The 30th Anniversary Conference of the Rencontres du Vietnam
ICISE, Quy Nhon, Vietn

Neutrino Astronomy

Recent updates from experiments

Aya Ishihara

ICEHAP, Chiba University, Japan

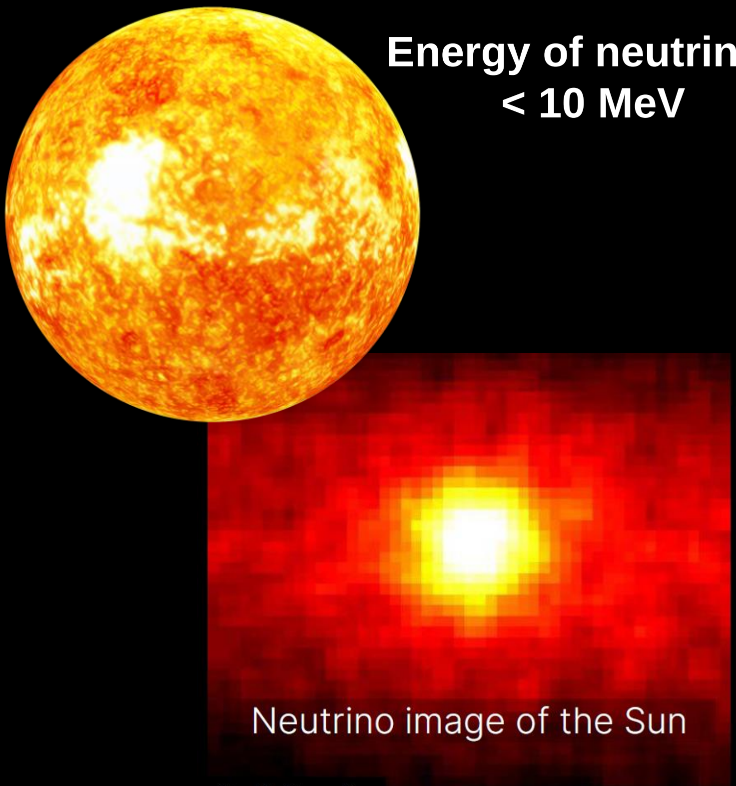
(http://www.icehap.chiba-u.jp/en/about/index.html)

Making invisible visible with neutrinos

- Neutrino can visualize the activities in the dense/obscured media

Energy of neutrinos
~ MeV

Energy of neutrinos
< 10 MeV

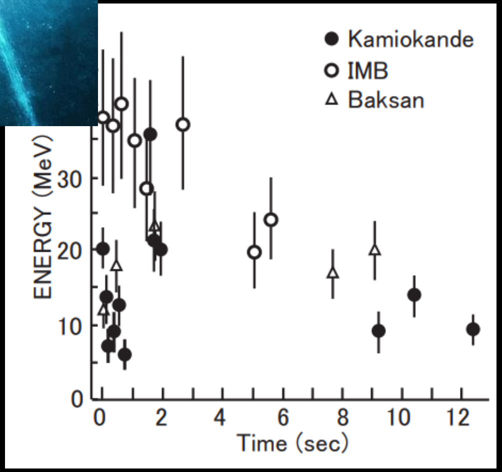


Credit: SuperK

Energy of neutrinos
< 100 MeV

SN1987a

Measured with Kamiokande, IMB, Baksan in 1987



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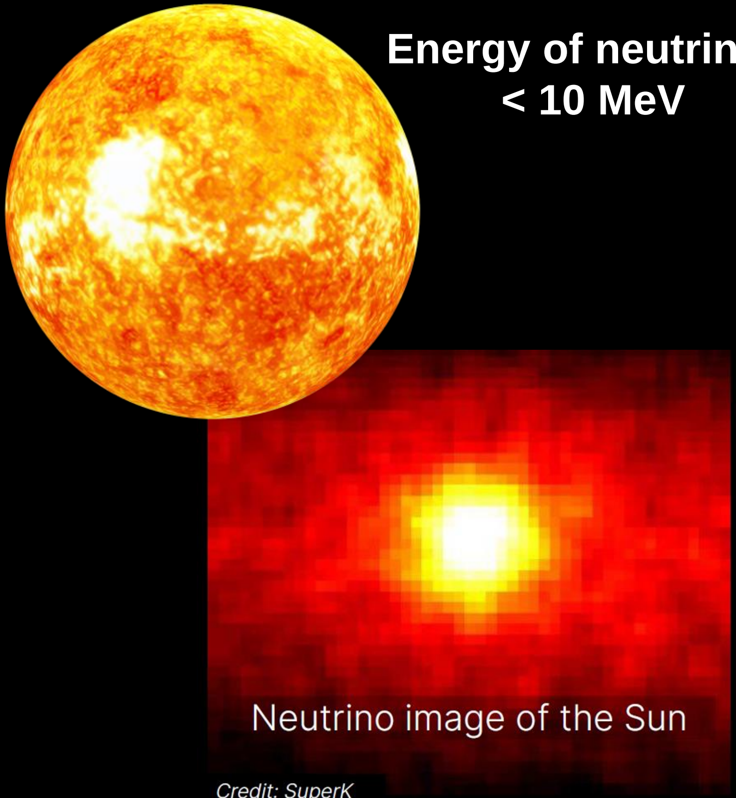

Credit: SuperK

Energy of neutrinos
< 100 MeV

SN1987a

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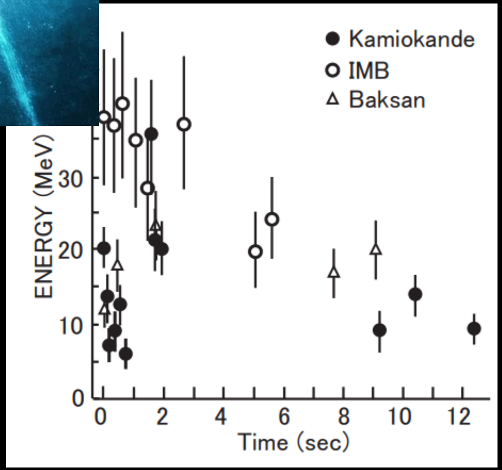
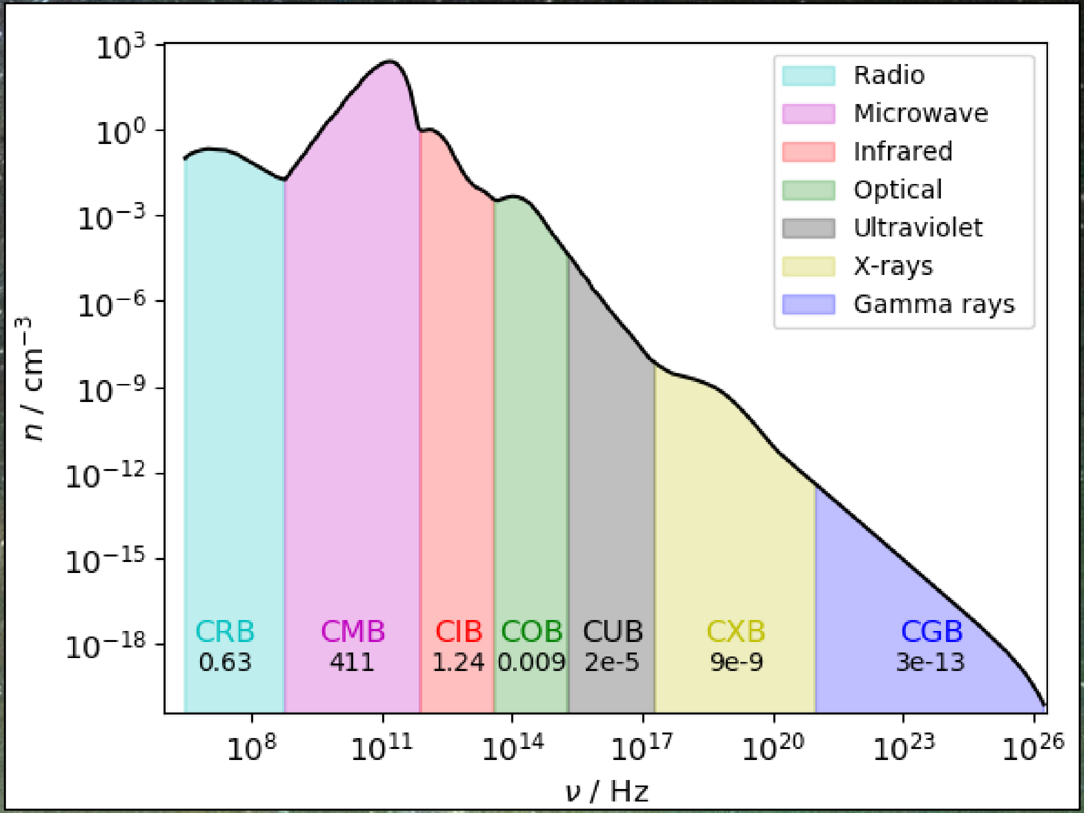


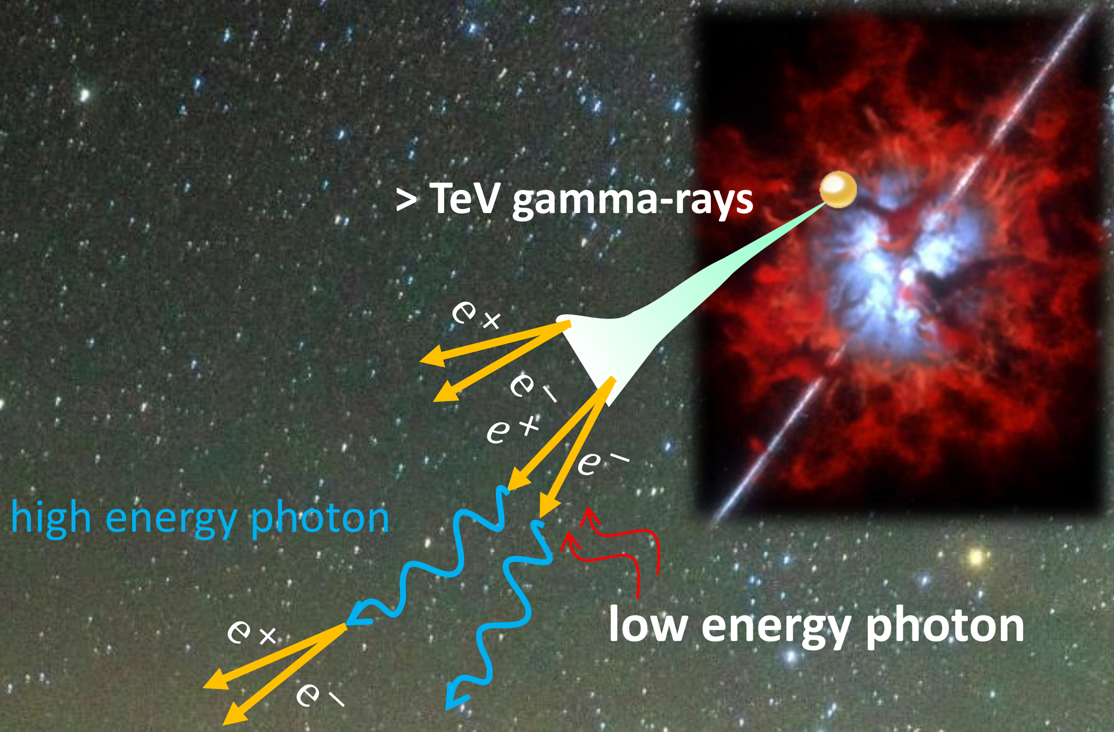
What can we see with 10 TeV – 10 PeV high energy neutrinos?

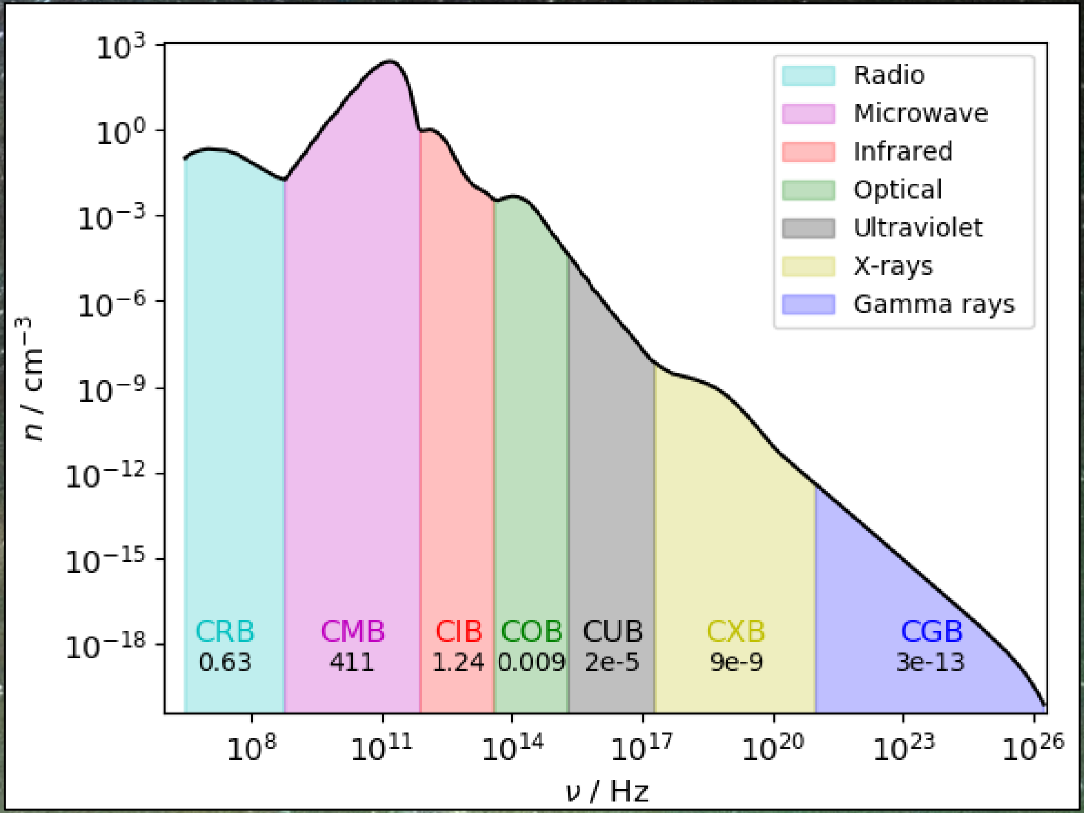
Invisible Universe?

Invisible Universe?

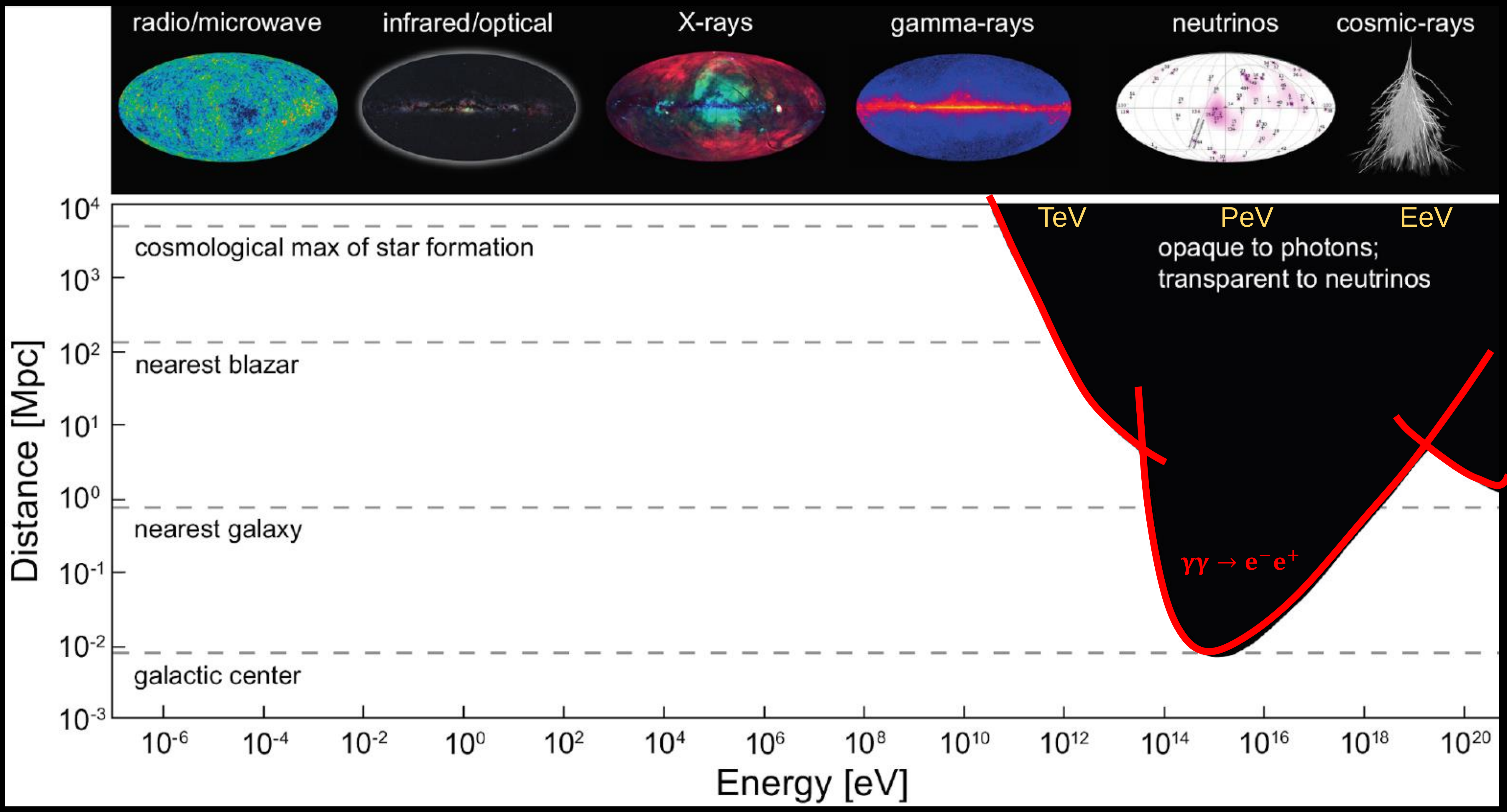


Invisible Universe !





