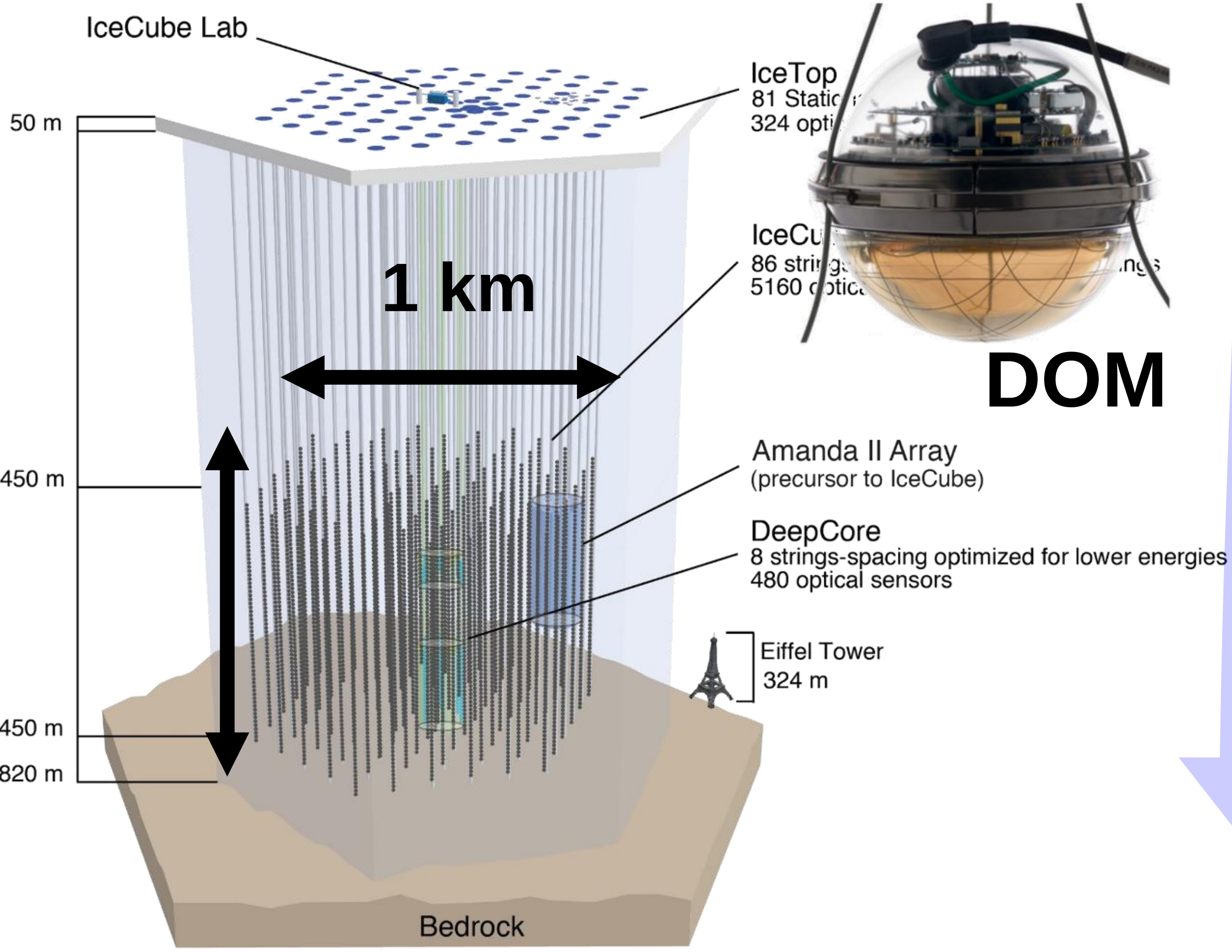
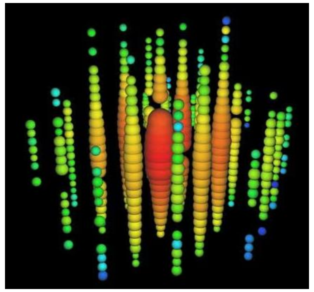
IceCube-Gen2

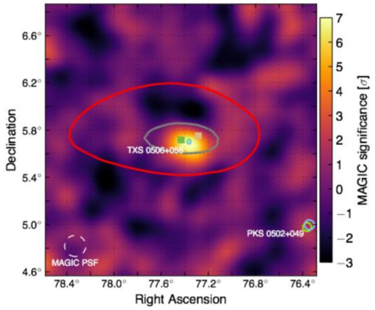
Nobuhiro Shimizu (Chiba University)

ICEHAP – international center for Hadron Astrophysics

IceCube







2011: Detector construction

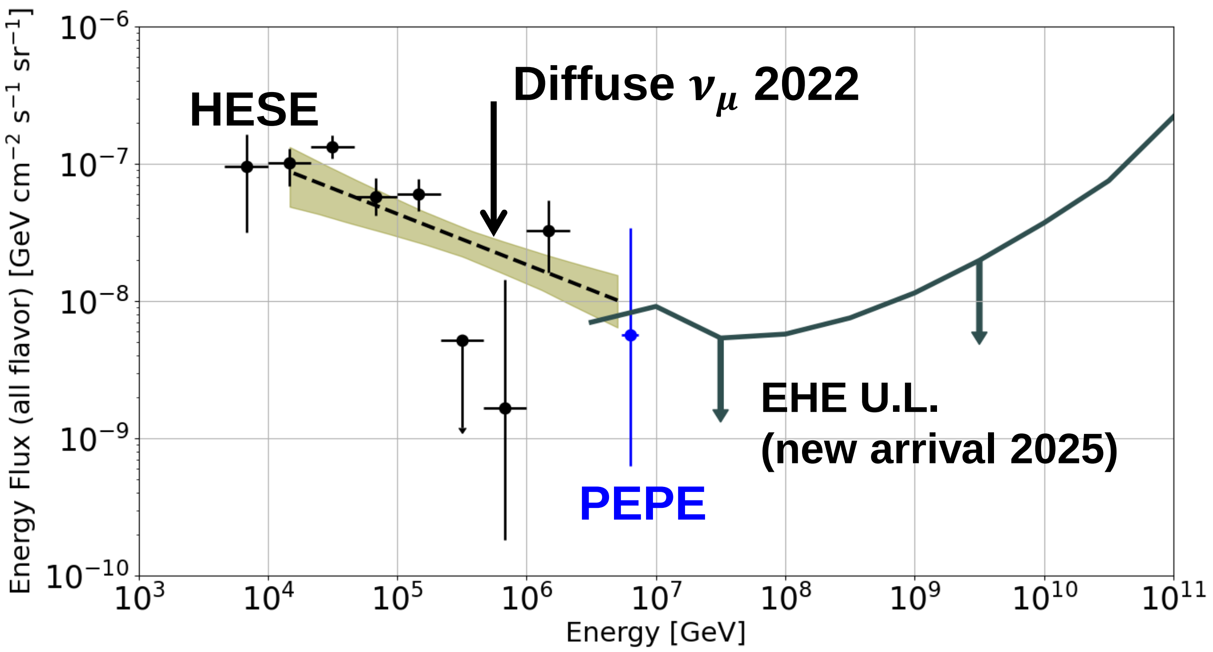
2013: Observation of astrophysical ν

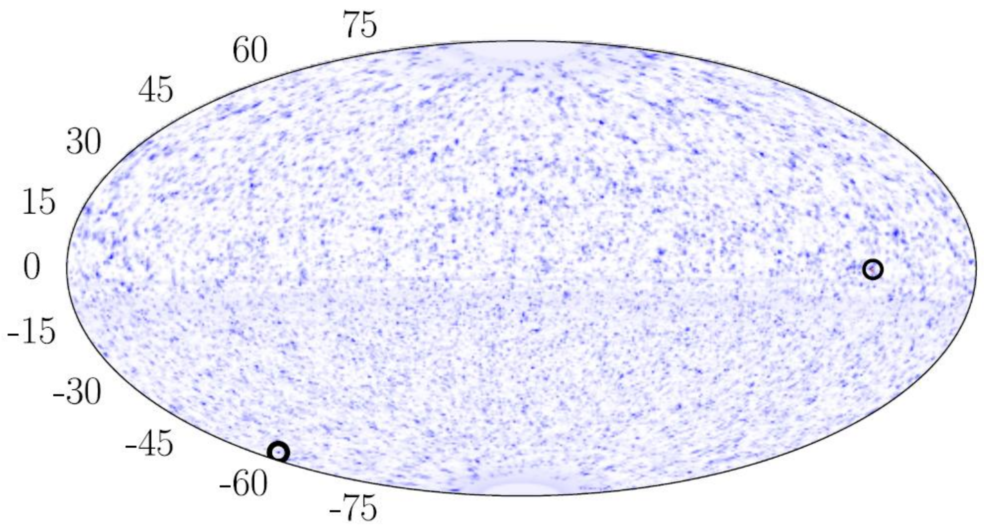
2017: Identification of a blazar
TXS 0506+056 as a ν-source

2022: Observation of ν from
Seyfert galaxy NGC1068

2023: Observation of ν Galactic plane

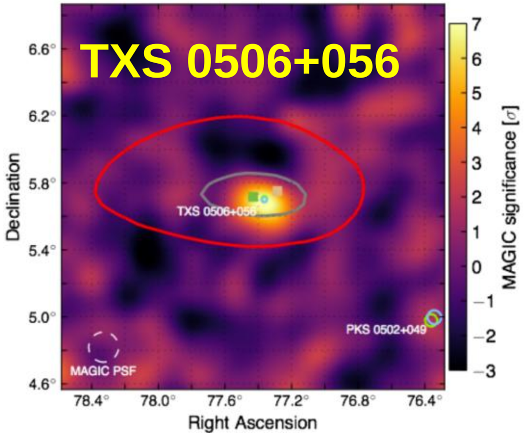
What IceCube told us: diffuse $\boldsymbol{\nu}$ flux



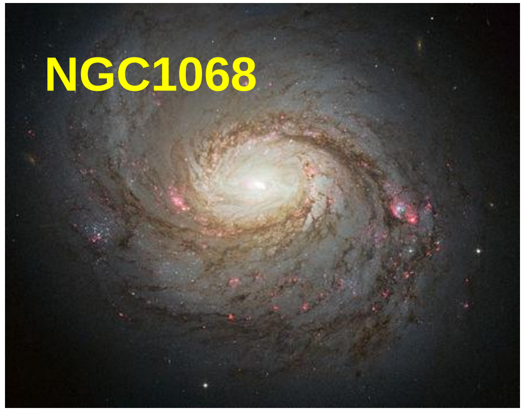


- Strong evidence of the astrophysical background $\boldsymbol{\nu}$ (a.k.a. diffuse $\boldsymbol{\nu}$ flux)
- $E^2\phi_\nu \sim \mathbf{10^{-7} - 10^{-8}}$ GeV$\cdot\,\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}\cdot\mathrm{sr}^{-1}$ at 10 TeV-1 PeV
- Consistent with isotropic distribution

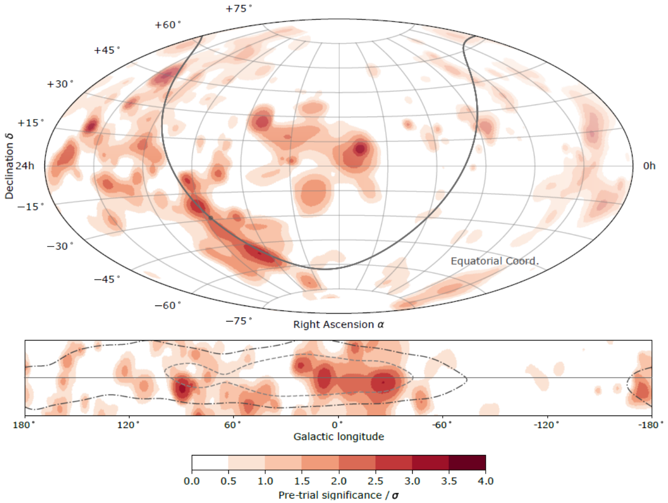
Where is the origin of the neutrinos?



