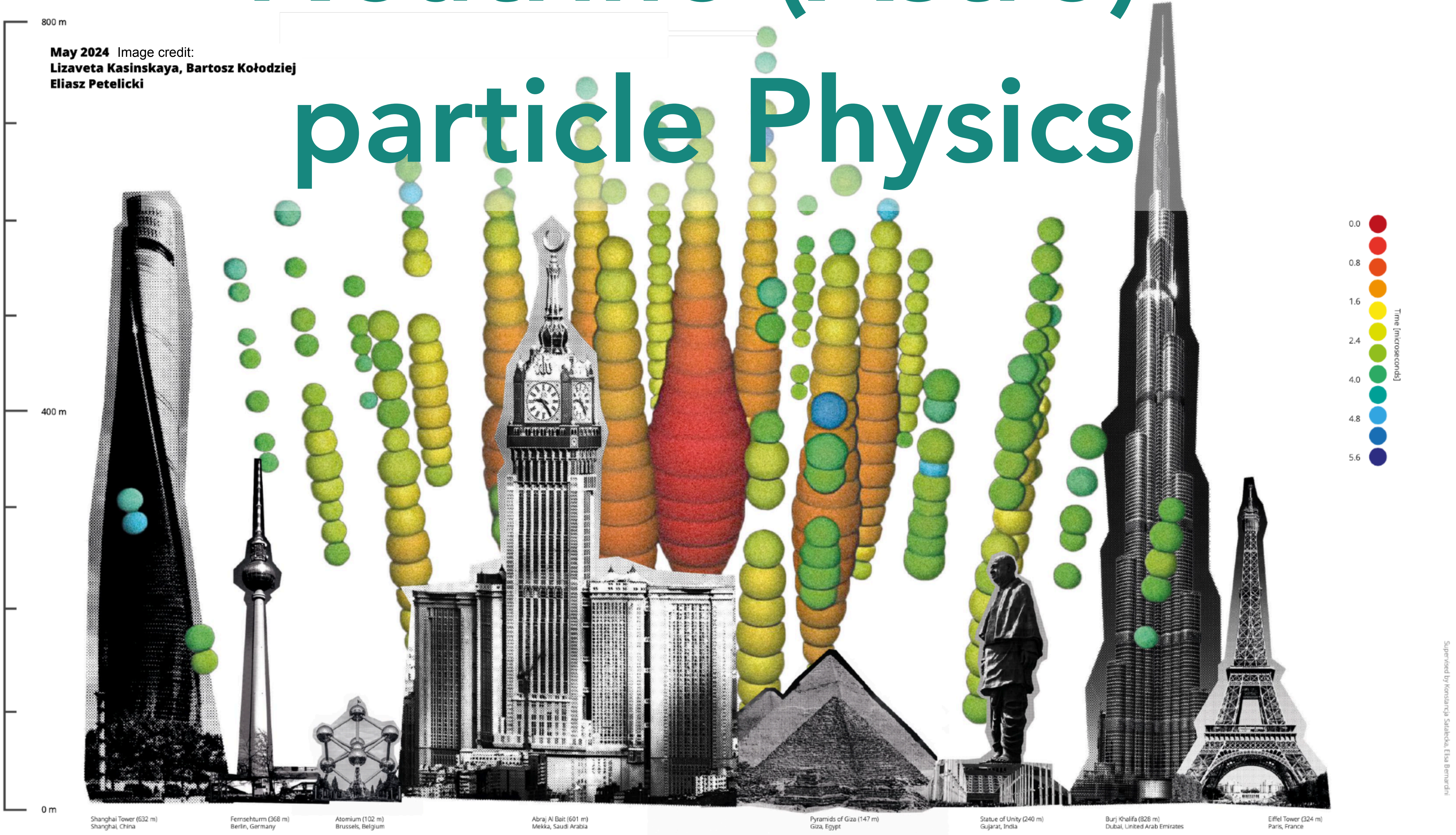
Neutrino (Astro)-particle Physics



May 2024 Image credit:
Lizaveta Kasinskaya, Bartosz Kołodziej
Eliasz Petelicki

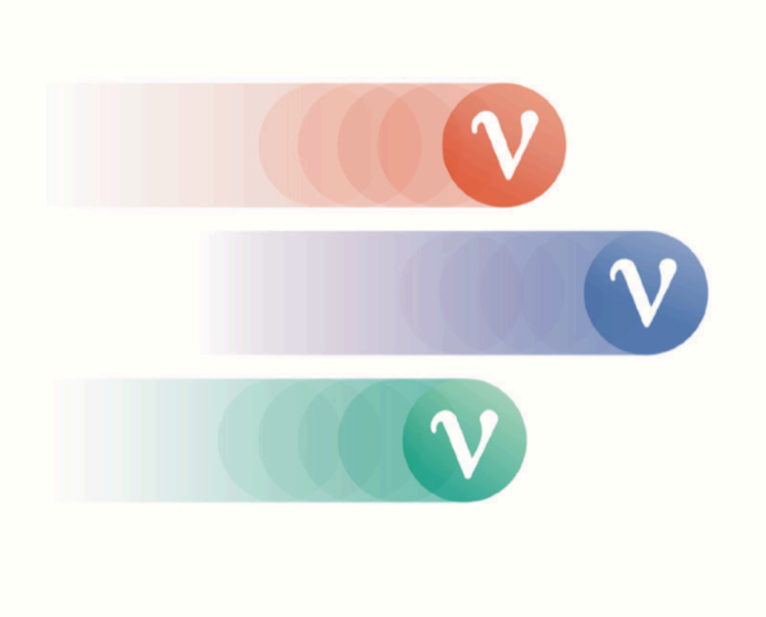
Supervised by Konstancja Satalecka, Elisa Bernardini

Elisa Bernardini
University of Padova (Italy)

Max-Planck-Institut für Physik — 24 May 2024

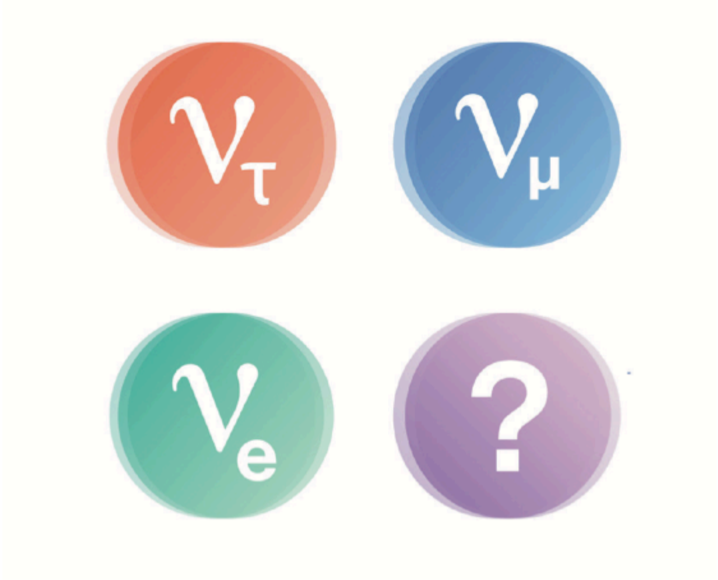
Areas of research in Neutrino Physics

Direct Mass Measurement

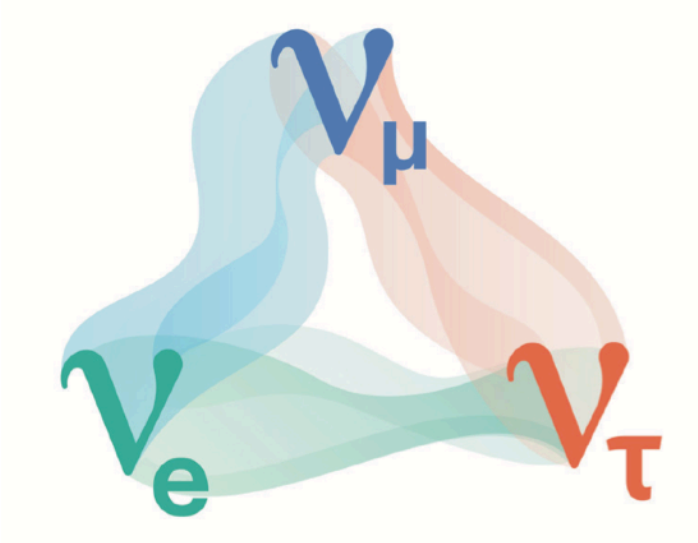


Neutrino-less 2β-decay

Sterile Neutrinos



Neutrino Oscillations Parameters



CP violation

Neutrino Mass Ordering

Neutrino cross section

…

Images credit: Symmetry Magazine / Sandbox Studio, Chicago

(Ultra High Energy) cosmic rays

Telescope Array recently reported the detection of a cosmic rays event with 244 EeV of energy, close to the 1991 “Oh-my-God!” particle by Fly’s Eye, with 320 EeV. The origin of cosmic rays and UHE cosmic rays in particular is one of the greatest unsolved mysteries in astroparticle physics, which might be accessed uniquely with neutrinos

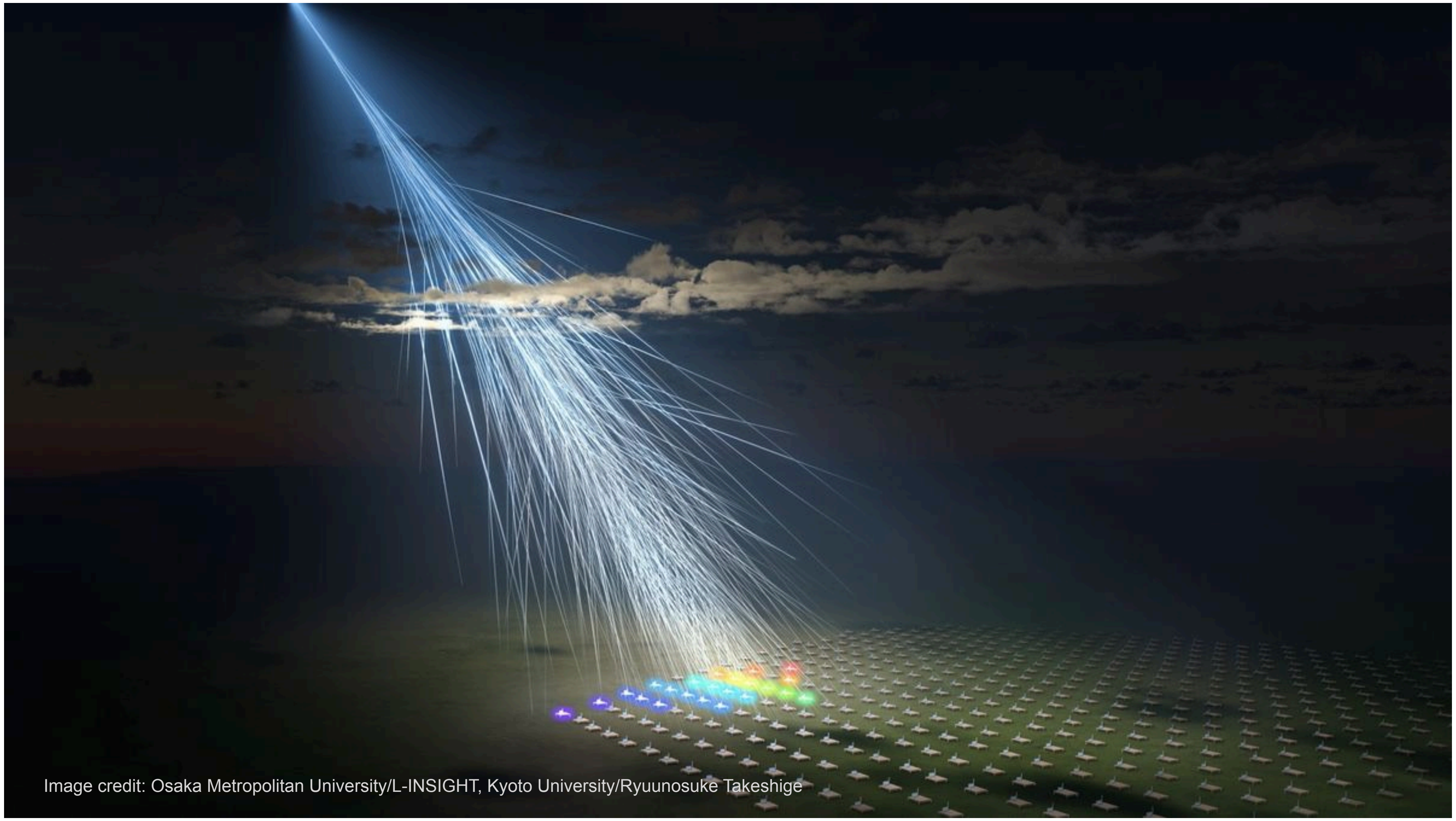
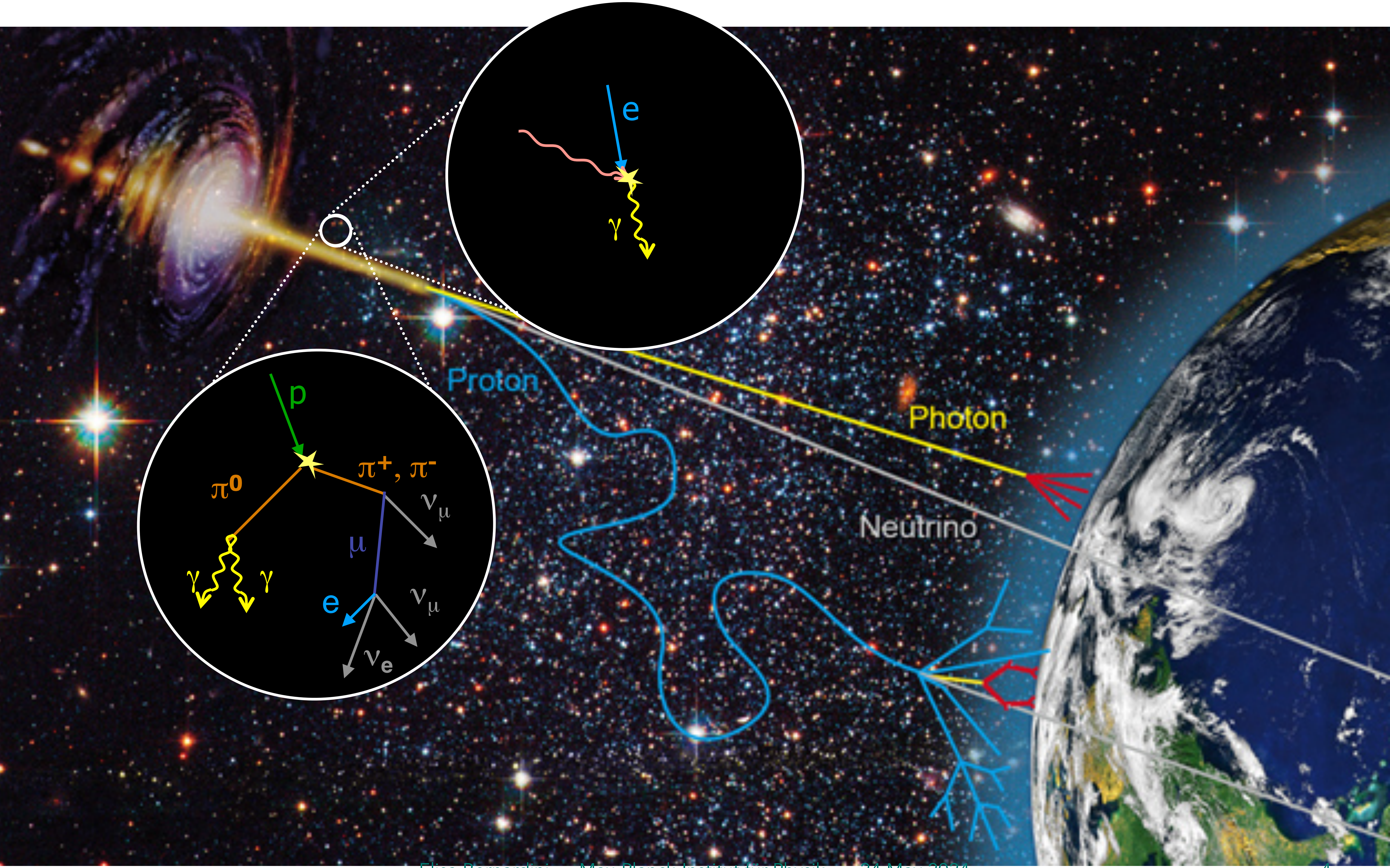
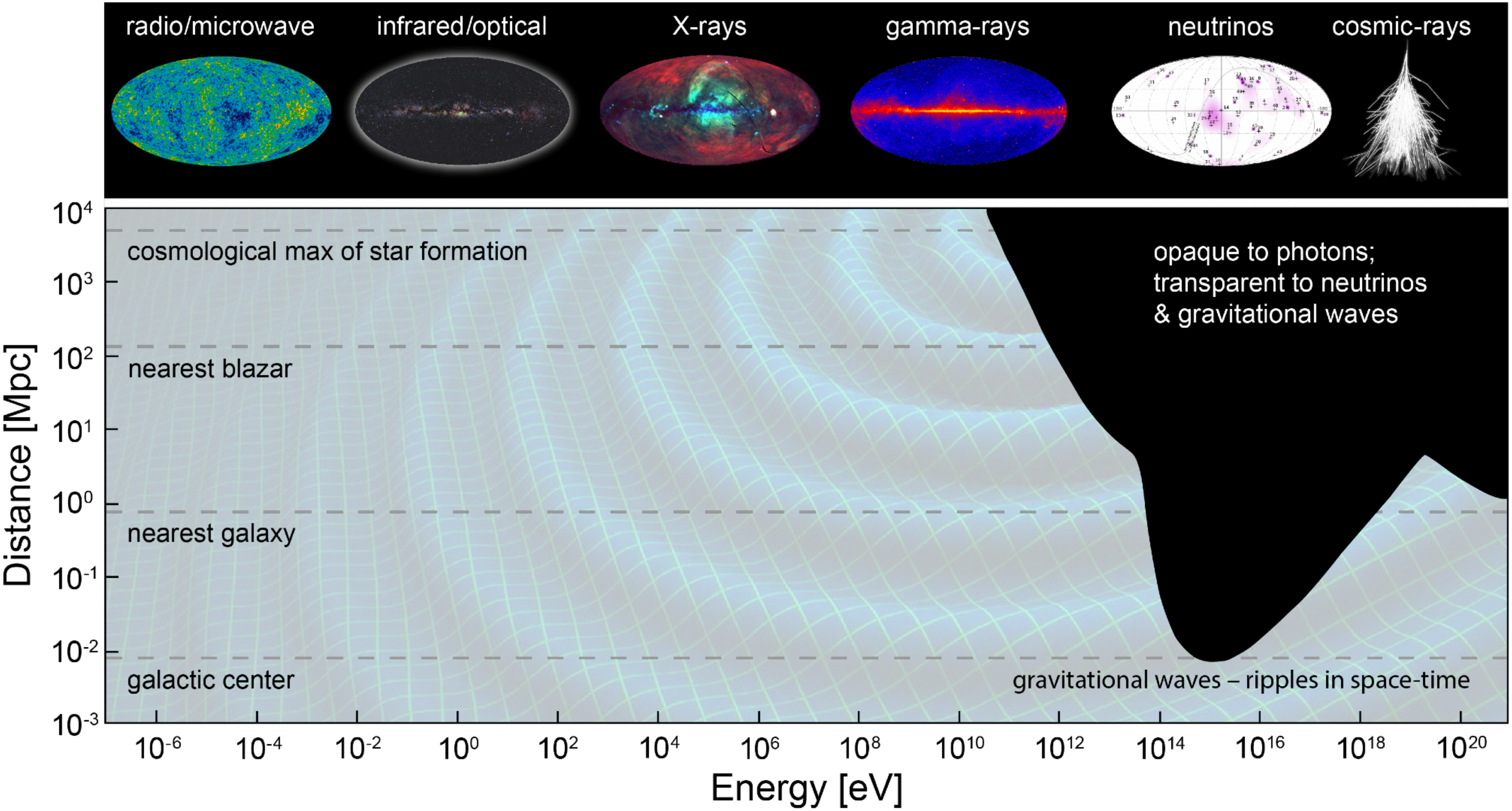


Image credit: Osaka Metropolitan University/L-INSIGHT, Kyoto University/Ryuunosuke Takeshige

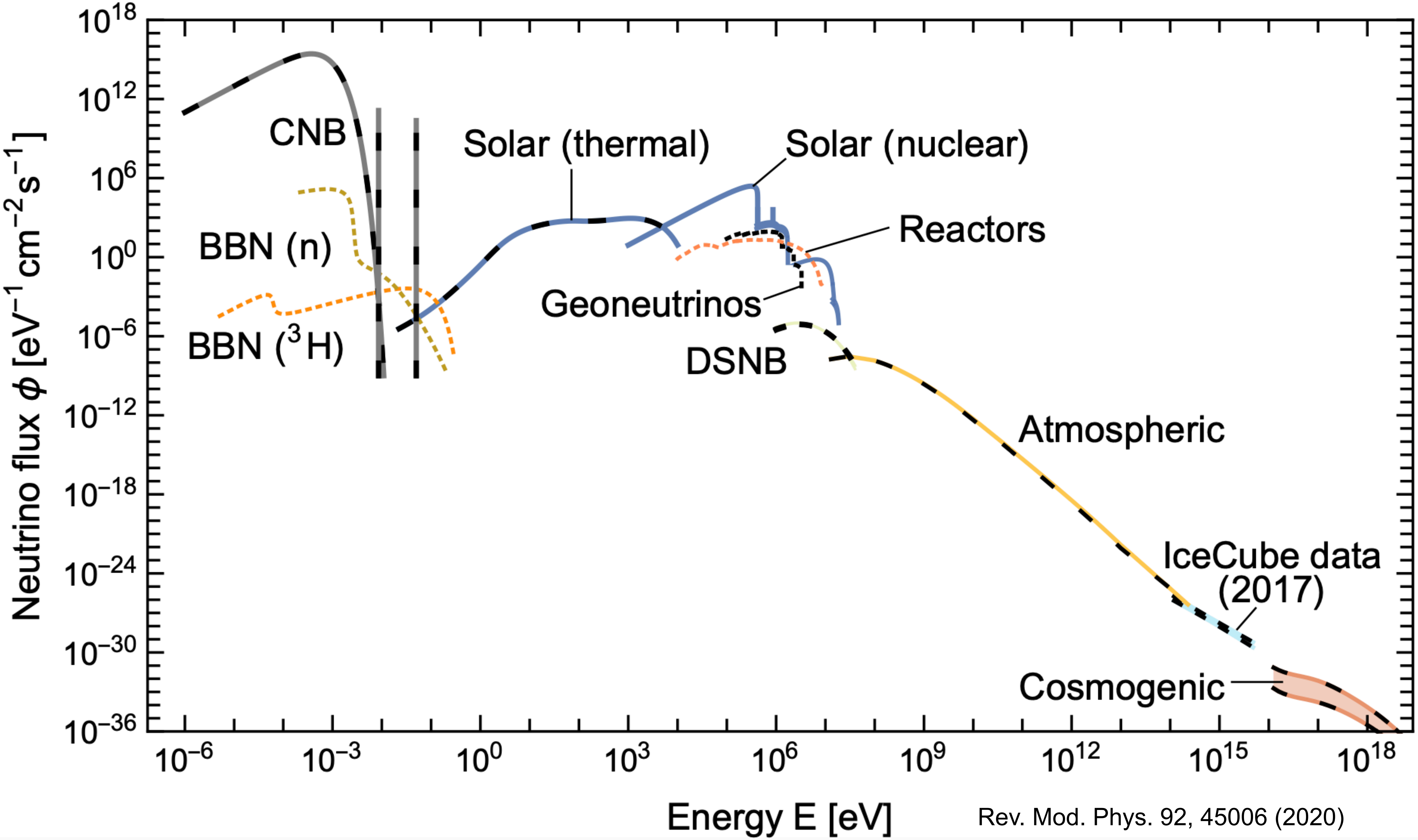
The multi-messenger paradigm



Why neutrino Astronomy?