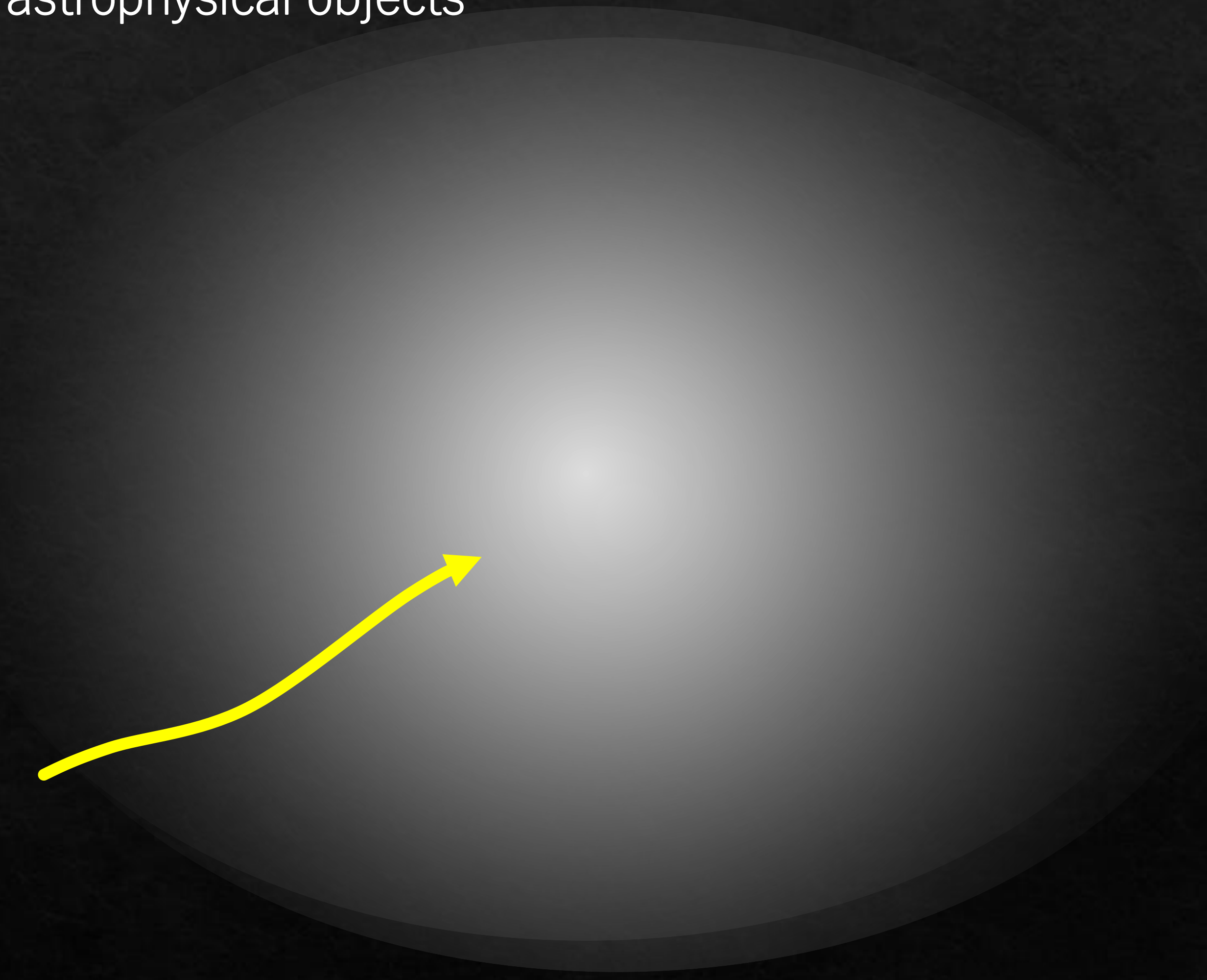
- >TeV photon attenuated with the extragalactic background light



radio/microwave
infrared/optical
X-rays
gamma-rays
neutrinos
cosmic-rays
TeV
PeV
EeV
opaque to photons;
transparent to neutrinos
cosmological max of star formation
nearest blazar
nearest galaxy
galactic center
$\gamma\gamma \to e^- e^+$
Distance [Mpc]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-6}
10^{-4}
10^{-2}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
Energy [eV]

How to create the high energy neutrinos

high energy (1～10^8TeV) cosmic-rays (proton and nuclei) interact with matter (gas, plasma) and photon field in the astrophysical objects

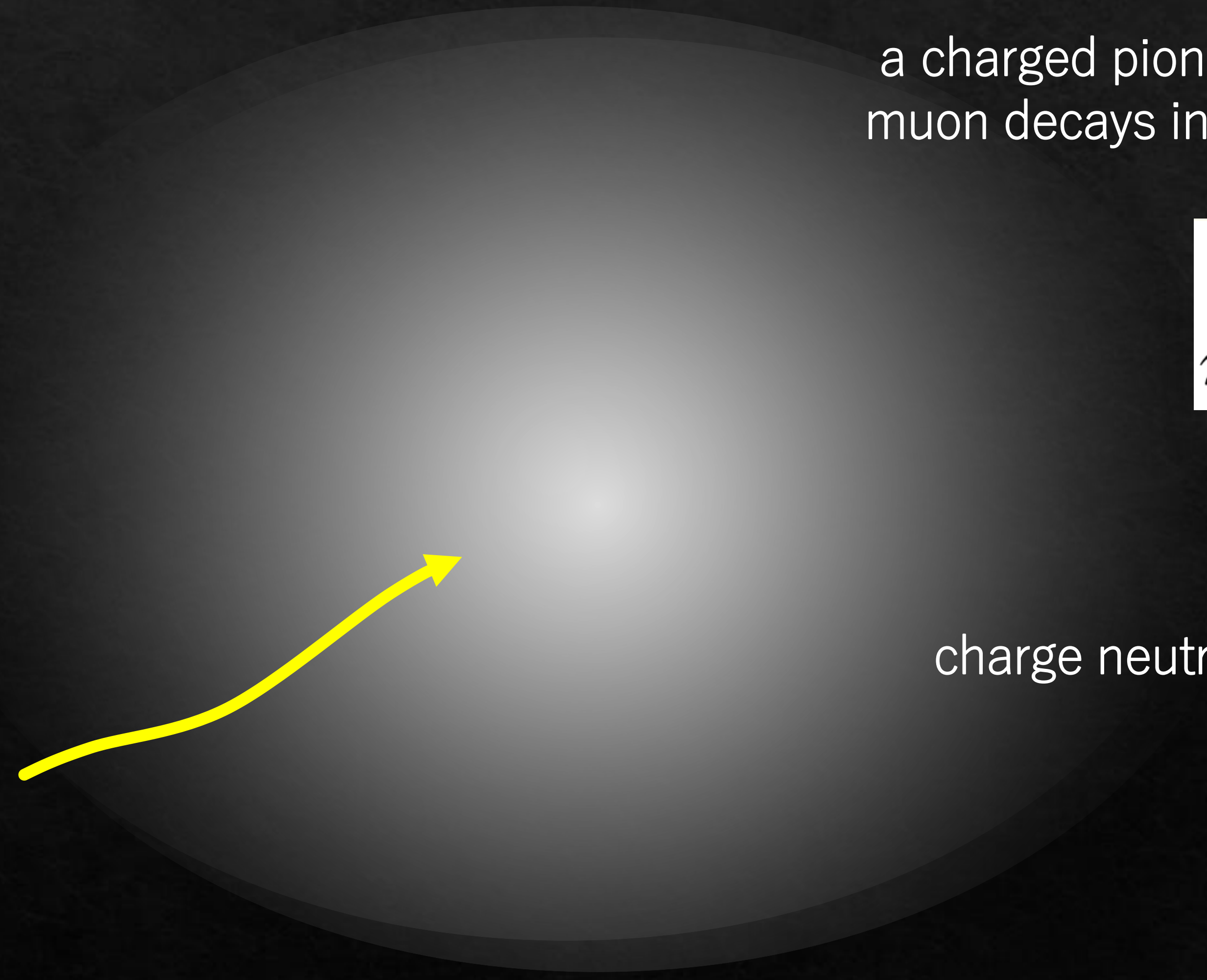


mesons (pions) are created
(both charged and neutral)

$$
\begin{aligned}
p + \gamma &\rightarrow n + \pi^{+} \\
p + \gamma &\rightarrow p + \pi^{0}
\end{aligned}
$$

$$
\begin{aligned}
p + p &\rightarrow p + p + \pi^{0} \\
p + p &\rightarrow p + n + \pi^{+} \\
p + p &\rightarrow p + p + \pi^{+} + \pi^{-} \ldots
\end{aligned}
$$

How to create the high energy neutrinos



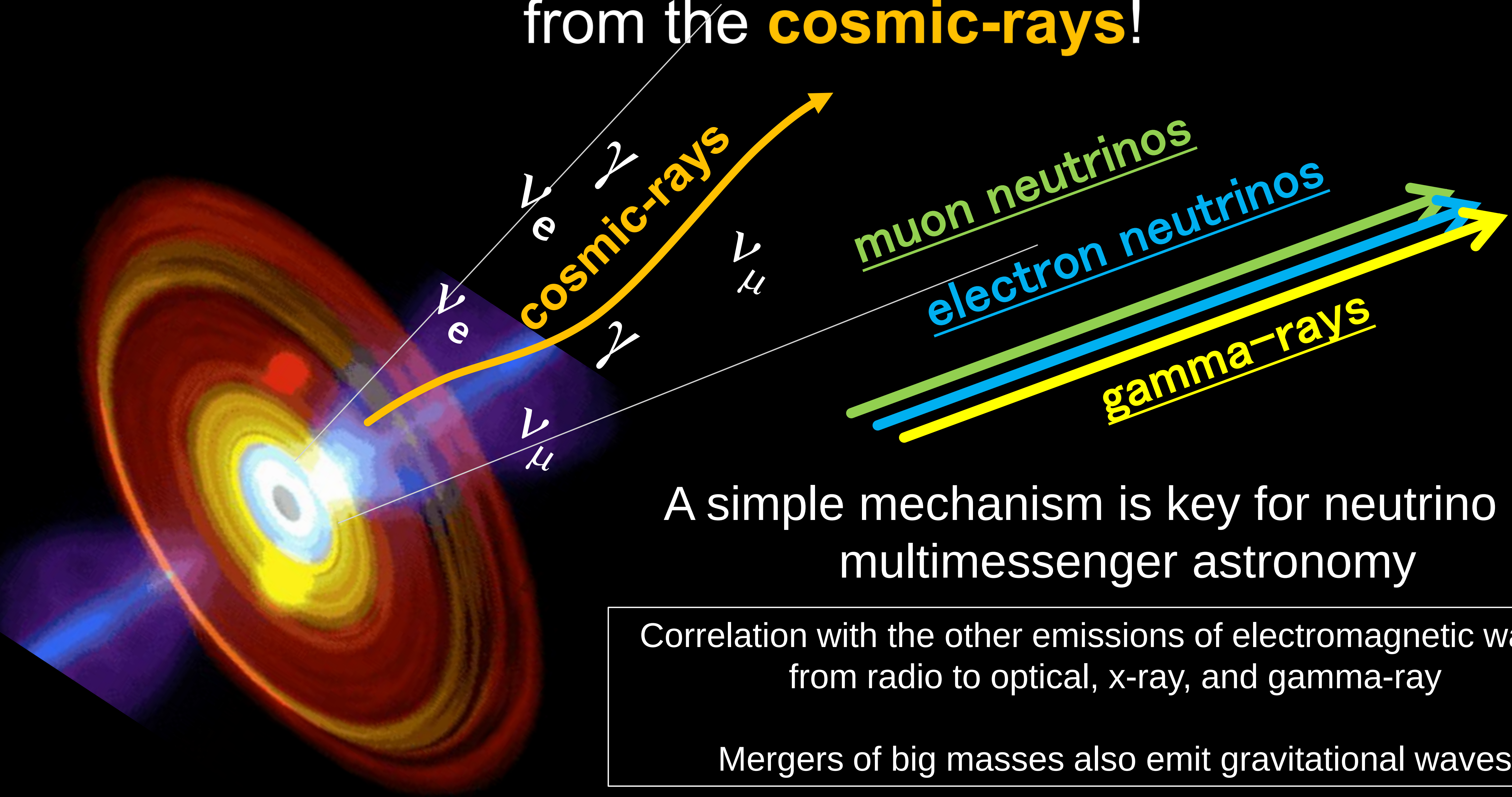
a charged pion decays into muon and neutrino, a muon decays into positron and (anti) neutrinos

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

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

charge neutral pions creates gamma-rays

When **neutrinos** are born, so are **gamma-rays**, from the **cosmic-rays**!

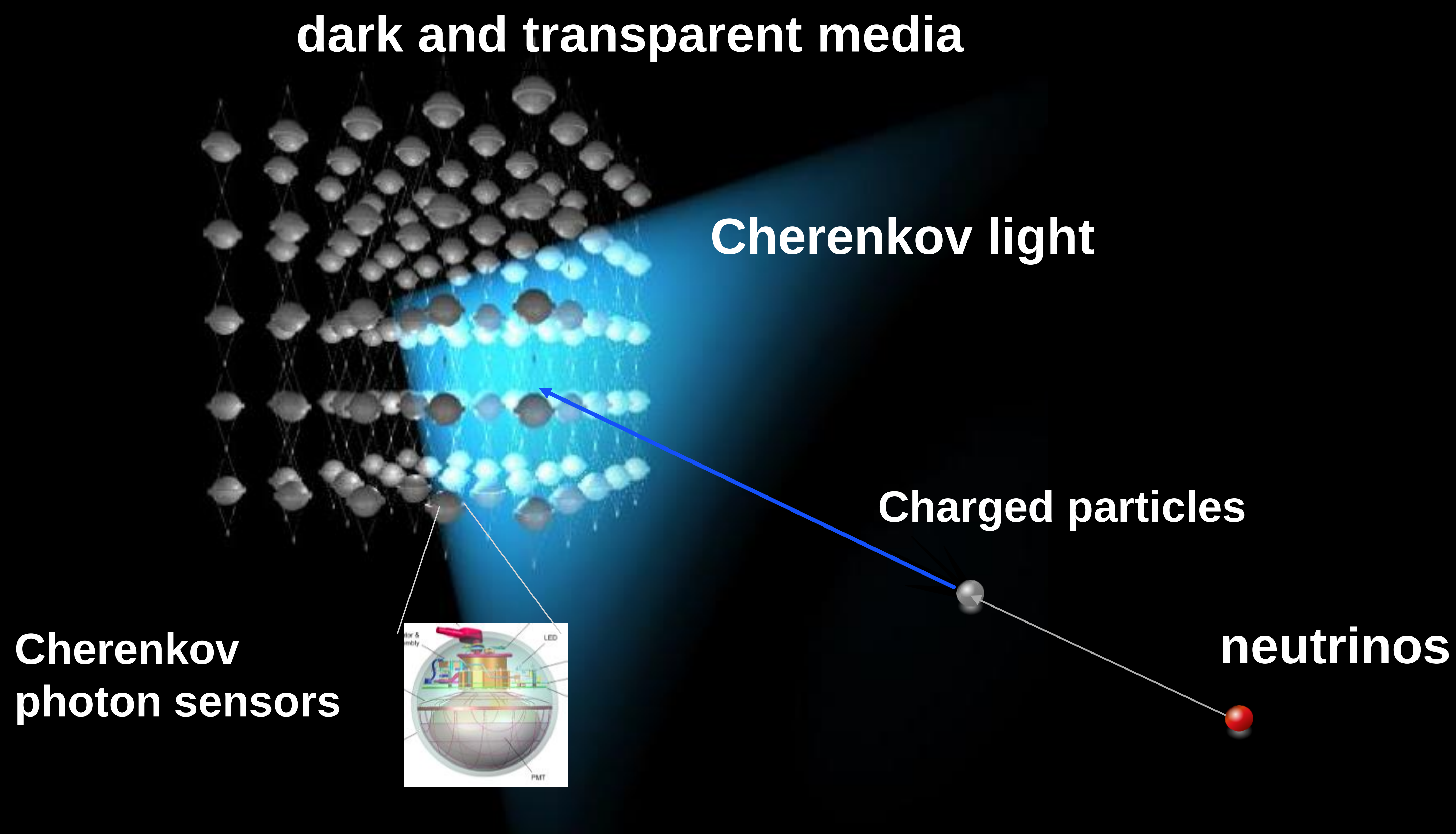


A simple mechanism is key for neutrino and multimessenger astronomy

Correlation with the other emissions of electromagnetic waves; from radio to optical, x-ray, and gamma-ray

Mergers of big masses also emit gravitational waves

How the neutrino telescopes looks like?

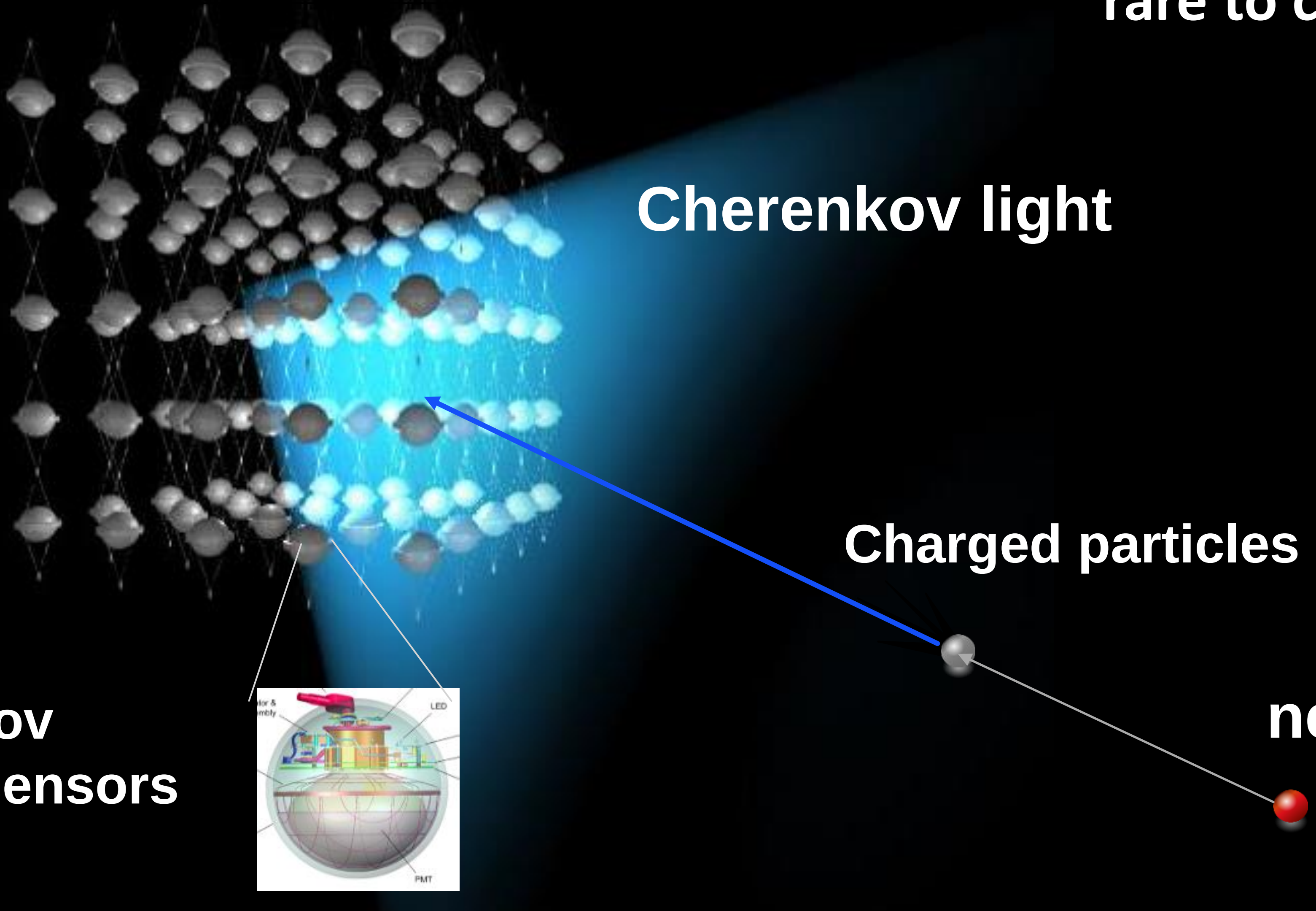


How the neutrino telescopes looks like?

