A new view of the universe with high-energy astrophysical neutrinos

International Center for Hadron AstroPhysics (ICEHAP), Chiba University

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Matter makes up everything in our daily life

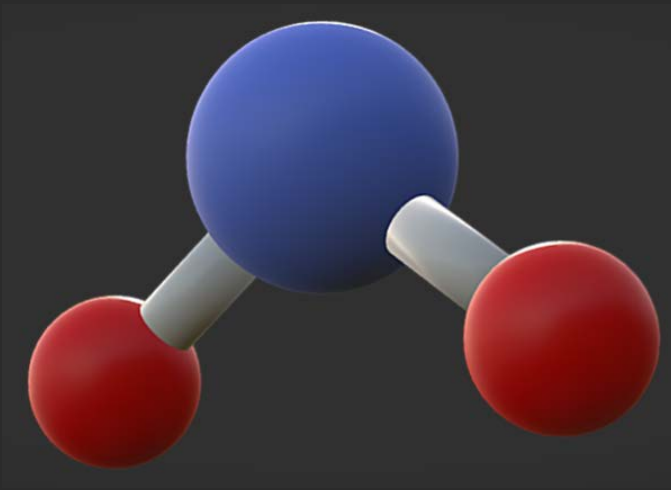
proton

neutron

atom
$O(10^{-10}\text{m})$

electron (-)

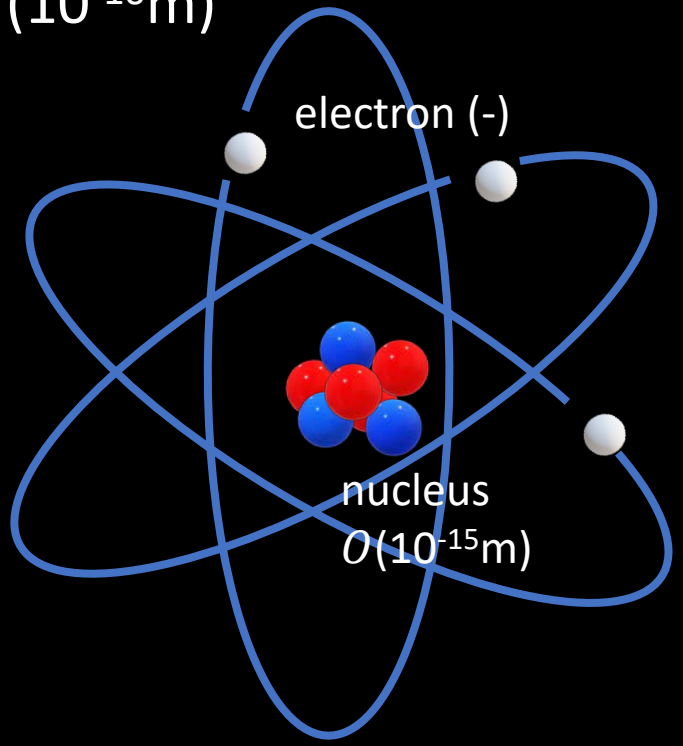
nucleus
$O(10^{-15}\text{m})$

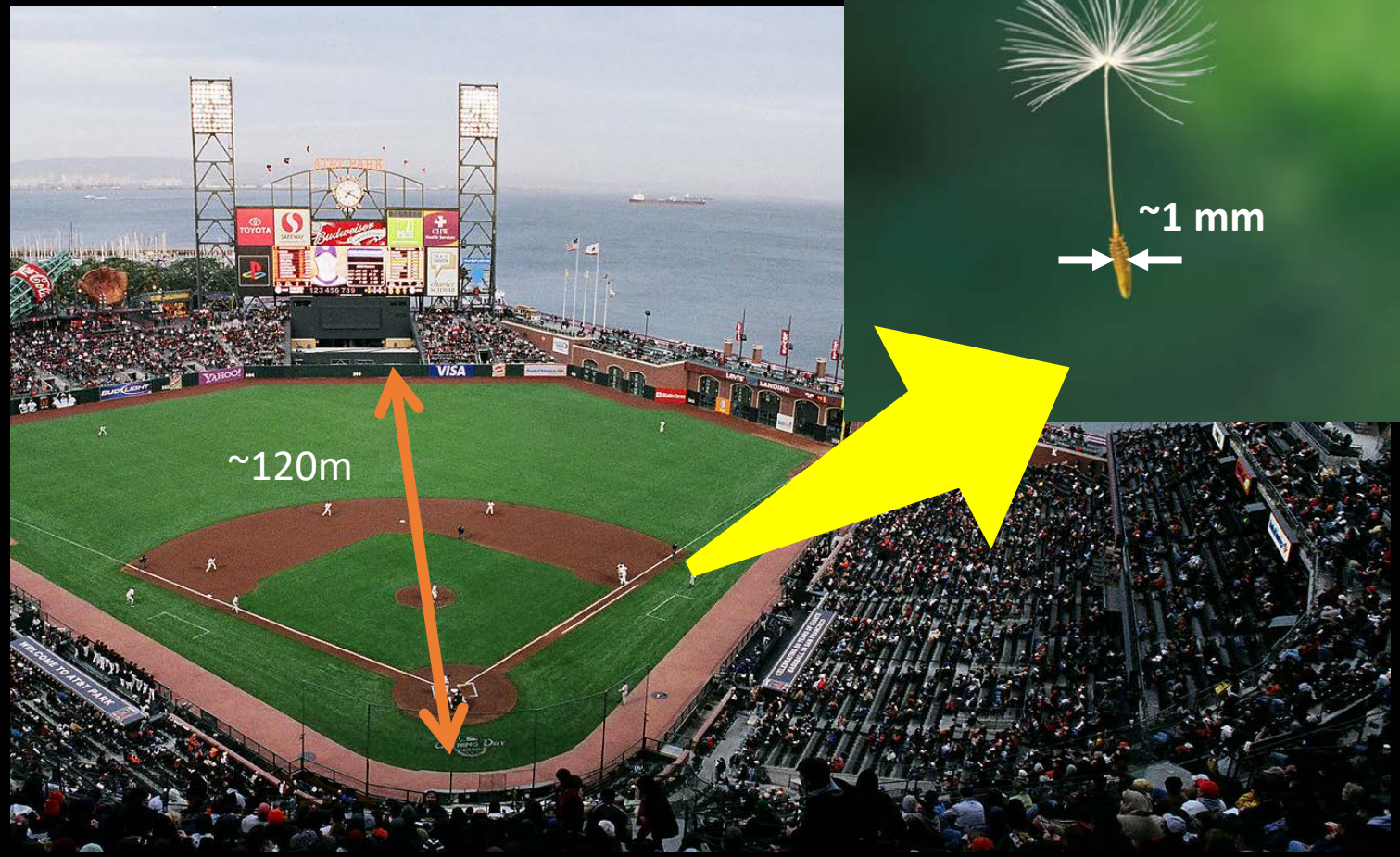


molecule
$\sim 3 \times 10^{-9}\text{m}$

if an atom was scaled to a baseball field
size of a proton

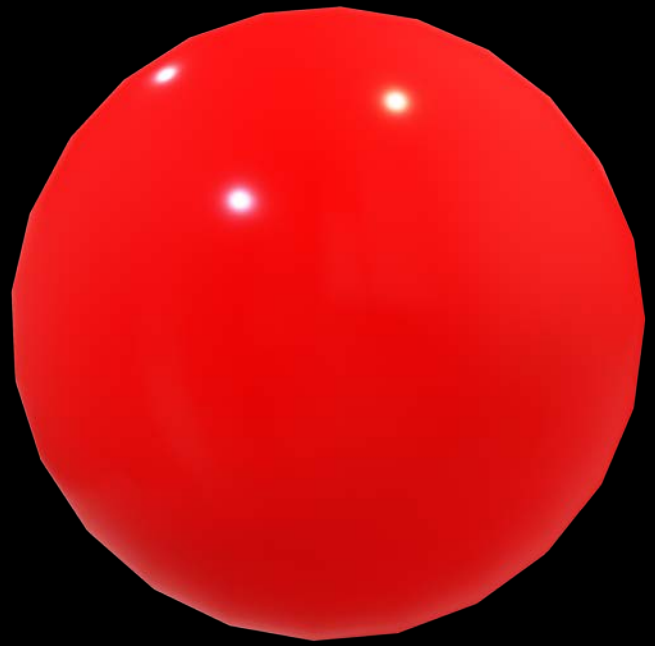
atom
$O(10^{-10}m)$

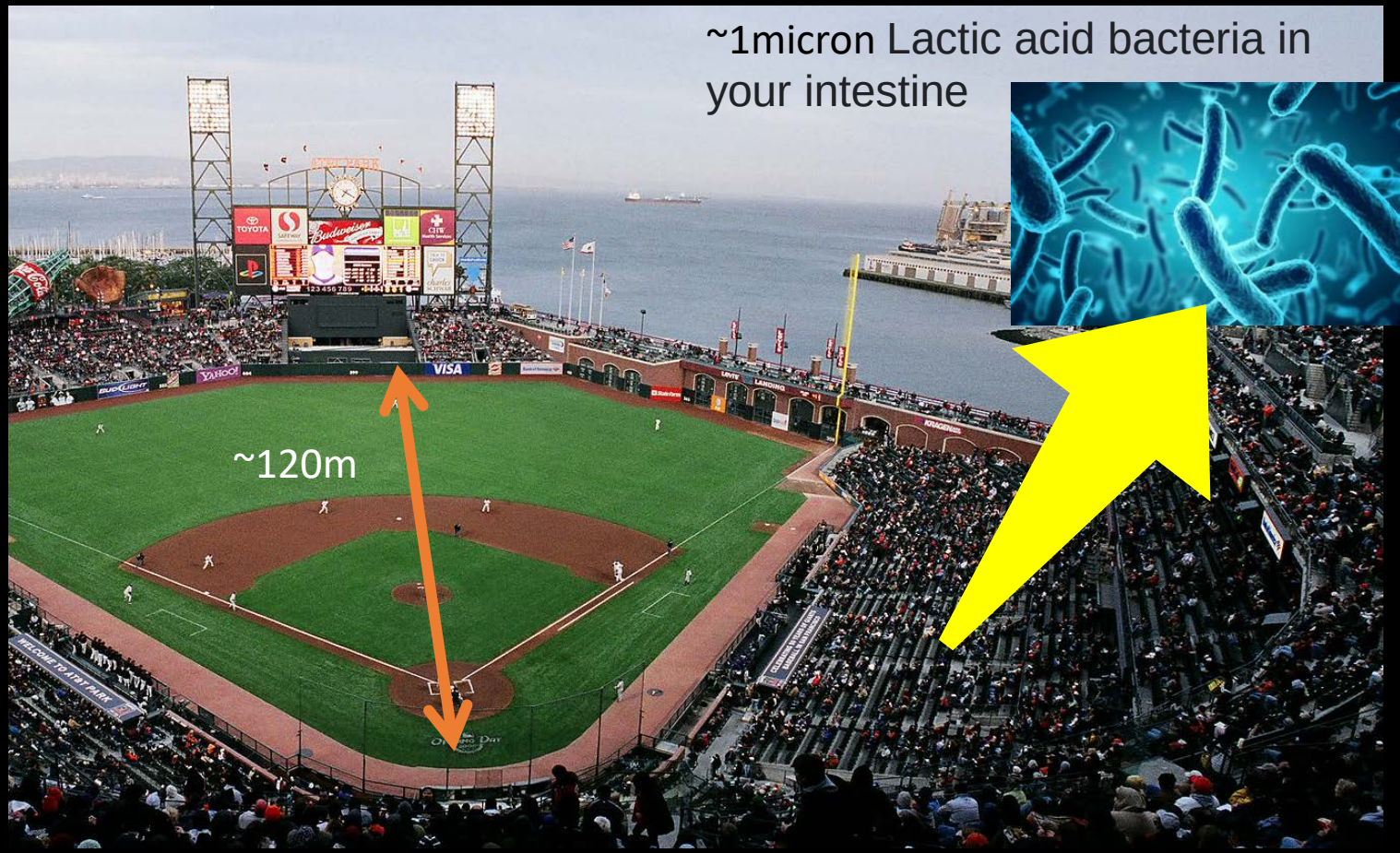




if a PROTON was scaled to a baseball field size of a NEUTRINO

proton
$O(10^{-15}\text{m})$





Earth is neutrino bright

Energy of neutrinos
~ MeV

Beta-decay

Production of geo neutrinos

neutron

proton

electron

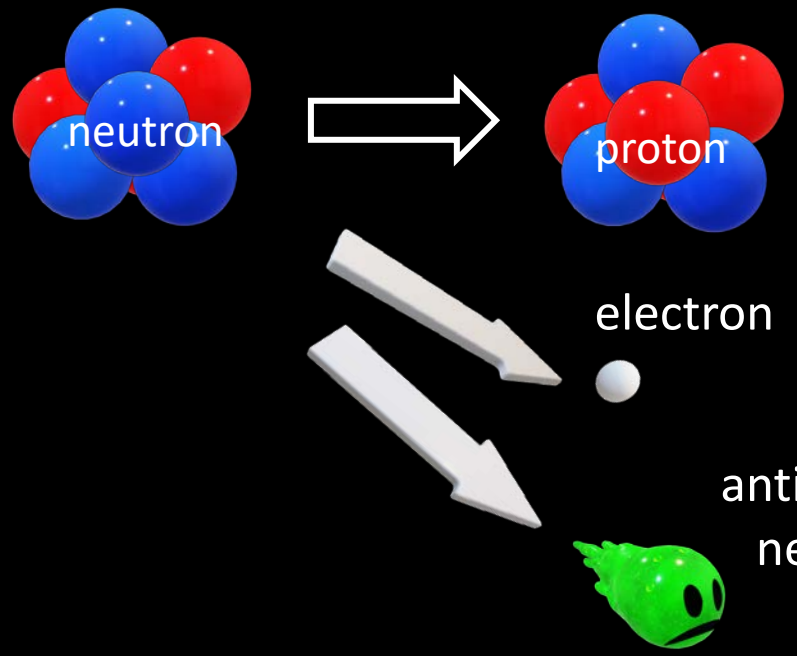
anti-electron
neutrinos

Earth is neutrino bright

Beta-decay in nucleus

$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \bar{\nu}_e$$

the original nucleus the nucleus with larger atomic number

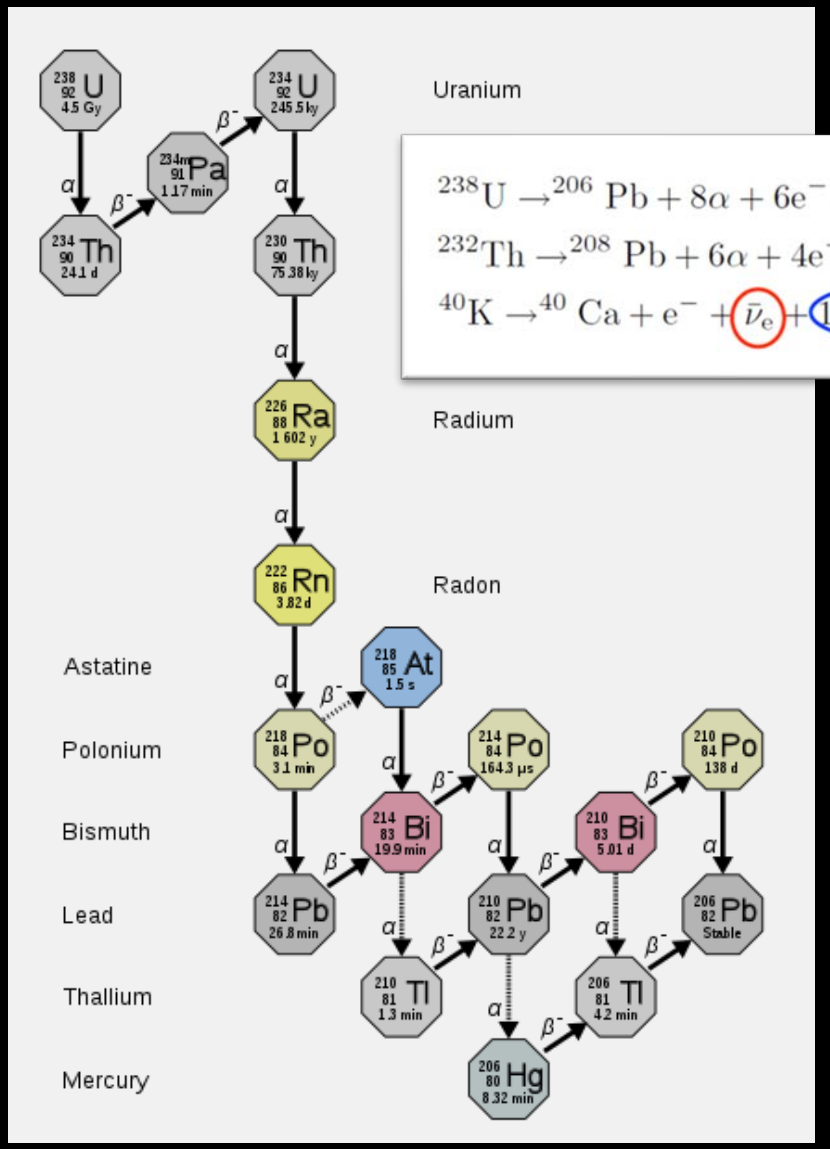


in nucleus,

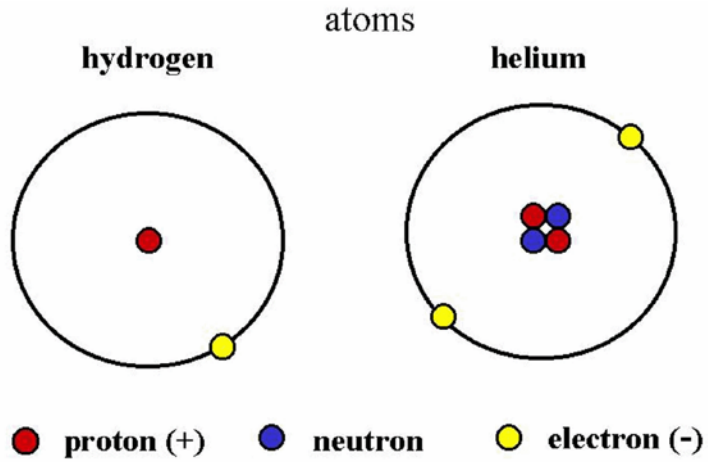
neutron + positron ⇔ proton + neutrino

proton + electron ⇔ neutron + neutrino

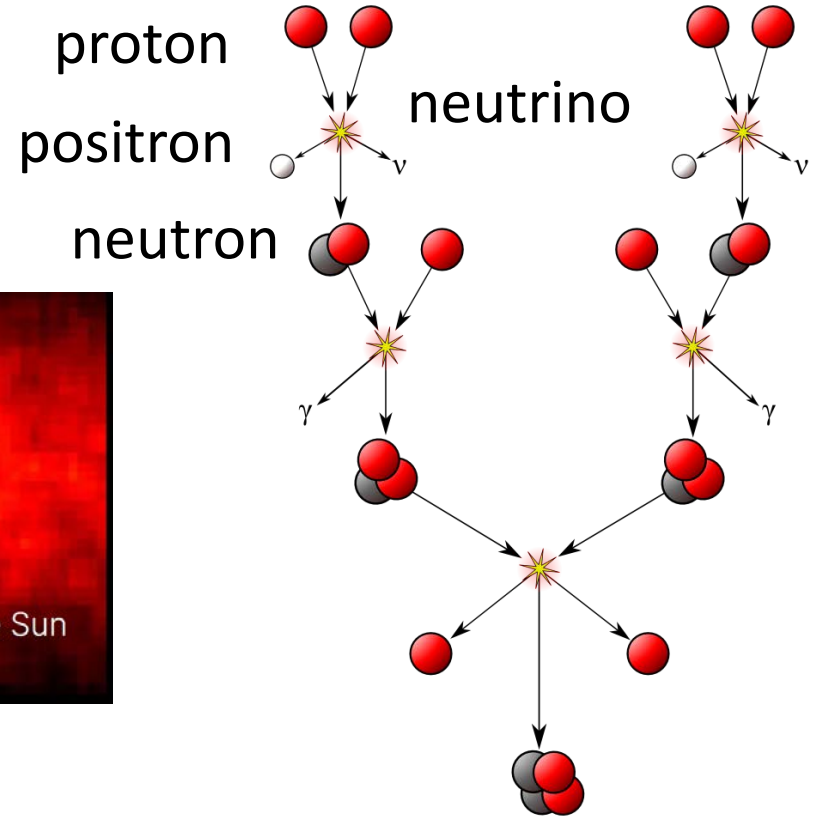
can also occur



Sun is neutrino bright



$4p \rightarrow He + 2e^{+} + 2\nu_e + energy$



Earth

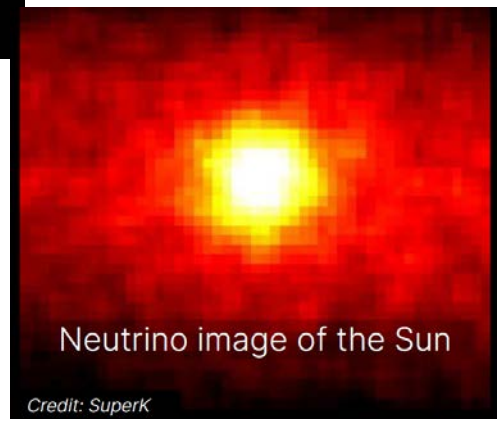
Energy of neutrinos ~ MeV

distance to the object 0 km

Sun

Energy of neutrinos ~ 10 MeV or less

distance to the object 149.6 million km (0.00001581 light year)



****Earth to the Galactic Center 28 kilo light years**

Neutrino bright explosion!

