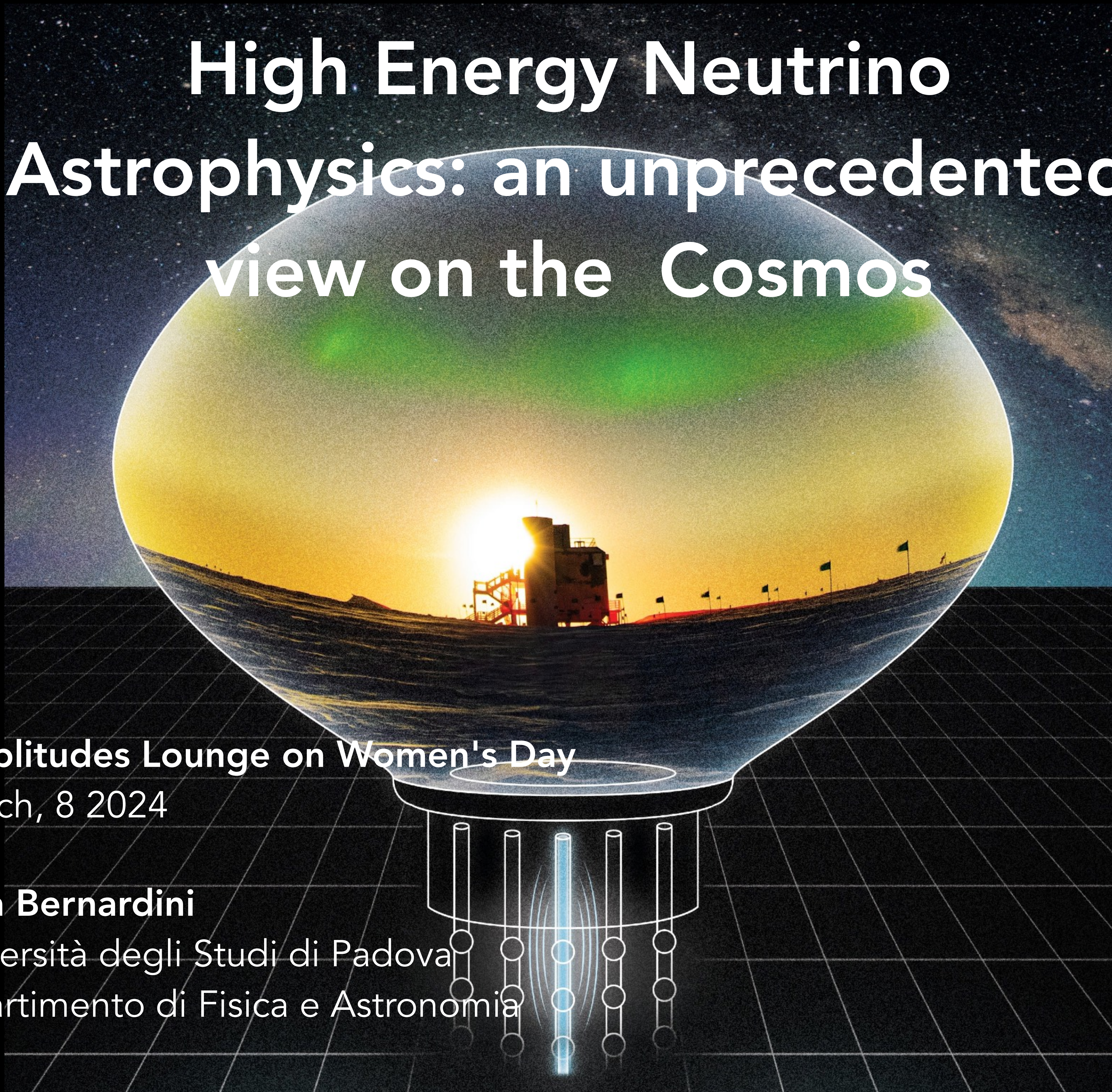


# High Energy Neutrino Astrophysics: an unprecedented view on the  Cosmos

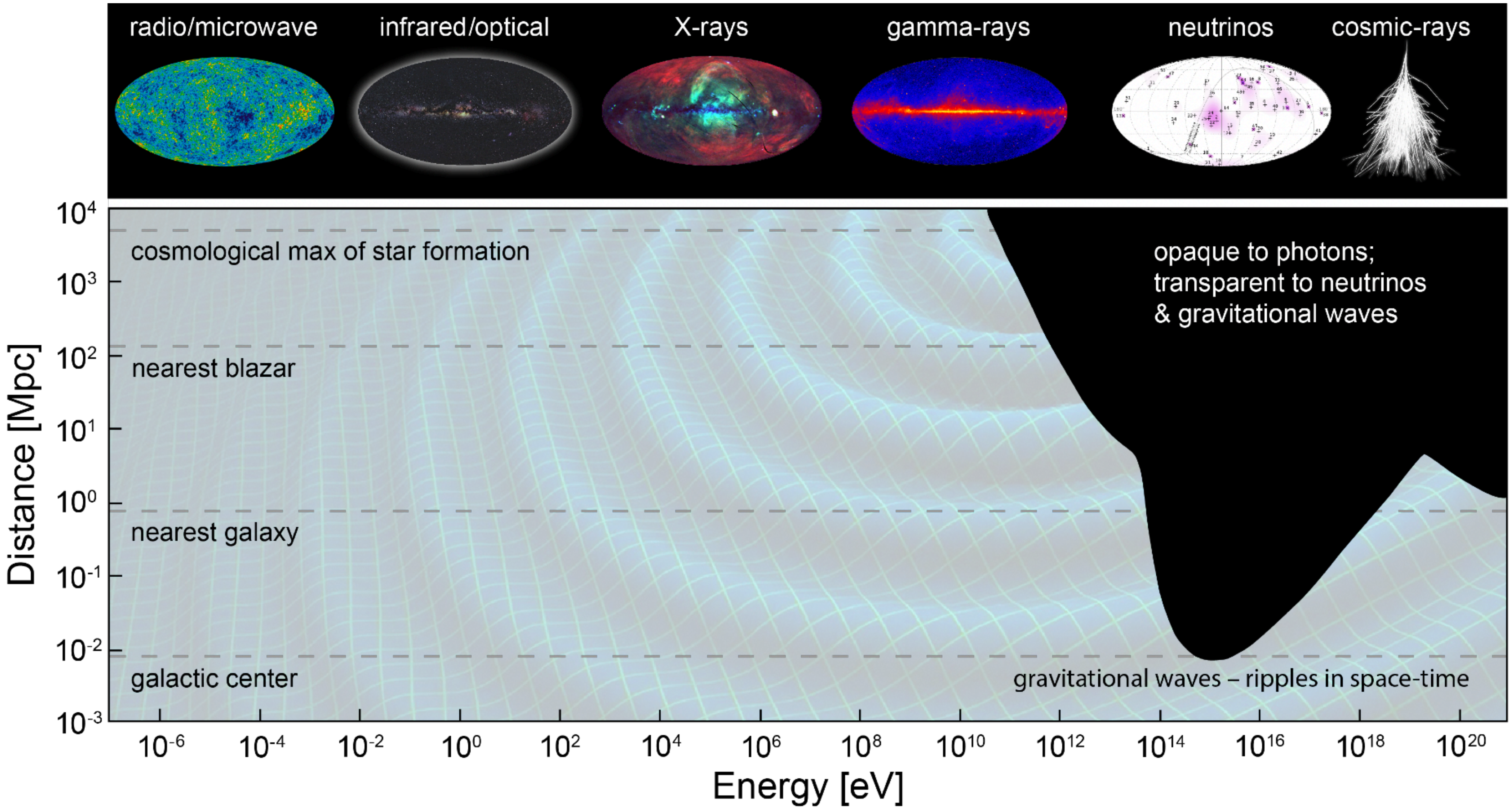
**Amplitudes Lounge on Women's Day**
March, 8 2024

**Elisa Bernardini**
Università degli Studi di Padova
Dipartimento di Fisica e Astronomia

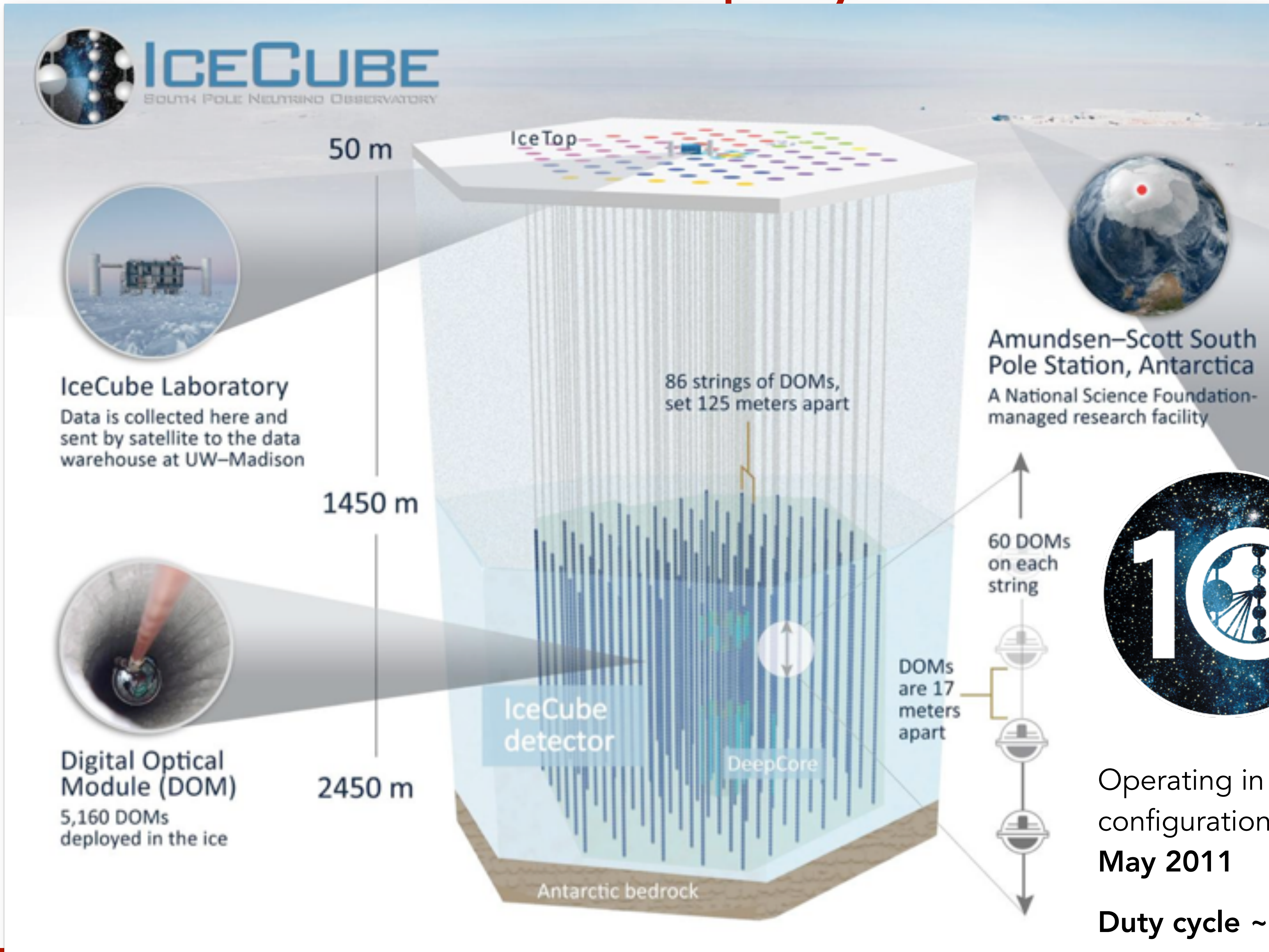
# Why neutrino Astrophysics?

Photons are absorbed in the Extragalactic Background Light (EBL)

Protons ($E>10^{20}$ eV) interact with the Cosmic Microwave Background (CMB)



# How Neutrino Astrophysics?




Operating in full configuration since **May 2011**

**Duty cycle ~99%**

# A History of Neutrino Astronomy in Antarctica

**F. Halzen & J. Learned @ 1st edition of Neutrino Telescopes in Venice (1988):**

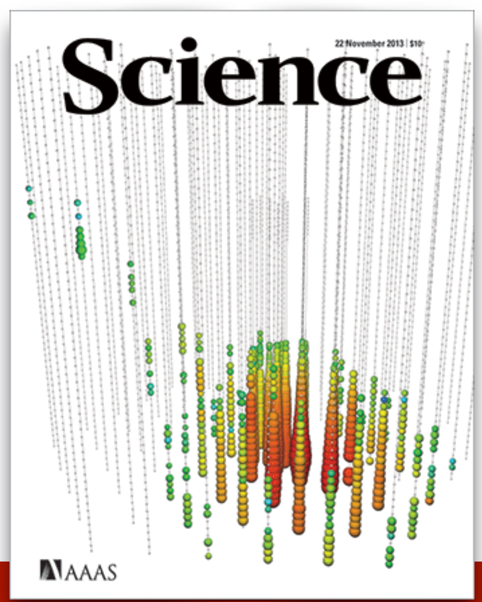
*"This is a detector that requires a number of happy accidents to make it feasible. But if these should come to pass, it may provide the least expensive route to a truly large neutrino telescope. Exploratory studies may begin at the South Pole Station within the next few years."*

Neutrino Telescopes Envisioned (**1960**)

- **1988** — Telescope in the Ice Envisioned
- **2000** — AMANDA Completed
- **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

**2007**


**2019**




**2018**


**2019**


**2022**

# A History of Neutrino Astronomy in Antarctica

IceCube Neutrino Observatory

First High Energy Atmospheric Neutrinos Detected by Baikal (**1996**)

Construction of ANTARES Started (**2002**)

Neutrino Telescopes Envisioned (**1960**)

- **1988** — Telescope in the Ice Envisioned
- **2000** — AMANDA Completed
- **2001** — Atmospheric Neutrinos Detected
- **2011** — IceCube Completed
- **2013** — Astrophysical Neutrinos Discovered
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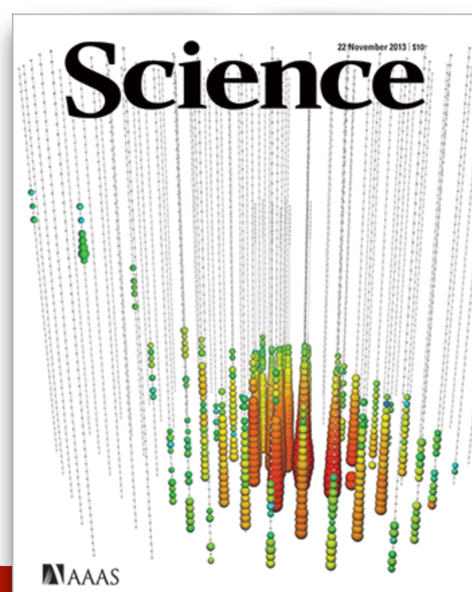
- **2023** — Third Source Milky Way Identified

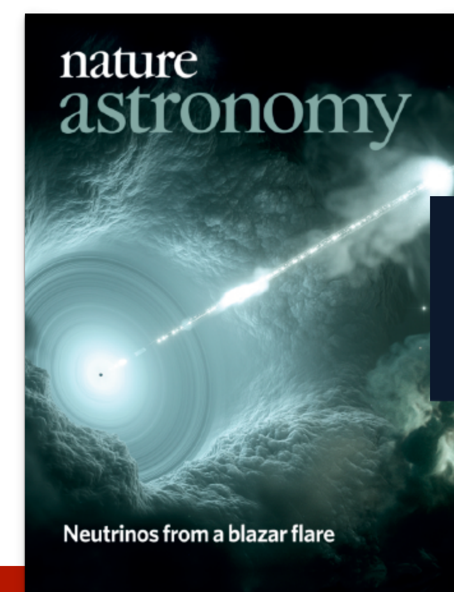
2007


2019




2018


2019



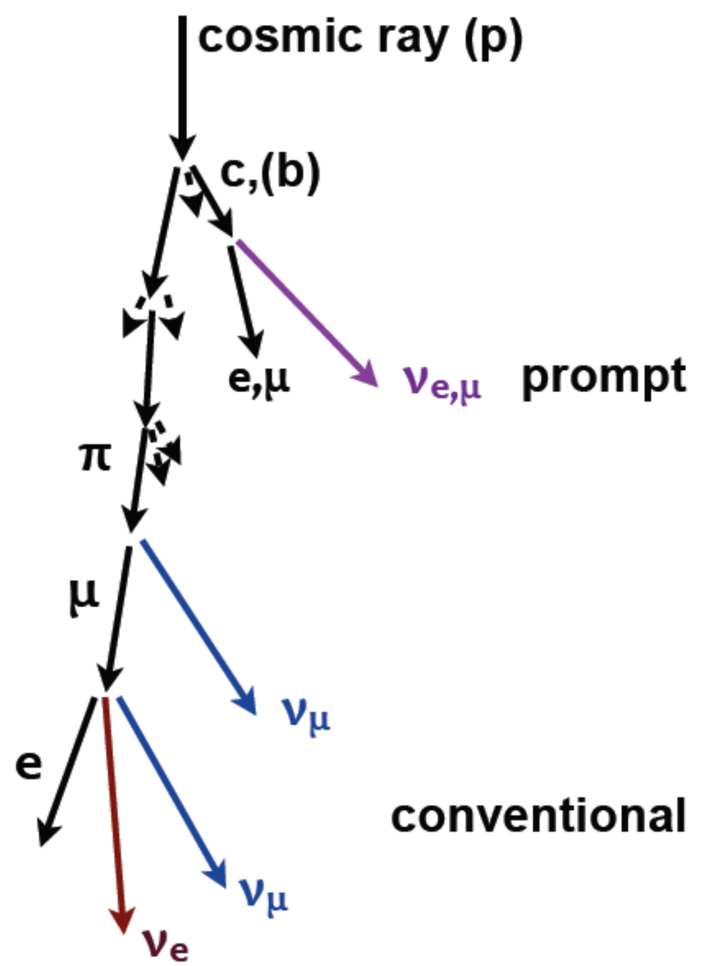

2022

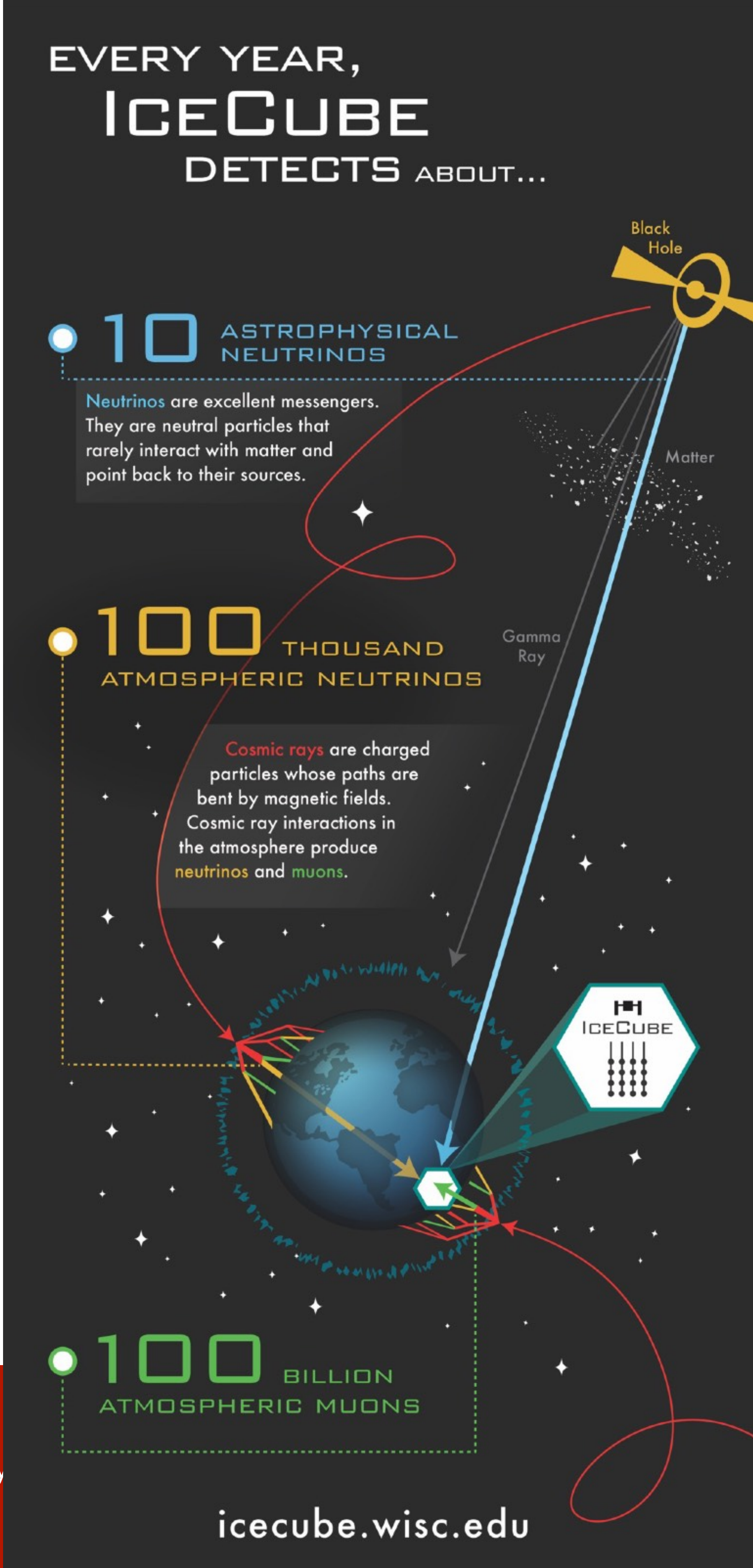
# Signal and backgrounds

atmospheric muons : ~ $10^{11}$ year$^{-1}$ (3000 per second)

