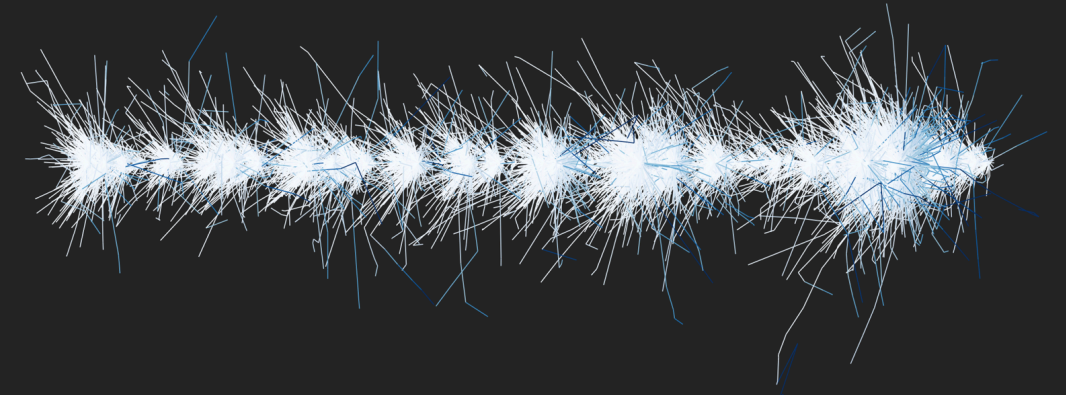
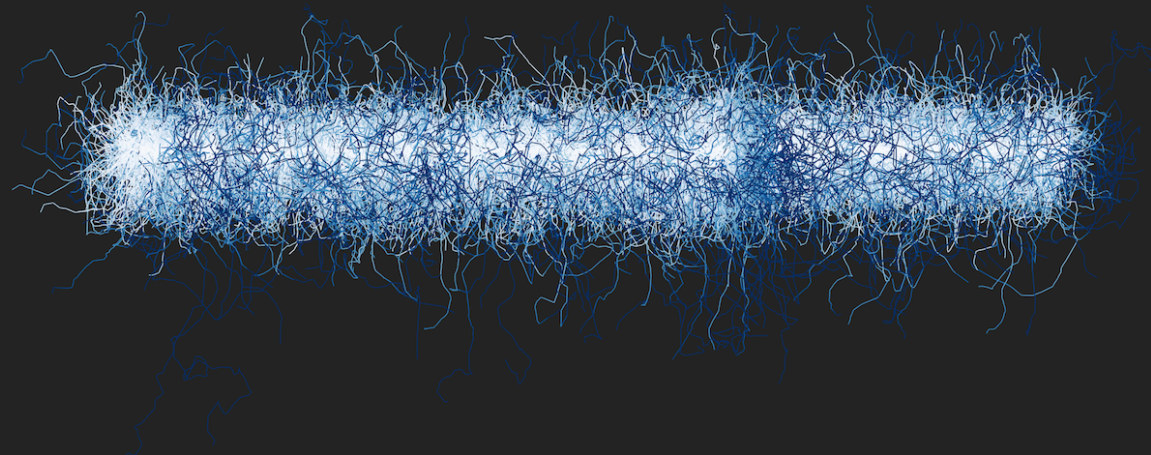


1 PeV muon track in ice

1 PeV muon track in water

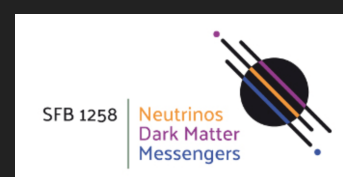


# NEUTRINO ASTRONOMY WITH ICECUBE AND THE PACIFIC OCEAN NEUTRINO EXPLORER (P-ONE): TOWARDS A PLANETARY SCALE TELESCOPE

*Seminar, Queen Mary University of London, 21.11.2019*

Elisa Resconi

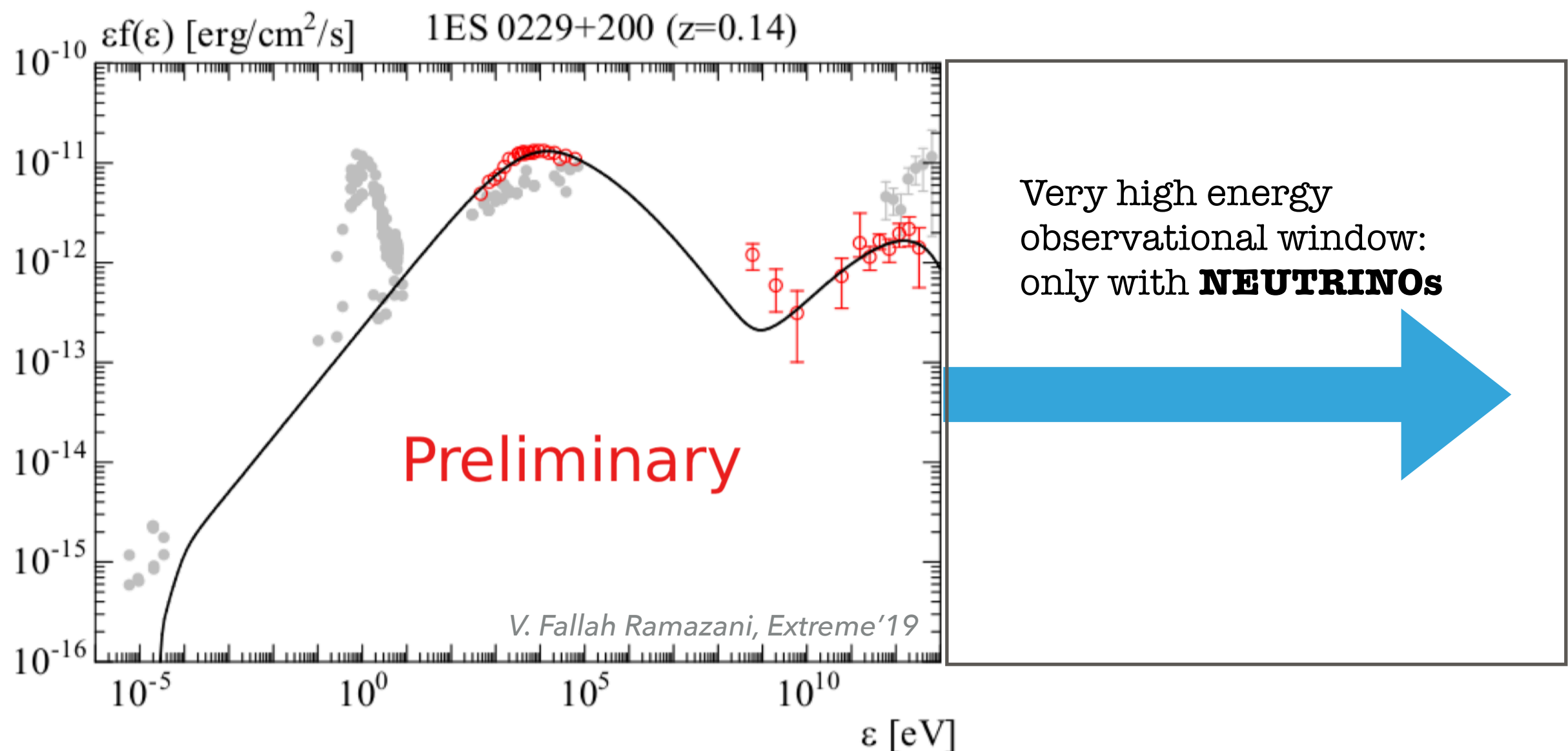
Experimental Physics with Cosmic Particles (ECP-TUM)



*Image: K. Krings (TUM)*

# WHY NEUTRINOS FOR ASTRONOMY?

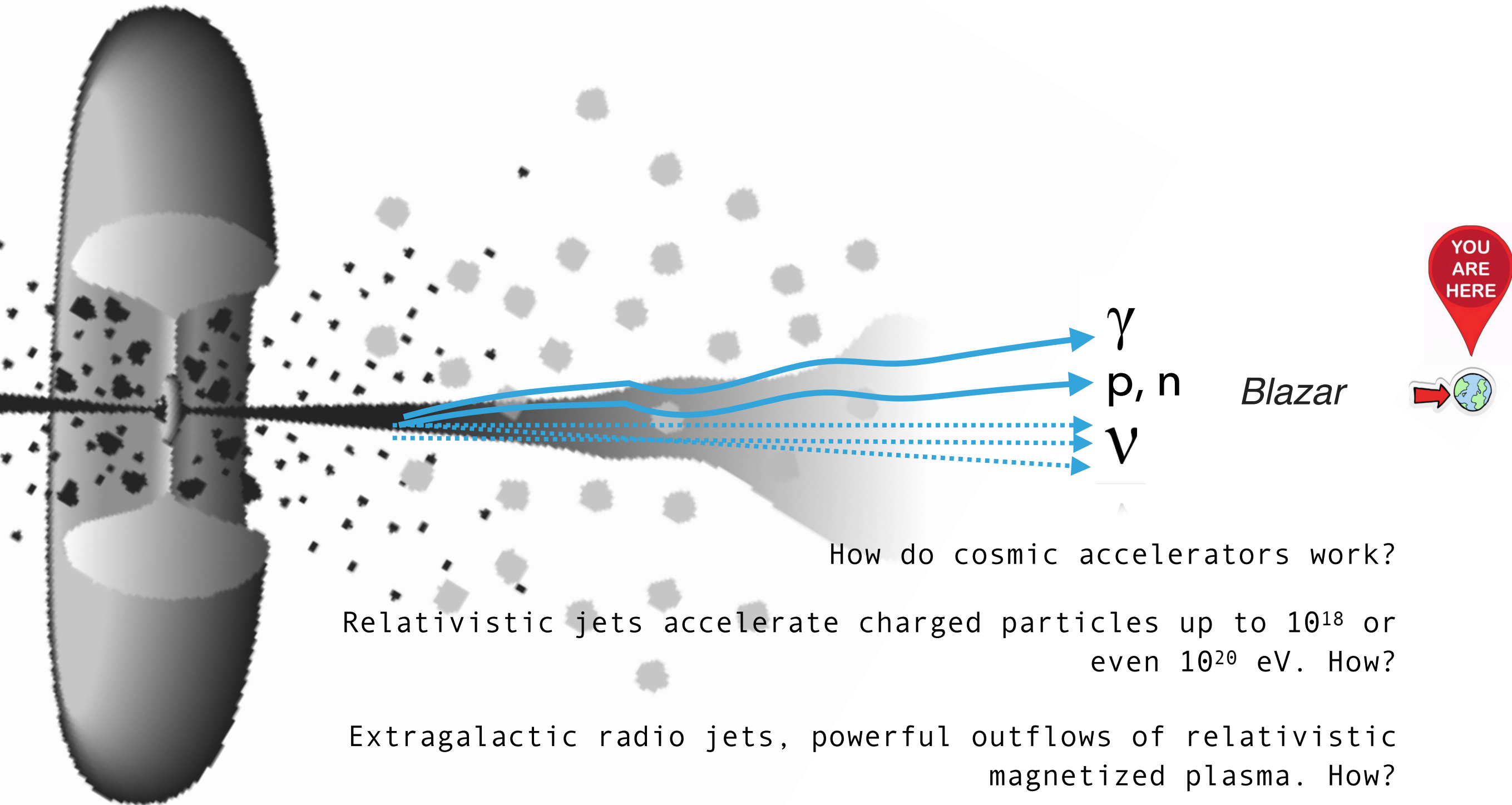
The universe is not transparent to photons  $>50\text{-}100\text{TeV}$  but it is transparent to neutrinos. [ $\sim 10\text{TeV} < 90\%$  gamma-ray photons from sources at  $z \sim 0.1$ ]<sup>1</sup>



<sup>1</sup> Dominguez, A. et al. Extragalactic background light inferred from AEGIS galaxy-SED-typefractions. MNRAS (2011)



# WHY NEUTRINO ASTRONOMY FOR PHYSICS?



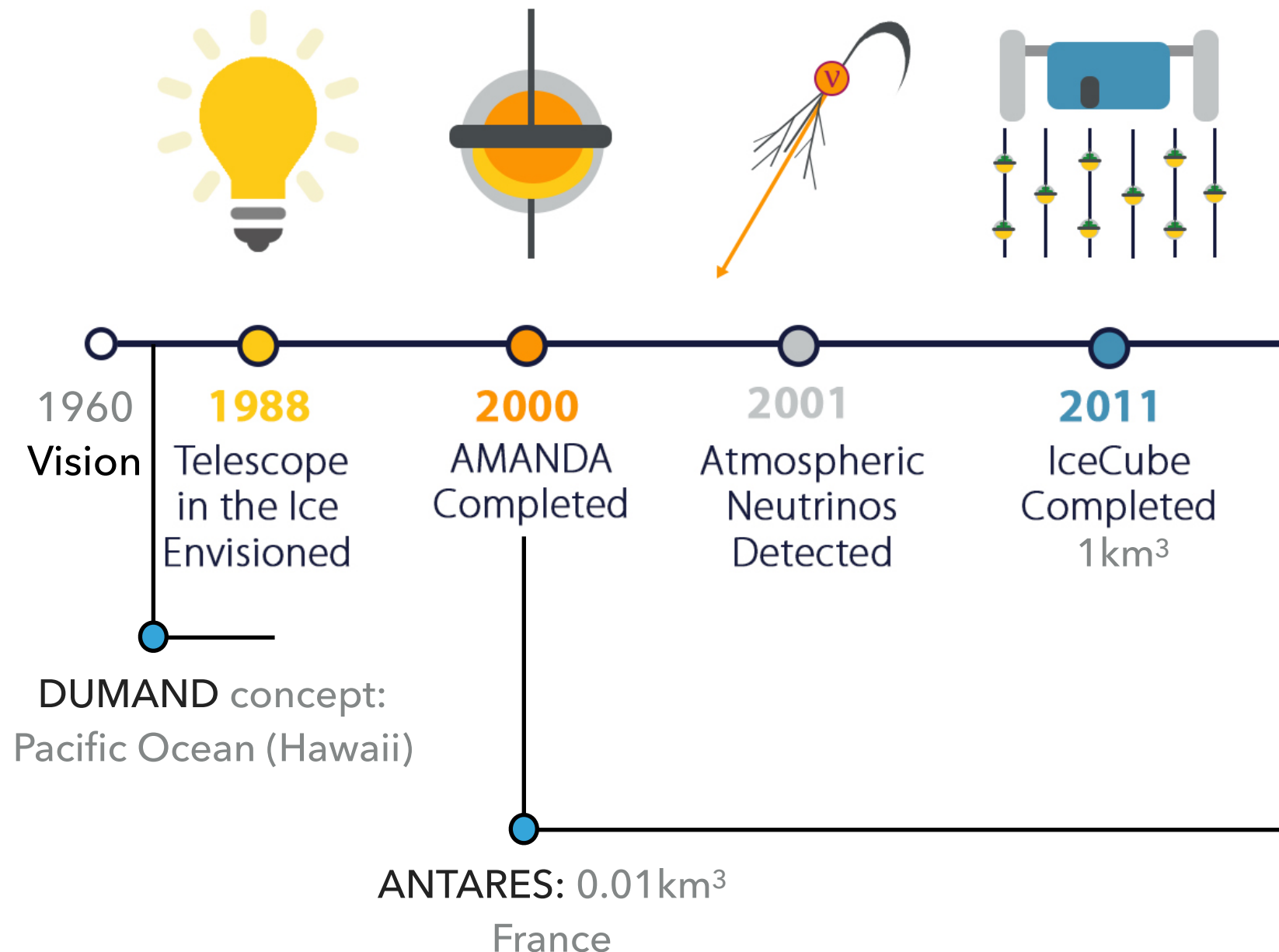
How do cosmic accelerators work?

Relativistic jets accelerate charged particles up to  $10^{18}$  or even  $10^{20}$  eV. How?

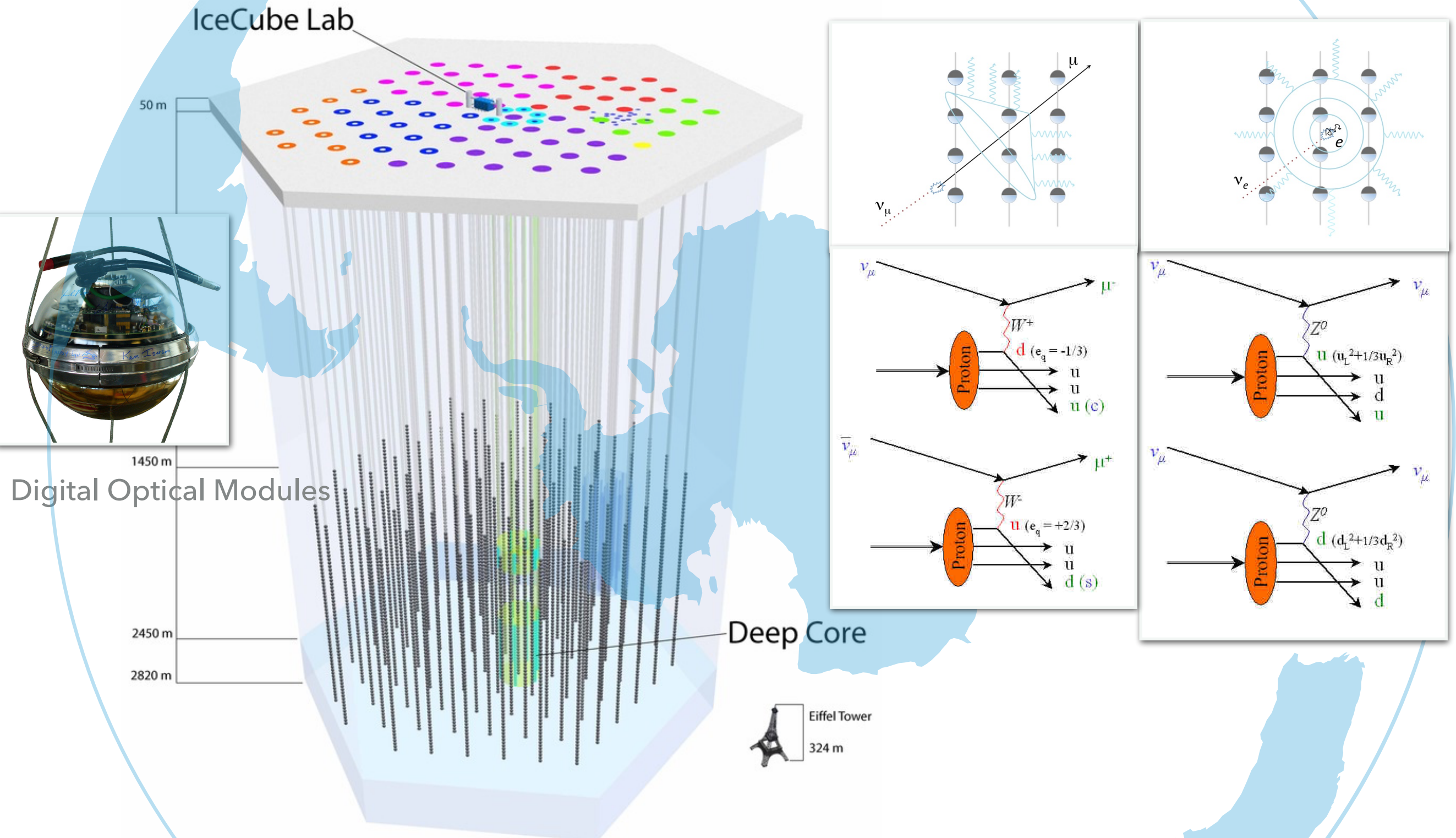
Extragalactic radio jets, powerful outflows of relativistic magnetized plasma. How?

Exotic physics at  $> 10^{18}$  eV (proton) energy scale?

