IceCube Highlights and Prospects for Multi-Messenger Astronomy

Yukiho Kobayashi (Chiba U.)

高エネルギー現象で探る宇宙の多様性Ⅳ @ ICRR, 11-13 November 2024

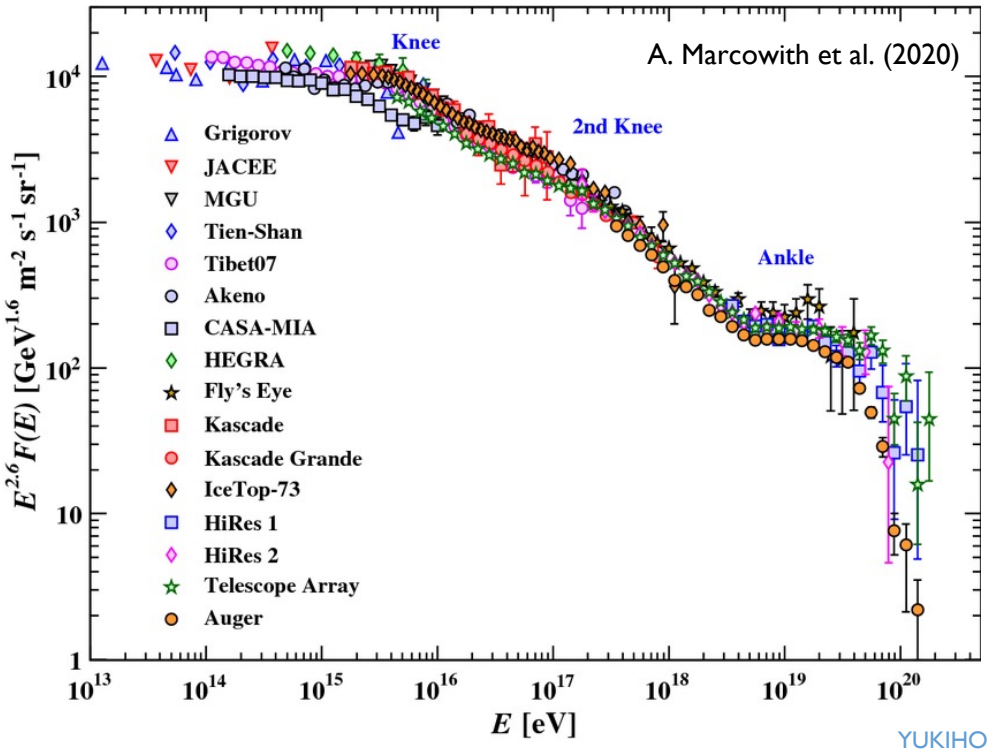
IceCube Neutrino Observatory

Chiba University ICEHAP

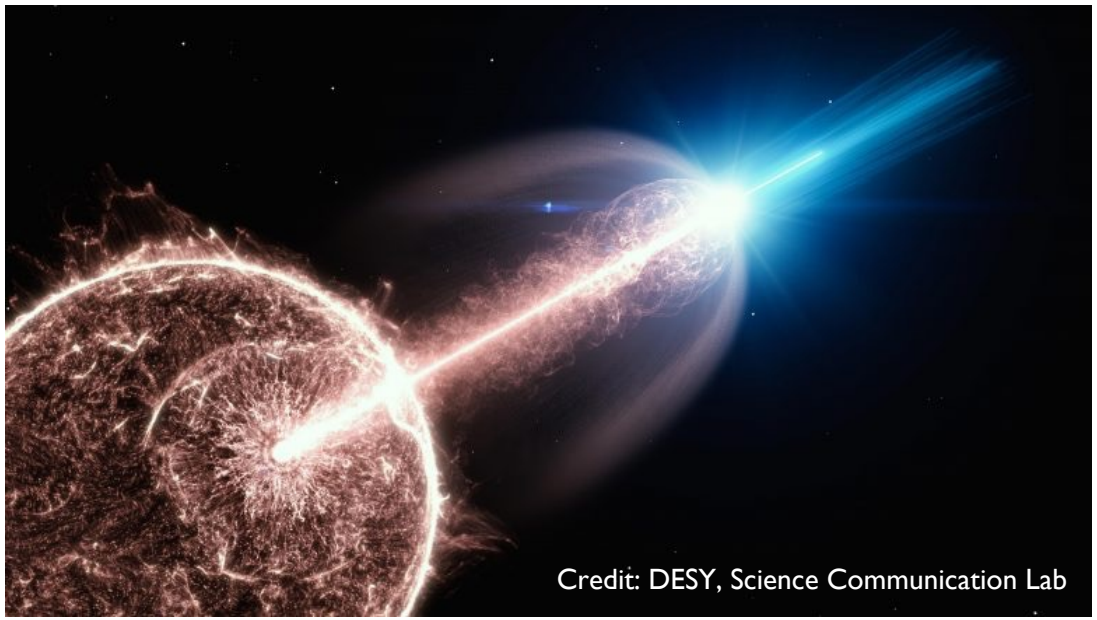
Introduction

General Targets

- Origin of cosmic rays
  - Where and how they are accelerated
    - AGNs? GRBs? Galactic sources?

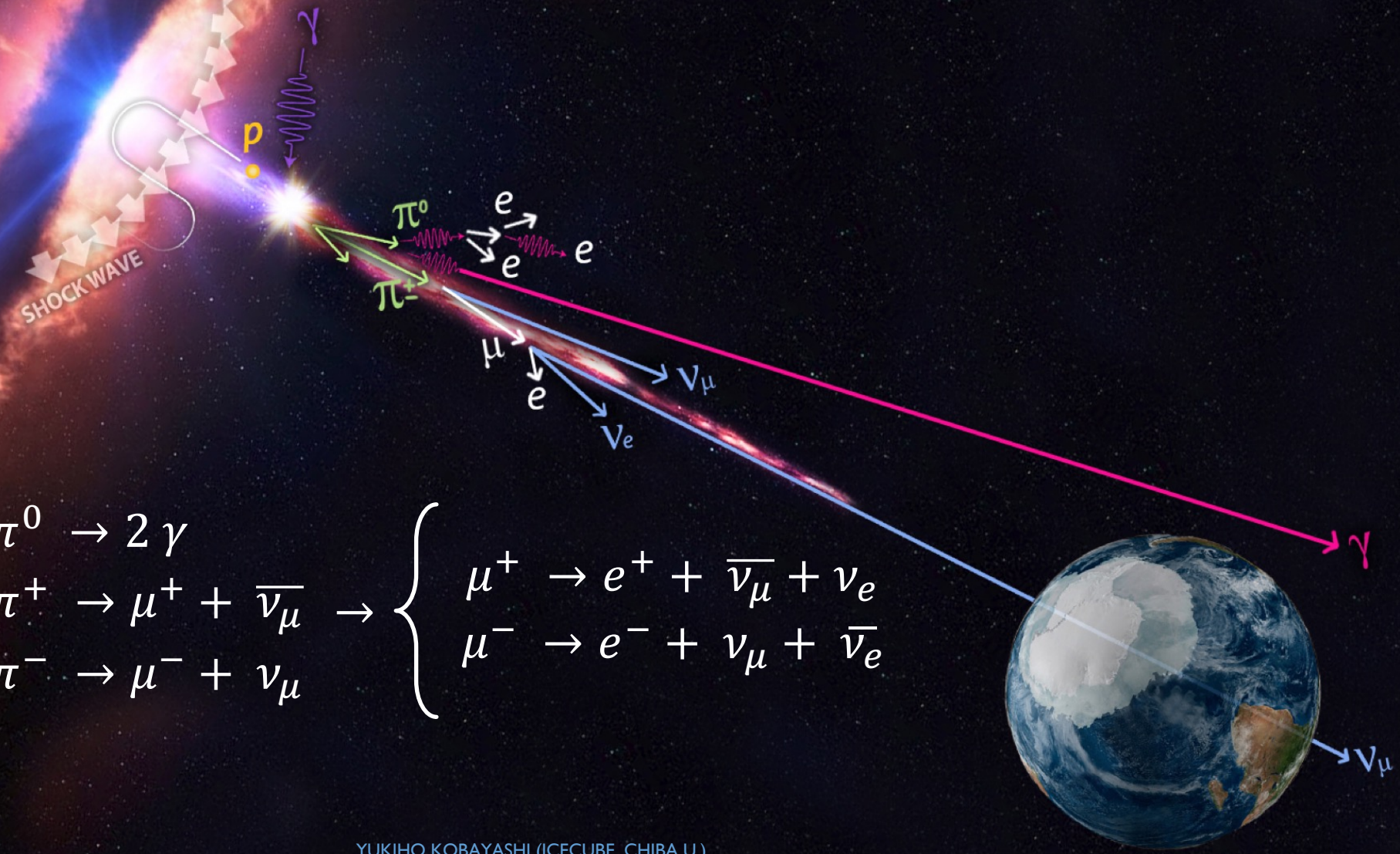


- High-energy astrophysical phenomena
  - AGBs, GRBs, SNe, Novae, TDRs, etc
  - Subphotospheric outflow in GRBs/SNe?



Credit: IceCube/NASA

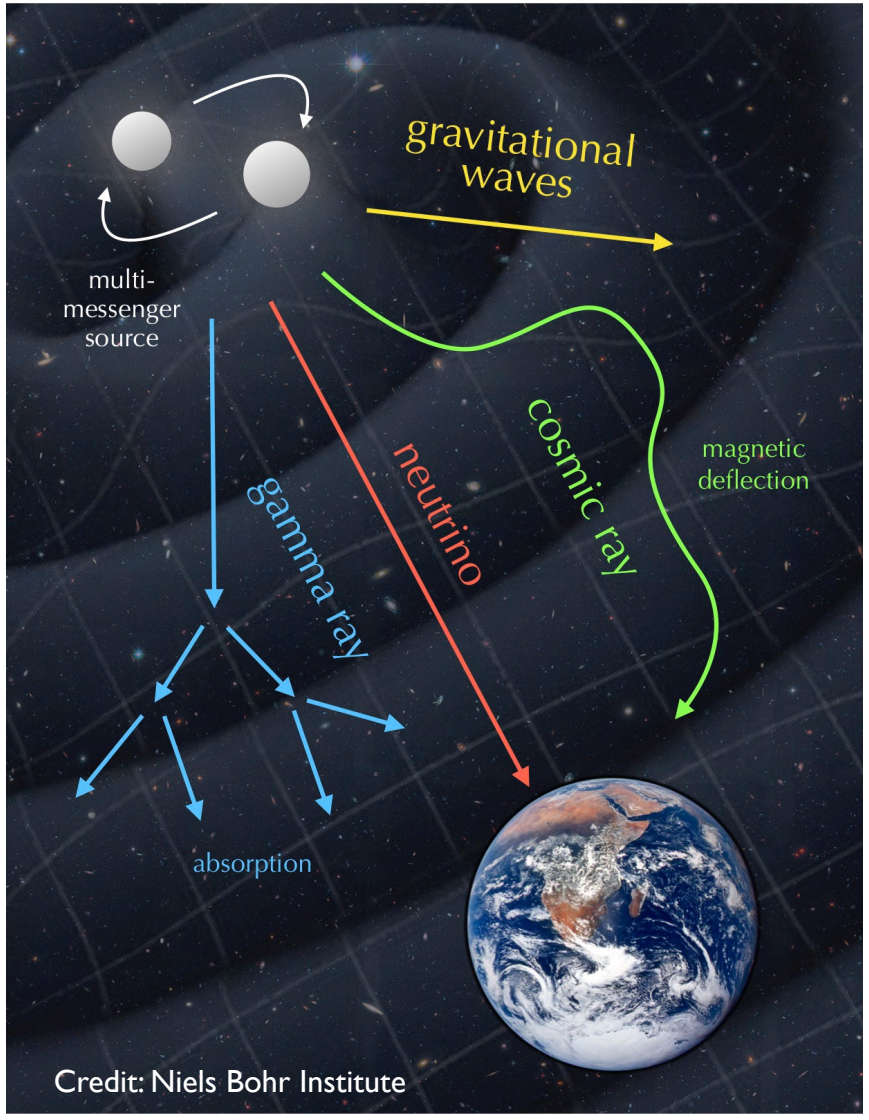
How Neutrinos are Produced



$$\begin{matrix} p + N \\ p + \gamma \end{matrix} \rightarrow \begin{cases} \pi^0 \rightarrow 2\gamma \\ \pi^+ \rightarrow \mu^+ + \overline{\nu_\mu} \\ \pi^- \rightarrow \mu^- + \nu_\mu \end{cases} \rightarrow \begin{cases} \mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e \\ \mu^- \rightarrow e^- + \nu_\mu + \overline{\nu_e} \end{cases}$$

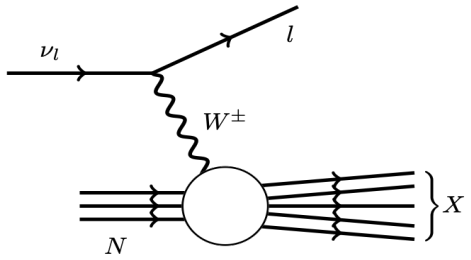
Why Neutrinos?