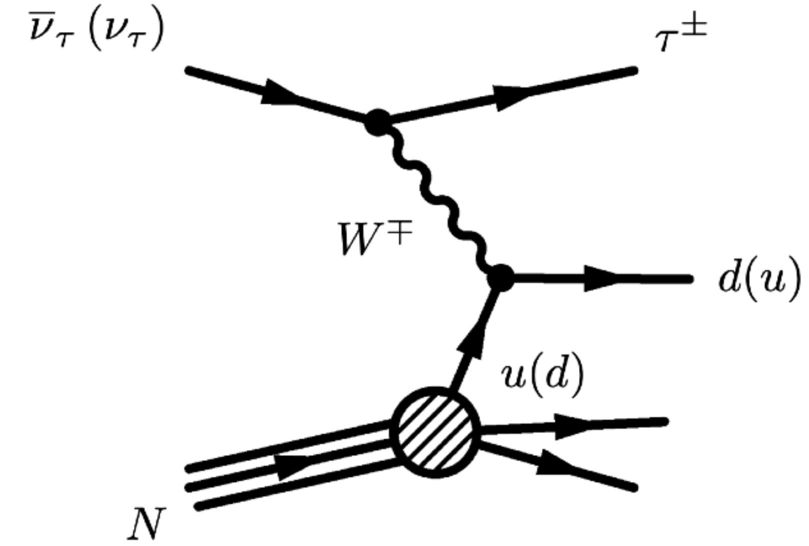
Neutrino fluxes across decades of energy



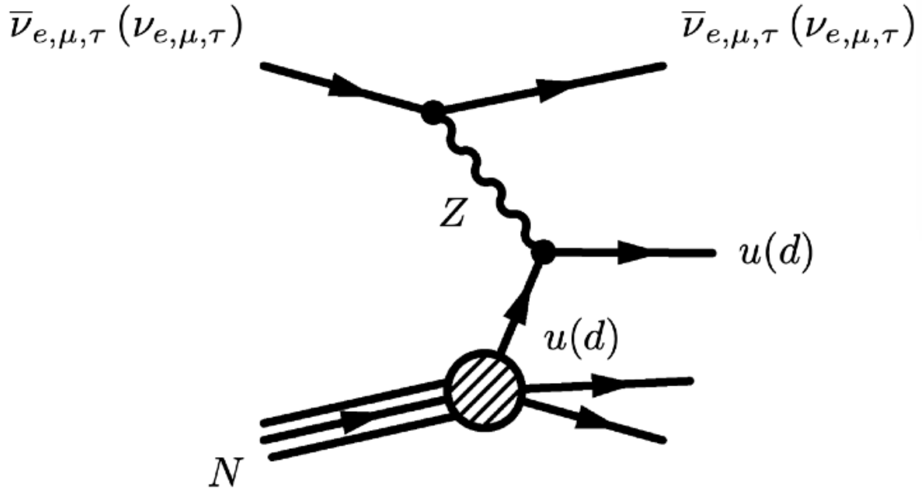
Rev. Mod. Phys. 92, 45006 (2020)

Challenge: low cross section

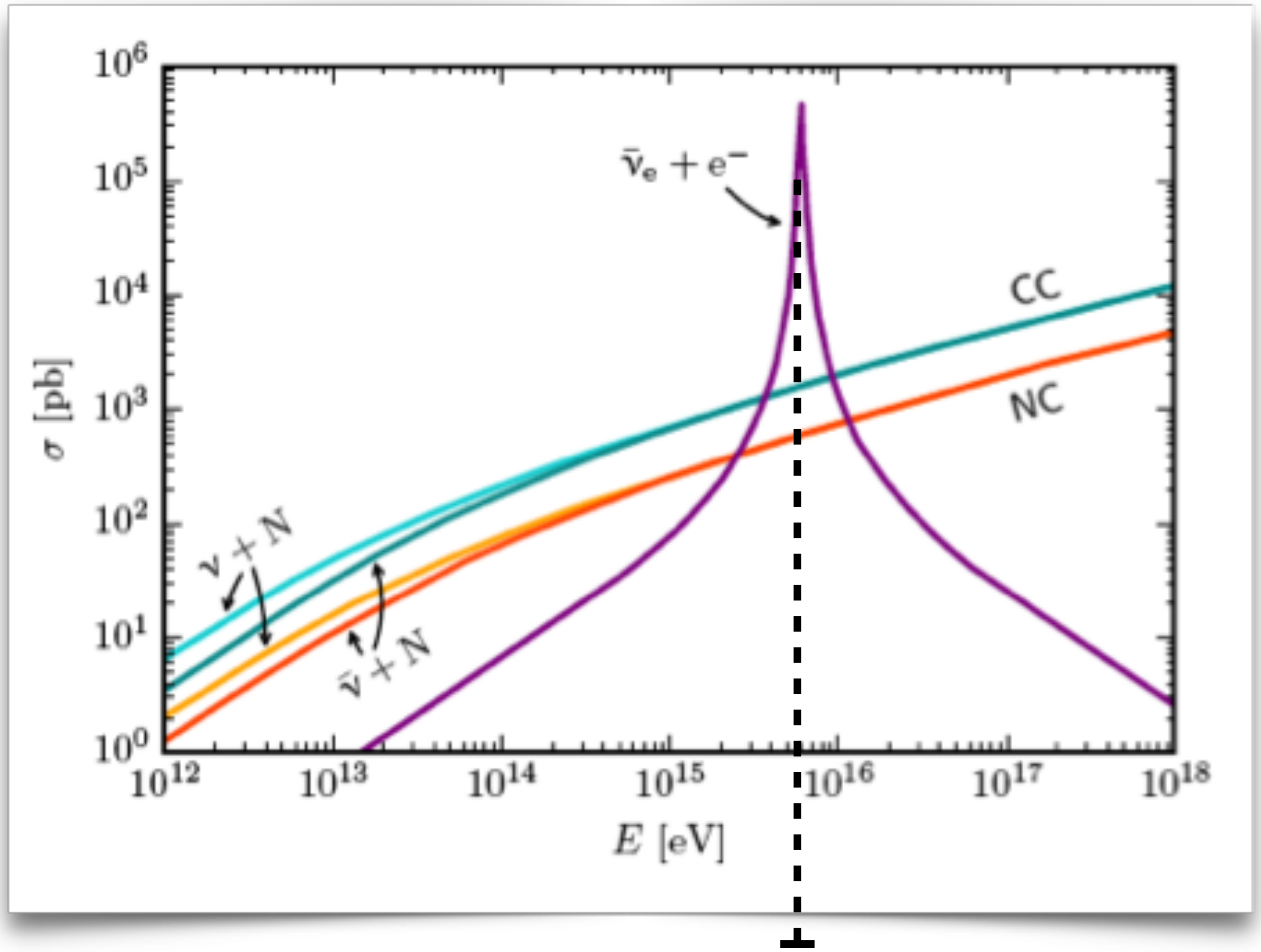
For a benchmark astrophysical flux $E_\nu^2\Phi_\nu \approx 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} **we need km^3-scale detectors!** ⇒ use natural water or ice. The first instrument reaching the required sensitivity is the IceCube neutrino telescope

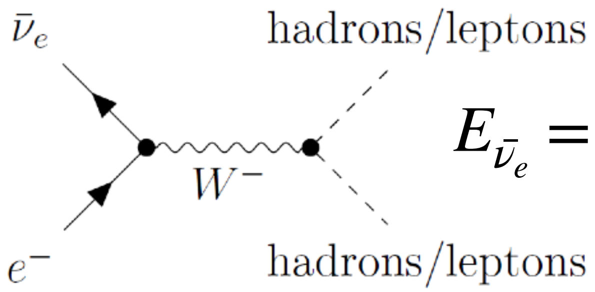


Charged current (CC)



Neutral current (NC)

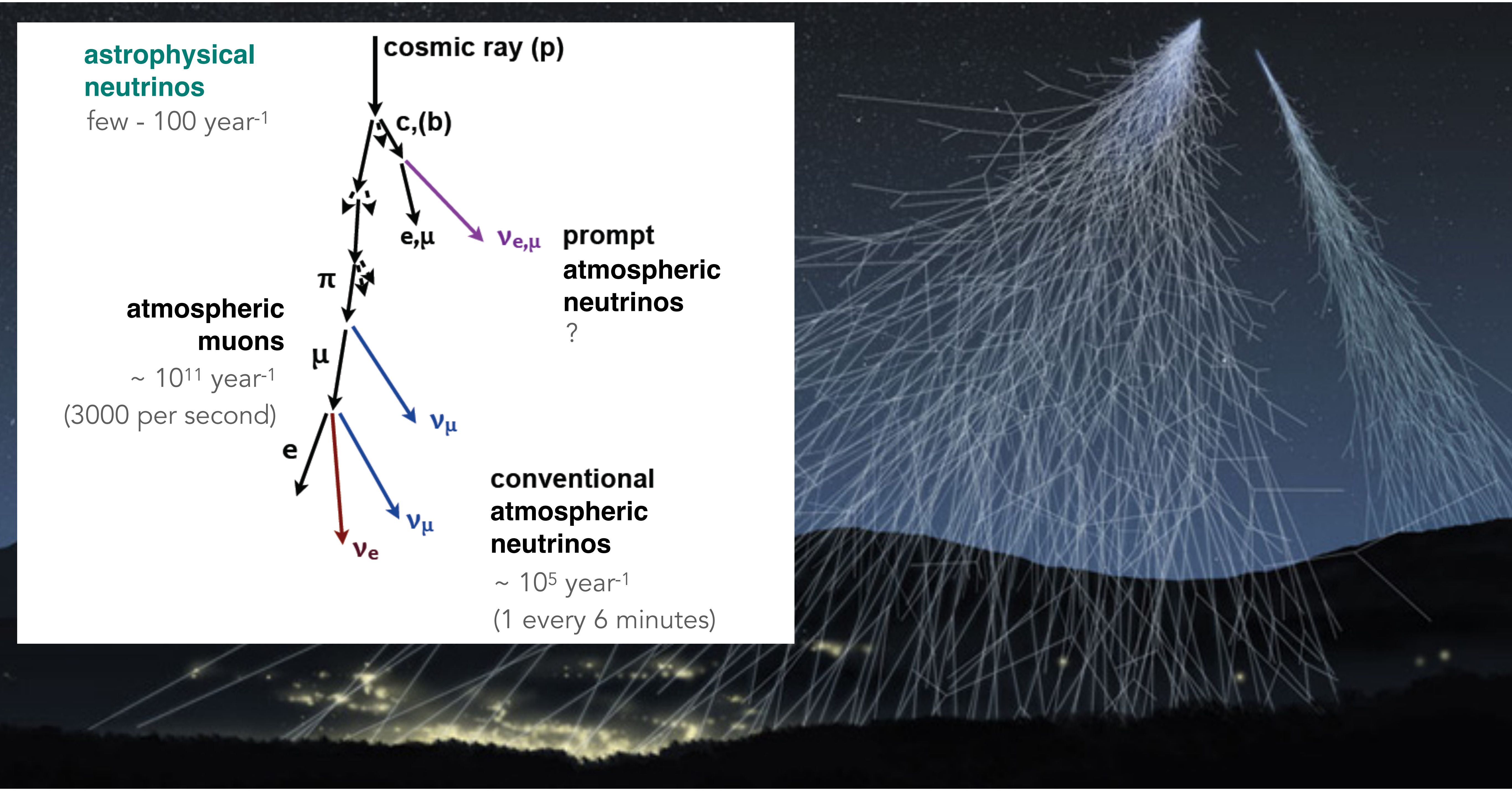




$E_{\bar\nu_e} = m_W^2/2m_e = 6.3$ PeV

Challenges: backgrounds

Event rates in **km^3-scale detectors** are **at least** of the order of **10^{10} events/year**: need important mass overburden to suppress the background from cosmic rays



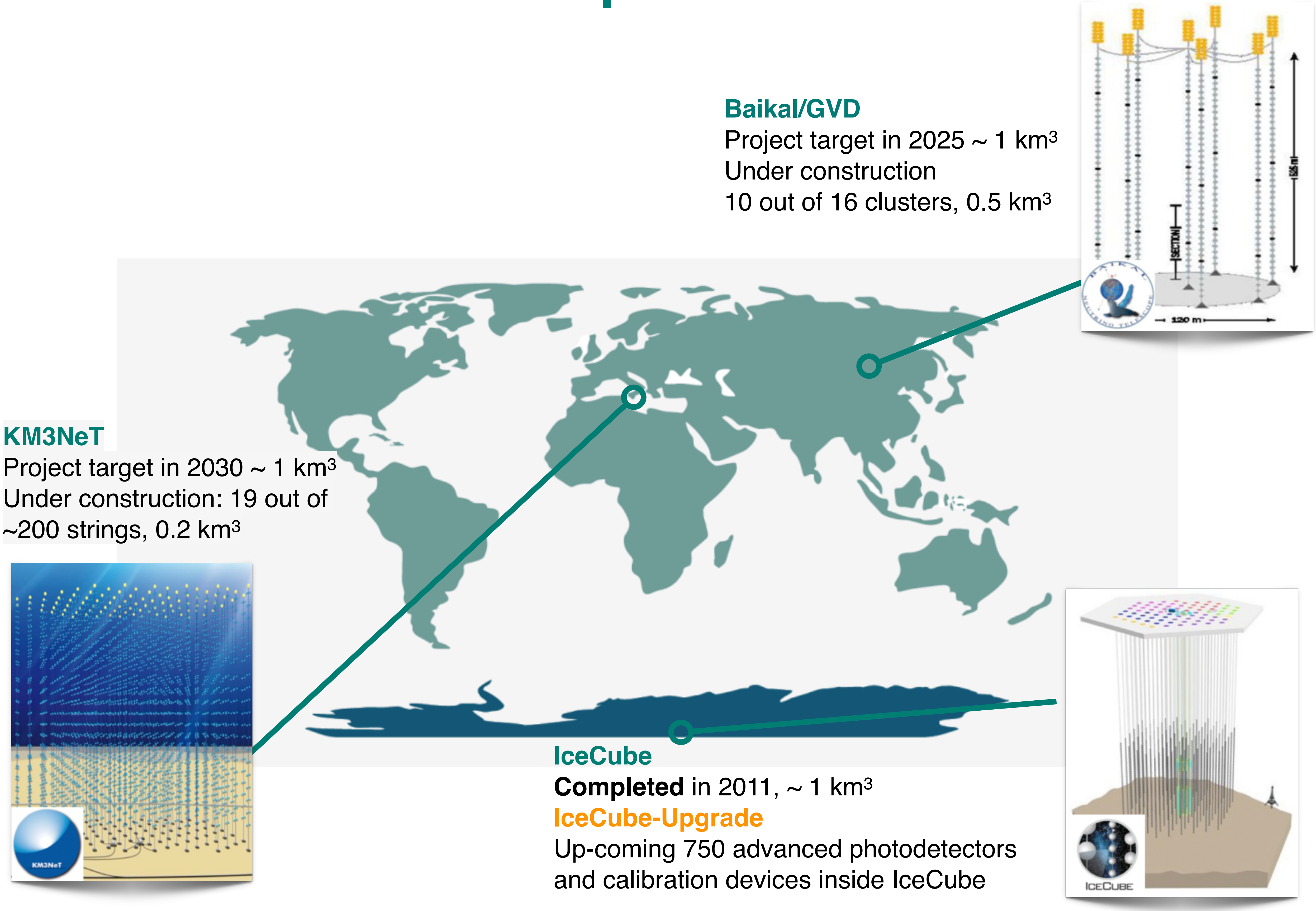
astrophysical neutrinos
few - 100 year^{-1}

prompt atmospheric neutrinos
?

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

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

Neutrino telescopes around the world



Baikal/GVD
Project target in 2025 ~ 1 km^3
Under construction
10 out of 16 clusters, 0.5 km^3

KM3NeT
Project target in 2030 ~ 1 km^3
Under construction: 19 out of ~200 strings, 0.2 km^3

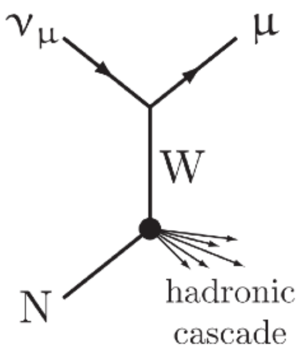
IceCube
Completed in 2011, ~ 1 km^3
IceCube-Upgrade
Up-coming 750 advanced photodetectors and calibration devices inside IceCube

Neutrino-event signatures

Through-going track (ν_μ)

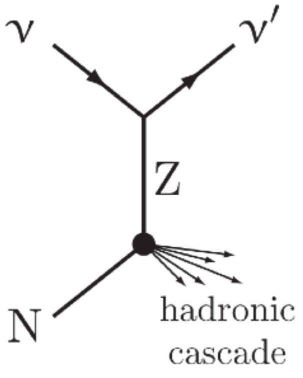
angular resolution: < 1°
only dE/dx measurements

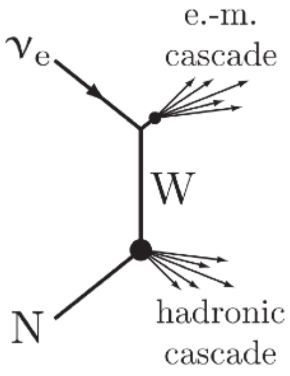
Log energy resolution: 20% of muon energy at detector entry

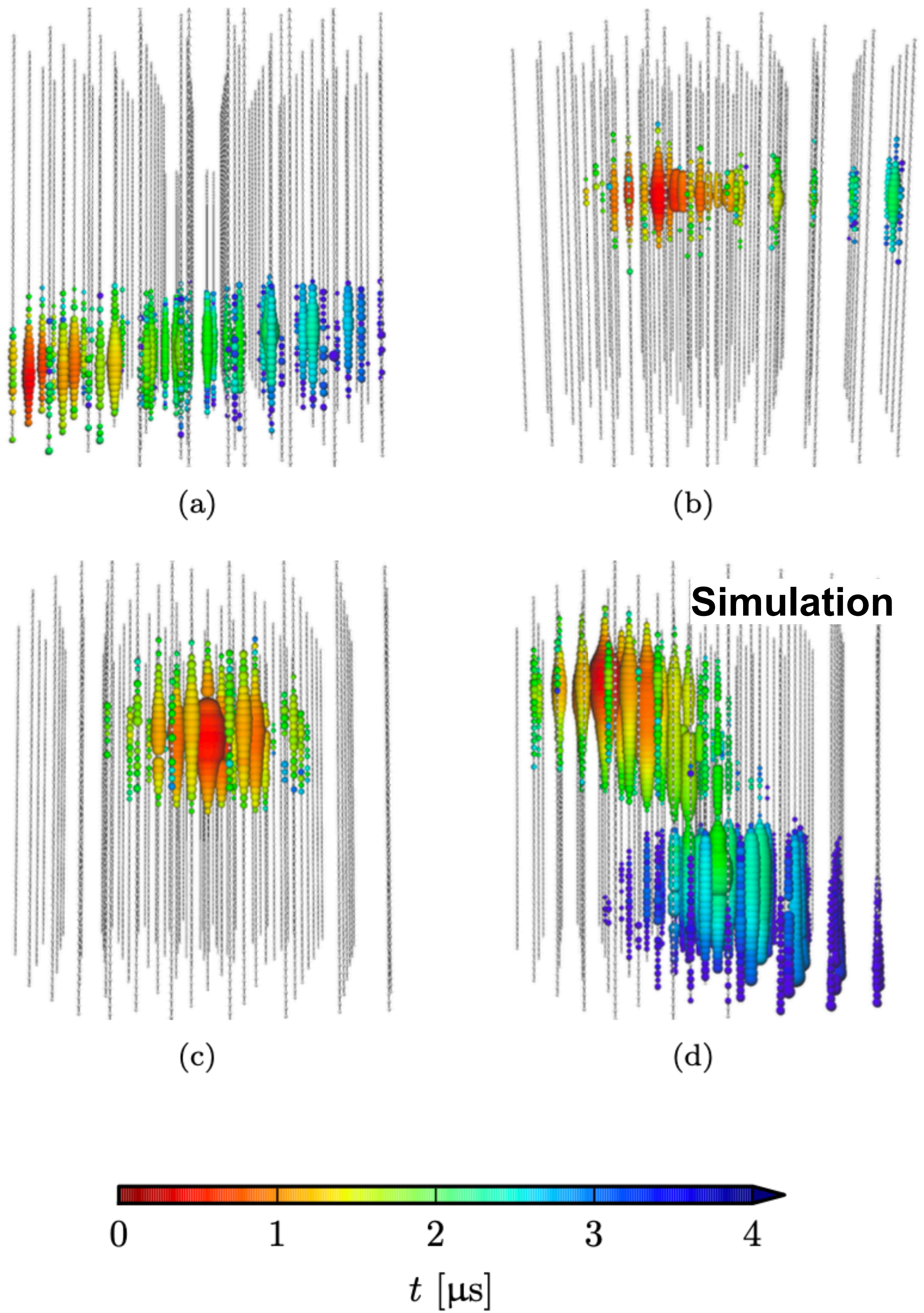


Cascade (ν_e, ν_μ, ν_τ)

angular resolution 5° - 15°
Log energy resolution:
0.1 x log(E_ν)



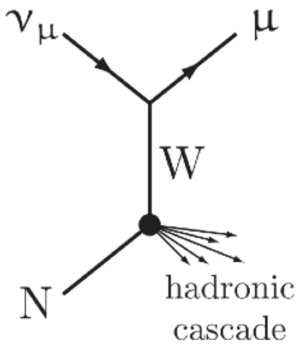




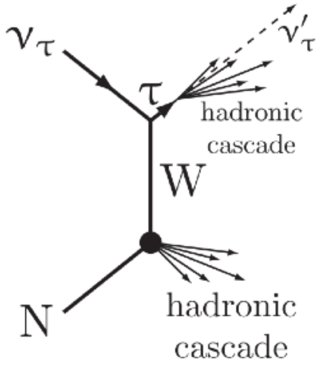
Starting track (ν_μ)

angular resolution: 1.5°
dE/dx + energy at vertex

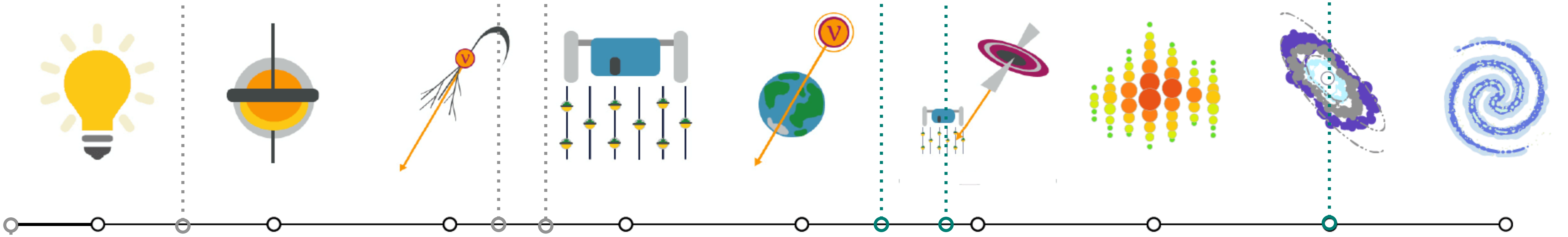
Log Energy Resolution:
0.3 x log(E_ν)



Double-Bang (ν_τ) E > O(PeV)



History of neutrino Astronomy in a nutshell



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

Construction of ANTARES Started (**2002**)

Construction of IceCube Started (**2004**)

Construction of KM3NeT Started (**2015**)

P-ONE initiative Started (**2017**)

TRIDENT initiative Started (**2022**)

1988 — Telescope in the Ice Envisioned

2000 — AMANDA Completed

2001 — Atmospheric Neutrinos Detected in ice

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

Neutrino Telescopes Envisioned (**1960**)

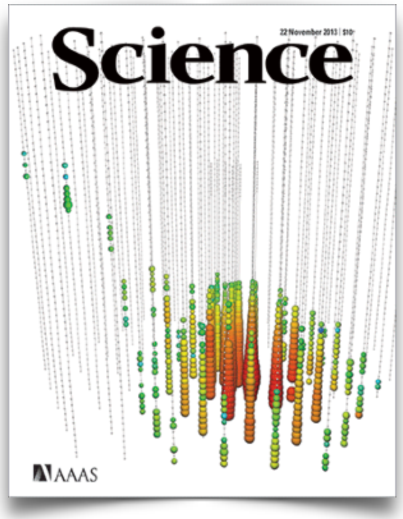
2007

Science

CATCHING Cosmic Clues

AAAS

2013



Science

AAAS

2018

Science

AAAS

NEUTRINOS FROM A BLAZAR

2019

nature astronomy

Neutrinos from a blazar flare

2022

Science

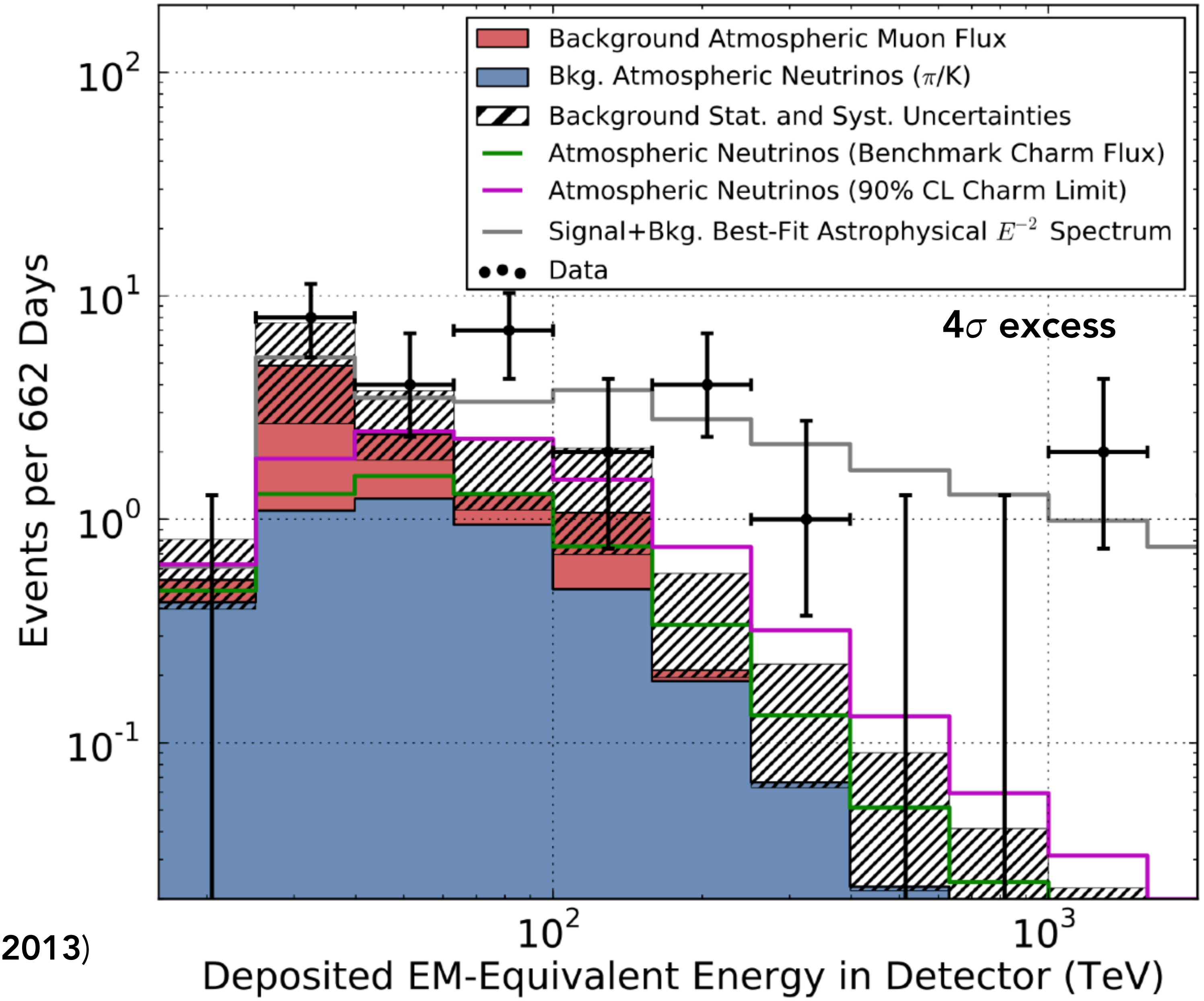
Neutrinos from an active galaxy pp. 474 & 538