# Milestones in Neutrino Astronomy



# THE ICECUBE NEUTRINO OBSERVATORY

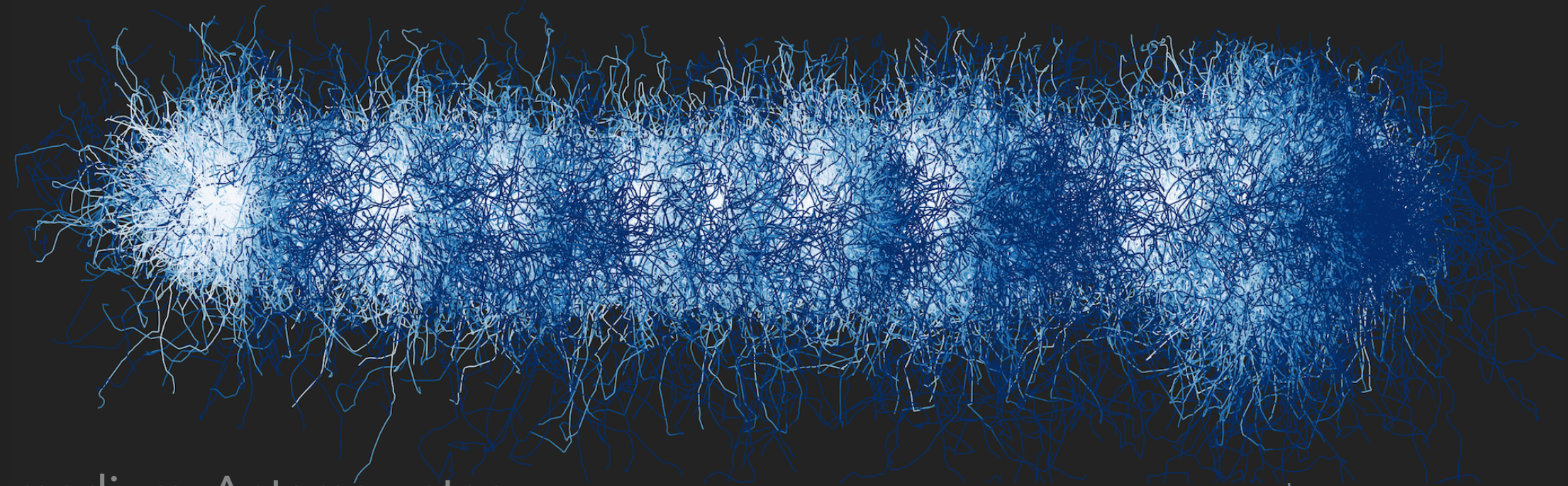




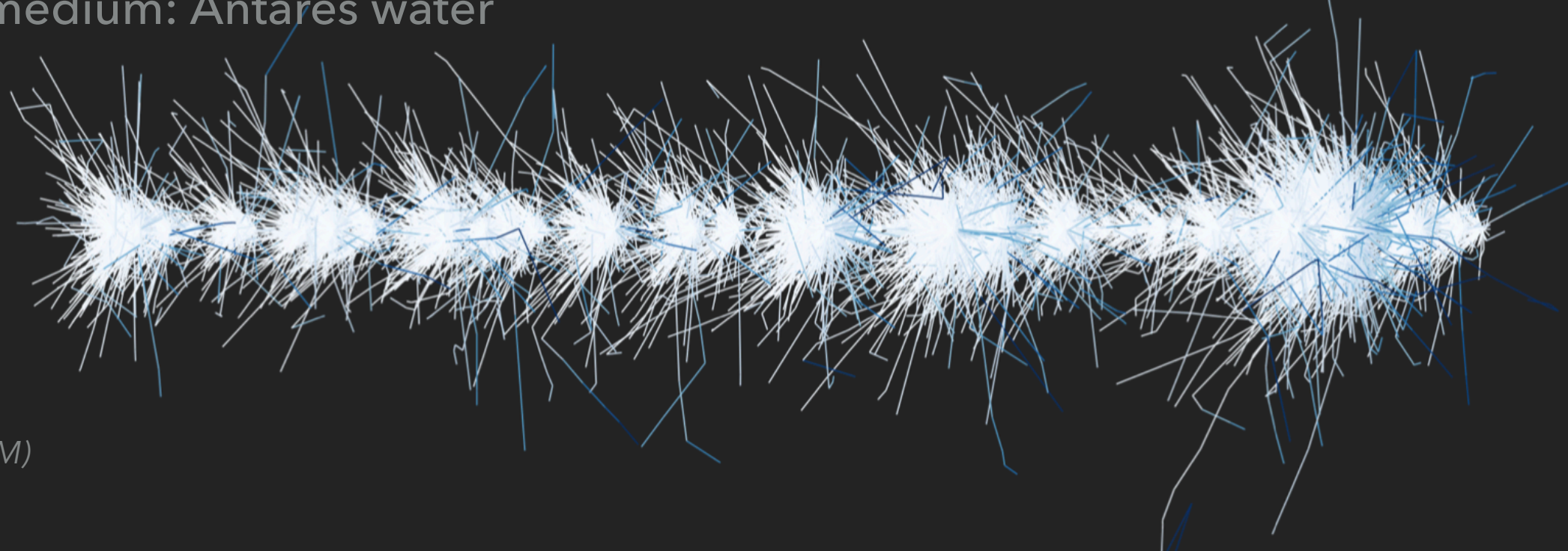
# HORIZONTAL HIGH ENERGY MUONS: THE SIGNATURE

1 PeV horizontal muon

medium: IceCube ice



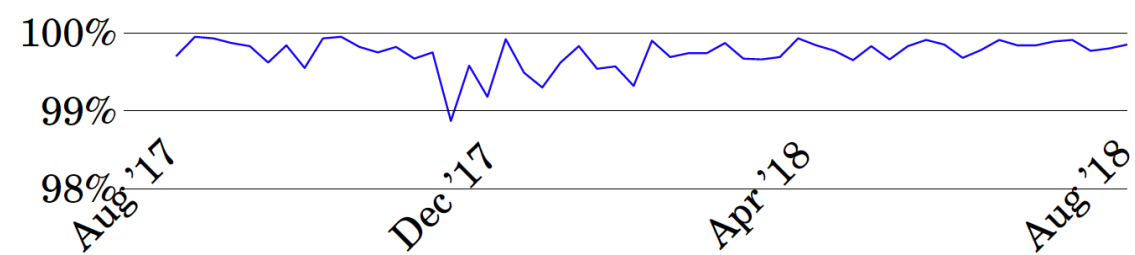
medium: Antares water





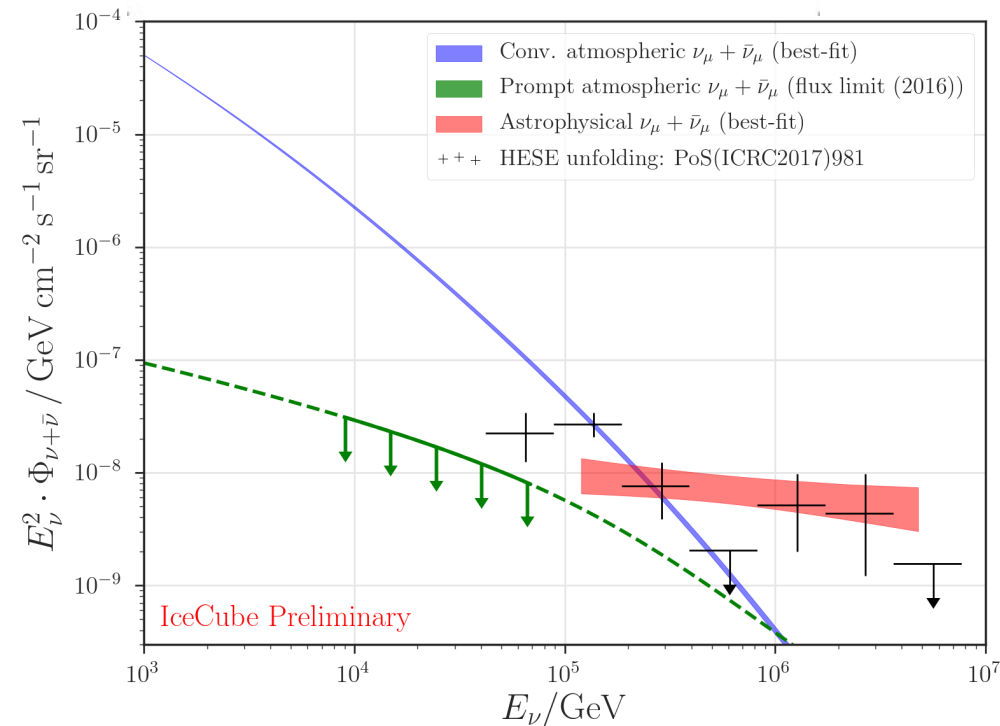
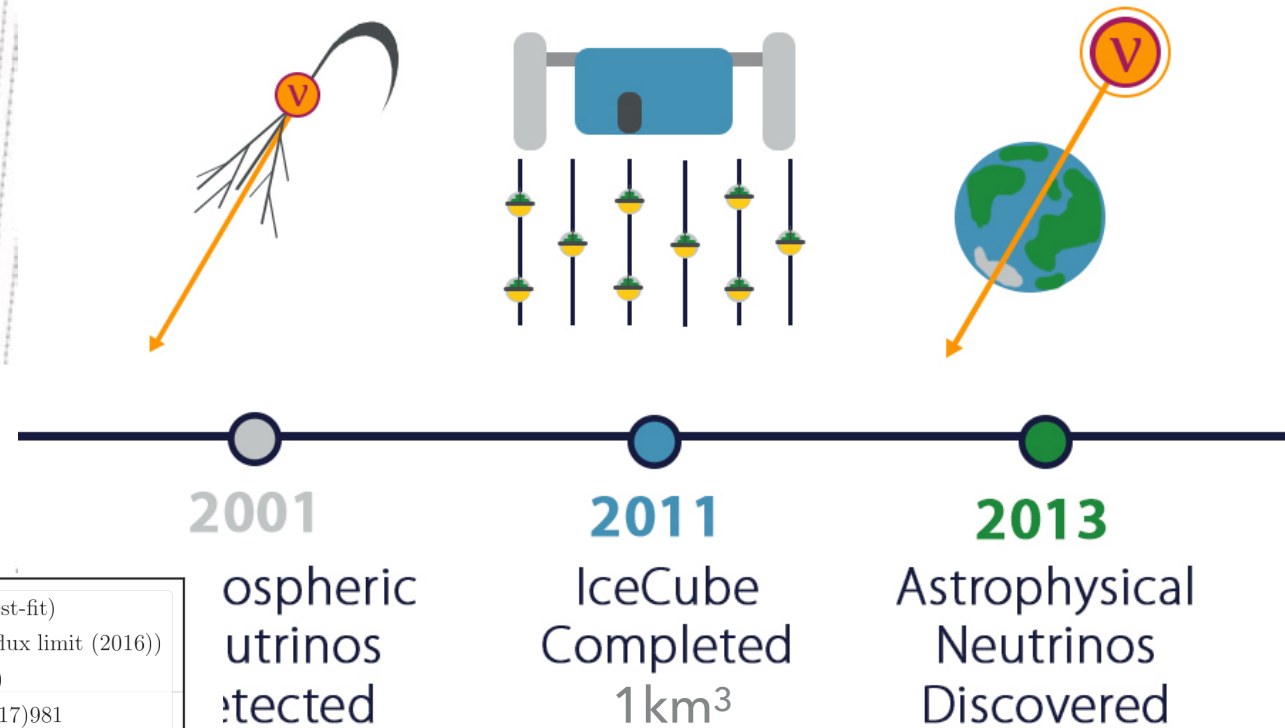
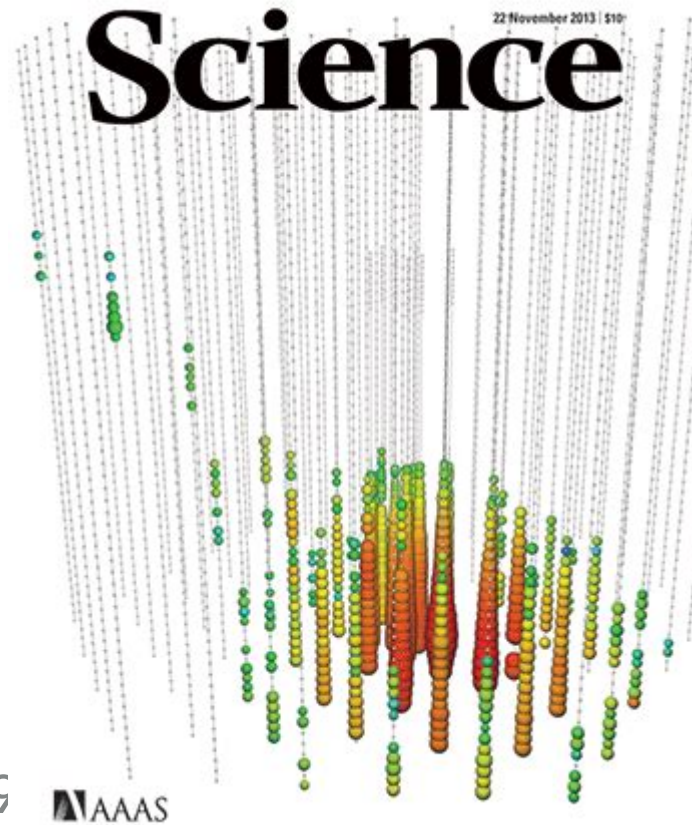


Uptime



99.85%

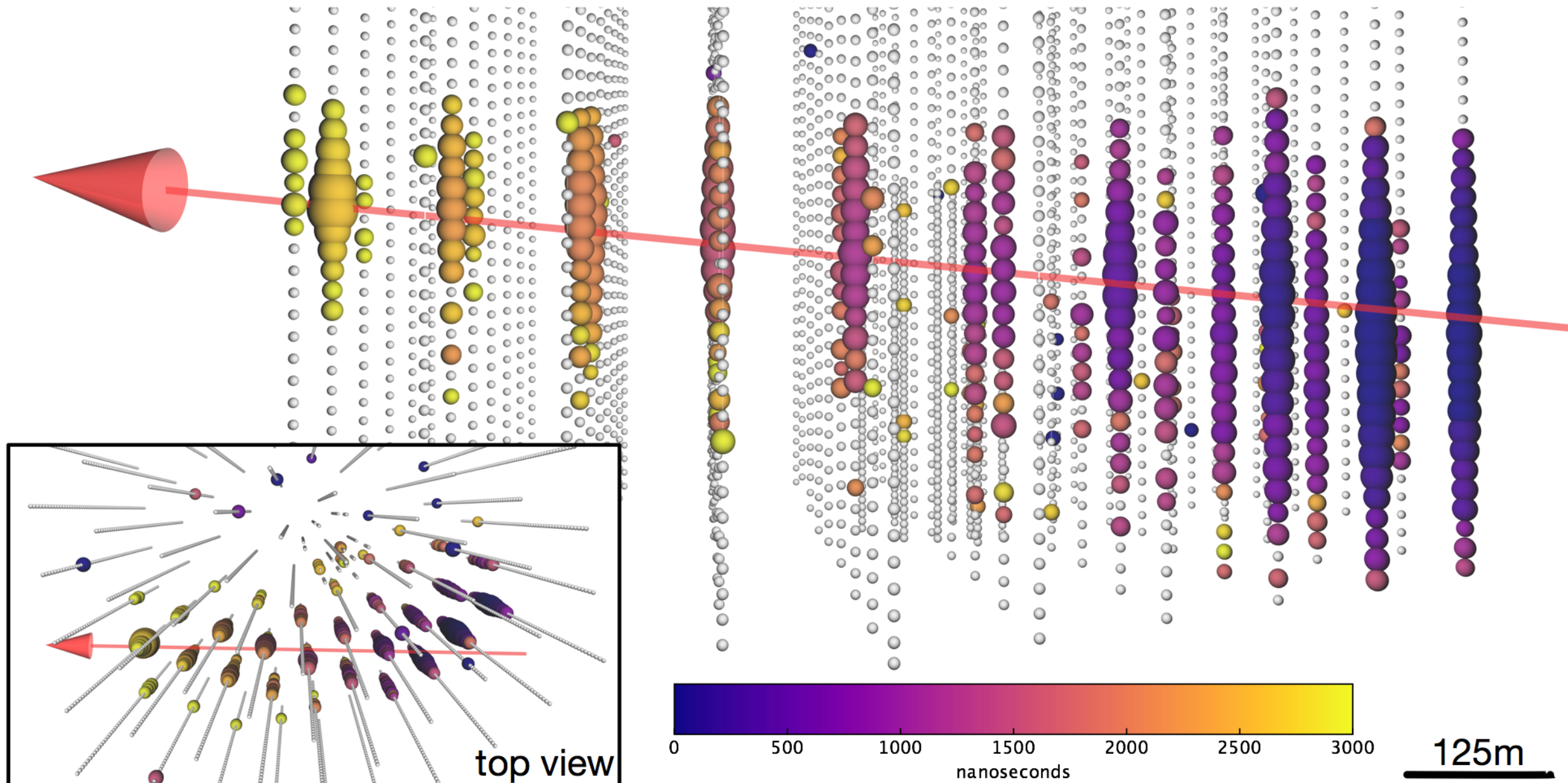
# Milestones in Neutrino Astronomy



IceCube discovery of *diffuse* astrophysics neutrinos



# 1) ICECUBE-170922A: NEUTRINO ALERT [ $\sim 290$ TEV, DEC $\sim 5.72$ DEG]



"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A", The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, 2018

## 2) More than twenty instruments reacted to the neutrino alert

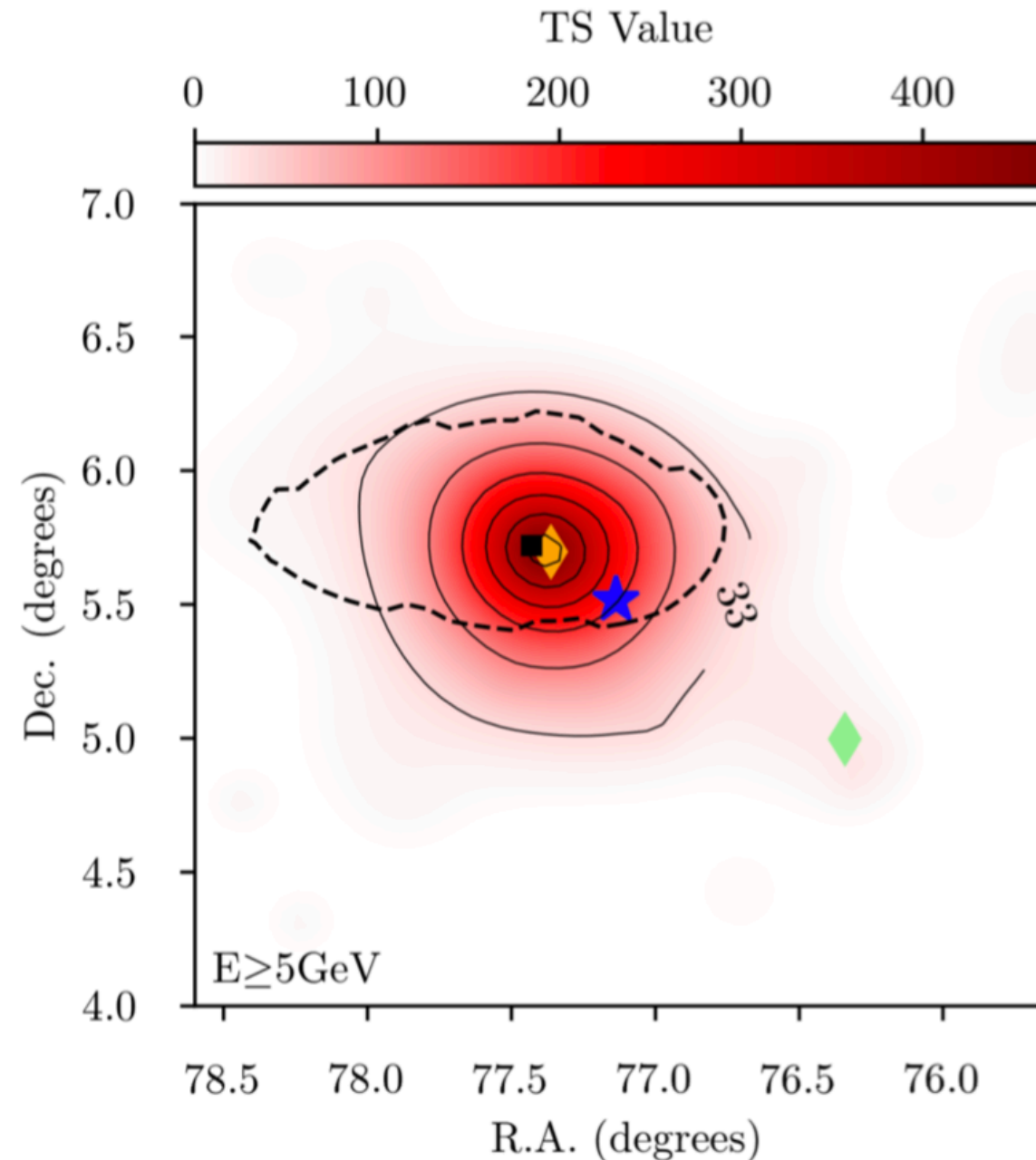
### Follow-up detections of IC170922 based on public telegrams



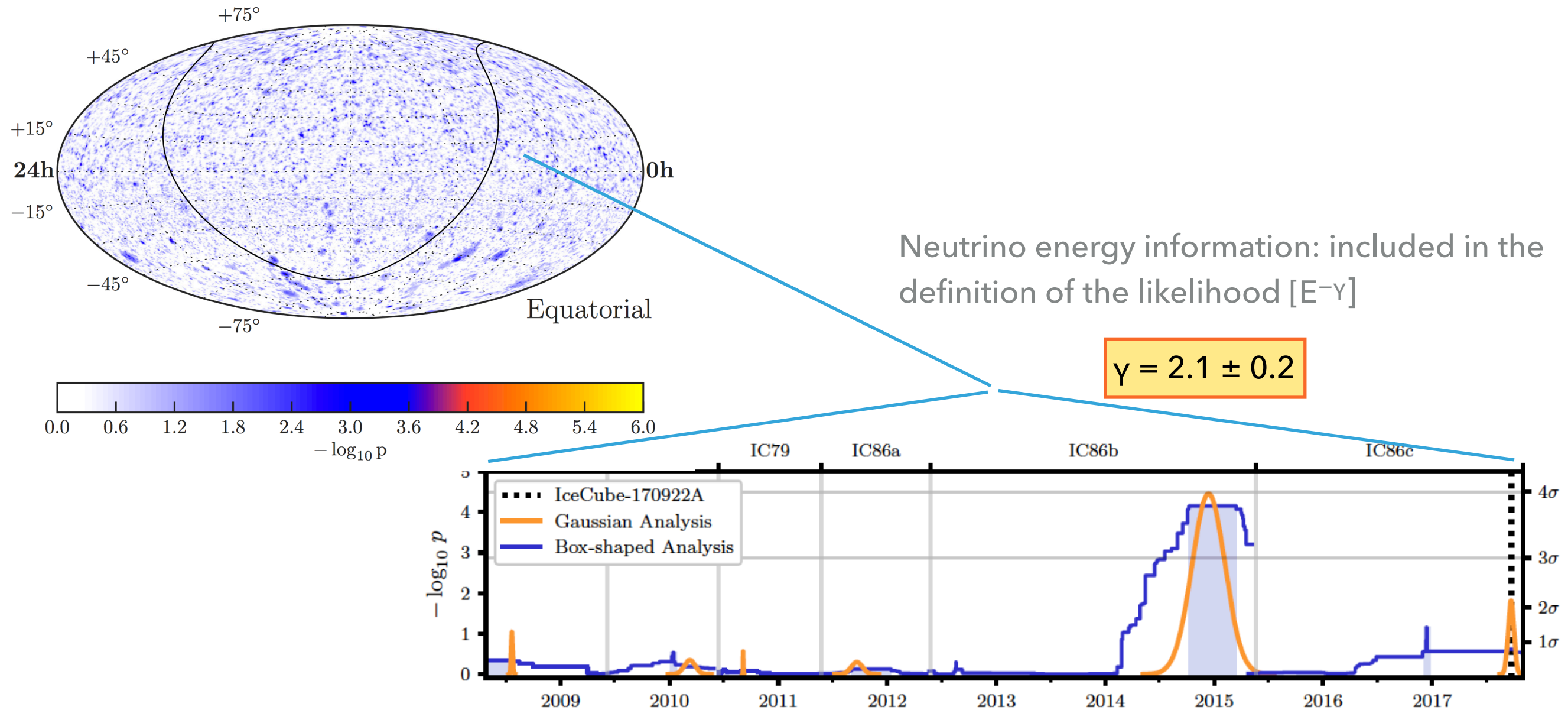


### 3) Identification of a flaring blazar: TXS 0506+056

“Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A”, The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, 2018