Measured with Kamiokande, IMB, Baksan in 1987

Earth

Energy of neutrinos ~ MeV

distance to the object 0 km

Sun

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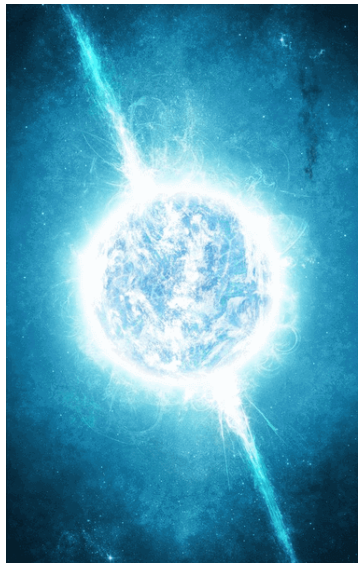
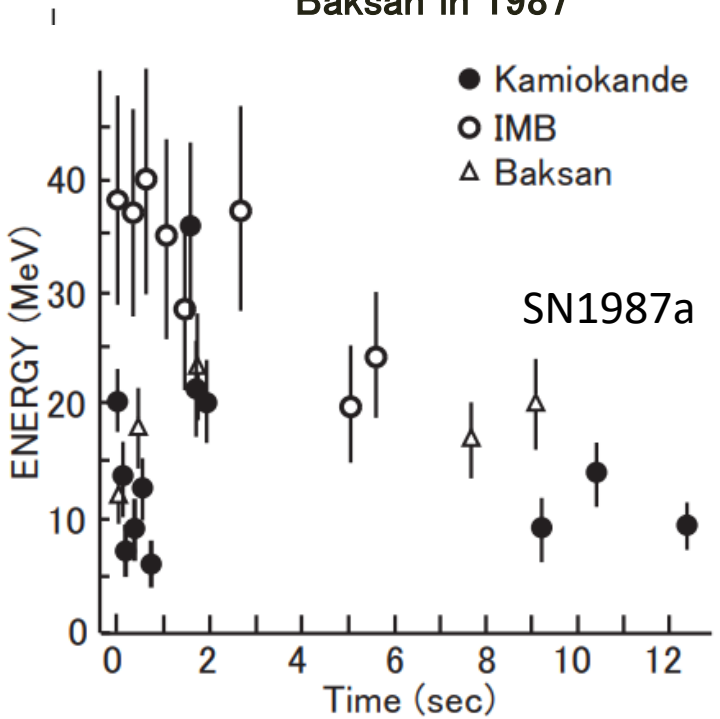
Supernova



Energy of neutrinos ~ 100 MeV or less

distance to the observed object 160 kilo light years



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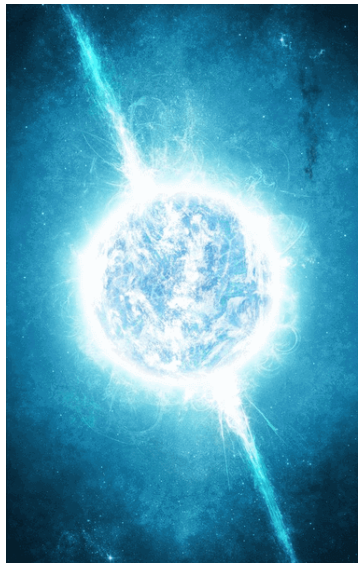
Supernova



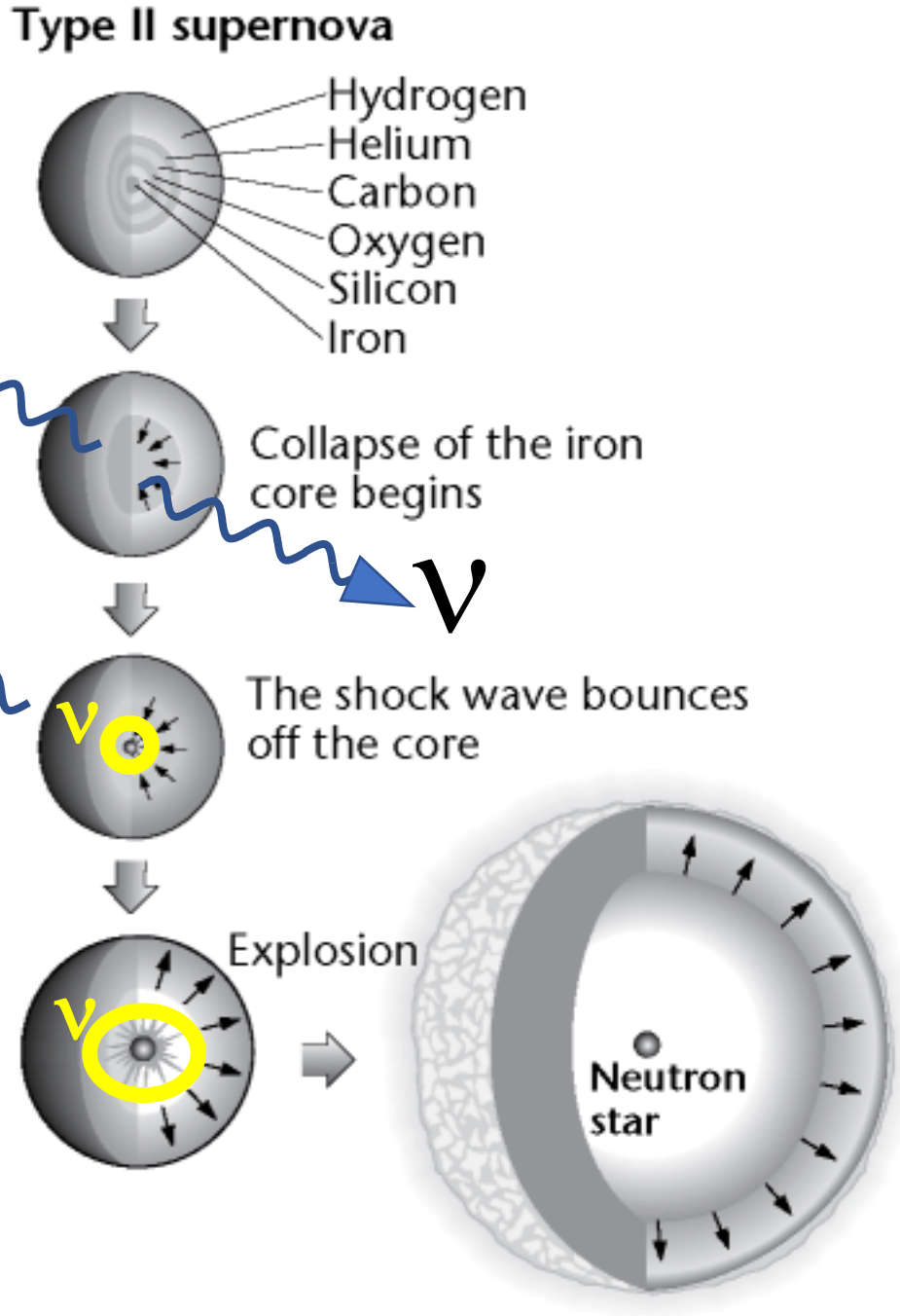
Energy of neutrinos
~ 100 MeV or less

proton + electron
⟶ neutron + neutrino

ν

ν

ν-confinement



1MeV-100MeV

Why we want to see the Universe with neutrinos?

1. to ***see*** the high-density states, such as the one formed in the supernova explosion, and where light can not be escaped

100,000MeV – 10,000,000,000MeV

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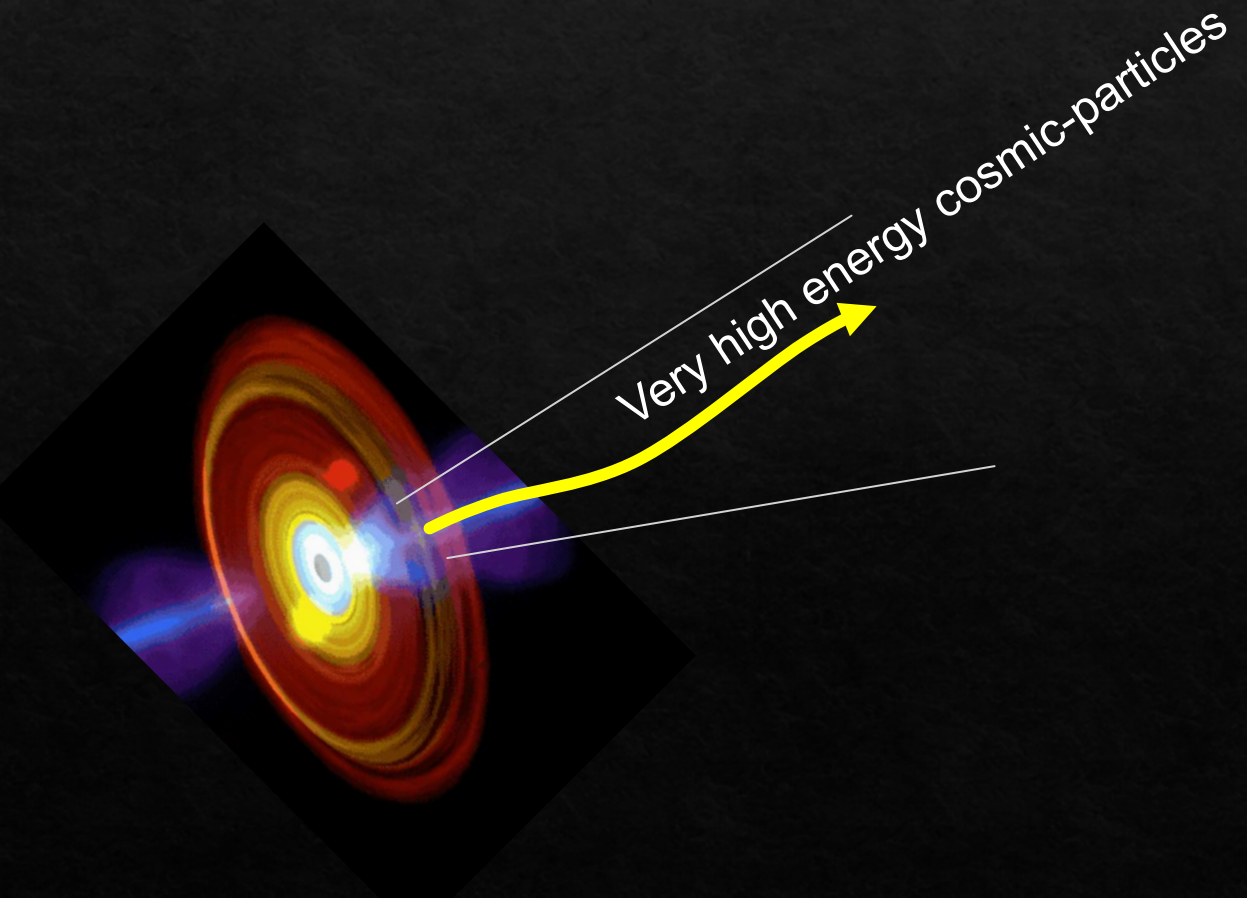
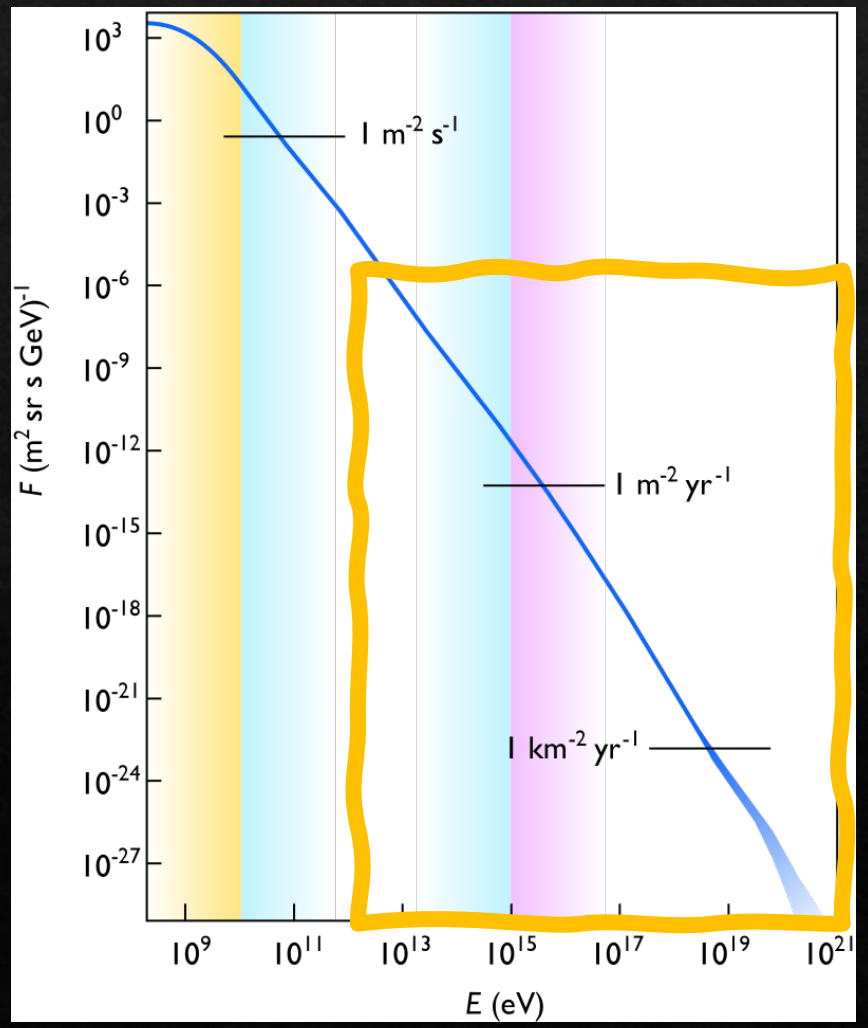
from 100,000MeV=0.1 TeV

to 10,000,000,000MeV=10000 TeV

How to create the high energy neutrinos

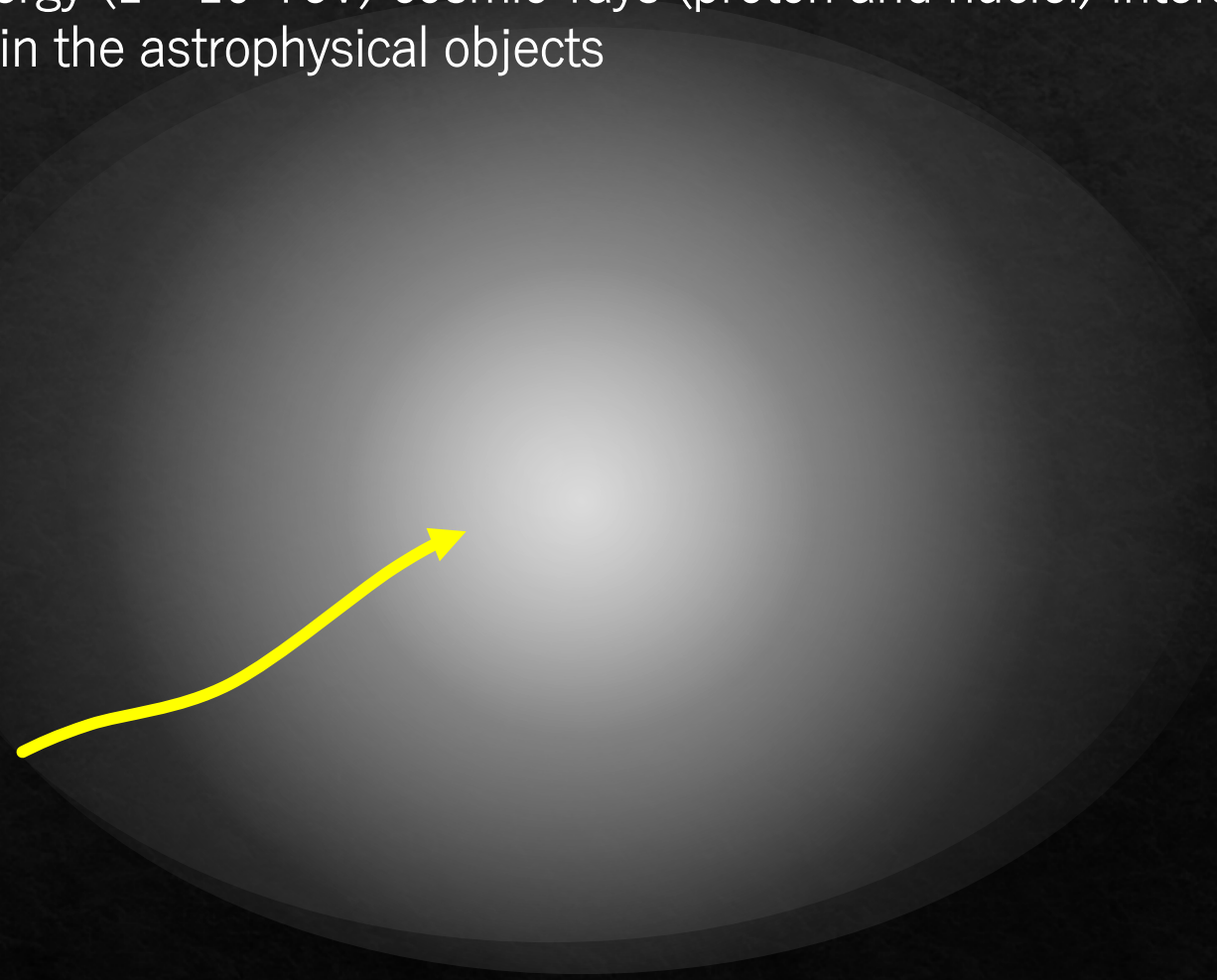
Somewhere in the Universe, ordinary matters (proton and nuclei) are accelerated to very high energy.
Particles beyond 10^8 TeV (10^{20} eV) observed





How to create the high energy neutrinos

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



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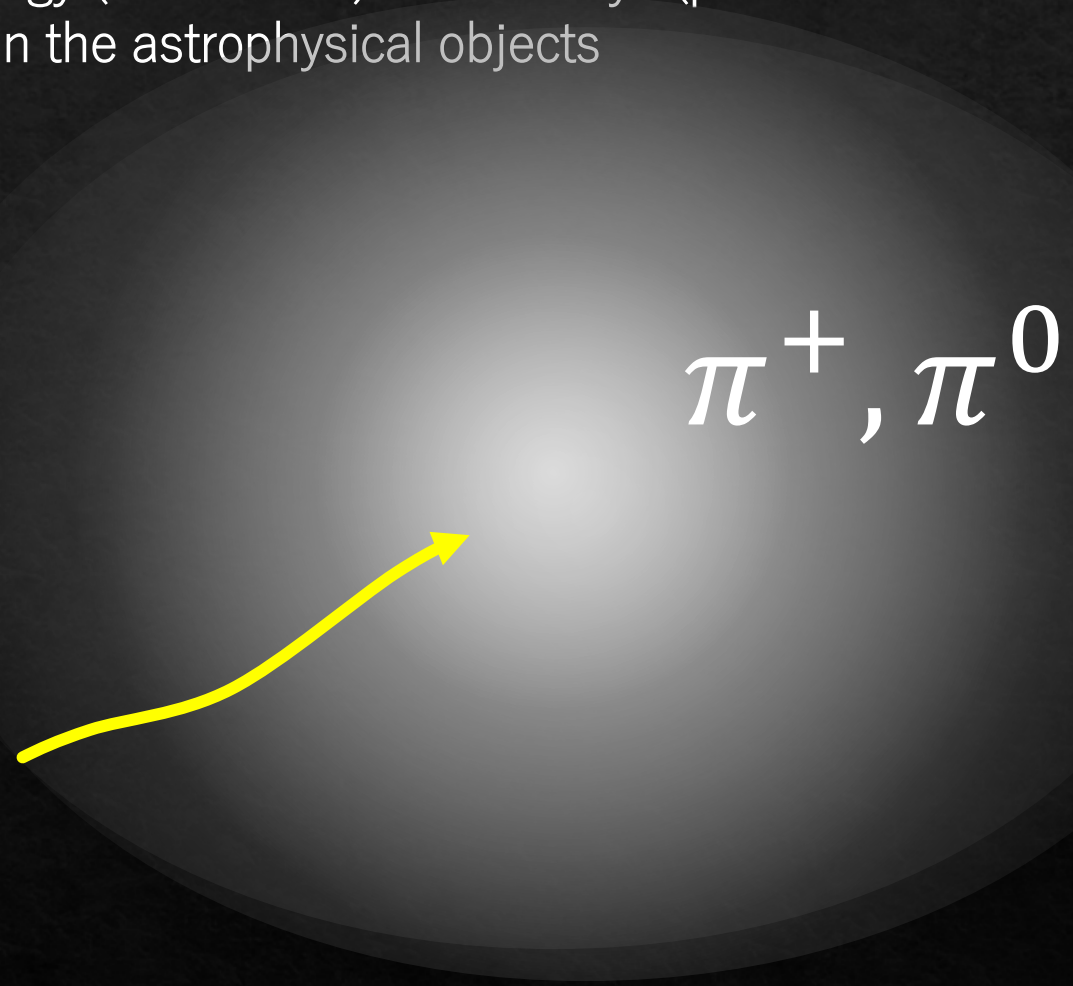


mesons (pions) are created
(both charged and neutral)