High energy neutrinos are rare to convert into light

> 1km^3

dark and transparent media



Cherenkov light

Charged particles

neutrinos

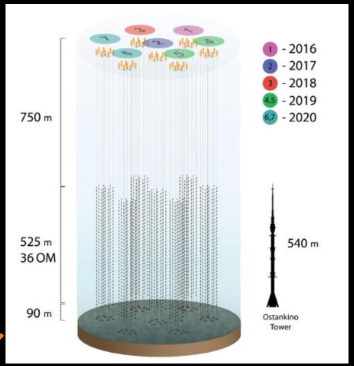
Cherenkov photon sensors

Neutrino Telescopes in operation around the world

Mediterranean Ocean

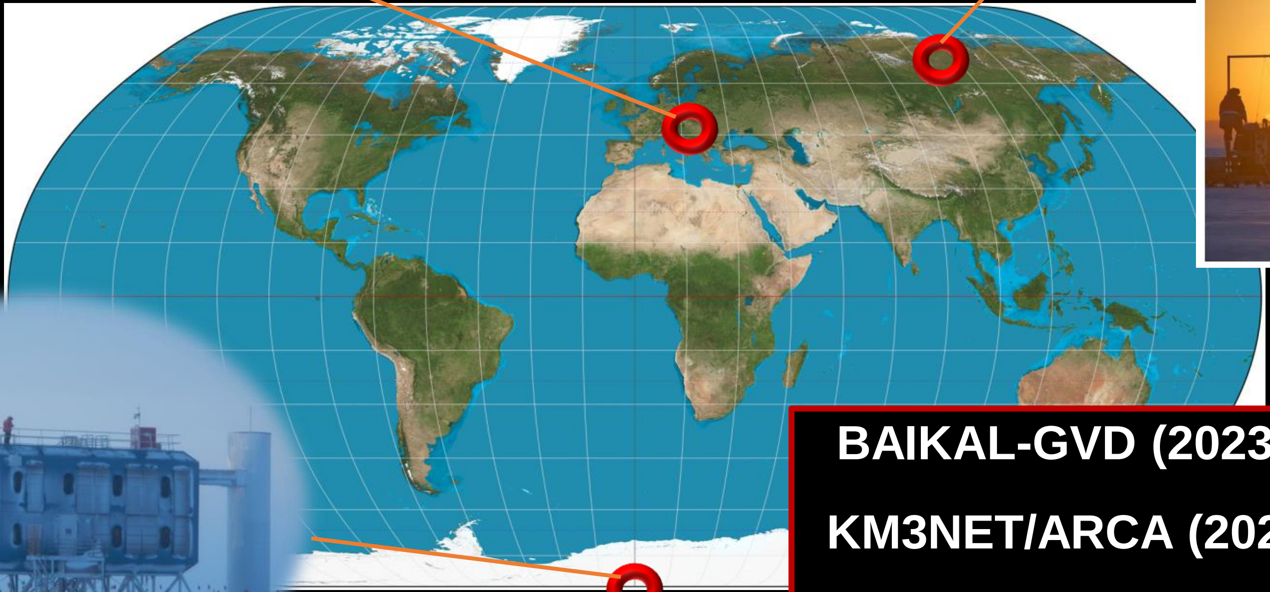
KM3NET – ARCA (HE array)
as of Aug 2023, 21 ARCA strings

BAIKAL-GVD



as of Aug 2023,
96 strings
3456 OMs

Lake Bikal



South Pole
Glacial ice

BAIKAL-GVD (2023, 96 x 36 = 3456 om) ~0. 5km^3

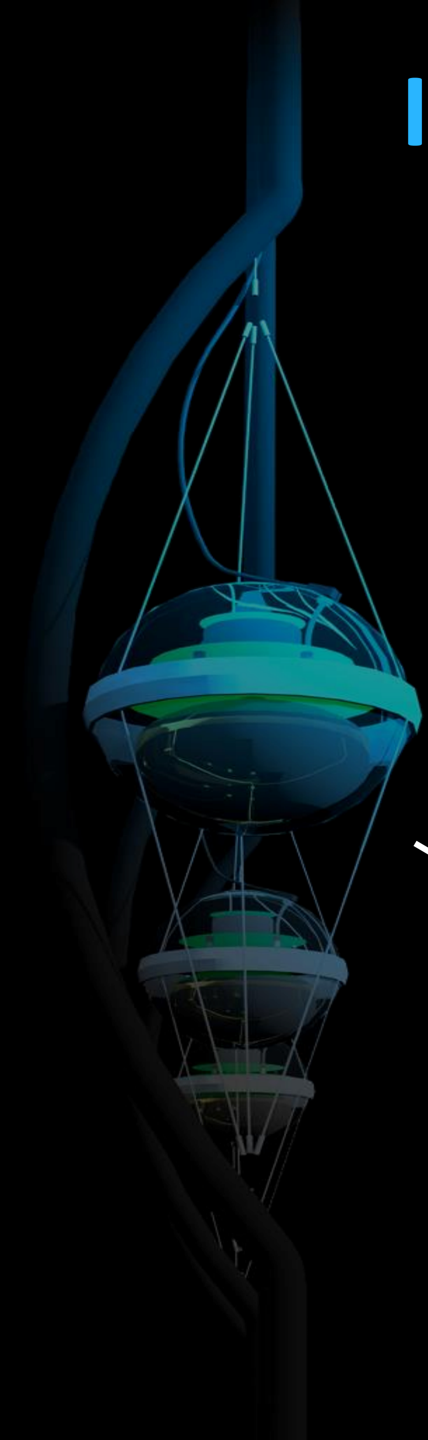
KM3NET/ARCA (2023, 21 x 18 = 378 om) ~0.1 km^3

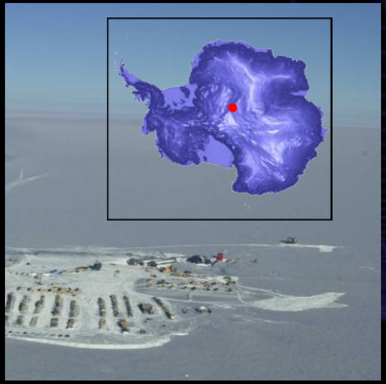
IceCube (since 2011, 5160 om) 1 km^3

IceCube: The South Pole Neutrino Detector

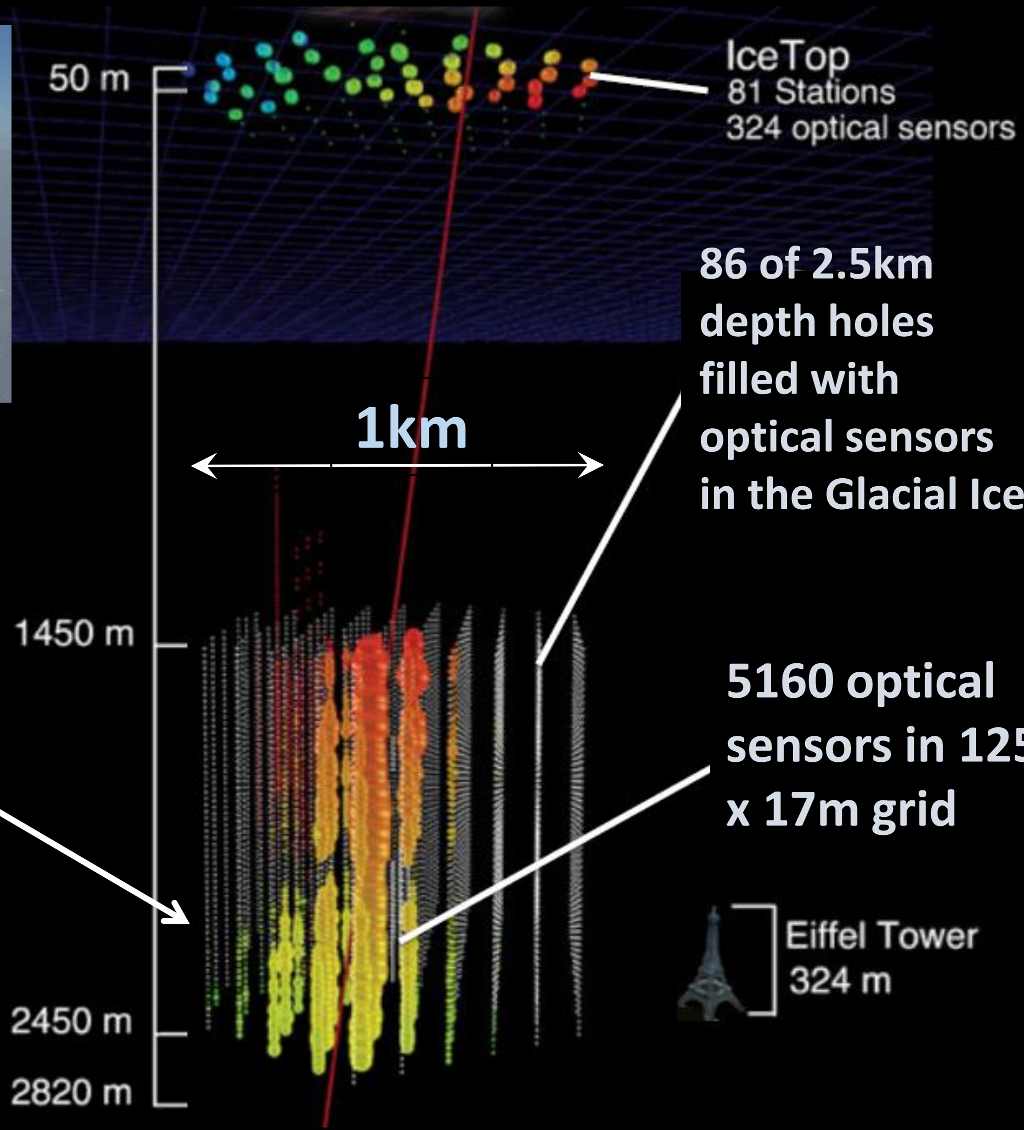
The largest underground particle detector

16,000 x SuperK tank!



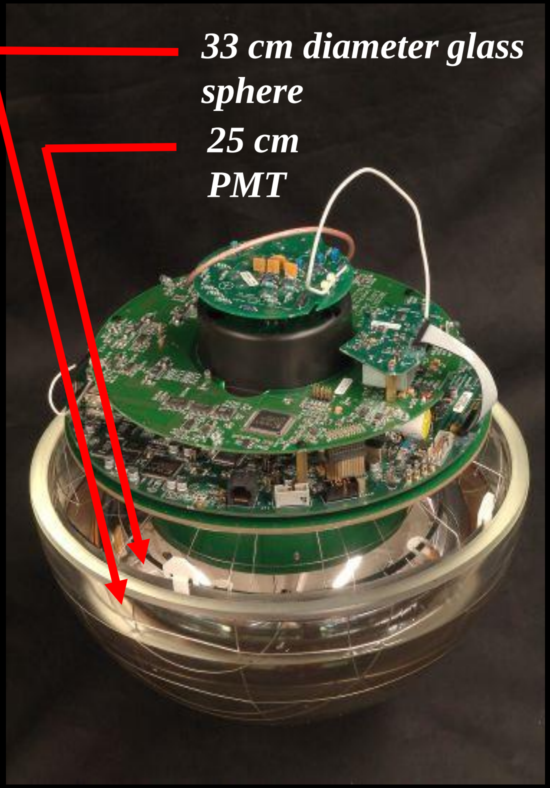


Amundsen-Scott South Pole station

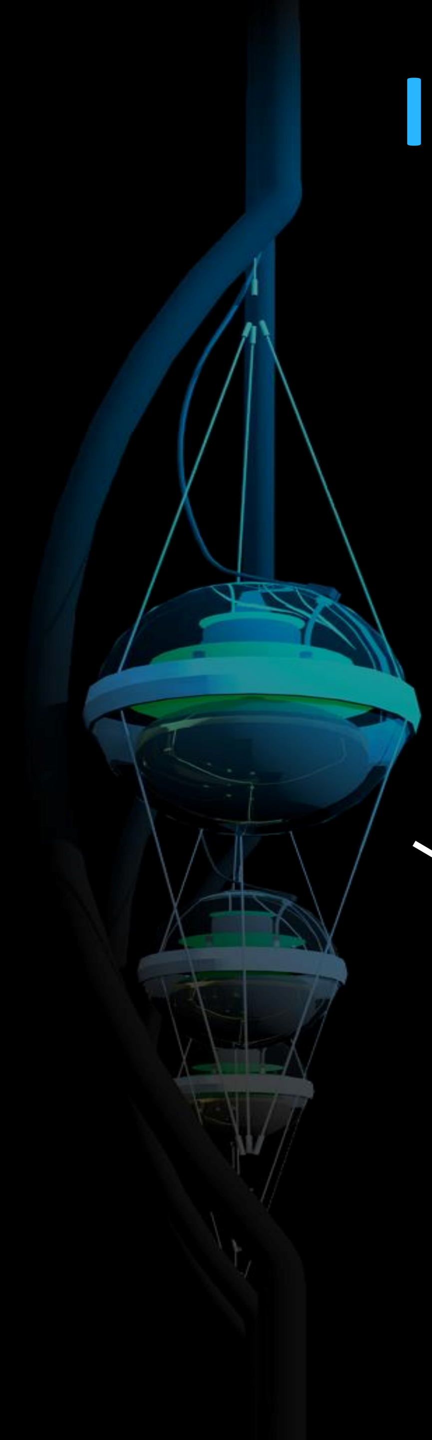


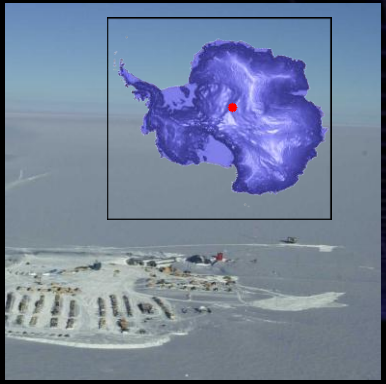
86 of 2.5km depth holes filled with optical sensors in the Glacial Ice

5160 optical sensors in 125m x 17m grid

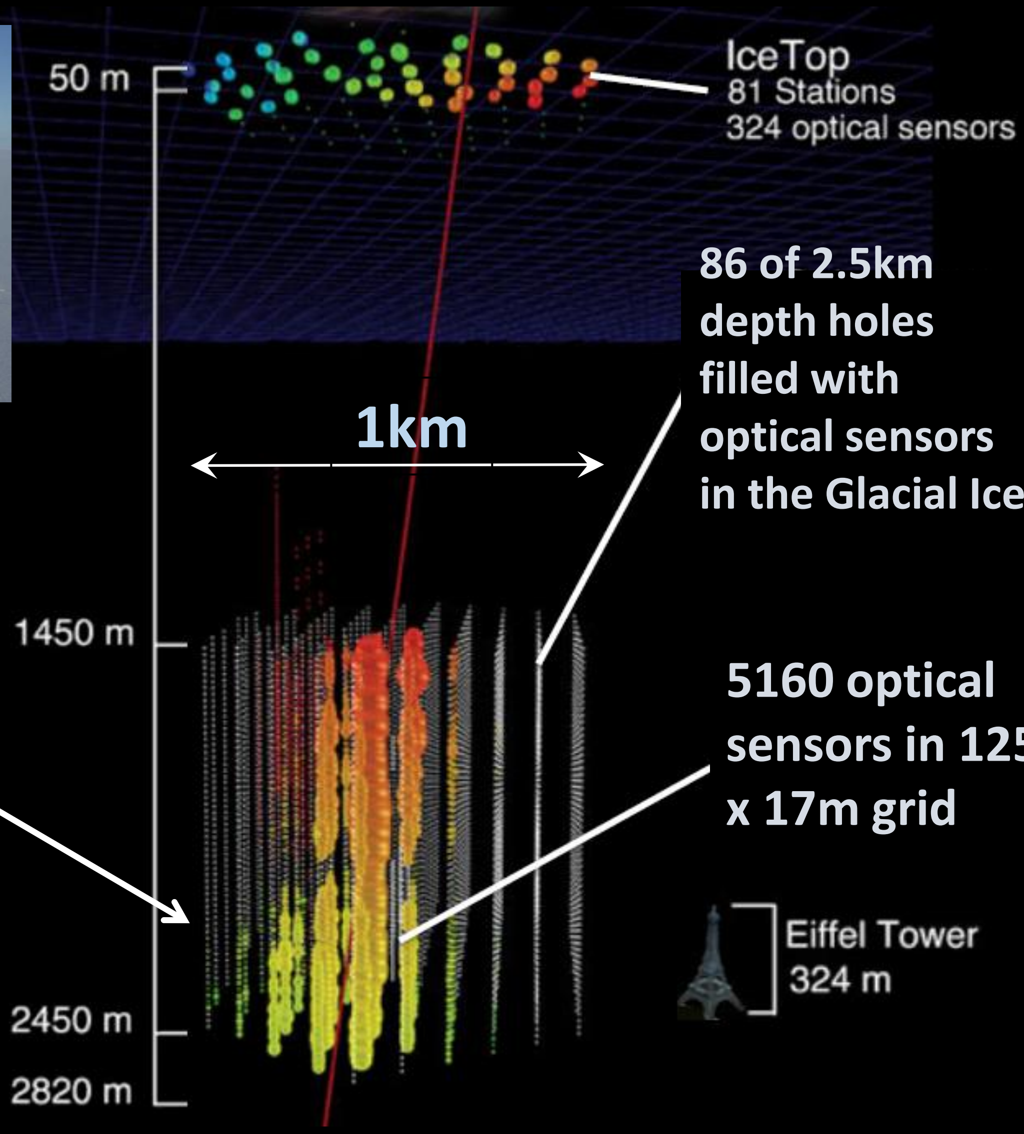


IceCube: The South Pole Neutrino Detector



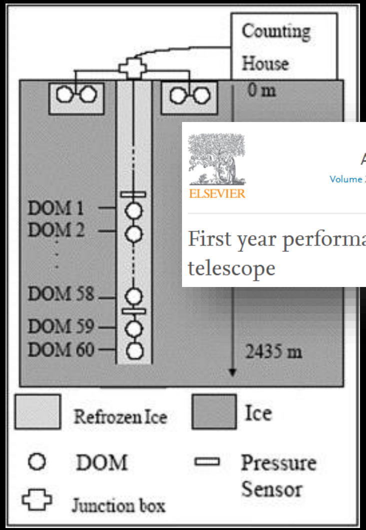


Amundsen-Scott South Pole station



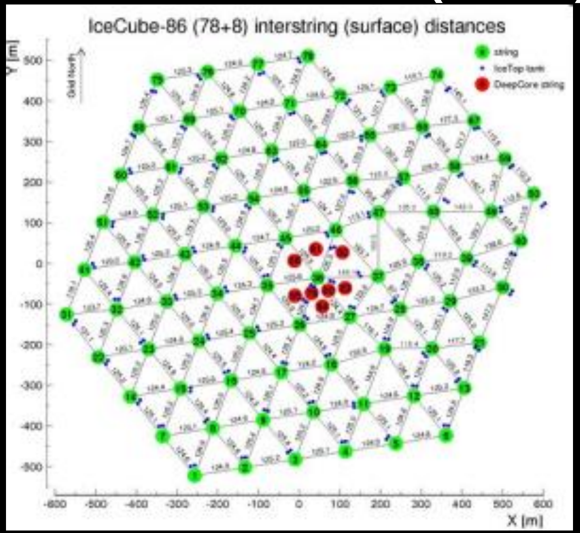
86 of 2.5km depth holes filled with optical sensors in the Glacial Ice

5160 optical sensors in 125m x 17m grid

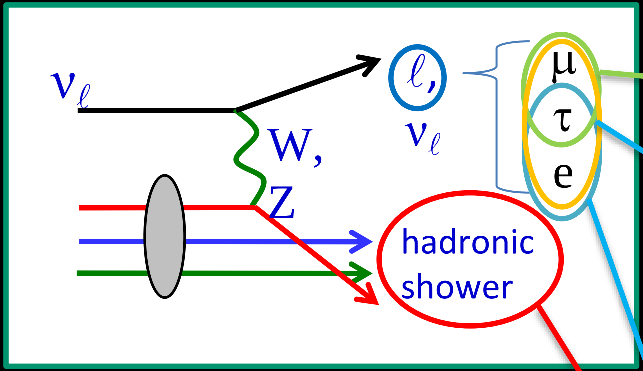


IC1 (2005-2006)

IC86 = full IceCube (2011~)

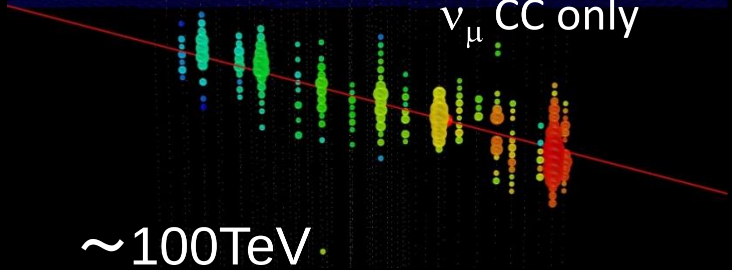


IceCube Flavor Identifications



Up-going muon track event

Good angular resolution



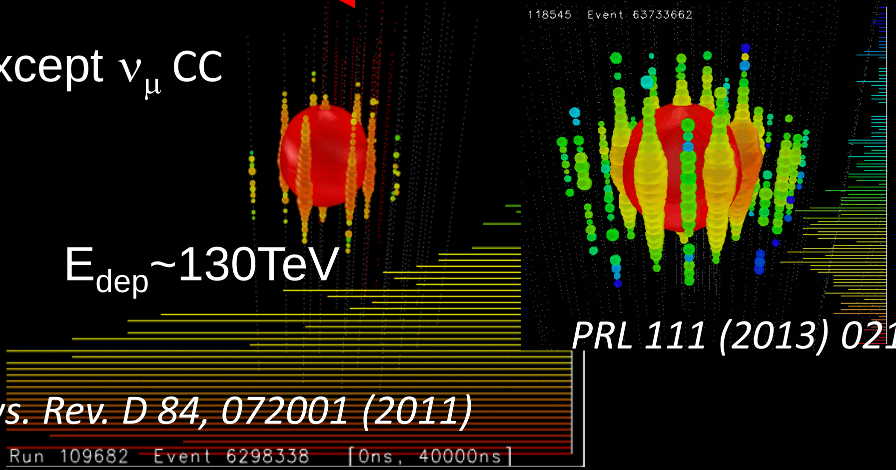
ν_μ CC only

∼100TeV

Cascade events

Good energy resolution

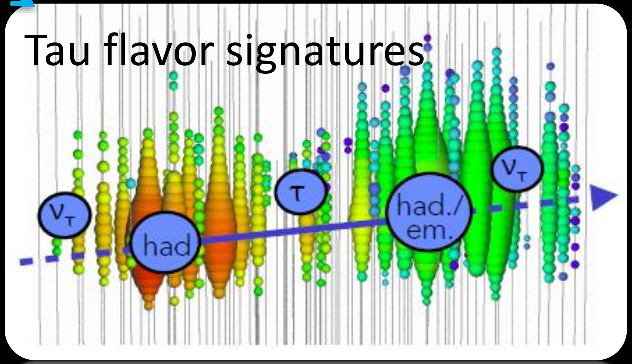
All except ν_μ CC



E_{dep}~130TeV

Phys. Rev. D 84, 072001 (2011)