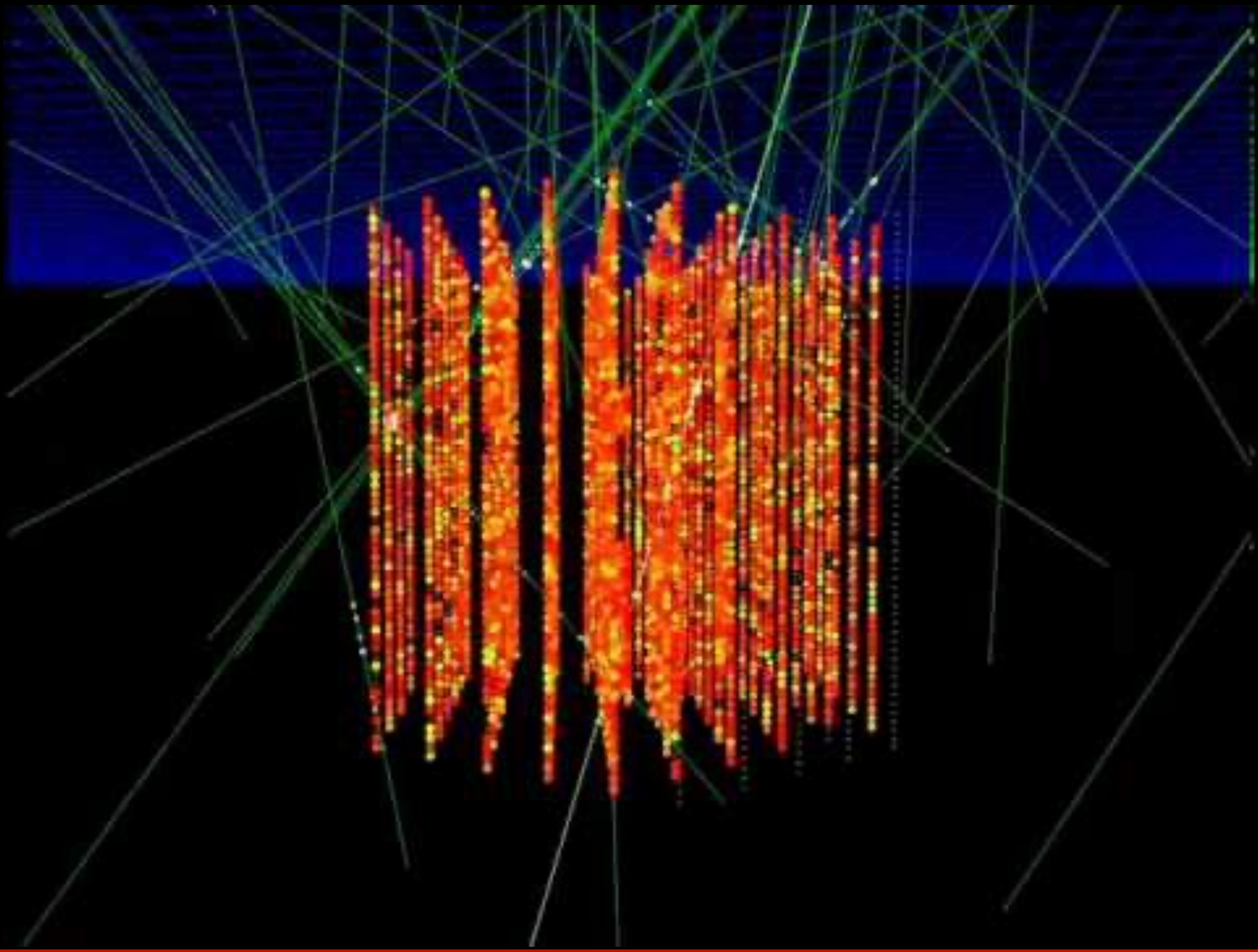
atmospheric neutrinos : ~ $10^{5}$ year$^{-1}$ (1 every 6 minutes)

astrophysical : ~ few -100 year$^{-1}$



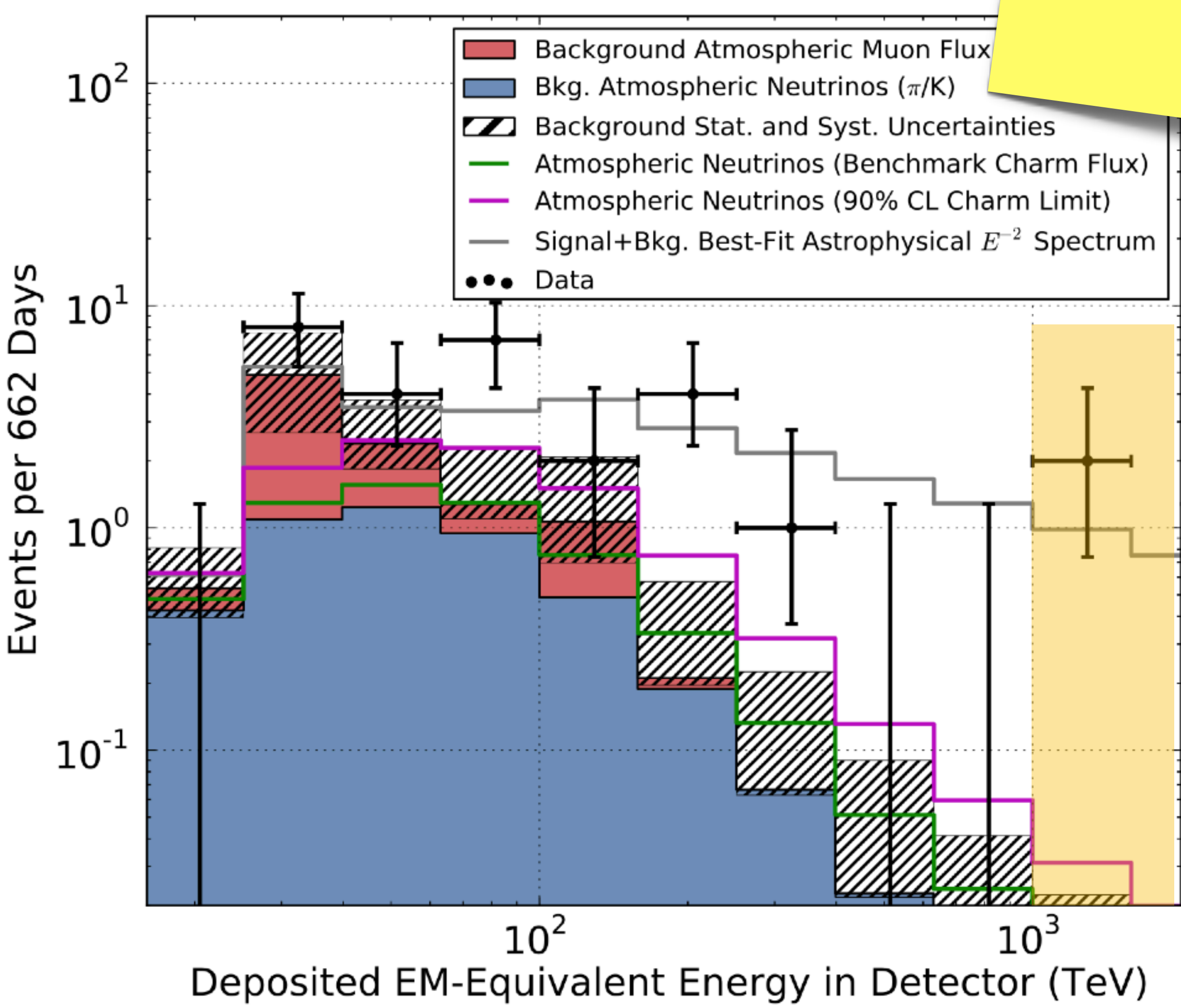
# 10 millisecondi di misure di IceCube



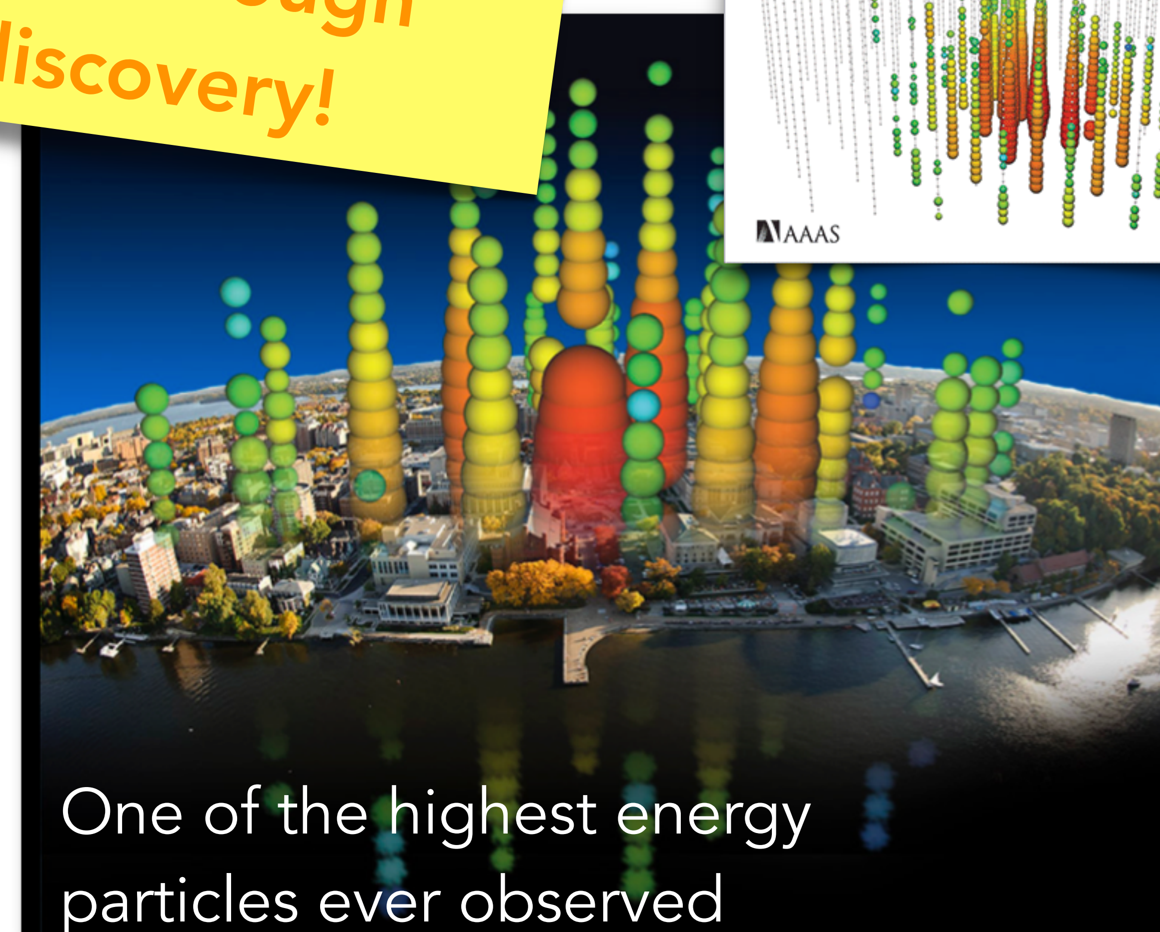
# Astrophysical neutrinos discovered

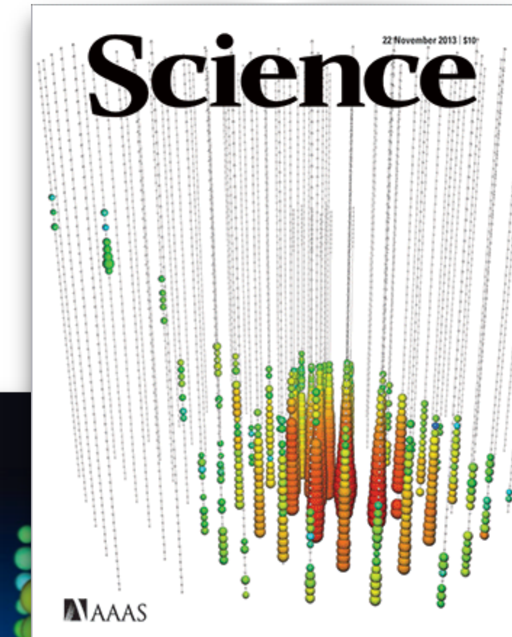
First evidence of neutrinos of astrophysical origin: flavors, directions, and energies inconsistent with those expected from the atmospheric muon and neutrino backgrounds (at 4 $\sigma$).

IceCube, Science 342, 1242856 (**2013**)