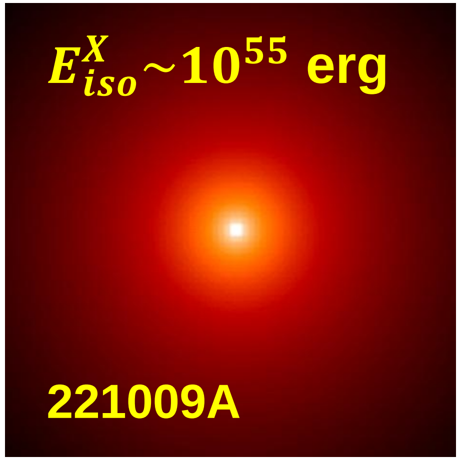
Identification of a blazar as a ν-source (2017)



Observation of ν by Seyfert galaxy (2022)



Observation of ν from galactic plane (2023)



NO observation of ν from BOAT GRB (2022)

Several objects are possible sources of neutrinos. However,
they are not sufficient to account for the magnitude of the total diffuse flux.

Achievement of our group

Physics Analyses (selected only)

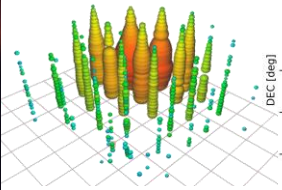
2012: First PeV neutrinos EHE Phys. Rev. Lett. **111**, 021103

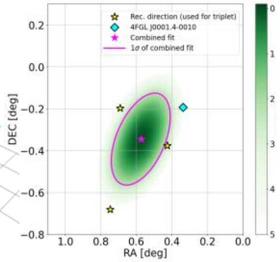
2017: First identification of neutrino source with a BLlac triggered by EHE alert

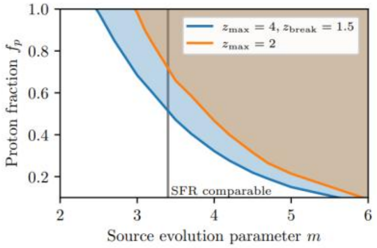
2021: An observation of Glashow resonance $\bar{\nu}_e + e^- \to W$ Nature **591**, 220 (2021)

new 2025: Constraint of ν-source parameters with a search for ν doublets and triplets arXiv:2501.09276 (ApJ accepted)

new 2025: A search for EHE ν with updated method, and a constraint on cosmic ray proton fraction arXiv:2502.01963







Hardware developments

2010 : Significant contribution on a calibration of PMTs in the IceCube sensor NIM A **618** 139

2015 - : Development of a new optical module (D-Egg) for IceCube-Upgrade

2019 - : Calibration and final acceptance test of the D-Eggs JINST **18** P04014

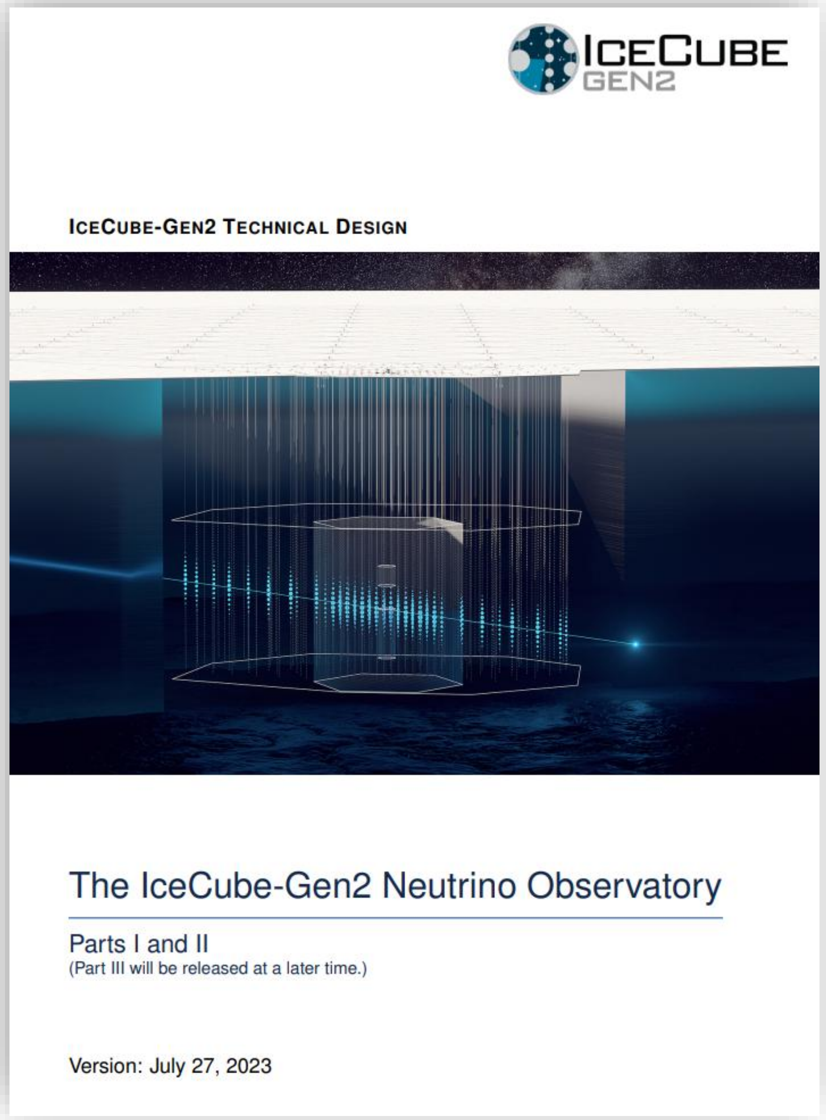
2019 - : Development of further new optical module (Gen2-DOM) for IceCube-Gen2
Leading R&D for Gen2 optical modules

Japanese team is one of the core institutes of IceCube

IceCube-Gen2

(c)Higgstan

IceCube-Gen2
Technical Design Report (TDR)



ICECUBE GEN2

ICECUBE-GEN2 TECHNICAL DESIGN

The IceCube-Gen2 Neutrino Observatory

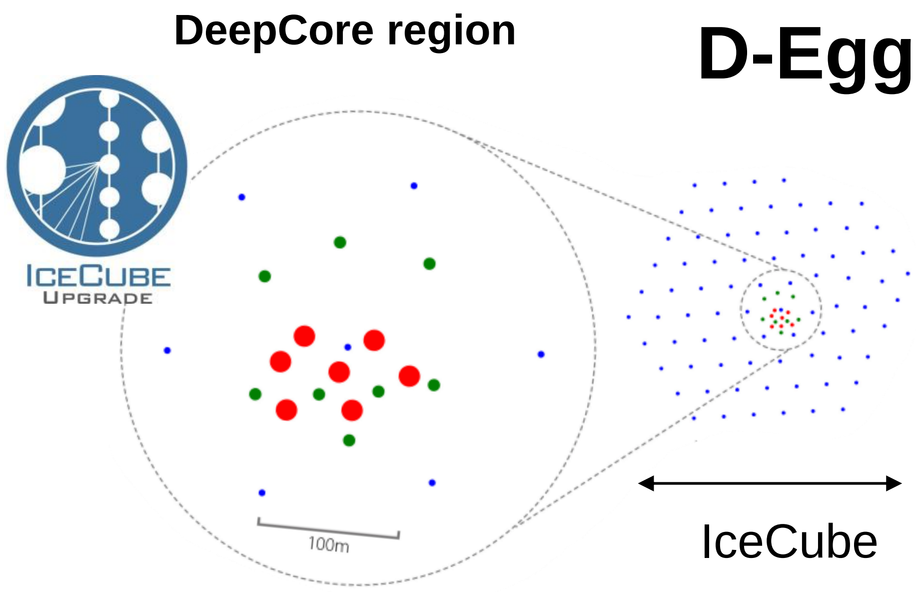
Parts I and II
(Part III will be released at a later time.)

Version: July 27, 2023

https://icecube-gen2.wisc.edu/science/publications/tdr/

IceCube-Upgrade (Gen2-phase1)

Already funded



D-Egg

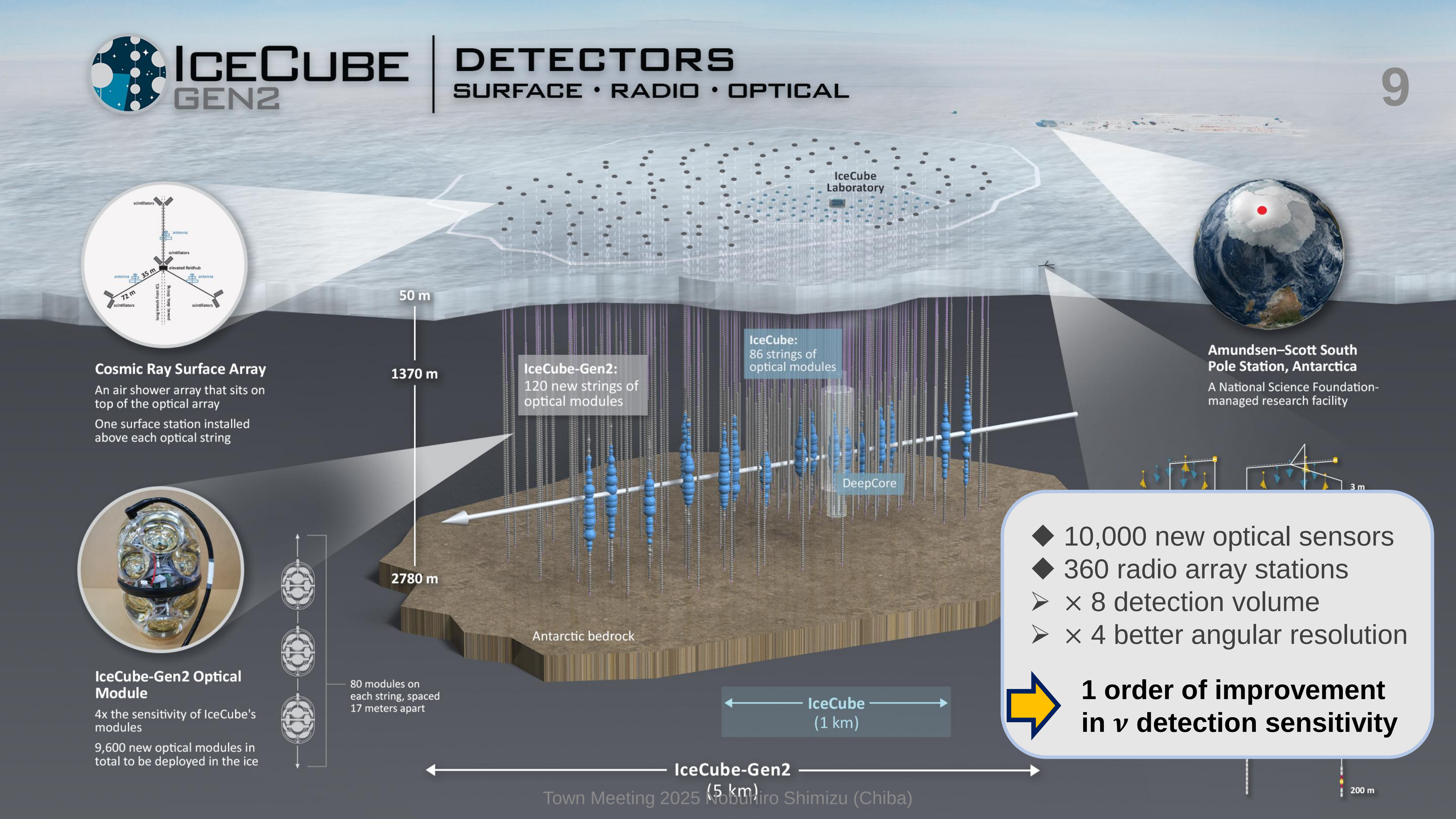
- Installation of 700 sensors 25/26 winter
- Targeting "Low" energy (GeV) neutrinos