BRAIN CONNECTIVITY

Cosmic neutrinos discovered

Breakthrough discovery

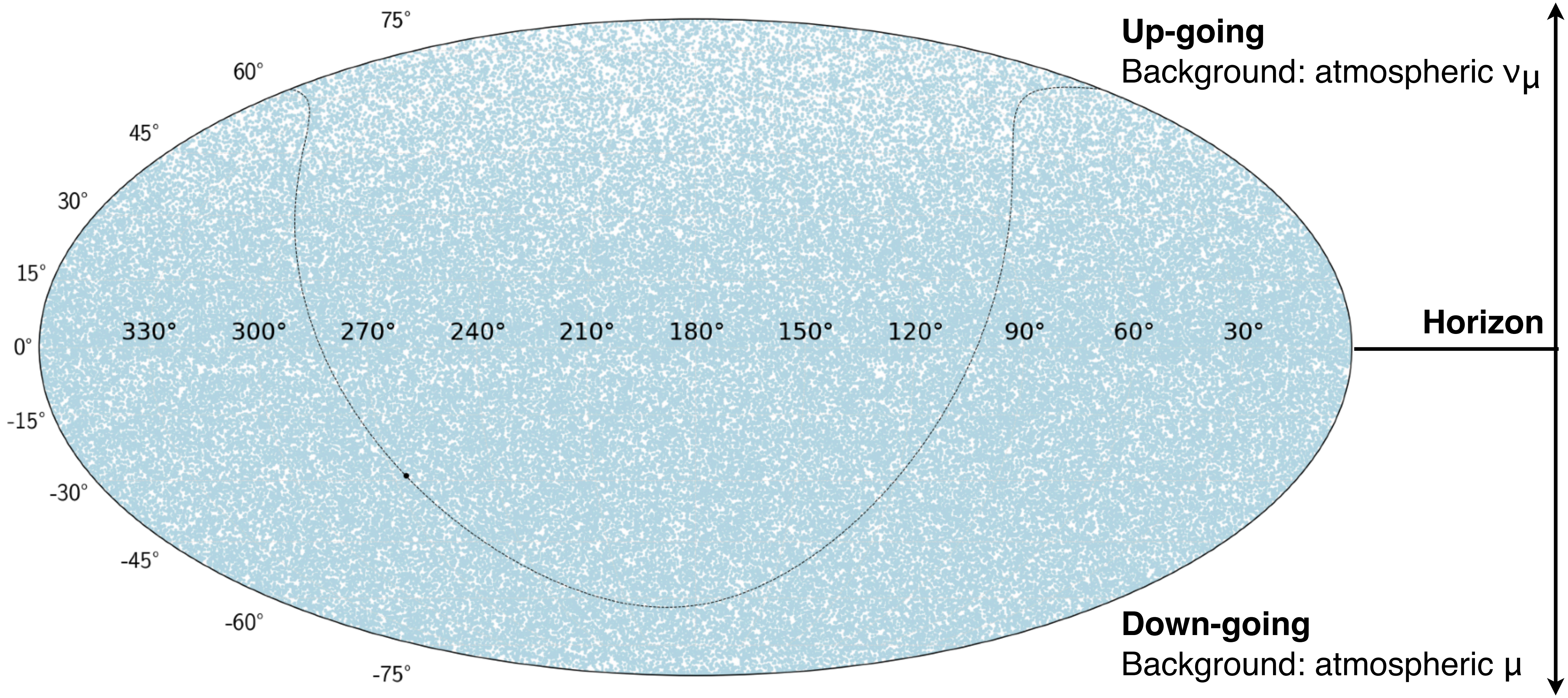
First evidence of neutrinos of cosmic origin in 2 years of IceCube data: flavors, directions and energies inconsistent with expectations from atmospheric muon and neutrino backgrounds. Subsequent and diverse analyses confirm an astrophysical flux at greater significance, with spectrum consistent with single power-law but more complex shapes suggested



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

Searching for Neutrino Point Sources

Allowing for more background and larger signal efficiencies it is possible to search for individual astrophysical sources as local event excesses. From the first year of full IceCube operations 138,322 neutrino candidates (**muon tracks**) recorded!

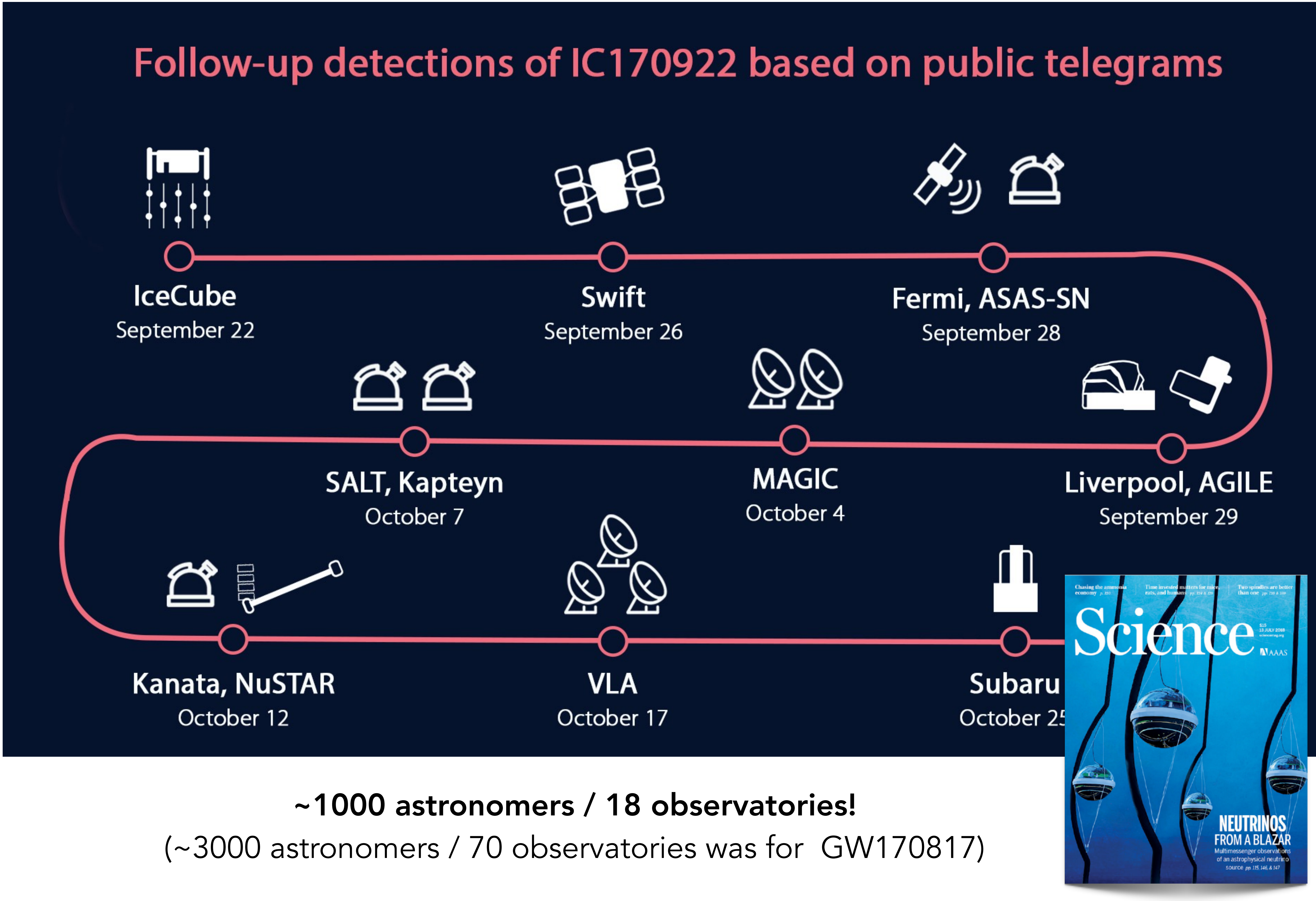


Up-going
Background: atmospheric ν_μ

Horizon

Down-going
Background: atmospheric μ

Equatorial coordinates



Follow-up detections of IC170922 based on public telegrams

IceCube
September 22

Swift
September 26

Fermi, ASAS-SN
September 28

Liverpool, AGILE
September 29

MAGIC
October 4

SALT, Kapteyn
October 7

Kanata, NuSTAR
October 12

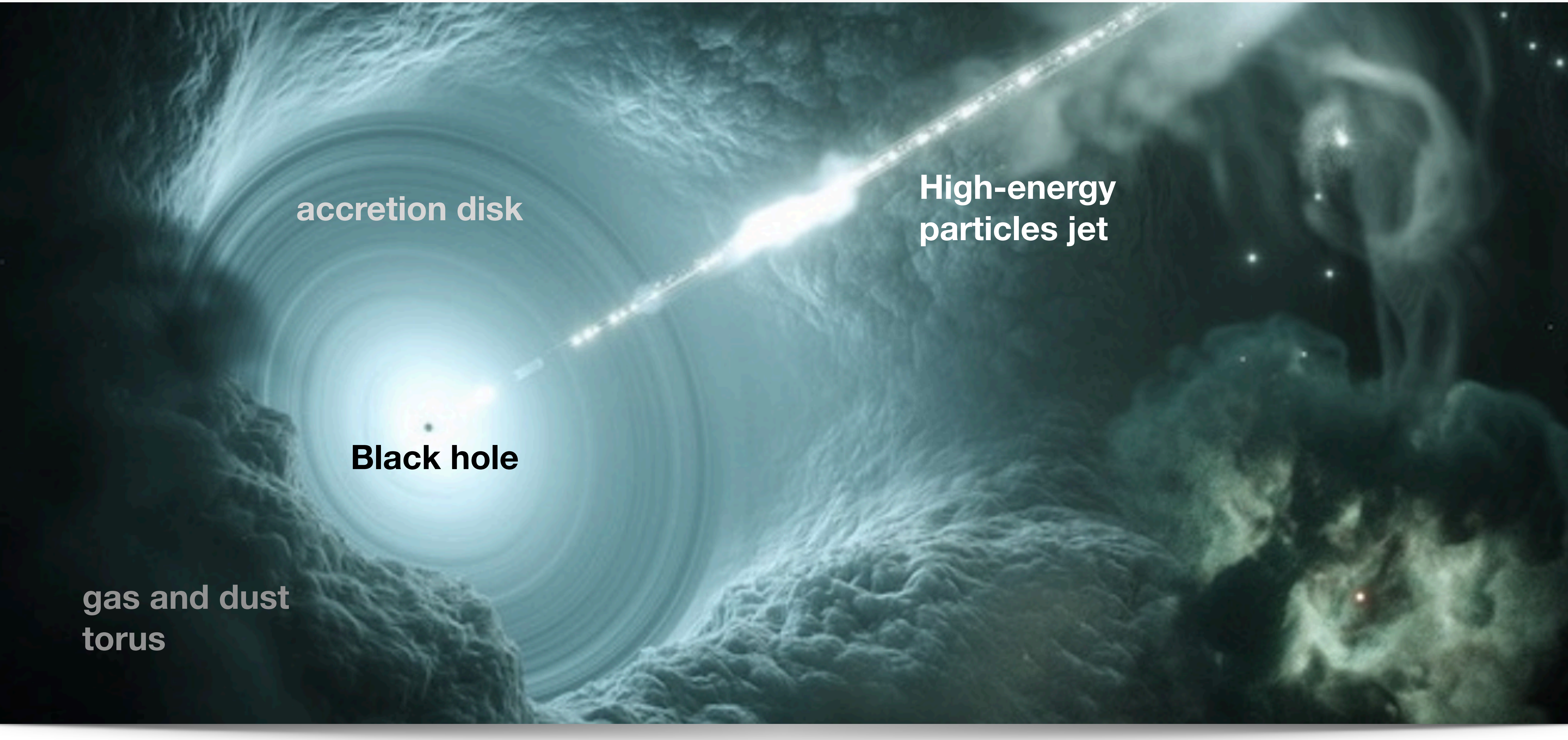
VLA
October 17

Subaru
October 25

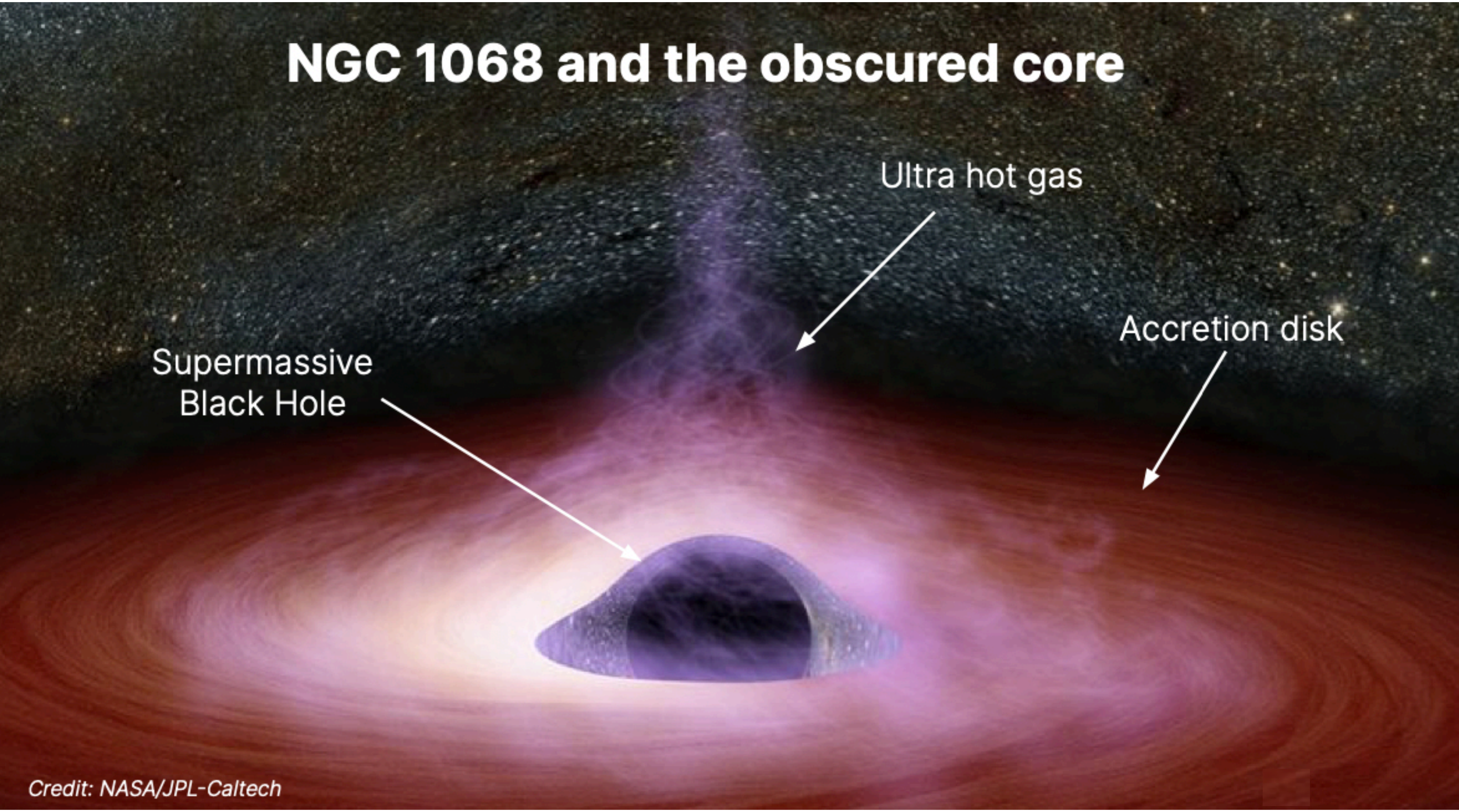
~1000 astronomers / 18 observatories!

(~3000 astronomers / 70 observatories was for GW170817)

High Energy neutrinos from TXS 0506+056



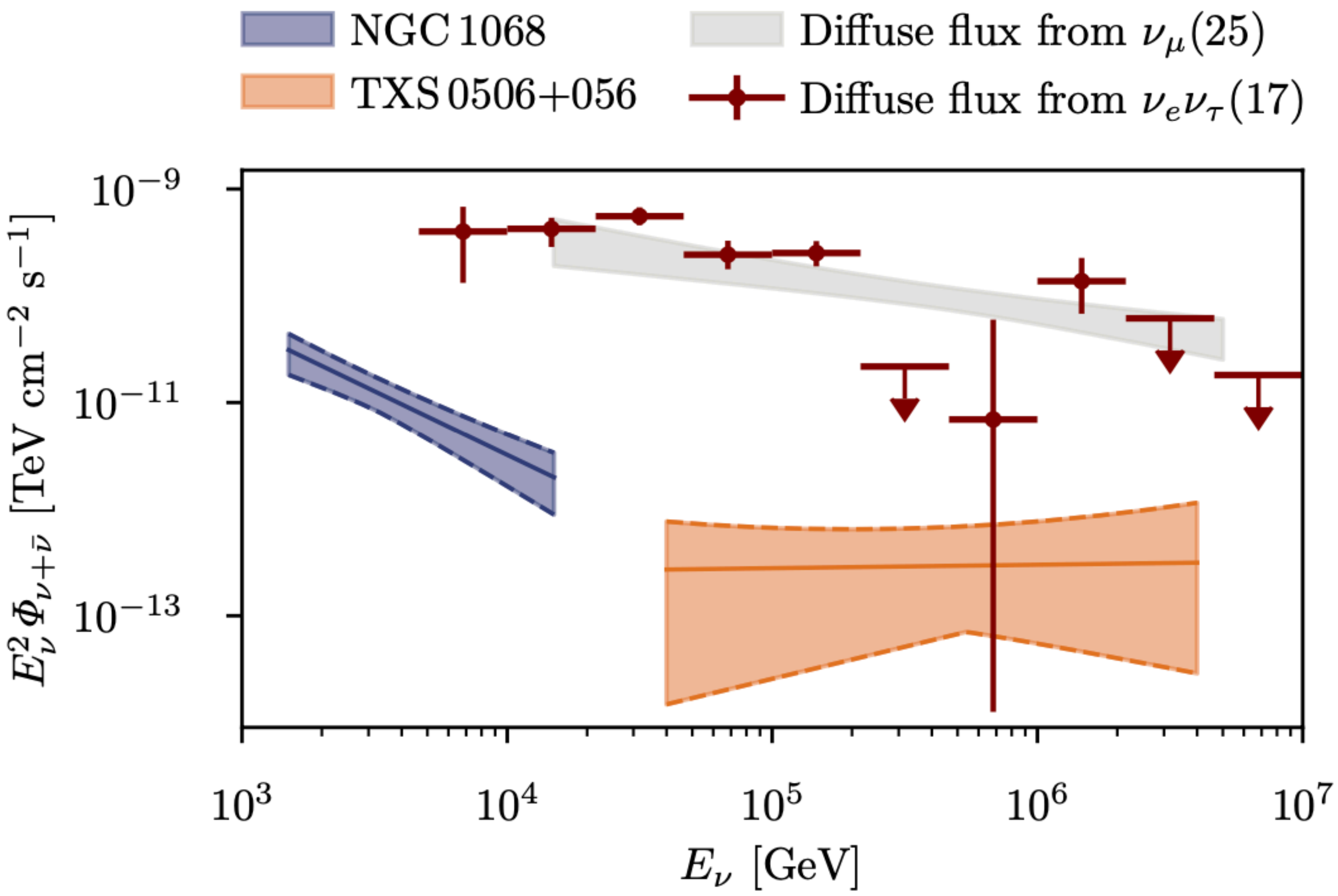
High Energy neutrinos from NGC 1068



Credit: NASA/JPL-Caltech

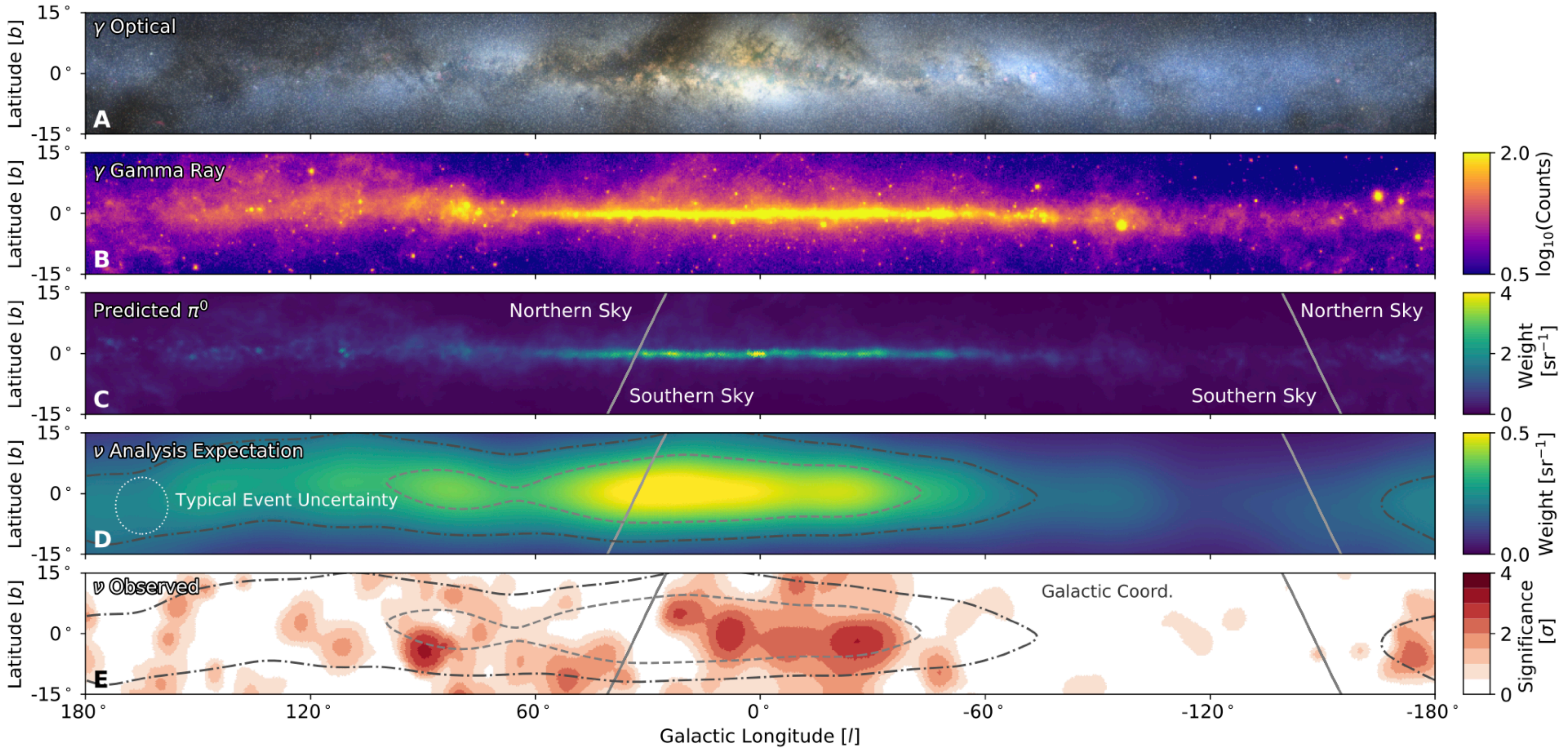
Room for astrophysical discovery

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.



