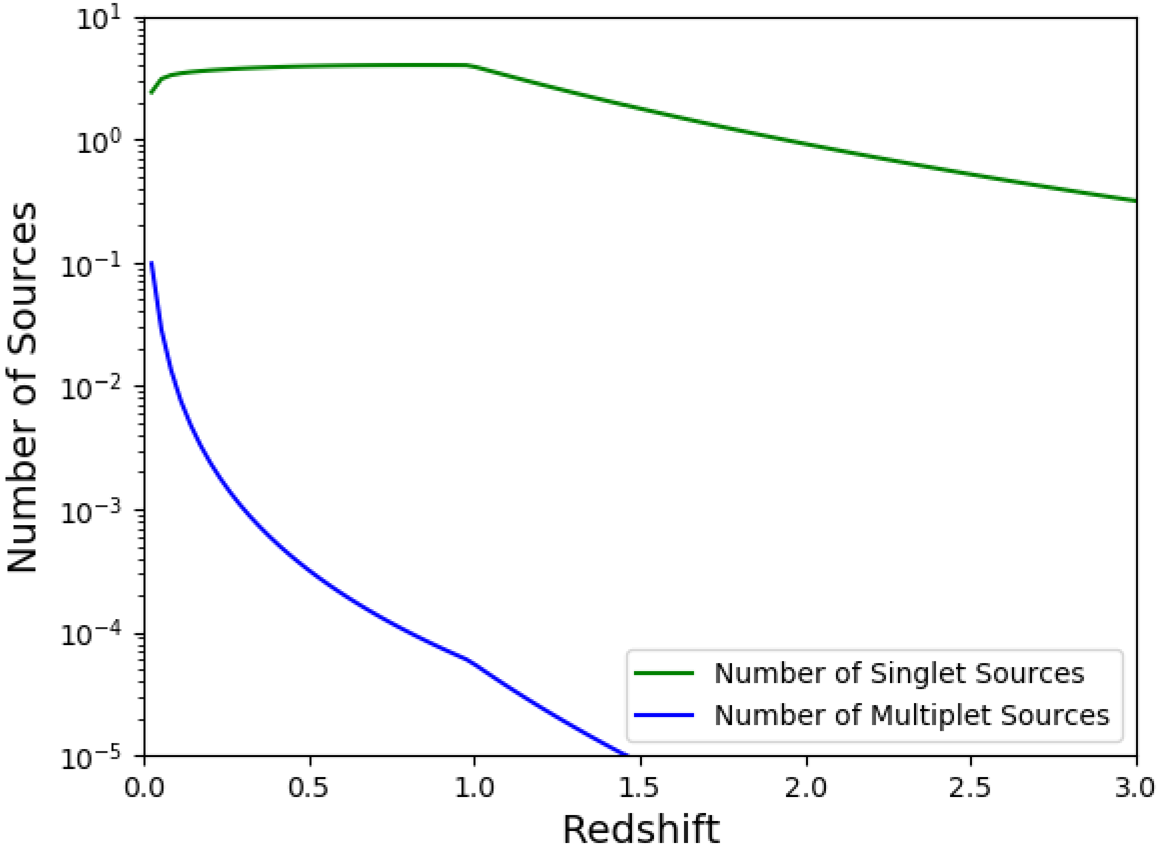
なぜ、ニュートリノ事象のカウンターパート探しが難しいか…
ニュートリノが非常に遠方からもやってこれるから!?

検出可能なニュートリノを放出する天体の分布

ν source distributions in the redshift space in $\Delta\Omega = \mathbf{2\pi}$

annual rate for $\boldsymbol{E_\nu^{PS}} = 3 \times 10^{49}\,\mathrm{erg}$

$\boldsymbol{\dot{\rho}_{eff}} = \mathbf{3 \times 10^3}\,Gpc^{-3}\,\mathrm{yr}^{-1}$



各transient天体からくるニュートリノの期待値

$$N_{PS} = \Delta T_{emission} \int d\Omega_{PS} \int dE\, A_{eff} \left(\frac{E_\nu^{PS} / \Delta T_{emission}}{4\pi d_z^2} \right)$$

この期待値のもとで、一つのニュートリノがIceCubeで観測可能される天体の数

$$N_{source}^{single} = \frac{\Delta\Omega}{4\pi} \int dV\, P_{n=1}^{poisson}(N_{PS}) \boldsymbol{\dot{\rho}_{eff} \Delta} T_{emission} (1+z)^3 \boldsymbol{\Psi(z)}$$

二つのニュートリノがIceCubeで観測可能な天体

$$N_{source}^{double} = \frac{\Delta\Omega}{4\pi} \int dV\, P_{n=2}^{poisson}(N_{PS}) \boldsymbol{\dot{\rho}_{eff} \Delta} T_{emission} (1+z)^3 \boldsymbol{\Psi(z)}$$

