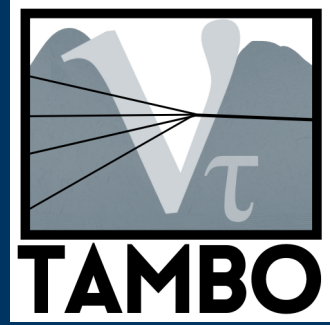




the David
Lucile & Packard
FOUNDATION

The future of neutrino astronomy with TAMBO

NNN24 @ Rio de Janeiro

31/10/24

Happy Halloween!

Pavel Zhelnin for the TAMBO collaboration



1846

2030s?



Le Verrier

Neptune



TAMBO

ν observatories

1846

2030s?



Le Verrier

Neptune

It's not that the tech isn't good enough,
the sky is so vast you need to know where to look



TAMBO

ν observatories

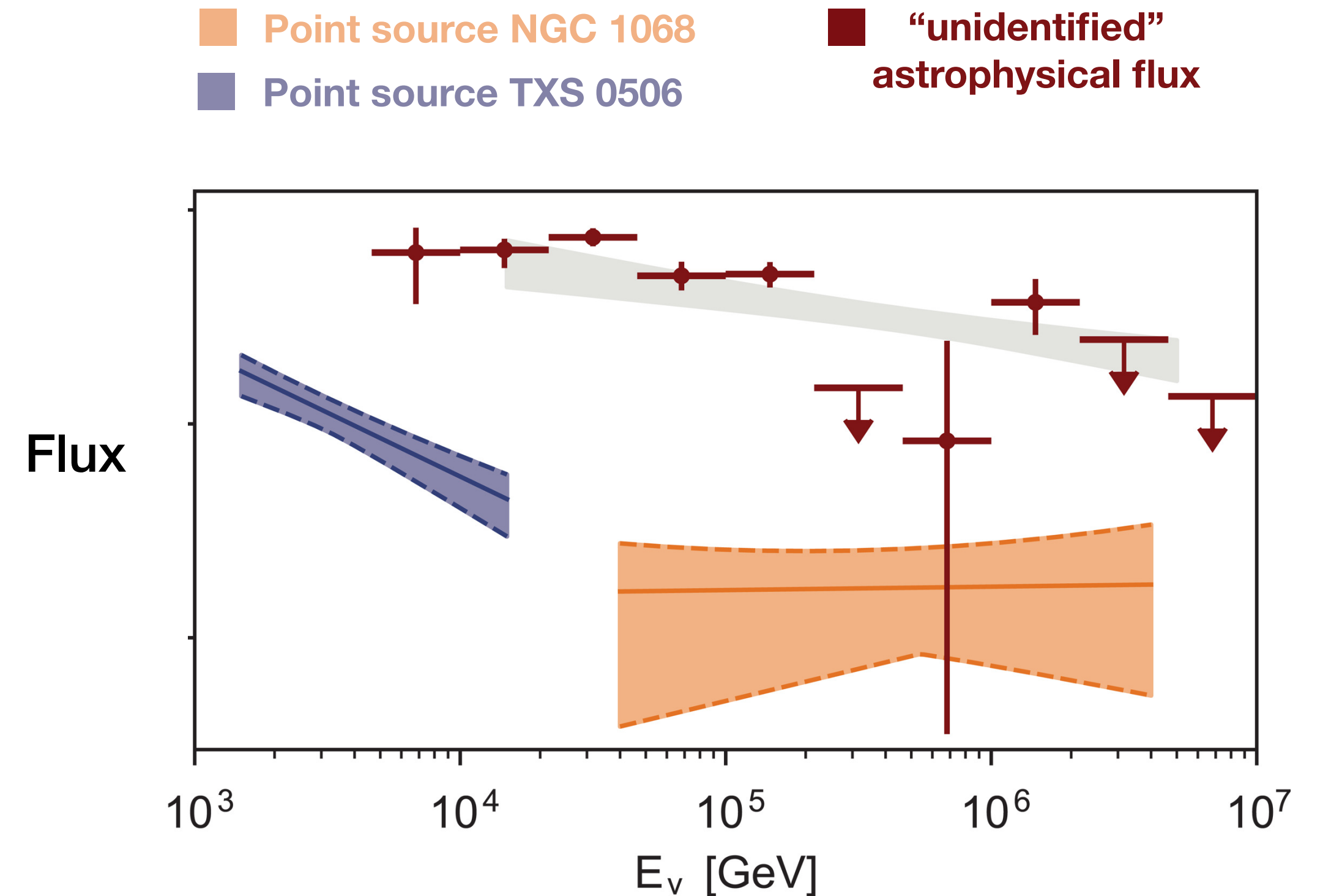
Overview

- Open Problems in Neutrino Astronomy
- How TAMBO works
- Physics Prospects
- Conclusion

Open Problems in Neutrino Astronomy

Where are ν point sources?

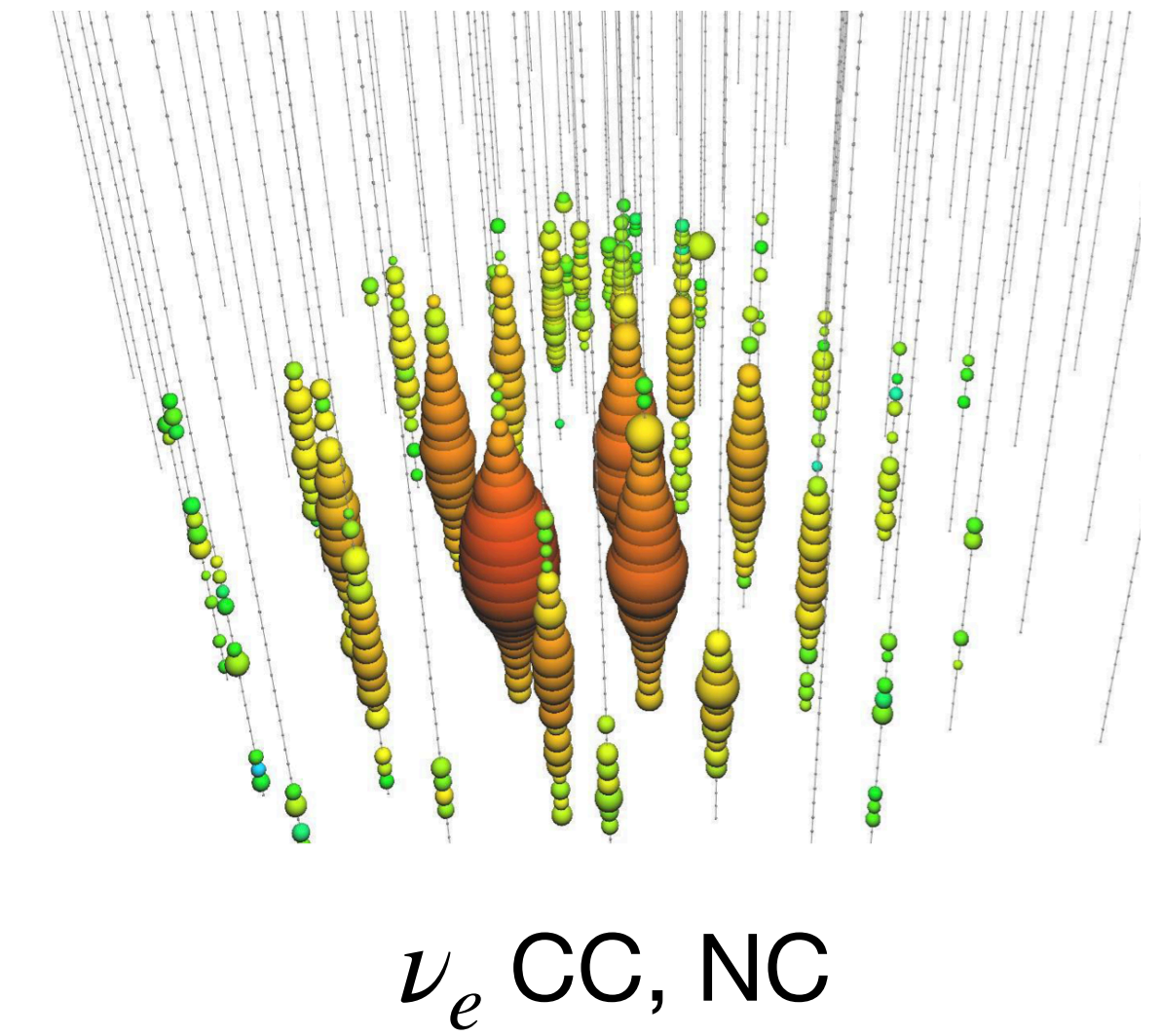
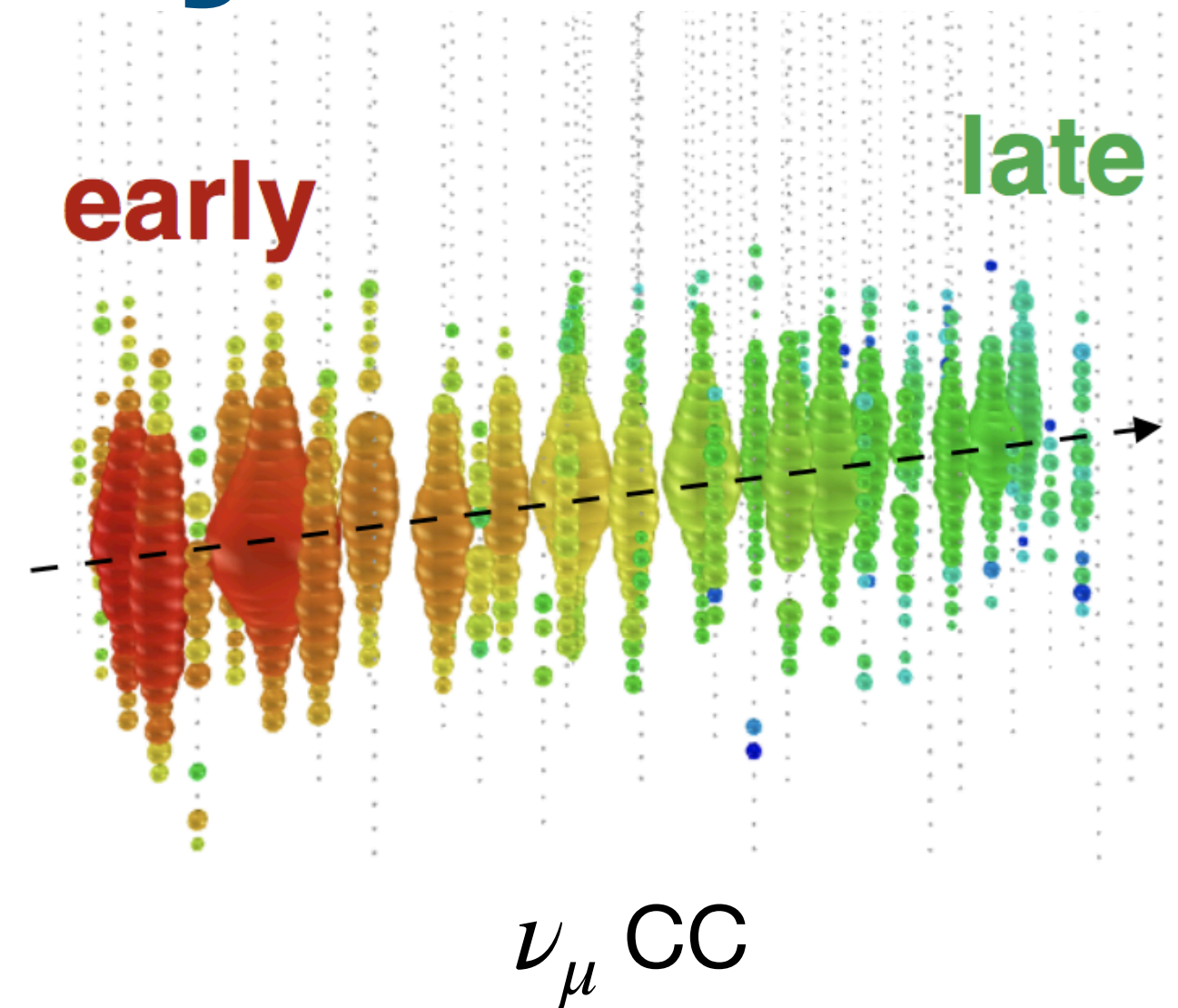
- **ν point source** - specific astro object that emits neutrinos
- **Why do we think they are out there?** In 2013, IceCube discovered an *unidentified* astro neutrino flux



- 11 years later: at least 2 point sources but flux is small
- More point sources out there but trouble knowing where to look

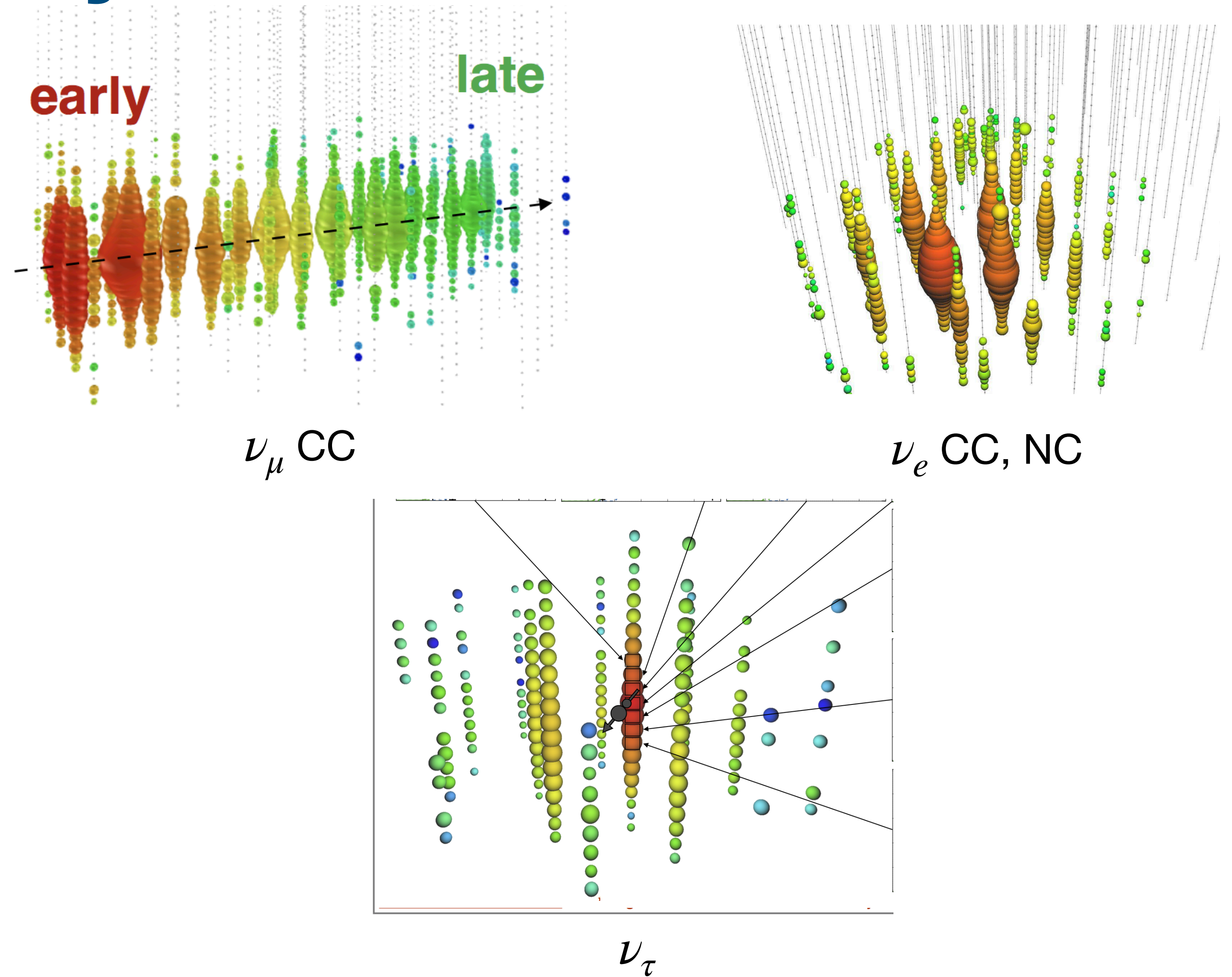
What is the astrophysical ν flavor ratio?