The Multi-messenger picture of the Milky Way

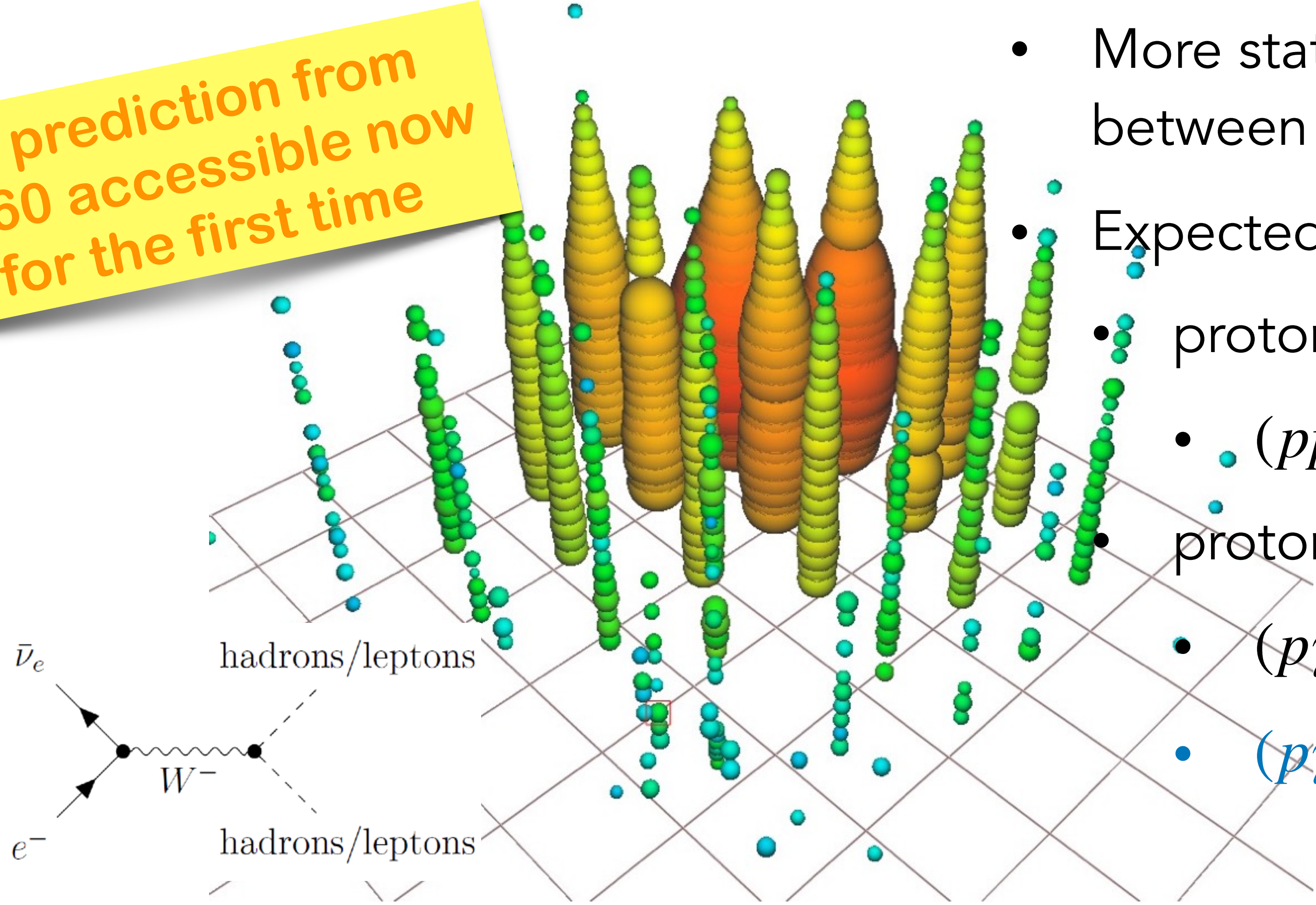
Machine learning techniques applied to ten years of IceCube data enabled identifying neutrino emission from the Galactic plane at 4.5σ by comparing event directions to prediction maps of locations in the sky where the galaxy was expected to shine in neutrinos.



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. 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.

A prediction from 1960 accessible now for the first time

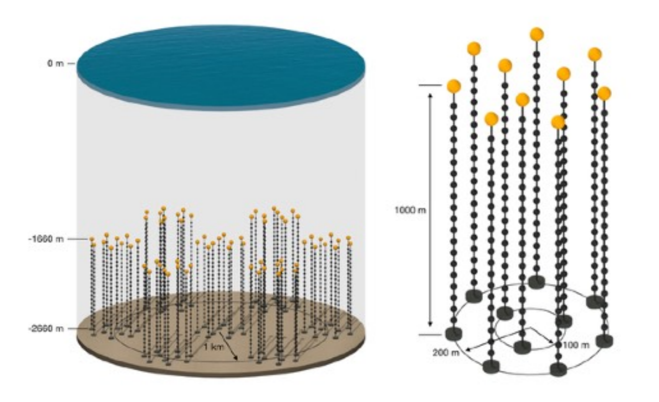


- More statistics will enable differentiating between different production scenarios
- Expected ratio $\bar{\nu}_e : \nu_e$:
  - proton-proton
    - $(pp)\ \ \bar{\nu}_e : \nu_e = 1 : 1$
  - proton-photon
    - $(p\gamma)\ \ \bar{\nu}_e : \nu_e = 1 : 3.5$
    - $(p\gamma,$ strong B-field$)\ \ \bar{\nu}_e : \nu_e = 0$

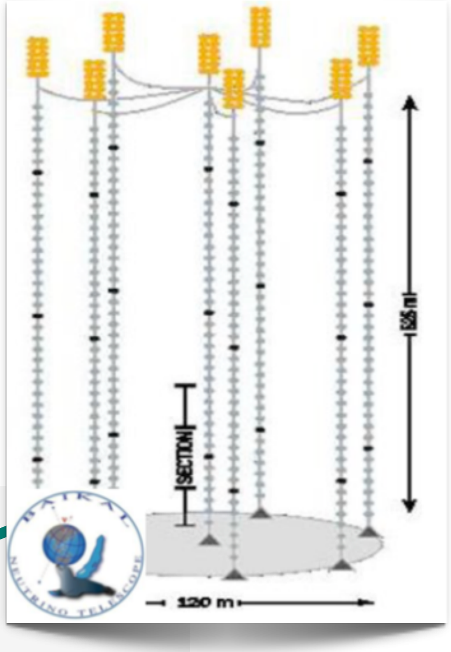
M. G. Aartsen et al. [IceCube Collaboration], Nature 591, 220 (**2021**)

Future neutrino telescopes

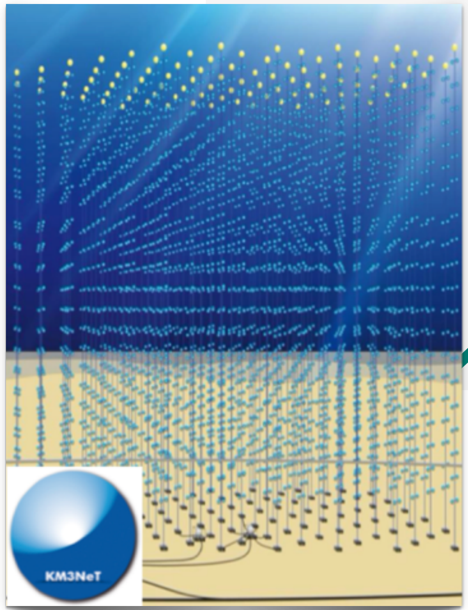
P-ONE
Project target ~ **several km³**
Under R&D / design

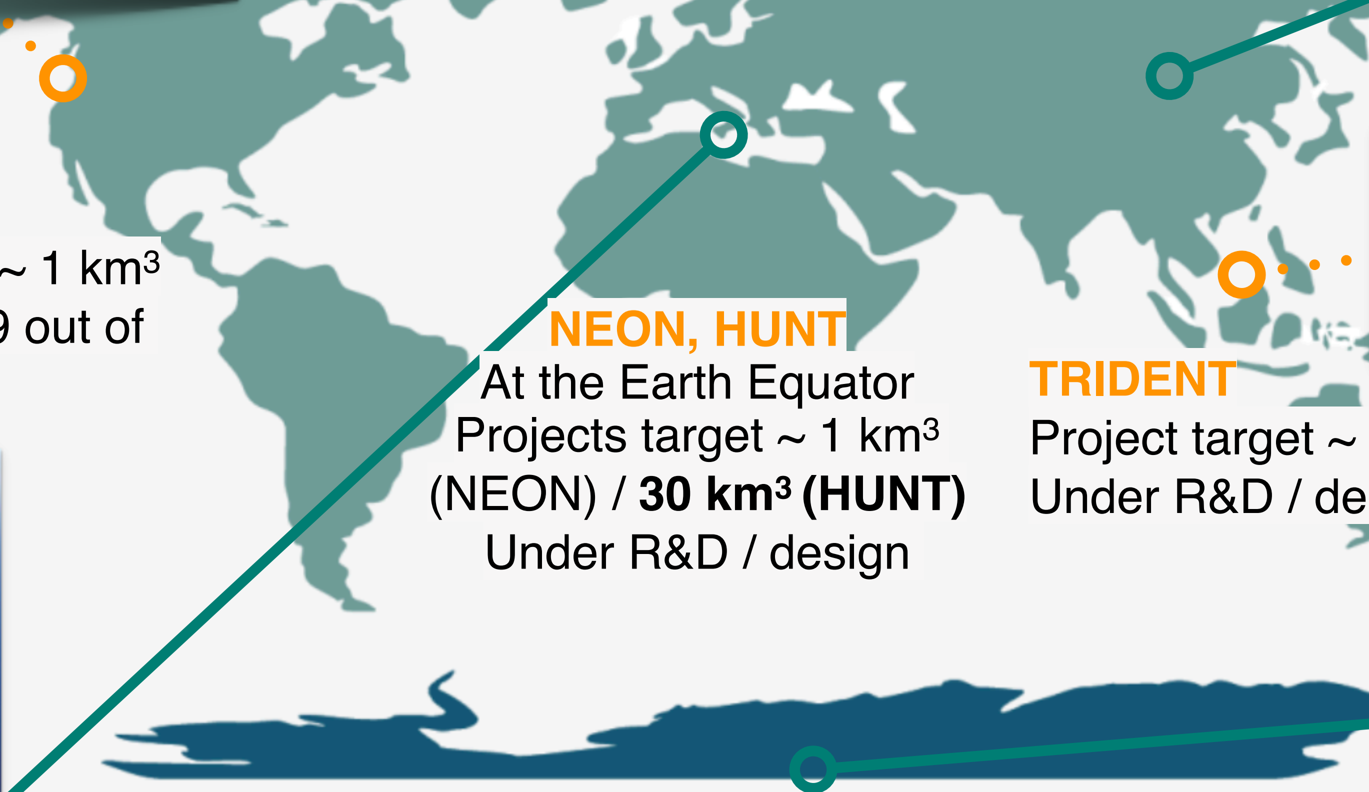


Baikal/GVD
Project target in 2025 ~ 1 km³
Under construction
10 out of 16 clusters, 0.5 km³



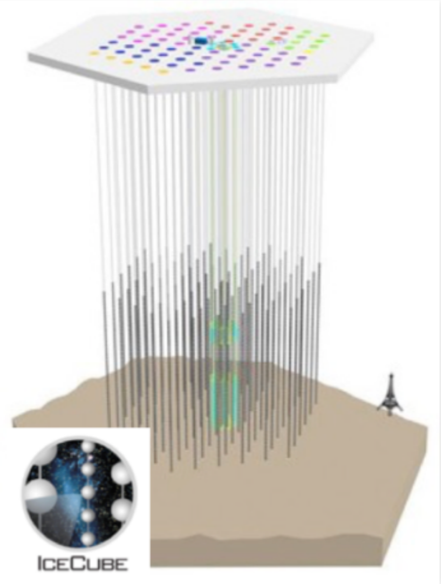
KM3NeT
Project target in 2030 ~ 1 km³
Under construction: 19 out of ~200 strings, 0.2 km³





NEON, HUNT
At the Earth Equator
Projects target ~ 1 km³ (NEON) / **30 km³ (HUNT)**
Under R&D / design

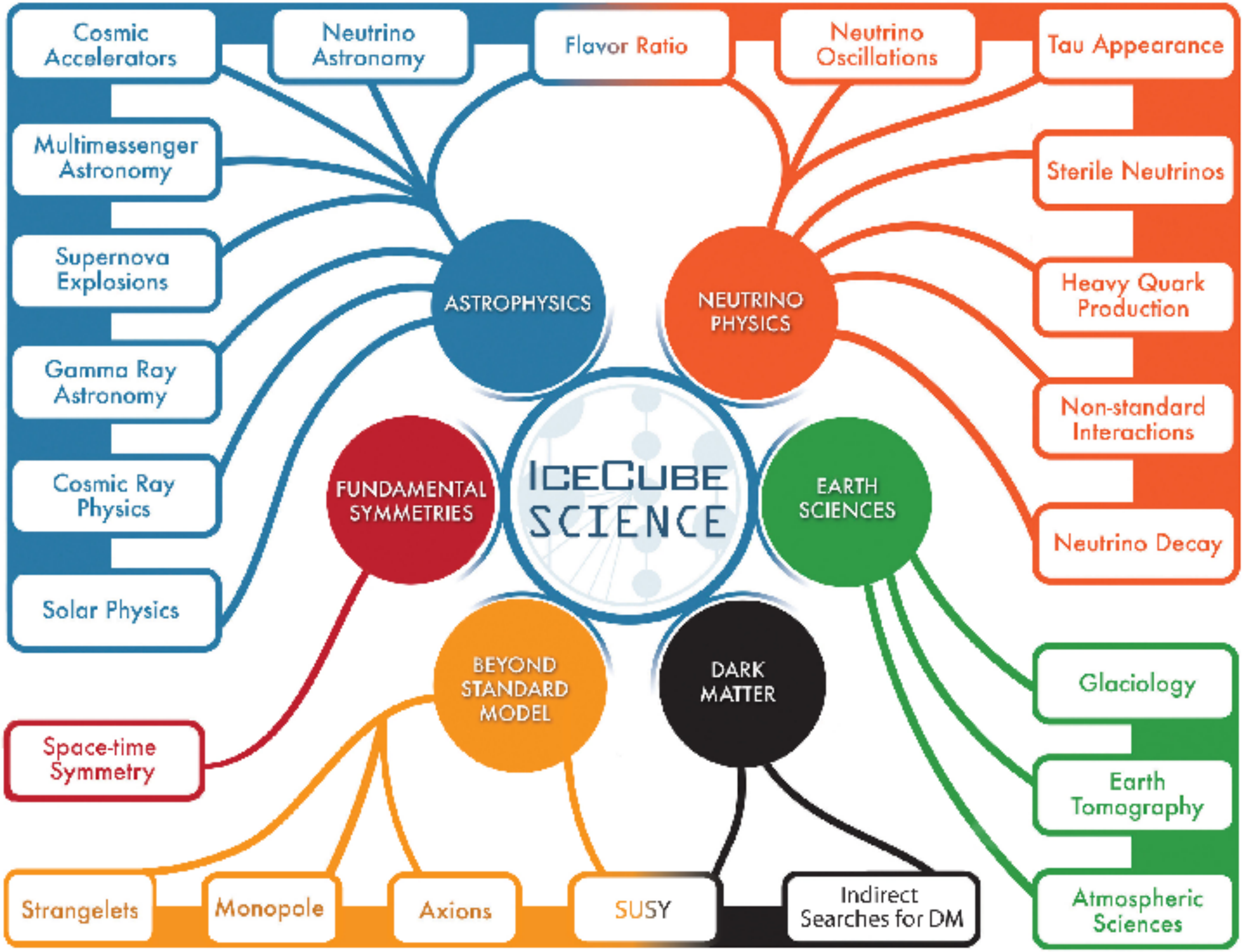
TRIDENT
Project target ~ **7.5 km³**
Under R&D / design



IceCube
Completed in 2011, ~ 1 km³

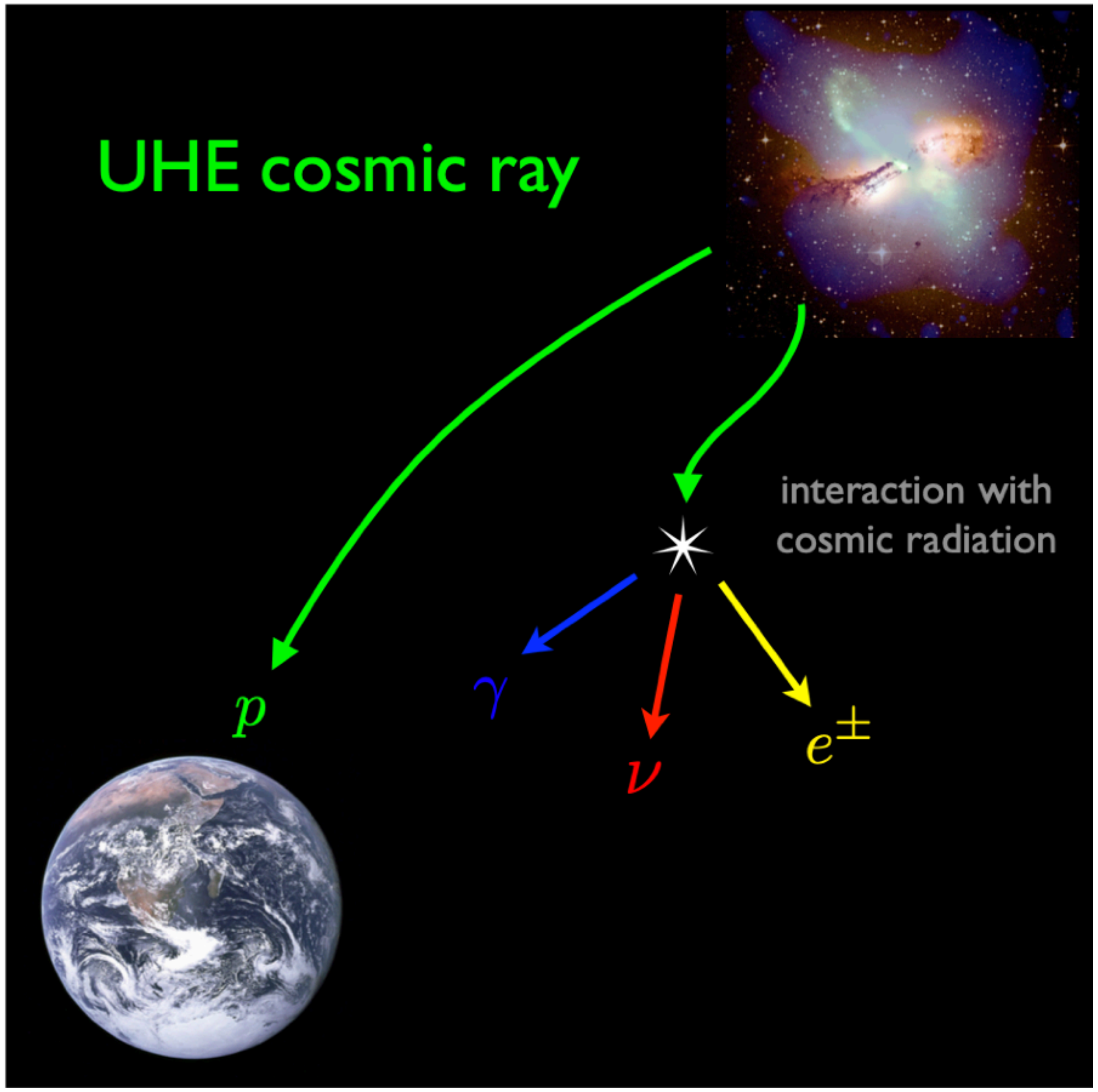
IceCube-Gen 2
Project target ~ **10 km³** + radio array
Under R&D / design

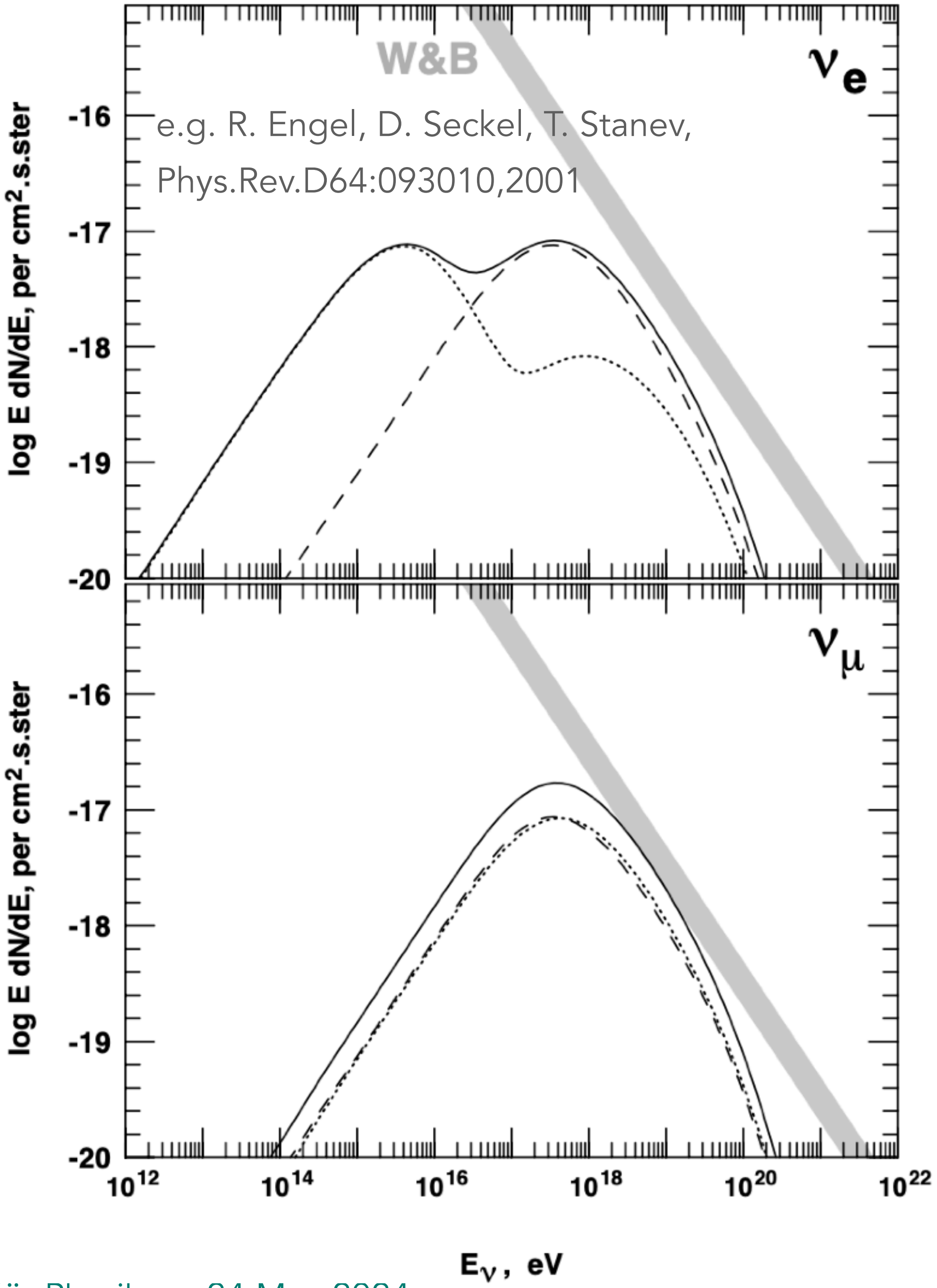
Astrophysics and Particle Physics with Neutrino Telescopes



A guaranteed “source” of neutrinos

Interaction of ultra-high-energy cosmic rays with the cosmic microwave background (CMB) provides a guaranteed source of ultra-high-energy neutrinos with intensity depending on the chemical composition of cosmic rays




e.g. R. Engel, D. Seckel, T. Stanev, Phys.Rev.D64:093010,2001

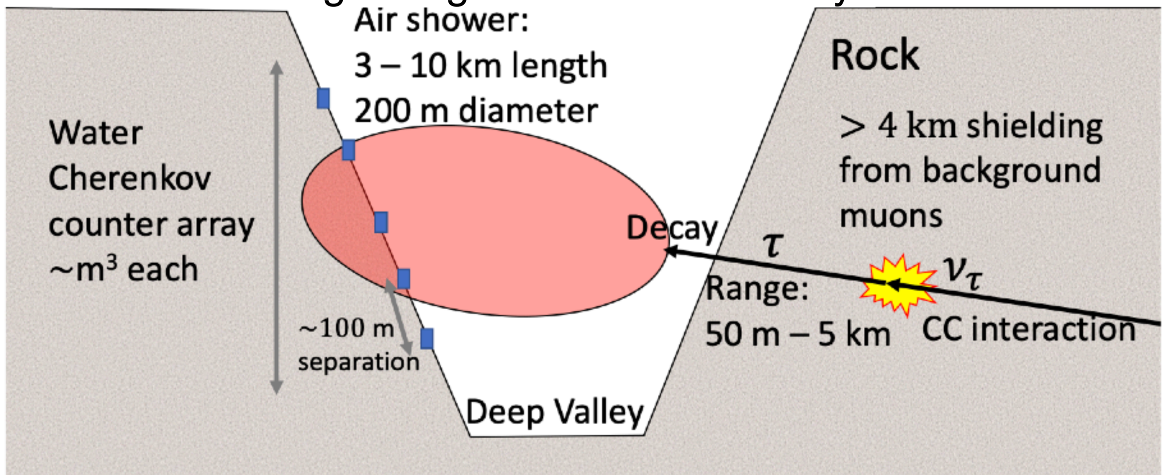
Future neutrino observatories

Tau neutrino interactions in the Earth's crust produce tau leptons that will decay in the vicinity of the detector triggering a particles shower