  ν oscillation & GeV-ν astrophysics

- Precise measurement of ice properties

- Chiba produced 300 optical modules (D-Egg)
- "Detectors made-in-Japan" have already arrived at Antarctica!


Project currently on schedule!



- ◆ 10,000 new optical sensors
- ◆ 360 radio array stations
- ➢ × 8 detection volume
- ➢ × 4 better angular resolution

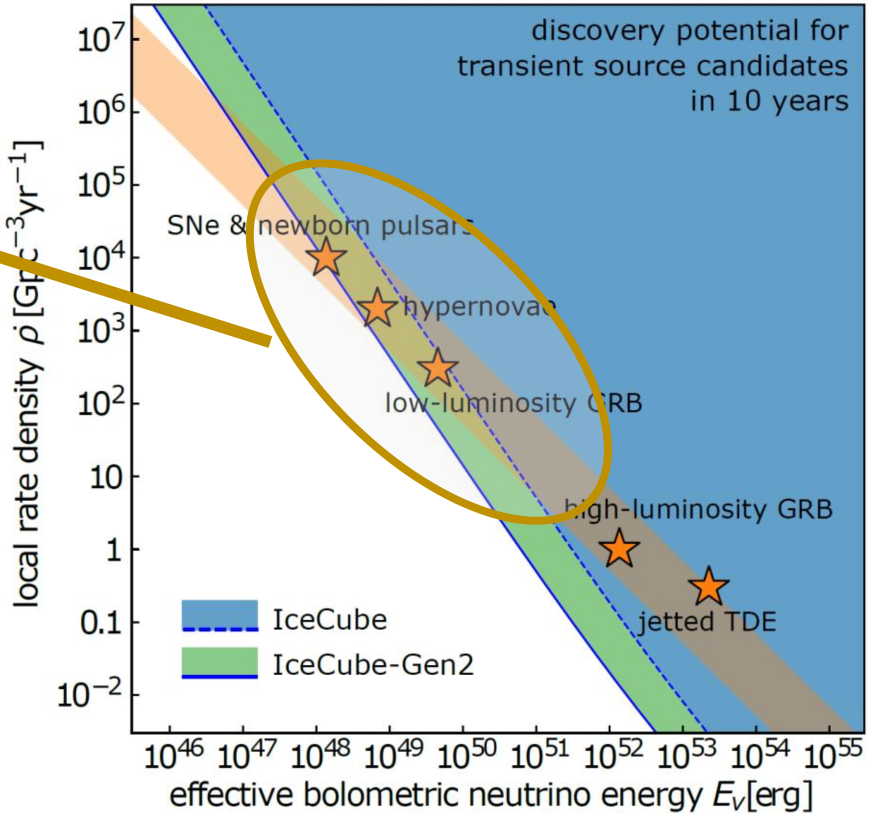
1 order of improvement in ν detection sensitivity

What IceCube-Gen2 delivers

$$\phi_\nu \propto \mathcal{E}_\nu \times \rho$$

$\mathcal{E}_\nu$: Neutrino emission energy per source
ρ : Source rate density

Dim but Frequent



Bright but Rare

There sources are not favored by measurement.

What IceCube-Gen2 delivers

$$\phi_\nu \propto \mathcal{E}_\nu \times \rho$$

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Bright but Rare

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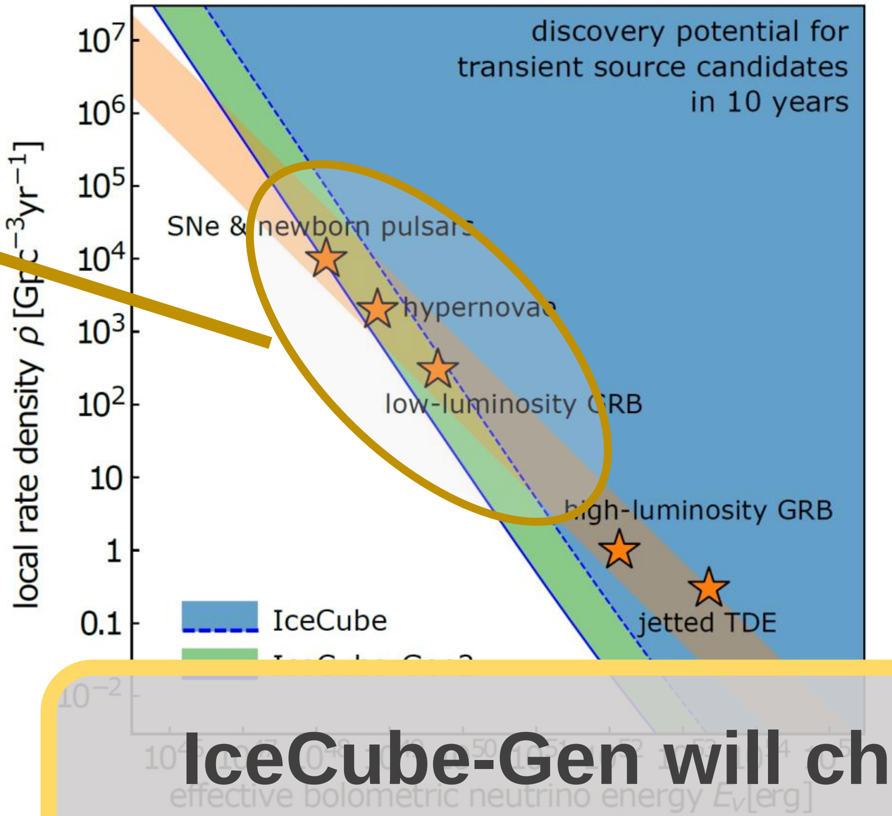


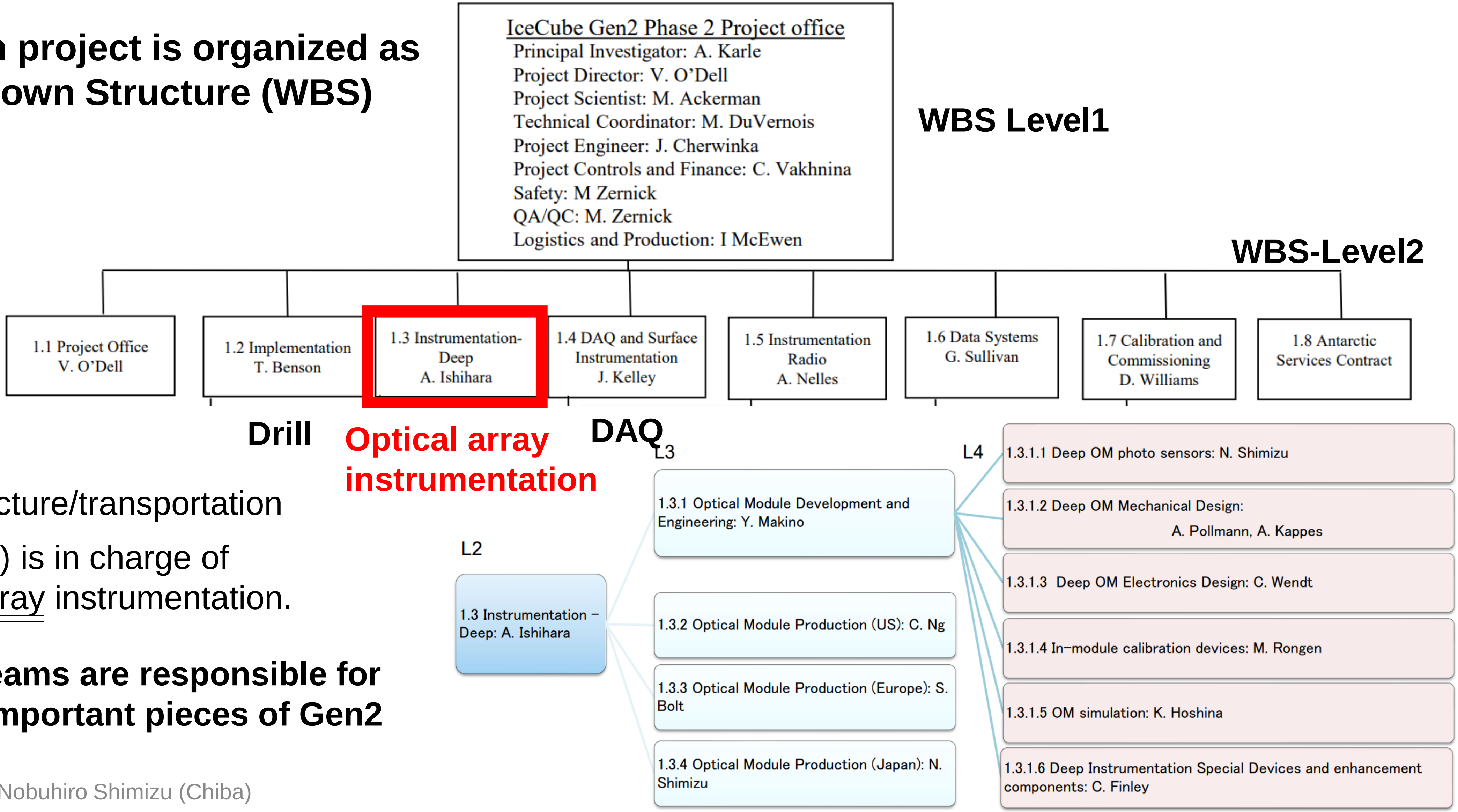
There sources are not favored by measurement.

