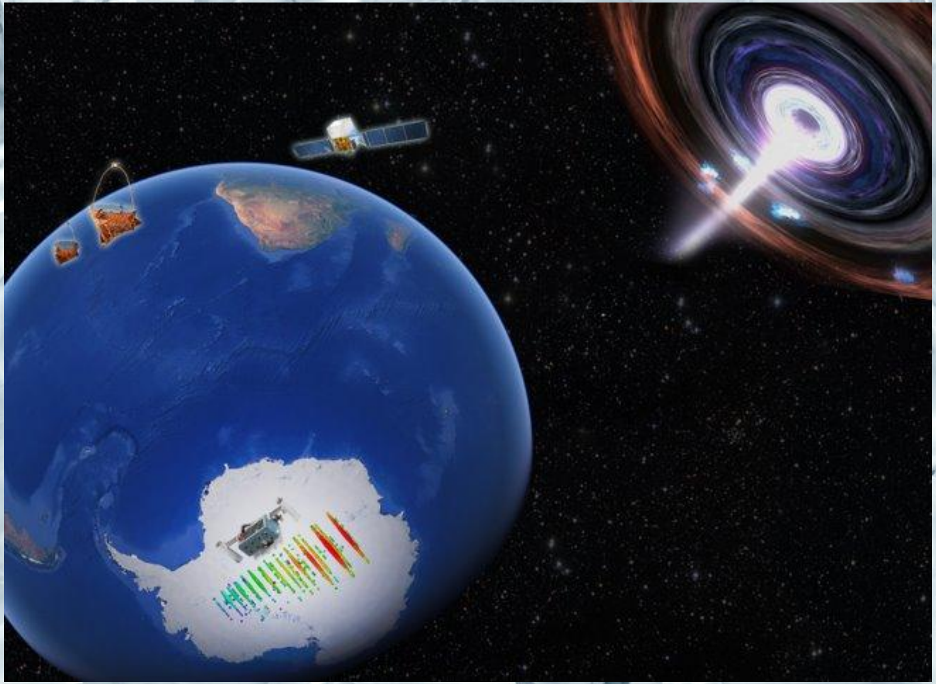
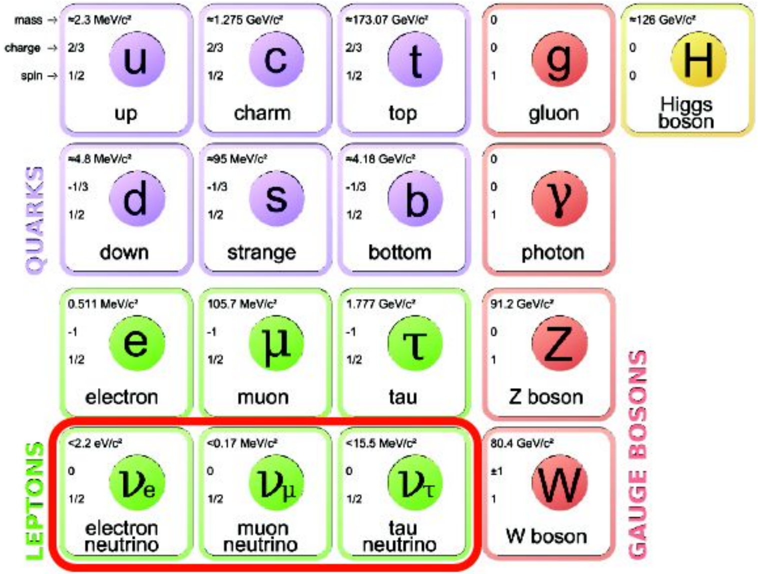
Neutrino astrophysics with IceCube

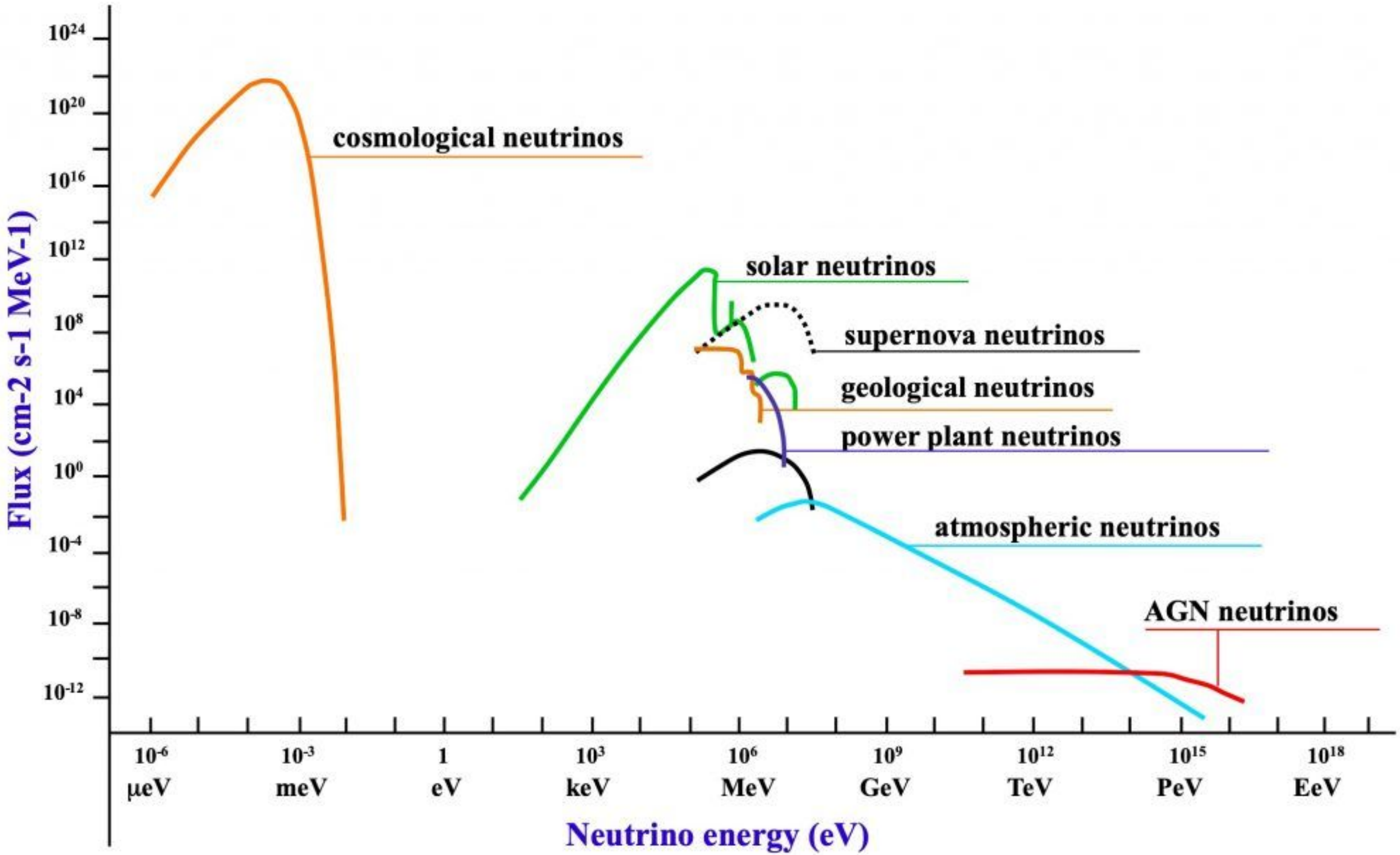


Patrick Hatch (Queen's University) for the IceCube collaboration
EIEIOO 2024

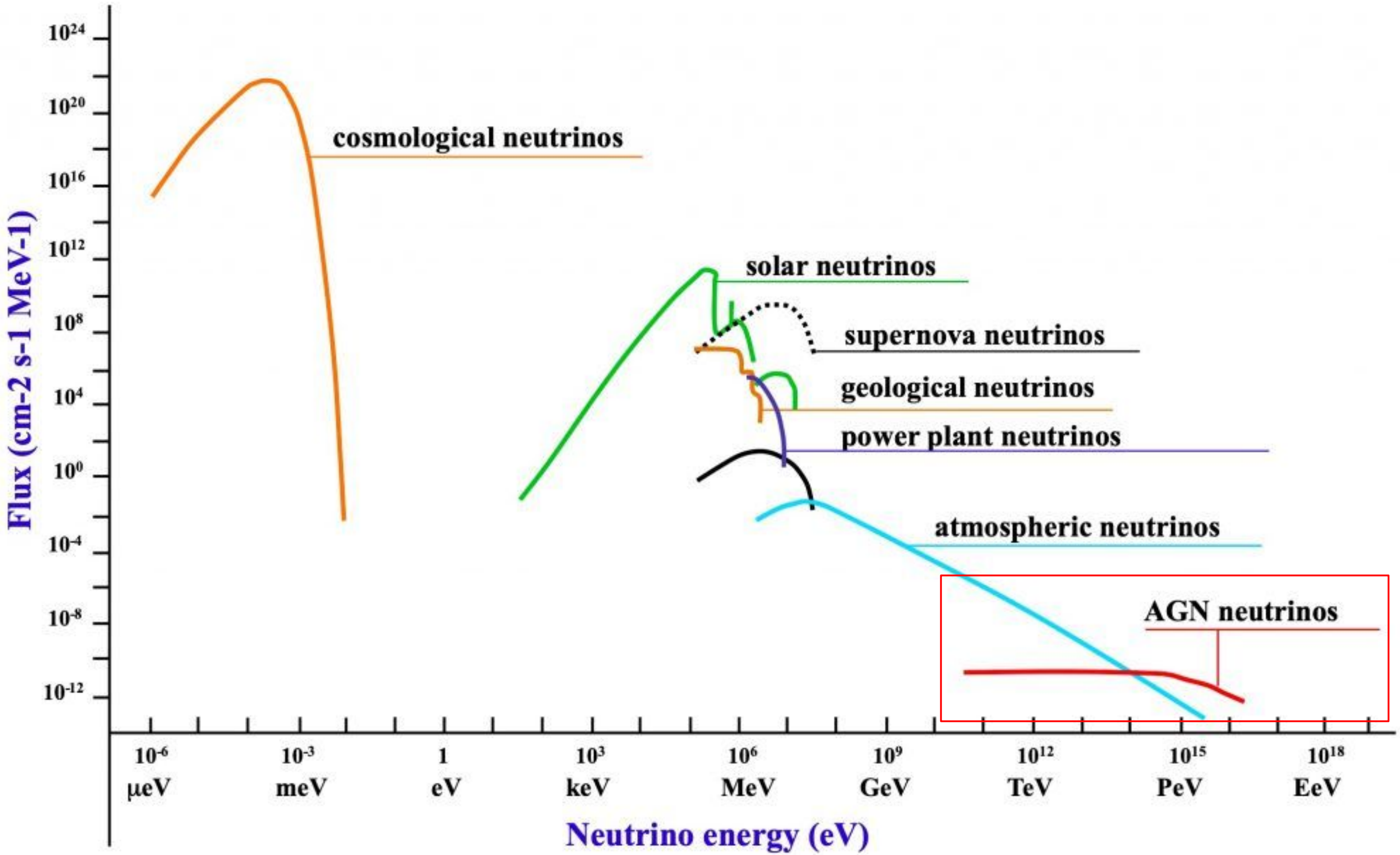
Neutrinos

- Neutrinos have already been introduced here
- VERY light, neutral particles
- Only interact very weakly
- Very prevalent in the universe
- Three flavours





Flux (cm-2 s-1 MeV-1)
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
10^{0}
10^{-4}
10^{-8}
10^{-12}
cosmological neutrinos
solar neutrinos
supernova neutrinos
geological neutrinos
power plant neutrinos
atmospheric neutrinos
AGN neutrinos
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy (eV)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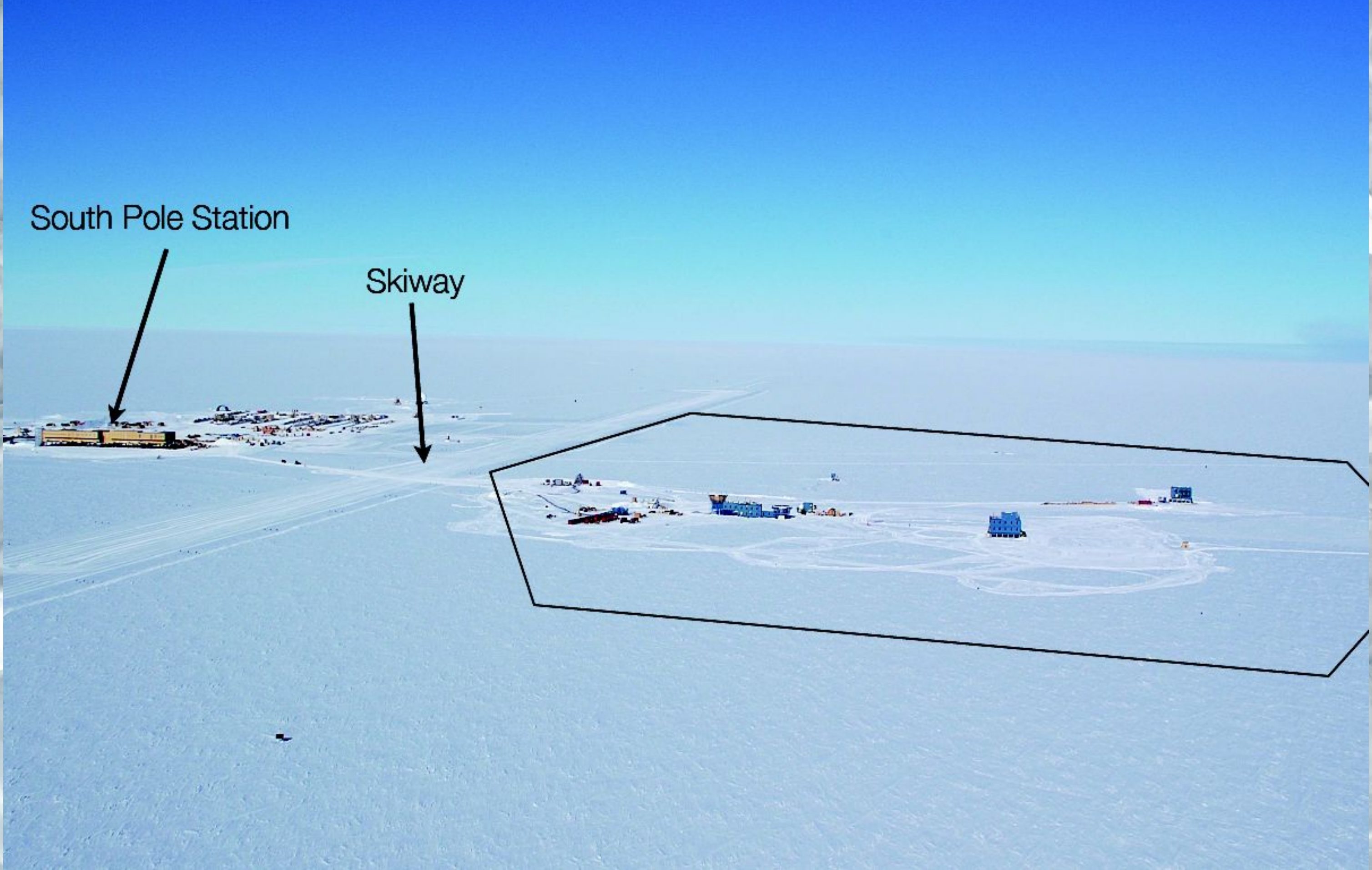
1 eV
10^3 keV
10^6 MeV
10^9 GeV
10^12 TeV
10^15 PeV
10^18 EeV
Neutrino energy (eV)

