

# The Tau Air-Shower Mountain-Based Observatory

Jeff Lazar

IFIC Topical Seminar

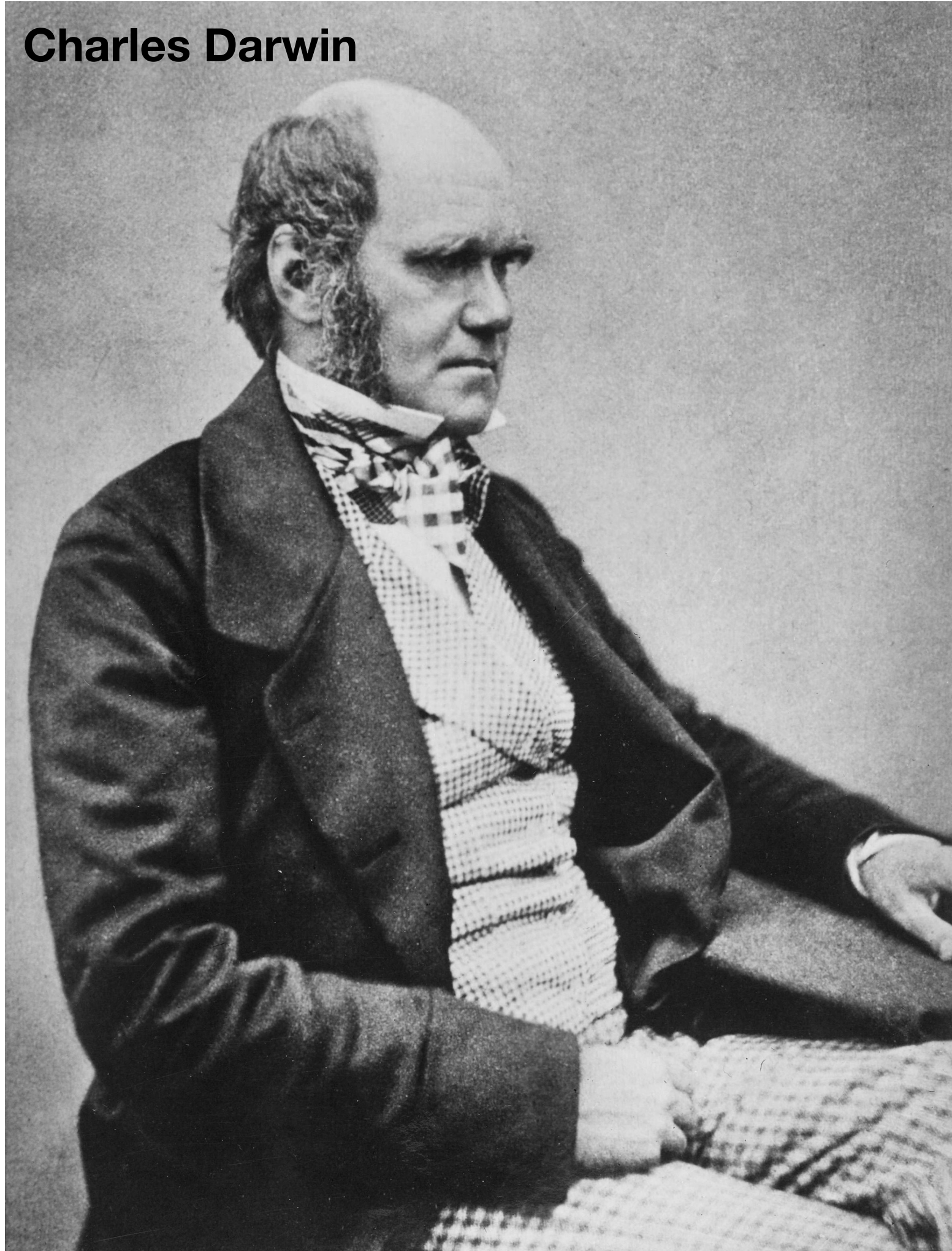
Valencia, Spain

13 Mar., 2024

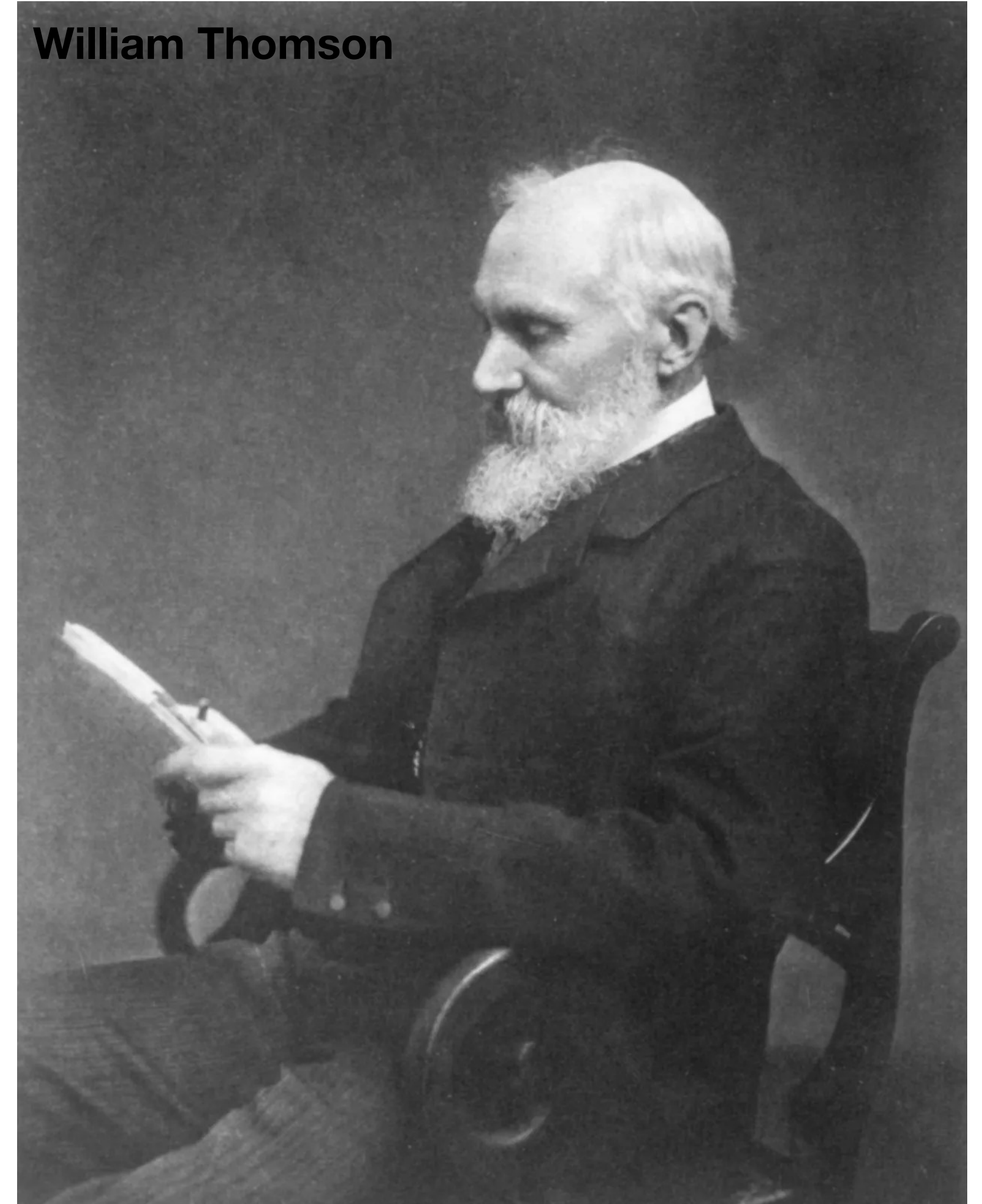


# How Does the Sun Shine ?

Charles Darwin

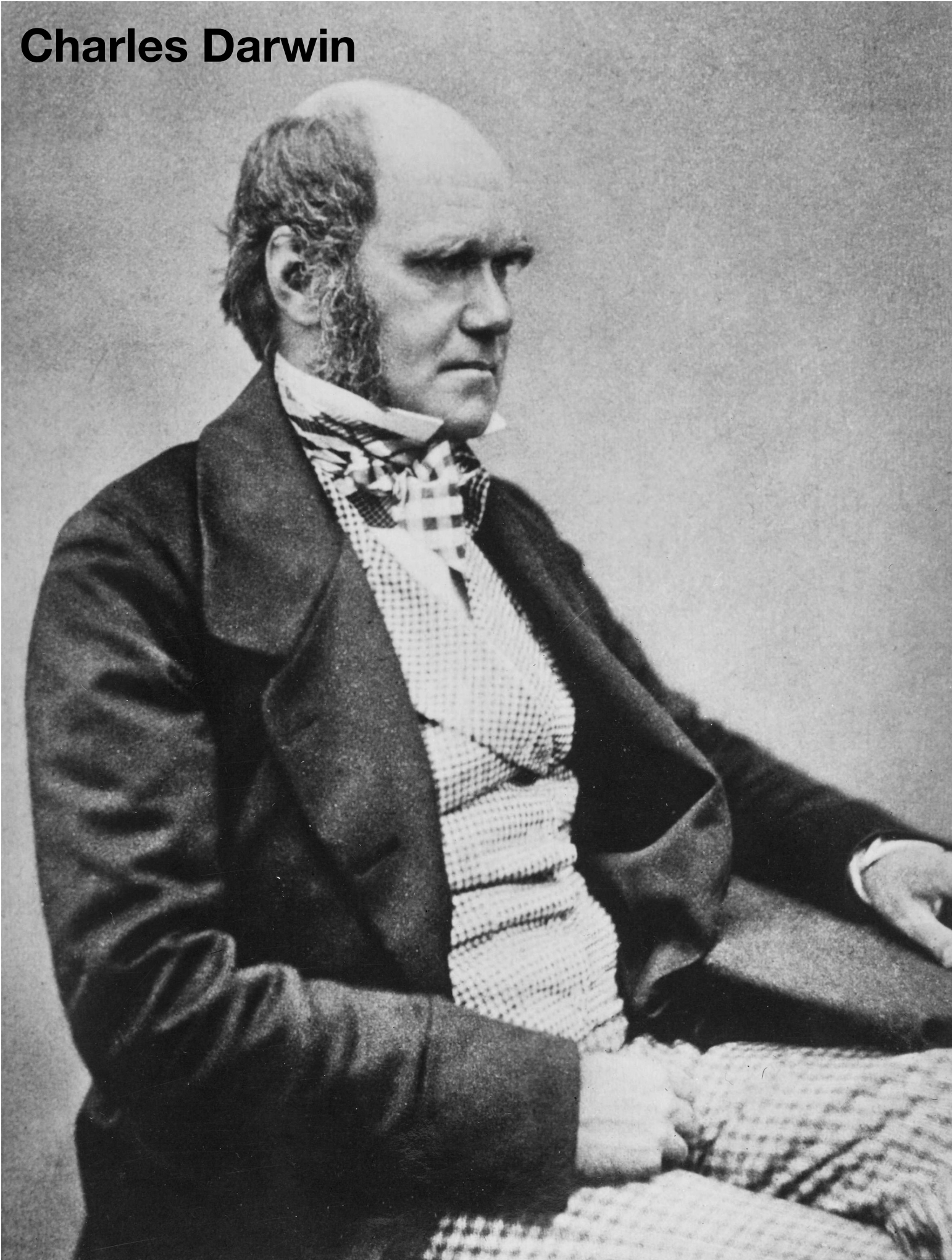


William Thomson



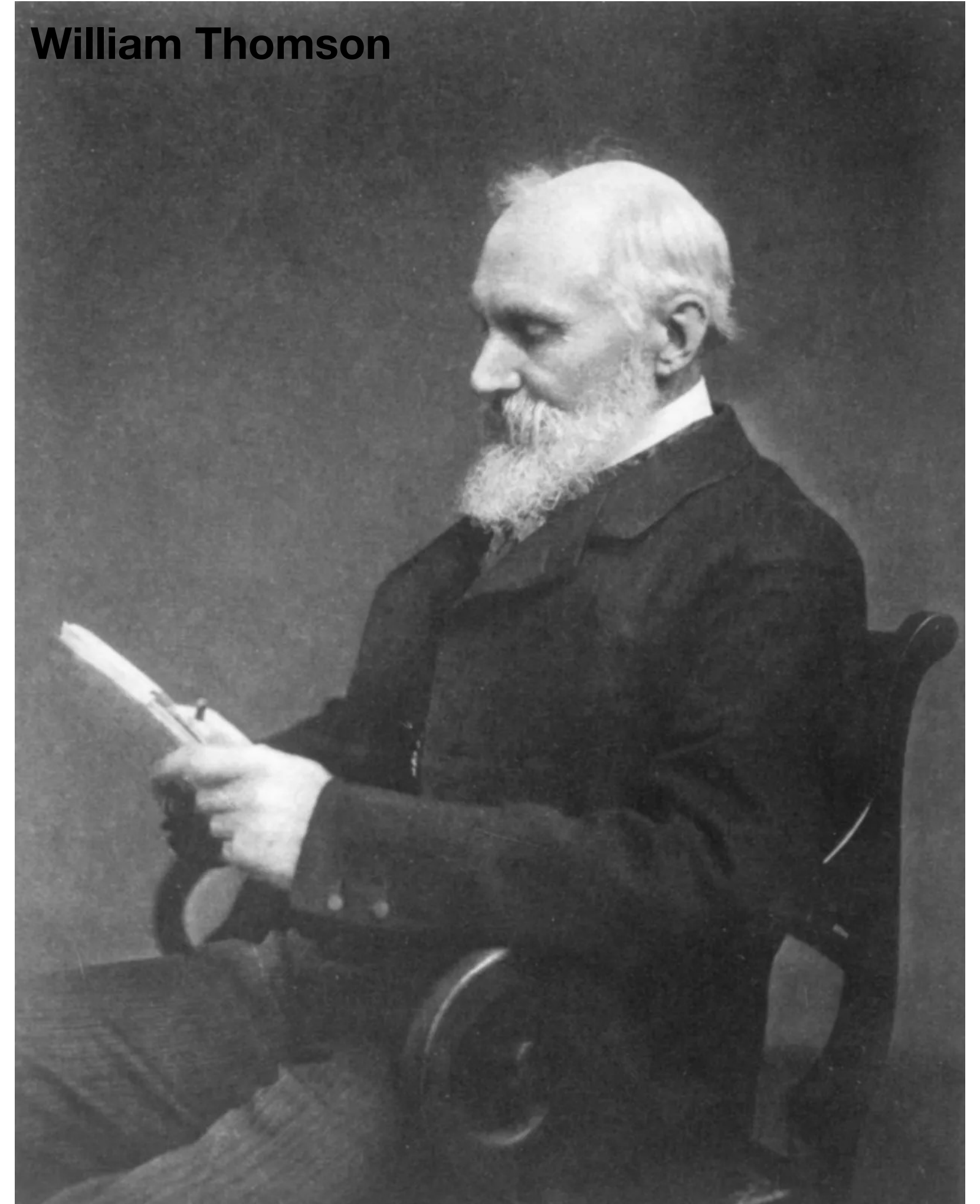
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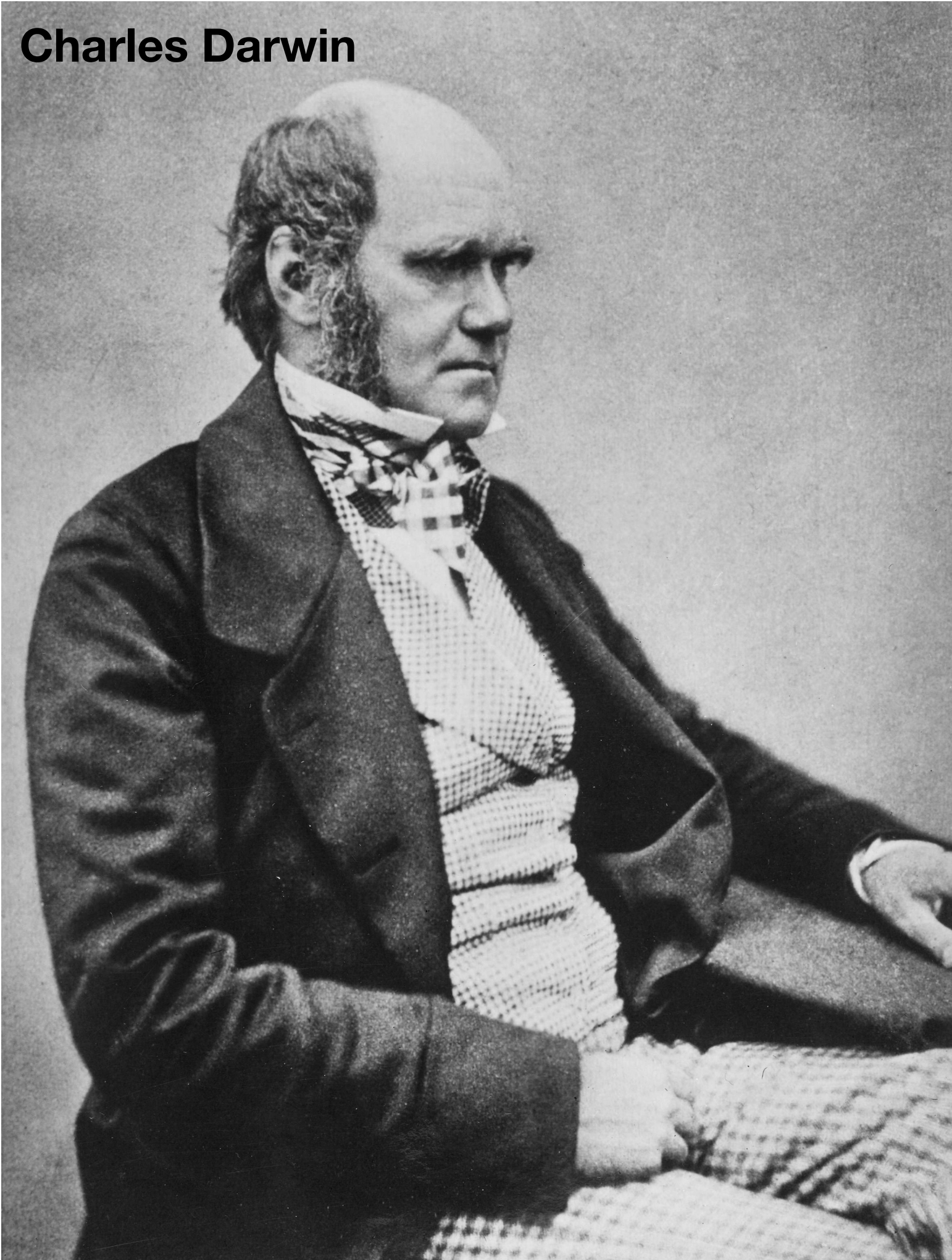
The Earth would need to exist for 300,000,000 years to give rise to the diversity of species I've observe. My observations of erosion in the Weald seem to support such a timeline.

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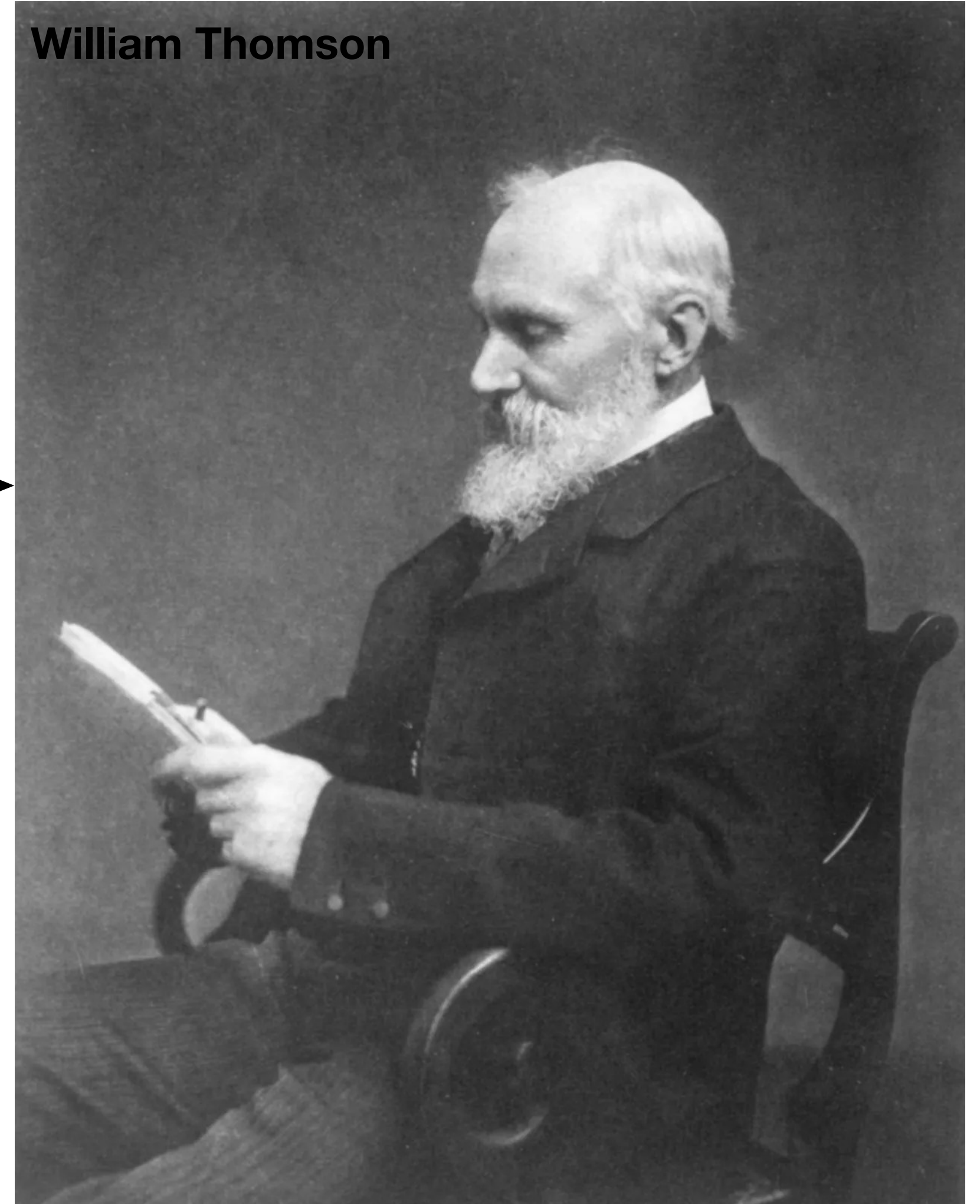
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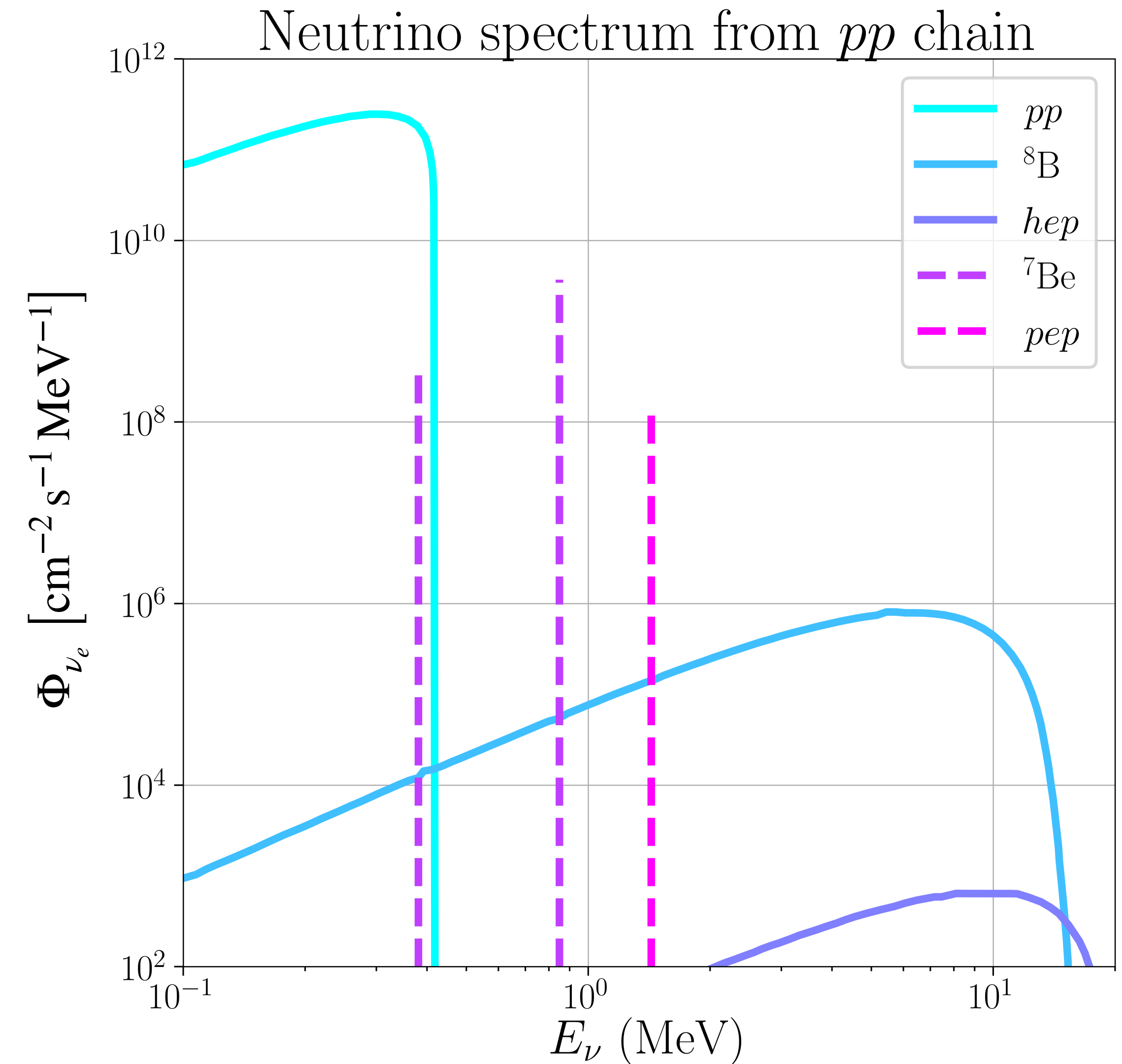
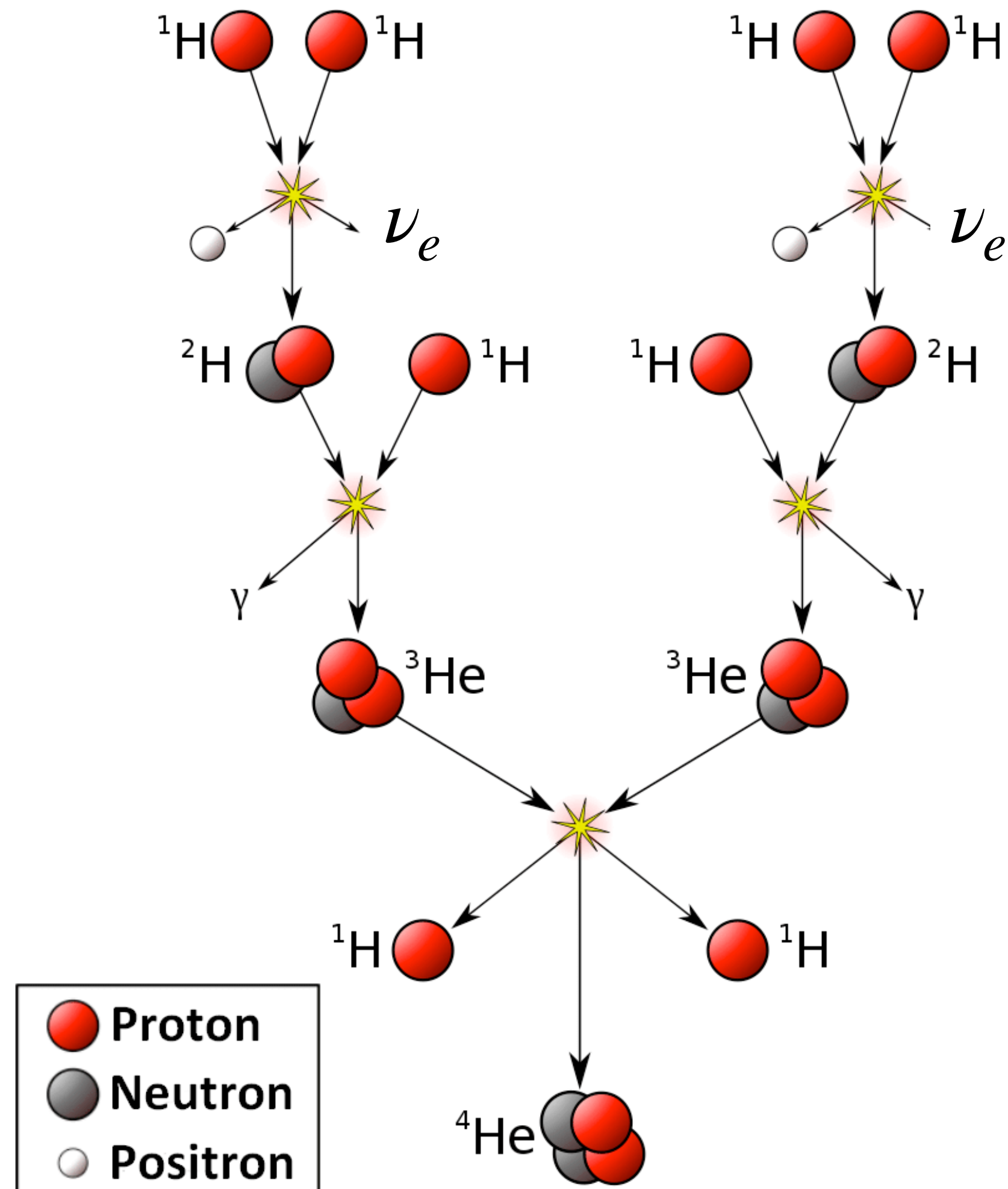
This can't be ! Chemical processes could only power the Sun for 30,000 years and gravitational processes are still well-short.

William Thomson



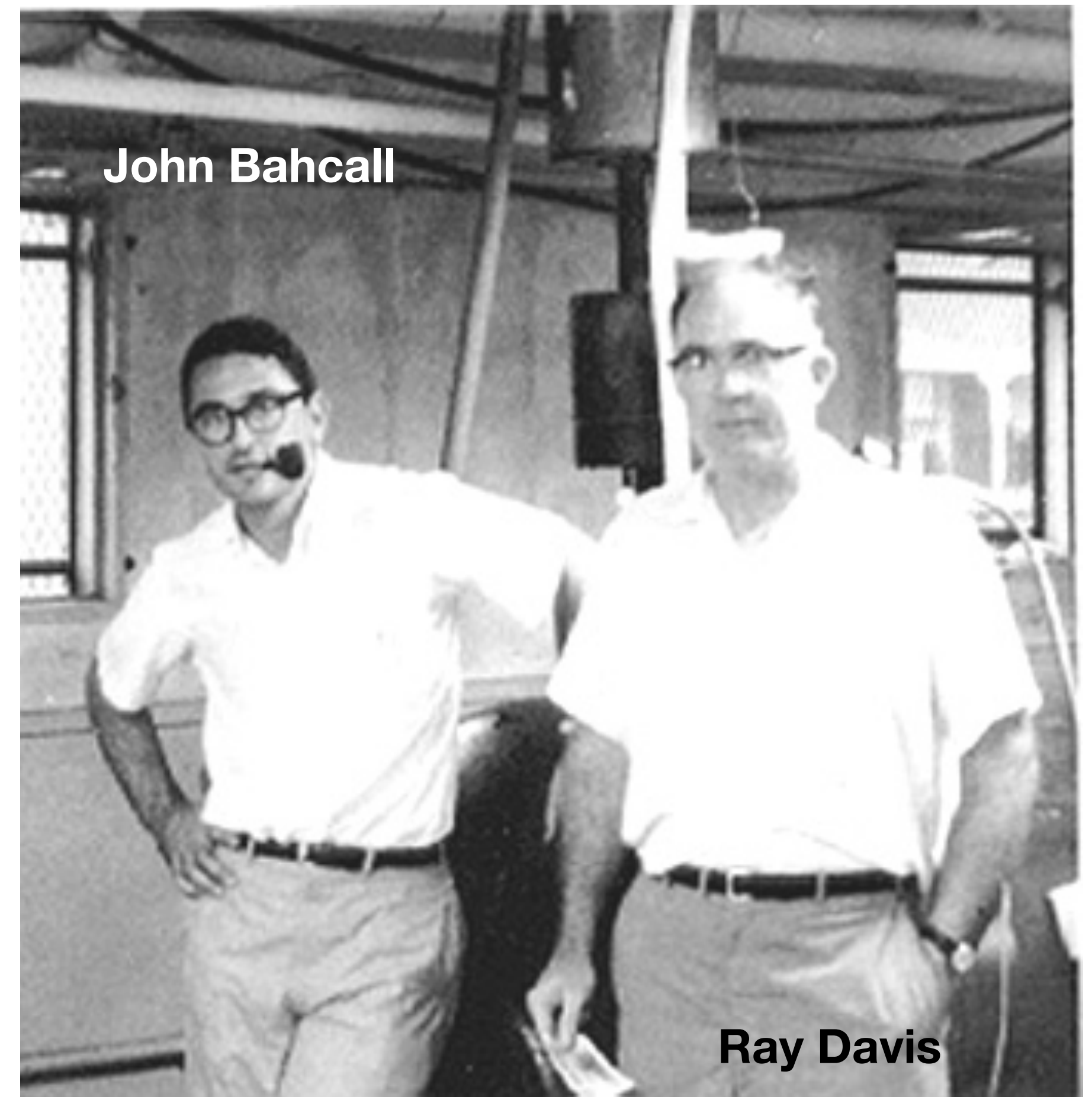
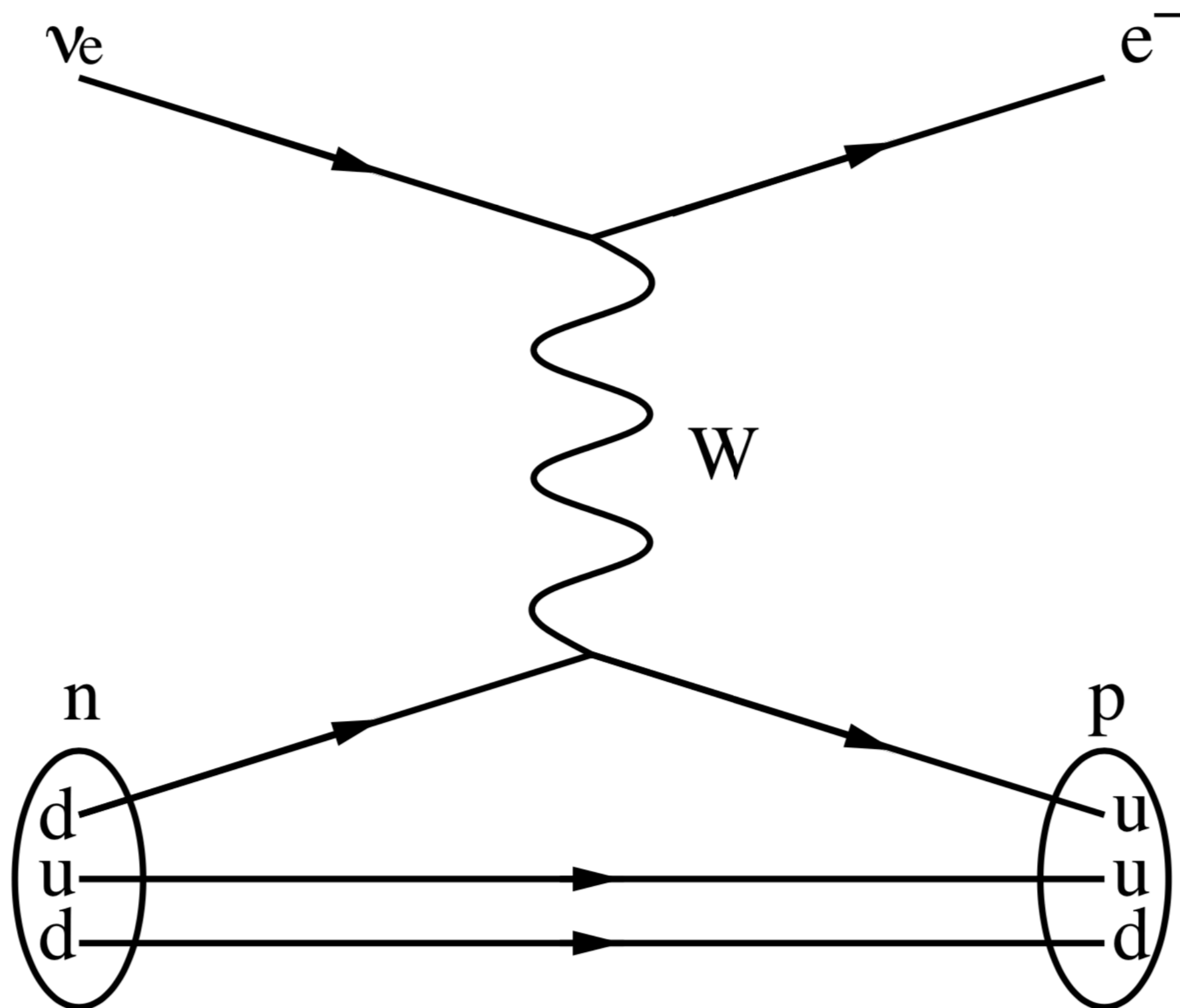
# How Does the Sun Shine ?

If the Sun generates energy from nuclear fusion, it will emit **electron** neutrinos



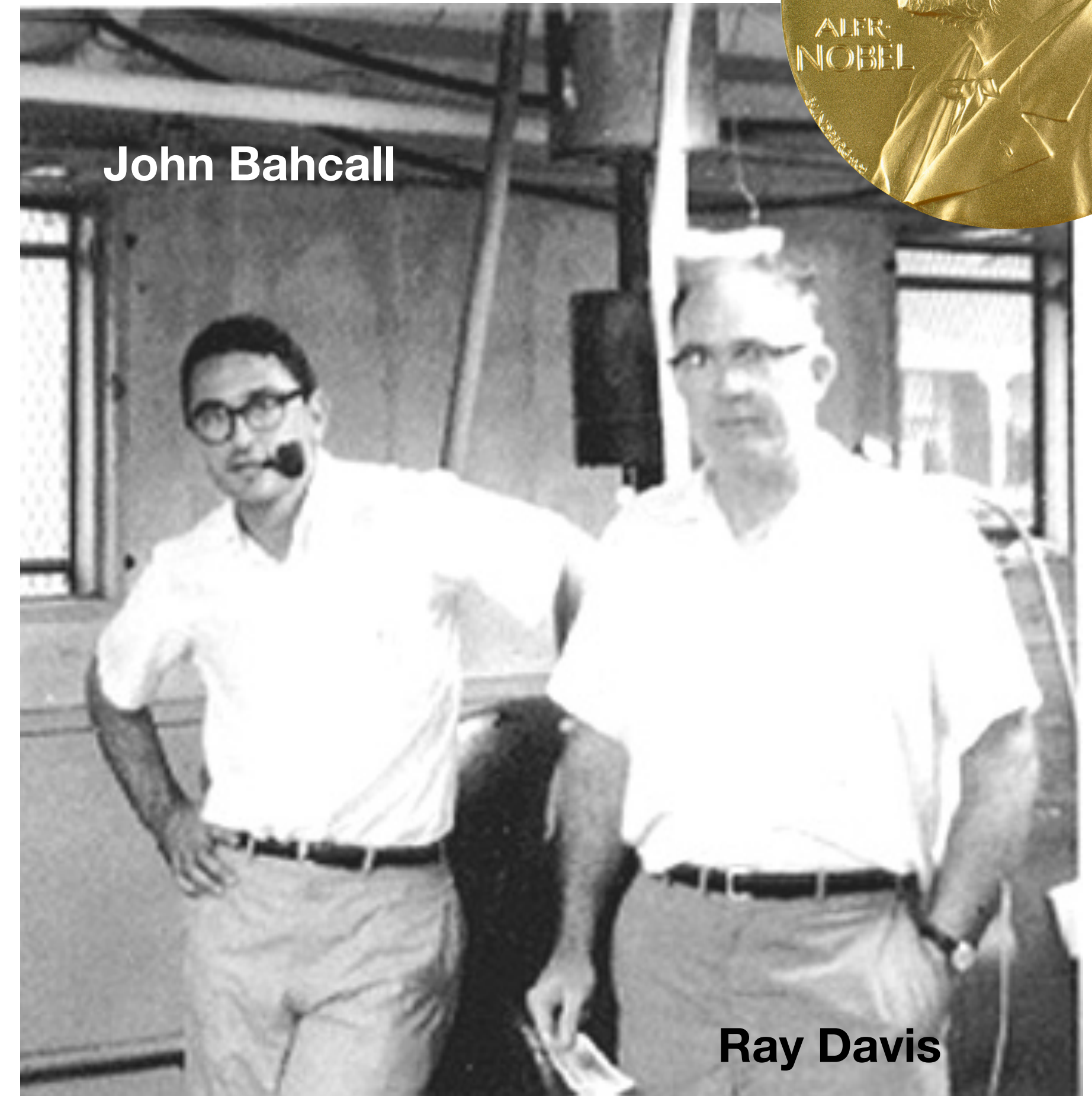
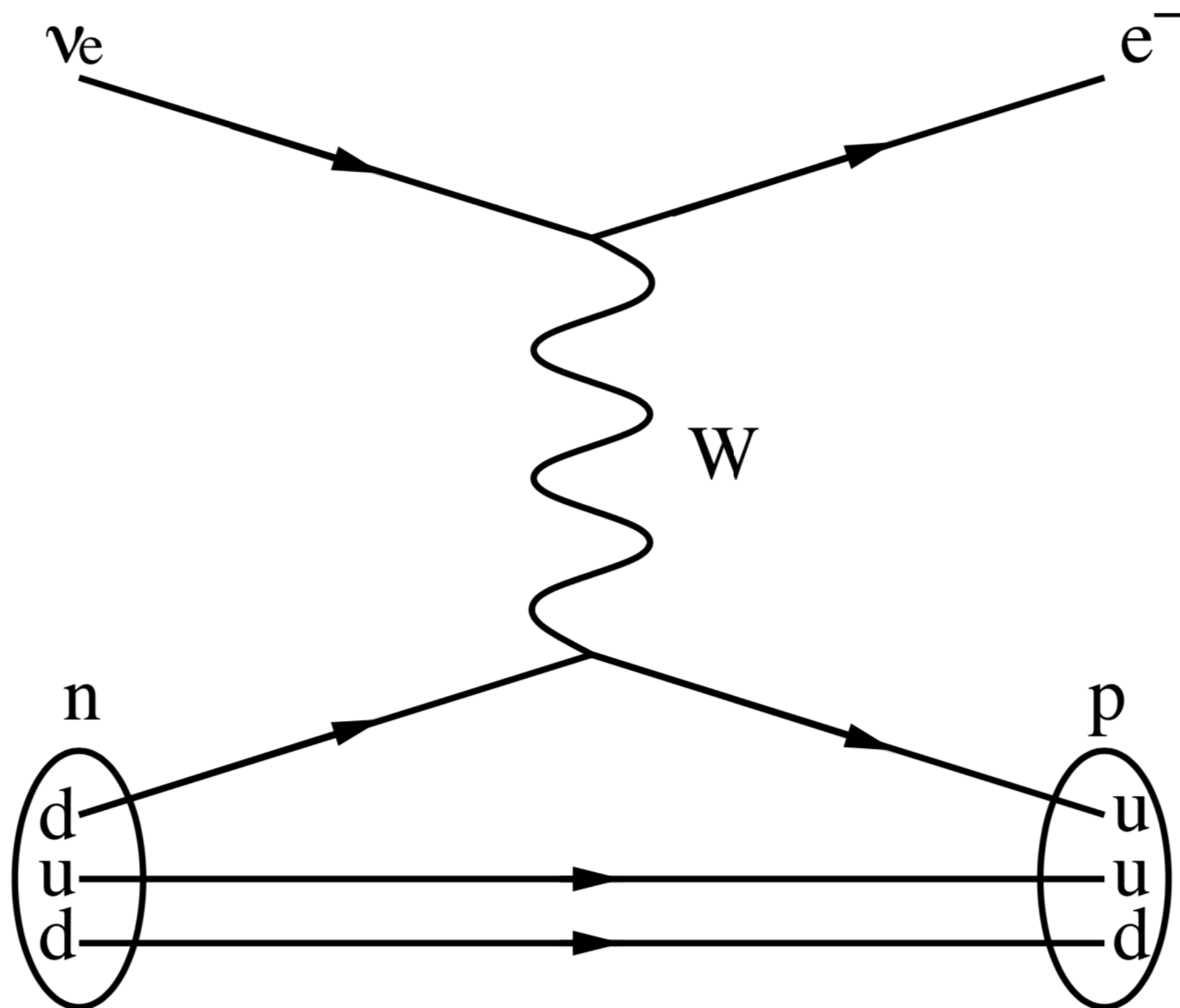
# Staring into the Sun

- Homestake experiment looked for solar  $\nu_e$  via  $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$
- First observation of solar neutrinos !



