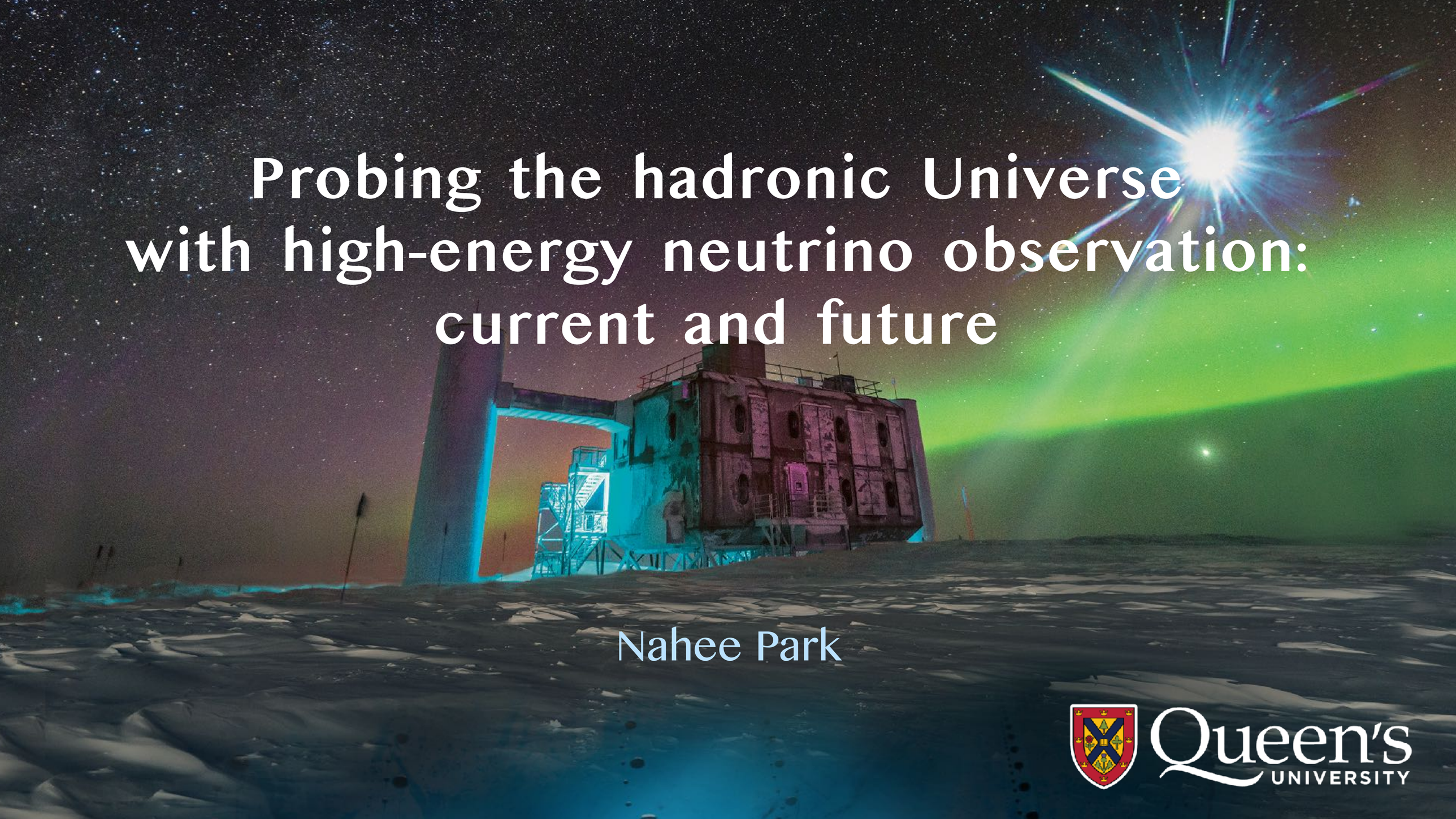
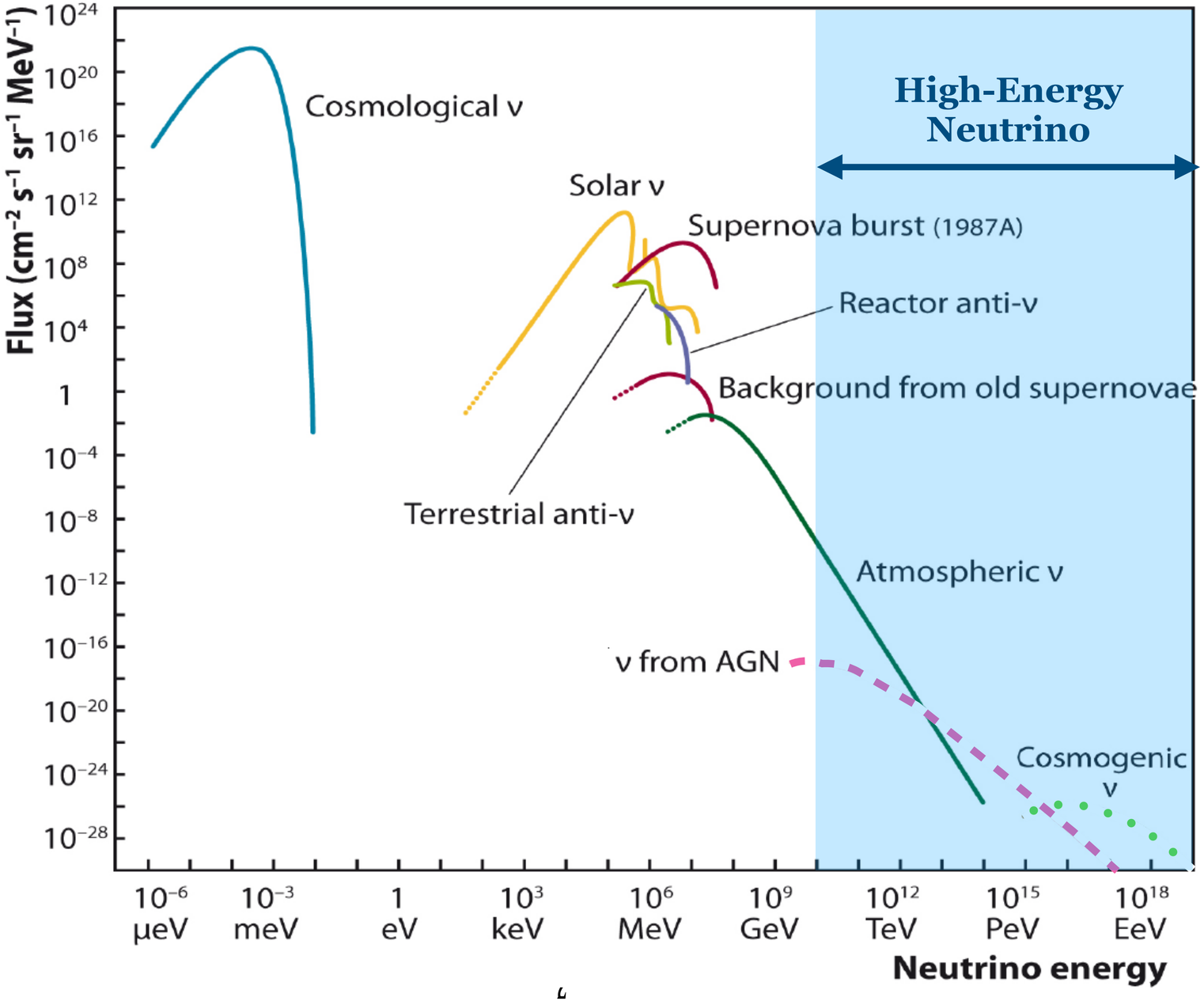


Probing the hadronic Universe with high-energy neutrino observation: current and future

