

# High-energy neutrino observations with IceCube

Nahee Park  
for the IceCube collaboration

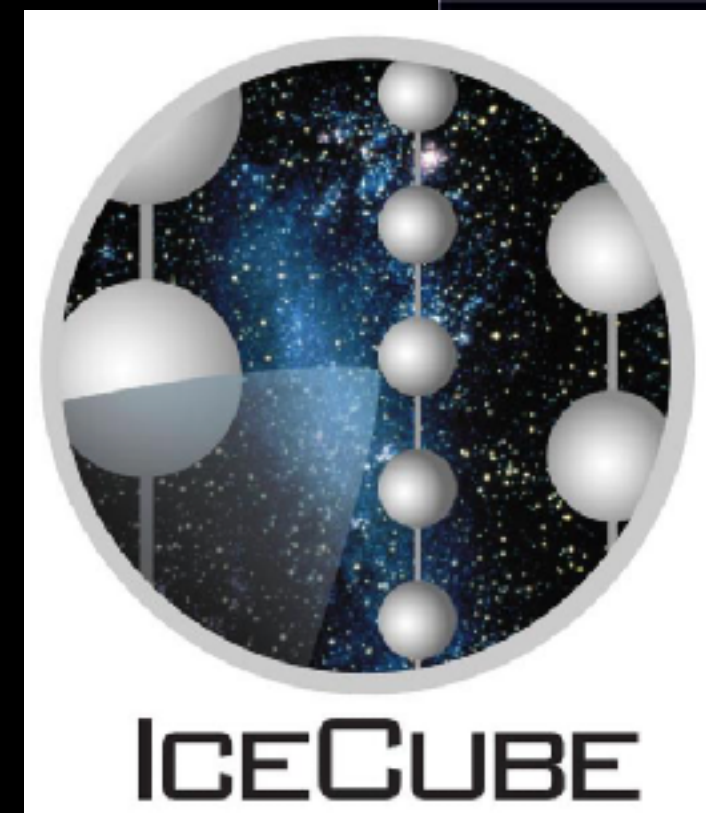
**NEUTRINO 2022**

XXX International Conference on Neutrino Physics and Astrophysics



**Queen's**  
UNIVERSITY






# More than 300 people from 56 institutions in 14 countries

 **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

 **ITALY**  
University of Padova

 **JAPAN**  
Chiba University

 **NEW ZEALAND**  
University of Canterbury

 **SOUTH KOREA**  
Sungkyunkwan University

 **SWEDEN**  
Stockholms universitet  
Uppsala universitet

 **SWITZERLAND**  
Université de Genève

 **TAIWAN**  
Academia Sinica

 **UNITED KINGDOM**  
University of Oxford

 **UNITED STATES**  
Clark Atlanta University  
Drexel University  
Georgia Institute of Technology  
Harvard University  
Lawrence Berkeley National Lab  
Loyola University Chicago  
Marquette University  
Massachusetts Institute of Technology  
Mercer University  
Michigan State University

Ohio State University  
Pennsylvania State University  
South Dakota School of Mines  
and Technology  
Southern University  
and A&M College  
Stony Brook University  
University of Alabama  
University of Alaska Anchorage  
University of California, Berkeley  
University of California, Irvine  
University of Delaware  
University of Kansas

University of Maryland  
University of Rochester  
University of Texas at Arlington  
University of Utah  
University of Wisconsin–Madison  
University of Wisconsin–River Falls  
Yale University

## THE ICECUBE COLLABORATION

### FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)  
Fonds Wetenschappelijk Onderzoek-Vlaanderen  
(FWO-Vlaanderen)

Federal Ministry of Education and Research (BMBF)  
German Research Foundation (DFG)  
Deutsches Elektronen-Synchrotron (DESY)

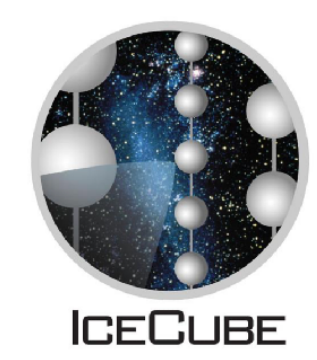
Japan Society for the Promotion of Science (JSPS)  
Knut and Alice Wallenberg Foundation  
Swedish Polar Research Secretariat

The Swedish Research Council (VR)  
University of Wisconsin Alumni Research Foundation (WARF)  
US National Science Foundation (NSF)

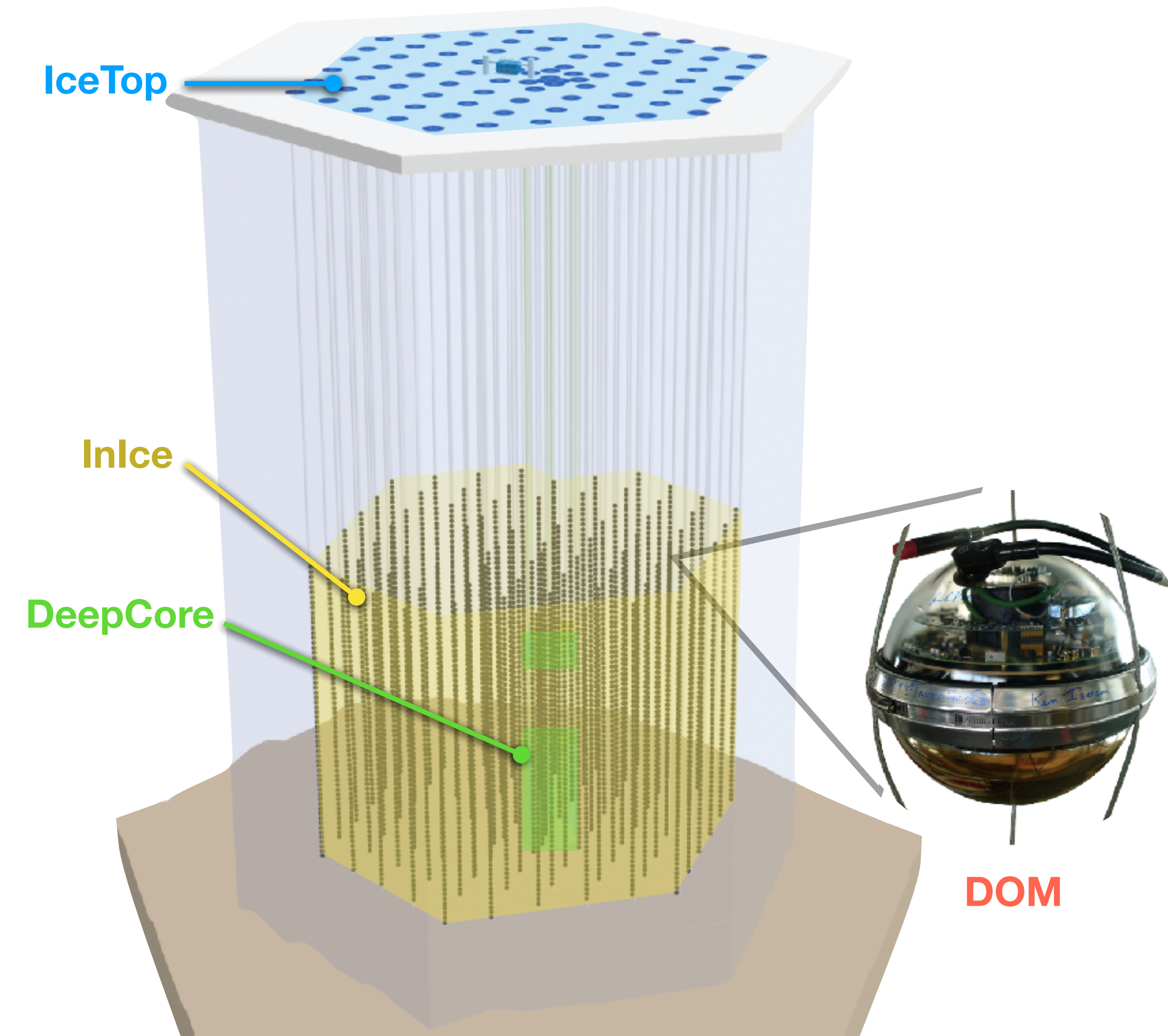


[icecube.wisc.edu](http://icecube.wisc.edu)





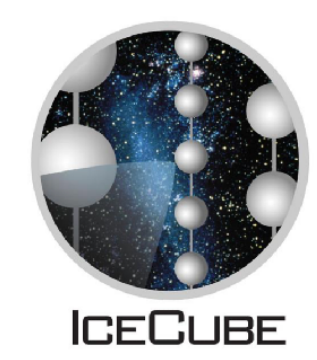
# The IceCube Neutrino Observatory



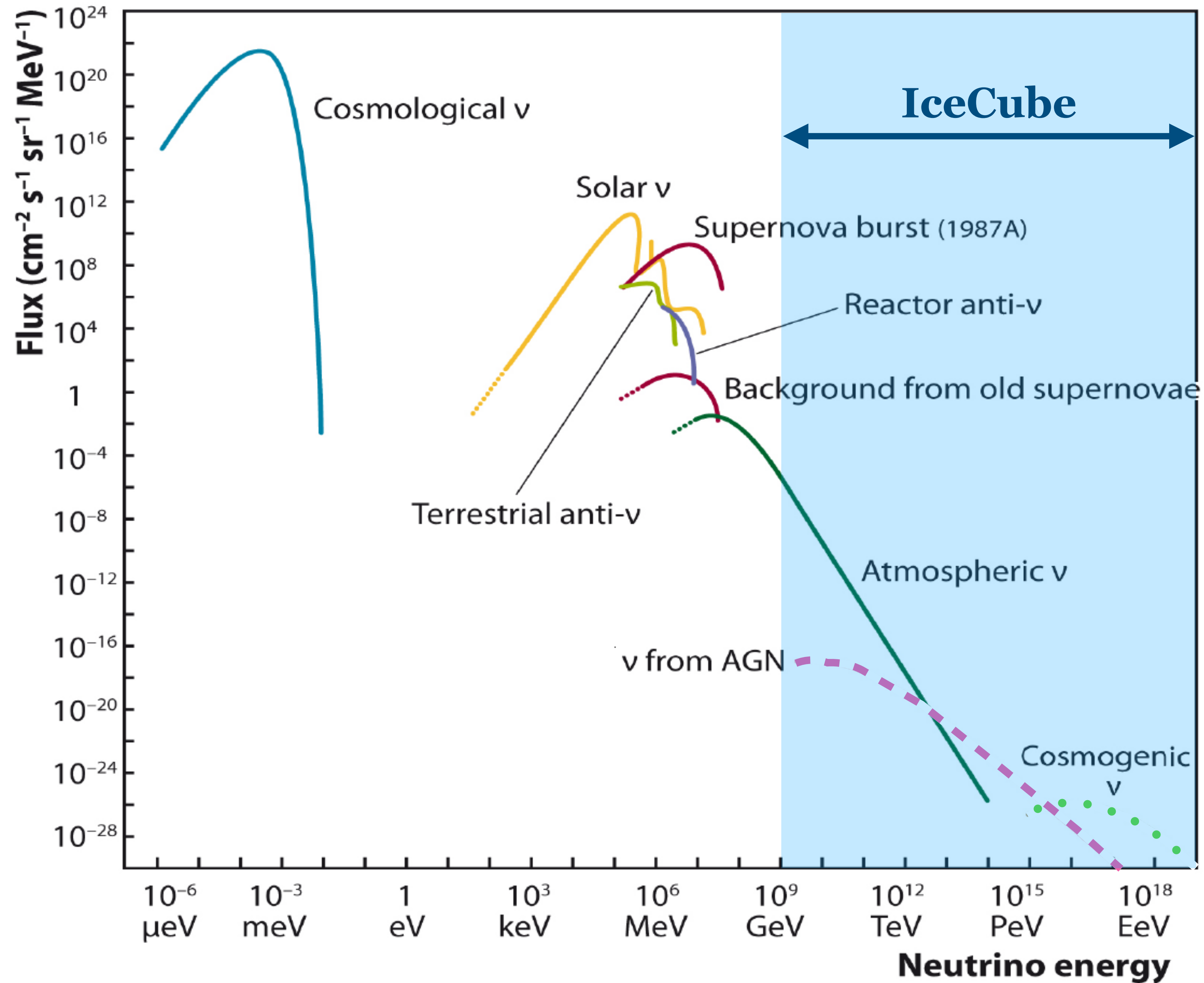
- First km<sup>3</sup> -scale neutrino detector
- 5160 digital optical modules (DOMs) deployed at depths between  $\sim 1.5$ -2.5 km
- Denser in-fill for O(10) GeV neutrinos (DeepCore)
- Surface air shower array (IceTop)
- Construction finished in Dec 2010