- Easy to separate ν_μ from everything else
- Difficult to separate ν_τ events from ν_e
- Leaves the ratio of astro $\nu_e : \nu_\mu : \nu_\tau$ outside SM-allowed region unconstrained



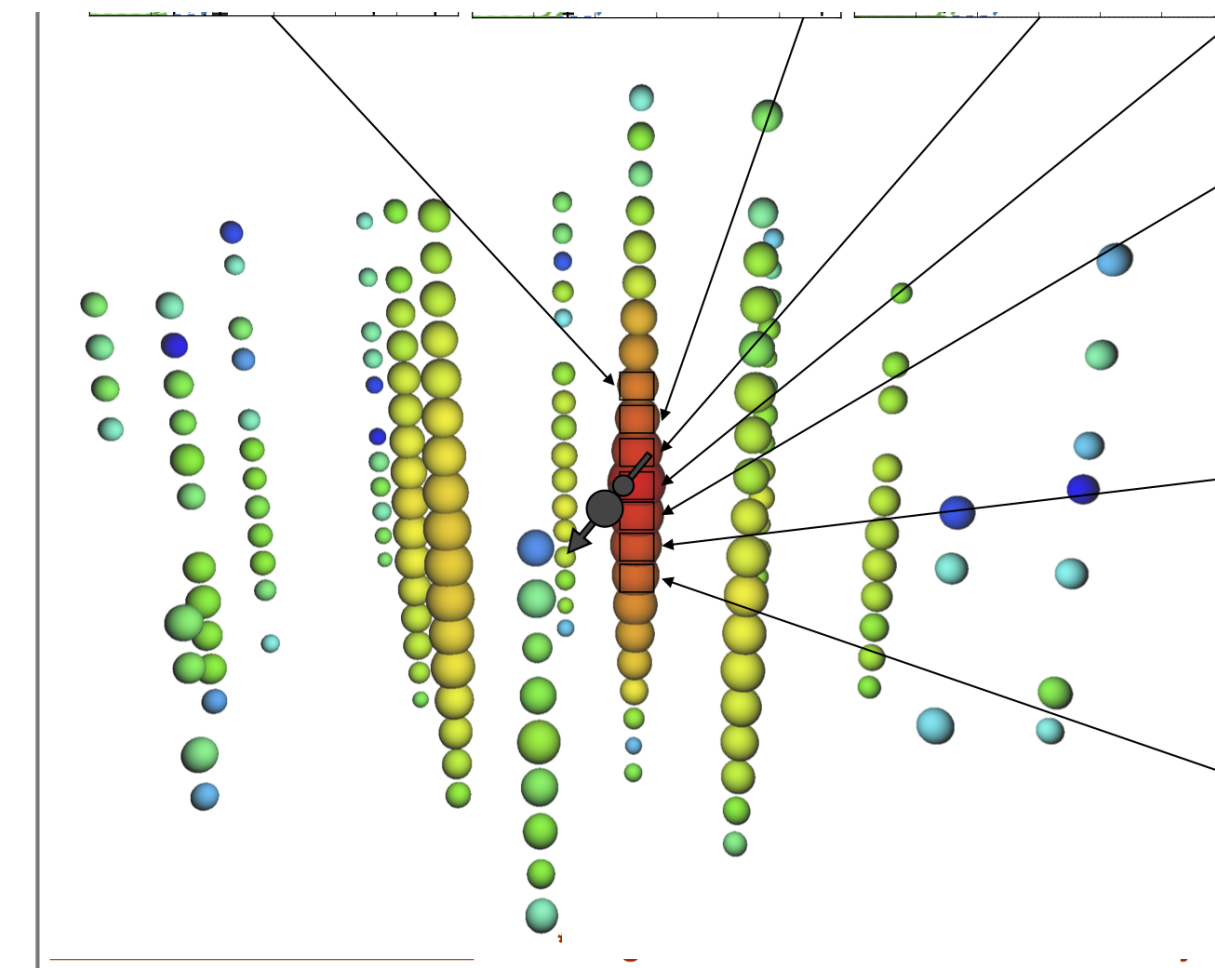
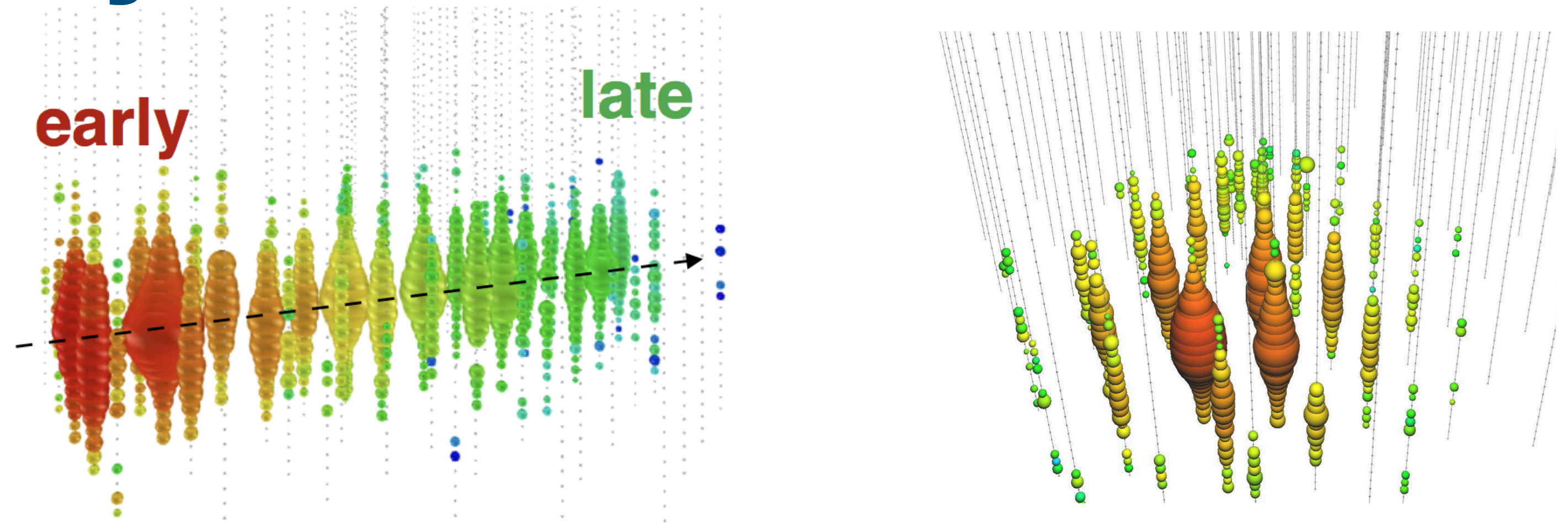
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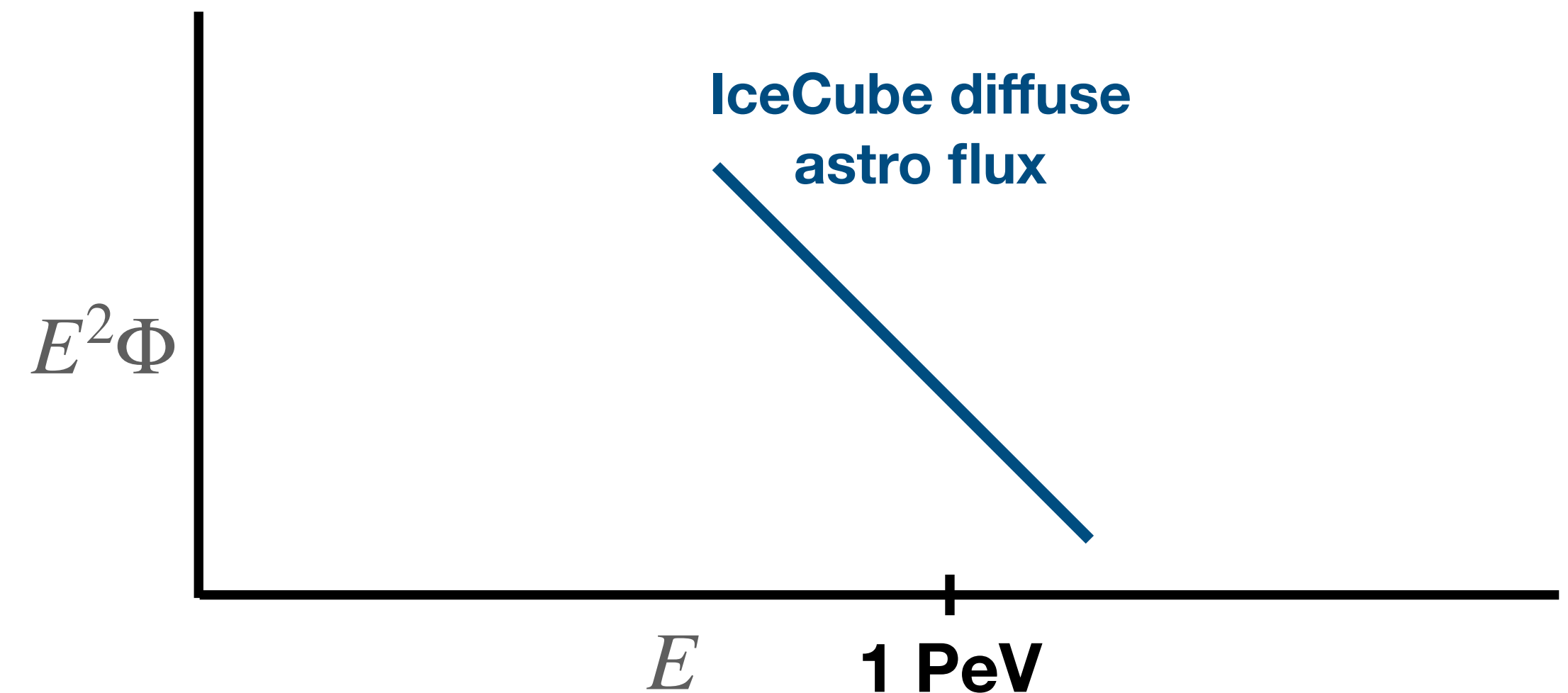


Can you
separate ν_e from ν_τ
without the labels?



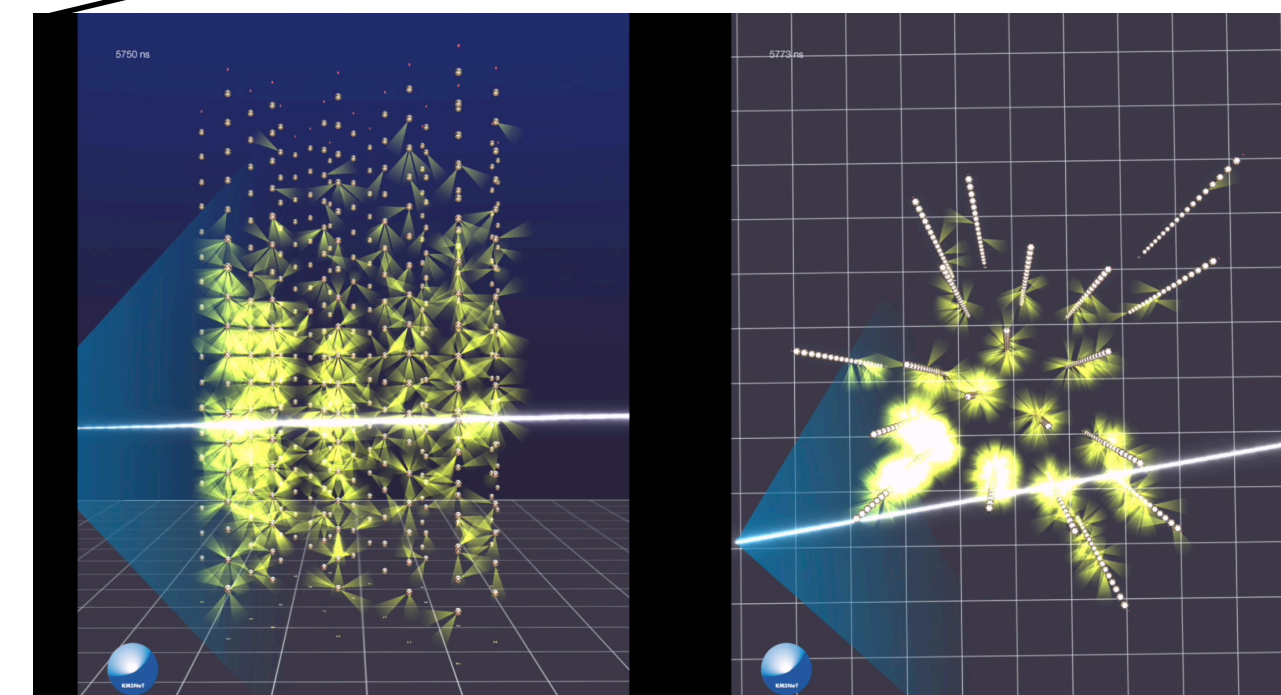
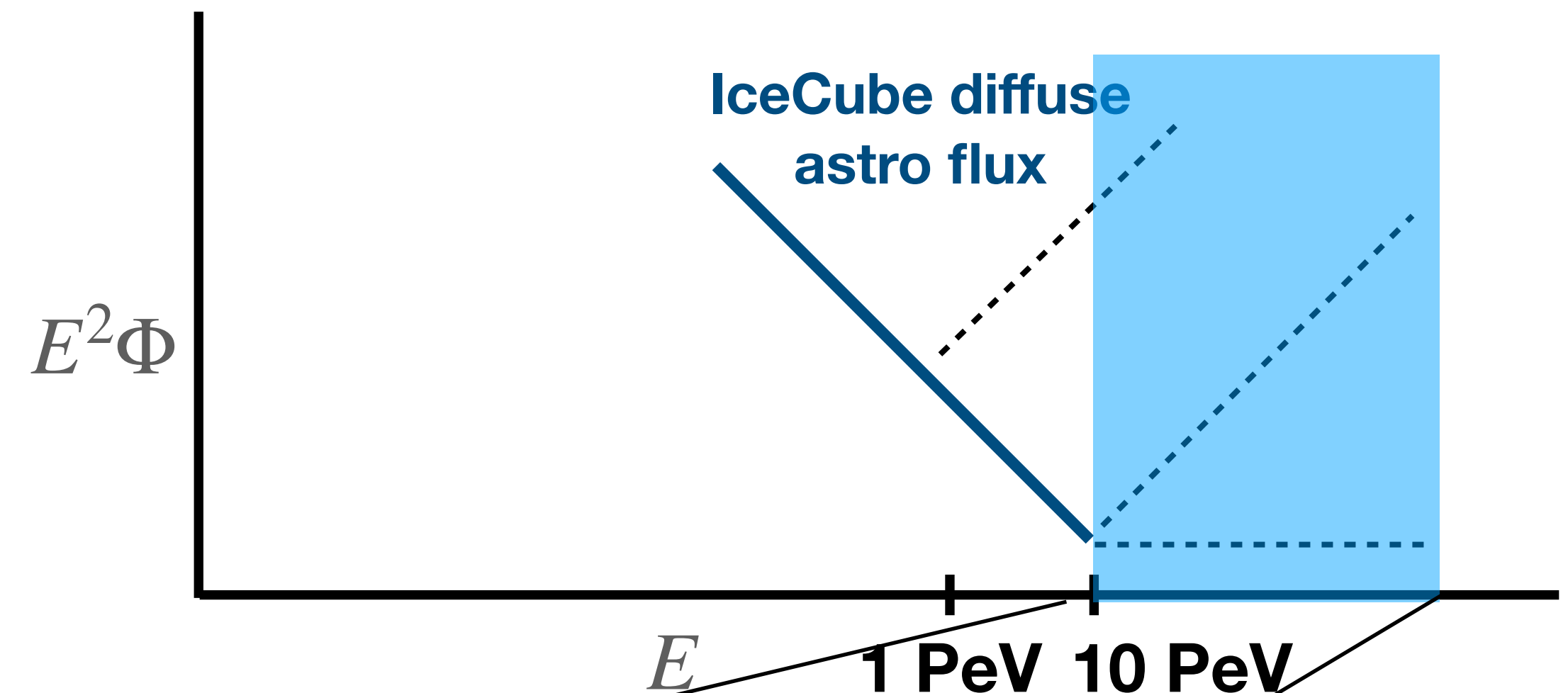
How does the ν spectrum behave > 1 PeV?

- We don't know the behavior of astrophysical neutrinos > 1 PeV



How does the ν spectrum behave > 1 PeV?