## 4) THE ICECUBE NEUTRINO FLARE



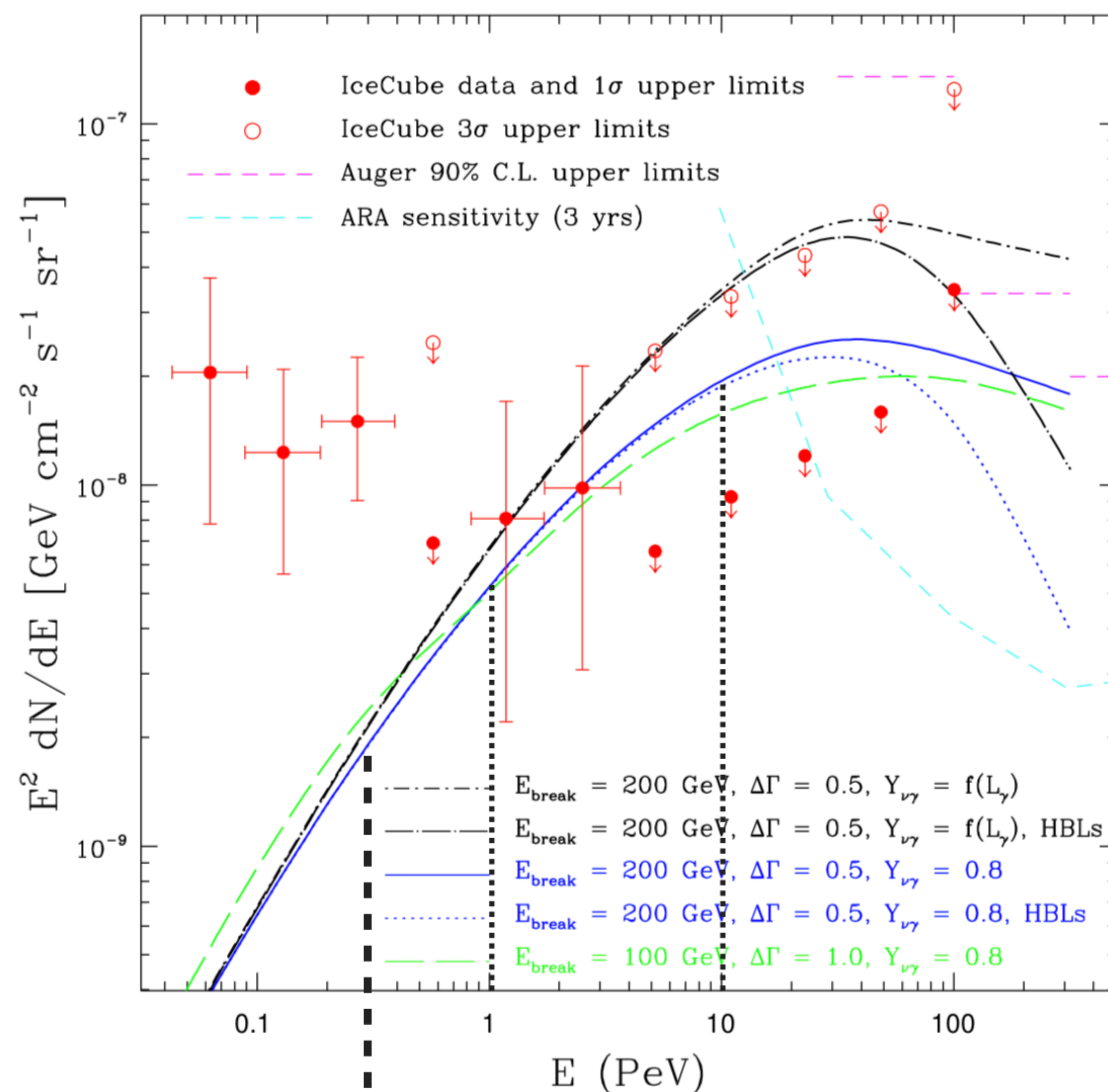
"Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert", IceCube Collaboration: M.G. Aartsen et al. *Science* 361, 147-151 (2018).



# THE AFTERMATH OF FIRST NEUTRINO ASSOCIATION TO A SOURCE (TXS 0506+056)

TXS0506+056 IS AN INTERMEDIATE BLAZAR, NOT A BL-LAC \*

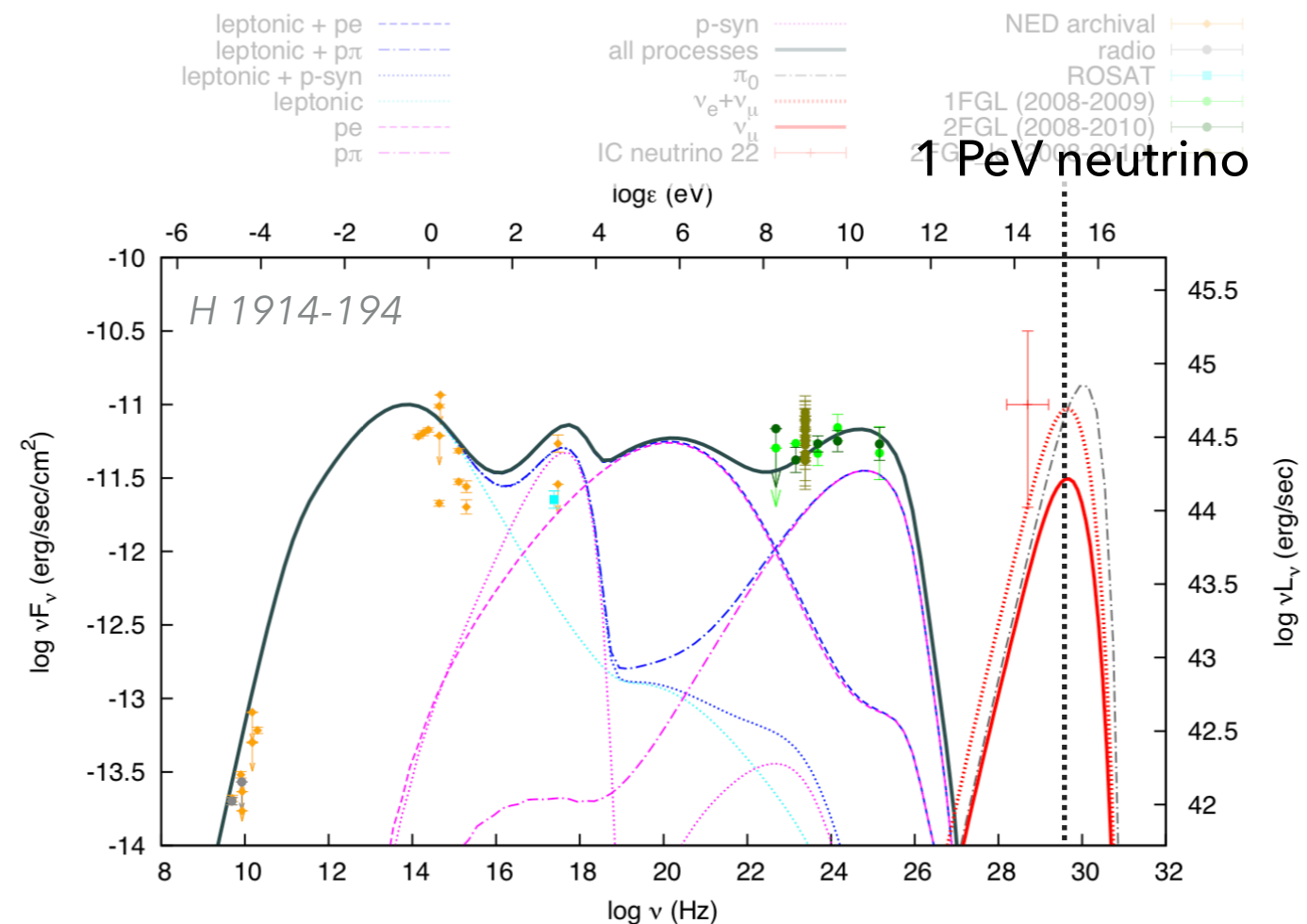
➔ EXPECTED NEUTRINOS FROM BLAZARS AT HIGH ENERGY



ICECUBE-170922A

P. Padovani, M. Petropoulou, P. Giommi, E. R.,  
MNRAS(2015)

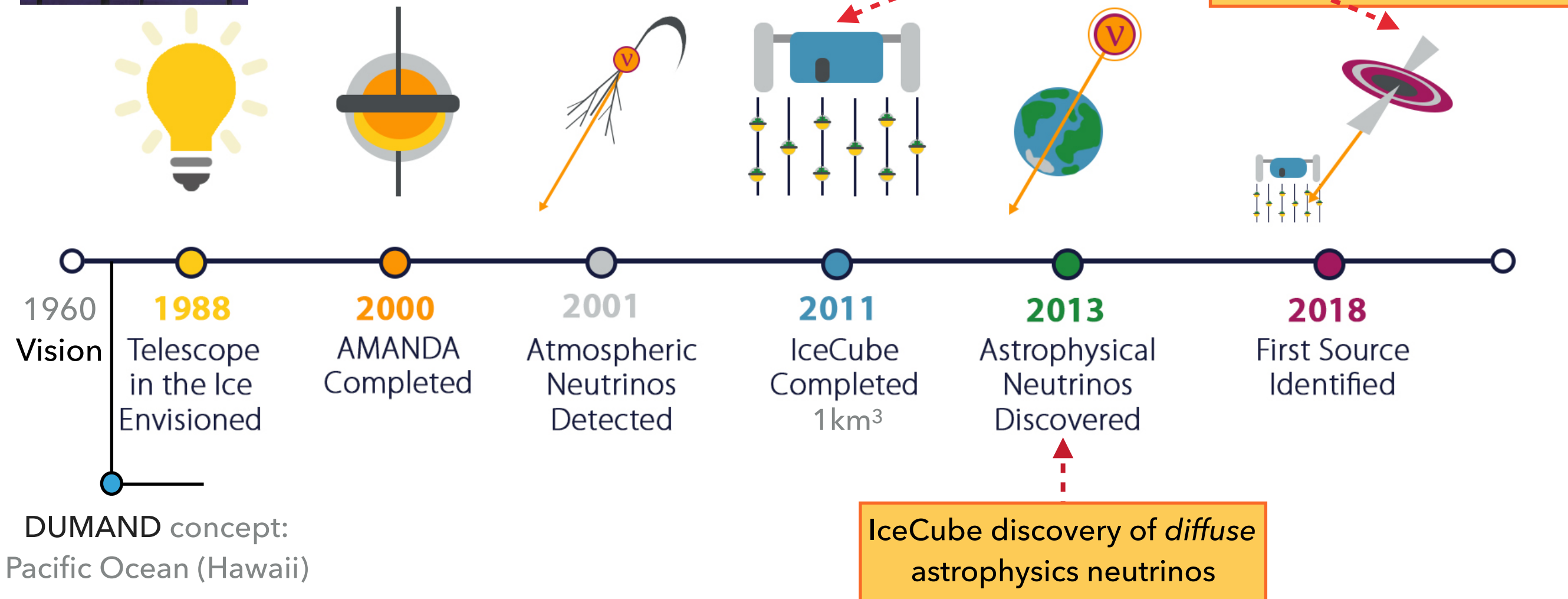
\* P. Padovani et al., MNRAS (2019)



M. Petropoulou, S. Dimitrakoudis, P. Padovani,  
A. Mastichiadis, E. R. MNRAS(2015)



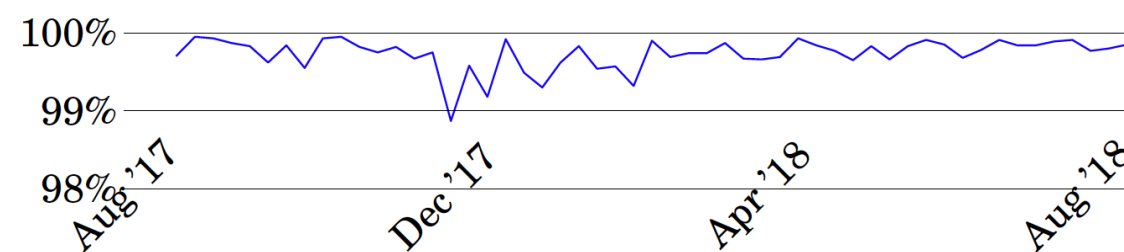
# Milestones in Neutrino Astronomy



For the first high energy neutrino source: 8 years of exposure from 1km<sup>3</sup> Neutrino Telescope -IceCube- under *ideal* detector conditions.



Uptime

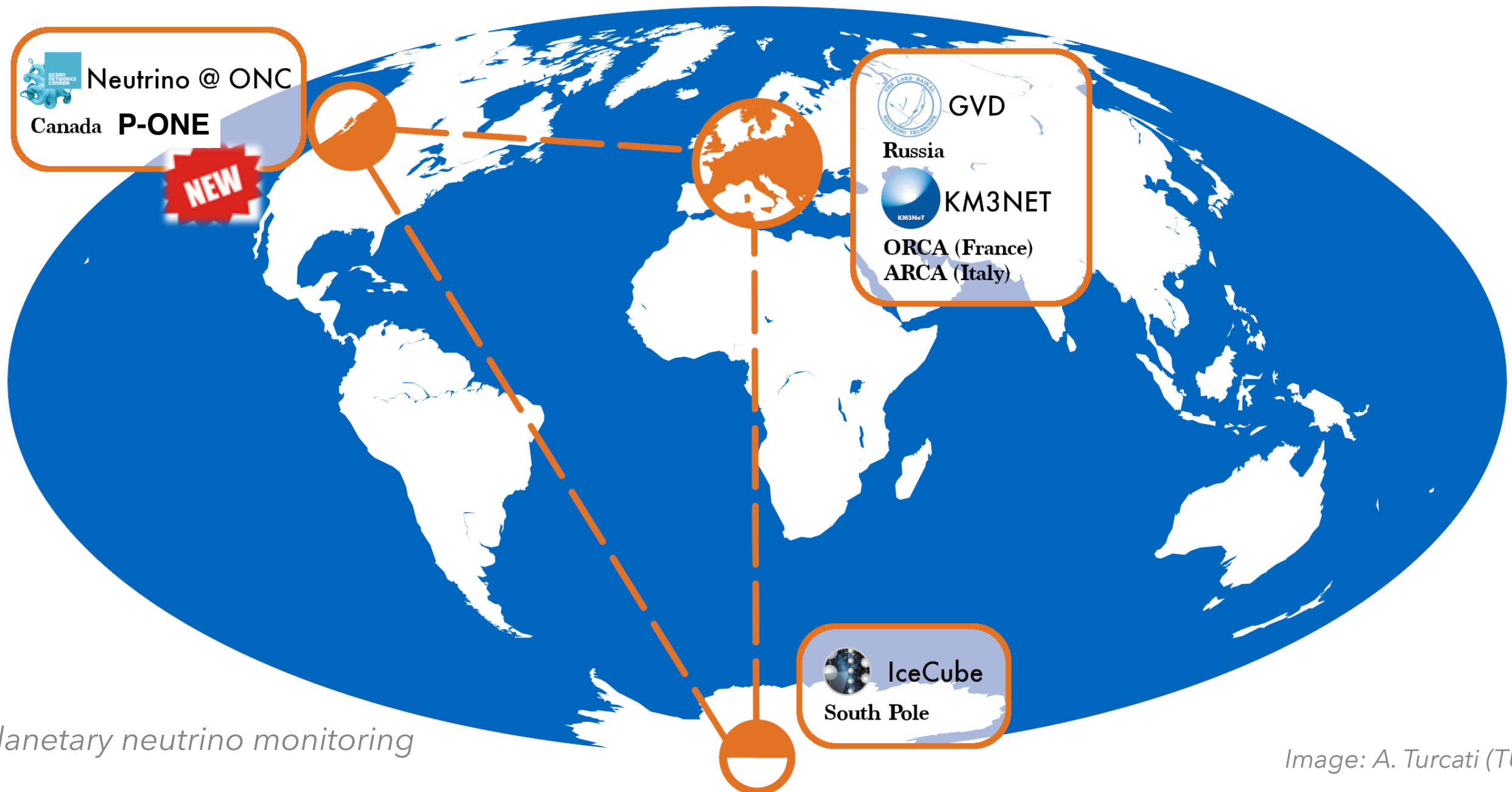


99.85%



What do we need in order to open the cosmic neutrino sky to more *routine* observations? 1) more NTs, 2) operate them together.

PLE $\nu$ M\*



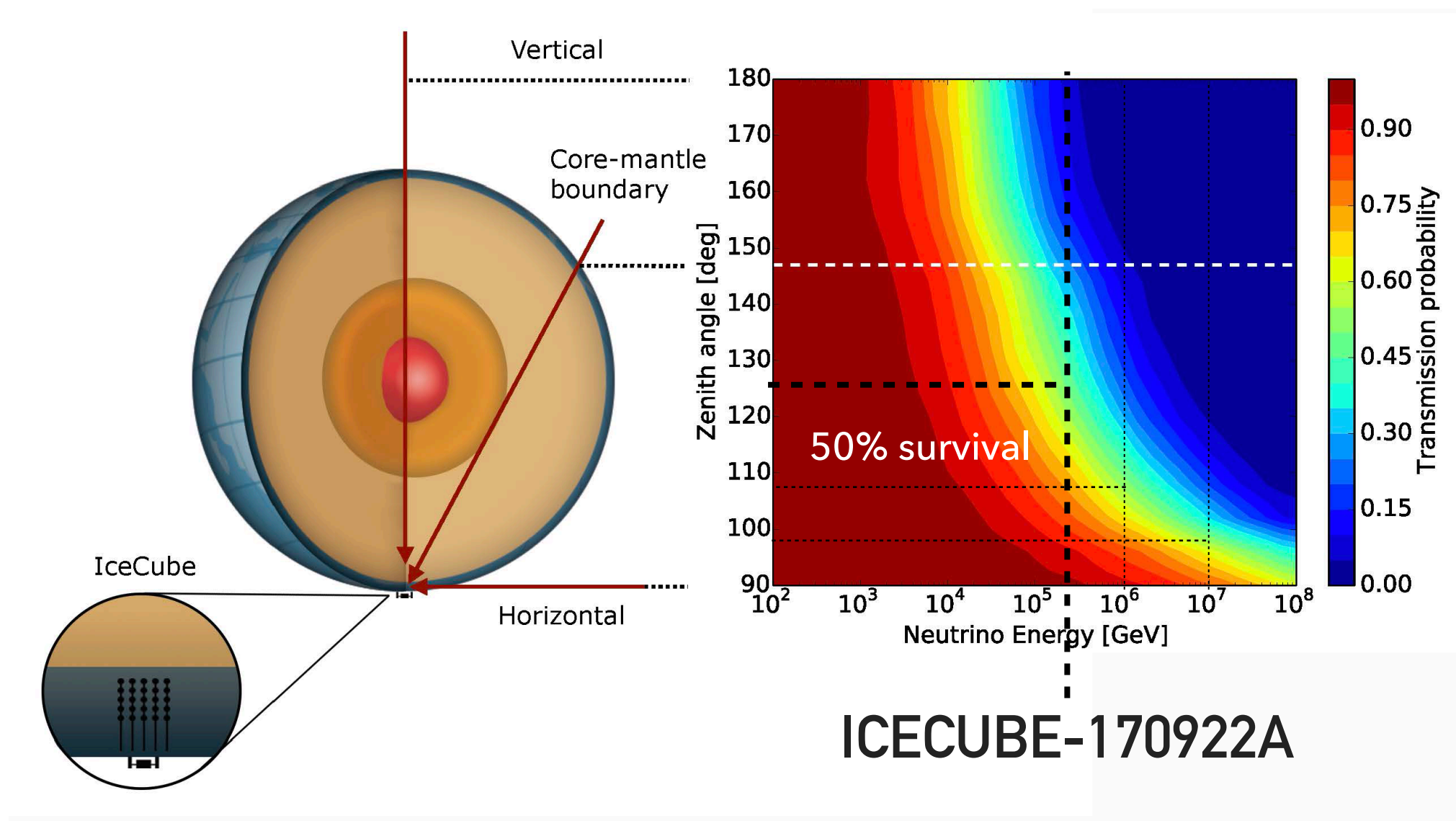
\*Planetary neutrino monitoring

Image: A. Turcati (TUM)

Why operate the NTs in PLENUM?