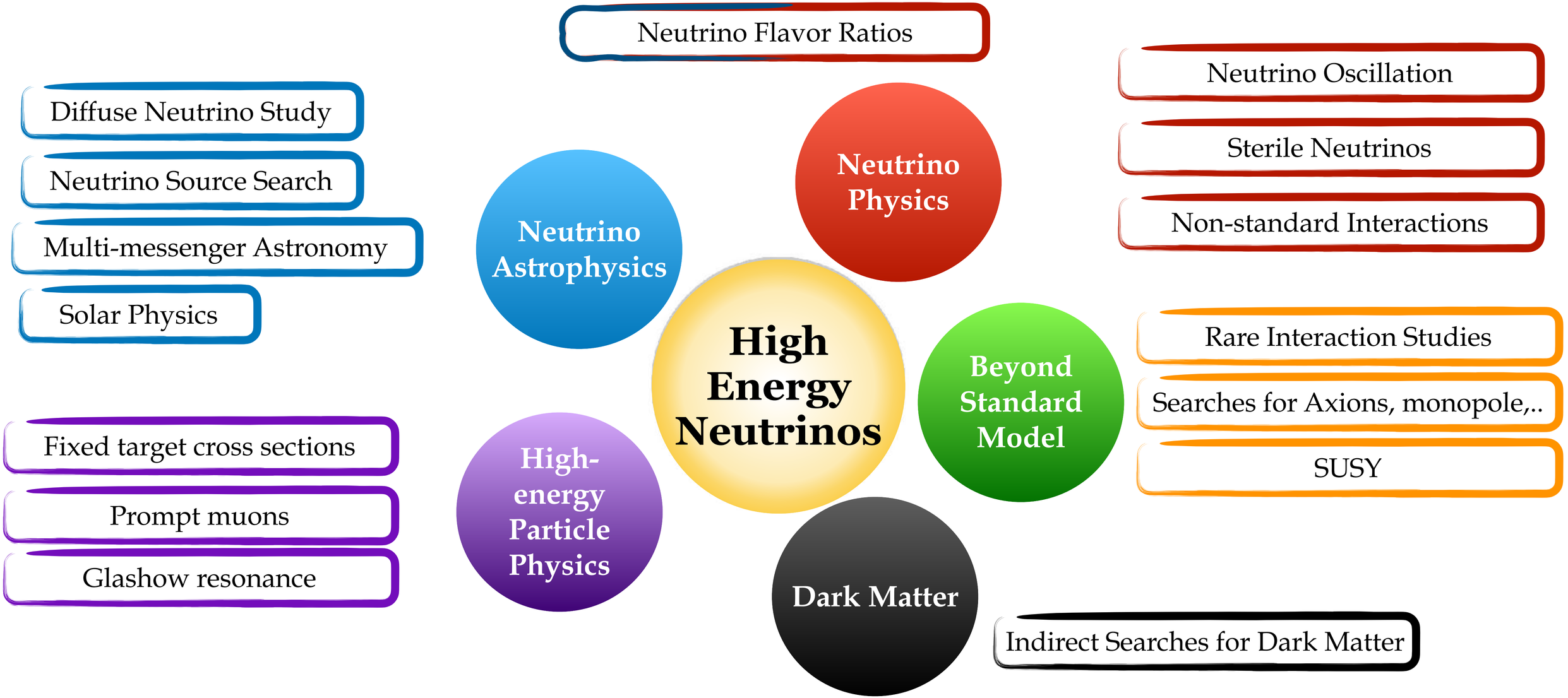
Nahee Park

Queen's UNIVERSITY

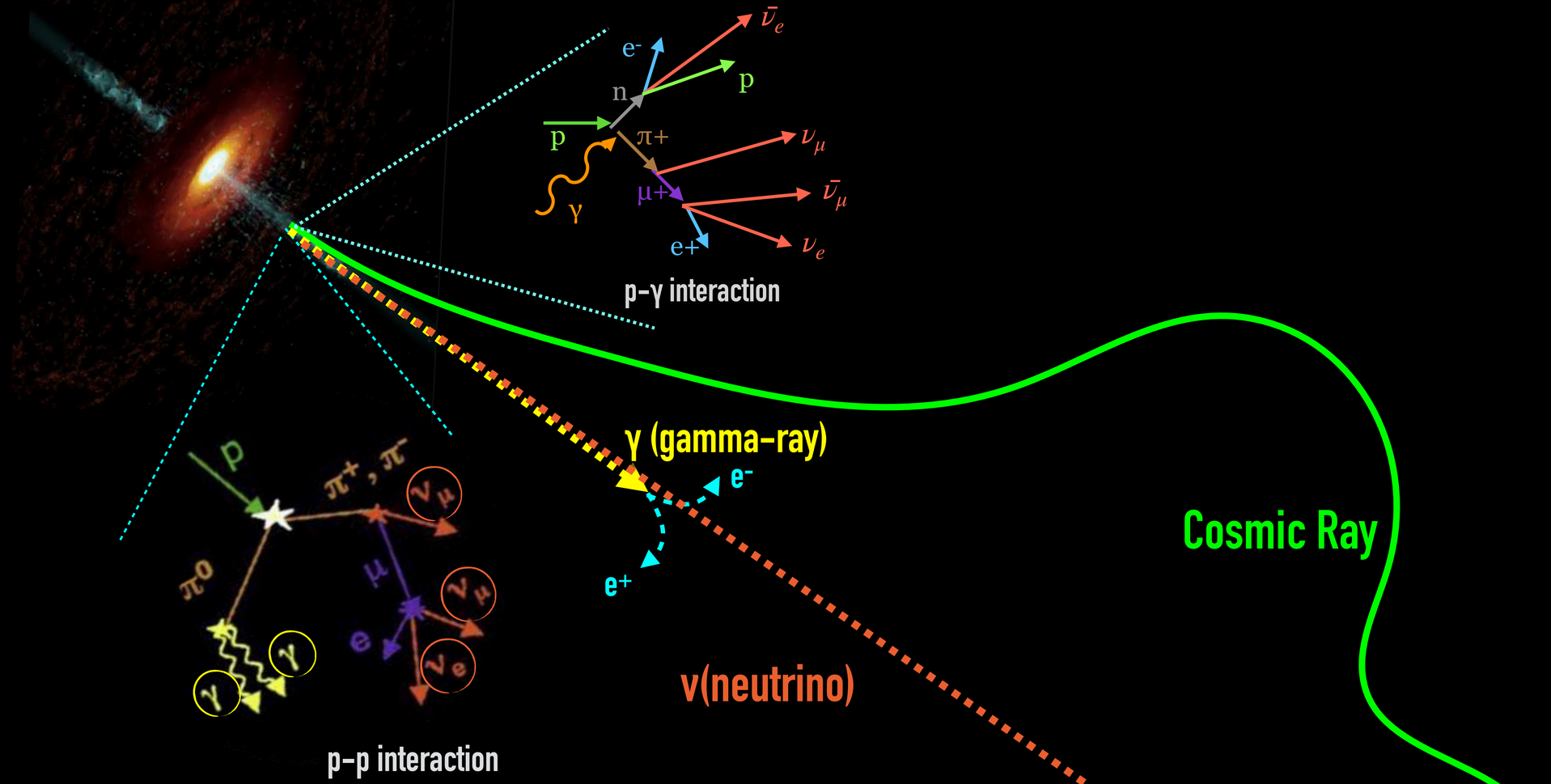
Neutrino Measurements



High Energy Neutrinos



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

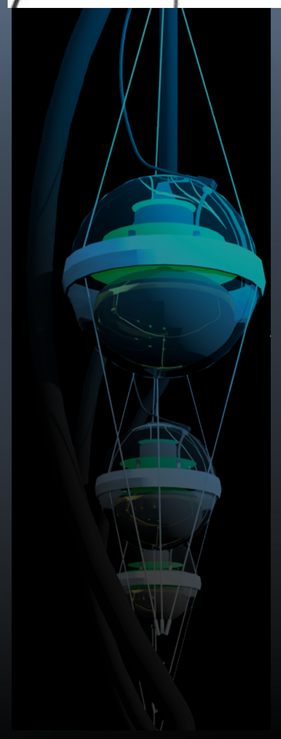


Horizon of VHE gamma-ray (>100 GeV (10^{11} eV)) : z~1

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

IceCube Observatory

- In-Ice array
  - 86 strings with each string contain 60 optical modules (total 5160 optical modules)
    - 10 inch PMT per module
  - threshold : ~ 100 TeV



~ 1 km

~ 1 km

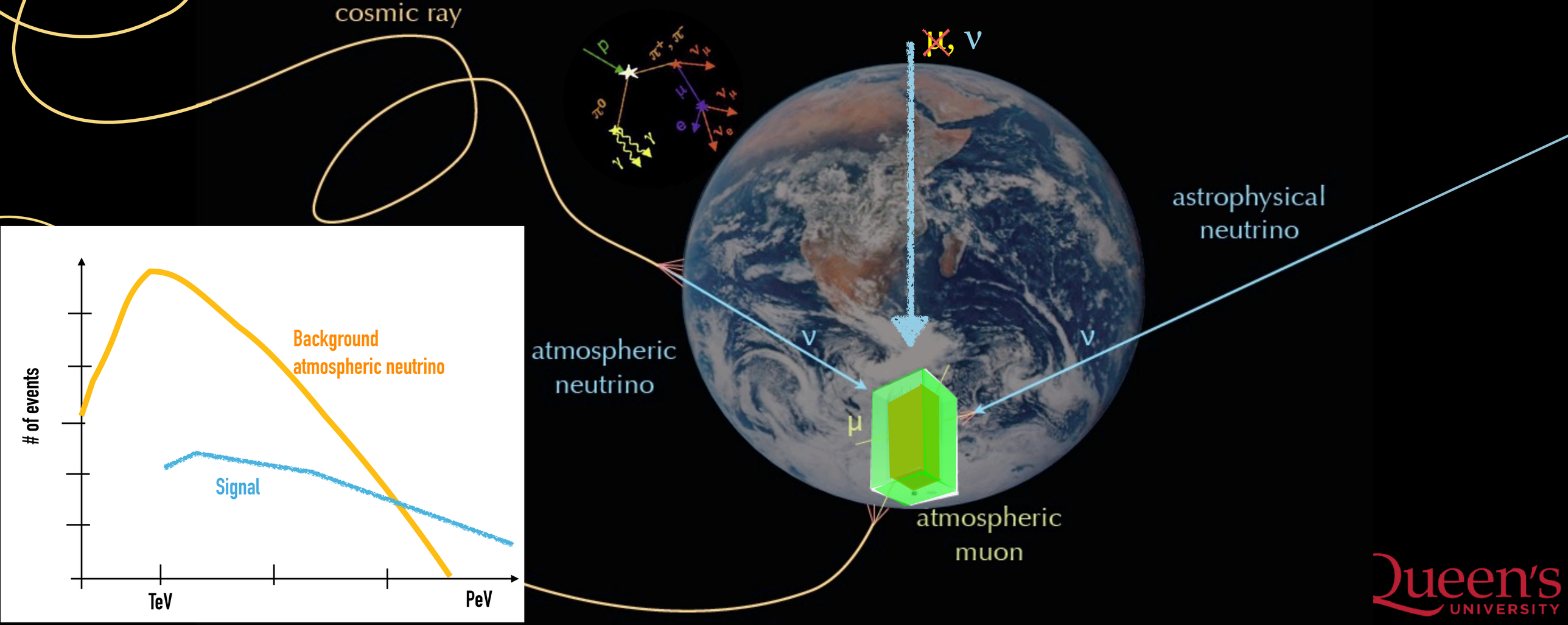
μ

ν_μ

1 cubic km detector designed for neutrino study
Located at the 1.5 km under South Pole
Start the deployment in 2004,
Completion of 86 strings in 2010