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

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

How to create the high energy neutrinos

② a charged pion decays into muon and neutrino,
a muon decays into positron and (anti) neutrinos

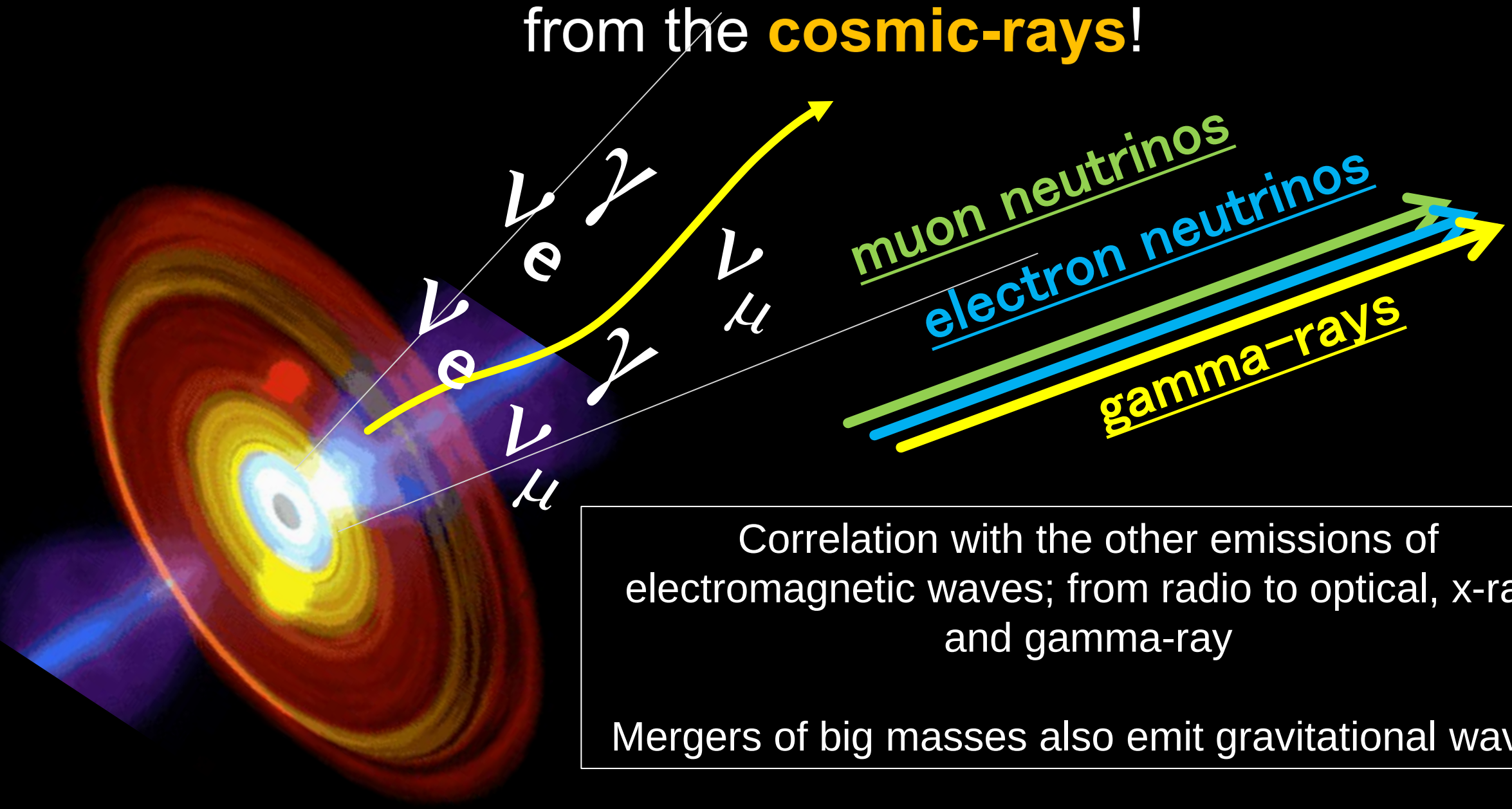
π^+, π^0

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

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

charge neutral pions creates gamma-rays

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



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

High energy neutrino is able to visualize the place where the high energy cosmic-particles are colliding

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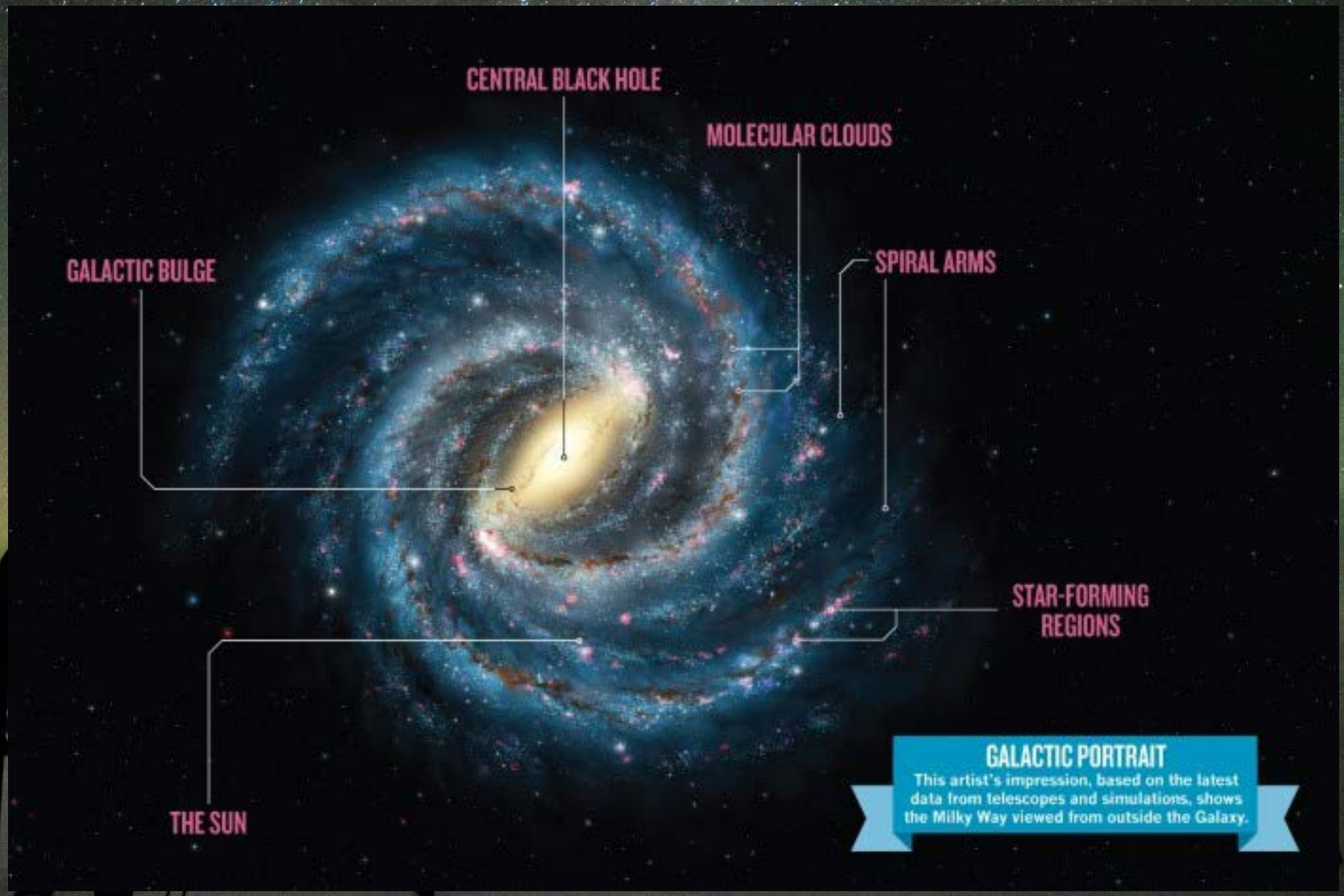
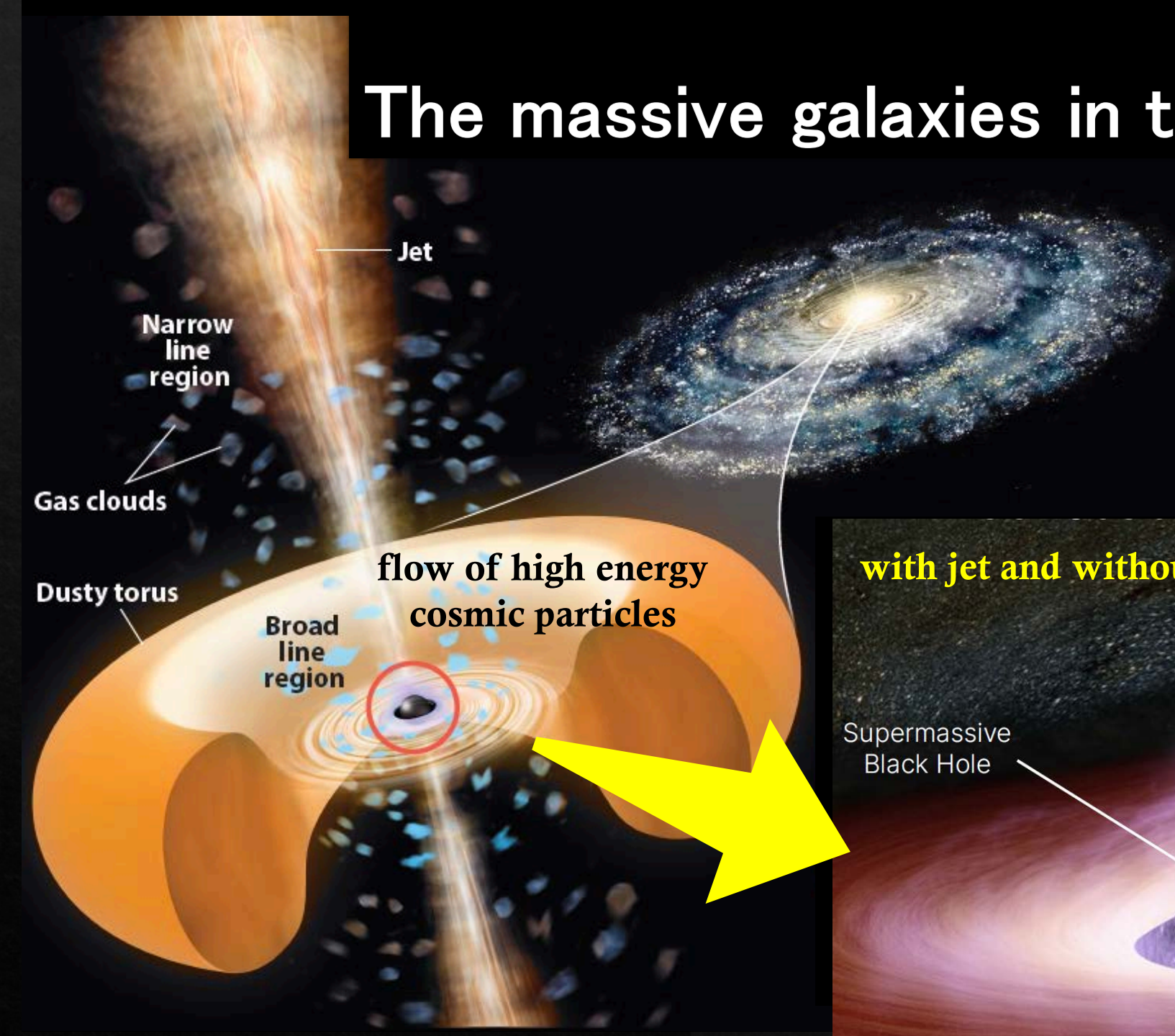
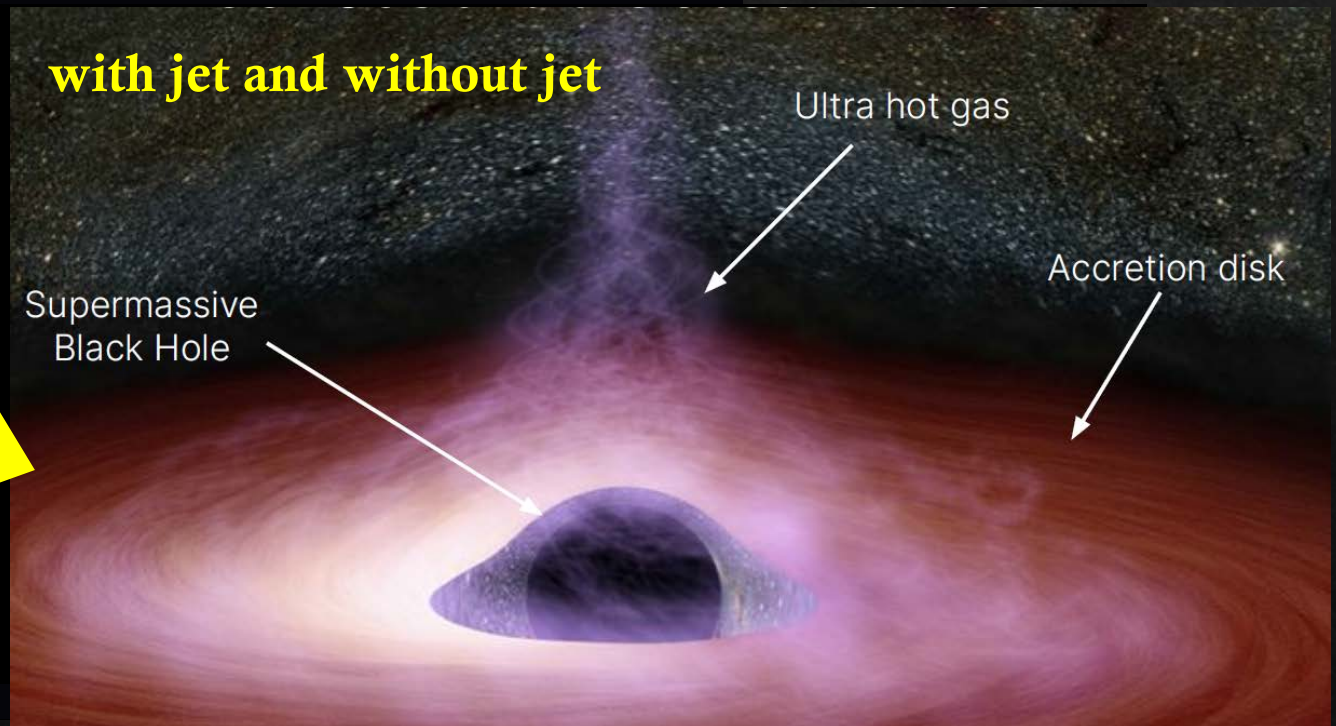


The massive galaxies in the far Universe

Active Galactic Nuclei (AGN)

- 10^{12} times brighter than Sun





0.1 TeV – 10,000 TeV

Why we want to see the Universe with neutrinos?

- to ***see*** the high-density states, such as the one formed in the supernova explosion, and where light can not be escaped
    - to identify the region where the high energy cosmic-rays interact
    - to build models with gamma-ray + the other multi-messengers

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- **to *see* the universe where light can not penetrate**