$\nu \to \gamma$ Follow up観測の発展に向けて

$\nu \otimes \nu$

- ニュートリノのみで点源を探す

$\gamma \to \nu$

- ニュートリノを放出し得る既知の天体の方向から来るニュートリノを探す

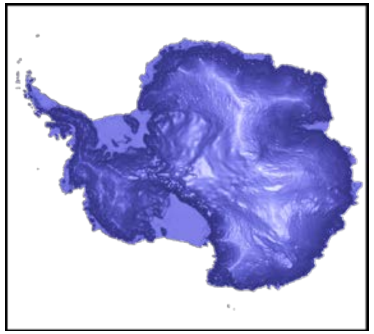
$\nu \to \gamma$

- ニュートリノが来た方向にある、最もニュートリノを放出し得る既知の天体を探す

- 複数のニュートリノ到来を知らせる速報システムを開発中
- 近傍天体にあるはずのカウンターパートに絞った探査が可能
- これにより、たくさんあるエラーサークルの中にたまたま入った天体を切り分ける
- ただし、期待できるそのような速報の数はまだ高くない

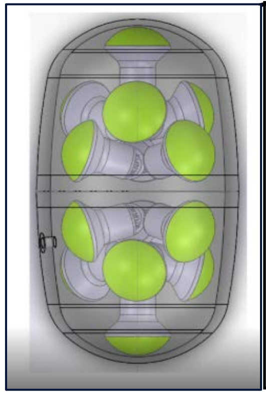
IceCube-Gen2 検出器

アムンゼンスコット南極点基地



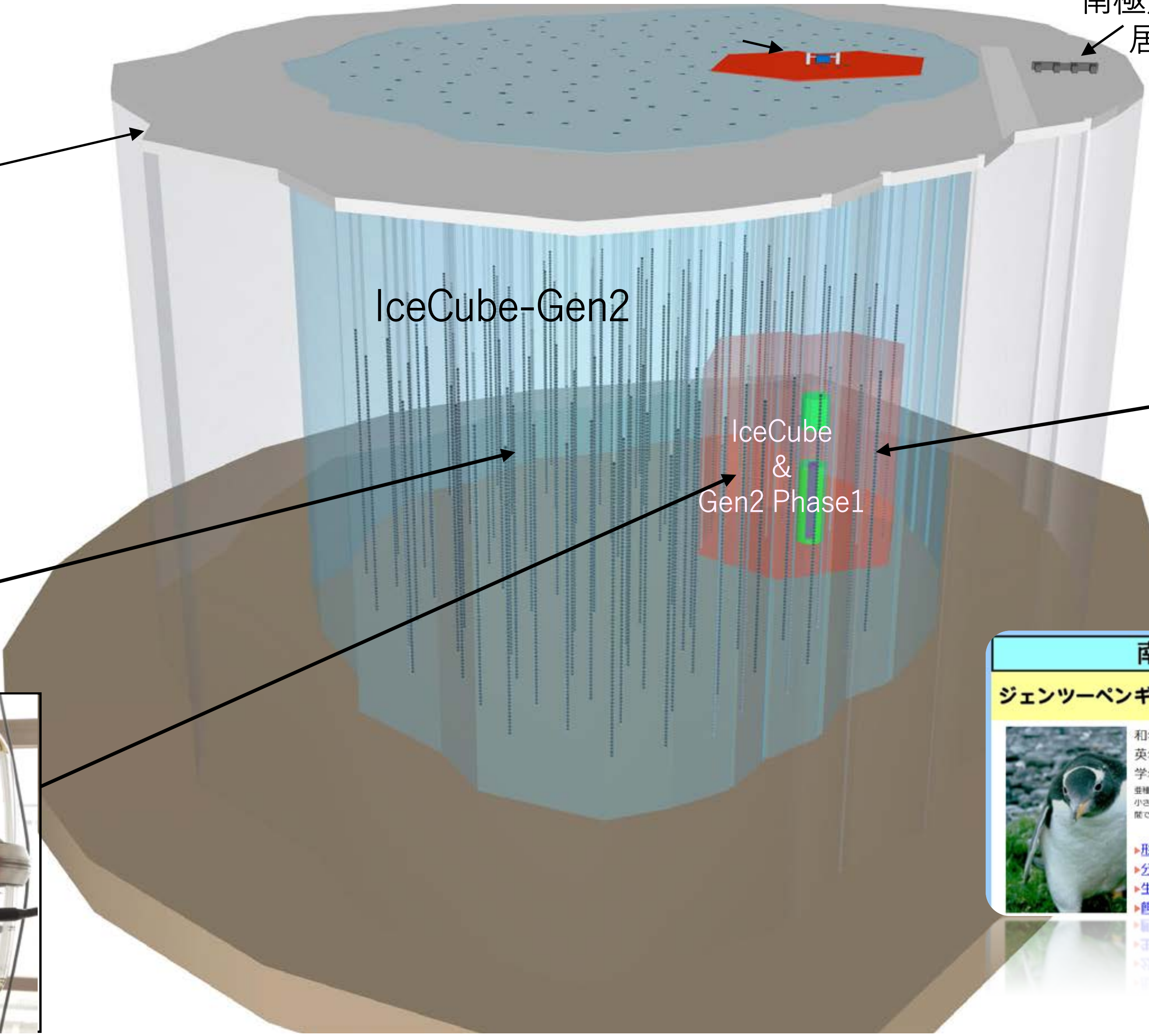
Gen2 Phase1長球型光検出器D-Egg
- 縦長で掘削費用および時間を大幅に削減