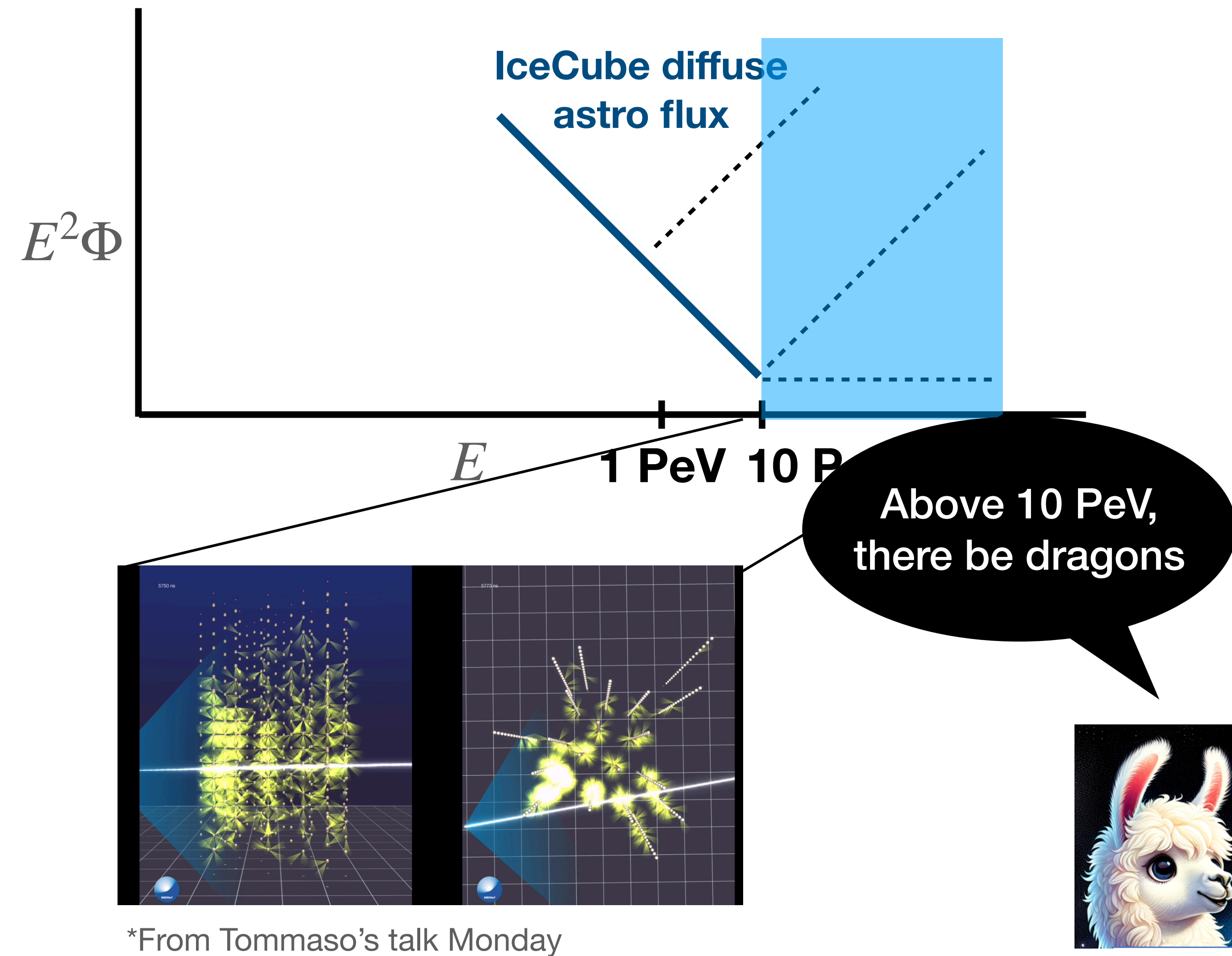
- We don't know the behavior of astrophysical neutrinos > 1 PeV
- The break from extended IceCube flux could @ 1 PeV, 10 PeV, X PeV or not all
- Cosmogenic neutrinos (GZK cutoff)
- KM3NeT event (transient or maybe source)?



*From Tommaso's talk Monday

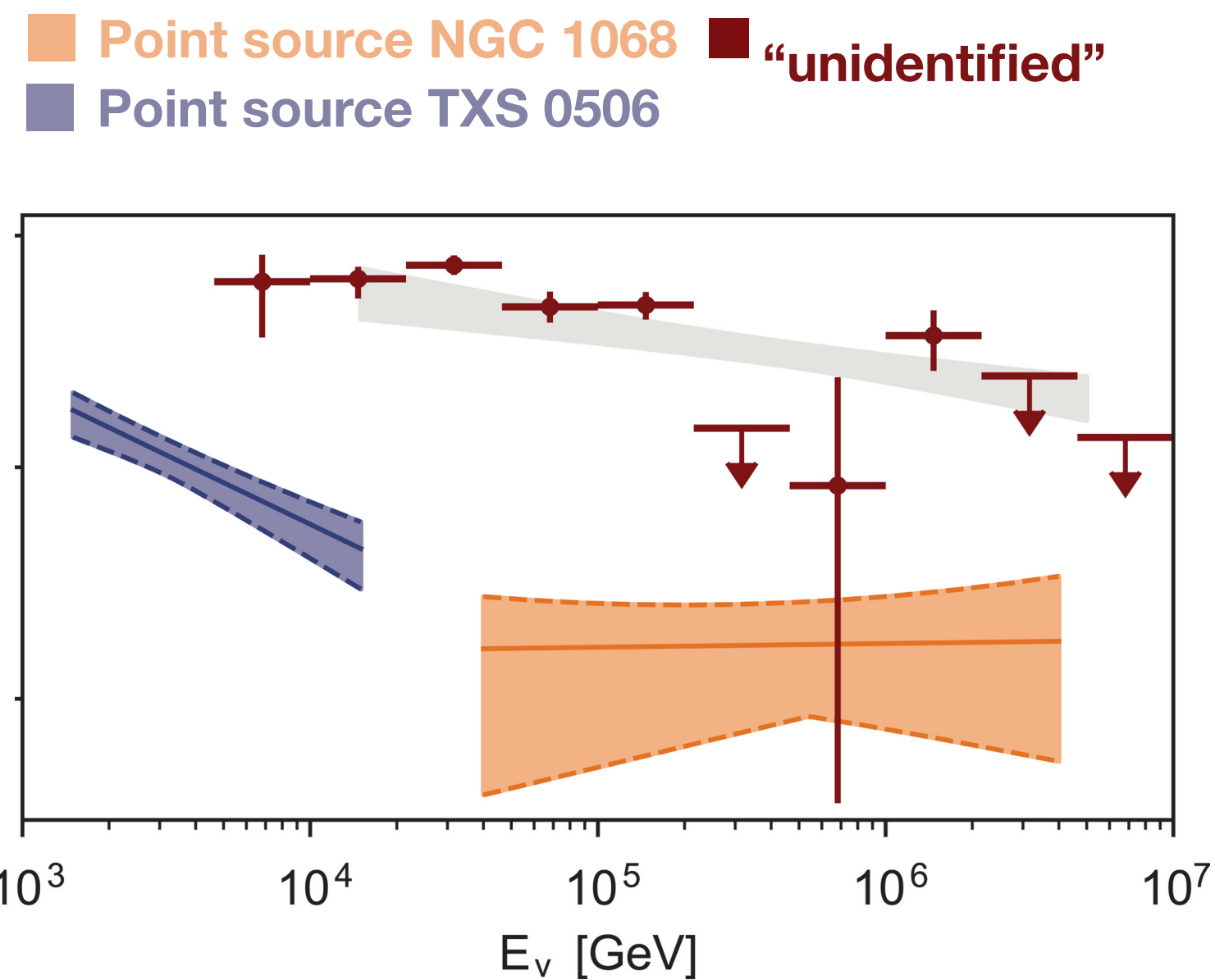
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- We don't know the behavior of astrophysical neutrinos > 1 PeV
- The break from the extended IceCube flux could happen at 1 PeV, 10 PeV, X PeV or not all
 - Cosmogenic neutrinos (GZK cutoff)
 - KM3NeT event (transient or maybe source)?
- Dedicated experiment to characterize flux above 1 PeV

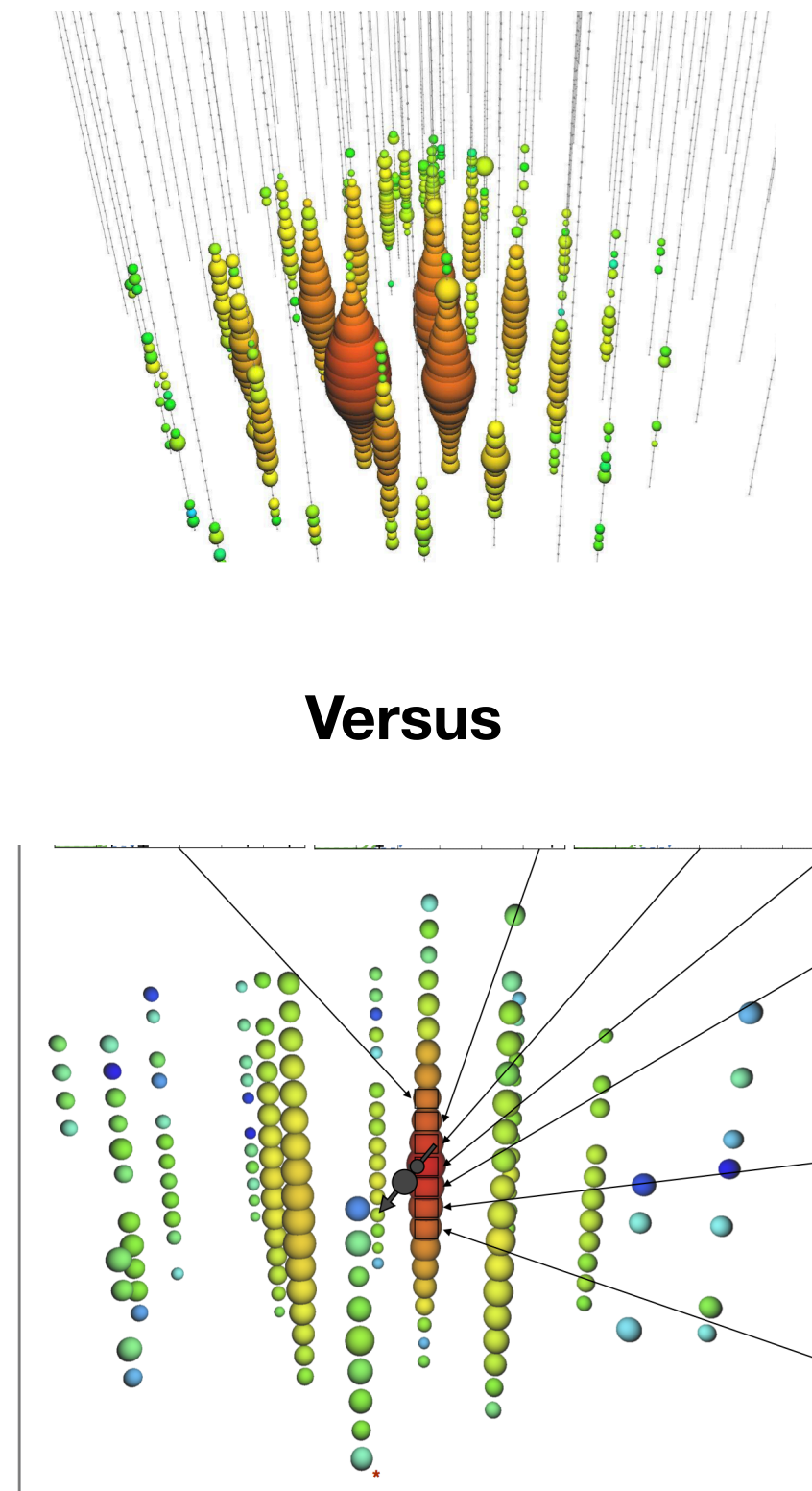


Science goals of TAMBO

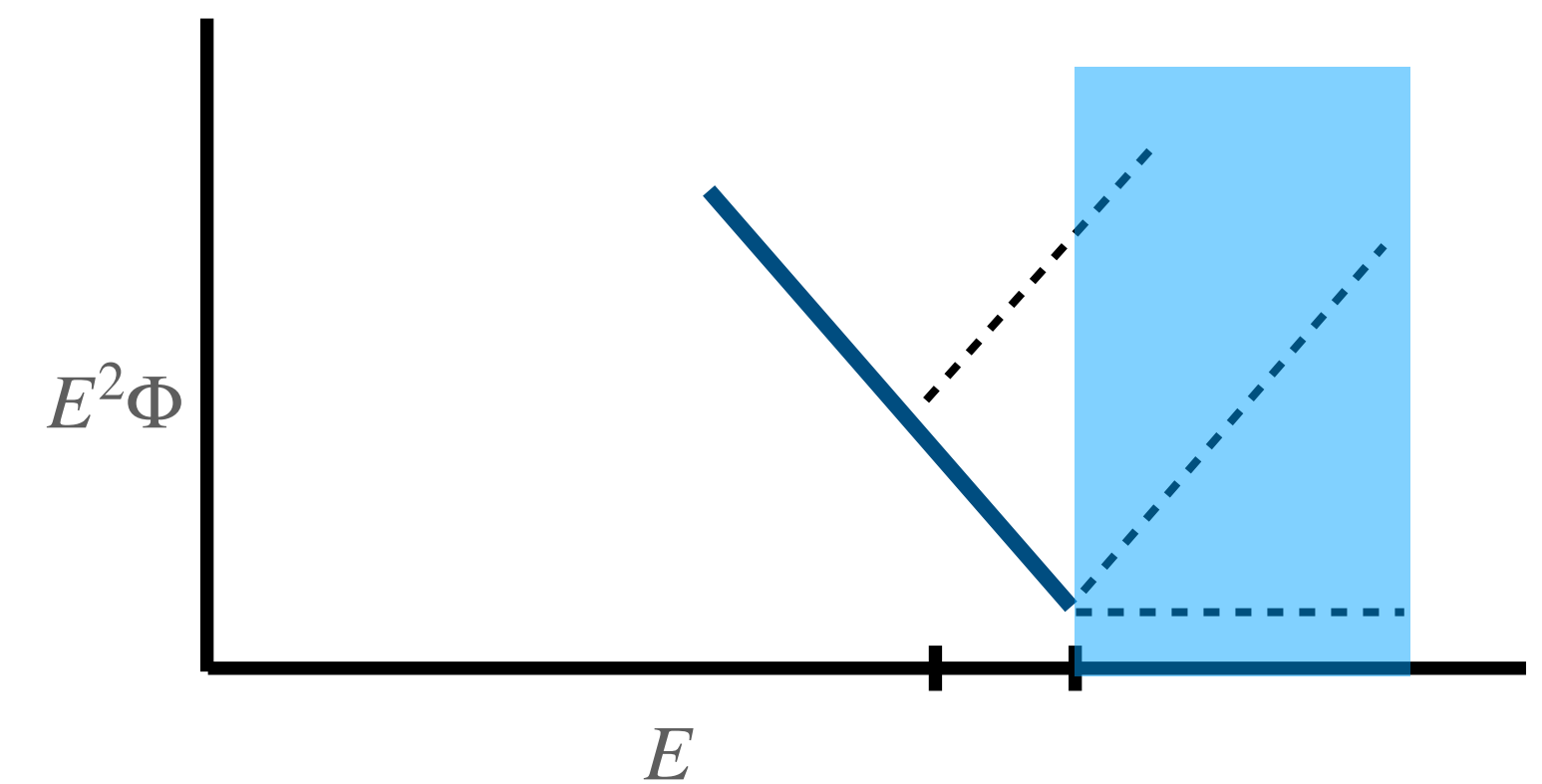
Discover new ν point sources



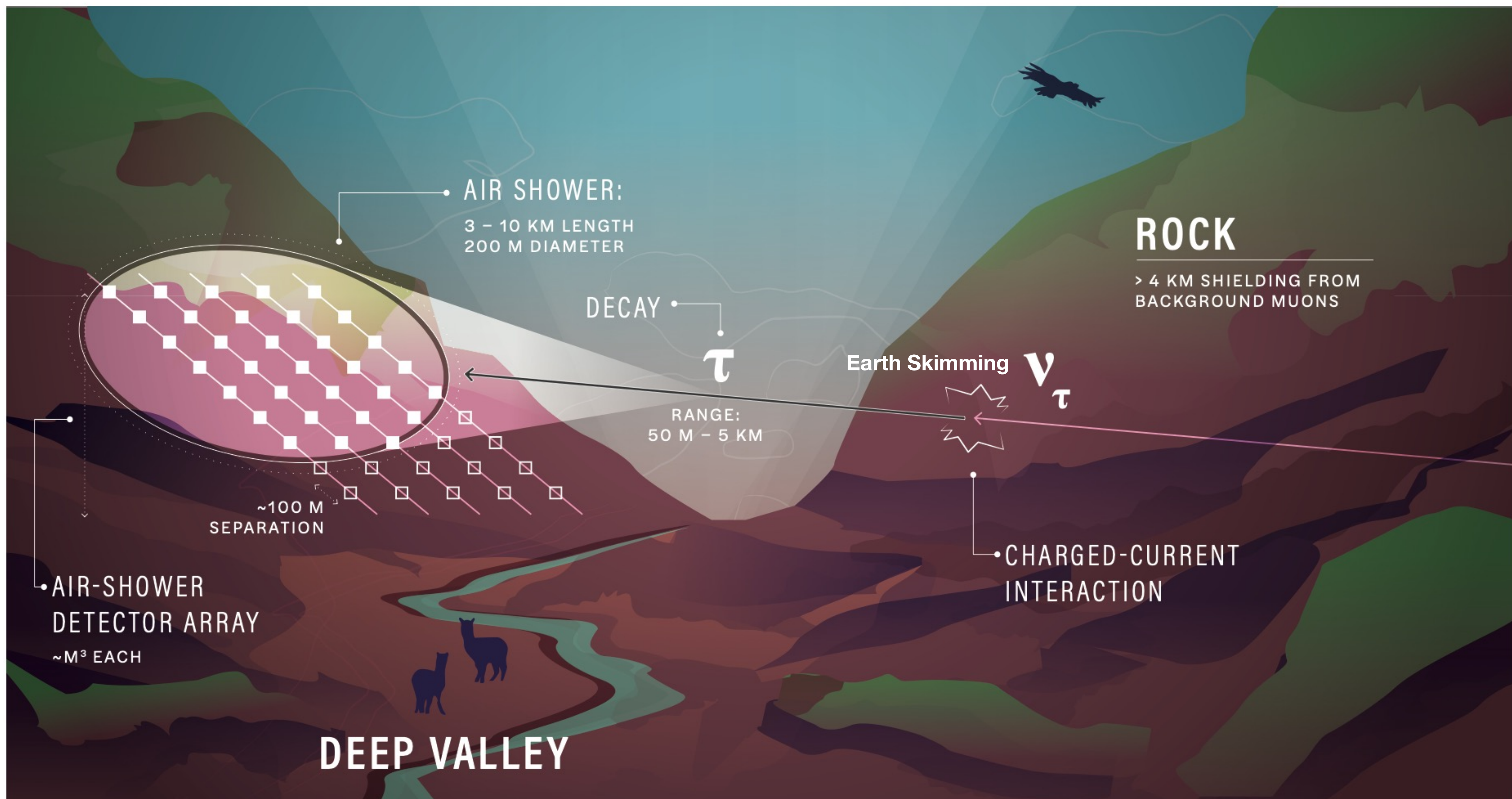
Constrain the astro flavor ratio
by measuring ν_τ component