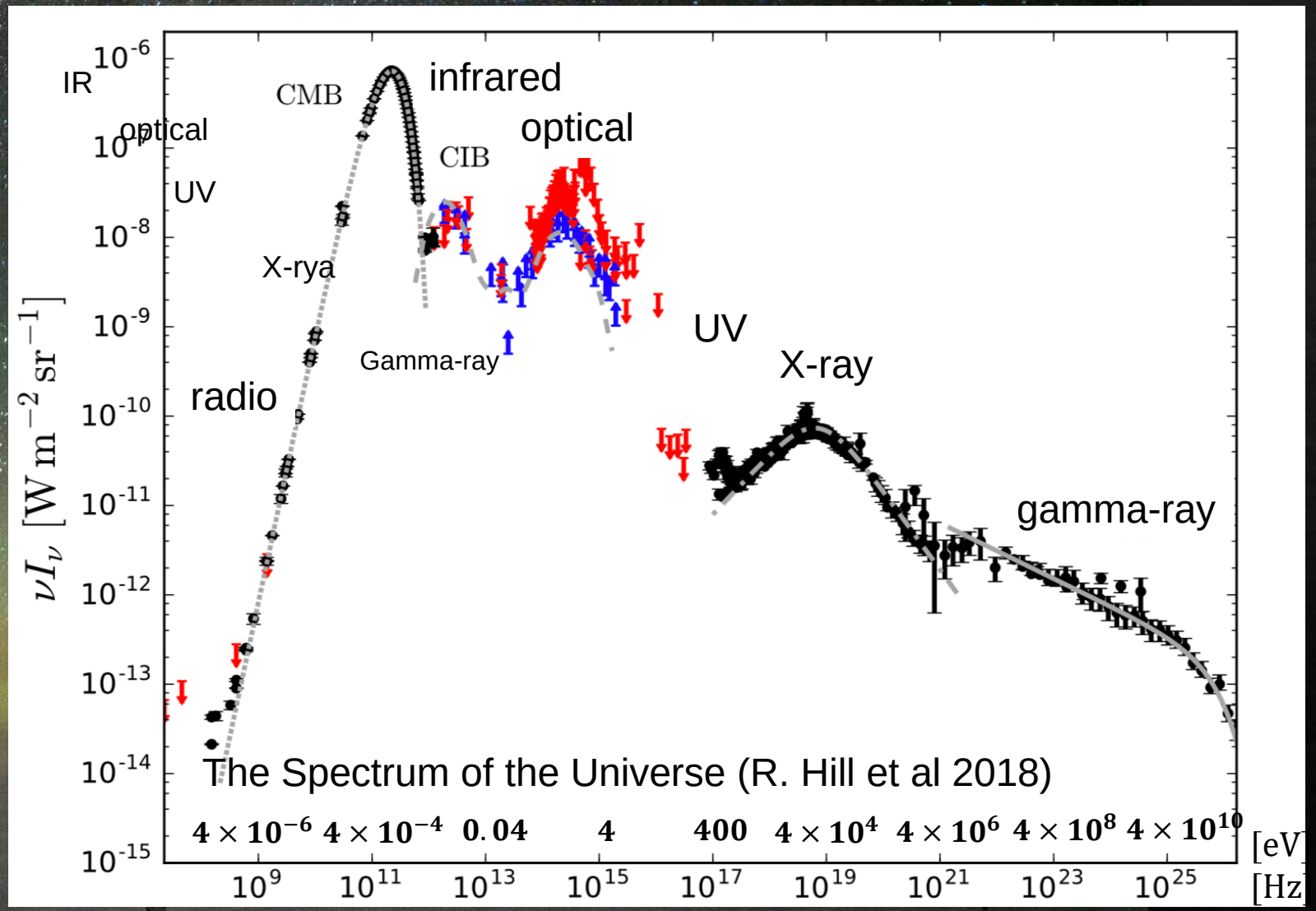
CCD/CMOS 400-700nm
1.8-3.8eV

- **why and where in the Universe, light can not penetrate?**

Martin Wolf, IceCube/NSF

CCD/CMOS 400-700nm
1.8-3.8eV

radio



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

Mean free path in a photon density n

$$\ell_{\gamma\gamma} \sim \frac{1}{\sigma_T n}$$

CCD/CMOS 400-700nm
1.8-3.8eV

radio

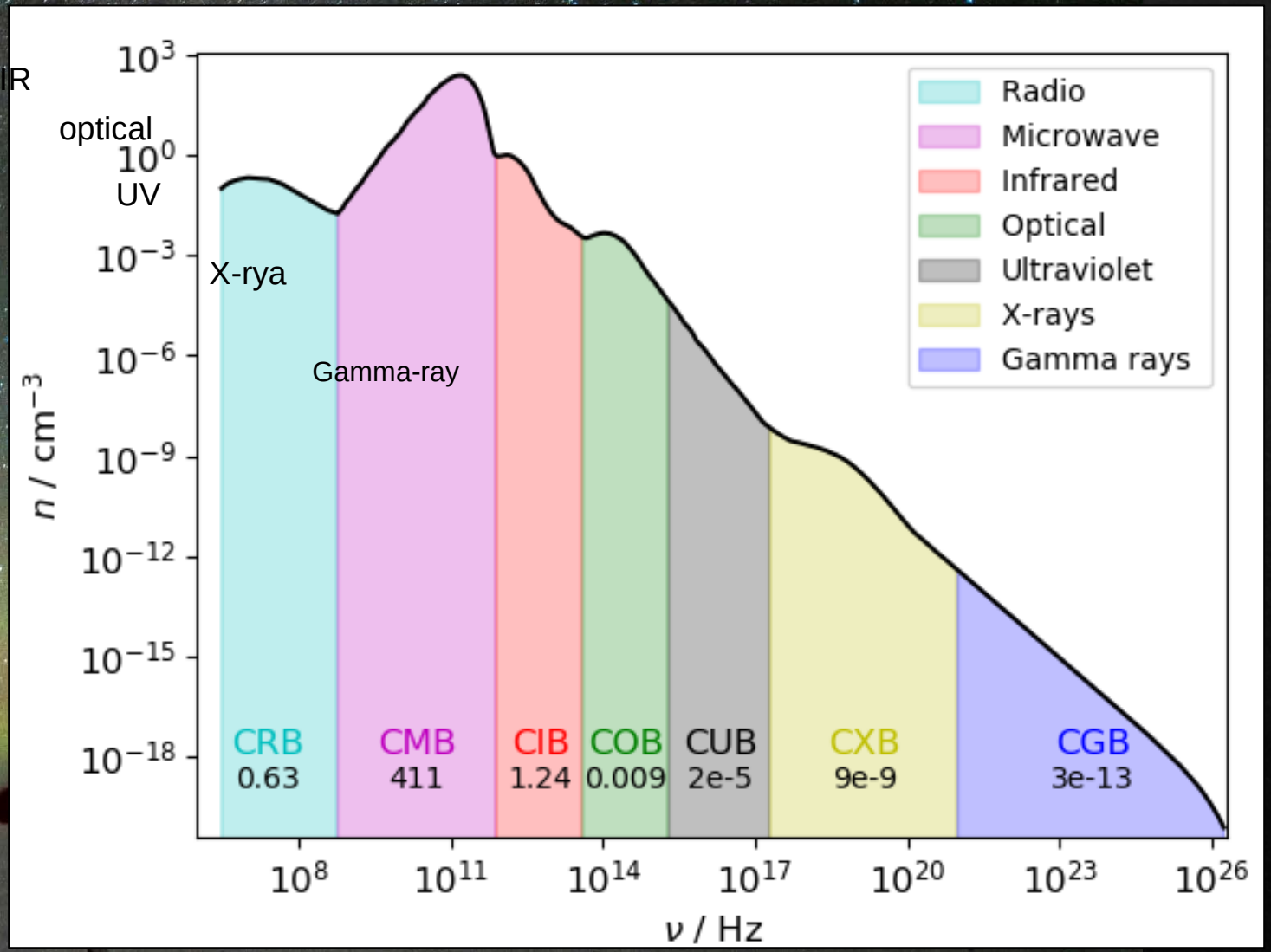
IR

optical

UV

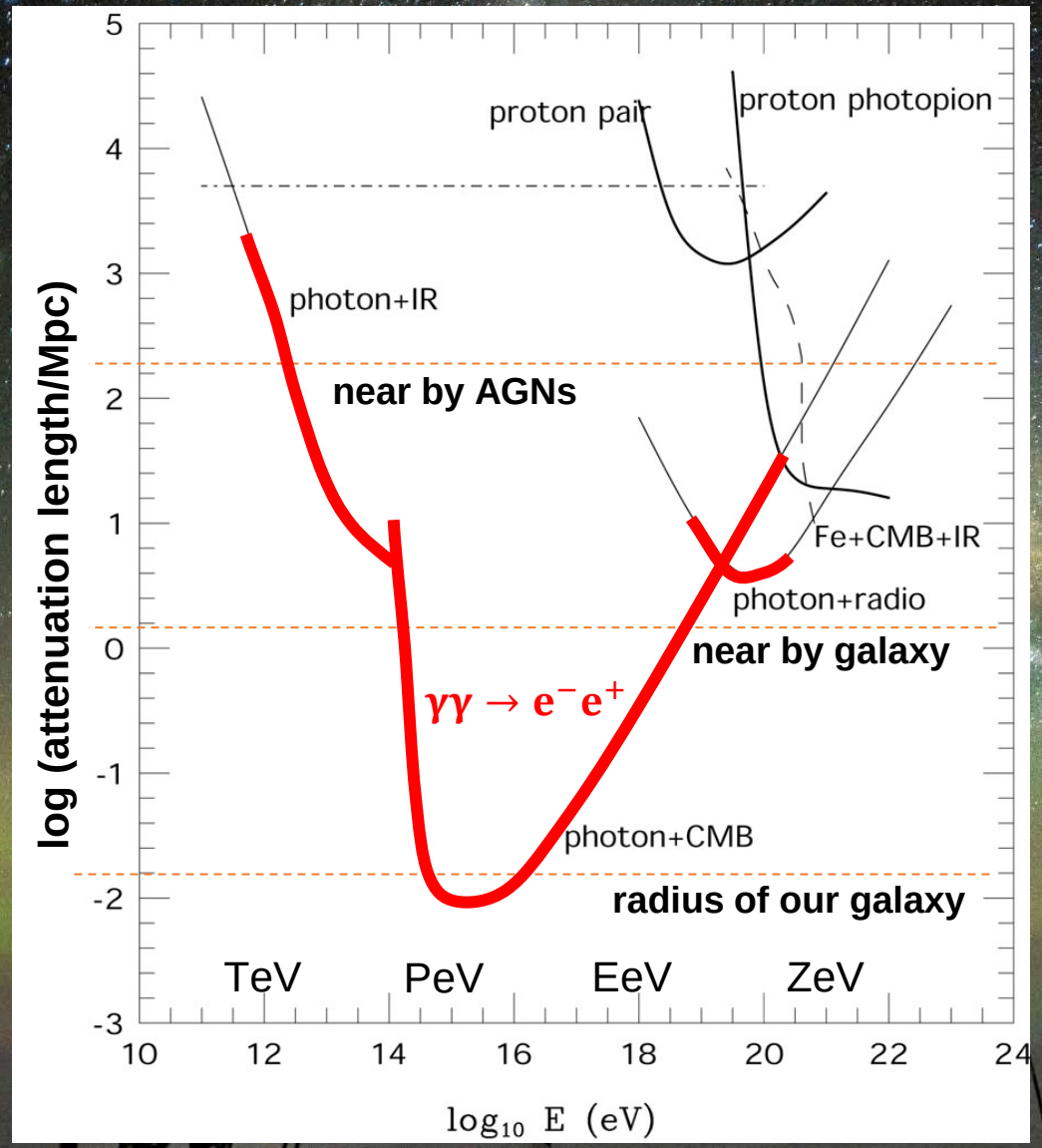
X-rya

Gamma-ray

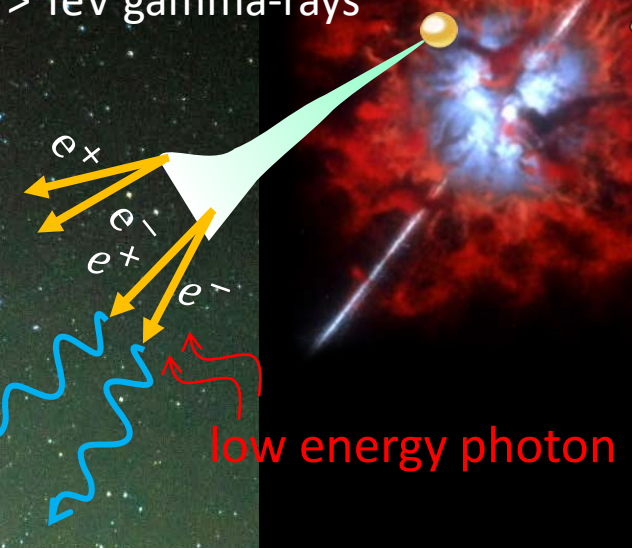


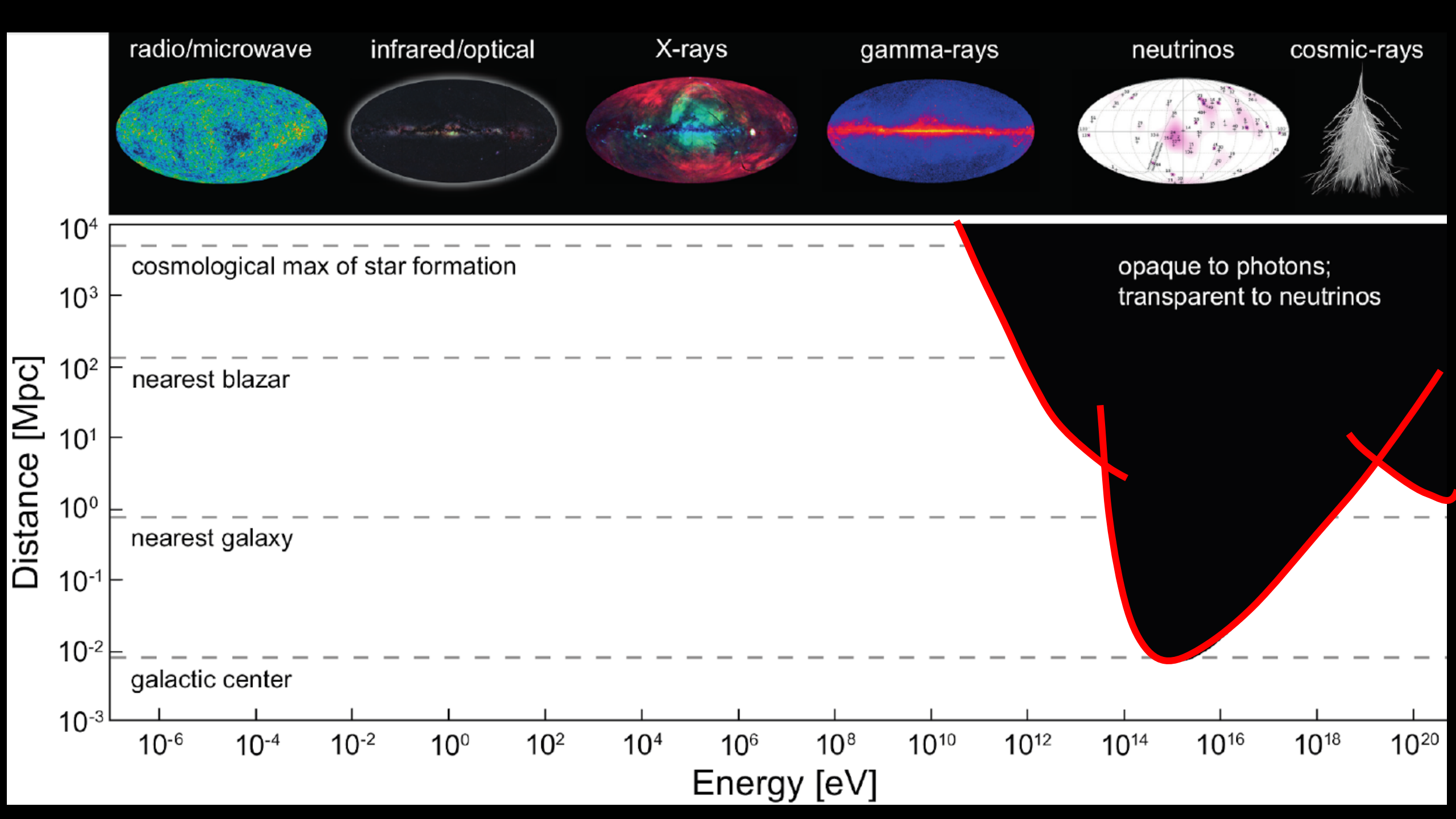
1Parsec(pc) = 3.26 light years

Tevatron, Pevatron, EeVatron, ZeVatron



Anchordoqui+
hep-ph/0206072v3




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

0.1 TeV – 10,000 TeV

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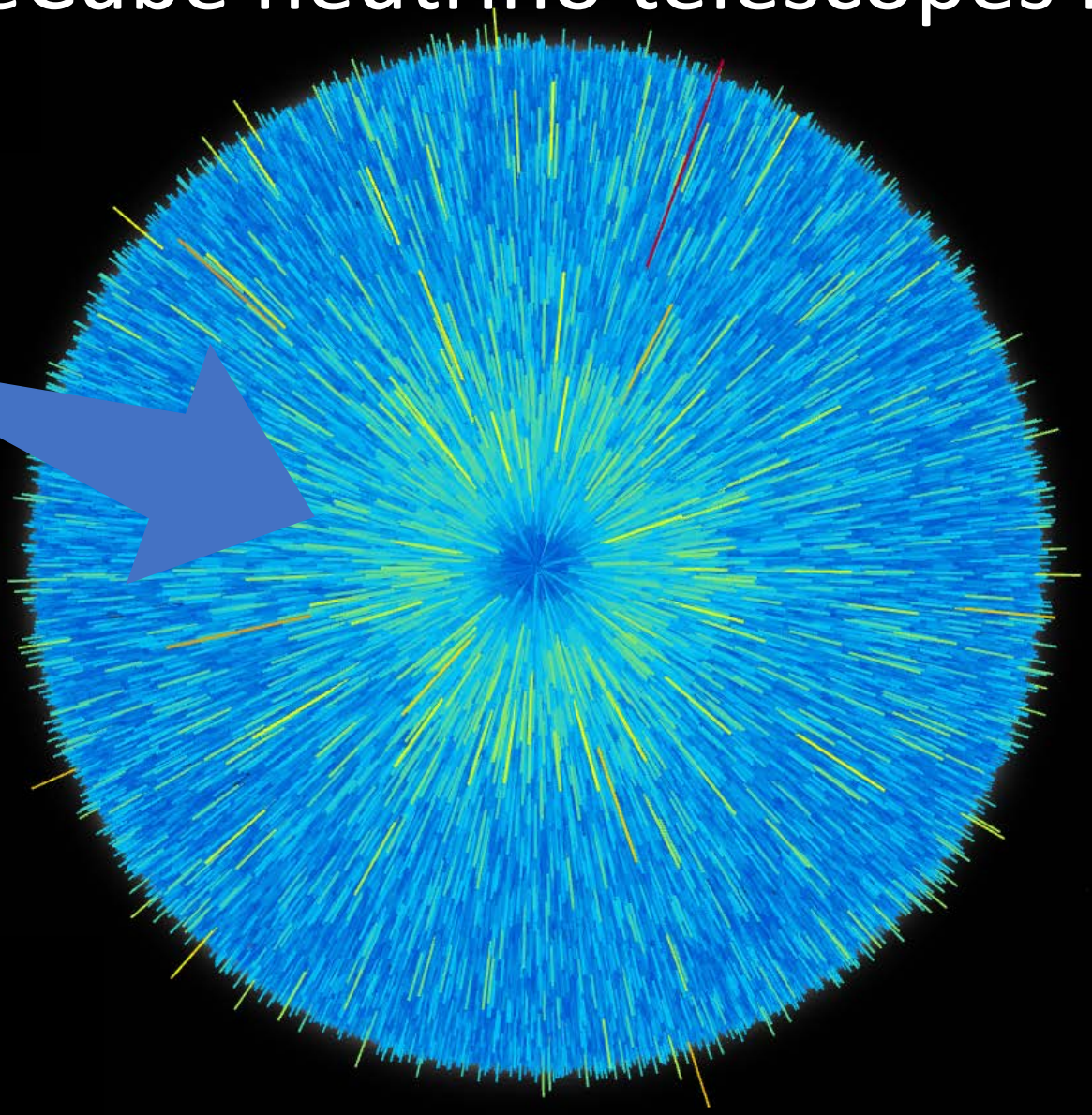
    - to identify the region where the high energy cosmic-rays interact
    - to build models with gamma-ray + the other multi-messengers

- **to *see* the universe where light can not penetrate**
- to use the universe as the elementary particle beam accelerator to explore the particle physics beyond man made accelerators can no reach (not covered)

Measured cosmic neutrinos with the IceCube neutrino telescopes in 10 years

where the telescopes are



Science 361, eaat1378 (2018)

IceCube-170922A alert to worldwide telescopes

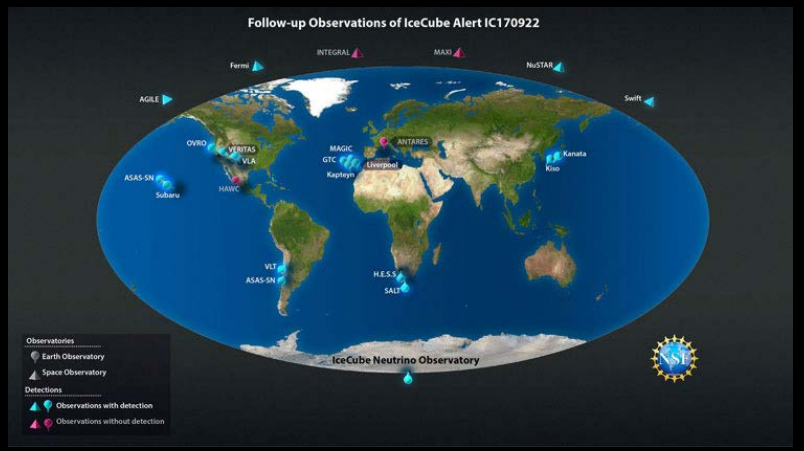
- 2017/9/22 20:54:30.43 UTC
- 5th and the most cosmic neutrino signal like EHE alert
- automated alert was distributed to observers just 43 seconds later

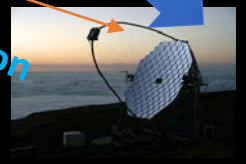
Fermi Telescope

Optical telescopes

Kanata telescope

...and many more telescope

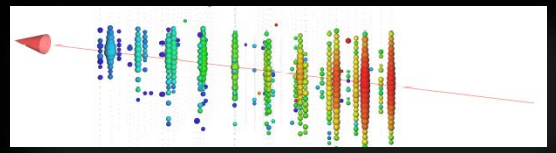




Magic telescope

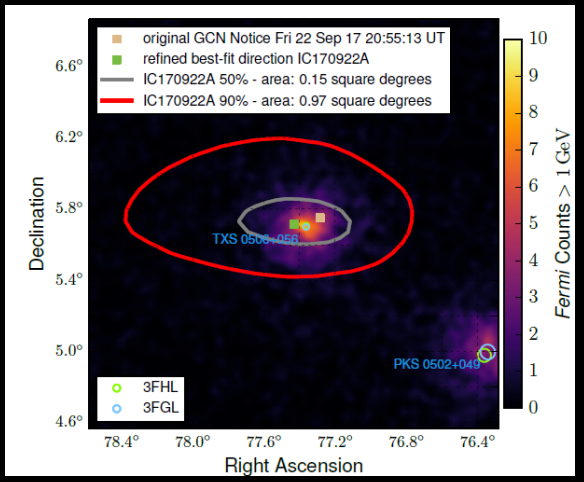
Multi-messenger view of TXS 0506+056

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



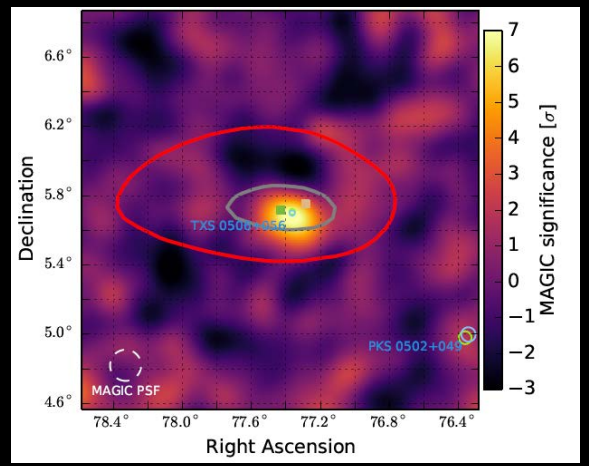
HE gamma-ray observations

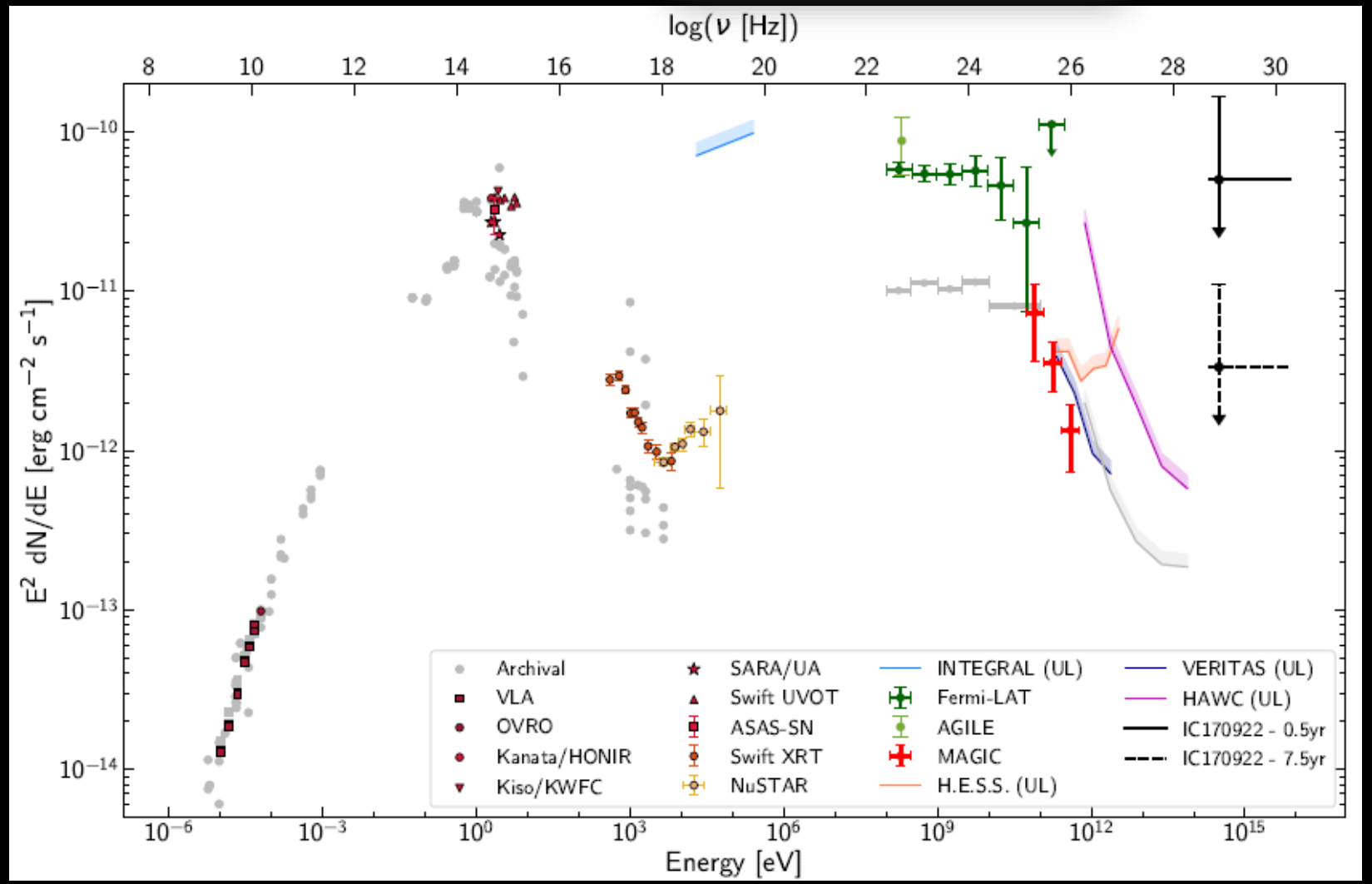
- Fermi-LAT(20MeV - 300 GeV) reported gamma-ray flare