PRL 111 (2013) 021103



From the first observation to the > 10 year sample

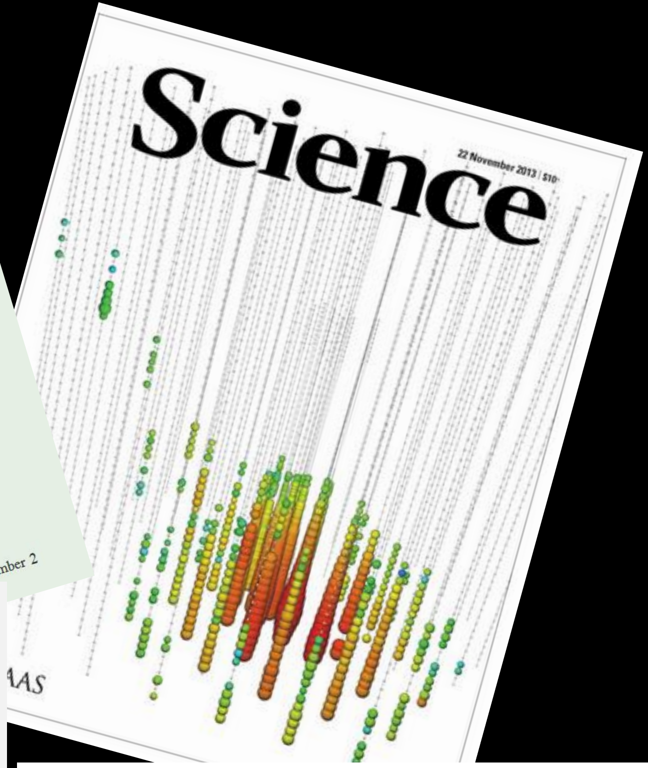
2013

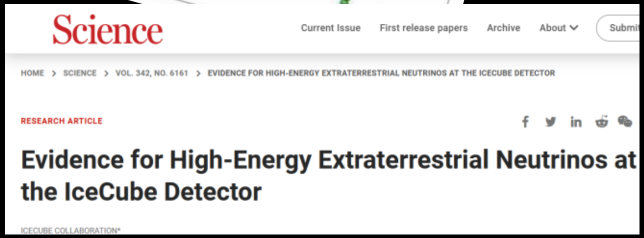
First Observation of PeV-Energy Neutrinos with IceCube

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

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

Published July 8, 2013

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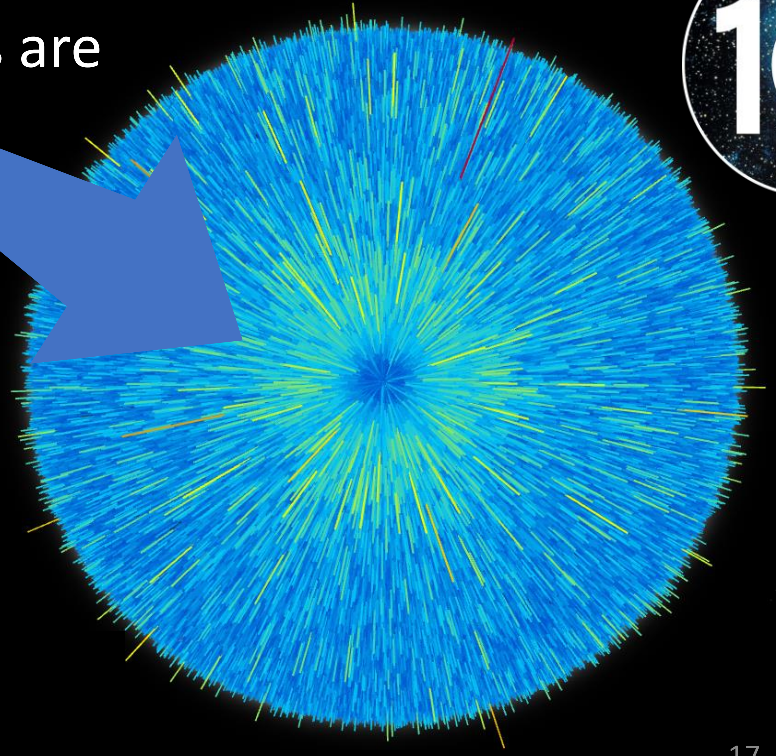
HOME > SCIENCE > VOL. 342, NO. 6161 > EVIDENCE FOR HIGH-ENERGY EXTRATERRESTRIAL NEUTRINOS AT THE ICECUBE DETECTOR
RESEARCH ARTICLE
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
ICECUBE COLLABORATION

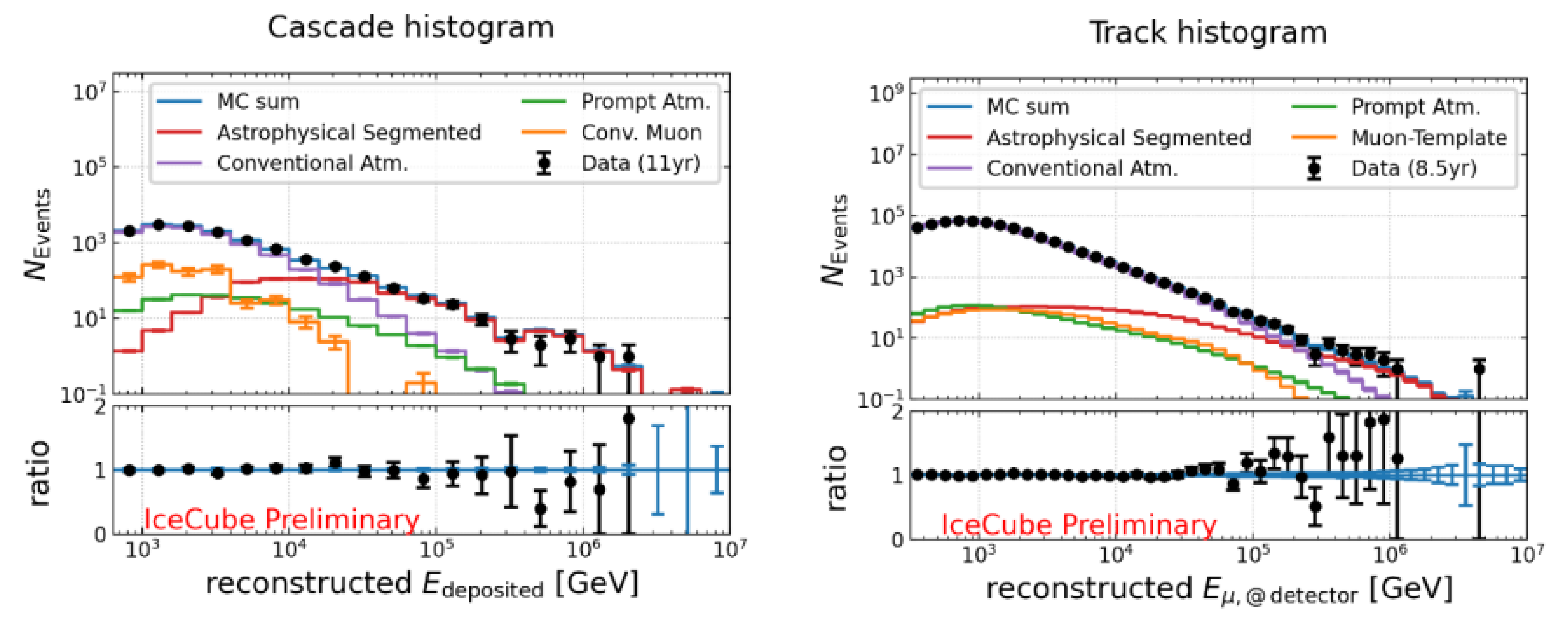
2023

Using the earth as the BG shield,
upward going muon neutrinos

where the
telescopes are



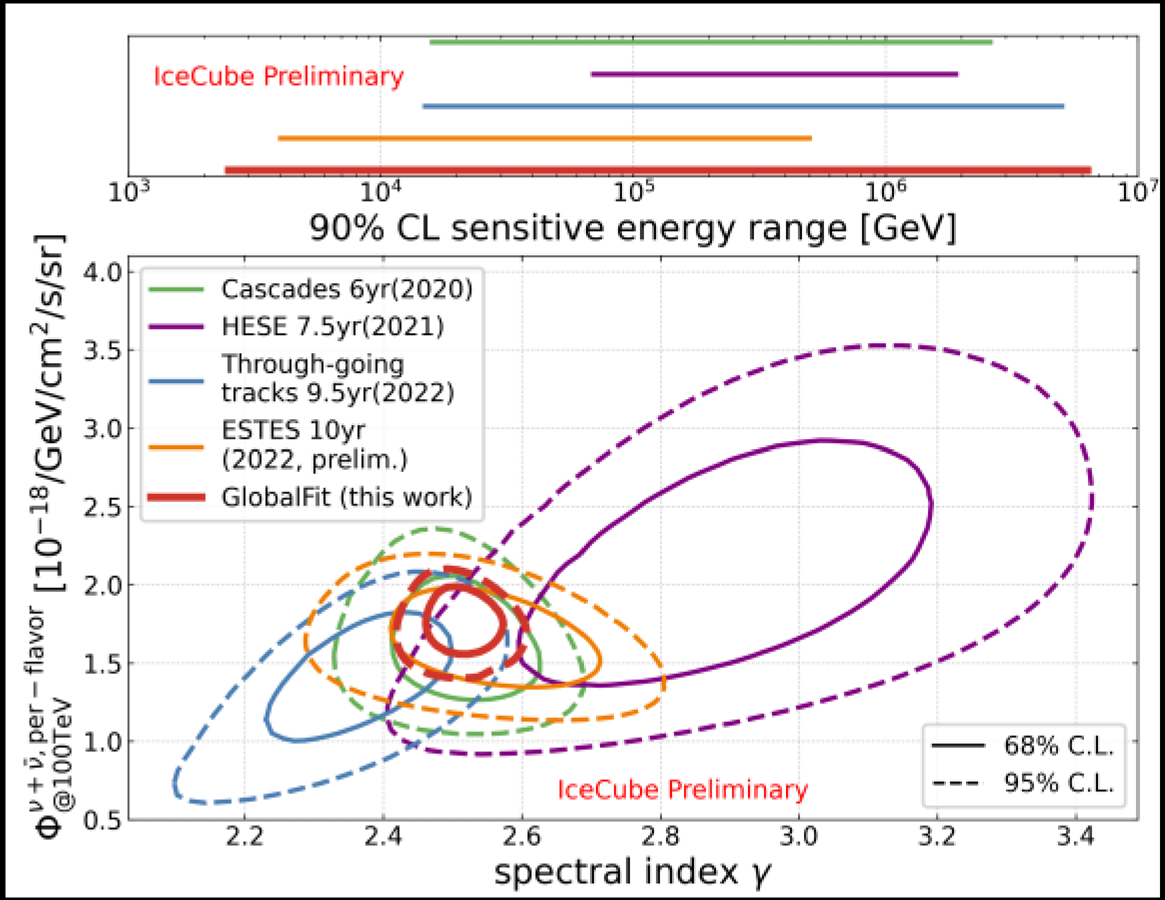
Diffuse Cosmic Neutrinos 10yrs observation with the IceCube neutrino telescope



Richard Naab, Erik Ganster, Zelong Zhang
for the IceCube collaboration at ICRC2023

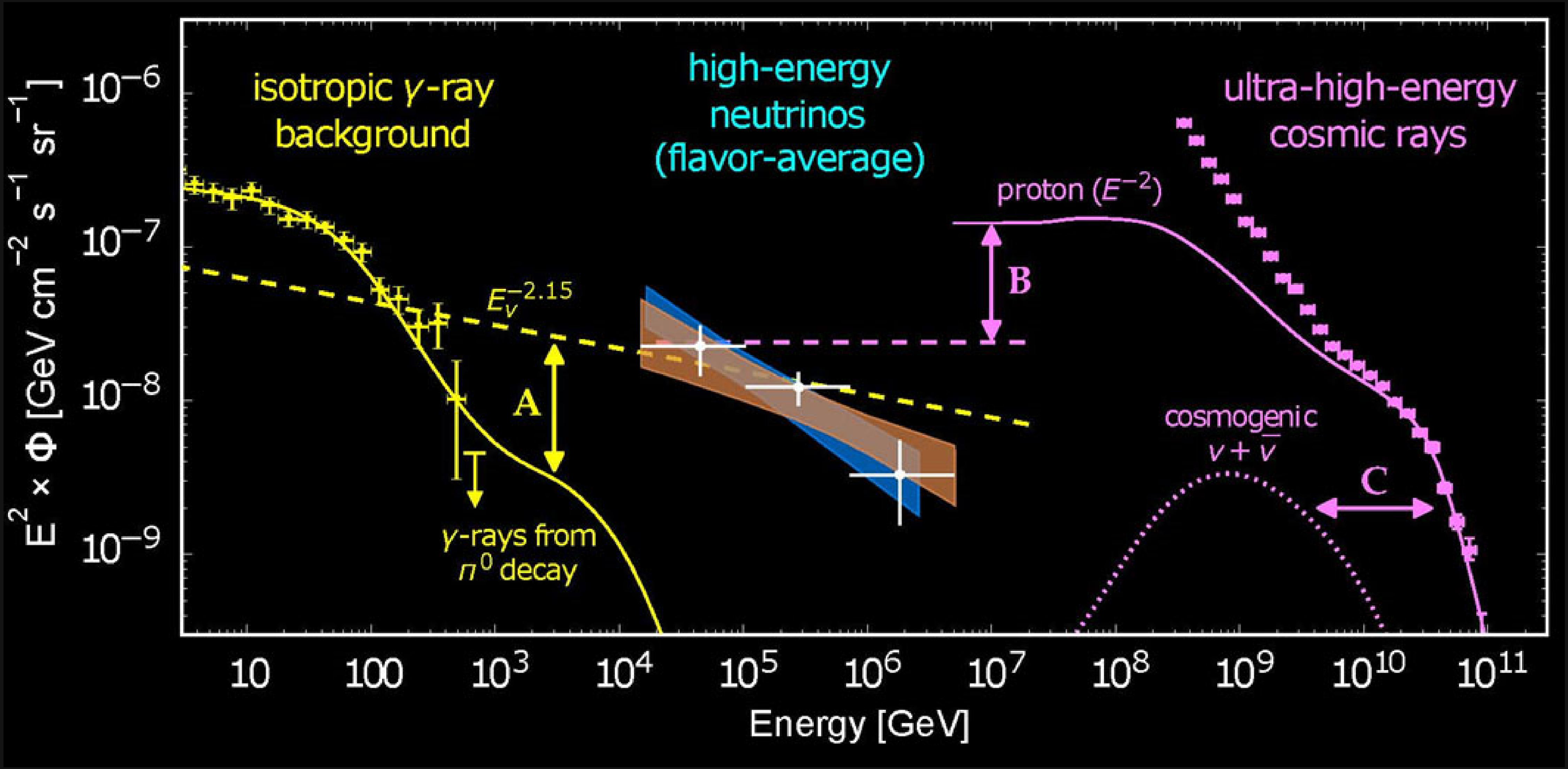
Diffuse Cosmic Neutrinos 10yrs observation with the IceCube neutrino telescope

$$\Phi_{\nu+\bar{\nu}} = \phi_{@100TeV}^{\nu+\bar{\nu}\ per\ flavor} \times \left(\frac{E_\nu}{100TeV}\right)^{-\gamma} \times 3 \times 10^{-18} \times GeV^{-1}cm^{-2}s^{-1}sr^{-1}$$



Richard Naab, Erik Ganster, Zelong Zhang
for the IceCube collaboration at ICRC2023v

Energy flux comparable to the diffuse messenger siblings

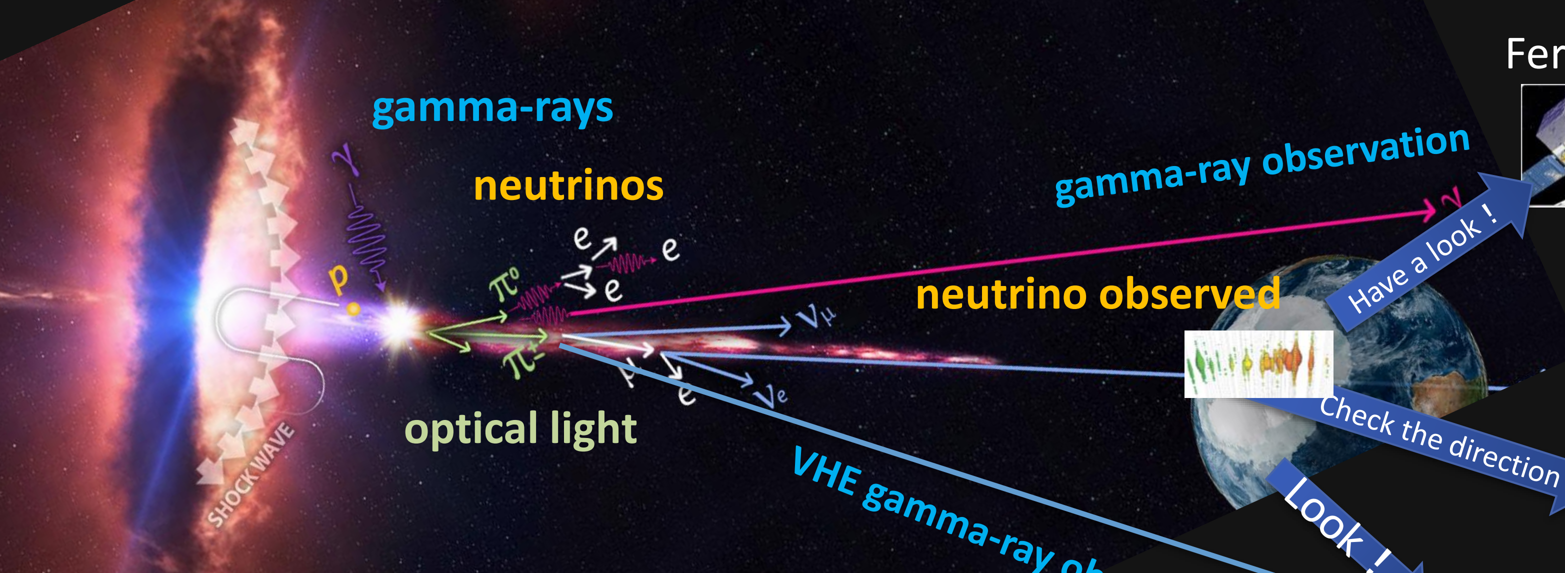


IceCube-Gen2 Collaboration, IceCube-Gen2 Technical Design: The IceCube-Gen2 Neutrino Observatory
https://icecube-gen2.wisc.edu/science/publications/TDR (2023)

First Observation of Neutrino Emitting Sources

Multimessenger observations of a flaring blazar TXS 0506+056 coincident with a high-energy neutrino IceCube-170922A

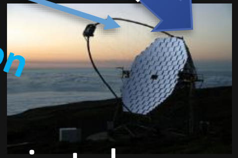
- 2017/9/22 20:54:30.43 UTC, IceCube-170922A alert just 43 seconds later from the event detection
- Triggering the observations of radio-to-VHE gamma-ray telescopes in the world



Fermi Telescope

Optical telescopes

Kanata telescope

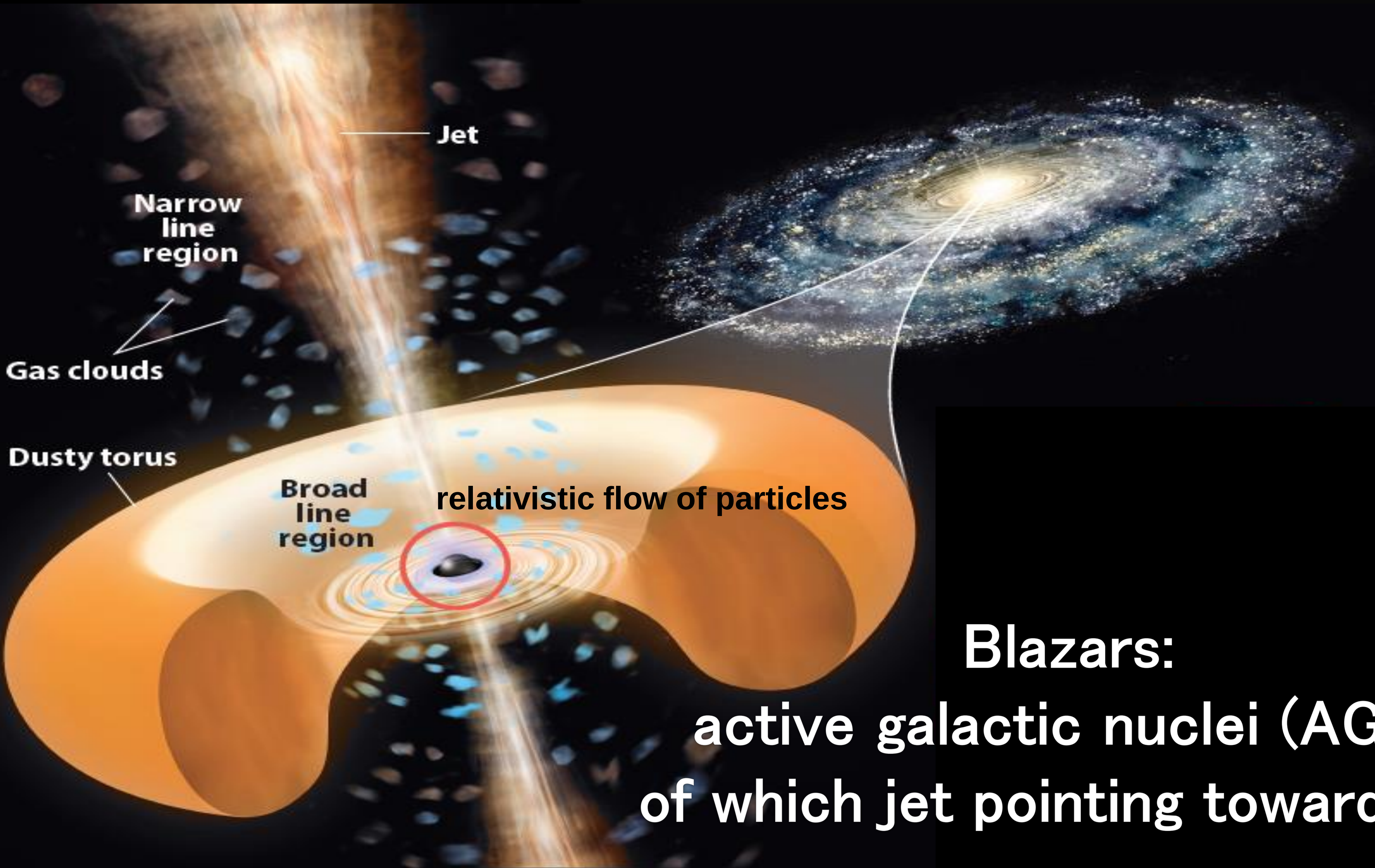


Magic telescope

...and many more telescope

SCIENCE
13 Jul 2018
Vol 361, Issue 6398
pp. 147-151
DOI: 10.1126/science.aat1378

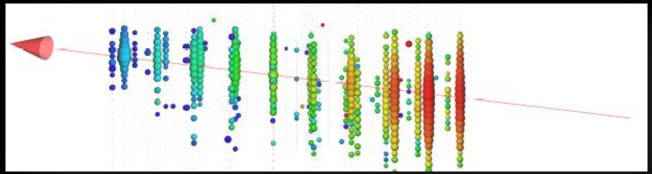
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