Characterize the 1-100 PeV
 ν flux



TAMBO



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) • COLCA VALLEY, PERU

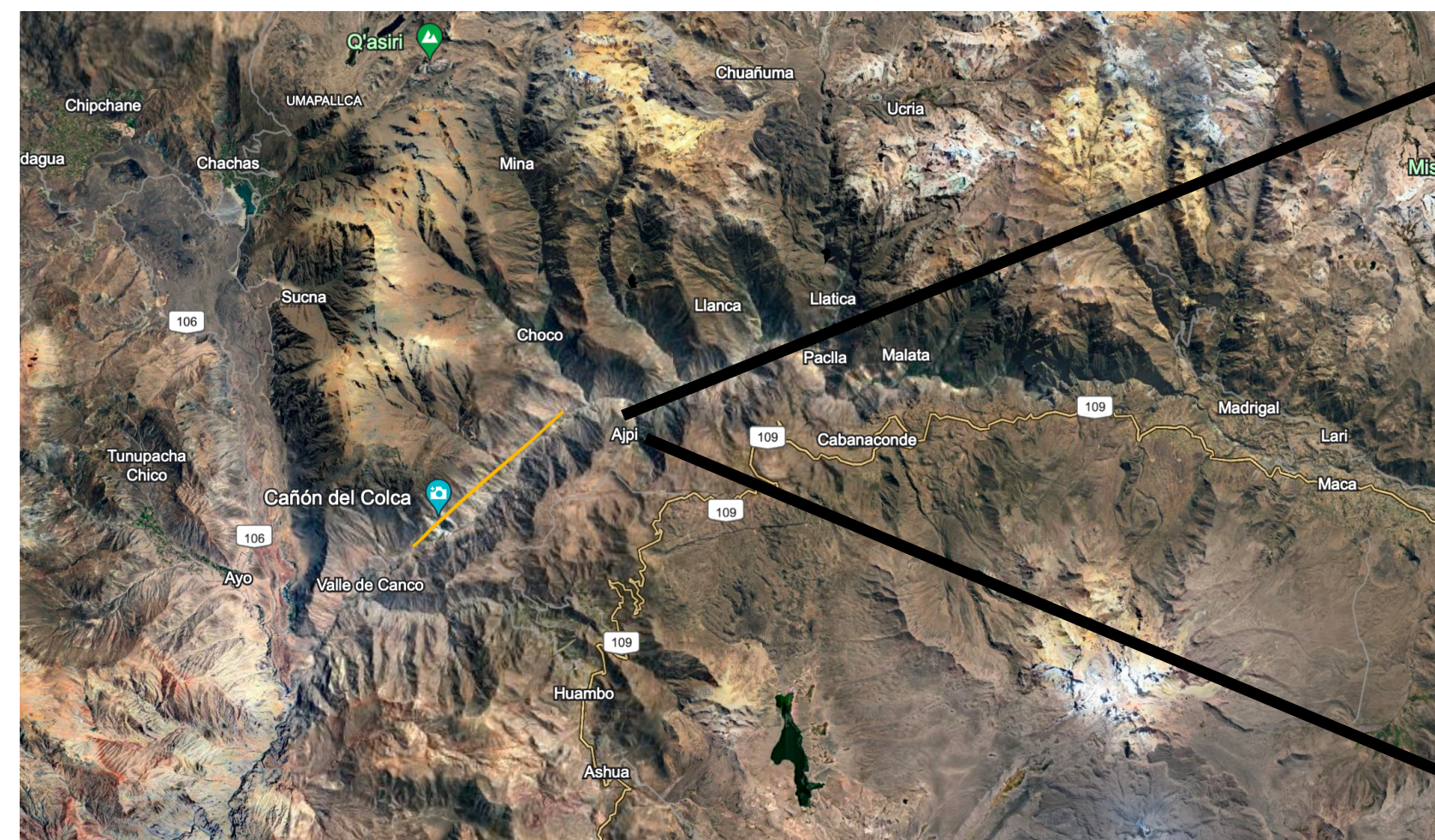
Valley requirements



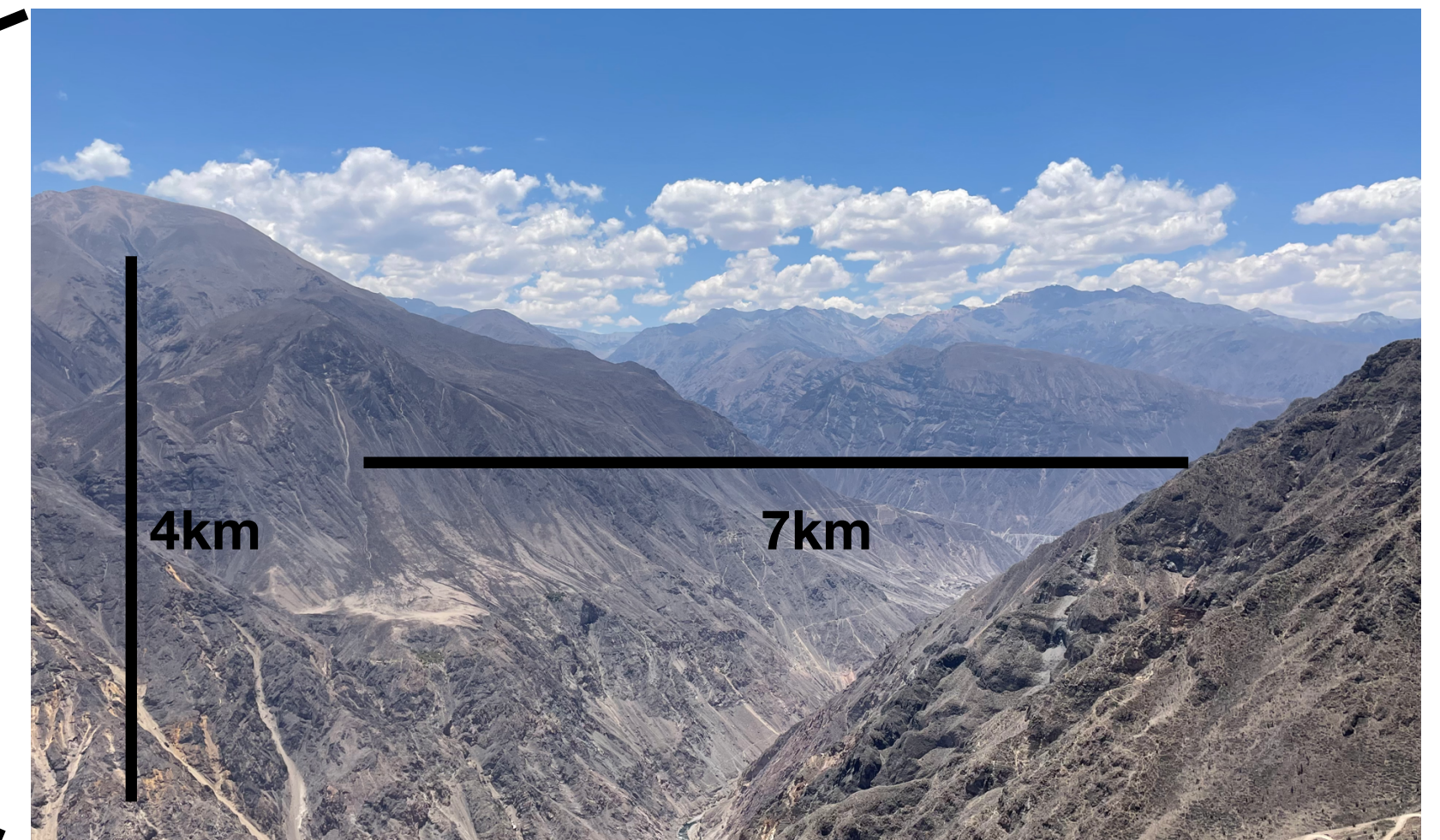
- Tall to maximize capturing Earth-skimming flux
- Width of 5-10 kilometers to capture τ decay + air shower
- Few options in the world - Colca Valley in Peru seems to best fit the description



Peru



Colca Valley

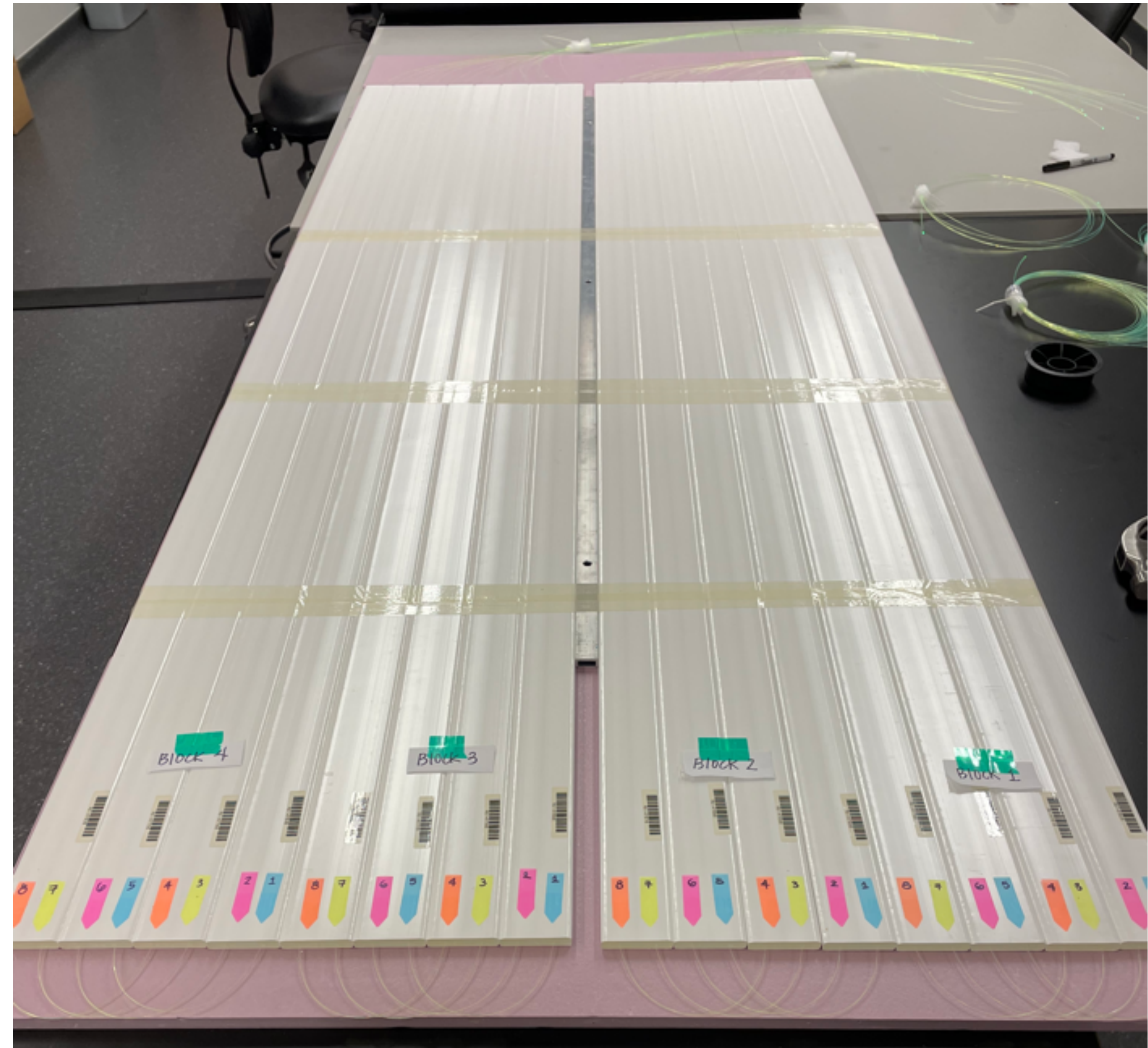
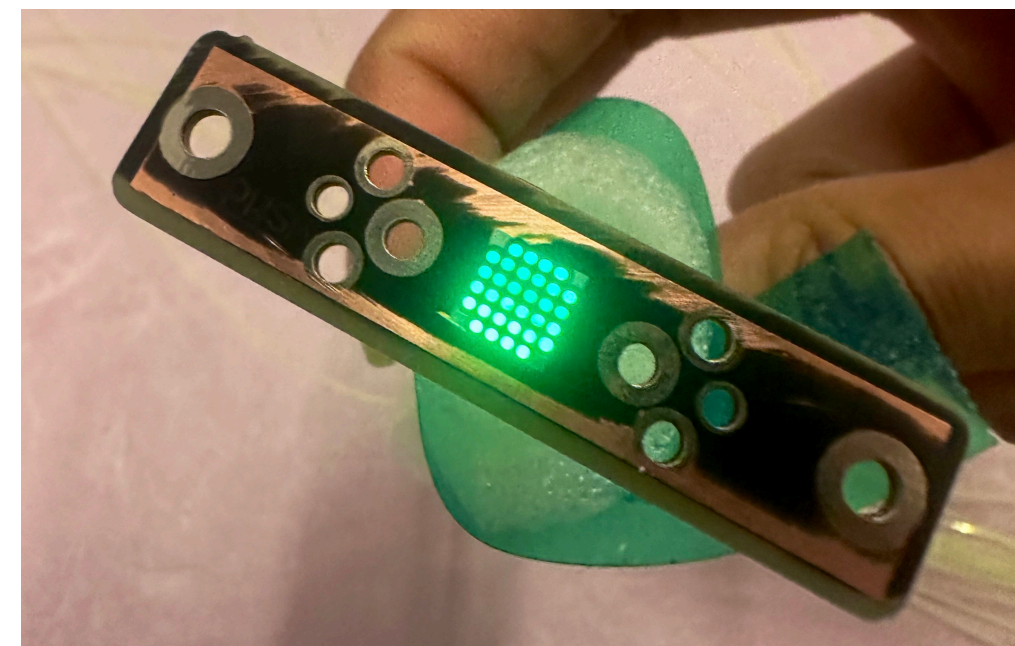
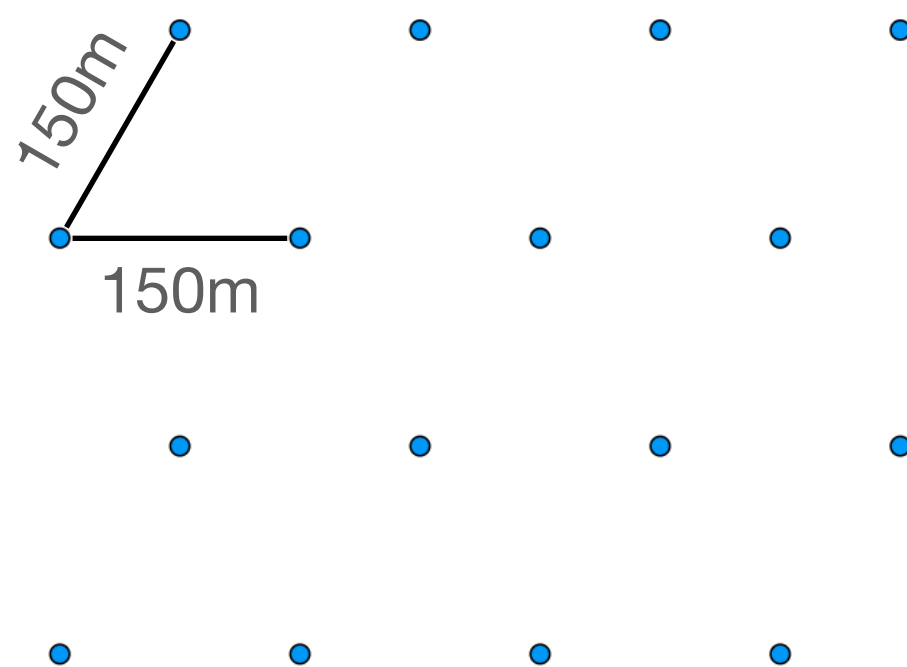