Signal & Background

- **Atmospheric muon ~ 10^{11}/year (~3000 events/second)**
- **Atmospheric neutrino→muon ~ 10^5/year (~10 event/hour)**
- **Cosmic neutrino→muon ~ 10/year**



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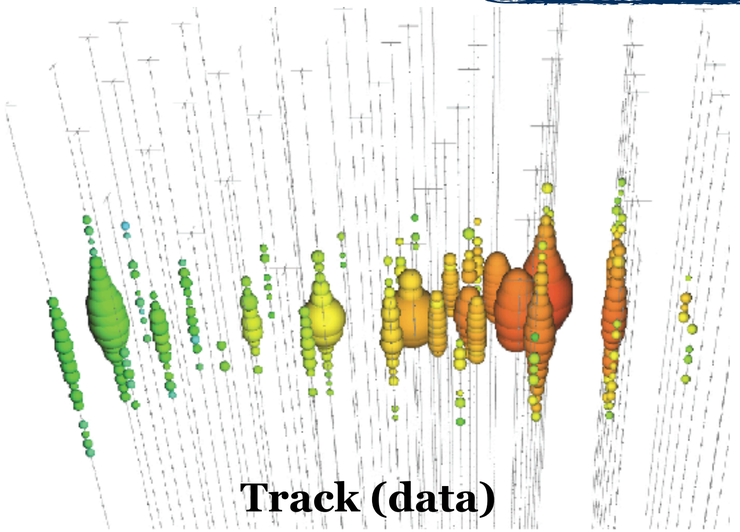
Observed Neutrino Event Types

Charged current

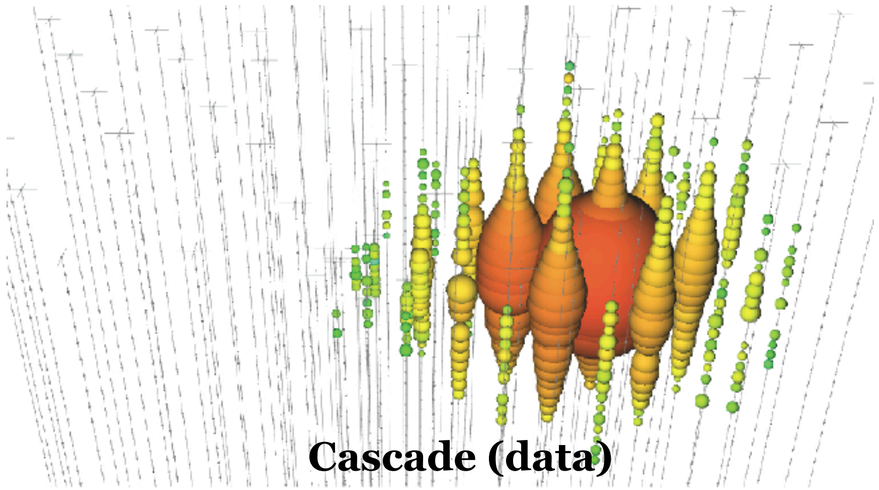
$$\nu_\mu + N \rightarrow \mu + X$$
$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X$$

Neutral current

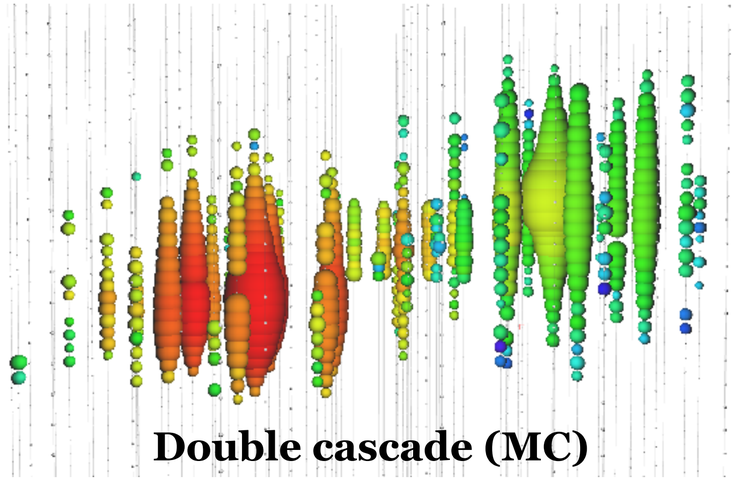
$$\nu_x + N \rightarrow \nu_x + N$$



Track (data)



Cascade (data)



Double cascade (MC)

Angular resolution ~ 0.2° ~ 1°
Energy resolution ~ factor of 2

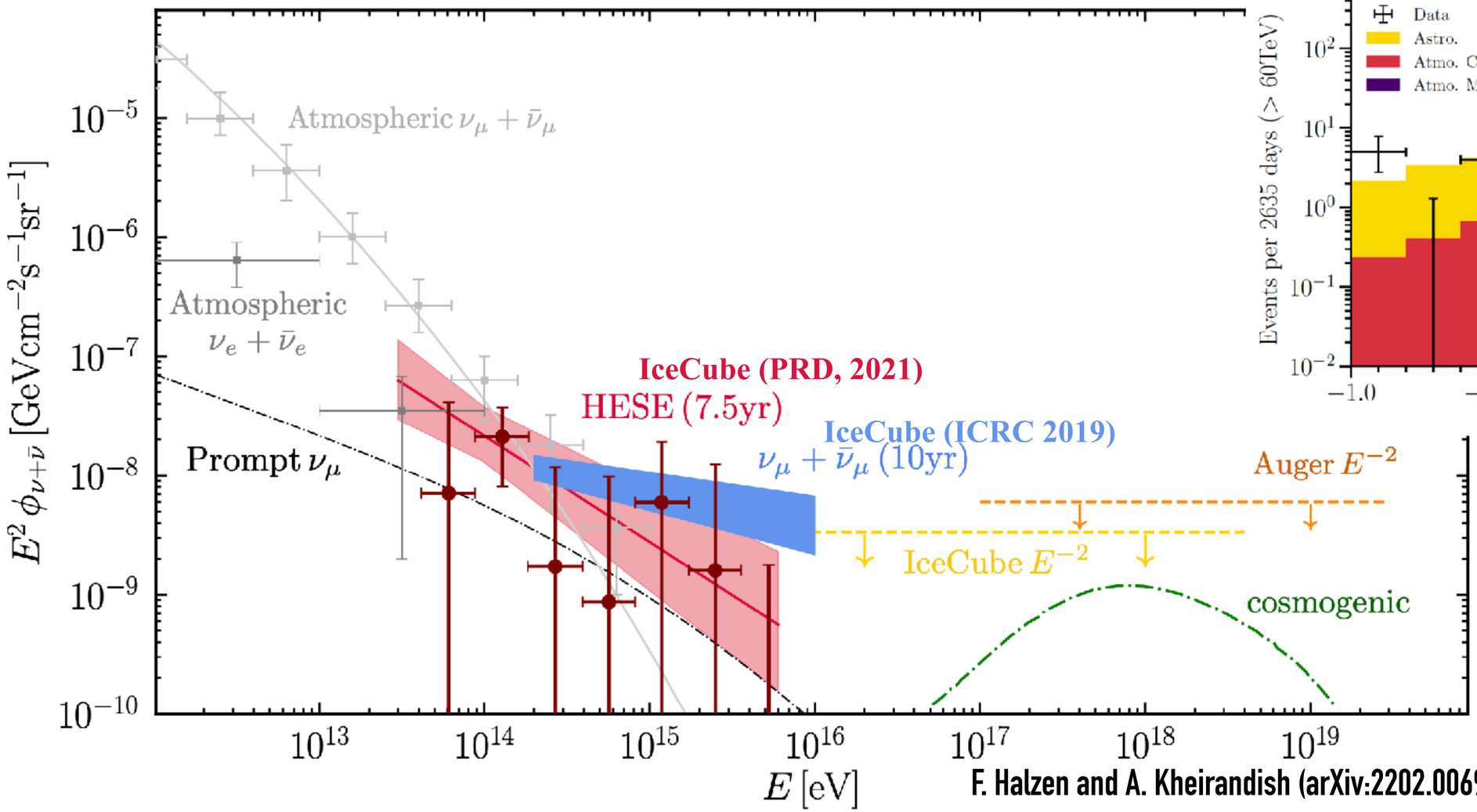
Angular resolution ~ 10 °
Energy resolution ~ 15% (>100 TeV)

Resolvable above 100 TeV deposited energy

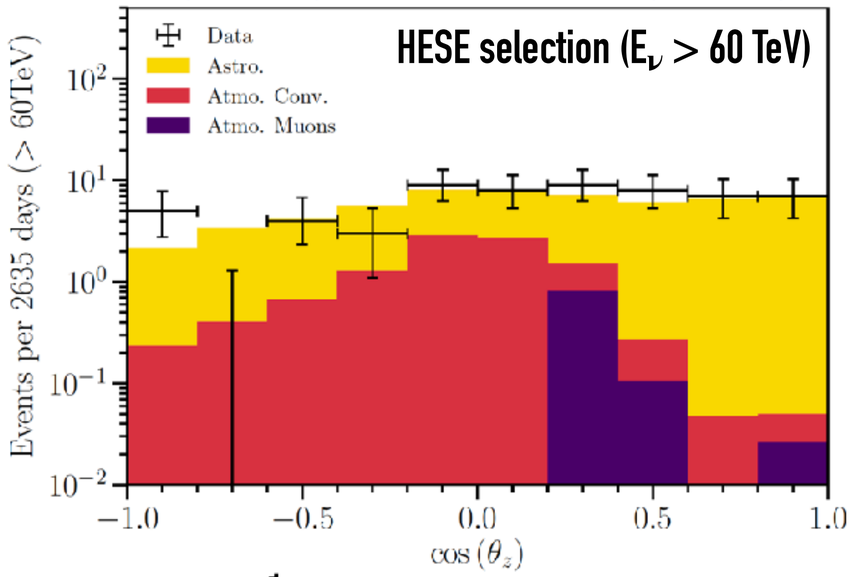
Earlier — Later

High-Energy Astronomical Neutrinos

IceCube has measured the astrophysical neutrino flux with multiple independent analyses



upgoing (North) downgoing (South)