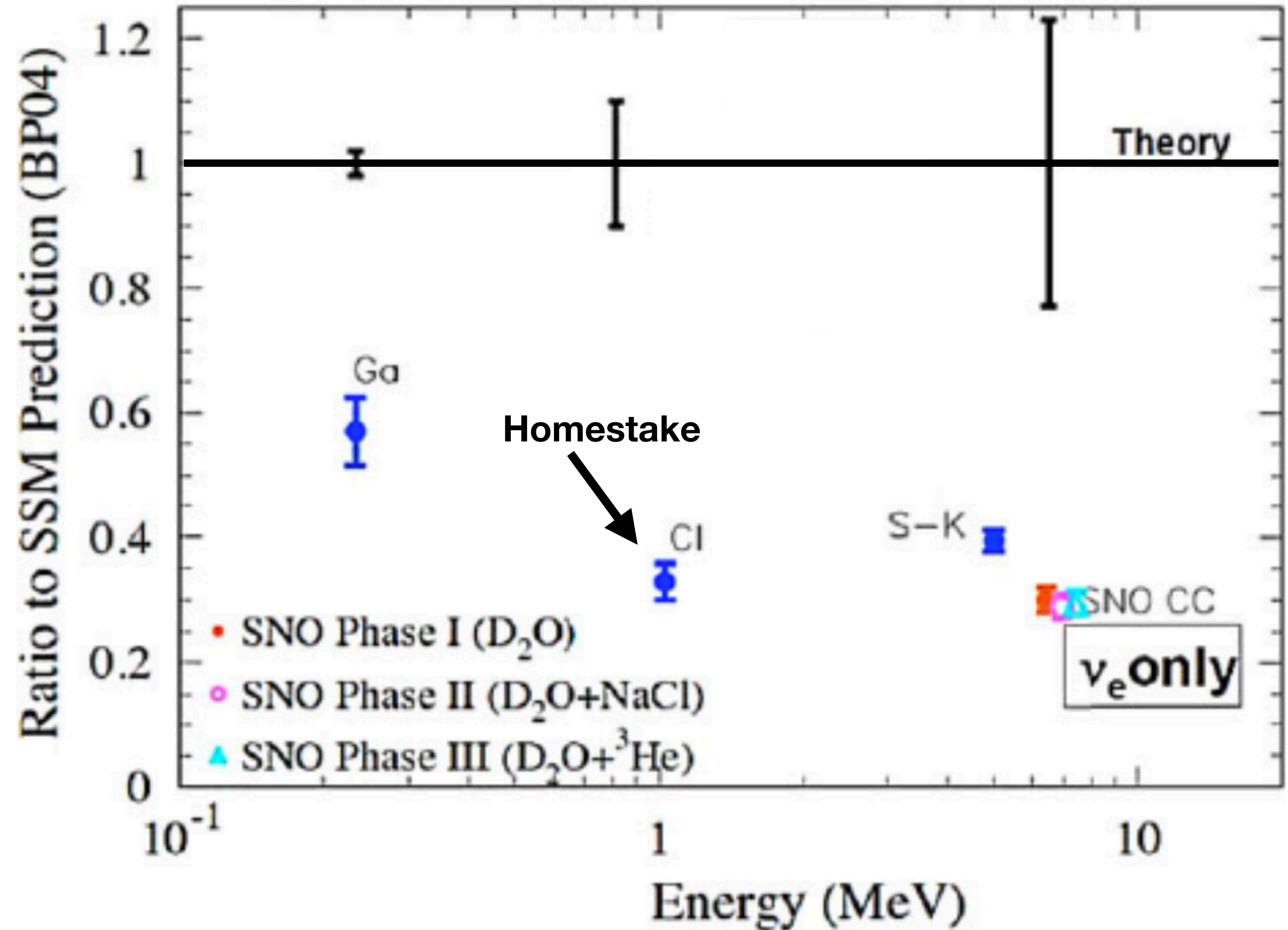
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# The Solar Neutrino Problem

- Flux measured by Homestake was in bad agreement with SSM prediction
- Many experiments continued to prod at this discrepancy, while theory is honed
- Discrepancy persisted

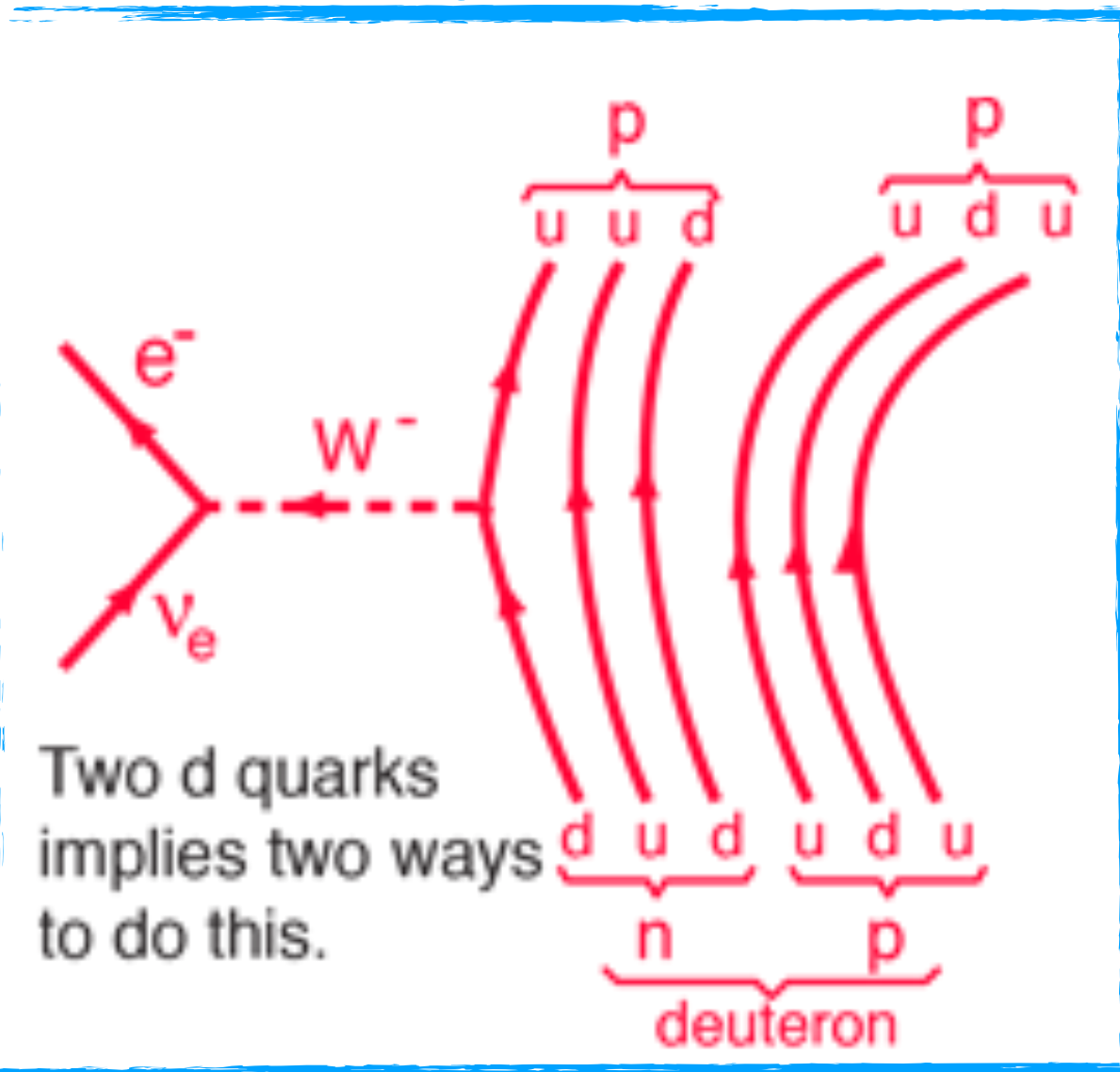


A. McDonald. doi:10.1002/201600031

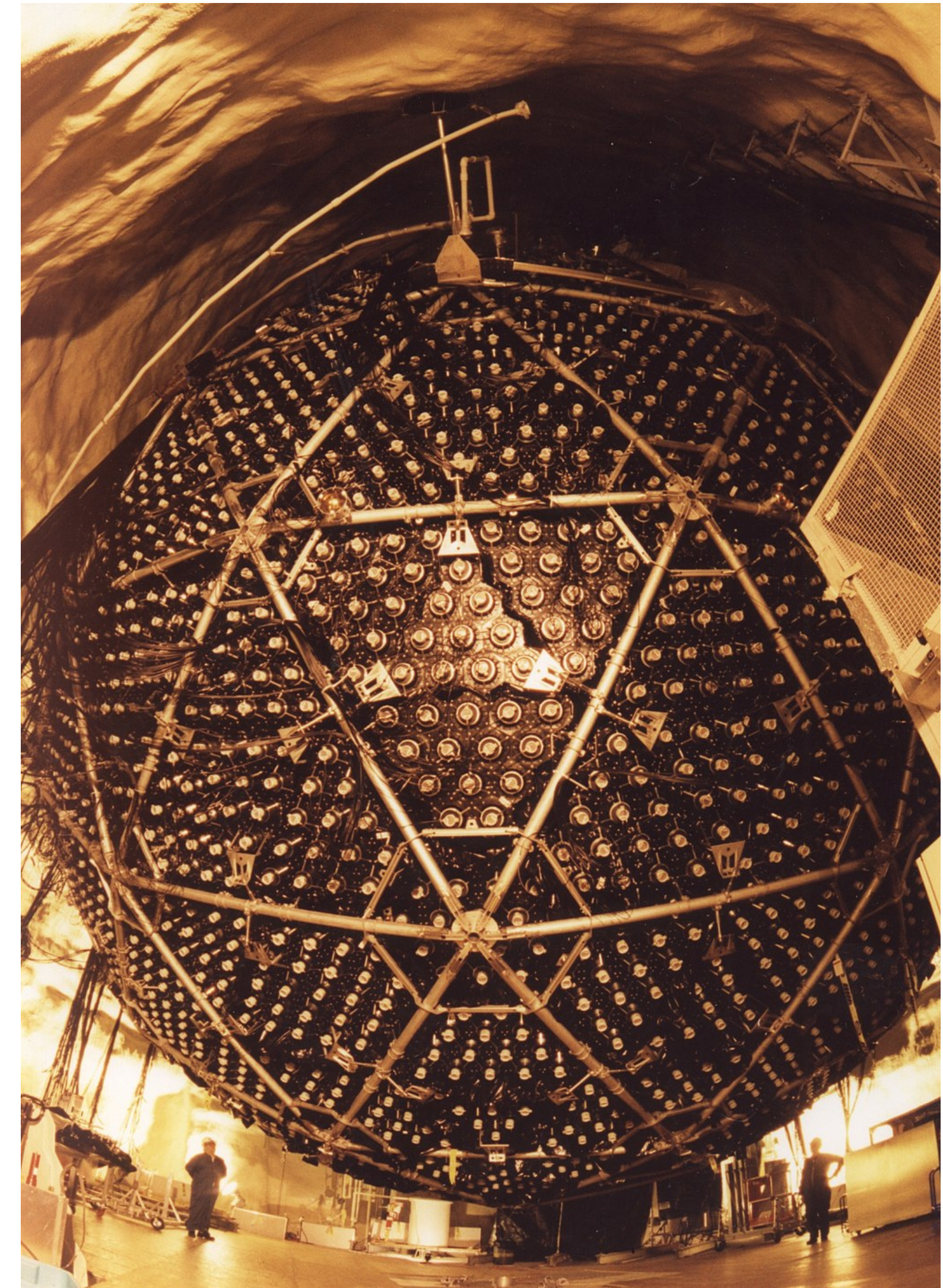
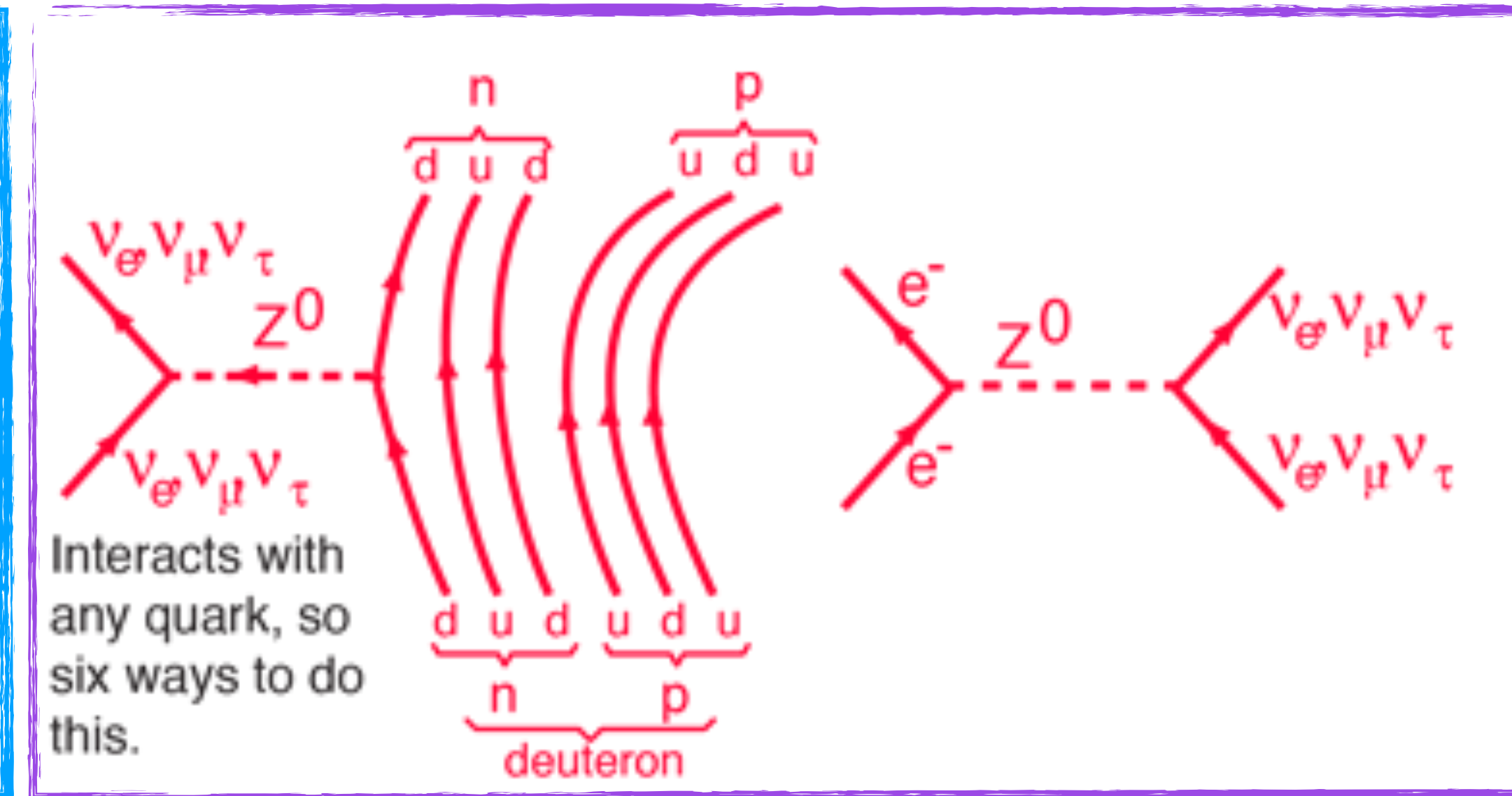
# Looking at New Flavors

- Sudbury Neutrino Observatory used heavy water water ( $D_2O$ ) to measure all-flavor NC processes

$\nu_e$  only

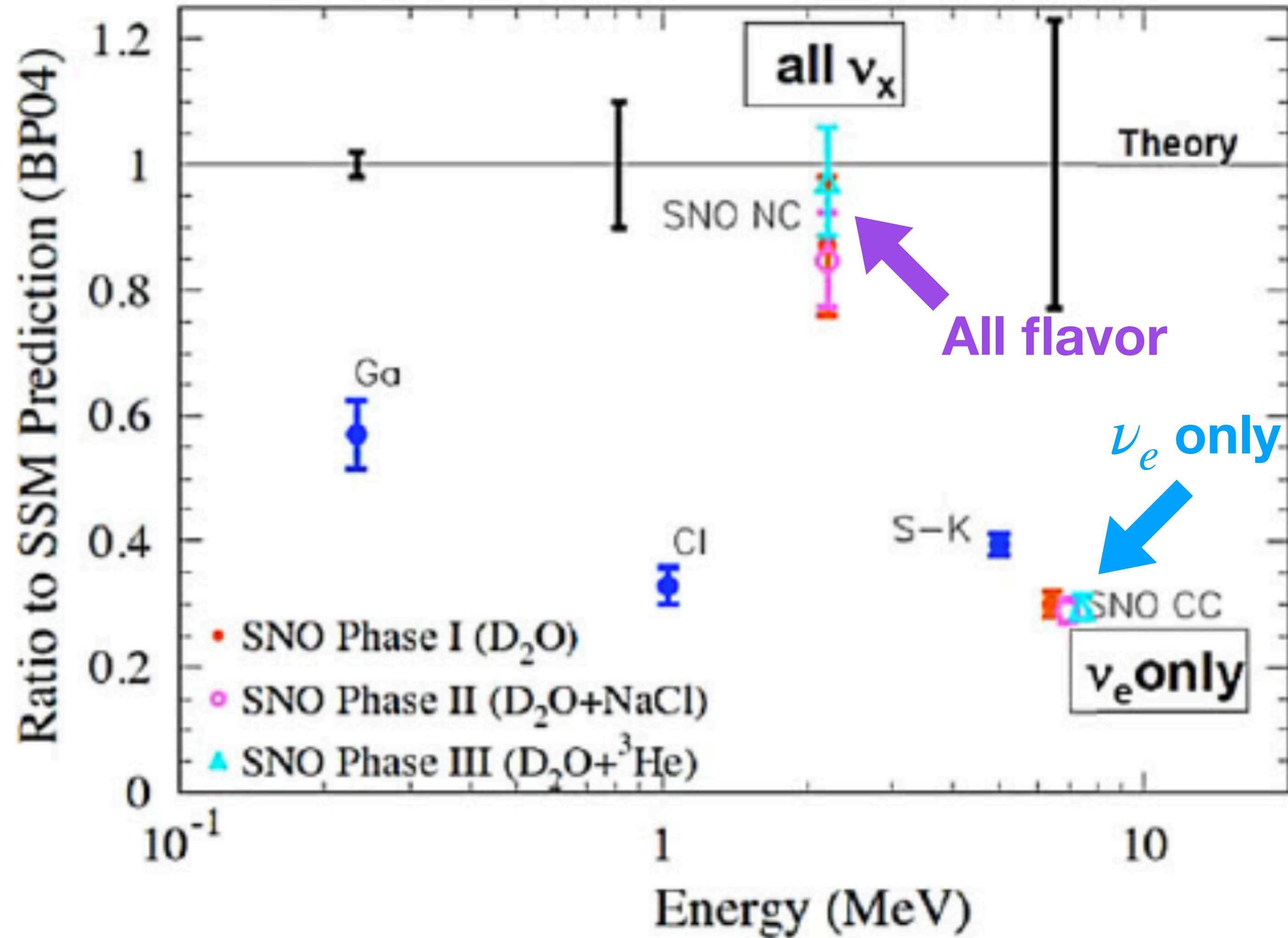


All flavor



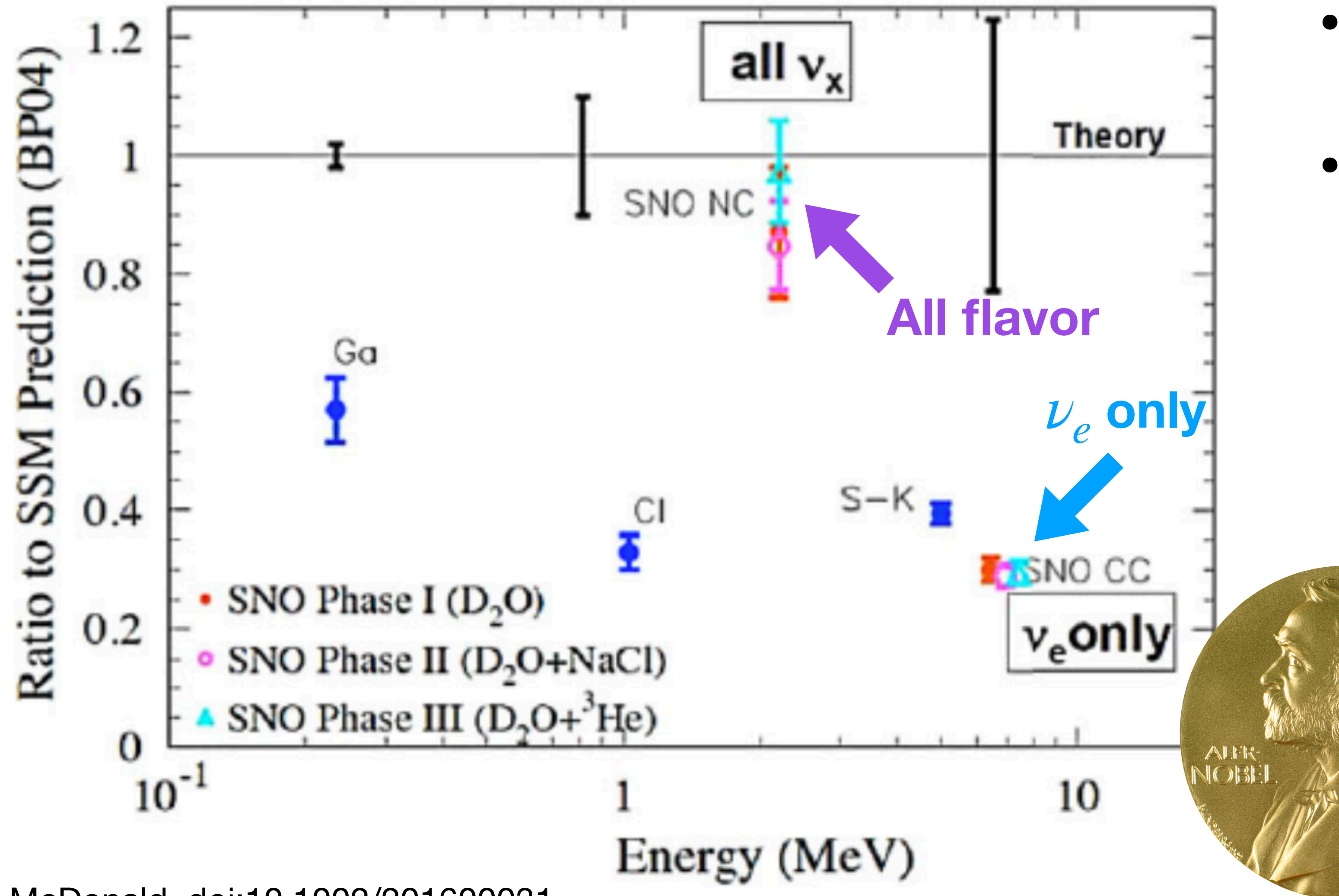
<http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/sno.html>

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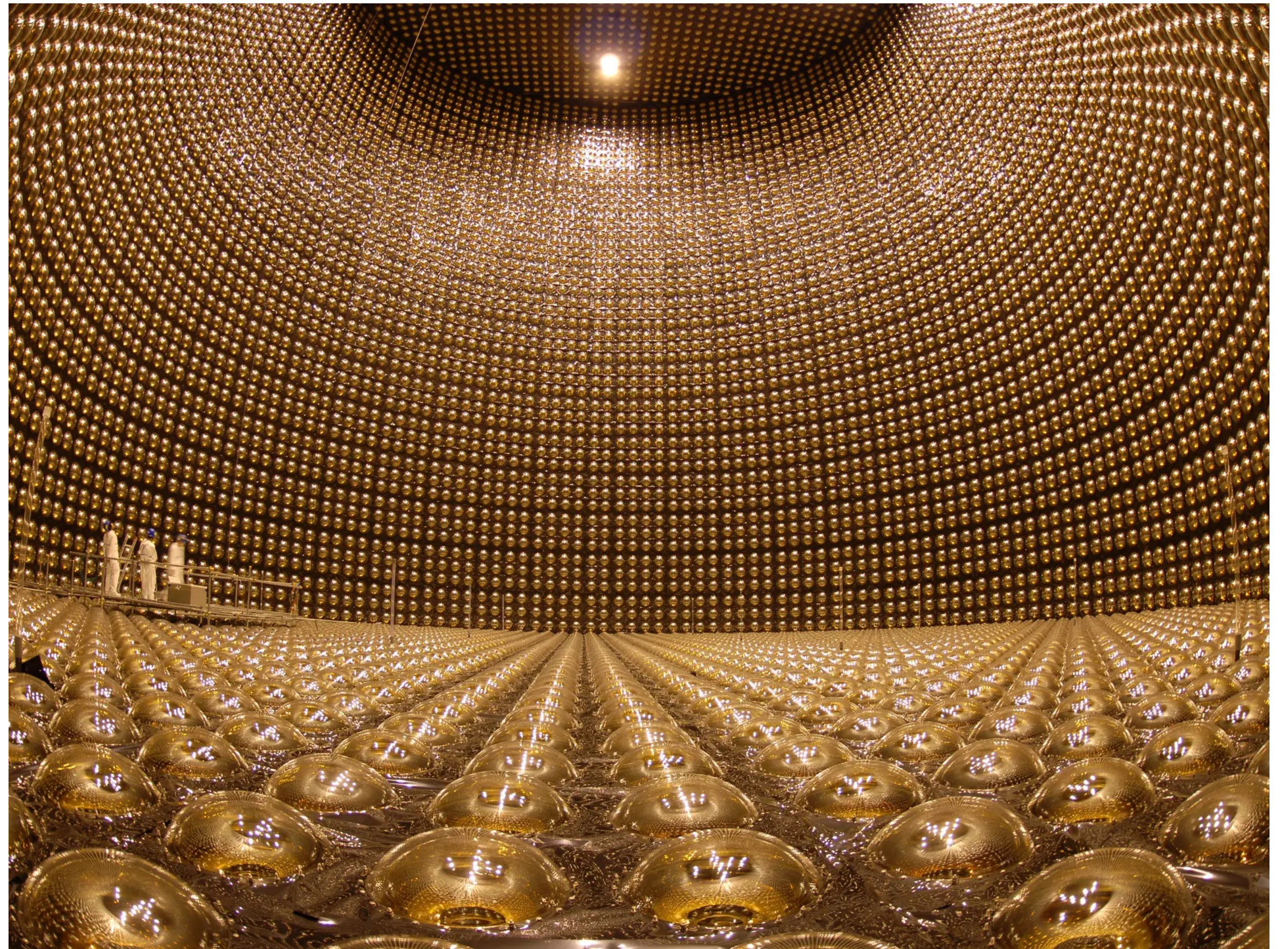
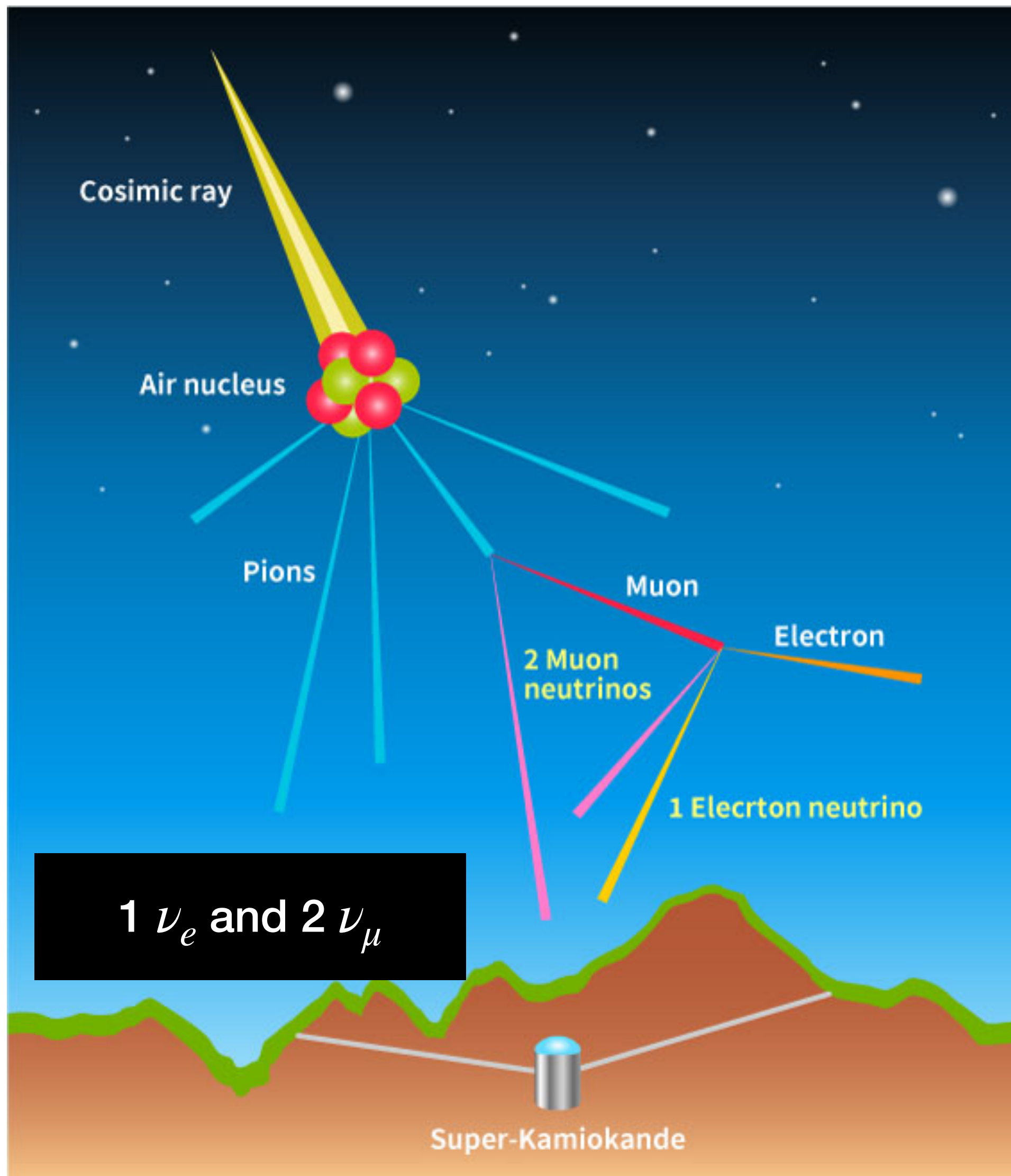
- Discrepancy observed in electron-only measurement
- All flavor measurement in agreement with theoretical predictions

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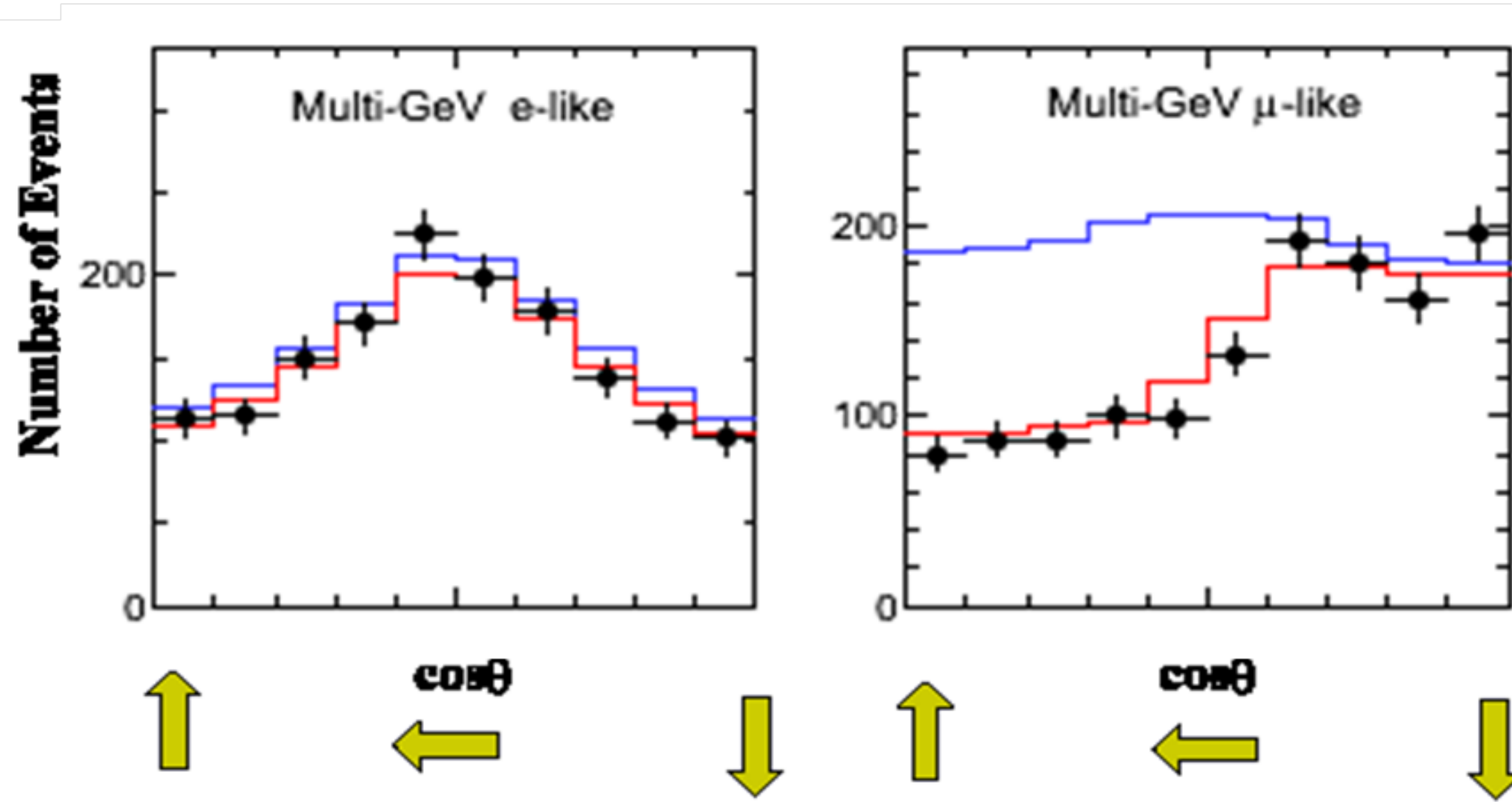


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# Looking at New Sources

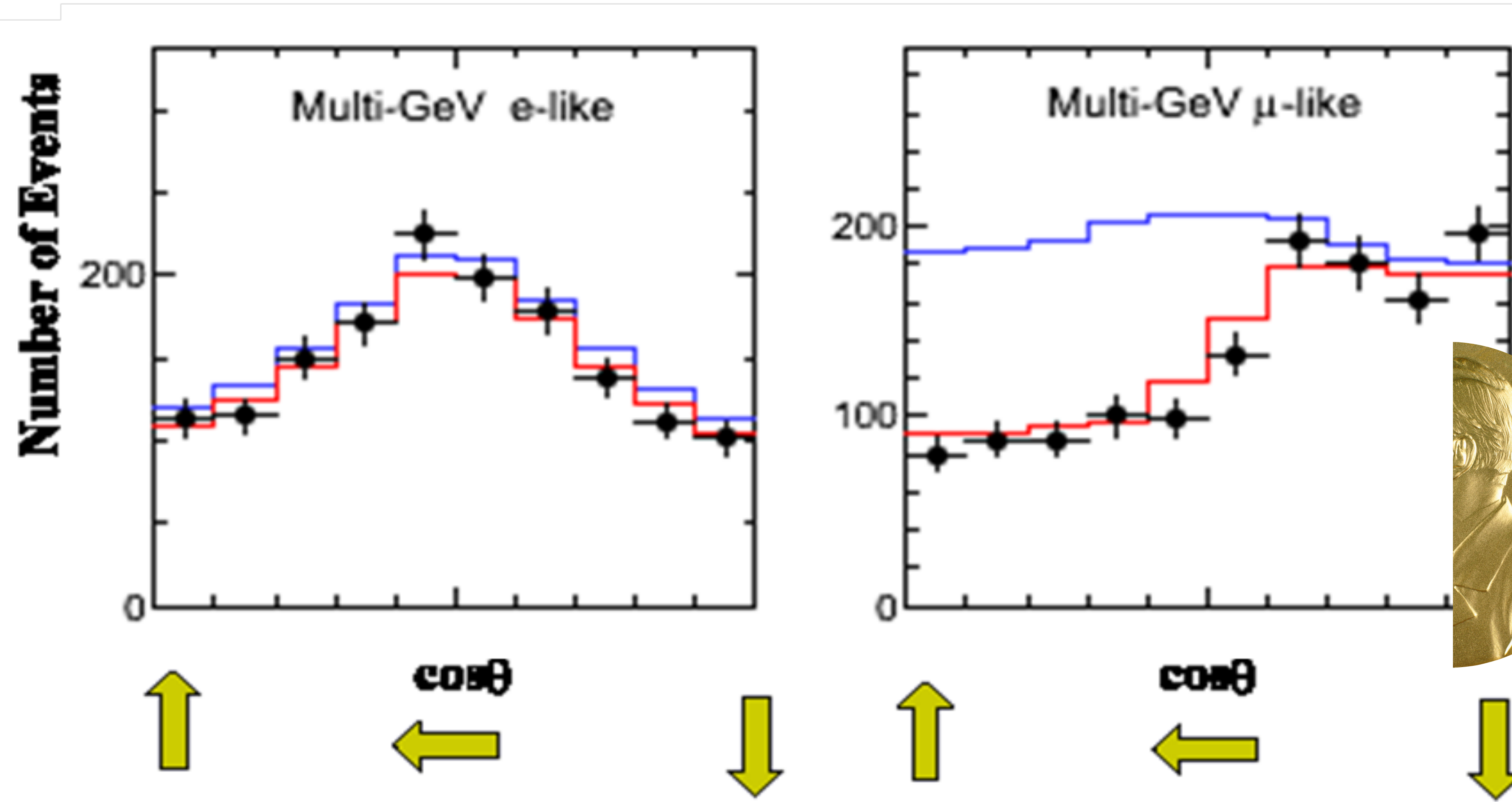


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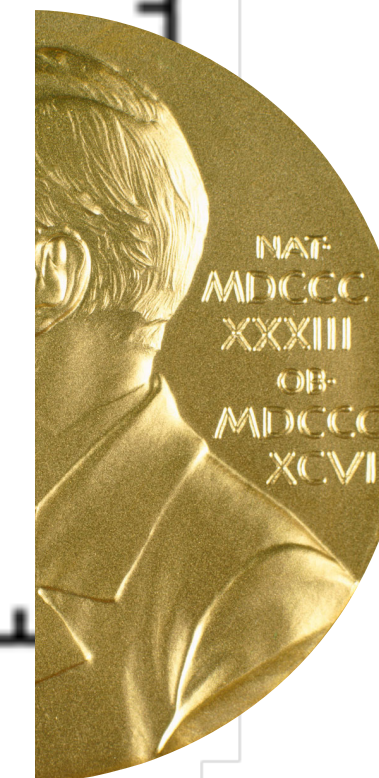


- SuperK saw a deficit of  $\nu_{\mu}$  coming through the Earth
- This confirmed neutrinos neutrino in-flight flavor change

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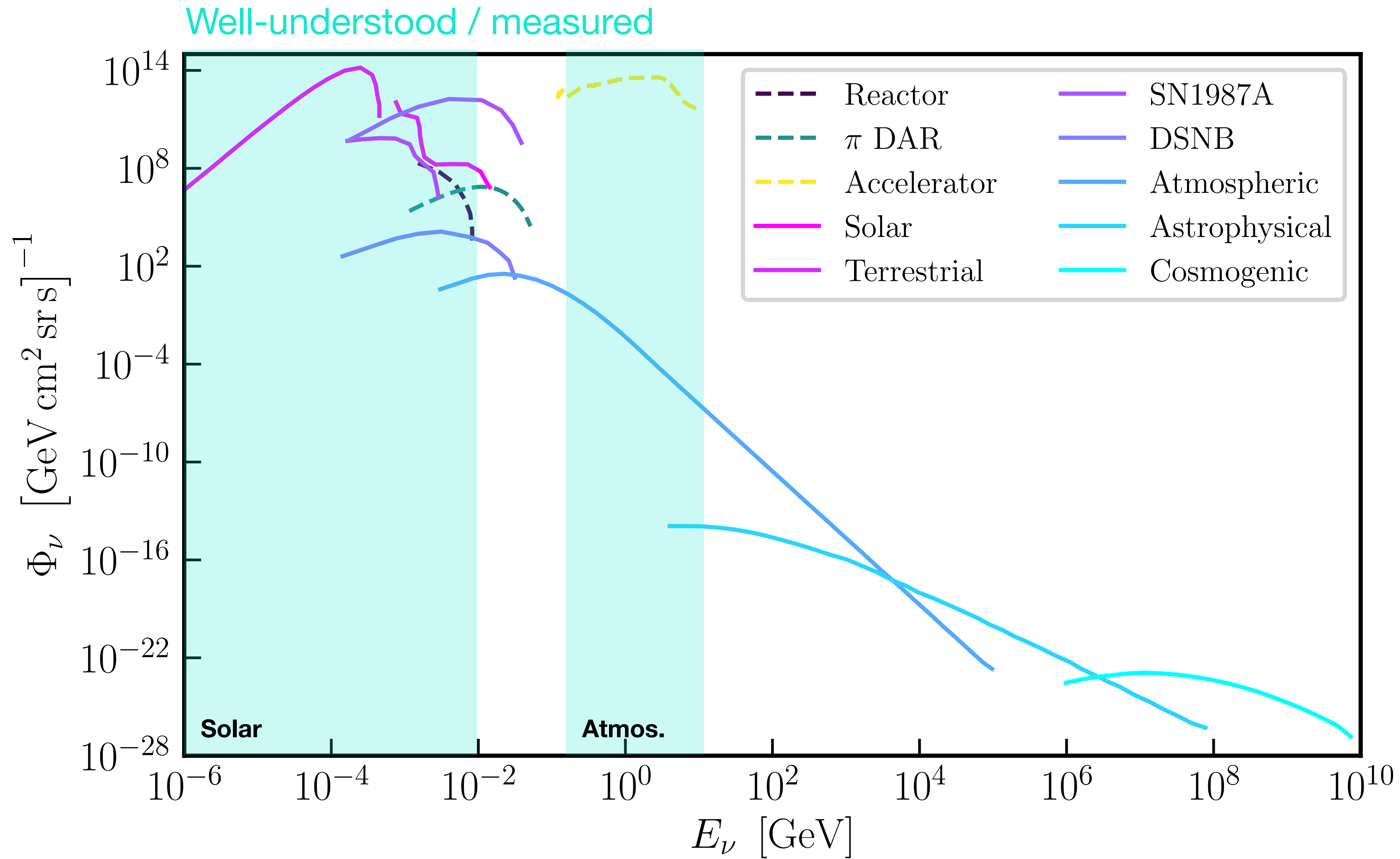


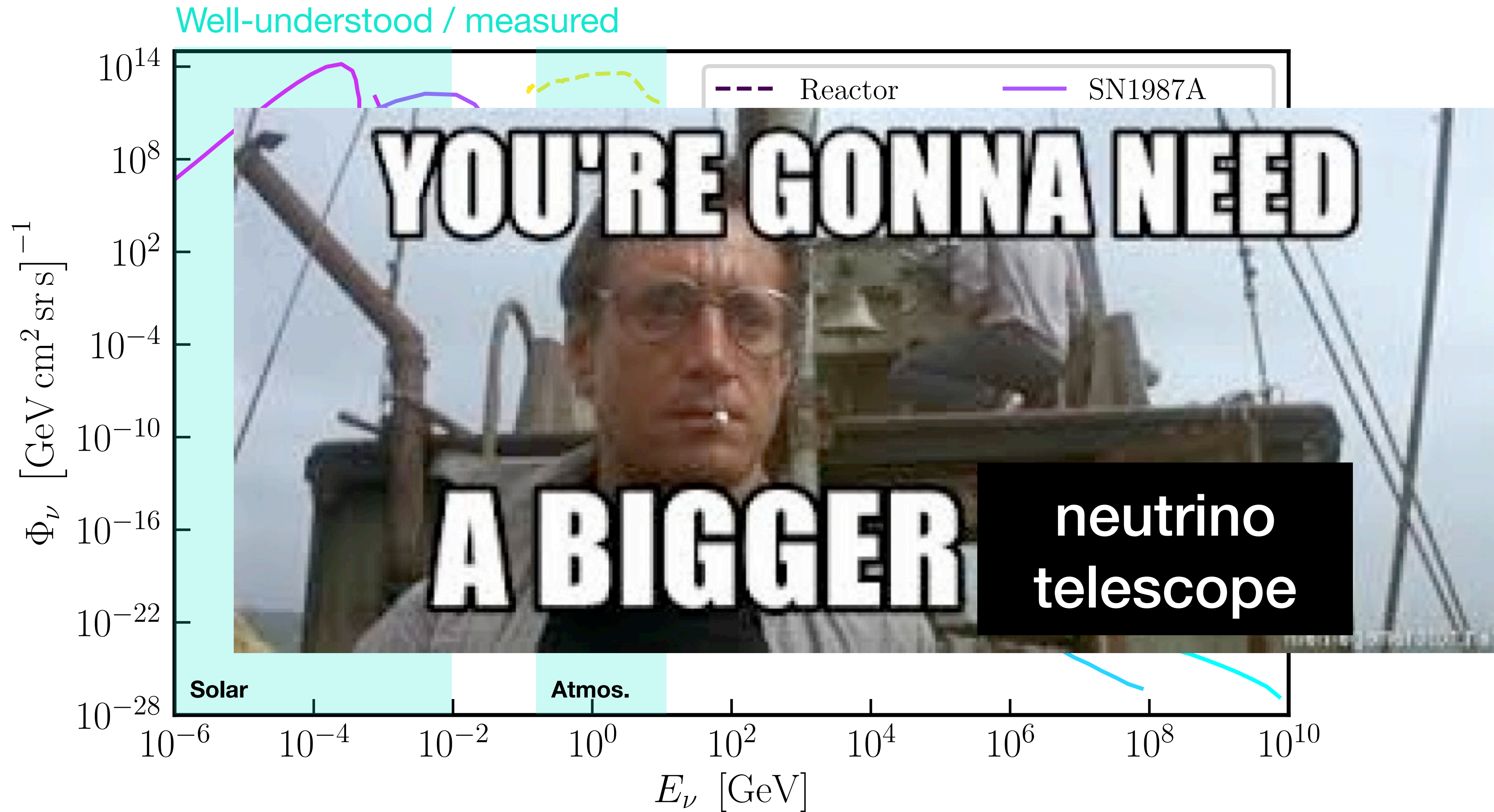


Understanding the *flavor*, *energy*, and *directional* information of non-terrestrial neutrinos have played a pivotal role in shaping our understanding of the Sun, neutrino physics, and the Standard Model more broadly

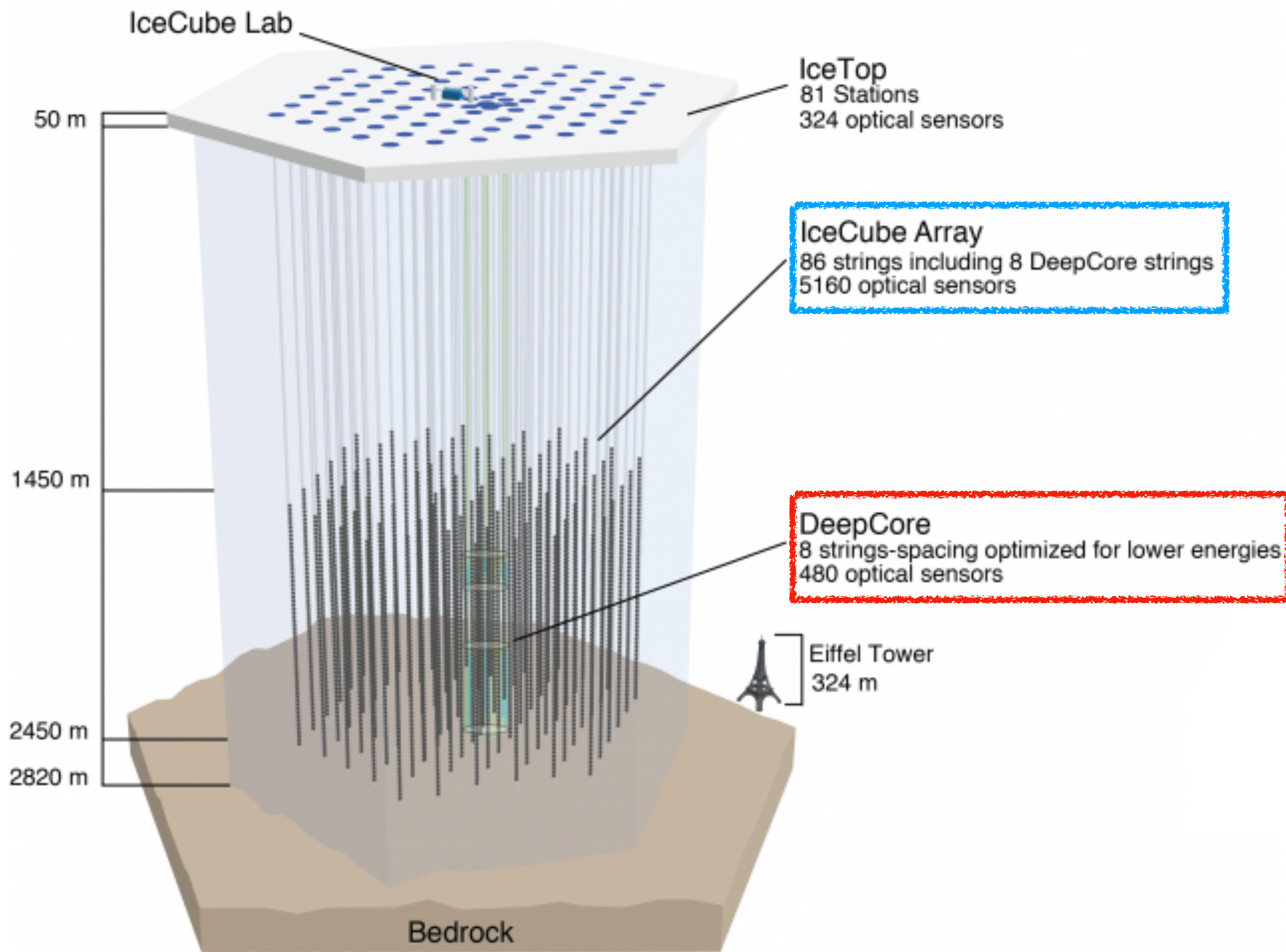
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**So, where do we go from here ?**



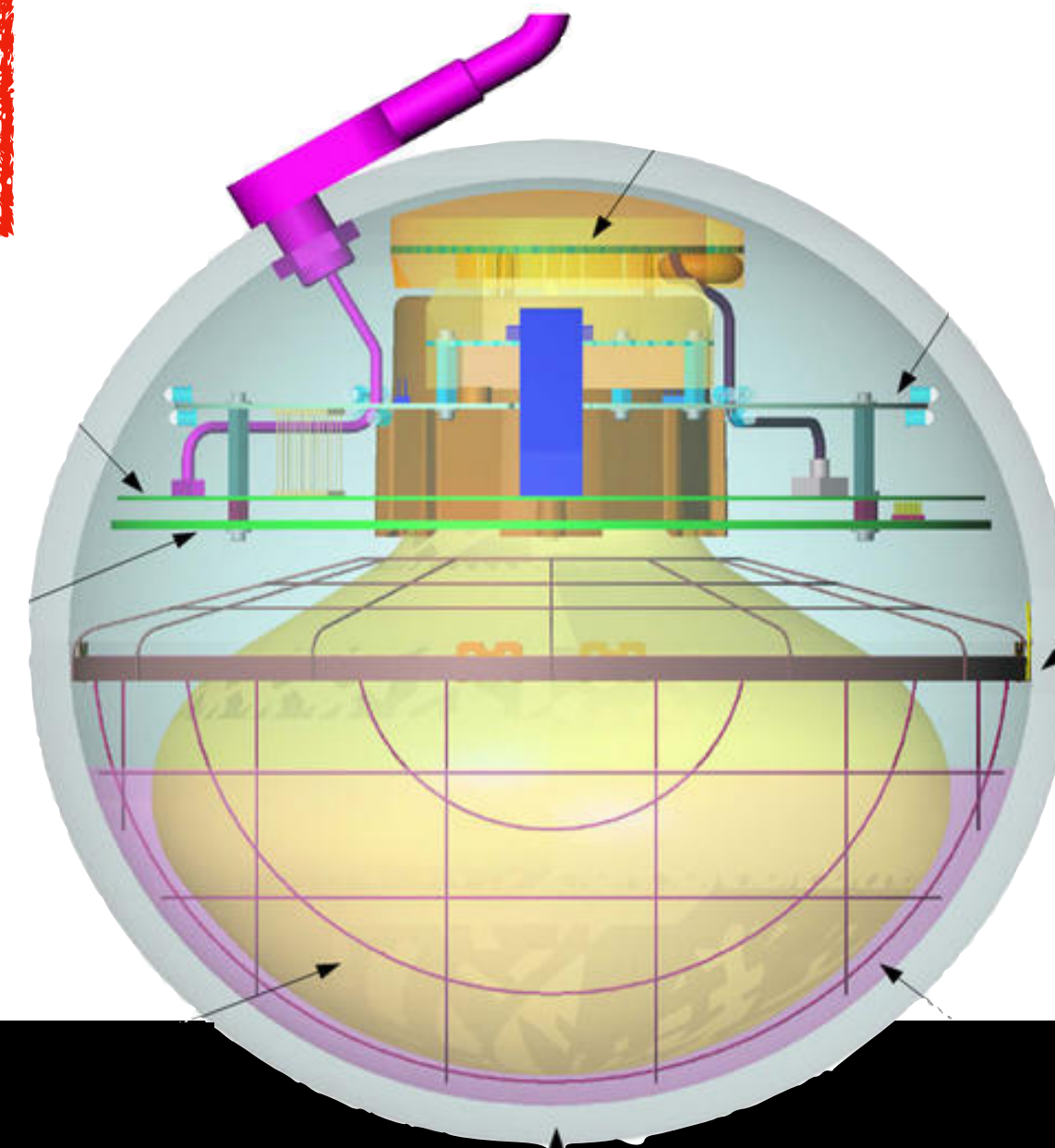


# The IceCube Neutrino Observatory



Gigaton scale detector of 5,160 light detecting digital optical modules (DOMs)