Test Site

Detectors / panels

- Current design: 5k modules spaced 150m apart in a triangular grid
- Scintillator bars with optical fibers coupled to the end which are themselves coupled to a SiPM
- ~cheap + well tested technology

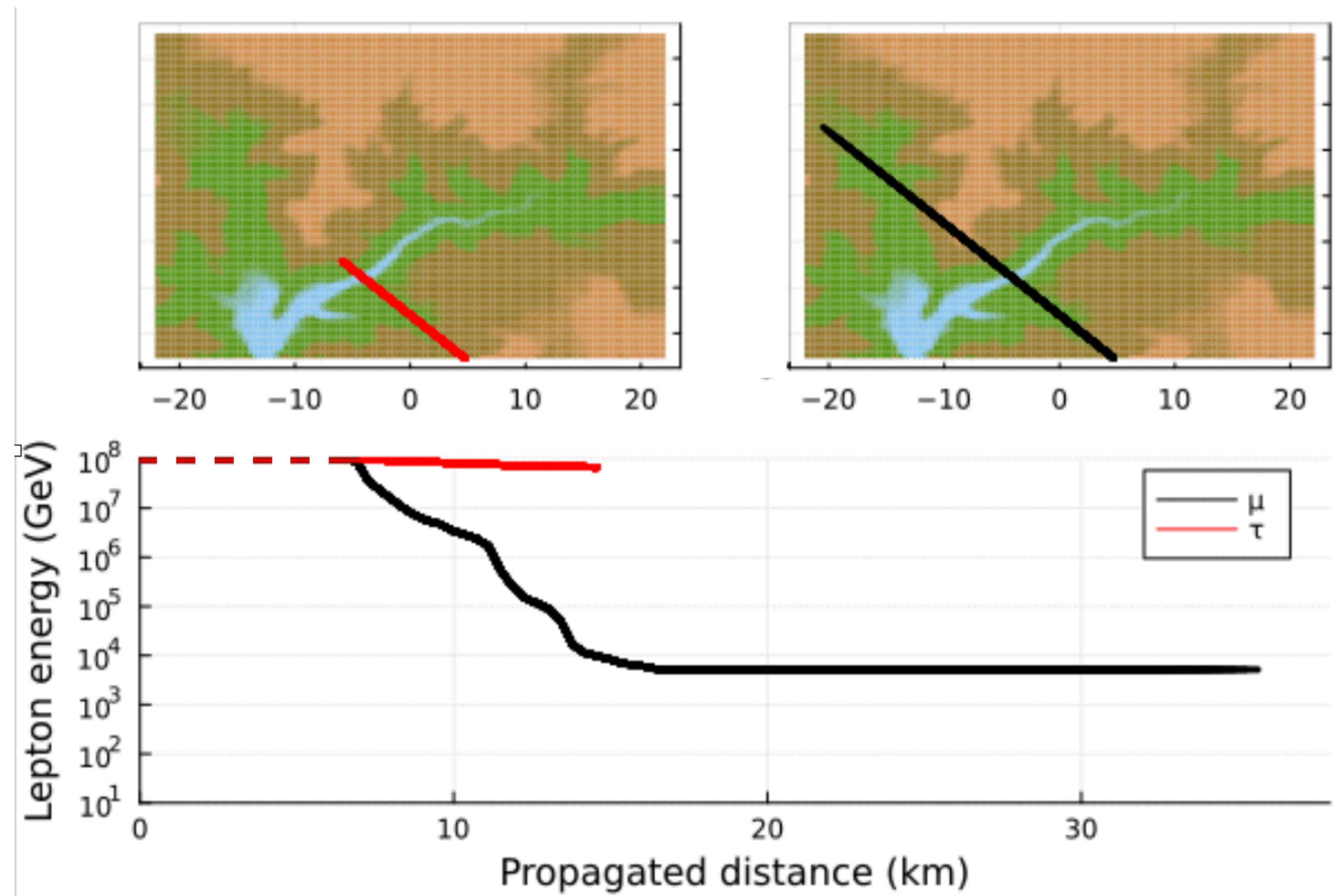
Array design



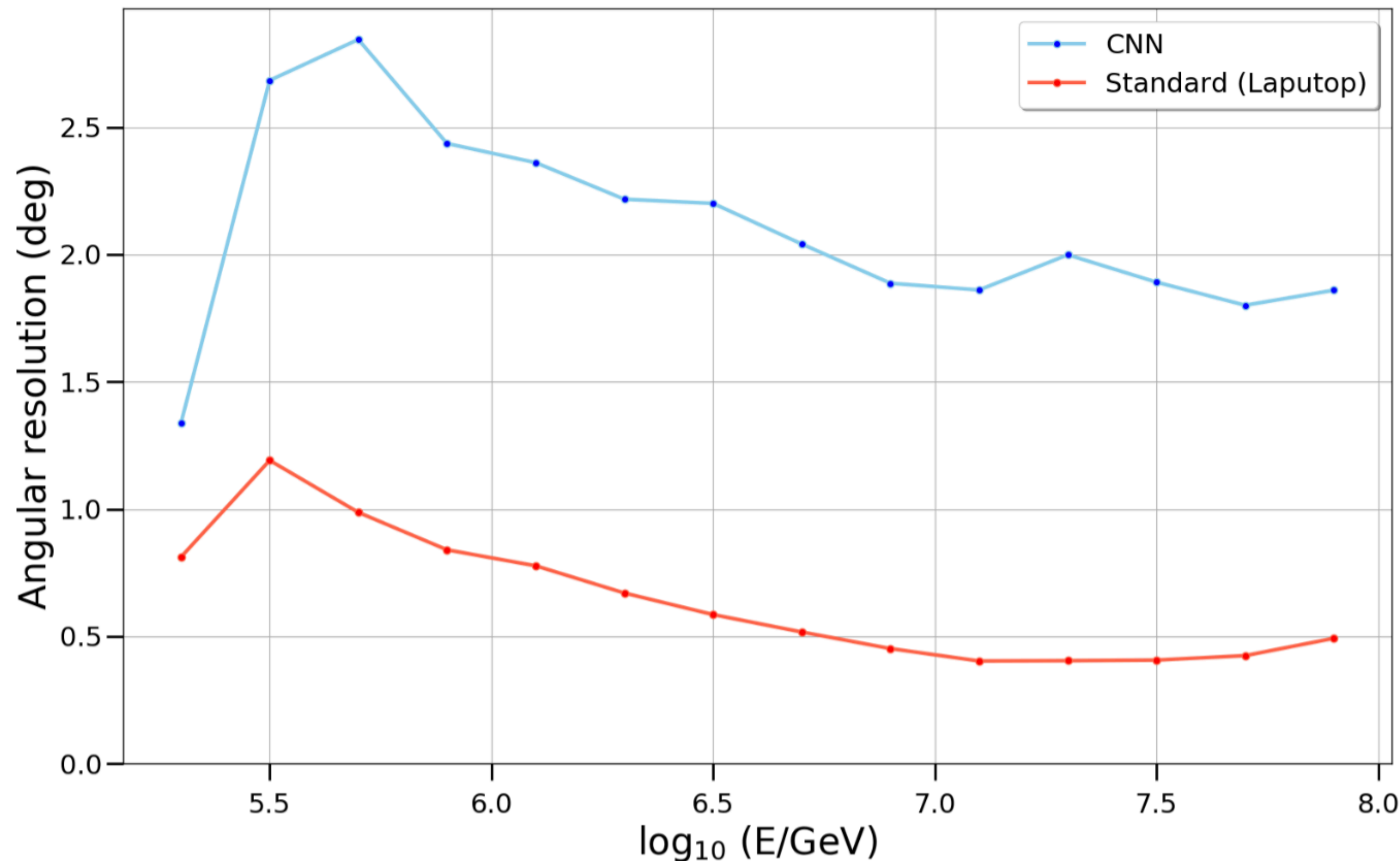
Physics prospects

TAMBO exclusively sees astro ν_τ

- Air-shower is exclusive to ν_τ
- μ^- travels a long time
- e^- entirely shielded by rock
- Too high energy for atmospheric ν_τ
- **Every ν_τ we observe is an astro ν_τ**



TAMBO can create a point source catalog

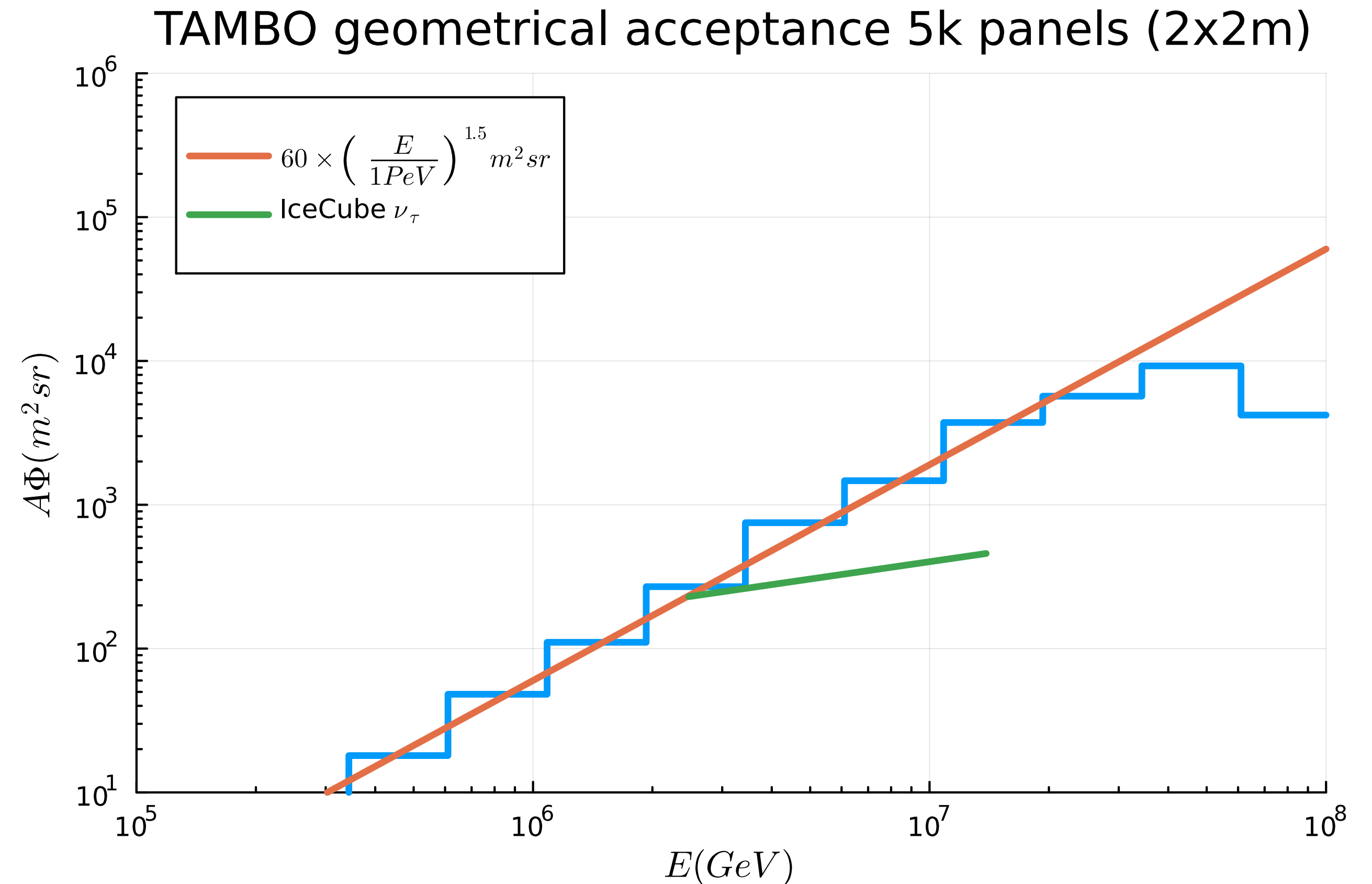


- TAMBO detects background free ν_τ s via air showers,
- Directional reco $< 1^\circ$
- Produces a “ ν_τ catalog”, ν observatories can use to conduct point source analyses

Source: Ian Bauwens Master's Thesis

TAMBO has exceptional sensitivity above 3 PeV

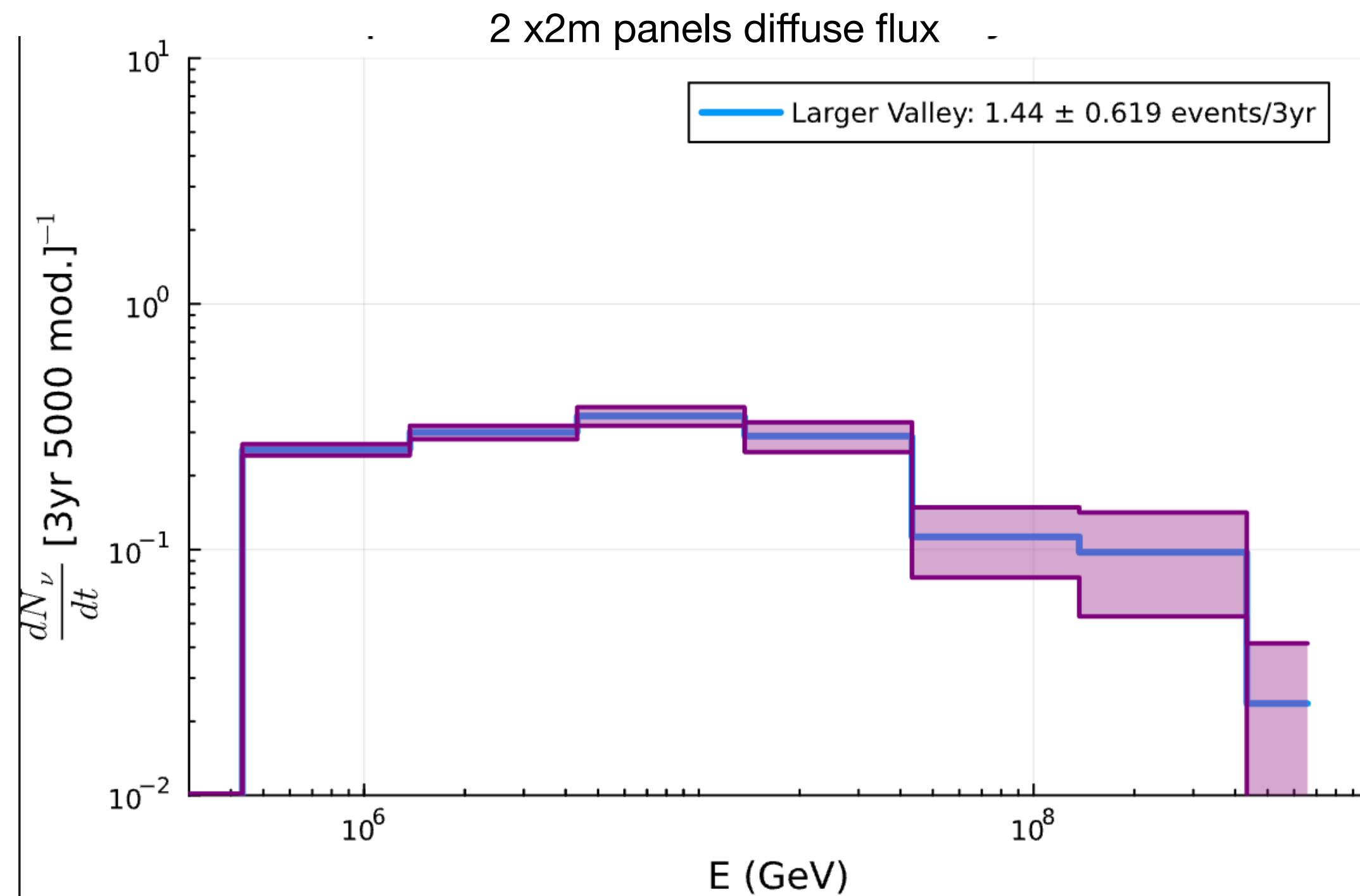
- Sensitive to 300 TeV-100 PeV energy
- More sensitive than IceCube > 3 PeV
- Thus, many more background free ν_τ s to help break $\nu_e \nu_\tau$ degeneracy



