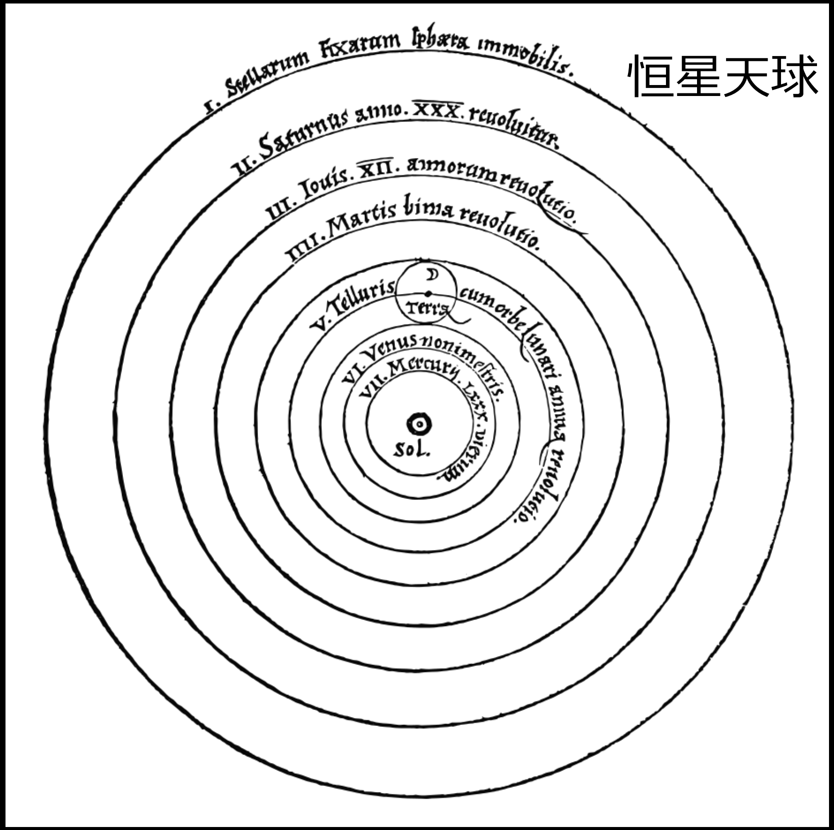
ニュートリノで探る高エネルギー宇宙

千葉大学 ハドロン宇宙国際研究センター
石原 安野

2021年度(第67回) 仁科記念講演会(ニュートリノ物理と宇宙)　2021年12月４日

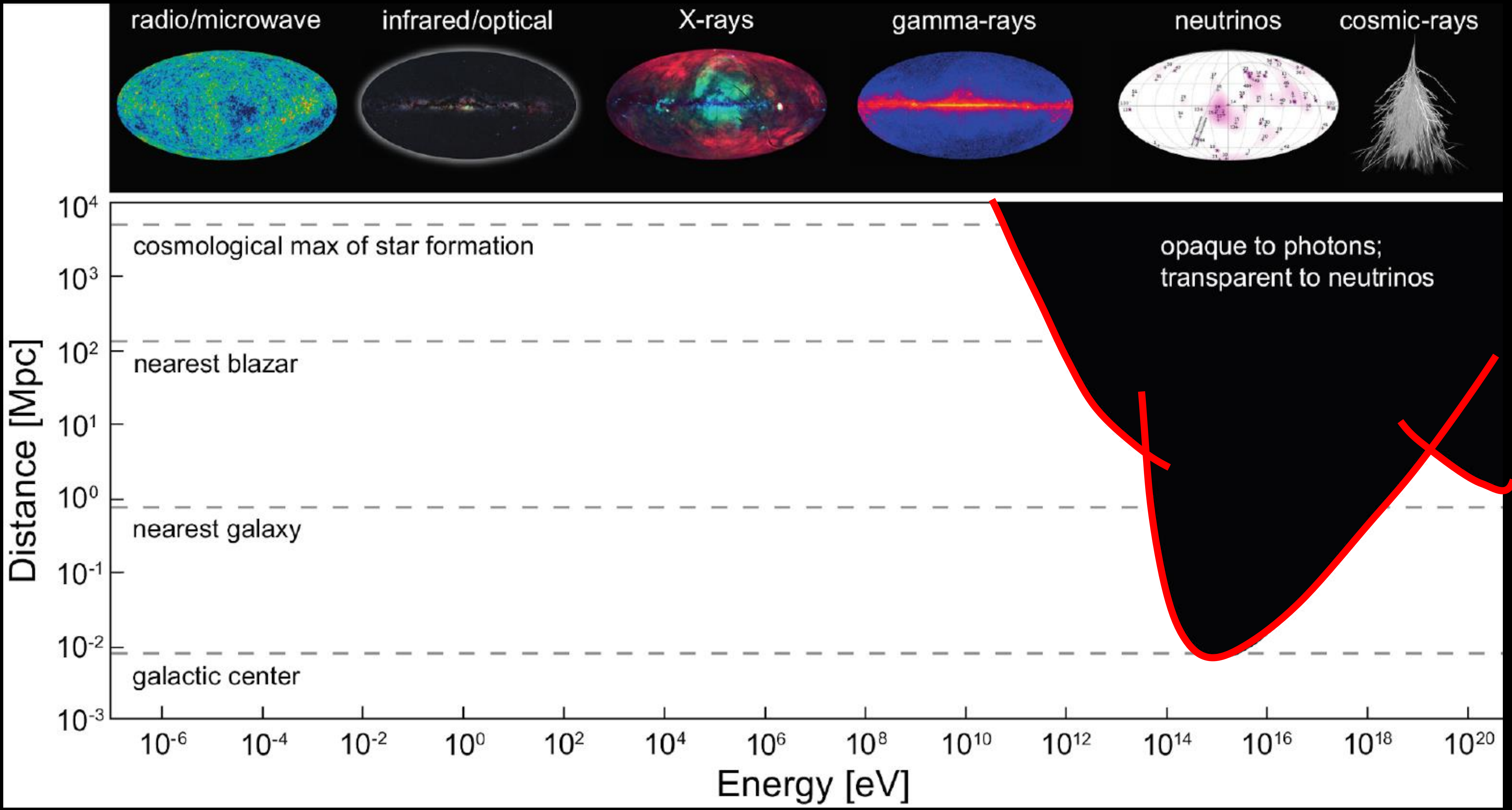


De revolutionibus orbium coelestium
Nicolaus Copernicus (1543)

A Perfit Description of the Celestiall Orbs
Thomas Digges (1576)

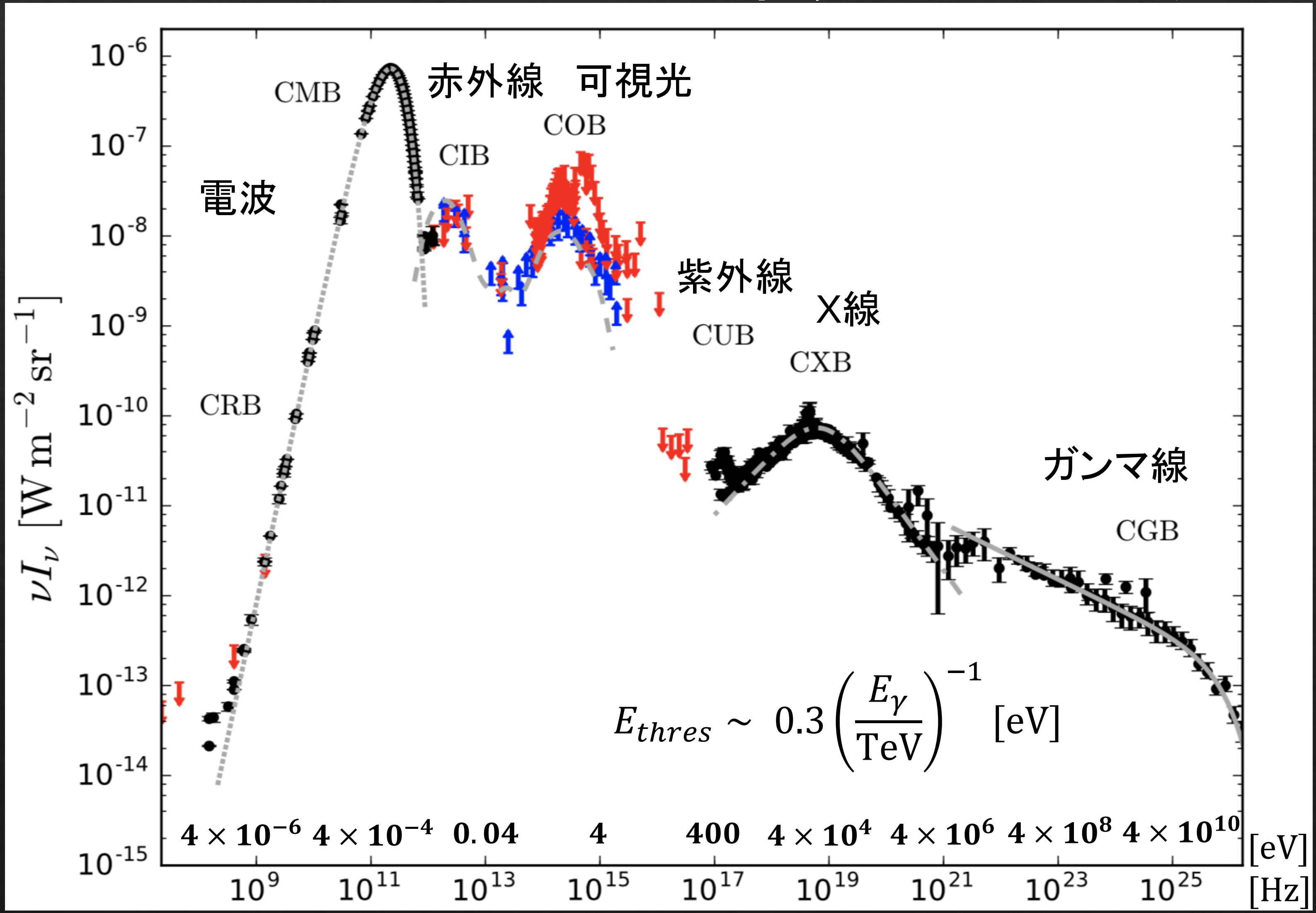
CCD/CMOS 400-700nm
1.8-3.8eV

Martin Wolf, IceCube/NSF


radio/microwave
infrared/optical
X-rays
gamma-rays
neutrinos
cosmic-rays
opaque to photons;
transparent to neutrinos
cosmological max of star formation
nearest blazar
nearest galaxy
galactic center
Distance [Mpc]
Energy [eV]

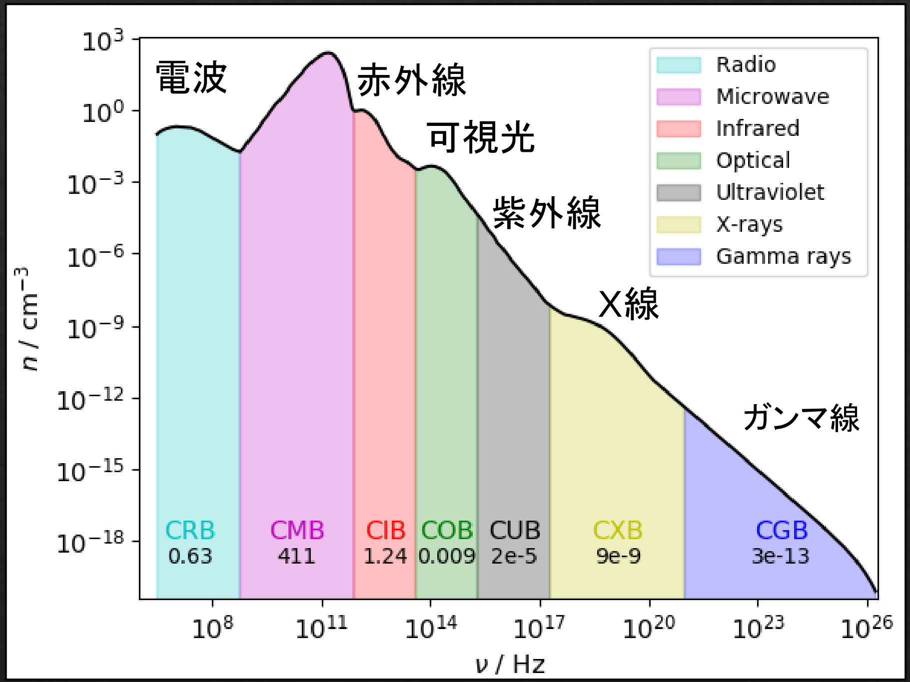
宇宙全体を満たす背景輻射

100PeV 1PeV 10TeV 100GeV 対応光子ビームのエネルギー



The Spectrum of the Universe (R. Hill et al 2018)

- 宇宙背景放射の中でもビッグバンの名残である宇宙マイクロ波背景放射は特に有名である
- しかし，宇宙はマイクロ波だけでなく，電波，赤外線，可視光，X 線そしてガンマ線で満たされている
- この微弱ながらも空一面に光っている放射は、「宇宙背景放射」と呼ばれている

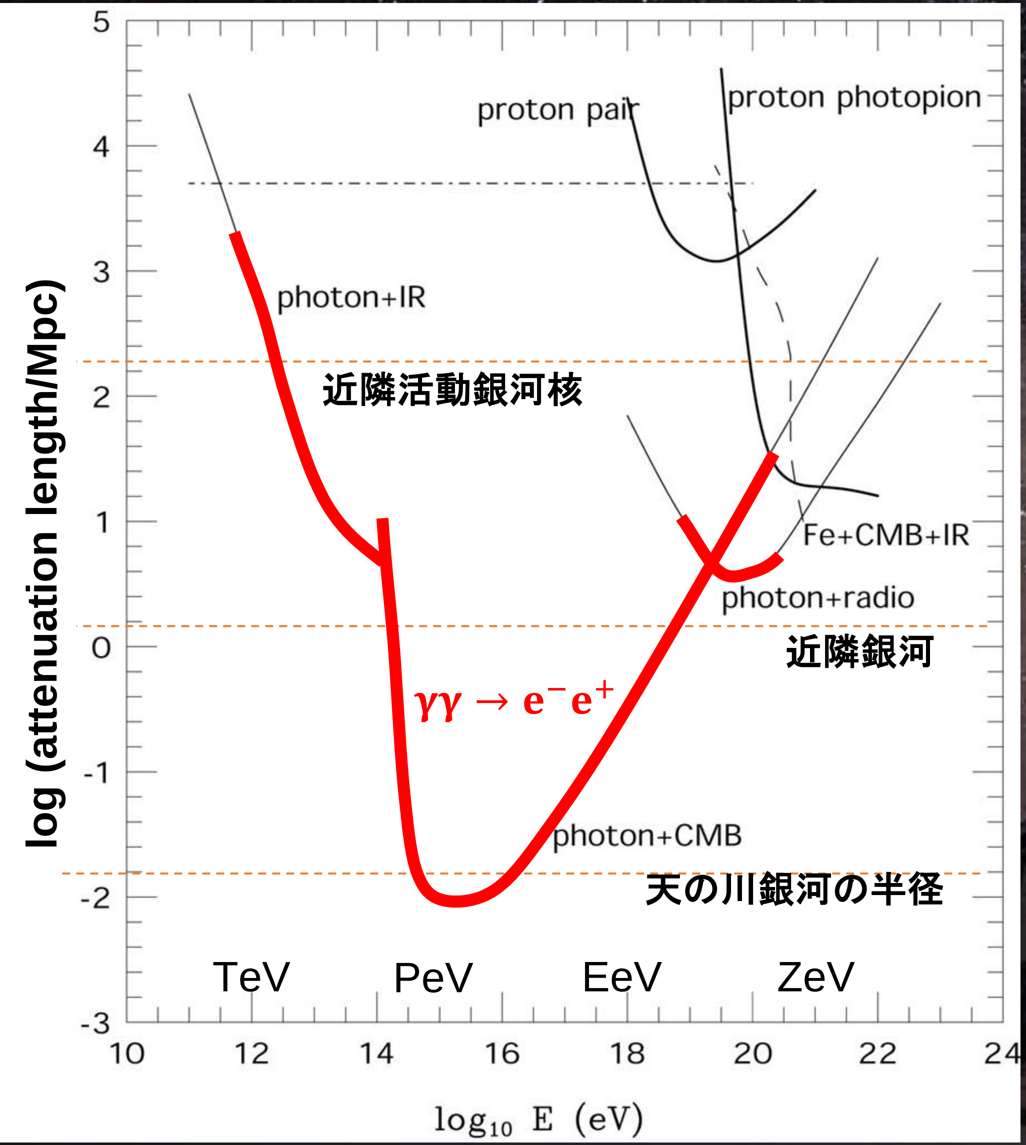


光子密度をnとすると

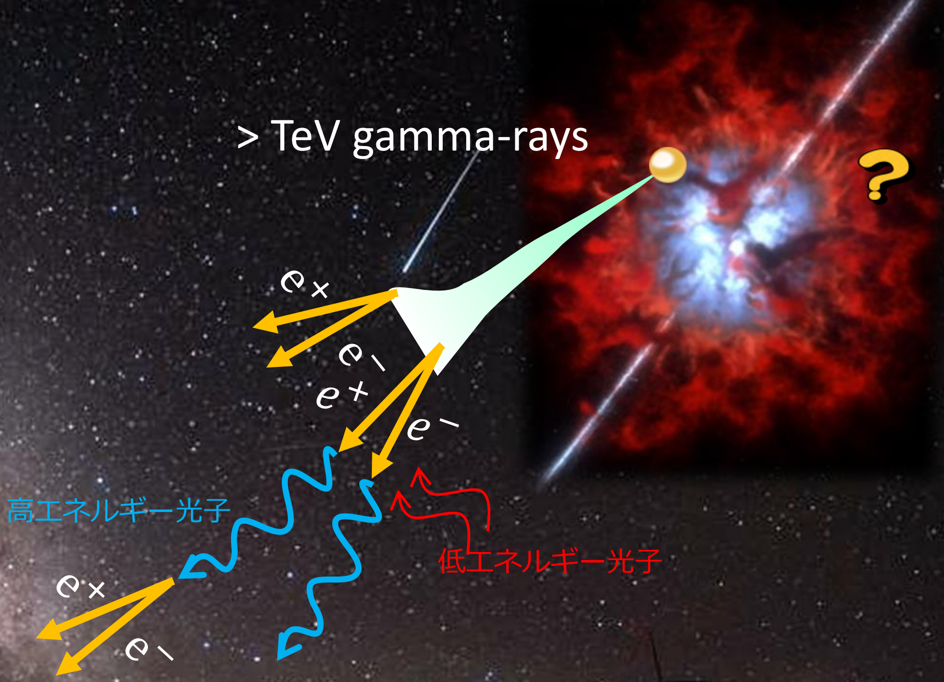
$$\ell_{\gamma\gamma} \sim \frac{1}{\sigma_T n} \sim 40\mathrm{Mpc}\left(\frac{n}{10^{-2}cm^{-3}}\right)^{-1}$$