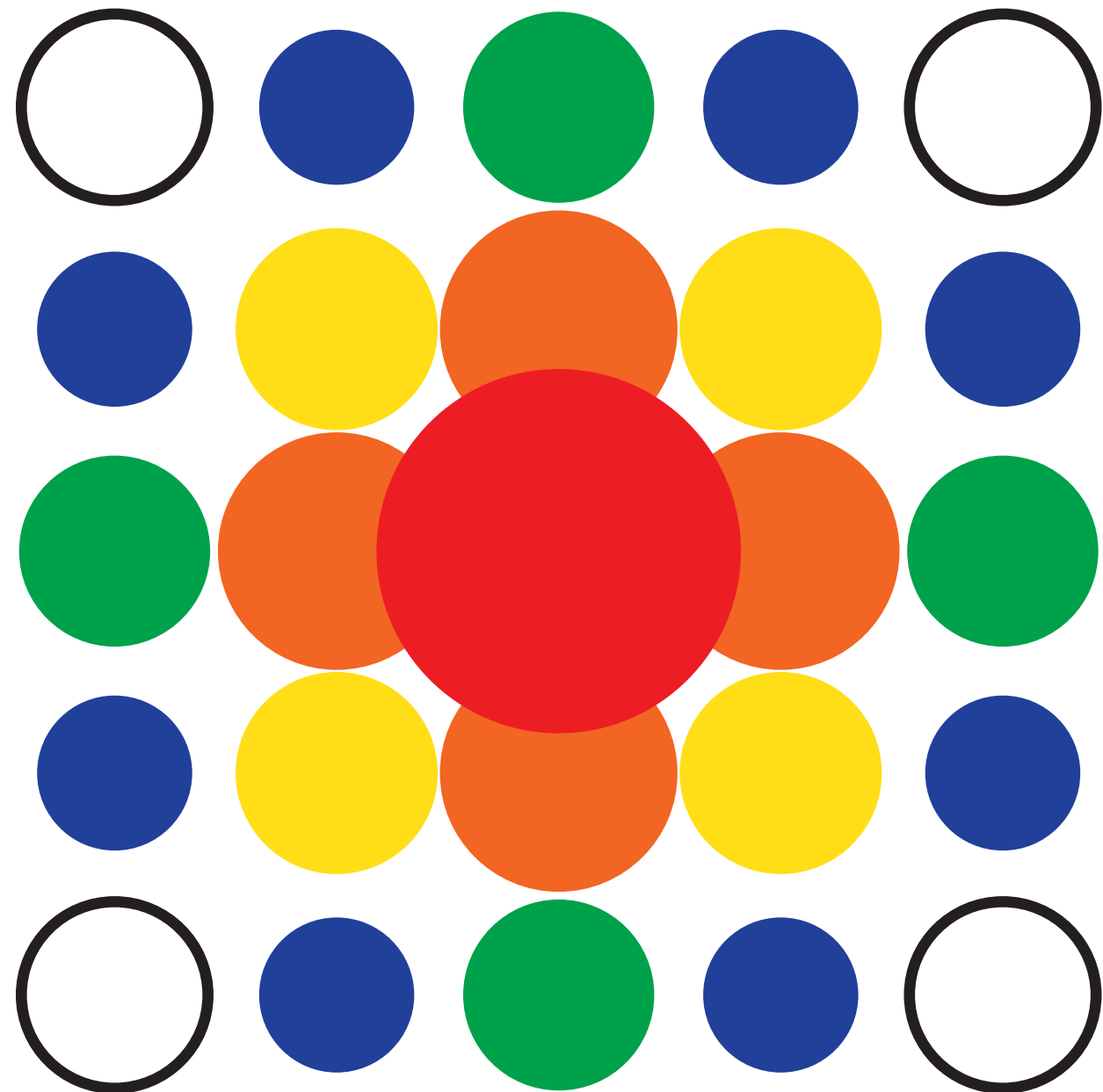
IceCube and DeepCore sensitive to high- and low-energy neutrinos



# Unfolding Light and Time

Cascades

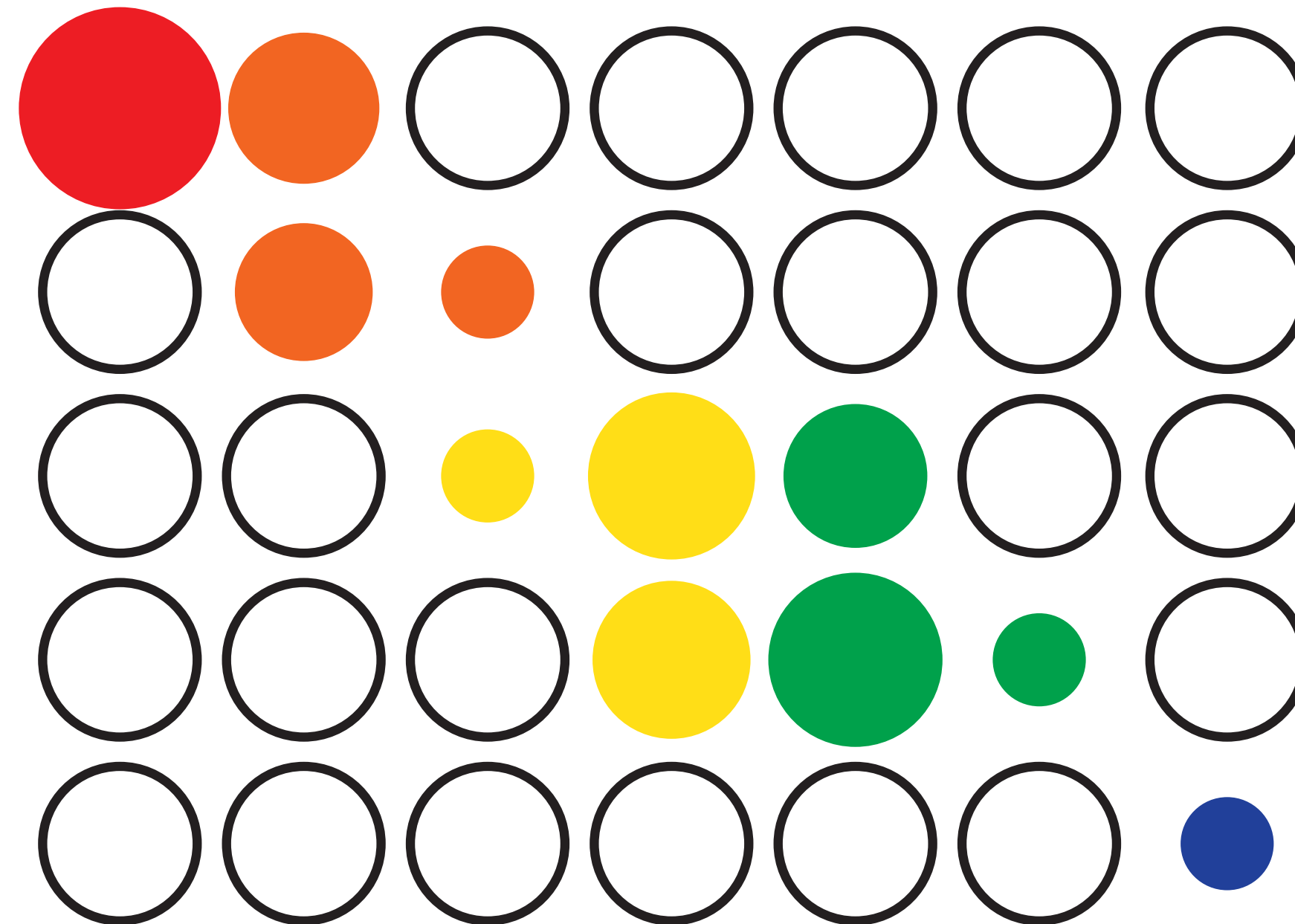
$\nu_e$  CC |  $\nu_\alpha$  NC



Great energy resolution, but angular reconstruction is challenging

Tracks

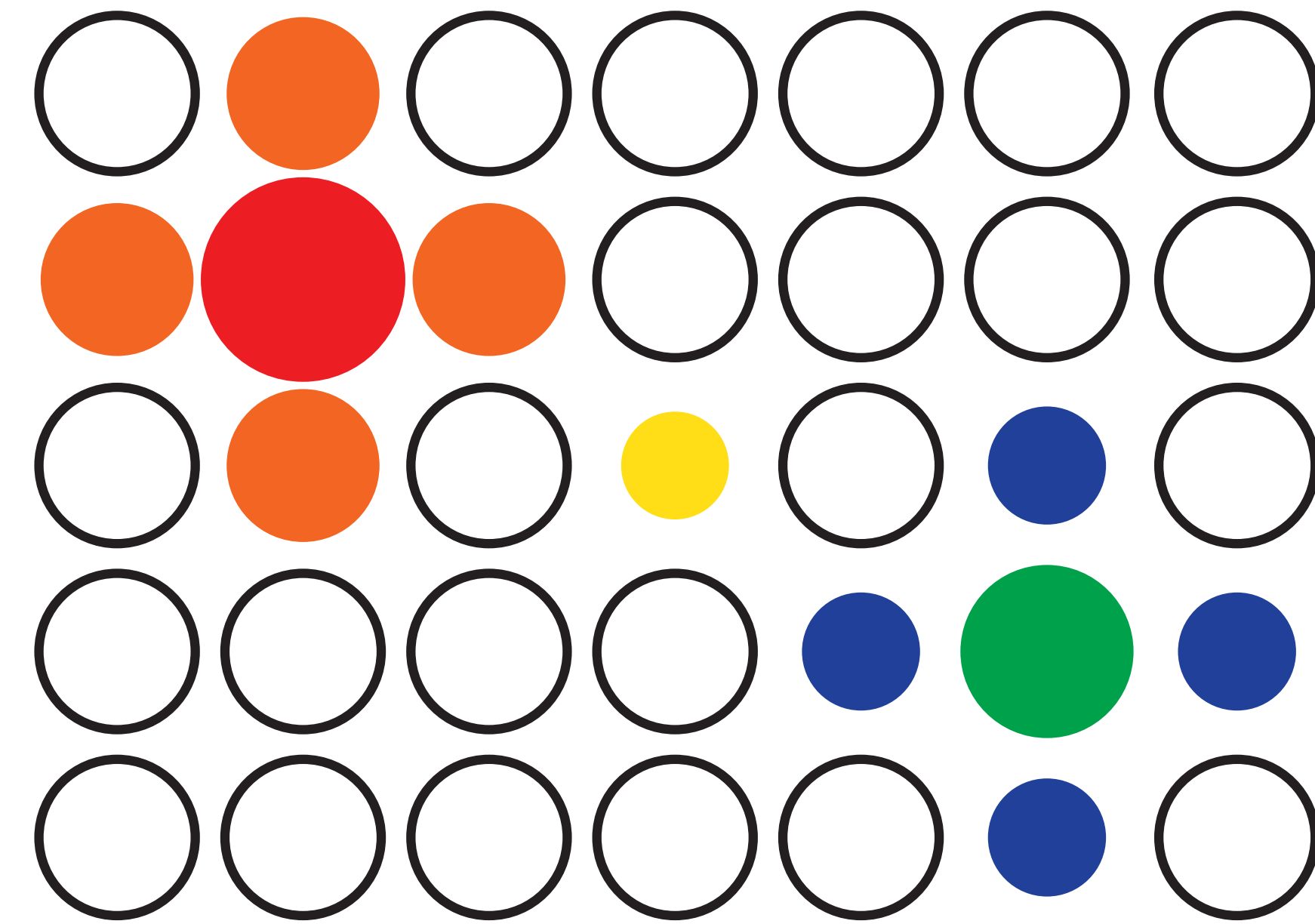
$\nu_\mu$  CC



Great directional resolution, but deposited energy not proportional to  $E_\nu$

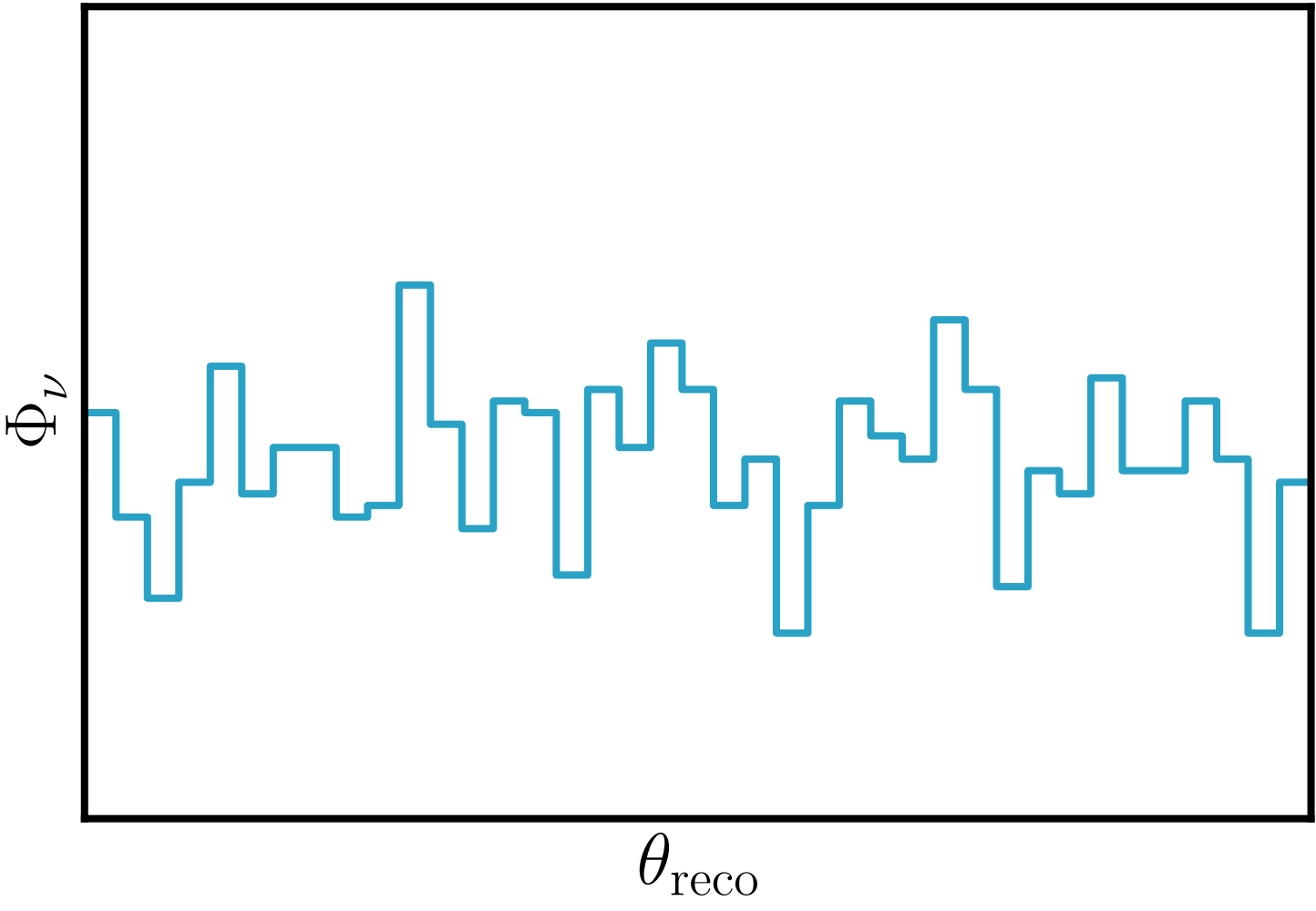
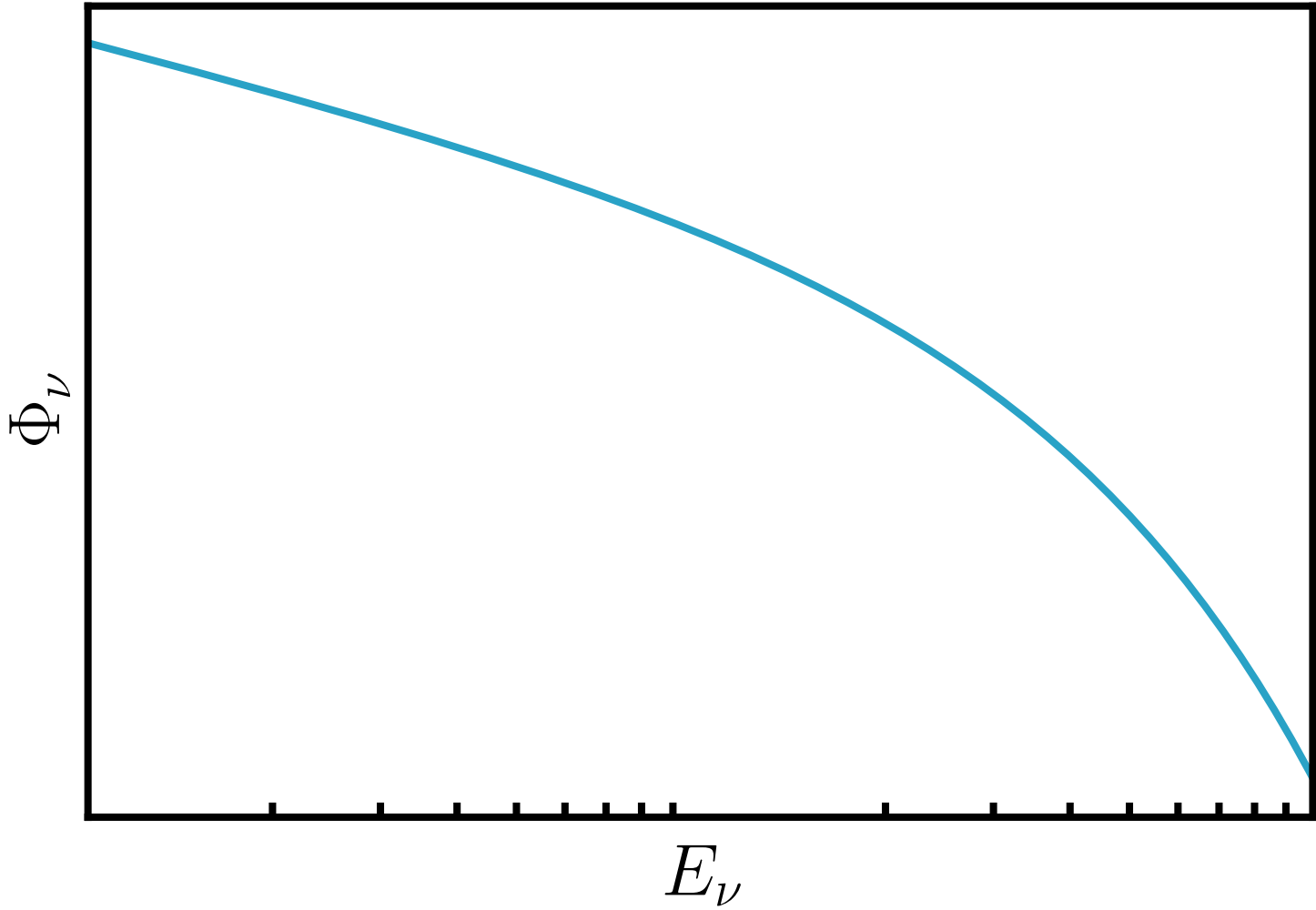
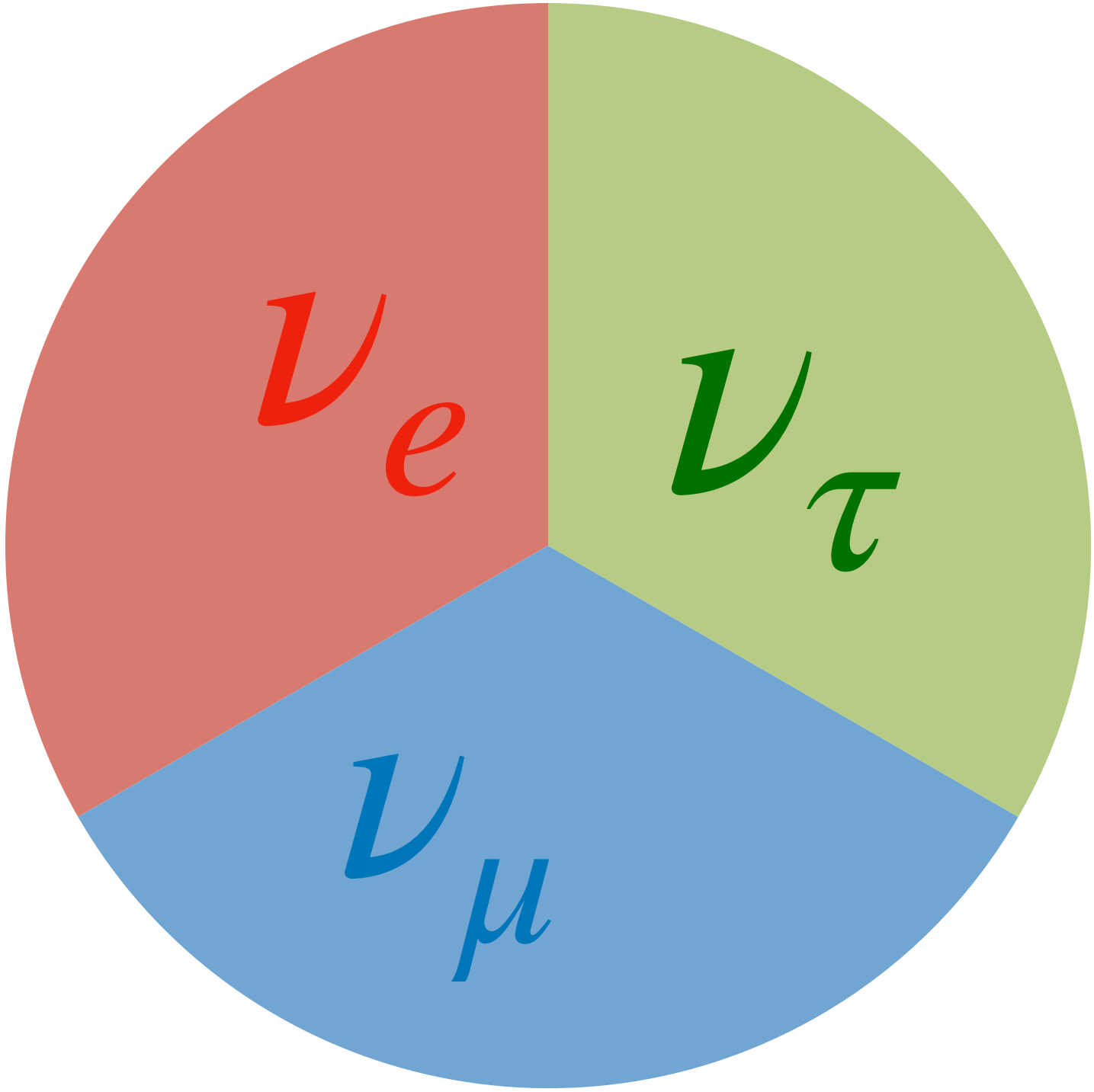
Double bangs

$\nu_\tau$  CC

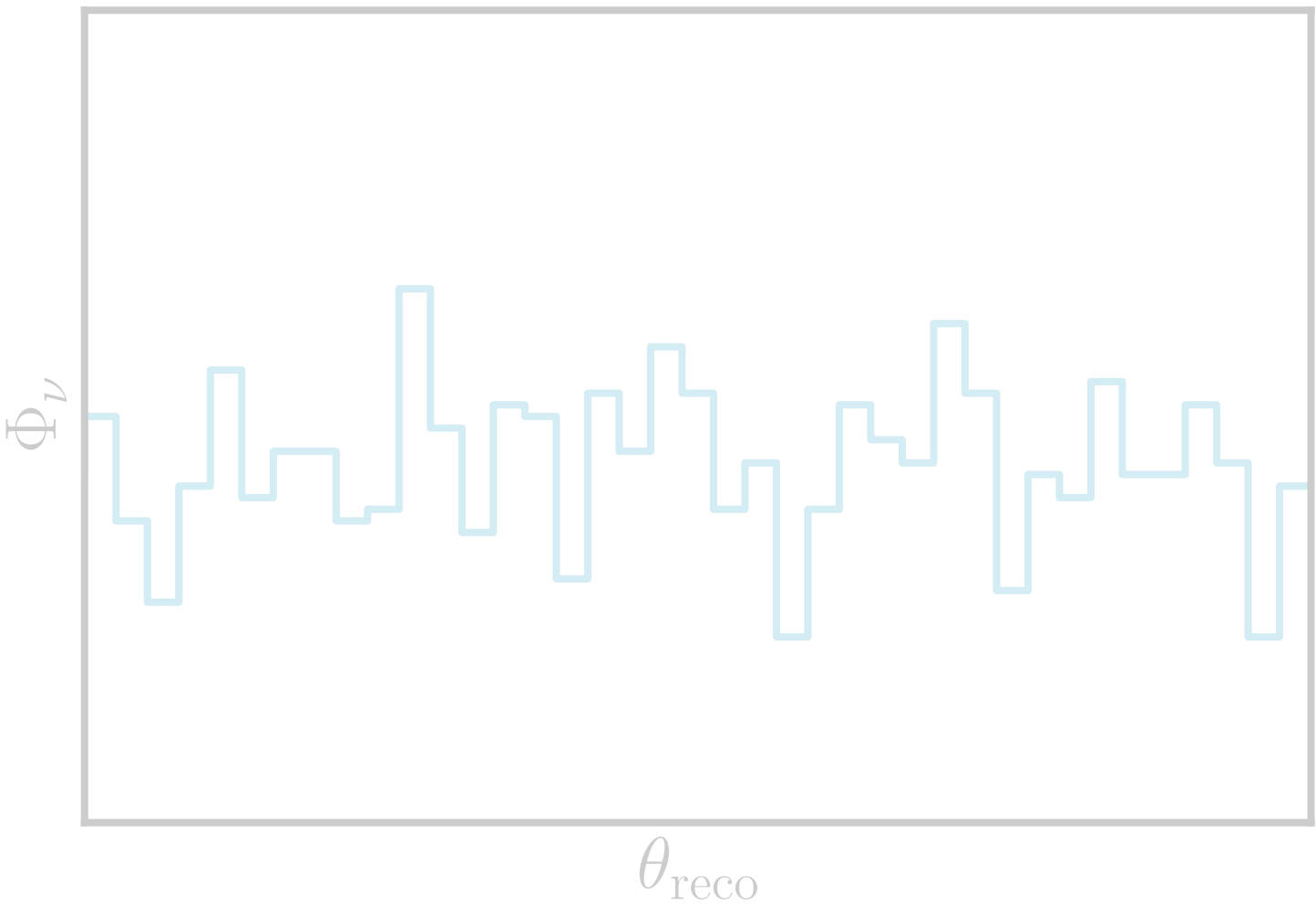
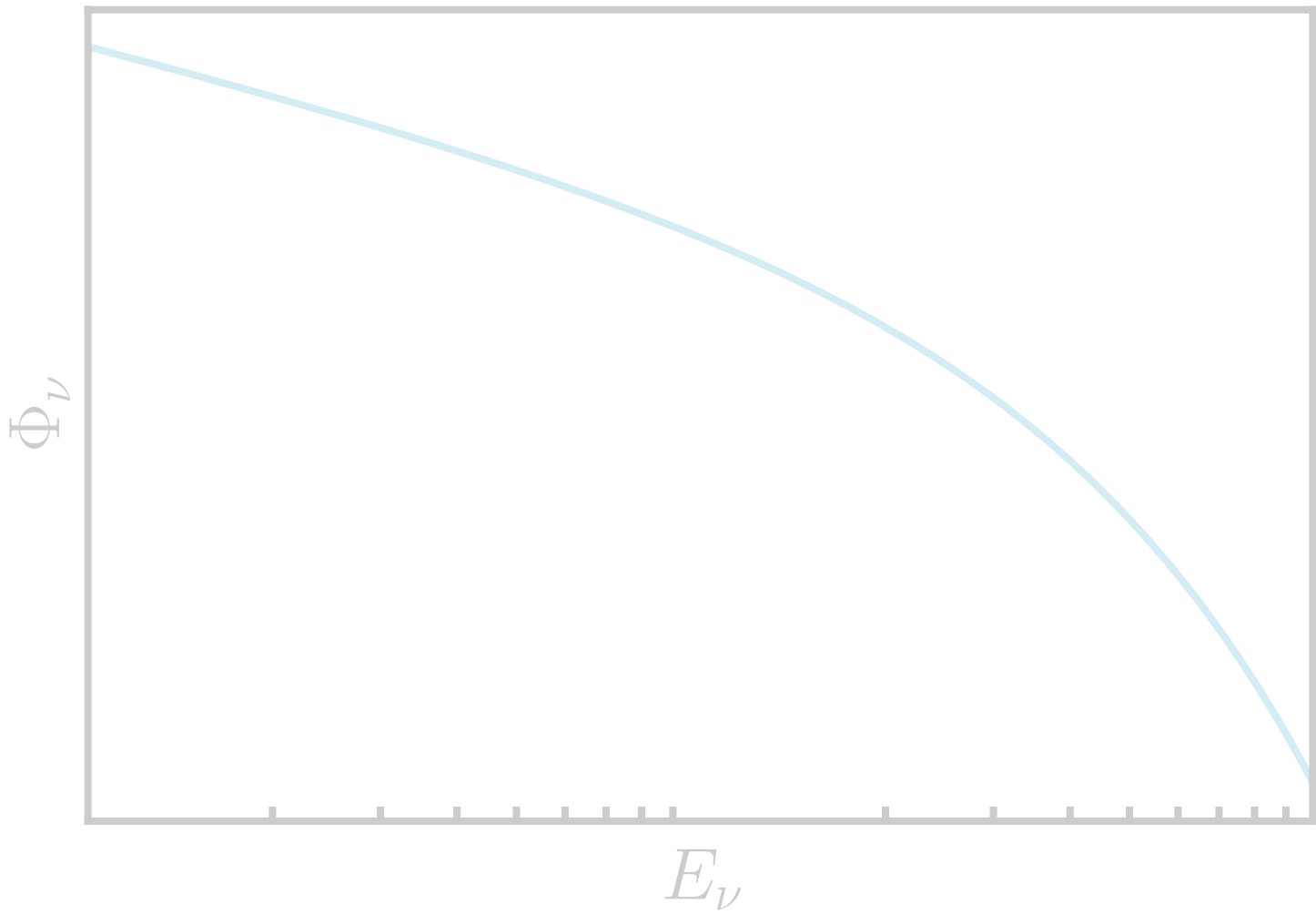
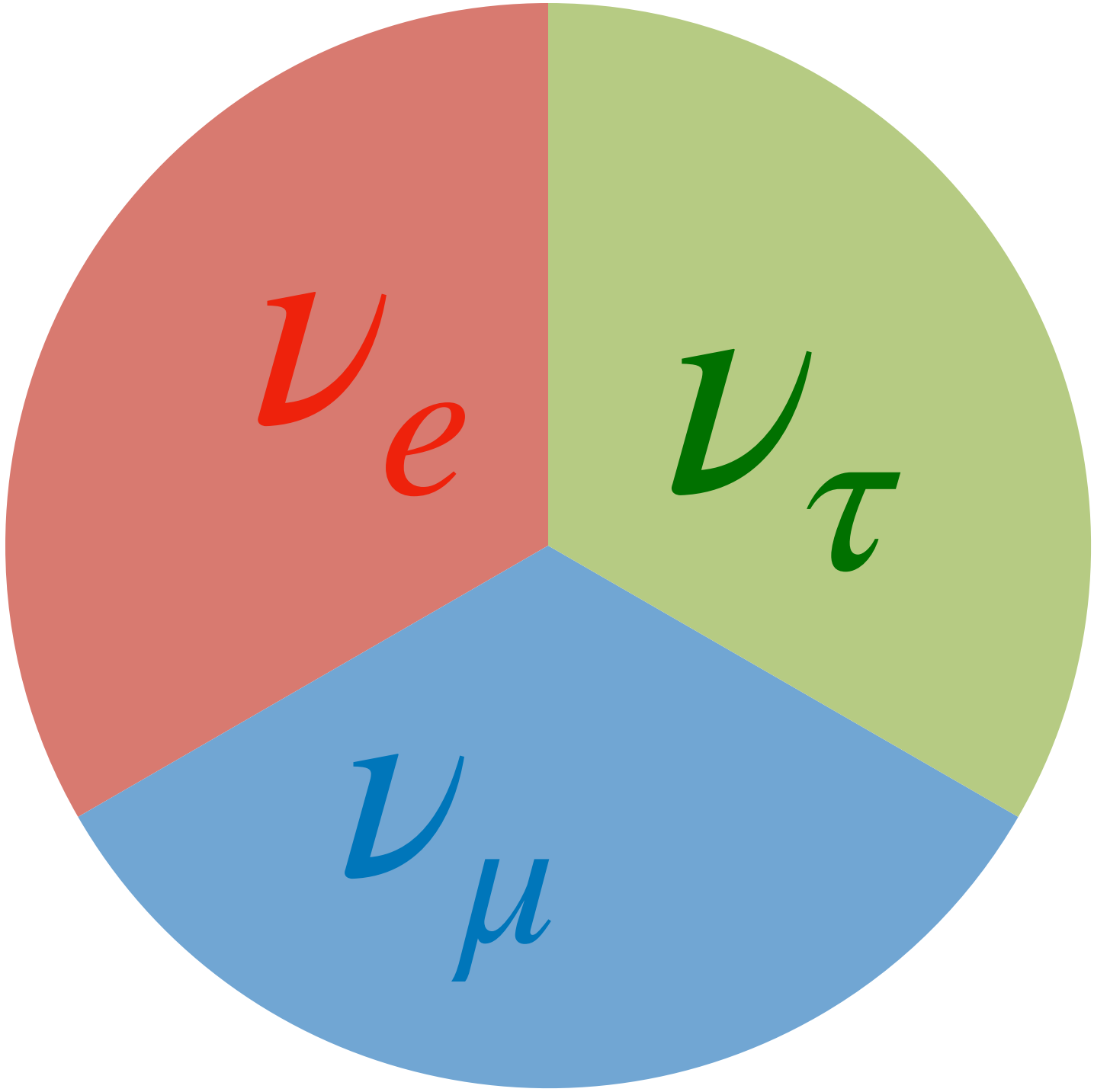


Signature of  $\nu_\tau$  CC events

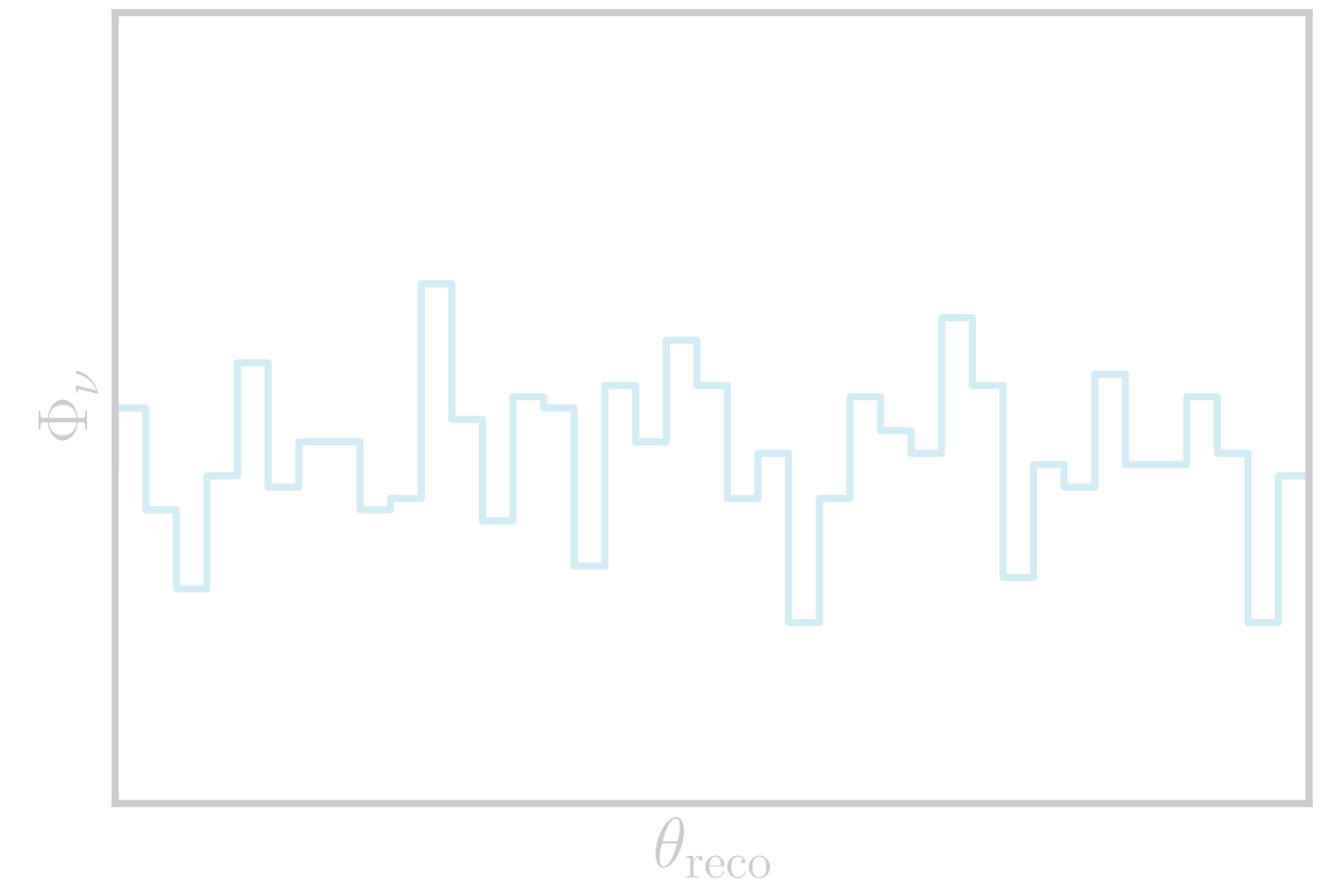
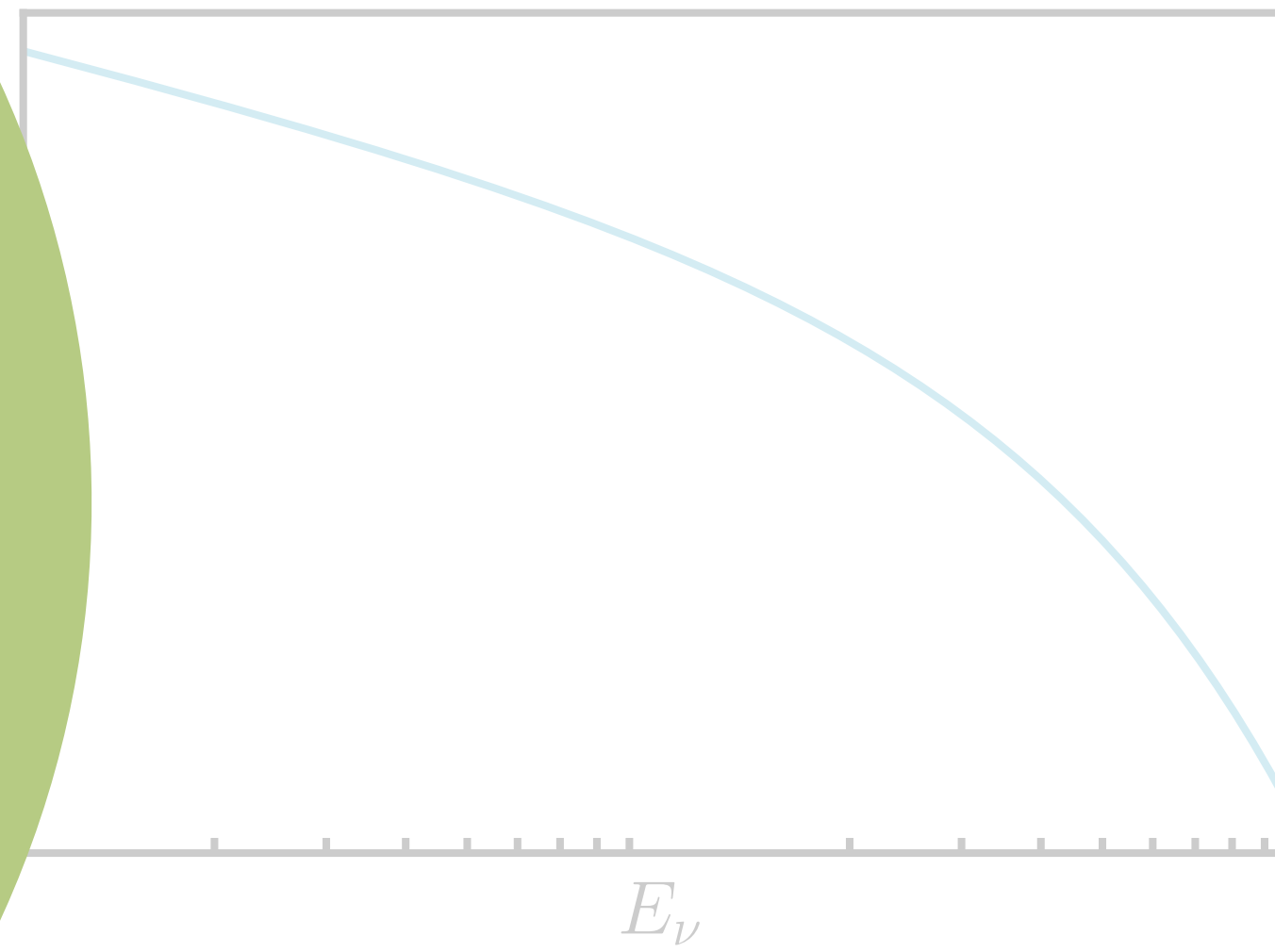
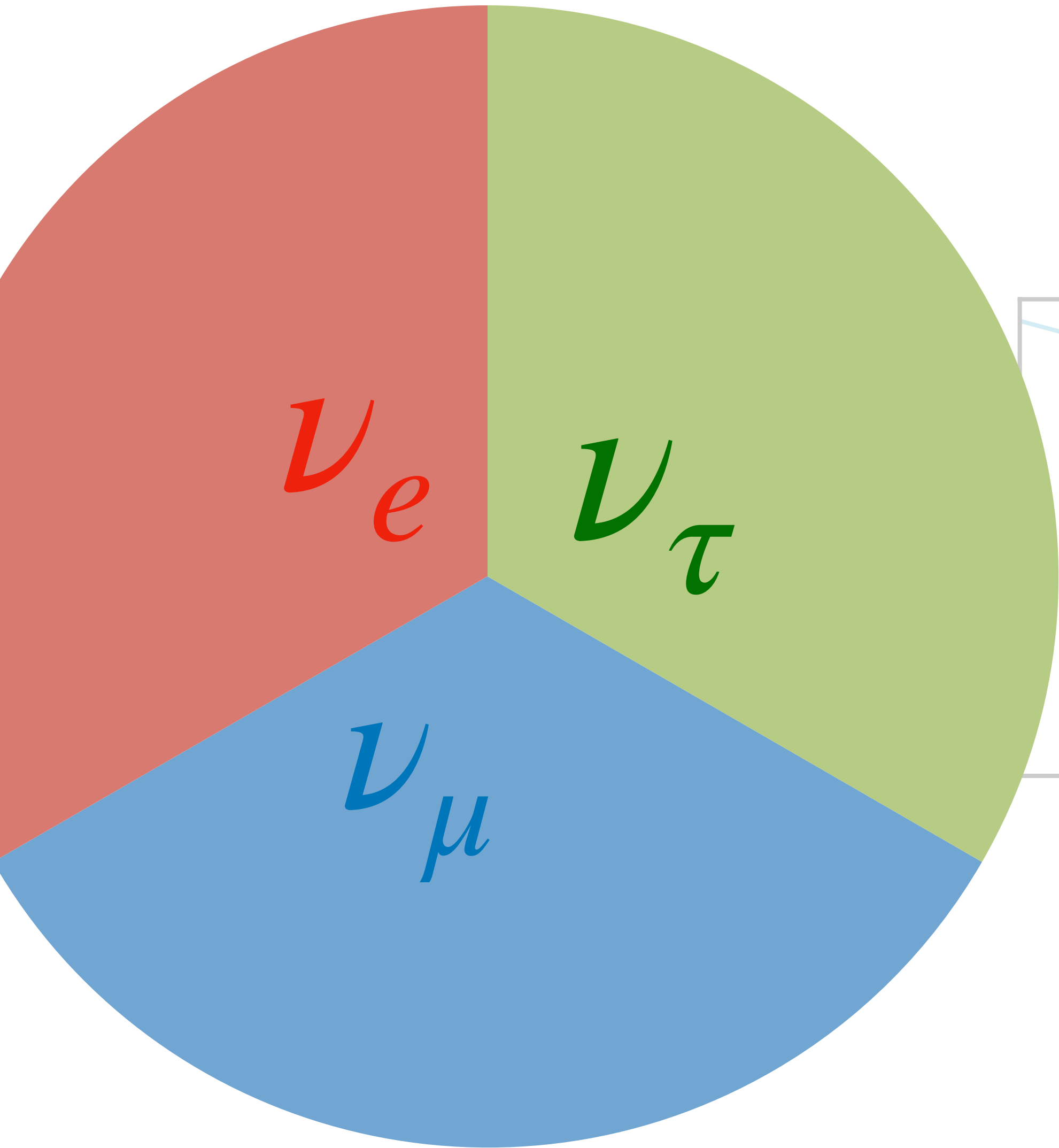
# What Do we look for