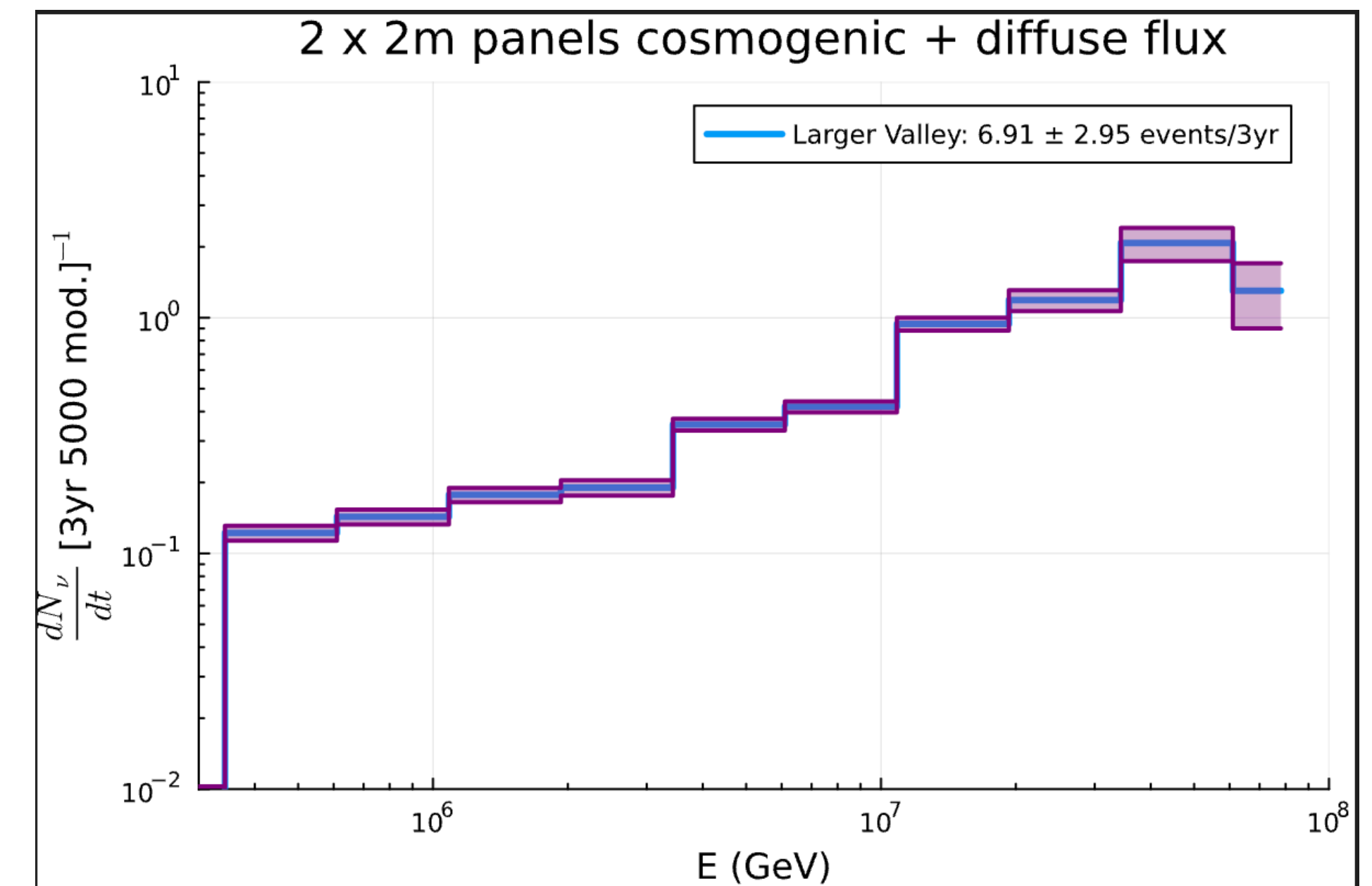
TAMBO is sensitive to cosmogenic ν models

- **1.44 events per 3 years** per 5k scintillator panels (2x2 meter) with IceCube extended flux
- **6.91 events** choosing Rodrigues model for cosmogenic ν flux, very sensitive to fluxes beyond 10 PeV!

TAMBO event rates with 5k detectors



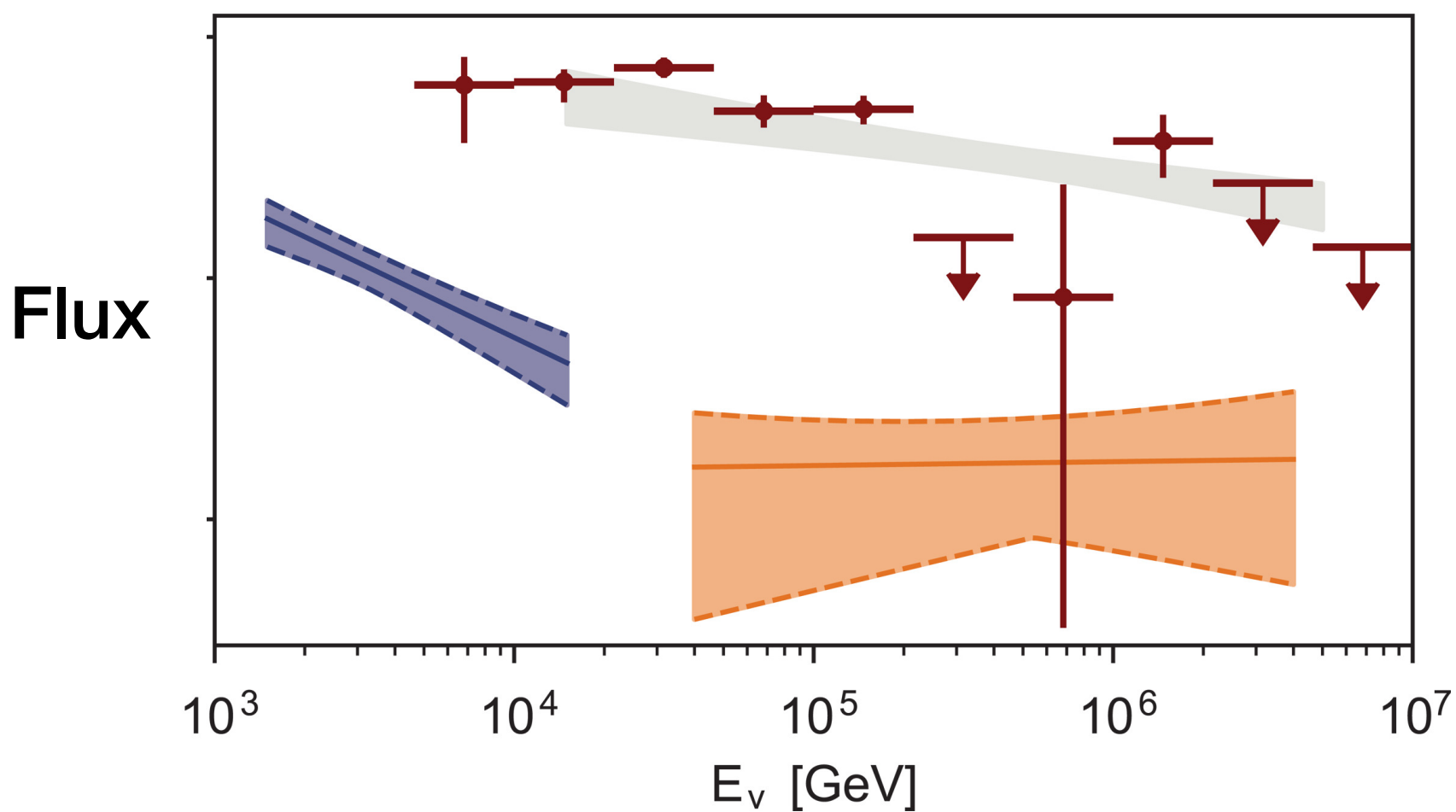
TAMBO event rates with 5k detectors



Science goals of TAMBO

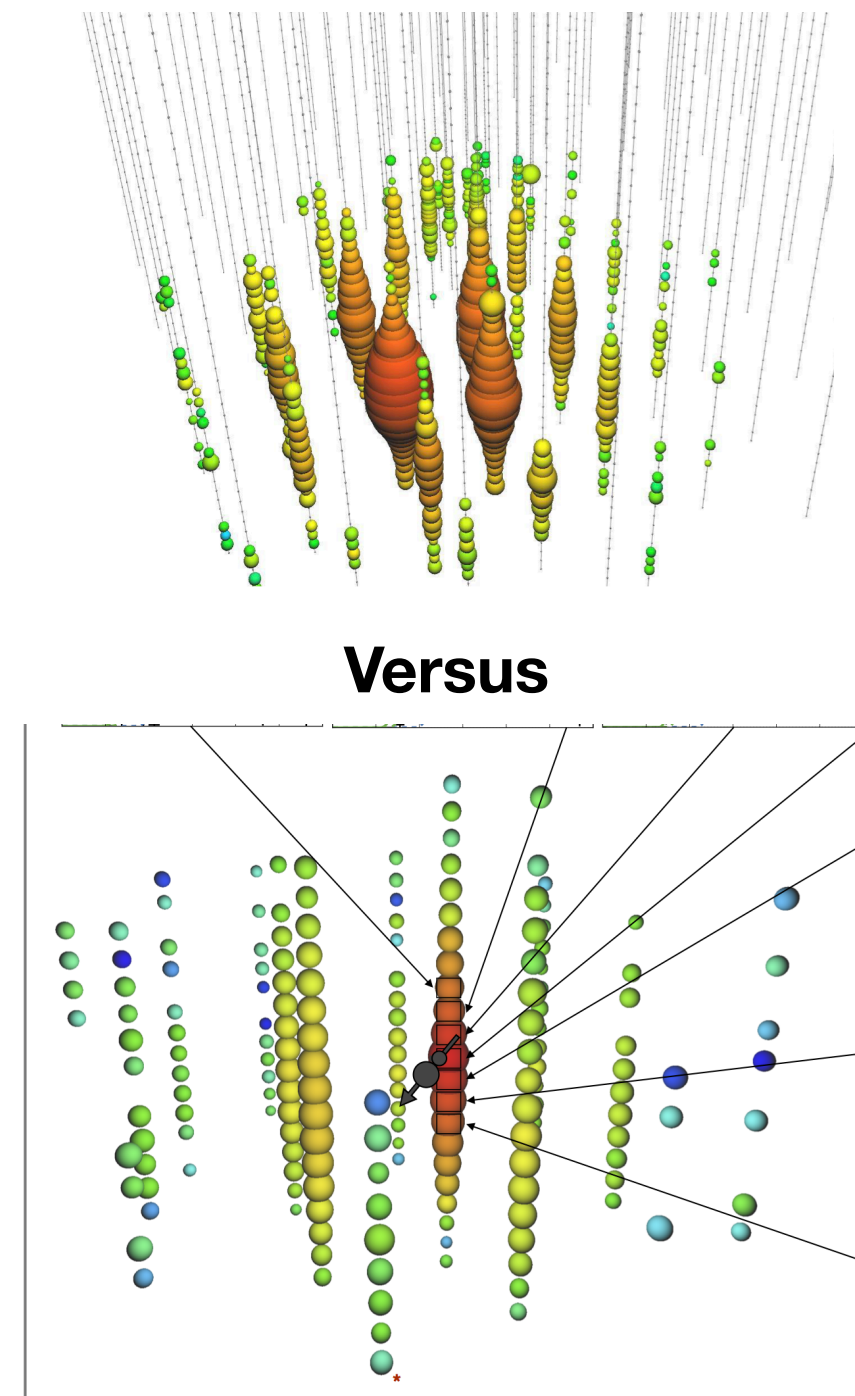
Discover new ν point sources

■ Point source NGC 1068
 ■ "unidentified"
■ Point source TXS 0506



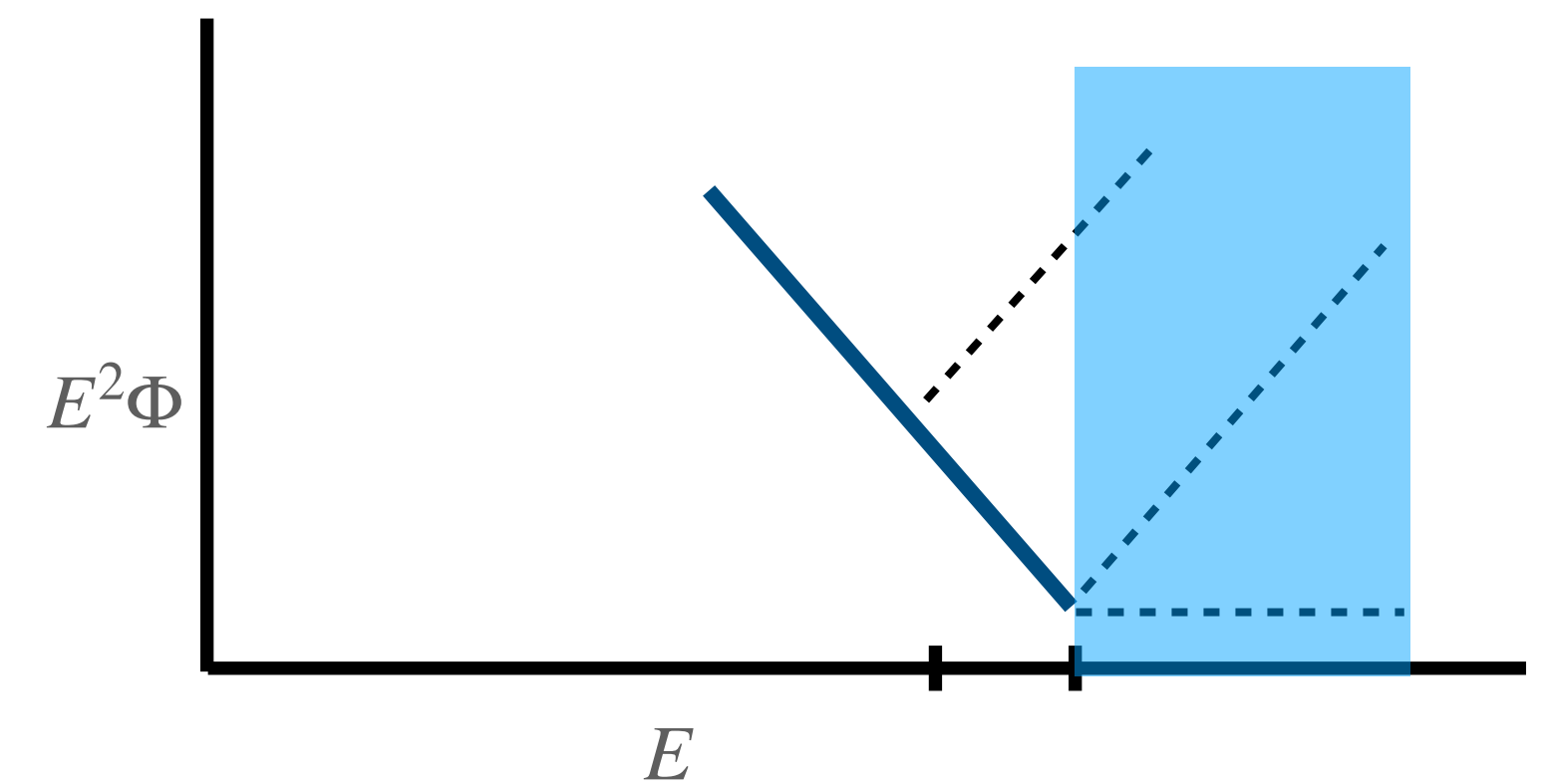
- High signal purity (low background)
- Great pointing resolution $< 1^\circ$
- Every ν_τ is a source

Constrain the astro flavor ratio by measuring ν_τ component



- Pure ν_τ channel
- Every trigger will help constrain astro flavor ratio

Characterize the 1-100 PeV ν flux



- Effective Area > 1 PeV better than IceCube for ν_τ
- Can test cosmogenic ν hypotheses

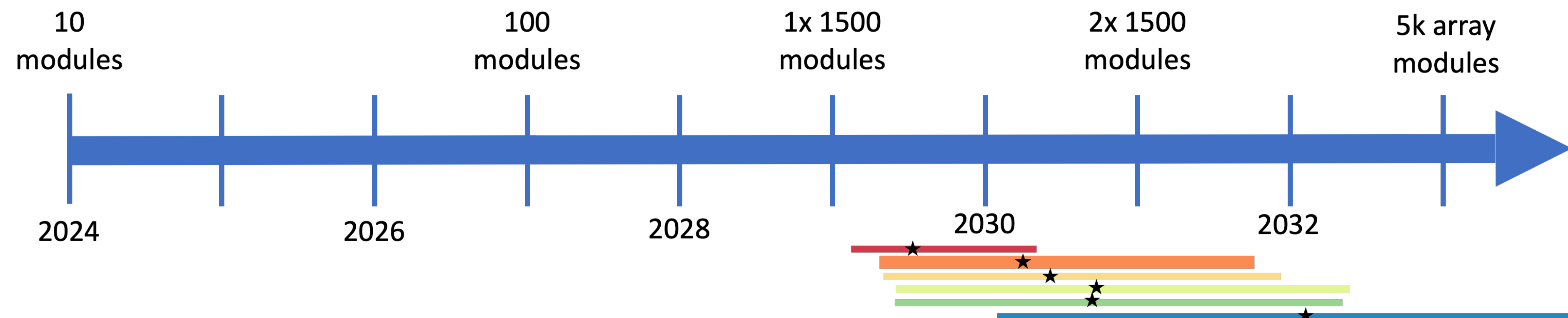
Conclusion

What's next for TAMBO

- Release full simulation ~ 99%
- Hardware development
 - Scintillator construction
 - DAQ system
- Deployment to test sites (US, Peru)
- Interested in joining? Contact (me or Carlos Argüelles) at pzhelnin@g.harvard.edu or carguelles@g.harvard.edu



TAMBO simulation development team





NOTE

PROJECTS MARKED IN **BLUE** ARE COMPLETE OR UNDER CONSTRUCTION.
PROJECTS MARKED IN **WHITE** ARE PROPOSED.