# Neutrino Measurements of IceCube

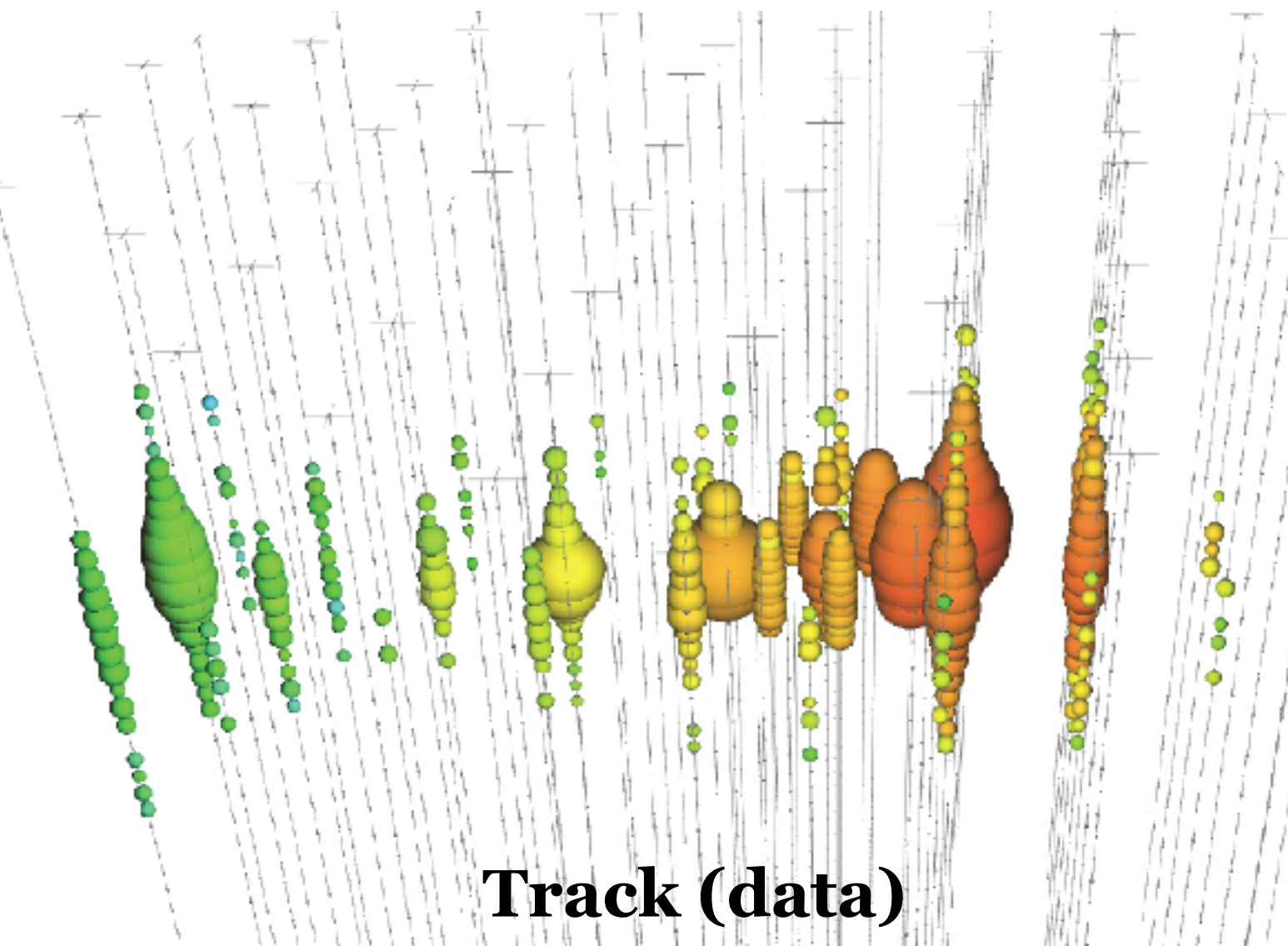




# Event Morphology

## Track

CC  $\nu_\mu$  interactions



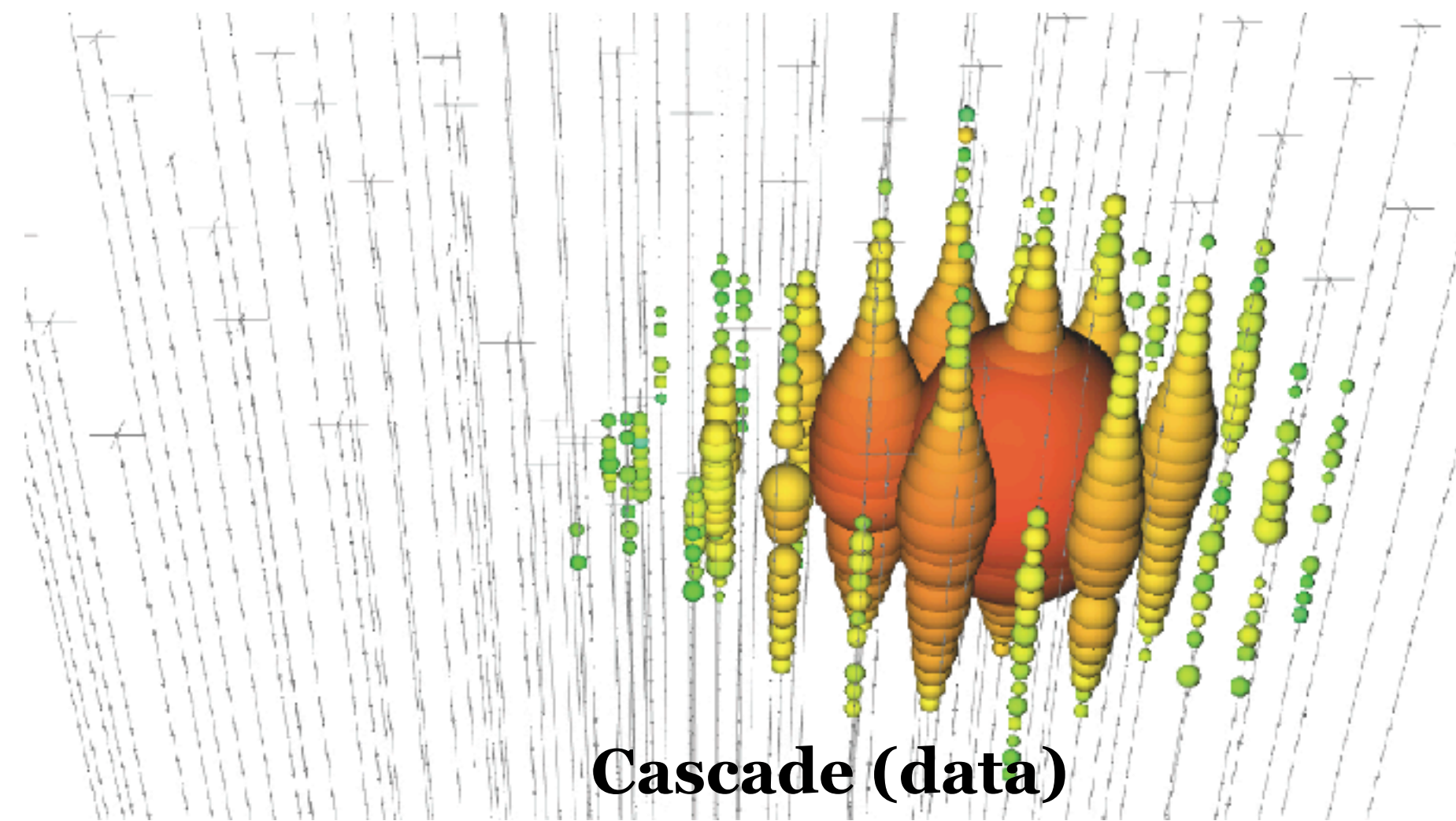
Angular resolution  $\sim 0.2 \sim 1^\circ$   
Energy resolution  $\sim$  factor of 2

## Cascade

NC interactions

CC  $\nu_e$  interactions

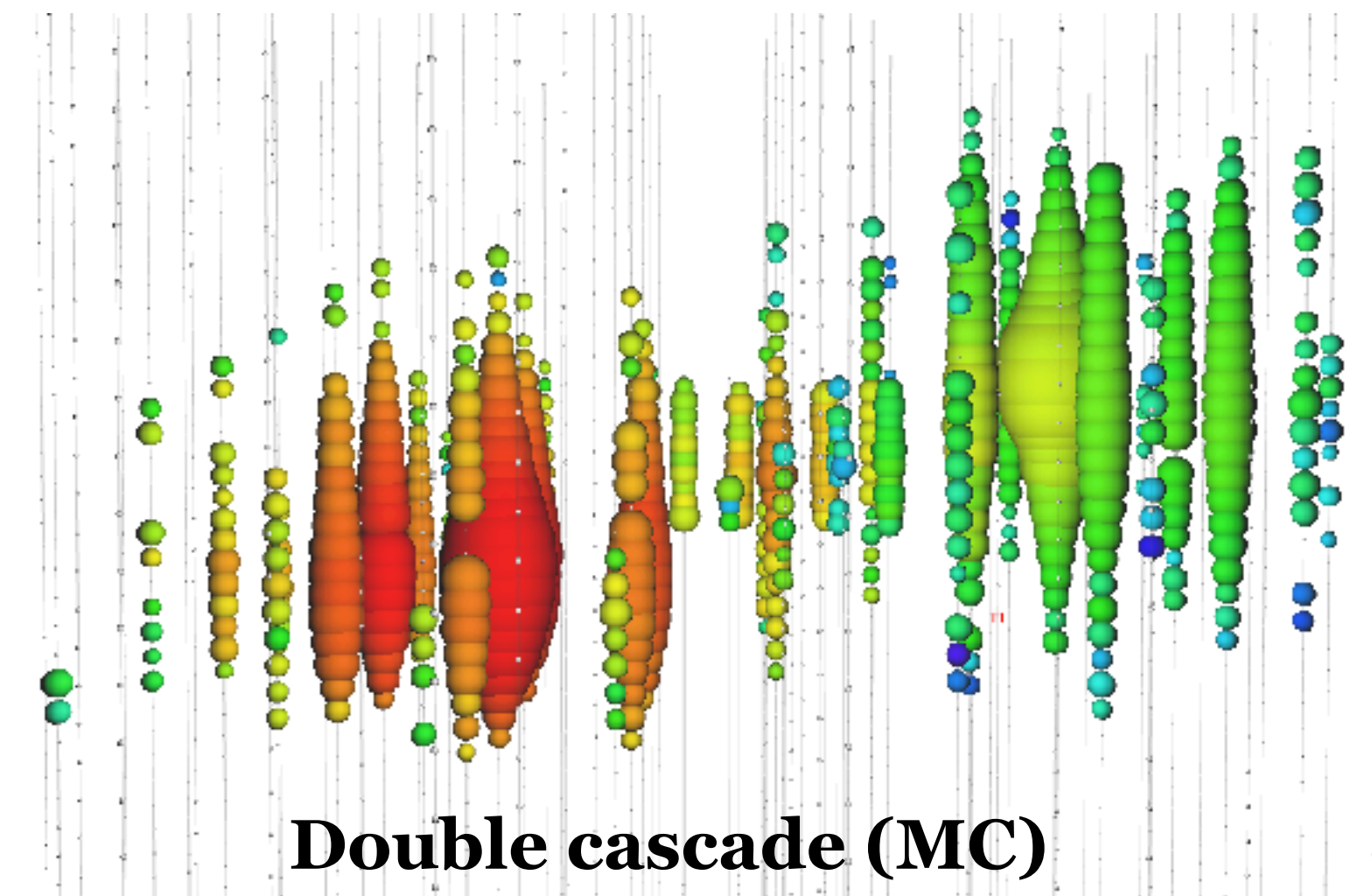
Most of CC  $\nu_\tau$  interactions



Angular resolution  $\sim 10^\circ$   
Energy resolution  $\sim 15\%$  ( $>100$  TeV)

## Double Cascade

CC  $\nu_\tau$  interactions



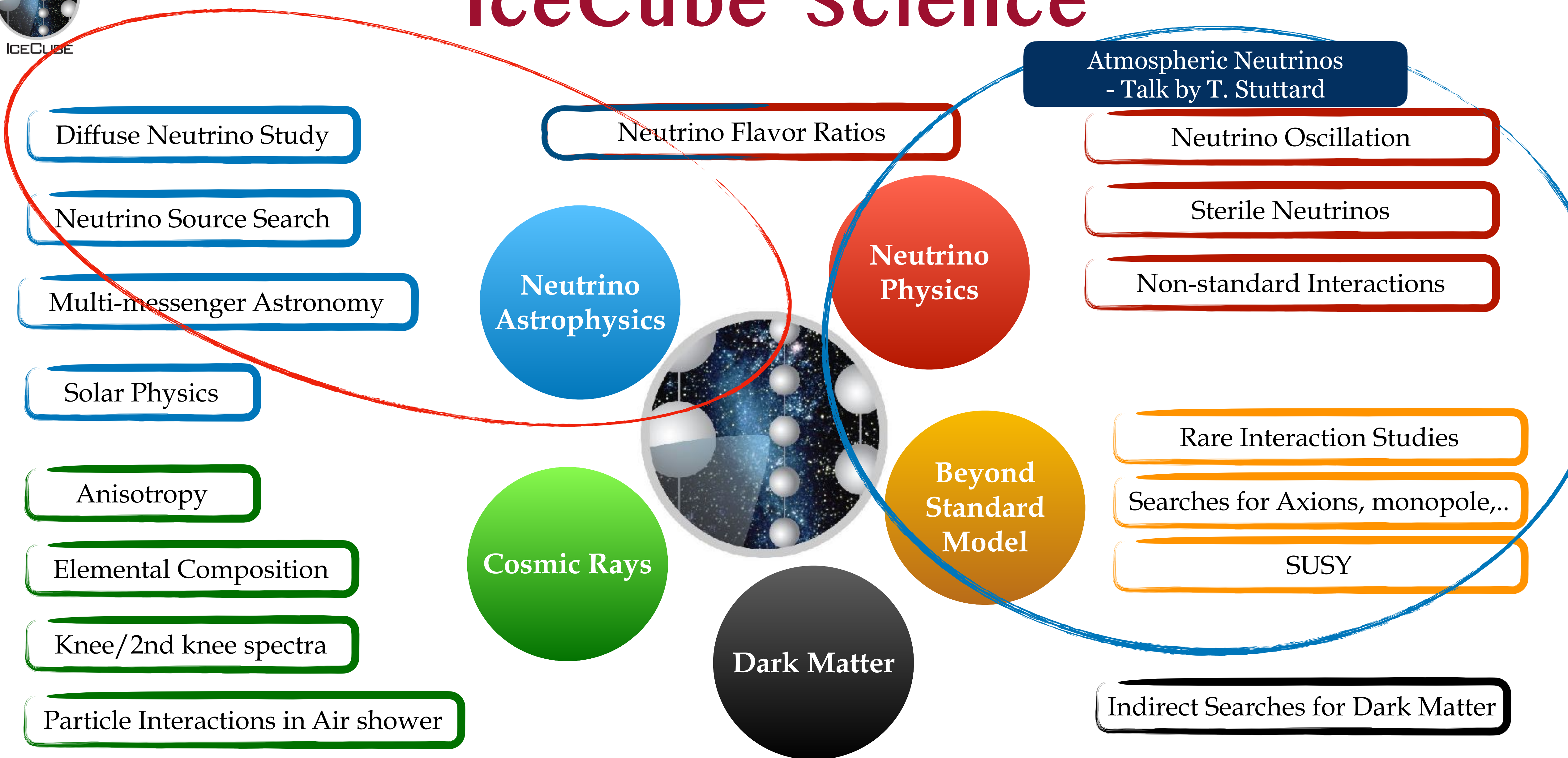
Resolvable above 100 TeV  
deposited energy

Earlier  Later



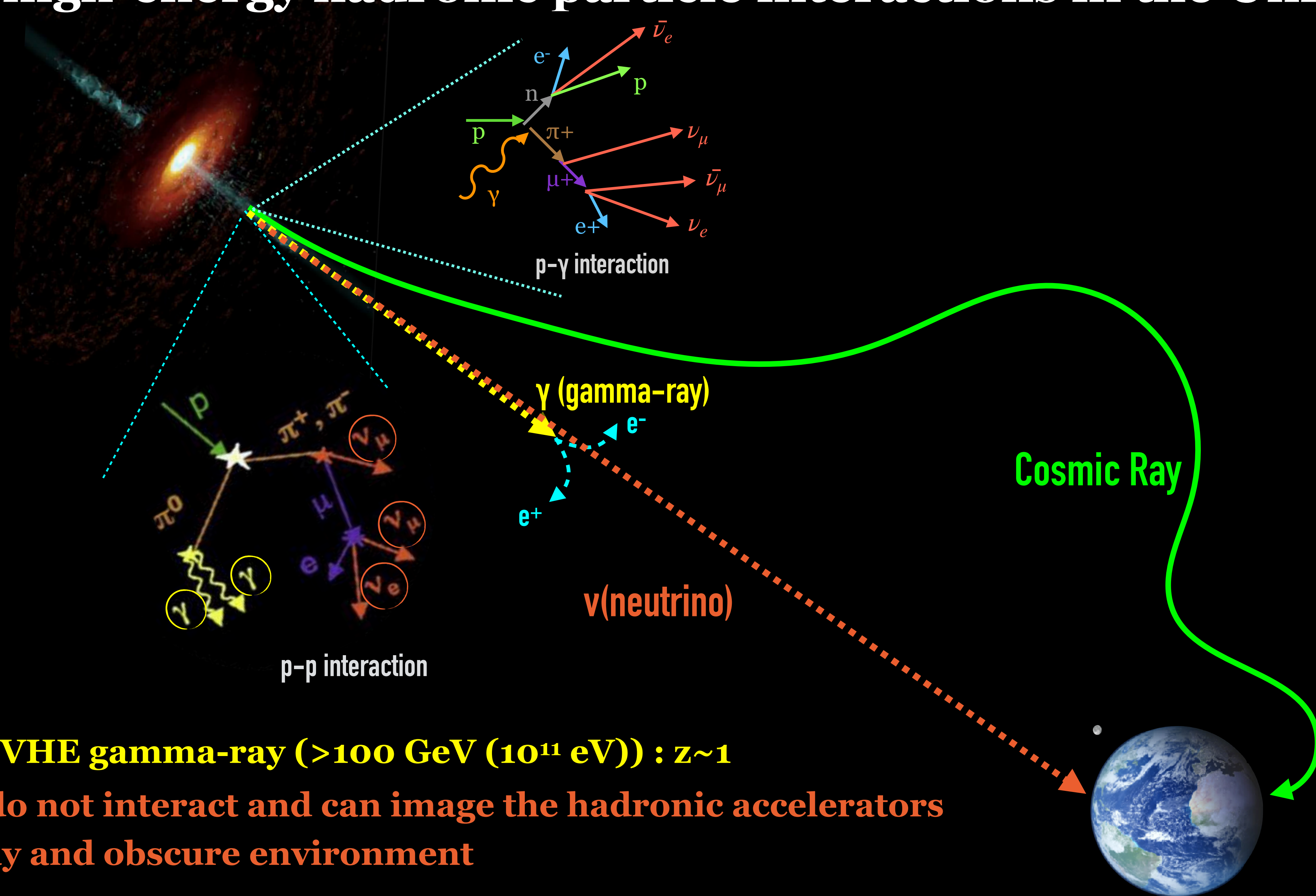


# IceCube Science





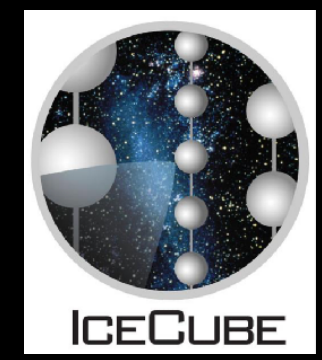
# Neutrino is the best messenger to study the high-energy hadronic particle interactions in the Universe



**Horizon of VHE gamma-ray ( $>100$  GeV ( $10^{11}$  eV)) :  $z \sim 1$**

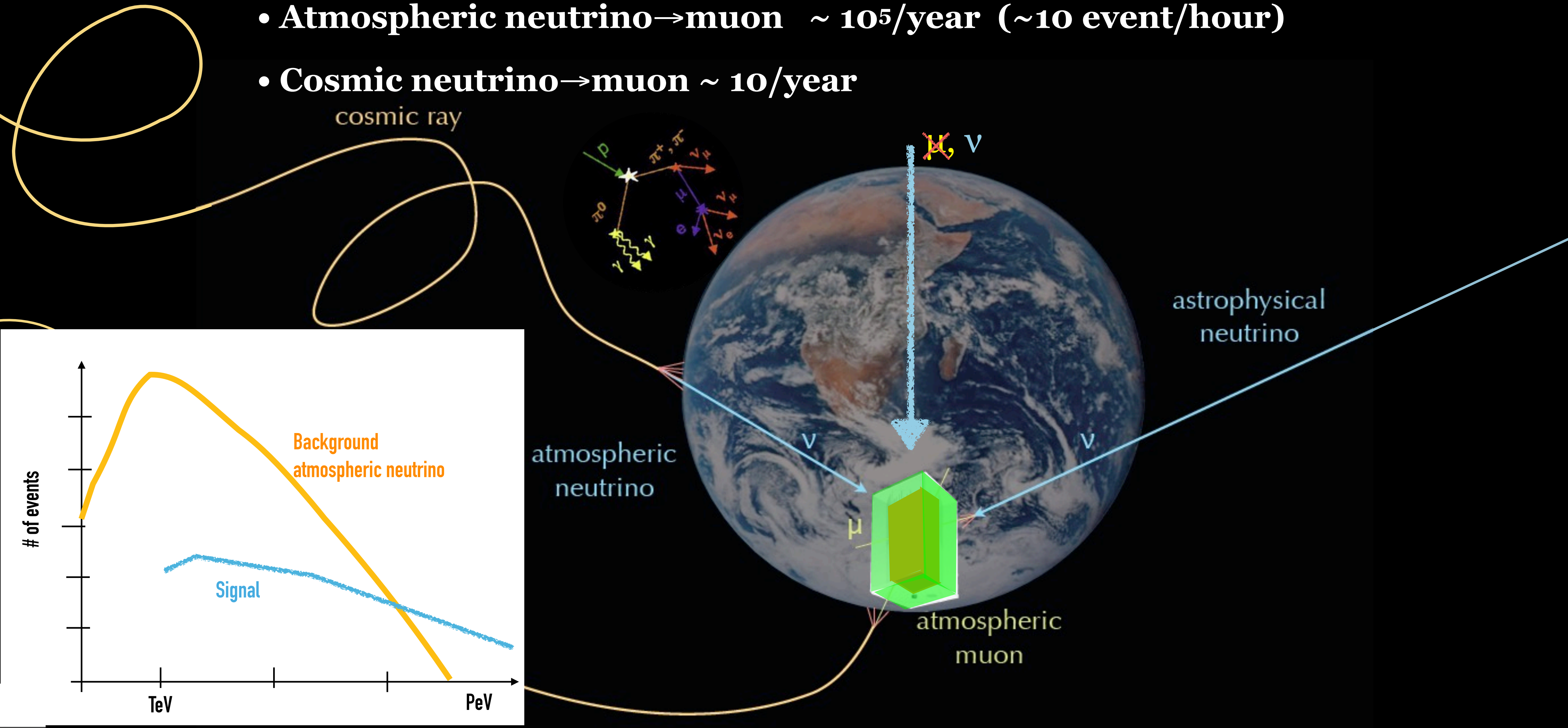
**Neutrinos do not interact and can image the hadronic accelerators farther away and obscure environment**