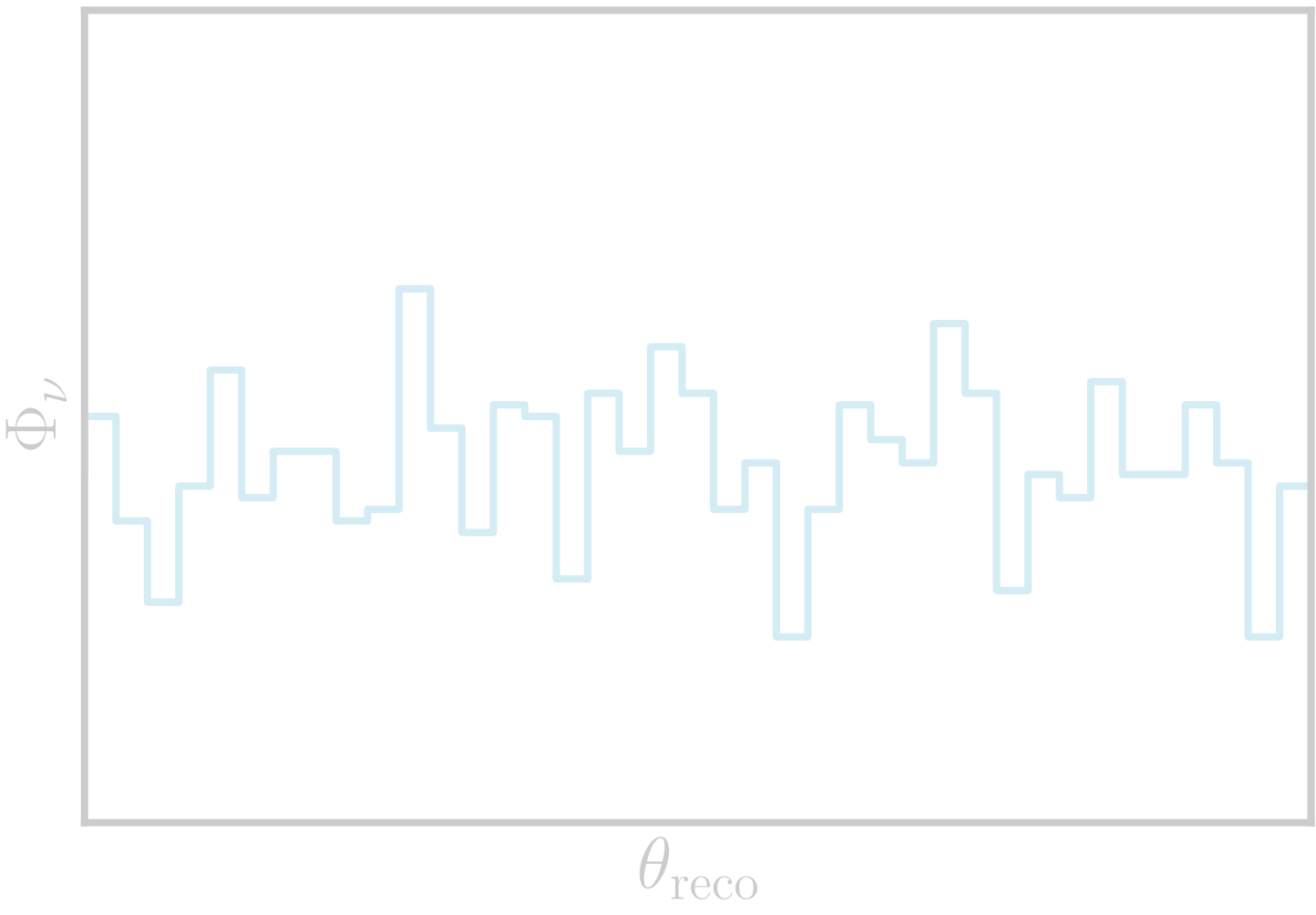
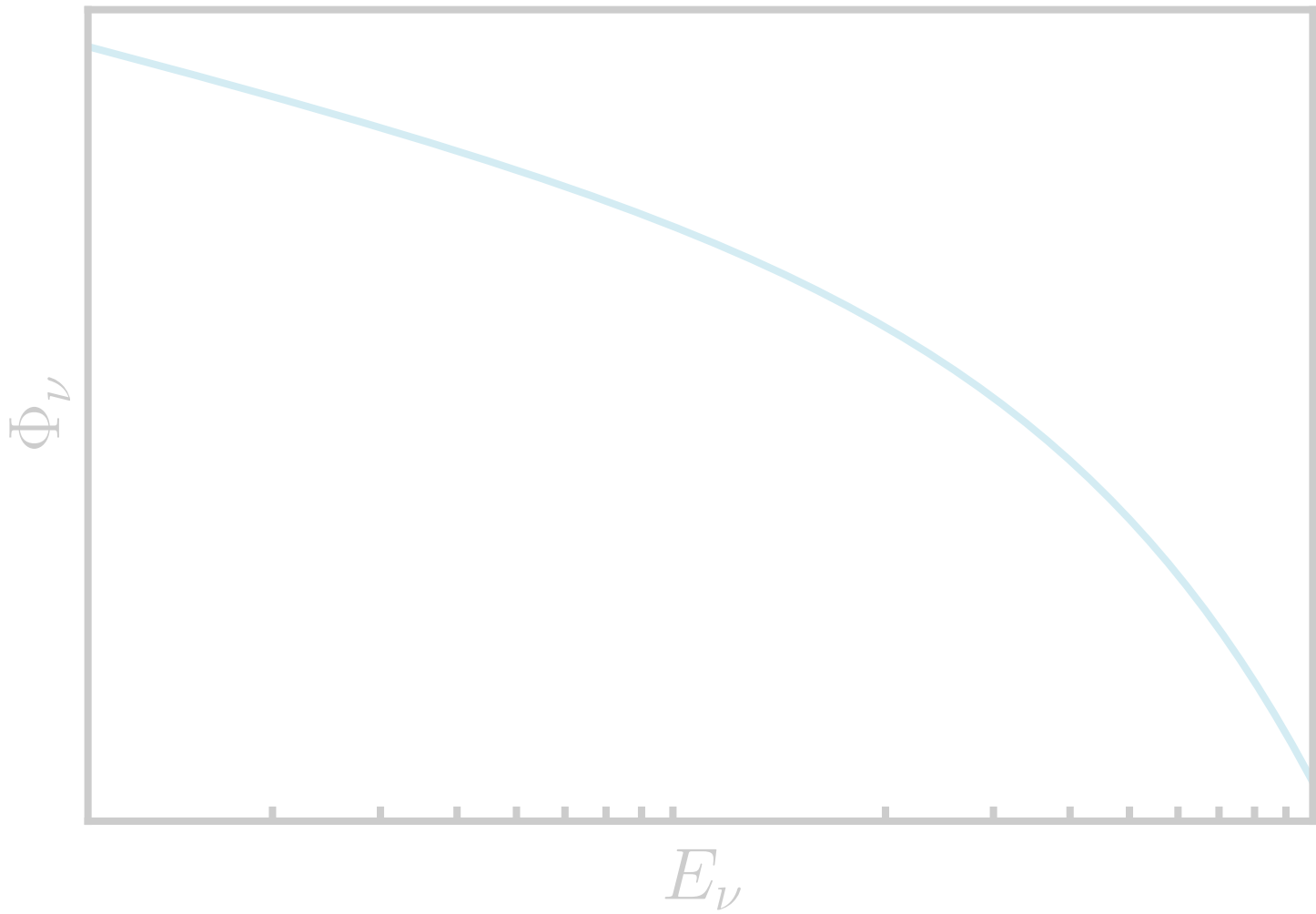
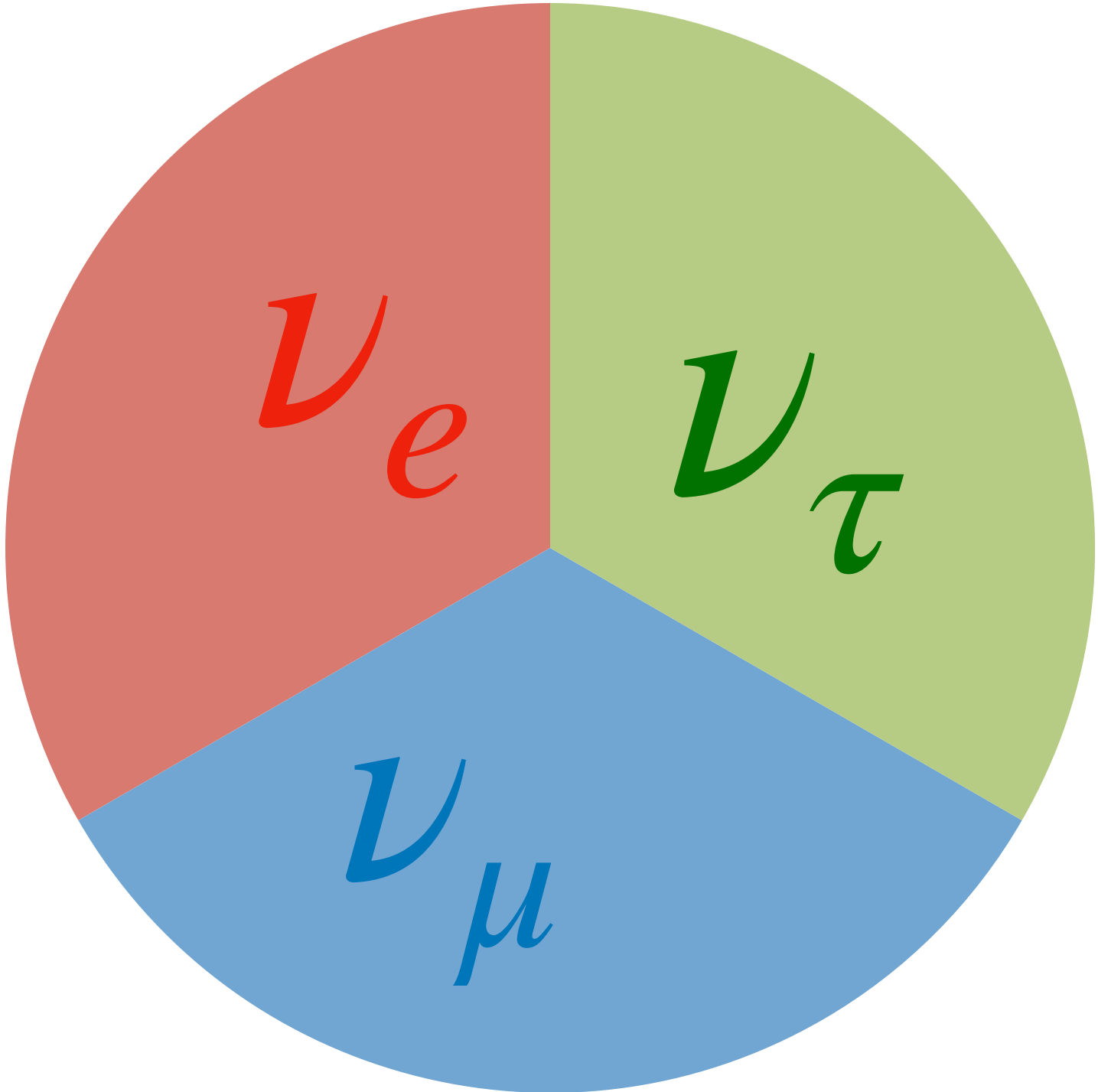
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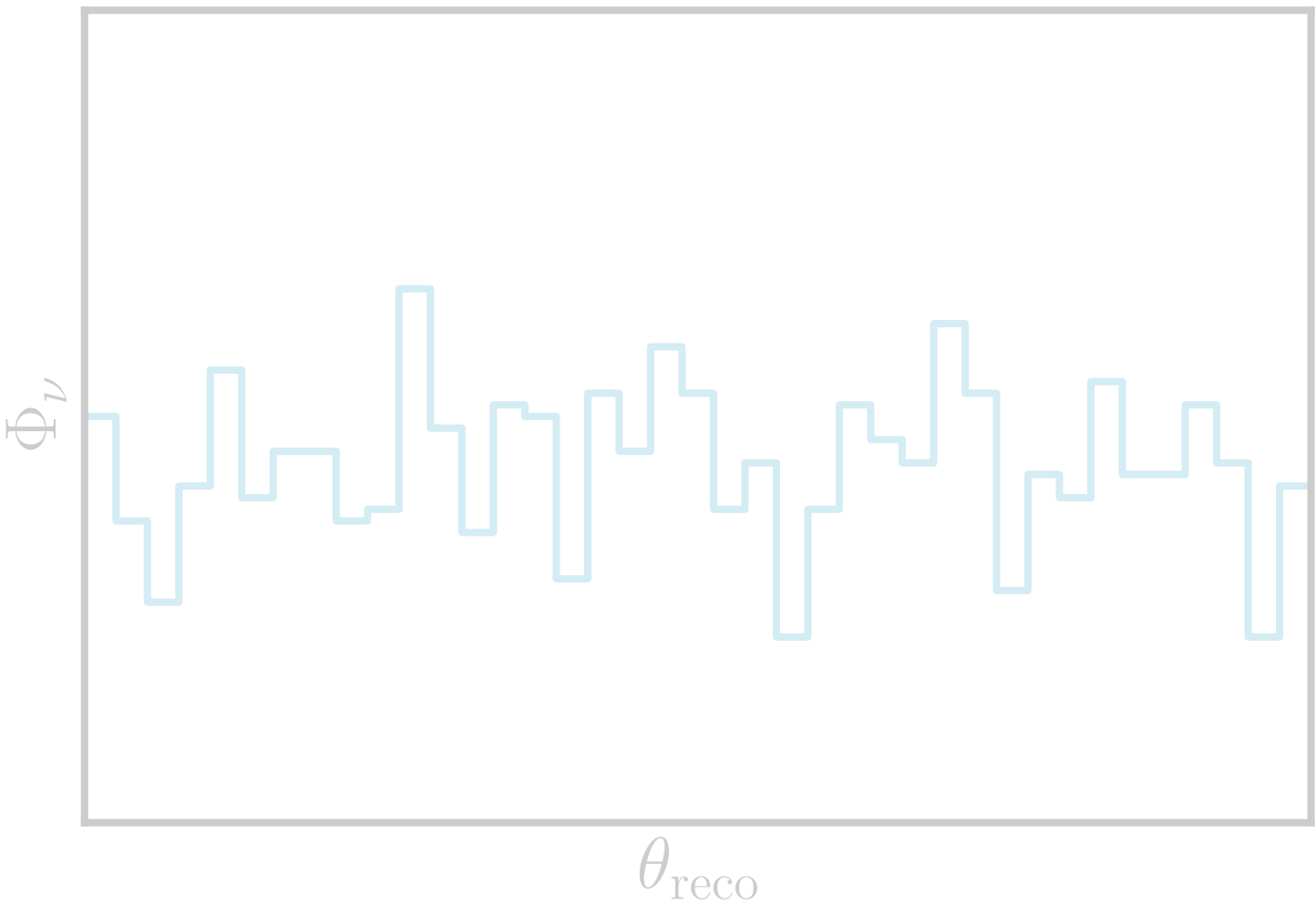
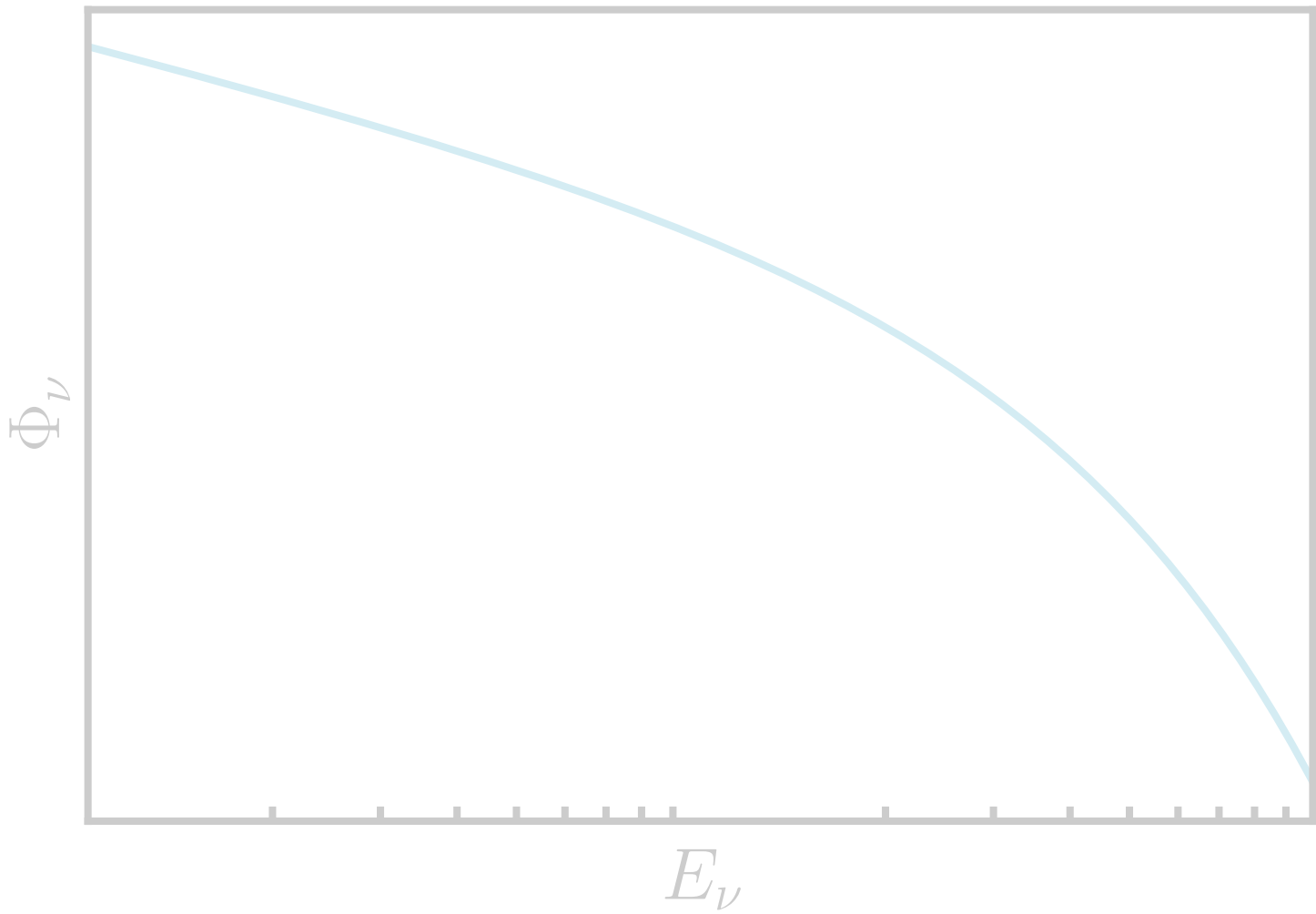
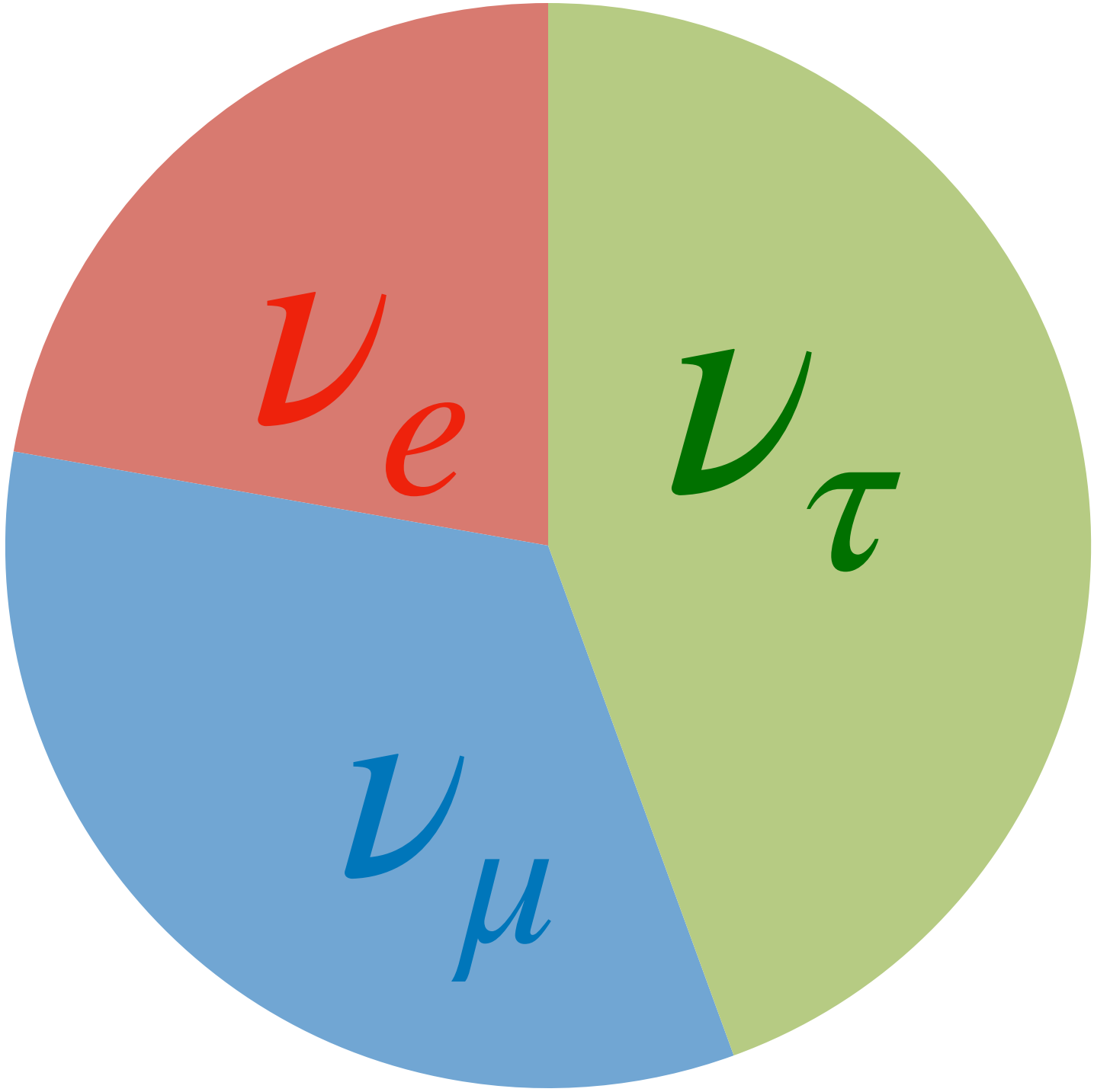
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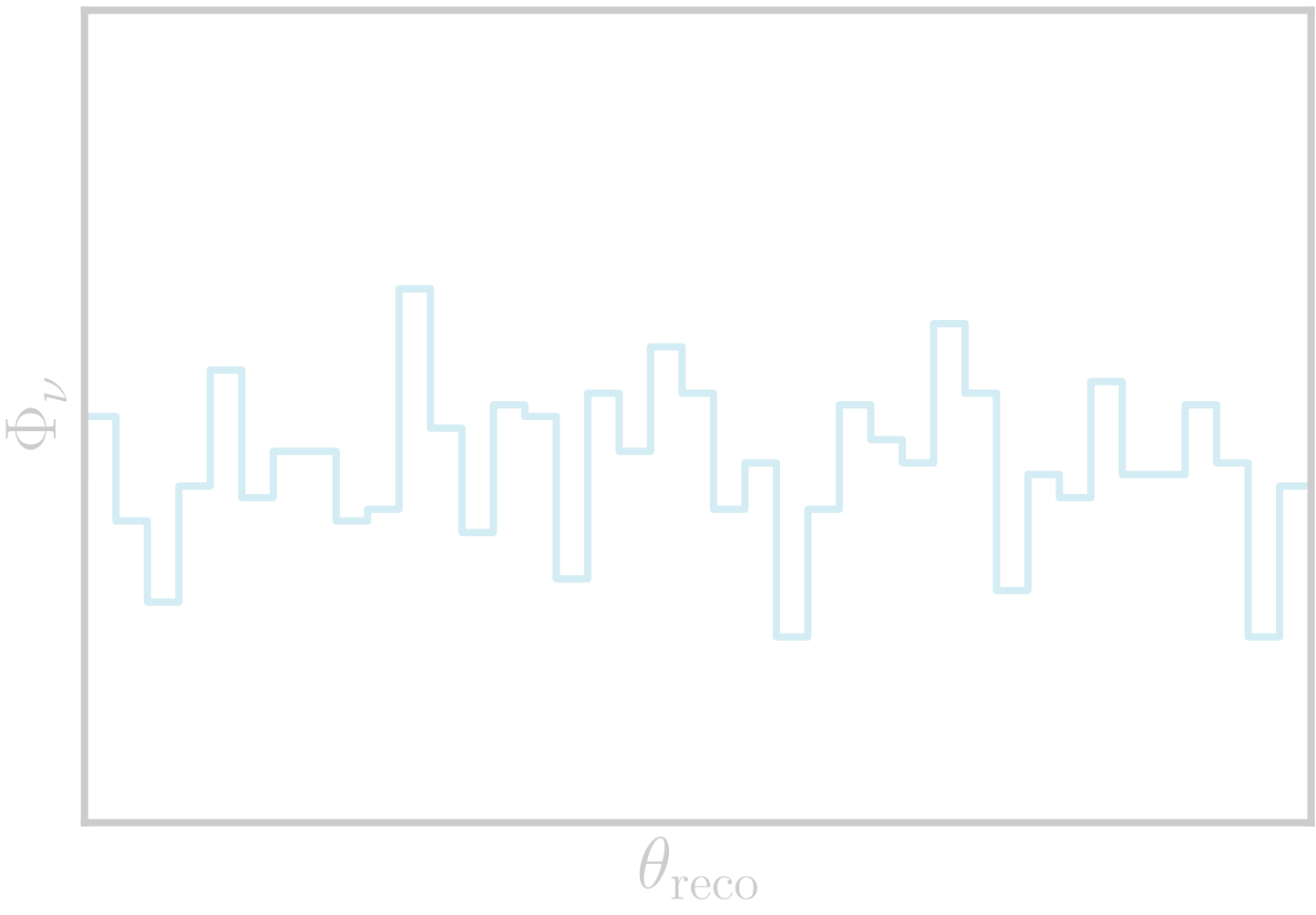
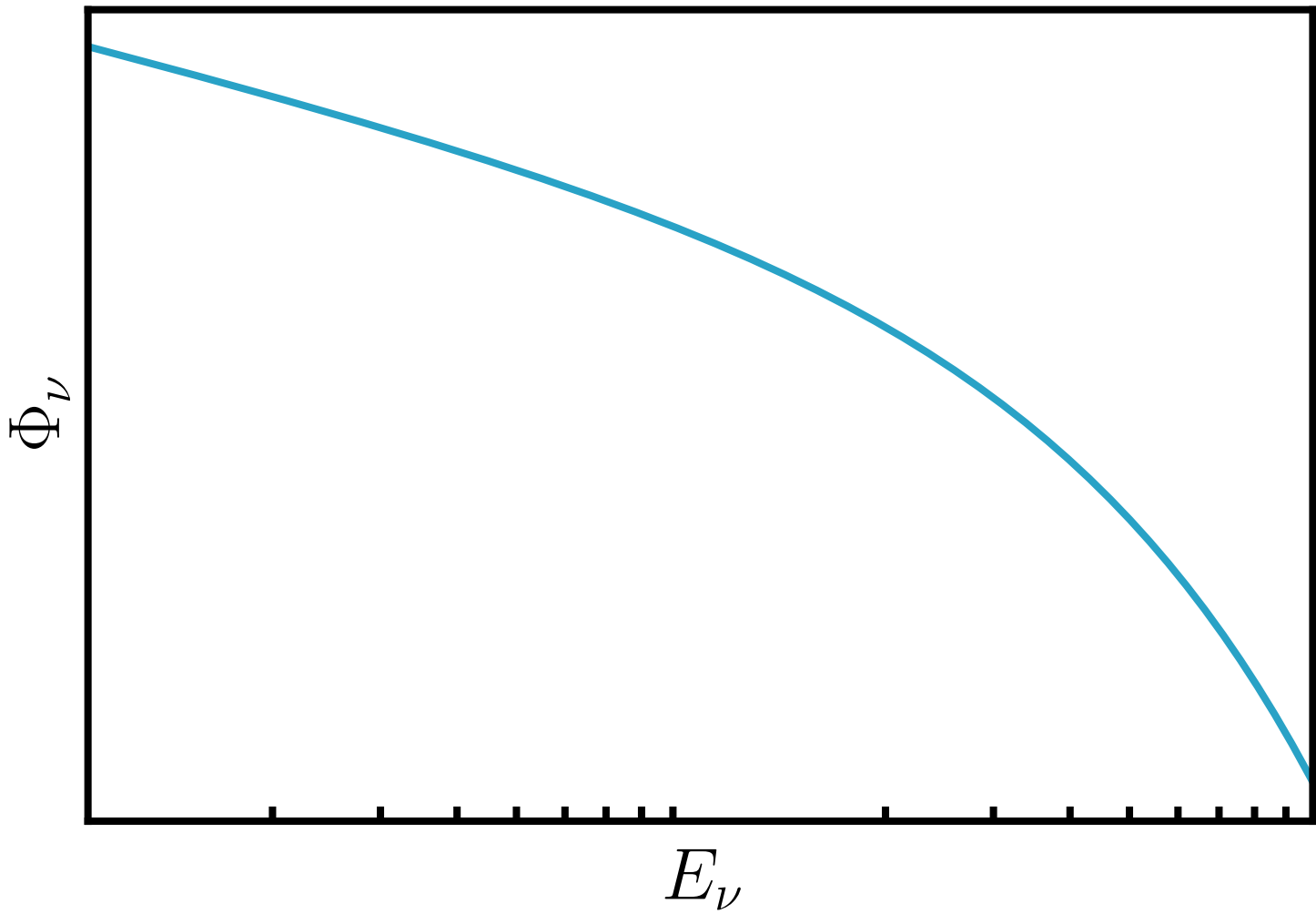
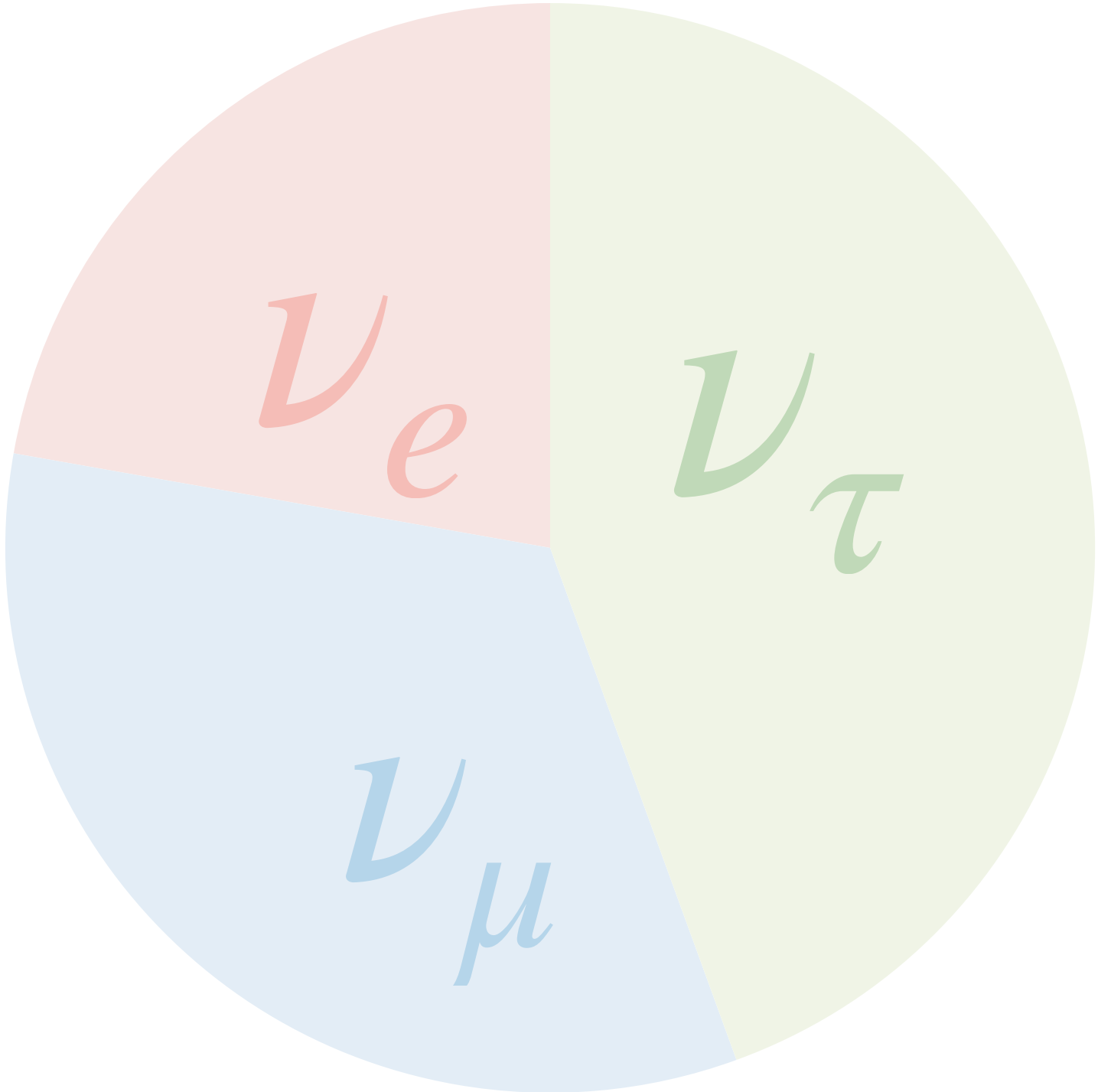
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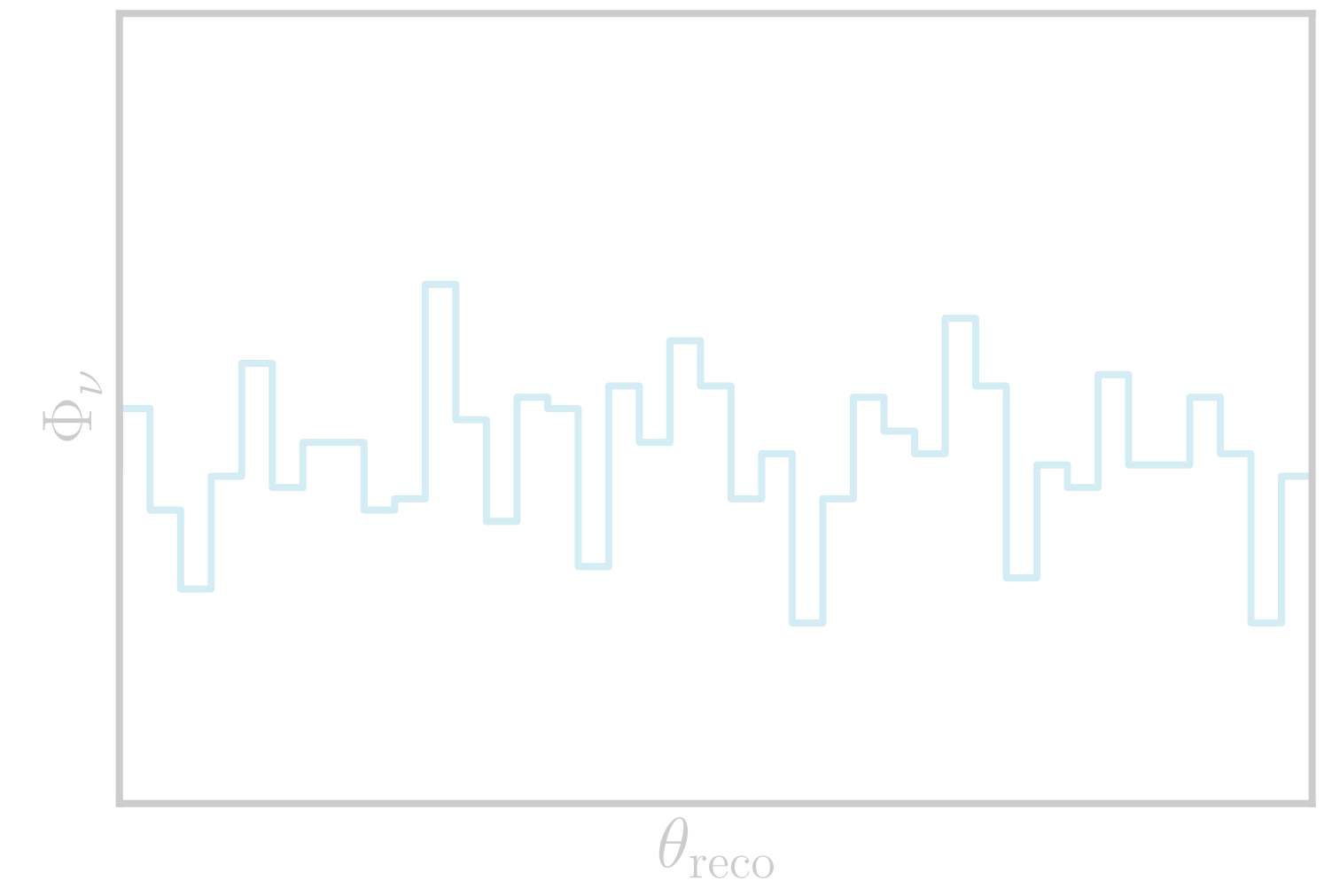
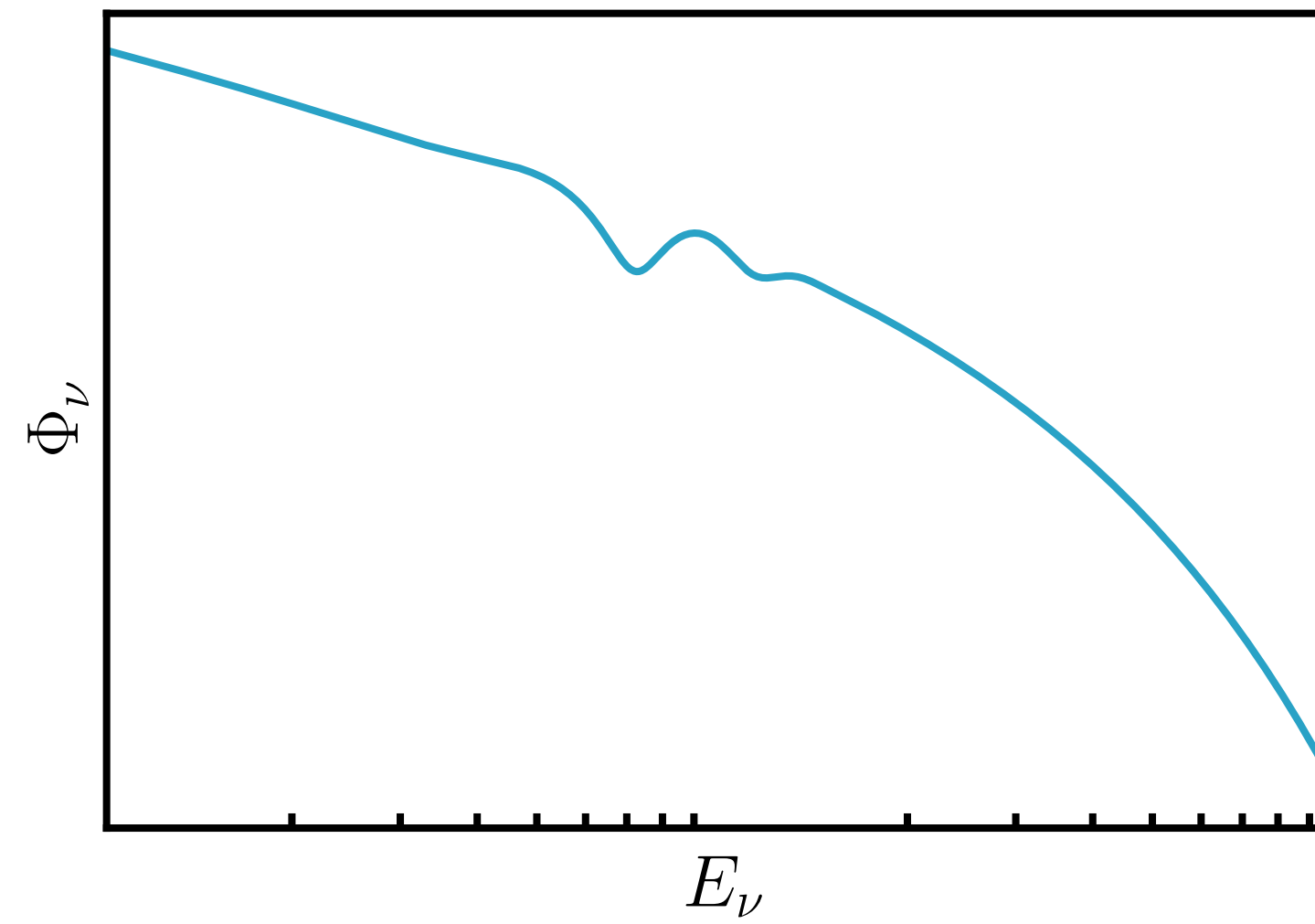
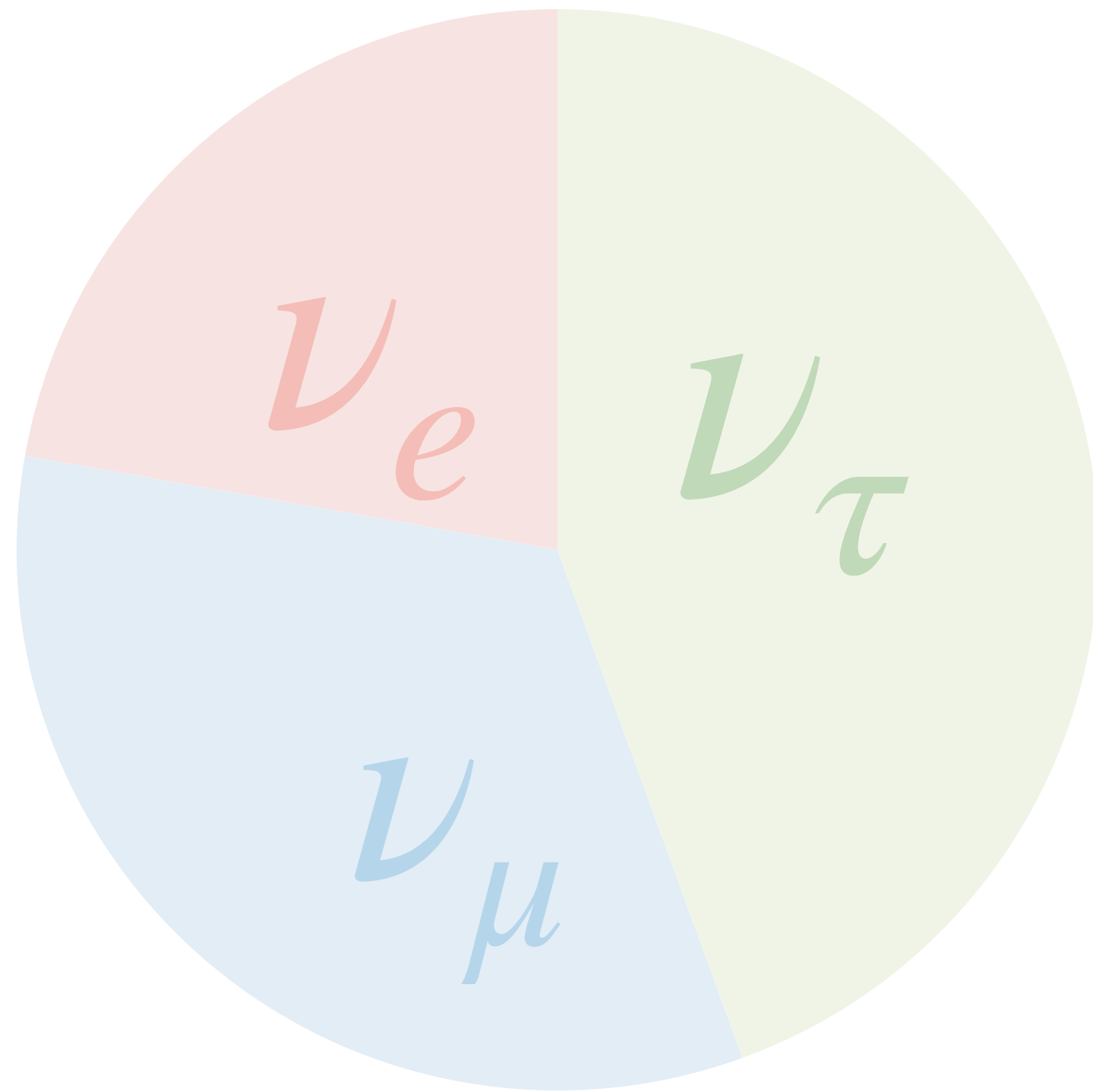
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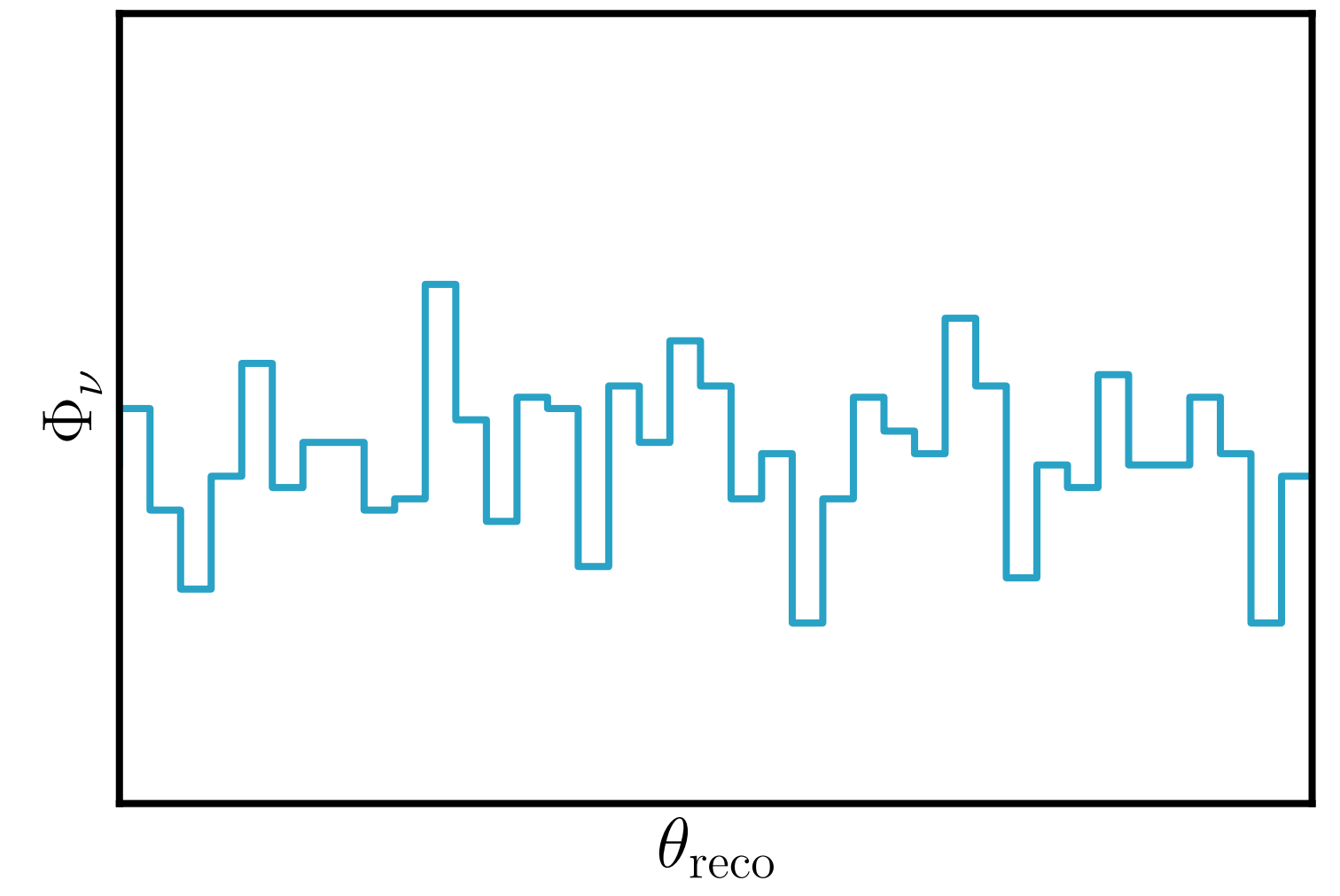
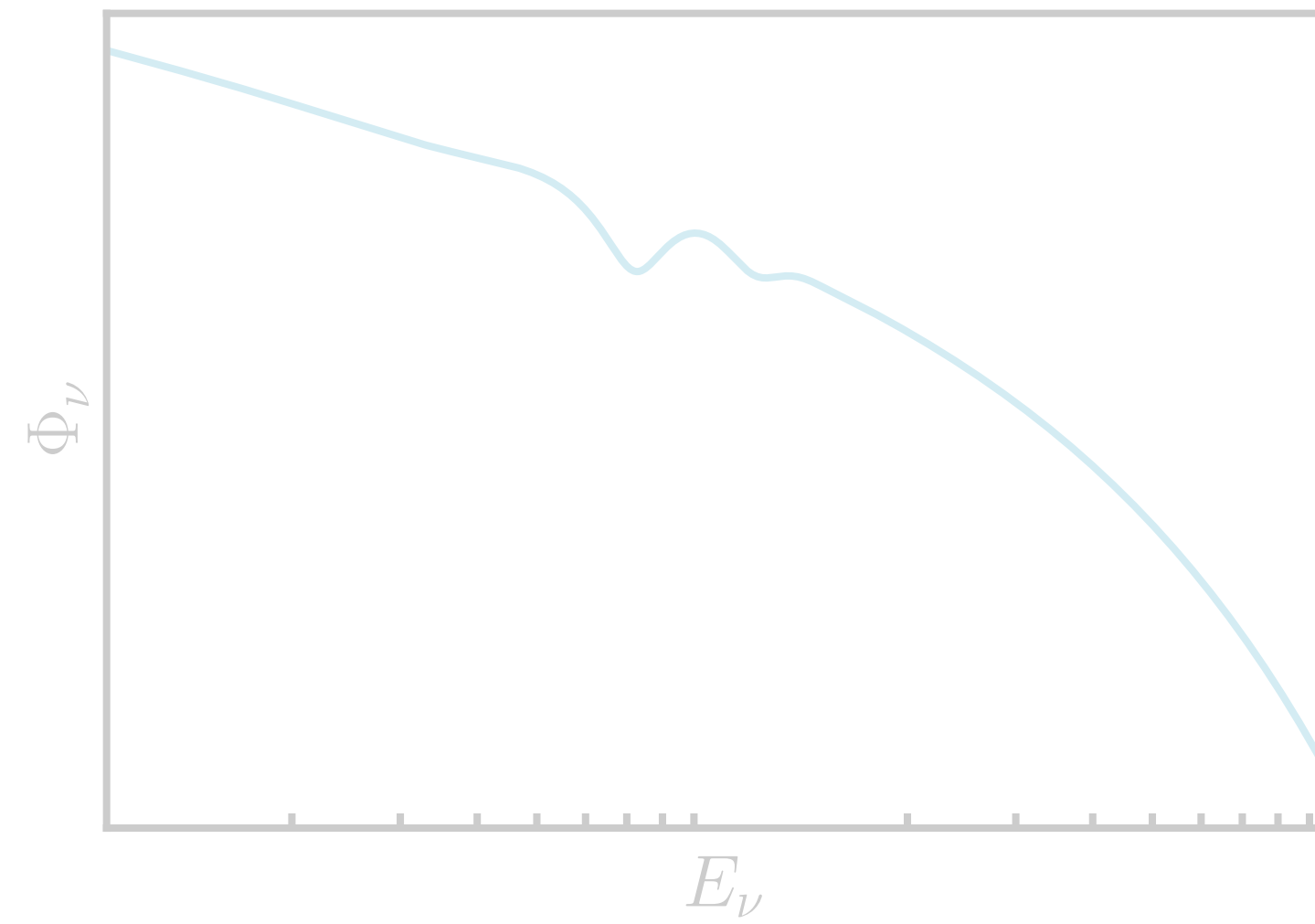
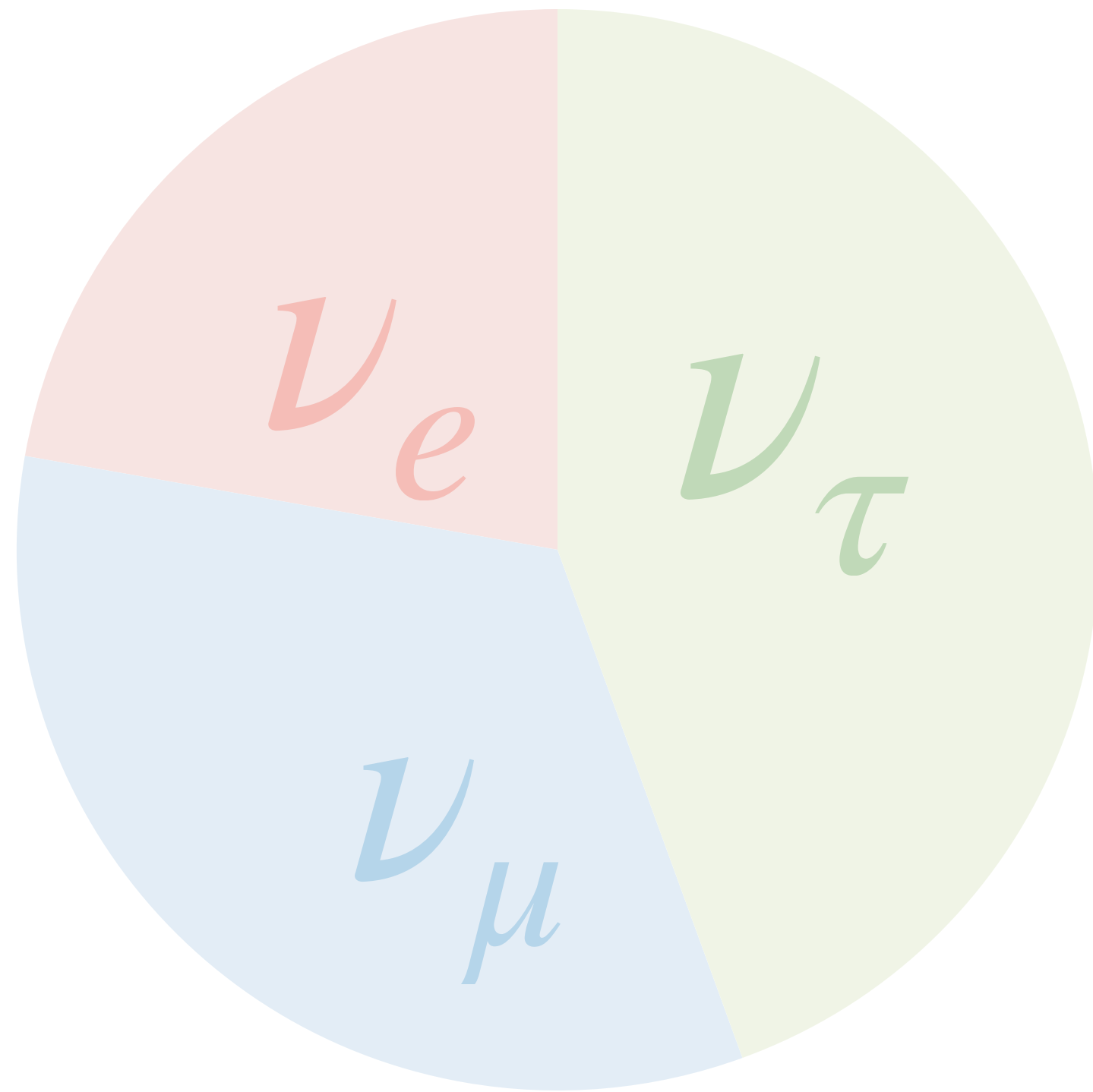
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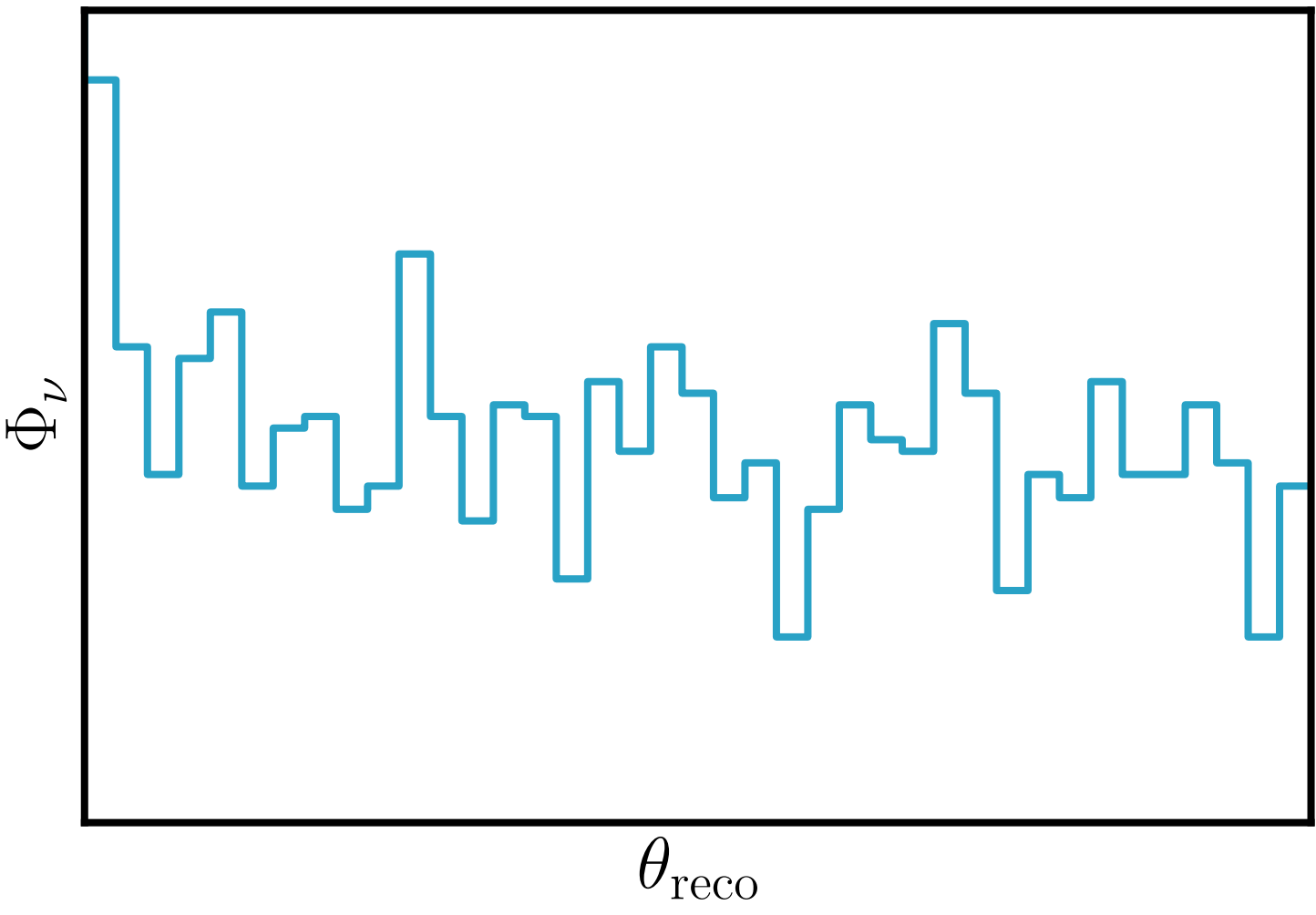
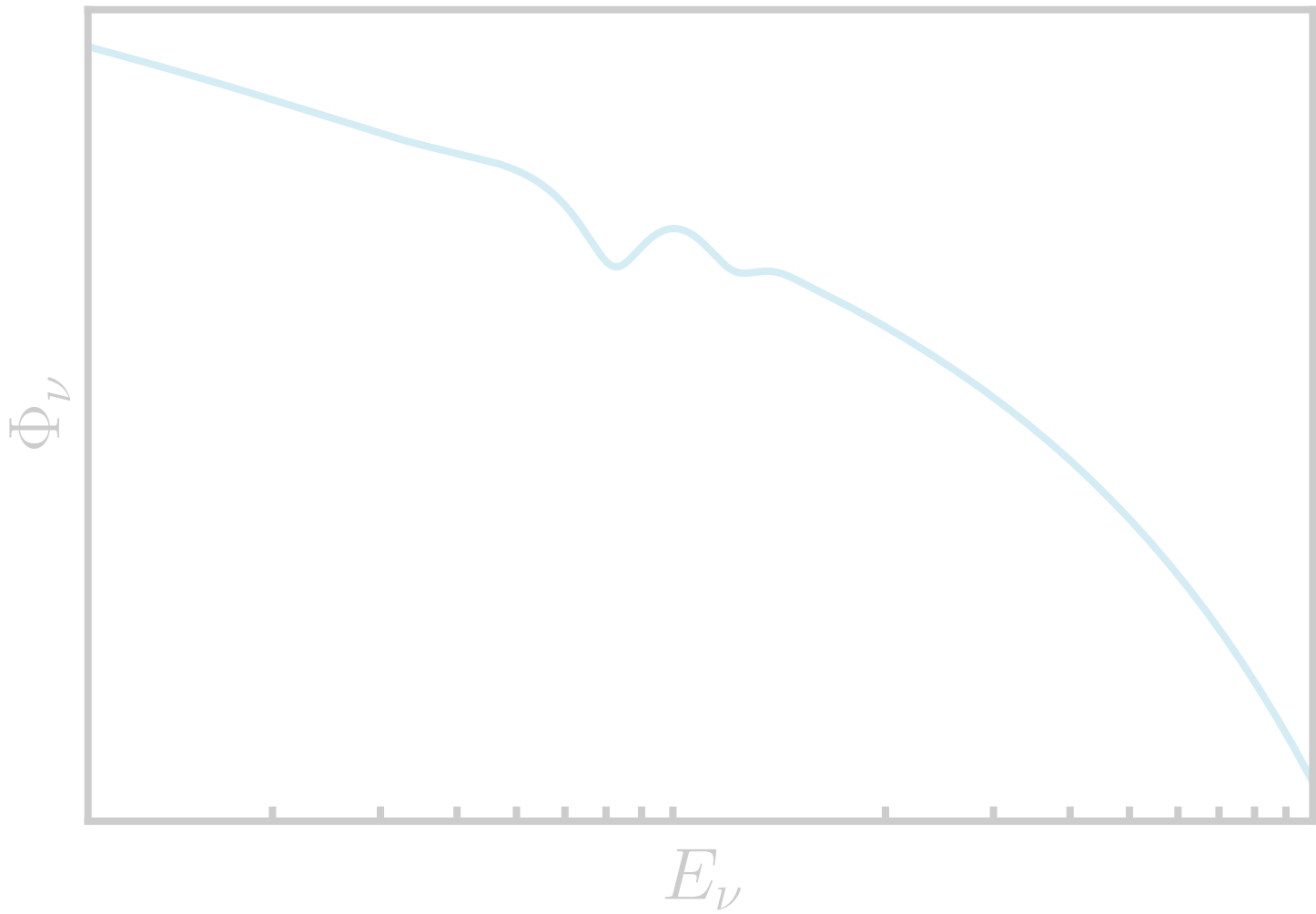
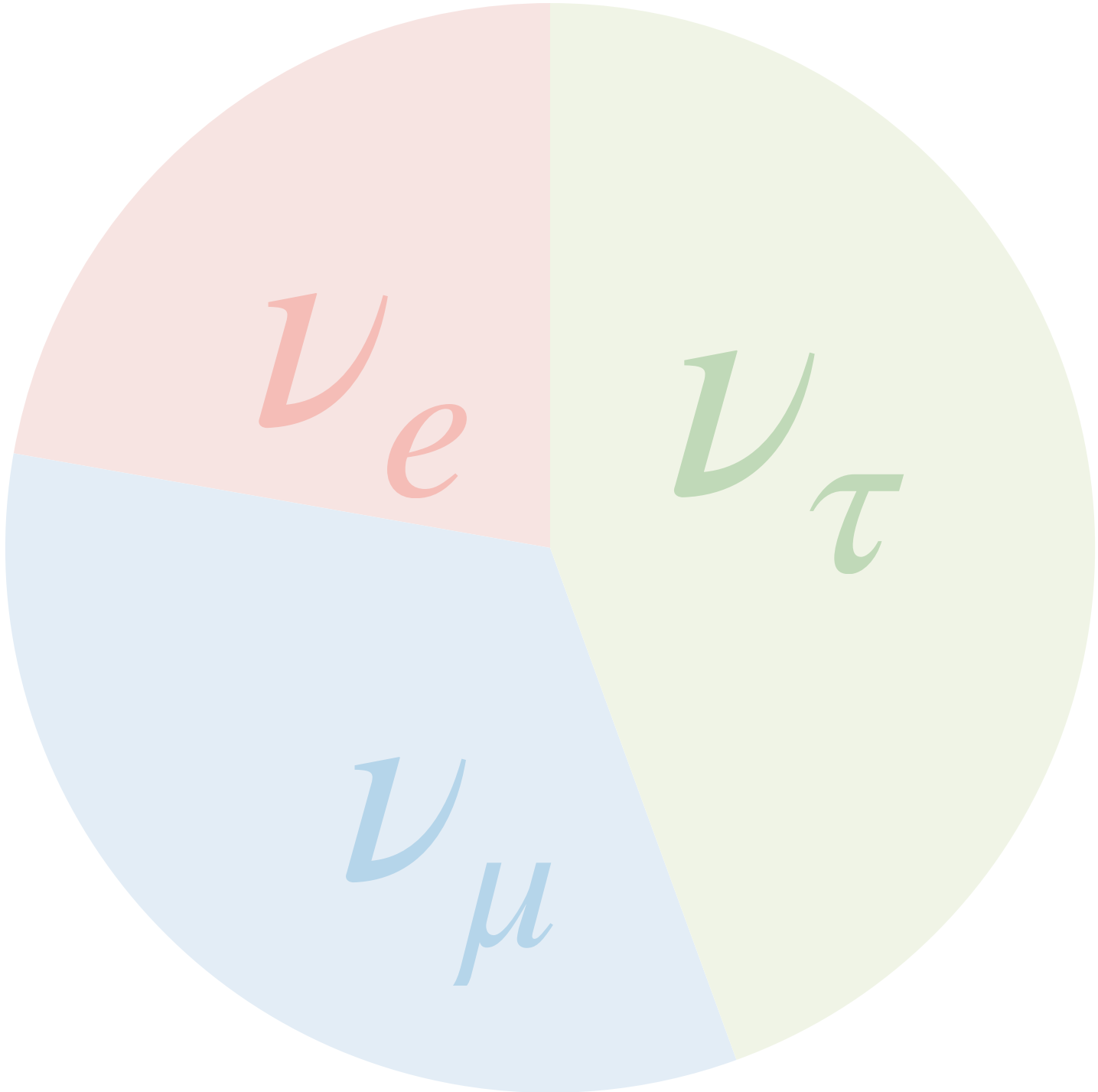
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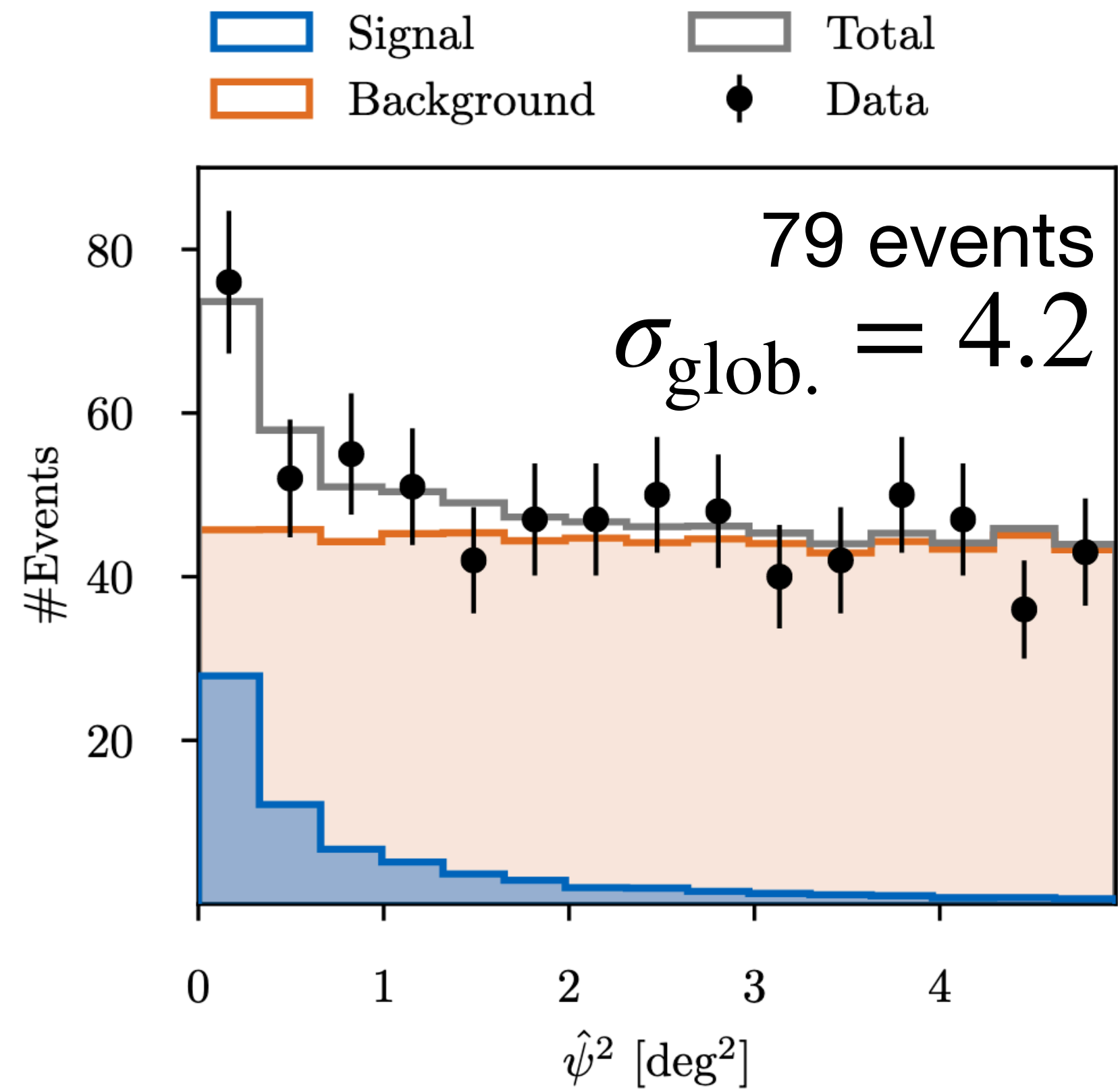
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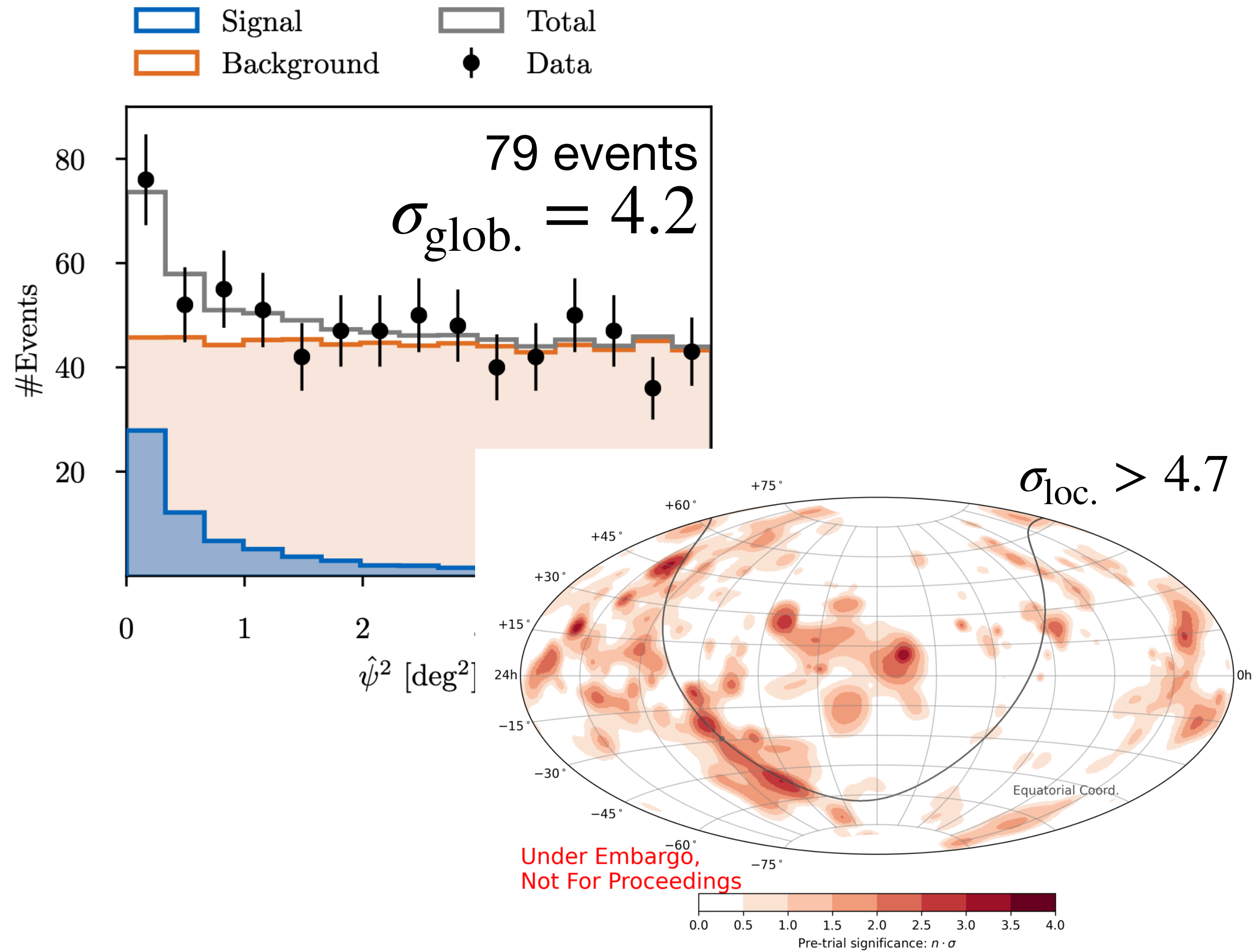
# A Decade of Delivering