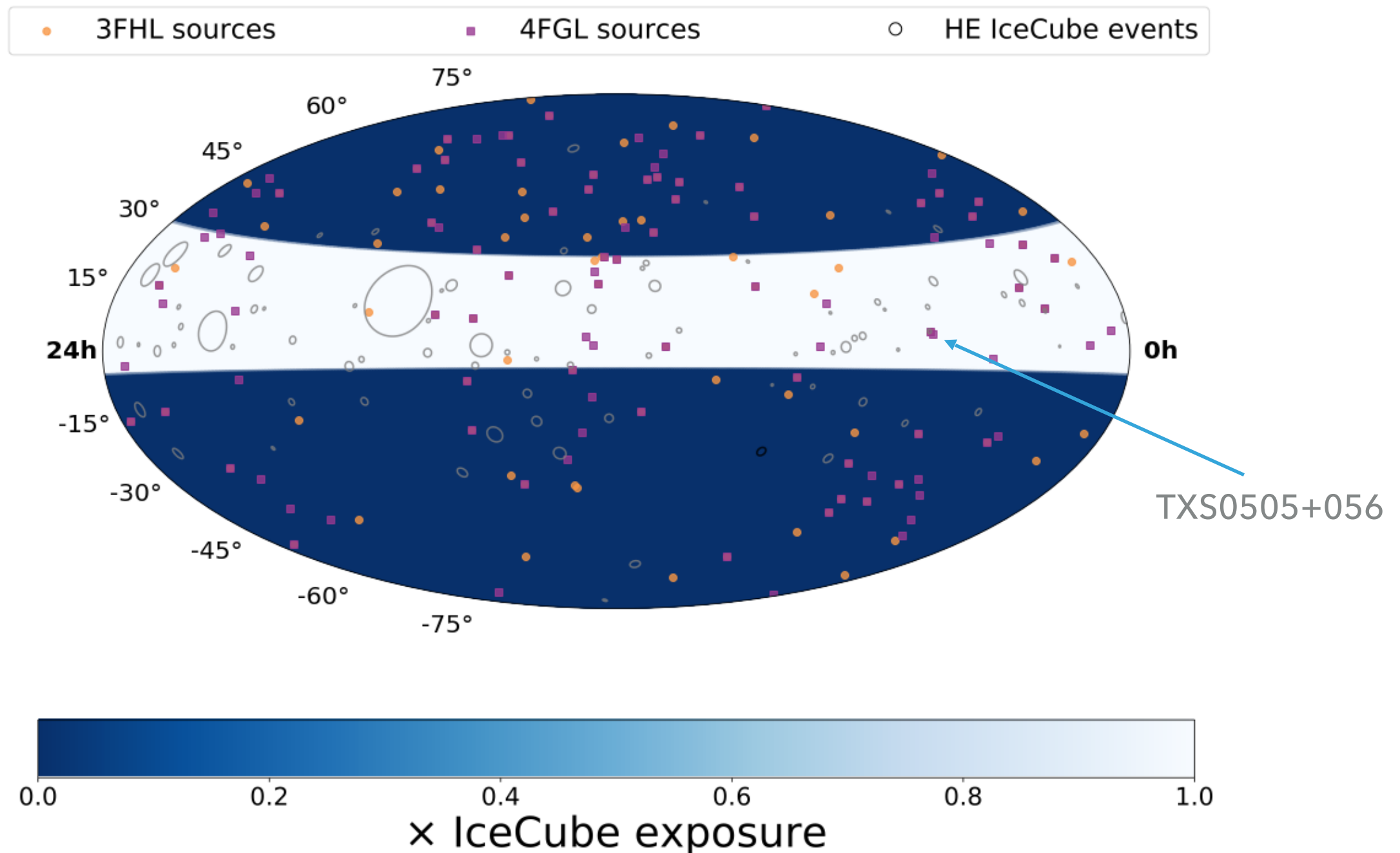
AT HIGH ENERGY THE EARTH IS OPAQUE TO NEUTRINOS

→ THE FIELD OF VIEW OF NTs ( $>50\text{TeV}$ ): THE HORIZON



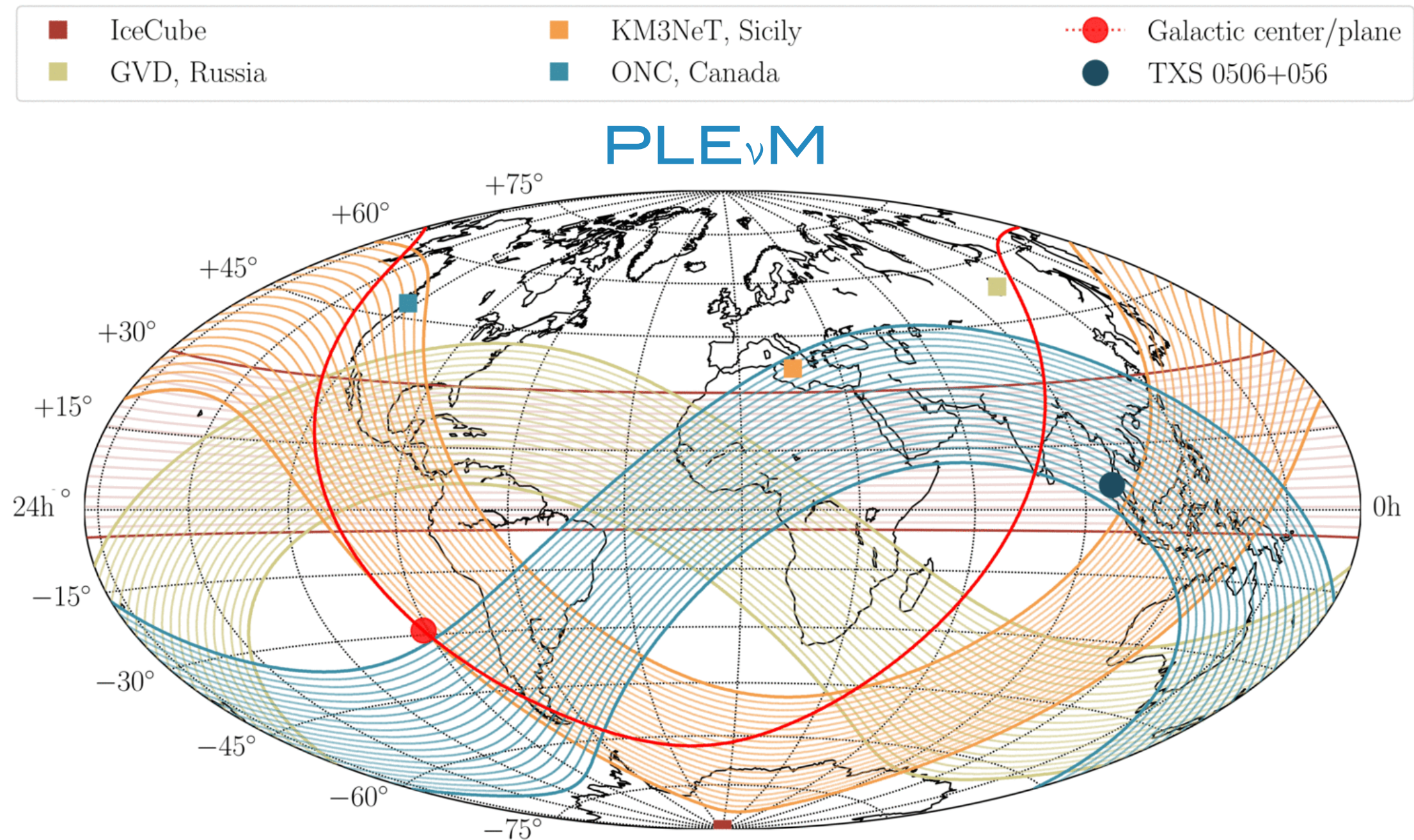
# ICECUBE FIELD OF VIEW AT HIGH ENERGIES ( $>50\text{TeV}$ )

## ABOUT 1/3 OF THE SKY COVERED



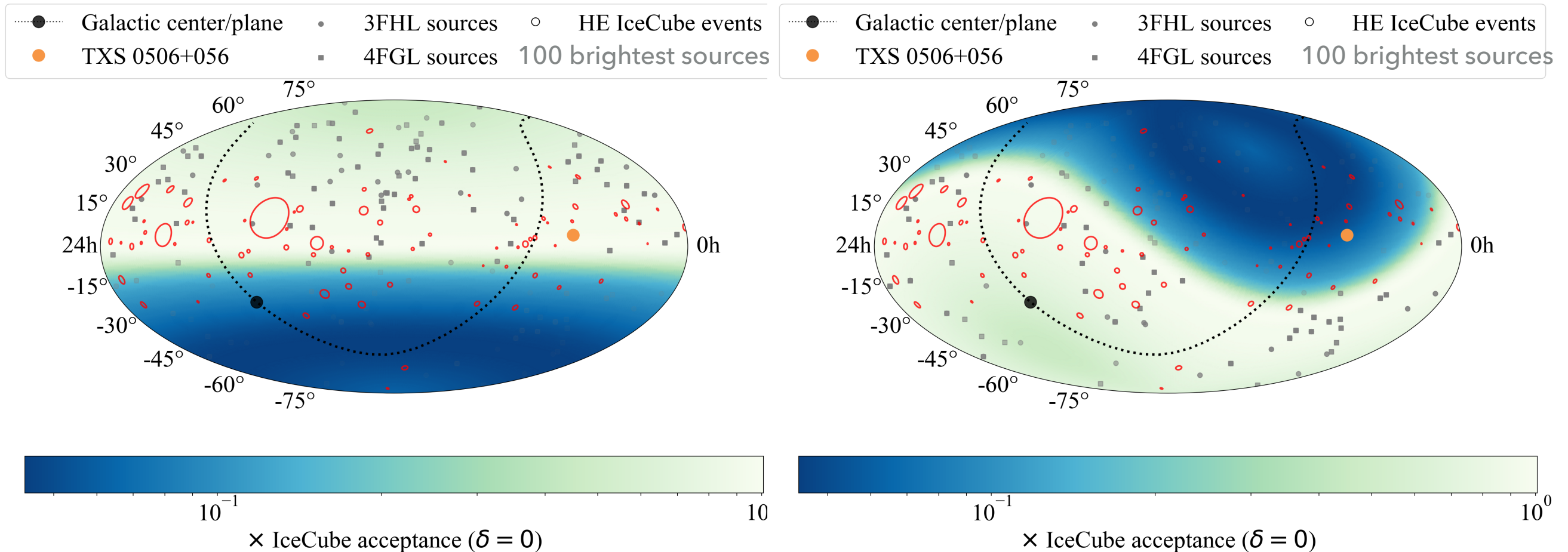


# THE FRONTIER: A PLANETARY NEUTRINO MONITORING SYSTEM



# ASSUME ONE ICECUBE @ BAIKAL, @ CAPO PASSERO, @ OCEAN NETWORKS CANADA

## PLE<sub>ν</sub>M



$$\text{IceCube acceptance} \equiv \int_0^\infty A_{\text{eff}}(\delta, E) \cdot E^{-\gamma} dE$$

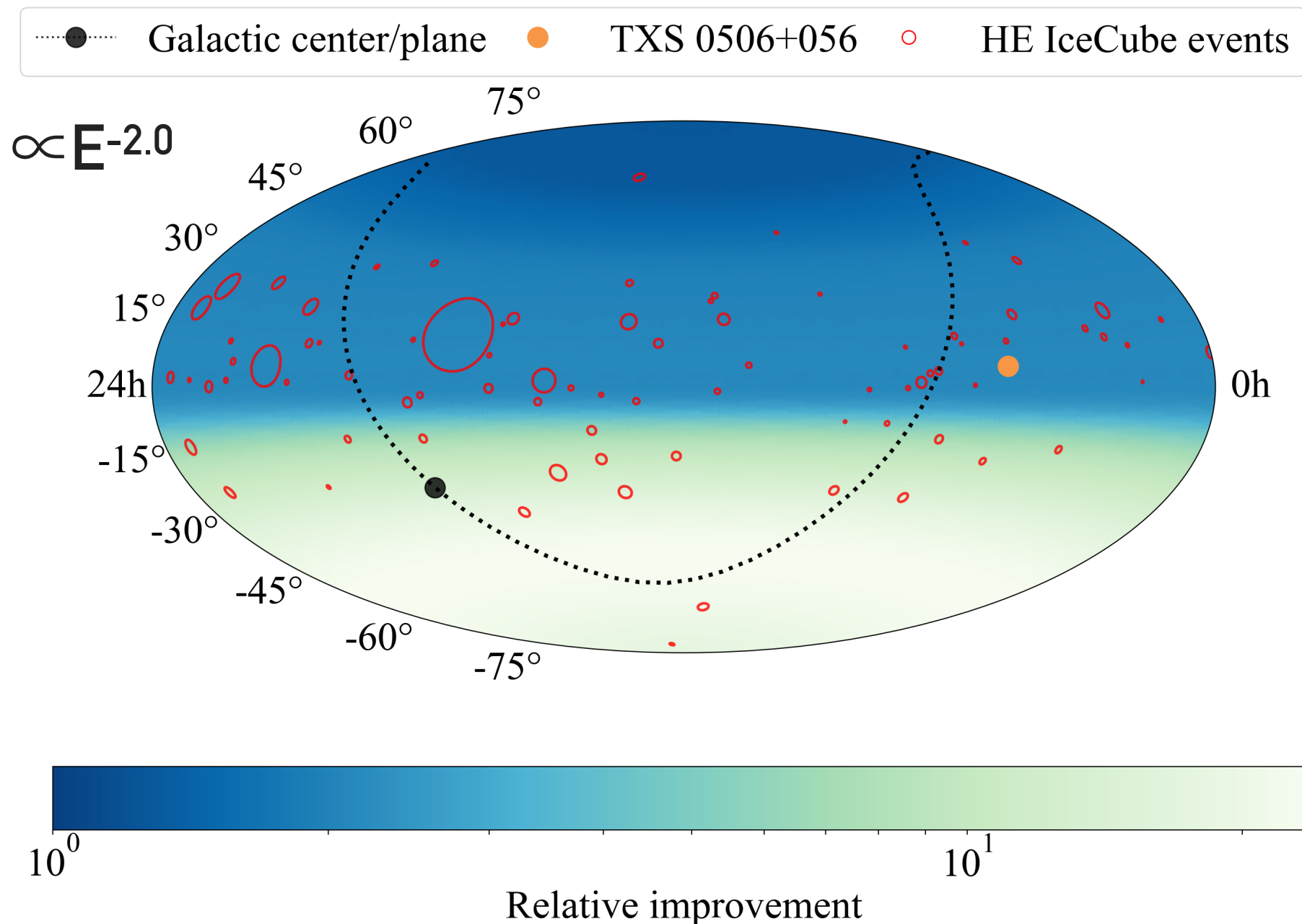
IceCube acceptance at the GVD location



PLE<sub>ν</sub>M

ICECUBE &amp; BAIKAL &amp; CAPO PASSERO &amp; OCEAN NETWORK CANADA

## ➔ RELATIVE IMPROVEMENT VS ICECUBE ALL SKY

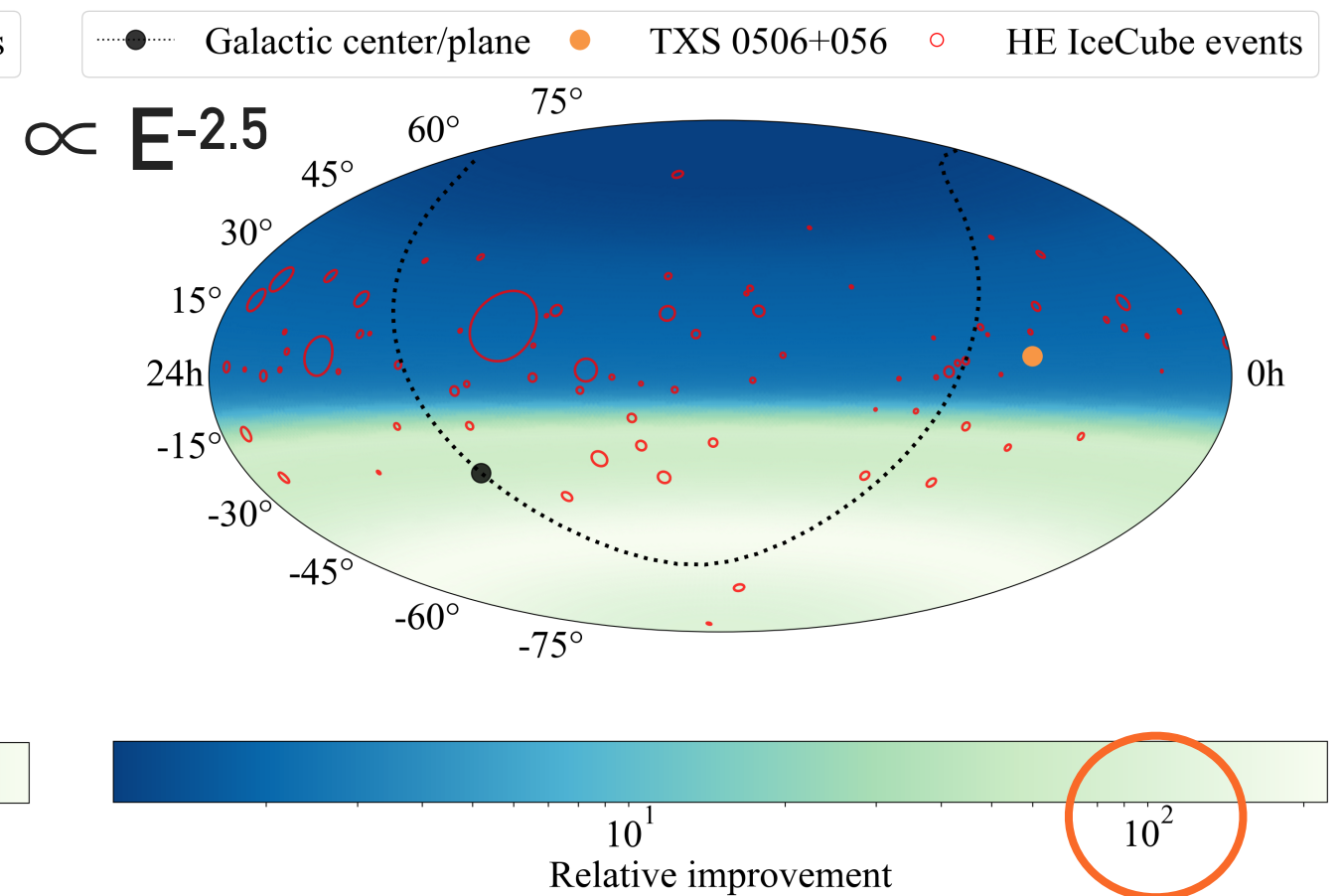
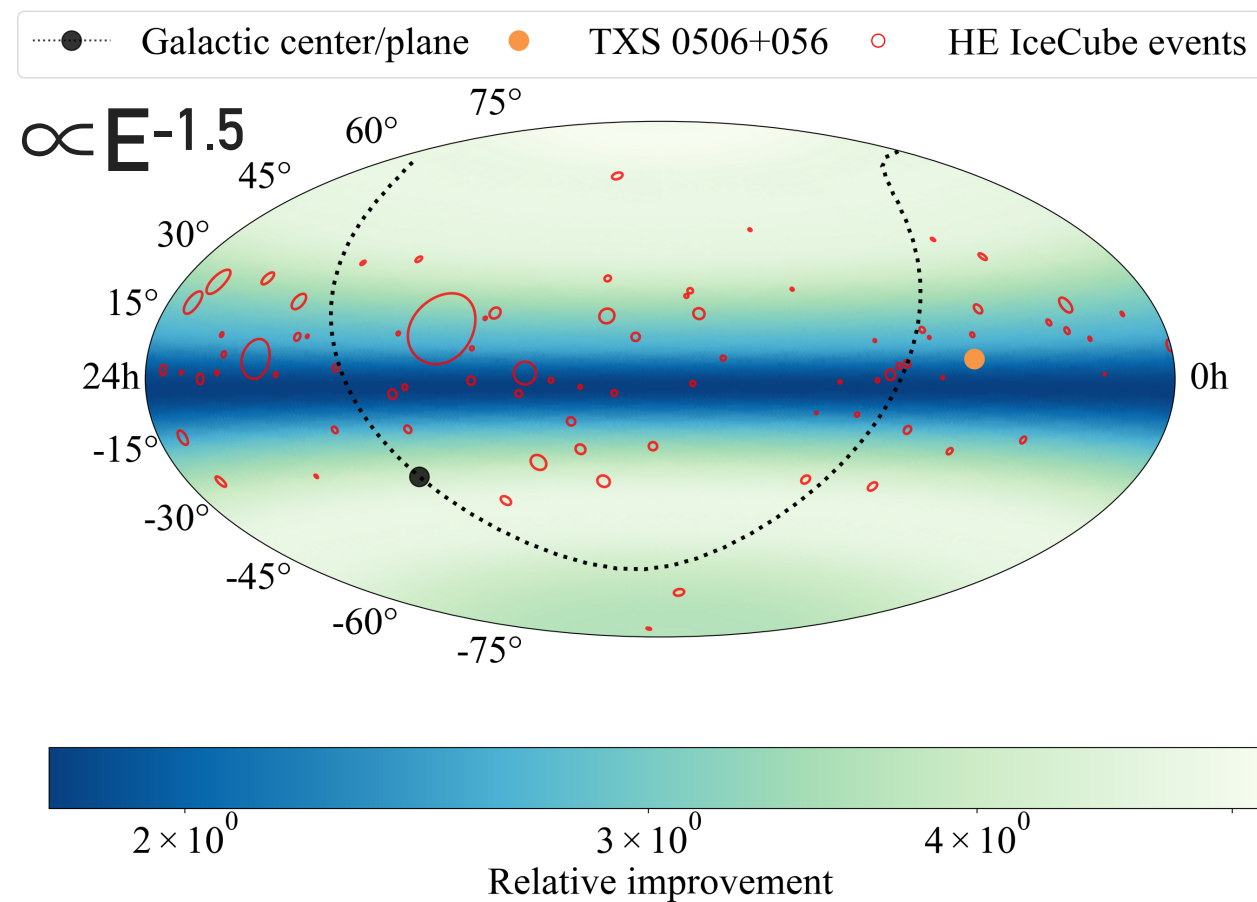