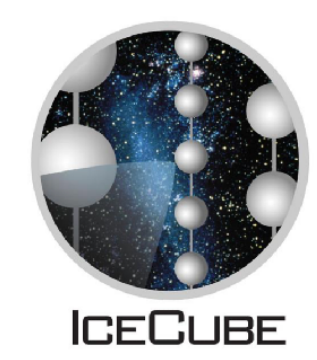


# Signal & Background

- Atmospheric muon  $\sim 10^{11}/\text{year}$  ( $\sim 3000$  events/second)
- Atmospheric neutrino  $\rightarrow$  muon  $\sim 10^5/\text{year}$  ( $\sim 10$  event/hour)
- Cosmic neutrino  $\rightarrow$  muon  $\sim 10/\text{year}$

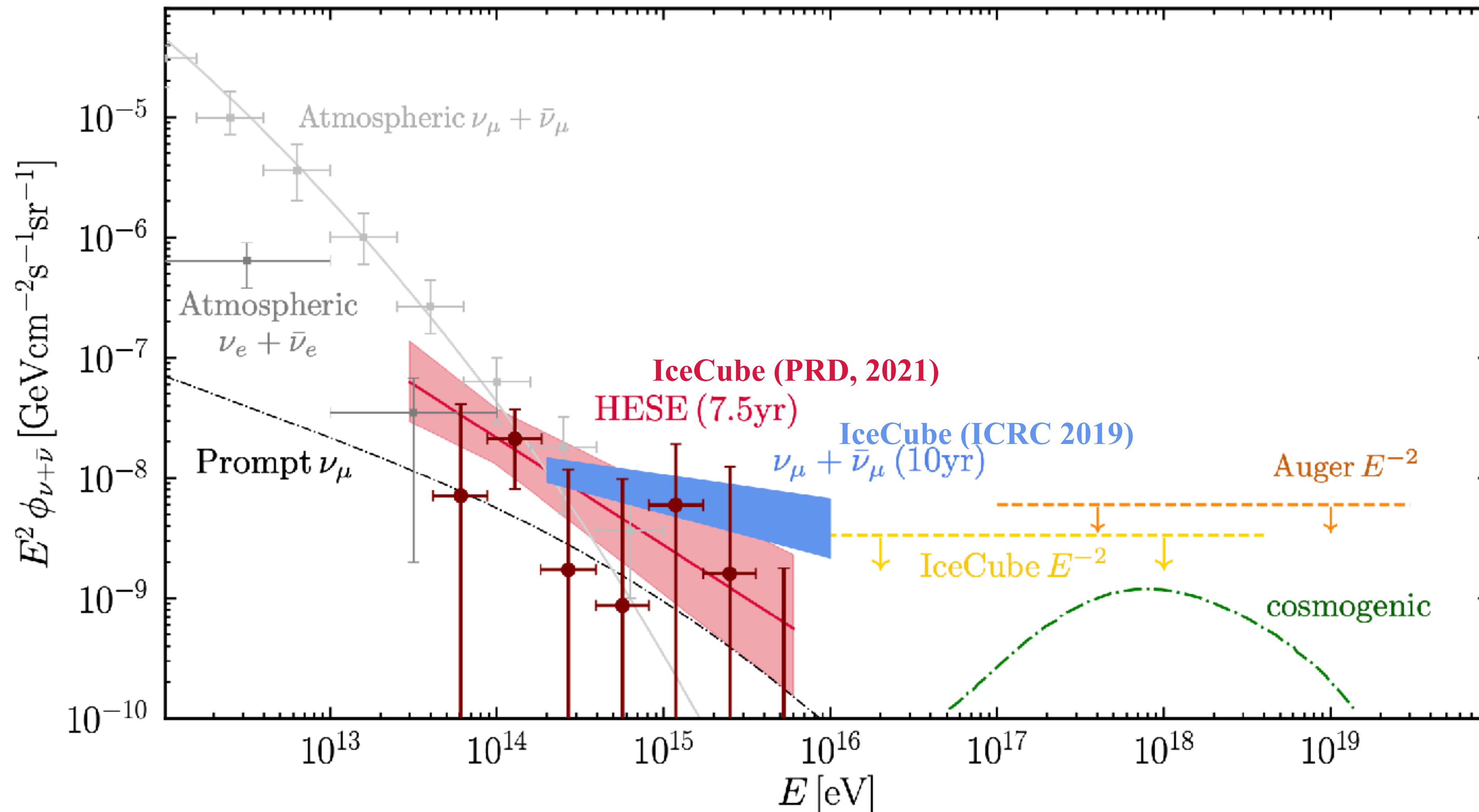




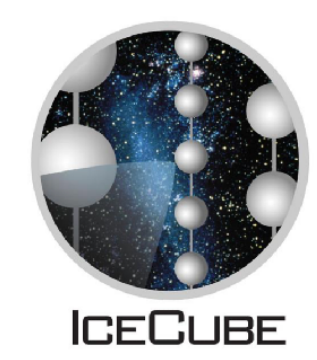


# High-Energy Astronomical Neutrinos

IceCube has measured the astrophysical neutrino flux with multiple independent analyses



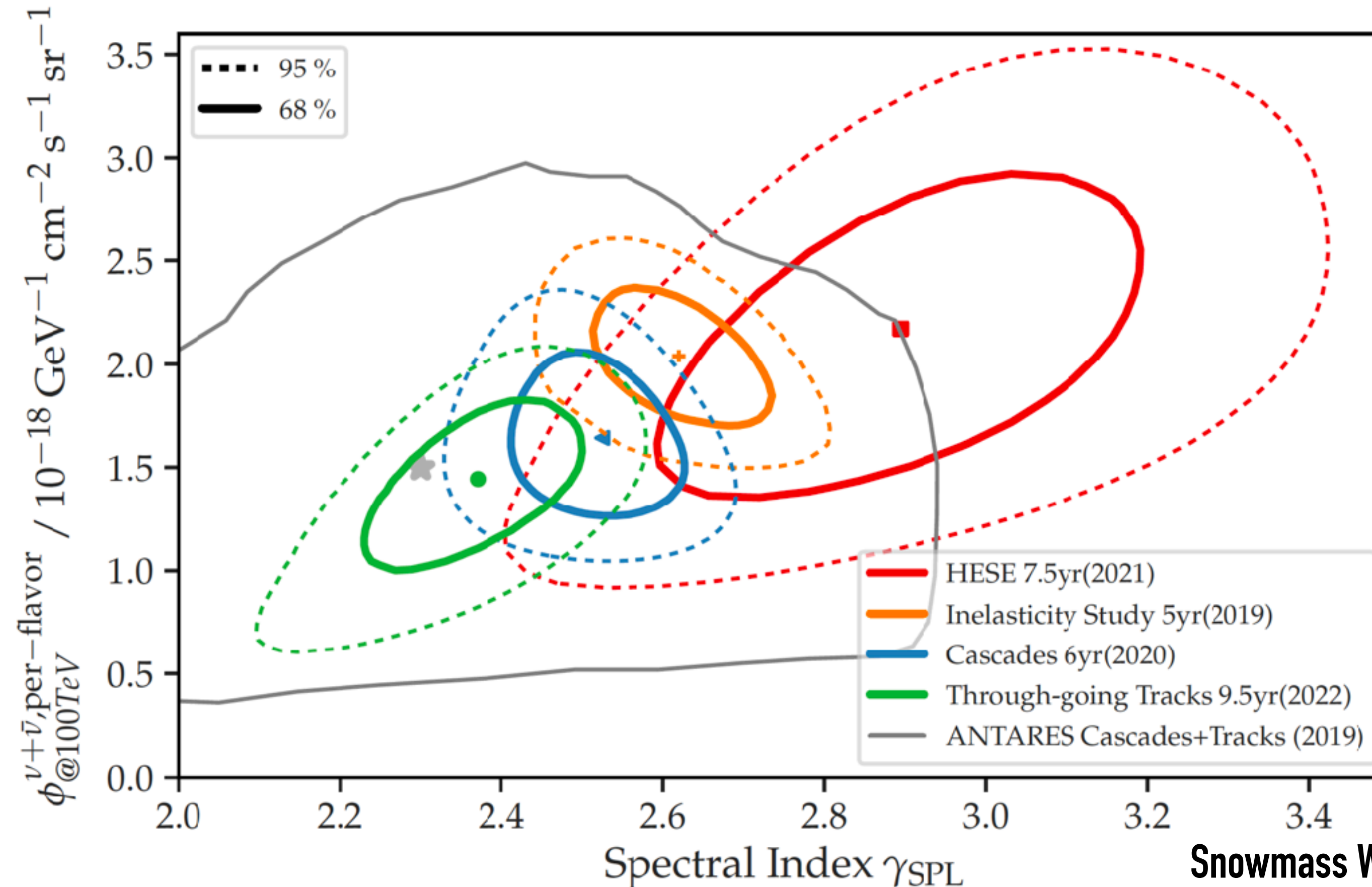




# High-Energy Astronomical Neutrinos

**IceCube has measured the astrophysical neutrino flux with multiple independent analyses**

- Independent event selection and analyses generally agree with the flux and index (assuming a single power-law distribution)
  - Slight tension may be caused by differences in flavour composition, energy range, background, ...

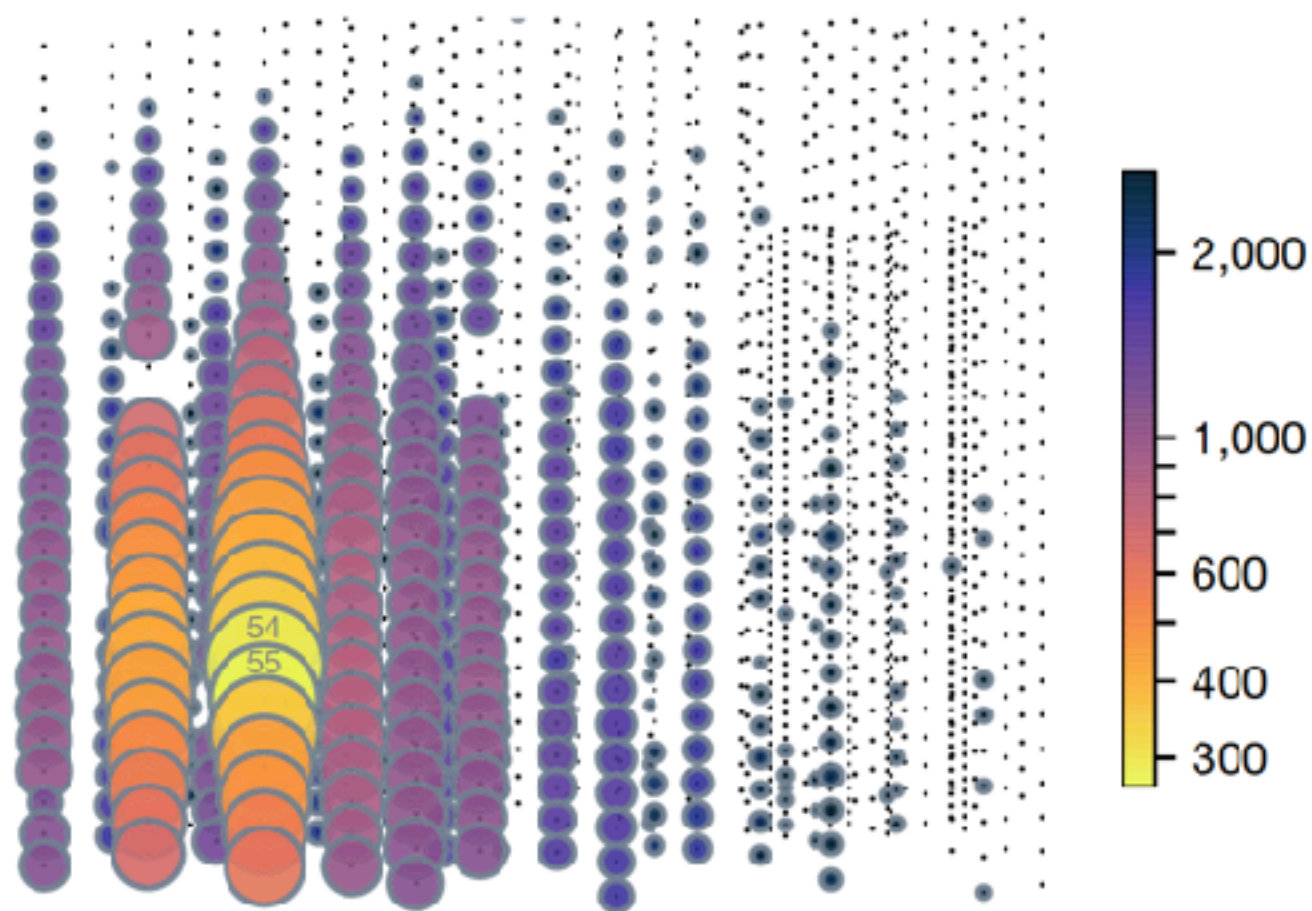




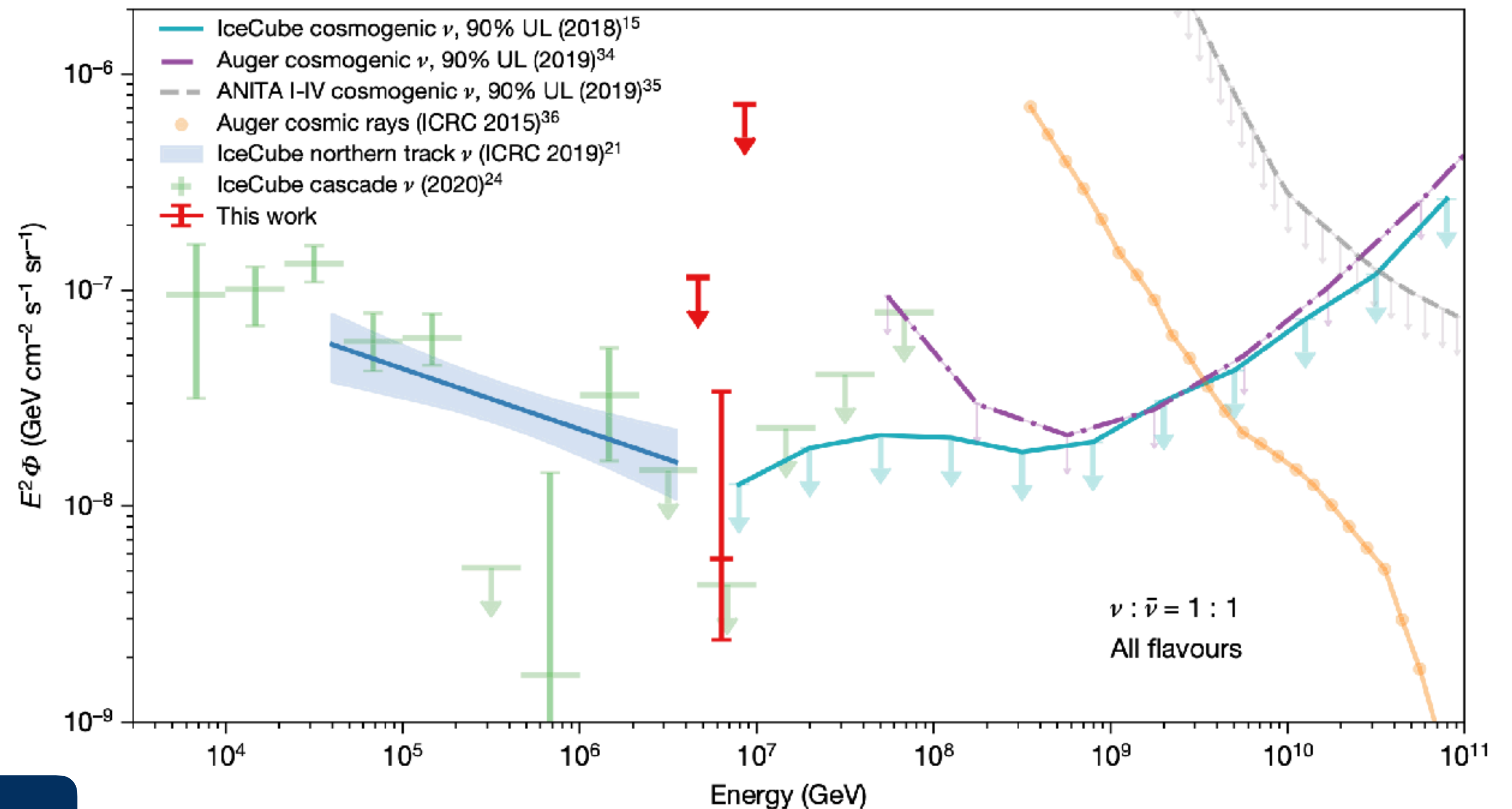
# Glashow Resonance

**IceCube detected a cascade event with an estimated energy of  $6.05 \pm 0.72$  PeV consistent with the resonant formation of a  $W^-$  boson predicted by Glashow**