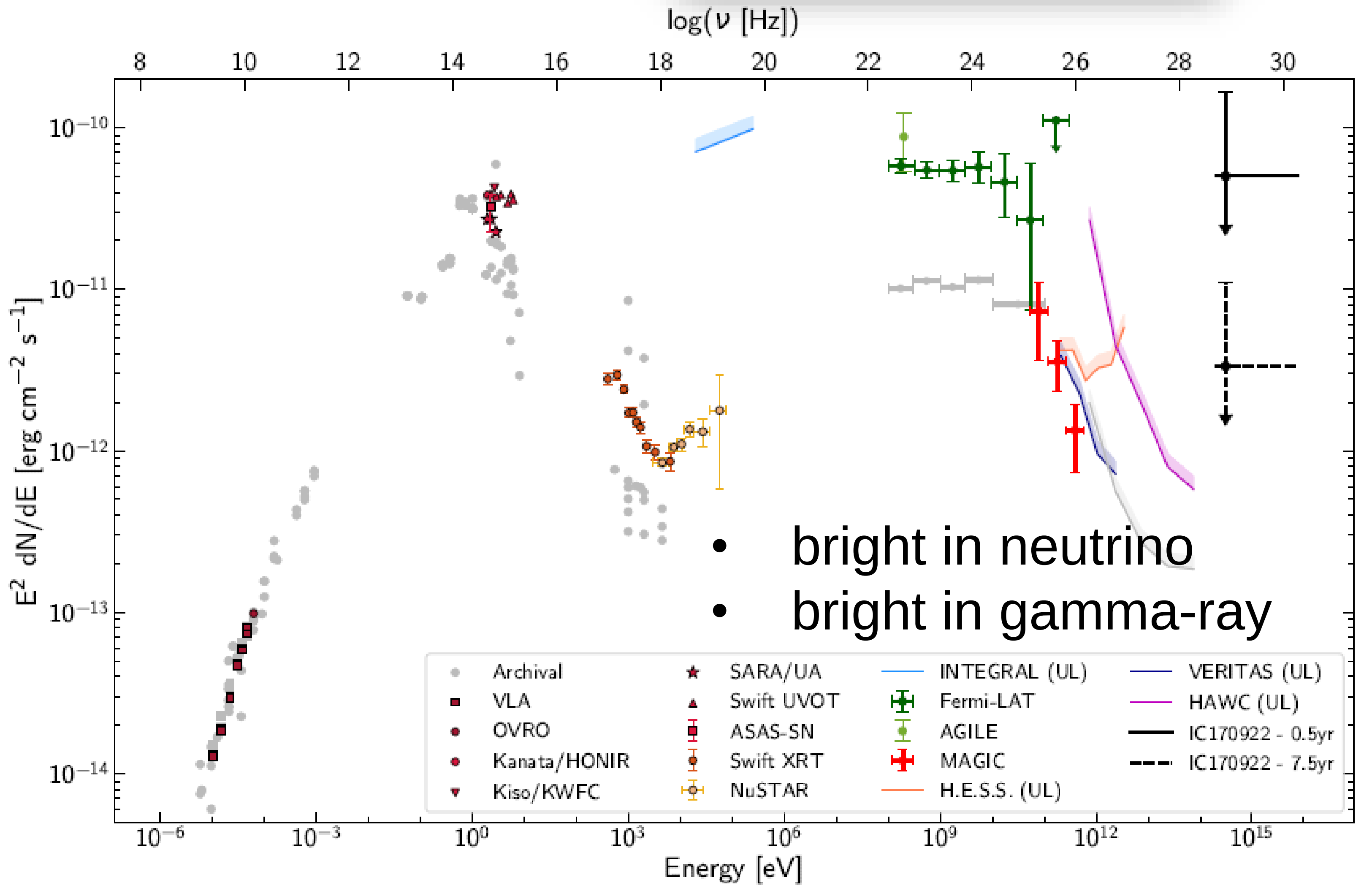


Blazars:
active galactic nuclei (AGN) of which jet pointing towards us

Multi-messenger view of TXS 0506+056

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

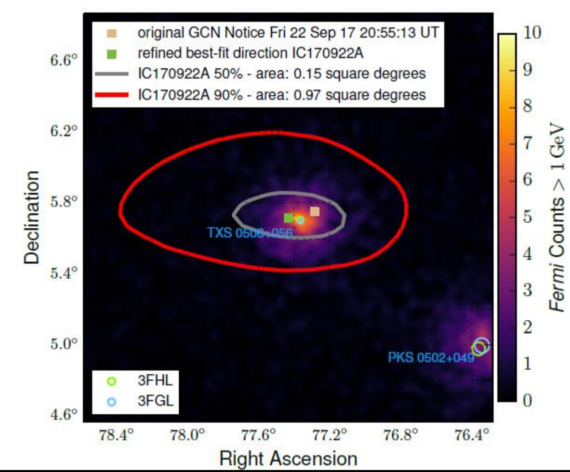




- bright in neutrino
- bright in gamma-ray

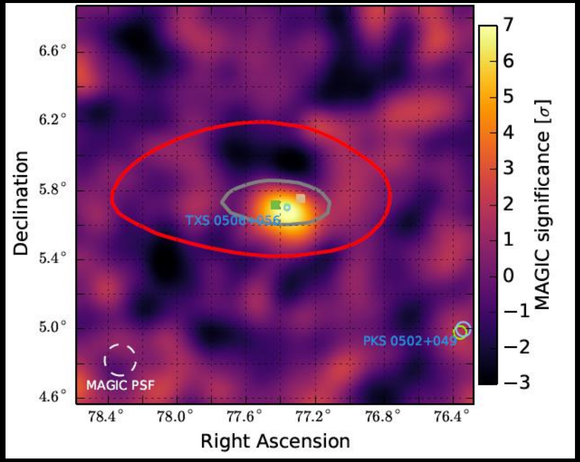
HE gamma-ray observations

- Fermi-LAT(20MeV - 300 GeV) reported gamma-ray flare



VHE gamma-ray observations

- VHE gamma-ray Magic telescope (E > 100GeV) with >6.2σ



Is blazar efficient neutrino emitter?

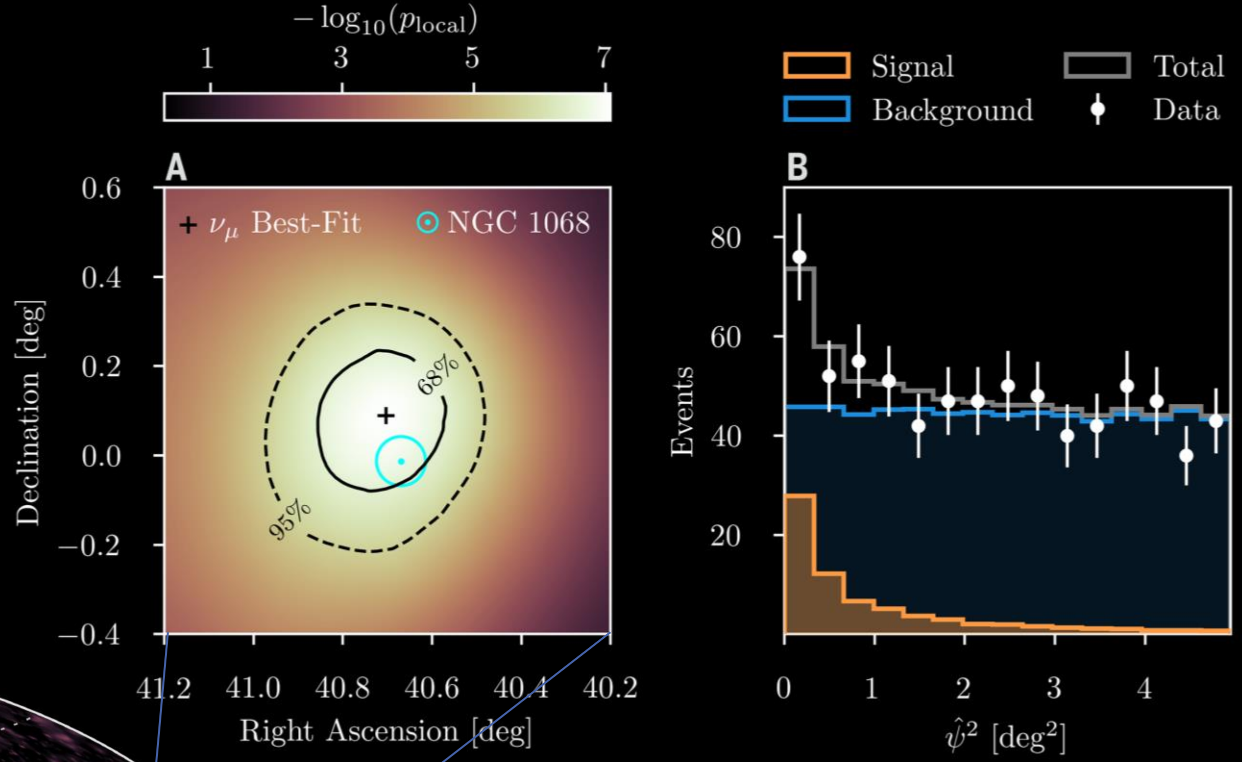
- **The Contribution of Fermi-2LAC Blazars to Diffuse TeV–PeV Neutrino Flux**, ApJ, 835 45 (2017)
    - Upper-limit on the contribution of >GeV gamma-rays emitting blazars to diffuse neutrino flux to be 27%

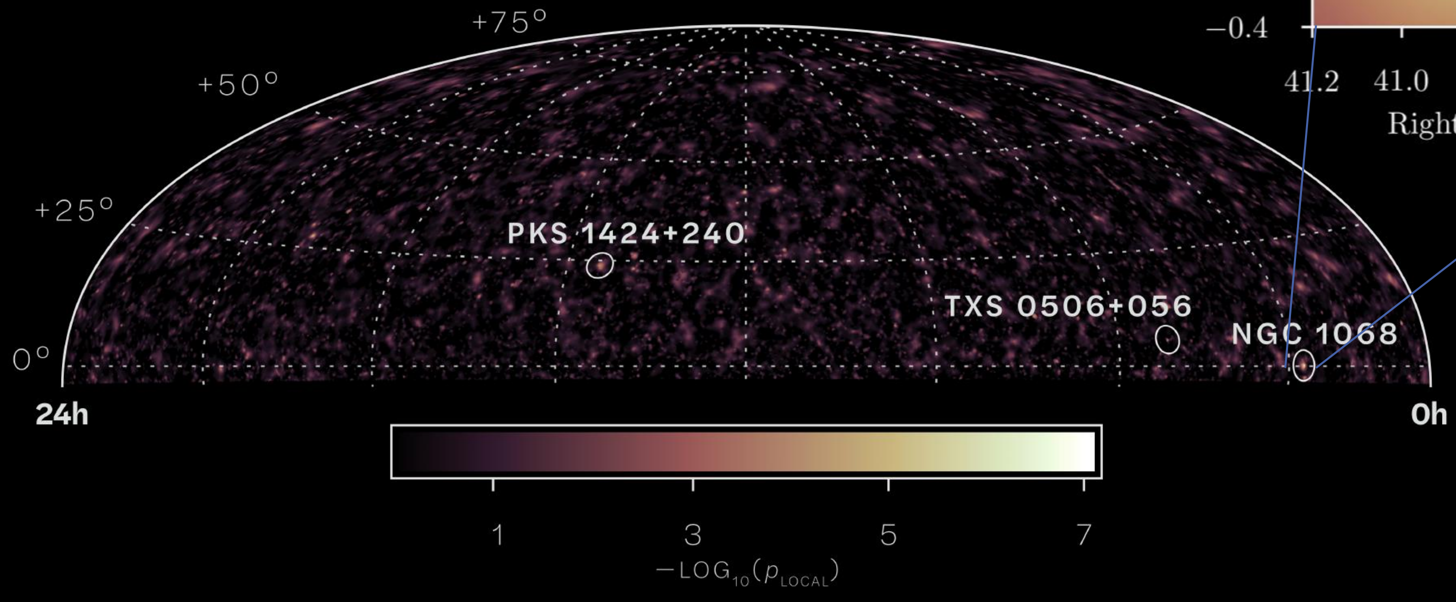
- **Search for Astrophysical Neutrinos from 1FLE Blazars with IceCube** ApJ 938 38 (2022)
    - Upper-limit on the contribution of MeV blazars to diffuse neutrino flux to be ~1%

First Evidence of Steady Neutrino Sources

Evidence for neutrino emission from the nearby active galaxy NGC 1068

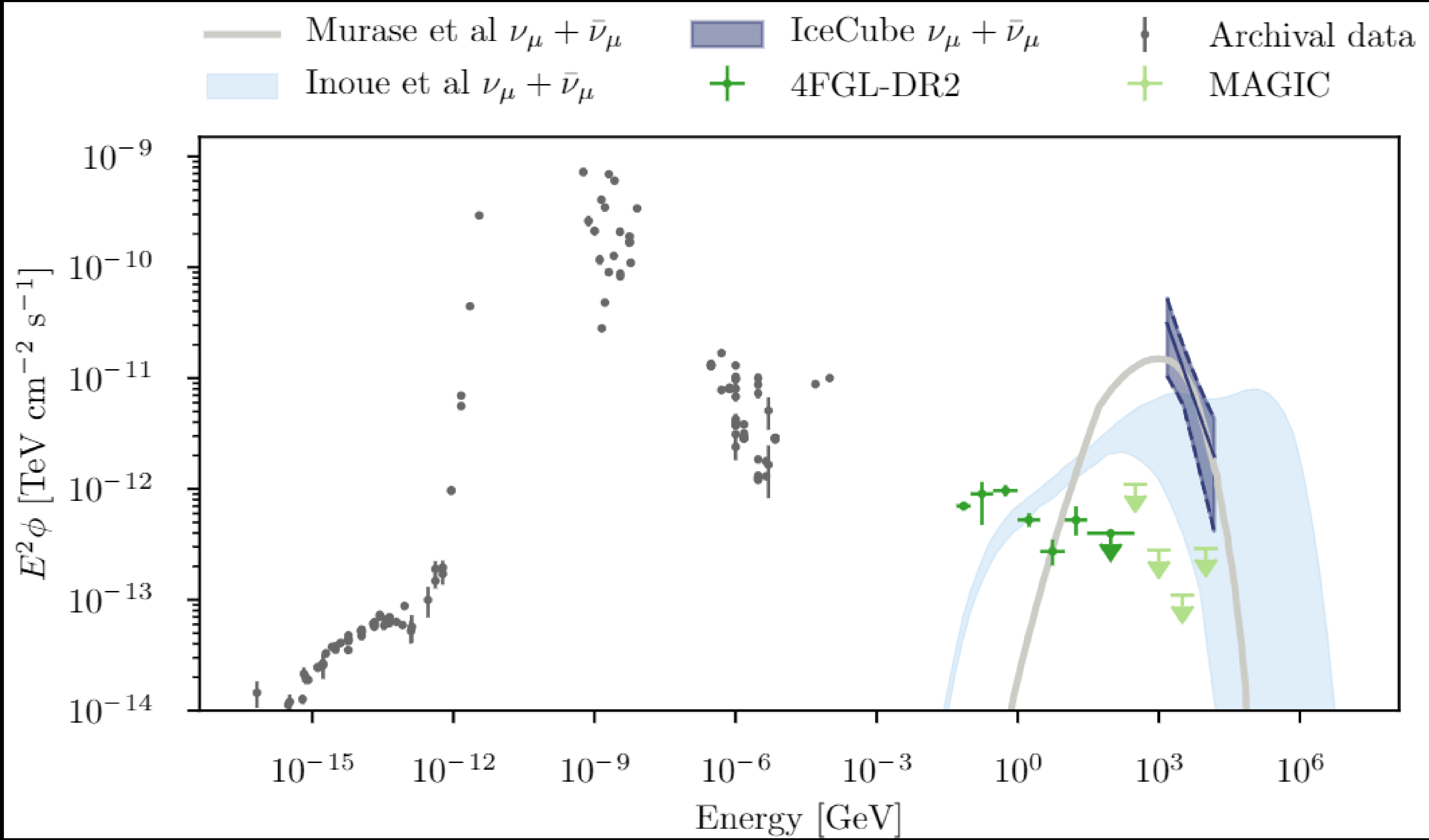
SCIENCE
04 November 2022
Vol 378, Issue 6619
pp. 538-543
DOI: 10.1126/science.abg3395