Tevatron, Pevatron, EeVatron, ZeVatron

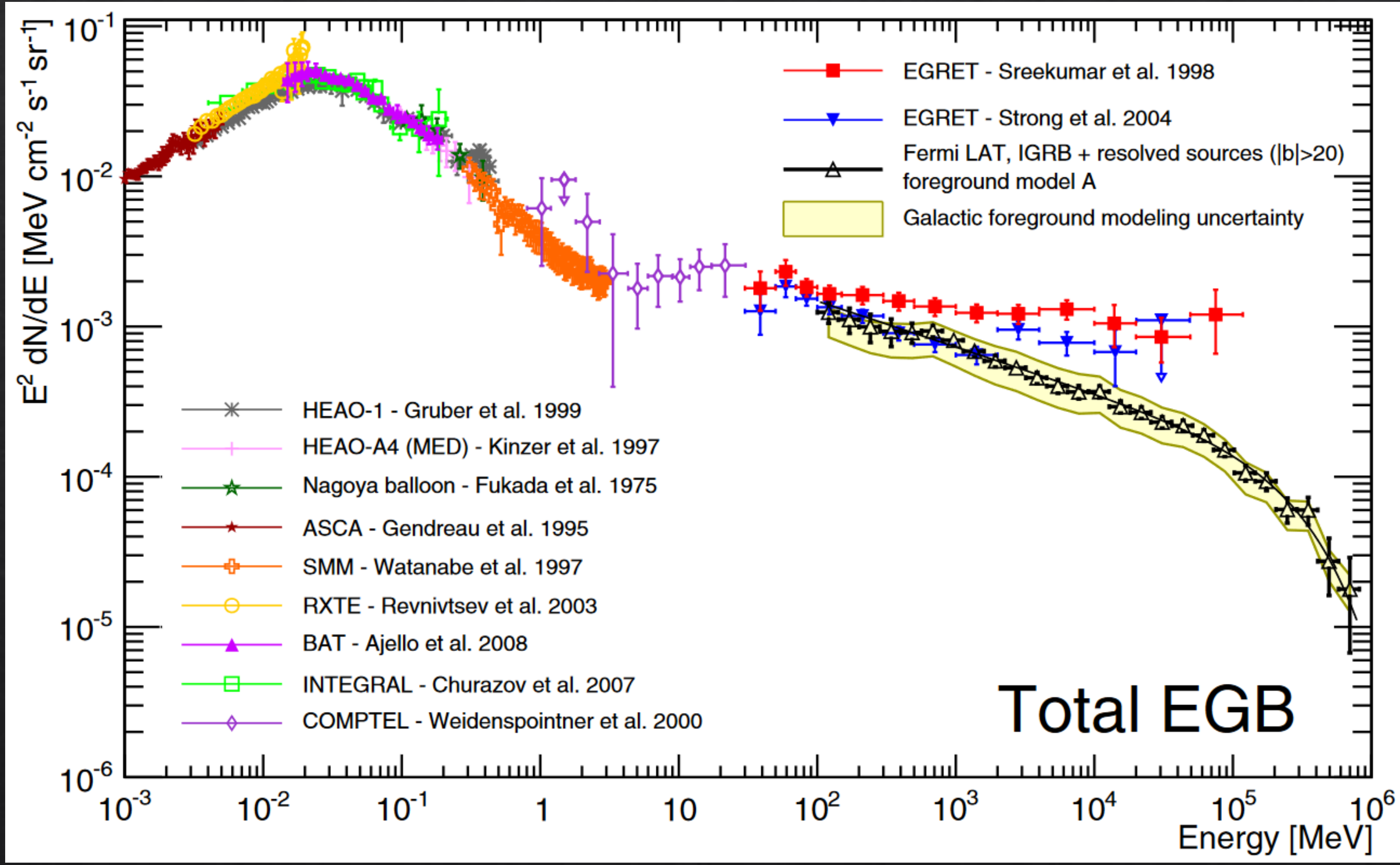
1Parsec(pc) = 3.26 light years



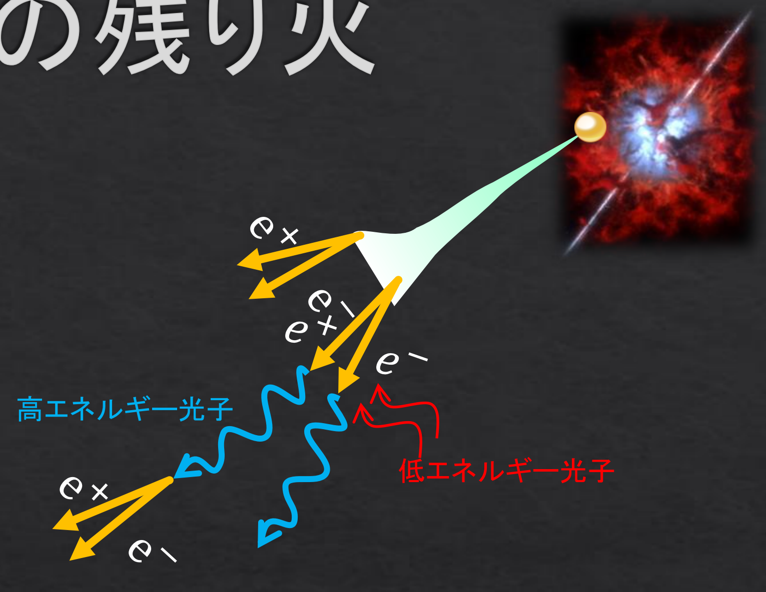
Anchordoqui+
hep-ph/0206072v3



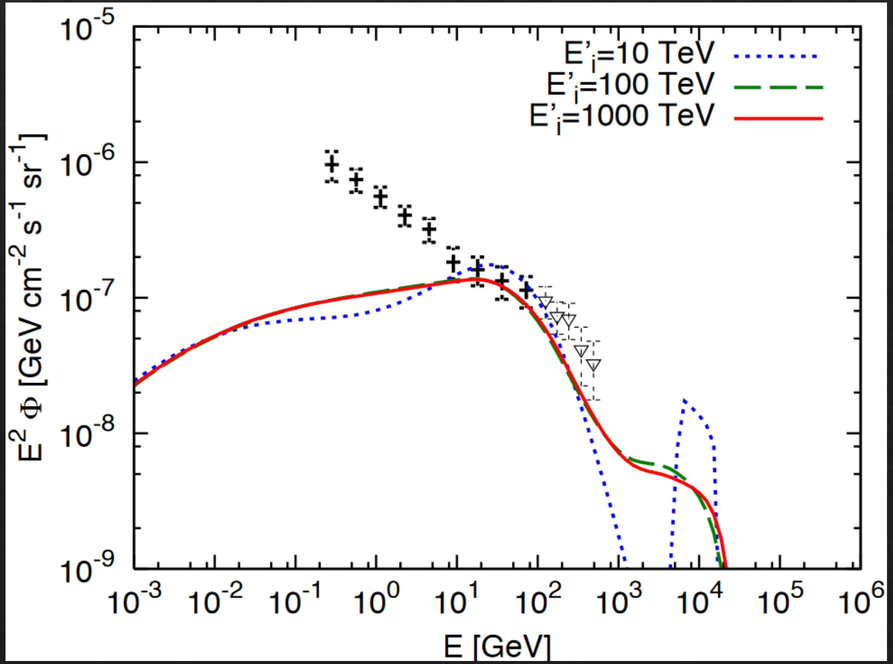
遠方高エネルギーガンマ線の残り火



M. Ackermann et al 2015 ApJ 799 86

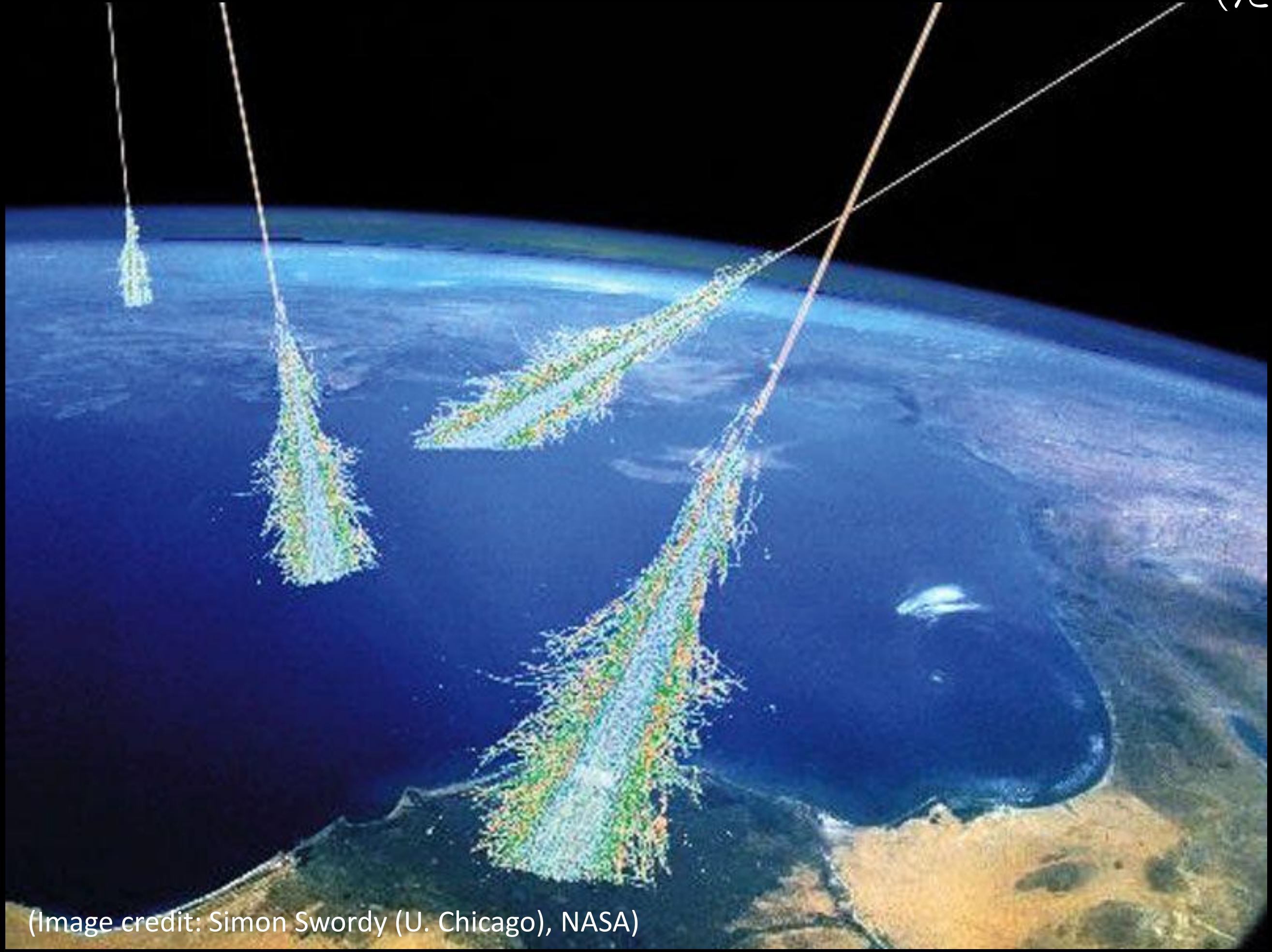


Murase *et al* JCAP08(2012)030



見えない宇宙には何が隠されているのか？

地球上で可視光の持つエネルギーの10^{20}倍ものエネルギーを持つ粒子が観測されている
（ただし、100平方キロメートルで一年観測して一回より少ない）



(Image credit: Simon Swordy (U. Chicago), NASA)

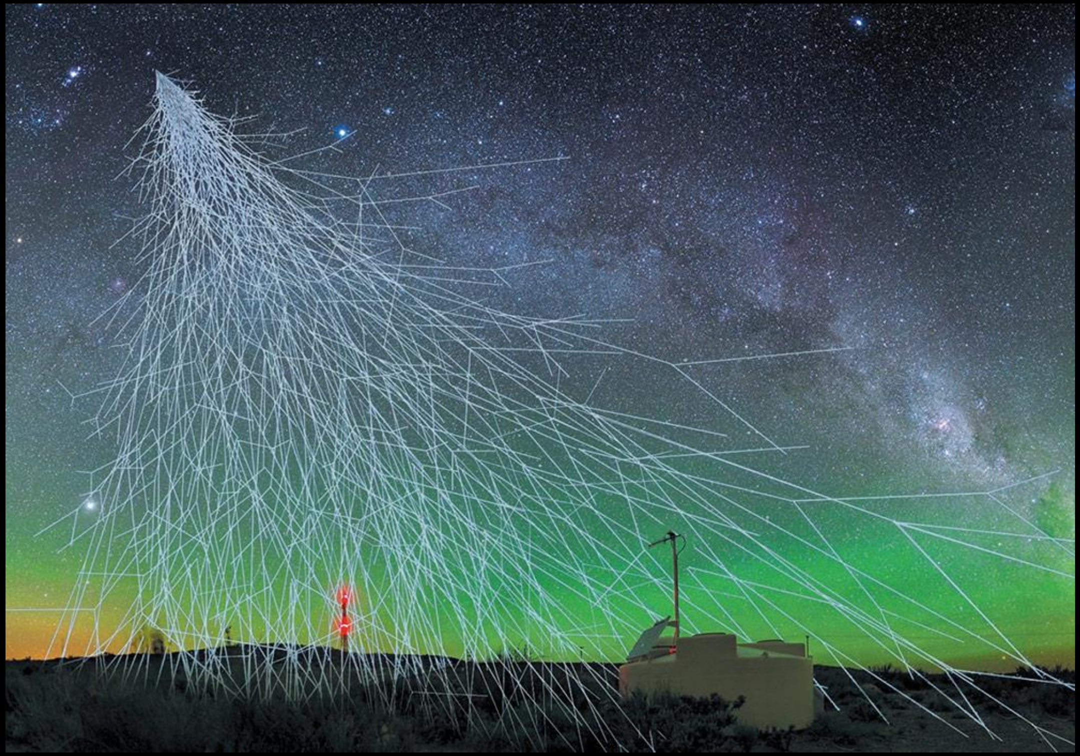


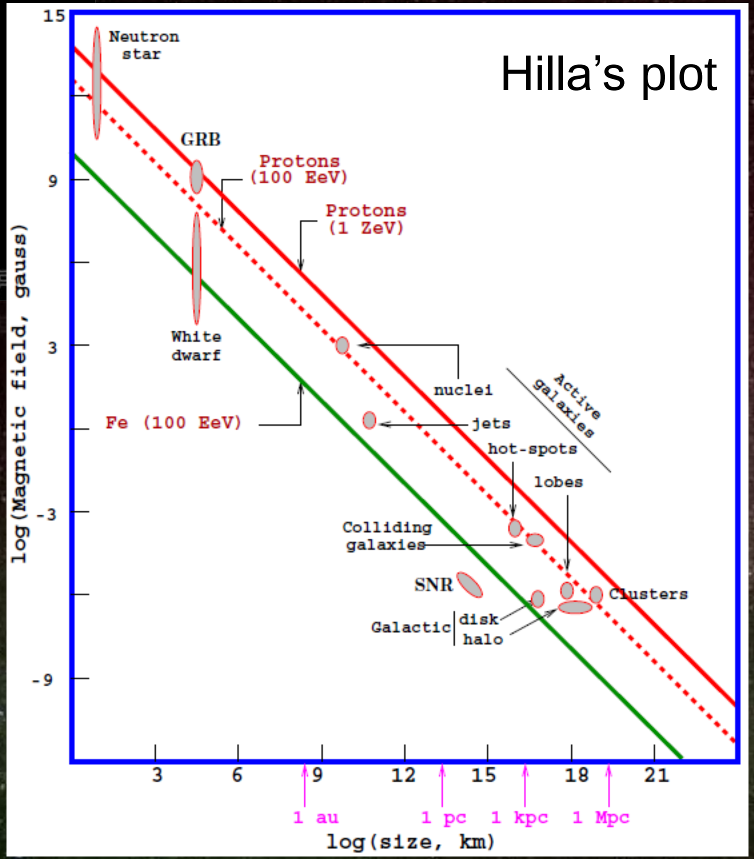
Image credit: A. Chantelauze / S. Staffi / L. Bret / Pierre Auger Observatory

見えない宇宙には何が隠されているのか？

宇宙で最も高いエネルギーを持つ粒子はどこから来ているのか

- **遠方**宇宙から飛来している
- 候補天体は大きいか磁場が強いかその両方かが必要

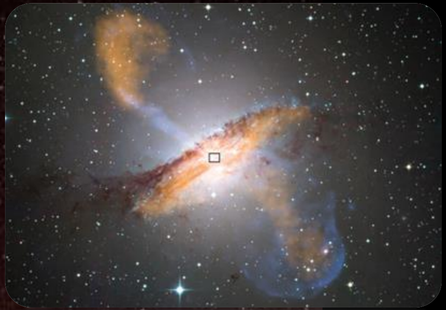
ガンマ線爆発



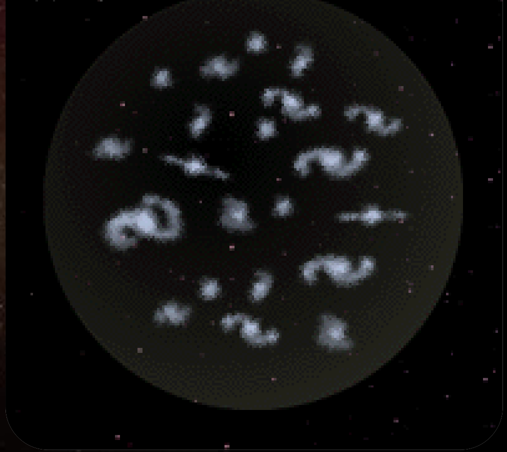
$E(\mathrm{EeV})$
$\sim Z B_{\mu G} R_{kpc}$

drawn by Murat Boratav

活動銀河核



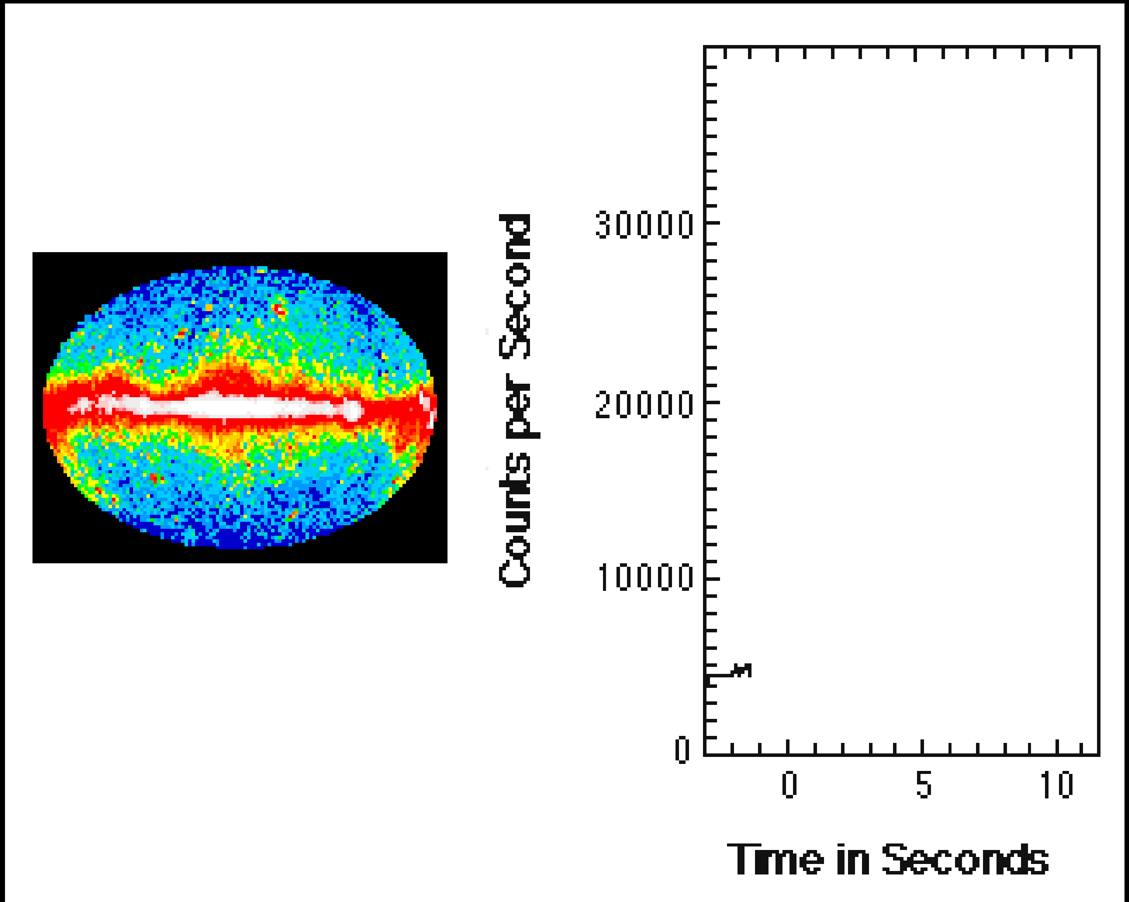
銀河団



ガンマ線バースト (そのほか重力崩壊型爆発)

ハイパーノバ　>　スーパーノバ

Credits: NASA, ESA and M. Kornmesser



A GRB detected by BATSE (from https://www.swift.ac.uk/)

活動銀河核

(クエーサー、セイファート銀河、ブレーザー)