IceCube-Gen will challenge various prime candidates of neutrino sources

>400 members
from 63 institutions in 15 countries

IceCube-Gen2 organization

IceCube-Gen project is organized as work Breakdown Structure (WBS)

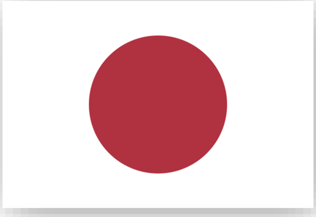


- US: infrastructure/transportation
- Aya. I (Chiba) is in charge of the optical array instrumentation.

➡ **Japanese teams are responsible for one of the important pieces of Gen2**

International funding supports

- On the roadmap in Astro2020
- P5 (US particle phys. panel) top 5 priority
- Plan to fund $280M for infrastructure etc
- Currently requesting $20M in *MSRI for preliminary design



- On MEXT roadmap 2023
- Request 50 億円 for OM** production (75%), and multi-messenger infrastructure (25%)

- Gen2 on Helmholtz roadmap
- Request, in total, €40M contribution
  €14M for OM** production
  €4M for surface station, €4M for radio

- Approved national funding
  for technical development $2.7M (2025-)

- Approved $5M grand for radio arrays.
- Large facility for OM** production at UCLouvain

ロードマップ2023 掲載計画概要

※カッコ内は実施主体（中核機関）
※＊はロードマップ2020からの継続掲載（５計画）

参考資料 1-2
科学技術・学術審議会
学術分科会（第90回）
令和6年2月2日

BSL-4施設を中核とした感染症研究拠点の形成＊（長崎大学）
BSL-4施設を中核とした世界トップレベルの感染症研究拠点を形成し、感染症の病態解明、診断・治療法の確立、有効な予防法の構築による国民の安全・安心の確保、WHO 等による国際的な感染症管理体制への貢献を通じ、世界の保健向上に資する。

スピントロニクス・量子情報学術研究基盤と連携ネットワーク＊（東京大学）
将来の量子科学・量子情報技術の中核となる分野である「スピントロニクス」について、卓越した研究機関のネットワークによる国際共同研究拠点を形成・強化し、革新的省エネルギーデバイス、古典・量子情報融合デバイスなどの新しい情報処理技術の実現に向けて不可欠の科学技術基盤を提供する。

多様な知が活躍できるパワーレーザー国際共創プラットフォーム：J-EPoCH計画（大阪大学レーザー科学研究所）
我が国の強みを活かした世界一の高繰り返し大型パワーレーザーによる国際共創プラットフォームをオールジャパン体制で構築し、量子真空の探査（場）、核融合エネルギーの探求（プラズマ）、超高圧新奇量子物質の創生（固体）を通して、エネルギー密度の高い極限的な量子科学の開拓で世界を先導する。

極低放射能環境でのニュートリノ研究（東北大学ニュートリノ科学研究センター）
神岡地下に建設したカムランド実験装置の高性能化により、素粒子原子核研究の最重要課題に挙げられる二重ベータ崩壊研究や、地球内部の組成や活動様式解明に挑む地球ニュートリノ観測、特徴的な低エネルギーニュートリノ天文学等を展開する。

IceCube-Gen2 国際ニュートリノ天文台による高エネルギーニュートリノ天文学・物理学研究（千葉大学ハドロン宇宙国際研究センター）
南極点直下に設置したIceCube検出器を世界15か国の連携により高度化し、世界最大のニュートリノ観測装置により高エネルギー宇宙ニュートリノの高感度観測を行う。電波からガンマ線まで分布する電磁波及び重力波との統合観測によるマルチメッセンジャー天文学を展開し、宇宙線の統合的理解、遠方宇宙や天体内部の探求に貢献する。

CTA国際宇宙ガンマ線天文台（東京大学宇宙線研究所）
次世代の国際宇宙ガンマ線天文台CTAにより、超高エネルギーガンマ線領域の世界唯一の天文大型施設として、極限宇宙の姿を捉え、ブラックホール、宇宙線の起源、暗黒物質などの解明を目指す。さらに、従来の電磁波・宇宙線観測に加え、重力波やニュートリノ観測と連携し、マルチメッセンジャー天文学の重要な一つの柱となる。

強磁場コラボラトリー：統合された次世代全日本強磁場施設の形成＊（東京大学物性研究所）
全日本的な強磁場施設の連携の下で世界最高性能の設備を組み合わせた独創的な戦略により、我が国が強みを持つ物質・材料科学-とりわけ、半導体、磁石、超伝導材料などの研究で世界を先導する。情報、エネルギー、医療等の課題解決に貢献するとともに、1200テスラ超強磁場下の学際的研究により宇宙、生命、化学などにおける未知現象を発見する。

30m光学赤外線望遠鏡計画TMT（自然科学研究機構国立天文台）
ハワイ島マウナケア山頂域に口径30m光学赤外線望遠鏡TMTを建設し、すばる望遠鏡の広域探査と連携して地球型系外惑星や宇宙の初代星等の観測を行う。膨張宇宙における星、銀河、元素生成等の全貌を理解し、惑星の形成や生命誕生という人類究極の課題に挑む。

超高温プラズマの「ミクロ集団現象」と核融合科学（自然科学研究機構核融合科学研究所）
超高温プラズマを高精度で制御・操作し、世界最高の分解能で計測する実験システムを構築することで、核融合炉のみならず宇宙・天体にも共通するプラズマに独特な揺らぎの発生原因とその影響を解明する。計測と理論・シミュレーションを連携し、核融合イノベーションを駆動する科学的指導原理の構築を目指す。

LiteBIRD－熱いビッグバン以前の宇宙を探索する宇宙マイクロ波背景放射偏光観測衛星＊（宇宙航空研究開発機構）
熱いビッグバン以前の宇宙に関する最有力仮説である「インフレーション宇宙理論」を検証するため、LiteBIRD衛星による宇宙マイクロ波背景放射の全天偏光観測から原始重力波を探索する。代表的インフレーション宇宙理論を検証することで、宇宙創生の謎に挑む。

アト秒レーザー科学研究施設＊（東京大学）
我が国で長年にわたって培われてきた先端レーザー技術と自由電子レーザー技術を集約し、アト秒レーザー科学研究施を建設する。物質中の電子の動きを実時間で捉えることにより、物理学、化学、生物学、工学、薬学、医学等の幅広い分野でイノベーション創出を目指す。

統合全球海洋観測システムOneArgoの構築と海洋融合研究の推進（東北大学）
全球海洋の深度2000mまでの水温・塩分を常時計測する現行のArgoフロート観測網を、海底まで、かつ、生物地球化学変数の計測にまで拡張する統合全球海洋観測システムOneArgoを構築する。海洋全層における気候変動シグナルの検出や、海洋酸性化・貧酸素化の実態把握と生態系の応答の解明等により、海洋融合研究を推進する。