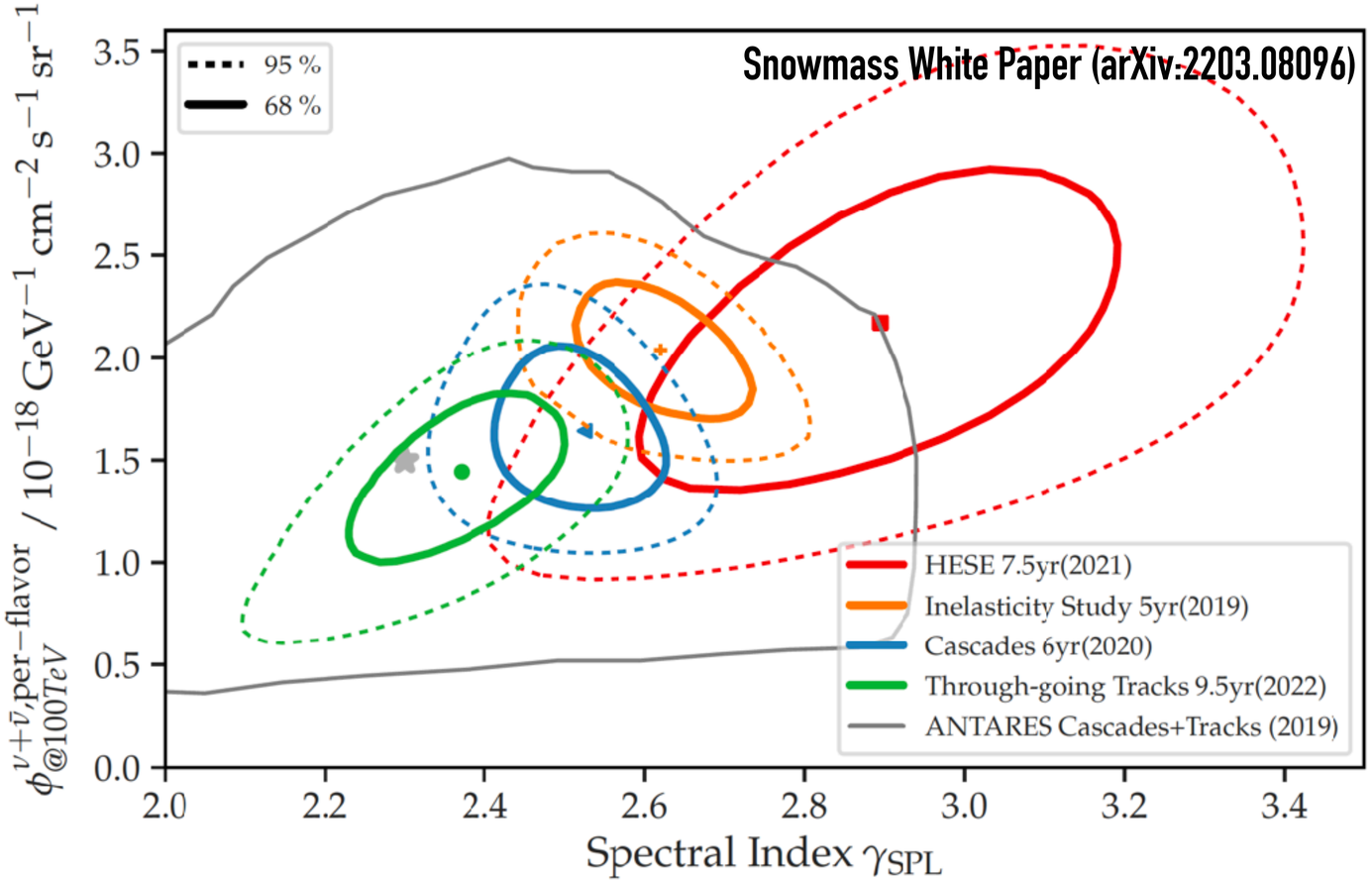


F. Halzen and A. Kheirandish (arXiv:2202.00694)

High-Energy Astronomical Neutrinos

IceCube has measured the astrophysical neutrino flux with multiple independent analyses

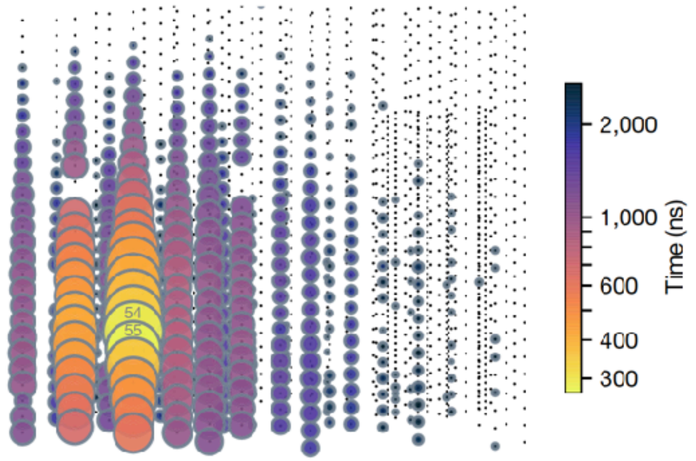
- Independent event selection and analyses generally agree with the flux and index (assuming a single power-law distribution)
  - Slight tension may be caused by differences in flavour composition, energy range, background, …



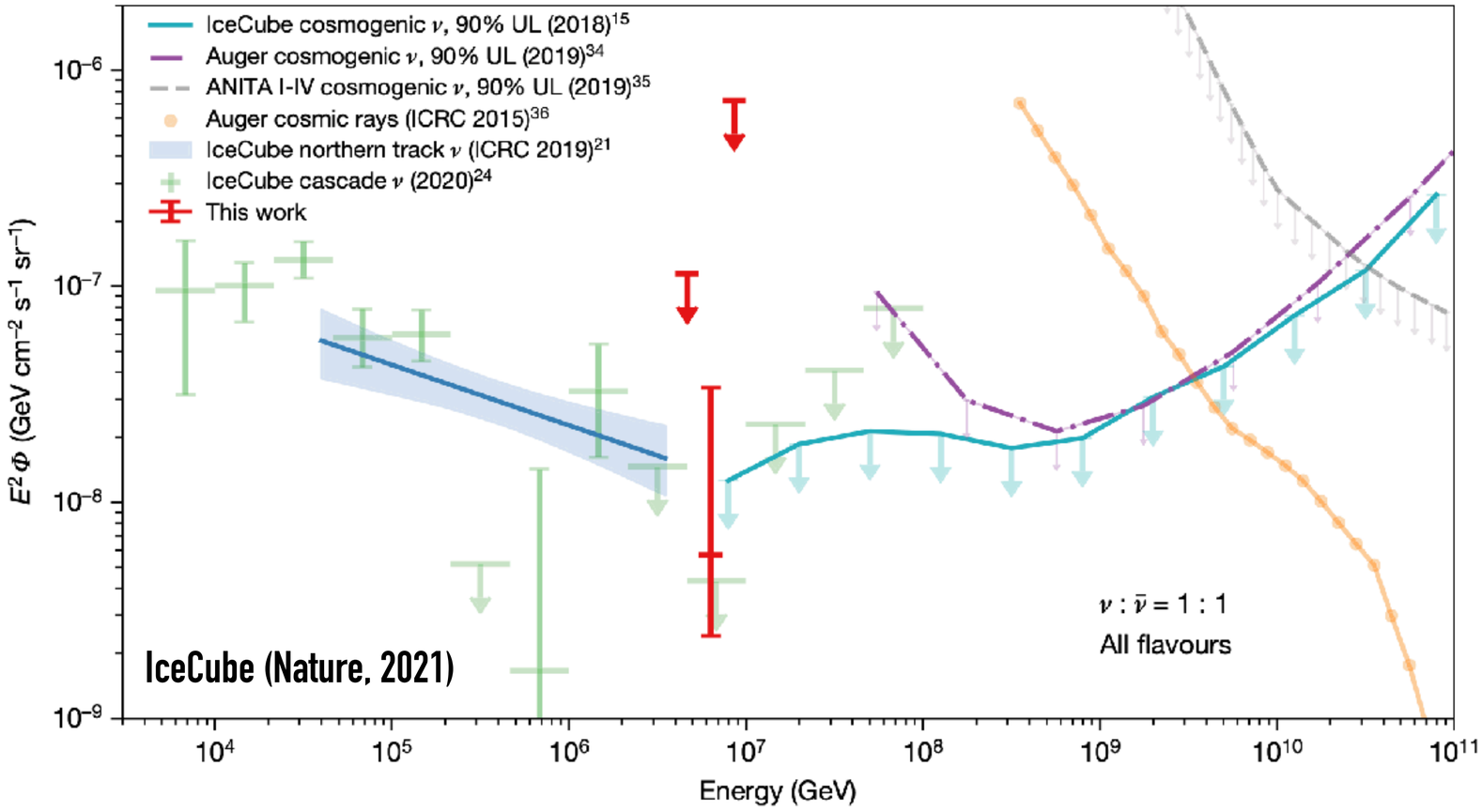
Glashow Resonance

IceCube detected a cascade event with an estimated energy of 6.05 ± 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