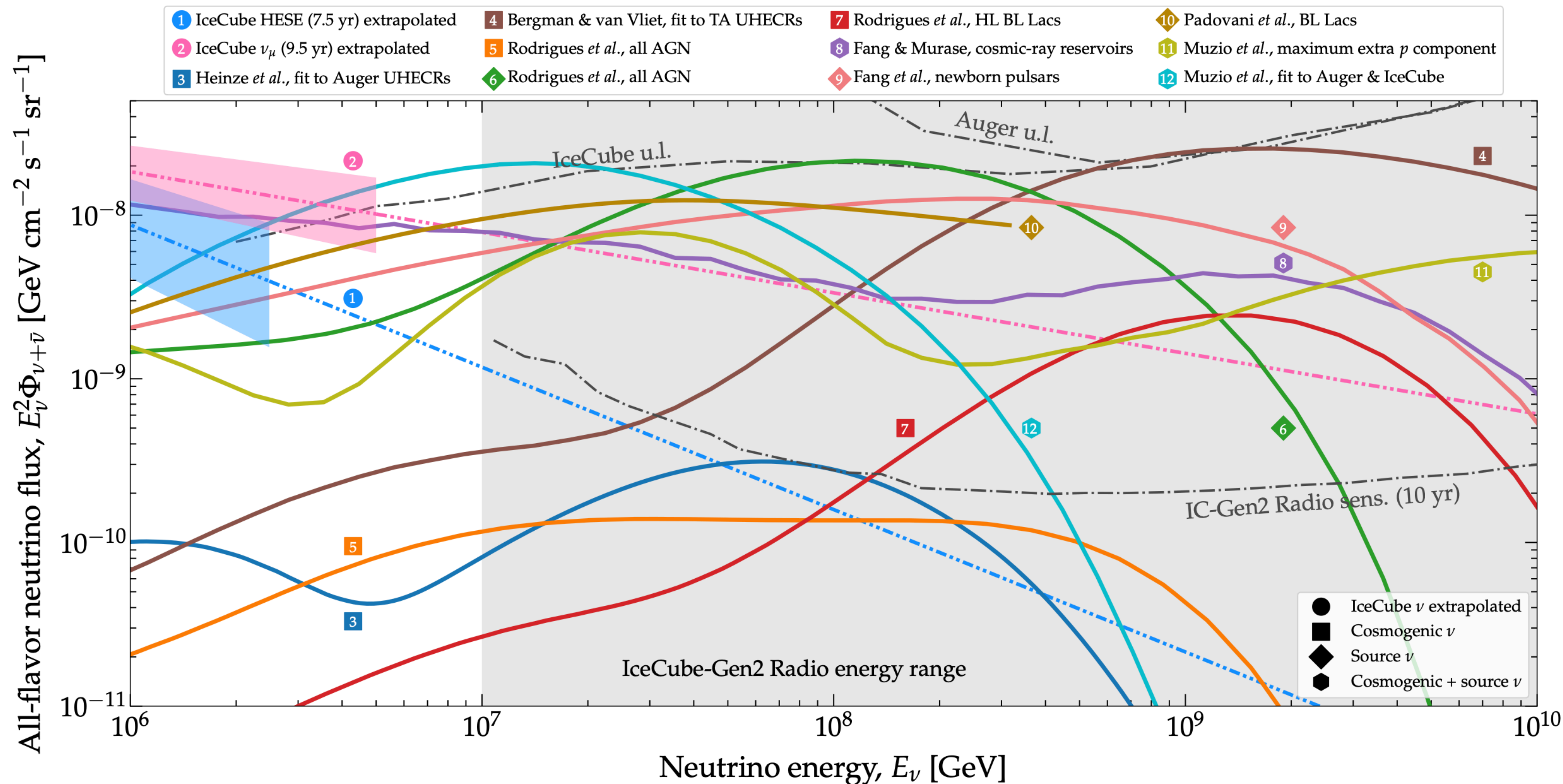
Credit: Carlos Argüelles-Delgado, William Thompson, and Jack Pairin

EARTH MAP TEXTURE CREDIT: VIDEO COPILOT

Obrigado!

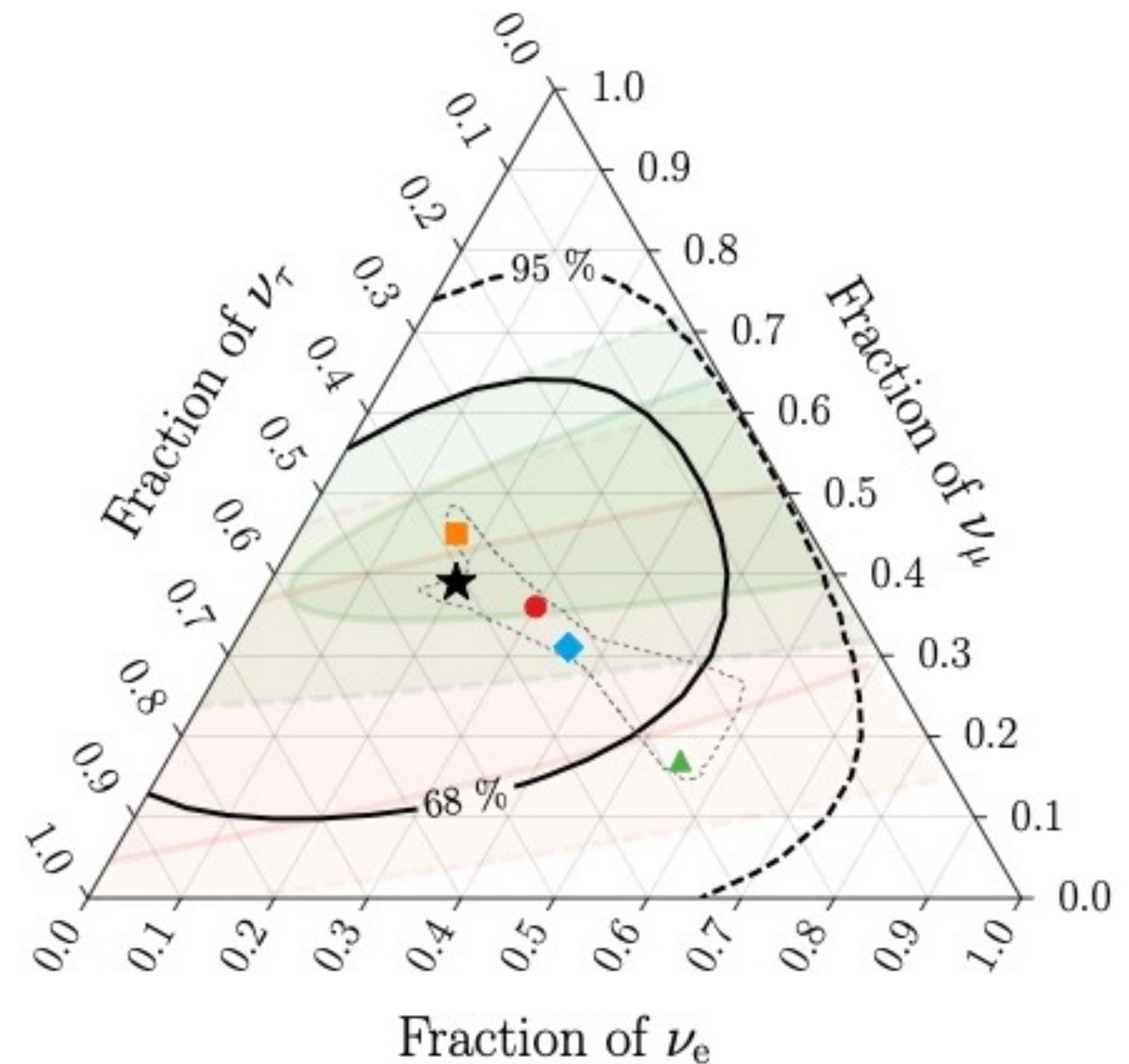
Backups

Cosmogenic models

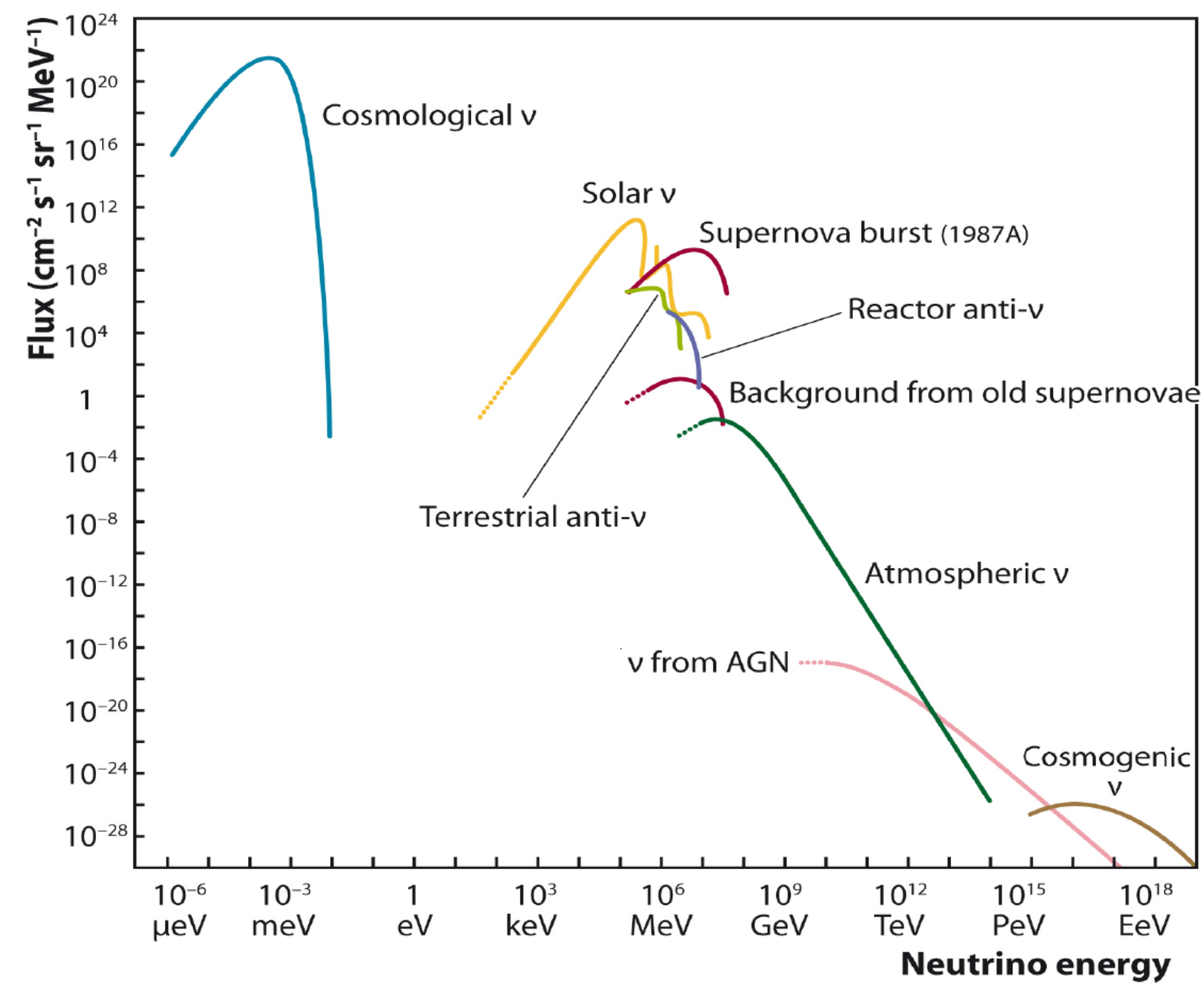


Tau neutrino flavor triangle

- Elongated contours corresponding to ν_e / ν_τ degeneracy



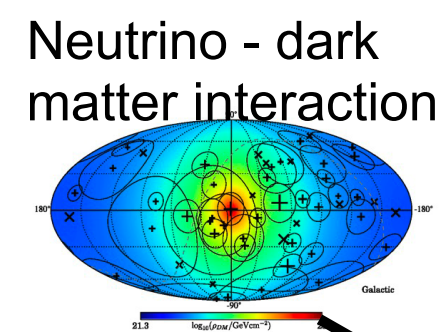
Neutrino fluxes



Why should we care about astro neutrino sources?

- They give us the opportunity to study neutrino physics on *very* long baselines
- Long baselines accumulate new physics
- Each source we see has a different baseline
- Therefore gives us sensitivity to different regions of phase space ($P \approx V(New) \times L$)
- More sources = more new physics we can probe