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

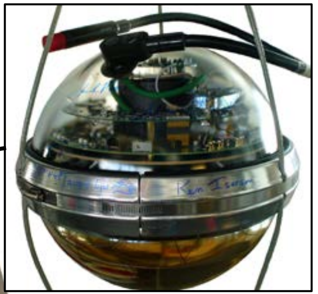


IceCubeコントロールルーム

南極点傍に立つ居住建屋



IceCube光検出器DOM



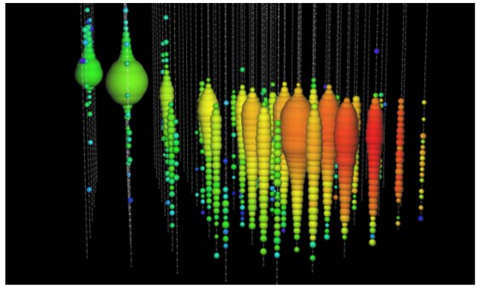

南極動物図鑑

ジェンツーペンギン Gentoo penguin

和名：ジェンツーペンギン（ゼンツーペンギン）
英名：Gentoo penguin
学名：*Pygoscelis papua*

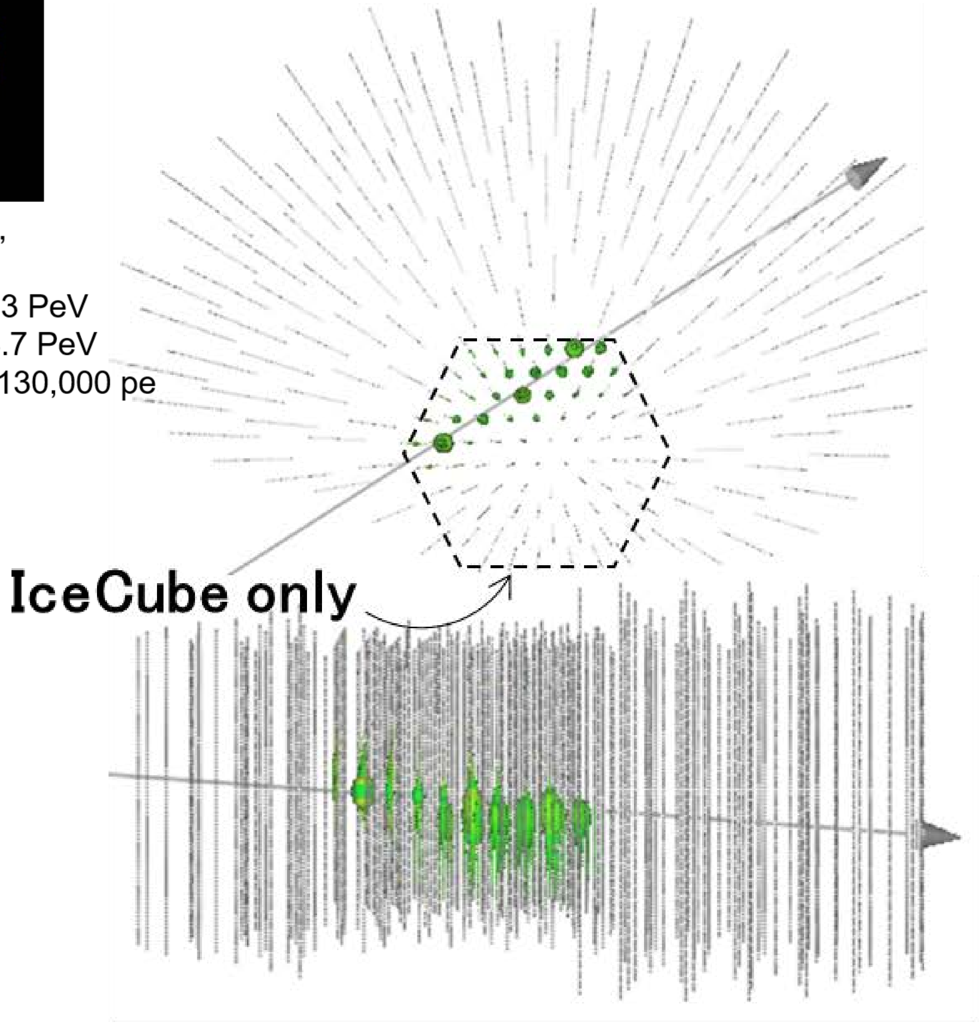
▸形態
▸分布
▸生息環境
▸餌と採餌行動

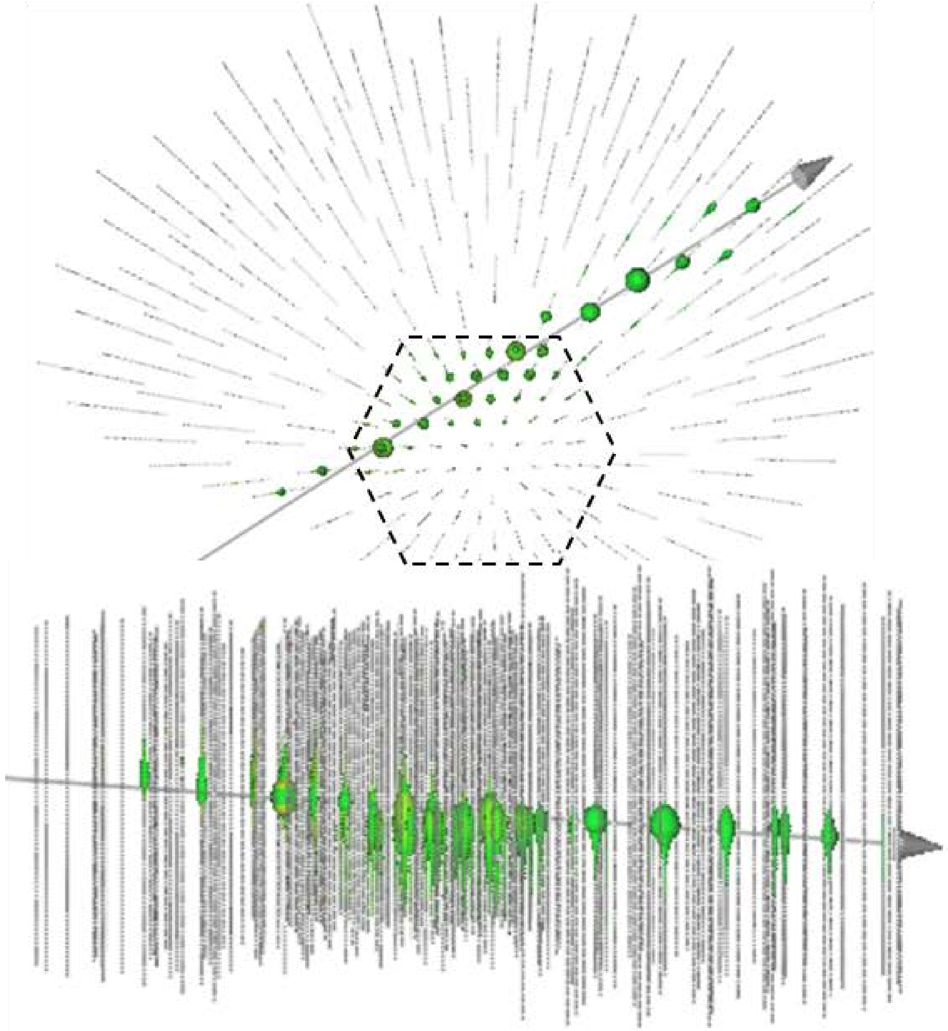
Angular resolution improvement with larger detector



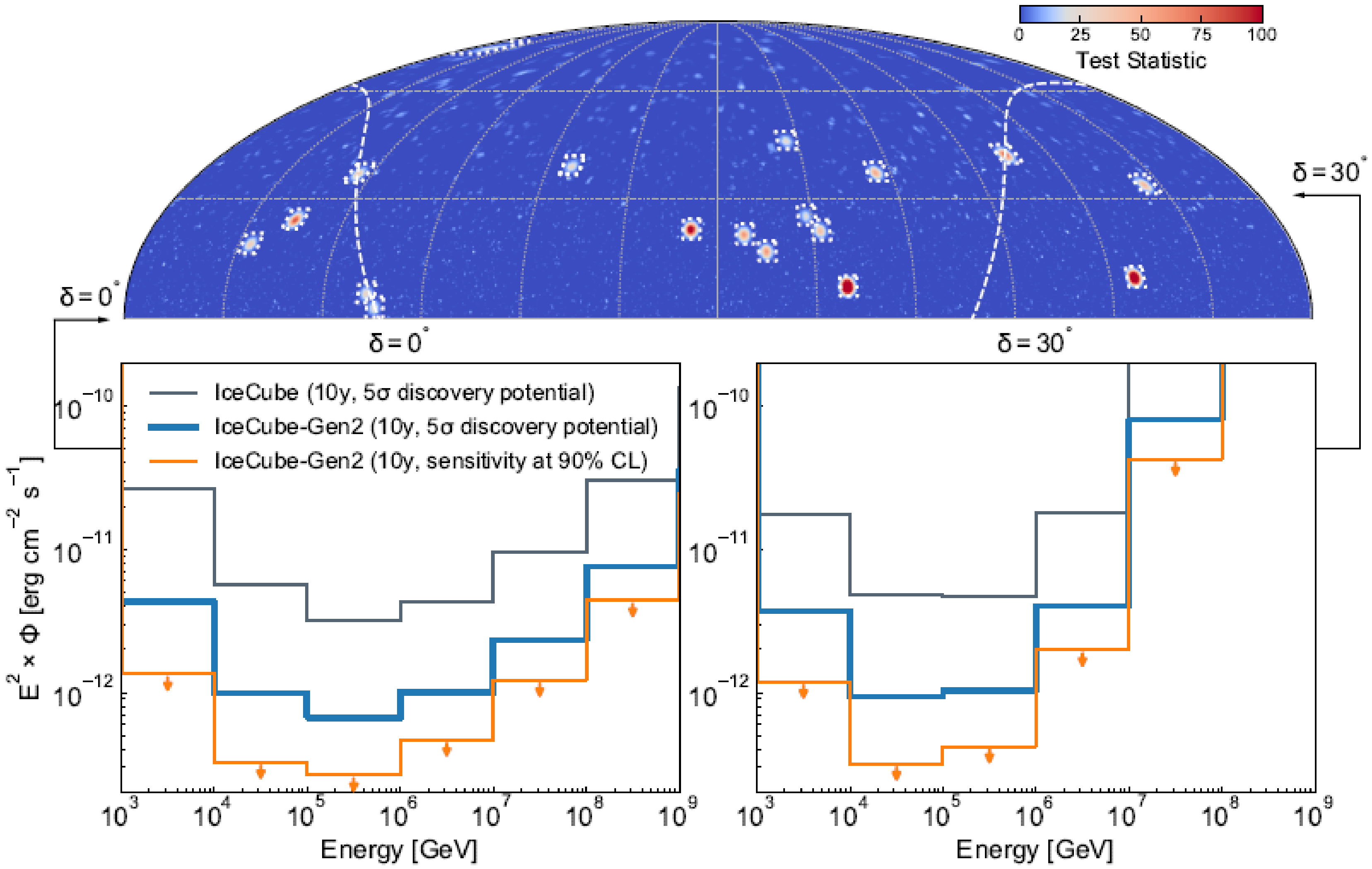
Highest energy event to date,
an upward-going track.