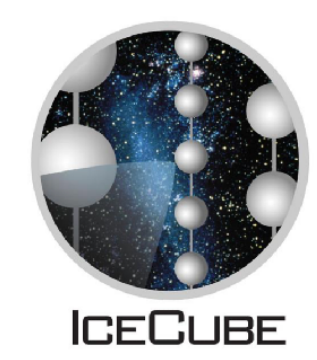
- Observed flux matches with the expectation from cross section and astrophysical neutrino flux



Photons from early muons  
“outrunning” the cascade



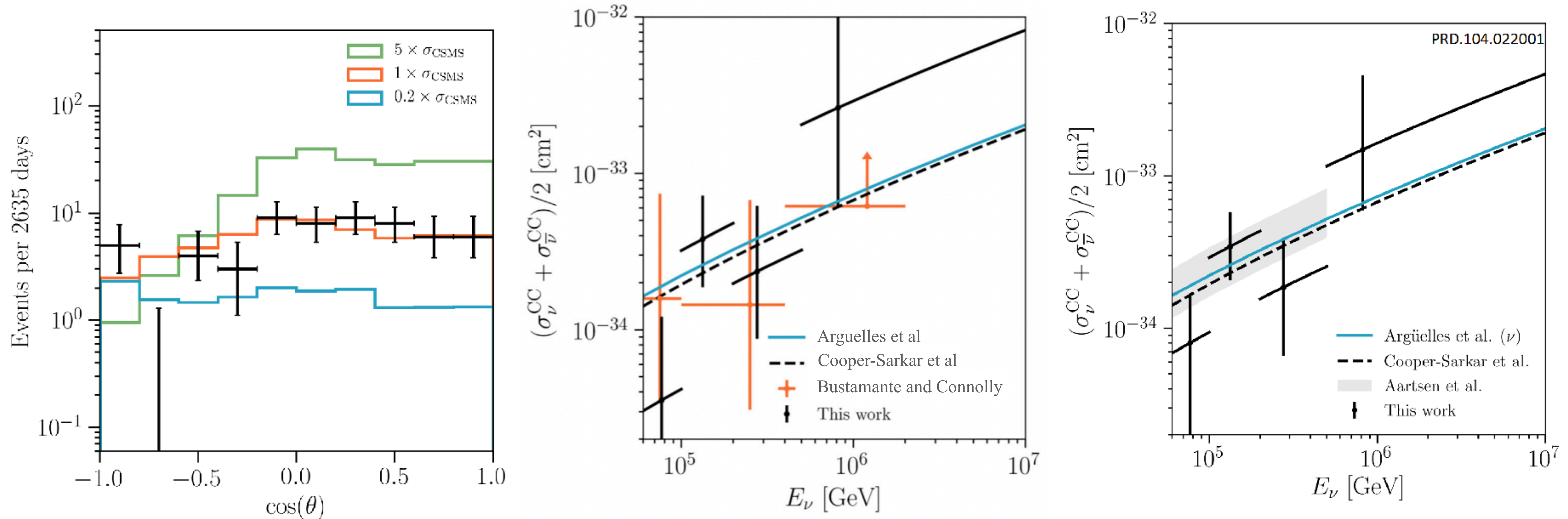




# Neutrino-nucleon Cross Section

## Neutrino cross section between 60 TeV and 10 PeV using in-Earth attenuation

- Measurements match with the expectation from the Standard Model



“Inelasticity distribution of neutrino interactions between 100 GeV and 1 TeV”  
- Poster IV-b/7F **MT05-086** by M. Liubarska

IceCube (PRD, 2021)



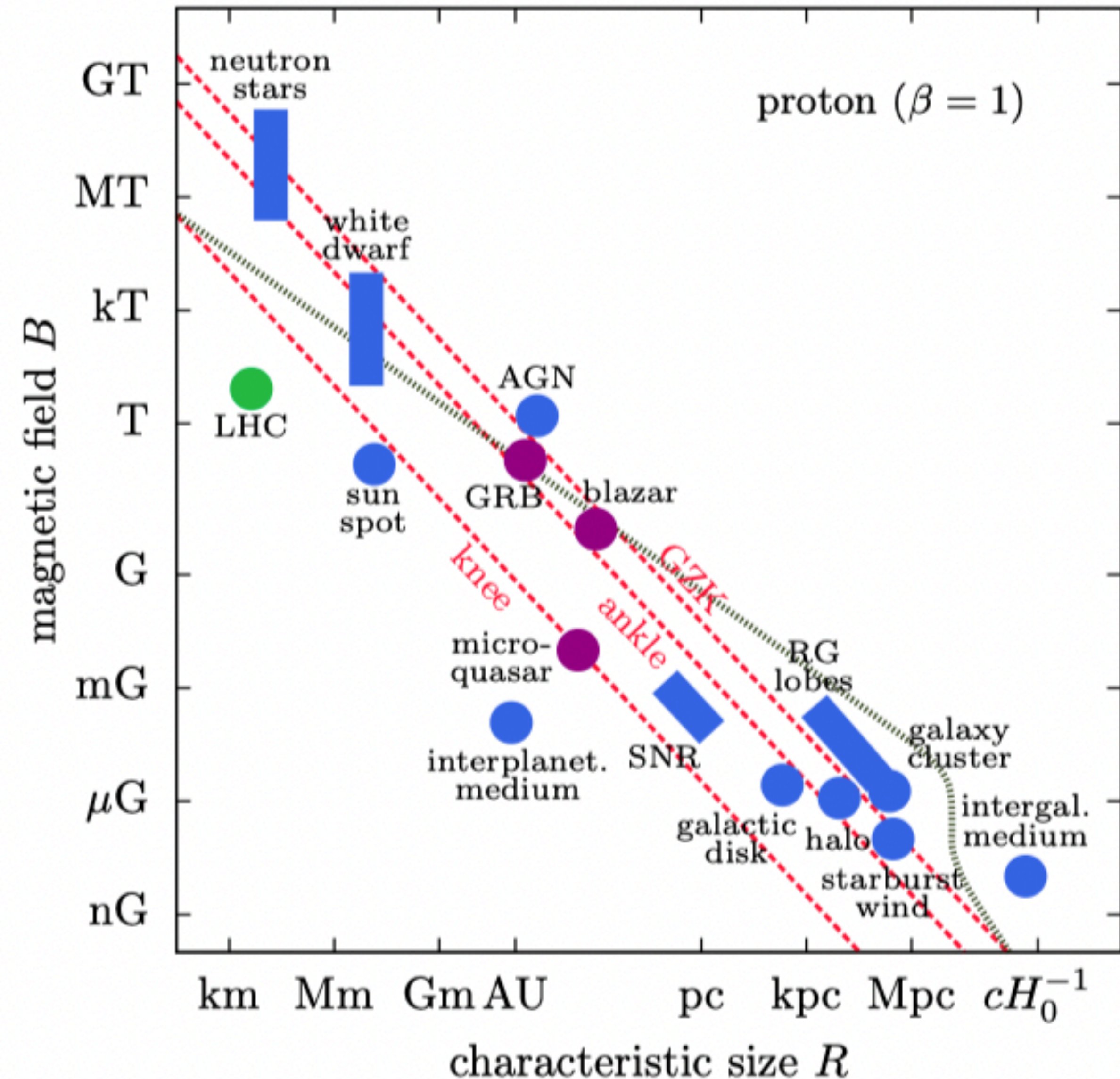
# Origin of astrophysical neutrinos

## Observed astrophysical diffuse emission is

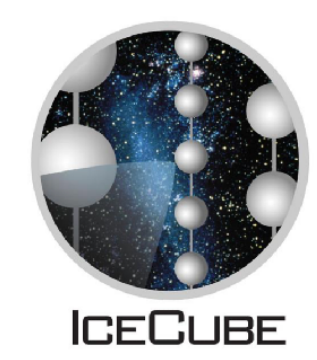
- Consistent with an isotropic distribution
- Galactic plane emission < 14%

## Source sites should

- Be able to accelerate particles to high energy ( $E > 100$  TeV)
- Have enough density (p-p) or target radiation field (p- $\gamma$ )



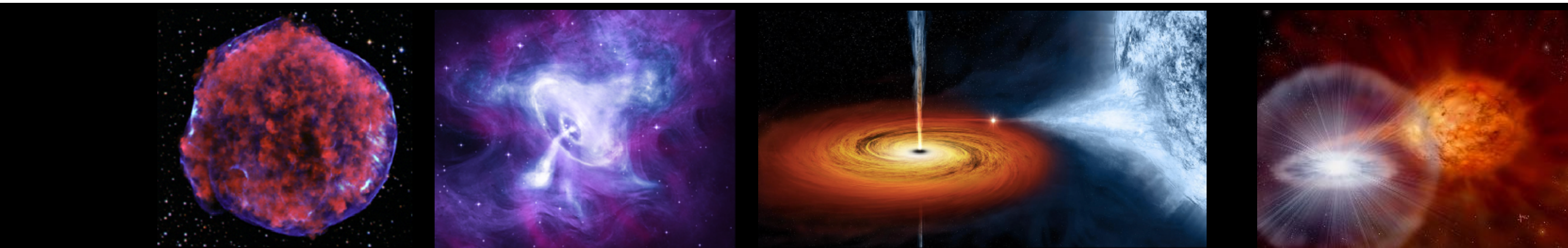




# Neutrino Sources: Galactic

## Galactic Sources

- Can use very-high-energy gamma-ray observations as a potential guide
  - Supernova Remnants, Pulsar Wind Nebulae, Binaries, Nova, ....
  - IACTs and ground arrays have reported more than hundreds of Galactic sources
- Recent gamma-ray observations by LHAASO report gamma rays with up to PeV range
  - **Emission measured from many gamma-ray sources is leptonic-dominated.**
  - **IceCube observations provide clear measurements of hadronic emission!**





# Neutrino Sources: Galactic

## Galactic source studies of IceCube include

- ⦿ Steady source studies
  - Supernova remnants, Pulsar Wind Nebulae, Unidentified TeV sources, ...
- ⦿ Transient source studies
  - Supernova, Binary, novae, ....

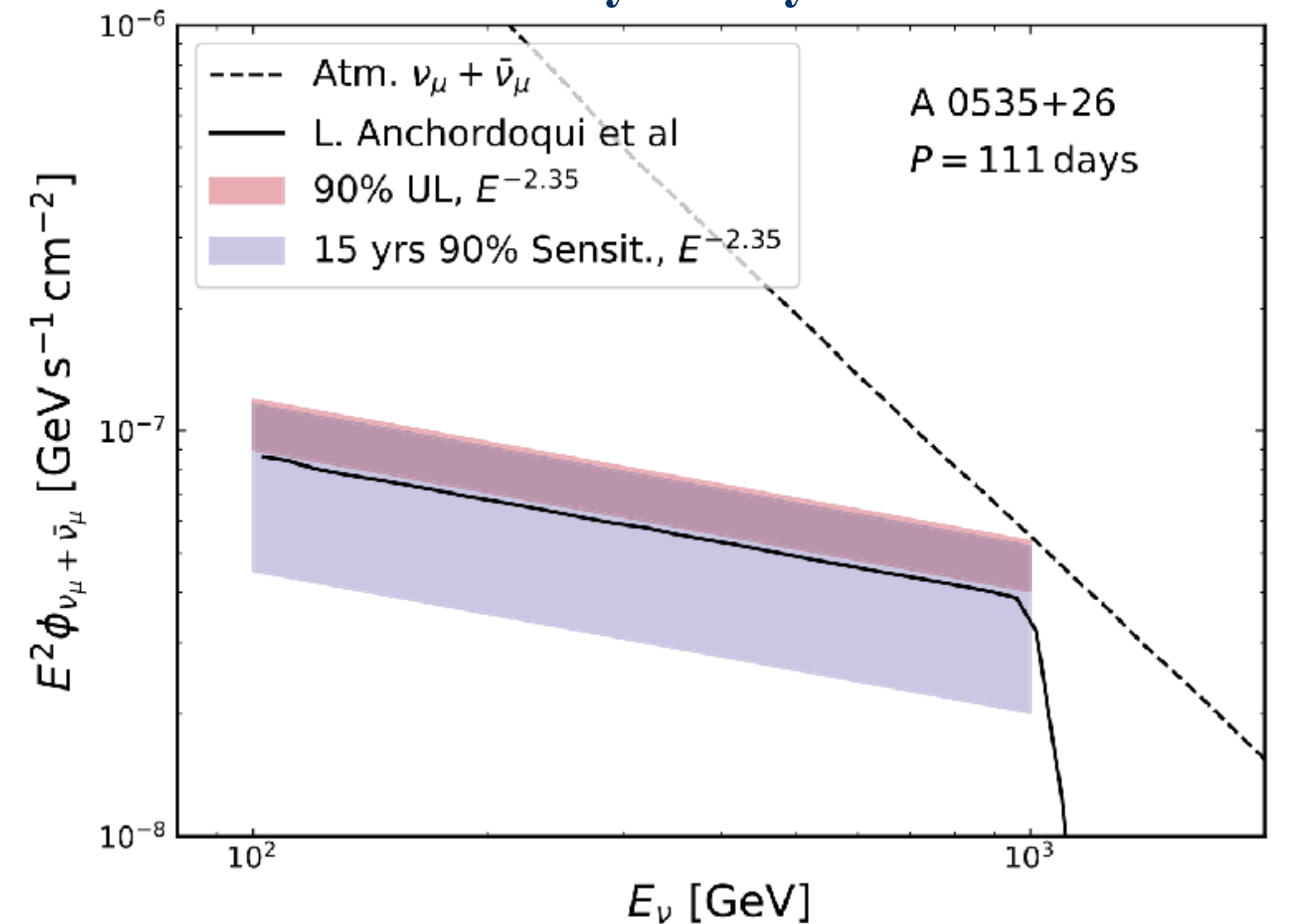
“Searches for neutrinos from LHAASO sources”  
- Poster IV-a/5F **MT12-072** by Y.L. Chang

“Searches for extended neutrino emission in the Galaxy”  
- Poster IV-b/6F **MT12-608** by M. U. Nisa

“Searches for neutrinos from magnetars”  
- Poster IV-b/5F **MT12-102** by A. Ghadimi

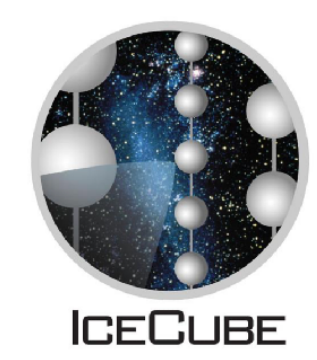
“Testing IceCube Sensitivity for Core collapse SN”  
- Poster IV-b/5F **MT12-278** by S. Griswold

### X-ray binary searches



IceCube (APJL, 2022)