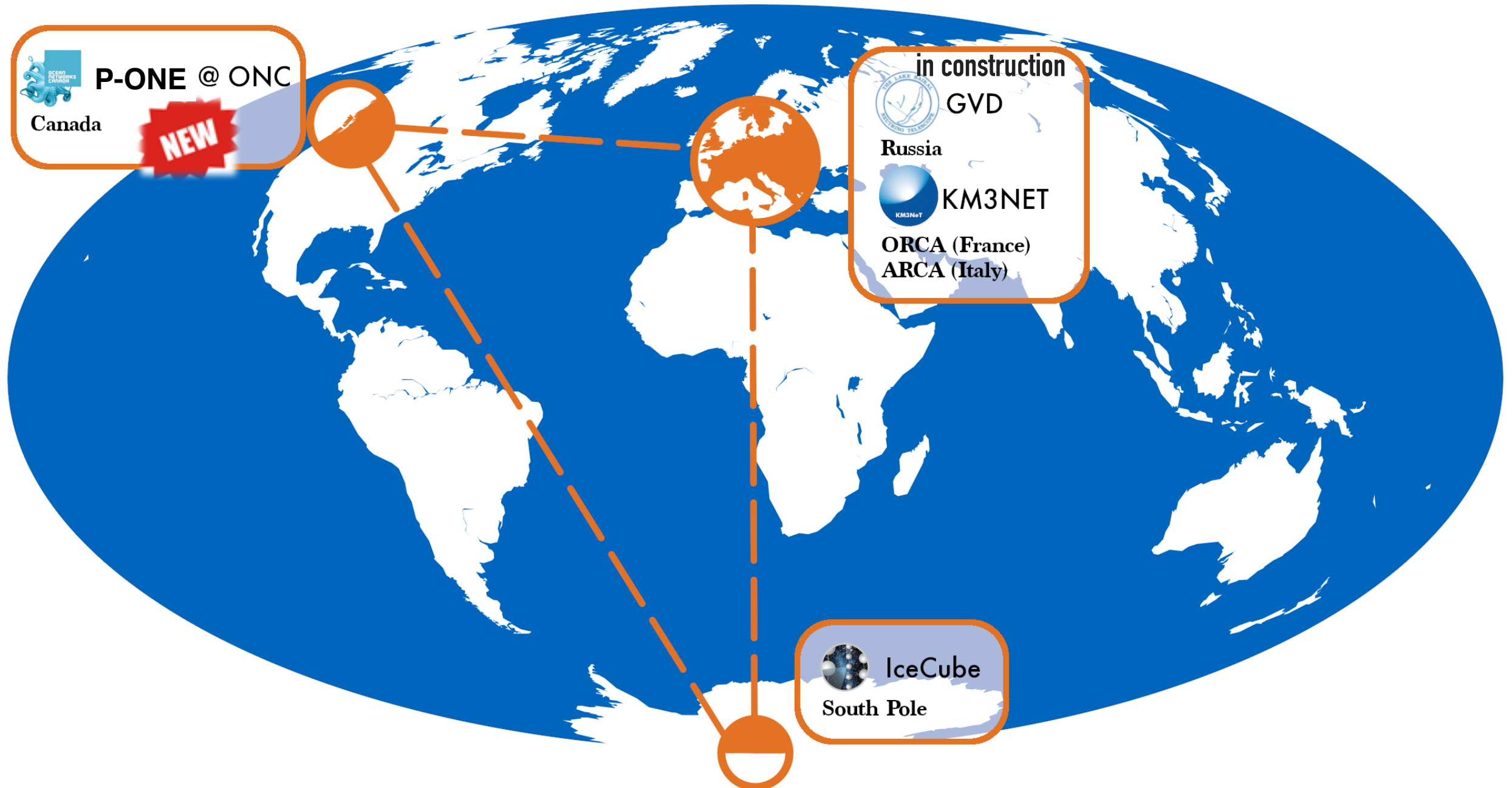
PLE<sub>ν</sub>M

ICECUBE &amp; BAIKAL &amp; CAPO PASSERO &amp; OCEAN NETWORK CANADA

➔ RELATIVE IMPROVEMENT VS ICECUBE ALL SKY



# PLEνM\*



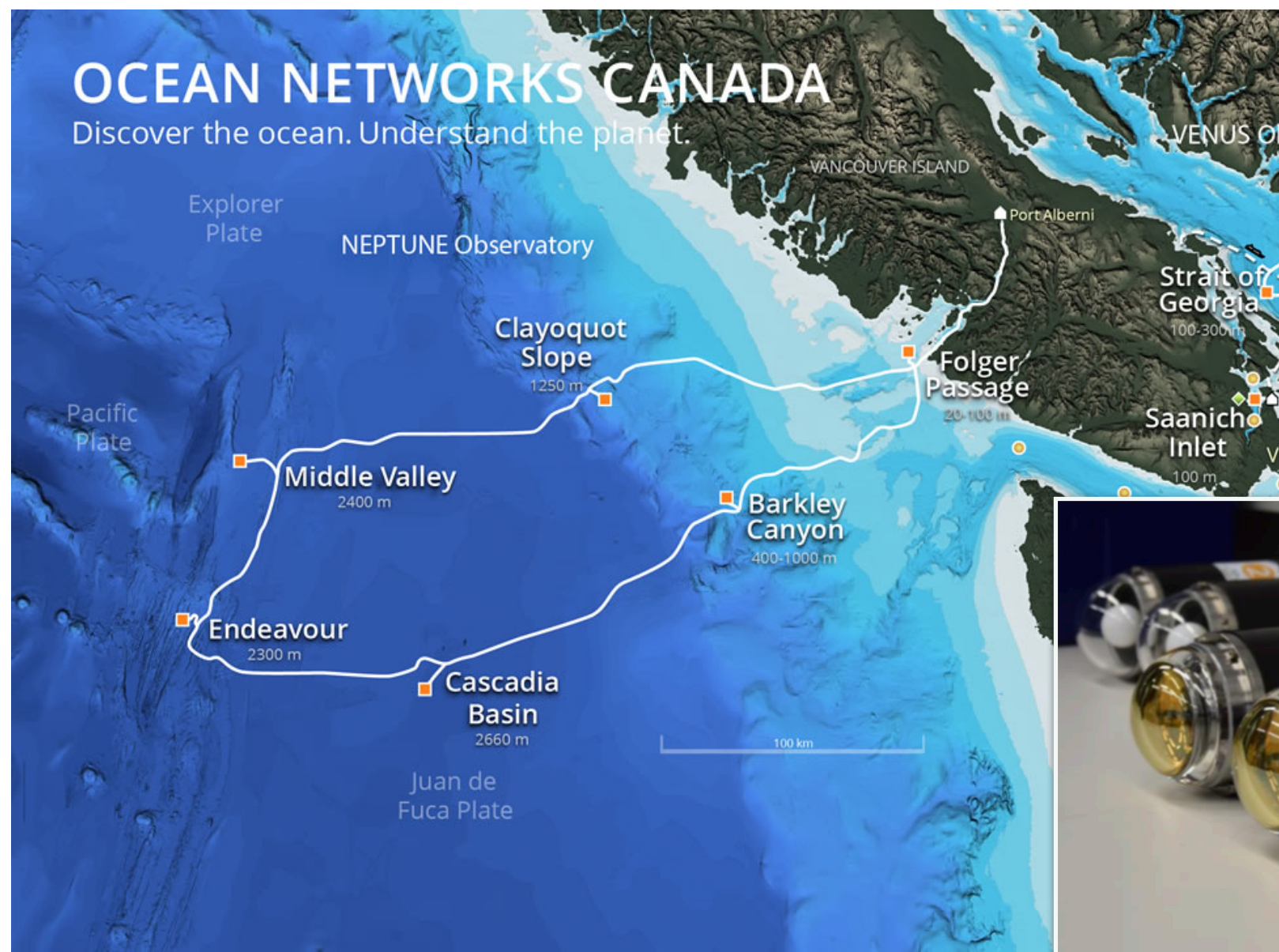
\* ... in a plenum, there are no empty places.  
(Bertrand Russell)



# PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE)

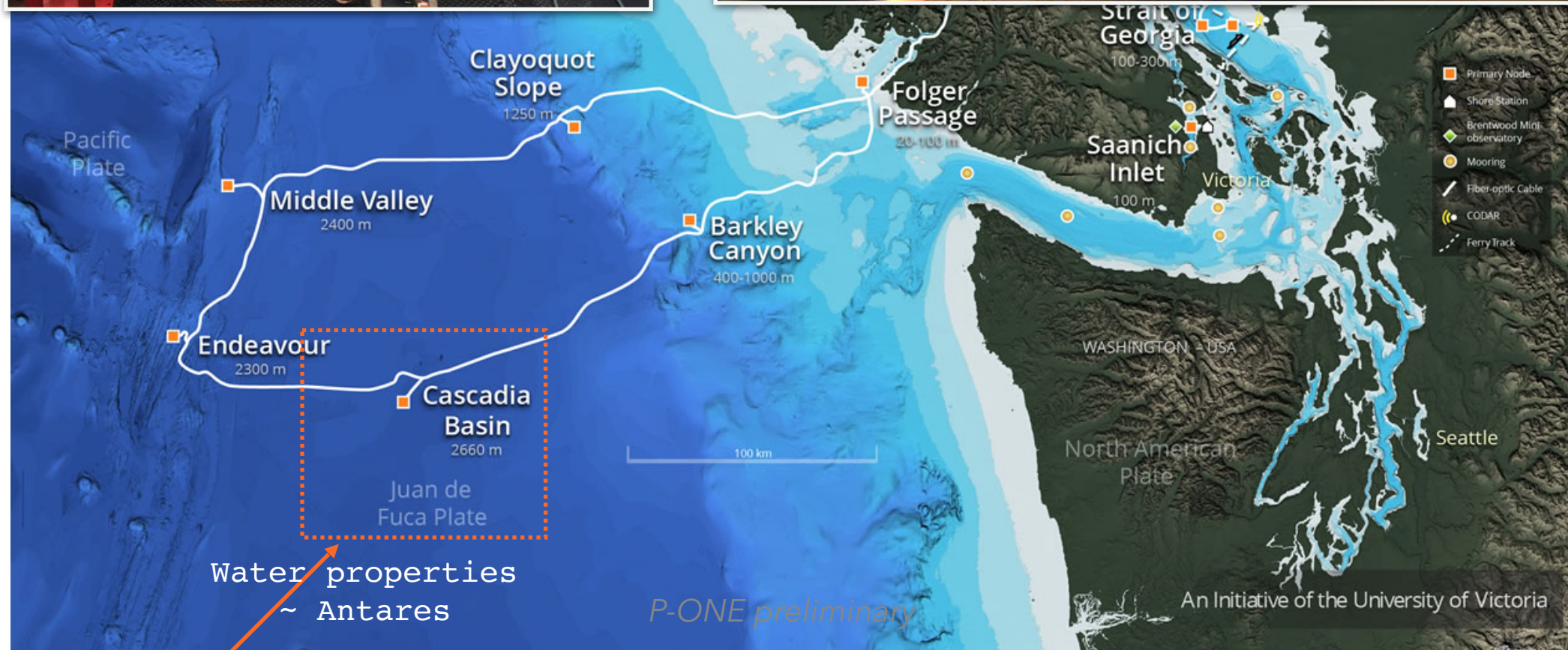
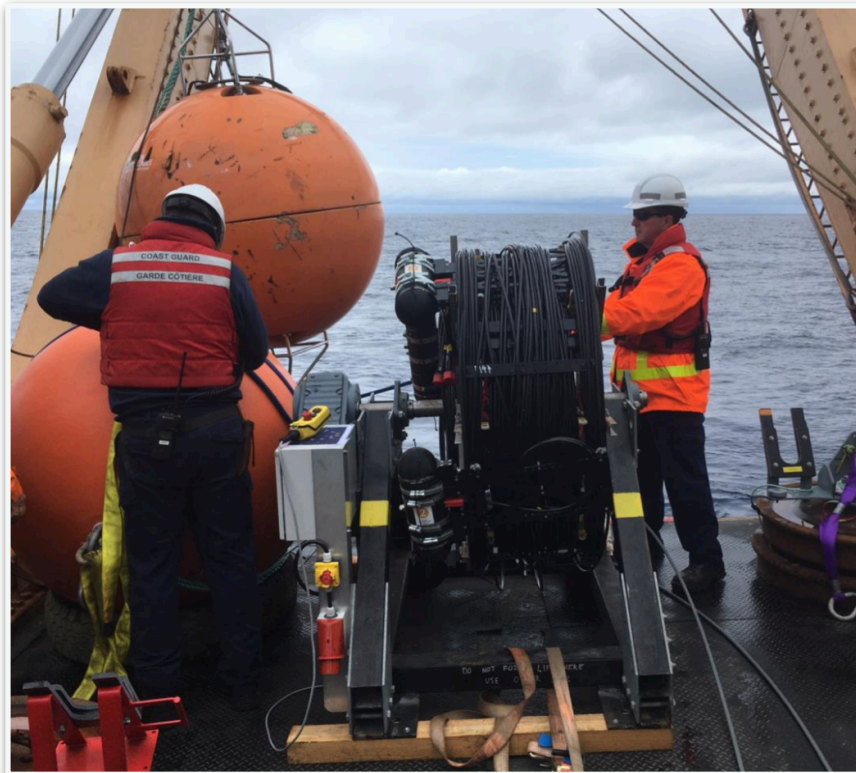
ONC (U. VICTORIA), U. OF ALBERTA, QUEEN'S U., SIMON FRASER UNIVERSITY, TU MUNICH

STRAW PATHFINDER DEPLOYED IN 2018, DATA TAKEN ON-GOING



M. Boemer et al., 'STRAW (STRings for Absorption length in Water): pathfinder for a neutrino telescope in the deep Pacific Ocean', JINST(2019), <https://arxiv.org/abs/1810.13265>





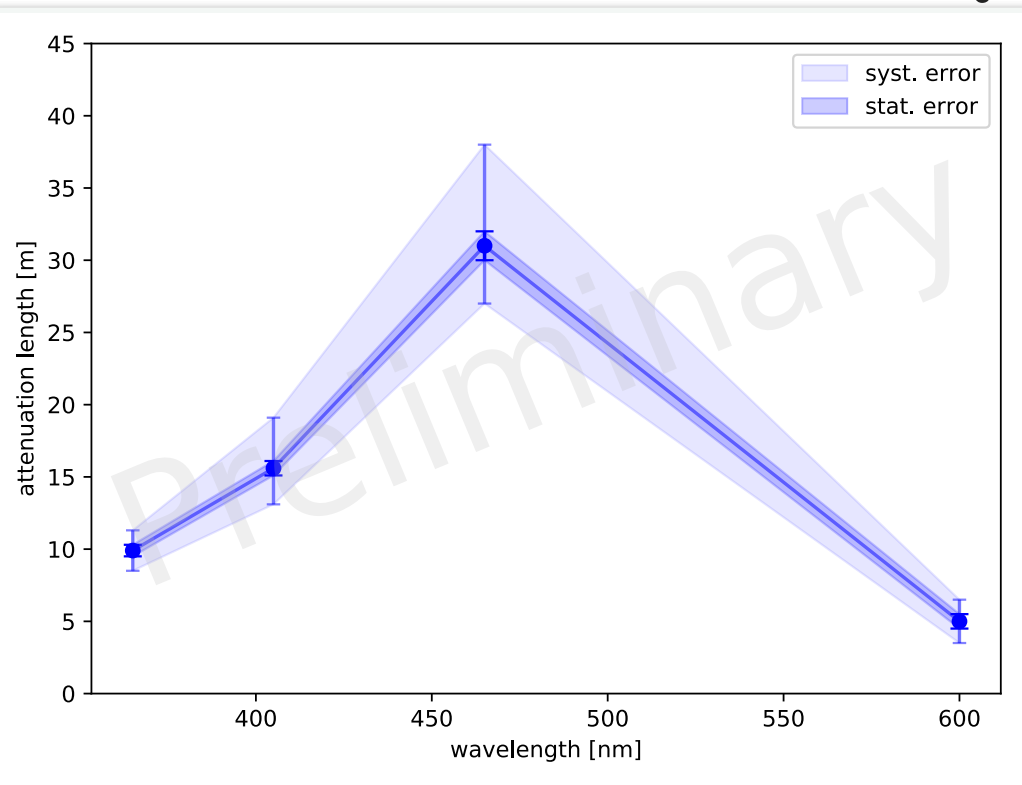
Huge volume available and (partly) cabled



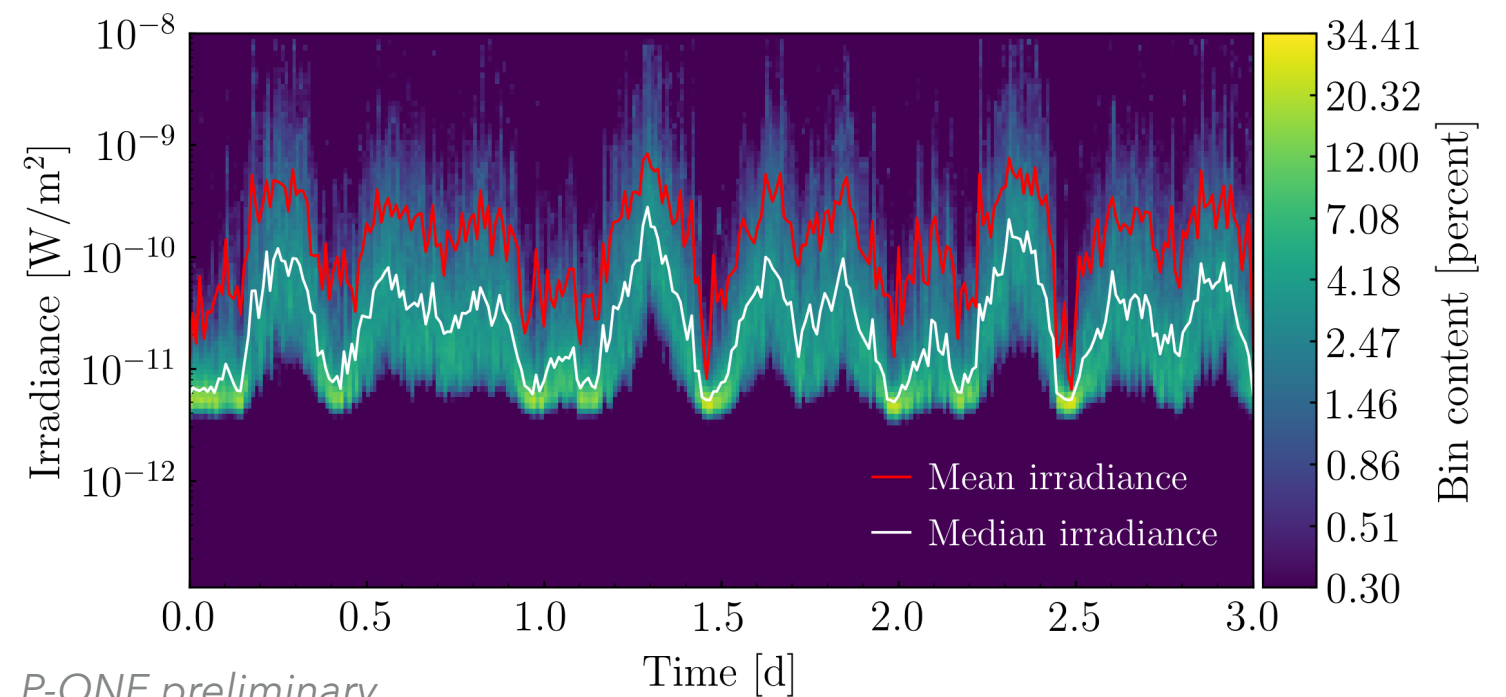
# PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE)

## STRAW PATHFINDER: PRELIMINARY RESULTS - NO SHOW STOPPERS

Result No.1: Attenuation length



Results No.2: Bioluminescence modulated as the ocean's tides



*P-ONE preliminary*

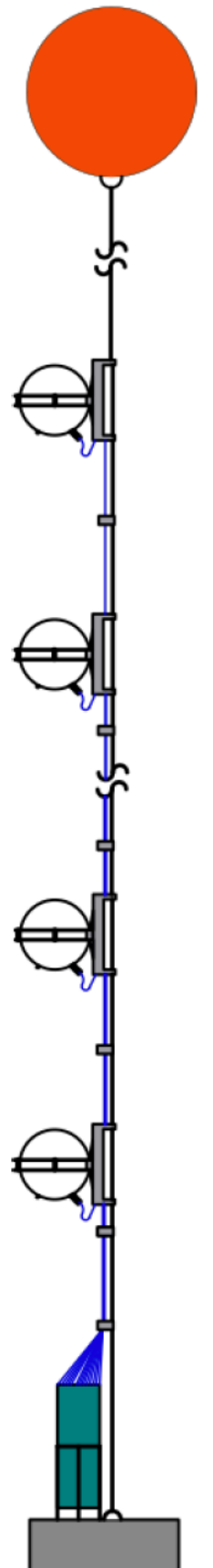
# PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE)

## STRAW-B PATHFINDER II: DEPLOYMENT IN 2020

*Test longer mooring (500m) and specialised devices. Complete qualification of the deep site.*