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

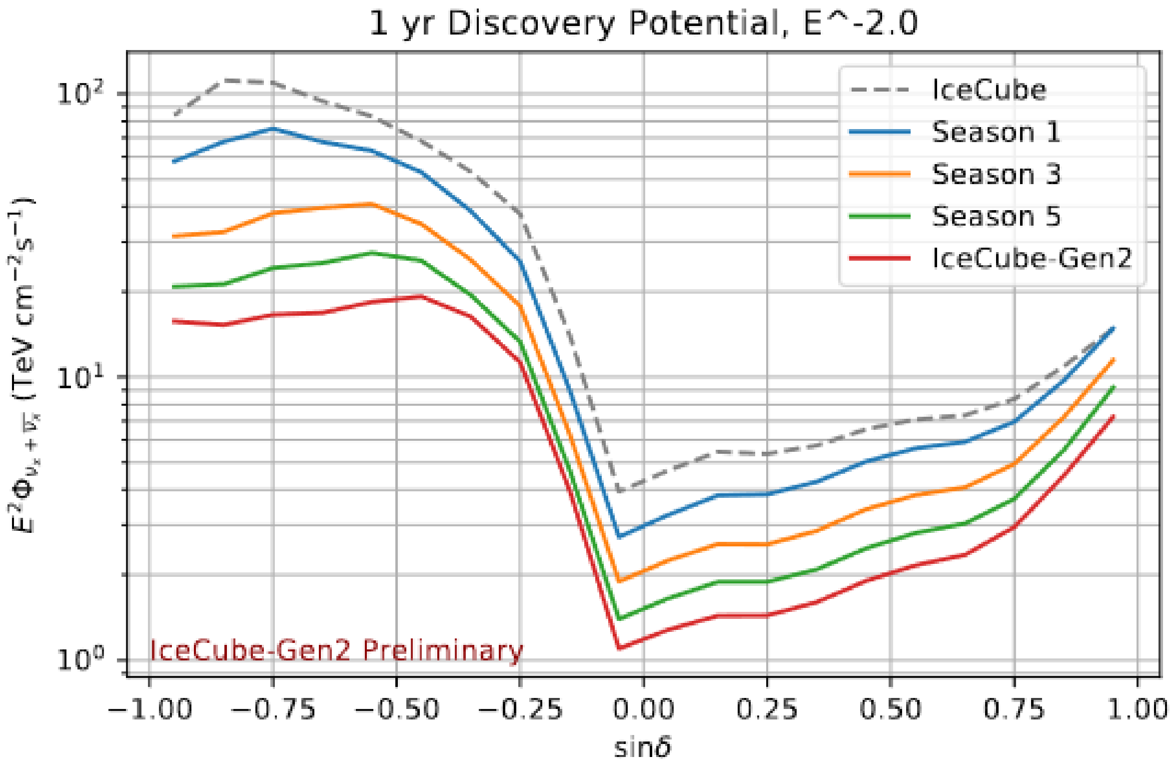


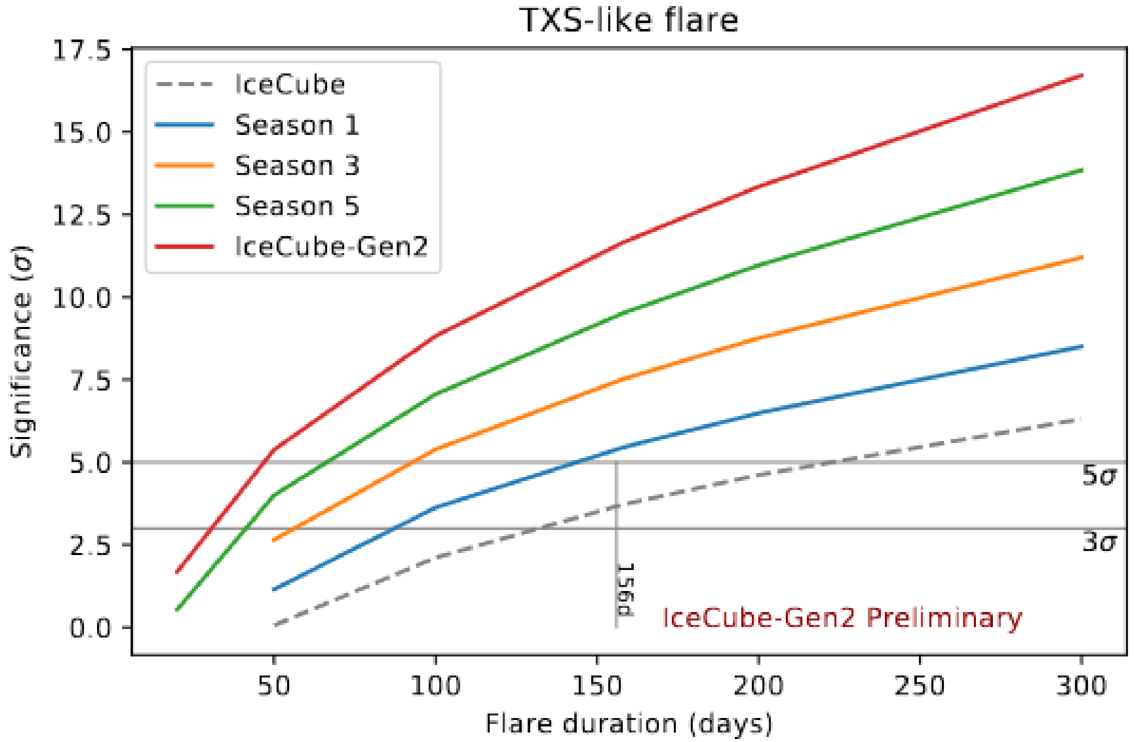


Expectation with more than 5 times better sensitivity



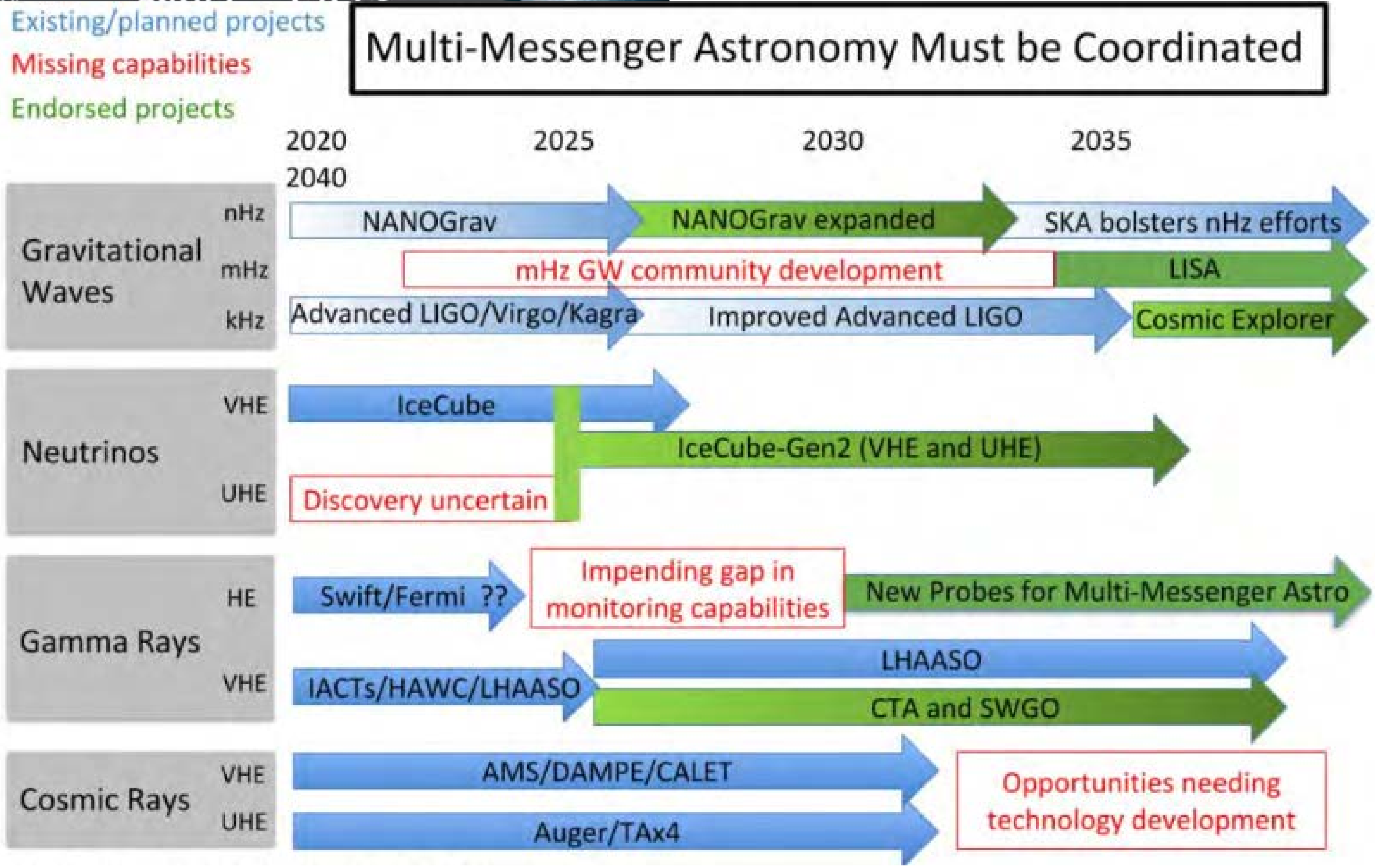
Intermediate sensitivities

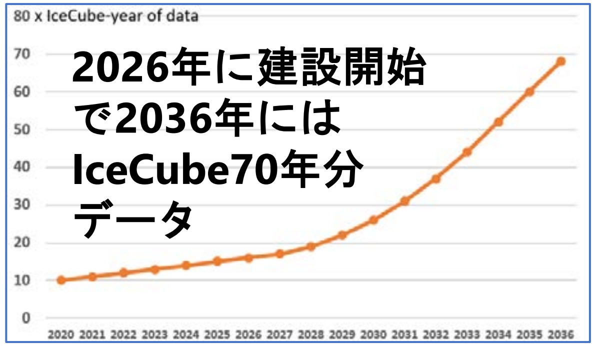




- Full sensitivity and good exposure is required for the detection of dimmer neutrino sources
- However for time-dependent flares such as TXS-like flare, deployment of first year or two, Gen2 becomes large enough to achieve 5σ *level* of observation
  - Partial construction is still valuable for time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