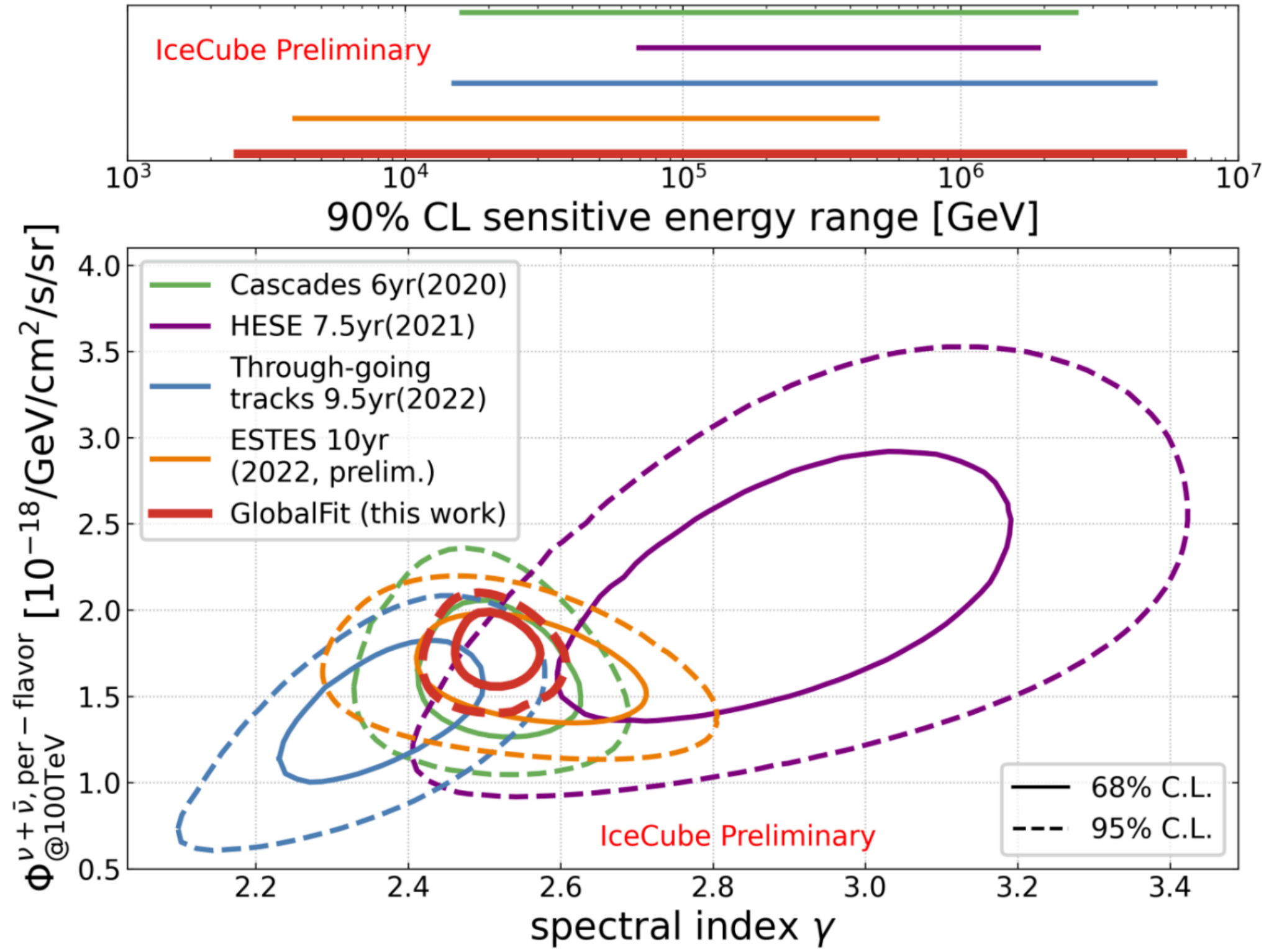
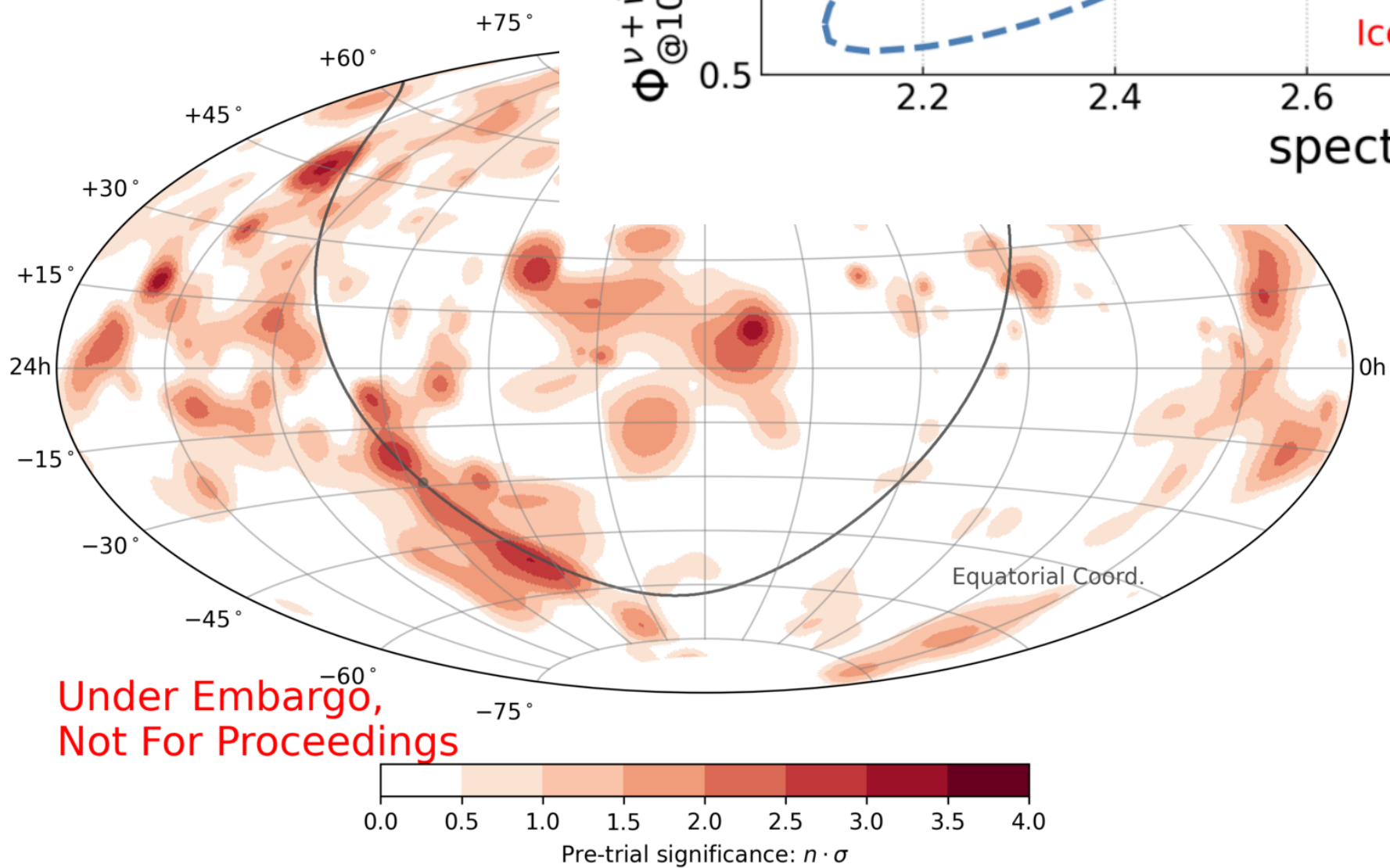
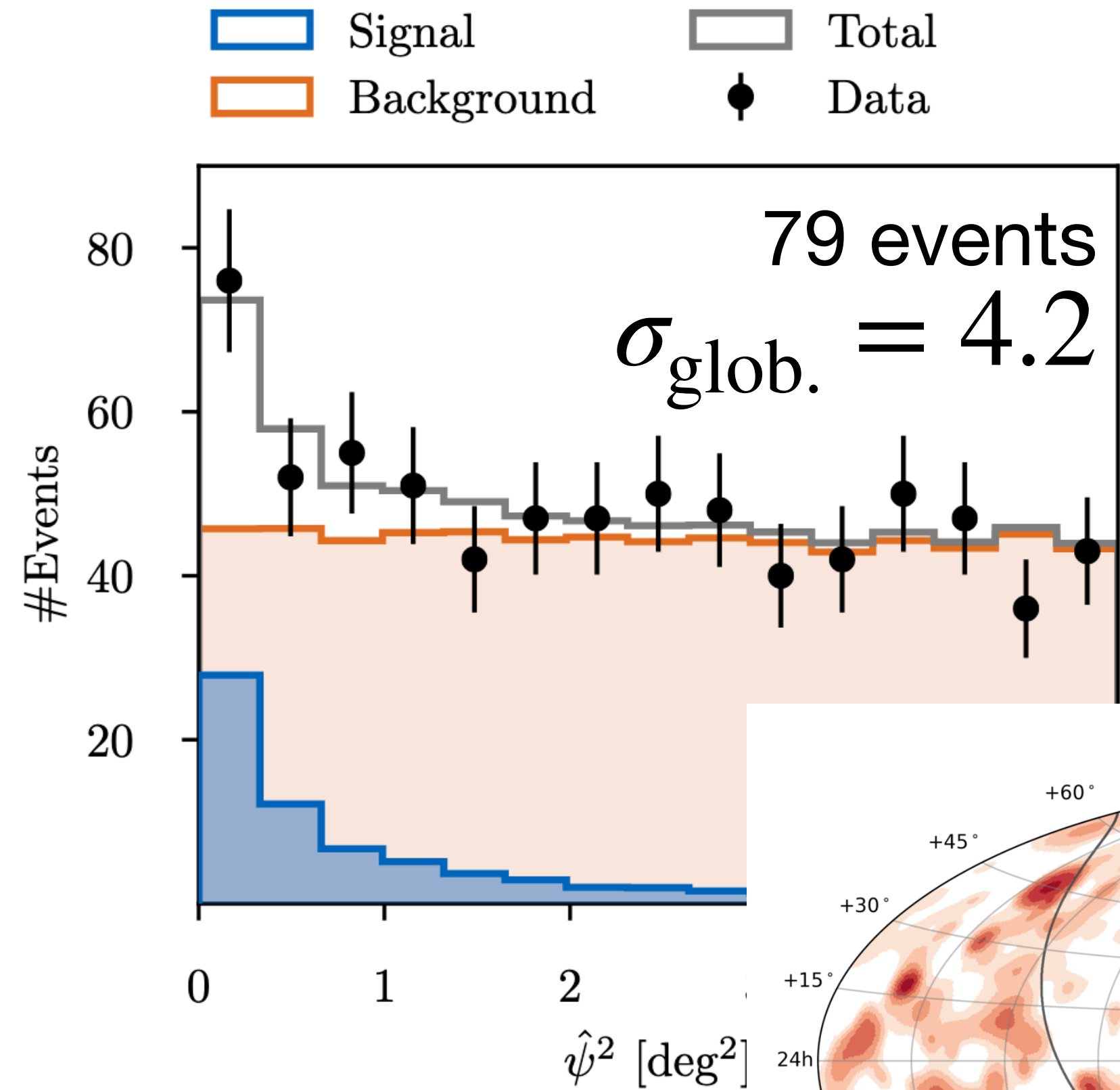
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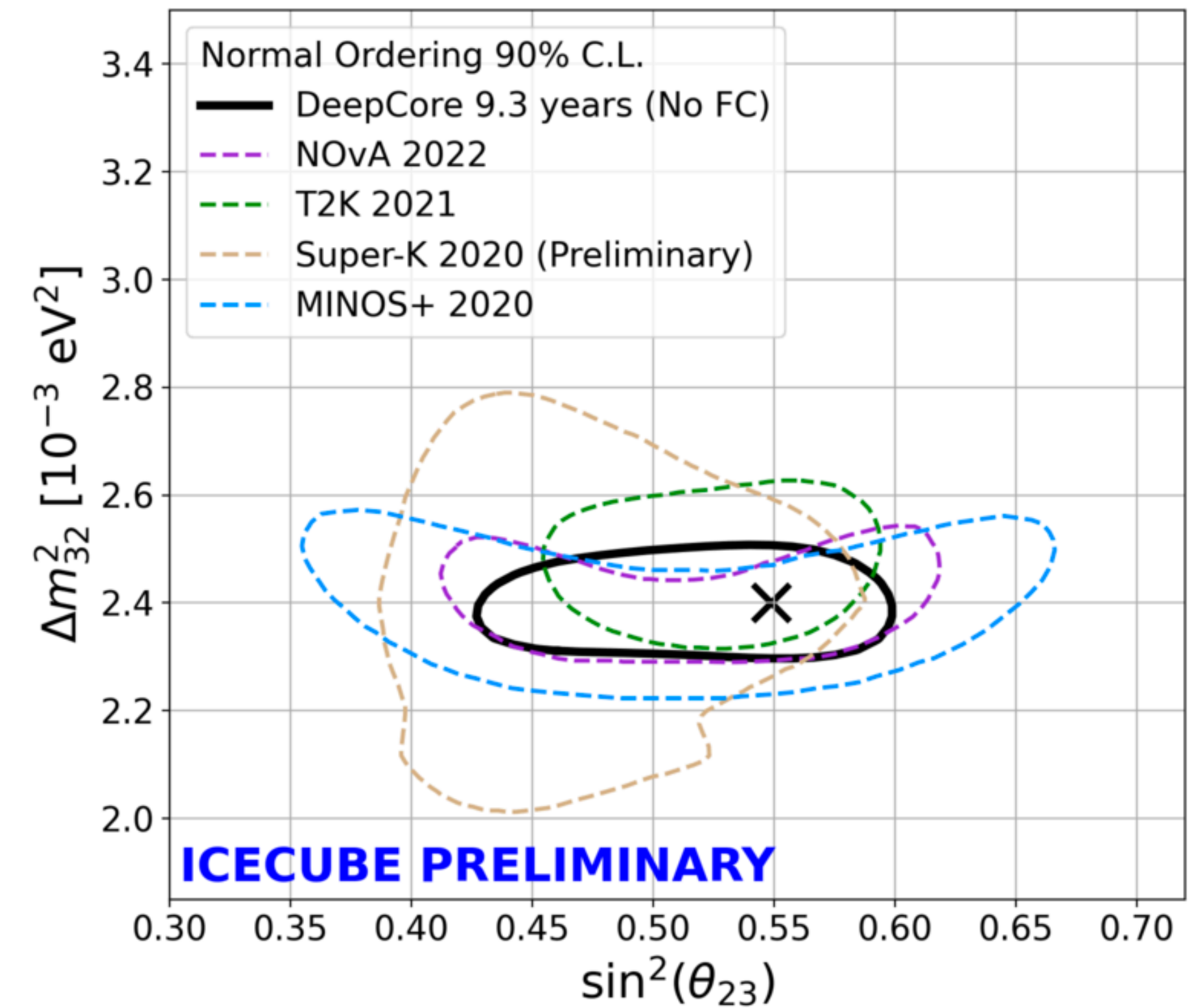
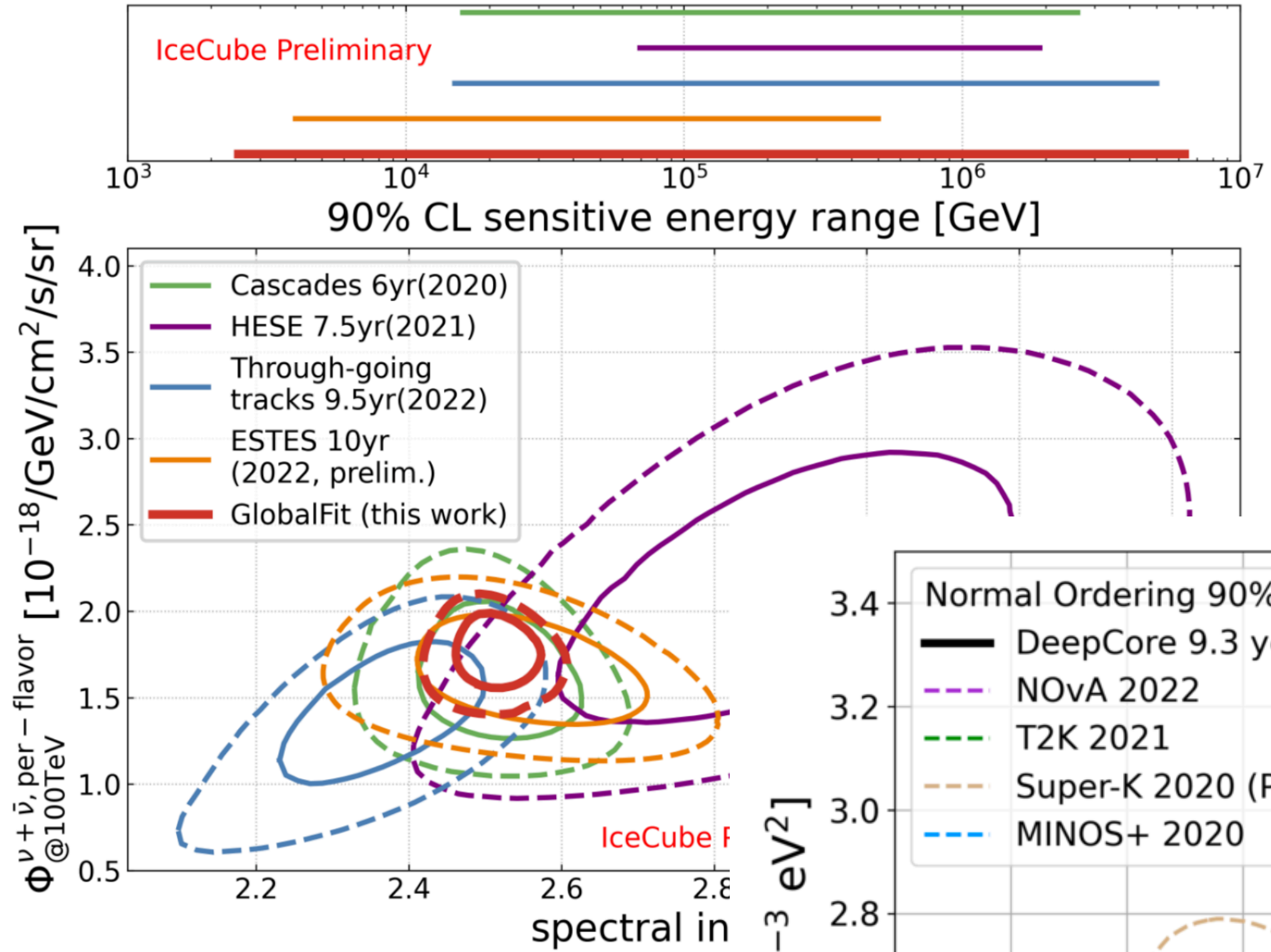
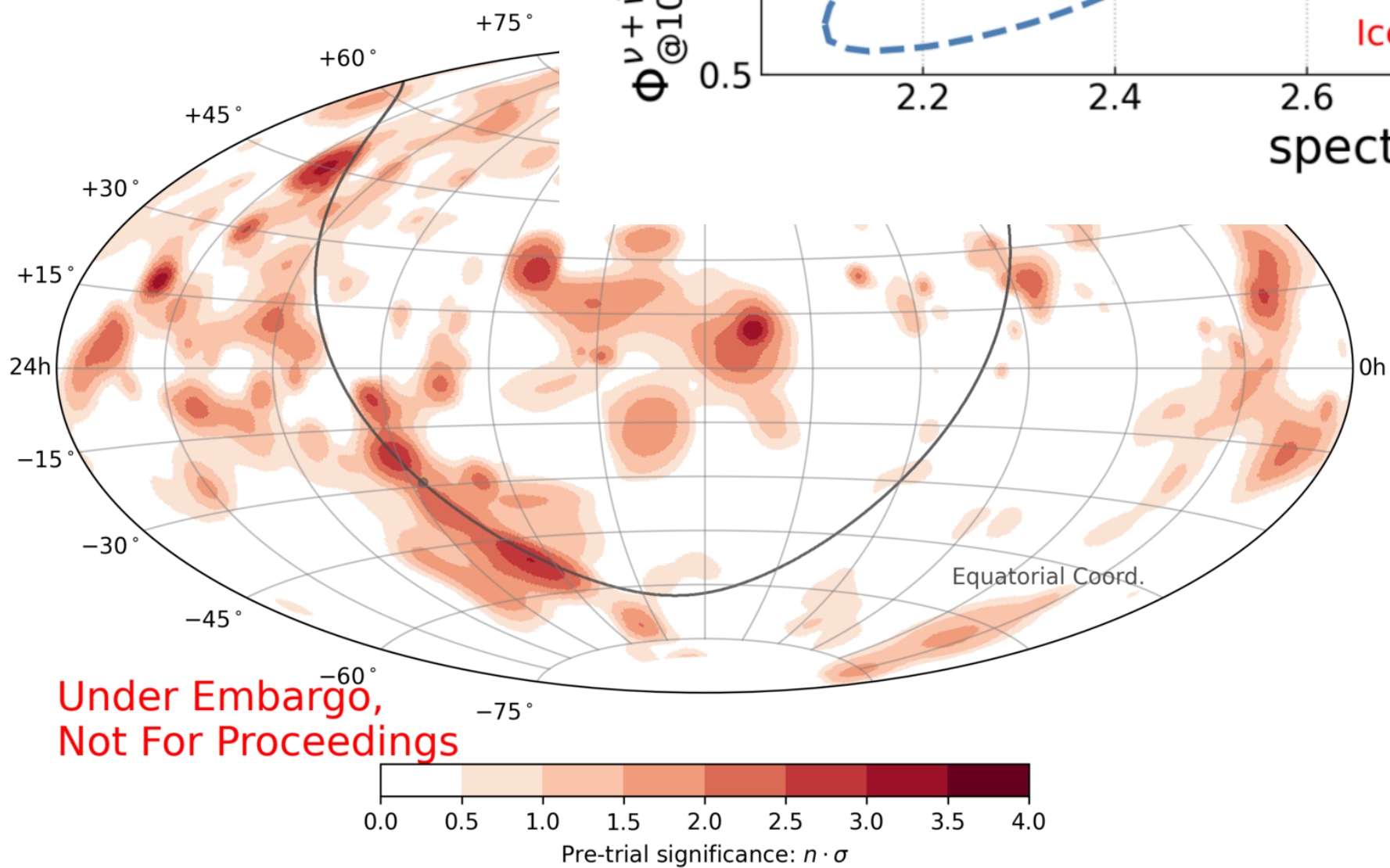
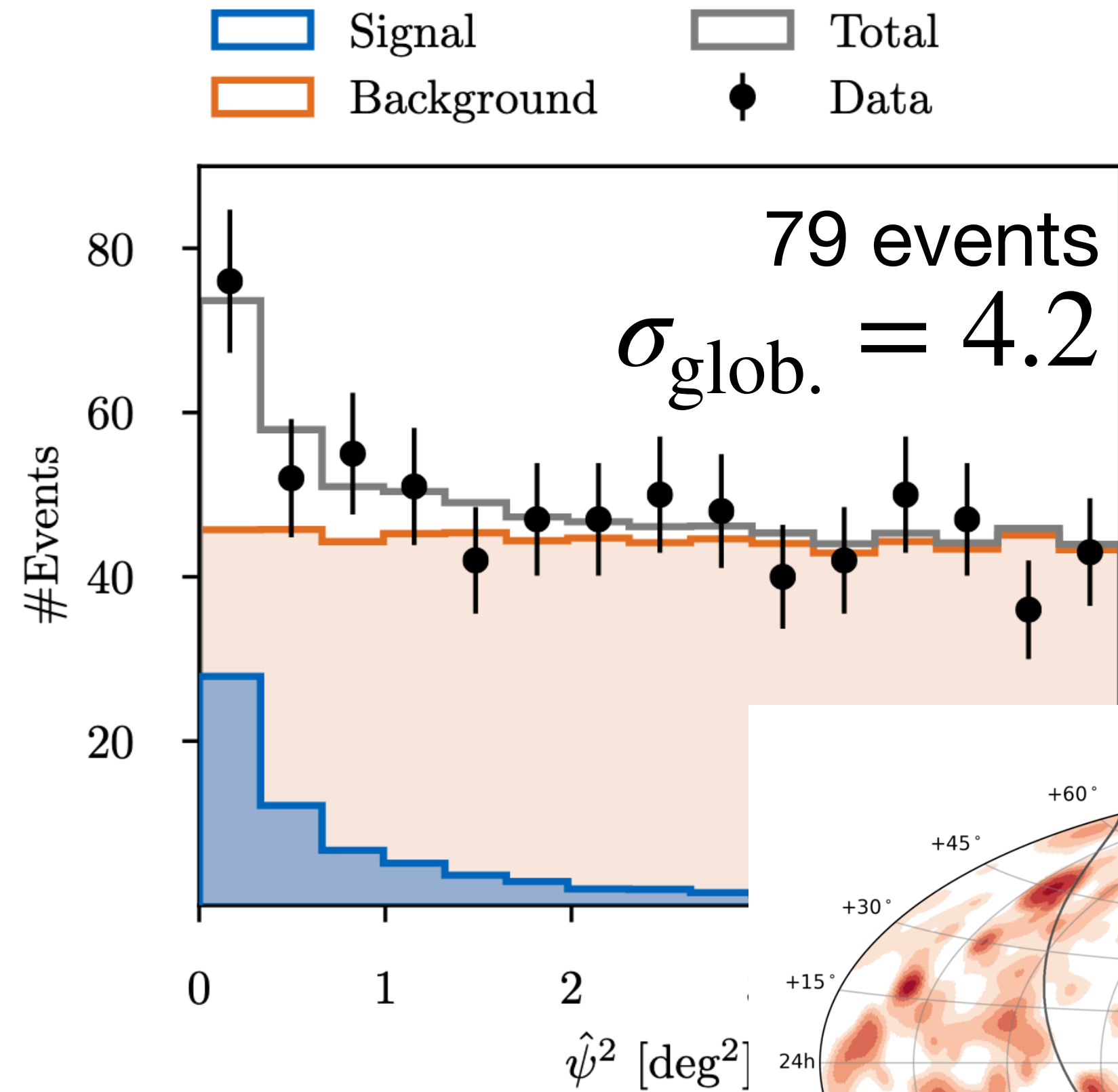
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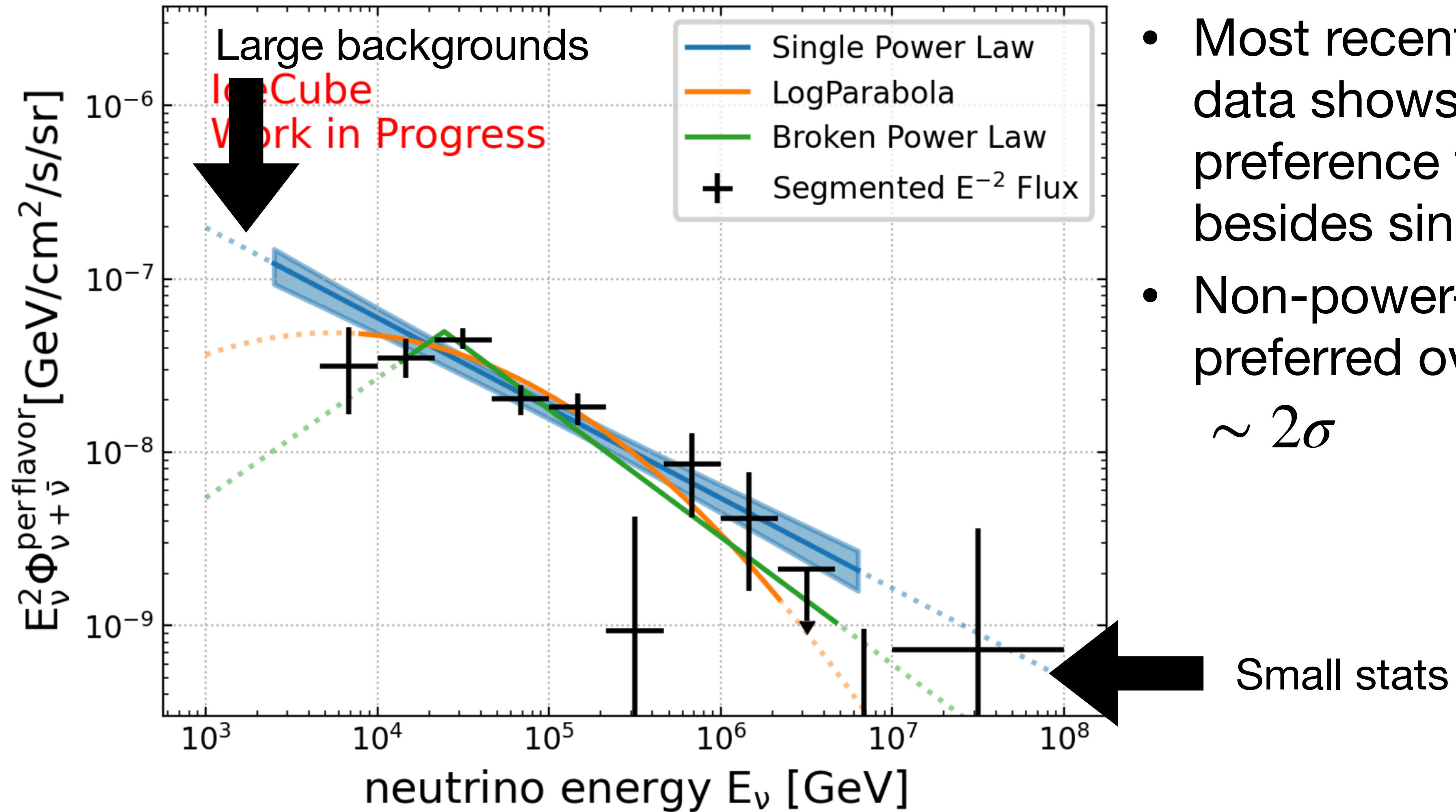
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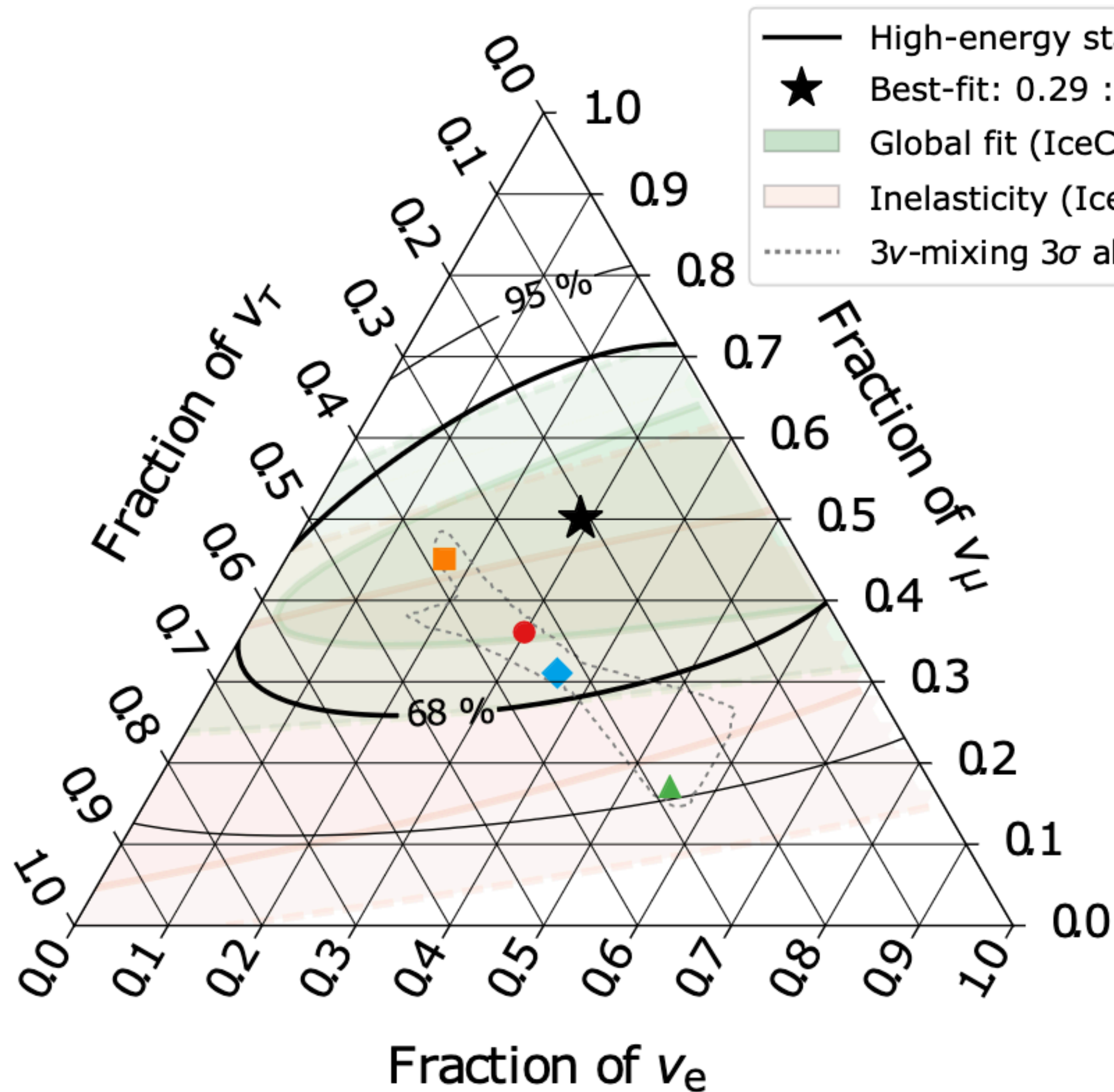