高速粒子の流れ

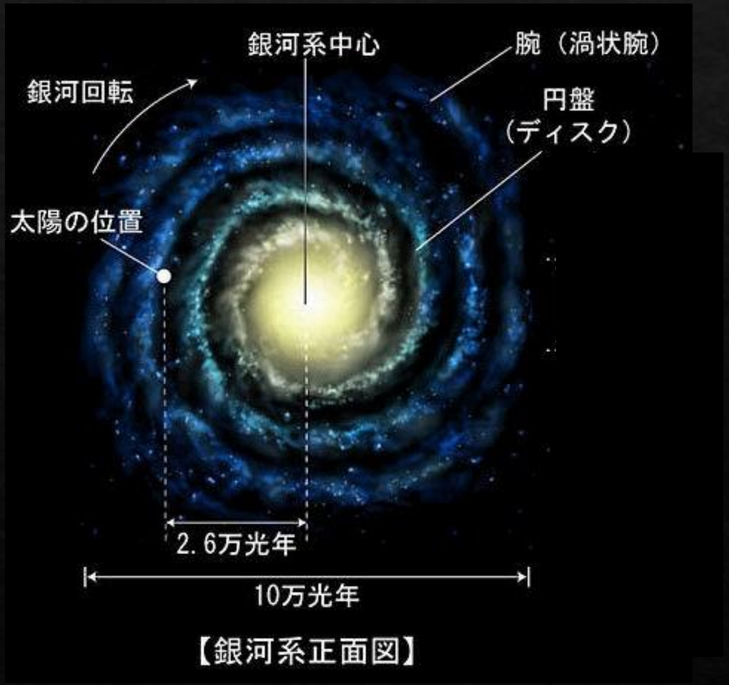
活動銀河核:中心に巨大ブラックホールを抱える遠方銀河

ブラックホール:太陽の10億倍質量　BHからの重力による運動

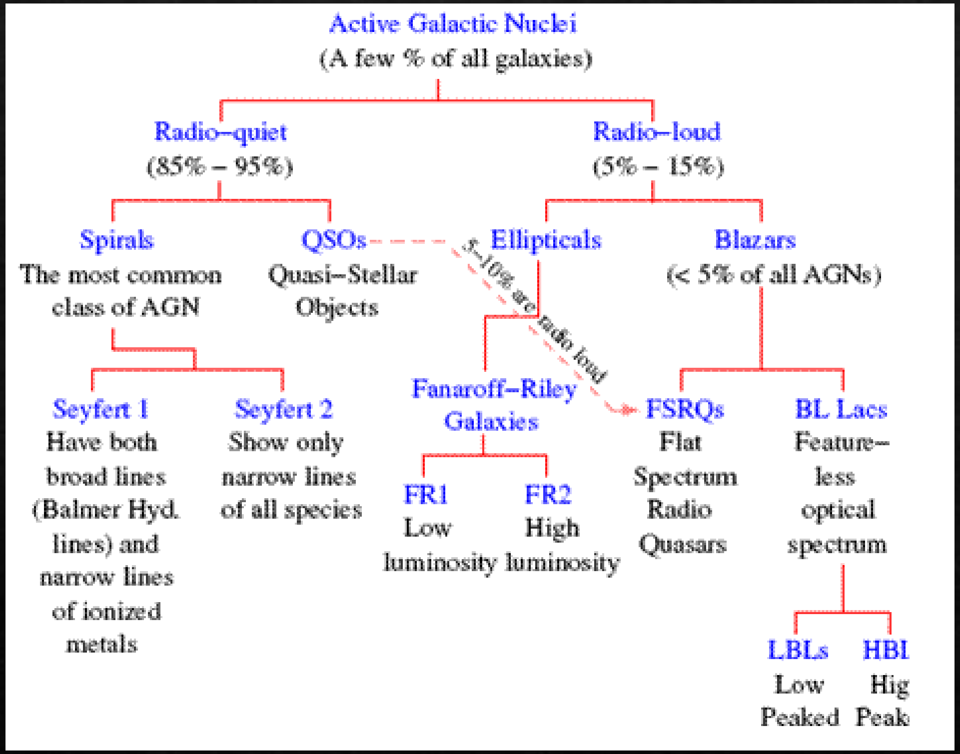
明るさ:太陽の一兆倍

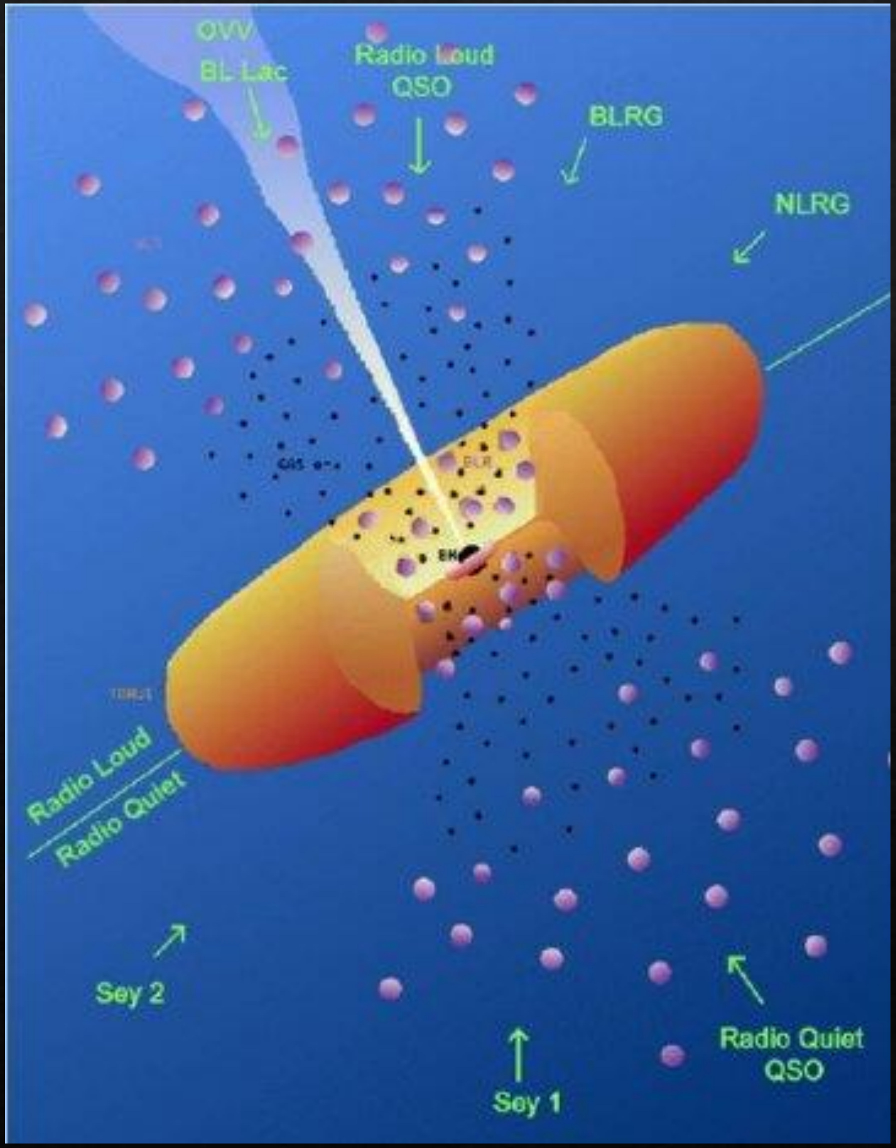
銀河

明るさの起源は核融合
たくさんの恒星で光る



活動銀河核の統一モデル

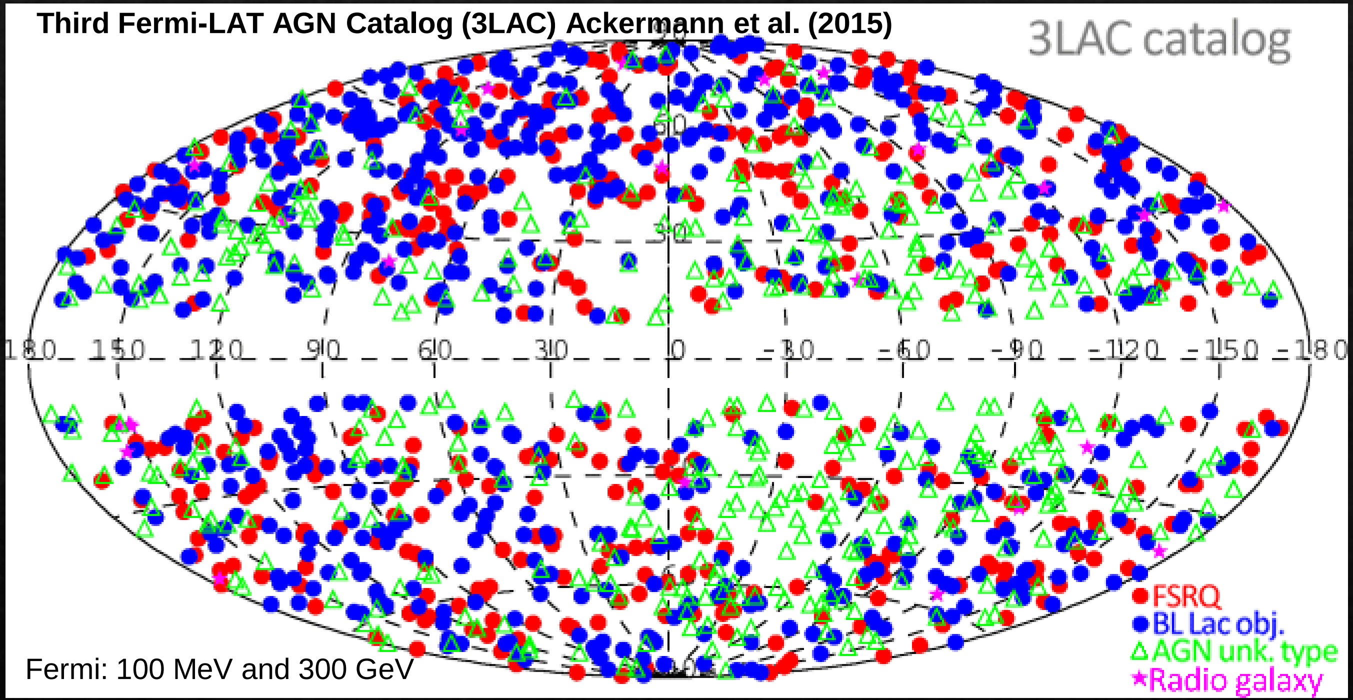


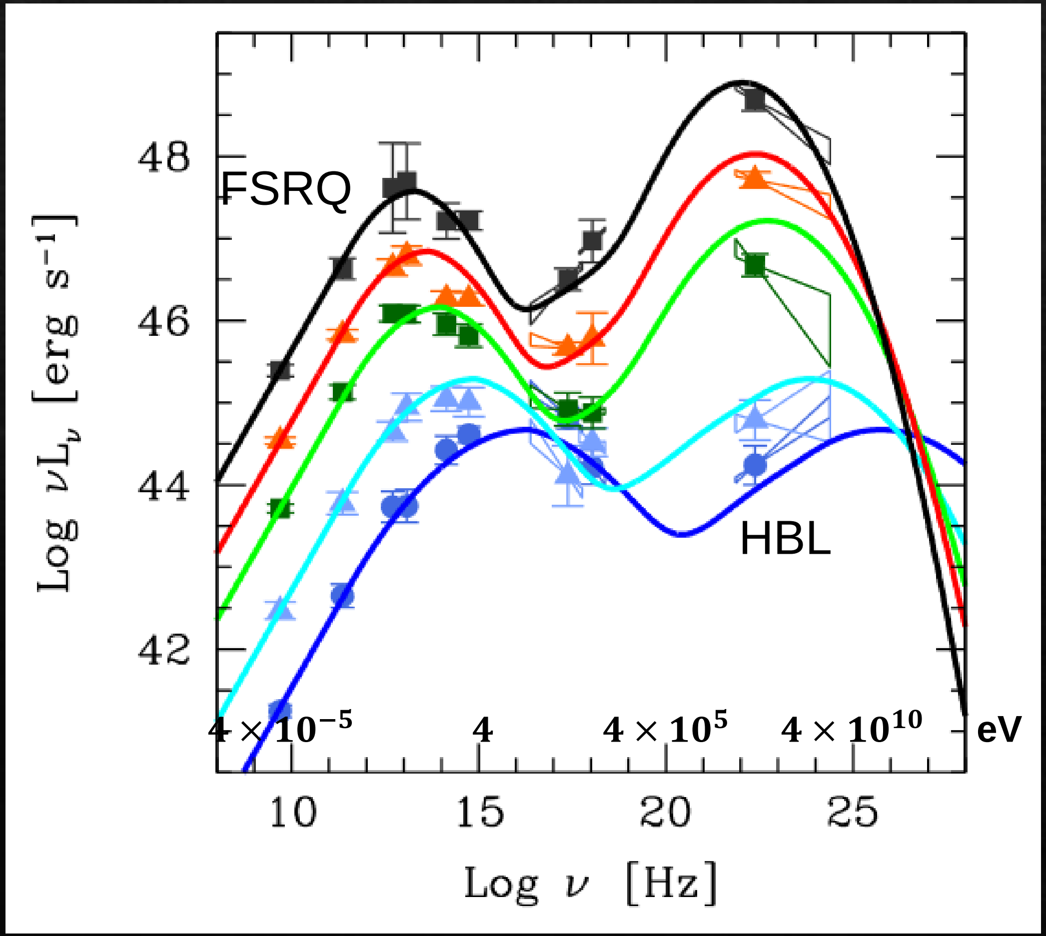


ブレーザー（活動銀河核）

活動銀河核からは超高速ジェットが放出されることがあり
このジェットをほぼ正面から観測したものがブレーザー

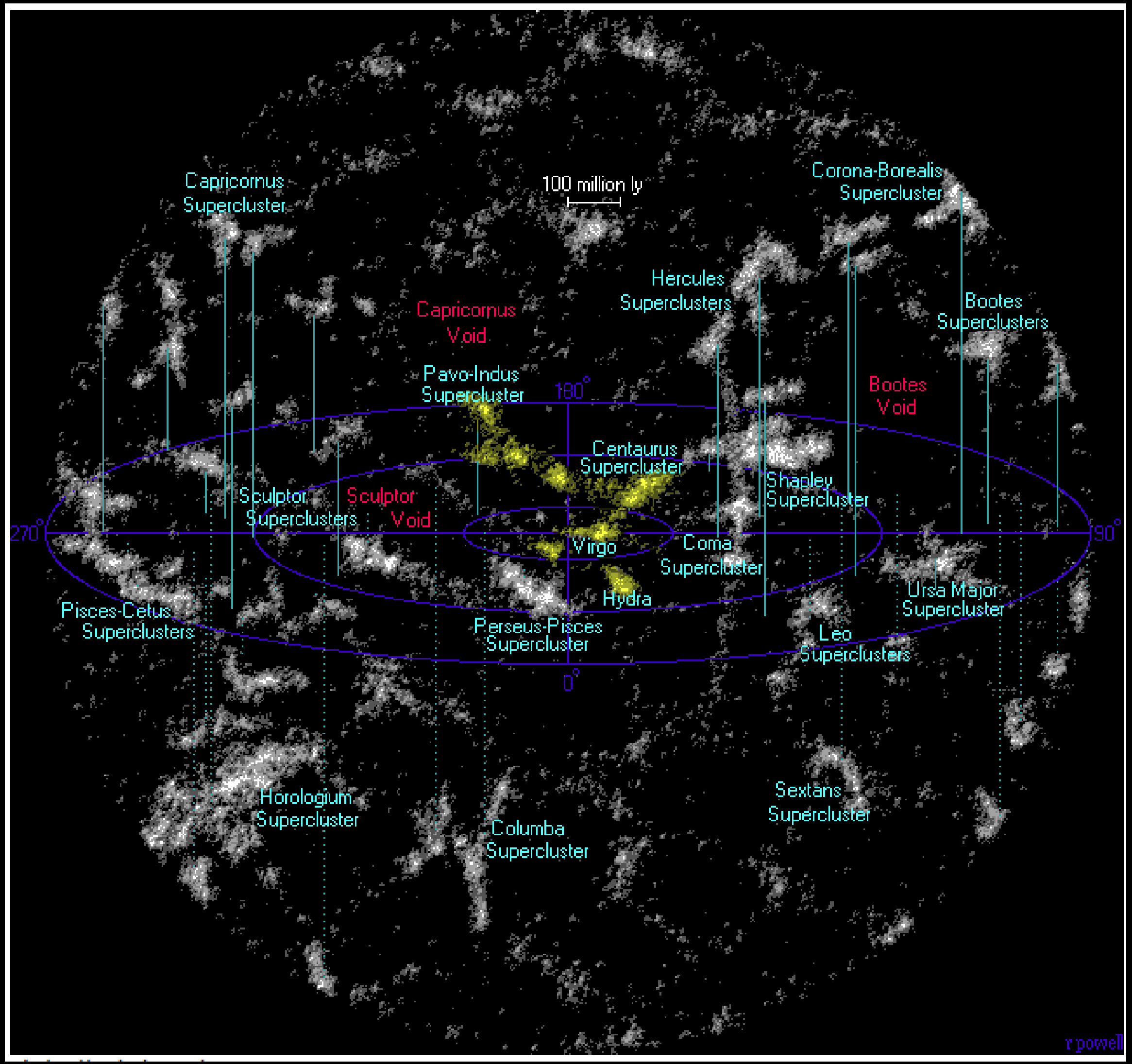
2ピーク スペクトラ
- 電波からX線領域にわたるシンクロトロン放射
- ガンマ線領域では逆コンプトン散乱



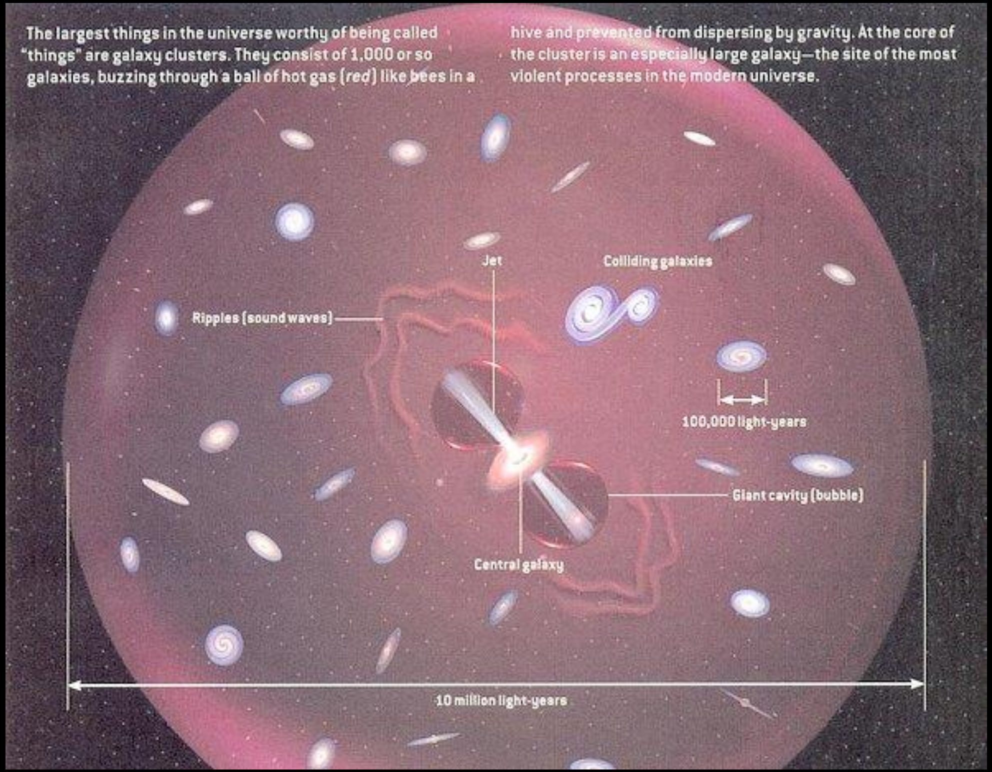


- ブレーザーは広い波長帯で非常に明るく、激しい時間変動
- 相対論的ビーミング効果で、電磁波のエネルギーは高くなり、強度も増幅され変動時間は短縮される

銀河団



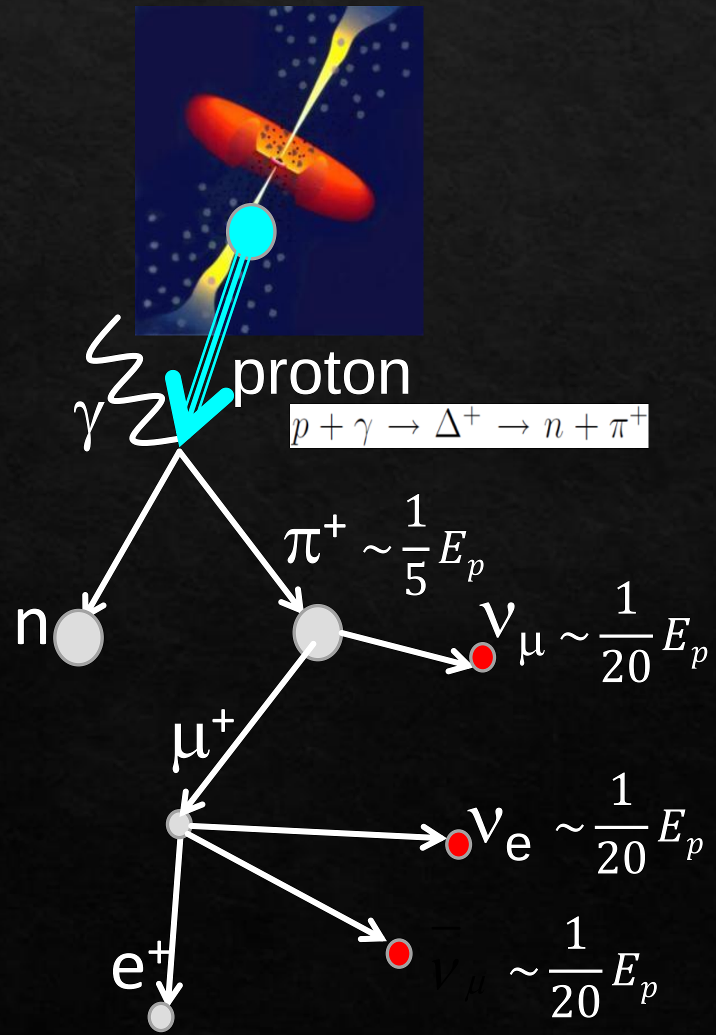
巨大構造はエネルギー貯蔵庫か?



https://universe-review.ca/R03-03-largescale.htm

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

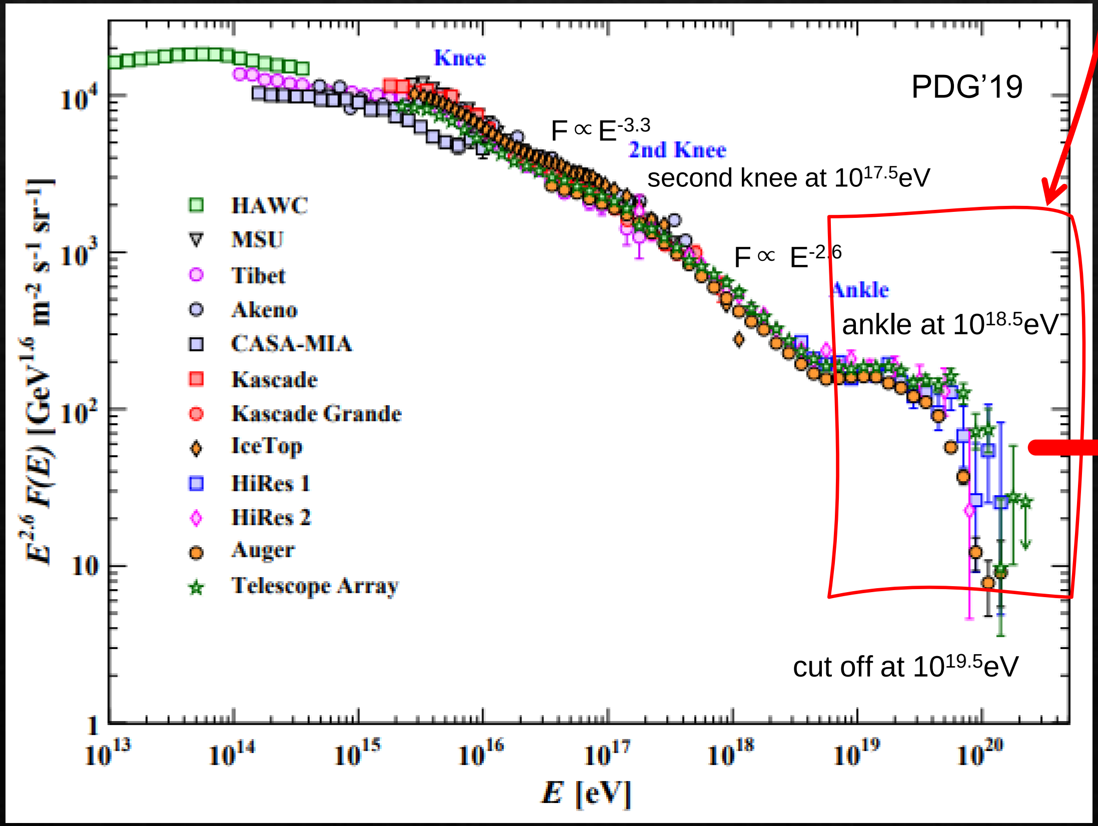
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

高エネルギー宇宙ニュートリノはどれくらい飛び交っているのか

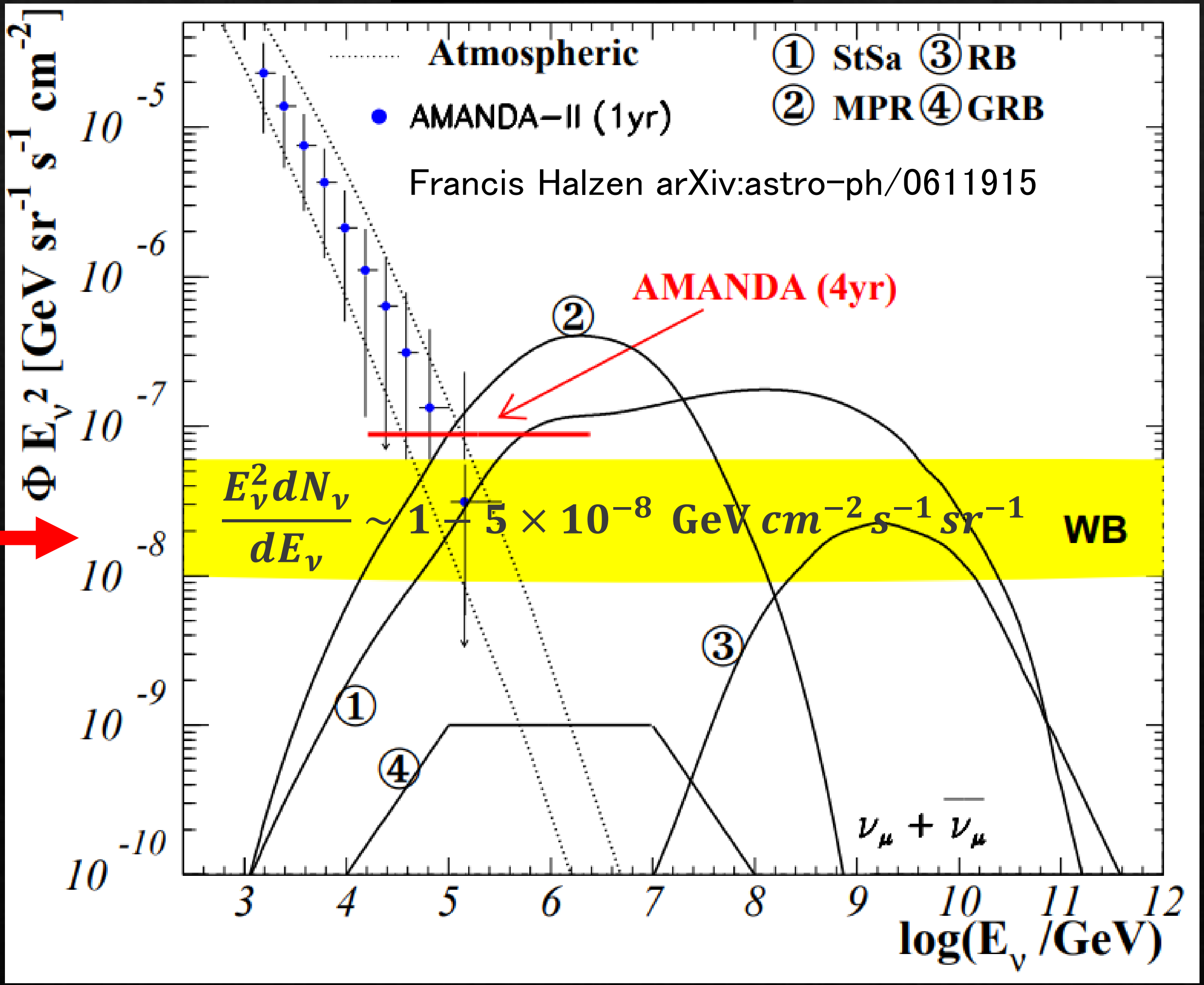
UHECR energy generation rate

$$\left(E_{CR}^2 \frac{dN_{CR}}{dE_{CR}}\right)_{z=0} \sim 10^{44}\ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}$$



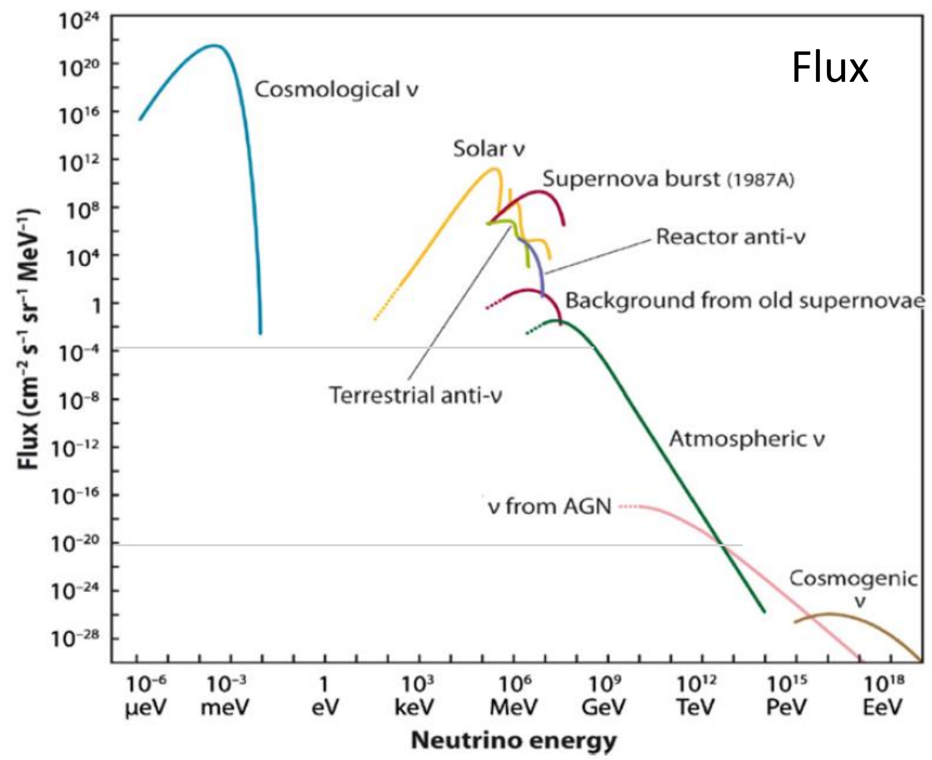
knowledge of astro neutrino flux as of 2006

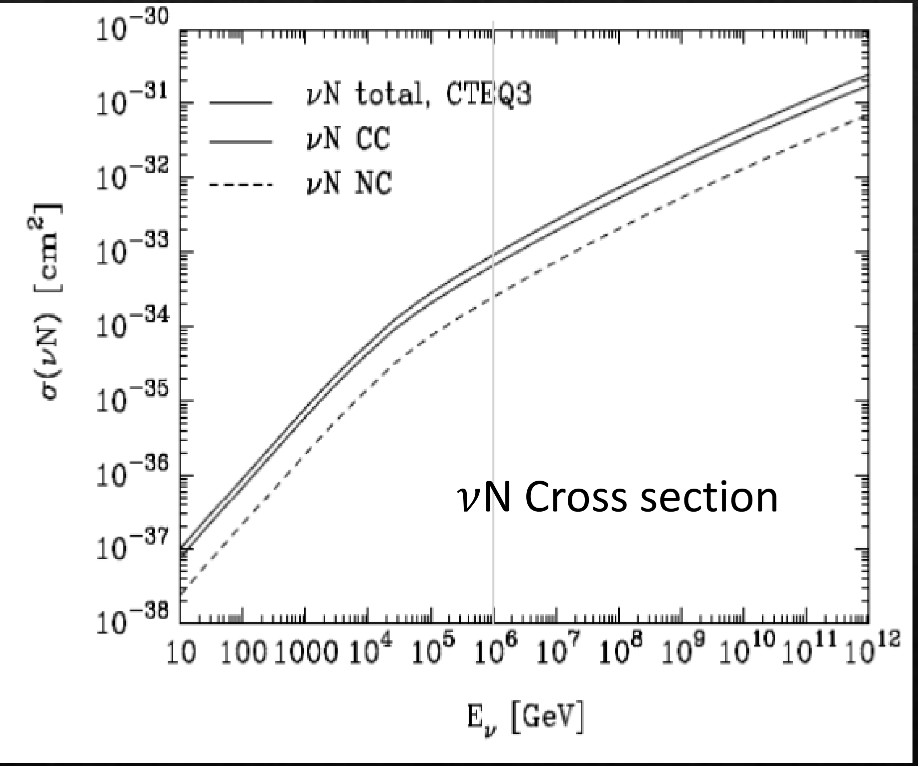
$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \sim \frac{1}{4} E_{CR}^2 \frac{dN_{CR}}{dE_{CR}}$$