- Neutral
  - No deflection by magnetic field
  - **Travel straight from source**
- Weak interaction only
  - No (little) interaction with photon (matter)
  - Travel cosmological distance **without significant attenuation**
  - Can probe **optically-thick environment**
- Specific to hadronic origin
  - **Smoking-gun** for cosmic ray accelerator

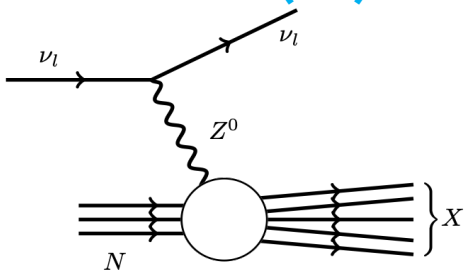


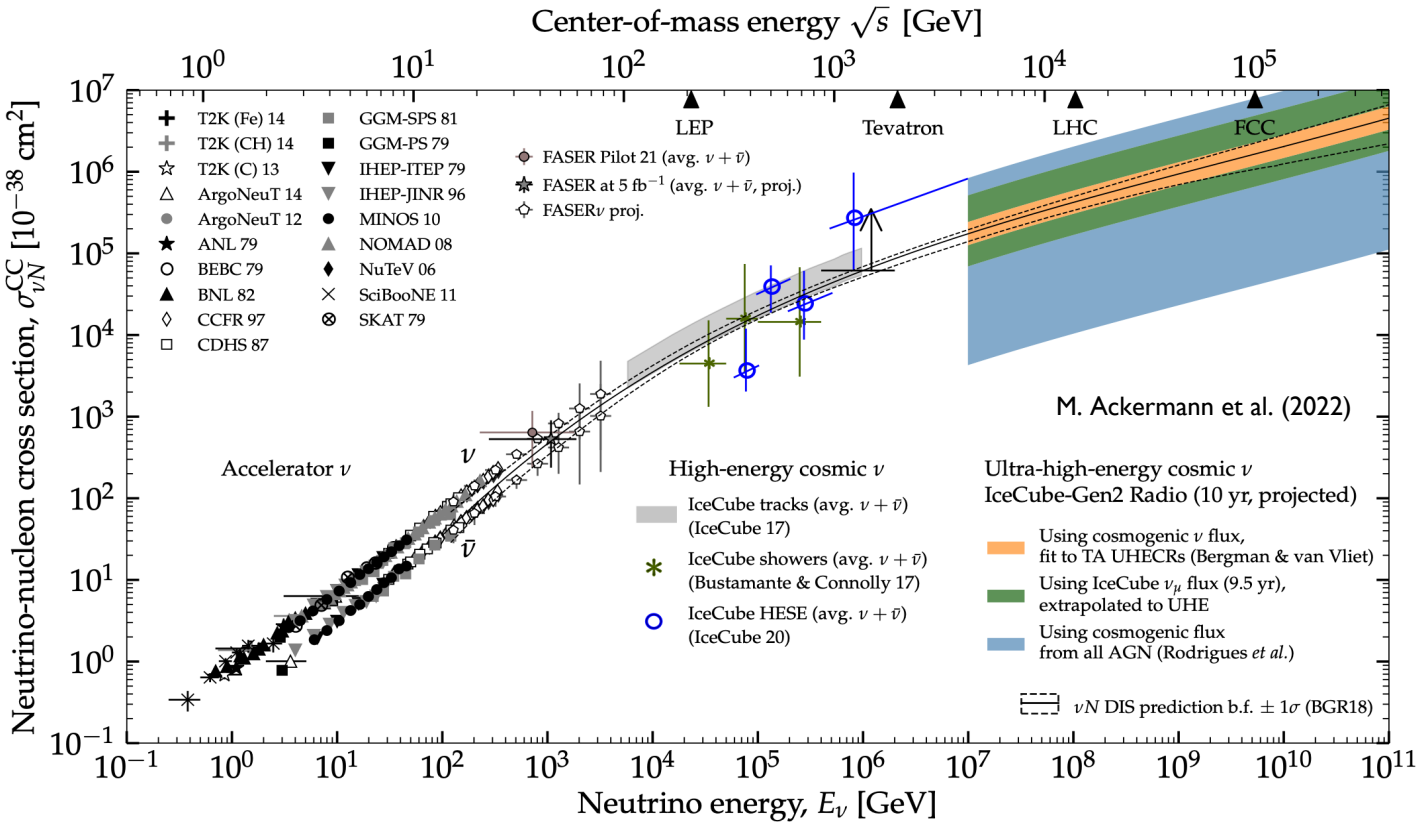
Neutrino Interaction

- Only weak interaction
- Deep inelastic scattering dominates at >10 GeV
  - Neutrino breaks up nucleus
  - **Charged current (CC)**

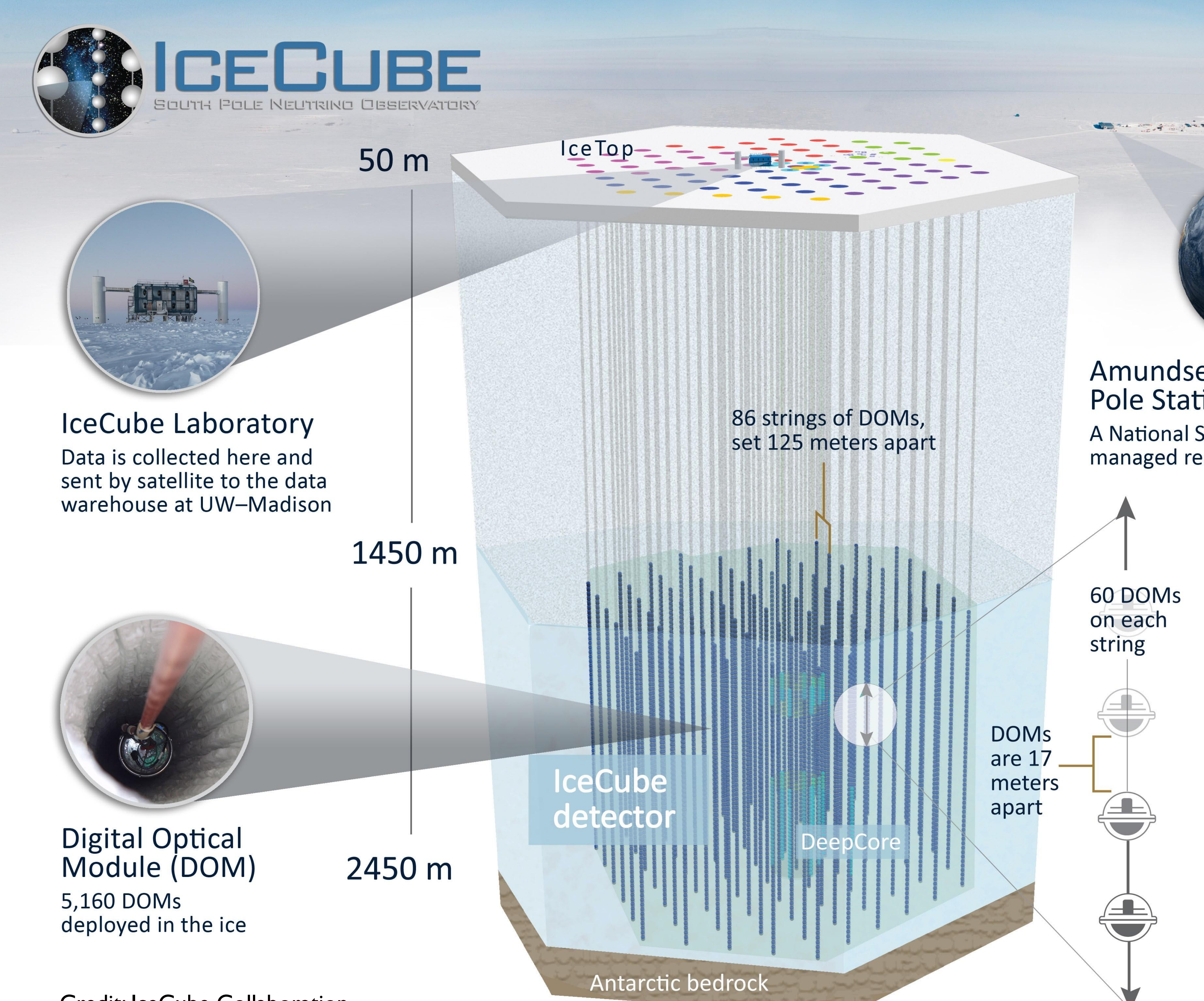


  - **Neutral current (NC)**





- **Tiny cross section: ~10^{-38} cm^2/GeV**
  - Need a water tank as large as solar system to catch all ν



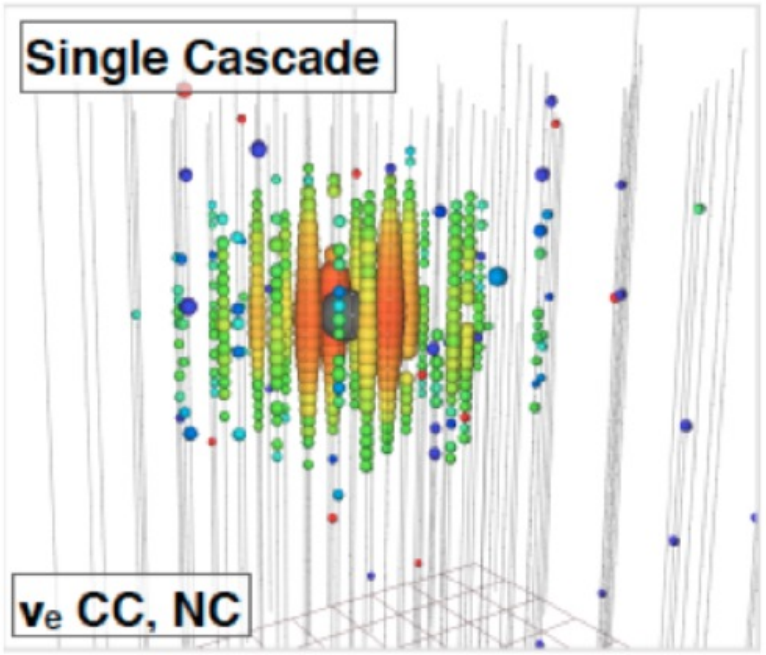
Credit: HiggsTan

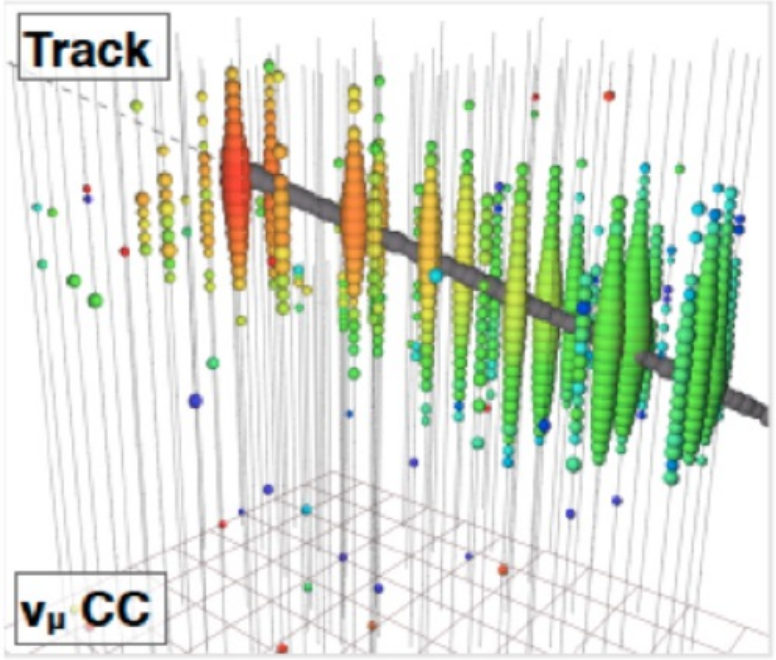
- Neutrino telescope instrumenting **1 km³ glacial ice on Antarctica**
- **5160 optical sensors** (86 strings * 60 modules)
- A_{eff} ~ 1 m^2 around 1-10 TeV