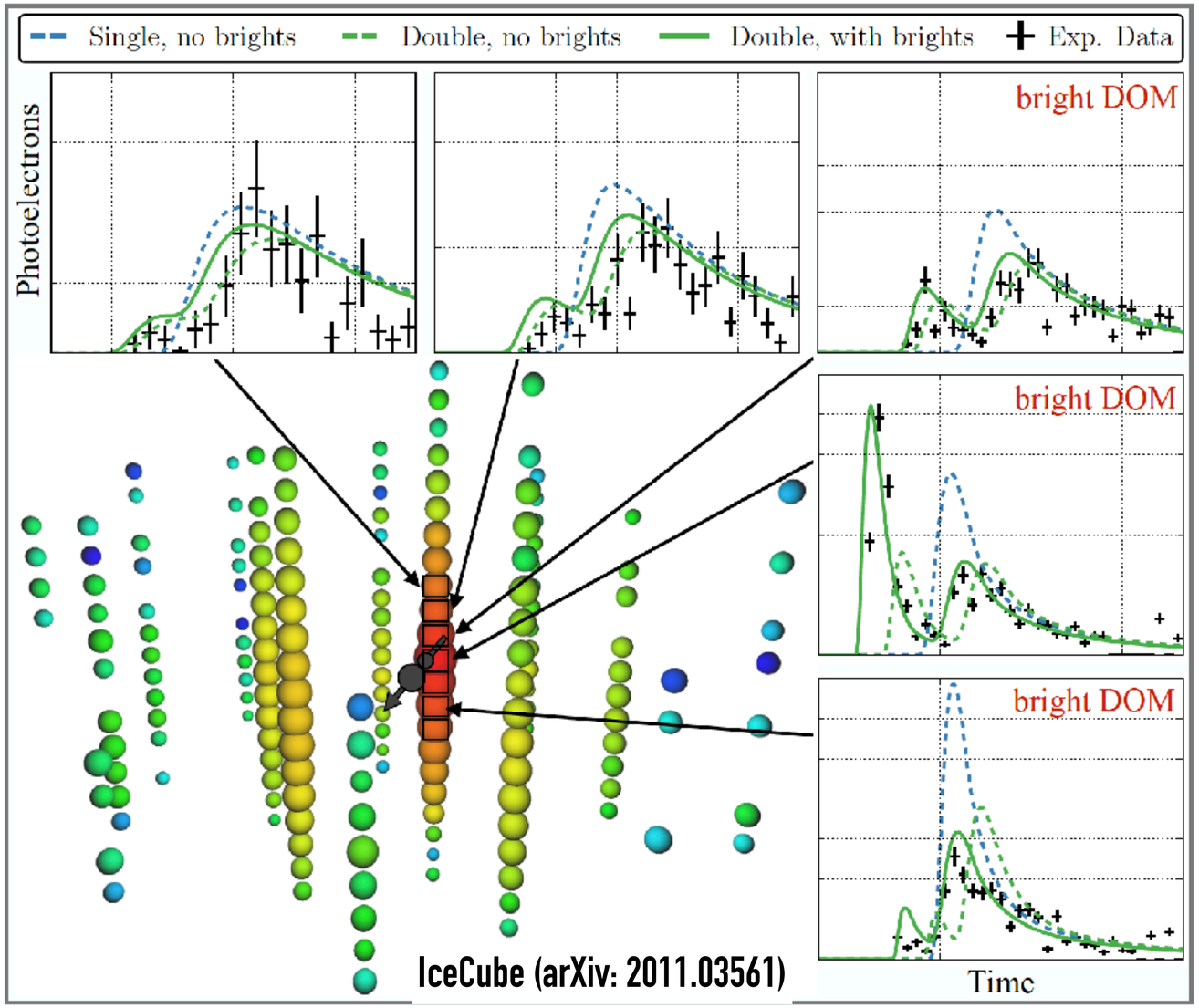


Photons from early muons "outrunning" the cascade



Astrophysical Tau Neutrino

Two candidate events for astrophysical tau neutrinos (7.5 yrs)



Origin of astrophysical neutrinos

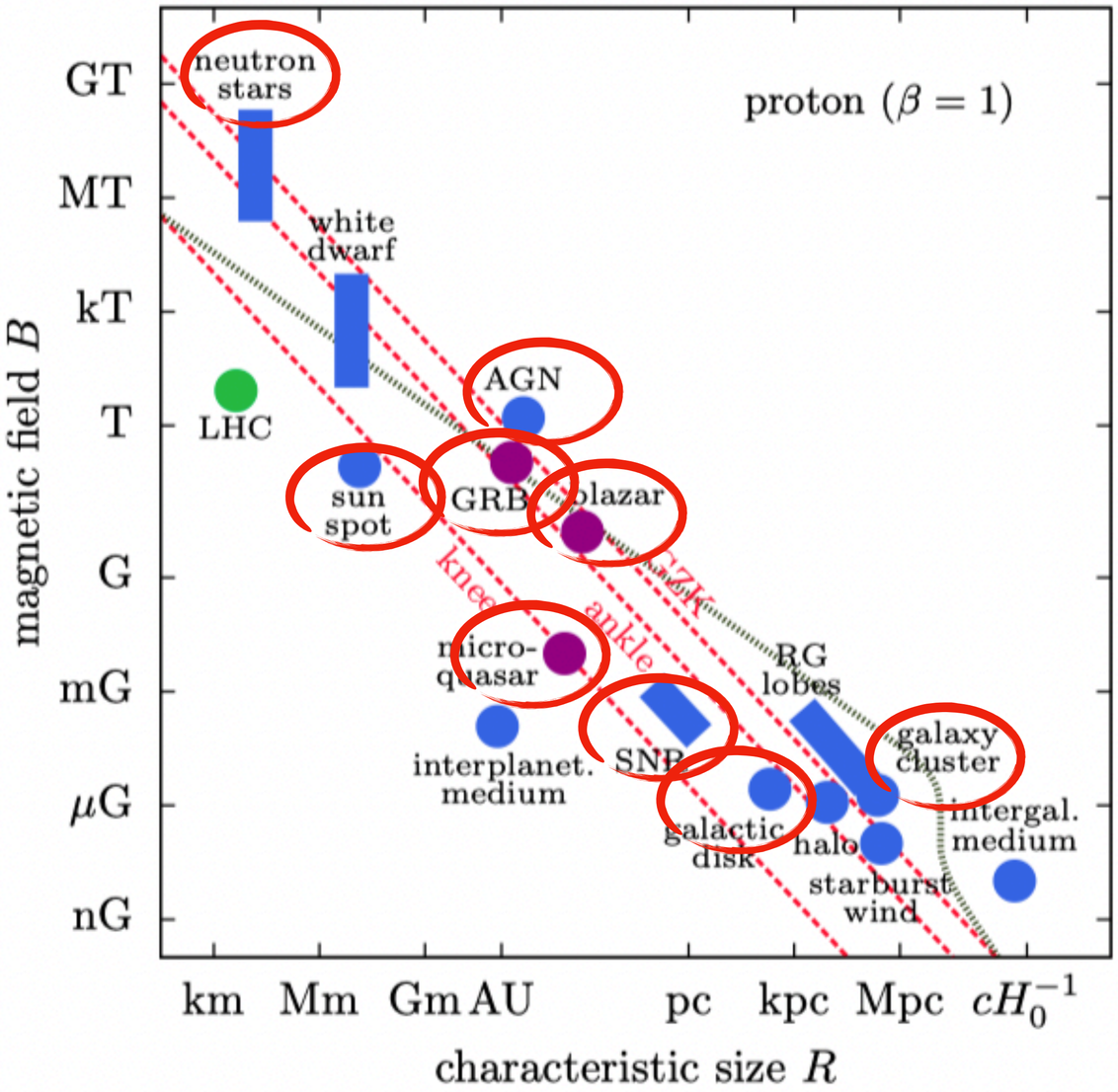
Observed astrophysical diffuse emission is

- 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-γ)



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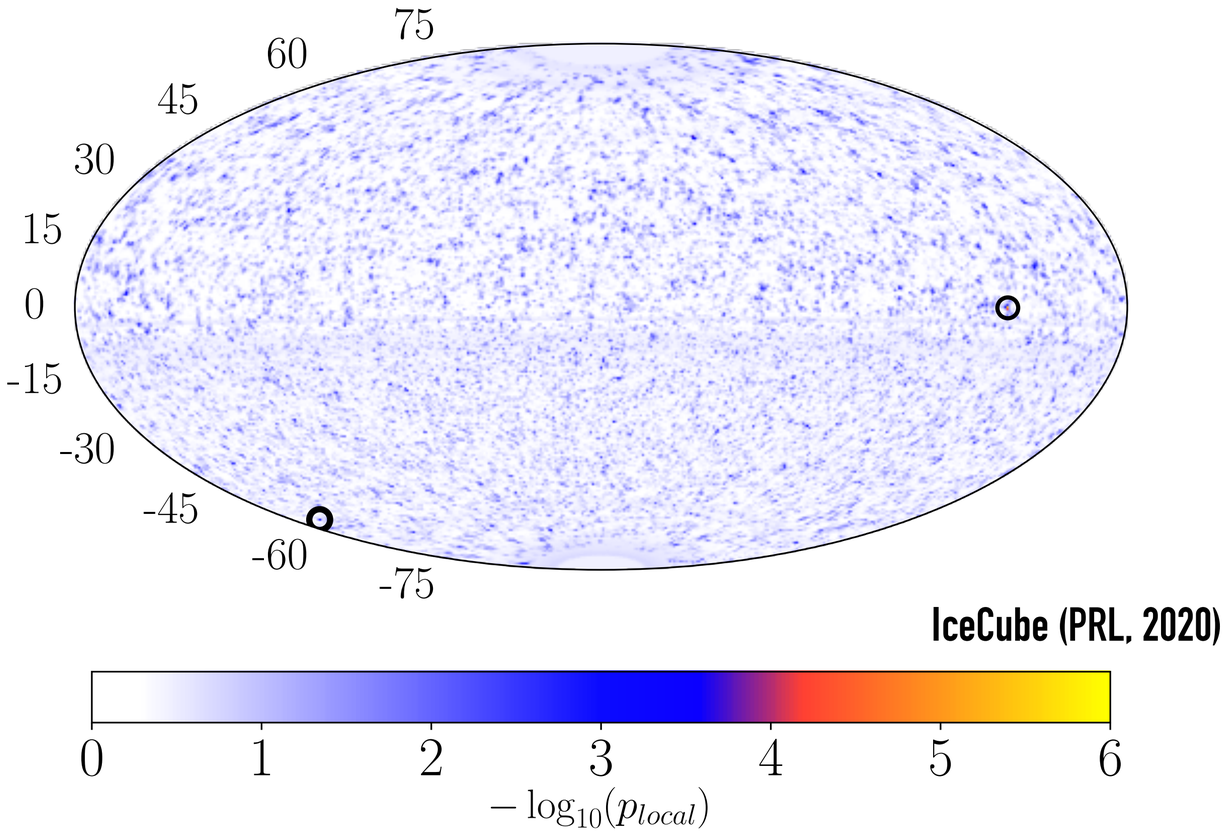
All-Sky Neutrino Searches