European countries are positive for supporting the project

*Middle scale research infrastructure **OM: optical module

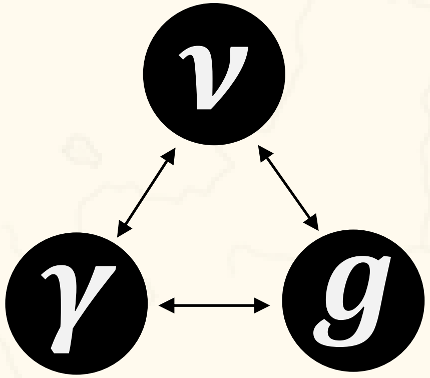
Our science strategy

(c)Higgstan

ICEHAP as a hub of Asia-pacific center

千葉大学
ハドロン宇宙国際研究センター
ICEHAP International Center for Hadron Astrophysics

Multi-Messenger astronomy



Creation of new science

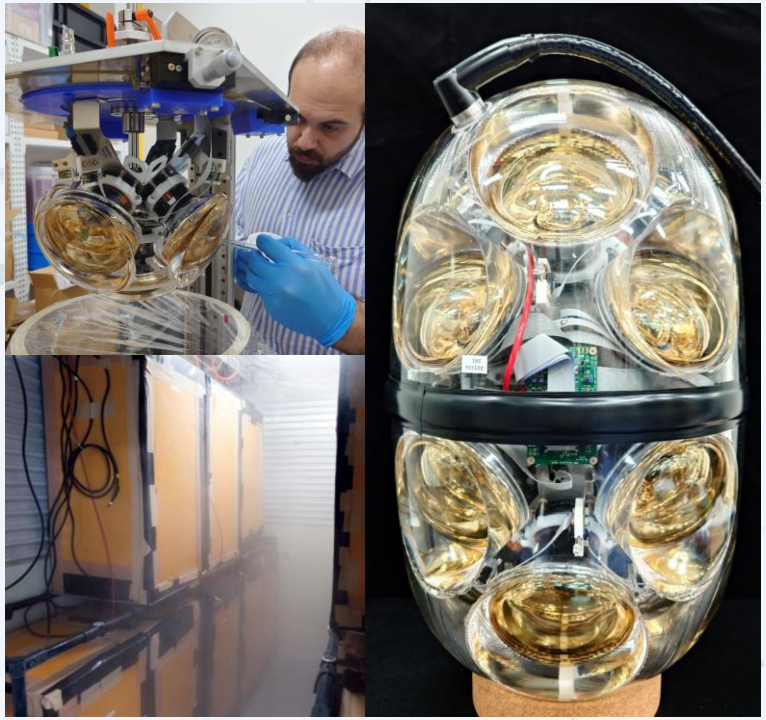
Optical module production

Collaboration with industry

Engineering

Education

Contribution to society



Lead astrophysics as one of the core centers in Asia

Joint research network with multi-messenger astronomy

Neutrinos are smoking guns for high energy astrophysical phenomena

➡ IceCube/IceCube-Gen2 provides various research topics with community

Several studies have already started under
学術変革A 2023：マルチメッセンジャー宇宙物理学

transient searches

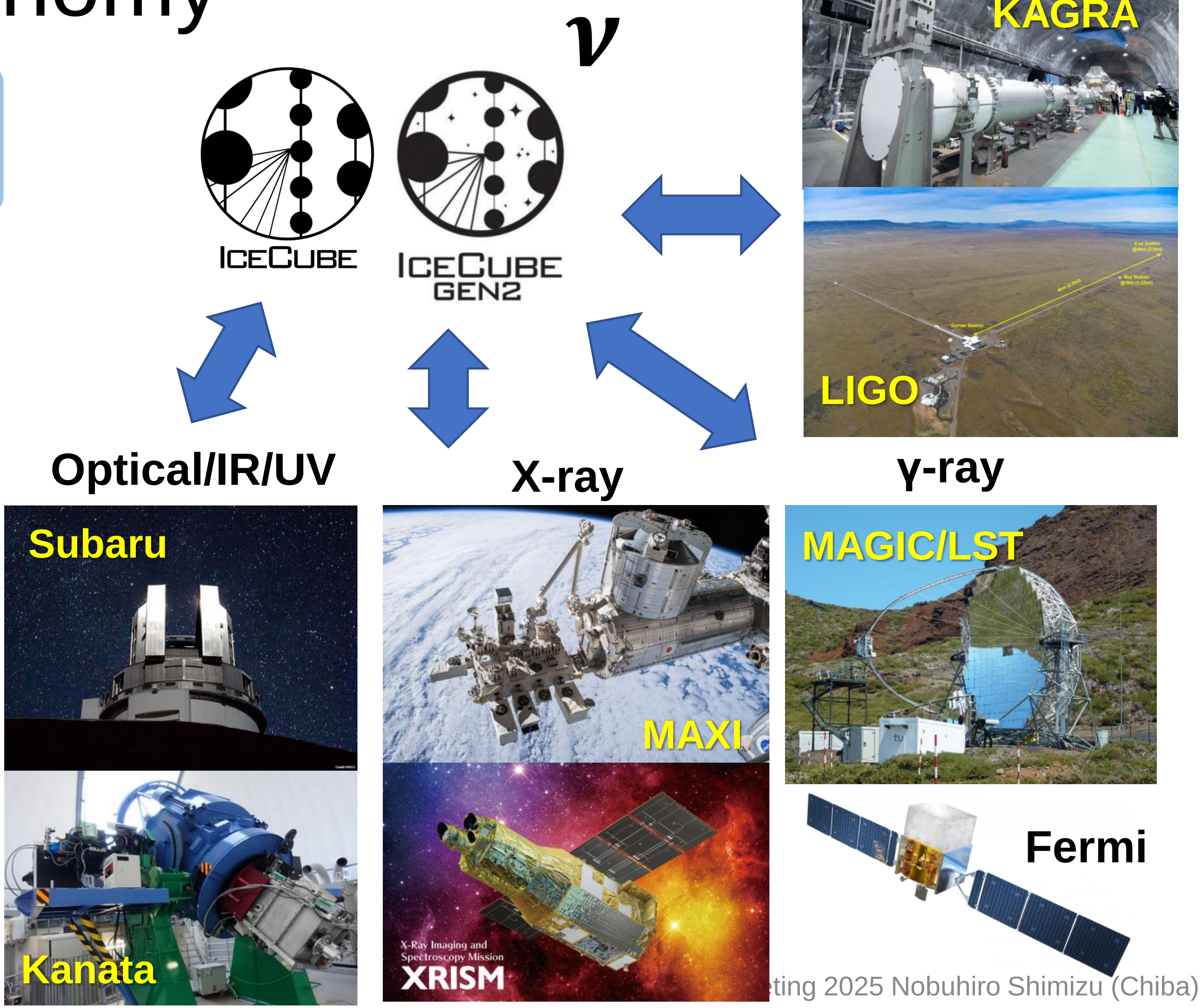
ν detection → other observatories

GRBs → ν NS-NS merger → ν

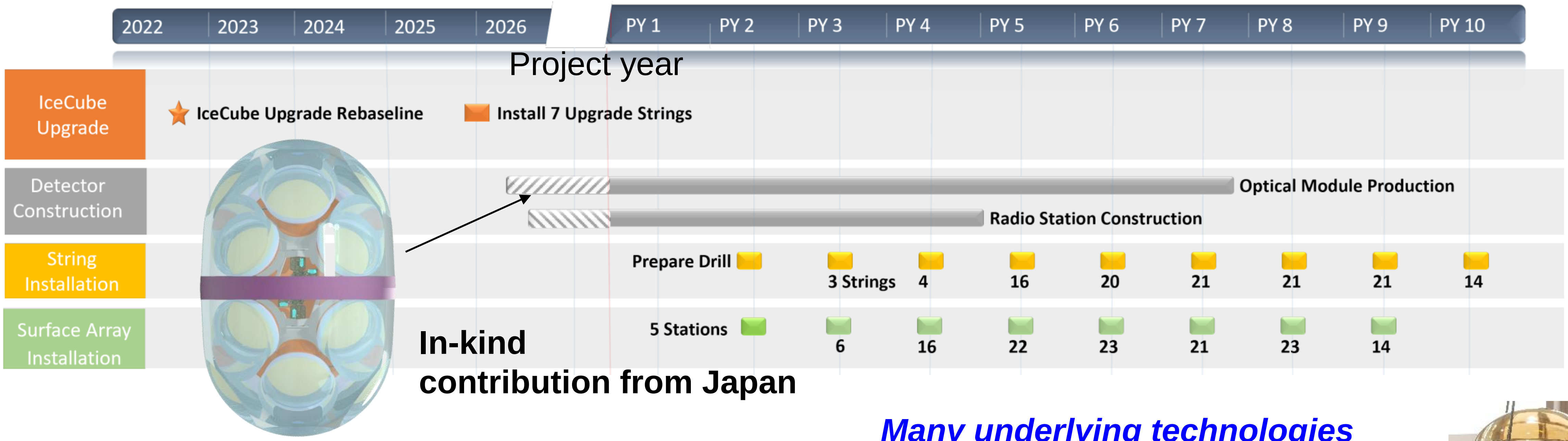
archival studies

X, γ ray source catalog → ν search

ν archival data ⇔ X-ray archival data



Optical module production



In-kind contribution from Japan

2025 - : IceCube-Upgrade, ice calibration

: Gen2 detector final R&D for mass production

2026 - : Mass production facility construction

: Gen2 detector first mass production for 1st string

2027 - : Large scale mass production

Many underlying technologies have been already established!

skilled young researchers experience of D-Eggs

industries support

Japan can be a core production facilities.

Plan to provide 30% of detectors for Gen2 optical array

Collaboration with industry and education

Key components

Hamamatsu：PMT
Okamoto-Glass：Glass Vessel
Shin-Etsu-Chemical：Silicone Gel

Production

Azuma　：Plastic sheets for gel
Miyazaki　：Plastic components
NME, SeisGadjet : Assembly

supplier & feedback from us

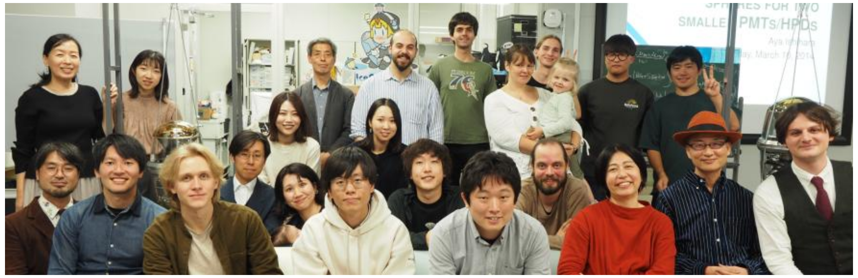
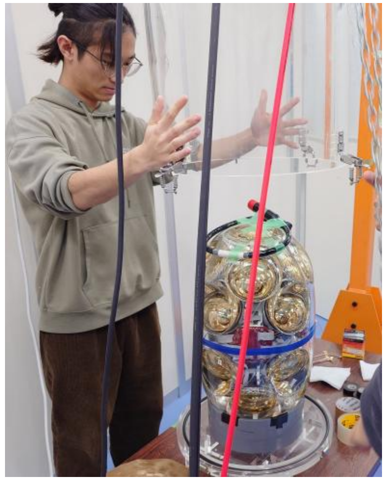
Chiba University

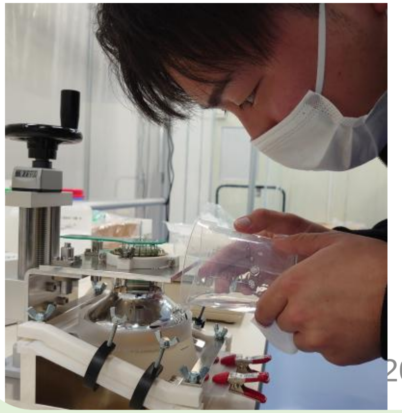
- Education of young resources in **international research environment**

Human resources → Industry

Significant in-kind contributions of detectors → IceCube, IceCube-Gen2

Our partnership is already matured.
Close to be ready to produce Gen2 detectors.



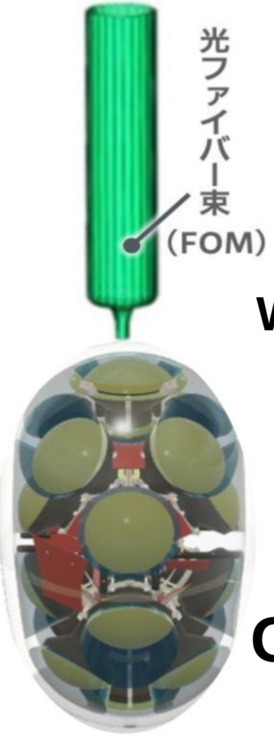
Masters' students

D-Egg projects: 7
Gen2 projects: 2
ARA projects: 2

“IceCube-Japan” is glowing

Osaka Metropolitan University IceCube-Gen2 Group

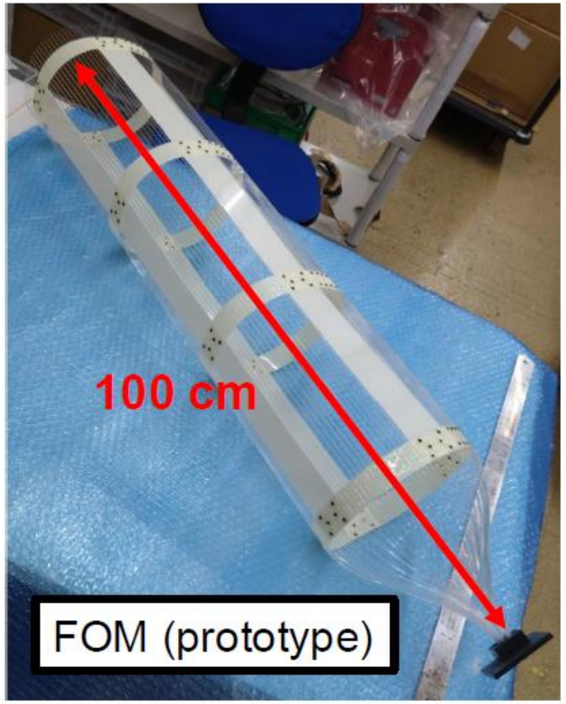
- ✓ Yoshiki Tsunesada
- ✓ Toshihiro Fujii
- ✓ Takuro Kobayashi (Graduate student)
- ✓ Tatsuki Ishii (Graduate student)
- ✓ Shinichiro Ohta (Graduate student)

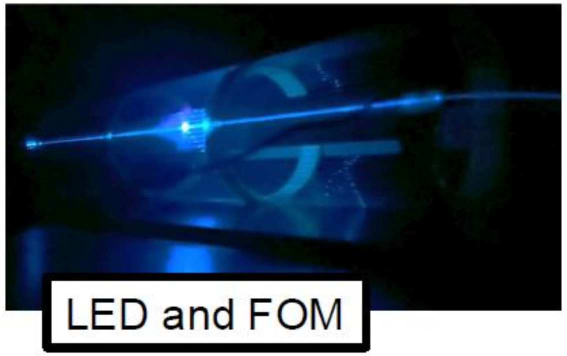


Passive detector with WLS fibers

WLS fibers

Gen2-DOM





- ➢ **Studies a new approach to improve the performance of the Gen2 detectors**
- ➢ **Please contact us if you would like to contribute IceCube-Gen2. Even with small scale project is welcomed!**