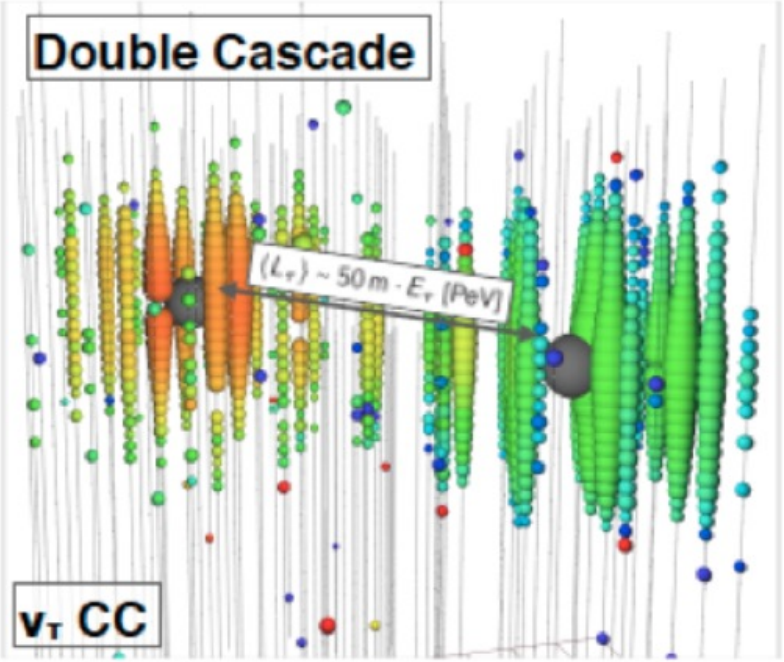
Credit: IceCube Collaboration

How Events Look like?

IceCube and KM3NeT Collaborations (2019)







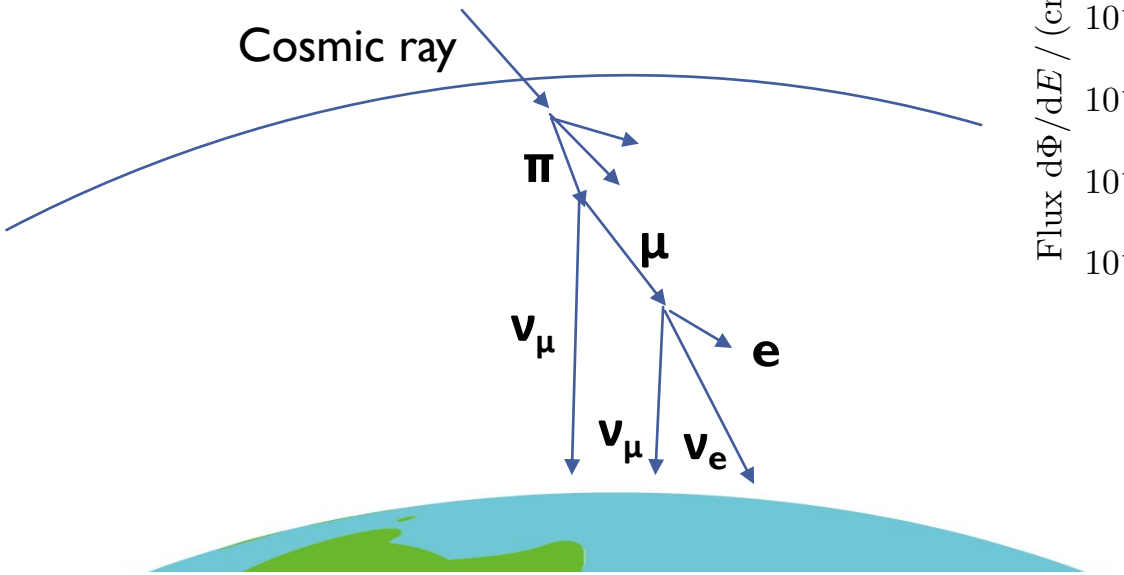
- Energy resolution: ≲ 10%
- Angular resolution: ≲10°

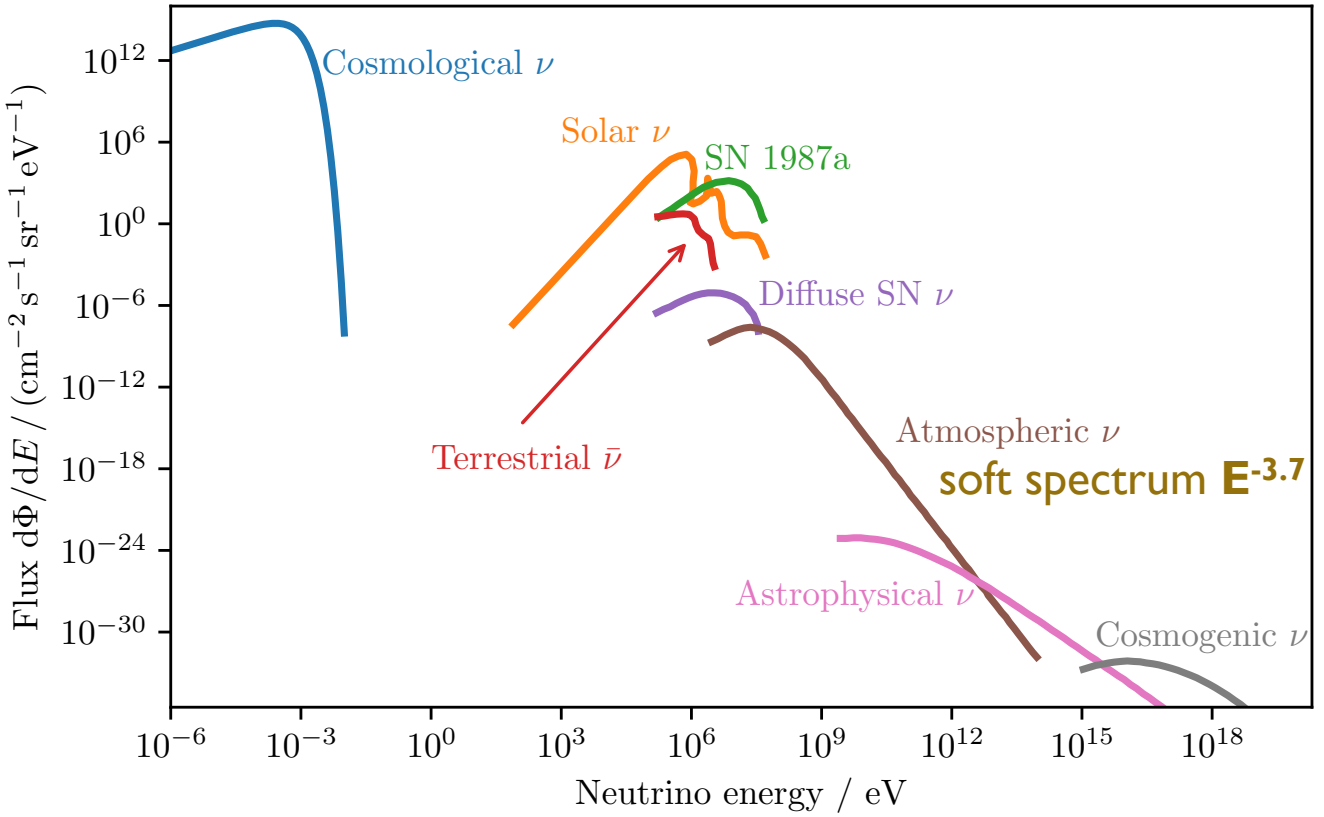
- Energy resolution: ~facror of 2
- Angular resolution: ≲ 1°

- Resolution between cascade/track
- Likely to be of astrophysical origin

Atmospheric Background

- Muons/neutrinos from cosmic-ray air showers are background
  - Atmospheric muons rate ~3 kHz
  - atm. ν spectrum ~$E^{-3.7}$

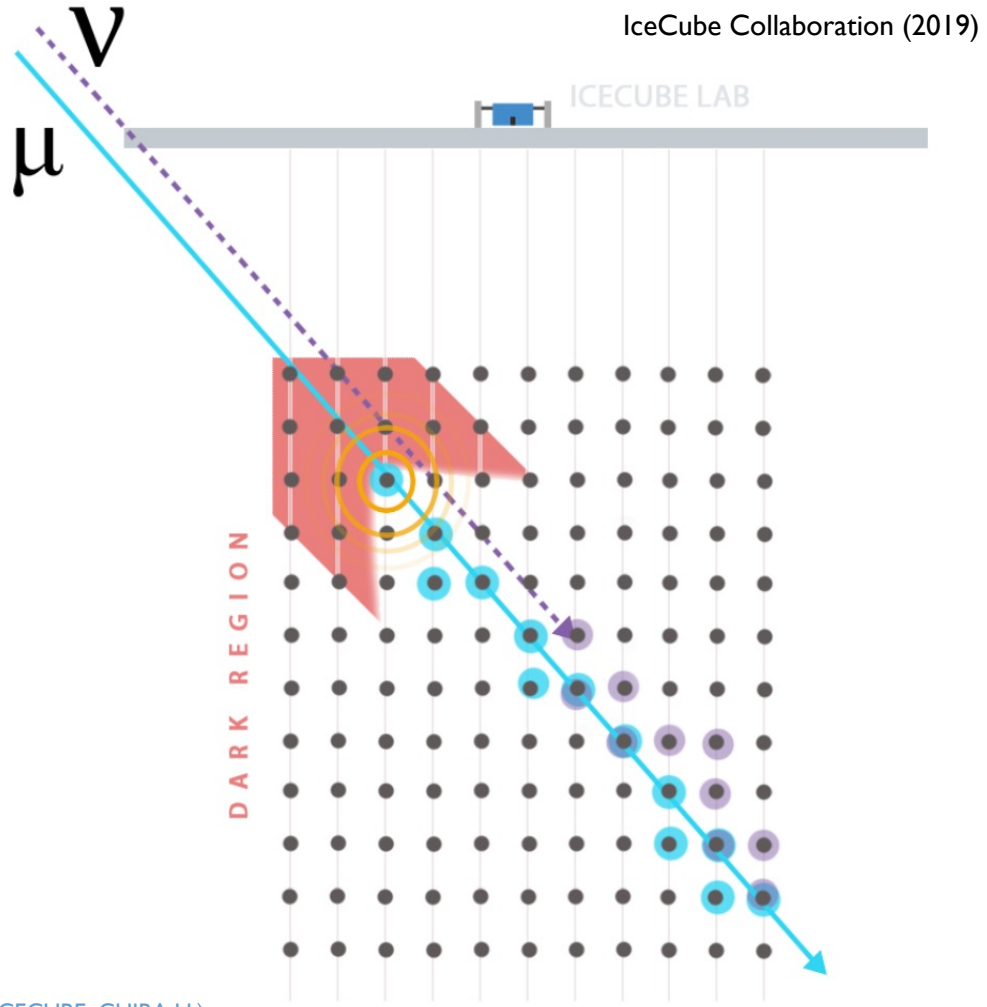




NOTE: atmospheric ν is useful for other analyses like cosmic-ray and oscillation studies

Efforts to Reject Atmospheric Background

- Choose **up-going tracks** (northern sky)
  - Muons are blocked by the earth
    (ν is also attenuated at ≳50 TeV though)
- Choose **cascades** → no muon
- **Veto using the outer layer of detector**
  - Choose "starting" tracks
    - Muon rate: 10^8 -> 10^4 /year
  - Boosted decision trees
    - Use energy loss in each segment of track
    - Muon rate: 10^4 -> 1 /year
- Rejecting muon bundles