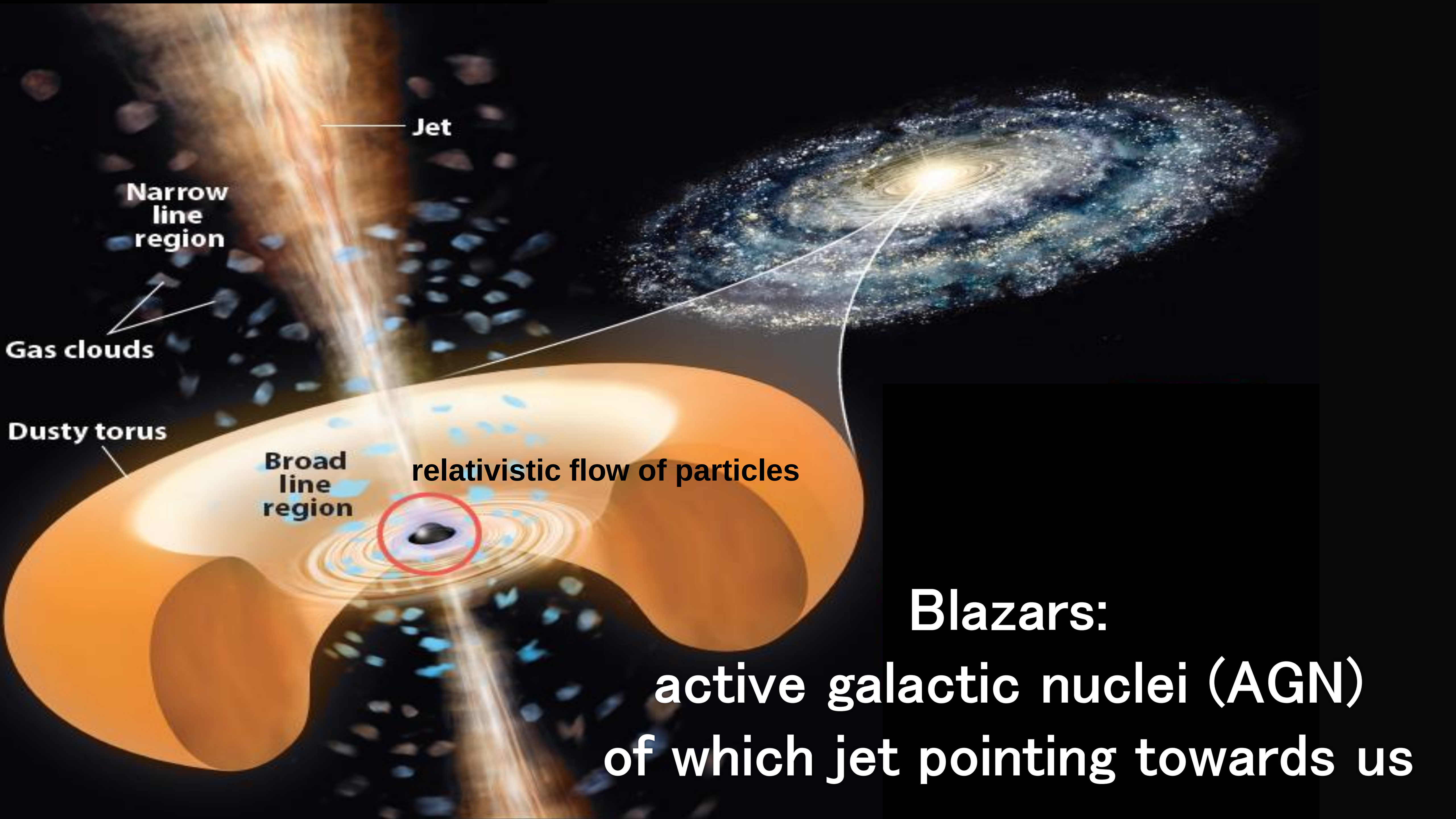




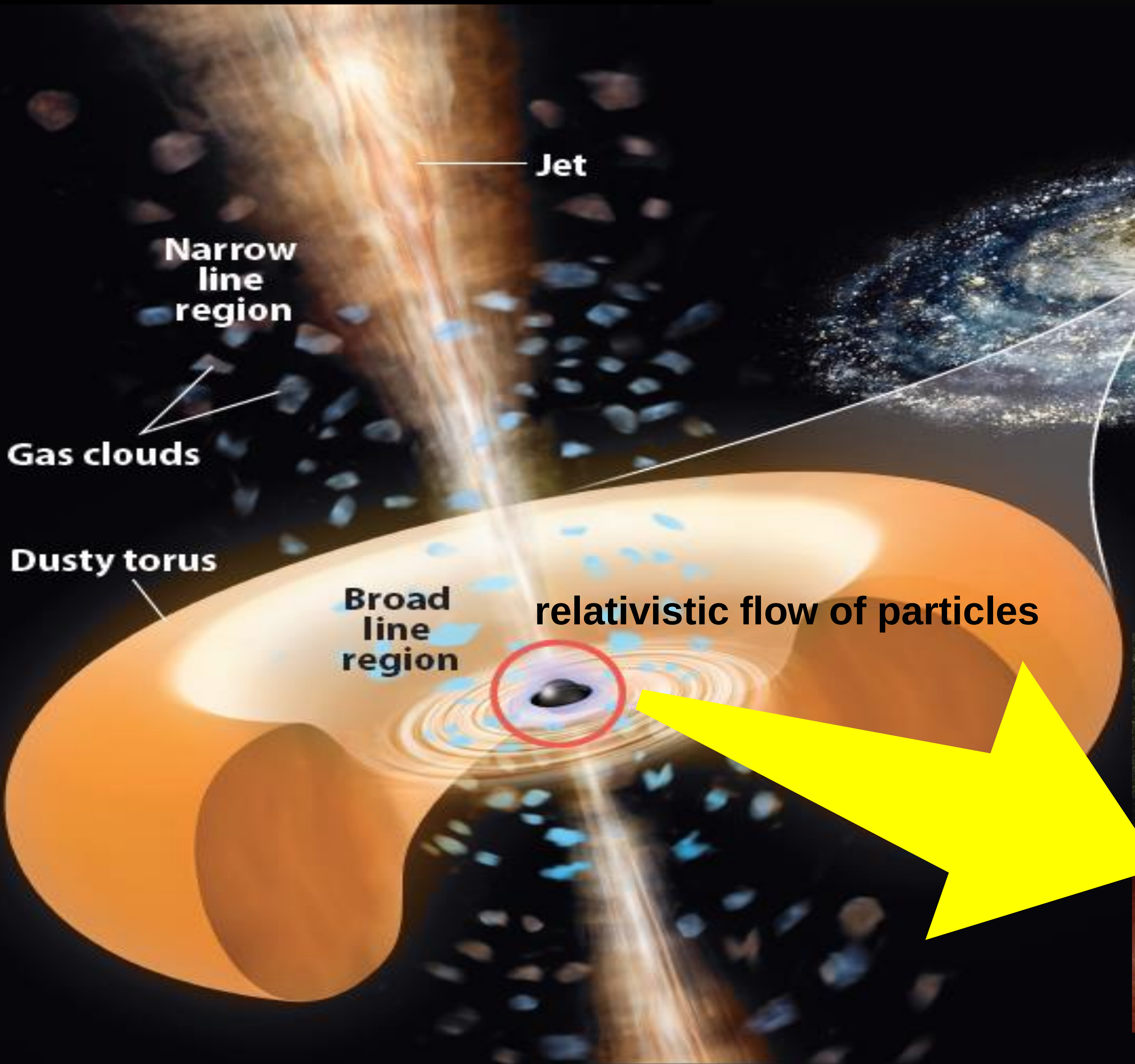
4.2σ after trial correction

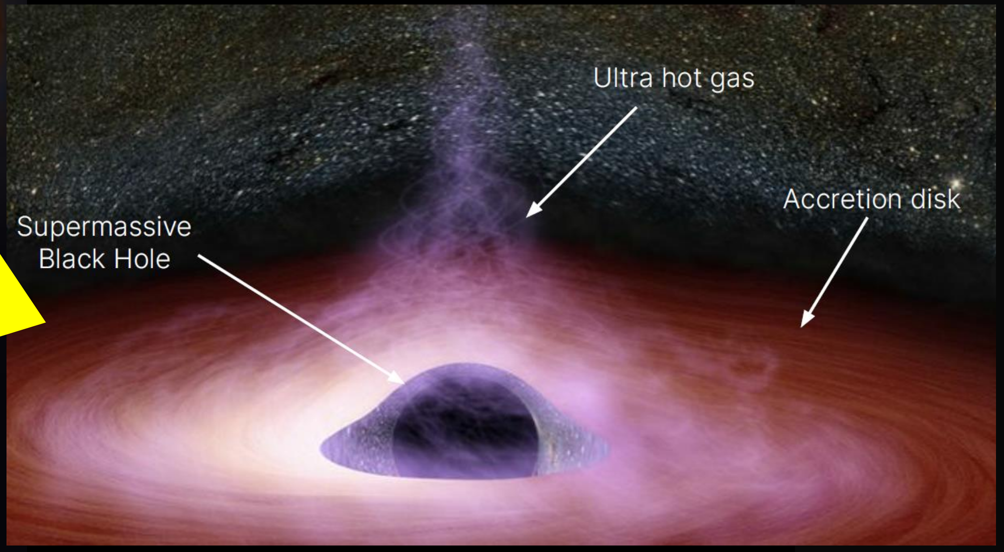
Multi-messenger view of M77 (NGC1068)



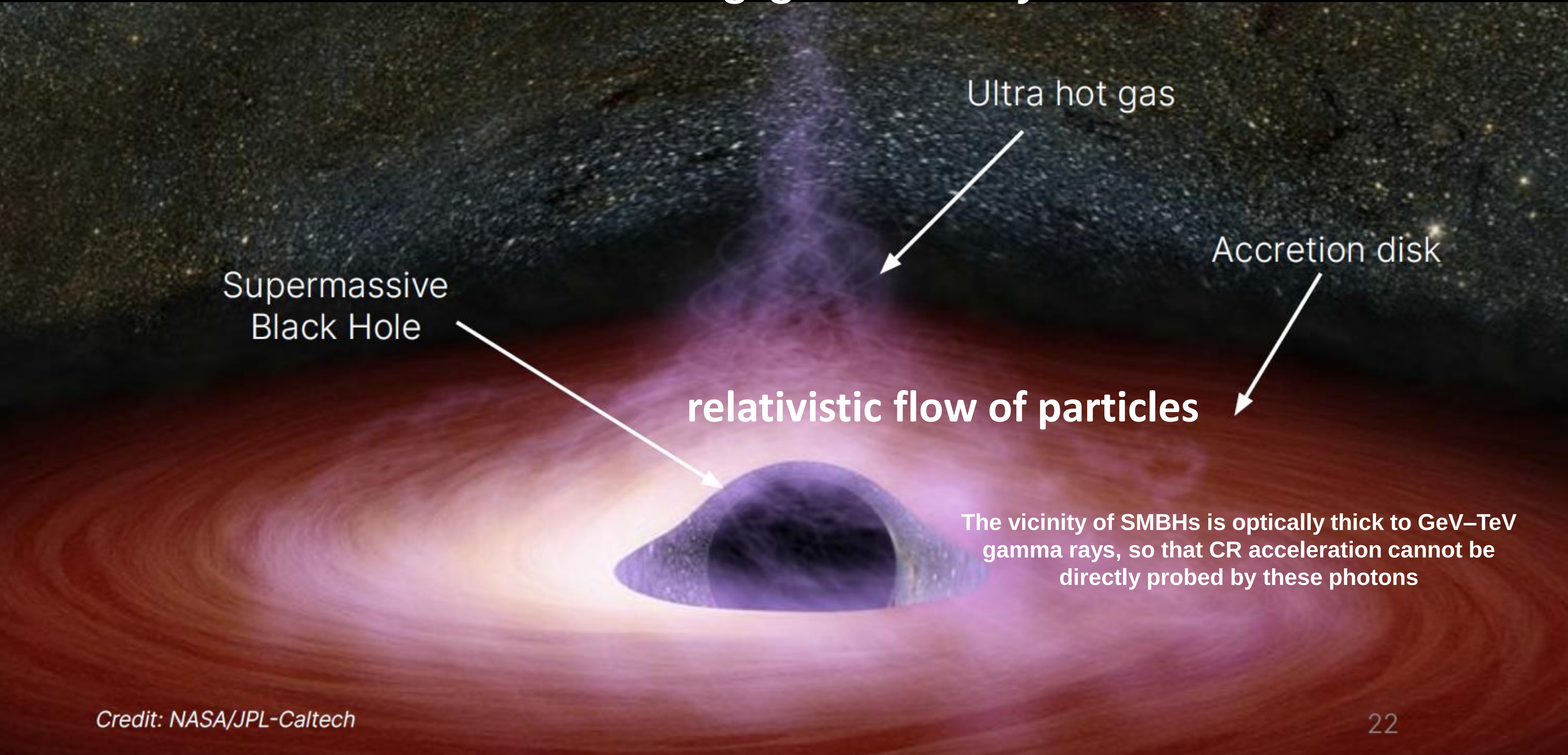

Jet
Narrow line region
Gas clouds
Dusty torus
Broad line region
relativistic flow of particles
Blazars:
active galactic nuclei (AGN)
of which jet pointing towards us

Core of starburst active galactic nuclei





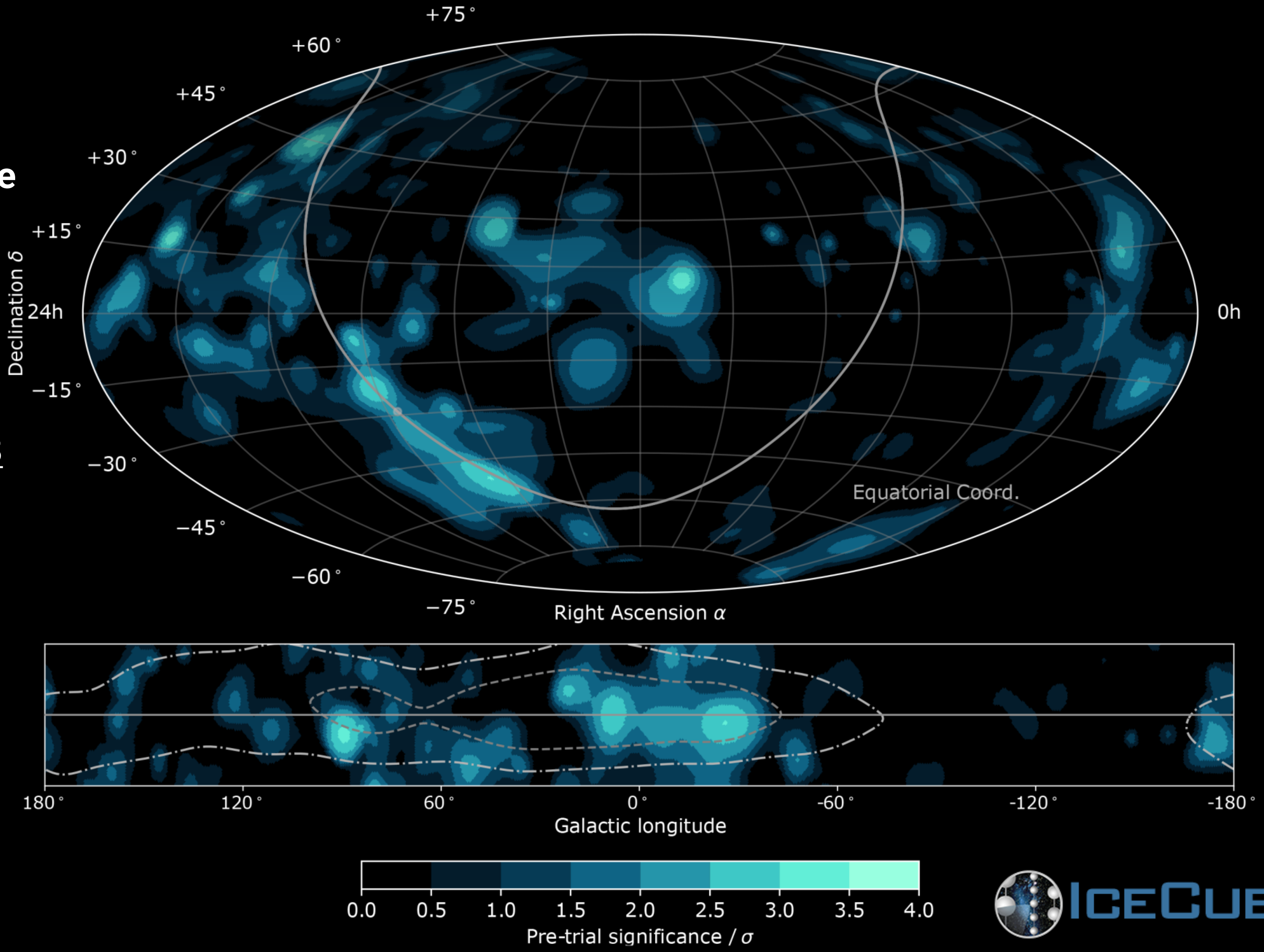
Cosmic-particles interact near the core of AGN obscuring gamma rays



Continuously Emitting Neutrino Sources

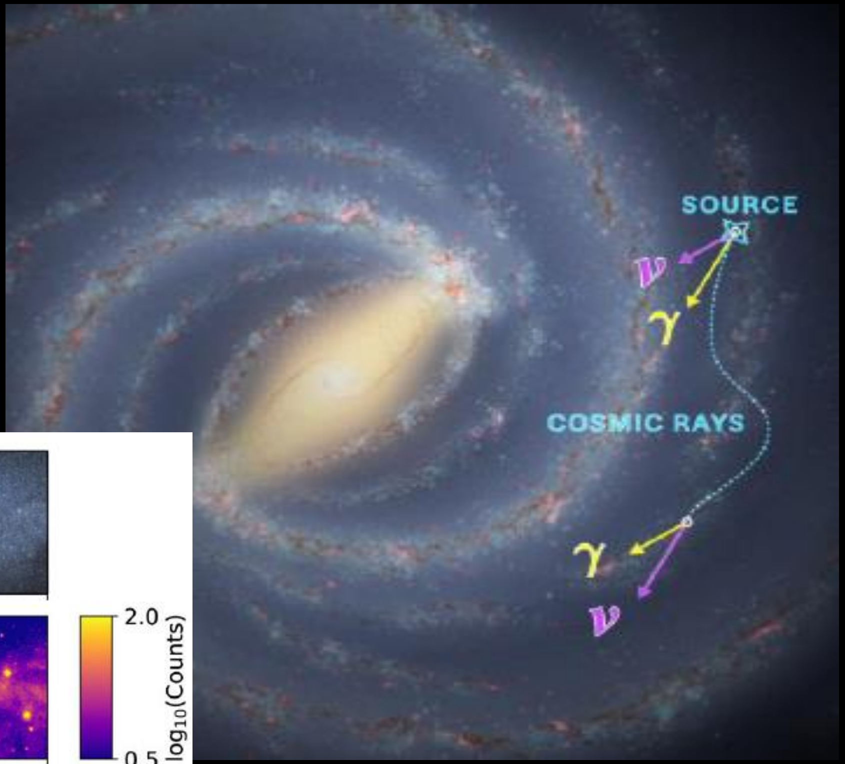
Observation of high-energy neutrinos from the Galactic plane

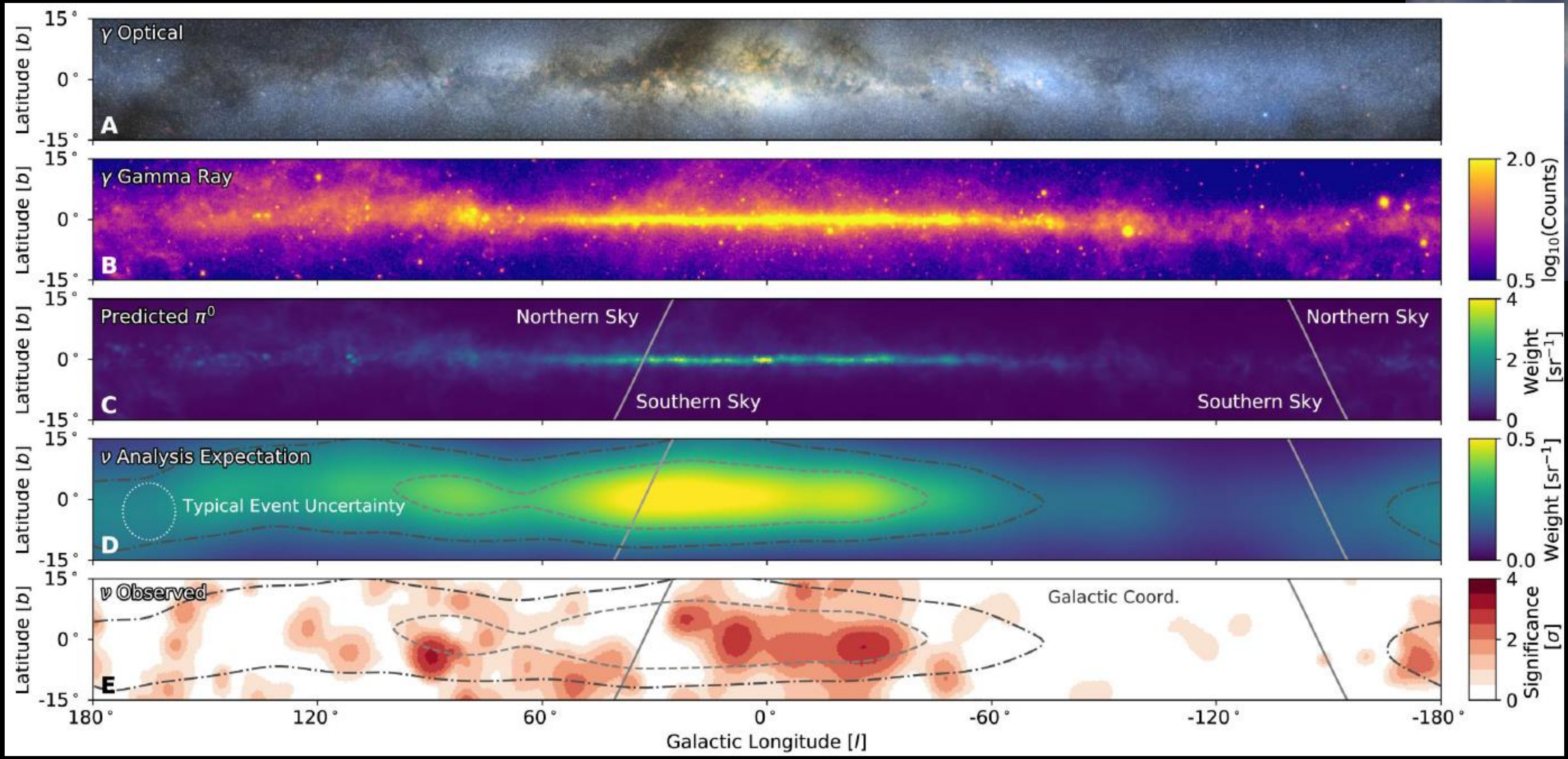
SCIENCE
29 Jun 2023
Vol 380, Issue 6652
pp. 1338-1343
DOI: 10.1126/science.adc9818