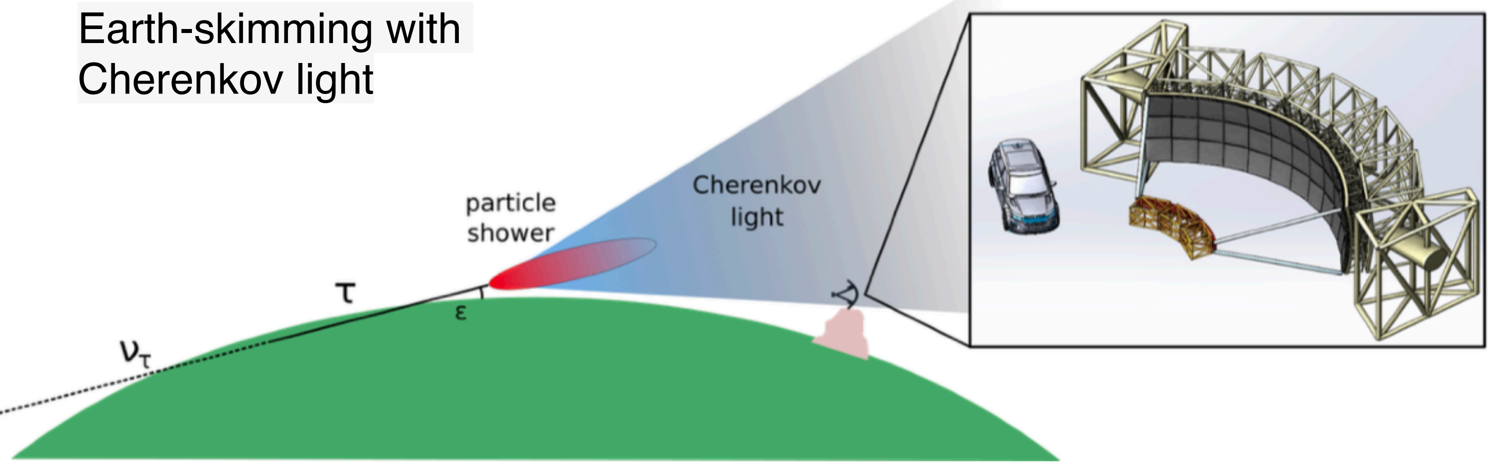
TRINITY (Earth-skimming with Cherenkov light)
Demonstrator in operation aims at detecting TXS 0506+506 in one year

Seel also **Ashra-NTA**

Earth skimming with ground detector arrays



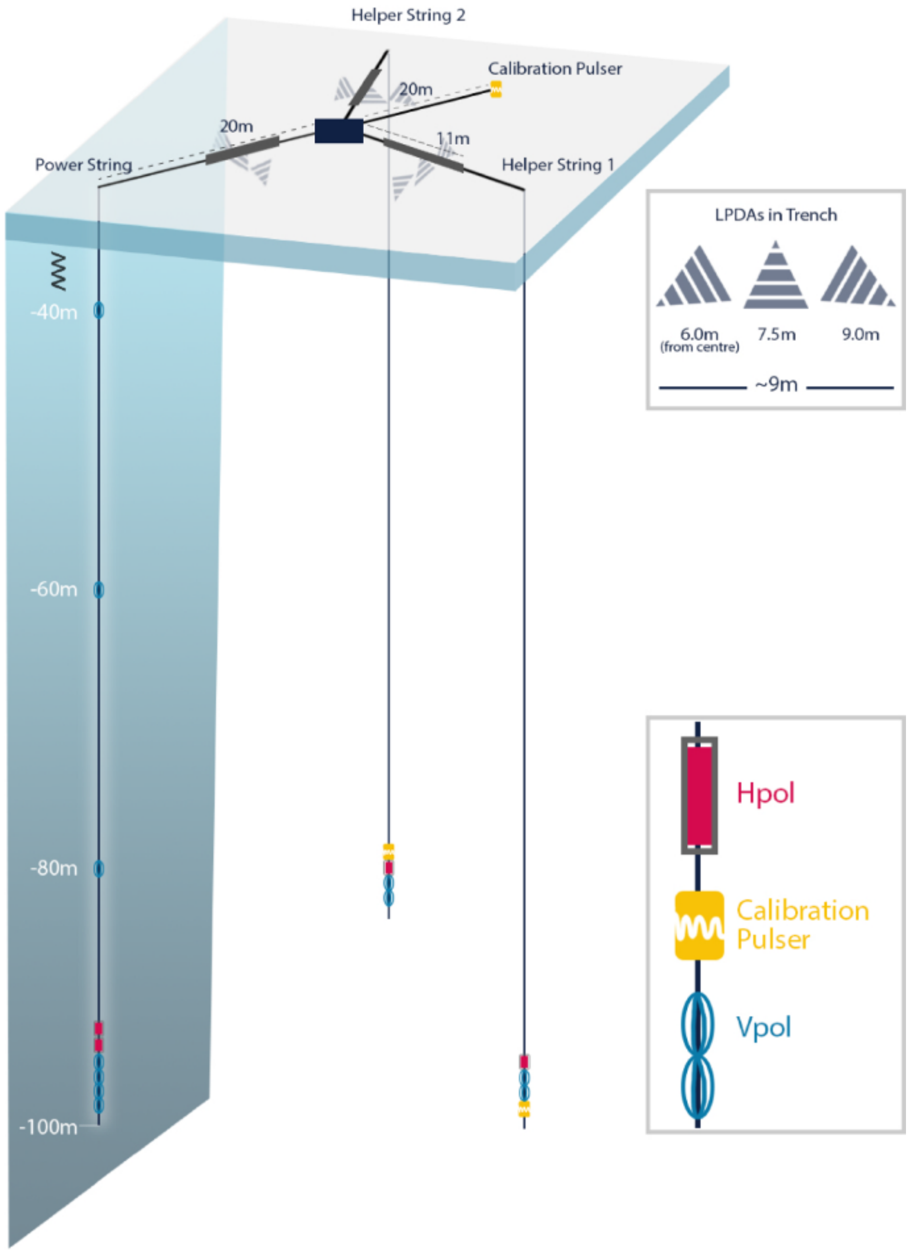
Earth-skimming with Cherenkov light

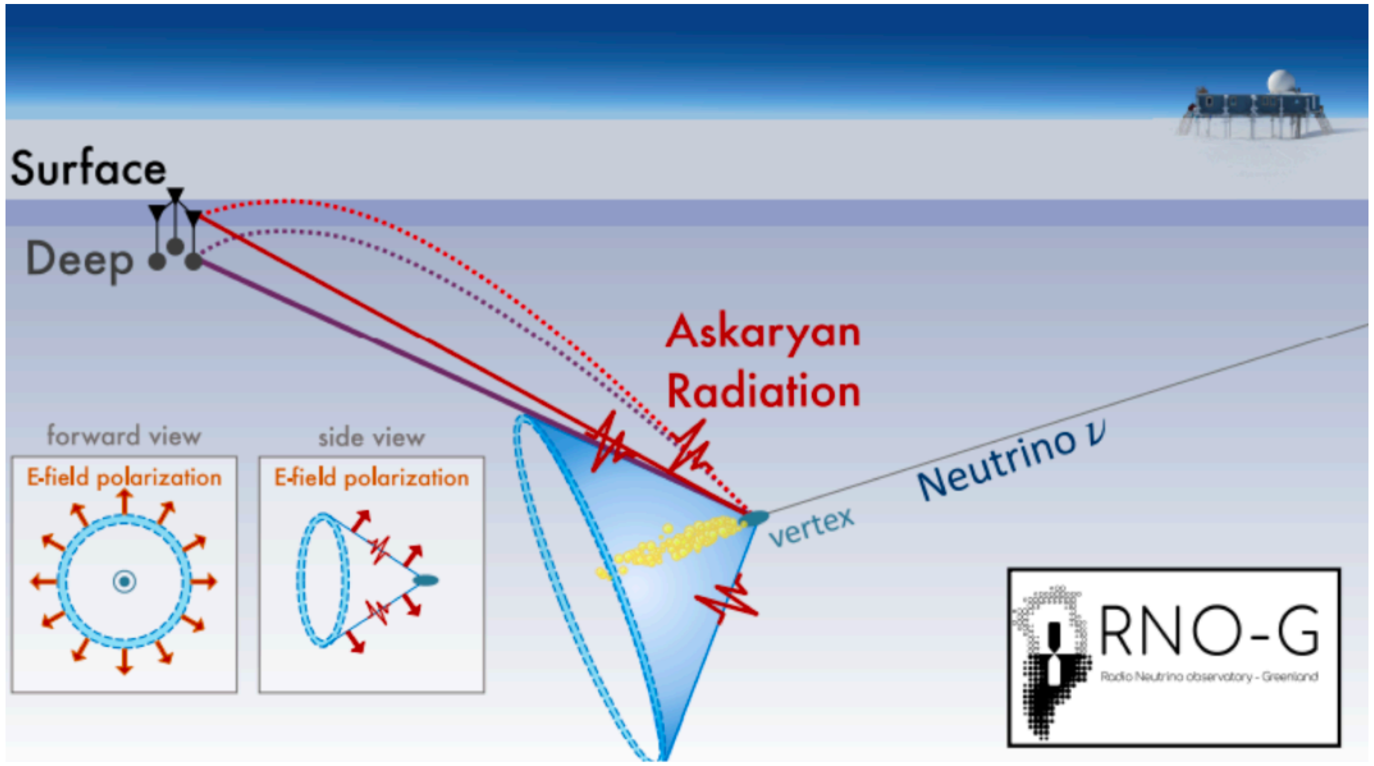


TAMBO (Earth skimming with ground detector arrays)
Project target ~at least an order of magnitude greater acceptance than IceCube
Under R&D / design
ν_τ in 1-100 PeV range

Radio Neutrino Observatory Greenland

Attenuation length of radio waves is *O*(1km) in ice, enabling sparse sampling and reduced costs for significantly larger sensitivities compared to optical instruments. Radio detection in ice (Askaryan effect) is sensitive to all-flavor neutrinos, with individual flavor discrimination to be investigated. RNO-G under construction in Greenland, will guide developments for IceCube-Gen2

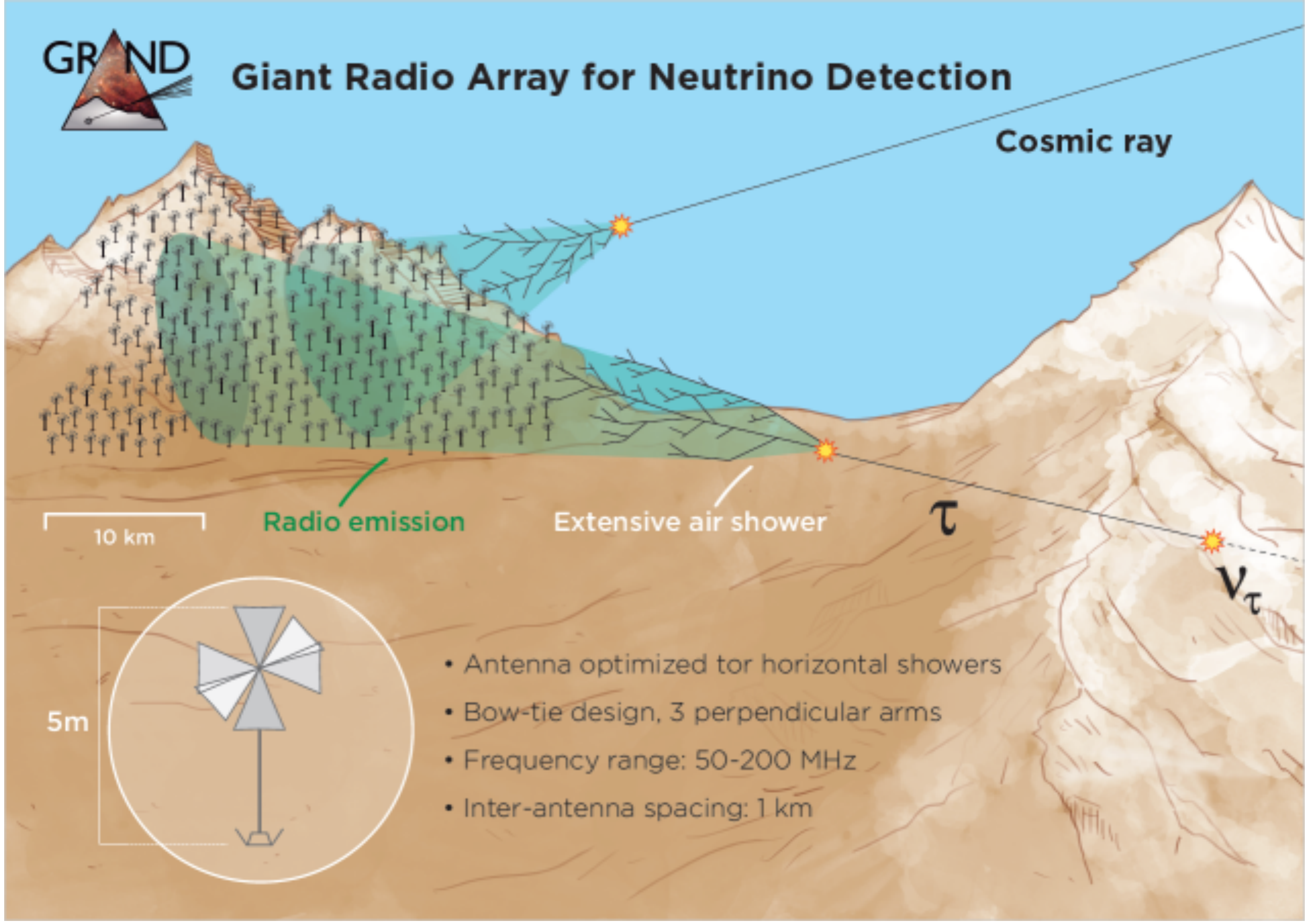




JINST 16 P03025 2021

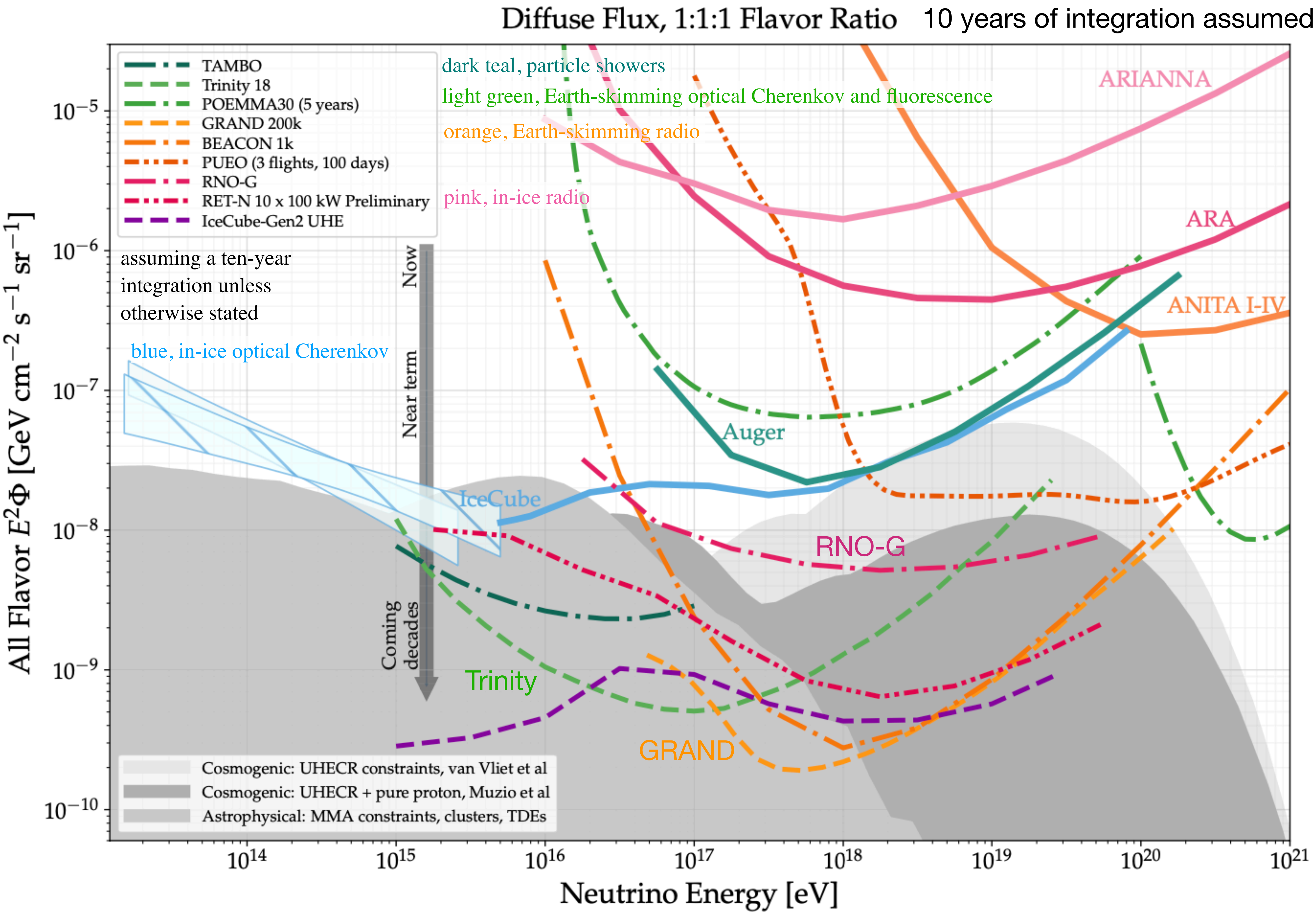
GRAND

Attenuation length of radio waves is O(10km) in air, enabling sparse sampling and reduced costs for significantly larger sensitivities compared to optical instruments. Radio detection in air (geomagnetic effect) is sensitive to to ν_τ only. GRAND will consist of moduli of 10 thousand antennas each, built in different sites.



Projected sensitivities to diffuse neutrinos

10 years of integration assumed



dark teal, particle showers

light green, Earth-skimming optical Cherenkov and fluorescence

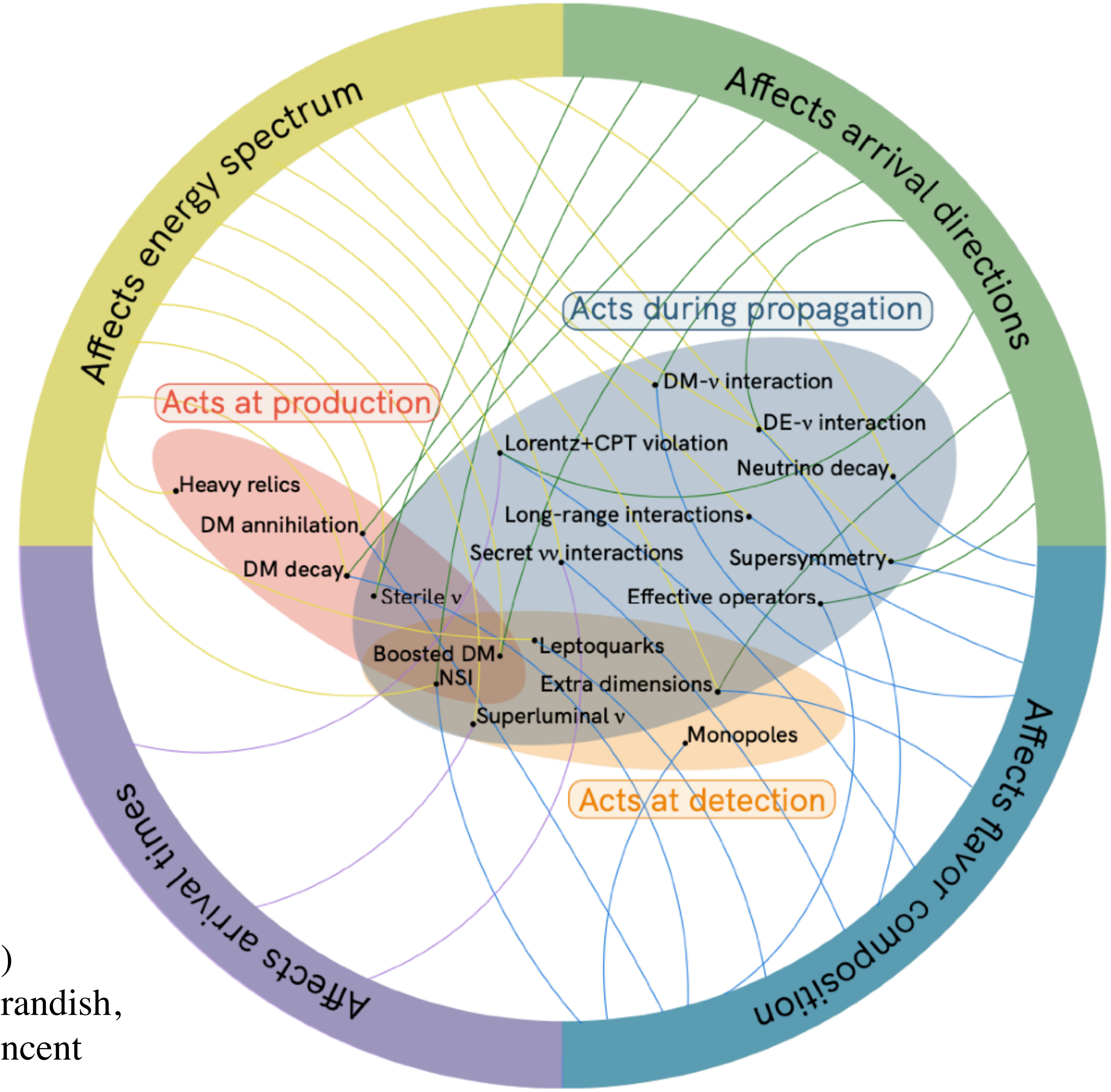
orange, Earth-skimming radio

pink, in-ice radio

blue, in-ice optical Cherenkov

New physics with high-energy neutrinos

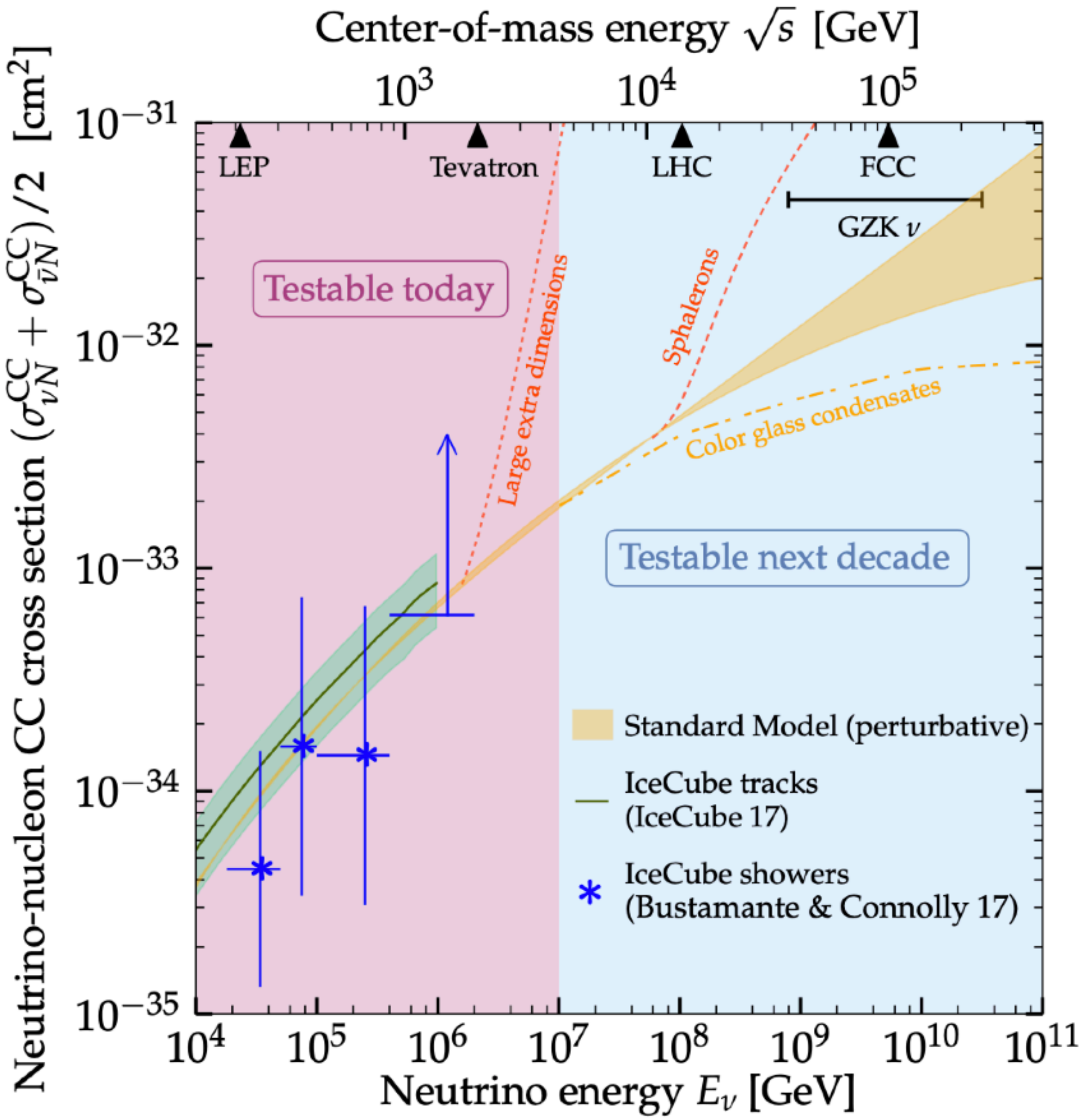
To access particle interactions beyond the TeV scale, particle beams made by cosmic accelerators are needed and especially fitting, with energies exceeding accelerators and reactors, bur also γ-ray and possibly even cosmic rays. Cosmic baselines enable the accumulation of tiny effect