# New shapes



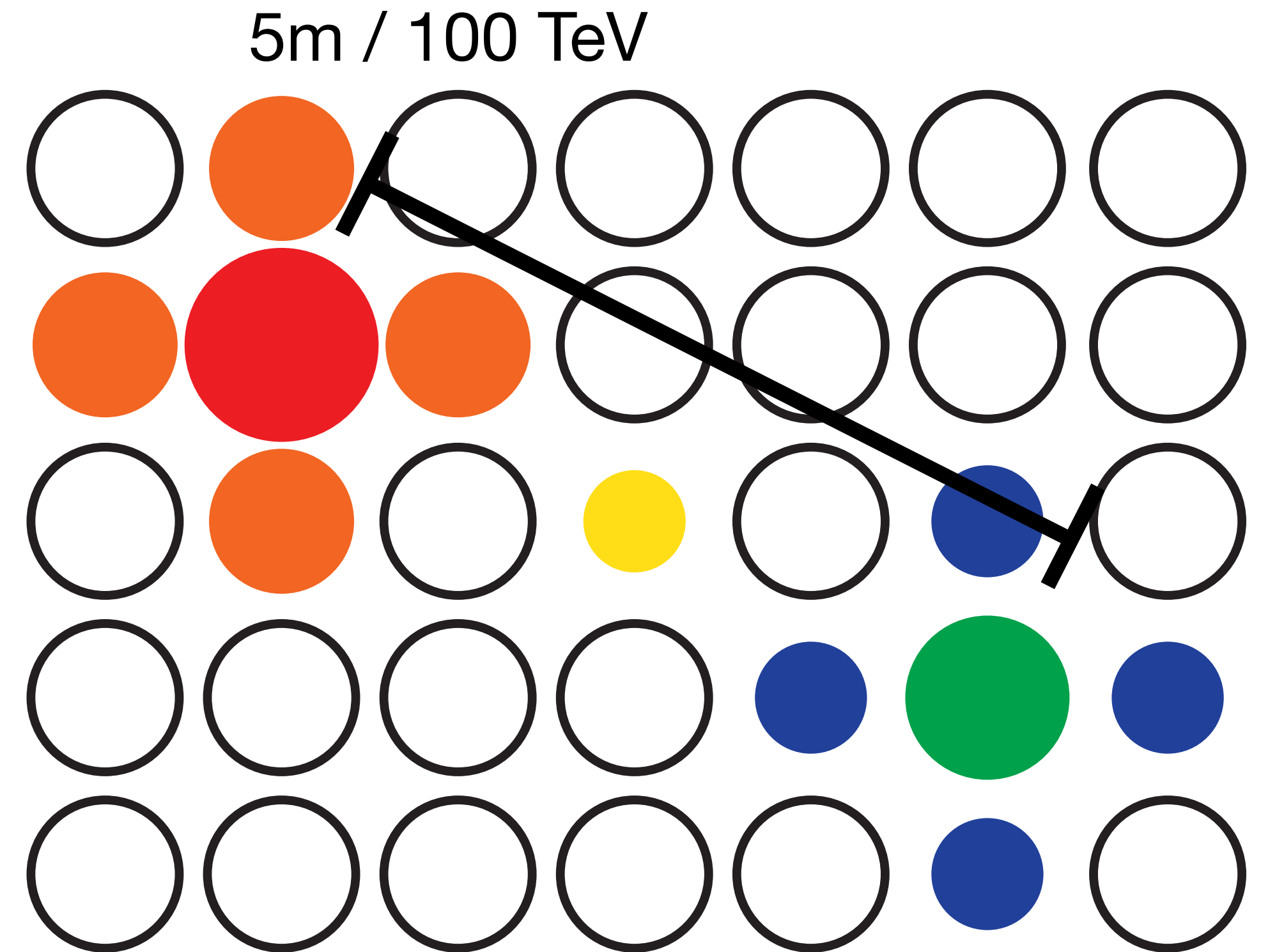
- Most recent global fit of the data shows a moderate preference flux models besides single power law
- Non-power-law spectra preferred over power law at  $\sim 2\sigma$

# Flavor Degeneracy

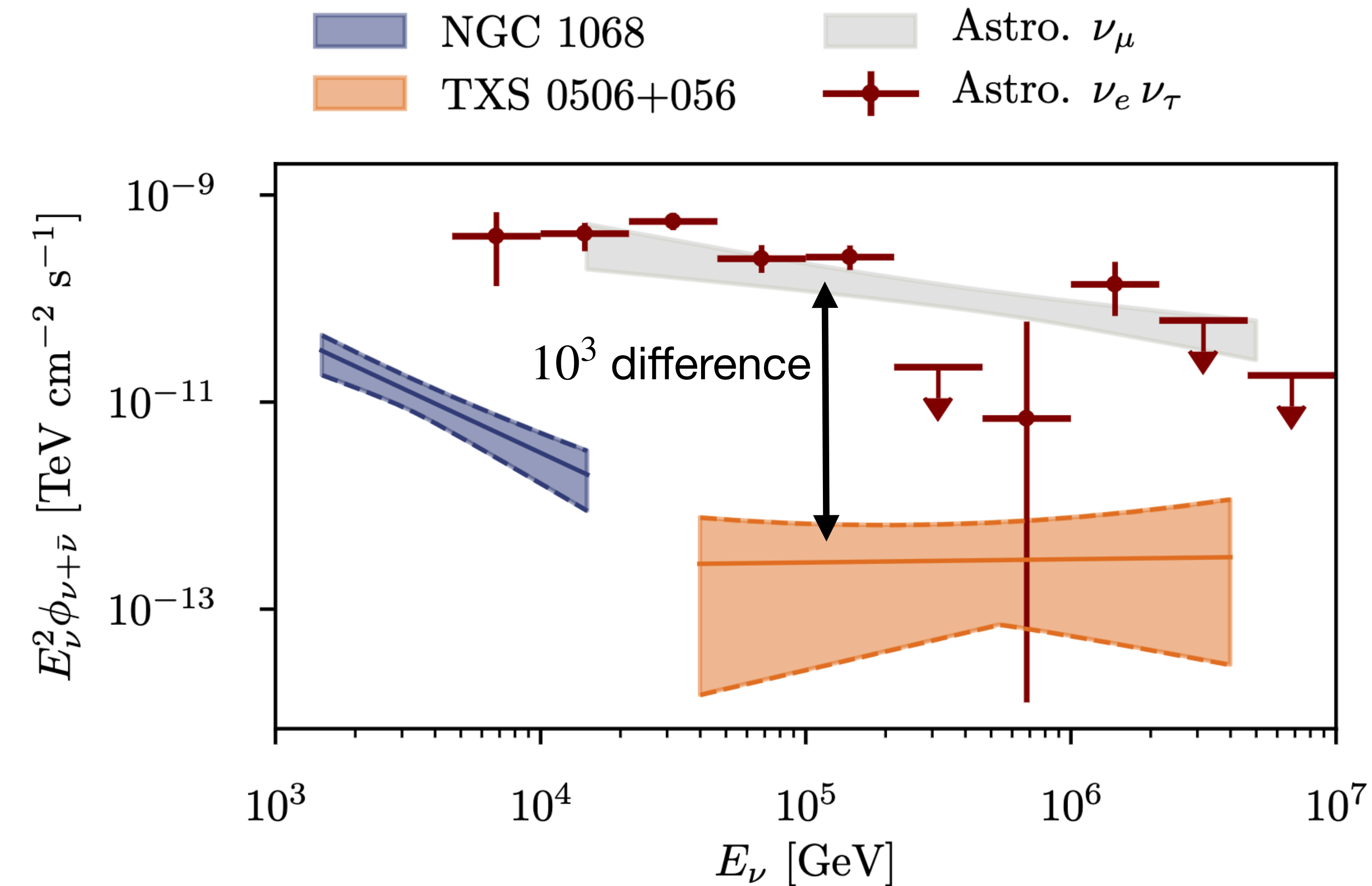


$\nu_e : \nu_\mu : \nu_\tau$  at source  $\rightarrow$  on Earth:

■	0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
●	1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
▲	1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
◆	1:1:0 $\rightarrow$ 0.36 : 0.31 : 0.33



# Where Are the Rest of the Sources ?

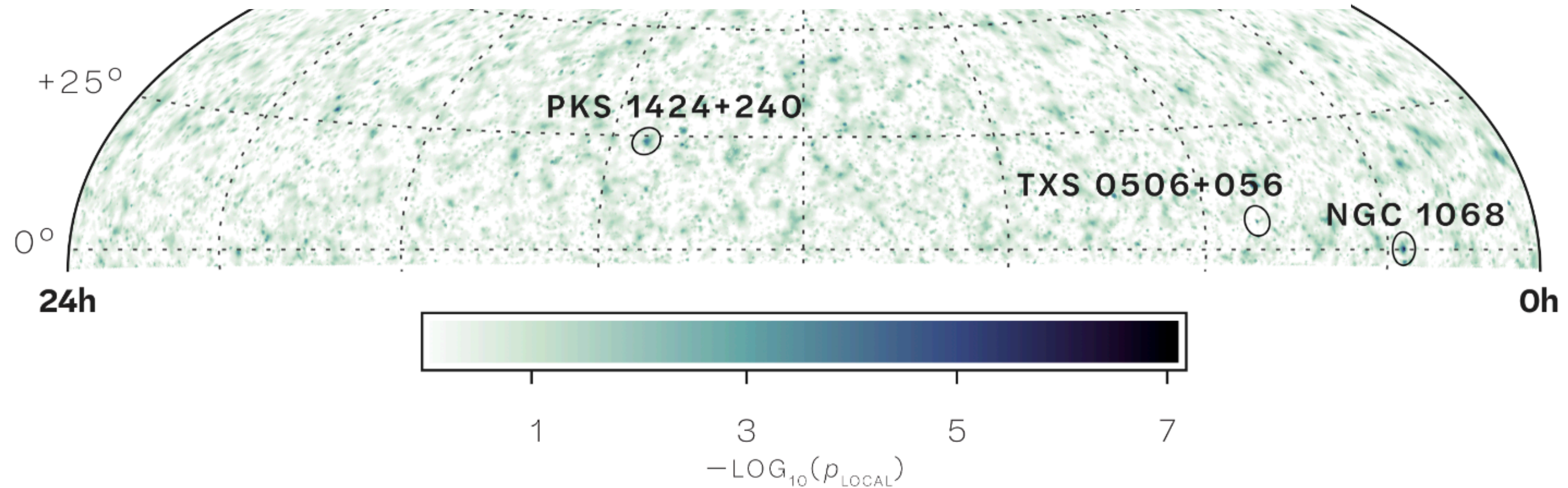


- IceCube has identified three point source candidates, two of which have enough event to fit a spectrum
- They can only make up a tiny fraction of the measured diffuse spectrum

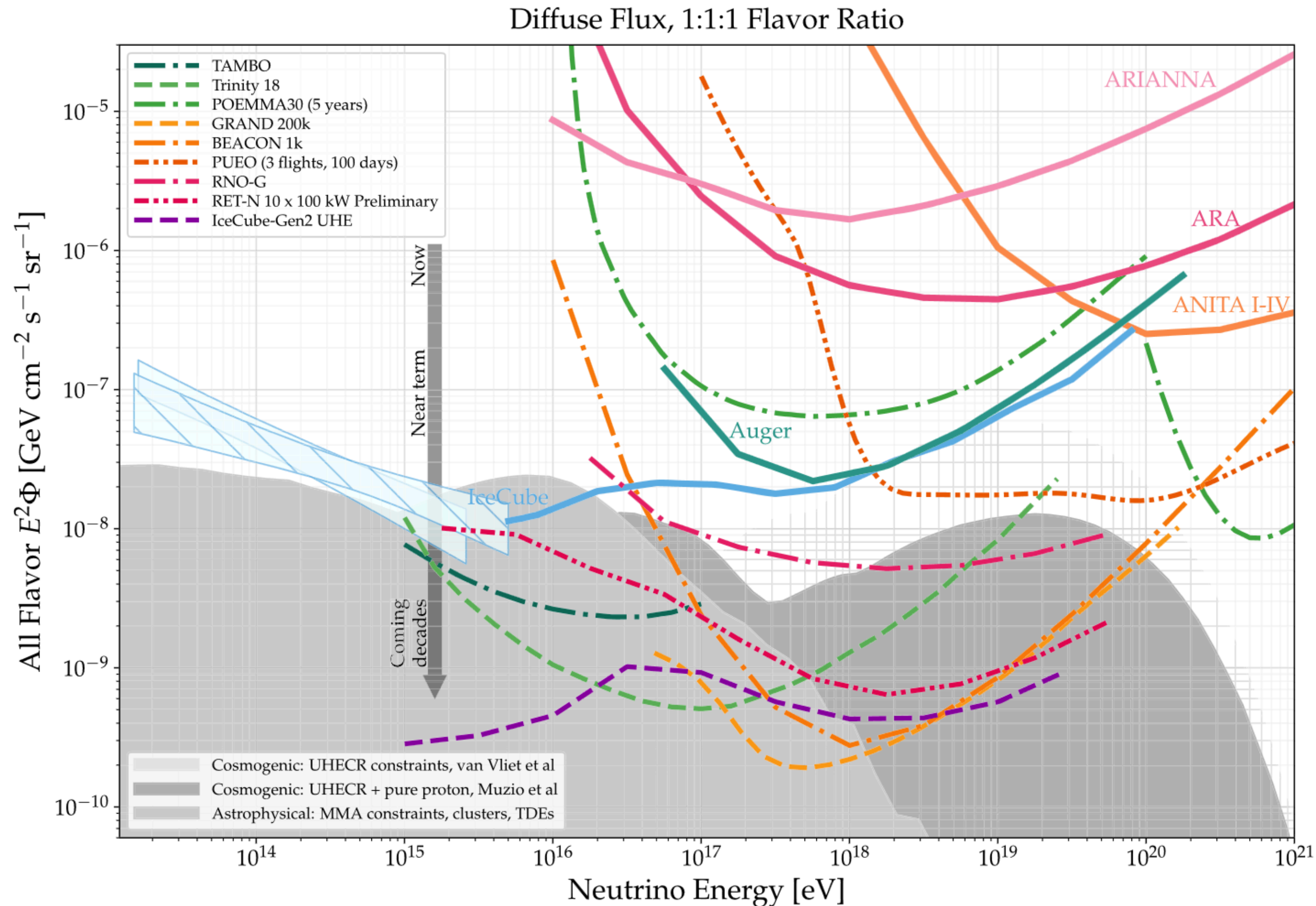
# Trials and Tribulations

Test type	Pre-trial p-value ( $p_{local}$ )	Post-trial p-value ( $p_{global}$ )
Northern Hemisphere scan	$5.0 \times 10^{-8}$ ( $5.3 \sigma$ )	$2.2 \times 10^{-2}$ ( $2.0 \sigma$ )
List of candidate sources, single test	$1.0 \times 10^{-7}$ ( $5.2 \sigma$ )	$1.1 \times 10^{-5}$ ( $4.2 \sigma$ )
List of candidate sources, binomial test	$4.6 \times 10^{-6}$ ( $4.4 \sigma$ )	$3.4 \times 10^{-4}$ ( $3.4 \sigma$ )

$\sim 445,000$  trials  
 $\implies 19.8 \frac{\text{trials}}{\sigma^2}$

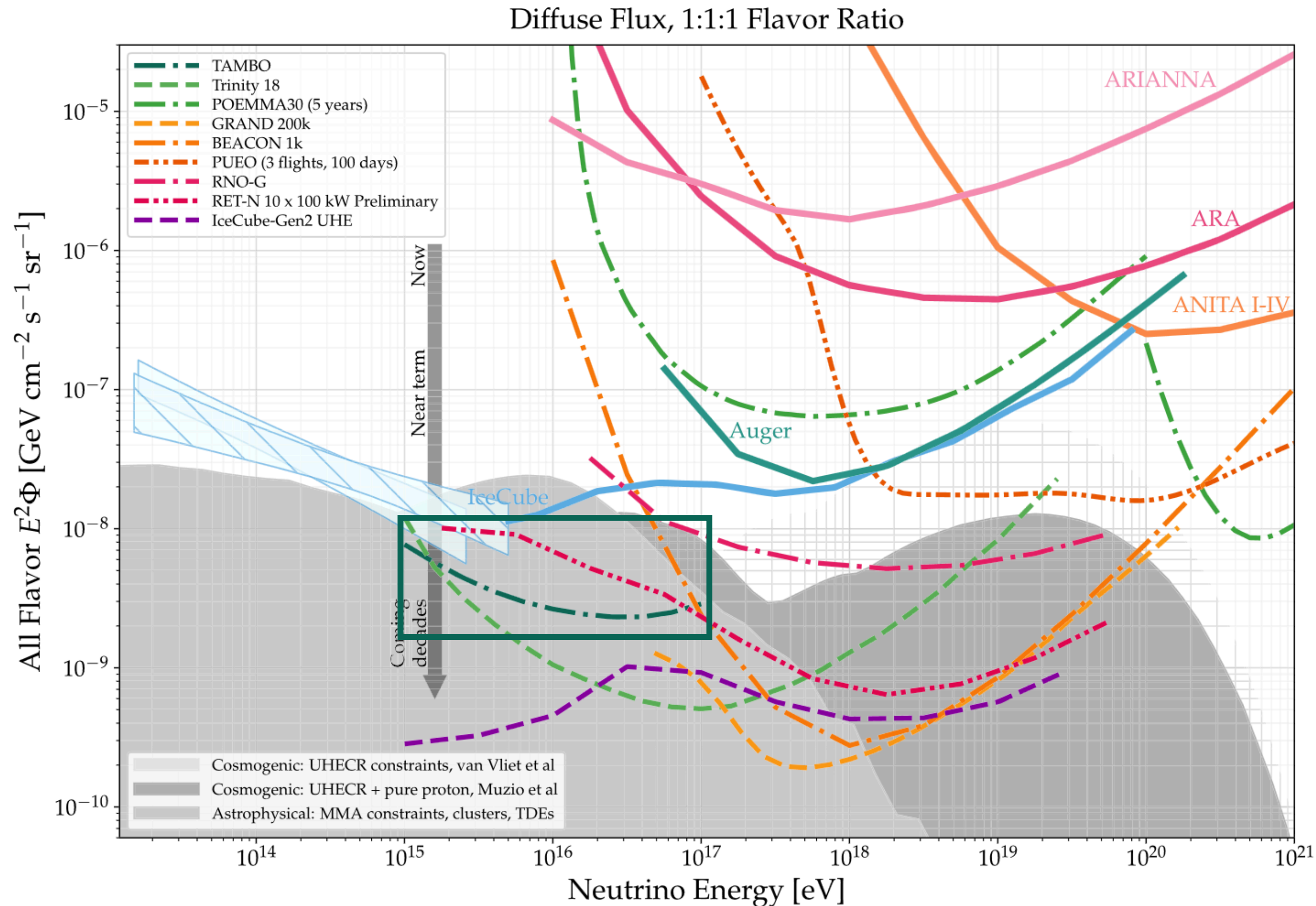


# We're Not Short on Ideas

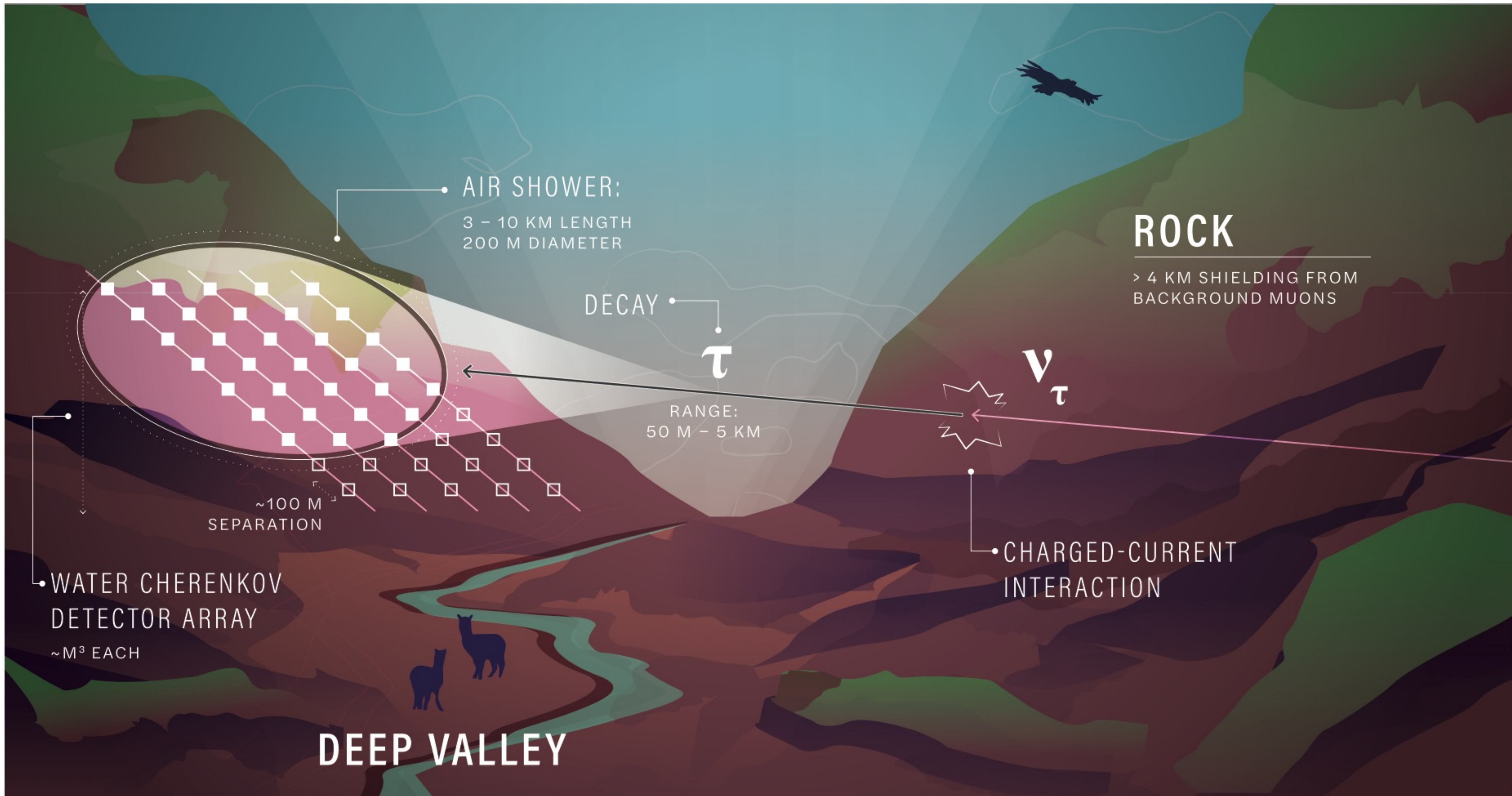


- Many next generation detectors will target 100 TeV to 10 EeV neutrinos
- New technologies and detector principles will enable this push

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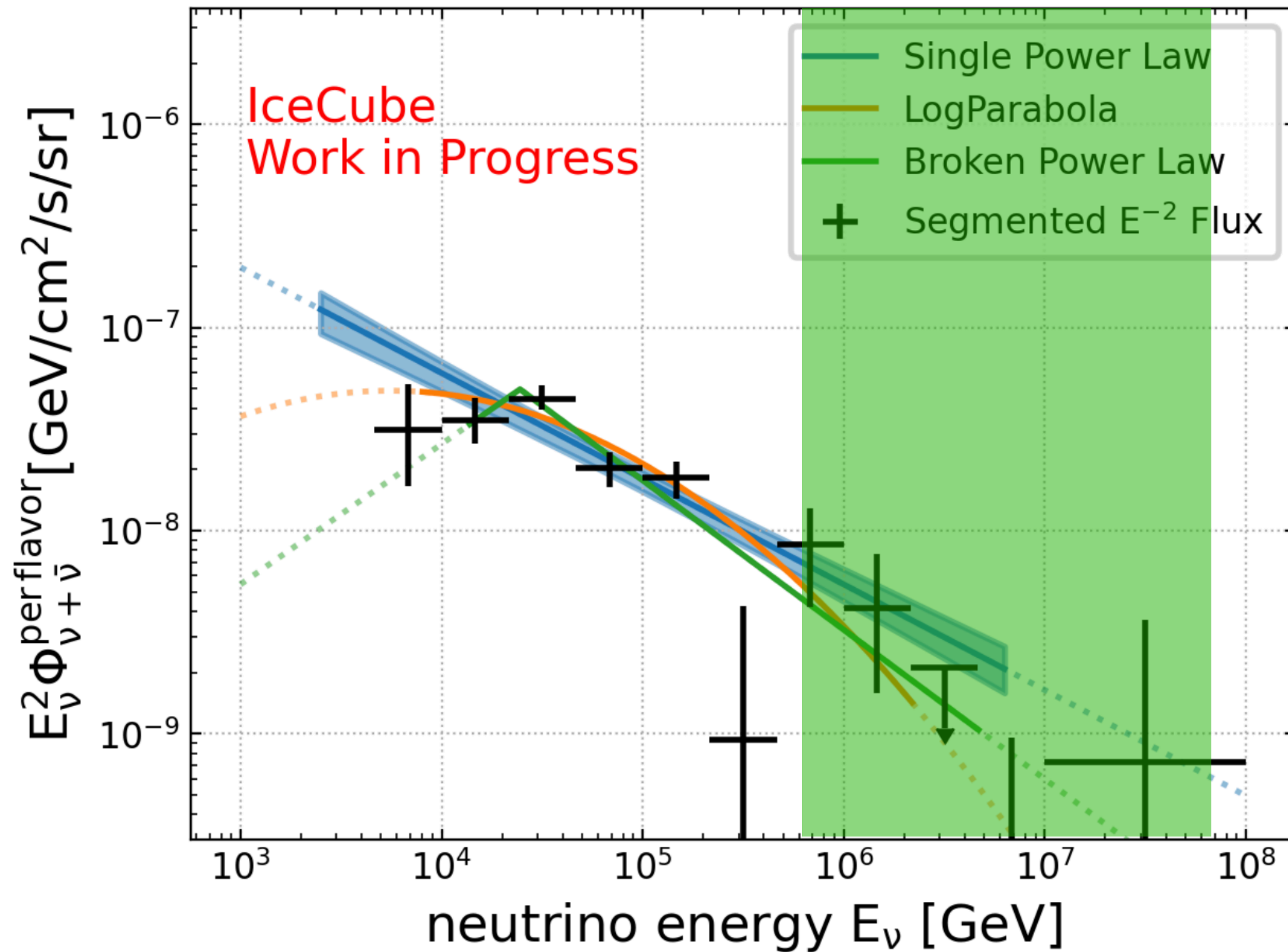


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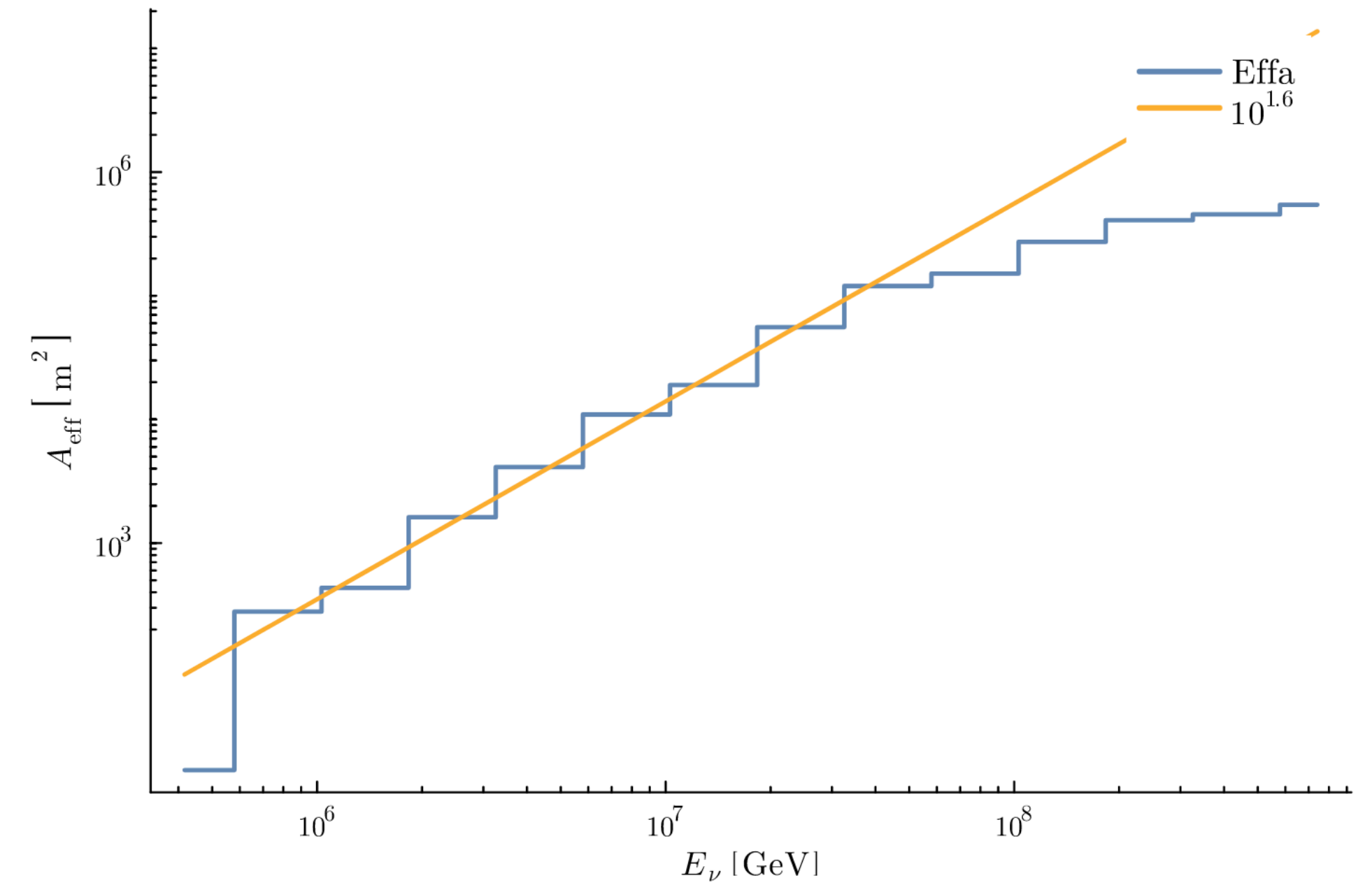


TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) • COLCA VALLEY, PERU

# Passing the Energy Baton



TAMBO regime

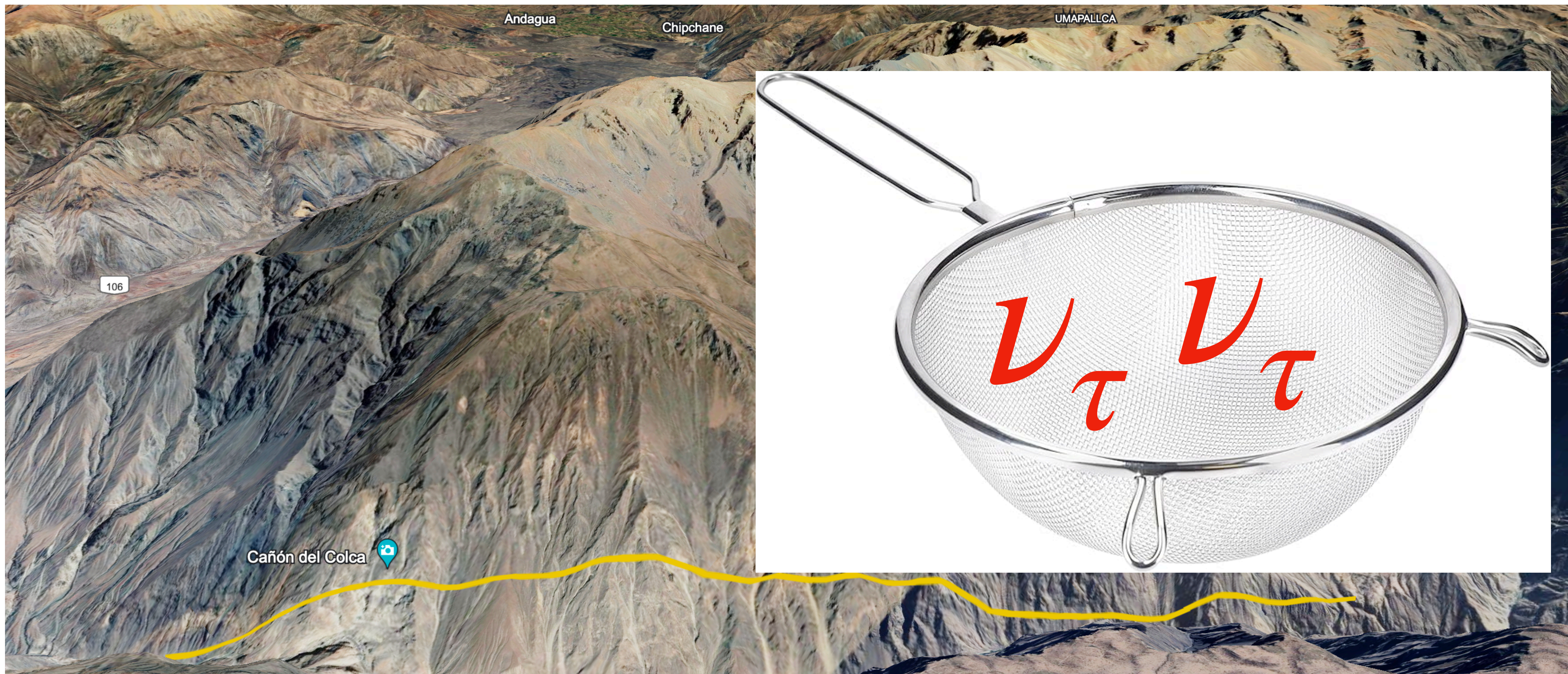


TAMBO becomes sensitive right towards the end of IceCube's sensitivity

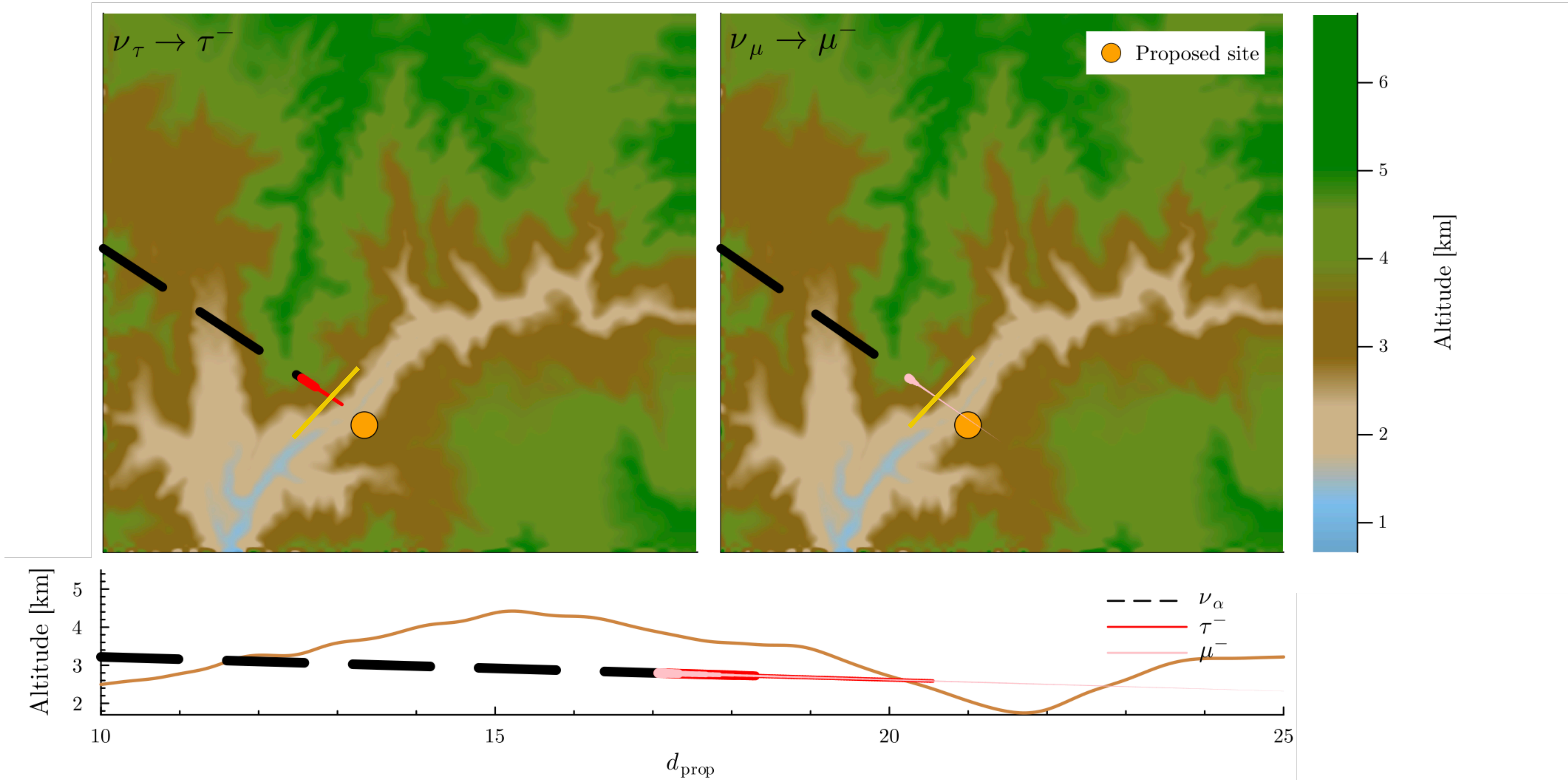
# A $\nu_\tau$ Sieve



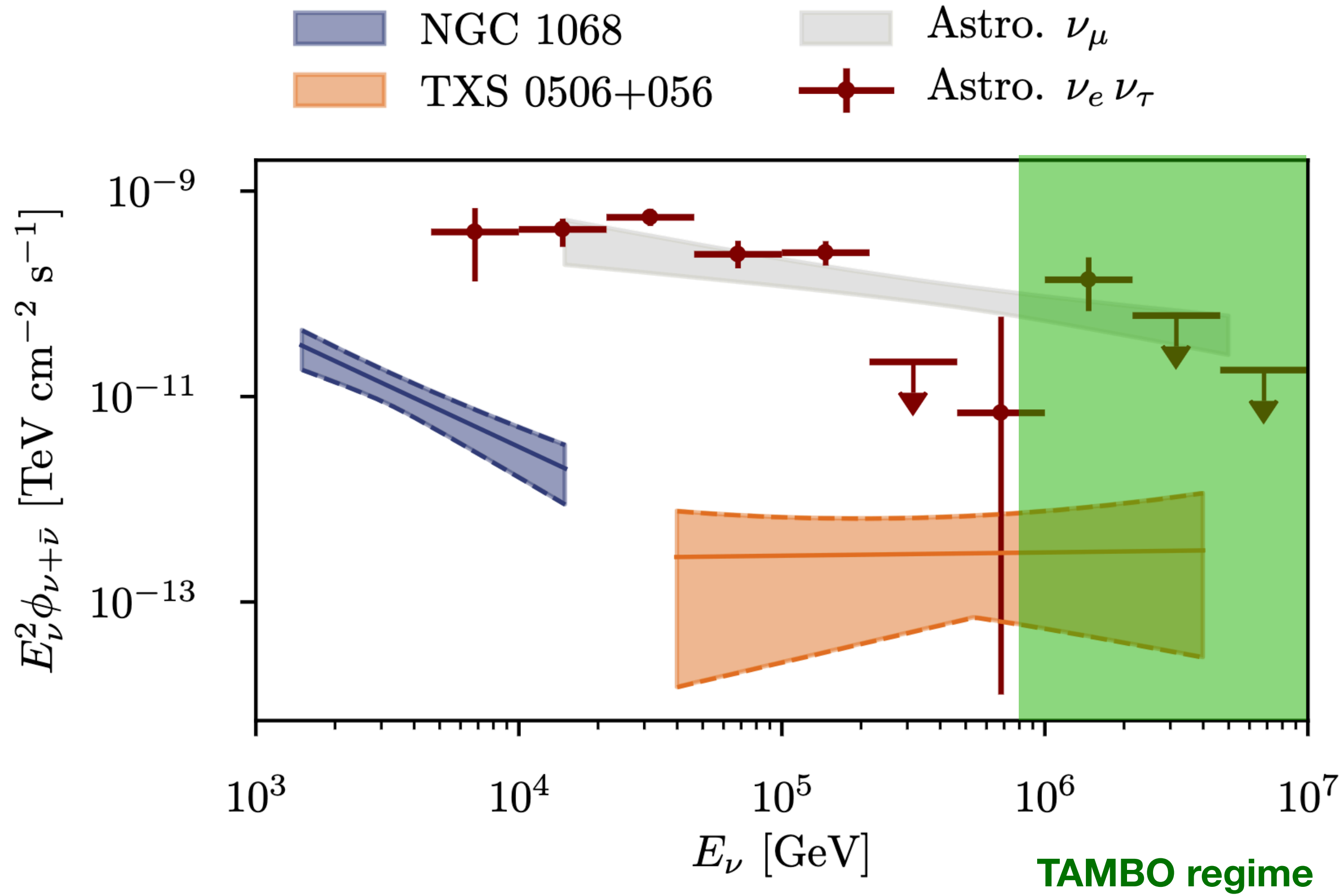
# A $\nu_\tau$ Sieve



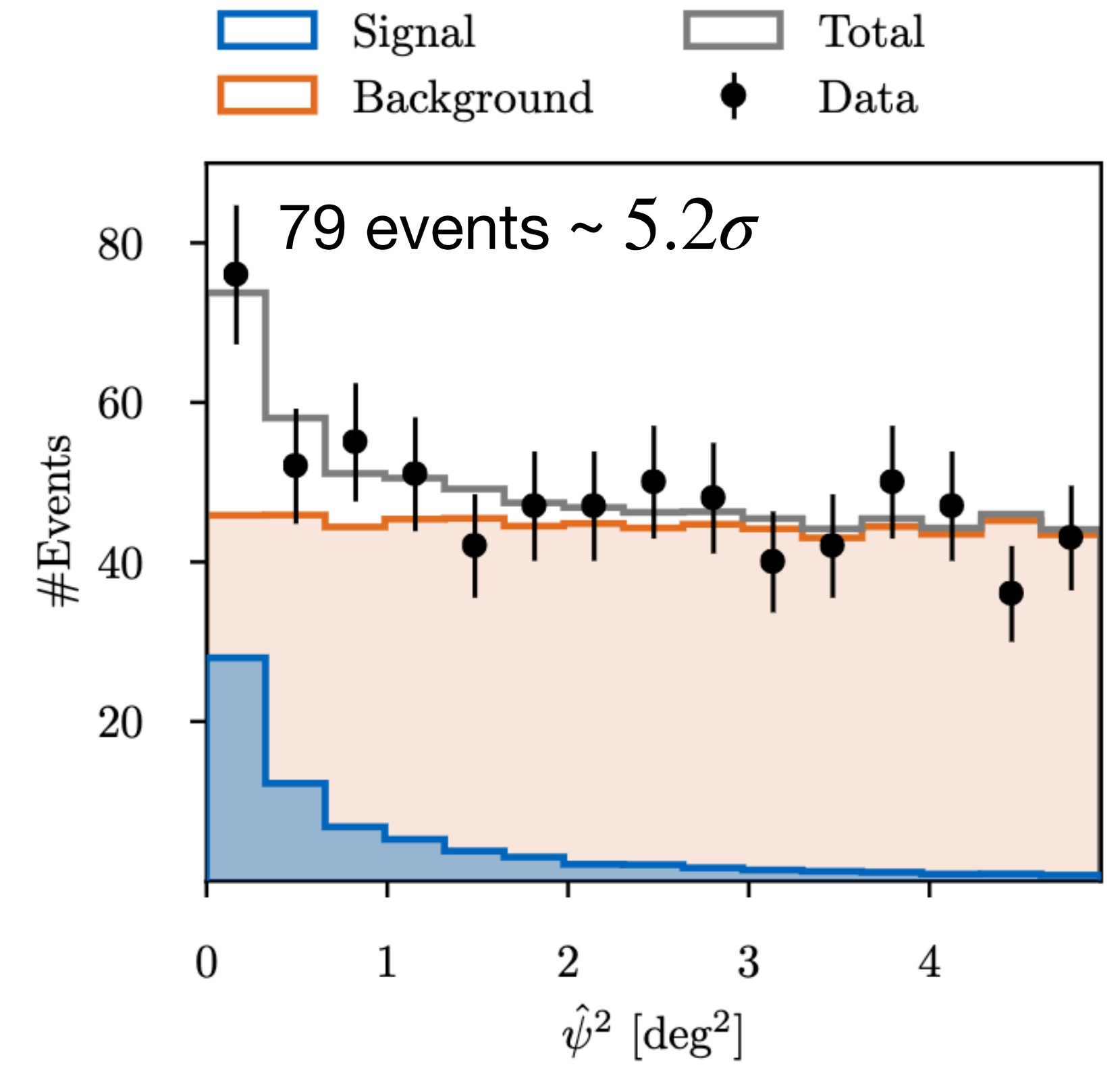
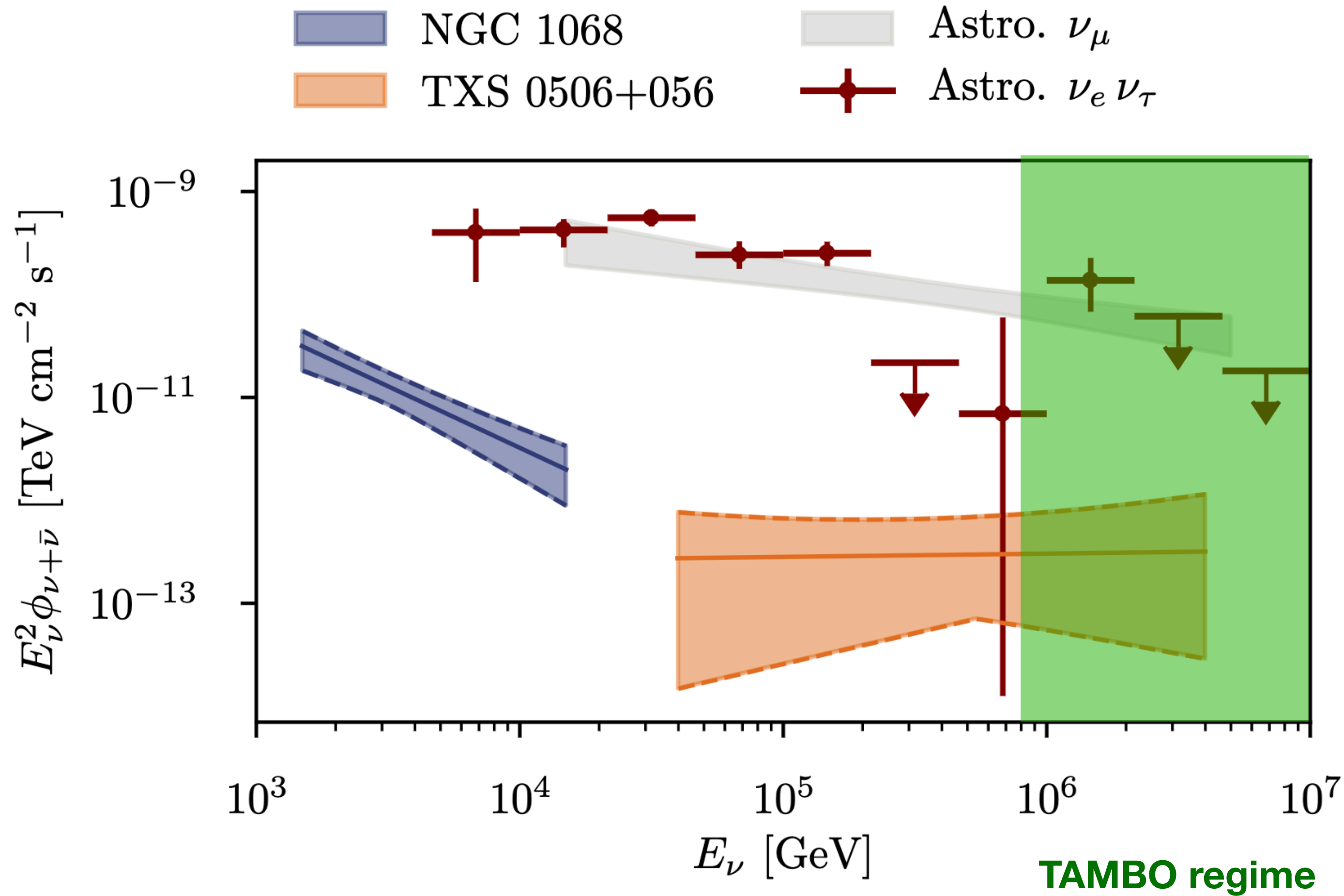
# A $\nu_\tau$ Sieve



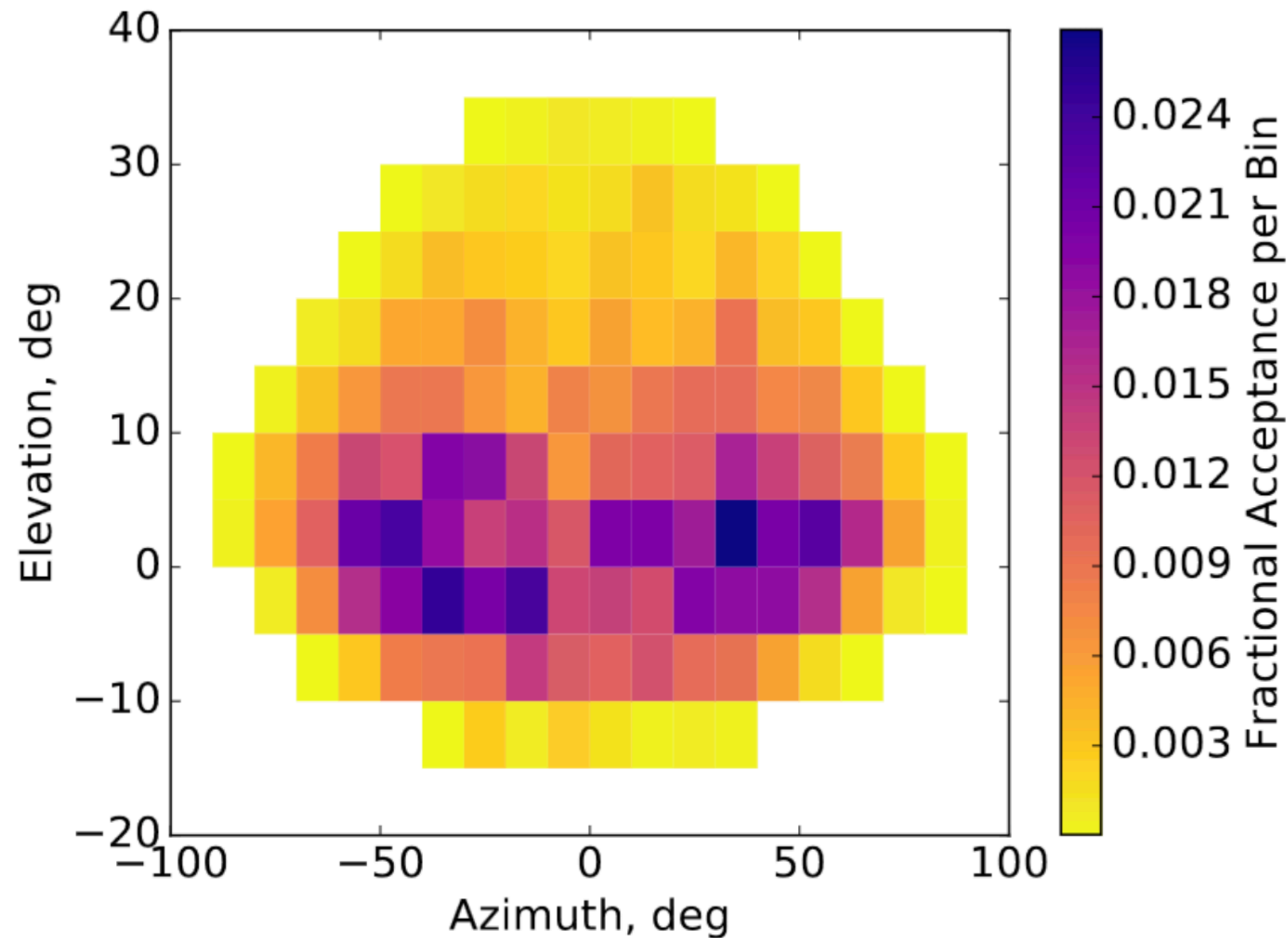
# Reminder: Power-Law Sources



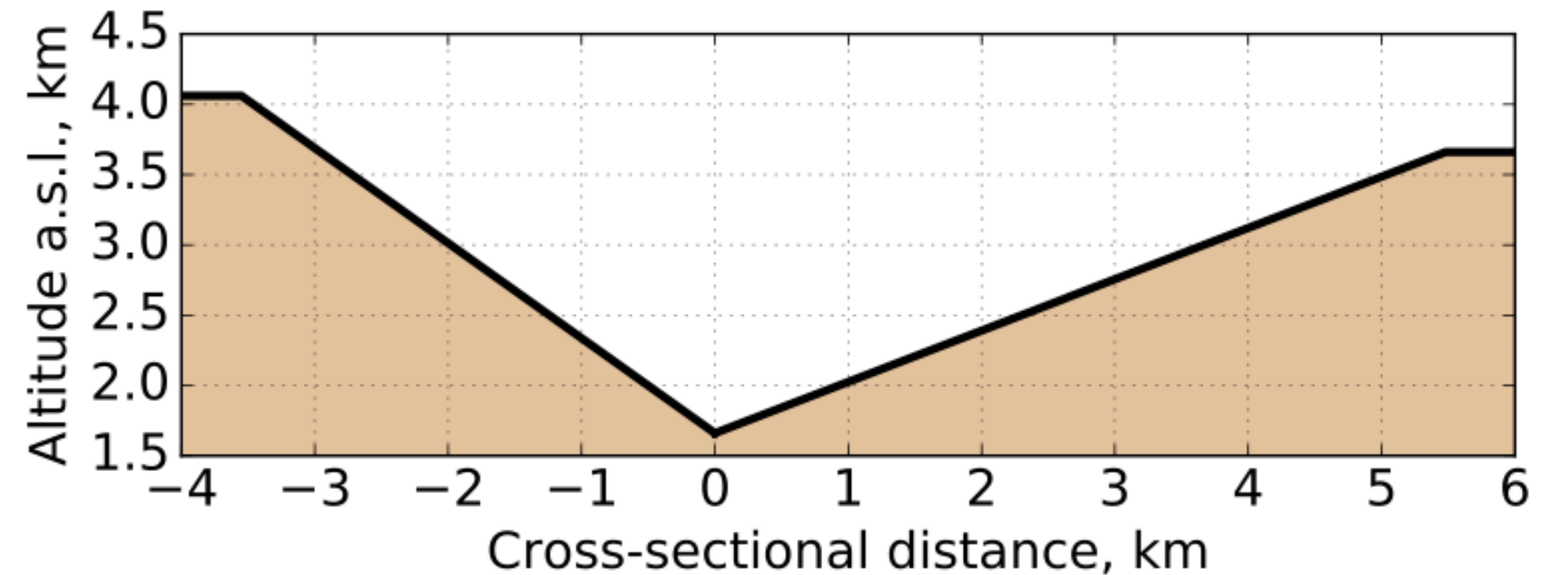
# Reminder: Power-Law Sources



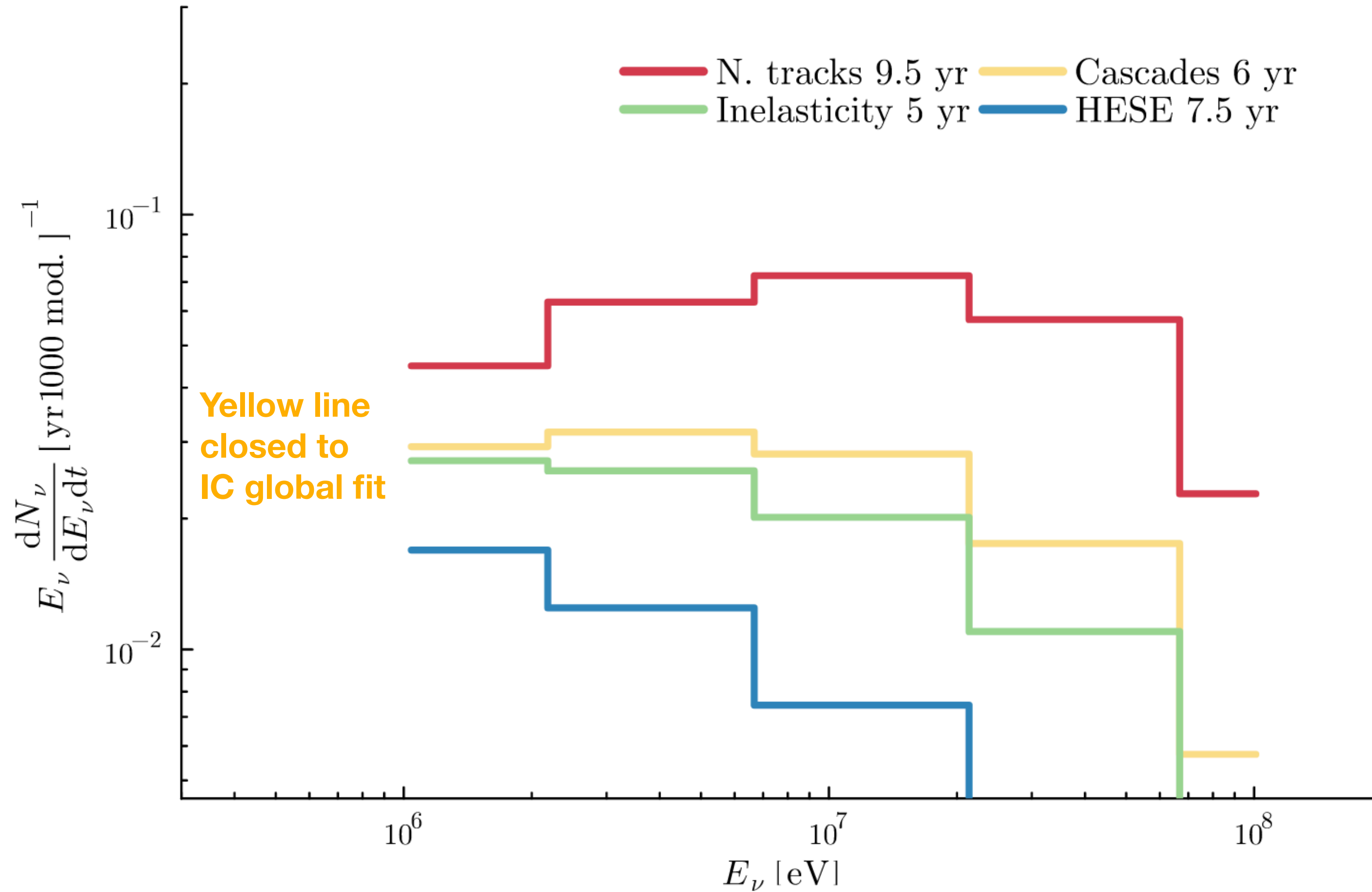
# An Initial Estimation



- 22\_000 Cherenkov water tanks with 150m interdetector spacing
- Triggering procedure to reject major background of coincident atmospheric muons

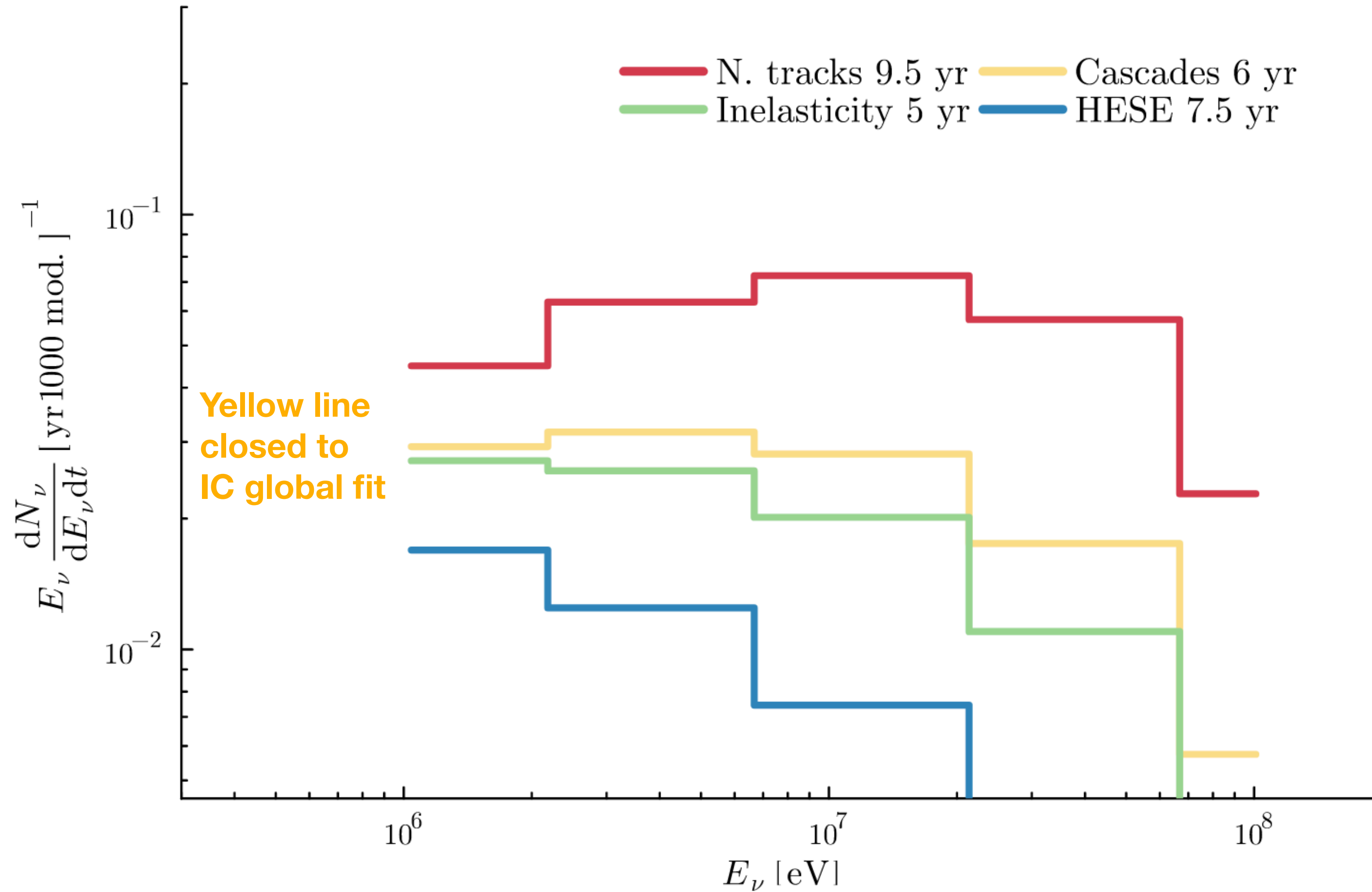


# An Initial Estimation



Conservative estimates and analytical approximations showed that we should expect between **0.27 and 0.04 detections per year per 1,000 detectors**

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Higher events rates incoming

# Site Selection Trip

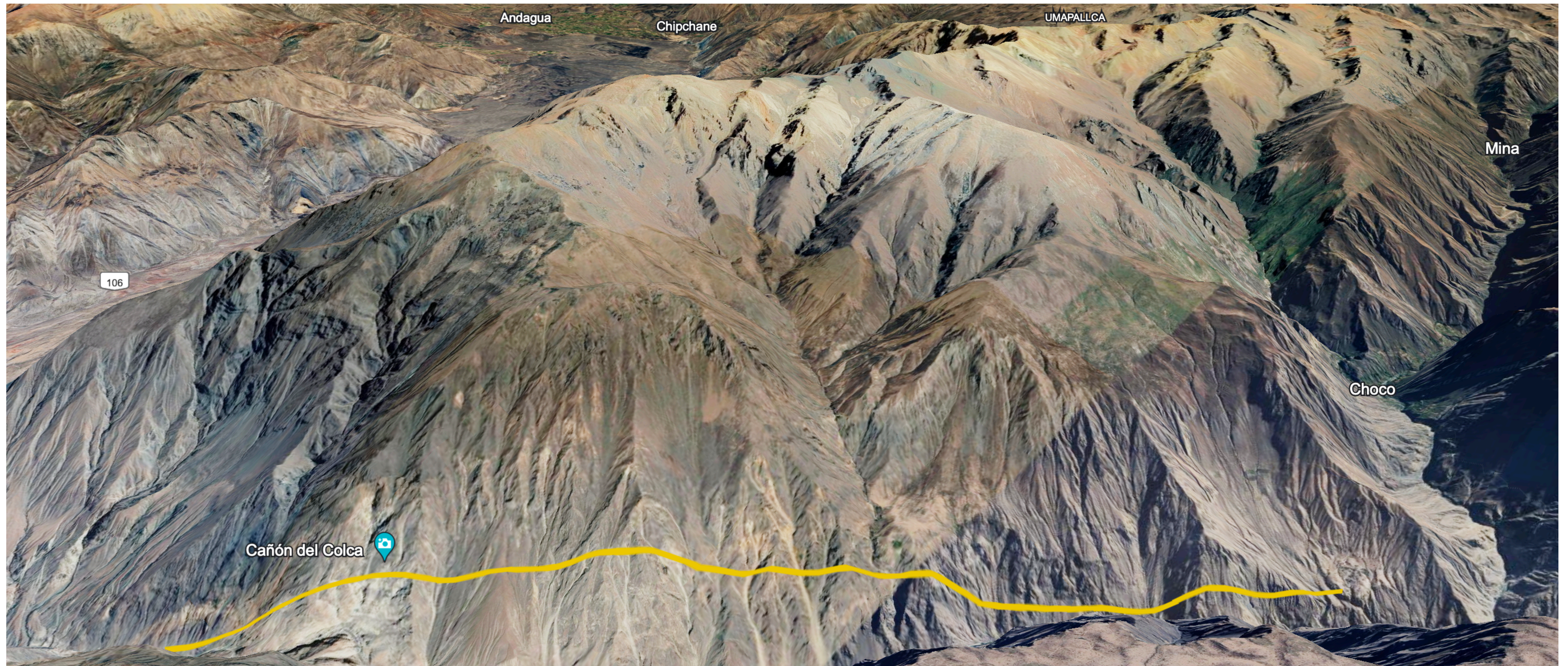


- A few of us from Harvard went to the Colca Valley to look at sites and assess infrastructure
- The planned site is very far out, but there are less remote places that are viable for a test array

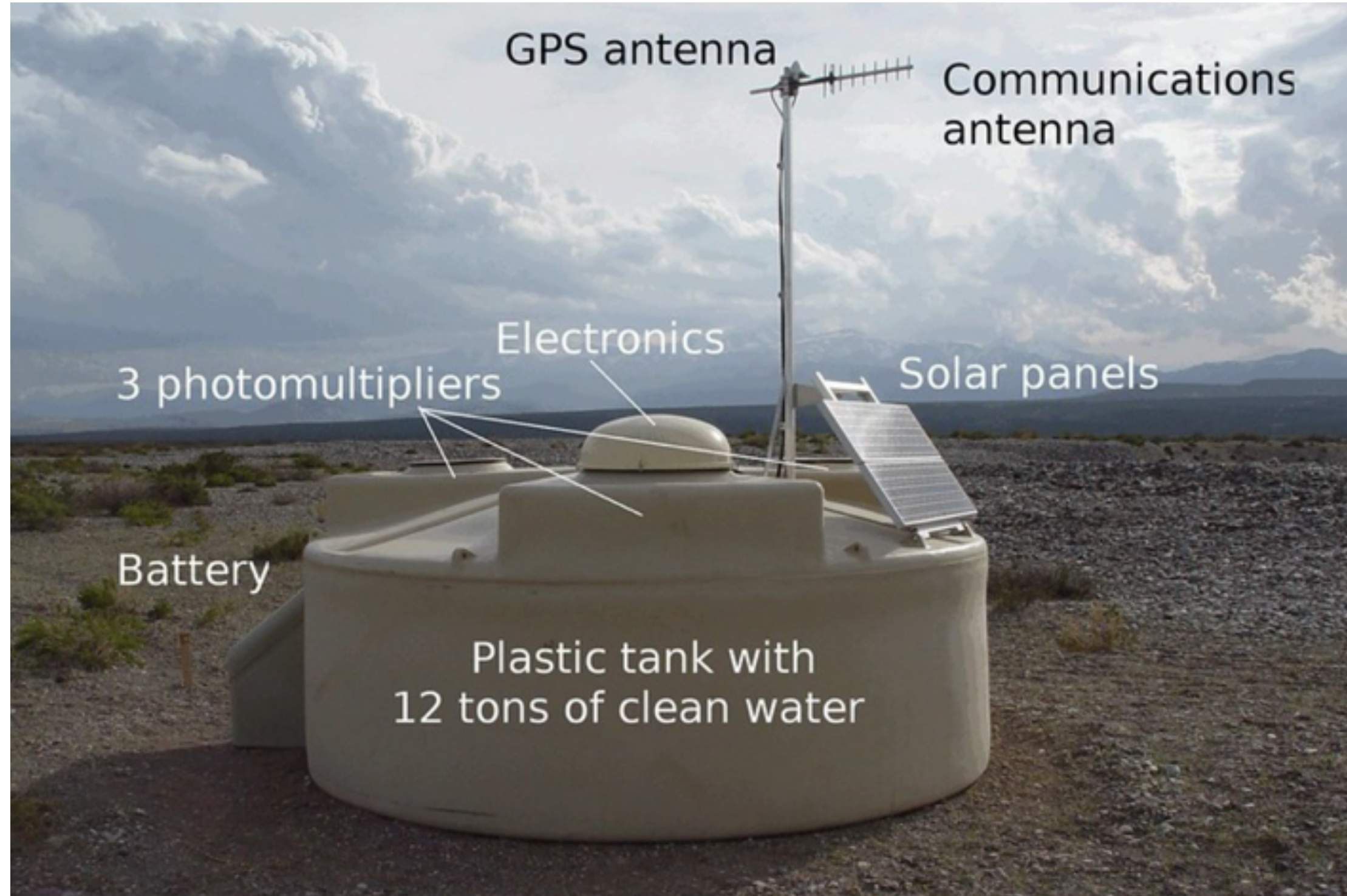
# Potential Test and Main Array Location



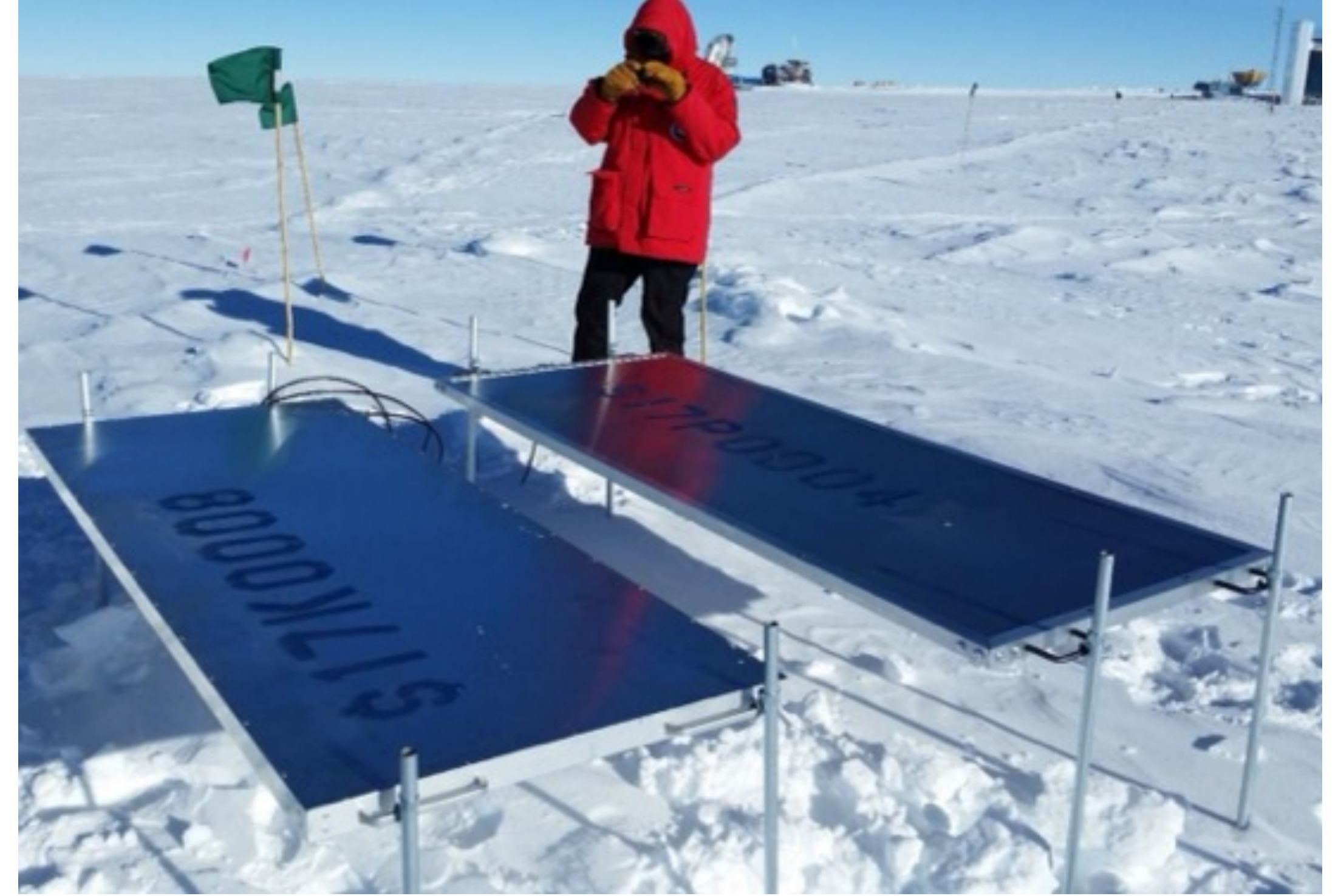
# Main Array Candidate Site



# Hardware Studies



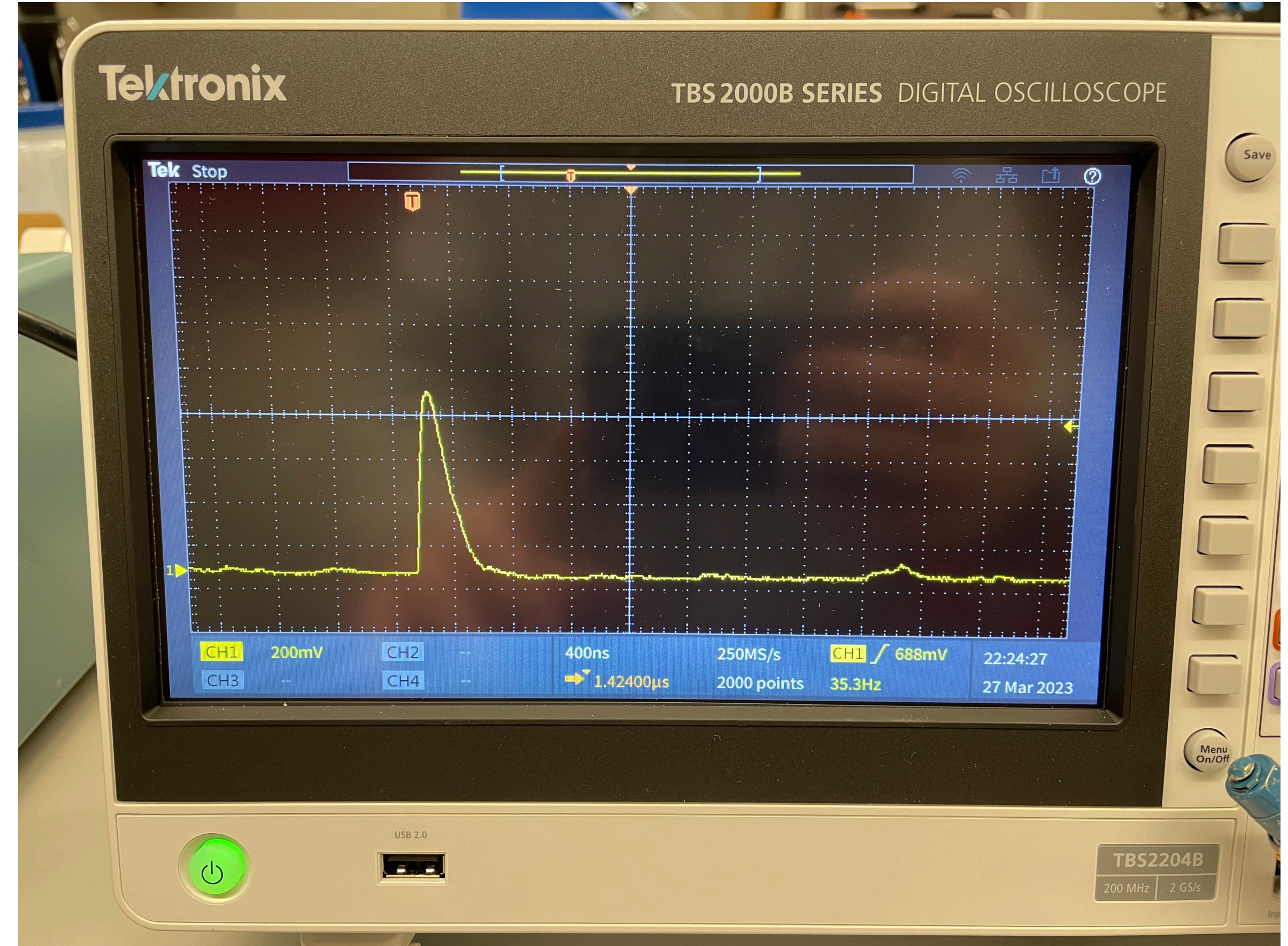
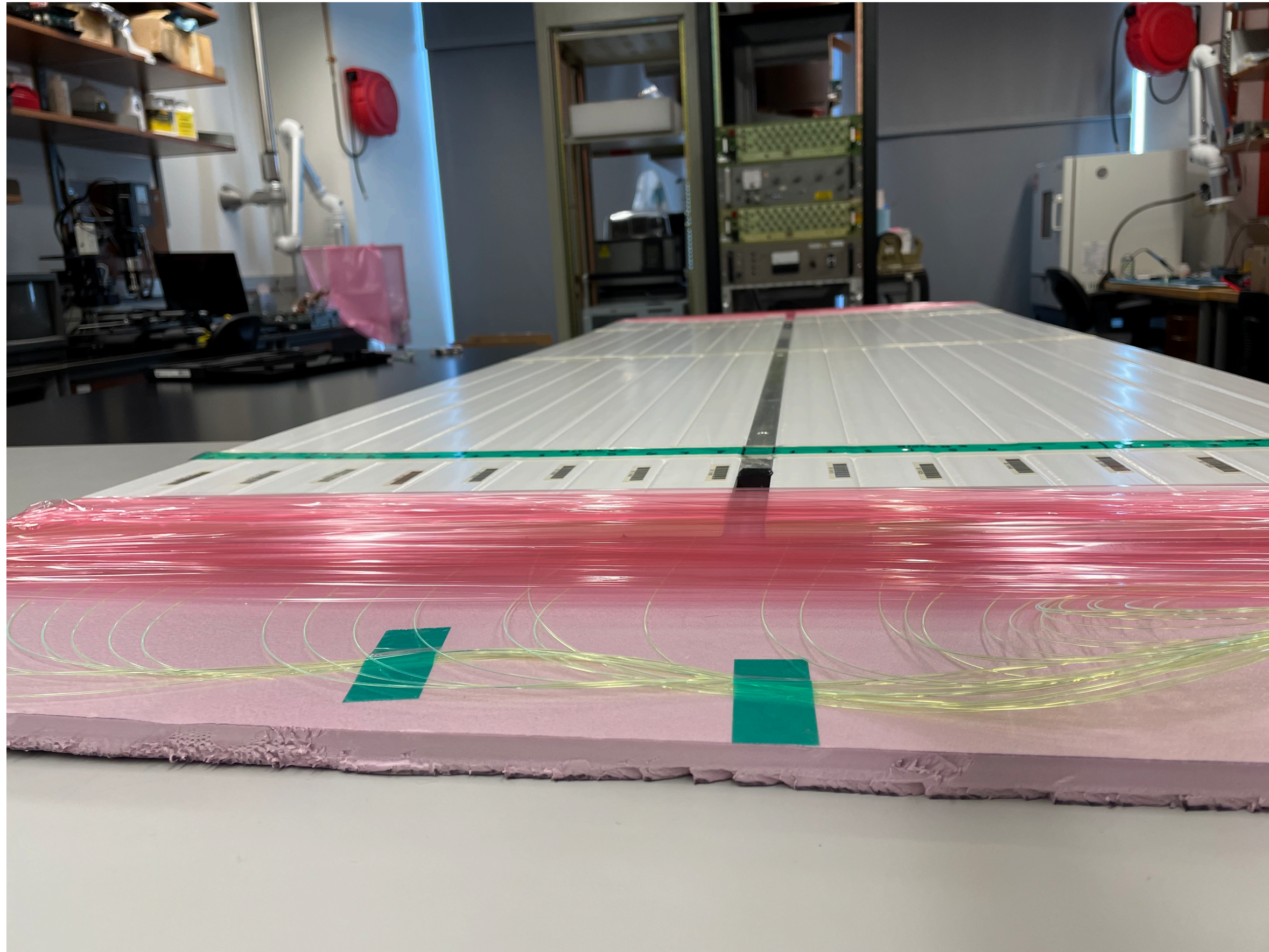
[Pierre Auger Collaboration, ICRC\(2021\)](#)



[IceCube Collaboration, EPJ Web Conf. \*\*210\*\* \(2019\)](#)

- Observatory is an array of thousands of individual detectors
- Two designs under consideration:
  - Water Cherenkov tanks → very well understood but heavy and expensive
  - Plastic scintillator panels → less well understood but 20x lighter and 2x cheaper

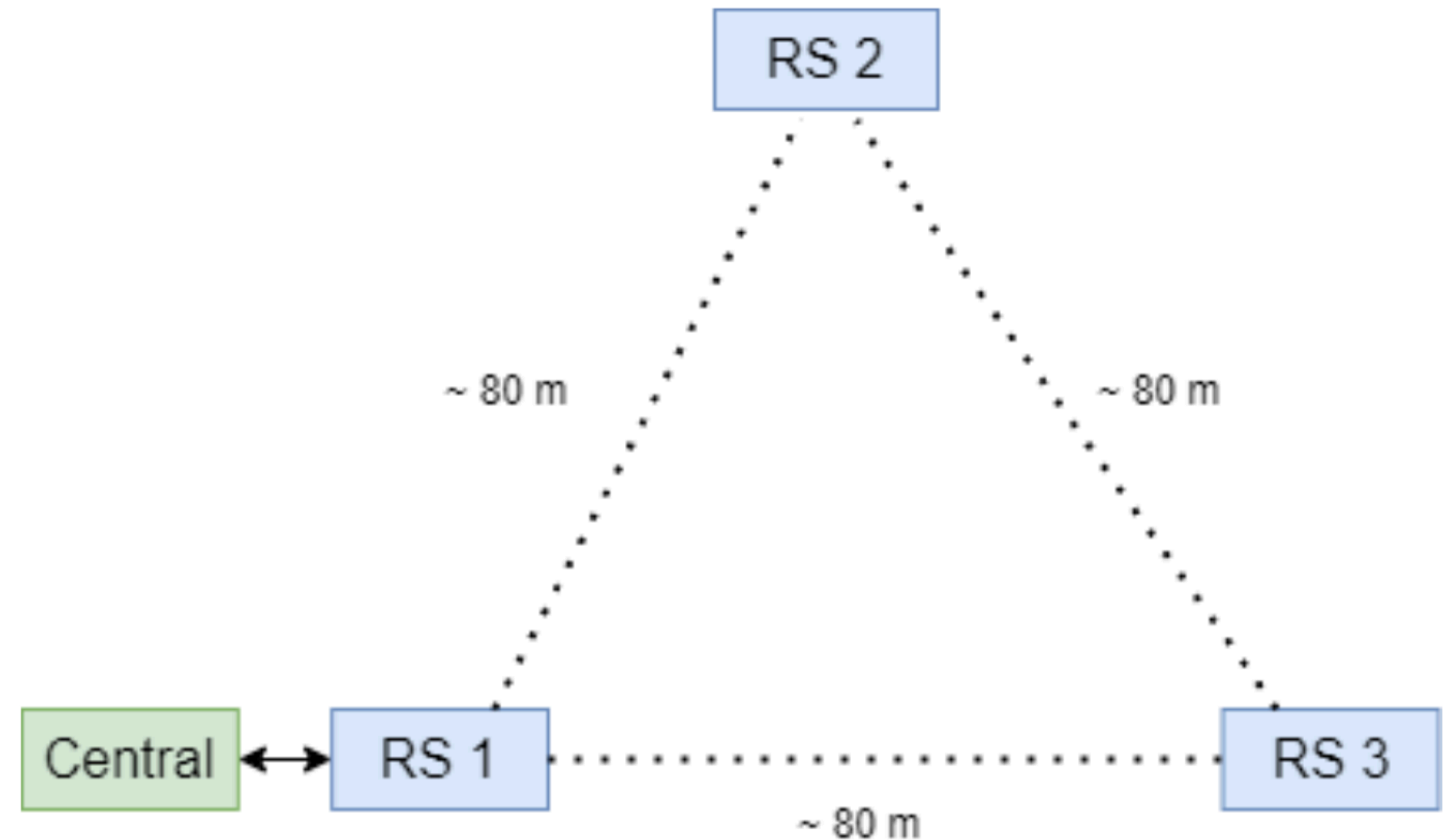
# First Light from Cosmic Rays



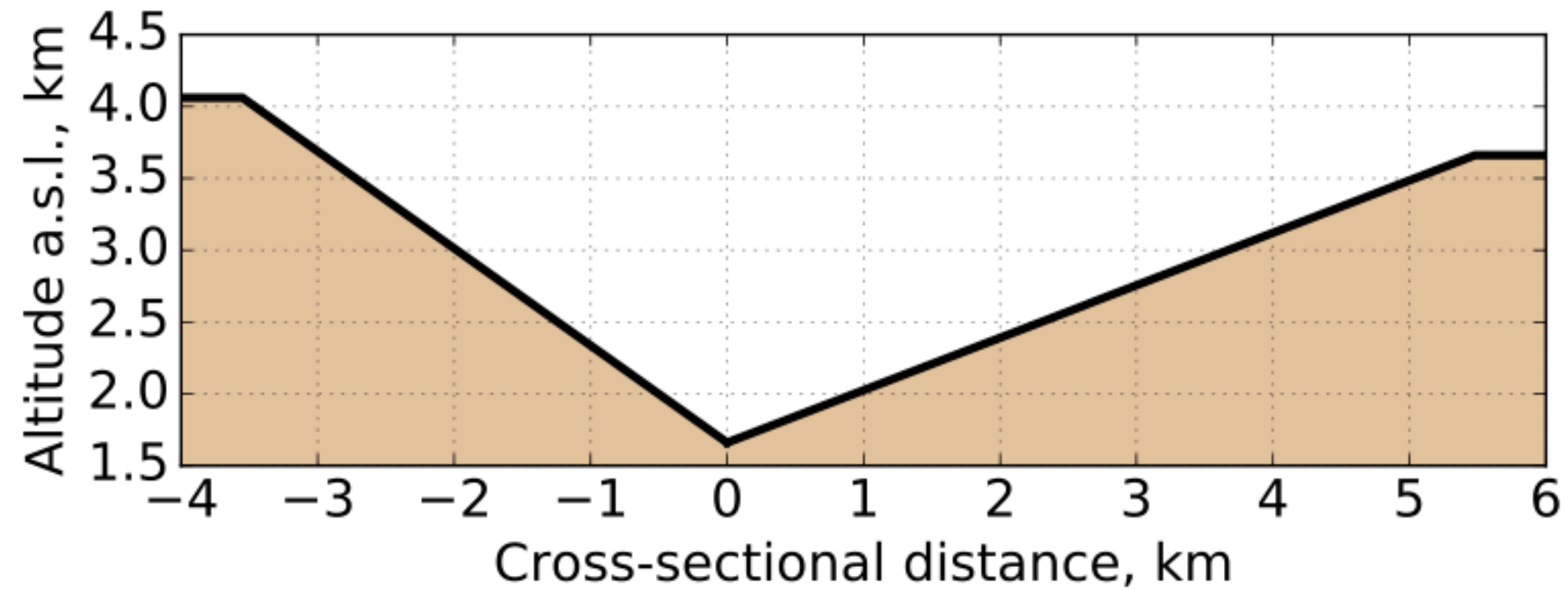
- First light from scintillator panels at Harvard
- Enough material to build 10 panels in total, which we expect to have by the end of the year