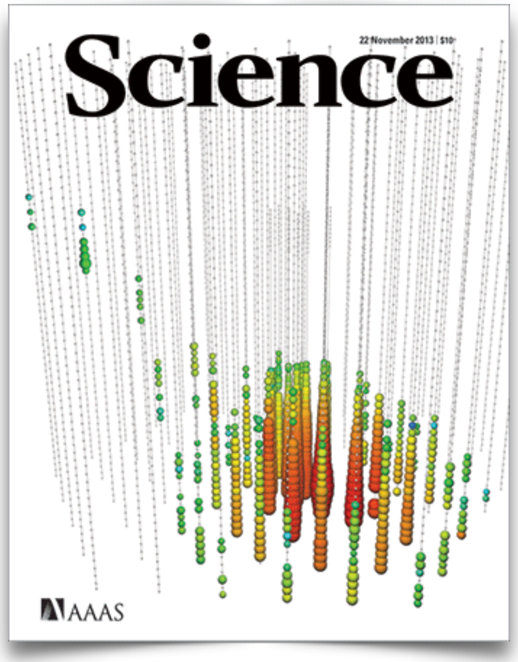


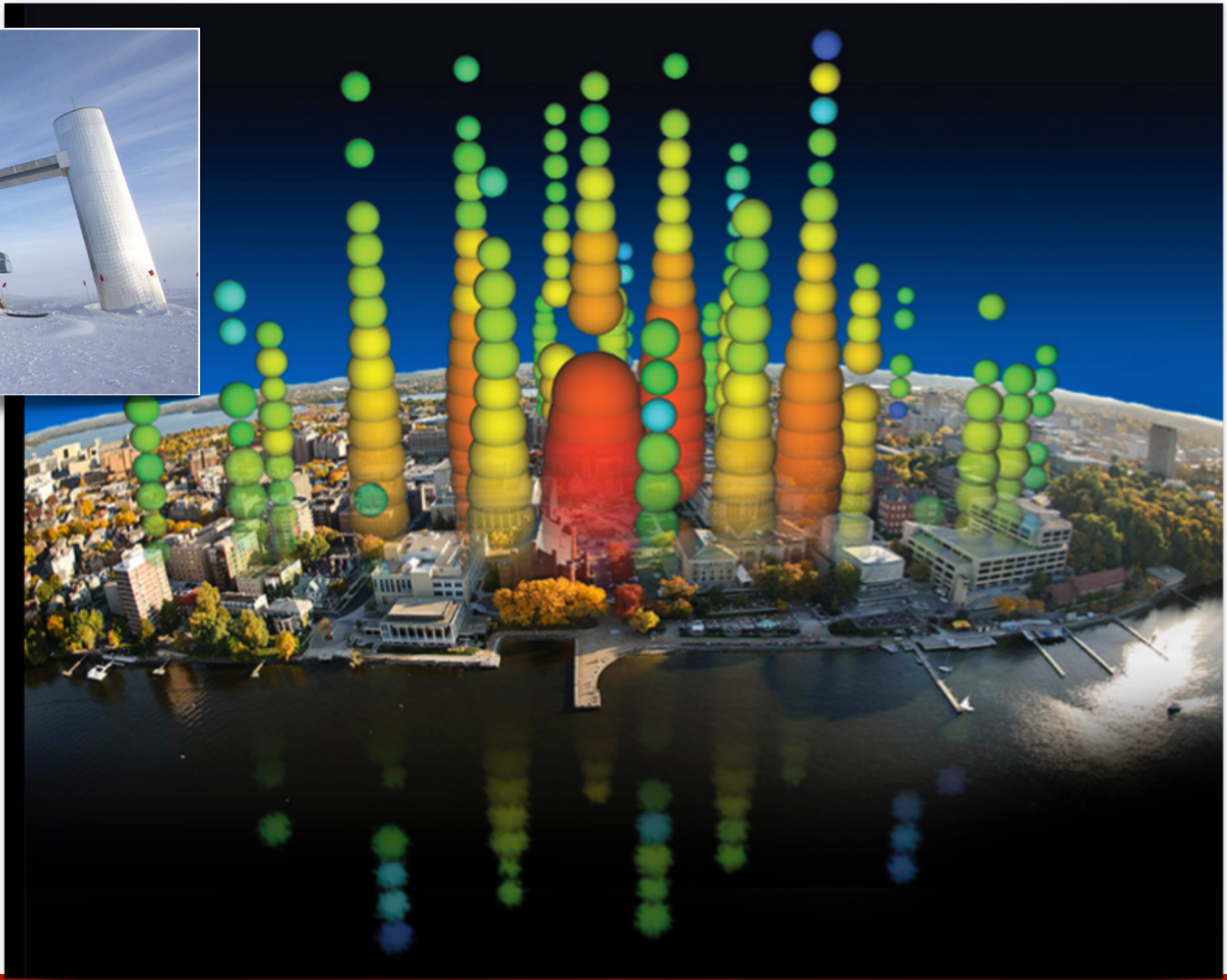

**Breakthrough discovery!**



# High energy cosmic neutrinos

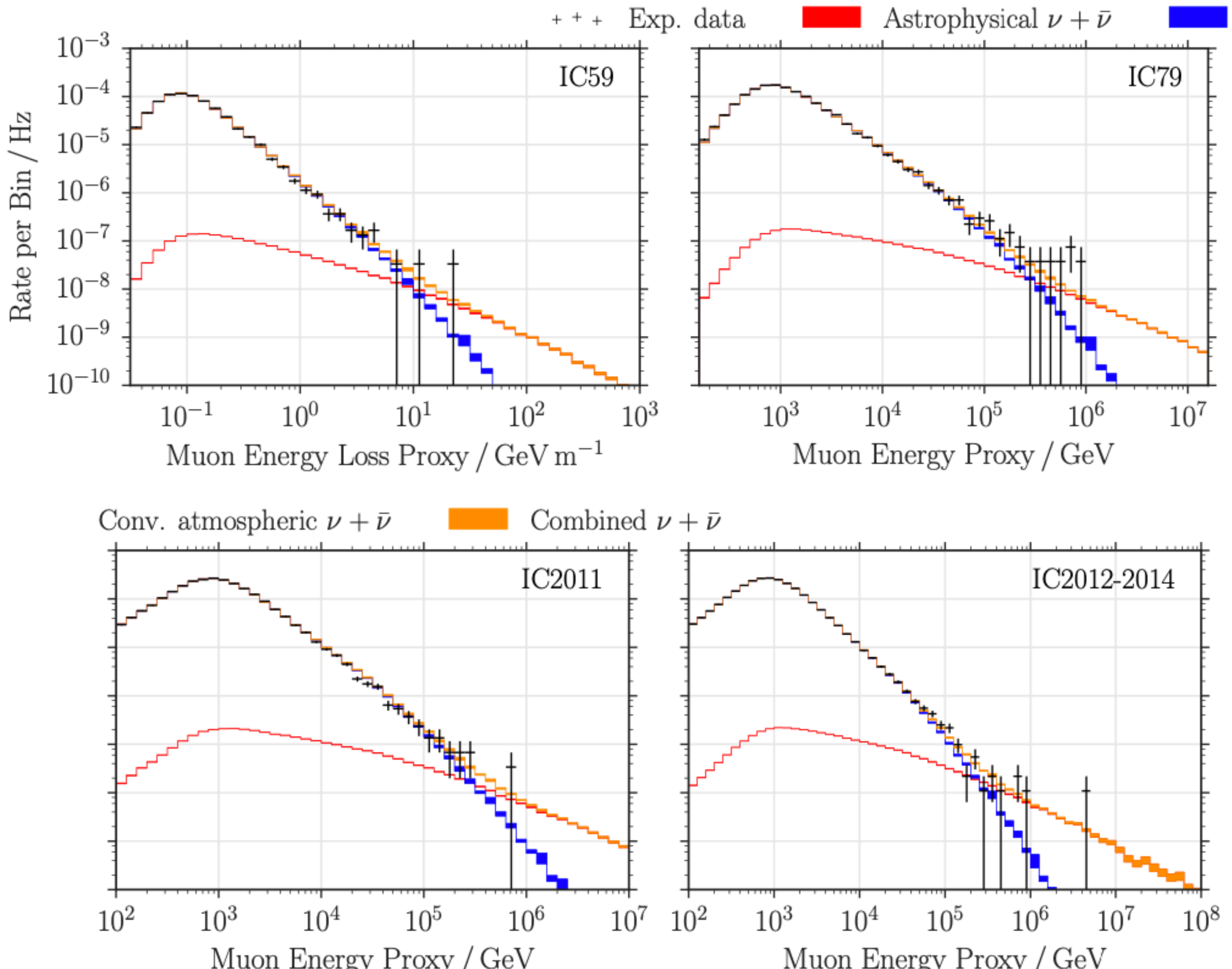



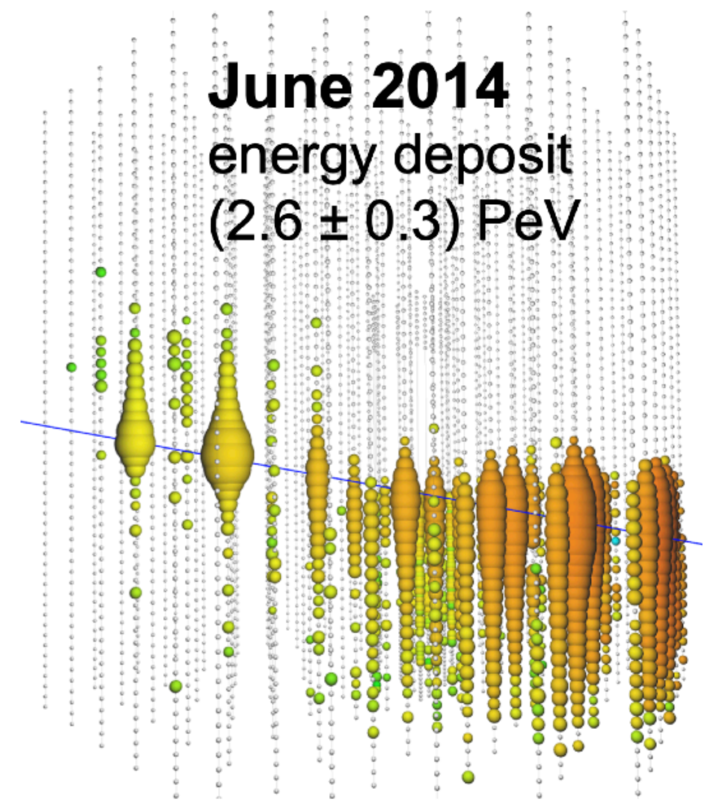



# Comparing energies

# Diffuse astrophysical neutrinos

A clear excess of high energy neutrinos emerges over the expected background in the Northern hemisphere with significance close to $7\sigma$ with 8 years of data

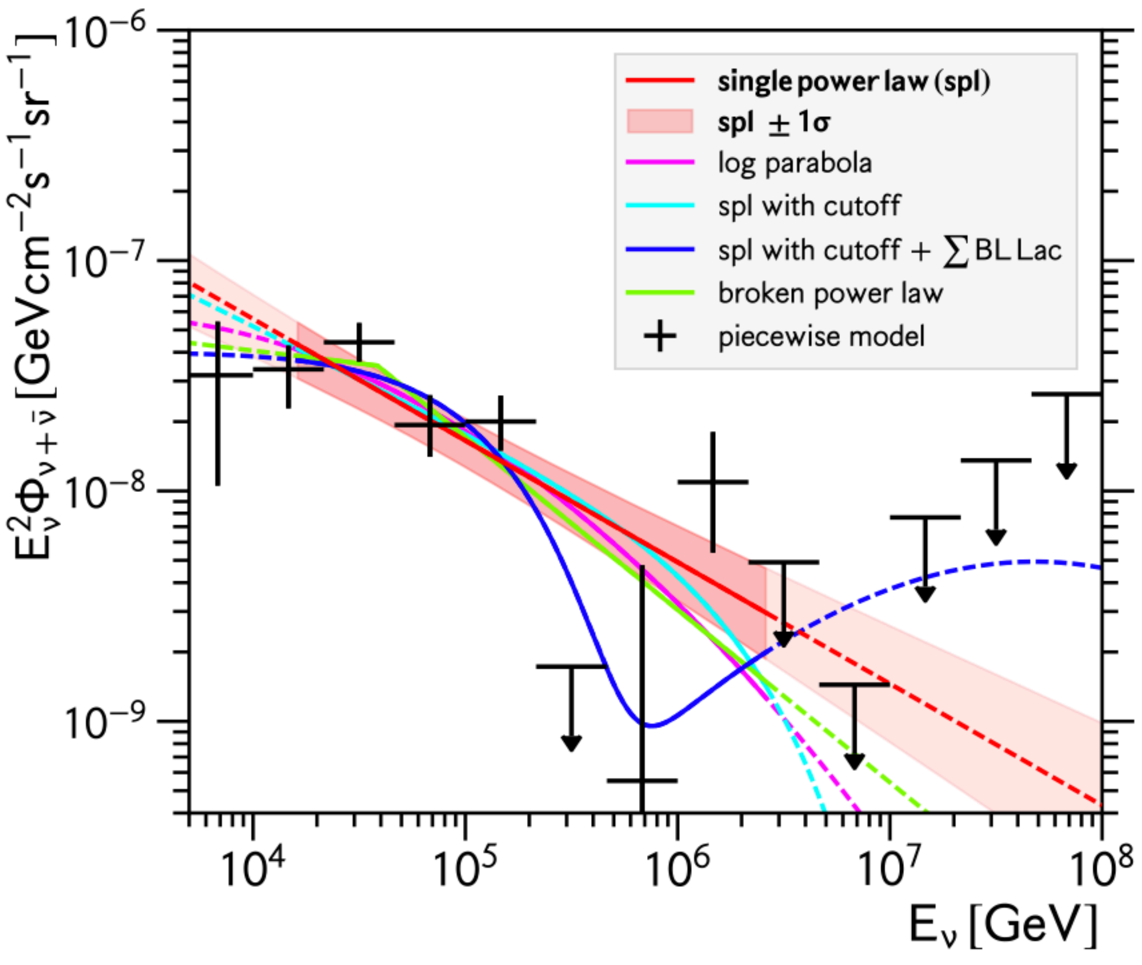


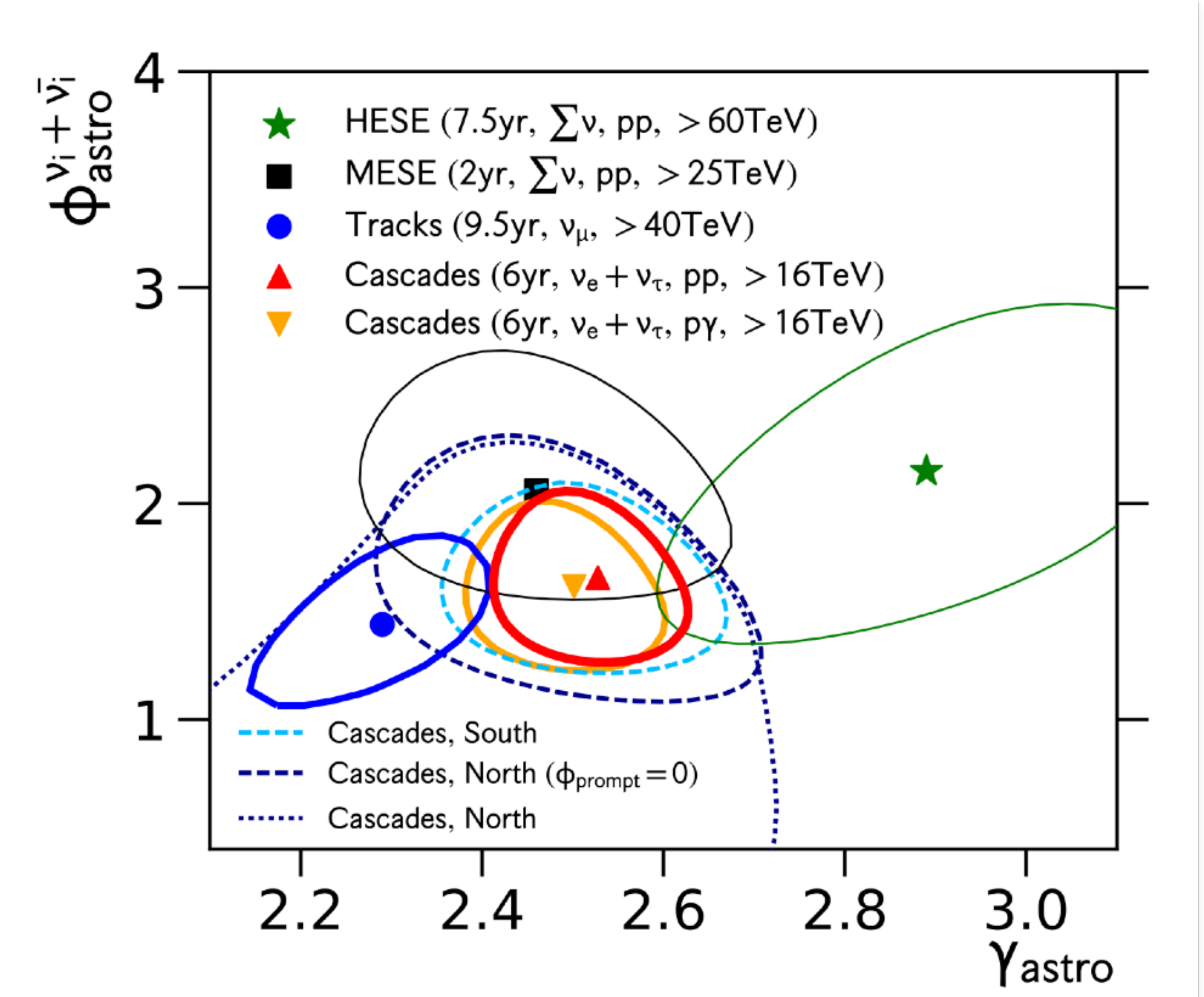

IceCube, Astrophys. J. 833 (2016)

# Reducing the background: cascades

Due to high neutrino energy resolution and low atmospheric neutrino backgrounds, cascades provide the most detailed characterisation of the neutrino flux at energies below ~ 100 TeV compared to other channels.

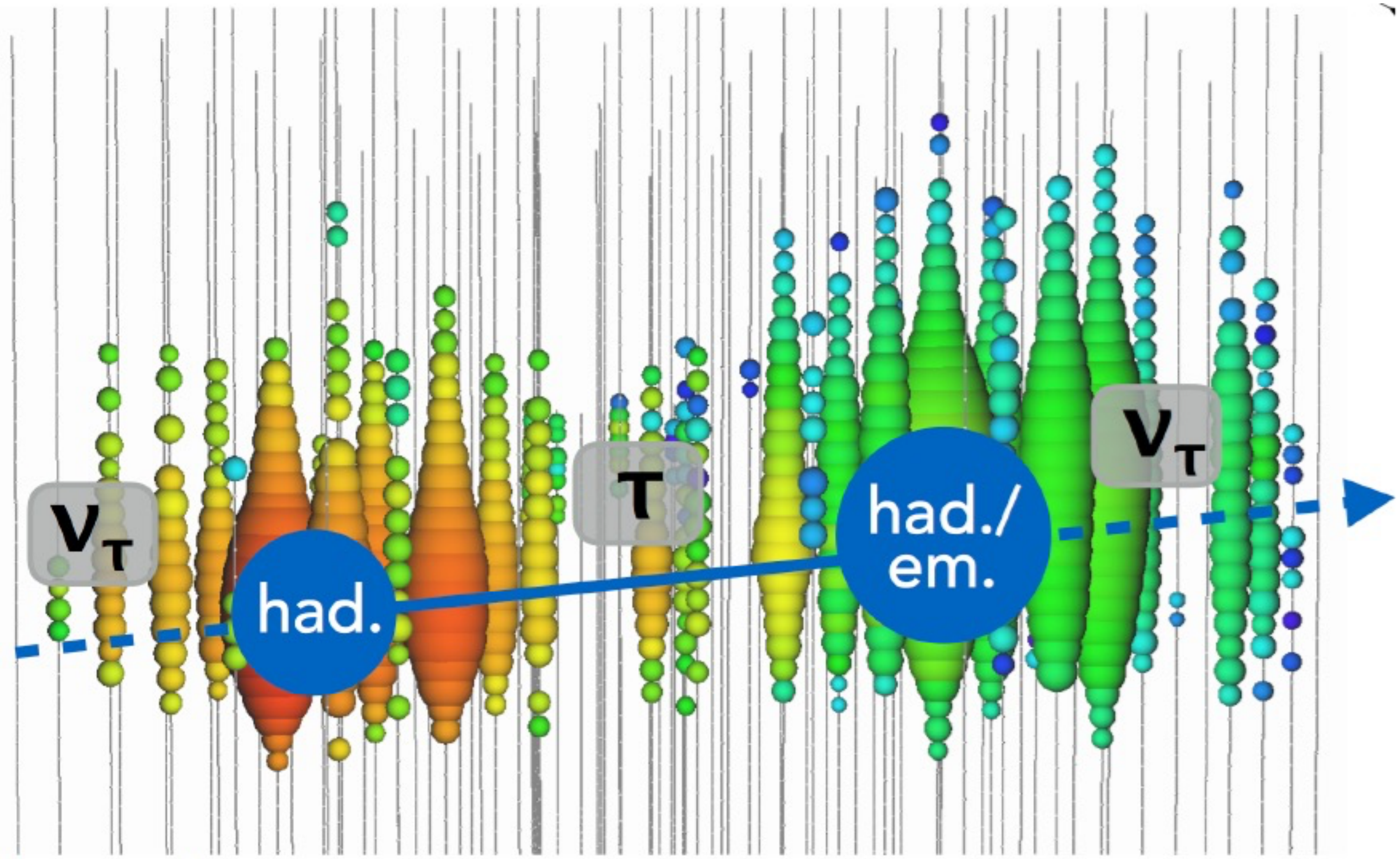



IceCube, Phys. Rev. Lett. 125, 121104 (2020)



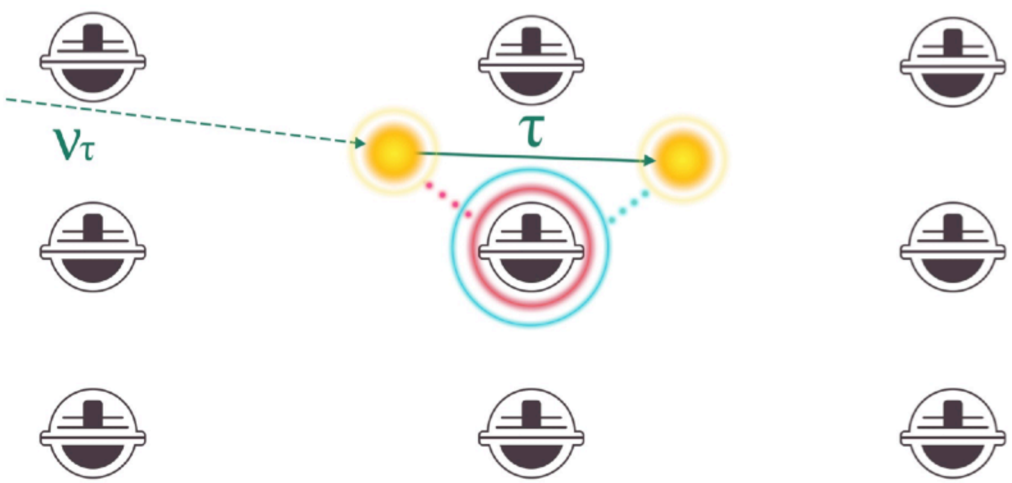
# Searching for tau neutrinos

Few tau neutrinos are expected from cosmic ray interactions in the atmosphere, even after oscillations. Tau neutrinos are also expected to be rarely produced in astrophysical sites, but emerge after oscillations over cosmic baselines. Tau neutrinos detected at Earth shall therefore most likely be astrophysical.

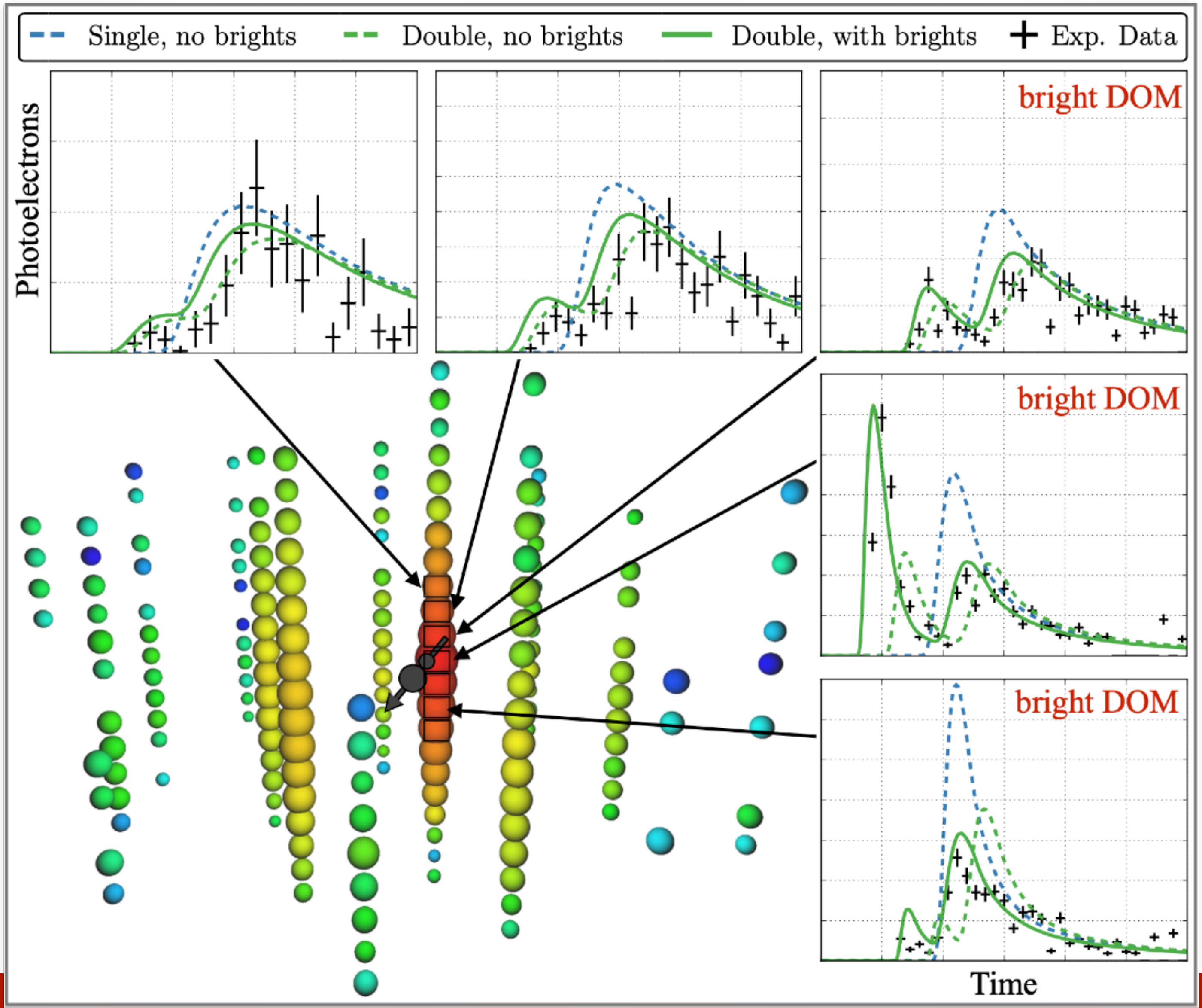


# Searching for tau neutrinos

Tau neutrinos produce a "double pulse" or "double bang" signature. Event selection looks at waveforms on individual DOMs. Two candidate tau neutrinos among the 60 HESE events found in 7.5 years of data. An astrophysical tau neutrino flux is indicated at 2.8σ significance.