Detector Wish List

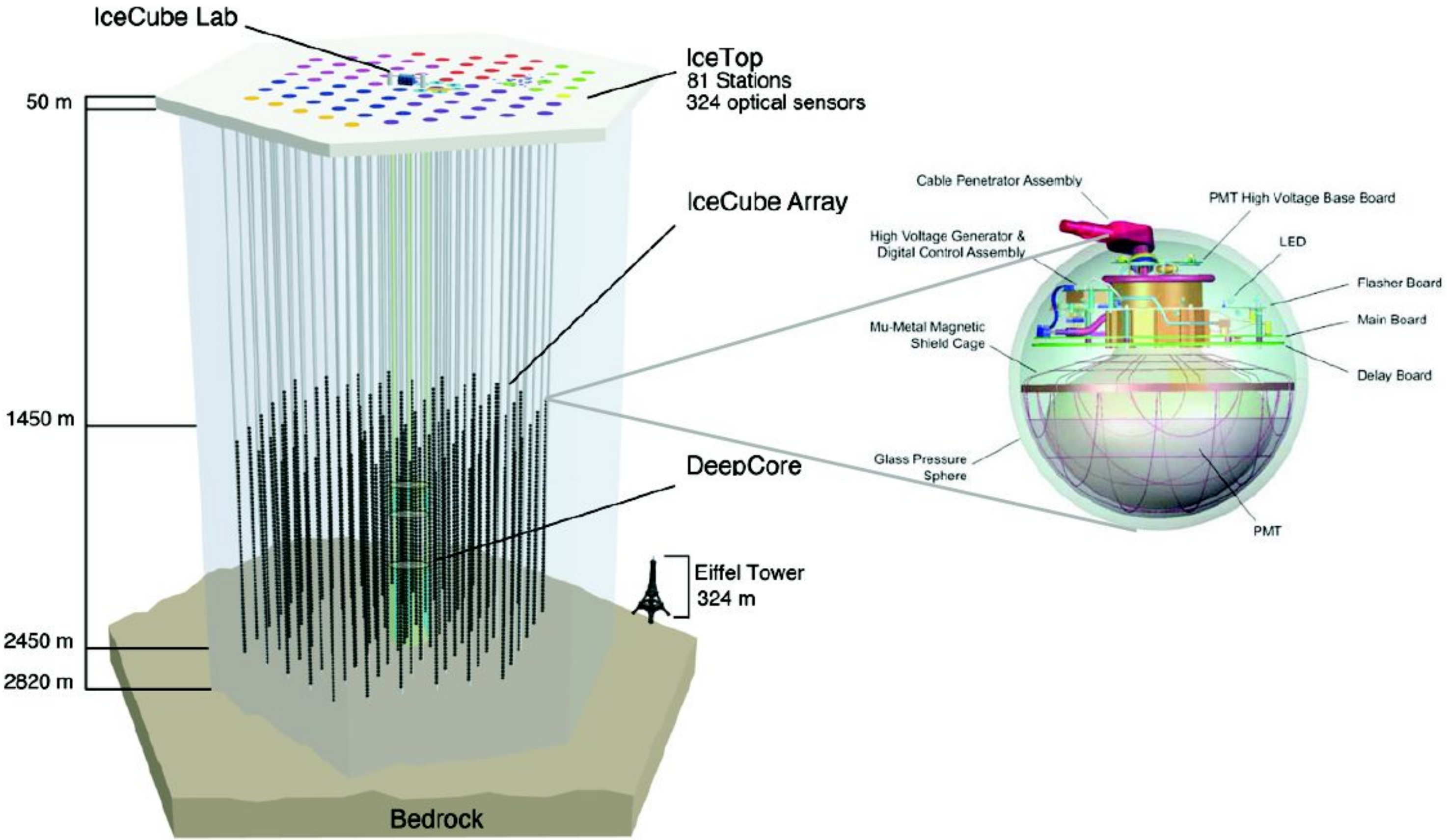
- In order to detect these neutrinos, a detector was needed which would:

1. Have a large target mass
2. Provide a very clear medium so that light can be detected
3. Be at least somewhat shielded from outside radiation

IceCube/DeepCore

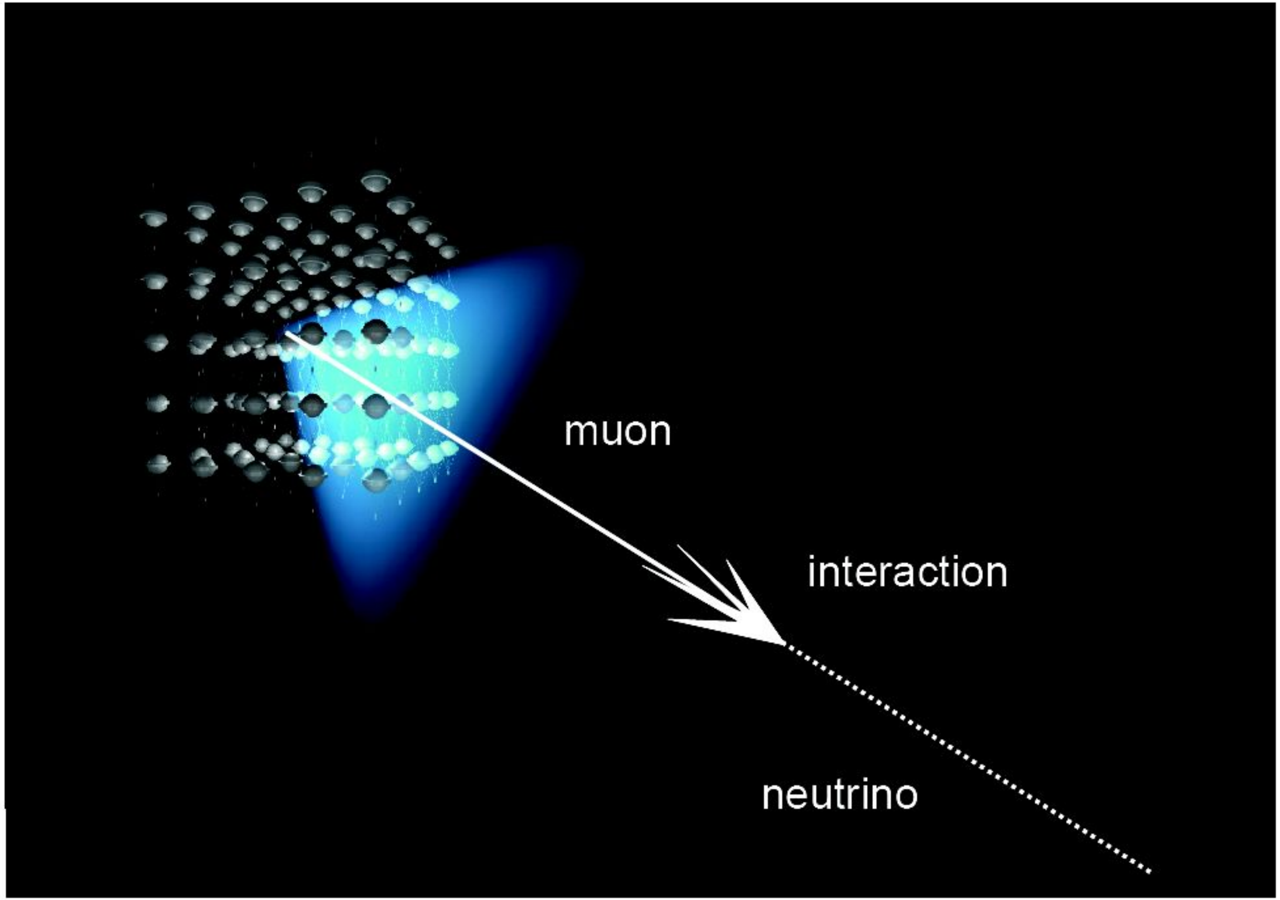


The IceCube Neutrino Telescope

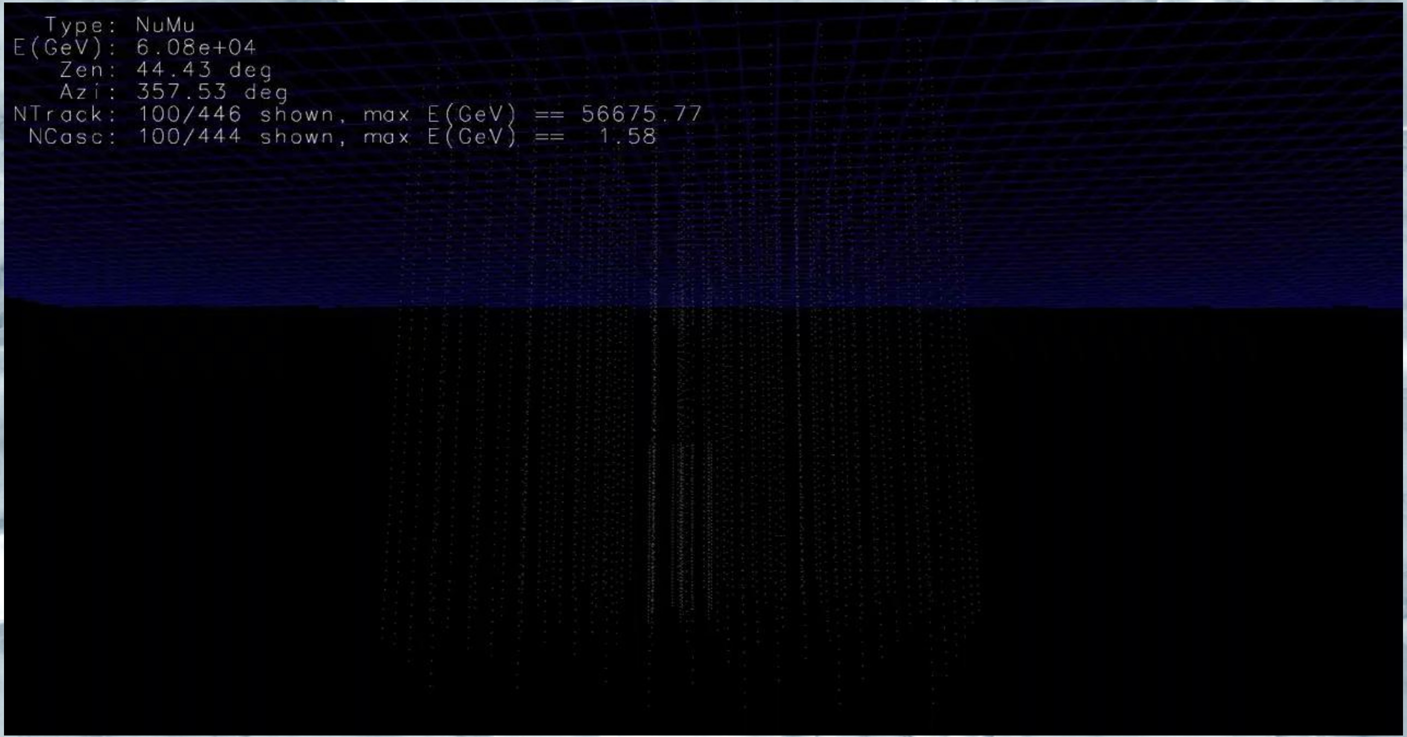


The IceCube Neutrino Telescope

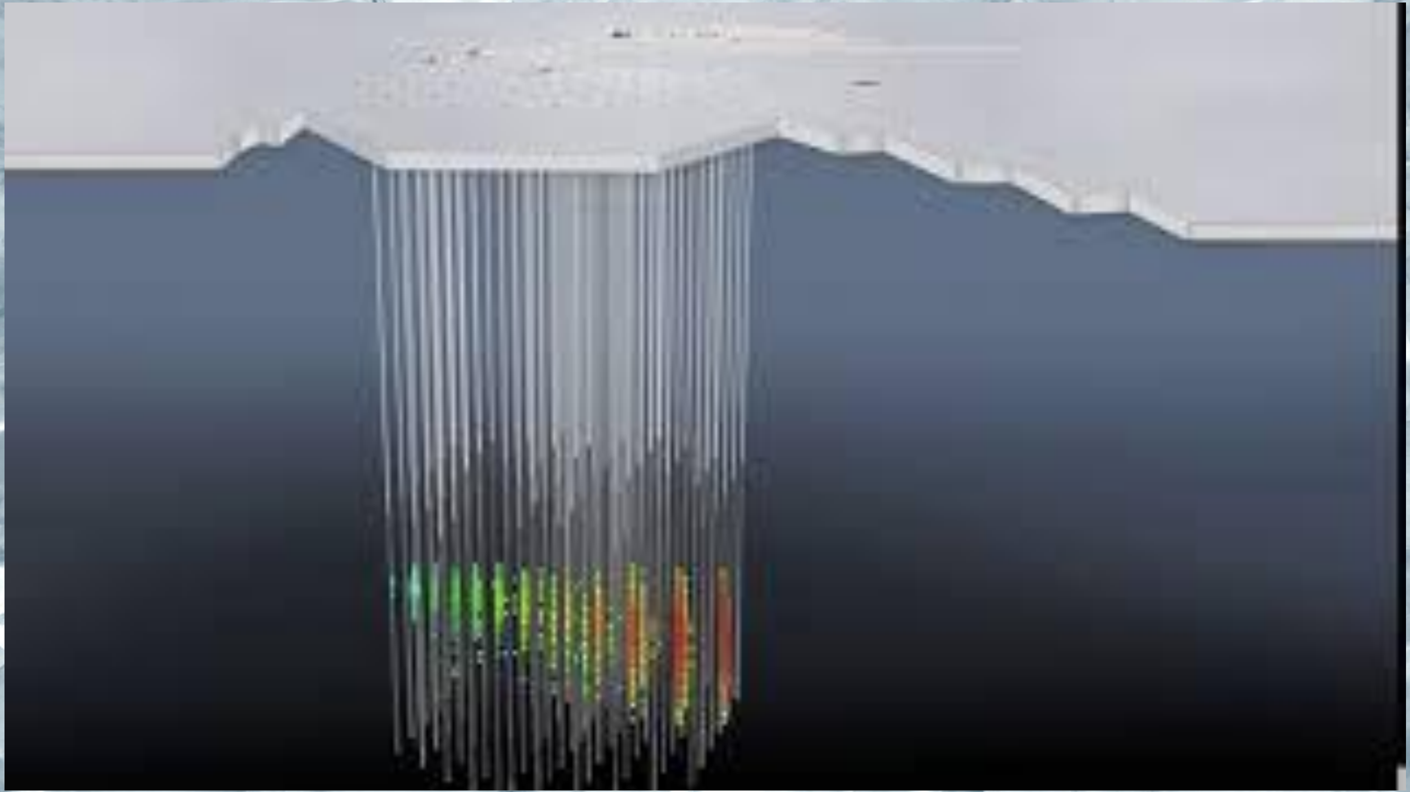
Detection Method



Event example (in moving picture form!)



What does this look like in detector data?