Cosmic Neutrino Detection Rates

$N_{\nu(}E) \sim \phi_{\nu}(E)$ x $\sigma_{\nu}(E)$ x Number of target





# of targets in 1 g/cm^3

density material

$\sim$

O(10) events per km^3

per year

$10^{-20}\ [cm^{-2}\ s^{-1}\ sr^{-1}\ \mathrm{MeV}^{-1}]$ $\sigma_{\nu p} \sim E_{\nu} \times 10^{-33}\ cm^2\ for\ 1\ \mathrm{PeV}\ neutrinos$ 体積10^6倍 頻度10^{-6}倍

$10^{-4}\ [cm^{-2}\ s^{-1}\ sr^{-1}\ \mathrm{MeV}^{-1}]$ $\sigma_{\nu p} \sim E_{\nu} \times 10^{-37}\ cm^2\ for\ 10\ \mathrm{GeV}\ neutrinos$

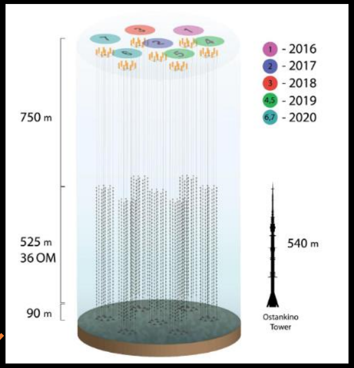
Neutrino Telescopes around the world

Mediterranean Ocean

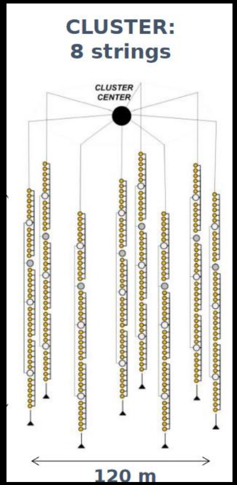
KM3NET Phase 1 – ARCA (HE array)
as of April 2021, 6 ARCA strings

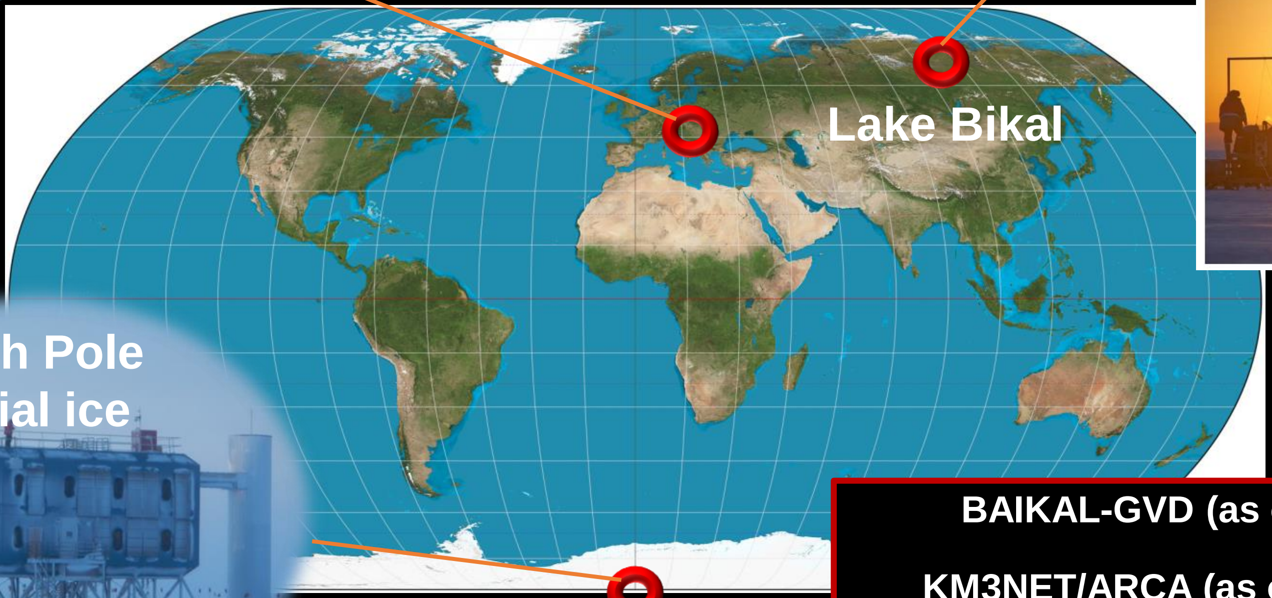
On Nov, 2021: 6 months of ARCA data taking with 6 detection units

BAIKAL-GVD



2021: Baikal-GVD 8clusters, 288 x 8=2304 optical modules





BAIKAL-GVD (as of April 2021) 0.4 km^3

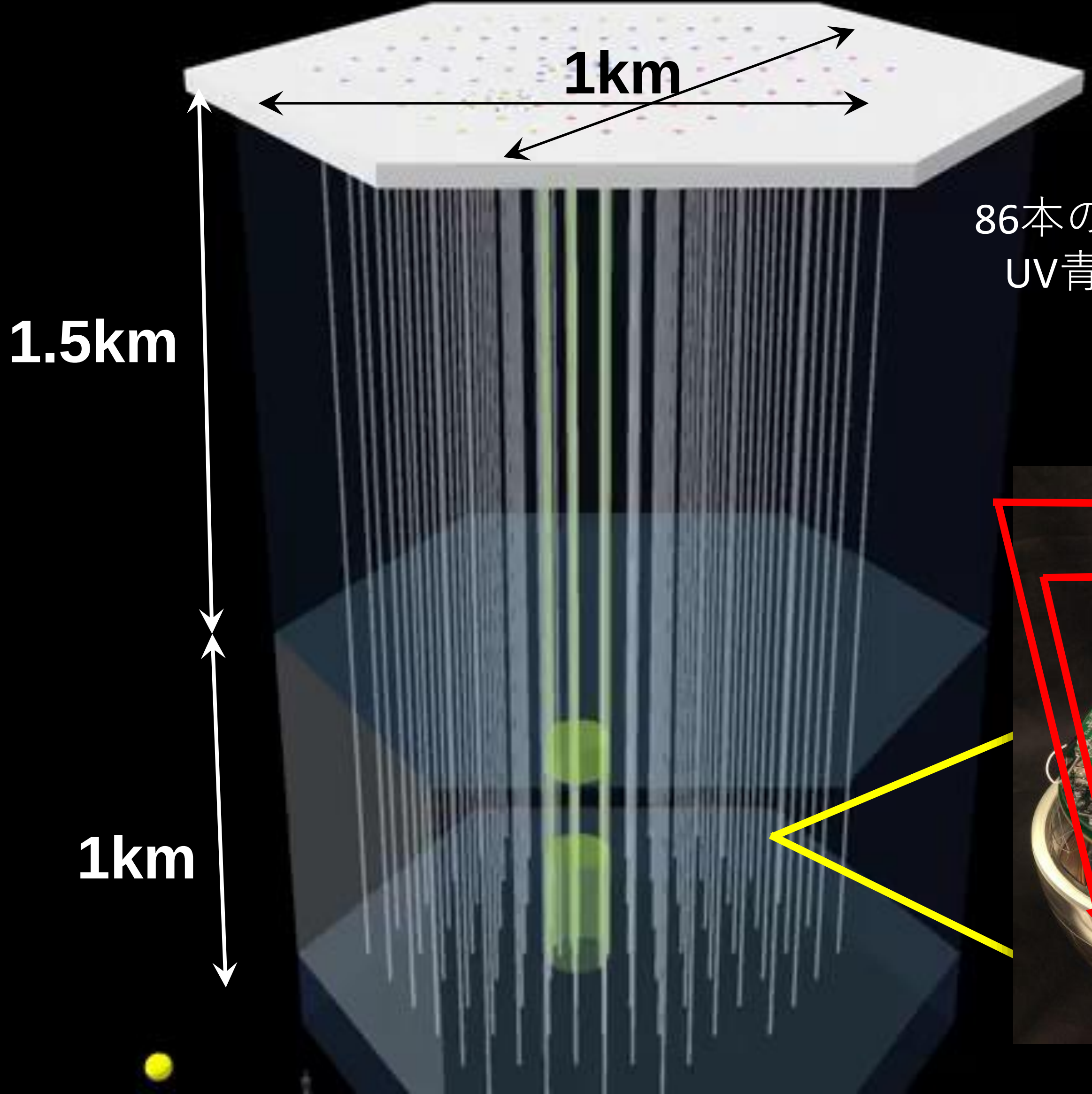
KM3NET/ARCA (as of April 2021) 0.015 km^3

IceCube (since 2011) 1km^3

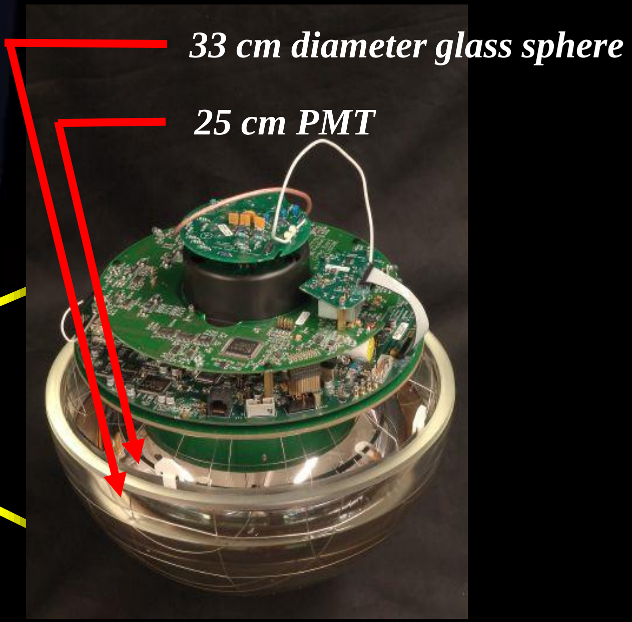
アイスキューブ検出器

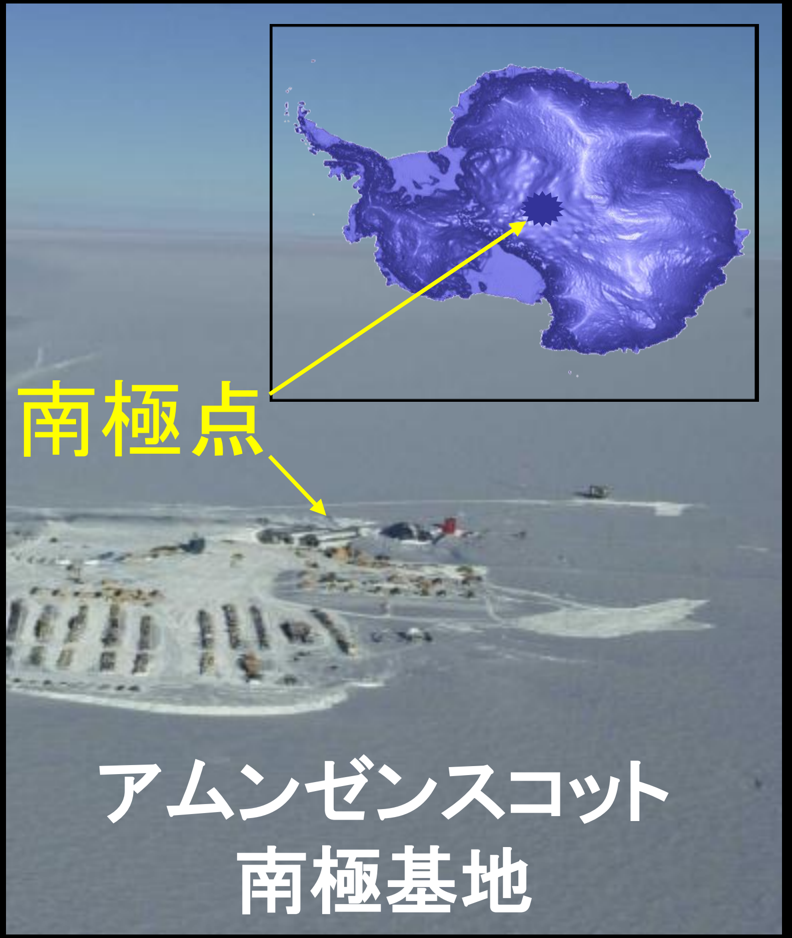
The largest underground particle detector

16,000 x SuperK tank!



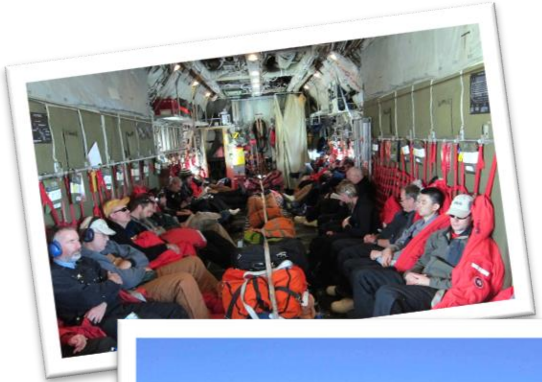
86本の2.5kmの穴の中に
UV青色光計測装置が
5160個!

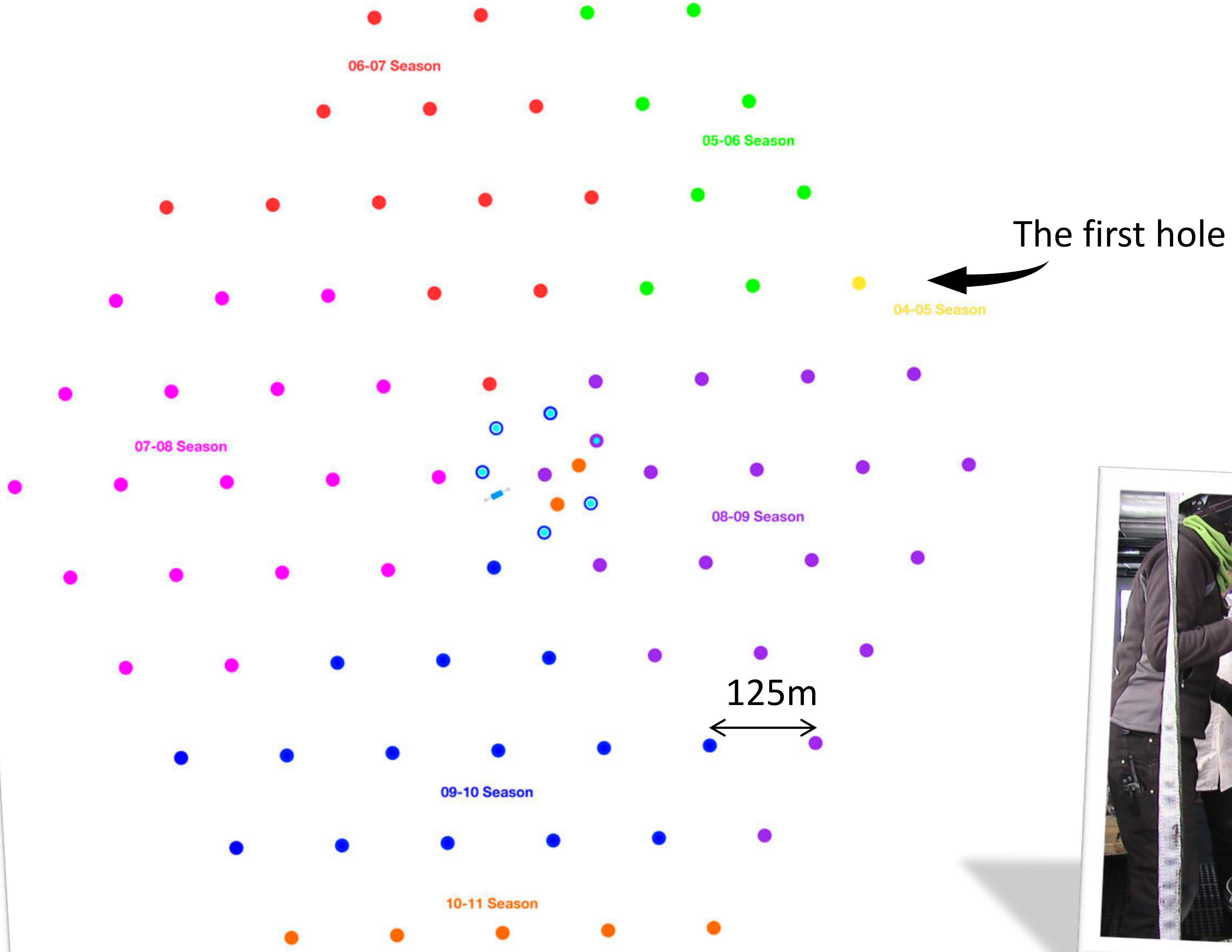




Construction of IceCube

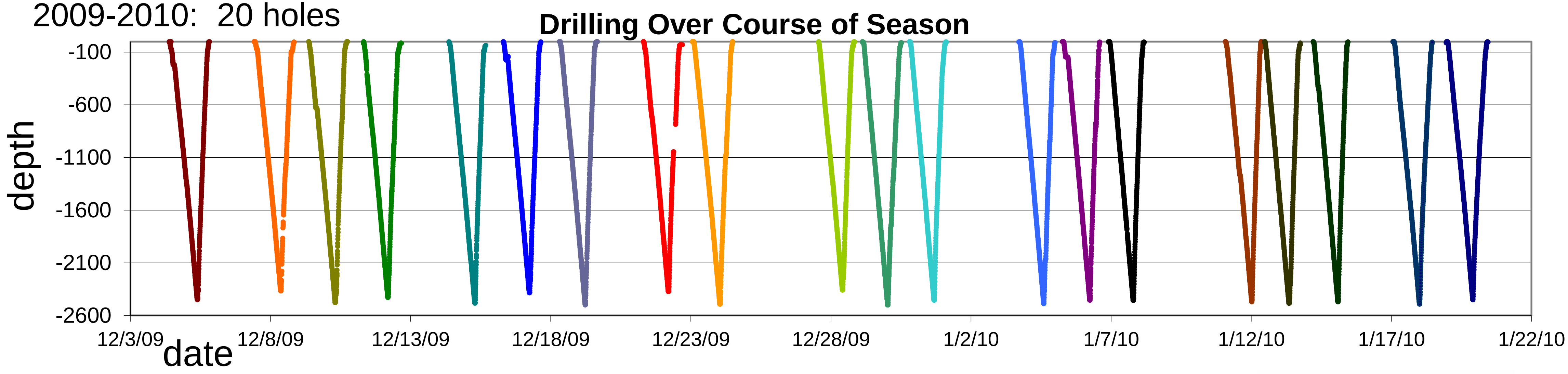
7yrs from the end of 2004 to the end of 2021

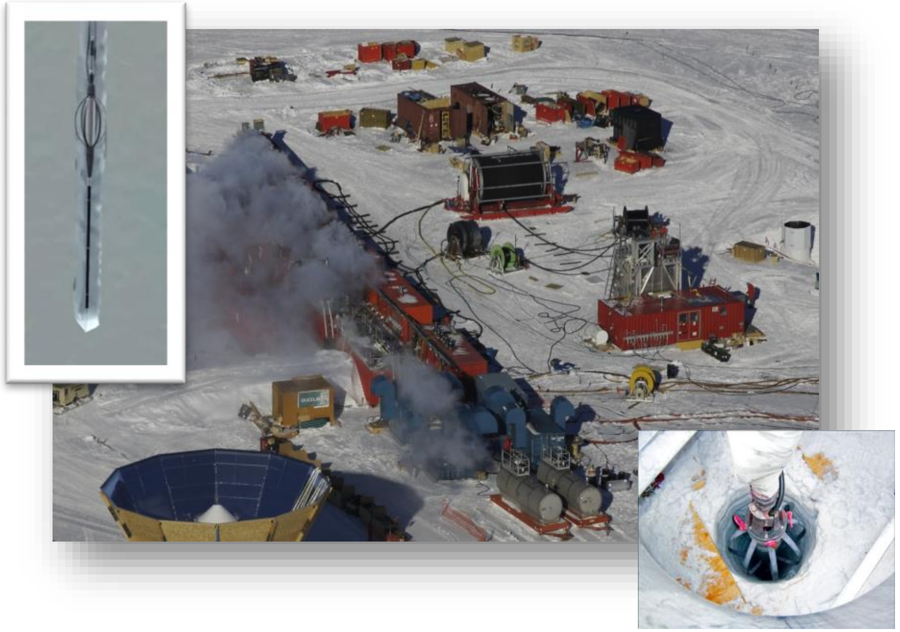


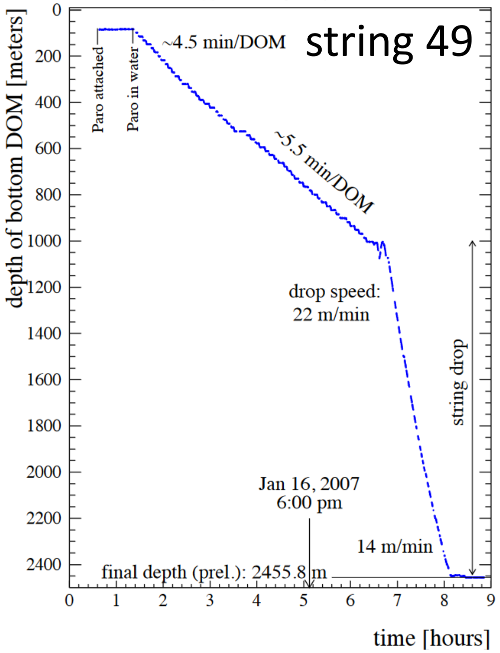


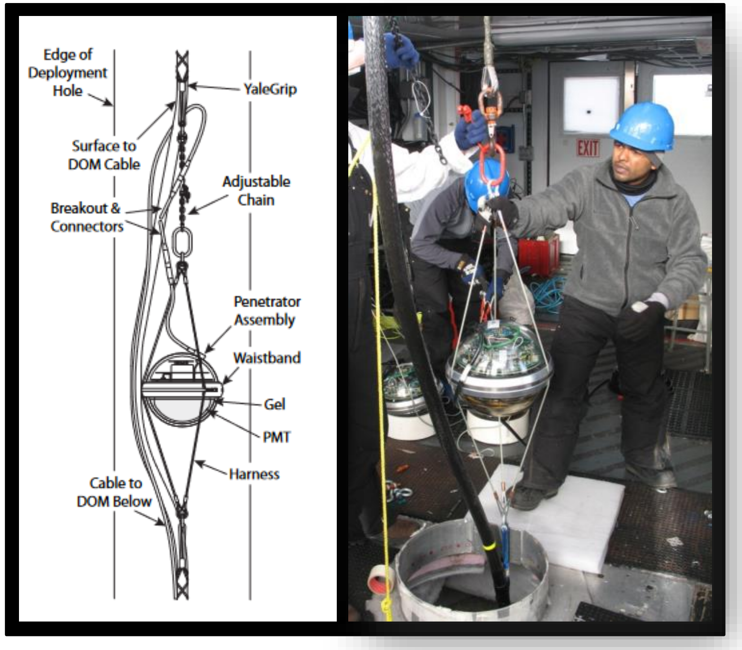
Deployment of optical sensors

2009-2010: 20 holes





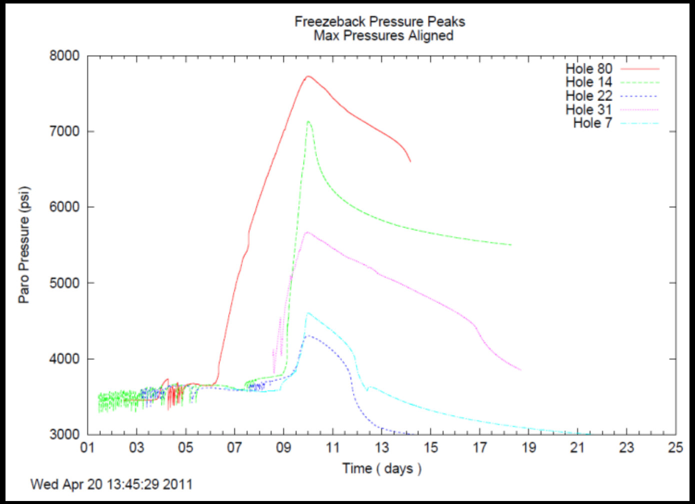


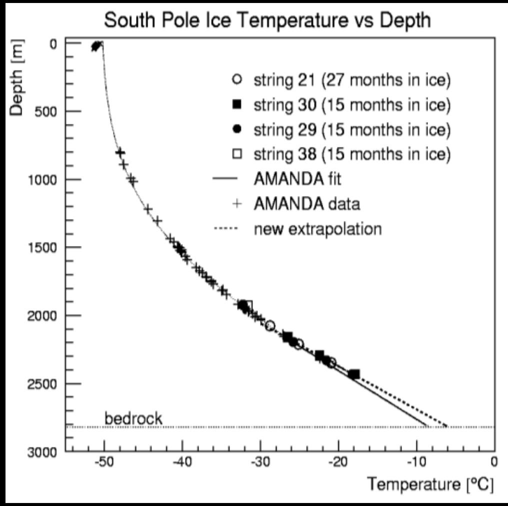


Environmental condition for optical sensors

- Once deployed, never be pulled out. Long lifetime
- High pressure (peak 8000 psi observed at the refreezing phase)
- Low temperature (depth dependent, -20C to -40C)
- Large heat/cold shock (at the deployment)
- Long rough travel

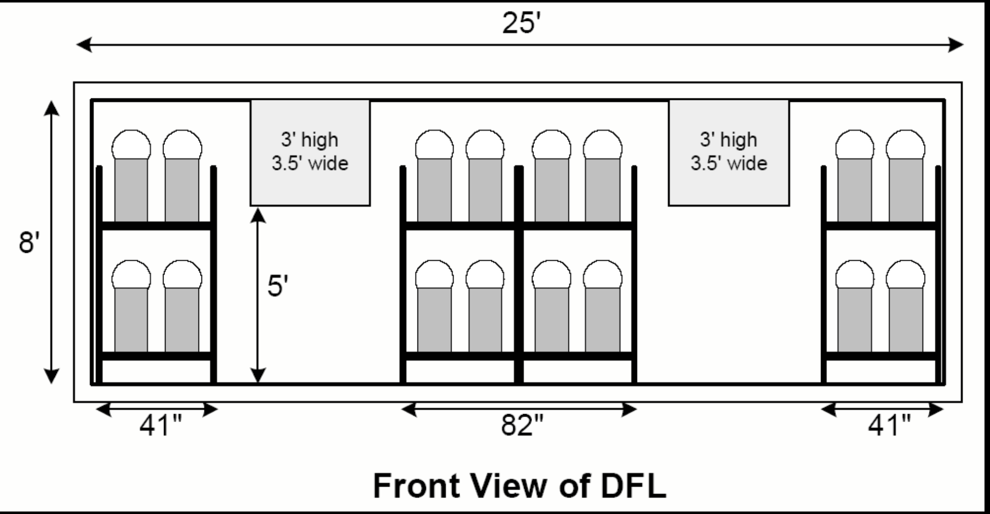
However, dark and cold environment is an ideal condition for photo sensors!