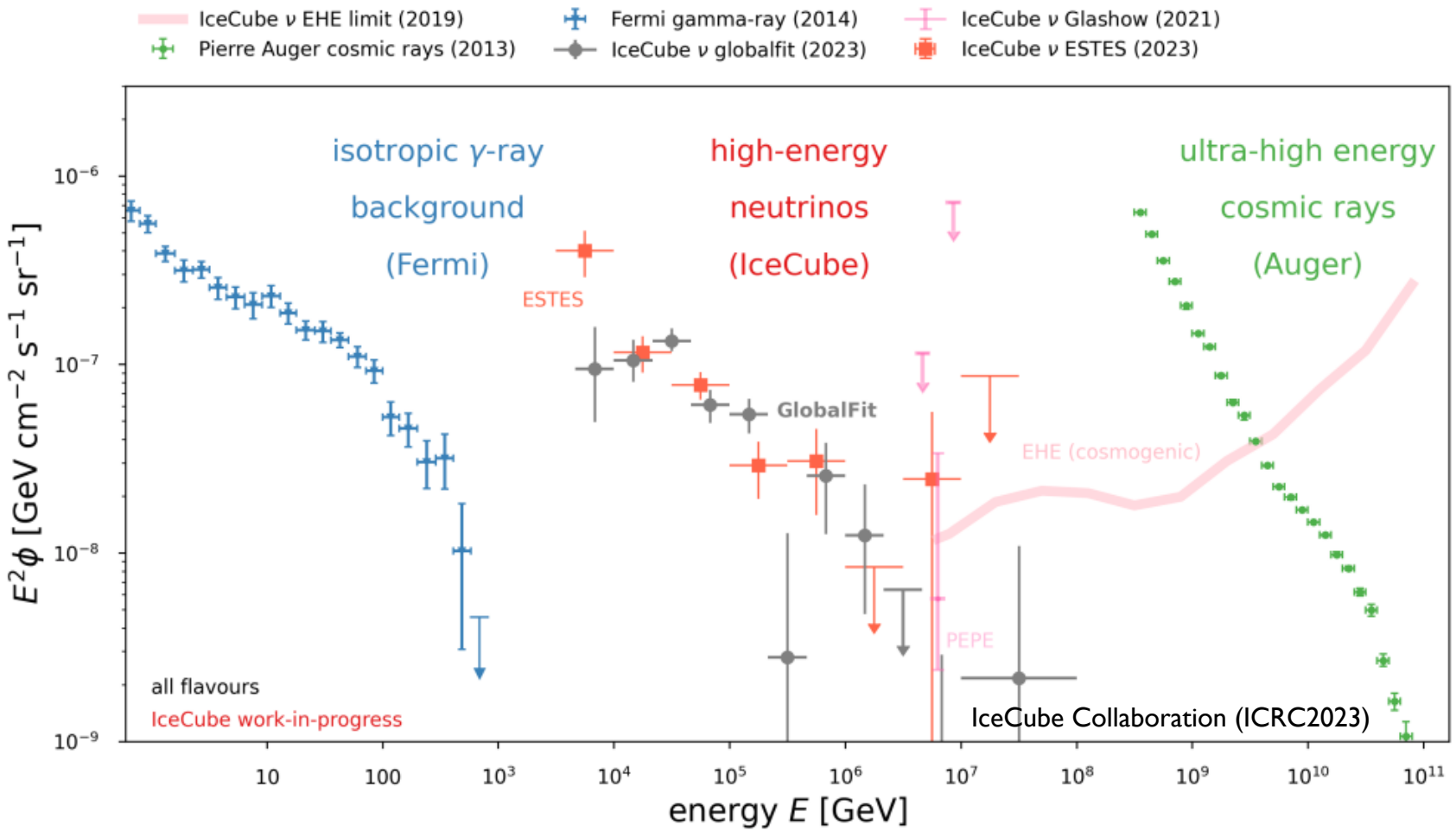


IceCube Collaboration (2019)

Recent Highlights from IceCube

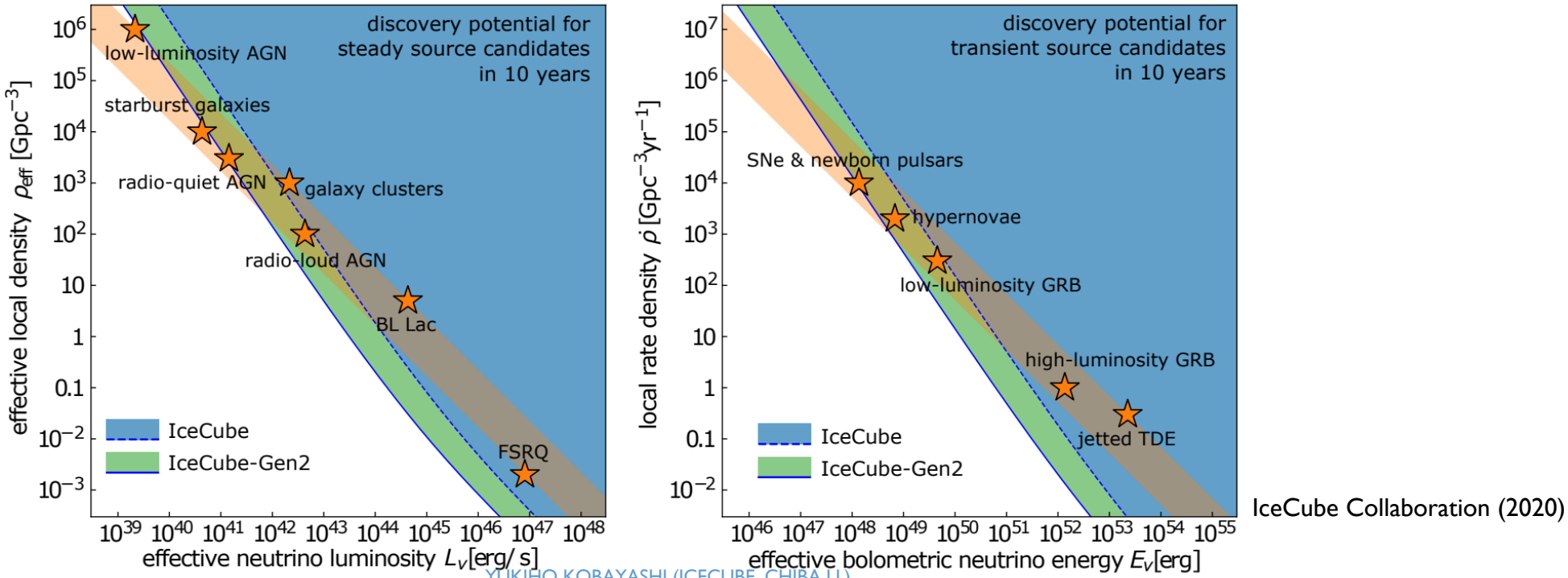
Diffuse Neutrino Flux

- Measured at TeV energies
- Using different event samples
  - GlobalFit (Cascade + Track)
  - ESTES (Starting track)
- Represented by Power-law spectrum
  - $\gamma \sim 2.6$



Origin of the Diffuse Neutrinos?

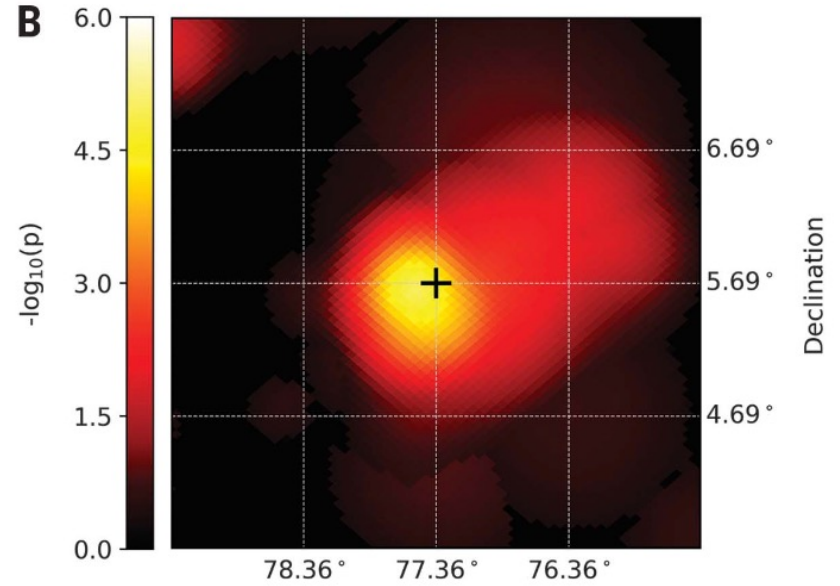
- We already know different types of sources can be contributing
  - Blazars (TXS 0506+056), Seyfert (NGC1068), Galactic Plane…
- The mystery is still to be solved (Gen-2 and multi-messenger will help)



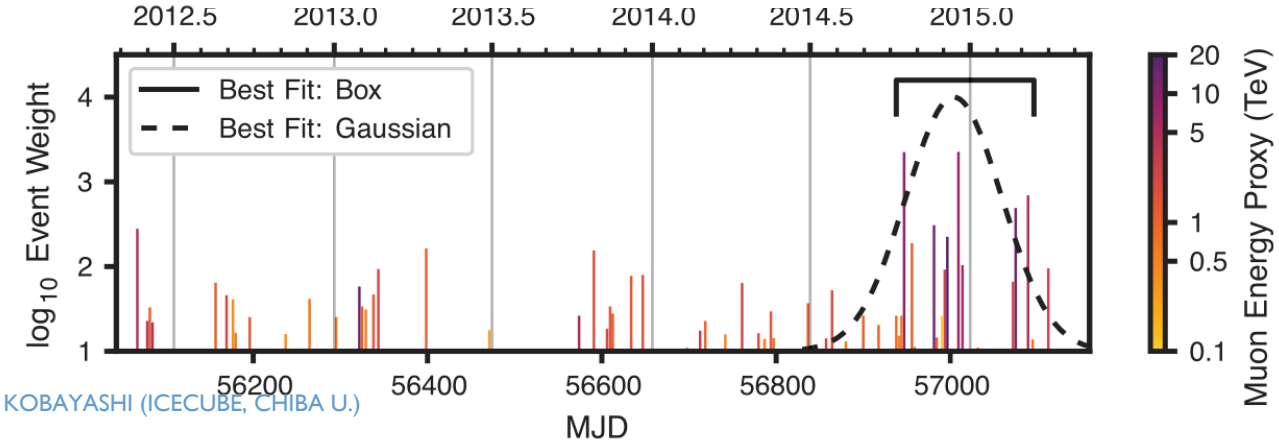
IceCube Collaboration (2020)

First High-energy ν Source: TXS 0506+056

- ~290 TeV neutrino candidate consistent with blazar TXS 0506+056 position
  - Public alert IceCube-20170922A
- **Coincident with gamma-ray flare** (Fermi, MAGIC)
  - 3σ-level coincidence
- Analyzing 9.5-year IceCube data, **3.5 σ signal** in Sep. 2014 to Mar. 2015
- Suggests blazars as high-energy cosmic-ray sources
- Dawn of MM astronomy with ν

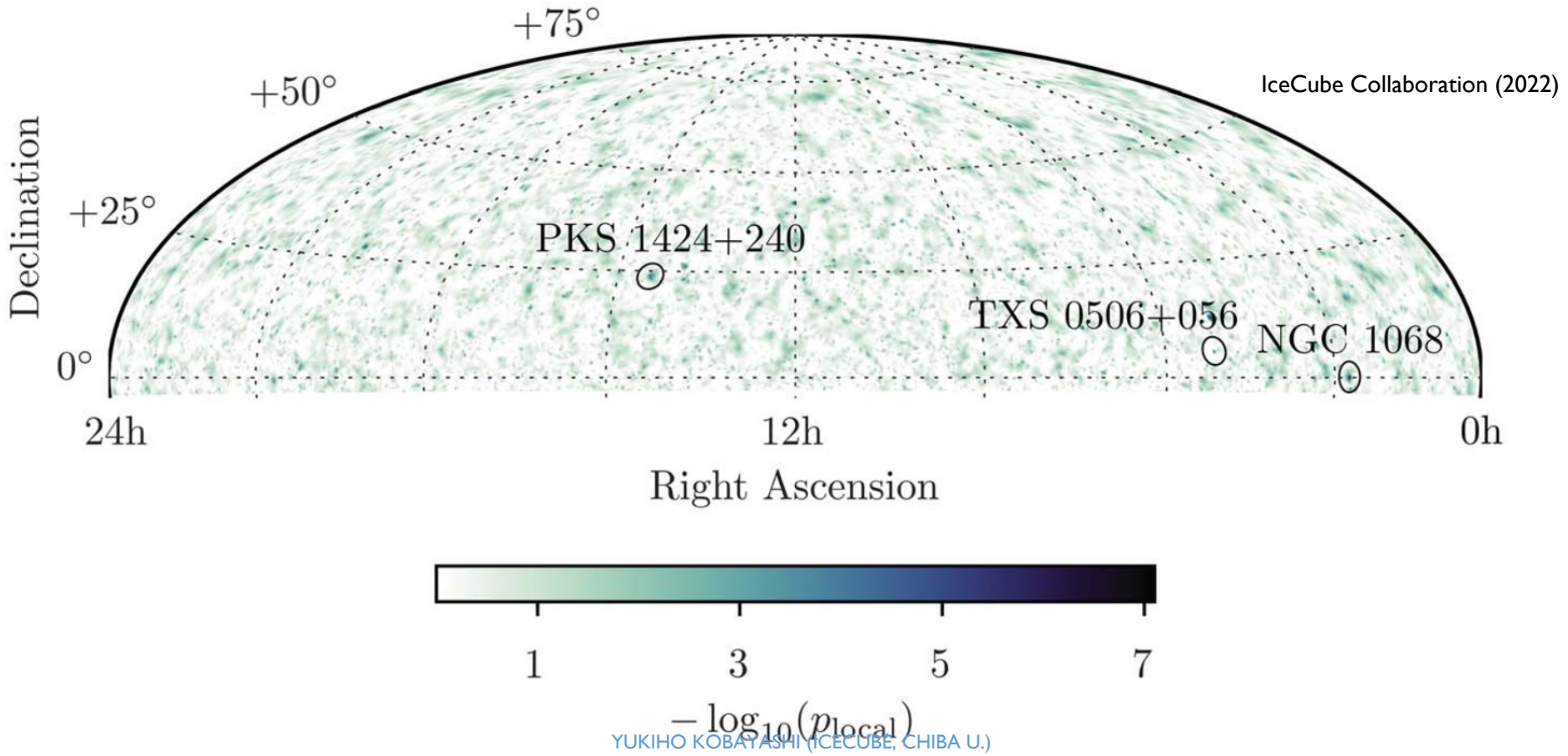


IceCube Collaboration (2018)