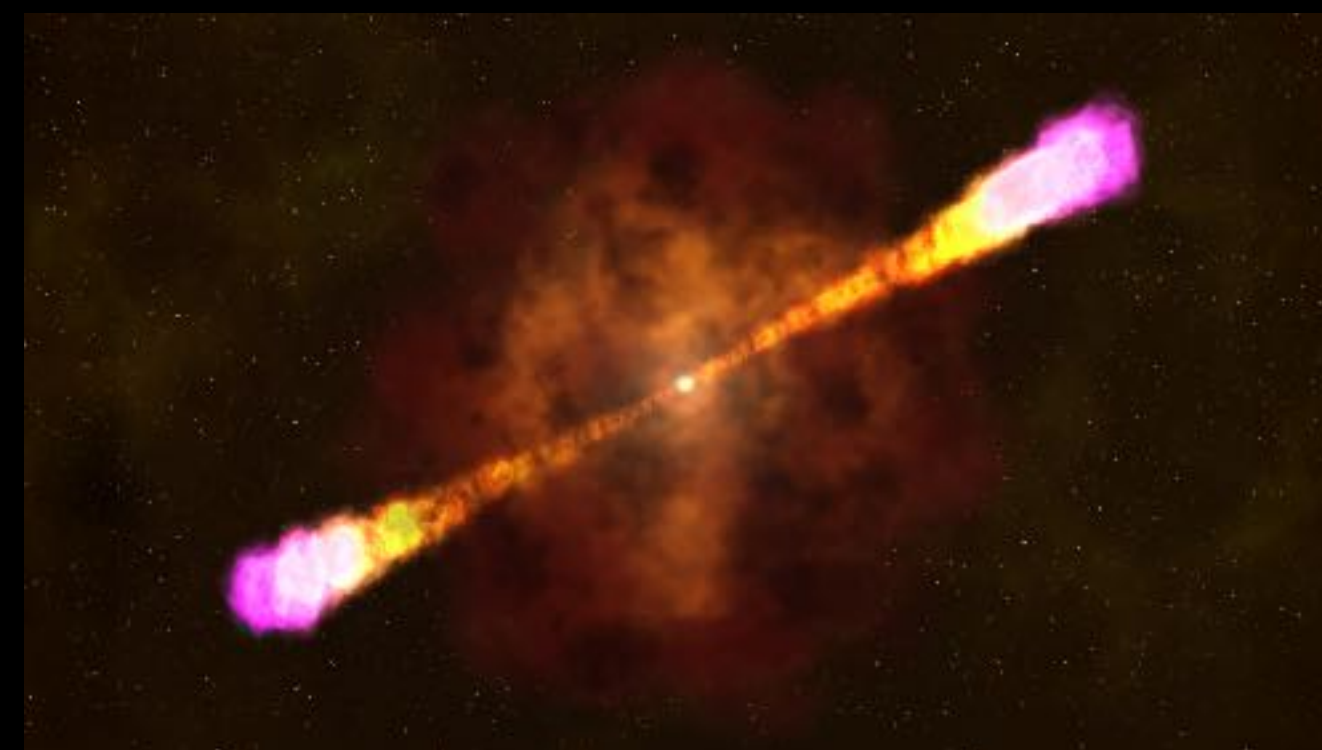
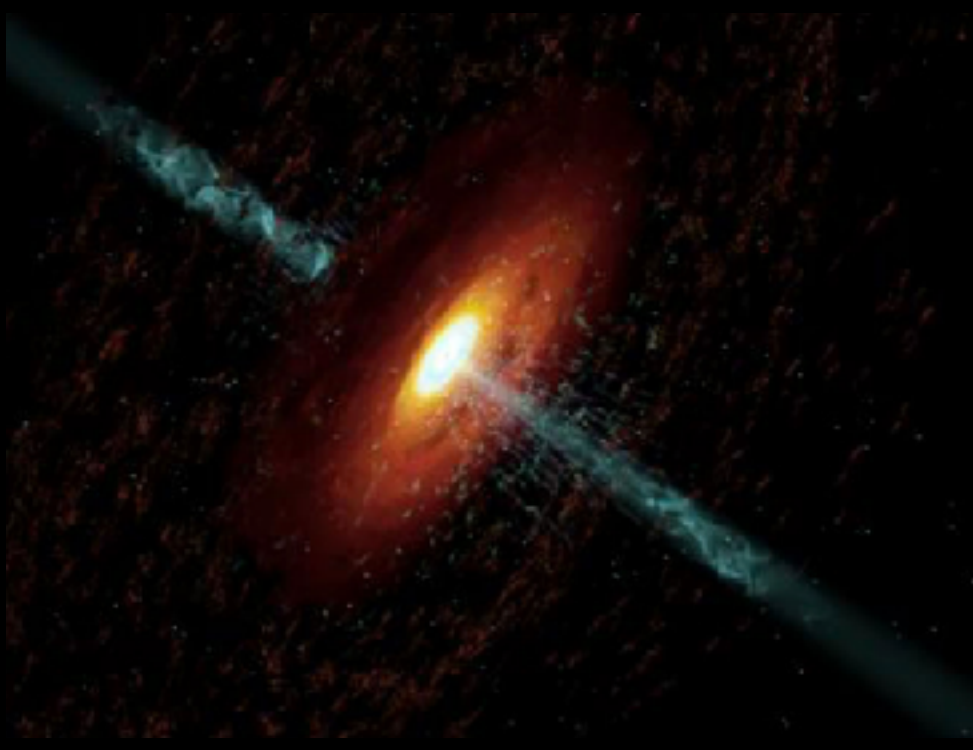




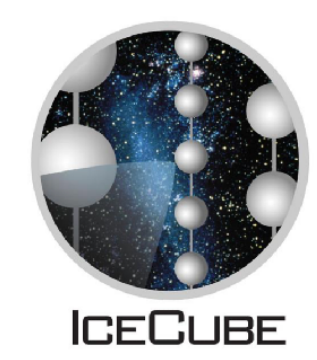
# Neutrino Sources: Extragalactic

## Extragalactic sources

- ⦿ Very-high-energy gamma-rays ( $E > 100$  GeV) cannot travel farther than  $z \sim 1$ 
  - Potential sources include active galactic nuclei (AGN), starburst galaxies, gamma-ray bursts, galactic cluster, ...
- Targeted source class searches
- Neutrino follow-up multi-messenger observations
- All-sky neutrino searches







# Extragalactic Neutrino Source Searches

## Extragalactic source studies of IceCube include

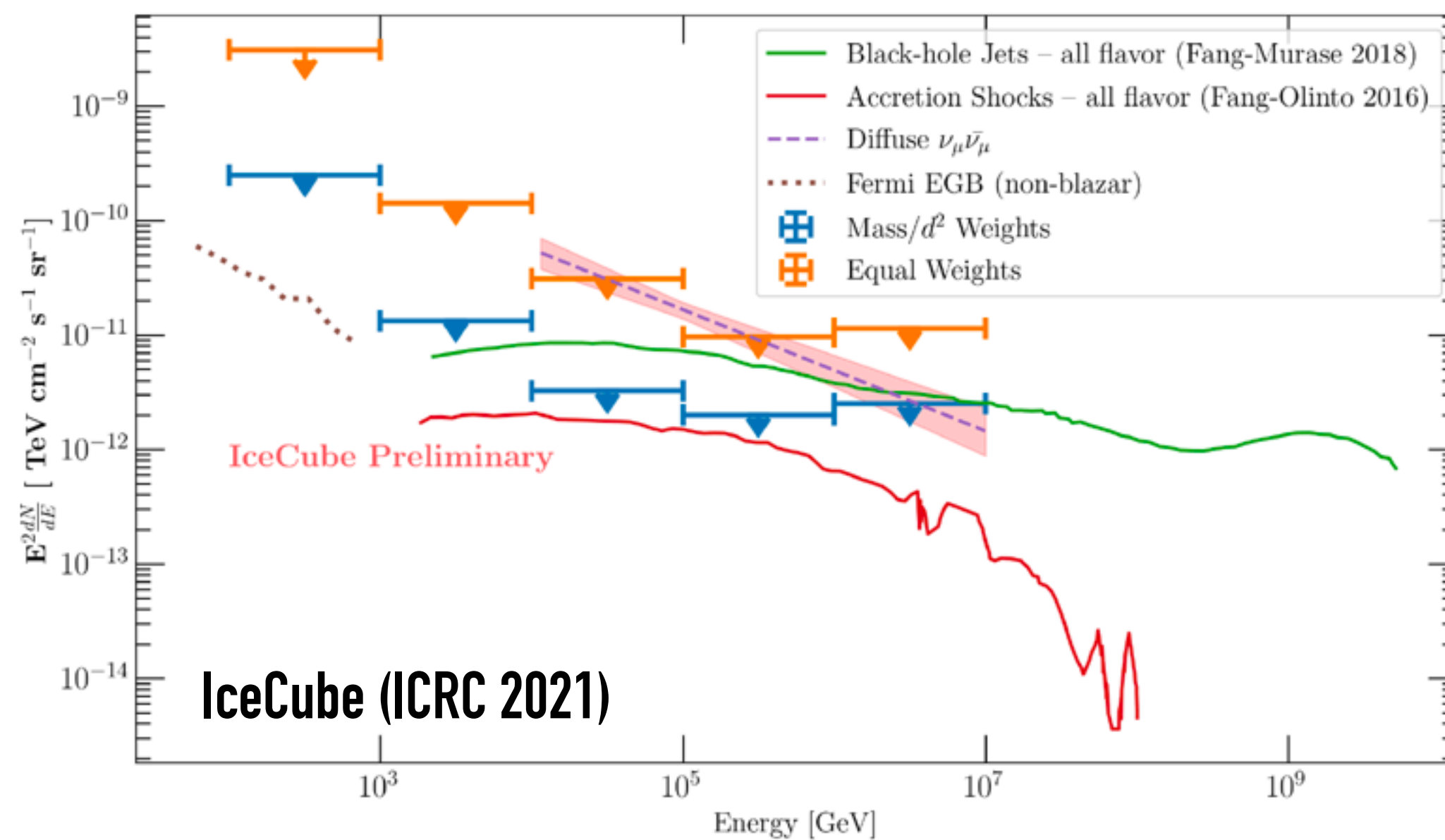
### ● Steady source searches

- AGNs, Starburst galaxies, Galactic cluster, Ultraluminous Infrared Galaxies, ...

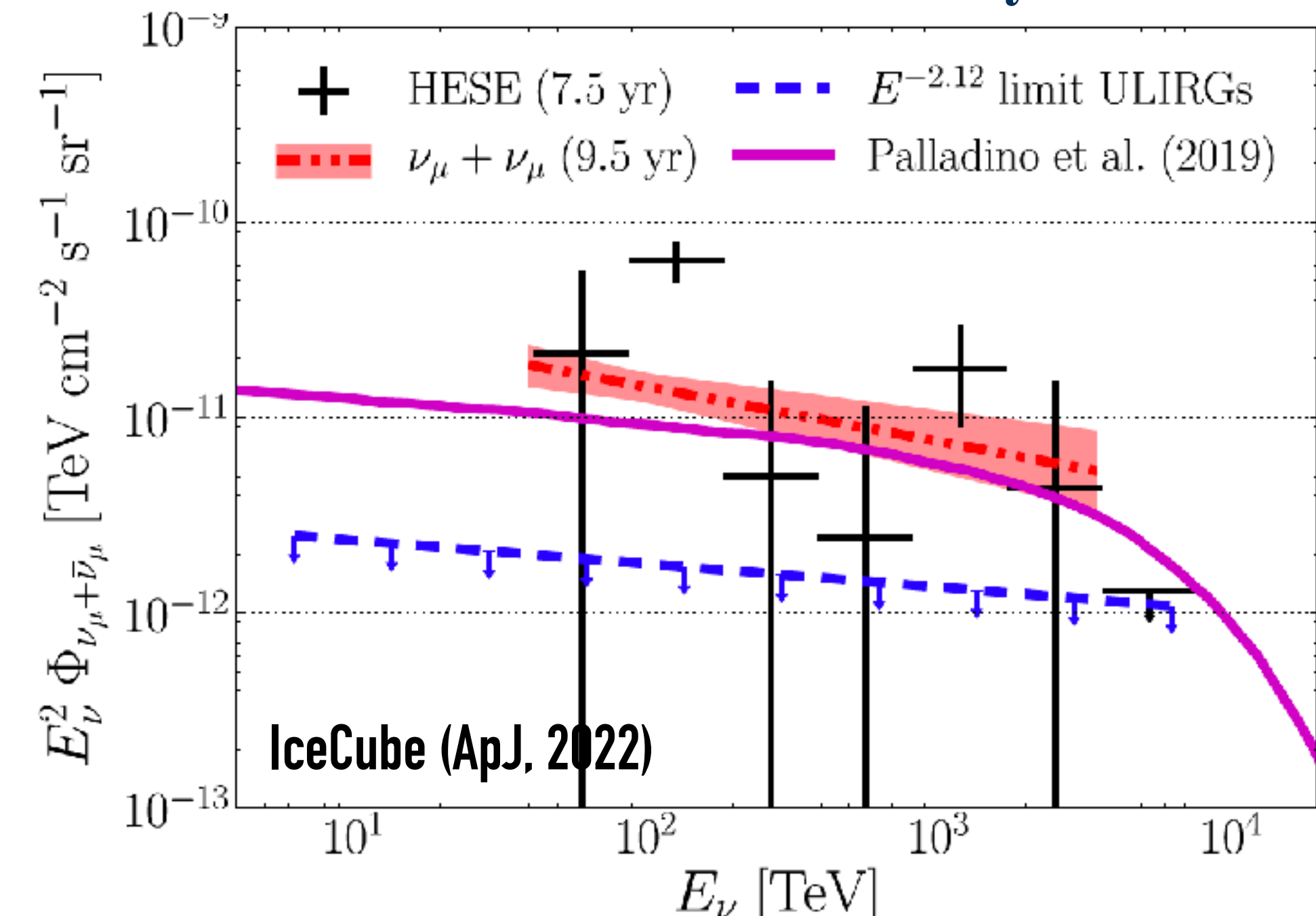
### ● Transient source searches

- GRBs, Flaring blazars, Tidal Disruption Event (TDE), Fast Radio Bursts (FRBs),...

### Galaxy Cluster



### Ultraluminous Infrared Galaxy Searches



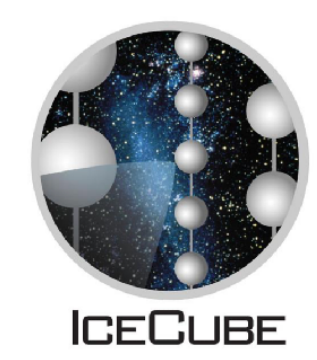
“Searches for neutrinos from FRBs”

- Poster IV-b/6F MT12-684 by M. Kovacevich

“Searches for neutrinos from 1FLE blazars”

- Poster IV-b/5F MT12-082 by M. Campana

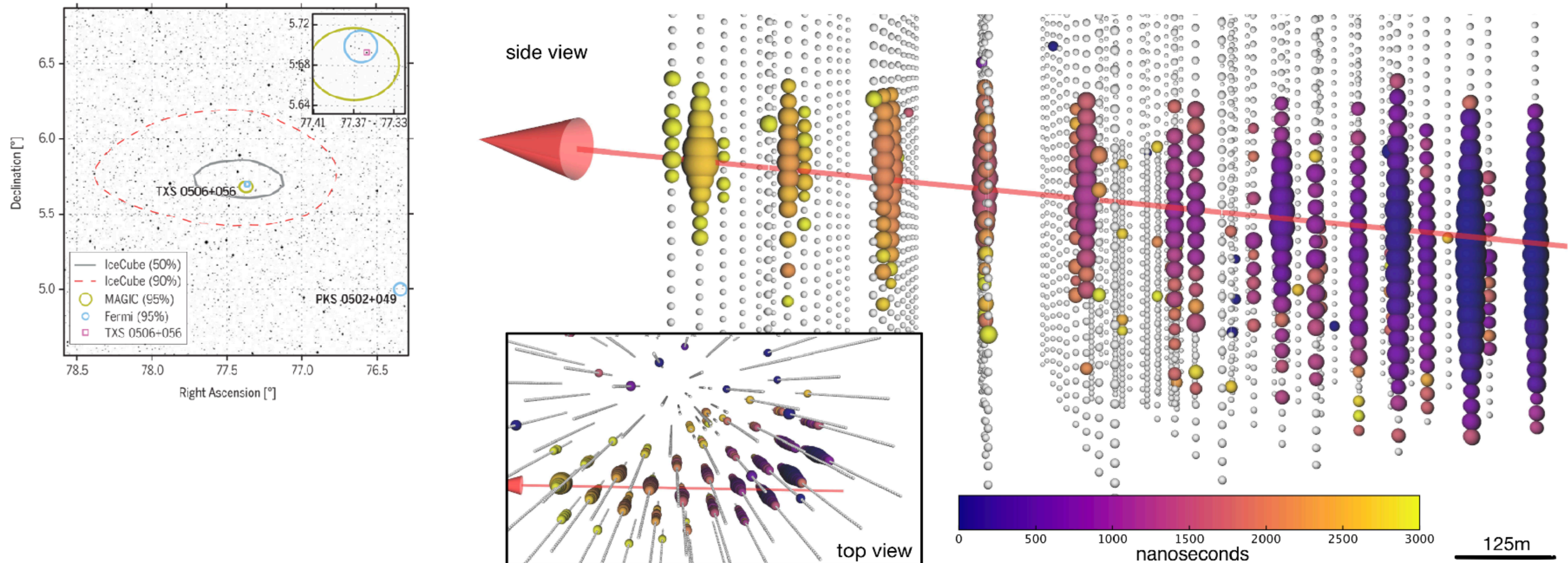




# Multi-messenger neutrino follow-up

## IceCube-170922A coincident with flaring blazar TXS 0506+056

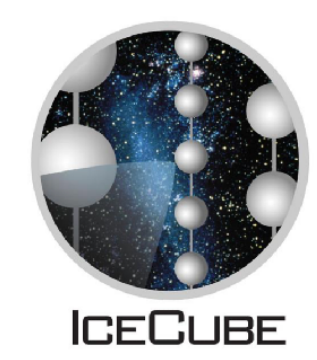
- Extreme high energy neutrino alert from IceCube followed by detection of very high energy photons from a flaring blazar



“Searches for gamma-rays from neutrino alerts”