Different event selections have different strength for neutrino searches

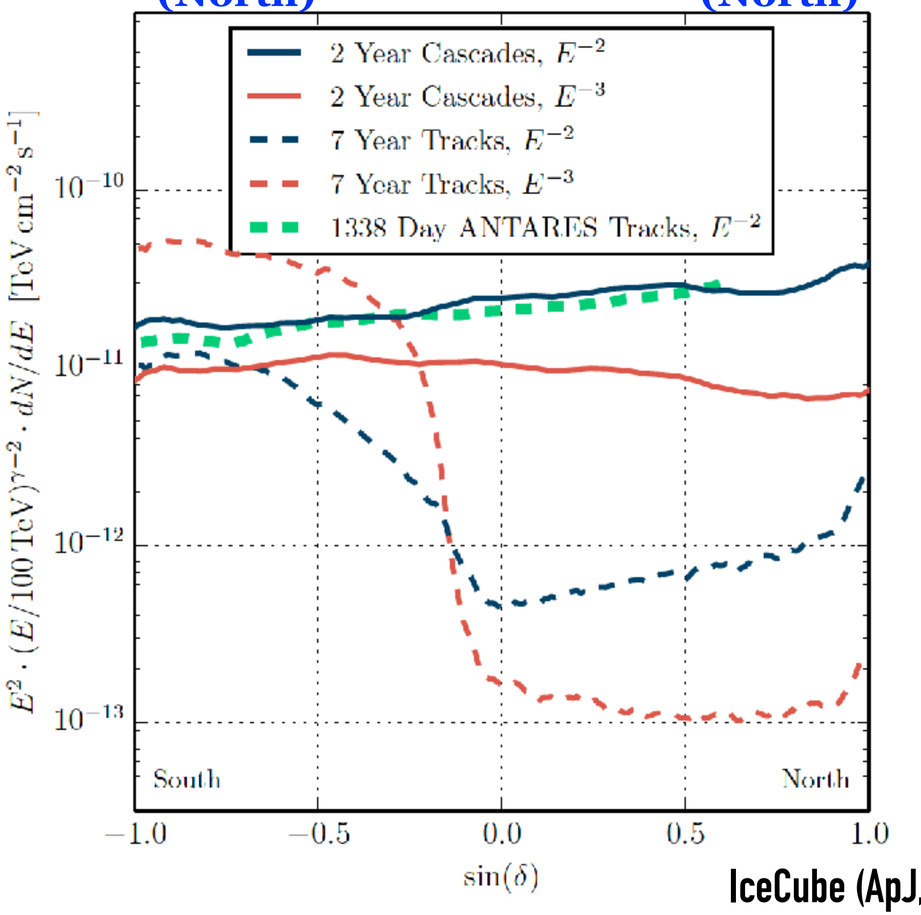
10 Year track-like events (E>10 TeV, $\mu+\nu_\mu$)

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



IceCube (PRL, 2020)

downgoing (North) **upgoing (North)**



IceCube (ApJ, 2019)

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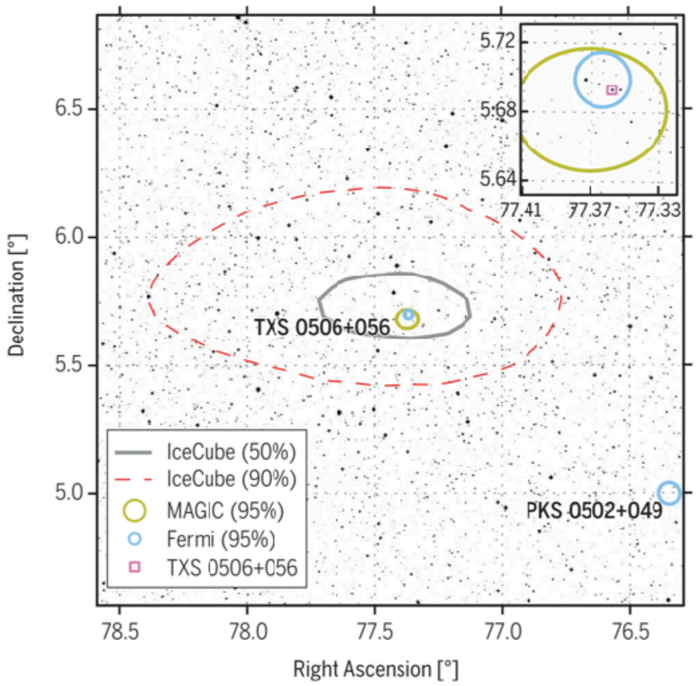
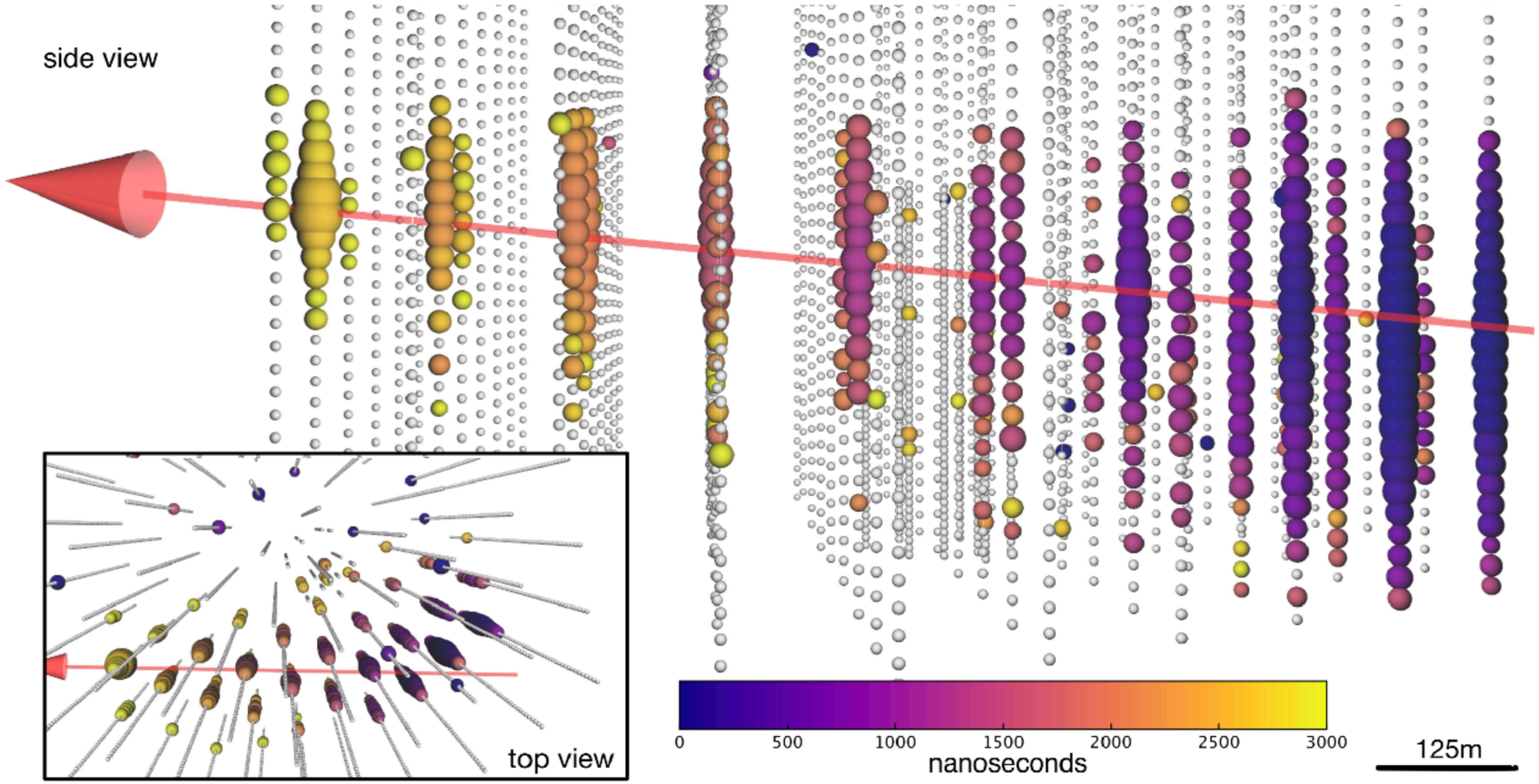
Multi-messenger neutrino follow-up