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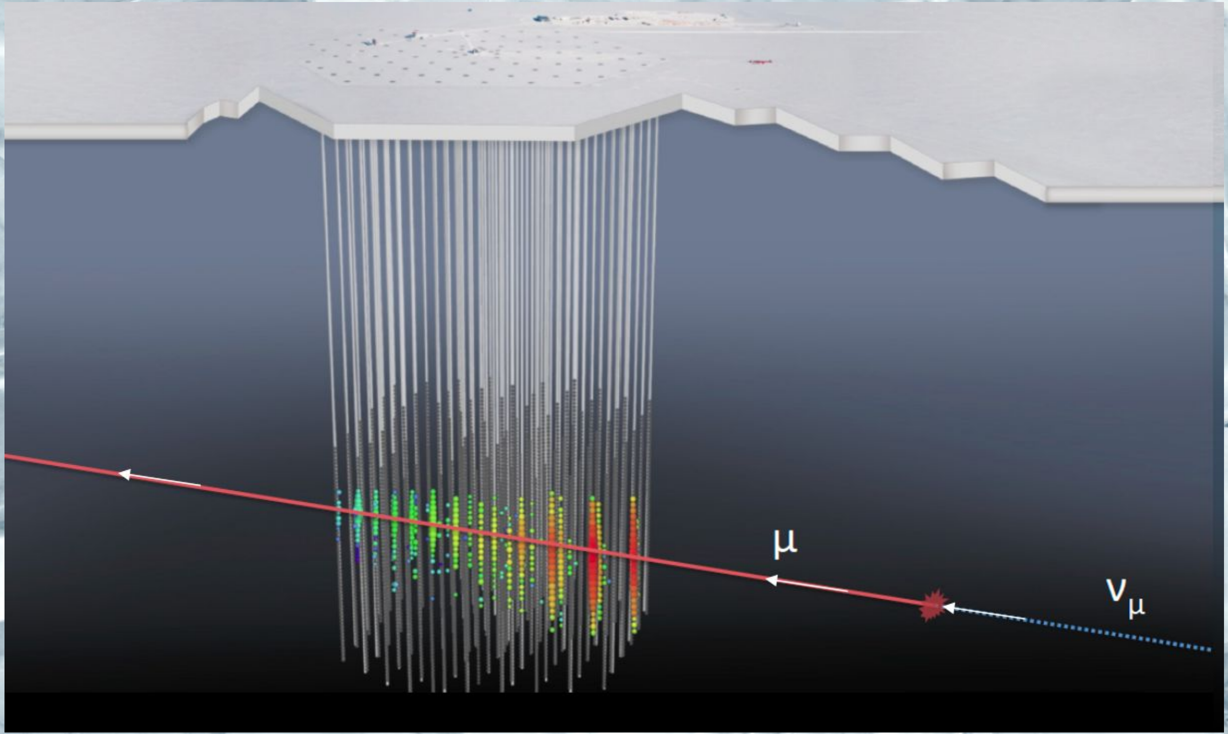
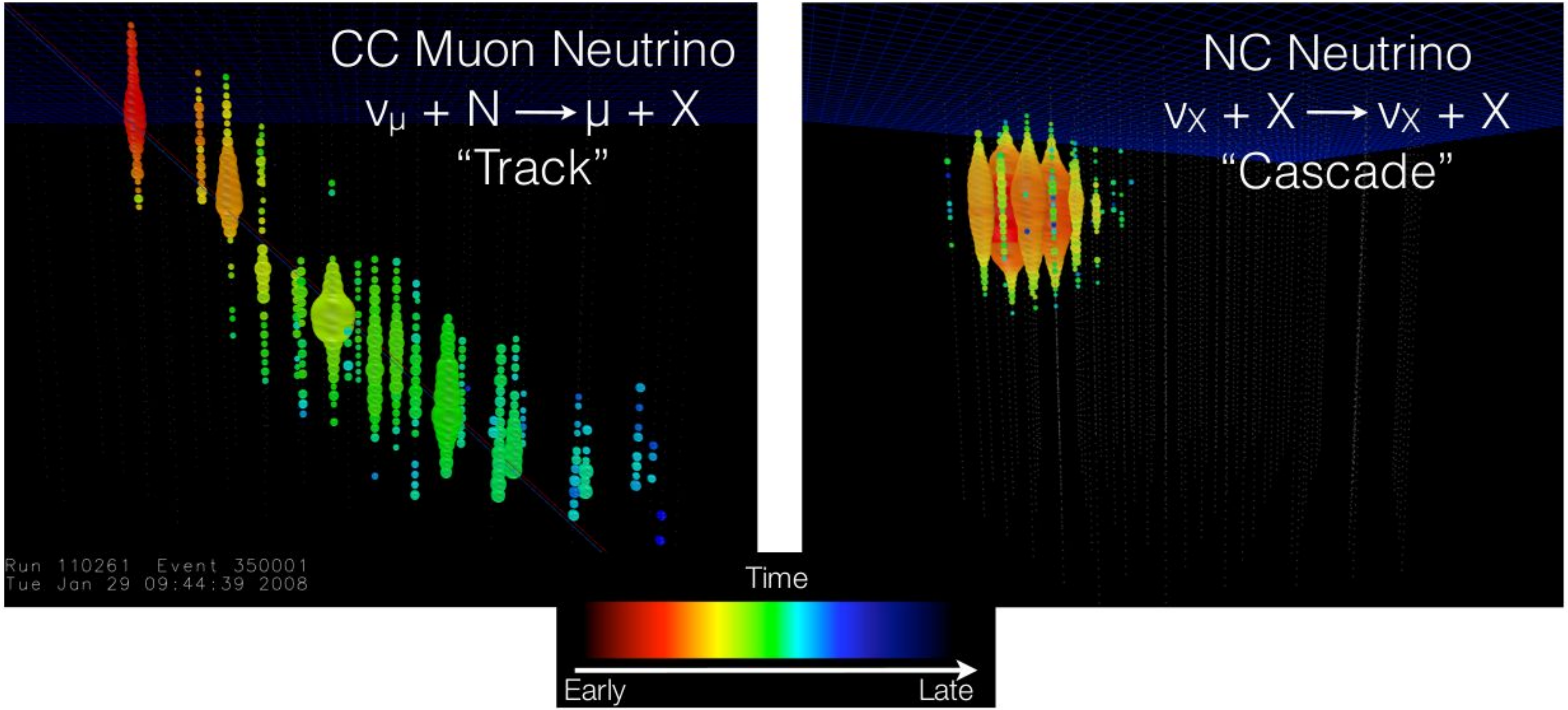
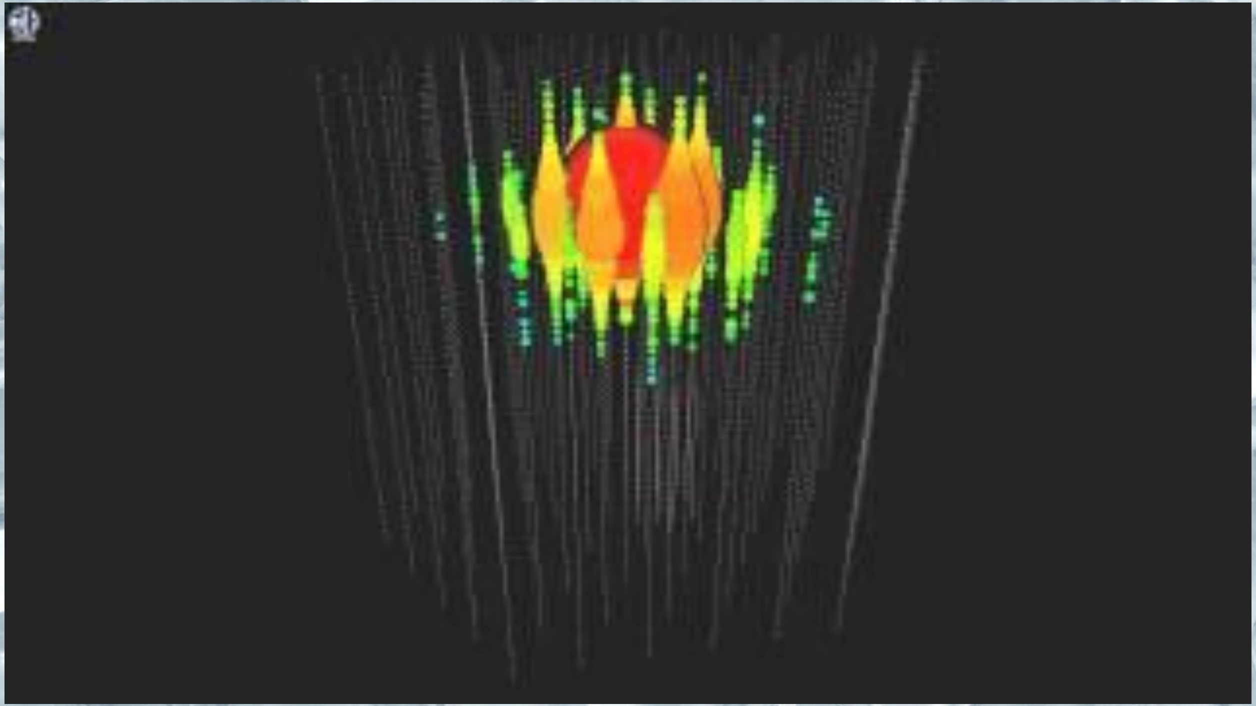


Events in the Detector



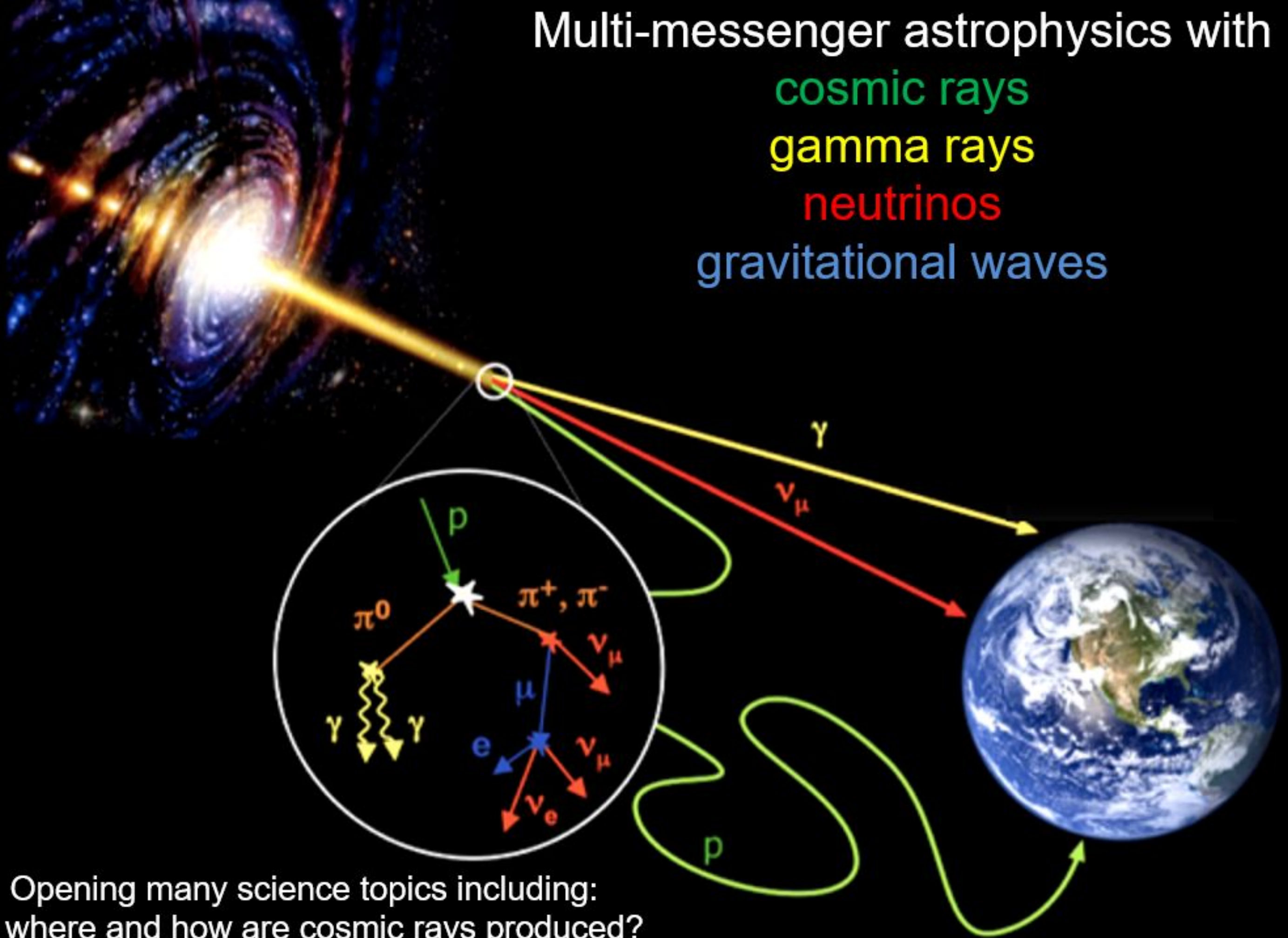
Cascades in action!



So you build a high-energy neutrino detector?

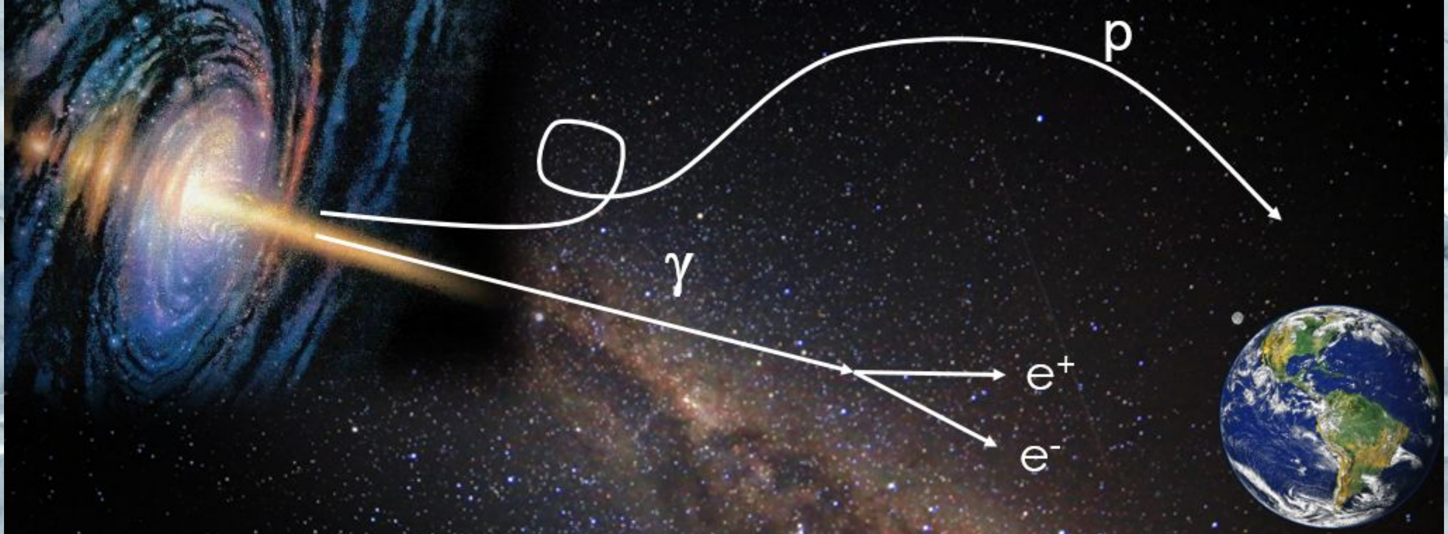
Why should I care??