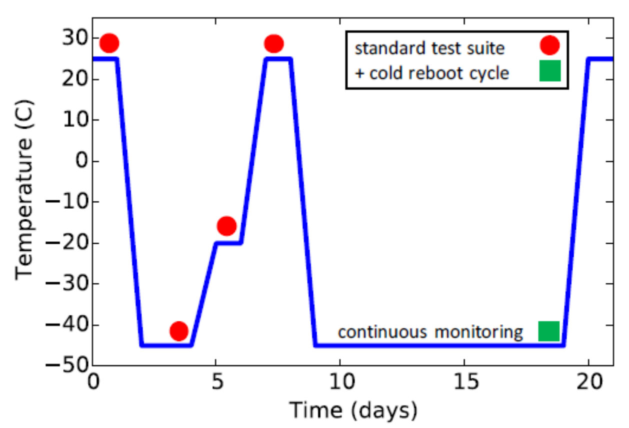


Final Acceptance Test (FAT)/
South Pole Acceptance Test (SPAT) Systems

Dark freezer lab at Madison, Wisconsin

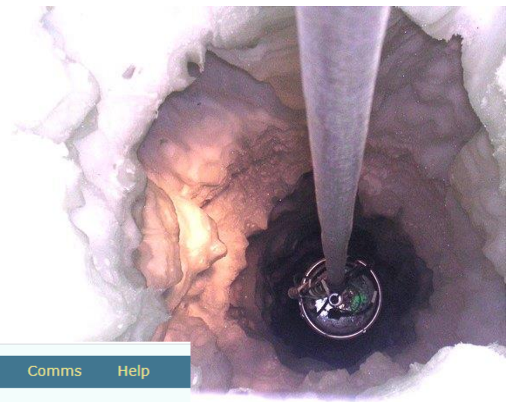


20 days of temperature cycle



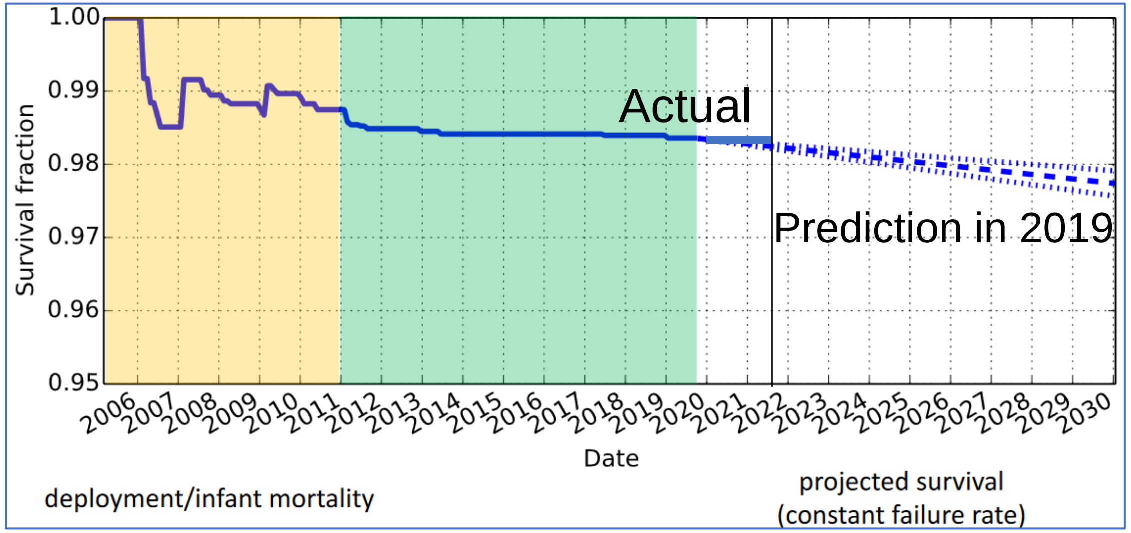
outer temperature at SP

IceCube Operation



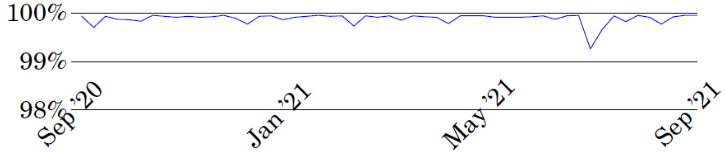
Partial operation has started since 2005, full operation since 2011

DOM Survival Rate: >98.3% (an extremely small post-deployment failure rate)

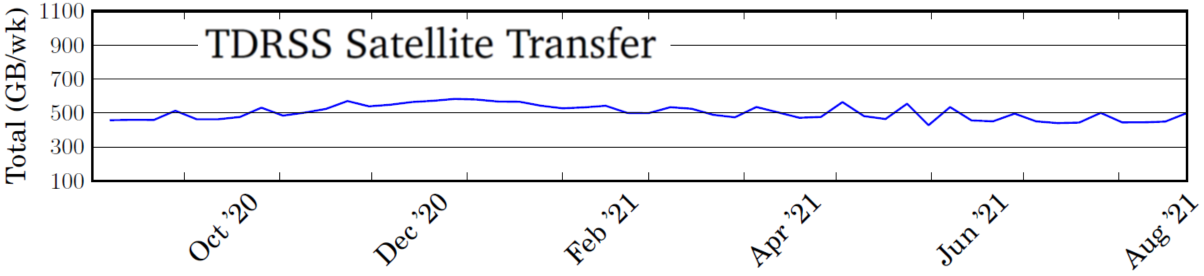


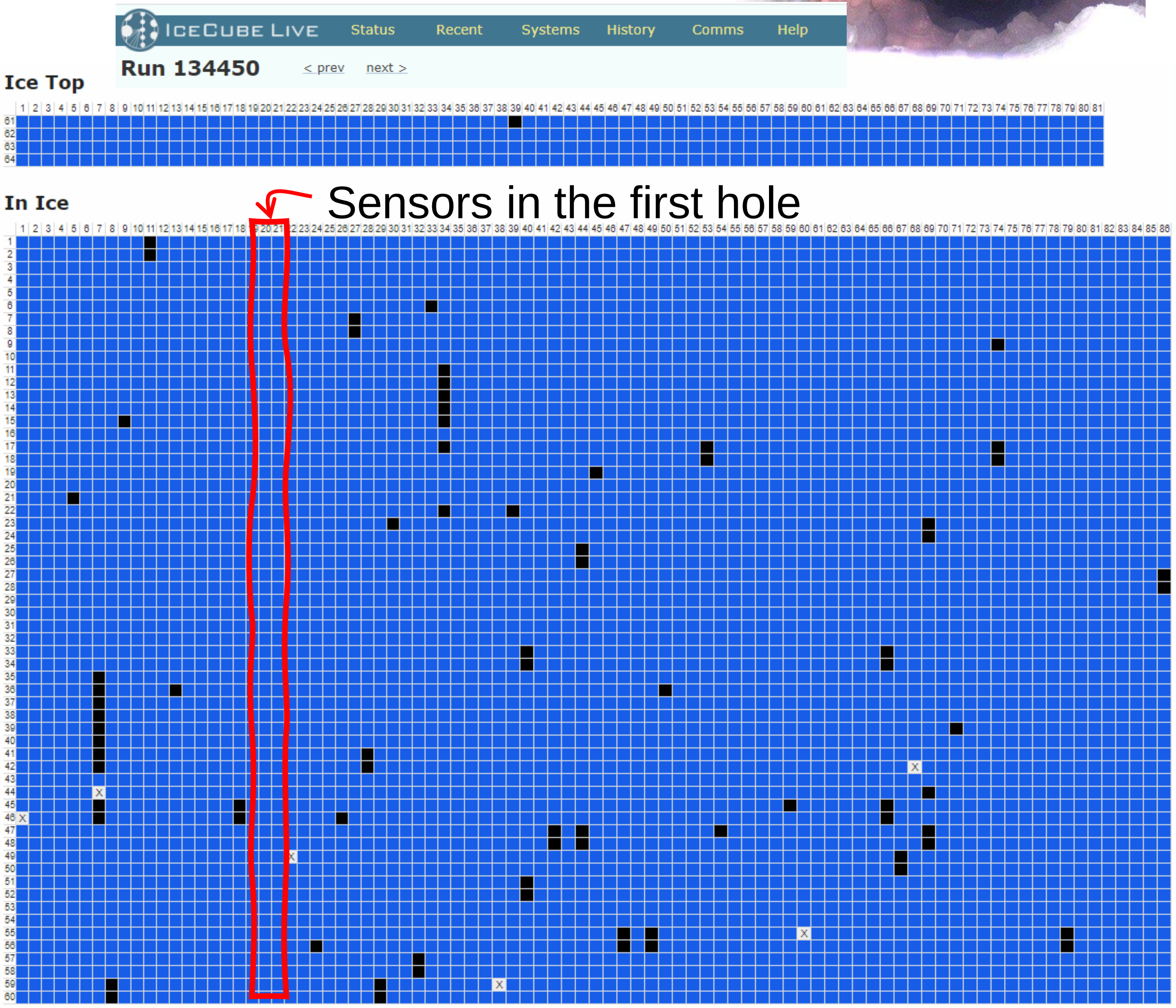
Run time: >99.5% uptime for 8 years

Uptime

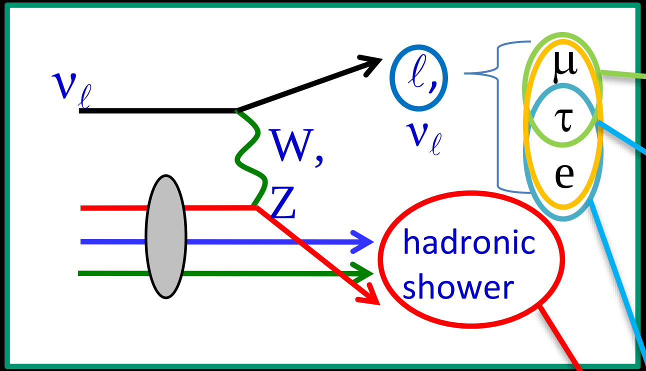


99.95%





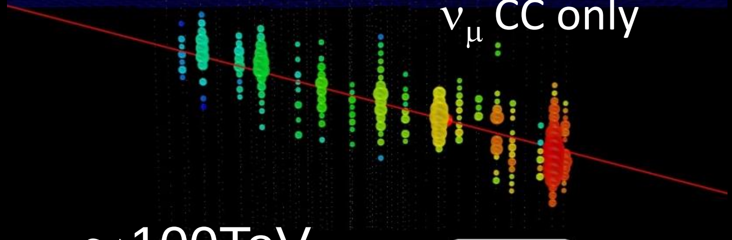
IceCube Flavor Identifications



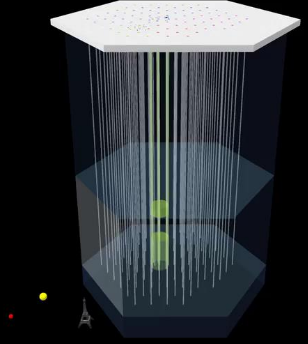
Up-going muon track event

Good angular resolution

ν_μ CC only



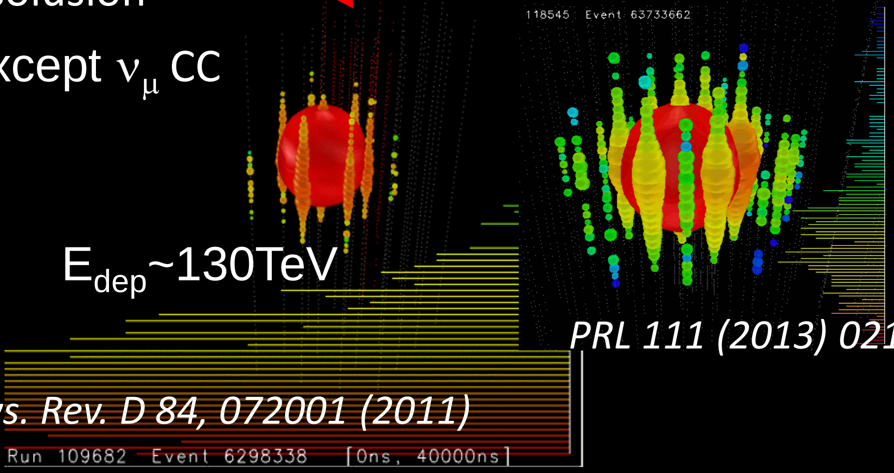
~100TeV



Cascade events

Good energy resolution

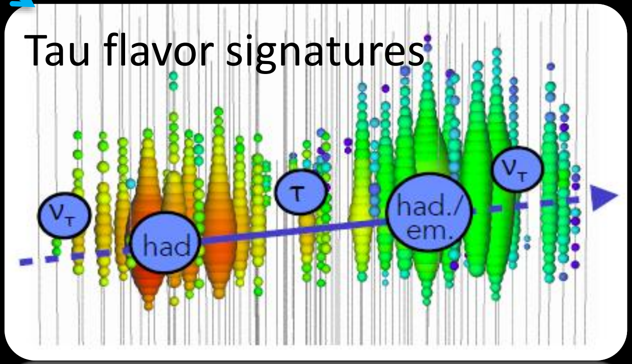
All except ν_μ CC



E_{dep}~130TeV

Phys. Rev. D 84, 072001 (2011)

PRL 111 (2013) 021103



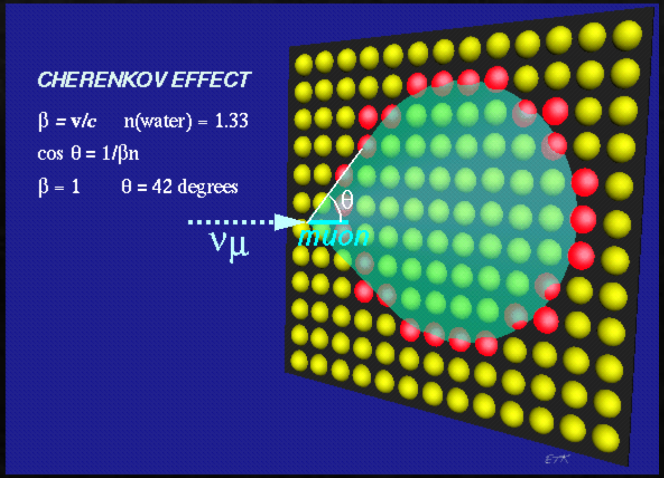
スーパーカミオカンデ事象との比較

super-KAMIOKANDE
検出器の大きさ
40m x 40m

IceCube 検出器の大きさ
1000m x 1000m x 1000m

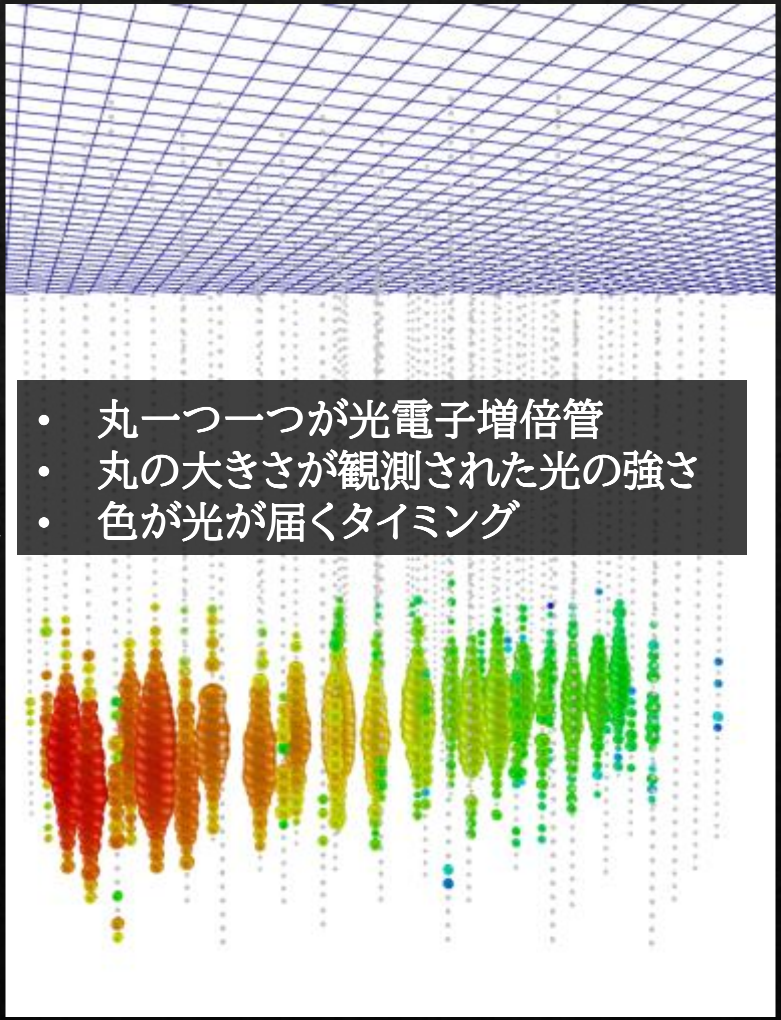
16000倍

事象の大きさ
6m x 6m



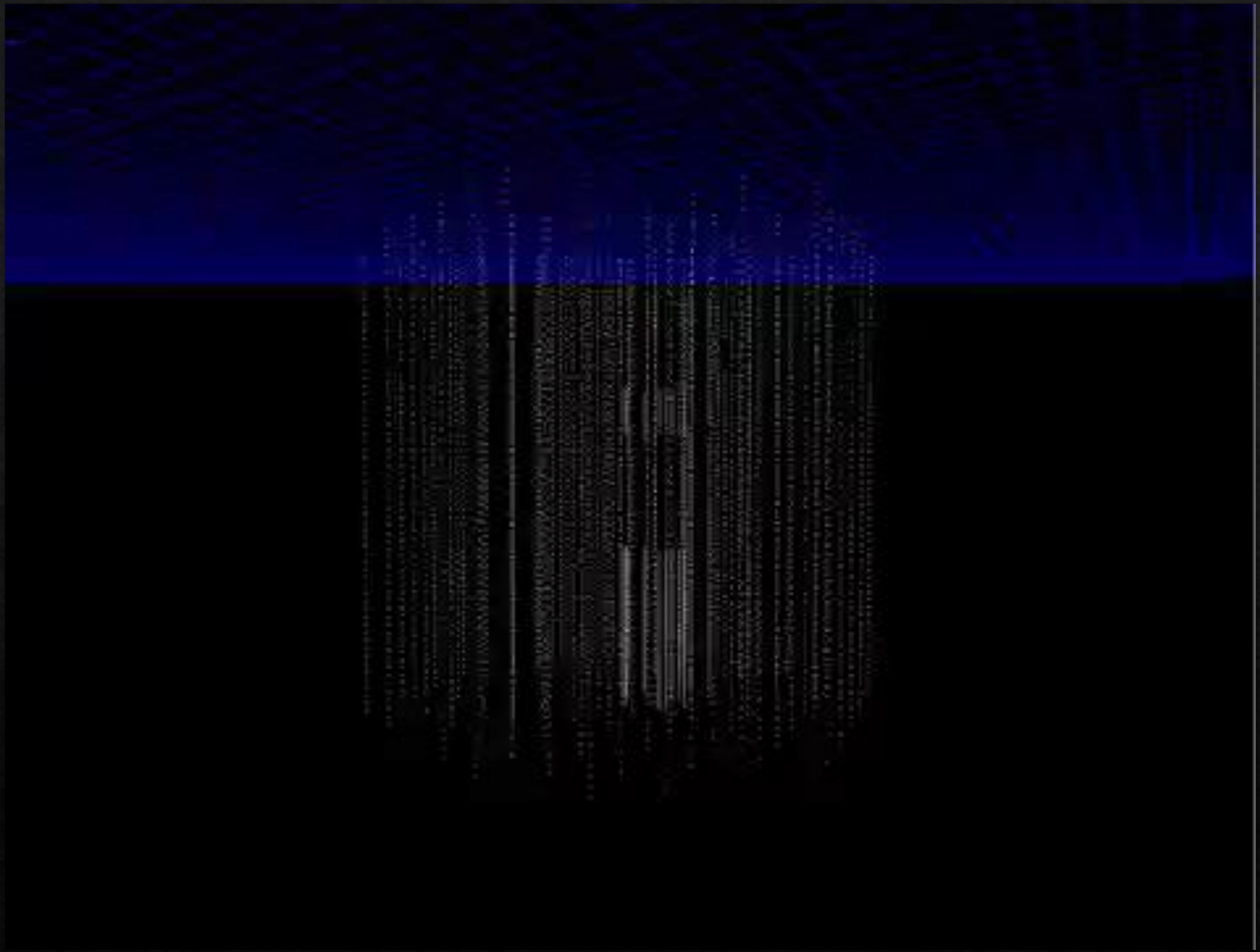
2D to 3D

IceCube 事象の大きさ
800m x 300m x 300m



- 丸一つ一つが光電子増倍管
- 丸の大きさが観測された光の強さ
- 色が光が届くタイミング

How the IceCube events look at the first sight…



10 milliseconds
movie

First observations of cosmic neutrinos

Energetic Neutrinos on Ice

July 8, 2013 • *Physics* 6, s93

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

2013

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

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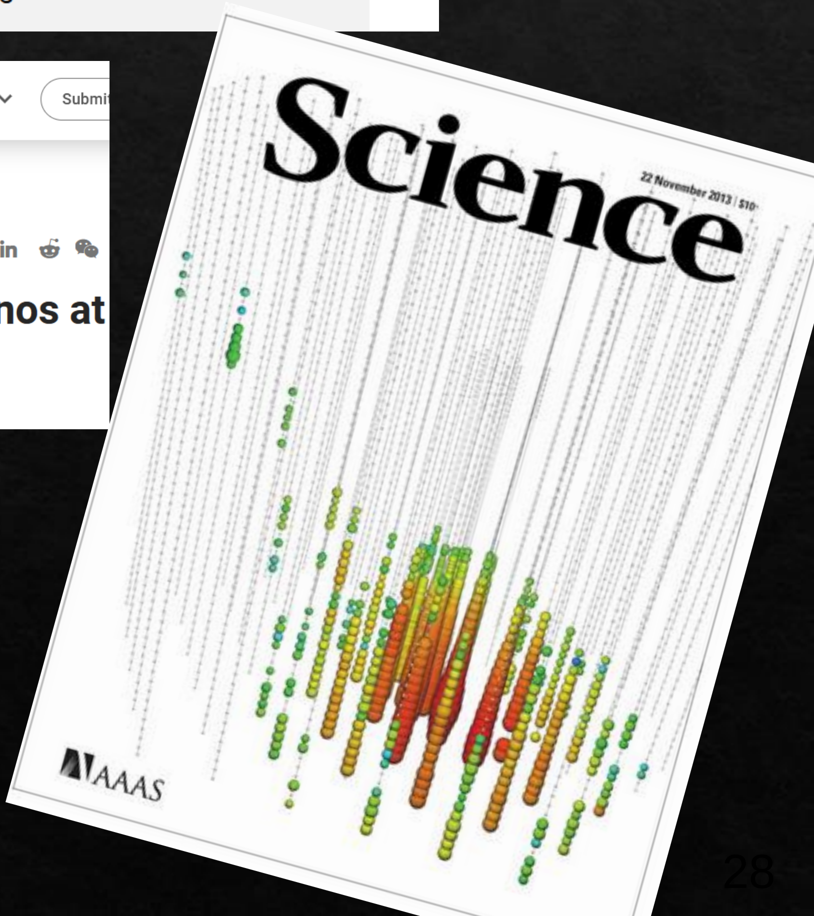
HOME > SCIENCE > VOL. 342, NO. 6161 > EVIDENCE FOR HIGH-ENERGY EXTRATERRESTRIAL NEUTRINOS AT THE ICECUBE DETECTOR