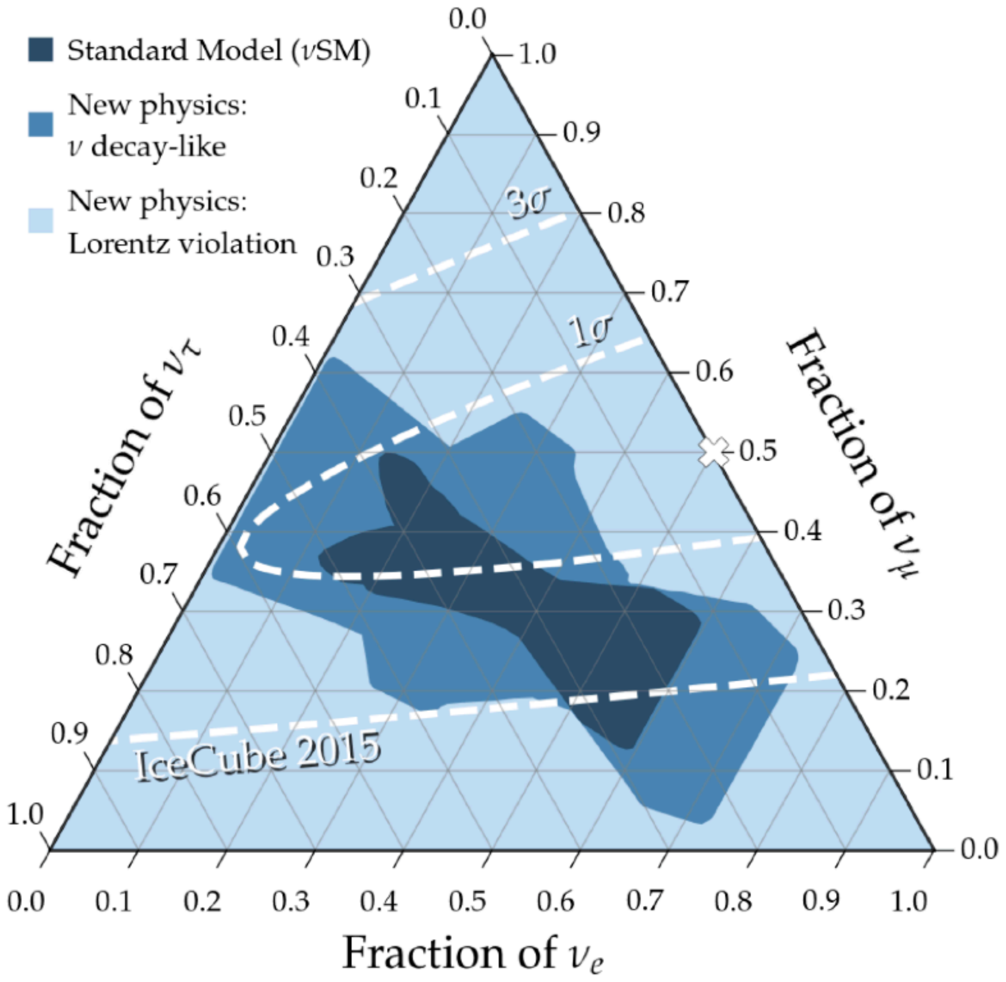


PoS ICRC2019 (1907.08690)
Argüelles, Bustamante, Kheirandish,
Palomares-Ruiz, Salvadó, Vincent

Example open questions

Future measurements of neutrino-nucleon cross section at EeV energies would probe BSM physics and test the structure of nucleons at $\sqrt{s} = 100$ TeV. Also, BSM physics, e.g. neutrino decay, Lorentz-invariance violation, interactions with dark matter etc. could introduce large deviations in the flavor ratios





Fundamental Physics with High-Energy Cosmic Neutrinos: Astro2020 Science White Paper, arXiv: 1903.04333

A few last thoughts

- The discovery of high-energy astrophysical neutrinos has opened a new era in astroparticle physics

- Upgraded detectors and advances in software and computing, including AI, will enable experiments to detect rare events with higher efficiency and purity

- Future improved characterisation of neutrinos in the TeV–PeV energy range and the eventual detection at even higher energies have far-reaching consequences:

  - Particle Physics: What is the nature of dark matter? Do new particles and interactions exist at the highest energies? Are there new fundamental symmetries? Owing to their high energies and cosmological-scale baselines, the highest energy neutrinos are uniquely positioned to address these questions

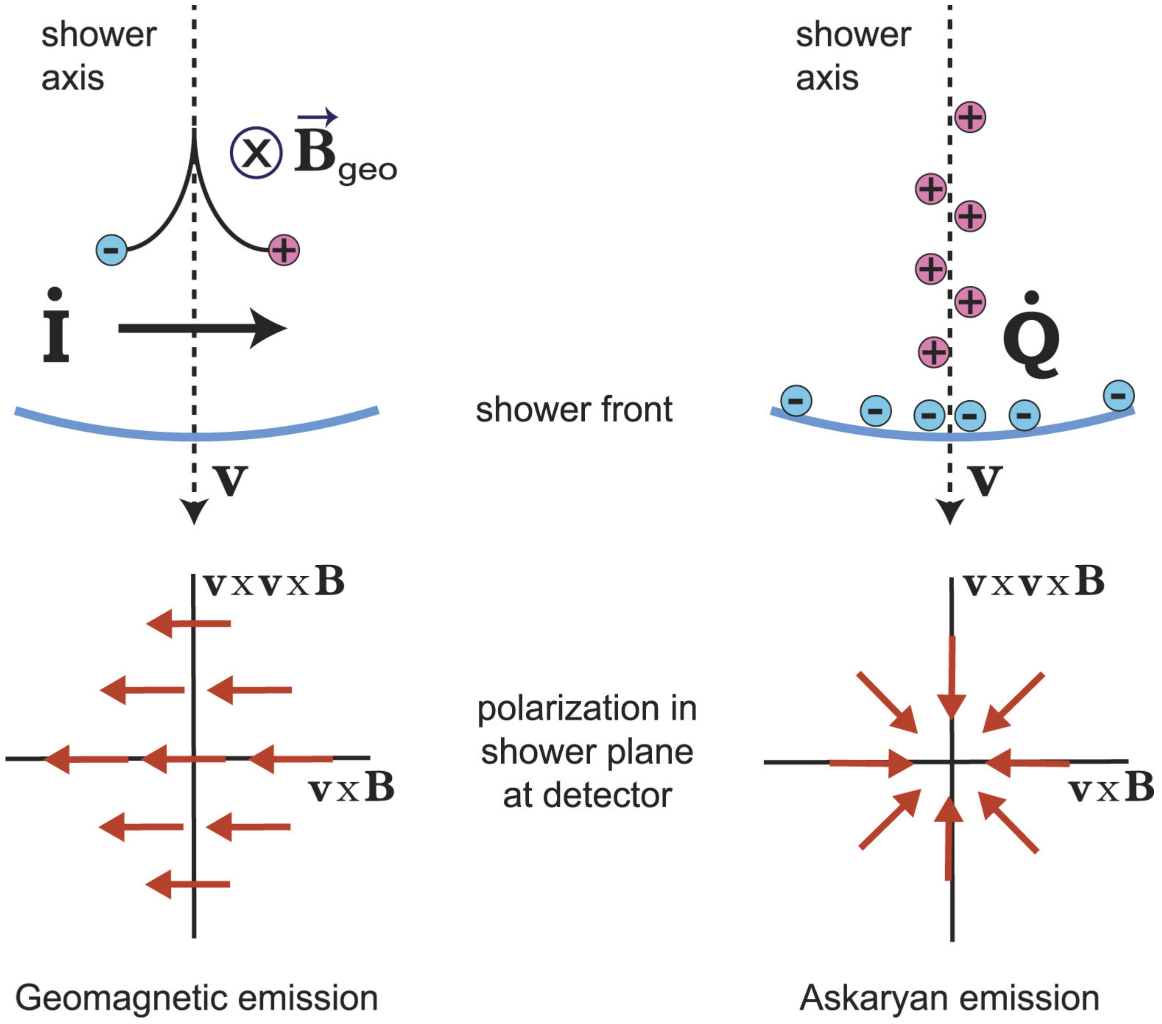
  - Astrophysics: neutrinos are key to understanding the origin of the highest-energy cosmic rays and gamma rays.

- Rich physics opportunities are ahead of us in the high-energy (HE, TeV–100 PeV) and ultra-high energy (UHE, ≥100 PeV) regime, whose potential has already been acknowledged by international panels like the US Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020) and the European Consortium for Astroparticle Physics (EuCAPT)

Radio signals from Extensive Air Showers

When the primary particle generating an extensive air shower in a medium is sufficiently energetic, a pulse in the radio band is also emitted. This is due to two different phenomena: the Askaryan effect and the geomagnetic effect. Their relative contribution depends on the density of medium in which the cascade propagates

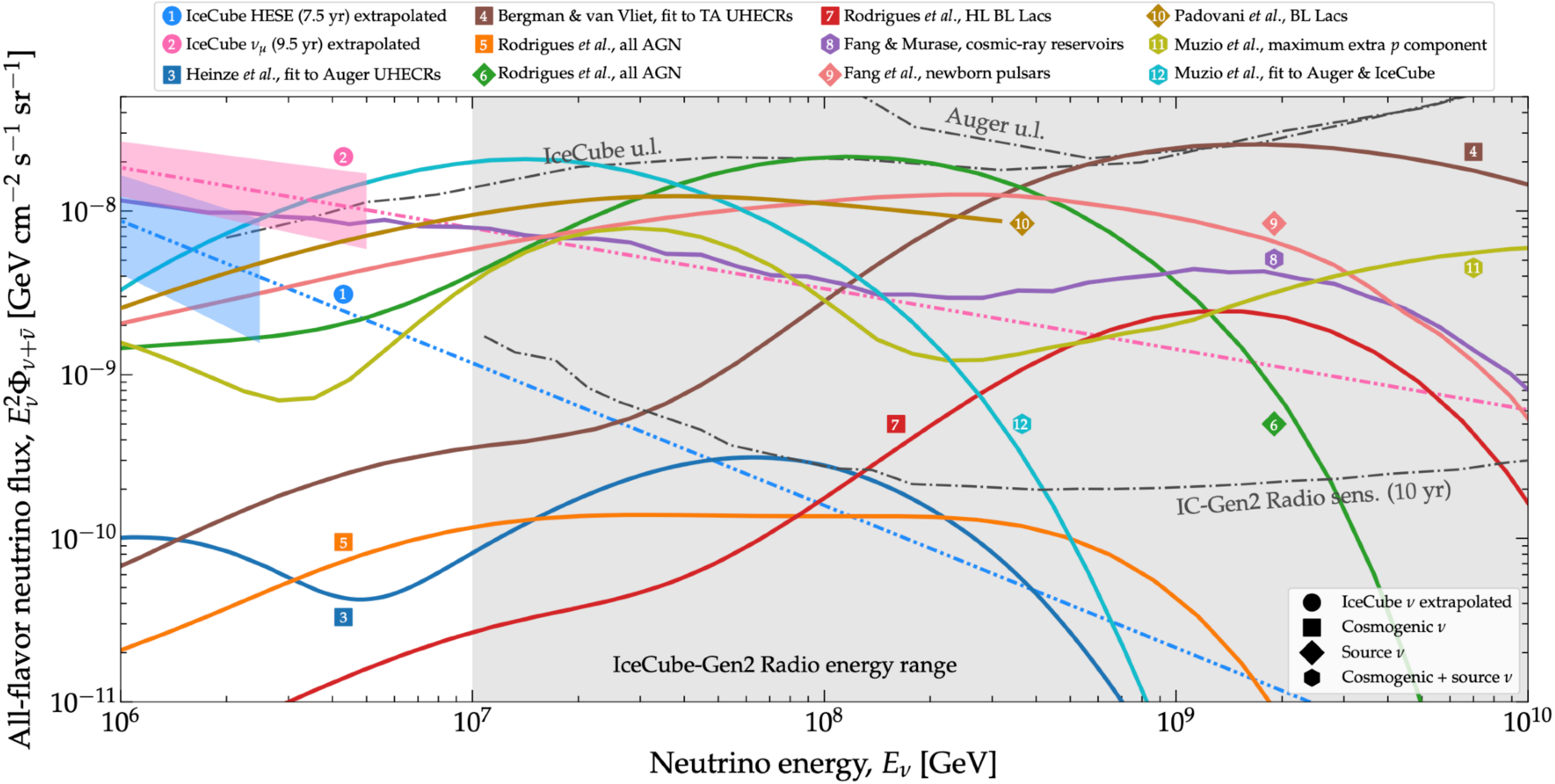
__Geomagnetic effect__: emission of radio waves due to the separation of particles of opposite charges moving in the Earth's magnetic field. ***Dominant in air,*** *because of limited annihilation of positrons*



Askaryan effect: *coherent radio emission generated by the accumulation of negative charges in the shower development, leading to a charge unbalance that evolves with time.* ***Dominant in dense media*** *(e.g. ice)*

image by F. G. Schröder

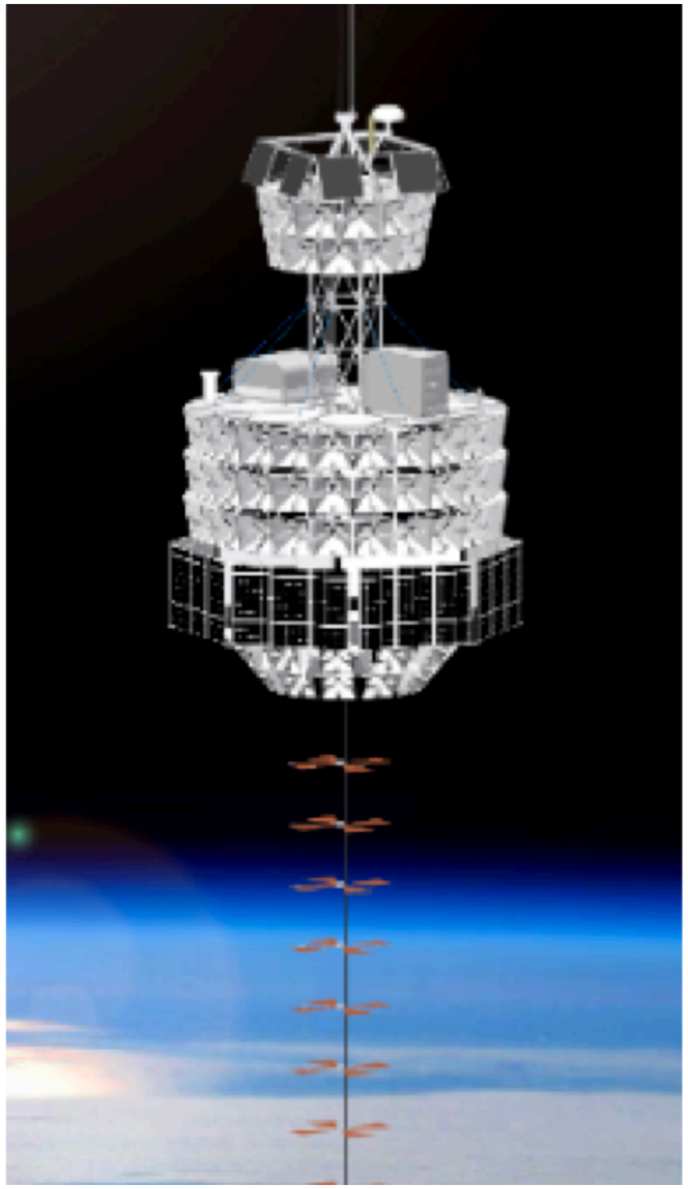
Benchmark diffuse ultra-high-energy neutrino flux models

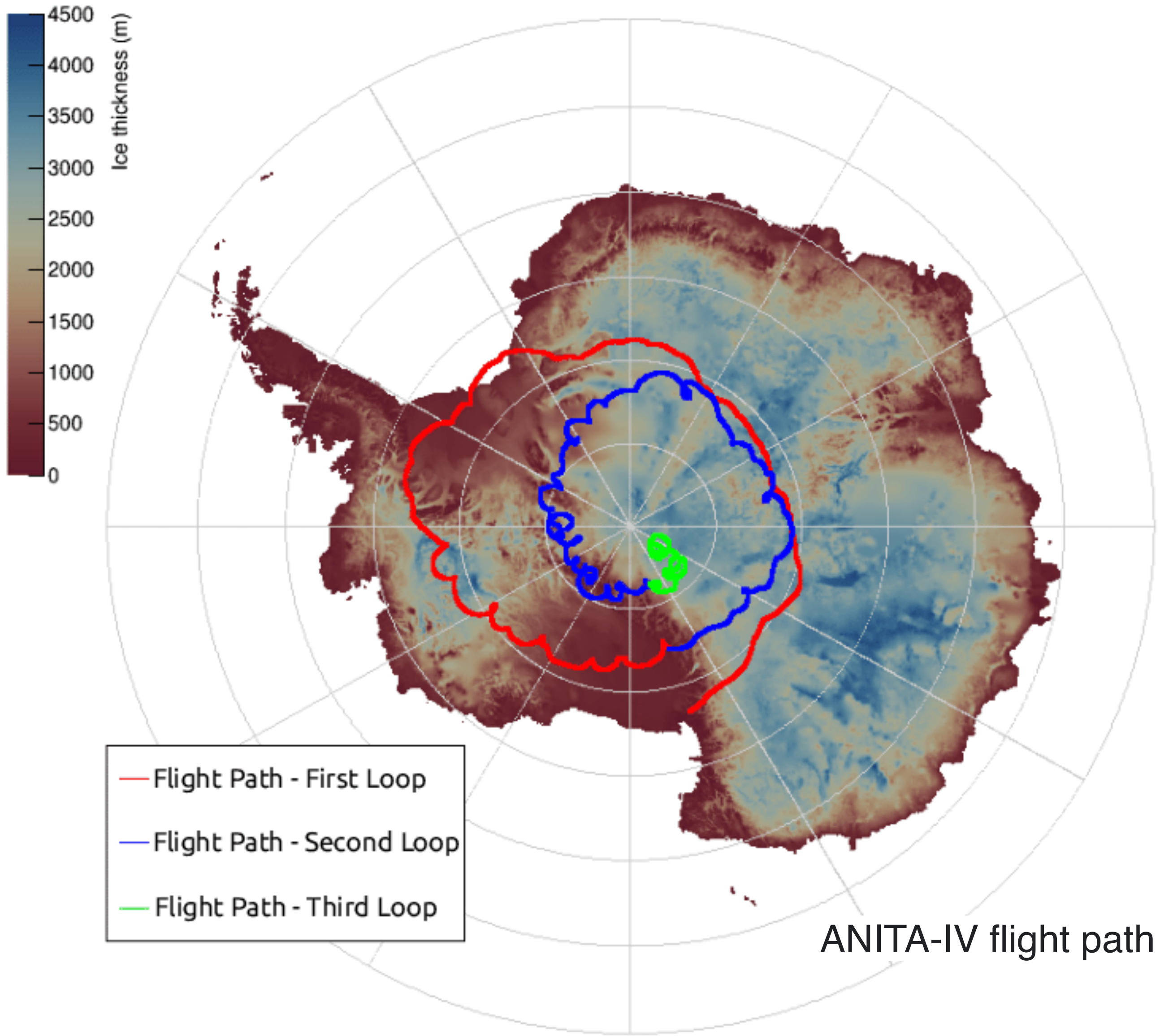


PoS ICRC2023 (2307.11055)
Valera, Bustamante, Glaser

The Payload for Ultrahigh Energy Observations (PUEO)

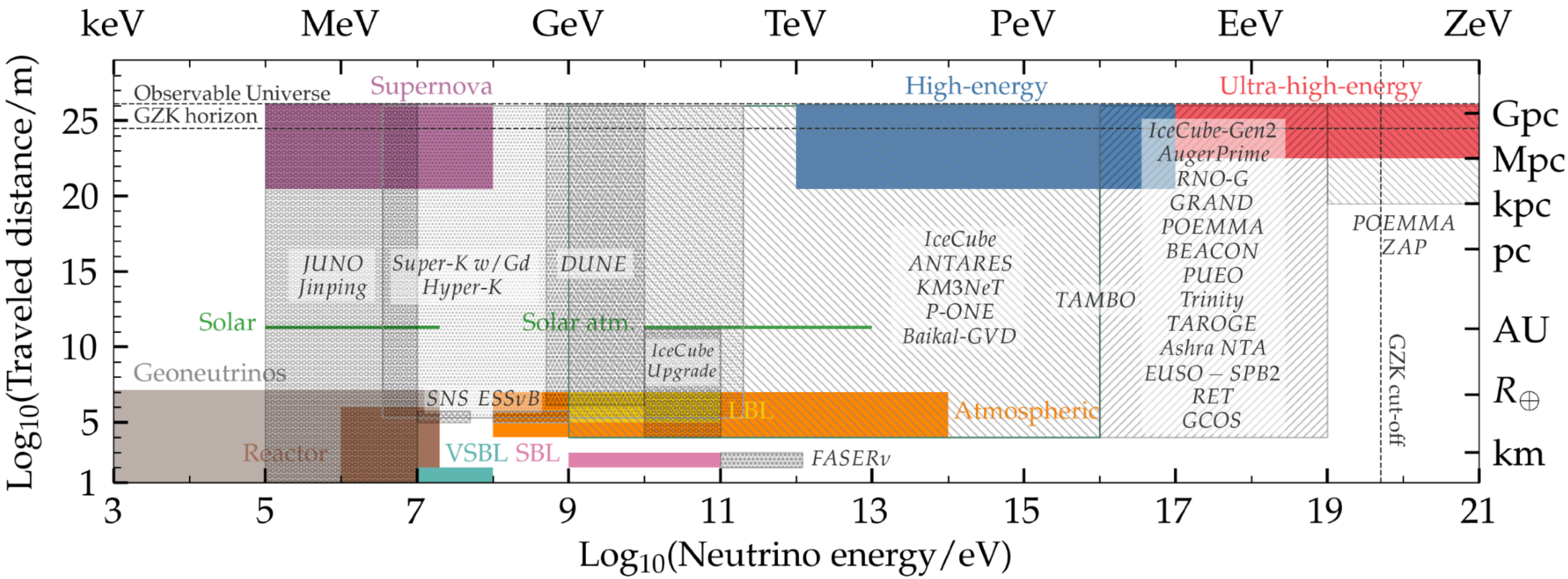
Searches for radio emission from showers initiated by a primary neutrino interacting in the Antarctic ice sheet that refracts out of the ice as well as radio emission from EAS. Based on prototyping work by ANITA. Selected for Pioneer Mission by NASA





ANITA-IV flight path

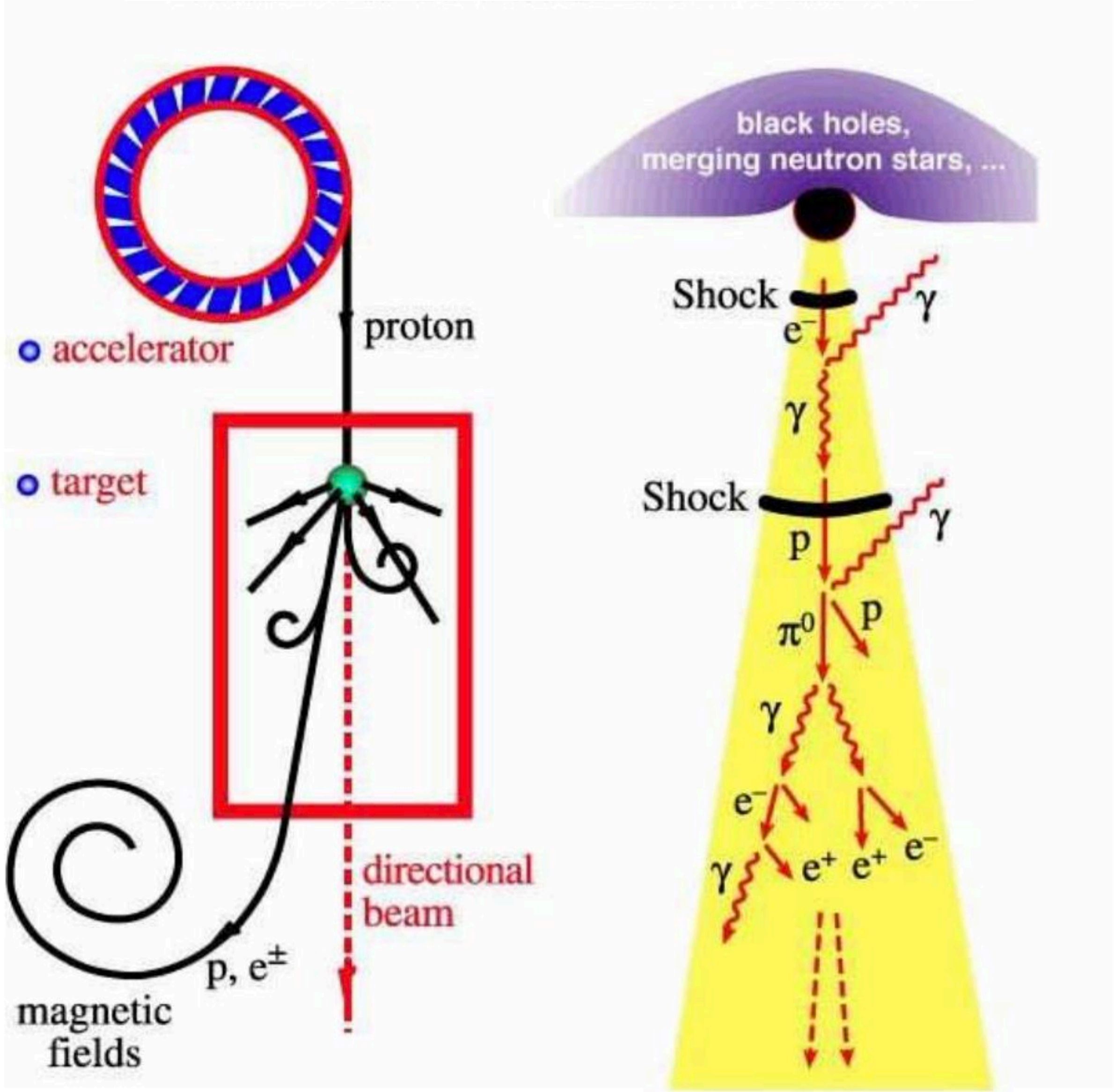
Neutrino sources and experimental landscape