Multi-messenger astrophysics with
cosmic rays
gamma rays
neutrinos
gravitational waves



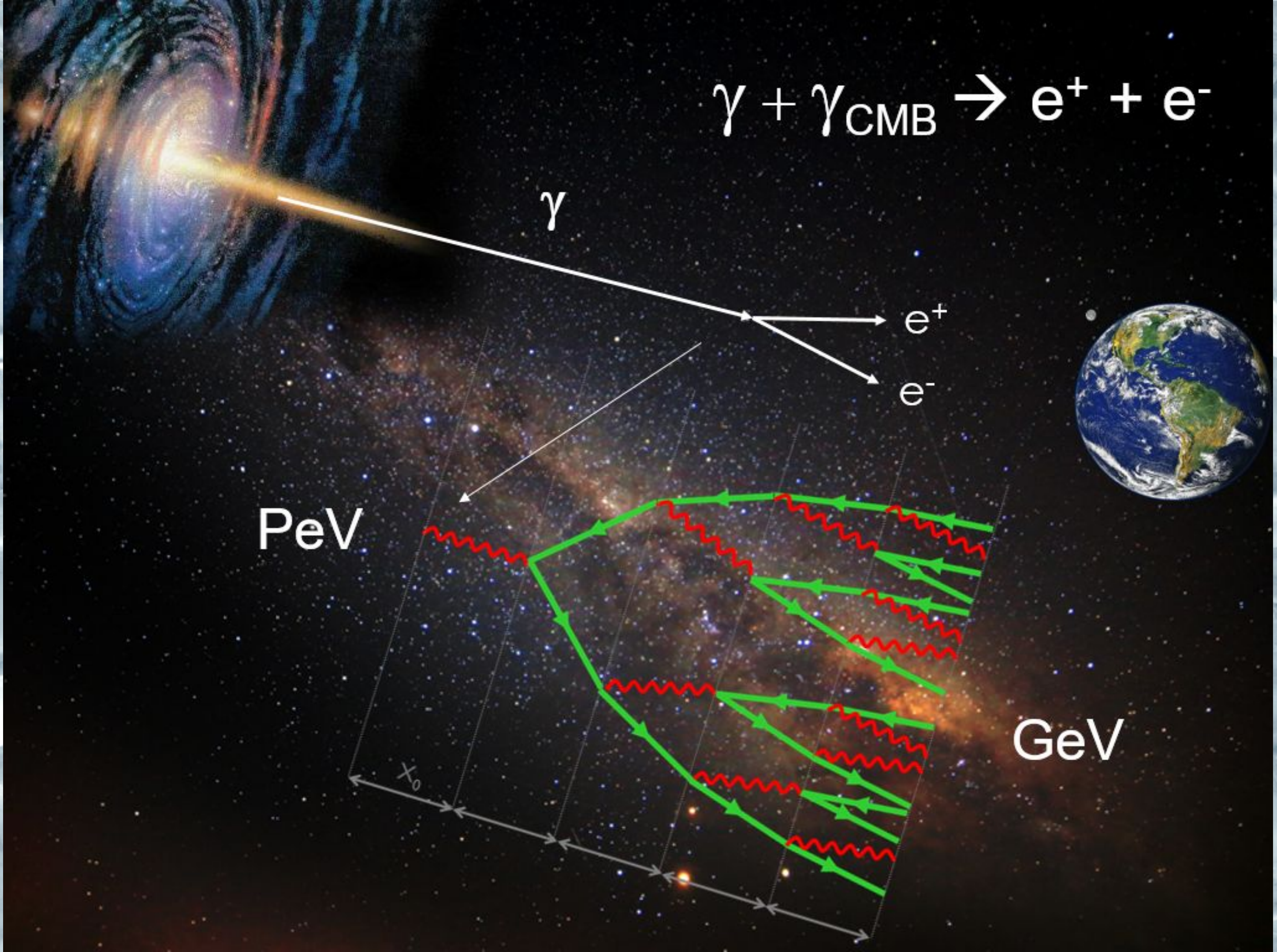
- Opening many science topics including: where and how are cosmic rays produced?
- Neutrinos indicate a hadronic (or exotic) source

The opaque Universe

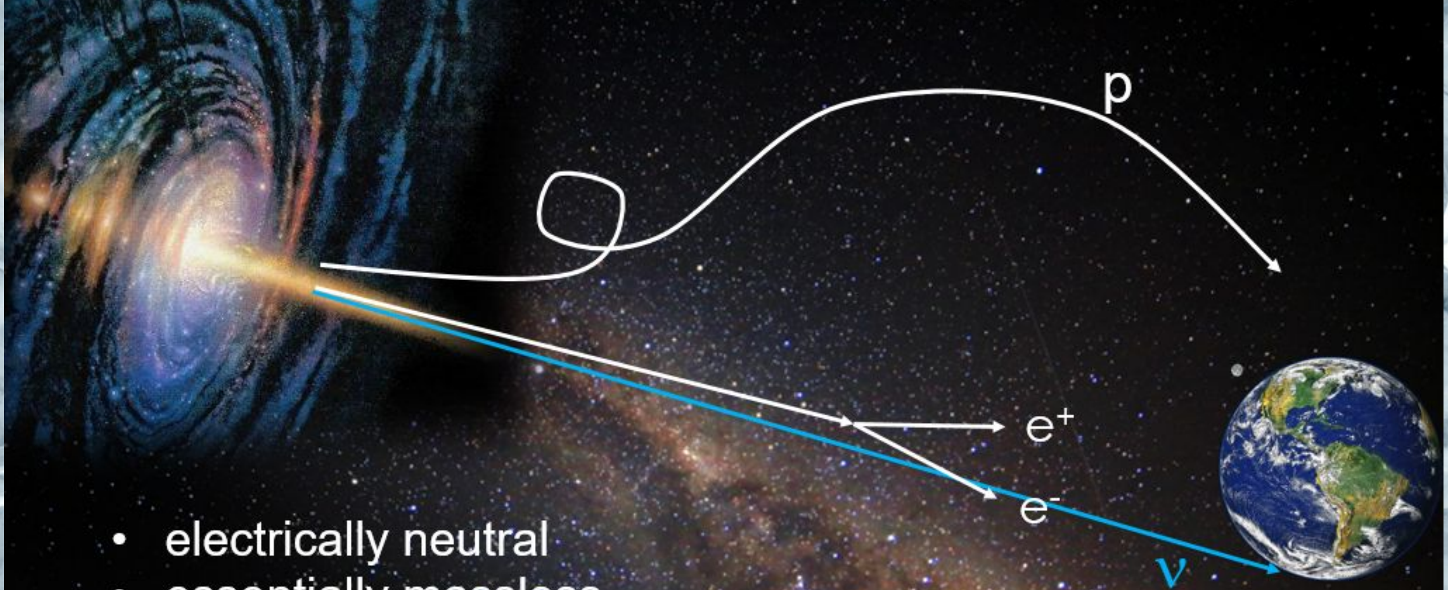


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

PeV photons interact with microwave photons ($411/cm^3$) before reaching our telescopes
enter: neutrinos

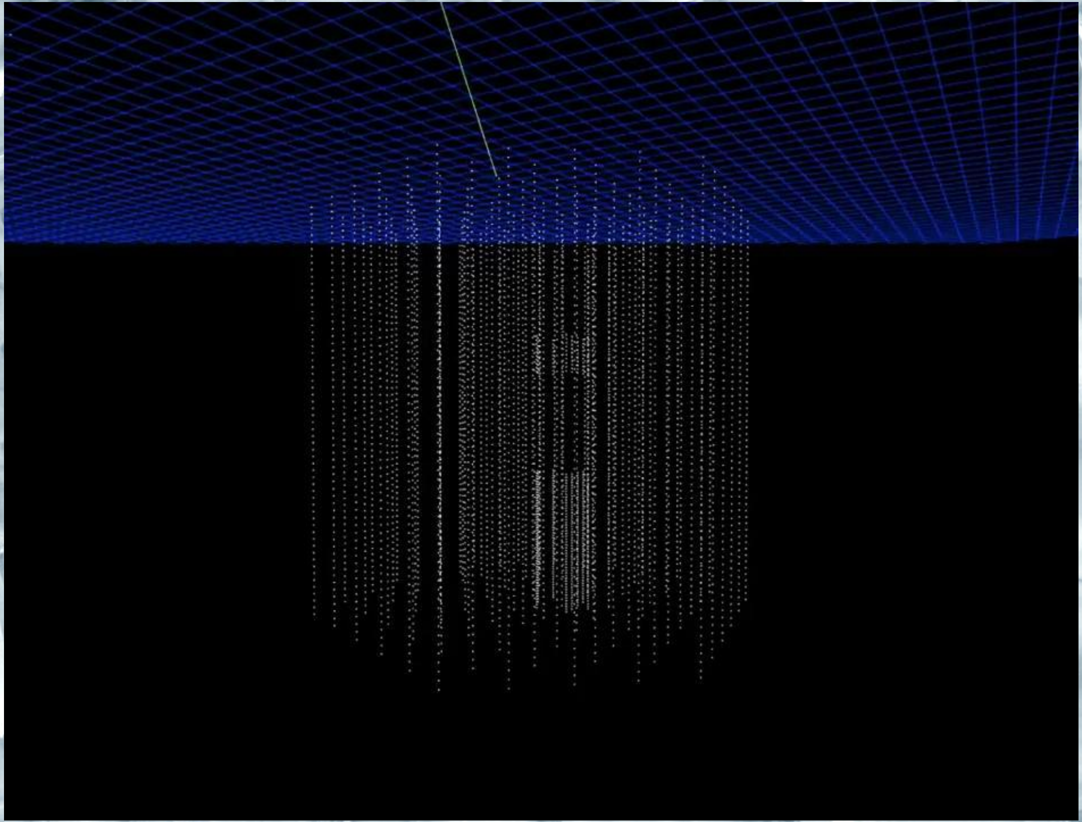

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0

Neutrinos? Perfect Messenger



- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect [redacted]



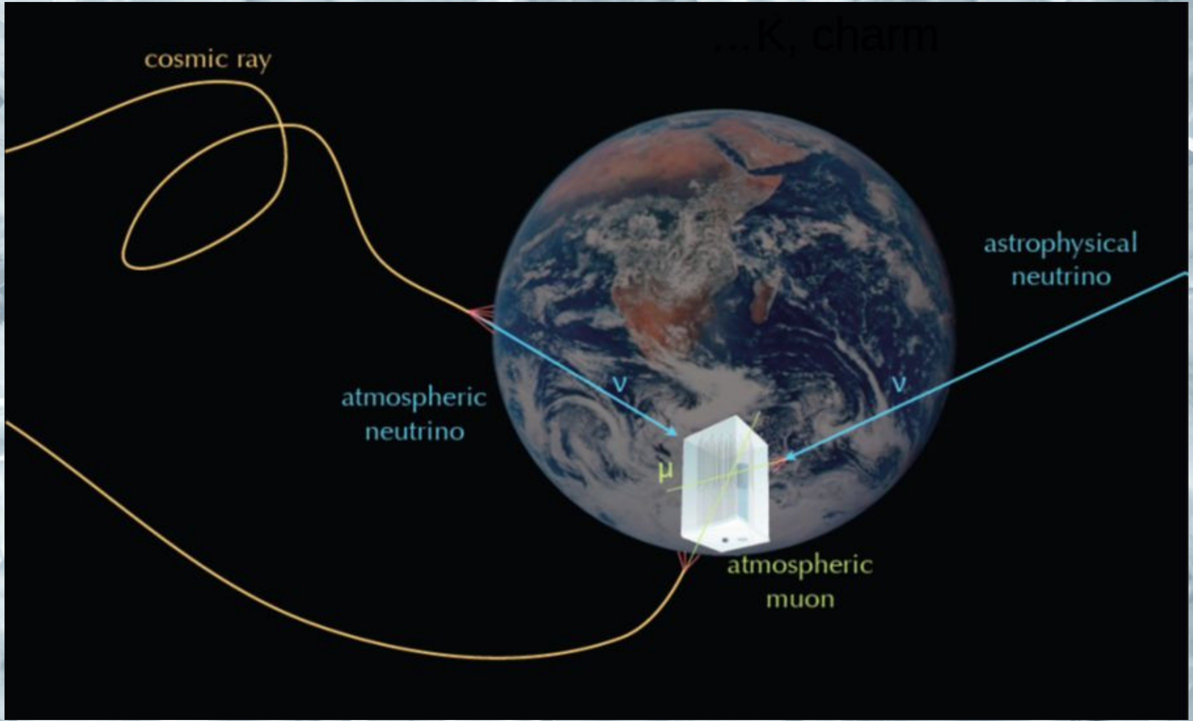
10 ms of data in IceCube 😵

Signals and Backgrounds

-Atmospheric muons: 10^{11} events per year

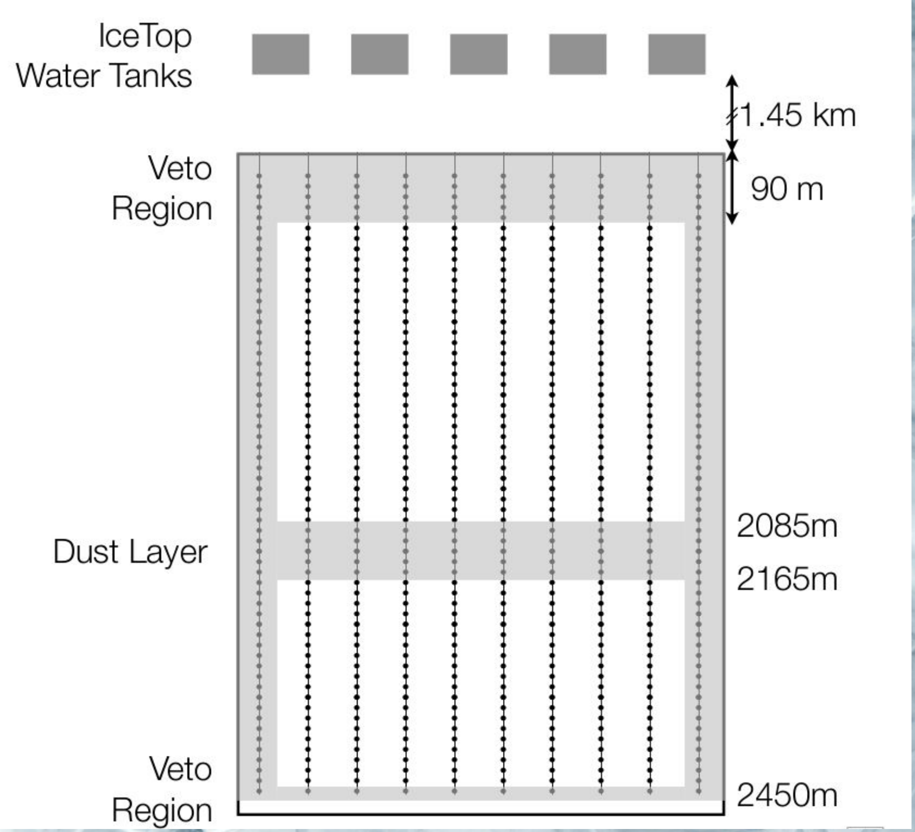
-Muons from atmospheric neutrinos: 10^{5} events per year

-Muons from astrophysical neutrinos: 120 events per year

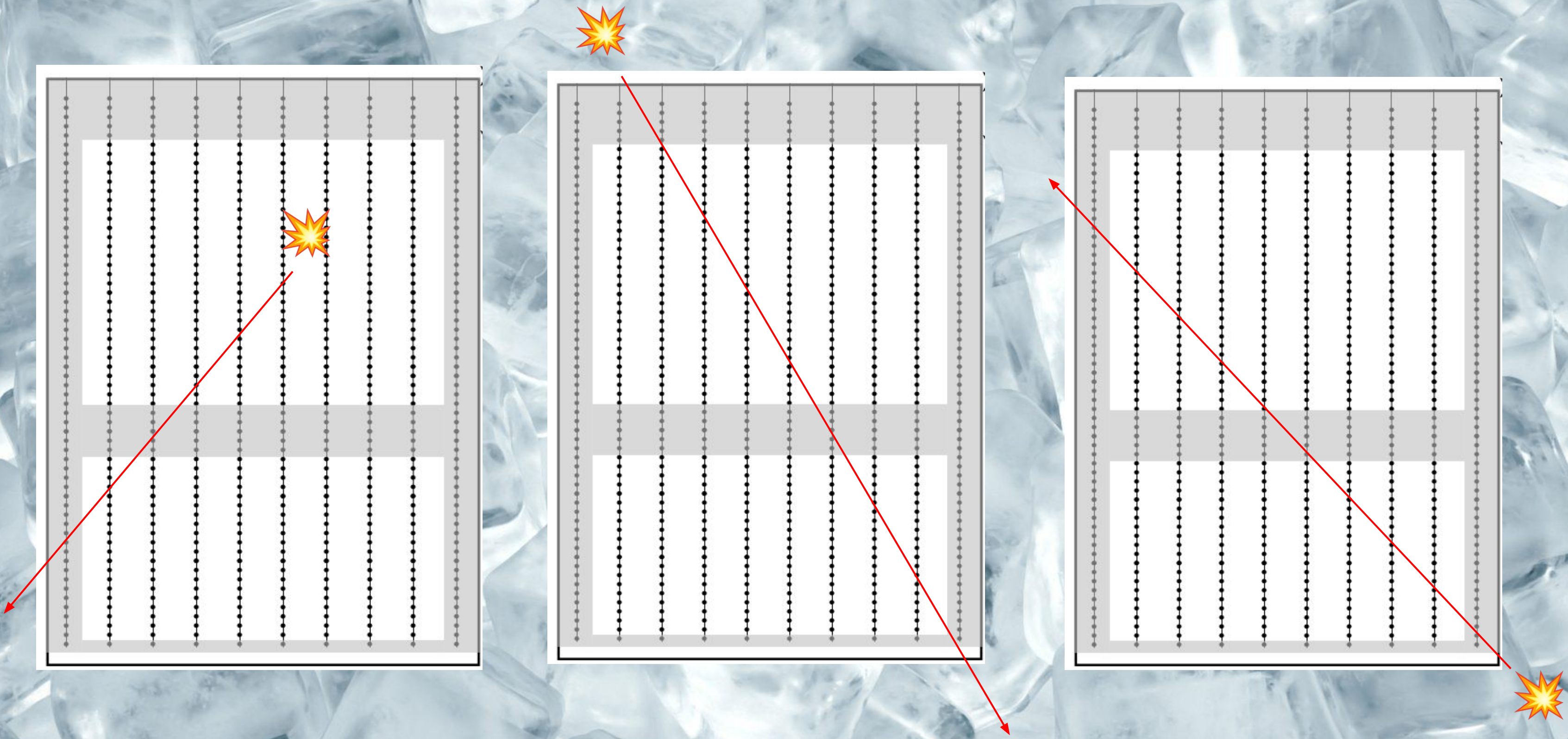


Event selection

-To remove any atmospheric muon contamination, we have specific event criteria that needs to be passed such that we only collect neutrino data