RESEARCH ARTICLE

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

ICECUBE COLLABORATION*

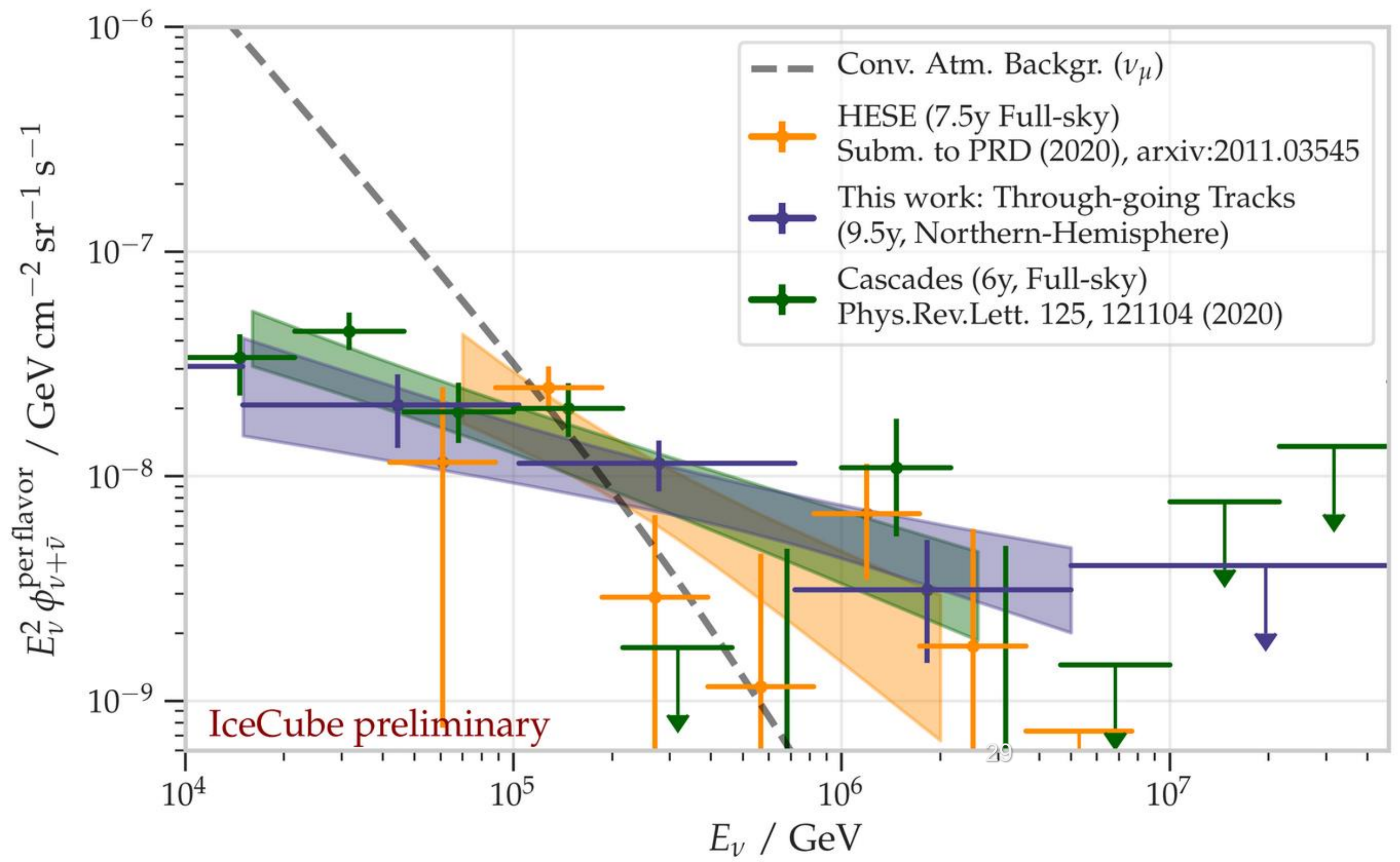


宇宙背景高エネルギーニュートリノ流量

Published and almost to be published samples

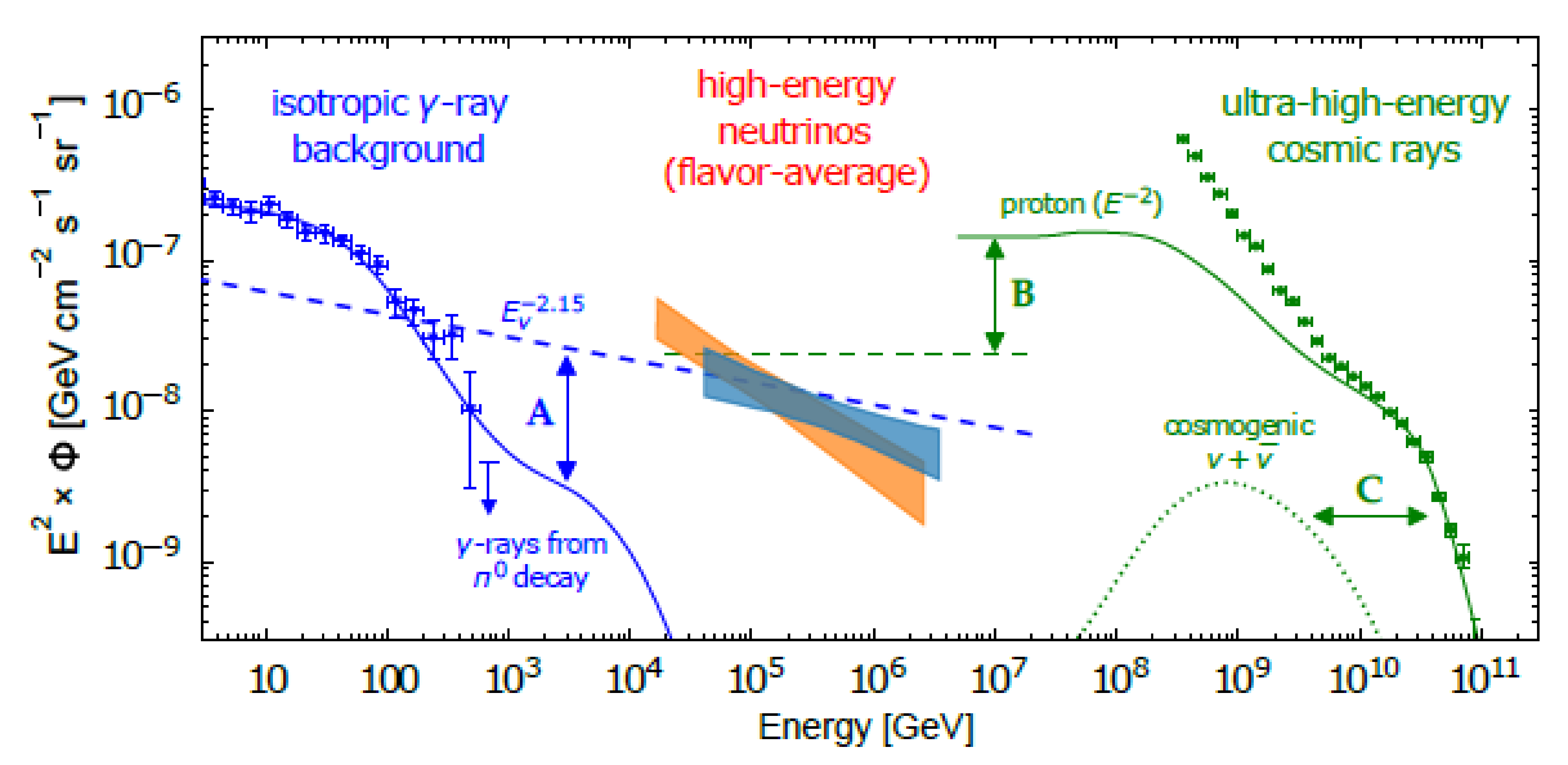
- Upgoing muon neutrino sample 9.5 years
- High energy starting event sample 7.5 years
- Cascade sample 6 years

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



実験デザインで考えた'optimistic'な流量に非常に近かった!

エネルギー生成率:
超高エネルギー宇宙線やガンマ線と同レベル



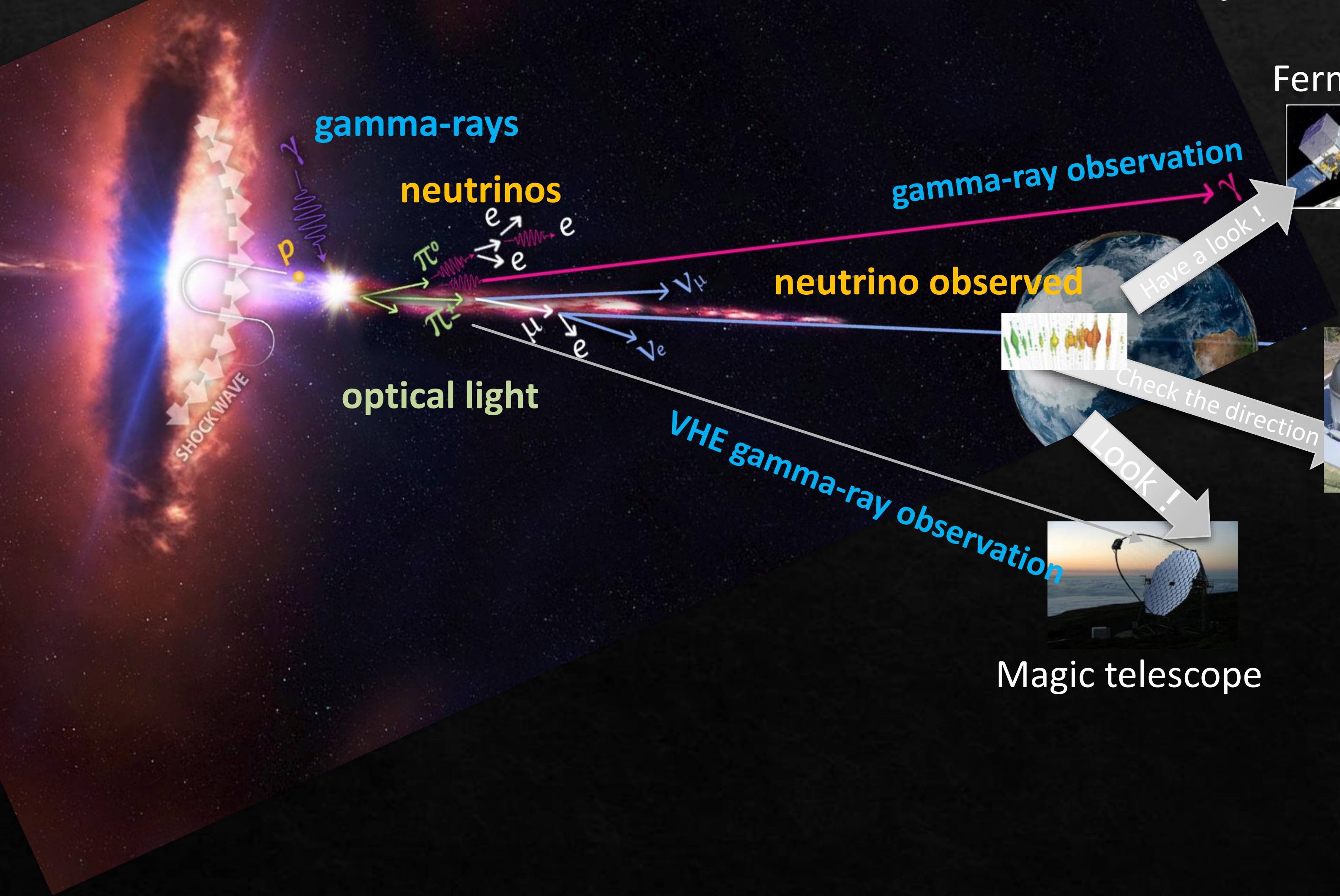
https://arxiv.org/abs/2008.04323

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

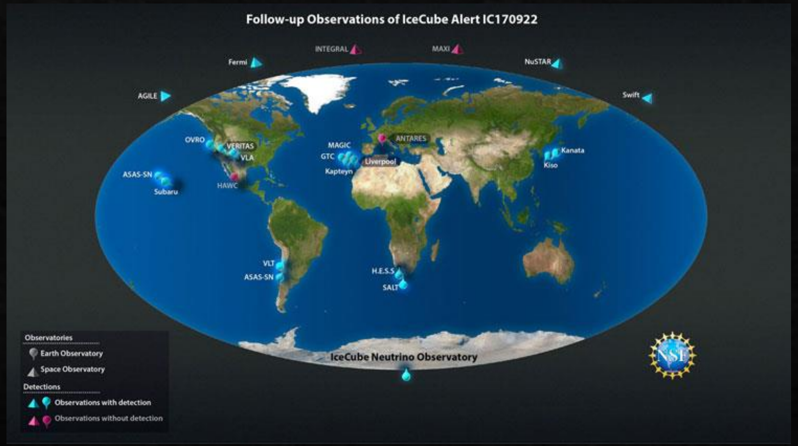


Fermi Telescope

Optical telescopes

Kanata telescope

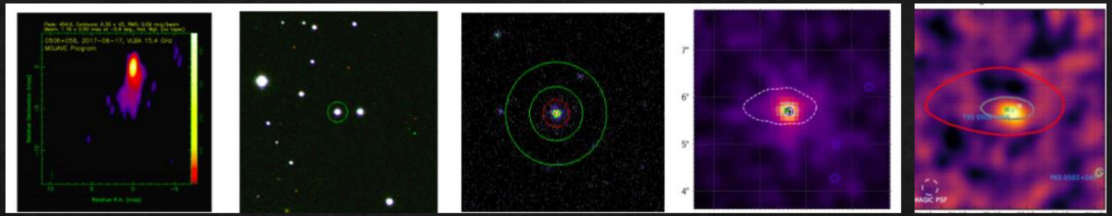
...and many more telescope



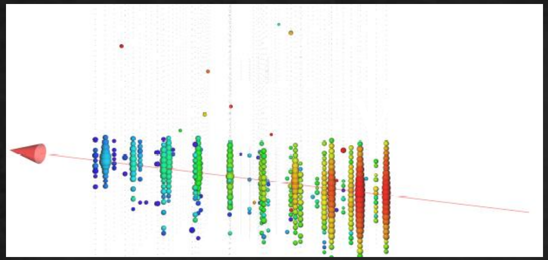
Magic telescope

Multiwavelength Campaign with ν

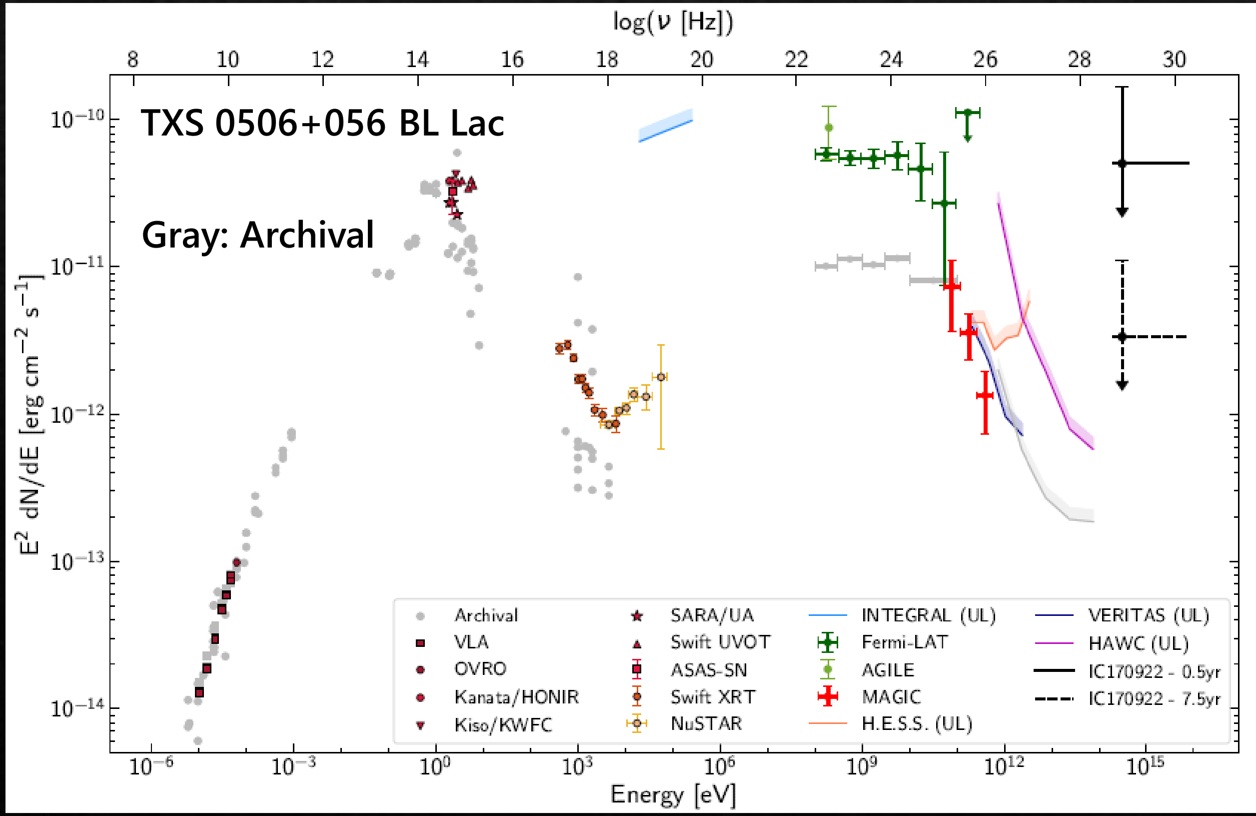
upward going neutrino induced muon track
23.7 ± 2.8 TeV muon energy loss in the detector