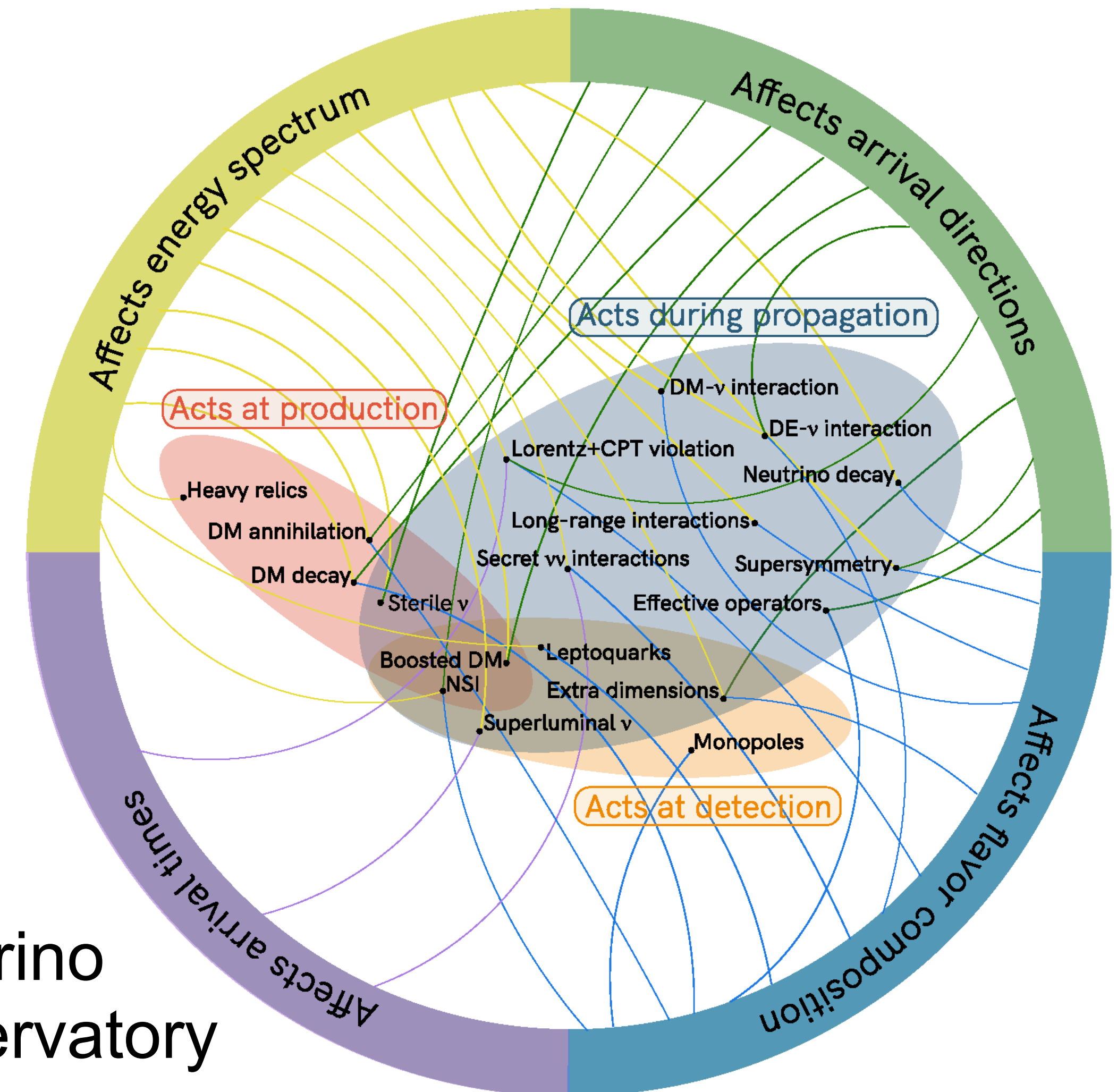
High energy
astrophysical
point source



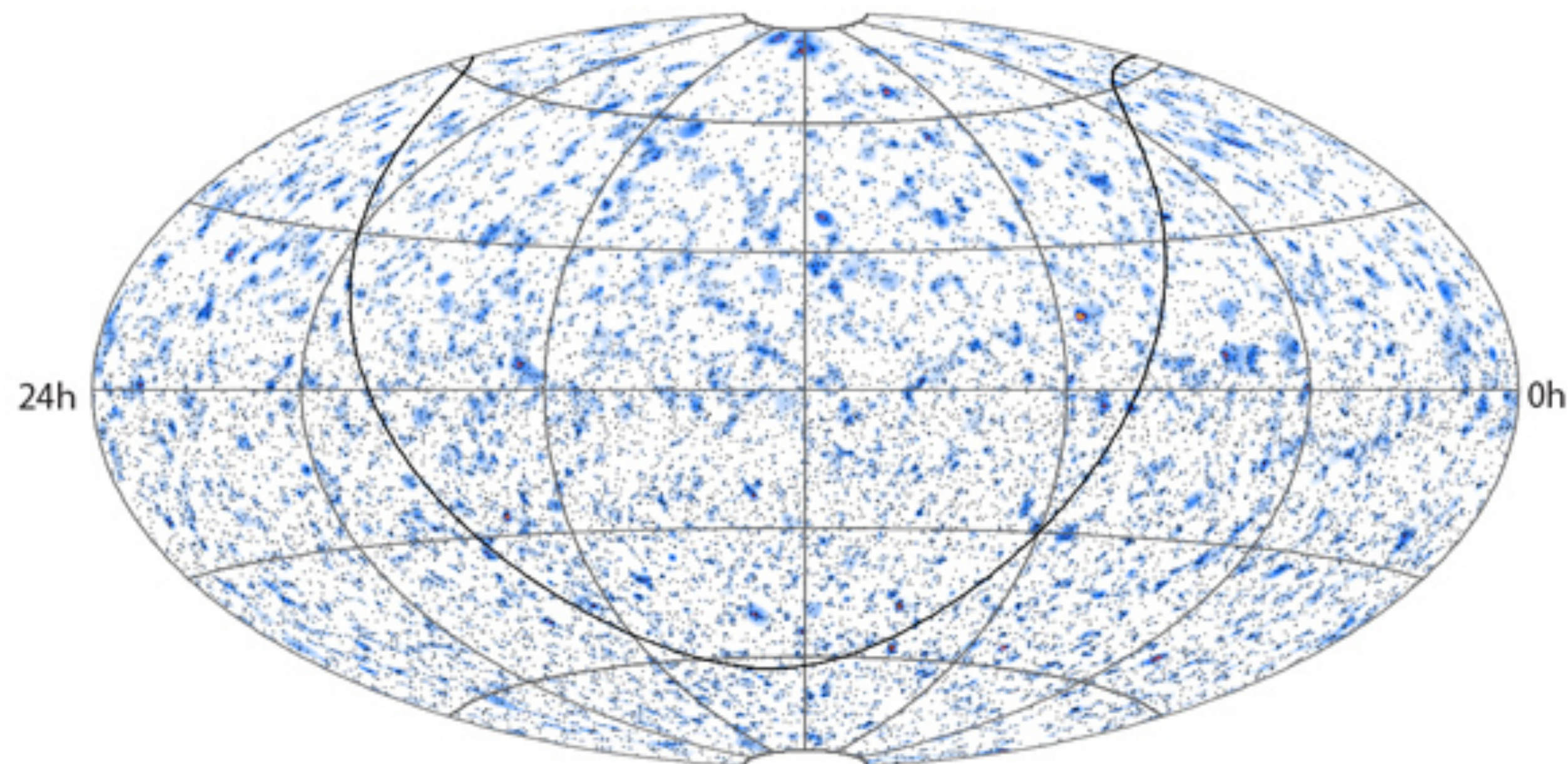
Etc.

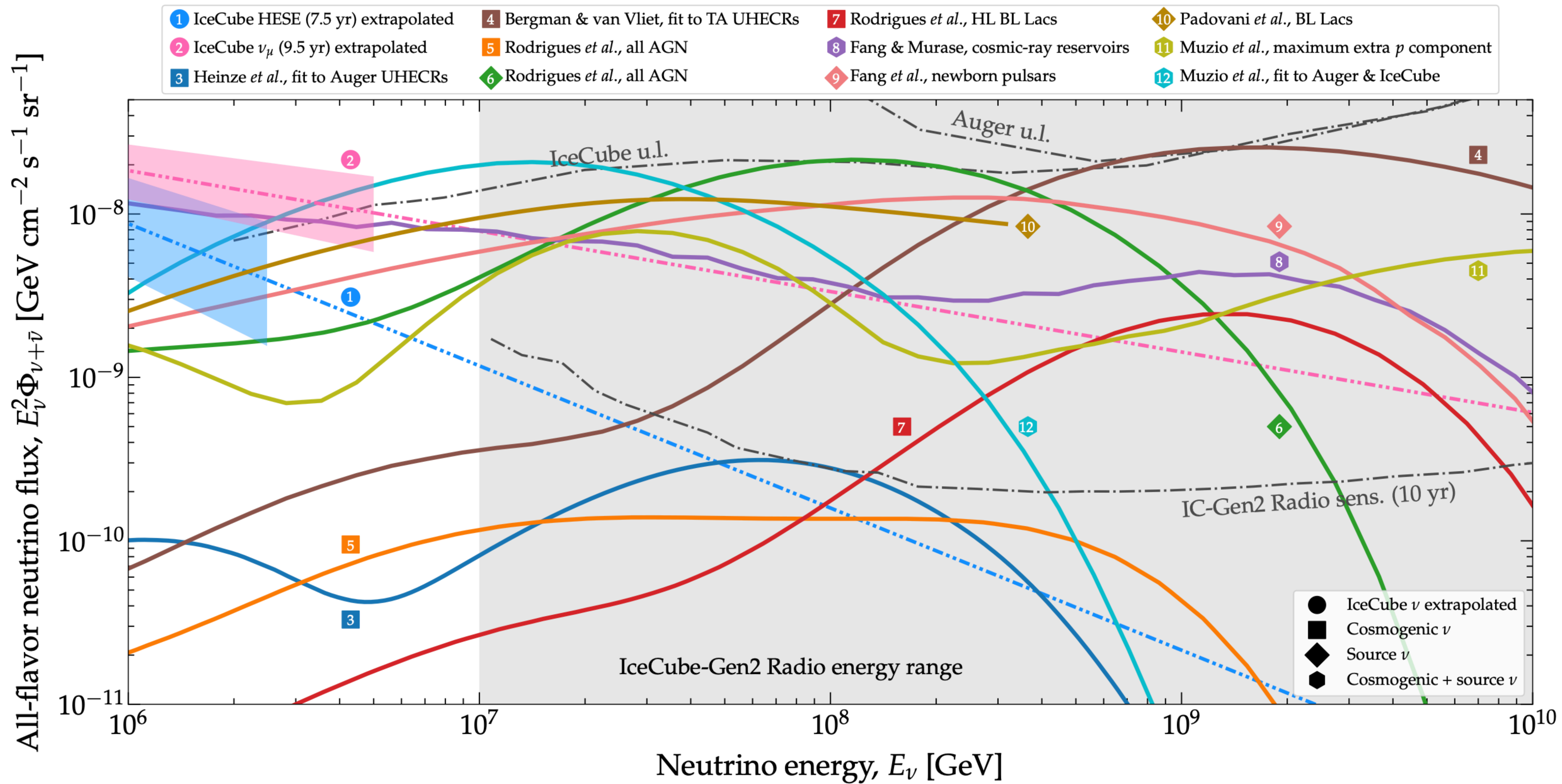
Neutrino
Observatory

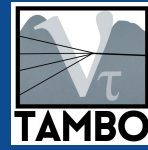
New Physics ???



Neutrino sky map







Advancements in Data Acquisition and Synchronization Systems for the TAMBO Experiment

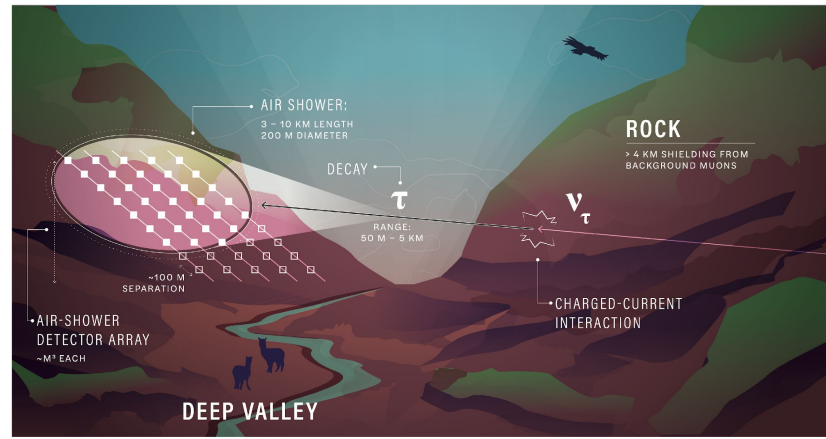
J. Tarrillo^{2,*}, D. A. Menendez¹, V. A. Centa¹, M. A. Milla¹, Ch. Briceño², A. M. Gago³, J. Bazo³ on behalf TAMBO collaboration

¹ Instituto de Radioastronomía INRAS, Pontificia Universidad Católica del Perú, Perú
² Department of Electrical Engineering, Universidad de Ingeniería y Tecnología, Perú
³ Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Perú
*jtarrillo@utec.edu.pe



Motivation

- The TAMBO experiment aims to investigate the tau neutrino component within the astrophysical neutrino flux.
- One of our ongoing endeavors involves identifying the optimal data acquisition system (DAQ) to be used in conjunction with the synchronization system.
- The synchronization system plays a crucial role in identifying the air shower initiated by the tau lepton as it exits the rock.



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) - COLCA VALLEY, PERU

Proposal

We present two distinct prototypes of the DAQ and synchronization system to be compared and help to propose a hybrid platform.

- Prototype 1:** The first DAQ prototype utilizes an FPGA for high-accuracy digital processing and 4-frequency beacon wireless detection for synchronization purposes.
- Prototype 2:** the second DAQ prototype is based on Red Pitaya platform and employs a wired synchronization system utilizing a disciplined-GPS clock.

The aim is to improve the technology for detecting tau neutrinos, considering the conditions in the Colca Valley.

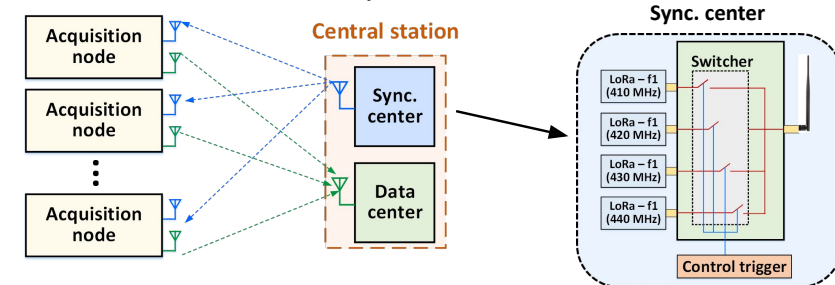
Prototype 1: FPGA-based and beacons

Synchronization concept

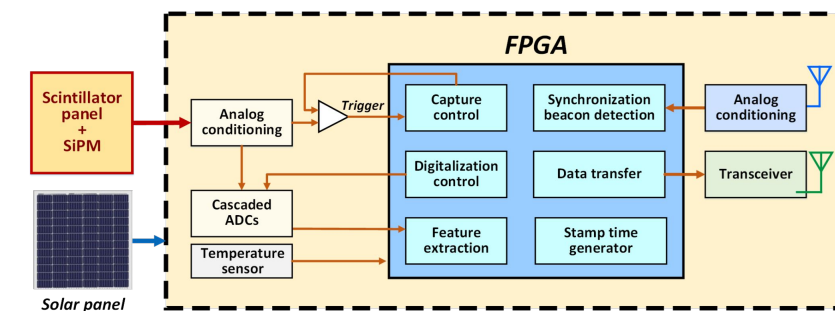
- Each node has a local coarse timer and a high-resolution timer.
- The synchronization center generates a beacon composed of 4 frequencies.
- When the nodes detect the beacon signal, the high-resolution timer is reset.

Architecture network

- Characteristics**
- Star topology.
 - Wireless data transfer and synchronization.



Node Architecture

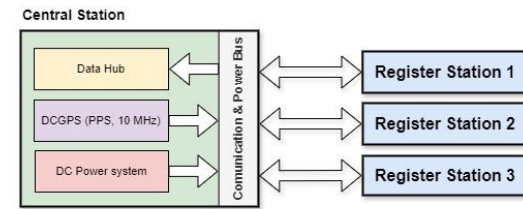


Characteristics

- Low-cost ADCs.
- Fault-tolerant RTL-level techniques.
- Autonomous power supply and low power design.

Prototype 2: Red Pitaya-based and GPS

Architecture network



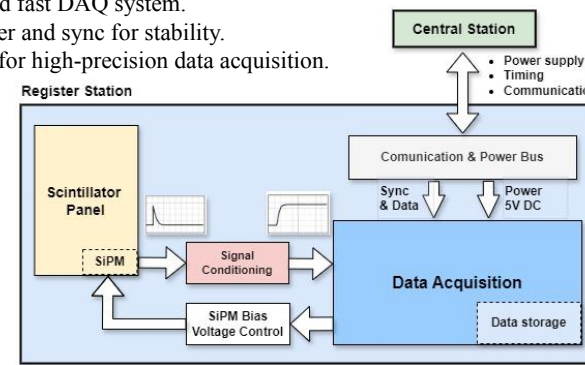
Characteristics

- Disciplined GPS to get accurate PPS & 10MHz.
- Mini PC Will manage data from the 3 stations.
- Power Supply management for the 3 stations.

Node Architecture

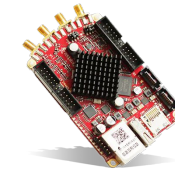
Characteristics

- Fast deployment.
- Reliable and fast DAQ system.
- Wired power and sync for stability.
- Optimized for high-precision data acquisition.



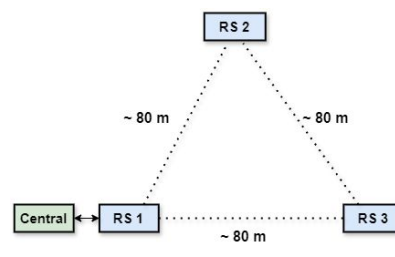
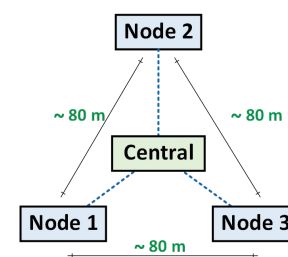
STEMlab 125-14 Z7020 (Red Pitaya)

- Dual core ARM cortex A9 + FPGA, powerful and versatile hardware.
- 14 bit ADC @ 125Msps, analog signal conditioning will give a wider pulse to digitize.
- UART, ext. clock, ext. trigger, test RS485 interface Ext. clock & ext. trigger will be used to synchronize stations (10MHZ & 1PPS).
- Linux OS, software development will be faster (python, c, VHDL).



Proposed testing schemes

The results of both prototypes will be compared



Prototype 1

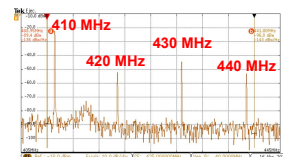
- Place: PUCP Campus.
- Equilateral triangle configuration.
- Proof of concepts:
 - Acquisition system.
 - Sync system.
 - Communication and data management
- Data Processing to get shower features.

Prototype 2

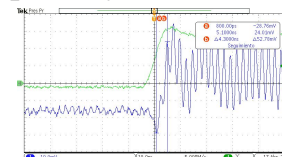
- Place: PUCP Campus.
- Equilateral triangle configuration.
- Proof of concept for register stations:
 - Test Red Pitaya platform for this task.
 - Sync system (~15 ns).
 - Communication and data management.
- Data Processing to get shower features.

Preliminary results and Conclusions

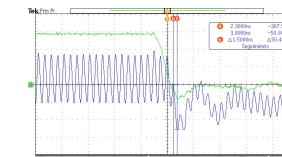
Prototype 1: Synchronization center



Generated frequencies (MHz): 410, 420, 430, 440



Delay time for starting the beacon: 4.3 ns approx.

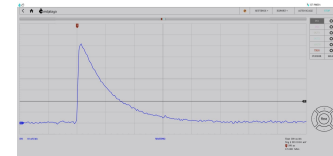


Delay time for finishing the beacon: 3.8 ns approx.

Prototype 2: Red Pitaya SiPM pulse register



Preliminary Red Pitaya board and scintillator setup



Registered pulse using Red Pitaya board

Conclusions

- A working prototype is expected to be working by the end of 2024.
- The network deployment will take an additional 2 to 3 months.