VHE gamma-ray observations

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





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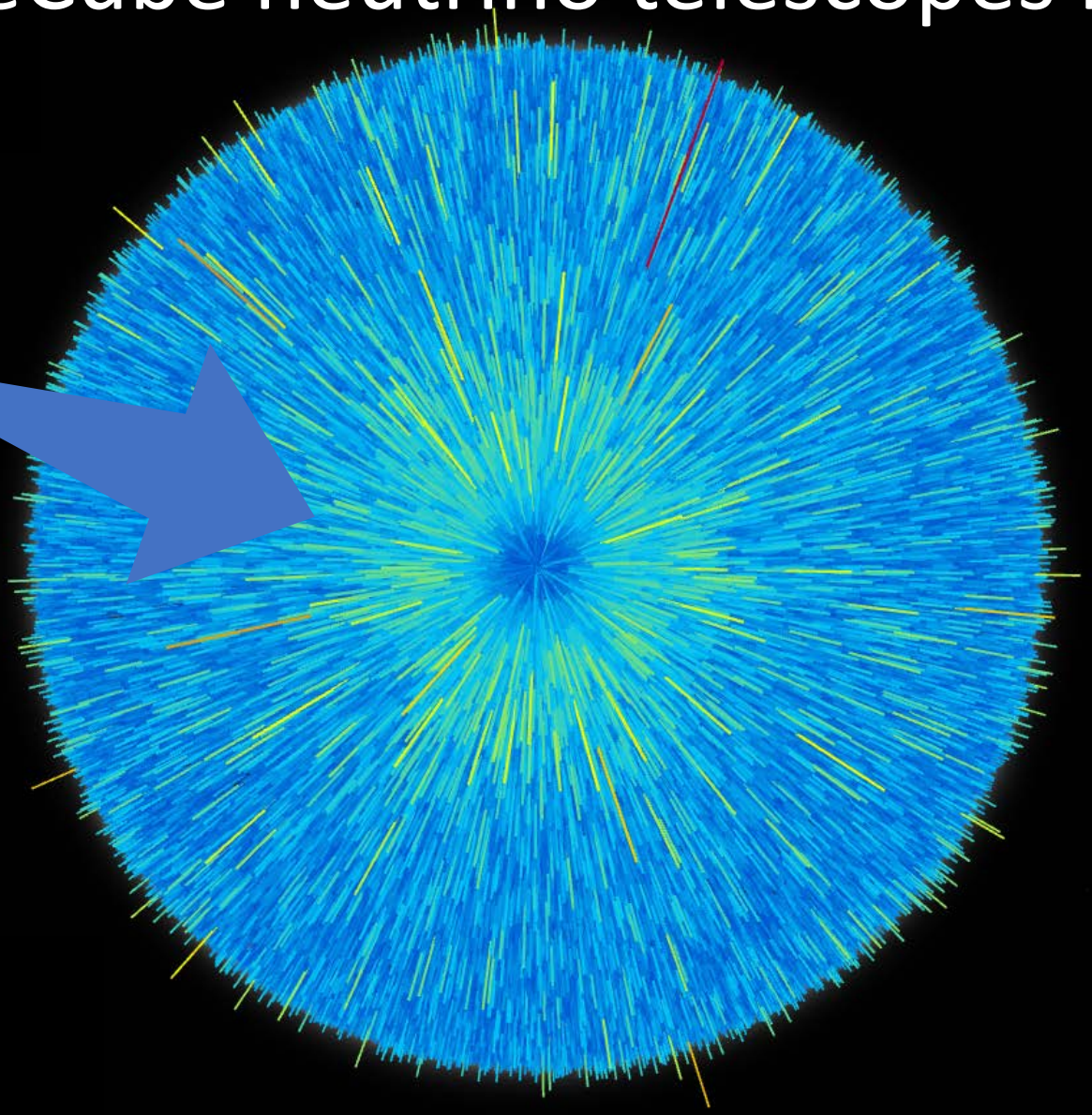


Science — Nov.4, 2022
RESEARCH

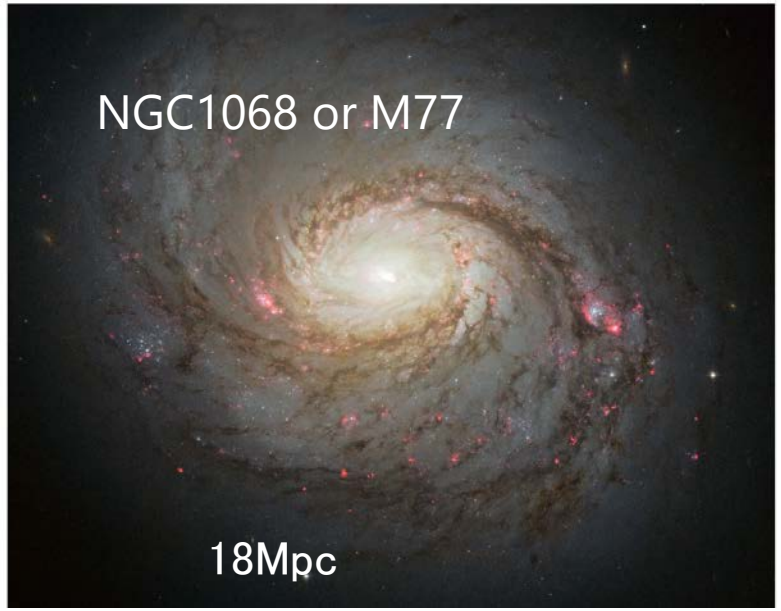
RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

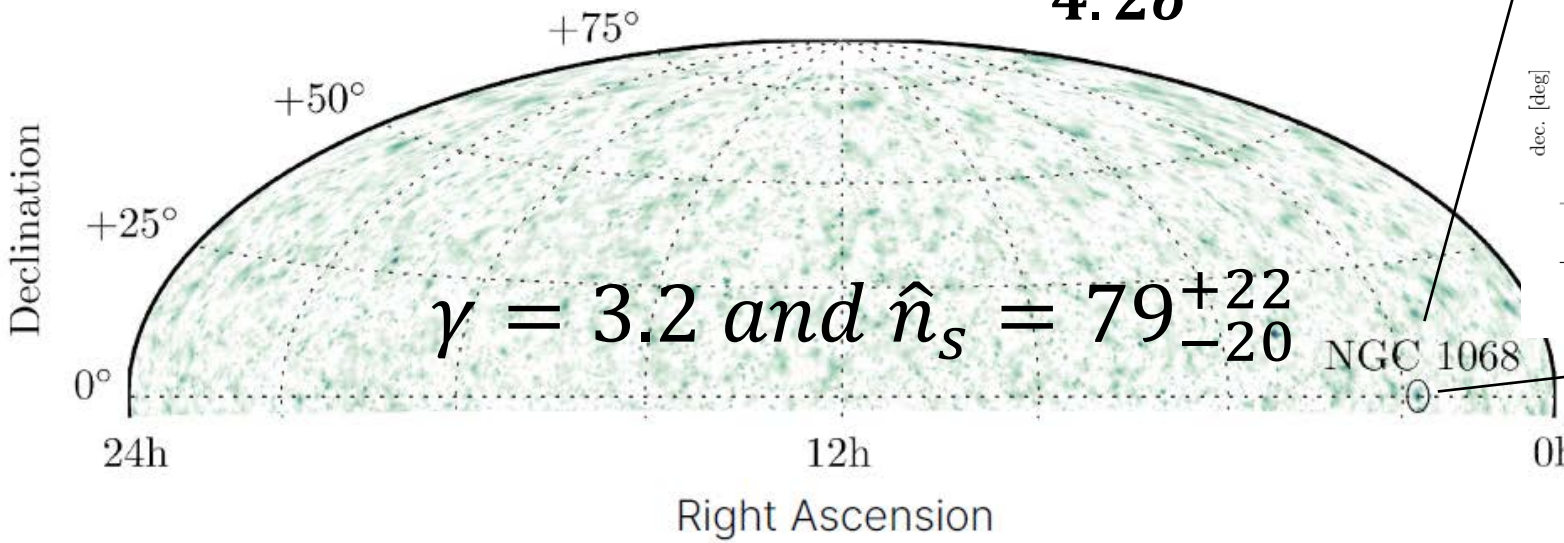
Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

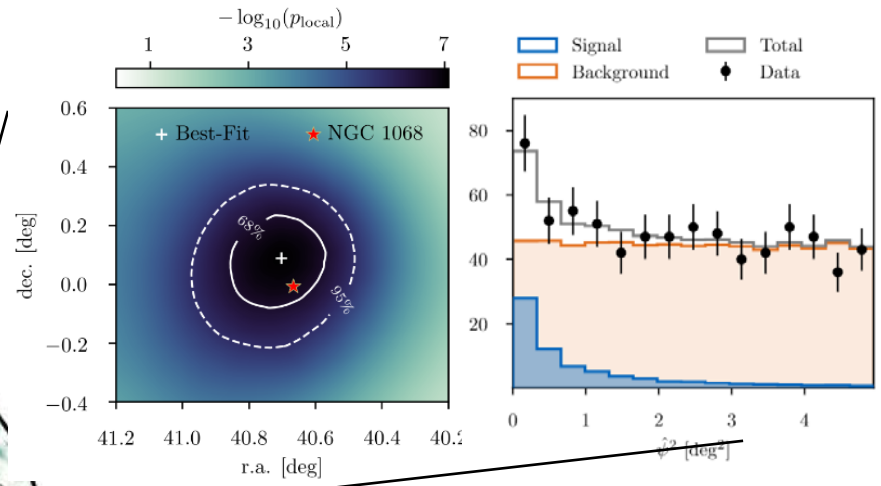
Very bright, well studied, spiral galaxy



$$global\ significance\ 4.2\sigma$$

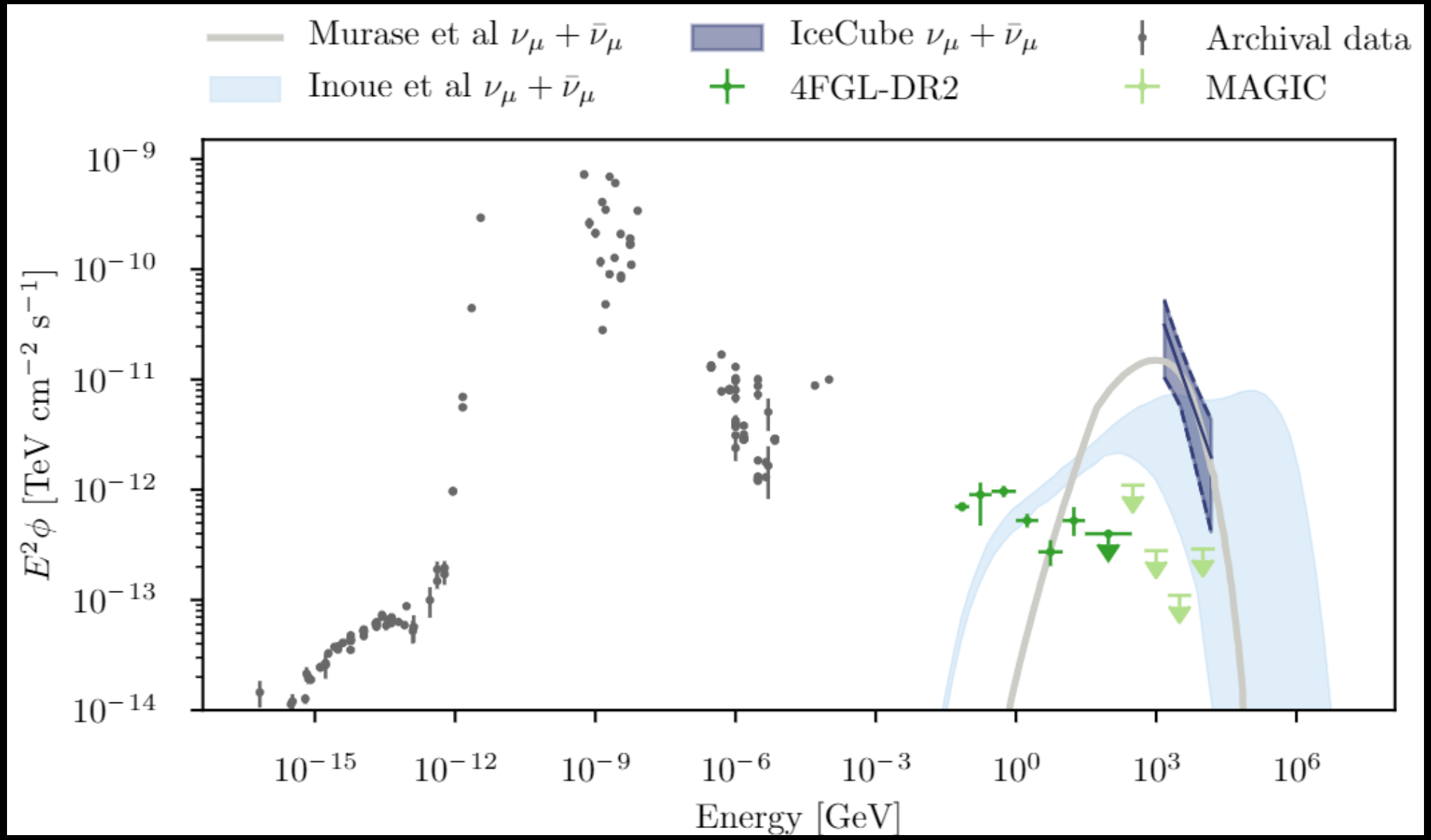


$$\gamma = 3.2\ and\ \hat{n}_s = 79^{+22}_{-20}$$

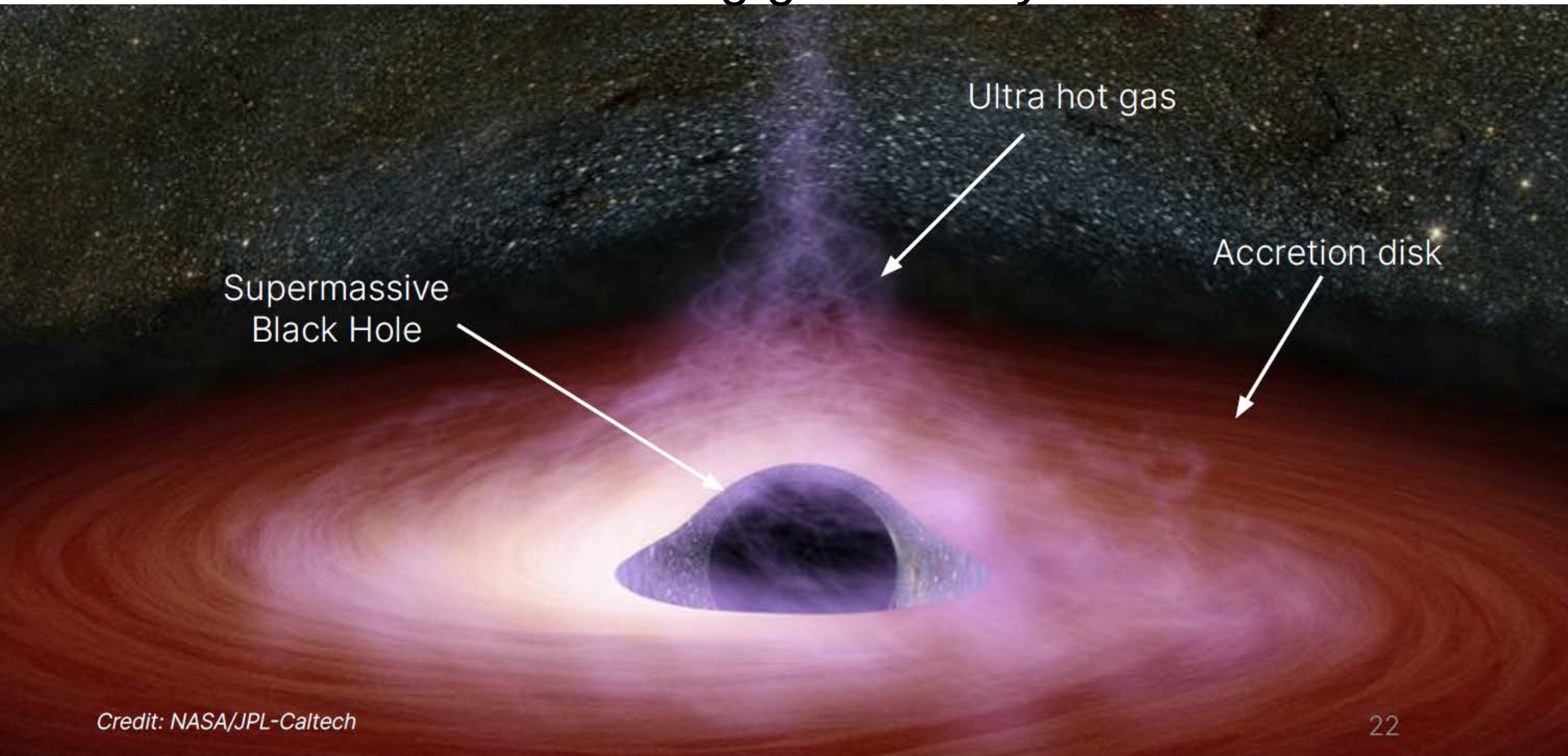


2011 and 2020.

Multi-messenger view of M77 (NGC1068)



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



Neutrino bright objects **before 2018**

Earth

Energy of neutrinos
~ MeV

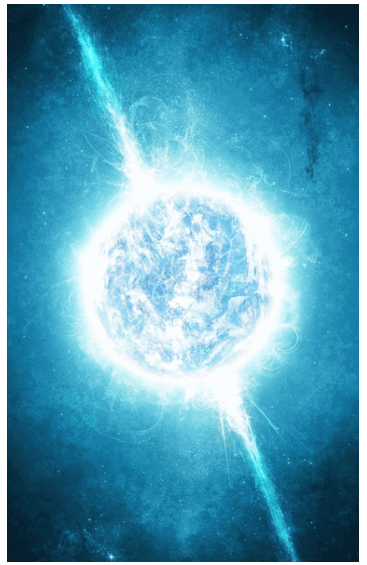
distance to the object
0 km

Sun

Energy of neutrinos
~ 10 MeV or less

distance to the object
149.6 million km
(0.00001581 light years)

Supernova



Energy of neutrinos
~ 100 MeV or less

distance to the observed
object 160 kilo light years

Neutrino bright objects **as of Today**

Earth

Energy of neutrinos
~ MeV

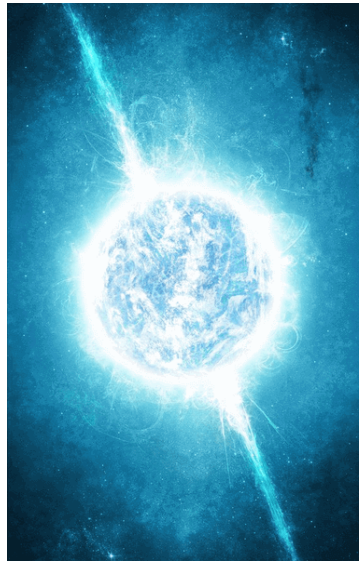
distance to the object
0 km

Sun

Energy of neutrinos
~ 10 MeV or less

distance to the object
149.6 million km
(0.00001581 light years)

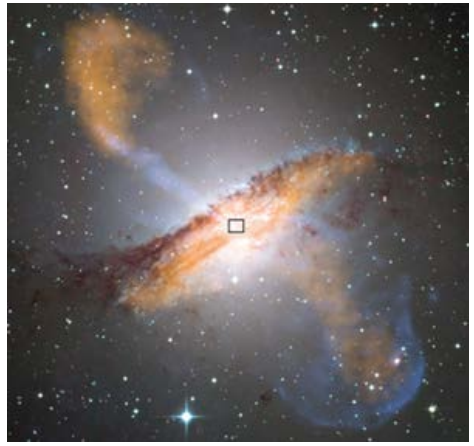
Supernova



Energy of neutrinos
~ 100 MeV or less

distance to the observed
object 160 kilo light years

AGN
Blazar



Energy of neutrinos
~ 100,000,000 MeV

distance to the observed
object 4,000,000,000 light years

AGN
Seyfert Galaxy

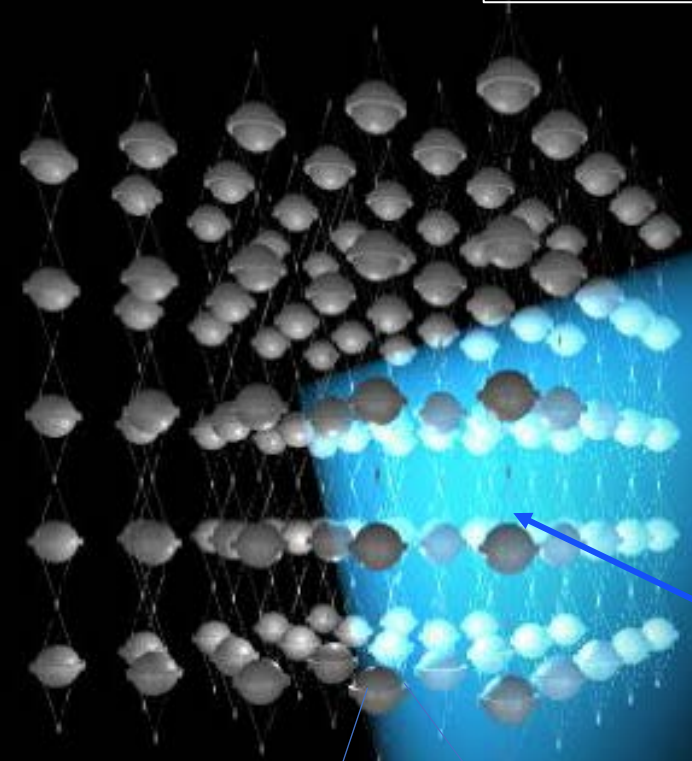
Energy of neutrinos
> 100,000 MeV

distance to the observed
object 60,000,000 light years

How the neutrino telescopes looks like?