High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper, arXiv: 2203.08096

The multi-messenger paradigm

Astrophysical beam dump



- proton-proton collisions ($\sigma_{pp} \approx$ 40-50 mb):

$$p + p \rightarrow \pi^{\pm} + \pi^{0} + K^{\pm} + K^{0} + p + n + \ldots$$

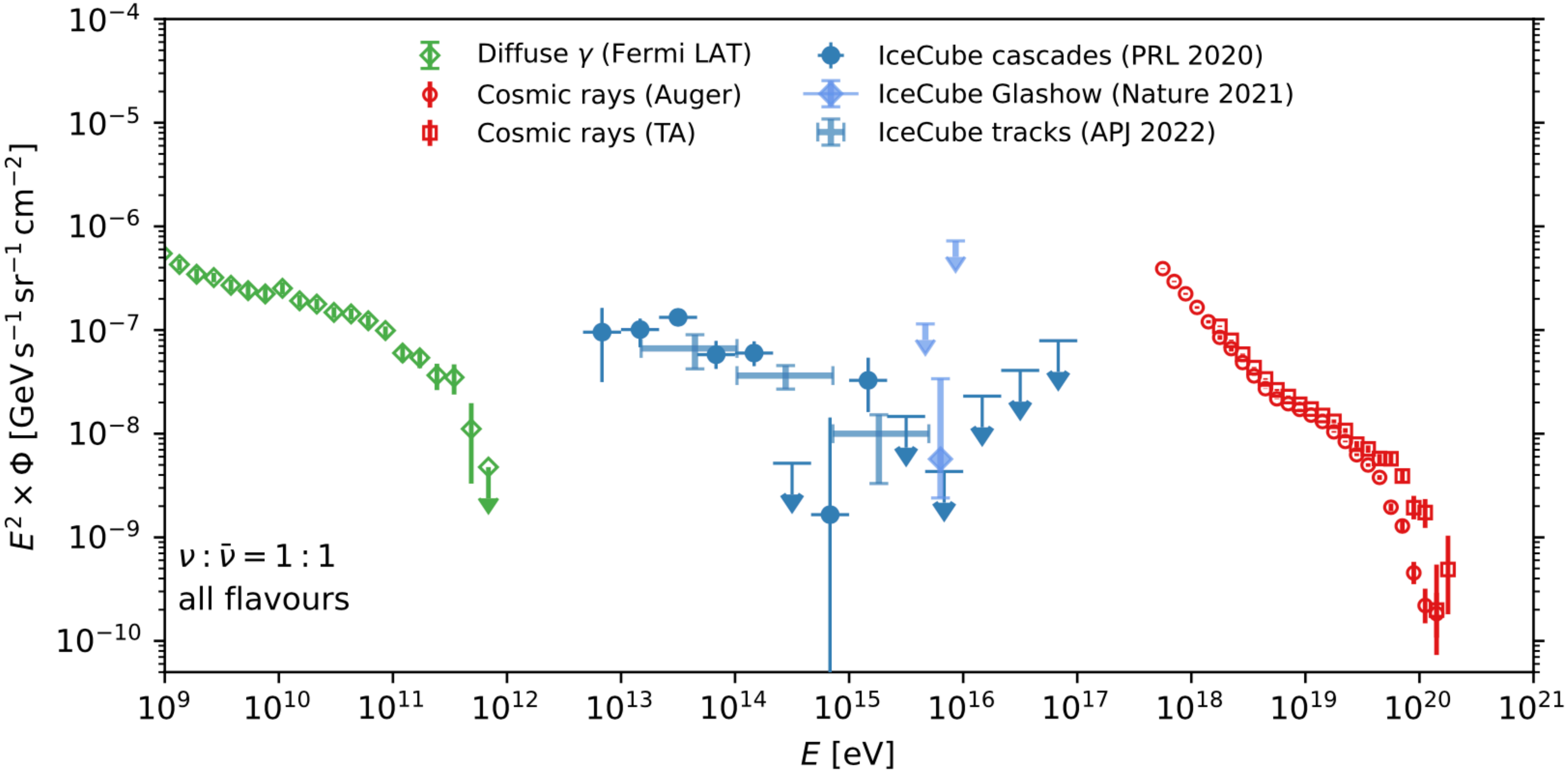
- proton-photon collisions (at the resonance $\sigma_{p\gamma} \approx$ 0.250 mb):

$$p + \gamma_{\epsilon} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0} & 2/3 \; of \; cases \\ n + \pi^{+} & 1/3 \; of \; cases \end{cases}$$

Cosmic Rays, Neutrinos and gamma-ray connection

The same energy flux is observed between the between Cosmic Rays, neutrinos and photons over different energy ranges, suggesting a strong multi-messenger relationship. Linking together observations of different messengers in time and space will offer a wealth of information that is not available with one messenger alone

High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper, arXiv: 2203.08096



Neutrino telescopes: the concept

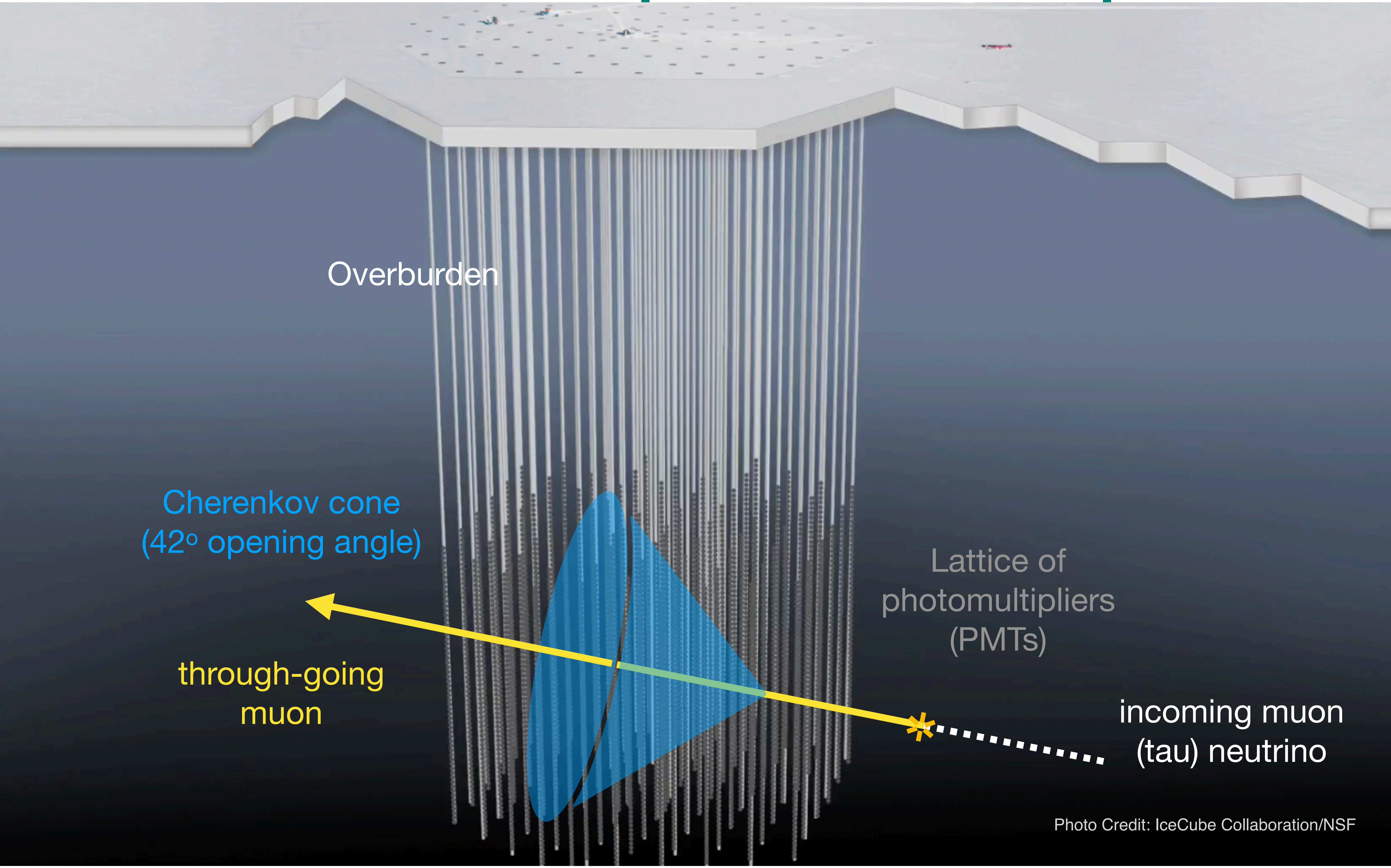
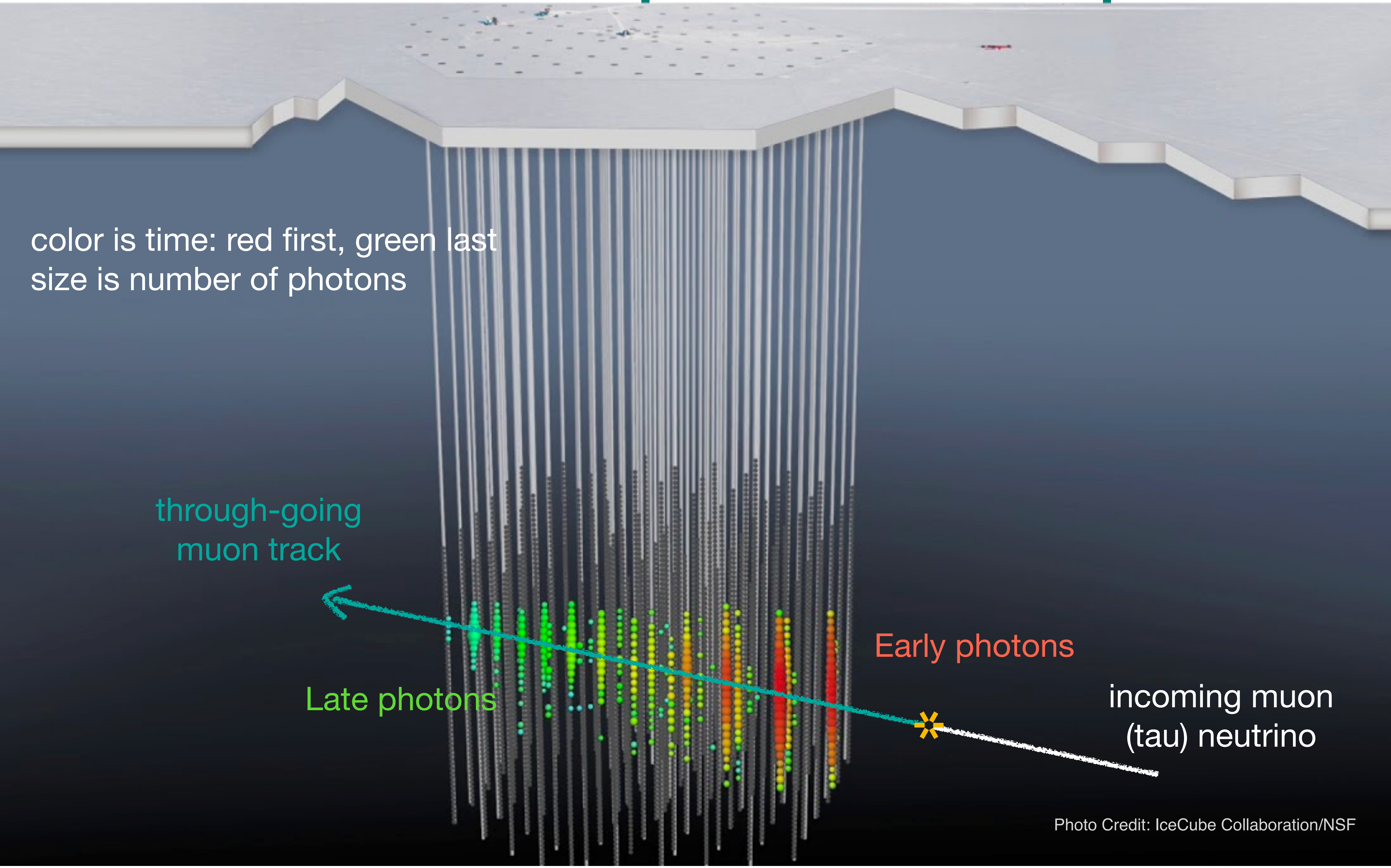


Photo Credit: IceCube Collaboration/NSF

Neutrino telescopes: the concept



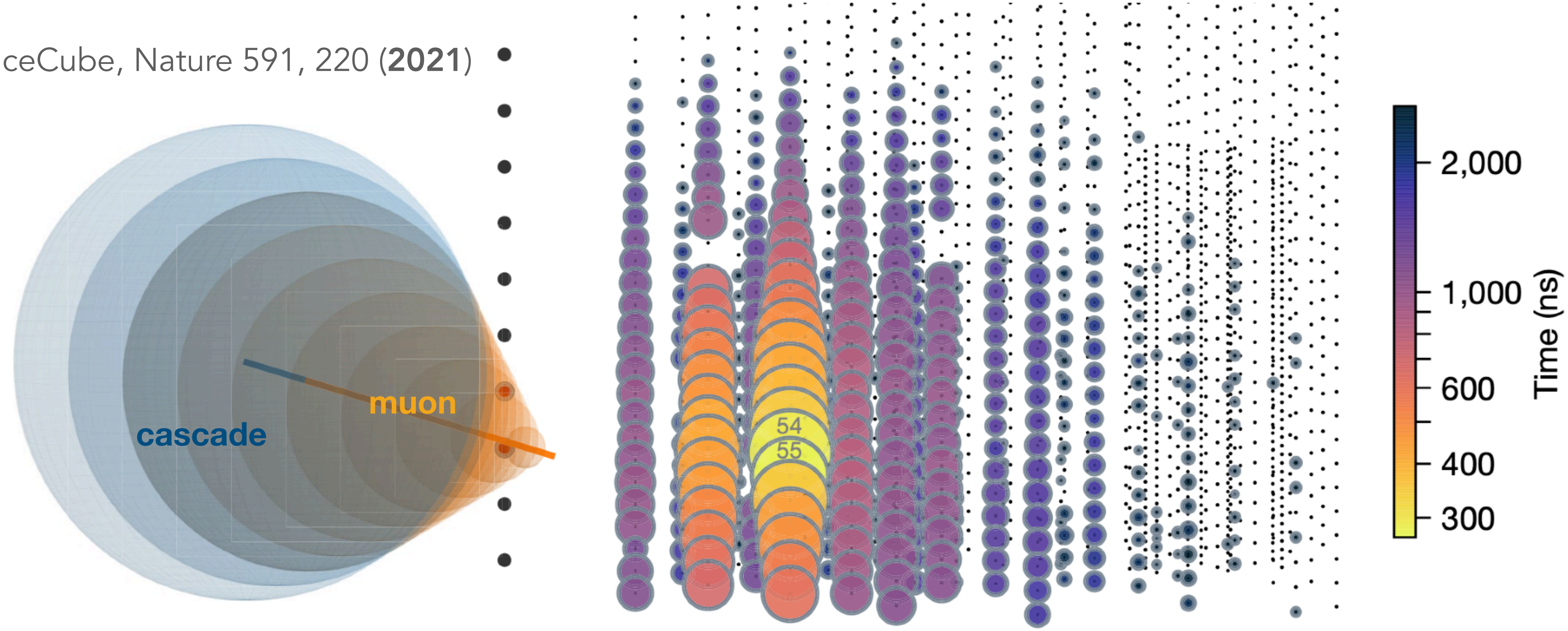
color is time: red first, green last
size is number of photons

Photo Credit: IceCube Collaboration/NSF

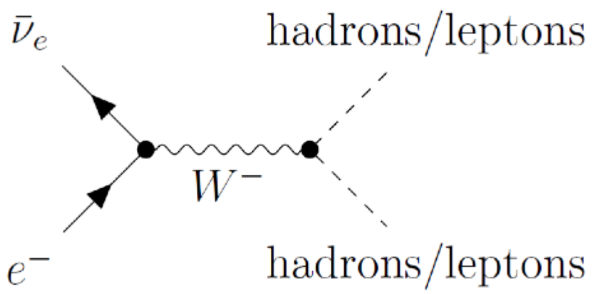
A neutrino at the Glashow resonance energy

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 Glashow-resonance event



$$E_{\bar{\nu}_e} = m_W^2/2m_e = 6.3 \text{ PeV}$$

A simulation of the photon burst detected during the Glashow resonance event. Each photon travels in a straight line until it is deflected by dust or other impurities in the ice surrounding IceCube's sensors.

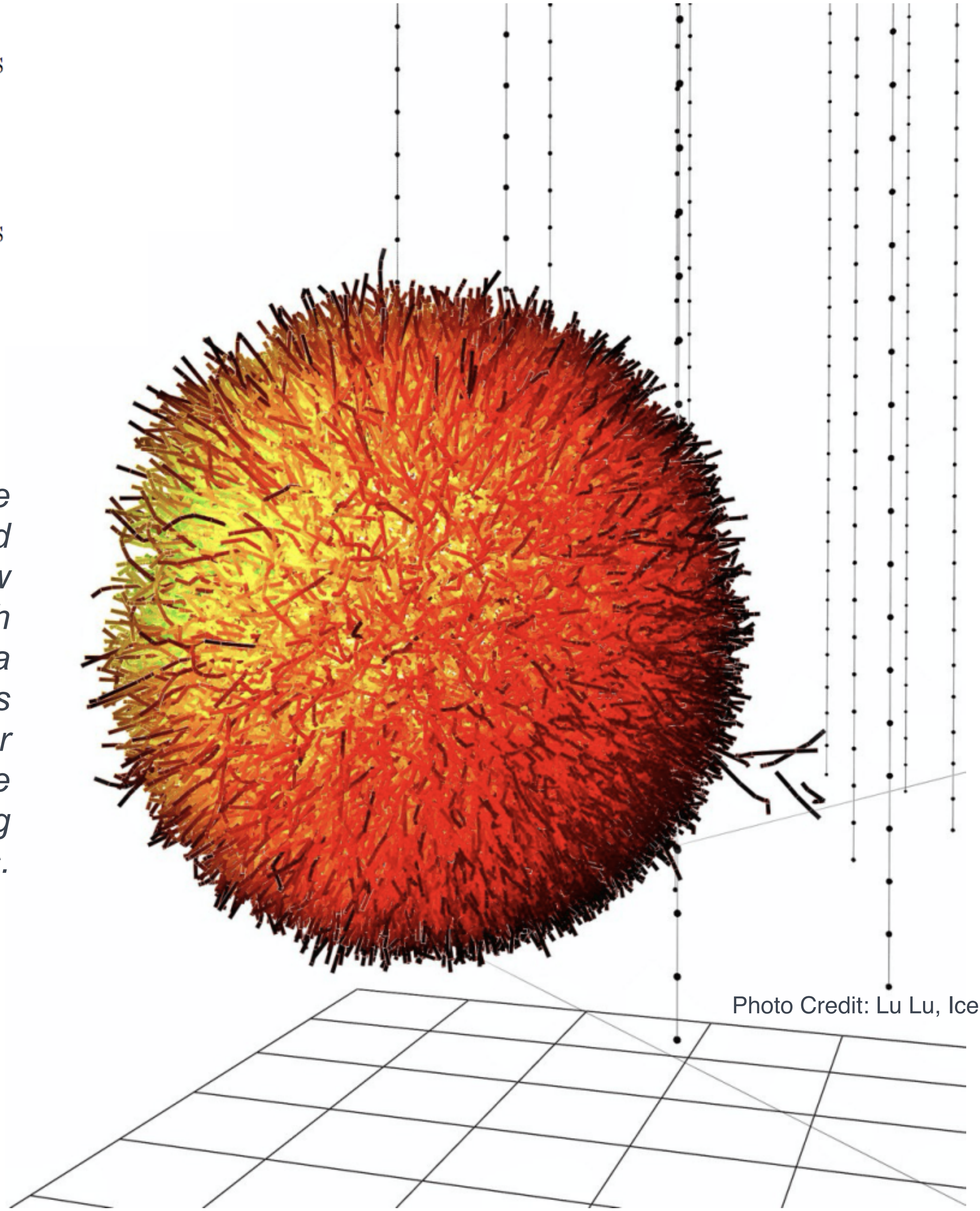
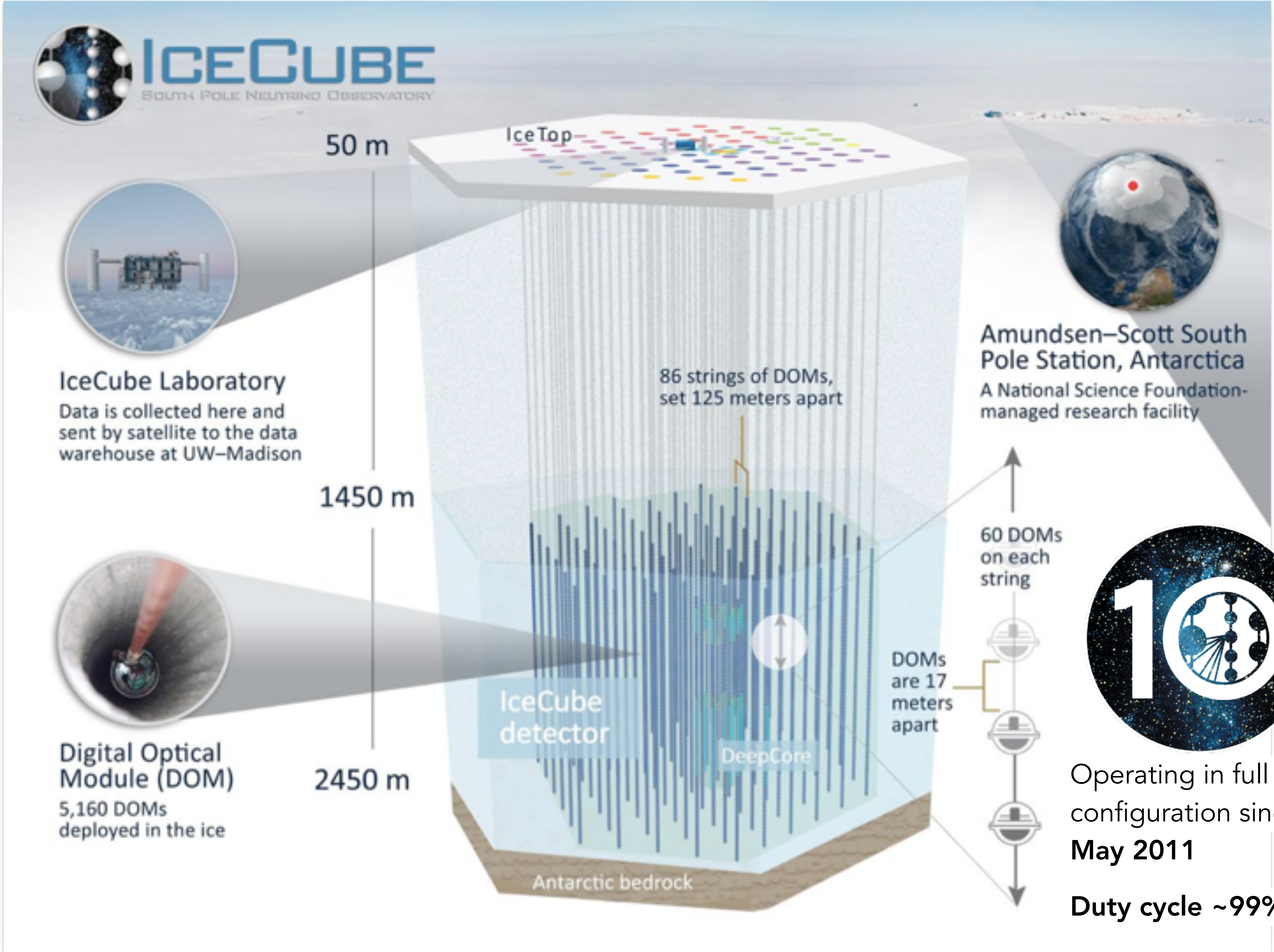