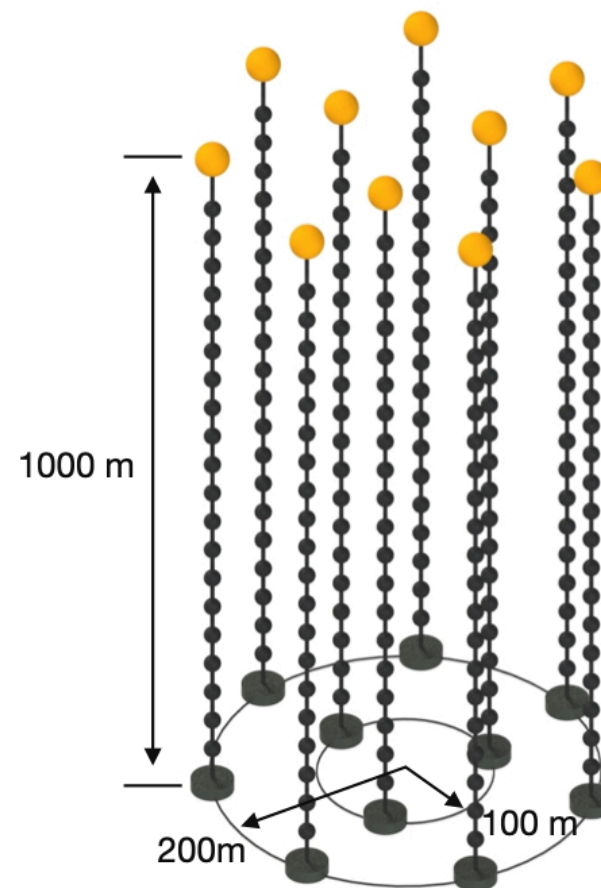
@TUM, 17-19//11/19





# PACIFIC OCEAN NEUTRINO EXPLORER (P-ONE)

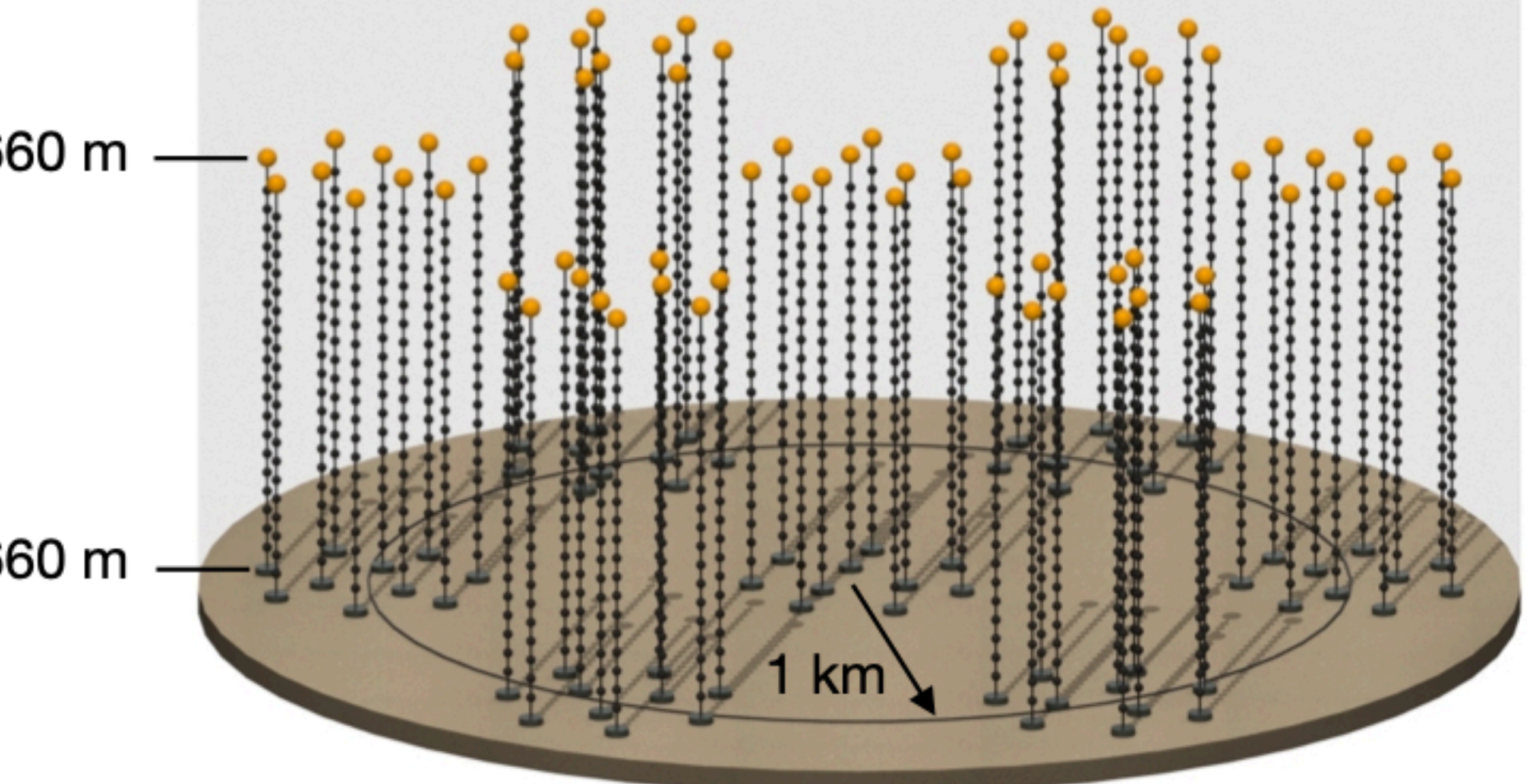
## PROPOSALS FOR FIRST 10 STRINGS BUNDLE IN PREPARATION



time scale: 2023-2024

# PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE)

➔ IN CONCEPTUAL DESIGN PHASE

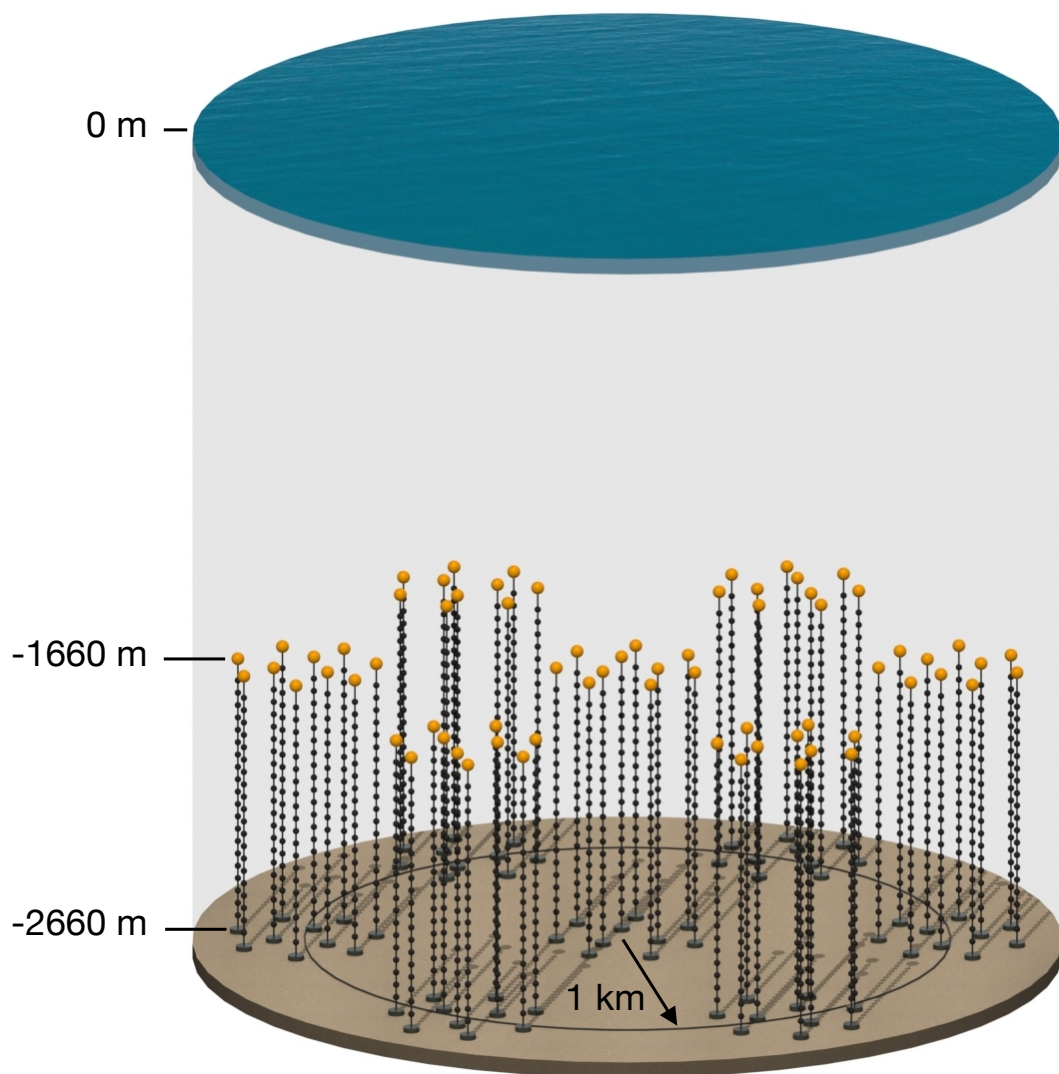




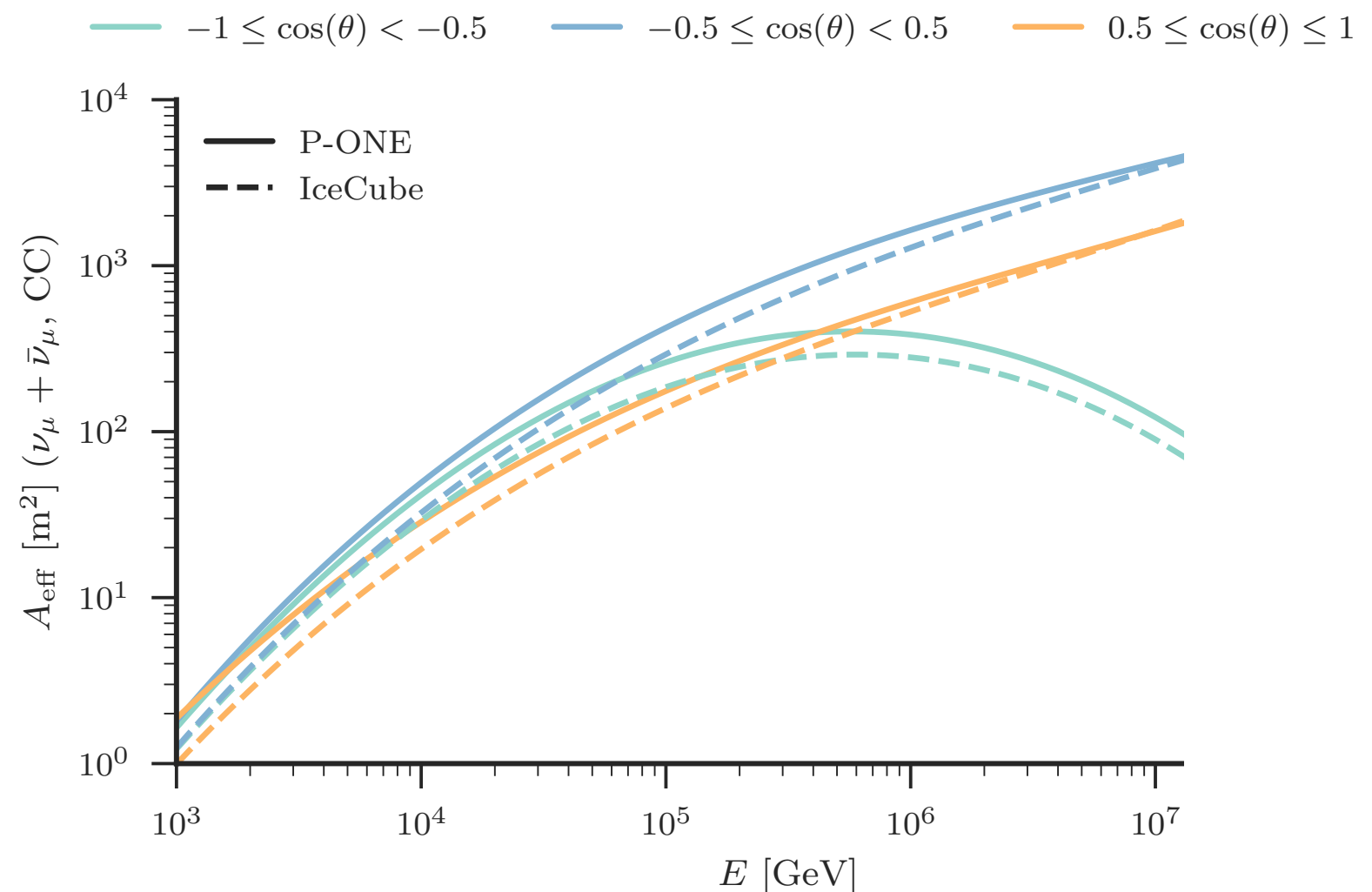
# PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE)

➔ IN CONCEPTUAL DESIGN PHASE

P-ONE AS OPTIMISED TELESCOPE FOR HE TRACKS:  $\sim 2 \times$  ICECUBE



time scale: 2026–2028



# ON THE ICECUBE SIDE: UPGRADE AND GEN2

## → ICECUBE AS MULTIPURPOSE EXPERIMENT

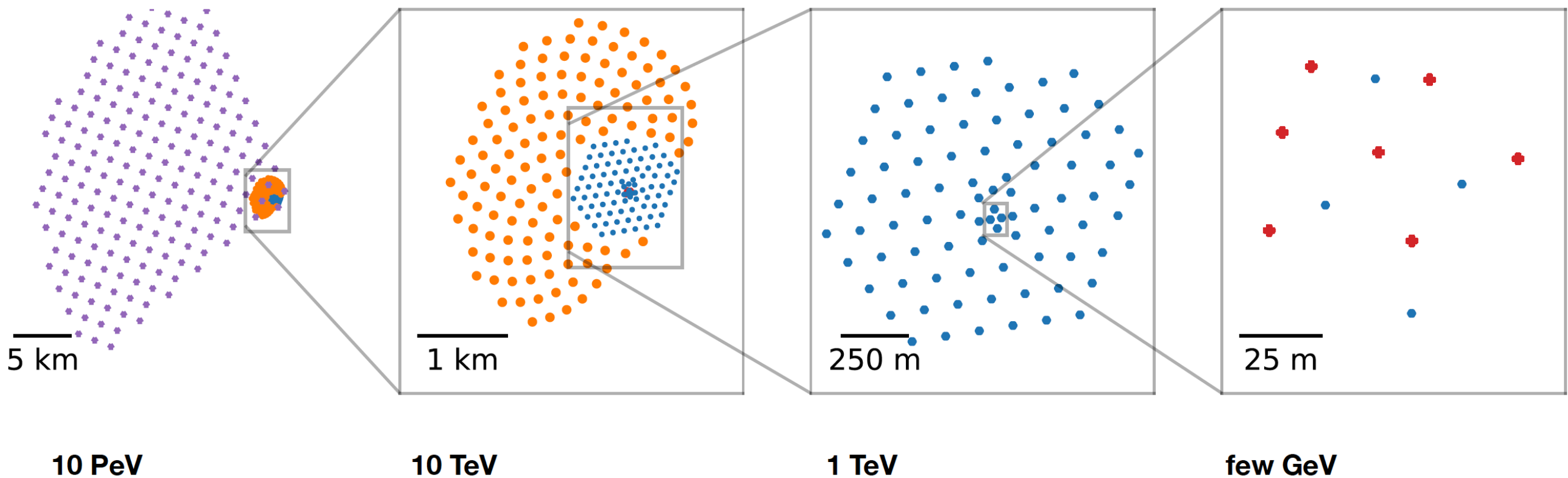
### UNDER DESIGN

Gen2-Radio

IceCube-Gen2

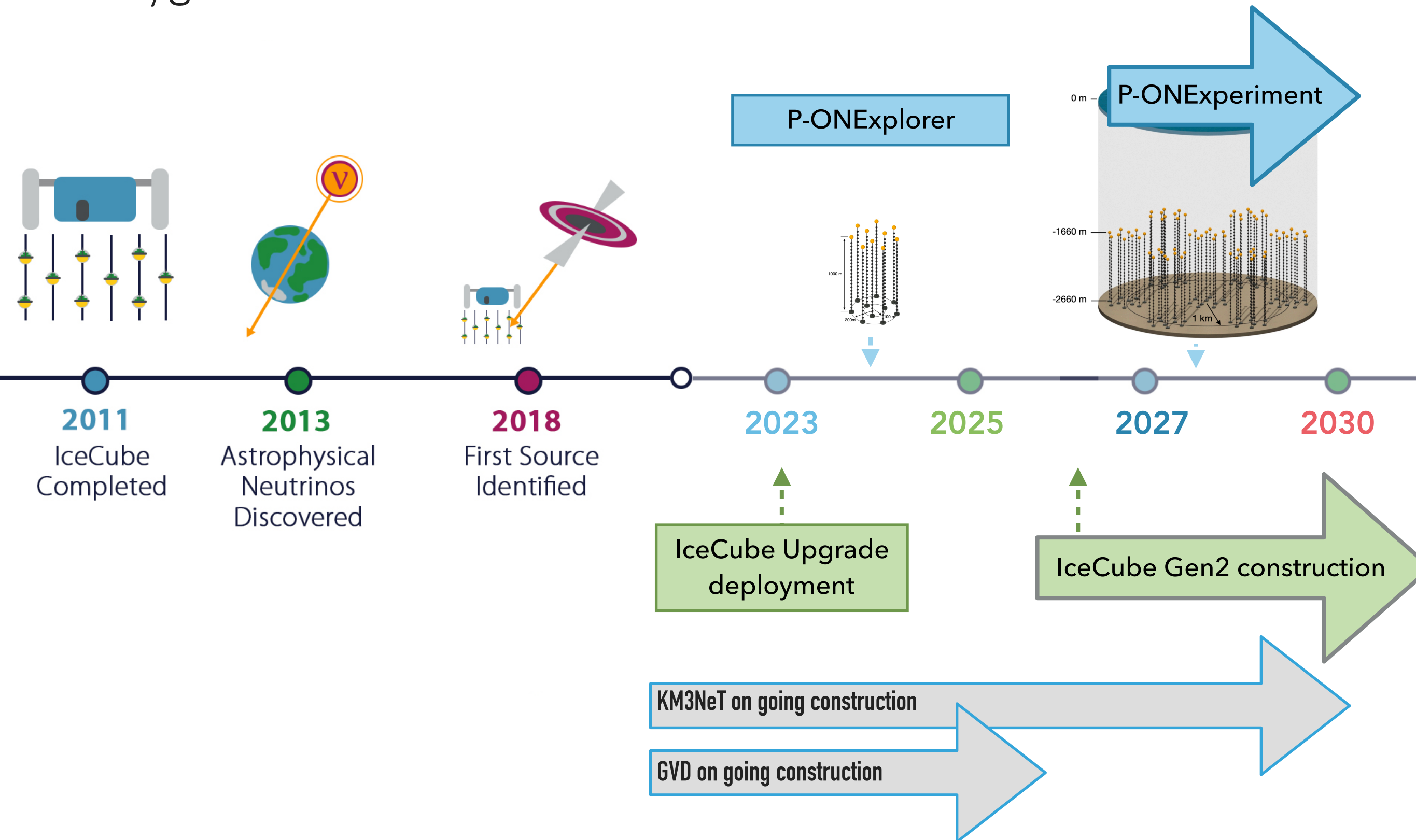
IceCube

IceCube Upgrade





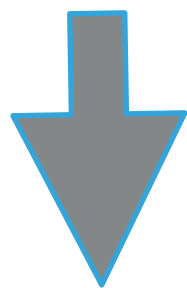
The decadal vision: from the single site telescope (IceCube) to the multi/global network.