Neutrino (Northern) Skymap

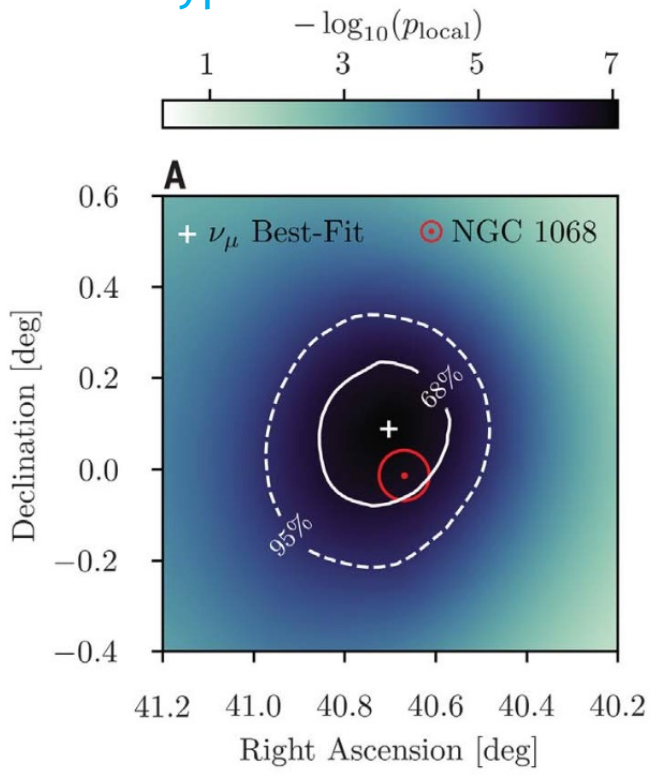
- Based on **upgoing tracks** in 10 years of IceCube data

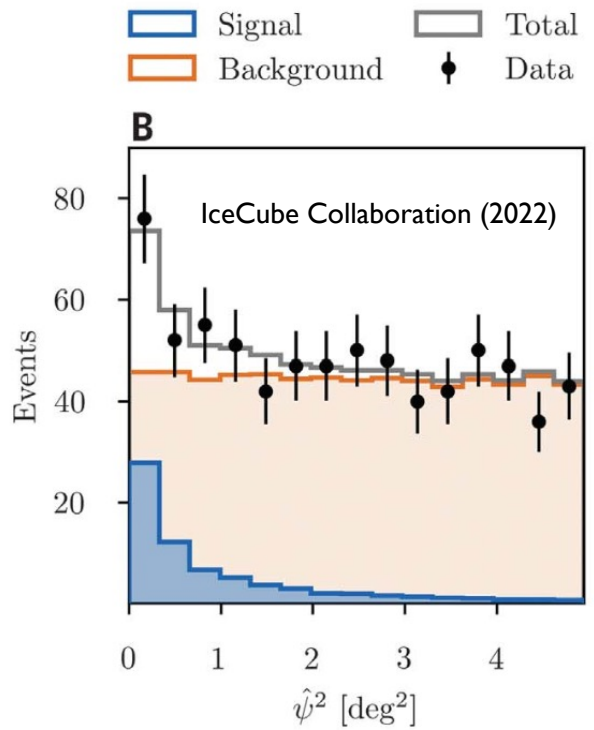


IceCube Collaboration (2022)

Steady Neutrino Emitter: NGC1068

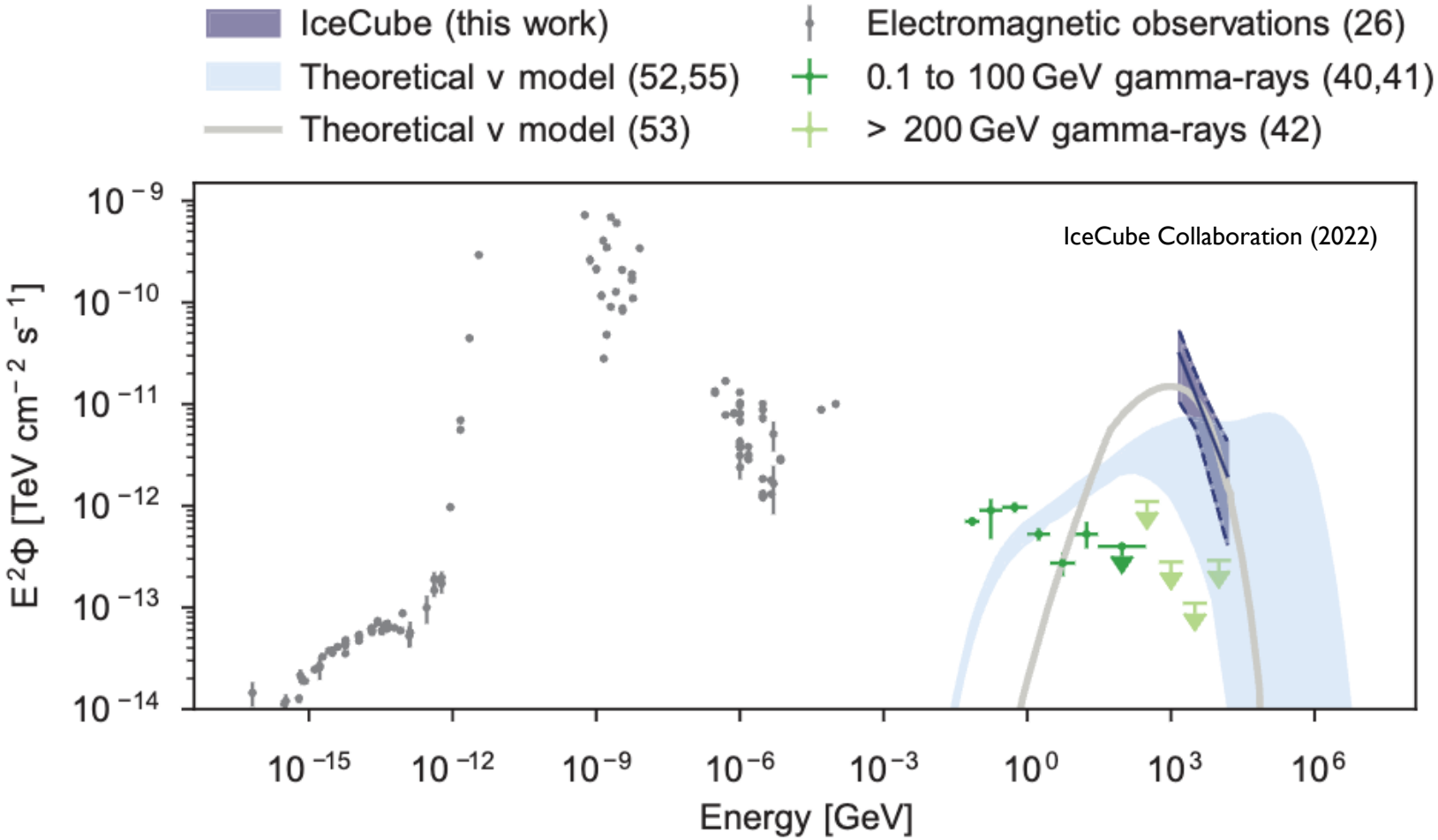
- Nearby (14.4 Mpc) Seyfert galaxy with vigorous starburst activity
- IceCube detected ~80 neutrinos (4.2σ) in 10 years
  - suggesting cosmic-ray acceleration in this type of sources





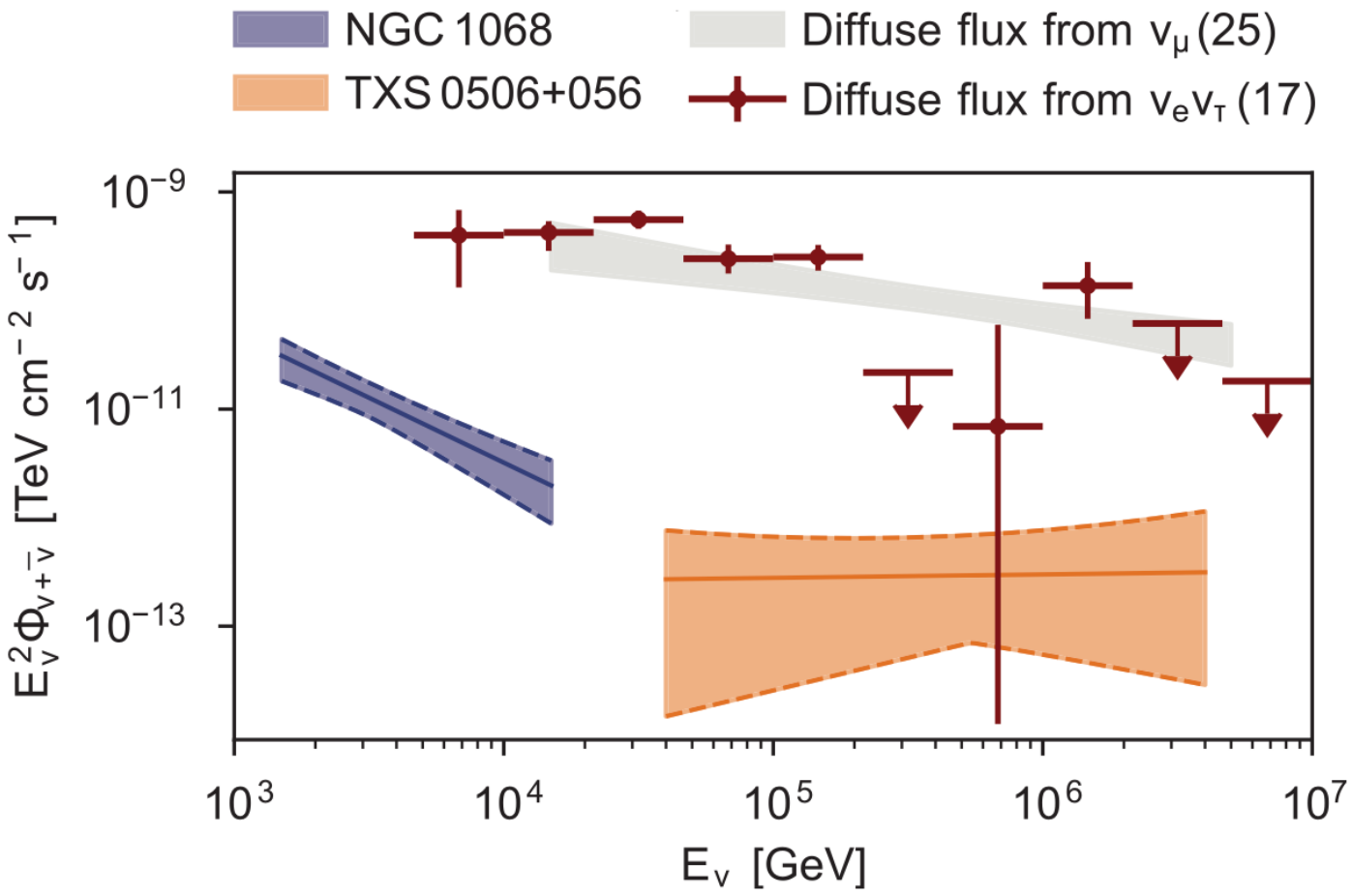
NGC1068 Spectrum

- Soft spectrum: ~$E^{-3.2}$
- Consistent spectrum with theory
  - Protons accelerated in coronae
- Neutrino brighter than gamma ray
  - Gamma rays may be absorbed by X-ray photons in coronae