# A First Proof of Concept

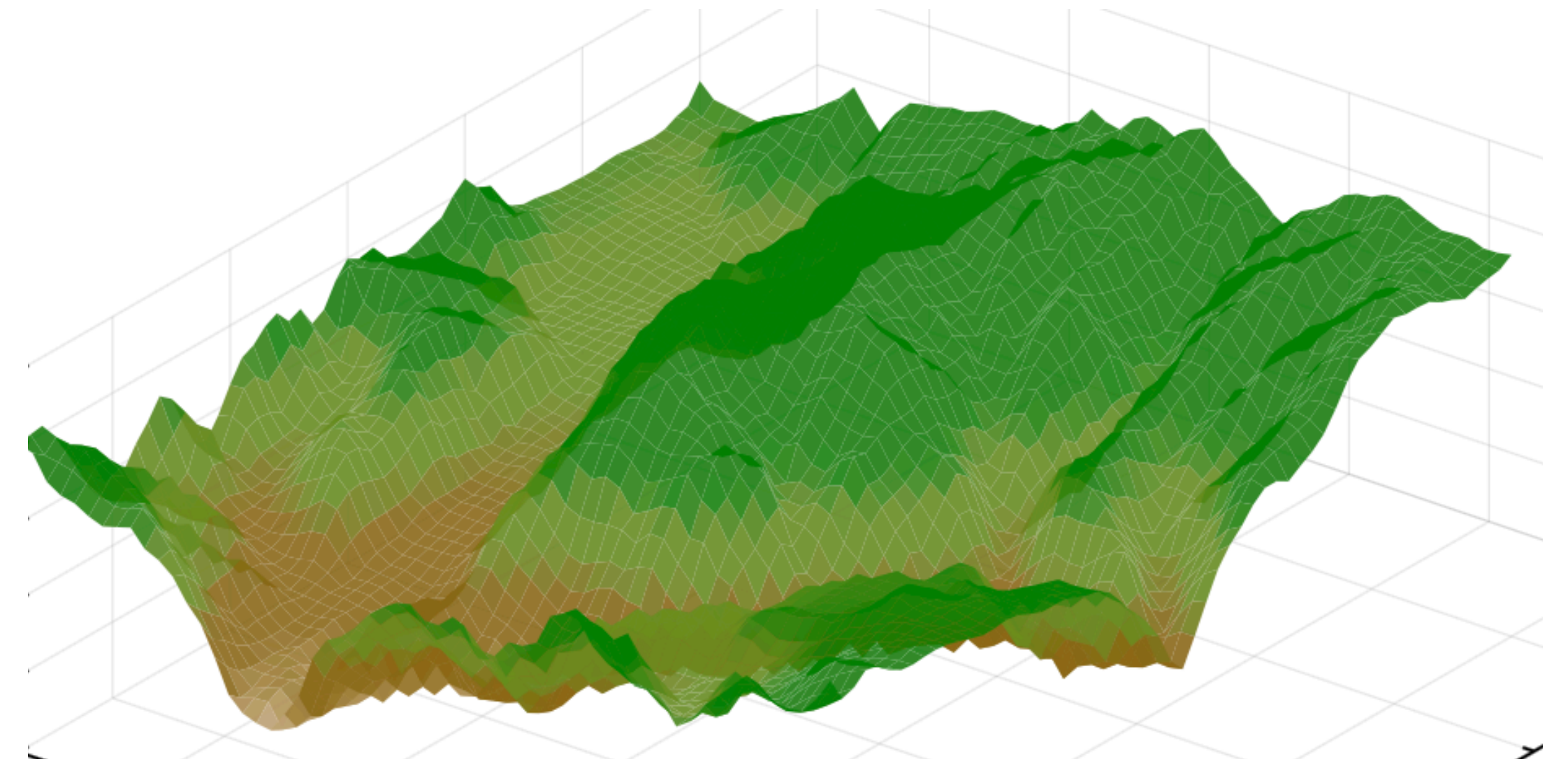
- A small, three station deployment in Lima will allow us to test:
  1. Inter-module communication
  2. Synchronisation protocol
  3. Data acquisition and management
- It *may* be possible to identify air showers with this set up



# Towards a Full Monte Carlo

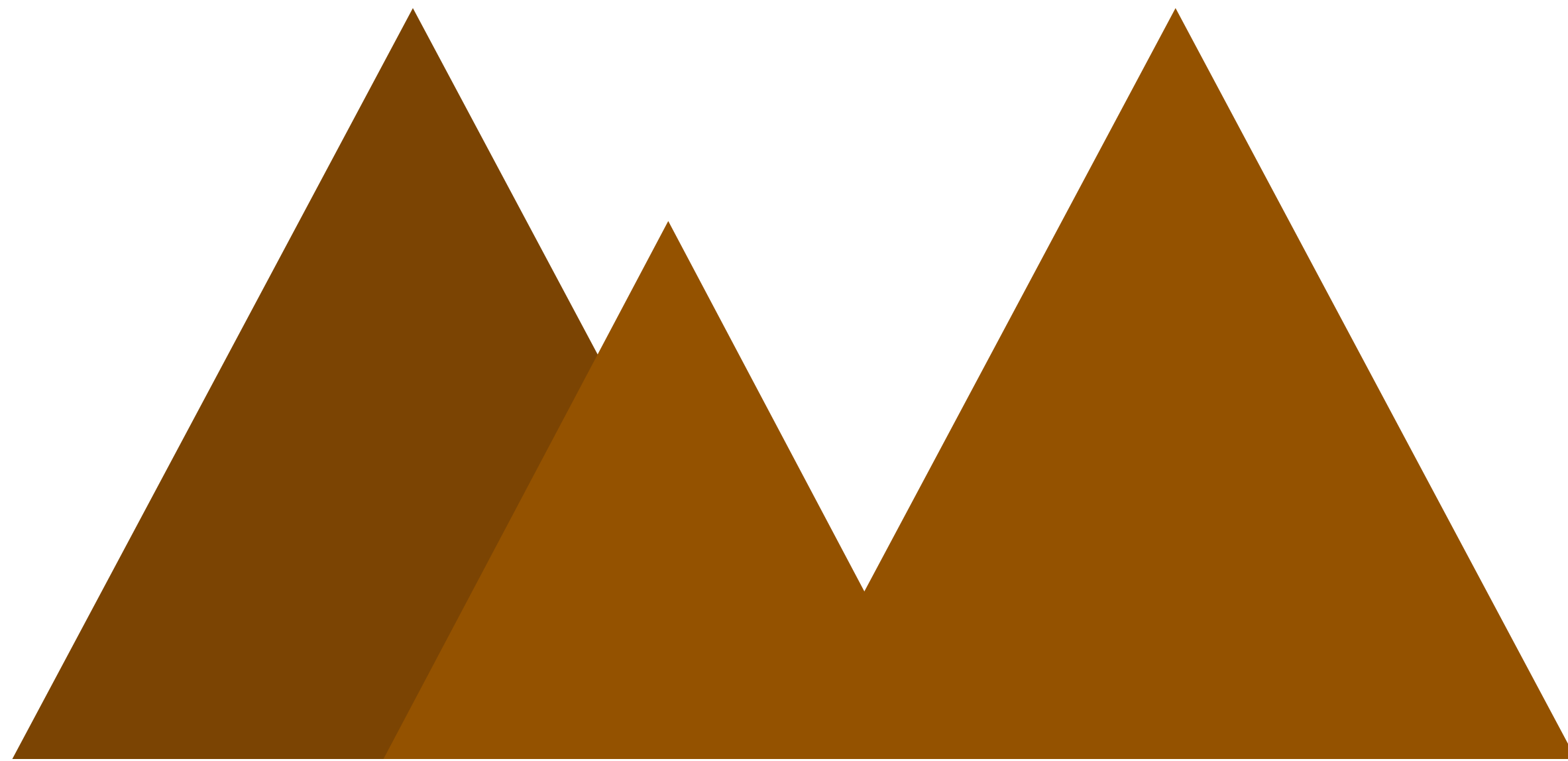


- Simplified geometry
- No treatment of  $\tau^\pm$  energy losses
- Approximation of air-shower physics



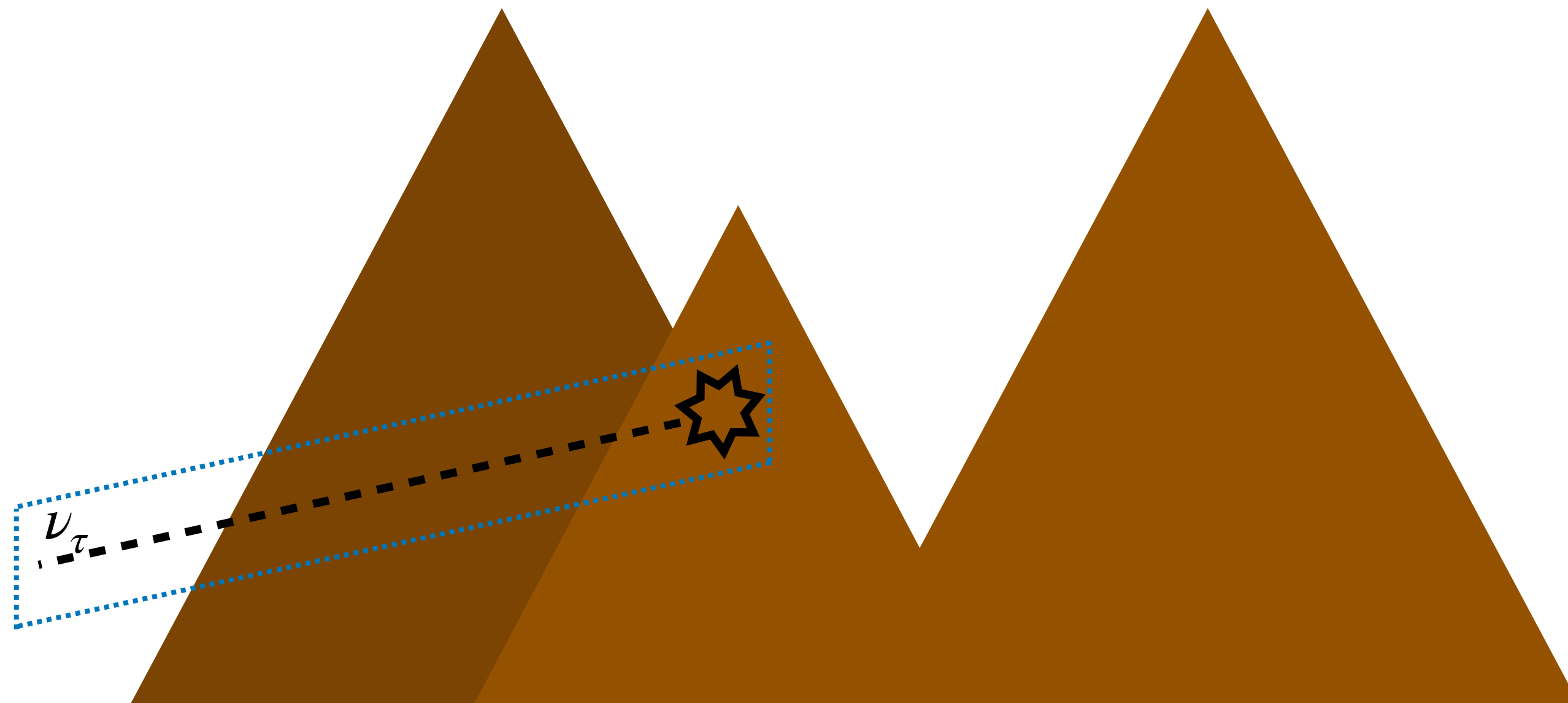
- Realistic valley geometry
- Full treatment of  $\tau^\pm$  energy losses
- (Less) approximation of air-shower physics

# Developing a Full Monte Carlo Chain

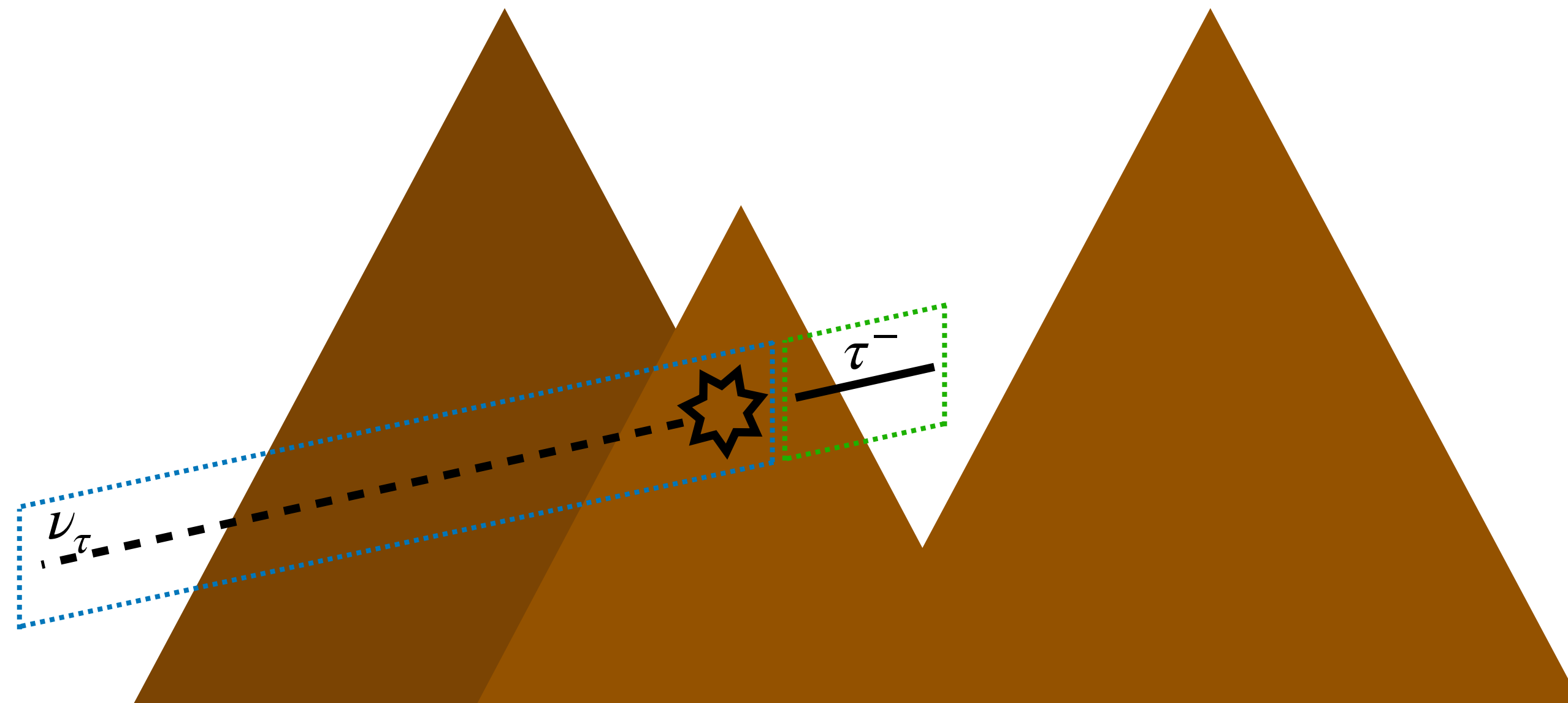


# Developing a Full Monte Carlo Chain

***Initial neutrino injection:*** Select initial neutrino properties, *i.e.* energy, direction, interaction vertex, *etc.*



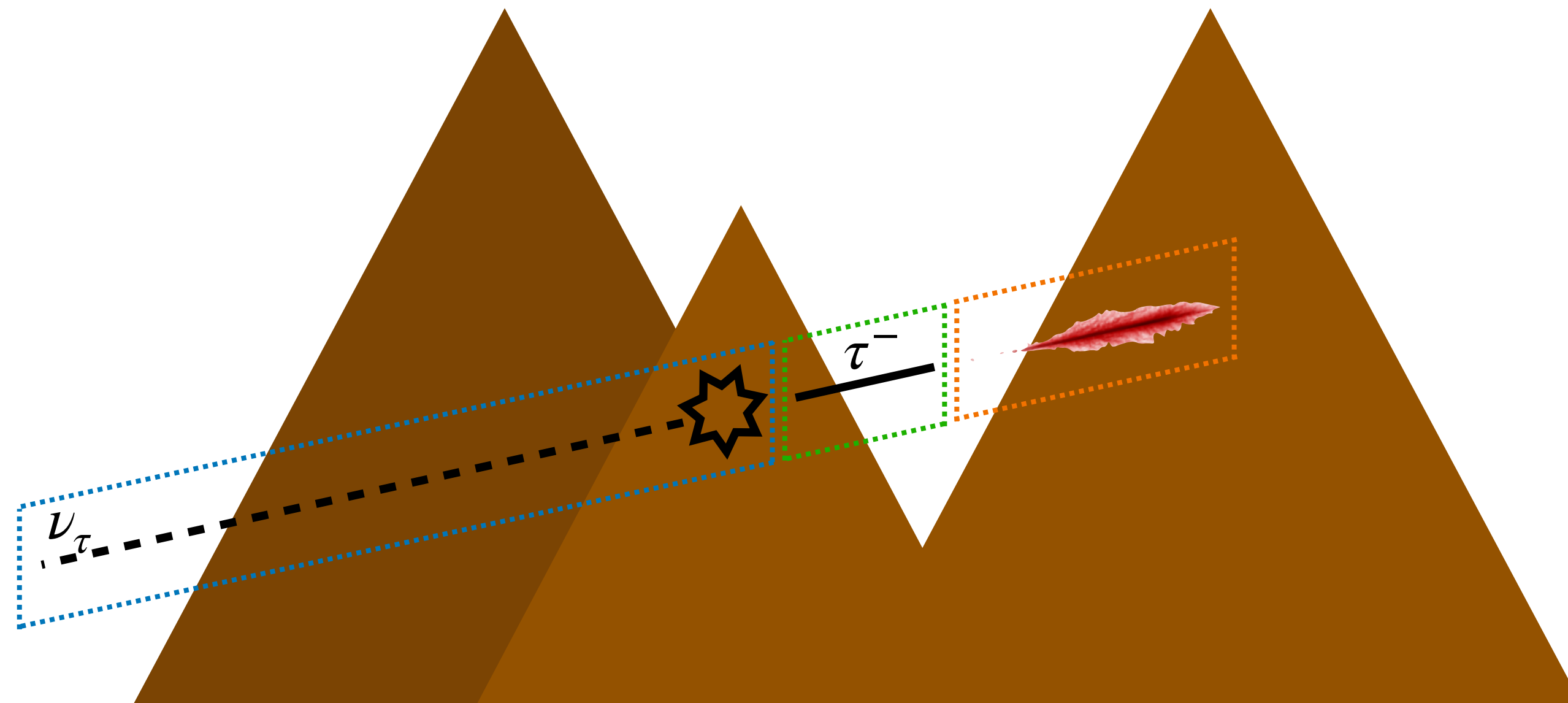
# Developing a Full Monte Carlo Chain



**Initial neutrino injection:** Select initial neutrino properties, *i.e.* energy, direction, interaction vertex, *etc.*

**Charged lepton propagation:** Propagate outgoing charged lepton, accounting for energy losses and decay, to find decay point

# Developing a Full Monte Carlo Chain

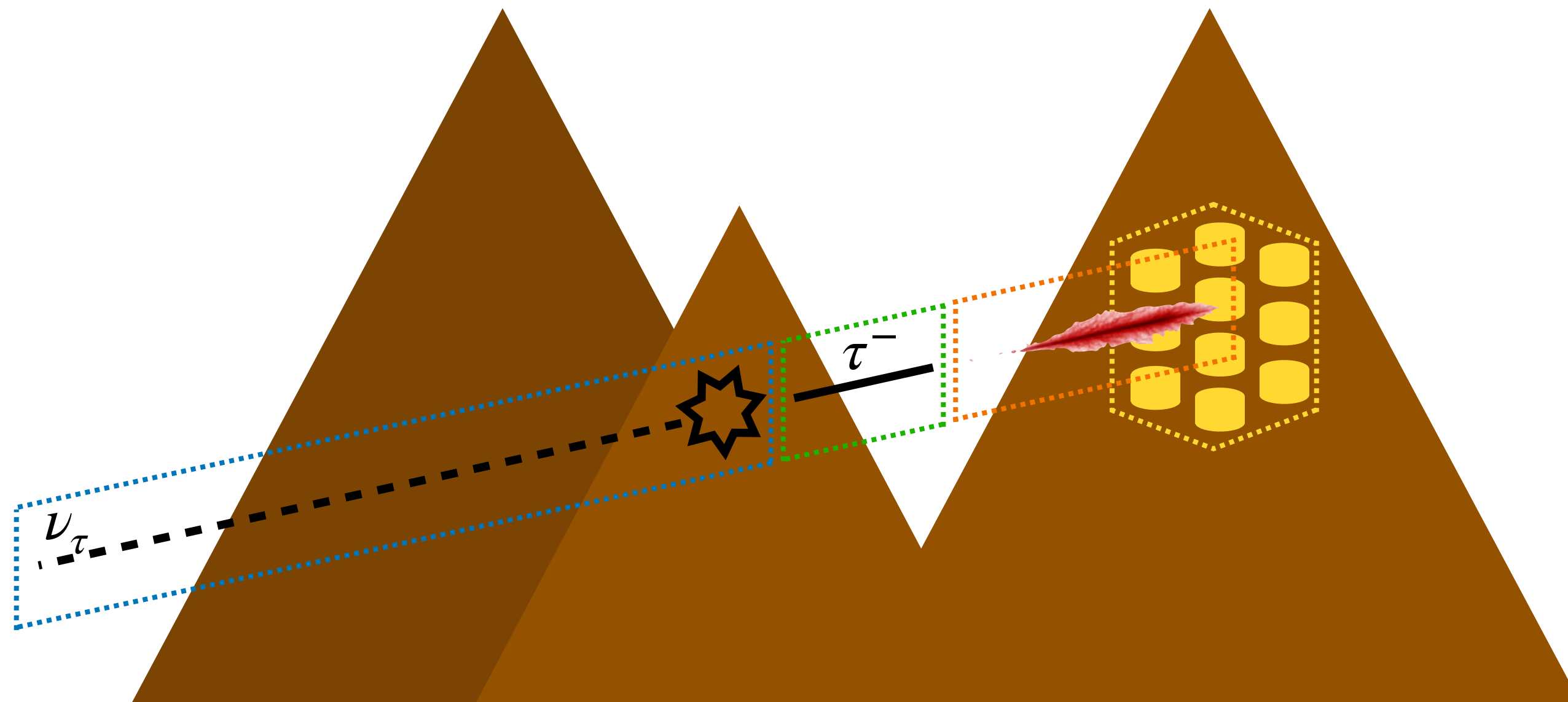


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# Developing a Full Monte Carlo Chain



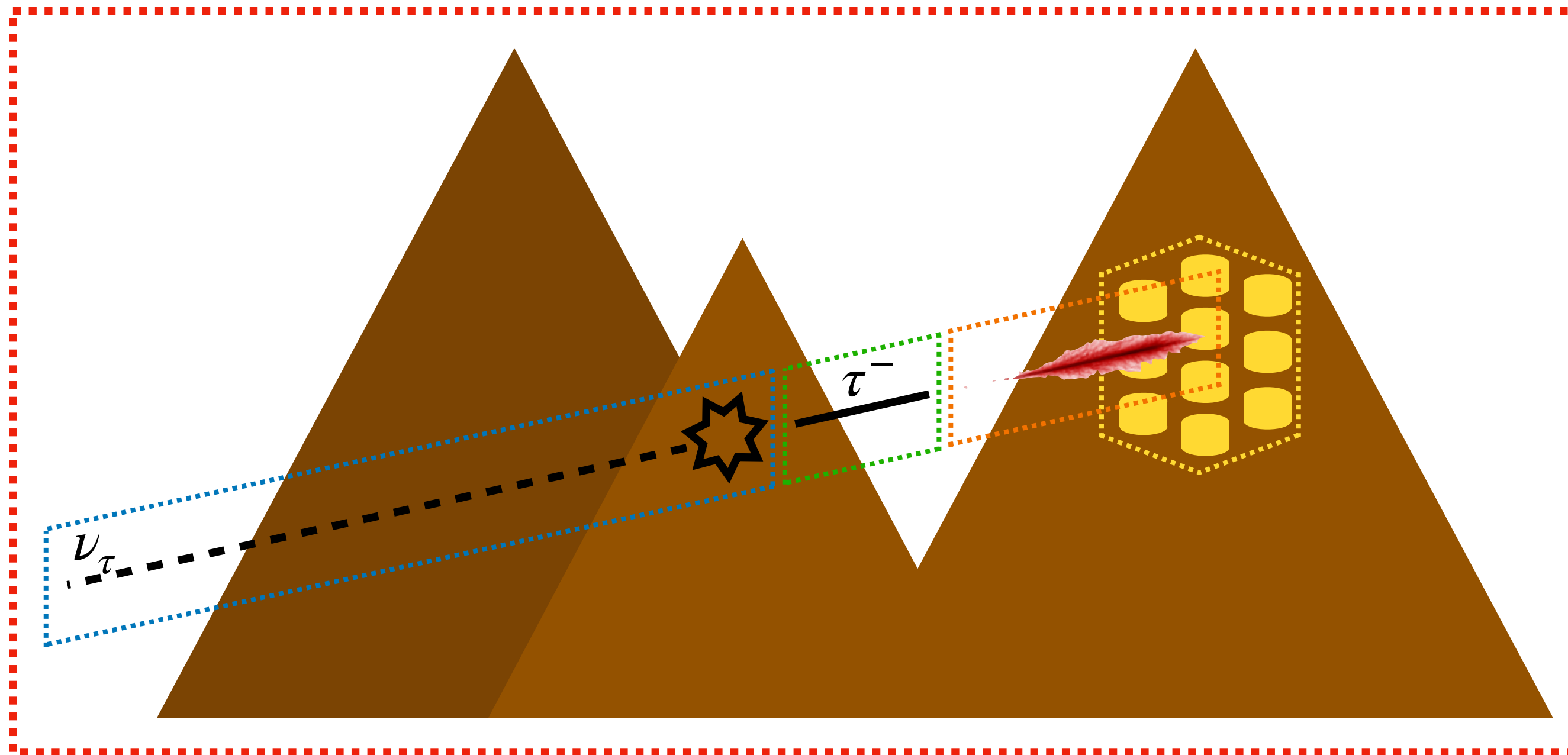
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# Developing a Full Monte Carlo Chain



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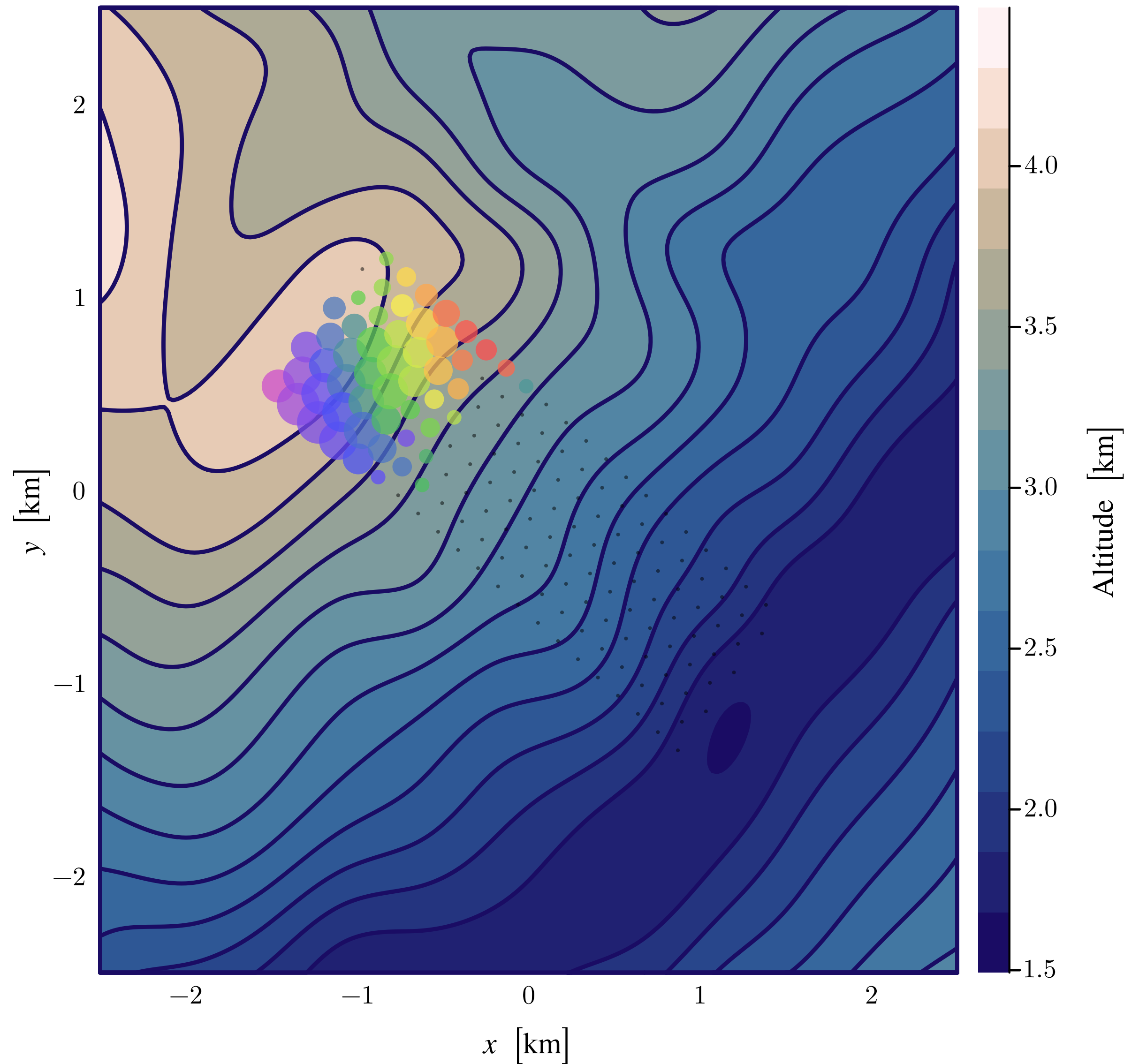
**Charged lepton propagation:** Propagate outgoing charged lepton, accounting for energy losses and decay, to find decay point

**Air-shower simulation:** Model shower development from lepton decay

**Detector response:** Simulate internal hardware to model what we will see

**Event weighting:** Remove unphysical remnants from selection of initial neutrino properties

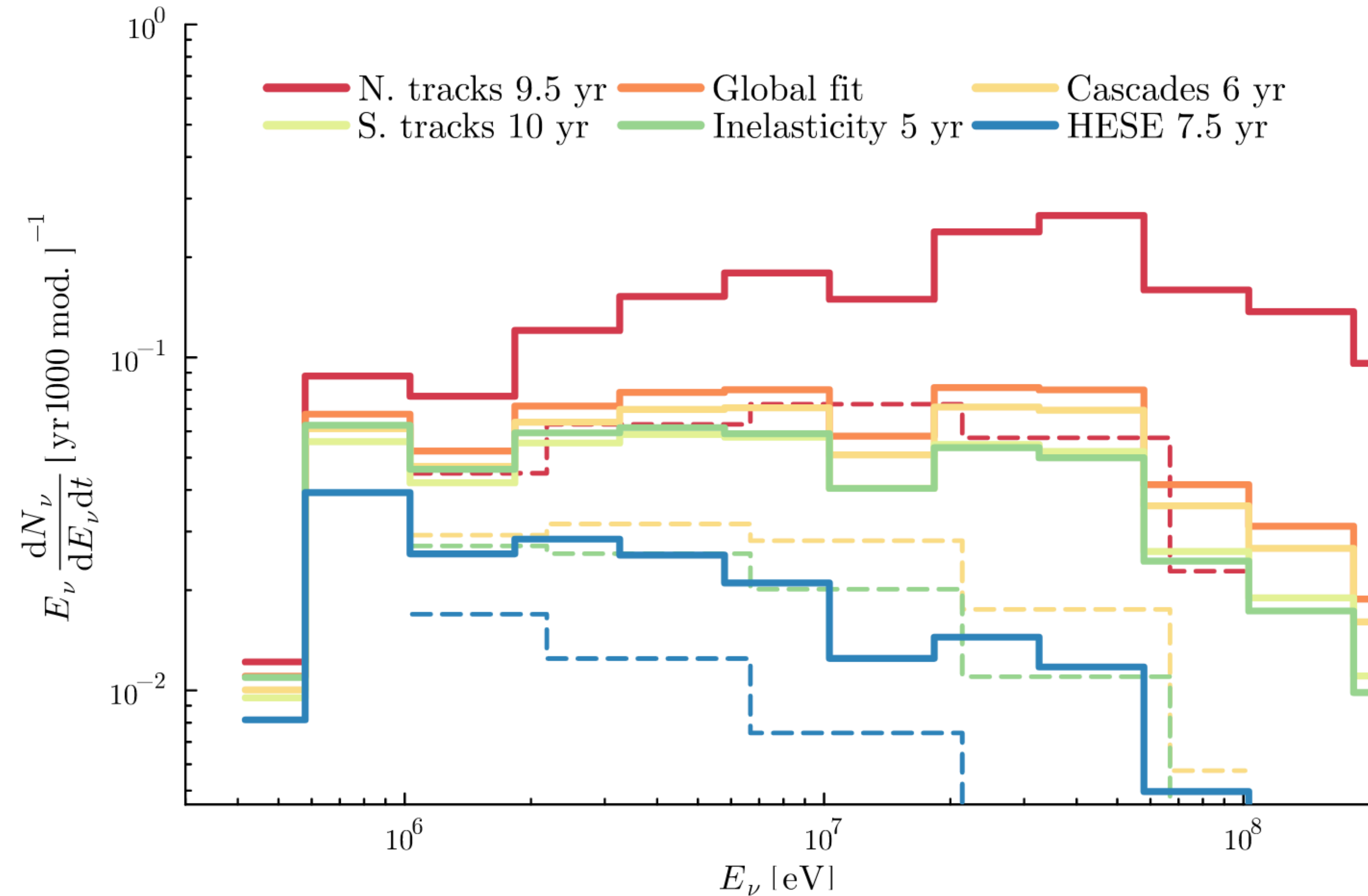
# Full Timing Information



- In addition to more accurate rate predictions, full MC enables:
  1. Pretty event displays
  2. Reconstruction development
- We are currently working with GraphNeT developers to make a preliminary reconstruction

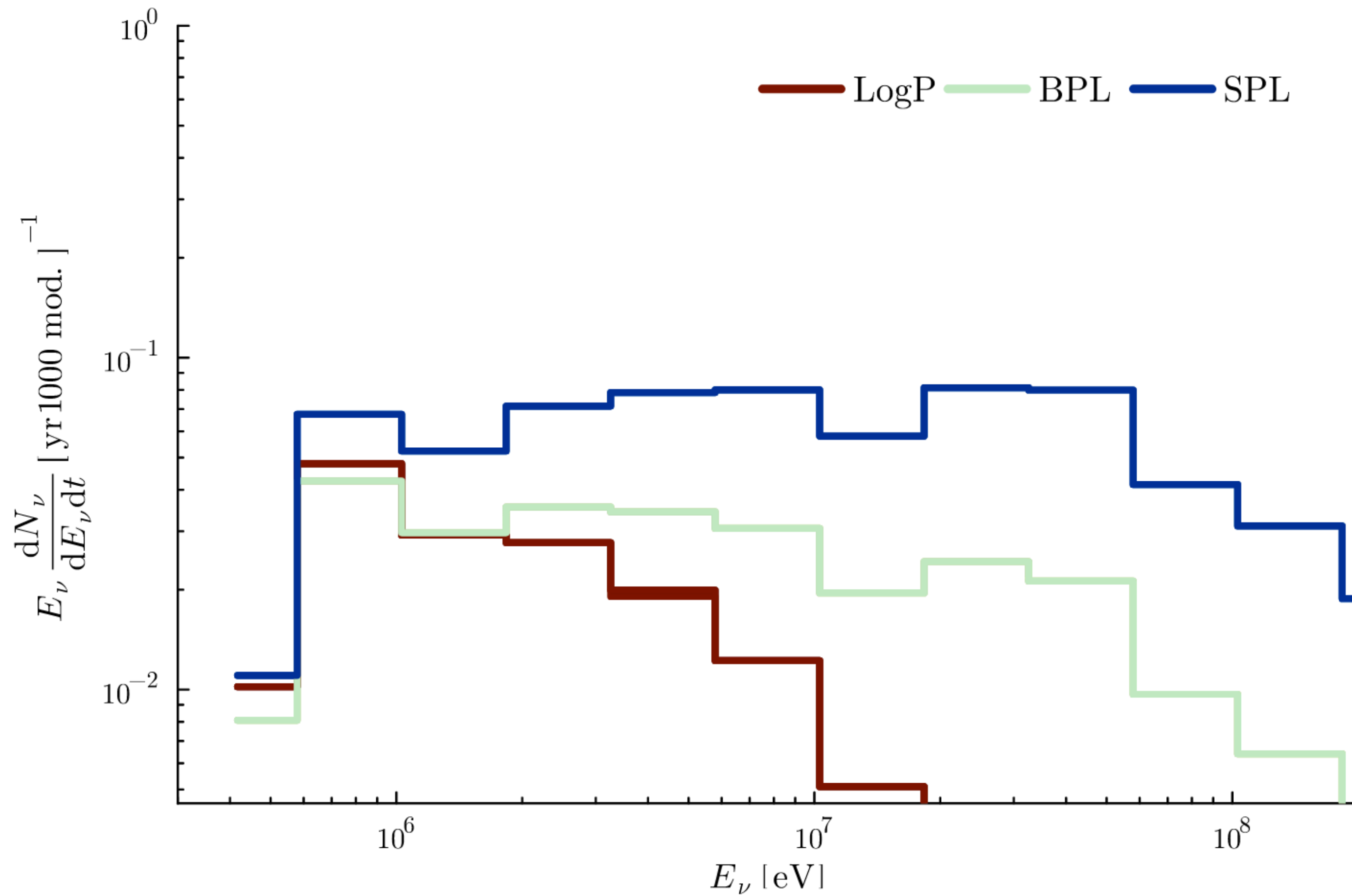
# Updated Event Rates

Solid: Updated MC prediction  
Dashed: Initial estimation



- Rates from the new calculation higher than initial estimation by a factor of ~2-3
- This ratio grows at the highest energies

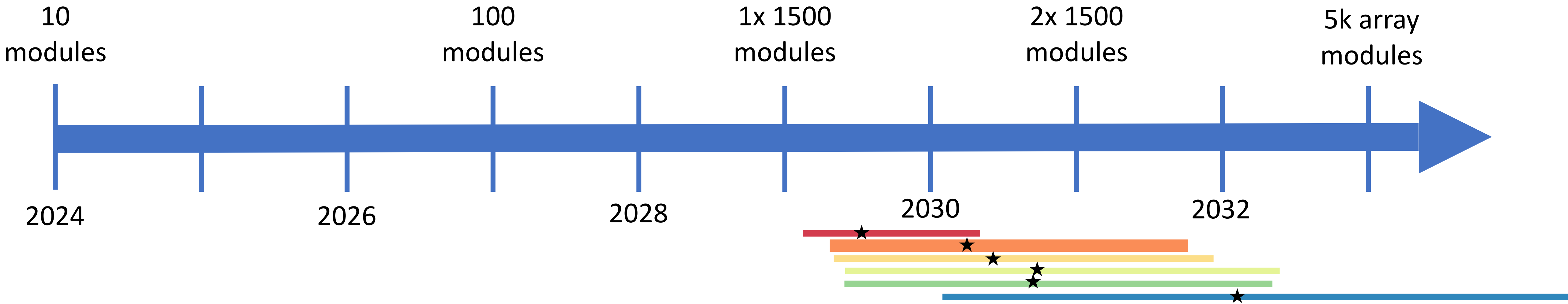
# Event Rates from Different Spectra



- In three years of data-taking on a 5000 module detector, we will be able to reject the SPL at  $> 3\sigma$

# Tentative Timeline

- Initially deploy ~10 modules for detector R&D
- Follow with ~100 modules for array R&D
- Full array could be deployed in 1500-module segments



# Commitment to Equity through Particle Physics

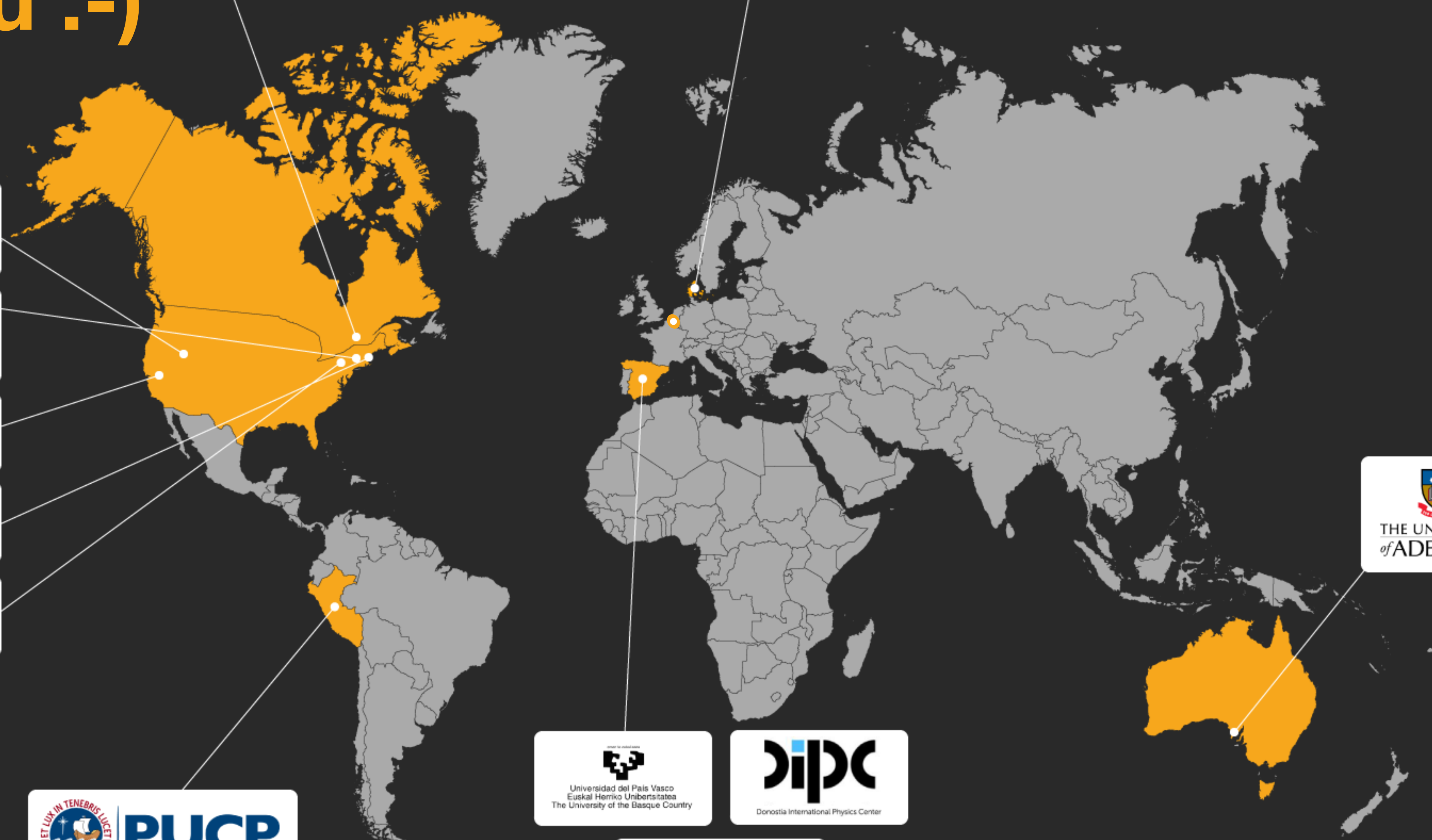
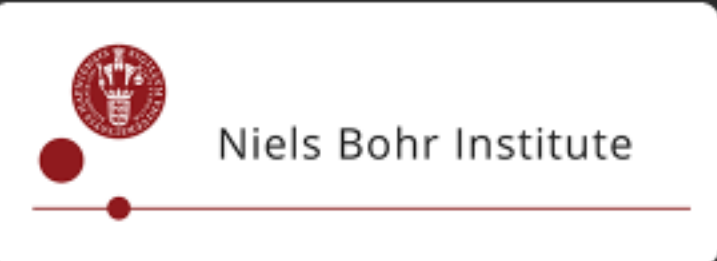
- Met with the mayor of Chivay to discuss potential partnerships between the collaboration and the local community
- Recently held a workshop at the Harvard Radcliffe Institute to explore different sociological aspects of particle physics experiments in different cultural contexts



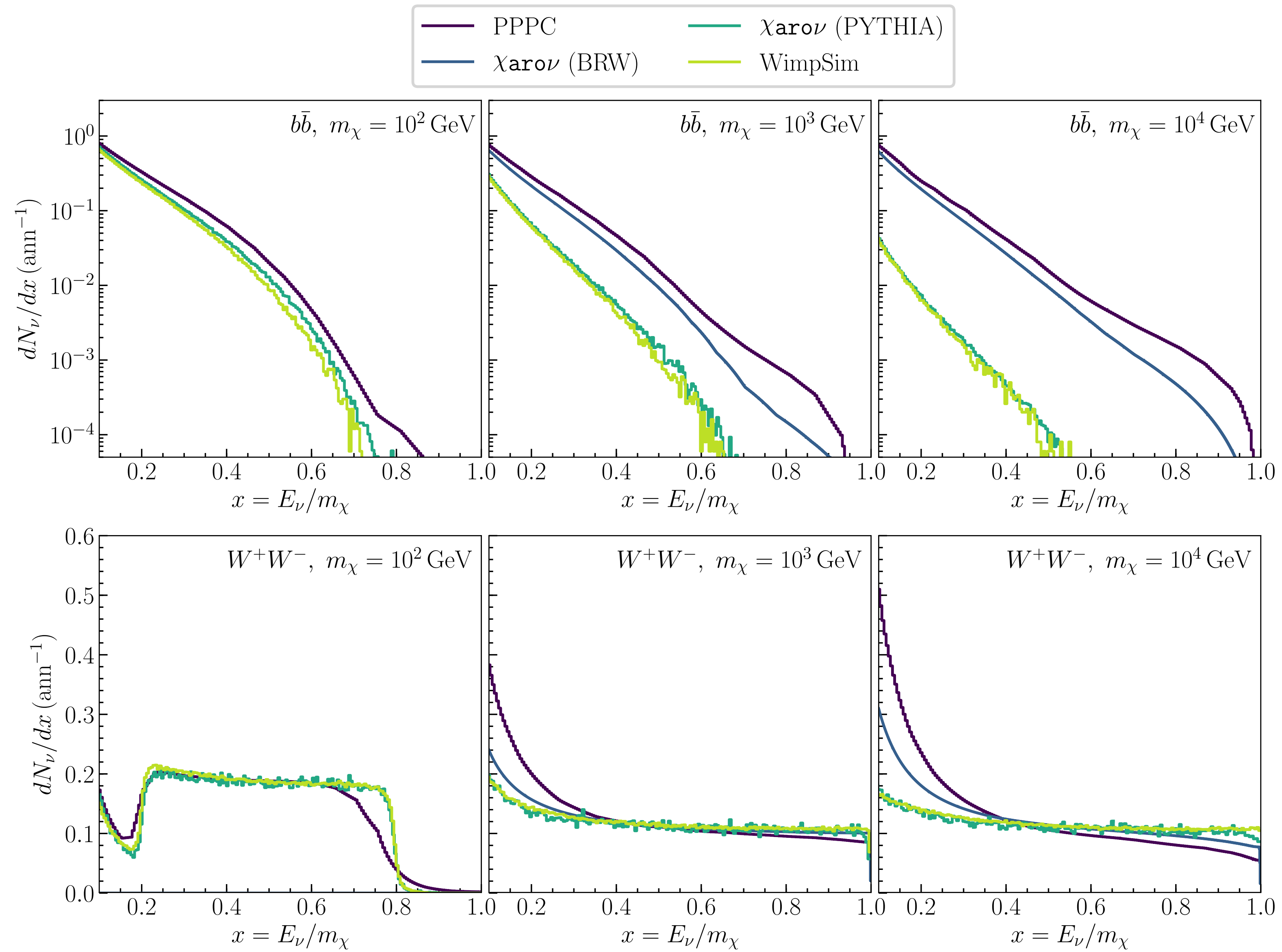
# Conclusions

- Neutrino telescopes have been crucial tools for understanding many areas of physics
- IceCube has opened the door to the neutrino Universe, with the most recent results showing the first evidence of galactic and extragalactic neutrino sources, world-leading limits on dark matter cross sections, and competitive results for neutrino oscillation parameters
- Neutrino telescopes that are sensitive to higher energy neutrinos, especially those in the energy range just above IceCube, will prove crucial to resolving some currently difficult problems

# Thank you :-)



# Backups



Reaction	Label	Flux ( $\text{cm}^{-2} \text{s}^{-1}$ )
$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$	<i>pp</i>	$5.95 \times 10^{10}$
$p + e^- + p \rightarrow {}^2\text{H} + \nu_e$	<i>pep</i>	$1.40 \times 10^8$
${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$	<i>hep</i>	$9.3 \times 10^3$
${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$	${}^7\text{Be}$	$4.77 \times 10^9$
${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$	${}^8\text{B}$	$5.05 \times 10^6$