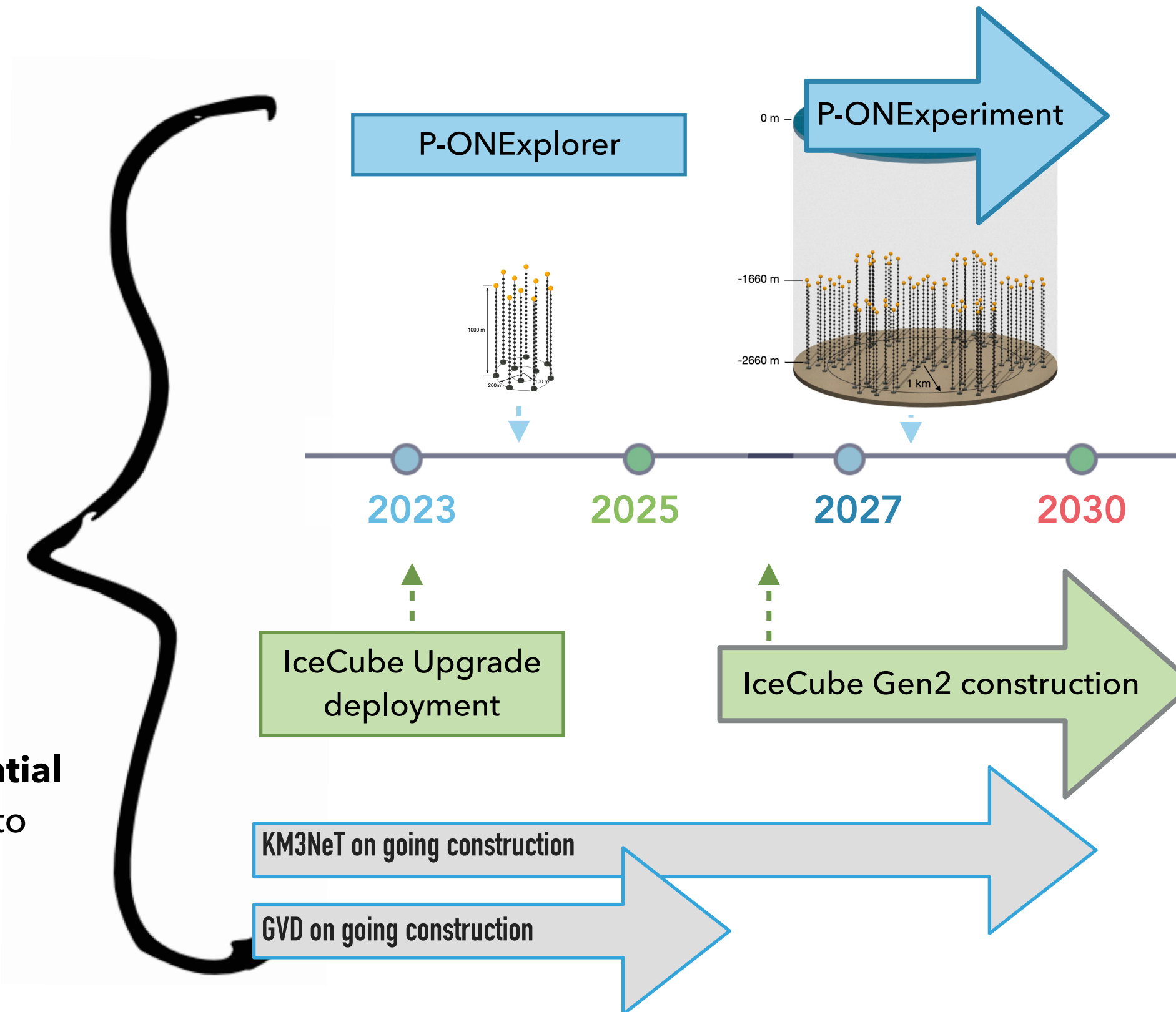
The decadal vision: from the single site telescope (IceCube) to the multi/global network.

## PLE<sub>ν</sub>M

- share hardware developments
- share software packages
- cross-calibration
- combined analyses
- on line sky monitor for astrophysical alerts



Boost of the **discovery potential** for cosmic accelerators up to factor 100!





# OUTLOOK

IceCube has pioneered the exploration of the universe with high-energy neutrinos as intergalactic probes.

The first association between neutrinos and an extragalactic source (TXS0506+056) in 2018. Aftermath:

- Blazars are viable HE neutrino sources and so far the only;
- Neutrino signal from blazars most probably 100 TeV - 100 PeV, most interesting region to explore;
- Neutrino absorption in the Earth significant effect, field of view at the horizon.

Need of more and larger neutrino telescopes around the planet Earth to cover the sky and boost the discovery potential.

Example: With 3xIceCube in the North overall improvement by a factor of 10-100, strong synergy.

New collaboration established with Ocean Networks Canada for a possible neutrino telescope named Pacific Ocean Neutrino Experiment (P-ONE): new insights into deep sea operations.

A path forward for IceCube Gen2 guaranteed.

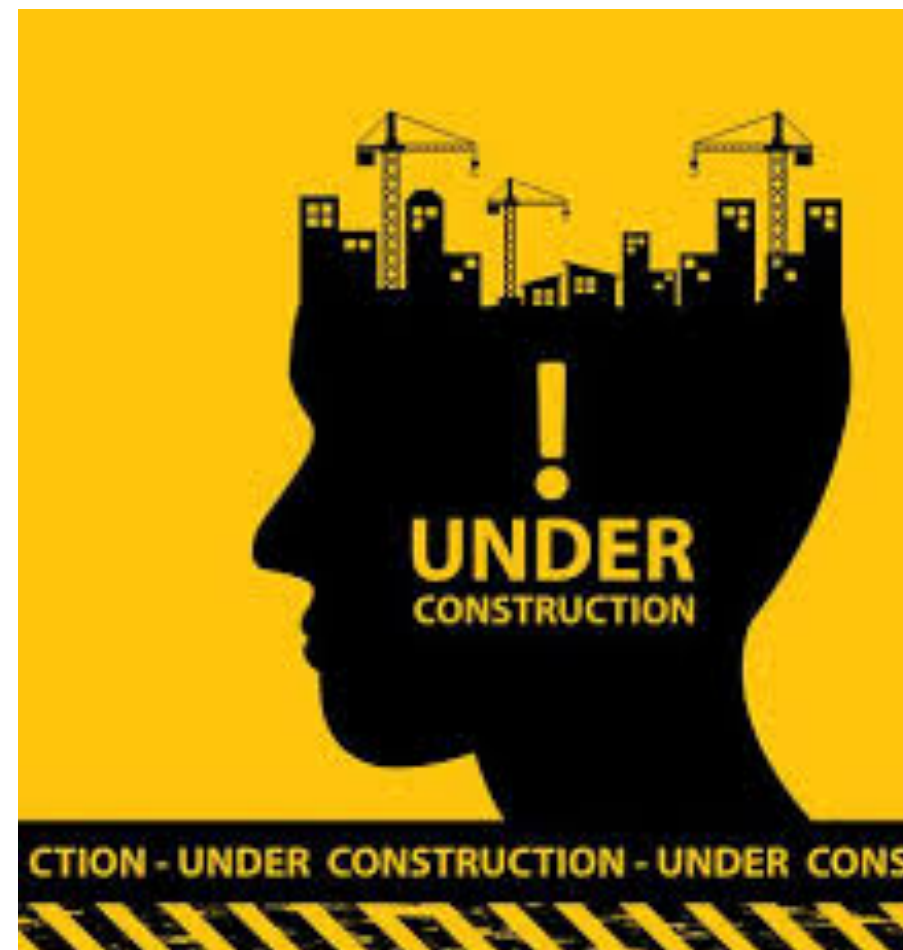
# LONG-TERM VISION

The next ten years will mark the emergence of multi-messenger astro/particle physics through numerous (potential) discoveries at the highest energies including:

- > macro and microscopic physics of particle acceleration in the vicinity of the black holes
- > search for the products of dark matter, exotic particles (also in the CR interaction in the atmosphere)
- > interaction of the accelerated particles producing the energetic photons and neutrinos

To achieve the golden era of multi-messenger astro/particle physics and explore the universe as laboratory for high energy physics, it is necessary to

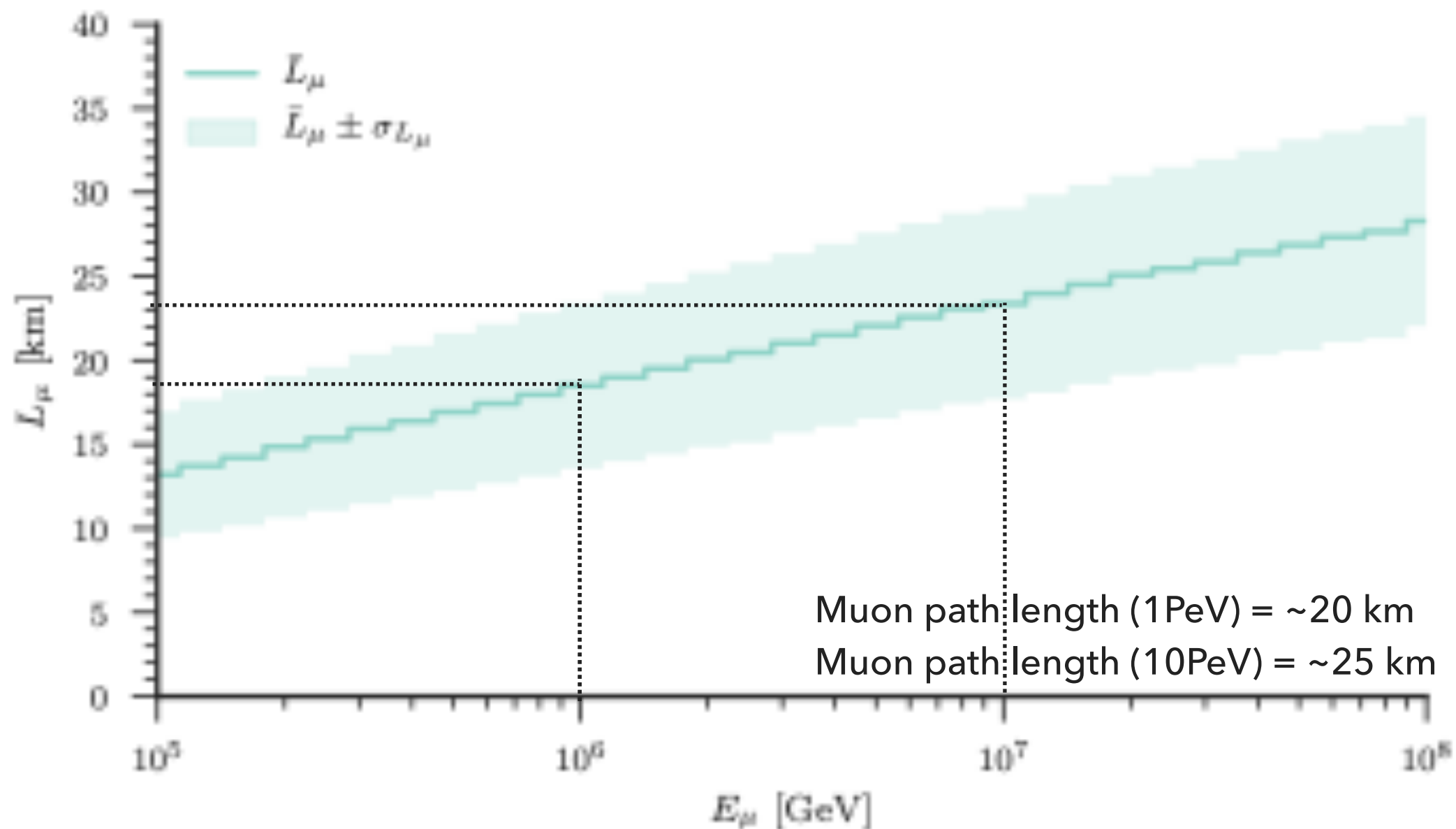
- 1) open the observation window to the whole sky with a coordinated effort among KM3NeT & GVD & IceCube & P-ONE = PLEvM
- 2) achieve energy flux sensitivity in the range of  $10^{-12} \text{ TeVcm}^{-2}\text{s}^{-1}$  through the optimisation of the neutrino telescopes (e.g. P-ONE) and broad band observatories (e.g. IceCube-Gen2)
- 3) and establish more collaboration with astronomers .and. physicists.