Event selection (interactive bit)



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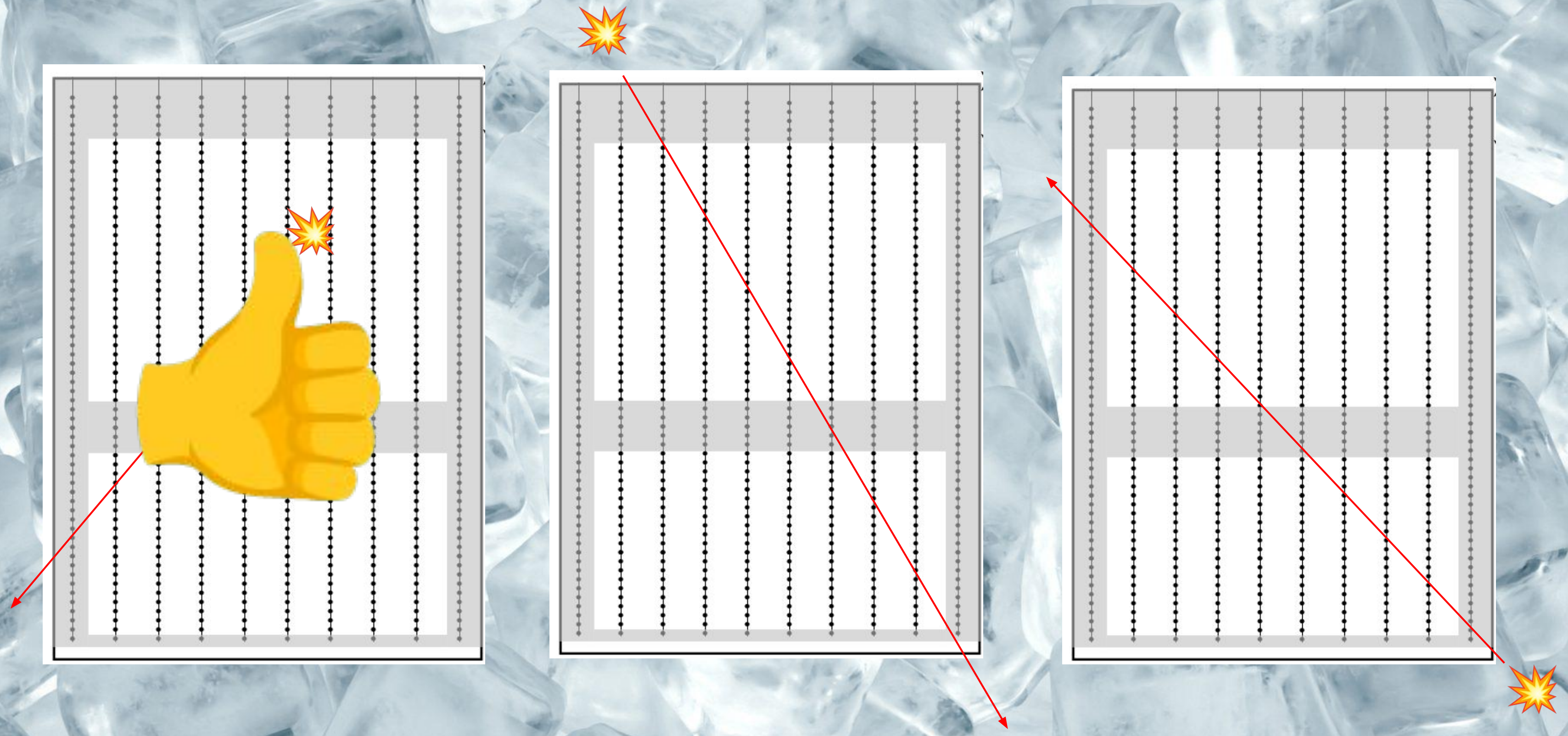

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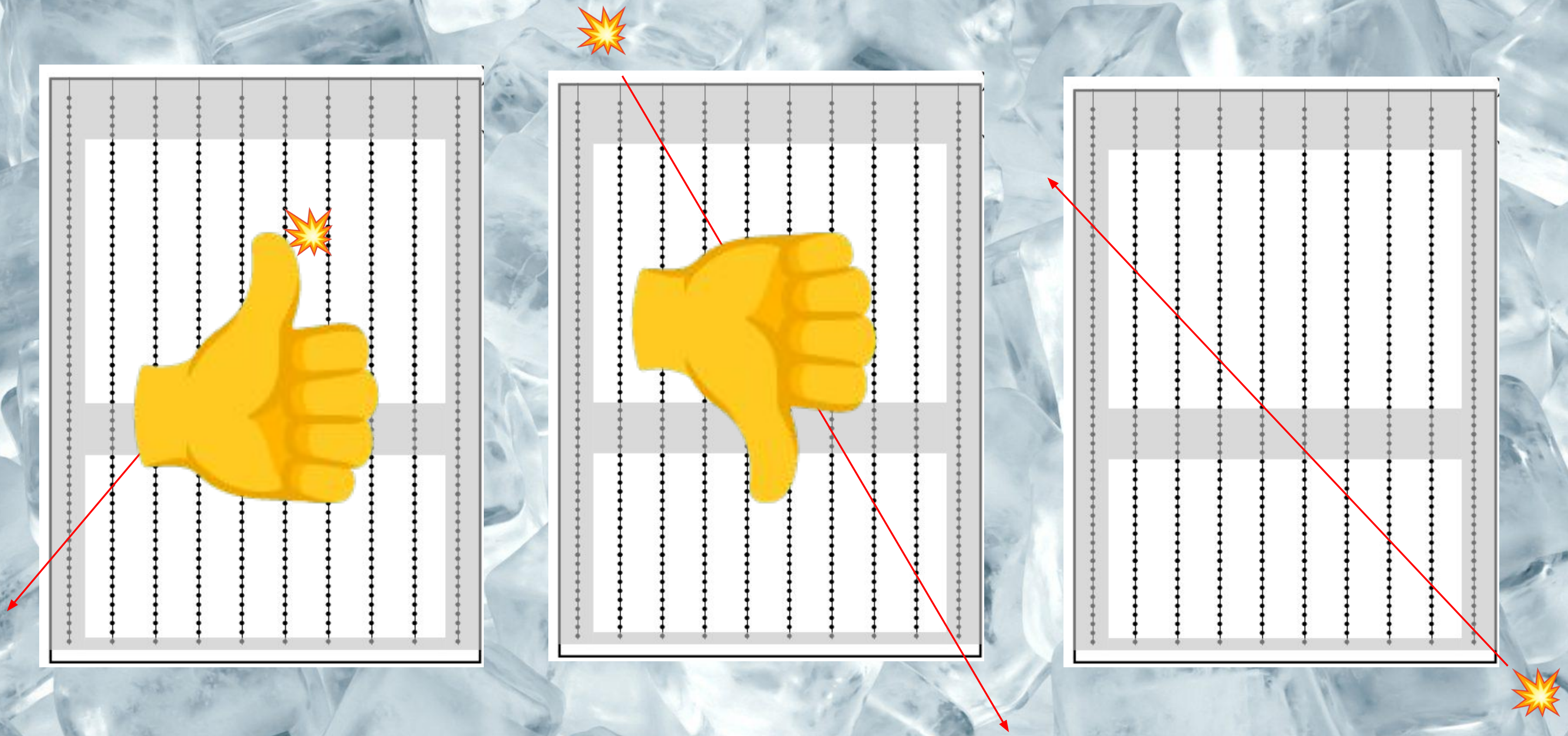

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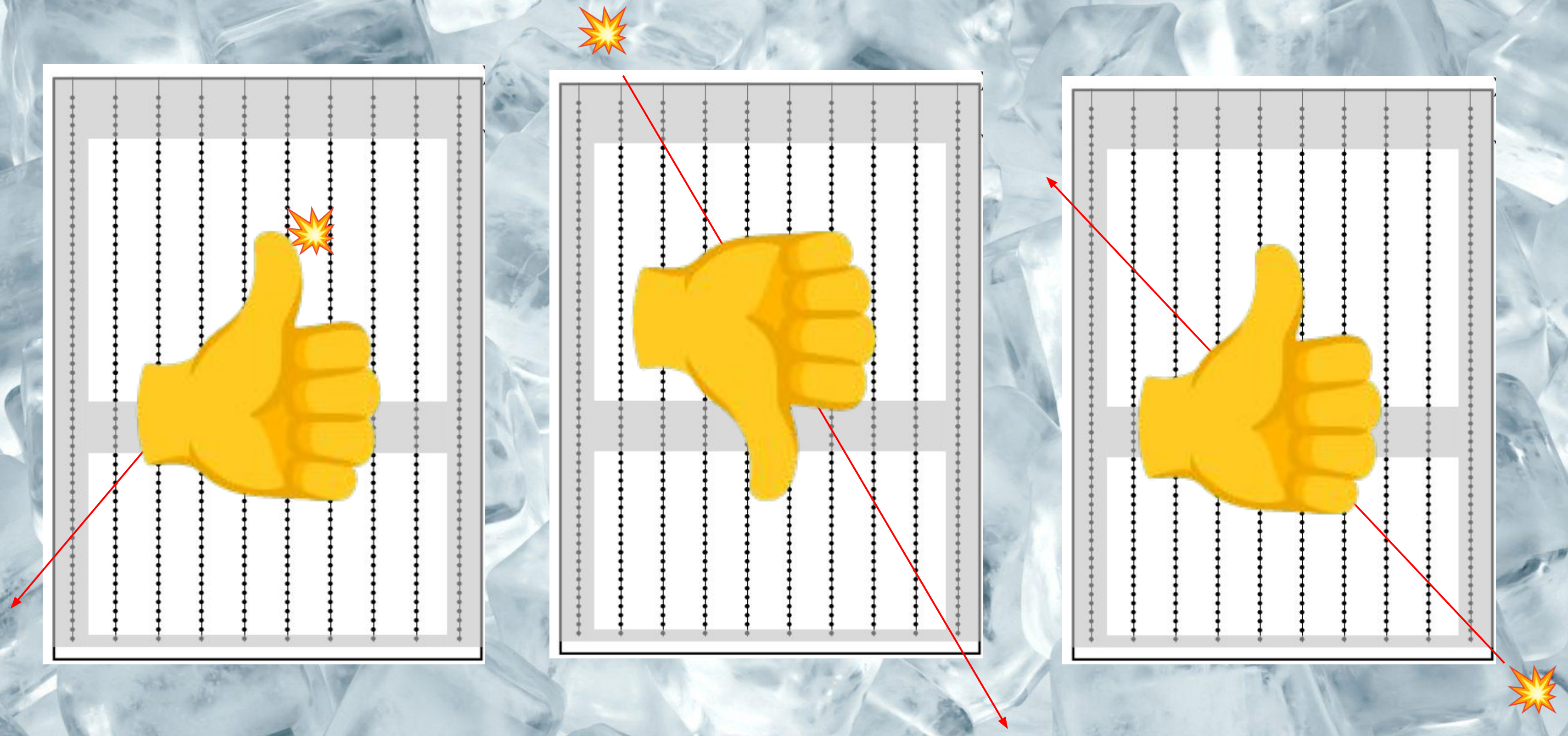
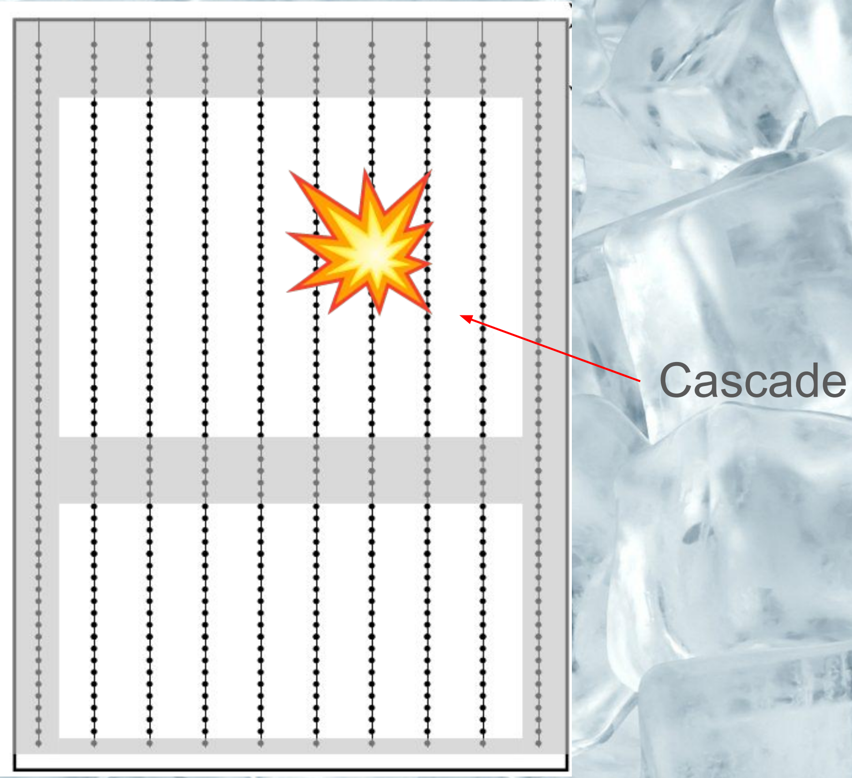


Event selection (bonus question)