A New View of the Milky way

- One of the most intensely scanned objects in the Universe

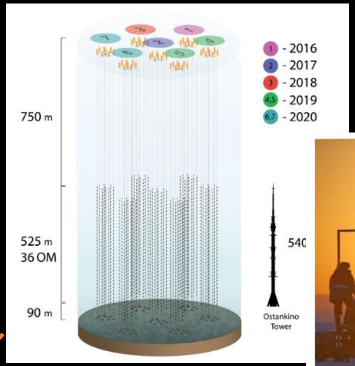


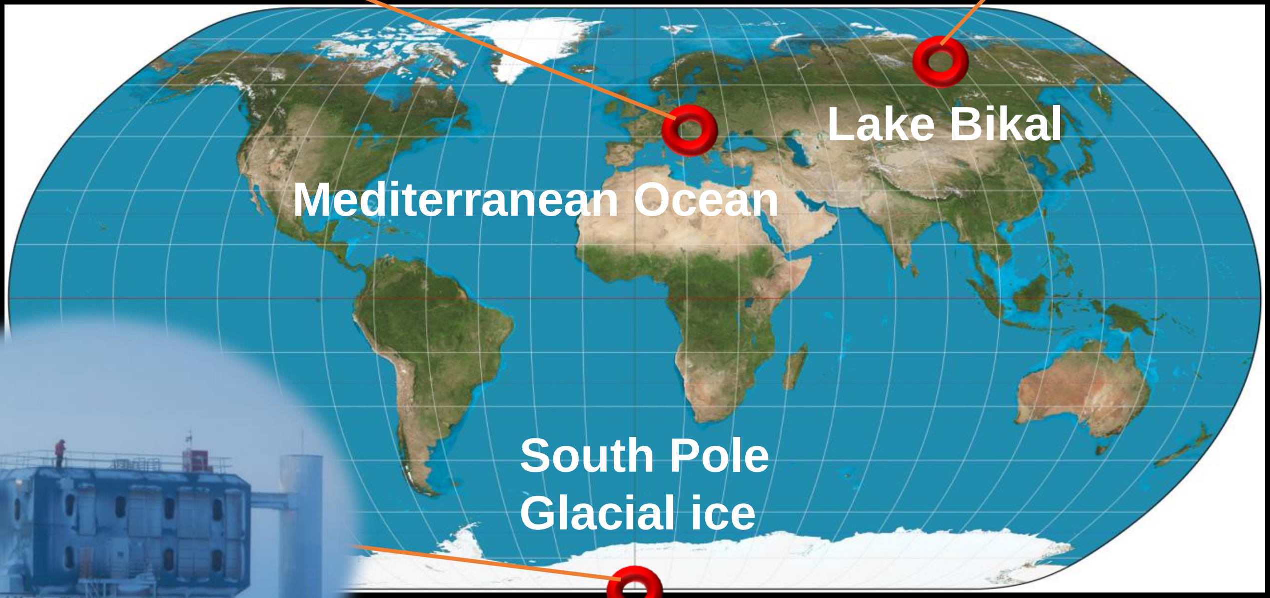


Future Neutrino Telescopes

KM3NET

BAIKAL-GVD





IceCube-Gen2

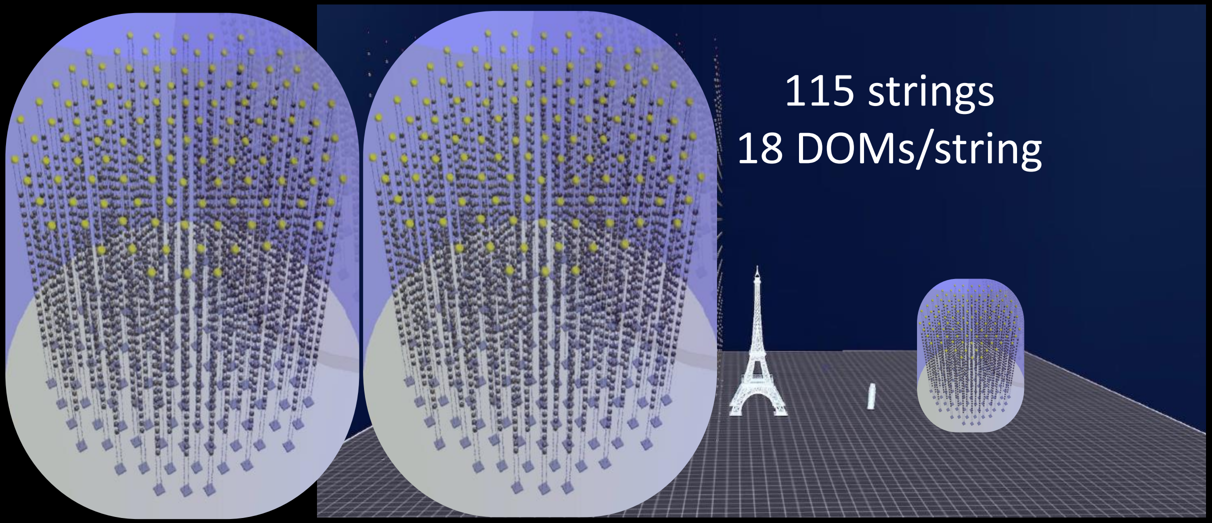
Also, not covered P-One, Trident (prototyping stage)

Beyond optical Cherenkov,
PUEO, Trinity, TAMBO, GRAND, Beacon, RNO-G, POEMMA, RET-N (…and more)

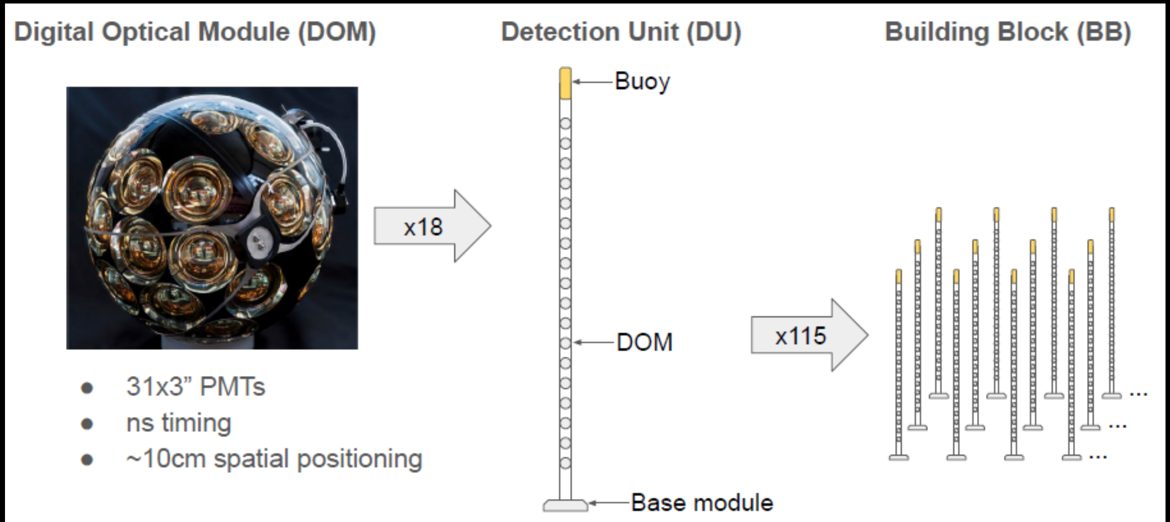
KM3NET: ARCA & ORCA

- horizontal separation: 90m and 20m
- vertical separation: 36m and 9m
- bottom depths: 3500m and 2440m
- instrumented mass: 500 x2 Mton and 7 Mton

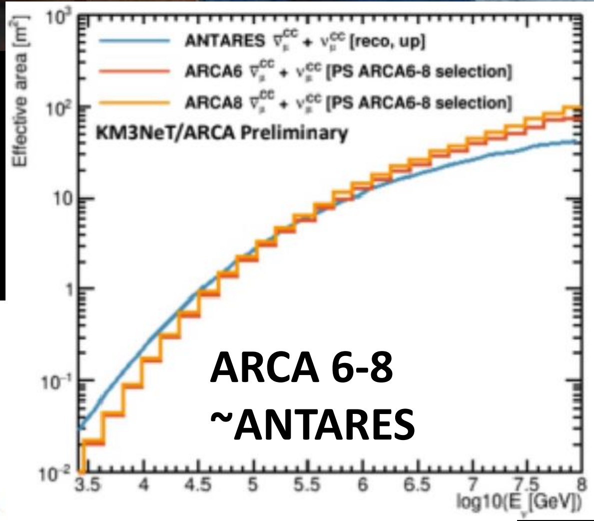
ARCA and ORCA

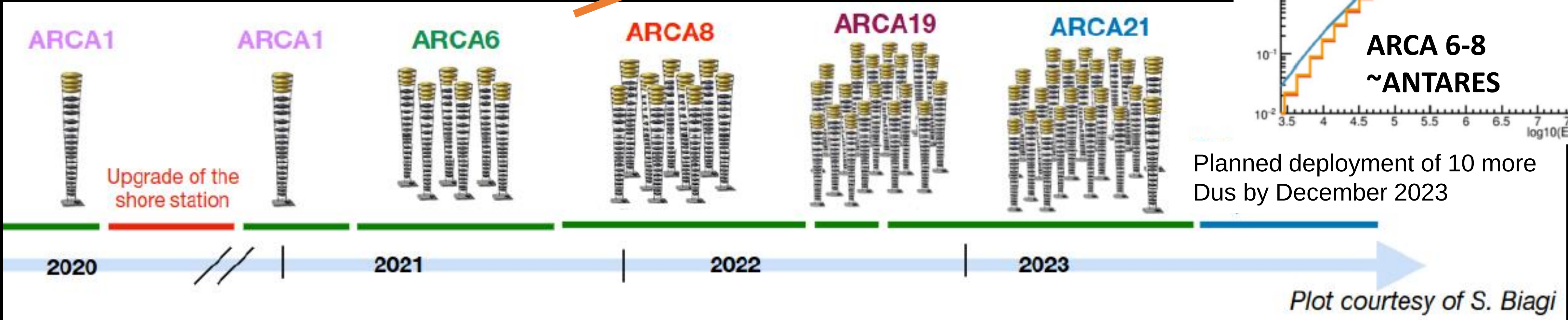


Status and prospects



- 21 DUs in operation (2022) ~ 0.1 Km^3
- 10 more DUs planned this year





Diffuse neutrino search with glowing DUs

	ARCA6 (102 days)		ARCA8 (212 days)		ARCA19 (51 days)		ARCA21 (67 days)	
	BDT score > 0.35	$\log E_{estimate} > 4.20$ GeV	BDT score > 0.27	$\log E_{estimate} > 4.04$ GeV	BDT score > 0.45	$\log E_{estimate} > 4.12$ GeV	BDT score > 0.40	$\log E_{estimate} > 4.36$ GeV
atm. $\nu + \bar{\nu}$	117.68	16.08	185.18	33.04	158.94	10.60	480.54	9.59
atm. μ	150.91	39.07	49.12	25.39	1.65	0.06	6.75	0.18
all atmospheric	268.59	55.15	234.30	58.43	160.59	10.66	487.11	9.77
cosmic $\nu + \bar{\nu}$	2.54	1.40	4.76	3.06	2.53	1.01	7.71	2.15
data	223	26	365	61	231	11	444	11

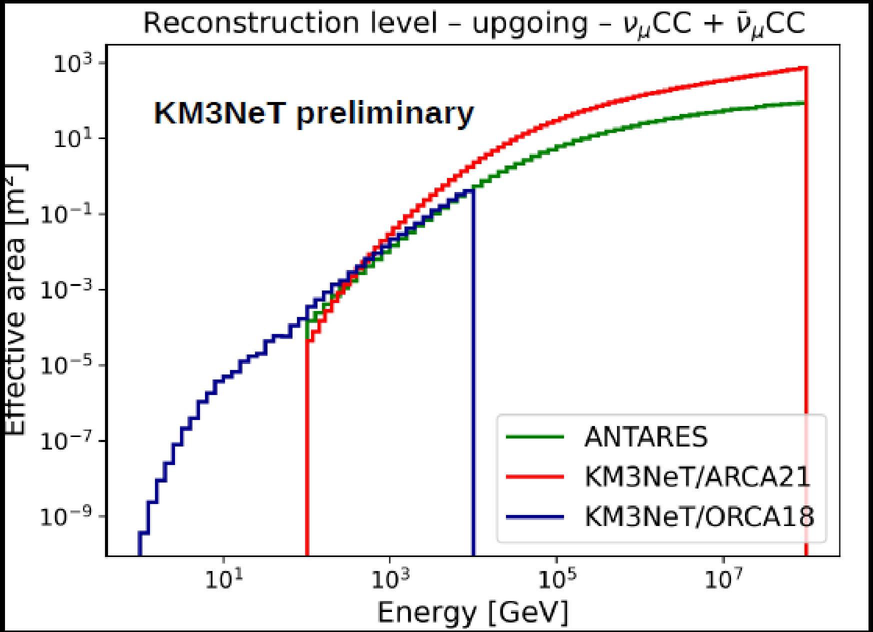
ARCA6: 1.37evts/100days (atm. 53evts/100 days)

ARCA8: 1.44evts/100days (atm. 28evts/100 days)

ARCA19: 1.98evts/100days (atm. 21evts/100 days)

ARCA21: 3.2evts/100days (atm. 15evts/100 days)

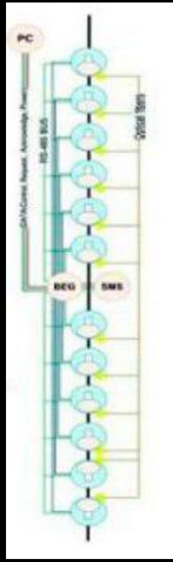
ARCA 21 ~ 3 x ANTARES

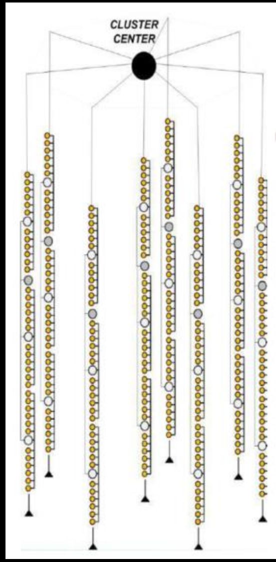


V. Tsourapis, E. Drakopoulou, C. Markou, A.Sinopoulou and E.Tzamariudaki (KM3NeT collaboration) at ICRC2023

Baikal-GVD

- clear water of the lake Baikal
- 96 strings in 8 construction seasons





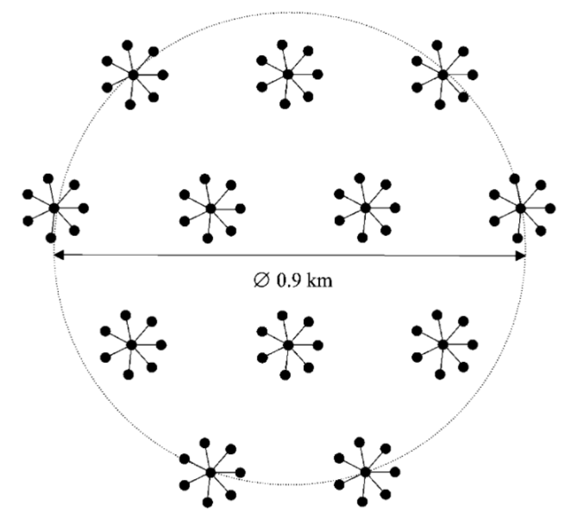
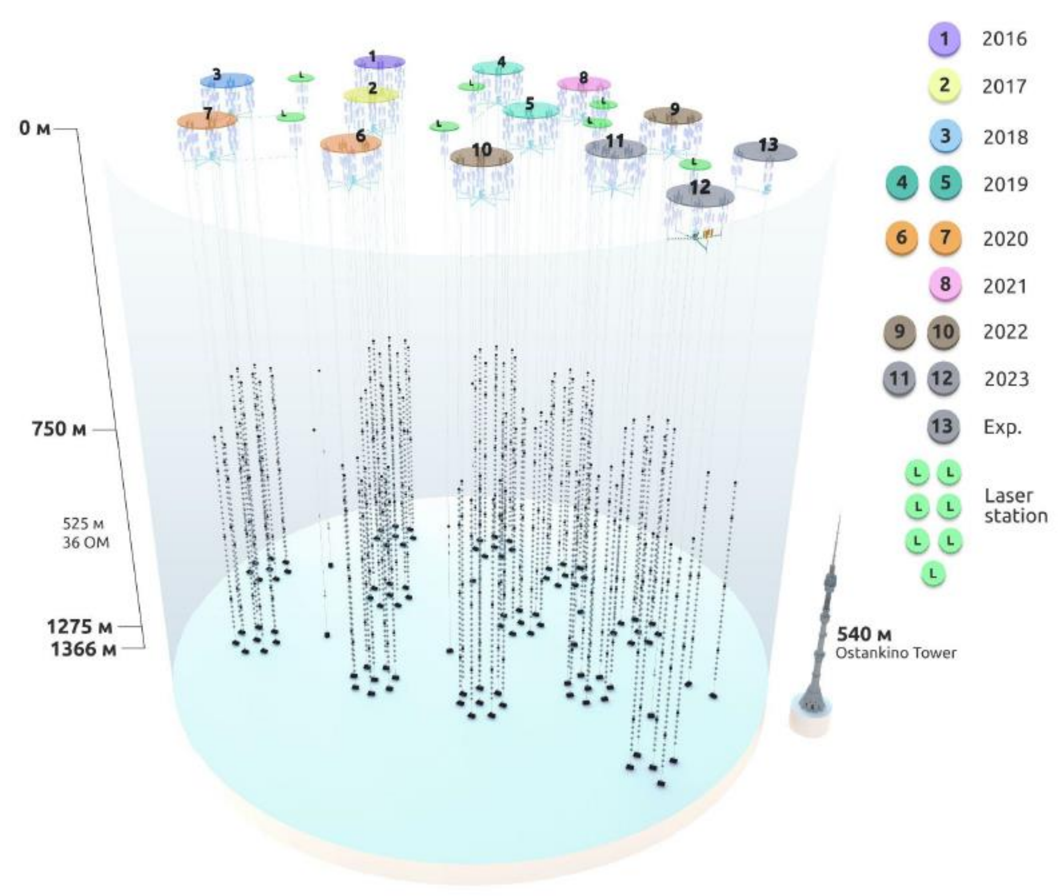


Fig. 5. Top view of GVD: 96 strings are grouped in 12 clusters.