radio optical x-ray γ-ray

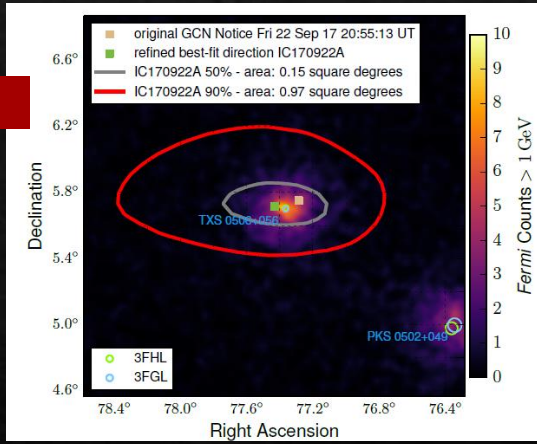


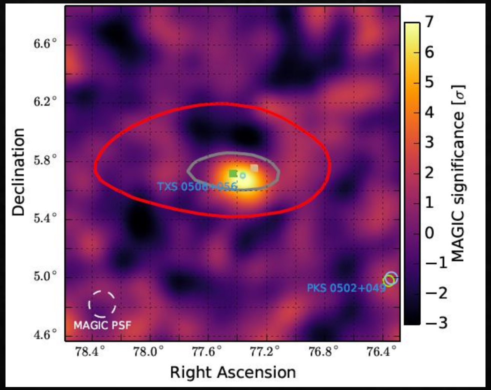
2018



HE gamma-ray observations

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



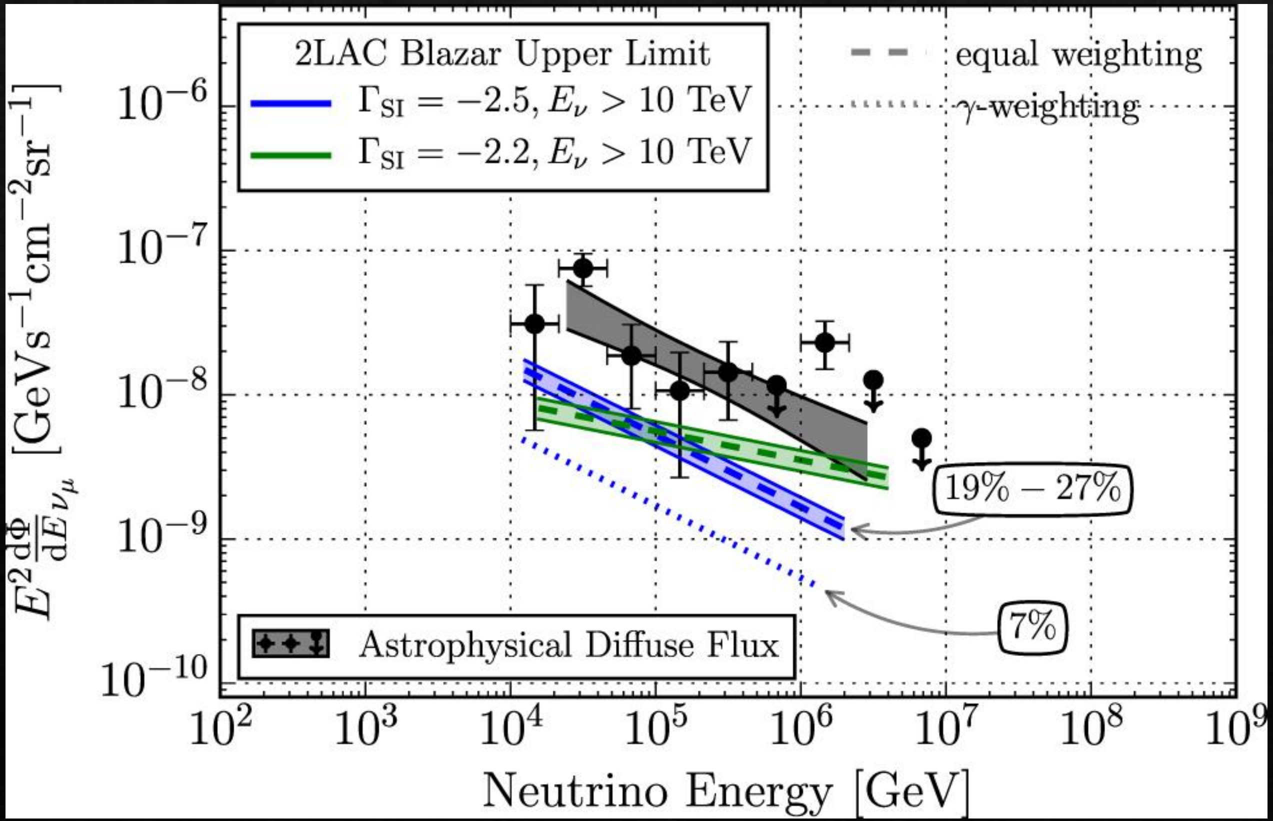


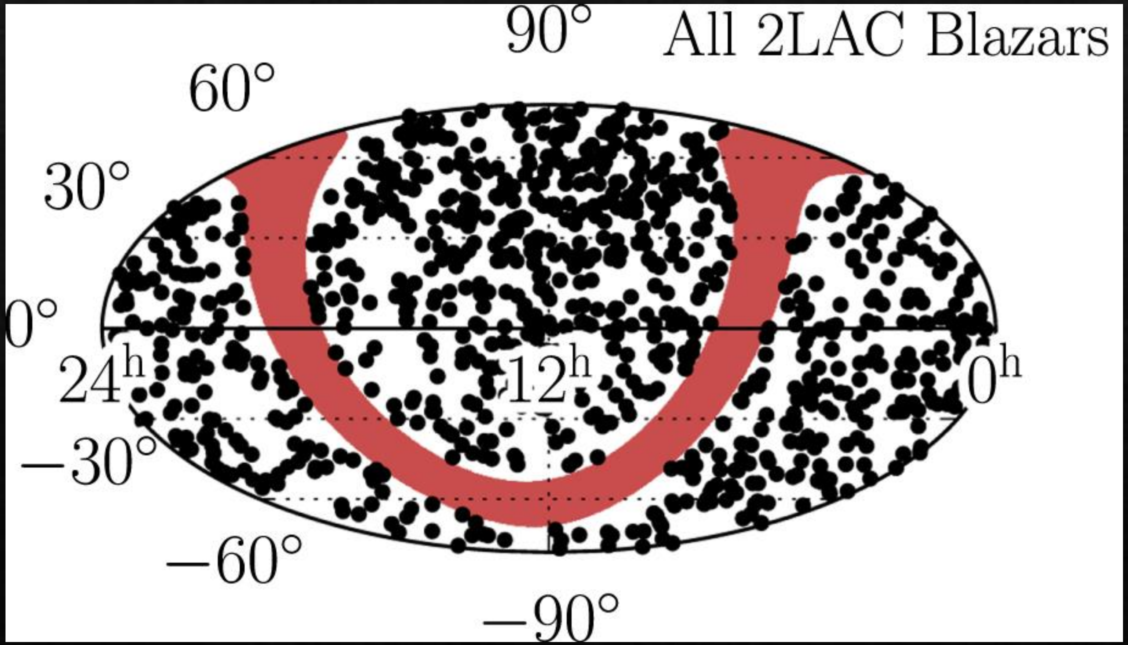
VHE gamma-ray observations

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

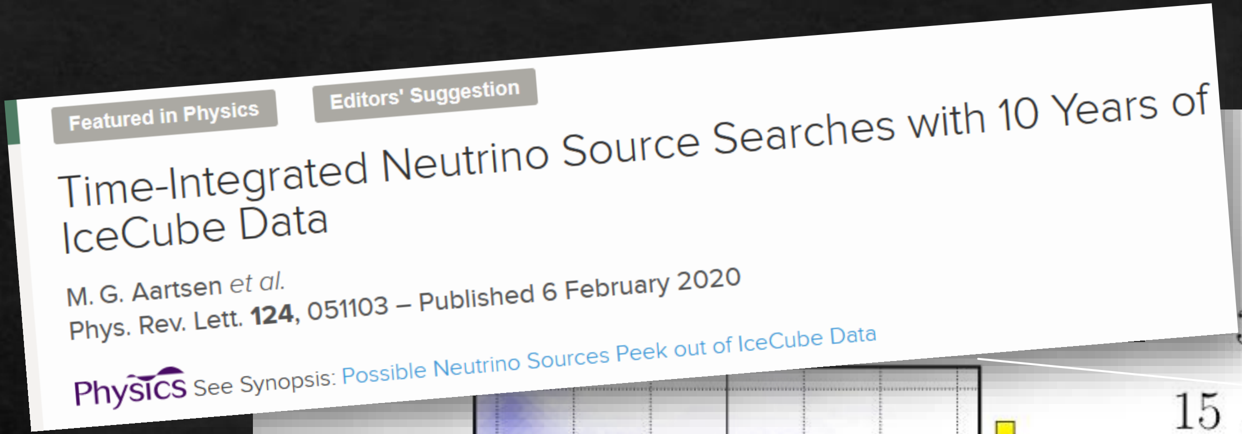
ブレーザー天体が宇宙ニュートリノ流量の起源か

- 既知のガンマ線で輝くブレーザーとの角度相関を調べた
- 部分的には説明できるが、主要生成天体ではない





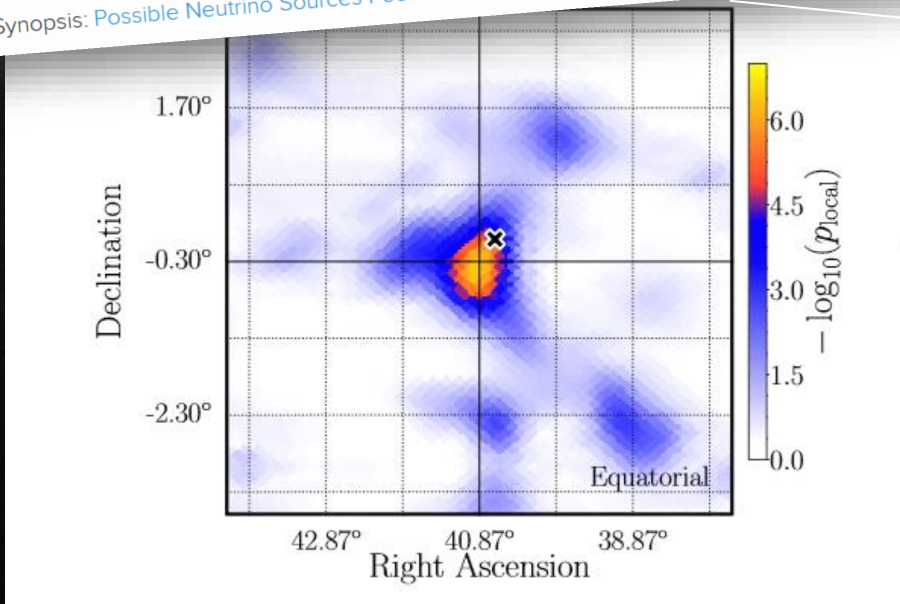
ニュートリノで恒常的に輝いている天体

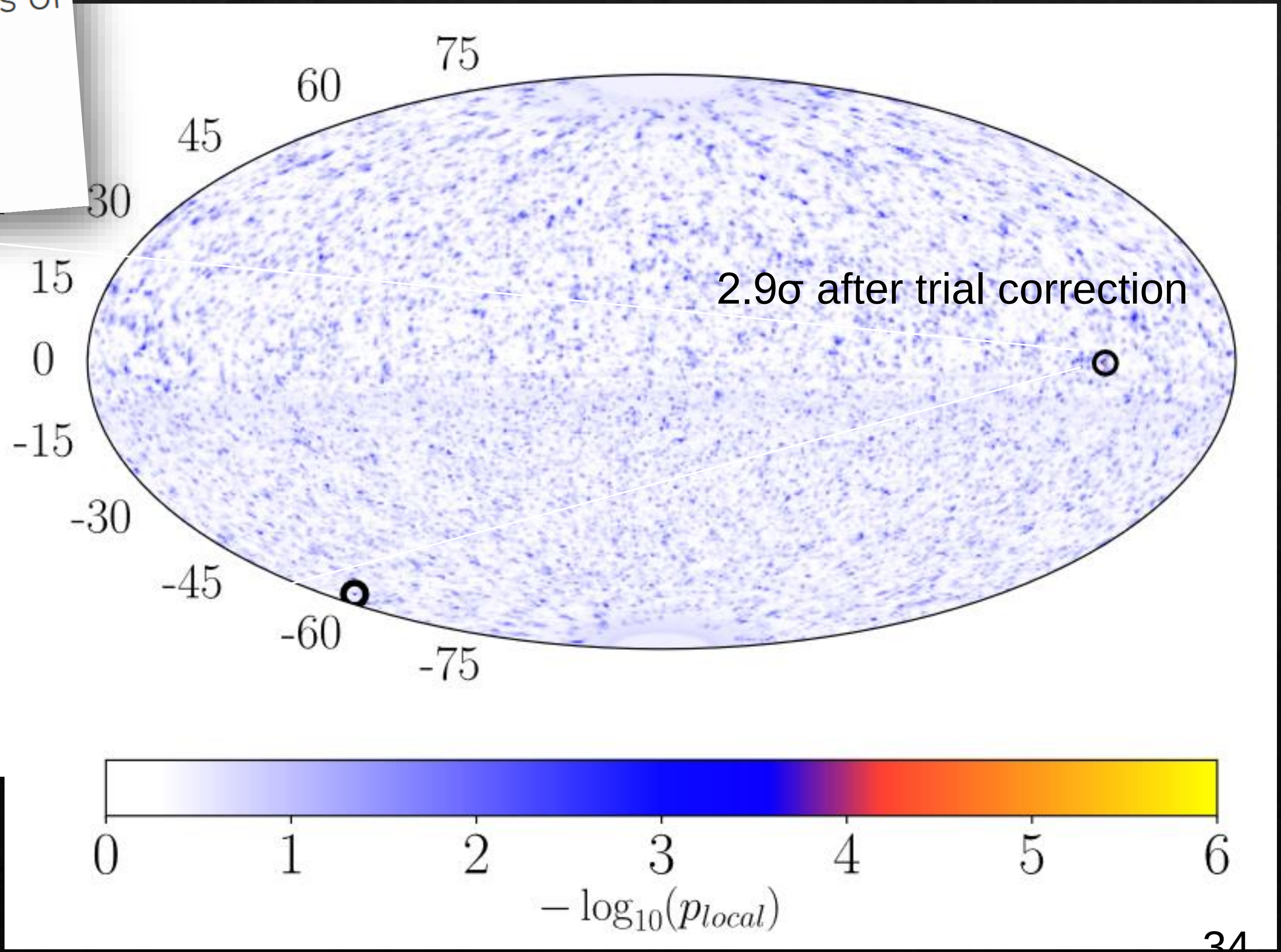

Featured in Physics
Editors' Suggestion

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





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

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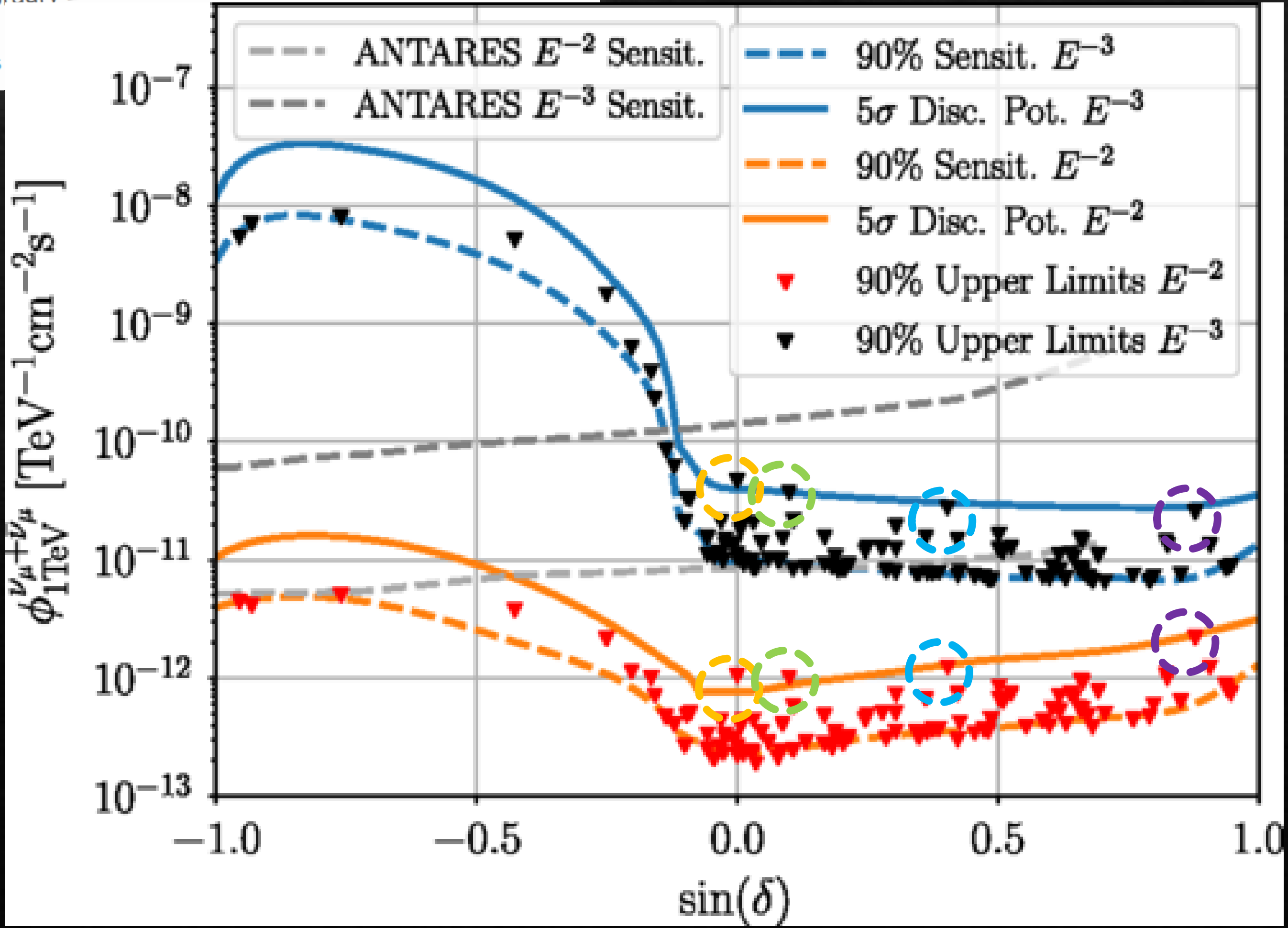
Physics See Synopsis: Possible Neutrino Sources



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

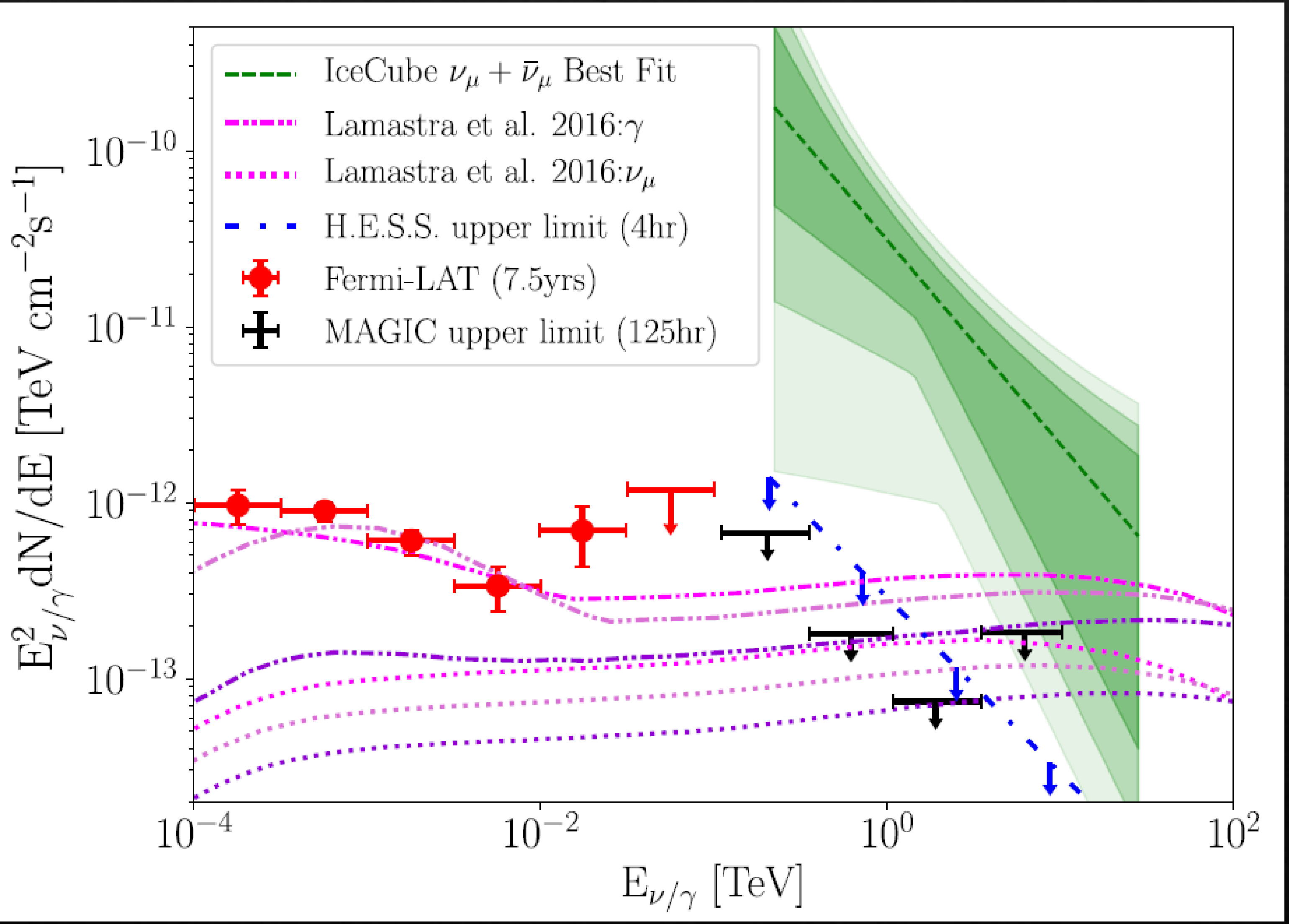
NGC 1068
(star burst AGN)

TXS 0506+056
(blazer AGN)

PKS 1424+240
(BL Lac Blazer AGN)

GB6 J1542+6129
(BL Lac Blazer AGN)

Best fit spectra for NGC1068



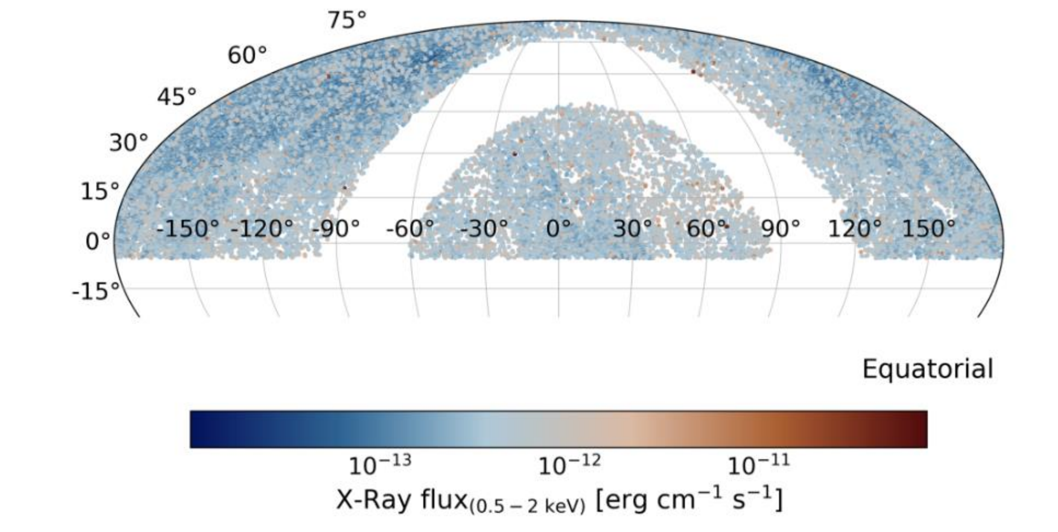
Estimated neutrino flux exceeding gamma-ray limits

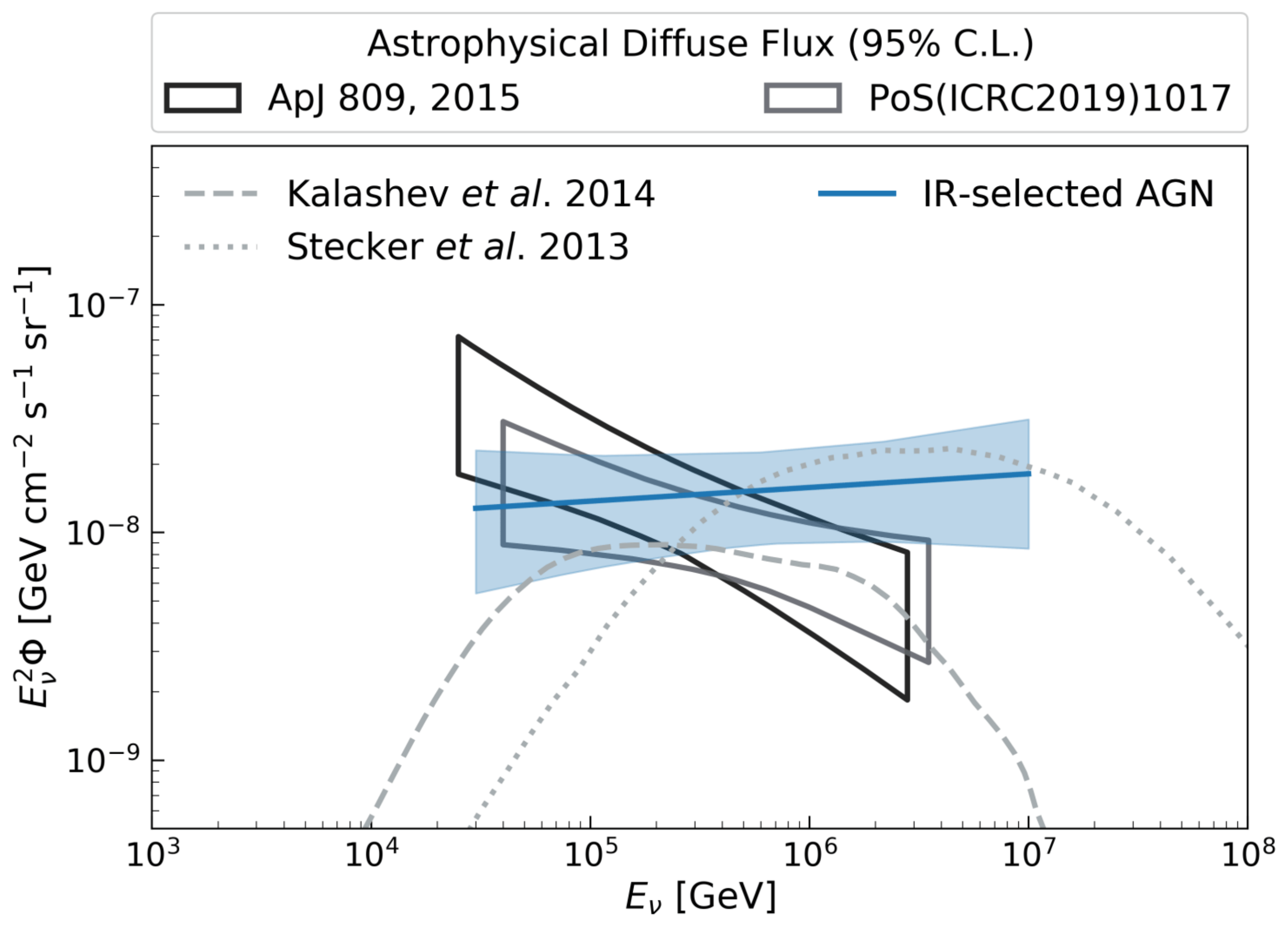
Obscured (不鮮明) AGN

- x-ray and IR bright AGN
- x-ray and radio bright AGN

主要生成天体である可能性

IceCube: http://arxiv.org/abs/2111.10169





これらの天体からニュートリノが来ていないという仮説は 2.6 sigmaで棄却

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

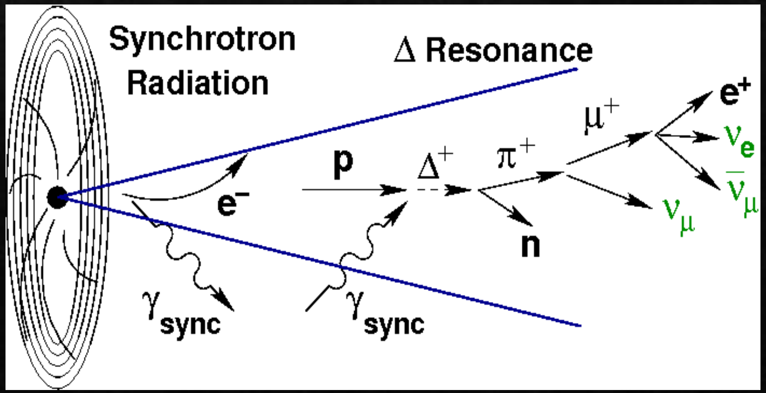
Published: 18 April 2012

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

IceCube Collaboration

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

[redacted] 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.