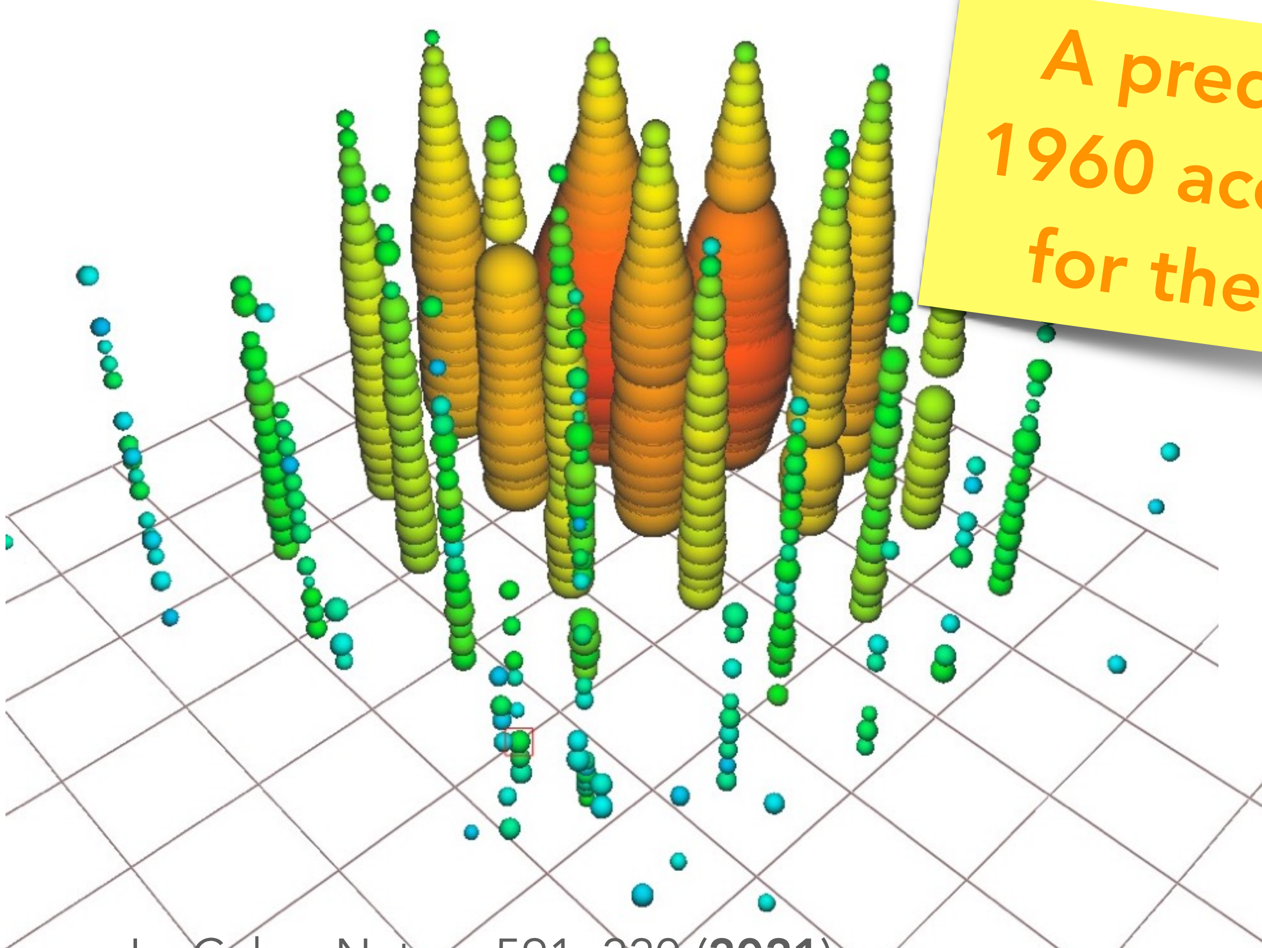



IceCube, Eur. Phys. J. C 82, 1031 (2022)



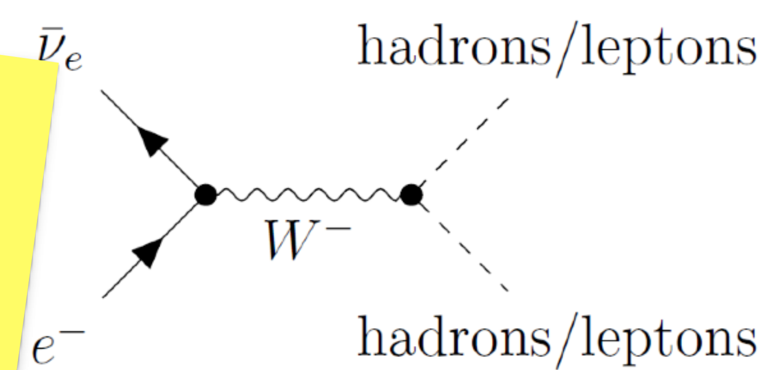
# A neutrino at the Glashow resonance energy

The resonant formation of a W⁻ boson from the interaction of a high energy anti-electron neutrino with an electron (Glashow resonance) is predicted at a peaking neutrino energy of 6.3 PeV in the rest frame of the electron. One such event found for the first time in 4.6 years of IceCube data! Given its energy and direction, it is classified as an astrophysical neutrino at the 5σ level.



IceCube, Nature 591, 220 (**2021**)

A prediction from 1960 accessible now for the first time!

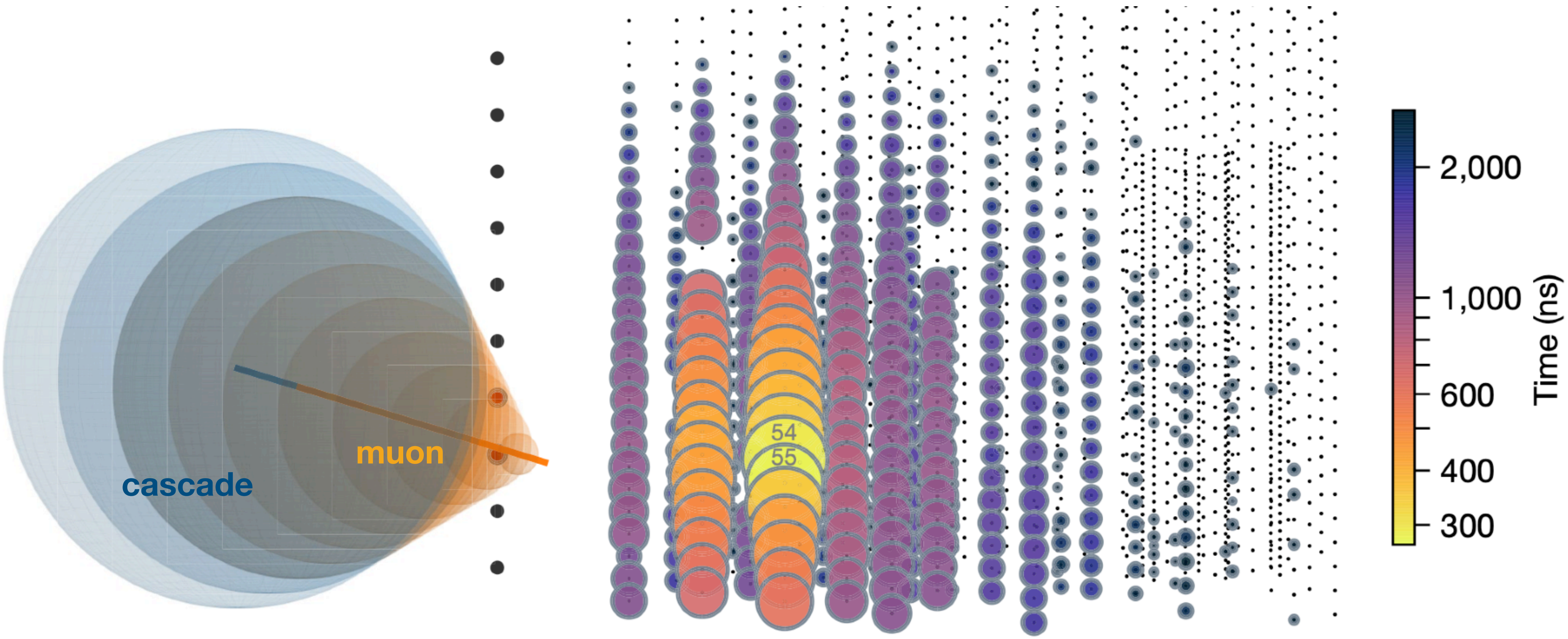



$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \begin{cases} \text{Hadrons (67\%)} \\ \text{Leptons (23\%)} \end{cases}$$

See also **Sheldon Glashow "The past and the future of neutrino science"** @ XIX International Workshop on Neutrino Telescopes, Venice (Italy) **2021**

# A neutrino at the Glashow resonance energy

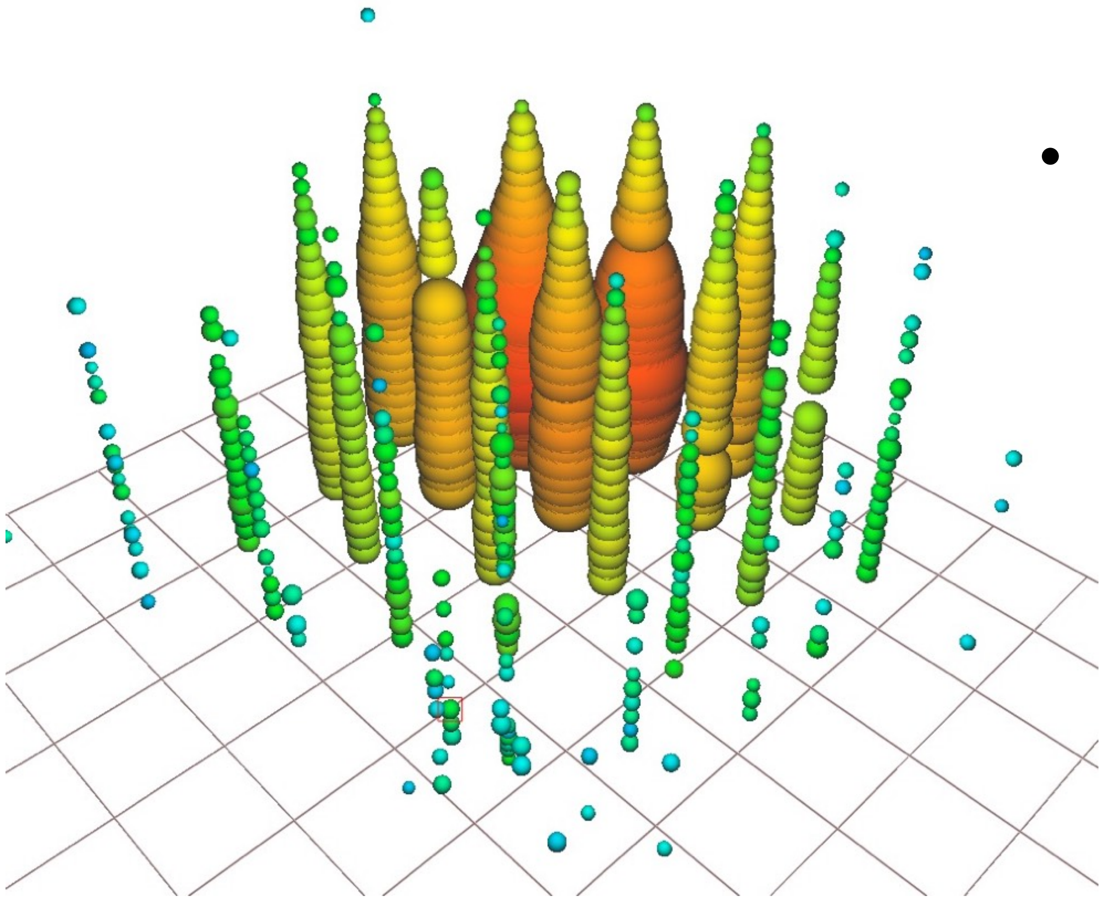
Early pulses are consistent with with an outgoing muon from the hadronic shower (with reconstructed energy ~ 26 GeV) and allow to conclude that the event is very likely to be of astrophysical origin.




IceCube, Nature 591, 220 (**2021**)

# A neutrino at the Glashow resonance energy

Simplified source models can already be tested with one Glashow resonance. Future facilities and multi-messenger associations will enable differentiating between different scenarios.

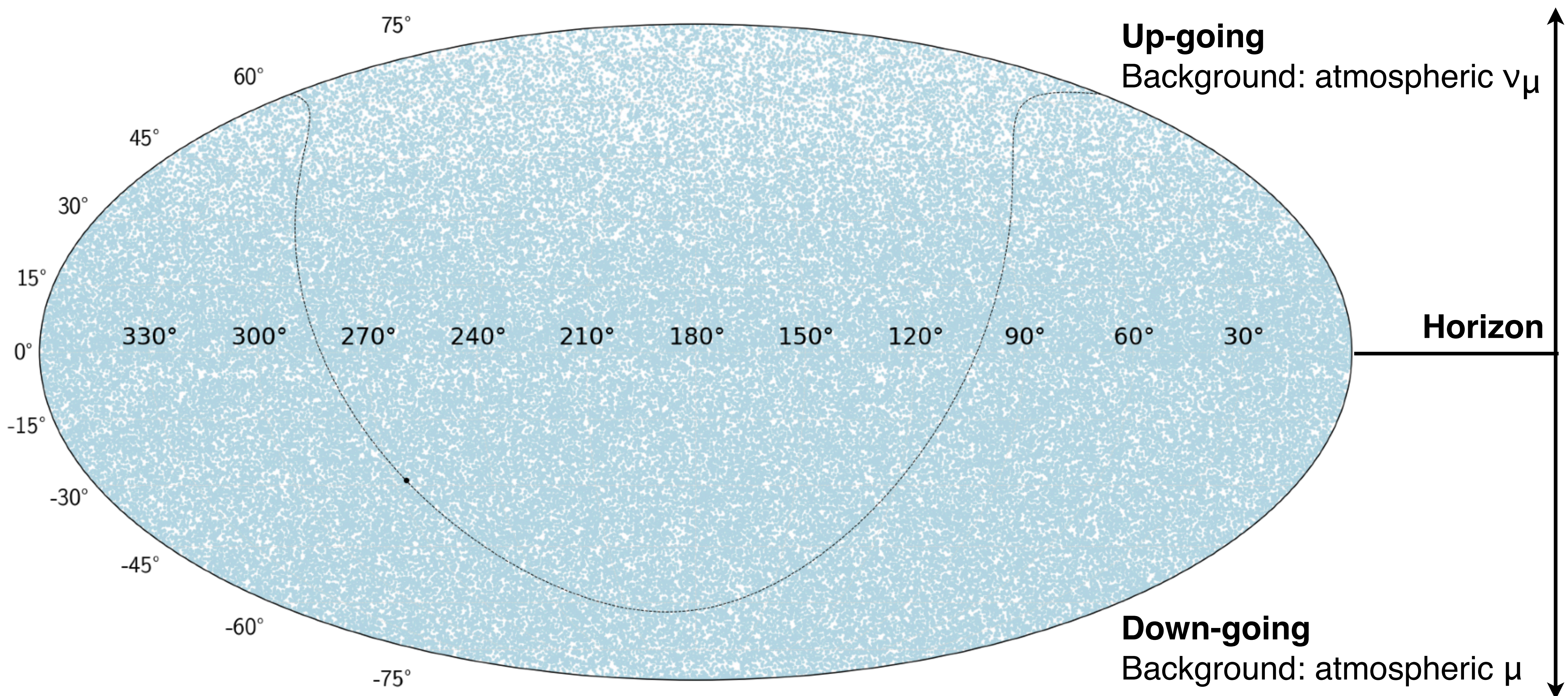


IceCube, Nature 591, 220 (2021)

- Expected ratio $\bar{\nu}_e : \nu_e$:
  - proton-proton
    - $(pp)\ \ \bar{\nu}_e : \nu_e = 1 : 1$
  - proton-photon
    - $(p\gamma)\ \ \bar{\nu}_e : \nu_e = 1 : 3.5$
    - $(p\gamma$, strong B-field$)\ \ \bar{\nu}_e : \nu_e = 0$

# Searching for Neutrino Point Sources

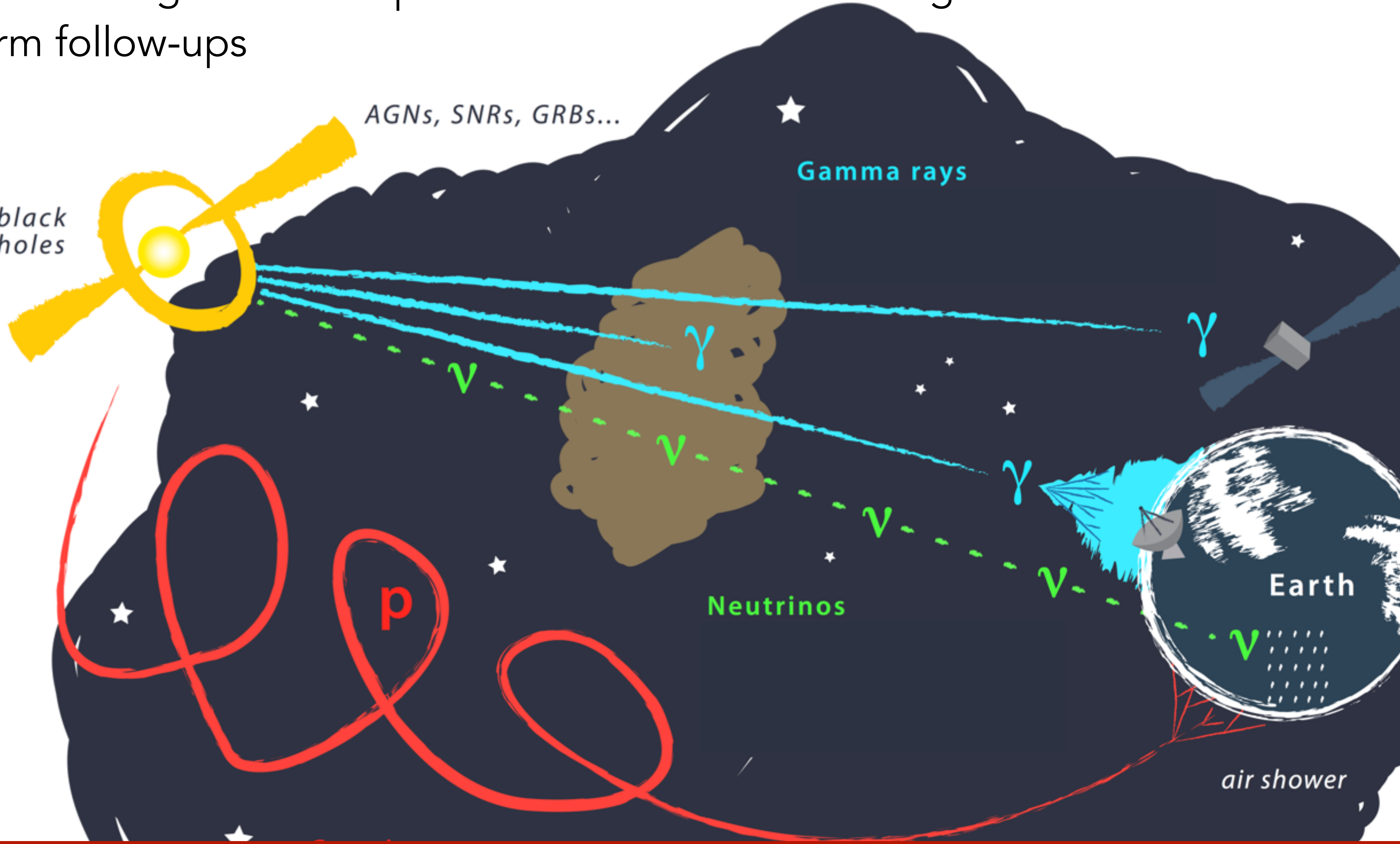
From the first year of full IceCube operations 138,322 neutrino candidates (**muon tracks**) recorded!