- Poster by I. Viale for FACT, H.E.S.S., MAGIC, and VERITAS

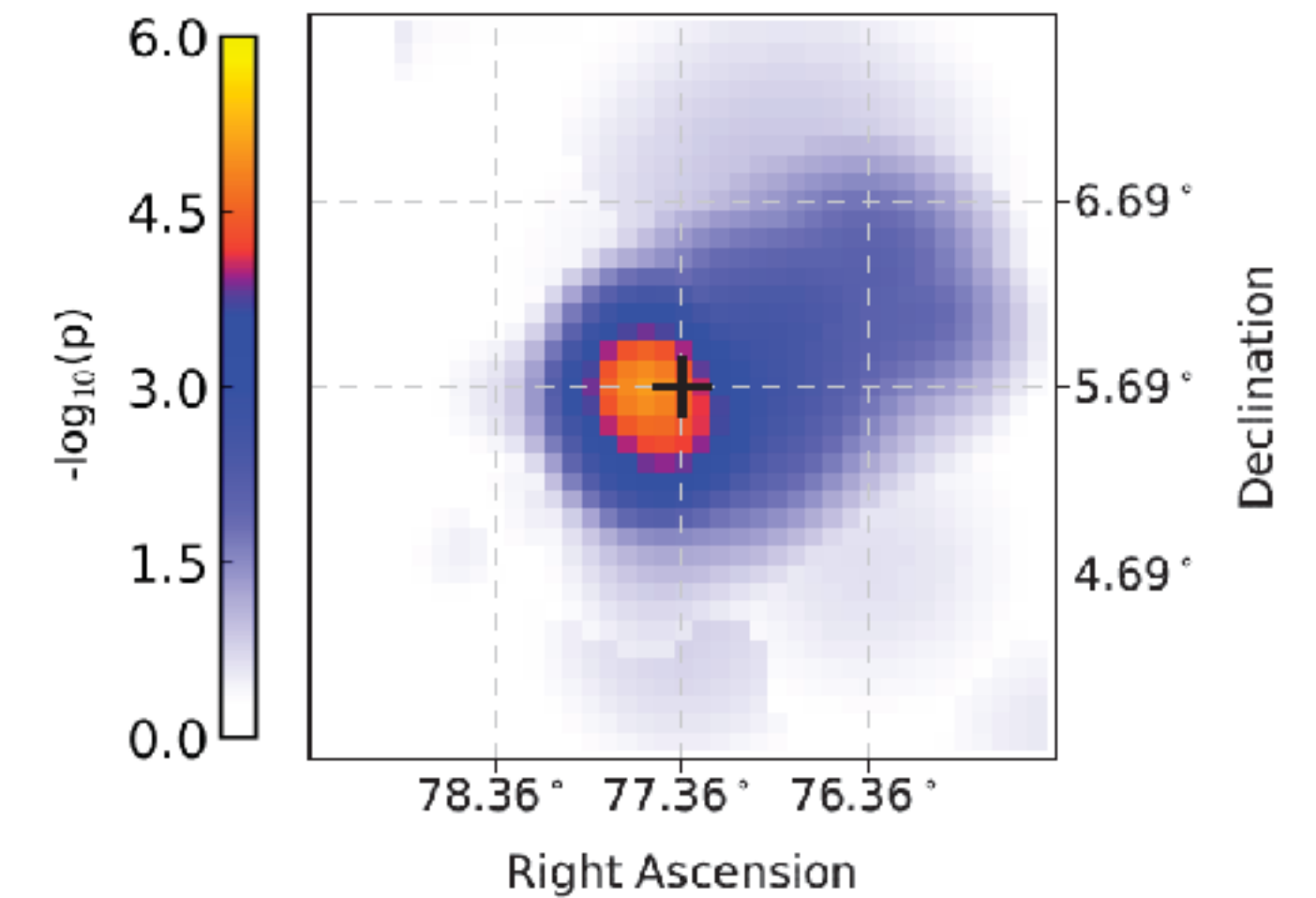
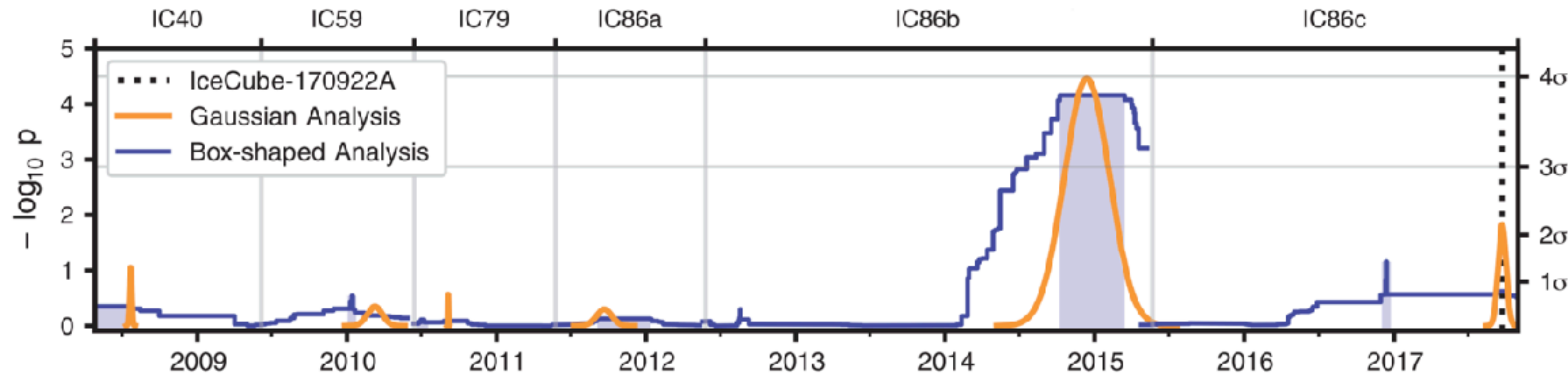




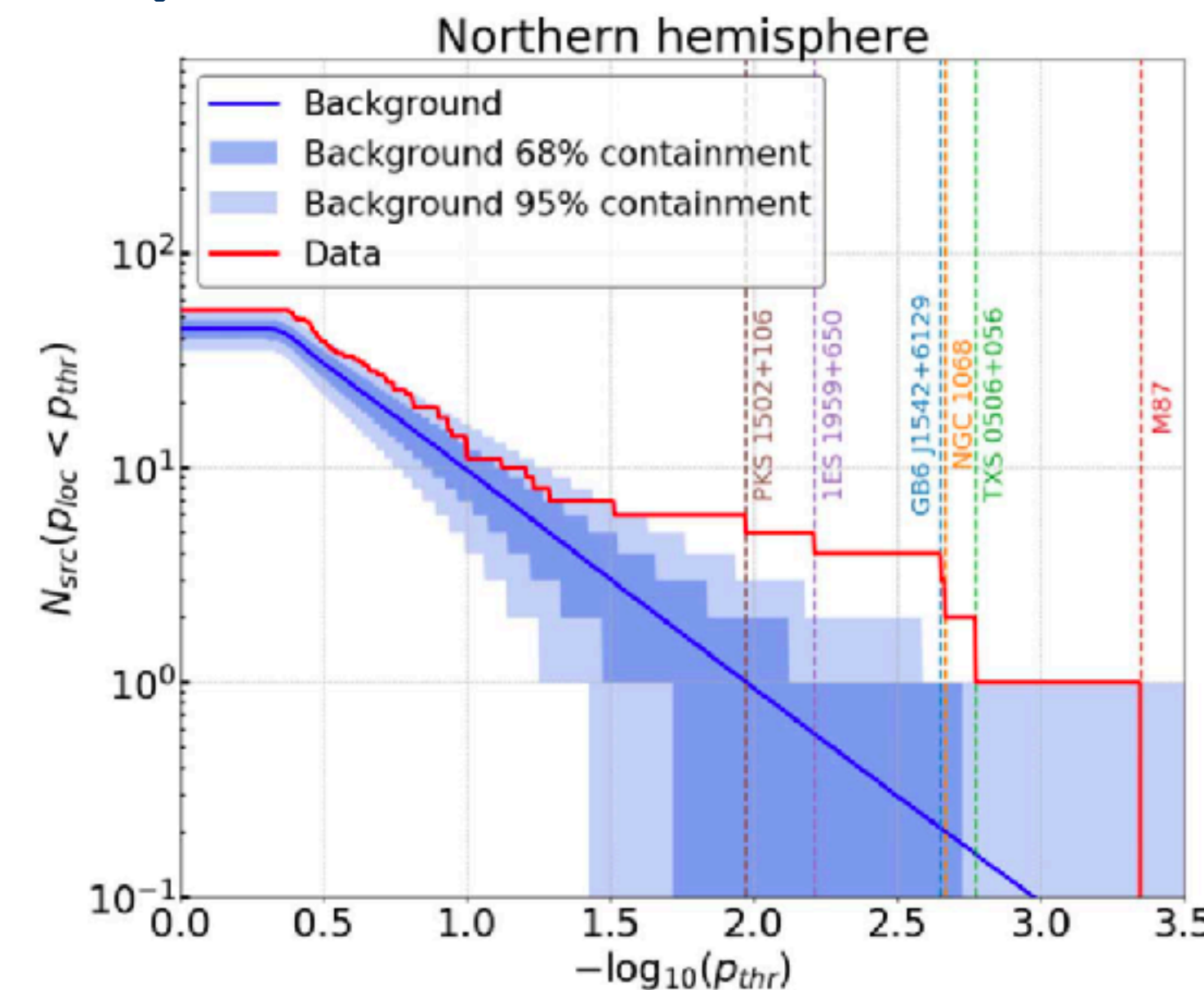
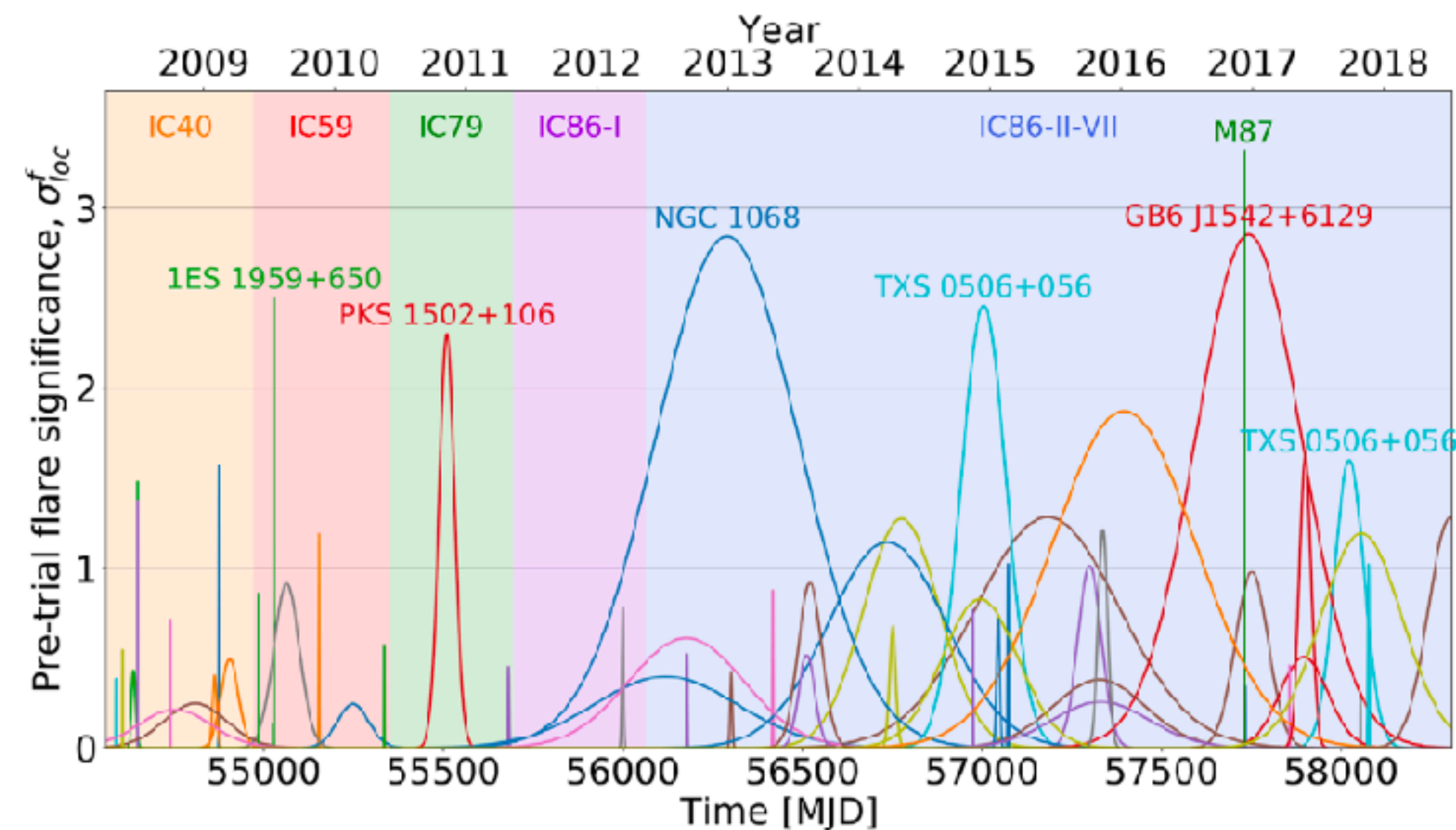
# Archival Neutrino Searches around TXS 0506+056

## Archival search found neutrino excess around 2014 around TXS 0506+056

- 13  $\pm$  5 events above the background over 100 days: significance of  $3.5\sigma$



## Multi-flare Searches with 10 years of data



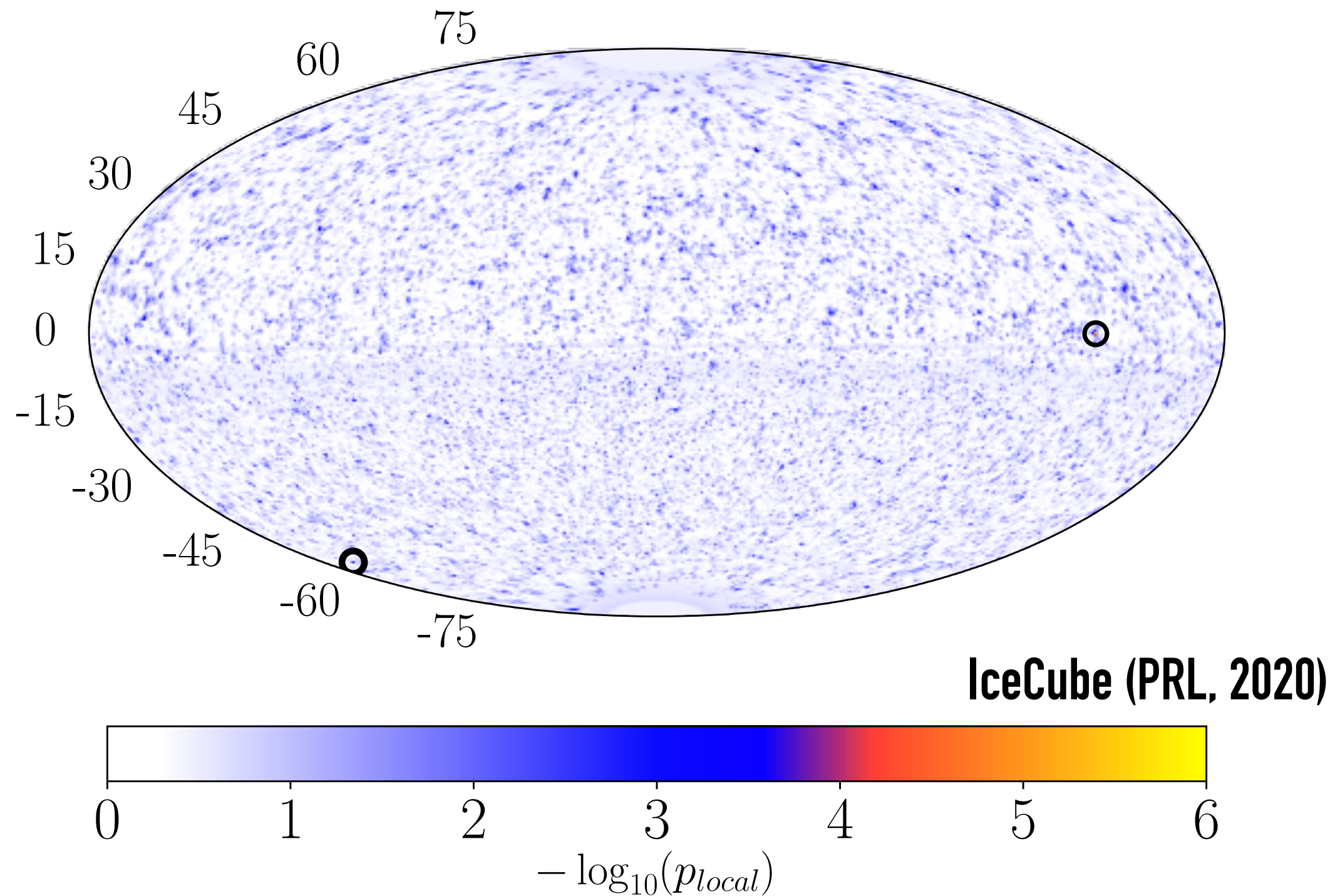


# All-Sky Neutrino Searches

**Different event selections have different strength for neutrino searches**

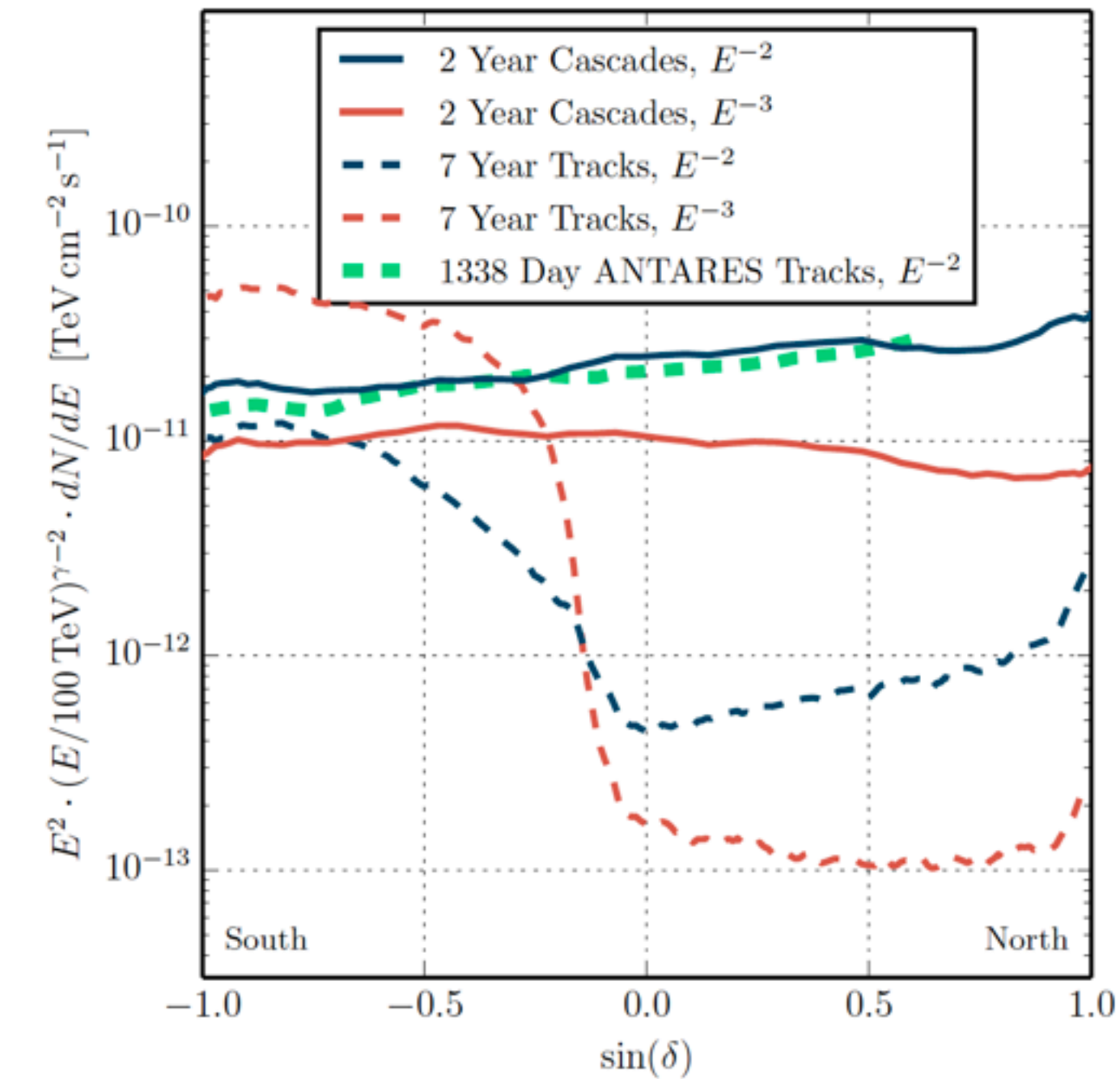
**10 Year track-like events ( $E > 10$  TeV,  $\mu + \nu_\mu$ )**