- Array of Hexagon cluster
- 7 strings 60 m from the center
- 36 OMs/string, vertically 15m apart between 700m and 1240m
- Ice-season installation, water-season operation

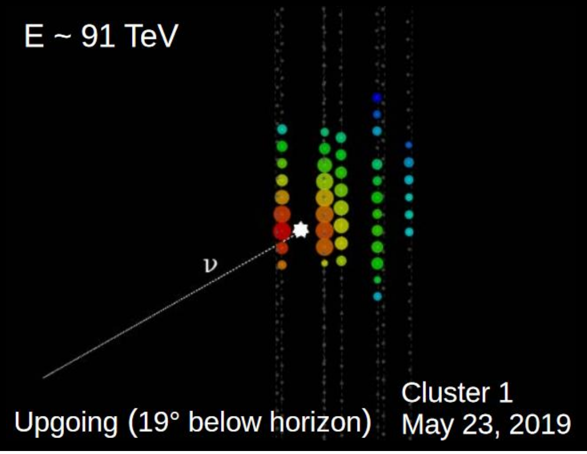
Baikal-GVD: arxiv/2211.09447

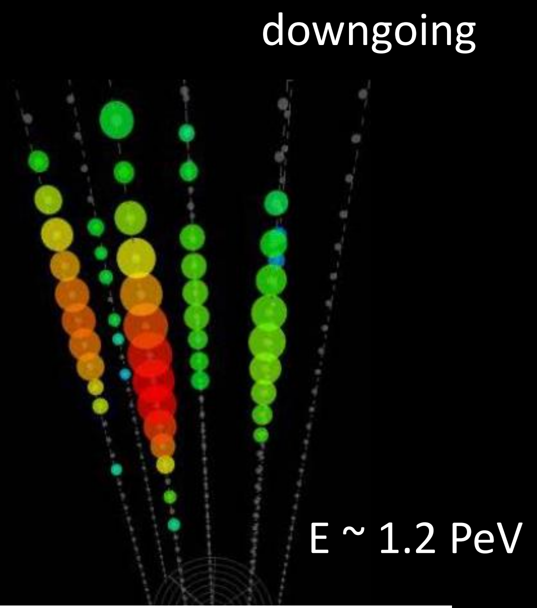
Astrophysical neutrino candidate events

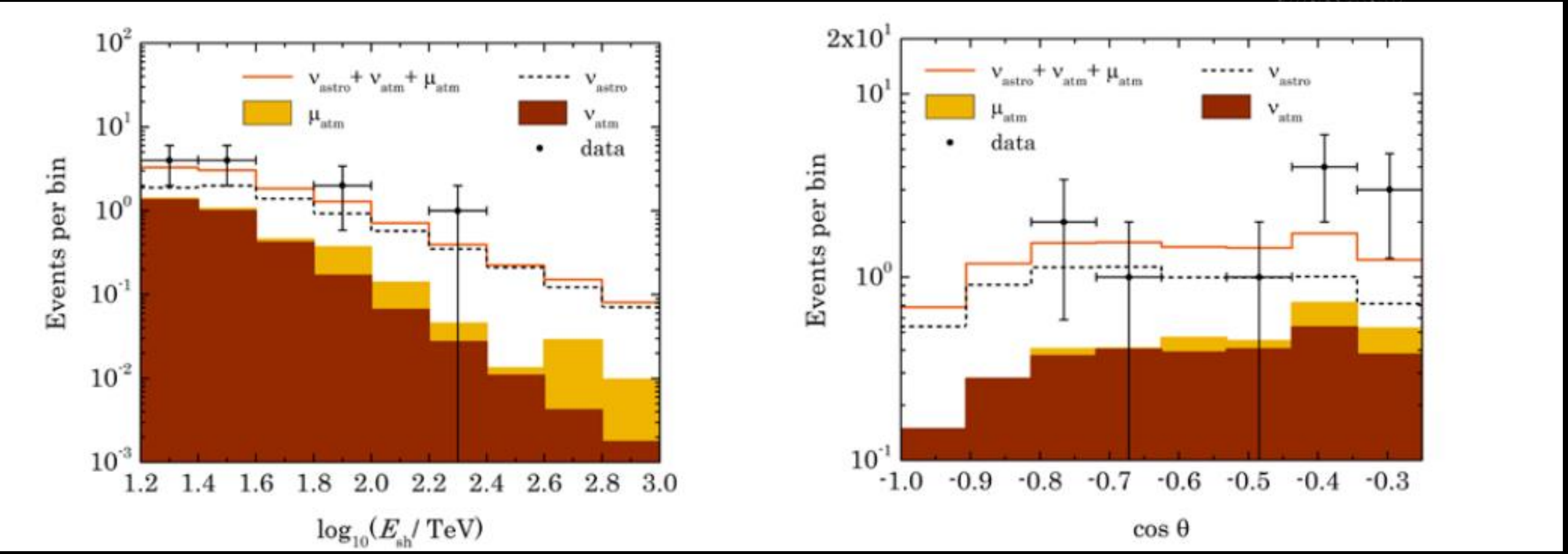
Search for the diffuse cosmic neutrinos using upgoing high energy (>100TeV) cascades

Expected:
0.95 events from atm. muons
3 events from atm. neutrinos
10 events for IceCube's $E^{-2.46}$ astrophysical flux

Found in data:
11 events







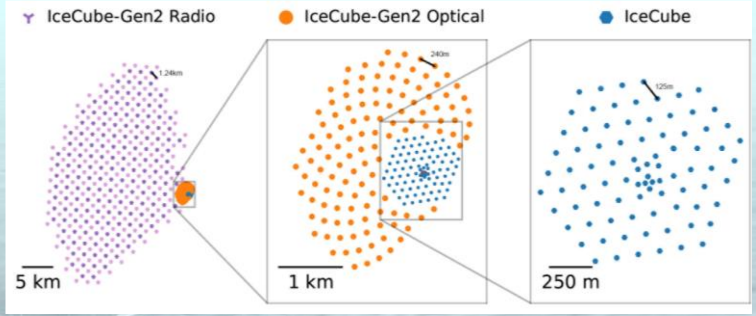
3σ observation of diffuse flux

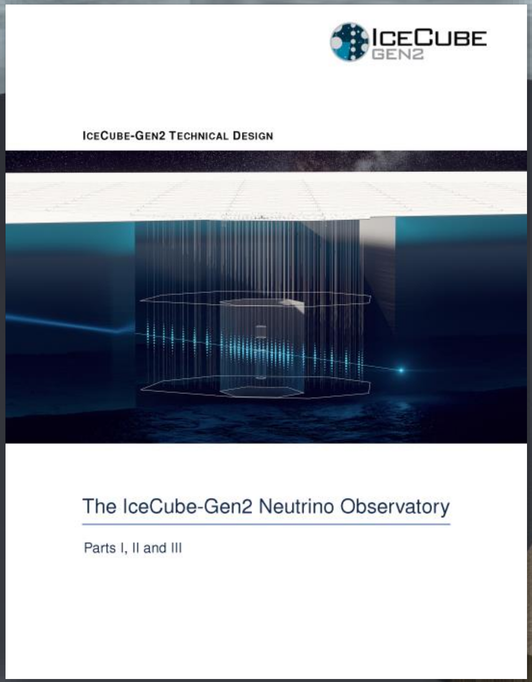
Baikal-GVD: arxiv/2211.09447

IceCube-Gen2 Neutrino Observatory

IceCube-Gen2 Collaboration

IceCube-Gen2 Technical Design: The IceCube-Gen2 Neutrino Observatory
https://icecube-gen2.wisc.edu/science/publications/TDR (2023)

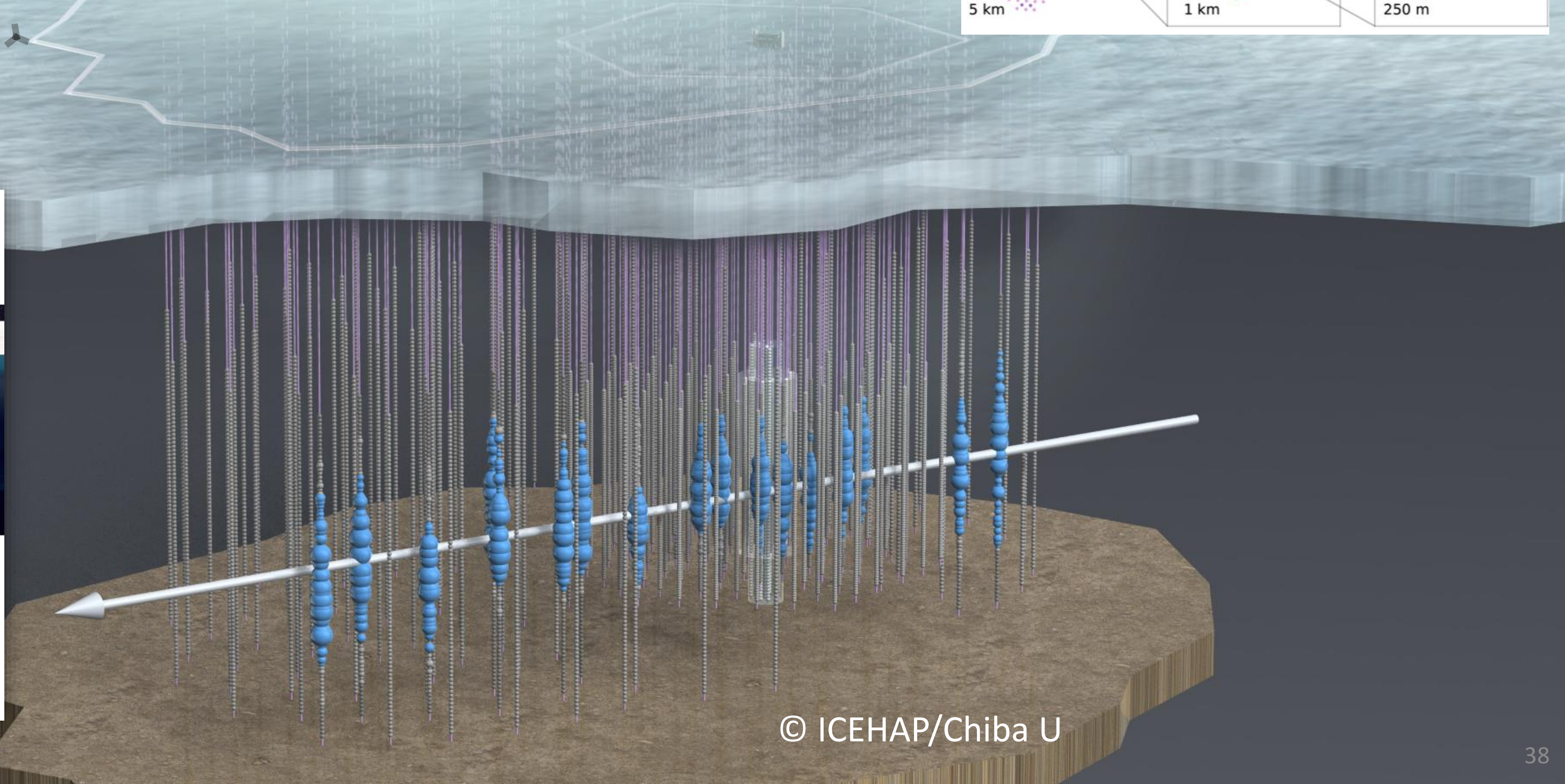



ICECUBE GEN2

ICECUBE-GEN2 TECHNICAL DESIGN

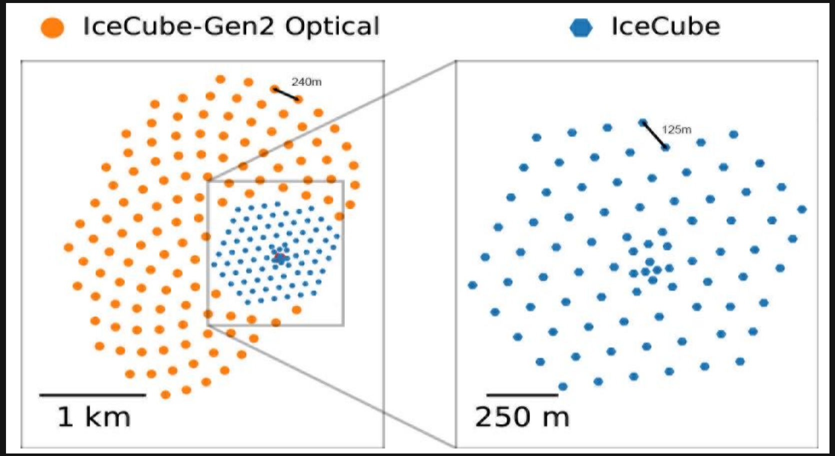
The IceCube-Gen2 Neutrino Observatory

Parts I, II and III



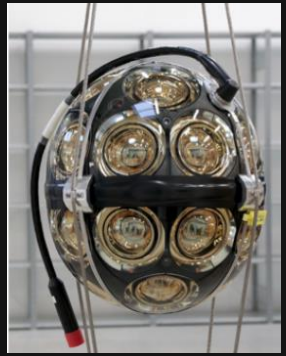
© ICEHAP/Chiba U

IceCube-Gen2 Optical Array



IceCube Upgrade(2025-26) ~700 new OMs

24 ch x 3'' PMT



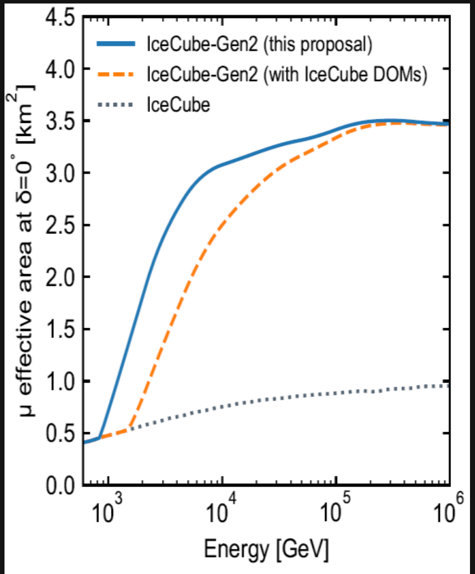
+

2ch x 8'' PMT

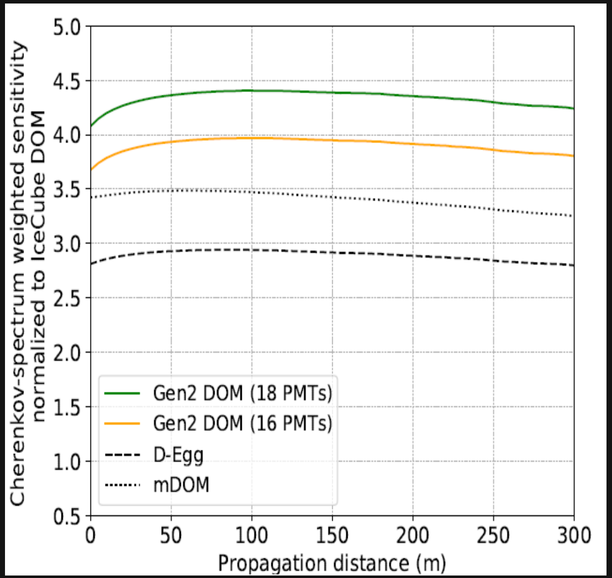
dia 36cm

dia 30cm

Gen2 DOM (18 PMTs)
Gen2 DOM (16 PMTs)



Critical to have good sensitivity for TeV energies

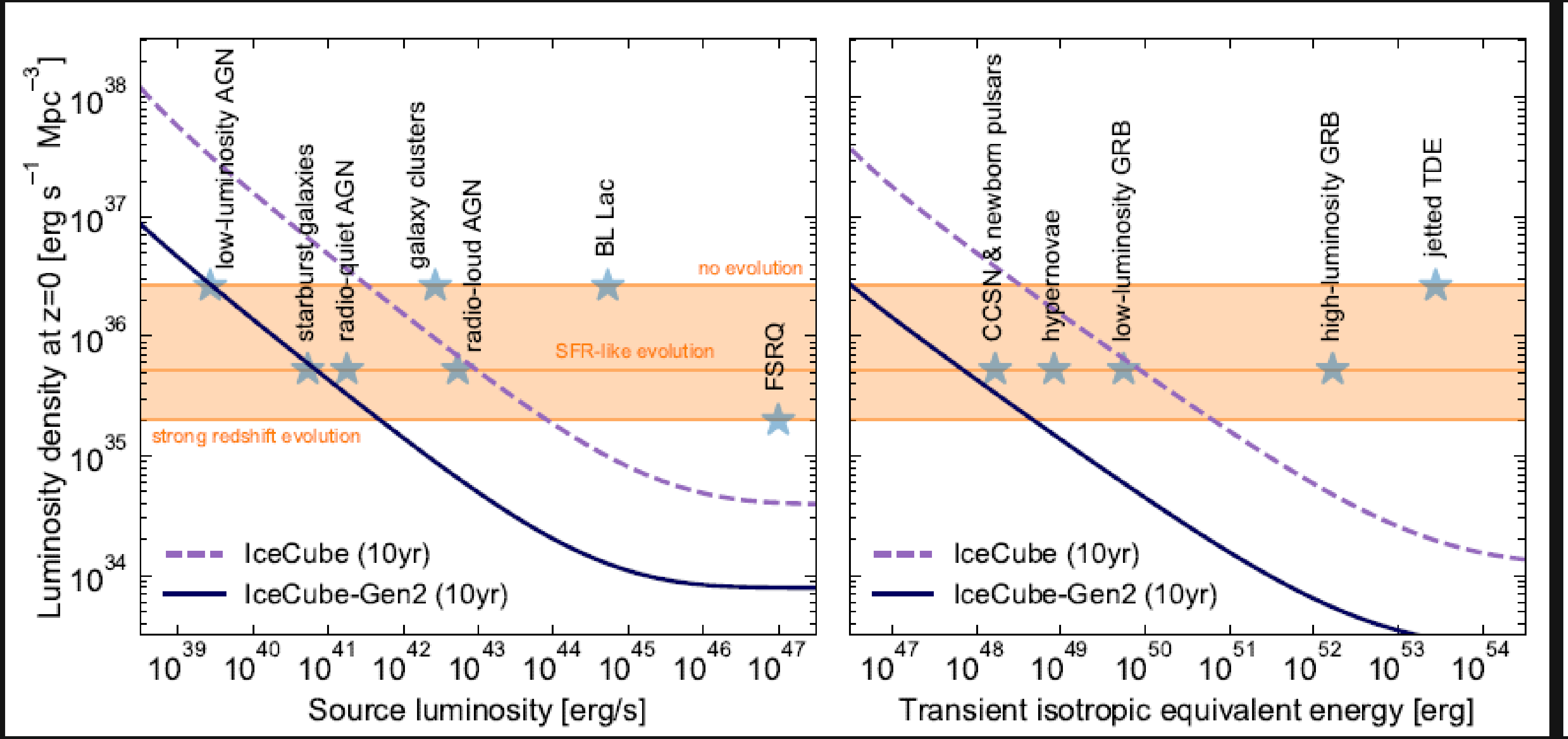


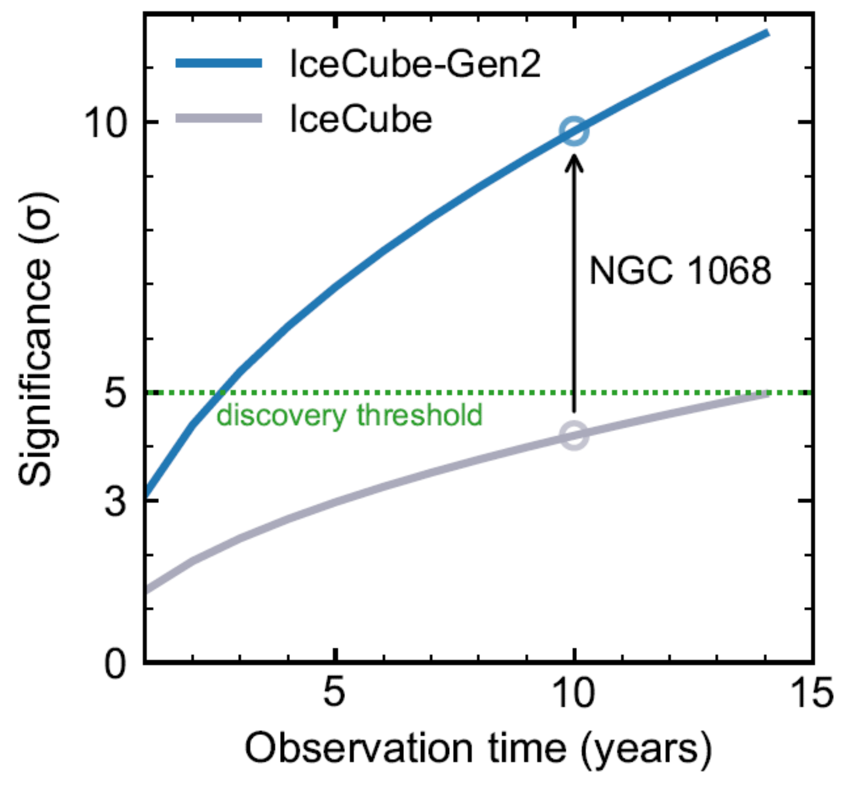
IceCube-Gen2 Collaboration, IceCube-Gen2 Technical Design: The IceCube-Gen2 Neutrino Observatory
https://icecube-gen2.wisc.edu/science/publications/TDR (2023)

IceCube-Gen2 Source Discovery Potential

Whole source classes of neutrinos from a few TeV to a few PeV!

IceCube-Gen2 Collaboration, IceCube-Gen2 Technical Design: The IceCube-Gen2 Neutrino Observatory
https://icecube-gen2.wisc.edu/science/publications/TDR (2023)





- IceCube-Gen2 is hoping for new collaborators from Asia
- ICEHAP (Japan) has established multimessenger section
  - Supports / tutorials for new data users
  - Welcoming visitors, such as summer students

THE ICECUBE-GEN2 COLLABORATION

https://icecube-gen2.wisc.edu/

AUSTRALIA
University of Adelaide

BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
Queen's University
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
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

INDIA
Tata Institute of Fundamental Research

ITALY
University of Padova

JAPAN
Chiba University
Osaka Metropolitan University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

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Mercer University
Michigan State University
Ohio State University
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South Dakota School of Mines and Technology
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Stony Brook University
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University of Kansas
University of Maryland
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University of Notre Dame
University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin–Madison
University of Wisconsin–River Falls
Whittier College
Yale University

ICECUBE GEN2

Summary

- The area of neutrino astronomy has opened with the 1 cubic kilometer IceCube detector, establishing analysis and calibration techniques.
- Neutrinos are starting to tell us about the origin of cosmic rays in the vicinity of the hidden Universe and obscured regions of high-energy astrophysical objects not accessible with the other methods.
- To achieve a full understanding of neutrino-emitting source classes, we anticipate the need for close to an order of magnitude increase in detection capabilities, KM3NET, BIKAL-GVD, and IceCube-Gen2.
- The on-going telescope constructions in Northern hemispheres. KM3NET-ARCA, BAIKAL-GVD, will observe IceCube-like flux with higher significance in a few year