Summary

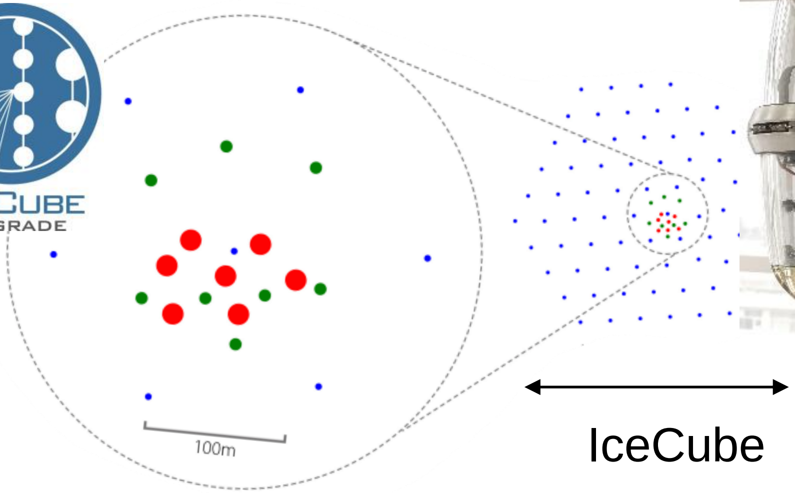
- IceCube has been characterizing the astrophysical diffuse neutrino flux
- IceCube-Gen2 will challenge the origin of neutrinos with 1 order better sensitivity
- Japanese team had been providing significant contributions with IceCube both by analysis and hardware: we are indeed leading the development of the core detector for the IceCube-Gen2
- We are also leading multi-messenger astronomy. Neutrinos always have synergies with other messengers, and thus provide various research topics for high energy astrophysical phenomena
- Stay tuned!

IceCube-Extension

◆IceCube-Upgrade (Gen2-Phase1)

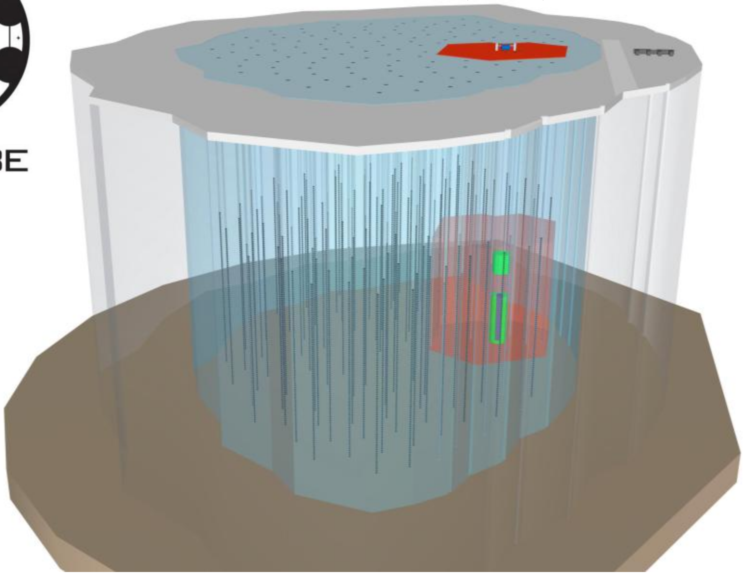
- Installation of 700 sensors
- "**Low**" energy neutrinos
  - ν oscillation & GeV-ν astrophysics
- Precise measurement of ice properties

⇨ ***Start data collection in 2026***



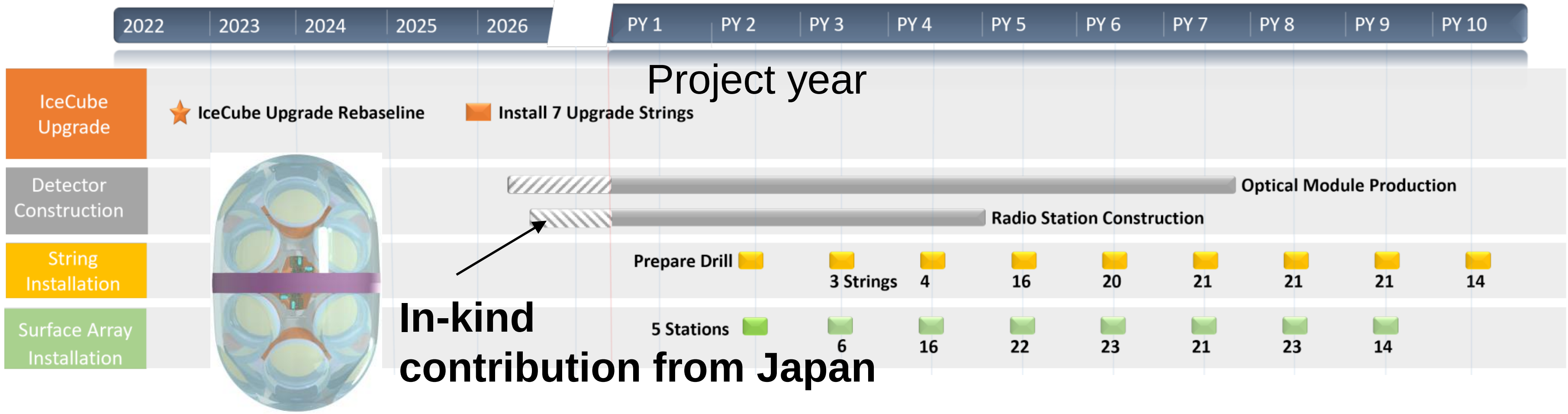
◆IceCube-Gen2

- Installation of new 10,000 sensors
- Aiming for "**High**" energy neutrinos



Backup

Strategy as Japanese team



Project year

In-kind contribution from Japan

千葉

CHIBA UNIVERSITY

大阪公立

Hardware & Calibration contribution

2025 - : IceCube-Upgrade, ice calibration
: Gen2 detector final R&D for mass production
2026 - : Gen2 detector first mass production for 1st string
2027 - : Large scale mass production

skilled young members
experience of D-Eggs

industries' support

Japan will be a hub of mass pro. facility
Plan to provide 30% of Gen2 optical array

Science contribution

IceCube-Upgrade

- Detector simulation for IceCube-Upgrade
- Low energy (GeV) astrophysical transients
- Tau-Flavor identification w/ NN and delayed photons by n

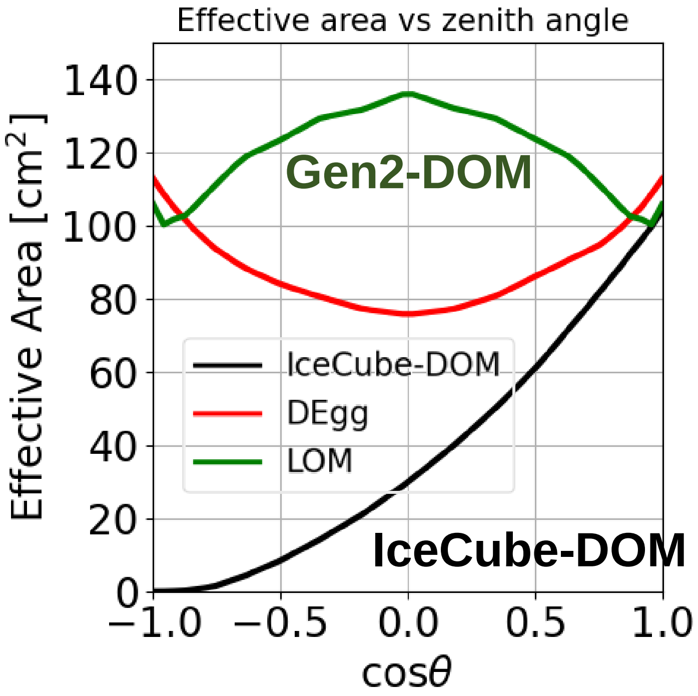
IceCube-Gen2

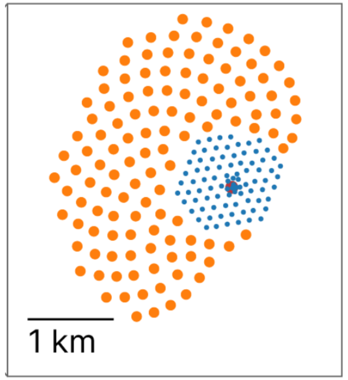
- Search for GZK neutrinos
- Search for neutrino radiation source
- Alert channels for Multi-messenger astronomy

Multi-messenger joint collaboration

- Will be covered later

Gen2-DOM development





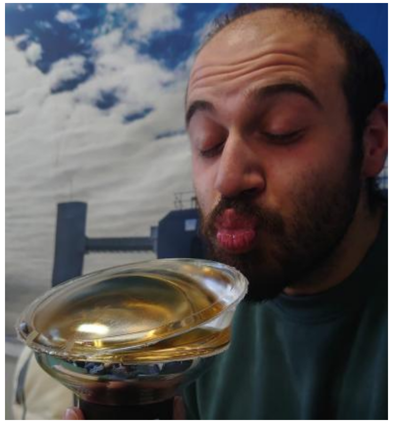
IceCube: 125 m spacing

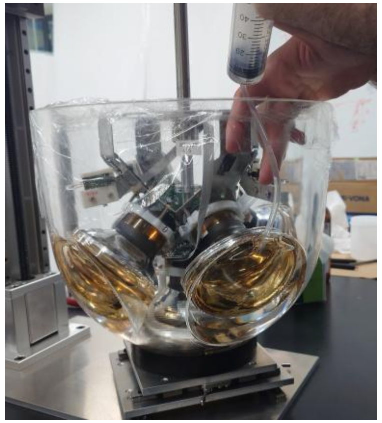
IceCube-Gen2: 240 m spacing

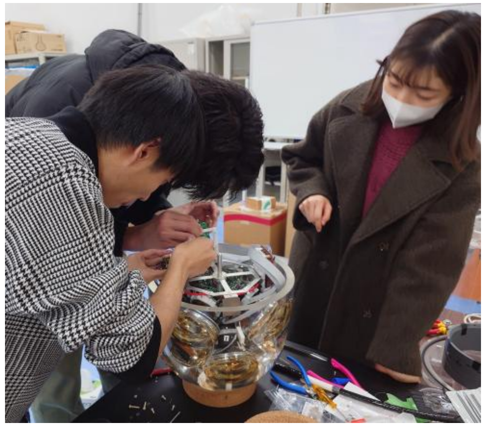
- Pack multi-PMTs in an egg-shaped glass
- Use silicone elastomer's light guide (gel pad) to efficiently lead photons up to PMTs
- High pressure-resistant glass with very small RI contamination