(<https://icecube.wisc.edu/data-releases/2021/01/all-sky-point-source-icecube-data-years-2008-2018/>)



→ **Good angular resolution**  
→ **Best sensitivity at Northern sky**

**7 Year Cascade events ( $E > 1$  TeV, all flavour)**

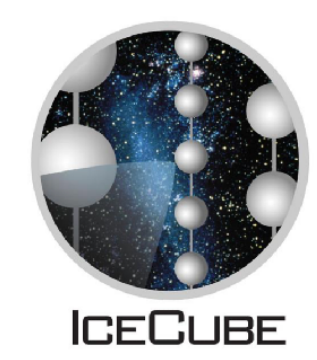


**IceCube (ApJ, 2019)**

→ **Lower energy coverage**  
→ **~Uniform sensitivity for all-sky**

“Diffuse neutrino flux and source searches from 1 to 100 TeV with starting muon tracks”  
- Poster by S. Mancina

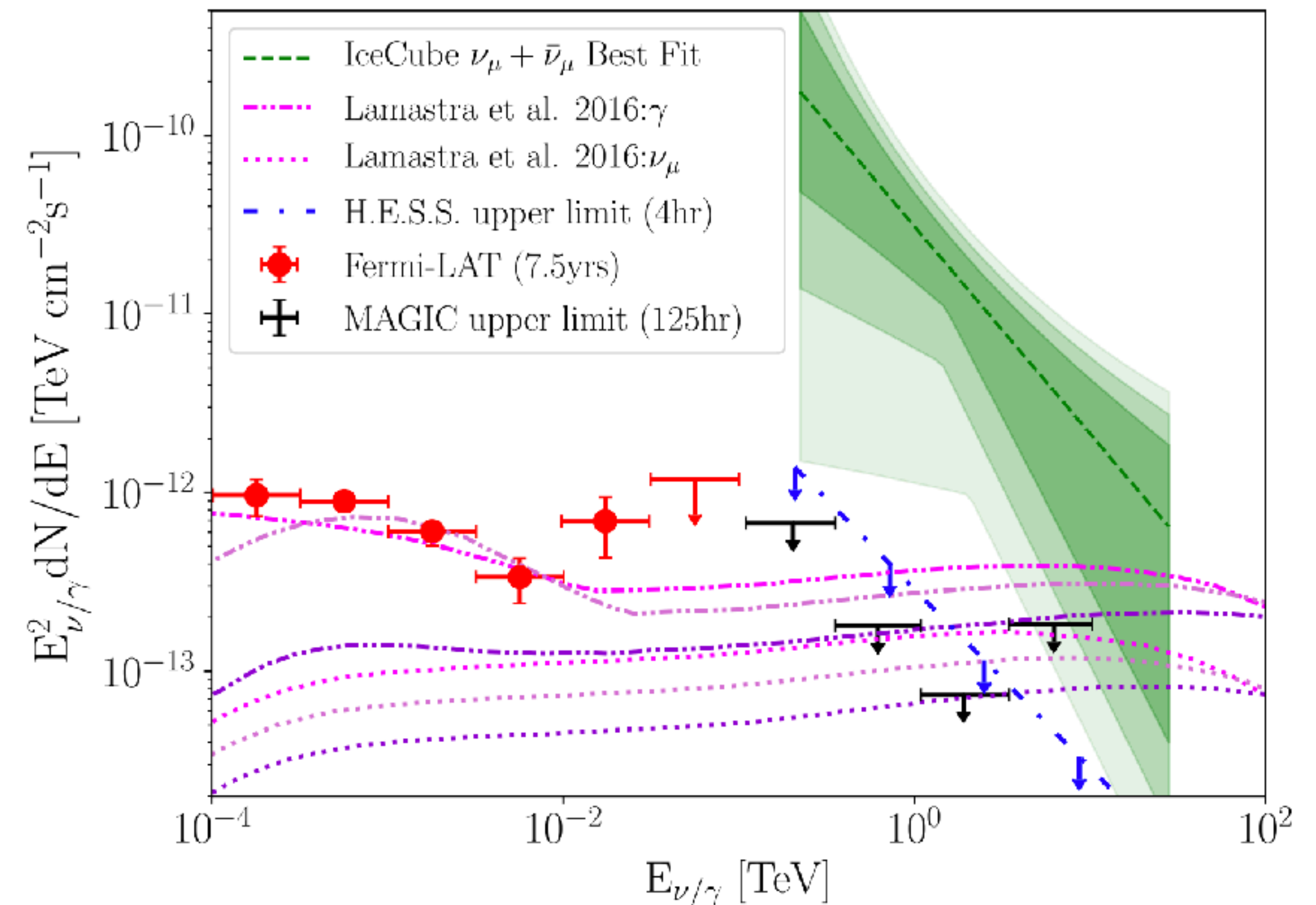
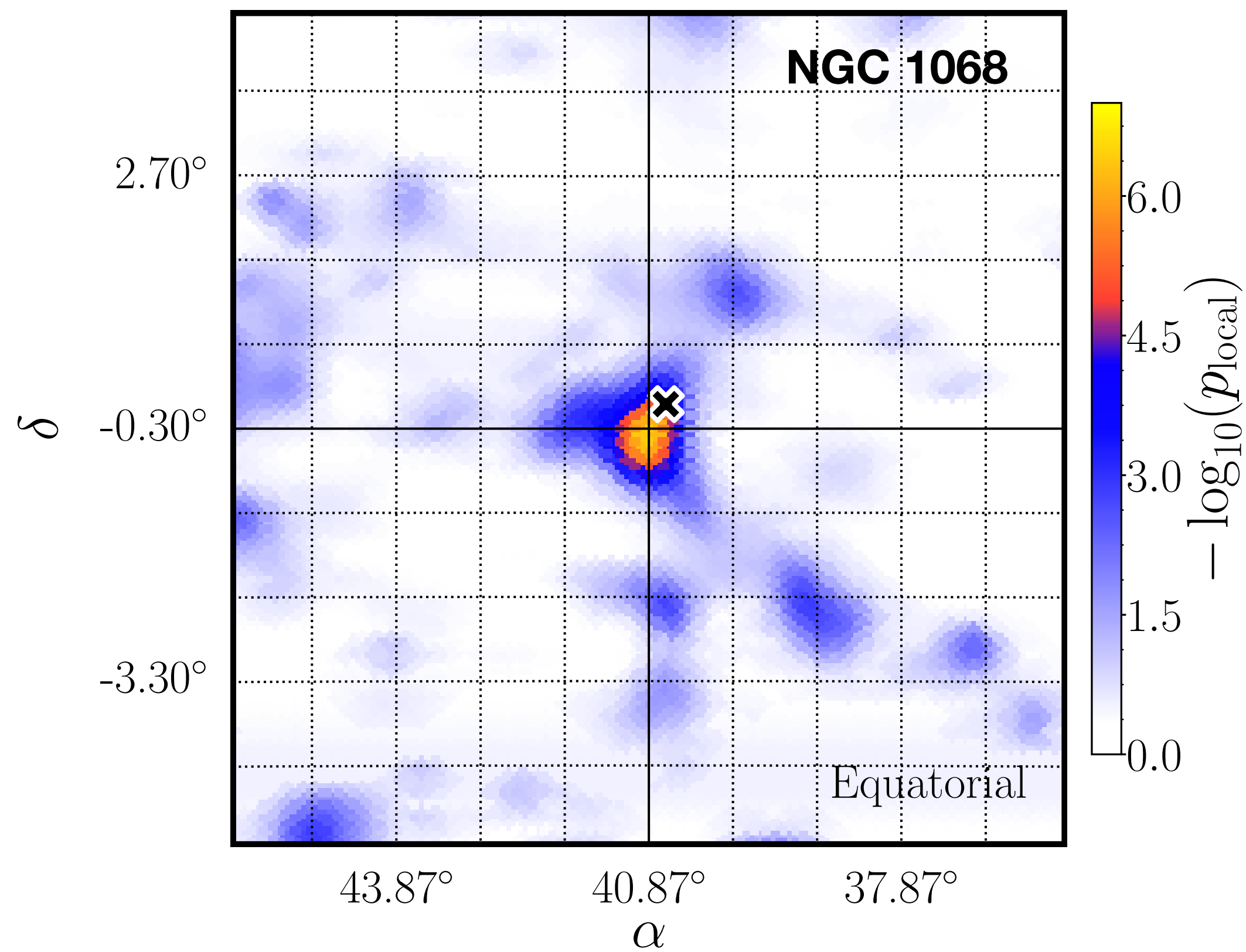




# Searches for point sources in 10 year data

**The most significant source in the Northern hemisphere: nearby Seyfert galaxy NGC 1068 w/ significance of  $2.9\sigma$**

- GeV gamma-ray based catalogue search inconsistent with background w/  $3.3\sigma$



“Searches for neutrinos from hard X-ray AGNs”  
- Poster IV-b/5F MT12-386 by S. Goswami

IceCube (PRL, 2020)



# Moving forward

## Astrophysical neutrino flux

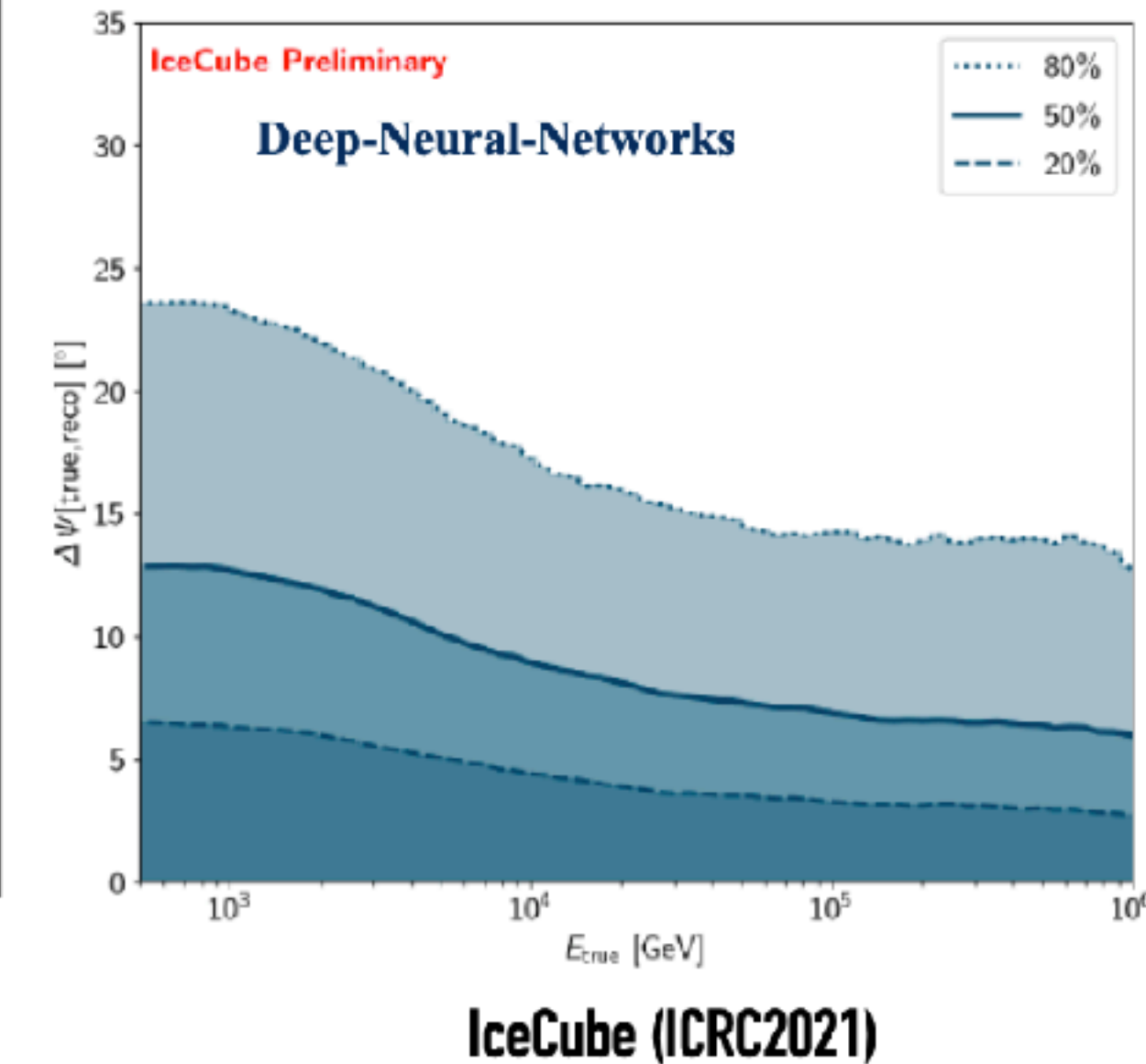
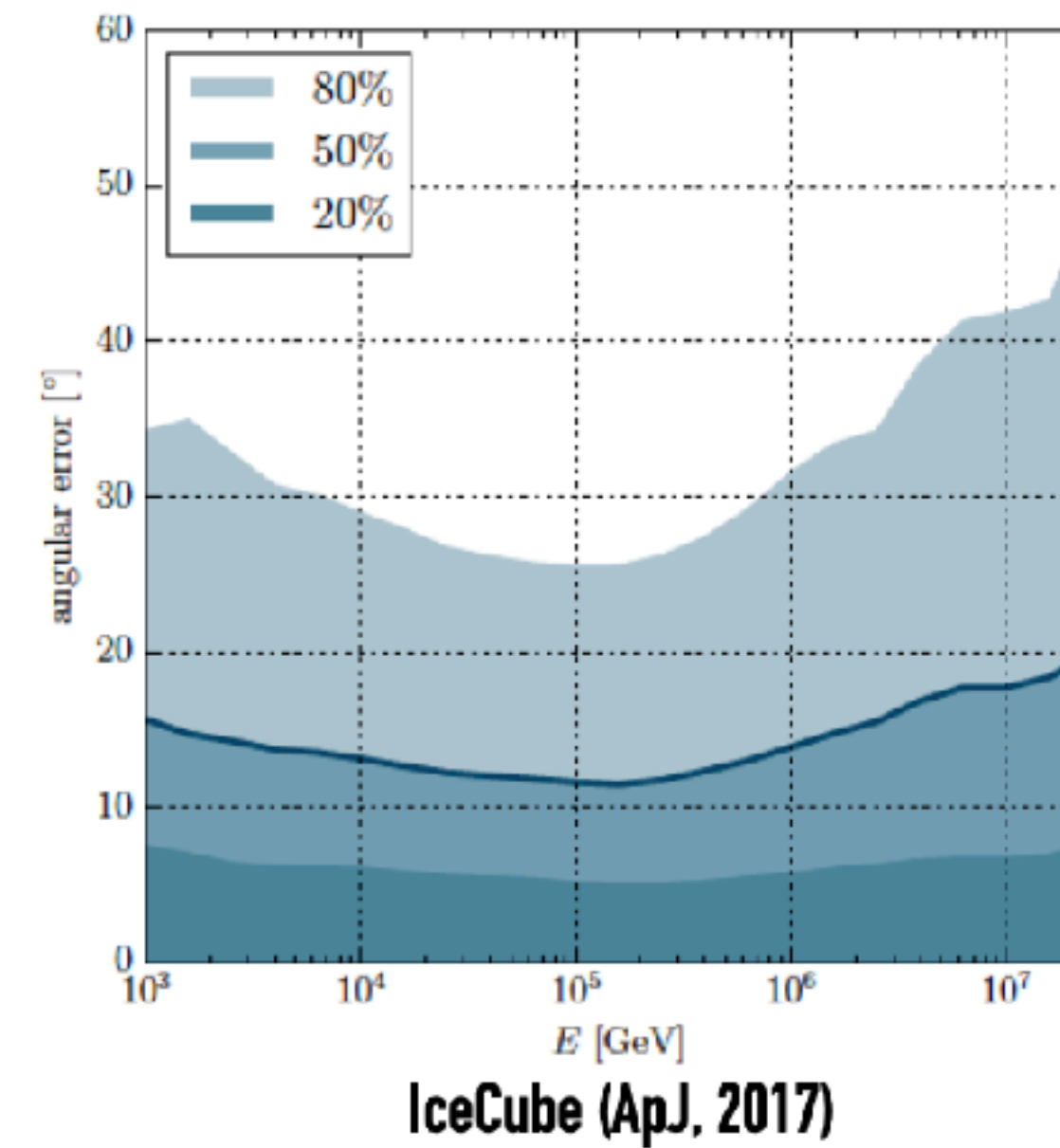
- More measurements  
(e.g. searching for HE  $\nu_\tau$ , different event selection,...)
- Combined analysis to study the properties

## Search for the origin of HE neutrino flux

- Improve analysis methods (e.g. ML)
- Multi-messenger observations
  - Neutrino searches for EM/gravitational wave triggered events
  - EM/gravitational wave followup of neutrino events
- Source population studies

→ To improve our knowledge of high-energy neutrinos, we need a larger and more sensitive neutrino detector!