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





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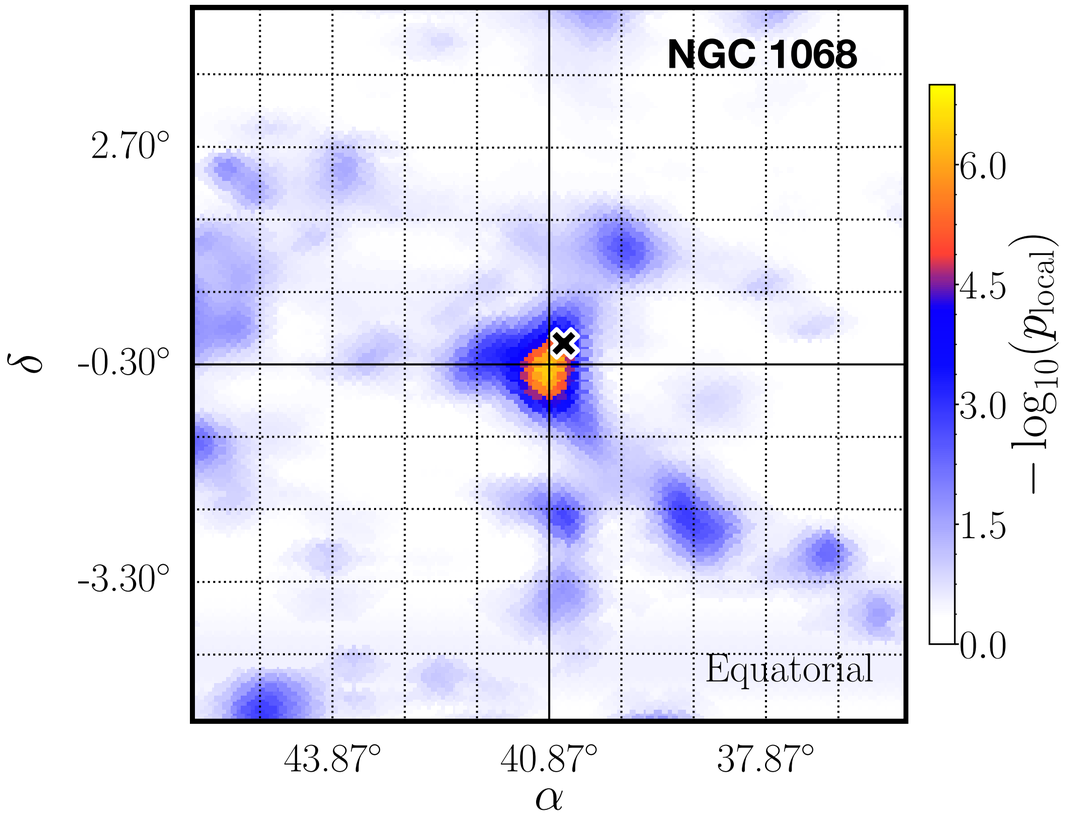
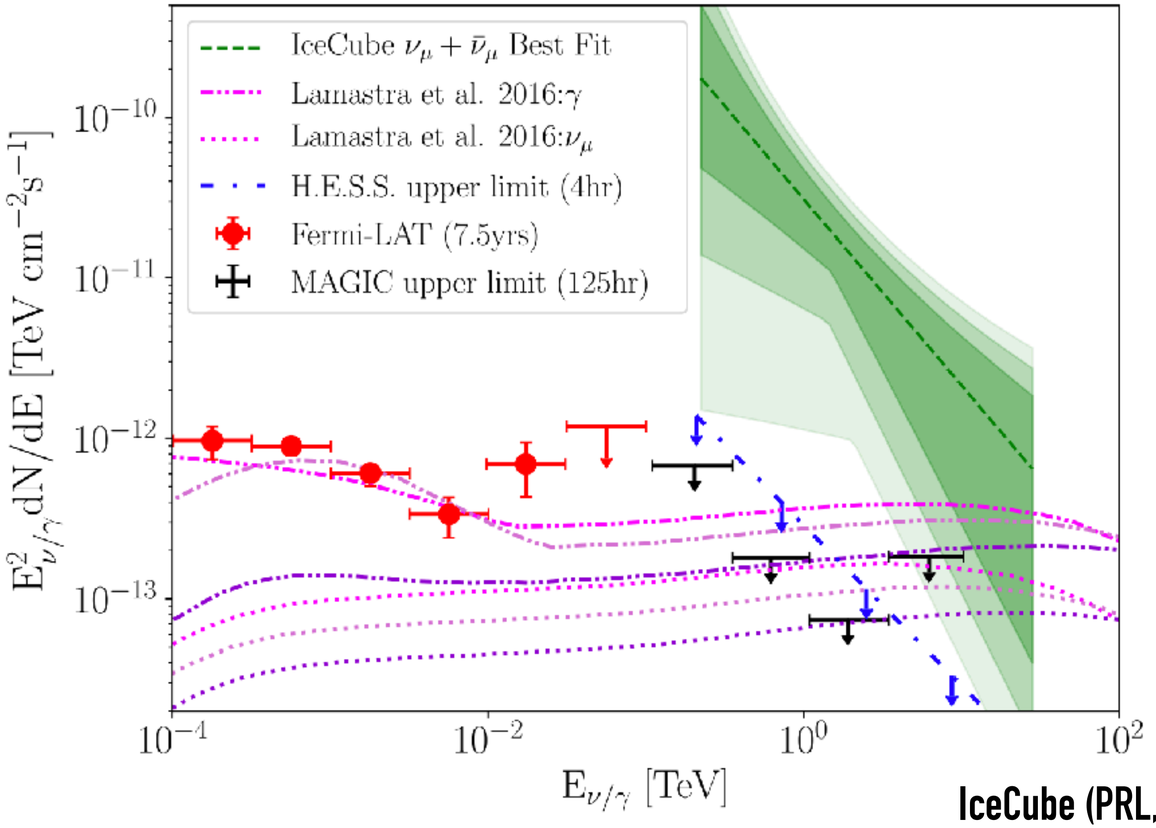
Searches for point sources in 10 year data

The most significant source in the Nothern hemisphere: nearby Seyfert galaxy NGC 1068 w/ significance of 2.9σ

- GeV gamma-ray based catalogue search inconsistent with background w/ 3.3σ





IceCube (PRL, 2020)

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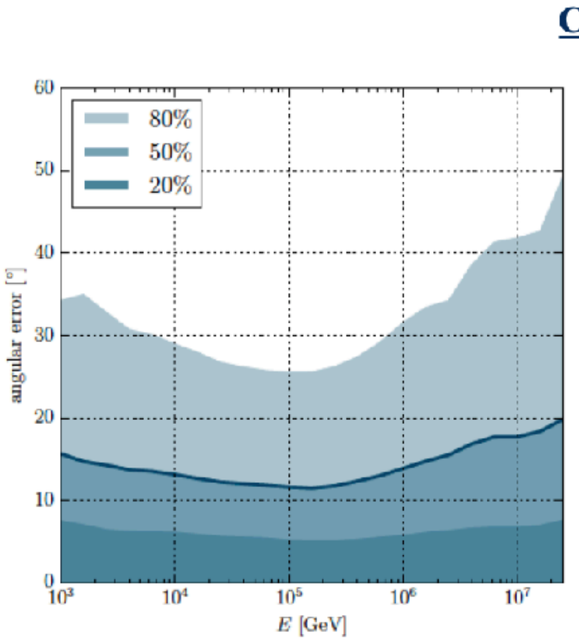
Moving forward

Astrophysical neutrino flux

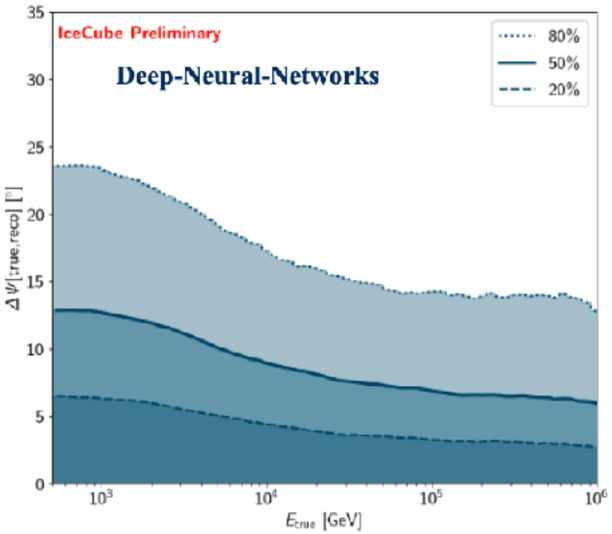
- More measurements
  (e.g. searching for HE ν_τ, different event selection,…)
- Combined analysis to study the properties