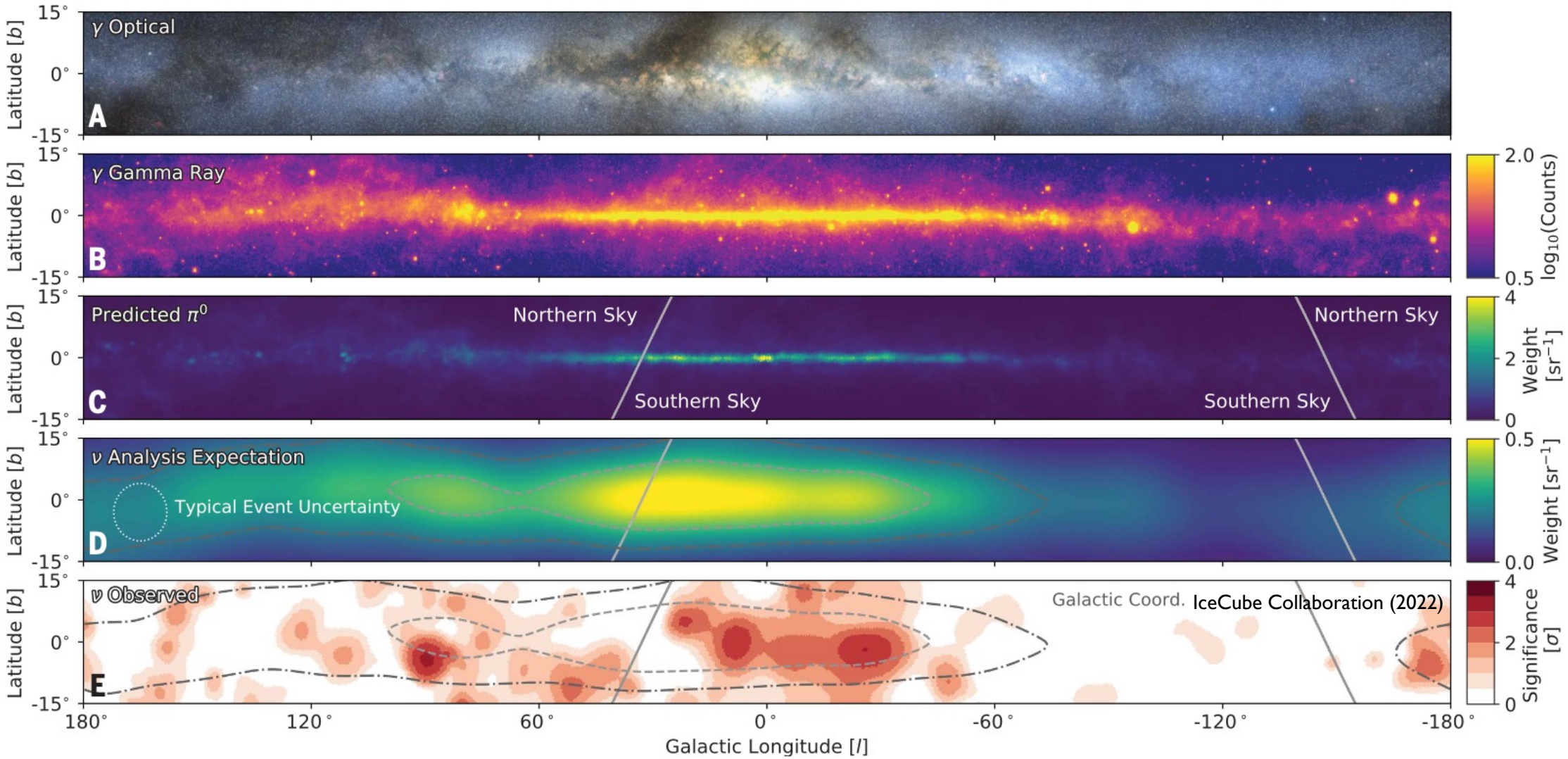


Comparison to Diffuse Flux

- ~1% contribution from each source to the diffuse flux
- Different spectra (and distances) between TXS 0506+056 and NGC 1068
  - Multiple populations (with different luminosity and density) may be contributing



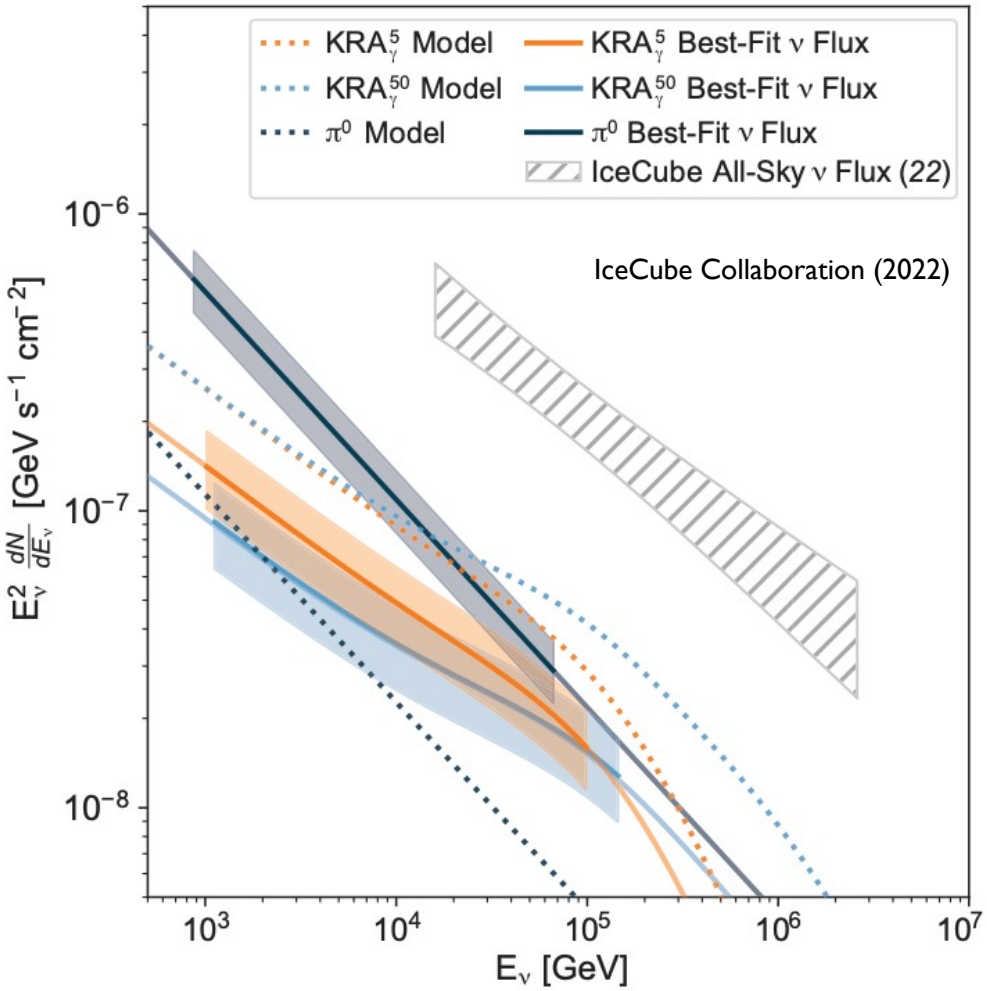
Neutrinos from Our Galaxy



IceCube Collaboration (2022)

Galactic Neutrino Search Results

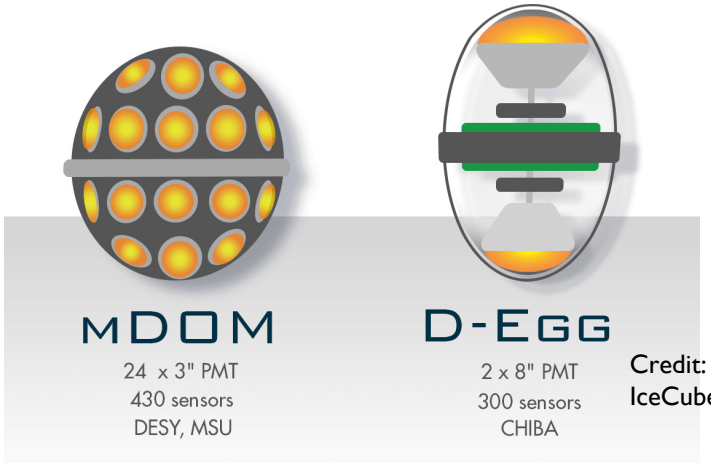
- Using **cascades** in 10 years of IceCube data
  - To see southern sky with less background
- **4.5σ detection of Galactic plane**
- Consistent with diffuse cosmic rays expected from gamma-ray observations
- ~10% contribution to diffuse flux
- Still lacking statistics to differentiate models or identify (possible) individual sources
- More work ongoing
  - Analysis with including tracks
  - Testing spatial dependence



Prospects with Coming Extensions

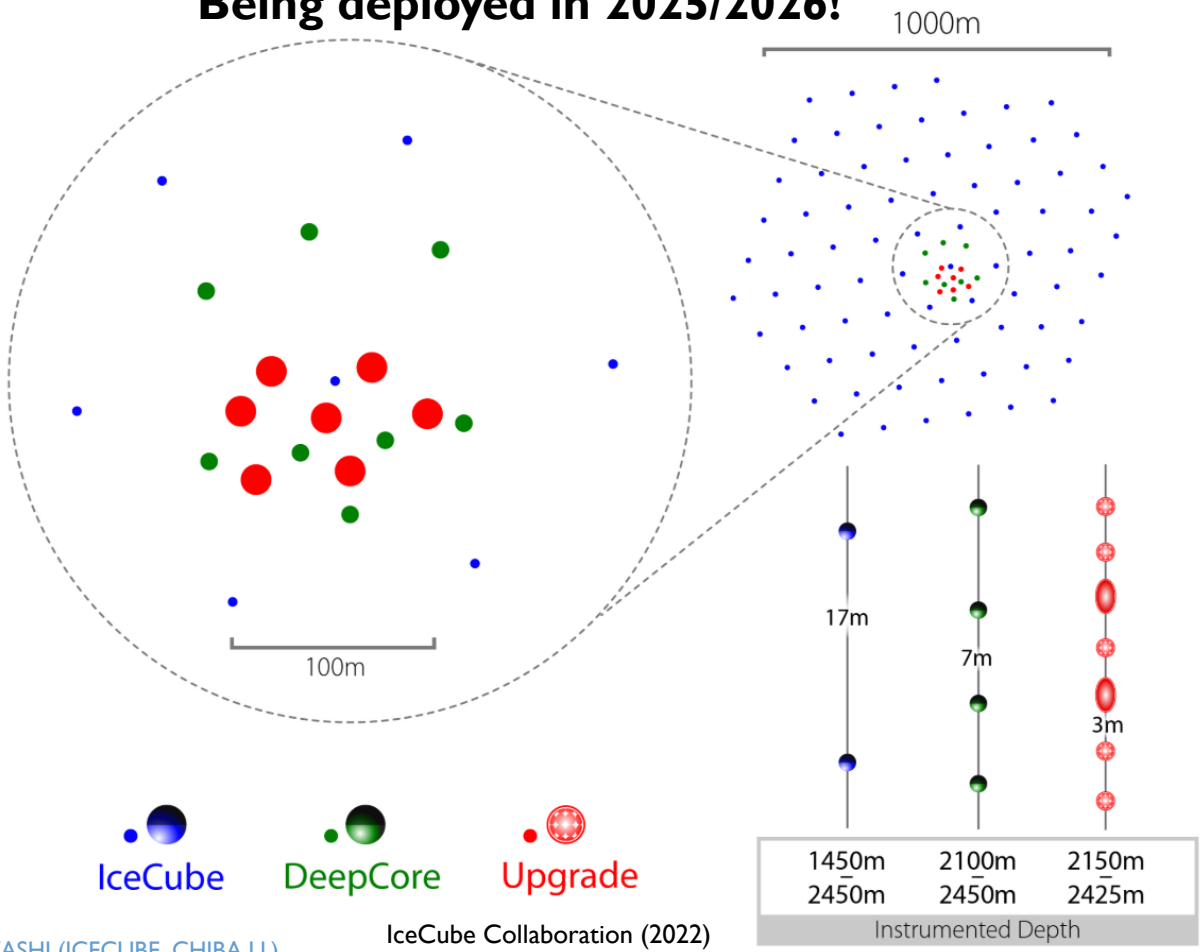
IceCube Upgrade

- **Low-energy (GeV) extension** of IceCube
  - Fiducial volume of ~2 Mt
  - Seven strings with **denser spacing**
    - ~20 m (horizontal) and ~3 m (vertical)
  - **Multi-PMT modules** for better sensitivity



Credit:
IceCube Collaboration

Being deployed in 2025/2026!