A factor of >4 improvement compared to IceCube-DOM

Compensates for the smaller density of detectors







Students and young researchers lead the tough developments

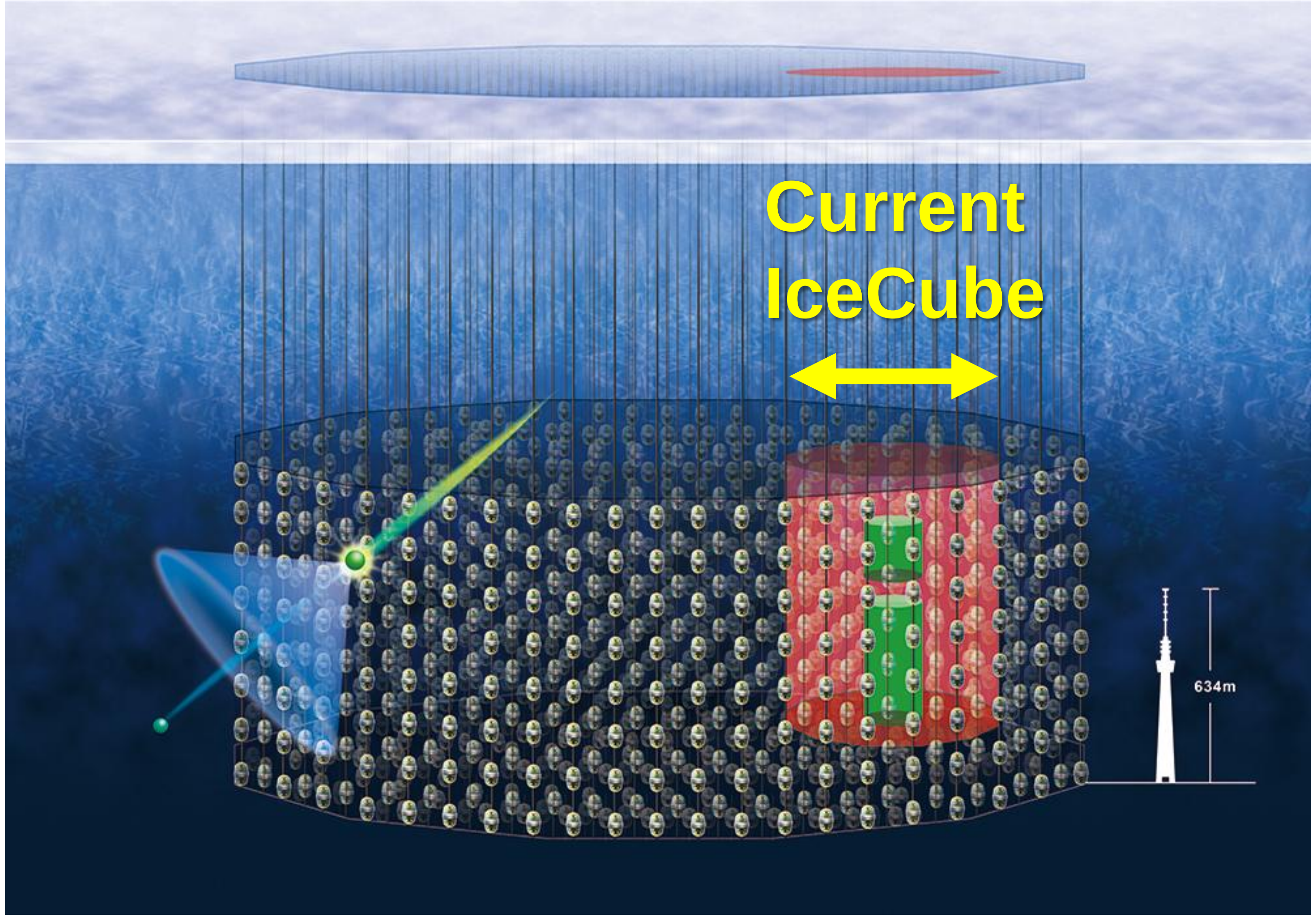
Various multi-messenger studies

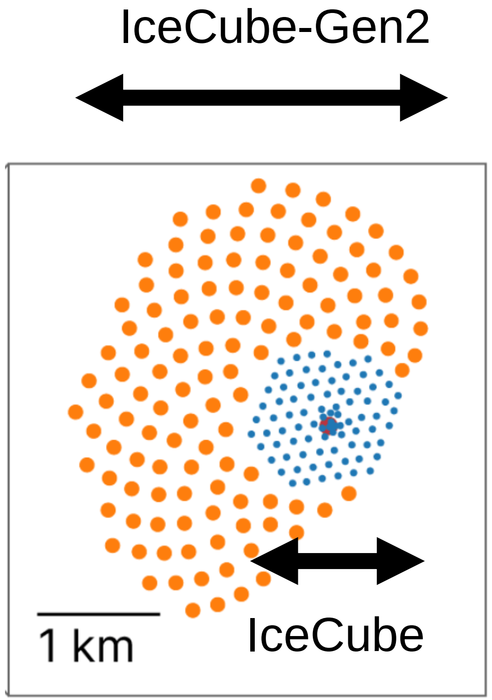
- MAXI & ν alert → NICER follow-up
- MAXI & ν signal correlation study
- MAXI subthreshold catalog → ν

- ν alert w/ X,γ known source → MAGIC/LST

- ν 30 days transients with archival data
  → ZTF archival data to constrain SNe/TDEs
- ν-alert dedicated for optical follow-up

IceCube-Gen2 array

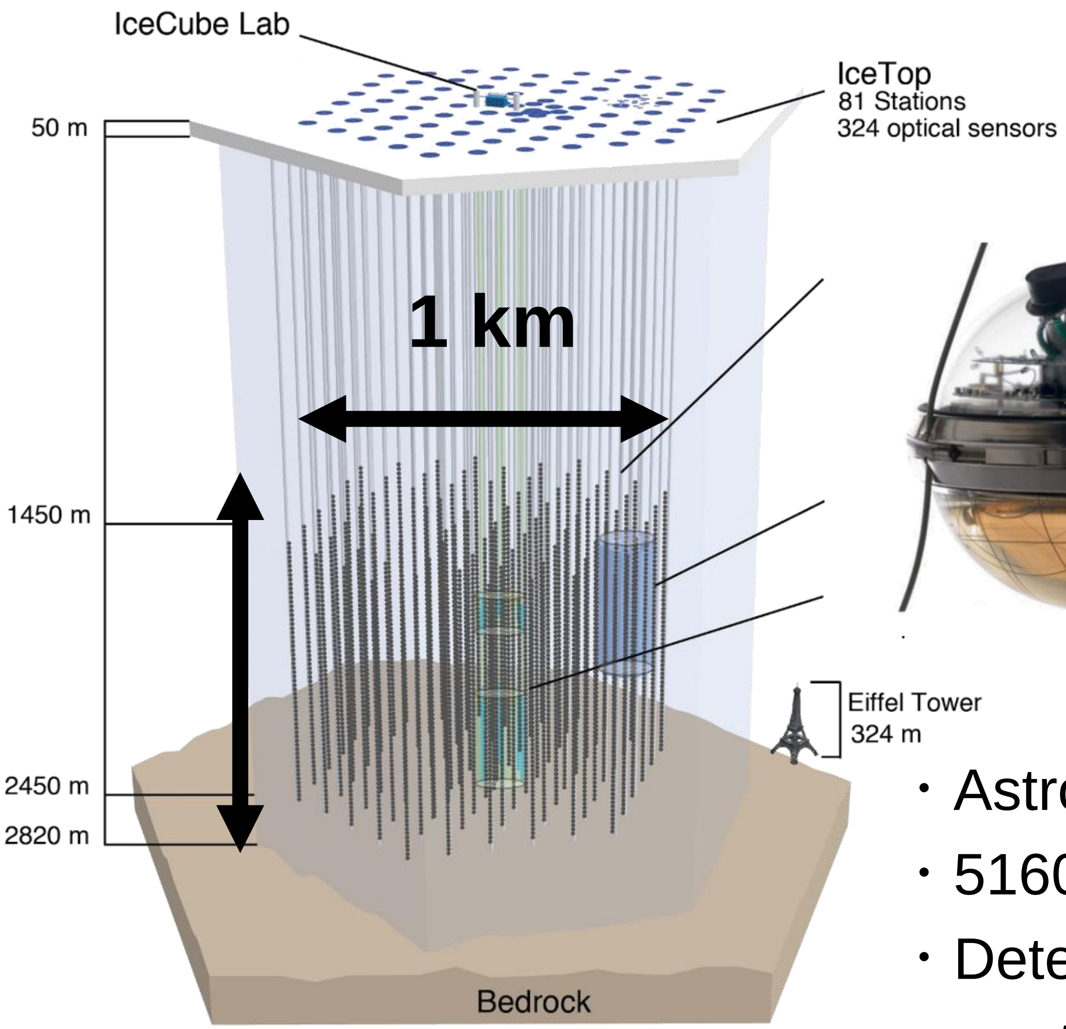




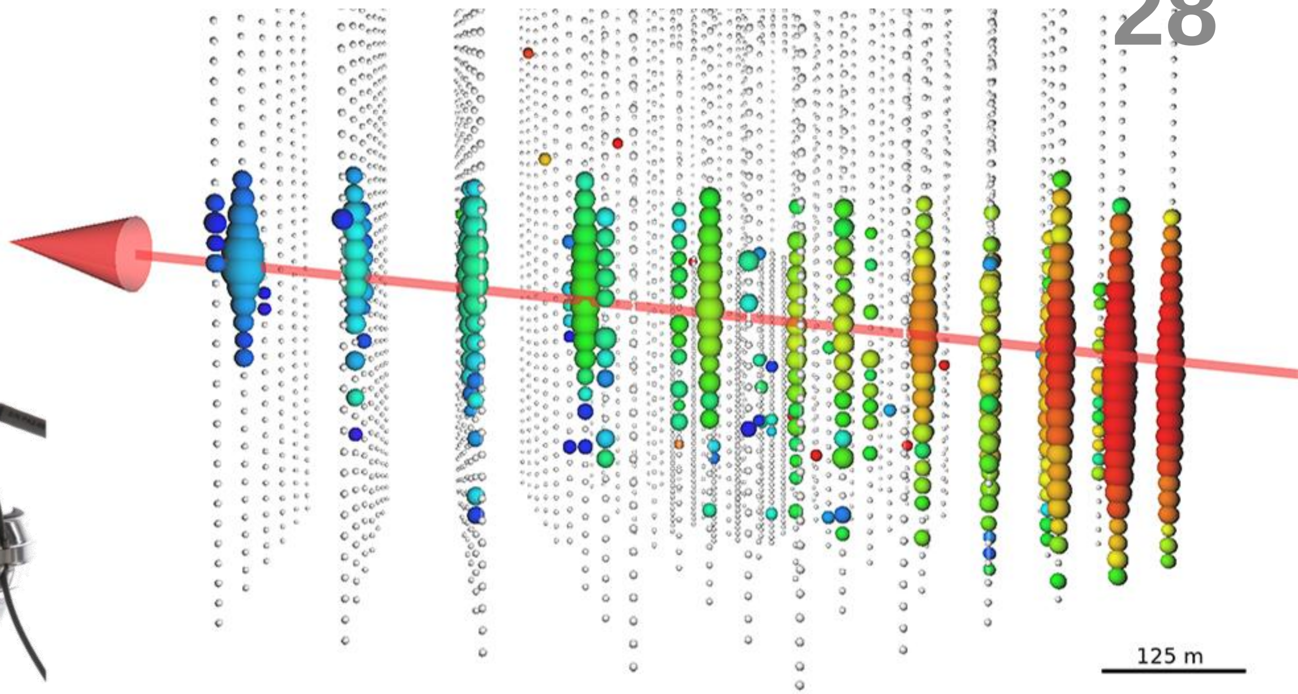
- 10,000 optical sensors
- × 2 bigger string separation
- x 4 more sensitive detectors