How the neutrino telescopes looks like?

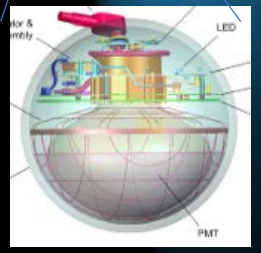
dark and transparent media



Cherenkov light

Charged particles

photon sensors



neutrinos

How the neutrino telescopes looks like?

measure the light
(CCD/CMOS)

dark and transparent media

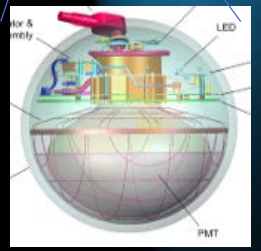
Convert neutrino to measurable light
(lenses)

Cherenkov light

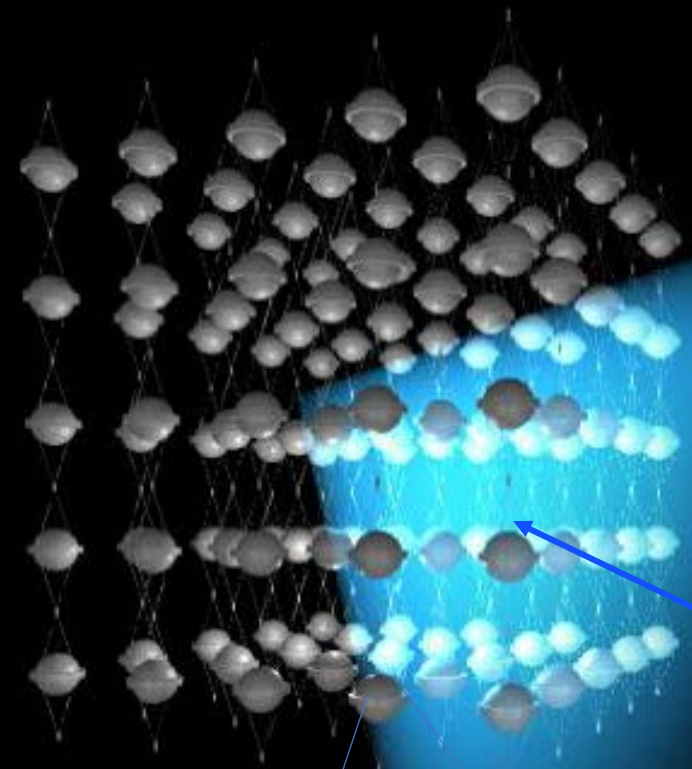
Charged particles

neutrinos

photon
sensors



How the neutrino telescopes looks like?

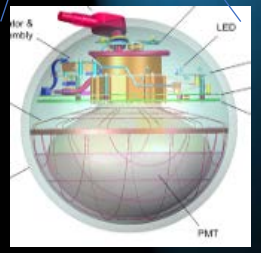


High energy neutrinos are rare to convert into light

> 1km^3

Charged particles

photon sensors



neutrinos

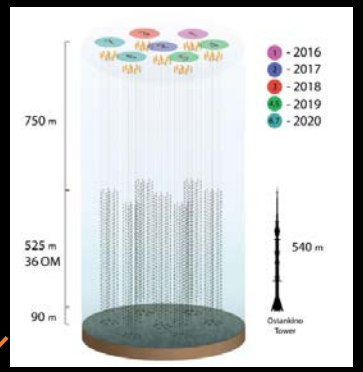
Neutrino Telescopes around the world

Mediterranean Ocean

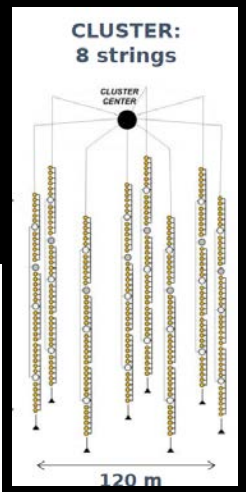
KM3NET ARCA (HE array)
as of Sept 2022, 21 ARCA
11 ORCA strings

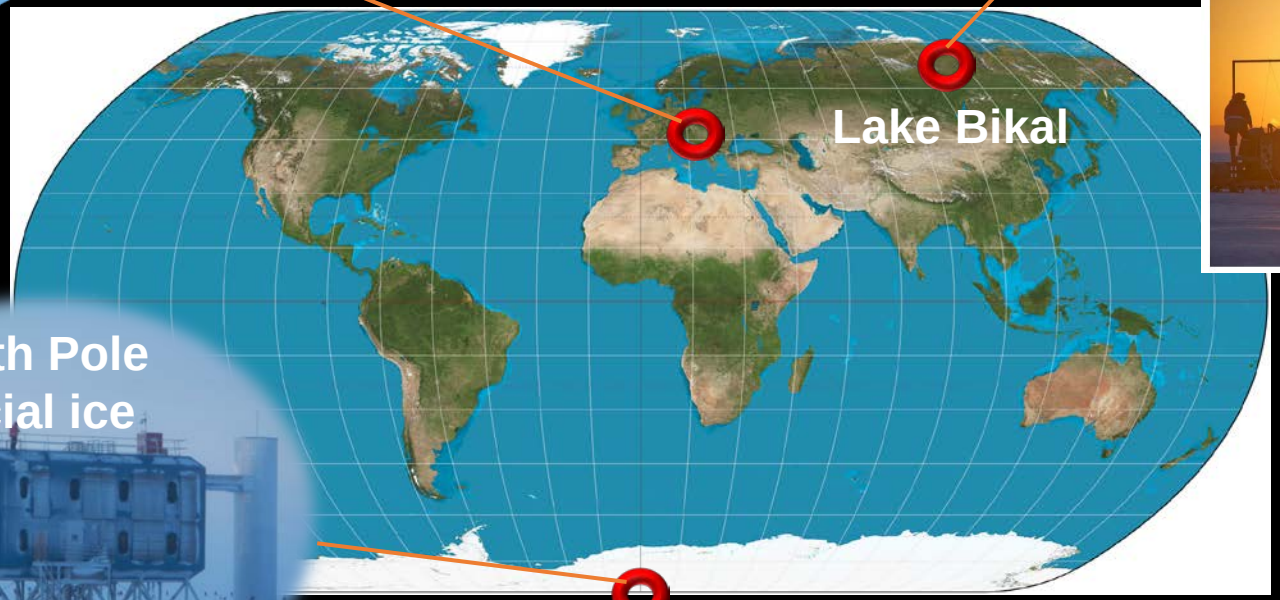
2008-2022: ANTARES 0.1km^3

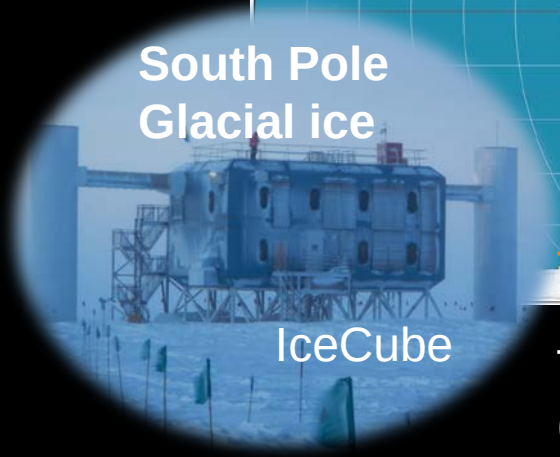
BAIKAL-GVD



2022: Baikal-GVD
10++clusters, 288 x 8=2916 optical modules





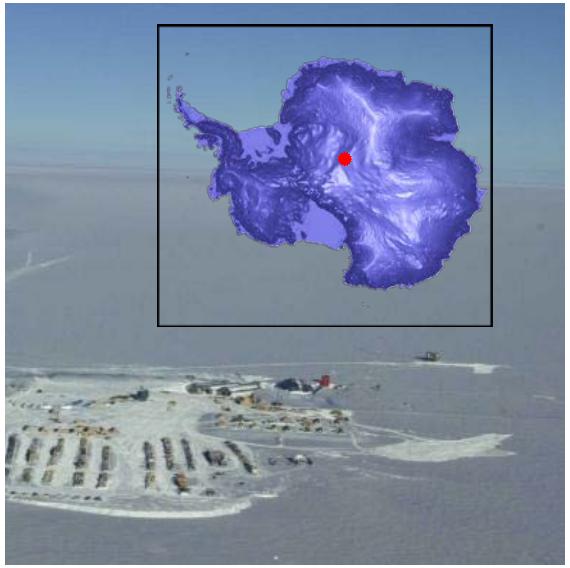


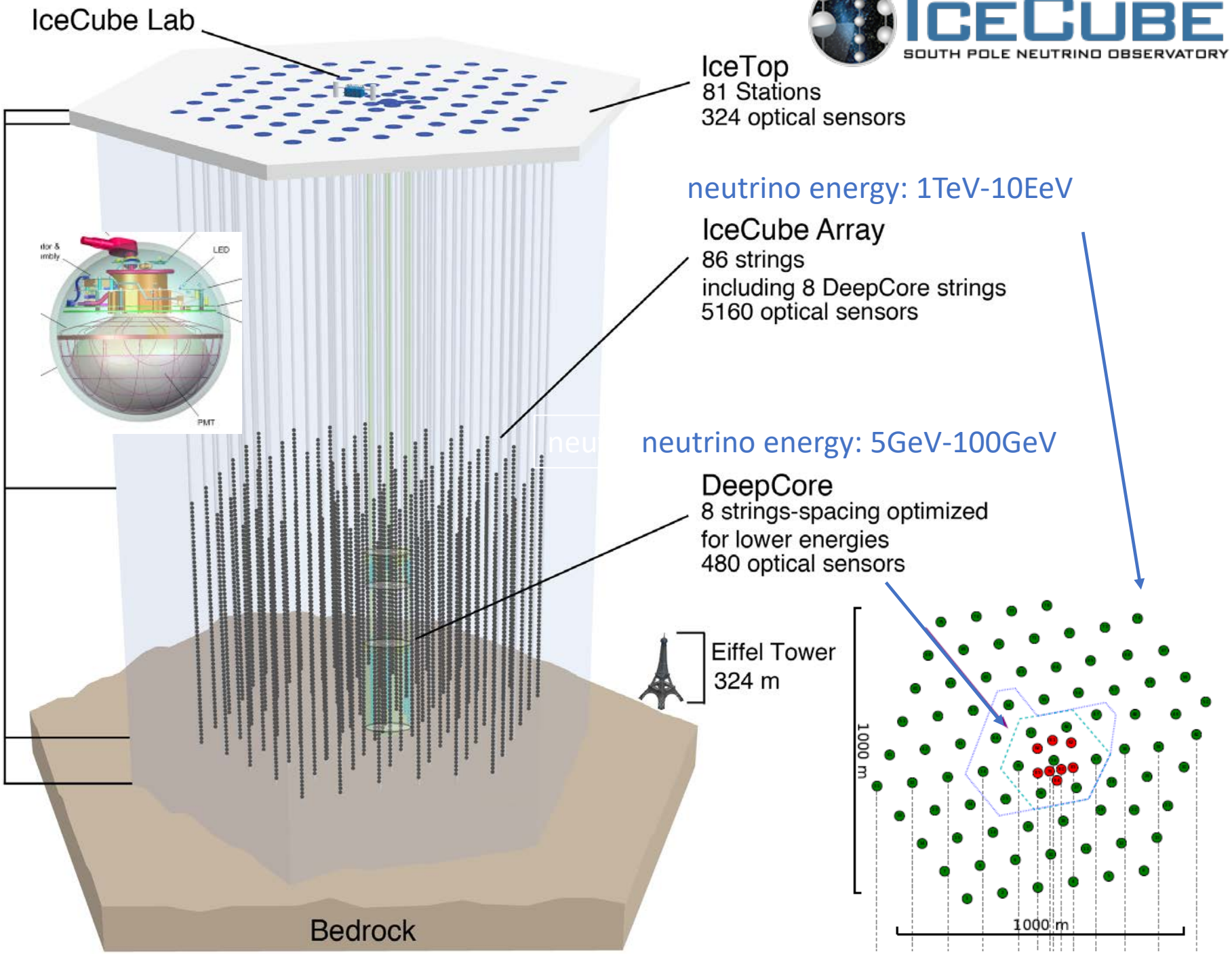
The first km^3-scale detector!
(full operation since 2011)

IceCube

The first km^3-scale detector!
(full operation since 2011)