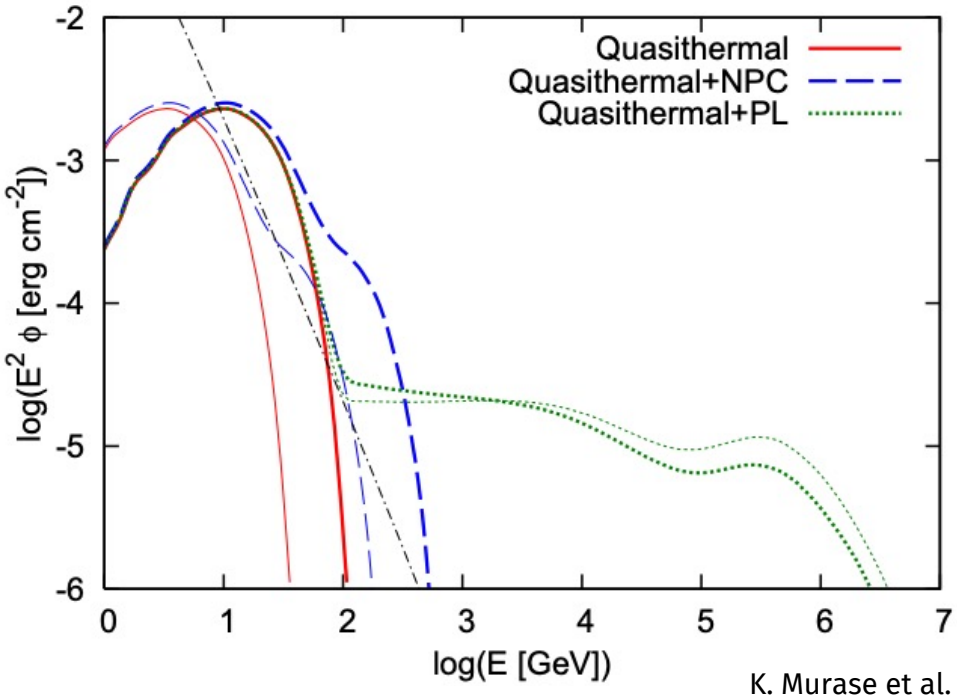


IceCube Collaboration (2022)

Quasithermal Neutrinos from GRBs/SNe

- Quasi-thermal neutrinos are predicted from **subphotospheric** outflow in GRBs/SNe
  - Arising from **neutron-proton collision**
    - Protons colliding with decoupled neutrons
    - **No need for shock acceleration**
  - Can be uniquely probed by neutrinos
    - Test subphotospheric scenario of GRB emission
    - Constrain baryon loading
  - **E_ν ~150 GeV** $\left(\frac{\Gamma}{500}\right)\left(\frac{\Gamma_{\rm rel}}{3}\right)$
    - Low-energy extension of IceCube is crucial!

LLGRB (E=10^{50} erg, d=10 Mpc)

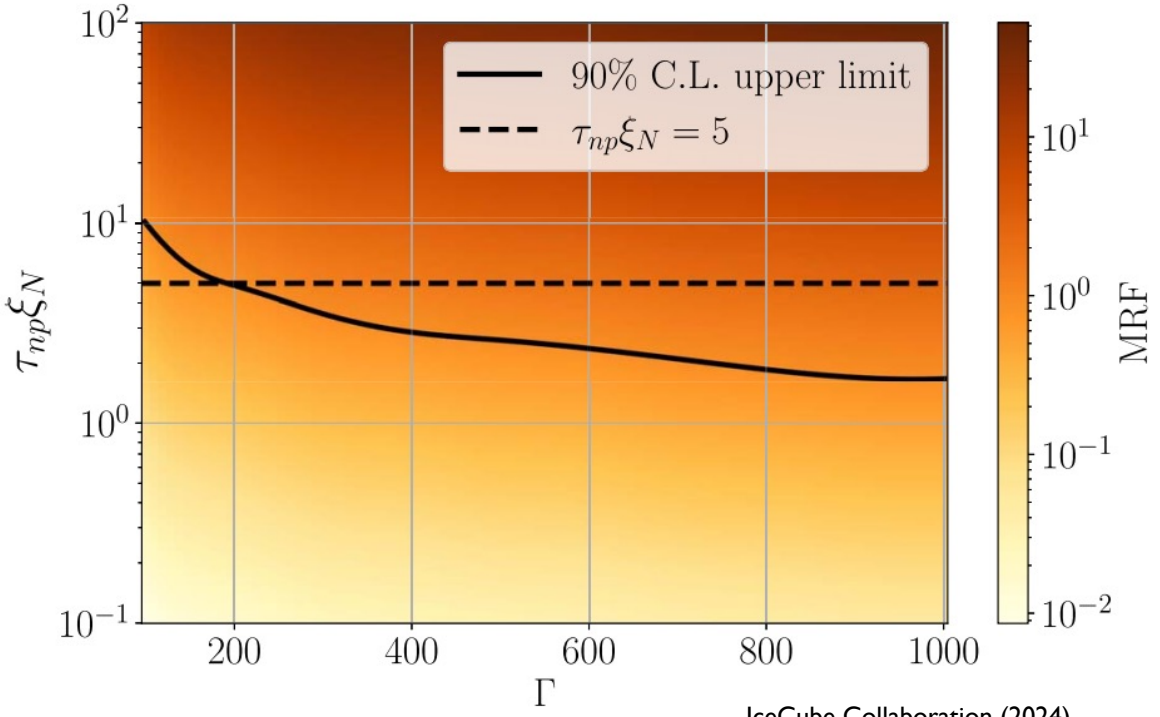


K. Murase et al. (2013)

Search with IceCube + DeepCore

- Analyzed the BOAT GRB + ~2300 stucked GRBs in IceCube + DeepCore data
- No significant detection
- Constraint on baryon loading

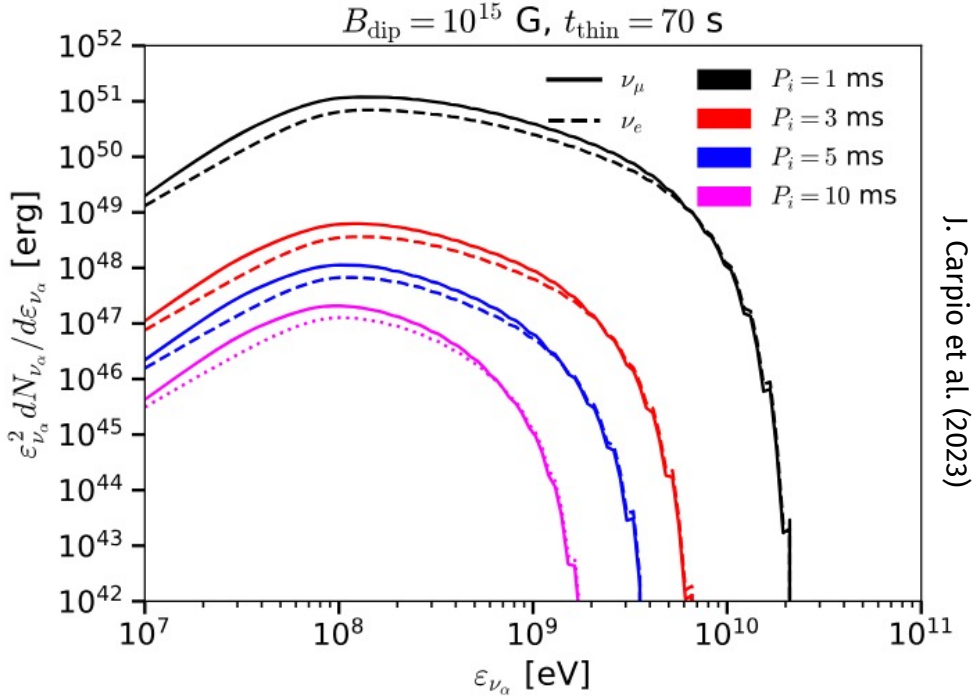
- Sensitivity will be improved by including Upgrade
  - Especially at low energies $\lesssim$ 10 GeV
  - Corresponding to $\Gamma \lesssim 100$
    - **Low-luminosity GRBs?**



IceCube Collaboration (2024)

Quasithermal ν from SNe

- Quasithermal neutrinos can arise from a core-collapse SNe, if a rotating and magnetized proto neutron star (PNS) is formed
  - Relativistic magnetized outflow accelerates neutrons, coupled with ions
  - Decoupled neutrons collide with decelerated ions at shock → π production
- 0.1 – 10 GeV neutrinos
  - Uniquely accessed by Upgrade (and HK)
- Neutrino production time scale $\lesssim$ 100 s
  - Almost background-free observation

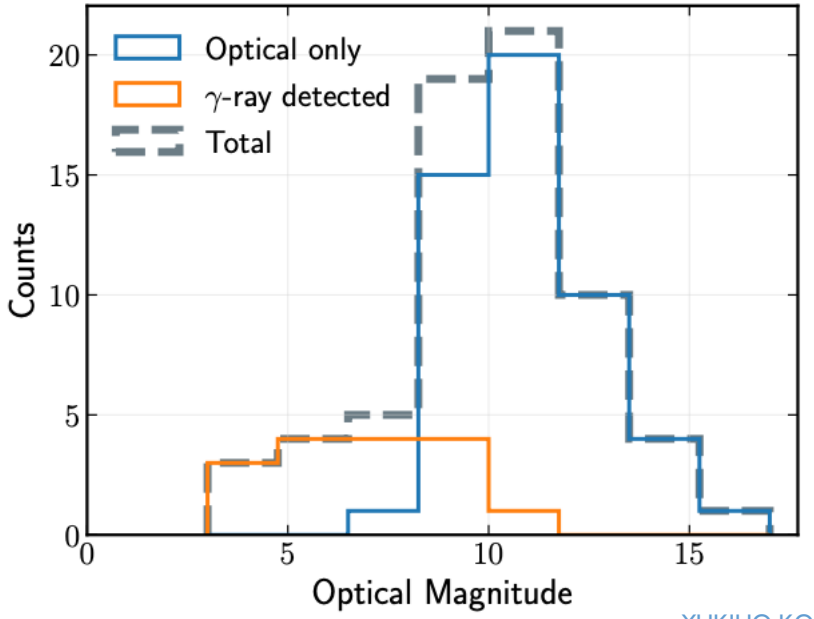


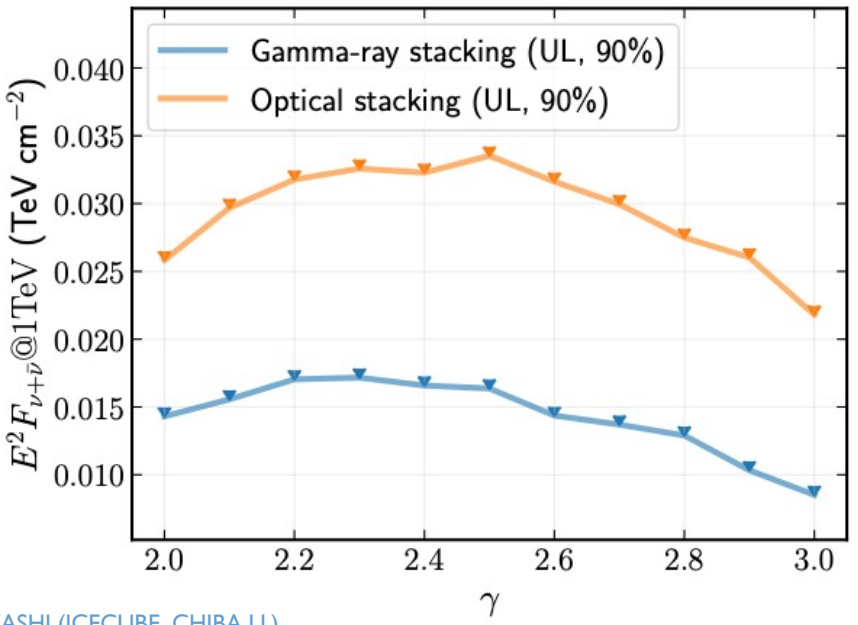
Novae

- Close binaries with a white dwarf accreting from its companion star
- Luminous eruptions caused by thermonuclear runaway
  - Some are recurrent
- Gamma-ray detection from >20 Galactic novae by Fermi-LAT
- In 2021, RS Oph was detected by MAGIC, H.E.S.S. and LST-1
  - Suggests hadronic origin of gamma rays
- Time evolution over days to months
  - Best laboratory to test shock acceleration

Novae search with IceCube+DeepCore

- Neutrinos from novae are searched
- Both individual search (got gamma-ray detected novae) and stucking analysis
- No significant detection. Placing upper limits.