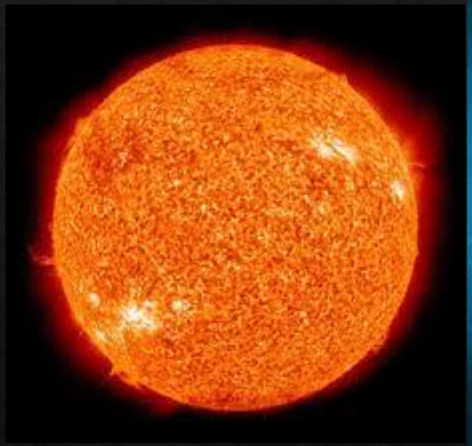


ニュートリノで光っている天体

地球

ニュートリノのエネルギー
<4MeV

太陽



ニュートリノのエネルギー
<20MeV

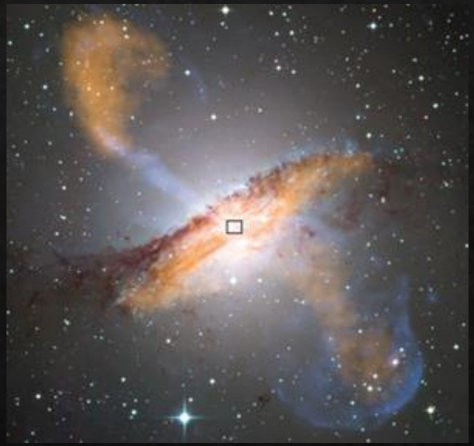
天体までの距離
1億4960万km
(0.00001581光年)

超新星爆発

ニュートリノのエネルギー
<100MeV

天体までの距離
16万光年
(160,000光年)

活動銀河核 ブレーザー



ニュートリノのエネルギー
>100,000,000MeV

天体までの距離
40億光年
(4,000,000,000光年)

活動銀河核 セイファート銀河

ニュートリノのエネルギー
>100,000MeV

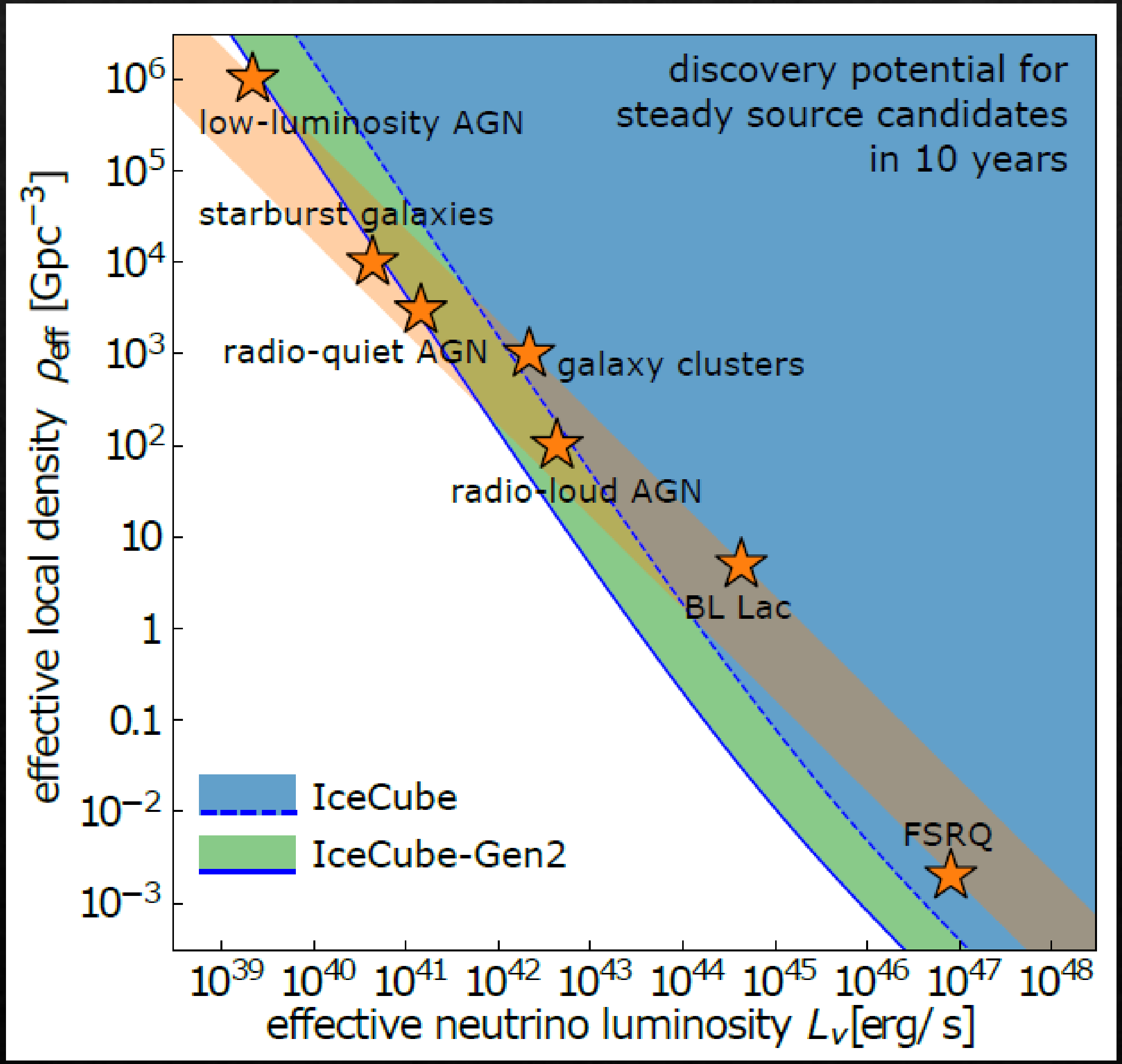
天体までの距離
6千万光年
(60,000,000光年)

活動銀河核 Obscured

**地球から銀河中心までの距離
2.8万光年

系統誤差の低減やデータを増やしたときの結果に注目!

Neutrino emitting steady source candidates



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

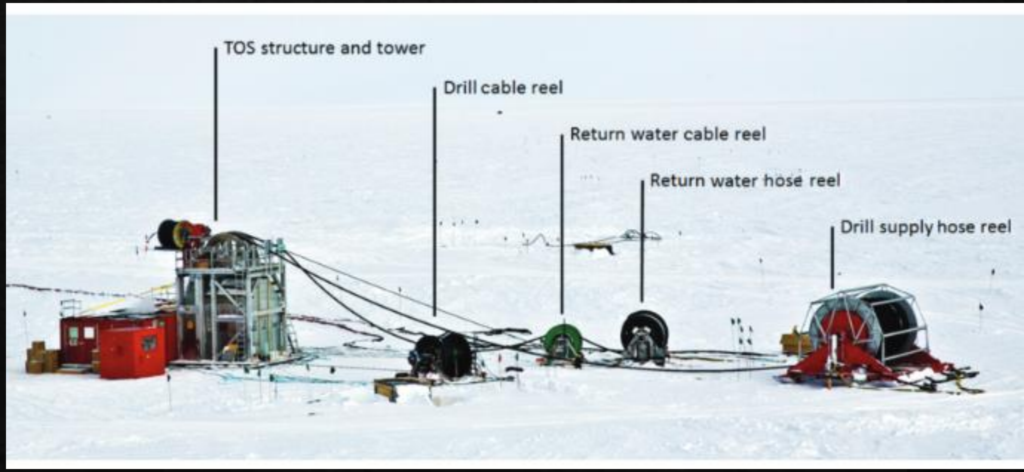
一方、各天体から期待できるニュートリノの数

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

から、稀で明るい点源からL_νに対して制限がかかり始める

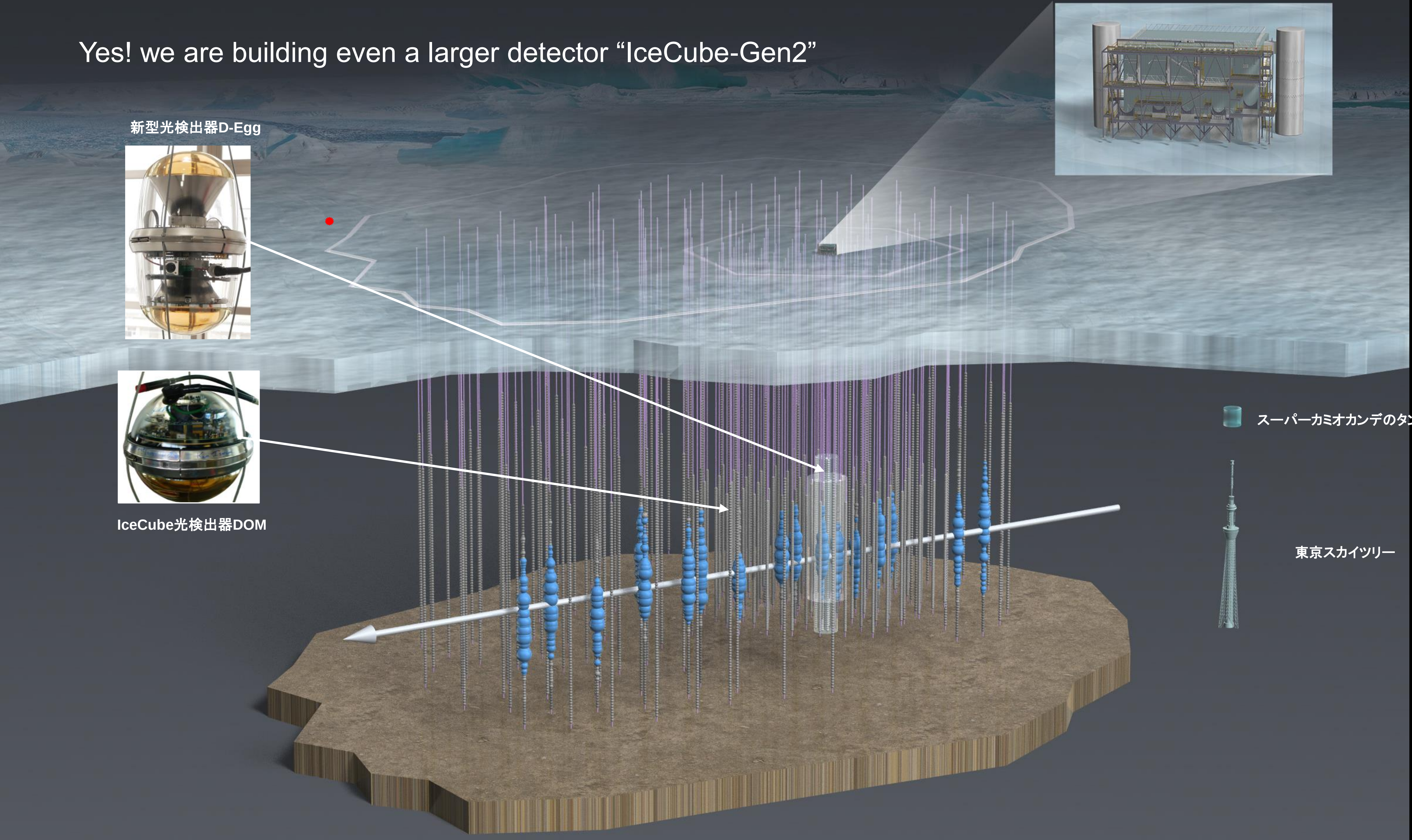
No one can stop us!

- この秋、Wisconsin州から南極に送られた荷物…



次の建設の準備が進行中

Yes! we are building even a larger detector "IceCube-Gen2"



千葉大学で開発された
新型光検出器モジュールD-Egg

紫外線透過耐圧ガラス (岡本硝子)
デザイン (日本海洋事業)

紫外線透過光結合ゲル(信越シリコン)

8” PMT R5912-100
(浜松ホトニクス)

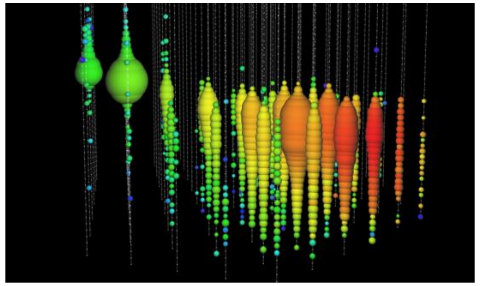
高圧電源ボード
(カイズワークス)

エレキボード
(プラックス)

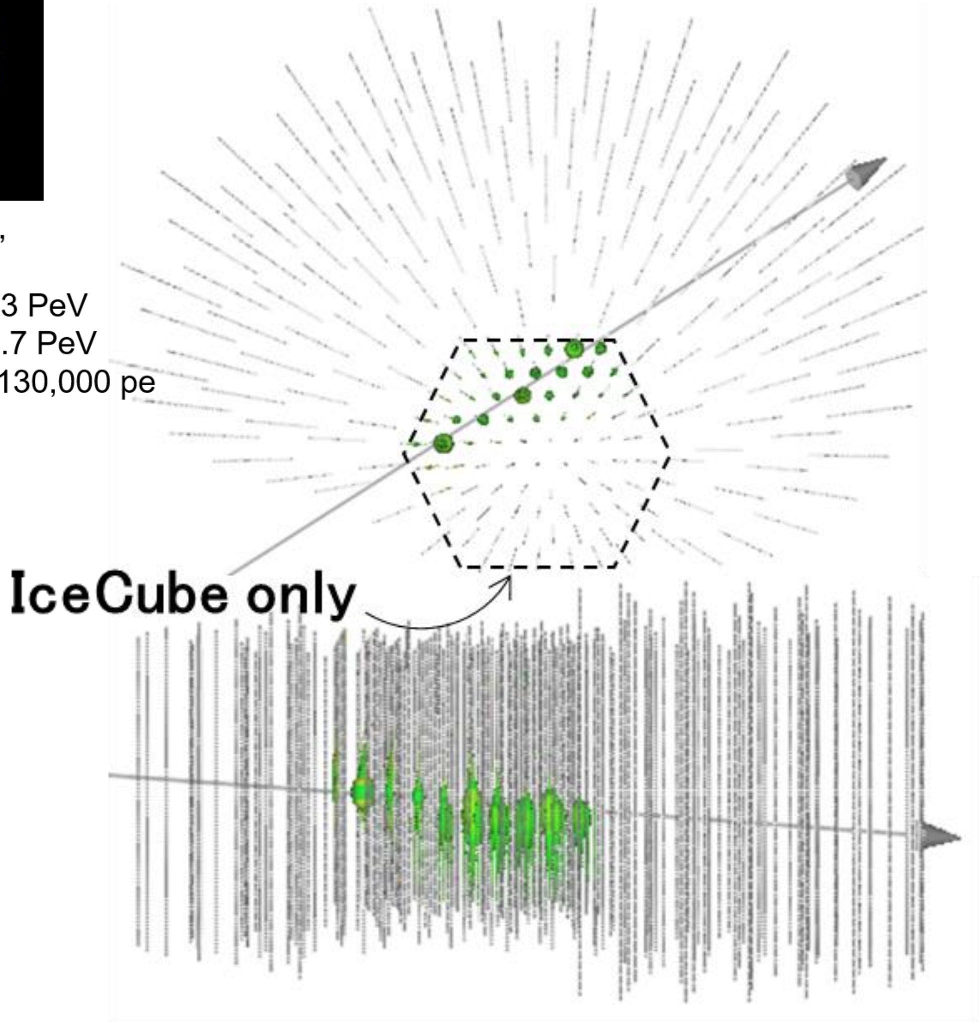
磁場シールド
(日立金属)

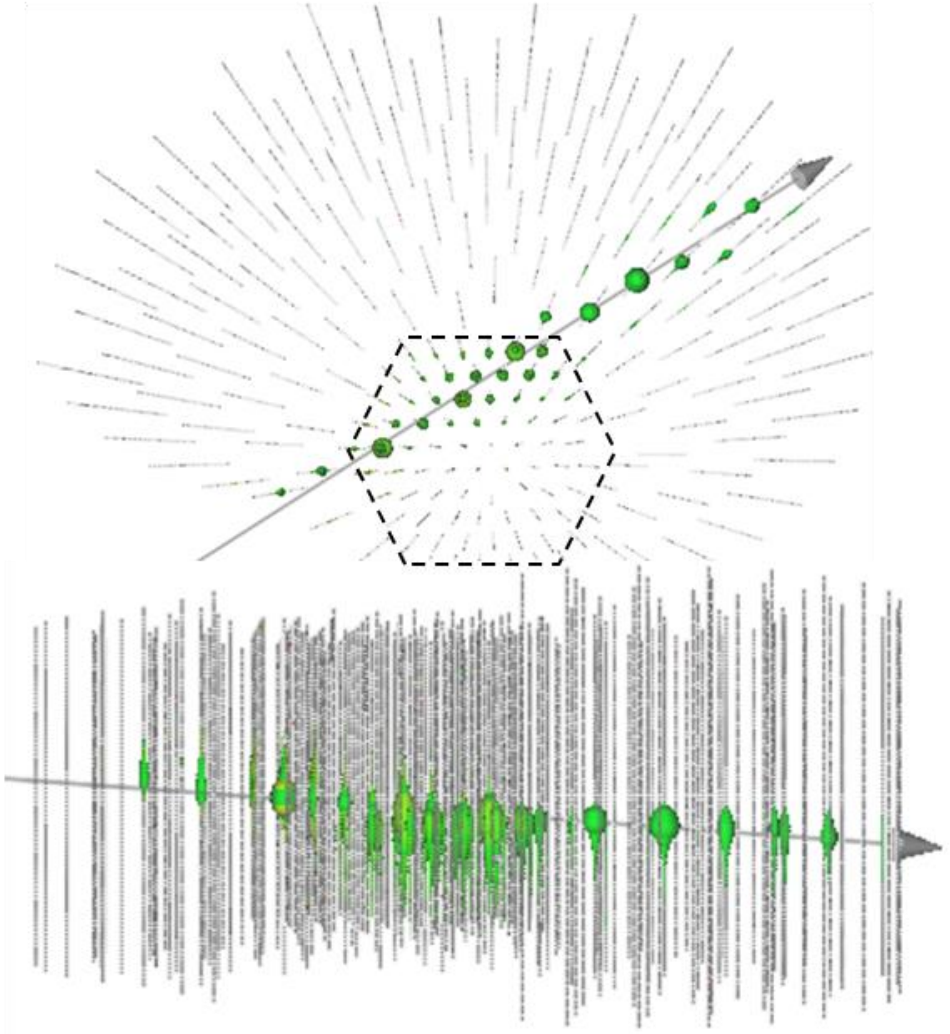
LEDリング

体積が大きくなることで角度分解能が向上

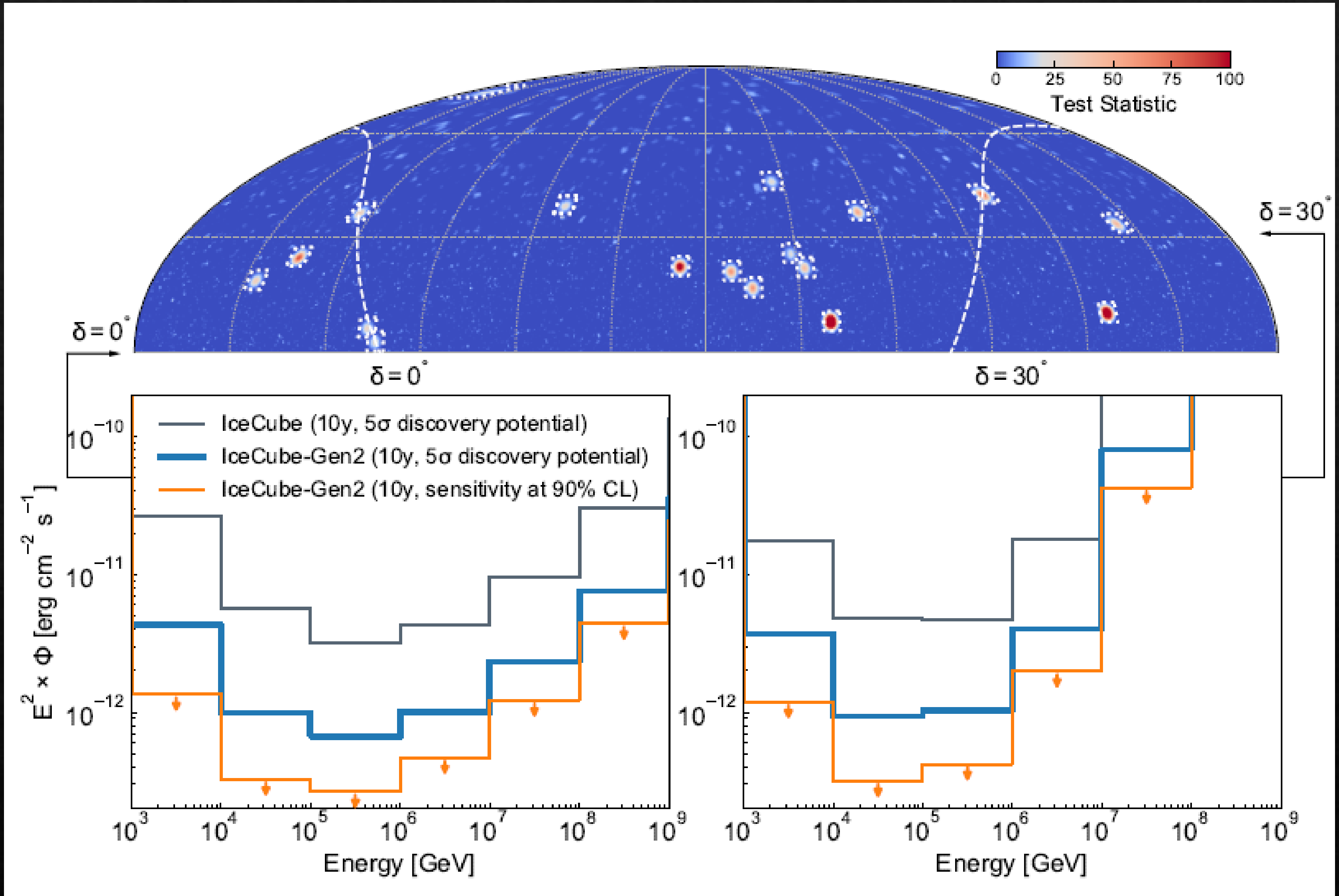


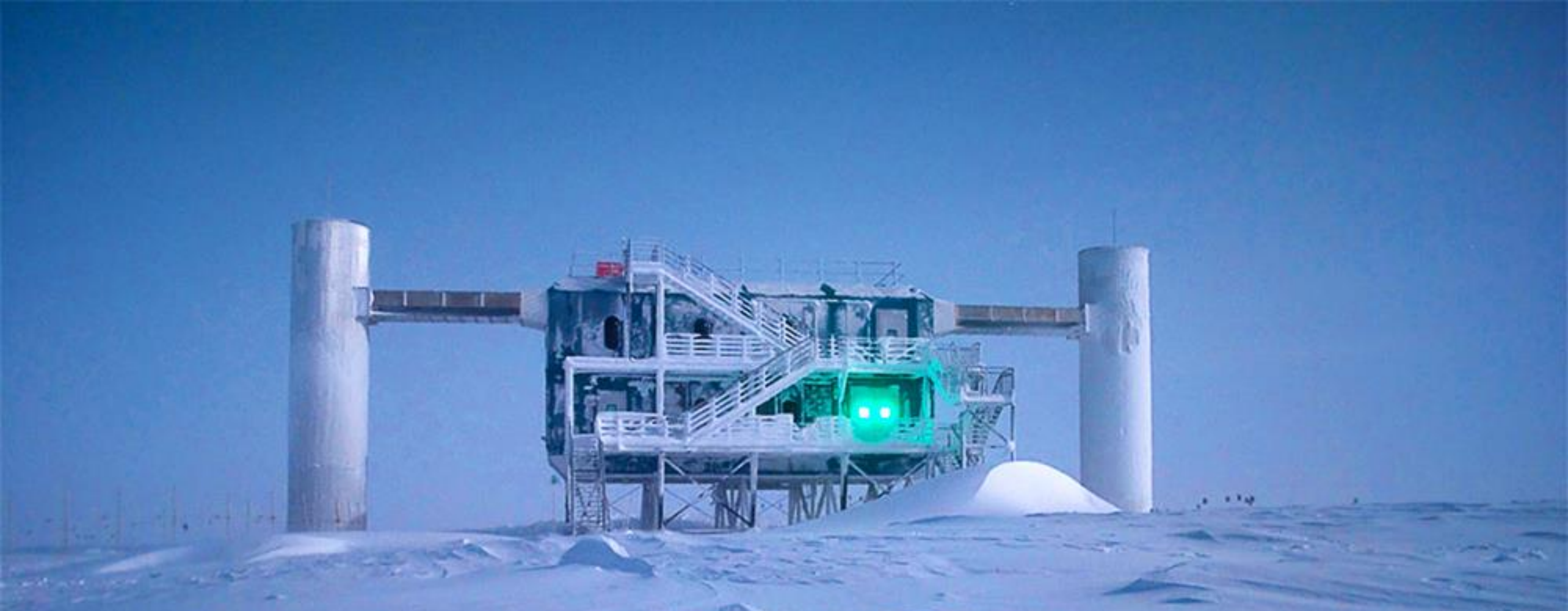
Highest energy event to date,
an upward-going track.
- Deposited energy 2.6±0.3 PeV
- Median neutrino energy 8.7 PeV
- Observed photoelectrons 130,000 pe





期待されるニュートリノ点源に対する感度





- 透過性の高いニュートリノは、光で見えない遠方宇宙の高エネルギー放射宇宙を見ることができる
- 1987年の超新星爆発以来25年間も観測されてなかった太陽系の外からくる宇宙ニュートリノの観測が2012年から進んでいる
- さまざまな望遠鏡と連携して観測を行うマルチメッセンジャー天文学によって高エネルギー放射天体の姿を明らかにする
- 確立した検出原理を発展させた次世代ニュートリノ望遠鏡計画IceCube-Gen2が進んでいる
- 日本グループは、物理解析、及び、検出器で最も重要な基幹部品である光検出器の開発の中心としても活躍中

http://icecube.wisc.edu

IceCube

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
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

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Massachusetts Institute of Technology
Michigan State University
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University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

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Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
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German Research Foundation (DFG)
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)

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