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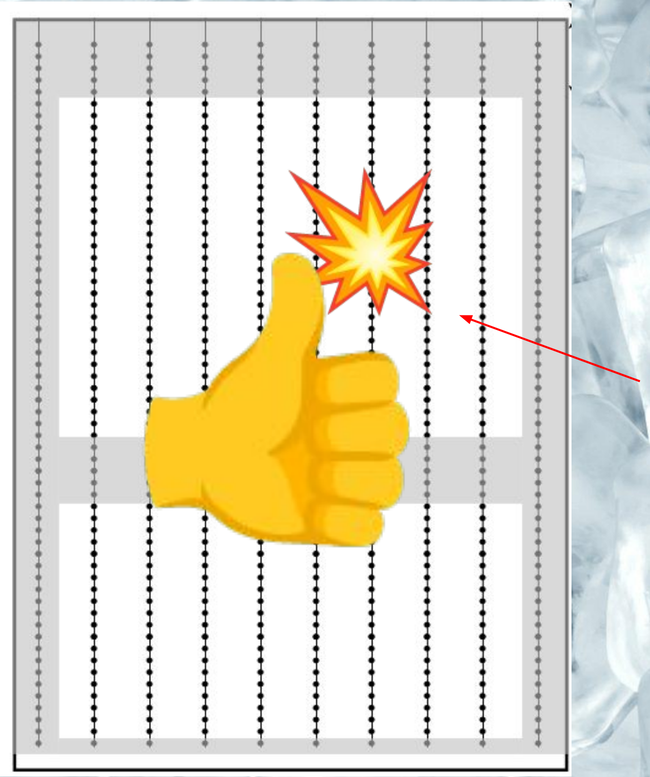
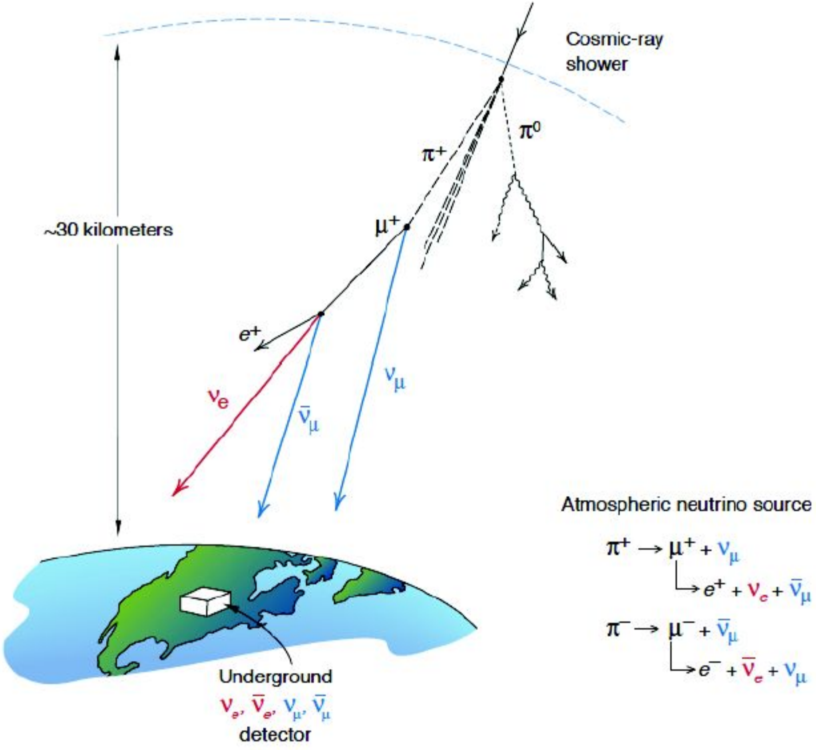
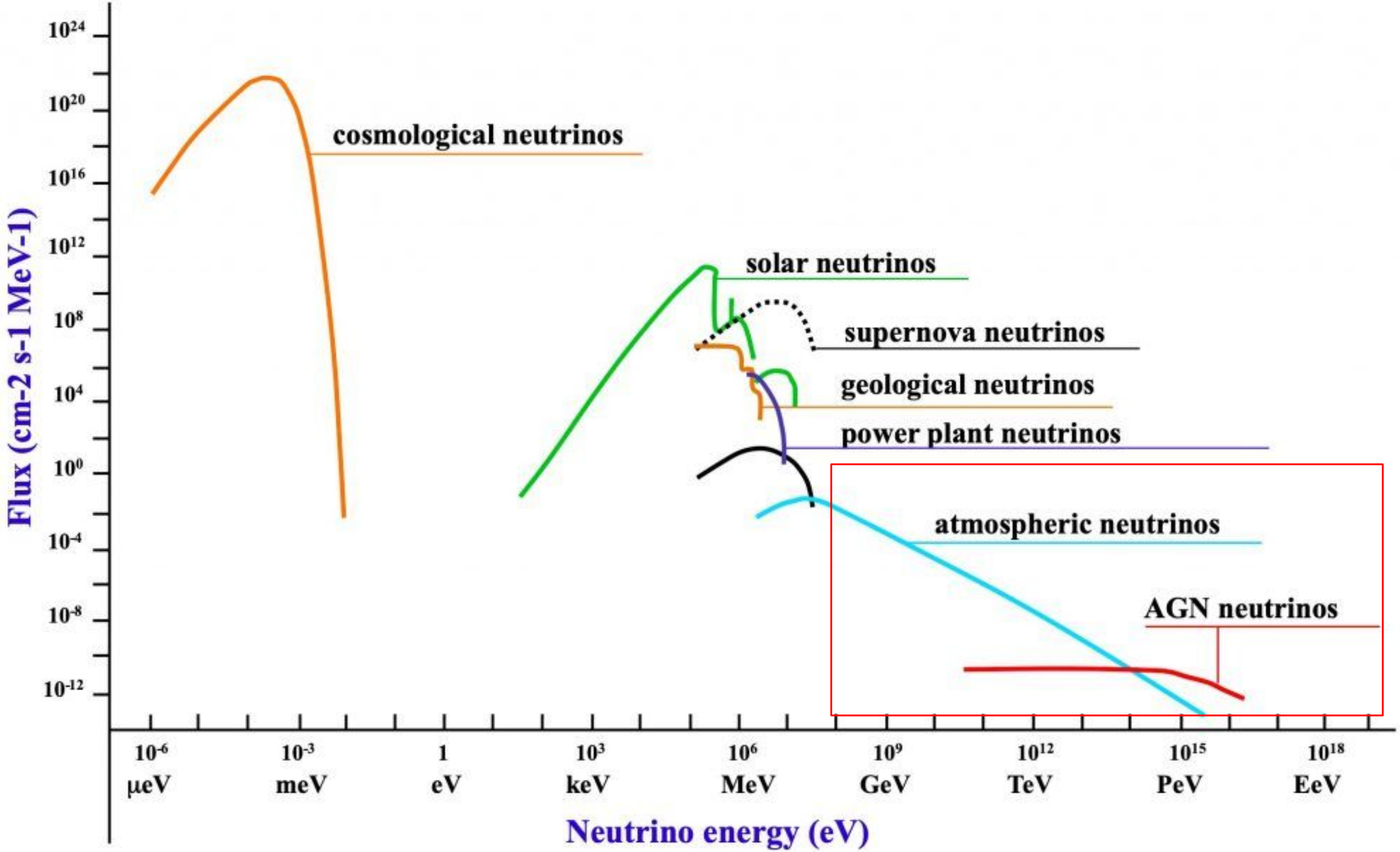


Atmospheric Neutrinos

- Source of neutrinos is the interaction of particles in the atmosphere
- These interactions produce neutrinos with an understood flux and flavour content

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10^{-3} meV
1 eV
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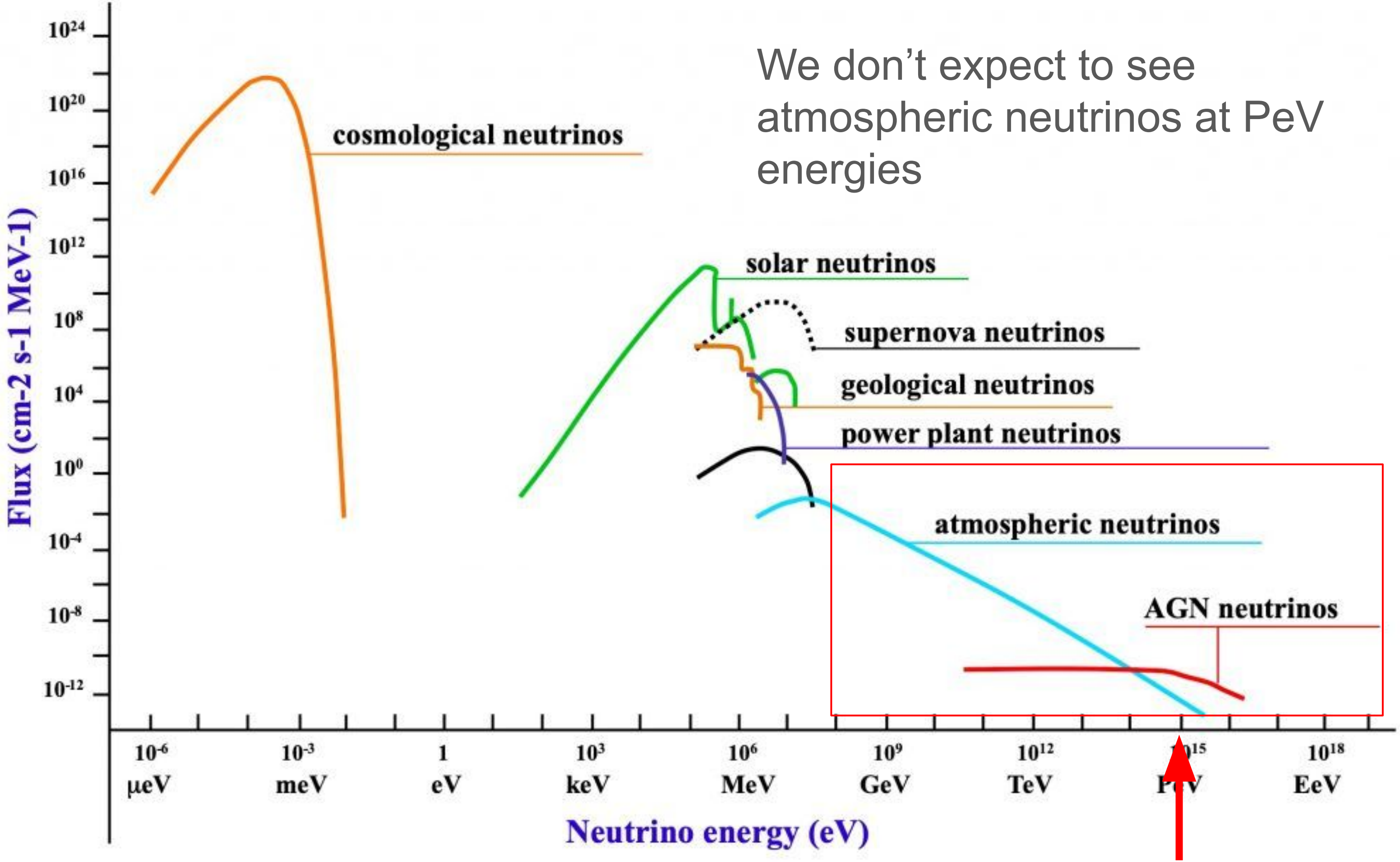
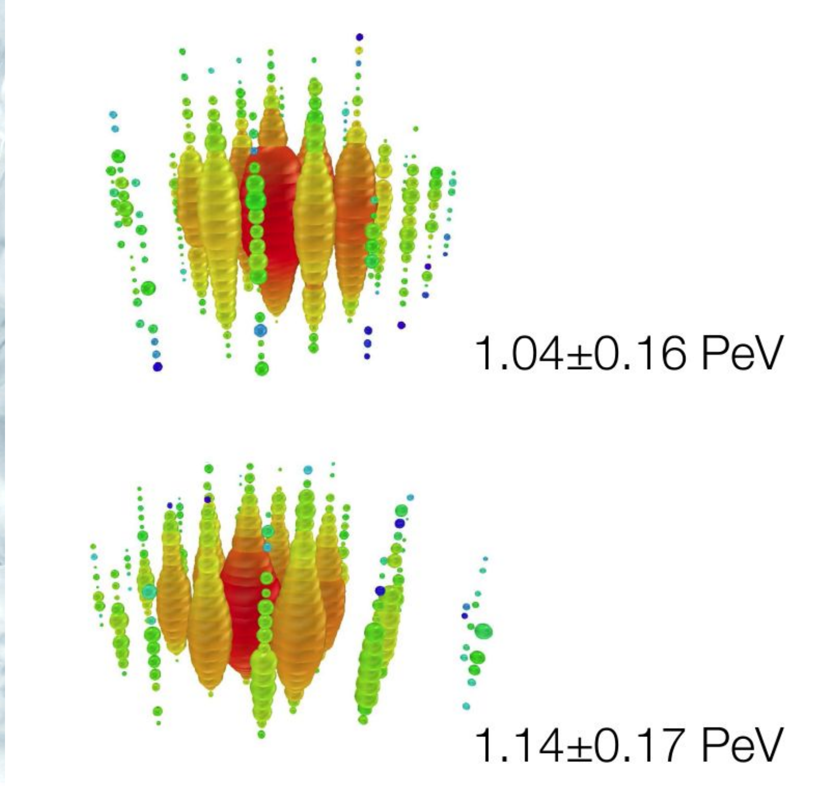
Neutrino energy (eV)

We don’t expect to see atmospheric neutrinos at PeV energies



First IceCube results

-Completely unexpectedly, two very high energy events were found!



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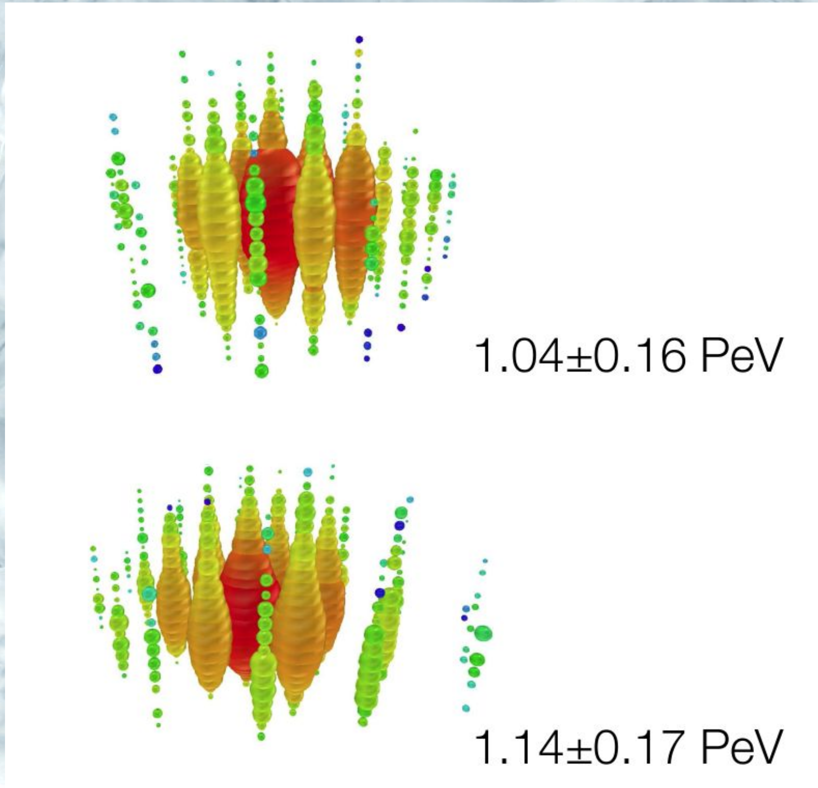