**Equatorial coordinates**

# Realtime Neutrino Astronomy

IceCube's nearly 100% uptime and continuous 4π steradian field of view make it an ideal observatory for multi-messenger programs, both to trigger other observatories enabling to collect quasi-simultaneous electromagnetic data as well as perform follow-ups



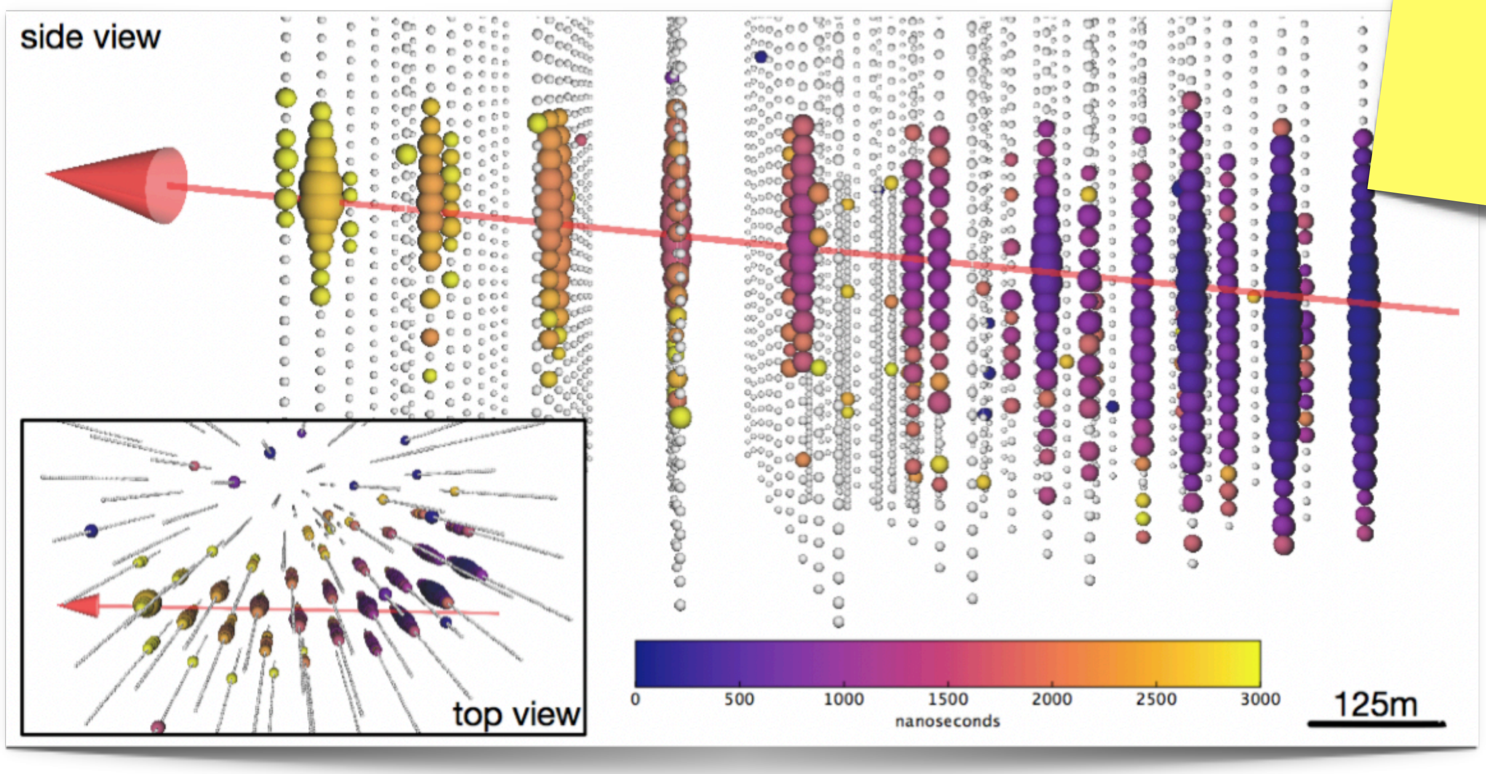
# Breakthrough in Multi-Messenger Astronomy

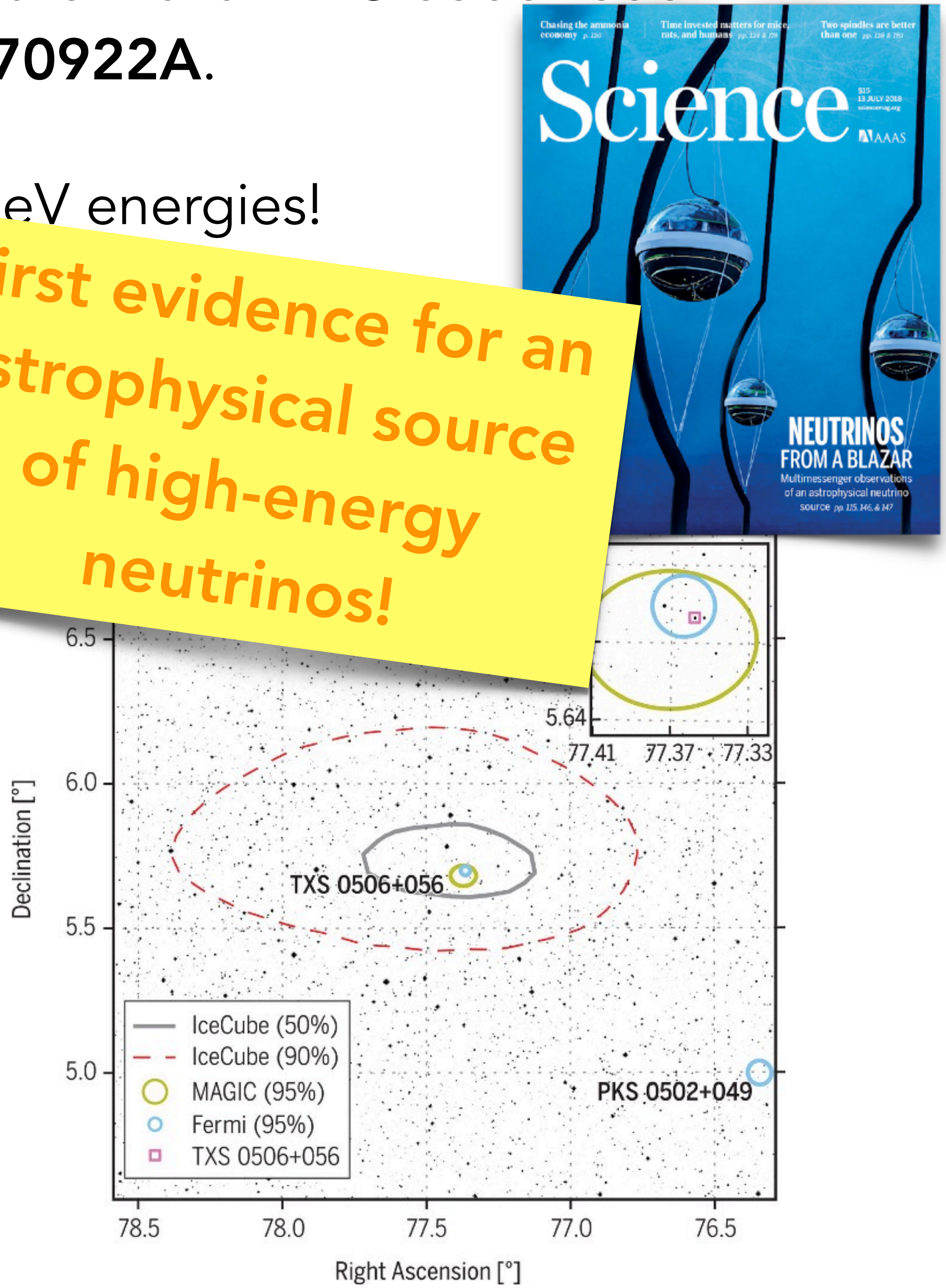
Compelling evidence for high-energy emission from the **Blazar TXS 0506+056** associated with the high-energy neutrino **IceCube-170922A**.

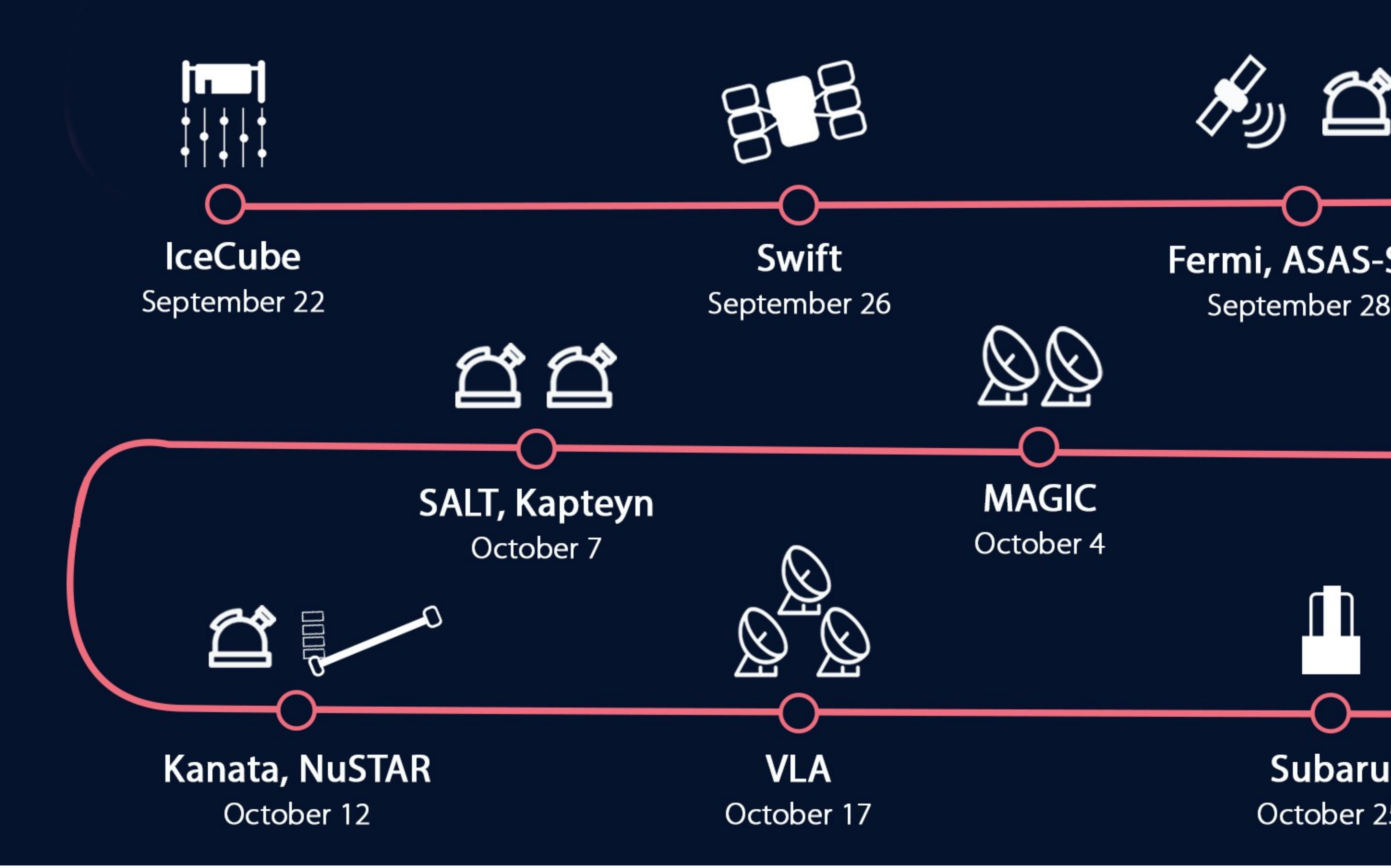
Identification of a cosmic hadron accelerator with >PeV energies!

First evidence for an astrophysical source of high-energy neutrinos!

IceCube, FERMI, MAGIC, ++., Science 361, 146 (**2018**)





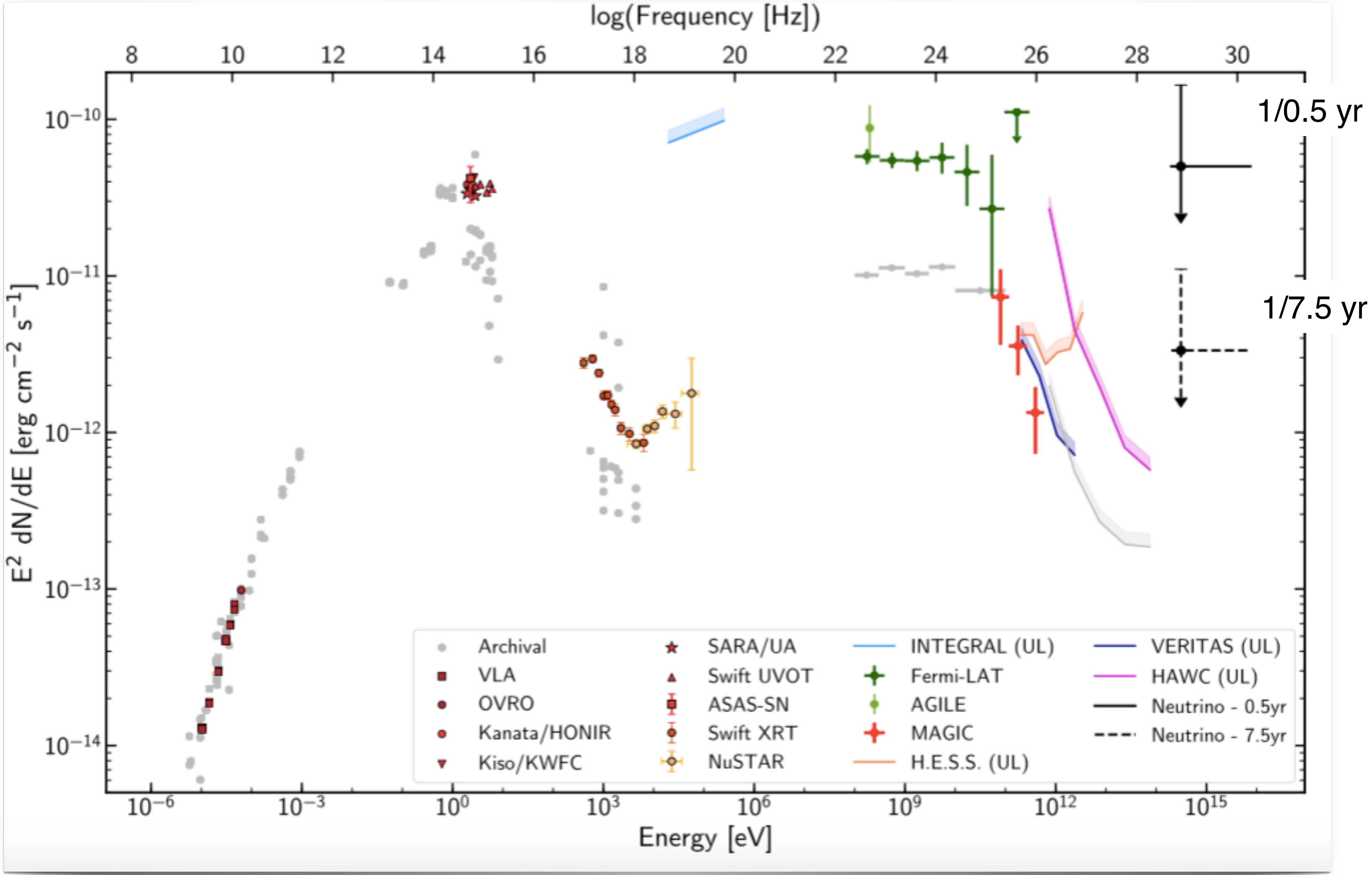


**~1000 astronomers / 18 observatories!**

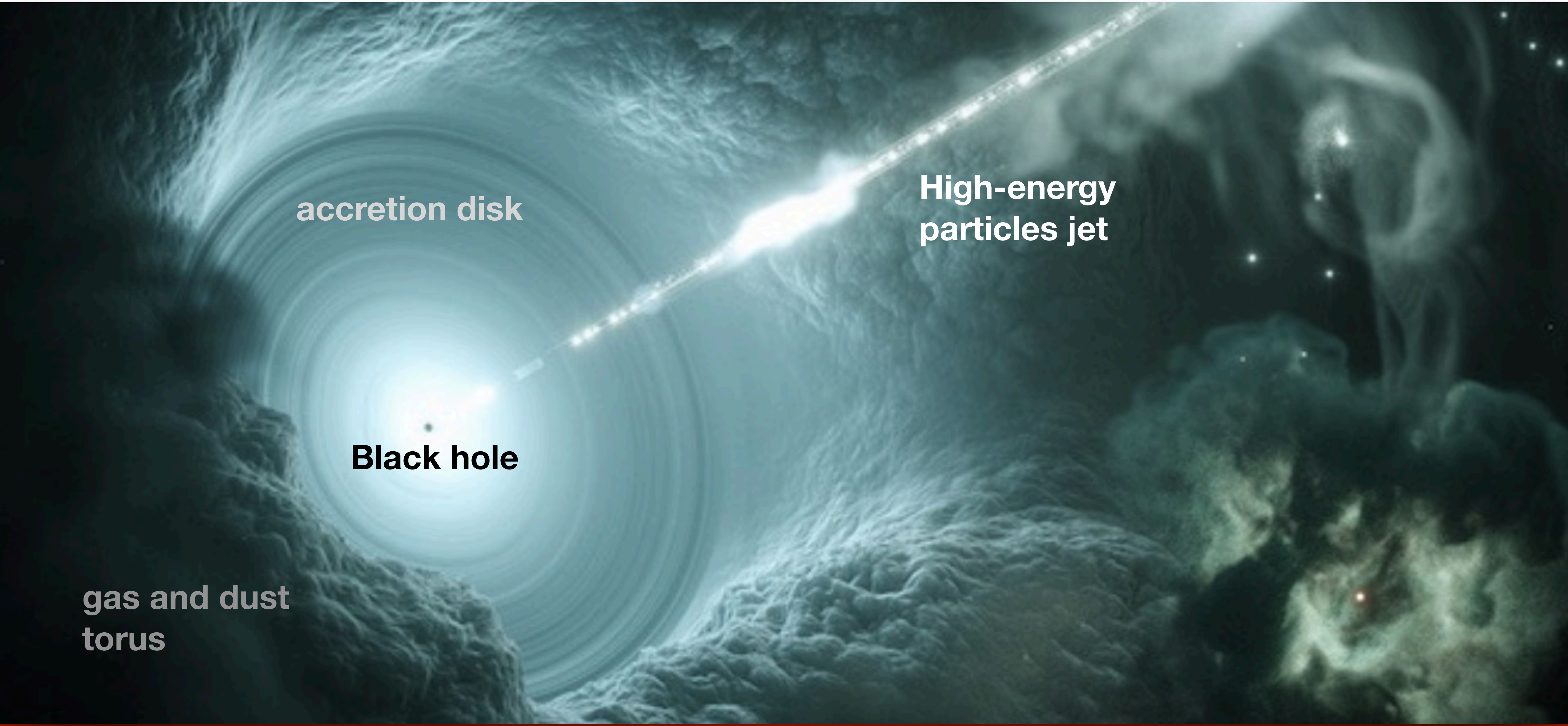
(~3000 astronomers / 70 observatories was for GW170817)

# The first multi-messenger SED

IceCube, FERMI, MAGIC, ++., Science 361, 146 (2018)