➡ **Detection volume : x8**
Angular resolution : x4

IceCube experiment



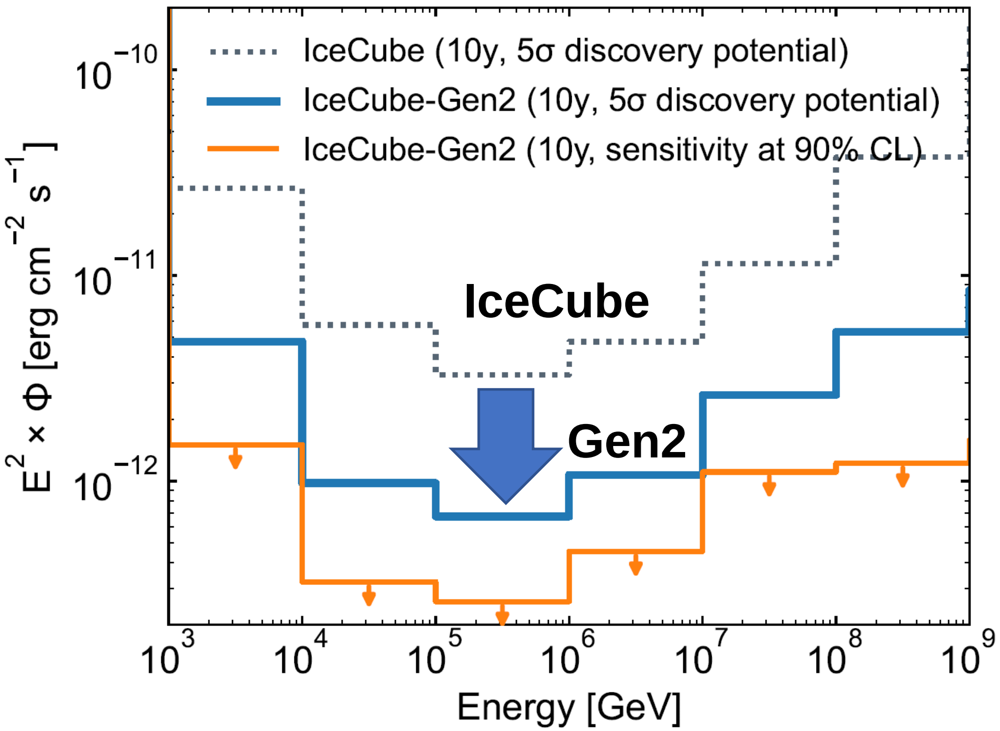
DOM

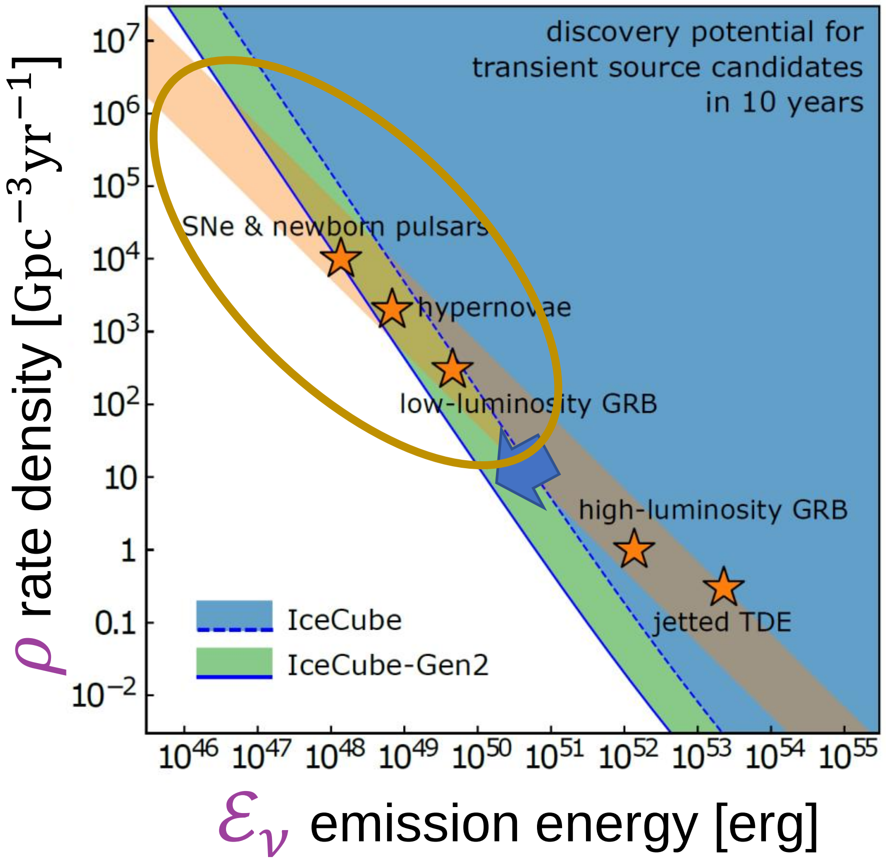


- Astrophysical neutrino telescope
- 5160 optical modules (DOM) in the ice of Antarctica 1 km^3
- Detect Cherenkov light from charged particles produced by neutrino interaction

Search for ν-emission sources with Gen2

5σ detection level





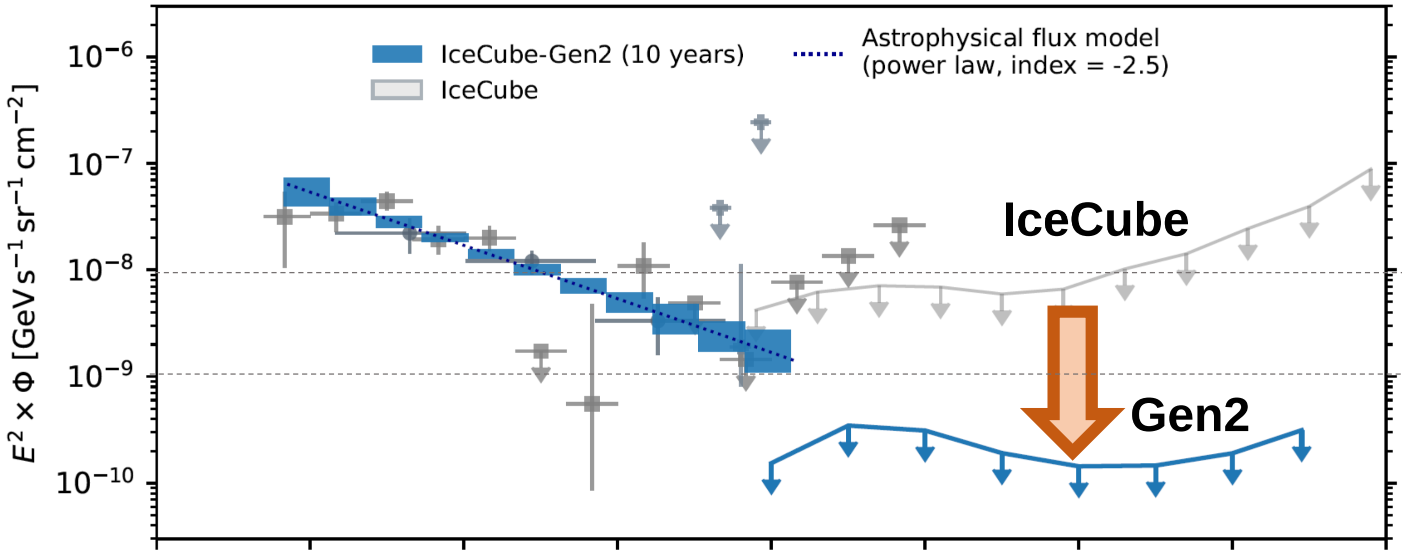
Source detection capability **x 8**

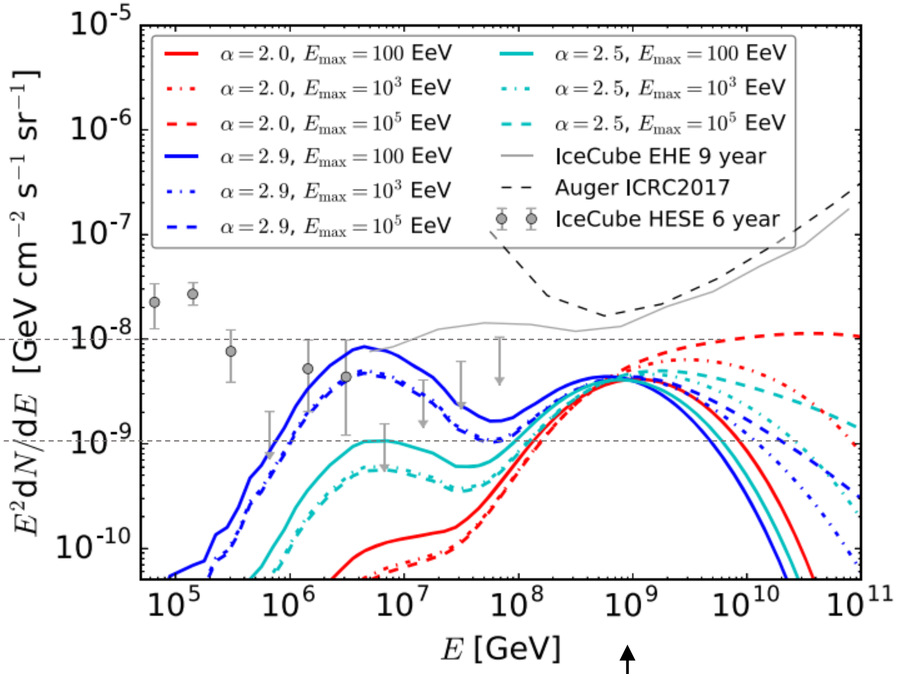
With the updated detectors, we can challenge dim but frequent transients.

Search for cosmogenic ν with Gen2

>PeV neutrinos from interaction between cosmic ray and CMB photons
a.k.a., **GZK neutrinos**

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^+ \rightarrow \nu_{GZK}$$





PeV

O(10) or bigger sensitivity reaches flux level of various model predictions!

What's next target?

$\boldsymbol{\phi_\nu} \propto \mathcal{E}_\nu \times \rho$

$\mathcal{E}_\nu$: Neutrino emission energy per source

ρ : Source rate density