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



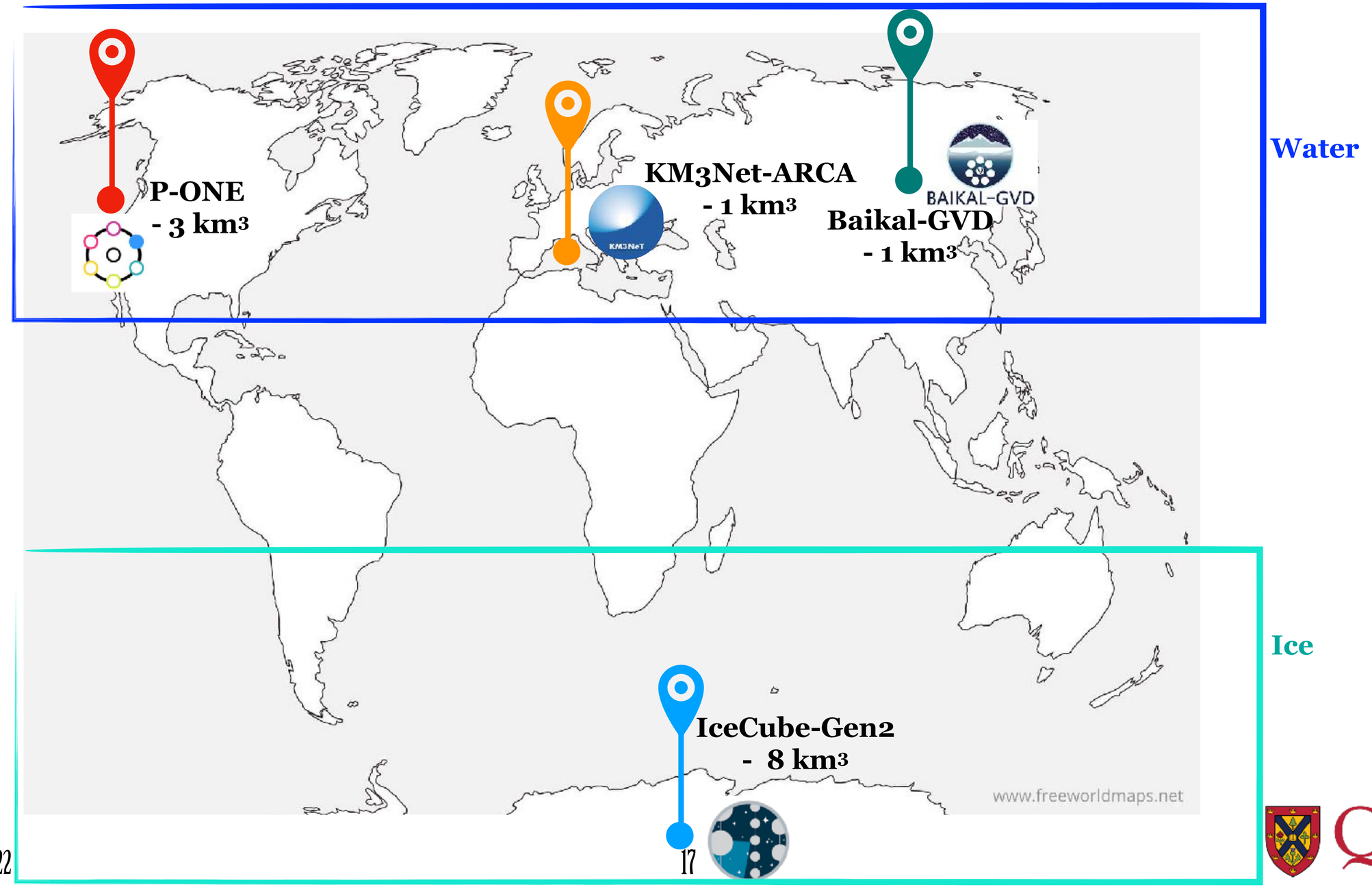
IceCube (ApJ, 2017)



IceCube (ICRC2021)

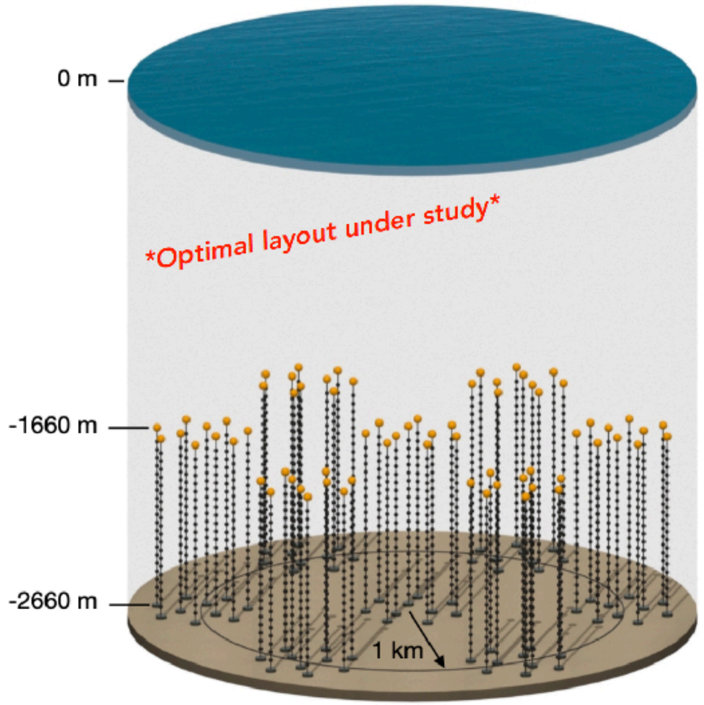
→ To improve our knowledge of high-energy neutrinos, we need larger and more sensitive neutrino detectors!

Future High Energy Neutrino Observatories

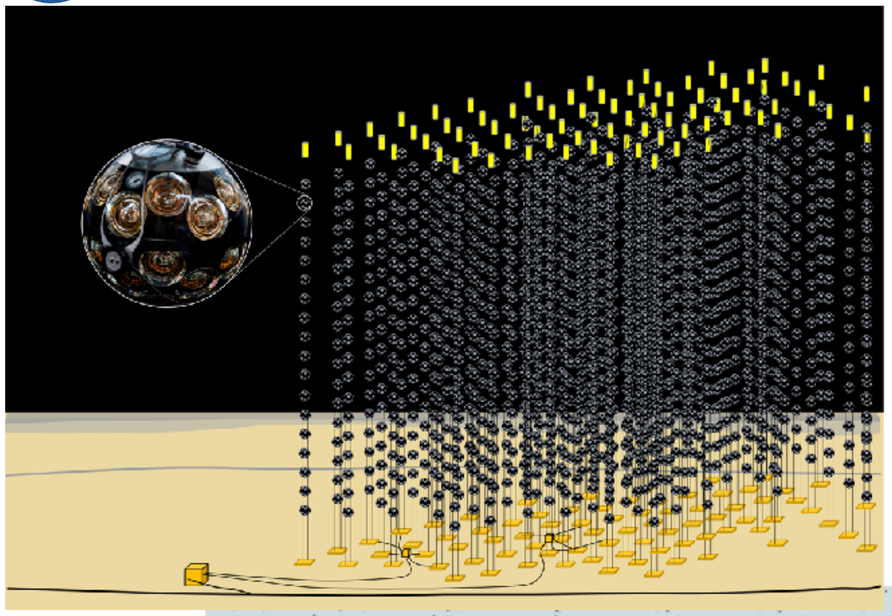


Future High Energy Neutrino Observatories

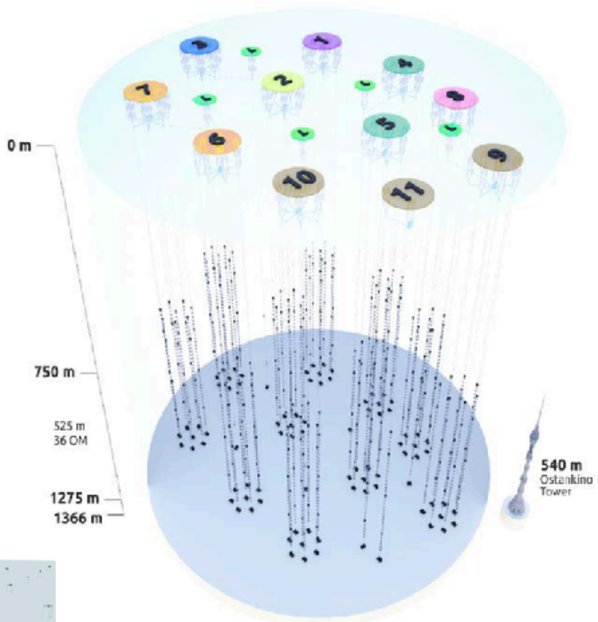
P-ONE - 3 km³



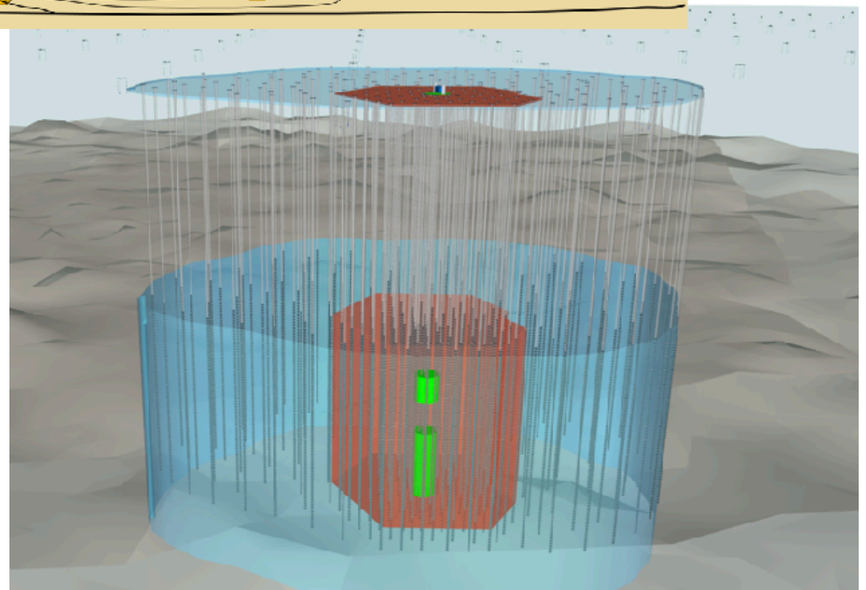
KM3Net-ARCA- 1 km³



Baikal-GVD- 1 km³



IceCube-Gen2 - 8 km³



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New Optical module

New Optical module design

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

KM3Net DOM

P-ONE DOM

Summary

IceCube has opened a new era for high-energy neutrino astrophysics.

- Astrophysical neutrino flux is firmly established. However, there are still many questions remaining to be answered including the origin of the flux.

Moving forward, we need larger high-energy neutrino observatories

- Essential to have multiple observatories in different medium/geographic locations
  - 1 successful neutrino multi-messenger observation in 10 years w/ 1 km^3 detector
  - 1 Glashow candidate / 2 tau-neutrino candidates in 5 years/8 years of searches
- Guaranteed to have many discoveries!