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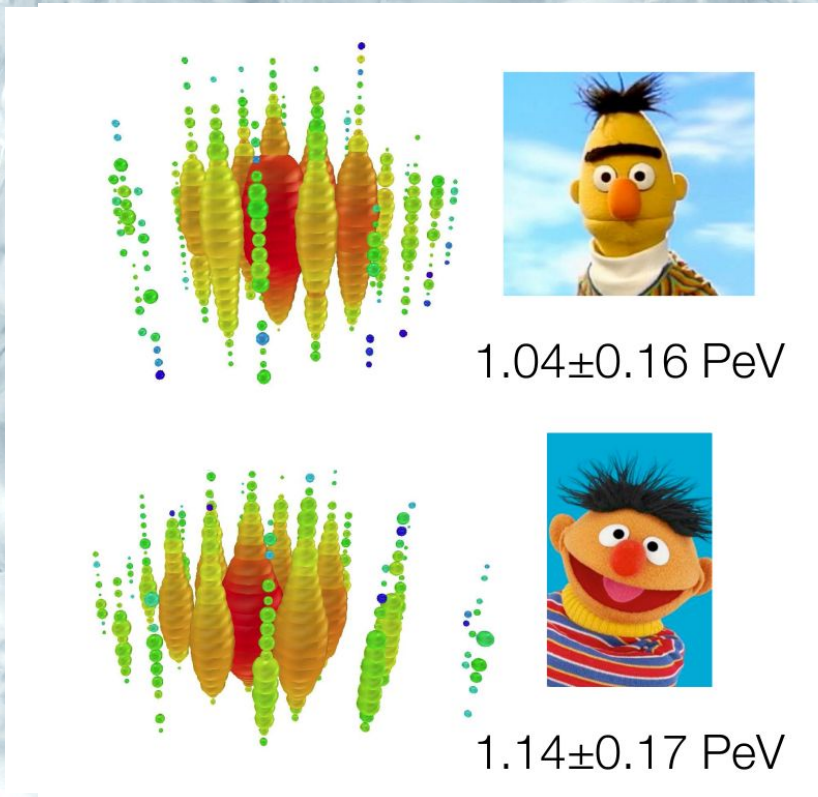


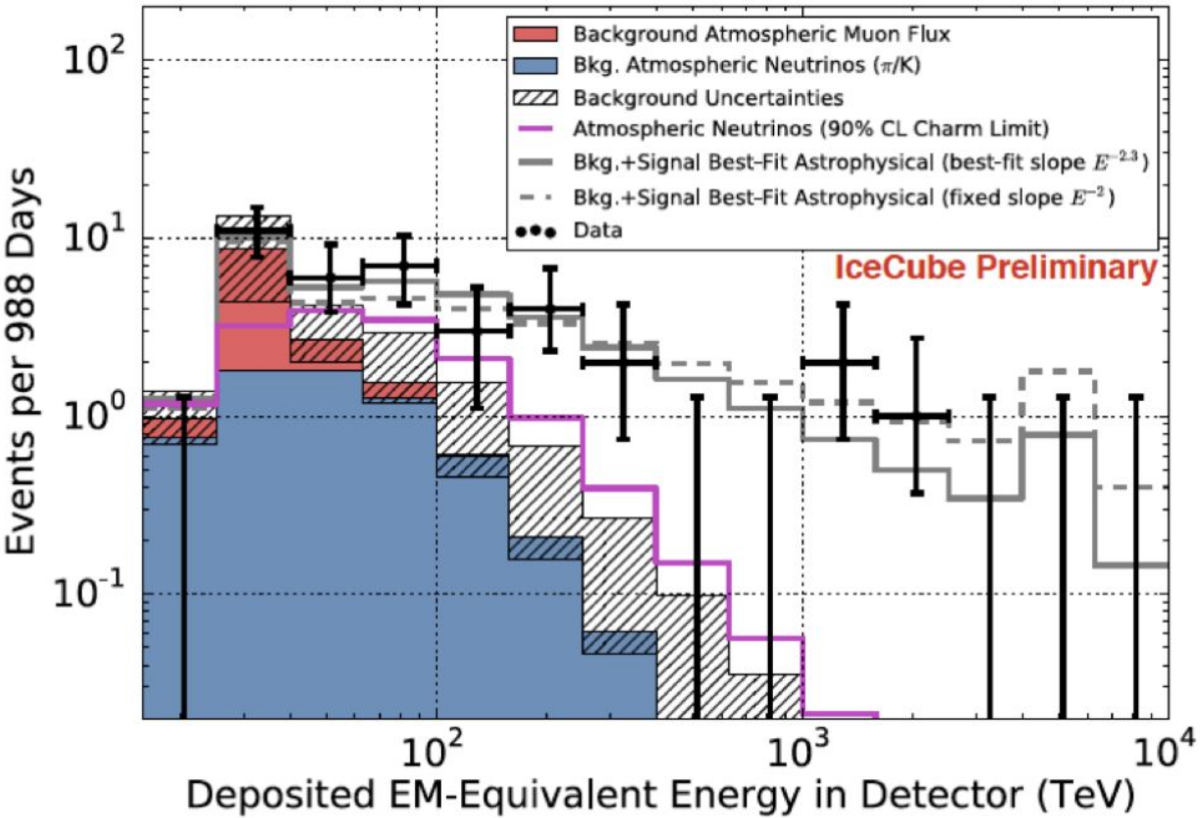
Predicted Results

Expected to see $10.6^{+5.0}_{-3.6}$

Actual Results

Actually saw 28 (in the first 2 years of data)

IceCube Results



(This has been updated to ~3 years)

But where are these high-energy neutrinos coming from??

A History of Neutrino Astronomy in Antarctica

- 1988 — Telescope in the Ice Envisioned
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- 2001 — Atmospheric Neutrinos Detected
- 2011 — IceCube Completed
- 2013 — Astrophysical Neutrinos Discovered
- 2018 — First Source TXS 0506+056 Identified
- 2021 — Glashow Resonance Neutrino Identified
- 2022 — Second Source NGC 1068 Identified
- 2023 — Third Source Milky Way Identified

A History of Neutrino Astronomy in Antarctica

ICECUBE NEUTRINO OBSERVATORY

NSF

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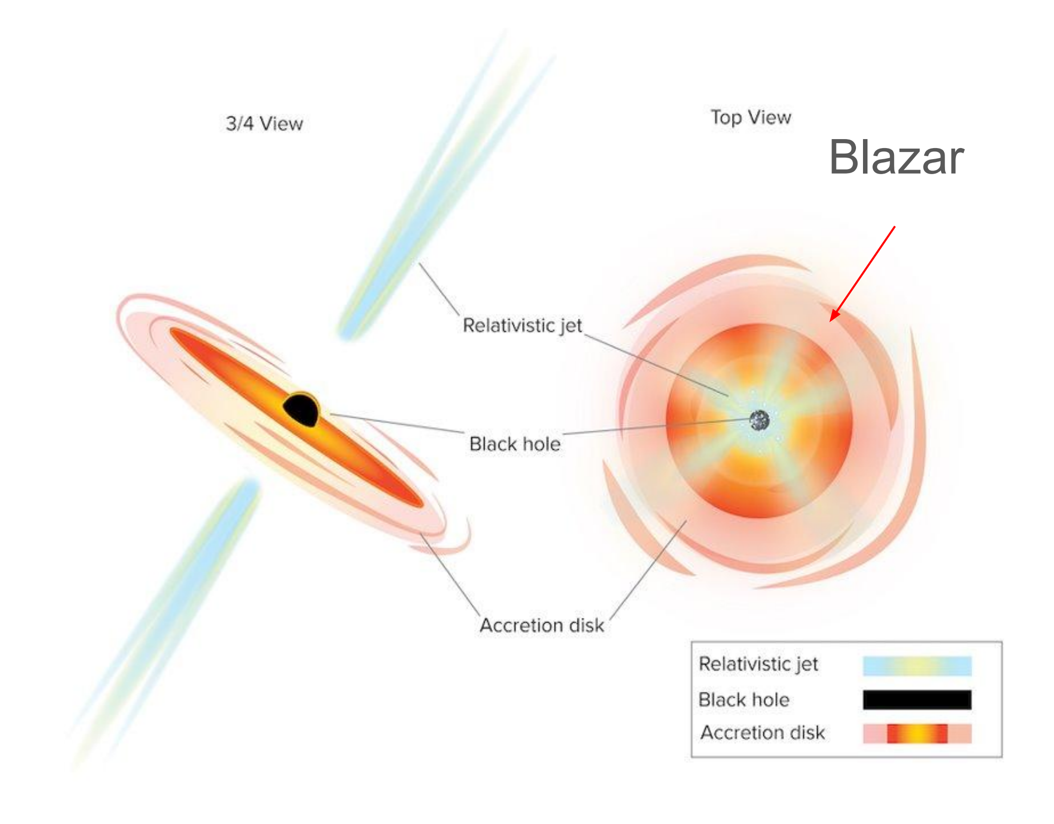
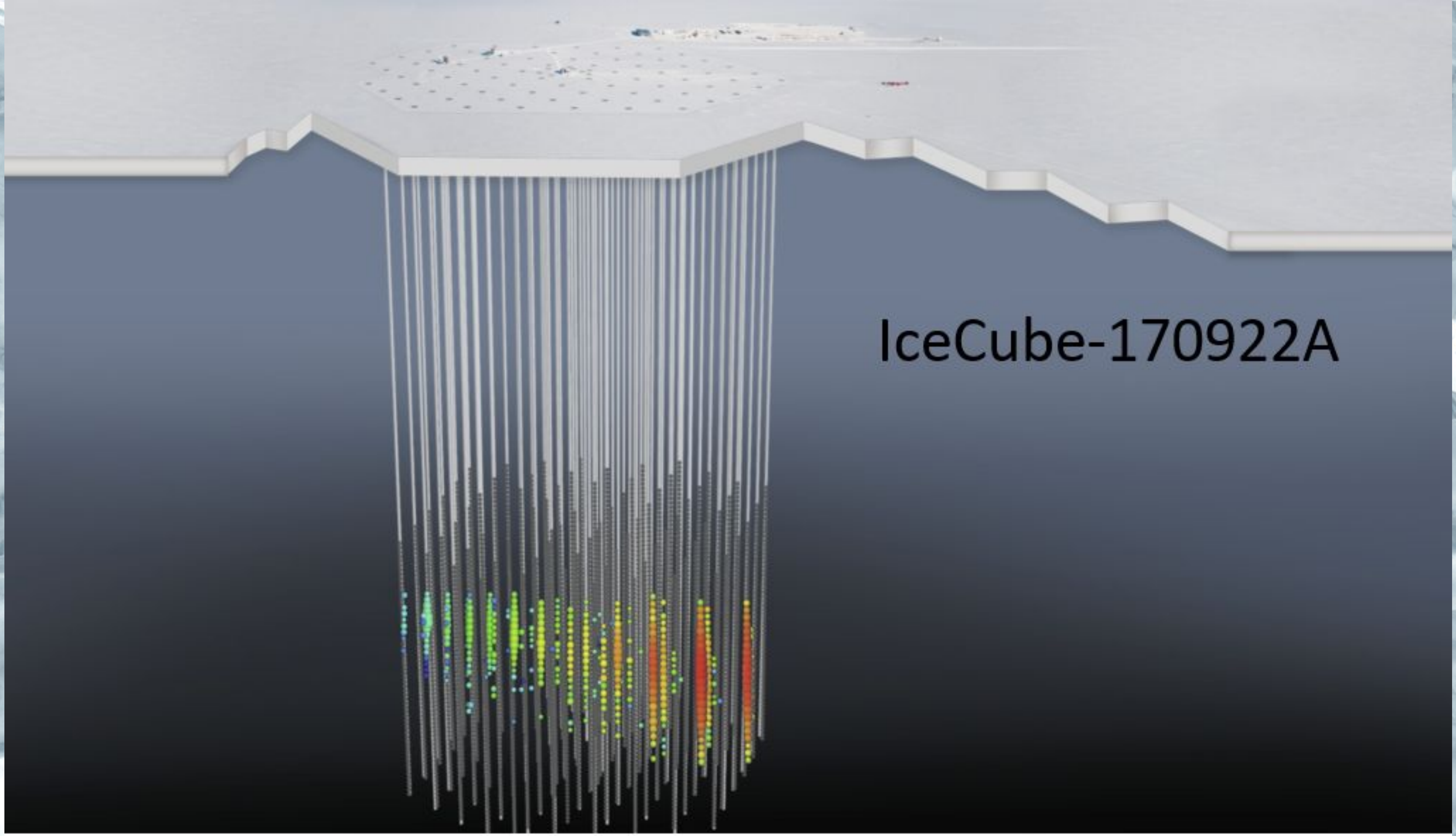
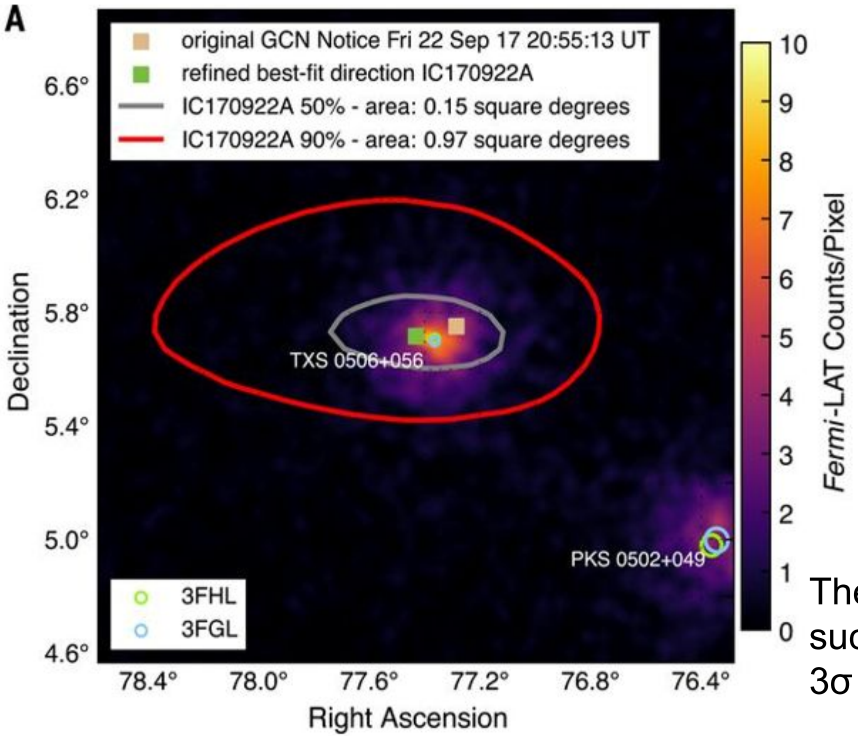
Neutrino source example: Active Galactic Nuclei





- A track with angular uncertainty ~1°
- Declination +5.7° , neutrino energy ~290 TeV
- Announced in public alert (GCN) 43 seconds after interaction

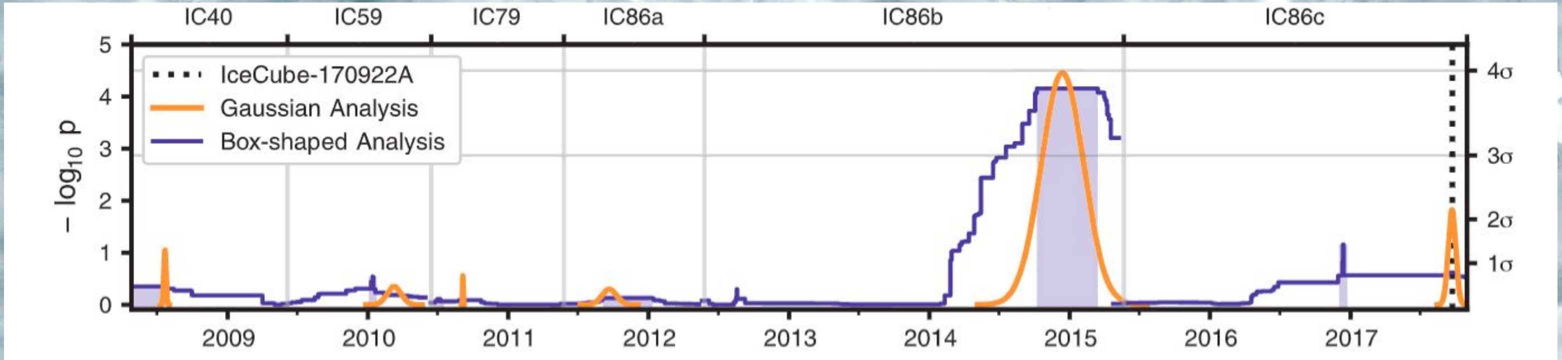
A flaring GeV gamma-ray blazar in the same direction as the neutrino