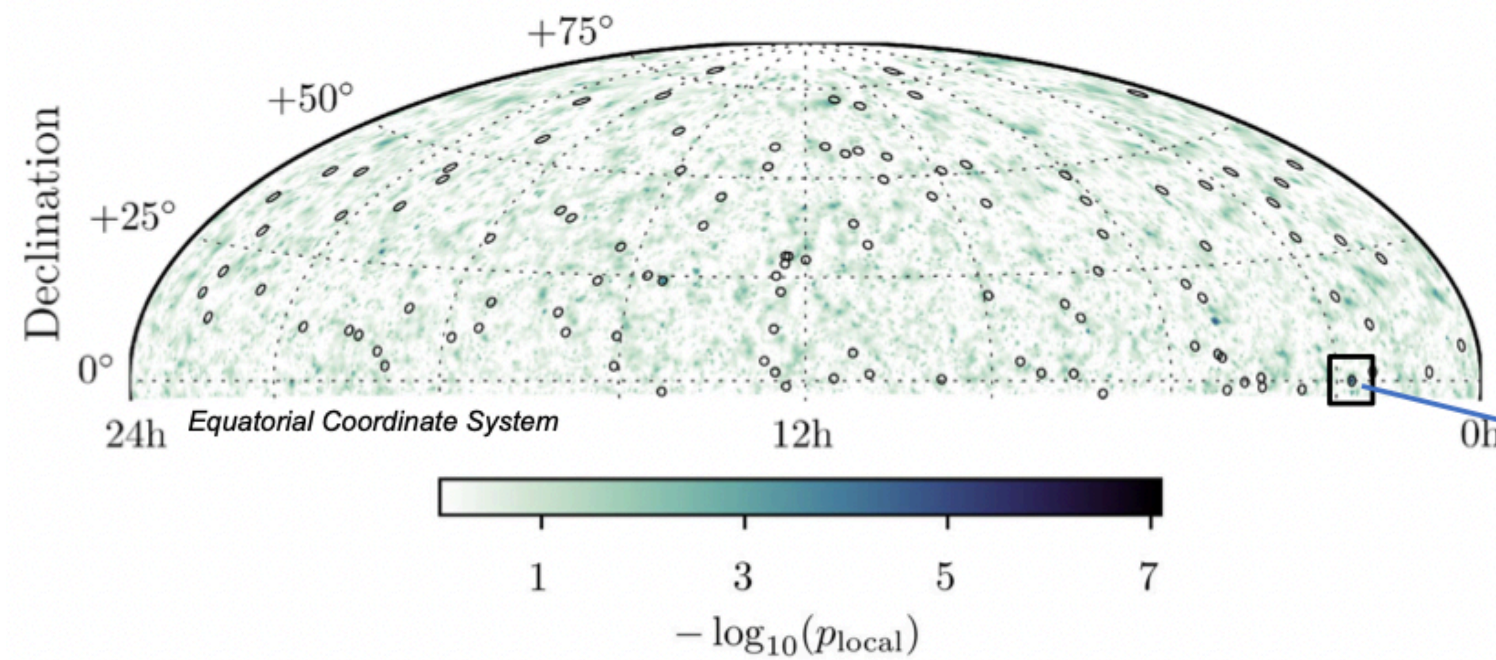
# Active Galactic Nuclei: Blazars

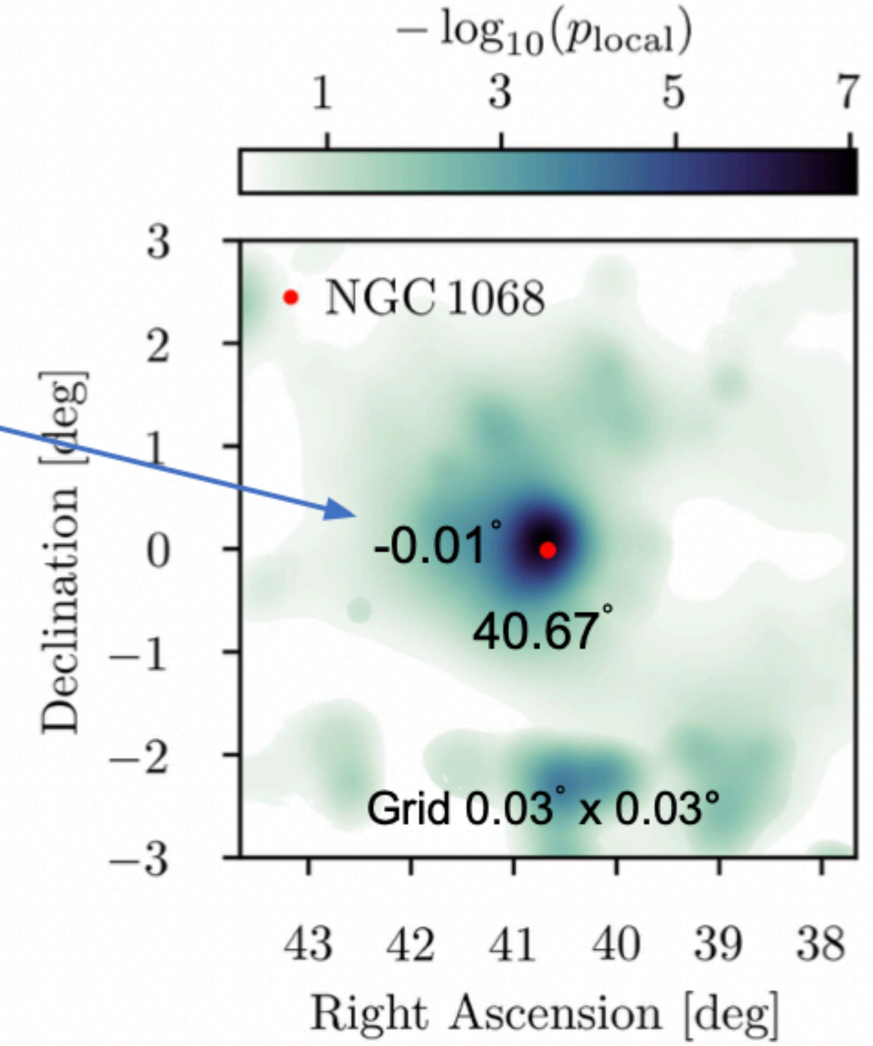


# Improved searches for p

**Second astrophysical source of high-energy neutrinos!**

A search on IceCube data with improved neutrino reconstruction and calibration methods yields evidence for the second astrophysical source of high energy neutrinos: the nearby active galaxy (Seyfert galaxy) NGC 1068 at 4.2$\sigma$. Other AGNs seen at ~3$\sigma$ and above, such as PKS 1424+240 and NGC 4151!



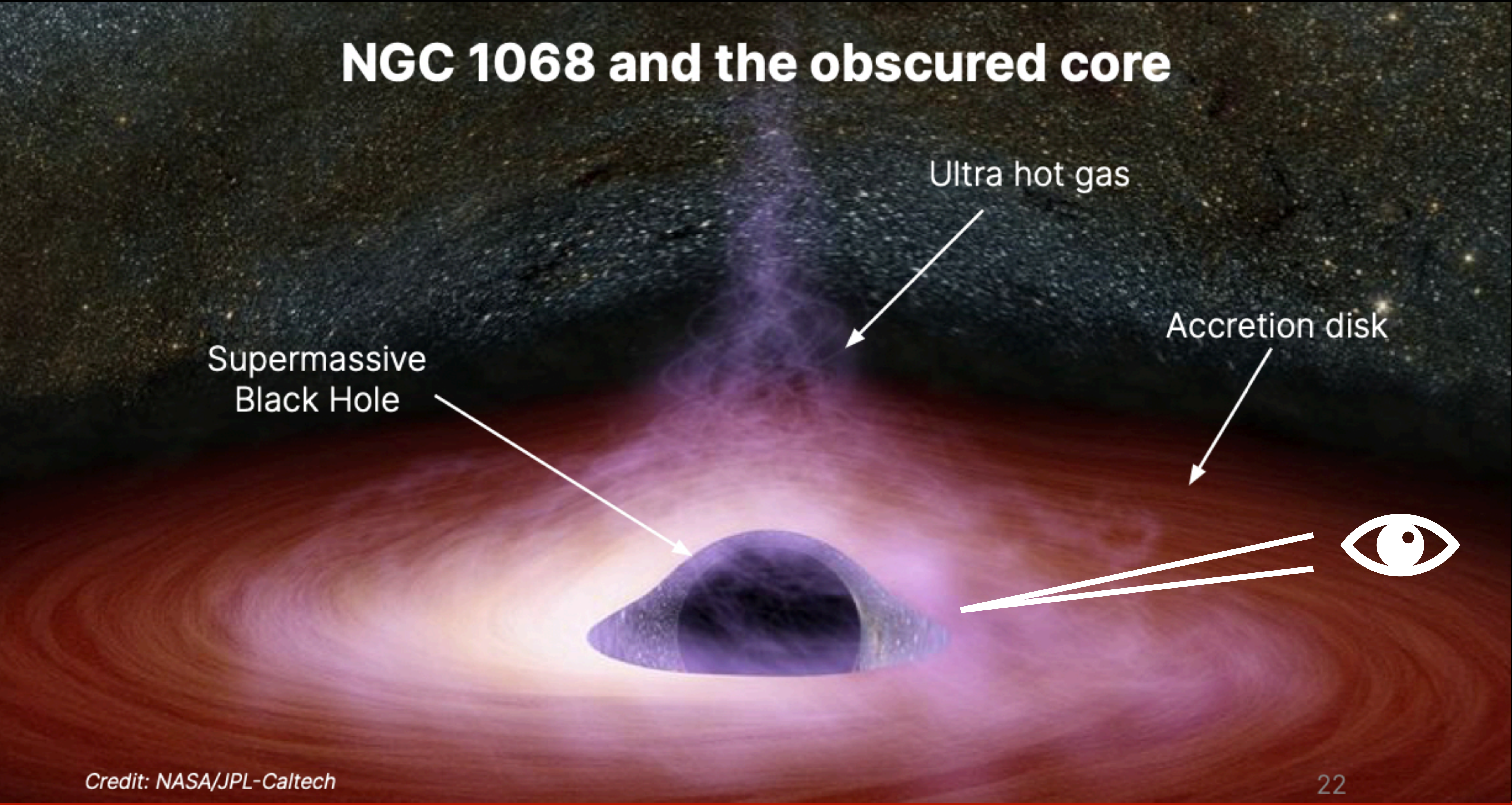

**NGC 1068 (Seyfert 2) is the most significant source**

$\hat{\gamma} = 3.2^{+0.2}_{-0.2} \pm 0.07(\textbf{sys}) \quad \hat{\mu}_{ns} = 79^{+22}_{-20} \pm 2(\textbf{sys})$

**global significance:** $4.2\sigma$

IceCube, Science 378, 6619 (2022)

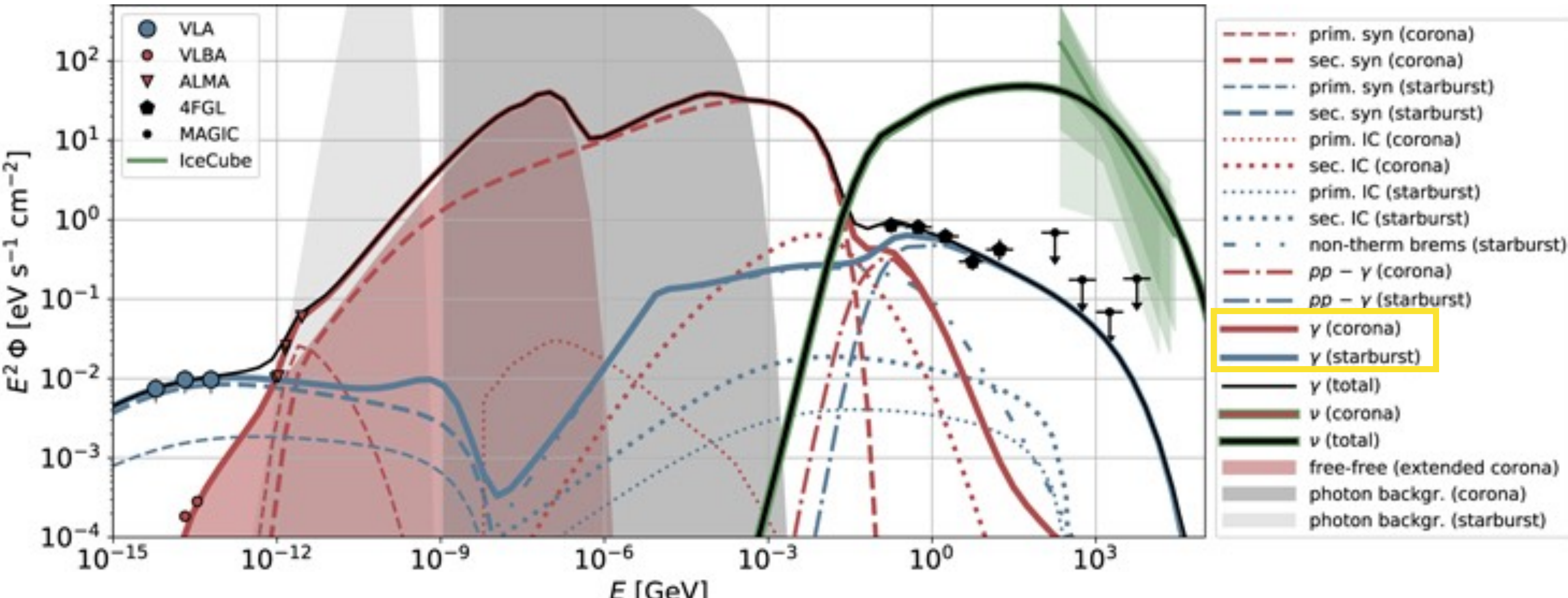
# Active Galactic Nuclei: Seyfert Galaxy



# Possible interpretation of NGC 1068

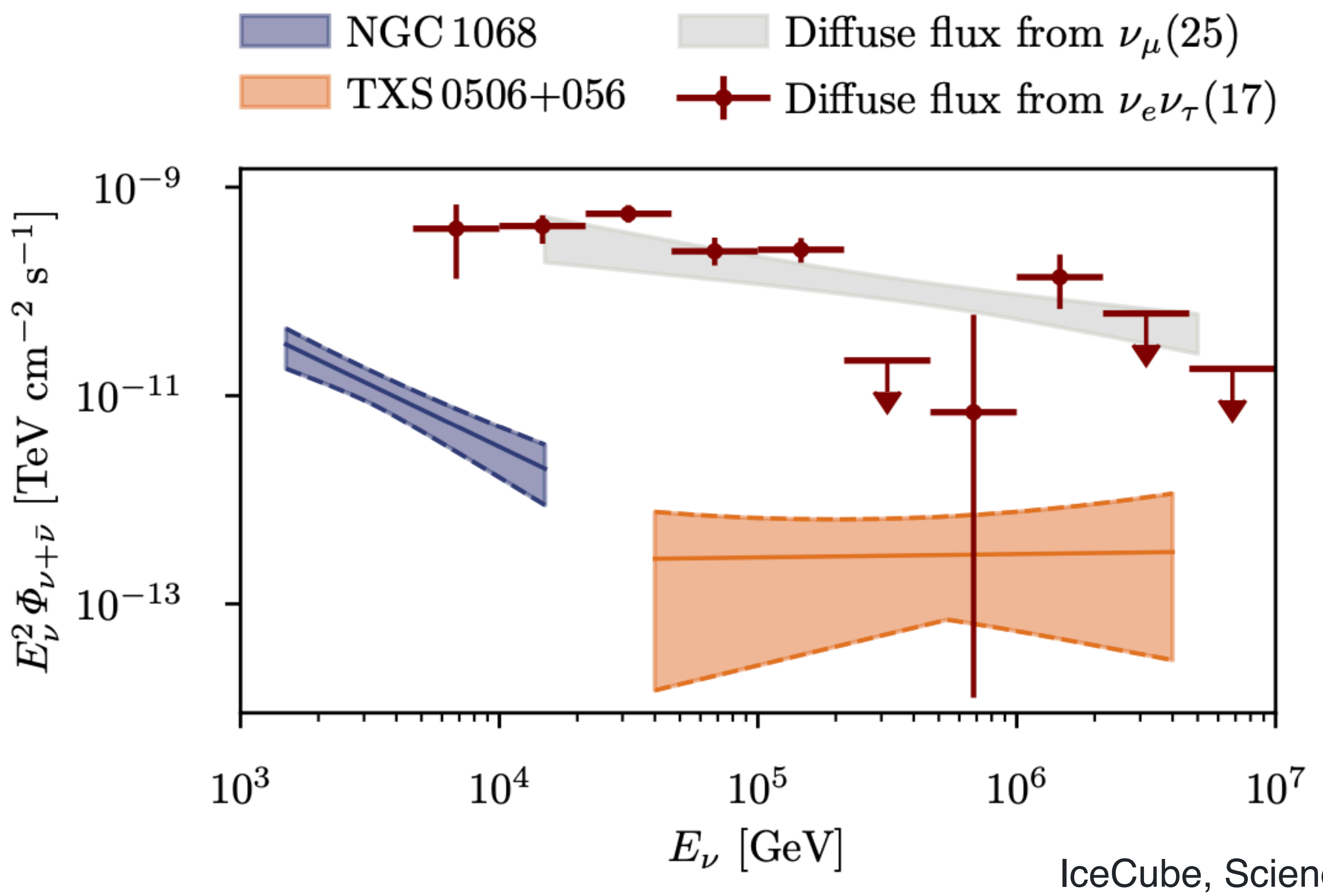
The emission at the highest and lowest energies is expected by this model to come from the starburst region (blue solid line) while the middle energies come from the AGN corona (red solid line). Neutrinos appear to come from the AGN corona.

Björn Eichmann *et al* 2022 ApJ 939 43



# Contribution to the cosmic diffuse flux

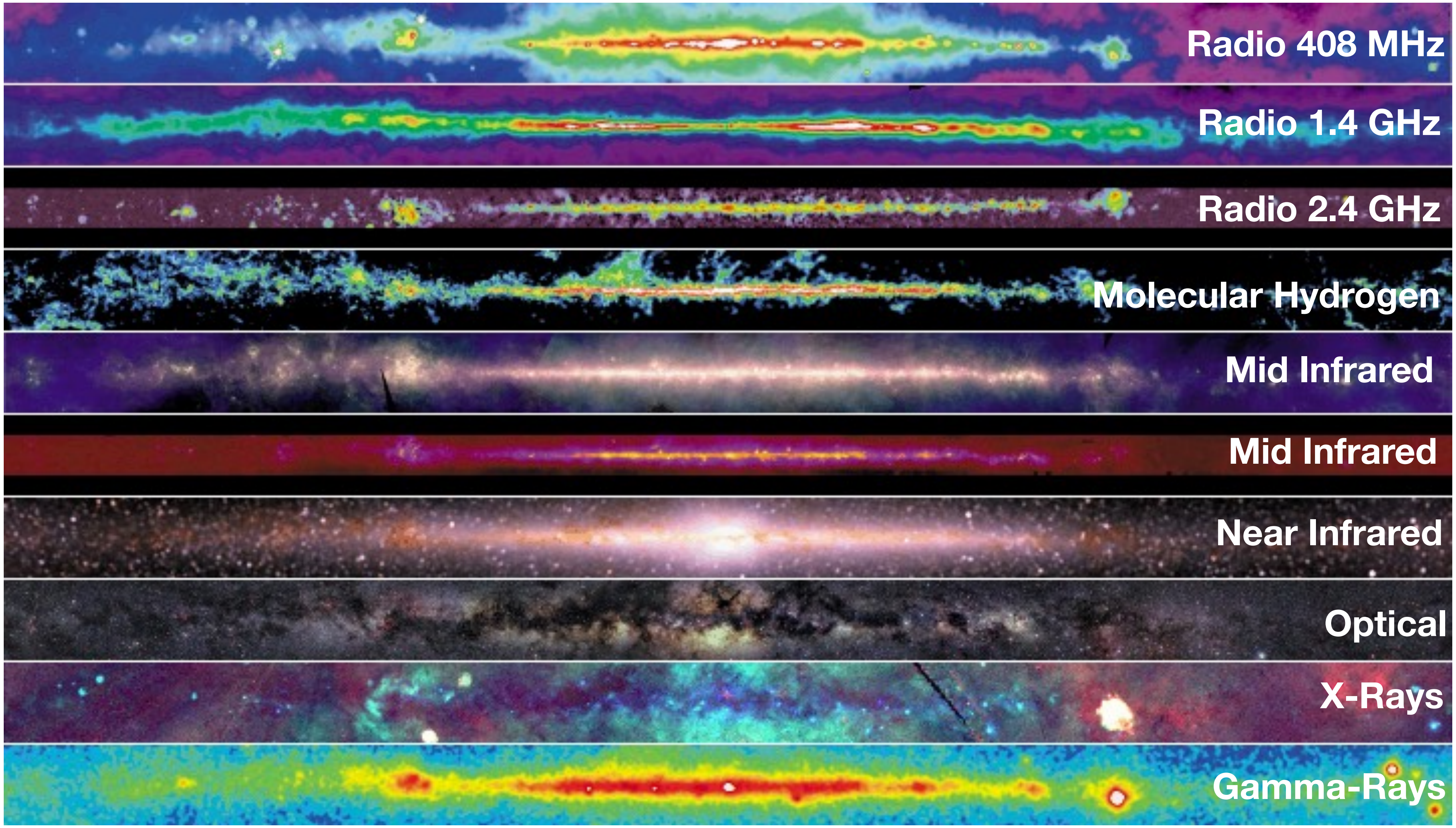
The contribution of TXS 0506+056 and NGC 1068 to the diffuse flux observed by IceCube is about 1%. Given the differences in spectrum and distance between NGC 1068 and TXS 0506+056, which is ~100 times farther away, there seems to be at least two populations of neutrino sources, which could differ in both density and luminosity by orders of magnitude.