In Astro2020 decadal survey





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
- **Diffuse**ニュートリノの流量を確立
- これまでに知られているガンマ線放出天体が恒常的ニュートリノ点源として見え始めており、**10**年分のデータがすでにパブリックになっている
- 南極点でニュートリノ事象を識別するオンライン速報から、ニュートリノ事象と望遠鏡信号との相関がみつかった
- 新たに近傍天体にフォーカスしたアラートチャンネルを開発中

手法は確立しつつある。さらに高統計・**high quality**データによる拡張計画が必須！

- 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
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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
Technische Universität Dortmund
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University of Kansas
University of Maryland
University of Rochester
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University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
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Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

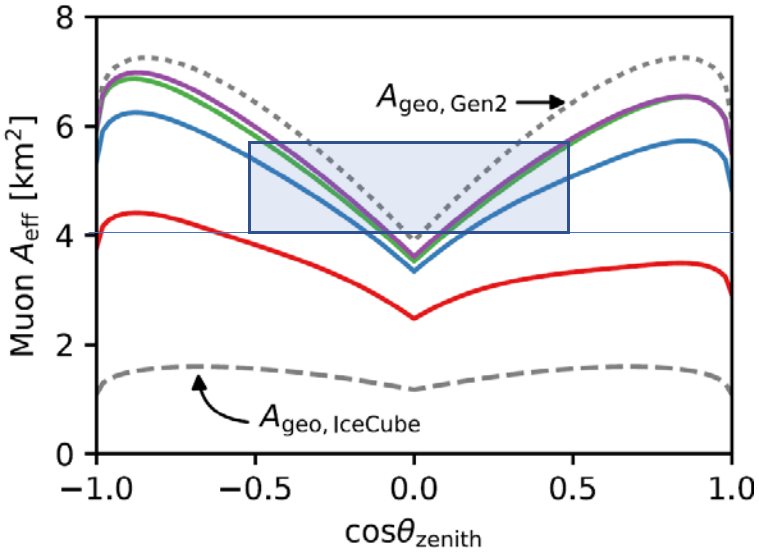
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

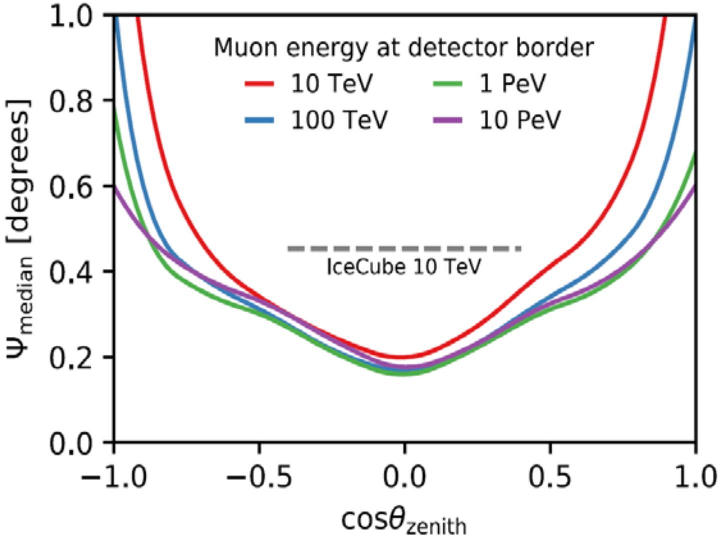

WISCONSIN

Backup

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

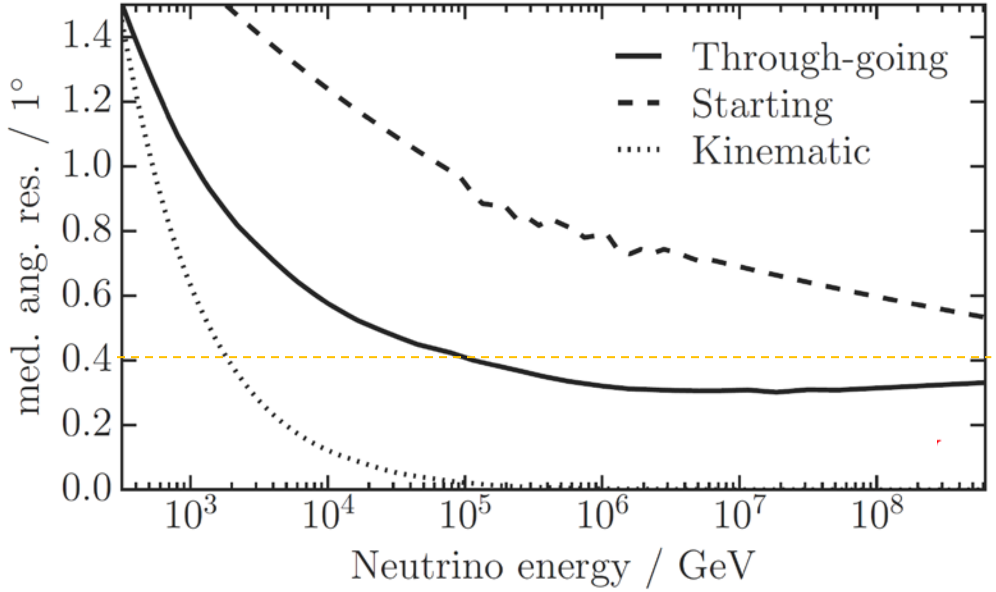
- **improvement with new optical sensors**
- **improvement with new calibration**