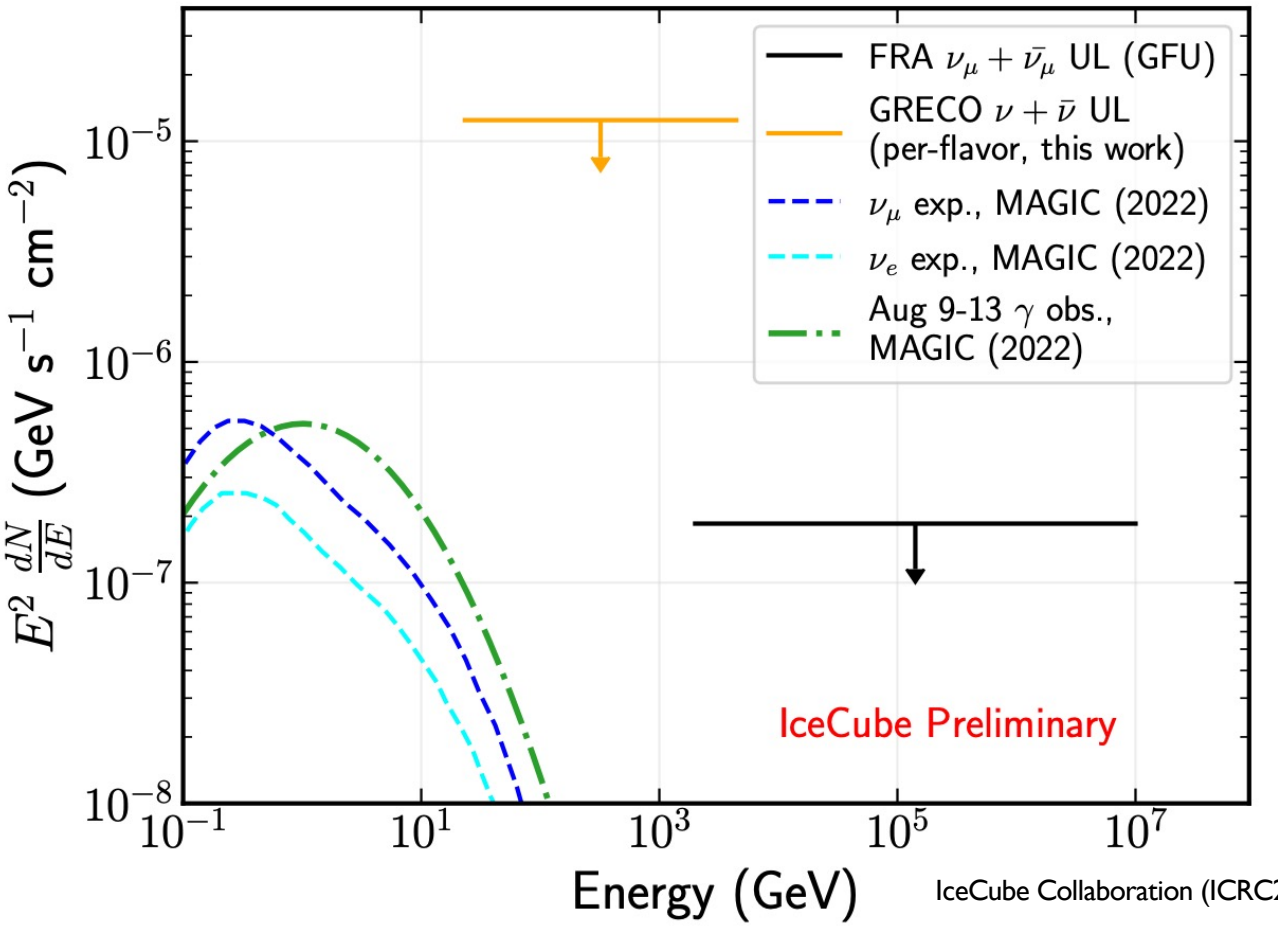




IceCube Collaboration (2024)

RS Oph

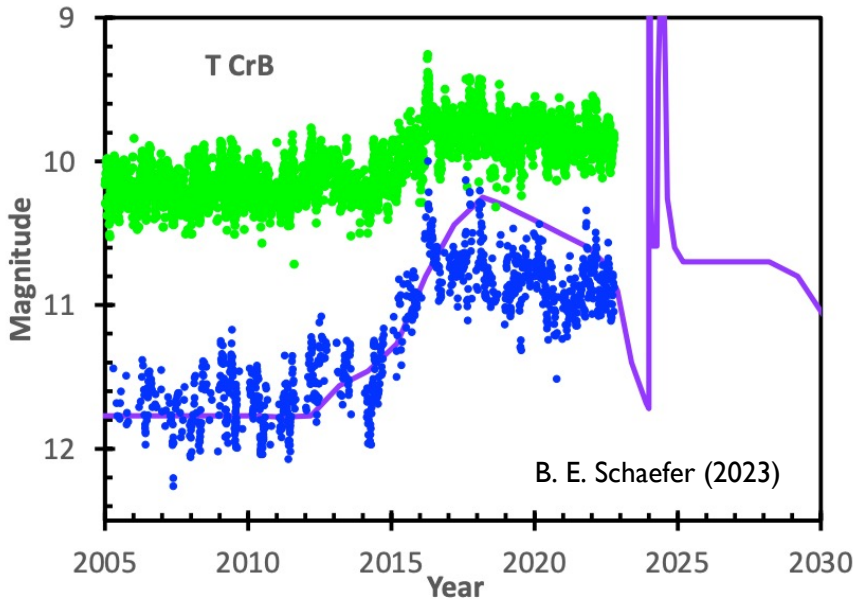
- Best-known recurrent nova
- ~15 years recurrence period
- 2021 outburst was was detected by MAGIC, H.E.S.S. and LST-1
  - Gamma-ray energy up to ~ 1 TeV
  - Suggests hadronic origin of gamma rays
- IceCube non-detection
  - fast response analysis (FRA)
    - Published on ATel
  - DeepCore (GRECO)
    - Reported at ICRC2023

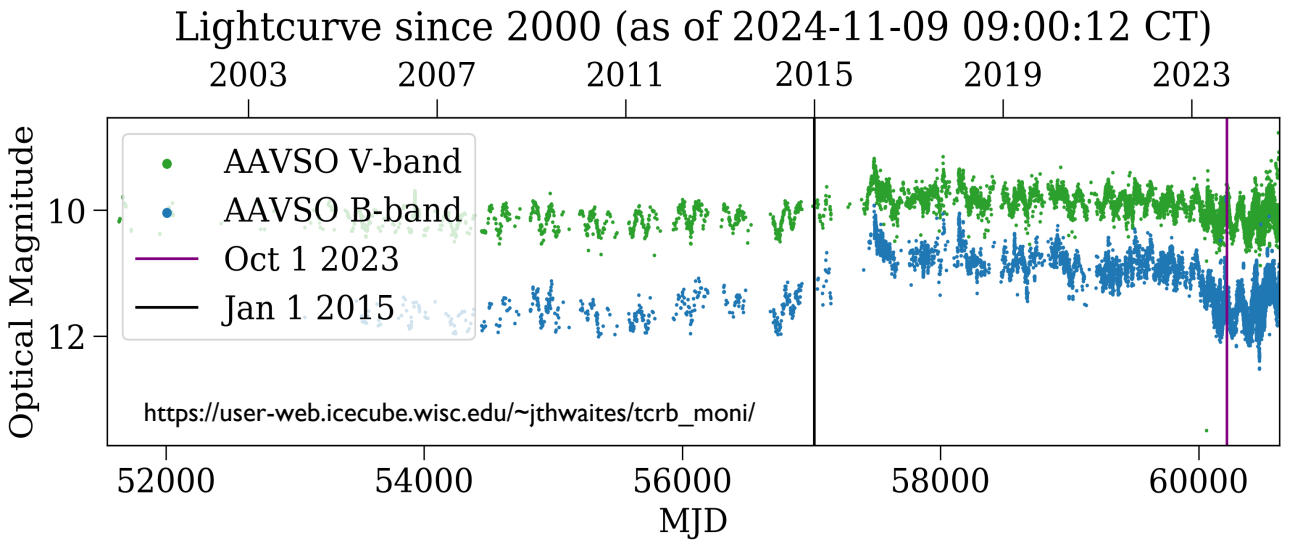


IceCube Collaboration (ICRC2023)

T Coronae Borealis (T CrB)

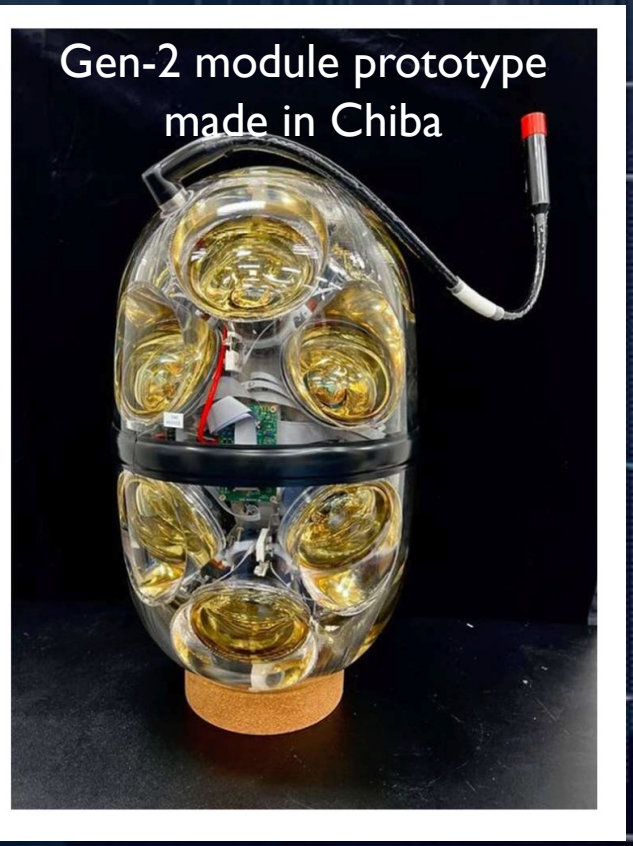
- A brighter (and closer) nova T CrB is coming soon
  - ~80 year period recurrent nova with two outbursts observed in the past (in 1866 and 1946)
  - Eruption predicted at 2025.5±1.3 and 2024.4±0.3. Can erupt any time soon!
  - Close to earth (~0.8 kpc) and in northern sky. The best target for IceCube (Upgrade)
    - Scaling by distance, ~can be ~10 times brighter than RS Oph





Further Expansion: IceCube-Gen2

- **Eight times larger** than the current IceCube. Aiming to complete by 2033
- Explore cosmic-ray accelerators in TeV-EeV energies (**five times better sensitivity**)



- **New module is being developed/tested at Chiba**

Credit: DESY, Science Communication Lab

Summary

- Neutrino is a crucial messenger from high-energy universe
- IceCube is a world-leading experiment to measure high-energy astrophysical neutrinos
- More and more neutrino sources are being detected
  - Diffuse flux, TXS 0506+056, NGC1068, Galactic Plane
- IceCube **Upgrade (GeV extension) is coming in 2025/2026**
  - Sensitivity improvement in GeV energy range
  - Best detector to search for GeV neutrino transients: GRBs, Sne/PNS, Novae
  - Not easy, but **"Chance favors the prepared mind"**
- TeV-PeV sensitivity will be improved by Gen-2
  - Hardware Development is intensively ongoing including at Chiba