IceCube, Science 378, 6619 (2022)

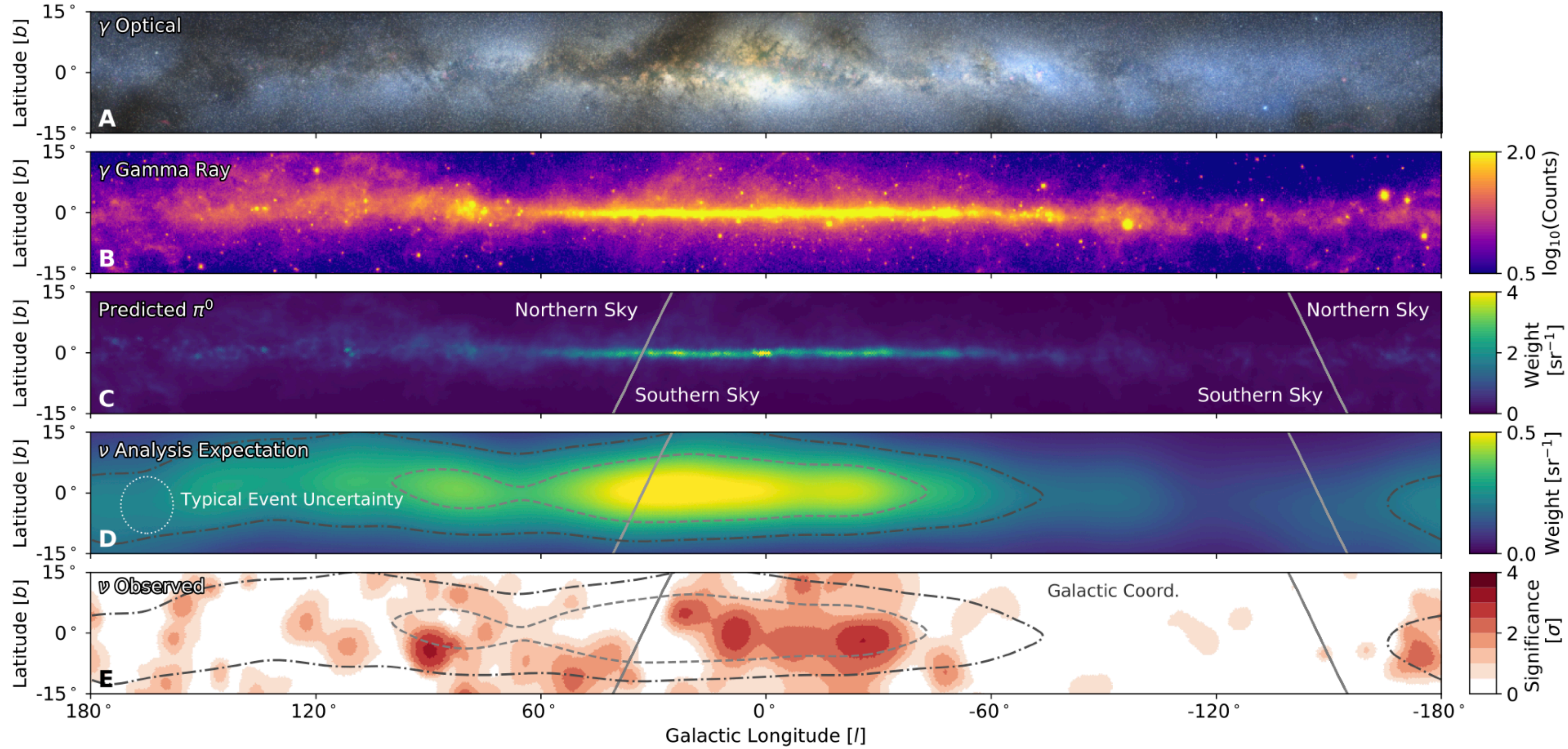
# Immagine multi-banda della Galassia

Fotoni di energia diverse forniscono informazioni chiave e complementari sui fenomeni fisici in atto in ambienti astrofisici



# Neutrinos from the galactic plane

Machine learning techniques applied to ten years of IceCube data enabled identifying neutrino emission from the Galactic plane at 4.5σ by comparing to a background-only hypothesis diffuse emission models of neutrinos from cosmic rays interaction with interstellar matter



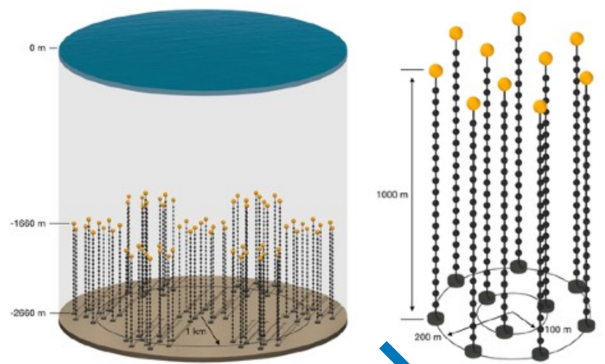
# Conclusions

- IceCube's discovery of cosmic high energy neutrinos opened a new window into the Universe
- Three distinctive astrophysical sources of high-energy neutrinos cleary identified:
    - The first found after an IceCube realtime alert, a Blazar
    - The second identified after improved neutrino reconstruction and calibration methods, a Seyfert Galaxy
    - The third identified after improved neutrino reconstruction and calibration methods and long exposure, the Milky Way
- Neutrino telescopes provide an unprecedented information on the most extreme phenomena in the Universe and enable to study for the first time astrophysical environments with tools other than photons

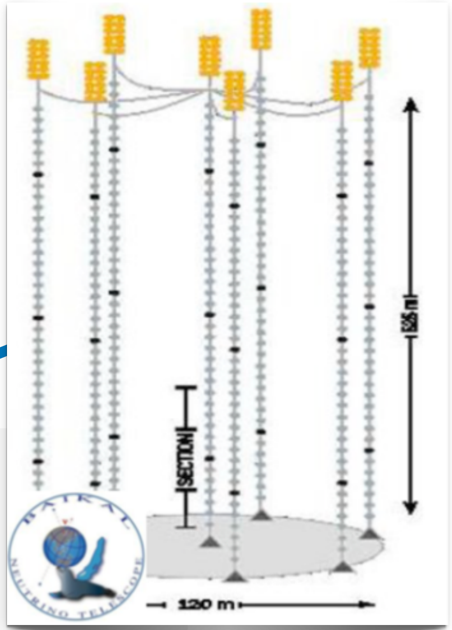
# Back-up

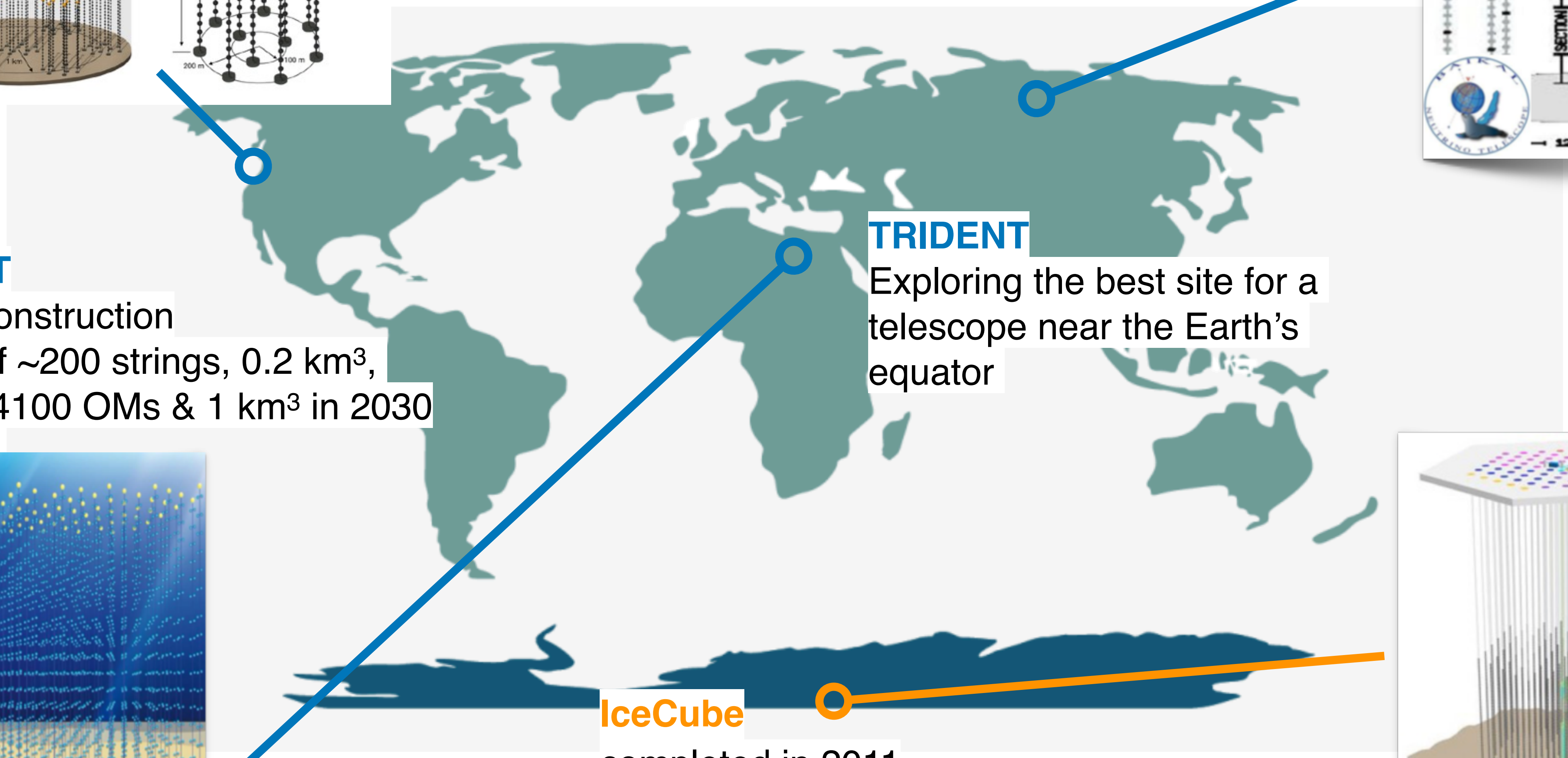
# Telescopi di neutrini nel mondo

**P-ONE**
Canada
R&D / design



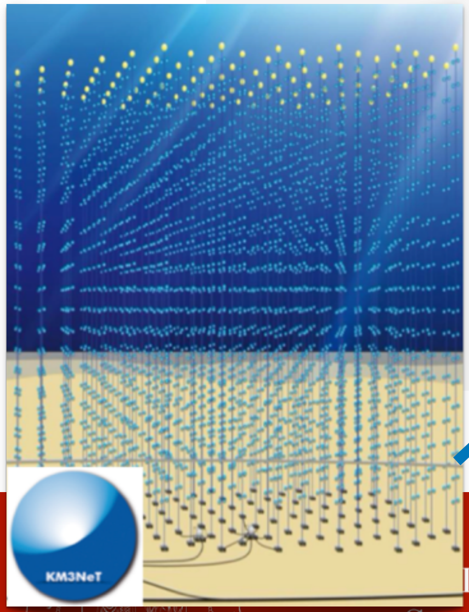
**Baikal/GVD**
Russia
3 out of 8 clusters, 0.4 km$^3$,
target 2304 OMs & 1 km$^3$



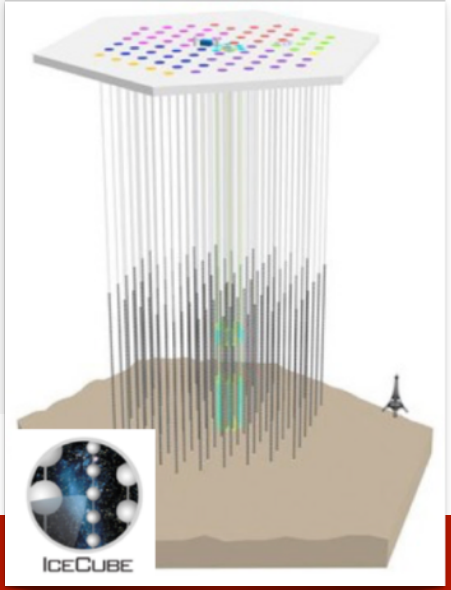


**TRIDENT**
Exploring the best site for a telescope near the Earth's equator

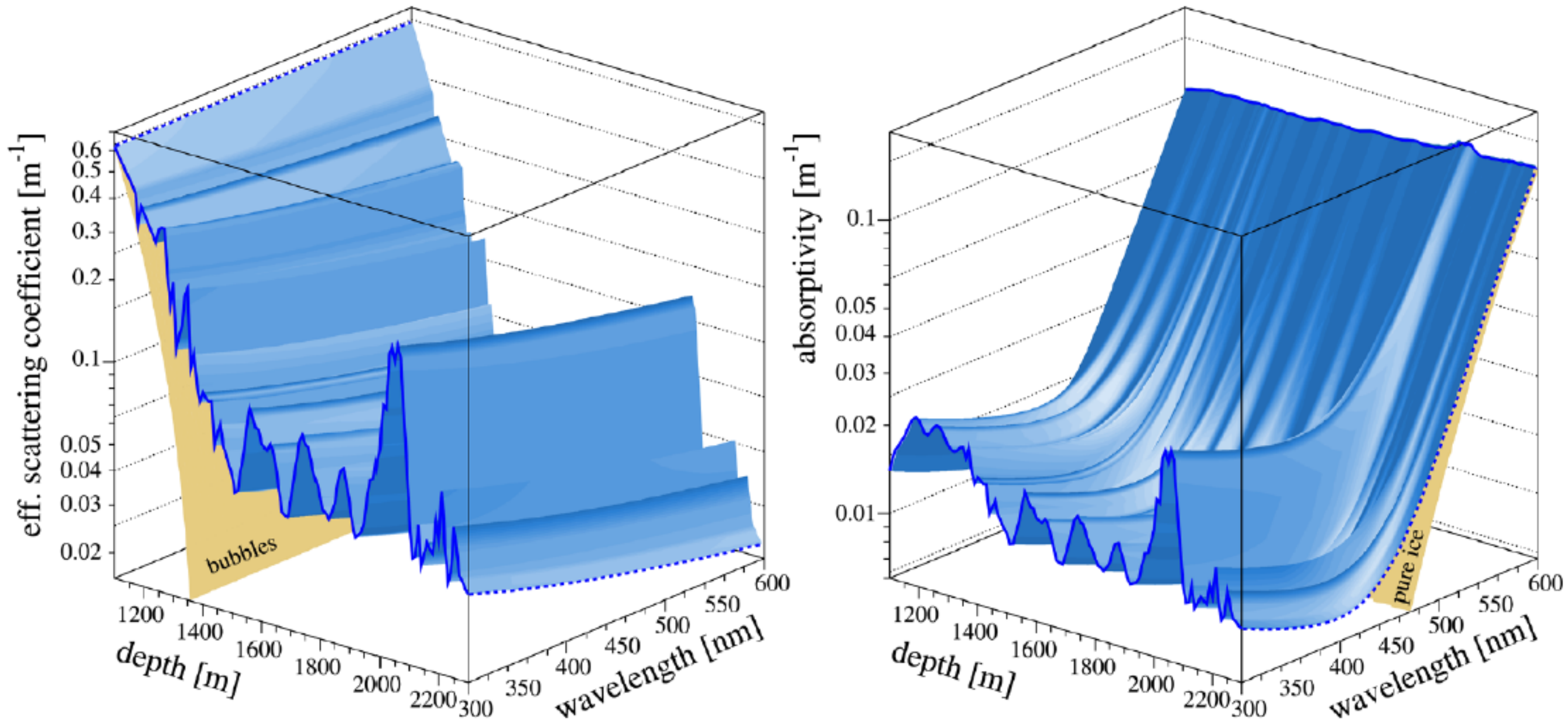
**KM3NeT**
Under construction
19 out of ~200 strings, 0.2 km$^3$,
target ~4100 OMs & 1 km$^3$ in 2030



**IceCube**
completed in 2011
5160 OMs, ~ 1km$^3$
Planned 10 times extension: IceCube-Gen2 with present and new technologies



# Ice optical properties

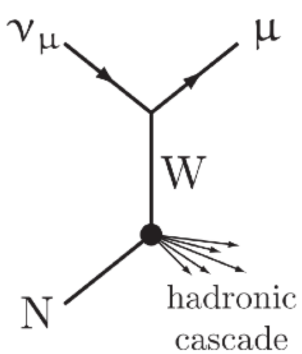



| Site | $L_{abs}$ (m) | $L_{eff}$ (m) |
| --- | --- | --- |
| **Lake Baikal**, 1 km depth | **18–22** | **150–250** (seasonal variations) |
| **Ocean** > 1.5 km depth | **40–70** (depends on site and season) | **200–300** (depends on site and season) |
| **Polar ice**, 1.5–2.0 km depth | ~**95** (average), reaches **300** in the lower part of IceCube | ~**20** (average), reaches **100** in the lower part of IceCube |
| **Polar ice**, 2.2–2.5 km depth | **100–350** | **30–130** |

# Event signatures

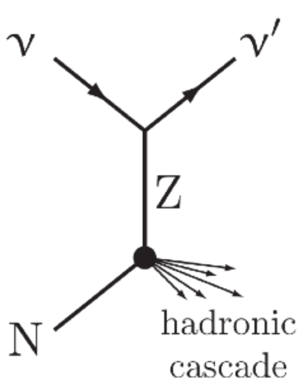
**Through-going track** ($\nu_\mu$)