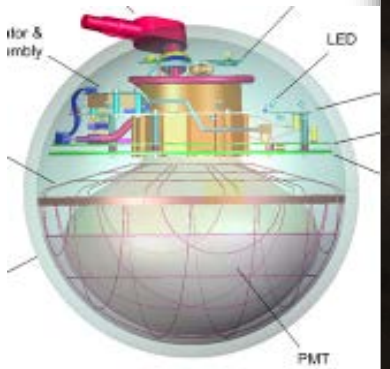
@ Amundsen-Scott South Pole station

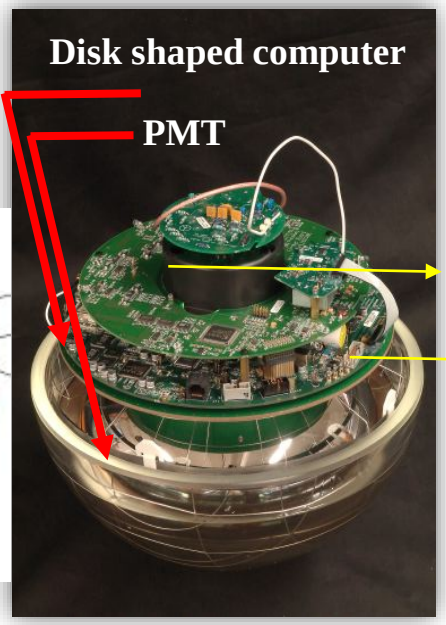




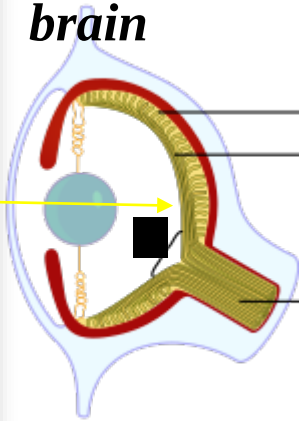
Eyes and lens

Eyes: Light Sensor Module



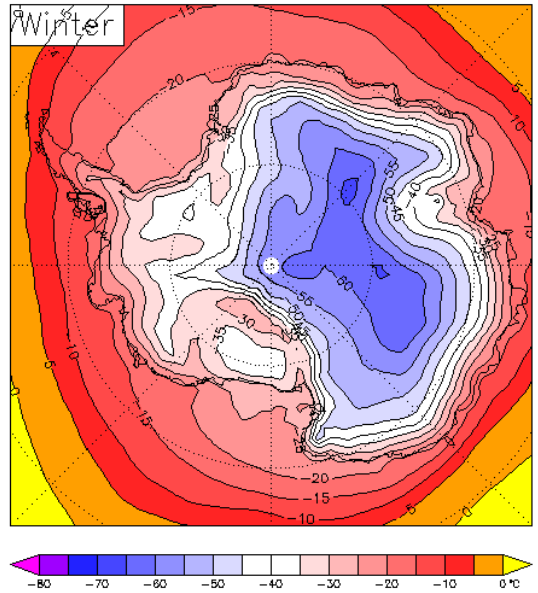


electronic signal to the brain

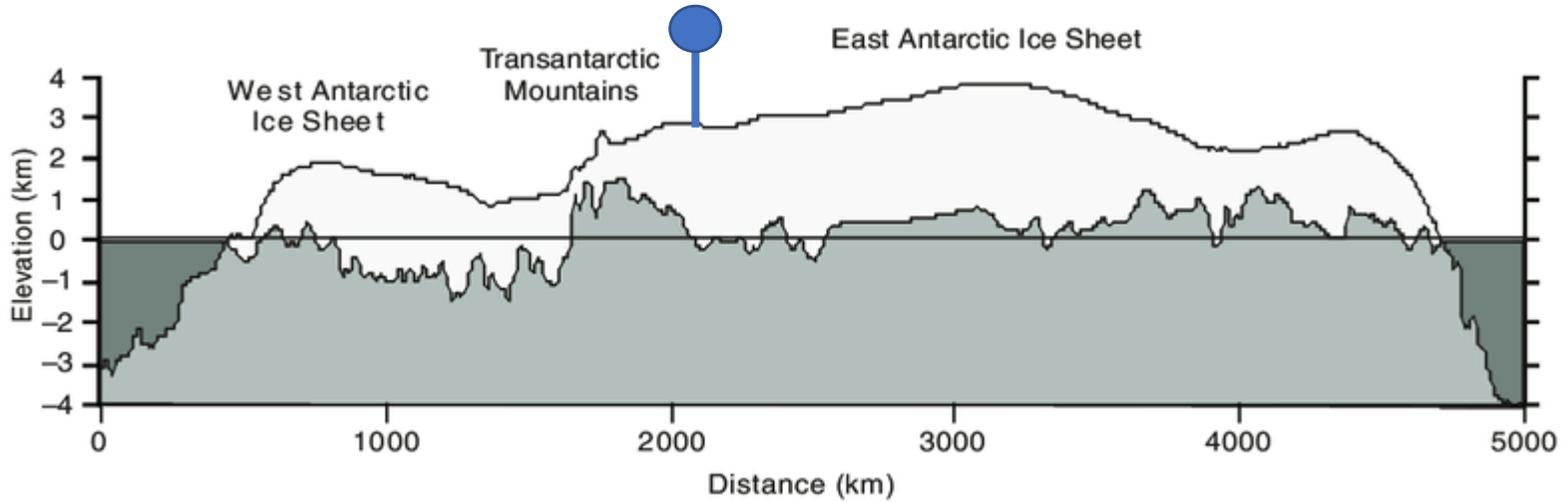


Lends: South Pole Glacial Ice

air temperature

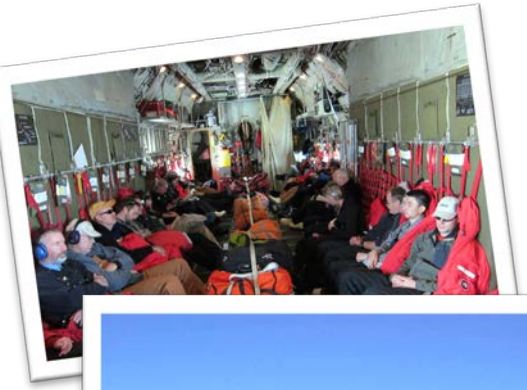


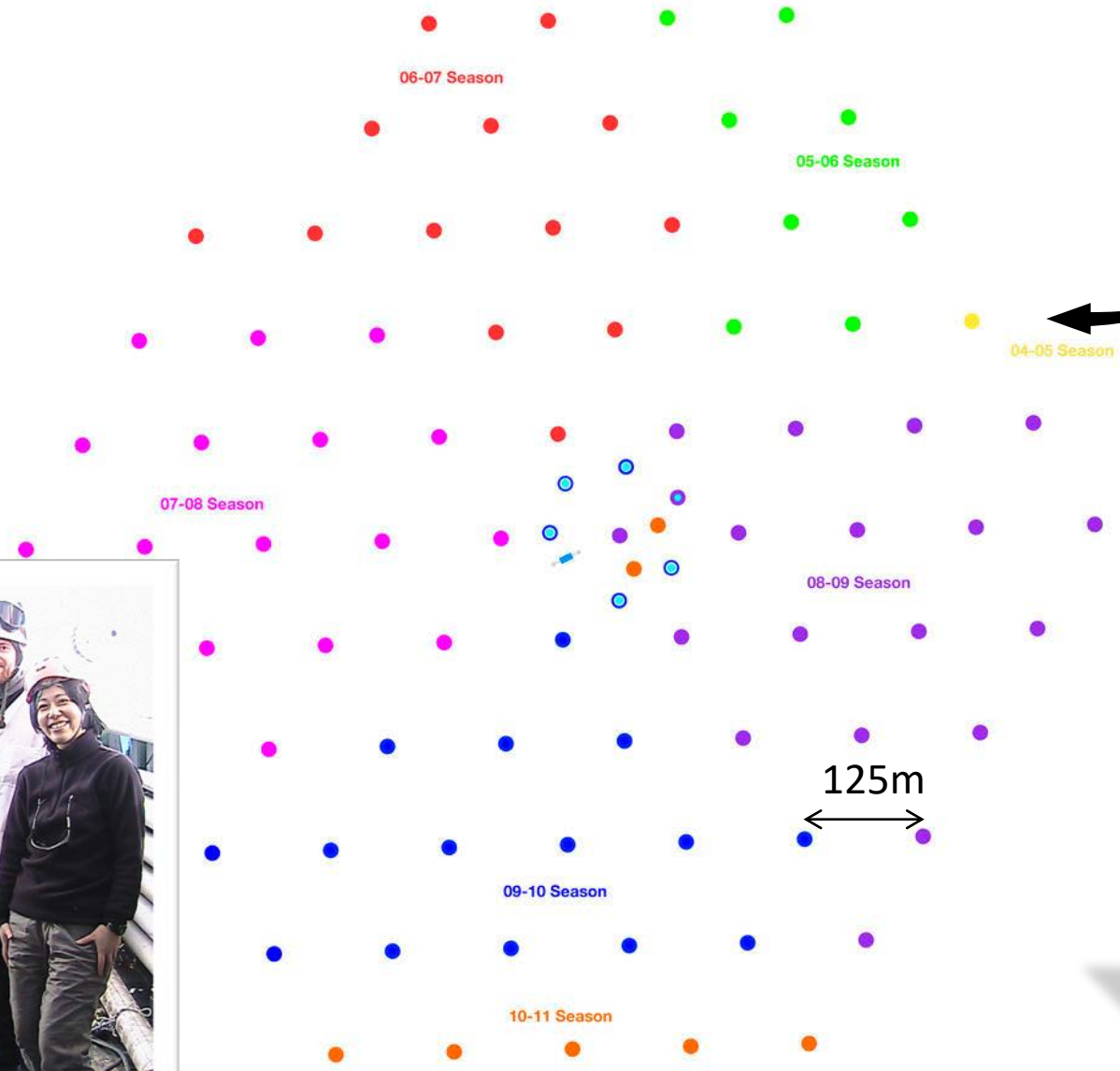
ice thickness



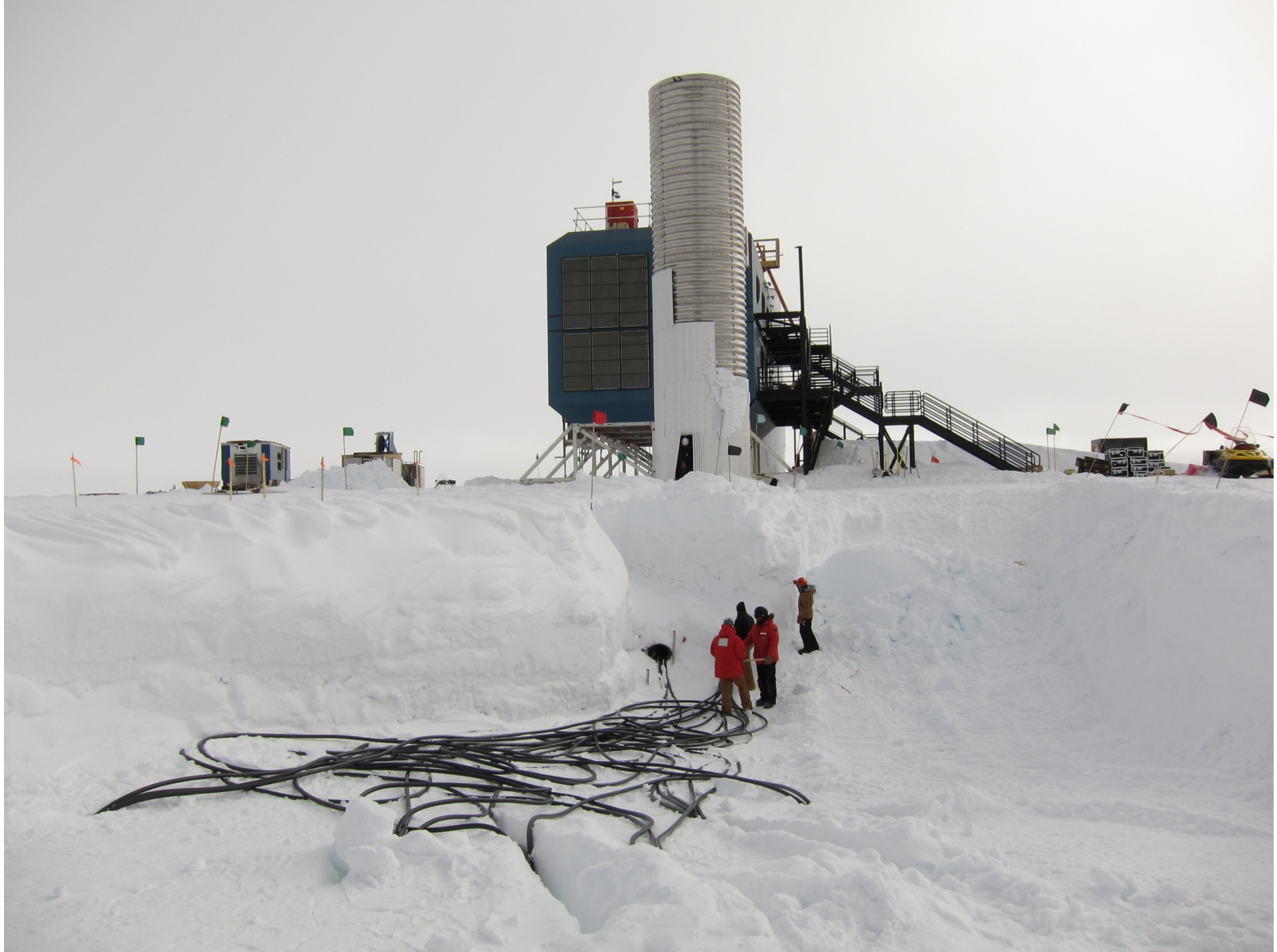
Construction of IceCube

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

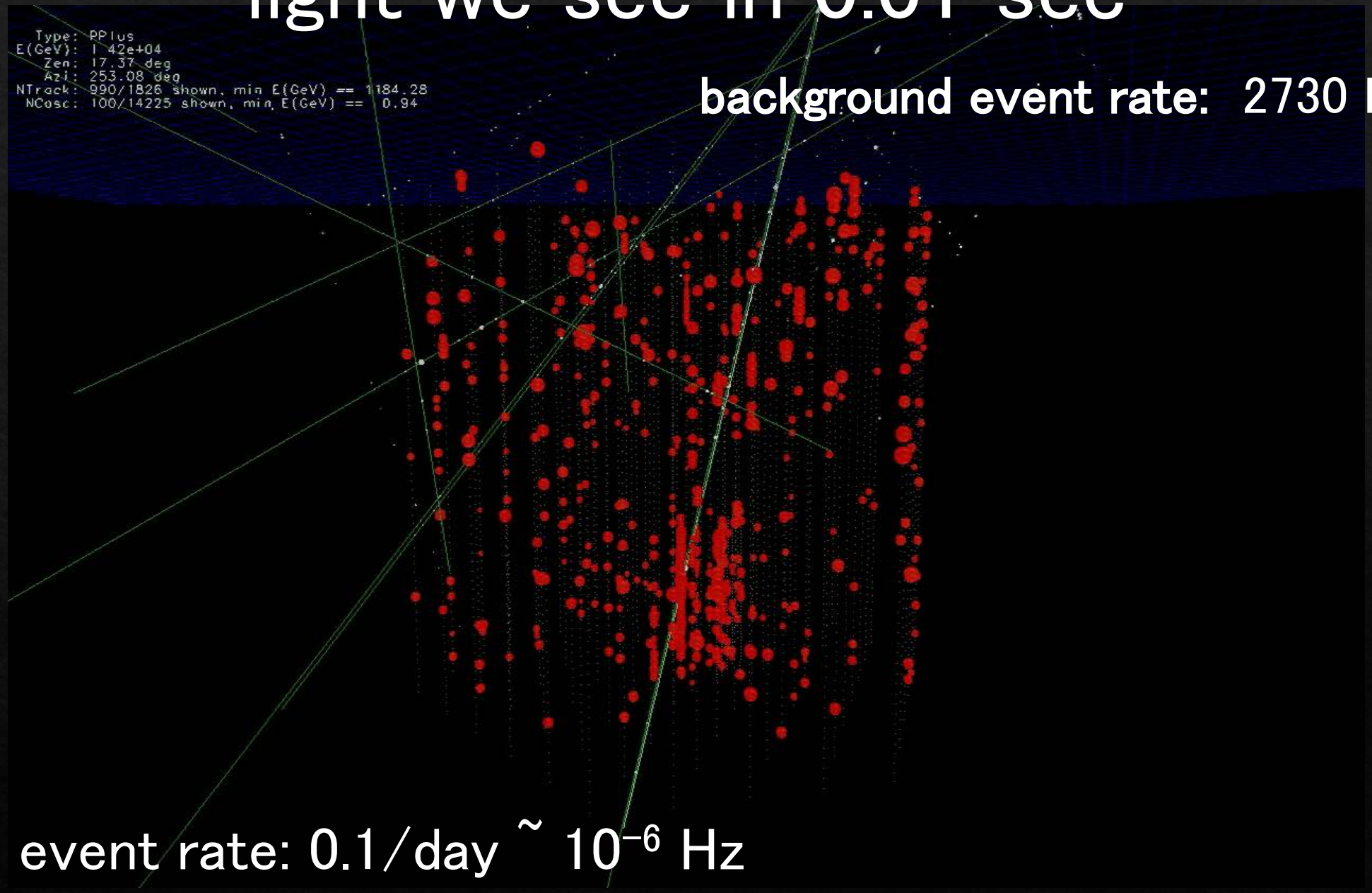




The first hole



light we see in 0.01 sec



background event rate: 2730 Hz

signal event rate: 0.1/day ~ 10^{-6} Hz

First observation of the high energy 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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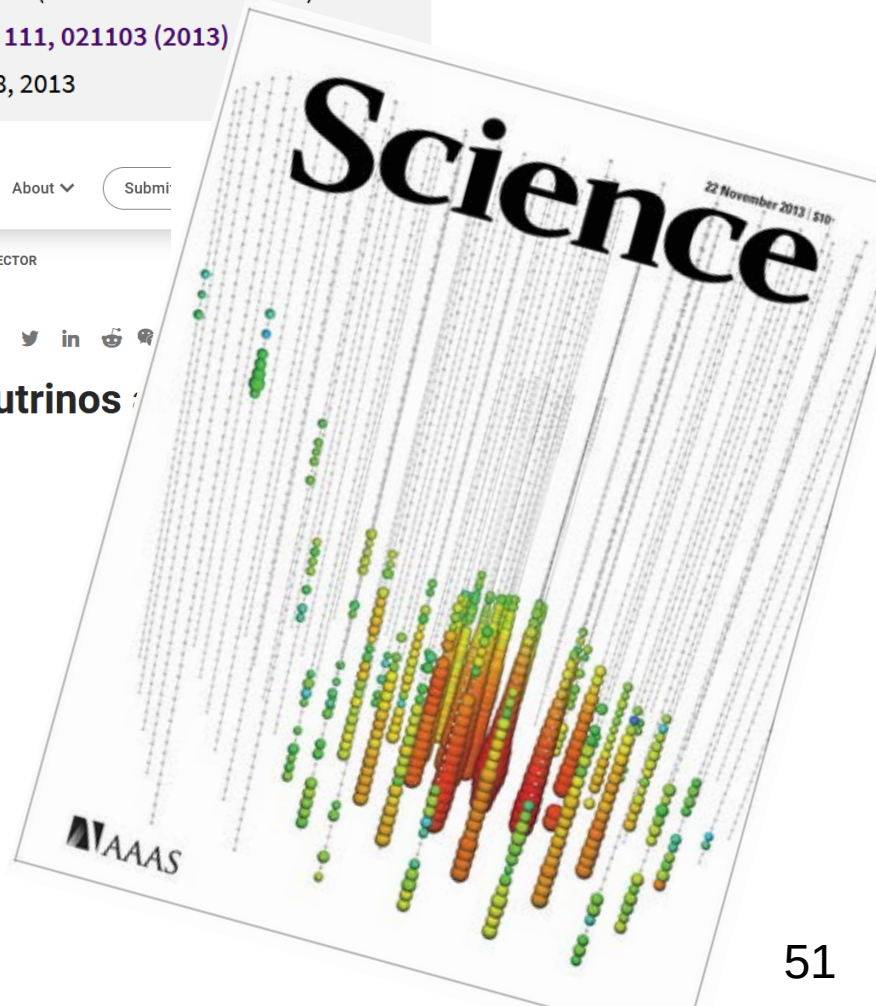
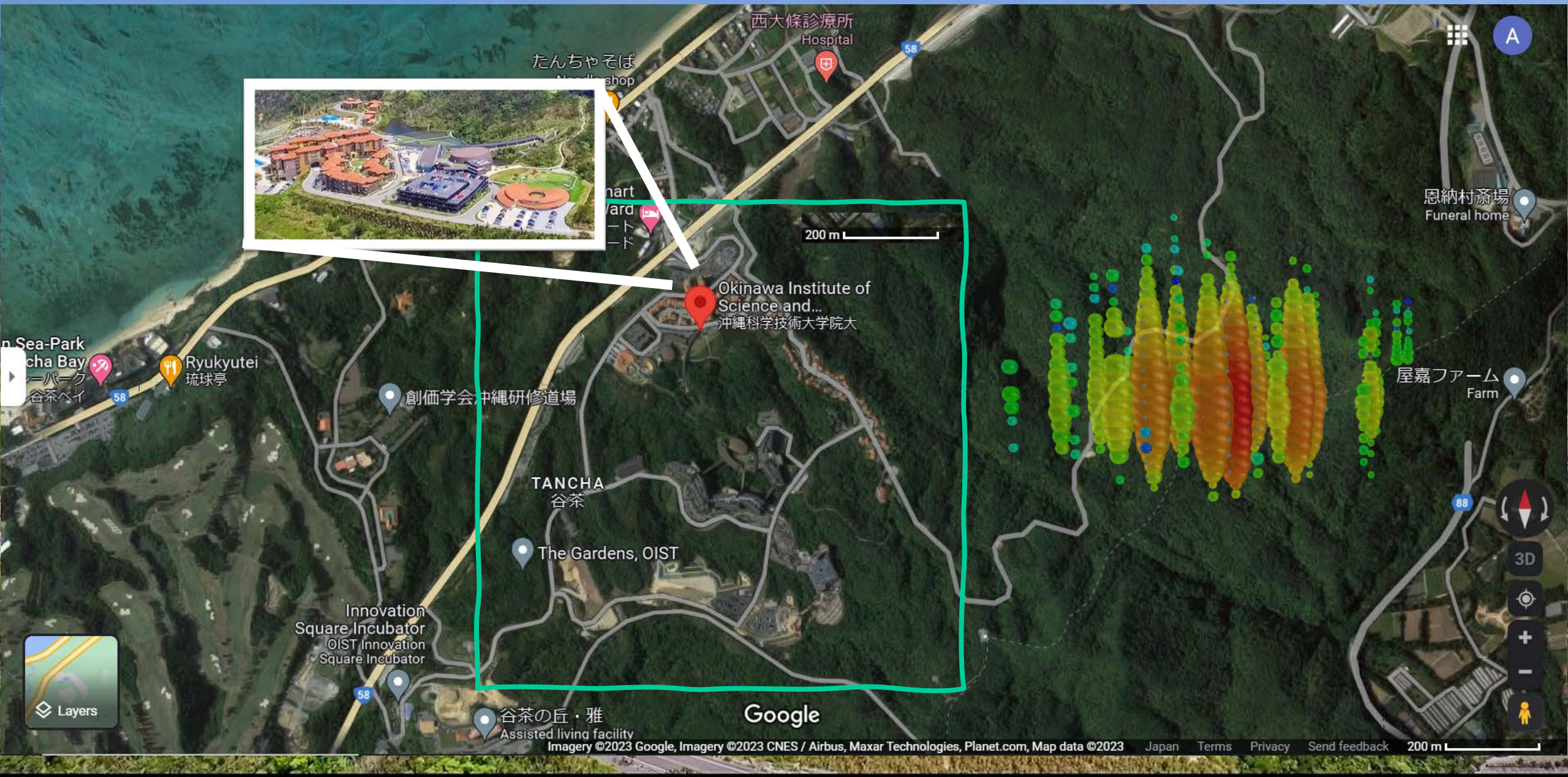
RESEARCH ARTICLE

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

ICECUBE COLLABORATION*




西大條診療所
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たんちゃそば
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Funeral home
200 m
Okinawa Institute of Science and...
沖縄科学技術大学院大
Ryukyutei
琉球亭
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屋嘉ファーム
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OIST Innovation Square Incubator
谷茶の丘・雅
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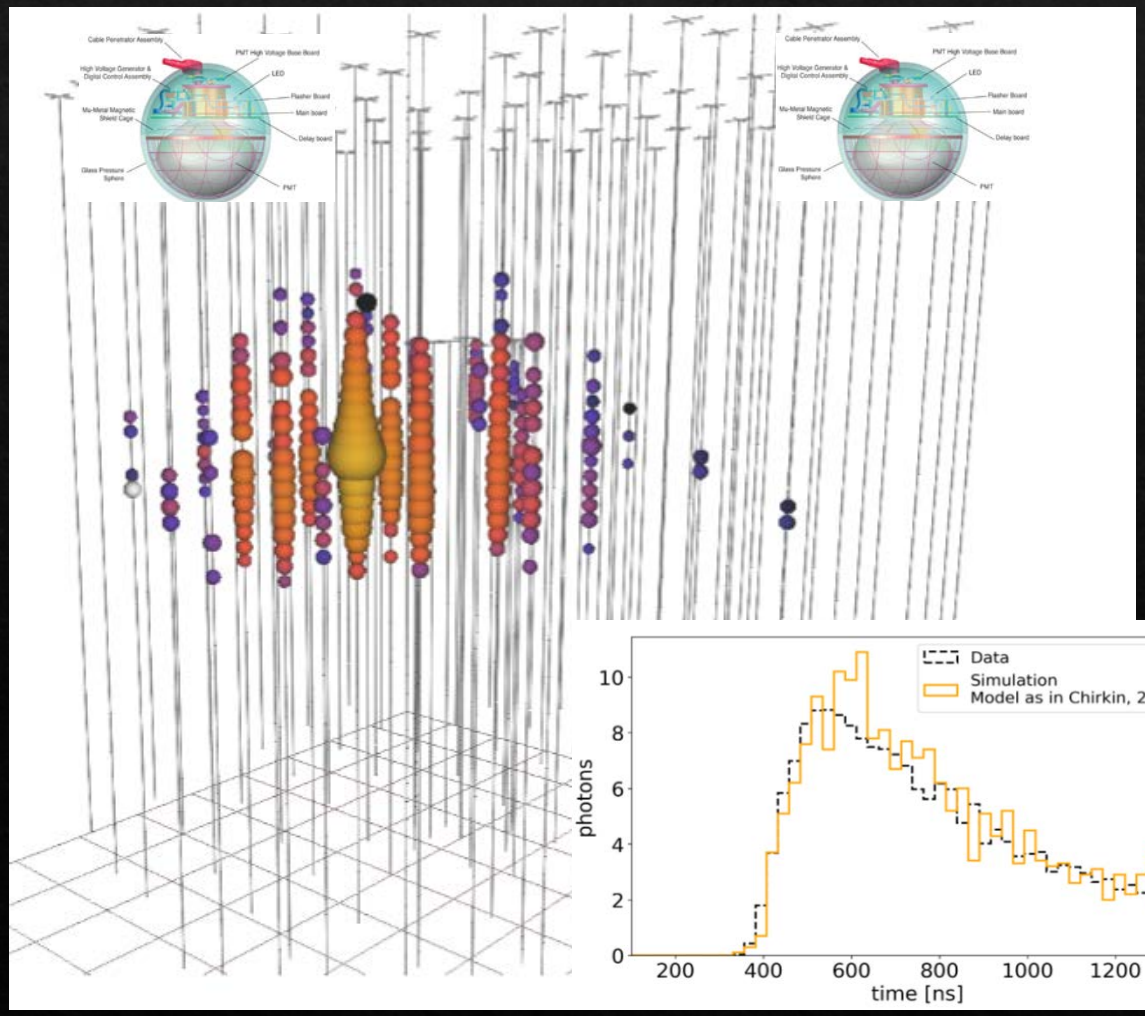
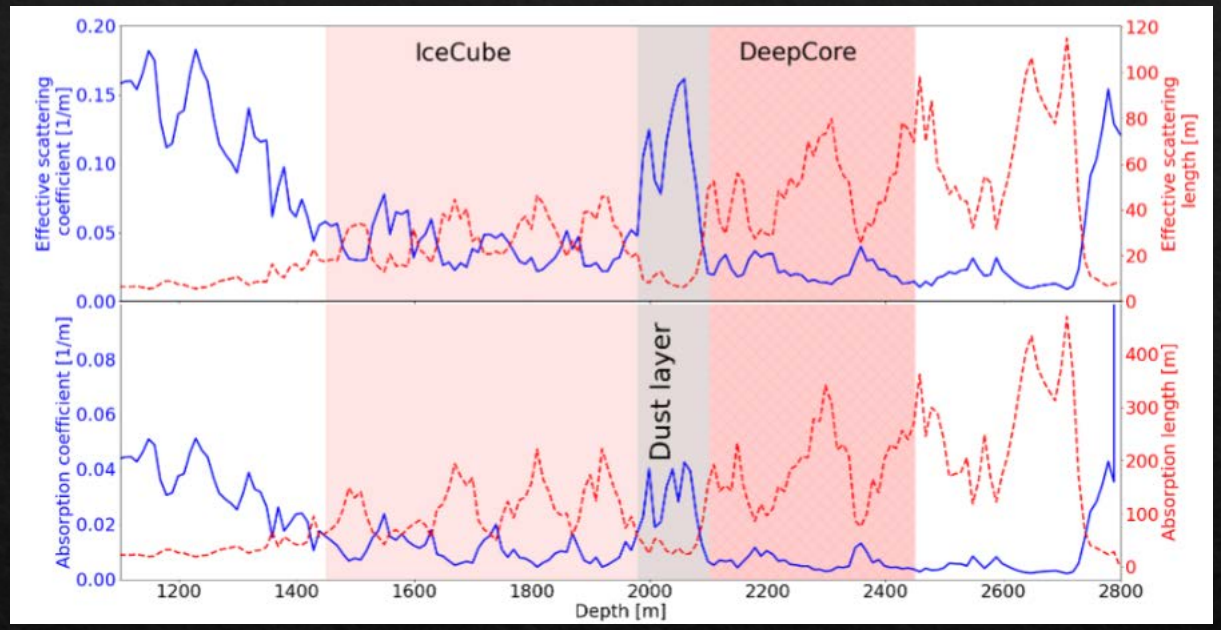
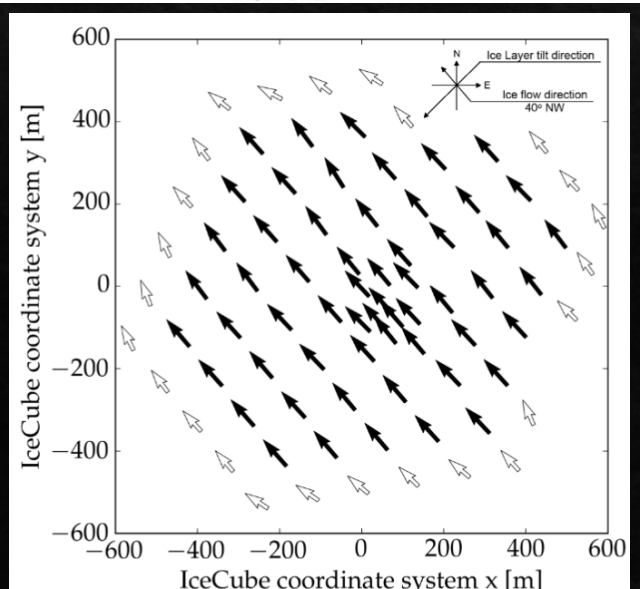
200 m