### Cascade







# IceCube Upgrade: near future

## Goals

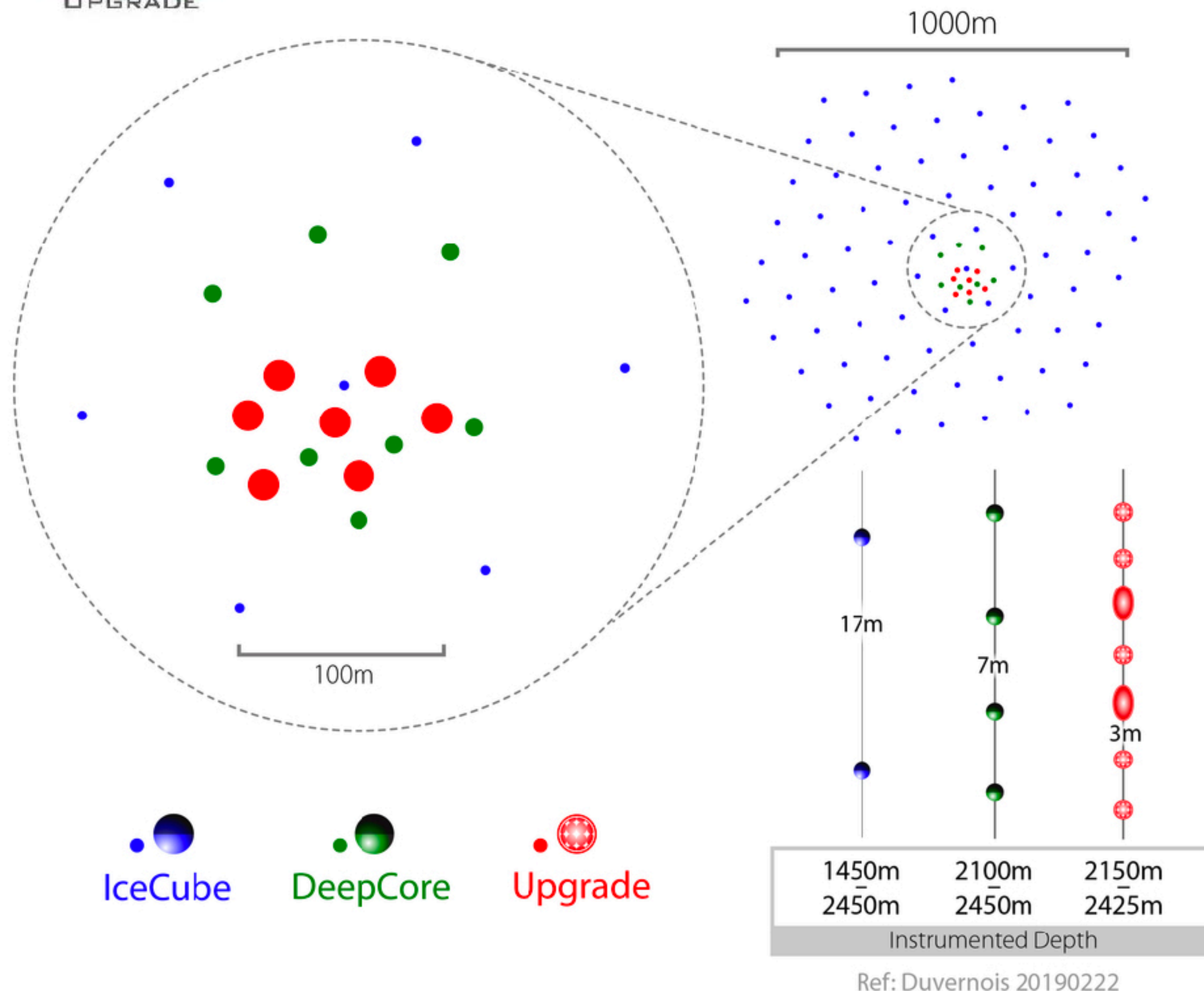
- Precision oscillation measurements
- Improved detector calibration
- R&D for IceCube-Gen2

## Key features

- > 800 new devices
- Reduced spacing between modules
- Explore deep ice down to 2.6 km

## Status

- Pandemic delayed the deployment
- Scheduled to start drilling in 2024-25  
String deployment in 2025-26!

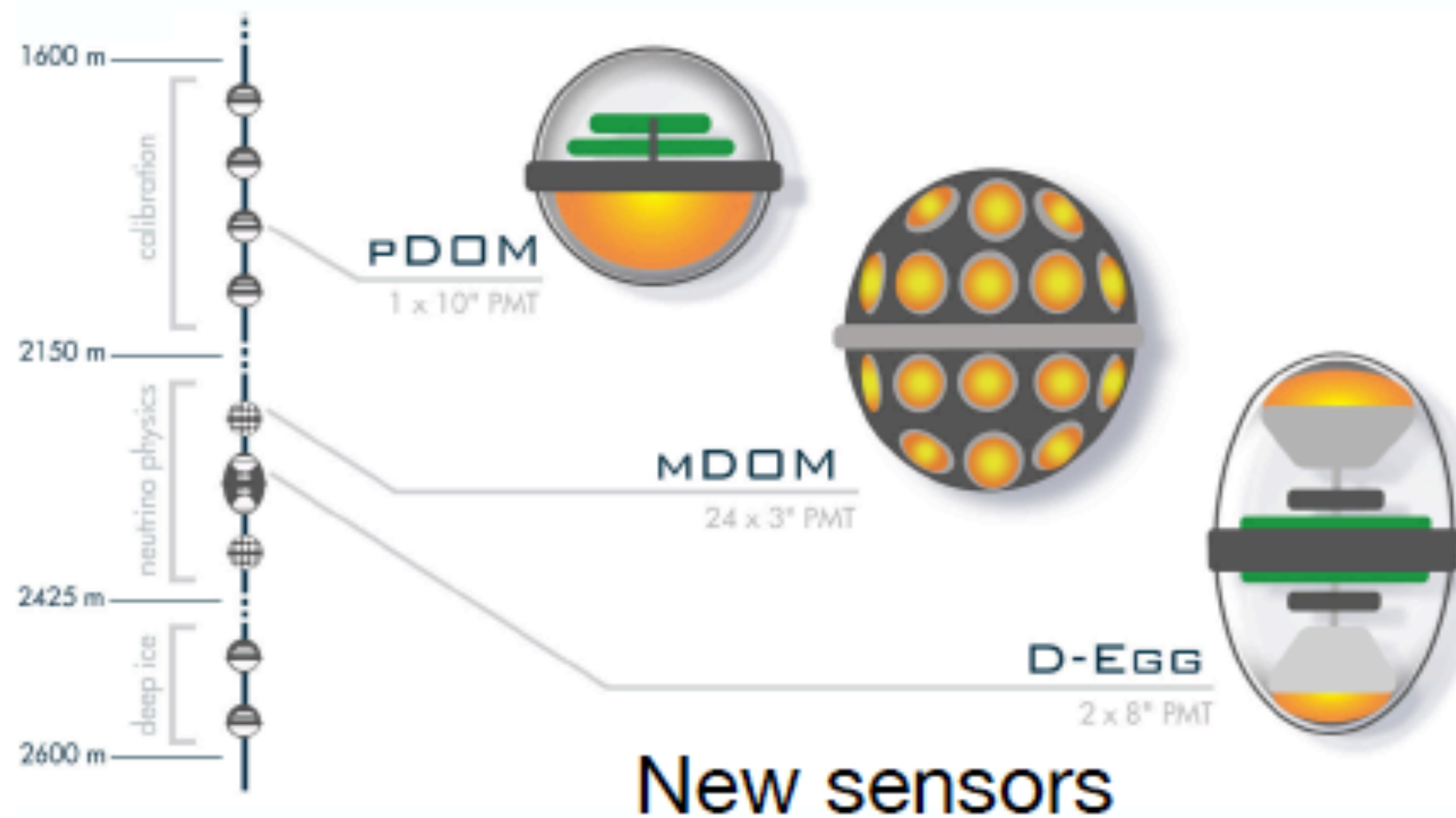




# IceCube Upgrade: near future

## New Optical module design

- Multi-PMTs per modules
  - Larger photocathode area
  - Increased angular acceptance



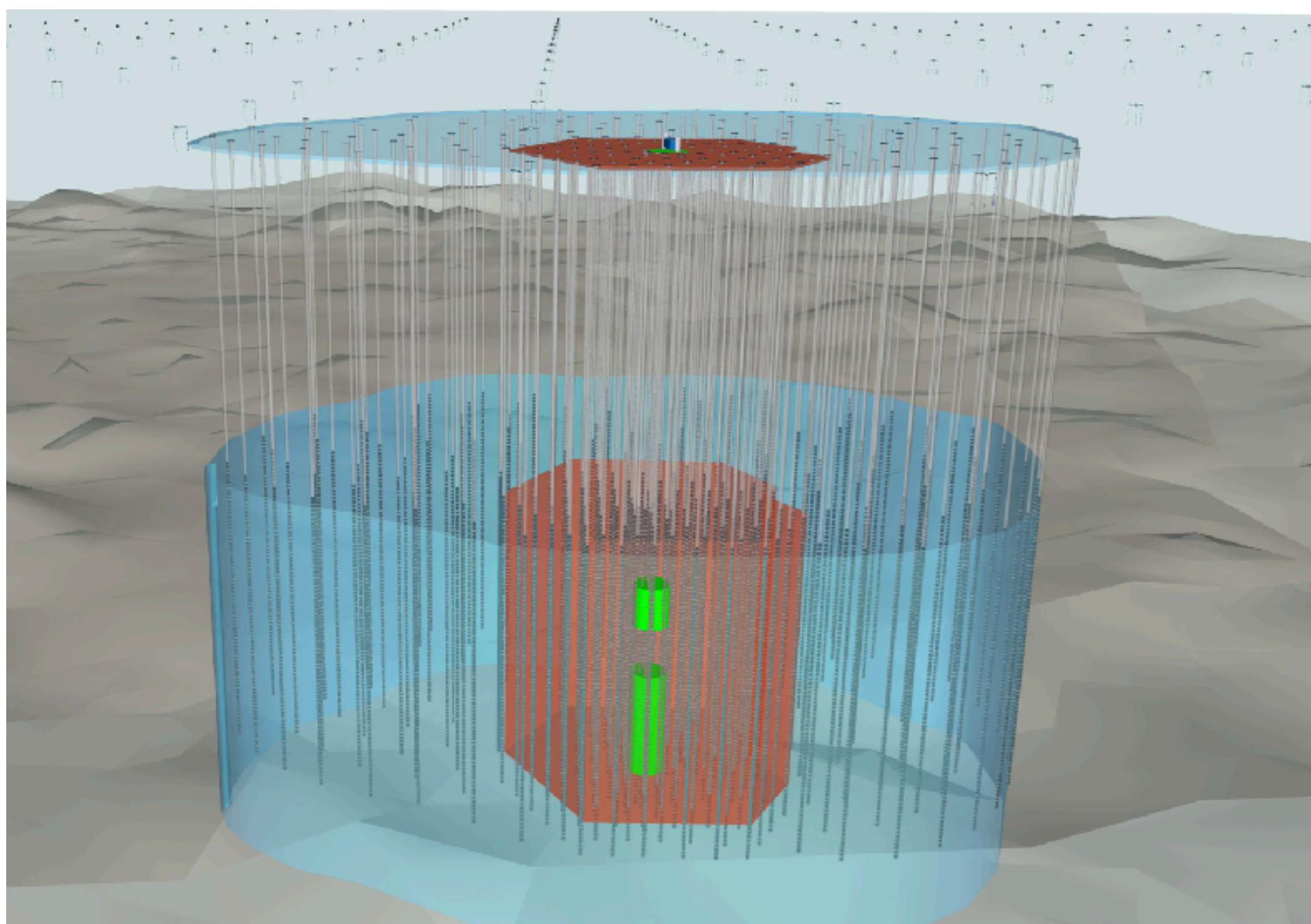
“Design and Performance Goals for the IceCube Upgrade”  
- Poster III-a/2F MT09-710 by J. Koskinen



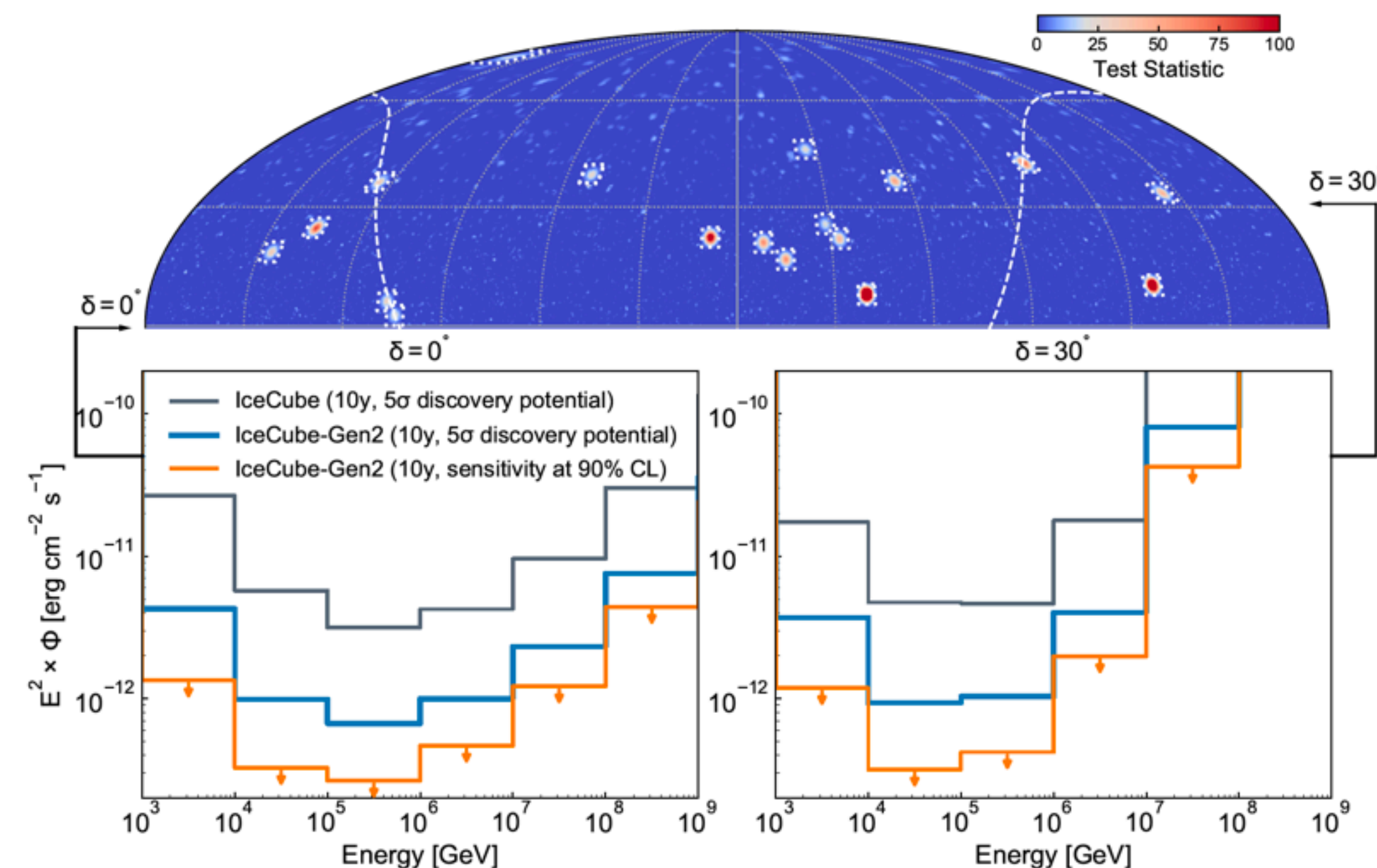
# IceCube Gen-2

## Designed to achieve five times better sensitivity than IceCube array

- Optical array: Eight times larger active volume compared to IceCube filled with improved optical module based on the R&D studies from IceCube Upgrade
- Surface air shower array: Matching with the optical array throughput,  $\sim 40$  times higher coincident events
- Radio array:  $\sim 500 \text{ km}^2$  area of the antenna array for the detection of EeV neutrinos



“Deep-ice Optical Sensor Array for IceCube-Gen2”  
- Poster IV-a/5F MT12-044 by A. Ishihara





Thank you!