Additional improvements

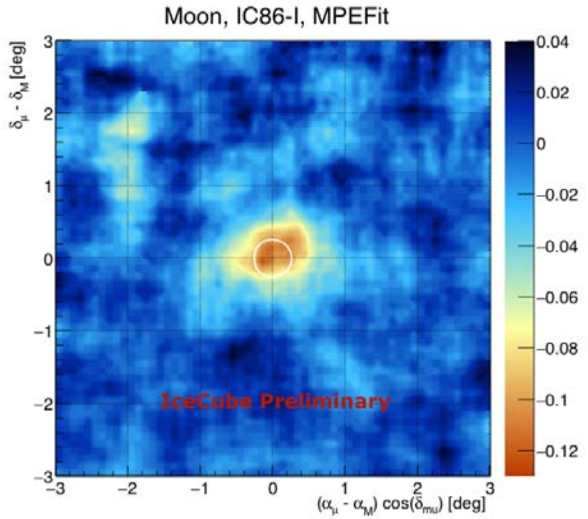
Tracks: induced by ν_μ CC interaction

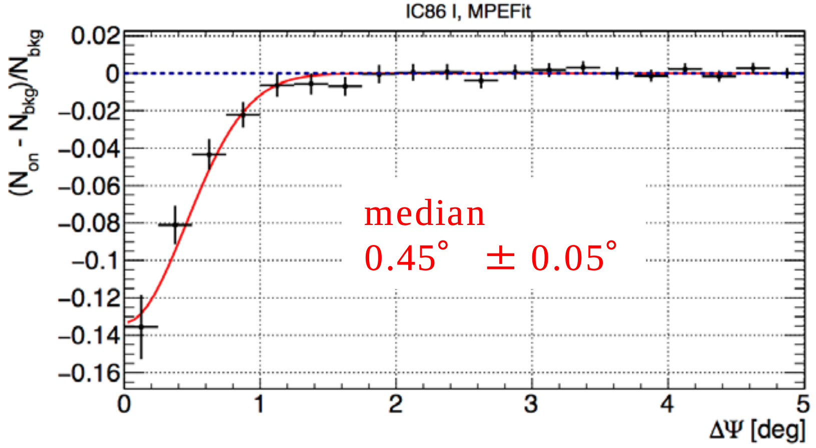
Angular resolution

Median resolution: 0.4° (> 100 TeV)



Moon shadow of cosmic ray muons using one year of data
(cosmic-ray primaries get absorbed in moon)





Large energy resolution for through going-muon as muon loose energy before arrival

- Δlog(E)~0.3 for muon energy deposit to muon energy

Information

IceCube-Gen2 Technical paper is upcoming the next!

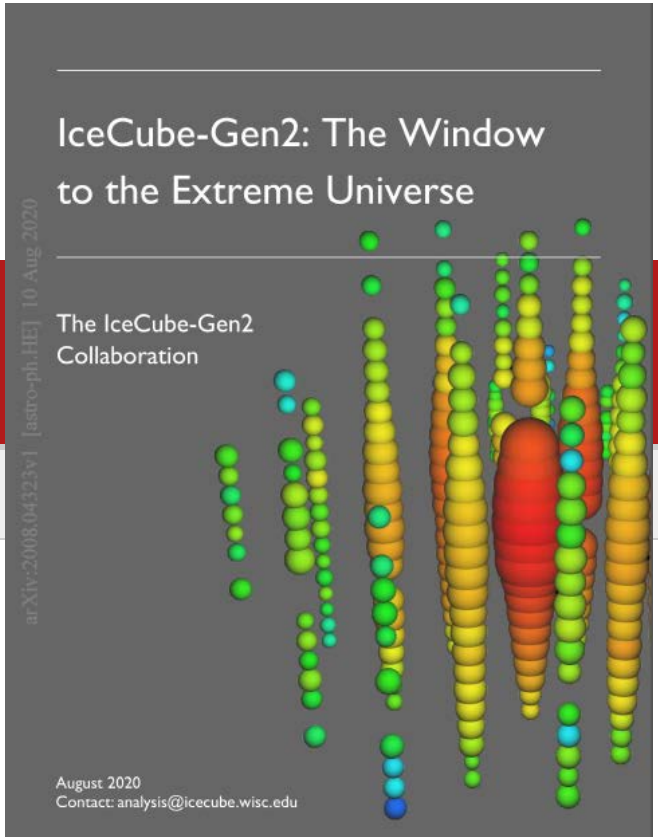
arXiv.org > astro-ph > arXiv:2008.04323

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