The significance of such a coincidence is 3σ

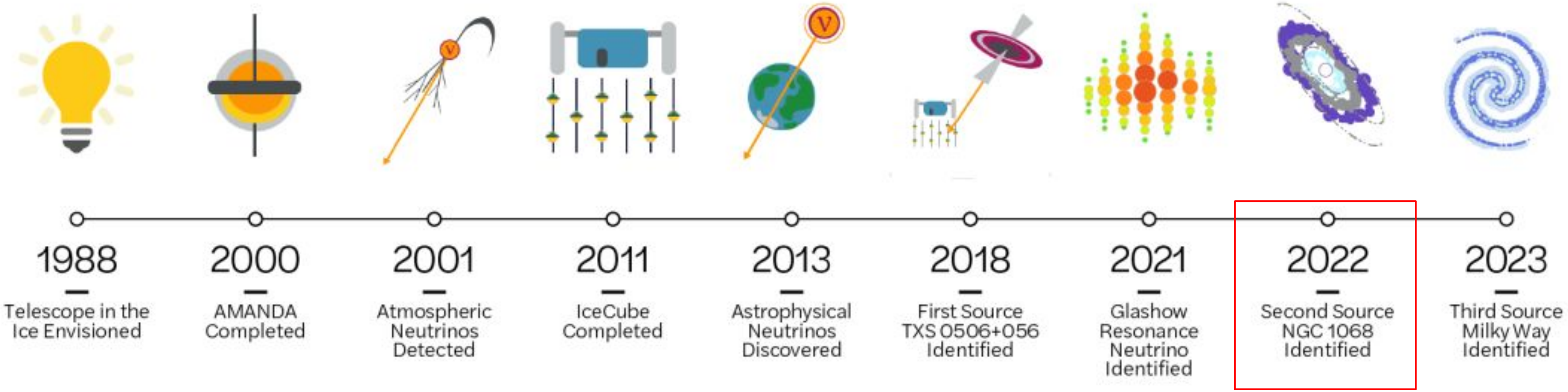
- 0.1° separation between blazar and best-fit neutrino direction
- MAGIC detected blazar for first time in VHE band

First significant neutrino source: TXS 0506+056



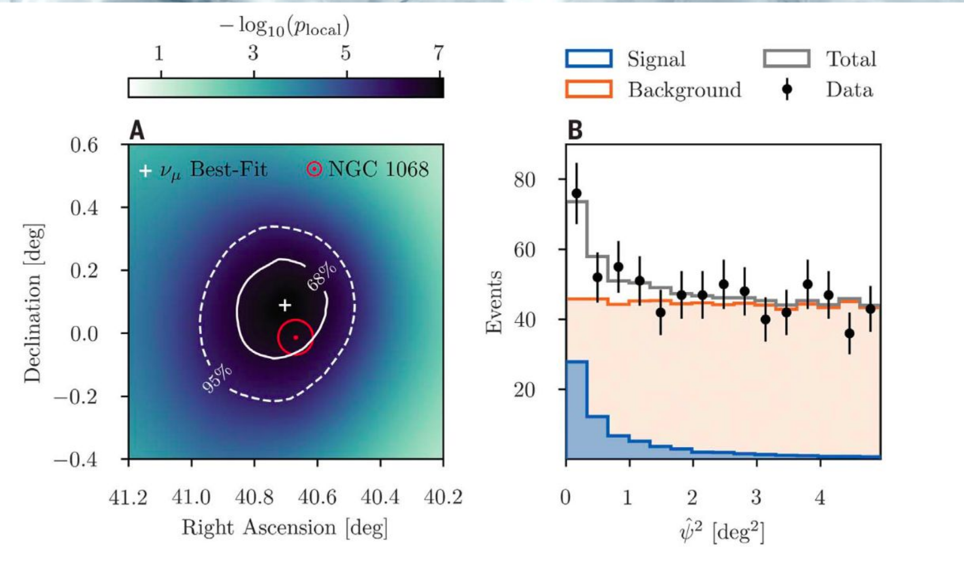
- TXS 0506+056 was found to have an excess of 13 ± 5 high-energy neutrino events above the expectation of atmospheric backgrounds between September 2014 and March 2015, giving the blazar a significance of 3.5σ

A History of Neutrino Astronomy in Antarctica



Second significant source: NGC 1068

-The Seyfert galaxy NGC 1068 was recently announced (as of January 2023) to have been found as a neutrino source with 4.2σ significance from 79 (+22 -20 uncertainty) more events than expected from the atmospheric and diffuse astrophysical neutrino backgrounds



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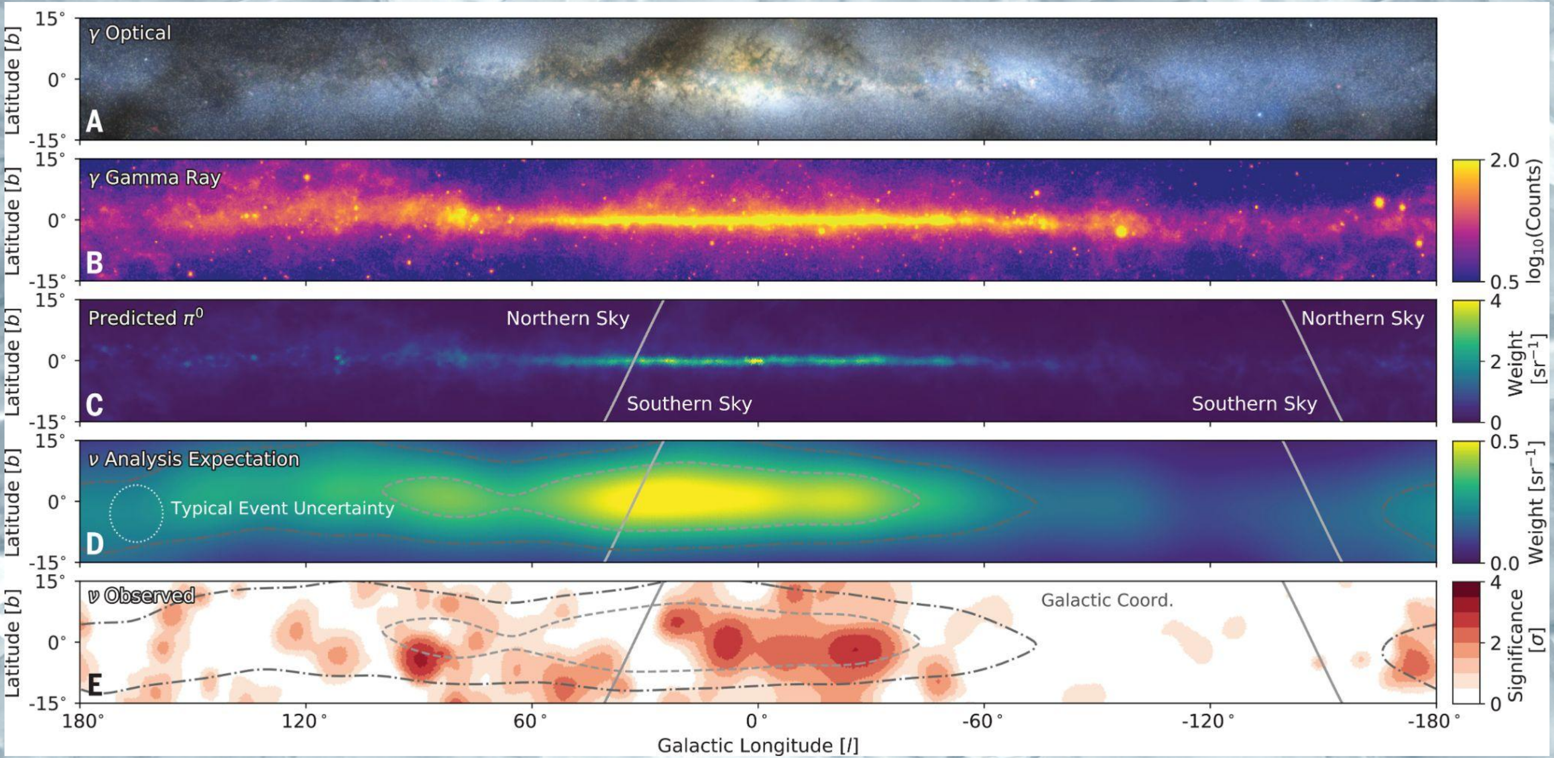
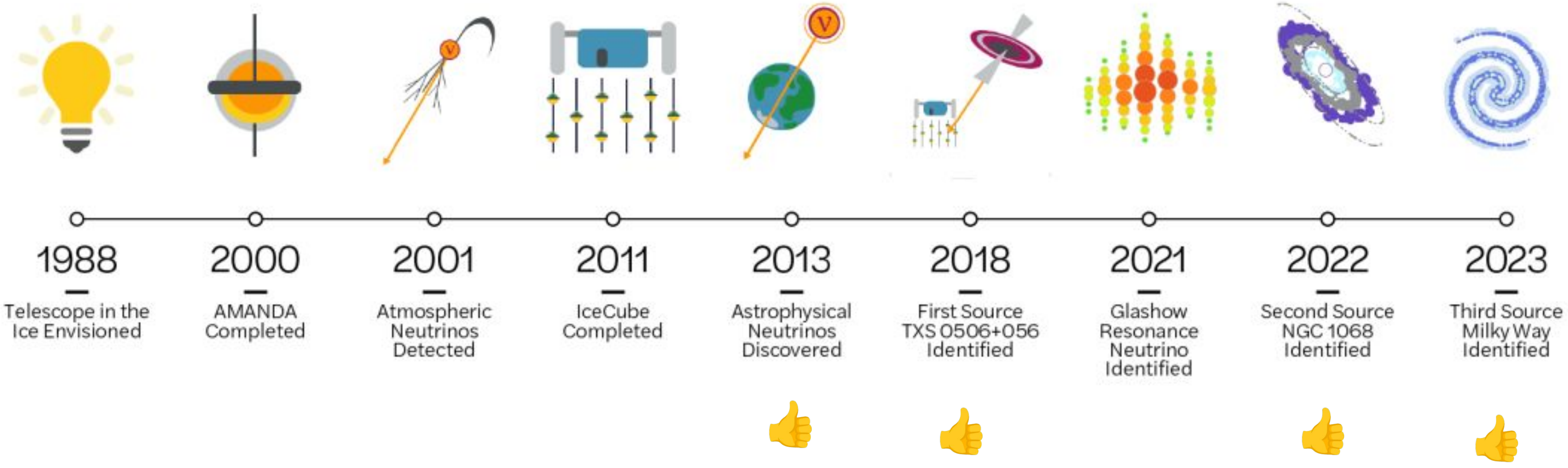
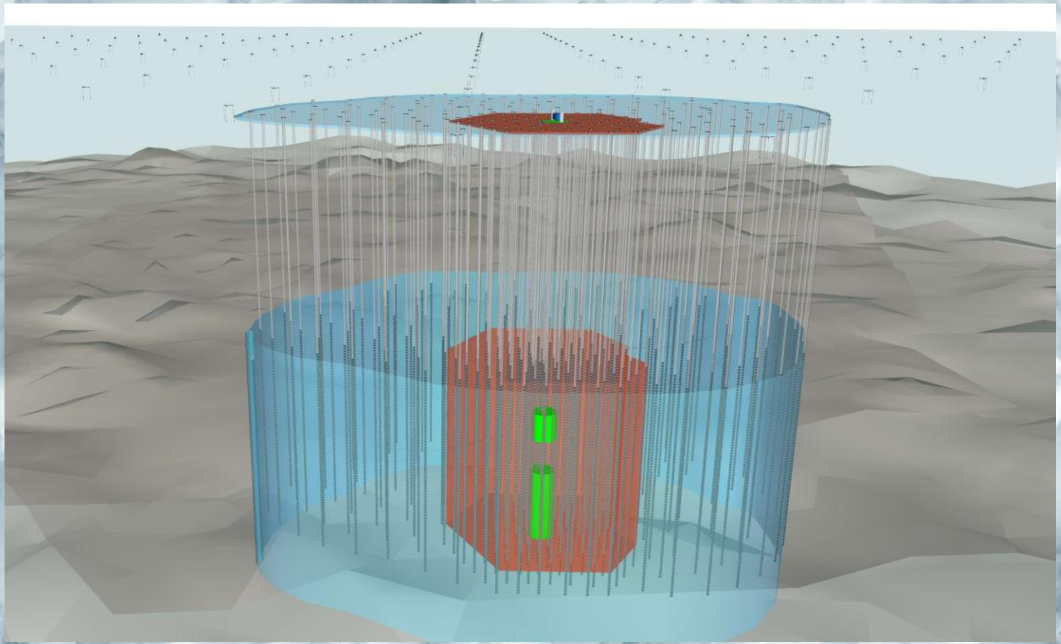
Galactic plane neutrinos



A History of Neutrino Astronomy in Antarctica

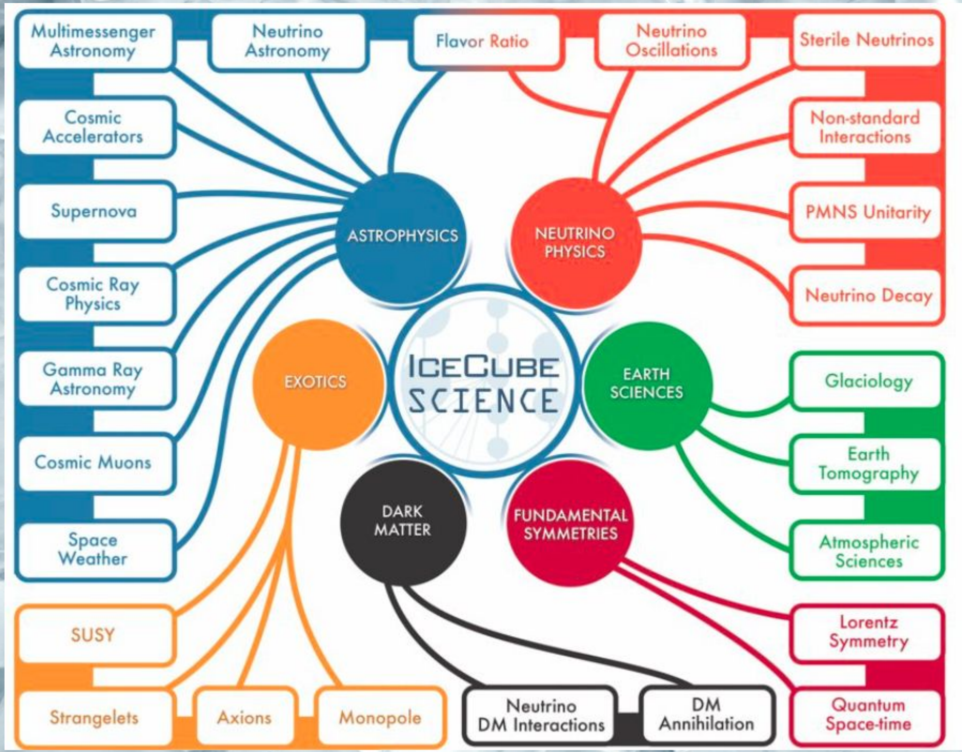


Future prospects: IceCube Gen2



Active volume of 8 km^3!

There's a lot of IceCube science that we don't have time to cover!



Conclusion

-It’s exciting time for neutrino astronomy!

-Neutrinos are useful astrophysical messengers but they are hard to detect!

-IceCube discovered a diffuse flux of high energy astrophysical neutrinos in 2013

-The most significant neutrino sources so far are AGNs NGC 1068 and TXS 0506+056 and our own galaxy!

-Lots of exciting neutrino astronomy to come!

Thank you!

IceCube Collaboration in Madison, WI (2022)