In-situ estimation of the South Pole ice crystal properties

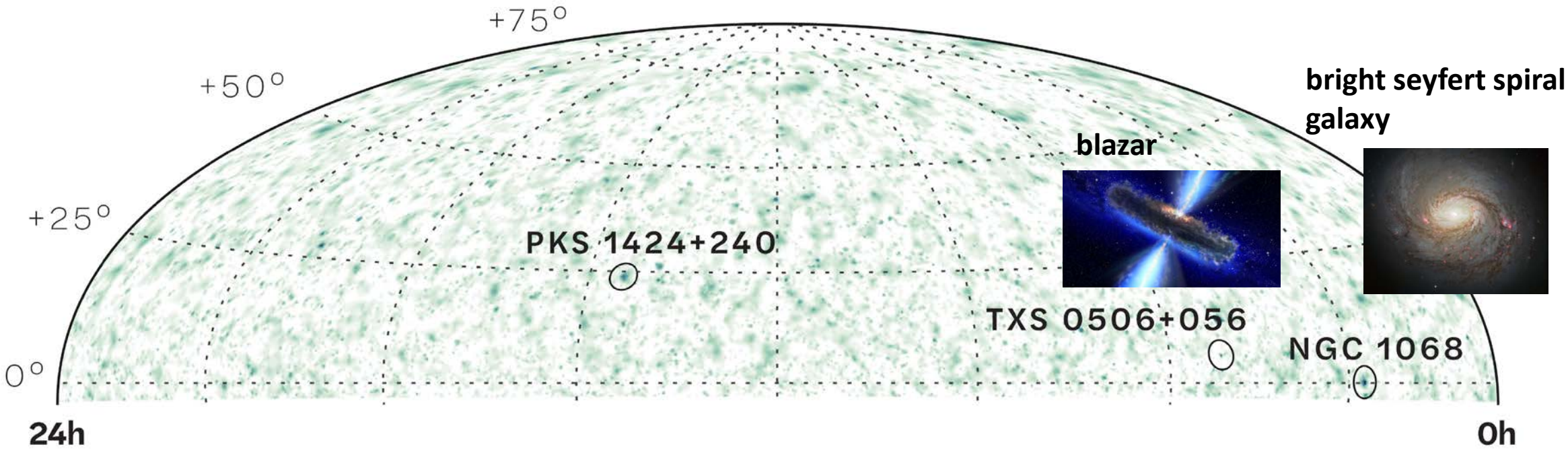
(accepted for the Cryosphere https://tc.copernicus.org/preprints/tc-2022-174/)





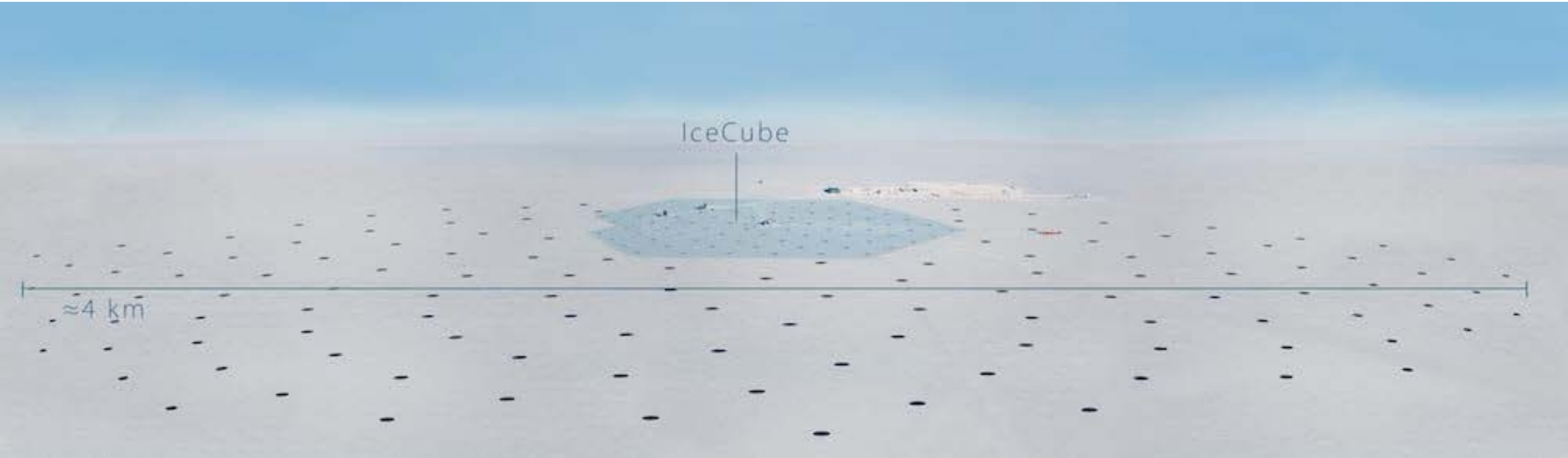


neutrino sky beyond our galaxy

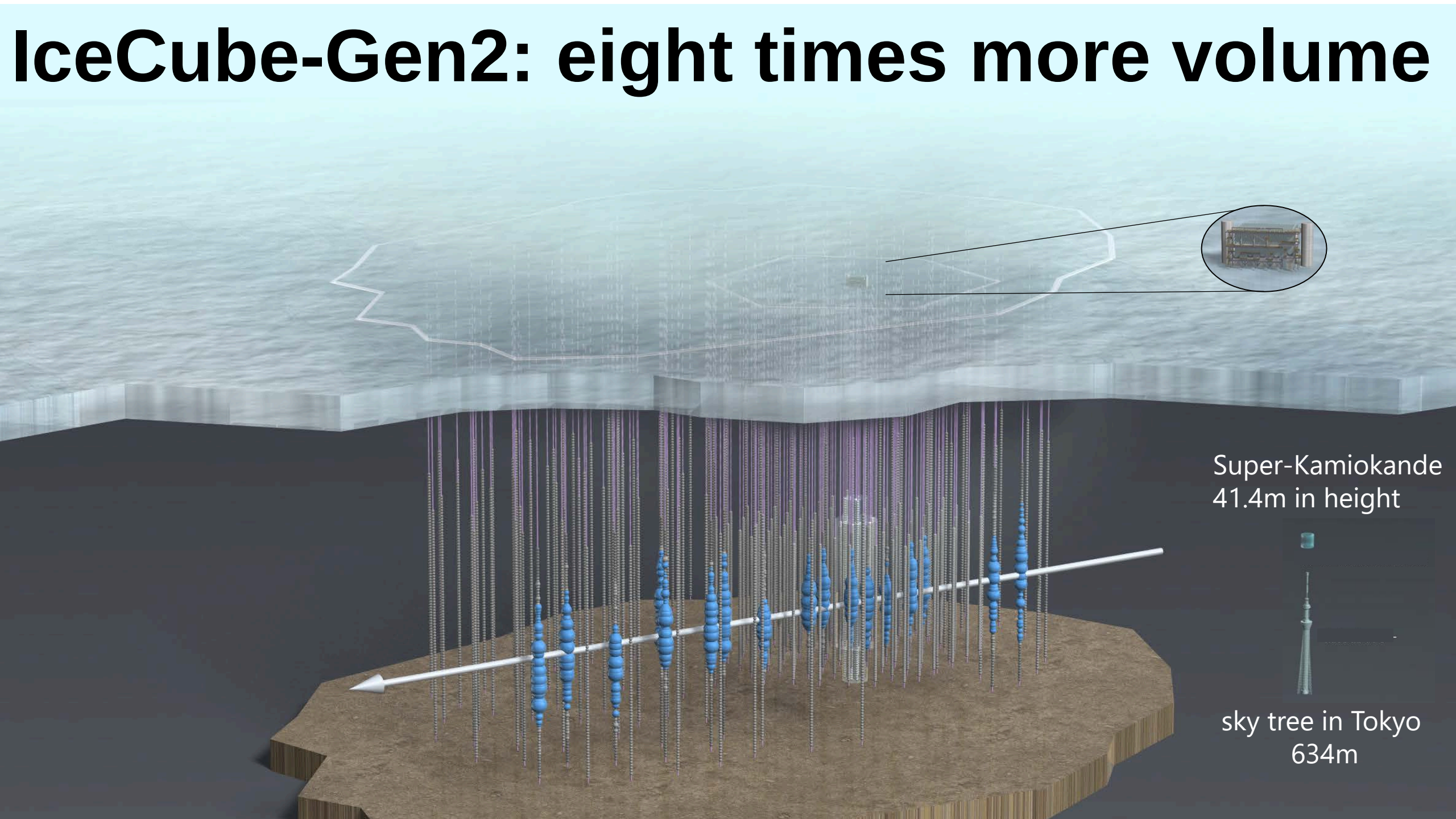


We are in the early phase of the neutrino astronomy

with a tiny 1km^3 telescope

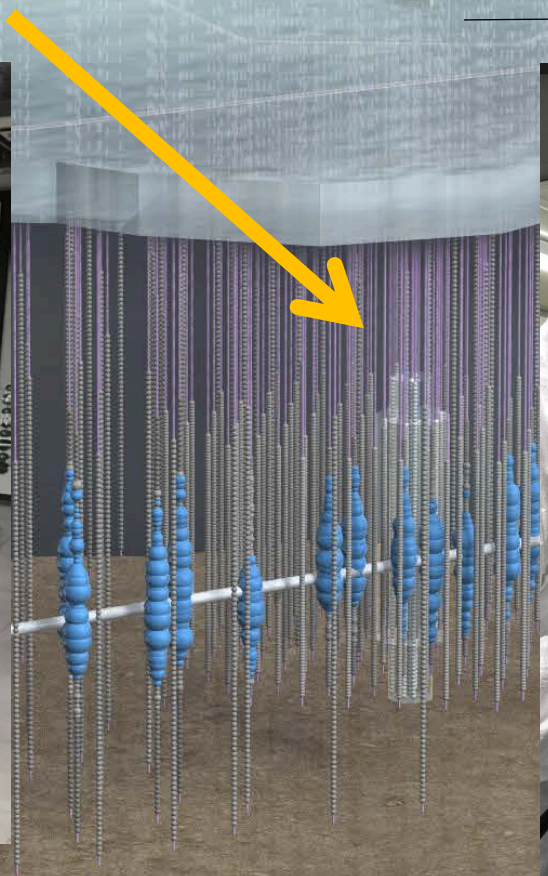


IceCube-Gen2: eight times more volume

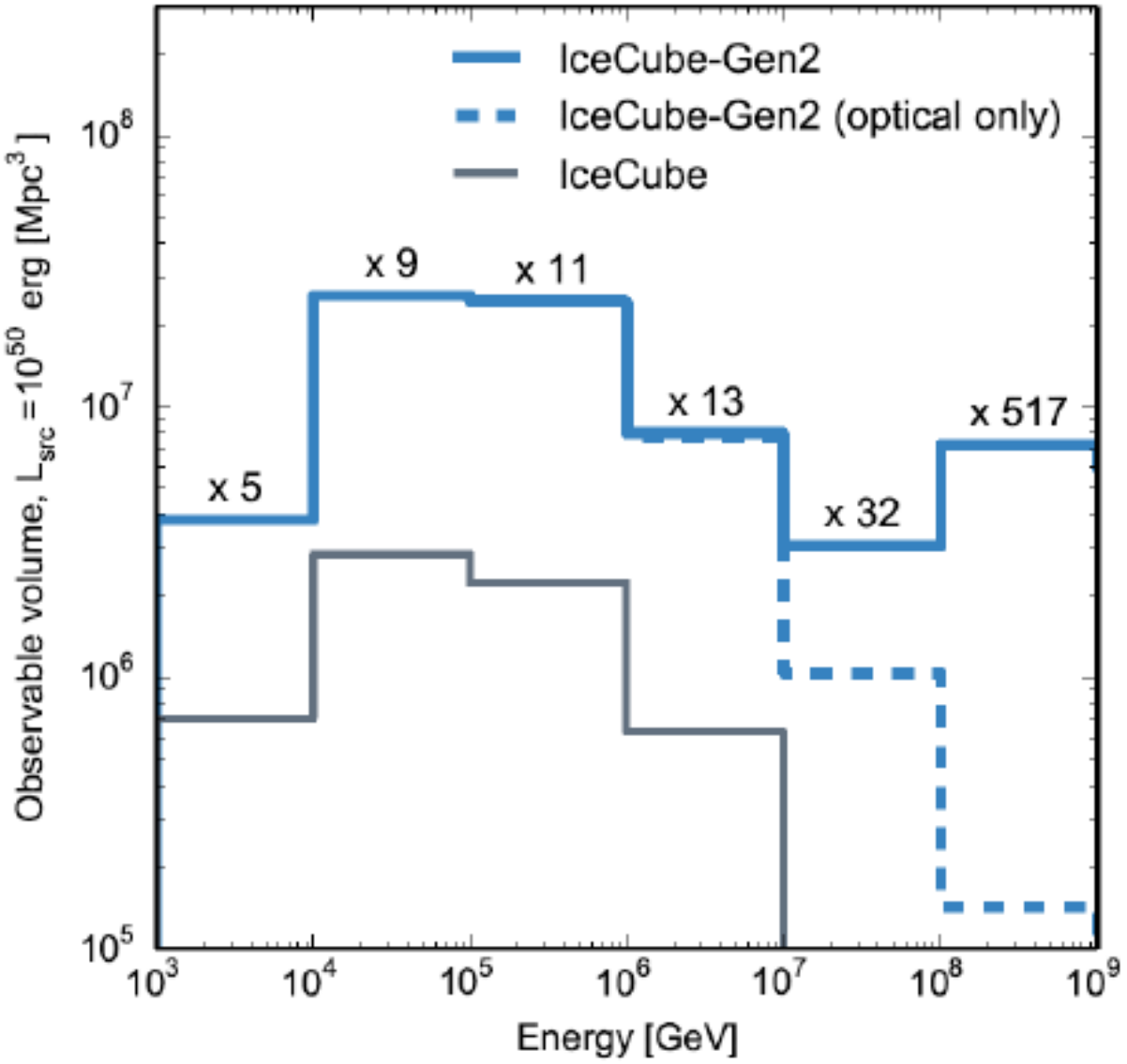


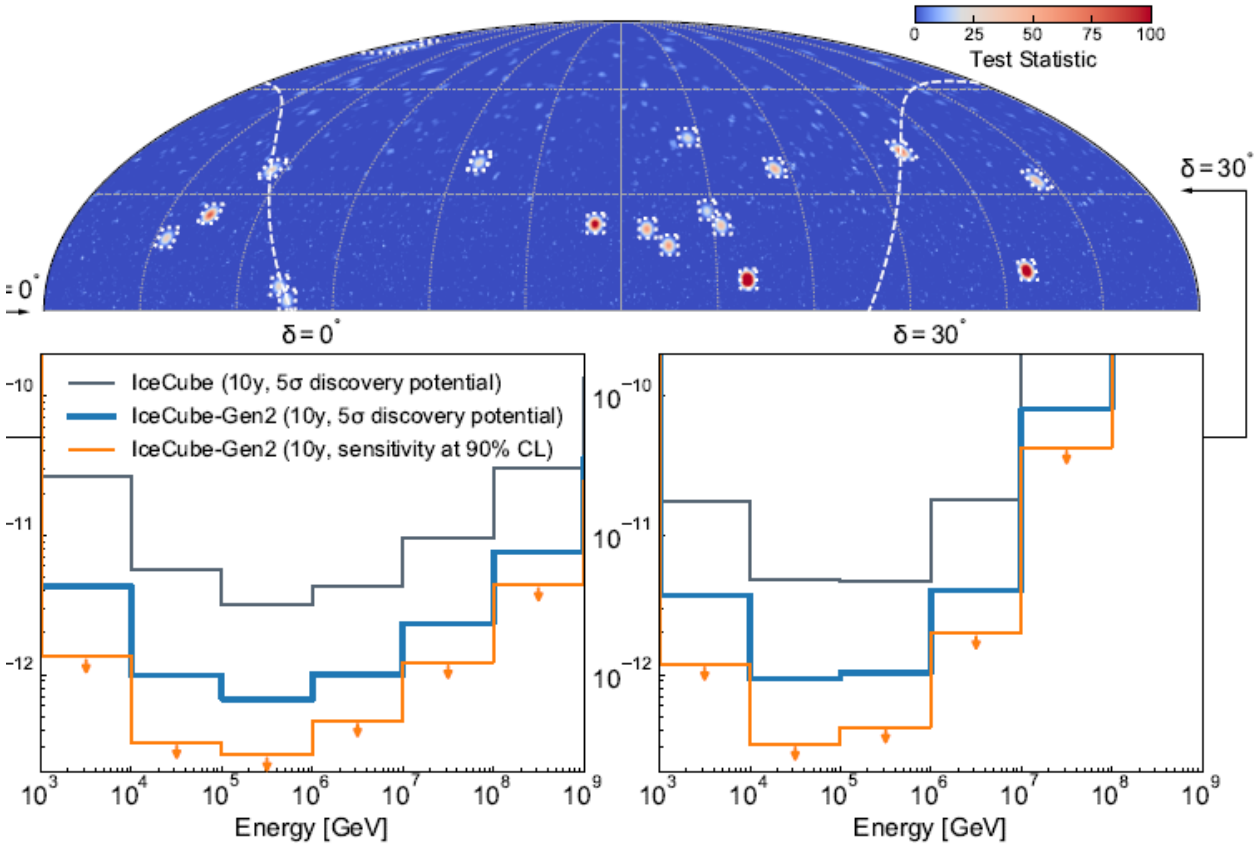
IceCube-Gen2: eight times more volume

to be installed in 2025



10 times more number of sources





- Universe is bright in neutrinos in high energy!
- Neutrinos connect the high energy particle production with the other form of radiations
- Two sources:
  1) evidence for neutrinos from flaring blazar TXS 0506+056
  2) evidence for neutrinos from nearby Seyfert galaxy NGC1068

- Neutrino sky is continued to be exciting and bright


http://icecube.wisc.edu
IceCube
THE ICECUBE COLLABORATION
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BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
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ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
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RWTH Aachen University
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