Photo Credit: Lu Lu, IceCube Collaboration

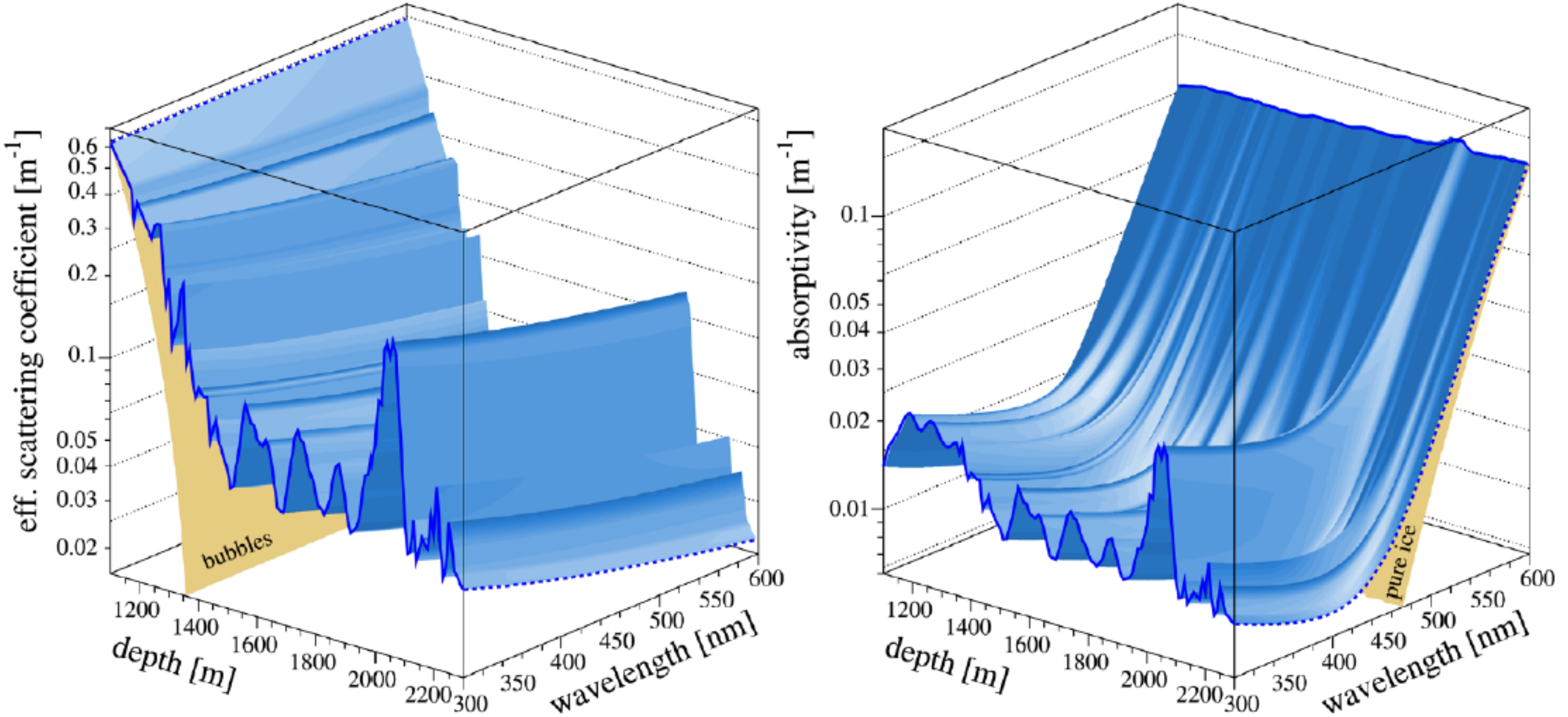
The IceCube Neutrino Observatory



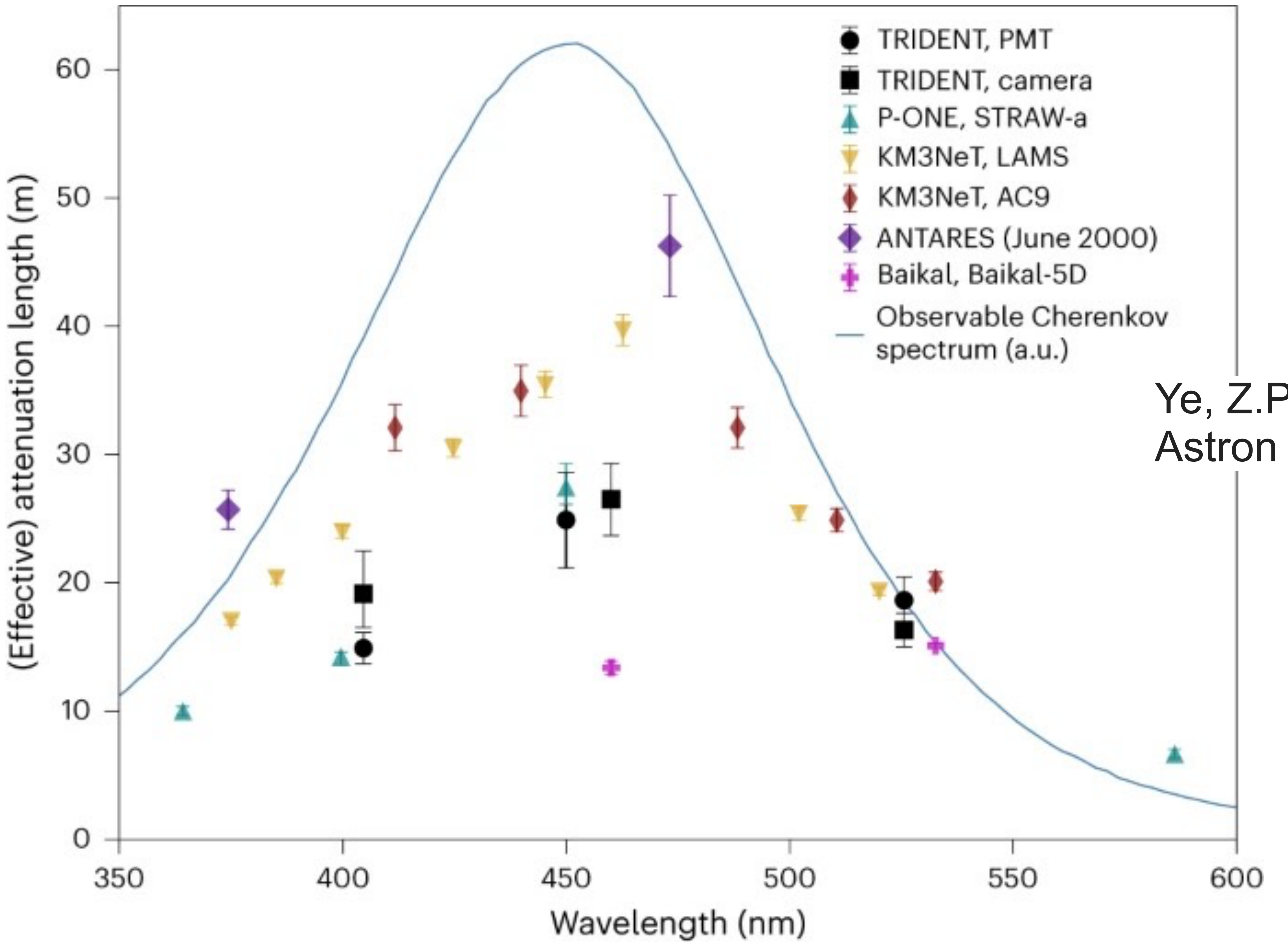
Operating in full configuration since **May 2011**

Duty cycle ~99%

Ice versus water: optical properties



Ice versus water: optical properties

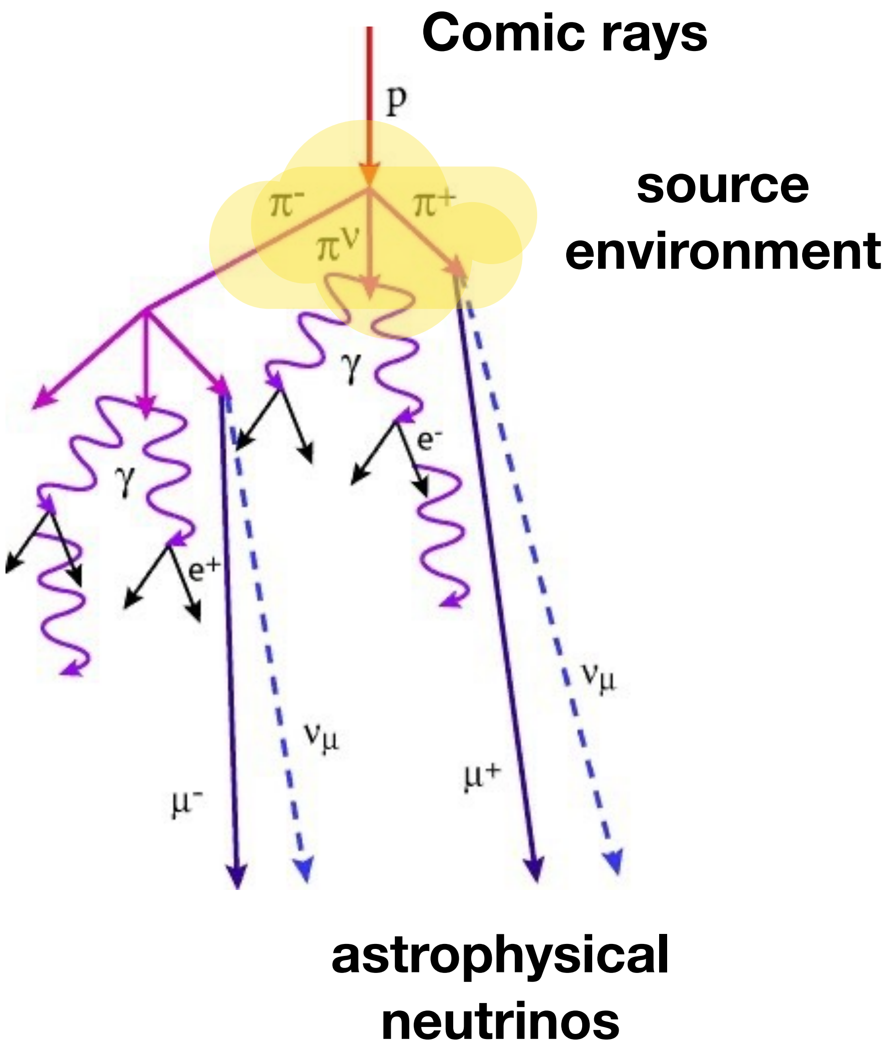


Ye, Z.P., Hu, F., Tian, W. et al. Nat Astron 7, 1497–1505 (2023)

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**

The Waxman-Bahcall bound (1998)

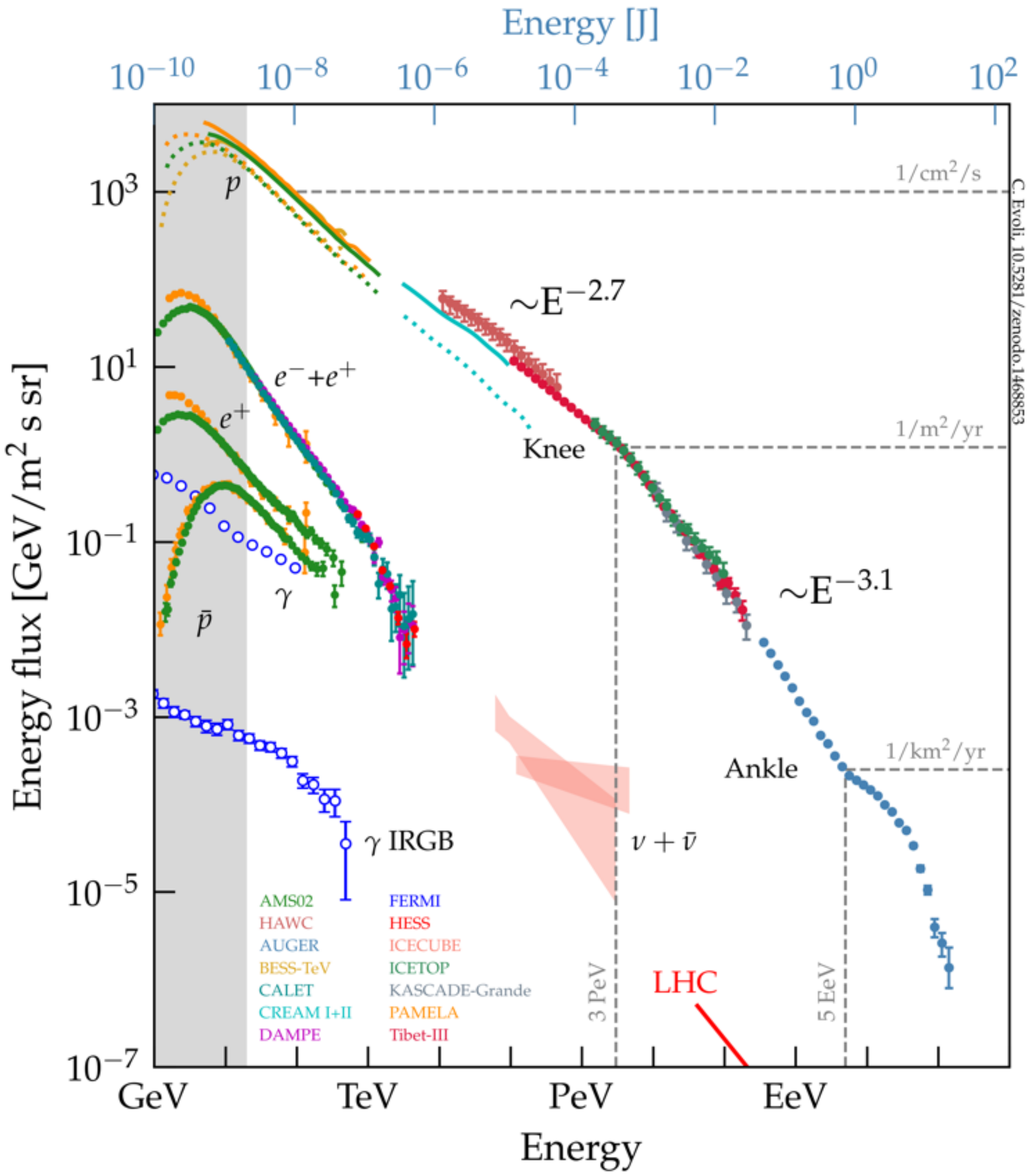
Cosmic Rays are detected with energies greater than $10^{20}\ eV$, most likely extragalactic above $\sim 5 \times 10^{18}\ eV$. The Waxmann-Bahcall bound is a prediction of the associated neutrino flux, not dependent on the details of the mechanisms powering the astrophysical sources, at the level of $O(10^5)$ neutrinos/km²/year at energies > 100 TeV



Comic rays

source environment

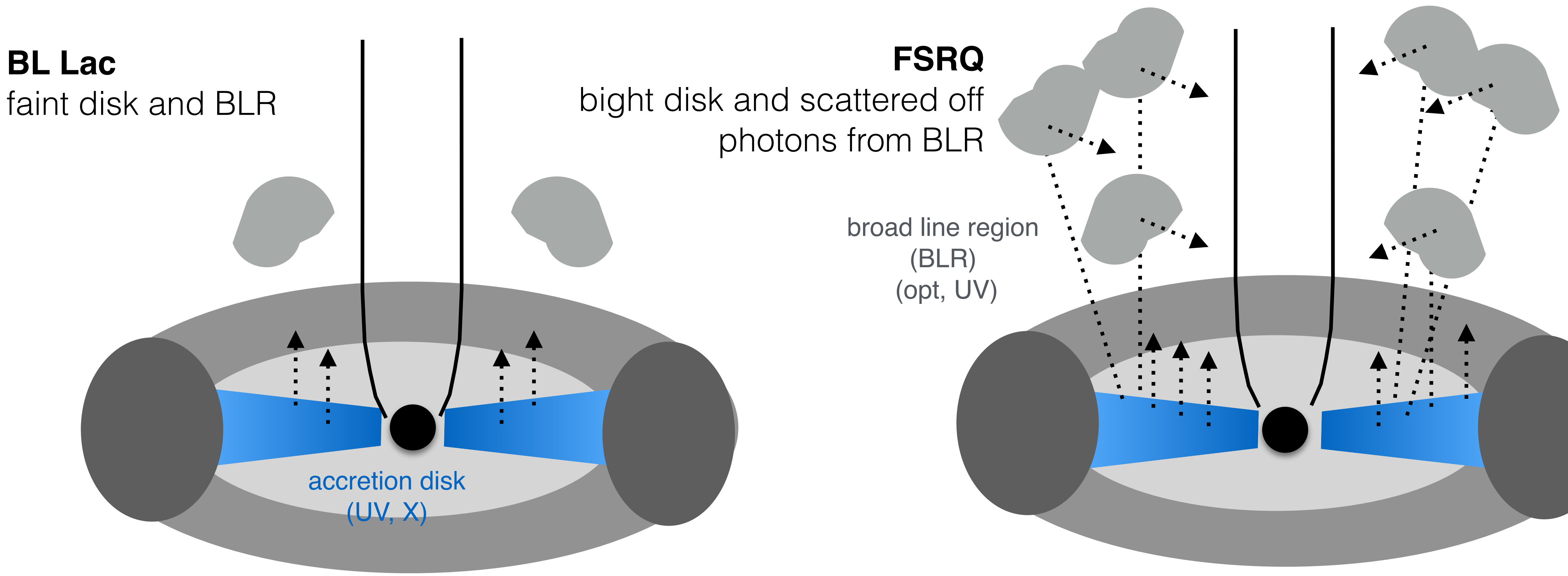
astrophysical neutrinos



C. Evoli, 10.5281/zenodo.1468853

Interpreting the multi-messenger data from TXS 0506+056

Most Blazar emission models assume that high-energy particles (electrons, protons, nuclei) are injected into the jet where they encounter target radiation (non-thermal emission by the high-energy particles, or external photons from the accretion disk, clouds or dust torus.



A neutrino emitter?

For $E_\nu \sim 300$ TeV, **interacting protons shall have energies $E_p \geq 6$ PeV** and must interact with photons with energies in the UV to soft X-ray range. Getting all the elements of this puzzle to **fit together is not easy**. Blazars seem to contain important clues on the origin of cosmic neutrinos and cosmic rays.

The Blazar TXS 0506+056

C. Righi, F. Tavecchio, and S. Inoue. Neutrino emission from BL Lac objects: the role of radiatively inefficient accretion flow

S. Ansoldi et al. The Blazar TXS 0506+056 Associated with a High-energy Neutrino: Insights into Extragalactic Jets and Cosmic

M. Cerruti, A. Zech, C. Boisson, G. Emery, S. Inoue, and J. P. Lenain. Leptohadronic single-zone models for the electromagnetic and neutrino emission of TXS 0506+056. *Mon.*

Shan Gao, Anatoli Fedynitch, Walter Winter, and Martin Pohl. Modelling the coincident observation of a high-energy neutrino and a bright blazar flare. *Nature Astronomy*, 3:88–92, 2019.

A. Keivani et al. A Multimessenger Picture of the Flaring Blazar TXS 0506+056: Implica- tions for High-energy Neutrino Emission and Cosmic-Ray Acceleration. ApJ, 864:84, 2018.

A. Gokus, S. Richter, F. Spanier, M. Kreter, M. Kadler, K. Mannheim, and J. Wilms. Decom- posing blazar spectra into 31,

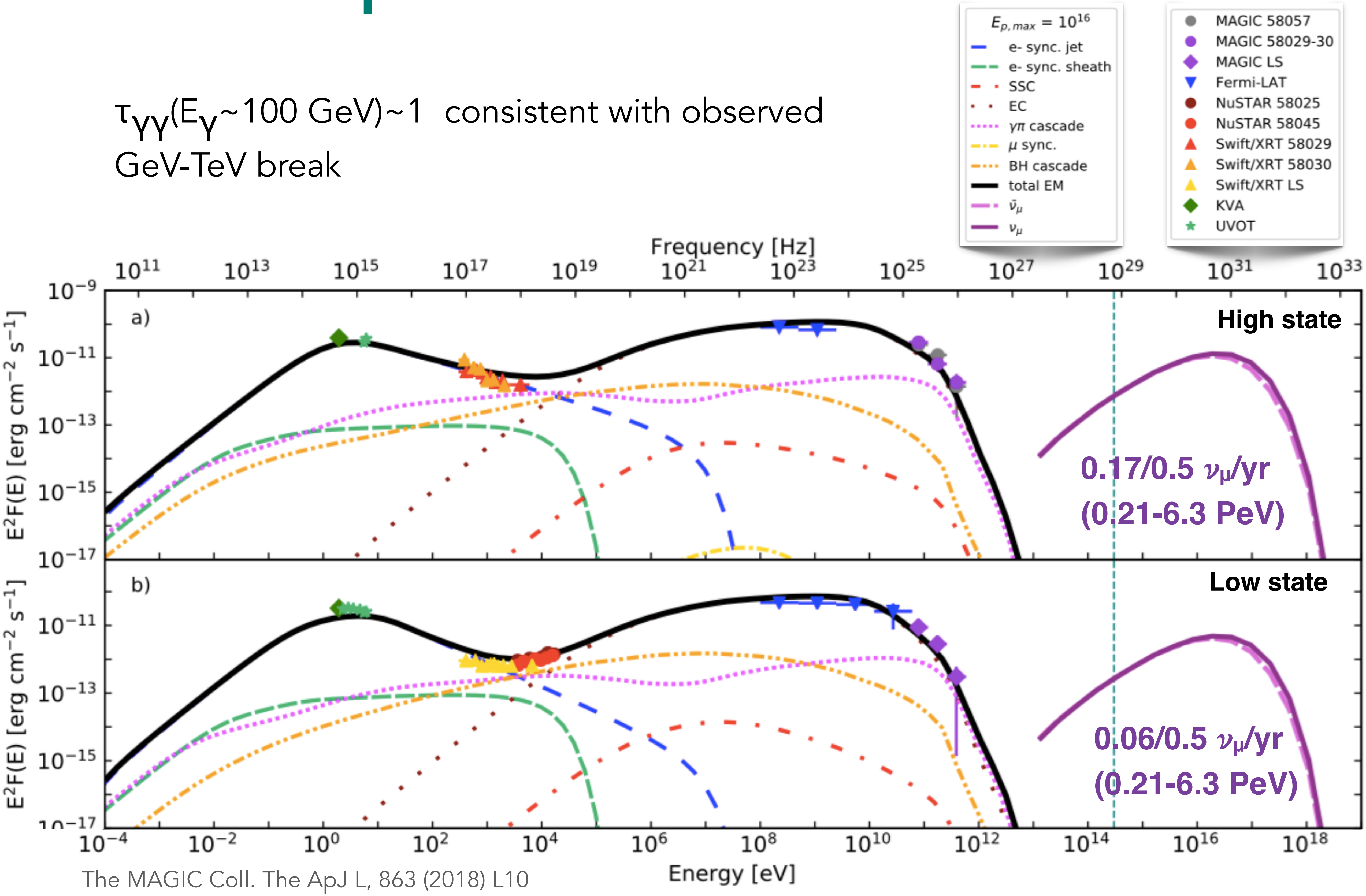
P. Padovani, P. Giommi, E. Resconi, T. Glauch, B. Arsioli, N. Sahakyan, M. Huber. Dissecting the region around IceCube-170922A: the blazar TXS 0506+056 as the first cosmic neutrino source. *Monthly Notices of the Royal Astronomical Society, Volume 480, Issue 1*

Ruo-Yu Liu, Kai Wang, Rui Xue, Andrew M. Taylor, Xiang-Yu Wang, Zhuo Li, and Huirong Yan. Hadronuclear interpretation of a high-energy neutrino event coincident with a blazar flare. *Phys.*

N. Sahakyan. Lepto-hadronic γ-ray and neutrino emission from the jet of TXS 0506+056. *Astrophys. J.*, 866(2):109, 2018.

An example from MM models

$\tau_{\gamma\gamma}(E_\gamma \sim 100\ \mathrm{GeV}) \sim 1$ consistent with observed GeV-TeV break



0.17/0.5 ν_μ/yr
(0.21-6.3 PeV)

0.06/0.5 ν_μ/yr
(0.21-6.3 PeV)

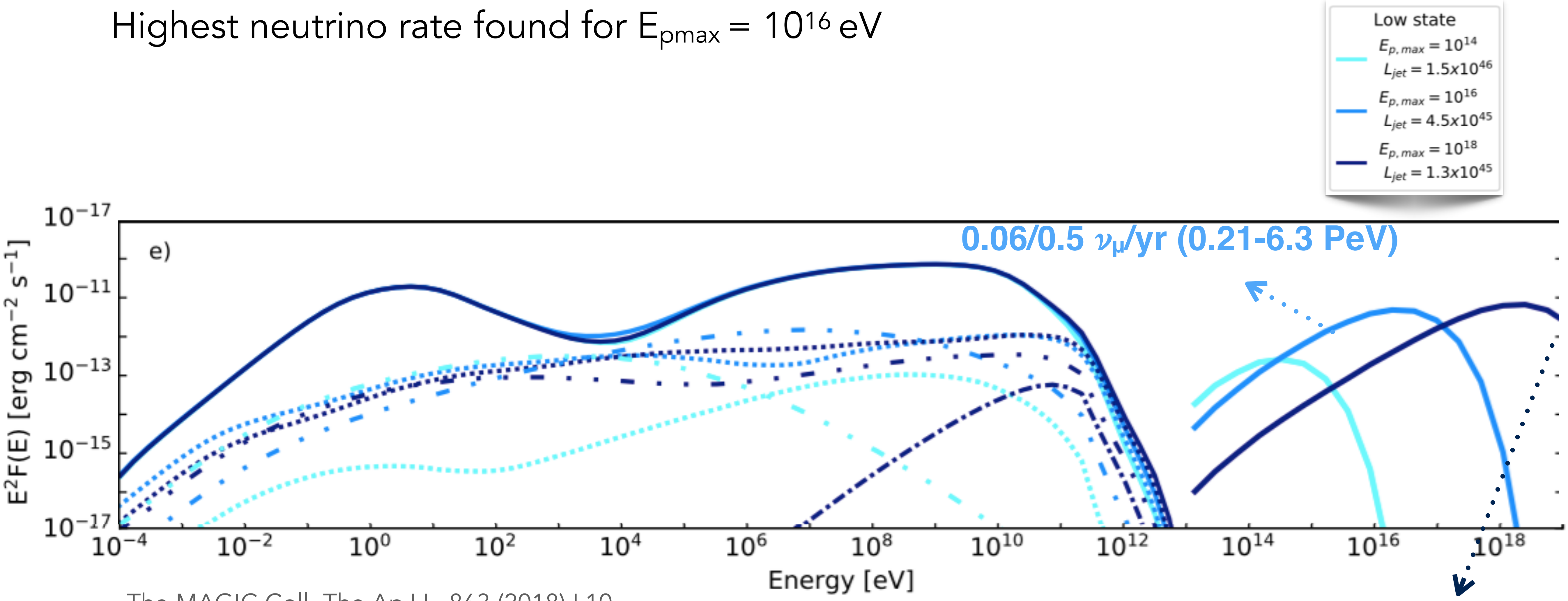
The MAGIC Coll. The ApJ L, 863 (2018) L10

An example from MM models

Results for MWL data similar to purely leptonic models without protons

Jet power 4×10^{45} to 10^{46} erg/s

Highest neutrino rate found for $E_{pmax} = 10^{16}$ eV



0.06/0.5 ν_μ/yr (0.21-6.3 PeV)

0.01/0.5 ν_μ/yr (0.27-23.4 PeV)

The MAGIC Coll. The ApJ L, 863 (2018) L10

The Multi-wavelength picture of the Milky Way