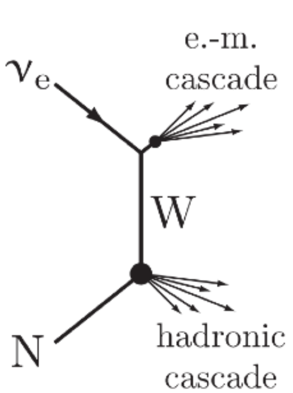
angular resolution < 1°
only dE/dx

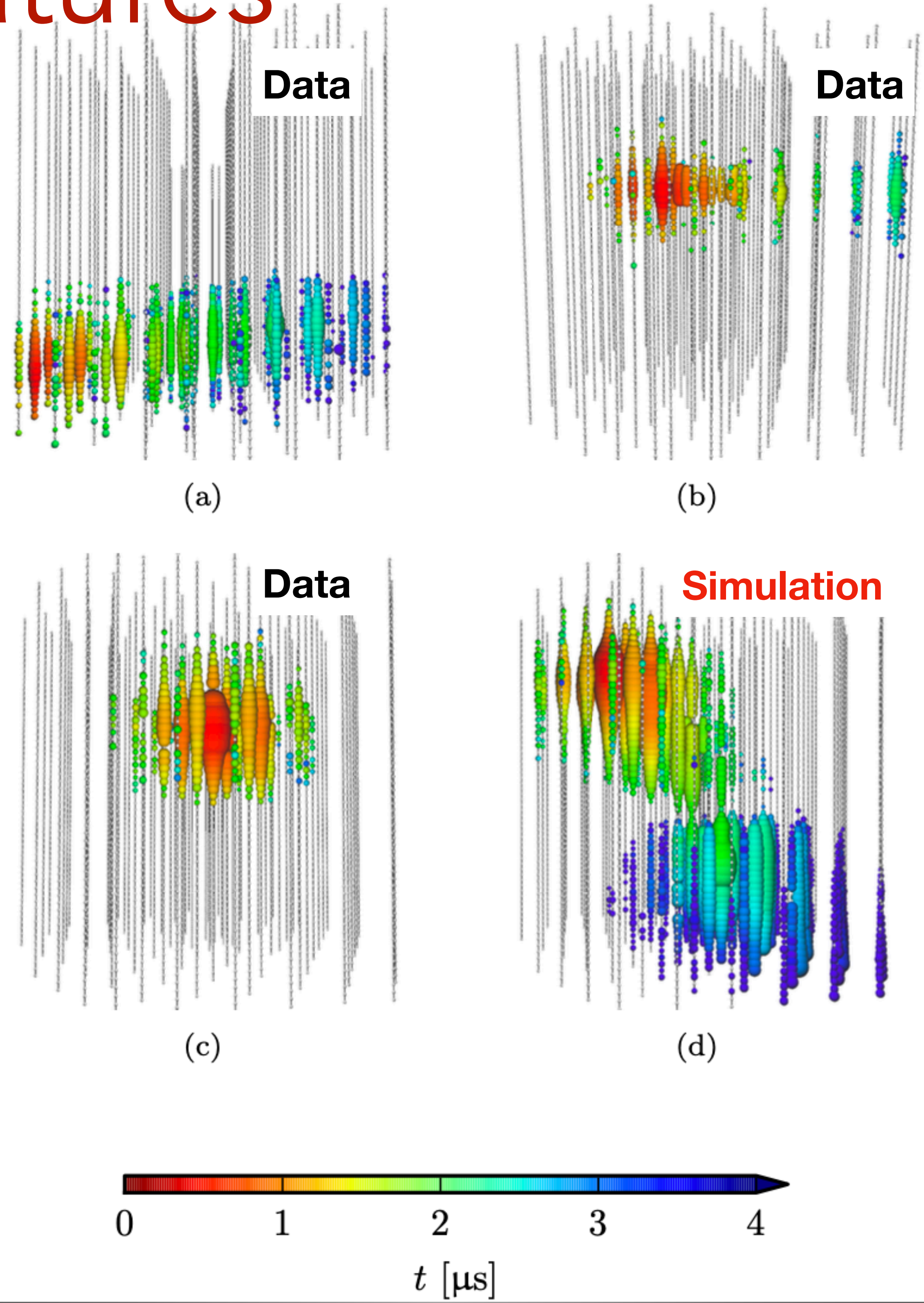



**Cascade** ($\nu_e$, $\nu_\mu$, $\nu_\tau$)

angular resolution at most down to ~5°
energy resolution ~ 15%

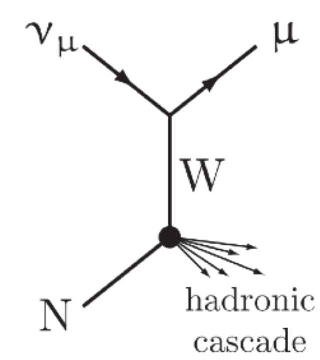


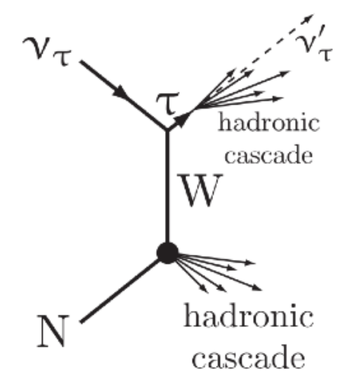

**Starting track** ($\nu_\mu$)

angular resolution < 1°
dE/dx + energy at vertex

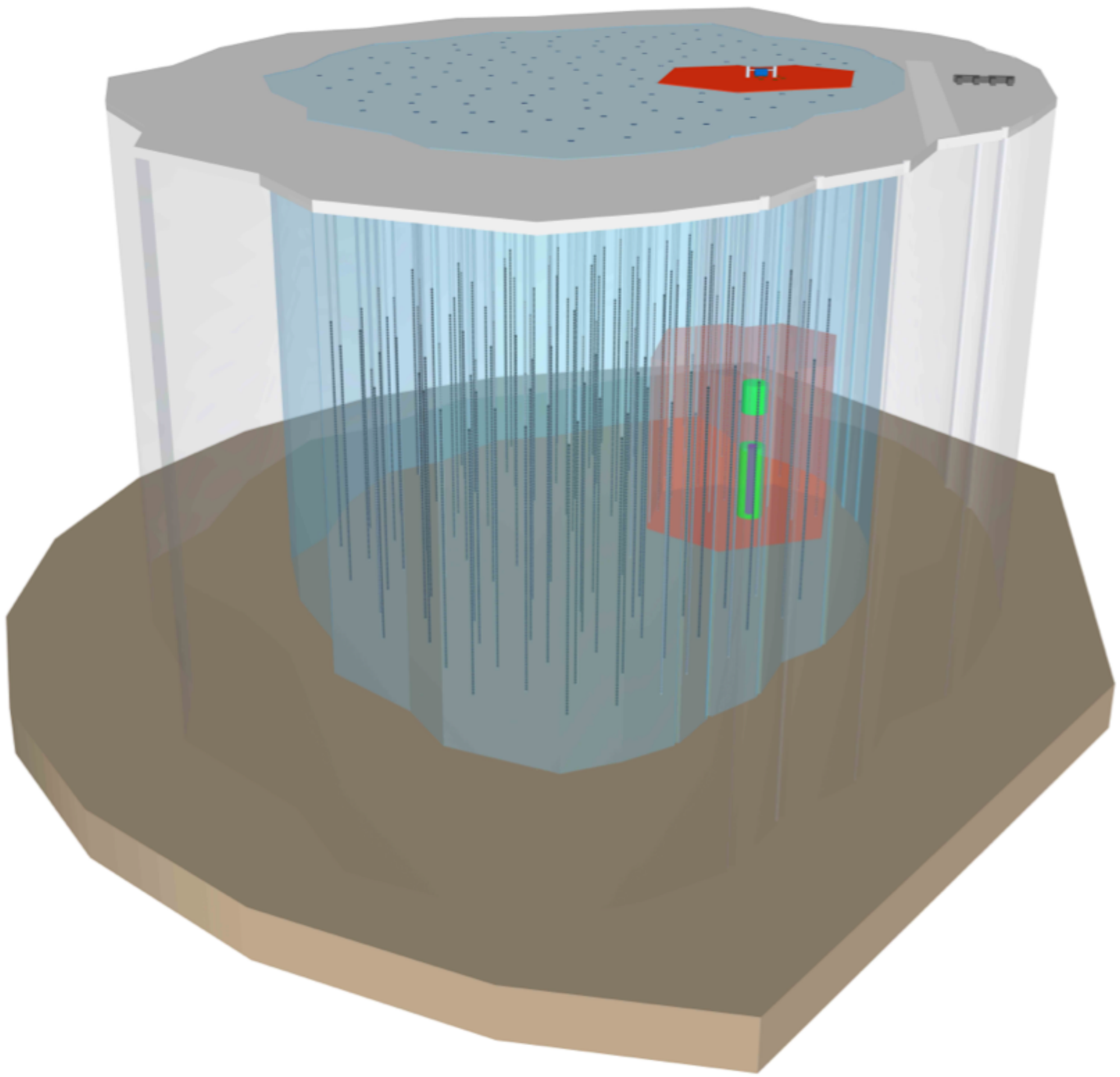



**Double-Bang** ($\nu_\tau$)

E > O(PeV)



# Future

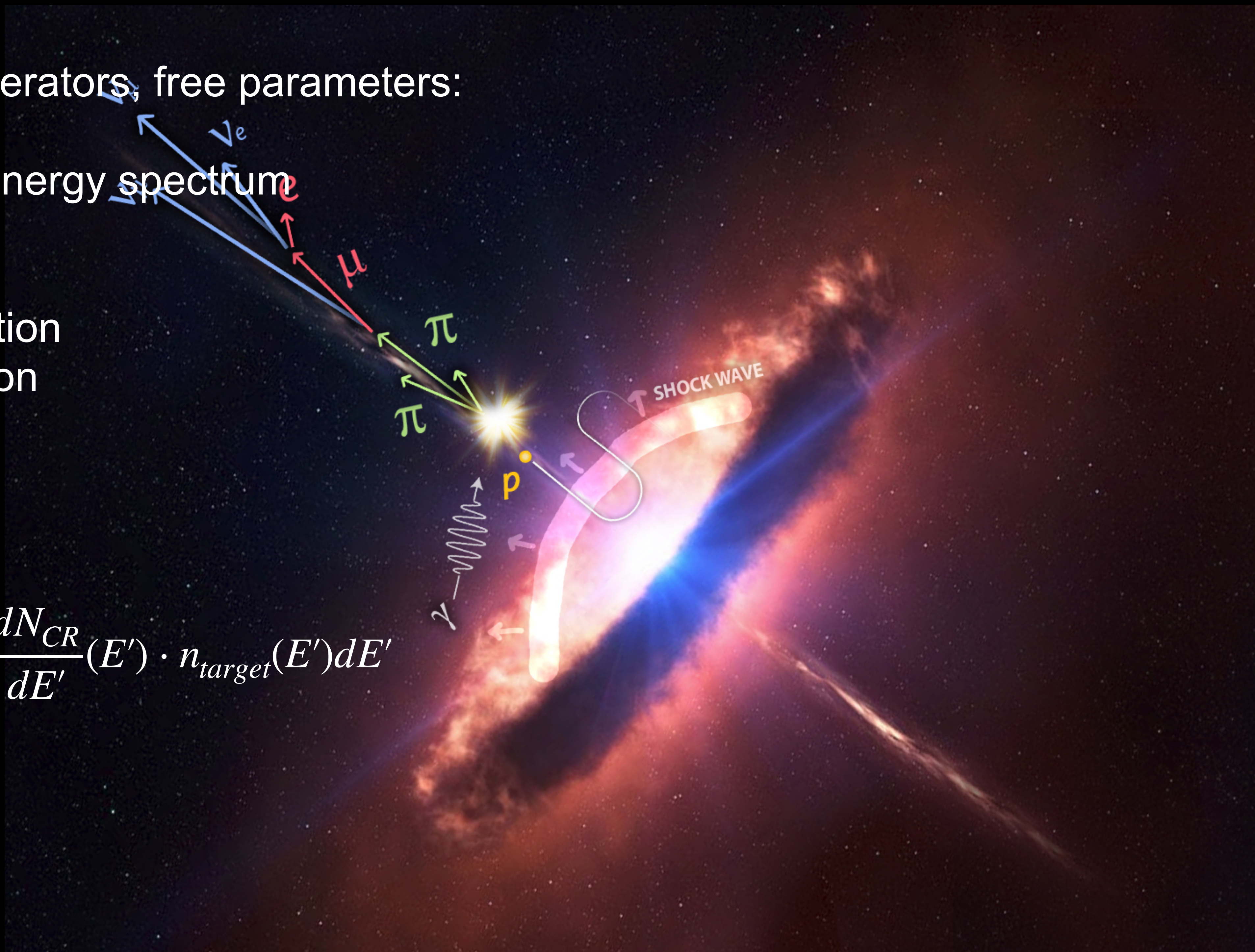


**IceCube-Gen 2 (in preparation)**
120 strings with 80 DOM/string,
1.35 to 2.7 km deep
10 times the instrumented volume of IceCube
better angular resolution

# Modeling a cosmic accelerator

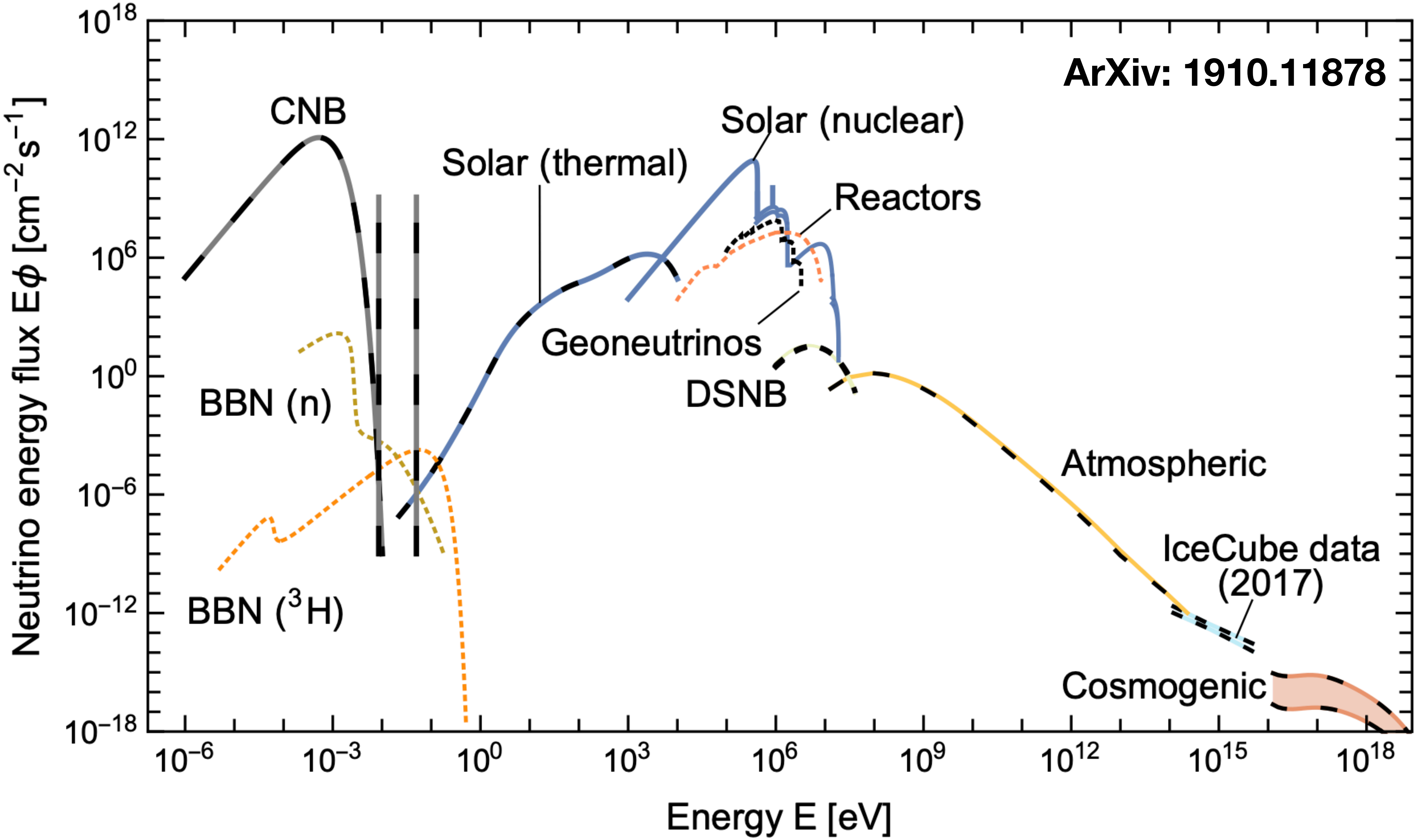
The extragalactic accelerators, free parameters:

- slope of power-law energy spectrum
- minimum energy
- maximum energy
- Cosmic ray composition
- cosmological evolution




$$\Phi_\nu \propto \int \eta(\sigma_{CR,...}, E') \cdot \frac{dN_{CR}}{dE'}(E') \cdot n_{target}(E') dE'$$

# Neutrino Spectrum at Earth

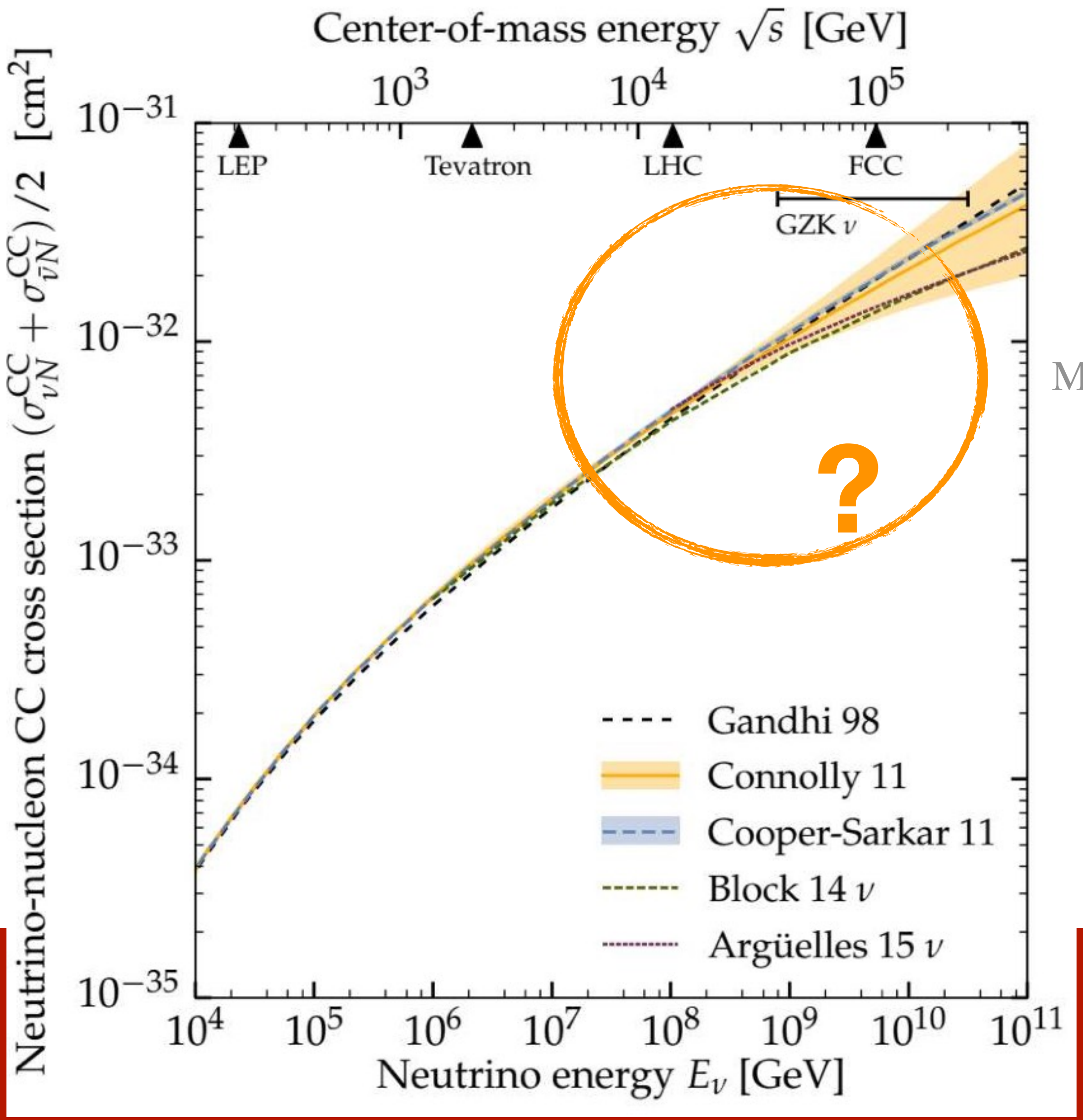


# Neutrino cross section

In the energy range 1 MeV $< E_\nu <$ 10 TeV the cross section for neutrino-nucleon interaction can be approximated as:

$$\sigma_\nu \approx 0{,}67 \cdot 10^{-38} E_\nu(GeV) \text{ cm}^2\text{/nucleon}$$

Experimentally, the cross section was measured recently up to few hundreds GeV and shall be extrapolated to describe what happens at higher energies




M. Bustamante & A. Connolly, 1711.11043

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# Research article

IceCube measured the cross section at unprecedented energies, by studying the angular distribution of atmospheric neutrinos as a function of energy.

**Measurement of the multi-TeV neutrino cross section with IceCube using Earth absorption**