# NEUTRINO INTERACTION CHANNEL - MUON TRACKS

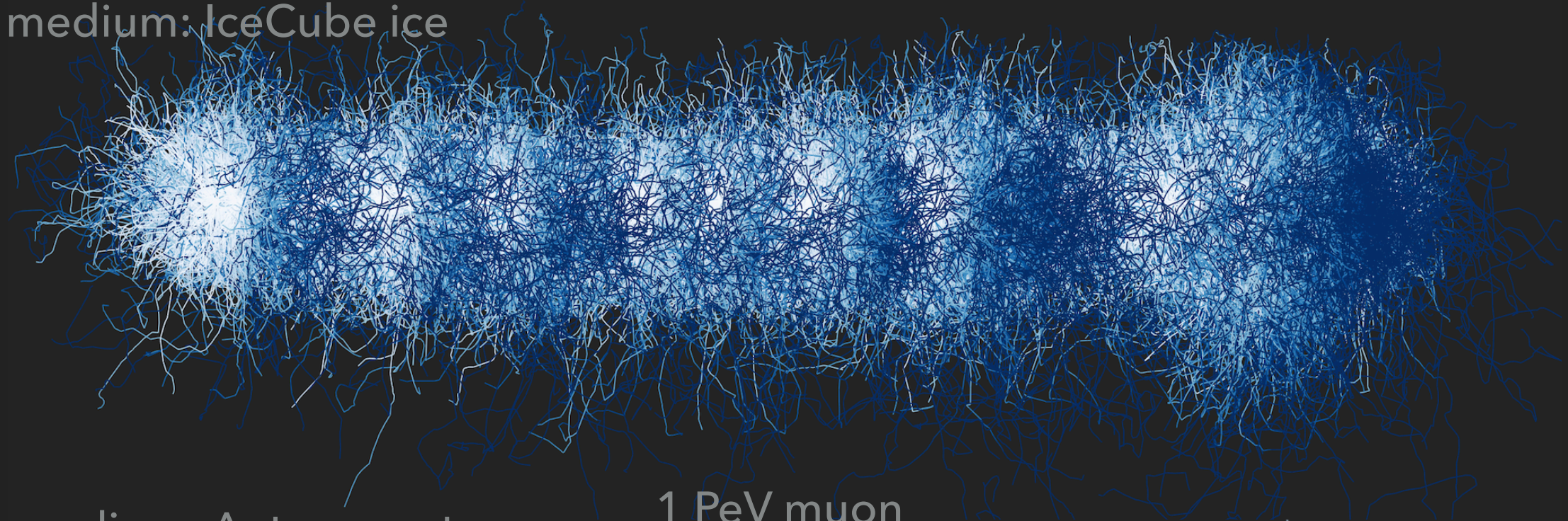
➔ **~1KM: SHORT FOR HIGH ENERGY MUONS**



# NEW ENTRY ON THE NEUTRINO MAP – PLENUM@ONC

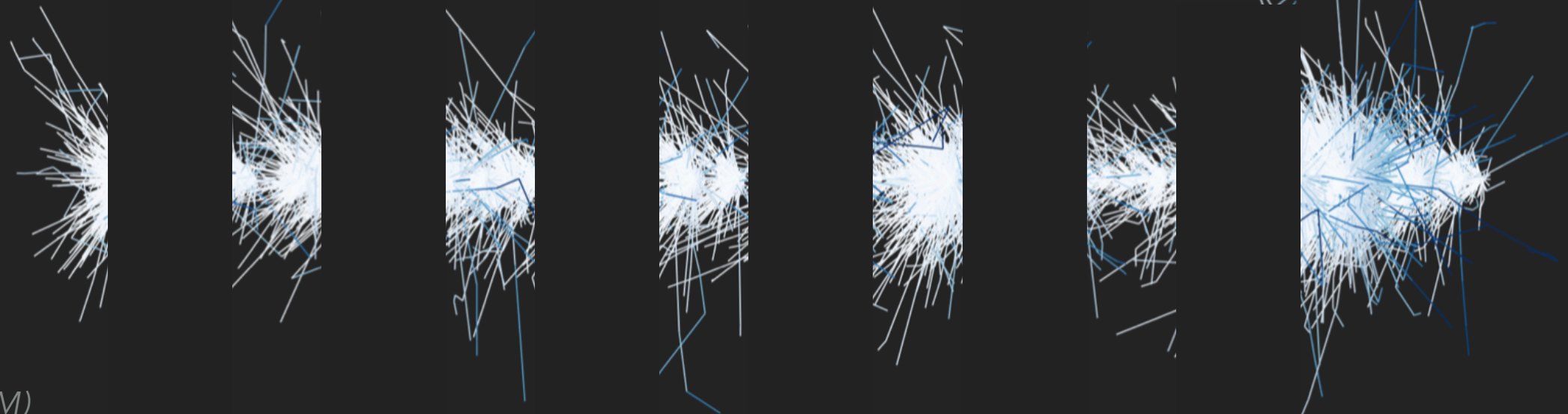
## BRAINSTORMING AROUND A SEGMENTED DETECTOR FOR HE HORIZONTAL TRACKS

medium: IceCube ice



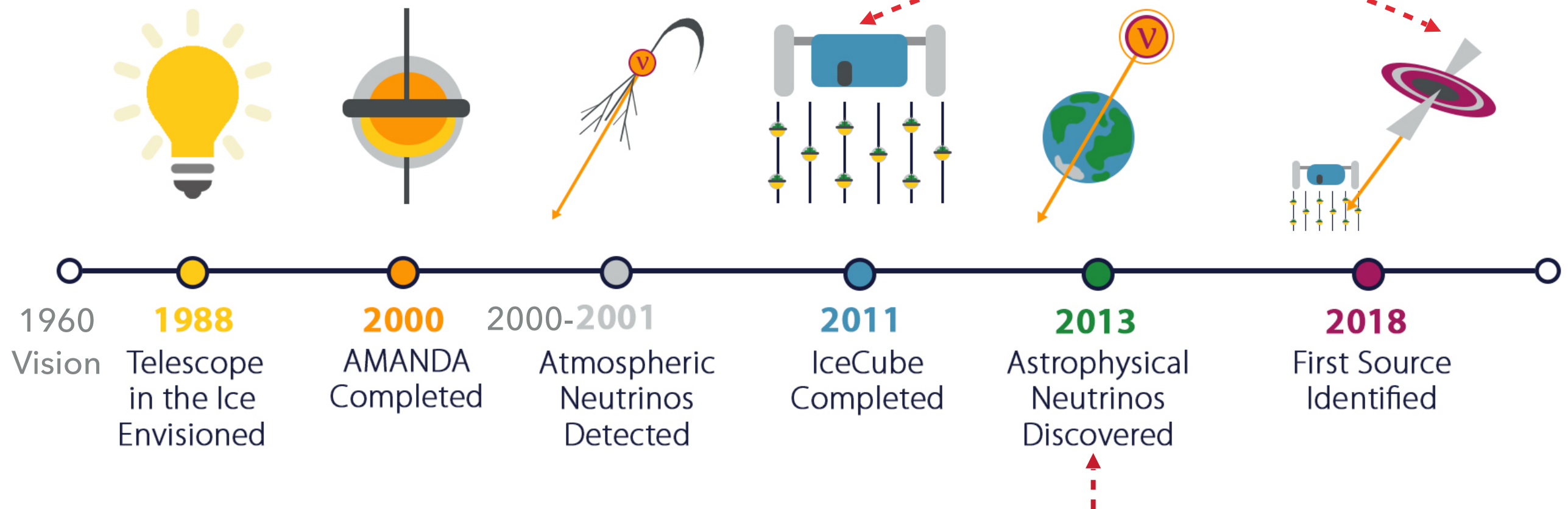
1 PeV muon

medium: Antares water



# A History of Neutrino Astronomy in Antarctica

IceCube and MM partners *first* association to a source

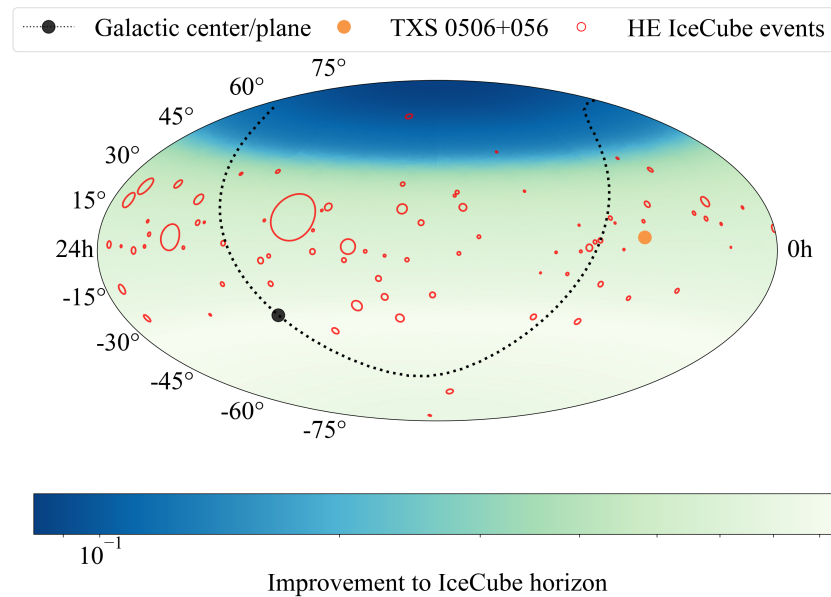


IceCube discovery of *diffuse* astrophysics neutrinos



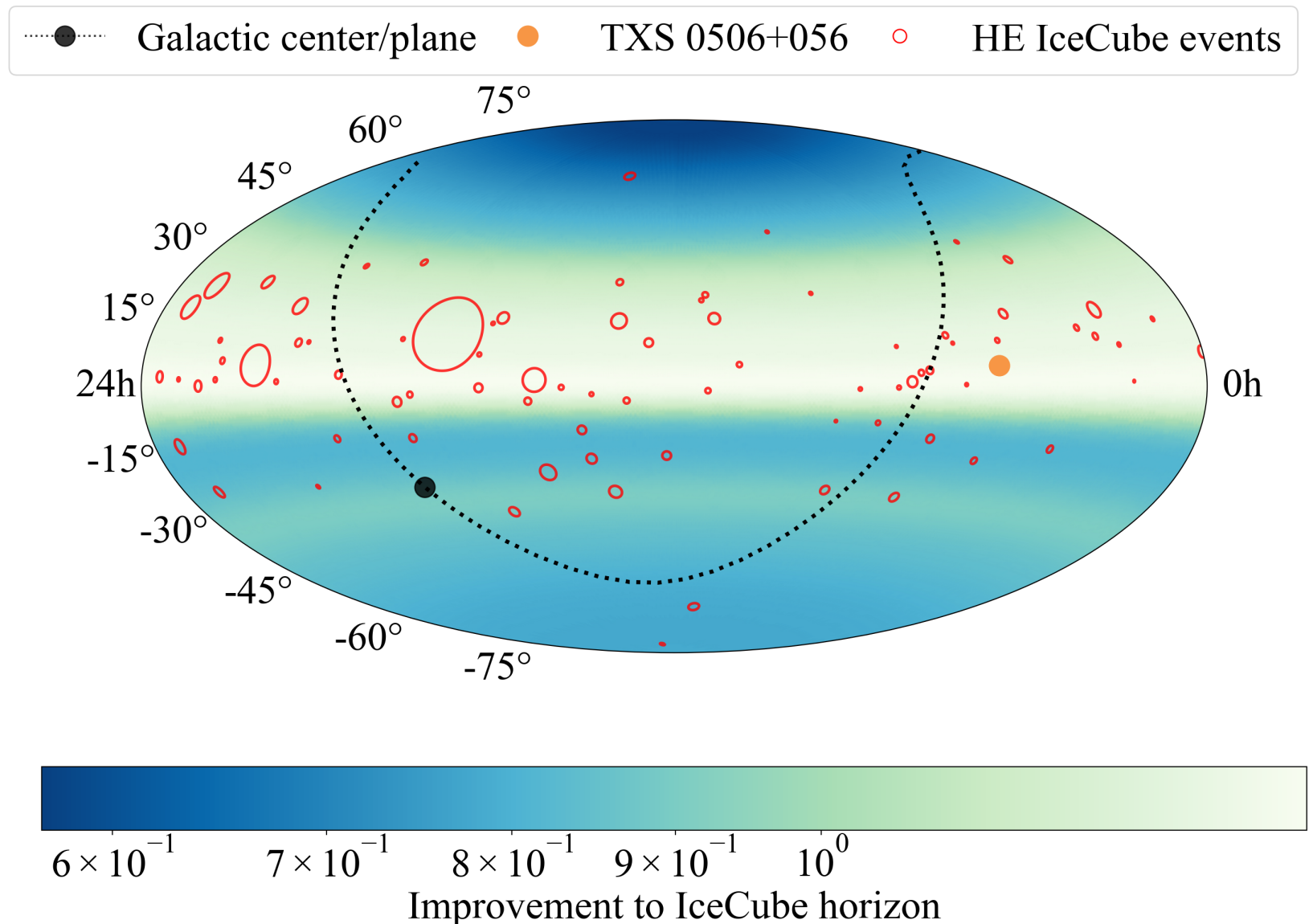
PLE<sub>ν</sub>M

## ICECUBE &amp; BAIKAL (OR ANOTHER SINGLE SITE IN THE NORTH)

➔ **RELATIVE IMPROVEMENT VS ICECUBE HORIZON BEST SENSITIVITY**

GVD only

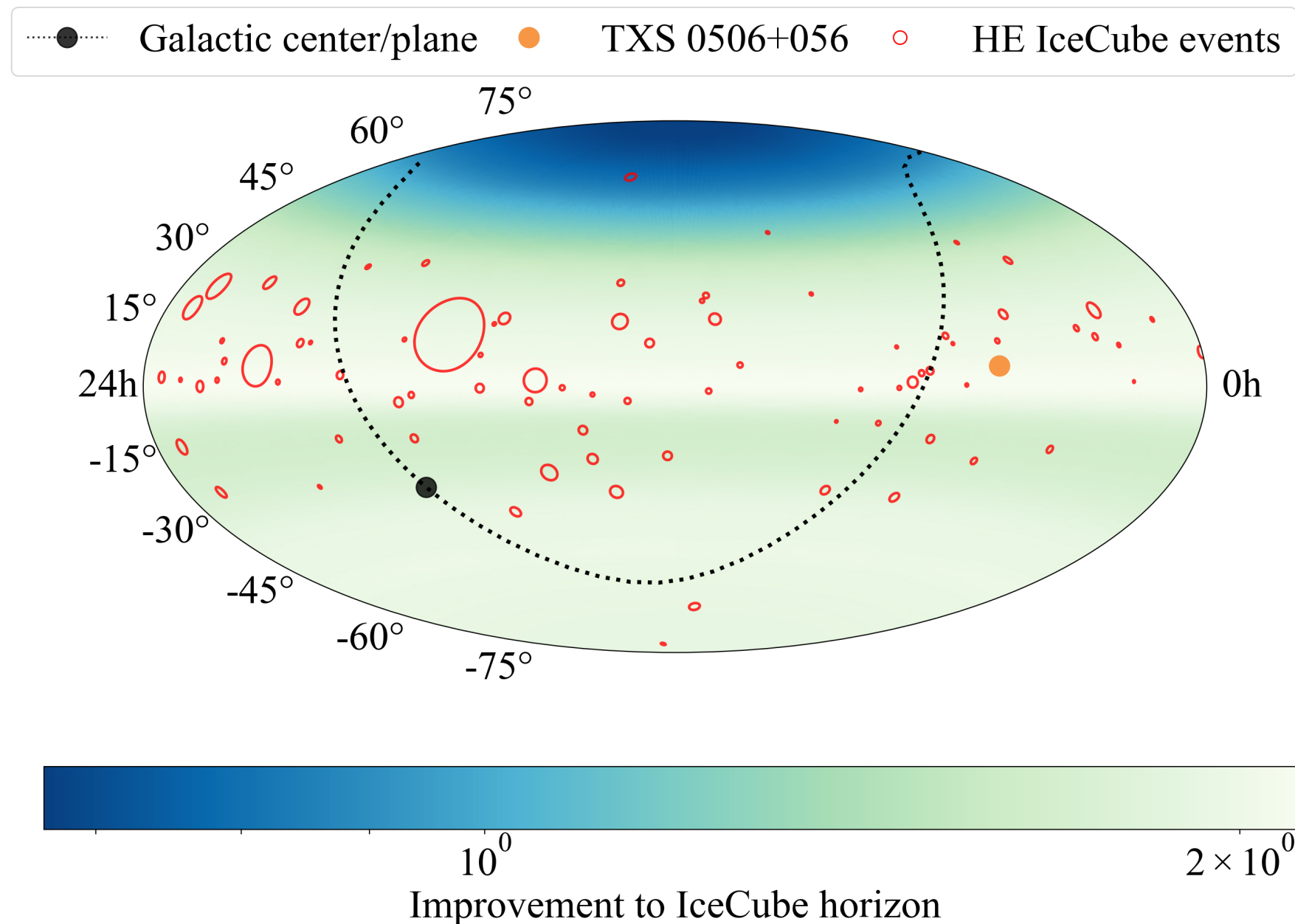
GVD+IceCube / IceCube horizon



on going study by M. Huber (TUM)

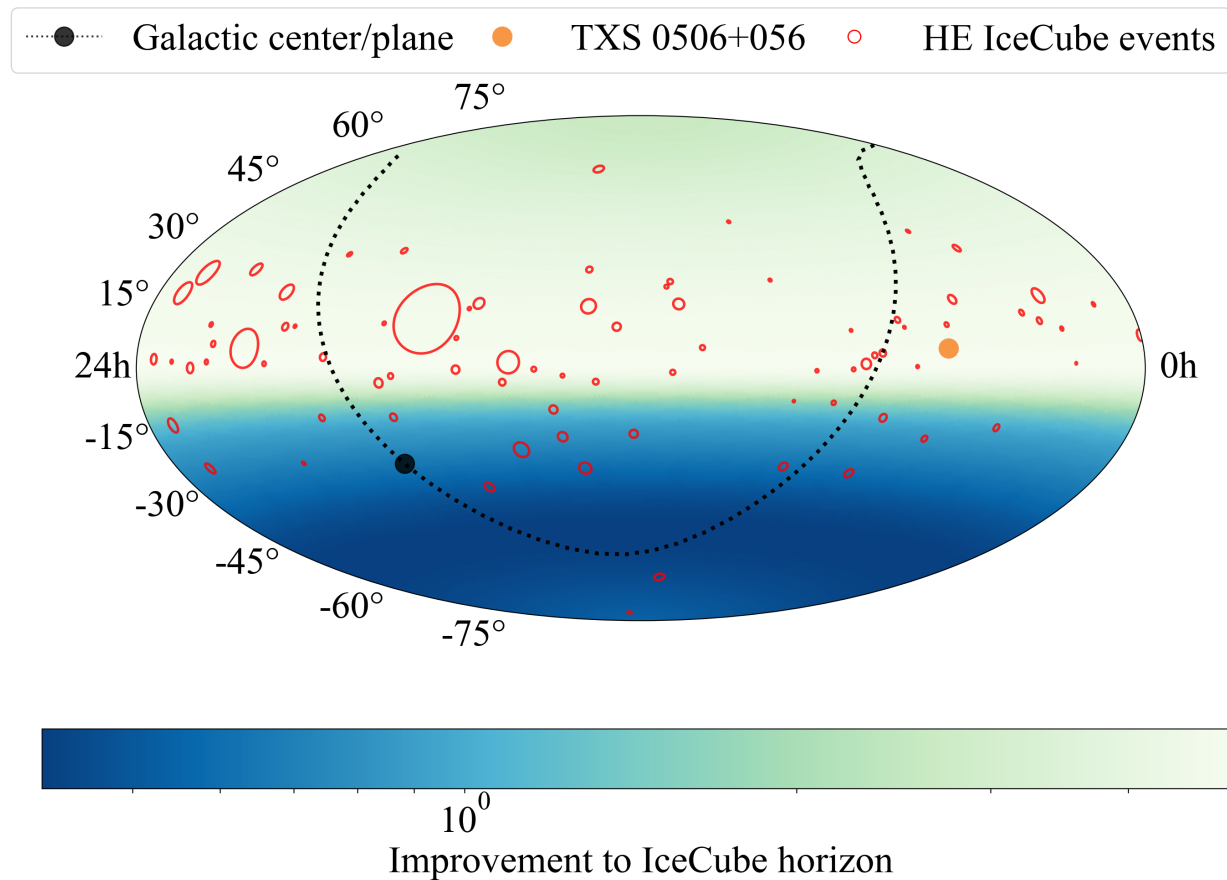
PLE<sub>ν</sub>M

ICECUBE &amp; BAIKAL &amp; CAPO PASSERO &amp; OCEAN NETWORK CANADA

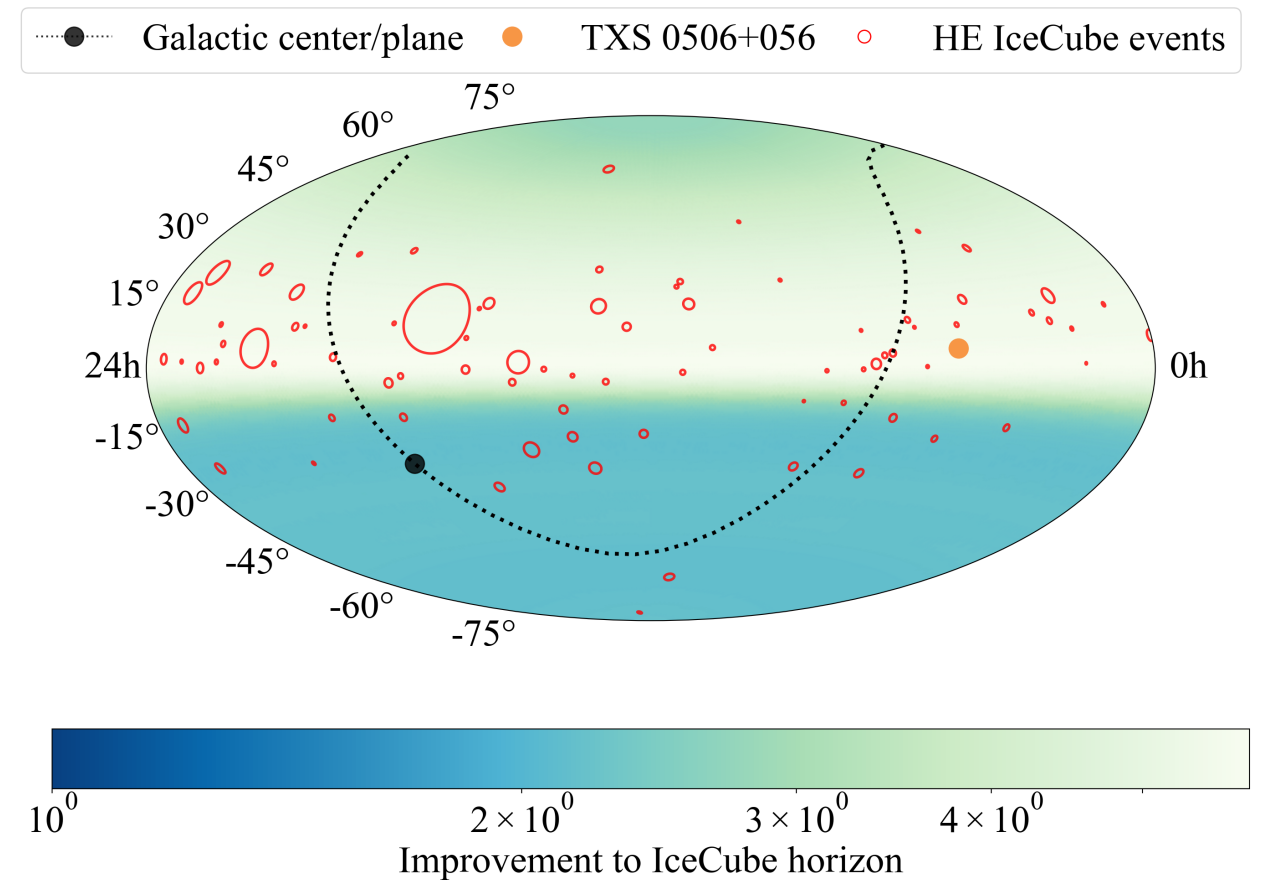
➔ **RELATIVE IMPROVEMENT VS ICECUBE HORIZON BEST SENSITIVITY**

PLE<sub>ν</sub>M➔ RELATIVE IMPROVEMENT VS ICECUBE HORIZON BEST SENSITIVITY

IceCube vs Gen2

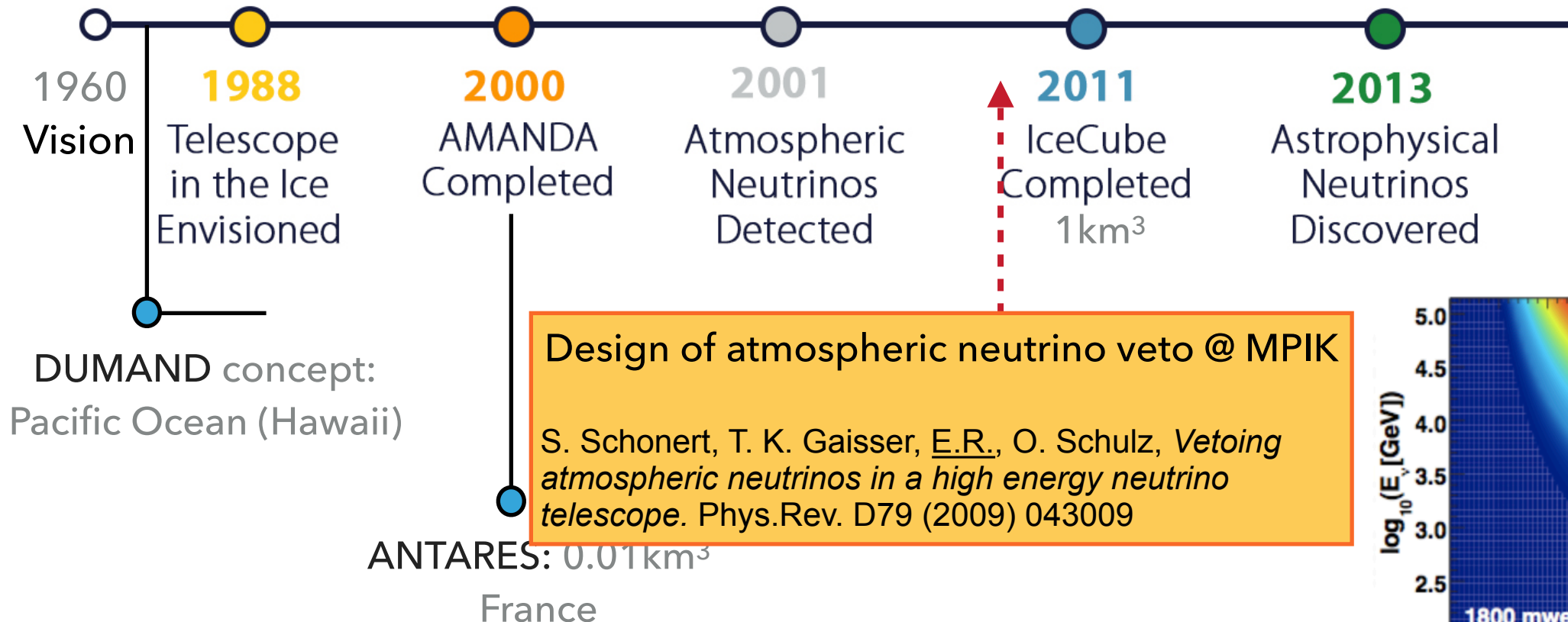
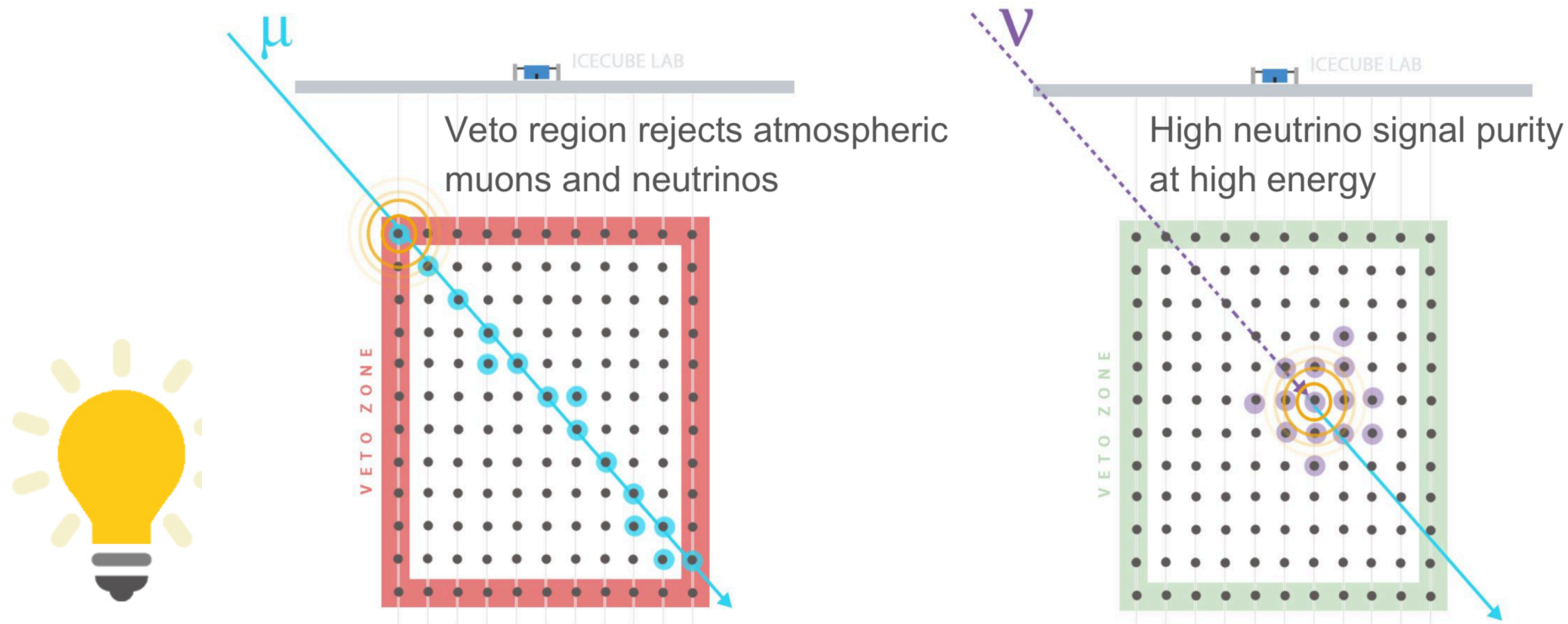


IceCube vs Gen2+GVD+KM3NeT+ONC



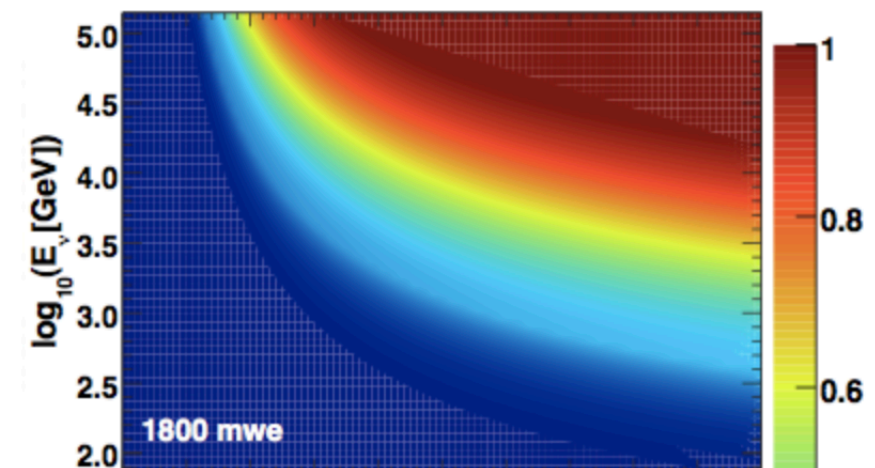


## Starting Events



### Design of atmospheric neutrino veto @ MPIK

S. Schonert, T. K. Gaisser, E.R., O. Schulz, *Vetoing atmospheric neutrinos in a high energy neutrino telescope*. Phys.Rev. D79 (2009) 043009



What do we need in order to open the cosmic neutrino sky to more *routine* observations?





What do we need in order to open the cosmic neutrino sky to more *routine* observations?

More OBSERVERS





# THE AFTERMATH OF TXS 0506+056: IS A BLAZAR

TXS0506+056 NEUTRINO CONTRIBUTION TO THE DIFFUSE: SMALL

➔ MUCH MORE TO DISCOVER OUT THERE!!

